Title: Bouncing

Date: Dec 20, 2016 11:00 AM

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Abstract: <p>In this talk, I will focus on cosmologies that replace the big bang with a big bounce. I will explain how, in these scenarios, the large-scale structure of the universe is determined during a contracting phase before the bounce and will describe the recent development of the first well-behaved classical (non-singular) cosmological bounce solutions.</p>

Bouncing

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Big-Bang Cosmology:

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"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

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-> solves homogeneity, flatness, and isotropy problem

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ekpyrotic contraction: $\varepsilon > 3$

-> solves homogeneity, flatness, and isotropy problem

-> eliminates causal horizon problem

$V(\phi)$:

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

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

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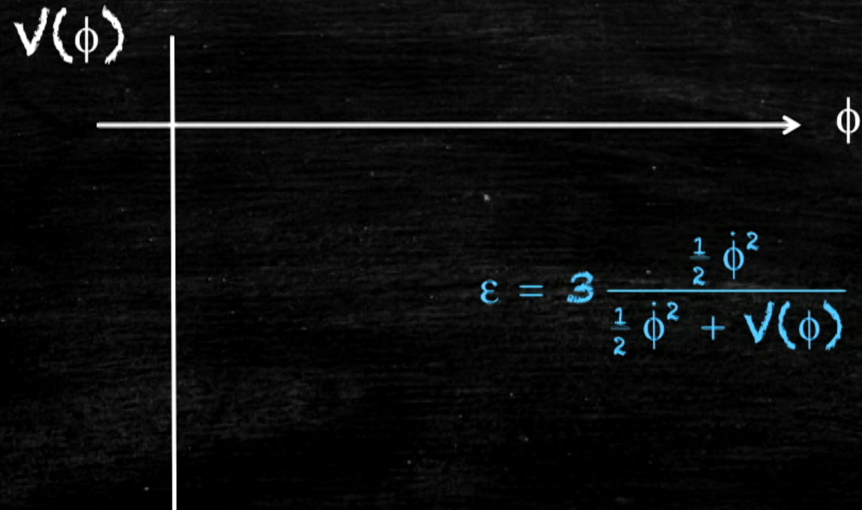

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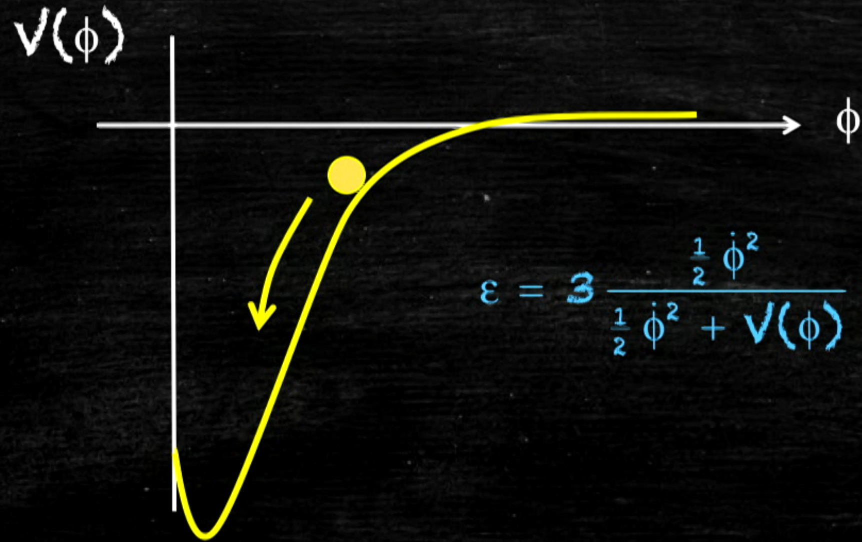
$V(\phi)$: flat & positive -> steep & negative

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



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

super-horizon modes "for free"

mode by mode picture:

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

super-horizon modes "for free"

