

Probing the primordial universe through gravitational waves

L. Sriramkumar

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

Conference on Cosmology, Astrophysics, and Particle Physics
SRM Institute of Science and Technology, Kattankulathur
January 30–February 2, 2025

Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications
- 7 Outlook



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, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, *Constraining the history of reheating with the NANOGrav 15-year data*, JCAP **01**, 118 (2025) [arXiv:2403.16963 [astro-ph.CO]].

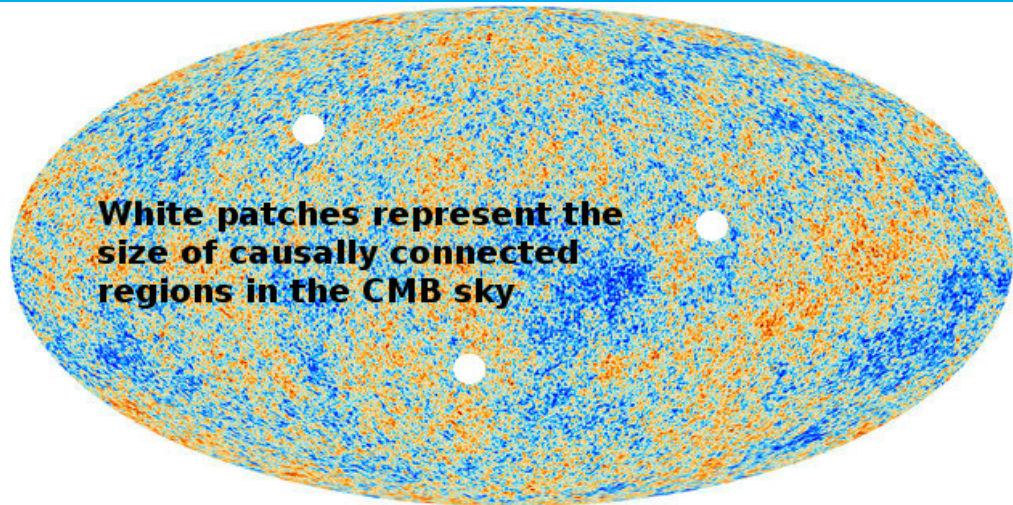


Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications
- 7 Outlook



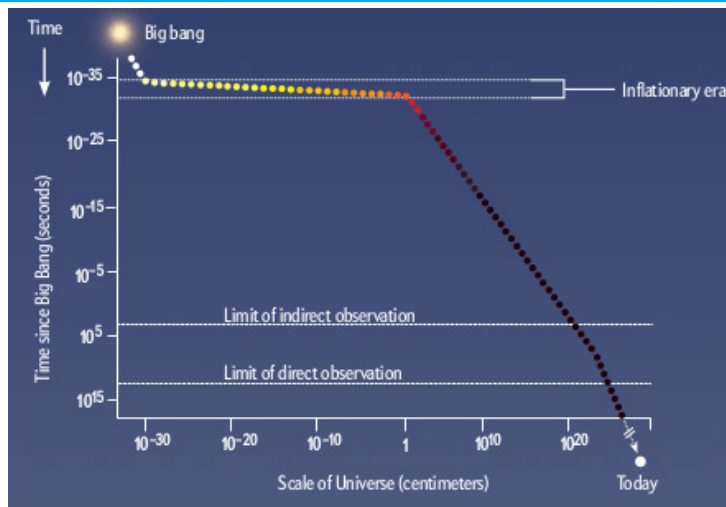
The horizon problem



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



Time and duration of inflation

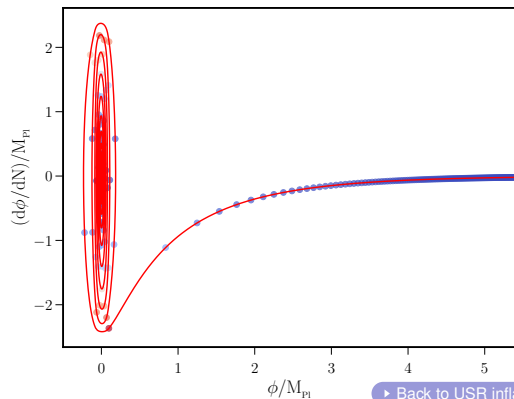
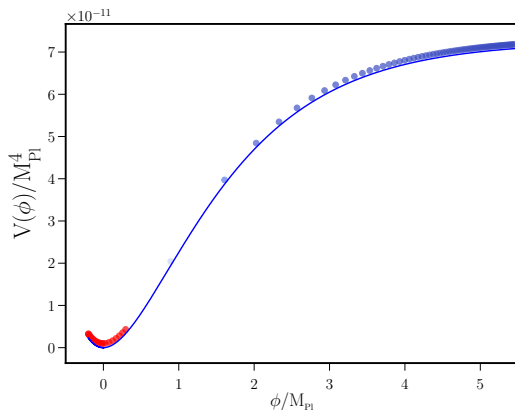


Inflation—a brief period of accelerated expansion—that is expected to have taken place during the very early stages of the universe, resolves the horizon problem¹.

¹Image from P. J. Steinhardt, *Sci. Am.* **304**, 18 (2011).



The inflationary attractor



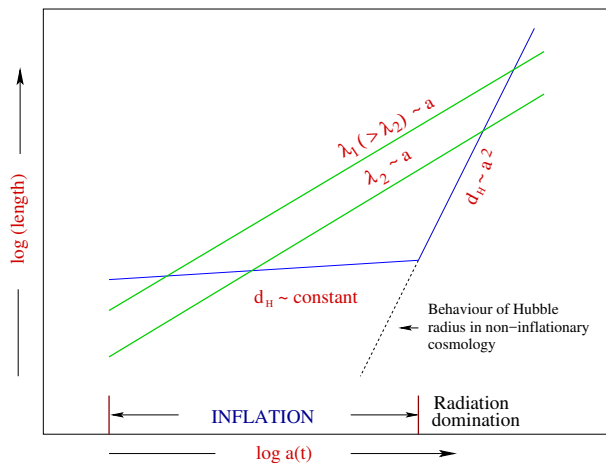
[▶ Back to USR inflation](#)

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.

²Figure from H. V. Ragavendra, *Observational imprints of non-trivial inflationary dynamics over large and small scales*, Ph.D. Thesis, Indian Institute of Technology Madras, Chennai, India (2022).



