Observing nulls in the primordial correlations through the HI 21-cm signal

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Workshop on 21-cm Cosmology

Indian Institute of Technology Madras, Chennai

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Plan of the talk

1. Need for inflation
2. Constraints on inflation from the CMB data
3. Enhancing the amplitude of scalar perturbations on small scales
4. Imprints of USR inflation in the HI 21-cm signal
5. Outlook

This talk is based on. . .

- S. Balaji, H. V. Ragavendra, S. K. Sethi, J. Silk and L. Sriramkumar, *Observing nulling of primordial correlations via the 21-cm signal*, Phys. Rev. Lett. **129**, 261301 (2022) [arXiv:2206.06386 [astro-ph.CO]].

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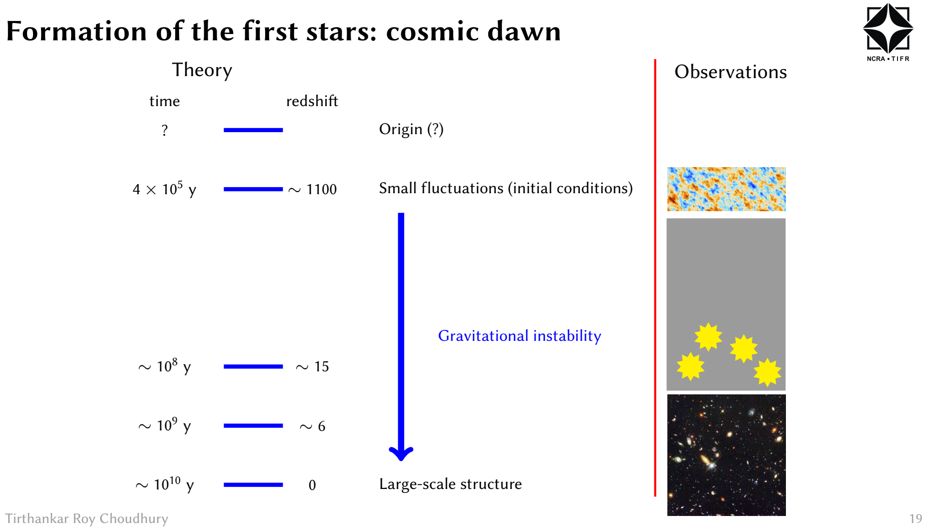
Inflation can seed the primordial perturbations



Formation of the first stars: cosmic dawn

Theory

time	redshift	
?		Origin (?)
4×10^5 y	~ 1100	Small fluctuations (initial conditions)
$\sim 10^8$ y	~ 15	
$\sim 10^9$ y	~ 6	
$\sim 10^{10}$ y	0	Large-scale structure

Gravitational instability

Observations

Tirthankar Roy Choudhury

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Inflation provides the mechanism for the generation of the primordial perturbations[1].

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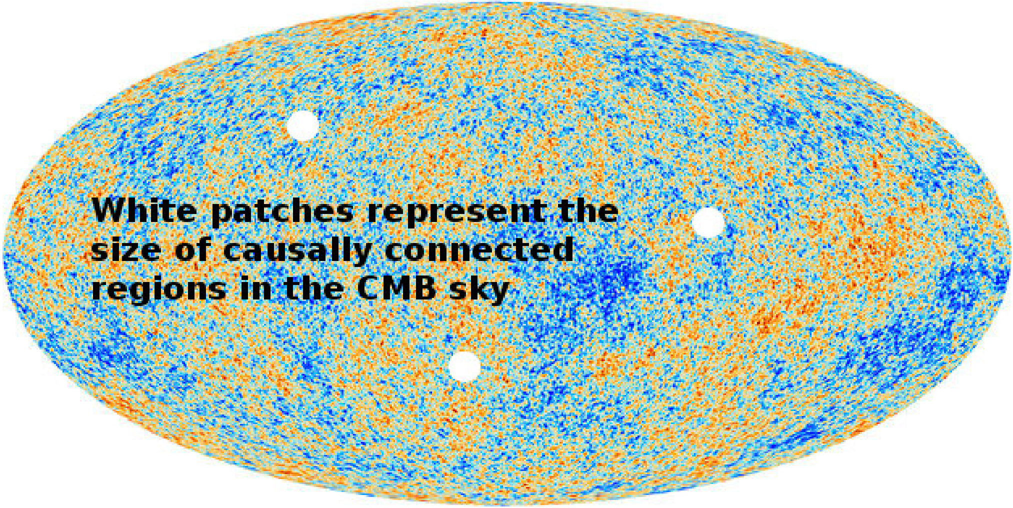
[1] Slide from talk by T. R. Choudhury (SKA-related science activities in India and future prospects) in this workshop.