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$H^{-1} \sim t$

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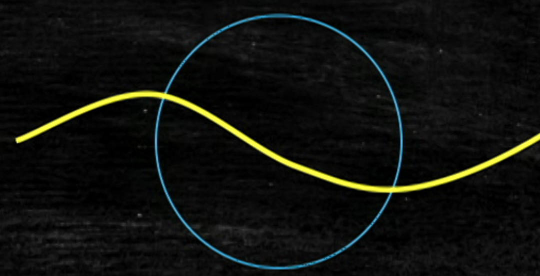

No ‘multimess’

inflation:
what you thought were typical
regions become atypical
-> theory breaks down, cannot
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$\delta\rho/\rho \sim 1$

natural "messer"

contraction:
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-> 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

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- typically produce too much non-gaussianity

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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

(+ cannot be realized with a single scalar field)

simplest ekpyrotic theory*

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

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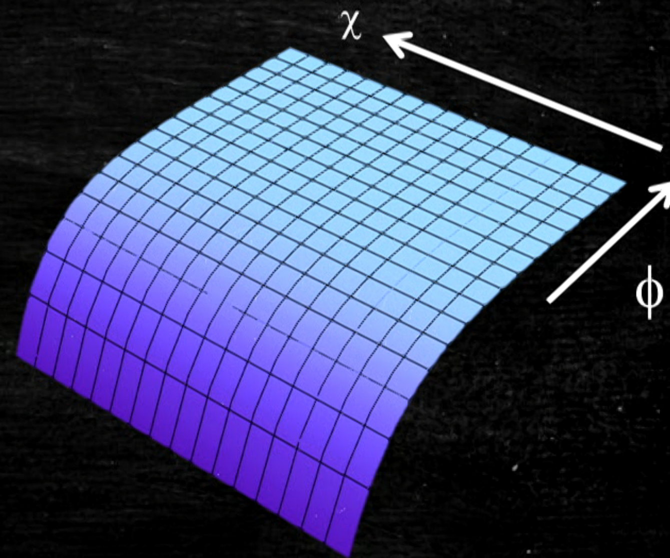

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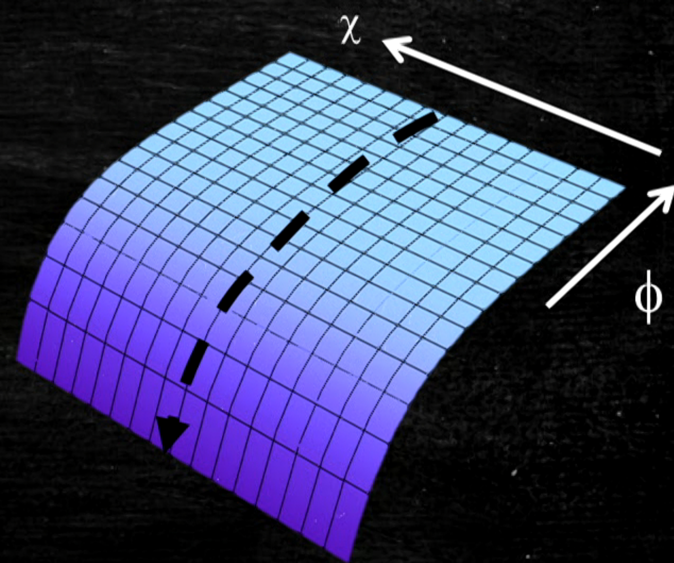
-> stable solutions



