Preheating: Characteristics and Constraints

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based on

2412.17359 with Yuko Urakawa

2310.13060 and 2412.12287 with Yanou Cui and Evangelos I. Sfakianakis

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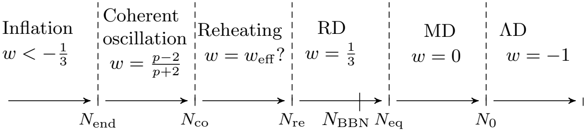
- A. Effects of local features in the inflationary potential on the preheating dynamics.
- B. Fragmentation of coherent scalar and their signatures.

Introduction

What is Inflation?



- ☛ Inflation is a period of exponential expansion of the universe in a state of negative pressure. i.e., $\ddot{a} > 0$,
- ☛ The 'right amount of inflation' solves the 'horizon' and 'flatness' problems and provides the initial condition for hot big bang evolution.
- ☛ The quantum fluctuations in the inflaton generates the seed for large scale structures.

Inflation and scalar field

- A period of negative pressure is easily achieved with a scalar field.

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi); \quad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

- Equations of motion

  (Einstein Field Equations in FLRW background):

  - Friedmann and Raychaudhuri equation

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3\mathrm{M_p^2}}\rho = \frac{1}{3\mathrm{M_p^2}}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

$$\dot{H} + H^2 = \left(\frac{\ddot{a}}{a}\right) = -\frac{1}{6\mathrm{M_p^2}}\left[\rho + 3p\right]$$

  - Klein-Gordon Equation
    $\ddot{\phi} + 3H\dot{\phi} + V' = 0.$

- Slow-roll parameters:

$$\epsilon_V = \frac{\mathrm{M_p^2}}{2}\left(\frac{V'}{V}\right)^2; \quad \eta_V = \mathrm{M_p^2}\frac{V''}{V}$$

- The amount of expansion ('efolds'):

$$\Delta N_{if} = \ln\left(\frac{a_f}{a_i}\right) = \int_{\phi_i}^{\phi_f} \frac{1}{\sqrt{2\epsilon_V}}\frac{|d\phi|}{\mathrm{M_p}}$$

What is the shape of inflationary potential

- Any potential satisfying the slow-roll conditions can sustain inflationary Universe.
- Simple potentials:
  - Quadratic: $\frac{1}{2}m^2\phi^2$
  - Quaratic: $\frac{1}{4}\lambda\phi^4$
- Observations can rule-out the (piece-wise) shape of the potentials.
- Potentials with plateaus on the large field ranges are preferred observationally.

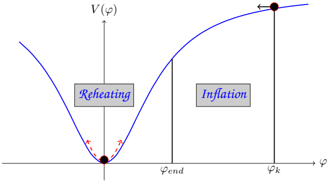


Figure: Inflation and reheating

Inflationary observables

- Perturbation to the scalar field: $\phi(\vec{x},t) = \phi_0(t) + \delta\phi(\vec{x},t)$
- Perturbation in the metric:

$$ds^2 = a(\eta)^2 \left[-(1+2\Psi(x,\eta))d\eta^2 + (1-2\Psi(x,\eta))d\vec{x}^2\right].$$

- The gauge-invariant combination-the curvature perturbation $\mathcal{R} = \Psi + \frac{H}{\dot{\phi}_0}\delta\phi$
- We quantize the curvature perturbation (some suitable re-scaled quantity $v \equiv z\mathcal{R}$, with $z = M_{\rm Pl} a\sqrt{2\epsilon_1}$.)
- Similarly we quantize the (already gauge invariant) tensor perturbation h_{ij}.

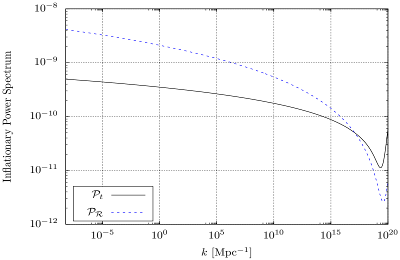
Inflationary observables:

The Scalar spectrum (CMB anisotopic patterns) and the Tensor spectrum–>The Gravitational waves (CMB B-mode).

$$\mathcal{P}_{\mathcal{R}} = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH} = A_s\left(\frac{k}{k_*}\right)^{n_s-1};$$

$$\mathcal{P}_t = \frac{2}{\pi^2}\frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH} = A_t\left(\frac{k}{k_*}\right)^{n_t};$$

- Spectral tilt $n_s = 1 - 6\epsilon_V + 2\eta_V$
- Scalar-to-tensor ratio $r = \frac{\mathcal{P}_t}{\mathcal{P}_{\mathcal{R}}} = 16\epsilon_V$



At the Planck pivot scale k_*

- $A_s = (2.196 \pm 0.060) \times 10^{-9}$.
- $n_s = 0.9649 \pm 0.0042$
- $r_{0.002} < 0.056$

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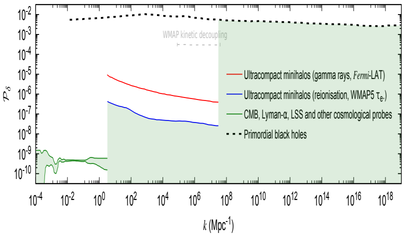