The 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

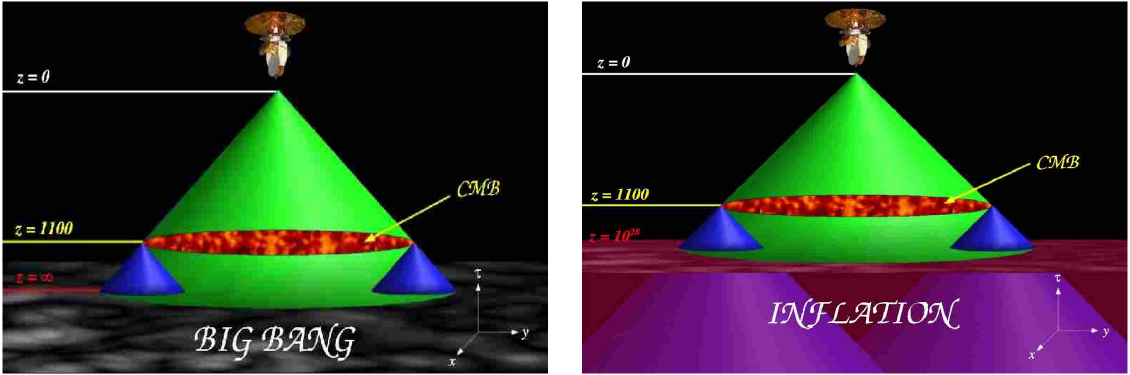


Illustration of the horizon problem (on the left) and its resolution (on the right) through an early and sufficiently long epoch of inflation[2].

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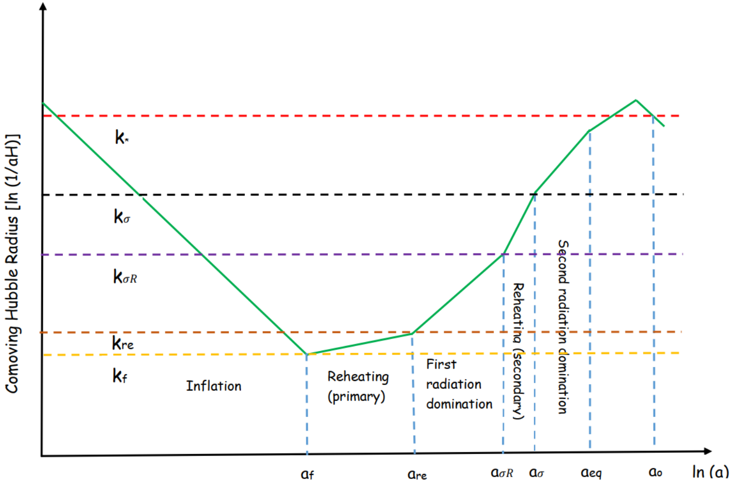
[2] Images from W. Kinney, astro-ph/0301448.

Behavior of the comoving wave number and Hubble radius



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[3].

