

H HEURISTICS

RESEARCH REPORT · OCTOBER 2026

The Architecture of Creation in the Universe

Physical Laws, Generative Processes and the
Recurring Structure of the Cosmos

Cosmology · Structure formation · Nucleosynthesis · Complexity

Hunter Hughes

H Heuristics · Architecture of Creation series

Contents

About This Report.....	6
How to read this report	6
Evidence grades	6
A note on the figures and calculations.....	7
How to cite.....	7
Executive Summary	8
The question	8
The thesis	8
Principal findings	8
What follows from it	9
1. Central Thesis and Scope	10
1.1 The observation	10
1.2 The thesis	11
1.3 What the thesis does and does not claim	12
1.4 Method and evidence standards	12
1.5 Place in the series	12
2. The Framework: Creation Structures at Cosmic Scale	14
2.1 Constraints, generators and filters	14
2.2 The five layers, read cosmically	15
2.3 Seven recurring patterns	16
2.4 Two equations that frame the rest	16
2.5 A note on the word 'creation'	17
3. Fundamental Conditions and Cosmic Evolution	18
3.1 The given: laws, constants and symmetries	18
3.2 Expansion and the hot Big Bang	18
3.3 Symmetry breaking and the separation of forces	19
3.4 Inflation and the seeds of structure	20
3.5 The first nuclei	21
3.6 Recombination, the dark ages and cosmic dawn	22
3.7 Fine-tuning: what the evidence shows	22
3.8 Precision and its tensions	22
4. The Architecture of Cosmic Structure	24
4.1 Gravity as generator	24
4.2 The role of dark matter	24
4.3 Sheets, filaments, nodes and voids	26
4.4 Where the web ends: the scale of homogeneity.....	26
4.5 Hierarchy built from the bottom up	27
4.6 A universal shape for haloes	28
5. Why Galaxies Share Similar Designs	30
5.1 The puzzle of similarity	30
5.2 Constraint: two components and one halo	31
5.3 Generator: angular momentum makes discs.....	32
5.4 Generator: mergers make spheroids.....	32
5.5 Generator: disc instabilities make bars and spirals	33
5.6 Filter: feedback and the tightness of scaling relations	34
5.7 Putting it together	35
5.8 What the architecture does not yet explain	36
6. Stars and the Architecture of Elements	37
6.1 How stars form	37
6.2 The stellar thermostat.....	37

6.3 Making the elements	38
6.4 The fingerprint in the Sun	40
6.5 Generations of stars	41
6.6 The history of star formation	41
7. Planetary Systems and the Emergence of Habitable Environments	43
7.1 Discs again	43
7.2 The temperature gradient sorts the materials	43
7.3 From dust to planets: aggregation and runaway growth	44
7.4 Orbital architecture and diversity	45
7.5 Differentiation and the making of an environment	45
7.6 Habitable zones	46
8. From Cosmic Structure to Life and Intelligence	48
8.1 A chain of conditions	48
8.2 Prebiotic chemistry: the ingredients are common	49
8.3 The origin of life: the weakest link	49
8.4 Major transitions and the role of energy	50
8.5 Intelligence, and what was not inevitable	51
9. Recurring Patterns Across Cosmic Scales	53
9.1 The pattern matrix	53
9.2 Shared mathematics: instabilities that select a scale	53
9.3 Power laws and scale-free aggregation	54
9.4 Analogies: what transfers and what does not	54
9.5 Does a common architecture exist?	55
10. Entropy, Irreversibility and the Persistence of Structure	56
10.1 The apparent paradox	56
10.2 Gravity's negative heat capacity	56
10.3 Where the entropy is	56
10.4 Structure as flow	57
11. The Long-Term Evolution of the Universe	58
11.1 The near future: stars and galaxies	58
11.2 Dark energy and the fate of expansion	58
11.3 The far future: eras of the universe	60
11.4 The architecture in reverse	61
12. Testing the Thesis: Predictions, Questions and Limits	62
12.1 Why the framework must be testable	62
12.2 Open research questions	62
12.3 Limits and risks of the framework	63
13. H Heuristics Propositions and Working Heuristics	64
13.1 Original propositions	64
13.2 Ten working heuristics	64
14. Conclusion: How Far Does a General Architecture Explain the Universe?	66
References	68
Glossary	73
Appendix A: Key Quantities	74
Appendix B: Simulation and Calculation Notes	75

List of Figures

Figure 1. The architecture of cosmic history	10
Figure 2. Cosmic structures in the space of mass and size	11
Figure 3. The creation structure at cosmic scale	15
Figure 4. Seven recurring structural patterns	16
Figure 5. The expansion history of the universe	19
Figure 6. The thermal history of the early universe	20
Figure 7. Freeze-out of neutrons before helium forms	21
Figure 8. The Hubble tension	23
Figure 9. Instabilities select a scale	24
Figure 10. Why galaxies need dark matter	25
Figure 11. The cosmic web emerging from noise	26
Figure 12. The transition to homogeneity	27
Figure 13. Hierarchical assembly.....	28
Figure 14. A universal halo profile	29
Figure 15. Thirty-six galaxies, one design	30
Figure 16. A small morphospace	31
Figure 17. Why rotation curves are flat.....	32
Figure 18. The winding problem and its solution	33
Figure 19. Galaxies obey simple laws	35
Figure 20. Most stars are small, and small stars live long	37
Figure 21. Fusion as a thermostat	38
Figure 22. The curve that governs the elements	39
Figure 23. Where the elements come from	40
Figure 24. The Sun's composition records how the elements were made	41
Figure 25. The universe has passed its peak of star formation	42
Figure 26. A temperature gradient sorts the materials	44
Figure 27. Aggregation with runaway growth	45
Figure 28. Differentiation	46
Figure 29. Habitable zones across stellar masses	47
Figure 30. The chain from cosmos to intelligence, with the strength of our understanding of each step	48
Figure 31. Major transitions in Earth's history.....	50
Figure 32. Energy rate density across cosmic and biological evolution	51
Figure 33. Where the recurring patterns operate.....	53
Figure 34. Power laws across scales	54
Figure 35. The entropy budget of the observable universe	57
Figure 36. Four futures for the expansion of the universe	59
Figure 37. Eras of the far future.....	60

List of Tables

Table 1. Evidence grades used in this report.....	6
Table 2. The five layers of the Architecture of Creation, applied to the universe	15

Table 3. Seven recurring patterns and their mathematical signatures 16

Table 4. Key cosmological parameters 19

Table 5. Independent lines of evidence for dark matter 25

Table 6. The creation structure of galaxies 36

Table 7. How stars end, by initial mass..... 40

Table 8. The chain of conditions linking cosmic evolution to life and intelligence 49

Table 9. Cosmic analogies classified by the depth of the similarity 55

Table 10. Cosmological futures under different dark-energy scenarios..... 59

Table 11. Testable predictions of the cosmic creation-structure thesis 62

Table 12. How far the architecture of cosmic creation explains the observable universe..... 66

Table 13. Glossary of key terms..... 73

Table 14. Key quantities used in this report 74

About This Report

This report asks how the universe built complexity out of simple beginnings, and whether the same structural principles recur at every stage. It is a major application of the framework set out in [The Architecture of Creation](#), the first report in the H Heuristics series of that name. That report asked why the same forms recur across unrelated systems, from sunflower spirals to basalt columns, and answered with a layered model in which physical constraints define a small space of viable forms, generative processes explore that space, and filters decide what persists. Here the same model is taken to the largest domain available: the observable universe, from its first second to its far future.

The report is written for readers who want a rigorous but readable account of modern cosmology and astrophysics, and for those interested in whether a general theory of structure formation is possible. It connects established science with the H Heuristics framework, but it keeps the two apart. Every major claim is graded for strength of evidence, analogies are labelled as analogies, and the original propositions of the framework are flagged as such wherever they appear.

How to read this report

Each section starts on a new page and can be read on its own. Sections 1 and 2 state the thesis and translate the framework into cosmic terms. Sections 3 to 8 follow the universe's structural evolution in order: fundamental conditions and the early universe (Section 3), the cosmic web (Section 4), why galaxies share similar designs (Section 5), stars and the elements (Section 6), planetary systems (Section 7), and the chain that leads to life and intelligence (Section 8). Sections 9 and 10 draw out the recurring patterns and the role of entropy. Section 11 examines long-term futures. Sections 12 to 14 state testable predictions, the framework's original propositions and an overall verdict.

Blue underlined text is a hyperlink. Links to the primary literature go to a DOI or an arXiv record where a specific result is cited, and to a reference article where a concept is introduced. Every link was checked for resolution before publication. A full reference list follows Section 14.

Evidence grades

Claims are graded using the same four-level scale as the rest of the series.

Table 1. Evidence grades used in this report

Grade	Meaning	Cosmic example
A: Established	Derived mathematically, or confirmed repeatedly by independent observation or experiment.	The universe is expanding and was once hot and dense
B: Well supported	Strong evidence from several lines of work, with unresolved detail or some dissent.	Inflation seeded the first density fluctuations
C: Plausible or contested	A credible mechanism and partial evidence; the field is actively debating it.	Life arises readily wherever conditions allow
D: Speculative	A hypothesis offered for testing, labelled as such wherever it appears.	The constants are selected from a multiverse

The grade describes our knowledge of a claim, not the claim's importance. Several of the most important questions in this report are graded C or D.

A note on the figures and calculations

The report contains 37 figures. Most were produced for this report. About half are original simulations or calculations of standard published models: a two-dimensional simulation of the cosmic web in the Zel'dovich approximation, a measurement of its transition to homogeneity, the growth of density fluctuations with and without dark matter, the freeze-out of neutrons before helium forms, a Press–Schechter halo mass function, a Milky-Way-like rotation curve, a demonstration of the spiral-arm winding problem, a Monte Carlo simulation of planetesimal growth, an order-of-magnitude entropy budget of the observable universe and the expansion history under four dark-energy scenarios. Each caption says what was computed. Figures marked illustrative are diagrams of a concept, not plots of measured data. One photograph, a mosaic of galaxies from the Hubble Space Telescope, is credited to NASA and ESA. Cosmological parameters are those of [Planck 2018](#) unless stated otherwise.

How to cite

Hughes, H. (2026). *The Architecture of Creation in the Universe: Physical Laws, Generative Processes and the Recurring Structure of the Cosmos*. H Heuristics Research Report, Architecture of Creation series. The report synthesises published research and presents original calculations and propositions, which are labelled as such.

Executive Summary

The question

About 13.8 billion years ago the observable universe was hotter than the core of any star, smoother than any surface made by people and almost entirely without structure. Today it contains atoms of 92 natural elements, hundreds of billions of galaxies arranged in a web of filaments and voids, stars in every stage of life, planets by the trillion and, on at least one of them, living systems that study the rest. This report asks how that happened, and whether the same principles of construction recur across its stages.

The defining question. How does the universe generate complexity from fundamental physical laws, and what recurring architecture connects its structures across space and time?

The thesis

The universe exhibits a progression from relatively simple physical conditions to increasingly differentiated structures. The thesis of this report is that this progression is generated by a small, recurring set of mechanisms. Fundamental laws act as **constraints** that define what can exist. Instabilities, chiefly gravitational, act as **generators** that turn small differences into large ones. Stability conditions and feedback act as **filters** that decide which structures persist. The same combination of constraints, generators and filters, called a creation structure in this series, recurs at every scale from atomic nuclei to superclusters. It does not imply a plan, a purpose or an inevitable outcome. It implies that the universe builds structure in a limited number of ways, and that those ways leave recognisable signatures.

Principal findings

- 1. Complexity was built in stages, each unlocked by a threshold.** Nuclei could form only once the universe had cooled below about 0.1 MeV, a few minutes after the hot Big Bang. Atoms formed at 3,000 K, 380,000 years later, releasing light and letting ordinary matter fall into the gravitational wells already dug by dark matter. Heavy elements had to wait for stars, rocky planets for heavy elements, and complex life for oxygen. Each threshold opened a new space of possible structures (Grade A for the sequence; the 'unlock' framing is an H Heuristics proposition).
- 2. Gravity is the master generator, because self-gravitating systems have negative heat capacity.** A star or galaxy that loses energy heats up and contracts, becoming more ordered locally while exporting entropy. This is why structure can grow without violating the second law of thermodynamics, and why the universe became lumpier rather than smoother (Grade A).
- 3. The cosmic web is what gravity does to near-uniform noise.** Density fluctuations of about one part in 100,000 at recombination grew into sheets, filaments, nodes and voids. This report's simulation reproduces the pattern from a few lines of physics, and shows that it averages out to uniformity on large scales, as surveys find beyond about 70 to 100 megaparsecs. Without dark matter the growth would have been about a hundred times too small for galaxies to form by today (Grade A).
- 4. Galaxies share designs because they are built from two components in a small possibility space.** Nearly every galaxy is a combination of a rotating disc and a pressure-supported spheroid inside a dark matter halo whose density profile has the same shape at every mass. Angular momentum conservation makes discs; mergers make spheroids; disc instabilities make bars and

logarithmic spiral arms; feedback regulates star formation. The result is a handful of morphologies and scaling relations so tight that galaxies can be used as distance markers (Grade A to B; some details remain contested).

5. **Stars are self-regulating fusion reactors that build the periodic table.** The steep temperature dependence of fusion makes stars thermostats. They convert hydrogen into heavier elements up to the iron peak, where nuclear binding energy is greatest, and supernovae, dying low-mass stars and neutron star mergers make the rest. The abundance pattern of the Sun still records this history: a Big Bang signature in hydrogen and helium, a deficit of fragile lithium, beryllium and boron, an excess of even-numbered elements, and an iron peak (Grade A).
6. **Planet formation repeats the galactic pattern at smaller scale.** Collapsing gas forms a rotating disc; solids aggregate; the largest bodies grow fastest; a temperature gradient sorts materials by condensation; and the planets then differentiate internally by density. More than 6,000 exoplanets show that the outcome is diverse and that the Solar System's architecture is unusual but not unique (Grade A to B).
7. **The chain from cosmos to life is well understood up to prebiotic chemistry, and poorly understood after it.** Asteroid samples contain amino acids and all five nucleobases, but the step from chemistry to biology has not been reproduced or observed. With a single example of life, the probability of each later step is unknown. The architecture explains why life's ingredients and settings are common; it does not show that life is (Grades B to D).
8. **Seven structural patterns recur across scales: aggregation, differentiation, branching, hierarchy, network formation, feedback and energy flow.** Some recurrences share mathematics, such as instabilities that select a characteristic scale. Others share a motif but not a mechanism. The report grades each and warns against treating resemblance as identity (Section 9).
9. **Structure is a flow, not a state.** Every persistent cosmic structure lives on a free-energy gradient that will run down. The entropy of the observable universe is dominated by supermassive black holes, with all stars and life a rounding error. In the standard cosmological model, star formation has already fallen to about a ninth of its peak, and the future is a long decline into a cold, dark, dilute state, though current data leave room for dark energy that evolves (Grade A for the trend; B to D for distant futures).
10. **A general architecture explains much of the organisation of the observable universe, but not its foundations.** It accounts well for how structure grows, why forms recur and why the statistics of galaxies, stars and planets are predictable even when individual objects are not. It does not explain the laws or constants themselves, the identity of dark matter and dark energy, the origin of the matter–antimatter asymmetry or the origin of life. Section 12 sets out the predictions by which the framework could fail.

What follows from it

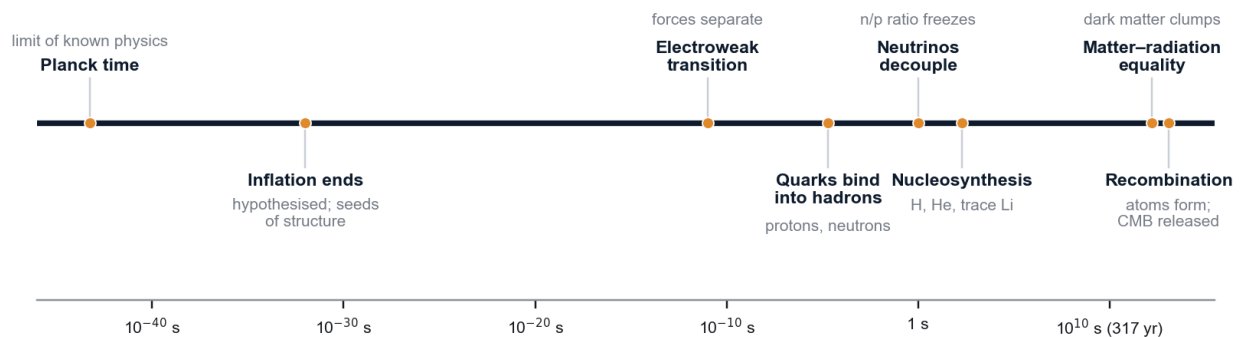
The practical payoff is a way of reading any cosmic structure. Before asking what a structure means, ask which constraint makes it possible, which instability generated it, which filter keeps it, and which energy flow pays for its persistence. That checklist, set out as ten working heuristics in Section 13, separates what the universe had to do from what it happened to do.

1. Central Thesis and Scope

1.1 The observation

The early universe was simple in a precise sense. A few hundred thousand years after the hot Big Bang it was a nearly uniform glow of hydrogen and helium nuclei, electrons, photons, neutrinos and dark matter at about 3,000 K, with temperature differences of roughly one part in 100,000 from place to place. That glow is still visible as the [cosmic microwave background](#), first detected by [Penzias and Wilson in 1965](#) and now measured to have a temperature of [2.72548 K](#). Nothing in it resembles a galaxy, a star or a planet.

A. The first 380,000 years (logarithmic time): the forces, particles and nuclei



B. The next 13.8 billion years (linear time): stars, galaxies, planets

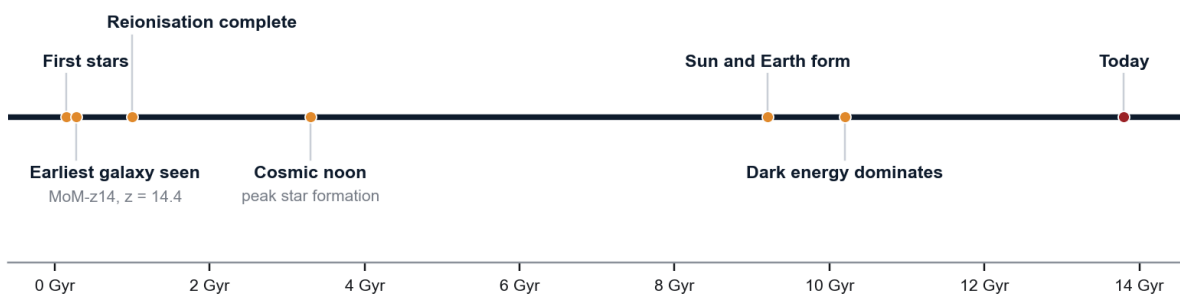


Figure 1. The architecture of cosmic history. Panel A uses a logarithmic scale for the first 380,000 years, when the forces, particles and light nuclei took their present form; panel B uses a linear scale for the 13.8 billion years since, when stars, galaxies and planets formed. Inflation is shown as hypothesised.

Source: H Heuristics, from *Planck Collaboration (2018)*, *Naidu et al. (2025)* and standard cosmology texts. Epoch times are approximate.

The universe today is organised on every scale. Quarks are bound into protons and neutrons, which are bound into the nuclei of 92 naturally occurring elements. Atoms form molecules, minerals and, on one planet at least, cells. Stars are grouped into galaxies, galaxies into groups and clusters, and clusters into a web of filaments and sheets surrounding vast voids. Figure 1 sets out the sequence in time, and Figure 2 shows how these structures occupy a narrow band of the space of possible masses and sizes.

Two features of this history stand out. The first is that structure grew without any external designer or blueprint: the same laws of physics that governed the uniform early universe produced the organised one.

The second is that the same kinds of structure recur at very different scales. Rotating discs appear around young stars and as galaxies. Hierarchies of smaller units within larger ones appear in nuclei, star clusters and superclusters. Branching histories describe both the assembly of galaxies and the evolution of species. The task of this report is to explain the first feature and to test whether the second reveals anything deep.

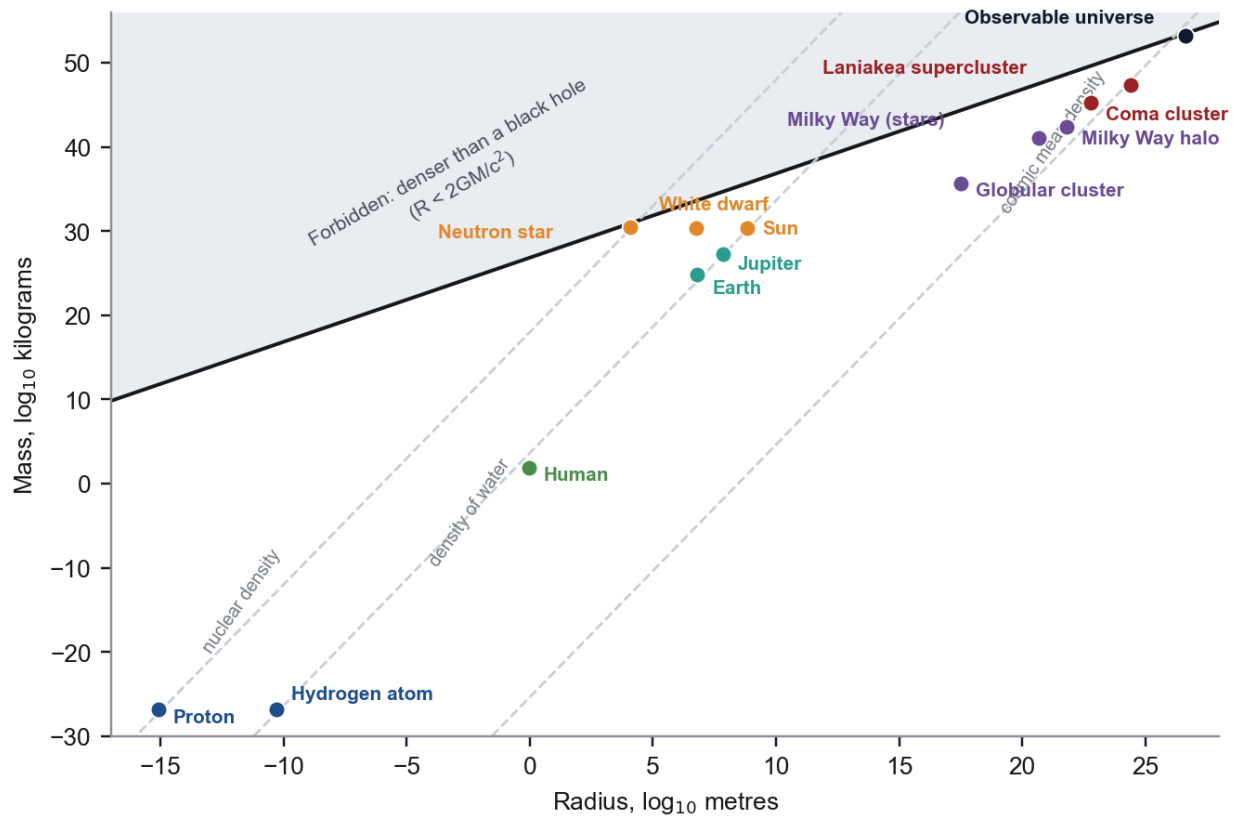


Figure 2. Cosmic structures in the space of mass and size. Objects lie between the line of nuclear density and the black hole limit, where an object's radius equals $2GM/c^2$. The observable universe lies close to its own black hole line, a known consequence of a near-critical density.

Source: H Heuristics calculation from standard values. Masses and radii are rounded; the Milky Way is shown for its stellar disc and for its dark matter halo.

1.2 The thesis

Thesis. The universe exhibits a remarkable progression from relatively simple physical conditions to increasingly differentiated structures. This progression is generated by a small, recurring set of mechanisms: fundamental laws that constrain what can exist, instabilities that amplify small differences into large ones, and stability conditions and feedback loops that decide which structures persist. These recurring combinations, called creation structures in this series, connect particles, atoms, stars, galaxies, planetary systems and potentially life.

The thesis makes three claims of increasing ambition. The first, that cosmic structure emerges from physical law acting on initial conditions without external direction, is the working assumption of modern astrophysics and is supported by the success of simulations that start from a measured early universe and end with something statistically indistinguishable from the observed one (Grade A). The second, that

the generative processes involved belong to a small number of mathematical types, is well supported for gravitational instability, nuclear fusion and aggregation, and partly supported elsewhere (Grade B). The third, that the recurrence of form across scales reveals common generative principles and not merely coincidence, is the distinctive contribution of the H Heuristics framework. It is graded B where shared mathematics can be shown and C or D where it cannot.

1.3 What the thesis does and does not claim

- **It does not claim that all structure follows one blueprint.** The foundational report in this series is explicitly pluralist. Recurrence has at least three distinct sources: shared physical constraint, shared machinery inherited from a common origin, and shared selection pressure acting on different systems. All three appear in the cosmos, and they must be distinguished case by case.
- **It does not claim that life or intelligence was inevitable.** The report connects cosmic evolution to the formation of chemical elements, planetary environments, biological complexity and intelligence without assuming that these outcomes had to happen or that the universe has a predetermined purpose. Where the evidence is a single example, the report says so.
- **It does not claim to explain the laws themselves.** The framework takes the laws of physics and the initial conditions of the universe as given. Why the laws are what they are, and why the early universe was in a state of very low gravitational entropy, are open questions that the framework cannot answer (Section 3.7 and Section 10).
- **It does claim that the generators and filters are few and identifiable.** If the thesis is right, the same small set of mechanisms should account for structure from nuclei to superclusters, and new observations should be explicable by those mechanisms without adding new ones at each scale. Section 12 lists observations that would count against this.

1.4 Method and evidence standards

The report synthesises peer-reviewed literature in cosmology, astrophysics, nuclear physics, planetary science, origin-of-life research and complexity science, together with observational results available to October 2026, including those of the Planck satellite, the Dark Energy Spectroscopic Instrument (DESI), the James Webb Space Telescope (JWST) and the NASA Exoplanet Archive. It distinguishes four kinds of statement: established scientific findings, hypotheses under active investigation, mathematical analogies, and original H Heuristics propositions. Established findings and hypotheses are graded A to D using the scale in Table 1. Analogies are labelled as such and assessed in Section 9.4. Original propositions are collected and labelled in Section 13.

Equations are included where they make an argument clearer. They are standard results and are cited to their sources. The original simulations are deliberately simple. They are designed to show mechanisms, not to compete with the large cosmological simulations whose results are cited alongside them.

1.5 Place in the series

[The Architecture of Creation](#) set out the general framework and applied it to natural form on Earth. [The Architecture of Creation and Development](#) applied the mathematics of diffusion to economic development. [The Architecture of Entropy](#) examined the mirror image: how organised structure is lost. [The Human Variant Hypothesis](#) asked how a shared developmental architecture generates recurring human form. This report supplies the cosmic foundation beneath all of them. It asks where structure came

from in the first place, and why the universe became a place in which the questions of the other reports could arise.

2. The Framework: Creation Structures at Cosmic Scale

2.1 Constraints, generators and filters

The foundational report defined a creation structure as the combination of constraints, generators and filters that produces a recurring form. Applied to the cosmos, the three components take specific forms, summarised in Figure 3.

Constraints are what the laws allow. They include the four fundamental interactions and their relative strengths, the conservation laws that follow from symmetries of nature, the speed of light, the quantum rules that govern matter, and the expansion history of the universe set by its contents. Constraints do not build anything. They define a space of possibilities and, more importantly, rule most of it out. A star more massive than about 150 to 300 solar masses cannot remain stable, a white dwarf above about 1.4 solar masses cannot support itself, and no nucleus is more tightly bound than those near iron.

Generators are the processes that explore the allowed space. In cosmology the dominant generator is gravitational instability: any region slightly denser than its surroundings attracts more matter and becomes denser still. Others include nuclear fusion and neutron capture, which build heavier nuclei from lighter ones; radiative cooling, which lets gas lose energy and condense; and collisions, mergers and accretion, which combine smaller bodies into larger ones. Generators are biased. They do not sample the space of possibilities uniformly, and the bias is a large part of why forms recur.

Filters decide what persists. A structure survives if it satisfies a stability condition: virial equilibrium for a galaxy cluster, hydrostatic equilibrium for a star, Toomre stability for a rotating disc, nuclear binding for an isotope. Filters also include feedback loops that hold a structure near an operating point, such as the stellar thermostat described in Section 6. Structures that fail a filter are destroyed, recycled or transformed into something that passes.