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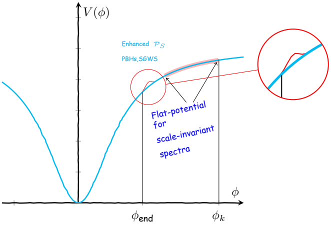
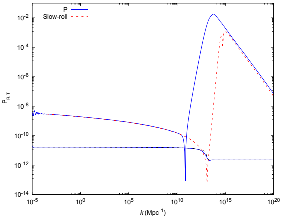
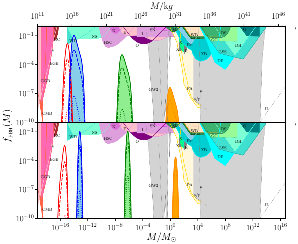
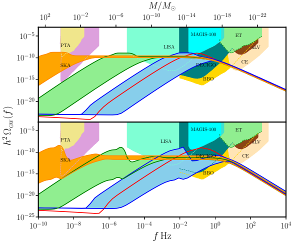
Potentials with features: rich phenomenology



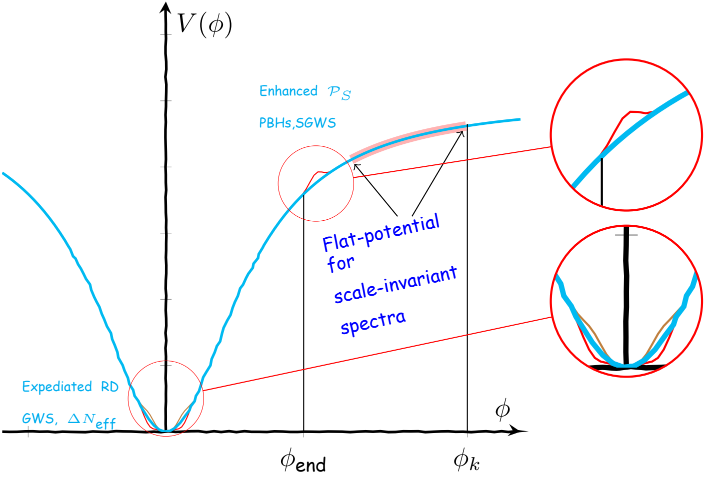




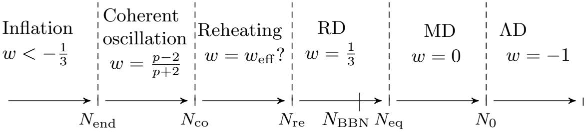


[H. V. Ragavendra, PS, L. Sriramkumar and J. Silk 2021]

Potentials with small-scale features: rich phenomenology?



Reheating after Inflation



- The colossal expansion during inflation leaves the Universe in a state of void with all of the energy in the coherently oscillating inflaton.
- The Standard Big Bang requires a radiation dominated Universe at around 10 MeV.
- The inflation decay to produce other fields and we recover the radiation dominated universe.
- The reheating stage is episodic: The non-linear preheating phase and the perturbative reheating.

Original Idea: Perturbative Reheating

- The *"old"* theory of reheating developed immediately after the idea of inflationary universe. (Abbott 1982, Dolgov 1982)
- Inflaton was considered as a collection of scalar particles each with a finite probability of decay.
- Inflaton decay to different channels depending upon the coupling $\nu\sigma\phi\chi^2$, $h\phi\bar{\psi}\psi$ (which associated tree-level decay-width that contributte to the total decay width $\Gamma_{\rm tot} = \Gamma_{\phi\to\chi\chi} + \Gamma_{\phi\to\bar{\psi}\psi}$).
- Reheating ends when $H = \Gamma_{\rm tot}$.
- Reheating temperature: $T_{\rm re} \simeq \sqrt{\Gamma_{\rm tot} M_{\rm Pl}} > 10$ MeV.

Preheating after Inflation

Kofman, Linde, Starobinsky 1994, 1997

- After inflation, the homogeneous inflaton field oscillates coherently.
- Decays to other field depending upon their coupling to inflaton.

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu\phi)^2 - V(\phi)}_{\text{Inflaton}} + \underbrace{\frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}m_\chi^2\chi^2}_{\text{Scalar field}} - \underbrace{\frac{1}{2}g^2\phi^2\chi^2}_{\text{Interaction term}} \quad (1)$$

- Quantum particle production in the presence of time dependent classical background.
- The mode functions for scalar field($a^{6/(n+2)}\chi_k = X_k$) satisfy Hill/Mathieu equation:

$$\ddot{X}_k + \omega_k^2 X_k = 0; \quad (2)$$

$$\omega_k^2 \equiv \frac{k^2}{a^2} + g^2\phi^2 \quad (3)$$

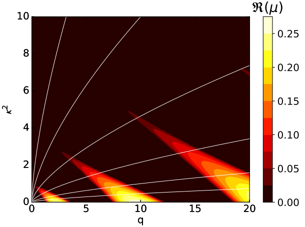
- The Hill/Mathieu equations

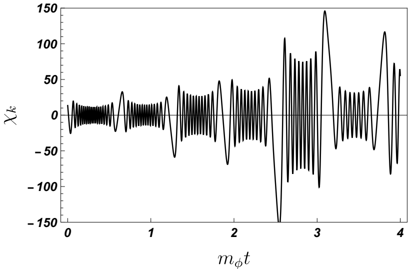
$$\ddot{X}_k + \left(\kappa^2 + q\phi(t)^2\right) X_k = 0$$

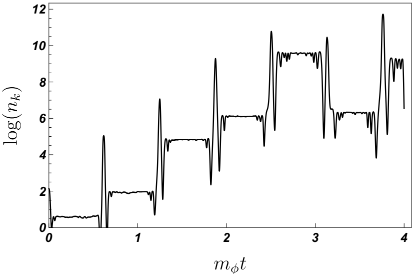
shows parametric growth depending upon the parameter (κ, q).

