Inflation and alternatives

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Plan of the talk

This talk is based on. . .

- D. Chowdhury, V. Sreenath and L. Sriramkumar, *The tensor bispectrum in a matter bounce*, JCAP **1511**, 002 (2015) [arXiv:1506.06475 [astro-ph.CO]].

Plan of the talk

Paddy before I started my thesis work

Paddy, in the (g)olden days at IUCAA (*c.* 1992), when he had won the Bhatnagar award.

Paddy when I finished my thesis

Paddy is unique. He is incredible. His enthusiasm and energy to discuss physics is admirable. His insight, amazing. Of course, he has his drawbacks. Potatoes and his phenomenal reluctance to exert himself physically can be named as two of them. Whatever physics I know, I owe to him. I wish to take this opportunity to thank him for his friendship, support and guidance. They proved invaluable to me.

Acknowledging Paddy in my thesis (*c.* 1997). Later, even when we have disagreed, it has helped me sharpen my arguments!

Plan of the talk

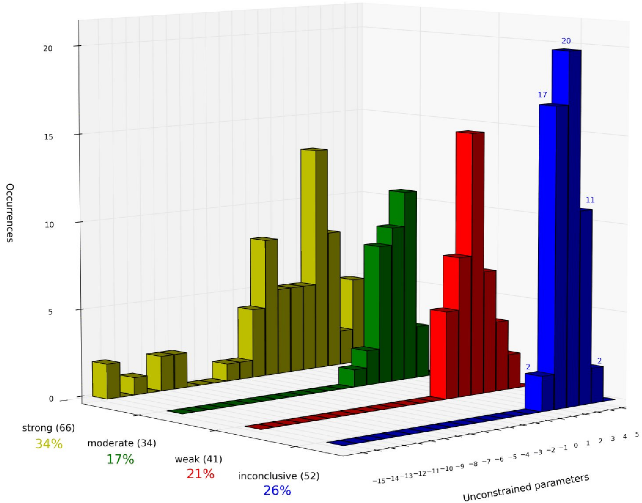
Proliferation of inflationary models

5-dimensional assisted inflation
anisotropic brane inflation
anomaly-induced inflation
assisted inflation
assisted chaotic inflation
boundary inflation
brane inflation
brane-assisted inflation
brane gas inflation
brane-antibrane inflation
braneworld inflation
Brans-Dicke chaotic inflation
Brans-Dicke inflation
bulky brane inflation
chaotic hybrid inflation
chaotic inflation
chaotic new inflation
D-brane inflation
D-term inflation
dilaton-driven inflation
dilaton-driven brane inflation
double inflation
double D-term inflation
dual inflation
dynamical inflation
dynamical SUSY inflation
eternal inflation
extended inflation
extended open inflation
extended warm inflation
extra dimensional inflation
F-term inflation
F-term hybrid inflation
false vacuum inflation
false vacuum chaotic inflation
fast-roll inflation
first order inflation
gauged inflation
generalised inflation
generalized assisted inflation
generalized slow-roll inflation
gravity driven inflation
Hagedorn inflation
higher-curvature inflation
hybrid inflation
hyperextended inflation
induced gravity inflation
induced gravity open inflation
intermediate inflation
inverted hybrid inflation
isocurvature inflation
K inflation
kinetic inflation
lambda inflation
large field inflation
late D-term inflation
late-time mild inflation
low-scale inflation
low-scale supergravity inflation
M-theory inflation
mass inflation
massive chaotic inflation
moduli inflation
multi-scalar inflation
multiple inflation
multiple-field slow-roll inflation
multiple-stage inflation
natural inflation
natural Chaotic inflation
natural double inflation
natural supergravity inflation
new inflation
next-to-minimal supersymmetric hybrid inflation
non-commutative inflation
non-slow-roll inflation
nonminimal chaotic inflation
old inflation
open hybrid inflation
open inflation
oscillating inflation
polynomial chaotic inflation
polynomial hybrid inflation
power-law inflation
pre-Big-Bang inflation
primary inflation
primordial inflation
quasi-open inflation
quintessential inflation
R-invariant topological inflation
rapid asymmetric inflation
running inflation
scalar-tensor gravity inflation
scalar-tensor stochastic inflation
Seiberg-Witten inflation
single-bubble open inflation
spinodal inflation
stable starobinsky-type inflation
steady-state eternal inflation
steep inflation
stochastic inflation
string-forming open inflation
successful D-term inflation
supergravity inflation
supernatural inflation
superstring inflation
supersymmetric hybrid inflation
supersymmetric inflation
supersymmetric topological inflation
supersymmetric new inflation
synergistic warm inflation
TeV-scale hybrid inflation

A (partial?) list of ever-increasing number of inflationary models[1]. Actually, it may not even be possible to rule out some of these models!

