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 — ***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:

DARK ENERGY

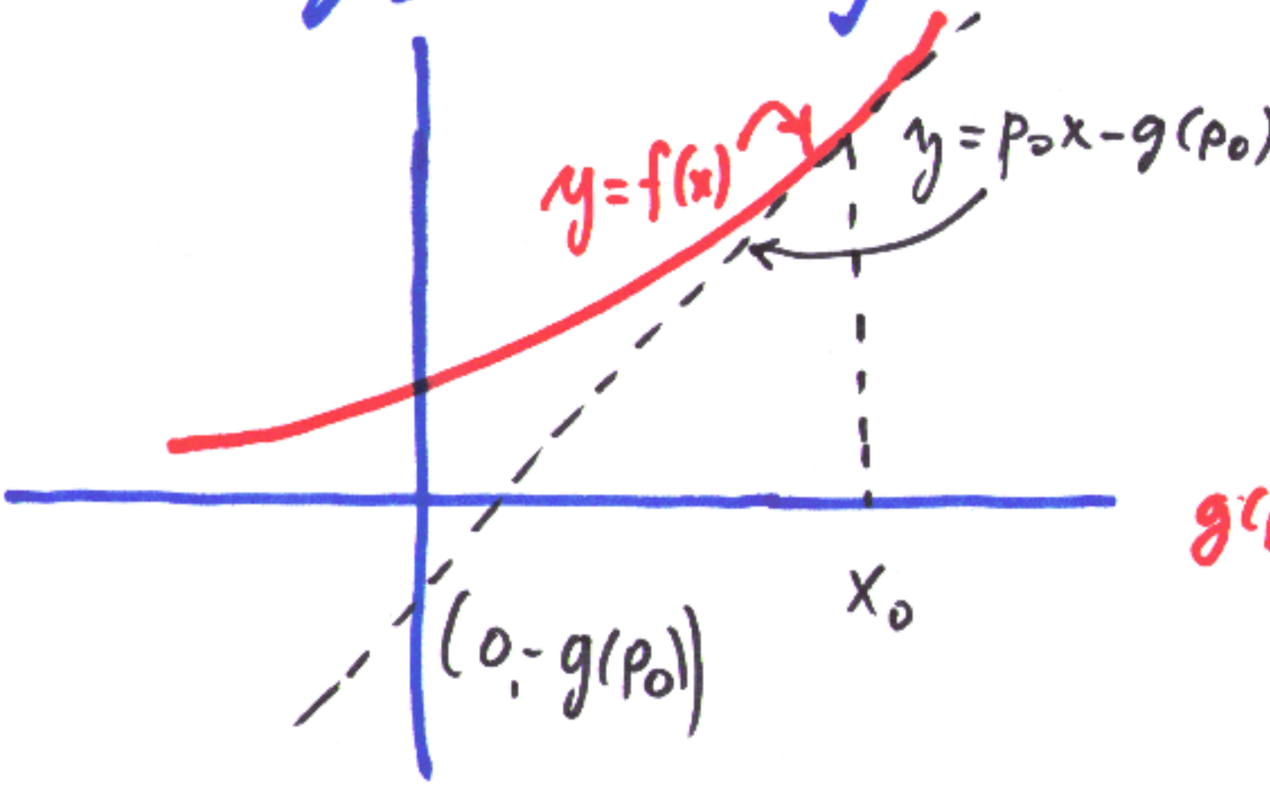
The situation with cosmological constant is **desperate** (by 60 orders of magnitude!) → desperate measures required?

