Decoding the mysteries of the early universe

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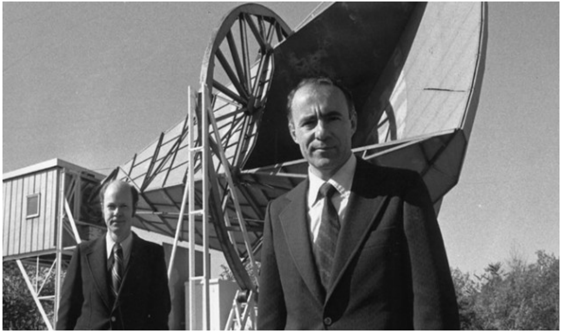
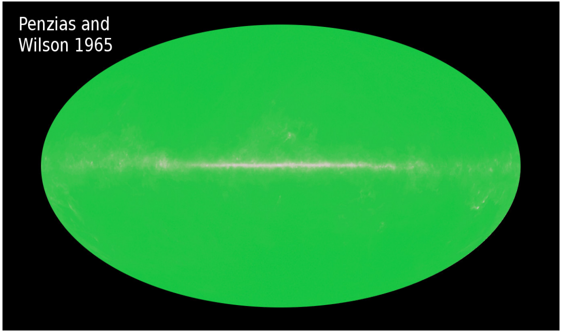
Plan of the talk

1. The cosmic microwave background (CMB)
2. The need for inflation
3. Constraints on inflation from Planck
4. Enhancing power on small scales
5. Implications for PBH formation and secondary GWs
6. Imprints of reheating on primary GWs
7. Outlook

Plan of the talk

Discovery of the CMB[1]



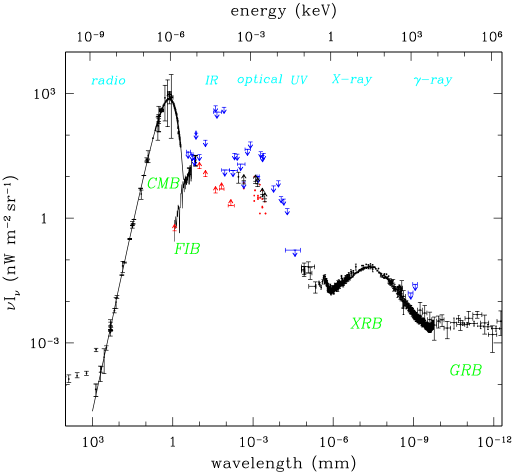


The horn antenna used by Penzias and Wilson (on the left) and the CMB as observed by them (on the right).

Anisotropies observed by COBE

[1] In this context, see, for instance, S. G. Brush, Sci. Am. **267**, 62 (1992).

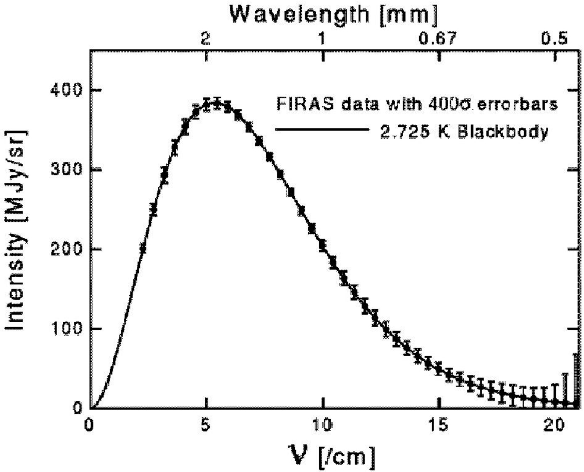
Spectrum of radiation in the universe



The spectral energy density of the cosmological background radiation has been plotted as a function of wavelength[2]. Note that the CMB contributes the most to the overall background radiation.

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

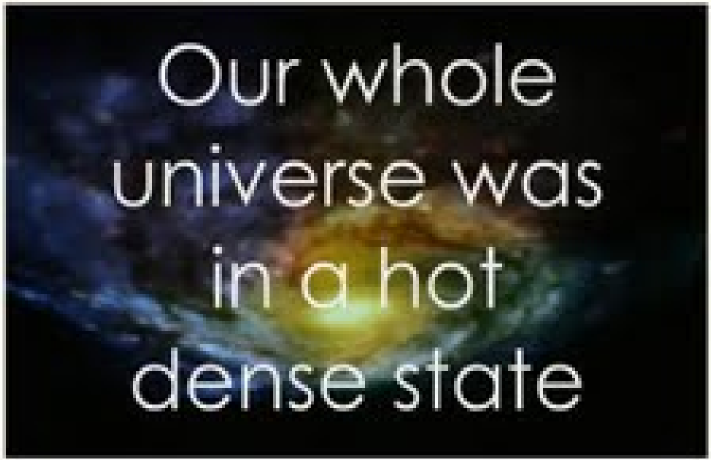
Thermal nature of the CMB



The spectrum of the CMB as measured by the COBE satellite[3]. It is a perfect Planck spectrum (corresponding to a temperature of 2.725° K) which is unlikely to be bettered in the laboratory. The error bars have been amplified 400 times so that they are visible!

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

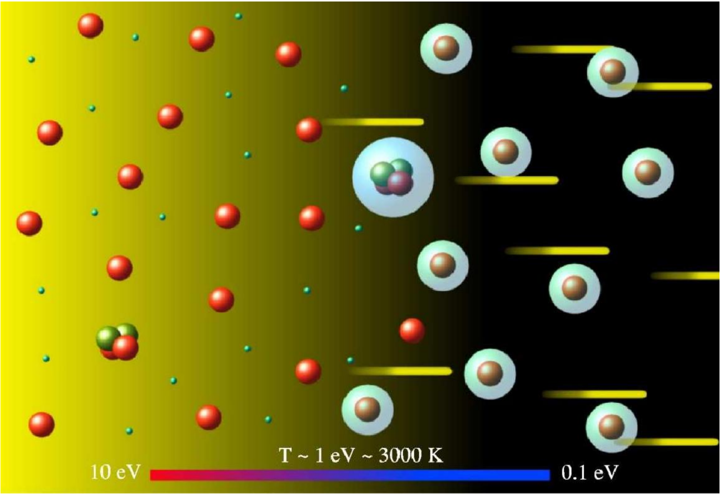
The big bang model seems popular!



