Probing inflation and reheating with gravitational waves

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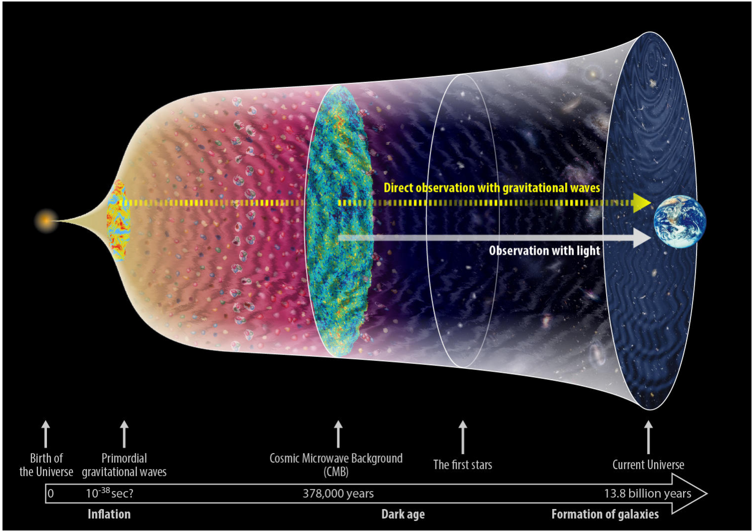
Plan of the talk

1. Primordial GWs: A direct probe of the early universe
2. Primary GWs—Perturbations generated from the quantum vacuum
3. Scalar-induced secondary GWs and the PTA observations
4. Impact of non-Gaussianities
5. Outlook

Plan of the talk

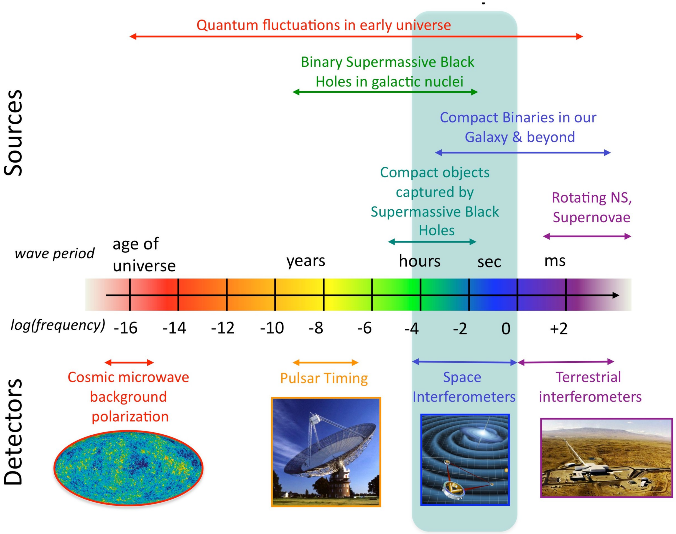
Decoding primordial physics with GWs



GWs provide a unique window to probe the primordial universe[1].

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

Sources and spectral range of GWs

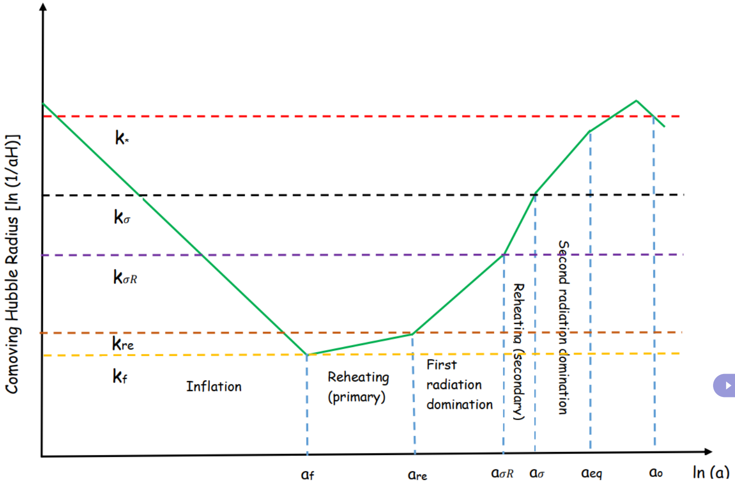


Different sources of GWs and the corresponding detectors[2].

