# Can bouncing scenarios generate primordial features?

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International Conference on Gravitation and Cosmology

IISER, Mohali

December 10–13, 2019

# Plan of the talk

# This talk is based on. . .

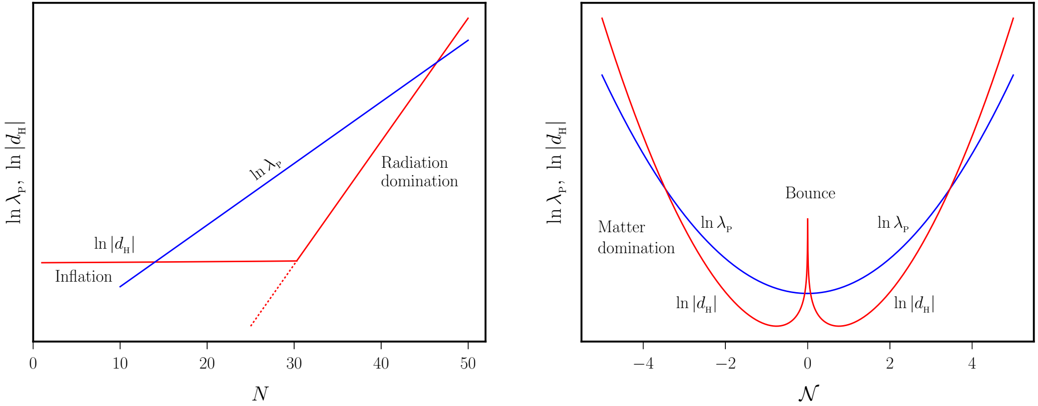
- R. N. Raveendran, D. Chowdhury and L. Sriramkumar, *Viable tensor-to-scalar ratio in a symmetric matter bounce*, JCAP **1801**, 030 (2018) [arXiv:1703.10061 [gr-qc]].
- R. N. Raveendran and L. Sriramkumar, *Viable scalar spectral tilt and tensor-to-scalar ratio in near-matter bounces*, Phys. Rev. D **100**, 083523 (2019) [arXiv:1812.06803 [astro-ph.CO]].
- R. N. Raveendran and L. Sriramkumar, *Primordial features from ekpyrotic bounces*, Phys. Rev. D **99**, 043527 (2019) [arXiv:1809.03229 [astro-ph.CO]].

# Classical bouncing scenarios as an alternative to inflation[1]

- Bouncing models correspond to situations wherein the universe initially goes through a period of contraction until the scale factor reaches a certain minimum value before transiting to the expanding phase.
- They offer an alternative to inflation to overcome the horizon problem, as they permit well motivated, Minkowski-like initial conditions to be imposed on the perturbations at early times during the contracting phase.
- However, matter fields may have to violate the null energy condition near the bounce in order to give rise to such a scale factor. Also, there exist (genuine) concerns whether such an assumption about the scale factor is valid in a domain where general relativity is expected to fail and quantum gravitational effects are supposed to take over.

[1] See, for instance, M. Novello and S. P. Bergliaffa, Phys. Rep. **463**, 127 (2008); D. Battefeld and P. Peter, Phys. Rep. **571**, 1 (2015).

# Overcoming the horizon problem in inflation and bounces




Behavior of the physical wavelength $\lambda_{\rm P} \propto a$ and the Hubble radius $d_{\rm H} = H^{-1}$ in inflationary[2] (on the left, with $a(N) \propto {\rm e}^{N}$) and bouncing scenarios[3] (on the right, with $a(\mathcal{N}) \propto {\rm e}^{\mathcal{N}^2}$).

[2]See, for example, E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley Publishing Company, New York, 1990), Fig. 8.4.

[3]Figure from, D. Chowdhury, *Inflation, bounces and primordial correlations*, Ph.D. Thesis, Indian Institute of Technology Madras, Chennai, 2018.

# Classical bounces and sources

Consider, for instance, bouncing models of the form

$$a(\eta) = a_0 \left(1 + \frac{\eta^2}{\eta_0^2}\right)^{1+\varepsilon} = a_0 \left(1 + k_0^2\, \eta^2\right)^{1+\varepsilon},$$

where $a_0$ is the value of the scale factor at the bounce (*i.e.* when $\eta = 0$), $\eta_0 = 1/k_0$ denotes the time scale of the duration of the bounce, and $\varepsilon > 0$.

The above scale factor can be achieved with the help of two fluids (with constant equation of state parameters) whose energy densities behave as

$$\rho_1 = \frac{\rho_0}{(a/a_0)^{(3+2\,\varepsilon)/(1+\varepsilon)}}, \quad \rho_2 = -\frac{\rho_0}{(a/a_0)^{2\,(2+\varepsilon)/(1+\varepsilon)}}.$$

where $\rho_0 = 12\, M_{\rm Pl}^2\, (k_0/a_0)^2\, (1+\varepsilon)^2$.

