Observer selection and fine-tuning puzzles in cosmology

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Oxford fine-tuning workshop  
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Outline

• Defining natural-ness and fine tuning
  – PPT viewpoint
  – Bayesian framework

• List of cosmological problems
  – Strange parameter coincidences
  – The vacuum challenge

• Modelling and observing dark energy
  – DE dynamics and tracking
  – Modifying gravity

• The ensemble approach
  – Physics of variable $\Lambda$
  – Priors and structure-formation posterior
  – Testability
Natural-ness in PP

- All dimensionless parameters should be $O(1)$
  - So all fundamental masses should derive from Planck scale (before running)
- Unless parameter = 0 is enforced by symmetry
  - Tiny parameter from symmetry breaking
- Quantum corrections should not be $>>$ observed value of any quantity (no fine-tuning)
  - e.g. electron self-energy
    \[
    \frac{\delta m_e}{m_e} = \frac{4\alpha}{3\pi} \left( \frac{\Lambda}{m_e} \right) \quad \text{(non-relativistic: un-natural)}
    \]
    \[
    \frac{\delta m_e}{m_e} = \frac{3\alpha}{2\pi} \ln \left( \frac{\Lambda}{m_e} \right) \quad \text{(relativistic: natural)}
    \]
  - Higgs mass has un-natural quadratic correction
Un-natural aspects of cosmology

• Coincidences of value
  – Baryon density ∼ DM density
  – Matter-radiation equality = recombination

• Coincidences of time (‘why now?’)
  – Vacuum density ∼ matter density
  – P(k) break scale ∼ nonlinear scale

• The nature of the vacuum density (‘Dark Energy’)
The baryon-DM coincidence

\[ \frac{\rho_B}{\rho_{DM}} = 0.184 \pm 0.004 \]

Unrelated quantities in the standard model. Baryon density set by CP violation (\(?\)):

\[ \frac{n_B}{n_\gamma} \equiv \epsilon \sim 10^{-9} \]

DM density set by freezeout (\(?\)):

\[ \frac{n_{DM}}{n_\gamma} \sim (\sigma \frac{mc}{\hbar} \frac{m_{PC}}{\hbar})^{-1} \]

So overall

\[ \frac{\rho_B}{\rho_{DM}} \sim \epsilon \left( \sigma \frac{m_{PC}}{\hbar} \frac{m_{PC}}{\hbar} \right) \]
The radiation-recombination coincidence

\[ 1 + z_{eq} = 24,000 \Omega_m h^2 \approx 3400 \]
\[ 1 + z_r \approx 1090. \]

Recombination is when thermal photons can ionize H

\[ kT_r \sim \frac{m_e c^2}{137^2} \]

m-r equality when \( kT n_\gamma \sim m_p c^2 n_B \)

\[ \Rightarrow \frac{n_B}{n_\gamma} \sim \frac{m_e/m_p}{137^2} \]
Bayesian view of parameters

• $P(p)$ represents state of knowledge about theory
  – i.e. $p$ has some definite (unknown) value

• Or perhaps genuine diversity within a multiverse?

• How to get a prior?
  – If $p$ can have either sign, reasonable to treat $dP/dp$ as constant near $p=0$ (e.g. for $\Lambda$)
  – But $p=0$ must not be special (e.g. Coleman-de Lucia bubble nucleation produces only negative curvature)
  – Otherwise tend to use Jaynes $dP/d\ln p = \text{const}$
Coincidences do happen

- Two independent parameters $x, y$ with uniform prior over 0 to 1
- $|x-y| < 0.025$ in 5% of experiments
- So coincidence to an order of magnitude plausible in a Jaynes prior with range 40 powers of 10
  - e.g. Baryon-DM coincidence may be just that
Most important challenge to naturalness in cosmology comes from Dark Energy
Russia tests nuclear-like 'vacuum bomb'

By Ashley Hall

Posted 7 hours 10 minutes ago

Russia has reasserted its role on the international stage by testing a new style of bomb which it claims is four times as destructive as any comparable US device.

The seven-tonne "vacuum bomb" has been described by the Russian military as being as powerful as a nuclear blast.

Russia-watchers say the test was designed to bolster political support for Russian President Vladimir Putin.

The test was announced on Russian television. The video showed a strategic bomber dropping the device over a testing ground, then a large explosion.

