Detectable Gravitational Wave Signals from Inflationary Preheating

based on Y. Cui & EIS, arXiv: 2112.00762 [hep-ph]

Evangelos Sfakianakis

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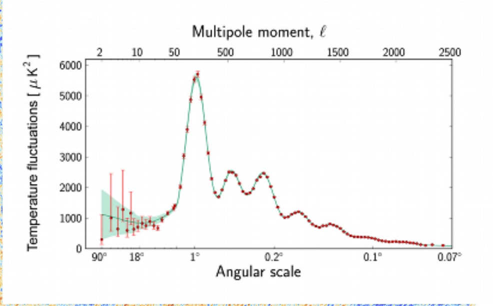
$$\boxed{\mathcal{P} = A_s (k/k_*)^{n_s - 1}}$$

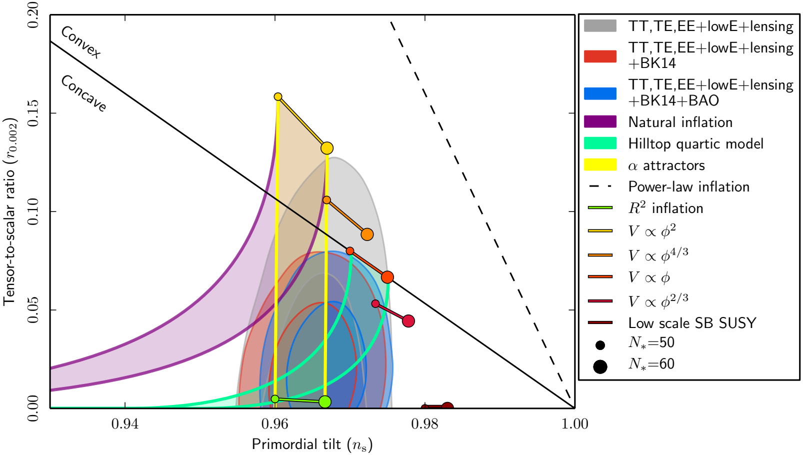
(Simple) Single field inflation:

- **Solves** horizon, flatness, monopole **problems**
- **Explains fluctuations** as stretched quantum mechanical perturbations
- Predicts a **nearly scale invariant** spectrum (of tunable amplitude)
- Predicts **Gaussian** perturbations



- Spectral index not flat by 5σ
- Spectral index running is small
- $|f_{NL}| \lesssim \mathcal{O}(1)$

Hints from the sky



Upper limit on gravitational waves from inflation.

Challenges in early universe cosmology

Inflation agrees with observations,
providing an elegant paradigm for the early universe

What we ponder:

- Transition to the **hot Big Bang** (reheating)
- **String Theory**
  - Axions & Moduli Fields
  - Inflation in String Theory & Swampland
- The **Standard Model** and beyond
  - Neutrinos
  - The Higgs & SM running

What we (hope to) see:

- **CMB**: LiteBird and CMB-S4 looking for B-modes
- **Relics** from the early universe
  - lepton number
  - Primordial Black Holes
  - Intergalactic magnetic fields
- Stochastic **Gravitational Waves** in LIGO and LISA

Natural (axion) inflation

An axion is an attractive candidate for the inflaton

$$\Downarrow$$

A field with a shift symmetry can only couple **derivatively**

E/M field | electrons, neutrinos, ...

$$\mathcal{L}_{\rm Int} \subset \boxed{\frac{\alpha}{8f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}} + \boxed{\frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi}$$

$$\updownarrow$$

$$\boxed{-\frac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu\partial_\alpha A_\beta}$$

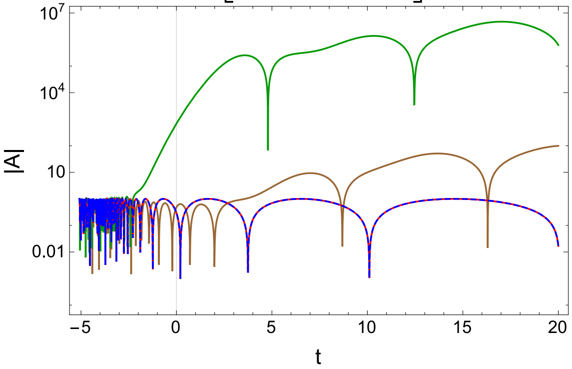
From a EFT perspective, we expect these terms to be present.

