Probing the physics of the early universe

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Thanu Padmanabhan Memorial Lecture, 35th Kerala Science Congress

Mar Baselios Christian College of Engineering and Technology, Kuttikkanam, Idukki

February 10–14, 2023

Plan of the talk

1. Thanu Padmanabhan: Brief personal and academic history
2. The need for inflation
3. Constraints on inflation from Planck
4. Enhancing power on small scales
5. Implications for formation of PBHs and generation of secondary GWs
6. Imprints of reheating on primary GWs
7. Summary

Plan of the talk

Personal history[1]

- Date of birth: March 10, 1957
- Place of birth: Thiruvananthapuram
- Parents: Lakshmi and Thanu Iyer
- Thanu Iyer worked in the forest department of the Government of Kerala

Paddy's parents.

Back

Paddy in September 2021

[1] Photos from Mathrubhumi (Malayalam Weekly), September 19, 2021.

Early education and later academic history[2]

- Early education
  - 1963–1972, I–X Standard, Government Karamana High School, Thiruvananthapuram
  - 1973–1974, Pre-degree, Government Arts College, Thiruvananthapuram
  - 1974–1977, B.Sc. Physics, University College, Thiruvananthapuram
  - 1977–1979, M.Sc. Physics, University College, Thiruvananthapuram
- Later academic history
  - 1979–1980, Doctoral student, Tata Institute of Fundamental Research, Mumbai
  - 1980–1983, Research Associate, Tata Institute of Fundamental Research, Mumbai
    Thesis supervisor: Jayant Narlikar
  - 1980–1992, Faculty, Tata Institute of Fundamental Research, Mumbai
  - 1992–2021, Faculty, Inter-University Centre for Astronomy and Astrophysics, Pune

[2] See J. S. Bagla and S. Engineer, *Prof. Padmanabhan: A personal and professional History*, in *Gravity and the Quantum*, Eds. J. S. Bagla and S. Engineer (Springer, Berlin, 2017).

Primary research interests and publications

Primary research interests of Prof. Padmanabhan:

- Quantum Theory
- Gravitation
- Cosmology and Structure Formation in the Universe

Prof. Padmanabhan published nearly 300 papers and reviews[3].

[3] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Doctoral students[4]

1. T. R. Seshadri (University of Delhi)
2. T. P. Singh (TIFR, Mumbai)
3. J. S. Bagla (IISER, Mohali)
4. L. Sriramkumar (IIT Madras)
5. K. Srinivasan (CFL, Bengaluru)
6. S. Shankaranarayanan (IIT Bombay)
7. Sunu Engineer (CEO of Embedded Computing Machines, Pune)
8. T. Roy Choudhury (NCRA, Pune)
9. Sudipta Sarkar (IIT, Gandhinagar)
10. Gaurang Mahajan (NCCS, Pune)
11. Dawood Kothawala (IIT Madras)
12. Sanved Kolekar (IIA, Bengaluru)
13. Suprit Singh (IIT, Delhi)
14. Krishna Parattu (IIT Mandi)
15. Sumanta Chakraborty (IACS, Kolkata)
16. Karthik Rajeev (IIT Bombay)

Joint students

17. Nissim Kanekar (NCRA, Pune)
18. Ali Nayeri (Chapman University, California, USA).

[4] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Books I: 1986-2006

1. J. V. Narlikar and T. Padmanabhan, *Gravity, Gauge Theories and Quantum Cosmology* (Reidel, Holland, 1986)
2. T. Padmanabhan, *Structure Formation in the Universe* (Cambridge University Press, Cambridge, England, 1993)
3. T. Padmanabhan, *Cosmology and Astrophysics through Problems* (Cambridge University Press, Cambridge, England, 1996)
4. T. Padmanabhan, *After the First Three Minutes—The Story of our Universe* (Cambridge University Press, Cambridge, England, 1998)
5. T. Padmanabhan, *Theoretical Astrophysics—Volume I: Astrophysical Processes* (Cambridge University Press, Cambridge, England, 2000)
6. T. Padmanabhan, *Theoretical Astrophysics—Volume II: Stars and Stellar Systems* (Cambridge University Press, Cambridge, England, 2001)
7. T. Padmanabhan, *Theoretical Astrophysics—Volume III: Galaxies and Cosmology* (Cambridge University Press, Cambridge, England, 2002)
8. T. Padmanabhan, *An Invitation to Astrophysics* (World Scientific, Singapore, 2006)

Books II: 2007-2019

9. T. Padmanabhan, *Quantum Themes: The Charms of the Microworld* (World Scientific, Singapore, 2009)
10. T. Padmanabhan, *Gravitation: Foundations and Frontiers* (Cambridge University Press, Cambridge, England, 2010)
11. T. Padmanabhan, *Sleeping Beauties in Theoretical Physics* (Springer, Heidelberg, 2015)
12. T. Padmanabhan, *Quantum Field Theory: The Why, What and How*, (Springer, Heidelberg, 2016)
13. T. Padmanabhan and V. Padmanabhan, *The Dawn of Science: Glimpses from History for the Curious Mind* (Springer, Heidelberg, 2019)

Awards and distinctions: 1977–2000[5]

