# Constraining the epoch of reheating with the NANOGrav 15-year data

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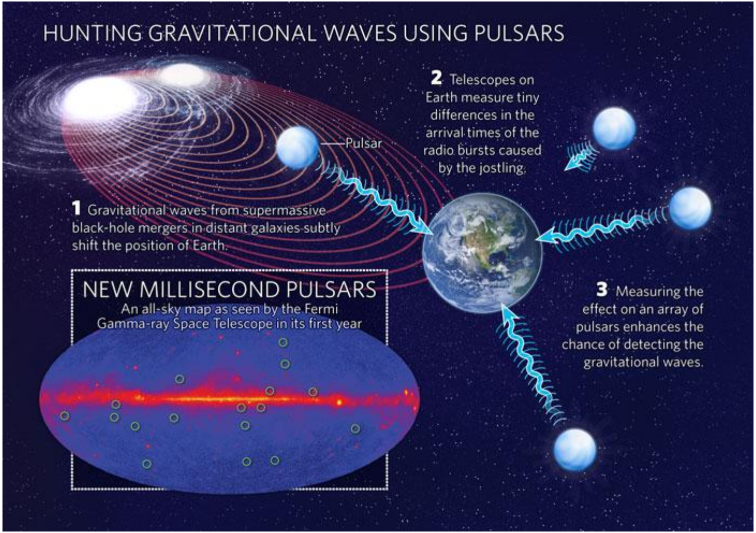
# Plan of the talk

# This talk is based on. . .

- 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], accepted for publication in JCAP.

# Plan of the talk

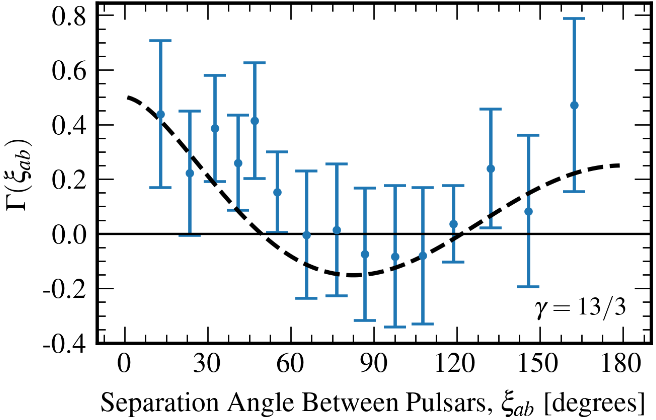
# Pulsar timing arrays (PTAs)




The PTAs monitor an array of millisecond pulsars[1].

[1] See https://ipta.github.io/mock_data_challenge/.

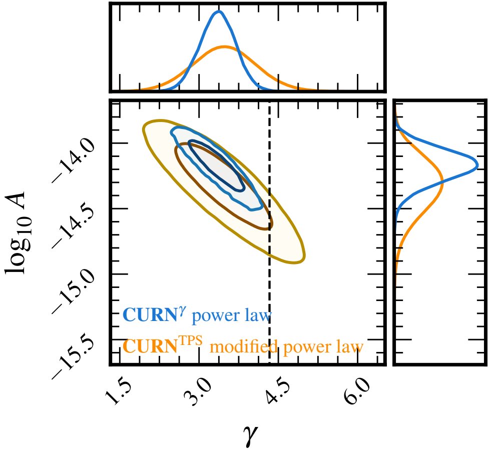
# Hellings-Downs curve




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 pattern[2].

[2] NANOGrav Collaboration (G. Agazie *et al.*), Astrophys. J. Lett. **951**, 1 (2023); For related discussion, see J. Yokoyama, arXiv:2105.07629 [gr-qc].