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]!

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

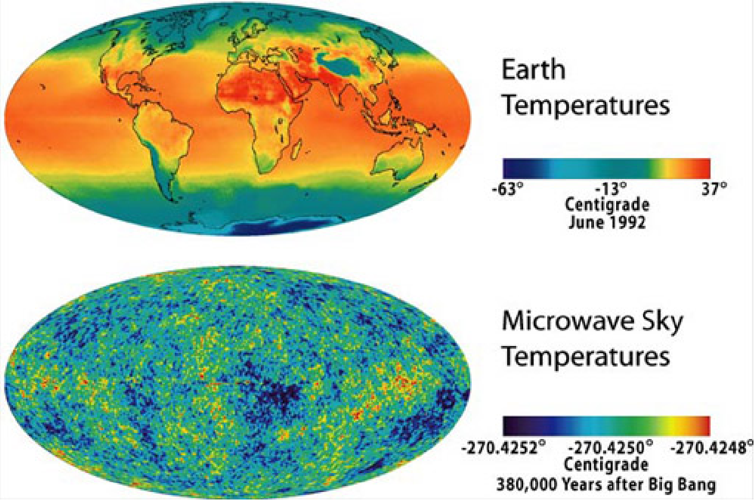
Decoupling of matter and radiation[5]



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

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

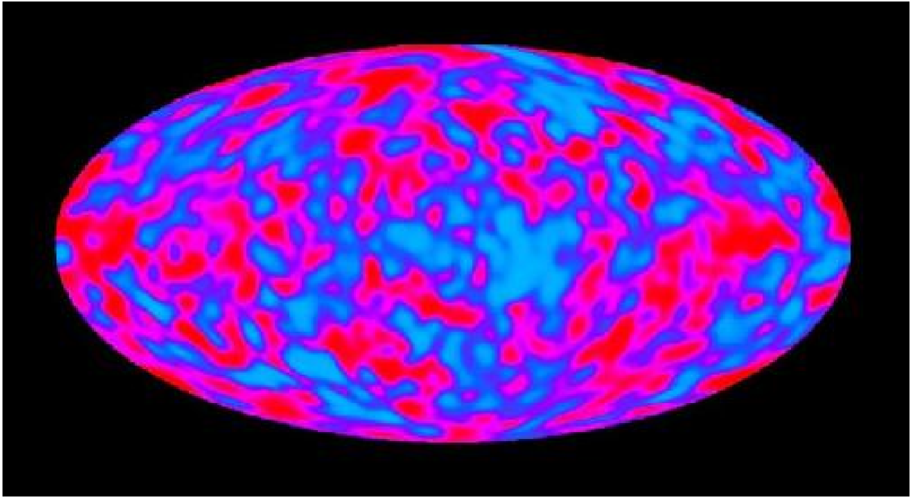
Projecting the last scattering surface



The temperature of the CMB on the last scattering surface can be projected on to a plane as the surface of the Earth is often projected[6].

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

Anisotropies in the CMB, as observed by COBE

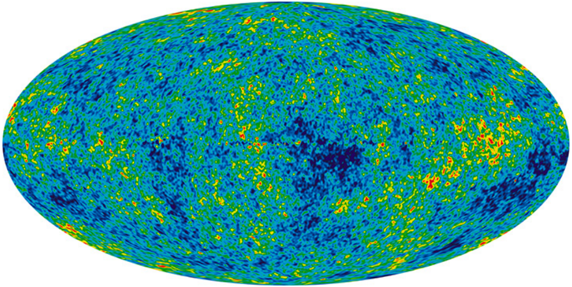


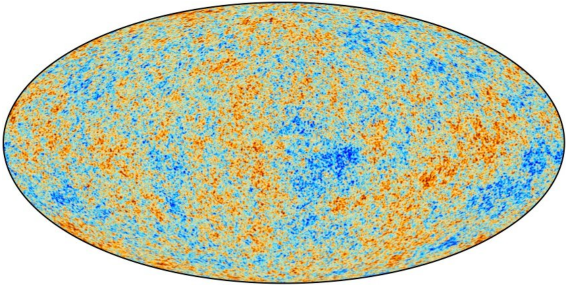
The fluctuations in the temperature of the CMB as seen by the COBE satellite[7]. The CMB turns out to be isotropic to one part in 10^5.

The smooth CMB

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

CMB anisotropies as seen by WMAP and Planck





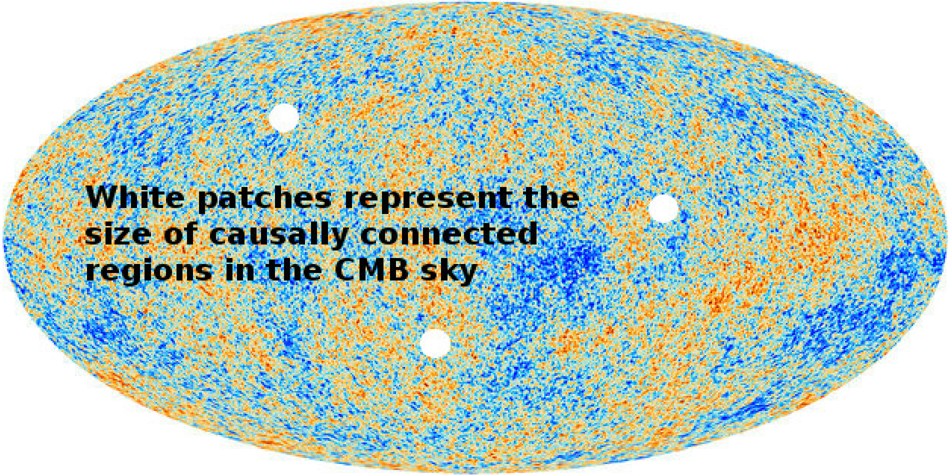
Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[8].
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[9]. The above images show temperature variations (as color differences) of the order of $200^{\circ}\,\mu\mathrm{K}$. These temperature fluctuations represent the seeds of all the structure around us today.

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

[9] Planck Collaboration (R. Adam *et al.*), Astron. Astrophys. **594**, A1 (2016).

