Detectable Gravitational Waves from Preheating and Particle Physics Phenomenology

The 2nd AEI and the 10th KIAS Workshop on BSM

Novermber 15, Jeju Island

Pankaj Saha

SEOULTECH

SEOUL NATIONAL UNIVERSITY OF SCIENCE & TECHNOLOGY

based on arXiv:2203.03059, 2211.XXXXX ...

in collaboration with Anish Ghoshal and Myeonghun Park

Introduction: Inflation and reheating

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2. The inflation ends with inflaton decaying into radiation and other matter species in a phase of reheating.

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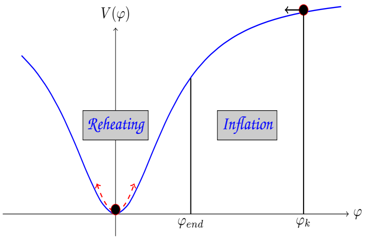
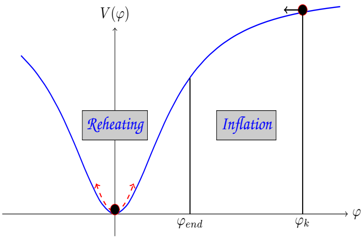
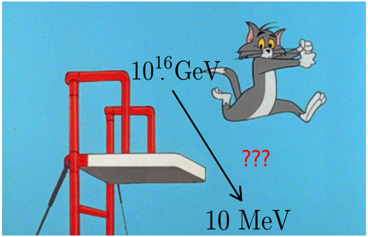


Introduction: Inflation and reheating

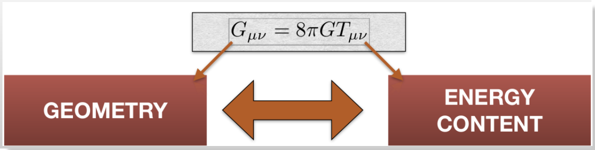
1. The universe expanded quasi-exponentially in a phase of Inflation in the early universe.
2. The inflation ends with inflaton decaying into radiation and other matter species in a phase of reheating.
3. Inflation (typical energy scale 10^{16}GeV) has several observables while there are no direct observables from reheating phase (The lower bound on reheating temperature is 10 MeV so as not to spoil the BBN).
4. Gravitational waves provide a *fresh set of eyes* for observing the primordial dark ages and to explore the connections between Particle Physics and Cosmology.



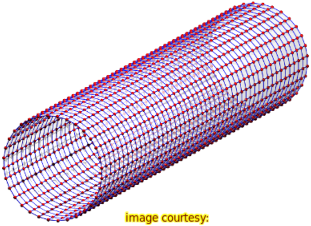


Introduction: Gravitational Waves

❶ General Relativity: *Space-time tells matter how to move; matter tells space-time how to curve*.



❷ Any changes in matter distribution changes the local space-time geometry (local expansion and contraction of space) and propagates away from the source as a wave travelling at the speed of light.



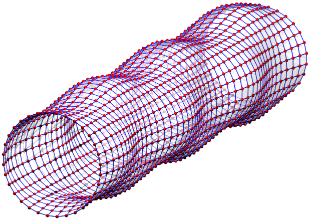


image courtesy:
www.einstein-online.info

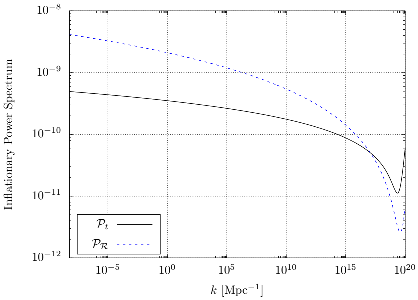
Gravitational Waves in the Early Universe

Inflationary GWs

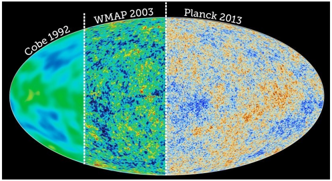
❶ Inflationary observables: The scalar spectrum (CMB anisotopic patterns) and the Tensor spectrum–>The Gravitational waves (CMB B-mode).

$$\mathcal{P}_{\mathcal{R}} = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH} ;$$

$$\mathcal{P}_t = \frac{2}{\pi^2}\frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH}$$



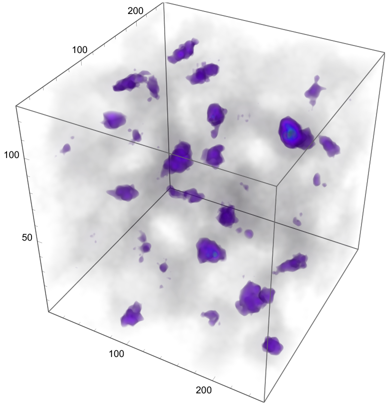
❷ Inflationary GWs spectrum: It is generated from the quantum vacuum and get stretched into classical stochastic waves. Presents the cleanest prediction of inflation.

