Gravitational waves from the early universe

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Colloquium

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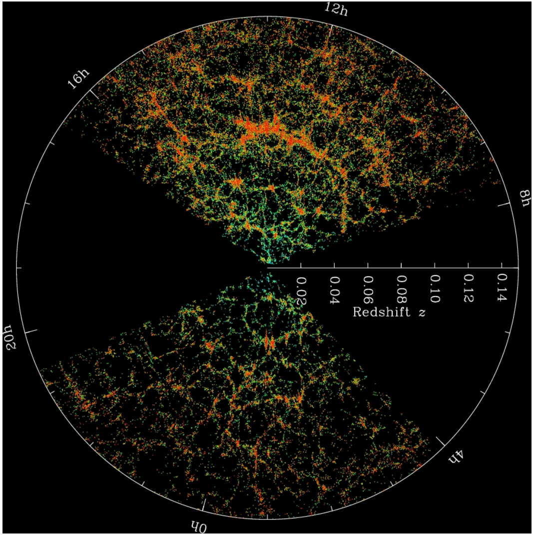
Plan of the talk

Plan of the talk

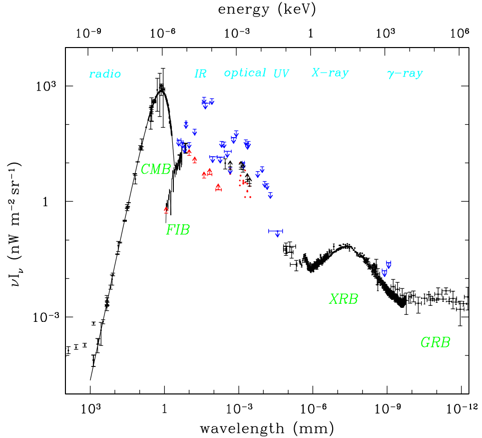
Distribution of galaxies in the universe

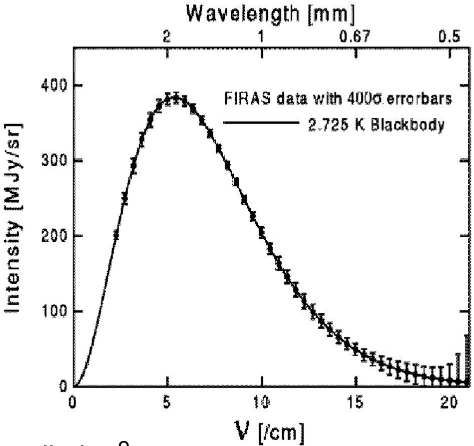


Distribution of galaxies as observed by the Sloan Digital Sky Survey[1].

[1] Image from https://www.sdss4.org/science/.

Radiation in the universe and cosmic microwave background (CMB)





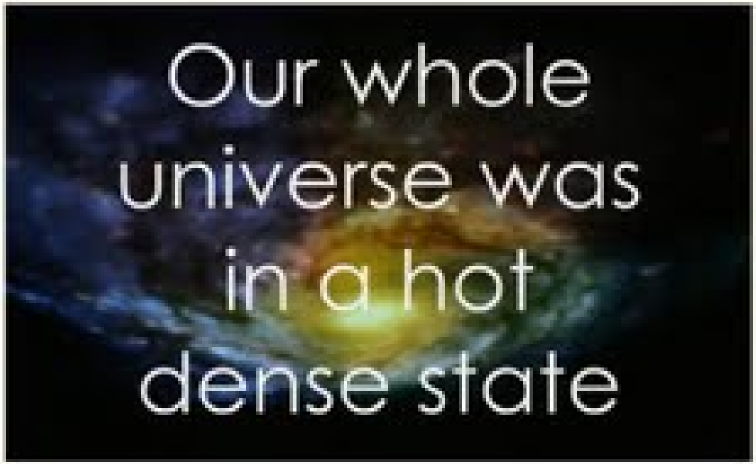
Left: Spectrum of the cosmological background radiation[2].

Right: Spectrum of the CMB as measured by COBE[3]. The CMB is a Planck spectrum corresponding to a temperature of 2.725° K.

[2] Figure from D. Scott, arXiv:astro-ph/9912038.

[3] Image from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

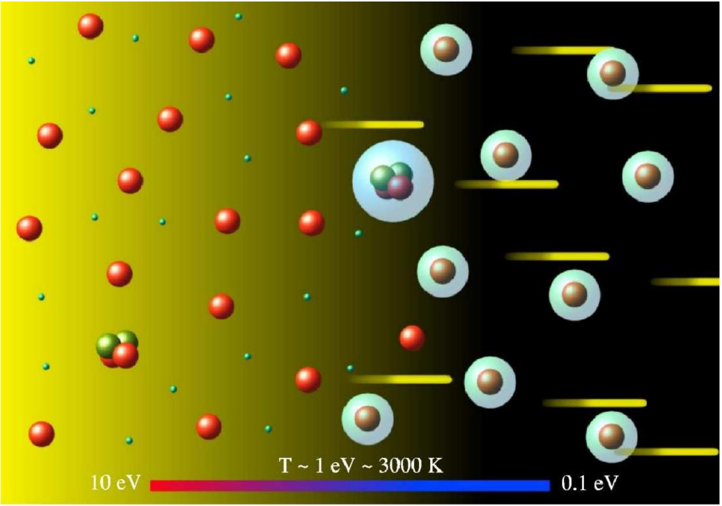
Big bang model seems popular!



The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom ‘The Big Bang Theory’[4]!

[4]See http://www.cbs.com/shows/big_bang_theory/.

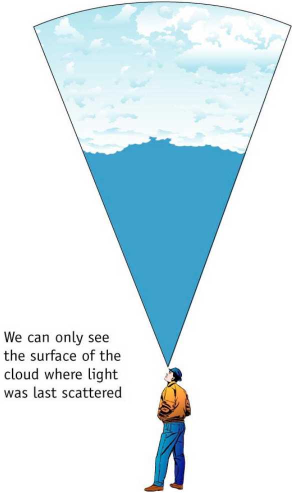
Decoupling of matter and radiation[5]

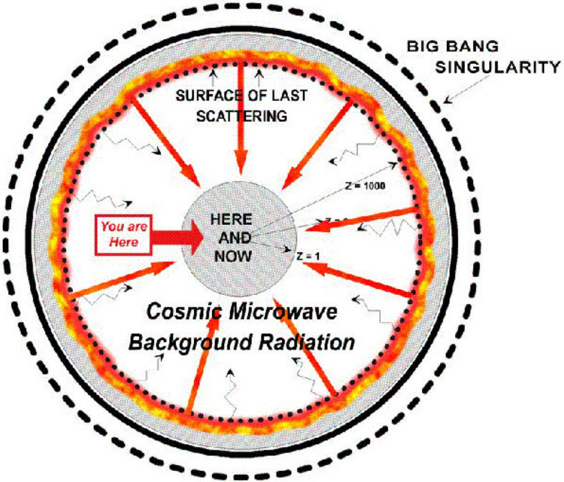


Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ$ K, which corresponds to a redshift of about $z \simeq 1000$.