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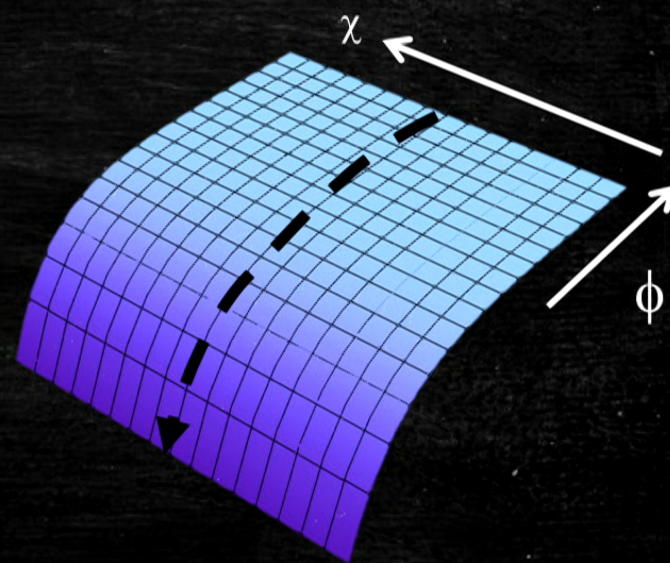
-> stable solutions

-> least tuned

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



Single-field scenario: anamorphic cosmology*

It's all about friction ... again!

FRW metric: $ds^2 = -dt^2 + a^2(t)\, dx_i dx^i$

Single-field scenario: anamorphic cosmology*

It's all about friction ... again!

assume: m/M_{Pl} time varying!

FRW metric: $ds^2 = -dt^2 + a^2(t)\, dx_i dx^i$ -> background

$$\Theta_{Pl} \equiv \left(H + \frac{\dot{M}_{Pl}}{M_{Pl}} \right) / M_{Pl}$$

friction experienced by curvature modes

$$\Theta_{m} \equiv \left(H + \frac{\dot{m}}{m} \right) / M_{Pl}$$

friction experienced by matter and radiation (background)

RECAP: advantages of ekpyrotic contraction

- familiar ingredients
- familiar symmetries
- classical initial conditions prior to smoothing phase
- no multimess
- simplest models fit observations (stable, least tuning, negligible nG)

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BUT . . .

is a cosmological bounce possible?

The challenge

2nd Friedmann eq: $\dot{H} = -(\rho + p)/2 = -\varepsilon H^2$

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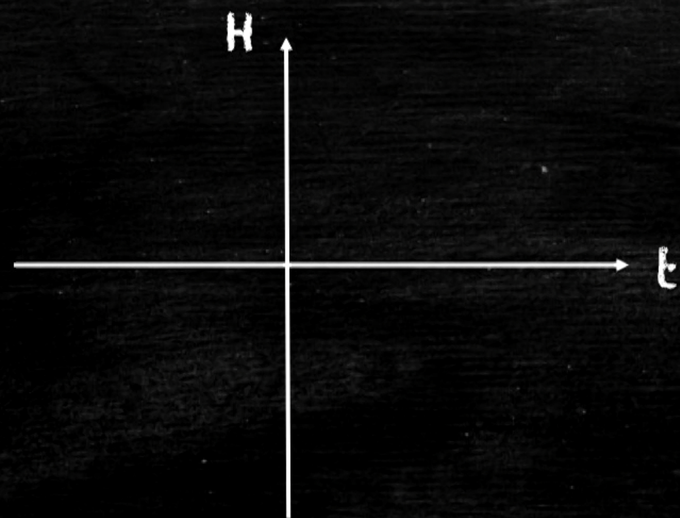

