Challenging the Cosmological Constant

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Overview

- Dark thoughts
- Where fields hide
  - *Environmental mass effects and chameleonic behavior*
- Changeling
  - *A chameleon that actually may work as quintessence*
- Summary
The concert of Cosmos?

■ Einstein’s GR: a beautiful theoretical framework for gravity and cosmology, consistent with numerous experiments and observations:
  ■ Solar system tests of GR
  ■ Sub-millimeter (non)deviations from Newton’s law
  ■ Concordance Cosmology!

■ How well do we REALLY know gravity?
  ■ Hands-on observational tests confirm GR at scales between roughly 0.1 mm and - say - about 100 Mpc; are we certain that GR remains valid at shorter and longer distances?

New tests?

Or, Dark Discords?
Cosmic coincidences?

- We have ideas for explaining the near identities of some relic abundances, such as *dark matter, baryon, photon and neutrino*: inflation+reheating, with Universe in thermal equilibrium (like it or not, at least it works)...
- However there’s much we do not understand; the worst problem:

**DARK ENERGY**

The situation with cosmological constant is **desperate** (by 60 orders of magnitude!) → desperate measures required?
Blessings of the dark curse 😊

- How do we get small $\Lambda$? Is it anthropic? Is it even $\Lambda$? Or do we need some *really weird* new physics?
- Age of discovery: the dichotomy between observations and theoretical thought forces a crisis upon us!
- A possible strategy: find all that needs explaining, and be careful about dismissals based on current theoretical prejudice (learning to be humble from the story of $\Lambda$ ...)
- Ultimately, perhaps both cosmological observations and LHC should be viewed as tests of *naturalness*...
Modified gravity v.s. $\Lambda$

$\int \sqrt{g} \, \Lambda$: a Legendre transform.

$y = f(x)$

$y = p_0 x - g(p_0)$

$p = \frac{dy}{dx}$

$g(p) = xp - y$

$(0, -g(p_0))$ $x_0$
Now: forget $f(x)$! Can reconstruct it by solving $g(y') = xy' - y$?

Solution not unique if we don't know $x_k$!

In GR: $x = \sqrt{\text{det} g}$ a nonpropagating pure gauge DOF: can be Anything!
We need a boundary condition!

GR: a landscape! Einstein already "blundered" in and out of it (1919)

Unimodular gravity:
\[ R^M_\nu - \frac{1}{4} \delta^M_\nu R = 8\pi G_N (T^M_\nu - \frac{1}{4} \delta^M_\nu T) \]

But: \[ \nabla_m T^m_\nu = 0 \Rightarrow 3\pi (R + 8\pi G_N T) = 0 \Rightarrow R + 8\pi G_N T = 0 \]

\[ \therefore R^M_\nu - \frac{1}{2} \delta^M_\nu R = 8\pi G_N (T^M_\nu + \Lambda \delta^M_\nu) \]

\[ \Lambda_{tot} = \langle T^{00} \rangle + \Lambda \]

Alternatively: we may seek non-standard dynamics with new degrees of freedom...
Dark Energy in the lab?

**The issue:** measuring $\Lambda$ the same as measuring the absolute zero point of energy.

- Only gravity can see it, at relevant scales
- Gravity is weak: we can see a tidal effect, $\sim H^2 r t$
- Too small to care unless we have really large scale exps (like Sne!)
- Non-gravitational physics cannot directly see $\Lambda$.
- An exception: quintessence fields might bring along new couplings

But quintessence fields constrained by gravity experiments. How to evade such no go theorems?

Environmental chameleon masses, similar to effective masses of electrons in crystals, dressed by phonons.

- Ordinary matter plays the role of phonons...

Damour, Polyakov, Khoury, Weltman
Consider a scalar with (almost) gravitational couplings to matter:

\[ \mathcal{L}_{\text{matter}}(g^{\mu\nu}e^{-2\alpha\phi/M_4}, \Psi) \]

In presence of matter stress energy, it’s effective potential is

\[ V_{\text{eff}}(\phi) = V(\phi) - T^\mu_\mu e^{\alpha w\phi/M_4} \]

It’s minimum and mass at the minimum are

\[ \partial_\phi V_{\text{eff}}(\phi_\ast) = 0 \quad m_\phi^2 = \partial_\phi^2 V_{\text{eff}}(\phi_\ast) \]

A good approximation for time scales \( \tau \ll 1/H \)

What happens when the field sits in this environmental minimum?

