Field Manual of Fine-Tuning

Chapter Notes: Dark Energy

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Physics Covered
Dark Energy, Cosmological Constant

Previous Chapter:
Unknown, likely inflation

Following Chapter:
Unknown, likely baryogengesis

Types of Fine-Tuning:
X small, for fundamental constants X such that process still happens. Fine tuning of potentials or of altered Lagrangians to explain dark energy, sometimes initial conditions (Tracking). Population of an ensemble through mutliverse methods, a physical toy model multiverse by shallow sloped scalar field as dark energy.

Directly explored Fine-Tuned Parameters:

- Λ: The cosmological constant
- w: The ratio of pressure to energy density
- $\dot{\lambda}$: The changing of dark energy
- $V(\phi)$: Potential for scalar field dark energy
- t_λ: The coincidence that dark energy just starts to dominate today

Indirectly explored Fine-Tuned Parameters:

- Ω_k: The curvature component of energy density
- $\mathcal{L}$: The matter lagrangian
- V_H: The Higgs vacuum expectation value

Assumed Background:

- Friedmann Equation
- Inflation (Stochastic) to populate multiverse
- Bayesian/Frequentist probability

Outline of Chapter:

Statement of the question: Why is Λ so small?

- What does it mean to be small? What units for Λ?
- Cancellation of 'vacuum energy' from matter and geometrical constant.
- Any Lagrangian based theory can have a constant added to it. How is this constant fine-tuned?
- There is very little hope for explaining Λ from fundamental physics. Solutions:
  - existence of (unknown) symmetry
  - observer selection
- We are in a universe where Λ is sufficiently large.
- Even if future observations reveals that Λ is dynamical, observer selection may play a role.
- Ideally, if we could fix Λ from some symmetry the anthropic principle wouldn't need to be invoked.
- Life cannot happen before recombination, hence observers have to live close to or after the matter-radiation equilibrium.
- Λ seems constant up to 10% in the last billion years.

Nature of probability: Bayesian or Frequentist

- Frequentist approach seems more comfortable than bayesian.
- Objection to Bayesian statistics: the need for a metatheory to tell what the priors are.
- From a frequentist point of view knowledge of the ensemble is required.
- *"What is random anyways"*, referring to the measurement problem.
- Bubble nucleation in de Sitter space: until bubble is formed you can't have a value for Λ.

Multiverse Interpretation of Fine-Tuning:

- A prescription for fundamental Physics that wouldn't allow observers to exist is clearly wrong.
- Multiverse from inflation (bubbles) rather than from QM interpretations.
- *"Inflation is the existence of subhorizon fluctuations"*
- Probability of seeing bubble collisions is very small.
- What does it mean to be an observer?
- *"For each winner there's gotta be a lot of losers"*, referring to the analogy between multiverse and lottery.
- *"There is no fine-tuning, there's just observer selection"*, in the sense that what we call fine-tuning is just the outcome of what "went right".
- *"The real question for cosmology is whether this ensemble [multiverse] actually exists."*, referring to the ensemble of possibilities that allow for observer selection.
- The multiverse, if it exists, will never be observed by anything.
- Different types of anthropic reasoning: Single universe anthropics: when in time are there observers vs multiverse anthropics: where (which multiverse(s)) are there observers
- Star formation rate peaks at redshift ~ 2. This coincides with the beginning of Λ dominance. Is this a coincidence? (probably yes)
- In a multiverse Λ takes arbitrary values at arbitrary points, cancelling effects of large number of observes in specific verses.
- Anthropic reasoning is not tautology, since we can predict a posterior for Λ.

Probability Measures on Λ:

- If Λ is dynamical, why hasn't it converged to zero?
- Is it possible to set a lower limit to Λ?
- There is nothing special about $\Lambda = 0$, so why don't we scan negative values?
- Jeffreys' prior cannot be applied to Λ in a straightforward way, since we can have $\Lambda < 0$ where $\log \Lambda$ is not defined.
- If $\Lambda < 0$ most of the growth of density fluctuations happen in the recollapse phase.

Dark Energy and Curvature:

- Why is the universe not curvature-dominated today?

- Weinberg-like type of argument brackets the value of curvature required for the existence of observers. Therefore, observer selection trims large curvatures.
- Is it possible to make a straightforward analogy between k and Λ? (No)
- Small value of curvature does not explain observer selection
- Inflation produces flatness: curvature gets damped exponentially as inflation proceeds.
- Larger curvature should produce more observers?

Dark Energy Models:

- Tracking models: equation of state is essentially that of the dominant term; kinetic and potential terms may be comparable.
- Tracking models fail to solve fine-tuning because they fail to solve their own fine-tuning.
- Different values of Λ in different bubbles due to quantum fluctuations of a flat potential $\rightarrow$ change in Λ, although small. Problems: slope of potential; dispersion of Λ in Weinberg's flat prior.
- k-essence models:
  - models with zero potential
  - tracking of effective Λ in the radiation era
  - "made-up" functions
  - priors in the space of functions instead of numbers
  - particle physics ideas (e.g. Higgs potential for inflaton) $\rightarrow$ GUT justified
  - k-essence doesn't connect to anything else and has no analogous matter models.
- Modified gravity theories are theories just like GR, containing a metric, etc. There are changes with respect to GR, but they don't make the theory substantially different than GR.
- Working with Λ in the geometrical side of the equations is just a matter of semantics.
- There is no motivation for the "classical" Λ, just a term in Einstein's equations.
- This Λ cannot be in the geometrical part of Einstein's equations.
- Zero point energy may not gravitate.

Galaxies and Lambda - Stars as a proxy for observers:

- Existence of observers favoured in galaxies that are efficient at making stars (e.g. Milky Way).
- Dwarf galaxies are not efficient at forming stars. Stars heat up the gas and the galaxy then blows it away. The more massive the galaxy the more likely it is for the gas to be gravitationally bound to the galaxy. Temperature of gas in galaxies is $\sim 10^4$ K.
- *"Eternity is really long, specially towards the end."* - referring to a Λ-dominated universe which tends to a de Sitter universe. Quote by W. Allen (probably).
- Up to now star formation might not have been very efficient. We might misleadingly be lead to be believe that star formation is getting constant, which is not.
- Cooling time of the gas in galaxies is usually taken as much larger than age of the universe. What will happen in the future?
- As long as there are DM halos there can be observers.
- Idea: run galaxy formation simulations far into the future. Possible outcome: everything evolves to becoming stars.

Discussion:

- Use fine-tuned-motivated arguments as a tool for discovery, coming from different assumptions which may seem absurd.
- Testability of the multiverse: direct vs. indirect evidence? Former is very unlikely.
- In the future we'll only see nearby galaxies and we won't see far away objects. How would a cosmologist in one of these galaxies see the universe if he isn't able to see anything other than his own galaxy? In this case each galaxy will be like a universe and others galaxies a multiverse.
- Error bars on Λ: when to stop? Moral compass for that: spending too much money for little results may not be worth it.
- Occam's razor favours models with fewer free parameters, but others may be equally likely.
- Aren't we just transferring the fine-tuning of Λ in the universe to a fine-tuning of a distribution in the multiverse?
- Anthropic constraints on running w: how sensitive is it to anthropics? Not very much. No real observer selection.