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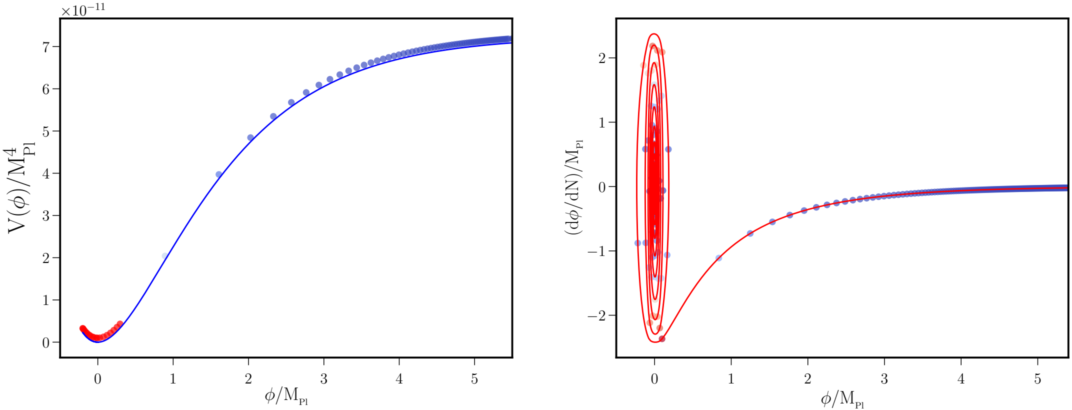
[3] Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, Phys. Rev. D **104**, 063513 (2021).

The inflationary attractor



Back to USR inflation

The 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)[4].

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[4] Figure credit H. V. Ragavendra.

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[5]. Actually, it may not even be possible to rule out some of these models!

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[5] 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).

The quadratic action governing the perturbations

One can show that, at the quadratic order, the action governing the curvature perturbation $\mathcal{R}$ and the tensor perturbation γ_{ij} are given by[6]

$$\mathcal{S}_2[\mathcal{R}(\eta, \boldsymbol{x})] = \frac{1}{2} \int \mathrm{d}\eta \int \mathrm{d}^3\boldsymbol{x}\ z^2 \left[\mathcal{R}'^2 - (\partial\mathcal{R})^2\right],$$

$$\mathcal{S}_2[\gamma_{ij}(\eta, \boldsymbol{x})] = \frac{M_{\mathrm{Pl}}^2}{8} \int \mathrm{d}\eta \int \mathrm{d}^3\boldsymbol{x}\ a^2 \left[\gamma_{ij}'^{\,2} - (\partial\gamma_{ij})^2\right].$$

These actions lead to the following equations of motion governing the scalar and tensor modes, say, f_k and h_k:

$$f_k'' + 2\,\frac{z'}{z}\,f_k' + k^2\,f_k = 0,$$

$$g_k'' + 2\,\frac{a'}{a}\,g_k' + k^2\,g_k = 0,$$

where $z = a\,M_{\mathrm{Pl}}\,\sqrt{2\,\epsilon_1}$, with $\epsilon_1 = -\,\mathrm{d}\ln H/\mathrm{d}N$ being the first slow roll parameter.

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[6] V. F. Mukhanov, H. A. Feldman and R. H. Brandenberger, Phys. Rep. **215**, 203 (1992).

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:

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

$$\mathcal{P}_{_{\rm T}}(k) = \frac{8}{M_{_{\rm Pl}}^2}\,\frac{k^3}{2\,\pi^2}\,\vert g_k(\eta_{\rm e})\vert^2,$$

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

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

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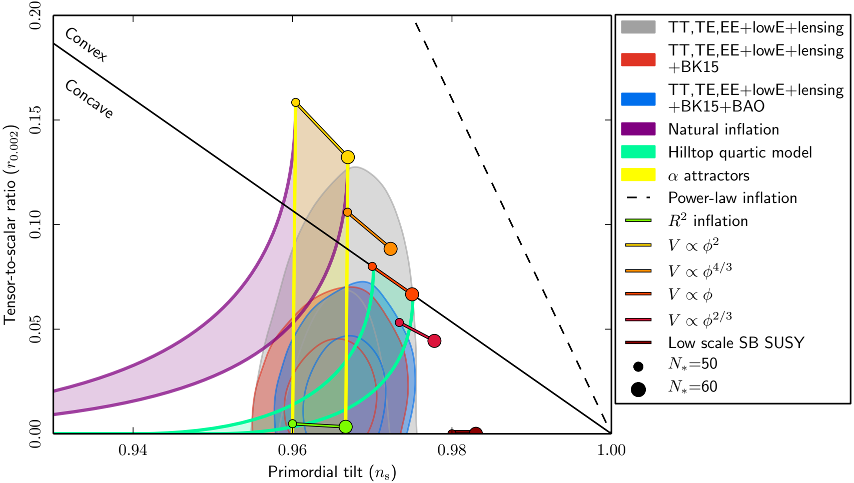
Performance of inflationary models in the $n_{\rm s}$-r plane



Joint constraints on $n_{\rm s}$ and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of some of the popular inflationary models[7].