- In the lab?
- Cosmologically?
Lab phenomenology

- We must pass the current laboratory bounds on sub-mm corrections to Newton’s law. The thin shell effect for the chameleons helps, since it suppresses the extra force by

\[ \sim m_\phi^{-1}/R \]

where \( R \) is the size of the object. For gravitational couplings this still yields

\[ m_\phi \gtrsim 10^{-3} \text{ eV} \quad \alpha \Delta \phi_* < M_4 \]

Khoury, Weltman
Cosmology

- **FRW equations:**
  
  \[ 3M_4^2 H^2 = \frac{\dot{\phi}^2}{2} + V + \rho e^{\alpha w \phi / M_4} \]
  
  \[ \dot{\rho} + 3(1 + w)H \rho = 0 \]
  
  \[ \ddot{\phi} + 3H \dot{\phi} + \frac{\partial V_{\text{eff}}}{\partial \phi} = 0 \]

- Can check: in a matter dominated universe, if the field sits in the minimum, the universe *does not* accelerate!

\[
\dot{H} = -\frac{\dot{\phi}^2}{2M_4^2} - \frac{\rho}{2M_4^2} e^{\alpha \phi / M_4} \approx -\frac{3}{2} H^2
\]

- For acceleration we must have generalized slow roll:

\[
\epsilon = \left| \frac{\dot{\rho}_{\text{cr}}}{H \rho_{\text{cr}}} \right| < 1 \quad \eta = \left| \frac{\dot{\epsilon}}{3H \epsilon} \right| < 1 \quad \rho_{\text{cr}} = 3M_4^2 H^2
\]
Cosmic phenomenology

- When $m_\phi > H$ we can check that

\[ \epsilon \sim (1 + w) \rho e^{\alpha \phi / M_4 / V} \]

\[ \eta \sim (1 + w)^2 \]

- This shows that unless we put dark energy by hand chameleon **WILL NOT** lead to accelerating universe!

- Thus we **MUST HAVE** slow roll!

\[ m_\phi \lesssim H_0 \]
Failure?

- Use the change of environment energy density between the lab and the outer limits to get a huge variation in the mass; for

\[ V_{eff}(\phi) = \frac{\lambda}{n} \phi^n + \frac{1}{2} \rho e^{\alpha \phi/M_4} \]

one finds \( \gamma < 1 \) for any \( n \), and

\[ m_\phi \propto \rho^\gamma \]

- Between the Earth, where \( \rho_{\text{Earth}} \approx \frac{g}{\text{cm}^3} \approx 10^{21} \text{eV}^4 \), and the outer limits, the mass can change by at most a factor of

\[ \left( \frac{M_4^2 H_0^2}{\rho_{\text{Earth}}} \right)^\gamma \approx 10^{-33\gamma} \]

- So for any \( \gamma < 1 \), and any integer \( n \), a chameleon which obeys the lab bounds **CANNOT** yield cosmic acceleration by itself!
Log changeling

- **An exception:** The log potential, where the mass scales linearly with density:
  \[ V \sim \ln \phi \quad m_\phi \sim \rho \]

- In more detail:
  \[ V_{\text{eff}}(\phi) = -\mu^4 \ln \left( \frac{\phi}{M} \right) + (1 - 3w)\rho e^{\alpha w \phi / M_4} \]

  where the scales are chosen as is usual in quintessence models
  \[ M \gtrsim M_4 \quad \mu \sim 10^{-3} \text{ eV} \]

- Rationale: we are **NOT** solving the cosmological constant problem! We are merely looking at possible signatures of such solutions. Yet, this may only require tunings in the gravitational sector...
- Now we look at cosmic history...
Effective potential

\[ V_{\text{eff}} = (1-3w)\rho \exp(\alpha_w \phi/M_4) - \mu^4 \ln(\phi/M) \]
Early universe evolution I

- During inflation, the field is fixed:

\[ V_{eff}(\phi) = -\mu^4 \ln\left(\frac{\phi}{M}\right) + 4\Lambda e^{4\alpha\phi/M_4} \]

yields

\[ \frac{\alpha\phi_*}{M_4} \sim \frac{\mu^4}{16\Lambda} \ll 1 \quad \text{and} \quad m^2_{\phi} \sim \frac{256\alpha^2\Lambda^2}{M_4^2\mu^4} \gg H_{inflation}^2 \]

- So the field is essentially decoupled!
- After inflation ends, at reheating

\[ \rho_{\text{radiation}}/\rho_{\text{matter}} \gtrsim T_{\text{reheating}}/eV \]

A huge number: we can ignore any non-relativistic matter density.
- During the radiation era the potential is just a pure, tiny log - so the field will move like a free field!
The field starts with a lot of kinetic energy, \( \phi^2 \sim \frac{\Lambda}{48\alpha^2} \) by equipartition, but this dissipates quickly. Nevertheless, before Hubble friction stops it, the field will move by

\[
\Delta \phi \sim \frac{\phi_{\text{initial}}}{H_{\text{inflation}}} \sim \frac{M_4}{4\alpha} \gg \phi_{\text{initial}}
\]

After it stops it will have a tiny potential energy and a tiny mass,

\[
V \approx \mu^4 \ln\left( \frac{4\alpha M}{M_4} \right) \quad m_{\phi}^2 \approx \frac{\alpha^2 \rho_{\text{matter}}}{M_4^2} \ll H_{\text{radiation}}^2
\]

And then, it will freeze: from this point on it \textbf{WAITS!}
However, this means the effective Newton’s constant during radiation era may be slightly bigger than on Earth. Recall

\[ G_{N_{eff}} \sim \frac{1}{M^2} \exp(\alpha_w \phi_*/M_4) \]

So during radiation epoch we will find that \( G_N/G_{N_0} \) as felt by heavy particles may be different from unity, but not exceeding \( e^{1/4} \sim 1.28 \)

This remains consistent with BBN as most of the universe is still relativistic. Further, the BBN bounds allow a variation of Newton’s constant of 5-20% (depending who you ask). Future data?