Note that the model depends only on the parameters $k_0/a_0$ and $\varepsilon$. While $\varepsilon = 0$ corresponds to the matter bounce scenario, $\varepsilon \ll 1$ corresponds to near-matter bounces.

# Driving near-matter bounces with scalar fields

Near-matter bounces with scale factor of the above form can also be achieved with the aid of two scalar fields, say, $\phi$ and $\chi$, that are governed by the action[4]

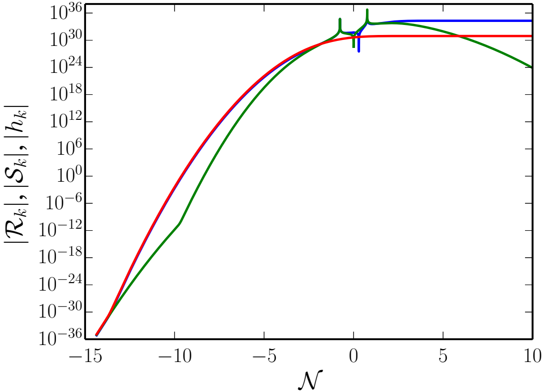
$$S[\phi, \chi] = -\int \mathrm{d}^4x \sqrt{-g} \left[\frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi + V(\phi) + U_0 \left(-\frac{1}{2}\,\partial_\mu\chi\,\partial^\mu\chi\right)^{(2+\varepsilon)/(1+\varepsilon)}\right],$$

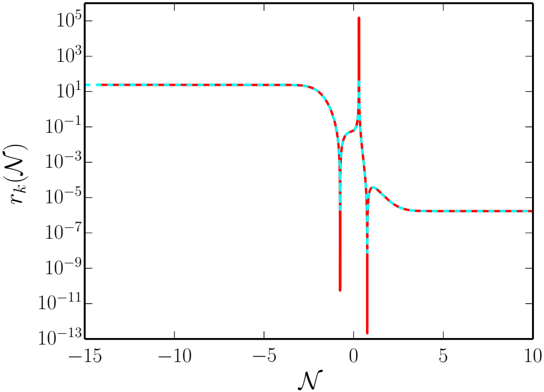
where $U_0$ is a constant of suitable dimensions, and the potential $V(\phi)$ is given by

$$V(\phi) = \frac{(3+4\,\varepsilon)}{(1+\varepsilon)}\,\frac{\rho_0}{12}\,\cosh^{-2\,(3+2\,\varepsilon)}\left[\frac{(\phi-\phi_0)/M_{\mathrm{Pl}}}{\sqrt{4\,(1+\varepsilon)\,(3+2\,\varepsilon)}}\right].$$

[4] R. N. Raveendran and L. Sriramkumar, arXiv:1812.06803 [astro-ph.CO].

# Viable power spectra in a near-matter bounce



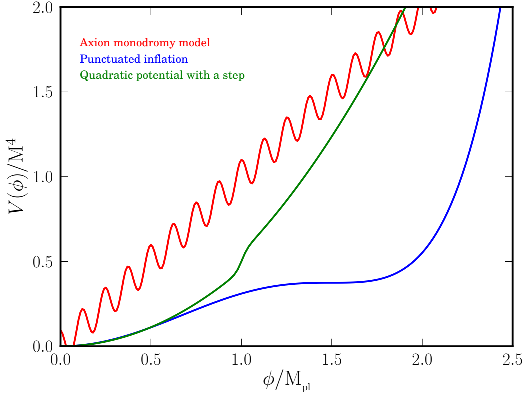



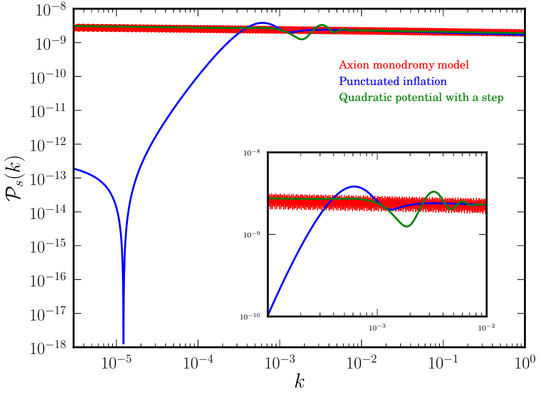

The evolution of the curvature (in blue), isocurvature (in green) and the tensor (in red) perturbations in a near-matter bounce that leads to a nearly scale invariant COBE normalized power spectrum of curvature perturbations with a spectral index of $n_{\mathrm{S}} \simeq 0.96$[5] (on the left), and the evolution of the tensor-to-scalar ratio in the matter bounce[6] (on the right).

