Current Themes in High Energy Physics and Cosmology
August 25-29,2014

Recent Progress on Cosmological Bounces & Bouncing Cosmologies

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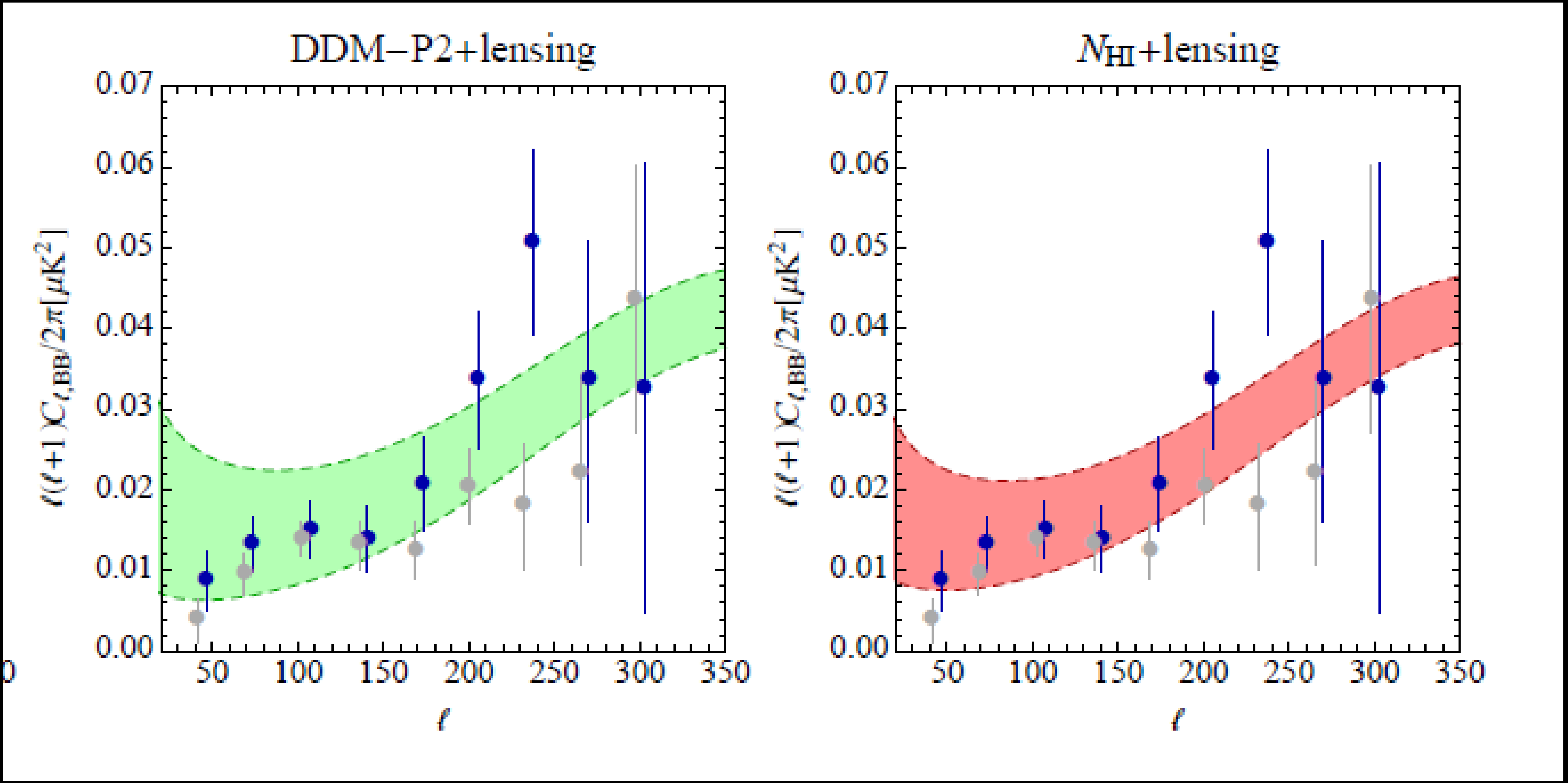
BICEP2



