Whither inflation?

L. Sriramkumar

Centre for Strings, Gravitation and Cosmology, Department of Physics,
Indian Institute of Technology Madras, Chennai, India

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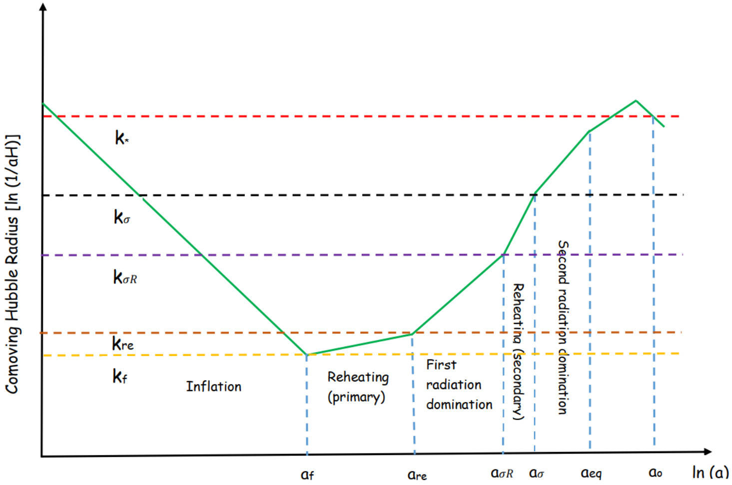
Plan of the talk

This talk is based on. . .

- M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, *Generating PBHs and small-scale GWs in two-field models of inflation*, JCAP **08**, 001 (2020) [arXiv:2005.02895 [astro-ph.CO]].
- H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, *Primordial black holes and secondary gravitational waves from ultra slow roll and punctuated inflation*, Phys. Rev. D **103**, 083510 (2021) [arXiv:2008.12202 [astro-ph.CO]].
- Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, *Decoding the phases of early and late time reheating through imprints on primordial gravitational waves*, Phys. Rev. D **104**, 063513 (2021) [arXiv:2105.09242 [astro-ph.CO]].
- H. V. Ragavendra and L. Sriramkumar, *Observational imprints of enhanced scalar power on small scales in ultra slow roll inflation and associated non-Gaussianities*, Galaxies **11**, 34 (2023) [arXiv:2301.08887 [astro-ph.CO]].
- S. Maity, H. V. Ragavendra, S. K. Sethi and L. Sriramkumar, *Loop contributions to the scalar power spectrum due to quartic order action in ultra slow roll inflation*, JCAP **05**, 046 (2024) [arXiv:2307.13636 [astro-ph.CO]].
- S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, Constraining the history of reheating with the NANOGrav 15-year data, arXiv:2403.16963 [astro-ph.CO].

Plan of the talk

Behavior of the comoving wave number and Hubble radius

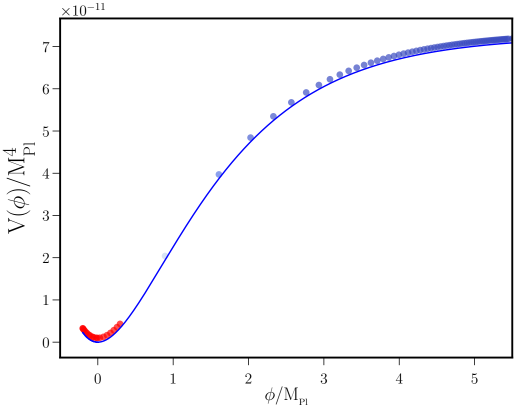


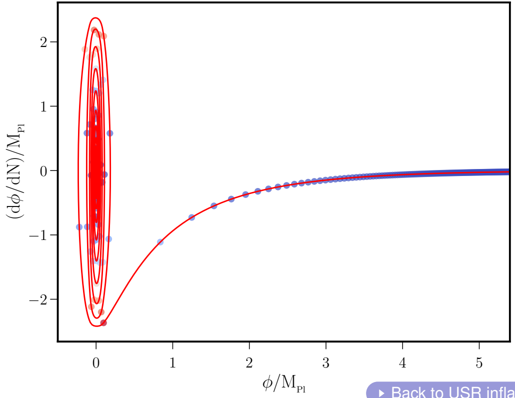
Back to primary GWs
Back to NANOGrav data

Behavior of the comoving wave number k (dashed horizontal lines in different colors) and the comoving Hubble radius $d_{\rm H}/a = (a\,H)^{-1}$ (in green) across different epochs[1].