- 1977, Gold medalist, B.Sc., Kerala University
- 1979, Gold Medalist, M.Sc., Kerala University
- 1984–1989, Young Associate of Indian Academy of Sciences
- 1984, INSA Young Scientist Award; Fifth Prize in Gravity Essay Contest (awarded by Gravity Research Foundation, USA)
- 1991, Fellow, Indian Academy of Sciences; Birla Science Prize
- 1993, Fellow, National Academy of Sciences
- 1995, Fellow, Maharashtra Academy of Sciences,
- 1996, Shanti Swarup Bhatnagar Award
- 1997, A. C. Banerji Memorial Lecture Award
- 2000, Millennium Medal (CSIR)

[5] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Awards and distinctions: 2001–2010[6]

- 2001, Fellow, Indian National Science Academy
- 2002, Sackler Distinguished Astronomer, Institute of Astronomy, Cambridge; Al-Khwarizmi International Award; Second Prize in Gravity Essay Contest
- 2003, Homi Bhabha Fellowship; Fifth Prize in Gravity Essay Contest; G. D. Birla Award for Scientific Research
- 2004, Miegunah Fellowship Award, University of Melbourne, Australia
- 2006, Third Prize in Gravity Essay Contest
- 2007, Padma Shri
- 2007, INSA Vainu-Bappu Medal
- 2008, First Prize in Gravity Essay Contest
- 2008, J. C. Bose Fellowship, Department of Science and Technology
- 2009, Infosys Science Prize in Physical Sciences, Infosys Science Foundation

[6] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Awards and distinctions: 2011–2021[7]

- 2011, Third World Academy of Sciences Prize in Physics
- 2012, Fifth Prize in Gravity Essay Contest; Fellow, Third World Academy of Sciences
- 2012–2013, Goyal Prize in Physical Sciences
- 2014, Third Prize in Gravity Essay Contest; Homi Bhabha Lecturer at UK (IoP-IPA award),
- 2018, Fourth Prize in Gravity Essay Contest
- 2019, M. P. Birla Memorial Award
- 2020, Fifth Prize in Gravity Essay Contest
- 2021, Fourth Prize in Gravity Essay Contest
- 2021, Kerala Sasthra Puraskaram (Lifetime Achievement Award of Government of Kerala)

Paddy's photo

[7] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

On the pursuit of physics

From the preface of *Sleeping Beauties in Theoretical Physics*

Theoretical physics is fun. Most of us indulge in it for the same reason a painter paints or a dancer dances—the process itself is so enjoyable! Occasionally, there are additional benefits like fame and glory and even practical uses; but most good theoretical physicists will agree that these are not the primary reasons why they are doing it. The fun in figuring out the solutions to Nature's brain teasers is a reward in itself[a].

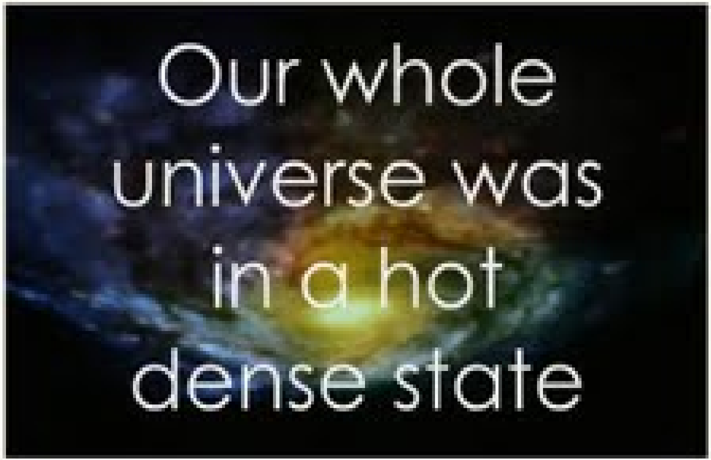
[a] T. Padmanabhan, *Sleeping Beauties in Theoretical Physics* (Springer, Heidelberg, 2015).

Paddy: A force of nature

Paddy was a *force of nature*, ‘full of energy, unstoppable, unchallengeable, and unforget-table’, much like gravitation that he strived all his life to understand.

Plan of the talk

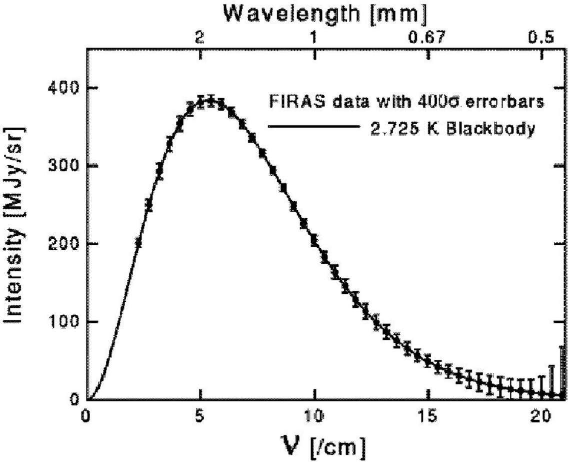
The big bang model seems popular!



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'[8]!