From inside the Hubble radius to super-Hubble scales



► Evolution of comoving lengths

The initial conditions are imposed in the sub-Hubble regime when the Fourier modes of the perturbations are well inside the Hubble radius (viz. when $k/(aH) \gg 1$) and the power spectra are evaluated when they sufficiently outside (i.e. as $k/(aH) \ll 1$)³.

³See, for instance, L. Sriramkumar, *Curr. Sci.* **97**, 868 (2009).



Characterizing the primordial perturbations

While comparing with the observations, for convenience, one often uses the following power law, template scalar and the tensor spectra:

$$\mathcal{P}_S(k) = A_S \left(\frac{k}{k_*} \right)^{n_S - 1}, \quad \mathcal{P}_T(k) = A_T \left(\frac{k}{k_*} \right)^{n_T},$$

with the spectral indices n_S and n_T assumed to be constant. The tensor-to-scalar ratio r is defined as

$$r(k) = \frac{\mathcal{P}_T(k)}{\mathcal{P}_S(k)}.$$

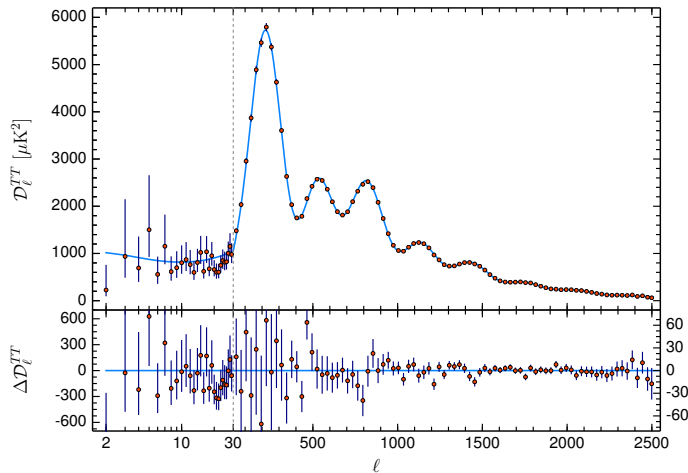


Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode**
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications
- 7 Outlook



CMB angular power spectrum from Planck

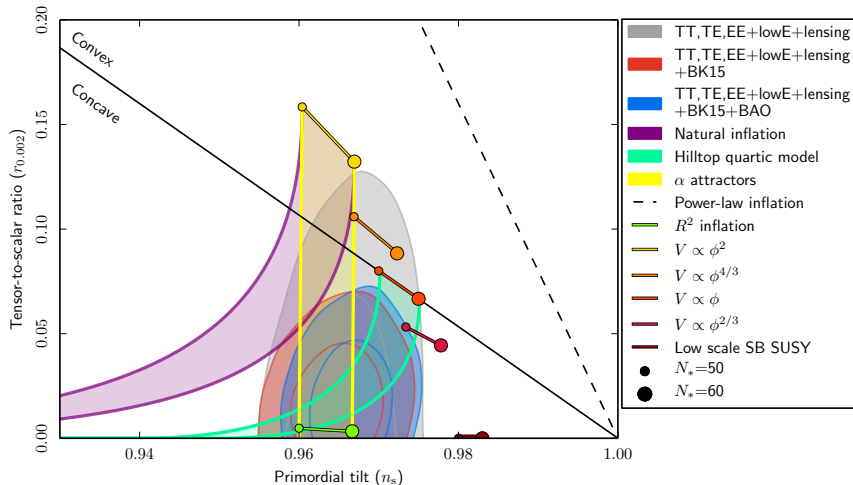


The CMB TT angular power spectrum from the Planck 2018 data (red dots with error bars) and the best fit Λ CDM model with a power law primordial spectrum (solid blue curve)⁴.

⁴Planck Collaboration (N. Aghanim *et al.*), *Astron. Astrophys.* **641**, A6 (2020).



Performance of inflationary models in the n_s - r plane

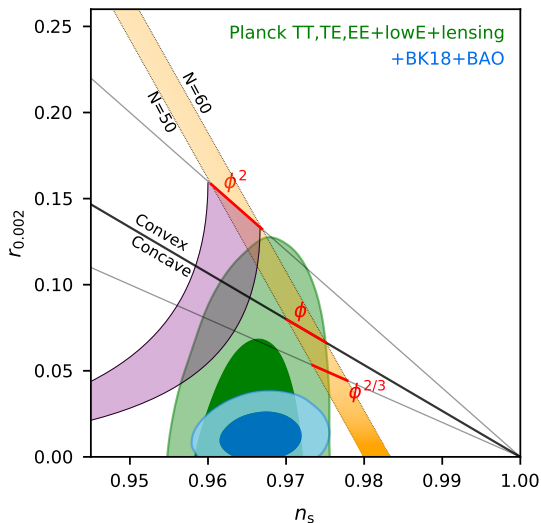


Joint constraints on n_s and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models⁵.

⁵Planck Collaboration (Y. Akrami *et al.*), *Astron. Astrophys.* **641**, A10 (2020).



Latest constraints on the tensor-to-scalar ratio r

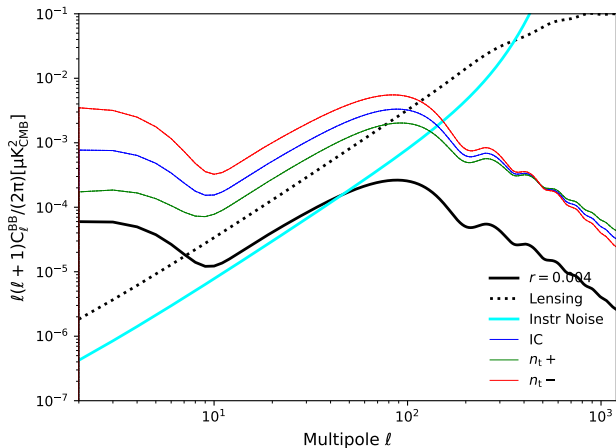


Latest constraints on the tensor-to-scalar ratio r from the BICEP/Keck telescopes⁶.

⁶BICEP/Keck Collaboration (P. A. R. Ade *et al.*), arXiv:2203.16556 [astro-ph.CO].



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 $r_{0.05} = 0.05$ have been plotted, along with the CMB lensing signal and the instrumental noise of a LiteBIRD-like configuration⁷.

⁷D. Paoletti, F. Finelli, J. Valiviita and M. Hazumi, *Phys. Rev. D* **106**, 083528 (2022).

