Bouncing

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Big-Bang Cosmology:

"what mechanism turned the quantum universe into a classical flat FRW space-time with the very specific large-scale features & ingredients we observe"?

Big Bang -> Big Bounce

"start smoothing when universe big & classical & there is plenty of time to generate the large-scale structure we observe"

smoothing contraction

$$3H^2 = \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4} + \frac{\sigma^2}{a^6} - \frac{k}{a^2} + \frac{\rho}{a^{2\varepsilon}}$$

$\varepsilon = 3/2\,(1+w)$, $w = p/\varrho$

ekpyrotic contraction: $\varepsilon > 3$

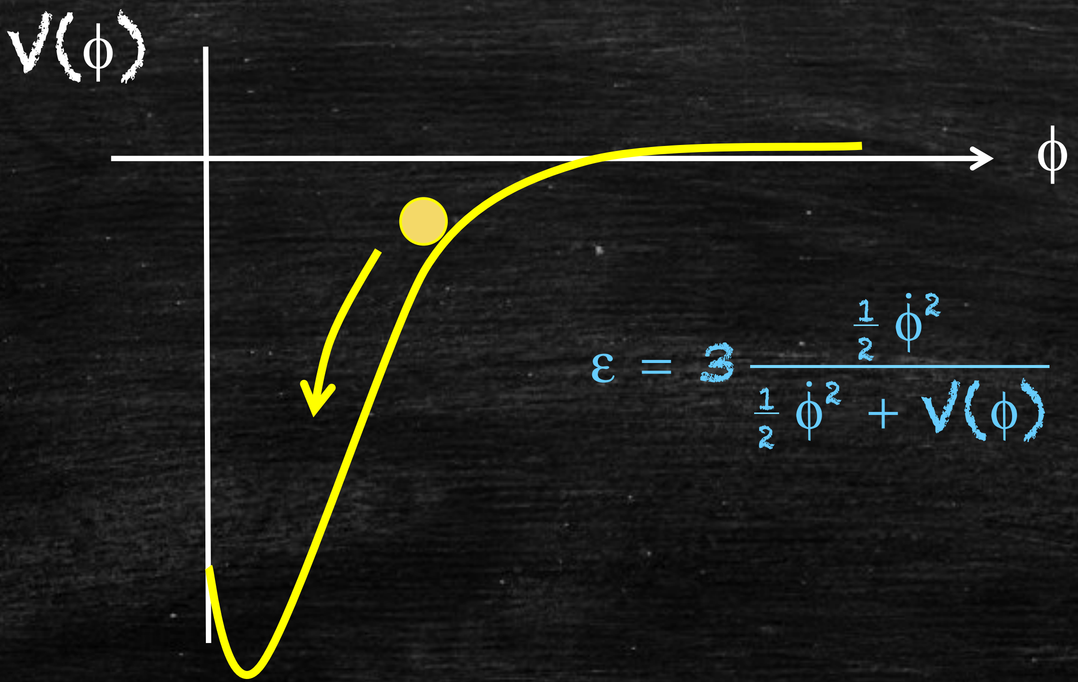
-> solves homogeneity, flatness, and isotropy problem

-> eliminates causal horizon problem

$V(\phi)$: flat & positive -> steep & negative

$$3H^2 = \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4} + \frac{\sigma^2}{a^6} - \frac{k}{a^2} + \frac{\rho}{a^{2\varepsilon}}$$