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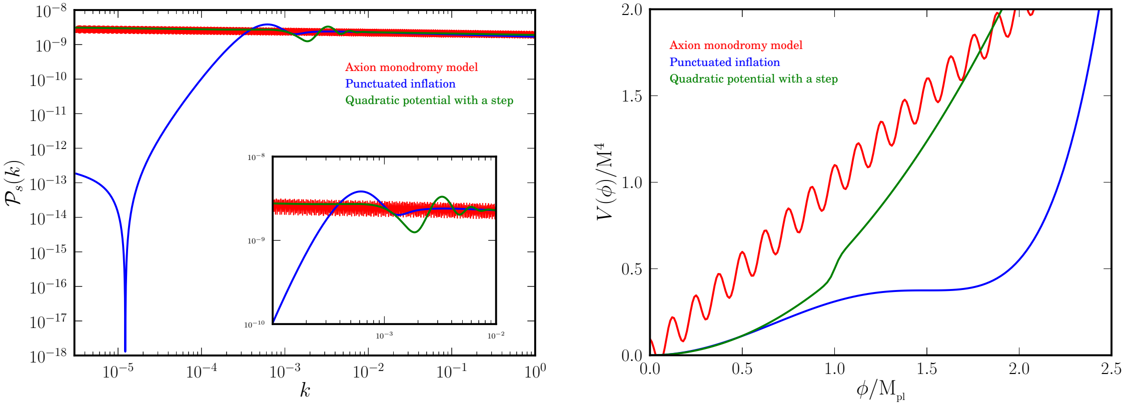
[7] Planck Collaboration (Y. Akrami *et al.*), Astron. Astrophys. **641**, A10 (2020).

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[8].

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[8] 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).

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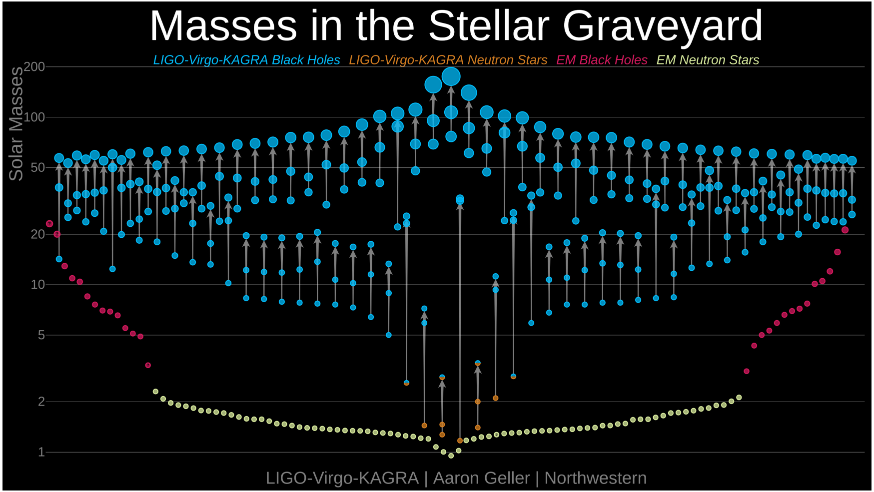
Coalescence of compact binaries observed by LIGO



The third Gravitational Wave Transient Catalog of mergers involving black holes and neutron stars observed by the LIGO-Virgo-KAGRA collaboration[9].

