

Inflationary Gravitational Waves as a Probe of Unknown Evolutionary History of the Universe

TAUN 2026 Spring Meeting @ IBS, Daejeon

Swagat Saurav Mishra

Senior Researcher[†]

[†] Cosmology, Gravity & Astroparticle Physics Group,
Centre for Theoretical Physics of the Universe (CTPU-CGA),
Institute for Basic Science (IBS), Daejeon, Korea

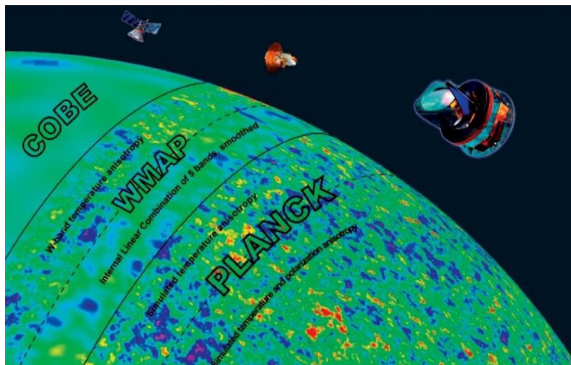
18 June 2026



Best Probes of the Early Universe

Cosmic Microwave Background (CMB) Radiation: TT, TE & EE

+ **BBN** + **LSS** + **BAO**



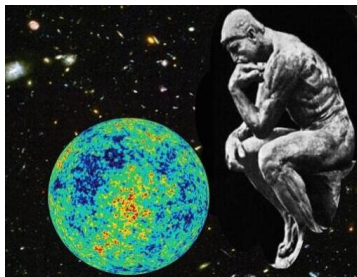
The Hot Big Bang Phase $T \gg 1\text{eV}$

⇒ What provides initial conditions for the hot Big Bang?

Initial Conditions for Structure Formation

LSS ← CMB ← Initial $\zeta(\vec{x})$ Gravitational Instability

Properties of (initial)
primordial fluctuations:



1. Adiabatic & **Super-Hubble** $\zeta(\vec{x})$
2. Almost scale-invariant

$$\mathcal{P}_\zeta = A_S \left(\frac{k}{k_*} \right)^{n_s - 1} \quad k_* = 0.05 \text{ Mpc}^{-1}$$

$$A_S \ll 1, \quad |n_s - 1| \ll 1$$

3. Nearly **Gaussian** ($\sigma \simeq 10^{-4}$)

$$\mathcal{P}[\zeta] = \mathcal{B} \exp \left[\frac{-\zeta^2}{2\sigma^2} \left(1 + f_{\text{NL}} \zeta + \dots \right) \right]$$

→ LSS, CMB ⇒ **Large-scale primordial fluctuations**

→ Origin ⇒ **Quantum fluctuations during INFLATION**

Modern/Extended Big Bang Model of Cosmology

The Hot Big Bang phase:

- Beginning of the Universe ✗
- End of an earlier epoch of accelerated expansion ✓

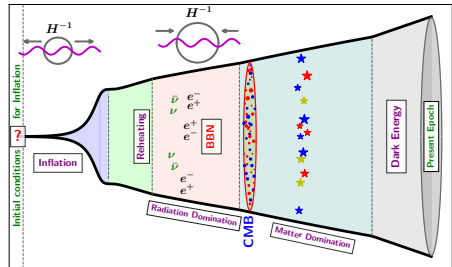
Inflation

Reheating

Hot Big Bang Phase

Matter Domination

Dark Energy



REHEATING: Origin of all primordial matter!

Cosmic Inflation: Transient Early Accelerated Expansion

(Prior to the hot-Big-Bang phase $T \gg 1 \text{ MeV}$)

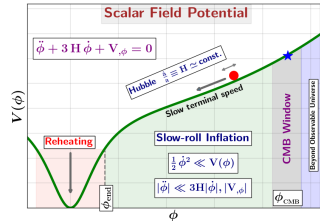
1. Background Dynamics: (Scalar condensate)

Quasi-Exponential expansion

$$\ddot{a} > 0 ; \quad a_{\text{end}} \simeq a_i e^{\Delta N}, \quad \Delta N > 60$$

(at least 60 e-folds of Inflation)

⇒ **Isotropic, Uniform & Flat Universe**



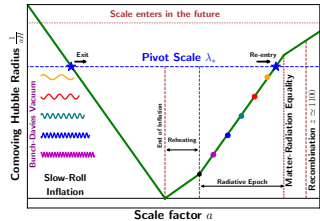
2. Small (linear) Perturbations:

Quantum fluctuations in
Inflating spacetime

⇒ **Seed fluctuations for hot Big Bang**

Origin of all Structure in the Universe !

CMB, LSS, GWs, PBHs ?



Standard: Single-field Slow-roll Inflation

System = Gravity ($g_{\mu\nu}$) + Scalar Field (ϕ)

$$S[g_{\mu\nu}, \phi] = \int d^4x \sqrt{-g} \left(\frac{m_p^2}{2} R - \frac{1}{2} \partial_\mu \phi \partial_\nu \phi g^{\mu\nu} - V(\phi) + \dots \right)$$

$$ds^2 = -\beta^2(t) dt^2 + a^2(t) \left[\left(e^{-2\Psi(t, \vec{x})} \delta_{ij} + 2h_{ij}(t, \vec{x}) \right) dx^i dx^j \right]$$

Two types of inflationary fluctuations ($m \ll H$) –

- 1) **Comoving Curvature Perturbations:** $-\zeta(t, \vec{x}) = \Psi + \frac{1}{\sqrt{2\epsilon_1}} \frac{\delta\phi}{m_p}$
- 2) **Transverse & traceless Tensor Perturbations:** $h_{ij}(t, \vec{x})$

Slow-roll regime: (**Slow terminal motion of ϕ**) $\epsilon_1, |\epsilon_2| \ll 1$

$$\epsilon_1 = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2m_p^2 H^2}; \quad \epsilon_2 = \frac{d \ln \epsilon_1}{dN}$$

Power-spectra: Linear Perturbation Theory

Slow-roll primordial power-spectrum on large scales –

(Around the CMB pivot scale $k_* = 0.05 \text{ Mpc}^{-1}$)

Scalar power spectrum

$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2} \left(\frac{H}{m_p} \right)^2 \frac{1}{\epsilon_1} = A_S \left(\frac{k}{k_*} \right)^{n_S - 1}$$

Scalar spectral index

$$n_S - 1 = -2\epsilon_1 - \epsilon_2 \ll 1$$

Tensor power spectrum

$$\mathcal{P}_\mathcal{T}(k) = \frac{2}{\pi^2} \left(\frac{H}{m_p} \right)^2 = A_\mathcal{T} \left(\frac{k}{k_*} \right)^{n_\mathcal{T}}$$