[1] Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

The inflationary attractor



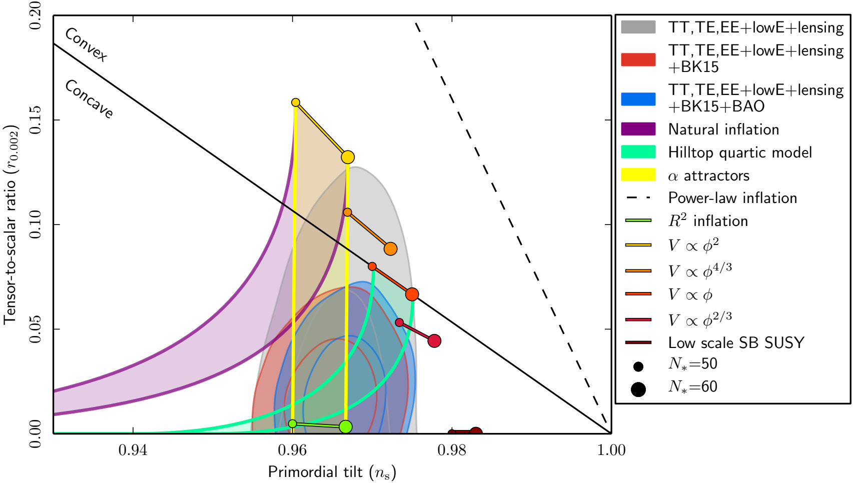


Back to USR inflation

The evolution of the scalar field in the popular Starobinsky model, which leads to slow roll inflation, is indicated (as circles, in blue and red) at regular intervals of time (on the left). Illustration of the behavior of the scalar field in phase space (on the right)[2].

[2] Figure credit H. V. Ragavendra.

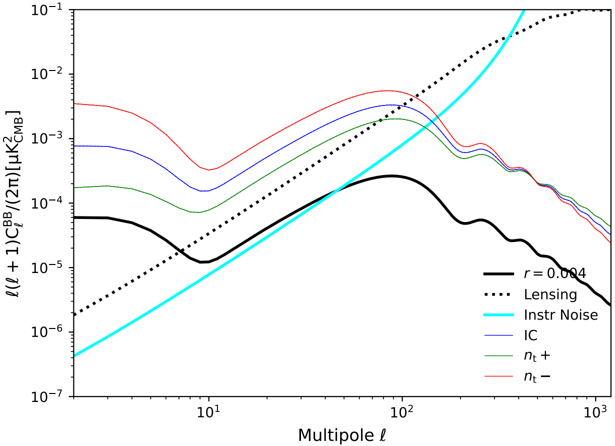
Performance of inflationary models in the n_s-r plane



Joint constraints on n_s and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models[3].

[3] Planck Collaboration (Y. Akrami *et al.*), Astron. Astrophys. **641**, A10 (2020).

Prospects of observing the imprints of the tensor perturbations

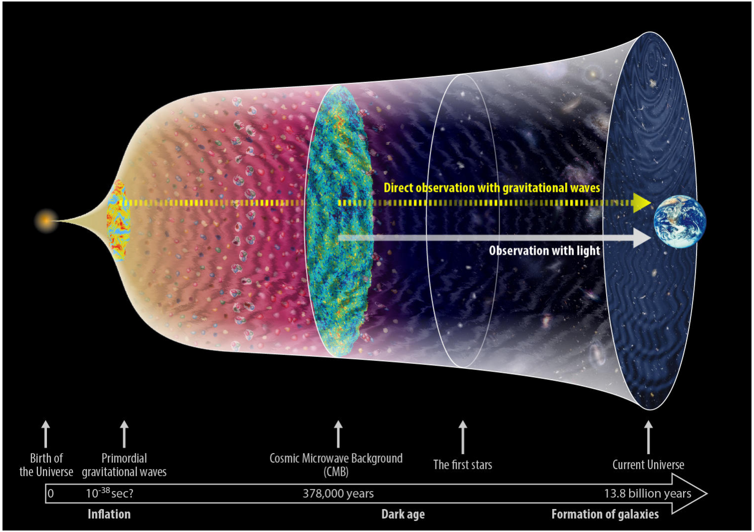


The B-mode angular power spectra of the CMB resulting from the primordial tensor perturbations for three models with $r_{0.05} = 0.05$ are plotted, along with the CMB lensing signal and the instrumental noise of a LiteBIRD-like configuration[4].