- Adshead, Giblin, Scully & **EIS**, arXiv: 1606.08474, 1502.06506
- Adshead & **EIS**, arXiv: 1508.00891, 1508.00881

Gauge field production

Decompose in two polarizations $(+, -)$.

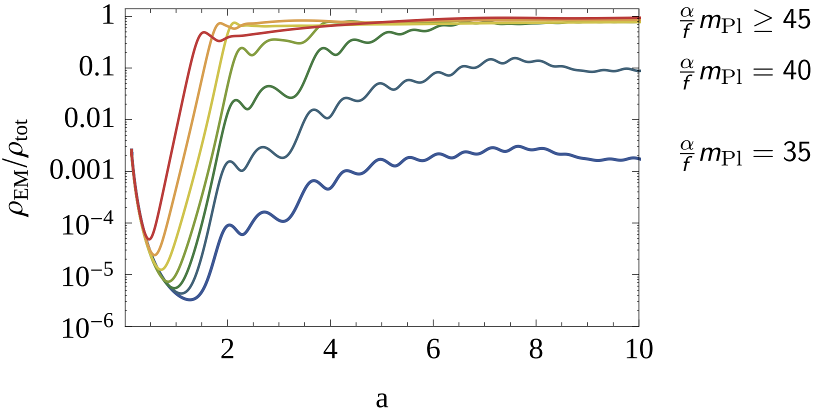
$$\ddot{A}_k^{\pm} + H\dot{A}_k^{\pm} + \left[\left(\frac{k}{a}\right)^2 \mp \frac{\alpha}{f}\frac{k}{a}\dot{\phi}\right] A^{\pm} = 0$$



Parity violating **exponential enhancement**.

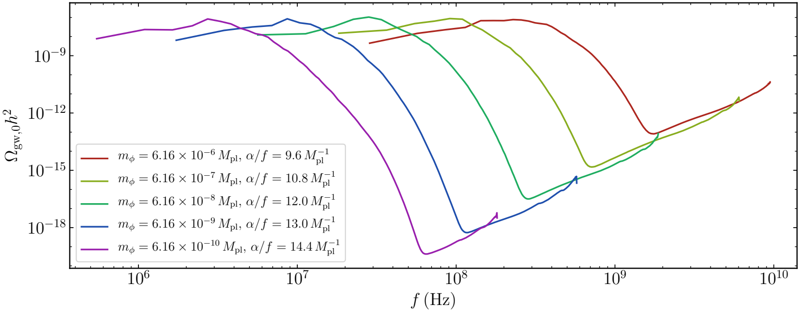
Gauge Field Preheating

Coupling the axion to E/M fields can lead to explosive transfer of energy from the inflaton.



Reheating occurs after a **single axion oscillation** for $\frac{\alpha}{f} m_{\rm Pl} > 45$.

Gauge field production leads to the **helical GW's**.



Adshead et al, 2020

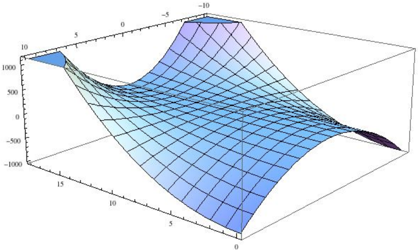
However, the large frequency makes them **unobservable at interferometers**.

