Probing the primordial universe with electromagnetic and gravitational waves

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The Brahmagupta Colloquium

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Indian Institute of technology Madras, Chennai

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Plan of the talk

1. The standard model of cosmology
2. The inflationary scenario
3. Constraints on inflation from the Planck CMB data
4. GWs provide a new window to the universe
5. Generating GWs in the early universe
6. Observations by the PTAs 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, 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]].

This talk is based on. . .

- 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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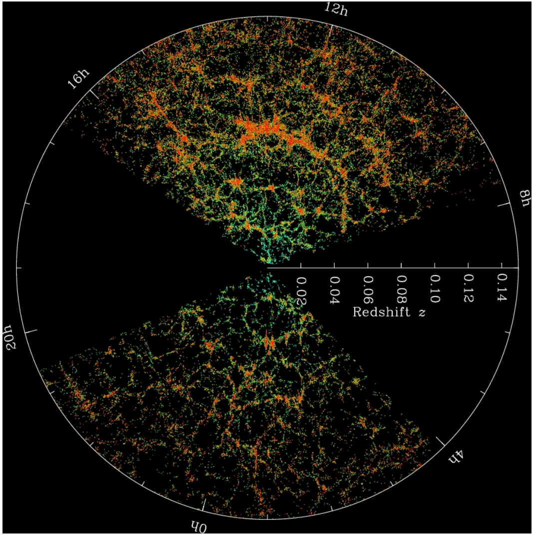
Distribution of galaxies in the universe



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

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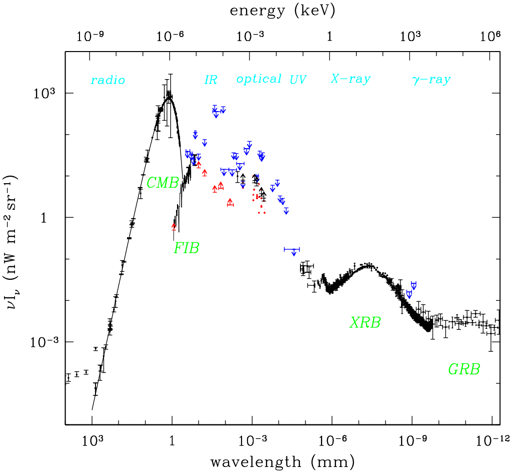
[1] Image from https://www.sdss4.org/science/.

Spectrum of radiation in the universe



The spectrum of the cosmological background radiation has been plotted as a function of wavelength[2]. Note that the cosmic microwave background (CMB) contributes the most to the background radiation.

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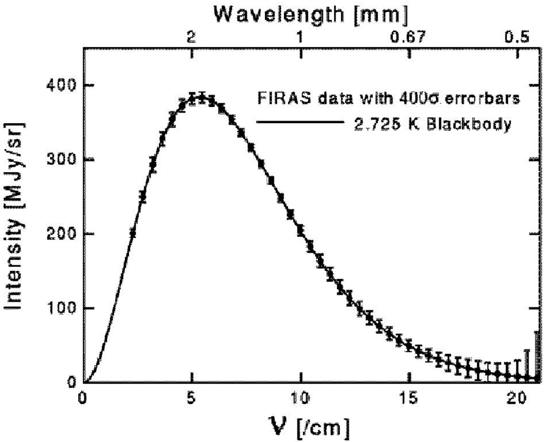
[2] Figure from D. Scott, arXiv:astro-ph/9912038.

Spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[3]. It is such a perfect Planck spectrum (corresponding to a temperature of $2.725^\circ\ \mathrm{K}$) that it is unlikely to be bettered in the laboratory. The error bars in the graph above have been amplified 400 times so that they can be seen!

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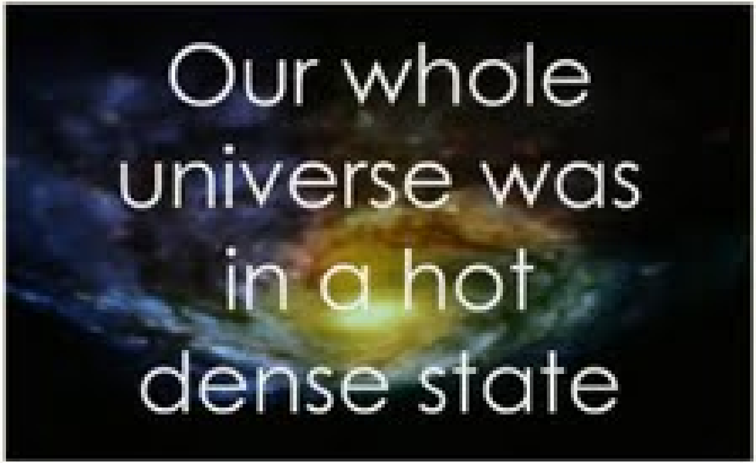
[3] Image from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

The 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]!

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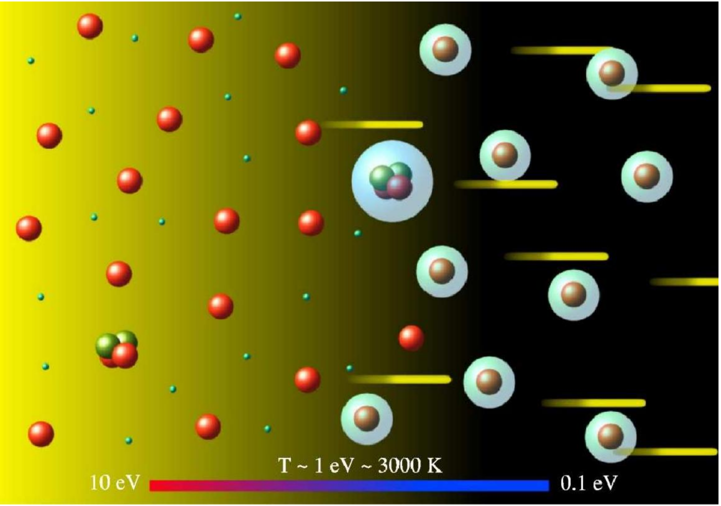
[4] See http://www.cbs.com/shows/big_bang_theory/.

Decoupling of matter and radiation[5]



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

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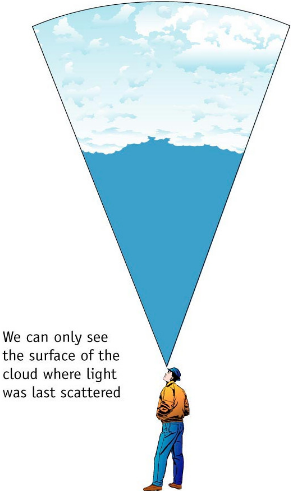
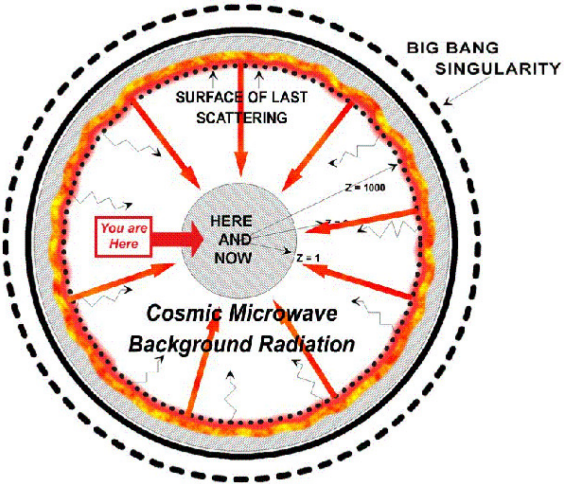
[5] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

Surface of last scattering and the free streaming of CMB photons


We can only see
the surface of the
cloud where light
was last scattered



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

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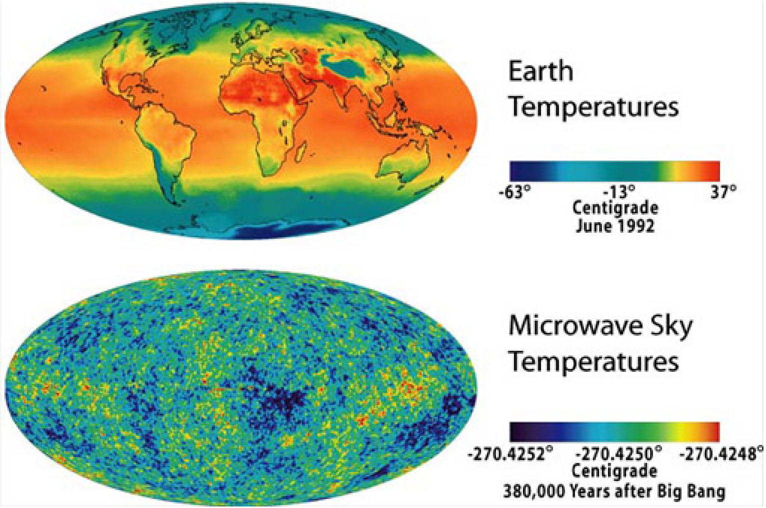
[6] Image from http://planck.caltech.edu/epo/epo-cmbDiscovery4.html.