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

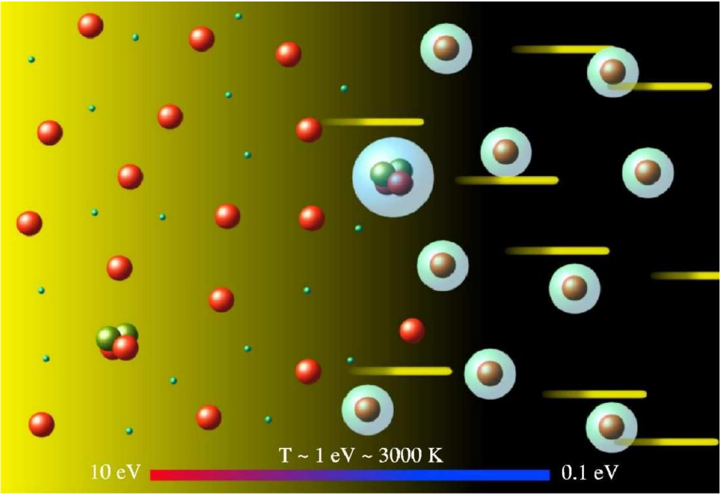
The cosmic microwave background (CMB)



The spectrum of the CMB as measured by the COBE satellite[9]. It is a perfect Planck spectrum, corresponding to a temperature of 2.725° K. The error bars have been amplified 400 times so that they are visible!

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

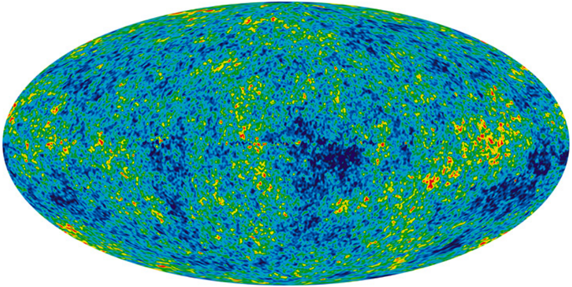
Decoupling of matter and radiation[10]

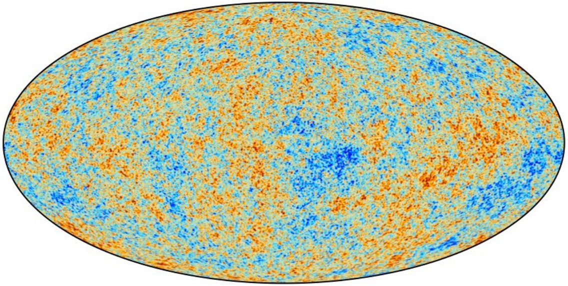


Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ$ K, which corresponds to a redshift of about $z \simeq 1000$.

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

CMB anisotropies as seen by WMAP and Planck

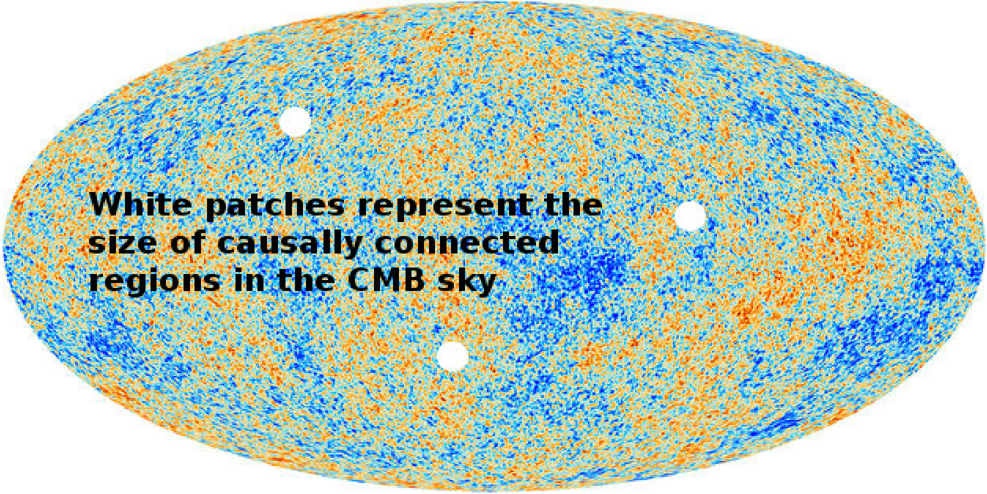




Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[11].
Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[12]. The above images show temperature variations (as color differences) of the order of $200^\circ\,\mu\mathrm{K}$.

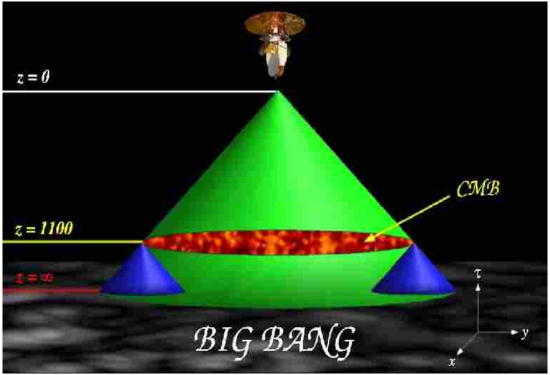
[11] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.
[12] Planck Collaboration (R. Adam *et al.*), Astron. Astrophys. **594**, A1 (2016).

