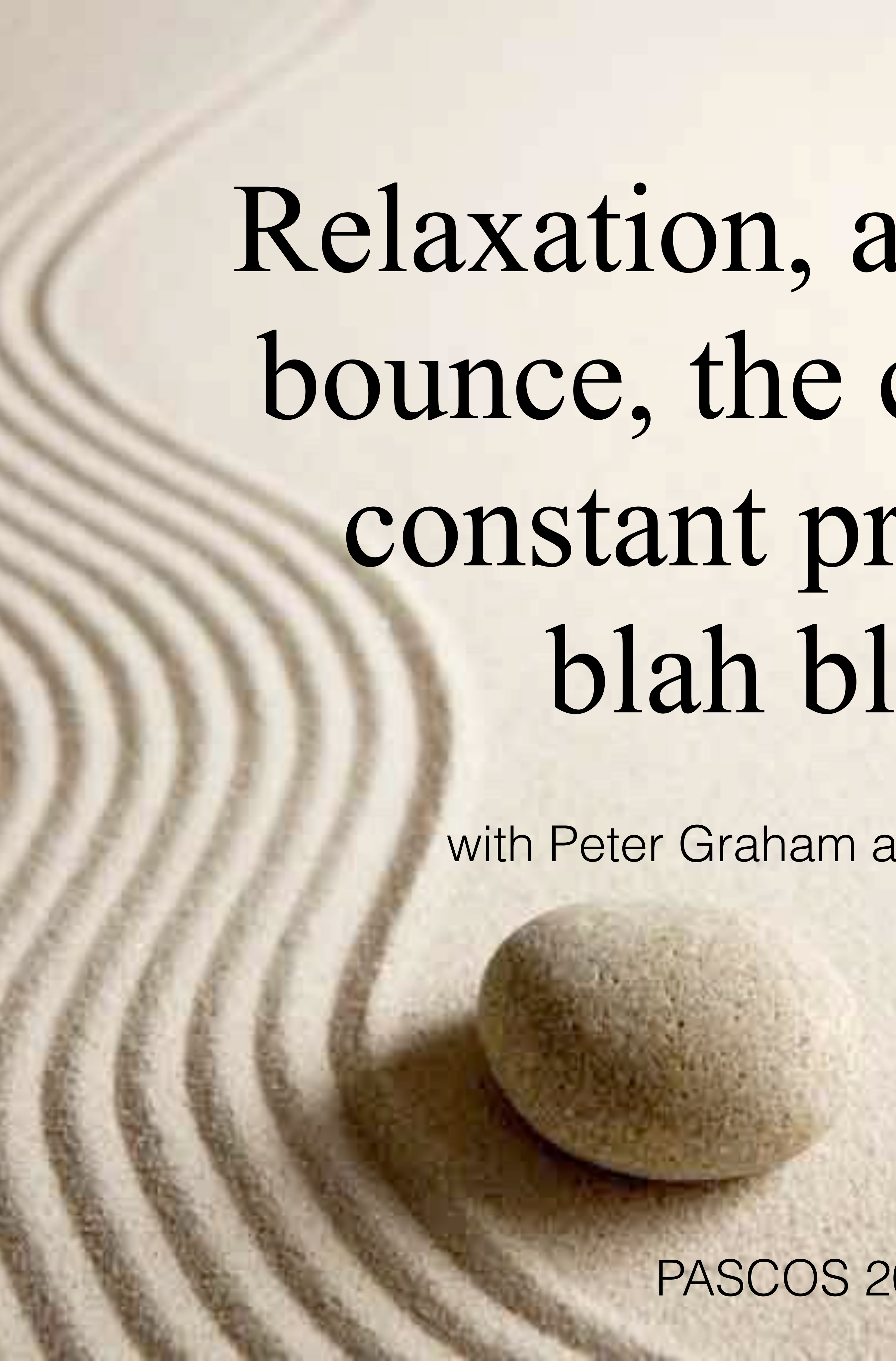


Relaxation, a non-singular bounce, the cosmological constant problem, and blah blah blah

with Peter Graham and Surjeet Rajendran

PASCOS 2017, Madrid

Fine-tuning in the Standard Model

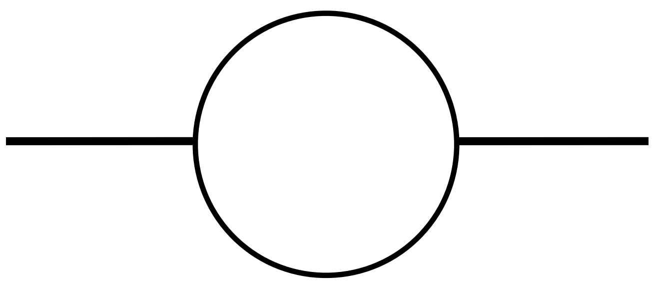
The Higgs mass and the cosmological constant are sensitive to the ultraviolet. Explanation of scales?

Approach	m_h^2	Λ
Symmetry	LHC?	Looks bad (Ramanism?)
Anthropics	atomic principle — heavy handed?	Weinberg (other parameters fixed)
Relaxation	yes, but should solve the CC too.	Getting there…

Warm up: The Hierarchy "Problem"

The Higgs mass in the standard model is sensitive to the ultraviolet.

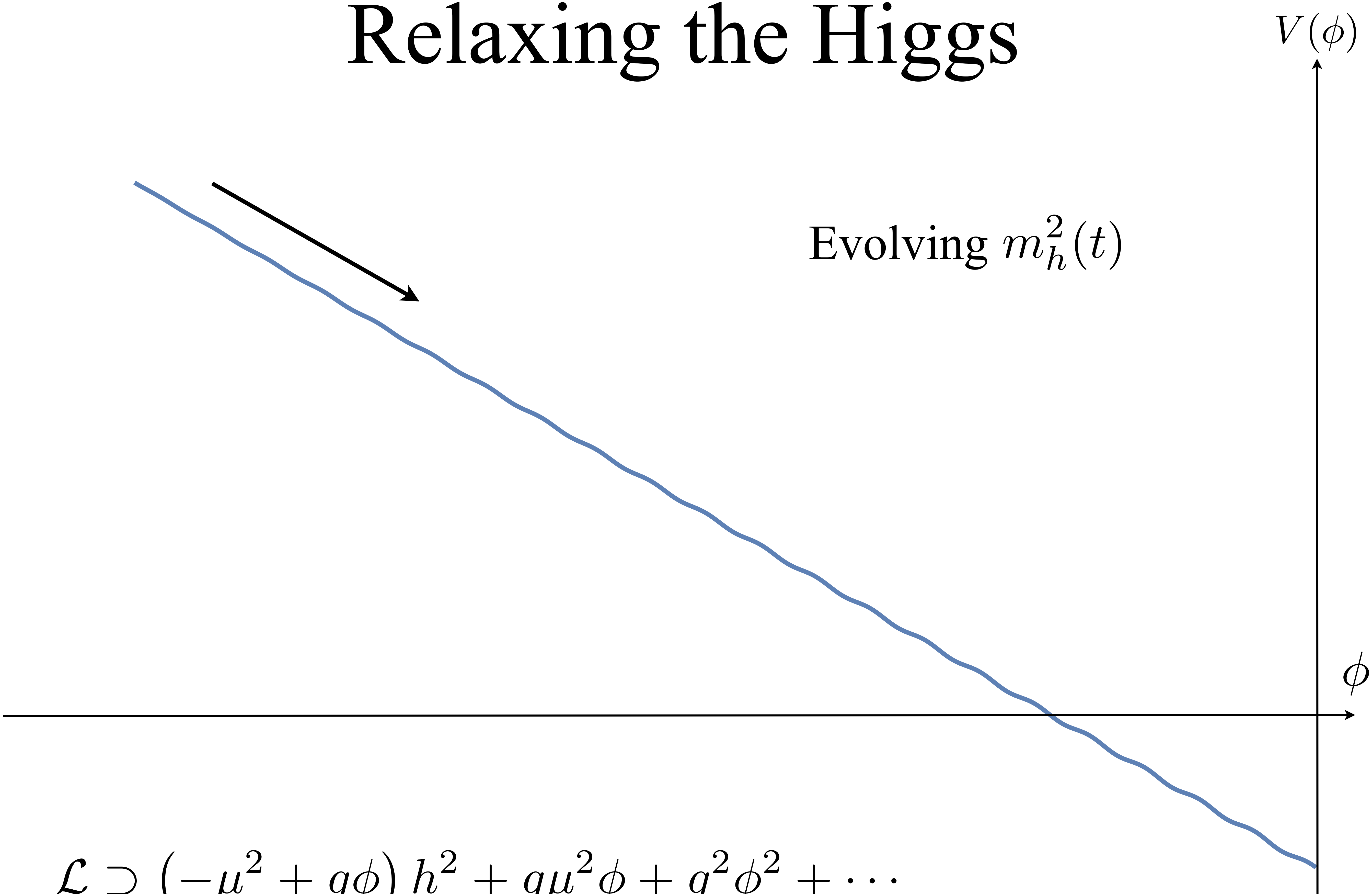
Instead of a new symmetry or new dynamics realized at the electroweak scale to cut off loops,
(SUSY, composite Higgs, EOFT)



Can a small EW scale come from dynamical relaxation?

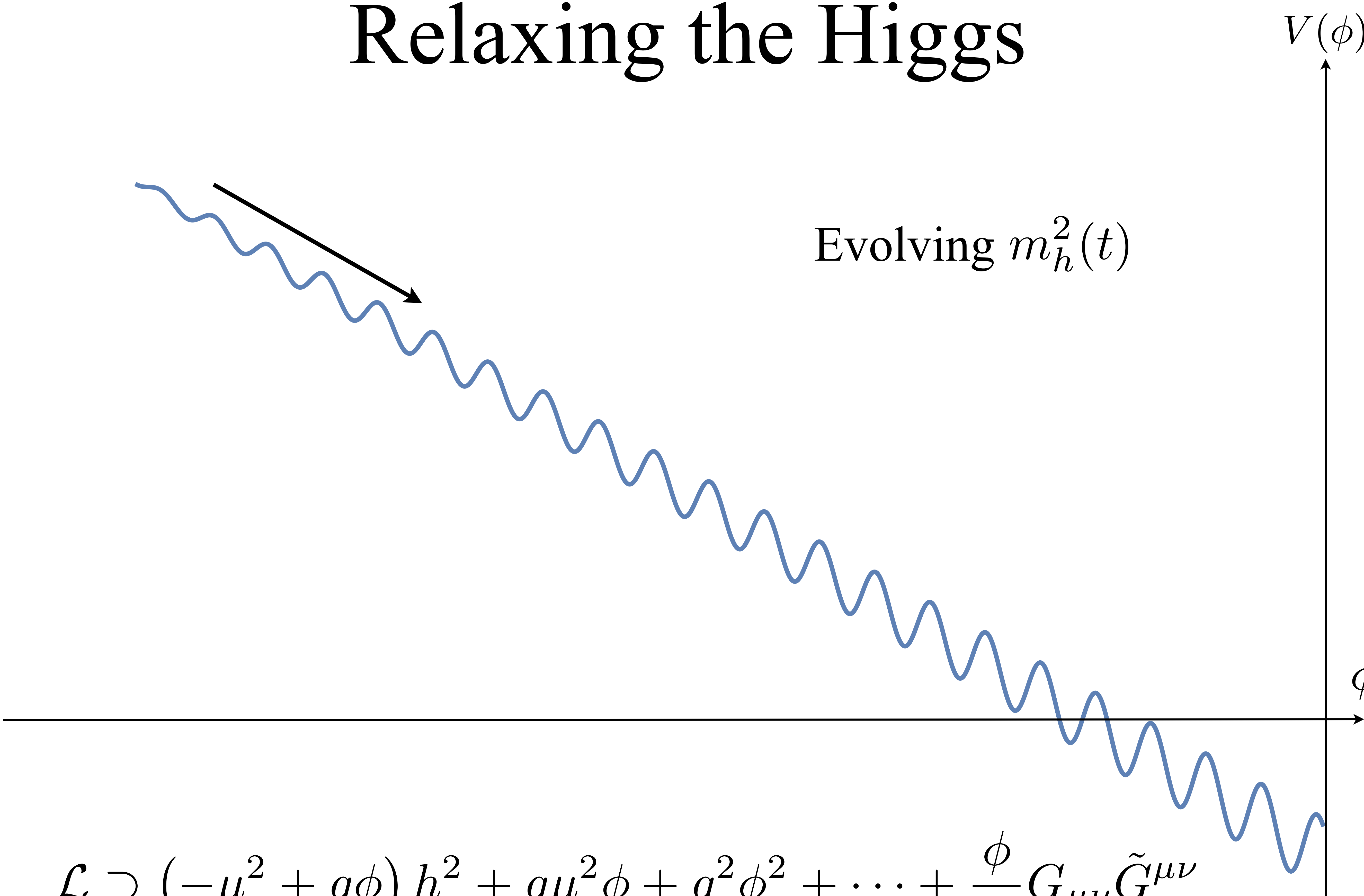
$$m_h^2(t)$$

Relaxing the Higgs



$$\mathcal{L} \supset \left(-\mu^2 + g\phi\right) h^2 + g\mu^2\phi + g^2\phi^2 + \cdots$$

Relaxing the Higgs



$$\mathcal{L} \supset \left(-\mu^2 + g\phi\right) h^2 + g\mu^2\phi + g^2\phi^2 + \cdots + \frac{\phi}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Higgs vev and the Periodic Potential

Barrier height (axion potential) can be approximated in the chiral Lagrangian (2 flavors):

$$V_{\text{axion}}\left(\frac{\phi}{f}\right) \sim \Lambda^4 \mathcal{F}\left(\frac{\phi}{f}\right) \sim f_\pi^2 m_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\phi}{2f}}$$