[4] D. Paoletti, F. Finelli, J. Valiviita and M. Hazumi, Phys. Rev. D **106**, 083528 (2022).

Plan of the talk

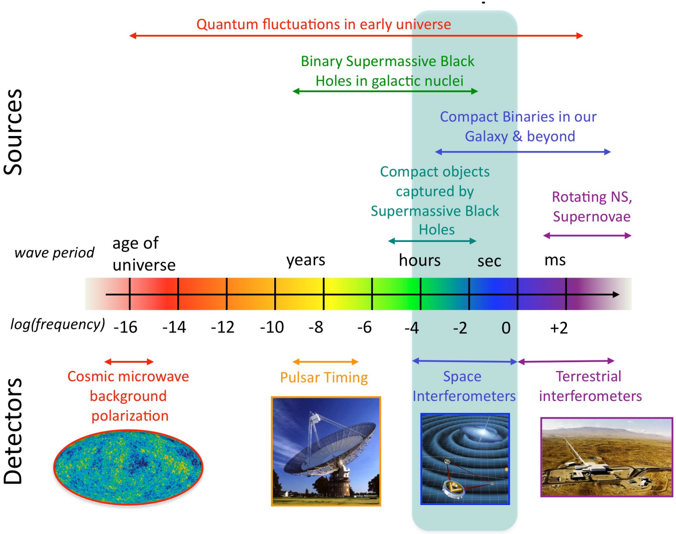
Probing the primordial universe through GWs



GWs provide a unique window to probe the primordial universe[5].

[5] Image from https://gwpo.nao.ac.jp/en/gallery/000061.html.

The spectral range of GWs

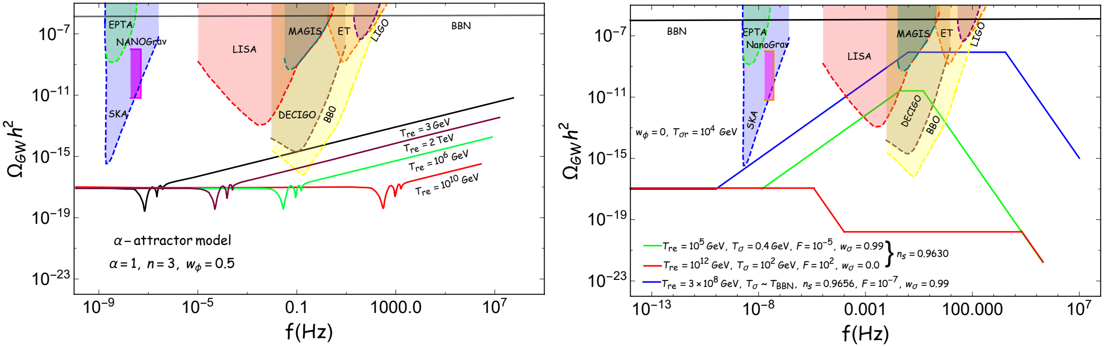


Different sources of GWs and corresponding detectors[6].

[6] J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Pearson Education, Delhi, 2003).

Plan of the talk

Effects on $\Omega_{\rm GW}(f)$ due to primary and secondary reheating



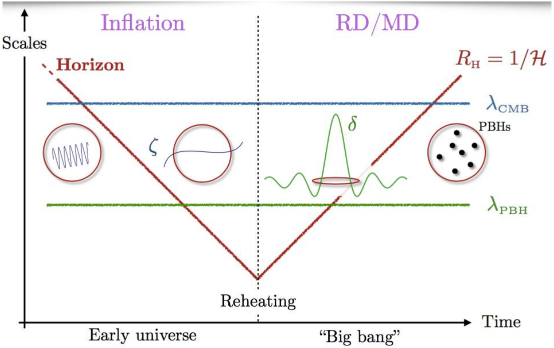
Left: The dimensionless spectral energy density of primary GWs today, viz. $\Omega_{\rm GW}$, is plotted in the conventional reheating scenario over a wide range of frequency f, for different reheating temperatures (in red, green, brown and black, on the left)[7].