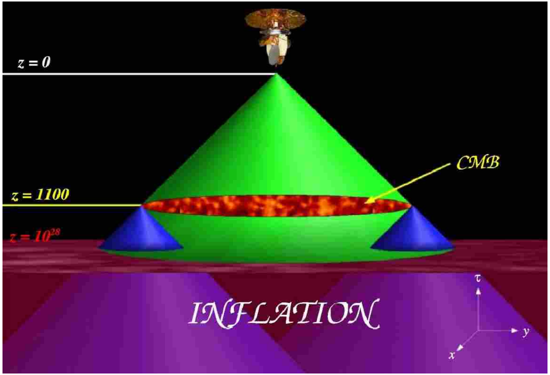
The horizon problem



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

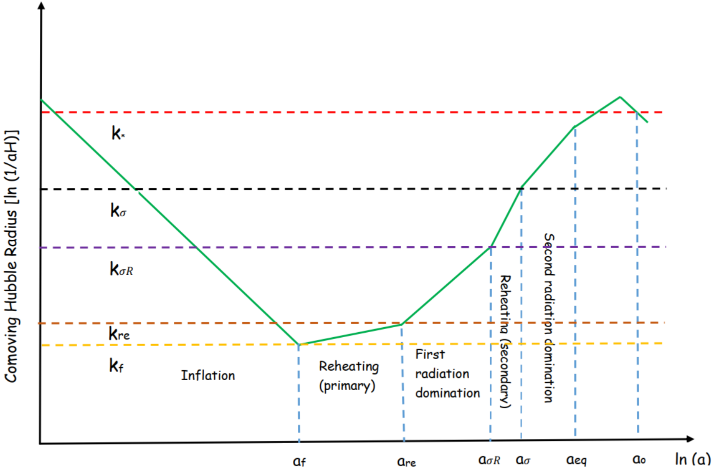




Another illustration of the horizon problem (on the left), and an illustration of its resolution (on the right) through an early and sufficiently long epoch of inflation[13].

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

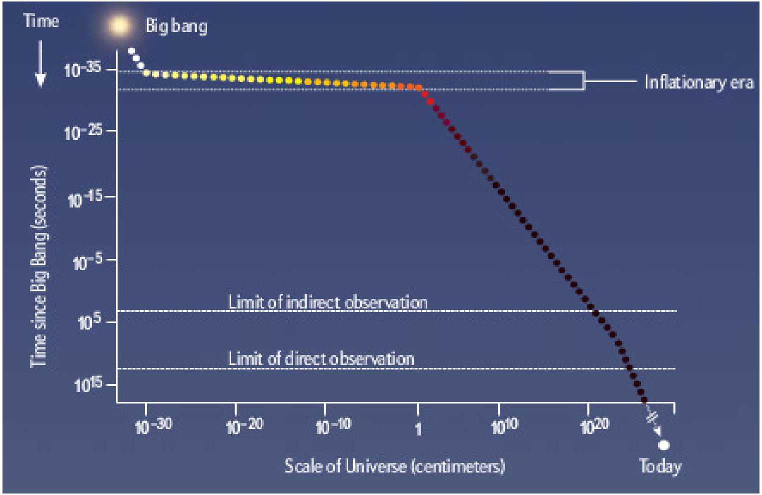
Behavior of comoving wave lengths and the Hubble radius



Behavior of the comoving wave lengths (horizontal lines in different colors) and the comoving Hubble radius $d_{\rm H}/a = (a\,H)^{-1}$ (in green) across different epochs[14].

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

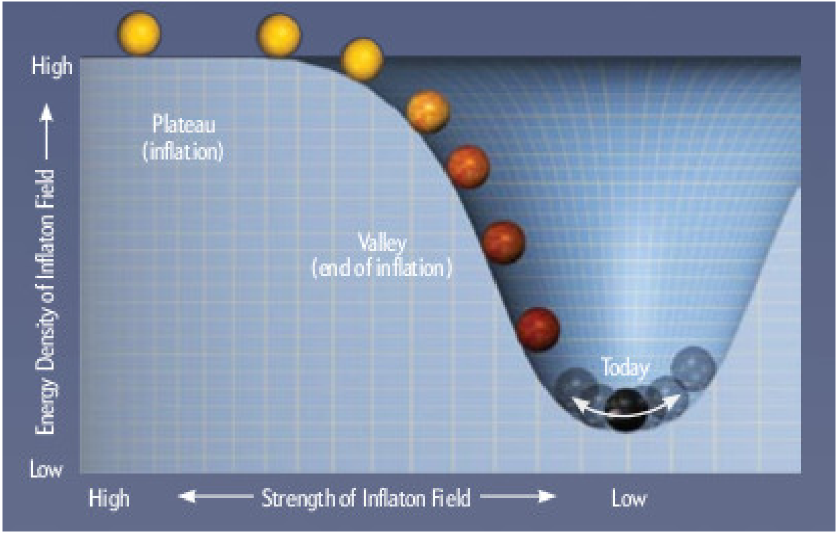
The time and duration of inflation



Inflation – a brief period of accelerated expansion – is expected to have taken place during the very stages of the universe[15].

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

Driving inflation with scalar fields

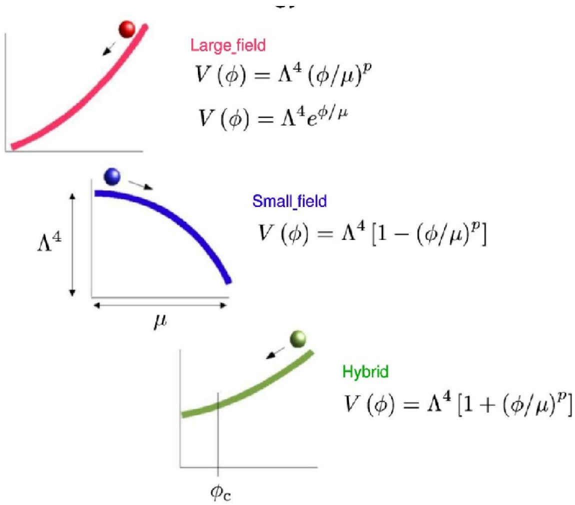


Back to reheating

Inflation can be achieved with scalar fields encountered in high energy physics[16].