Around the normal EW scale:

$$\Lambda^4 \sim 4\pi f_\pi^3 m_u \sim 4\pi f_\pi^3 y_u \langle h \rangle$$

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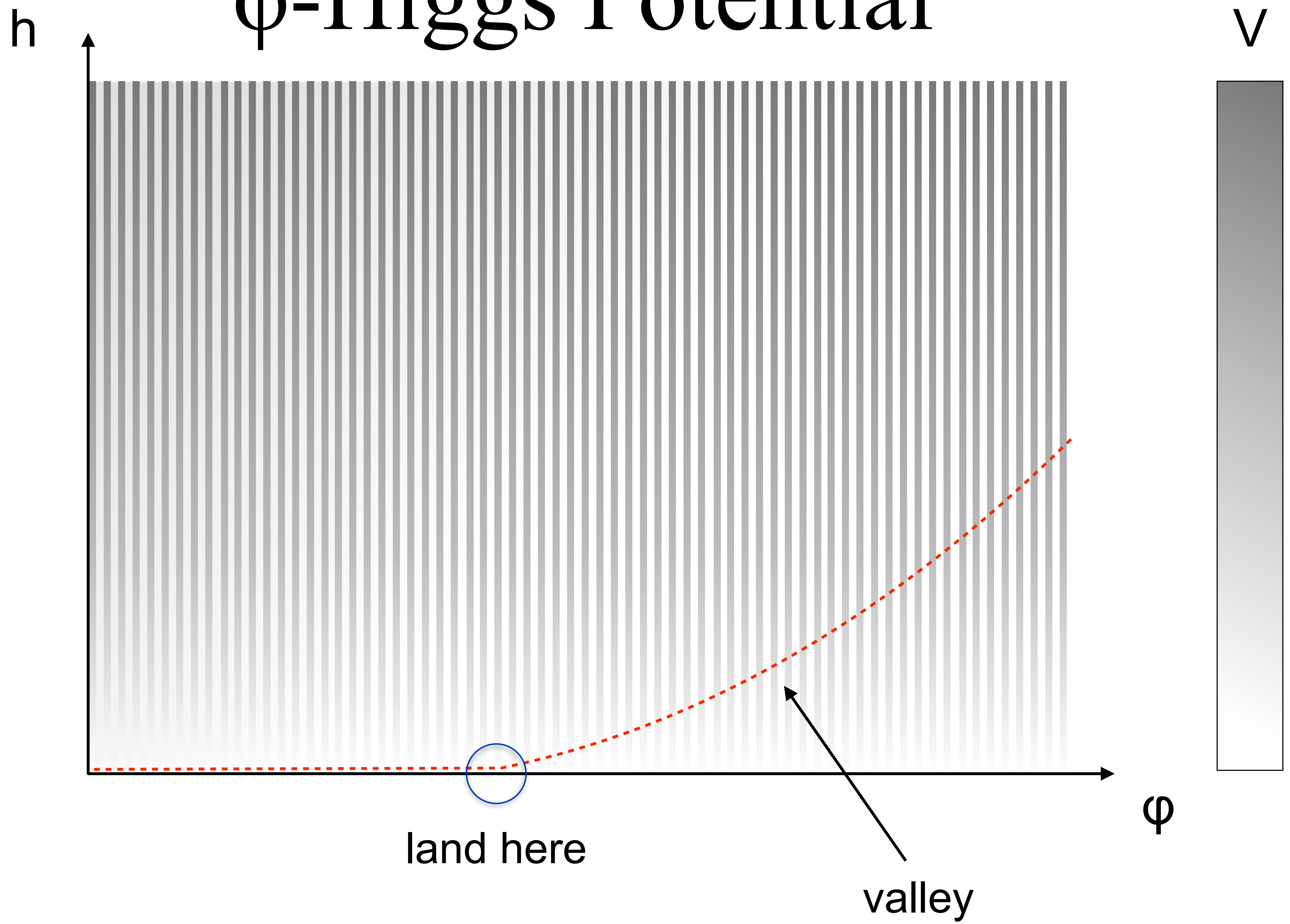
Higgs vev grows barriers and STOPS evolution

φ-Higgs Potential



Solve Strong CP

Use the axion - just stop it earlier!

Relaxion **relaxes Higgs vev to much smaller values.**
A second rolling increases the Higgs vev to the weak scale (perhaps from inflation).

Ask Me Later

Slope much smaller: $gM^2 f \sim \theta\,\Lambda^4$

$$\mathcal{L} \supset (-M^2 + \kappa\sigma^2 + g\phi)|h|^2 + gM^2\phi + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

e.g., waterfall field from inflation

Can couple to one of many operators in the standard model — will contribute to the Higgs via loops!

Bound on cutoff!

$$M^6 < \theta \, \frac{\Lambda^4 M_{\rm pl}^3}{f}$$

or

$$M < 100 \text{ TeV} \left(\frac{\theta}{10^{-10}} \right)^{\frac{1}{6}} \left(\frac{10^{10} \text{ GeV}}{f} \right)^{\frac{1}{6}}$$

For another time/talk: Thermal Relaxion

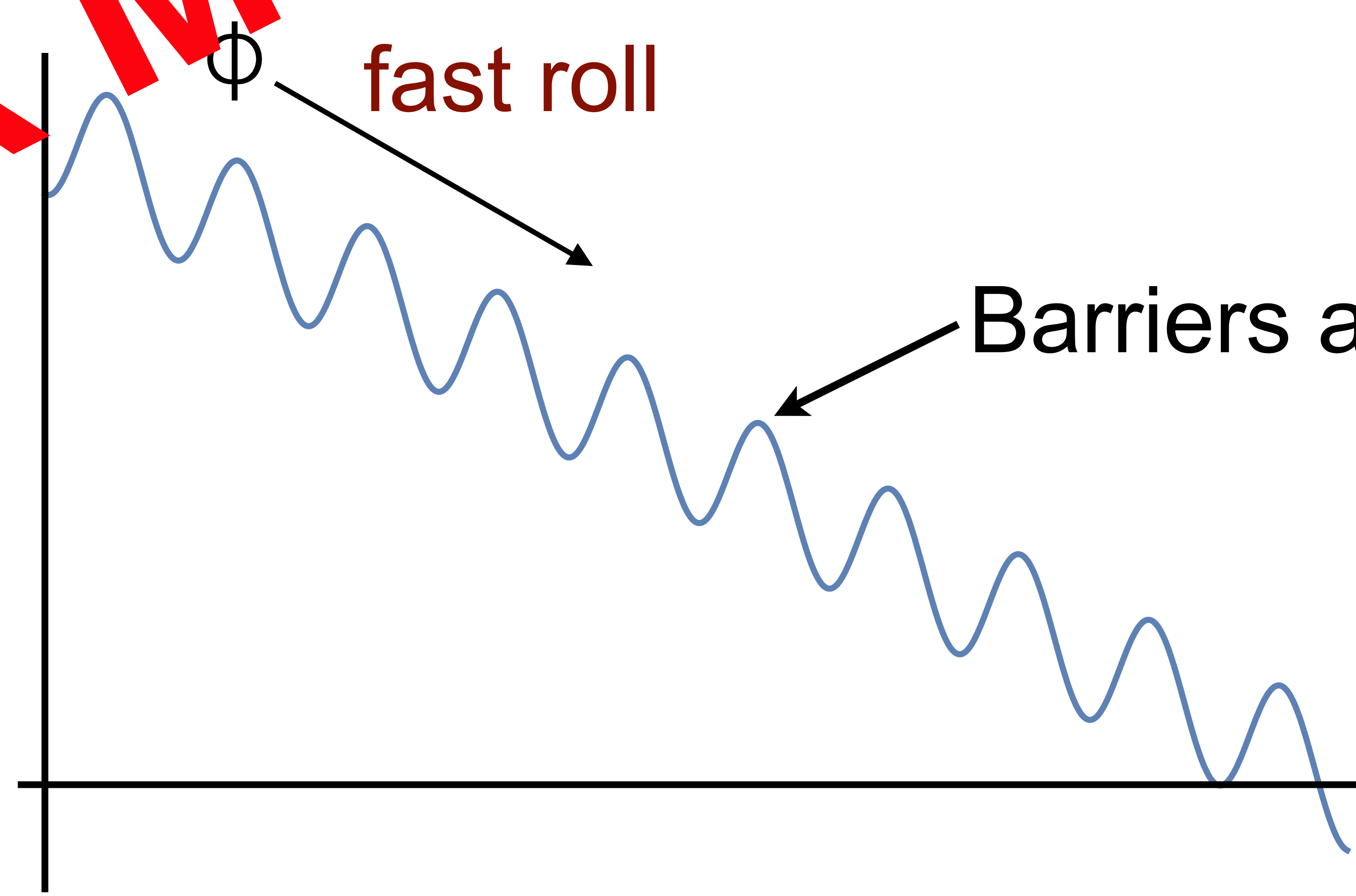
Constant Barriers, Variable Dissipation?

same structure: $\mathcal{L} \supset \left(-\mu^2 + g\phi\right) h^2 + g\mu^2\phi + g^2\phi^2 + \cdots + \frac{\phi}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$

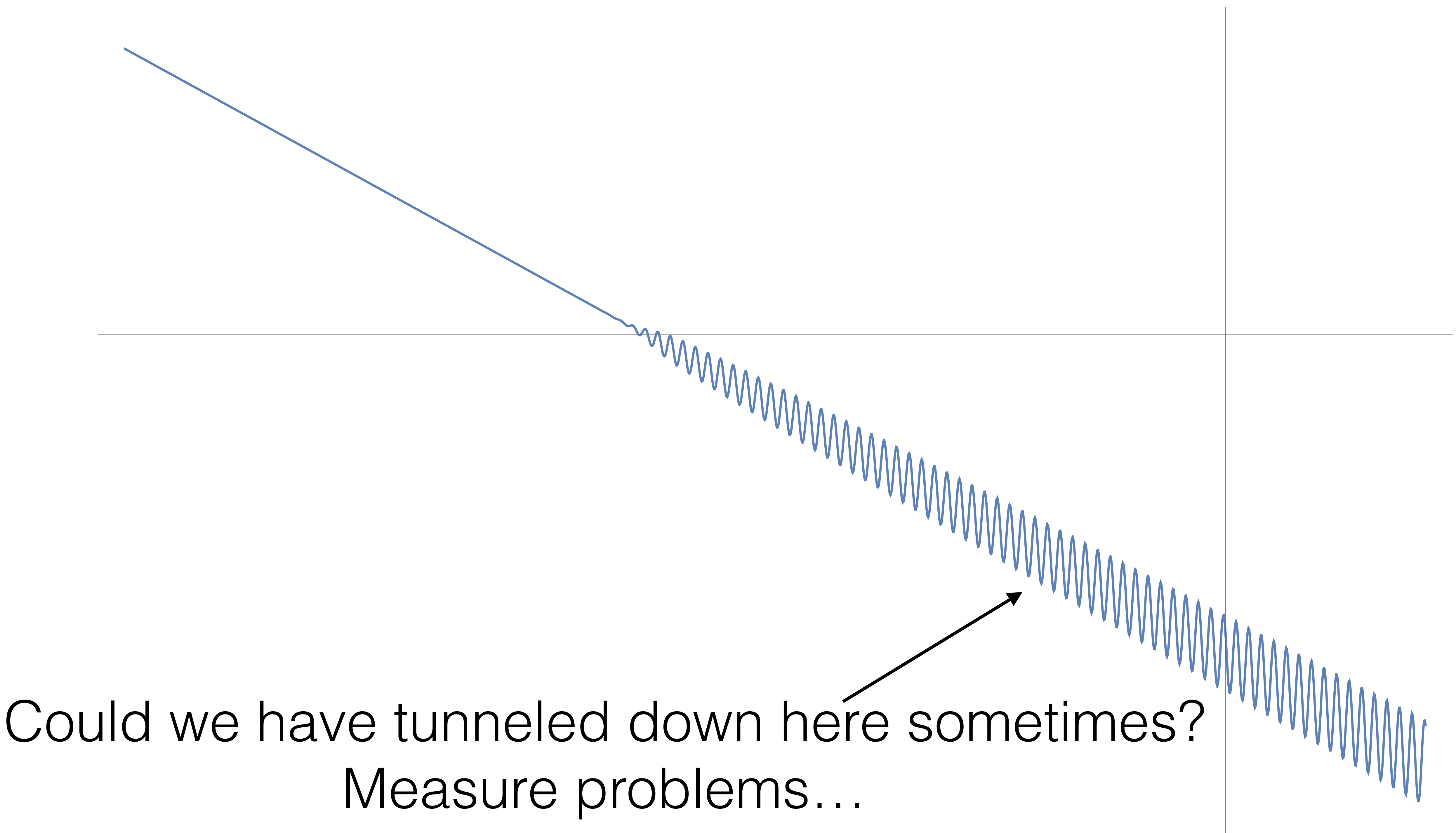
not QCD

Ask Me Later

- Take initial value of Φ so that $m_h^2 < 0$
- Φ fast rolls. Cold universe, dominated by Φ rolling.
- $m_\Phi > m_h$ => Φ decays to higgs



Many vacua consistent with anthropic CC?