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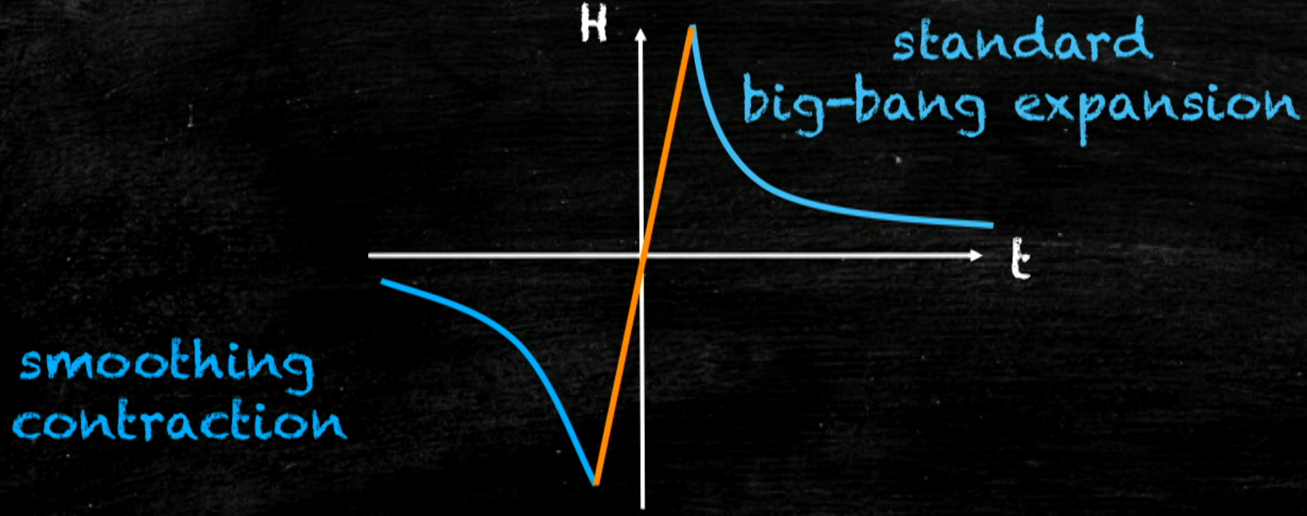

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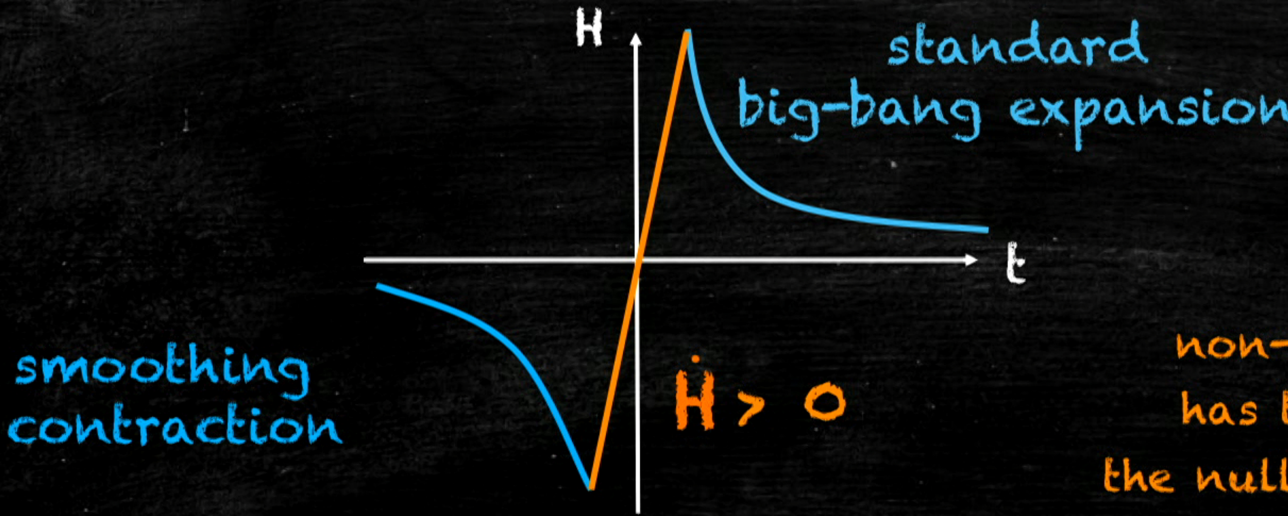

non-singular bounce
has to stably violate
the null energy condition!

first attempts: ghost condensate

$$L = \frac{1}{2} M_{Pl}^2 R - \frac{1}{2} k(\phi)(\partial\phi)^2 + \frac{1}{4} M_{Pl}^{-4} q(\phi)(\partial\phi)^4 - V(\phi)$$