[5] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

Surface of last scattering and free streaming CMB photons

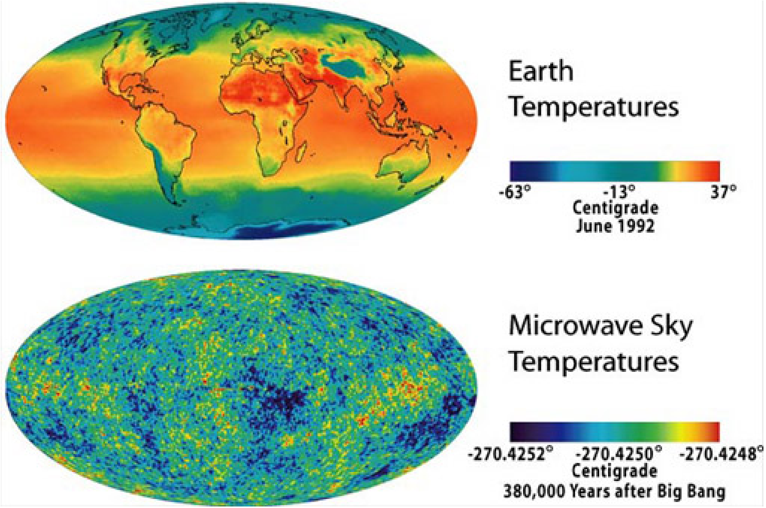




CMB photons stream to us freely from the surface of last scattering when radiation decoupled from matter[6].

[6]Image from http://planck.caltech.edu/epo/epo-cmbDiscovery4.html.

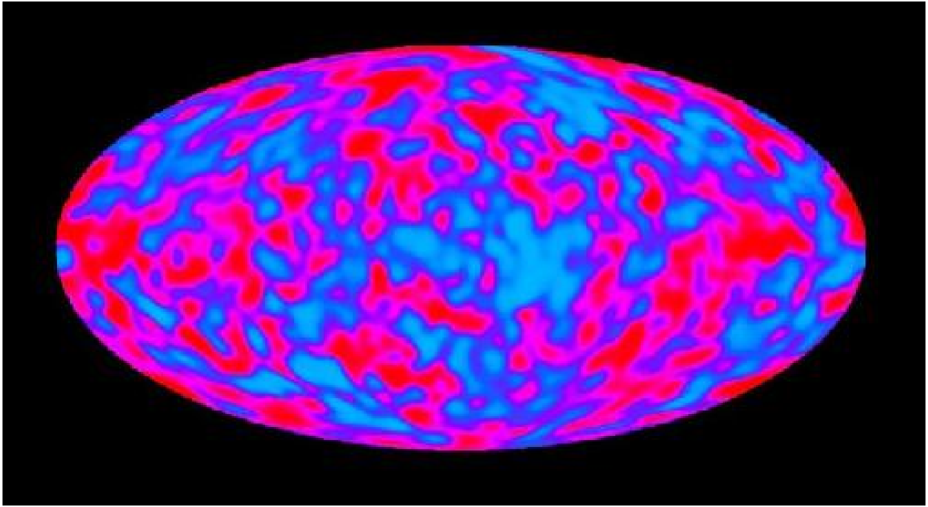
Projecting the surface of last scattering



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 projection[7].

[7] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html.

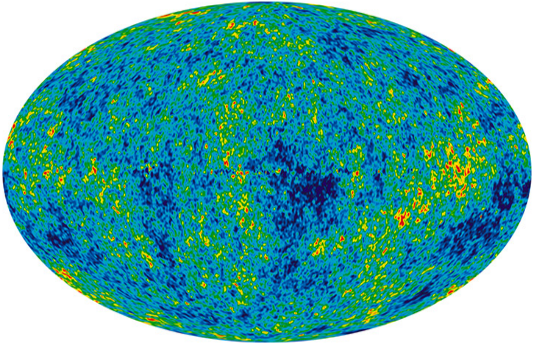
Anisotropies in the CMB

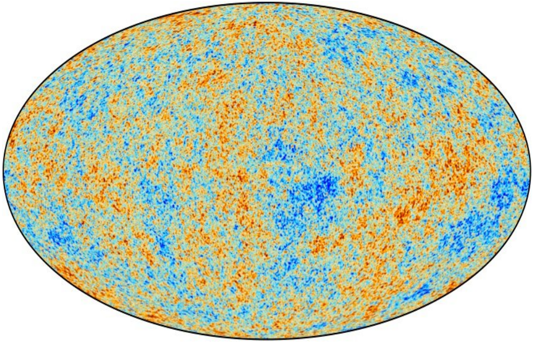


The fluctuations in the temperature of the CMB as seen by COBE[8]. The CMB turns out to be isotropic to one part in 10^5.

[8] Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.

Anisotropies in the CMB as observed by WMAP and Planck





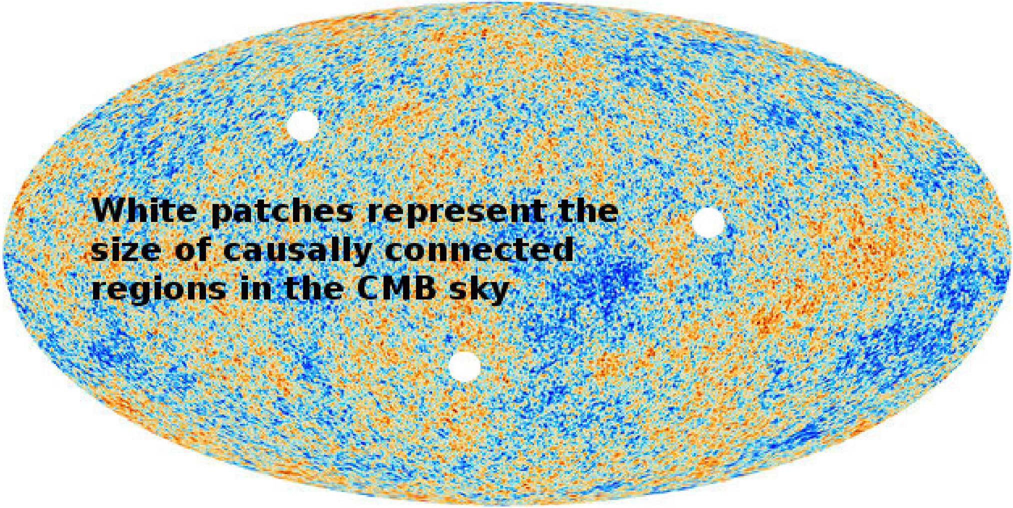
Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[9].
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[10]. The above images show temperature variations (as color differences) of the order of $200\,\mu\mathrm{K}$.

[9] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.