Parametric Resonance

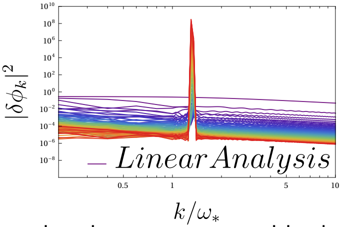
- The Mathieu/Hill has the solution: $X_k \propto e^{\mu t}$, μ is the Floquet co-efficient.
- The bands show the region in the (q,κ^2) space where the solution will have exponential growth.

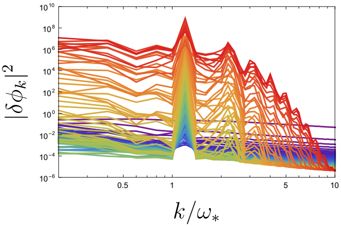






Backreaction and rescattering





The produced quanta grow and back-reacts: shutting down preheating.

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi + g^2\langle\chi^2\rangle\phi = 0, \tag{4}$$

$$\langle\chi^2\rangle = \frac{1}{2\pi}\int dk k^2 |\chi_k|^2. \tag{5}$$

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + g^2\phi_0^2(t)\right)\chi_k = -\frac{g^2\phi_0(t)}{(2\pi)^3}\int d^3k' \chi_{\mathbf{k}-\mathbf{k}'}\delta\phi_{\mathbf{k}'} - \frac{g^2}{(2\pi)^3}\int d^3k' d^3k'' \chi_{\mathbf{k}-\mathbf{k}'+\mathbf{k}''}\delta\phi_{\mathbf{k}'}\delta\phi_{\mathbf{k}''} \tag{6}$$

The Hartree approximation corresponds to neglecting the scattering between Fourier modes.

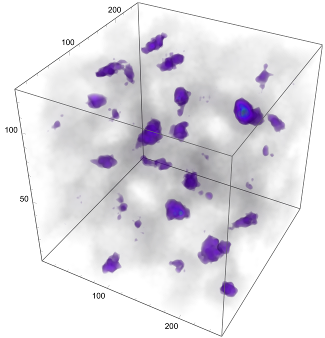
Preheating: Lattice Simulation

- The energy density of the universe just after inflation is in the form of homogeneous inflaton field.
- This energy starts decaying into fluctuations of the inflaton and other fields at the onset of preheating.
- The initial stage of preheating is marked by exponential growth of decay product due to resonance.
- The production of these highly inhomogeneous non-thermal products continues until back-reaction effects renders the preheating inefficient.
- The system is highly non-linear and we have to resort to numerical schemes. Also, the effects of back-reaction can be incorporated numerically.

Fragmentation of coherent scalar source GWs

- The scattering of the classical inhomogeneities from coherent scalar fragmentation lead to Gravitational waves.
- Add complementary channel to other sources (inflationary GWs, GWs from PT).
- Observed frequency depends on the typical Hubble $f_{\text{peak}} \propto \sqrt{H} \propto \sqrt{m_{\text{Scalar}}}$

[Easther, Giblin, Jr., and Lim 2007]



Gravitational Waves in Lattice

- The EoMs

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + \frac{\partial V}{\partial \phi} = 0,$$
$$\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \frac{\partial V}{\partial \chi} = 0,$$
$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(V + \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\chi}^2 + \frac{1}{2a^2}|\nabla\phi|^2 + \frac{1}{2a^2}|\nabla\chi|^2\right),$$

- 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 fields ($\Pi_{ij} = \sum_a \partial f_i^{(a)} \partial f_j^{(a)}$])

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

The observed GWs spectrum today:

- The GW energy density is given by

$$\rho_{\rm GW}(t) = \frac{M_{\rm Pl}^2}{4} \langle \dot{h}_{ij}(\mathbf{x},t) \dot{h}_{ij}(\mathbf{x},t) \rangle_{\mathcal{V}}, \tag{7}$$

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

$$\begin{aligned} \Omega_{\rm GW,0} h^2 &= \frac{h^2}{\rho_{\rm crit}} \frac{d\rho_{\rm GW}}{d\ln k}\bigg|_{t=t_0} = \frac{h^2}{\rho_{\rm crit}} \frac{d\rho_{\rm GW}}{d\ln k}\bigg|_{t=t_e} \frac{a_e^4 \rho_e}{a_0^4 \rho_{\rm crit,0}} \\ &= \Omega_{\rm rad,0} h^2 \Omega_{\rm GW,e} \left(\frac{a_e}{a_*}\right)^{1-3w} \left(\frac{g_*}{g_0}\right)^{-1/3}, \end{aligned} \tag{8}$$