[1] From E. P. S. Shellard, *The future of cosmology: Observational and computational prospects*, in *The Future of Theoretical Physics and Cosmology*, Eds. G. W. Gibbons, E. P. S. Shellard and S. J. Rankin (Cambridge University Press, Cambridge, England, 2003).

Performance of inflationary models against the data



The efficiency of the inflationary paradigm leads to a situation wherein, despite the strong constraints, a variety of models continue to remain consistent with the data[2].

[2] J. Martin, C. Ringeval, R. Trotta and V. Vennin, JCAP **1403**, 039 (2014).

Can inflation be falsified?

The difficulty with the inflationary paradigm

A theory that predicts everything predicts nothing[a].

[a] P. J. Steinhardt, Sci. Am. **304**, 36 (2011).

Plan of the talk

Bouncing scenarios as an alternative paradigm[3]

- 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.

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

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- 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.

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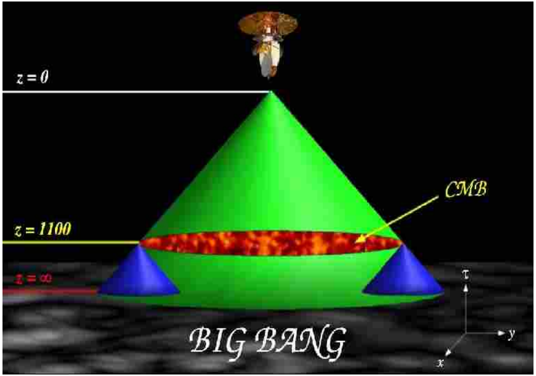
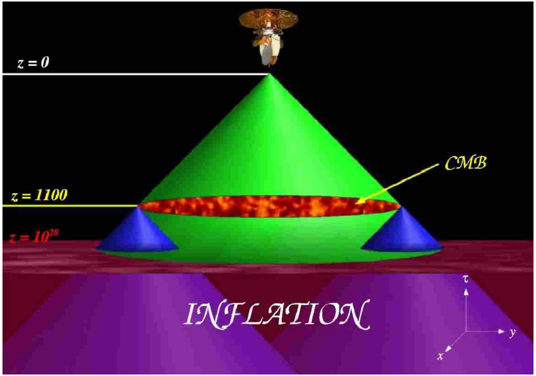
- They offer an alternative to inflation to overcome the horizon problem, as they permit well motivated, Minkowski-like initial conditions to be imposed on the perturbations at early times during the contracting phase.
- However, matter fields *will* have to violate the null energy condition near the 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 can be supposed to fail and quantum gravitational effects are expected to take over.

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

The resolution of the horizon problem in inflation





Left: The radiation from the CMB arriving at us from regions separated by more than the Hubble radius at the last scattering surface (which subtends an angle of about 1° today) could not have interacted before decoupling.

[4] Images from W. Kinney, astro-ph/0301448.