Tensor spectral index

$$n_\mathcal{T} = -2\epsilon_1 \ll 1$$

Tensor-to-scalar Ratio:

$$r = \frac{A_\mathcal{T}}{A_S} = 16\epsilon_1 = -8n_\mathcal{T} \ll 1$$

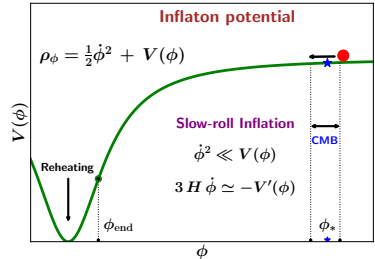
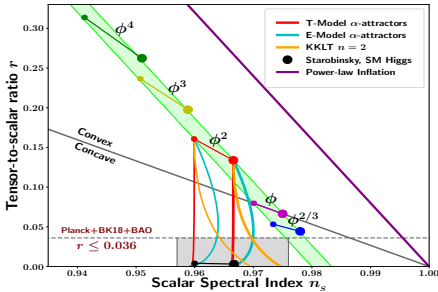
⇒ **Tiny fluctuations** that are **nearly scale invariant**

**Liddle, Parsons, Barrow (1994); Baumann TASI (2009); **SSM Inflation Lectures (2024)

Observational Constraints (Planck Legacy+BICEP/Keck)

$$A_s = 2.1 \times 10^{-9} ; \quad n_s \simeq 0.965 ; \quad r \leq 0.036 \quad (\text{ACT, SPT Updates})$$

$$\Rightarrow H^{\text{inf}} \leq 10^{13} \text{ GeV} \quad \Rightarrow \quad E^{\text{inf}} \leq 10^{16} \text{ GeV} ; \quad \epsilon_1 \lesssim -\epsilon_2$$

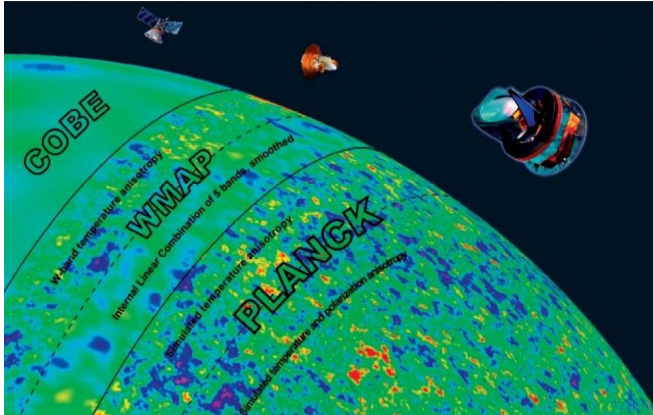


Latest Data [BICEP/Keck + Planck] \Rightarrow On CMB scales :

Single-field slow-roll paradigm of Inflation & Concave, e.g. asymptotically-flat potentials!

**Planck(2018); **BICEP/Keck(2021); **SSM & Sahni(2022), **Bhatt, SSM et.al.(2022)

Graceful-Exit from Inflation → hot Big Bang



→ Origin of the fluctuations in the plasma (✓)

Inflationary quantum fluctuations

→ Origin of the constituents of the plasma (hot Big Bang) ?

Inflaton Decay & Reheating

What happened to other fields during inflation?

- Observations favour ‘**single-field slow-roll**’ inflation.
- ‘**Cold inflationary paradigm:**’ $\Rightarrow \rho_\chi, \rho_\psi \ll \rho_\varphi$
& Negligible coupling to external fields $g^2, h \ll 1$

$$S[\varphi, \chi, \psi] = - \int d^4x \sqrt{-g} \left[\frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi + V(\varphi) + \frac{1}{2} \partial_\mu \chi \partial^\mu \chi + \frac{1}{2} m_{0\chi}^2 \chi^2 \right. \\ \left. + \bar{\psi} (i\gamma^\mu \partial_\mu + m_{0\psi}) \psi \right. \\ \left. + \frac{1}{2} g^2 \varphi^2 \chi^2 + h \psi \bar{\psi} \varphi + \dots \right]$$

\Rightarrow particle production during inflation can be neglected.

- Effects of the small coupling ?
 - ① **Primordial Non-Gaussianity:** inflaton interactions.
 - ② Decay of the inflaton field: **Reheating the universe.**

General Reheating Dynamics

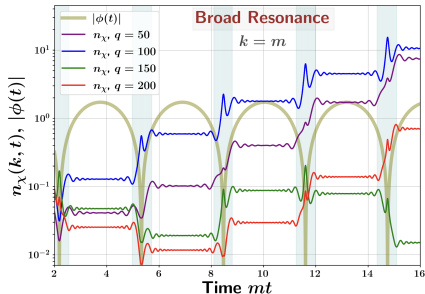
1) Non-perturbative inflaton decay: (Early stages)

$$\mathcal{L}_{\text{int}} \supset -\frac{1}{2}g^2\varphi^2\chi^2 \text{ for } g^2 \geq 4\left(\frac{m}{\phi_0}\right)^2$$

⇒ Broad-band resonance for

⇒ **Explosive growth** $n_\chi \propto e^{\mu_k t}$

$$m \simeq 10^{-5} m_p, \phi_0 \simeq 0.2 m_p \Rightarrow g^2 \geq 10^{-8}$$



2) Perturbative inflaton decay: (certainly at late times)

$$\varphi\varphi \longrightarrow \chi\chi \text{ for } g^2 < 10^{-8}; \quad \varphi \longrightarrow \bar{\psi}\psi \text{ for } h \lesssim 10^{-2}$$

3) Coherent Oscillations:

For $h, g \sim 0$, the inflaton condensate oscillates for a long time

$$\phi(t) = \phi_0(t) \cos(mt); \quad \langle w_\phi \rangle \simeq 0 \Rightarrow \rho_\phi \propto a^{-3}$$

⇒ universe remains **condensate-dominated** × (**Not Correct!**)

Shape of the Inflationary Potential: Concave

→ Asymptotically flat potentials:

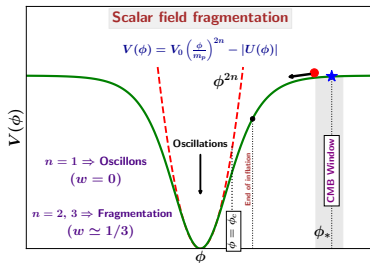
$$V(\phi) = V_0 \left(\frac{\phi}{m_p} \right)^2 - |U(\phi)|$$

have ‘**attractive self-interaction**’

⇒ **Scalar field fragmentation**

⇒ **Cosmological Solitons : Oscillons**

→ **Oscillons** are oscillating non-topological pseudo-solitons!
(Self-supported, localised, long-lived non-linear configurations)



Oscillon Formation: Two important inferences

1) From generic initial conditions at the end of Inflation!

2) In presence of large-enough external couplings.

Yamaguchi, Li (CTPU-CGA)

⇒ **Post-inflationary dynamics is expected to be complicated**

**Amin *et. al.* (2010-2020), Mahbub & SSM (2023), **Shafi, SSM, Copeland *et. al.* (2024)

Cosmic Inflation: Targets for 2025-2045

Theoretically

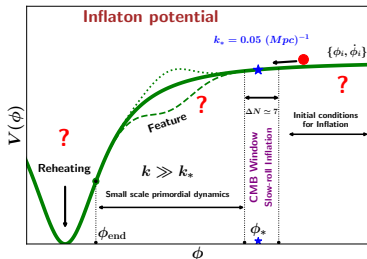
Origin of Inflaton field?