with $\varepsilon > 3$



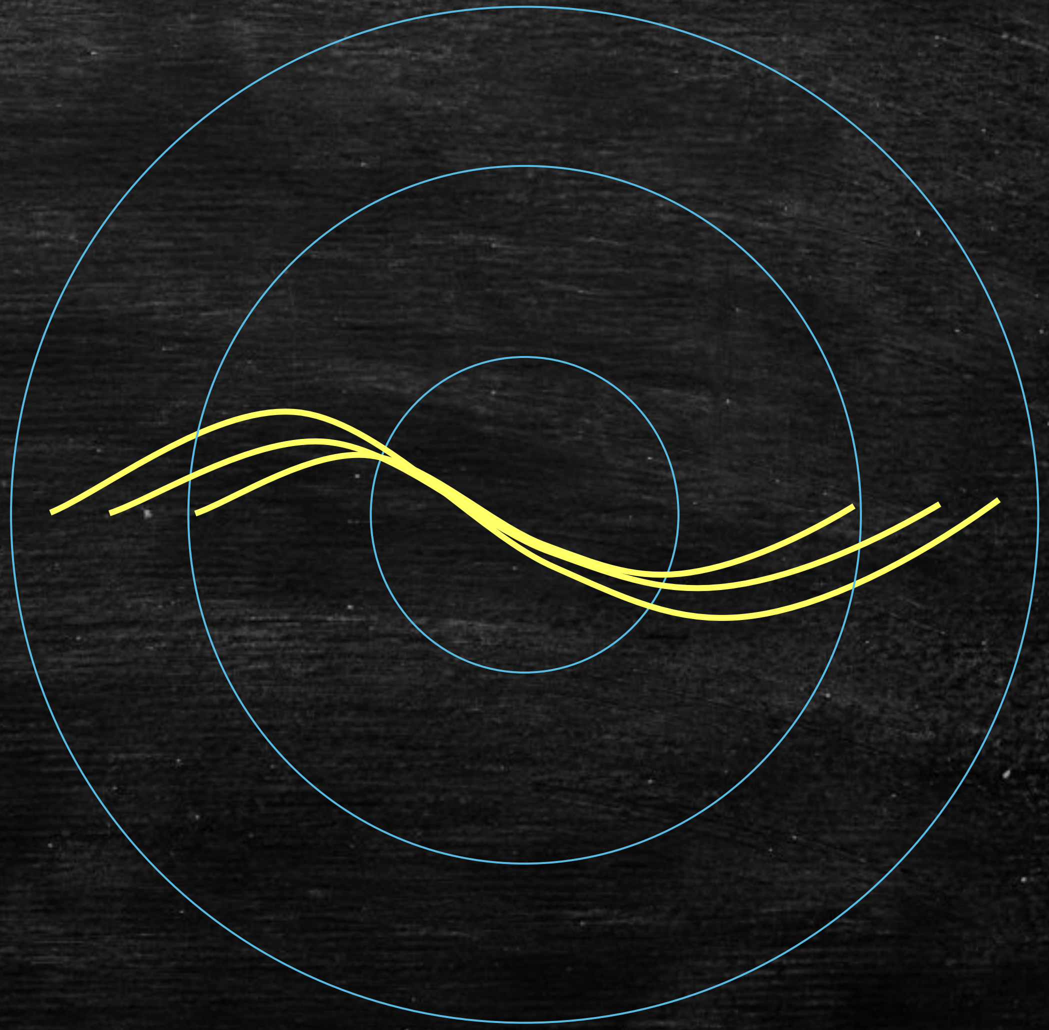
$$\varepsilon = 3\,\frac{\frac{1}{2}\dot{\phi}^2}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} > 3$$

super-horizon modes "for free"

mode by mode picture:

$t \to 0$: $a \sim (-t)^{1/\varepsilon}$,

$H^{-1} \sim t$



No multiverse

inflation:
what you thought were typical regions become atypical
-> theory breaks down, cannot trust predictions

$\delta\rho/\rho \sim 1$

natural "messer"

contraction:
what you thought were typical regions remain typical
-> theory remains valid, can trust predictions

$\delta\rho/\rho \ll 1$

natural smoother

(earlier) no-goes

smoothing contracting scenarios with scale-invariant curvature perturbation spectrum

- admit no stable background solutions
- require more tuning (than those with the wrong spectrum)
- typically produce too much non-gaussianity
- cannot bounce