[16] 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[17]. Often, these potentials are classified as small field, large field and hybrid models.

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

Spectral indices and the tensor-to-scalar ratio

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

$$\mathcal{P}_{\rm S}(k) = \frac{k^3}{2\,\pi^2}\,|f_k(\eta_{\rm e})|^2,$$
$$\mathcal{P}_{\rm T}(k) = 8\,\frac{k^3}{2\,\pi^2}\,|g_k(\eta_{\rm e})|^2,$$

with $\eta_{\rm e}$ corresponding to suitably late times during inflation.

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

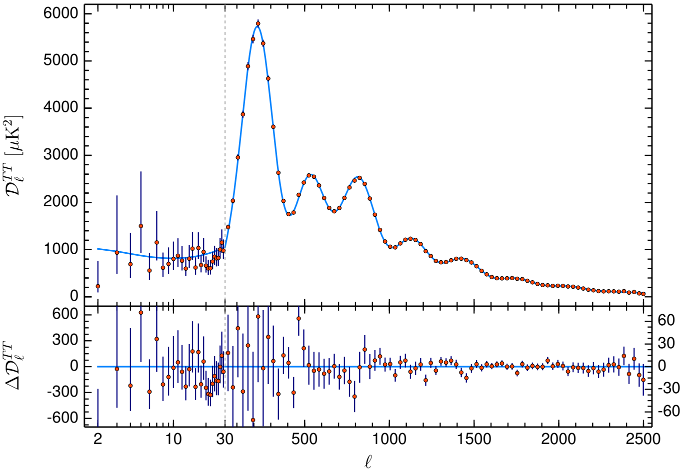
$$\mathcal{P}_{\rm S}(k) = A_{\rm S}\,\left(\frac{k}{k_\ast}\right)^{n_{\rm S}-1}, \qquad \mathcal{P}_{\rm T}(k) = A_{\rm T}\,\left(\frac{k}{k_\ast}\right)^{n_{\rm T}},$$

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

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

Plan of the talk

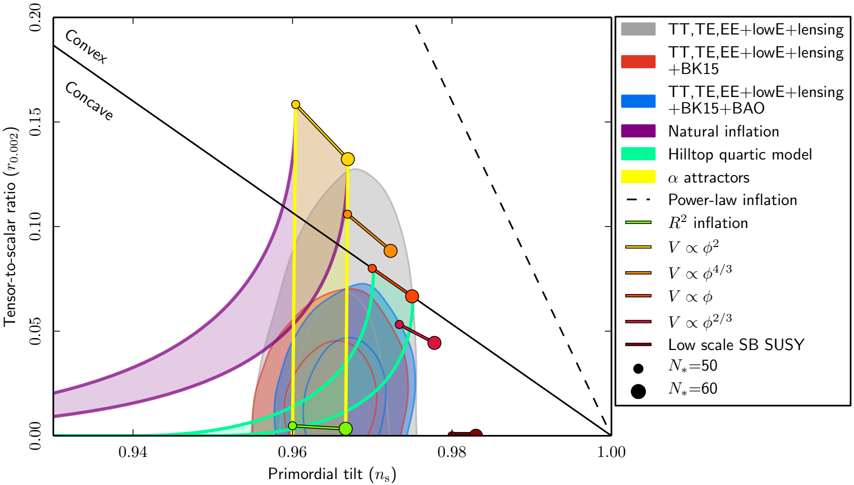
CMB angular power spectrum from Planck



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)[18]

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

Performance of inflationary models in the n_s-r plane

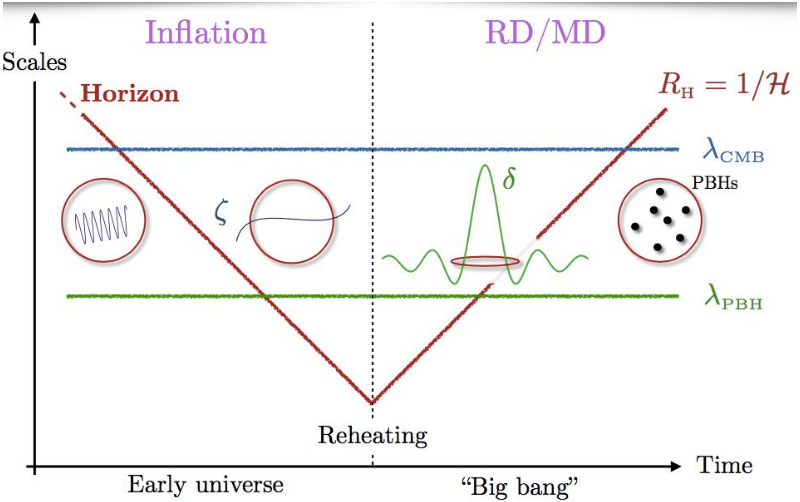


Joint constraints on n_s and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models[19].