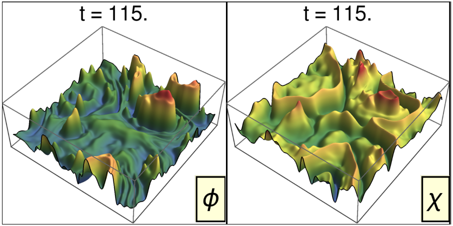


Gravitational Waves from Early Universe

GWs during preheating

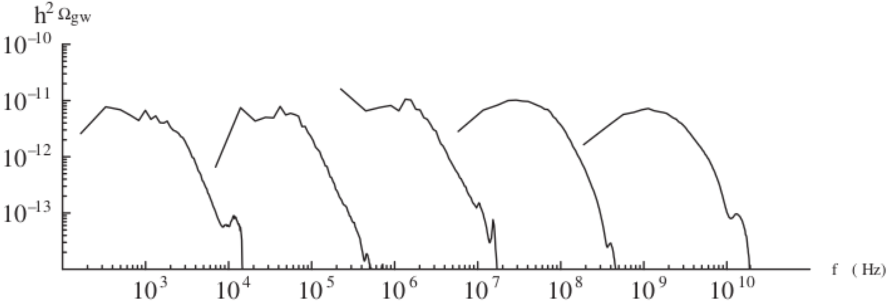
1. Add complementary channel to inflationary GWs.
2. GWs production during preheating is a consequence of the scattering of the classical inhomogeneities.
3. Observed frequency depends on the Hubble (typically high frequency): $f_{\text{peak}} \propto \sqrt{H}$





Detectable Gravitational Waves from Preheating

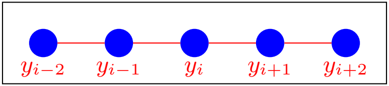
- The effective potential during reheating: $V(\phi) \propto m^2\phi^2$
- Peak frequency: $f_{\text{peak}} \propto \sqrt{H} \propto \sqrt{m}$
- Take m^2 as a free parameter.



Easther, Giblin, Jr., and Lim **PRL** 99, 221301 (2007)

Gravitational Waves in Lattice

Finite Difference Codes:
LATTICEEASY
Defrost
HLATTICE
GABE
$\mathcal{C}$osmo$\mathcal{L}$attice



$$\frac{d^2y}{dx^2} \approx \frac{y_{i+1} - 2y_i + y_{i-1}}{(\delta x)^2}$$

pseudo-spectral code:
PSpectRe

$$\boxed{\nabla^2 \to -\vec{k} \cdot \vec{k}}$$

Free from differencing noise.

Gravitational Waves in Lattice

- The Model: $V = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2$

→ The EoMs

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + \frac{\partial V}{\partial \phi} = 0,$$

$$\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \frac{\partial V}{\partial \chi} = 0,$$

$$H^2 = \frac{1}{3M_{\mathrm{Pl}}^2}\left(V + \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\chi}^2 + \frac{1}{2a^2}|\nabla\phi|^2 + \frac{1}{2a^2}|\nabla\chi|^2\right),$$

- Gravitational waves being transverse and traceless (TT) part of the metric perturbation in the synchronous gauge sourced by TT-part of the anisotropic stress of the scalar field ($\Pi_{ij} = [\partial\phi_i\partial\phi_j]^{\mathrm{TT}}$)

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} + \frac{\partial V}{\partial \phi} = \frac{2}{M_{\mathrm{Pl}}^2 a^2}\Pi_{ij}$$

The observed GWs spectrum today:

- The GW energy density is given by

$$\rho_{\rm GW}(t) = \frac{M_{\rm Pl}^2}{4}\langle \dot{h}_{ij}(\mathbf{x},t)\dot{h}_{ij}(\mathbf{x},t)\rangle_{\mathcal{V}}, \tag{1}$$

