

# Deciphering the physics of the early universe with gravitational waves

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Indian Institute of Astrophysics, Bengaluru  
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# Plan of the talk

- 1 The need for inflation
- 2 Constraints on inflation from the CMB data
- 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 the stochastic GW background
- 7 Outlook



# This talk is based on...

- ◆ H. V. Ragavendra, D. Chowdhury and L. Sriramkumar, *Suppression of scalar power on large scales and associated bispectra*, Phys. Rev. D **106**, 043535 (2022) [arXiv:2003.01099 [astro-ph.CO]].
- ◆ M. Braglia, D. K. Hazra, L. Sriramkumar and F. Finelli, *Generating primordial features at large scales in two field models of inflation*, JCAP **08**, 025 (2020) [arXiv:2004.00672 [astro-ph.CO]].
- ◆ 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]].



## This talk is based on...

- ◆ 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. Maiti, D. Maity and L. Sriramkumar, *Constraining inflationary magnetogenesis and reheating via GWs in light of PTA data*, arXiv:2401.01864 [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*, in preparation.

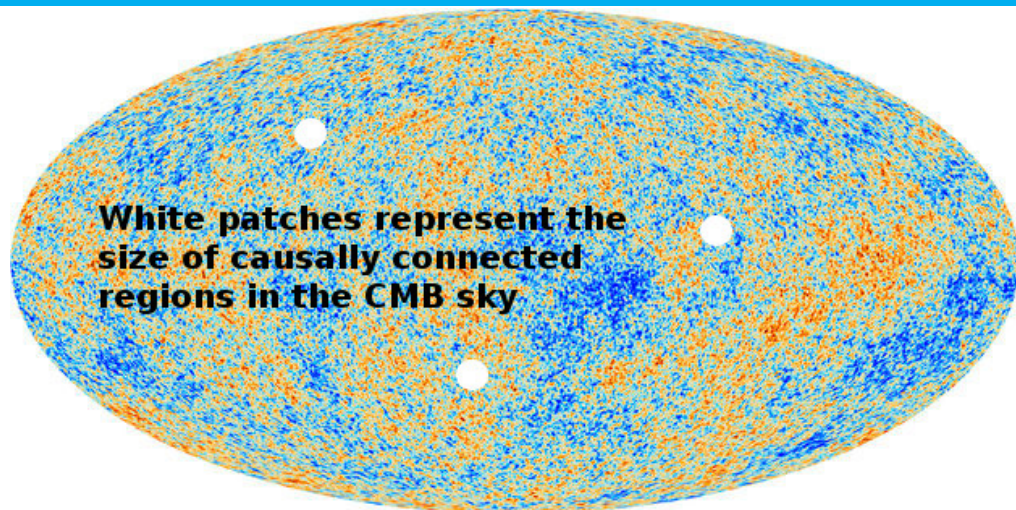


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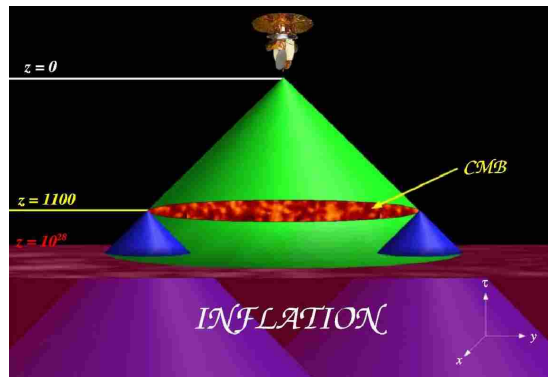
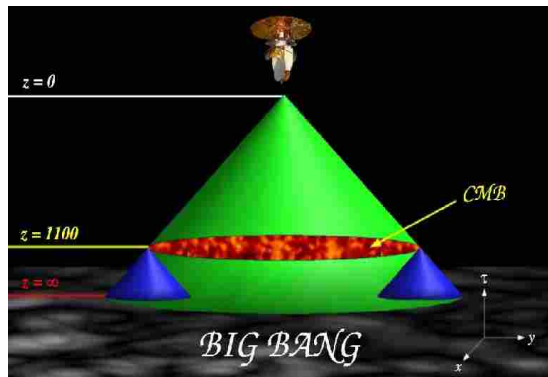
# The horizon problem



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  $1^\circ$  today, could not have interacted before decoupling.



# The resolution of the horizon problem in the inflationary scenario

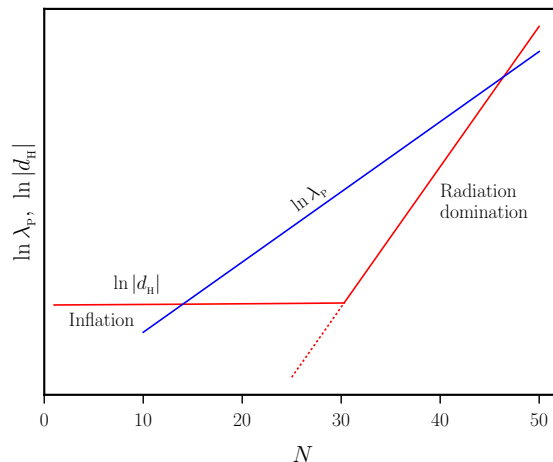


Another illustration of the horizon problem (on the left), and an illustration of its resolution (on the right) through an early and sufficiently long epoch of inflation<sup>1</sup>.

<sup>1</sup>Images from [W. Kinney, astro-ph/0301448](#).



# Bringing the modes inside the Hubble radius



► Evolution of comoving lengths

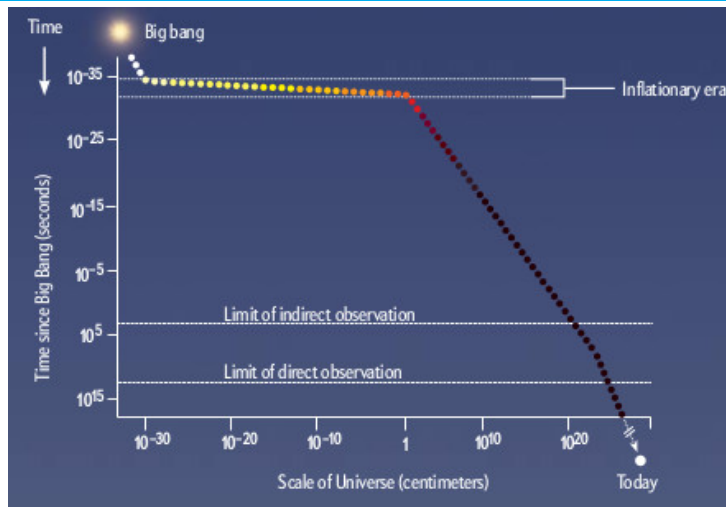
The physical wavelength  $\lambda_p \propto a$  (in blue) and the Hubble radius  $d_H = H^{-1}$  (in red) in the inflationary scenario<sup>2</sup>. The scale factor is expressed in terms of e-folds  $N$  as  $a(N) \propto e^N$ .

<sup>2</sup>See, for example, E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley Publishing Company, New York, 1990), Fig. 8.4.





# Time and duration of inflation

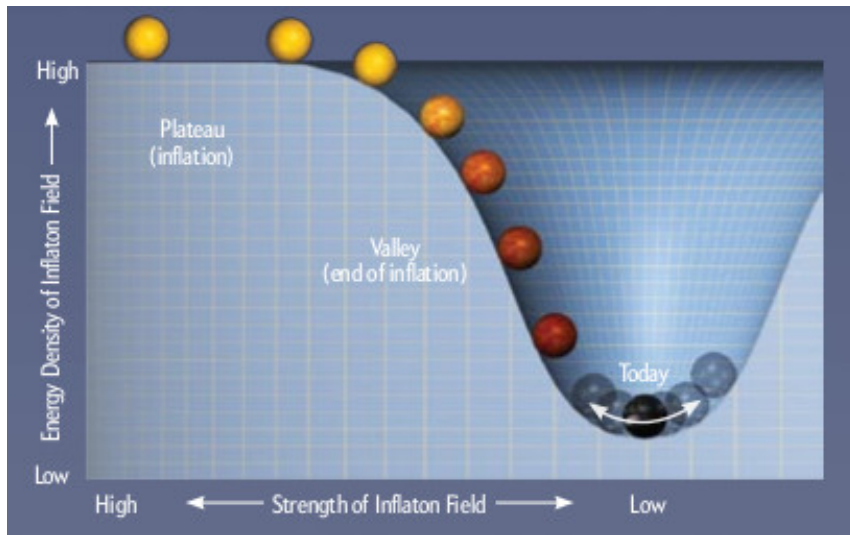


Inflation—a brief period of accelerated expansion—is expected to have taken place during the very early stages of the universe<sup>3</sup>.