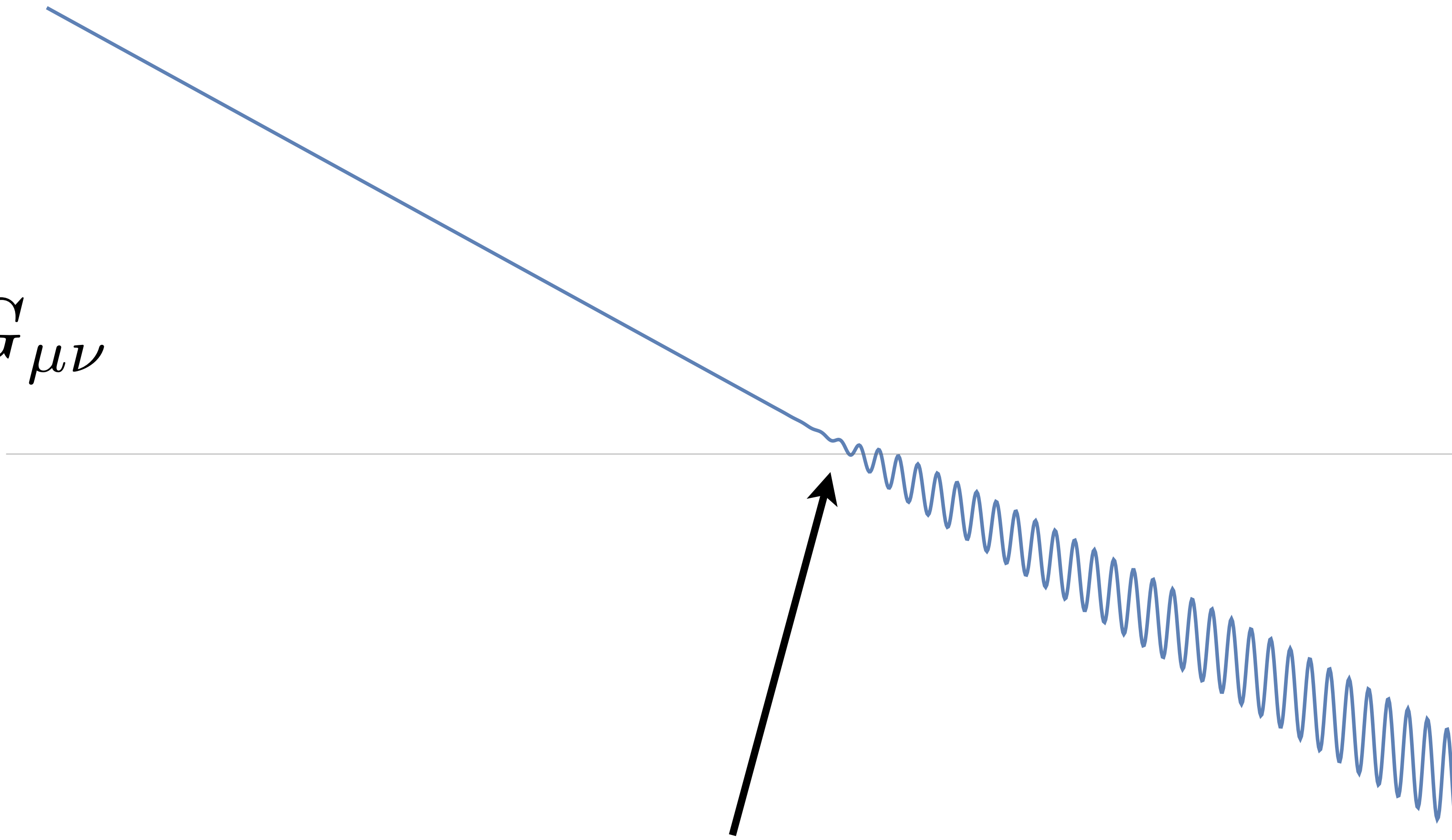


Rest of Talk

- CC solution a la Abbott
- The Born Again Universe
- To Do

The Abbott Model

$$\mathcal{L} = \Lambda + g^3\phi + \frac{1}{g^2}G^{\mu\nu}G_{\mu\nu}$$



$R \sim H^2 \sim (10^{-43}\ \mathrm{GeV})^2$

Sensing the CC

$$\mathcal{L} \supset \Lambda + g^3\phi + \text{Trigger that couples to gravity (only thing that sees the CC)}$$

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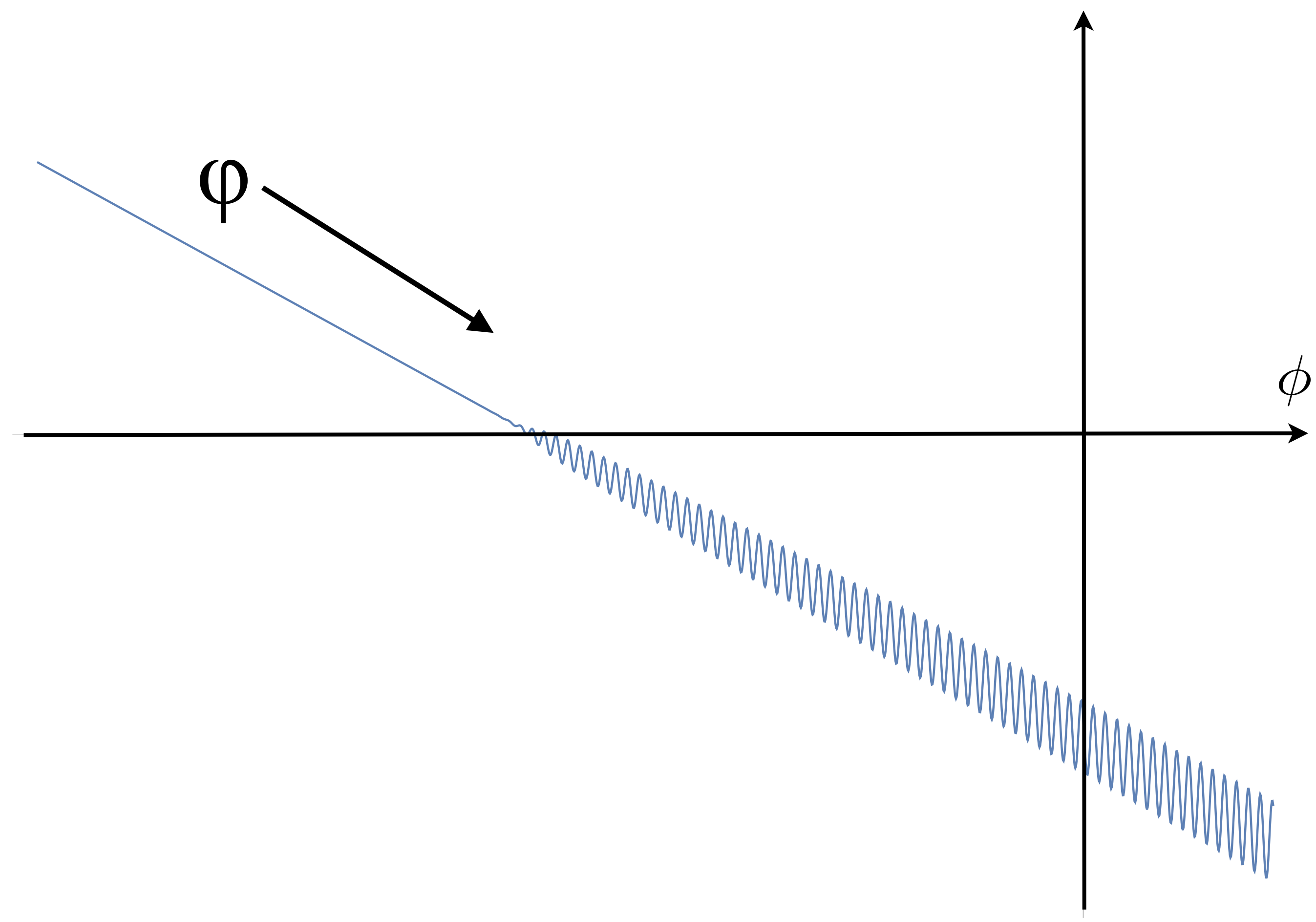
Universal Gravitation:
Only sensitive to cosmological constant when it dominates.



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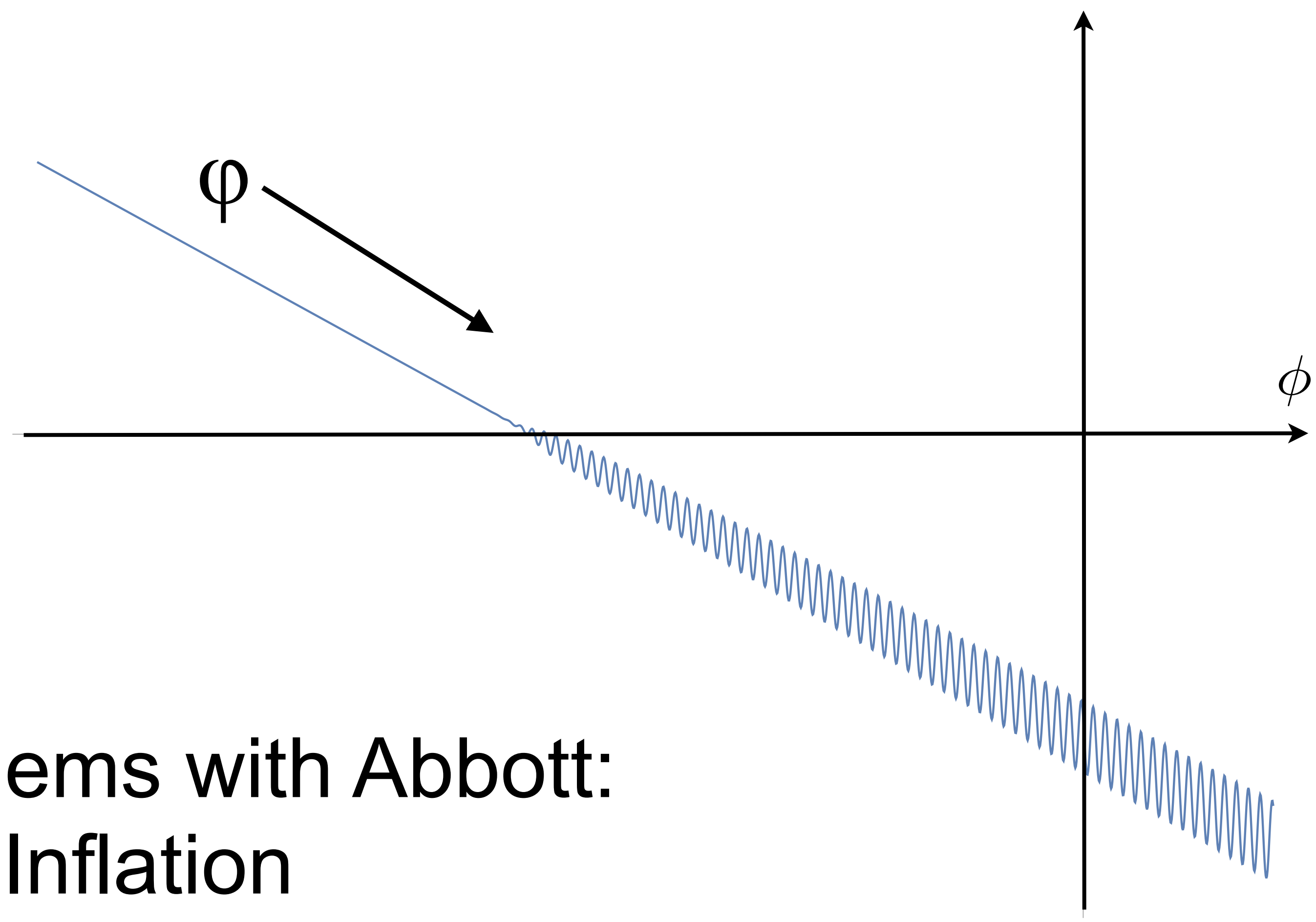

Two Problems with Abbott:

- Eternal Inflation
- Universe Empty

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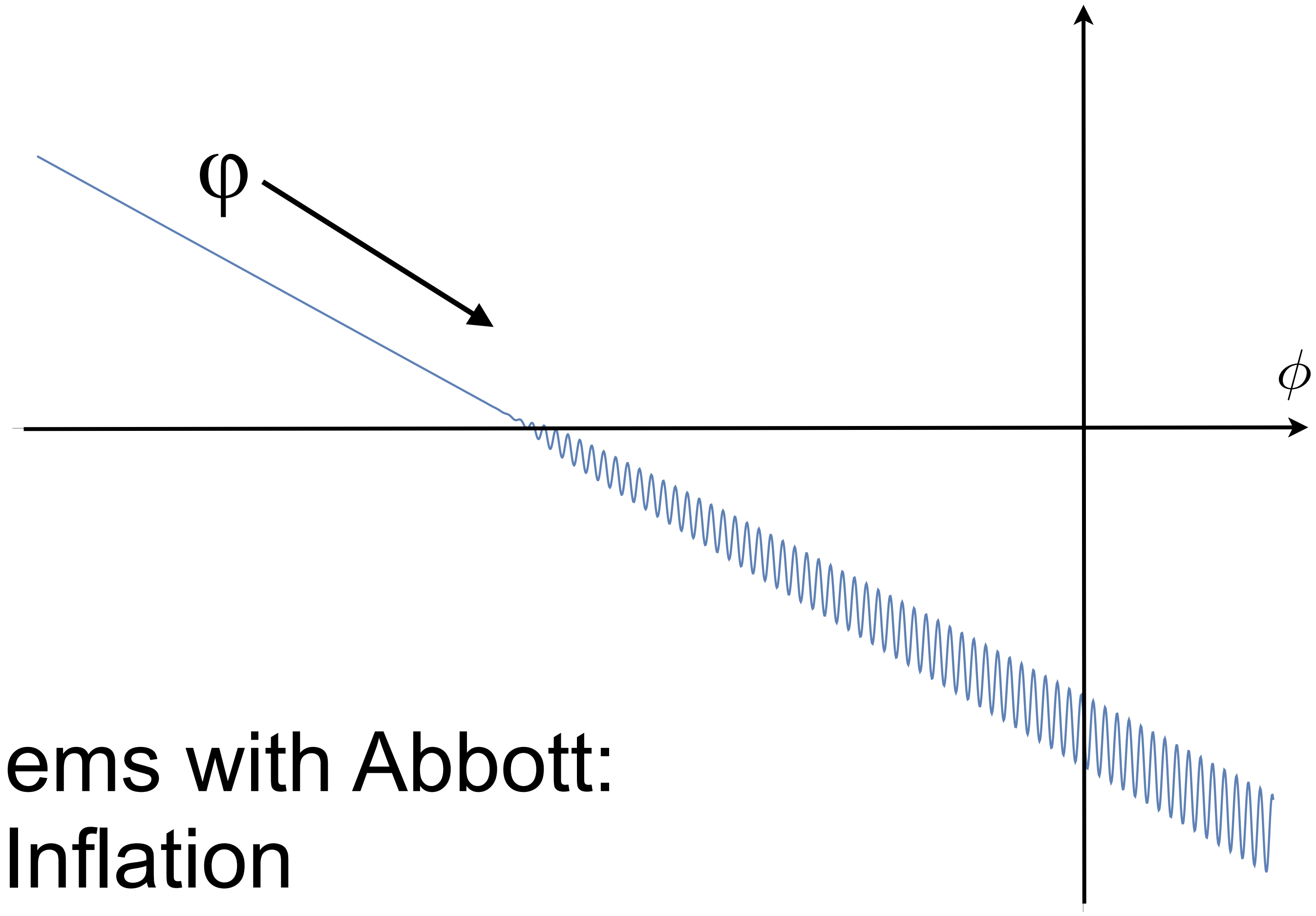


Two Problems with Abbott:
- Eternal Inflation
- Universe Empty

How do we reheat?