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

Plan of the talk

Behavior of the comoving wave number and Hubble radius

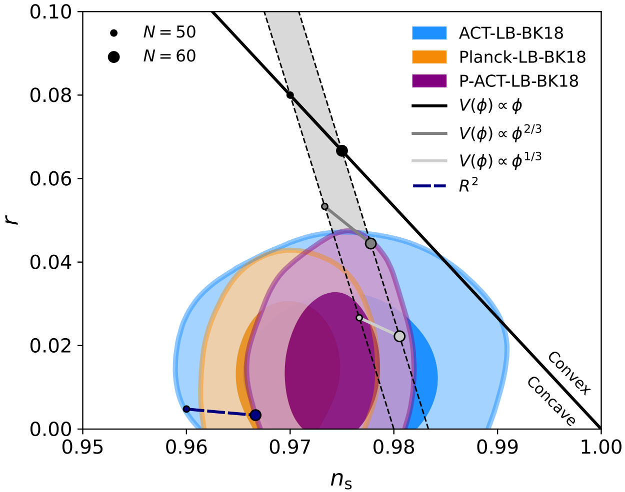


Back to reheating
Back to SGWs and PTA data

Behavior of the comoving wave number k (horizontal lines in different colors) and the comoving Hubble radius $d_{\mathrm{H}}/a = (a\,H)^{-1}$ (in green) across different epochs[3].

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

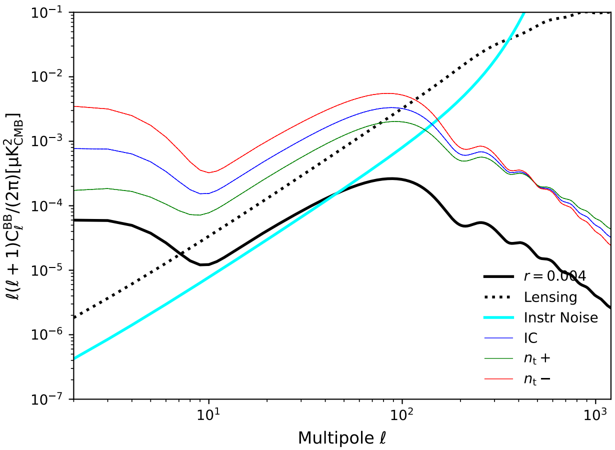
Performance of inflationary models in the $n_{\rm s}$-r plane



Latest constraints on $n_{\rm s}$ and r from ACT, in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models[4].

[4] ACT Collaboration (E. Calabrese *et al.*), arXiv:2503.14454 [astro-ph.CO].

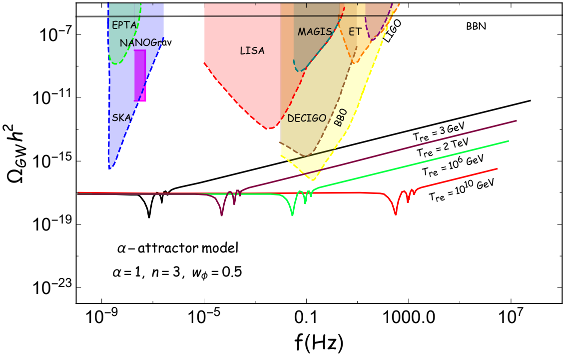
Prospects of observing the imprints of primary GWs in the CMB

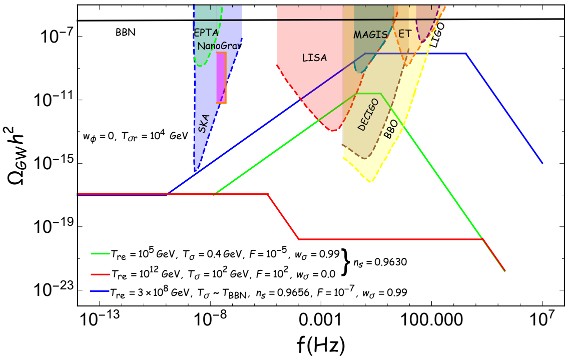


The B-mode angular power spectra of the CMB resulting from the primary tensor perturbations for models with $r_{0.05} = 5 \times 10^{-2}$ and $r_{0.05} = 4 \times 10^{-3}$ have been plotted, along with the CMB lensing signal and the instrumental noise of a LiteBIRD-like configuration[5].