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

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NO quantum ghost instability

next attempts: NEC-violation with L_3 Horndeski matter

$$L = \frac{1}{2} M_{Pl}^2 R - \frac{1}{2} k(\phi)(\partial\phi)^2 + \frac{1}{4} M_{Pl}^{-4} q(\phi)(\partial\phi)^4 - V(\phi) + \frac{1}{2} M_{Pl}^{-3} b(\phi)(\partial\phi)^2 \Box\phi$$

Background:

$$3H^2 = \rho = \frac{1}{2} k(\phi)\dot{\phi}^2 + \frac{3}{4} q(\phi)\dot{\phi}^4 + V - \frac{1}{2} b'(\phi)\dot{\phi}^4 + 3Hb(\phi)\dot{\phi}^3,$$

$$-2\dot{H} = \rho + p = k(\phi)\dot{\phi}^2 + q(\phi)\dot{\phi}^4 - b'(\phi)\dot{\phi}^4 + 3Hb(\phi)\dot{\phi}^3 - b(\phi)\ddot{\phi}\dot{\phi}^2$$

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- motivated by fundamental symmetries: conformal & Galilean shift ($\phi \rightarrow \phi + b_\mu x^\mu$)
- seems to appear naturally in UV-complete theories:
  -> in SUGRA,
  -> in higher-dimensional theories with branes, etc.

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Libanov, Mironov, Rubakov 2016
Kobayashi 2016

$$B(t) = a^{-1}(t)\frac{d}{dt}\left(a(t)\gamma(t)^{-1}\right) - 1 > 0$$

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Libanov, Mironov, Rubakov 2016
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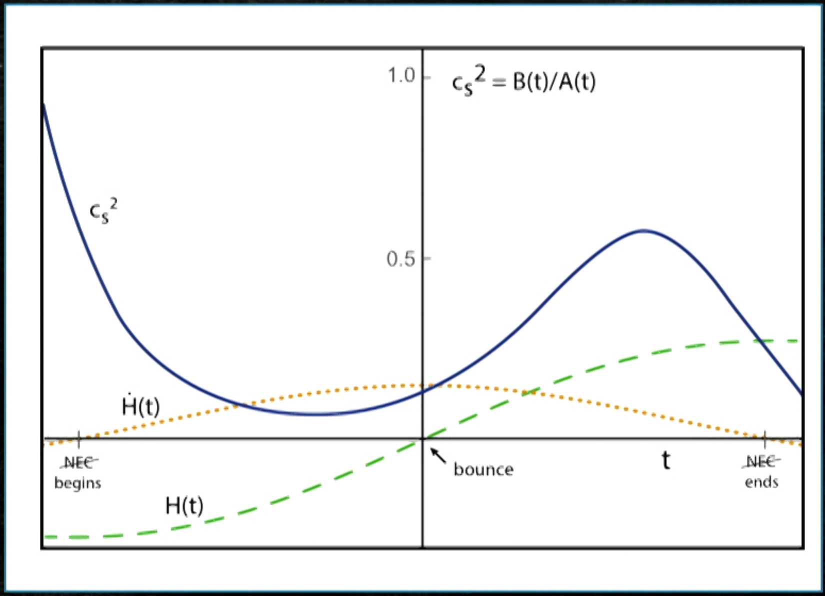
$$B(t) = a^{-1}(t)\frac{d}{dt}\left(a(t)\gamma(t)^{-1}\right) - 1 > 0 \quad \text{where} \quad \gamma(t) = H - \tfrac{1}{2}b\dot{\phi}^3$$

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

'guilt by association' *

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



What is the source of the bad behavior?

$$\frac{a(t)}{\gamma(t)}\Big|_{t_0} - \frac{a(t)}{\gamma(t)}\Big|_{t} \geq \int_{t}^{t_0} a(t)\, dt$$

-> add L_4 Horndeski interaction:

