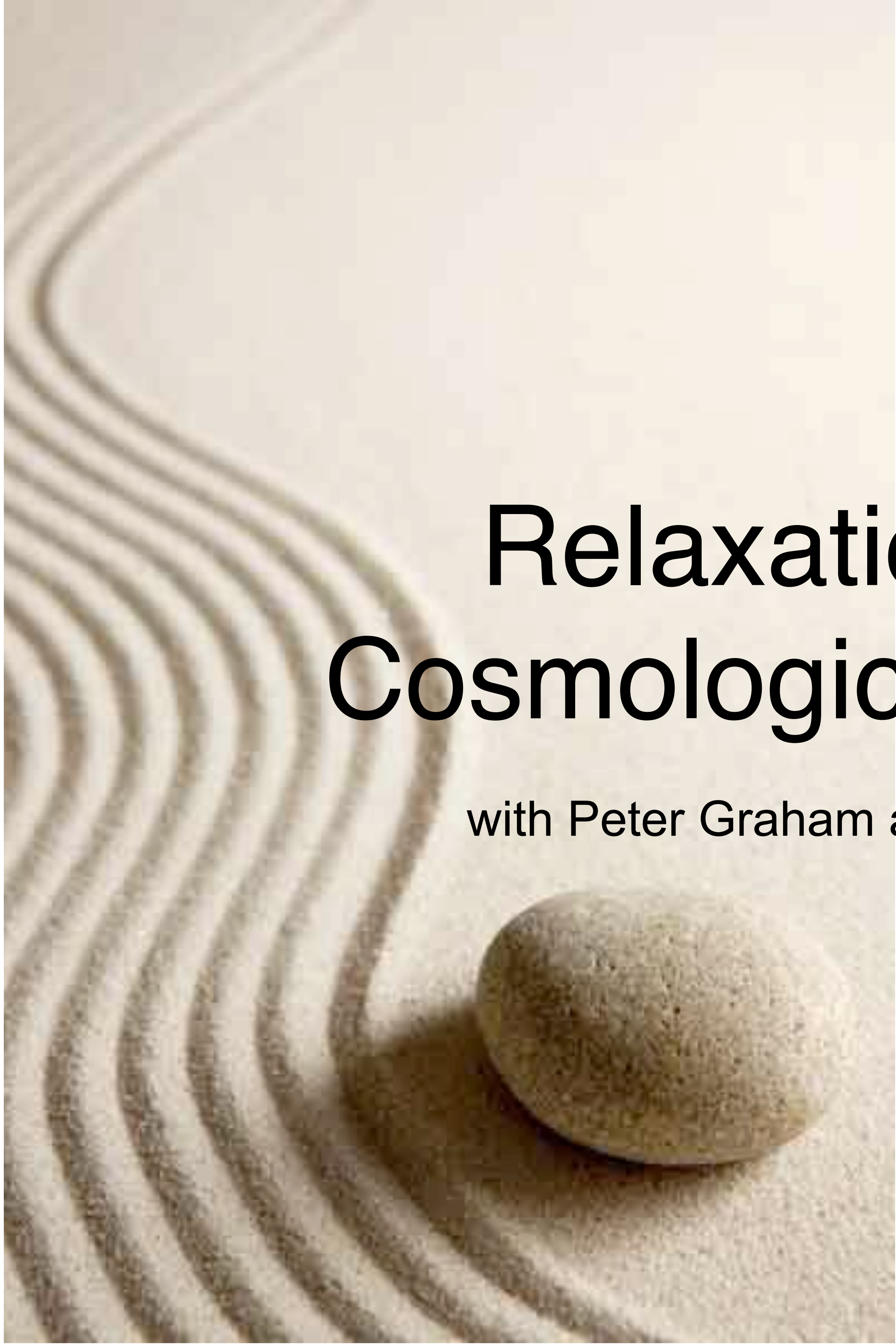


Relaxation of the Cosmological Constant

with Peter Graham and David *E.* Kaplan

The Born Again Universe +
Work in preparation +
Work in progress

The Cosmological Constant Problem

Λ Λ

Observed: 10^{-12} eV^4 **Theory: 10^{48} eV^4**

Why?

Symmetry? **Standard Model?** **Gravity?**

4000 BC **1947** **2000s**

New way to get small numbers

Time Evolution

Time evolution can change our expectations of naturalness

Initial Formation

+ millions of years

Dissipation is central - eroded sand needs to go somewhere

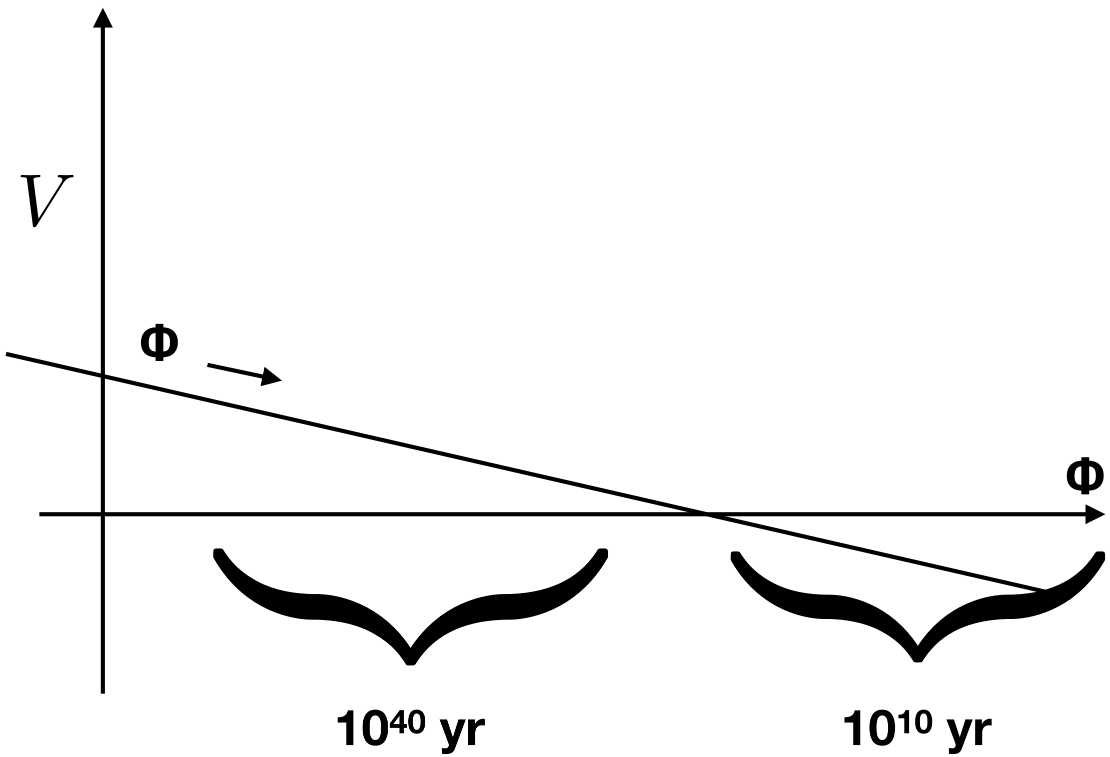
Slow Dissipative process => light, weakly coupled field.
Testable!

