Title: Converting entropy to curvature perturbations after a cosmic bounce

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Abstract: <p>In this talk, I will show how entropy perturbations created during a contracting phase and converted into adiabatic/curvature perturbations after a bounce form the dominant contribution to the observed temperature ï¬,uctuations in the CMB.
In [arXiv:1607.05663] we have studied two-ï¬•eld bouncing cosmologies in which primordial perturbations are created in either an ekpyrotic or a matter-dominated contraction phase. We then used a non-singular ghost condensate bounce model to follow the perturbations through the bounce into the expanding phase of the universe. In contrast to the adiabatic perturbations, which on large scales are conserved across the bounce, entropy perturbations can grow signiï¬•cantly during the bounce phase. If they are converted into adiabatic/curvature perturbations after the bounce, they typically form the dominant contribution to the observed temperature ï¬,uctuations in the microwave background, which can have several beneï¬•cial implications. For ekpyrotic models, this mechanism loosens the constraints on the amplitude of the ekpyrotic potential while naturally suppressing the intrinsic amount of non-Gaussianity. For matter bounce models, the mechanism ampliï¬•es the scalar perturbations compared to the associated primordial gravitational waves with the consequence that the tensor-to-scalar ratio is typically reduced by an order of magnitude or so, bringing it close to current observational bounds.</p>

Converting entropy to curvature perturbations *after* a cosmic bounce

Angelika Fertig

Work with Jean-Luc Lehners, Enno Mallwitz and Edward Wilson-Ewing

arXiv:1607.05663 [hep-th]

PI Cosmology Seminar, 06 Sept 2016

Take-home points

Adiabatic perturbations are conserved across the bounce on large scales [Battarra et al 2014; Koehn et al 2016], whereas **entropy pert.s can grow significantly**.

If they are converted into adiabatic pert.s **after** the bounce, they typically form the **dominant contribution to the CMB** temperature fluctuations.

Take-home points

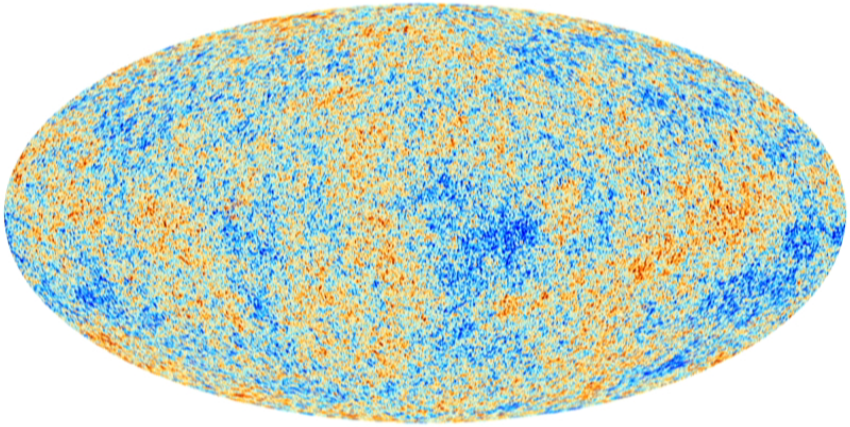
Adiabatic perturbations are conserved across the bounce on large scales,
whereas **entropy pert.s can grow significantly**.

If they are converted into adiabatic pert.s **after** the bounce, they typically form the **dominant contribution to the CMB** temperature fluctuations.

Consequences for:

- **ekpyrotic models:** constraints on the amplitude of the ekpyrotic potential are loosened & **intrinsic NG is suppressed**.
- **matter bounce models:** **tensor-to-scalar ratio r is lowered** due to amplified scalar pert.s compared to the primordial gravitational waves.

Goal: Explain the origin of structure



Structure formation via collapse from small primordial pert.s

Density fluct.s arose from **amplification of quantum pert.s** via particular cosmological dynamics:

Accelerated **expansion** = inflation

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Contraction:
- slow high-pressure contraction = ekpyrosis
- matter-dominated pressure-free contraction

More than one scalar field

Entropy/isocurvature in addition to adiabatic/curvature pert.s

→ **Entropy pert. acts as a source for curvature pert.**

⇒ Curvature pert. present at onset of hot BB phase can have an involved pre-history

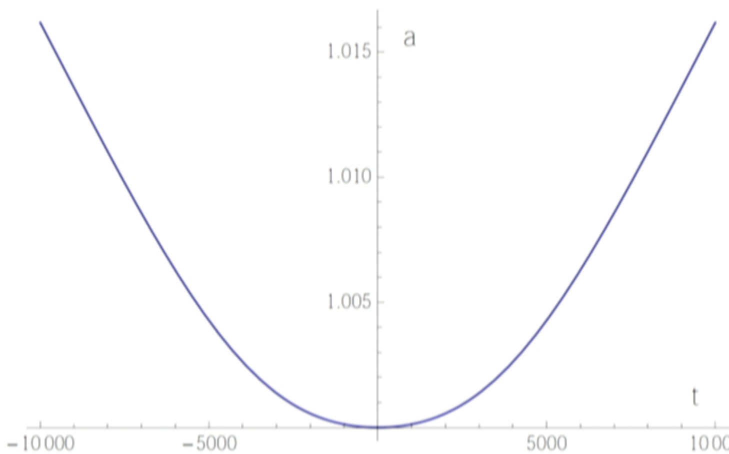
Note: Once/ if the universe reaches thermal equilibrium during the hot BB phase, the entropy pert.s disappear
[Weinberg 2004]