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].

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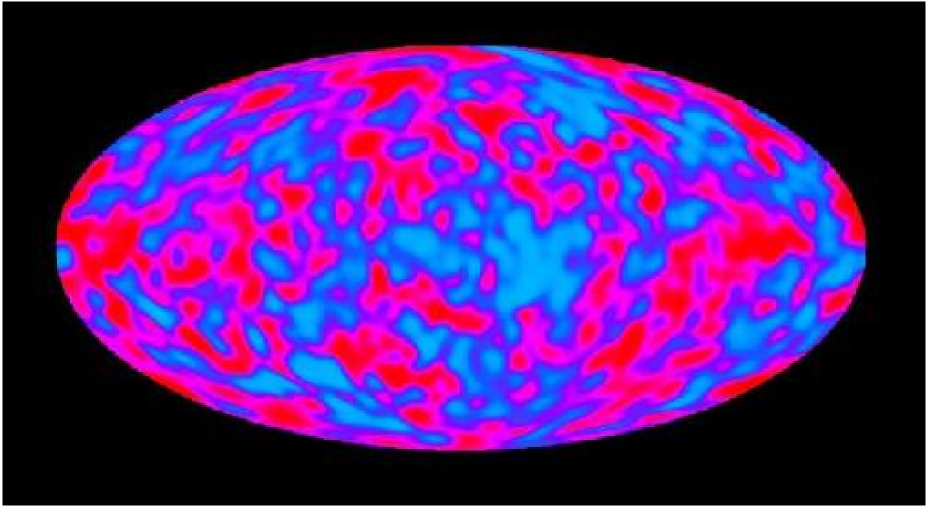
[7] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html.

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.

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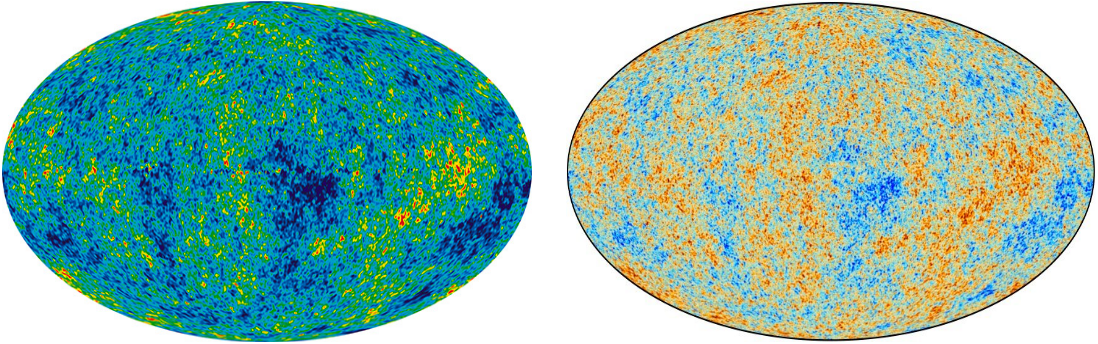
[8] Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.

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[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 $200\,\mu\mathrm{K}$.

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

[10] P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].

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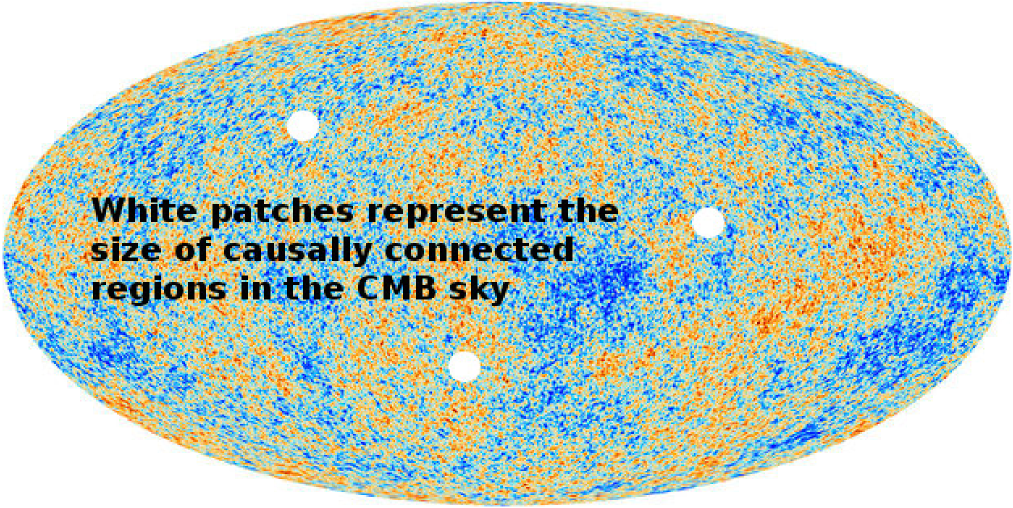
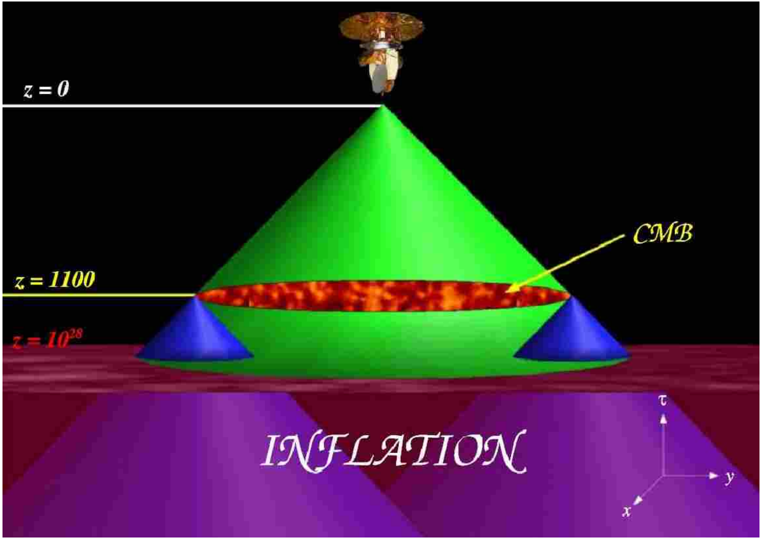
The horizon problem



White patches represent the size of causally connected regions in the CMB sky

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.

Inflation resolves the horizon problem



An early and sufficiently long epoch of inflation resolves the horizon problem[11].

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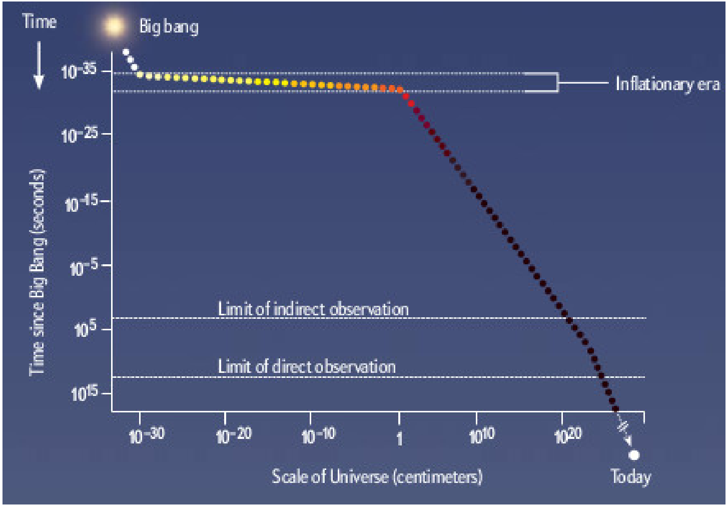
[11] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

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].

