Field Manual of Fine-Tuning

Chapter Notes: Standard Model

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Physics Covered
Dark Matter

Previous Chapter:
Unknown, possibly structure formation

Following Chapter:
Unknown

Types of Fine-Tuning:

Ω_X/Ω_b, Ω_X/Ω_Λ small or large, so that expansion won't hamper structure formation
A/B (dimensionless) too large/small, where A and B are ratio of quantities such as masses.

Directly explored Fine-Tuned Parameters:

- Ω_X: dark matter density
- Ω_r: radiation density
- Ω_b: baryon density
- Ω_Λ: the dark energy density

Indirectly explored Fine-Tuned Parameters:

- n_b: density of baryons
- $\bar{n}_b$: density of anti-baryons
- n_γ: density of radiation
- m_ν: neutrino mass
- t_λ: the coincidence that dark energy just starts to dominate today
- w: the ratio of pressure to energy density

Assumed Background:

- Early universe Cosmology
- Friedmann Equation
- Particle Physics

Outline of Chapter:

Introduction

- Evidence for DM: indirect.
- Analogy with BHs: we can infer it from orbits.
- Dark matter effectively plays no role for life (probably).
- DM does play an important role in structure formation though.

Particle aspects & WIMPs

- Mass spectrum too large, but probably not fine-tuned.
- If DM interacts only gravitationally, how do we gravitationally detect a single particle?
- We have a minimalist idea of there being only one type of DM. There might be a whole dark sector. *"Imagine you are from the 'dark side'. You would probably start saying that baryons are only of one kind."*
- If $m_X \ll$ eV and $m_X \gg$ TeV couldn't there be some degree of fine- tuning, since these masses are nowhere close to the masses of known particles?
- Annihilation cross section related to $m_W \rightarrow$ "WIMP miracle".

Cosmological aspects & Structure formation

- Neutrino masses are also relevant for structure formation.
- Besides large structures (galaxies), dark matter also provide the initial conditions for the formation of stars.
- The creation and annihilation rates were faster than the expansion rate. When $T < M$ creation and annihilation rates became smaller than the expansion rate, so they would no longer be in equilibrium, freezing out with some particular abundances.
- Where it froze out depends on the interaction cross section of WIMPs and matter.
- The mass is not as important as the cross section. To leading order the masses cancel out.
- One can have structure formation with baryons only, but in this case we would have bottom-up formation; with DM it is top-down. Formation of structures would also occur later.
- Relationship between relative abundance of baryons and dark matter density ($\eta \equiv n_b - \bar{n}_b/n_\gamma \sim 10^{-9}$) $\rightarrow$ directly affects formation of structures.
- What would happen if $\eta \sim 1$?

Modified Gravity vs. Dark Matter

- Parametrised newtonian expansion including r^{-3} term can be used to effectively describe things. Why do we prefer a DM rather than such an effective theory?
- Top-down approach: assume a theory that contains DM with a given mass and show that it correctly describes reality.
- Bottom-up approach: infer the mass of DM from measurements; effective theory approach $\rightarrow$ Leaves room for modified gravity theories?

General

- Connection DM-DE: only a coincidence in names? Theories of interacting DE-DM.
- The real nature of DM is "irrelevant" in some contexts. For instance, in structure formation simulation only the existence of DM is relevant, not its mass and cross section.
- After more than a decade, DM has not been detected. When should we stop the search?
- Search stops when recoils induced by neutrinos can mimick the detection of DM [plot of cross section as a function of mass], it becomes hard to directly detect it. We'll need to reevaluate the whole idea of WIMPs.
- Typicality of Bullet-like clusters, and "direct" evidence for DM.
- If DM is self-interacting and interaction is significantly large, then the bullet cluster would make DM clump behind, like baryons. Is this an indication that self-interaction of dark matter is small?
- Eventually DM masses need to be explained $\rightarrow$ GUT required?

Fine-Tuning Issues

- How would a universe with no DM look like? We might have galaxies (fewer), but timescales for the formation of structures are certainly different.
- Baryon-to-DM ratio is not a strict bound like the value for the cosmological constant derived by Weinberg.
- Is there a "coincidence problem" for dark matter, i.e., is the density of DM such that observers should be here now?
- "The anthropic principle is an excuse not to think about things."
- The coincidence problem including dark matter: compare rate of expansion and how fast structures form.
- Distribution of DM and life on Earth: impact of comets, etc, due to DM in the proximity of our Solar System (e.g. DM driving impacts that might've caused the extinction of dinosaurs).