Blessings of the dark curse ☺

- How do we get small 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: find all that needs explaining, and be careful about dismissals based on current theoretical prejudice (learning to be humble from the story of Λ …)
- Ultimately, perhaps both cosmological observations and LHC should be viewed as tests of *naturalness*…

Modified gravity v.s. Λ

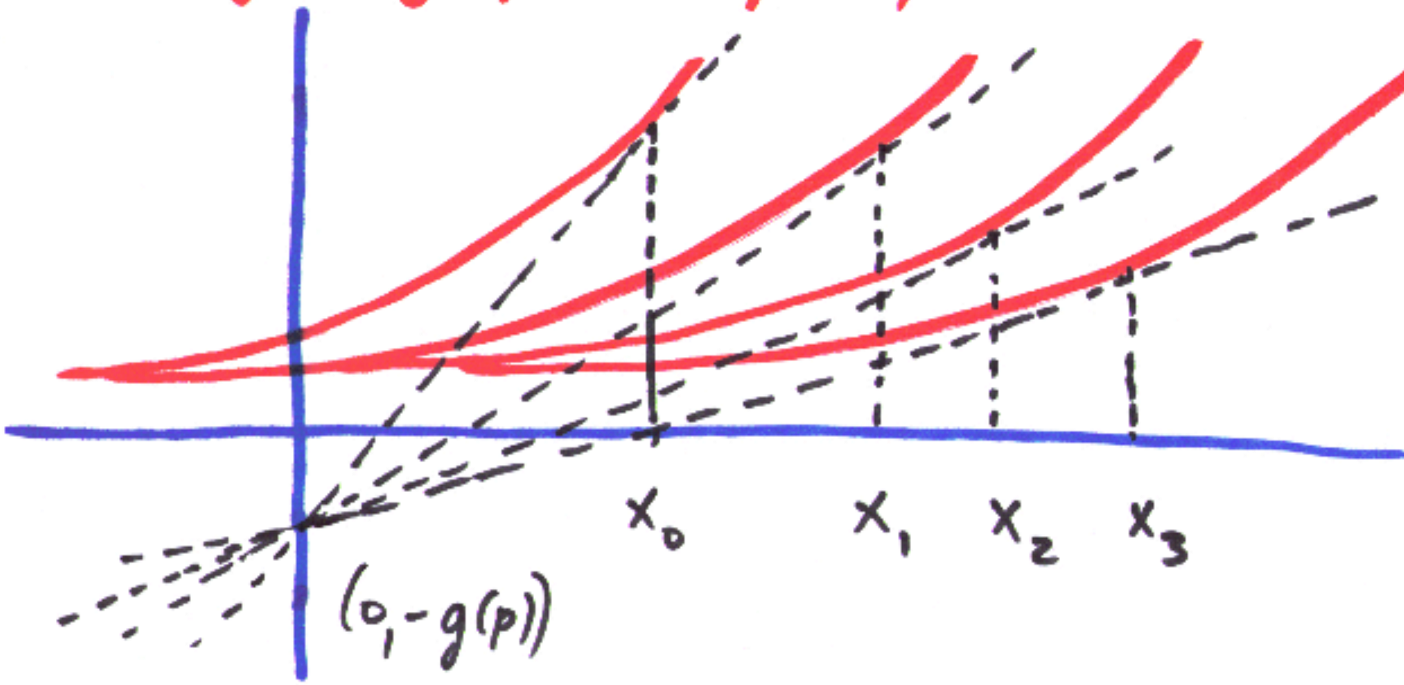
$\int \sqrt{g}\,\Lambda$: a Legendre transf.



$p = \frac{\partial y}{\partial x}$

$g(p) = xp - y$

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: $X = \sqrt{\det g}$ 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:

$$R^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu R = 8\pi G_N \left(T^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu T\right)$$

But: $\nabla_\mu T^\mu{}_\nu = 0 \rightarrow \partial_\mu (R + 8\pi G_N T) = 0 \rightarrow R + 8\pi G_N (T + 4\Lambda) = 0$

$$\therefore \; R^\mu{}_\nu - \frac{1}{2}\delta^\mu{}_\nu R = 8\pi G_N \left(T^\mu{}_\nu + \Lambda \delta^\mu{}_\nu\right)$$

$$\Lambda_{tot} = \langle T^0{}_0 \rangle + \Lambda$$

Alternatively: we may seek non-standard dynamics with new degrees of freedom...