Could Λ erode over time?

Relaxation of the Cosmological Constant

$$\mathcal{L} \supset \Lambda^4 - g^3 \phi$$

Start with large positive Λ^4,
Slowly rolling ϕ



Inflating universe,
slowly changing vacuum energy

Vacuum energy gets very small,
Universe very cold

Vacuum energy eventually zero - universe crunches, gets hot

Key Point: Make Universe Bounce - get hot universe with small vacuum energy

Outline

1. Why?
2. Model
3. Bouncing Universe?
4. Experimental Tests?
5. Conclusions

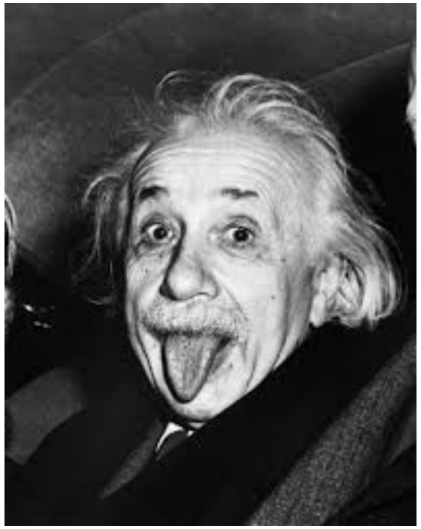
Why?

Cancellation of Λ

$$\mathcal{L} \supset \Lambda^4$$

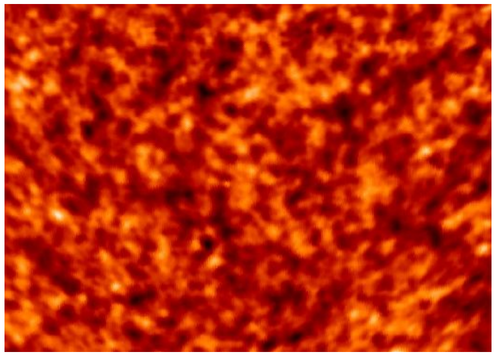
Want to set to zero. How to sense?

Key Point: Vacuum energy only couples through Gravity



Universal Gravitation

Gravity senses total energy in the universe, cannot distinguish individual components



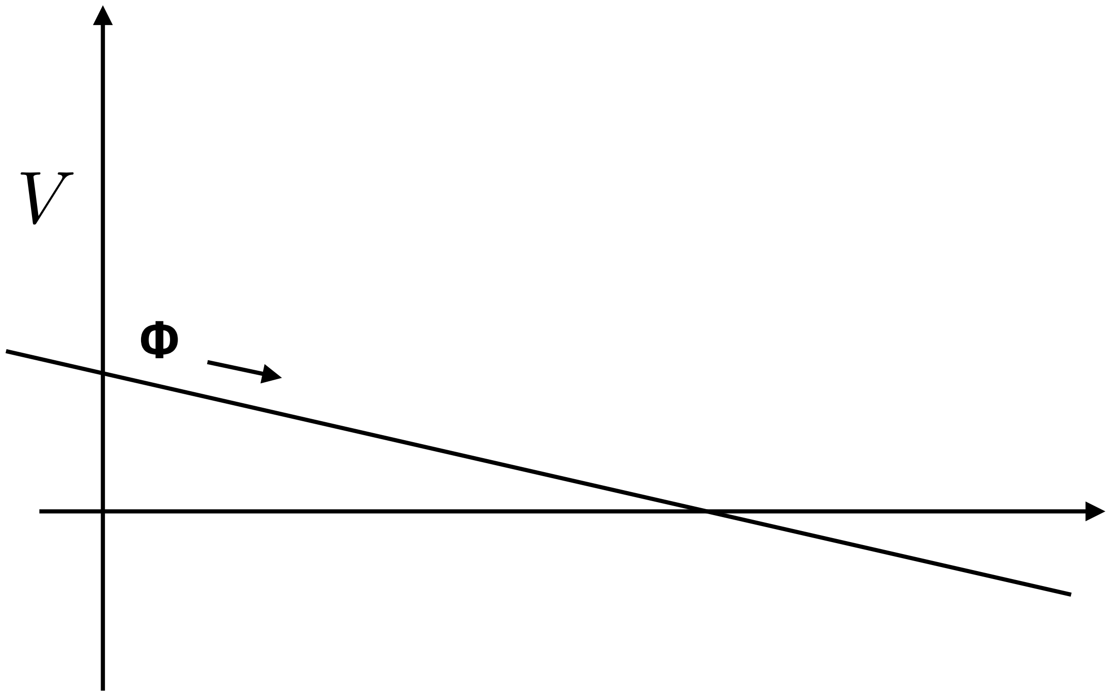
Hot early universe?
Gravity cannot sense Λ alone

Need Λ domination i.e. inflation

Bounce?

$$\mathcal{L} \supset \Lambda^4 - g^3 \phi$$

Inflation, vacuum energy slowly decreases



Need to reduce vacuum energy to ~ 10^{-12} eV^4

Other energy densities (e.g. radiation), smaller than 10^{-12} eV^4

10^{10} years ago, universe had radiation with density 10^{24} eV^4

Need to reheat cold empty universe

Key Point: Energy not conserved in gravity! Reheat with a bounce!