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

Effects on primary GWs due to reheating





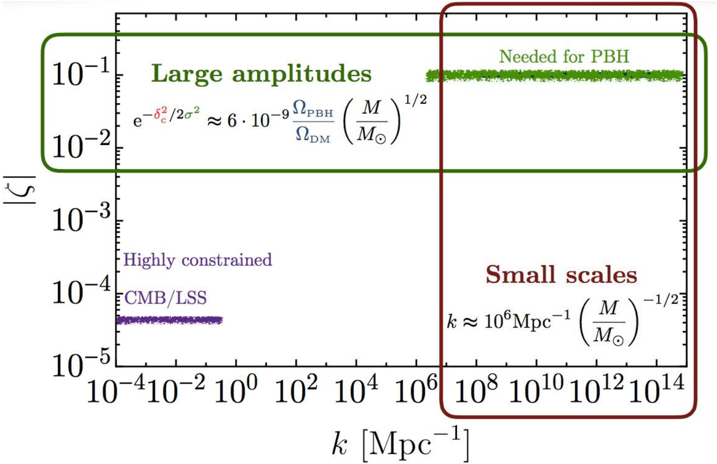
▸ Evolution of comoving lengths

The dimensionless spectral energy density of primary GWs today, viz. $\Omega_{\rm GW}$, is plotted over a wide range of frequency f, for different reheating scenarios and reheating temperatures[6]. Note that $n_{\rm GW} = 2\,(3\,w_{\rm re} - 1)/(3\,w_{\rm re} + 1)$.

[6]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).

Plan of the talk

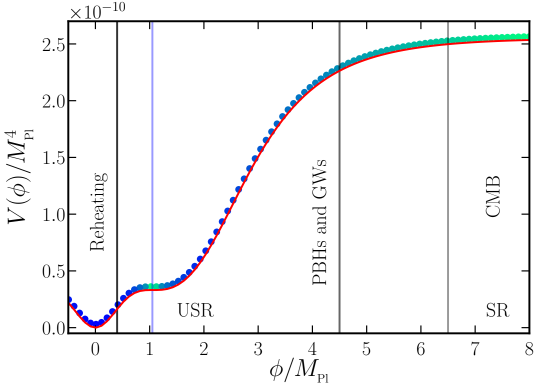
Amplitude required to form significant number of PBHs

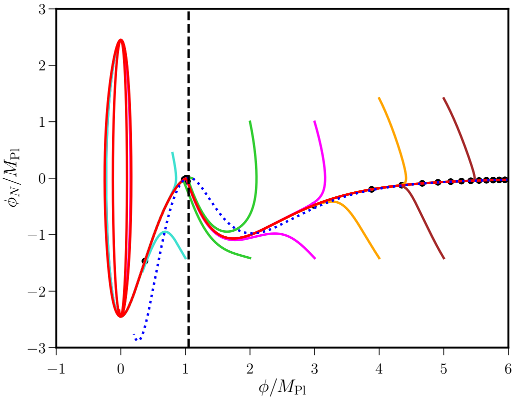


In order to form significant number of primordial black holes (PBHs), the amplitude of the perturbations on small scales has to be large enough such that the dimensionless amplitude of the scalar perturbation is close to unity[7].

[7] Figure credit G. Franciolini.