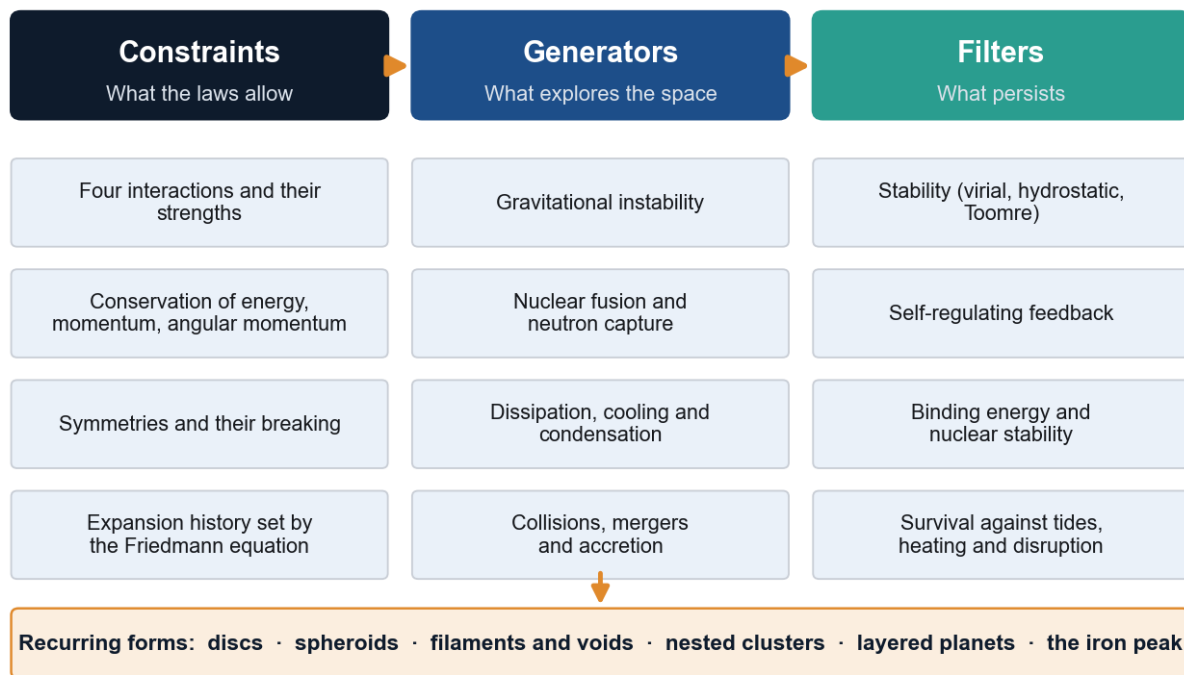


Figure 3. The creation structure at cosmic scale. Constraints set by physical law define what can exist; generators explore that space with a bias; filters select what persists. The recurring forms of the universe are the outputs that pass all three.

Source: H Heuristics, adapting the framework of *The Architecture of Creation* (2026). Illustrative.

2.2 The five layers, read cosmically

The foundational report organised creation structures into five layers. Each has a cosmic counterpart, shown in Table 2. The mapping is not perfect, since the biological and reproductive layers have no strict analogue before life, but it shows where each kind of explanation operates.

Table 2. The five layers of the Architecture of Creation, applied to the universe

Layer	General meaning	Cosmic counterpart	Example
Fundamental	Laws, symmetries and constants that constrain everything	Four interactions, conservation laws, constants, initial conditions	Gravity is 10^{36} times weaker than electromagnetism between two protons
Geometric	Shapes favoured by the constraints	Spheres (stars, planets), discs (galaxies, protoplanetary discs), filaments and sheets	Rotating, cooling gas settles into a disc
Biological	How living systems build form	Prebiotic chemistry and life (Section 8)	Amino acids in asteroid Bennu
Emergent	Order from local rules without a designer	Cosmic web, stellar feedback, galaxy scaling relations	Filaments from gravitational collapse
Reproductive and evolutionary	Heredity, selection and repetition	Stellar generations and chemical enrichment; selection by stability	Each generation of stars is richer in metals

Source: H Heuristics. The biological and reproductive layers apply in the strict sense only after the origin of life; the cosmic counterparts listed for them are analogues, graded C.

2.3 Seven recurring patterns

A central question for this report is whether recurring mathematical and structural patterns reveal common generative principles across cosmic scales. Seven patterns recur often enough to be examined systematically. They are shown schematically in Figure 4, defined in Table 3 and assessed scale by scale in Section 9.

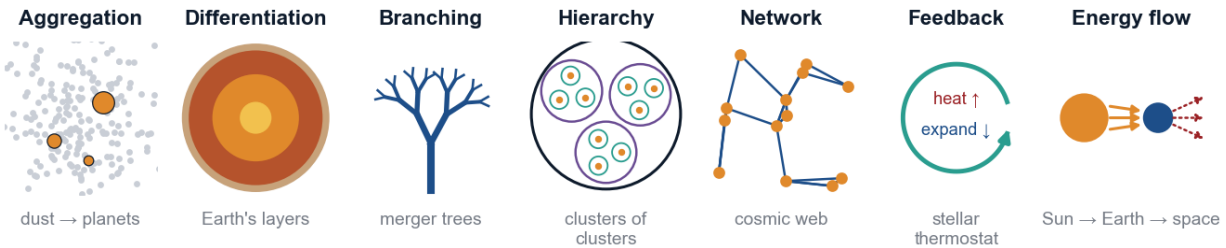


Figure 4. Seven recurring structural patterns. Each appears at several cosmic scales; whether a shared appearance reflects a shared mechanism is assessed in Section 9.

Source: H Heuristics. Illustrative.

Table 3. Seven recurring patterns and their mathematical signatures

Pattern	Definition	Typical mathematical signature	Cosmic examples
Aggregation	Small units combine into larger ones	Coagulation equations; power-law size spectra; runaway growth	Planetesimals, haloes, galaxies, nuclei
Differentiation	A uniform system separates into distinct parts	Symmetry breaking; settling in a potential; phase separation	Forces after the Big Bang, stellar onion shells, planetary cores
Branching	One lineage splits into several, or several merge into one	Trees and merger histories; branching ratios	Halo merger trees, nuclear reaction networks, phylogenies
Hierarchy	Units nested within larger units	Self-similar scaling; bottom-up assembly	Quarks to nuclei to atoms; stars to galaxies to clusters
Network formation	Nodes linked by persistent connections	Graph structure; caustics of a flow; percolation	Cosmic web, reaction networks, metabolism
Feedback	Output of a process modifies its own rate	Negative feedback sets a stable operating point; positive feedback causes runaway	Stellar thermostat, galactic star formation, climate
Energy flow	Free energy degrades as it passes through a system	Entropy production; dissipative structures	Sunlight through Earth's climate and biosphere

Source: H Heuristics. Symmetry breaking, treated here under differentiation, is also scored separately in Section 9.

2.4 Two equations that frame the rest

Two relationships do much of the work in what follows. The first is the Friedmann equation, derived from general relativity for a universe that is the same everywhere and in every direction. It relates the expansion rate H to the density of the universe's contents:

$$H^2 = (8\pi G / 3) \rho - kc^2 / a^2 \quad (1)$$

where a is the scale factor, which measures the size of the universe relative to today, ρ is the total density, G is the gravitational constant and k describes spatial curvature, which observations find to be consistent with zero. Each component dilutes at a different rate as the universe expands: radiation as a^{-4} , matter as a^{-3} and a cosmological constant not at all. That simple fact divides cosmic history into a radiation era, a matter era and the present era of dark energy (Figure 5).

The second is the condition for gravitational instability, derived by [James Jeans in 1902](#). A region of gas collapses if it is larger than the Jeans length,

$$\lambda_J = c_s (\pi / G\rho)^{1/2} \quad (2)$$

where c_s is the speed of sound in the gas. Below this scale pressure pushes back faster than gravity can pull in; above it, gravity wins. Equation 2 is the first appearance of a pattern that recurs throughout the report: an instability that selects a characteristic scale because an amplifying force competes with a restoring one (Section 9.2).

2.5 A note on the word 'creation'

The word creation is used in this series in a structural sense: the process by which organised, differentiated structures come into being from less organised ones. It does not presuppose a creator, and it does not exclude one. The physical sciences have nothing to say about ultimate purpose, and the report does not attempt to settle questions that lie outside them. Where the framework touches on those questions, as in the discussion of fine-tuning in Section 3.7, the report states what the evidence shows and where it stops.

3. Fundamental Conditions and Cosmic Evolution

3.1 The given: laws, constants and symmetries

Every creation structure begins with constraints, and the deepest constraints in the universe are its laws. Four fundamental interactions are known. The strong interaction binds quarks into protons and neutrons and holds nuclei together. The electromagnetic interaction binds electrons to nuclei and atoms to each other, and governs light and chemistry. The weak interaction allows neutrons and protons to change into one another, which makes nuclear fusion in stars possible. Gravity, by far the weakest, acts on everything with mass or energy and, because it is always attractive and has unlimited range, dominates on large scales.

The relative strengths of these interactions are fixed by dimensionless constants. The best known is the [fine-structure constant](#), about $1/137$, which sets the strength of electromagnetism. The ratio of the proton's mass to the electron's is about 1,836. Between two protons, the electrical repulsion exceeds the gravitational attraction by a factor of about 10^{36} . That enormous ratio is a constraint with visible consequences: gravity can only dominate when enormous numbers of particles act together, which is why the smallest gravitationally bound objects that are round under their own weight are around a few hundred kilometres across, and why stars contain about 10^{57} atoms.

Conservation laws are a second layer of constraint. [Emmy Noether](#) showed in 1918 that every continuous symmetry of the laws of physics implies a conserved quantity. Symmetry under shifts in time gives conservation of energy; under shifts in space, conservation of momentum; under rotation, conservation of angular momentum. The last of these is one of the most important constraints in this report. It is why collapsing clouds of gas form spinning discs instead of points, and so why discs recur in galaxies, around young stars and in the rings of giant planets (Grade A).

3.2 Expansion and the hot Big Bang

The universe is expanding. [Edwin Hubble's 1929 paper](#) showed that more distant galaxies recede faster, as expected if space itself is stretching. Run backwards, the expansion implies an early state of extreme density and temperature. Three independent lines of evidence establish that this hot, dense state occurred (Grade A): the cosmic microwave background, whose spectrum is the most perfect blackbody ever measured; the abundances of the lightest elements, which match predictions of nuclear reactions in the first minutes (Section 3.5); and the observed evolution of galaxies with distance, which shows that the universe looked different in the past.

The Friedmann equation (Equation 1), combined with measurements of the universe's contents, gives its expansion history (Figure 5). The [Planck satellite's final results](#) give an age of 13.787 ± 0.020 billion years and a composition today of about 5 per cent ordinary matter, 27 per cent dark matter and 68 per cent dark energy. The key parameters are listed in Table 4. The proportions change with time because each component dilutes differently. Radiation dominated for the first 51,000 years or so; matter until about 10 billion years; and dark energy since, which is why the expansion is now [accelerating](#).

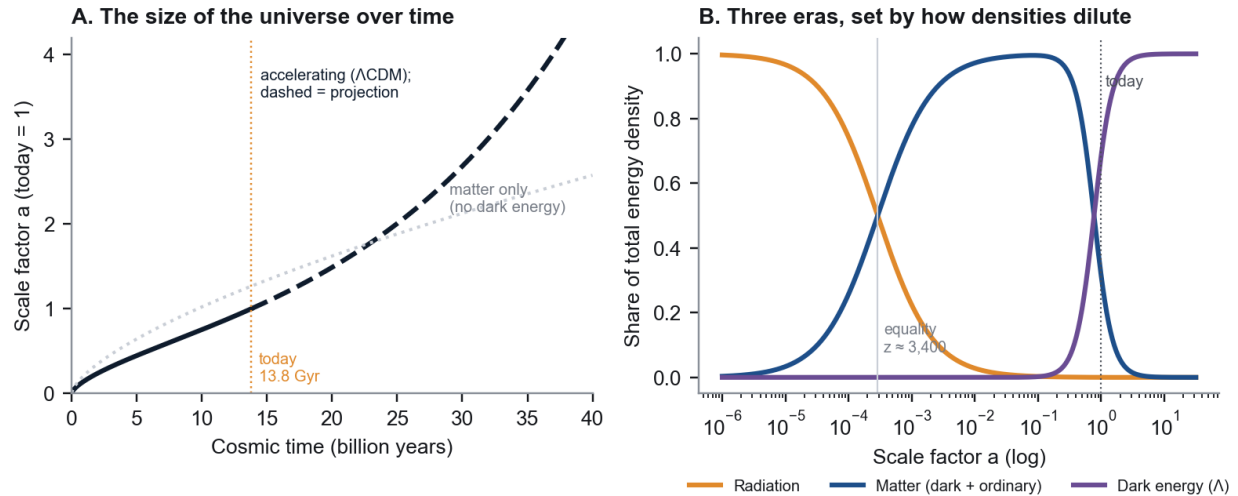


Figure 5. The expansion history of the universe. (A) The scale factor against cosmic time in the standard Λ CDM model, computed from the Friedmann equation with Planck 2018 parameters; the dotted line shows a universe of matter alone with the same expansion rate today. (B) The share of the total energy density in radiation, matter and dark energy. Each component dilutes at a different rate, dividing history into three eras.

Source: H Heuristics calculation from the Friedmann equation with $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.315$ (Planck Collaboration 2018). The computed age is 13.79 billion years.

Table 4. Key cosmological parameters

Quantity	Value	What it controls
Age of the universe	$13.787 \pm 0.020 \text{ Gyr}$	Time available for structure to form
Hubble constant H_0	$67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (CMB)	Present expansion rate; contested, see Section 3.8
Matter density Ω_m	0.315 ± 0.007	Strength of gravitational growth
Baryon density $\Omega_b h^2$	0.0224 ± 0.0001	Light-element abundances; acoustic peaks
Dark energy density Ω_Λ	0.685 ± 0.007	Late-time acceleration; future of growth
Spectral index n_s	0.965 ± 0.004	Relative amplitude of fluctuations on large and small scales
Fluctuation amplitude σ_8	0.811 ± 0.006	Clumpiness of matter today on $8 h^{-1} \text{ Mpc}$ scales
CMB temperature	$2.72548 \pm 0.00057 \text{ K}$	Thermal history; photon density of 411 per cm^3

Source: Planck Collaboration (2018), base Λ CDM, TT,TE,EE+lowE+lensing; Fixsen (2009) for the CMB temperature.

3.3 Symmetry breaking and the separation of forces

The early universe was hot enough that some of today's distinctions did not yet exist. At temperatures above about 100 GeV, reached in the first trillionth of a second, the electromagnetic and weak interactions behaved as one electroweak force and the W and Z particles that carry the weak force were massless. As the universe cooled through that temperature, the Higgs field acquired a non-zero value throughout space and the symmetry broke: the W and Z bosons gained mass, the weak force became short-ranged, and electromagnetism emerged as a separate interaction. This is established physics, confirmed by the discovery of the Higgs boson in 2012 (Grade A for the electroweak transition; whether all four forces were once unified at still higher energies is Grade C to D).

At about 20 microseconds, when the temperature fell to roughly 150 MeV, free quarks and gluons were confined into protons, neutrons and other hadrons. The thermal history is shown in Figure 6. Each threshold is a differentiation event in the sense of Table 3: a uniform state separates into distinct kinds of thing, and the new kinds become the building blocks of the next stage. Symmetry breaking is how a universe governed by simple, symmetric laws comes to contain asymmetric, structured outcomes. As [Philip Anderson argued in 1972](#), each level of organisation can obey its own effective rules precisely because symmetries are broken on the way up.

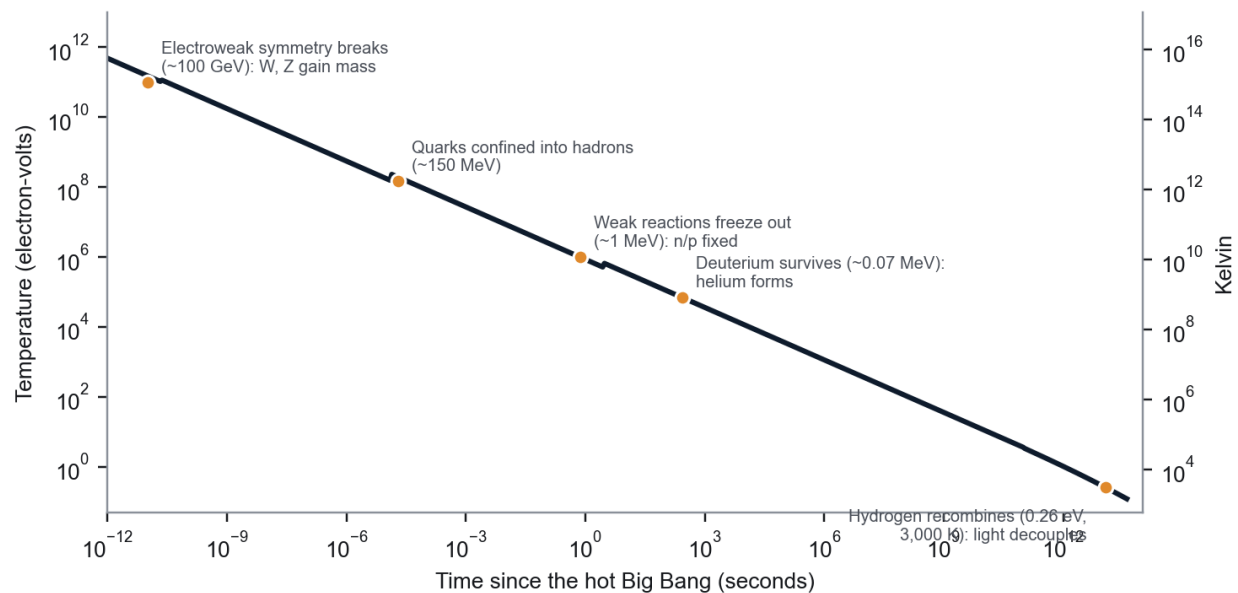


Figure 6. The thermal history of the early universe. Temperature falls as the inverse square root of time in the radiation era, with small steps as particle species annihilate. Each marked threshold allowed a new kind of structure to form or to persist.

Source: H Heuristics calculation: $T = 1.55 g^{1/4} t^{1/2}$ MeV in the radiation era, with standard values of g , joined to $T = T_0/a(t)$ from the Λ CDM expansion after 10^{11} s.

3.4 Inflation and the seeds of structure

If the hot Big Bang began from a smooth state, where did the tiny density differences that later grew into galaxies come from? The leading answer is [cosmic inflation](#), proposed by Alan Guth in 1981 and developed by others. Inflation posits a brief period of accelerated expansion, perhaps lasting around 10^{-32} seconds, which stretched a tiny region to a size larger than the observable universe. This would explain why the universe is so nearly flat and why regions that appear never to have been in contact have the same temperature.

Inflation also offers a generator for structure. Quantum fluctuations in the field driving inflation would have been stretched to cosmic scales and frozen in as small differences in density. The theory predicts that these differences should be nearly, but not exactly, the same in amplitude on all scales, with slightly more power on large scales, and that they should follow a Gaussian distribution. [Planck's measurements](#) find exactly this: a spectral index of 0.965, distinguishable from the scale-invariant value of 1 at more than eight standard deviations, and no detectable departure from Gaussian statistics. Inflation is graded B: its predictions have been confirmed, but the field responsible has not been identified, its energy scale is unknown and the primordial gravitational waves it should also produce have not yet been detected.

Key point. If inflation is correct, the largest structures in the universe began as quantum fluctuations. The cosmic web is quantum noise, amplified by gravity over 13.8 billion years. That is the most dramatic example in this report of a generator turning small differences into large ones.

3.5 The first nuclei

One second after the hot Big Bang, at a temperature of about 1 MeV, weak reactions converting neutrons into protons and back became slower than the expansion. The ratio of neutrons to protons froze at about one to six and then fell slowly as free neutrons decayed with a mean lifetime of about 880 seconds. Deuterium nuclei, the first step towards helium, were destroyed by energetic photons as fast as they formed, until the universe had cooled to about 0.08 MeV a few minutes later. Almost every surviving neutron was then locked into helium-4.

Figure 7 reproduces this calculation in simplified form. It gives a helium mass fraction of 0.23, against 0.247 from full reaction-network codes and about 0.245 observed. The predictions of [Big Bang nucleosynthesis](#) for deuterium, helium-3 and helium-4 agree with observation across four orders of magnitude in abundance, using a single parameter, the density of ordinary matter, that is measured independently from the cosmic microwave background. The [primordial deuterium abundance](#) is now known to one per cent. The agreement is graded A. The exception is lithium-7, observed in old stars at about a third of the predicted abundance: the cosmological lithium problem remains unsolved and is most often attributed to depletion in stellar atmospheres (Grade C).

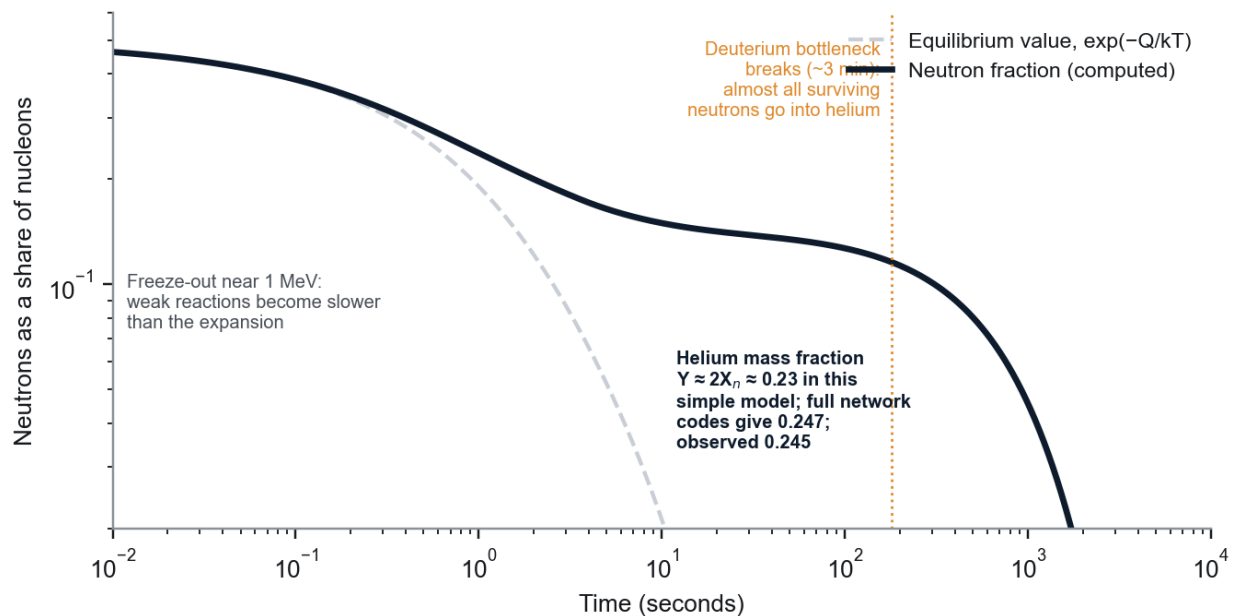


Figure 7. Freeze-out of neutrons before helium forms. The neutron fraction tracks its equilibrium value until weak reactions become too slow at about 1 MeV, then declines through free-neutron decay until the deuterium bottleneck breaks. The surviving neutrons set the helium abundance.

Source: H Heuristics calculation using the weak rates of Bernstein, Brown and Feinberg (1989), a neutron lifetime of 879.4 s and a suppression of lepton-induced rates after electron-positron annihilation. Simplified; full network results from Cyburt et al. (2016).

Big Bang nucleosynthesis is an example of a creation structure in miniature. The constraints are nuclear binding energies and the expansion rate. The generator is a short burst of nuclear reactions. The filter is binding: the absence of any stable nucleus with mass number 5 or 8 blocks the path to heavier elements,

so the early universe made almost nothing beyond helium. The universe had to wait for stars, with their much longer timescales and higher densities, to bridge that gap.

3.6 Recombination, the dark ages and cosmic dawn

For 380,000 years the universe was an opaque plasma in which photons scattered constantly off free electrons. When the temperature fell to about 3,000 K, electrons and nuclei combined into neutral atoms, and light could travel freely. That release, at a redshift of about 1,090, is the cosmic microwave background. Its tiny temperature variations, about one part in 100,000, record the density pattern at that moment, and the characteristic sizes of its hot and cold spots record sound waves that rippled through the plasma before it became transparent.

After recombination came the dark ages, a period of some 100 million years with no sources of light. The first stars probably formed in small dark matter haloes between about 100 and 200 million years after the Big Bang. JWST has pushed direct observation of galaxies to within 300 million years of the beginning: the most distant spectroscopically confirmed galaxy, [MoM-z14](#), is seen at a redshift of 14.44, about 280 million years after the Big Bang, following [JADES-GS-z14-0](#) at 14.32. Ultraviolet light from the first generations of stars and galaxies reionised the intergalactic hydrogen, a process complete by about a billion years.

3.7 Fine-tuning: what the evidence shows

Many physicists have noted that the constants and initial conditions appear to fall within narrow ranges compatible with complex structure. If the cosmological constant were much larger, matter would have been dispersed before galaxies could form; [Steven Weinberg used this in 1987](#) to predict a small positive value before it was observed. If the strong force were slightly different, the excited state of carbon-12 that allows stars to make carbon might not sit at the right energy. [Fred Hoyle predicted that state in 1953](#) from the existence of carbon, and it was found at [7.65 MeV](#) shortly afterwards; later work suggests that carbon-based life tolerates [shifts in the light quark masses of a few per cent](#).

The evidence for some sensitivity is real, and [reviews by Barnes](#) and [Tegmark and colleagues](#) catalogue it. Its interpretation is contested. [Fred Adams has argued](#) that many constants could vary over wide ranges and still permit stars and complex chemistry, and that our universe may not be optimal for structure. Explanations range from deeper laws not yet known, to a multiverse in which observers necessarily find themselves in a hospitable region, to design arguments that lie outside physics. The framework of this report does not adjudicate. It treats the constants as constraints and grades every explanation of their values D.

3.8 Precision and its tensions

The standard model of cosmology fits an extraordinary range of data with six parameters, but cracks are visible. The best known is the Hubble tension (Figure 8). Measurements based on the early universe, such as [Planck's](#) $67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and the [Atacama Cosmology Telescope's](#) 68.2, disagree with the [SH0ES distance-ladder value](#) of 73.0 based on Cepheid variable stars and supernovae. JWST has not settled the matter: the [Chicago–Carnegie programme](#) finds about 70.4 using red giant stars, while [the SH0ES team argues](#) that sample selection explains the difference and that JWST confirms its higher value.

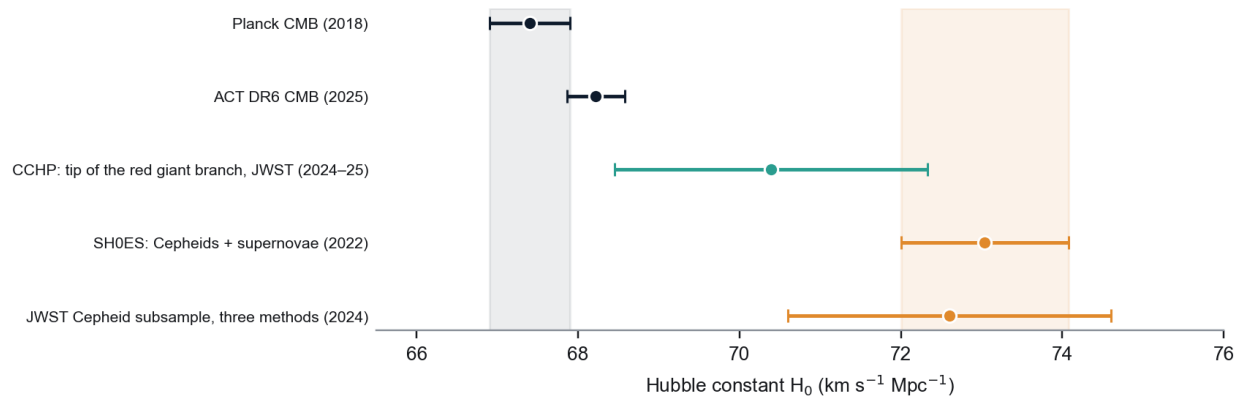


Figure 8. The Hubble tension. Measurements from the early universe cluster near 67 to 68 $\text{km s}^{-1} \text{Mpc}^{-1}$; distance-ladder measurements from Cepheids cluster near 73. Red-giant measurements with JWST lie between.

Source: Planck Collaboration (2018); Louis et al. (2025); Riess et al. (2022, 2024); Freedman et al. (2025). Error bars are one standard deviation; the CCHP bar combines statistical and systematic terms in quadrature.

A second crack concerns dark energy. The [second data release of DESI](#), mapping the imprint of primordial sound waves in more than 14 million galaxies and quasars, finds that combined with other data it prefers dark energy that weakens over time, at a significance of 2.8 to 4.2 standard deviations depending on which supernova sample is included. Independent analyses are more cautious. If confirmed, the result would mean that the cosmological constant is not constant, with large consequences for the long-term future (Section 11). Both tensions are graded C: real discrepancies whose resolution, whether in measurement systematics or new physics, is unknown.

Key points. The fundamental layer supplies the constraints: four interactions with very different strengths, conservation laws that follow from symmetry, an expansion history set by the universe's contents, and initial fluctuations of one part in 100,000. The early universe was a sequence of thresholds at which symmetries broke and new structures could form. What is not explained is why the laws, constants and initial conditions are what they are.

4. The Architecture of Cosmic Structure

4.1 Gravity as generator

At recombination the universe was smooth to one part in 100,000. Today, a typical galaxy is a million times denser than the cosmic average. The process that bridged that gap is gravitational instability: a region slightly denser than average attracts more matter than its surroundings and its density contrast grows. The same instability, in the form of Equation 2, governs the collapse of gas clouds into stars. Figure 9 shows the dispersion relation in its simplest form, and its counterpart for a rotating disc, which Section 5 shows to be central to the design of galaxies.