Capabilities

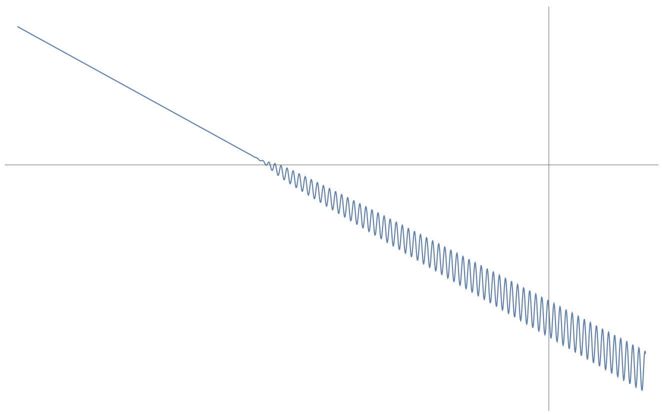
$$\mathcal{L} \supset \Lambda + g^3\phi + \ldots$$

Φ rolls, tunes cosmological constant in empty universe.
Reheat with a bounce.

Weinberg?

$$V, V' \approxeq 0$$

Relaxion = Large Number of Minima



Phase Transitions?

Reheating => hot universe, vacuum energy goes up

Sub-dominant. Expand, cool, return to tuned value

Bounce + Tuning?

Hot universe => Φ rolls. Λ_{eff} changes

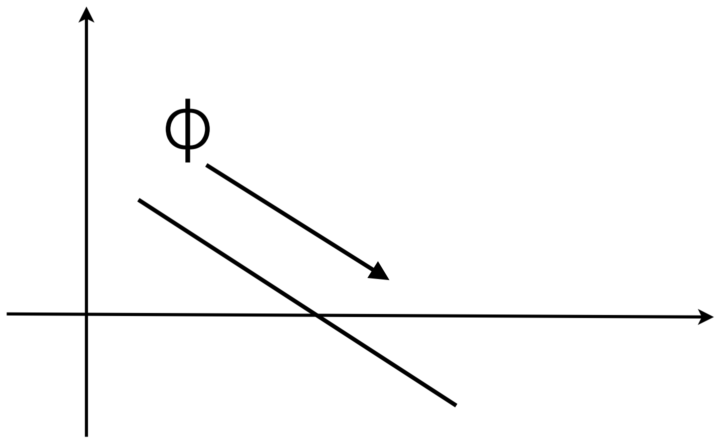
Small change - tuning >> bounce

Likely leads to changing Λ_{eff}

Model

Main Ingredient

$$\mathcal{L} \supset \Lambda^4 - g^3\phi + \frac{\phi}{f_a} F\tilde{F}$$



Generates Friction

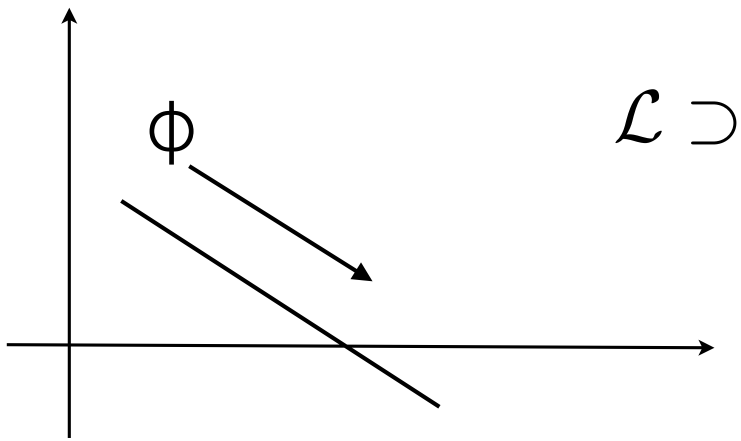
$$\ddot{A}_\pm + \left(m_A^2 + k^2 \mp \frac{\dot{\phi}}{f_a} \right) A_\pm = 0$$

Key Points

$A_\pm$ tachyonic when $\frac{\dot{\phi}}{f_a} \gtrapprox m_A$ — Trigger

$\dot{\phi} \approxeq \mathcal{O}(100) f_a H \quad \langle F^2 \rangle \approxeq f_a g^3$ — >> H^4