[5] R. N. Raveendran and L. Sriramkumar, Phys. Rev. D **100**, 083523 (2019).

[6] R. N. Raveendran and L. Sriramkumar, JCAP **1801**, 030 (2018).

# Generating features in the inflationary scenario




Inflationary potentials that admit departures from slow roll (on the left) and the corresponding scalar power spectra (on the right). These spectra lead to a better fit to the CMB data than the more conventional, nearly scale invariant spectra[7].

[7] R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **0901**, 009 (2009); D. K. Hazra, M. Aich, R. K. Jain, L. Sriramkumar and T. Souradeep, JCAP **1010**, 008 (2010); M. Aich, D. K. Hazra, L. Sriramkumar and T. Souradeep, Phys. Rev. D **87**, 083526 (2013).

# Achieving stable contraction

The power law scale factor

$$a(\eta) = a_1 \left(\frac{\eta}{\eta_1}\right)^{2/(\lambda^2-2)}$$

corresponding to the constant equation of state $w = (\lambda^2 - 3)/3$, can be driven with the aid of a canonical scalar field described by the exponential potential

$$V(\phi) = V_0 \exp -\left(\frac{\lambda\,\phi}{M_{\mathrm{Pl}}}\right) = -\frac{2}{(a_1\,\eta_1)^2}\,\frac{\lambda^2-6}{(\lambda^2-2)^2}\,\exp -\left(\frac{\lambda\,\phi}{M_{\mathrm{Pl}}}\right).$$

It can be easily shown that, in an expanding universe, the solutions are stable when $\lambda^2 < 6$. Whereas, in a contracting universe, the solutions are found to be stable (*i.e.* they are attractors) when $\lambda^2 > 6$.

Note that, when $\lambda^2 > 6$, the potential $V(\phi)$ is *negative definite* resulting in $w > 1$. Such a *stiff* equation of state leads to a period of slow contraction (*i.e.* an ekpyrotic phase), which generates a *strongly blue* curvature perturbation spectrum[8].

[8] See, for instance, A. M. Levy, A. Ijjas and P. J. Steinhardt, Phys. Rev. D **92**, 063524 (2015).

# Extending the single field model

The model we shall consider involves two scalar fields $\phi$ and $\chi$, which are governed by the following action consisting of the potential $V(\phi,\chi)$ and a function $b(\phi)$[9]:

$$S[\phi,\chi] = \int \mathrm{d}^4x\,\sqrt{-g}\,\left[-\frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi - \frac{\mathrm{e}^{2\,b(\phi)}}{2}\,\partial_\mu\chi\,\partial^\mu\chi - V(\phi,\chi)\right].$$

We shall work with the potential $V(\phi,\chi) = V_{\mathrm{ek}}(\phi) = V_0\,\mathrm{e}^{-\lambda\,\phi/M_{\mathrm{Pl}}}$ and choose $b(\phi) = \mu\,\phi/(2\,M_{_{\mathrm{Pl}}})$, where $\lambda$ and $\mu$ are positive constants.

To convert the isocurvature perturbations into curvature perturbations, since the field $\phi$ dominates during the ekpyrotic phase, we shall require a turn along the $\chi$ direction. We achieve such a turn by multiplying the original potential $V_{\mathrm{ek}}(\phi)$ by the term[10]

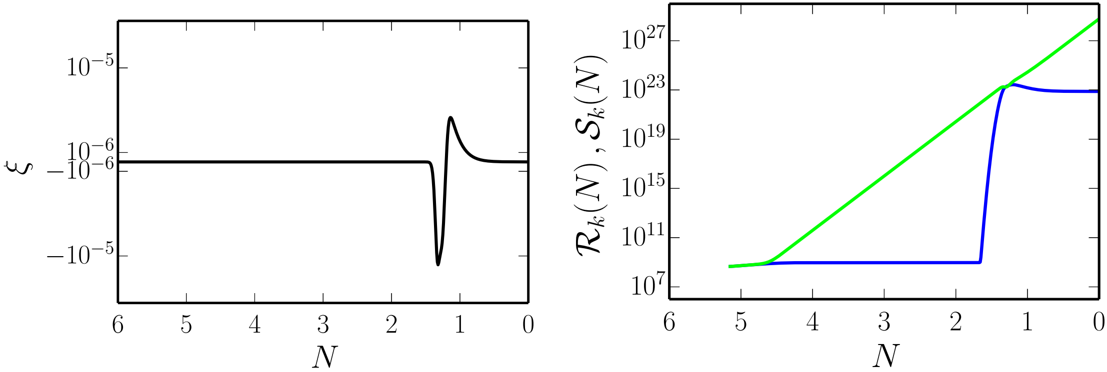
$$V_{\mathrm{c}}(\phi,\chi) = 1 + \beta\,\chi\,\exp-\left(\frac{\phi-\phi_{\mathrm{c}}}{\Delta\phi_{\mathrm{c}}}\right)^2,$$

where $\beta$, $\phi_{\mathrm{c}}$ and $\Delta\phi_{\mathrm{c}}$ are constants.