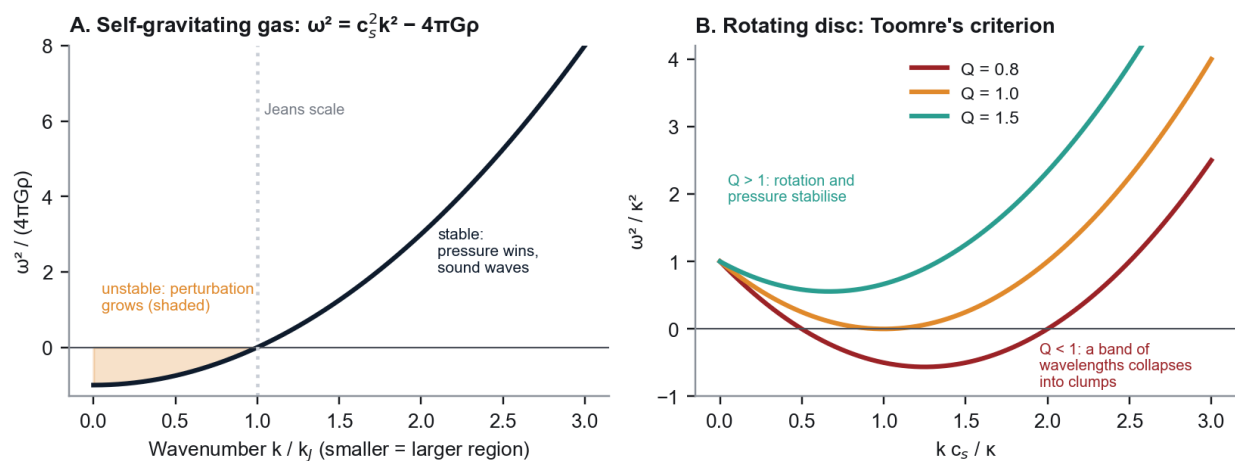


Figure 9. Instabilities select a scale. (A) In a self-gravitating gas, perturbations larger than the Jeans scale grow, because gravity outpaces pressure; smaller ones oscillate as sound waves. (B) In a rotating disc, rotation stabilises the largest scales and pressure the smallest; only when the Toomre parameter Q falls below 1 does a band of intermediate wavelengths become unstable.

Source: H Heuristics calculation from the standard dispersion relations $\omega^2 = c_s^2 k^2 - 4\pi G \rho$ (Jeans 1902) and $\omega^2 = \kappa^2 - 2\pi G \Sigma |k| + c_s^2 k^2$ (Toomre 1964).

In an expanding universe, growth is slower than in a static one, because expansion pulls matter apart. In the matter era the density contrast δ of a region grows in proportion to the scale factor, satisfying the linear growth equation

$$d^2\delta/dt^2 + 2H d\delta/dt = 4\pi G \rho_m \delta \quad (3)$$

in which the expansion term $2H d\delta/dt$ acts as friction. This simple result has a striking consequence. Between recombination and today the universe has expanded by a factor of about 1,100. If fluctuations in ordinary matter started at one part in 100,000 and grew in proportion to the scale factor, they would reach about one per cent today: far too small to have formed any galaxy.

4.2 The role of dark matter

The resolution is dark matter. Before recombination ordinary matter was locked to radiation, whose pressure prevented it from clumping. Dark matter, which does not interact with light, was free to start growing from the end of the radiation era, about 51,000 years after the Big Bang. By recombination it had already formed potential wells that ordinary matter fell into as soon as it was released. Figure 10 shows

the calculation: with dark matter, density contrasts on galaxy scales exceed unity well before today; without it, they reach about 0.01.

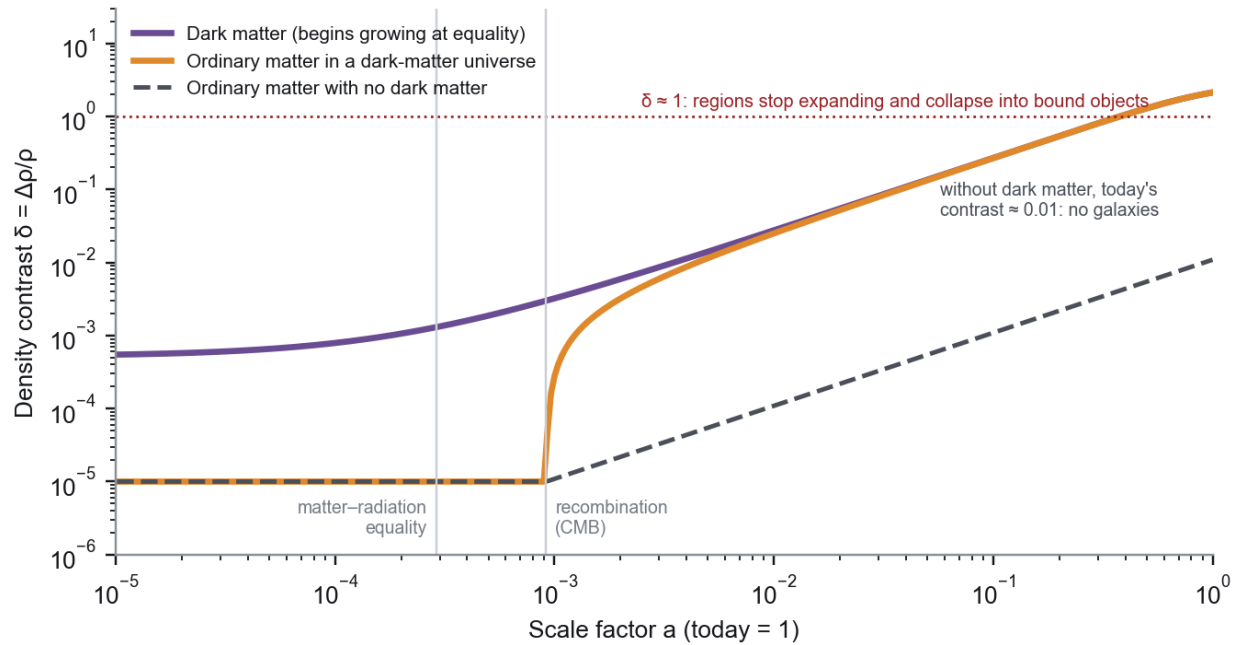


Figure 10. Why galaxies need dark matter. Dark matter perturbations grow slowly in the radiation era and then in proportion to the scale factor; ordinary matter is held at the CMB level until recombination and then falls into the dark matter wells. Without dark matter, ordinary matter would reach a density contrast of only about 0.01 by today.

Source: H Heuristics calculation: Mészáros equation through matter–radiation equality, Λ CDM growth factor at late times, baryon catch-up $\delta b = \delta c(1 - \text{arcc}/a)$. Normalisation on galaxy scales is illustrative.

The case for dark matter does not rest on structure growth alone. It is one of the best-attested conclusions in astrophysics because independent lines of evidence, using different physics, point to the same amount of unseen mass (Table 5). Its identity is unknown. Decades of laboratory searches for weakly interacting massive particles have found nothing, and alternatives including axions, sterile neutrinos and primordial black holes are under investigation. The existence of dark matter is graded A; any particular candidate is C or D.

Table 5. Independent lines of evidence for dark matter

Evidence	What is observed	Key reference
Galaxy clusters	Galaxies move too fast to be held by visible mass	Zwicky (1937)
Galaxy rotation curves	Orbital speeds stay flat far beyond the visible disc	Rubin and Ford (1970)
Gravitational lensing	Mass maps show more mass than light	Weak and strong lensing surveys
Colliding clusters	Mass separated from hot gas in the Bullet Cluster	Clowe et al. (2006)
CMB acoustic peaks	Peak heights require non-baryonic matter at about five times ordinary matter	Planck (2018)
Large-scale structure	Growth from 10^{-5} to today's web requires dark matter	Springel et al. (2005)

Modified-gravity theories such as MOND reproduce galaxy rotation curves well but struggle with clusters, lensing and the CMB.

4.3 Sheets, filaments, nodes and voids

Gravitational collapse is not spherical. In 1970 [Yakov Zel'dovich](#) showed that a region of slightly higher density generally collapses first along its shortest axis, forming a flattened sheet, which he called a pancake. Collapse then continues along a second axis to form a filament, and along the third to form a dense node. [Bond, Kofman and Pogosyan](#) showed in 1996 how the pattern of the initial fluctuations determines this web, with filaments forming bridges between the peaks that become clusters of galaxies.

Figure 11 shows the process in an original two-dimensional simulation. Particles start on a near-uniform grid, displaced slightly by a random Gaussian field like the one measured in the CMB. As the growth factor increases, streams of particles cross and pile up along caustics, producing a network of filaments meeting at knots and surrounding empty regions. No rule for drawing filaments was specified. The web emerges from the initial noise and the law of gravity.

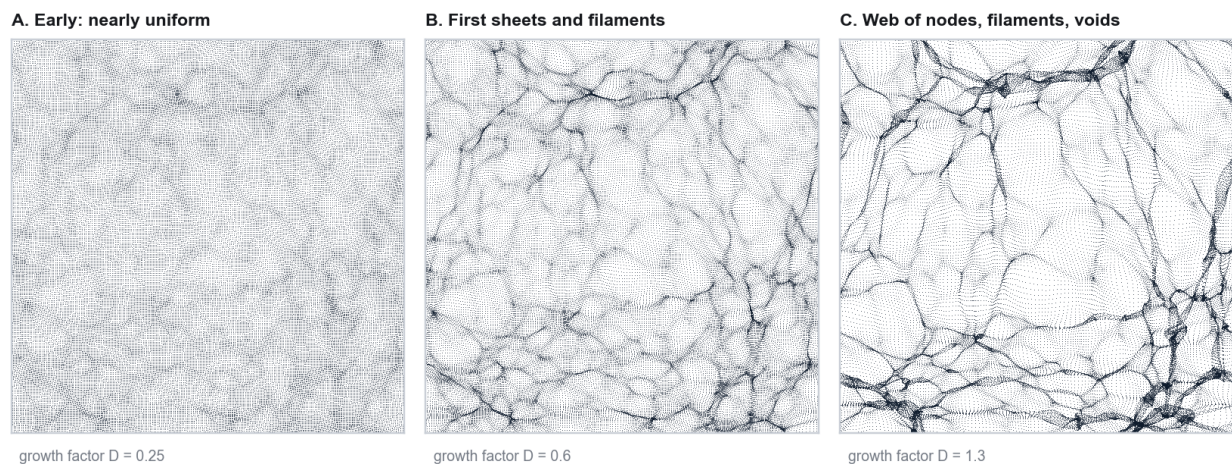


Figure 11. The cosmic web emerging from noise. A two-dimensional simulation in the Zel'dovich approximation: 65,536 particles displaced from a uniform grid by a Gaussian random field, shown at three values of the linear growth factor D . Filaments, nodes and voids appear without being specified.

Source: H Heuristics simulation. Power spectrum $P(k) \propto k^{-1.2}$ with a Gaussian cut-off; periodic box; seed 7. The Zel'dovich approximation is accurate until streams cross and is illustrative thereafter.

Full three-dimensional simulations, starting with the [Millennium Simulation](#) and continuing with [Illustris](#), [EAGLE](#) and [IllustrisTNG](#), confirm the picture and quantify it. [Cautun and colleagues](#) estimate that today roughly half of all mass lies in filaments, which occupy only about 6 per cent of the volume, while voids fill around three-quarters of space but hold only about 15 per cent of the mass. Different methods for [classifying the web](#) disagree on details but agree on this broad architecture. The structure has been mapped directly in surveys of millions of galaxies, and our own Milky Way lies on the outskirts of the [Laniakea supercluster](#), a basin of attraction about 160 megaparsecs across containing around 10^{17} solar masses.

4.4 Where the web ends: the scale of homogeneity

The web is not fractal on all scales. Count galaxies within spheres of increasing radius around each galaxy, and on small scales the count rises more slowly than the volume, because galaxies lie on filaments and sheets. On large enough scales it rises in proportion to the volume, as it would for a uniform distribution. The [WiggleZ survey](#) found this transition at about $70 \text{ h}^{-1} \text{ Mpc}$. Figure 12 measures the same

transition in this report's simulation: the correlation dimension rises from below 1, where matter lies on lines and in knots, towards 2, the value for a uniform distribution in two dimensions.

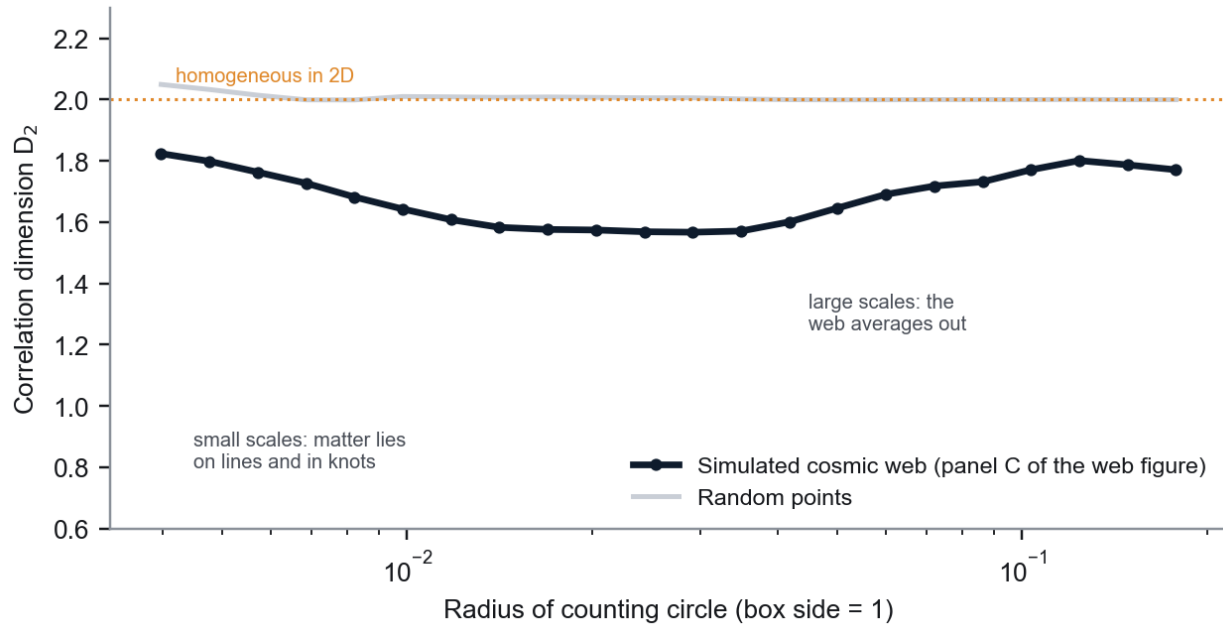


Figure 12. The transition to homogeneity. The correlation dimension D_2 , measured by counting neighbours within circles of increasing radius, rises towards the uniform value of 2 as circles grow larger than the typical filament spacing. Random points give 2 at all scales.

Source: H Heuristics calculation on 60,000 particles from panel C of the cosmic web figure, 3,000 centres, periodic boundaries. In three dimensions surveys find D_2 approaching 3 above about $70 h^{-1} \text{ Mpc}$ (Scrimgeour et al. 2012).

The transition matters for the framework. It shows that the cosmic web is a structure with a characteristic scale, set by the distance gravity has been able to pull matter together in the age of the universe, not an infinitely nested hierarchy. A second characteristic scale is printed on top of it: the [baryon acoustic oscillation](#) scale of about 150 megaparsecs, the distance sound waves travelled in the plasma before recombination. Galaxies are slightly more likely to be found at that separation from one another, and DESI uses the feature as a standard ruler.

4.5 Hierarchy built from the bottom up

In the standard model, structure forms hierarchically. Small dark matter haloes collapse first, because fluctuations are largest on small scales, and larger haloes are assembled by mergers and accretion of smaller ones. [White and Rees](#) proposed in 1978 that galaxies form when gas cools inside these haloes. [Press and Schechter](#) had shown in 1974 how to calculate the number of haloes of each mass from the statistics of the initial fluctuations. Figure 13 shows both: an illustrative merger tree, in which today's halo is the trunk and its many progenitors are branches, and the Press–Schechter mass function computed for this report, in which the cut-off at high mass moves steadily upward as time passes.

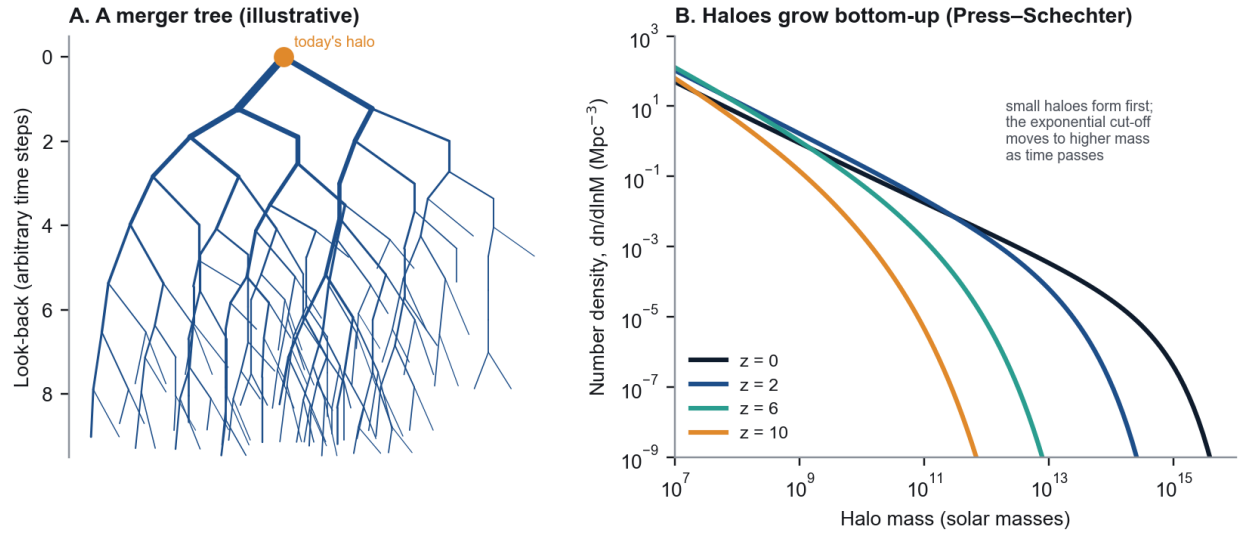


Figure 13. Hierarchical assembly. (A) An illustrative merger tree: today's halo, at the top, was assembled from many smaller progenitors, with line width proportional to mass. (B) The number density of dark matter haloes by mass at four redshifts, computed from the Press–Schechter formalism. Small haloes form first; the exponential cut-off shifts to higher mass over time.

Source: *H Heuristics*. Panel A is a random branching model (illustrative). Panel B uses the BBKS transfer function with $\Gamma = \Omega_m h$, $n_s = 0.965$, $\sigma_8 = 0.811$ and the Λ CDM growth factor.

Hierarchy, branching and aggregation appear here together, and their combination is a recurring motif. A merger tree is a branching structure read backwards; the mass function is the outcome of aggregation; and the nested result, with galaxies inside groups inside clusters inside superclusters, is a hierarchy. The same motif appears in the coagulation of planetesimals (Section 7) and, with heredity instead of gravity, in the tree of life (Section 8).

4.6 A universal shape for haloes

One of the most surprising results of cosmological simulations is that dark matter haloes of very different masses have nearly the same internal structure. [Navarro, Frenk and White](#) found in 1996 that the density of simulated haloes falls as r^{-1} near the centre and as r^{-3} in the outskirts, with a gentle transition at a scale radius r_s :

$$\rho(r) = \rho_s / [(r / r_s)(1 + r / r_s)^2] \quad (4)$$

Figure 14 shows four haloes spanning a factor of 10 million in mass, from a dwarf galaxy's to a cluster's. Their densities differ by orders of magnitude, but rescaled by their characteristic radius and density they fall on a single curve. Smaller haloes are more concentrated, because they formed earlier when the universe was denser, but the shape is the same.

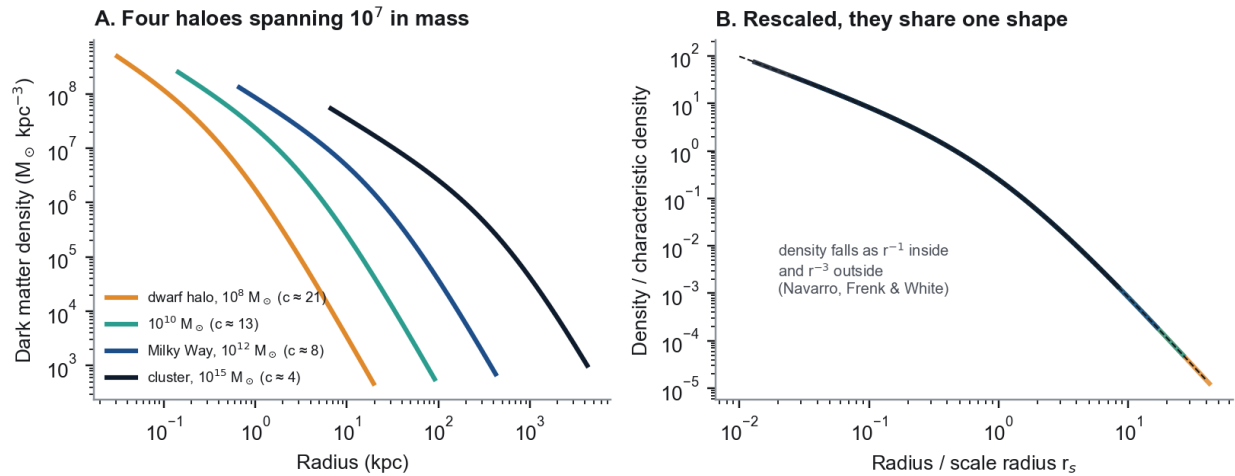


Figure 14. A universal halo profile. (A) Navarro–Frenk–White density profiles for haloes from 10^8 to 10^{15} solar masses, with concentrations from a published concentration–mass relation. (B) Rescaled by scale radius and characteristic density, all four fall on one curve.

Source: H Heuristics calculation using the NFW profile (Navarro, Frenk and White 1997) and the concentration–mass relation of Dutton and Macciò (2014), $\log c = 0.905 - 0.101 \log(M/10^{12} h^{-1} M_{\odot})$.

Why should haloes share a shape? The leading explanation is that violent relaxation during repeated mergers erases memory of initial conditions, driving every halo towards the same statistical equilibrium. This is a clear example of a filter producing recurrence: very different assembly histories are funnelled into a single outcome. It is also the first reason, developed in Section 5, why galaxies themselves share designs. The NFW form is graded B: it describes simulated haloes well, but whether real dwarf galaxies have the predicted central cusps, or flatter cores, remains debated.

Key points. Gravity amplified fluctuations of one part in 100,000 into the cosmic web, but only because dark matter began growing before ordinary matter was free to. The web has a characteristic architecture of sheets, filaments, nodes and voids, a scale above which it becomes uniform, and a hierarchical assembly history. Dark matter haloes, the scaffolding of every galaxy, converge on a single universal shape.

5. Why Galaxies Share Similar Designs

5.1 The puzzle of similarity

Look at Figure 15. It shows 36 galaxies photographed by the Hubble Space Telescope, each tens of millions of light years away, each containing tens of billions of stars, each with its own history of mergers, gas accretion and star formation spanning more than ten billion years. They were selected because they host both Cepheid variable stars and Type Ia supernovae, which makes them useful for measuring the Hubble constant, not because they look alike. Yet they plainly do. Almost every one is a flattened disc with a brighter central bulge, and most show spiral arms winding outward from the centre, often two of them, often starting from a central bar.

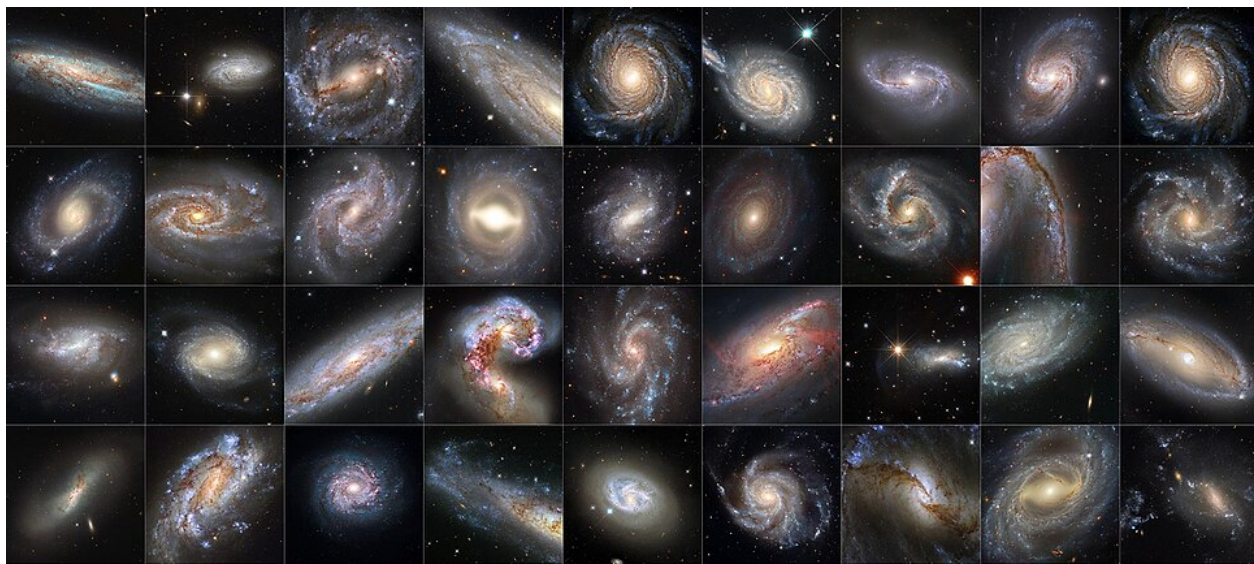


Figure 15. Thirty-six galaxies, one design. Hubble Space Telescope images of galaxies that host both Cepheid variables and Type Ia supernovae, used by the SH0ES team to calibrate the Hubble constant. Despite independent histories, nearly all are discs with a central bulge, and most have spiral arms.

Image credit: NASA, ESA, Adam G. Riess (STScI, JHU). Used for its scientific content; see Riess et al. (2022).

The similarity is not an artefact of selection. When [Edwin Hubble classified galaxies in 1926](#), he found that almost all could be placed on a single sequence running from smooth ellipticals, through lens-shaped S0 galaxies, to spirals with progressively smaller bulges and more open arms, with a parallel branch of barred spirals (Figure 16). A century of observation has added irregular galaxies, dwarf spheroidals and rare oddities, but the basic menu remains short. This section asks why: why do galaxies share similar designs?

The answer in one sentence. Galaxies share designs because they are assembled from only two structural components, a rotating disc and a pressure-supported spheroid, inside dark matter haloes of universal shape, under the same physics of gravity, angular momentum, cooling and feedback, which together leave a very small space of stable forms.

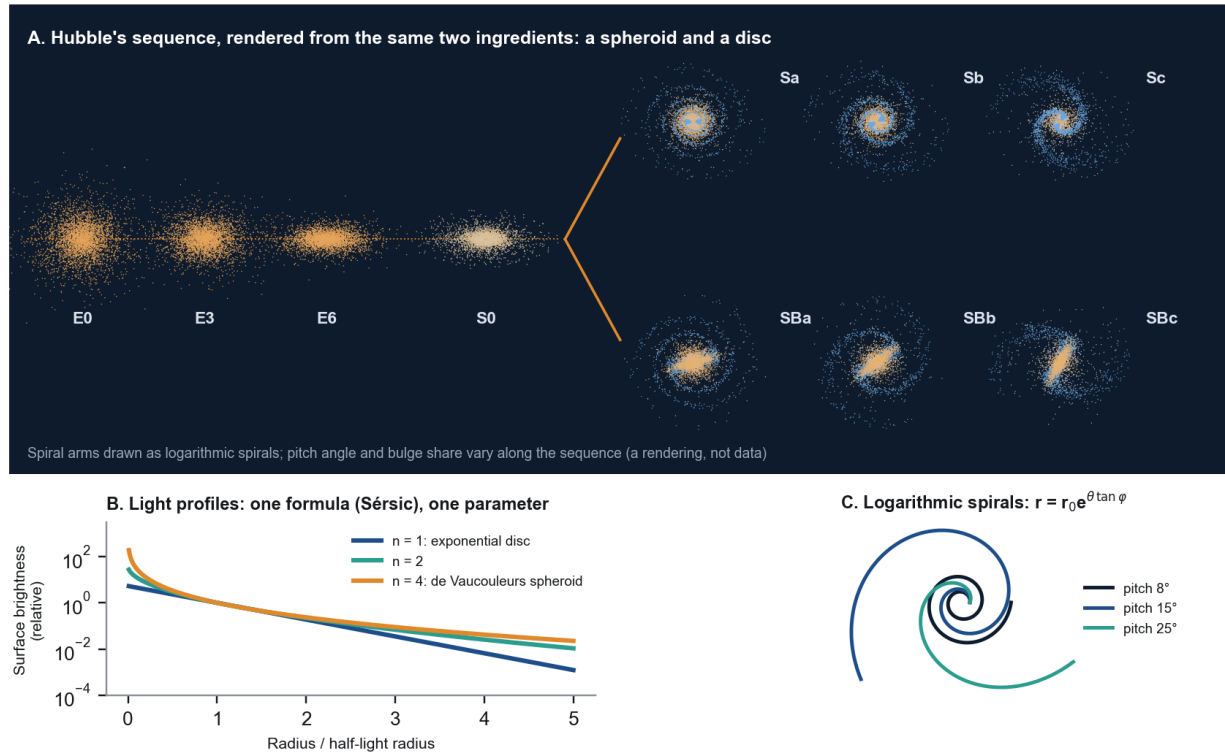


Figure 16. A small morphospace. (A) Hubble's sequence rendered from two ingredients, a spheroid and a disc, by varying the bulge share, the flattening of the spheroid, the presence of a bar and the pitch angle of the spiral arms. (B) Galaxy light profiles follow one formula, the Sérsic law, with a single shape parameter n . (C) Spiral arms are close to logarithmic spirals, whose shape is fixed by one angle.