Simplest Model



$$\mathcal{L} \supset \Lambda_i^4 - g^3\phi + \frac{\phi}{f_a} F\tilde{F}$$

Let ϕ roll through 0, no barriers

1. No Eternal Inflation: $g \gtrsim \Lambda_i^2/M_{pl}$

2. C.C set by Kinetic Energy: $g^3 M_{pl} \lesssim \mathrm{meV}^4$

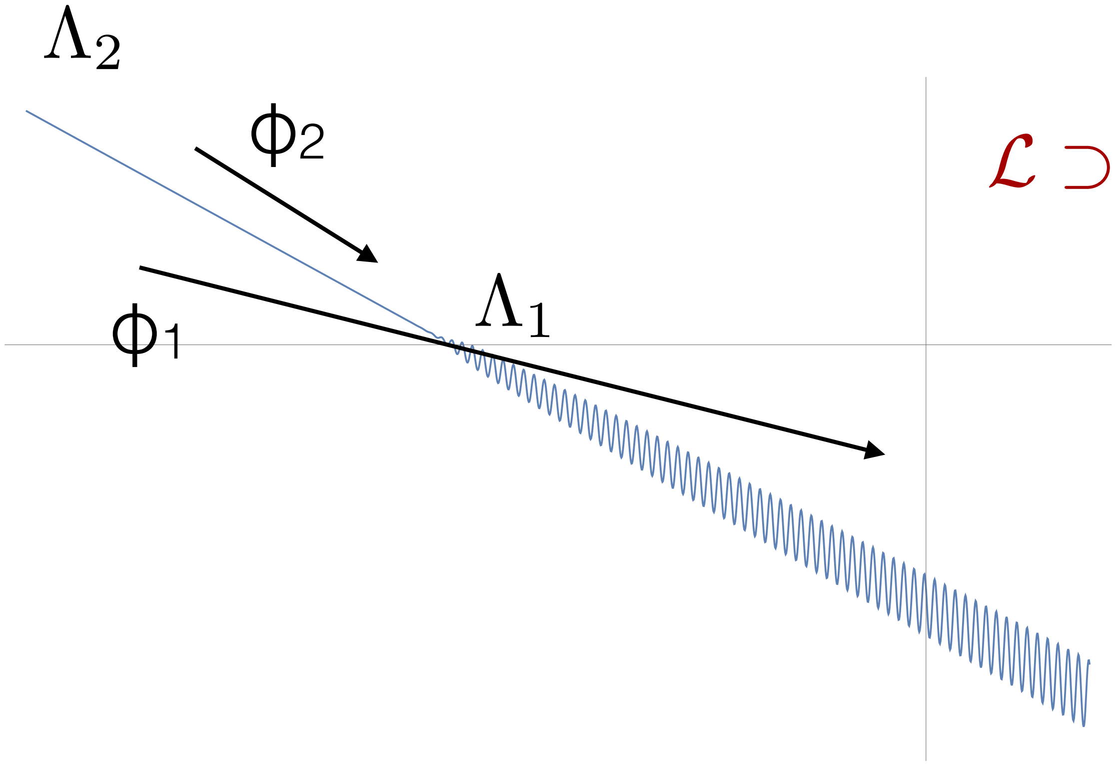
$$\Lambda_i \lesssim \left(\mathrm{meV}^2 M_{pl}\right)^{\frac{1}{3}} \sim 10 \text{ MeV}$$

Can check story works (reheating, small c.c. change today)

Turtles All the Way

Higher Cut-off?

Need larger slope at top to combat eternal inflation



$$\mathcal{L} \supset \Lambda_2^4 - \left(\frac{\Lambda_2^2}{M_{pl}}\right)^3 \phi_2 + \frac{\phi_2}{f} F\tilde{F}$$

$$- \left(\frac{\Lambda_1^2}{M_{pl}}\right)^3 \phi_1 + \frac{\phi_1}{f} F\tilde{F}$$

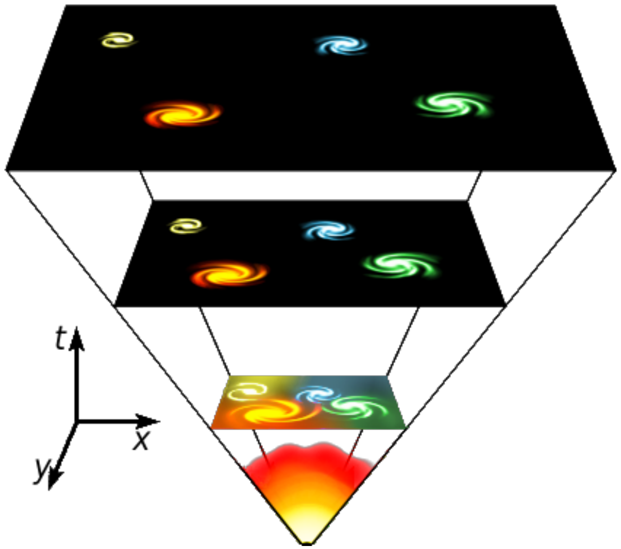
Key Point: ϕ_2 rolls faster at lower c.c.
Use friction to raise barrier

$$\Lambda_2 \lessapprox \left(M_{pl}^2 \Lambda_1^4\right)^{\frac{1}{6}}$$

No Bounce

Bouncing Universe

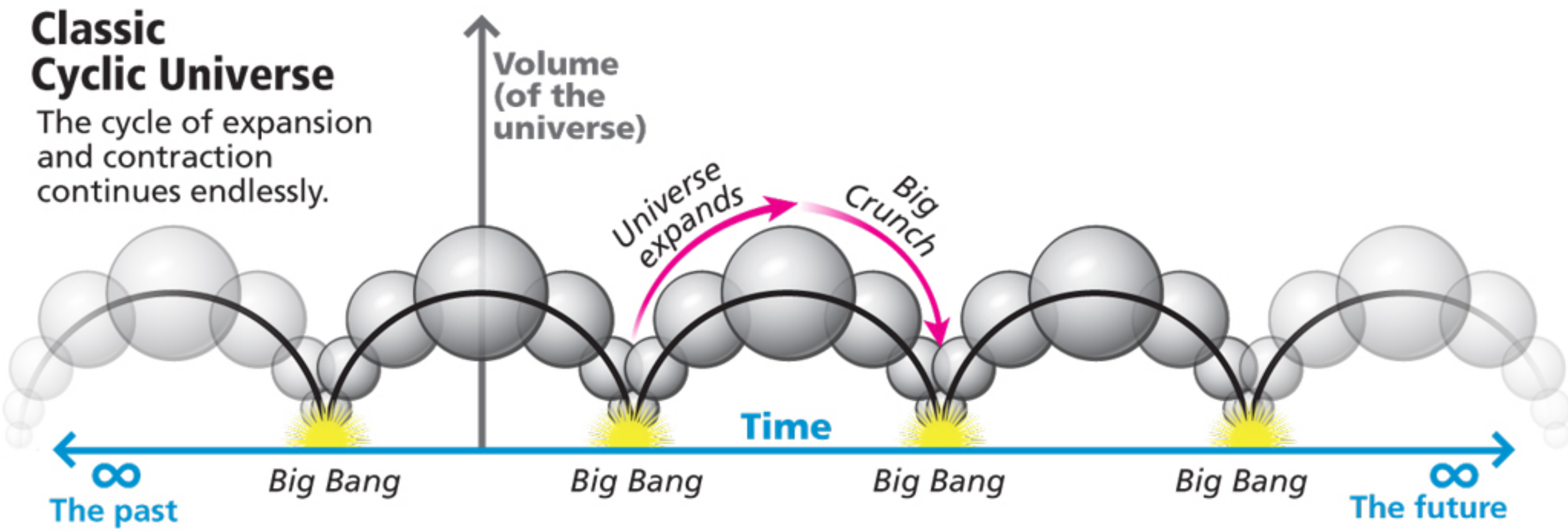
Bouncing Cosmology



Independently Motivated

Singularity not removed by inflation

Infinite Past?