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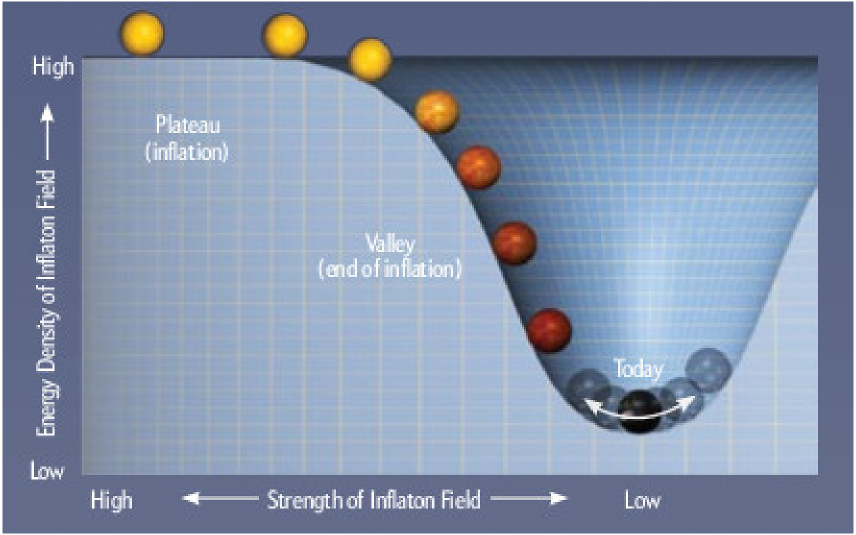
[12] Image from P. J. Steinhardt, Sci. Am. **304**, 18 (2011).

Driving inflation with scalar fields



Inflation can be achieved with scalar fields encountered in high energy physics[13].

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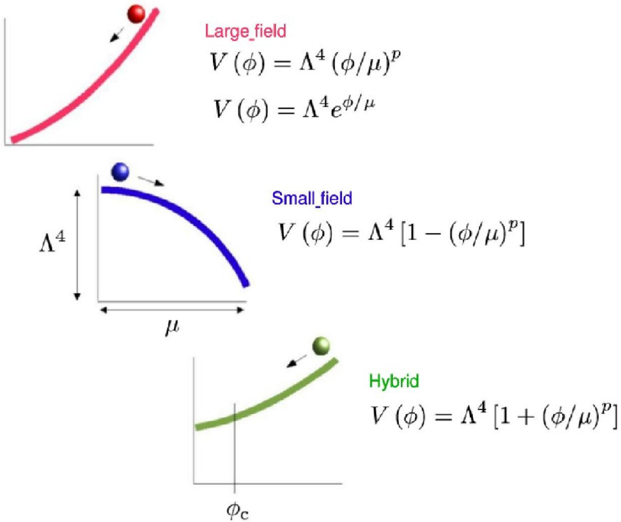
[13] Image from P. J. Steinhardt, Sci. Am. **304**, 34 (2011).

A variety of potentials to choose from



A variety of scalar field potentials have been considered to drive inflation[14].

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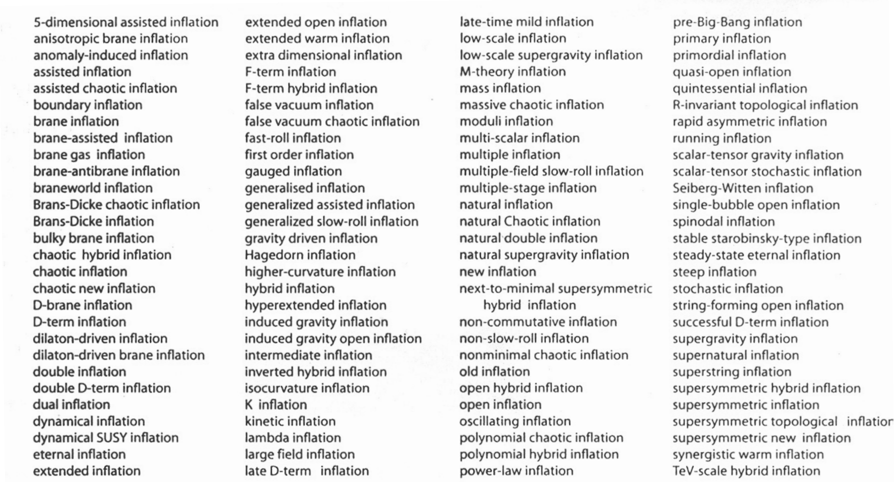
[14] Image from W. Kinney, astro-ph/0301448.

Proliferation of inflationary models



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

A partial list of ever-increasing number of inflationary models[15]. Actually, it may not even be possible to rule out some of these models!

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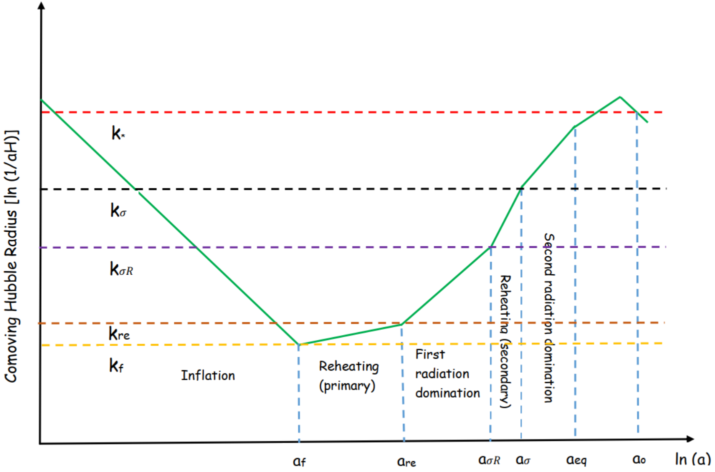
[15] From E. P. S. Shellard, *The future of cosmology: Observational and computational prospects*, in *The Future of Theoretical Physics and Cosmology*, Eds. G. W. Gibbons, E. P. S. Shellard and S. J. Rankin (Cambridge University Press, Cambridge, England, 2003).

Origin of the primordial perturbations

- The vacuum fluctuations in the scalar fields that drive inflation lead to perturbations in the metric. 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.
- Whereas, the tensor perturbations, *i.e.* the gravitational waves (GWs), can be generated even in the absence of sources.

Behavior of the comoving wave number and Hubble radius



Back to reheating

Behavior of the comoving wave number k (horizontal lines in different colors) and the comoving Hubble radius $d_{\rm H}/a = (a\,H)^{-1}$ (in green) across different epochs[16].

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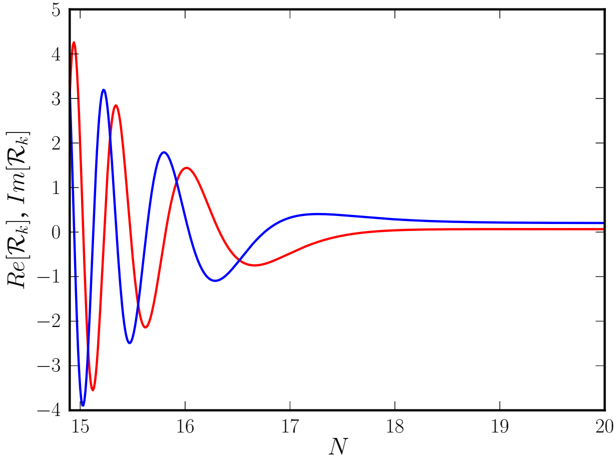
[16] Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

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[17].