Source: H Heuristics. Panel A is a rendering, not data; panels B and C are calculated from the Sérsic law, $I(R) = I_e \exp\{-b_n[(R/R_e)^{1/n} - 1]\}$, and $r = r_0 \exp(\theta \tan \varphi)$.

5.2 Constraint: two components and one halo

The first part of the answer is that the space of possible galaxy structures is small. A self-gravitating collection of stars can be supported against collapse in only two ways: by ordered rotation, which produces a thin disc, or by random motions, which produce a rounder, pressure-supported spheroid. Every galaxy in Hubble's sequence is a mixture of these two components in different proportions. Their light profiles reinforce the point. Discs follow an exponential decline in brightness with radius; large spheroids follow a steeper-cored profile described by [de Vaucouleurs](#); and both are special cases of a single formula with one shape parameter, the Sérsic index n (Figure 16, panel B). A family of forms described by so few numbers is the signature of a small possibility space.

Beneath the visible components is a dark matter halo, typically containing five to ten times more mass within the galaxy's outer edge and far more beyond it. Section 4.6 showed that haloes of all masses share one density profile. Galaxies are therefore built in gravitational containers of a standard shape, scaled up or down. That is a powerful source of similarity, and it explains a classic observation: rotation curves that stay flat far beyond the visible disc, as [Vera Rubin and Kent Ford found for Andromeda in 1970](#). Figure 17 decomposes a Milky-Way-like rotation curve computed for this report. At 30 kiloparsecs from the centre, the stars and gas alone would give an orbital speed of about 100 km s^{-1} ; the total, including the halo, is about 200 km s^{-1} .

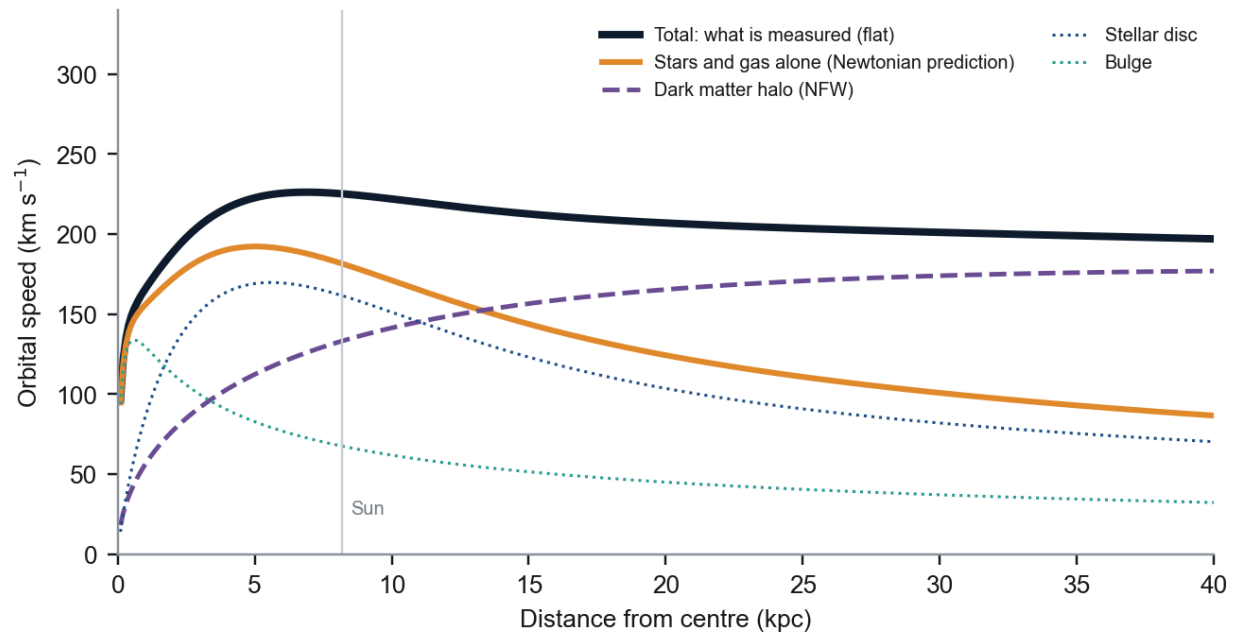


Figure 17. Why rotation curves are flat. Orbital speed in a Milky-Way-like galaxy computed from an exponential stellar disc, a gas disc, a bulge and a dark matter halo. The visible components alone predict a falling curve; the halo holds it flat.

Source: H Heuristics calculation. Stellar disc $4.5 \times 10^{10} M_{\odot}$ with scale length 2.6 kpc (Freeman formula); gas disc $1.2 \times 10^{10} M_{\odot}$; Hernquist bulge $10^{10} M_{\odot}$; NFW halo $1.1 \times 10^{12} M_{\odot}$, $c = 10$. The computed speed at the Sun's radius is 225 km s^{-1} .

5.3 Generator: angular momentum makes discs

Why are discs so common? The answer is angular momentum, conserved by Noether's theorem. As a dark matter halo forms, tidal forces from its neighbours set it spinning slightly, as [Jim Peebles showed in 1969](#). The spin is small: a dimensionless spin parameter λ of about 0.035, with a [roughly log-normal spread](#) between haloes. Gas inside the halo shares that spin. Gas, unlike dark matter, can radiate energy away and cool. As it cools it sinks, and as it sinks it spins faster, like a spinning skater pulling in their arms, until rotation balances gravity. Collapse stops in the plane of rotation but not perpendicular to it, so the gas settles into a thin, rotating disc.

[Fall and Efstathiou \(1980\)](#) and [Mo, Mao and White \(1998\)](#) turned this into a quantitative model. If gas conserves its specific angular momentum as it cools, the disc's scale length is roughly $\lambda/\sqrt{2}$ times the radius of the halo, which predicts discs of a few kiloparsecs in haloes like the Milky Way's, as observed. The same mechanism, at a scale ten billion times smaller, makes the protoplanetary discs from which planets form (Section 7). Disc formation is the clearest example in this report of one constraint, angular momentum conservation, plus one generator, dissipative cooling, producing the same form at very different scales (Grade A).

5.4 Generator: mergers make spheroids

If discs are the default, where do ellipticals and bulges come from? The leading answer is mergers. When two galaxies of similar mass collide, their stars, which almost never hit one another, are flung onto randomised orbits. The ordered rotation of the discs is converted into random motion, and the remnant settles into a spheroid. [Alar and Juri Toomre's simulations of 1972](#) reproduced the tidal tails and bridges seen in interacting galaxies, and the merger hypothesis for ellipticals has since been supported by

simulations and by the shells, streams and kinematic oddities found in many ellipticals. Major mergers are graded B as the main origin of massive ellipticals; many bulges, called pseudobulges, instead grow slowly from [internal processes in the disc](#).

The position of a galaxy on the Hubble sequence therefore records, in part, the balance between two generators acting over its history: quiet accretion of gas, which builds discs, and mergers, which build spheroids. A galaxy that has had no major merger for many billions of years, like the Milky Way, is disc-dominated. One in the centre of a dense cluster, where mergers and gas stripping were frequent, is likely to be elliptical. Morphology is a structural readout of environment and history.

5.5 Generator: disc instabilities make bars and spirals

Spiral arms present a famous puzzle. Galaxies rotate differentially: stars near the centre complete an orbit faster than stars farther out. If spiral arms were fixed bands of material, differential rotation would wind them ever tighter. In the Milky Way the Sun takes about 230 million years to orbit once, so arms made of stars would have wound around dozens of times during the galaxy's life, producing patterns far tighter than those observed. Figure 18 demonstrates this winding problem with a flat rotation curve: after only a billion years, two initially straight arms have become tightly wound spirals.

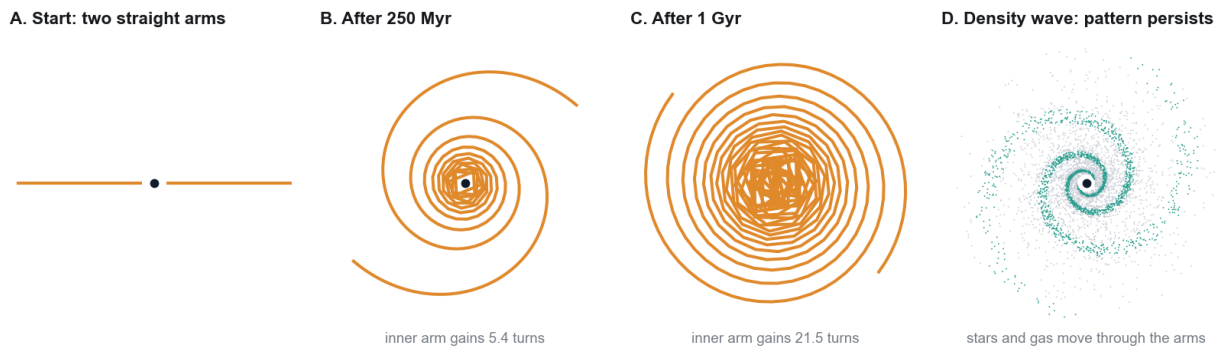


Figure 18. The winding problem and its solution. (A–C) Two straight material arms in a disc with a flat rotation curve of 220 km s^{-1} : after 1 billion years the inner arm has completed about 21 more turns than the outer, producing a far tighter spiral than real galaxies show. (D) A density wave: a rigidly rotating two-armed logarithmic pattern through which stars and gas flow, which keeps its shape.

Source: H Heuristics calculation. Panels A–C: $\phi(R, t) = \phi_0 + (v/R)t$. Panel D: a stellar disc with surface density modulated by a two-armed logarithmic spiral of pitch angle 15° (illustrative).

The leading resolution, proposed by [Lin and Shu in 1964](#), is that many spiral arms are density waves: patterns of enhanced density that rotate more slowly than the stars, which pass through them like cars through a traffic jam. Gas is compressed as it enters an arm, triggering star formation, which is why arms are lined with bright young stars. Simulations show that many spirals are not long-lived waves but recurrent, transient patterns generated by [swing amplification](#) of small disturbances, continually forming and dissolving. Either way, the arms are a pattern, not a fixed set of stars (Grade B).

The key is the disc instability shown in Figure 9, panel B. [Alar Toomre showed in 1964](#) that a rotating disc is stable against local collapse when

$$Q = \sigma \kappa / (3.36 G \Sigma) > 1 \quad (5)$$

where σ is the random velocity of the stars, κ the epicyclic frequency set by the rotation curve and Σ the surface density. Discs in real galaxies tend to sit near $Q \approx 1$ to 2. This is a filter in the framework's sense, and it is self-regulating: if a disc becomes too cold and dense, it forms clumps and spiral arms that heat it;

if it becomes too hot, it cannot sustain arms, and fresh gas cools it again. Near-marginal stability means that spiral arms are generated continuously, and that their shape depends mainly on the rotation curve, through κ and the shear. Because rotation curves are similar, spirals are similar.

Bars arise from the same family of instabilities. [Ostriker and Peebles](#) showed in 1973 that cold, self-gravitating discs are violently unstable to forming bars unless embedded in a massive halo, one of the earliest theoretical arguments for dark haloes. Bars are seen in roughly half to two-thirds of nearby disc galaxies, depending on how they are counted, and drive gas inward, feeding central star formation and building pseudobulges.

Why logarithmic spirals in particular? A logarithmic spiral is the only curve that keeps the same shape when scaled: every turn is a magnified copy of the one inside it, with a constant angle between the arm and a circle around the centre. Density-wave theory in the tight-winding limit yields arms of approximately constant pitch angle wherever the disc's properties change smoothly with radius, and a constant pitch angle defines a logarithmic spiral. The recurrence of the form is therefore not mysterious: it is what a self-similar pattern looks like in a disc whose properties vary smoothly with radius (Grade B). Claims that galactic spirals follow the golden ratio, by contrast, do not survive measurement: observed pitch angles range from under 10 degrees to over 40 (Grade D for any golden-ratio rule).

5.6 Filter: feedback and the tightness of scaling relations

The strongest evidence that galaxies are built by a common architecture is not their appearance but their numbers. Galaxies obey scaling relations far tighter than their varied histories would suggest (Figure 19).

- **The baryonic Tully–Fisher relation.** The total mass of stars and gas in a disc galaxy is proportional to the fourth power of its flat rotation speed, $M_b \approx 47 V_f^4$ in solar masses and kilometres per second, according to [McGaugh](#). The relation holds across [about five decades of mass](#) with an intrinsic scatter of about 0.1 dex, which is why it can be used to measure distances.
- **The radial acceleration relation.** In [153 galaxies with high-quality rotation curves](#), the observed acceleration at each radius is [predicted by the visible matter alone](#) through a single function, with little scatter. Whether this is a natural outcome of galaxy formation with dark matter, or evidence for modified gravity, is one of the liveliest debates in the field (Grade C for either interpretation).
- **The star-forming main sequence.** Most star-forming galaxies form stars at a rate roughly proportional to their stellar mass, along a [sequence whose normalisation has fallen](#) about thirtyfold over the last ten billion years.
- **Black hole scaling.** The mass of the central supermassive black hole correlates tightly with the mass and velocity dispersion of the host's bulge, at about [half a per cent of the bulge mass](#).
- **Colour bimodality.** Galaxies divide into a [blue cloud of star-forming discs and a red sequence](#) of quiescent, mostly spheroidal systems, with relatively few in the 'green valley' between.

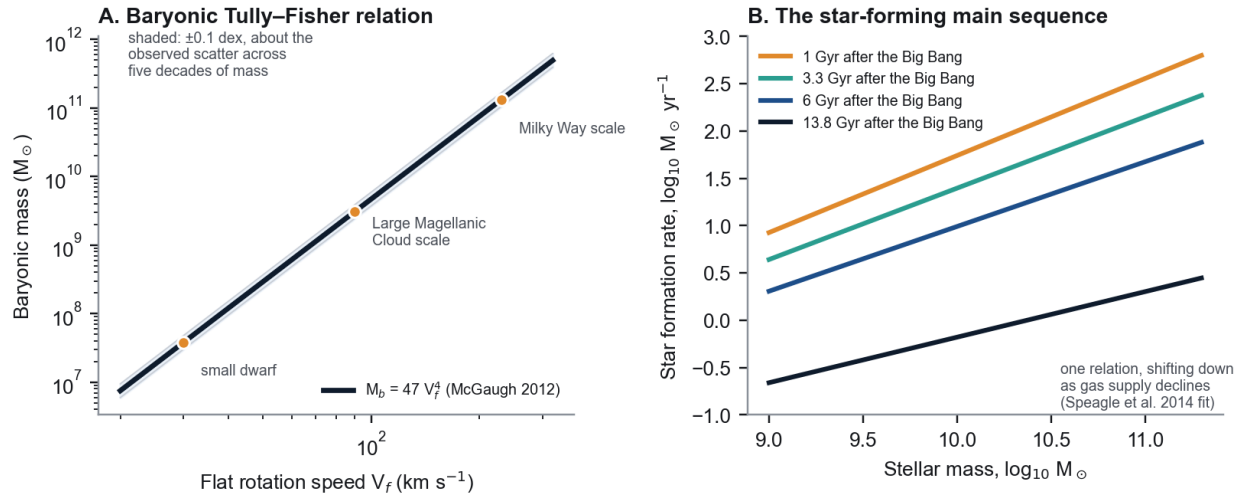


Figure 19. Galaxies obey simple laws. (A) The baryonic Tully–Fisher relation: baryonic mass scales as the fourth power of the flat rotation speed, with observed scatter of about 0.1 dex. (B) The star-forming main sequence at four cosmic times: star formation rate rises nearly in proportion to stellar mass, and the whole relation drops as galaxies run short of gas.

Source: *H Heuristics*, plotting the relations of McGaugh (2012), $M_b = 47 V_f^4$, and Speagle et al. (2014), $\log \text{SFR} = (0.84 - 0.026t) \log M^* - (6.51 - 0.11t)$. Marked points illustrate scales, not individual galaxies.

Tight relations need a mechanism that erases history. The leading candidate is feedback. When gas forms stars, the most massive stars explode as supernovae within a few million years, heating and expelling gas and suppressing further star formation. In massive galaxies, energy from accretion onto the central black hole does the same on a larger scale. The result is a self-regulating system, often modelled as a [gas regulator or 'bathtub'](#): inflow fills the tub, star formation and outflow drain it, and the level settles at an equilibrium set by the inflow rate. Galaxies on the main sequence are in this equilibrium. Feedback also explains why galaxy formation is inefficient: [even in the most efficient haloes](#), around the Milky Way's mass, only about a fifth of the available ordinary matter has been turned into stars.

Quenching, the shutting down of star formation, moves galaxies from the blue cloud to the red sequence. It is driven by black hole feedback, by the heating of gas in massive haloes and by environmental effects in clusters. The bimodality is therefore a filter's signature: galaxies sit in one of two stable states, and the transition between them is quick, which is why few are caught in between.

5.7 Putting it together

Table 6 sets out the creation structure of galaxies in the framework's terms. The answer to why galaxies share similar designs has four parts. The possibility space is small, because self-gravitating stellar systems can be supported only by rotation or by random motion. The containers are standard, because dark matter haloes converge on a universal profile. The generators are shared: angular momentum and cooling make discs, mergers make spheroids, and disc instabilities make bars and spiral arms. And the filters erase history, because marginal stability and feedback hold galaxies near a small number of equilibrium states.

Table 6. The creation structure of galaxies

Component	Mechanism	Recurring outcome	Grade
Constraint	Gravity; conservation of angular momentum; only two modes of support (rotation, random motion)	Discs and spheroids; a short Hubble sequence	A
Constraint	Universal dark matter halo profile from violent relaxation	Flat rotation curves; similar structure at all masses	B
Generator	Tidal torques and dissipative cooling of gas	Exponential discs of predictable size	A
Generator	Mergers randomising stellar orbits	Ellipticals and classical bulges	B
Generator	Disc instabilities, density waves and swing amplification	Bars; logarithmic spiral arms	B
Filter	Toomre stability near $Q \approx 1$	Continuous regeneration of spiral structure	B
Filter	Supernova and black hole feedback; quenching	Tight scaling relations; red and blue populations	B

Source: *H Heuristics synthesis of the literature cited in this section.*

There is a further consequence of galaxy similarity, and it is a practical one. Because galaxies and the stars within them are similar, astronomers can use them as standard candles and rulers. Cepheid variables obey a period–luminosity relation; Type Ia supernovae have nearly standard peak brightness; the Tully–Fisher relation turns a rotation speed into a mass and thus a distance. The galaxies in Figure 15 were imaged precisely because their similarity makes the universe measurable. Recurrence is not only a curiosity of the architecture; it is the basis of cosmic surveying.

5.8 What the architecture does not yet explain

The standard model of galaxy formation is not complete, and several observations test it. JWST has found more [bright galaxies at very early times](#) than many models predicted, suggesting that early star formation was more efficient or less suppressed than assumed (Grade C). Some dwarf galaxies appear to have flatter central densities than the cusps of Equation 4, the core–cusp problem; feedback may flatten them, or dark matter may have properties not yet included. The tightness of the radial acceleration relation is regarded by some as a natural outcome of feedback and by others as evidence for modified gravity. And the diversity of rotation curves among dwarf galaxies of similar mass is larger than simple models predict. [Naab and Ostriker](#) and [Somerville and Davé](#) review these problems. None overturns the architecture described here, but each marks a place where the filters, especially feedback, are not yet understood in detail.

Key points. Galaxies look alike because they are combinations of a disc and a spheroid inside haloes of universal shape, shaped by the same generators (cooling with angular momentum, mergers and disc instabilities) and held near equilibrium by the same filters (marginal stability and feedback). Their similarity is strong enough to make them distance markers. The remaining puzzles concern the details of feedback and the nature of dark matter, not the overall design.

6. Stars and the Architecture of Elements

6.1 How stars form

Stars form inside cold, dense clouds of molecular hydrogen, typically tens of light years across and containing thousands to millions of solar masses. Within them, the Jeans instability of Equation 2 operates on a smaller scale: regions denser than their surroundings collapse, fragment and collapse again, forming filaments and cores that give birth to stars in clusters. [McKee and Ostriker](#) and [Kennicutt and Evans](#) review the theory and observations. The process is strikingly inefficient: only a few per cent of a cloud's gas becomes stars in each free-fall time, because turbulence, magnetic fields and radiation from young stars resist collapse. Star formation is a generator restrained by feedback, the same combination that regulates whole galaxies.

The distribution of masses with which stars are born, the initial mass function, is one of the most consistent quantities in astrophysics (Figure 20). [Edwin Salpeter showed in 1955](#) that above about one solar mass the number of stars falls as $m^{-2.35}$. [Pavel Kroupa's](#) form adds a flattening below half a solar mass. With it, about three-quarters of hydrogen-burning stars are red dwarfs of less than half a solar mass, while fewer than one star in two hundred is massive enough to end as a supernova. Those rare massive stars nonetheless hold about a fifth of the mass of each new generation and do most of the chemical work. Whether the initial mass function is truly universal or varies in extreme environments, such as the cores of giant ellipticals, is debated (Grade B for near-universality).

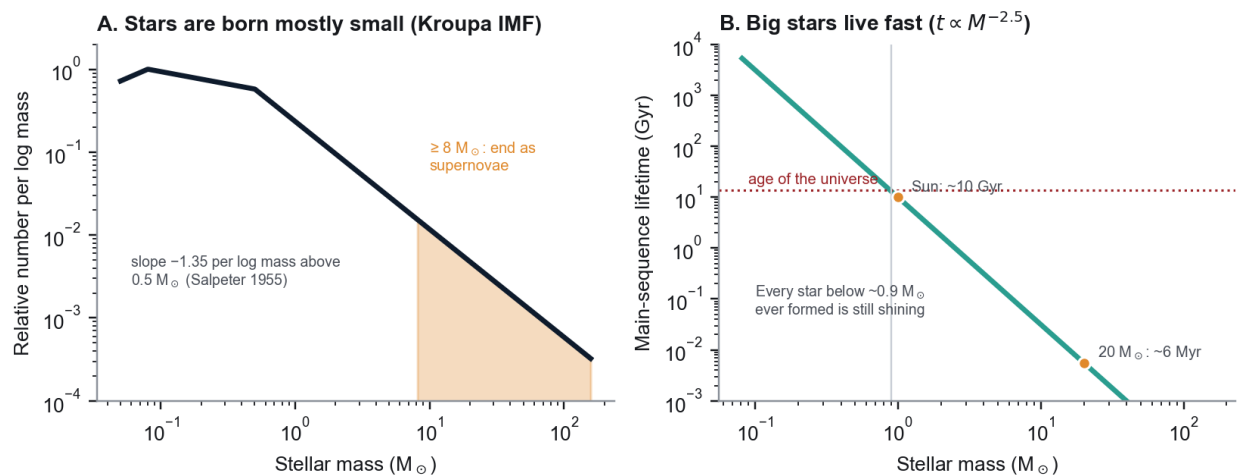


Figure 20. Most stars are small, and small stars live long. (A) The Kroupa initial mass function, per logarithmic interval of mass; stars above eight solar masses, which end as supernovae, are shaded. (B) Main-sequence lifetime falls steeply with mass. No star below about 0.9 solar masses has yet exhausted its core hydrogen.

Source: H Heuristics calculation. IMF slopes -0.3 , -1.3 and -2.3 in dN/dm with breaks at 0.08 and $0.5 M_{\odot}$ (Kroupa 2001); lifetimes approximated as $10 \text{ Gyr} \times (M/M_{\odot})^{(-2.5)}$.

6.2 The stellar thermostat

A star is a ball of gas in which gravity pulling inward is balanced by pressure pushing outward. The condition is hydrostatic equilibrium,

$$dP/dr = -G M(r) \rho(r) / r^2 \quad (6)$$

and it makes stars one of the most elegant examples of a feedback loop in nature. Suppose the core of a star produced energy slightly too fast. The extra heat would raise the pressure, the core would expand, its temperature would fall and the rate of fusion, which depends steeply on temperature, would drop back. If the core produced too little energy it would contract, heat up and speed up. A star is a thermostat whose set point is fixed by its mass (Grade A).

Figure 21 shows why the thermostat is so effective. The proton–proton chain, which powers the Sun, releases energy at a rate rising roughly as the fourth power of temperature near 15 million kelvin. The CNO cycle, in which carbon, nitrogen and oxygen act as catalysts, rises as nearly the twentieth power, and dominates in stars somewhat more massive than the Sun, whose cores exceed about 18 million kelvin. The triple-alpha process, which fuses helium into carbon, rises more steeply still. Steep dependence means that a tiny change in temperature produces a large change in power, so the feedback is strong.

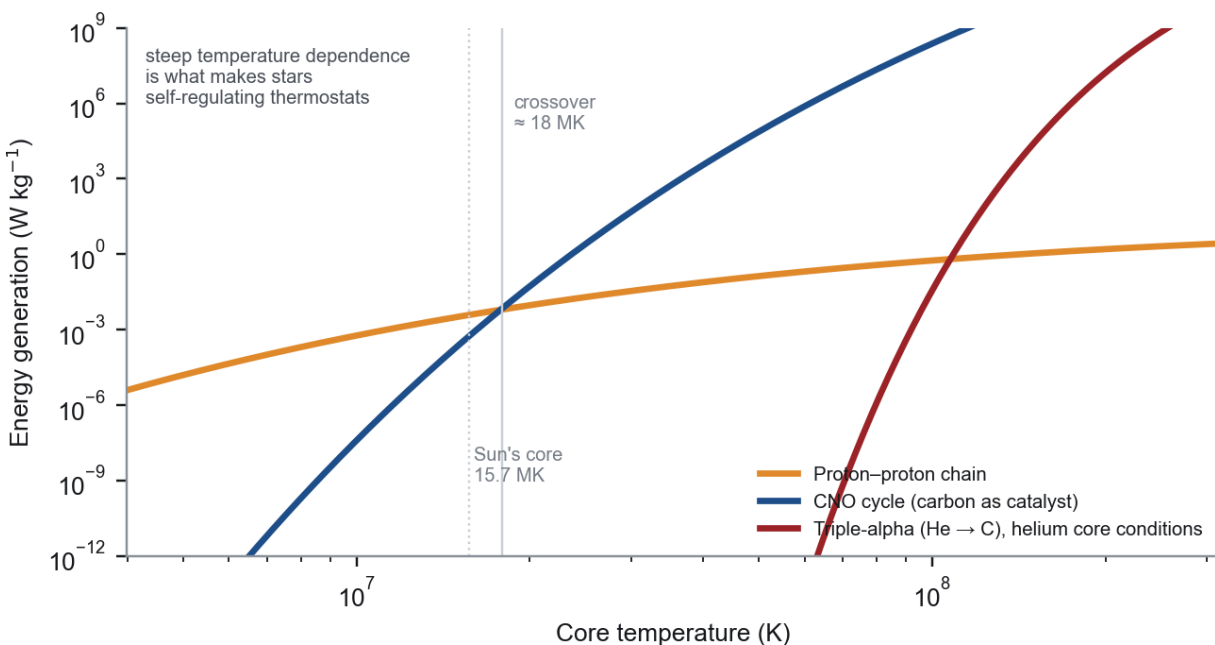


Figure 21. Fusion as a thermostat. Energy generation rates for the proton–proton chain, the CNO cycle and the triple-alpha process. The steep rise with temperature is what makes stars stable; the crossover from pp to CNO near 18 million K separates Sun-like stars from more massive ones.

Source: *H Heuristics* calculation using standard approximations to the reaction rates (Carroll and Ostlie, *An Introduction to Modern Astrophysics*), with $\rho = 1.5 \times 10^5 \text{ kg m}^{-3}$, $X = 0.70$, $X_{\text{CNO}} = 0.01$ for hydrogen burning and $\rho = 10^8 \text{ kg m}^{-3}$ for helium burning.

The Sun converts about 600 million tonnes of hydrogen into helium each second, turning about four million tonnes of mass into energy. It has done so for 4.6 billion years with a luminosity that has risen by only about 40 per cent. That long, steady burn, made possible by the thermostat, is one of the preconditions for life on Earth (Section 7.5).