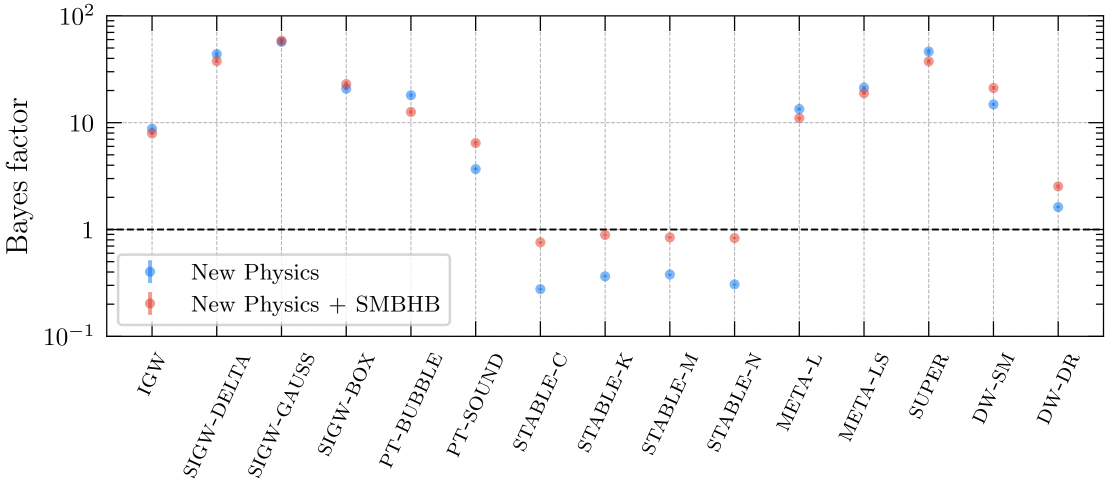
# Constraints on the spectral amplitude and index of GWs




Constraints on the amplitude $A$ and the index $\gamma$ of the stochastic background of GWs from the NANOGrav 15-year data[3].

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

# Stochastic GW background observed by pulsar timing arrays (PTAs)

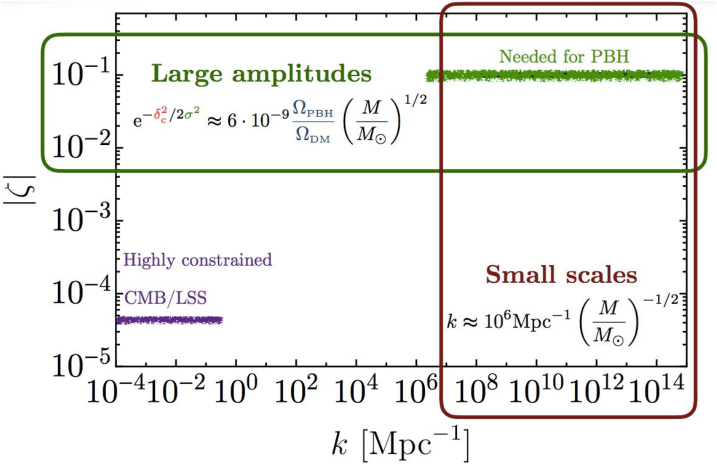



The Bayesian evidence for a variety of astrophysical and cosmological sources for the stochastic GW background suggested by the observations of the PTAs[4].

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

# Plan of the talk

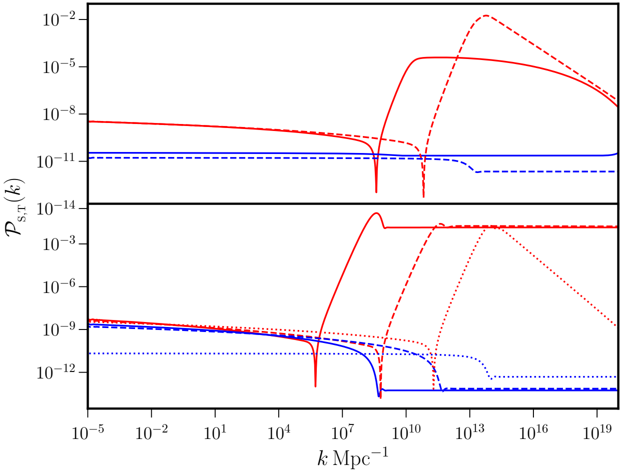
# Amplitude required to form significant number of PBHs




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 unity[5].

[5] Figure credit G. Franciolini.

# Power spectra in ultra slow roll inflation

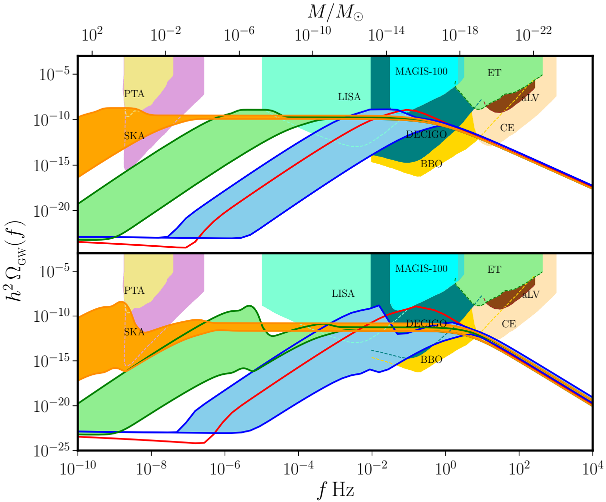



The scalar (in red) and the tensor power (in blue) spectra arising in different models permitting a brief epoch of ultra slow roll inflation[6].