<sup>3</sup>Image from P. J. Steinhardt, *Sci. Am.* **304**, 18 (2011).



# Driving inflation with scalar fields

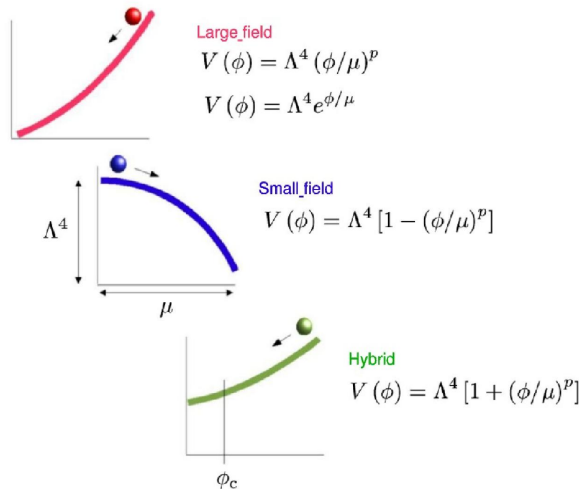


Inflation can be achieved with scalar fields encountered in high energy physics<sup>4</sup>.

<sup>4</sup>Image from P. J. Steinhardt, *Sci. Am.* **304**, 34 (2011).



# A variety of potentials to choose from

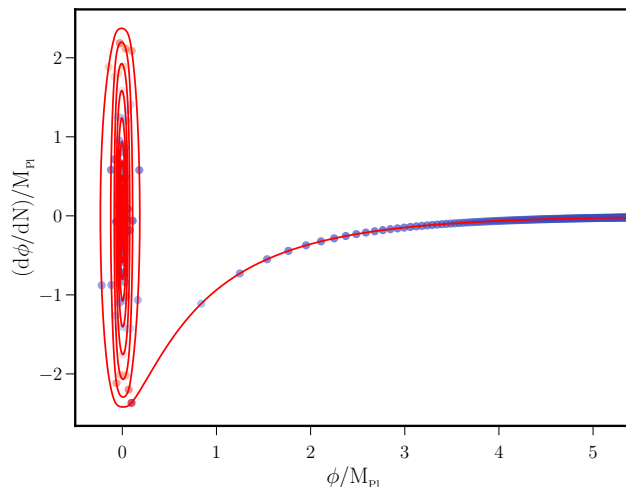


A variety of scalar field potentials have been considered to drive inflation<sup>5</sup>. Often, these potentials are classified as small field, large field and hybrid models.

<sup>5</sup>Image from [W. Kinney, astro-ph/0301448](https://arxiv.org/abs/astro-ph/0301448).



# The inflationary attractor



▶ Back to USR inflation

▶ Back to reheating

Behavior of the scalar field in phase space in the case of the popular Starobinsky model, which admits slow roll inflation<sup>6</sup>.

<sup>6</sup>Figure credit [H. V. Ragavendra](#).



# Proliferation of inflationary models

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

A (partial?) list of ever-increasing number of inflationary models<sup>7</sup>. Actually, it may not even be possible to rule out some of these models!

<sup>7</sup> 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).



# The quadratic action governing the perturbations

One can show that, at the quadratic order, the action governing the curvature perturbation  $\mathcal{R}$  and the tensor perturbation  $\gamma_{ij}$  are given by<sup>8</sup>

$$\mathcal{S}_2[\mathcal{R}(\eta, \mathbf{x})] = \frac{1}{2} \int d\eta \int d^3\mathbf{x} z^2 \left[ \mathcal{R}'^2 - (\partial\mathcal{R})^2 \right],$$

$$\mathcal{S}_2[\gamma_{ij}(\eta, \mathbf{x})] = \frac{M_{\text{Pl}}^2}{8} \int d\eta \int d^3\mathbf{x} a^2 \left[ \gamma'_{ij}{}^2 - (\partial\gamma_{ij})^2 \right].$$

These actions lead to the following equations of motion governing the scalar and tensor modes, say,  $f_k$  and  $h_k$ :

$$f_k'' + 2 \frac{z'}{z} f_k' + k^2 f_k = 0,$$

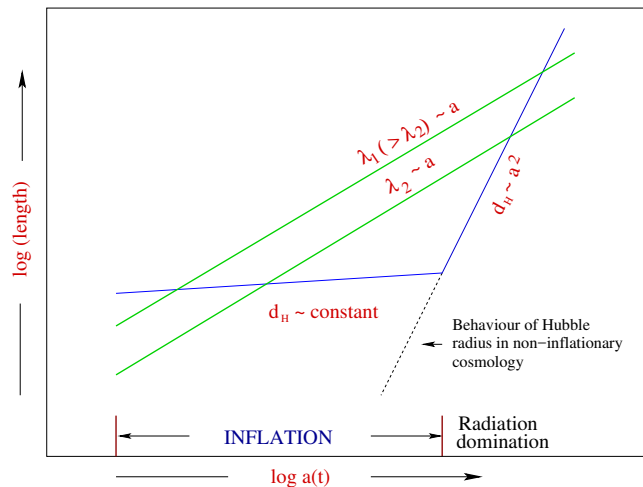
$$g_k'' + 2 \frac{a'}{a} g_k' + k^2 g_k = 0,$$

where  $z = a M_{\text{Pl}} \sqrt{2\epsilon_1}$ , with  $\epsilon_1 = -d \ln H / dN$  being the first slow roll parameter.

<sup>8</sup>V. F. Mukhanov, H. A. Feldman and R. H. Brandenberger, Phys. Rep. **215**, 203 (1992).



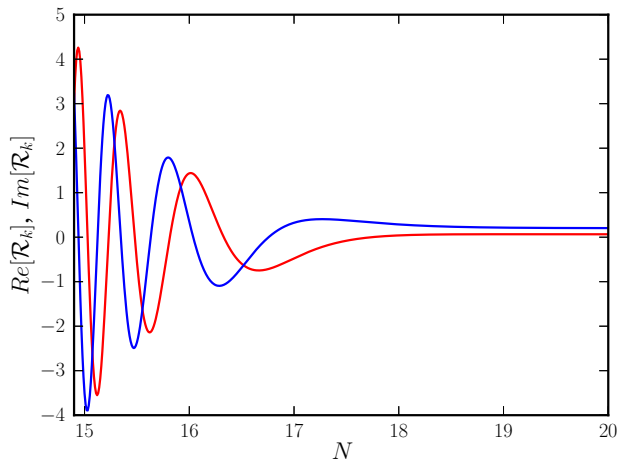
# From inside the Hubble radius to super-Hubble scales



The initial conditions are imposed in the sub-Hubble regime when the modes 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  $k/(aH) \ll 1$ ).



# Typical evolution of the perturbations



Typical evolution of the real and the imaginary parts of the scalar modes during slow roll inflation. The mode considered here leaves the Hubble radius at about 18 e-folds<sup>9</sup>.

<sup>9</sup>Figure from V. Sreenath, *Computation and characteristics of inflationary three-point functions*, Ph.D. Thesis, Indian Institute of Technology Madras, Chennai, India (2015).





## Spectral indices and the tensor-to-scalar ratio

The scalar and tensor power spectra, viz.  $\mathcal{P}_S(k)$  and  $\mathcal{P}_T(k)$ , can be expressed in terms of the Fourier modes  $f_k$  and  $g_k$  as follows:

$$\mathcal{P}_S(k) = \frac{k^3}{2\pi^2} |f_k(\eta_e)|^2,$$

$$\mathcal{P}_T(k) = \frac{8}{M_{\text{Pl}}^2} \frac{k^3}{2\pi^2} |g_k(\eta_e)|^2,$$

with  $\eta_e$  corresponding to suitably late times during inflation.