- The null hypothesis – lensing + dust – cannot be rejected
- Any claim of tensor, esp. "r=0.2", makes no sense scientifically
- No systematics paper
- Planck dust map available on September Nth, where N < 4

"Classic" Inflationary Picture

Typical initial conditions
Simple inflaton potentials with minimum tuning

→ inflation

→ smooth and flat universe
+ predictions of n_s, α, n_t, r, …

OUTDATED

Ijjas, PJS. Loeb, PLB (2013, 2014)
Guth, Kaiser, Nomura, PLB (2014)
Linde, arxiv1402.0526 (2014)

An Alternative Inflationary Picture?

~~Typical initial conditions~~

Simple inflaton potentials with minimum tuning

→ inflation

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Ijjas, PJS. Loeb, PLB (2013, 2014)
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An Alternative Inflationary Picture?

~~Typical initial conditions~~

$$H^2 = \frac{8\pi G}{3}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V\right) - \frac{k}{a^2}$$

$$\boxed{\sim \frac{1}{a^6}} \qquad \sim \frac{1}{a^2} \qquad \boxed{\sim \ln a} \qquad \sim \frac{1}{a^2}$$

Ijjas, PJS. Loeb, PLB (2013, 2014)
Guth, Kaiser, Nomura, PLB (2014)
Linde, arxiv1402.0526 (2014)

An Alternative Inflationary Picture?

~~Typical initial conditions~~

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An Alternative Inflationary Picture?