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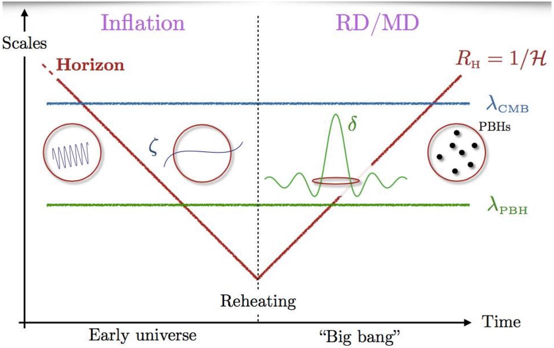
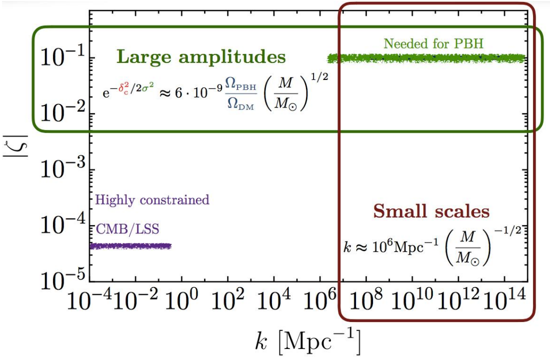
[9] Image from https://www.ligo.caltech.edu/LA/image/ligo20211107a.

Formation of primordial black holes (PBHs)





BHs can form in the primordial universe when perturbations with significant amplitudes on small scales re-enter the Hubble radius during the epoch of radiation dominated epoch[10].

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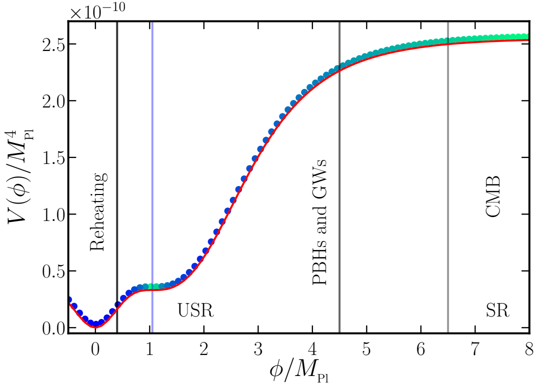
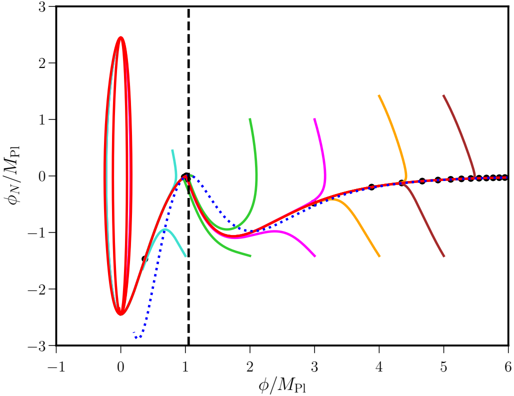
[10] Figures from G. Franciolini, arXiv:2110.06815 [astro-ph.CO].

Single-field models admitting ultra slow roll inflation





▸ Inflationary attractor

Potentials which contain a point of inflection lead to ultra slow roll (USR) inflation[11].

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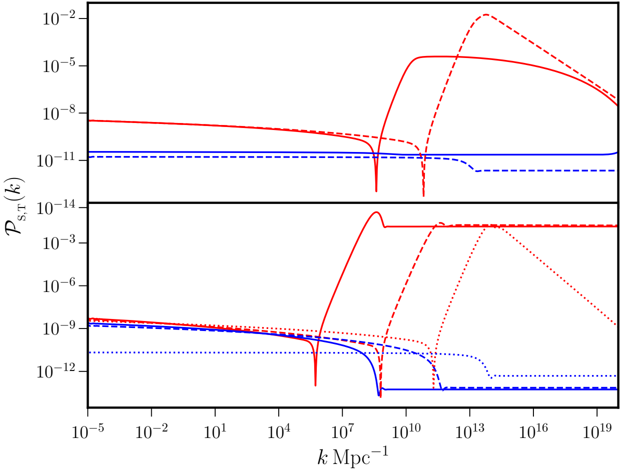
[11] See, for example, J. Garcia-Bellido and E. R. Morales, Phys. Dark Univ. **18**, 47 (2017); I. Dalianis, A. Kehagias and G. Tringas, JCAP **01**, 037 (2019).
Figures credits, H. V. Ragavendra and S. Maity.