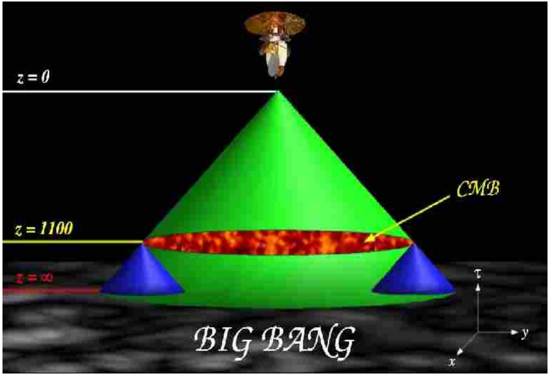
Plan of the talk

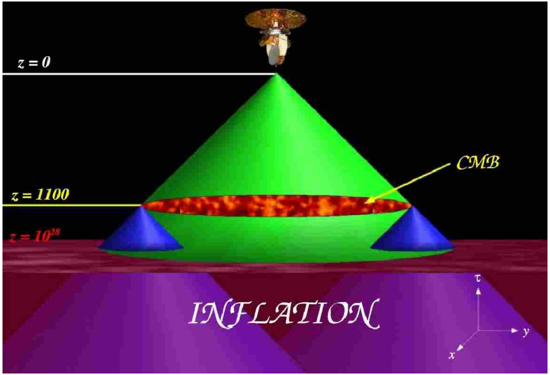
The horizon problem



The radiation from the CMB arriving at us from regions separated by more than the Hubble radius at the last scattering surface, which subtends an angle of about 1° today, could not have interacted before decoupling.

The resolution of the horizon problem in the inflationary scenario

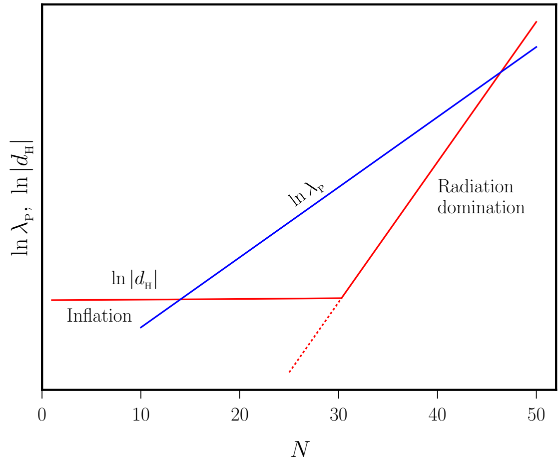




Another illustration of the horizon problem (on the left), and an illustration of its resolution (on the right) through an early and sufficiently long epoch of inflation[10].

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

Bringing the modes inside the Hubble radius

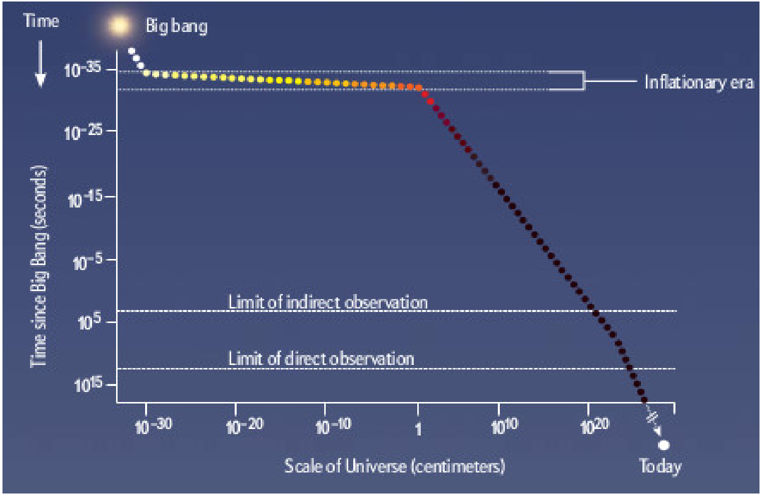


Evolution of comoving lengths

The physical wavelength $\lambda_{\mathrm{P}} \propto a$ (in blue) and the Hubble radius $d_{\mathrm{H}} = H^{-1}$ (in red) in the inflationary scenario[11]. The scale factor is expressed in terms of e-folds N as $a(N) \propto \mathrm{e}^N$.

[11] See, for example, E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley Publishing Company, New York, 1990), Fig. 8.4.

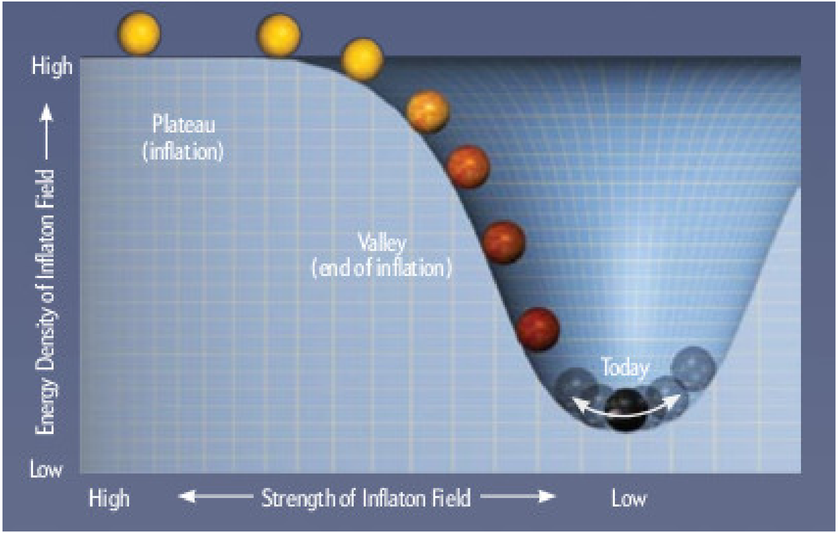
The time and duration of inflation



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

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

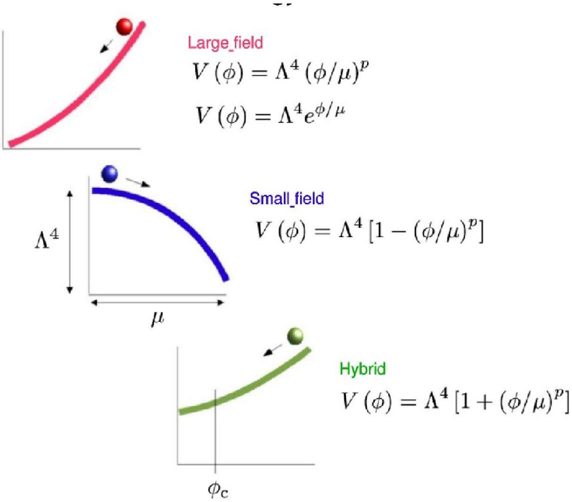
Driving inflation with scalar fields



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

[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]. Often, these potentials are classified as small field, large field and hybrid models.