- The observed frequency corresponding to a wave vector k is

$$f = 1.32 \times 10^{10} \frac{k}{\sqrt{M_{\rm Pl} H_e}} \tag{9}$$

Summary of preheating

A. Behavior of the EOS parameter.

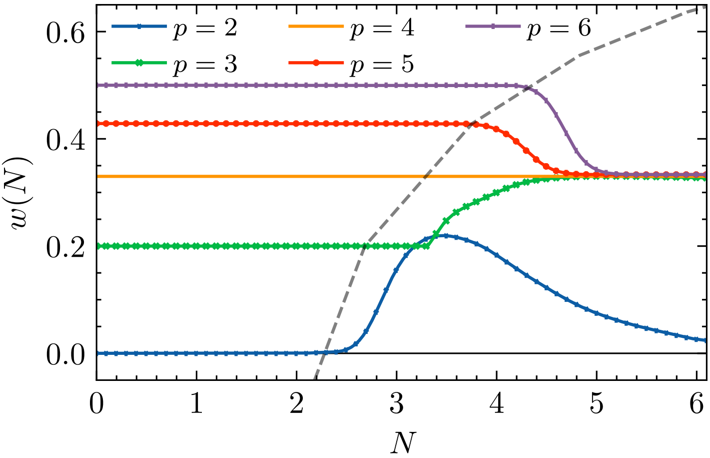
A typical scalar potential around the minima can be described by a simple power-law behavior $V(\phi) \propto \phi^n$. The EOS for preheating for a system dominated by such a scalar field shows the following pattern:

(i) At the initial stage of coherent oscillation of the scalar condensate, the effective oscillation averaged EOS is $w = (n-2)/(n+2)$ [Mukhanov 2005].

(ii) For scalar field models with $n \geq 3$, $w \to 1/3$ irrespective of the coupling [Lozanov 2016h,Lozanov 2017,Maity 2018].

(iii) For quadratic models with four-legged interactions, EoS initially increases from zero, reaching a maximum of around $w \sim 0.3$, and eventually falls back to zero. If we consider a trilinear interaction, the EOS, on the contrary, jumps to a plateau value and keeps a constant value [Dufaux 2006]. However, the EOS never reaches the radiation EOS after preheating.

Evolution of EOS during preheating: Long-time simulation



Summary of preheating

B. Other general characteristics

(i) Consists of three distinct phases:
   1. Parametric Resonance,
   2. Non-linear phase and back-reaction.
   3. Saturation.

(ii) The final-stage is likely described by perturbative reheating.

(iii) Source high-frequency GWs from classical inhomogeneities.

Preheating with potential features

What type of features will be helpful for us: Some observations

1. Preheating is really a small-scale phenomena. The amplitude reduces to $1/10$ of its initial amplitude just after the first oscillation.
2. Preheating with potential terms higher than ϕ^2 is '*better*'.
3. We should not change the potential before the end of inflation.
4. As the inflaton amplitude is decreasing, the features should be in a place such that their effect is imprinted on preheating for sufficient duration.

Preheating with potential features

- We take the *base* $m^2\phi^2$ potential with Gaussian steps/bumps at $\pm\phi_S$

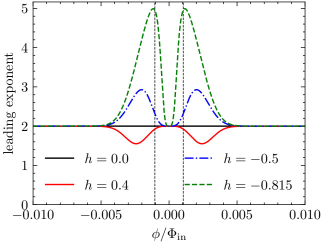
$$V(\phi) = V_0(\phi)\left(1 + \sum_i \delta_i(\phi)\right)$$

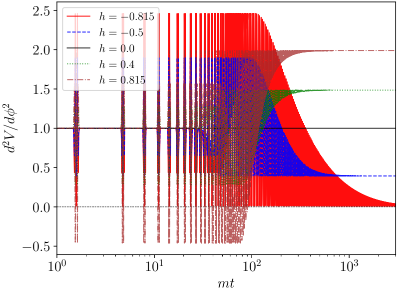
$$\begin{aligned} V(\phi) &= \frac{1}{2}m^2\phi^2\left(1 + h\exp\left(-\frac{1}{2}\frac{(\phi-\phi_S)^2}{\sigma^2}\right) + h\exp\left(-\frac{1}{2}\frac{(\phi+\phi_S)^2}{\sigma^2}\right)\right), \\ &= \frac{1}{2}m^2\phi^2\left(1 + 2h\exp\left(-\frac{1}{2}\frac{\phi^2+\phi_S^2}{\sigma^2}\right)\cosh\left(\frac{\phi_S\,\phi}{\sigma^2}\right)\right) \end{aligned}$$

- Emergent higher-power terms at small field values modify the preheating dynamics without altering the model prediction on CMB Scales.

Emergent higher-power terms

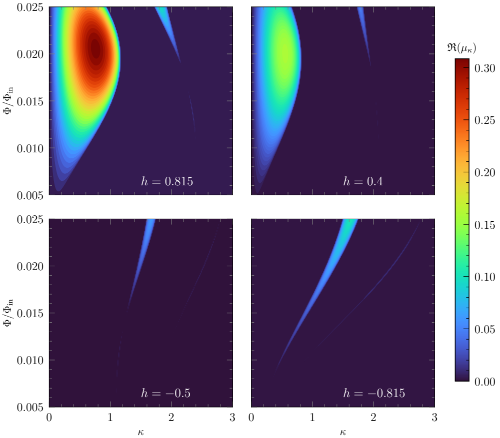
- There emerges higher-power terms $V(\phi) > |\phi|^2$.
- The effective mass decreases for dip terms (helping energy dilution for the inflaton component).