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

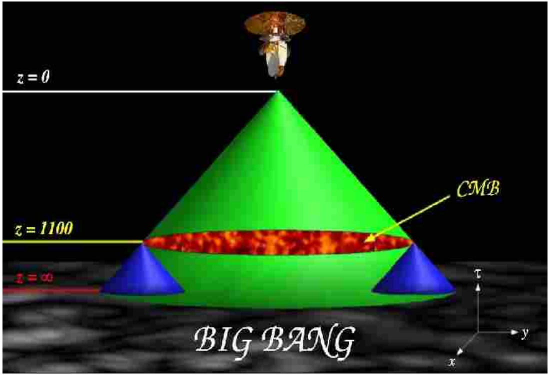
Plan of the talk

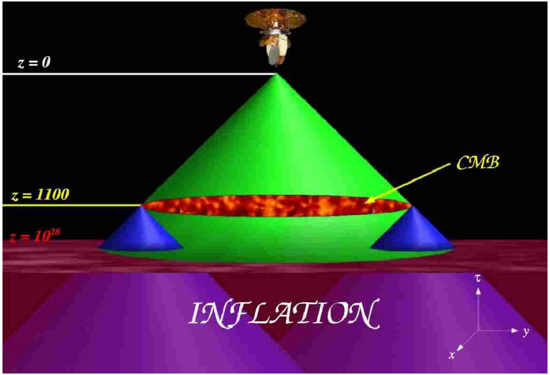
Horizon problem



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

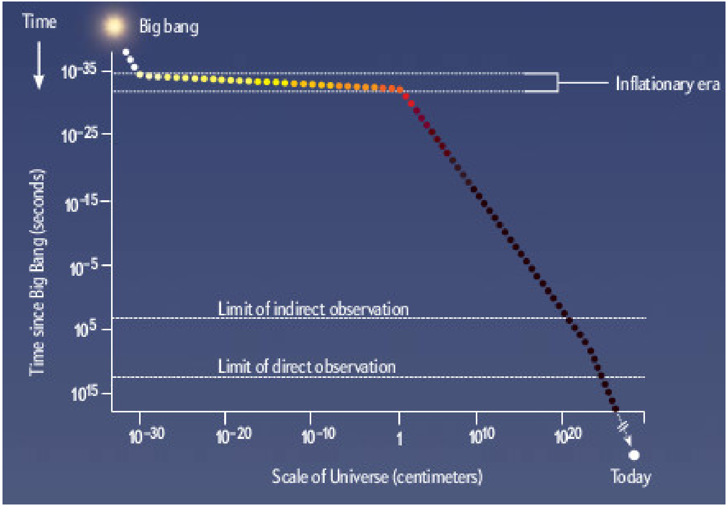




Another illustration of the horizon problem (on the left), and an illustration of its resolution (on the right) through an early and sufficiently long epoch of inflation[11].

[11] Images from W. Kinney, astro-ph/0301448.

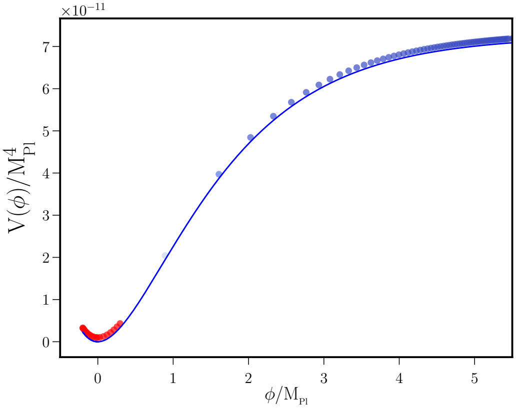
Time and duration of inflation

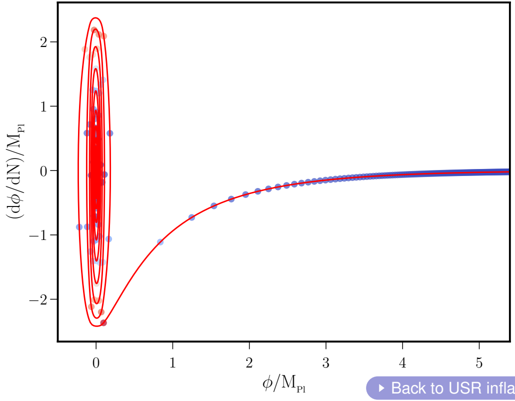


Inflation—a brief period of accelerated expansion—is expected to have taken place during the very early stages of the universe[12].

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

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)[13].

[13] Figure 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:

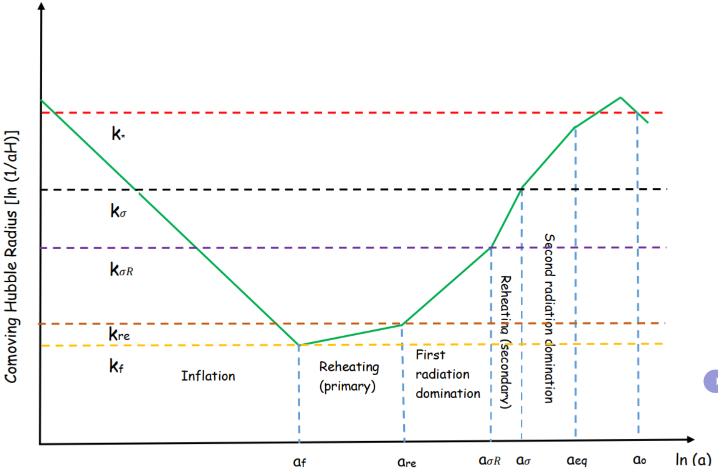
- The quantum fluctuations associated with the scalar fields that drive inflation are responsible for the primordial perturbations. The perturbations in the metric and matter are related through the Einstein's equations.
- The scalar perturbations leave the largest imprints on the CMB, and are primarily 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 polarization[14].

[14] See, 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 $d_{\mathrm{H}}/a = (a\,H)^{-1}$ (in green) across different epochs[15].

[15] Md. 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 spectra[16]:

$$\mathcal{P}_{_{\rm S}}(k) = A_{_{\rm S}}\,\left(\frac{k}{k_\ast}\right)^{n_{\rm S}-1}, \qquad \mathcal{P}_{_{\rm T}}(k) = A_{_{\rm T}}\,\left(\frac{k}{k_\ast}\right)^{n_{\rm T}},$$

where $A_{_{\rm S}}$ and $A_{_{\rm T}}$ denote the scalar and tensor amplitudes, $k_\ast$ represents the so-called pivot scale at which the amplitudes are quoted, while the spectral indices $n_{_{\rm S}}$ and $n_{_{\rm T}}$ are assumed to be constant.

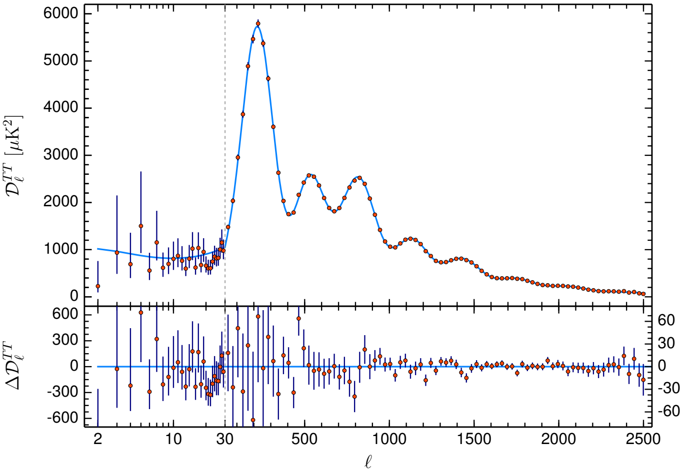
The tensor-to-scalar ratio r is defined as