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

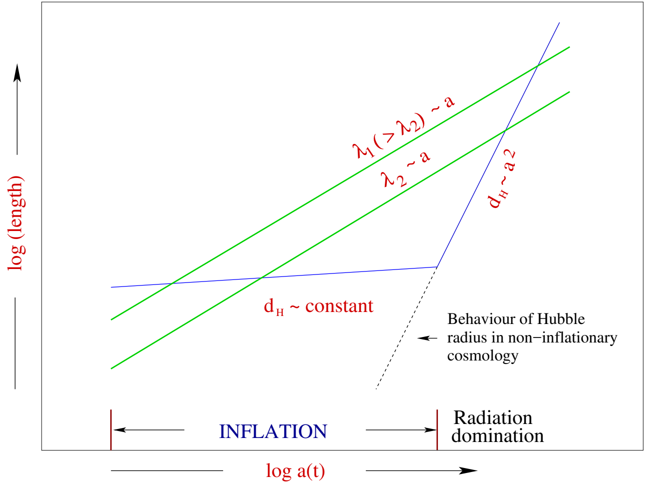
Proliferation of inflationary models

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 inflatior
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!

[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).

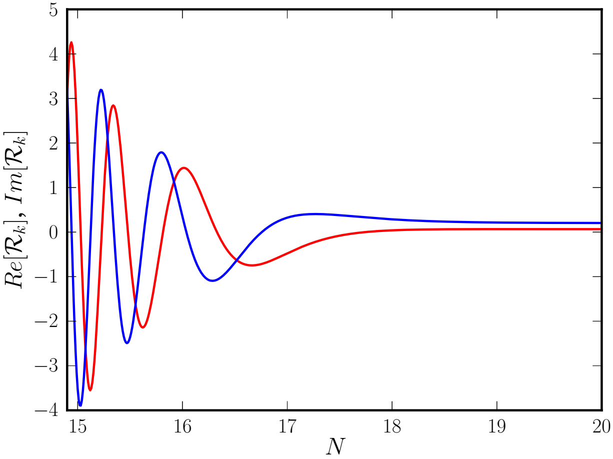
From inside the Hubble radius to super-Hubble scales



Back to formation of PBHs

The initial conditions are imposed in the sub-Hubble regime when the modes are well inside the Hubble radius (*viz.* when $k/(a\,H) \gg 1$) and the power spectra are evaluated when they sufficiently outside (*i.e.* as $k/(a\,H) \ll 1$).

Typical evolution of the perturbations



Typical evolution of the real and the imaginary parts of the scalar modes during slow roll inflation. The mode considered here leaves the Hubble radius at about 18 e-folds[16].

[16]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 for the scalar and the tensor spectra:

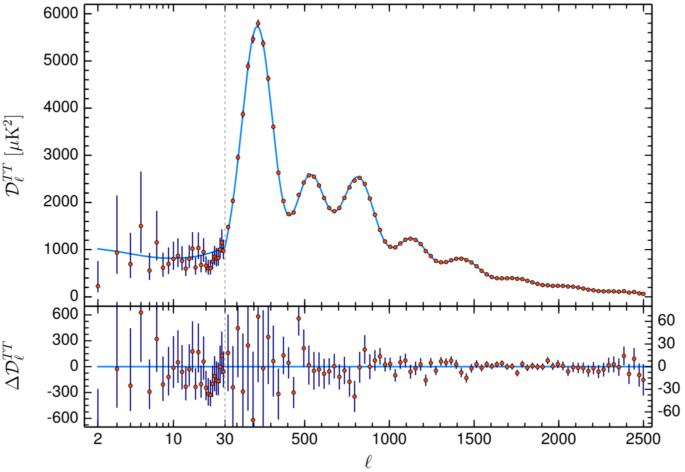
$$\mathcal{P}_{_{\mathrm{S}}}(k) = A_{_{\mathrm{S}}}\,\left(\frac{k}{k_*}\right)^{n_{_{\mathrm{S}}}-1}, \qquad \mathcal{P}_{_{\mathrm{T}}}(k) = A_{_{\mathrm{T}}}\,\left(\frac{k}{k_*}\right)^{n_{_{\mathrm{T}}}},$$

where the spectral indices $n_{_{\mathrm{S}}}$ and $n_{_{\mathrm{T}}}$ are assumed to be constant. The tensor-to-scalar ratio r is defined as

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

Plan of the talk

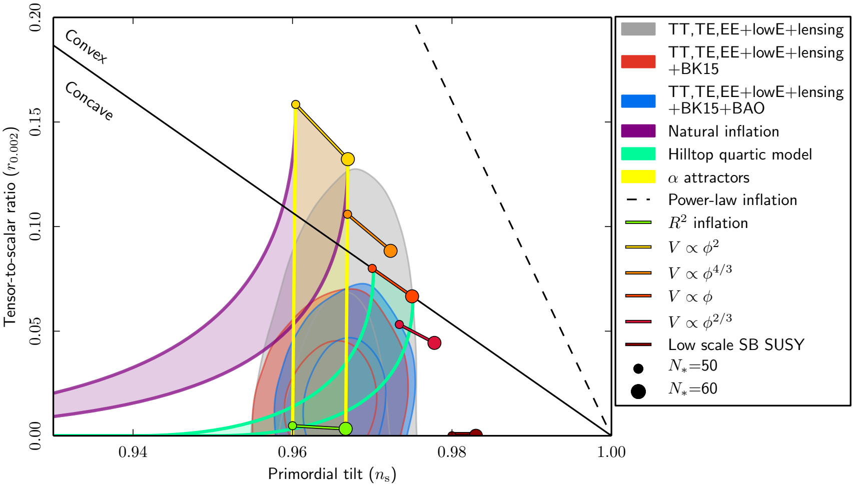
CMB angular power spectrum from Planck



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



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[18].