Back to analytical form for the power spectrum

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

# $\Omega_{\rm GW}(f)$ in ultra slow roll inflation

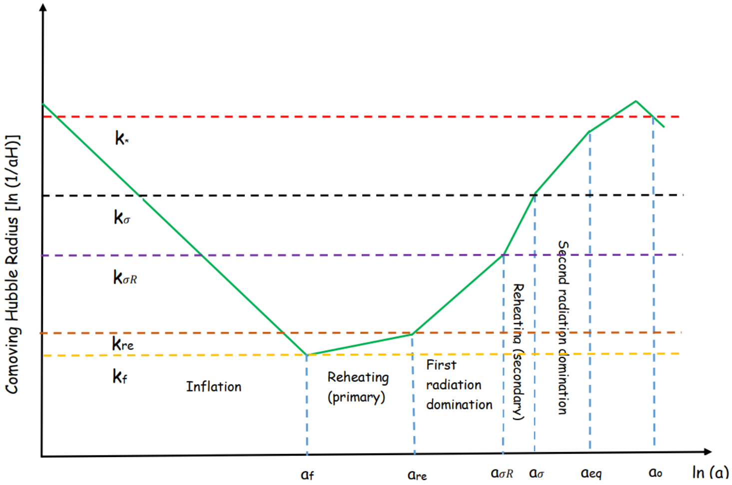



The dimensionless spectral density of GWs $\Omega_{\rm GW}(f)$ arising in a few different models of ultra slow roll inflation[7].

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

# Plan of the talk

# Behavior of the comoving wave number and Hubble radius




Behavior of the comoving wave number $k$ (horizontal lines in different colors) and the comoving Hubble radius $d_{\rm H}/a = (a\,H)^{-1}$ (in green) across different epochs[8].

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

# Shape of the inflationary scalar power spectrum

We assume that the inflationary scalar power spectrum is given by[9]

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

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

Power spectra in USR inflation

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

We shall assume that the threshold value of the density contrast for the formation of PBHs is given by[10]:

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

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

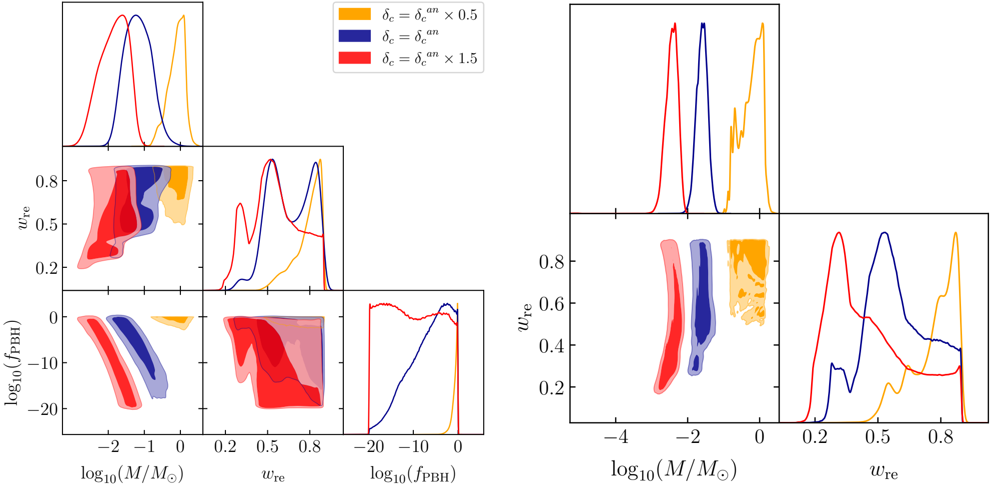
[10] In this context, see T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D **88**, 084051 (2013).

