

Gravitational waves from the early universe

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Plan of the talk

- 1 Standard model of cosmology
- 2 Inflationary scenario and constraints from the CMB
- 3 GWs provide a new window to the universe
- 4 Generation of GWs in the early universe
- 5 Observations by the PTAs and the stochastic GW background
- 6 Outlook

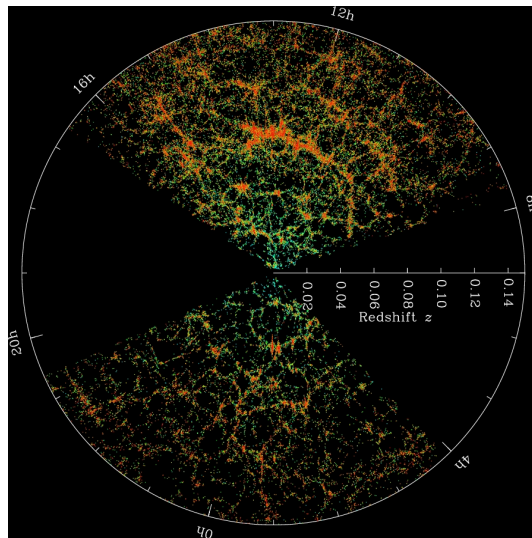


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Distribution of galaxies in the universe

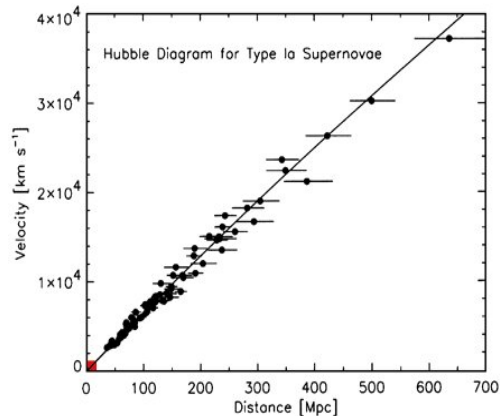
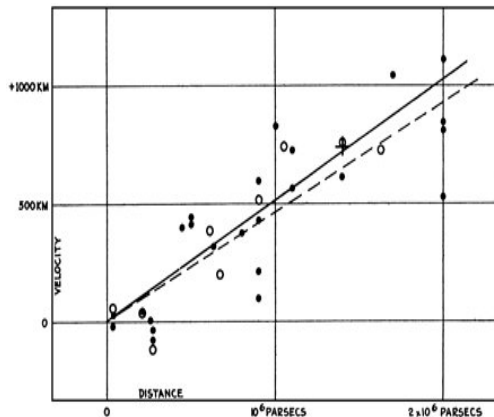


Distribution of galaxies as observed by the Sloan Digital Sky Survey¹.

¹Image from <https://www.sdss4.org/science/>.



Hubble's law and the expanding universe



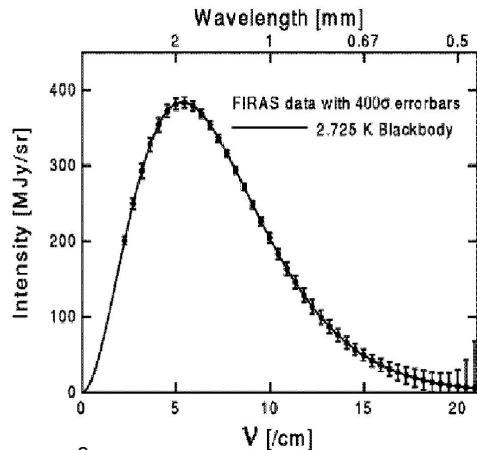
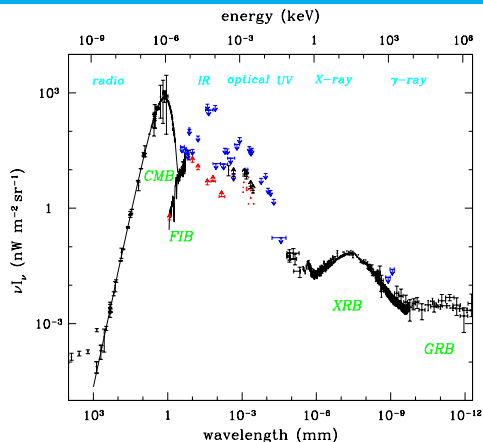
Left: Original Hubble data. The slope of the two fitted lines are about **500** km/sec/Mpc and **530** km/sec/Mpc.

Right: A more recent Hubble diagram. The slope of the straight line is found to be about **72** km/sec/Mpc. The small red region marks the span of Hubble's original diagram².

²R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).



Cosmic microwave background (CMB)



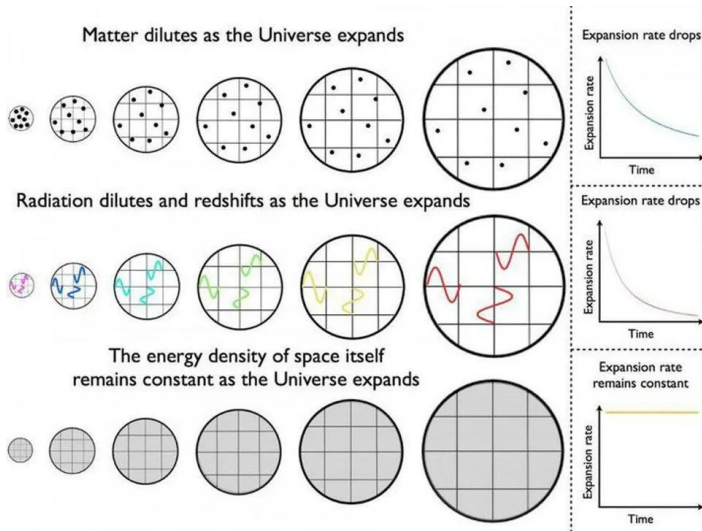
Left: Spectrum of cosmological background radiation³.

Right: Spectrum of the CMB as measured by Cosmic Background Explorer (COBE)⁴. It is a nearly perfect thermal spectrum corresponding to a temperature of 2.725°K today.

³Figure from D. Scott, arXiv:astro-ph/9912038.

⁴Image from http://www.astro.ucla.edu/~wright/cosmo_01.htm.

Evolution of energy densities in the universe

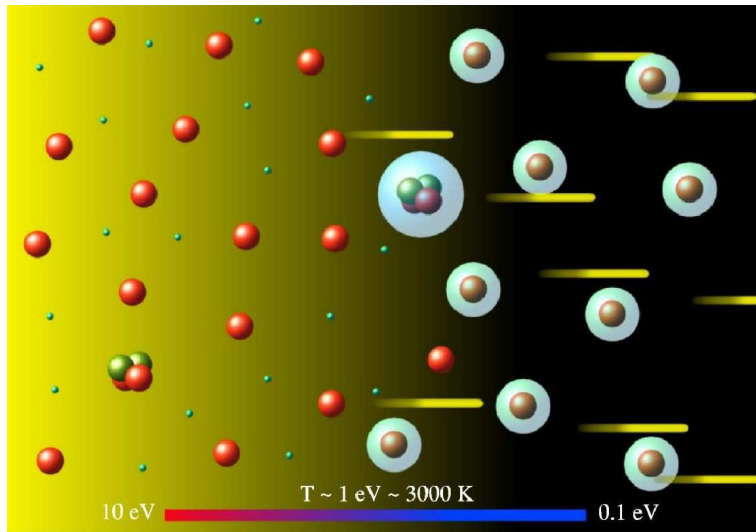


Evolution of energy densities in the universe according to general relativity⁵.