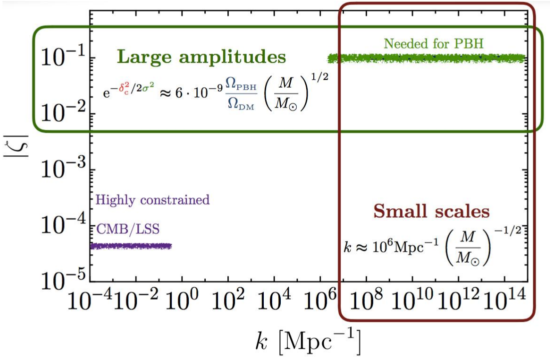
Right: The spectral energy density of primary GWs in scenarios involving a second phase of reheating.

Evolution of comoving lengths

[7] See, for example, K. Nakayama, S. Saito, Y. Suwa and J. Yokoyama, JCAP **0806** 020 (2008); Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

Production of primordial black holes (PBHs) during radiation domination

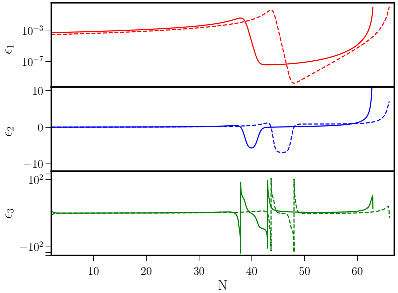


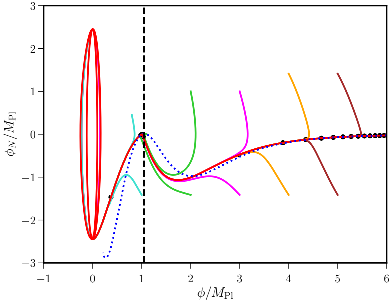


BHs can form in the primordial universe when perturbations with significant amplitudes on small scales re-enter the Hubble radius during the epoch of radiation dominated epoch[8].

[8] Figures from G. Franciolini, arXiv:2110.06815 [astro-ph.CO].

Single-field models admitting ultra slow roll inflation





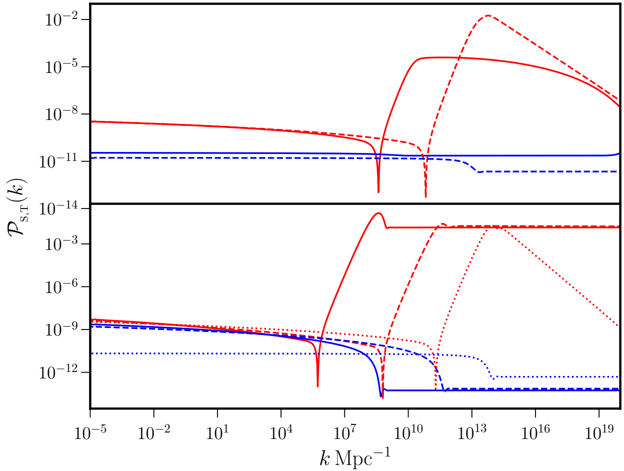
Potentials containing a point of inflection and leading to ultra slow roll inflation[9]: ▸ Inflationary attractor

$$\mathrm{USR1}: V(\phi) = V_0\, \frac{6\,x^2 - 4\,\alpha\,x^3 + 3\,x^4}{(1+\beta\,x^2)^2}, \text{ with } x = \phi/v,\ v \text{ being a constant},$$

$$\mathrm{USR2}: V(\phi) = V_0\, \left\{\tanh\left(\frac{\phi}{\sqrt{6}\,M_{_{\rm Pl}}}\right) + A\,\sin\left[\frac{\tanh\left[\phi/\left(\sqrt{6}\,M_{_{\rm Pl}}\right)\right]}{f_\phi}\right]\right\}^2.$$

[9] See, for example, J. Garcia-Bellido and E. R. Morales, Phys. Dark Univ. **18**, 47 (2017);
C. Germani and T. Prokopec, Phys. Dark Univ. **18**, 6 (2017);
I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019).