# Best-fit values

| Model | Parameter | Prior | Mean value | | |
|---|---|---|---|---|---|
| R4pF | $\log_{10}\left(\frac{k_{\rm peak}}{\rm Mpc^{-1}}\right)$ | $[6, 9]$ | $7.62^{+0.35}_{-0.41}$ | | |
| | $\log_{10}(A_0)$ | $[-3, 0]$ | $-1.23^{+0.38}_{-0.66}$ | | |
| | $w_{\rm re}$ | $[0.1, 0.9]$ | $0.52 \pm 0.23$ | | |
| | $n_0$ | $[-3.0, -1.5]$ | $-2.26 \pm 0.43$ | | |
| R3pF | $\log_{10}\left(\frac{k_{\rm peak}}{\rm Mpc^{-1}}\right)$ | $[6, 9]$ | $7.54^{+0.36}_{-0.44}$ | | |
| | $\log_{10}(A_0)$ | $[-3, 0]$ | $-1.26^{+0.26}_{-0.64}$ | | |
| | $w_{\rm re}$ | $[0.1, 0.9]$ | $0.55^{+0.39}_{-0.14}$ | | |
| | | | $\mathbf{0.5\,\delta_c^{an}}$ | $\boldsymbol{\delta_c^{an}}$ | $\mathbf{1.5\,\delta_c^{an}}$ |
| R3pB | $\log_{10}\left(\frac{M}{M_\odot}\right)$ | $[-6, 3.5]$ | $-0.12^{+0.28}_{-0.15}$ | $-1.18^{+0.35}_{-0.39}$ | $-1.85^{+0.49}_{-0.30}$ |
| | $\log_{10}(f_{\rm PBH})$ | $[-20, 0]$ | $-0.67^{+0.68}_{-0.16}$ | $-6.6^{+6.5}_{-1.9}$ | $-10.2^{+8.2}_{-9.6}$ |
| | $w_{\rm re}$ | $[0.1, 0.9]$ | $0.78^{+0.11}_{-0.030}$ | $0.66^{+0.23}_{-0.19}$ | $0.55 \pm 0.17$ |
| R2pB | $\log_{10}\left(\frac{M}{M_\odot}\right)$ | $[-6, 3.5]$ | $-0.24^{+0.38}_{-0.45}$ | $-1.60^{+0.16}_{-0.14}$ | $-2.45^{+0.20}_{-0.13}$ |
| | $w_{\rm re}$ | $[0.1, 0.9]$ | $0.77^{+0.13}_{-0.038}$ | $0.59 \pm 0.16$ | $0.464^{+0.095}_{-0.25}$ |

The best-fit values arrived at upon comparison with the NANOGrav 15-year data.

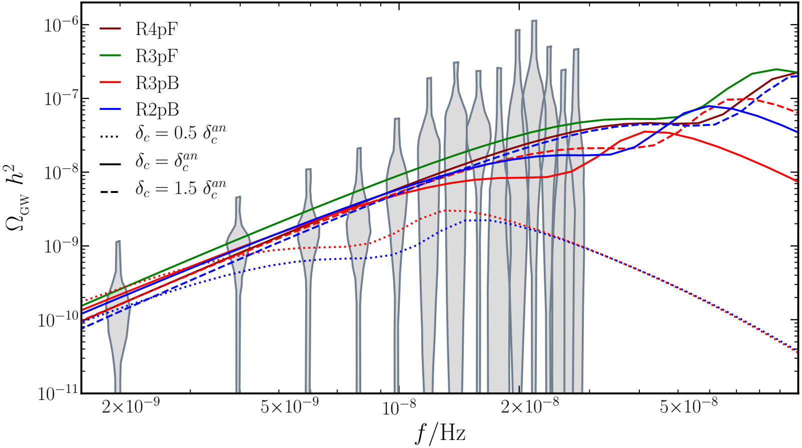
# Constraints on the epoch of reheating




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 data[11].

[11] S. 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

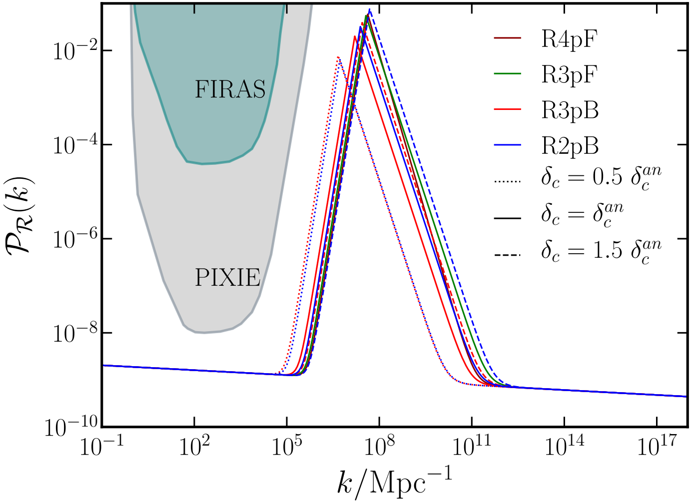



Epoch of reheating

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[12].