⁵Image from <https://www.forbes.com/sites/startswithabang/2021/08/25/how-small-was-the-universe-at-the-start-of-the-big-bang/>.



Decoupling of matter and radiation⁶

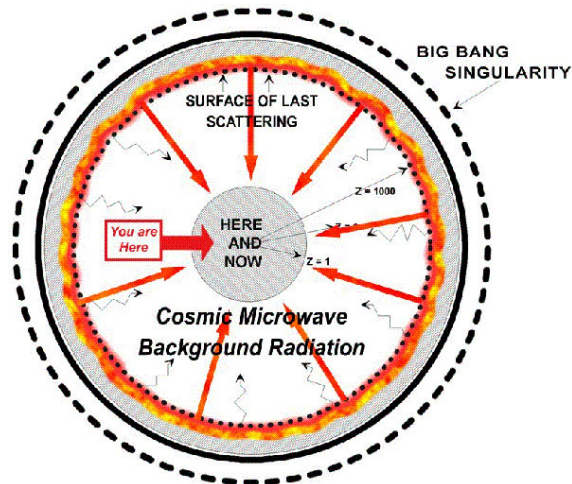
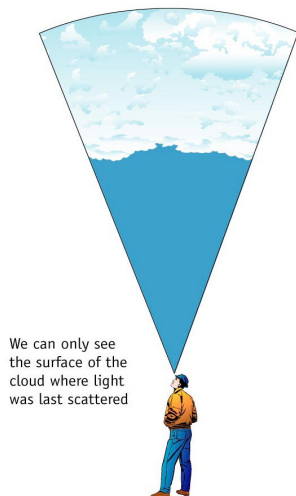


Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ \text{ K}$.

⁶Image from W. H. Kinney, [arXiv:astro-ph/0301448v2](https://arxiv.org/abs/astro-ph/0301448v2).



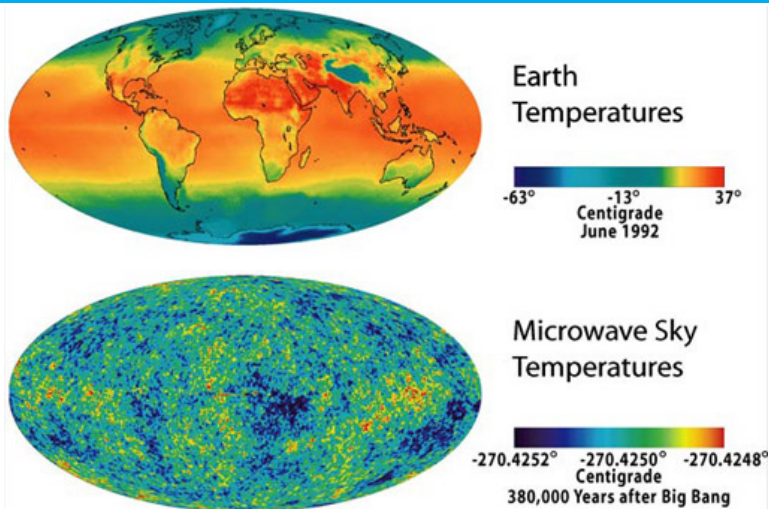
Surface of last scattering and free streaming CMB photons



CMB photons stream to us freely from the surface of last scattering⁷.

⁷Image from <http://planck.caltech.edu/epo/epo-cmbDiscovery4.html>.

Projecting the surface of last scattering

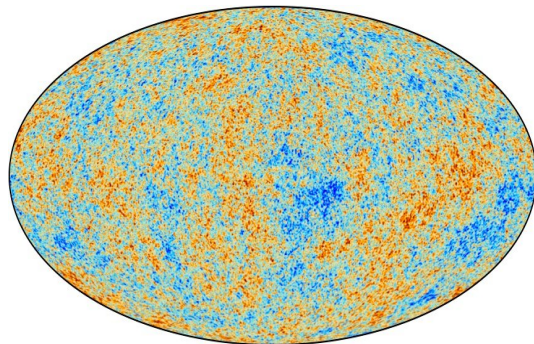
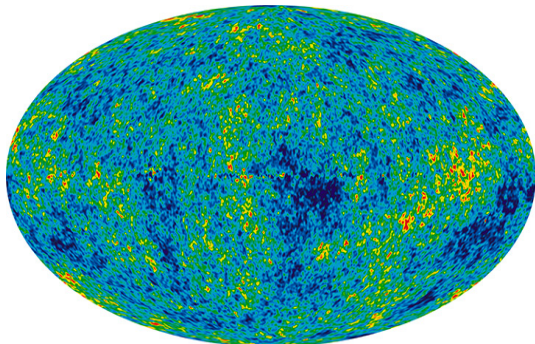


As the surface of the Earth is often illustrated, the temperature of the CMB on the surface of last scattering can be projected on to a plane using the Mollweide projection⁸.

⁸Image from <http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html>.



Anisotropies in the CMB as observed by WMAP and Planck



Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data⁹.

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and 408 MHz observations¹⁰. The above images show temperature variations (as color differences) of the order of $200 \mu\text{K}$.

⁹Image from <http://wmap.gsfc.nasa.gov/media/121238/index.html>.

¹⁰Planck Collaboration (P. A. R. Ade *et al.*), *Astron. Astrophys.* **594**, A1 (2016).