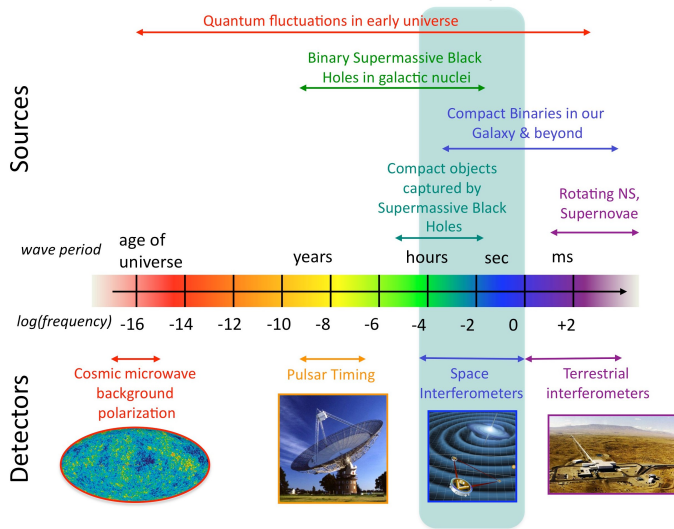


Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe**
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications
- 7 Outlook



The spectrum of GWs

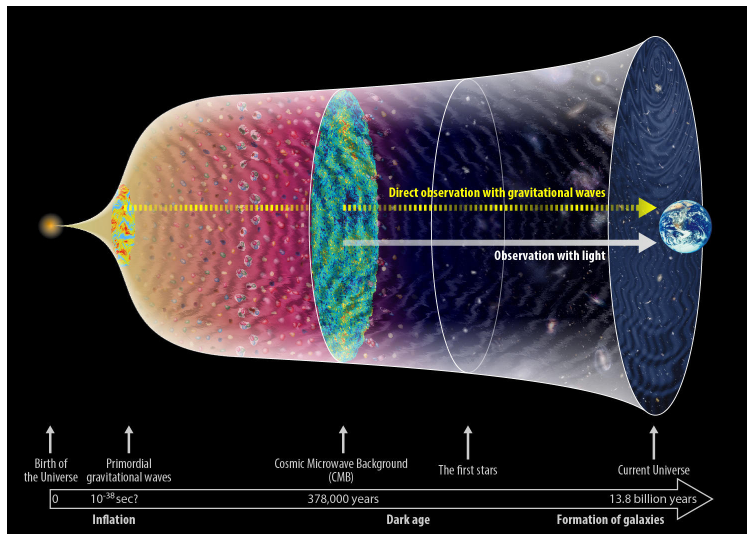


Different sources of GWs and corresponding detectors⁸.

⁸J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Pearson Education, Delhi, 2003).



Probing the primordial universe through GWs



GWs provide a unique window to probe the primordial universe⁹.

⁹Image from <https://gwpo.nao.ac.jp/en/gallery/000061.html>.

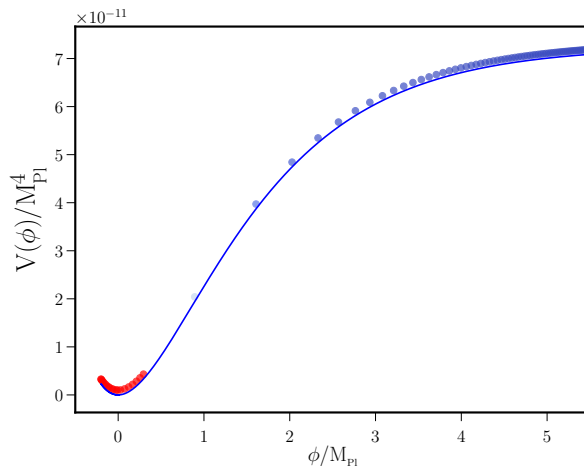


Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs**
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications
- 7 Outlook



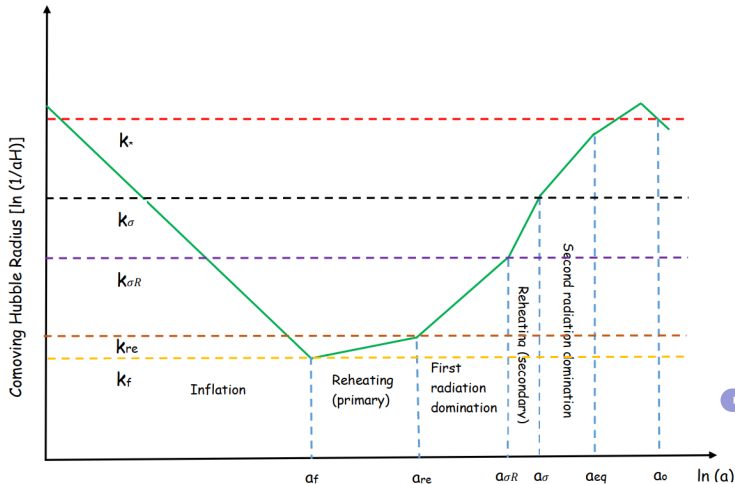
Evolution of the scalar field in an inflationary potential



The evolution of the scalar field in the so-called Starobinsky model has been indicated (as circles, in blue and red) at regular intervals of time. Inflation is terminated as the field approaches the bottom of the potential (near the light blue dot). Thereafter, the field oscillates at the bottom of the potential (indicated by the red dots).



Behavior of the comoving wave number and Hubble radius



► Evolution of physical lengths

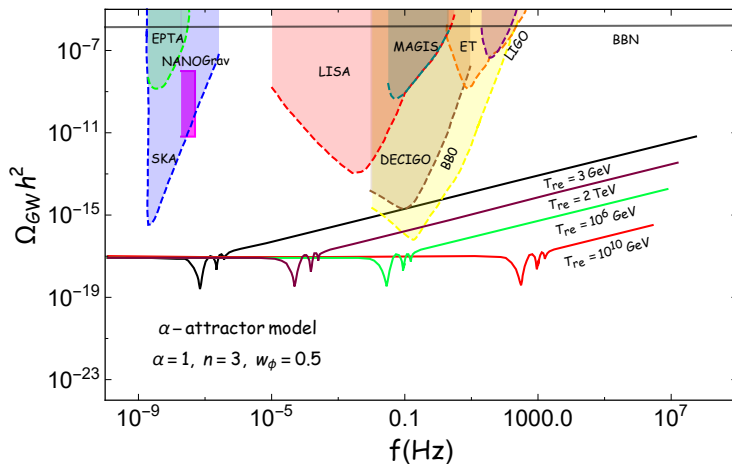
► Back to secondary GWs

Behavior of the comoving wave number k (horizontal lines in different colors) and the comoving Hubble radius $d_H/a = (aH)^{-1}$ (in green) across different epochs¹⁰.