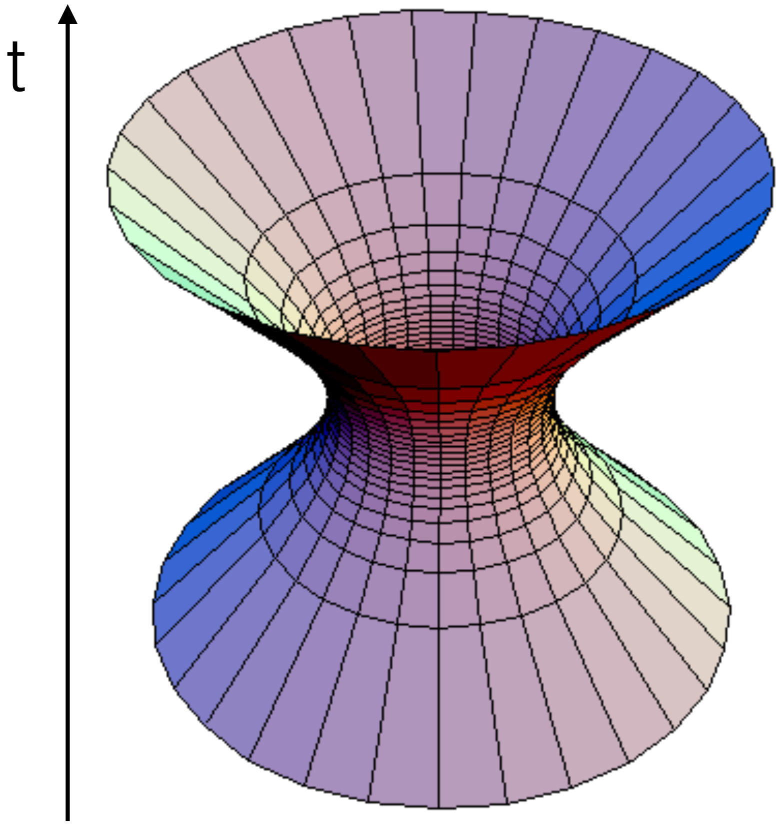


Why not?

Bouncing Cosmology

Generic Requirement?

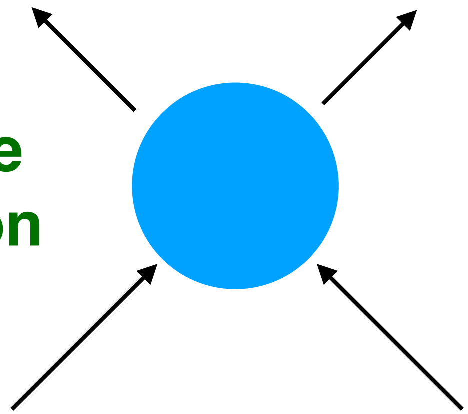
Need converging geodesics to diverge



Collapsing matter, gravity gets stronger

Can matter never escape strong gravity?

Black Hole Evaporation



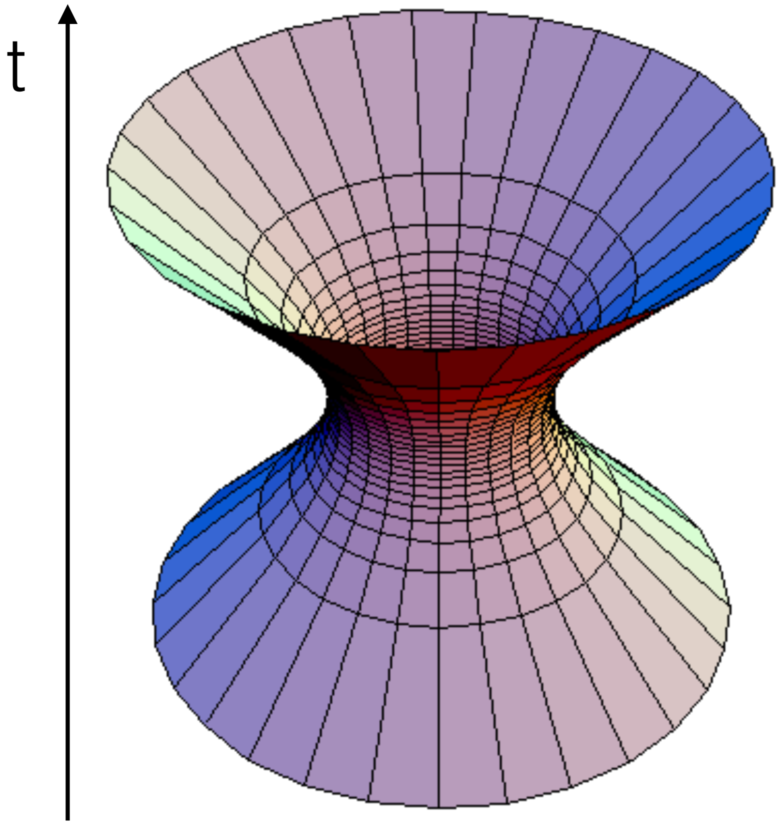
Key Point: Matter could escape gravitational singularities

Singular Bounce likely possible. Non singular bounce??

Bouncing Cosmology

Generic Requirement?