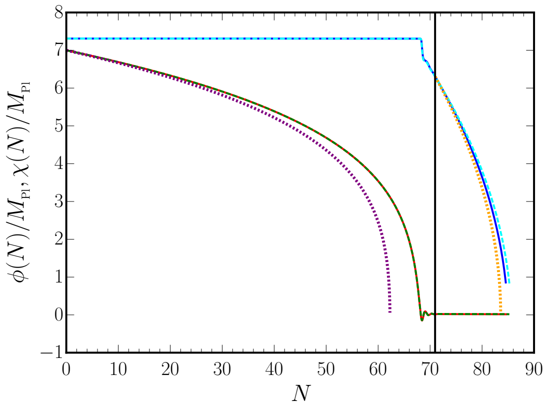
Power spectra in ultra slow roll inflationary models

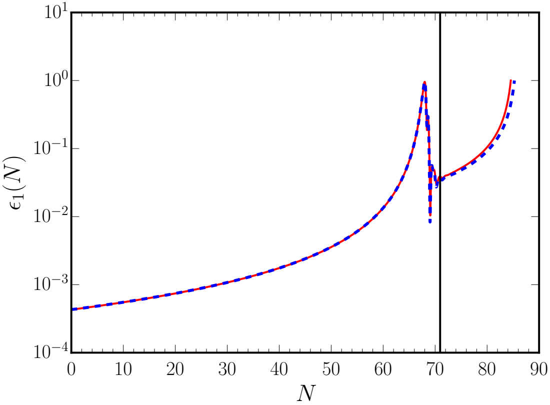


The scalar and the tensor power spectra (in red and blue) arising in various inflationary models that permit a phase of ultra slow roll[10].

[10] H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021).

Achieving enhanced power on small scales in two-field models

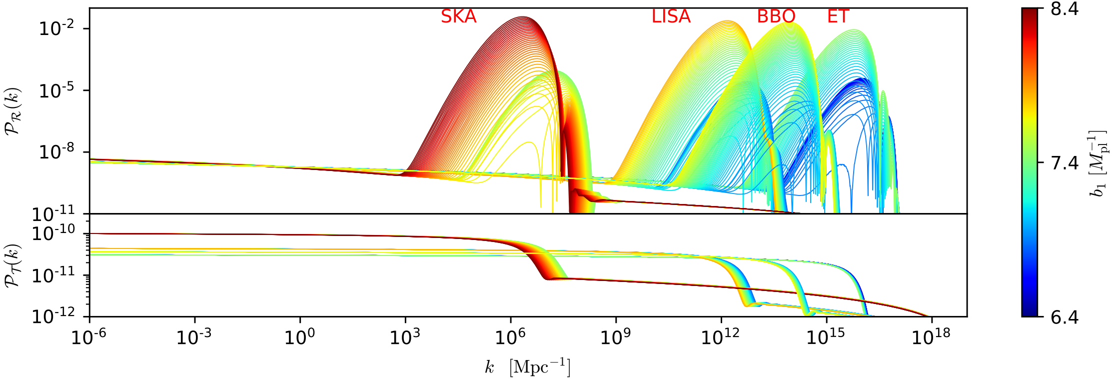




Behavior of the two scalar fields ϕ and χ (in blue and red, on the left) and the first slow roll parameter ϵ_1 (on the right) in the two field model of interest[11]. Note that there arises a turn in the field space around $N = 70$, when the first slow roll parameter begins to decrease before increasing again, leading to the termination of inflation.

[11] M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

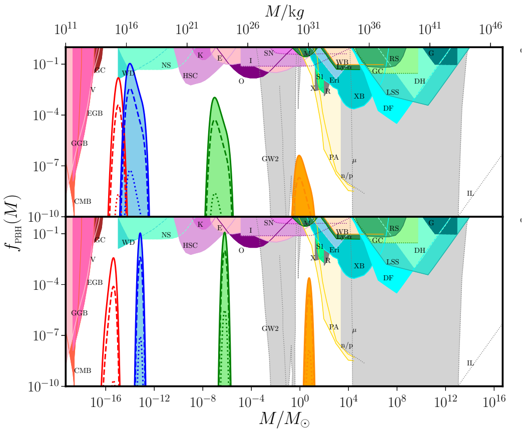
Enhanced scalar power on small scales in two-field models

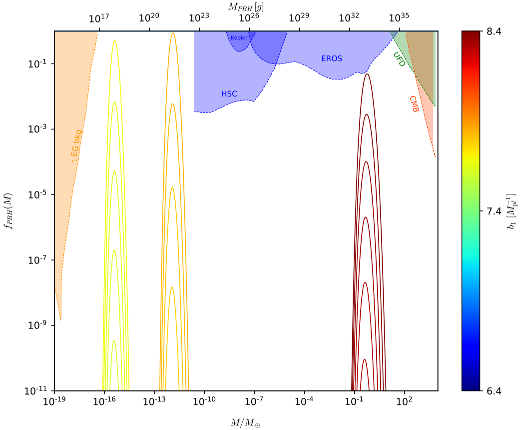


The scalar (on top) and the tensor (at the bottom) power spectra evaluated at the end of inflation have been plotted for a few different sets of initial conditions for the fields and a range of values of one of the parameters of the model[12].