Left behind - a flattened block of flats surrounded by scorched earth.
Possible explanations for Dark Energy

(1) Denial

(2) Cosmological constant (1917)

\[ G^{\mu\nu} + \Lambda g^{\mu\nu} = -8\pi G T^{\mu\nu} \Rightarrow \rho_{\text{vac}}^{\text{eff}} = \frac{\Lambda}{8\pi G} \]

cf. \[ \nabla^2 \Phi = 4\pi G \rho \rightarrow \nabla^2 \Phi + \lambda = 4\pi G \rho \]

(3) Vacuum energy (Nernst 1916, then 1960s)

(4) Dynamical ‘Dark Energy’ (1980s/1990s)

- Empirical \( w = P / \rho c^2 \); fit \( w(a) = w_0 + w_a(1-a) \)

- ‘Quintessence’: use inflationary technology of \( w<0 \) from scalar fields
The zero-point energy of the vacuum

\[ \rho_{\text{vac}} = \sum_{0}^{E_{\text{max}}} \frac{\hbar \omega}{2} \sim E_{\text{max}}^4 \]

New physics causes cutoff of high-energy modes. Common to set \( E_{\text{max}} = E_{\text{Planck}} \): origin of \( 10^{120} \) discrepancy.

But this is just radiation with occupation no. = \( \frac{1}{2} \)

\[ \Rightarrow P_{\text{vac}} = \rho_{\text{vac}} / 3 \Rightarrow w = 1/3 \neq -1 \]

Need relativistic cutoff procedure.
Renormalized vacuum density for particle of mass $m$ and cutoff scale $M$:

$$\rho_{\text{vac}} = \left[ \frac{c^3}{\hbar^3} \right] \frac{m^4}{32\pi^2} \ln(m/M): \text{cf. } \frac{M^4}{16\pi^2}$$

(Koksma & Prokopec 1105.6296)

Real vacuum problem is that observed energy scale is at meV level, not TeV: discrepancy of 15 powers of 10, not 120

**The bare $\Lambda$ can absorb divergence**

Zeldovich 1968

Sakharov 1968

$$\rho_{\text{vac}}^{\text{eff}} = \rho_{\text{vac}} + \frac{\Lambda}{8\pi G}$$

- un-natural?
Dynamics: perhaps DE is declining towards a low value
Quintessence

Ratra & Peebles (1988): consider rolling scalar field with an arbitrary potential as dynamical vacuum energy

\[ \ddot{\phi} + 3H \dot{\phi} + \frac{dV}{d\phi} = 0 \]
\[ H^2 = \frac{\dot{R}^2}{R^2} = \frac{8\pi}{3} m_p^{-2} \rho \]
\[ \rho = \rho_{\text{matter}} + \frac{\dot{\phi}^2}{2} + V \]
\[ P = \frac{\dot{\phi}^2}{2} - V \]

Two equations of state for the vacuum:

(1) Potential dominates: \( w = -1 \)

(2) Kinetic term dominates: \( w = +1 \) \( \Rightarrow \rho_v \propto a^{-6} \)

- thus redshift away kinetic term: leaves ‘frozen’ field that is indistinguishable from \( \Lambda \)
Tracker solutions: explaining $\rho_{DE} \sim \rho_m$

Suppose $\rho_m \propto a^{-\alpha}$

Look for a solution with fixed $\rho_v/\rho_m$

- not slow-roll, since need $K \propto V$

Solution: $V(\phi) \propto \exp[-\lambda \sqrt{8\pi} \phi/M_p]$ with $\rho_v/\rho_m = \alpha/\lambda^2$

But tracks equally well in matter and radiation era, and is an attractor. Can only ‘switch on’ $w = -1$ today if we fine-tune a feature in the potential
Is dark energy empirically different from $\Lambda$ ?
Sensitivity to the vacuum

Vacuum affects $H(z)$ via Friedmann equation:

$$H^2(z) = H^2_0 \left[ \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_V (1+z)^3 (1+w) + (1-\Omega) (1+z)^2 \right]$$

matter \hspace{1cm} radiation \hspace{1cm} vacuum

Alters $D(z)$ via $r = \int c \, dz / H(z)$

And growth via $2H \, d\delta/dt$ term
in growth equation

Effects of $w$ are:

(1) Small (need $D$ to 1% for $w$ to 5%)