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[17] 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

While comparing with the observations, for convenience, one often uses the following power law, template scalar and the tensor spectra[18]:

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

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

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

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

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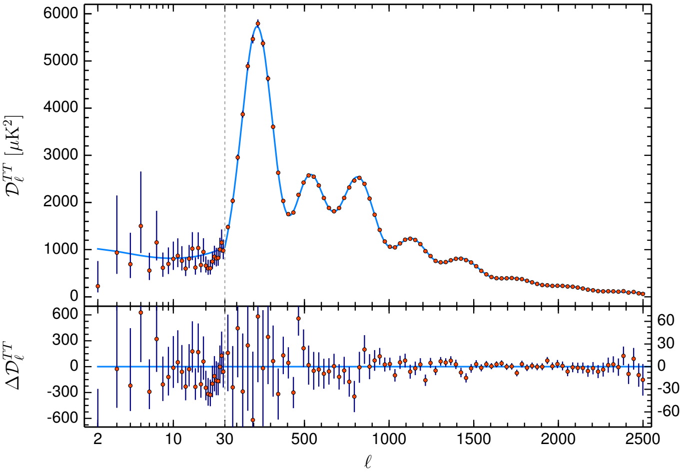
CMB angular power spectrum from Planck



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)[19]

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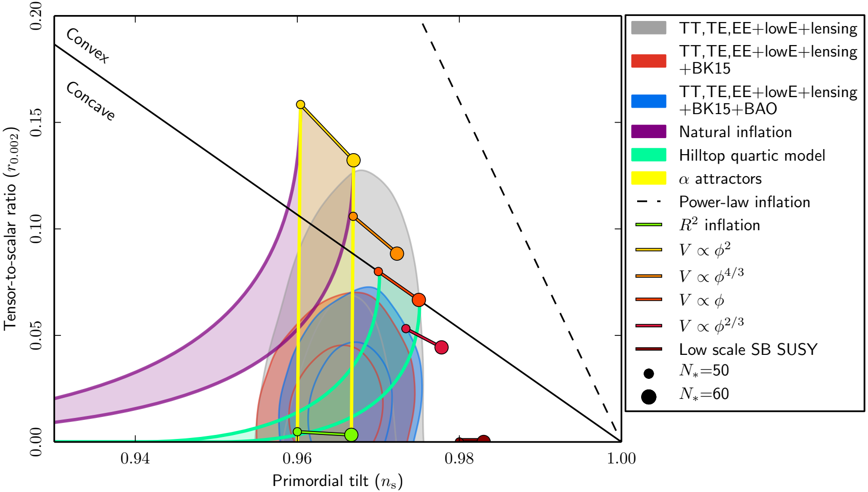
[19] Planck Collaboration (N. Aghanim *et al.*), Astron. Astrophys. **641**, A6 (2020).

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[20].

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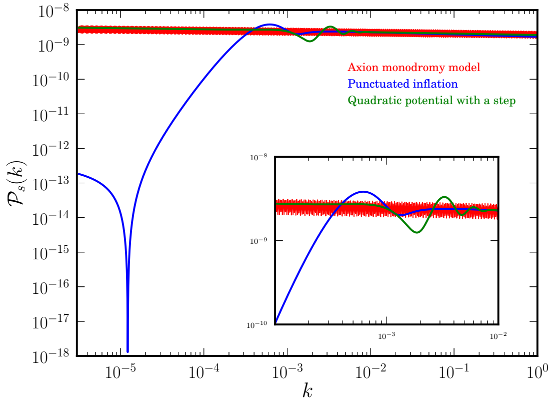
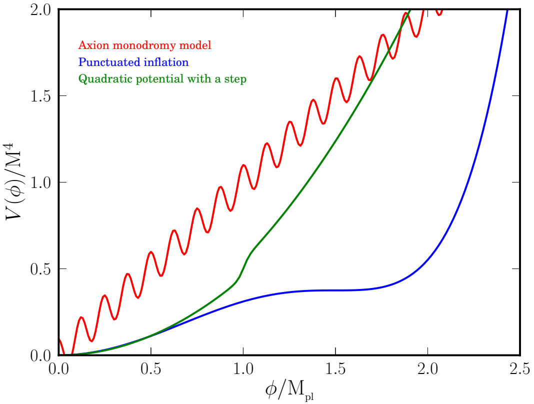
[20] Planck Collaboration (Y. Akrami *et al.*), Astron. Astrophys. **641**, A10 (2020).

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[21].

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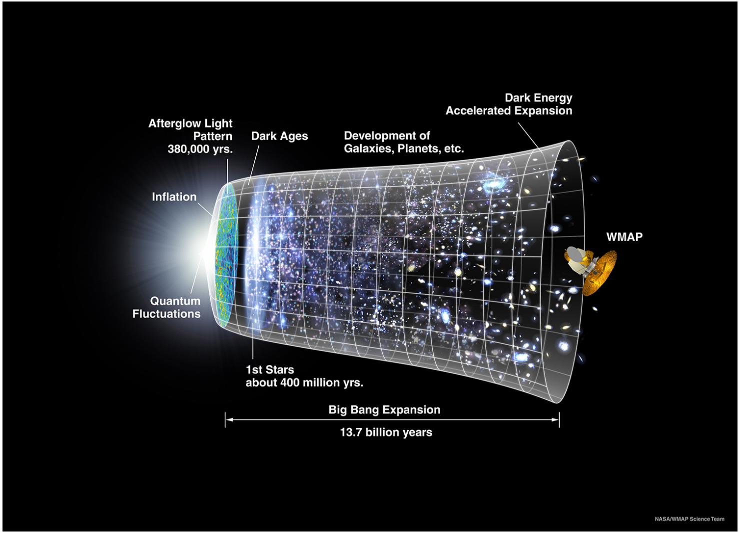
[21] R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **01**, 009 (2009);
D. K. Hazra, M. Aich, R. K. Jain, L. Sriramkumar and T. Souradeep, JCAP **10**, 008 (2010);
M. Aich, D. K. Hazra, L. Sriramkumar and T. Souradeep, Phys. Rev. D **87**, 083526 (2013);
For a recent discussion,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

Timeline of the universe



NASA/WMAP Science Team

Observations of GWs

A pictorial timeline of the universe[22].

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

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Some essential properties of GWs

- The GWs are small disturbances in a given spacetime (very much like ripples in water), which travel at the speed of light.
- They satisfy the wave equation in the given background spacetime.
- The GWs are transverse in nature and are characterized by two degrees of polarization[23].

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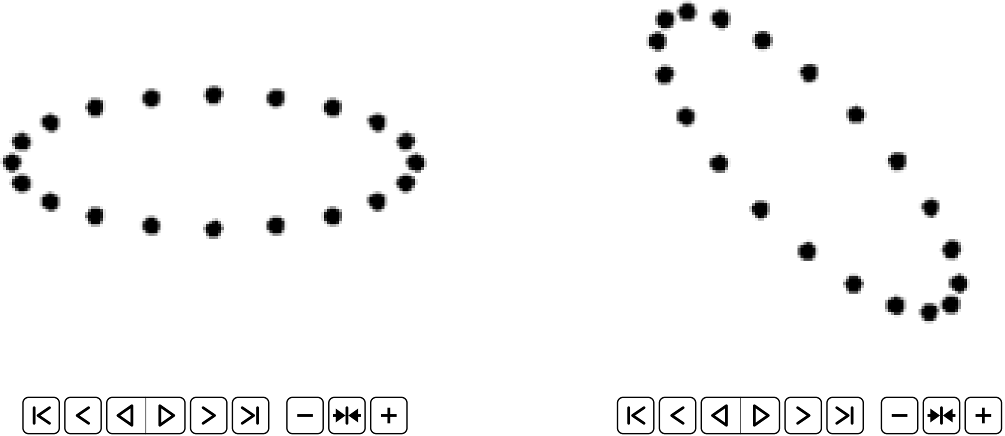
[23] J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Pearson Education, Delhi, 2003).

Polarization of GWs



A GW impinging on a ring of masses leads to oscillations of the particles depending on the polarization of the wave: plus (on the left) and cross (on the right)[24].

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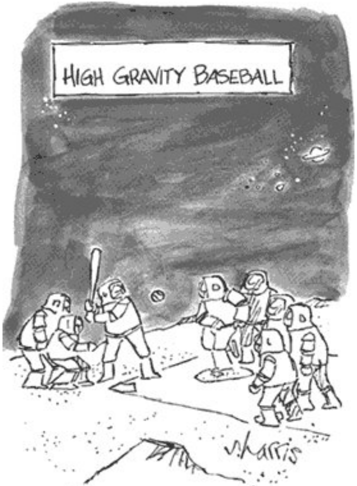
[24] J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Pearson Education, Delhi, 2003).

Sources of GWs[25]

In order to generate GWs of detectable amplitude, the gravitational fields of the sources ought to be very strong.