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Motivates the search for a non-standard dynamics with new degrees of freedom...

Dark Energy in the lab?

- **The issue:** measuring Λ 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 Λ.
  - An exception: quintessence fields might bring along new couplings
- 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

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

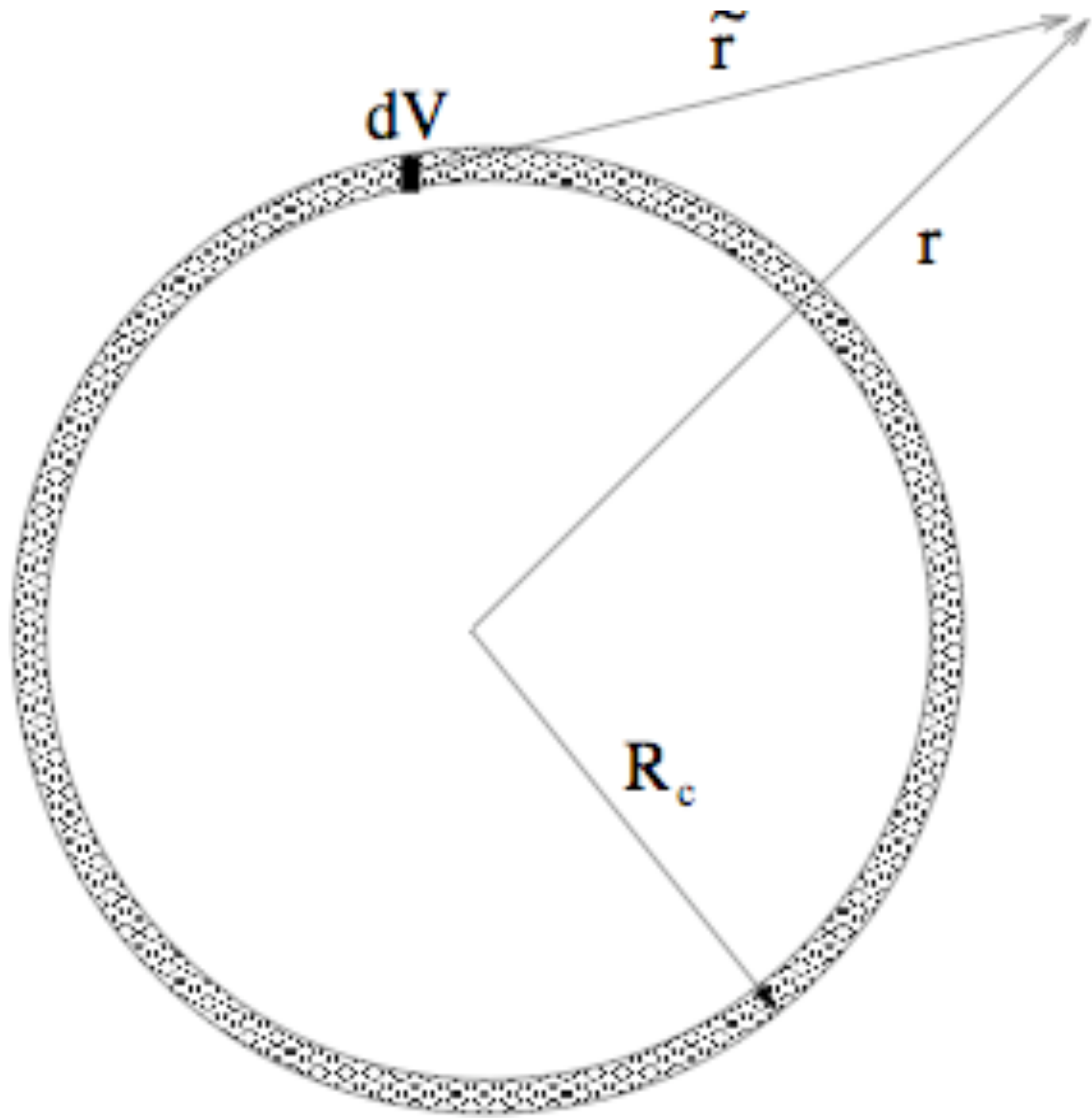
- We must pass the current laboratory bounds on sub-mm corrections to Newton's law. The thin shell effect for the chameleons helps, since it suppresses the extra force by