Need converging geodesics to diverge



Raychaudhuri's Equation

$$\frac{d\hat{\theta}}{d\lambda} = -\frac{1}{2}\hat{\theta}^2 - 2\hat{\sigma}^2 + 2\hat{\omega}^2 - T_{\mu\nu}U^\mu U^\nu$$

$$\text{Divergence} \implies \frac{d\hat{\theta}}{d\lambda} > 0$$

$$T_{\mu\nu}U^\mu U^\nu < 0 \text{ or } \hat{\omega} \neq 0$$

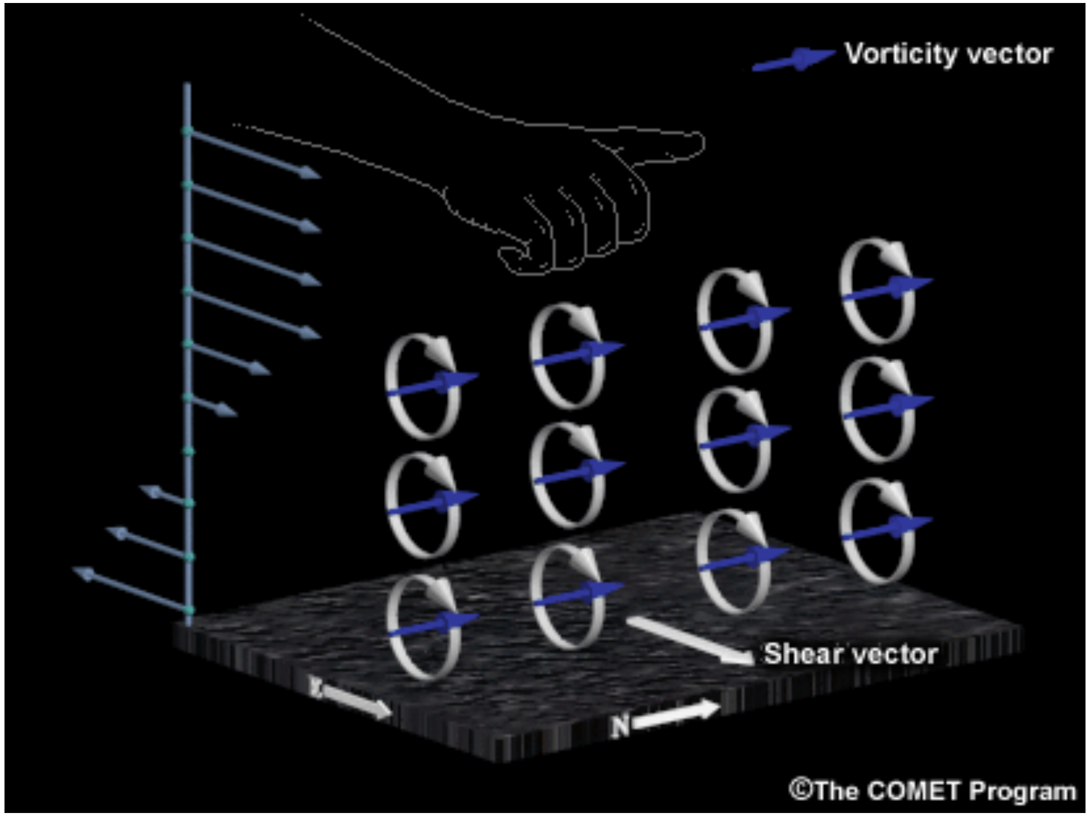
Null Energy Violation → $T_{\mu\nu}U^\mu U^\nu < 0$

Vorticity → $\hat{\omega} \neq 0$

Vorticity

$$\frac{d\hat{\theta}}{d\lambda} = -\frac{1}{2}\hat{\theta}^2 - 2\hat{\sigma}^2 + 2\hat{\omega}^2 - T_{\mu\nu}U^\mu U^\nu$$

Combat attractive gravity with centrifugal motion

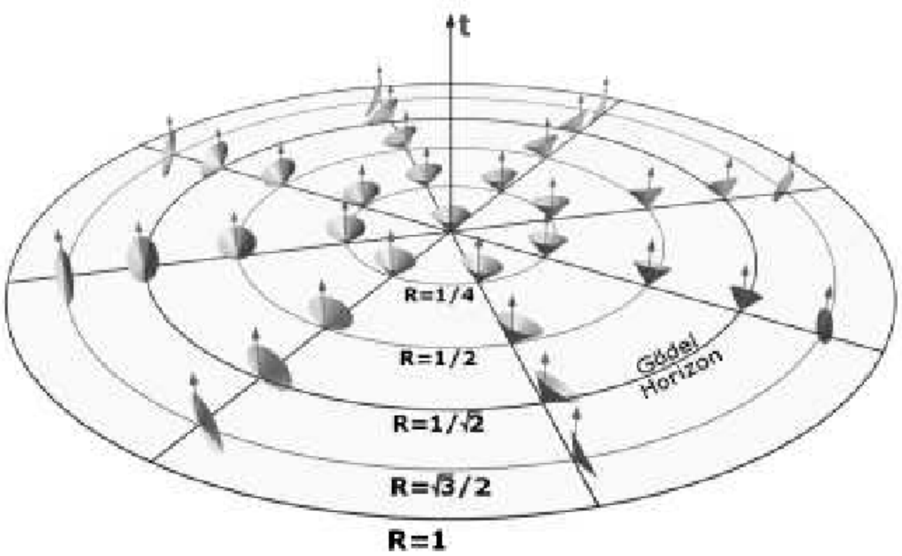


Why not use this term?

To avoid Null Energy violation, need global vorticity

Godel Universe

$$ds^2 = \frac{2}{\omega^2}\left(-dt^2 + dr^2 + dy^2 - \left(\sinh^4 r - \sinh^2 r\right) d\phi^2 - 2\sqrt{2}\sinh^2 r d\phi dt\right)$$



Cosmological Constant + Spinning Dust

Static Universe: Gravity balanced by rotation

Closed time-like curves for r > 1

Does not describe region of space-time where we live

The Born Again Universe

Have vorticity everywhere, without closed time-like curves?