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

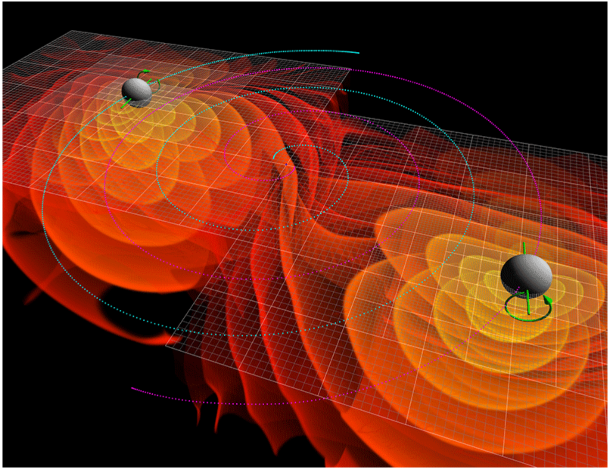
Plan of the talk

Laser interferometer gravitational wave observatory (LIGO)

Views of the 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[19].

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

Radiation from inspiralling binary black holes (BHs)

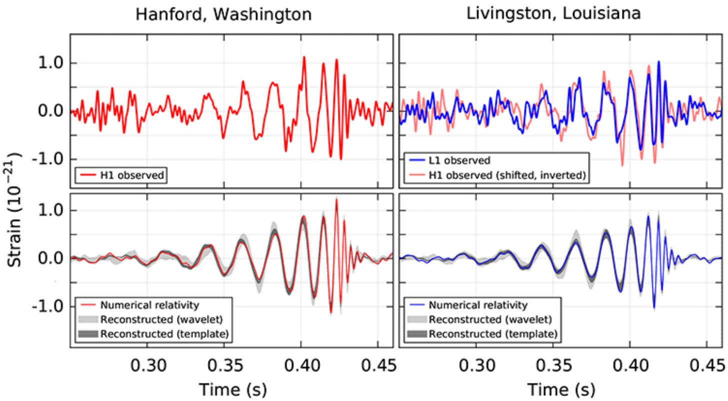


Play movie

Numerical simulations of gravitational waves (GWs) emitted due to the coalescence of two BHs. The figure illustrates the amplitude of the emitted GWs (as orange contours), the orbits of the BHs (as blues lines) and their spins (as green arrows)[20].

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

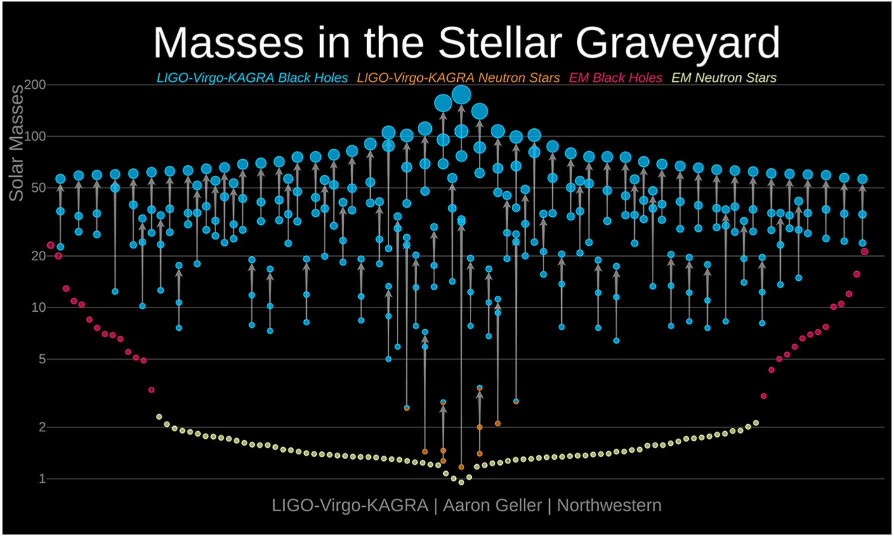
Signals of a binary BH merger at the two LIGO detectors



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, obtained from numerical simulations[21].

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

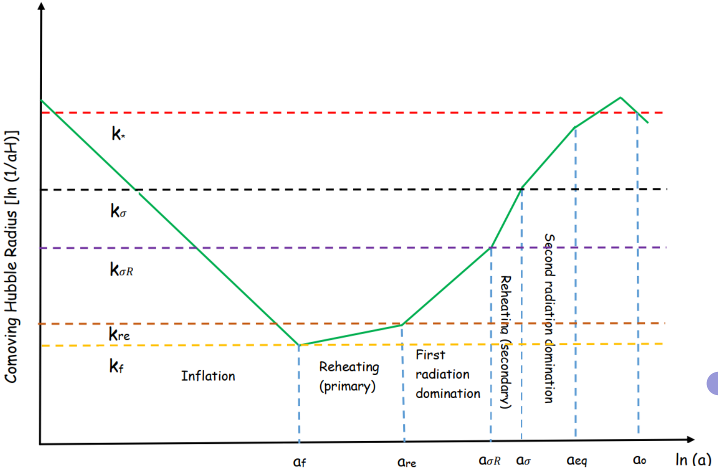
Catalog of merging compact objects



A catalog of close to a hundred merging compact binaries[22].

[22]Figure from https://cns.utexas.edu/news/new-gravitational-wave-catalog-reveals-black-holes-of-all-shapes-and-sizes.