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

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

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

Khoury, Weltman



r̃
dV
r
R_c

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 we must have generalized slow roll:

$$\epsilon = |\frac{\dot{\rho}_{cr}}{H\rho_{cr}}| < 1 \qquad \eta = |\frac{\dot{\epsilon}}{3H\epsilon}| < 1 \qquad \rho_{cr} = 3M_4^2H^2$$

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?

- 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 $\rho_{Earth} \sim \mathrm{g/cm^3} \sim 10^{21}\,\mathrm{eV^4}$, 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 ***CANNOT*** yield cosmic acceleration by itself!

Some theorems and "theorems"…

- Integrate $\nabla^2\phi = -\partial_\phi V_{eff}$
- For spatial distributions in flat space, $\phi'' = \frac{\alpha\rho}{M_4} + \ldots$
- So the Gauss theorem yields

$$\int dV\,\phi'' = \frac{\Delta\phi}{\ell} R^2 \text{ for } \ell \leq R \quad \text{but}: \ = \Delta\phi\ell \text{ for } \ell > R$$

$$\int dV\,\rho = \rho R^3 \text{ for } \ell \leq R \quad \text{but}: \ = \rho R^3 + \rho_{vacuum}\ell^3 \text{ for } \ell > R$$

Shell thickness I

- When $\ell \leq R$, we get

$$\frac{\ell}{R} \sim \frac{\Delta\phi}{\alpha M_4} \frac{1}{\Phi_{Newton}}$$

- For typical potentials, $\Phi_{Newton} \sim 10^{-9} - 10^{-5}$ and for couplings $\alpha \sim 1$ and field variation $\Delta\phi \sim M_4$ it would seem that $\ell/R \sim 10^5 - 10^9$ suggesting that for a galaxy with $R \sim 100kPc$ we have $\ell \sim 10GPc > 1/H$
- This would be bad, since it would suggest that screening profiles never set up…
- But this is silly! We are using the wrong formula!
- The point: when $\ell > R$ we cannot ignore ρ_{vacuum}!