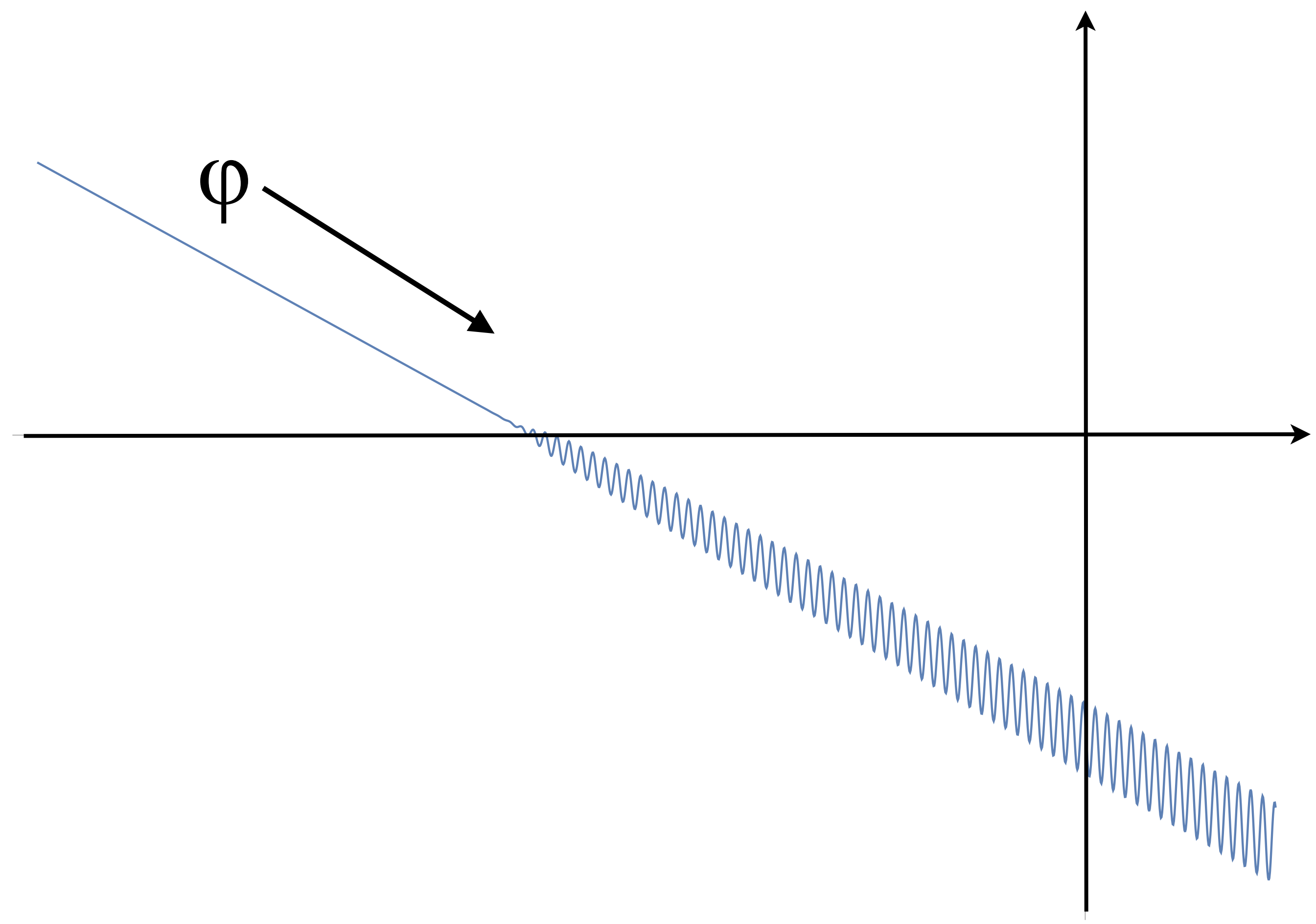
Reheating Abbott

Can we simply inject energy?

Would violate the Null Energy Condition (NEC):

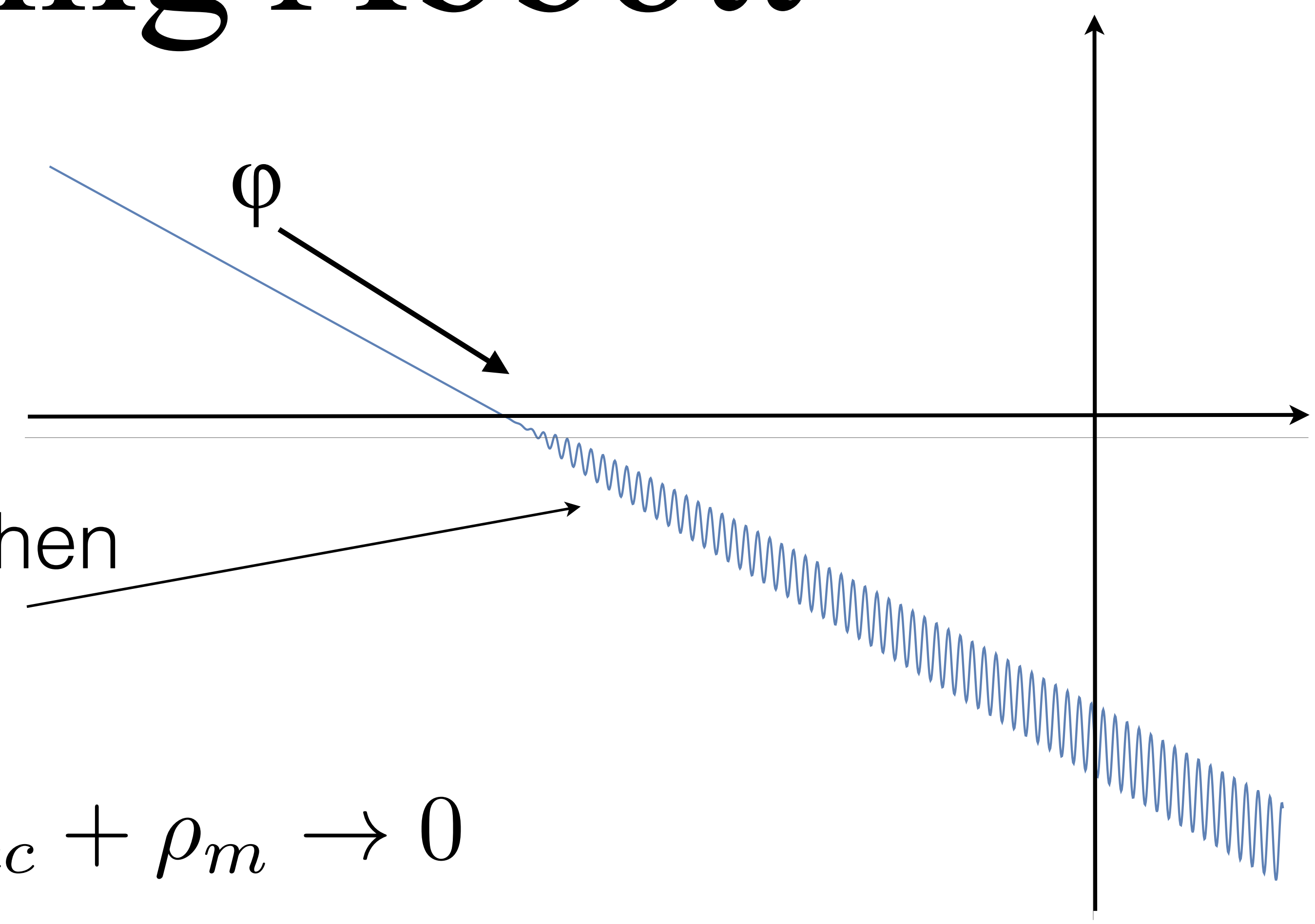
$$n^\mu n^\nu T_{\mu\nu} < 0$$

$$\rho + p < 0$$



May be true (see Alberte, et al, 2016), but so far only a very low-energy EFT and not clear how to UV complete.

Reheating Abbott



What if scanning stops when
$\Lambda_{eff} \sim$ - meV^4

$$H^2 \sim \rho_{cc} + \rho_m \to 0$$

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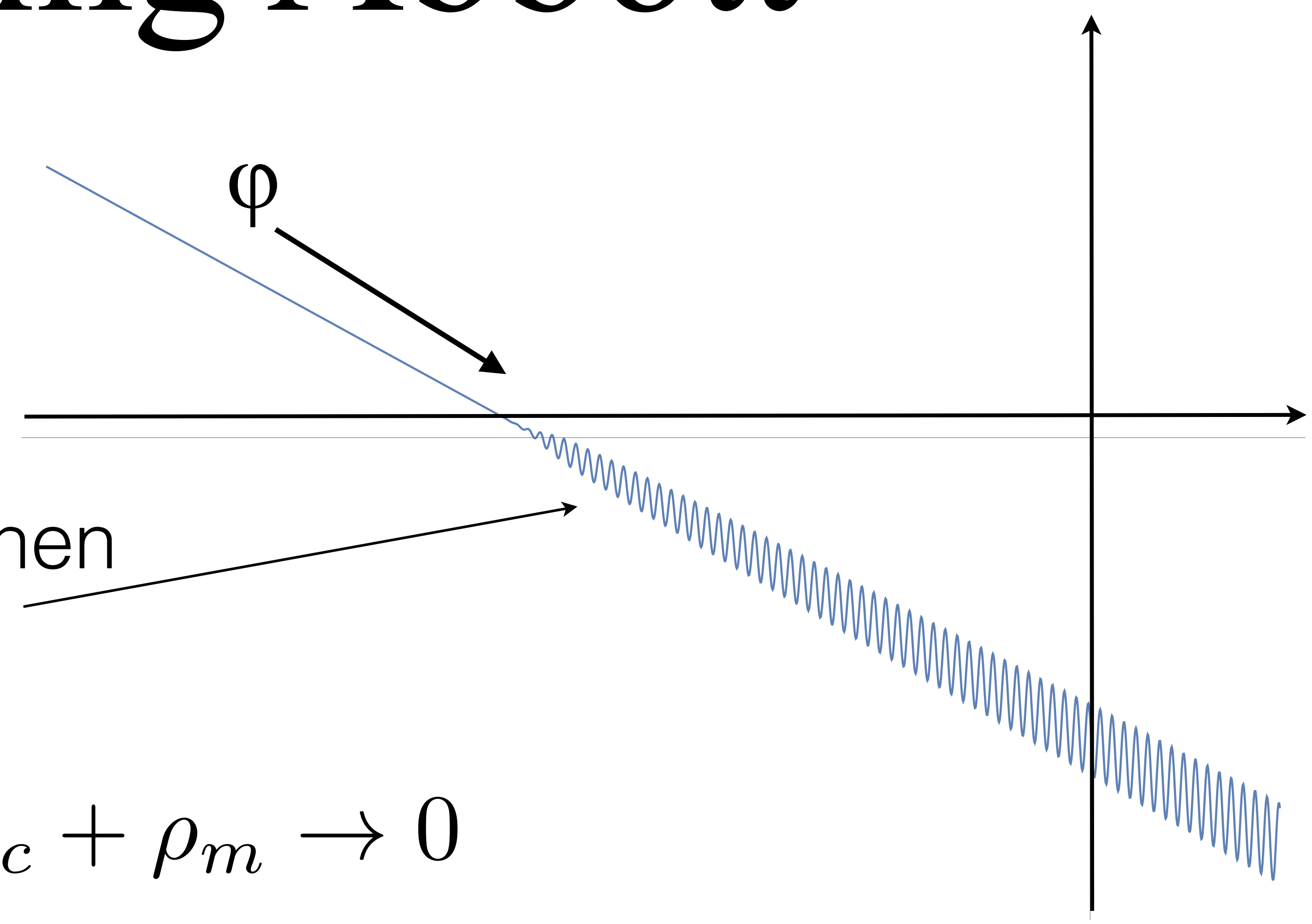

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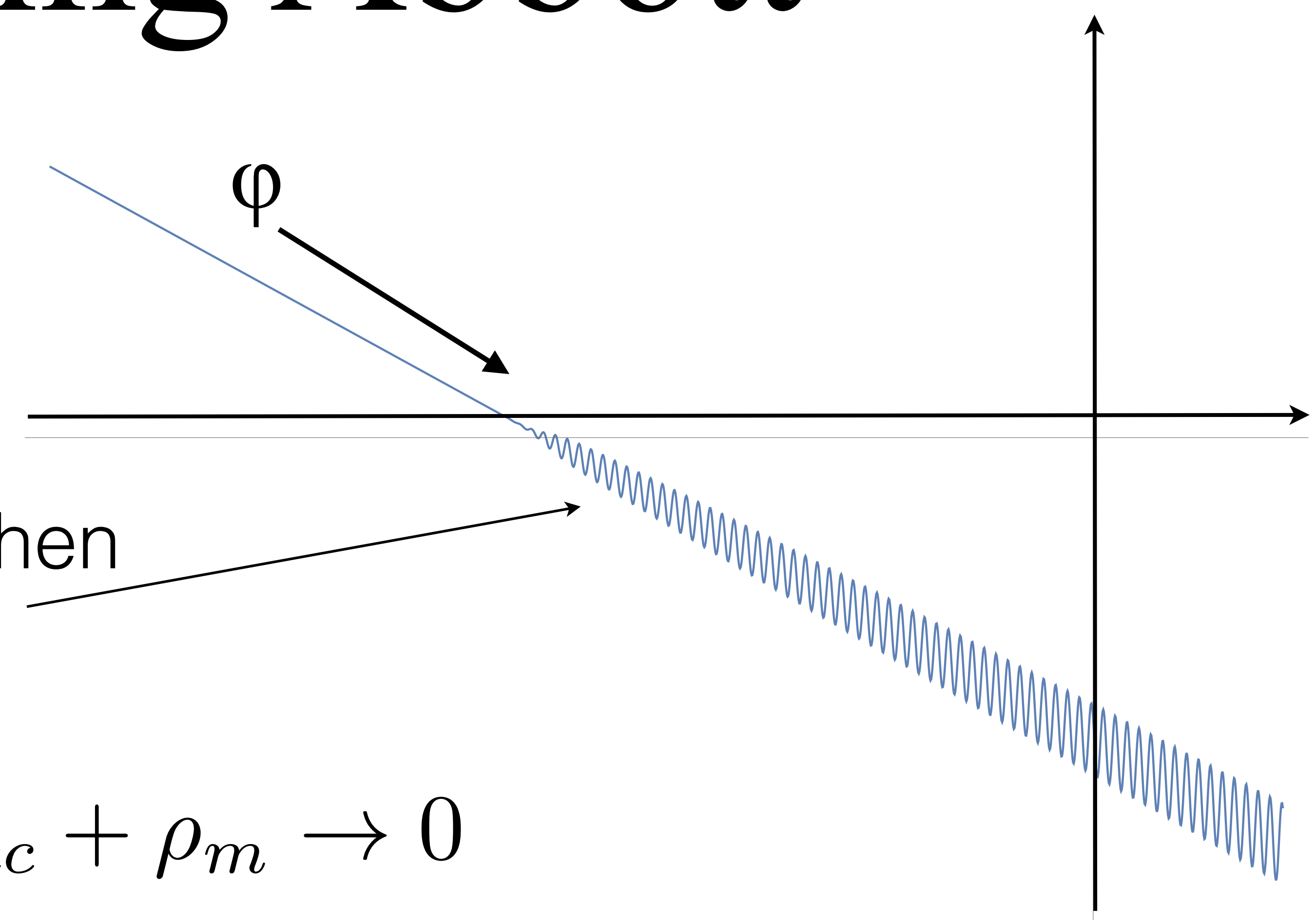