6.3 Making the elements

Stars are also the factories in which nearly every element heavier than helium was made. The theory was set out in the landmark paper of [Burbidge, Burbidge, Fowler and Hoyle](#) in 1957, often called B²FH. Its logic rests on a single curve: the binding energy per nucleon of atomic nuclei (Figure 22). Binding energy rises steeply from hydrogen through helium, carbon and oxygen to a broad peak near iron-56 and nickel-

62, then declines slowly towards uranium. Fusing light nuclei into heavier ones up to the iron peak releases energy, which is what powers stars. Beyond iron, fusion absorbs energy, so stars cannot build heavier elements by fusion at all.

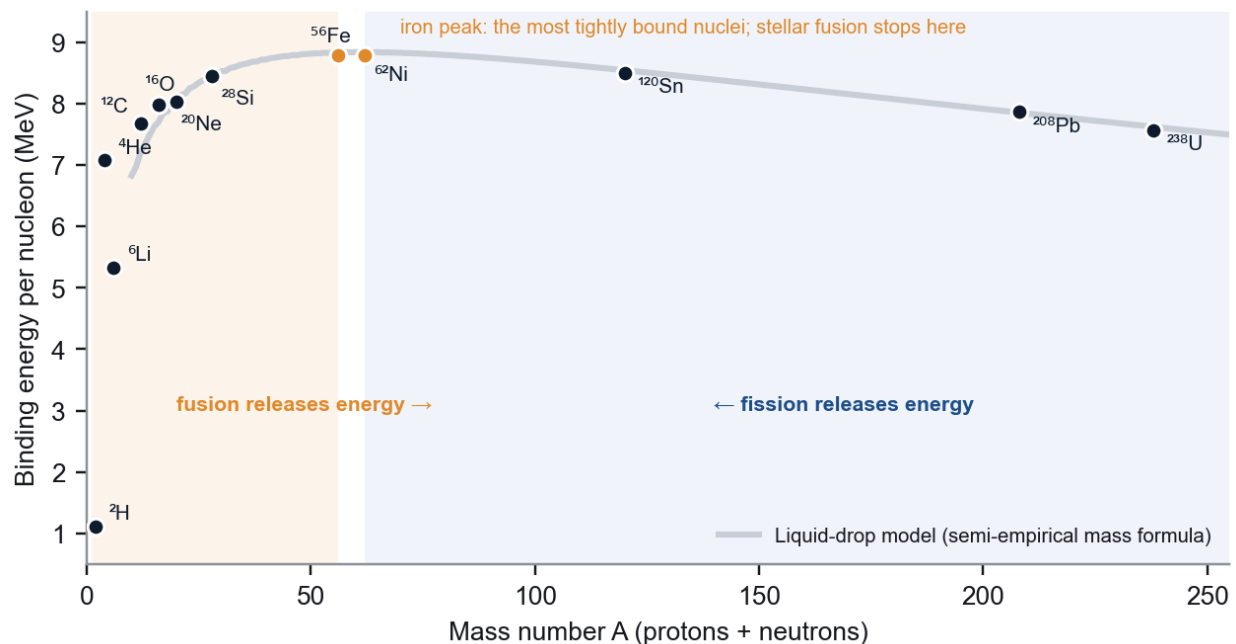


Figure 22. The curve that governs the elements. Binding energy per nucleon from the liquid-drop model, with measured values for selected nuclei. Fusion releases energy up to the iron peak; fission releases energy beyond it. The peak is why stellar fusion ends at iron.

Source: H Heuristics calculation with the semi-empirical mass formula ($a_V = 15.75$, $a_S = 17.8$, $a_C = 0.711$, $a_A = 23.7$ MeV), choosing the most stable Z for each A; measured values from standard nuclear data tables.

Each stage of a star's life fuses the ash of the previous stage. Hydrogen burns to helium. When core hydrogen is exhausted, the core contracts and heats until helium fuses to carbon through the triple-alpha process, which depends on the excited state of carbon-12 predicted by Hoyle (Section 3.7), and carbon captures another helium nucleus to make oxygen. In stars above about eight solar masses, the sequence continues through neon, oxygen and silicon burning, producing an onion-like structure of shells around an iron core ([Woosley, Heger and Weaver 2002](#)). This is differentiation driven by gravity and nuclear physics together: a star that began uniform ends as a series of concentric layers of increasingly heavy elements.

Elements beyond iron are made mostly by neutron capture. In the slow process, or s-process, which operates in the late stages of low- and intermediate-mass stars, nuclei absorb neutrons one at a time and have time to decay between captures, building elements such as strontium, barium and lead. In the rapid process, or r-process, a flood of neutrons is captured faster than nuclei can decay, building the heaviest elements, including gold, platinum and uranium. The detection of gravitational waves from the neutron star merger [GW170817](#) in 2017, followed by the glow of a kilonova, confirmed that such mergers [produce r-process elements](#) in quantity (Grade A for mergers as a site; their share of the total relative to rare kinds of supernova is Grade C).

Figure 23 summarises where the elements come from, simplified from [Jennifer Johnson's periodic table of origins](#). The pattern is a map of the generators: the Big Bang for hydrogen and helium; cosmic-ray collisions for lithium, beryllium and boron; exploding massive stars for oxygen, silicon and calcium;

exploding white dwarfs for much of the iron; dying low-mass stars for carbon, nitrogen and the s-process elements; and merging neutron stars for gold and platinum. Table 7 lists how stars of different mass end. Table 7 lists how stars of different mass end.

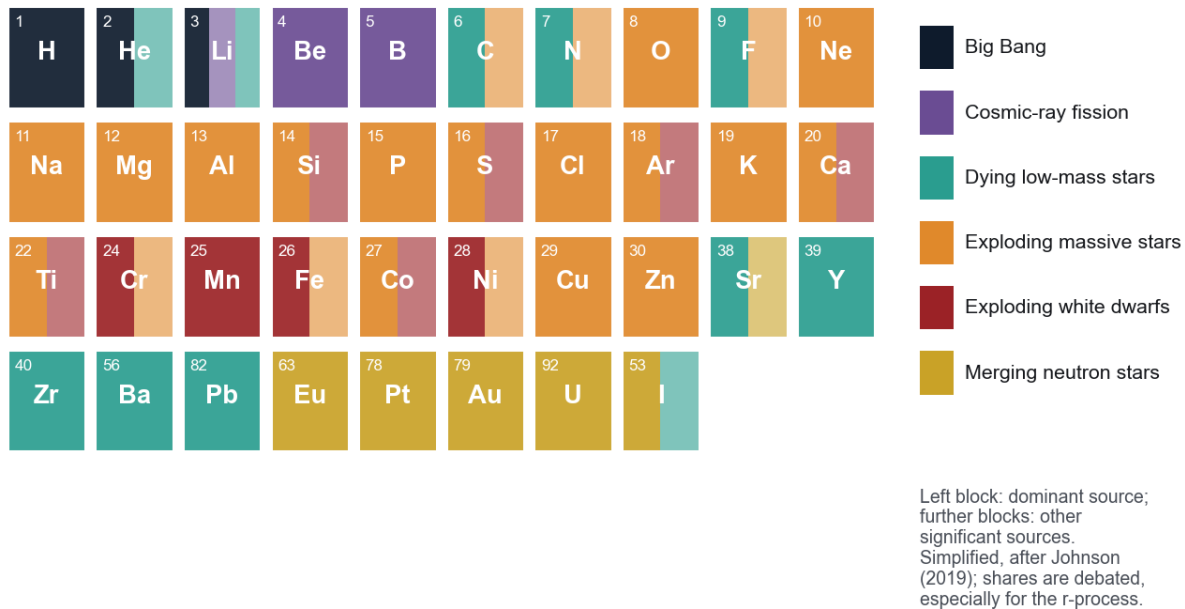


Figure 23. Where the elements come from. Each tile is coloured by the dominant source of that element in the Solar System, with other significant sources shown as further blocks.

Source: H Heuristics, simplified after Johnson (2019) and Kobayashi, Karakas and Lugaro (2020). Attributions are approximate; shares for several elements, especially the r-process elements, are debated.

Table 7. How stars end, by initial mass

Initial mass	Main-sequence life	Final stages	Remnant	Elements returned
Below 0.5 M_☉	Over 50 Gyr	None yet in the universe's history	Helium white dwarf (future)	None yet
0.5–8 M_☉	About 50 Gyr to 50 Myr	Red giant; asymptotic giant branch; planetary nebula	Carbon–oxygen white dwarf	Carbon, nitrogen, s-process elements
8–25 M_☉	About 50 to 7 Myr	Successive burning to an iron core; core-collapse supernova	Neutron star	Oxygen to calcium; some iron
Above about 25 M_☉	Under 7 Myr	Collapse, with or without a supernova	Black hole	Varies; some fall back
White dwarf in a binary	n/a	Accretion or merger beyond 1.4 M _☉	None (Type Ia supernova)	Iron-peak elements

Sources: Woosley, Heger and Weaver (2002); Heger et al. (2003); Smartt (2009). Mass boundaries are approximate and depend on composition, rotation and binarity; the 1.4 M_☉ limit is from Chandrasekhar (1931).

6.4 The fingerprint in the Sun

The history of element formation is written in the composition of the Sun (Figure 24). By mass, the [solar photosphere](#) is about 74 per cent hydrogen, 25 per cent helium and 1.3 per cent everything else. Within that small remainder the abundance pattern carries four signatures of the generators that made it: a Big Bang signature in hydrogen and helium; a deep trough at lithium, beryllium and boron, fragile nuclei that

fusion destroys instead of making; a sawtooth in which elements with even atomic number are more abundant than their odd neighbours, because the main stellar pathways add helium-4 nuclei, each with two protons; and a peak at iron, the endpoint of fusion. The pattern is a record of creation structures acting over billions of years.

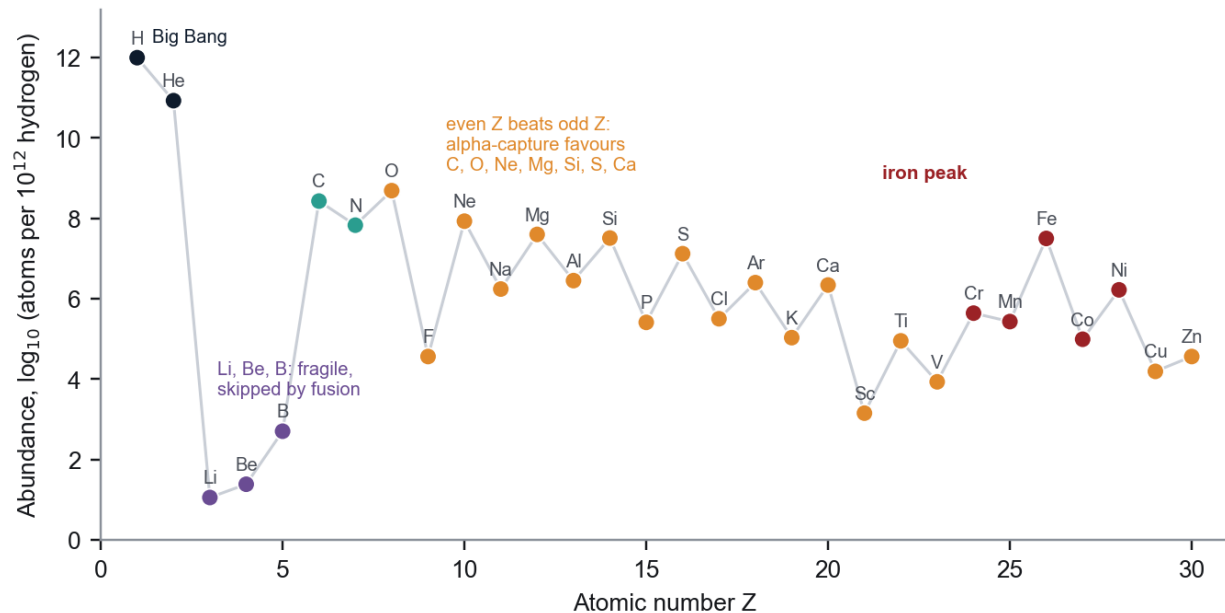


Figure 24. The Sun's composition records how the elements were made. Photospheric abundances for the first 30 elements on a logarithmic scale, relative to 10¹² hydrogen atoms. Note the lithium–boron trough, the even–odd sawtooth and the iron peak.

Source: Asplund et al. (2009), photospheric values. Colours: Big Bang (navy), cosmic-ray spallation (purple), CNO-processed (teal), alpha and iron-group elements (orange and red).

6.5 Generations of stars

Elements made in one generation of stars are returned to the interstellar medium by winds and explosions and incorporated into the next. This is the closest cosmic analogue to heredity, and it gives the reproductive layer of the framework a non-biological counterpart. Each generation starts richer in heavy elements, which astronomers call metals. Metals change the physics of the next generation: they make gas cool more efficiently, allowing smaller clouds to collapse, and they provide the raw material for rocky planets. The first stars, known as Population III, formed from pristine hydrogen and helium and were probably [massive](#), perhaps tens to hundreds of solar masses ([Bromm and Larson 2004](#)). None has been observed directly; finding their signature is a major goal for JWST (Grade B for their existence and high typical mass).

The chemical record of some ancient stars preserves single events. Stars in the ultra-faint dwarf galaxy Reticulum II are enriched in r-process elements by a factor of hundreds relative to similar galaxies, consistent with [a single neutron star merger](#) having seeded the whole galaxy. That is the cosmic equivalent of a founder effect in population genetics: a rare event that leaves a lasting signature on everything that follows.

6.6 The history of star formation

The rate at which the universe forms stars has changed dramatically (Figure 25). Using the compilation of [Madau and Dickinson](#), the cosmic star formation rate rose for the first three billion years, peaked at a redshift of about 1.9 during 'cosmic noon', around 3.5 billion years after the Big Bang, and has since fallen by a factor of about nine. Integrating the curve, half of all the stars ever formed already existed by a redshift of about 1.3, when the universe was under five billion years old. Star formation is now in long-term decline, because gas is being used up and new supplies are not reaching galaxies fast enough. The architecture of stellar creation has already passed its peak (Grade A).

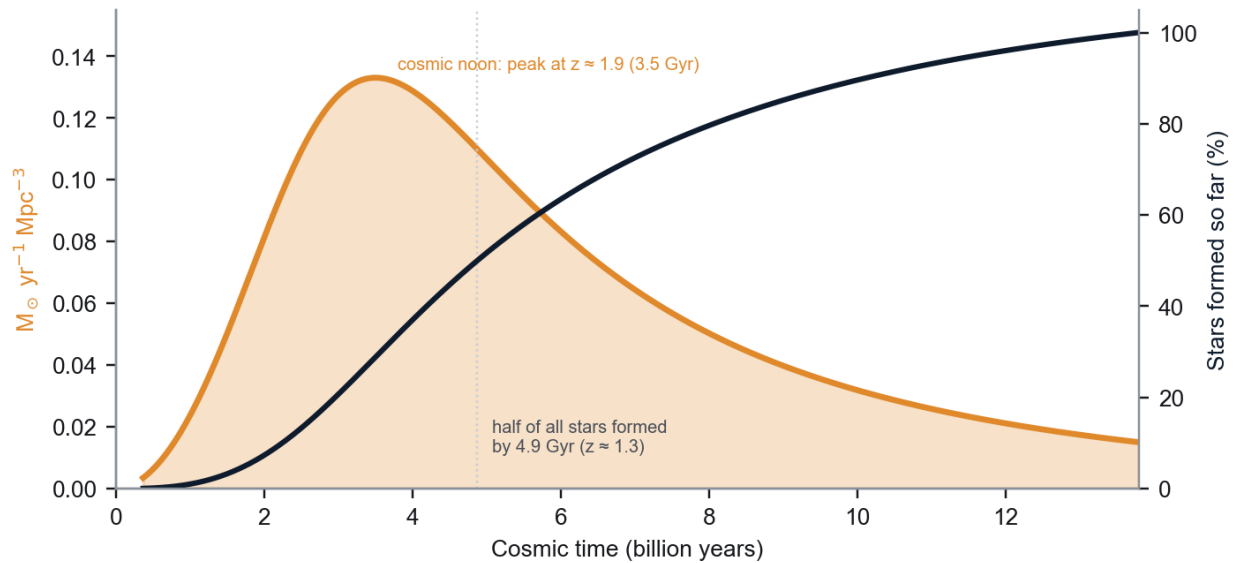


Figure 25. The universe has passed its peak of star formation. The cosmic star formation rate density (orange) and the cumulative share of today's stars already formed (navy). Star formation peaked at cosmic noon and has since fallen about ninefold.

Source: H Heuristics calculation from the fitting function of Madau and Dickinson (2014), $\psi(z) = 0.015(1+z)^{2.7} / [1 + ((1+z)/2.9)^{5.6}] M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$, converted to cosmic time with Planck 2018 parameters and a return fraction of 0.27.

Key points. Stars are gravitational structures stabilised by a nuclear thermostat. Their initial mass function is close to universal; their lives are set by their masses; and their deaths seed the next generation with heavier elements. The binding energy curve explains why fusion stops at iron, and the Sun's composition preserves the record of every generator that built it. Cosmic star formation peaked about ten billion years ago.

7. Planetary Systems and the Emergence of Habitable Environments

7.1 Discs again

When a dense core in a molecular cloud collapses to form a star, it carries angular momentum. For the same reason as in a galaxy (Section 5.3), the infalling material cannot fall straight onto the young star but settles into a flattened, rotating disc of gas and dust. Protoplanetary discs are a near-universal accompaniment to star formation. ALMA's [image of the young star HL Tauri](#) in 2014 showed a disc less than a million years old already marked by concentric rings and gaps, likely carved by forming planets. Discs last only a few million years before the gas is dispersed by the star's radiation, so planet formation is a race against time.

The recurrence is exact in kind but differs by a factor of about ten billion in scale. A galactic disc and a protoplanetary disc share the same constraint, angular momentum conservation, and the same generator, dissipation, which removes energy but not angular momentum. In both, viscous or gravitational processes then move mass inward and angular momentum outward. The disc is one of the clearest cases in this report of a form that recurs because the same constraint and generator operate (Grade A).

7.2 The temperature gradient sorts the materials

Close to the young star the disc is hot; far from it, cold. As a result, different materials condense at different distances (Figure 26). In the classic [minimum-mass solar nebula](#) of Chushiro Hayashi, temperature falls as the inverse square root of distance, from about 280 K at Earth's distance. Inside about 2.7 astronomical units only rock and metal can condense. Beyond that, at the snow line, water ice becomes solid and the mass of solid material available jumps several-fold. The Solar System's architecture, with small rocky planets inside and giant planets outside, is a direct readout of that gradient. Its oldest solids, calcium–aluminium-rich inclusions in meteorites, [formed 4,567.3 million years ago](#), the conventional start of the Solar System.

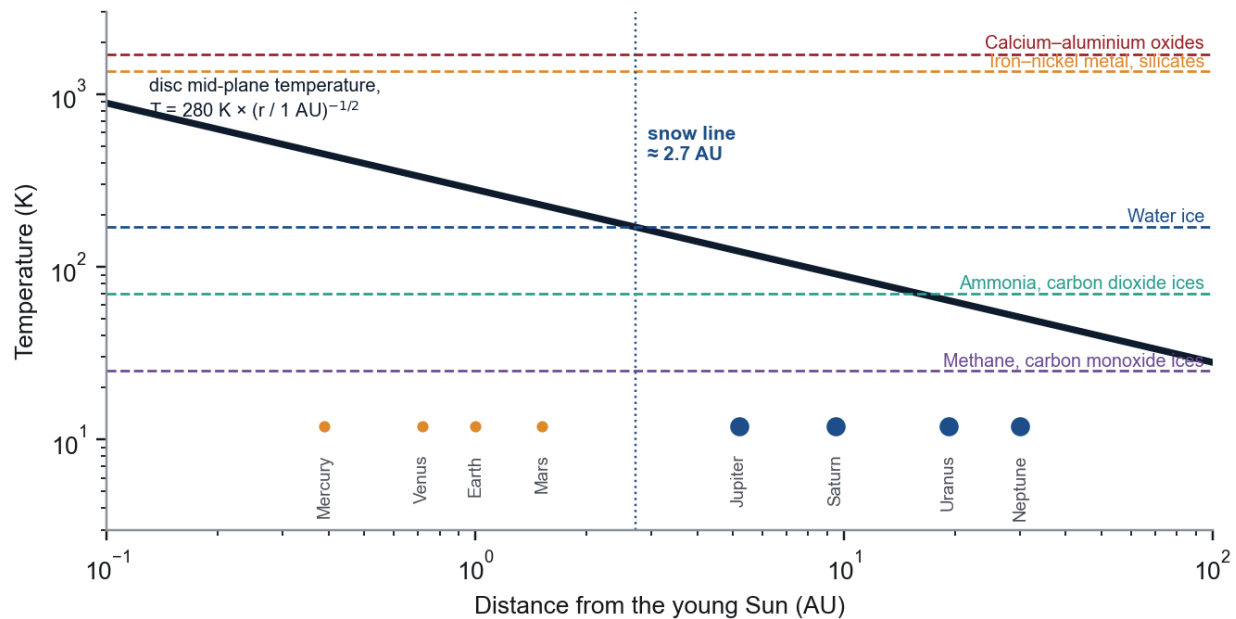


Figure 26. A temperature gradient sorts the materials. Mid-plane temperature in a simple model of the solar nebula, with approximate condensation temperatures of key materials. Rocky planets formed inside the water snow line; giant planets formed beyond it.

Source: H Heuristics calculation, $T = 280 \text{ K} (r / 1 \text{ AU})^{(-1/2)}$ (Hayashi 1981). Condensation temperatures are approximate and depend on pressure. Real discs evolve and the snow line moves over time.

7.3 From dust to planets: aggregation and runaway growth

Planets are built by aggregation over about forty orders of magnitude in mass, from micron-sized dust grains to bodies thousands of kilometres across. The first steps are well understood: grains stick by electrostatic forces into fluffy aggregates. The middle steps were long a puzzle, because metre-sized bodies drift inward rapidly and tend to bounce or fragment instead of sticking. A leading solution is the [streaming instability](#), in which solid particles moving through gas spontaneously concentrate into dense filaments that collapse gravitationally into planetesimals tens to hundreds of kilometres across. Planetesimals then grow by collisions and by sweeping up small 'pebbles' ([Raymond and Morbidelli 2022](#)).

Once bodies are large enough, gravity enhances their collision cross-sections, an effect called gravitational focusing, and growth becomes a runaway: the largest bodies grow fastest. Figure 27 shows this in an original Monte Carlo simulation of 1,500 equal bodies colliding with probabilities set by geometry and gravitational focusing. The outcome has the two features seen in real systems and in the halo mass function of Section 4.5: a smooth, power-law-like spectrum of small bodies, and a few giants that pull away. By the end of the run, one body holds 69 per cent of the total mass and is twelve times more massive than the next.

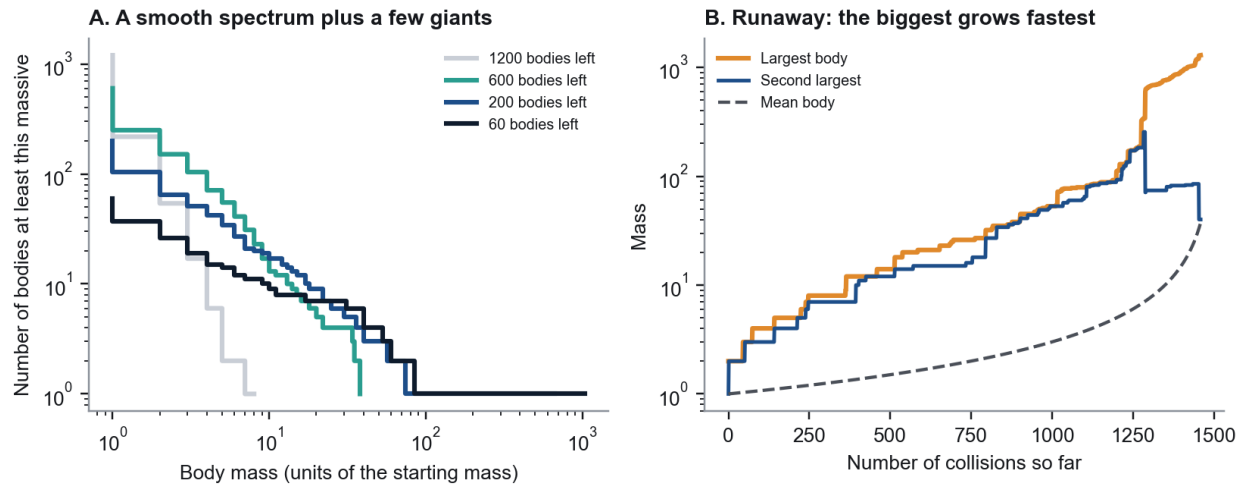


Figure 27. Aggregation with runaway growth. A Monte Carlo simulation of 1,500 initially equal bodies merging with a collision rate set by geometric cross-section and gravitational focusing. (A) The cumulative mass spectrum at four stages. (B) The largest body separates from the rest: a runaway.

Source: H Heuristics simulation. Kernel $K = (n + r_j)^2 [1 + \Theta(m_i + m_j)/(n + r_j)]$, $r \propto m^{1/3}$, $\Theta = 2$, exact stochastic (Gillespie) algorithm, seed 3. Illustrative of the mechanism, not a model of the Solar System.

Runaway growth is followed in real discs by oligarchic growth, in which several large embryos each dominate their own zone, and then by a chaotic phase of giant impacts. Earth's Moon is thought to have formed in [one such impact](#), between the proto-Earth and a Mars-sized body. Beyond the snow line, embryos of about ten Earth masses grew fast enough to capture gas from the disc and become giant planets.

7.4 Orbital architecture and diversity

Planets do not necessarily stay where they formed. Interactions with the disc and with each other can move them inward or outward. The [Nice model](#) proposes that the giant planets of the Solar System migrated after the gas dispersed, scattering small bodies and possibly causing a spike in impacts. The [Grand Tack model](#) proposes that Jupiter migrated inward and then outward, which would explain why Mars is so small. Both are graded C: they explain several features of the Solar System but are not uniquely established.

The discovery of planets around other stars has transformed the field. The [NASA Exoplanet Archive](#) passed 6,000 confirmed planets in September 2025. They reveal [architectures very different from ours](#): hot Jupiters orbiting their stars in days, compact systems of several planets packed closer than Mercury is to the Sun, and an abundance of planets between Earth and Neptune in size, a type absent from the Solar System. [Zhu and Dong](#) estimate that about 30 per cent of Sun-like stars host such planets within about one astronomical unit. There is also a [gap in the radius distribution](#) near 1.5 to 2 Earth radii, separating rocky super-Earths from gas-enveloped sub-Neptunes, and planets within a system tend to be [similar in size and regularly spaced](#), like peas in a pod. Planet formation is therefore both diverse and patterned: individual outcomes vary, but the statistics show recurring structure (Grade B).

7.5 Differentiation and the making of an environment

Once a planet is large enough, heat from accretion, from radioactive decay and from the separation of materials melts its interior, and the materials sort themselves by density. Iron sinks to form a core,

silicates form a mantle, and the lightest rocks float to the top as crust. Figure 28 shows the result for Earth: density rises from under 3 grams per cubic centimetre in the crust to about 13 in the inner core. The figure also compares the mean densities of bodies across the Solar System, which group into rock-and-metal worlds, ice-rich moons and gas giants. Differentiation is a recurring creation structure in its own right: a uniform body under gravity becomes layered, just as a massive star does.

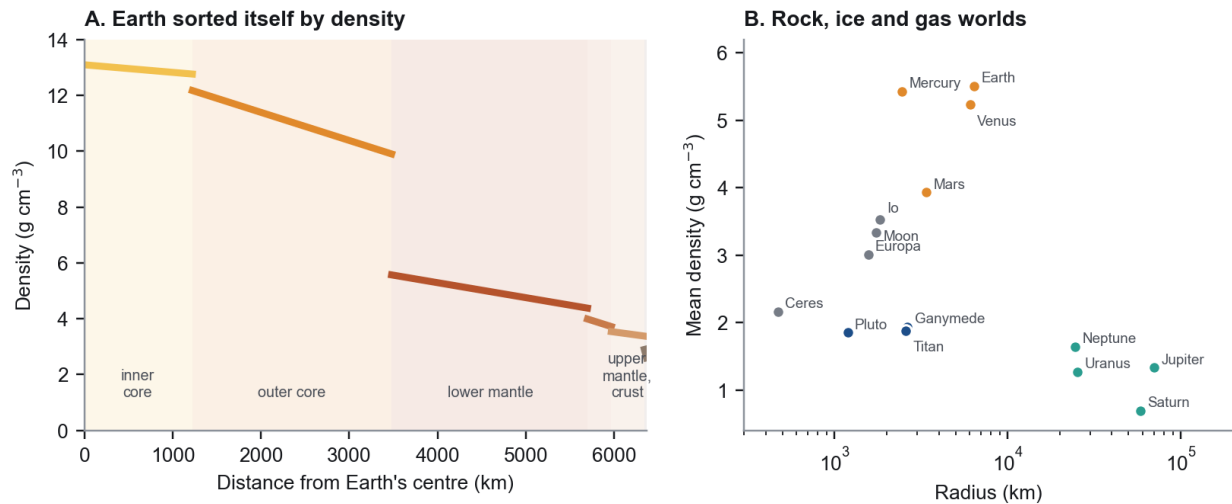


Figure 28. Differentiation. (A) Earth's density with depth: iron sank to form the core, silicates formed the mantle, and light rock floated to the surface. (B) Mean density against radius for bodies in the Solar System: rocky planets, icy moons and giant planets form distinct groups.