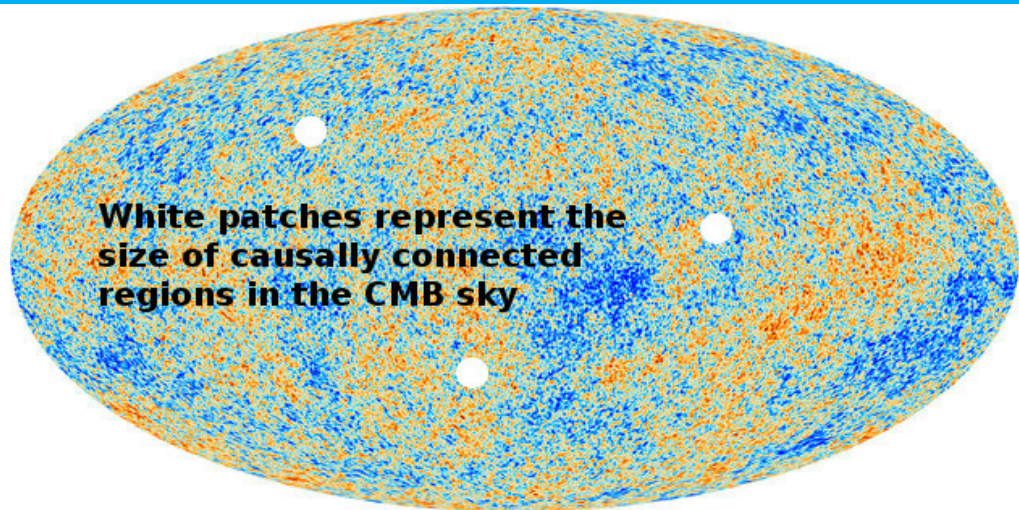


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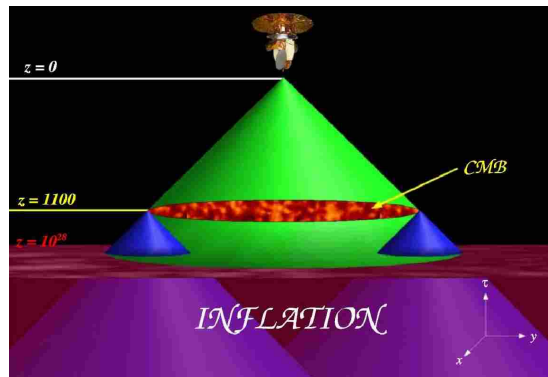
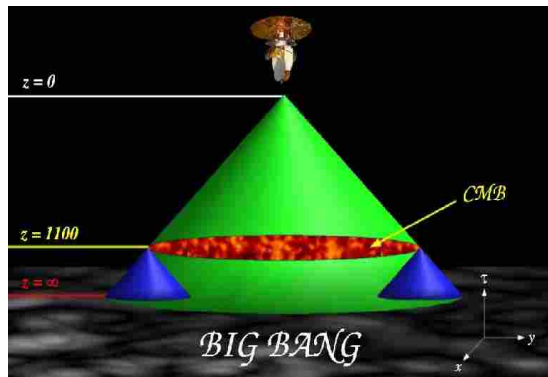
Horizon problem



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.



Resolution of the horizon problem in the inflationary scenario

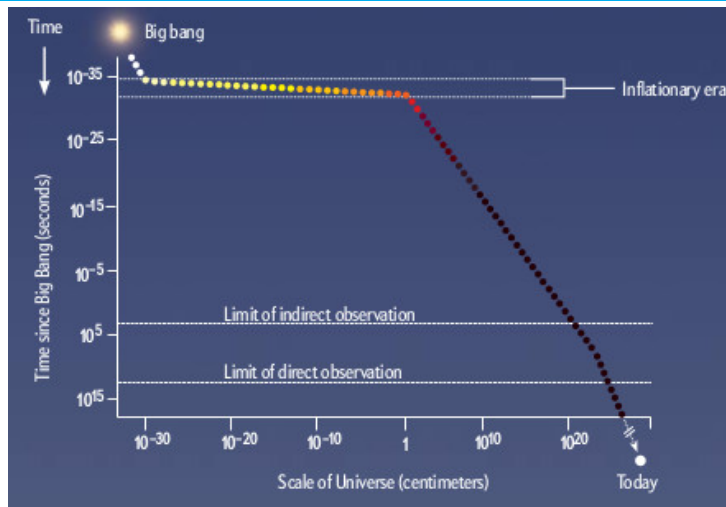


Another illustration of the horizon problem (on the left), and an illustration of its resolution (on the right) through an early and sufficiently long epoch of inflation¹¹.

¹¹Images from W. Kinney, [astro-ph/0301448](https://arxiv.org/abs/astro-ph/0301448).



Time and duration of inflation

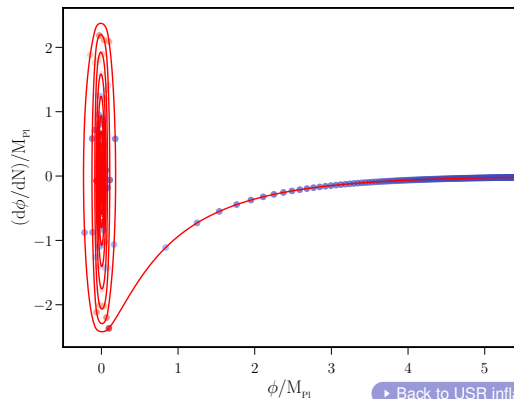
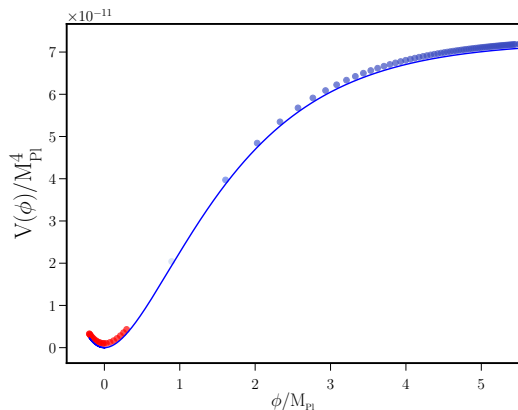


Inflation—a brief period of accelerated expansion—is expected to have taken place during the very early stages of the universe¹².

¹²Image from P. J. Steinhardt, *Sci. Am.* **304**, 18 (2011).



Inflationary attractor



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)¹³.

¹³Figure 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).



Origin of the primordial perturbations

Scalar perturbations:

- ◆ The quantum fluctuations associated with the scalar fields that drive inflation are responsible for the primordial perturbations. The perturbations in the metric and matter are related through the Einstein's equations.
- ◆ The scalar perturbations leave the largest imprints on the CMB, and are primarily responsible for the inhomogeneities in the distribution of matter in the universe.

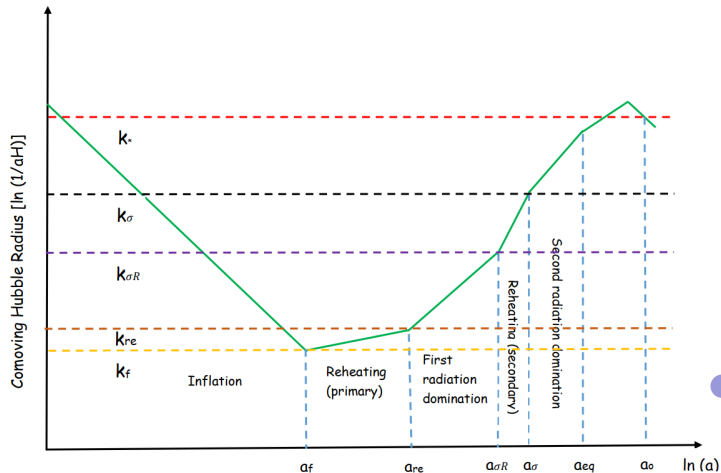
Tensor perturbations:

- ◆ The tensor perturbations, i.e. gravitational waves (GWs), can be generated even in the absence of sources.
- ◆ GWs are small disturbances in a given spacetime (much like ripples in water), which travel at the speed of light. They satisfy the wave equation in the given background spacetime.
- ◆ GWs are transverse in nature and are characterized by two degrees of polarization¹⁴.

¹⁴See, for example, J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Pearson Education, Delhi, 2003).



Behavior of the comoving wave number and Hubble radius



▶ Back to reheating

▶ Back to formation of PBHs

▶ Back to SGWs and PTA data

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 epochs¹⁵.

¹⁵Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).



Describing the primordial perturbations

While comparing with the observations, for convenience, one often uses the following power law, template scalar and the tensor spectra¹⁶:

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

where A_S and A_T denote the scalar and tensor amplitudes, k_* represents the so-called pivot scale at which the amplitudes are quoted, while the spectral indices n_S and n_T are assumed to be constant.