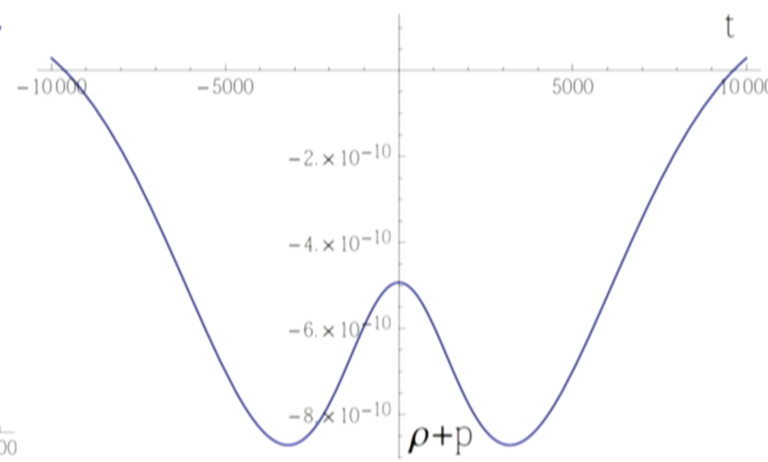
A bounce

Replace the big bang with a bounce: $\dot{H} = -\frac{1}{2}(\rho + p) > 0$
for a flat universe.

Bounce: • singular ($a \to 0$) or • non-singular ($a \to a_{\min} > 0$)

Non-singular implies **NEC violation**: $\rho + p < 0$





A ghost condensate bounce

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{R}{2} + P(X,\phi) - \frac{1}{2}(\partial\chi)^2 - V(\phi,\chi) \right]$$

$$X \equiv -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi = -\frac{1}{2}(\partial\phi)^2 \qquad V(\phi) = -\frac{2V_0}{e^{-\sqrt{2\epsilon}\phi} + e^{\sqrt{2\epsilon}\phi}}$$

ϕ drives the bounce, while χ is transverse (in field space) to the background trajectory during the bounce phase.

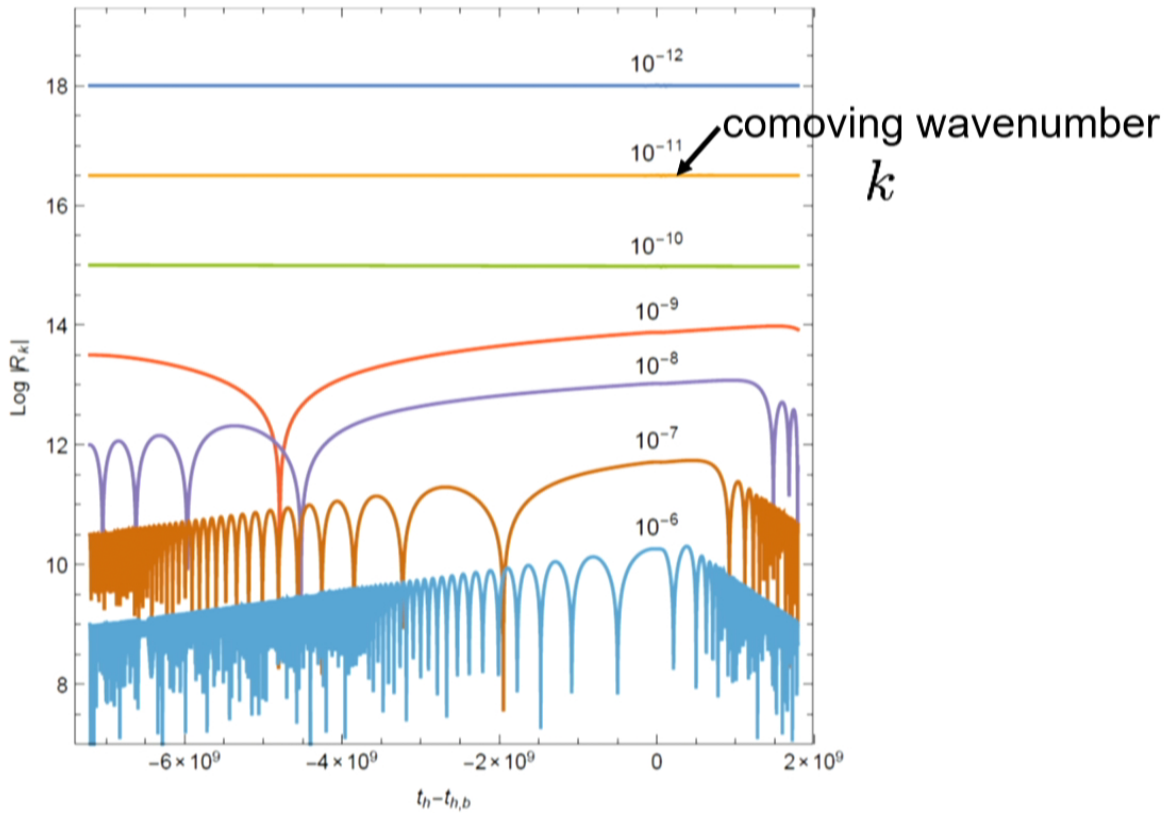
$$P(X,\phi) = K(\phi)X + Q(\phi)X^2$$

$$K(\phi) = 1 - \frac{2}{\left(1+\frac{1}{2}\phi^2\right)^2} \qquad Q(\phi) = \frac{q}{\left(1+\frac{1}{2}\phi^2\right)^2}$$

During the ghost-condensate phase:
$K(\phi)$ changes its sign to -ve values while $Q(\phi)$ is turned on.
[Creminelli et al 2006, 2007; Buchbinder et al 2007]

$\Rightarrow$ NEC violation and bounce
$\Rightarrow$ **fluct.ns** do not become ghost-like, due to the influence of the higher-derivative terms. [Arkani-Hamed et al 2004]

Curvature pert.s through a ghost-condensate bounce



Long-wavelength curvature modes are conserved.