Source: (A) approximate Preliminary Reference Earth Model (Dziewonski and Anderson 1981); (B) NASA planetary fact sheets.

Differentiation built the features that make Earth habitable. The liquid outer core generates a magnetic field that shields the atmosphere from the solar wind. The mantle convects, driving plate tectonics, which recycles carbon between the atmosphere, oceans and rocks. That cycle acts as a long-term thermostat: [Walker, Hays and Kasting](#) showed in 1981 that if Earth warms, rock weathering speeds up and draws down carbon dioxide, cooling the planet, and if it cools, weathering slows and volcanic carbon dioxide accumulates. That is the same logic as the stellar thermostat of Section 6.2 operating through geochemistry over hundreds of thousands of years. Zircon crystals show that [liquid water was present 4.4 billion years ago](#), within about 150 million years of Earth's formation.

7.6 Habitable zones

A planet can hold liquid water on its surface only within a range of distances from its star, the habitable zone. The classic estimate by [Kasting, Whitmire and Reynolds](#) was refined by [Kopparapu and colleagues](#), who place the conservative habitable zone of the present Sun between about 0.99 and 1.70 astronomical units. Because stellar luminosity rises steeply with mass, the zone moves outward for brighter stars and inward for dimmer ones (Figure 29). Several of the best-known temperate exoplanets, such as Proxima Centauri b and TRAPPIST-1e, orbit red dwarfs so closely that they are probably tidally locked and exposed to strong flares. Whether such planets can retain atmospheres is a central question for JWST (Grade C).

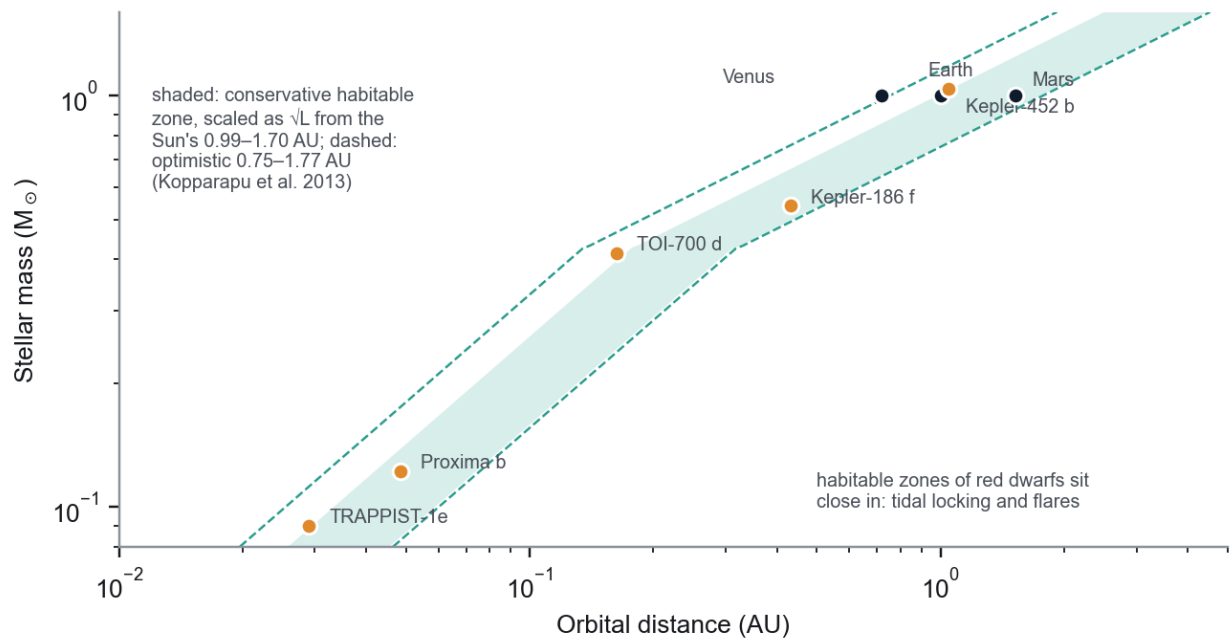


Figure 29. Habitable zones across stellar masses. The conservative habitable zone (shaded) and optimistic limits (dashed), scaled with stellar luminosity, with Solar System planets and selected exoplanets.

Source: H Heuristics calculation scaling the solar limits of Kopparapu et al. (2013) as $\sqrt{L}$, with $L \propto M^4$ above $0.43 M_{\odot}$ and $L = 0.23 M^{2.3}$ below. Planet data from the NASA Exoplanet Archive; values rounded.

Habitability is not a single number. It depends on a planet's mass, atmosphere, water inventory, tectonic activity, magnetic field and history, and on the star's activity and evolution. The Sun was about 30 per cent fainter when Earth formed, yet Earth had liquid water, the faint young Sun problem, which is most often explained by stronger greenhouse warming early on. At galactic scale, some authors define a [galactic habitable zone](#) where metallicity is high enough for rocky planets but supernovae are not too frequent (Grade C).

Key points. Planet formation reproduces the galactic pattern at a scale ten billion times smaller: angular momentum makes a disc, aggregation builds bodies, gravity produces runaway growth and differentiation layers the result. A temperature gradient sorts materials, giving rocky planets inside and giants outside. The resulting environments carry their own thermostats. Exoplanets show that outcomes are diverse but statistically patterned.

8. From Cosmic Structure to Life and Intelligence

8.1 A chain of conditions

This report asks how cosmic evolution connects to biological complexity and intelligence without assuming that these outcomes were inevitable. The connection can be described as a chain of conditions, each of which had to be met before the next could follow (Figure 30). Laws and constants permitted stable nuclei, atoms and chemistry. The hot Big Bang made hydrogen and helium. Gravity built galaxies, which retained the gas from which successive generations of stars formed, and stars made carbon, oxygen, nitrogen, phosphorus, sulphur and iron. Planetary discs turned those elements into rocky planets, some of which offered liquid water, energy gradients and long-term stability. On at least one, chemistry became biology.

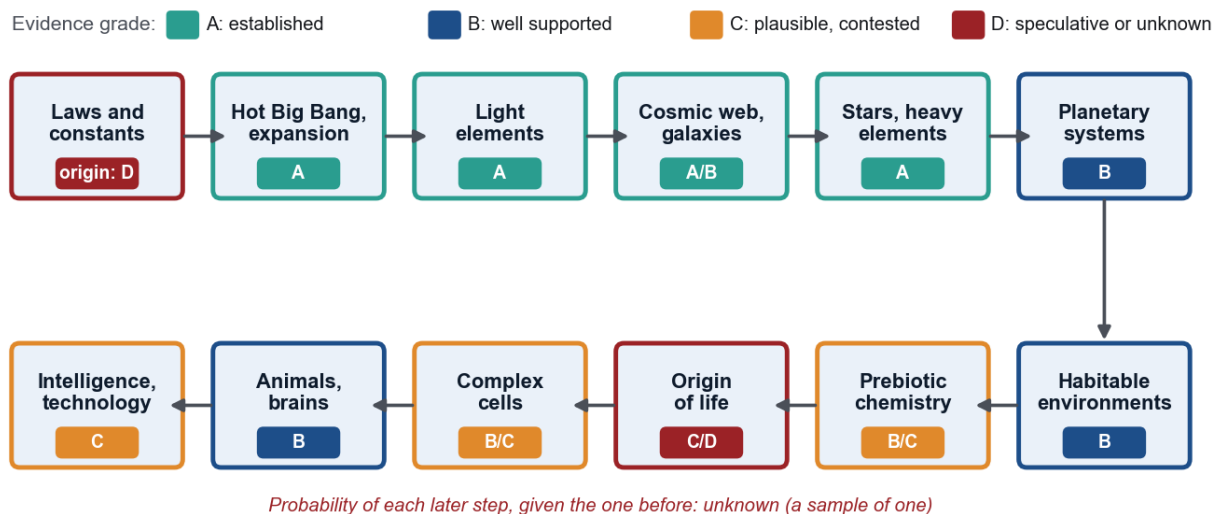


Figure 30. The chain from cosmos to intelligence, with the strength of our understanding of each step. The early links are established physics; the origin of life is the weakest link; and the probability of each later step, given the one before, is unknown.

Source: H Heuristics assessment using the evidence grades of this report. Illustrative.

The chain is well understood up to the formation of habitable environments and poorly understood after. The early links are physics and chemistry that operate everywhere; they explain why the ingredients and settings for life are common in the universe. The later links have been observed only once, on Earth, and some have never been reproduced. Table 8 grades each link, distinguishing what is known from what is assumed.

Table 8. The chain of conditions linking cosmic evolution to life and intelligence

Link	What is known	What is not known	Grade
Elements of life	C, H, N, O, P, S are among the most abundant reactive elements; made in stars	Whether other chemistries could support life	A
Organic molecules	Formed in space, in meteorites and in laboratory simulations	Which inventory reached early Earth	A–B
Habitable planets	Rocky planets in habitable zones are common	How many keep water, atmospheres and stable climates	B
Origin of life	Earliest widely accepted evidence 3.5 billion years ago; possibly earlier	The pathway from chemistry to replication; how likely it is	C–D
Complex cells	Arose once, by symbiosis, about 2 billion years ago or less	Why only once; how improbable	B–C
Animals and brains	Arose about 0.6 billion years ago after oxygen rose	Whether oxygen was the main trigger	B
Intelligence	Evolved once to technological level, in the last 0.3 million years	Whether it is a common or rare evolutionary outcome	C–D

Source: H Heuristics synthesis. Grades describe the state of knowledge, not the probability of the step.

8.2 Prebiotic chemistry: the ingredients are common

The chemistry of life uses elements that are among the most common in the universe. Leaving aside the inert gases helium and neon, hydrogen, oxygen, carbon and nitrogen are the four most abundant elements in the Sun (Figure 24). Organic molecules form readily wherever these elements meet energy. In 1953 [Stanley Miller](#) passed electric sparks through a mixture of gases thought to resemble the early atmosphere and produced amino acids within days. Radio astronomers have identified over 300 molecules in interstellar space, including many organics. The [Murchison meteorite](#), which fell in Australia in 1969, contains dozens of amino acids.

The strongest recent evidence comes from the asteroid Bennu, sampled by NASA's OSIRIS-REx mission and returned to Earth in 2023. Analysis of the pristine samples [published in 2025](#) found 14 of the 20 amino acids used in proteins on Earth and all five nucleobases used in DNA and RNA, together with abundant ammonia. A companion paper found [salt minerals left by evaporating brines](#), showing that Bennu's parent body once hosted liquid water. Notably, the amino acids were present in nearly equal left- and right-handed forms, whereas life uses only one, so the asteroid does not explain biology's chirality. The conclusion is that the building blocks of life are produced by ordinary chemistry and delivered widely (Grade A to B).

8.3 The origin of life: the weakest link

How chemistry became biology is unknown. Competing hypotheses include an 'RNA world', in which self-copying RNA molecules preceded DNA and proteins; 'metabolism first' scenarios, in which self-sustaining reaction networks came before genetic replication; and settings ranging from warm ponds that dried and refilled to alkaline hydrothermal vents on the sea floor, whose natural gradients of acidity resemble the energy-harvesting gradients that all cells use. Each has experimental support for particular steps; none has produced a system that replicates and evolves from plausible starting chemistry (Grade C for each hypothesis; Grade D for any claim about the overall pathway).

Evidence about timing is better. The [last universal common ancestor](#) of all living things was already a sophisticated cell. A [2024 molecular-clock study](#) placed it about 4.2 billion years ago, within a few hundred million years of Earth's formation. Stromatolites, layered structures built by microbial mats, are widely accepted as evidence of life 3.5 billion years ago (Figure 31). Life therefore appeared early. It is tempting to conclude that it arises readily, but [Spiegel and Turner](#) showed that early emergence on a single planet is weak evidence, because observers could only exist on planets where life started early enough for intelligence to evolve before the star brightened. [Kipping's](#) objective Bayesian analysis finds that the early start favours rapid abiogenesis, while remaining much less informative about how often intelligence follows.

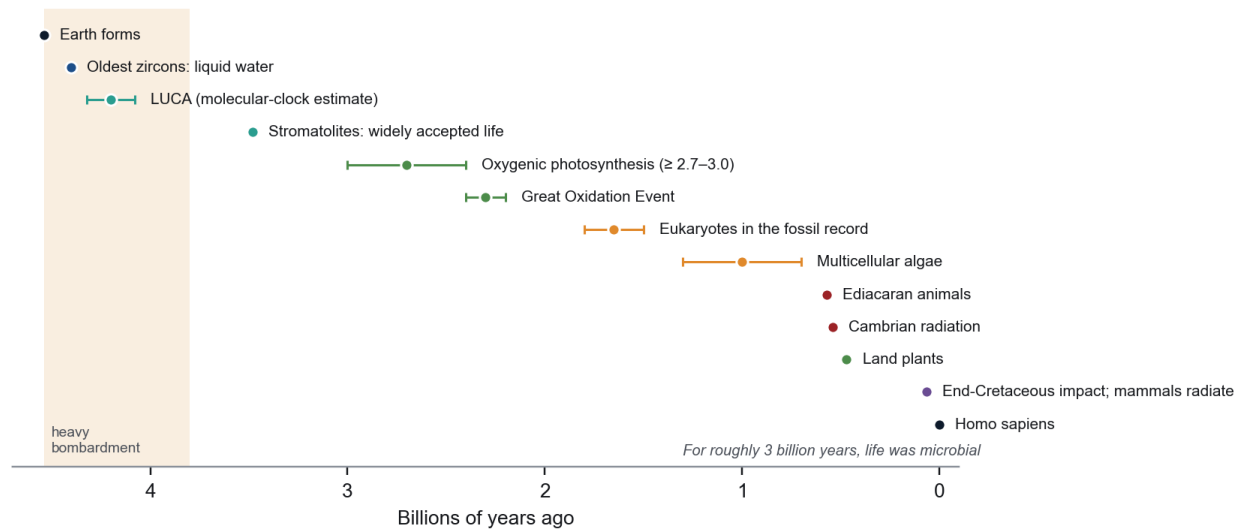


Figure 31. Major transitions in Earth's history. Life appeared within a few hundred million years of the planet's formation, but for some three billion years it was microbial. Complex cells, multicellular life and animals came late; Homo sapiens appeared in the last 0.01 per cent of Earth's history.

Source: H Heuristics compilation from Wilde et al. (2001), Moody et al. (2024), Lyons, Reinhard and Planavsky (2014) and standard geological timescales. Error bars indicate the spread of published estimates; all dates are approximate.

8.4 Major transitions and the role of energy

The history of life after its origin is punctuated by what [John Maynard Smith and Eörs Szathmáry](#) called the major transitions: points at which previously independent units combined into a new, higher-level unit and new ways of transmitting information arose. Examples include the origin of chromosomes, of complex (eukaryotic) cells, of sex, of multicellularity, of societies and of language. They are hierarchy-building events in exactly the sense of Table 3: aggregation followed by integration and differentiation.

Several transitions appear to have been gated by energy. [Lane and Martin](#) argue that the eukaryotic cell, which arose when one microbe came to live inside another and became the mitochondrion, gained an enormous increase in energy available per gene, allowing much larger genomes and more complex cells. The rise of oxygen in the atmosphere, in the [Great Oxidation Event](#) about 2.3 billion years ago and a later rise before the Cambrian, made the energy-rich metabolism of large animals possible. Each is an 'unlock' in the sense of Section 13: a threshold that opened a new space of possible structures (Grade B).

[Eric Chaisson](#) has proposed a single quantity to track this progression across cosmic and biological evolution: energy rate density, the free energy flowing through a system per unit mass per unit time. Figure 32 plots his estimates. The values rise from about 0.5 erg per second per gram for the Milky Way, through 2 for the Sun and about 75 for Earth's climate system, to roughly 20,000 for animals and 150,000

for the human brain. The trend is striking and supports the framework's emphasis on energy flow. But the metric is contested: it compares very different kinds of system, the choice of boundaries affects the numbers, and a high throughput is not the same as complexity. It is graded C.

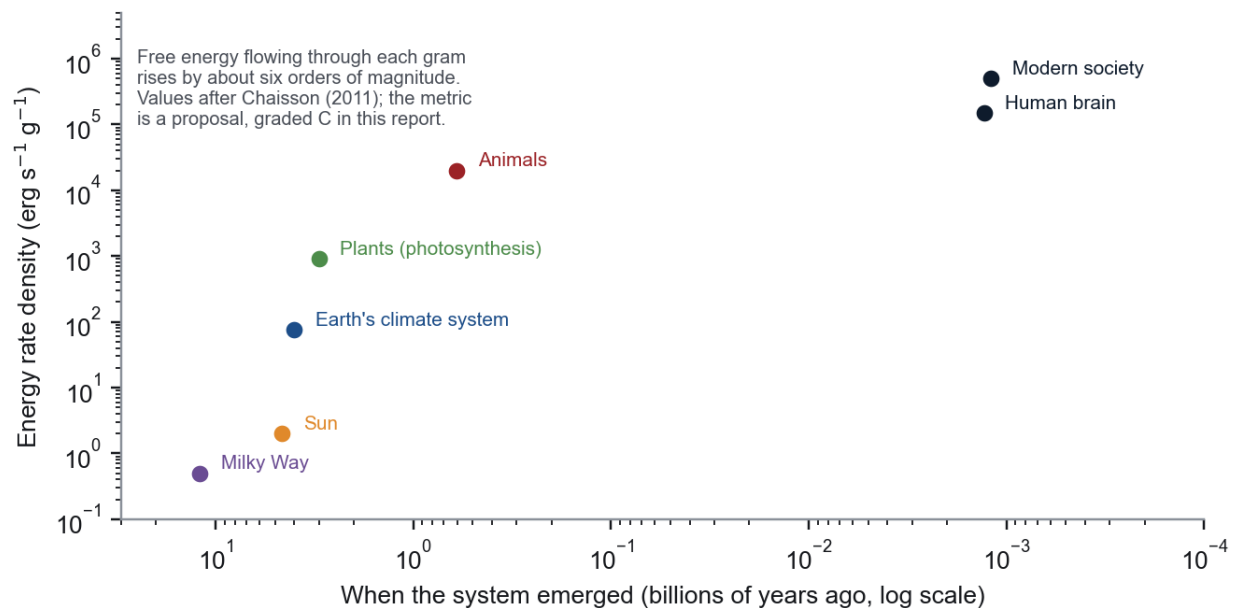


Figure 32. Energy rate density across cosmic and biological evolution. The free energy flowing through each gram of a system rises by about six orders of magnitude from galaxies to human society.

Source: values after Chaisson (2011), plotted against approximate time of emergence. The metric is a proposal, graded C in this report.

There is also a thermodynamic argument that driven systems tend to evolve towards configurations that absorb and dissipate energy efficiently. [Jeremy England](#) derived a bound linking the rate of self-replication to entropy production, and suggested that, under some conditions, the emergence of replicators may be thermodynamically favoured. Others emphasise information: [Walker and Davies](#) argue that the origin of life is best understood as a transition in how information controls matter. These are serious hypotheses (Grade C to D) that would, if confirmed, connect life to the energy-flow and feedback patterns that recur throughout the cosmos.

8.5 Intelligence, and what was not inevitable

Intelligence capable of technology has arisen once on Earth, in a lineage of primates, in the last few hundred thousand years of a 4.5-billion-year history. The palaeontologist Stephen Jay Gould argued that replaying the tape of life would give a different result each time; the palaeontologist Simon Conway Morris argued that convergent evolution, the repeated independent invention of eyes, flight and other solutions, means that some outcomes recur. The foundational report concluded that evolution is both contingent and channelled. Applied to intelligence, the honest conclusion is that it is unknown whether intelligence is a common outcome wherever complex life exists or an extreme rarity.

The framework of this report explains why the universe contains the ingredients, settings and energy flows that life on Earth uses, and why some of the patterns of biological organisation, such as hierarchy, networks and feedback, echo those of cosmic structure. It does not show that life, complexity or intelligence were bound to occur, and it gives no reason to believe that the universe was directed towards

them. The search for biosignatures on exoplanets, with JWST and future telescopes, is the most direct test available (Section 12).

Key points. The cosmic architecture makes the ingredients of life common: the elements are abundant, organic chemistry is widespread and habitable environments exist. The step from chemistry to biology is the weakest link and has not been reproduced. Major transitions in the history of life were often unlocked by new energy sources. The architecture explains the stage; it does not show that the play had to be performed.

9. Recurring Patterns Across Cosmic Scales

9.1 The pattern matrix

Sections 3 to 8 followed the universe's history. This section reads across it. Figure 33 scores each of the seven patterns of Table 3, plus symmetry breaking, at each of seven scales, using the evidence grades of this report. The grade in each cell is a judgement of how well established it is that the pattern operates at that scale, not of how important it is.

	Particles & forces	Nuclei & atoms	Stars	Galaxies	Cosmic web	Planets	Life
Aggregation	B	A	A	A	A	A	B
Differentiation	A	A	A	A	A	A	A
Branching	C	A	—	A	B	B	A
Hierarchy	A	A	B	A	A	B	A
Network formation	—	A	C	B	A	B	A
Feedback	—	—	A	B	C	B	A
Energy flow	B	A	A	B	C	A	A
Symmetry breaking	A	C	C	B	B	B	B

Figure 33. Where the recurring patterns operate. Each cell grades the evidence that a pattern is a real and significant feature of structure formation at that scale; a dash means the pattern does not meaningfully apply.

Source: H Heuristics judgement, based on the evidence reviewed in Sections 3 to 8.

Three things stand out. First, aggregation and differentiation are universal: at every scale, smaller units combine and uniform systems separate into distinct parts. Second, hierarchy is nearly universal, but its source changes: nuclear and atomic hierarchies are fixed by quantum mechanics, cosmic hierarchies are assembled by gravity over time, and biological hierarchies are assembled by evolution through the major transitions. Third, feedback becomes more prominent as structures become more complex: it is absent at the level of particles, essential in stars and galaxies, and pervasive in life.

9.2 Shared mathematics: instabilities that select a scale

The most robust cross-scale pattern is mathematical. Many structure-forming processes share the same form: a perturbation grows because of an amplifying effect and is resisted by a restoring effect, and the balance between the two selects a characteristic scale. The Jeans instability (Equation 2) pits gravity against pressure and selects the Jeans length. The Toomre instability (Equation 5) adds rotation, leaving a band of unstable wavelengths that sets the spacing of spiral arms and the size of star-forming clumps. The streaming instability concentrates dust into filaments of a characteristic width. Beyond astronomy, the

same family includes the Rayleigh–Taylor instability of a heavy fluid above a light one and the [Turing instability](#) that the foundational report used to explain spots and stripes on animals.

In each case a dispersion relation, linking growth rate to wavelength, has the form shown in Figure 9: negative (unstable) over a range of wavelengths, with a fastest-growing mode. This is a genuine shared mathematical structure, not a loose resemblance, and it explains why structures at very different scales have characteristic sizes instead of a continuum. It is graded A as mathematics and B as an organising principle for cosmic structure.

9.3 Power laws and scale-free aggregation

A second recurring mathematical pattern is the power law. The initial mass function of stars, the low-mass end of the halo mass function, the clustering of galaxies, the size distribution of planetesimals and many other cosmic distributions are approximately power laws over wide ranges (Figure 34). Power laws arise naturally from aggregation processes whose rules have no built-in scale, such as gravity, and from hierarchical processes in which the same step is repeated at each level.

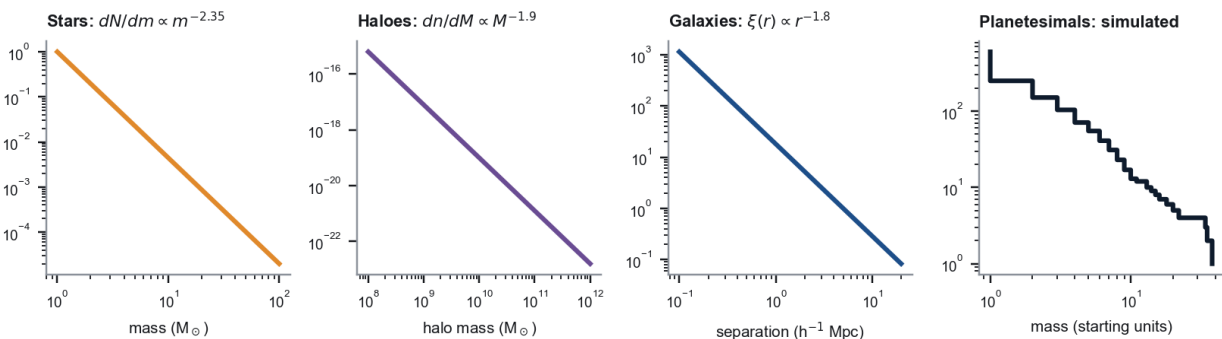


Figure 34. Power laws across scales. (A) The Salpeter slope of the stellar initial mass function. (B) The approximate slope of the low-mass halo mass function in cold dark matter. (C) The galaxy two-point correlation function. (D) The cumulative mass spectrum from this report's planetesimal simulation.

Source: H Heuristics. Panels A to C plot standard published relations (Salpeter 1955; Press and Schechter 1974; a correlation length of $5 h^{-1}$ Mpc and slope -1.8); panel D is from the coagulation simulation.

Caution is needed. Many different mechanisms produce power laws, so the existence of one says little about the mechanism behind it, and apparent power laws in limited data are often better fitted by other forms. The recurrence of power laws is evidence that cosmic structure is often built without a preferred scale. It is not evidence that the same mechanism operates everywhere. The pattern is graded A as a description and C as a unifying explanation.

9.4 Analogies: what transfers and what does not

The framework's central question, whether recurring patterns reveal common generative principles, turns on distinguishing three kinds of similarity. Some similarities are mathematical: the same equations apply, so the same behaviour follows. Some are structural: the same motif, such as a branching tree, is produced by different mechanisms. And some are superficial: forms look alike but share neither equations nor mechanisms. Table 9 classifies some of the most commonly cited cosmic analogies.

Table 9. Cosmic analogies classified by the depth of the similarity

Similarity	Type	Assessment	Grade
Galactic discs and protoplanetary discs	Mathematical	Same constraint (angular momentum) and generator (dissipation)	A
Jeans, Toomre and Turing instabilities	Mathematical	Same class of dispersion relation with a selected scale	A
Stellar and planetary layering	Mathematical	Settling of denser material in a gravitational potential	A
Stellar thermostat and carbonate–silicate thermostat	Structural	Same negative-feedback logic, different physics and timescales	B
Halo merger trees and the tree of life	Structural	Both branching histories; one driven by gravity, one by heredity and selection	B
Cosmic web and neural networks	Structural	Comparable network statistics but unrelated mechanisms	C
Spiral galaxies, hurricanes and nautilus shells	Superficial	Logarithmic spirals from different processes; the shared shape reflects self-similar growth, not a shared cause	C
Golden ratio in galaxies	Superficial	Not supported by measured pitch angles	D

Source: H Heuristics. 'Grade' refers to the claim of a shared generative principle, not to the existence of the resemblance.

The lesson is the one stated in the foundational report: before asking what a pattern means, ask which layer produced it. Mathematical similarities are the strongest evidence for a common architecture, because the same equation guarantees the same behaviour. Structural similarities suggest that some motifs are easy for many kinds of generator to reach. Superficial similarities are a warning against reading too much into shapes.

9.5 Does a common architecture exist?

On the evidence of this report, the answer is a qualified yes. A small number of generators, chiefly gravitational instability, nuclear fusion, dissipative cooling and aggregation, together with a small number of filters, chiefly virial and hydrostatic equilibrium, marginal stability and negative feedback, account for most of the structure in the universe from nuclei to superclusters. These mechanisms recur because the same laws apply everywhere and because the same constraints, especially conservation of energy and angular momentum, rule out most alternatives. That is a genuine common architecture.

The qualification is that the architecture is not a single blueprint. The mechanisms combine differently at each scale, and new mechanisms, such as heredity, appear at the transition to life. The architecture is better described as a toolkit than a template, and the same tool produces similar products in different workshops. That is precisely the pluralist conclusion of the foundational report, now extended from natural forms on Earth to the cosmos as a whole.

10. Entropy, Irreversibility and the Persistence of Structure

10.1 The apparent paradox

The [second law of thermodynamics](#) states that the entropy of an isolated system never decreases. Entropy is often described as disorder. How, then, did a smooth early universe become one full of structure? If the universe is the ultimate isolated system, and its entropy has risen ever since the Big Bang, the growth of galaxies, stars, planets and life seems to run against the grain.

The resolution has two parts. The first is that local decreases in entropy are allowed provided that larger increases occur elsewhere. A refrigerator cools its interior by heating the room more. Every structure in this report is an open system that exports entropy to its surroundings. The second part is less familiar and more important for cosmology: gravity reverses the usual relationship between uniformity and entropy.