Self-Resonance improves the overall preheating

- Due to the emergent higher-power terms, there is self-resonance in the ϕ-sector.



Inflaton amplitude

- Large inflaton amplitude as we decreases h make the interaction $g^2\phi^2\chi^2$ last longer.

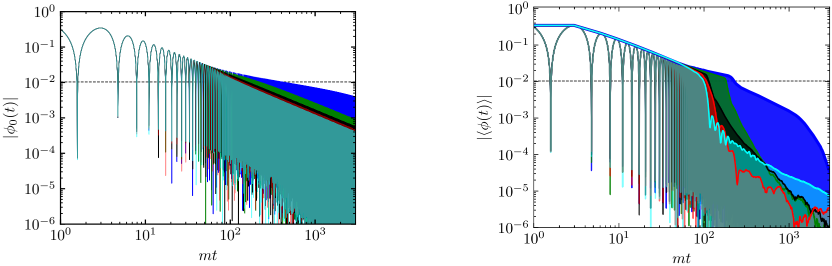
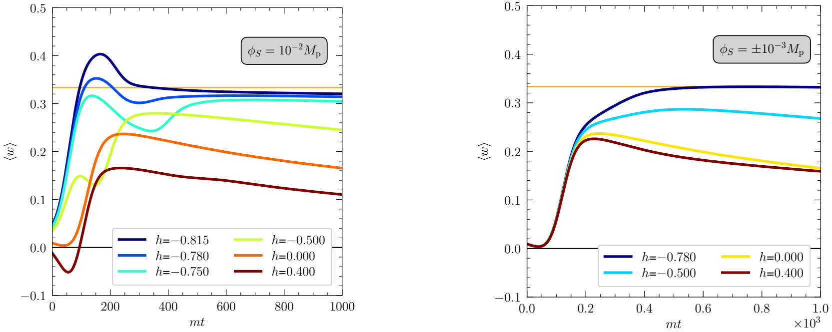
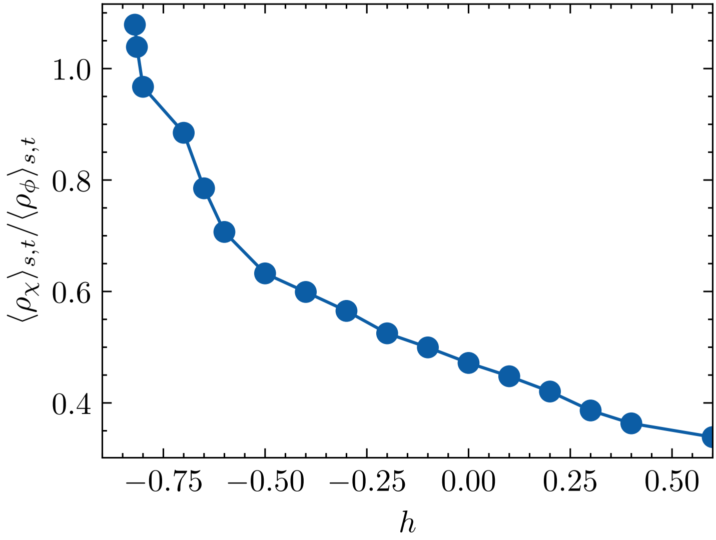


Fig: Inflaton amplitude from back-ground solution (left) and full-numeric solution for h (from blue, green, black, red and cyan for $h = -0.815$, -0.5, 0.0, 0.4, and -0.815, respectively).

- Evolution of the EoS after inflation with $m^2\phi^2$-inflation.
- Moving the steps closer to the minima will stabilize the EoS.
- Trilinear interaction ($\phi\chi^2$) can also stabilize the EOS.



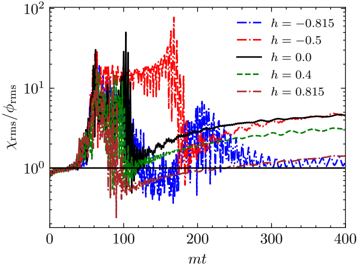
Improved energy-transfer with features



Self-resonance after quadratic inflation

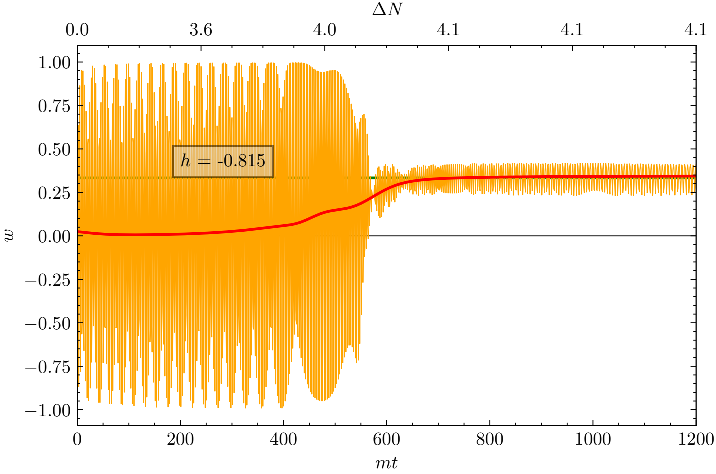
High frequency GWs

- The initial phase of the preheating will be identical to the base case, the χ sector initially drives the resonance in all cases, reflected in the initial growth of the ratio.
- The production of $\delta\phi$ due to rescattering from χ particles via processes such as $\chi_k \chi_k \to \delta\phi_k \delta\phi_k$ lowers this ratio.
- The rescattering of χ particles against the inflaton zero modes, $\chi_k \phi_0 \to \chi_k \delta\phi_k$, also effectively produces both $\delta\phi_k$ and χ particles, which again increases the ratio.
- This ratio starts to fall when the back reaction kicks in.
- The additional growth of $\delta\phi$ fluctuations due to self-resonance for the cases with $h \neq 0$ keeps the ratio close to one for a longer duration.