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

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

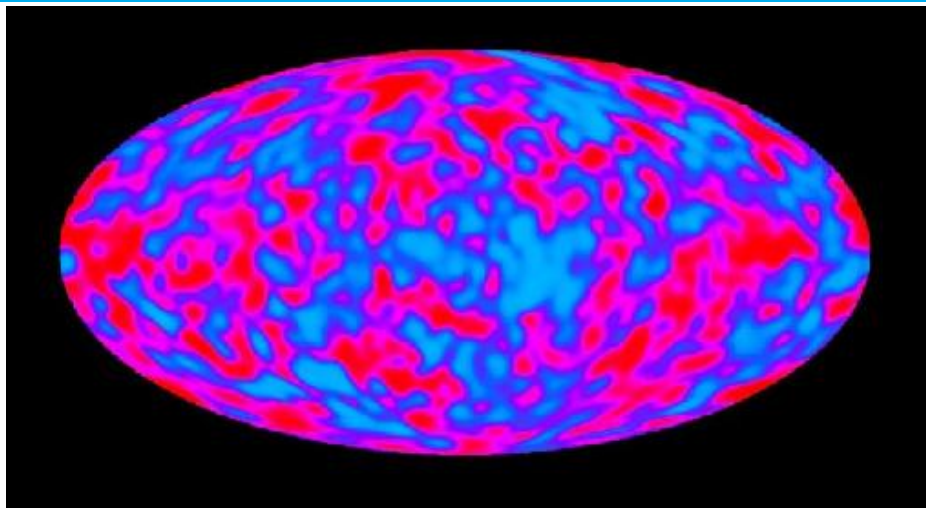


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# Anisotropies in the CMB

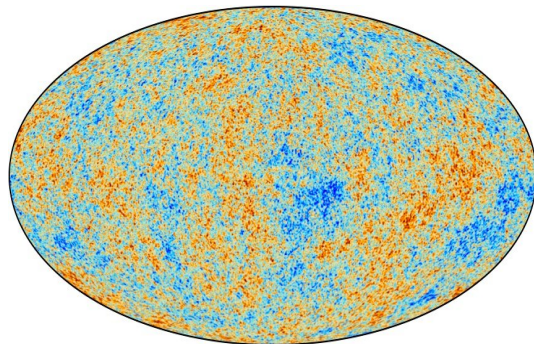
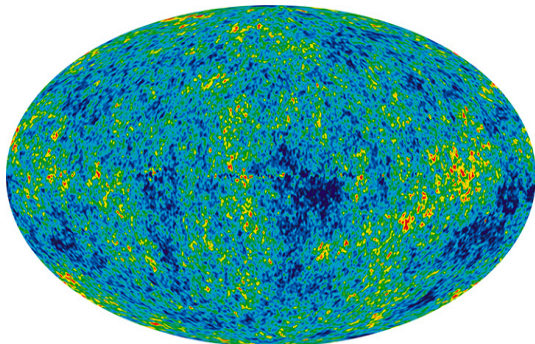


The fluctuations in the temperature of the CMB as seen by COBE<sup>10</sup>. The CMB turns out to be isotropic to one part in  $10^5$ .

<sup>10</sup>Image from [http://aether.lbl.gov/www/projects/cobe/COBE\\_Home/DMR\\_Images.html](http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html).



# Anisotropies in the CMB as seen by WMAP and Planck



**Left:** All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data<sup>11</sup>.

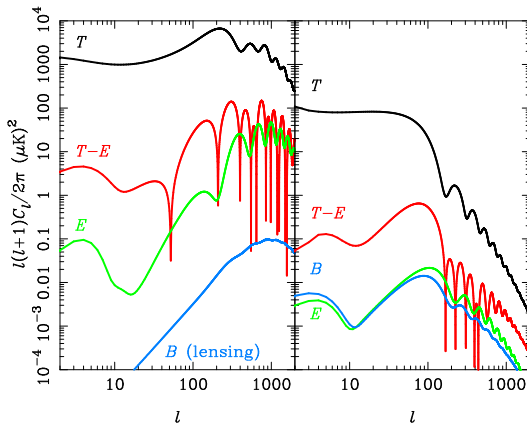
**Right:** CMB intensity map derived from the joint analysis of Planck, WMAP, and 408 MHz observations<sup>12</sup>. The above images show temperature variations (as color differences) of the order of  $200 \mu\text{K}$ .

<sup>11</sup> Image from <http://wmap.gsfc.nasa.gov/media/121238/index.html>.

<sup>12</sup> P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].



# Theoretical angular power spectra<sup>13</sup>

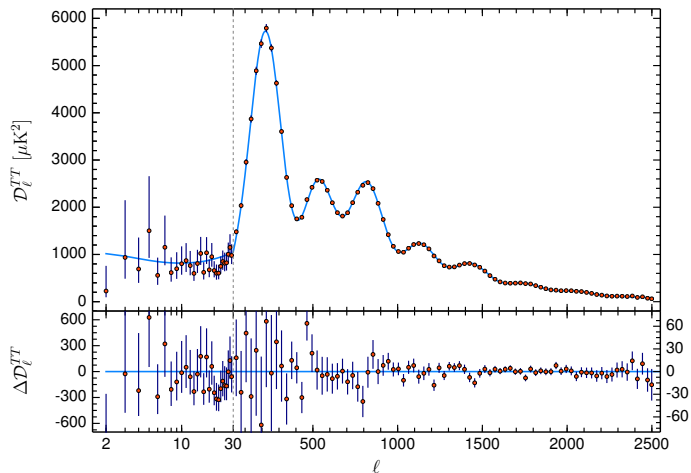


The *theoretically* computed, angular power and cross-correlation spectra of the CMB arising due to scalars (on the left) and tensors (on the right) corresponding to a tensor-to-scalar ratio of  $r = 0.24$ . The B-mode spectrum induced by weak gravitational lensing has also been shown (in blue) in the panel on the left.

<sup>13</sup>Figure from, A. Challinor, arXiv:1210.6008 [astro-ph.CO].



# CMB angular power spectrum from Planck

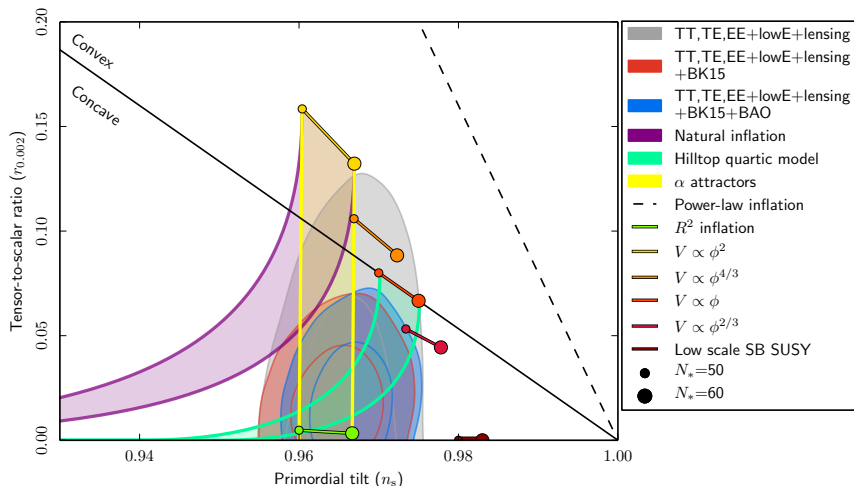


The CMB TT angular power spectrum from the Planck 2018 data (red dots with error bars) and the best fit  $\Lambda$ CDM model with a power law primordial spectrum (solid blue curve)<sup>14</sup>

<sup>14</sup>Planck Collaboration (N. Aghanim *et al.*), *Astron. Astrophys.* **641**, A6 (2020).



# Performance of inflationary models in the $n_s$ - $r$ plane

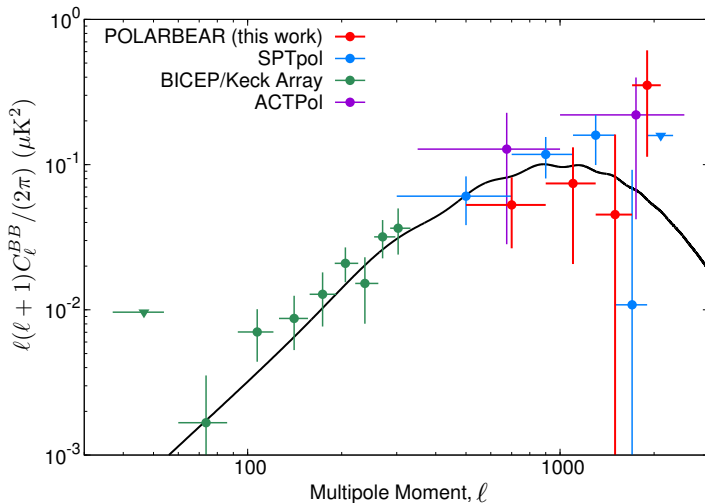


Joint constraints on  $n_s$  and  $r_{0.002}$  from Planck in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models<sup>15</sup>.