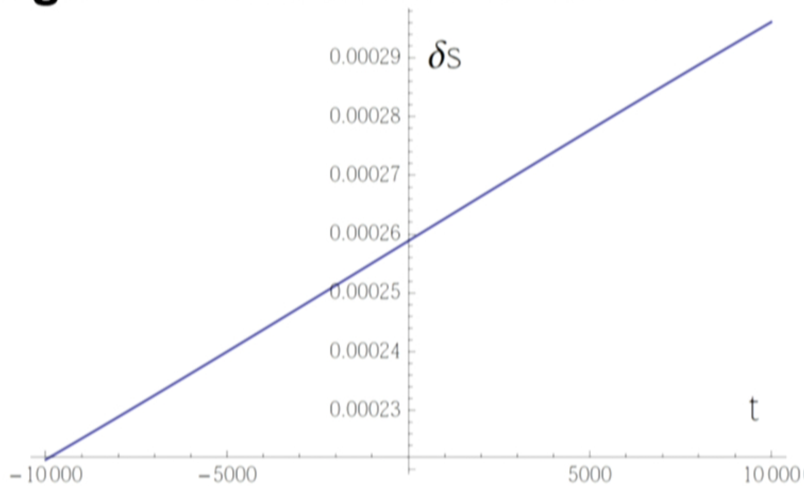
[Battarra et al 2014; Koehn et al 2016]

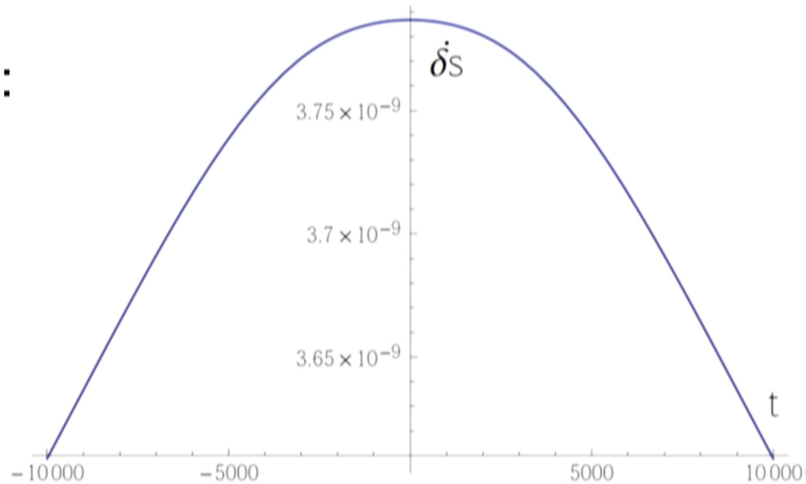
Entropy pert.s through a ghost-condensate bounce

stable
transverse
potential
$V_{ss} = V_{sss} = 0$

$$\delta s \sim A\,\mathrm{Erf}\left(\frac{t}{\sqrt{6q}}\right) + B$$

condition for amplification:
entropy pert.s
are not frozen
at the onset of
the bouncing phase,
i.e. $\dot{\delta s} \neq 0$

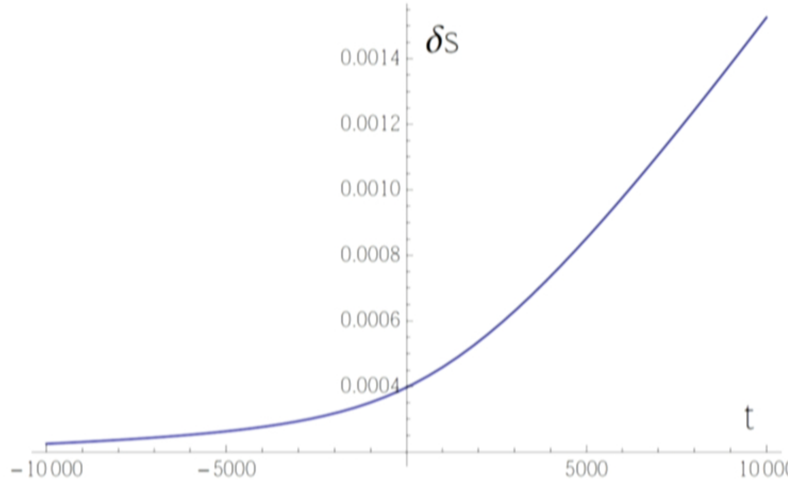




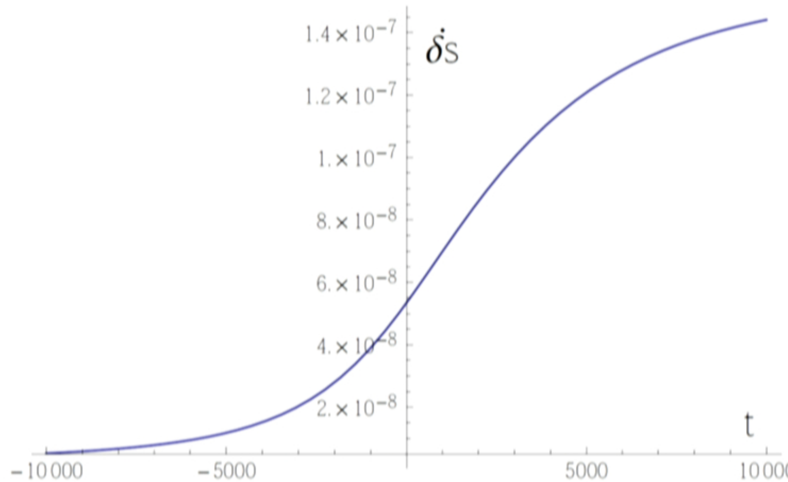
Entropy pert.s through a ghost-condensate bounce

unstable
transverse
potential
$V_{ss} \neq 0$

$\Rightarrow$ additional amplification of the entropy pert.s.