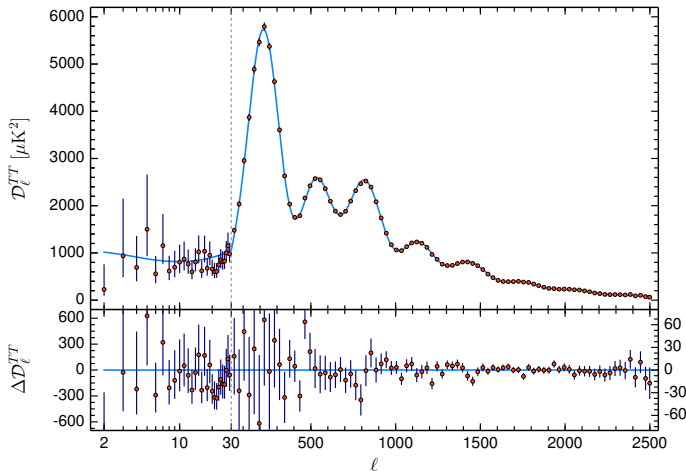
The tensor-to-scalar ratio r is defined as

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

¹⁶See, for instance, L. Sriramkumar, *Curr. Sci.* **97**, 868 (2009).



CMB angular power spectrum from Planck

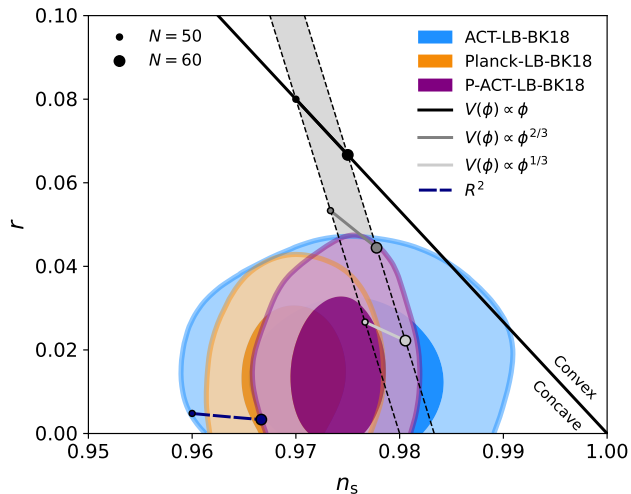


The CMB TT angular power spectrum from the Planck 2018 data (red dots with error bars) and the best fit ΛCDM model with a power law primordial spectrum (solid blue curve)¹⁷

¹⁷Planck Collaboration (N. Aghanim *et al.*), *Astron. Astrophys.* **641**, A6 (2020).



Performance of inflationary models in the n_s - r plane

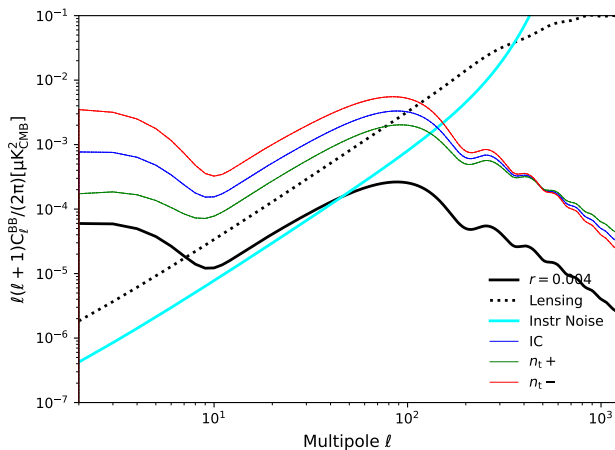


Latest constraints on n_s and r from ACT, in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models¹⁸.

¹⁸ACT Collaboration (E. Calabrese *et al.*), arXiv:2503.14454 [astro-ph.CO].



Prospects of observing the imprints of the tensor perturbations

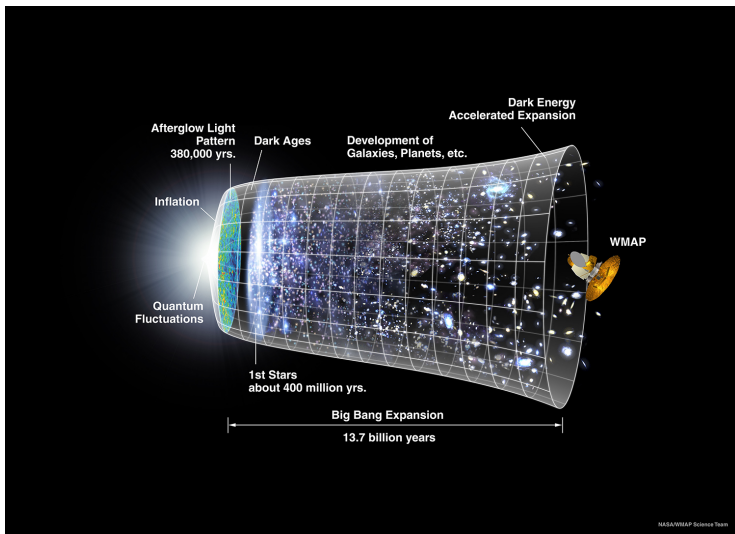


The B-mode angular power spectra of the CMB resulting from the primary tensor perturbations for models with $r_{0.05} = 0.05$ have been plotted, along with the CMB lensing signal and the instrumental noise of a LiteBIRD-like configuration¹⁹.

¹⁹D. Paoletti, F. Finelli, J. Valiviita and M. Hazumi, *Phys. Rev. D* **106**, 083528 (2022).



Timeline of the universe



► Observations of GWs

A pictorial timeline of the universe²⁰.

²⁰See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

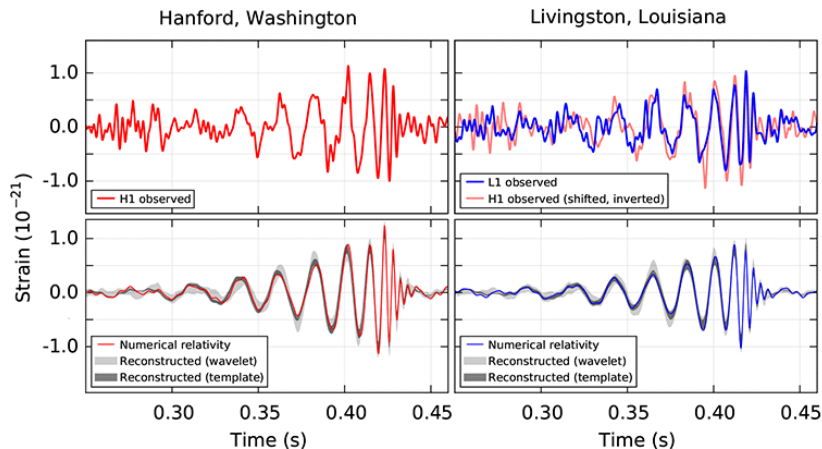


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First observation of GWs from coalescing binary BHs