Shell thickness II

- Instead: when $\ell > R$ we have, using Einstein's eqs,

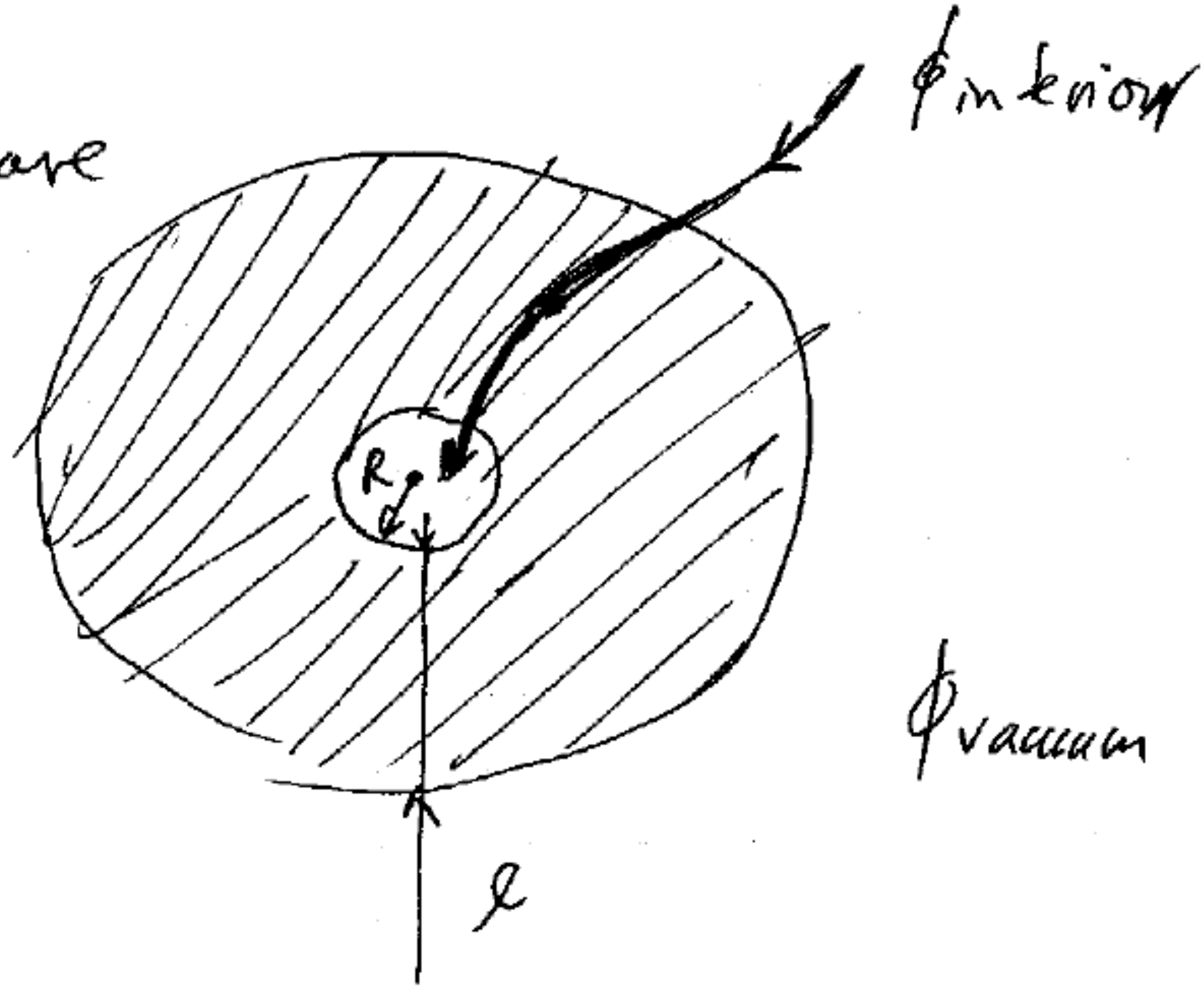
$$\frac{\Delta\phi}{\alpha M_4}\ell \sim R_S + H^2\ell^2\ell$$

- Therefore

$$\ell \sim \sqrt{\frac{\Delta\phi}{\alpha M_4}}\frac{1}{H}$$

- Field *does* readjust within the Hubble scale!!!

we have



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:

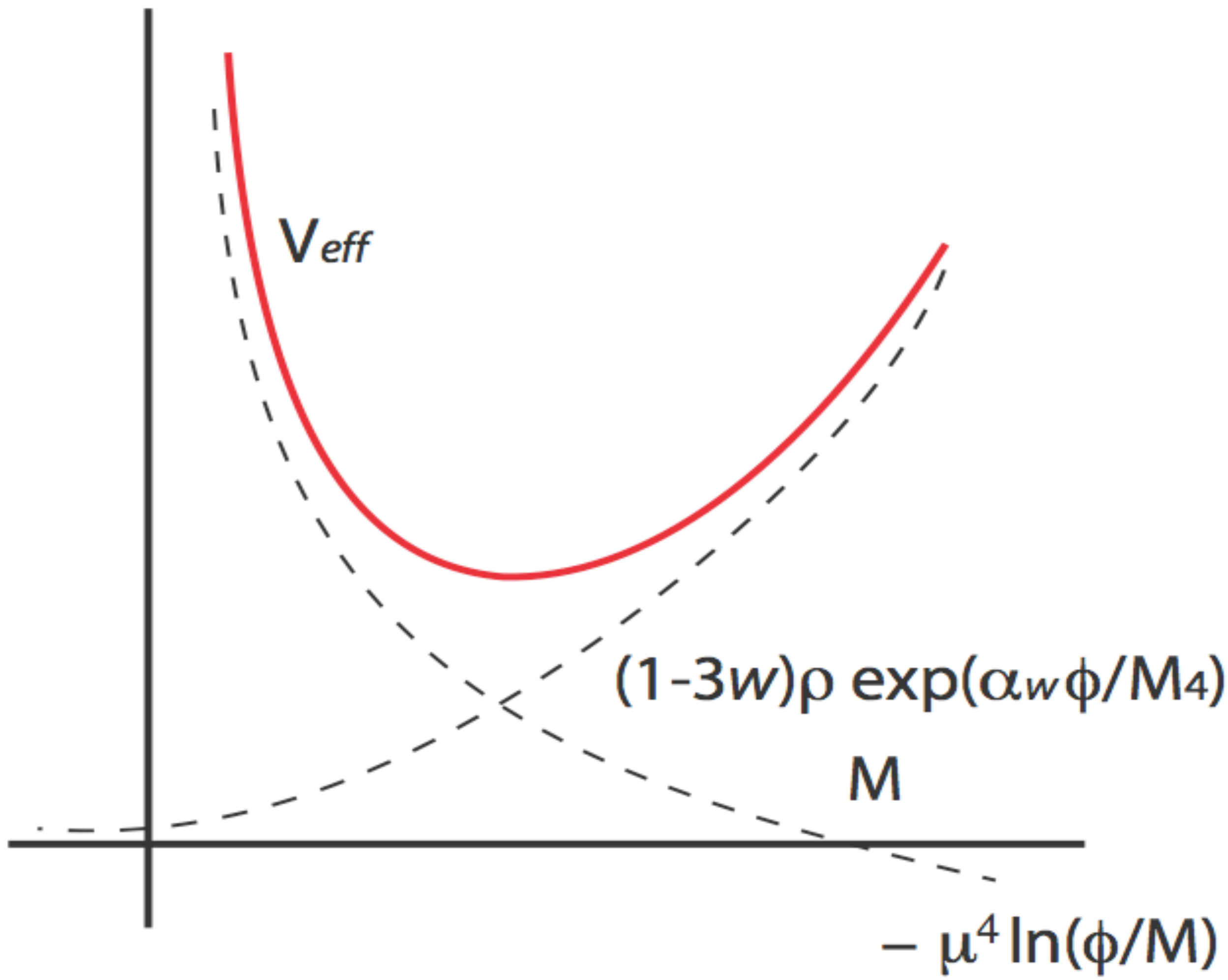
$$V_{eff}(\phi) = -\mu^4 \ln\left(\frac{\phi}{M}\right) + (1-3w)\rho\, e^{\alpha w \phi / M_4}$$

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. Yet, this may only require tunings in the gravitational sector…
- Now we look at cosmic history…

Effective potential



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

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

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

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

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!

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,

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

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

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 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