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

Plan of the talk

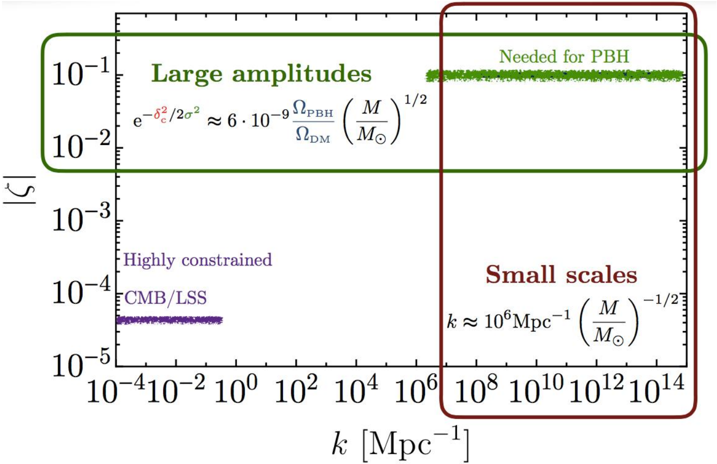
Formation of black holes in the early universe



Black holes can form when perturbations with significant amplitudes reenter the Hubble radius during the radiation dominated epoch[20].

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

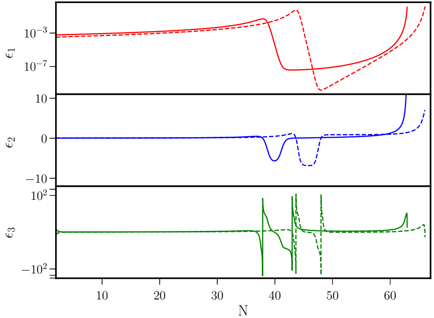
Amplitude required to form significant number of PBHs

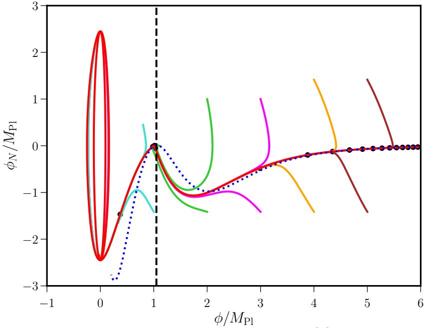


In order to form significant number of primordial black holes (PBHs), the amplitude of the perturbations on small scales has to be large enough such that the dimensionless amplitude of the scalar perturbation is close to unity[21].

[21] Figure credit G. Franciolini.

Potentials admitting ultra slow roll inflation





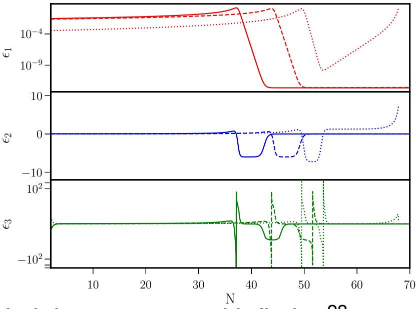
Potentials leading to ultra slow roll inflation (with $x = \phi/v$, v being a constant)[22]:

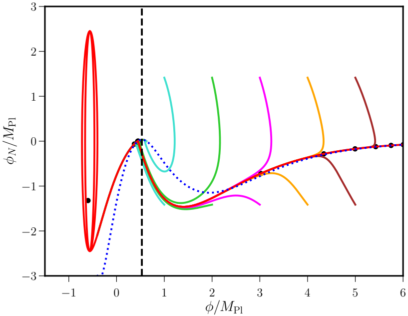
$$\mathrm{USR1}: V(\phi) = V_0\, \frac{6\, x^2 - 4\, \alpha\, x^3 + 3\, x^4}{(1 + \beta\, x^2)^2},$$

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

[22] 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





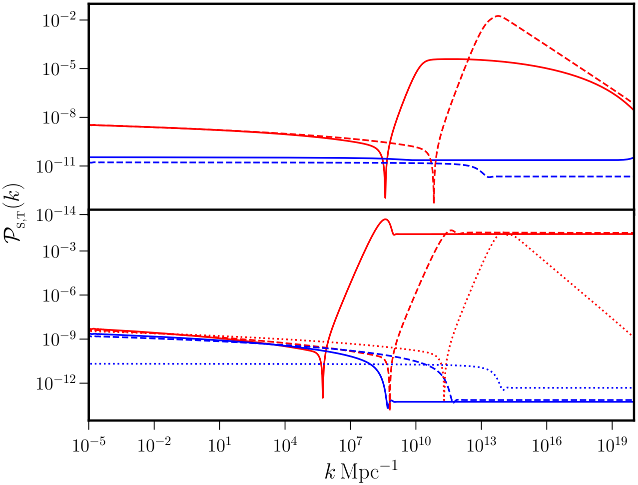
Potentials admitting punctuated inflation[23]:

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

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

[23] 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



Scalar and tensor power spectra arising in the ultra slow roll and punctuatued inflationary models (in red and blue)[24].