Single-field models admitting ultra slow roll (USR) inflation

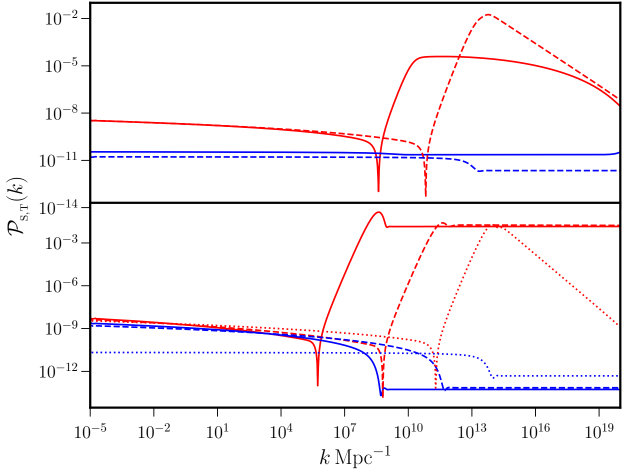




Potentials which contain a point of inflection generically admit a period of USR inflation[8].

[8] See, for example, C. Germani and T. Prokopec, Phys. Dark Univ. **18**, 6 (2017); I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019). Figures credits, H. V. Ragavendra and S. Maity.

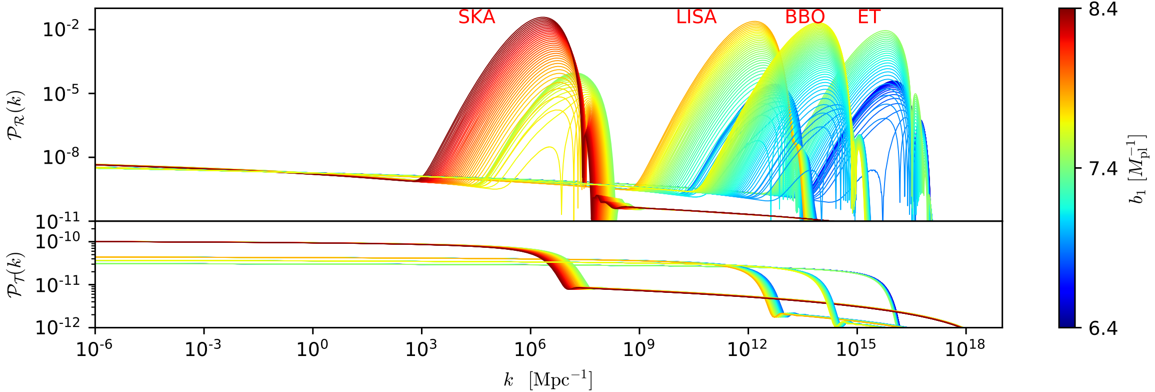
Power spectra in models permitting USR inflation



Scalar (in red) and the tensor (in blue) power spectra arising in different single-field models that permit a period of USR inflation[9].

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

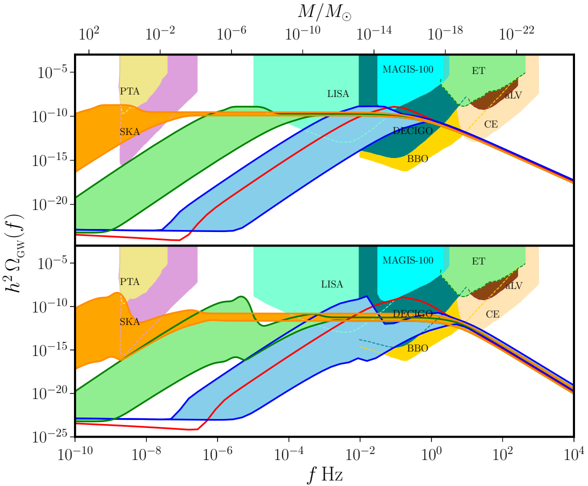
Enhanced scalar power on small scales in the two-field model



The scalar (on top) and the tensor (at the bottom) power spectra arising in the two-field model have been plotted for a few different sets of initial conditions for the fields and a range of values of a particular parameter[10].