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

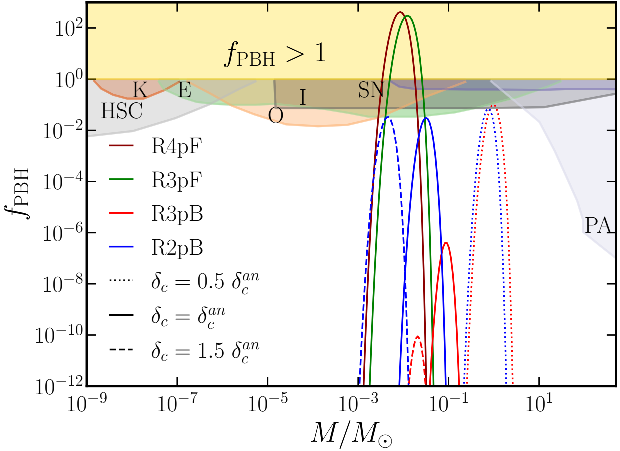
# Constraints from spectral distortions




Constraints on the scalar power spectrum from spectral distortions in the CMB[13].

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

# Formation of PBHs during the epoch of reheating




The fraction of PBHs that constitute the dark matter density today, viz. $f_{\rm PBH}(M)$ is plotted for a given reheating temperature and the best-fit values of the parameters in the different models[14].

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

# Bayesian evidence

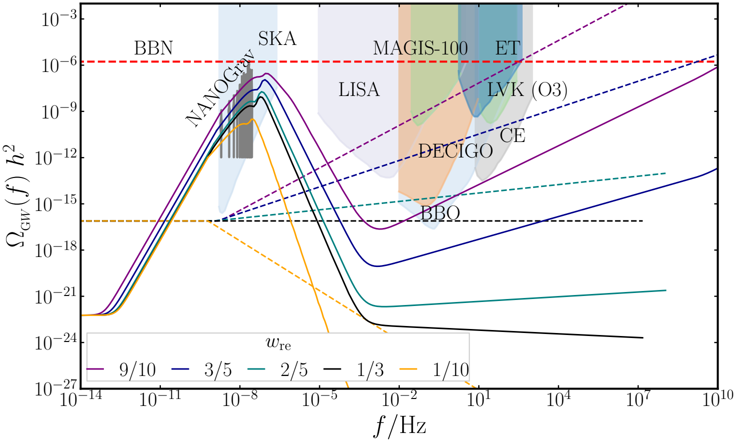
| Model X | Model Y | $\mathrm{BF}_{Y,X}$ | | |
|---|---|---|---|---|
| | | $\delta_{\mathrm{c}} = 0.5\,\delta_{\mathrm{c}}^{\mathrm{an}}$ | $\delta_{\mathrm{c}} = \delta_{\mathrm{c}}^{\mathrm{an}}$ | $\delta_{\mathrm{c}} = 1.5\,\delta_{\mathrm{c}}^{\mathrm{an}}$ |
| SMBHB | R2pB | $1.7 \pm .06$ | $260.04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

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 scenario of merging supermassive binary black holes.

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

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

# Generation of secondary GWs during the epoch of reheating




Epoch of reheating

The dimensionless spectral energy density of primary and secondary GWs today $\Omega_{\rm GW}(f)$ have been plotted for a given reheating temperature and different values of the parameter describing the EoS during reheating[15].

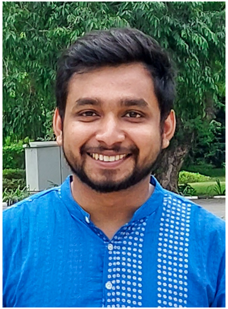
[15] S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, arXiv:2403.16963 [astro-ph.CO], accepted in JCAP.

# Plan of the talk

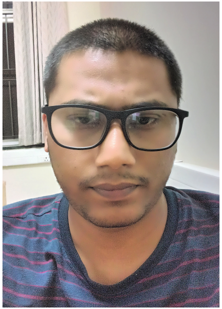
# Outlook

- In this work, we assumed a specific functional form for the primordial scalar power spectrum and examined the production of PBHs and the scalar-induced, secondary GWs during the phase of reheating, which precedes the standard epoch of radiation domination.
- Specifically, we accounted for the uncertainties in the conditions for the formation of PBHs and ensured that the extent of PBHs produced remains within the observational bounds.
- We found that the scalar-induced SGWB generated during a phase of reheating with a steeper equation of state (than that of radiation) fit the NANOGrav 15-year data with a stronger Bayesian evidence than the astrophysical scenario involving GWs produced by merging supermassive binary black holes.

# Collaborators



Suvashis Maity



Nilanjandev Bhaumik

Md. Riajul Haque

Debaprasad Maity

Thank you for your attention