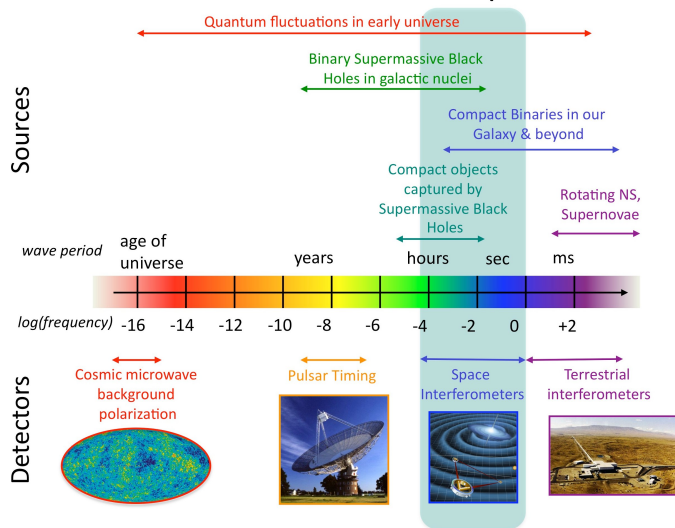


GWs from the merger of two black holes (BHs) as observed by the Laser Interferometer Gravitational-Wave Observatory (LIGO) at Hanford and Livingston (on top left and right). The expected signal, obtained using numerical simulations, is included (at the bottom)²¹

²¹Figure from [LIGO Scientific and Virgo Collaborations \(B. P. Abbott *et al.*\), Phys. Rev. Lett. **116**, 061102 \(2016\).](#)



Sources and spectral range of GWs

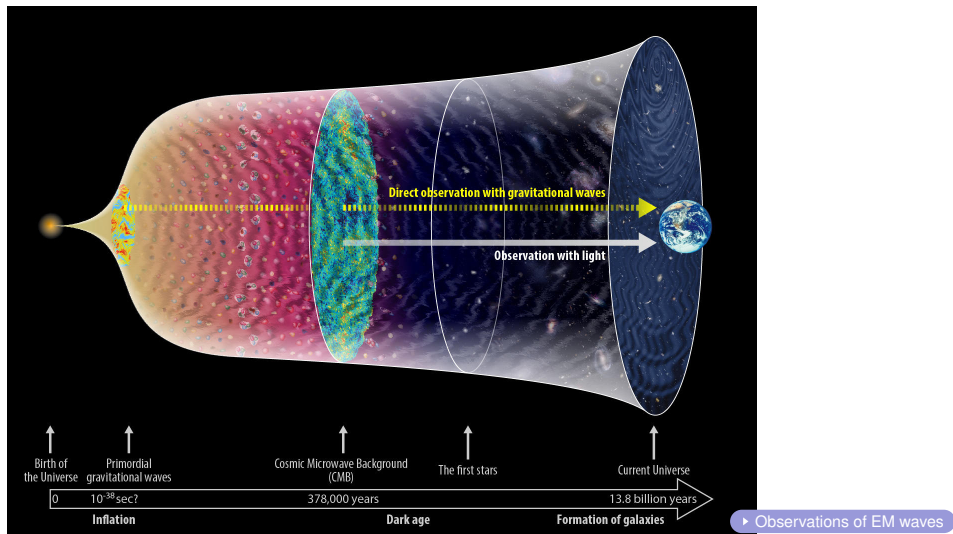


Different sources of GWs and the corresponding detectors²².

²²J. 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 universe²³.

²³Image from <https://gwpo.nao.ac.jp/en/gallery/000061.html>.

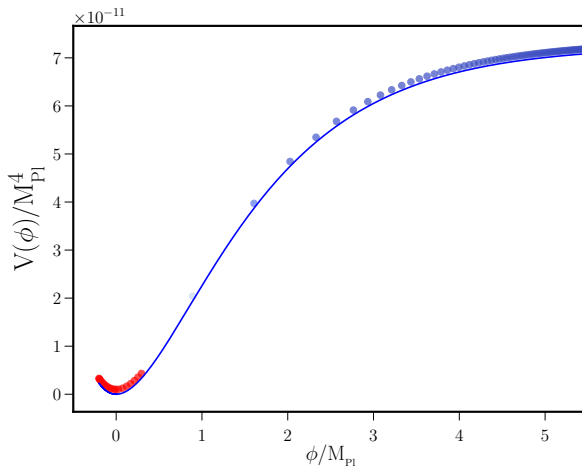


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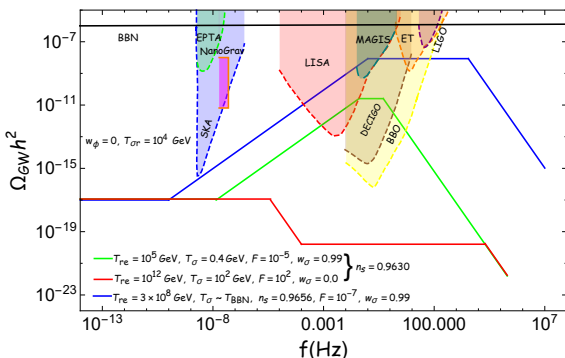
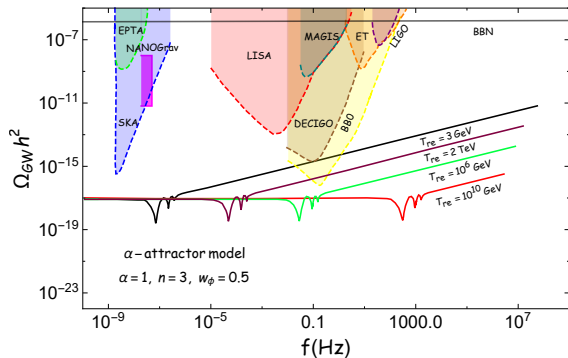


Evolution of the scalar field in an inflationary potential



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).



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

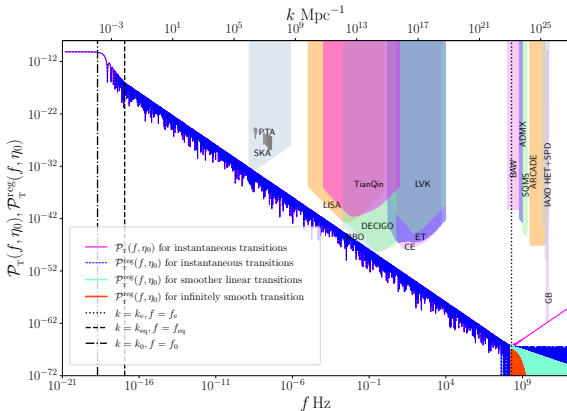
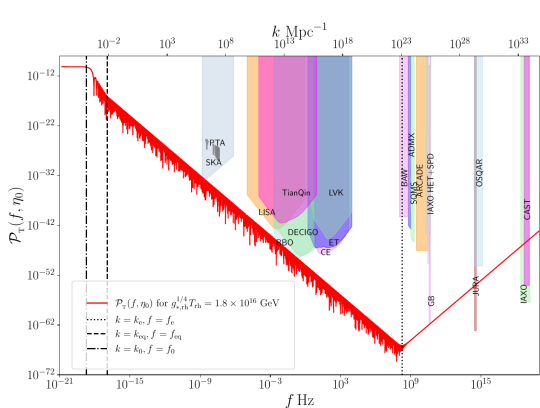
► Evolution of comoving lengths

The dimensionless spectral energy density of primary GWs today, viz. Ω_{GW} , has been plotted, over a wide range of frequencies f , in the standard (on the left) and non-standard (on the right) reheating scenarios²⁴.

²⁴ Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).