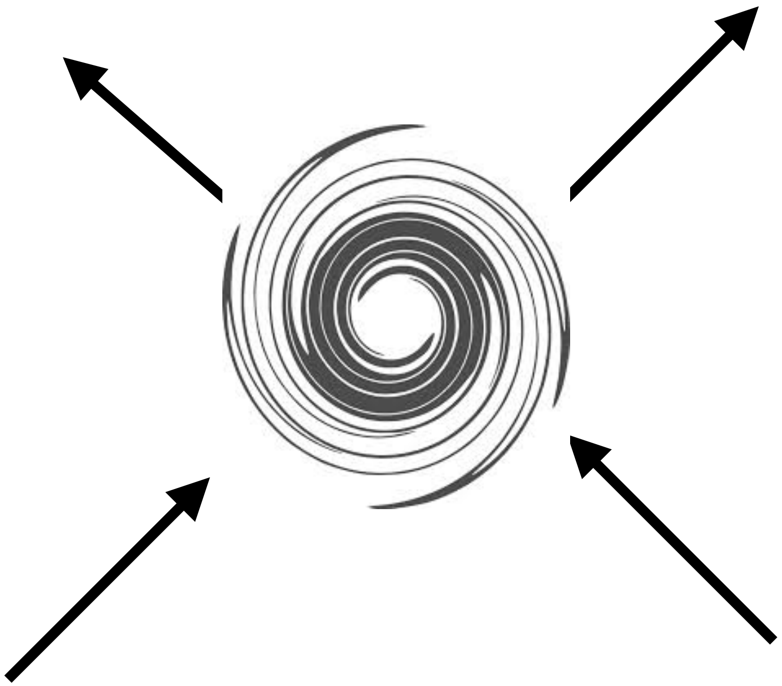
Distant points rotate -> Closed time-like curve

To avoid singularity, just need rotation everywhere

Key Point: Rotate into compact extra-dimensions?

Space-Time: R^4 x T^3

Non-singular bounce without closed time-like curves?



The Metric

Space-Time: R^4 X T^3

$$ds^2 = -dt^2 + a(t)^2 \, d\vec{x}^2 + b^2 \left(d\theta^2 + d\phi_1^2 + d\phi_2^2\right) - 2\epsilon b \left(\sin\theta \, dt d\phi_1 + \cos\theta \, dt d\phi_2\right)$$

↓ Standard

↓ **Vorticity**

Geodesics along R4 forced to move into extra-dimensions

Plug in for a(t), use Einstein's Equations to get stress-tensor

Can the required stress-tensor be made?

4D effective field theory?

The Stress Tensor

$$ds^2 = -dt^2 + a(t)^2\, d\vec{x}^2 + b^2\left(d\theta^2 + d\phi_1^2 + d\phi_2^2\right) - 2\epsilon b\left(\sin\theta\, dt d\phi_1 + \cos\theta\, dt d\phi_2\right)$$

$$T_{tt} = -M_7^5\left(\frac{3\epsilon^2 a''(t)}{a(t)} + \frac{3\left(\epsilon^2 - 1\right) a'(t)^2}{a(t)^2} - \frac{3\epsilon^2}{4b^2}\right)$$

$$T_{xx} = T_{yy} = T_{zz} = -M_7^5\left(-2\left(\epsilon^2 - 1\right) a(t) a''(t) - \left(\epsilon^2 - 1\right) a'(t)^2 + \frac{\epsilon^2 a(t)^2}{4b^2}\right)$$

Consider 4D geodesic during bounce. Null Energy?

$$T_{tt} + \frac{T_{xx}}{a(t)^2} \approx \frac{\epsilon^2}{2b^2} - 2\frac{\ddot{a}}{a}$$

Vorticity combats gravity, for weak bounce

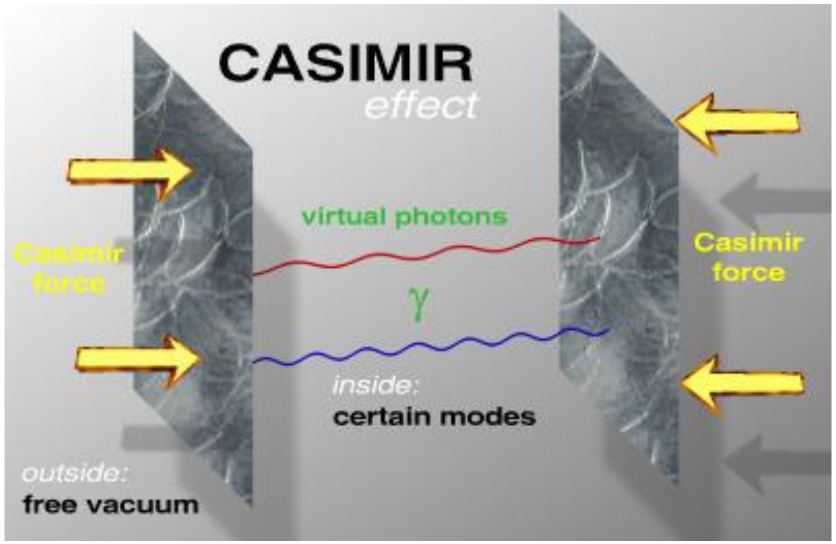
The Stress Tensor

$$ds^2 = -dt^2 + a(t)^2\, d\vec{x}^2 + b^2\left(d\theta^2 + d\phi_1^2 + d\phi_2^2\right) - 2\epsilon b\left(\sin\theta\, dt d\phi_1 + \cos\theta\, dt d\phi_2\right)$$

Null Energy Condition not violated for 4D geodesics

Violated for geodesics into extra-dimensions

But can use Casimir!



$$T_{\mu\nu} = T_C + T_M$$

Have Proven: T_M preserves dominant energy condition

Don't know: Microphysics of T_M

The Loophole

$$\frac{d\hat{\theta}}{d\lambda} = -\frac{1}{2}\hat{\theta}^2 - 2\hat{\sigma}^2 + 2\hat{\omega}^2 - T_{\mu\nu}U^{\mu}U^{\nu}$$

$$ds^2 = -dt^2 + a\left(t\right)^2 d\vec{x}^2 + b^2\left(d\theta^2 + d\phi_1^2 + d\phi_2^2\right) - 2\epsilon b\left(\sin\theta\, dtd\phi_1 + \cos\theta\, dtd\phi_2\right)$$

$$T_{\mu\nu} = T_C + T_M$$

Null Energy Condition in extra-dimensions

4D geodesics carry vorticity into extra-dimensions, avoiding focusing. Need T^3.

Metric clearly globally hyperbolic

4D effective field theory?