10.2 Gravity's negative heat capacity

For an ordinary gas in a box, the highest-entropy state is uniform: molecules spread out evenly. For a self-gravitating system, the opposite is true. The virial theorem states that for a bound system in equilibrium the total energy equals minus the kinetic energy,

$$E = -K \tag{7}$$

so if the system loses energy, for example by radiating light, its kinetic energy and therefore its temperature rise. Self-gravitating systems have negative heat capacity: they heat up as they lose energy. A contracting gas cloud heats up until fusion ignites; a star that loses energy contracts and heats its core. Clumping under gravity, combined with the radiation of energy into space, increases total entropy. Uniformity is a low-entropy state for gravitating matter, and the cosmic web, galaxies and stars are the universe's way of increasing its entropy (Grade A).

This is why gravity is the master generator of cosmic structure. It is the one force that, acting on large numbers of particles, spontaneously produces order locally while increasing entropy overall. The smooth early universe was, in gravitational terms, extraordinarily far from equilibrium, and its history since has been a release of that disequilibrium.

10.3 Where the entropy is

Figure 35 shows an order-of-magnitude entropy budget for the observable universe, calculated for this report. The cosmic microwave background photons and relic neutrinos each carry about 10^{89} to 10^{90} units of Boltzmann's constant k , together about 10^{10} k for every baryon. All the stars together carry about 10^{80} k , and the diffuse gas between them a little more. Black holes dwarf everything else: stellar-mass black holes carry about 10^{98} k , and the supermassive black holes at the centres of galaxies about 10^{104} k , according to [Egan and Lineweaver](#). The maximum entropy that could fit within the cosmic event horizon is about 10^{122} k .

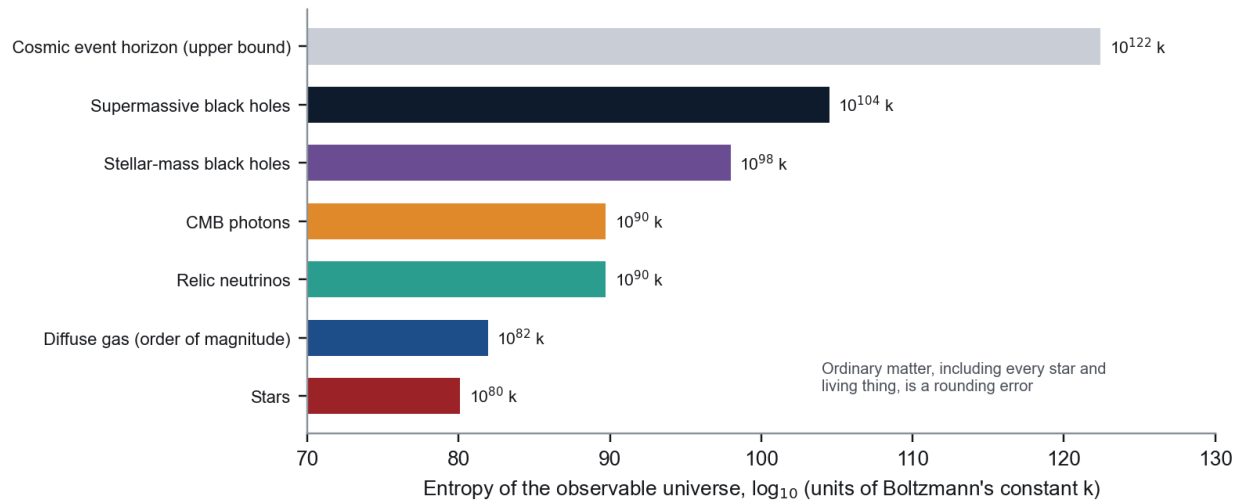


Figure 35. The entropy budget of the observable universe. Black holes dominate; the photons of the cosmic microwave background and the relic neutrinos come next; stars and all ordinary matter are negligible. The cosmic event horizon sets an upper bound.

Source: H Heuristics order-of-magnitude calculation for a sphere of radius 46.5 billion light years: photon entropy density $1,479 \text{ k cm}^{-3}$ at 2.7255 K ; neutrinos at $4/11$ of the photon temperature cubed; stars at $\sim 20 \text{ k per baryon}$; stellar black holes at 10^8 of $10 M_{\odot}$ per $6 \times 10^{10} M_{\odot}$ of stars. Supermassive black holes and horizon from Egan and Lineweaver (2010).

Two conclusions follow. The universe's entropy is today about 10^{18} times below its maximum, so there is a vast reservoir of free energy still to be released, and structure can continue forming for a very long time. And the early universe must have had extraordinarily low gravitational entropy, an initial condition that the physics of this report does not explain. [Roger Penrose](#) has emphasised how special this initial state was, and proposals such as that of [Carroll and Chen](#) attempt to explain it. The origin of the low-entropy beginning is graded D.

10.4 Structure as flow

Every structure in the universe persists only while energy flows through it. A star persists while fusion replaces the energy it radiates. A galaxy keeps forming stars while gas flows in. Earth's biosphere persists because sunlight arrives from a $5,772 \text{ K}$ source and leaves as infrared radiation at about 255 K : for every photon received, Earth radiates about twenty, exporting the entropy that life and weather generate. [Ilya Prigogine](#) called such systems dissipative structures, and won the 1977 Nobel Prize in Chemistry for their theory.

This connects the present report to its companion, [The Architecture of Entropy](#), which argued that 'persistent structure is a flow, not a state', and that organised systems unravel when the rate of loss exceeds the rate of restoration. The cosmic version is the same principle on the largest scale. Structures are eddies in a flow of free energy that began with the low-entropy Big Bang. They persist while the flow continues and dissolve when it runs down. Section 11 asks how long that will take.

Key points. Structure formation does not violate the second law. Gravity's negative heat capacity makes clumping an entropy-increasing process, and every structure exports entropy to its surroundings. Black holes hold almost all the universe's entropy; stars and life are a rounding error. The universe is still far from its maximum entropy, but its low-entropy origin is unexplained.

11. The Long-Term Evolution of the Universe

11.1 The near future: stars and galaxies

The Sun is about halfway through its life on the main sequence. Its luminosity is rising by about one per cent every hundred million years; in roughly a billion years Earth is expected to lose its oceans to a runaway or moist greenhouse, and in about five billion years the Sun will swell into a red giant, before shedding its outer layers and leaving a white dwarf about the size of Earth. The architecture that made Earth habitable, a stable star and a self-regulating climate, has a finite lifetime.

The Milky Way's future is less certain than once thought. For decades it was expected to merge with the Andromeda galaxy in about 4.5 billion years. A [2025 study by Sawala and colleagues](#), combining Hubble and Gaia data and including the gravitational influence of the Large Magellanic Cloud and the Triangulum galaxy, found only about a 50 per cent chance of a merger within the next ten billion years. If it occurs, the two spirals will be transformed into an elliptical galaxy, the mechanism of Section 5.4.

The decline in star formation shown in Figure 25 will continue. As gas is consumed and fewer fresh supplies reach galaxies, star formation will dwindle over tens to hundreds of billions of years. The smallest red dwarfs, with masses near 0.1 solar masses, can burn for over a trillion years, so the universe will shine dimly for a very long time, but the age of active creation of new stars is already past its peak.

11.2 Dark energy and the fate of expansion

The long-term future depends above all on dark energy. If it is a cosmological constant, as in the standard model, the expansion will accelerate forever. Galaxies beyond our local group will recede beyond the cosmic horizon within about 100 to 150 billion years, leaving each bound group as an isolated island in an otherwise empty, cold universe. Figure 36 compares four scenarios computed for this report, and Table 10 summarises them.

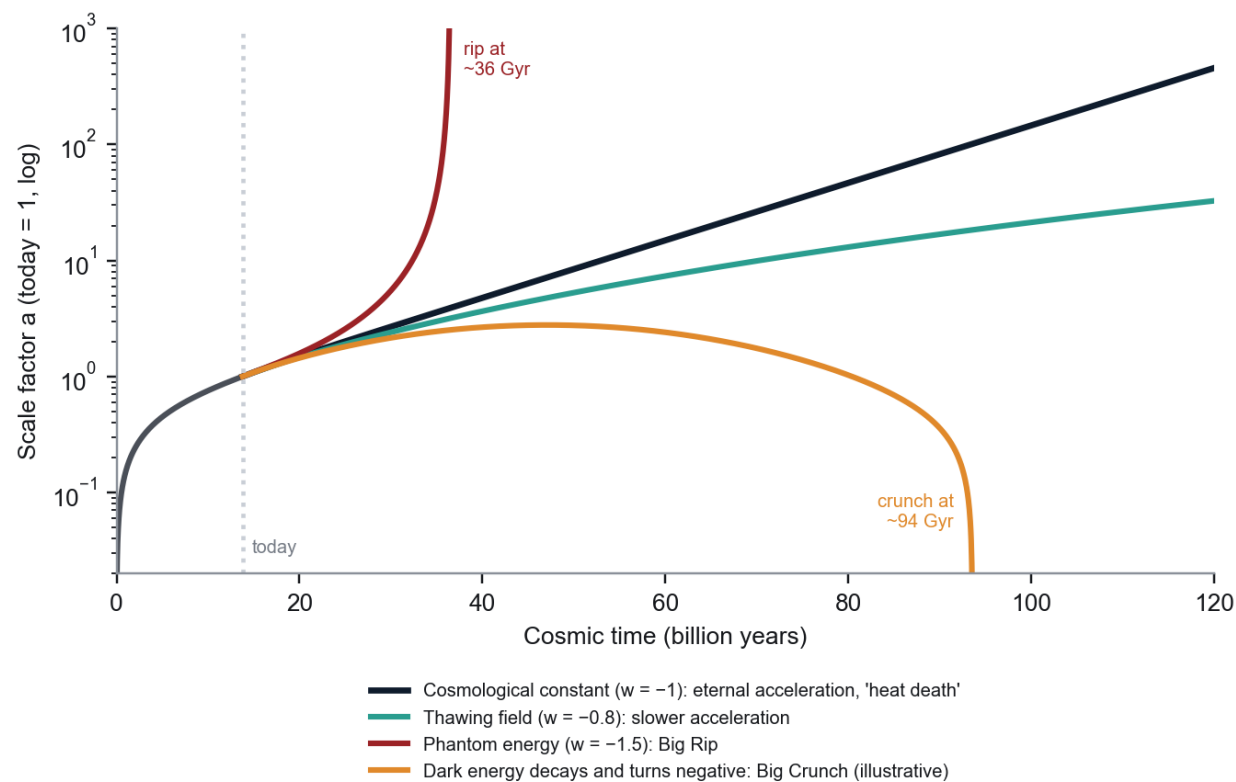


Figure 36. Four futures for the expansion of the universe. The scale factor under a cosmological constant, a slowly thawing dark-energy field, phantom energy and an illustrative dark energy that decays and turns negative. All four share the same past; their futures diverge within a few tens of billions of years.

Source: H Heuristics calculation integrating the Friedmann equations forward from today with $\Omega_m = 0.315$. The phantom case ($w = -1.5$) reaches a Big Rip about 23 billion years from now, consistent with Caldwell, Kamionkowski and Weinberg (2003). The crunch case uses $\rho_{DE} \propto 1 - \ln a$ and is illustrative of a class of models, not a fit to data.

Table 10. Cosmological futures under different dark-energy scenarios

Scenario	Dark energy	Outcome	Status of evidence
Heat death (Big Freeze)	Cosmological constant, $w = -1$	Eternal acceleration; isolated galaxy groups; stars burn out; black holes evaporate	Standard model; consistent with most data
Slower freeze	Thawing field, $w > -1$	Acceleration weakens; similar long-term outcome	Favoured by DESI combinations at $2.8\text{--}4.2\sigma$
Big Rip	Phantom energy, $w < -1$	Expansion tears apart galaxies, stars, planets, atoms in finite time	Current dark energy $w < -1$ is disfavoured; past phantom-like behaviour is allowed by DESI fits
Big Crunch	Dark energy decays and turns negative, or curvature dominates	Expansion halts and reverses; collapse	Possible in some evolving-field models; speculative
Vacuum decay	A lower-energy state of the Higgs field exists	Bubble of new vacuum expands at light speed	Theoretically possible; timescale far beyond present age if it exists

Sources: Adams and Laughlin (1997); Caldwell, Kamionkowski and Weinberg (2003); DESI Collaboration (2025). All long-range futures are graded C or D: they depend on extrapolating dark energy far beyond the range of data.

The [DESI results](#) are therefore of more than technical interest. If dark energy is weakening, the assumption of eternal exponential expansion is wrong, and the far future could look very different. The current data do not yet decide the question, and the extrapolation from a few billion years of measured behaviour to trillions of years is enormous. Long-range futures should be read as conditional scenarios, not forecasts.

11.3 The far future: eras of the universe

If expansion continues indefinitely, [Fred Adams and Gregory Laughlin](#) divided the future into eras (Figure 37). In the present stelliferous era, lasting up to about 10^{14} years, stars form and shine. In the degenerate era that follows, the universe is dominated by white dwarfs, neutron stars, brown dwarfs and black holes, with occasional collisions producing new stars. If protons decay, as many unified theories predict, all ordinary matter will eventually dissolve; [Super-Kamiokande](#) has shown that the proton's lifetime is at least 2.4×10^{34} years for its most commonly predicted decay mode. In the black hole era, the only structures left are black holes, which slowly evaporate by [Hawking radiation](#): a black hole of one solar mass in about 10^{67} years, the largest in about 10^{100} years. After that comes a dark era of photons, neutrinos and particles spread ever more thinly.

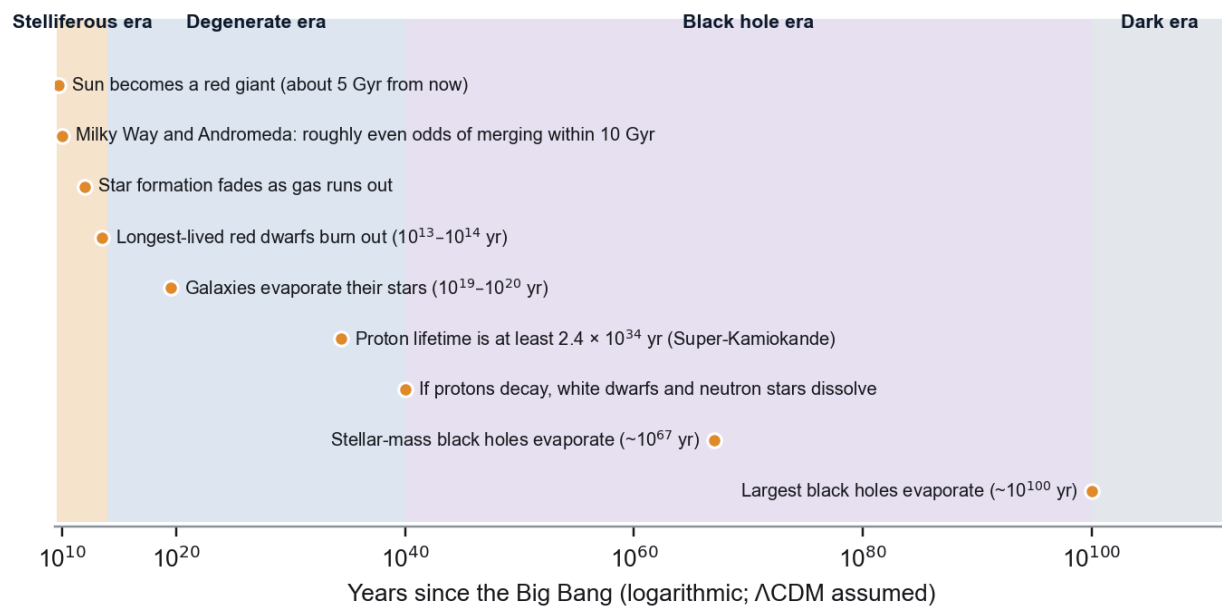


Figure 37. Eras of the far future. On a logarithmic timescale, the present age of star formation is a brief opening chapter. Structure persists longest in black holes, which eventually evaporate.

Source: H Heuristics, after Adams and Laughlin (1997); proton-lifetime bound from Super-Kamiokande (2020); Milky Way–Andromeda probability from Sawala et al. (2025). All timescales assume a cosmological constant and are approximate.

[Freeman Dyson](#) argued in 1979 that life and intelligence might in principle persist indefinitely in an open universe by slowing their metabolism as the universe cooled. [Krauss and Starkman](#) showed that in an accelerating universe this is impossible, because the energy available within any horizon is finite. In the standard model, the architecture of creation described in this report is a transient phase in a universe that will end cold, dark and nearly empty (Grade B for the overall trajectory given a cosmological constant; Grade C to D for specific timescales beyond about 10^{14} years).

11.4 The architecture in reverse

The long-term future is the creation structure run down. The constraints remain: the laws do not change. But the generators lose their fuel. Gravitational instability runs out of new material as expansion isolates bound systems; fusion runs out of hydrogen; cooling runs out of gas. And the filters, which selected stable structures, now preside over a slow attrition, as even the most stable objects evaporate or decay. The companion report on entropy describes this process for civilisations and ecosystems. Its cosmic version is the most complete example: creation is a phase, not a permanent state.

Key points. The Sun will become a red giant in about five billion years; the Milky Way has roughly even odds of merging with Andromeda within ten. Star formation has passed its peak. If dark energy is a cosmological constant, the universe will expand forever into isolated, cooling islands, with structure persisting longest in black holes. DESI's evidence for evolving dark energy keeps other futures open.

12. Testing the Thesis: Predictions, Questions and Limits

12.1 Why the framework must be testable

A framework that explains everything explains nothing. The foundational report listed predictions by which its thesis could fail; this report does the same for the cosmos. The predictions below follow from the claim that a small set of generators and filters accounts for cosmic structure. Each names the observations that would test it and the result that would count against the framework.

Table 11. Testable predictions of the cosmic creation-structure thesis

#	Prediction	Test and data	Would count against
1	Galaxy scaling relations emerge early and tighten with time, because feedback-regulated equilibrium takes time to establish	JWST, Euclid and ALMA measurements of Tully–Fisher and main-sequence scatter at $z > 3$	Relations as tight at $z = 6$ as today, or no relation at all
2	Spiral-arm pitch angle tracks the shear of the rotation curve, as density-wave and swing-amplification theory require	Pitch angles and rotation curves for large samples (Rubin LSST, SKA)	No correlation between pitch angle and shear
3	The cosmic web's large-scale statistics are set by the initial power spectrum and gravity alone, independent of galaxy physics	Comparing DESI, Euclid and Rubin web statistics with dark-matter-only simulations	Large-scale web statistics requiring new physics beyond gravity and Λ CDM initial conditions
4	Heavy r-process elements are enriched in rare, lumpy events, so their abundance in old stars scatters widely	Spectroscopic surveys of metal-poor stars and dwarf galaxies	Uniform r-process enrichment in the oldest populations
5	The first stars were massive and leave distinctive chemical and spectral signatures	JWST searches for helium-rich, metal-free emission at $z > 10$; abundance patterns of the most metal-poor stars	No massive Population III signatures in deep surveys
6	Planetary systems cluster into a few architectural classes, with within-system regularity	TESS, PLATO, Roman and Gaia exoplanet demographics	Random, uncorrelated planet sizes and spacings within systems
7	If abiogenesis is chemically channelled, biosignatures appear on some temperate rocky planets	JWST, the Extremely Large Telescope and the Habitable Worlds Observatory, 2030s–2040s	Not decisive: a null result on a few dozen planets constrains, but cannot exclude, common life
8	Structure formation and entropy production track the cosmic star formation rate, both now in decline	Cosmic star formation and black hole accretion histories	A rise in star formation rate density in the late universe

Source: H Heuristics. Predictions 1, 2 and 6 test the framework's claim that filters erase history; 3 and 5 test its claim that the generators are few; 7 tests its limits.

12.2 Open research questions

The ten questions below are the most important for the architecture of cosmic creation. Each is a question the framework raises but cannot answer by itself.

1. **What is dark matter?** The generator of all cosmic structure is unidentified. Its particle properties determine the smallest structures that form, and so the lower limit of the cosmic hierarchy.
2. **Is dark energy constant?** The answer determines the long-term future of all structure (Section 11). DESI's final results, Euclid and Rubin should sharpen the evidence within a few years.
3. **What caused the primordial fluctuations?** Detection of primordial gravitational waves by CMB experiments would confirm inflation and fix its energy scale.
4. **Why is there more matter than antimatter?** About six baryons survived the mutual annihilation of matter and antimatter for every ten billion photons. Without that asymmetry no structure of ordinary matter would exist. Its origin is unknown.
5. **What resolves the Hubble tension?** A measurement error, or new physics in the early universe?
6. **Why are galaxy scaling relations so tight?** Is the radial acceleration relation an outcome of feedback with dark matter, or a sign of modified gravity?
7. **Were the first stars as massive as predicted, and how did the first black holes grow so fast?** JWST's early galaxies and quasars challenge simple models.
8. **How common are Earth-like planetary environments?** That is, rocky planets with water, plate tectonics and long-lived climate regulation.
9. **How did life begin, and how often does it?** This is the weakest link in the chain of Section 8.
10. **Is there a quantitative measure of cosmic complexity?** Energy rate density is one proposal; information-based measures are another. A good metric would turn the framework's central claim into a measurable trend.

12.3 Limits and risks of the framework

- **Explanatory inflation.** Labels such as aggregation or feedback can be applied to almost anything. The framework adds value only where it identifies a shared mechanism or shared mathematics, as in Section 9.2. Elsewhere it is a vocabulary, not an explanation.
- **Hindsight.** It is easy to describe a known history as a sequence of creation structures. The test is whether the framework predicts things not yet observed. Most of the predictions in Table 11 are consistent with standard astrophysics; their value is in making the framework's commitments explicit.
- **Anthropic bias.** We observe a universe compatible with observers. Arguments from the apparent ease of structure formation must allow for the fact that we could not observe one where it failed.
- **Sample of one.** For life and intelligence, all generalisation rests on Earth. The framework should not be used to claim that the universe 'tends towards' life or mind.
- **Dependence on unknowns.** Dark matter and dark energy are placeholders for physics not yet understood. If either turns out to be something unexpected, parts of the architecture described here would need revision.

13. H Heuristics Propositions and Working Heuristics

13.1 Original propositions

The following propositions are original to the H Heuristics framework. They go beyond the established science reviewed in Sections 3 to 11 and are offered for testing. Each is graded.

1. **The unlock principle (Grade C).** Cosmic history is a sequence of thresholds at which a new interaction becomes dominant or a new material becomes available: nuclei at 0.1 MeV, atoms at 3,000 K, efficient cooling once metals exist, rocky planets once dust exists, complex life once oxygen exists. Each unlock opens a new space of possible structures, and the pace of creation is set by the spacing of unlocks, not by any steady tendency towards complexity.
2. **The scale-selection principle (Grade B).** Where cosmic structure has a characteristic size, it is set by an instability in which an amplifying effect competes with a restoring one: gravity against pressure, rotation or shear. Structures without a characteristic size arise from aggregation with scale-free rules. Every cosmic size distribution should be classifiable as one or the other, or as a combination.
3. **The regulated-flow principle (Grade B).** Every long-lived cosmic structure is held at an operating point by negative feedback on its energy throughput: stars by the nuclear thermostat, galaxies by feedback-regulated star formation, Earth by the carbonate–silicate cycle, organisms by homeostasis. Long life without negative feedback should be rare.
4. **The contingency gradient (Grade C).** At large scales, cosmic structure is constraint-dominated and statistically predictable; at small scales it is history-dominated. The statistics of haloes, galaxies, stars and planets are predictable even where individual objects are not. Predictability should decline from the cosmic web to galaxies to planetary systems to biospheres.
5. **The two-component morphospace of galaxies (Grade B).** Galaxy similarity results from a morphospace with only two structural components and one universal container. Departures from galaxy scaling relations should be explicable by recent mergers, environment or feedback events, not by new components.
6. **Gravity as the master generator (Grade A for the physics; B as a framing).** Because self-gravitating systems have negative heat capacity, gravity is the only interaction that spontaneously creates local order on large scales while increasing global entropy. All other generators in this report operate inside structures that gravity built.
7. **Recurrence as a measure of constraint (Grade C).** The more often a form recurs across unrelated cosmic systems, the more tightly the constraints restrict the possibility space. Discs, spheres and filaments recur because few alternatives are dynamically stable; the rarity of other shapes is itself evidence about the constraints.

13.2 Ten working heuristics

The framework condenses into ten rules of thumb for reading any cosmic structure.

1. **Ask what the laws forbid before asking what they produce.** Constraints explain more of the universe's appearance than generators.

2. **Find the instability.** Where structure has a characteristic size, look for the competition between amplification and restoration that selected it.
3. **Follow the angular momentum.** Discs appear wherever rotating material can lose energy but not spin.
4. **Look for the thermostat.** Long-lived structures are held near an operating point by negative feedback.
5. **Separate shared mathematics from shared appearance.** Similar shapes do not imply similar causes.
6. **Read composition as history.** The abundances of elements record which generators acted and when.
7. **Expect hierarchy to be assembled, not given.** Except for the quantum hierarchy of particles, cosmic hierarchies were built bottom-up over time.
8. **Trust the statistics, not the individual.** The architecture predicts populations far better than single objects.
9. **Count the free energy.** Every structure is a flow; ask what pays for its persistence and how long the payment lasts.
10. **Grade the evidence.** At each link in the chain from cosmos to mind, state how much is known, and stop where the evidence stops.

14. Conclusion: How Far Does a General Architecture Explain the Universe?

This report asked how the universe generates complexity from fundamental physical laws, and what recurring architecture connects its structures across space and time. Its answer is that a small set of generators, above all gravitational instability, nuclear fusion, dissipative cooling and aggregation, acting within constraints set by the laws of physics, and filtered by stability and feedback, account for the emergence, organisation and evolution of the observable universe from its first seconds to the present. Table 12 summarises how far that answer goes.

Table 12. How far the architecture of cosmic creation explains the observable universe

Question	How well the architecture explains it	Main uncertainty
Why the laws and constants are as they are	Not at all: they are taken as given	Origin of laws; fine-tuning (D)
Why the early universe was smooth and low in entropy	Partly: inflation is a candidate	Inflation unconfirmed; initial conditions (C–D)
How the light elements formed	Fully, apart from lithium	Lithium problem (C)
How the cosmic web formed	Fully, given dark matter	Identity of dark matter
Why galaxies share similar designs	Largely: two components, universal haloes, shared generators and filters	Feedback details; early galaxies; small-scale problems (B–C)
How stars live and make the elements	Fully in outline	r-process sites; massive-star deaths (B–C)
How planetary systems and habitable environments form	Largely	Planetesimal formation; migration; habitability (B–C)
How life began	Only the ingredients and setting	Pathway and probability (C–D)
Why intelligence arose	Not meaningfully	Sample of one (D)
What the future holds	Conditionally	Nature of dark energy (C–D)

Source: H Heuristics assessment.

Three conclusions stand out. First, the architecture is real. The recurrence of discs, spheroids, filaments, hierarchies and thermostats across scales separated by factors of billions is not coincidence. It follows from the same constraints, especially conservation of energy and angular momentum and the negative heat capacity of self-gravitating matter, operating through the same small family of instabilities and feedback loops. The answer to why galaxies share similar designs is a particularly clear case: two components, a universal container and a handful of generators and filters leave room for only a few stable forms.

Second, the architecture explains organisation better than origins. It accounts for how structure grows and why forms recur, given the laws and initial conditions. It does not explain the laws, the constants, the low-entropy beginning, the matter–antimatter asymmetry or the identity of dark matter and dark energy. These are where current science is most uncertain, and they are outside the framework's reach.

Third, the architecture explains the stage for life, not the play. The universe makes the elements of life in stars, the organic molecules in space and on asteroids, and habitable environments on planets. Whether those ingredients and settings generally lead to biology, and biology to intelligence, is unknown. The framework gives no grounds for thinking that the universe was aimed at life or mind, and no grounds for thinking that it could not produce them often. That question will be answered, if at all, by observation.

The universe, on this account, is neither a machine following a blueprint nor a random accident. It is a system in which simple laws, acting on nearly uniform beginnings, repeatedly generate a limited repertoire of forms, selected by stability and paid for by flows of free energy that will eventually run down. Within that architecture, a planet formed on which some of its matter became able to ask how it all came about. The other reports in the series apply the same principles at the scale of life, economies and civilisations; the principles traced here, constraint, generation, selection and flow, are the foundation beneath them all.

References

Links go to a DOI or arXiv record where available. H Heuristics reports are listed first.