(2) Degenerate with changes in $\Omega_m$

To measure $w$ to a few %, we need independent data on $\Omega_m$ and to be able to control systematics to ~ parts in 1000

**Rule of 5**
The BAO ruler in BOSS

\[ \log_{10} P(k) / h^{-3}\text{Mpc}^3 \]

- Standard
  - CMASS DR9
- best-fit model
  \[ \chi^2 = 81.5 / 59 \]
Direct measures of $D(z)$

$z=0.6$: WiggleZ (1105.2862): 4% measure of $D(z)$ from 130k $z$’s

$z=0.57$: BOSS (1303.4666): 3% measure of $D(z)$ from 264k $z$’s

Consistent with standard cosmology
The equation of state: present knowledge

Combined:

\[ w = -0.926^{+0.051}_{-0.075} \]

Future probes need to achieve <1% accuracy in D(z)
Dark energy or modified gravity?

Dark energy: inferred assuming $H(z)$ comes from standard Friedmann equation.

Focus on equation of state $w = \frac{P}{\rho c^2} (= -1?)$ assumes DE is a real substance - but is it?

$$H^2(z) = H_0^2 \left[ (1-\Omega)(1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_{DE} (1+z)^{3(1+w)} \right]$$

Curvature: matter: radiation: extra term from non-Einstein?
Phenomenology of modified gravity

- Adopt longitudinal gauge (in effect gauge-invariant)

\[ d\tau^2 = (1 + 2\Psi) dt^2 - (1 - 2\Phi) \gamma_{ij} dx^i dx^j \]

Einstein: \( \nabla^2 \Phi / a^2 = 4\pi G \bar{\rho} \delta \) and \( \Psi = \Phi \)

- In MG, potentials can differ ('slip': affects lensing), plus Poisson equation is modified.

- No standard notation. Good refs are Skordis (0806.1238) or Daniel et al. (1002.1962). Assume modifications negligible at high \( z \), since no DE then:

\[ \Phi = (1 + \omega(a, k)) \Psi; \quad \nabla^2 \Phi = \mu(a, k) 4\pi G \bar{\rho} \delta \]

- Combine to affect growth of fluctuations

\[ d\ln \delta / d\ln a \simeq \Omega_m(a)^\gamma; \quad \gamma_{\text{Einstein}} = 0.55 \]
Mock 2dFGRS from Hubble volume
real space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003
Mock 2dFGRS from Hubble volume

z-space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003
Growth rate: consistent with Einstein
Complementary data: gravitational lensing

Image distortion depends on

- Geometry: angular diameter distance (Dark Energy)
- Dynamics: growth of structure (Modified Gravity)

Potentially most accurate probe, but effect is small: ~1% extra image ellipticity needs to be measured precisely
Overall MG constraints \((1212.3339)\)

\[
\Psi = [1 + \mu(k, a)]\Psi_E \\
(\Psi + \Phi) = [1 + \Sigma(k, a)](\Psi_E + \Phi_E)
\]

Relation to effective \(G\) and slip are:

\[
1 + \mu = (G'/G)/\eta; \\
1 + \Sigma = (G'/2G)(1 + 1/\eta)
\]
So for now we need to take standard gravity and physical DE seriously.
Two problems for all explanations of DE

Still have to solve the classical vacuum energy problem

\[ \mathcal{L}_{k\text{-essence}} \rightarrow \mathcal{L}_{k\text{-essence}} + \text{const} \]
dynamics unaffected

The why now problem

The future is vacuum dominated
The answer to ‘why now’ must be anthropic

• One-universe anthropic
  – Life (structure) only after matter-radiation equality
  – But life possible before and after $\Lambda$ domination

• Many-universe anthropic
  – Postulate ensemble of universes with different $\Lambda$ (at least) – e.g. ‘bubbles’ predicted in some inflation models
  – Predates landscape, but requires new physics for variable $\Lambda$
  – Ask if structure formation can differ between universes
The P(k) coincidence

Variance in density

Nonlinear evolution is close to destroying all information below the break

Reasonable: flat portion must be nonlinear to get full collapse

But growth has almost saturated: much larger $\Lambda$ would prevent nonlinearity
Weinberg’s prediction

The cosmological constant problem

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Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