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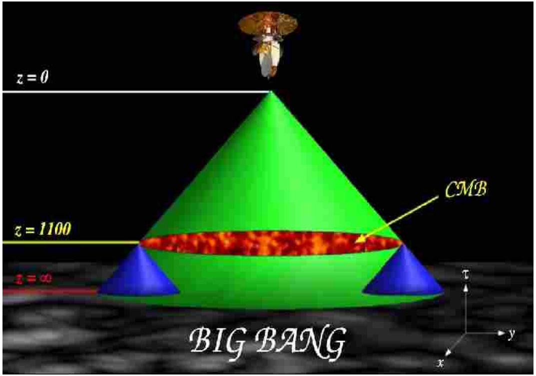
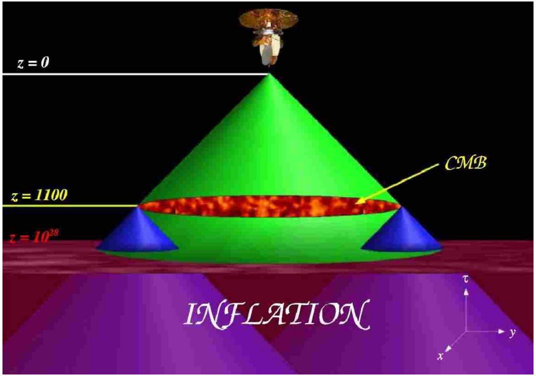
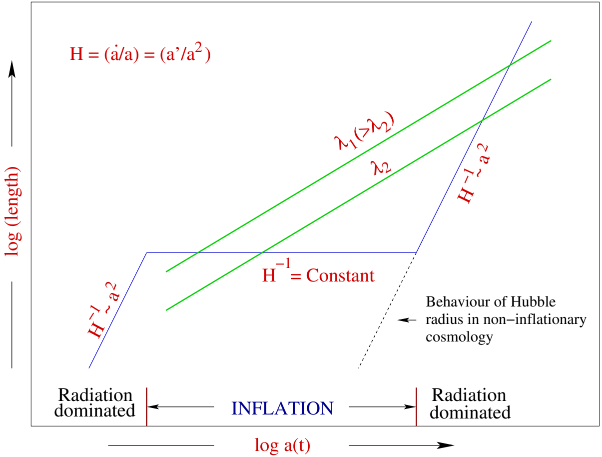




Left: The radiation from the CMB arriving at us from regions separated by more than the Hubble radius at the last scattering surface (which subtends an angle of about 1° today) could not have interacted before decoupling.
Right: An illustration of how an early and sufficiently long epoch of inflation helps in resolving the horizon problem[4].

[4] Images from W. Kinney, astro-ph/0301448.

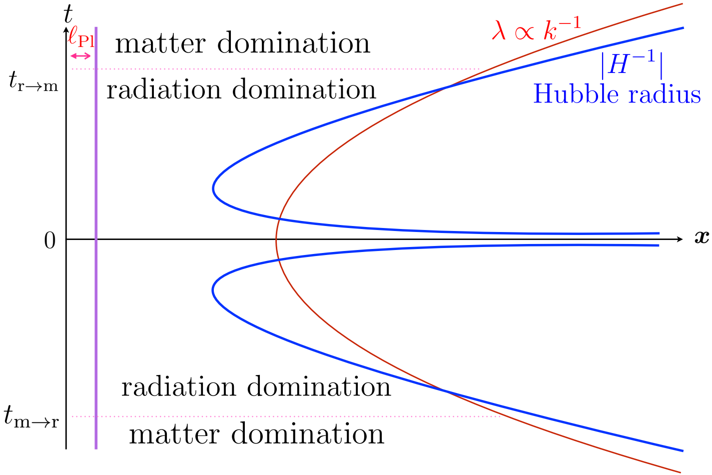
Bringing the modes inside the Hubble radius



The behavior of the physical wavelength $\lambda_{\rm P} \propto a$ (the green lines) and the Hubble radius H^{-1} (the blue line) during inflation and the radiation dominated epochs[5].

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

Overcoming the horizon problem in bouncing models



Evolution of the physical wavelength and the Hubble radius in a bouncing scenario[6].

[6] Figure from, D. Battefeld and P. Peter, Phys. Rept. **571**, 1 (2015).

Violation of the null energy condition near the bounce

Recall that, according to the Friedmann equations

$$\dot{H} = -\,4\,\pi\,G\,(\rho + p)\,.$$

In any bouncing scenario, the Hubble parameter is negative before the bounce, crosses zero at the bounce and is positive thereafter.

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It can be shown that, if the modes of cosmological interest have to be inside the Hubble radius at early times during the contracting phase, *the universe needs to undergo non-accelerated contraction*.

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In such cases, one finds that $\dot{H}$ *will* be positive near the bounce, which implies that $(\rho + p)$ has to be negative in this domain. In other words, the null energy condition needs to be violated in order to achieve such bounces.