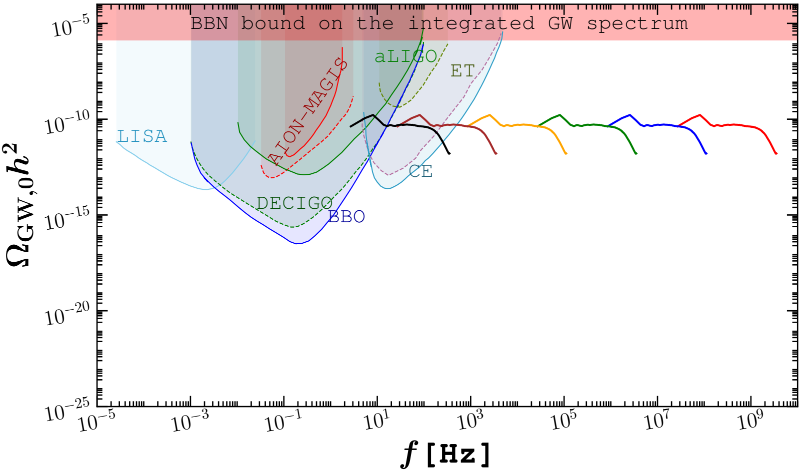
- The spectrum of the energy density of GWs (per logarithmic momentum interval) observable today:

$$\begin{aligned}\Omega_{{\rm GW},0}h^2 &= \frac{h^2}{\rho_{\rm crit}}\frac{d\rho_{\rm GW}}{d\ln k}\bigg|_{t=t_0} = \frac{h^2}{\rho_{\rm crit}}\frac{d\rho_{\rm GW}}{d\ln k}\bigg|_{t=t_e}\frac{a_e^4\rho_e}{a_0^4\rho_{{\rm crit},0}} \\ &= \Omega_{{\rm rad},0}h^2\Omega_{{\rm GW},e}\left(\frac{a_e}{a_*}\right)^{1-3w}\left(\frac{g_*}{g_0}\right)^{-1/3}, \end{aligned} \tag{2}$$

- The observed frequency corresponding to a wave vector k is

$$f = 1.32\times 10^{10}\frac{k}{\sqrt{M_{\rm Pl}H_e}} \tag{3}$$

Observable GWs spectrum from Preheating

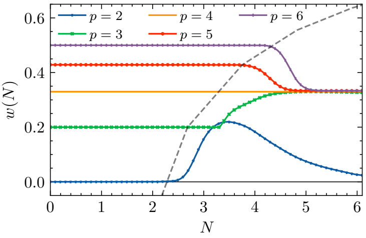


Phenomenology-I: Inflaton as Dark Matter

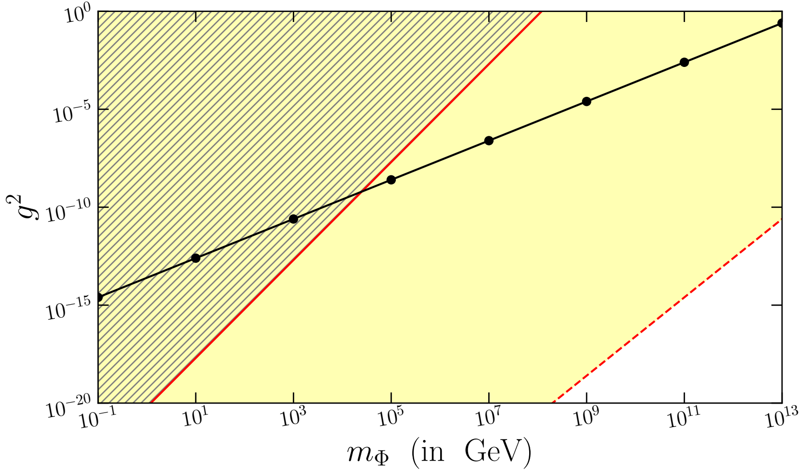
1. Incomplete inflaton decay for massive inflaton with four-legged interactions.
2. The frozen inflaton component can act as dark matter candidate. Reheating will complete via higgs coupled to inflaton.
3. The ratio of the average energy density of this oscillation mode to the number density of photons being given by (Liddle 2008):

$$\xi_{\mathrm{dm},0} \equiv \frac{\rho_\phi}{n_{\gamma,0}} \simeq 0.04 \left(\frac{m_\Phi}{M_{\mathrm{Pl}}}\right)^{1/2} \left(\frac{\Phi_*}{M_{\mathrm{Pl}}}\right)^2 M_{\mathrm{Pl}}, \tag{4}$$