$$r(k) = \frac{\mathcal{P}_{_{\rm T}}(k)}{\mathcal{P}_{_{\rm S}}(k)}.$$

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

Plan of the talk

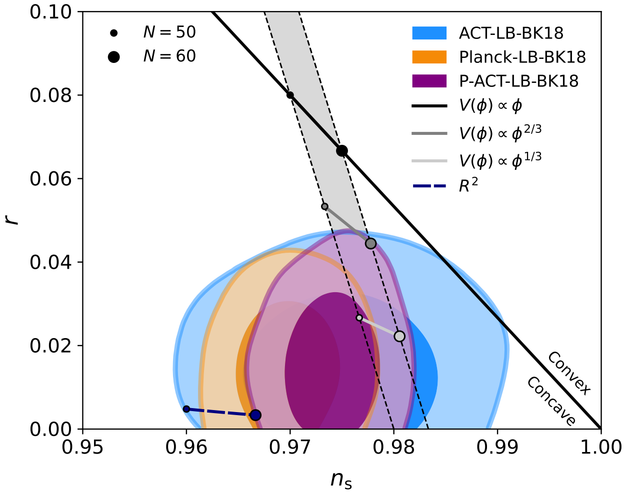
CMB angular power spectrum from Planck



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]

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

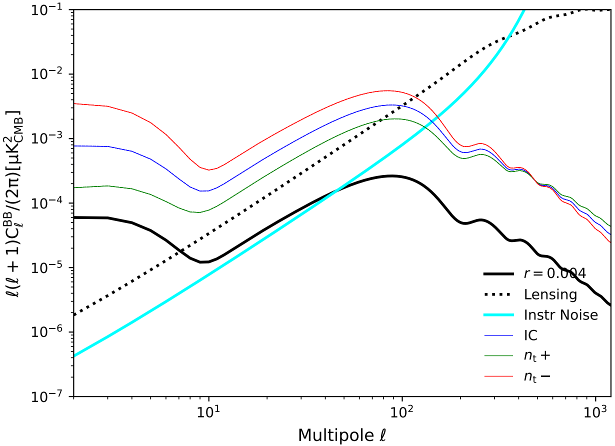
Performance of inflationary models in the n_s-r plane



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 models[18].

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

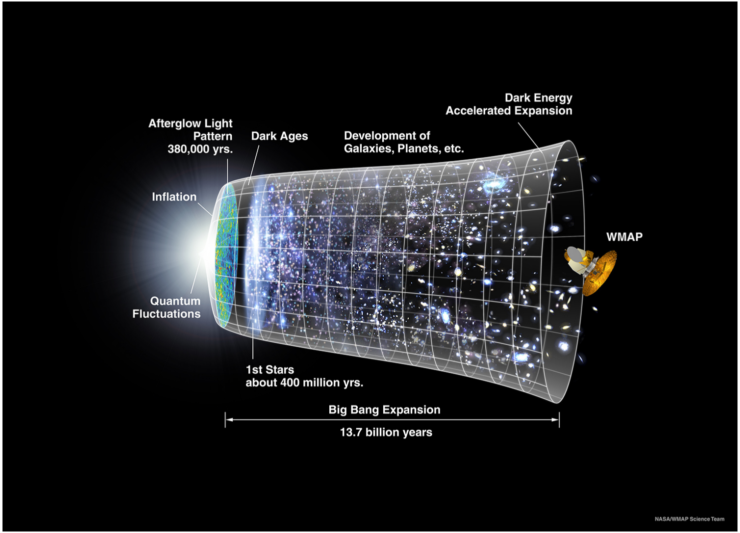
Prospects of observing the imprints of the tensor perturbations



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 configuration[19].

[19] D. 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 universe[20].

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

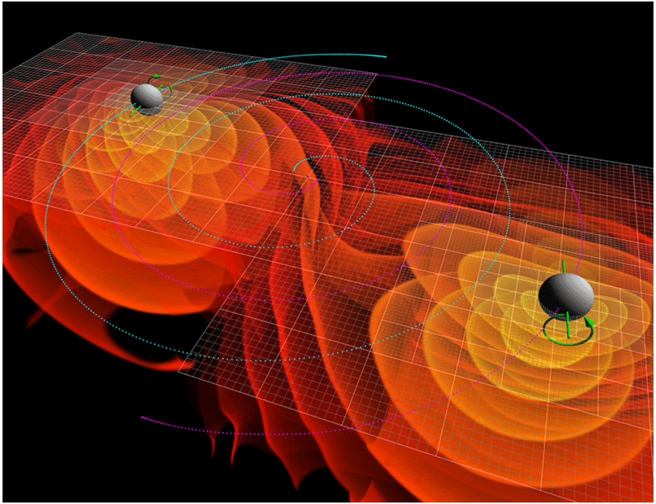
Plan of the talk

Laser Interferometer Gravitational-Wave Observatory (LIGO)

Views of LIGO at Hanford (on the left) and at Livingston (on the right). These observatories are essentially Michelson-Morley interferometers with rather long arms (of length about 4 km) that are extremely sensitive to the smallest disturbances of the mirrors[21].

[21] Images from https://www.advancedligo.mit.edu/summary.html.

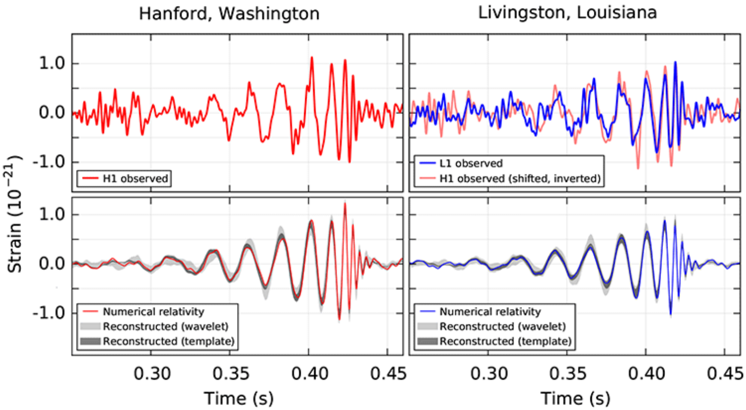
GWs from coalescing binary black holes (BHs)



Numerical simulations of the GWs emitted by the coalescence of two BHs. The orange contours represent the GWs and the blue lines represent the orbits of the BHs[22].

[22] Image from E. Berti, Physics **9**, 17 (2016).

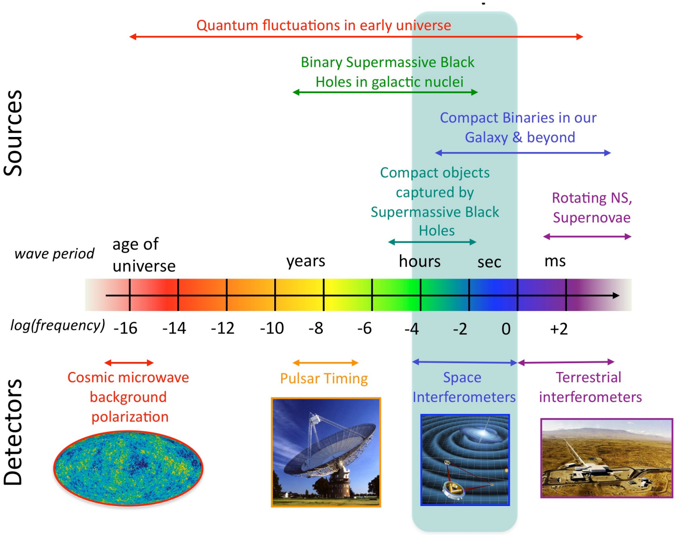
First observation of the merger of binary BHs



On September 14, 2015, similar signals were observed in both of LIGO's interferometers. The top panels show the measured signal in the Hanford (top left) and Livingston (top right) detectors. The bottom panels show the expected signal produced by the merger of two BHs, based on numerical simulations[23].