Single or Multi-field?

Primordial Interactions?

Cosmological Correlators?

Yamaguchi, Yamada, Zhu (CTPU-CGA)



Phenomenologically

Primordial Tensors (GWs)?

Inflaton Decay & Reheating?

Small-scale Inflationary Dynamics?

Primordial Non-Gaussianity (PNG)?

Observationally

B-Mode Polarization

GW Observatories

PNG from CMB, LSS

PNG from 21 cm

SYNERGY: LSST, LiteBIRD, Euclid, aLIGO, LISA, PTA, Einstein Telescope, LHC, FCC

Accessing New Physics from the Early Universe

→ Early Universe is Nature's ultimate HEP laboratory!

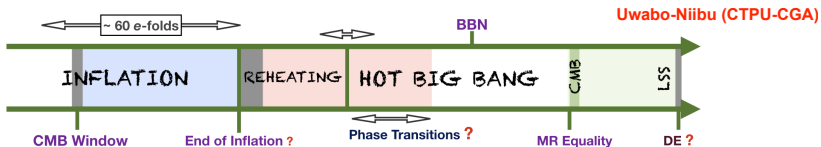
Many Members (CTPU-CGA)

→ Fundamental Observables: **Cosmological Correlators**

(Scattering cross-section σ , Decay Rates Γ in Particle Colliders)

Initial Fluctuations → **Time Evolution** → **Observed Data**

1. **Primordial Relics**: PBHs, Solitons (e.g. Oscillons), Heavy Nuclei
2. **Primordial Signals**: **Stochastic GWs**, Photons (CMB), Neutrinos



→ Probing BSM Physics & Cosmology in between

$$1 \text{ MeV} \leq E \leq 10^{16} \text{ GeV}$$

Tensor Power Spectrum at the end of Inflation

$$\text{Polarization } h_{ij} = \frac{1}{\sqrt{2}} \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix} = \epsilon_{ij}^+ h_+ + \epsilon_{ij}^\times h_\times$$

$$\Rightarrow S^{(2)}[h_+, h_\times] = \frac{1}{2} \int d\tau d^3\vec{x} \left(\frac{am_p}{2} \right)^2 \sum_{\lambda=+,\times} [(h_\lambda')^2 - (\partial_i h_\lambda)^2]$$

Power spectrum definition

$$\mathcal{P}_\mathcal{T}(k) = \frac{k^3}{2\pi^2} [|h_+|^2 + |h_\times|^2] = 2 \times \frac{k^3}{2\pi^2} |h_+|^2$$

which at the end of inflation on super-Hubble scales $k \ll aH$

$$\mathcal{P}_\mathcal{T}(k) \Big|_{k \ll aH} = \frac{2}{\pi^2} \left(\frac{H}{m_p} \right)^2 \simeq A_\mathcal{T} \left(\frac{k}{k_*} \right)^{n_\mathcal{T}} ; \quad n_\mathcal{T} = -2\epsilon_1 = -\frac{r}{8}$$

→ Remain frozen/constant on outside Hubble radius

→ Initial conditions for tensor propagation post inflation

**Starobinsky (1979) Pioneering work on dS GWs

Post-inflationary Evolution of Tensor Modes

Inflationary Output \rightarrow Reheating \rightarrow Hot Big Bang Input

Inflationary Tensor Modes \rightarrow Primordial GWs

Inflationary Scalar Modes \rightarrow CMB Acoustic Waves \rightarrow LSS

Tensor mode functions satisfy

$$h_k''^\lambda + 2 \left(\frac{a'}{a} \right) h_k'^\lambda + k^2 h_k^\lambda = 0$$

For **post-inflationary epoch** with **EoS** w_{re}

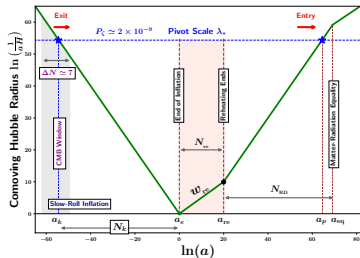
$$\frac{a'}{a} = a_i H_i \left[1 + \frac{a_i H_i (\tau - \tau_i) (1 + 3w_{\text{re}})}{2} \right]^{-1}$$

General solution

$$h_k^\lambda(y) = \frac{1}{(\alpha y)^{\alpha - \frac{1}{2}}} \left[A_k J_{(\alpha - \frac{1}{2})}(\alpha y) + B_k J_{-(\alpha - \frac{1}{2})}(\alpha y) \right] \quad \alpha = \frac{2}{(1 + 3w_{\text{re}})}$$

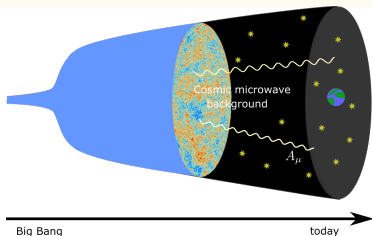
**SSM Lecture Notes [arXiv:2403.10606]

Coeffs. $\{A_k, B_k\}$; $y = \frac{k}{aH}$

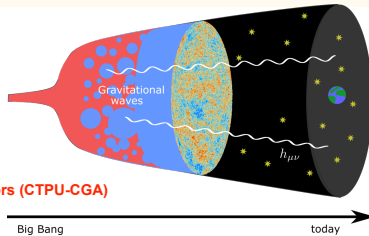


GWs: Messengers from the Early Universe

- Probing **Energy Scale of Inflation** via **CMB B-Mode Missions**
- **Canonical assumption**: Radiation Domination all the way till the end of Inflation (**Special!**)
- Early Universe is expected to host a number of distinct epochs (**Generic!**)
- Probing these unknown epochs *via* **Gravitational Waves**
- Physics is encoded in the **Amplitude & Tilt** of the GW spectrum



Many Members (CTPU-CGA)



EM Waves from Recombination

GWs from very early Universe

Grishchuk(1975) (FLRW); **Starobinsky (1979) (dS/Inflation **Pioneering work)

Spectral Energy Density of Primordial GWs

Definition:
$$\Omega_{\text{GW}}(\tau, k) = \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \ln k}$$

$$\rho_{\text{GW}}(\tau) = \frac{m_p^2}{8a^2(\tau)} \int d \ln k \frac{k^3}{\pi^2} \left[\overline{|h_k^{\prime\lambda}(\tau)|^2} + k^2 \overline{|h_k^\lambda(\tau)|^2} \right]$$

$$\frac{d\rho_{\text{GW}}}{d \ln k} = \frac{m_p^2}{8a^2(\tau)} \frac{k^3}{\pi^2} \left[\overline{|h_k^{\prime\lambda}(\tau)|^2} + k^2 \overline{|h_k^\lambda(\tau)|^2} \right] \simeq \frac{m_p^2}{8a^2(\tau)} \frac{k^5}{\pi^2} \overline{|h_k^\lambda(\tau)|^2}$$