Behavior of the comoving wave numbers and Hubble radius

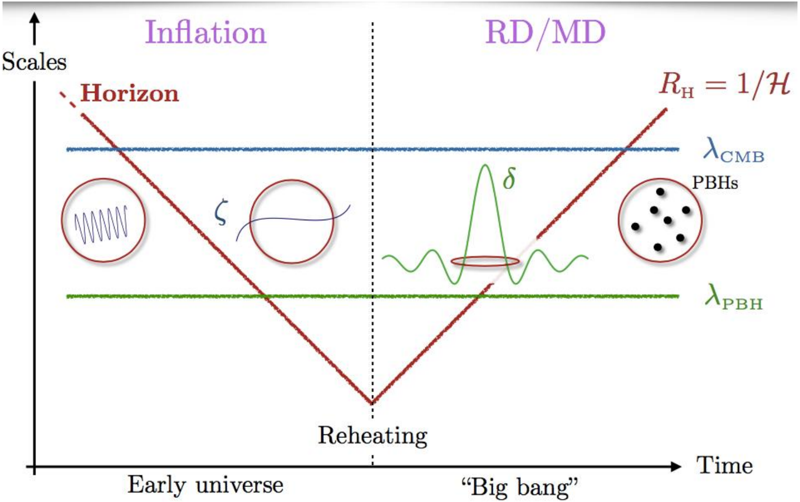


Evolution of physical lengths
Back to reheating

Behavior of the comoving wave numbers k (horizontal lines in different colors) and the comoving Hubble radius $d_{\mathrm{H}}/a = (a\,H)^{-1}$ (in green) across different epochs[23].

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

Formation of BHs in the early universe

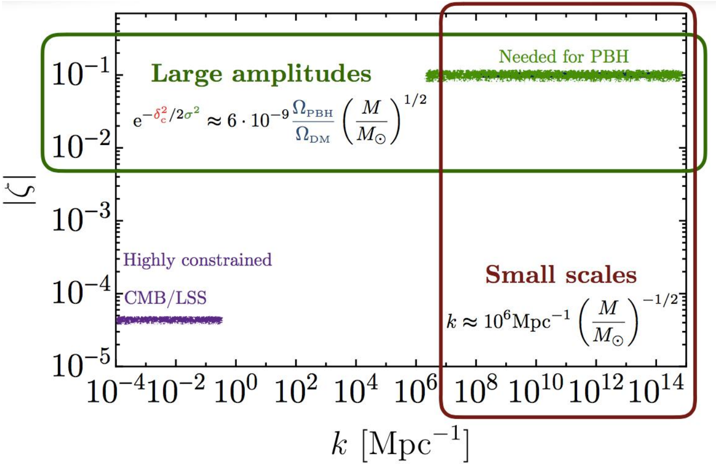


Back to $f_{\rm PBH}$

Primordial black holes (PBHs) can form when perturbations with significant amplitudes reenter the Hubble radius during the radiation dominated epoch[24].

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

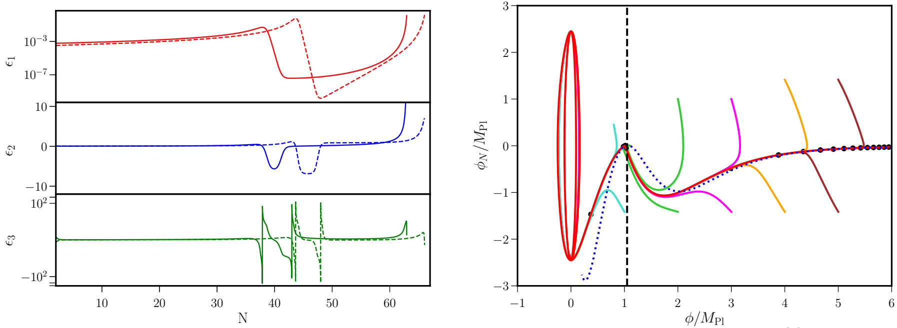
Amplitude required to form significant number of PBHs



In order to form significant number of BHs, 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[25].

[25] Figure credit G. Franciolini.

Potentials admitting ultra slow roll inflation



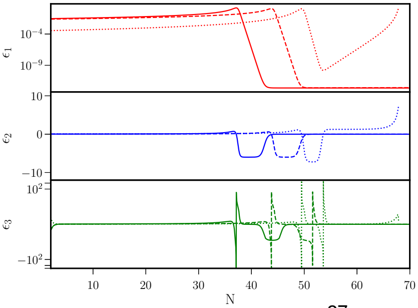
Potentials leading to ultra slow roll inflation (with $x = \phi/v$, v being a constant)[26]:

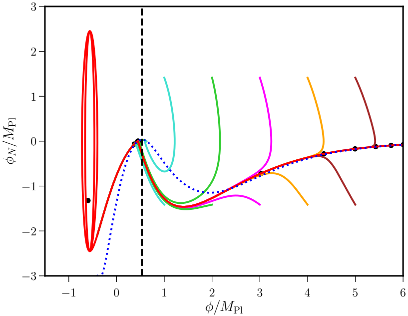
$$\mathrm{USR1}: V(\phi) = V_0 \, \frac{6\,x^2 - 4\,\alpha\,x^3 + 3\,x^4}{(1+\beta\,x^2)^2},$$

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

[26] J. Garcia-Bellido and E. R. Morales, Phys. Dark Univ. **18**, 47 (2017); I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019).

Potentials permitting punctuated inflation





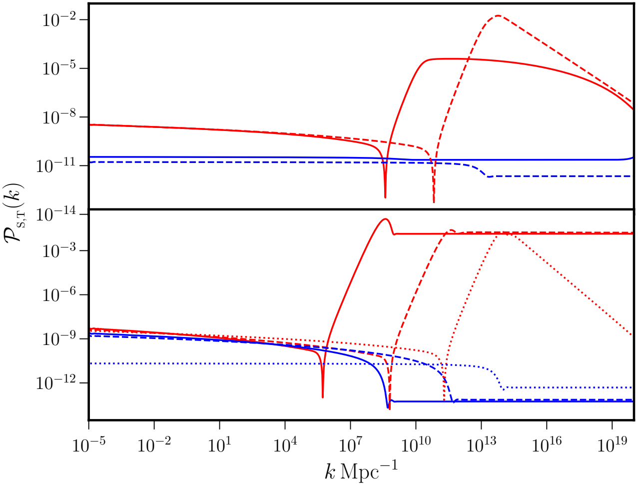
Potentials admitting punctuated inflation[27]:

$$\mathrm{PI1}: V(\phi) = V_0\,\left(1+B\,\phi^4\right), \quad \mathrm{PI2}: V(\phi) = \frac{m^2}{2}\,\phi^2 - \frac{2\,m^2}{3\,\phi_0}\,\phi^3 + \frac{m^2}{4\,\phi_0^2}\,\phi^4,$$

$$\mathrm{PI3}: V(\phi) = V_0\,\left[c_0 + c_1\,\tanh\left(\frac{\phi}{\sqrt{6\,\alpha}\,M_{\rm Pl}}\right) + c_2\,\tanh^2\left(\frac{\phi}{\sqrt{6\,\alpha}\,M_{\rm Pl}}\right) + c_3\,\tanh^3\left(\frac{\phi}{\sqrt{6\,\alpha}\,M_{\rm Pl}}\right)\right]^2.$$

[27] D. Roberts, A. R. Liddle and D. H. Lyth, Phys. Rev. D **51**, 4122 (1995);
R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **01**, 009 (2009);
I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019).