Power spectra in models permitting USR inflation



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[12].

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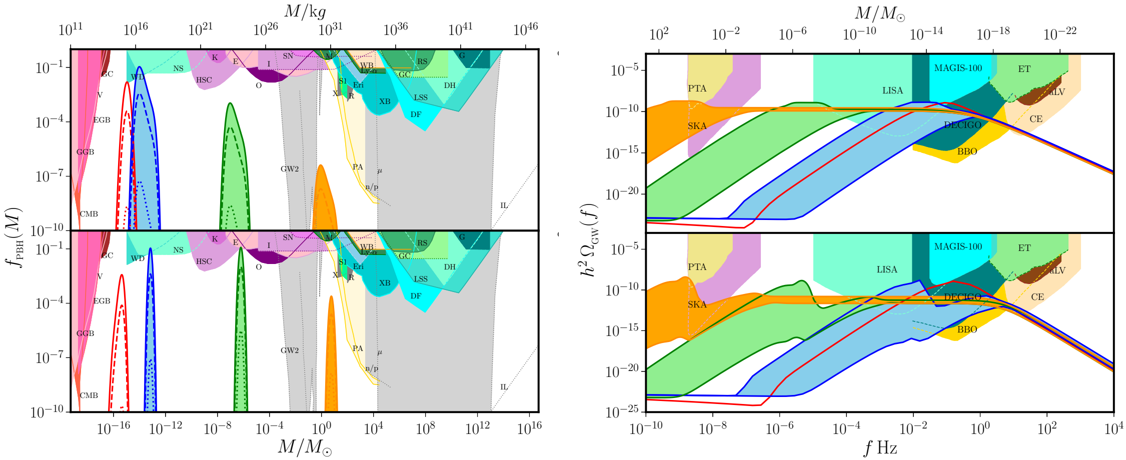
[12] H. V. Ragavendra, P. Saha, L. Sriramkumar and J. Silk, Phys. Rev. D **103**, 083510 (2021).
Also see H. V. Ragavendra and L. Sriramkumar, Galaxies **11**, 34 (2023).

$f_{\rm PBH}(M)$ and $\Omega_{\rm GW}(f)$ in models leading to USR inflation



The fraction of PBHs contributing to the cold dark matter density today $f_{\rm PBH}(M)$ and the dimensionless spectral density of GWs $\Omega_{\rm GW}(f)$ arising in the models of ultra slow roll inflation[13].

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

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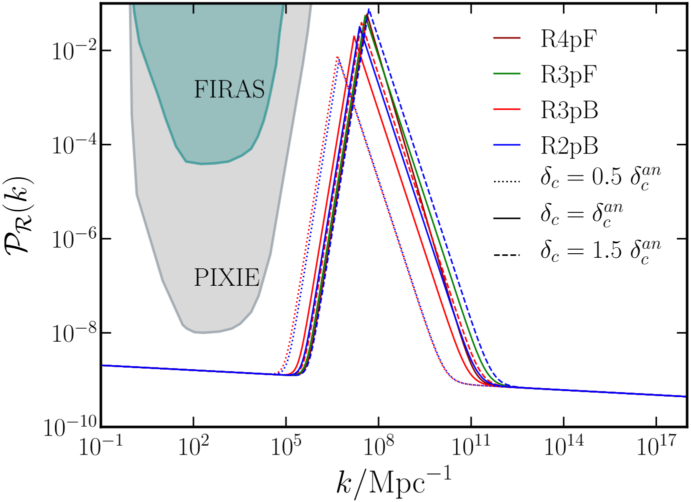
Constraints from spectral distortions



Constraints on the scalar power spectrum from spectral distortions in the CMB[14].