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

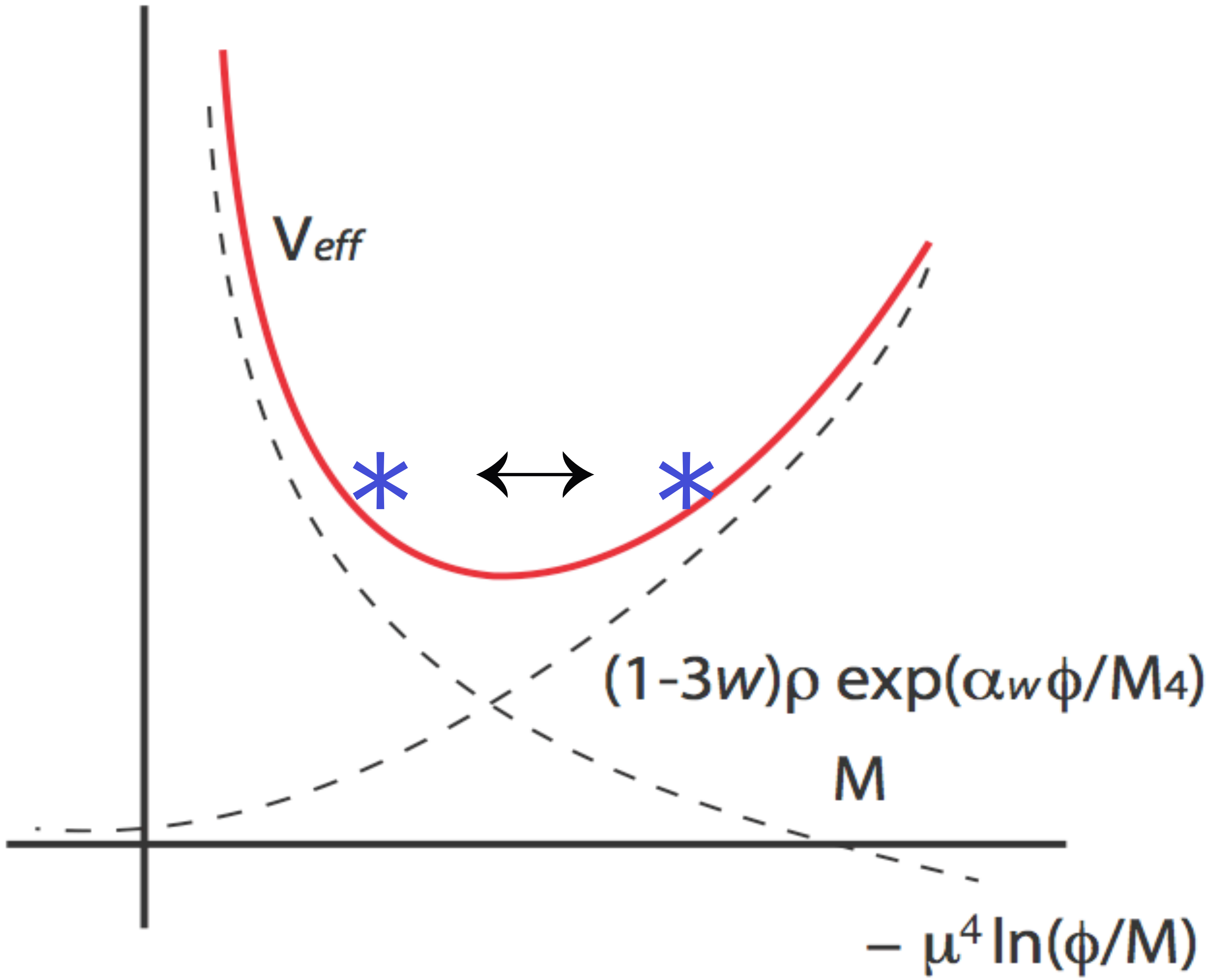
- However the field will NOT go to this minimum everywhere immediately. Since

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

  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 ρ grows very big, the minima are 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 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?…