<sup>15</sup>Planck Collaboration (Y. Akrami *et al.*), *Astron. Astrophys.* **641**, A10 (2020).



# Constraints on the B-mode polarization of the CMB



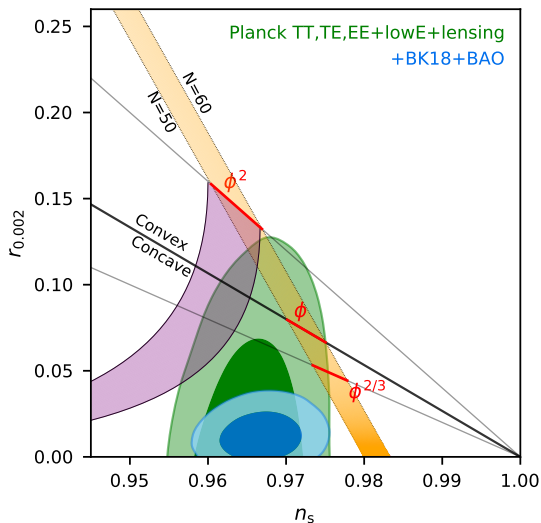
Constraints on the B-mode, angular power spectrum of the CMB from two years of POLARBEAR data<sup>16</sup>.

<sup>16</sup>POLARBEAR Collaboration (P. A. R. Ade *et al.*), *Ap. J.* **848**, 141, (2017).





# Latest constraints on the tensor-to-scalar ratio $r$

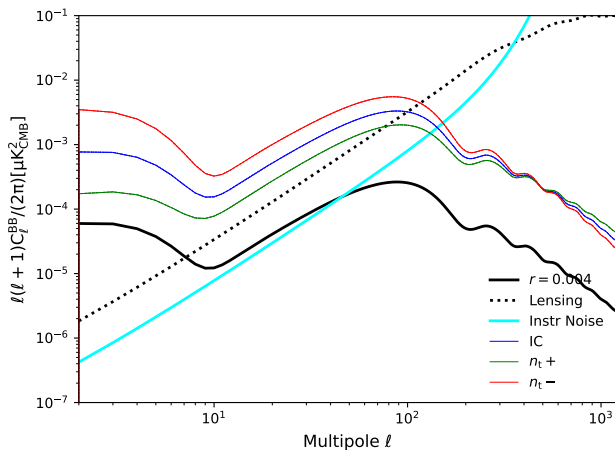


Latest constraints on the tensor-to-scalar ratio  $r$  from the BICEP/Keck telescopes<sup>17</sup>.

<sup>17</sup>BICEP/Keck Collaboration (P. A. R. Ade *et al.*), arXiv:2203.16556 [astro-ph.CO].



# Prospects of observing the imprints of the tensor perturbations

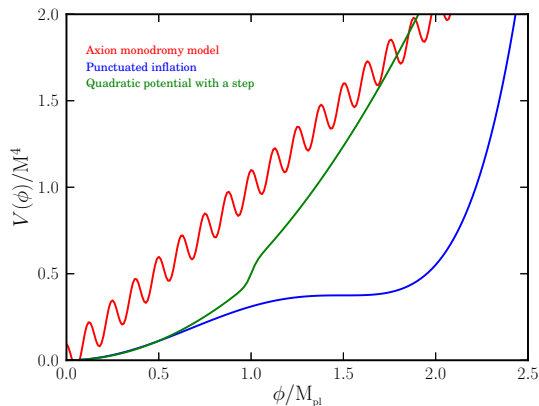
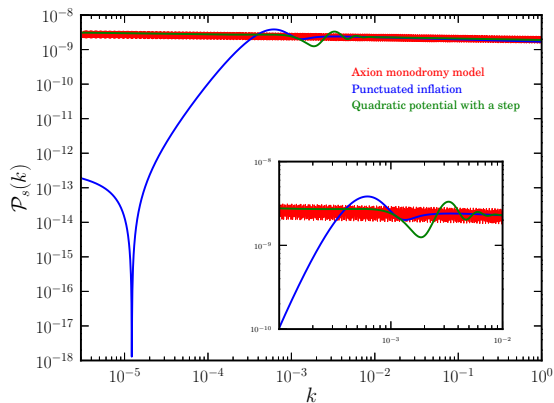


The B-mode angular power spectra of the CMB resulting from the primordial tensor perturbations for three models with  $r_{0.05} = 0.05$  have been plotted, along with the CMB lensing signal and the instrumental noise of a LiteBIRD-like configuration<sup>18</sup>.

<sup>18</sup>D. Paoletti, F. Finelli, J. Valiviita and M. Hazumi, *Phys. Rev. D* **106**, 083528 (2022).



# Spectra leading to an improved fit to the CMB data



The scalar power spectra (on the left) arising in different inflationary models (on the right) that lead to a better fit to the CMB data than the conventional power law spectrum<sup>19</sup>.

<sup>19</sup> R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **01**, 009 (2009);  
 D. K. Hazra, M. Aich, R. K. Jain, L. Sriramkumar and T. Souradeep, JCAP **10**, 008 (2010);  
 M. Aich, D. K. Hazra, L. Sriramkumar and T. Souradeep, Phys. Rev. D **87**, 083526 (2013);  
 For a recent discussion, see H. V. Ragavendra, D. Chowdhury and L. Sriramkumar, Phys. Rev. D **106**, 043535 (2022).

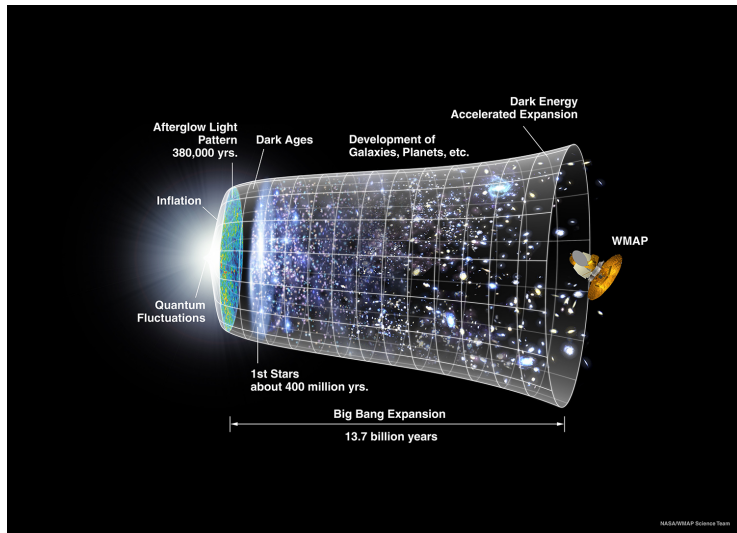


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# Timeline of the universe

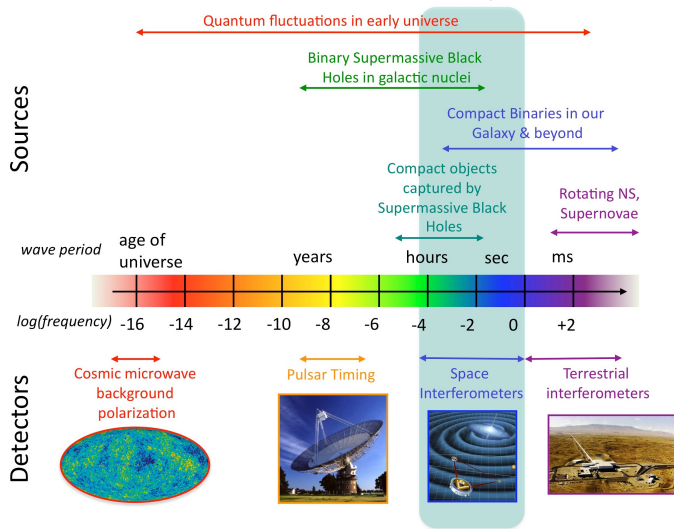


## A pictorial timeline of the universe<sup>20</sup>.

<sup>20</sup>See [http://wmap.gsfc.nasa.gov/media/060915/060915\\_CMB\\_Timeline150.jpg](http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg).