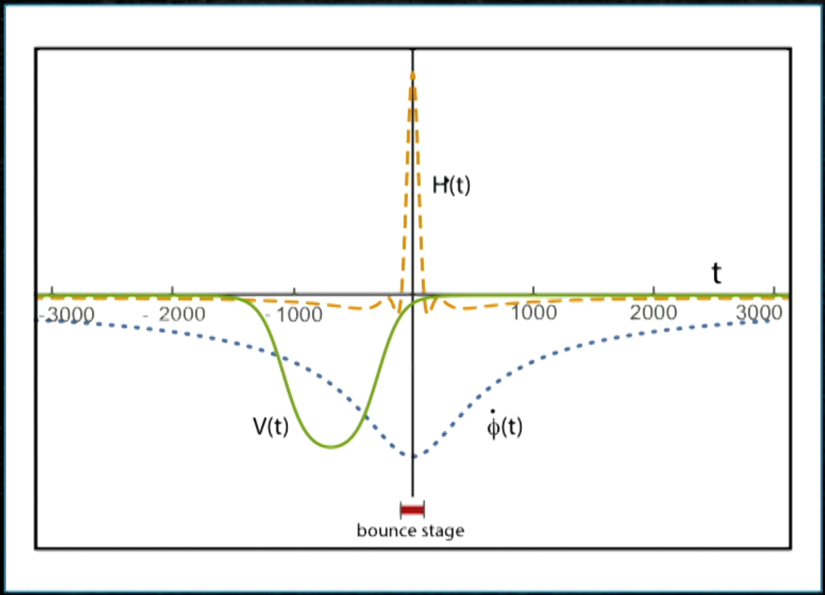
What is the source of the bad behavior?

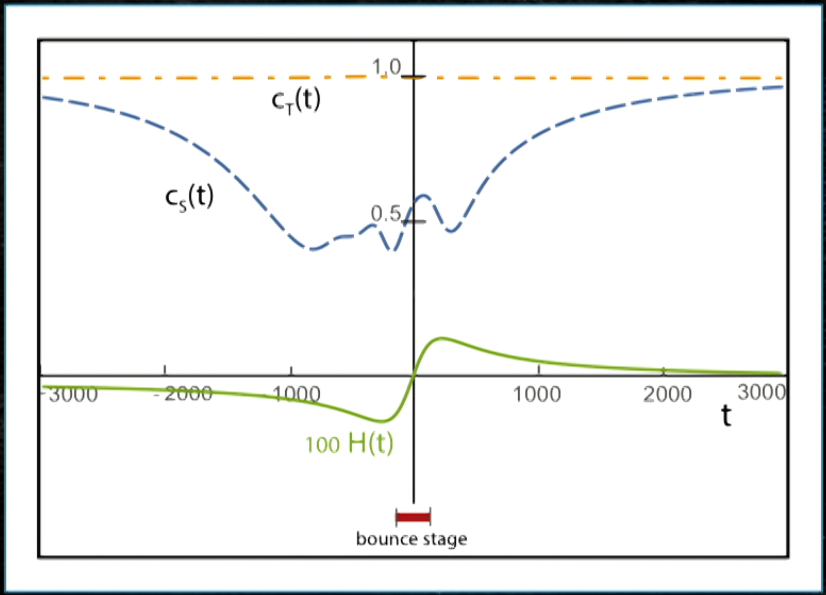
$$\frac{a(t)}{\gamma(t)}\Big|_{t_0} - \frac{a(t)}{\gamma(t)}\Big|_{t} \geq \int_t^{t_0} a(t)\,dt$$

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

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

collaborators & references

ekpyrotic theory with non-canonical kinetic term

AI, J.-L. Lehners, P.J. Steinhardt, PRD 89 (2014) 123520

A. Levy, AI, P.J. Steinhardt, PRD 92 (2015) 063524

anamorphic cosmology

AI, P.J. Steinhardt, JCAP 10 (2015) 001

AI, arXiv:1610.02752

fully stable non-singular bounce

AI, P.J. Steinhardt, PRL 117 (2016) 121304

AI, P.J. Steinhardt, PLB 764 (2016) 289

AI, to appear soon

full-blown numerical analysis of non-singular bounces

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

SUGRA implementation

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