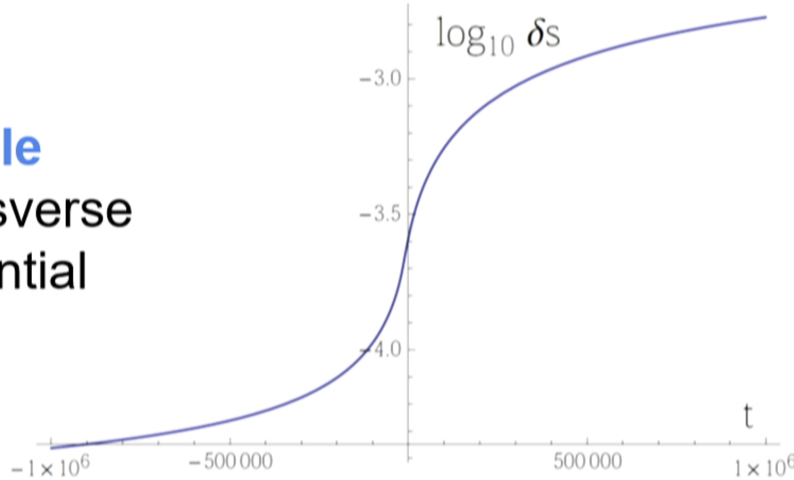


But: require more special initial conditions (trajectories close to the ridge)

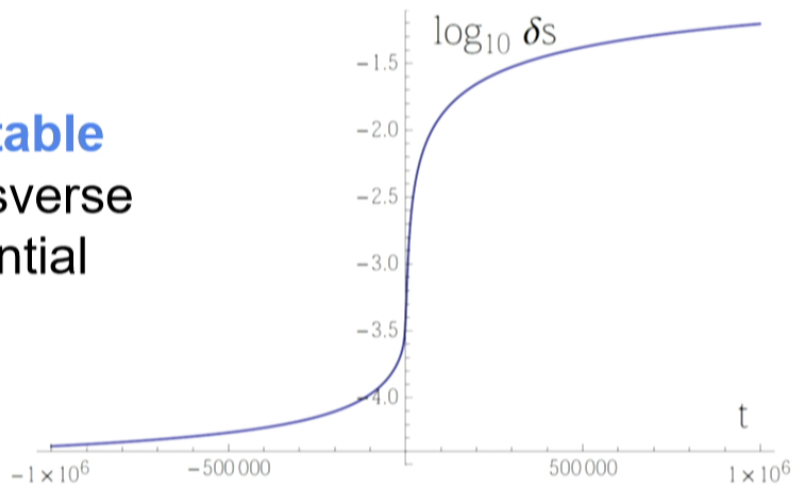


Entropy pert.s through kinetic & bounce phases

stable
transverse
potential



unstable
transverse
potential



Kinetic phase:

$\delta s \sim C \ln t + D$

$\Rightarrow$ **logarithmic growth**

conditional upon $\dot{\delta s} \neq 0$

otherwise $\delta s = D$

$\Rightarrow$ no growth

Combined effect of kinetic & bounce phases: significant overall amplification of entropy pert.s

Perturbations through a ghost-condensate bounce

- Flat, non-singular ghost condensate bounce model to follow the pert.s through the bounce into the expanding phase of the universe.
- Adiabatic pert.s: conserved across the bounce on large scales, but
- **Entropy pert.s can grow significantly during the bounce phase.**
- If they are converted into adiabatic/curvature pert.s *after* the bounce, they typically form the dominant contribution to the observed temperature fluctuations in the CMB.

A bounce

Replace the big bang with a bounce: $\dot{H} = -\frac{1}{2}(\rho + p) > 0$
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Bounce: • singular ($a \to 0$) or • non-singular ($a \to a_{\min} > 0$)

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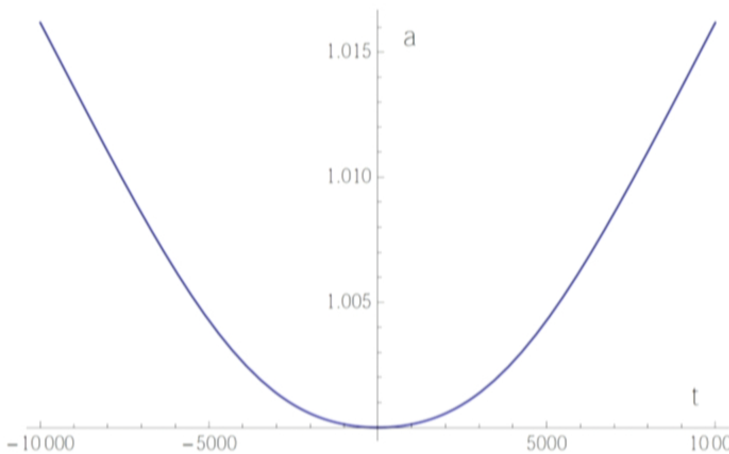