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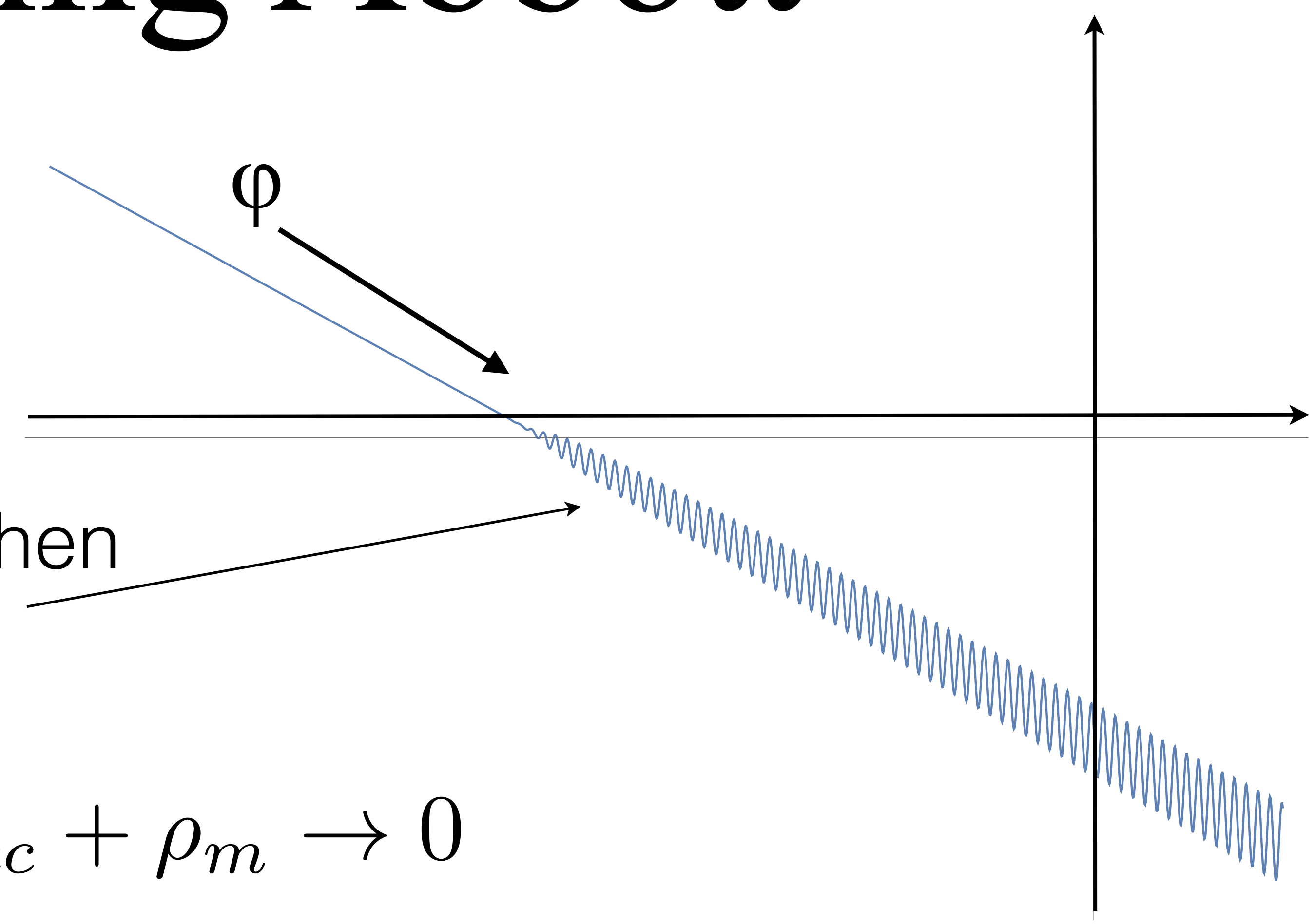

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Crunching universe gets hot.

Tantalizing Possibility: Make the Universe undergo a calculable, non-singular bounce (But how???).

Sets small Λ_{eff}. Reheats to hot big bang.

Advantage of this solution

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

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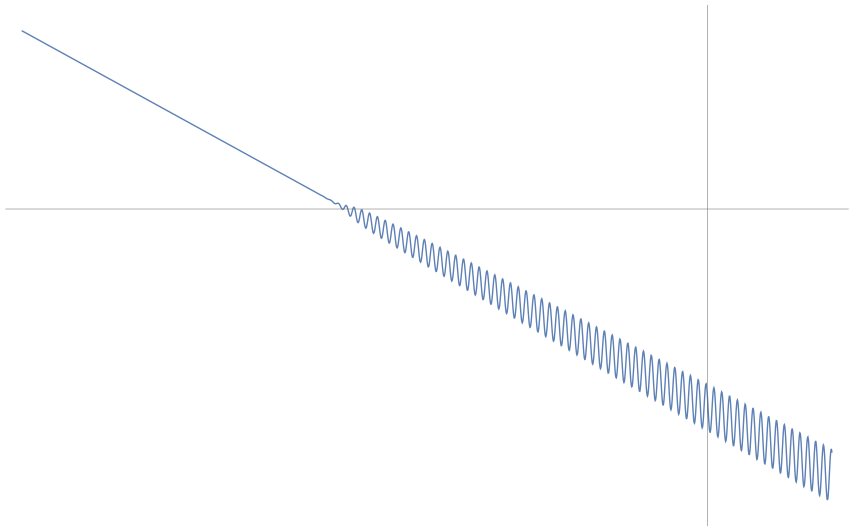
↓

Weinberg?

$$V, V' \approxeq 0$$

Like Relaxion = Large Number of Minima



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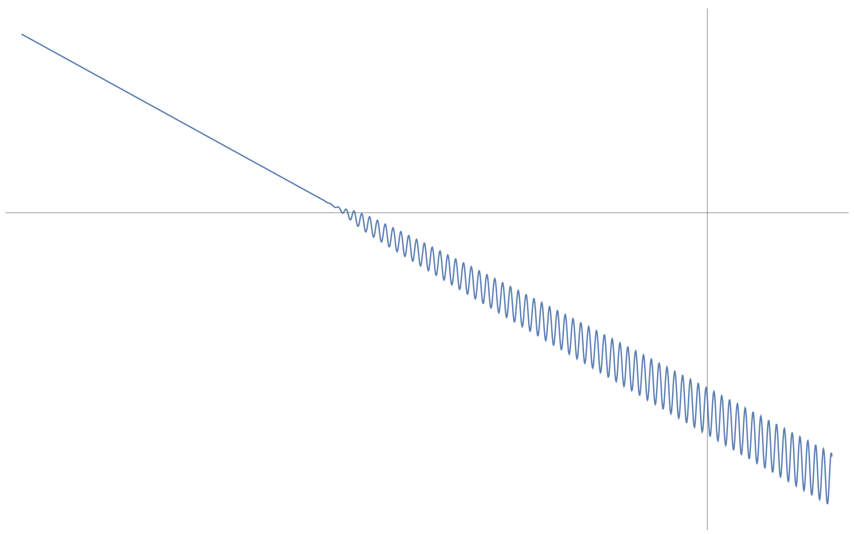

Phase Transitions?

Tuned in SM vacuum!

Reheating => hot universe, vacuum energy goes up, cools back to same tuned vacuum.

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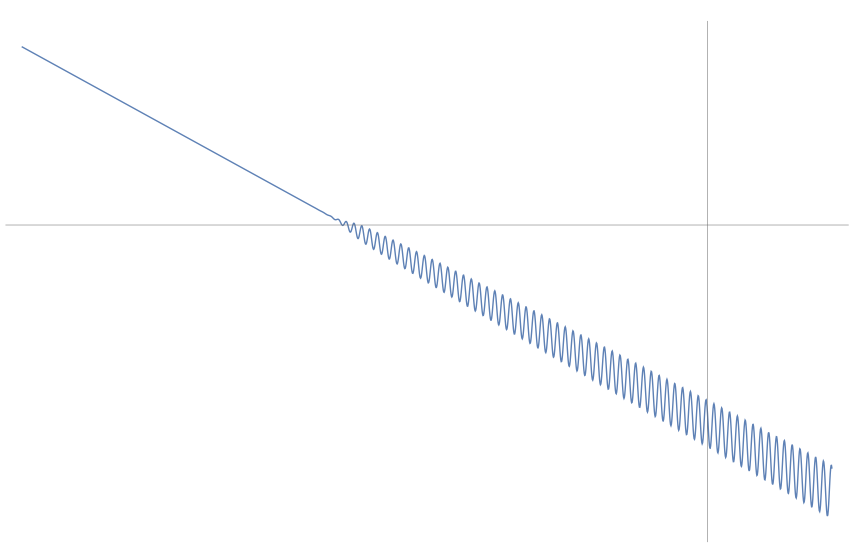

Phase Transitions?

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Reheating => hot universe, vacuum energy goes up, cools back to same tuned vacuum.

Bounce + Tuning?

$$\tau_{tuning} >> \tau_{bounce} \sim H_0^{-1}$$

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

Observable: Likely leads to changing Λ_{eff} today.

Bouncing

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What matter causes a bounce?

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e.g., in a flat, homogenous, isotropic universe (FRW).

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$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho \qquad \frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\left(\rho + 3p\right)$$

$$\frac{\ddot{a}}{a} - \left(\frac{\dot{a}}{a}\right)^2 = -\frac{12\pi}{3}G\left(\rho + p\right)$$

$$\text{At minimum, } \dot{a} = 0, \ddot{a} > 0 \implies \rho + p < 0$$

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Matter needs to violate the Null Energy Condition

Energy Conditions

Null Energy Condition

Perfect Fluid: $\rho + p > 0$, or $w > -1$

Potential Issue: Negative energy states - vacuum decay

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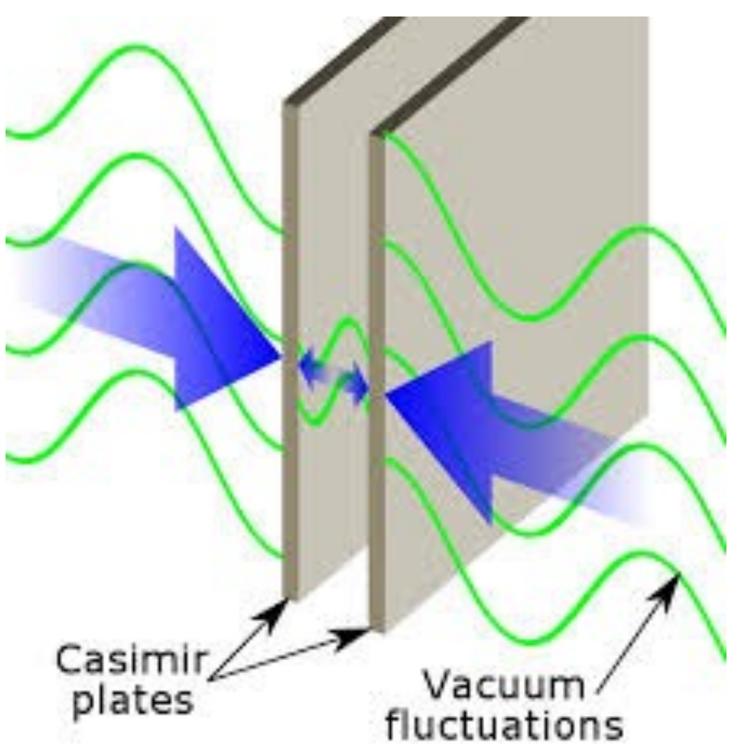
Known Stable Violations

Local Casimir energy



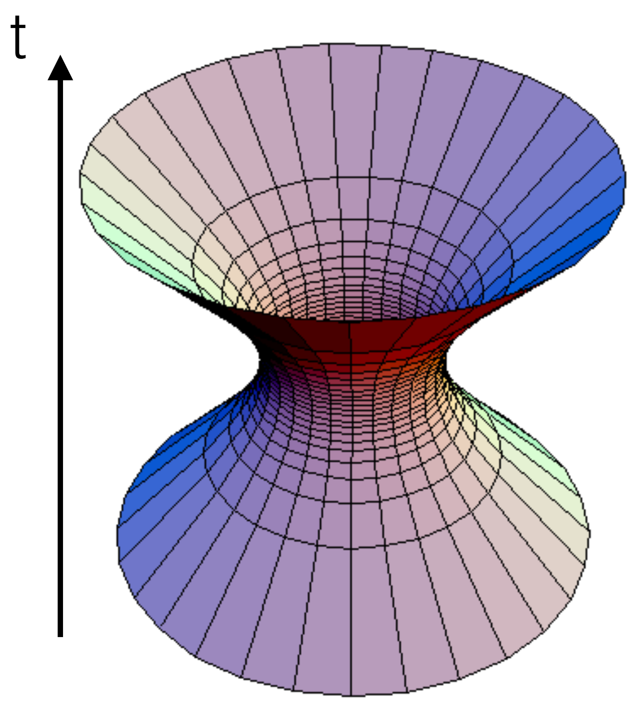
Casimir in compact dimensions.

$$T_{\mu\nu} = \rho \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix}$$

Bouncing Cosmology

Generic Requirement?