Classical bounces and sources

Consider for instance, bouncing models of the form

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

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 $q > 0$. We shall assume that the scale k_0 associated with the bounce is of the order of the Planck scale $M_{_{\rm Pl}}$.

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Note that, when $q = 1$, during very early times wherein $\eta \ll -\eta_0$, the scale factor behaves as in a matter dominated universe (*i.e.* $a \propto \eta^2$). Therefore, the $q = 1$ case is often referred to as the matter bounce scenario. In such a case, the energy densities of the two fluids behave as $\rho_1 = 12\,k_0^2\,M_{_{\rm Pl}}^2\,a_0/a^3$ and $\rho_2 = -12\,k_0^2\,M_{_{\rm Pl}}^2\,a_0^2/a^4$.

E-$\mathcal{N}$-folds

The conventional e-fold N is defined $N = \log(a/a_{\rm i})$ so that $a(N) = a_{\rm i}\exp N$. However, the function e^N is a monotonically increasing function of N.

[7] L. Sriramkumar, K. Atmjeet and R. K. Jain, JCAP **1509**, 010 (2015).

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In completely symmetric bouncing scenarios, an obvious choice for the scale factor seems to be[7]

$$a(\mathcal{N}) = a_0 \exp(\mathcal{N}^2/2),$$

with $\mathcal{N}$ being the new time variable that we shall consider for integrating the differential equation governing the background as well as the perturbations.

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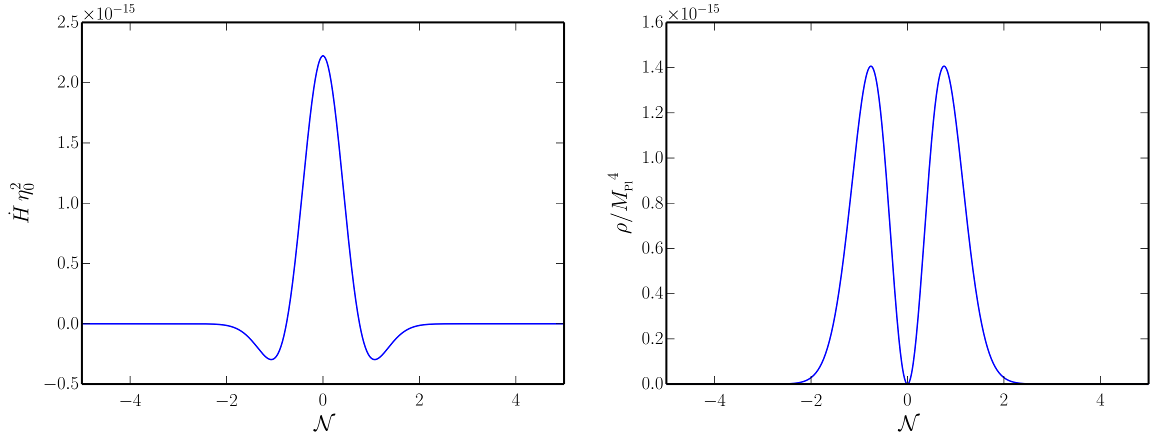
We shall refer to the variable $\mathcal{N}$ as e-$\mathcal{N}$-fold since the scale factor grows roughly by the amount ${\rm e}^{\mathcal{N}}$ between $\mathcal{N}$ and $(\mathcal{N}+1)$.

[7] L. Sriramkumar, K. Atmjeet and R. K. Jain, JCAP **1509**, 010 (2015).

Behavior of $\dot{H}$ and ρ in a matter bounce



The behavior of $\dot{H}$ (on the left) and the total energy density ρ (on the right) in a symmetric matter bounce scenario has been plotted as a function of $\mathcal{N}$. Note that the maximum value of ρ is much smaller than $M_{\rm Pl}^4$, which suggests that the bounce can be treated completely classically.

Duality between de Sitter inflation and matter bounce

It is known that the solutions to the equations of motion governing the scalar and tensor perturbations are invariant under a certain transformation referred to as the duality transformation[8].

[8] D. Wands, Phys. Rev. D **60**, 023507 (1999).