¹⁰Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).



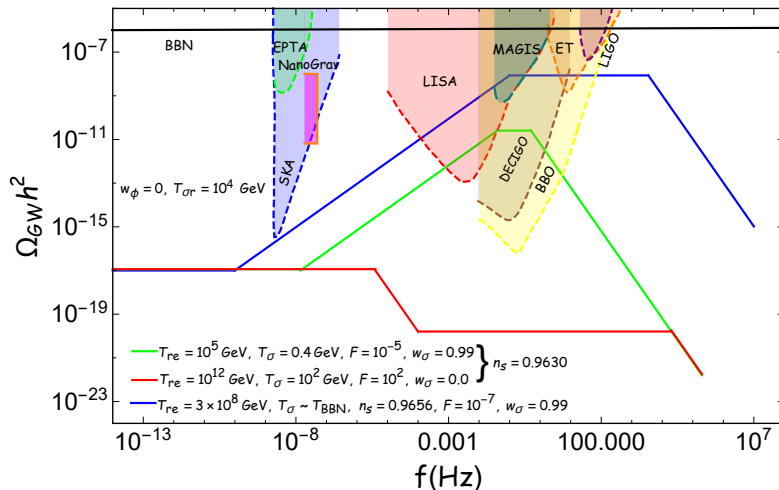
Effects on $\Omega_{\text{GW}}(f)$ due to reheating



The behavior of the dimensionless spectral energy density of primary GWs today, viz. Ω_{GW} , has been plotted, over a wide range of frequency f , for different reheating temperatures (in red, green, brown and black)¹¹.

¹¹Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).



Effects on $\Omega_{\text{GW}}(f)$ due to late time entropy production

The dimensionless spectral energy density of primary GWs observed today $\Omega_{\text{GW}}(f)$ has been plotted in a scenario involving late time production of entropy¹².

¹²Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

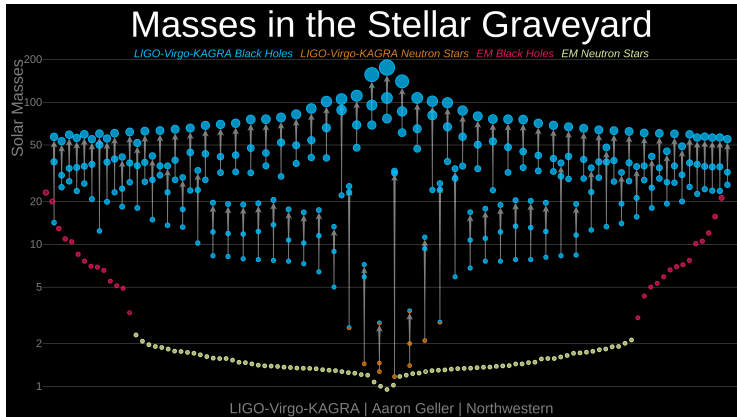


Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales**
- 6 NANOGrav 15-year data and its implications
- 7 Outlook



Coalescence of compact binaries observed by LIGO

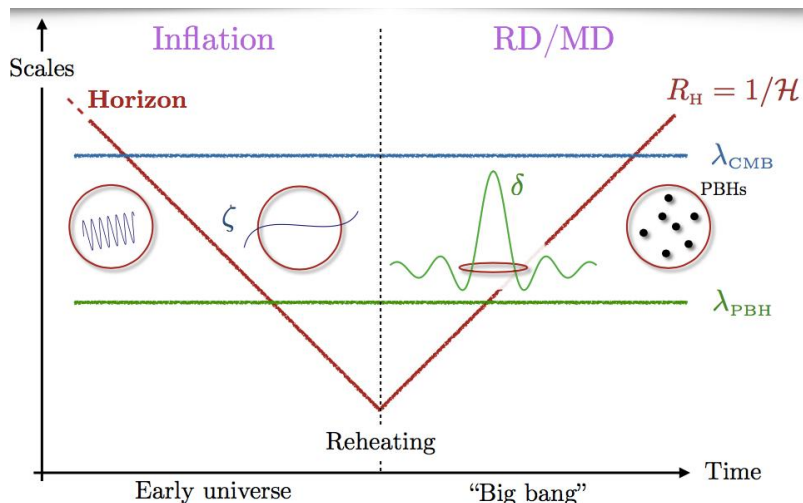


In November 2021, the LIGO-Virgo-KAGRA Collaboration released the results of the second-half of their third observing run. This third GW Transient Catalog is the largest catalog of mergers involving black holes and neutron stars released thus far and includes events released in prior observing runs¹³.

¹³Image from <https://www.ligo.caltech.edu/LA/image/ligo20211107a>.



Formation of primordial black holes (PBHs)

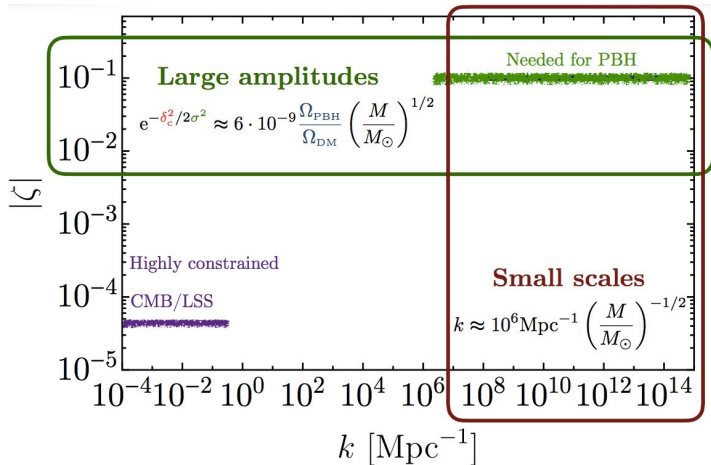


BHs can form in the primordial universe when perturbations with significant amplitudes on small scales reenter the Hubble radius during the radiation dominated epoch¹⁴.

¹⁴Figure from G. Franciolini, [arXiv:2110.06815 \[astro-ph.CO\]](https://arxiv.org/abs/2110.06815).