Need congruence of converging geodesics to diverge



Raychaudhuri's Equation for $\hat{\theta} = \hat{g}_{\mu\nu}\nabla^\mu U^\nu$

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

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

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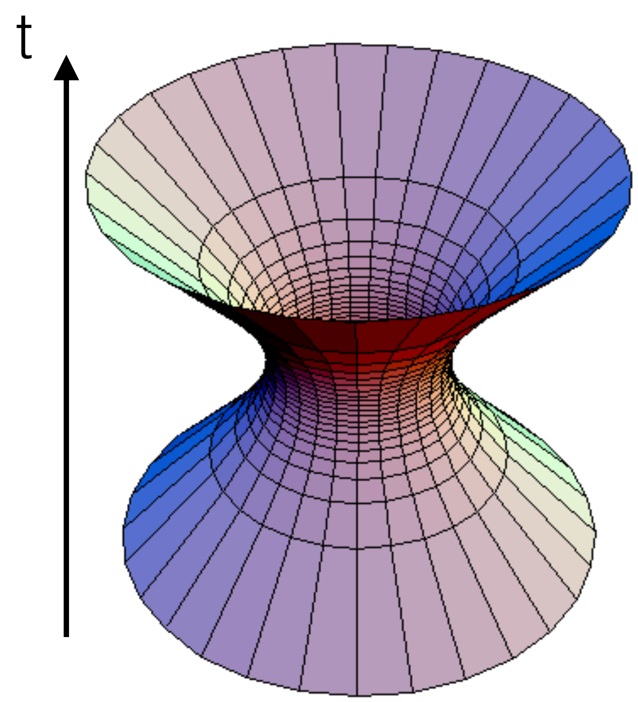

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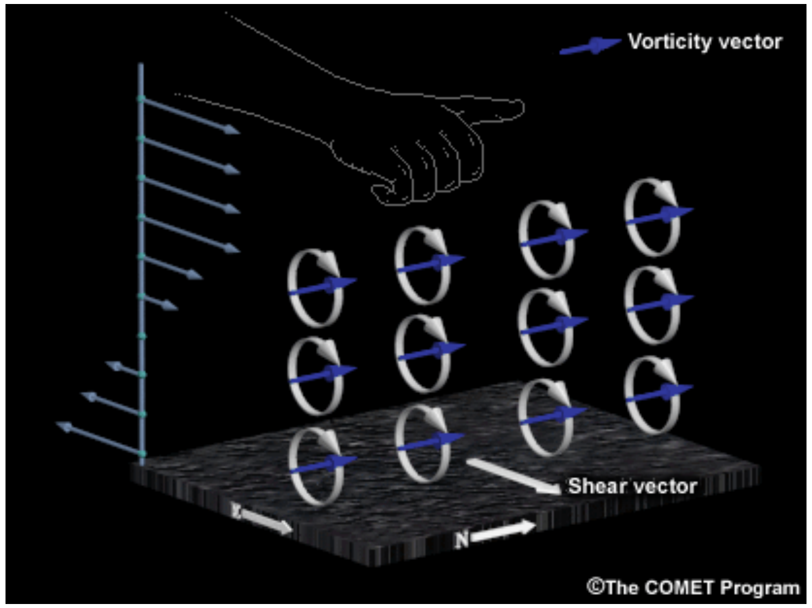
$$\text{Divergence} \implies \frac{d\hat{\theta}}{d\lambda} > 0$$

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

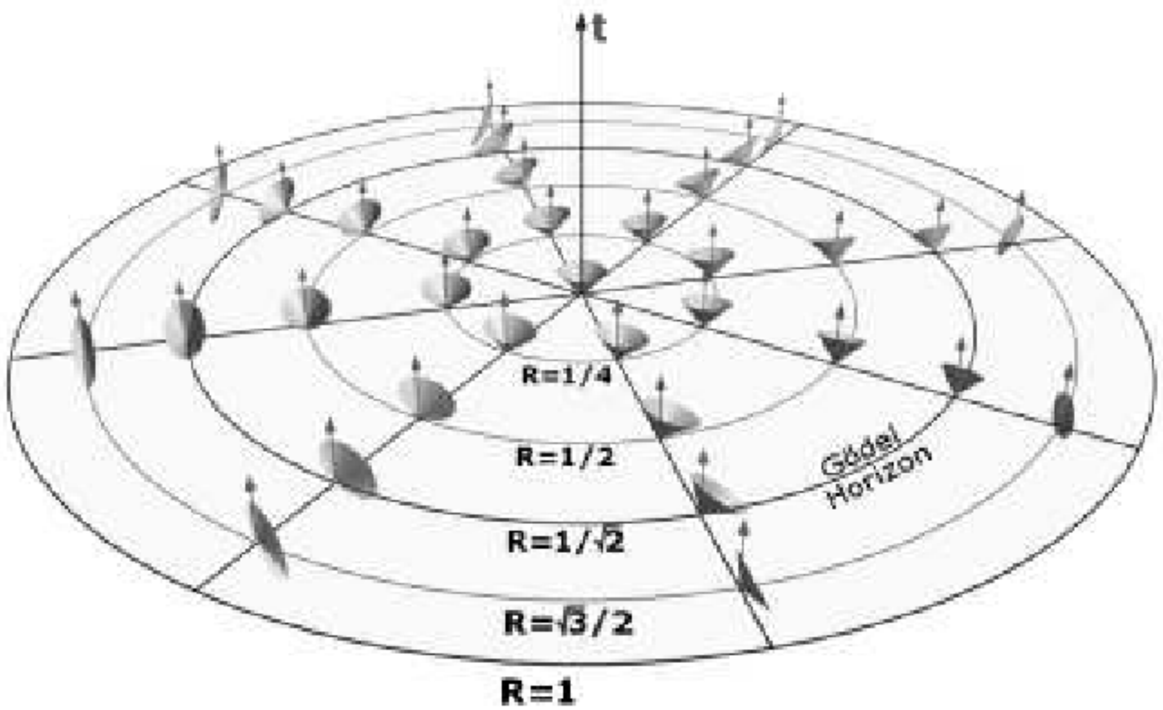
↓ Null Energy Violation

↓ Vorticity



Godel Metric

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



Cosmological Constant + Spinning Dust

Stationary Universe: Gravity balanced by rotation

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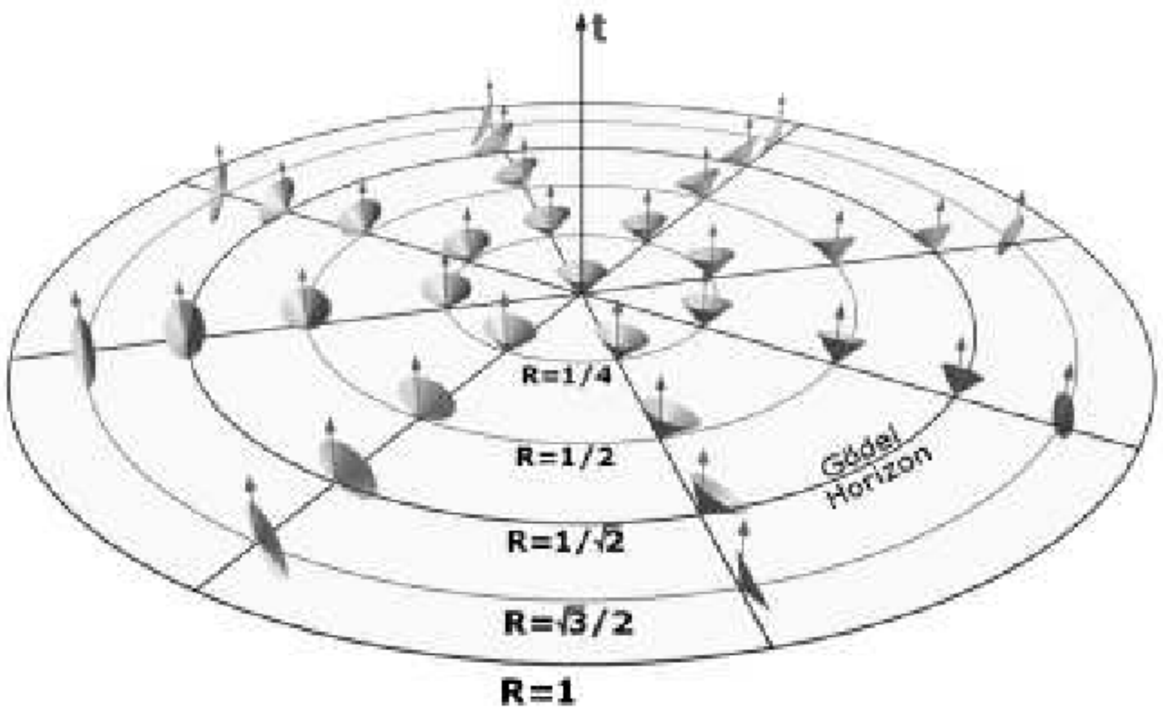

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Closed time-like curves for r > 1(bad?)

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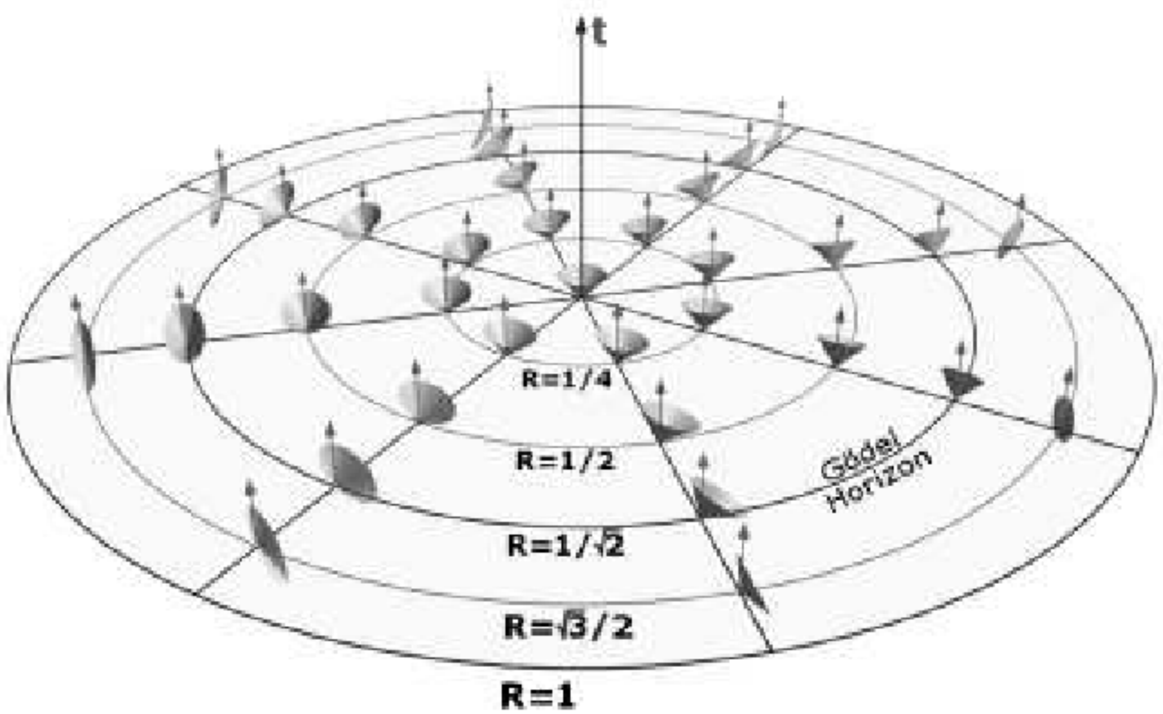

Cosmological Constant + Spinning Dust

Stationary Universe: Gravity balanced by rotation

Closed time-like curves for $r > 1$(bad?)

Put vorticity in compact dimensions!

Our Ansatz

Space-Time: $R^4 \times T^3$

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

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↓ FRW

↓ Standard Compact

↓ **Vorticity**
Geodesics along R^4 forced to move into extra-dimensions

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Geodesics along R^4 forced to move into extra-dimensions

Plug in a bouncing *a(t)* and use Einstein's Equations to get energy-momentum tensor

The E-M Tensor

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

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

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

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Consider 4D geodesic during bounce. NEC?

for $\frac{b^2 a''}{a}, \epsilon^2 \ll 1 \quad => \quad T_{tt} + \frac{T_{xx}}{a\left(t\right)^2} \approx M_7^5\left(\frac{\epsilon^2}{2b^2} - 2\frac{\ddot{a}}{a}\right)$

Vorticity combats gravity, for weak bounce

The E-M Tensor

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

NEC not violated for 4D geodesics

However, violated for geodesics into extra-dimensions

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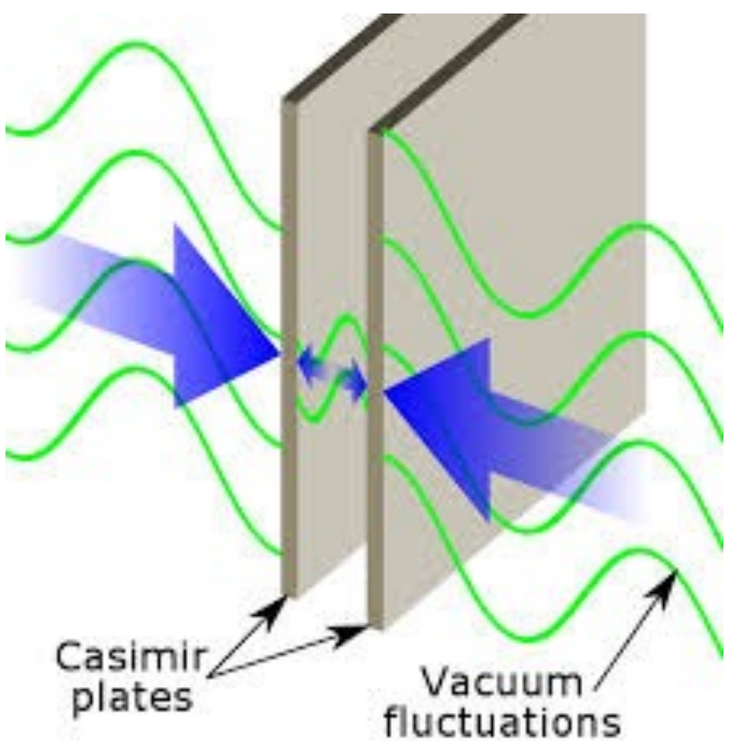
NEC not violated for 4D geodesics

However, violated for geodesics into extra-dimensions

But can use Casimir!



