Challenging the Cosmological Constant

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Based on: work to appear next week

Overview

- Dark thoughts
- Where fields hide
  - *Environmental mass effects and chameleonic behavior*
- Changeling
  - *A chameleon that actually* ***works*** *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 ***New tests?***
  - Sub-millimeter (non)deviations from Newton's law ***New tests?***
  - Concordance Cosmology! ***Or, Dark Discords?***
- 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?

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 the cosmological constant is desperate (by at least 60 orders of magnitude!) → desperate measures required?

Blessings of the dark curse ☺

- How do we get small Λ? Is it anthropic? Is it even Λ? 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 is to determine all that needs explaining, and be careful about dismissals based on current theoretical prejudice (learning to be humble from the story of Λ …)

Could we look for DE in the lab?

- **The issue:** measuring Λ is 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, $\sim H^2\, r\, t$
  - But this is too small to care unless we have really large scale experiments and have them run a long long time (like Sne!)
  - Non-gravitational physics cannot directly see Λ.
  - An exception: quintessence fields might bring along new couplings
- But quintessence fields are constrained by gravity experiments. How could we evade such no go theorems?
- Environmental effects: chameleon masses, very similar to effective masses of electrons in crystals, which differ from vacuum masses because of the corrections from phonons.
  - In this case, ordinary matter plays the role of phonons…

Chameleon

- Consider a scalar with (almost) gravitational couplings to matter:

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

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

$$V_{eff}(\phi) = V(\phi) - T^{\mu}{}_{\mu}\, e^{\alpha_w \phi/M_4}$$

- It's minimum and mass at the minimum are

$$\partial_\phi V_{eff}(\phi_*) = 0 \qquad m_\phi^2 = \partial_\phi{}^2 V_{eff}(\phi_*)$$

  - 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

$$\sim m_\phi^{-1}/\mathcal{R}$$

where $\mathcal{R}$ is the size of the object. For gravitational couplings this still yields

$$m_\phi \gtrsim 10^{-3}\,\mathrm{eV} \qquad \alpha\Delta\phi_* < M_4$$

Cosmology

- FRW equations:

$$3M_4^2H^2 = \frac{\dot\phi^2}{2} + V + \rho\, e^{\alpha_w\phi/M_4}$$
$$\dot\rho + 3(1+w)H\rho = 0$$
$$\ddot\phi + 3H\dot\phi + \frac{\partial V_{eff}}{\partial\phi} = 0$$

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

$$\dot H = -\frac{\dot\phi^2}{2M_4^2} - \frac{\rho}{2M_4^2}e^{\alpha\phi/M_4} \simeq -\frac{3}{2}H^2$$

- For acceleration to occur we must have generalized slow roll:

$$\epsilon = |\frac{\dot\rho_{cr}}{H\rho_{cr}}| < 1 \qquad \eta = |\frac{\dot\epsilon}{3H\epsilon}| < 1$$

where

$$\rho_{cr} = 3M_4^2H^2$$

Cosmic phenomenology

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

$$\epsilon \simeq (1+w)\rho e^{\alpha\phi/M_4}/V \qquad \eta \simeq (1+w)^2$$

- 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?

- The trick is to use the change of environment energy density between the lab and the outer limits to generate a huge variation in the mass. The lab bounds immediately exclude linear and quadratic potentials. For other polynomials, the effective potential and mass at the minimum are

$$V_{eff}(\phi) = \frac{\lambda}{n}\phi^n + \frac{1}{2}\rho e^{\alpha\phi/M_4} \qquad m_\phi^2 \simeq (n-1)\lambda^{1/(n-1)}\left(\frac{\alpha}{M_4}\right)^{\frac{n-2}{n-1}}\rho^{\frac{n-2}{n-1}}$$

- Therefore, $m_\phi \propto \rho^\gamma$ $\qquad \gamma = \frac{n-2}{2(n-1)}$

- Between the Earth, where $\rho_{Earth} \sim \mathrm{g/cm^3} \sim 10^{21}\,\mathrm{eV}^4$, and the outer limits, the mass can change by at most a factor of

$$\left(\frac{M_4^2 H_0^2}{\rho_{Earth}}\right)^\gamma \simeq 10^{-33\gamma}$$

- So for any $\gamma < 1$, and any integer n, a chameleon which obeys the lab bounds <u>***CANNOT***</u> yield cosmic acceleration by itself!