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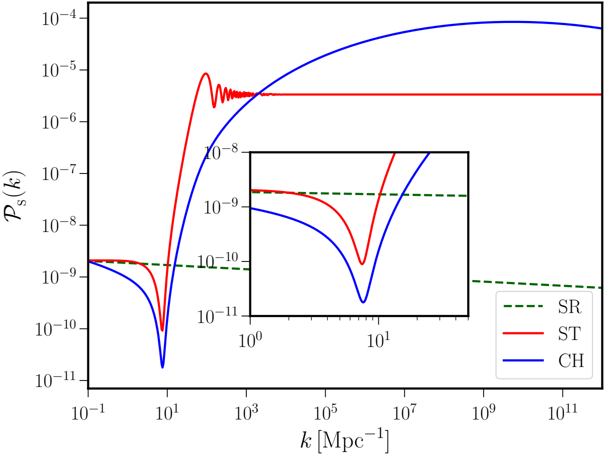
[14] S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, arXiv:2403.16963 [astro-ph.CO].

Scalar power spectra with a sharp dip



Power spectra from two inflationary models (ST and CH) that are consistent with the constraints on spectral distortions from FIRAS. The inset highlights the dip at $k = 7.6\,\mathrm{Mpc}^{-1}$, where the HI signal is expected to be most sensitive to the primordial power spectrum[15].

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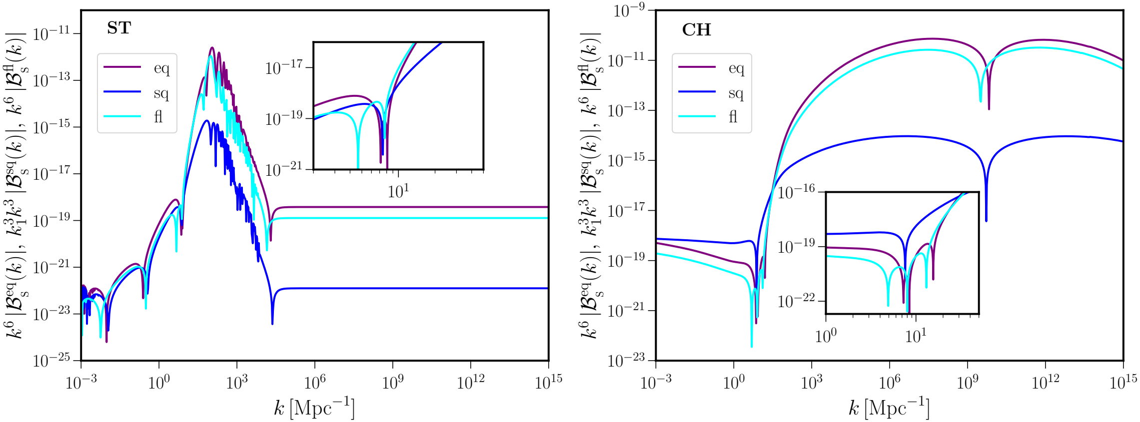
[15] S. Balaji, H. V. Ragavendra, S. K. Sethi, J. Silk and L. Sriramkumar, Phys. Rev. Lett. **129**, 261301 (2022).

Corresponding inflationary bispectra



Scalar bispectra arising in the two inflationary models have been illustrated in the equilateral (eq), squeezed (sq) and flattened (fl) limits. The bispectra also exhibit a sharp dip at the same location as the power spectra[16].

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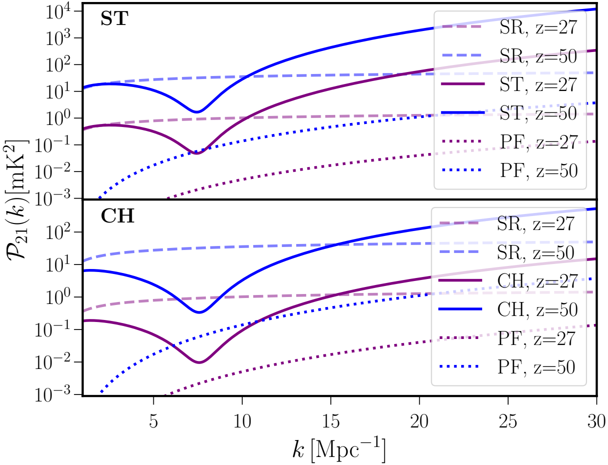
[16] S. Balaji, H. V. Ragavendra, S. K. Sethi, J. Silk and L. Sriramkumar, Phys. Rev. Lett. **129**, 261301 (2022).