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

The two field model of interest

It has been noticed that two scalar fields ϕ and χ governed by the following action:

$$S[\phi, \chi] = \int \mathrm{d}^4x\,\sqrt{-g}\,\left[-\frac{1}{2}\,\partial^\mu\phi\,\partial_\mu\phi - \frac{f(\phi)}{2}\,\partial^\mu\chi\,\partial_\mu\chi - V(\phi,\chi)\right]$$

described by a potential such as

$$V(\phi,\,\chi) = V_0\,\frac{\phi^2}{\phi_0^2+\phi^2} + \frac{m_\chi^2}{2}\,\chi^2$$

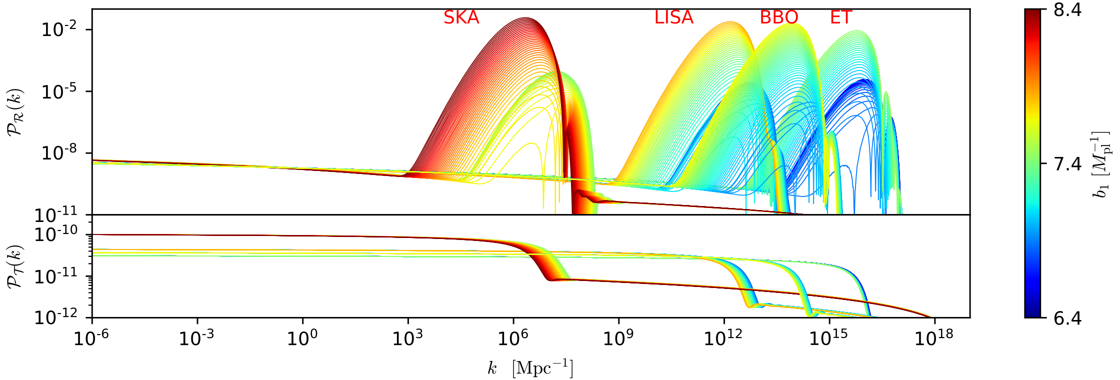
and the non-canonical coupling functions

$$f_1(\phi) = \mathrm{e}^{2\,b_1\,\phi} \quad \text{or} \quad f_2(\phi) = \mathrm{e}^{2\,b_2\,\phi^2}$$

can lead to features in the scalar power spectrum[25].

[25] M. Braglia, D. K. Hazra, L. Sriramkumar and F. Finelli, JCAP **08** 025 (2020).

Enhanced power on small scales in two field models

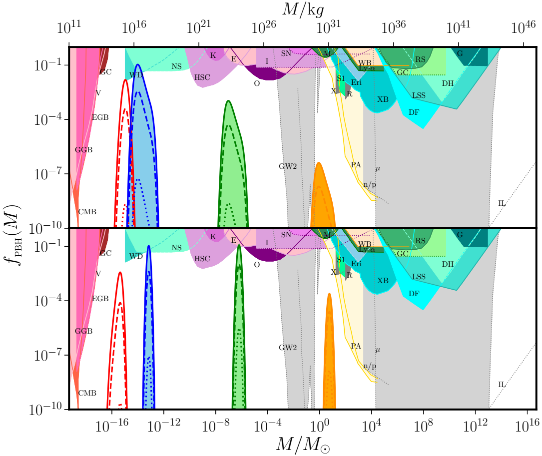


The scalar (on top) and the tensor (at the bottom) power spectra evaluated at the end of inflation have been plotted for a few different sets of initial conditions for the fields and a range of values of the parameter b_1[26].

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

Plan of the talk

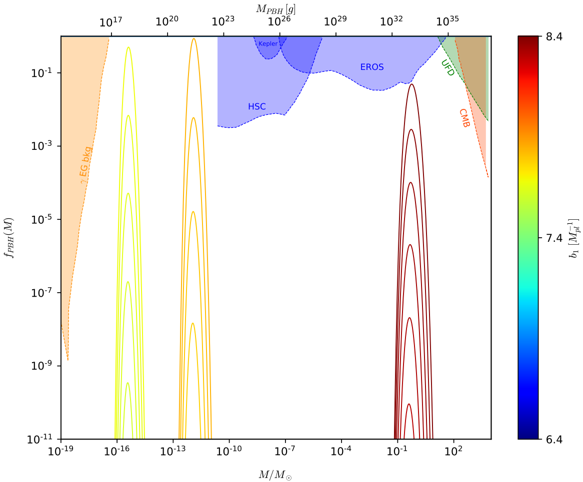
$f_{\rm PBH}(M)$ in ultra slow roll and punctuated inflation



The fraction of PBHs contributing to the dark matter density today $f_{\rm PBH}$ has been plotted as a function of the mass M of the PBHs for the various models of interest, viz. USR2 and PI3 (in red, on top and at the bottom)[27].

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

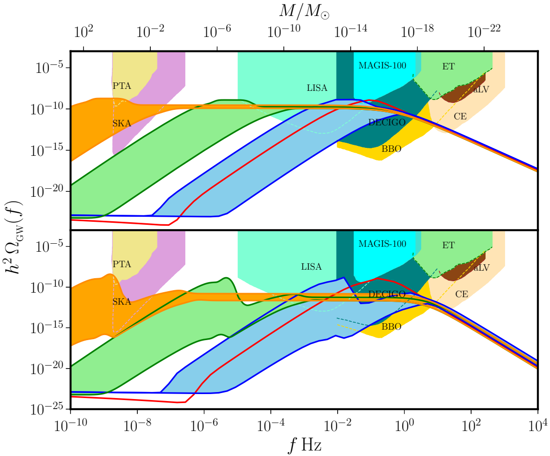
$f_{\rm PBH}(M)$ in the two field model



The fraction of PBHs contributing to the dark matter density today $f_{\rm PBH}(M)$ in the two field model of our interest[28].