Self-resonance after quadratic inflation with features

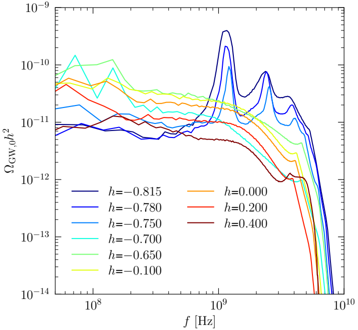
- Preheating can happen through self-resonance even if the inflationary potential is quadratic.



How to probe these features?

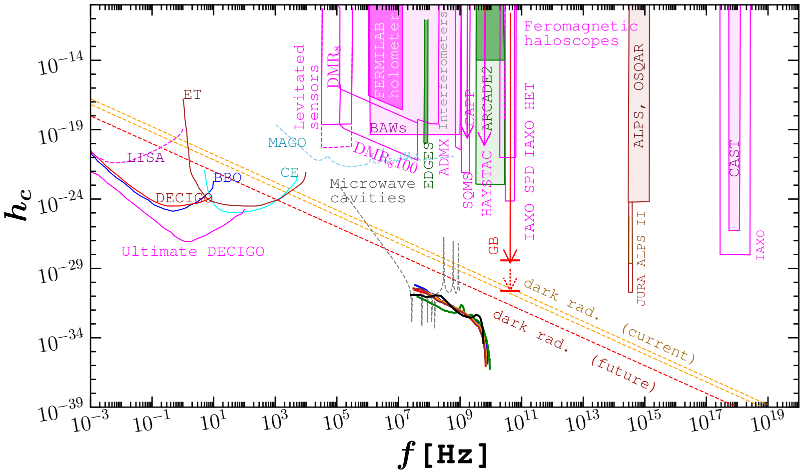
High frequency GWs

- The amplitude of produced GWs is substantial $\approx 10^{-10}$.
- The required strain sensitivity needed to detect a signal of fixed amplitude scales as cube of the frequency, leading to tremendous technological challenges.



How to probe these features?

High frequency GWs detectors?



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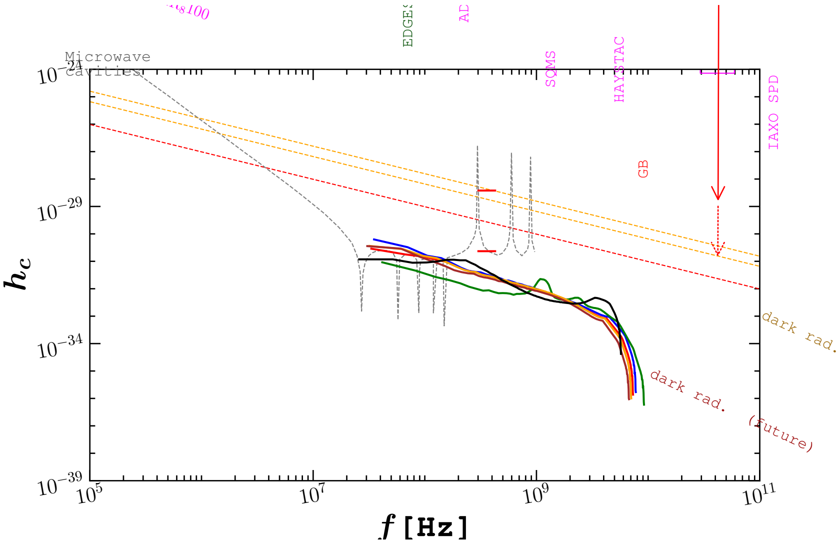
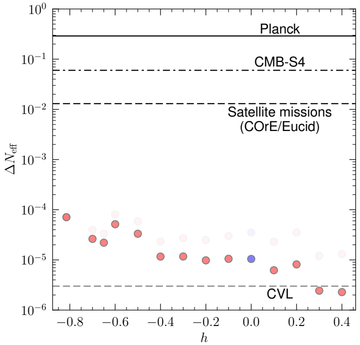


How to probe these features?

Contribution to the effective number of relativistic d.o.f

- The produced GWs in this phase are sub-hubble; consequently, their contribution to the energy density scales as radiation [Caprini 2018]. We assume that SGWB accounts for this additional d.o.f at the time of decoupling.
- We define the deviation of the effective number of relativistic d.o.f from the Standard Model: $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff,SM}$.

$$\frac{h_0^2\Omega_{\rm GW,0}}{h_0^2\Omega_{\gamma,0}} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{\rm eff}, \quad (10)$$



Summary

- Preheating is really (very) small-scale phenomena.
- Preheating is possible solely due to these features irrespective of the shape at CMB scales or interaction to other fields — *the Potential Surge Preheating*.
- Such features through their signatures in GWS, $\Delta N_{\rm eff}$, (anything else?) will help us to reconstruct the full shape of the inflaton potential.

