Cosmology, fine-tuning, and anthropic reasoning

Christian Wüthrich

http://www.wuthrich.net/

Introduction to Philosophy of Physics
USI, Spring 2018

Philosophy of cosmology

C Smeenk and G Ellis (2017). Philosophy of cosmology. In E. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/entries/cosmology/

> [*T*]*here are two main issues that make the philosophy of cosmology unlike that of any other science. The first is,*
>
> *The uniqueness of the Universe: there exists only one universe, so there is nothing else similar to compare it with, and the idea of 'Laws of the universe' hardly makes sense.*
>
> *This means it is the historical science* par excellence*: it deals with only one unique object that is the only member of its class that exists physically... The second is*
>
> *Cosmology deals with the physical situation that is the context in the large for human existence: the universe has such a nature that our life is possible.*
>
> *This means that although it is a physical science, it is of particular importance in terms of its implications for human life...*

ΛCDM: The cosmological standard model

The ‘standard model’ of cosmology consists in the following elements:

- Friedmann-Lemaître-Robertson-Walker (FLRW) spacetime, a family of models of GR
  - initial singularity: ‘hot big bang’
  - small departures from FLRW spacetime to enable structure formation
- ordinary matter (though not all visible), ca. 5% of mass-energy density
- cold dark matter (= ‘slow’, non-ordinary matter), ca. 26%
- dark energy and/or cosmological constant Λ, ca. 69%
- may or may not include inflationary period, and hence ‘inflaton field’

ΛCDM: The cosmological standard model

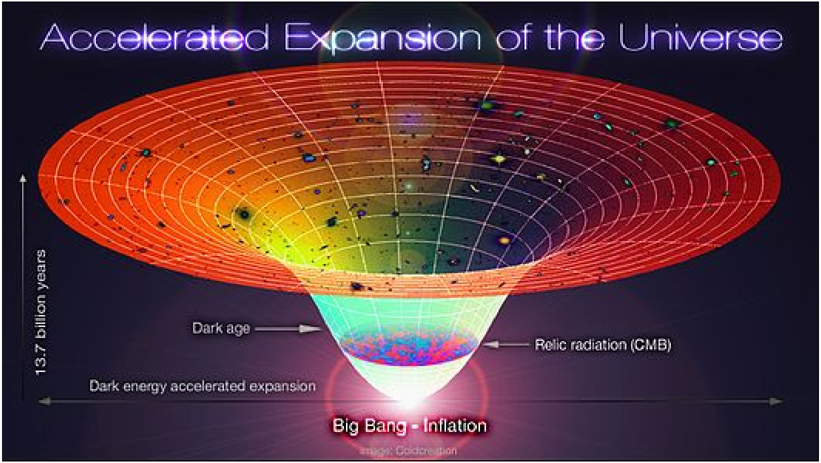


Figure: The expansion of the universe according to the standard model

From basic principles to FLRW spacetimes

Principle (Cosmological)

Both the spacetime structure and the matter distribution are spatially isotropic about us.

- The cosmological principle is reasonably well confirmed by the distribution of the cosmic microwave background radiation and the large-scale distribution of luminous matter in galaxies.

From basic principles to FLRW spacetimes

Principle (Copernican)

We are not privileged observers.

- The Copernican principle is a (plausible, but unconfirmed) assumption.
- Together, the two principles imply that all observers see a spatially isotropic universe.
- This, in turn, implies that the universe is spatially homogenous.
- It can be shown that the FLRW spacetimes are the only spatially isotropic and homogeneous spacetimes in GR.

FLRW spacetimes

- In these spacetimes, there is a natural foliation into spatial slices totally ordered by a 'cosmic time', because there is only one way in which FLRW spacetimes can be foliated to have constant spatial curvature.
- The cosmic time is the time measured by observers at rest with respect to the matter content (and so their worldlines are orthogonal to the spatial folia).