# The spectrum of GWs

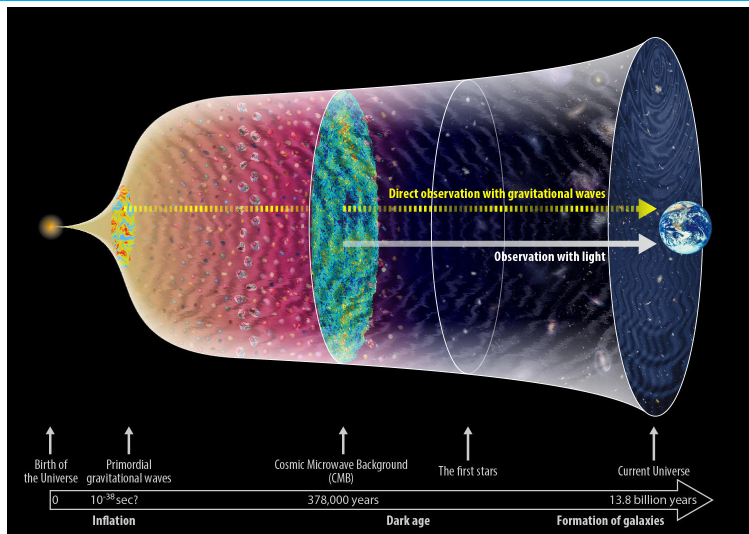


Different sources of GWs and corresponding detectors<sup>21</sup>.

<sup>21</sup> J. 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 universe<sup>22</sup>.

<sup>22</sup>Image from <https://gwpo.nao.ac.jp/en/gallery/000061.html>.



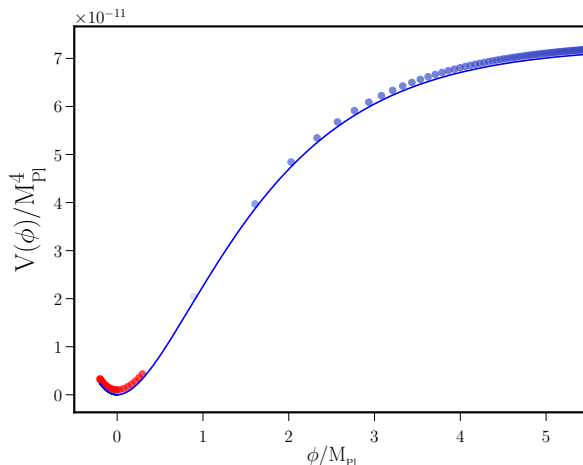
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# Evolution of the scalar field in an inflationary potential

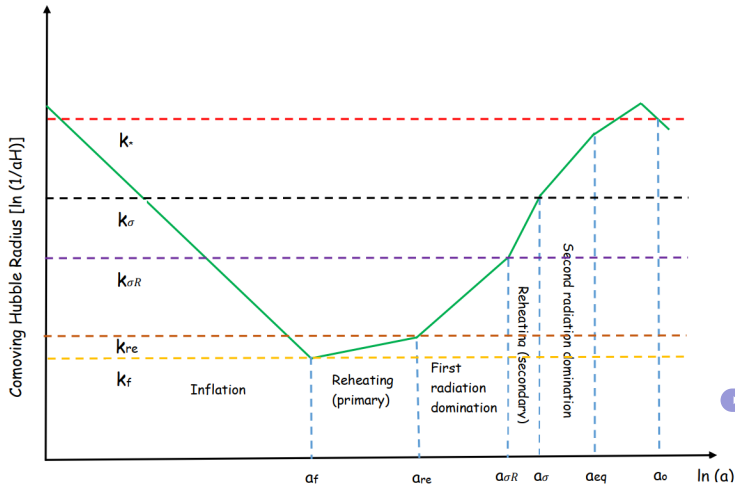


► Inflationary attractor

The evolution of the scalar field in the 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

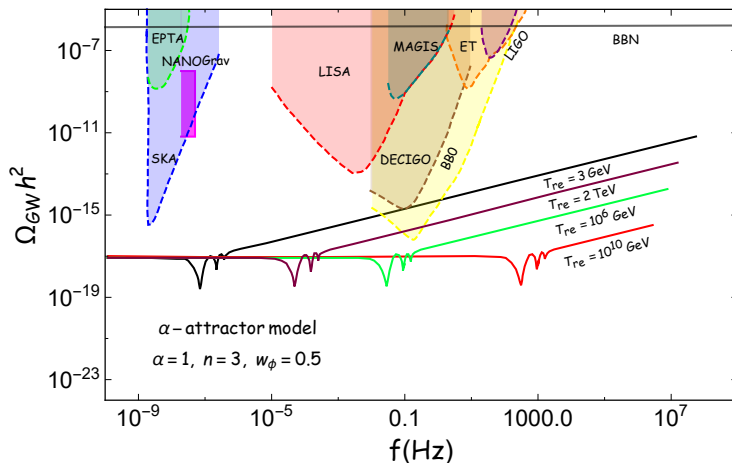
► Back to secondary GWs

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 epochs<sup>23</sup>.

<sup>23</sup> Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).



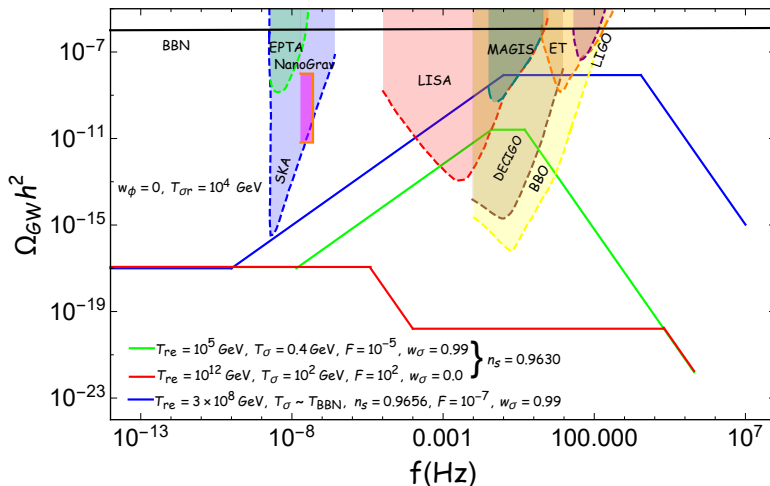
# Effects on $\Omega_{\text{GW}}(f)$ due to reheating



The behavior of the dimensionless spectral energy density of primary GWs today, viz.  $\Omega_{\text{GW}}$ , has been plotted, over a wide range of frequency  $f$ , for different reheating temperatures (in red, green, brown and black)<sup>24</sup>.

<sup>24</sup>Md. 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 entropy<sup>25</sup>.

<sup>25</sup>Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

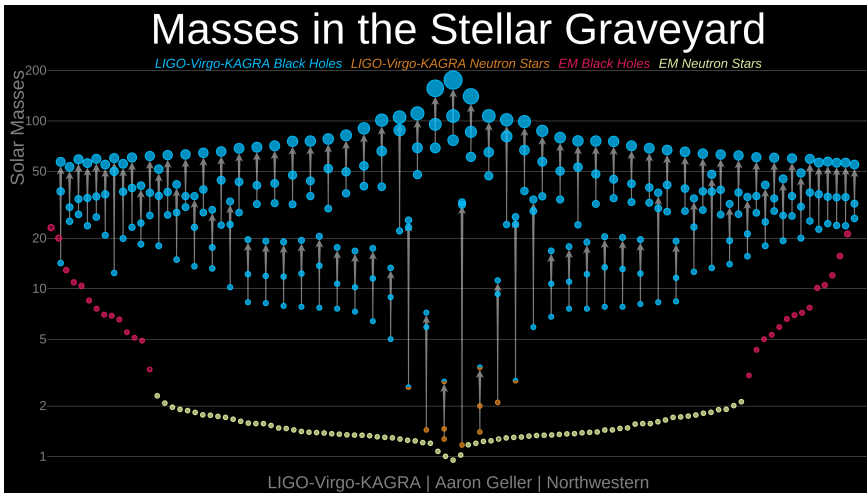


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# Coalescence of compact binaries observed by LIGO

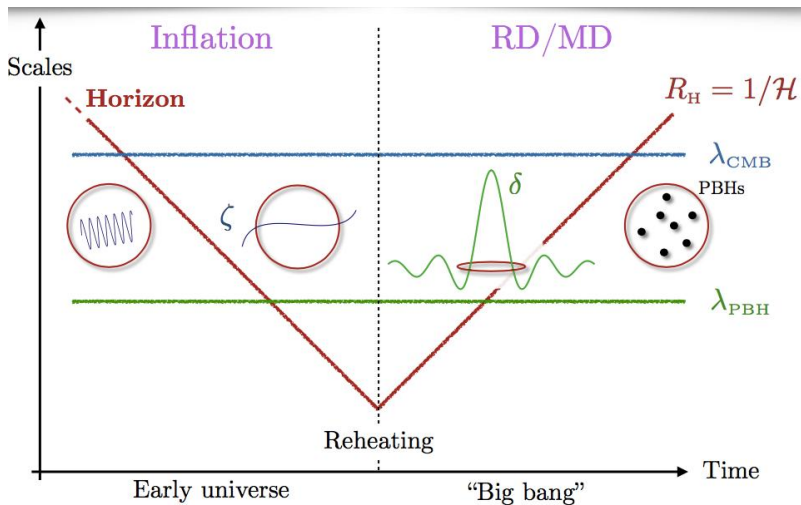


The third GW Transient Catalog of mergers involving black holes and neutron stars observed by the LIGO-Virgo-KAGRA collaboration<sup>26</sup>.