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

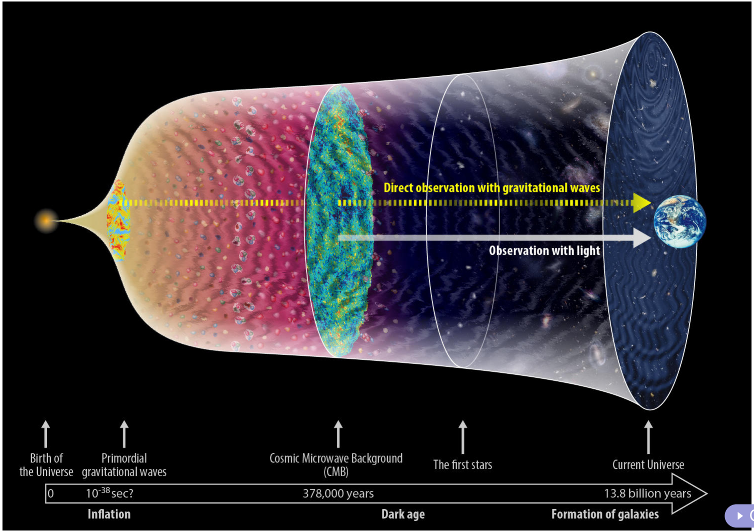
Sources and spectral range of GWs



Different sources of GWs and the corresponding detectors[24].

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

Probing the primordial universe through GWs



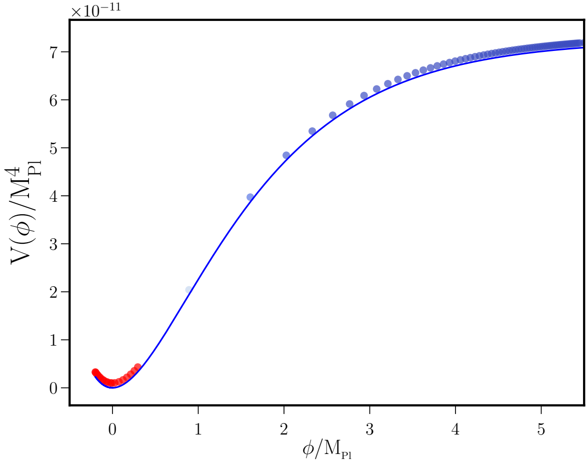
▸ Observations of EM waves

GWs provide a unique window to probe the primordial universe[25].

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

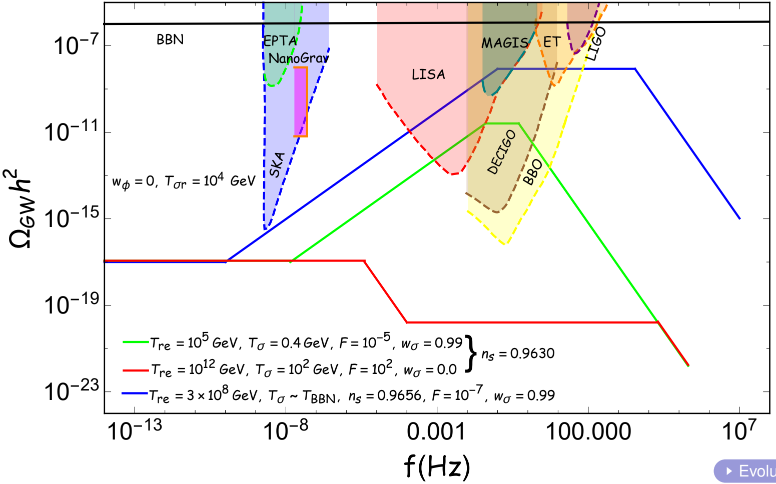
Plan of the talk

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 primary GWs due to late time entropy production

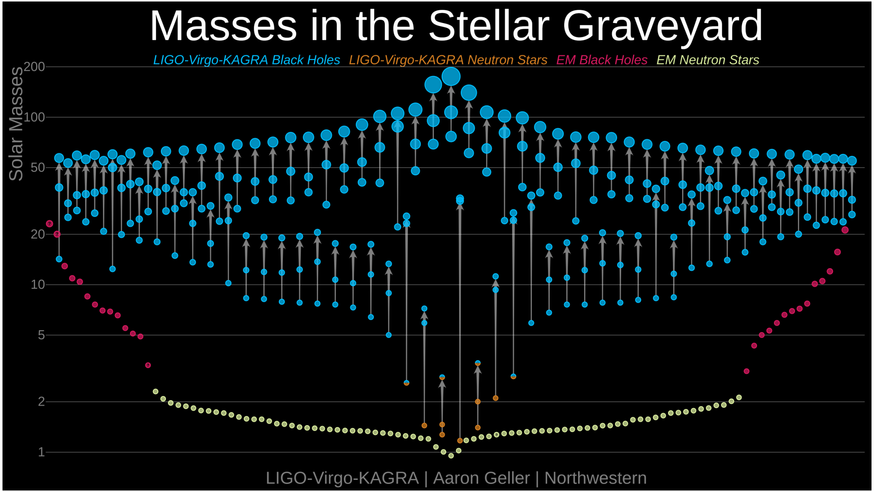


Evolution of comoving lengths

The dimensionless spectral energy density of primary GWs observed today $\Omega_{\rm GW}(f)$ has been plotted in a scenario involving late time production of entropy[26].

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

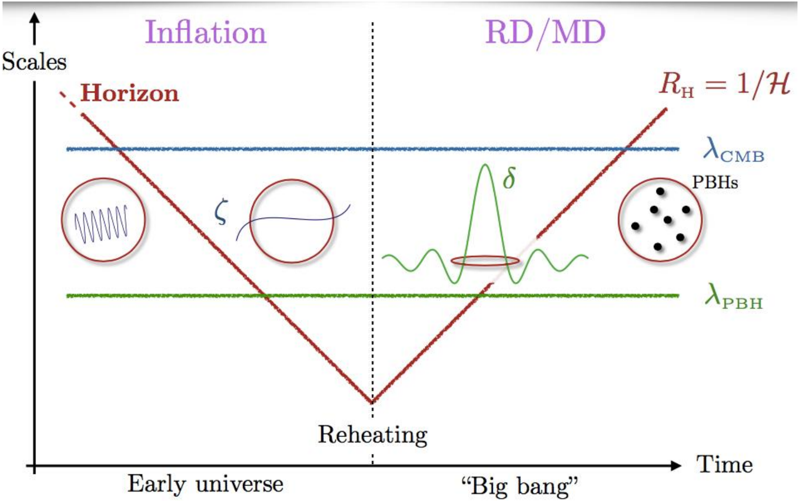
Coalescence of compact binaries observed by LIGO



The third GW Transient Catalog of mergers involving BHs and neutron stars observed by the LIGO-Virgo-KAGRA collaboration[27].