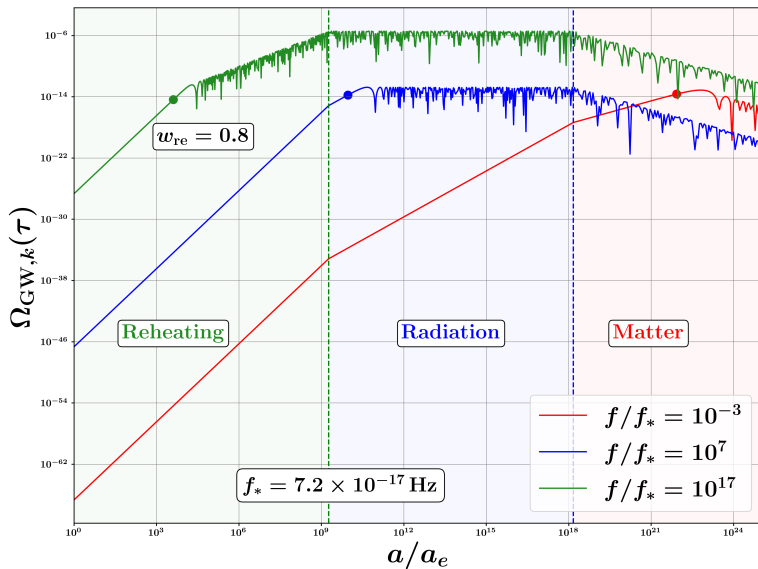
GW Spectral energy density (for $k \gg aH$)

$$\Omega_{\text{GW}}(\tau, k) = \frac{k^2}{12 a^2(\tau) H^2(\tau)} \mathcal{P}_h(\tau, k)$$

With
$$\mathcal{P}_h(\tau, k) = \frac{k^3}{2\pi^2} \left(\overline{|h_k^+(\tau)|^2} + \overline{|h_k^\times(\tau)|^2} \right) = \frac{k^3}{\pi^2} \overline{|h_k^\lambda(\tau)|^2}$$

**Isaacson Approximation (1968)

Evolution of GW Spectral Energy Density

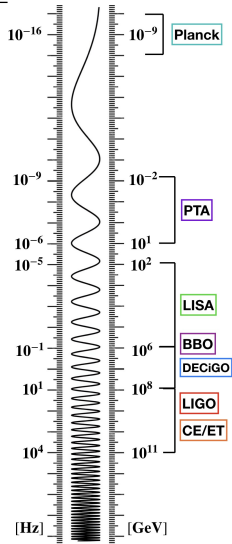


Present-epoch Frequency of GWs

$$f_k = 1.03 \times 10^{-8} \left(\frac{g_{s,0}}{g_{s,T_k}} \right)^{1/3} g_{*,T_k}^{1/4} \left(\frac{E_k}{\text{GeV}} \right) \text{ Hz}$$

E_k : Hubble-entry epoch Energy scale of GWs

Cosmic Events	Energy scale	f_k (Hz)
M-R Equality	~ 1 eV	1.4×10^{-17}
Onset of BBN	~ 1.4 MeV	1.8×10^{-11}
QCD PT	~ 320 MeV	3.7×10^{-9}
Electro-Weak SB	~ 240 GeV	2.7×10^{-6}
Baryogenesis	$\gtrsim 10$ TeV	$\gtrsim 1.4 \times 10^{-4}$



PTA \rightarrow QCD , LISA $\rightarrow \gtrsim$ EW-Higgs , LIGO $\rightarrow \gtrsim 10^8$ GeV

\Rightarrow **GW Observatories** are **HEP Detectors**

Inflationary GW Spectral Energy Density

RD Epoch $\Omega_{\text{GW}}^{\text{RD}}(f) \simeq \left(\frac{r A_S}{24}\right) \Omega_{0r} \left(\frac{f}{f_*}\right)^{n_\tau} \quad 0 < |n_\tau| \leq 0.005$

Reheating $\Omega_{\text{GW}}^{\text{re}}(f) \propto f^{n_{\text{GW}}}$

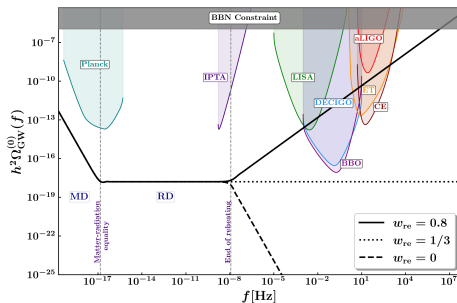
GW Spectral Tilt

$$n_{\text{GW}}(w) = n_\tau + 2 \left(\frac{w_{\text{re}} - 1/3}{w_{\text{re}} + 1/3} \right)$$

→ **Red-tilted** for $w_{\text{re}} < \frac{1}{3}$

→ **Flat-spectrum** for $w_{\text{re}} = \frac{1}{3}$

→ **Blue-tilted** for $w_{\text{re}} > \frac{1}{3} \Rightarrow$ Stiff-matter dominated



Range of $\{w_{\text{re}}, N_{\text{re}}\}$ leading to detectable GWs?

Observationally Favorable: { High r , Stiff(er) w_{re} , Low T_{re} }

Ultra-long stiff matter phase: Over-production of GWs

GWs as a Probe of Unknown Reheating History

Range of $\{w_{\text{re}}, N_{\text{re}}\}$ leading to detectable GWs in aLIGO, LISA

Journal of **C**osmology and **A**stroparticle **P**hysics
An IOP and SISSA journal

Ability of LIGO and LISA to probe the equation of state of the early Universe

Daniel G. Figueroa and Erwin H. Tanin

Institute of Physics, Laboratory of Particle Physics and Cosmology (LPPC),
École Polytechnique Fédérale de Lausanne (EPFL),
CH-1015 Lausanne, Switzerland

E-mail: daniel.figueroa@epfl.ch, ehtanin@gmail.com

Observationally Favorable: { **High** r , **Stiff(er)** w_{re} , **Low** T_{re} }

Ultra-long stiff matter phase: Over-production of GWs

GWs as a Probe of Unknown Early History

→ Reheating Dynamics is Complex!

→ Early Universe is expected to exhibit **Phase Transitions**

Even in SM of Particle Physics

1. Electron-positron Annihilation
2. QCD Phase Transition
3. Electro-Weak Phase Transition

→ **Additional BSM Phase Transitions**

+ Moduli fields, Topological defects...

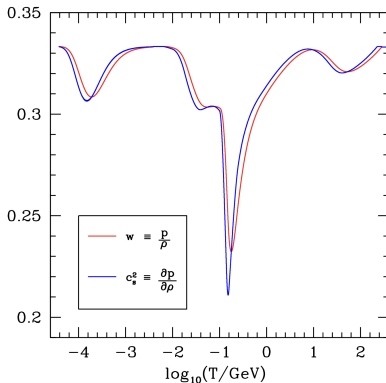
EoS of early Universe is Dynamic

**Allahverdi *et. al.* [arXiv:2006.16182]

The First Three Seconds:

A Review of Possible Expansion Histories of the Early Universe




Major Global Effort



GWs as a Probe of Unknown Reheating History

- Reheating Dynamics is Complex!
- Early Universe might exhibit Phase Transitions
- Likely involving multiple epochs with $\{w_1, w_2, \dots, w_n\}$

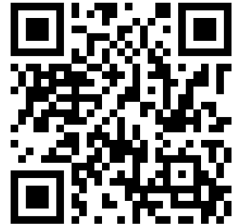
Inflationary Gravitational Waves as a probe of the unknown post-inflationary primordial Universe

Athul K. Soman ^a, Swagat S. Mishra ^b, Mohammed Shafi ^a, Soumen Basak^a

^aSchool of Physics, Indian Institute of Science Education and Research, Thiruvananthapuram, 695551, India.