<sup>26</sup>Image from <https://www.ligo.caltech.edu/LA/image/ligo20211107a>.



# Formation of primordial black holes (PBHs)

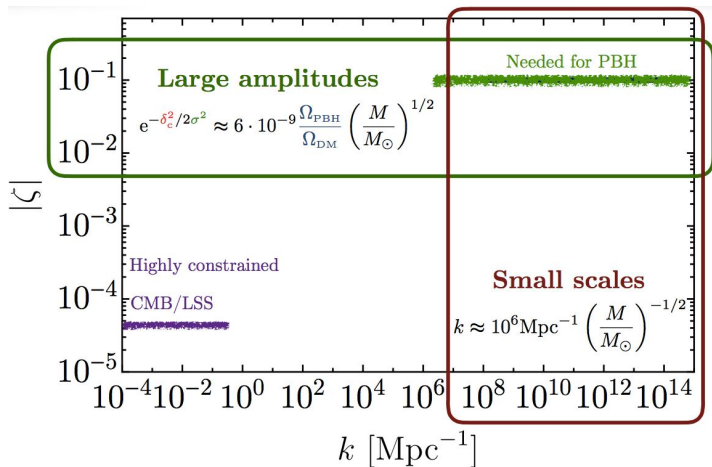


BHs can form in the primordial universe when perturbations with significant amplitudes on small scales reenter the Hubble radius during the radiation dominated epoch<sup>27</sup>.

<sup>27</sup>Figure from G. Franciolini, arXiv:2110.06815 [astro-ph.CO].



# Amplitude required to form significant number of PBHs



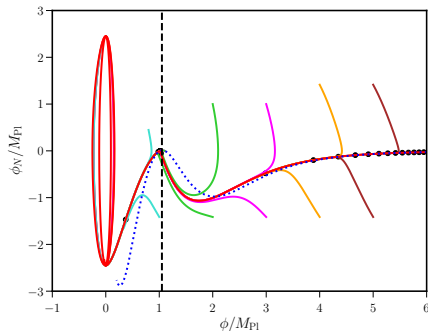
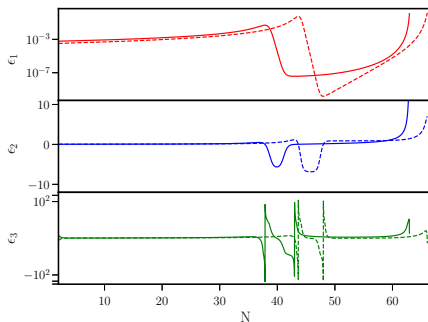
In order to form significant number of black holes, the amplitude of the perturbations on small scales has to be large enough such that the dimensionless amplitude of the scalar perturbation is close to unity<sup>28</sup>.

<sup>28</sup>Figure credit G. Franciolini.





# Single-field models admitting ultra slow roll inflation



Potentials leading to ultra slow roll inflation (with  $x = \phi/v$ ,  $v$  being a constant)<sup>29</sup>:

► Inflationary attractor

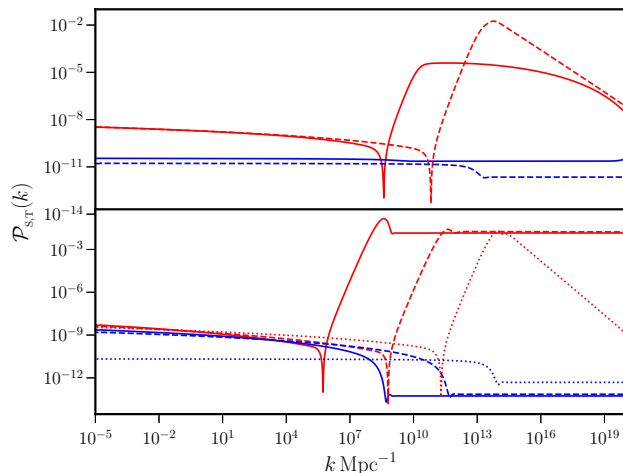
$$\text{USR1} : V(\phi) = V_0 \frac{6x^2 - 4\alpha x^3 + 3x^4}{(1 + \beta x^2)^2},$$

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

<sup>29</sup> J. Garcia-Bellido and E. R. Morales, Phys. Dark Univ. **18**, 47 (2017);  
I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019).



# Power spectra in models permitting ultra slow roll inflation

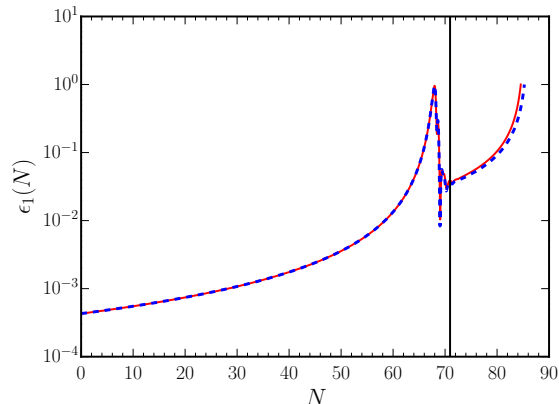
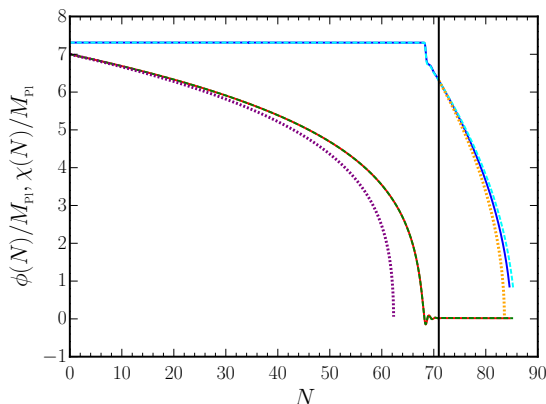


The scalar (in red) and the tensor (in blue) power spectra arising in various single field models that permit a period of ultra slow roll inflation<sup>30</sup>.

<sup>30</sup>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).



# Non-trivial inflationary dynamics in the two-field model

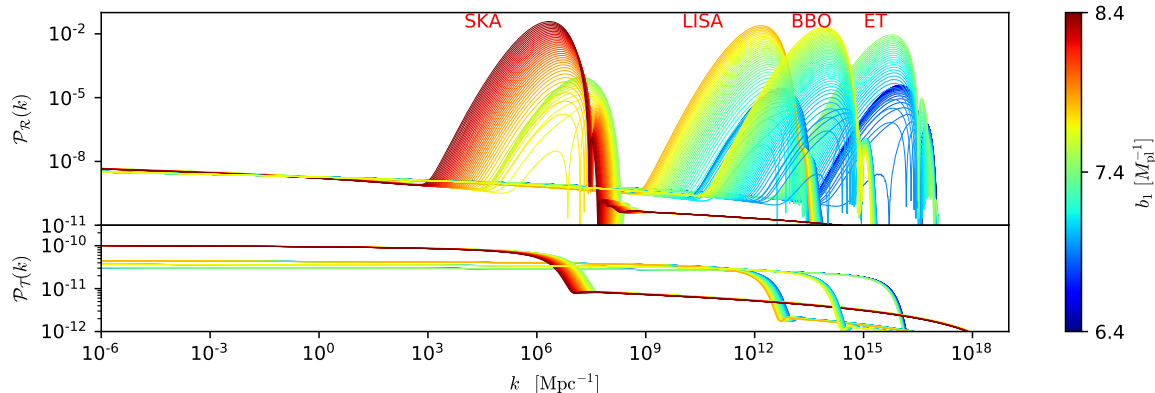


Behavior of the two scalar fields  $\phi$  and  $\chi$  (in blue and red, on the left) and the first slow roll parameter  $\epsilon_1$  (on the right) in the two field model of our interest<sup>31</sup>. Note that there arises a turn in the field space around  $N = 70$ , when the first slow roll parameter begins to decrease before increasing again, leading to the termination of inflation.