Reviews of Modern Physics, Vol. 61, No. 1, January 1989

A large cosmological constant would interfere with the appearance of life in different ways, depending on the sign of \( \lambda_{\text{eff}} \). For a large positive \( \lambda_{\text{eff}} \), the universe very early enters an exponentially expanding de Sitter phase, which then lasts forever. The exponential expansion interferes with the formation of gravitational condensations, but once a clump of matter becomes gravitationally bound, its subsequent evolution is unaffected by the cosmological constant. Now, we do not know what weird forms life may take, but it is hard to imagine that it could develop at all without gravitational condensations out of an initially smooth universe. Therefore the anthropic principle makes a rather crisp prediction: \( \lambda_{\text{eff}} \) must be small enough to allow the formation of sufficiently large gravitational condensations (Weinberg, 1987).

This result suggests strongly that if it is the anthropic principle that accounts for the smallness of the cosmological constant, then we would expect a vacuum energy density \( \rho_V \sim (10-100)\rho_{\text{M}_0} \), because there is no anthropic reason for it to be any smaller.

Is such a large vacuum energy density observationally allowed? There are a number of different types of astronomical data that indicate differing answers to this question.
How to get a variable $\Lambda$

Simplest idea: linear potential (Linde, Vilenkin, Garriga) with quantum fluctuations + inflationary multiverse

Not dependent on string landscape

Note negative $\Lambda$ equally likely

$V(\varphi)$

$V=0$

$\varphi$

$\delta \varphi$
Bayesian mediocrity

Assume you are a randomly-selected member of all observers ever generated in the multiverse

\[ \text{Bayes: } P(\Lambda | \text{observer}) \propto P_{\text{prior}}(\Lambda) N_{\text{gal}}(\Lambda) \]

Take prior on vacuum energy constant over small range around zero (not a special value)

Number of galaxies depends on fraction of universe collapsed into mass near that of Milky Way

\[ M_G \sim \alpha^5 \left( \frac{\hbar c}{G m_p^2} \right)^2 \left( \frac{m_p}{m_e} \right)^{1/2} m_p \]
Fixed
$T = 2.73 \, \text{K}$
OK if we want to predict $\Lambda$ in our universe

$\Omega_v = 1 - \Omega_m$

uncertain $\Omega_m \, h^2$
Positivity of $\rho_{\text{vac}}$?

- $P(\Lambda > 0)$:
  - 0.25 ($T_{\text{max}} = 10$)
  - 0.03 ($T_{\text{max}} = 30$)

  for negative $\Lambda$, most structure forms after turnaround

Mild preference for a recollapsing universe

- $P(|\Lambda| < \text{obs value})$:
  - 0.1 ($T_{\text{max}} = 10$)
  - 0.02 ($T_{\text{max}} = 30$)
Is this really the right explanation for Λ?

(many feel it is no explanation at all)
The impact of DE on Galaxy Formation

- Is the ‘turndown’ in star-formation rate connected to DE?
- How would things look if $\Lambda$ were larger?
Semianthropic galaxy formation

Ingredients:
• DM halo merging
• Cooling of gas
• Stars from cold gas
• Central black holes
• Feedback from SNe and BH to heat or remove gas

Can match inefficiency of star formation (only 4% of baryons in stars)

− Observer weighting is fraction of baryons in stars
− but what about in the very long term?
“Eternity is very long – especially towards the end”
Semianthropic galaxy formation

Vacuum domination means growth of DM haloes is switching off:

fixed population in the far future (redshift $z = -1$)

Freezeout below galaxy masses if $\Lambda$ were much larger

Fraction of DM density per $d \ln M$
Semianthropic galaxy formation

M. Koprowski: run Galform into future. No clear asymptote of stellar baryon fraction

- possible that all baryons cool given time: would remove observer bias on $\Lambda$
Testing the multiverse?

• If Weinberg’s explanation for $\Lambda$ were to founder, what then?
  – Could argue that cosmological enquiry is impossible in far future as galaxies lose causal contact
  – Still no alternative that explains coincidence

• Other ensembles remain to be explored
  – $\Lambda$ might vary in a manner coupled with other parameters that could affect observers (baryon density, fluctuation amplitude)
    • But then not so easy to get priors without a detailed physical theory
  – Nevertheless, can generate models that are testable (to a limited extent)
  – Most progress if we can probe physics of variable $\Lambda$ directly in other ways