Amplitude required to form significant number of PBHs

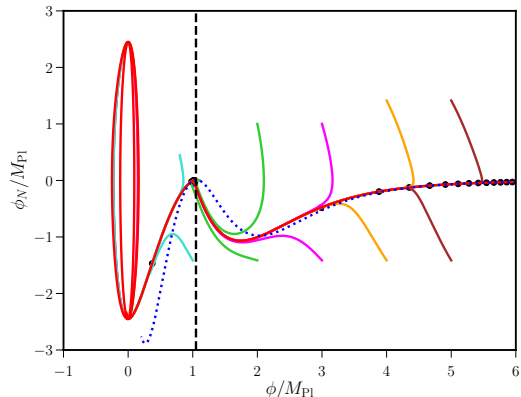
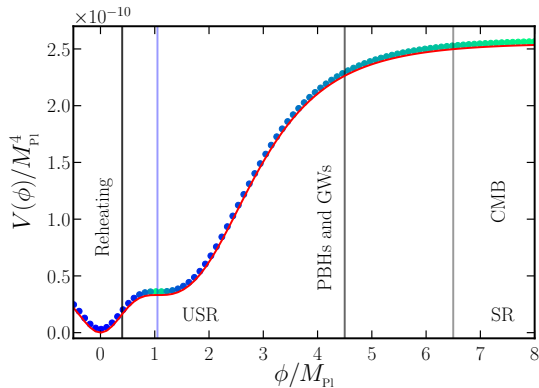


In order to form significant number of black holes, the amplitude of the perturbations on small scales has to be large enough such that the dimensionless amplitude of the scalar perturbation is close to unity¹⁵.

¹⁵Figure credit G. Franciolini.



Single-field models admitting ultra slow roll inflation



► Inflationary attractor

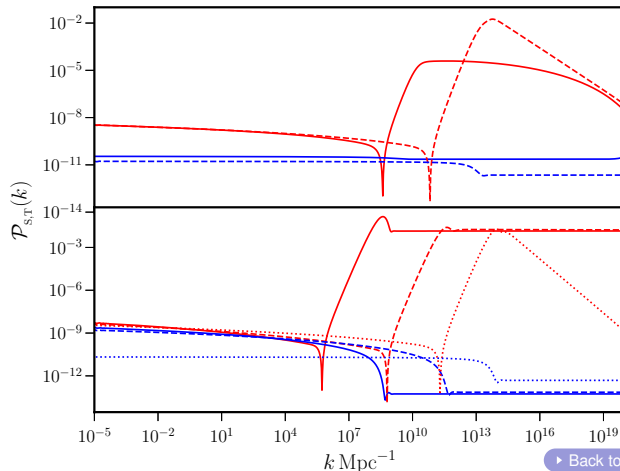
Potentials which contain a point of inflection lead to ultra slow roll (USR) inflation¹⁶.

¹⁶See, for example, J. Garcia-Bellido and E. R. Morales, *Phys. Dark Univ.* **18**, 47 (2017);
I. Dalianis, A. Kehagias and G. Tringas, *JCAP* **01**, 037 (2019).

Figures credits, S. Maity and H. V. Ragavendra.



Power spectra in models permitting USR inflation



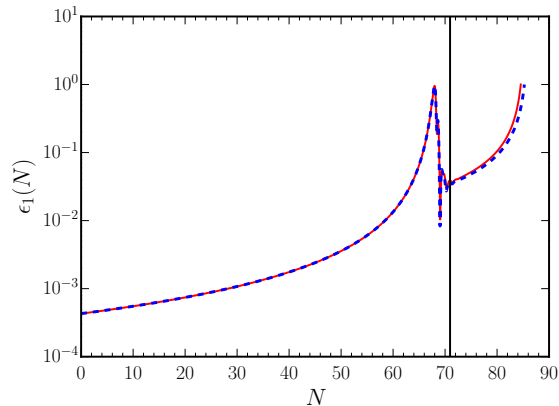
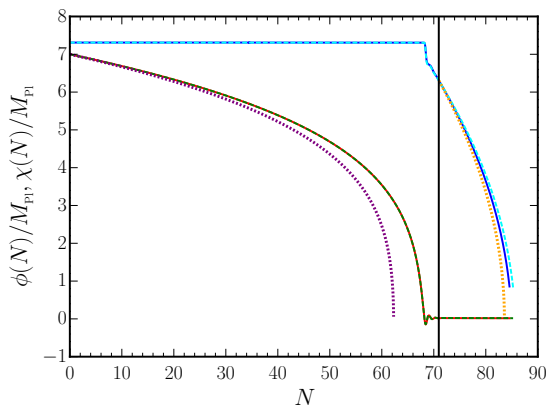
▶ [Back to analytical form of the power spectrum](#)

Scalar (in red) and the tensor (in blue) power spectra arising in different single-field models that permit a period of USR inflation¹⁷.

¹⁷H. 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).



Non-trivial inflationary dynamics in a two-field model

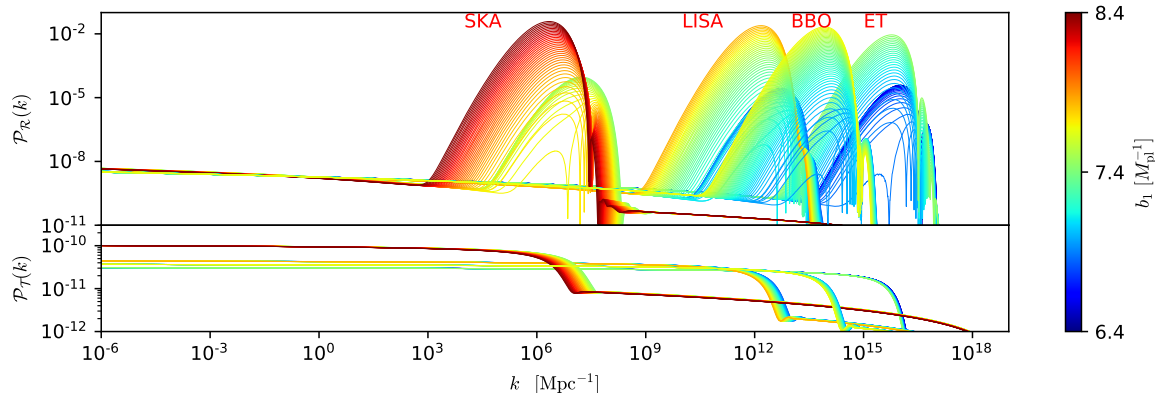


Behavior of the two scalar fields ϕ and χ (in blue and red, on the left) and the first slow roll parameter ϵ_1 (on the right) in the two field model of our interest¹⁸. Note that there arises a turn in the field space around $N = 70$, when the first slow roll parameter begins to decrease before increasing again, leading to the termination of inflation.