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

Can shown: T_M preserves Dominant Energy Condition

Don't know: Microphysics of T_M

The Effective Theory

$$g^{(7)}_{AB} = (det\Phi)^{-1/5} \left(\begin{array}{cc} g_{\mu\nu} + B^a_\mu B^b_\nu \Phi_{ab} & B^c_\mu \Phi_{ca} \\ B^c_\nu \Phi_{cb} & \Phi_{ab} \end{array} \right)$$

$$G^{(7)}_{tt} = G_{tt} - \frac{1}{4}((\partial_\theta B^{\phi 1}_t)^2 + (\partial_\theta B^{\phi 2}_t)^2) - (B^{\phi 1}_t \partial^2_\theta B^{\phi 1}_t + B^{\phi 2}_t \partial^2_\theta B^{\phi 2}_t) + \cdots$$

$$G^{(7)}_{xx} = G_{xx} + \frac{a(t)^2}{4}((\partial_\theta B^{\phi 1}_t)^2 + (\partial_\theta B^{\phi 2}_t)^2) + \cdots$$

The Effective Theory

$$g_{AB}^{(7)} = (det\Phi)^{-1/5} \begin{pmatrix} g_{\mu\nu} + B_\mu^a B_\nu^b \Phi_{ab} & B_\mu^c \Phi_{ca} \\ B_\nu^c \Phi_{cb} & \Phi_{ab} \end{pmatrix}$$

$$G_{tt}^{(7)} = G_{tt} - \frac{1}{4}((\partial_\theta B_t^{\phi 1})^2 + (\partial_\theta B_t^{\phi 2})^2) - (B_t^{\phi 1} \partial_\theta^2 B_t^{\phi 1} + B_t^{\phi 2} \partial_\theta^2 B_t^{\phi 2}) + \cdots$$

$$G_{xx}^{(7)} = G_{xx} + \frac{a(t)^2}{4}((\partial_\theta B_t^{\phi 1})^2 + (\partial_\theta B_t^{\phi 2})^2) + \cdots$$

Can Show: KK mode of source + KK gravivector = 4D null-energy violation!

Density of NEC violating particles - causes bounce

Instabilities pushed to KK scale - UV completed!

The Effective Theory

Massive vector coupled to background current:

$$\mathcal{L} \supset \frac{1}{g^2} F^{\mu\nu} F_{\mu\nu} - m^2 A^\mu A_\mu - e A_\mu J^\mu$$

E.O.M. give a vev for t-component of A, which produces NEC violation.

Source's microscopic description, however, may include large positive contributions to NEC to remove global violation.

To Do

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Experimental consequences of light field

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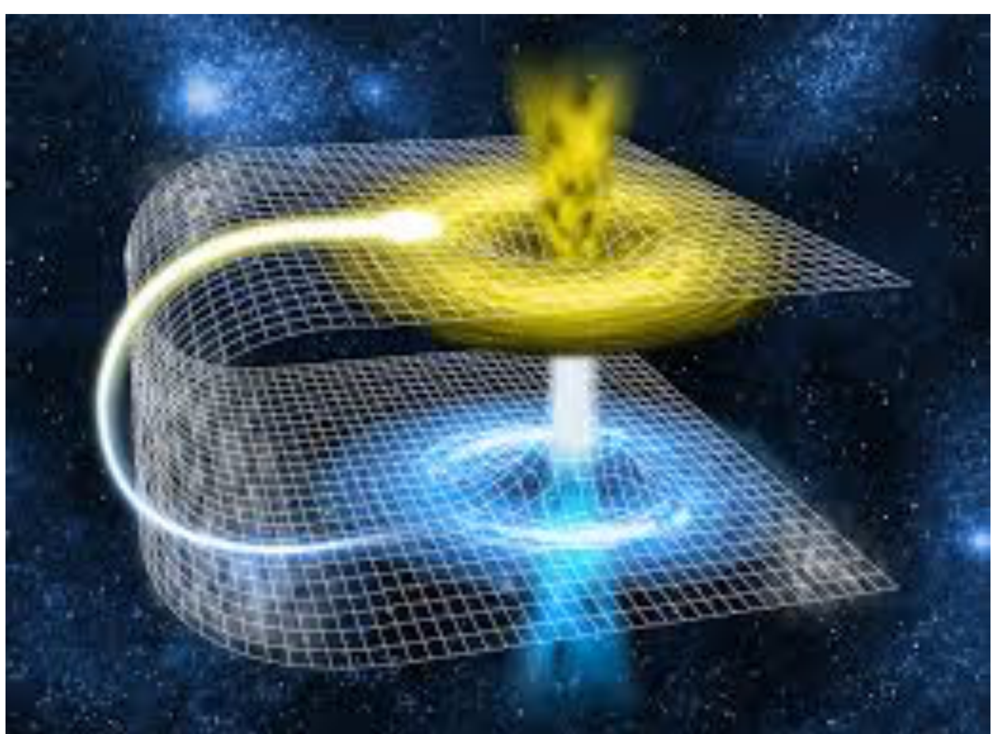


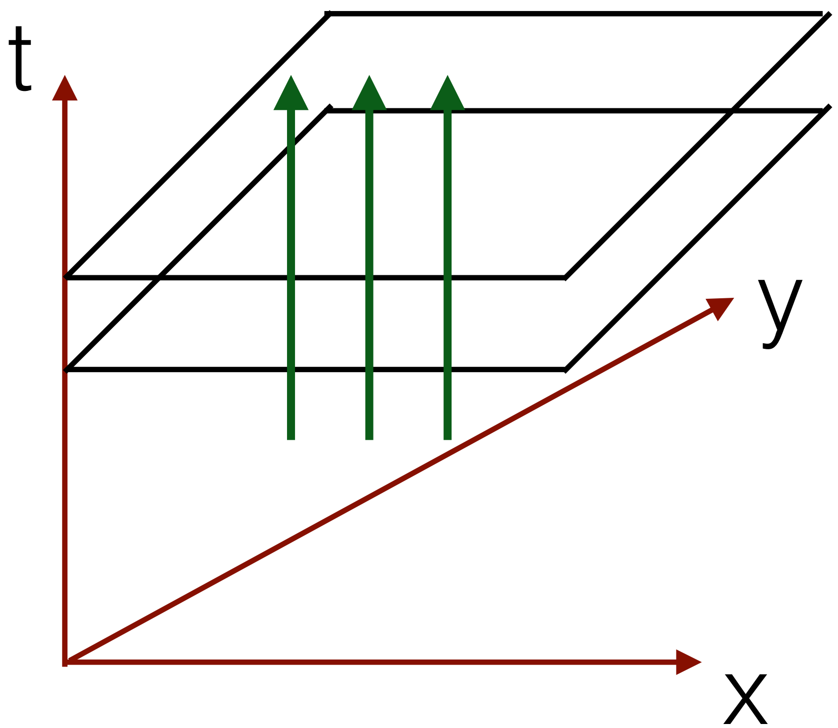
Similar construction provides **traversable wormholes**

Other consequences?

Thanks

“Ask Me Later” Slides

Why we needed NECv?
Global Hyperbolicity



Nice Time Slices: Time-like geodesic orthogonal to space-like hyper surface

Provides Cauchy Surface

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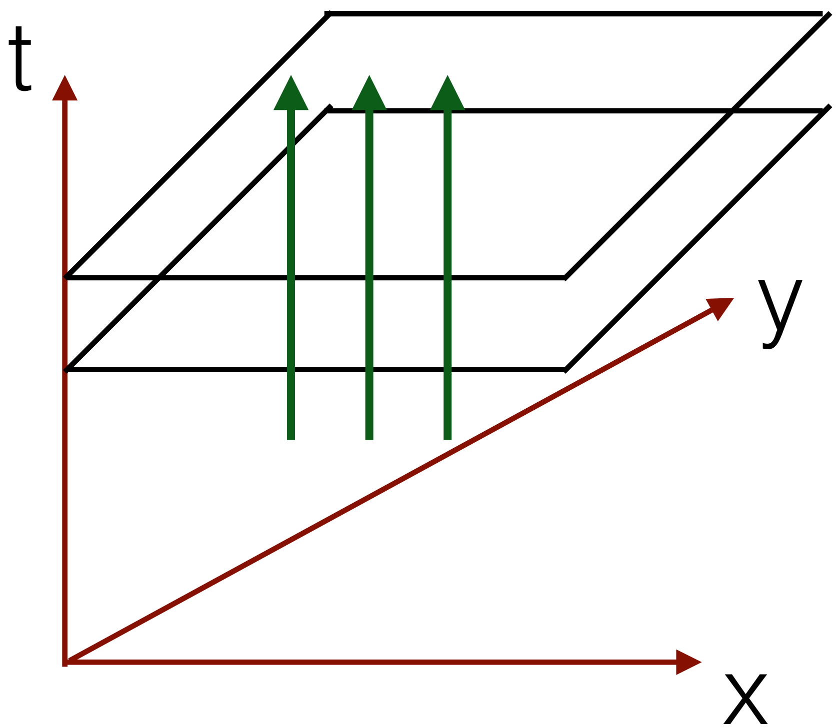

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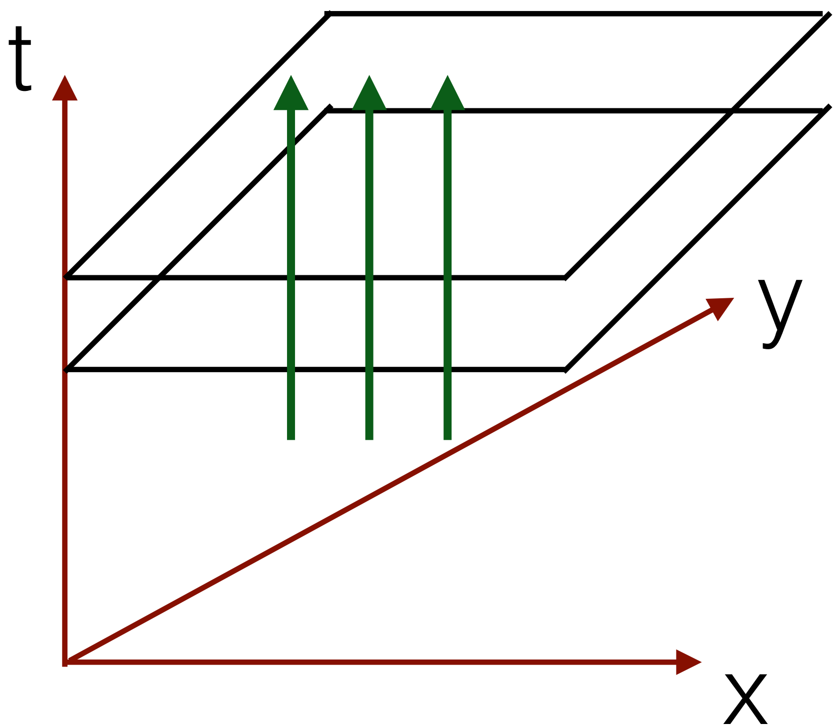

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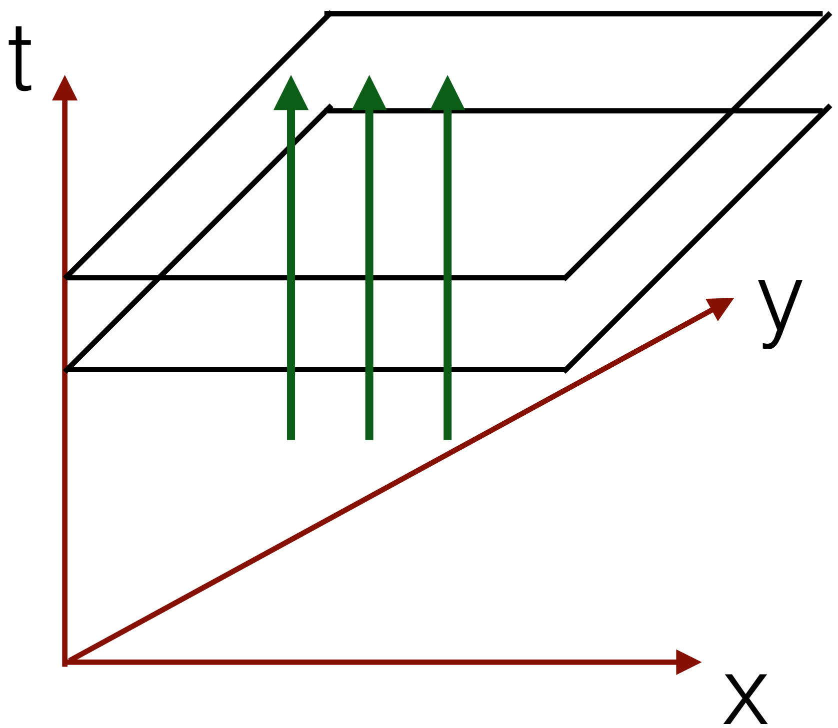

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Caveat: Time-like curves could generate time direction

The Loophole

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

Null Energy Condition safely violated in extra-dimensions
(Casimir Energies, Orientifolds)

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Null Energy Condition safely violated in extra-dimensions (Casimir Energies, Orientifolds)

Closed-time like curve requires long distance - cut off using compact extra-dimensions

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

The Loophole

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

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

Null Energy Condition in extra-dimensions

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

Metric clearly globally hyperbolic

Solve Strong CP

Use the axion - just stop it earlier!

Relaxion **relaxes Higgs vev to much smaller values.**
A second rolling increases the Higgs vev to the weak scale (perhaps from inflation).

Slope much smaller: $gM^2 f \sim \theta\,\Lambda^4$

$$\mathcal{L} \supset (-M^2 + \kappa\sigma^2 + g\phi)|h|^2 + gM^2\phi + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

e.g., waterfall field from inflation

Can couple to one of many operators in the standard model — will contribute to the Higgs via loops!