Log changeling

- ***An exception!*** The log potential, where the mass scales linearly with density:

$$V \sim \ln \phi \qquad\qquad m_\phi \sim \rho$$

- In more detail:

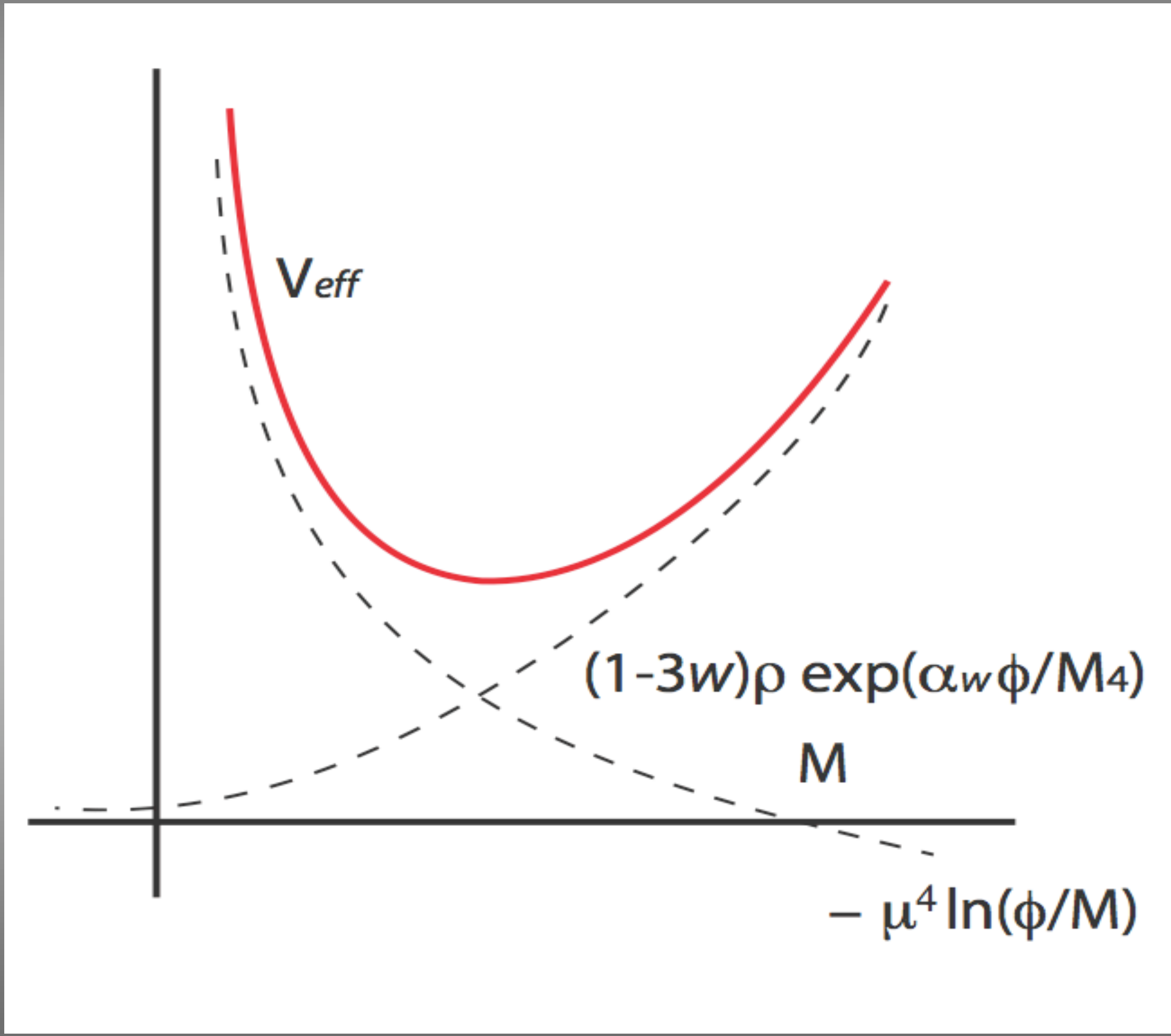
$$V_{eff}(\phi) = -\mu^4 \ln\left(\frac{\phi}{M}\right) + (1-3w)\rho\, e^{\alpha_w \phi / M_4}$$

where the scales are chosen as is usual in quintessence models

$$M \gtrsim M_4 \qquad\qquad \mu \sim 10^{-3}\,\mathrm{eV}$$

- Rationale: we are ***NOT*** solving the cosmological constant problem! We are merely looking at possible signatures of such solutions elsewhere.
- Now we look at cosmic history…

Effective potential



Early universe evolution I

- During inflation, the field is fixed:

$$V_{eff}(\phi) = -\mu^4 \ln\Big(\frac{\phi}{M}\Big) + 4\Lambda\, e^{4\alpha\phi/M_4}$$

yields

$$\frac{\alpha\phi_*}{M_4} \simeq \frac{\mu^4}{16\Lambda} \ll 1 \qquad m_\phi^2 \simeq \frac{256\alpha^2\Lambda^2}{M_4^2\mu^4} \gg H_{inflation}^2$$

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

$$\rho_{radiation}/\rho_{matter} \gtrsim T_{reheating}/\mathrm{eV}$$

which is easily a huge number. So during radiation domination we can completely neglect any non-relativisitc matter density.