FLRW spacetimes

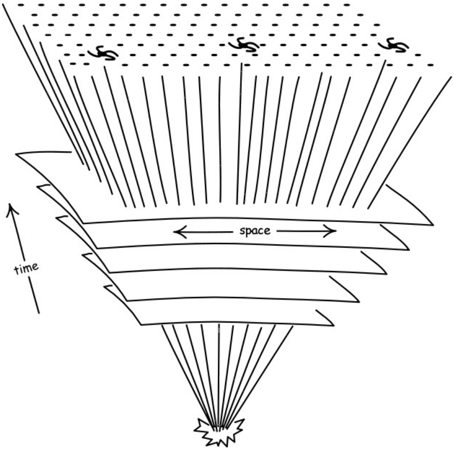
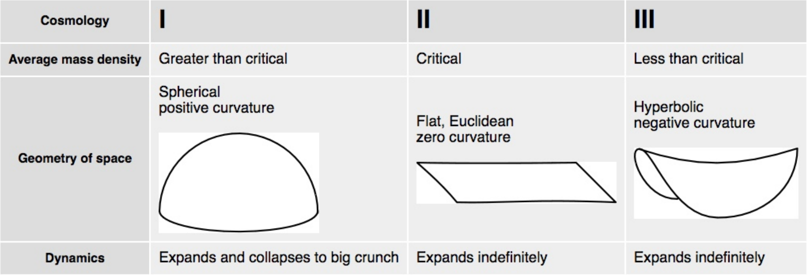


Figure: An expanding FLRW spacetime (Image: Norton, Einstein for Everyone)

FLRW spacetimes

- Since the spatial folia have constant curvature, there are exactly three possibilities for their geometry (if they are simply-connected):
  1. positive: spherical geometry
  2. zero: Euclidean, flat geometry
  3. negative: hyperbolic geometry



Cosmology	I	II	III
Average mass density	Greater than critical	Critical	Less than critical
Geometry of space	Spherical positive curvature	Flat, Euclidean zero curvature	Hyperbolic negative curvature
Dynamics	Expands and collapses to big crunch	Expands indefinitely	Expands indefinitely

Figure: Three spatial geometries (Image: Norton, Einstein for Everyone)

FLRW spacetimes

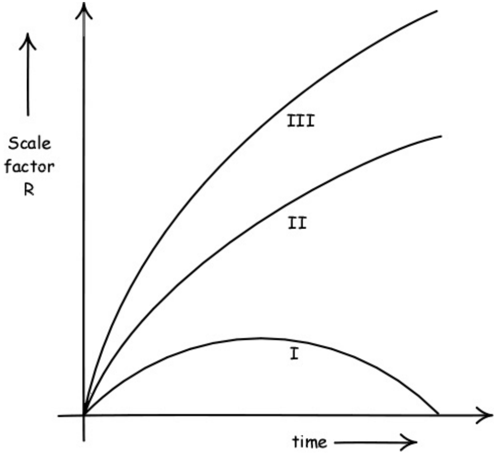


Figure: The scale factor in the three spatial geometries (Image: Norton, Einstein for Everyone)

Three basic features of FLRW spacetimes

C Smeenk and G Ellis (2017). Philosophy of cosmology. In E. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/entries/cosmology/

1. The universe is dynamical, i.e., changes over time, with seven discernible epochs: quantum gravity, inflation, big bang nucleosynthesis, decoupling, dark ages, structure formation, dark energy domination
2. The expansion rate varies over time and depends on which type of matter dominates.
3. Models with ordinary matter have a singularity at a finite time in the past ('big bang')

Alternative models

There exist several alternative models which are weakly empirically equivalent to the standard model, i.e., equally consistent with the data to date:

- Bianchi models (Spatially homogeneous and anisotropic, with intermediate 'isotropization')
- inhomogeneous spherically symmetric models (though they can be ruled out on an individual basis)

Open questions

The standard model leaves open questions regarding...

- the nature of dark matter, dark energy, and the inflaton field,
- structure formation,
- and what would constitute potential falsifiers, i.e., observations which would disconfirm it.