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For instance, recall that the Mukhanov-Sasaki variable corresponding to the tensor perturbations satisfies the differential equation

$$u_k'' + \left(k^2 - \frac{a''}{a}\right) u_k = 0.$$

Given a scale factor a, the corresponding dual, say, $\tilde{a}$, which leads to the same equation for the variable u_k is given by

$$a(\eta) \to \tilde{a}(\eta) = C\, a(\eta) \int_{\eta_*}^{\eta} \frac{\mathrm{d}\bar{\eta}}{a^2(\bar{\eta})},$$

where C and η_* are constants.

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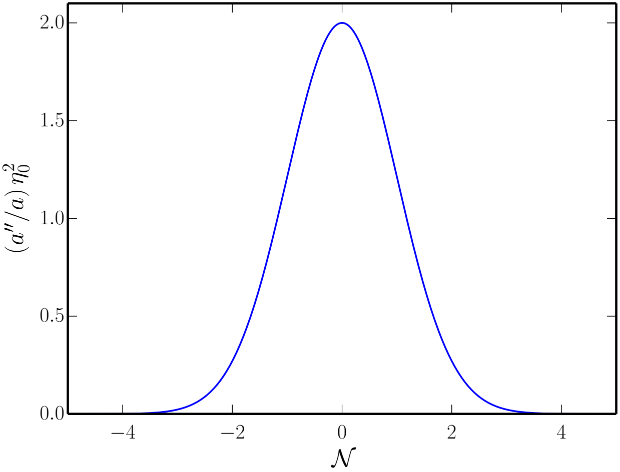
It is straightforward to show that the dual solution to de Sitter inflation corresponds to the matter bounce.

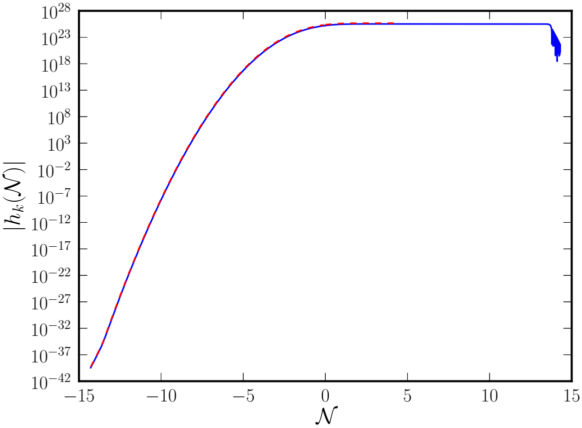
[8] D. Wands, Phys. Rev. D **60**, 023507 (1999).

The behavior of a''/a in a matter bounce



The behavior of the quantity a''/a has been plotted as a function of $\mathcal{N}$ for the matter bounce scenario of interest. Note that the maximum value of a''/a is of the order of k_0^2.

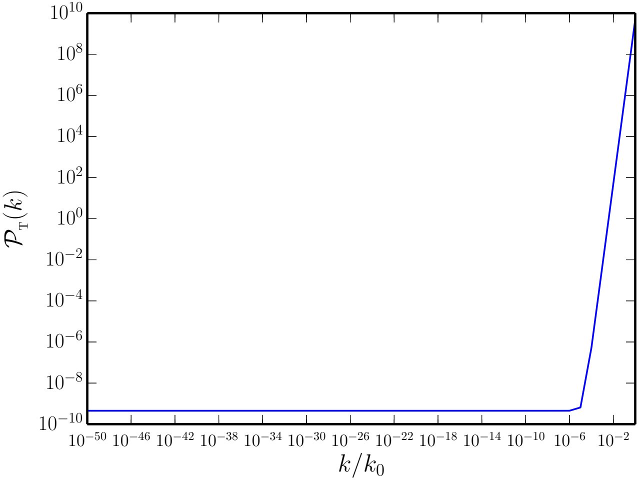
Evolution of the tensor modes across the bounce



A comparison of the numerical results (in blue) with the analytical results (in red) for the amplitude of the tensor mode $|h_k|$ corresponding to the wavenumber $k/k_0 = 10^{-20}$. We have set $k_0/M_{\rm Pl} = 1$ and $a_0 = 10^5$, which lead to a tensor power spectrum that is consistent with the observations[9].