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

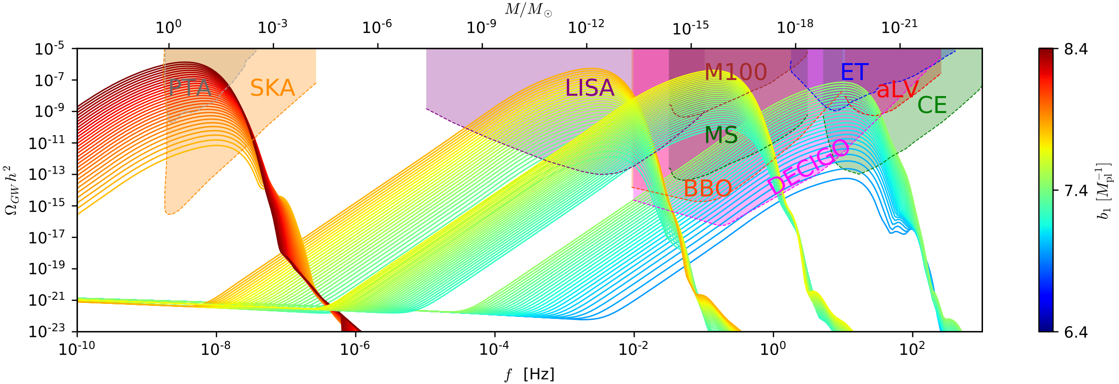
Secondary GWs in single-field models permitting USR inflation



The dimensionless density parameter $\Omega_{\rm GW}$ arising in the single-field models leading to an epoch of USR inflation has been plotted as a function of the frequency f[11].

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

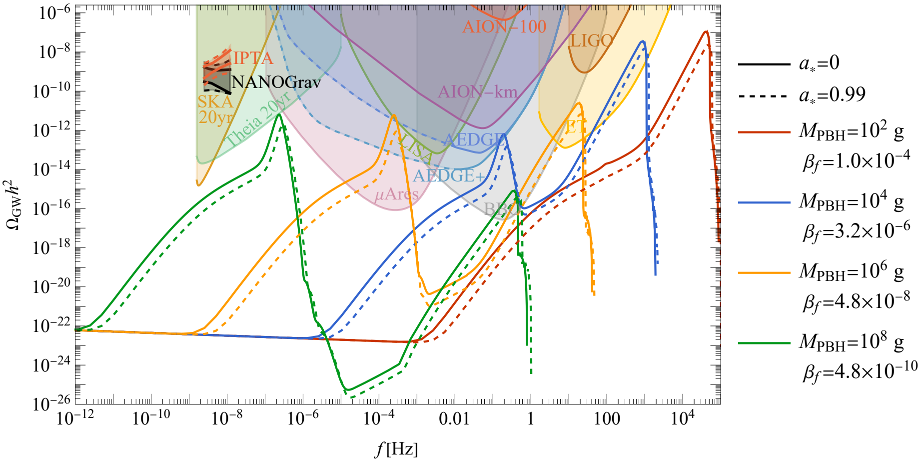
Secondary GWs in the two-field model



The dimensionless density parameter $\Omega_{\rm GW}(f)$ 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 a parameter describing the model[12].

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

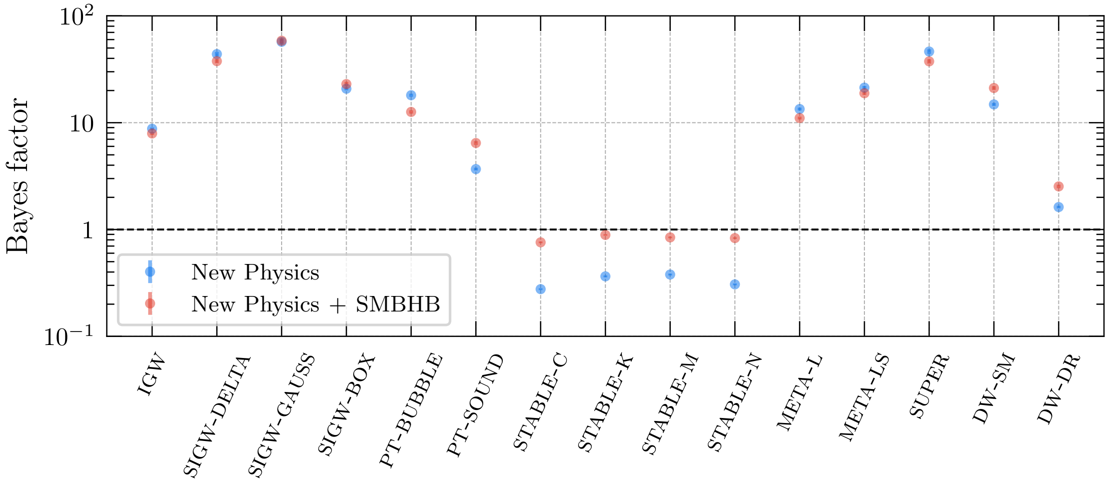
Spectral energy density of secondary GWs with a double peak