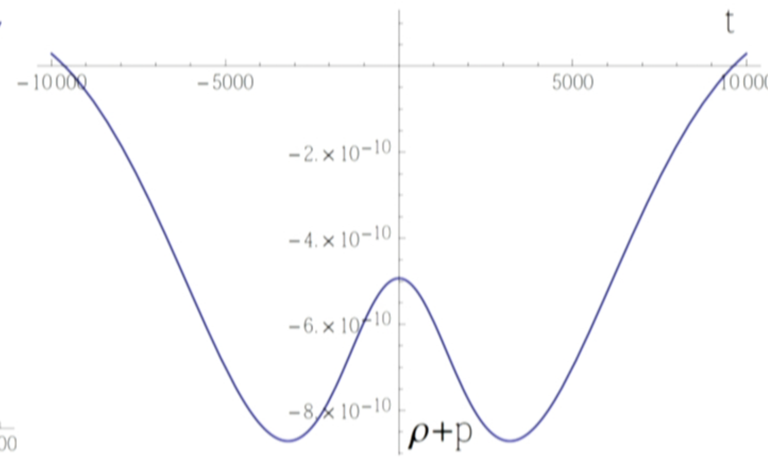

Consequences for ekpyrotic models

This mechanism

- naturally suppresses the intrinsic amount of **non-Gaussianity**,
- loosens the constraints on the **amplitude of the ekpyrotic potential.**

Ekpyrotic contracting phase

Friedmann equ.: $3H^2 = \frac{-3\kappa}{a^2} + \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4} + \frac{\sigma^2}{a^6} + \frac{\rho_\phi}{a^{2\epsilon}}$

Scalar field with a very stiff equation of state $\epsilon > 3$ dominates the dynamics in a contracting universe.

Modelled with $V(\phi) = -V_0 e^{\sqrt{2\epsilon}\phi}$

Scaling solution:

$$a \propto (-t)^{1/\epsilon}, \quad \phi = \sqrt{\frac{2}{\epsilon}} \ln \left[-\left(\frac{V_0 \epsilon^2}{\epsilon - 3} \right)^{1/2} t \right], \quad \epsilon = \frac{c^2}{2} = \frac{3}{2}(1+w)$$

If this phase lasts long enough, homogeneous curvature and anisotropies will be suppressed to such an extent that they become irrelevant for the rest of the evolution.

Ekpyrotic perturbations

Perturbations in the scalar field ϕ stay quantum [Battarra&Lehners 2013]
& have a blue spectrum [Lyth 2002]

$\rightarrow$ need a second field χ

Two possibilities; adding a scalar χ with a

- canonical kinetic term and an unstable potential,
  [Notari&Riotto 2002; Finelli 2002; Lehners et al 2007]
- non-minimal kinetic coupling to ϕ and a stable potential.
  [Qiu et al 2013; Li 2013; Fertig et al 2014; Ijjas et al 2014]

2-step **entropic mechanism**:

1. Pert.s in χ are **entropy pert.s**, which are amplified and can become (nearly) scale-invariant.
2. These can then act as **seeds for the curvature pert.s**.

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Conversion

$$V(\phi) = -\frac{2V_0}{e^{-\sqrt{2\epsilon}\phi} + e^{\sqrt{2\epsilon}\phi}} \left(1 + \frac{1}{2}\epsilon\chi^2 + \frac{1}{3!}\epsilon^{3/2}\kappa_3\chi^3\right) + V_{\rm rep}$$

κ_3 parameterizes the tilt of the unstable direction.

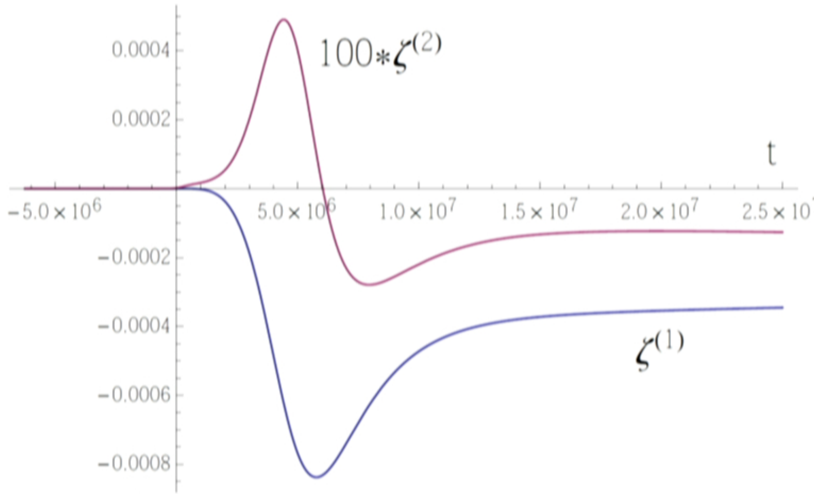
Repulsive potential: a smooth (Gaussian-shaped) barrier oriented at an angle to the background trajectory.

Overall scale of the repulsive potential chosen such that the **conversion is efficient**.
$\Rightarrow$ greater structure formation
$\Rightarrow$ narrow range of predictions for non-Gaussian corrections
Open problem: justify this assumption in a more fundamental context.