Power spectrum of primary GWs today



► Evolution of comoving lengths

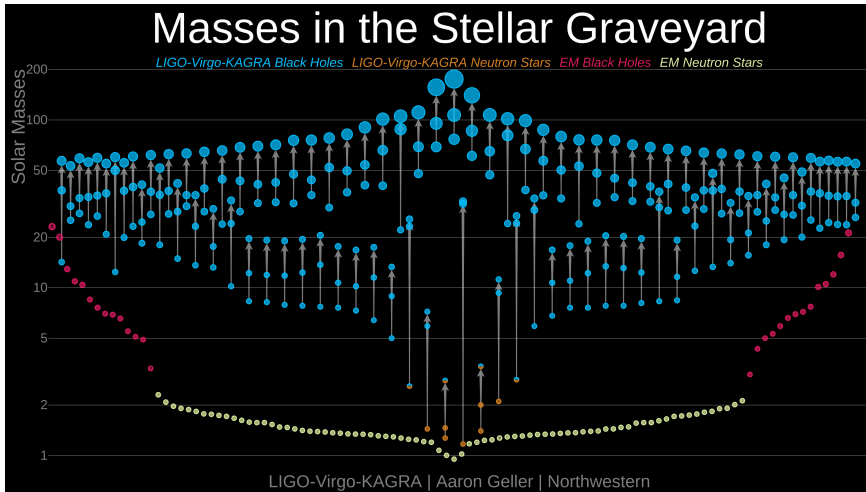
The actual and the regularized power spectrum of primary GWs today have been plotted assuming $r \simeq 0.034$ in the case of instantaneous (on the left) and smoother (on the right) transitions from de Sitter inflation to the epochs of radiation and matter domination²⁵.

²⁵ A. Hoory, J. Martin, A. Paul and L. Sriramkumar, JCAP **05**, 080 (2026);

A. Hoory, J. Martin, A. Paul and L. Sriramkumar, arXiv:2605.18286 [astro-ph.CO].



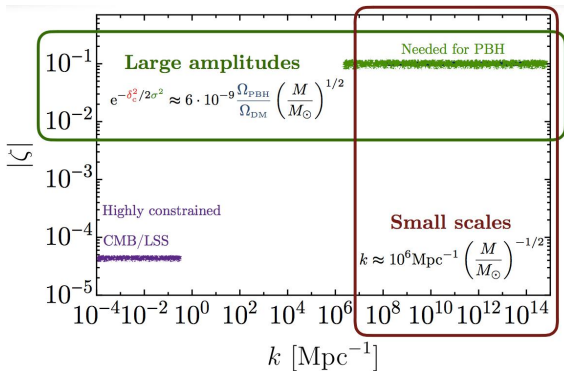
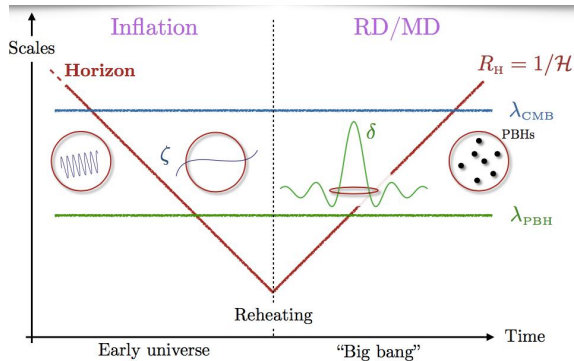
Coalescence of compact binaries observed by LIGO



The third GW Transient Catalog of mergers involving BHs and neutron stars observed by the LIGO-Virgo-KAGRA collaboration²⁶.

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

Formation of BHs in the early universe



Left: Primordial BHs (PBHs) can form when perturbations with significant amplitudes reenter the Hubble radius during the radiation dominated epoch²⁷. ▶ Evolution of comoving lengths

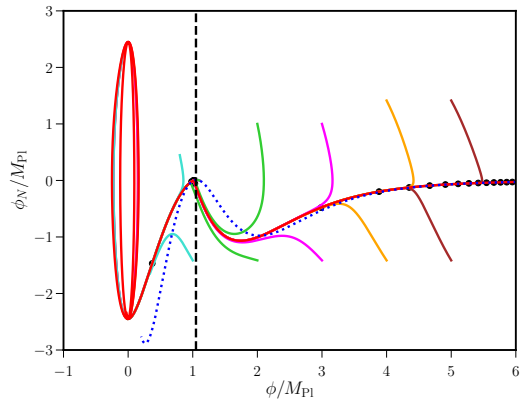
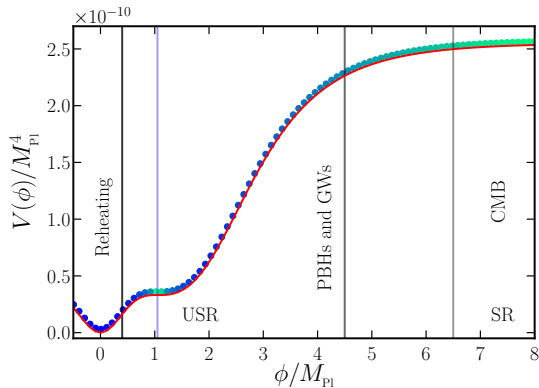
Right: To form significant number of PBHs, the amplitude of the perturbations on small scales has to be close to unity²⁸.

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

²⁸Figure credit G. Franciolini.



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



► Inflationary attractor

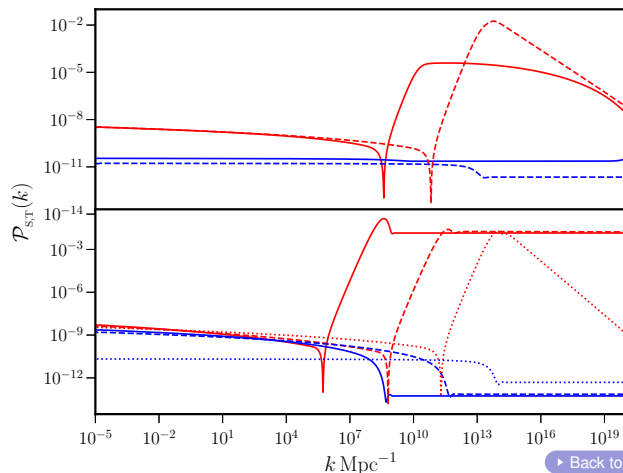
Potentials which contain a point of inflection generically admit a period of USR inflation²⁹.

²⁹See, 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



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

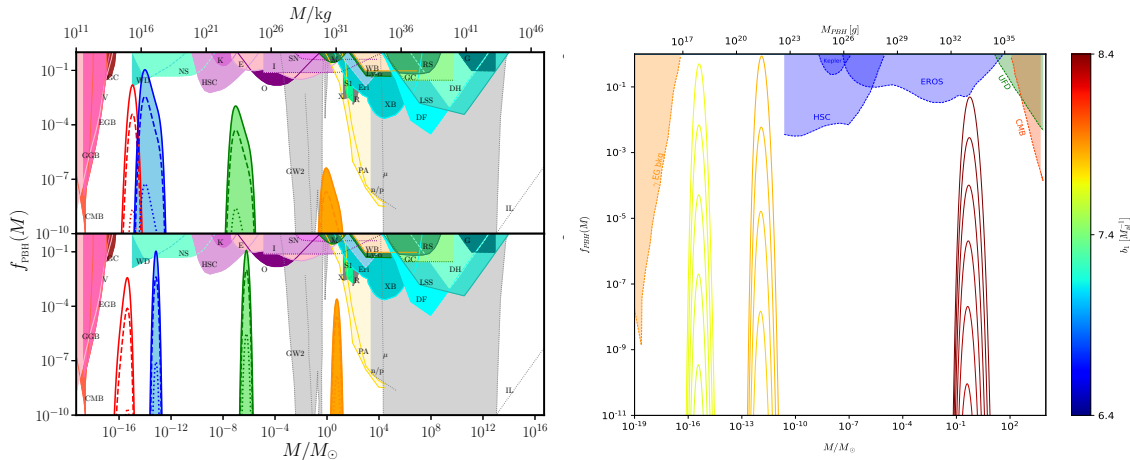
Scalar (in red) and the tensor (in blue) power spectra arising in different single-field models that permit a period of USR inflation³⁰.