[9] D. Chowdhury, V. Sreenath and L. Sriramkumar, JCAP **1511**, 002 (2015)

The tensor power spectrum after the bounce



The tensor power spectrum, evaluated analytically, has been plotted as a function of k/k_0 for a wide range of wavenumbers. We have set $k_0/M_{_{\rm Pl}} = 1$, $a_0 = 10^5$ as in the previous figure. Note that the power spectrum is scale invariant for $k/k_0 \ll 10^{-5}$.

Plan of the talk

Tensor bispectrum and non-Gaussianity parameter

The tensor bispectrum, evaluated at the conformal time, say, $\eta_{\rm e}$, is defined as

$$\langle\hat{\gamma}_{m_1n_1}^{\boldsymbol{k}_1}(\eta_{\rm e})\,\hat{\gamma}_{m_2n_2}^{\boldsymbol{k}_2}(\eta_{\rm e})\,\hat{\gamma}_{m_3n_3}^{\boldsymbol{k}_3}(\eta_{\rm e})\rangle = (2\,\pi)^3\,\mathcal{B}_{\gamma\gamma\gamma}^{m_1n_1m_2n_2m_3n_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) \times\,\delta^{(3)}\left(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3\right)$$

and, for convenience, we shall set

$$\mathcal{B}_{\gamma\gamma\gamma}^{m_1n_1m_2n_2m_3n_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = (2\,\pi)^{-9/2}\,G_{\gamma\gamma\gamma}^{m_1n_1m_2n_2m_3n_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3).$$

[10] V. Sreenath, R. Tibrewala and L. Sriramkumar, JCAP **1312**, 037 (2013).

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As in the scalar case, one can define a dimensionless non-Gaussianity parameter to characterize the amplitude of the tensor bispectrum as follows[10]:

$$h_{_{\rm NL}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = -\left(\frac{4}{2\,\pi^2}\right)^2\,\left[k_1^3\,k_2^3\,k_3^3\,G^{m_1n_1m_2n_2m_3n_3}_{\gamma\gamma\gamma}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\right] \times\,\left[\Pi^{\boldsymbol{k}_1}_{m_1n_1,m_2n_2}\,\Pi^{\boldsymbol{k}_2}_{m_3n_3,\bar{m}\bar{n}}\,k_3^3\,\mathcal{P}_{_{\rm T}}(k_1)\,\mathcal{P}_{_{\rm T}}(k_2) + \mbox{five permutations}\right]^{-1}.$$

[10] V. Sreenath, R. Tibrewala and L. Sriramkumar, JCAP **1312**, 037 (2013).

The third order action and the tensor bispectrum

The third order action that leads to the tensor bispectrum is given by[11]

$$S^3_{\gamma\gamma\gamma}[\gamma_{ij}] = \frac{M_{\rm Pl}^2}{2}\int {\rm d}\eta \int {\rm d}^3\boldsymbol{x}\, \left[\frac{a^2}{2}\,\gamma_{lj}\,\gamma_{im}\,\partial_l\partial_m\gamma_{ij} - \frac{a^2}{4}\,\gamma_{ij}\,\gamma_{lm}\,\partial_l\partial_m\gamma_{ij}\right].$$

[11] J. Maldacena, JHEP **0305**, 013 (2003).

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The tensor bispectrum calculated in the perturbative vacuum using the Maldacena formalism, can be written in terms of the modes h_k as follows:

$$\begin{aligned} G^{m_1n_1m_2n_2m_3n_3}_{\gamma\gamma\gamma}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) &= M_{\rm Pl}^2 \Big[\Big(\Pi^{\boldsymbol{k}_1}_{m_1n_1,ij}\,\Pi^{\boldsymbol{k}_2}_{m_2n_2,im}\,\Pi^{\boldsymbol{k}_3}_{m_3n_3,lj} - \frac{1}{2}\,\Pi^{\boldsymbol{k}_1}_{m_1n_1,ij}\,\Pi^{\boldsymbol{k}_2}_{m_2n_2,ml}\,\Pi^{\boldsymbol{k}_3}_{m_3n_3,ij}\Big)\,k_{1m}\,k_{1l} \\ &\quad + \text{five permutations}\Big] \\ &\quad \times \Big[h_{k_1}(\eta_{\rm e})\,h_{k_2}(\eta_{\rm e})\,h_{k_3}(\eta_{\rm e})\,\mathcal{G}_{\gamma\gamma\gamma}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) + \text{complex conjugate}\Big], \end{aligned}$$