The Effective Theory

$$ds^2 = -dt^2 + a\left(t\right)^2 d\vec{x}^2 + b^2\left(d\theta^2 + d\phi_1^2 + d\phi_2^2\right) - 2\epsilon b\left(\sin\theta\, dtd\phi_1 + \cos\theta\, dtd\phi_2\right)$$

$$T_{tt} = -M_7^5\left(\frac{3\epsilon^2 a''(t)}{a(t)} + \frac{3\left(\epsilon^2 - 1\right)a'(t)^2}{a(t)^2} - \frac{3\epsilon^2}{4b^2}\right)$$

$$T_{xx} = T_{yy} = T_{zz} = -M_7^5\left(-2\left(\epsilon^2 - 1\right)a(t)a''(t) - \left(\epsilon^2 - 1\right)a'(t)^2 + \frac{\epsilon^2 a(t)^2}{4b^2}\right)$$

Vorticity terms contribute like a null-energy violating term

Can Show: In 4D, KK modes of source + gravivector violate NEC!

4D NEC Violation

$$\mathcal{L} \supset (\partial_\mu \phi)^2 + f(\partial_\mu \phi) + V(\phi)$$

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi + \frac{\partial f}{\partial \partial_\mu \phi} \partial_\nu \phi + g_{\mu\nu} \mathcal{L}$$

Need minus signs.
Ghosts/Causality

No contribution to NEC.
V irrelevant

Lorentz Violation

$$\mathcal{L} \supset \partial_\mu \phi \partial_\nu \phi + A_\mu J^\mu + \ldots$$

Background vector allows new possibilities

UV complete to Lorentz invariant higher dimensional theory

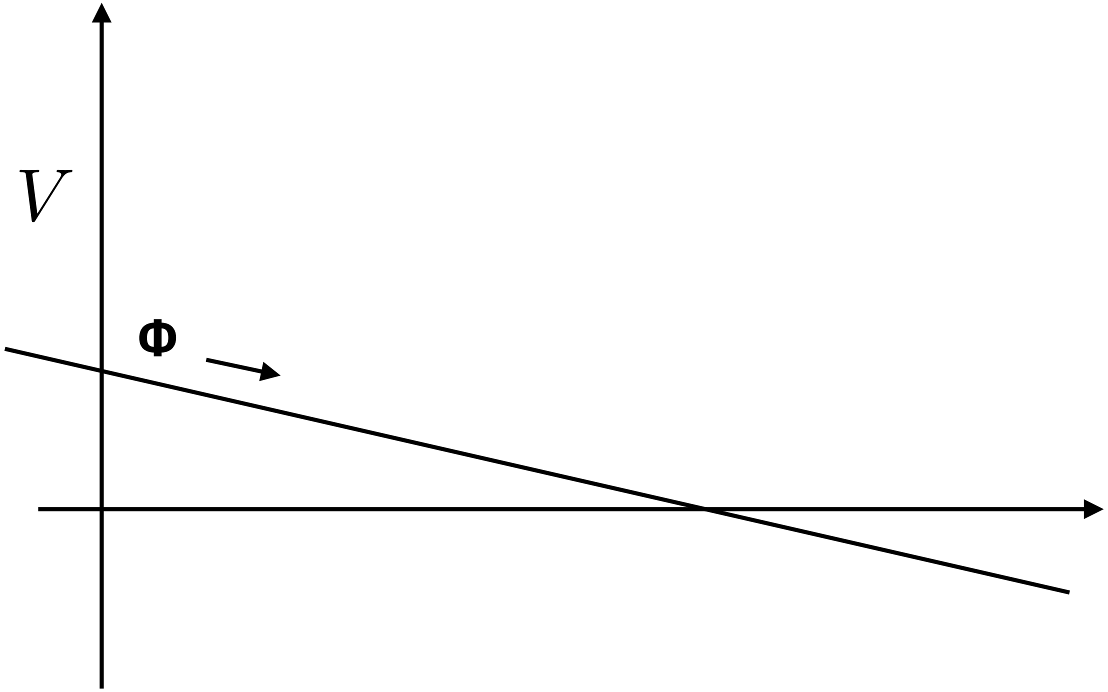
Experimental Tests

Dark Energy

$$\mathcal{L} \supset \Lambda^4 - g^3\phi$$

Slowly rolling ϕ, changing dark energy

$$w = \frac{\dot{\phi}^2 - V}{\dot{\phi}^2 + V}$$



Cosmological measurements of the equation of state of dark energy

Can ϕ couple to the standard model?

Laboratory measurements of the Dark Energy?

Direct Detection of Dark Energy

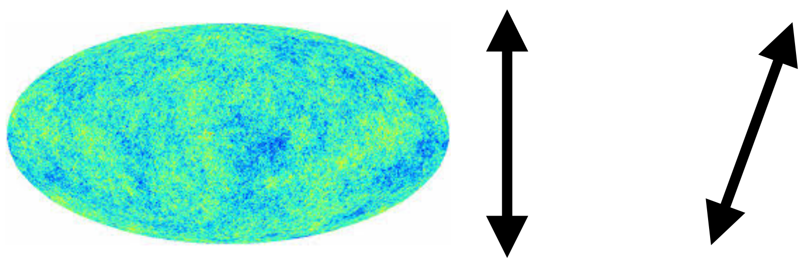
How can ϕ interact, while still having a small slope?

Axion-like interactions!

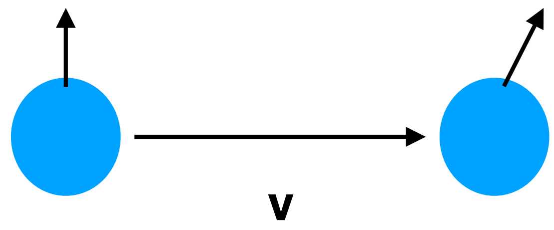
$$\mathcal{L} \supset \Lambda^4 - g^3\phi + \frac{\phi}{f_a}F\tilde{F} + \frac{\partial_\mu \phi}{f_a}\bar{\Psi}\gamma^\mu\gamma_5\Psi$$

Rotates polarization of light with dark energy evolution

Rotates spins moving against dark energy



CMB Polarization Experiments



Axion Dark Matter

Conclusions

Relaxation of the Vacuum Energy

Time →

Λ —Time→ Λ

Time Evolution is a new way to get small numbers

Testable in cosmological and laboratory experiments