¹⁸M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).



Enhanced power on small scales in the two-field model

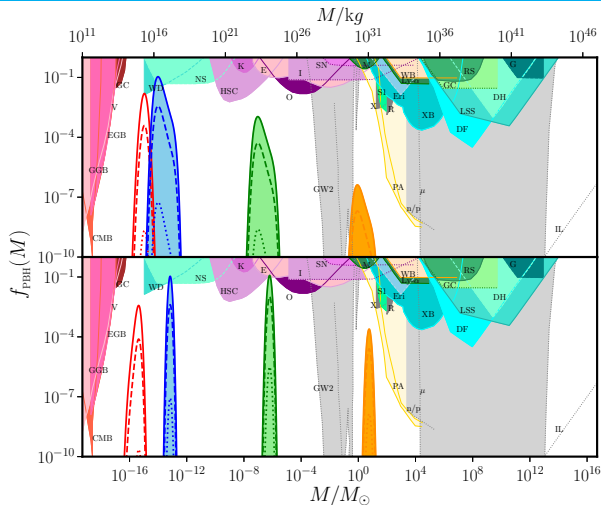


The scalar (on top) and the tensor (at the bottom) power spectra evaluated at the end of inflation have been plotted for a few different sets of initial conditions for the fields and a range of values of a particular parameter¹⁹.

¹⁹ M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).



$f_{\text{PBH}}(M)$ in ultra slow roll and punctuated inflation

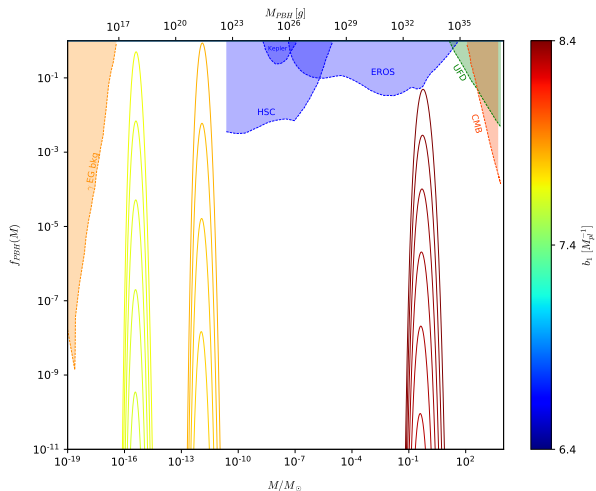


The fraction of PBHs contributing to the cold dark matter density today $f_{\text{PBH}}(M)$ has been plotted for different models, viz. USR2 (on top, in red) and PI3 (at the bottom, in red)²⁰.

²⁰H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021).



$f_{\text{PBH}}(M)$ in the two-field model

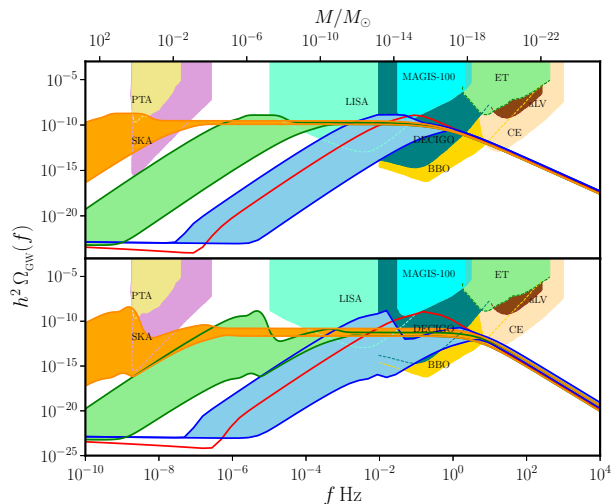


The fraction of PBHs contributing to the dark matter density today $f_{\text{PBH}}(M)$ in the two-field model of our interest²¹.

²¹ M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).



$\Omega_{\text{GW}}(f)$ in ultra slow roll and punctuated inflation

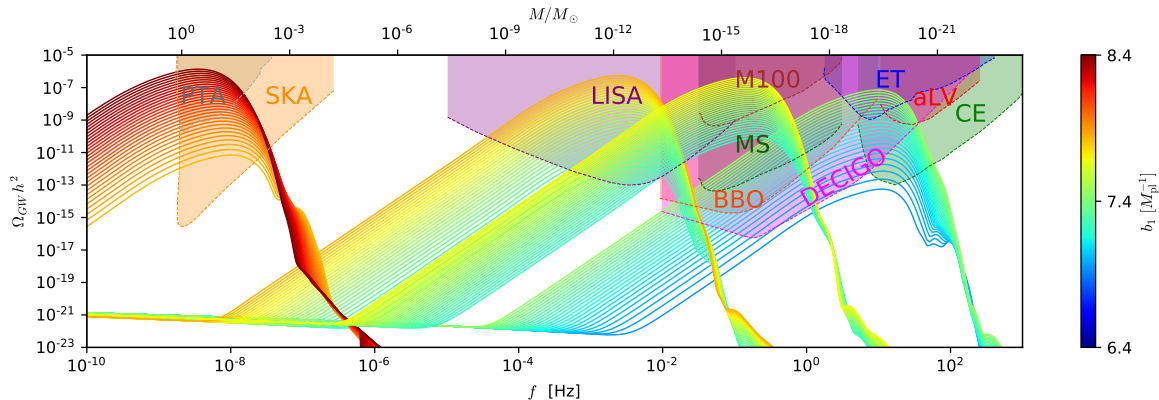


The dimensionless spectral density of GWs $\Omega_{\text{GW}}(f)$ arising in the models of USR2 (in red, on top) as well as PI3 (in red, at the bottom)²².

²²H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021).



$\Omega_{\text{GW}}(f)$ in the two-field model



The dimensionless spectral density of GWs $\Omega_{\text{GW}}(f)$ 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 the parameter b_1 ²³.