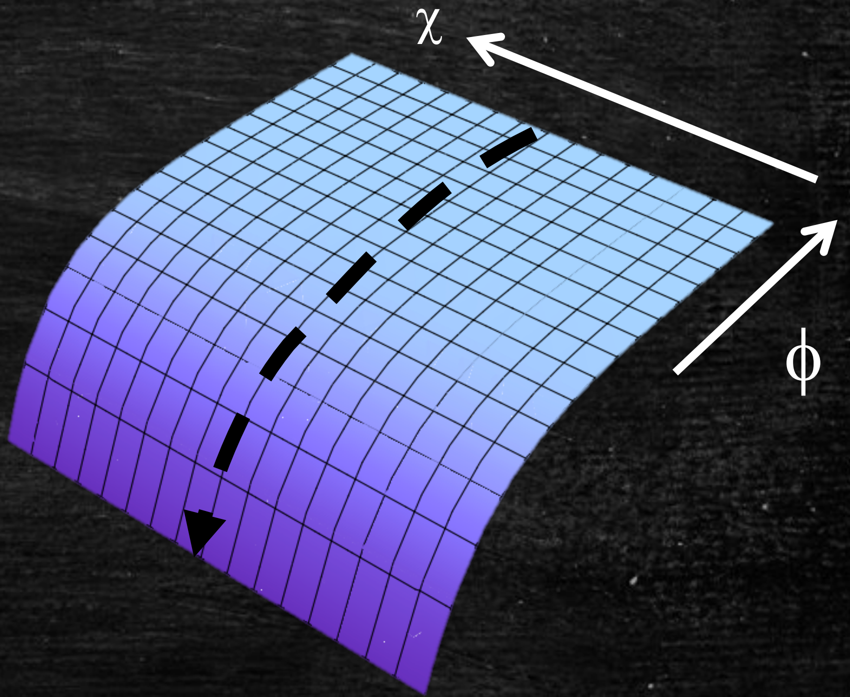
simplest ekpyrotic theory

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 + V_o e^{-\sqrt{2\epsilon}\phi} - \frac{1}{2}\Omega^2(\phi)(\partial\chi)^2\right)$$