^bSchool of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK.

E-mail: athul19@iisertvm.ac.in, swagat.mishra@nottingham.ac.uk,
mohammedshafi18@alumni.iisertvm.ac.in, sbasak@iisertvm.ac.in

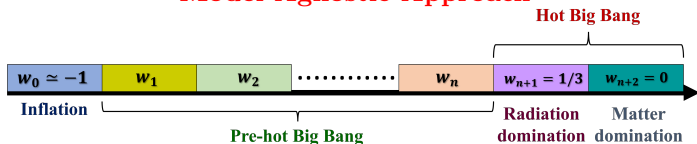


Soman, **SSM, Shafi & Basak [arXiv:2407.07956]

Multiple EoS Parameters during Reheating

Multiple transitions in the EoS after inflation

Model Agnostic Approach



Assumptions

- Instantaneous Transitions in EoS

$$w_{\text{re}} = w_1 + (w_2 - w_1) \Theta(\tau - \tau_1) + (w_3 - w_2) \Theta(\tau - \tau_2) + \dots$$

\Rightarrow Mode functions $h_k^\lambda(\tau)$ via Israel junction matching

- Large scale inflationary **GWs to be detectable** via CMB B-mode in the upcoming decade, *i.e.* $r \gtrsim 0.001$

Q. Parameter space leading to GW detection via GW observatories

Soman, **SSM, Shafi & Basak [arXiv:2407.07956] (2024)

Determining Coefficients $\{A_k, B_k\}$ in $h_k^\lambda(\tau)$

- Inflationary output as Initial conditions for Tensor modes
⇒ For any post-inflationary epoch at Hubble-entry $\tau < \tau_k$

$$h_k^\lambda(\tau_k) = h_{k, \text{inf}}^\lambda ; \quad h_k^{\prime\lambda}(\tau_k) = 0$$

- Apply Israel Junction matching conditions at transition

$$h_{k, \text{Before}}^\lambda(\tau_1^-) = h_{k, \text{After}}^\lambda(\tau_1^+) \quad (\text{Continuity})$$

$$h_{k, \text{Before}}^{\prime\lambda}(\tau_1^-) = h_{k, \text{After}}^{\prime\lambda}(\tau_1^+) \quad (\text{Differentiability})$$

Standard Cosmological transitions:

Inflation → **Reheating** → **RD** → **MD**

$$\Rightarrow w = -1 \quad \rightarrow \quad w = w_{\text{re}} \quad \rightarrow \quad w = 1/3 \quad \rightarrow \quad w = 0$$

**Allen (1988) **Sahni (1990), **Giovanni (1990s)

Solved Expressions for Coefficients $\{A_k, B_k\}$

$$A_{k,m+1} = \frac{(\alpha_{m+1} y_m)^{(\alpha_{m+1} - \frac{1}{2})}}{(\alpha_m y_m)^{(\alpha_m - \frac{1}{2})}} \left[\frac{(g_2 f_3 + g_4 f_1) A_{k,m} + (f_2 f_3 - f_4 f_1) B_{k,m}}{f_1 g_3 + g_1 f_3} \right]$$

$$B_{k,m+1} = \frac{(\alpha_{m+1} y_m)^{(\alpha_{m+1} - \frac{1}{2})}}{(\alpha_m y_m)^{(\alpha_m - \frac{1}{2})}} \left[\frac{(g_2 g_3 - g_4 g_1) A_{k,m} + (f_2 g_3 + f_4 g_1) B_{k,m}}{f_1 g_3 + g_1 f_3} \right]$$

With

$$g_1 = J_{(\alpha_{m+1} - \frac{1}{2})}(\alpha_{m+1} y_m), \quad f_1 = J_{-(\alpha_{m+1} - \frac{1}{2})}(\alpha_{m+1} y_m)$$

$$g_2 = J_{(\alpha_m - \frac{1}{2})}(\alpha_m y_m), \quad f_2 = J_{-(\alpha_m - \frac{1}{2})}(\alpha_m y_m)$$

$$g_3 = J_{(\alpha_{m+1} + \frac{1}{2})}(\alpha_{m+1} y_m), \quad f_3 = J_{-(\alpha_{m+1} + \frac{1}{2})}(\alpha_{m+1} y_m)$$

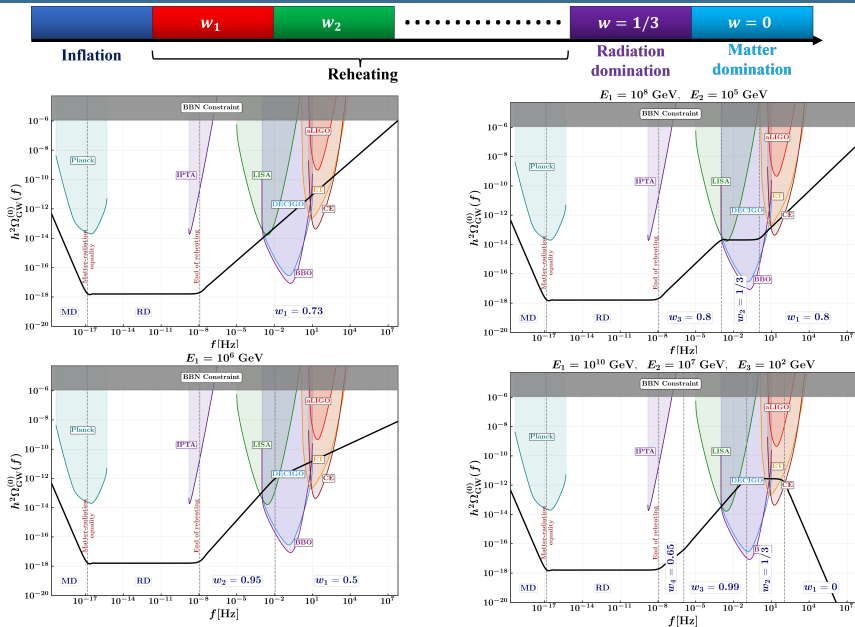
$$g_4 = J_{(\alpha_m + \frac{1}{2})}(\alpha_m y_m), \quad f_4 = J_{-(\alpha_m + \frac{1}{2})}(\alpha_m y_m)$$

$$h_{k,n}^\lambda(y) = \frac{1}{(\alpha_n y)^{\alpha_n - \frac{1}{2}}} \left[A_{k,n} J_{(\alpha_n - \frac{1}{2})}(\alpha_n y) + B_{k,n} J_{-(\alpha_n - \frac{1}{2})}(\alpha_n y) \right]$$