[27] Image from https://www.ligo.caltech.edu/LA/image/ligo20211107a.

Formation of BHs in the early universe

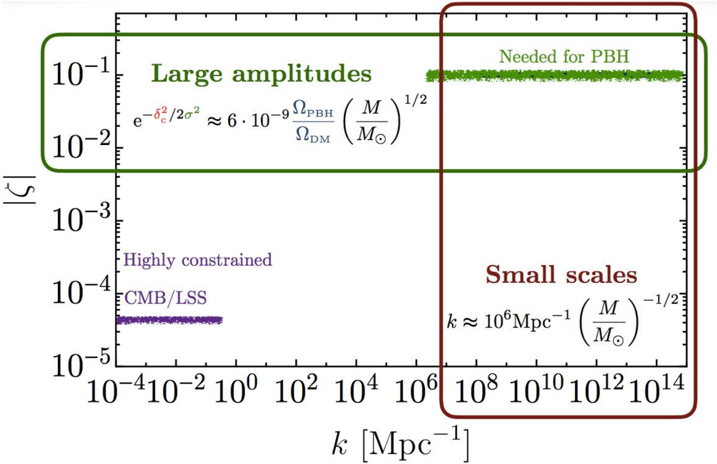


BHs can form when perturbations with significant amplitudes reenter the Hubble radius during the radiation dominated epoch[28].

Evolution of comoving lengths

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

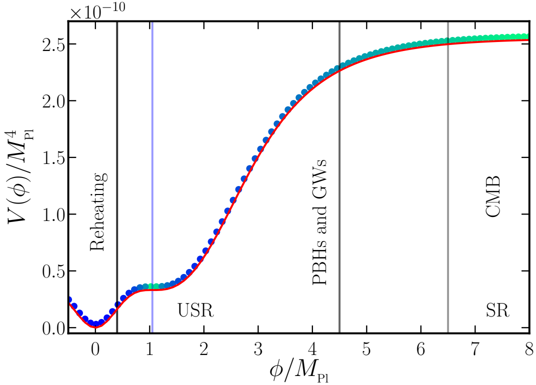
Amplitude for producing significant number of primordial BHs (PBHs)

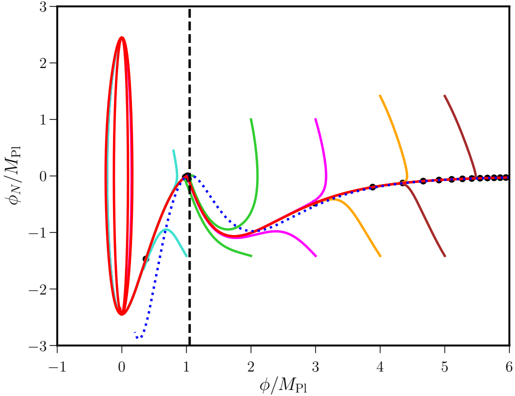


In order to form significant number of PBHs, the amplitude of the perturbations on small scales has to be large enough such that the dimensionless amplitude of the scalar perturbation is close to unity[29].

[29] Figure 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 inflation[30].

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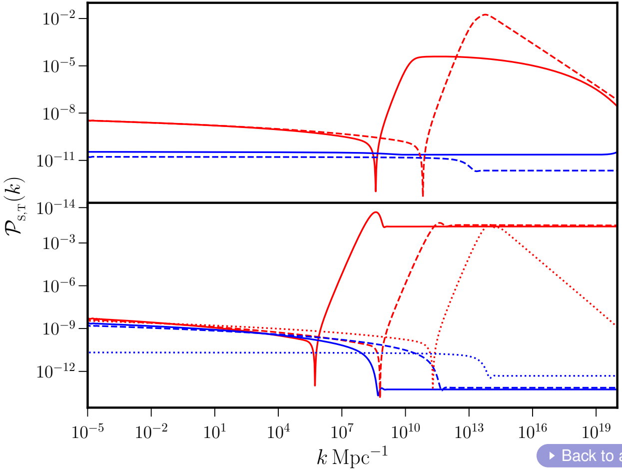
[30] See, for example, C. Germani and T. Prokopec, Phys. Dark Univ. **18**, 6 (2017); I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019). Figures credits, H. V. Ragavendra and S. Maity.

Power spectra in models permitting USR inflation

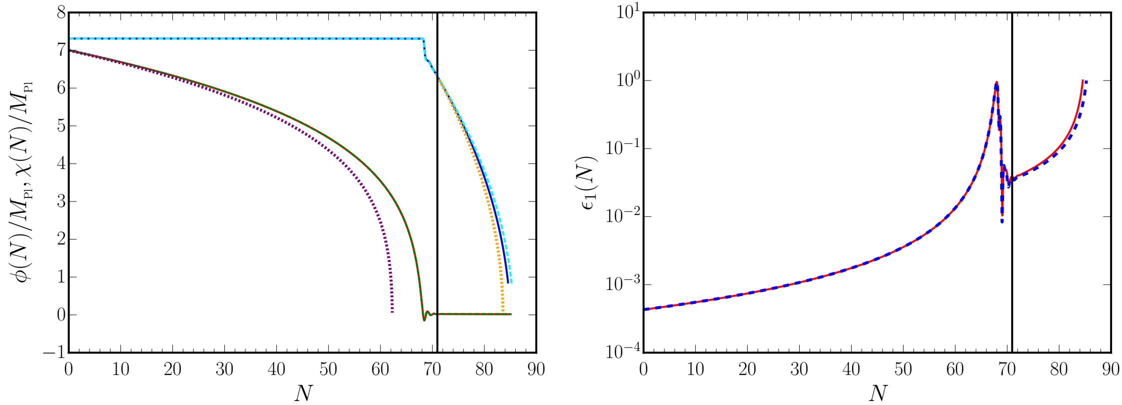


▸ Back to analytical form of the power spectrum

Scalar (in red) and the tensor (in blue) power spectra arising in different single-field models that permit a period of USR inflation[31].

[31] 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).

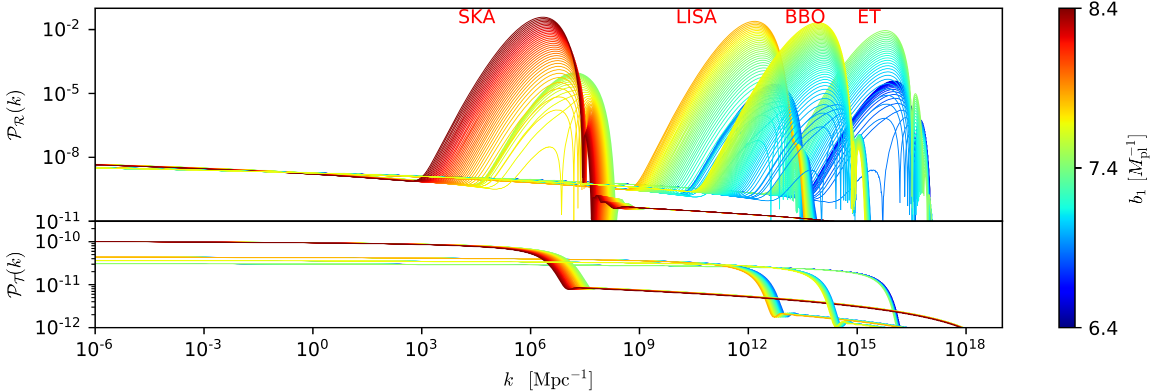
Non-trivial inflationary dynamics in a two-field model



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 interest[32].