Underdetermination

C Smeenk and G Ellis (2017). Philosophy of cosmology. In E. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/entries/cosmology/

- When philosophers of science speak of underdetermination of theory by evidence, they mean that distinct theories, giving quite different accounts of the world, are equally compatible with a given body of data.
- Cosmology is certainly subject to this form of underdetermination, but also to a second kind:
- The causal past sets very weak constraints on global properties of spacetime; specifically, the causal past of any spacetime event can be part of distinct spacetimes.
- Illustration on black board

Origins of the universe

- Usually in science, initial (or boundary) conditions are not thought to stand in need of explanation—they are considered extraneous to the target of explanation.
- In cosmology, however, many think that we need a 'theory of the initial state', explaining e.g. the required early 'flatness' and 'uniformity' of the spacetime structure.
- Extrapolating backwards from the present, there is no 'first moment' of time, but still all worldlines have finite proper time.
- At earlier times, the universe is denser and smaller.
- The 'initial' state' according to the standard model is preceded by a singularity, where the equations of GR break down.
- 'Singularity theorems': the universe is temporally finite in the past in a broad class of realistic models

Theories of the initial state

There are three main ways to 'explain' the 'initial state':

1. Dynamically: the dynamical evolution washes away anisotropies of earlier 'generic' or 'random' states and 'flattens' the universe (e.g., Misner's 'chaotic cosmology programme', inflationary cosmology)
2. Extremely special 'initial state': giving an account of the very special 'initial state', which is necessary to explain time's arrow (e.g. Penrose's Weyl curvature hypothesis, or his 'conformal cyclic cosmology')
3. 'Branch point': instead of starting in an 'initial state', our universe comes into being by branching off from a larger multiverse

- The third approach, in itself, does not really give an explanation of the uniformity and flatness of the universe. Hence, it is usually combined with one of the two approaches.

The limits of science

Cosmology raises basic questions about scientific methodology and its limits:

- What falls under the purview of science in the first place, i.e., what stands in need of explanation in the first place?
- What is in principle even amenable to scientific explanation? What would count as an adequate explanation of the origins of the universe?
- Given the uniqueness of the universe and of its origin, does it even make sense to talk about 'laws' in cosmology?

Anthropic reasoning: selection effect

General idea:

The physical conditions necessary for human life impose a selection effect on what we observe.

Eddington, Arthur (1939). *The Philosophy of Physical Science*. Cambridge University Press.

> *Let us suppose that an ichthyologist is exploring the life of the ocean. He casts a net into the water and brings up a fishy assortment. Surveying his catch, he proceeds in the usual manner of a scientist to systematise what it reveals. He arrives at two generalisations: (1) No sea-creature is less than two inches long. (2) All sea-creatures have gills. These are both true of his catch, and he assumes tentatively that they will remain true however often he repeats it... An onlooker may object that the first generalisation is wrong. "There are plenty of sea-creatures under two inches long, only your net is not adapted to catch them"...*

Dirac's 'large number hypothesis'

Dirac, Paul A M (1937). The cosmological constants. *Nature* **139**: 323.

- Dirac: the age of the universe expressed in terms of fundamental constants of atomic physics is a very large number (of the order 10^{39})
- This number coincides with other large, dimensionless number defined in terms of fundamental constants...
- This inspired him to postulate that the large numbers co-vary, maintaining this order of magnitude agreement.
- E.g., the gravitational constant G is inversely proportional to the cosmic time.
- Dicke (1961): creatures like us can only exist with restricted interval of comic time, and so we can ever only have evidence that Dirac's hypothesis holds for those periods

Carter's anthropic principles

Carter, Brandon (1974). Large number coincidences and the anthropic principle in cosmology. In M S Longair (ed.), *Confrontation of Cosmological Theory with Observational Data*, Dordrecht: Reidel, pp. 291-298.

Principle (Weak anthropic principle (WAP))

[W]e must be prepared to take account of the fact that our location in the universe is necessarily privileged to the extent of being compatible with our existence as observers. (293)

⇒ Our observations are, by necessity, biased towards detecting conditions compatible with our existence.

⇒ observation selection effect

- WAP: with respect to location; can be strengthened to the entire universe (possibly as part of a multiverse)

Carter's anthropic principles

Carter, Brandon (1974). Large number coincidences and the anthropic principle in cosmology. In M S Longair (ed.), *Confrontation of Cosmological Theory with Observational Data*, Dordrecht: Reidel, pp. 291-298.