[9] See, for example, A. Ijjas, J.-L. Lehners and P. J. Steinhardt, Phys. Rev. D **89**, 123520 (2014).

[10] R. N. Raveendran and L. Sriramkumar, Phys. Rev. D **99**, 043527 (2019).

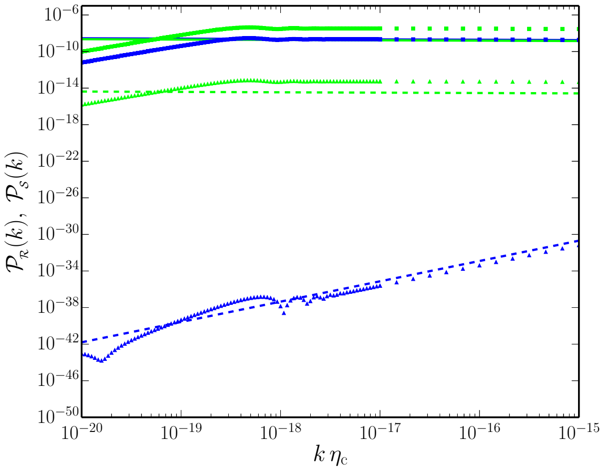
# Converting isocurvature perturbations into curvature perturbations




The behavior of the coupling function $\xi$ (on the left) and the corresponding effects on the curvature (in blue) and the isocurvature (in green) perturbations (on the right) have been plotted as a function of e-folds $N$. Note that time runs forward from left to right and the choice of $N = 0$ is arbitrary[11].

[11] R. N. Raveendran and L. Sriramkumar, Phys. Rev. D **99**, 043527 (2019).

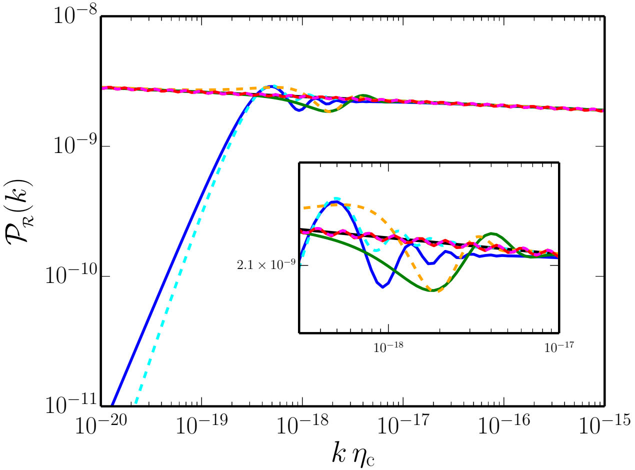
# The effects of conversion on the power spectra




The spectra of the curvature and the isocurvature perturbations (in blue and green, respectively), have been plotted prior to (as dashed lines and triangles) as well as during the turn (as solid lines and squares) in field space[12].

[12] R. N. Raveendran and L. Sriramkumar, Phys. Rev. D **99**, 043527 (2019).

# Features from ekpyrosis




The power spectra of the curvature perturbation with the three types of features generated in the ekpyrotic (solid lines) and the inflationary (dashed lines) scenarios have been plotted over scales of cosmological interest[13].

[13] R. N. Raveendran and L. Sriramkumar, Phys. Rev. D **99**, 043527 (2019).

# Summary

- Features in the primordial spectra can lead to strong constraints on the physics of the early universe.
- Many of the simpler and fine tuned bouncing models would prove to be unsustainable if future observations confirm the presence of features. *For the first time*, we have constructed bouncing scenarios which lead to features that have often been found to provide an improved fit to the CMB data.
- Though we have evaluated the spectra prior to the bounce, since the scales associated with the bounce are expected to be significantly different from the scales of cosmological interest, the shape of the spectra we have arrived at are unlikely to be altered by the dynamics of the bounce[14].
- It has been pointed out that, quite generically, the scalar non-Gaussianities generated in bounces may turn out be larger than the current constraints[15]. We are currently working towards evaluating the complete scalar bispectrum in bouncing models[16].

[14] See, for example, A. Fertig, J.-L. Lehners, E. Mallwitz and E. Wilson-Ewing, JCAP **1610**, 005 (2016).

[15] Y. B. Li, J. Quintin, D. G. Wang and Y. F. Cai, JCAP **1703**, 031 (2017).

[16] J.-L. Lehners, Adv. Astron. **2010**, 903907 (2010).

Thank you for your attention