<sup>31</sup>M. 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

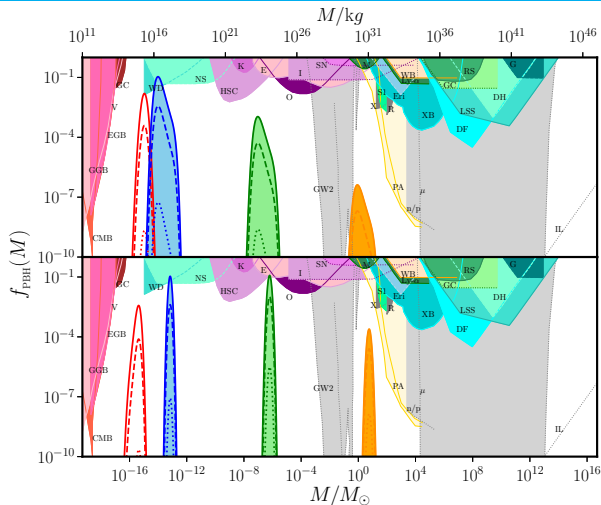


The scalar (on top) and the tensor (at the bottom) power spectra evaluated at the end of inflation have been plotted for a few different sets of initial conditions for the fields and a range of values of a particular parameter<sup>32</sup>.

<sup>32</sup>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

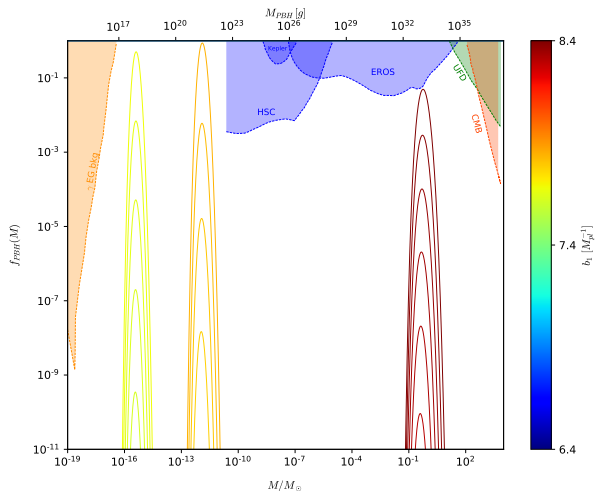


The fraction of PBHs contributing to the cold dark matter density today  $f_{\text{PBH}}(M)$  has been plotted for different models, viz. USR2 (on top, in red) and PI3 (at the bottom, in red)<sup>33</sup>.

<sup>33</sup>H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, *Phys. Rev. D* **103**, 083510 (2021).



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

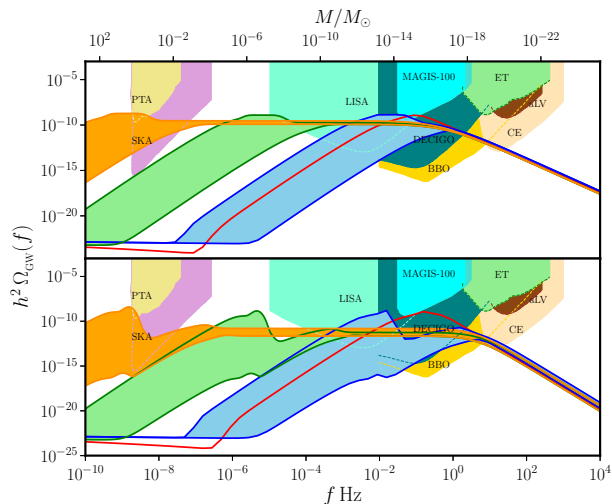


The fraction of PBHs contributing to the dark matter density today  $f_{\text{PBH}}(M)$  in the two-field model of our interest<sup>34</sup>.

<sup>34</sup> 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

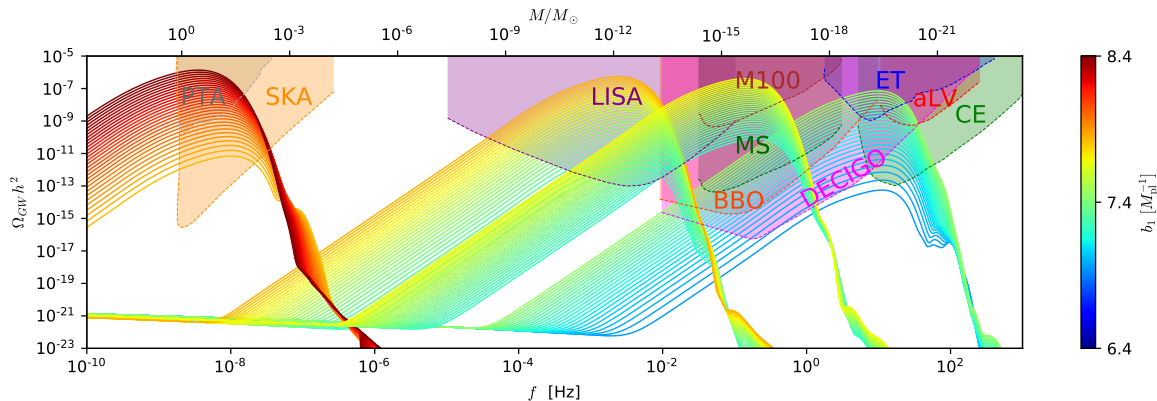


The dimensionless spectral density of GWs  $\Omega_{\text{GW}}(f)$  arising in the models of USR2 (in red, on top) as well as PI3 (in red, at the bottom)<sup>35</sup>.

<sup>35</sup>H. 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  $b_1$ <sup>36</sup>.

<sup>36</sup> M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).



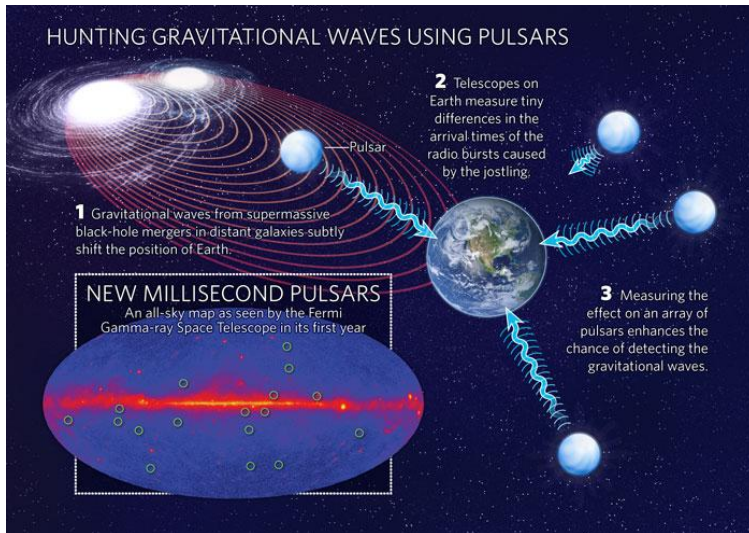


# Plan of the talk

- 1 The need for inflation
- 2 Constraints on inflation from the CMB data
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- 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 the stochastic GW background**
- 7 Outlook



# Pulsar timing arrays (PTAs)

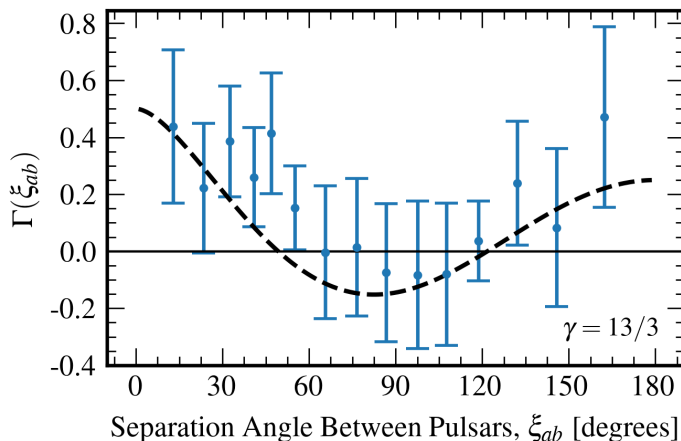


The PTAs monitor an array of millisecond pulsars<sup>37</sup>.

<sup>37</sup>See [https://ipta.github.io/mock\\_data\\_challenge/](https://ipta.github.io/mock_data_challenge/).