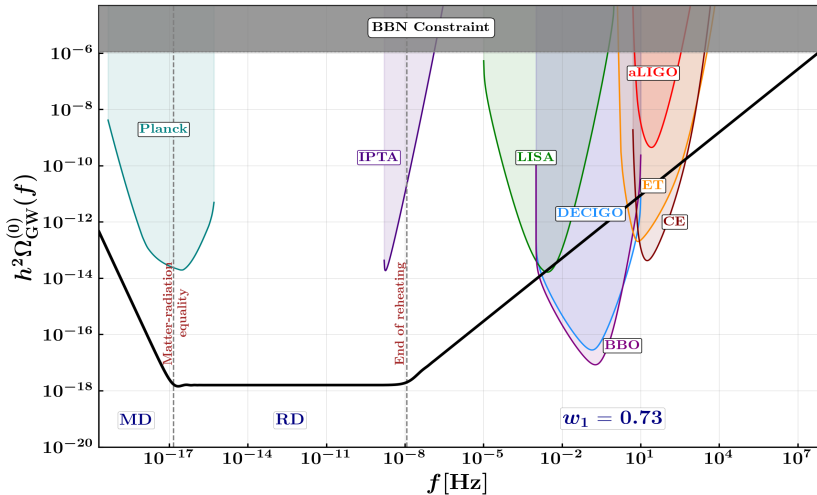
Compute Ω_{GW}

Soman, **SSM, Shafi & Basak (2024)

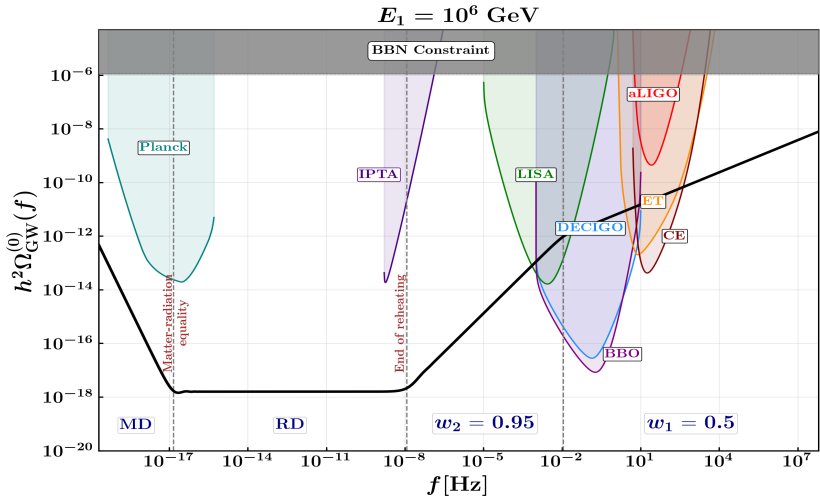
Multiple EoS Parameters during Reheating



EoS Dependence of the GW Spectrum



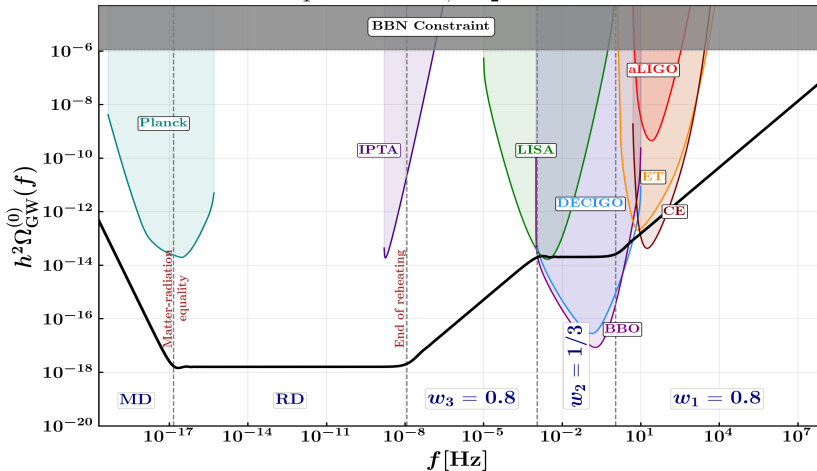
EoS Dependence of the GW Spectrum



EoS Dependence of the GW Spectrum



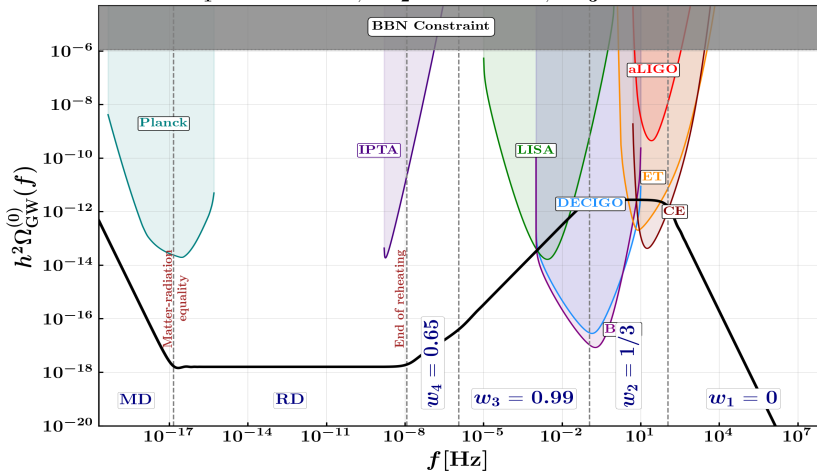
$E_1 = 10^8 \text{ GeV}, E_2 = 10^5 \text{ GeV}$



EoS Dependence of the GW Spectrum

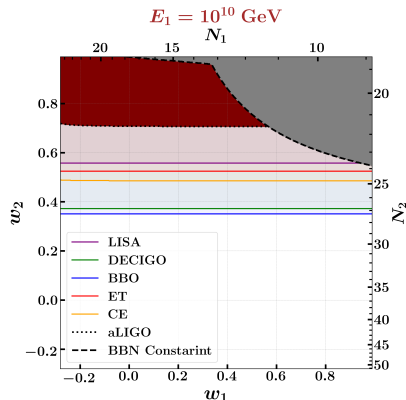
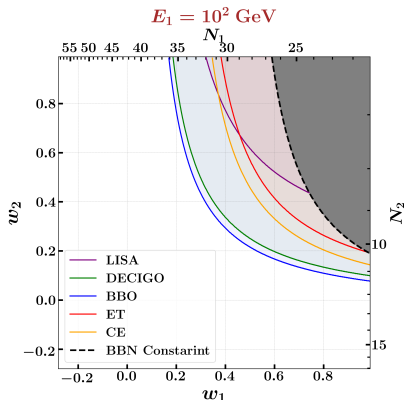


$$E_1 = 10^{10} \text{ GeV}, \quad E_2 = 10^7 \text{ GeV}, \quad E_3 = 10^2 \text{ GeV}$$