²³ M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

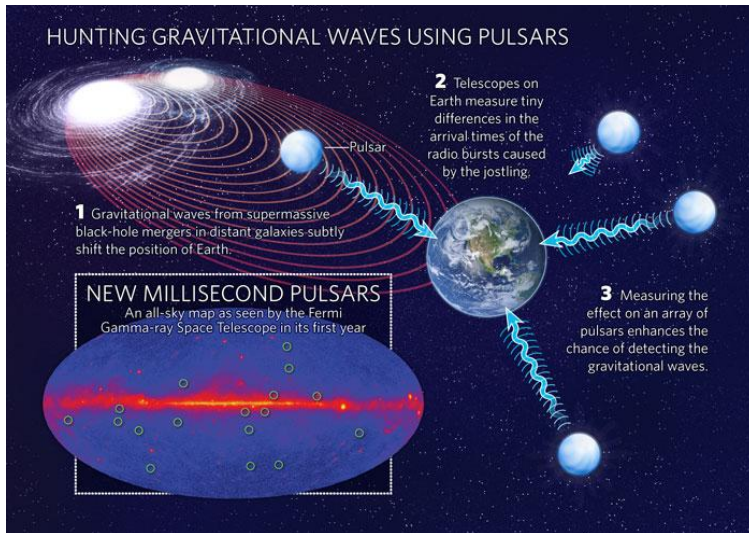


Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications**
- 7 Outlook



Pulsar timing arrays (PTAs)

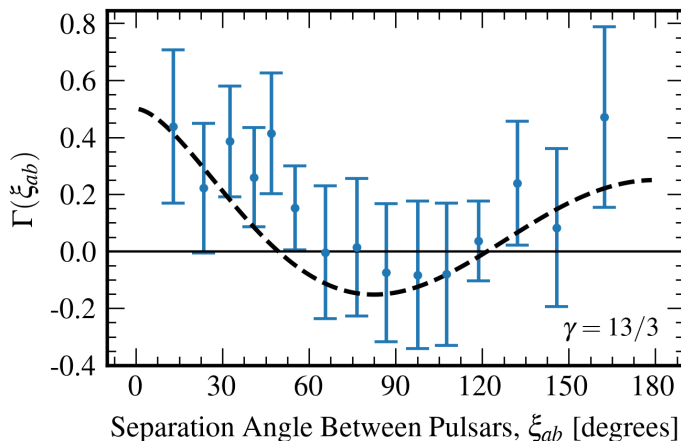


The PTAs monitor an array of millisecond pulsars²⁴.

²⁴See https://ipta.github.io/mock_data_challenge/.



Hellings-Downs curve

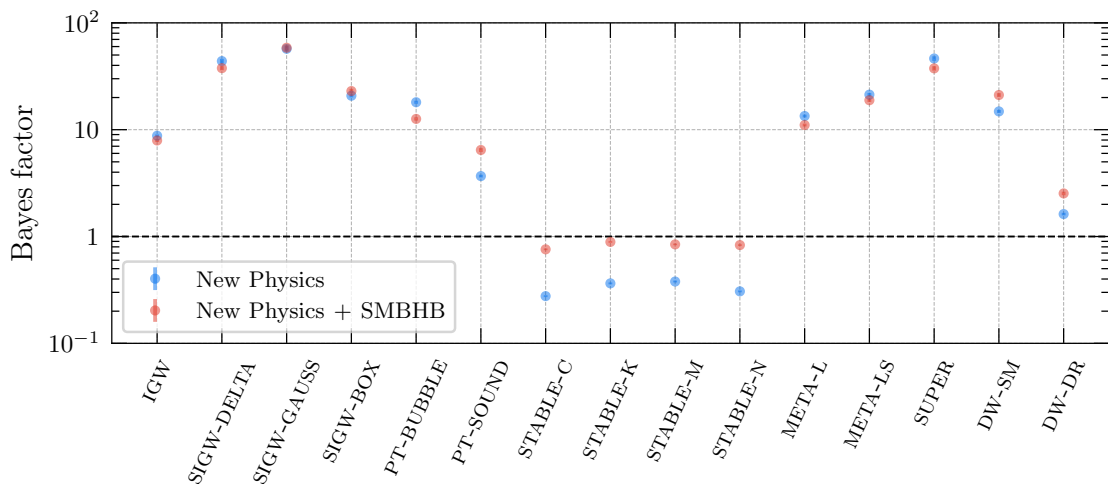


The inter-pulsar correlations measured from 2,211 distinct pairings in the 67-pulsar array of the NANOGrav 15-year data. The dashed black line shows the Hellings-Downs correlation pattern²⁵.

²⁵ NANOGrav Collaboration (G. Agazie *et al.*), *Astrophys. J. Lett.* **951**, 1 (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 ²⁶.

²⁶ NANOGrav Collaboration, *Astrophys. J. Lett.* **951**, L11 (2023).



Shape of the inflationary scalar power spectrum

We assume that the inflationary scalar power spectrum is given by²⁷

$$\mathcal{P}_S(k) = A_S \left(\frac{k}{k_*} \right)^{n_S - 1} + A_0 \begin{cases} \left(\frac{k}{k_{\text{peak}}} \right)^4 & k \leq k_{\text{peak}}, \\ \left(\frac{k}{k_{\text{peak}}} \right)^{n_0} & k \geq k_{\text{peak}}, \end{cases}$$

where A_S and n_S are the amplitude and spectral index of the power spectrum at the CMB pivot scale of $k_* = 0.05 \text{ Mpc}^{-1}$.

► Power spectra in USR inflation

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

We shall assume that the threshold value of the density contrast for the formation of PBHs is given by²⁸:

