Rethinking Λ

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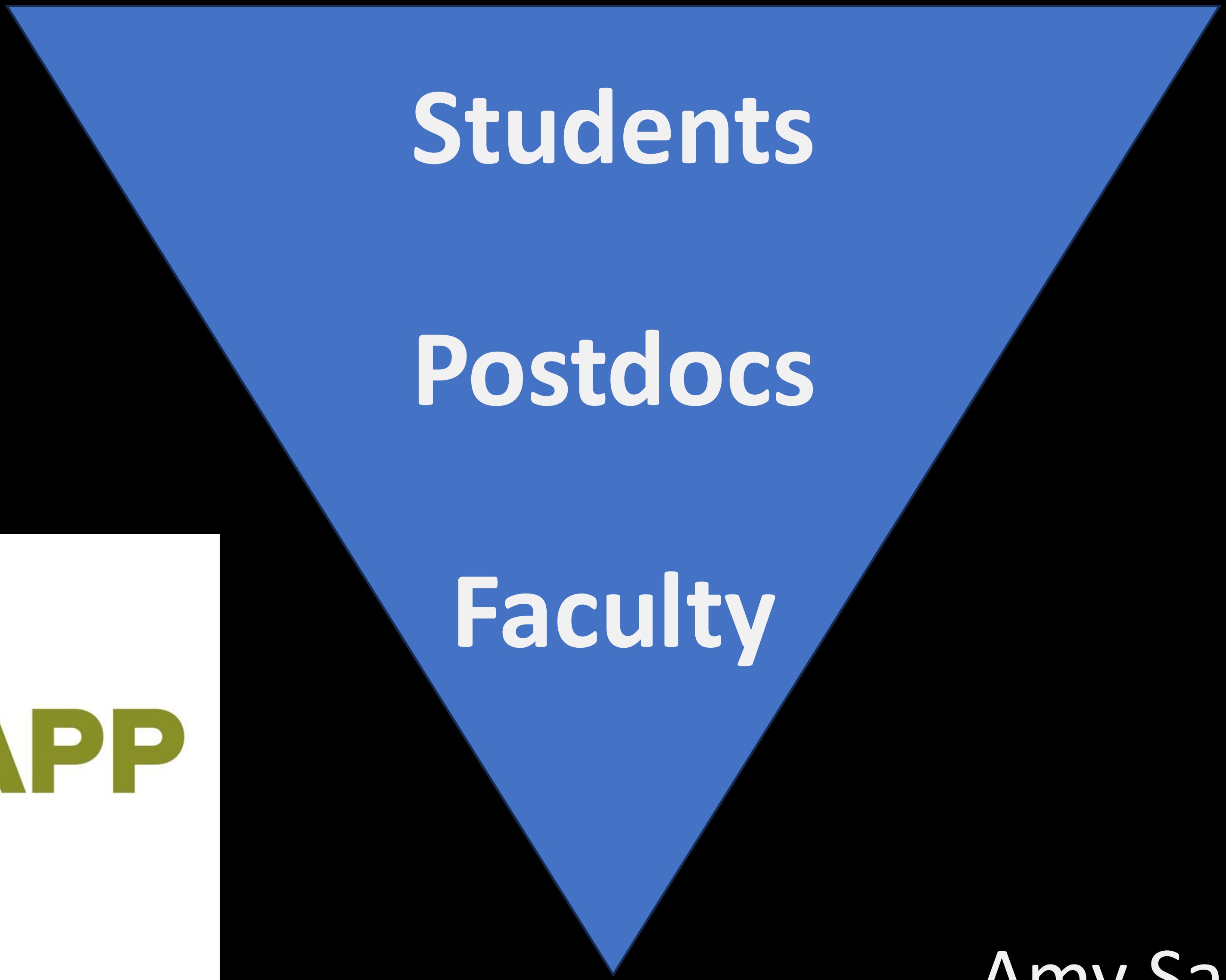

Amy Sardone’s talk.