Strong sources of GWs include

- Rotating neutron stars
- Exploding supernovae
- Coalescing binary neutron stars or black holes
- Supermassive binary black holes at the centre of galaxies
- Fluctuations in the early universe

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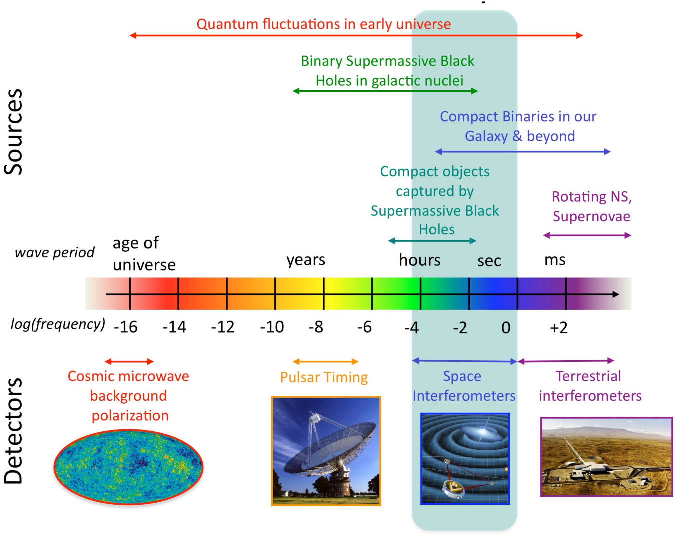
[25] Cartoon from http://www.sciencecartoonsplus.com/gallery/physics/galphys2b.php.

The spectrum of GWs



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period: age of universe, years, hours, sec, ms

log(frequency): -16, -14, -12, -10, -8, -6, -4, -2, 0, +2

Detectors

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Terrestrial interferometers

Different sources of GWs and corresponding detectors[26].

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

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[27].

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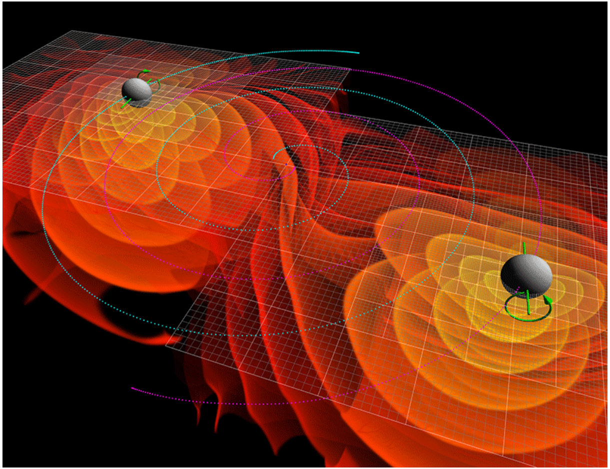
[27] Images from https://www.advancedligo.mit.edu/summary.html.

GWs from inspiralling black holes (BHs)



Numerical simulations of the GWs emitted by the coalescence of two black holes. The orange contours represent the amplitude of the GWs and the blue lines represent the orbits of the black holes[28].

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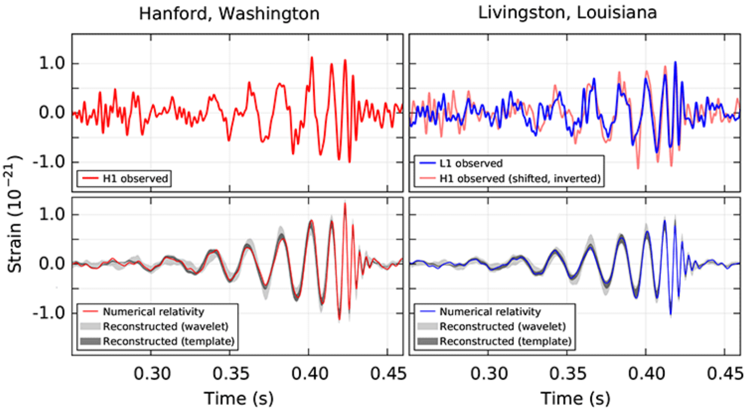
[28] Image from E. Berti, Physics **9**, 17 (2016).

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[29].

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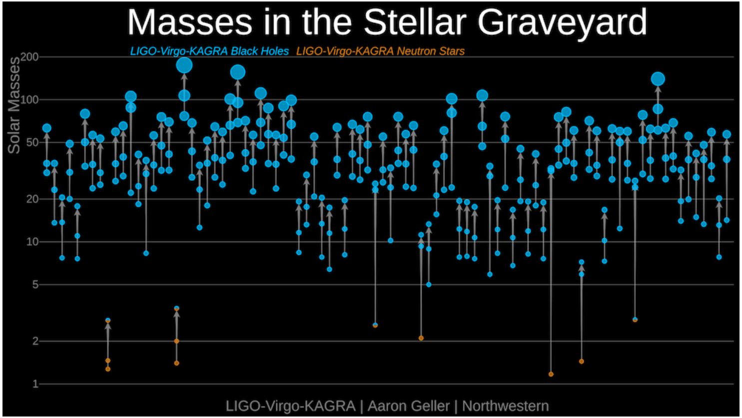
[29] Figure from B. P. Abbott *et al.*, Phys. Rev. Lett. **116**, 061102 (2016).

Coalescence of compact binaries observed by LIGO



▸ Formation of PBHs

On November 7, 2021, the LIGO-Virgo-KAGRA Collaboration released the results of the second-half of their third observing run (O3b). This third GW Transient Catalog (GWTC-3) is the largest catalog of mergers involving black holes and neutron stars released thus far and includes events released in prior observing runs[30].

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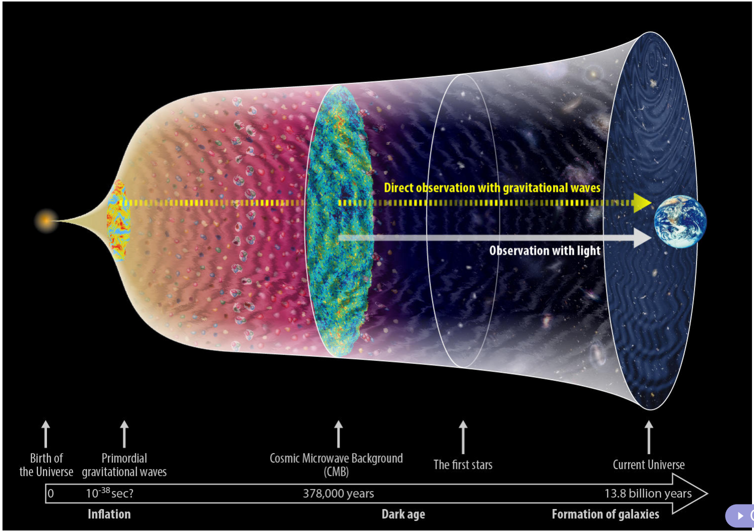
[30] Image from https://www.ligo.org/detections/O3bcatalog.php.

Probing the primordial universe through GWs



▸ Observations of EM waves

GWs provide a unique window to probe the primordial universe[31].

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

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2. The inflationary scenario
3. Constraints on inflation from the Planck CMB data
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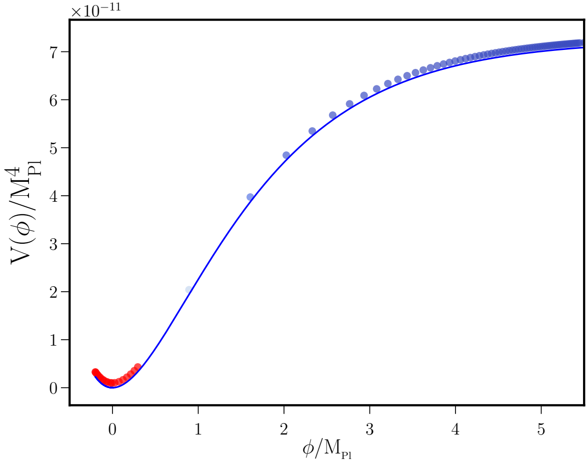
5. Generating GWs in the early universe
6. Observations by the PTAs and the stochastic GW background
7. Outlook

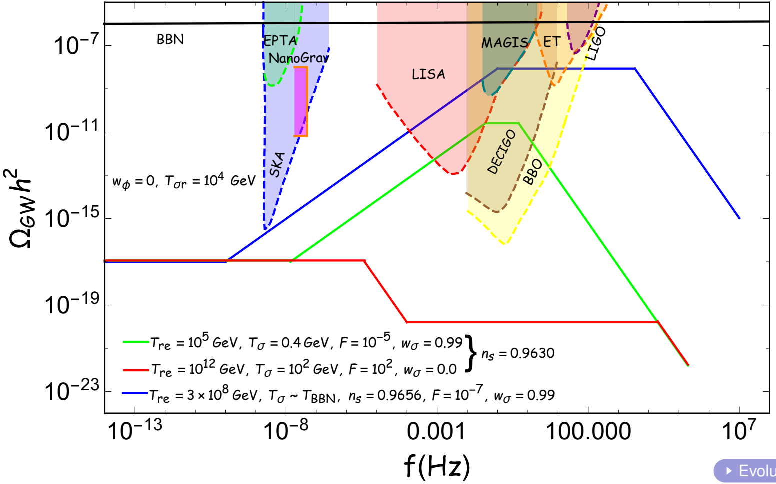
Evolution of the scalar field in an inflationary potential



▸ GWs induced by PMFs

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 $\Omega_{\rm GW}(f)$ 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[32].