# Hellings-Downs curve

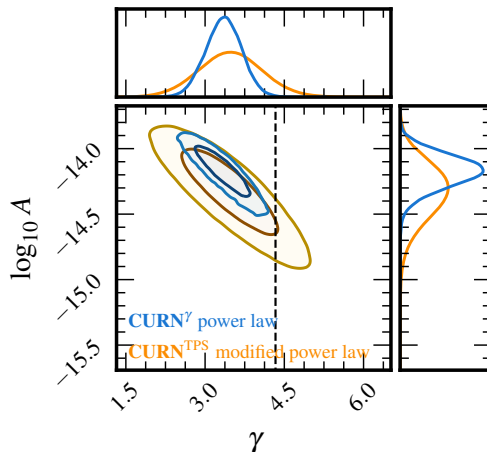


The inter-pulsar correlations measured from 2,211 distinct pairings in the 67-pulsar array of the NANOGrav 15-year data. The dashed black line shows the Hellings-Downs correlation pattern<sup>38</sup>.

<sup>38</sup>NANOGrav Collaboration (G. Agazie *et al.*), *Astrophys. J. Lett.* **951**, 1 (2023).



# Constraints on the spectral amplitude and index of GWs

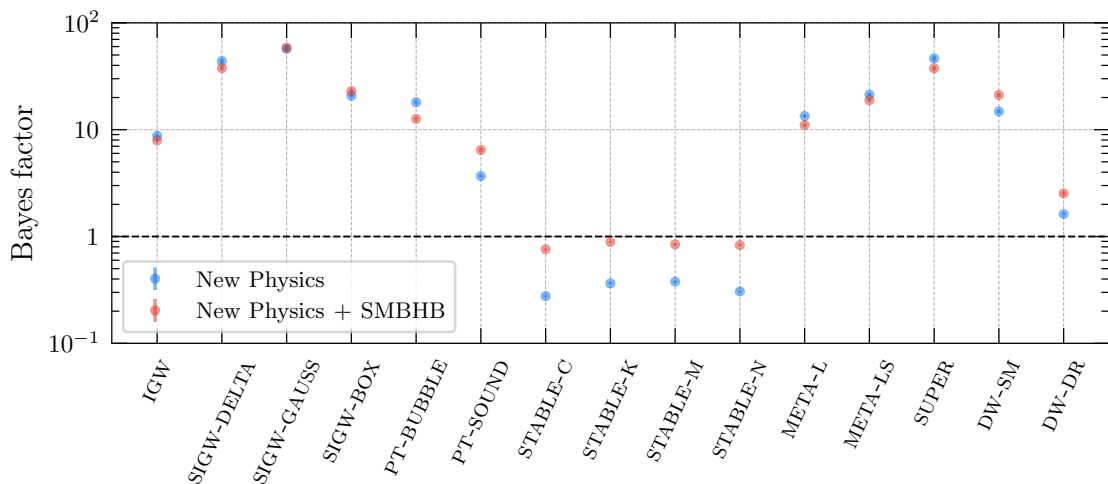


Constraints on the amplitude  $A$  and the index  $\gamma$  of the stochastic background of GWs from the NANOGrav 15-year data<sup>39</sup>.

<sup>39</sup>NANOGrav Collaboration (G. Agazie *et al.*), *Astrophys. J. Lett.* **951**, 1 (2023).



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

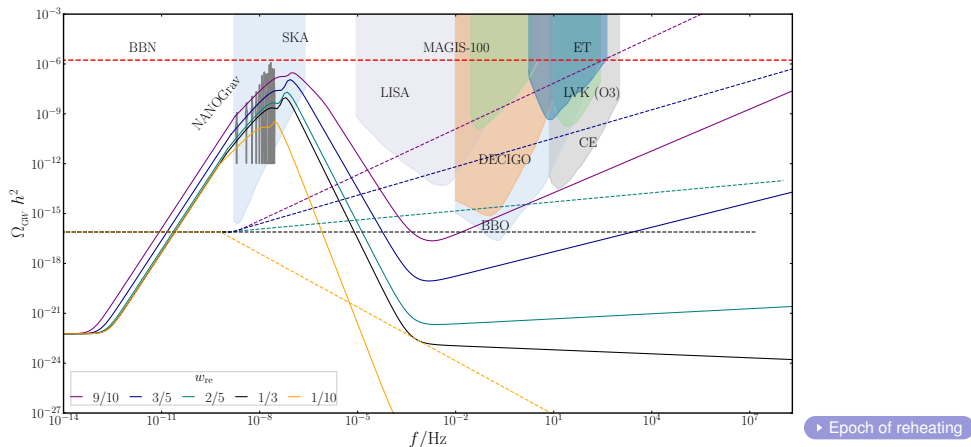


The Bayesian evidence for a variety of astrophysical and cosmological sources for the stochastic GW background suggested by the observations of the PTAs<sup>40</sup>.

<sup>40</sup> NANOGrav Collaboration (G. Agazie *et al.*), *Astrophys. J. Lett.* **951**, 1 (2023).



# Generation of secondary GWs during the epoch of reheating

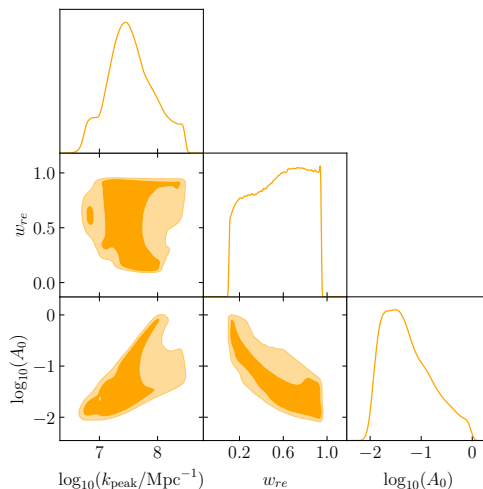


The dimensionless spectral energy density of primary and secondary GWs today  $\Omega_{\text{GW}}(f)$  have been plotted for a given reheating temperature and different values of the parameter describing the equation of state during reheating<sup>41</sup>.

<sup>41</sup>S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, in preparation.



# Constraints on the epoch of reheating

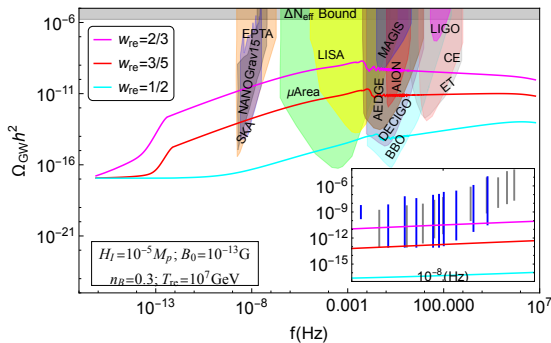
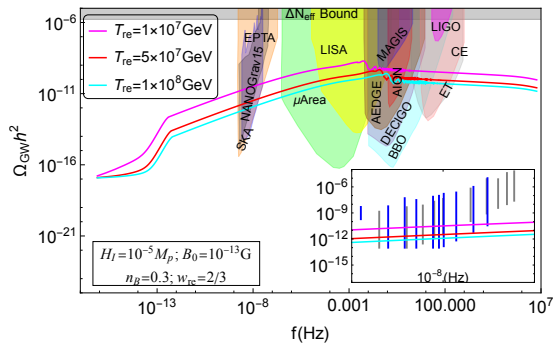


Constraints on the parameters describing the primordial scalar power spectrum and the epoch of reheating, arrived at upon comparison with the NANOGrav 15-year data<sup>42</sup>.

<sup>42</sup>S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, in preparation.



# Secondary GWs induced by primordial magnetic fields (PMFs)



The dimensionless spectral energy density of secondary GWs observed today  $\Omega_{\text{GW}}(f)$ , induced by the PMFs, have been plotted for different reheating temperatures (on the left) and different values of the parameter describing the equation of state during reheating (on the right)<sup>43</sup>.

<sup>43</sup> S. Maiti, D. Maity and L. Sriramkumar, arXiv:2401.01864 [astro-ph.CO].





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# 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



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Debika Chowdhury



Matteo Braglia



Dhiraj Hazra



Fabio Finelli



George Smoot



Alexei Starobinsky



Pankaj Saha



## Collaborators II



Joseph Silk



Md. Riajul Haque



Debaprasad Maity



Tanmoy Paul



Subhasis Maiti



Suvashis Maity



Nilanjandev Bhaumik



Thank you for your attention