-> stable solutions

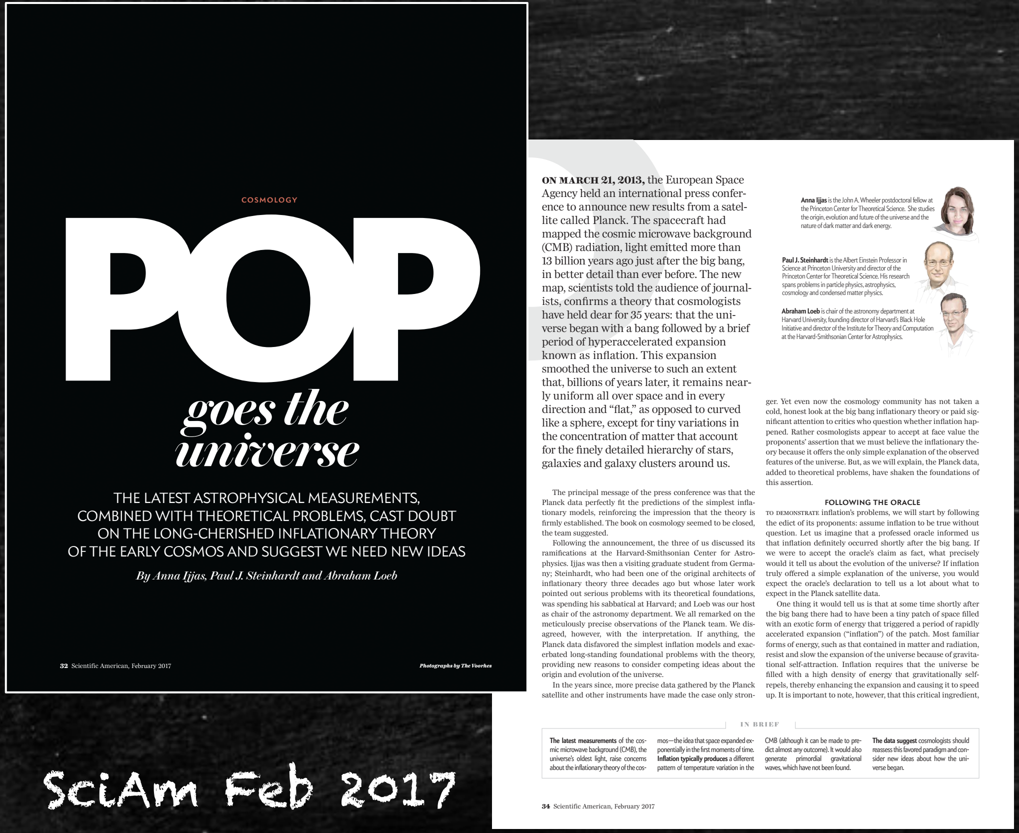
-> least tuned

-> generic: $f_{NL} = 0$
   from ekpyrotic phase



Not so in inflationary cosmology

Simplest textbook models are ruled out or strongly disfavored by Planck2013, Planck2015 and other CMB experiments.


COSMOLOGY

POP
goes the universe

THE LATEST ASTROPHYSICAL MEASUREMENTS, COMBINED WITH THEORETICAL PROBLEMS, CAST DOUBT ON THE LONG-CHERISHED INFLATIONARY THEORY OF THE EARLY COSMOS AND SUGGEST WE NEED NEW IDEAS

By Anna Ijjas, Paul J. Steinhardt and Abraham Loeb

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Photographs by The Voorhes

ON MARCH 21, 2013, the European Space Agency held an international press conference to announce new results from a satellite called Planck. The spacecraft had mapped the cosmic microwave background (CMB) radiation, light emitted more than 13 billion years ago just after the big bang, in better detail than ever before. The new map, scientists told the audience of journalists, confirms a theory that cosmologists have held dear for 35 years: that the universe began with a bang followed by a brief period of hyperaccelerated expansion known as inflation. This expansion smoothed the universe to such an extent that, billions of years later, it remains nearly uniform all over space and in every direction and "flat," as opposed to curved like a sphere, except for tiny variations in the concentration of matter that account for the finely detailed hierarchy of stars, galaxies and galaxy clusters around us.

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Abraham Loeb is chair of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics.

The principal message of the press conference was that the Planck data perfectly fit the predictions of the simplest inflationary models, reinforcing the impression that the theory is firmly established. The book on cosmology seemed to be closed, the team suggested.

Following the announcement, the three of us discussed its ramifications at the Harvard-Smithsonian Center for Astrophysics. Ijjas was then a visiting graduate student from Germany; Steinhardt, who had been one of the original architects of inflationary theory three decades ago but whose later work pointed out serious problems with its theoretical foundations, was spending his sabbatical at Harvard; and Loeb was our host as chair of the astronomy department. We all remarked on the meticulously precise observations of the Planck team. We disagreed, however, with the interpretation. If anything, the Planck data disfavored the simplest inflation models and exacerbated long-standing foundational problems with the theory, providing new reasons to consider competing ideas about the origin and evolution of the universe.

In the years since, more precise data gathered by the Planck satellite and other instruments have made the case only stronger. Yet even now the cosmology community has not taken a cold, honest look at the big bang inflationary theory or paid significant attention to critics who question whether inflation happened. Rather cosmologists appear to accept at face value the proponents' assertion that we must believe the inflationary theory because it offers the only simple explanation of the observed features of the universe. But, as we will explain, the Planck data, added to theoretical problems, have shaken the foundations of this assertion.

FOLLOWING THE ORACLE

TO DEMONSTRATE inflation's problems, we will start by following the edict of its proponents: assume inflation to be true without question. Let us imagine that a professed oracle informed us that inflation definitely occurred shortly after the big bang. If we were to accept the oracle's claim as fact, what precisely would it tell us about the evolution of the universe? If inflation truly offered a simple explanation of the universe, you would expect the oracle's declaration to tell us a lot about what to expect in the Planck satellite data.