~~Typical initial conditions~~

~~Simple~~ inflaton potentials with ~~minimum~~ tuning

→ inflation

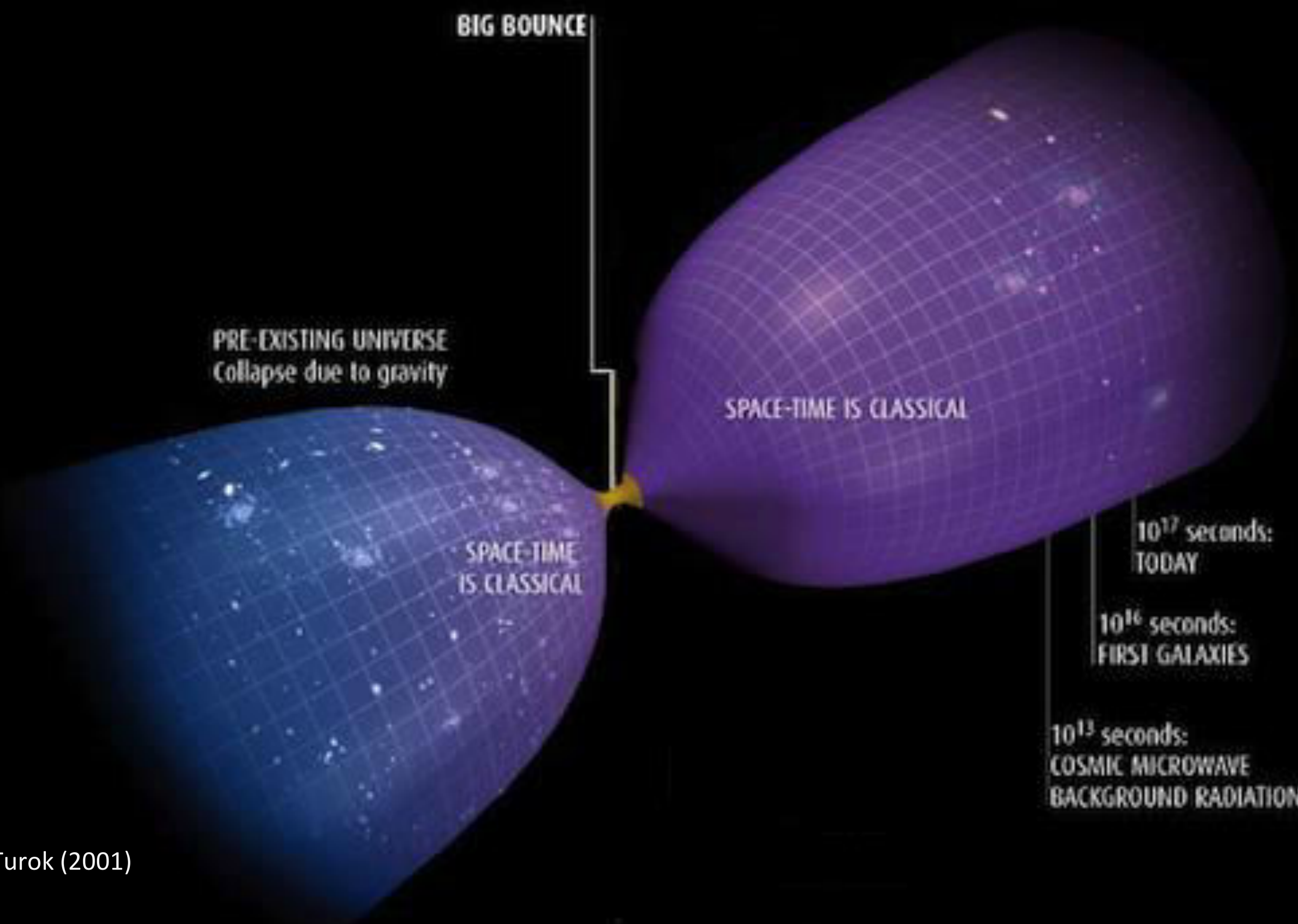
→ ~~smooth and flat universe~~

+ multiverse of n_s, α, n_t, r, …

Ijjas, PJS. Loeb, PLB (2013, 2014)
Guth, Kaiser, Nomura, PLB (2014)
Linde, arxiv1402.0526 (2014)

Why Bounce?

Why Bounce?



Khoury, Ovrut, PJS, Turok (2001)
PUS & Turok (2002)

Why Bounce?

simple solution to flatness & homogeneity problems

$$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} - \frac{k}{a^2} + \textit{inhomogeneities}$$

$$\boxed{\sim \frac{1}{a^2}}$$

$$+\frac{\sigma^2}{a^6} + \frac{8\pi G}{3}\left(\frac{\rho_\phi}{a^{2\varepsilon}}\right)$$