Principle (Strong anthropic principle (SAP))

[*T*]*he universe (and hence the fundamental parameters on which it depends) must be such as to admit within it the creation of observers within it at some stage. (294)*

- SAP has often been misinterpreted along teleological lines, e.g. by Barrow and Tipler (1986).

Weinberg's 'anthropic prediction'

Weinberg, Steven (1987). Anthopic bound on the cosmological constant. *Physical Review Letters* **59**: 2607-2610.

- Weinberg: there exist anthropic bounds on Λ (because of its impact on structure formation)
- Weinberg: what is the value of Λ that a 'typical' observer would see?
- Assumption: observers occupy different regions in a multiverse with different values for Λ
- Assumption: the prior probability assigned to different values of Λ is uniform within anthropic bounds (version of the principle of indifference)

$\Rightarrow$ 'typical observers' should expect to observe a value for Λ close to the mean of the anthropic interval

$\Rightarrow$ Weinberg's prediction for Λ

Problems with anthropic predictions like this

C Smeenk and G Ellis (2017). Philosophy of cosmology. In E. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/entries/cosmology/

1. Reference class problem: what is the appropriate reference class? What is typical with respect to one reference class is not typical with respect to another (conscious observers vs carbon-based life form)
2. Problems with the principle of indifference: what justifies the use of indifference here; what makes us 'randomly chosen' among a chosen reference class?
3. Universe may not be infinite, or we may not live in a multiverse

Illustration: Doomsday argument

- Assumption (typicality): We are ‘typical’ humans with respect to our birth rank being randomly selected among all humans who ever lived.

⇒ We should expect that roughly the same number of people have been born before us as after us.

⇒ Given current population growth rates, if this is true, then a catastrophic drop in human population is imminent.

- It seems as if an advocate of indifference is committed to these kinds of consequences.

Fine-tuning

- The existence of life minimally requires the existence of complex structures, which in turn sensitively depends on the values of fundamental constants of nature.
- Yet, these values of constants are ultimately contingent.
- Fine-tuning arguments: "shouldn't something as fundamental as the complexity of the universe be explained by the laws or basic principles of the theory, and not left to brute facts regarding the values of various constants?" (Smeenk and Ellis, §4.2)
- Formulations of fine-tuning arguments often introduce probabilistic considerations.
- Probabilities are generally epistemic, not objective (except arguably for multiverses).

The main responses to fine-tuning

1. Empiricist denial: No clear problem has ever been identified. We need contingent facts as well as the laws to explain.
2. New Physics: News laws of physics, or new constraints on the space of possible values of the constants of nature, eliminate the need to fine-tune.
3. Designer: A particular kind of designer (one likely to create a universe such as ours) would explain the apparent fine-tuning.
4. Multiverse: Fine-tuning results of selection from a large set of universes.

(3) Modern design argument from fine-tuning

If the strong nuclear force were to have been as little as 2% stronger (relative to the other forces), all hydrogen would have been converted into helium. If it were 5% weaker, no helium at all would have formed and there would be nothing but hydrogen. If the weak nuclear force were a little stronger, supernovas could not occur, and heavy elements could not have formed. If it were slightly weaker, only helium might have formed. If the electromagnetic forces were stronger, all stars would be red dwarfs, and there would be no planets. If it were a little weaker, all stars would be very hot and short-lived. If the electron charge were ever so slightly different, there would be no chemistry as we know it. Carbon (^{12}C) only just managed to form in the primal nucleosynthesis.

Ernan McMullin (1993, 378)

Indifference Principle and Anthropic Principle in Cosmology. *Stud. Hist. Phil. Sci.* 24 (1993): 359-389.

Probabilistic version of the argument

Let AC stand for so-called anthropic coincidences such as that there are 3 dimensions not 2 or 4, neutrino mass is 5×10^{-34} kg instead of 5×10^{-35} kg, gravity not 1 part in 1040 stronger, omega so close to 1...

Probabilistic version of the argument

Principle (Likelihood or Confirmation Principle)

Observation O supports hypothesis H_1 more than it supports hypothesis H_2 if and only if $P(O/H_1) > P(O/H_2)$.