One thing it would tell us is that at some time shortly after the big bang there had to have been a tiny patch of space filled with an exotic form of energy that triggered a period of rapidly accelerated expansion ("inflation") of the patch. Most familiar forms of energy, such as that contained in matter and radiation, resist and slow the expansion of the universe because of gravitational self-attraction. Inflation requires that the universe be filled with a high density of energy that gravitationally self-repels, thereby enhancing the expansion and causing it to speed up. It is important to note, however, that this critical ingredient,

IN BRIEF

The latest measurements of the cosmic microwave background (CMB), the universe's oldest light, raise concerns about the inflationary theory of the cosmos—the idea that space expanded exponentially in the first moments of time. **Inflation typically produces** a different pattern of temperature variation in the CMB (although it can be made to predict almost any outcome). It would also generate primordial gravitational waves, which have not been found. **The data suggest** cosmologists should reassess this favored paradigm and consider new ideas about how the universe began.

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$n_s - 1 \approx -2\varepsilon \approx -.03$

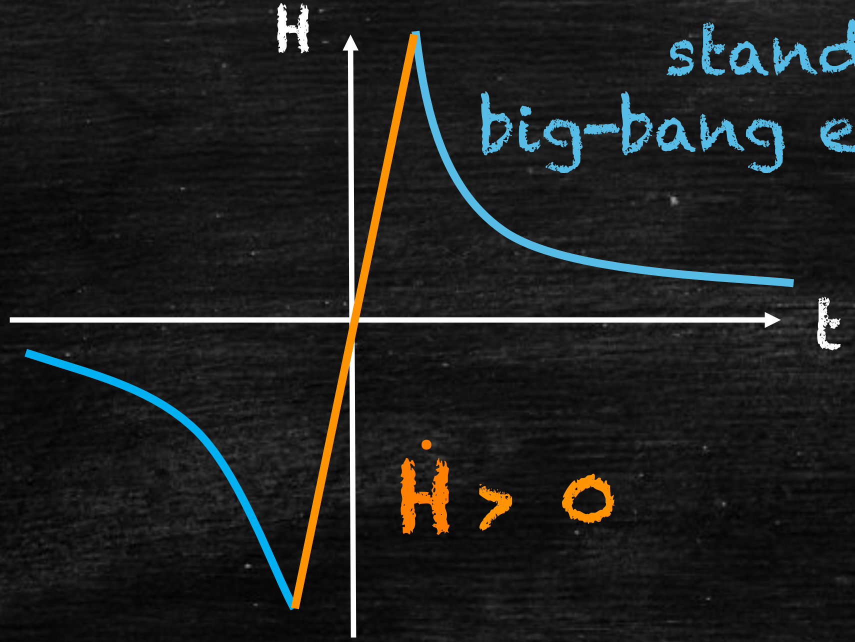
$r \approx 16\varepsilon \approx .4$

Observational issues for the first time since 1981!

is a cosmological bounce possible?

The challenge

2nd Friedmann eq: $\dot{H} = -(\rho + p)/2 = -\varepsilon H^2 \leq 0$ "null energy condition"



standard big-bang expansion

smoothing contraction

non-singular bounce has to stably violate the null energy condition!

NEC-violation with Horndeski matter

action: $S = \int d^4x\sqrt{-g}\left(\frac{1}{2}R + L\right)$ where

$$L = P(X,\phi) + G^{(3)}(X,\phi)\Box\phi + G^{(4)}_{,X}(X,\phi)\left((\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right) + G^{(4)}(X,\phi)R$$
$$+G^{(5)}_{,X}(X,\phi)\left((\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right) - 6G_{\mu\nu}\nabla^\mu\nabla^\nu G^{(5)}(X,\phi)$$

background:
$$3H^2 = 2XP_{,X} - P + 6X\dot\phi HG_{3,X} - 2XG_{3,\phi} - 6H^2G_4 + 24H^2X(G_{4,X} + XG_{4,XX})$$
$$- 12HX\dot\phi G_{4,\phi X} - 6H\dot\phi G_{4,\phi} + 2H^3X\dot\phi(5G_{5,X} + 2XG_{5,XX}) - 6H^2X(3G_{5,\phi} + 2XG_{5,\phi X})$$