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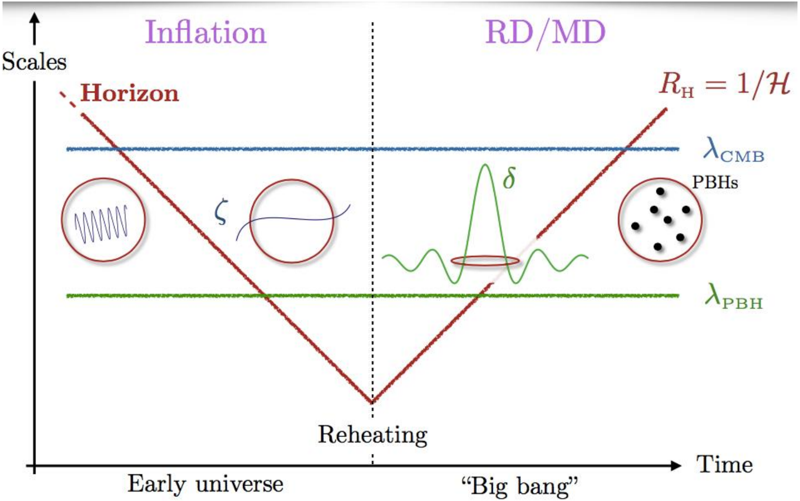
[32] Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

Formation of BHs in the early universe



BHs can form when perturbations with significant amplitudes reenter the Hubble radius during the radiation dominated epoch[33].

Observations by LIGO

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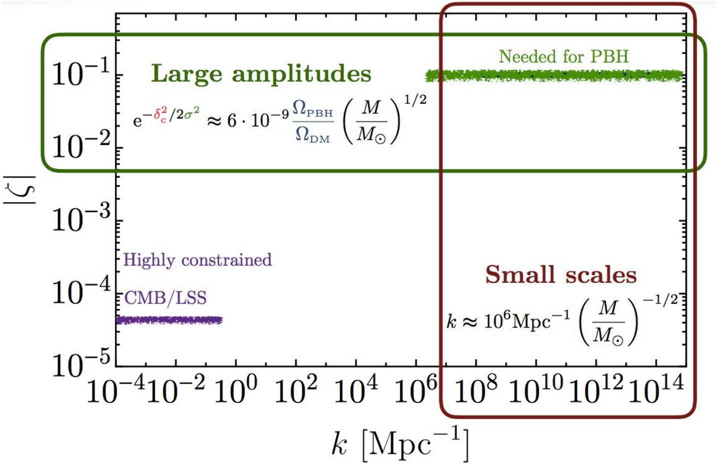
[33] Figure from G. Franciolini, arXiv:2110.06815 [astro-ph.CO].

Amplitude required to form significant number of PBHs



In order to form significant number of primordial black holes (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[34].

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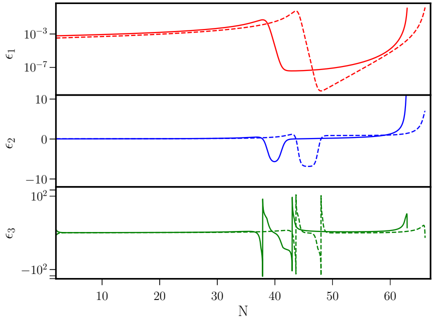
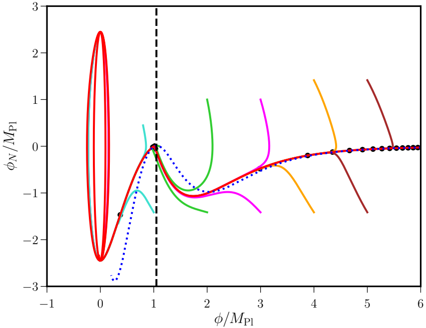
[34] Figure credit G. Franciolini.

Single-field models permitting ultra slow roll inflation





Potentials leading to ultra slow roll inflation (with $x=\phi/v$, v being a constant)[35]:

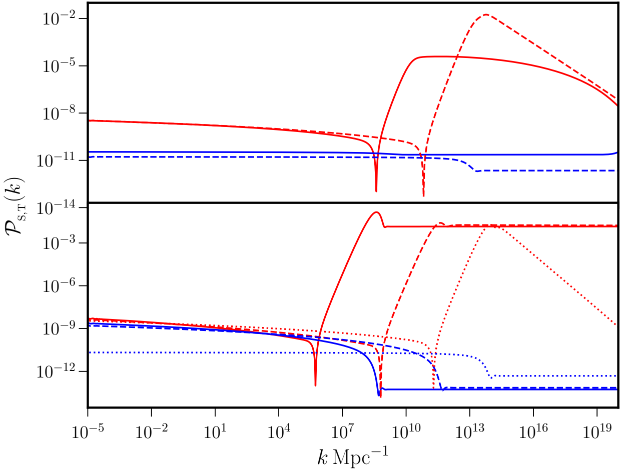
$$\mathrm{USR1}:\ V(\phi)\ =\ V_0\,\frac{6\,x^2-4\,\alpha\,x^3+3\,x^4}{(1+\beta\,x^2)^2},$$

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

---

[35] 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 of ultra slow roll inflation

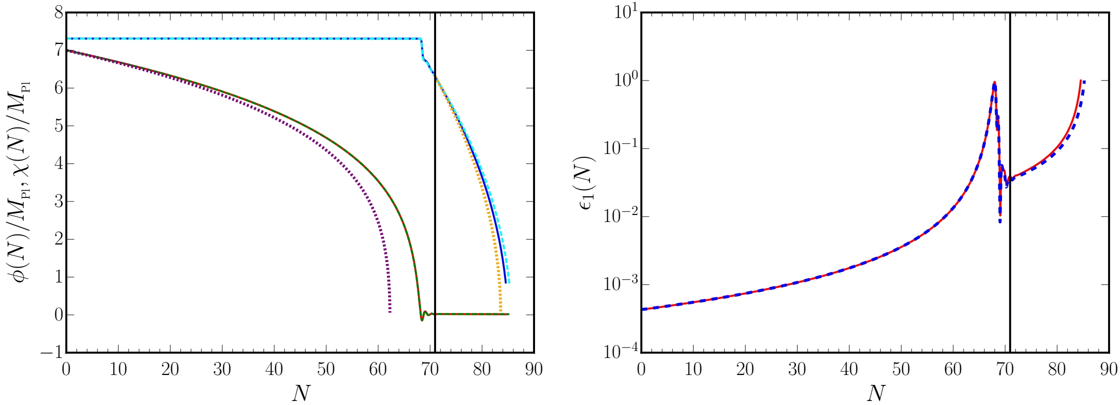


The scalar (in red) and the tensor (in blue) power spectra arising in various single field models that permit a period of ultra slow roll inflation[36].

---

[36] 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

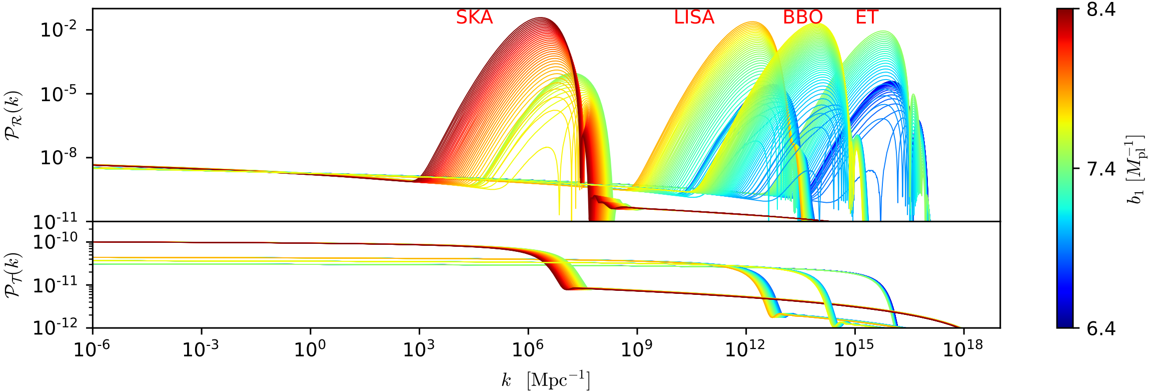


Behavior of the two scalar fields ϕ and χ (in blue and red, on the left) and the first slow roll parameter ϵ_1 (on the right) in the two field model of our interest[37]. Note that there arises a turn in the field space around $N = 70$, when the first slow roll parameter begins to decrease before increasing again, leading to the termination of inflation.