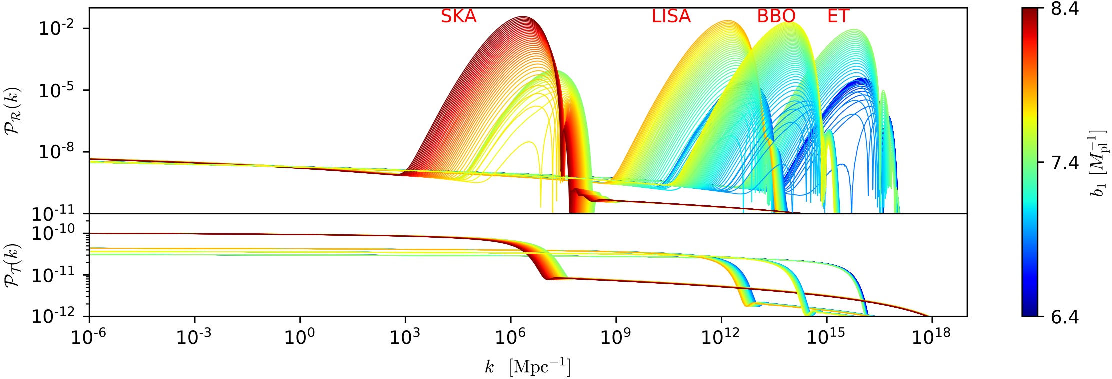
Power spectra in ultra slow roll and punctuated inflation



The scalar (in red) and the tensor (in blue) power spectra arising in the various inflationary models[28].

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

Enhanced power on small scales in two field models



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 the parameter b_1[29].

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

Plan of the talk

Time scale of evaporation of PBHs

Recall that BHs of mass M emit Hawking radiation which is thermal in nature, with the temperature

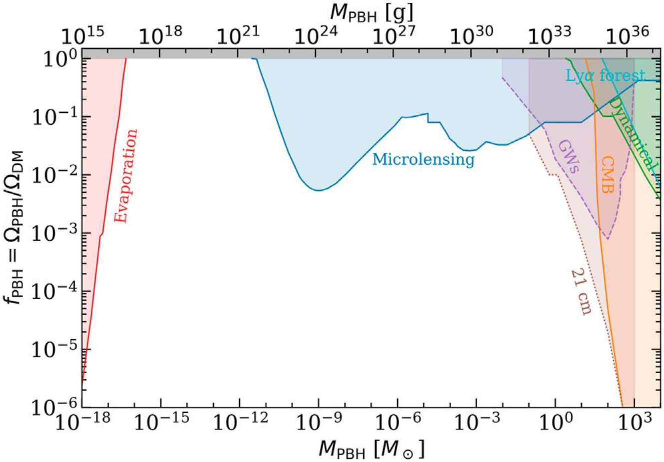
$$k_{\rm B}\, T = \frac{\hbar\, c^3}{4\,\pi\, M}.$$

These BHs will evaporate over a time scale of

$$t_{\rm ev} = \frac{60\, G^2\, M^3}{\pi^3\, \hbar\, c^4}\, \left(\frac{M}{M_\odot}\right)^3 = 2.5 \times 10^{63}\, \left(\frac{M}{M_\odot}\right)^3\, {\rm yrs.}$$

This implies that PBHs with mass $M \lesssim 10^{-18}\, M_\odot$ would have evaporated by now.

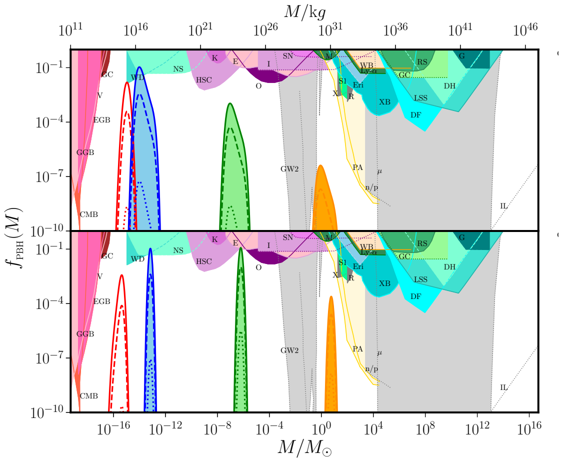
Constraints on $f_{\rm PBH}(M)$



Observational constraints on the quantity $f_{\rm PBH}(M)$, i.e. the fractional energy density of PBHs that constitute cold dark matter today[30].

[30] P. Villanueva-Domingo, O. Mena and S. Palomares-Ruiz, Front. Astron. Space Sci. **8**, 681084 (2021);
For latest constraints, see https://github.com/bradkav/PBHbounds/blob/master/README.md.

$f_{\rm PBH}(M)$ in ultra slow roll and punctuated inflation

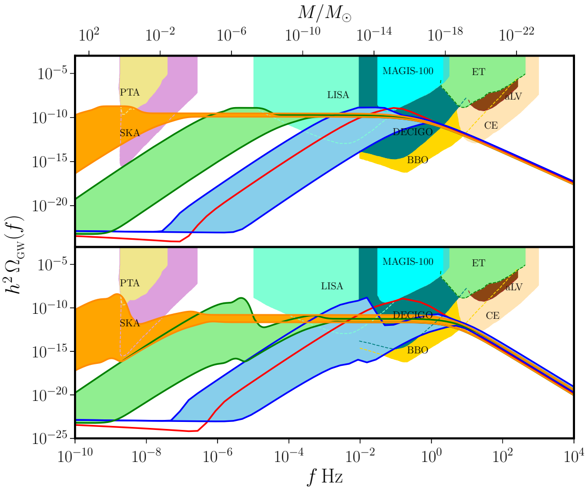


Formation of PBHs

The fraction of PBHs contributing to the dark matter density today $f_{\rm PBH}(M)$ has been plotted for the different models of interest, viz. USR2 (on top, in red) and PI3 (at the bottom, in red)[31].