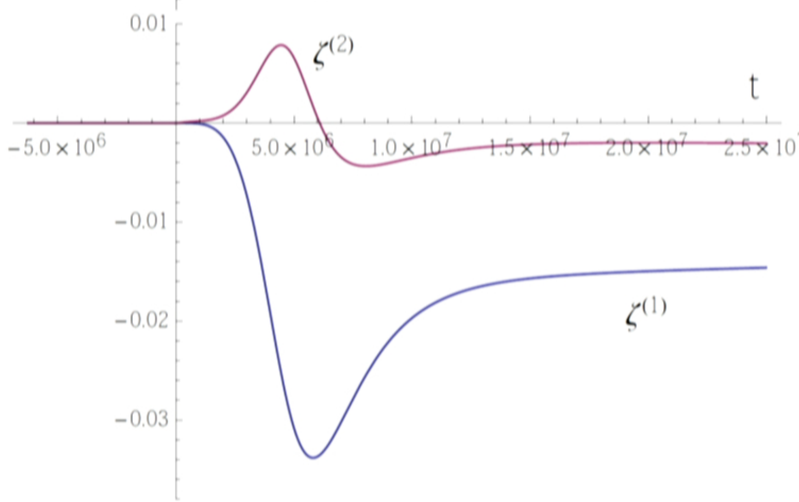
Curvature pert.s through bounce & conversion phases

bounce with

stable transverse potential, $V = V(\phi)$



unstable transverse potential with $\kappa_3 = 0$



Ekpyrotic results for efficient conversions

bounce with

stable transverse potential, $V = V(\phi)$

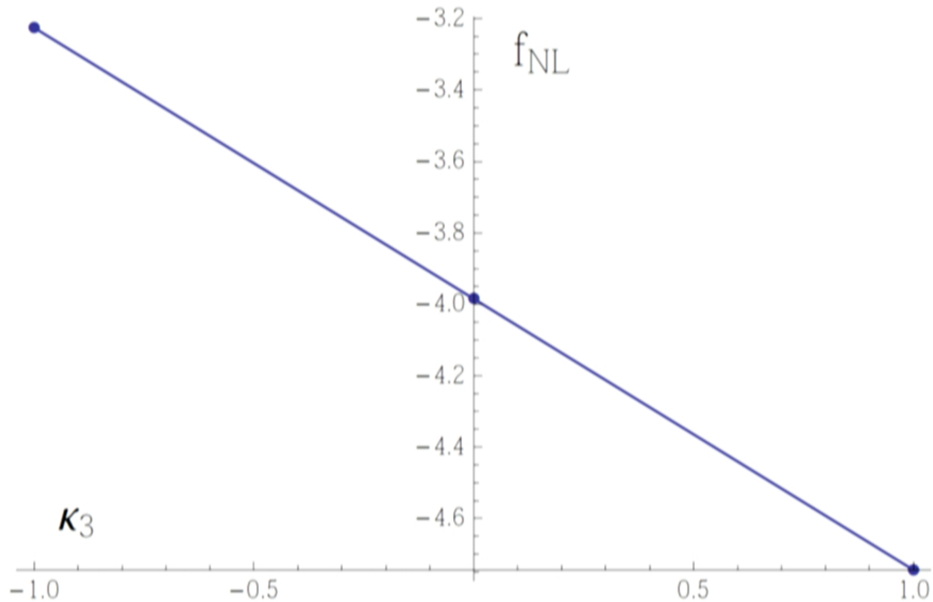
$$\mathcal{R}_{\text{final}} = -3.5 \times 10^{-4}$$
$$\frac{\mathcal{R}_{\text{final}}}{\delta s_{\text{conv-beg}}} = -0.18$$
$$f_{\text{NL}} = -4.0$$

unstable transverse potential with $\kappa_3 = 0$

$$\mathcal{R}_{\text{final}} = -1.5 \times 10^{-2}$$
$$\frac{\mathcal{R}_{\text{final}}}{\delta s_{\text{conv-beg}}} = -0.20$$
$$f_{\text{NL}} = -3.6$$

So far: entropy pert.n was **Gaussian** before the conversion
$\Rightarrow$ relevant case for non-minimally coupled ekpyrotic models

In ekpyrotic models with an **unstable ekpyrotic potential**, there can already be a significant **intrinsic NG** in the entropy pert., due to $\kappa_3 \neq 0$:



Comparison to conversion before the bounce

Conversion

after bounce,
⇒ **weak dependence on κ_3**:
intrinsic O(2) term ~ O(1) term,
→ its rel. importance to
(O(1) term)^2 is lessened.

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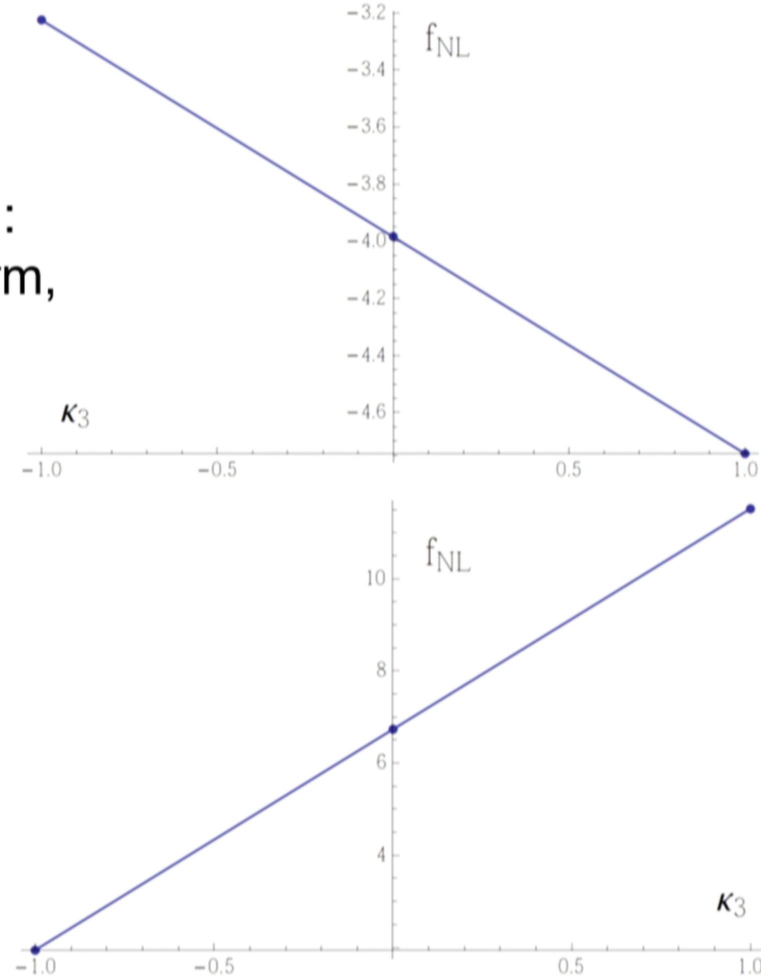
before bounce:
main contribution from
a possible **intrinsic NG**,
neglecting nonlinearities
of the conversion process.