$$\varepsilon \equiv \tfrac{3}{2}(1+w) \geq 3 \qquad a(t) = (-t)^{1/\varepsilon}$$

See also Xue et al, PRD88, 083509 (2013)

Why Bounce?

simple solution to flatness & homogeneity problems

evades the multiverse/unpredictability problem

can be made geodesically complete

Bouncing Fears?

branes & extra dimensions?
Khoury, Ovrut, PJS & Turok (2002)

no-go thm: background must be unstable
if it produces scale-invariant spectrum?
Wesley & Tolley (2007)

no-go thm: cannot produce adiabatic spectrum (directly)
Creminelli, Nicolis, Zaldarriaga (2007)

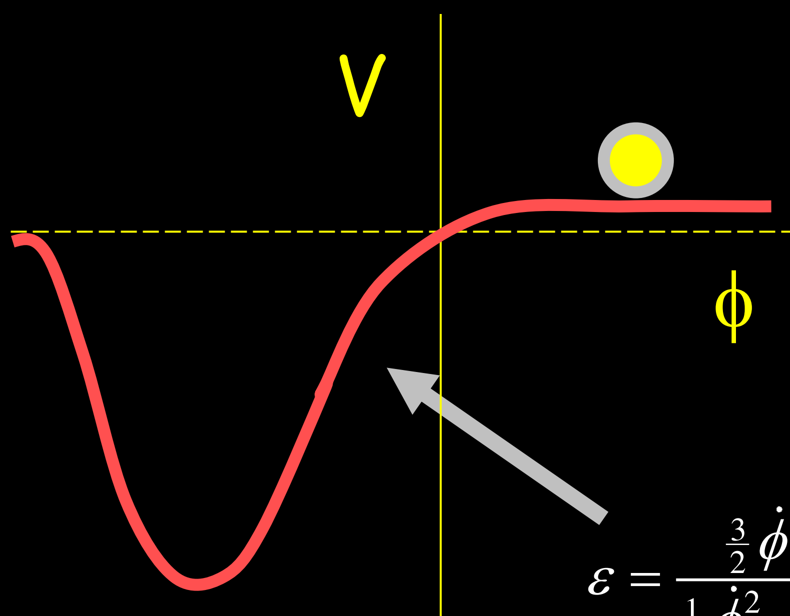
$f_{NL} \sim O(10)$
Lehners et al (2007); Finelli (2002)