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

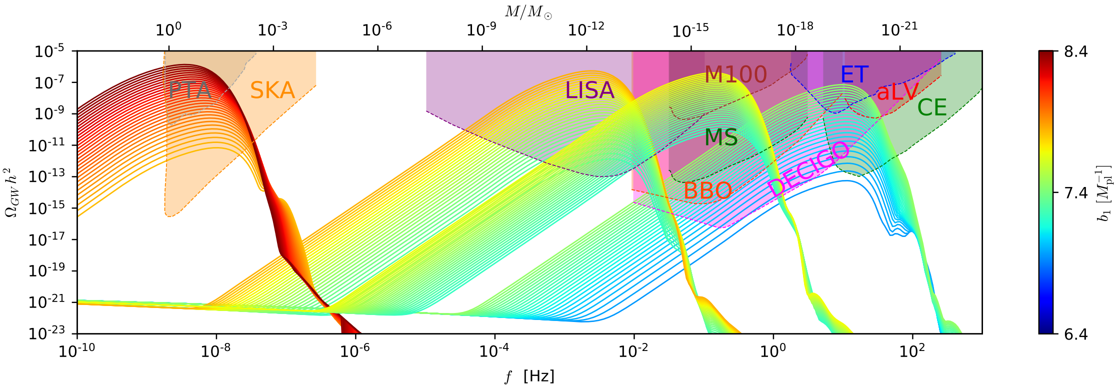
$\Omega_{\rm GW}(f)$ in ultra slow roll and punctuated inflation



The dimensionless spectral energy density of GWs $\Omega_{\rm GW}$ arising in the models of USR2 (in red, on top) and PI3 (in red, at the bottom) has been plotted as a function of the frequency f[32].

[32] 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

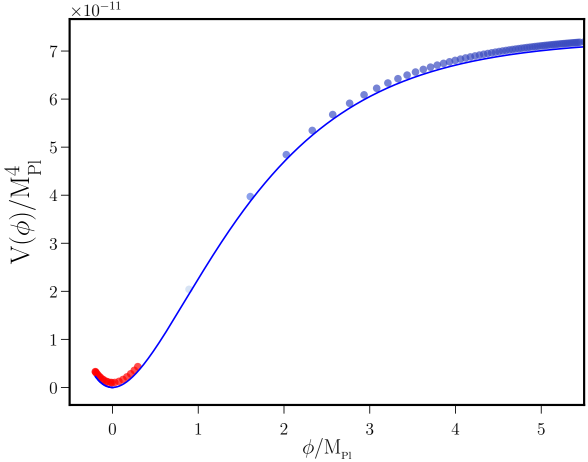


The dimensionless spectral energy density of GWs $\Omega_{\rm GW}(f)$ arising in the two field model has been plotted for a set of initial conditions for the background fields as well as a range of values of the parameter b_1[33].

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

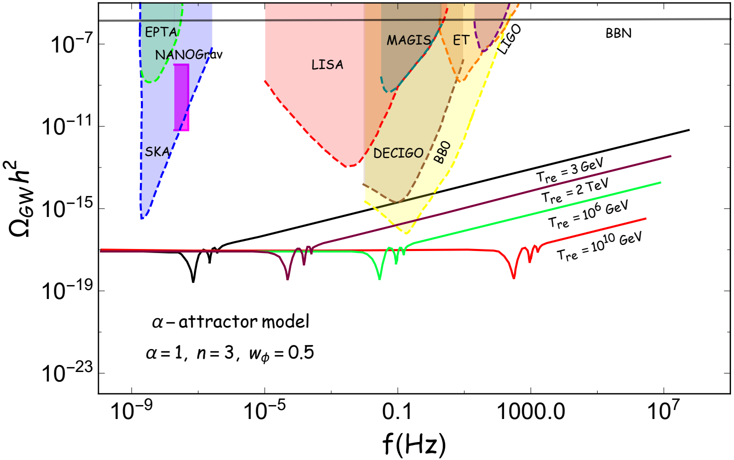
Plan of the talk

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 $\Omega_{\rm GW}(f)$ due to reheating

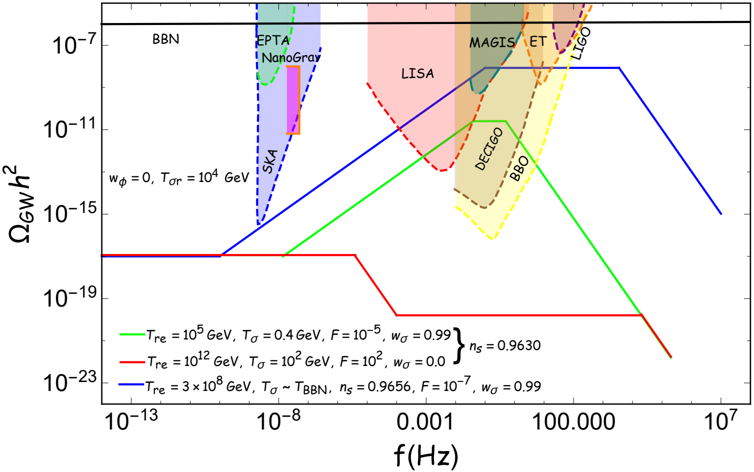


The behavior of the dimensionless spectral energy density of *primary* GWs today, viz. $\Omega_{\rm GW}(f)$, has been plotted over a wide range of frequencies for different reheating temperatures (in red, green, brown and black)[34].

Evolution of comoving lengths

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

Effects on $\Omega_{\rm GW}(f)$ due to late time entropy production



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.

Plan of the talk

Outlook

The measurements of the anisotropies in the CMB on large scales and the sensitivity of the ongoing and forthcoming GW observatories on small scales provide a wide lever arm to help us constrain the physics operating in the early universe.

Thank you for your attention