Constraint on amplitude of the ekpyrotic potential

For conversion **before** the bounce:

$$\langle \mathcal{R}^2 \rangle \equiv \int \frac{\mathrm{d}k}{k} \Delta_{\mathcal{R}}^2 \approx \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \frac{\epsilon V_{\text{ek-end}}}{100\pi^2} k^{n_S - 1}$$

Matching to the observed value of $\Delta_{\mathcal{R}}^2 = 2.4 \times 10^{-9}$ leads to an estimated depth of the potential of $|V_{\text{ek-end}}| \approx (10^{-2} M_{\text{Pl}})^4$ (around the GUT scale).

For conversion **after** the bounce:
Final amplitude of the curvature pert. is enhanced by approximately two to four orders of magnitude.
$\Rightarrow$ **Potential does not have to become quite so deep:**

$$|V_{\text{ek-end}}| \approx [(10^{-4} - 10^{-3}) M_{\text{Pl}}]^4$$

Consequences for ekpyrotic models

This mechanism

- naturally suppresses the intrinsic amount of **non-Gaussianity**, ✓
- loosens the constraints on the **amplitude of the ekpyrotic potential.** ✓

Also: $-5 \lesssim f_{\rm NL} \lesssim +5$ (efficient conversion),

consistent with observations: $f_{\rm NL} = 0.8 \pm 10.0 \quad (2\sigma)$ **[Planck 2015]**

Consequences for matter bounce models

This mechanism amplifies the scalar pert.s compared to the associated primordial gravitational waves, lowering the **tensor-to-scalar ratio r**.

Two-field matter bounce model

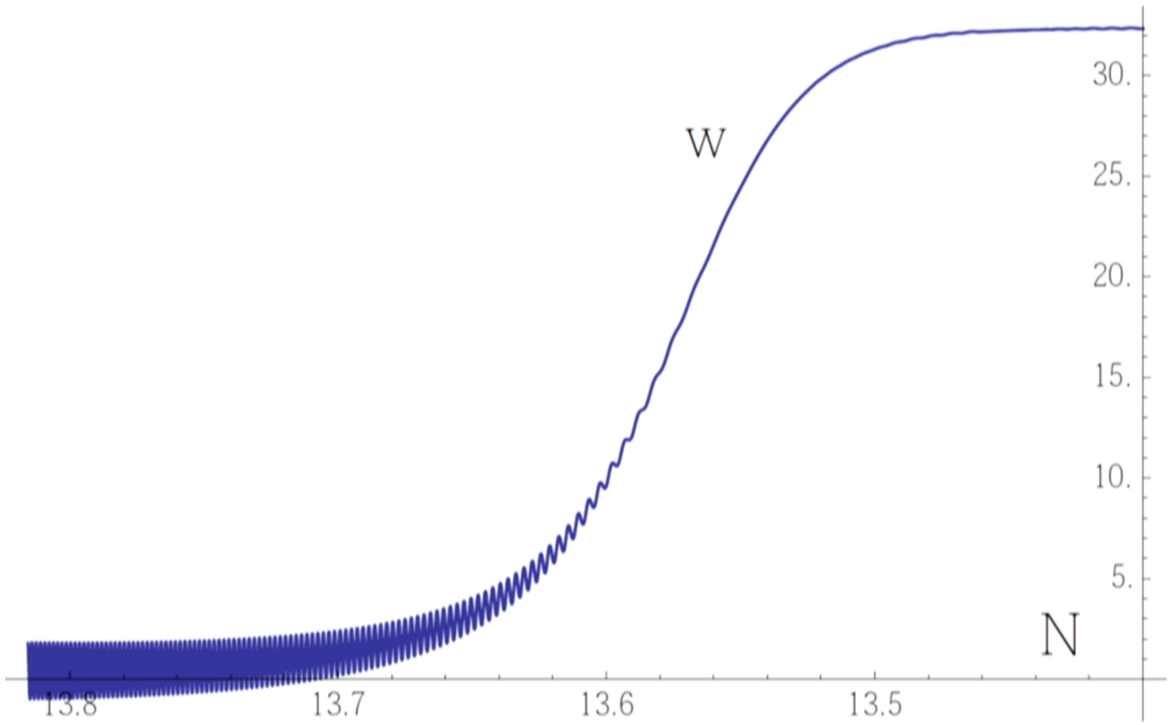
Two scalar fields: $V(\phi, \chi) = \frac{1}{2}m^2\chi^2 - V_0 e^{c\phi}$ **[Cai et al 2013]**