WARNING

Wildly speculative talk ahead.

$$\Lambda = \frac{256\pi^8}{15} \times 1.2985 \times \frac{G}{\hbar^3 c^7} \times (k_\mathrm{B} T_\mathrm{CMB})^4$$

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Plug in $T_{\mathrm{CM}B} = 2.7255\ \mathrm{K}$: $\Lambda = 1.1024 \times 10^{-52}\ \mathrm{m}^{-2}$

Comparison to data

CMB-only constraint: $\Lambda = (1.080 \pm 0.021) \times 10^{-52}\ \mathrm{m}^{-2} (+1.1\sigma)$

CMB-+DESI Constraint: $\Lambda = (1.131 \pm 0.013) \times 10^{-52}\ \mathrm{m}^{-2} (-2.2\sigma)$

How I Got There

The Problem With Λ

- Λ is usually thought of as characterizing the vacuum energy density.
    - Perturbations to FRW can be decomposed into Fourier modes.
    - From quantum mechanics, each Fourier mode contributes a ground state energy $\frac{1}{2}\hbar\omega$.
    - Adding over all modes, and truncating at the Planck scale: $\frac{\rho_{\mathrm{ground}}}{\rho_\Lambda} = \ell_{\mathrm{Pl}}^2\Lambda \sim 10^{-122}$

Rethinking Λ

Suppose we had discovered the acceleration of the Universe before we discovered quantum mechanics.

- GR would be described in terms of G, c, and Λ.
- These constants describe the natural units of the Universe!
  - They define an Einstein length, time, mass.
  - Current universe looks very natural in Einstein units.

But how does $\hbar$ fit?

Rethinking Λ

- $\hbar$ is a quantum of action
  - A system is classical if its action scale $A/\hbar \gg 1$.
  - The natural action scale of the Universe is the Einstein action.

$$\frac{A_E}{\hbar} \sim \frac{1}{\ell_{\mathrm{Pl}}^2 \Lambda} \sim 10^{122}$$

The Universe is a very classical system!

This talk: what happens if we take this idea seriously?

Λ and Quantum Gravity

- We will postulate that Λ is a fundamental constant of nature, on par with G, c, and $\hbar$.

- The classical theory of gravity is not GR, but GRΛ!
  - GRΛ should be the classical limit of quantum gravity .
  - Λ should be an *input* to quantum gravity.

➢ Let’s just see what happens if we run with this.

A Toy Model of the Vacuum

- Quantum mechanically, metric perturbations behave like simple harmonic oscillators.
  - We assume the ground state energy *does not gravitate.*
  - Also assume that *if the mode is quantum mechanical,* its excess energy does gravitate.
    - Need a role for "when is a mode quantum mechanical."

When Does a Mode Gravitate?

- Only modes in a specific window gravitate:

$$k_{\min} \leq k \leq k_{\max}$$

$k_{\min}$: Long wavelength, low energy, classical.*

Quantum modes have $k > k_{\min}$

*ask later if interested.

$k_{\max}$: GR = EFT, breaks down if $k > k_{\max}$

Threshold is set by the quantum gravity.

Only relevant scales are k_{Pl} and k_{Λ}:

$$\boxed{k_{\max} = \sqrt{k_{\mathrm{Pl}} k_{\Lambda}}}$$

Key Assumption!

Vacuum-Powered Inflation

- Gravitating modes are vacuum energy: Universe inflates.
- Only modes with $k_{\mathrm{min}} \leq k \leq k_{\mathrm{max}}$ gravitate.
- As Universe inflates, more modes become classical.
  - k_{min} increases with time
  - Modes that classicalize shed excess energy into radiation.
  - When k_{min} reaches k_{max}, inflation ends.

Λ governs when inflation ends!

Connecting Λ to the CMB

- Λ governs both the total vacuum energy *and* when inflation terminates!
  - ➢ Λ determines radiation density at the end of inflation!
  - ➢ Sets T_{end} $\xrightarrow[\text{Entropy conservation}]{}$ Predicts T_{CMB}
  - ➢ Invert relation to get $\Lambda(T_{\mathrm{CMB}})$:

$$\Lambda = \frac{256\pi^8}{15} \times 1.2985 \times \frac{G}{\hbar^3 c^7} \times (k_{\mathrm{B}} T_{\mathrm{CMB}})^4$$

Why This Might Be Interesting: Falsification Targets

- Formula for Λ has *no free parameters.*
  - Prediction for Λ is extremely precise (uncertainty < 0.1%)

- Model also predicts n_s: $n_s = 0.9659$

  Uncertainty in prediction: $\sim 0.1\%$

- Model will be falsified if DESI's hints of dynamical dark energy are confirmed.

Caveats

- The definitions of k_{min} and k_{max} were guesses.
- The expression for $\Lambda(T_{\text{CMB}})$ assumes the Standard Model.
  - New physics beyond the reach of the LHC would alter the Standard Model prediction.
- The perturbations predictions assume Starobinsky-like perturbations. (I think this is ok, but you can ask me later).

Summary

- We assumed that Λ is a fundamental constant of nature.
  - Λ must be an *input* to a quantum theory of gravity.
  - Λ sets the high-k cutoff of its semiclassical description!

This ties the early and late Universe phenomenologies together.

Predicts Λ with zero-free-parameters.