Hybrid Inflation

Multiple fields

$\Downarrow$

qualitatively different behavior



Hybrid Inflation (Linde, 1994):

a slow rolling field triggers a phase transition
$\Rightarrow$ destabilizes a second field
$\Rightarrow$ Inflation ends

1. (light) real timer scalar field
2. (heavy) complex waterfall scalar field

$$V(\phi,\psi) = V_0 + m_\psi^2 \psi^2 - m_0^2 \left[1 - \left(\frac{\psi}{\psi_c}\right)^r\right] |\phi|^2$$

Result: **Large Spike at Small Scales!!** (e.g. Guth & EIS, 2012)

A hybrid^2 model

An attempt to combine **hybrid** and **natural** inflation

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \sum_i \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi \right.$$
$$\left. -V(\psi,\phi_i) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4f}\sum_i \frac{\phi_i}{\Lambda_i}F_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

where

$$V(\psi,\phi_i) = V_0 + V_1(\psi) - \frac{m_0^2(\phi_i)^2}{2}\left(1-\frac{\psi^2}{\psi_0^2}\right) + \frac{g}{4}(\phi_i)^4$$

Waterfall Field Dynamics

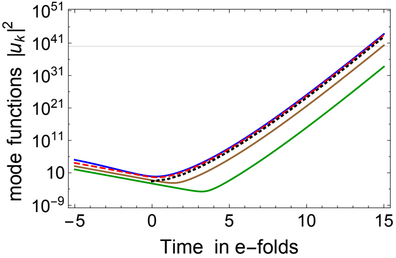
$$\ddot{\psi} + 3H\dot{\psi} + m_\psi^2 \psi = 0$$

$$\ddot{\phi}_i + 3H\dot{\phi}_i + \left[\frac{k^2}{a^2} + m_\phi^2(t)\right]\phi_i = 0$$

where

$$m_\phi^2(t) = -m_0^2\left(1 - \frac{\psi^2}{\psi_0^2}\right)$$

Waterfall field modes grow exponentially

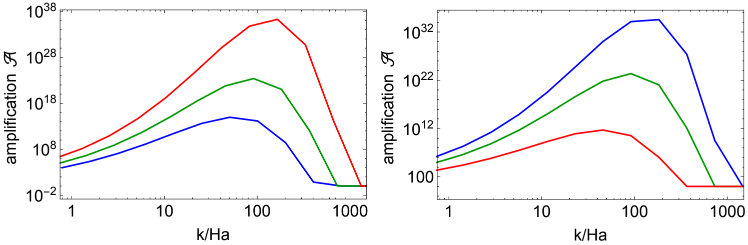


$$\phi_i(\vec{x}, t) = \phi_i(\vec{x}, t_c)e^{\int_{t_c}^{t} dt' \lambda(t')}$$

where $\quad \frac{\lambda(t)}{H} \simeq -\frac{3}{2} + \sqrt{\frac{9}{4} + \frac{m_0^2}{H^2}\left(1 - e^{-2\frac{m_\psi^2}{3H^2}t}\right)}$

Gauge field Dynamics

Peaked spectrum with $\frac{k_{\rm peak}}{aH} \sim \frac{\lambda}{10H}\frac{H}{\Lambda_{i,\rm min}}\frac{M_{\rm Pl}}{H}$.



Gauge field energy density $\rho_A \sim \mathcal{A}^2 k_{\rm peak}^4/a^4$,
where $\mathcal{A}$ is the amplification factor.

Complete preheating requires $\rho_{\rm infl} \simeq \rho_A$, leading to

$$\mathcal{A} \sim \left(\frac{M_{\rm Pl}}{H}\right)\left(\frac{k_{\rm peak}}{aH}\right)^2.$$

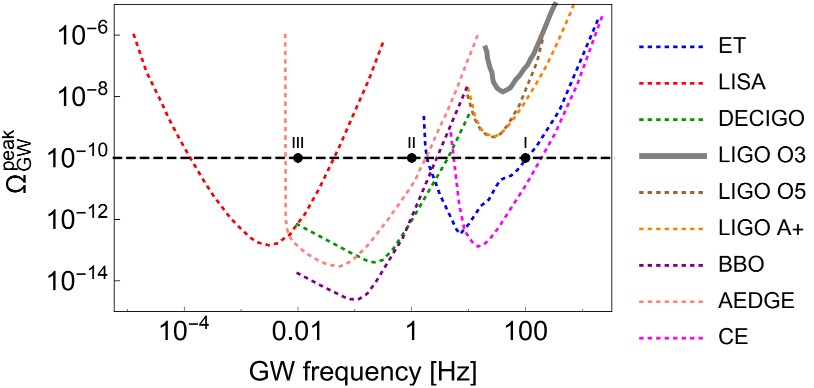
GW signals

A simple way to estimate GW production (Giblin & Thrace, 2014)