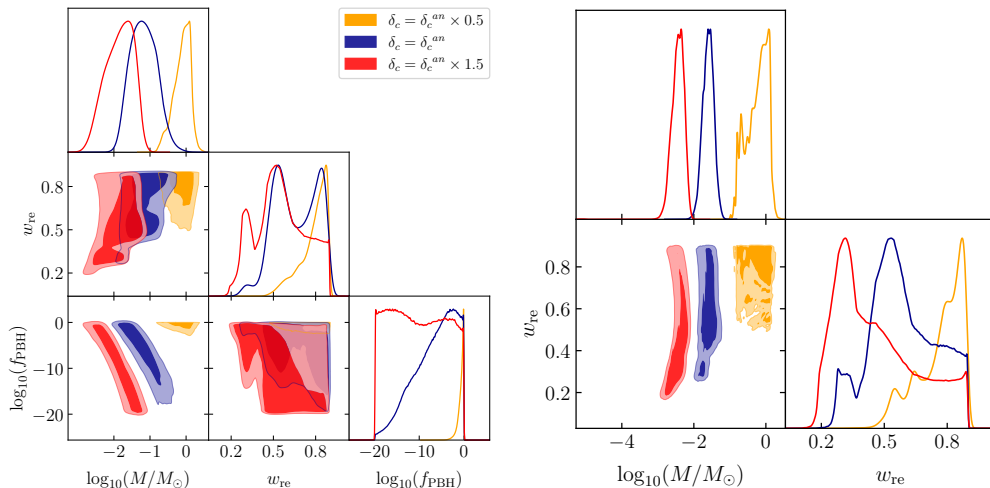
$$\delta_c^{\text{an}} = \frac{3(1 + w_{\text{re}})}{5 + 3w_{\text{re}}} \sin^2 \left(\frac{\pi \sqrt{w_{\text{re}}}}{1 + 3w_{\text{re}}} \right).$$

²⁷For other forms of spectra, see [G. Domènech, S. Pi, A. Wang and J. Wang, arXiv:2402.18965 \[astro-ph.CO\]](#).

²⁸In this context, see [T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D **88**, 084051 \(2013\)](#).



Constraints on the epoch of reheating

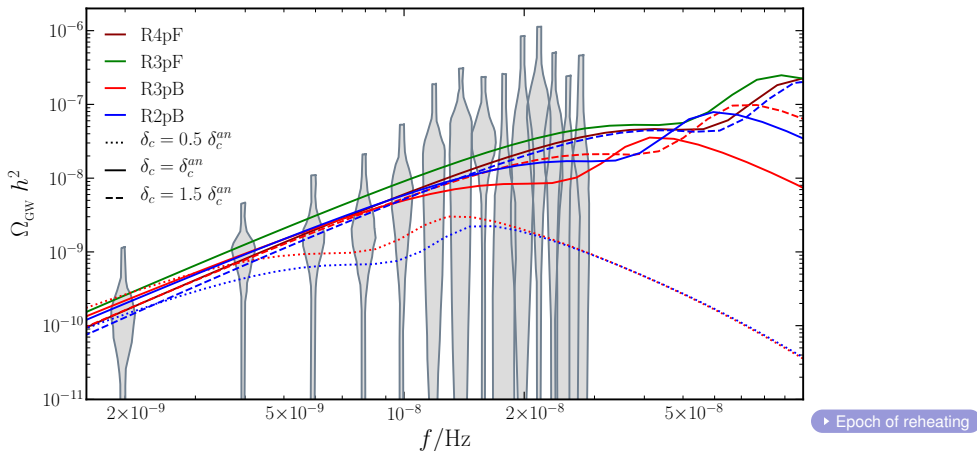


Constraints on the parameters in the models R3pB (on the left) and R2pB (on the right), arrived at upon comparison with the NANOGrav 15-year data²⁹.

²⁹S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, arXiv:2403.16963 [astro-ph.CO], accepted in JCAP.



Generation of secondary GWs during the epoch of reheating

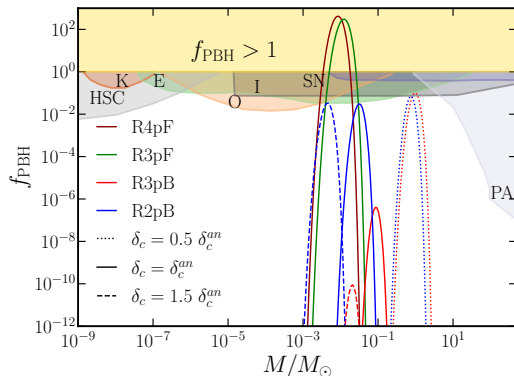
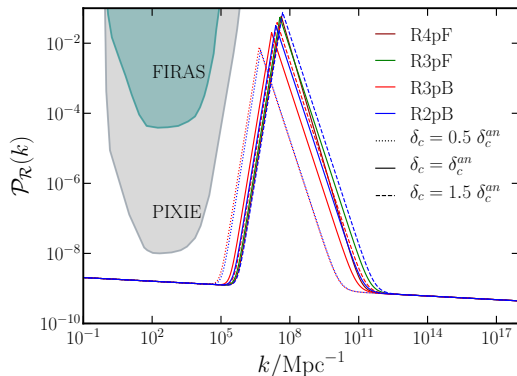


The dimensionless spectral energy density of the secondary GWs today $\Omega_{\text{GW}}(f)$ is plotted for a given reheating temperature and the best-fit values of the parameters in the different models³⁰.

³⁰S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, arXiv:2403.16963 [astro-ph.CO], accepted in JCAP.



Power spectra and the extent of PBHs formed



Scalar power spectra (on the left) and the extent of PBHs formed (on the right). We have assumed a specific reheating temperature and have plotted the fraction of PBHs that constitute the dark matter density today, viz. $f_{\text{PBH}}(M)$, for the best-fit values of the parameters in the different models³¹.

³¹S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, JCAP **01**, 118 (2025).



Bayesian evidence

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

The Bayesian factors $\text{BF}_{Y,X}$ 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 scenario that involves mergers of supermassive binary black holes (SMBHB).

Bayesian factors $\text{BF}_{Y,X}$ that far exceed unity indicate strong evidence for the model Y with respect to the model X .

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



Plan of the talk

- 1 Need for inflation
- 2 The holy grail: Observing the primordial B-mode
- 3 GWs provide a new window to the universe
- 4 Reheating can boost the strengths of primary GWs
- 5 Generation of GWs by enhanced scalar perturbations on small scales
- 6 NANOGrav 15-year data and its implications
- 7 Outlook**



Outlook

- ◆ If one of the future CMB missions—such as LiteBIRD (Lite, Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection), Primordial Inflation Explorer (PIXIE) or Exploring Cosmic History and Origin (ECHO, a proposed Indian effort)—detect the signatures of the primordial GWs, it will help us arrive at strong constraints on the dynamics during inflation and reheating.
- ◆ The observations by LIGO are a culmination of almost fifty years of effort to detect GWs. They have opened up a new window to observe the universe.
- ◆ The observations by the PTAs and their possible implications for the stochastic GW background offer a wonderful opportunity to understand 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 (LISA), Einstein Telescope and Cosmic Explorer, can be expected to provide us with an unhindered view of the primordial universe.



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



Nilanjandev Bhaumik



Thank you for your attention