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

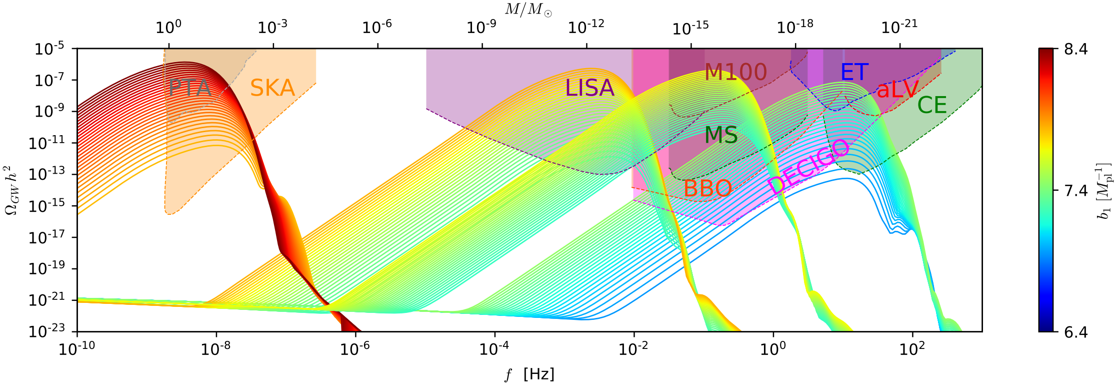
$\Omega_{\rm GW}(f)$ in ultra slow roll and punctuated inflation



The dimensionless density parameter $\Omega_{\rm GW}$ of secondary gravitational waves (GWs) arising in the models of USR2 and PI3 (in red, on top and at the bottom) have been plotted as a function of the frequency f[29].

[29] 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

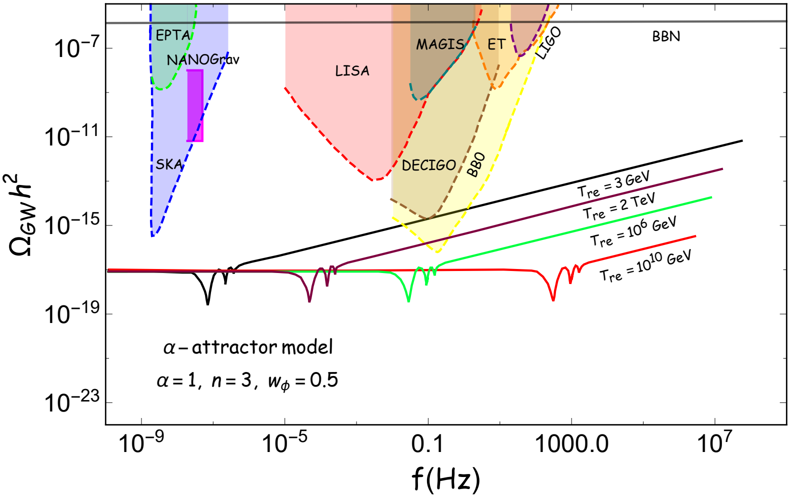


The dimensionless spectral density $\Omega_{\rm GW}(f)$ in the two field model has been plotted for a set of initial conditions of the background fields as well as a range of values of the parameter b_1[30].

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

Plan of the talk

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

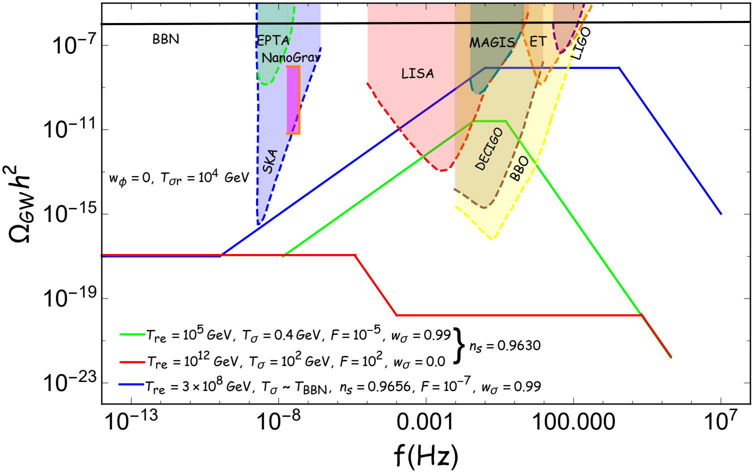


Behavior of the scalar field

The dimensionless spectral energy density of *primary* GWs today, viz. $\Omega_{\rm GW}(f)$, has been plotted for different reheating temperatures (in red, green, brown and black)[31].

[31] 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

Summary

- Inflationary models permitting an epoch of ultra slow roll lead to enhanced power on small scales, resulting in significant production of PBHs and increased strengths of secondary GWs.
- The two field models require less amount of fine tuning to generate features in the primordial spectrum[32].
- A secondary phase of reheating with a suitable equation of state parameter leads to primary GWs with significantly high amplitudes[33].

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Talk based on

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- H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, *PBHs and secondary GWs 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*, arXiv:2301.08887 [astro-ph.CO], invited review, to appear in Galaxies.

Thank you for your attention