no theory for the bounce/
incompatible with string theory

Ekpyrotic: ultra-slow contraction – $a(t) \sim (-t)^{1/\varepsilon} << 1/3$

$$S = \int d^4x \sqrt{-g}\,[\tfrac{1}{2}R \boxed{-\tfrac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \tfrac{1}{2}\Omega^2(\phi)(\partial_\mu \chi)^2}\,]$$

Two fields w/*stable* attractor solution



$$\varepsilon = \frac{\frac{3}{2}\dot{\phi}^2}{\frac{1}{2}\dot{\phi}^2 + V} >> 3$$

2nd field: χ
entropic pert's
→ curvature

from conversion only:
$f_{NL} \sim O(\text{few})$

Li, PLB 724 (2014)
Fertig, Lehners, Mallwitz, PRD 89 (2014)
Ijjas, PJS. Lehners, PRD 89, (2014)

Anamorphic: scalar-tensor + ordinary contraction

$$S = \int d^4x \sqrt{-g}\, [\boxed{\tfrac{1}{2} f(\phi) R - \tfrac{1}{2} k(\phi)(\partial_\mu \phi)^2} - V(\phi) + \rho_m]$$

$$\bar{H}^2 = \frac{1}{3}\left\{\frac{1}{2}\left[\frac{(3/2)(f')^2 + k(\phi) f}{f^2}\right]\dot{\phi}^2 + \frac{V}{f}\right\} + \frac{\sigma^2}{f^2 a^6} - \frac{k}{a^2}$$

$$H \equiv \frac{d \ln(a)}{dt} < 0$$

but

$$\bar{H} \equiv \frac{d \ln(a\sqrt{f})}{dt} > 0$$

$$-\frac{d \ln(\bar{H}^2 / f)}{d \ln(a\sqrt{f})} < 2$$

Ijjas, PJS. Lehners, to appear, (2014)

Anamorphic: scalar-tensor + ordinary contraction

$$S = \int d^4x \sqrt{-g}\, [\boxed{\tfrac{1}{2} f(\phi) R - \tfrac{1}{2} k(\phi)(\partial_\mu \phi)^2} - V(\phi) + \rho_m]$$

$$f(\phi) = \xi\phi^2 \qquad k(\phi) = -1 \qquad V(\phi) \sim \phi^n$$

Li, PLB (2014)

Key differences from ekpyrotic:

- *single field*
- *adiabatic directly (no conversion needed)*
- *Can adjust ξ and n to get n_s=0.96 and r ~0.1*
- *f_{NL} ~ O(1)*

Ijjas, PJS. Lehners, to appear, (2014)

What about the bounce?

non-singular vs. singular

Bars, PJS & Turok, Fortsh Phys, to appear (2014); Bars, PJS & Turok, PRD 89, 061302 (2014);
Bars, PJS & Turok, PLB276, 50 (2013); Bars, PJS & Turok, PRD 89, 043515 (2014);
Bars, Chen, PJS & Turok, PRD 86, 083542 (2012); Bars, Chen, PJS & Turok, PLB 715, 278 (2012)

a proposal

Note that, near the bounce, the effective action simplifies:

$$S = \int d^4x\sqrt{-g}[\frac{1}{2\kappa^2}R(g) - \frac{1}{2}(\partial\sigma)^2 \text{ + radiation}]$$