- H Heuristics (2026). *The Architecture of Creation: Mathematical Structures, Generative Laws, and the Recurrence of Form in Nature*. Hughes, H. researchreports.hheuristics.com/reports/architecture-of-creation/
- H Heuristics (2026). *The Architecture of Creation and Development*. Hughes, H. researchreports.hheuristics.com/reports/architecture-of-creation-and-development/
- H Heuristics (2026). *The Architecture of Entropy: Thermodynamics, Complexity and the Systemic Unraveling of Civilisations*. Hughes, H. researchreports.hheuristics.com/reports/architecture-of-entropy/
- H Heuristics (2026). *The Human Variant Hypothesis*. Hughes, H. researchreports.hheuristics.com/reports/human-variant-hypothesis/
- Abel, T., Bryan, G. L. and Norman, M. L. (2002). The formation of the first star in the universe. *Science* 295, 93. arxiv.org/abs/astro-ph/0112088
- Adams, F. C. (2019). The degree of fine-tuning in our universe — and others. *Physics Reports* 807, 1. arxiv.org/abs/1902.03928
- Adams, F. C. and Laughlin, G. (1997). A dying universe: the long-term fate and evolution of astrophysical objects. *Reviews of Modern Physics* 69, 337. arxiv.org/abs/astro-ph/9701131
- ALMA Partnership (2015). First results from high angular resolution ALMA observations toward the HL Tau region. *ApJL* 808, L3. arxiv.org/abs/1503.02649
- Alpher, R. A., Bethe, H. and Gamow, G. (1948). The origin of chemical elements. *Physical Review* 73, 803. doi.org/10.1103/PhysRev.73.803
- Anderson, P. W. (1972). More is different. *Science* 177, 393. doi.org/10.1126/science.177.4047.393
- Asplund, M., Grevesse, N., Sauval, A. J. and Scott, P. (2009). The chemical composition of the Sun. *ARA&A* 47, 481. arxiv.org/abs/0909.0948
- Baldry, I. K. et al. (2004). Quantifying the bimodal color–magnitude distribution of galaxies. *ApJ* 600, 681. arxiv.org/abs/astro-ph/0309710
- Barnes, L. A. (2012). The fine-tuning of the universe for intelligent life. *PASA* 29, 529. arxiv.org/abs/1112.4647
- Behroozi, P. S., Wechsler, R. H. and Conroy, C. (2013). The average star formation histories of galaxies in dark matter halos from $z = 0$ –8. *ApJ* 770, 57. arxiv.org/abs/1207.6105
- Bond, J. R., Kofman, L. and Pogosyan, D. (1996). How filaments of galaxies are woven into the cosmic web. *Nature* 380, 603. arxiv.org/abs/astro-ph/9512141
- Bernstein, J., Brown, L. S. and Feinberg, G. (1989). Cosmological helium production simplified. *Reviews of Modern Physics* 61, 25. doi.org/10.1103/RevModPhys.61.25
- Bland-Hawthorn, J. and Gerhard, O. (2016). The Galaxy in context: structural, kinematic and integrated properties. *ARA&A* 54, 529. arxiv.org/abs/1602.07702
- Bromm, V. and Larson, R. B. (2004). The first stars. *ARA&A* 42, 79. arxiv.org/abs/astro-ph/0311019
- Bullock, J. S. et al. (2001). A universal angular momentum profile for galactic halos. *ApJ* 555, 240. arxiv.org/abs/astro-ph/0011001
- Burbidge, E. M., Burbidge, G. R., Fowler, W. A. and Hoyle, F. (1957). Synthesis of the elements in stars. *Reviews of Modern Physics* 29, 547. doi.org/10.1103/RevModPhys.29.547
- Caldwell, R. R., Kamionkowski, M. and Weinberg, N. N. (2003). Phantom energy and cosmic doomsday. *PRL* 91, 071301. arxiv.org/abs/astro-ph/0302506
- Canup, R. M. and Asphaug, E. (2001). Origin of the Moon in a giant impact near the end of the Earth's formation. *Nature* 412, 708. doi.org/10.1038/35089010
- Carniani, S. et al. (2024). Spectroscopic confirmation of two luminous galaxies at a redshift of 14. *Nature* 633, 318. arxiv.org/abs/2405.18485
- Carroll, S. M. and Chen, J. (2004). Spontaneous inflation and the origin of the arrow of time. arxiv.org/abs/hep-th/0410270
- Cautun, M. et al. (2014). Evolution of the cosmic web. *MNRAS* 441, 2923. arxiv.org/abs/1401.7866

- Chaisson, E. J. (2011). Energy rate density as a complexity metric and evolutionary driver. *Complexity* 16, 27. doi.org/10.1002/cplx.20323
- Chandrasekhar, S. (1931). The maximum mass of ideal white dwarfs. *ApJ* 74, 81. doi.org/10.1086/143324
- Clowe, D. et al. (2006). A direct empirical proof of the existence of dark matter. *ApJL* 648, L109. arxiv.org/abs/astro-ph/0608407
- Connelly, J. N. et al. (2012). The absolute chronology and thermal processing of solids in the solar protoplanetary disk. *Science* 338, 651. doi.org/10.1126/science.1226919
- Cooke, R. J., Pettini, M. and Steidel, C. C. (2018). One percent determination of the primordial deuterium abundance. *ApJ* 855, 102. arxiv.org/abs/1710.11129
- Cybur, R. H., Fields, B. D., Olive, K. A. and Yeh, T.-H. (2016). Big Bang nucleosynthesis: present status. *Reviews of Modern Physics* 88, 015004. arxiv.org/abs/1505.01076
- DESI Collaboration (2025). DESI DR2 Results II: measurements of baryon acoustic oscillations and cosmological constraints. arxiv.org/abs/2503.14738
- Dobbs, C. and Baba, J. (2014). Dawes Review 4: spiral structures in disc galaxies. *PASA* 31, e035. arxiv.org/abs/1407.5062
- Dunbar, D. N. F., Pixley, R. E., Wenzel, W. A. and Whaling, W. (1953). The 7.68-MeV state in C¹². *Physical Review* 92, 649. doi.org/10.1103/PhysRev.92.649
- Dutton, A. A. and Macciò, A. V. (2014). Cold dark matter haloes in the Planck era. *MNRAS* 441, 3359. arxiv.org/abs/1402.7073
- Dziewonski, A. M. and Anderson, D. L. (1981). Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors* 25, 297. [doi.org/10.1016/0031-9201\(81\)90046-7](https://doi.org/10.1016/0031-9201(81)90046-7)
- Dyson, F. J. (1979). Time without end: physics and biology in an open universe. *Reviews of Modern Physics* 51, 447. doi.org/10.1103/RevModPhys.51.447
- Egan, C. A. and Lineweaver, C. H. (2010). A larger estimate of the entropy of the universe. *ApJ* 710, 1825. arxiv.org/abs/0909.3983
- Eisenstein, D. J. et al. (2005). Detection of the baryon acoustic peak in the large-scale correlation function of SDSS luminous red galaxies. *ApJ* 633, 560. arxiv.org/abs/astro-ph/0501171
- England, J. L. (2013). Statistical physics of self-replication. *Journal of Chemical Physics* 139, 121923. doi.org/10.1063/1.4818538
- Epelbaum, E. et al. (2013). Viability of carbon-based life as a function of the light quark mass. *PRL* 110, 112502. arxiv.org/abs/1212.4181
- Fall, S. M. and Efsthathiou, G. (1980). Formation and rotation of disc galaxies with haloes. *MNRAS* 193, 189. doi.org/10.1093/mnras/193.2.189
- Fixsen, D. J. (2009). The temperature of the cosmic microwave background. *ApJ* 707, 916. arxiv.org/abs/0911.1955
- Freedman, W. L. et al. (2025). Status report on the Chicago–Carnegie Hubble Program (CCHP). *ApJ* 985, 203. arxiv.org/abs/2408.06153
- Fulton, B. J. et al. (2017). The California-Kepler Survey III: a gap in the radius distribution of small planets. *AJ* 154, 109. arxiv.org/abs/1703.10375
- Glavin, D. P. et al. (2025). Abundant ammonia and nitrogen-rich soluble organic matter in samples from asteroid (101955) Bennu. *Nature Astronomy* 9, 199. doi.org/10.1038/s41550-024-02472-9
- Guth, A. H. (1981). Inflationary universe: a possible solution to the horizon and flatness problems. *Physical Review D* 23, 347. doi.org/10.1103/PhysRevD.23.347
- Hawking, S. W. (1974). Black hole explosions? *Nature* 248, 30. doi.org/10.1038/248030a0
- Hayashi, C. (1981). Structure of the solar nebula, growth and decay of magnetic fields and effects of magnetic and turbulent viscosities on the nebula. *Prog. Theor. Phys. Suppl.* 70, 35. doi.org/10.1143/PTPS.70.35
- Heger, A. et al. (2003). How massive single stars end their life. *ApJ* 591, 288. arxiv.org/abs/astro-ph/0212469
- Hoyle, F. (1954). On nuclear reactions occurring in very hot stars. *ApJS* 1, 121. doi.org/10.1086/190005
- Hubble, E. (1926). Extragalactic nebulae. *ApJ* 64, 321. doi.org/10.1086/143018
- Hubble, E. (1929). A relation between distance and radial velocity among extra-galactic nebulae. *PNAS* 15, 168. doi.org/10.1073/pnas.15.3.168
- Jeans, J. H. (1902). The stability of a spherical nebula. *Phil. Trans. R. Soc. A* 199, 1. doi.org/10.1098/rsta.1902.0012
- Ji, A. P. et al. (2016). R-process enrichment from a single event in an ancient dwarf galaxy. *Nature* 531, 610. arxiv.org/abs/1512.01558

- Johnson, J. A. (2019). Populating the periodic table: nucleosynthesis of the elements. *Science* 363, 474. doi.org/10.1126/science.aau9540
- Kasen, D. et al. (2017). Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event. *Nature* 551, 80. arxiv.org/abs/1710.05463
- Kasting, J. F., Whitmire, D. P. and Reynolds, R. T. (1993). Habitable zones around main sequence stars. *Icarus* 101, 108. doi.org/10.1006/icar.1993.1010
- Kennicutt, R. C. and Evans, N. J. (2012). Star formation in the Milky Way and nearby galaxies. *ARA&A* 50, 531. arxiv.org/abs/1204.3552
- Kipping, D. (2020). An objective Bayesian analysis of life's early start and our late arrival. *PNAS* 117, 11995. doi.org/10.1073/pnas.1921655117
- Kobayashi, C., Karakas, A. I. and Lugaro, M. (2020). The origin of elements from carbon to uranium. *ApJ* 900, 179. arxiv.org/abs/2008.04660
- Kopparapu, R. K. et al. (2013). Habitable zones around main-sequence stars: new estimates. *ApJ* 765, 131. arxiv.org/abs/1301.6674
- Kormendy, J. and Ho, L. C. (2013). Coevolution (or not) of supermassive black holes and host galaxies. *ARA&A* 51, 511. arxiv.org/abs/1304.7762
- Kormendy, J. and Kennicutt, R. C. (2004). Secular evolution and the formation of pseudobulges in disk galaxies. *ARA&A* 42, 603. arxiv.org/abs/astro-ph/0407343
- Krauss, L. M. and Starkman, G. D. (2000). Life, the universe, and nothing: life and death in an ever-expanding universe. *ApJ* 531, 22. arxiv.org/abs/astro-ph/9902189
- Kroupa, P. (2001). On the variation of the initial mass function. *MNRAS* 322, 231. arxiv.org/abs/astro-ph/0009005
- Lane, N. and Martin, W. (2010). The energetics of genome complexity. *Nature* 467, 929. doi.org/10.1038/nature09486
- Lelli, F., McGaugh, S. S. and Schombert, J. M. (2016). SPARC: mass models for 175 disk galaxies. *AJ* 152, 157. arxiv.org/abs/1606.09251
- Libeskind, N. I. et al. (2018). Tracing the cosmic web. *MNRAS* 473, 1195. arxiv.org/abs/1705.03021
- Lilly, S. J. et al. (2013). Gas regulation of galaxies. *ApJ* 772, 119. arxiv.org/abs/1303.5059
- Lin, C. C. and Shu, F. H. (1964). On the spiral structure of disk galaxies. *ApJ* 140, 646. doi.org/10.1086/147955
- Lineweaver, C. H., Fenner, Y. and Gibson, B. K. (2004). The galactic habitable zone and the age distribution of complex life in the Milky Way. *Science* 303, 59. arxiv.org/abs/astro-ph/0401024
- Louis, T. et al. (2025). The Atacama Cosmology Telescope: DR6 power spectra, likelihoods and Λ CDM parameters. arxiv.org/abs/2503.14452
- Lyons, T. W., Reinhard, C. T. and Planavsky, N. J. (2014). The rise of oxygen in Earth's early ocean and atmosphere. *Nature* 506, 307. doi.org/10.1038/nature13068
- Madau, P. and Dickinson, M. (2014). Cosmic star-formation history. *ARA&A* 52, 415. arxiv.org/abs/1403.0007
- Maynard Smith, J. and Szathmáry, E. (1995). The major evolutionary transitions. *Nature* 374, 227. doi.org/10.1038/374227a0
- McCoy, T. J. et al. (2025). An evaporite sequence from ancient brine recorded in Bennu samples. *Nature* 637, 1072. doi.org/10.1038/s41586-024-08495-6
- McGaugh, S. S. et al. (2000). The baryonic Tully–Fisher relation. *ApJL* 533, L99. arxiv.org/abs/astro-ph/0003001
- McGaugh, S. S. (2012). The baryonic Tully–Fisher relation of gas-rich galaxies as a test of Λ CDM and MOND. *AJ* 143, 40. arxiv.org/abs/1107.2934
- McGaugh, S. S., Lelli, F. and Schombert, J. M. (2016). Radial acceleration relation in rotationally supported galaxies. *PRL* 117, 201101. arxiv.org/abs/1609.05917
- McKee, C. F. and Ostriker, E. C. (2007). Theory of star formation. *ARA&A* 45, 565. arxiv.org/abs/0707.3514
- Miller, S. L. (1953). A production of amino acids under possible primitive Earth conditions. *Science* 117, 528. doi.org/10.1126/science.117.3046.528
- Mo, H. J., Mao, S. and White, S. D. M. (1998). The formation of galactic disks. *MNRAS* 295, 319. arxiv.org/abs/astro-ph/9707093
- Moody, E. R. R. et al. (2024). The nature of the last universal common ancestor and its impact on the early Earth system. *Nature Ecology & Evolution* 8, 1654. doi.org/10.1038/s41559-024-02461-1
- Naab, T. and Ostriker, J. P. (2017). Theoretical challenges in galaxy formation. *ARA&A* 55, 59. arxiv.org/abs/1612.06891

- Naidu, R. P. et al. (2025). A cosmic miracle: a remarkably luminous galaxy at $z = 14.44$ confirmed with JWST. arxiv.org/abs/2505.11263
- Navarro, J. F., Frenk, C. S. and White, S. D. M. (1997). A universal density profile from hierarchical clustering. *ApJ* 490, 493. arxiv.org/abs/astro-ph/9611107
- Ostriker, J. P. and Peebles, P. J. E. (1973). A numerical study of the stability of flattened galaxies. *ApJ* 186, 467. doi.org/10.1086/152513
- Peebles, P. J. E. (1969). Origin of the angular momentum of galaxies. *ApJ* 155, 393. doi.org/10.1086/149876
- Penzias, A. A. and Wilson, R. W. (1965). A measurement of excess antenna temperature at 4080 Mc/s. *ApJ* 142, 419. doi.org/10.1086/148307
- Pillepich, A. et al. (2018). Simulating galaxy formation with the IllustrisTNG model. *MNRAS* 473, 4077. arxiv.org/abs/1703.02970
- Planck Collaboration (2020). Planck 2018 results VI: cosmological parameters. *A&A* 641, A6. arxiv.org/abs/1807.06209
- Planck Collaboration (2020). Planck 2018 results X: constraints on inflation. *A&A* 641, A10. arxiv.org/abs/1807.06211
- Press, W. H. and Schechter, P. (1974). Formation of galaxies and clusters of galaxies by self-similar gravitational condensation. *ApJ* 187, 425. doi.org/10.1086/152650
- Raymond, S. N. and Morbidelli, A. (2022). Planet formation: key mechanisms and global models. arxiv.org/abs/2002.05756
- Riess, A. G. et al. (1998). Observational evidence from supernovae for an accelerating universe and a cosmological constant. *AJ* 116, 1009. arxiv.org/abs/astro-ph/9805201
- Riess, A. G. et al. (2022). A comprehensive measurement of the local value of the Hubble constant. *ApJL* 934, L7. arxiv.org/abs/2112.04510
- Riess, A. G. et al. (2024). JWST validates HST distance measurements. arxiv.org/abs/2408.11770
- Rubin, V. C. and Ford, W. K. (1970). Rotation of the Andromeda nebula from a spectroscopic survey of emission regions. *ApJ* 159, 379. doi.org/10.1086/150317
- Salpeter, E. E. (1955). The luminosity function and stellar evolution. *ApJ* 121, 161. doi.org/10.1086/145971
- Sawala, T. et al. (2025). No certainty of a Milky Way–Andromeda collision. *Nature Astronomy*. doi.org/10.1038/s41550-025-02563-1
- Schaye, J. et al. (2015). The EAGLE project. *MNRAS* 446, 521. arxiv.org/abs/1407.7040
- Scrimgeour, M. I. et al. (2012). The WiggleZ Dark Energy Survey: the transition to large-scale cosmic homogeneity. *MNRAS* 425, 116. arxiv.org/abs/1205.6812
- Smartt, S. J. (2009). Progenitors of core-collapse supernovae. *ARA&A* 47, 63. arxiv.org/abs/0908.0700
- Somerville, R. S. and Davé, R. (2015). Physical models of galaxy formation in a cosmological framework. *ARA&A* 53, 51. arxiv.org/abs/1412.2712
- Speagle, J. S. et al. (2014). A highly consistent framework for the evolution of the star-forming 'main sequence' from $z \sim 0$ –6. *ApJS* 214, 15. arxiv.org/abs/1405.2041
- Spiegel, D. S. and Turner, E. L. (2012). Bayesian analysis of the astrobiological implications of life's early emergence on Earth. *PNAS* 109, 395. arxiv.org/abs/1107.3835
- Springel, V. et al. (2005). Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature* 435, 629. arxiv.org/abs/astro-ph/0504097
- Super-Kamiokande Collaboration (2020). Search for proton decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$. *Physical Review D* 102, 112011. arxiv.org/abs/2010.16098
- Tegmark, M., Aguirre, A., Rees, M. J. and Wilczek, F. (2006). Dimensionless constants, cosmology and other dark matters. *Physical Review D* 73, 023505. arxiv.org/abs/astro-ph/0511774
- Toomre, A. (1964). On the gravitational stability of a disk of stars. *ApJ* 139, 1217. doi.org/10.1086/147861
- Toomre, A. and Toomre, J. (1972). Galactic bridges and tails. *ApJ* 178, 623. doi.org/10.1086/151823
- Tsiganis, K., Gomes, R., Morbidelli, A. and Levison, H. F. (2005). Origin of the orbital architecture of the giant planets of the Solar System. *Nature* 435, 459. doi.org/10.1038/nature03539
- Tully, R. B., Courtois, H., Hoffman, Y. and Pomarède, D. (2014). The Laniakea supercluster of galaxies. *Nature* 513, 71. arxiv.org/abs/1409.0880
- Vazza, F. and Feletti, A. (2020). The quantitative comparison between the neuronal network and the cosmic web. *Frontiers in Physics* 8, 525731. doi.org/10.3389/fphy.2020.525731
- Vogelsberger, M. et al. (2014). Introducing the Illustris Project. *MNRAS* 444, 1518. arxiv.org/abs/1405.2921

- Walker, J. C. G., Hays, P. B. and Kasting, J. F. (1981). A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. *JGR* 86, 9776. doi.org/10.1029/JC086iC10p09776
- Walker, S. I. and Davies, P. C. W. (2013). The algorithmic origins of life. *J. R. Soc. Interface* 10, 20120869. arxiv.org/abs/1207.4803
- Walsh, K. J. et al. (2011). A low mass for Mars from Jupiter's early gas-driven migration. *Nature* 475, 206. arxiv.org/abs/1201.5177
- Weinberg, S. (1987). Anthropic bound on the cosmological constant. *PRL* 59, 2607. doi.org/10.1103/PhysRevLett.59.2607
- Weiss, L. M. et al. (2018). The California-Kepler Survey V: peas in a pod. *AJ* 155, 48. arxiv.org/abs/1706.06204
- Weiss, M. C. et al. (2016). The physiology and habitat of the last universal common ancestor. *Nature Microbiology* 1, 16116. doi.org/10.1038/nmicrobiol.2016.116
- White, S. D. M. and Rees, M. J. (1978). Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering. *MNRAS* 183, 341. doi.org/10.1093/mnras/183.3.341
- Wilde, S. A. et al. (2001). Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature* 409, 175. doi.org/10.1038/35051550
- Winn, J. N. and Fabrycky, D. C. (2015). The occurrence and architecture of exoplanetary systems. *ARA&A* 53, 409. arxiv.org/abs/1410.4199
- Woosley, S. E., Heger, A. and Weaver, T. A. (2002). The evolution and explosion of massive stars. *Reviews of Modern Physics* 74, 1015. doi.org/10.1103/RevModPhys.74.1015
- Youdin, A. N. and Goodman, J. (2005). Streaming instabilities in protoplanetary disks. *ApJ* 620, 459. arxiv.org/abs/astro-ph/0409263
- Zel'dovich, Ya. B. (1970). Gravitational instability: an approximate theory for large density perturbations. *A&A* 5, 84. ui.adsabs.harvard.edu/abs/1970A%26A.....5...84Z
- Zhu, W. and Dong, S. (2021). Exoplanet statistics and theoretical implications. *ARA&A* 59, 291. arxiv.org/abs/2103.02127
- Zwicky, F. (1937). On the masses of nebulae and of clusters of nebulae. *ApJ* 86, 217. doi.org/10.1086/143864

Glossary

Table 13. Glossary of key terms

Term	Meaning
Baryon	A particle made of three quarks, such as a proton or neutron; in cosmology, shorthand for ordinary matter
Baryon acoustic oscillation	A preferred separation of about 150 Mpc between galaxies, imprinted by sound waves before recombination
Cosmic microwave background	Radiation released at recombination, now cooled to 2.7255 K
Cosmic web	The network of sheets, filaments, nodes and voids into which matter is arranged on large scales
Creation structure	In this series, the combination of constraints, generators and filters that produces a recurring form
Dark energy	The unknown component, about 68 per cent of the universe's energy density, that drives accelerating expansion
Dark matter	Matter that does not interact with light, about 27 per cent of the energy density; identity unknown
Density wave	A pattern of enhanced density in a disc that rotates at a different speed from the material passing through it
Feedback	Energy and momentum injected by stars and black holes that regulate further star formation
Halo	A roughly spherical, gravitationally bound concentration of dark matter in which a galaxy forms
Initial mass function	The distribution of masses with which stars are born
Jeans length	The minimum size above which a self-gravitating region collapses (Equation 2)
ΛCDM	The standard cosmological model: a cosmological constant (Λ) plus cold dark matter
Metals	In astronomy, all elements heavier than helium
Nucleosynthesis	The formation of atomic nuclei, in the Big Bang, in stars, or in explosive events
Recombination	The formation of neutral atoms 380,000 years after the Big Bang, when the universe became transparent
Redshift (z)	The stretching of light by cosmic expansion; $1 + z$ equals the factor by which the universe has expanded since the light was emitted
r-process, s-process	Rapid and slow neutron capture, the two main routes to elements heavier than iron
Scale factor (a)	The size of the universe relative to today
Toomre Q	The stability parameter of a rotating disc; $Q < 1$ means it is unstable to clumping (Equation 5)
Virial theorem	For a bound gravitating system in equilibrium, the kinetic energy equals minus half the potential energy, so total energy equals minus the kinetic energy

Appendix A: Key Quantities

Table 14. Key quantities used in this report

Quantity	Value	Source
Age of the universe	13.787 ± 0.020 Gyr	Planck (2018)
Radius of the observable universe	About 46.5 billion light years (14.3 Gpc)	Standard Λ CDM
Recombination	$z \approx 1,090$; about 380,000 years	Planck (2018)
Matter–radiation equality	$z \approx 3,400$; about 51,000 years	Planck (2018)
Primordial helium mass fraction	$Y_p \approx 0.245$	Cyburt et al. (2016)
Primordial deuterium	$D/H \approx 2.53 \times 10^{-5}$	Cooke et al. (2018)
Baryon-to-photon ratio	$\eta \approx 6.1 \times 10^{-10}$	Planck (2018)
CMB temperature fluctuations	About 1 part in 100,000	Planck (2018)
Scale of homogeneity	About $70 \text{ h}^{-1} \text{ Mpc}$	Scrimgeour et al. (2012)
Baryon acoustic scale	About 147 Mpc (comoving)	Planck (2018); DESI (2025)
Mass and volume in filaments	About 50 per cent of mass, 6 per cent of volume	Cautun et al. (2014)
Milky Way rotation speed at the Sun	About 230 km s^{-1}	Bland-Hawthorn and Gerhard (2016)
Baryonic Tully–Fisher normalisation	$M_b \approx 47 \text{ V}_r^4 \text{ M}_\odot (\text{km s}^{-1})^{-4}$	McGaugh (2012)
Peak of cosmic star formation	$z \approx 1.9$; about 3.5 Gyr	Madau and Dickinson (2014), this report
Sun's core temperature	About 15.7 million K	Standard solar models
Solar composition by mass (X, Y, Z)	0.738, 0.249, 0.013	Asplund et al. (2009)
Water snow line in the solar nebula	About 2.7 AU	Hayashi (1981), this report
Confirmed exoplanets	More than 6,000 (September 2025)	NASA Exoplanet Archive
Earliest widely accepted evidence of life	About 3.5 billion years ago	Stromatolite record
Entropy of supermassive black holes	About $3 \times 10^{104} \text{ k}$	Egan and Lineweaver (2010)
Proton lifetime lower bound ($p \rightarrow e^+ \pi^0$)	$2.4 \times 10^{34} \text{ years}$	Super-Kamiokande (2020)

Values are rounded. 'This report' indicates a value computed here from the cited model.

Appendix B: Simulation and Calculation Notes

All calculations were written in Python with NumPy and SciPy and are reproducible from fixed random seeds. They are designed to illustrate mechanisms, not to reproduce published simulations in detail.

- **Expansion history (Figure 5, Figure 36).** The Friedmann equation was integrated with $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.315$ and $\Omega_r = 9.1 \times 10^{-5}$, giving an age of 13.79 Gyr. Future scenarios were integrated forward from today: constant $w = -1, -0.8$ and -1.5 , and an illustrative decaying dark energy with $\rho_{DE} \propto 1 - \ln a$, integrated with the second Friedmann equation through turnaround. The phantom case reaches a Big Rip about 23 Gyr from now; the illustrative crunch occurs about 80 Gyr from now.
- **Neutron freeze-out (Figure 7).** The neutron fraction was integrated with the weak rates of Bernstein, Brown and Feinberg (1989), suppressed by $\exp[-(m_e/T - 1)]$ below the electron mass to mimic annihilation, a neutron lifetime of 879.4 s and a time–temperature relation joining $0.86 \text{ t}^{-1/2} \text{ MeV}$ to $1.15 \text{ t}^{-1/2} \text{ MeV}$. The neutron fraction at 180 s is 0.116, giving $Y \approx 0.23$; full codes give 0.247.
- **Growth of structure (Figure 10).** The Mészáros equation was solved through matter–radiation equality, multiplied by the ratio of the Λ CDM to Einstein–de Sitter growth factors at late times. Baryons were held at 10^{-5} until recombination and then followed $\delta_b = \delta_c(1 - a_{\text{rec}}/a)$. The normalisation on galaxy scales is illustrative.
- **Cosmic web (Figure 11, Figure 12).** A Gaussian random field with $P(k) \propto k^{-1.2}$ and a Gaussian cut-off was generated on a 256^2 periodic lattice; displacements were computed in the Zel'dovich approximation, $x = q + D s(q)$, with the divergence of s normalised to unit variance. The correlation dimension was measured from neighbour counts around 3,000 centres among 60,000 particles.
- **Halo mass function (Figure 13).** The BBKS transfer function with $\Gamma = \Omega_m h$, $n_s = 0.965$ and $\sigma_8 = 0.811$, a top-hat window, the Press–Schechter multiplicity function and the Λ CDM linear growth factor.
- **Rotation curve (Figure 17).** Exponential stellar and gas discs (Freeman formula), a Hernquist bulge and an NFW halo, with parameters in the caption. The computed speed is 225 km s^{-1} at 8.2 kpc and 201 km s^{-1} at 30 kpc, against 101 km s^{-1} from baryons alone.
- **Planetesimal coagulation (Figure 27).** An exact stochastic simulation of 1,500 equal bodies with kernel $K = (r_i + r_j)^2[1 + \Theta(m_i + m_j)/(r_i + r_j)]$, $\Theta = 2$, run until 40 bodies remained. At 60 bodies, the largest held 69 per cent of the mass and was 12 times more massive than the second largest.
- **Entropy budget (Figure 35).** Photon entropy density $(4\pi^2/45)(kT/\hbar c)^3 k$ at 2.7255 K, $1,479 \text{ k cm}^{-3}$, over a sphere of radius 46.5 Gly, giving $5.3 \times 10^{89} k$; neutrinos 0.95 times the photon value; stars 7 per cent of 8.9×10^{79} baryons at about 20 k per baryon; stellar black holes 10^8 of $10 M_\odot$ per $6 \times 10^{10} M_\odot$ of stars, each with Bekenstein–Hawking entropy $4\pi GM^2 k/\hbar c$. Supermassive black holes and the horizon bound are taken from Egan and Lineweaver (2010), whose photon and neutrino estimates agree in order of magnitude.
- **Other figures.** The Sérsic profiles, logarithmic spirals, winding pattern, initial mass function, fusion rates, binding energy curve, condensation temperatures, interior density profile and habitable zones are calculated from the standard formulae given in their captions.