Parameter space for a single transition $w_1 \rightarrow w_2$

Low reheating temperature $E_{re} = 10 \text{ MeV}$



- Detectable parameter space: **Colour-Shaded** regions
- BBN Constraints: **Dark-Grey** regions
- LIGO Constraints: **Deep-Maroon** regions

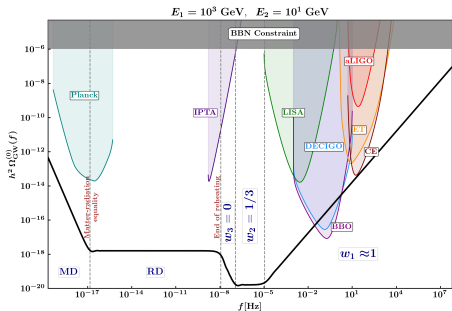
****Soman & Shafi**

****Details in [GitHub Repository](#)**

Application to a String Theory inspired Scenario

**Apers, Conlon, Copeland *et al.* [2401.04064]

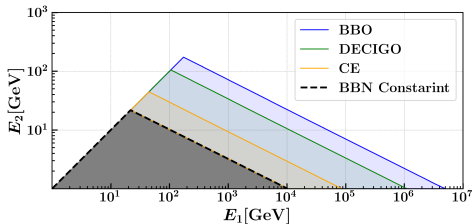
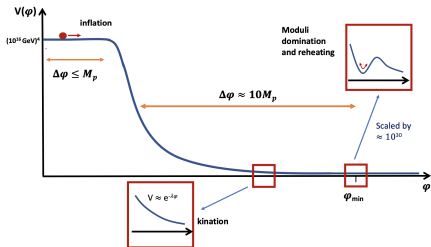
String Theory & The First-half of the Universe



Radiation-potential equality

Kinetic-potential equality

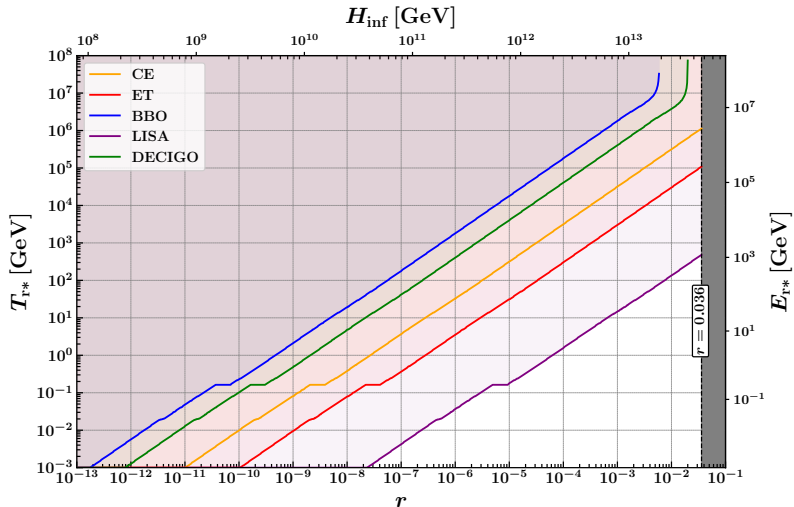
Tracker



Reheating

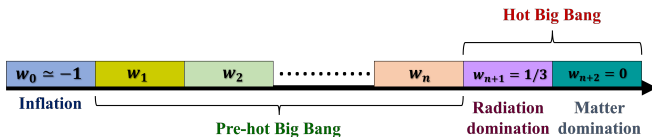
**Soman, SSM, Shafr & Basak [2407.07956]

Effect of low tensor-to-scalar ratio

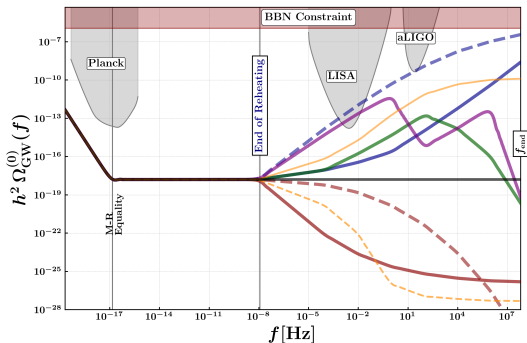


Only the non-shaded region will be detectable!

Morphological Zoo of Inflationary GW Spectra



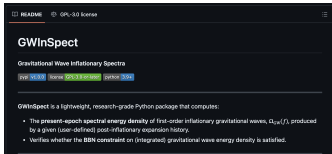
PREPARED FOR SUBMISSION TO A JOURNAL



Morphological Zoo of Inflationary Gravitational Wave Spectra imprinted by a Sequence of Post-Inflationary Epochs

Swagat S. Mishra ^{1,2},^{*} Athul K. Soman ^{3,4},^{*}

¹School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK.
²Cosmology, Gravity, and Astroparticle Physics Group, Center for Theoretical Physics of the Universe (CTPU-CGU), Institute for Basic Science (IBS), Daejeon, 34126, Korea.
³International School for Advanced Studies (SISSA), via Bonomea 265, 34136 Trieste, Italy.
 E-mail: swagat.mishra@nottingham.ac.uk, skuruvai@siissa.it



PYTHON Package: **GWInSpect**

** **SSM** & Soman (2025) [arXiv:2510.25672]

Ongoing & future work on GWs

- Application to **concrete phenomenological scenarios**
- **Smooth (non-instantaneous) transitions** of EoS parameters
- **Scalar-induced (2nd-order) GWs** for multiple EoS
- **Preheating, Reheating & other pre-hot Big Bang GW sources**
- **Breaking degeneracies** between various **stochastic GW signals**

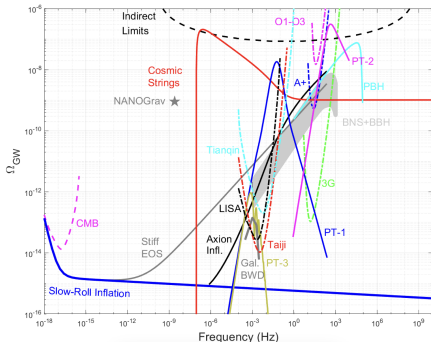
Wide variety of EU Signals

Detection of Early-Universe Gravitational Wave Signatures and Fundamental Physics

**Caldwell *et. al.*

[arXiv:2203.07972]