B. Many faces of Parametric Resonance

- B.1: Resonance from ultra-light spectator scalar, all dark matter and nHz GWs signal.
- B.2: Resonance from complex spectator scalar and baryogenesis.

B1. Resonance in the spectator scalar

- Simple renormalizable (spectator) scalars:

$$\text{Model A:} \quad V = \frac{m_\phi^2}{2}\phi^2 + \frac{g}{2}\phi^2\chi^2, \tag{11}$$

$$\text{Model B:} \quad V = \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\chi}{4}\chi^4 + \frac{\sigma}{2}\phi\chi^2, \tag{12}$$

$$\text{Model C:} \quad V = \frac{\lambda}{4}\phi^4, \tag{13}$$

$$\text{Model D:} \quad V = \frac{\lambda}{4}\phi^4 + \frac{g}{2}\phi^2\chi^2, \tag{14}$$

- Solve the system of equations including the tensor perturbations equations for GWs in a Radiation-dominated universe.

Isocurvature bound

- The fluctuations in spectators are uncorrelated with the density perturbations, leading to isocurvature perturbations.
- The spectrum for the massive and massless scalar are:

$$\mathcal{P}_S \sim \left(\frac{m_\phi}{H_I}\right)^2; \qquad \mathcal{P}_S \sim \sqrt{\lambda_\phi}.$$

- CMB data restricts the amount of isocurvature perturbations as: $\mathcal{P}_S \lesssim 0.04\mathcal{P}_\zeta$
- Our model parameters are thus restricted to: $m_\phi \lesssim 10^{-5}H_I$ and $\lambda_\phi \lesssim 10^{-20}$.

GWs across many decades of frequency

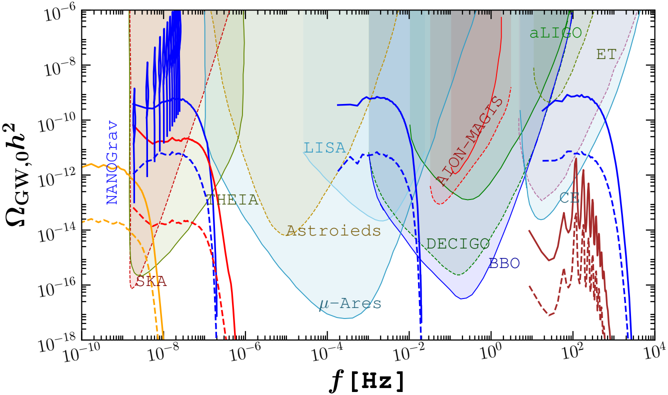


Figure: The Produced GWs spectrum for different mass of the spectator and when the scalar component corresponds to 1% and 10% of the total energy density of the Universe. [Yanou Cui, PS,and Evangelos I. Sfakianakis Phys.Rev.Lett.133,021004(2024)]

Complementary searches

Dark matter and Dark Radiation

- The relic abundance of ϕ particles:

$$\Omega_{\phi,0} \equiv \frac{\rho_{\phi},0}{\rho_{\text{tot},0}} = \frac{\frac{1}{2}m_{\phi}^{2}\phi_{\text{end}}^{2}}{3M_{\text{Pl}}^{2}H_{0}^{2}}\frac{g_{*,0}}{g_{*,\text{end}}}\left(\frac{T_0}{T_{\text{end}}}\right)^{3} \tag{15}$$

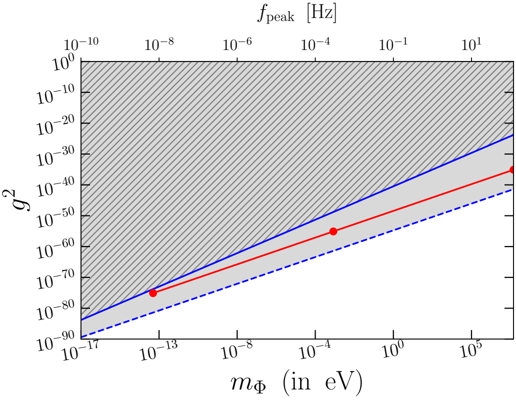
- GWs contribution (amplitude $\approx 10^{-9}$) to new relativistic degrees of freedom is negligible.

$$\frac{\Omega_{\text{GW},0}h^2}{\Omega_{\gamma,0}h^2} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{\text{eff}} \tag{16}$$

- The 'massless' components can act as non-thermally produced dark radiation and will lead to additional contributions to ΔN_{eff}

$$\Delta N_{\text{eff}} = \frac{\hat{g}_{*}\hat{T}^{4}}{\frac{7}{4}T^{4}} = \frac{4}{7}\alpha\xi\hat{g}_{*}\left(\frac{g_{*}}{\hat{g}_{*}}\right)^{4/3}\left(\frac{\hat{g}_{*,\text{osc}}}{g_{*,\text{osc}}}\right)^{1/3}. \tag{17}$$

The spectator scalar as all of dark matter and NANOGrav



- Take home message: There may be a spectator scalar that accounts all the DM of the Universe and has just imprinted its signature in the NANOGrav and other PTA detectors.