- During the radiation era the potential is just a pure, tiny log - so the field will move like a free field!

Early universe evolution II

- The field starts with a lot of kinetic energy, $\dot{\phi}^2 \sim \frac{\Lambda}{48\alpha^2}$ by equipartition, but this dissipates quickly. Nevertheless, before Hubble friction stops it, the field will move by

$$\Delta\phi \sim \dot{\phi}_{initial}/H_{inflation} \sim \frac{M_4}{4\alpha} \gg \phi_{initial}$$

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

$$V \simeq \mu^4 \ln(\frac{4\alpha M}{M_4}) \qquad m_\phi^2 \simeq \frac{\alpha^2 \rho_{matter}}{M_4^2} \ll H^2_{radiation}$$

- And then, it will freeze: from this point on it will just ***WAIT!***

Early universe evolution III

- However, this means the effective Newton's constant during radiation era may be slightly bigger than on Earth. Recall

$$G_{N\,eff} \sim \frac{1}{M_4^2} \exp(\alpha_w \phi_* / M_4)$$

- 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 may affect nucleosynthesis - but should remain - roughly - consistent with the current nucleosynthesis bounds which allow a variation of Newton's constant to within 5-20% (depending who you ask). After all, most of the universe is still relativistic at those times. But, future data may be more sensitive probe of this…
- Bounds from Oklo are trivial - by the time Oklo reaction started, the field fell to its minimum on Earth, bringing Newton's constant to its lab value.

Into the matter era…

- Eventually non-relativistic matter overtakes radiation. The potential changes again, to the w=0 limit, and the minimum shifts to

$$\frac{\alpha\phi}{M_4} \simeq \frac{\mu^4}{\rho_{matter}}$$

- However the field will NOT go to this minimum immediately. Since

$$m_\phi^2 \simeq \frac{\alpha^2 \rho_{matter}}{M_4^2} < \frac{\rho_{matter}^2}{3M_4^2} = H_{matter}^2$$

for 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 begins to form and ρ grows very big, the minima will however be pulled back towards the origin and the mass will be greater

$$m_\phi^2 \gg H_{matter}^2$$

- There the field will fall in and pull the Newton's constant to its terrestrial value. However, there may be ***signatures left*** in large scale structure. Since gravity will initially be stronger, such regions may seem to have more dark matter .

Onset of late acceleration…

- Eventually at the largest scales, ρ will drop below μ^4, after which the universe will begin to accelerate, with potential and initial mass