Resulting HI power spectrum



The HI intensity power spectra arising from the two inflationary models have been plotted at the redshifts of $z = 27$ and $z = 50$. We have also included the power spectra due to Poisson fluctuations (PF) at the corresponding redshifts[17].

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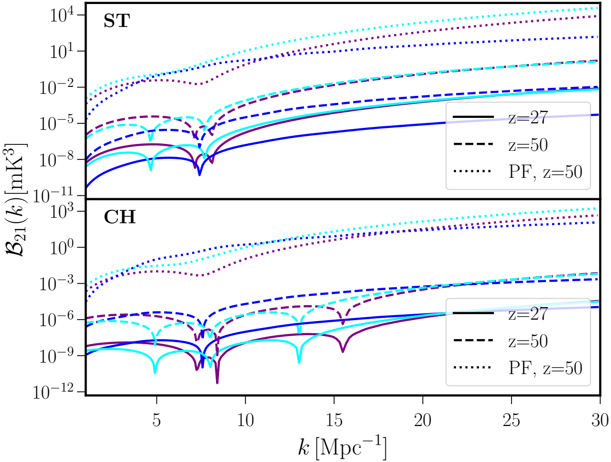
[17] S. Balaji, H. V. Ragavendra, S. K. Sethi, J. Silk and L. Sriramkumar, Phys. Rev. Lett. **129**, 261301 (2022).

Resulting HI bispectrum



HI intensity bispectra arising from the two inflationary models have been illustrated in the equilateral, squeezed and the flattened limits. The associated PF have also been indicated[18].

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[18] S. Balaji, H. V. Ragavendra, S. K. Sethi, J. Silk and L. Sriramkumar, Phys. Rev. Lett. **129**, 261301 (2022).

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Outlook

- In the models we have considered, the sharp dips arise over the scales $1 \lesssim k \lesssim 10\,\mathrm{Mpc}^{-1}$. The strength of the HI signal at such scales is of the order of 10–$1000\,(\mathrm{mK})^2$ in the frequency range 25–$50\,\mathrm{MHz}$ for the redshift range $z \simeq 25$–50.
- While the signal at $z \simeq 25$ is accessible to SKA-Low[19], we expect the signal at $z \simeq 50$ to be more pristine (i.e. less contaminated by astrophysical processes close to the era of cosmic dawn) and dominant.
- Such a signal could be explored by planned lunar missions[20]. Under suitable assumptions, these missions can achieve the brightness temperature sensitivity of 1–$10\,(\mathrm{mK})^2$ over the scales of interest[21].

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[19] L. V. E. Koopmans *et al.*, PoS **AASKA14**, 001 (2015).

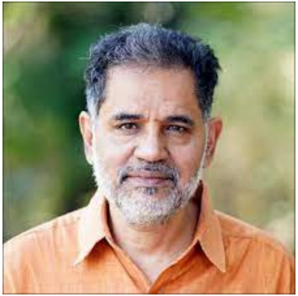
[20] S. Furlanetto *et al.*, arXiv:1903.06212 [astroph.CO];
P. S. Cole and J. Silk, Mon. Not. Roy. Astron. Soc. **501**, 2627 (2021);
L. V. E. Koopmans *et al.*, Exper. Astron. **51**, 1641 (2021).

[21] S. Paul *et al.*, Astrophys. J. **833**, 213 (2016);
S. R. Furlanetto, S. P. Oh, and E. Pierpaoli, Phys. Rev. D **74**, 103502 (2006).

Collaborators

Shyam Balaji

H. V. Ragavendra



Shiv Sethi

Joseph Silk

Thank you for your attention