---

[37] 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

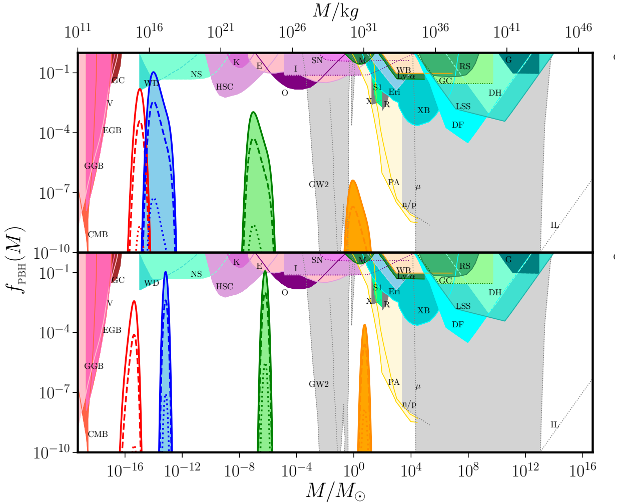


The scalar (on top) and the tensor (at the bottom) power spectra evaluated at the end of inflation have been plotted for a few different sets of initial conditions for the fields and a range of values of a particular parameter[38].

---

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

$f_{\rm PBH}(M)$ in models of ultra slow roll inflation

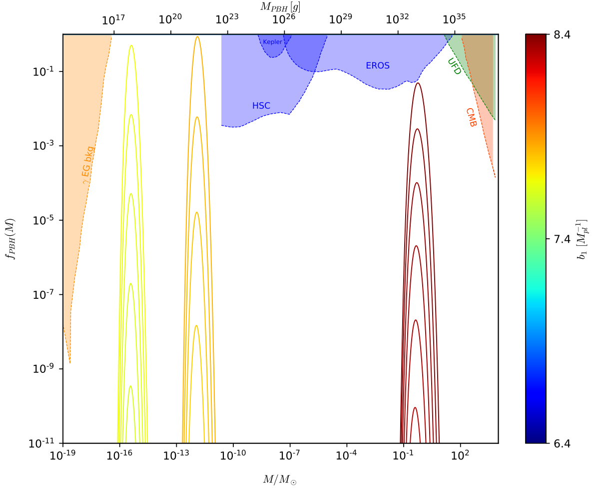


The fraction of PBHs contributing to the dark matter density today $f_{\rm PBH}(M)$ has been plotted for different models and scenarios of interest[39].

---

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

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

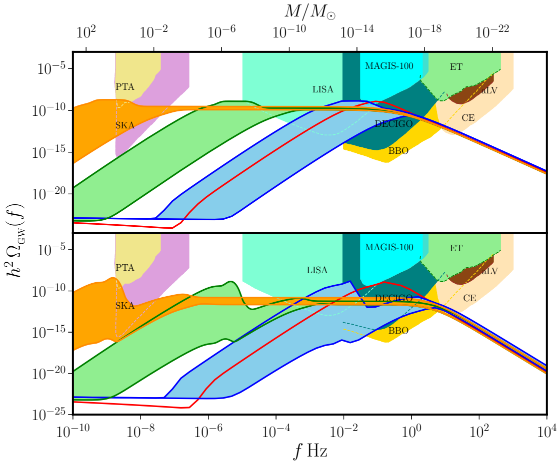


The fraction of PBHs contributing to the dark matter density today $f_{\rm PBH}(M)$ in the two-field model of our interest[40].

---

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

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

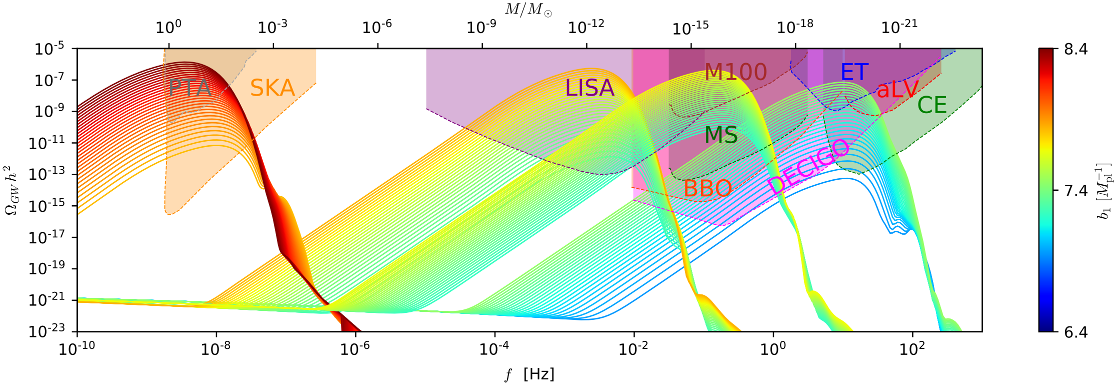


The dimensionless density parameter $\Omega_{\rm GW}$ arising in the models and reconstructed scenarios leading to an epoch of ultra slow roll inflation has been plotted as a function of the frequency f[41].

---

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

$\Omega_{\rm GW}(f)$ 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[42].

---

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

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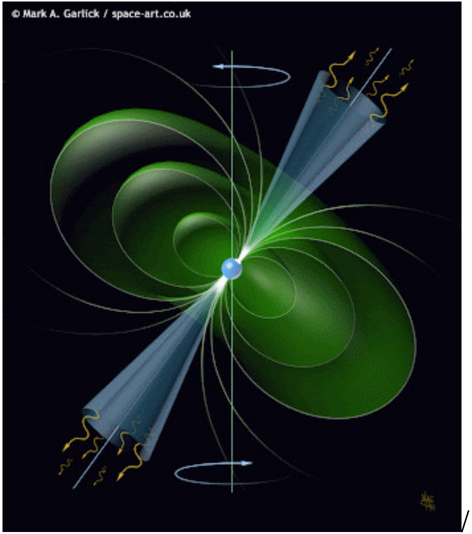
Pulsars



Pulsars are dense and rotating neutron stars that emit regular beams of light[43].

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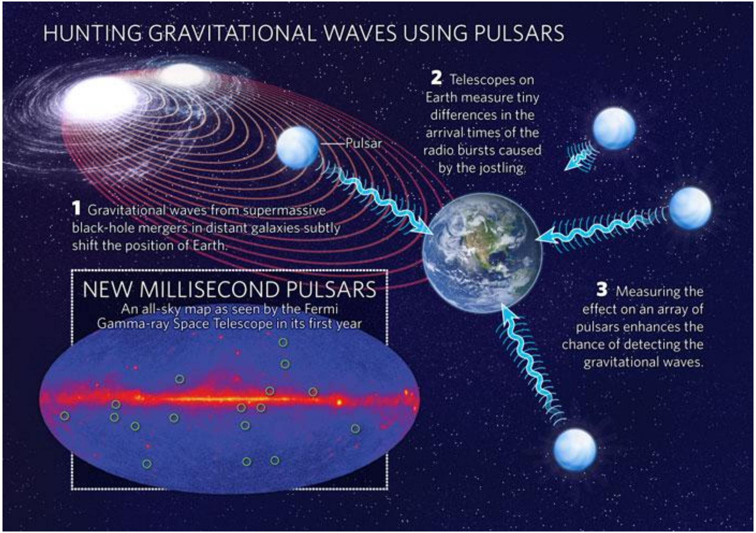
[43] Image from https://dmr-astronomersclub.blogspot.com/2012/07/what-is-pulsar.html.

Pulsar timing arrays (PTAs)



The PTAs monitor an array of millisecond pulsars[44].