Smooth & Flat; Can ignore potentials and gradients; Ultralocal

Bars, PJS & Turok, Fortsh Phys, to appear (2014); Bars, PJS & Turok, PRD 89, 061302 (2014);
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Smooth & Flat; Can ignore potentials and gradients; Ultralocal

"Weyl invariant extension" (the same theory written a novel way!):

$$\boxed{S = \int d^4x\sqrt{-g}\left[\frac{(\partial\phi)^2-(\partial s)^2}{2} + \frac{\phi^2-s^2}{12}R \text{ + radiation}\right]}$$

Weyl invariant: $g_{\alpha\beta} \rightarrow e^{2\omega(x)}\, g_{\alpha\beta}$, $\phi \rightarrow e^{-\omega(x)}\, \phi$ and s$\rightarrow e^{-\omega(x)}\, s$

Can choose $\omega(x)$ *so that* $\frac{1}{12}(\phi^2 - s^2) = 1/2\kappa^2$ *to recover Einstein eqs.*

Every solution of the Einstein equations

$$S = \int d^4x\sqrt{-g}[\frac{1}{2\kappa^2}R(g) - \frac{1}{2}(\partial\sigma)^2 \text{ + radiation}]$$

. . . is also a solution of the Weyl invariant extension . . .

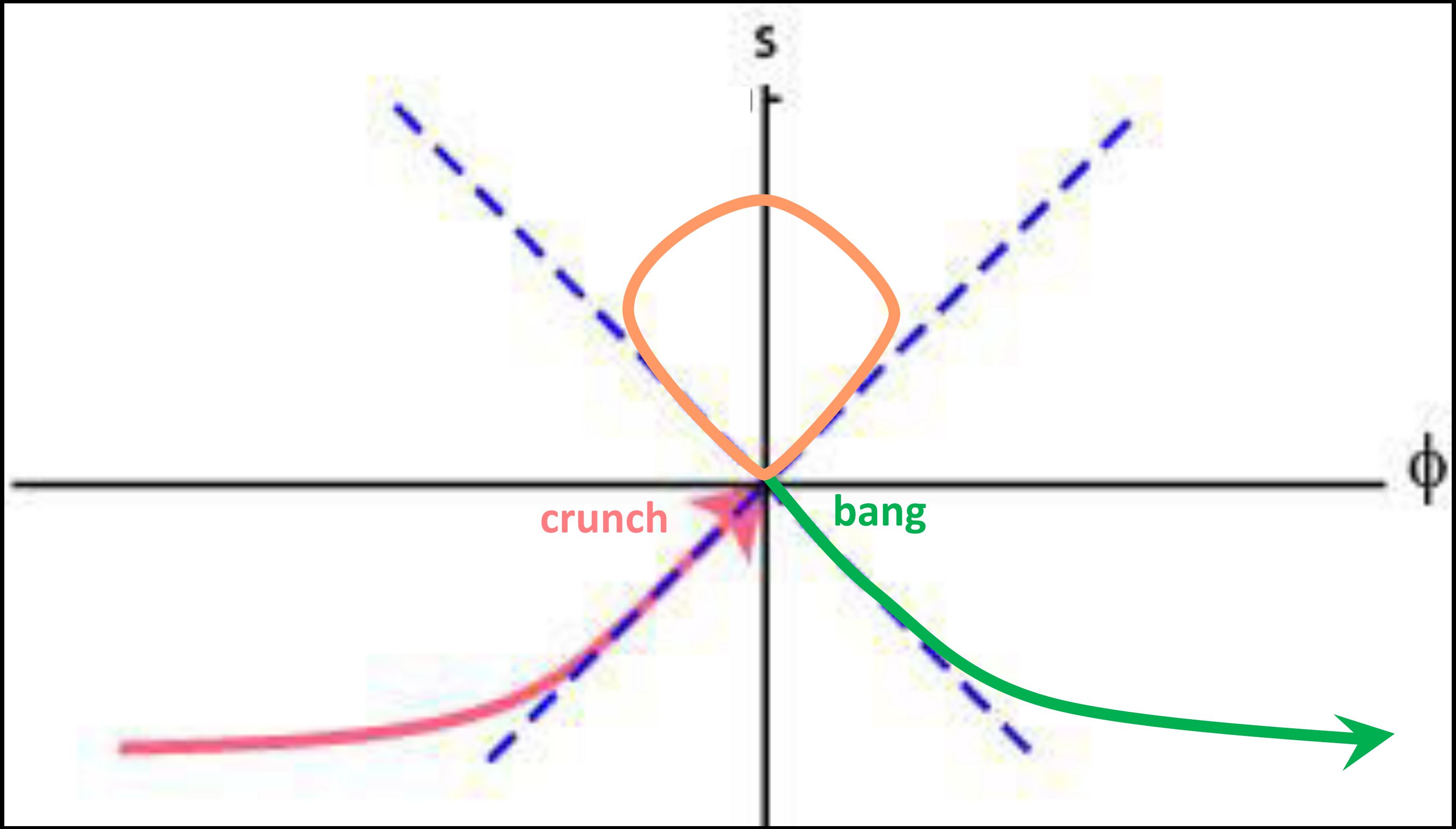
$$S = \int d^4x\sqrt{-g}\left[\frac{(\partial\phi)^2 - (\partial s)^2}{2} + \frac{\phi^2 - s^2}{12}R \text{ + radiation}\right]$$