³⁰H. 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).



Formation of PBHs in single-field and two-field models of inflation

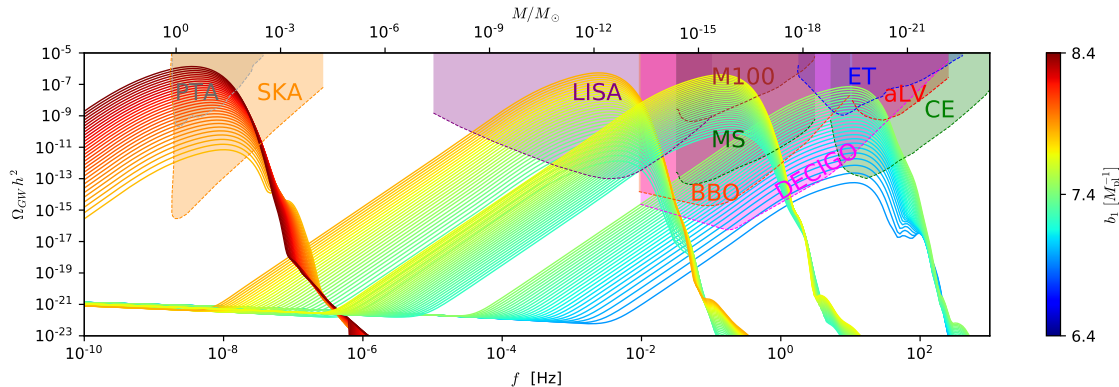


The fraction of PBHs contributing to the dark matter density today $f_{\text{PBH}}(M)$ arising in different single-field³¹ and two-field³² inflationary models.

³¹ H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021).

³² M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

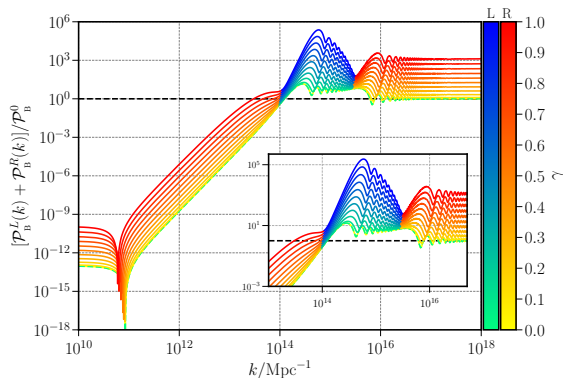
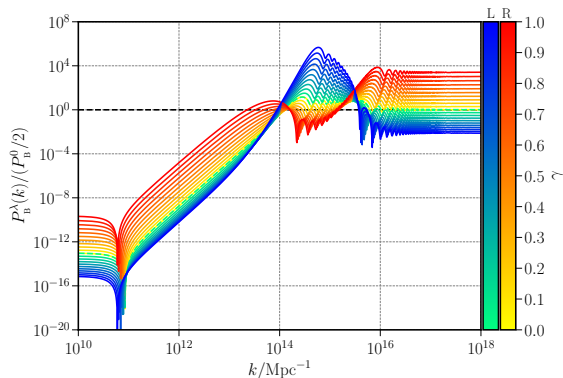
Secondary GWs in the two-field model



The dimensionless density parameter $\Omega_{\text{GW}}(f)$ 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 a parameter describing the model³³.

³³ M. Braglia, D. K. Hazra, F. Finelli, G. F. Smoot, L. Sriramkumar and A. A. Starobinsky, JCAP **08**, 001 (2020).

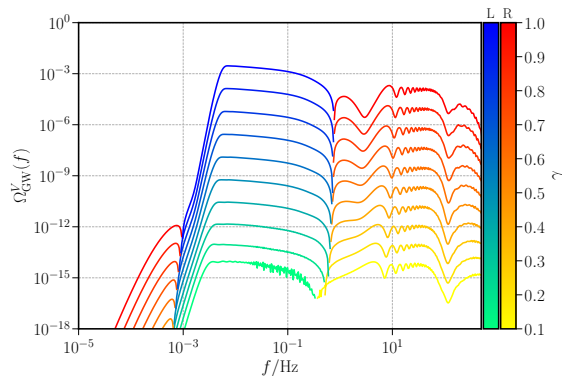
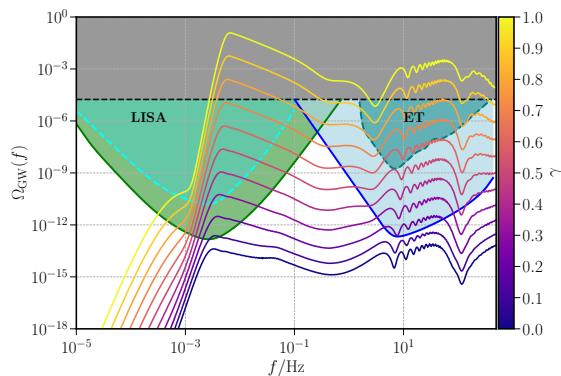
Generation of helical magnetic fields during inflation



The power spectra of helical magnetic fields generated in a multi-phase scenario of magnetogenesis. We have highlighted (in the inset, on the right) the range of wave numbers which lead to the maximum impact on the spectral energy density of secondary GWs. In particular, note that the helicity of the power spectrum changes around the peak.



Secondary GWs generated by the helical magnetic fields



The total (on the left) and the difference (on the right) in the spectral energy densities of secondary GWs induced by the two polarizations of the helical magnetic fields. Note that the change in the helicity of the primordial magnetic fields is transferred to the chirality of the GWs around the peak³⁴.

³⁴H. V. Ragavendra, G. Tasinato and L. Sriramkumar, *Phys. Rev. D* **113**, 103547 (2026).

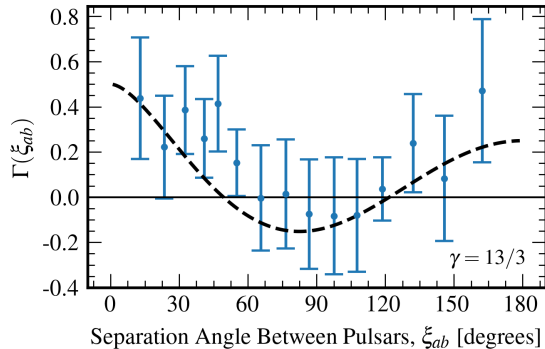
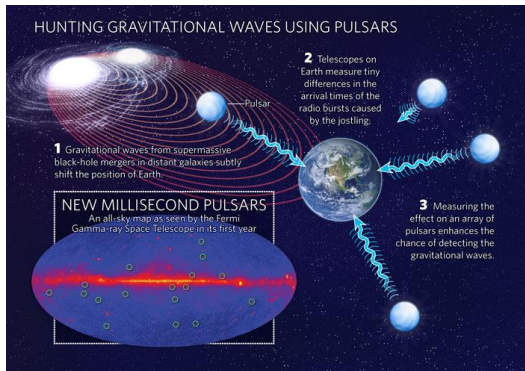


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Pulsar timing arrays (PTAs) and the Hellings-Downs curve



Left: The PTAs monitor an array of millisecond pulsars³⁵.