$$V \simeq \mu^4 \ln(\frac{4\alpha M}{M_4}) \sim \mu^4$$

$$m_\phi^2 \simeq 16 \frac{\alpha^2 \mu^4}{M_4^2}$$

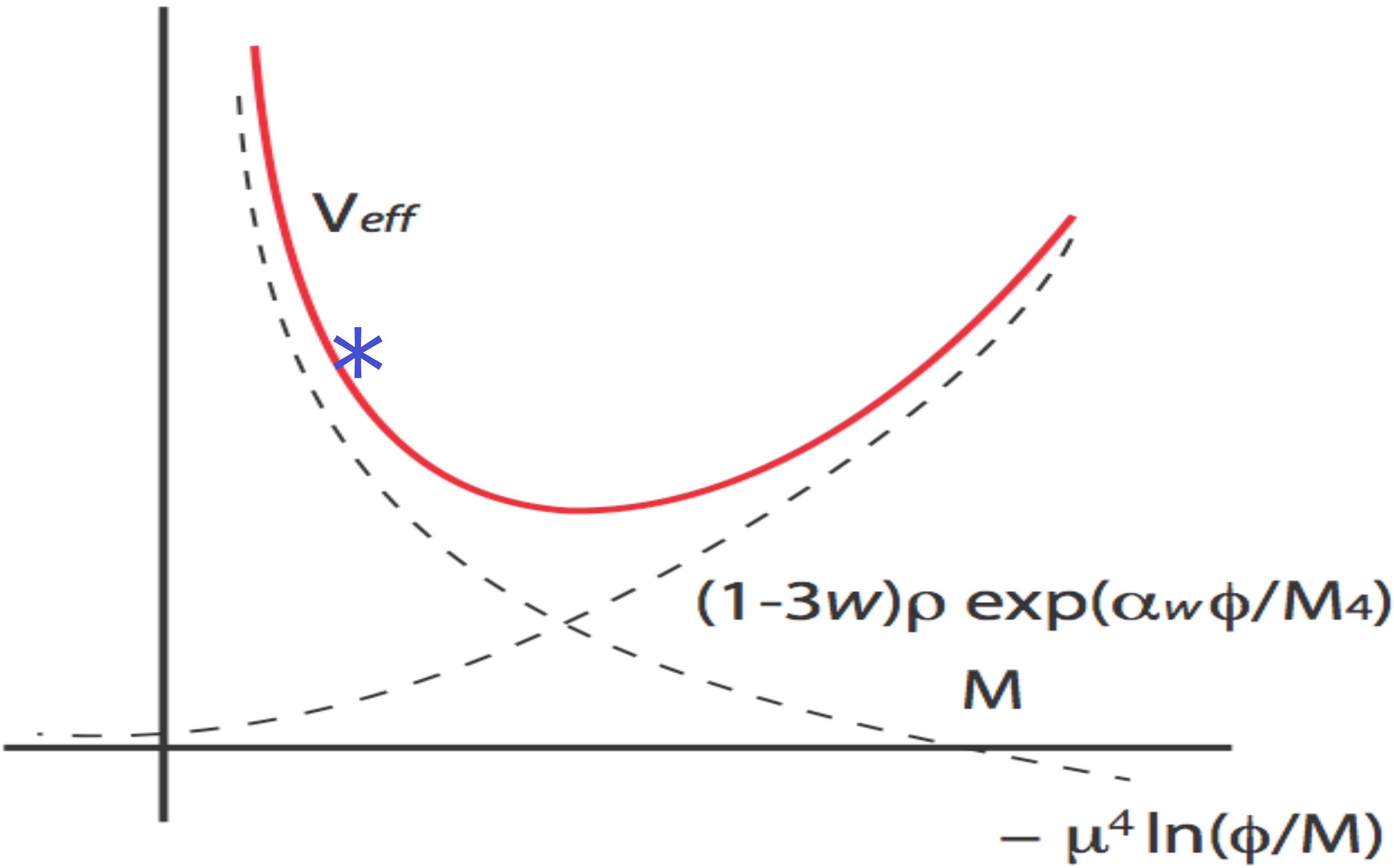
- The field mass there supports acceleration as long as $\alpha < (4\sqrt{3})^{-1}$. Because $\mu \sim 1/\phi$ and ϕ grows slow roll improves - but eventually V hits zero!
- Before that happens, the time and field evolution are related by

$$\frac{\mu^2 M_4}{\sqrt{3}} \Delta t \simeq \int_{\frac{M_4}{4\alpha}}^{\phi} d\phi \phi \ln^{1/2}(\frac{M}{\phi})$$

- We maximize the integral by taking $\phi = M$ and evaluating it using the Euler $\Gamma(3/2)$ function. That yields

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

$$H_0 \simeq \frac{\mu^2}{\sqrt{3} M_4}$$


Veff
(1-3w)ρ exp(αwϕ/M4)
M
− μ4 ln(ϕ/M)

Seeing 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 - a more natural case than having it much higher than the Planck scale - and argued to be realized in controlled UV completions, e.g. in string theory - as opposed to the other limit - we find that α is within an order of magnitude of unity.
- The scalar-matter coupling is

$$g_\phi \sim \frac{\alpha}{M_4}$$

- The mass is $m \sim (\alpha/10)$ eV.
- This means that the scalar forces may be close to the current lab bounds!

Seeing 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 an effective equation of state $w \neq -1$. Indeed, from

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

when M is close to the Planck scale, this occurs when $\Delta\tau \sim 1/H$.

- Subsequently the field dynamics may even collapse the universe, as the potential grows more negative.
- As a result there may be imprints of $w \neq -1$ in the sky too.
- It appears that the search strategy would be to look for correlations between excess of dark matter in young structures and signs of $w \neq -1$
- Too early for this?…

Summary

- Do the successes of General Relativity really demand General Relativity?
  - *If they do, we will be forced to deal face-on with the greatest failure of General Relativity: the Cosmological Constant (and perhaps, the dreadful Anthropics itself…)*
- But: maybe we can avoid the problem by changing gravity away from GR; usually this introduces new degrees of freedom
- Thus it is important to seek out useful benchmarks which can yield alternative predictions in addition to those that support ΛCDM

  1) to compare with the data

  2) to explore decoupling limits

  3) to test dangers from new forces
- A logarithmic changeling is one such model which allows for correlations between the lab tests and the sky surveys
- More work needed: maybe new realms of gravity await