QCD breaks EW Symmetry and mixes with the Higgs — barriers even with positive squared mass

$$m_h^2 > 0 \qquad \Lambda^4 \sim 16\pi^2 \frac{f_\pi^6}{m_h^2} \frac{\mathrm{Tr}Y \, \mathrm{Det}Y}{\sum \mathrm{subDet}Y}$$

$$\Lambda^4 \sim 16\pi^2 \frac{f_\pi^6}{m_h^2} y_u$$

positive Higgs mass ~ 400 GeV produces a tiny enough barrier

For another time/talk: Thermal Relaxion

Constant Barriers, Variable Dissipation?

same structure:

not QCD

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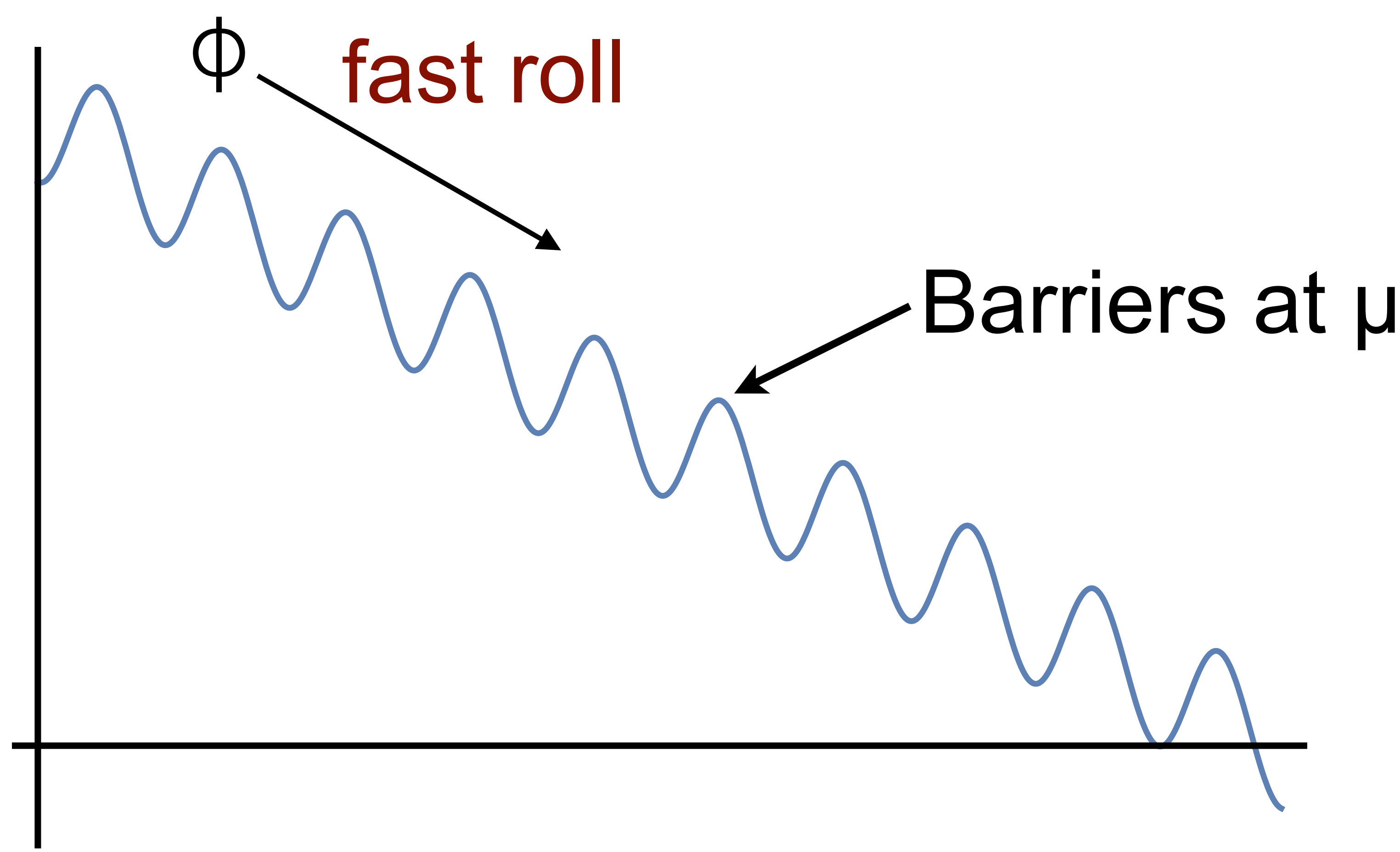
- Take initial value of Φ so that $m_h^2 < 0$
- Φ fast rolls. Cold universe, dominated by Φ rolling.
- $m_\Phi > m_h$ => Φ decays to higgs



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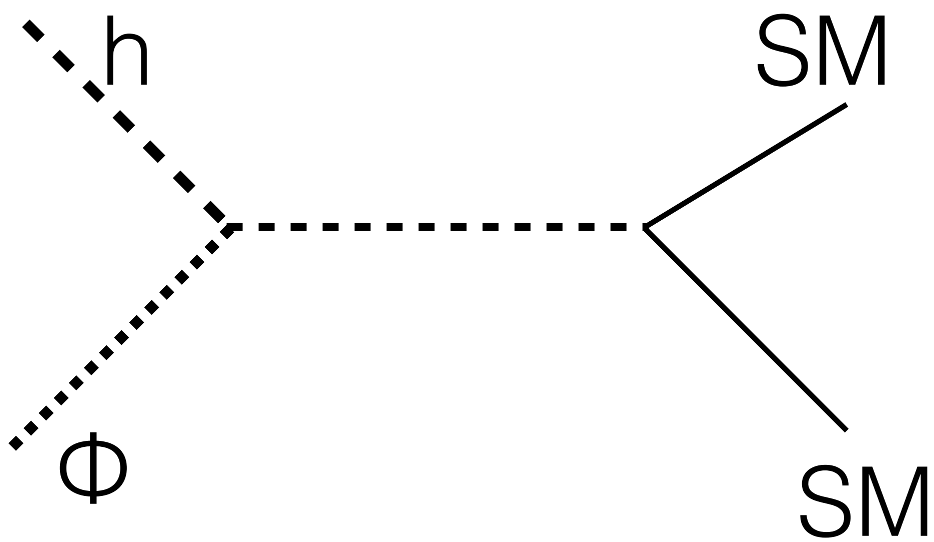

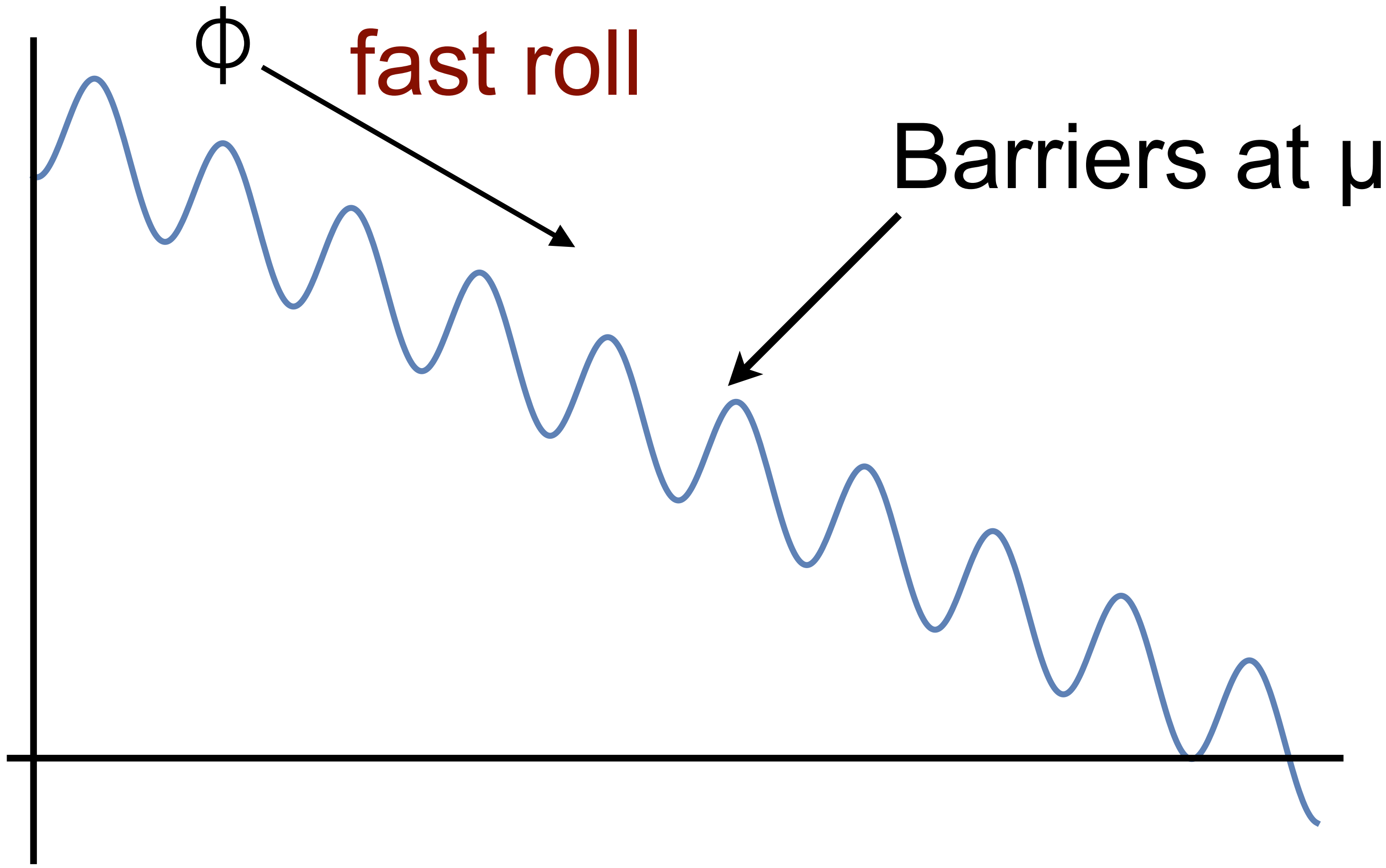

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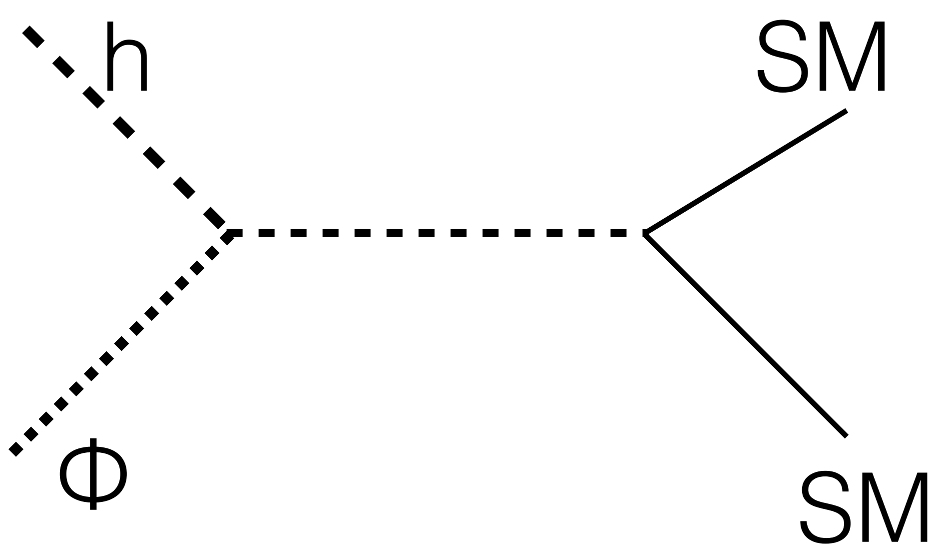

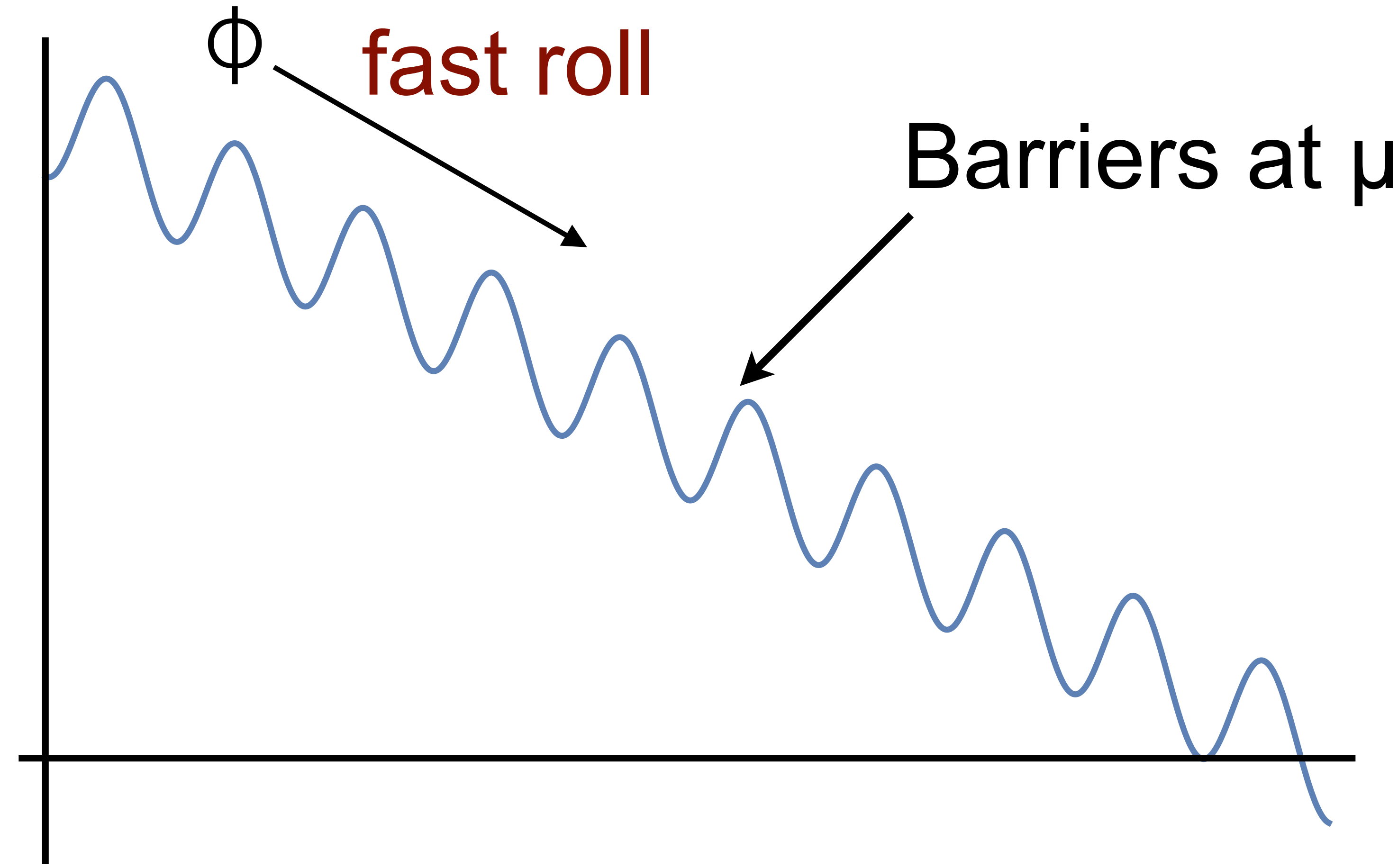

Efficient Reheating.
Removes kinetic energy from Φ

μ ~ 100 TeV. Within one Hubble time.