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

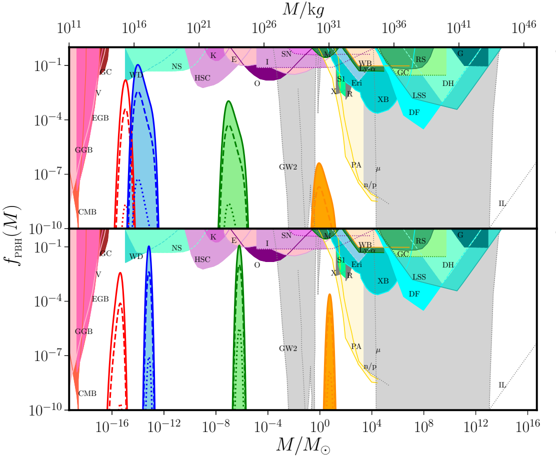
Enhanced scalar power on small scales in the two-field model

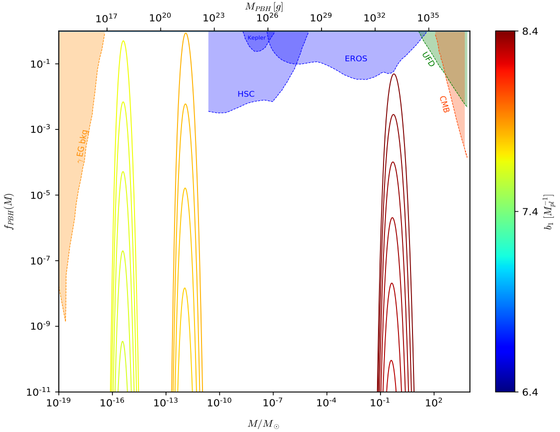


The scalar (on top) and the tensor (at the bottom) power spectra arising in the two-field model have been plotted for a few different sets of initial conditions for the fields and a range of values of a particular parameter[33].

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

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



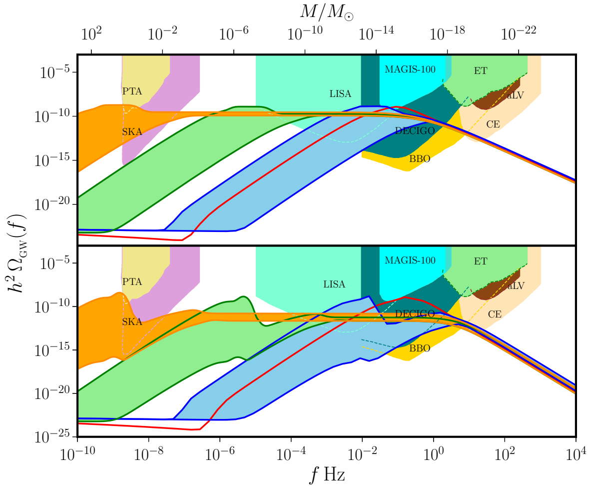


The fraction of PBHs contributing to the dark matter density today $f_{\rm PBH}(M)$ arising in different single-field[34] and two-field[35] inflationary models.

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

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

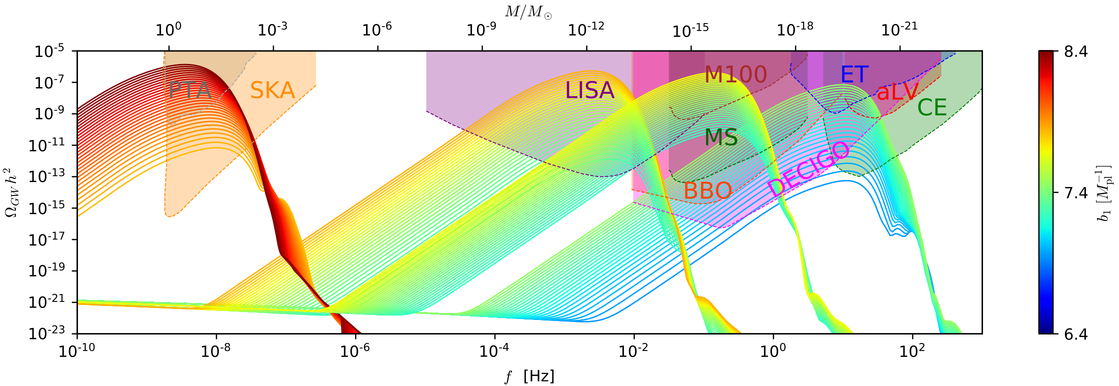
Secondary GWs in single-field models permitting USR inflation



The dimensionless density parameter $\Omega_{\rm GW}$ arising in the single-field models leading to an epoch of USR inflation has been plotted as a function of the frequency f[36].

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

Secondary GWs in the two-field model

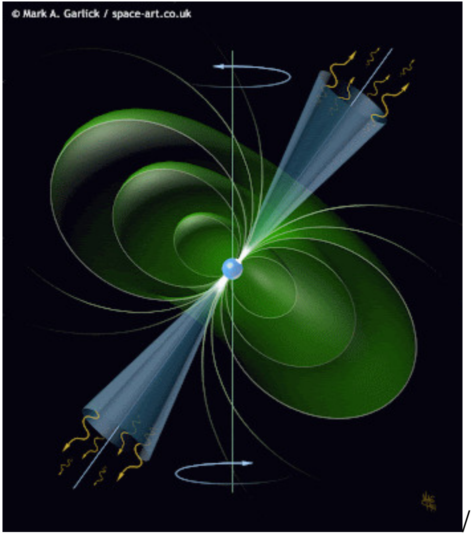


The dimensionless density parameter $\Omega_{\rm GW}(f)$ arising in the two-field model has been plotted for a set of initial conditions for the background fields as well as a range of values of a parameter describing the model[37].

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

Plan of the talk

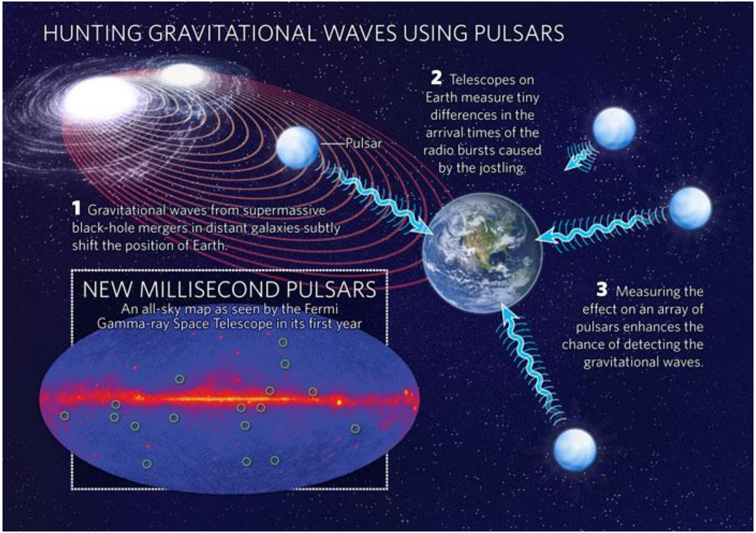
Pulsars



Pulsars are dense and rotating neutron stars that emit regular beams of light[38].