$$\nu_{GW}^{\mathrm{peak}} = 2.7 \times 10^{10} \frac{k_*}{\sqrt{M_{\mathrm{Pl}}\, H}}\, \mathrm{Hz}\,,$$
$$\Omega_{\mathrm{GW}}^{\mathrm{peak}} = 2.3 \times 10^{-4}\, \alpha^2\, \beta\, w \left(\frac{k_*}{\sigma}\right) \left(\frac{H_*}{k_*}\right)^2 .$$

- α: fraction of the energy in the GW source relative to the Universe's total energy density
- β:encodes the anisotropy of the source
- w: EOS of the universe
- k_*: peak wavenumber of the source spectrum
- σ: width of the source spectrum

Signals and experiments



Summary

A rare realistic way to probe low-scale inflation

- A simple model leading to **detectable GW signals from preheating**, using axions and dark photons in a hybrid inflation setup
- **Helical GW's** provide a distinguishing feature
- Associated **PBH production** provides more correlated observables

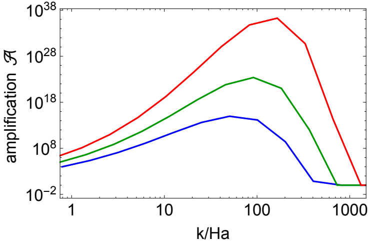
We thank the KITP for its hospitality.

The density perturbations spike leads to the formation of PBH's with $M = (M_{\rm Pl}^2/H_*)e^{2N_*}$ and probability

$$\beta_{\rm BH}(M) = erfc\left(\frac{\zeta_c}{\sqrt{2}\sigma}\right) \simeq \frac{\sqrt{2}\sigma}{\sqrt{\pi}\zeta_c} e^{-\zeta_c^2/(2\sigma^2)}$$

$H/M_{\rm Pl}$	m_0	Λ/H	$N_{\rm wf}$	$\nu_{\rm GW}^{\rm peak}$	$\Omega_{\rm GW}^{\rm peak}$	$M_{\rm BH}$
10^{-20}	$6\,H$	10^{18}	14.2	$100\,{\rm Hz}$	10^{-10}	$10^{-5}\,M_\odot$
10^{-20}	$15\,H$	10^{18}	6.2	$100\,{\rm Hz}$	10^{-10}	$10^{-13}\,M_\odot$
10^{-24}	$7\,H$	10^{22}	14	$1\,{\rm Hz}$	10^{-10}	$0.1\,M_\odot$
10^{-30}	$8\,H$	10^{27}	14.5	$10^{-3}\,{\rm Hz}$	10^{-10}	$10^{5}\,M_\odot$
10^{-30}	$12\,H$	10^{27}	10	$10^{-3}\,{\rm Hz}$	10^{-10}	$10\,M_\odot$

Maximum amplified wavenumber: $k_{\max}/(aH) \simeq (\Lambda_{i,\min} H)^{-1} \lambda \dot{\phi}_{\rm end}$
where $\dot{\phi}_{\rm end} = \lambda \phi_{\rm end} \sim \lambda M_{\rm Pl}$,
while the peak is at $\frac{k_{\rm peak}}{aH} \sim \frac{\lambda}{10H} \frac{H}{\Lambda_{i,\min}} \frac{M_{\rm Pl}}{H}$.



Gauge field energy density $\rho_A \sim \mathcal{A}^2 k_{\rm peak}^4/a^4$,
where $\mathcal{A}$ is the amplification factor.
Complete preheating requires $\mathcal{A} \sim (M_{\rm Pl}/H)\,(k_{\rm peak}/aH)^2$