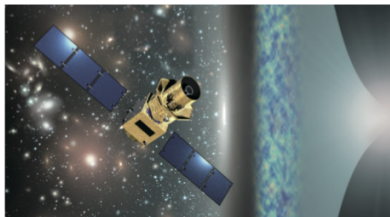
Snowmass White Paper



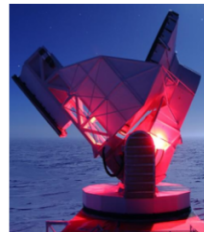
Upcoming Observational Missions



Simons Observatory



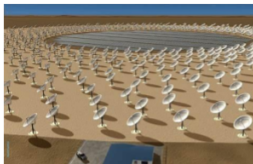
LITEBird



BICEP-II/KECK



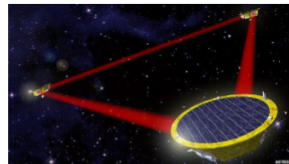
CMB S-4



Square Kilometer Array



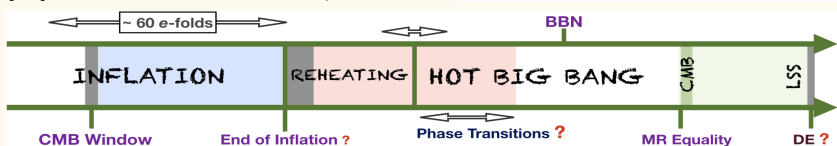
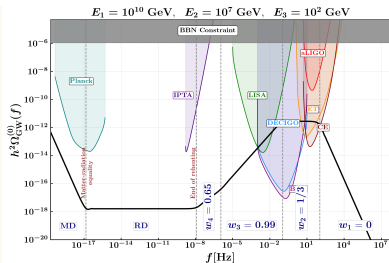
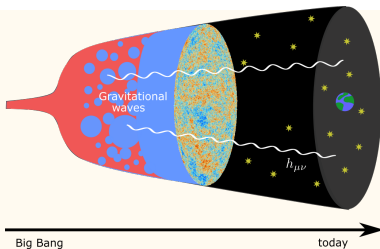
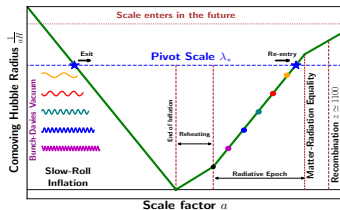
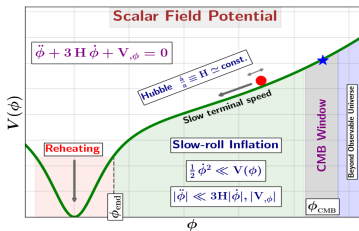
South Pole Telescope



LISA

EXTRA SLIDES

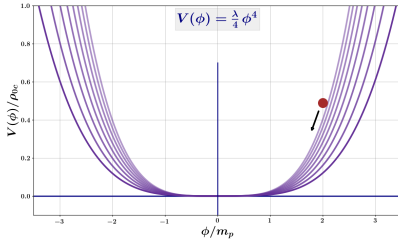
Probing Inflation & Post-inflationary Dynamics with GWs



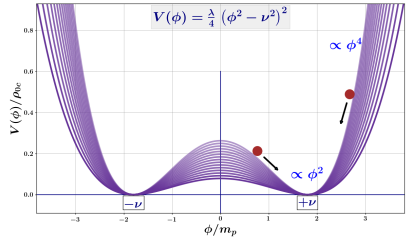
Zoo of Slow-roll Inflationary Potentials

$\{r, n_s\} \leftarrow$ Shape of the inflaton potential

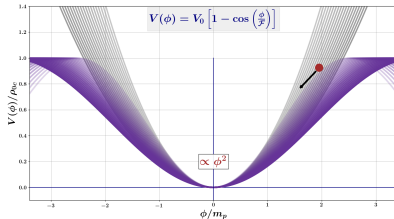
Monomial Potentials



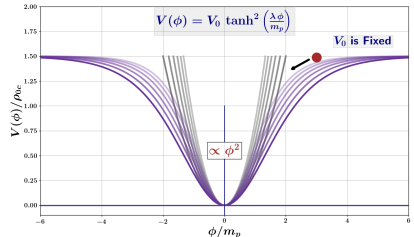
Symmetry-breaking Potentials



PNGB Axionic Potentials



Asymptotically-flat Potentials



Planck 2018 (+ BICEP/Keck) & ACT 2025

Planck Modes:

Multipoles : $l \in [2, 2500]$

Comoving Scales :

$$\Rightarrow k \in [0.0005, 0.5] \text{ Mpc}^{-1}$$

Planck Results \Rightarrow $n_s \simeq 0.965$

ACT Modes:

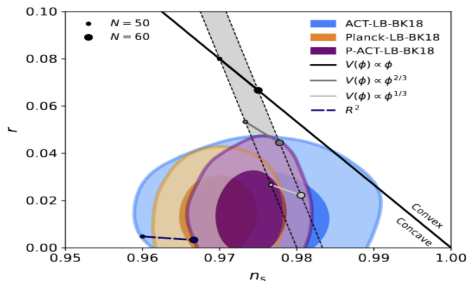
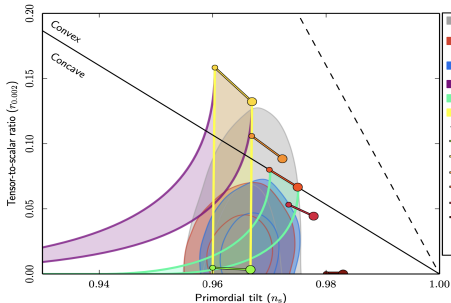
Multipoles : $l \in [600, 4000]$

Comoving Scales :

$$\Rightarrow k \in [0.05, \gtrsim 1] \text{ Mpc}^{-1}$$

ACT Results \Rightarrow $n_s \simeq 0.974$

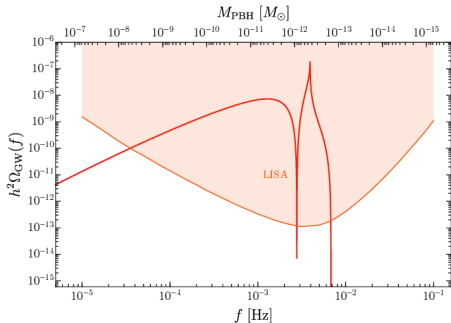
\Rightarrow Slightly more scale-invariant



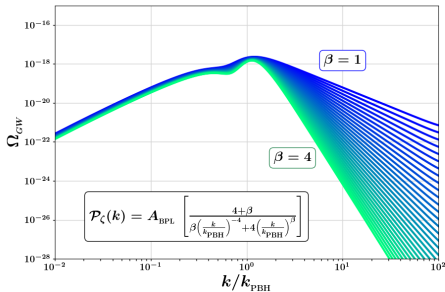
Scalar-induced second order GWs

$$h_k^{(2)''} + 2 \left(\frac{a'}{a} \right) h_k^{(2)'} + k^2 h_k^{(2)} = \mathcal{S}^{(1)}(k, \tau) \propto \int_{\vec{q}} \zeta_{\vec{k}}^{(1)}(\vec{q}) \zeta_{\vec{k}}^{(1)}(\vec{k} - \vec{q})$$

$$S(k, \tau) = 4 \int \frac{d^3 q}{(2\pi)^3} e_{lm} q^l q^m \left[\frac{5+3w}{3(1+w)} \Phi_q \Phi_{k-q} + \frac{2}{3(1+w)} \left(\frac{\Phi_q \Phi'_{k-q} + \Phi'_q \Phi_{k-q}}{\mathcal{H}} + \frac{\Phi'_q \Phi'_{k-q}}{\mathcal{H}^2} \right) \right]$$



Dirac Delta function \mathcal{P}_ζ



Broken Power-law \mathcal{P}_ζ