. . . and also a solution of other gauge-fixed versions (e.g., g = a =1)

$$\int d\tau\left\{\frac{1}{2e}\left[-\dot{\phi}^2 + \dot{s}^2 + \frac{\kappa^2}{6}(\phi^2 - s^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2)\right] - e\rho_r\right\}$$

but … geodesically incomplete solutions in one gauge
may be geodesically complete solutions in the other !

$$a_E^2 \equiv \frac{\kappa^2}{6}\left(\phi^2 - s^2\right)$$



$$\int d\tau \left\{ \frac{1}{2e}\left[-\dot{\phi}^2 + \dot{s}^2 + \frac{\kappa^2}{6}(\phi^2 - s^2)(\dot{\alpha}_1^2 + \dot{\alpha}_2^2)\right] - e\rho_r \right\}$$

Weyl invariance can be extended
to all currently known physics

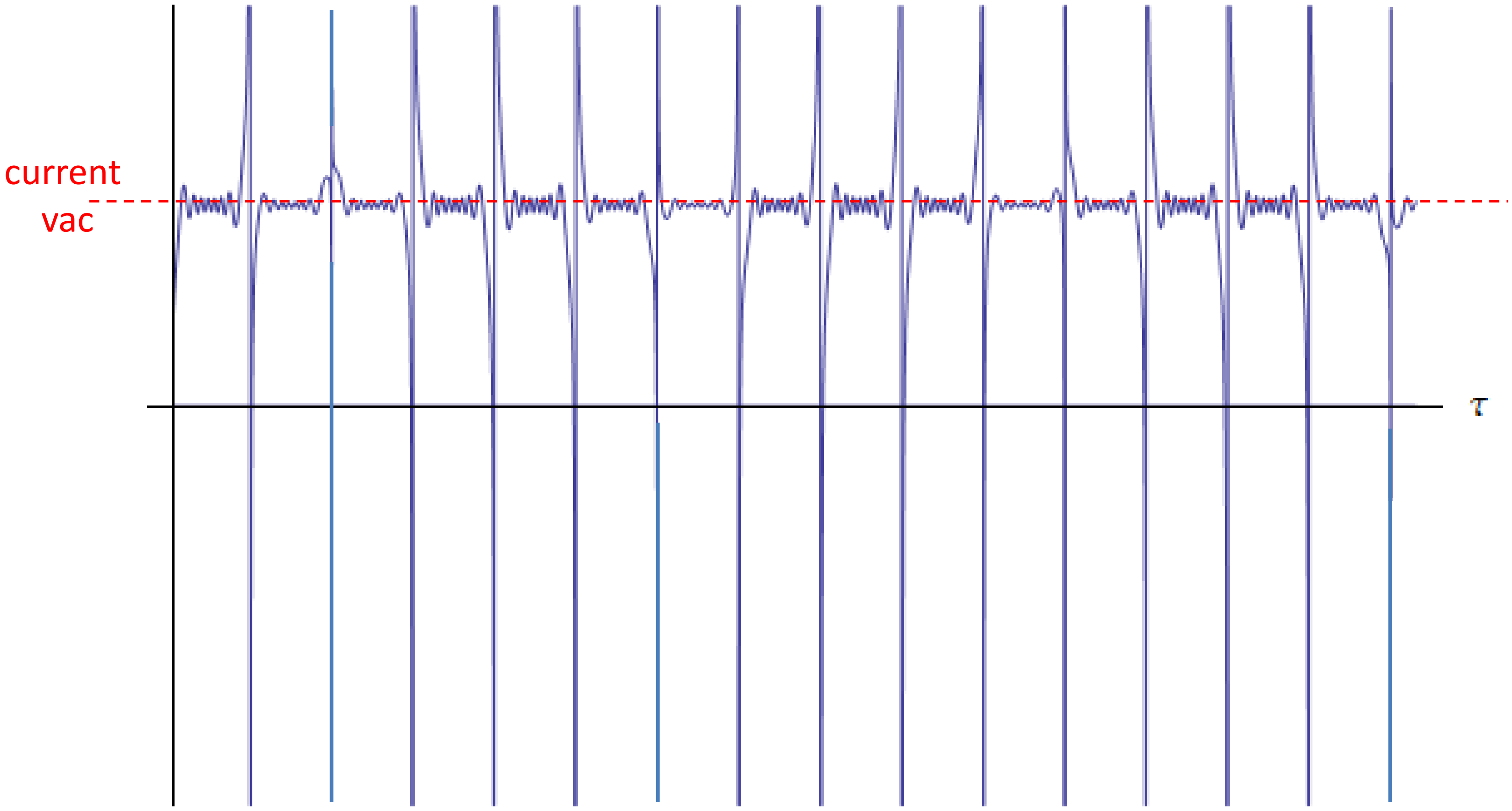
$$\mathcal{L}(x) = \begin{array}{c} \frac{1}{12}\left(\phi^2 - 2H^\dagger H\right) R(g) \\ +g^{\mu\nu}\left(\frac{1}{2}\partial_\mu\phi\partial_\nu\phi - D_\mu H^\dagger D_\nu H\right) \\ -\left(b\phi^4 + \frac{\lambda}{4}\left(H^\dagger H - \xi^2\phi^2\right)^2\right) \\ +L_{\mathrm{SM}}\left(\begin{array}{c} \text{quarks, leptons , gauge bosons,} \\ \text{Yukawa couplings to } H \end{array}\right) \end{array}$$

$$g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu},\ \phi \to \Omega\phi,\ H \to \Omega H,$$
$$\psi_{q,l} \to \Omega^{3/2}\psi_{q,l},\ A_\mu^{\gamma,W,Z,g} \to \Omega^0 A_\mu^{\gamma,W,Z,g}$$