B2. Parametric Resonance with a Complex Scalar and Affleck-Dine baryogenesis

- We consider a complex scalar field Φ (SM gauge singlet) with canonical kinetic terms, Einstein gravity and a simple renormalizable polynomial potential:

$$V(\Phi) = \lambda_\Phi \left|\Phi\right|^4 + m_\phi^2 \left|\Phi\right|^2 - A(\Phi^n + \Phi_*^n) \tag{18}$$

- For $n \geq 4$, the asymmetry is generated at high-scales (earlier), while for $n = 2$, the asymmetry is generated at the when the oscillation is determined by the quadratic term. The oscillation averaged asymmetry is just sufficient to satisfy the observational value. [Llyod-Stubbs & J. Macdonald 2020, ibid 2022]
- The real and imaginary components of Φ, satisfies:

$$\ddot{\phi}_{\mathrm{R}} + 3H\dot{\phi}_{\mathrm{R}} + m_R^2\phi_R + \lambda_\phi(\phi_R^2 + \phi_I^2)\phi_R = 0, \tag{19}$$

$$\ddot{\phi}_{\mathrm{I}} + 3H\dot{\phi}_{\mathrm{I}} + m_I^2\phi_I + \lambda_\Phi(\phi_R^2 + \phi_I^2)\phi_I = 0, \tag{20}$$

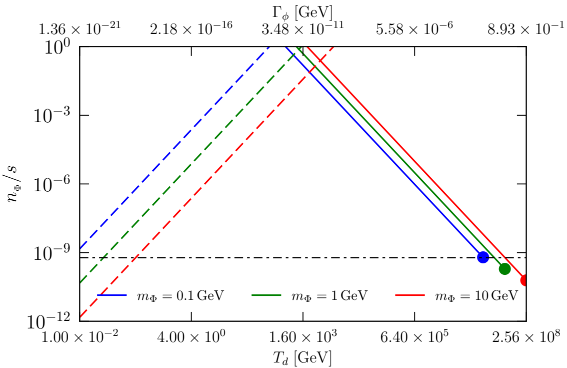
- The field remains frozen at ϕ_{in} and it starts rolling/oscillating when $H = H_{\mathrm{osc}} \simeq \sqrt{V_{,|\Phi|}/|\Phi|}$. The oscillation is initially dominated by Φ^4 term.

- When the amplitude drops to When the amplitude drops below $|\Phi_*| = m_\Phi/\sqrt{\lambda_\Phi}$ at t= t_*, the oscillation is dominated by quadratic terms.
- The co-moving baryon asymmetry generated during the time $t > t_*$

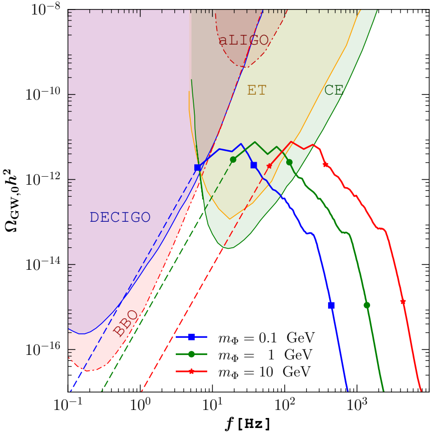
$$\left(\frac{a(t)}{a_{\rm in}}\right)^3 n_B(t) \simeq 4A\phi_{\rm R,in}\phi_{\rm I,in}\left(\frac{\phi_{\rm in}}{\phi_*}\right)\times$$
$$\int_{t_*}^{t} dt' \cos\left(m_{\rm R}(t'-t_*)\right)\sin\left(m_{\rm I}(t'-t_*)\right)e^{-\Gamma_\Phi(t'-t_*)}, \qquad (21)$$

- Evaluating the above integral for $t \to \infty$ and factoring in the expansion during the RD Universe, we express n_B/s as

$$\frac{n_B}{s} = \begin{cases} \left(\frac{4\alpha^3}{\lambda_\Phi k_{T_d}^6}\right)^{1/4} \epsilon_\Phi \frac{m_\Phi M_{\rm Pl}}{T_d^2}\sin(2\theta); & \gamma_\Phi \gg 2\epsilon_\Phi \\ \left(\frac{\alpha^3 k_{T_d}^2}{64\lambda_\Phi}\right)^{1/4} \frac{1}{\epsilon_\Phi}\frac{T_d^2}{m_\Phi M_{\rm Pl}}\sin(2\theta); & \gamma_\Phi \ll 2\epsilon_\Phi \end{cases} \qquad (22)$$



- The maximum baryon-to-photon ratio $n_B/s|_{\max} = n_\Phi/s$ (neglecting possible washout and the sphaleron factor) for three different masses of the scalar field as a function of the temperature T_d of the Φ decay.



- GW spectrum originating from the AD model for same three benchmark masses of Φ as the last figure

Outlook

- Simple models can lead to successful baryogenesis while sourcing detectable GW signals with a peak frequency of O(10-100) Hz, within reach of experiments such as ET and CE.
- The characteristic new physics scale, characterized by m_Φ, intriguingly lies in the range of $\mathcal{O}(0.1 - 10)$ GeV, while the transfer of the Φ asymmetry to the SM B- or L-asymmetry requires interactions between the new physics sector and the SM states. Hence, from this well-motivated scenario, a new, natural complementarity arises between SGWB detection and laboratory searches for new particle physics across the energy, intensity, and neutrino frontiers.
- The specifics of the complementary laboratory signal depend on the details of the asymmetry transfer mechanism.
- Many other complementary searches possible...


Thank you!
(ありがとうございました)