[12] M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

Extent of PBH formation in single and two-field models





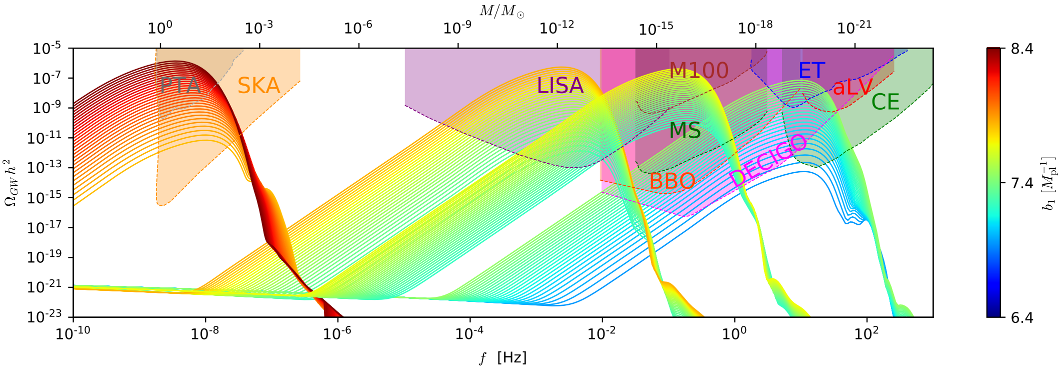
Left: The fraction of PBHs contributing to the cold dark matter density today $f_{\rm PBH}(M)$ has been plotted in single-field models permitting ultra slow roll inflation[13].

Right: The quantity $f_{\rm PBH}(M)$ in the two-field model of interest[14].

[13] H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021).

[14] M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

Strengths of scalar-induced, secondary GWs in the two-field model



The dimensionless spectral density of GWs $\Omega_{\rm GW}(f)$ arising in the two-field model has been plotted for a set of initial conditions for the background fields as well as a range of values of one of the parameters[15].

[15] M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

Plan of the talk

Shape of the inflationary scalar power spectrum

We assume that the inflationary scalar power spectrum is given by[16]

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm S}-1} + A_0 \begin{cases} \left(\dfrac{k}{k_{\rm peak}}\right)^4 & k \le k_{\rm peak} \\ \left(\dfrac{k}{k_{\rm peak}}\right)^{n_0} & k \ge k_{\rm peak} \end{cases},$$

where $A_{\rm s}$ and $n_{\rm S}$ are the amplitude and spectral index of the power spectrum at the CMB pivot scale of $k_* = 0.05\,{\rm Mpc}^{-1}$.

▸ Evolution of comoving lengths

We set the reheating temperature to the rather low value of $T_{\rm re} = 50\,{\rm MeV}$.

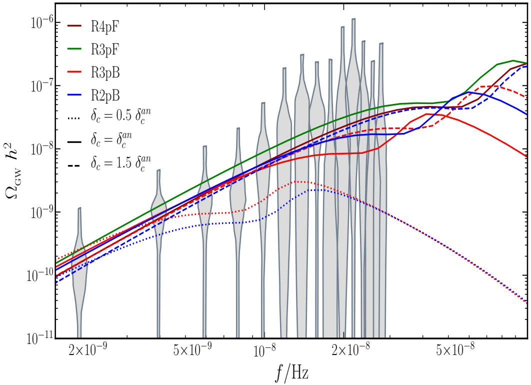
We shall assume that the threshold value of the density contrast for the formation of PBHs is given by[17]:

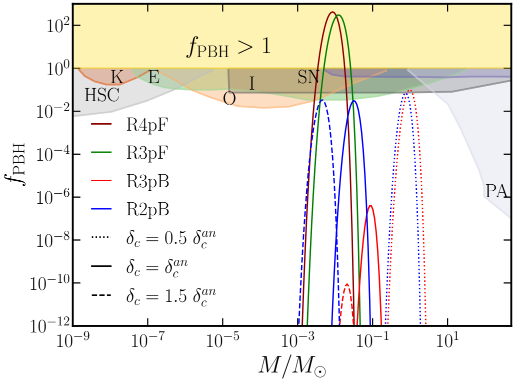
$$\delta_{\rm c}^{\rm an} = \frac{3\,(1+w_{\rm re})}{5+3\,w_{\rm re}}\,\sin^2\left(\frac{\pi\,\sqrt{w_{\rm re}}}{1+3\,w_{\rm re}}\right).$$

[16] For other forms of spectra, see G. Domènech, S. Pi, A. Wang and J. Wang, arXiv:2402.18965 [astro-ph.CO].