$$a^{-3}\frac{d}{dt}(a^3J) = P_{,\phi} \quad \text{where}$$
$$J = \dot\phi P_{,X} + 6HXG_{3,X} - 2\dot\phi G_{3,\phi} + 6H^2\dot\phi(G_{4,X} + 2XG_{4,XX}) - 12HXG_{4,\phi X} + 2H^3X(3G_{5,X} + 2XG_{5,XX}) - 6H^2\dot\phi(G_{5,\phi} + XG_{5,\phi X})$$

perturbations: $\zeta = -H\frac{\delta\phi}{\dot\phi}$ 'co-moving gauge'

$$S^{(2)}_\zeta = \int d^4x\, a^3(t)\left(A(t)\dot\zeta^2 - \frac{B(t)}{a^2(t)}(\nabla\zeta)^2\right) \qquad c_s^2 = B(t)/A(t)$$

Why Horndeski matter?

- foundations secure (all classical field theory)

- most general Lorentz-invariant scalar-tensor theory with second-order eqs. of motion

  -> evades Ostragadski ghost
  -> can be tested in non-linear regime using numerical GR

- motivated by fundamental symmetries: conformal &
  Galilean shift ($\phi \to \phi + b_\mu x^\mu$)

- seems to appear naturally in UV-complete theories:
  -> in SUGRA,
  -> in higher-dimensional theories with branes, etc.

but … Rubakov @Princeton May '16: no-go

L_3 Horndeski cosmologies that have no ghost or gradient instabilities must encounter a singularity

Libanov, Mironov, Rubakov 2016
Kobayashi 2016

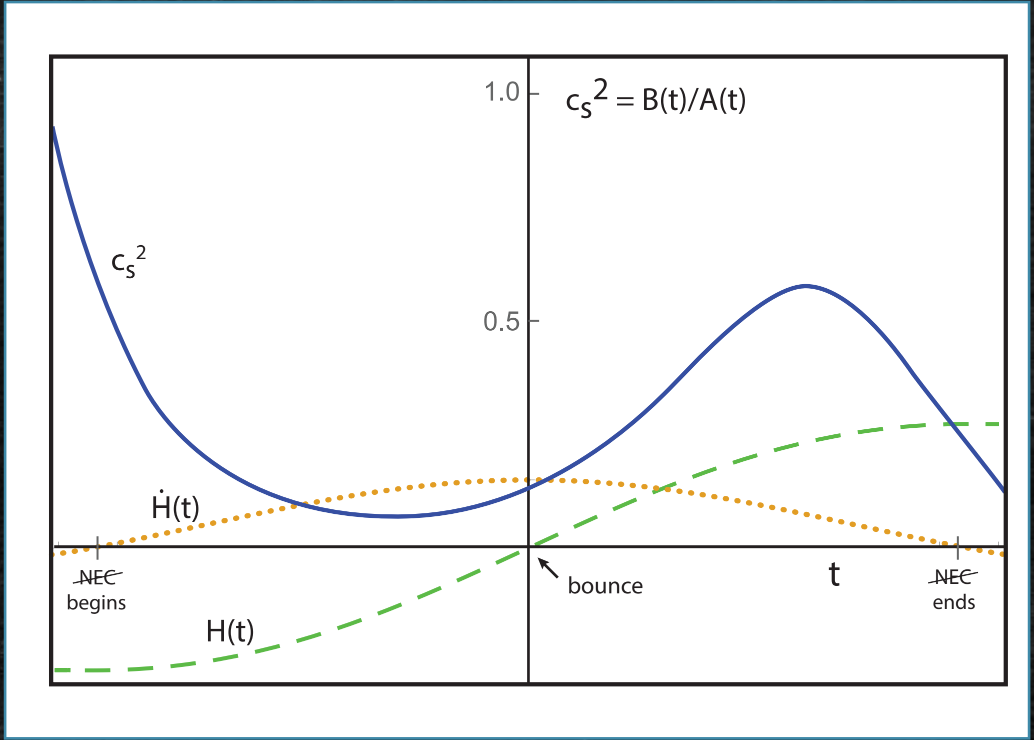
$$B(t) = a^{-1}(t)\,\frac{d}{dt}\left(a(t)\gamma(t)^{-1}\right) - 1 > 0 \qquad \text{where} \qquad \gamma(t) = H - \tfrac{1}{2}b\dot{\phi}^3$$