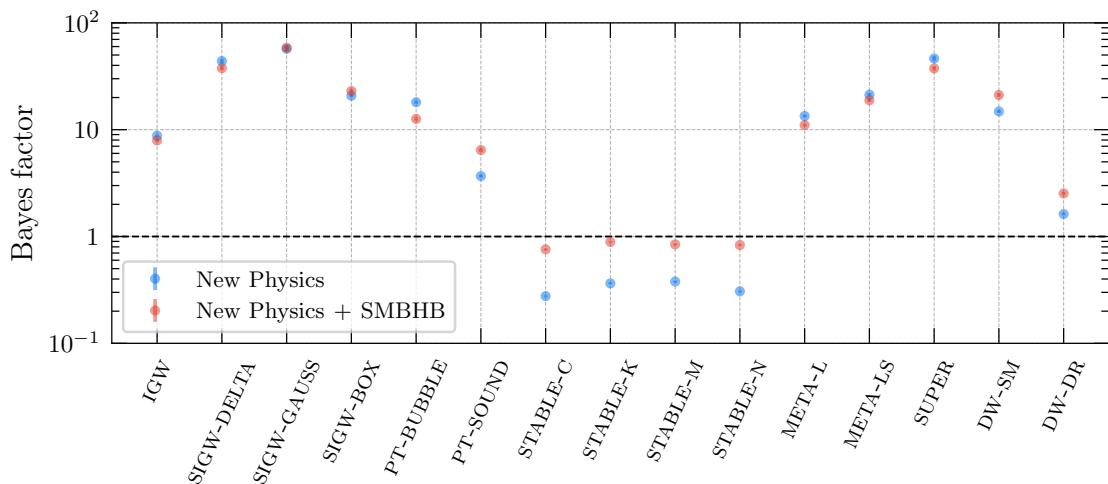
Right: The inter-pulsar correlations measured from 2,211 distinct pairings in the 67-pulsar array of the NANOGrav 15-year data. The dashed black line shows the Hellings-Downs correlation pattern³⁶.

³⁵ See https://ipta.github.io/mock_data_challenge/.

³⁶ NANOGrav Collaboration (G. Agazie *et al.*), *Astrophys. J. Lett.* **951**, 1 (2023).



Stochastic GW background observed by the PTAs



The Bayesian evidence for a variety of astrophysical and cosmological sources for the stochastic GW background suggested by the observations of the PTAs³⁷.

³⁷ NANOGrav Collaboration (G. Agazie *et al.*), *Astrophys. J. Lett.* **951**, 1 (2023).



Shape of the inflationary scalar power spectrum

We assume that the inflationary scalar power spectrum is given by³⁸

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

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 by³⁹:

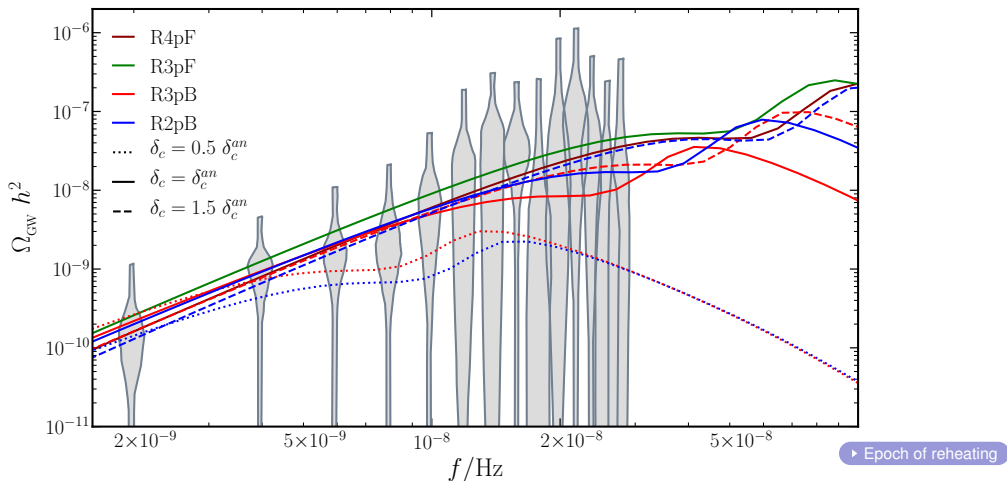
$$\delta_c^{\text{an}} = \frac{3(1 + w_{\text{re}})}{5 + 3w_{\text{re}}} \sin^2 \left(\frac{\pi \sqrt{w_{\text{re}}}}{1 + 3w_{\text{re}}} \right).$$

³⁸For other forms of spectra, see [G. Domenech, S. Pi, A. Wang and J. Wang, JCAP 08, 054 \(2024\)](#).

³⁹In this context, see [T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D 88, 084051 \(2013\)](#).



Generation of secondary GWs during the epoch of reheating



The dimensionless spectral energy density of the secondary GWs today $\Omega_{\text{GW}}(f)$ has been plotted for a given reheating temperature and the best-fit values of the parameters⁴⁰.

⁴⁰S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, JCAP **01**, 118 (2025).



Plan of the talk

- 1 Standard model of cosmology
- 2 Inflationary scenario and constraints from the CMB
- 3 GWs provide a new window to the universe
- 4 Generation of GWs in the early universe
- 5 Observations by the PTAs and the stochastic GW background
- 6 Outlook



Outlook

- ◆ The increasingly precise observations of the CMB by future missions such as Lite-BIRD (Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection), Primordial Inflation Explorer (PIXIE) and Exploring Cosmic History and Origin (ECHO, a proposed Indian effort) can be expected to help us improve the current constraints on the primordial correlations.
- ◆ 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 in the early universe.
- ◆ Over the coming decades, GW observatories such as the Laser Interferometer Space Antenna, Einstein Telescope and Cosmic Explorer, can be expected to provide us with an unhindered view of the primordial universe.



This talk was based on... I

- ◆ 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]].



This talk was based on... II

- ◆ A. Hoory, J. Martin, A. Paul and L. Sriramkumar, **Primary gravitational waves at high frequencies I: Origin of suppression in the power spectrum**, JCAP **05**, 080 (2026) [arXiv:2512.03959 [astro-ph.CO]].
- ◆ H. V. Ragavendra, G. Tasinato and L. Sriramkumar, **Chiral gravitational waves from multi-phase magnetogenesis**, Phys. Rev. D **113**, 103547 (2026) [arXiv:2602.16575 [astro-ph.CO]].
- ◆ A. Hoory, J. Martin, A. Paul and L. Sriramkumar, **Primary gravitational waves at high frequencies II: Emergence of the exponential cut-off in the power spectrum**, arXiv:2605.18286 [astro-ph.CO].



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Thank you for your attention