[17] In this context, see T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D **88**, 084051 (2013).

Generation of PBHs and secondary GWs during reheating





Left: The dimensionless spectral energy density of the secondary GWs today $\Omega_{\rm GW}(f)$ is plotted for a given reheating temperature and the best-fit values of the parameters in the different models.

Right: The corresponding fraction of PBHs that constitute the dark matter density today[18].

[18] S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, arXiv:2403.16963 [astro-ph.CO].

Bayesian evidence

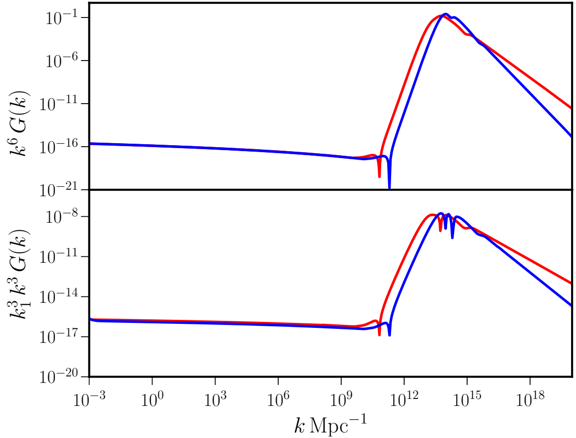
Model X	Model Y	$\mathrm{BF}_{Y,X}$		
		$\delta_c = 0.5\,\delta_c^{an}$	$\delta_c = \delta_c^{an}$	$\delta_c = 1.5\,\delta_c^{an}$
SMBHB	R2pB	$1.7 \pm .06$	260.04 ± 19.21	350.61 ± 27.36

The Bayesian factors $\mathrm{BF}_{Y,X}$ for the model `R2pB` that invokes primordial physics as the source of the stochastic GW background observed by the NANOGrav 15-year data, when compared to the astrophysical SMBHB model.

Clearly, when $\delta_c = \delta_c^{an}$ and $\delta_c = 1.5\,\delta_c^{an}$, the NANOGrav 15-year data strongly favors the model `R2pB` when compared to the SMBHM model.

Plan of the talk

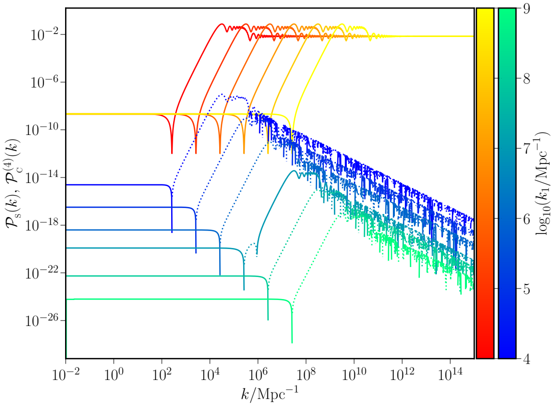
The scalar bispectrum in ultra slow roll inflation

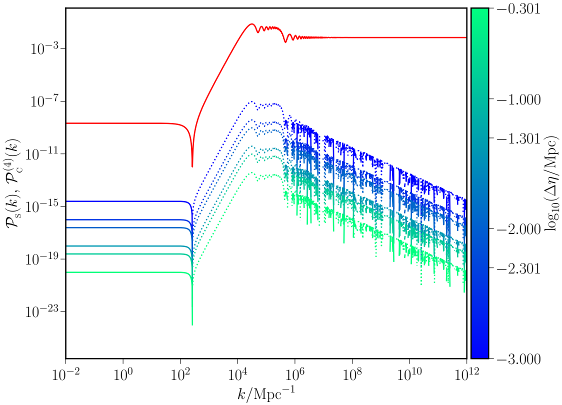


The amplitude of the dimensionless scalar bispectra is plotted in the equilateral (on top) and squeezed limits (at the bottom) for two inflationary models (in red and blue) that permit a brief phase of ultra slow roll[19].