- 1^{st} massive field χ dominates
- 2^{nd} ekpyrotic field ϕ dominates and 3^{rd} turns into a ghost condensate field

Scale-invariant **curvature & entropy pert.s** generated in a contracting universe dominated by a pressureless fluid:

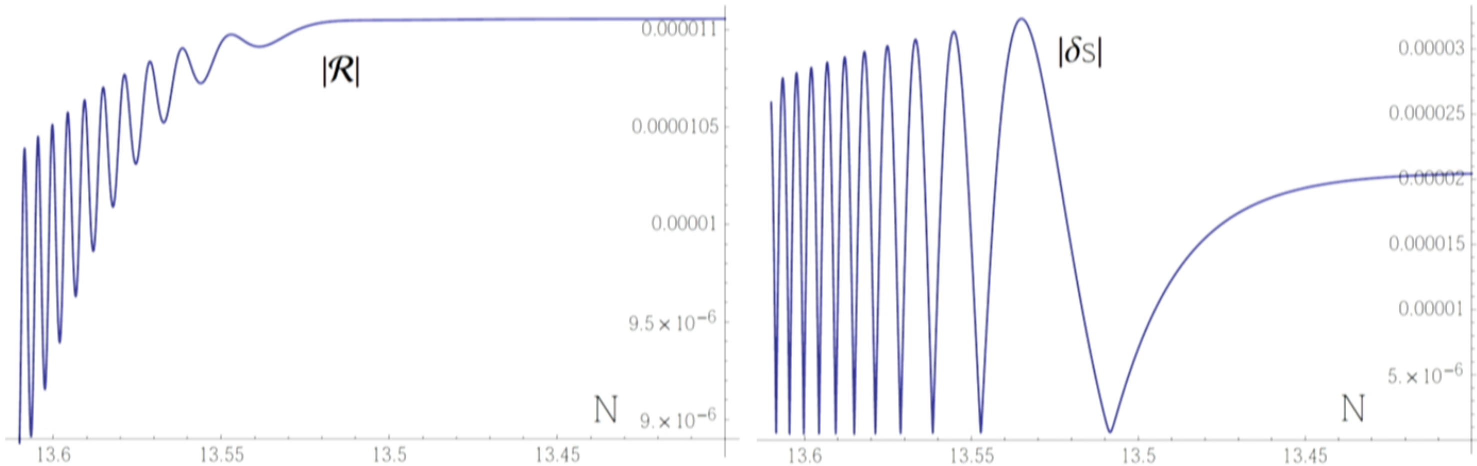
- **Curvature pert.s** remain frozen during the ekpyrotic and bounce phases,
- **Entropy pert.s** can grow and provide the dominant contribution to the curvature pert.s if the conversion *after* the bounce is efficient.

Evolution of the effective eos of the background



Transition from matter-dominated to ekpyrotic phase occurs when the effective eos stops oscillating around 0 and grows to a large constant value. Here, at $\mathcal{N} \approx 13.7$.

Evolution of pert.s during matter & ekpyrotic phases



Curvature pert.:
oscillate w/ growing amplitude during the matter phase, freeze during the ekpyrotic phase when $\dot{\theta} \to 0$

Entropy pert.:
oscillate w/ growing amplitude during the matter phase, non-trivial evolution for $m^2 > H^2$

Evolution of pert.s during ekpyrotic & bounce phases

Key points:

1. $\mathcal{R}(t_{\text{ek-beg}}) \sim \delta s(t_{\text{ek-beg}})$
2. $\mathcal{R} \to \text{const}$ shortly after the onset of the ekpyrotic phase;
3. For the entropy pert.s not to freeze, ekpyrotic phase has to be sufficiently short and to end before $m^2 < H^2$
4. Then in the next phase $\dot{\delta s} \neq 0$ necessarily and δs will grow during the bounce and kinetic-dominated phases

   - by two or three orders of magnitude depending on the transverse potential;

   - by one or two orders of magnitude if the transverse potential is negligible, due to the kinetic phase.

$\Rightarrow$ After the bounce, the entropy pert.s have a significantly larger amplitude than the curvature pert.s.

Conversion after the bounce

In the simplest matter bounce models, the tensor-to-scalar ratio is typically predicted to be too large: [Quintin et al 2015]

The equation of motion for the tensor modes generates essentially the same dynamics as for the curvature pert., s.t. the tensor-to-scalar ratio is

$$r = \frac{\Delta_h(k)^2}{\Delta_{\mathcal{R}}(k)^2} = \mathcal{O}(1) \qquad \text{cf.} \quad r < 0.12 \quad (2\sigma)$$ [Bicep2&Planck 2015]

Here: amplitude of entropy pert.
- grows by at least an order of magnitude during the bounce,
- becomes the dominant contribution to the curvature pert. (following an efficient conversion process after the bounce)

$\rightarrow$ increases amplitude of curvature pert.s w.r.t. tensor pert.s:

$$\boxed{r \lesssim \mathcal{O}(10^{-2})}$$

Take-home points

Adiabatic perturbations are conserved across the bounce on large scales,
whereas **entropy pert.s can grow significantly**.

If they are converted into adiabatic pert.s **after** the bounce, they typically form the **dominant contribution to the CMB** temperature fluctuations.

Consequences for:

- **ekpyrotic models:** constraints on the amplitude of the ekpyrotic potential are loosened & **intrinsic NG is suppressed**.
- **matter bounce models:** **tensor-to-scalar ratio r is lowered** due to amplified scalar pert.s compared to the associated primordial gravitational waves.