- $P(\text{AC}/\text{God}) > P(\text{AC}/\text{Chance})$
- Therefore, the hypothesis that God exists is better confirmed than the hypothesis of chance.
- Assumption: no 'third hypothesis' like evolution to get in the way.

But...

Compare with:

O_1. You hear a noise in the attic.

G_1. The noise occurred due to gremlins living in attic.

G_2. The noise occurred due to chance.

$$\Rightarrow \quad P(O_1/G_1) > P(O_1/G_2)$$

- What we really need is a comparative assessment of $P(H_i/O)$; but:

Math Fact

$$P(H_1/O) > P(H_2/O) \text{ iff } P(O/H_1)P(H_1) > P(O/H_2)P(H_2)$$

$\Rightarrow$ so the 'prior' probabilities $P(H_i)$ matter!

The anthropic objection

- Main idea: inference from AC to design breaks down once bias arising from observation selection effects is properly taken into account.

⇒ Not $P(\text{AC/God}) > P(\text{AC/Chance})$ is relevant inequality, but instead the much more problematic $P(\text{AC/God and OSE}) > P(\text{AC/Chance and OSE})$, where OSE refers to observation selection effects.

- However, $P(\text{AC/God and OSE}) = P(\text{AC/Chance and OSE}) = 1$, and so the inequality no longer holds and the inference to design is blocked
- Principle of Total Evidence: all evidence must be taken into account, such as—relevantly—our existence

Further criticism: the nature of the probabilities

- Do we have a good definition of fine-tuning? The argument seems to assume an a priori probability metric; but why that one?
- It's difficult to justify an objective probability metric; better understood as subjective probabilities.

(4) Multiverse

A multiverse is an ensemble of universes varying in their fundamental constants.

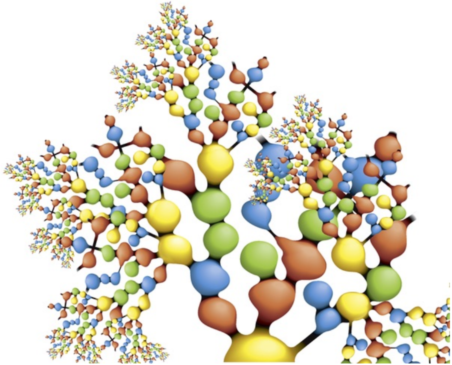
(4) Multiverse

- It is assumed that in a multiverse, all possible values of the fundamental constants are realized in some universe.

$\Rightarrow$ Most of these universes will be inhospitable for life, but some will be just right.

- Suppose there is a principled way of assigning probabilities over the individual universes.
- Then this approach would explain fine-tuning if our calculations show that we observe typical values for life-permitting universes.

Eternal inflation



- variation of duration of rapid expansion (inflationary phase) in different universes
- kernel of off-spring universes within parent universe

Evaluation

- Just as for the design hypothesis, the inference to the multiverse hypothesis can be cast in probabilistic terms.
- All considerations concerning the design hypothesis apply *mutatis mutandis*.
- In the case of eternal inflation, we may obtain a physical probability metric, which delivers objective probabilities.
- Nevertheless, the physics is very speculative.
- The inference to the multiverse is based purely on anthropic reasoning, as there are no empirical signatures (so far).

The inverse gambler's fallacy charge

Hacking, Ian (1987). The inverse gambler's fallacy: the argument from design. The anthopic principle applied to Wheeler Universes. *Mind* **96**: 331-340.

White, Roger (2000). Fine-tuning and multiple universes. *Noûs* **34**: 260-267.

- Gambler's fallacy: "mistaken belief that, if something happens more [less] frequently than normal during a given period, it will happen less [more] frequently in the future."

  (https://en.wikipedia.org/wiki/Gambler's_fallacy)

- Inverse gambler's fallacy (Hacking 1987): fallacious inference from apparently rare event to the conclusion that there have likely been many similar, but more typical events in the past
- Charge: argument from fine-tuning to multiverse commits this fallacy by "supposing that the existence of many other universes makes it more likely that this one—the only one that we have observed—will be life-permitting" (White 2000, 263)