[38] Image from https://dmr-astronomersclub.blogspot.com/2012/07/what-is-pulsar.html.

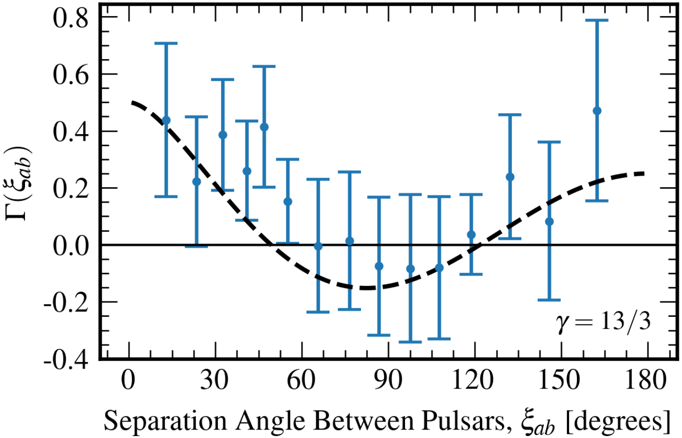
Pulsar timing arrays (PTAs)



The PTAs monitor an array of millisecond pulsars[39].

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

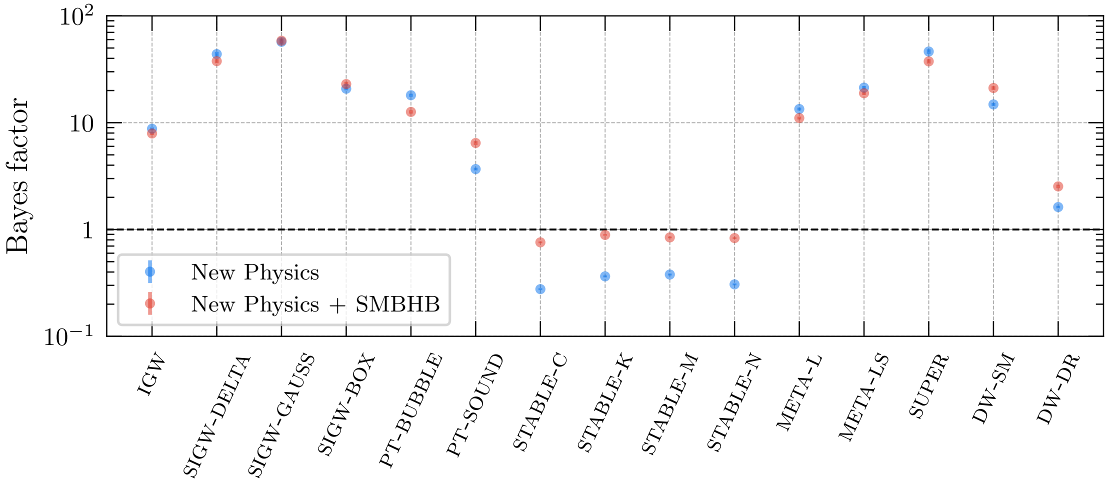
Hellings-Downs curve



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[40].

[40] 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[41].

[41] 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 by[42]

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

where A_{S} and n_{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 $T_{\mathrm{re}} = 50\,\mathrm{MeV}$.

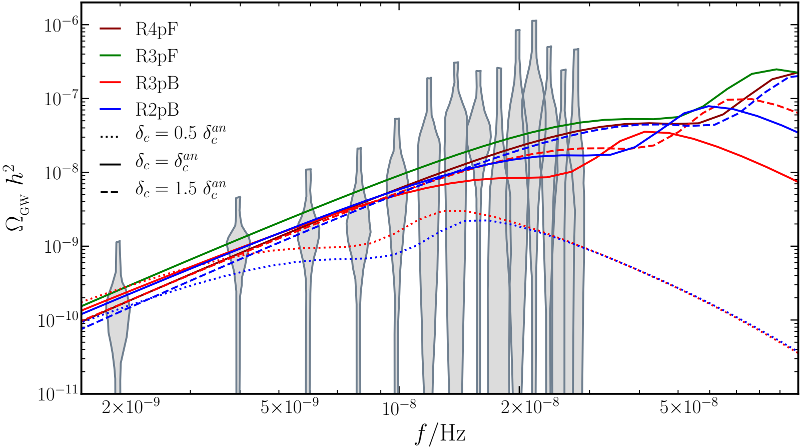
We shall assume that the threshold value of the density contrast for the formation of PBHs is given by[43]:

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

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

[43] In 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

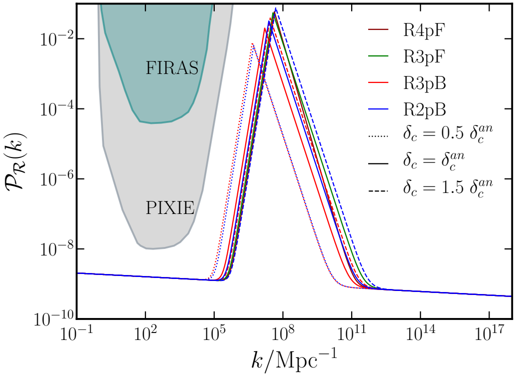


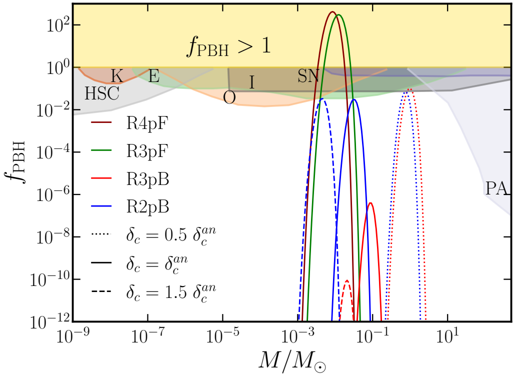
Epoch of reheating

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[44].

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

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. $f_{\mathrm{PBH}}(M)$, for the best-fit values of the parameters in the different models[45].

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

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 ± 19.21	350.61 ± 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 that involves mergers of supermassive black hole binaries.

Plan of the talk

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. . .

- 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]].

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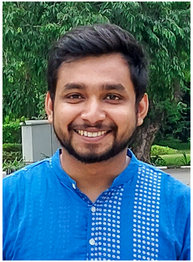
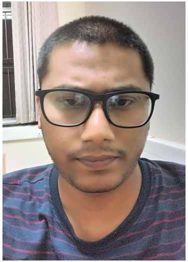


Suvashis Maity



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Thank you for your attention