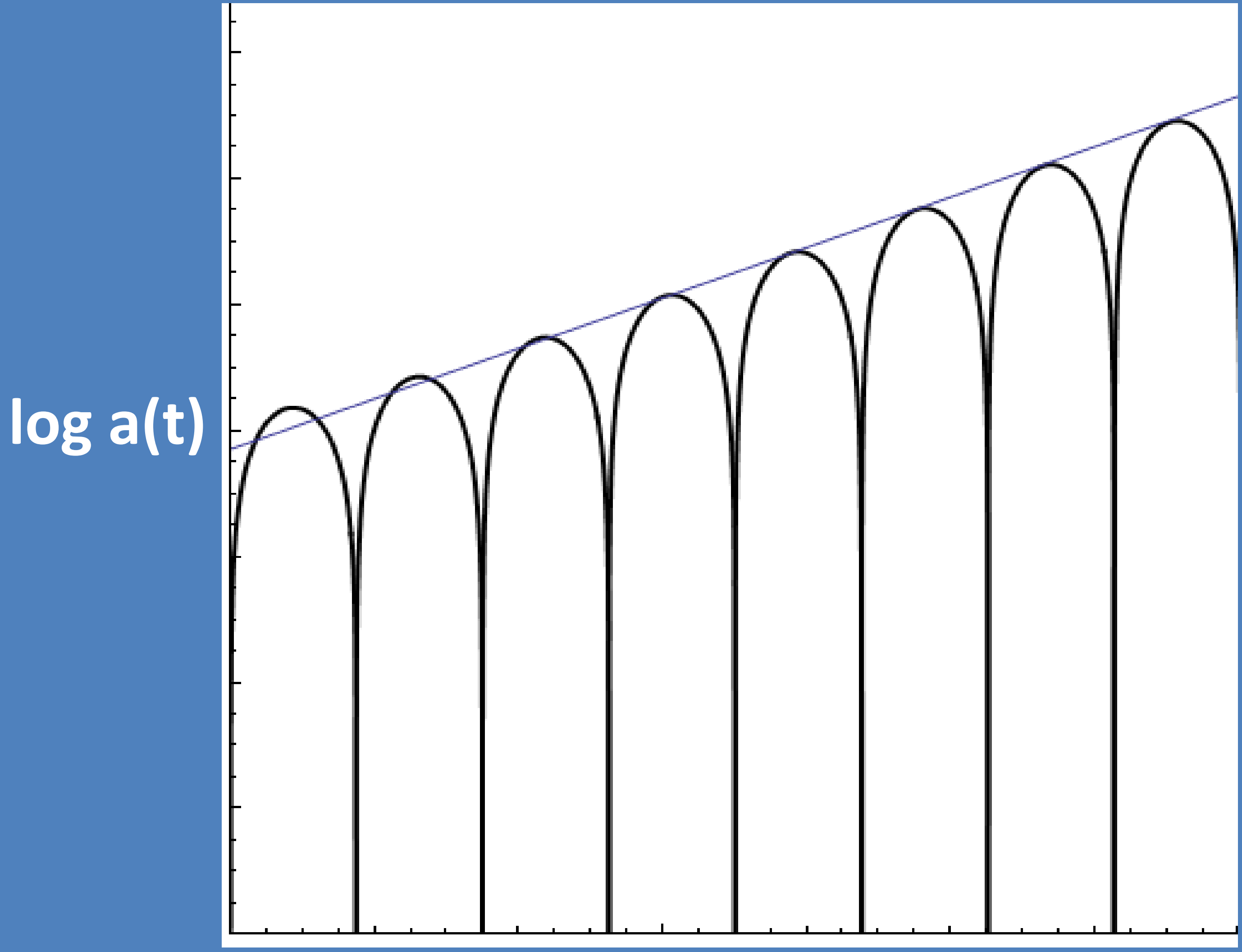
$$H(x) = \left(\begin{array}{c} 0 \\ \frac{1}{\sqrt{2}}\left|s(x)\right| \end{array}\right)$$

can also add dark matter and r-handed ν's

higgs



INCREASING ENTROPY EACH CYCLE BY CONSTANT FACTOR CAUSES VOLUME TO GROW FROM CYCLE TO CYCLE



Geodesically complete!

(evades Borde, Guth, Vilenkin (2004) theorem & the "initial conditions" problem)

Bars, PJS, Turok (Fortschr Phys 2014)

can reformulate string theory with a local scale symmetry in target space without *any* fundamental lengths such that the fundamental length in string theory

– the string tension –

emerges from gauge fixing a field.