The dimensionless density parameter $\Omega_{\rm GW}(f)$ associated with the secondary GWs in a scenario where the distribution of ultra-low mass PBHs can induce additional isocurvature perturbations[13].

[13] N. Bhaumik, A. Ghoshal, R. K. Jain and M. Lewicki, JHEP **05**, 169 (2023).

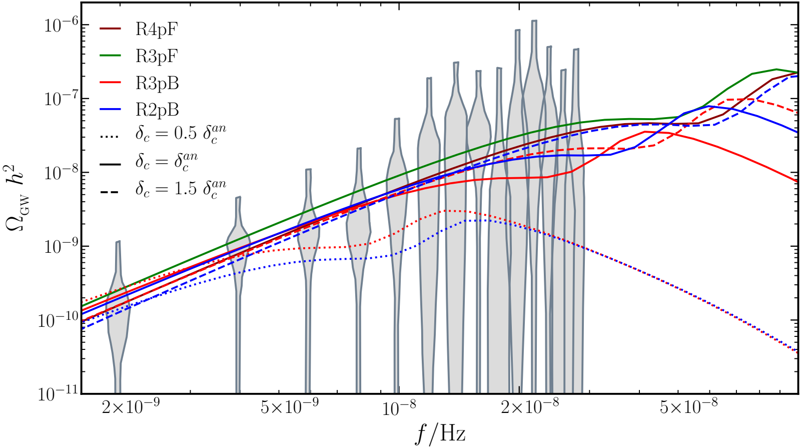
Stochastic GW background observed by pulsar timing arrays (PTAs)



The Bayesian evidence for a variety of astrophysical and cosmological sources for the stochastic GW background suggested by the observations of the PTAs[14].

[14] NANOGrav Collaboration (G. Agazie *et al.*), Astrophys. J. Lett. **951**, 1 (2023).

Generation of secondary GWs during the epoch of reheating

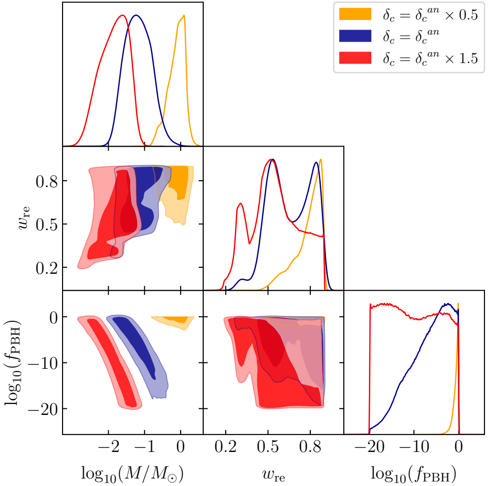


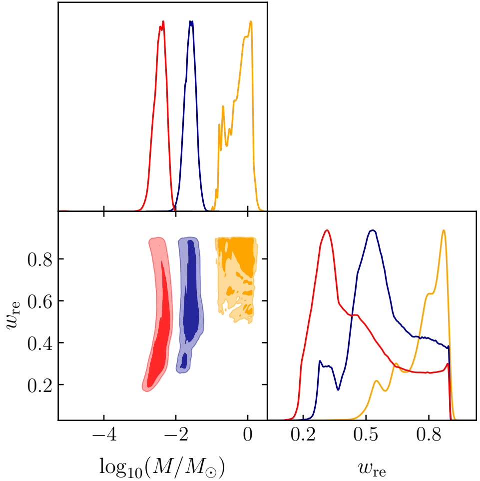
Epoch of reheating

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[15].