 Bounds from Oklo are trivial - by the time Oklo reaction started, the field should have fallen to its minimum on Earth.
Into the matter era...

- Eventually non-relativistic matter overtakes radiation. The minimum shifts to
  \[
  \frac{\alpha \phi}{M_4} \simeq \frac{\mu^4}{\rho_{\text{matter}}}
  \]

- However the field will NOT go to this minimum everywhere immediately. Since
  \[
  m_\phi^2 \simeq \frac{\alpha^2 \rho_{\text{matter}}}{M_4^2} < \frac{\rho_{\text{matter}}^2}{3M_4^2} = H_{\text{matter}}^2
  \]
  as long as \( \rho > \mu^4 \), if the couplings are slightly subgravitational, \( \alpha < 1/\sqrt{3} \), the field will remain in slow roll at the largest scales, suspended on the potential slope.

- Where structure forms and \( \rho \) grows very big, the minima are pulled back towards the origin and the mass will be greater
  \[
  m_\phi^2 \gg H_{\text{matter}}^2
  \]

- There the field will fall in and oscillate around the minimum, behaving as a CDM component dissipating its value (by \( > 10^{-7} \)), and pulling the Newton’s constant down. The leftover will collapse to the center, further reducing field value inside overdensities. There may be signatures left in large scale structure?...
Onset of late acceleration...

- Eventually at the largest scales, $\rho$ will drop below $\mu^4$, after which the universe will begin to accelerate, with potential and initial mass
  \[ V \simeq \mu^4 \ln \left( \frac{4\alpha M}{M_4} \right) \simeq \mu^4 \quad m_\phi^2 \simeq 16 \frac{\alpha^2 \mu^4}{M_4^2} \]

- The field mass there supports acceleration as long as $\alpha < (4 \sqrt{3})^{-1}$. Because $\mu \sim 1/\phi$ and $\phi$ grows slow roll improves - but eventually $V$ hits zero!

- Before that happens, the time and field evolution are related by
  \[ \frac{\mu^2 M_4}{\sqrt{3}} \Delta t \simeq \int_{M_4/4\alpha}^{\phi} d\phi \phi \ln^{1/2} \left( \frac{M}{\phi} \right) \]

- We maximize the integral by taking $\phi = M$ and evaluating it using the Euler $\Gamma(3/2)$ function. That yields
  \[ \Delta t \simeq \sqrt{\frac{3\pi}{32}} \frac{M^2}{\mu^2 M_4} \quad H_0 \simeq \frac{\mu^2}{\sqrt{3} M_4} \]
$V_{\text{eff}}

(1-3w)\rho \exp(\alpha_w \phi / M_4)

\mu^4 \ln(\phi / M)$
Seeking an e-fold in the lab

- To get an e-fold of acceleration, which is all it takes to explain all the late universe acceleration, we need $\Delta \tau H > 1$, which yields
  \[ M \gtrsim \left( \frac{32}{\pi} \right)^{1/4} M_4 \simeq 1.78 M_4 \]

- This and positivity of the potential translate to
  \[ \frac{M_4}{4M} < \alpha \lesssim \frac{1}{4\sqrt{3}} \]

- Taking the scale $M$ close to the Planck scale - as argued to be realized in controlled UV completions, e.g. in string theory - as opposed to the other limit - we find that $\alpha$ is within an order of magnitude of unity.

- The scalar-matter coupling and the mass are
  \[ g_\phi \sim \frac{\alpha}{M_4} \quad m_\phi \sim \frac{\alpha \rho_{\text{matter}}}{M_4 \mu^2} \sim \frac{\alpha}{10} \text{ eV} \]

- This means that the scalar forces is close to the current lab bounds!
Seeking an e-fold in the sky

- Further since the potential vanishes at $\phi = M$ and the field gets there within a Hubble time, it will have $\omega \neq -1$. Indeed, from

$$\Delta t \approx \sqrt{\frac{3\pi}{32}} \frac{M^2}{\mu^2 M_4}$$

with $M$ close to Planck scale, this gives $\Delta \tau \sim 1/H$.

- Subsequently the field dynamics may even collapse the universe, as the potential grows more negative.

- As a result there may be imprints of $\omega \neq -1$ in the sky. So: look for correlations between DM excess in young structures and $\omega \neq -1$. 
Summary

- Do the successes of GR really demand GR?
  - *If so, must* deal with the greatest failure of General Relativity: the Cosmological Constant (and perhaps, accept Anthropics itself...)

- Could we avoid the problem by changing gravity?...

- Important to seek out useful benchmarks which can yield alternative predictions to those that support ΛCDM
  - 1) to compare with the data
  - 2) to explore decoupling limits
  - 3) to test dangers from new forces

- A log changeling: correlations between the lab and the sky

- More work needed: maybe new realms of gravity await?

- Alternatively: it’s really Λ and we will be forced to live with anthropics or we need to get REALLY creative...