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

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

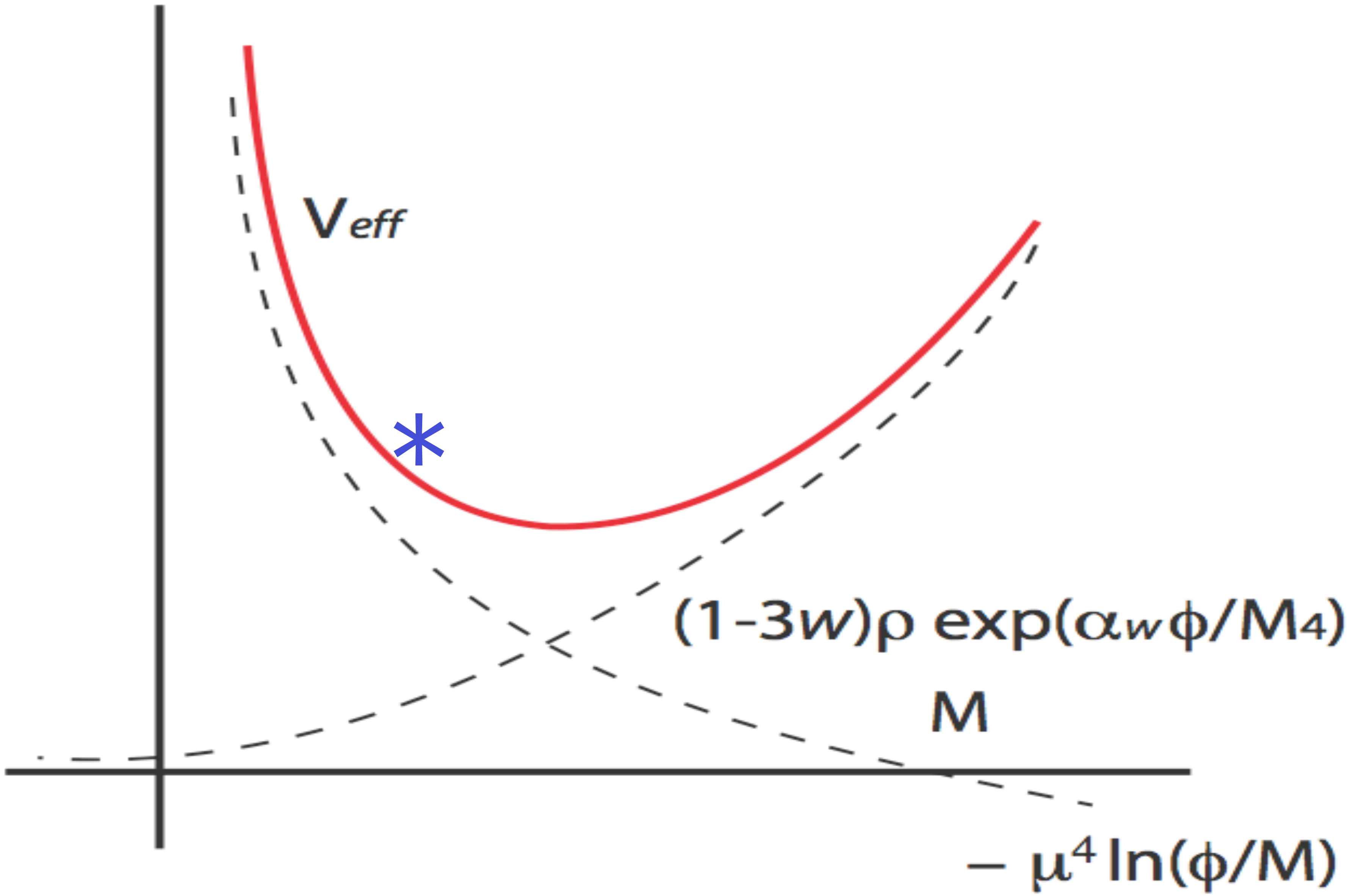
$$V \simeq \mu^4 \ln(\frac{4\alpha M}{M_4}) \sim \mu^4 \qquad m_\phi^2 \simeq 16\frac{\alpha^2\mu^4}{M_4^2}$$

- 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

$$\Delta t \simeq \sqrt{\frac{3\pi}{32}}\frac{M^2}{\mu^2 M_4} \qquad H_0 \simeq \frac{\mu^2}{\sqrt{3}M_4}$$



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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

$$M \gtrsim (\frac{32}{\pi})^{1/4} M_4 \simeq 1.78\, M_4$$

- 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 α is within an order of magnitude of unity.
- The scalar-matter coupling and the mass are

$$g_\phi \sim \frac{\alpha}{M_4} \qquad m_\phi \sim \frac{\alpha \rho_{matter}}{M_4 \mu^2} \sim \frac{\alpha}{10}\,\mathrm{eV}$$

- 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 $w \neq -1$. Indeed, from

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

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 $w \neq -1$ in the sky. So: look for correlations between DM excess in young structures and $w \neq -1$

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…

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