[15] S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, JCAP **01**, 118 (2025).

Constraints on the epoch of reheating



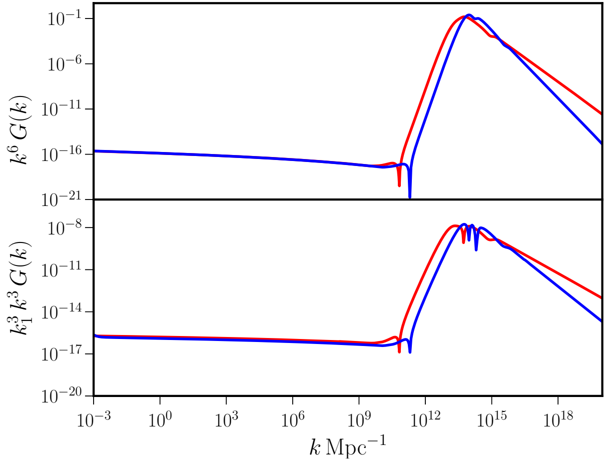


Constraints on the parameters of the two models `R3pB` (on the left) and `R2pB` (on the right), arrived at upon comparison with the NANOGrav 15-year data[16].

[16] S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, JCAP **01**, 118 (2025).

Plan of the talk

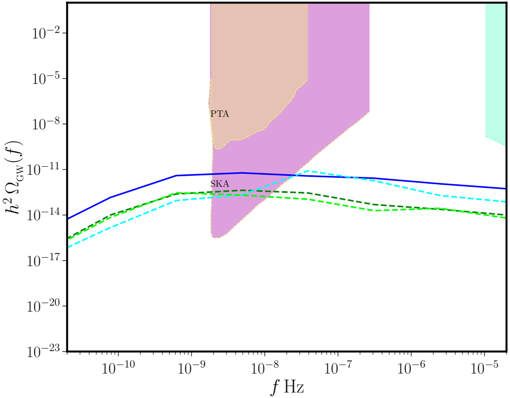
Scalar bispectrum in USR inflation

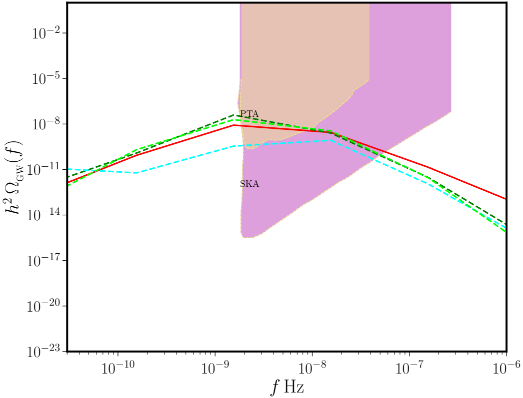


The amplitude of the dimensionless scalar bispectra is plotted in the equilateral (on top) and squeezed limits (at the bottom) for two models that permit USR inflation. The bispectra have approximately the same shape as the corresponding power spectra[17].

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

Secondary GWs including effects due to non-Gaussianities





The dimensionless spectral energy density of secondary GWs, including effects due to non-Gaussianities (indicated in dashed lines), in models that admit USR inflation[18].

[18] H. V. Ragavendra, Phys. Rev. D **105**, 063533 (2022).

Plan of the talk

Outlook

- The detection of the B-mode polarization of the CMB will allow us to determine the energy scale of inflation.
- The observations by the PTAs offer an opportunity to decode the physics operating over a wider range of scales in the early universe.
- During the coming decades, GW observatories such as the Laser Interferometer Space Antenna, Einstein Telescope and Cosmic Explorer, can be expected to provide us with additional constraints on primordial GWs.

Thank you for your attention