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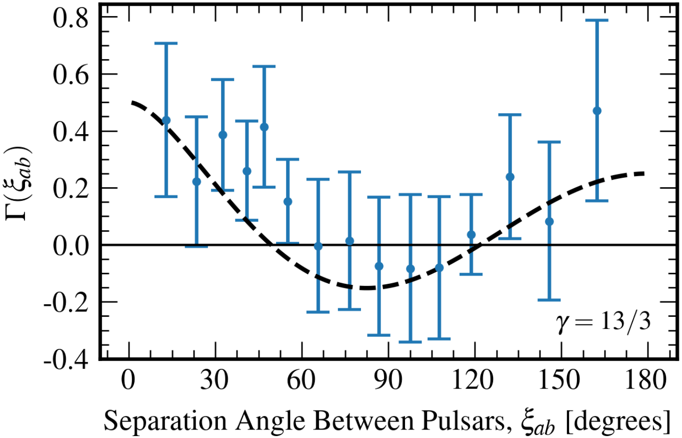
[44] See https://ipta.github.io/mock_data_challenge/.

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[45].

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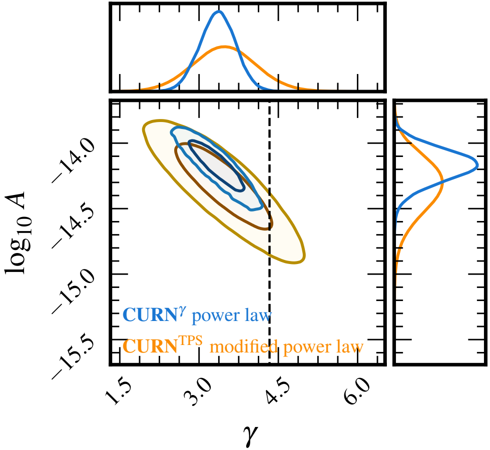
[45] NANOGrav Collaboration (G. Agazie *et al.*), Astrophys. J. Lett. **951**, 1 (2023).

Constraints on the spectral amplitude and index of GWs

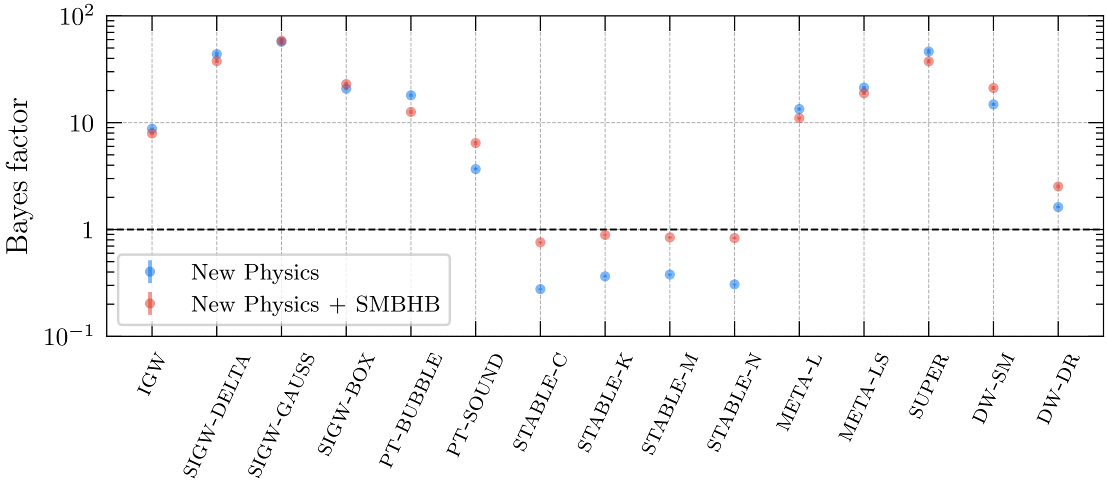


Constraints on the amplitude A and the index γ of the stochastic background of GWs from the NANOGrav 15-year data[46].

---

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

Stochastic GW background observed by pulsar timing arrays (PTAs)

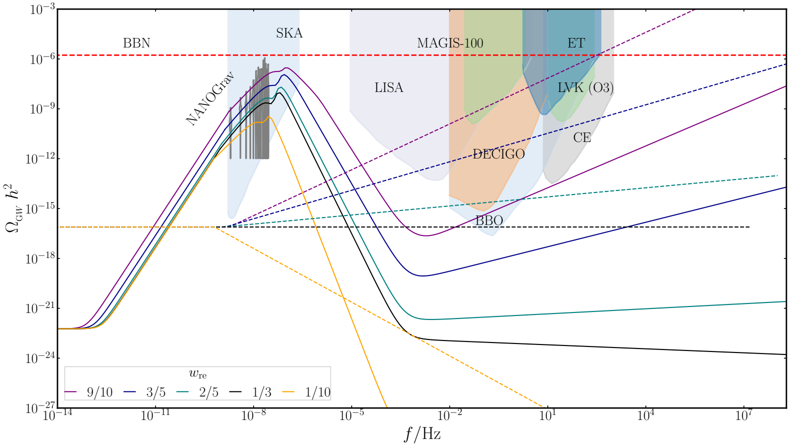


The Bayesian evidence for a variety of astrophysical and cosmological sources for the stochastic GW background suggested by the observations of the PTAs[47].

---

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

Generation of secondary GWs during the epoch of reheating



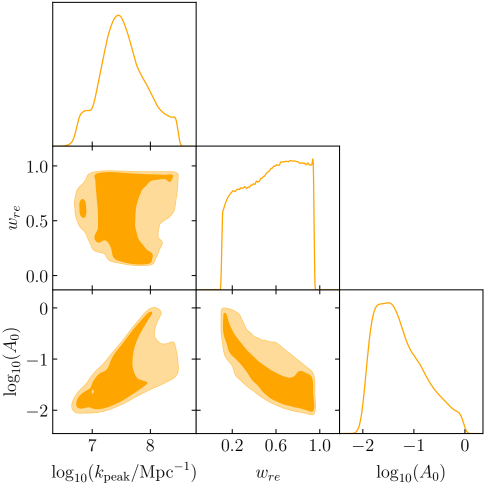
▸ Epoch of reheating

The dimensionless spectral energy density of primary and secondary GWs today $\Omega_{\rm GW}(f)$ have been plotted for a given reheating temperature and different values of the parameter describing the equation of state during reheating[48].

---

[48] S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, in preparation.

Constraints on the epoch of reheating

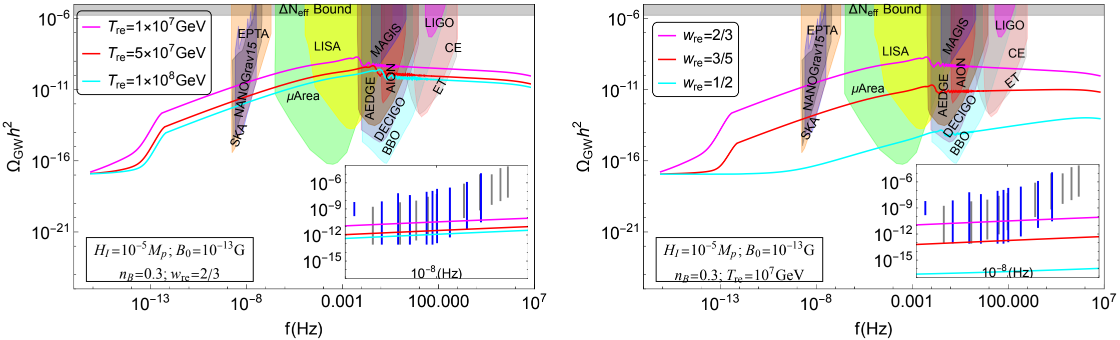


Constraints on the parameters describing the primordial scalar power spectrum and the epoch of reheating, arrived at upon comparison with the NANOGrav 15-year data[49].

---

[49] 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 $\Omega_{\rm GW}(f)$, 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)[50].

---

[50] S. Maiti, D. Maity and L. Sriramkumar, arXiv:2401.01864 [astro-ph.CO].

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Outlook

- The increasingly precise observations of the CMB by future missions such as Lite-BIRD (Lite, 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 (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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George Smoot

Alexei Starobinsky

Pankaj Saha

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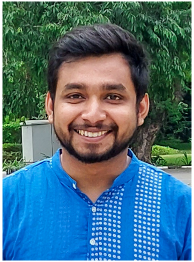
Joseph Silk

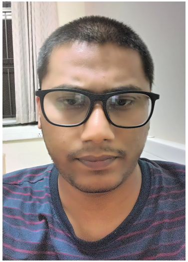

Md. Riajul Haque


Debaprasad Maity


Tanmoy Paul


Subhasis Maiti


Suvashis Maity


Nilanjandev Bhaumik

Thank you for your attention