$$\boxed{\left.\frac{a(t)}{\gamma(t)}\right|_{t_0} - \left.\frac{a(t)}{\gamma(t)}\right|_{t} \geq \int_t^{t_0} a(t)\,dt}$$

blow-up at some finite time $t<t_0$

‘guilt by association’

It is not clear that the blow-up must occur during the bounce!



Blow-up has nothing to do with NEC violation ->

Stable NEC violation is possible!

What is the source of the bad behavior?

$$\frac{a(t)}{\gamma(t)}\Big|_{t_0} - \frac{a(t)}{\gamma(t)}\Big|_{t} \geq \int_t^{t_0} a(t)\, dt \quad \rightarrow \quad \frac{a(t)A_h^2(t)}{\gamma(t)}\Big|_{t_0} - \frac{a(t)A_h^2(t)}{\gamma(t)}\Big|_{t} \geq \int_t^{t_0} a(t) B_h\, dt$$

bad behavior is feature of L_3 Horndeski!

-> add L_4 Horndeski interaction:

$$L_3 + G^{(4)}_{,X}(X,\phi)\left((\Box\phi)^2 - (\nabla_\mu \nabla_\nu \phi)^2 \right) + G^{(4)}(X,\phi) R$$

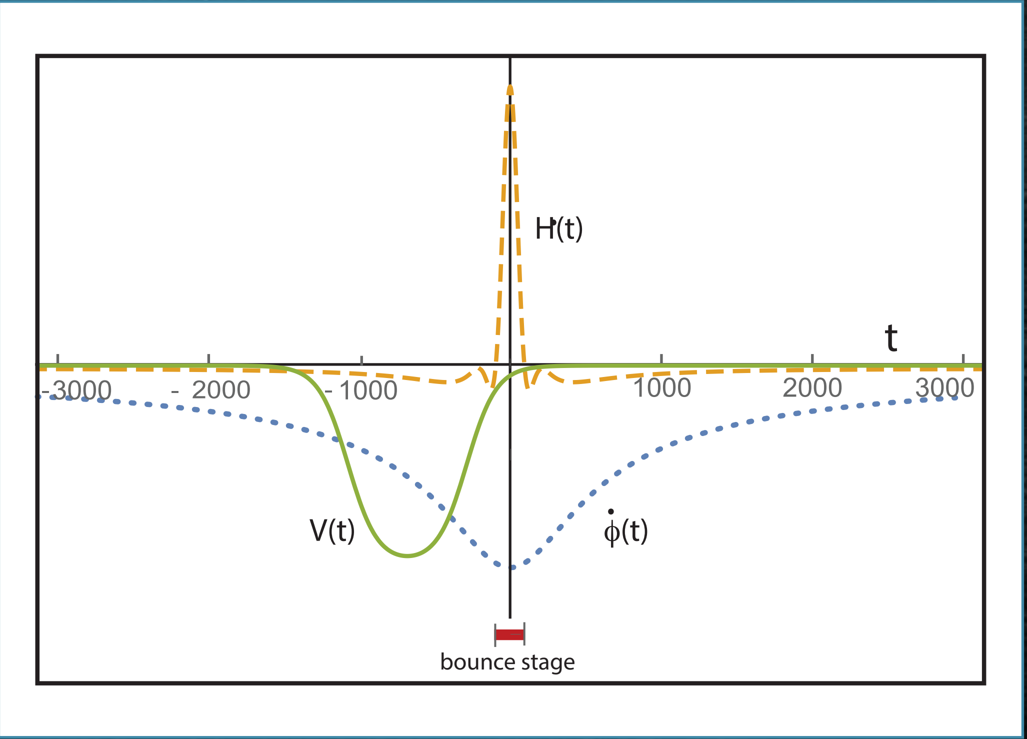
modifies expression for $B(t)$:

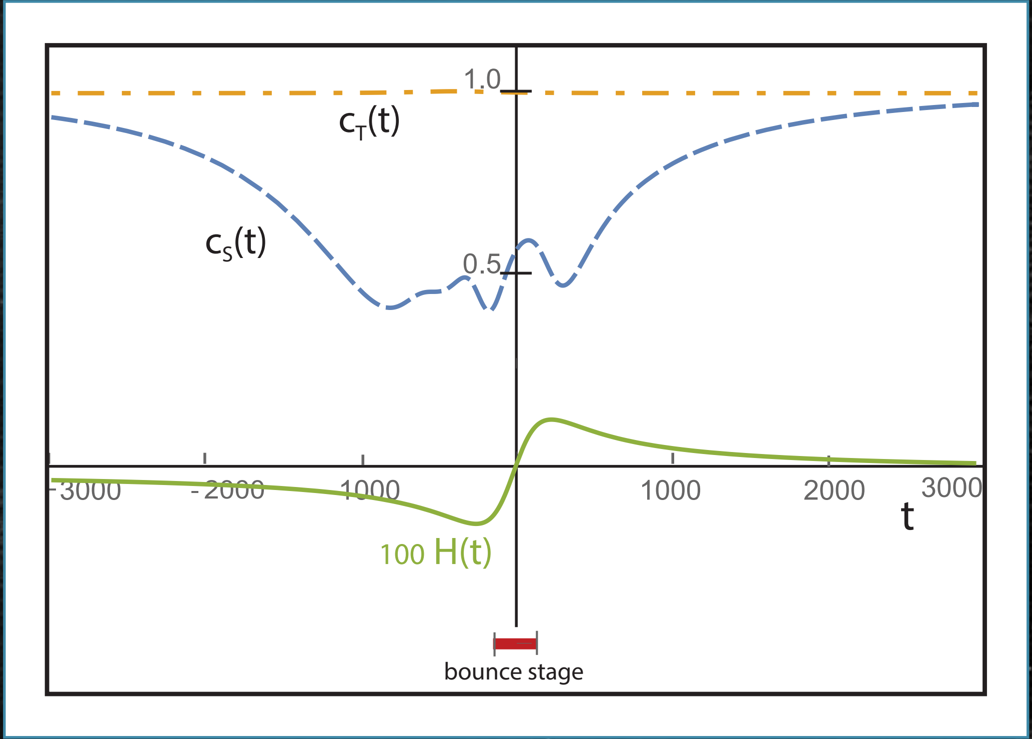
$$B(t) = a^{-1}(t) \frac{d}{dt}\left(a(t) \frac{A_h^2(t)}{\gamma(t)} \right) - B_h(t)$$

where

$$S^{(2)}_{h_{ij}} = \int d^4x\, a^3(t) \left(A_h(t) (\dot{h}_{ij})^2 - \frac{B_h(t)}{a^2(t)} (\nabla h_{ij})^2 \right)$$

An example that works





Summary & Outlook

Classical non-singular bounces are possible and can be embedded into fully stable cosmologies.

Ongoing & future work:

-> simplification: replace L_4 by multi-field L_3 scenario

-> test in non-linear regime using numerical GR

-> brane picture/SUGRA implementation

-> observational implications

-> compare with quantum bounce

...

collaborators & references

ekpyrotic theory with non-canonical kinetic term

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fully stable non-singular bounce

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AI, to appear soon

full-blown numerical analysis of non-singular bounces

AI, V. Paschalidis, F. Pretorius, P.J. Steinhardt, in preparation

Brane/SUGRA implementation

R. Deen, AI, B. Ovrut, P.J. Steinhardt, in preparation