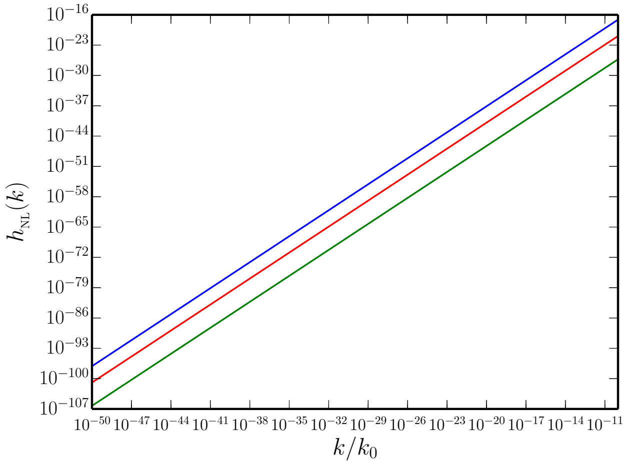
where $\mathcal{G}_{\gamma\gamma\gamma}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$ is described by the integral

$$\mathcal{G}_{\gamma\gamma\gamma}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = -\frac{i}{4}\int_{\eta_{\rm i}}^{\eta_{\rm e}} \mathrm{d}\eta\; a^2\, h^{*}_{k_1}\, h^{*}_{k_2}\, h^{*}_{k_3},$$

with $\eta_{\rm i}$ denoting the time when the initial conditions are imposed on the perturbations.

[11] J. Maldacena, JHEP **0305**, 013 (2003).

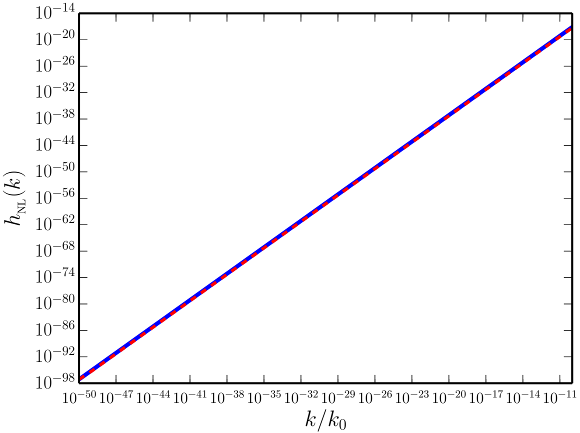
The contributions due to the three domains



The contributions to the non-Gaussianity parameter $h_{\rm NL}$ in the equilateral limit from the first (in green), the second (in red) and the third (in blue) domains have been plotted as a function of k/k_0. Clearly, the third domain gives rise to the maximum contribution to $h_{\rm NL}$ [12].

[12] D. Chowdhury, V. Sreenath and L. Sriramkumar, JCAP **1511**, 002 (2015)

The complete contribution to $h_{\rm NL}$



The behavior of $h_{\rm NL}$ in the equilateral (in blue) and the squeezed (in red) limits plotted as a function of k/k_0. The resulting $h_{\rm NL}$ is considerably small when compared to the values that arise in de Sitter inflation wherein $3/8 \lesssim h_{\rm NL} \lesssim 1/2$. Moreover, we find that $h_{\rm NL}$ behaves as k^2 in the equilateral and the squeezed limits, with similar amplitudes[13].

[13] D. Chowdhury, V. Sreenath and L. Sriramkumar, JCAP **1511**, 002 (2015).

Plan of the talk

Issues confronting bouncing models

- In inflation, any classical perturbations present at the start will decay. In contrast, they grow strongly in bouncing models. So, these need to be assumed to be rather small if smooth bounces have to begin.

[14] L. E. Allen and D. Wands, Phys. Rev. **70**, 063515 (2004).

[15] Y-F. Cai, R. Brandenberger and X. Zhang, Phys. Letts. B **703**, 25 (2011).

[16] J. Quintin, Z. Sherkatghanad, Y-F. Cai and R. Brandenberger, Phys. Rev. D **92**, 062532 (2015).

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Collaborators: current and former students

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Thank you for your attention