[19] H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021); H. V. Ragavendra and L. Sriramkumar, Galaxies **11**, 34 (2023).

Loop contributions for late onset of ultra slow roll

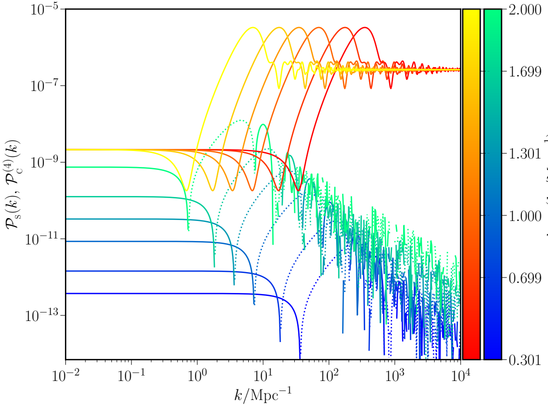


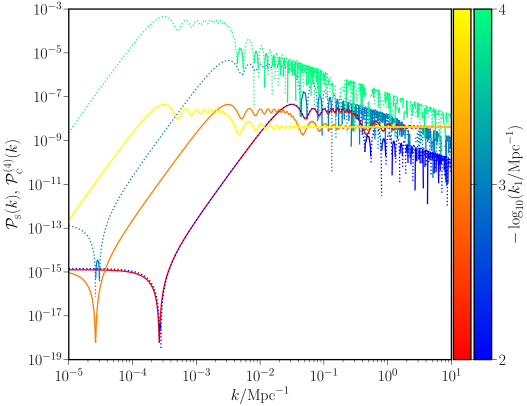


The power spectrum at the first order $\mathcal{P}_{\rm s}(k)$ and the loop contributions $\mathcal{P}_{\rm C}^{(4)}(k)$ due the dominant term in the action at the quartic order have been illustrated for different values of the parameters involved[20].

[20] S. Maity, H. V. Ragavendra, S. K. Sethi and L. Sriramkumar, JCAP **05**, 046 (2024).

Loop contributions for intermediate and early onsets of ultra slow roll





The power spectrum at the first order $\mathcal{P}_{\rm S}(k)$ and the loop contributions $\mathcal{P}_{\rm C}^{(4)}(k)$ have been illustrated for intermediate (on the left) and early (on the right) onsets of ultra slow roll. Note that, as the phase of ultra slow roll sets in earlier and earlier, the contributions from the loops prove to be larger and larger.

Plan of the talk

Outlook

- If future CMB missions—such as LiteBIRD, PIXIE or ECHO (a proposed Indian effort)—detect the signatures of the primordial GWs, it can lead to strong constraints on the dynamics during inflation and reheating.
- The observations by the PTAs has opened up a new window to probe primordial physics. Forthcoming GW observatories such as LISA, Einstein Telescope and Cosmic Explorer, can be expected to provide us with an unhindered view of the primordial universe.
- On the theoretical front, the role of non-Gaussianities in the formation of PBHs and the generation of GWs and the corrections to the power spectra due to the higher order terms in the action, remain to be understood satisfactorily.

Collaborators I

Matteo Braglia

Dhiraj Hazra

Fabio Finelli

George Smoot

Alexei Starobinsky

H. V. Ragavendra

Pankaj Saha

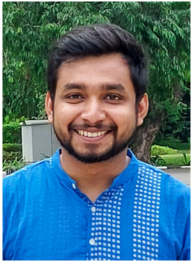
Joseph Silk

Collaborators II

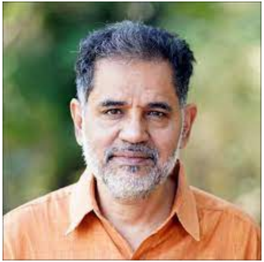
Md. Riajul Haque

Debaprasad Maity

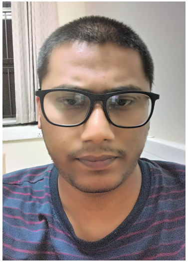
Tanmoy Paul



Suvashis Maity



Shiv Kumar Sethi



Nilanjandev Bhaumik

Thank you for your attention