3. The current dark matter per photon $\xi_{\mathrm{dm},0} = 1.1 \times 10^{-27} M_{\mathrm{Pl}}$



Result



10^0
10^{-5}
10^{-10}
10^{-15}
10^{-20}
g^2
10^{-1}
10^1
10^3
10^5
10^7
10^9
10^{11}
10^{13}
m_Φ (in GeV)

Phenomenology-II: Matter-antimatter Asymmetry

- A complete decay of inflaton is possible via perturbative decay term (The original proposal of reheating).
- Inflaton can decay into right-handed neutrinos. The successive decays of the right-handed neutrinos into Higgs and lepton doublets will bring in efficient reheating and can also generate the baryon asymmetry of the universe via non-thermal leptogenesis.
- Preheating produces a non-zero intial density of the daughter fields, thereby enhances the baryon-to-photon ratio compared to the ordinary reheating scenario.
- The parameters fixed from preheating are jointly probed in GWs detectors and the measurement for baryon asymmetry.

The Perturbative decay of inflaton

- The Boltzmann eqs (Antusch 2018):

$$\dot{n}_\phi(t) + 3H(t)n_\phi(t) + \Gamma_\phi n_\phi(t) = 0,$$
$$\dot{n}_N(t) + 3H(t)n_N(t) + \Gamma_N n_N(t) - 2\Gamma_\phi n_\phi(t) = 0,$$
$$\dot{\rho}_{\rm rad}(t) + 4H(t)\rho_{\rm rad}(t) - \Gamma_N m_N n_N(t) - \left(1 - 2\frac{m_N}{m_\phi}\right)\Gamma_\phi m_\phi n_\phi(t) = 0,$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_{\rm Pl}^2}\left(\rho_\phi + \rho_N + \rho_{\rm rad}\right) \tag{5}$$

- Equation for the evolution of the effective lepton number density n_L (Antusch 2010):

$$\dot{n}_L(t) + 3H(t)n_L(t) = \epsilon\, \Gamma_N n_N(t) \tag{6}$$

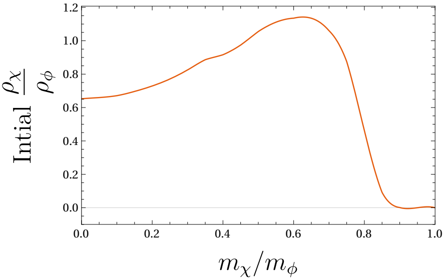
ϵ is the CP-violation per RH-neutrino decay.

Possible extensions

- The baryon to photon ratio .

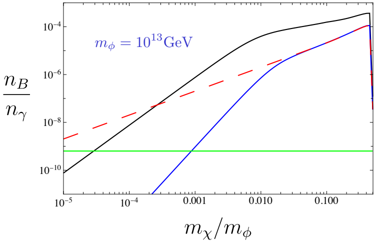
$$\left|\frac{n_B}{n_\gamma}\right| \sim \left|\frac{n_L}{s}\right| = 10^{-15}\frac{T_{\rm re}}{\rm GeV}\frac{m_\chi}{m_\phi},, \tag{7}$$

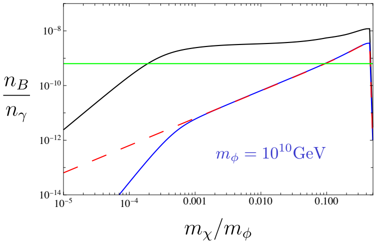
- Preheating produce a non-zero initial density of the daughter fields.

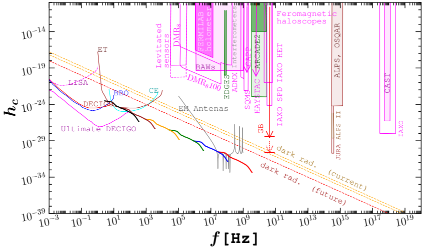


Result

Observed baryon-to-photon ration and corresponding GWs strain.







Summary and Outlook

What we observe is not nature in itself but nature exposed to our method of questioning—Werner Heisenberg

- ✍ In absensce of other observables/signatures, Gravitational waves can help us explore the primordial dark ages.
- ✍ The frozen inflaton component can solve the mystery of dark matter in the universe.
- ✍ The successive deay of right-handed neutrino can solve the puzzle of matter-antimater asymmetry of our universe.
- ✍ GWs are useful tool to explore other particle physics and cosmology connection.

—— Thank You! ——