Production of gravitational waves during inflaton

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Motivation

Inflation predicts a stochastic background of GWs

$$\mathcal{P}_t \propto \frac{H^2}{M_P^2}$$

H ↘ during inflation ☛ slightly red spectrum

+

CMB constraints

$\Omega_{GW} < 10^{-15}$

Motivation

But!

Inflaton can interact with other forms of matter

&

Rolling of inflaton can excite their vacuum fluctuations

Additional sources of GWs

(rolling of inflaton faster towards the end of inflation, more efficient particle production at smaller scales)

(*typically 2 → 1 processes ⇒ nongaussian statistics*)

constrained at CMB scales, not at LISA scales

Motivation

But!

Inflaton can interact with other forms of matter
&
Rolling of inflaton can excite their vacuum fluctuations

Additional sources of GWs

(rolling of inflaton faster towards the end of inflation, more efficient particle production at smaller scales)

(*GWs inherit properties of excited degrees of freedom*)

A well studied example

If inflaton is a pseudoscalar with (broken) shift symmetry

(well motivated by naturalness),

it interacts with *(abelian)* gauge field via

$$\mathcal{L}_{\phi FF} = \frac{\phi}{f}\,\epsilon_{\alpha\beta\gamma\delta}\,F^{\alpha\beta}\,F^{\gamma\delta}$$

(f=constant with dimensions of a mass)

The helicity-λ mode functions A_λ are coupled to $\phi(t)$:

$$A_\lambda'' + \left(k^2 + \lambda \frac{\phi'}{f} k\right) A_\lambda = 0$$

for λ=-, the "mass term" is negative and large for ~*1* Hubble time:

Exponential amplification of right handed modes only!

parity violating system,
parity violating gauge modes

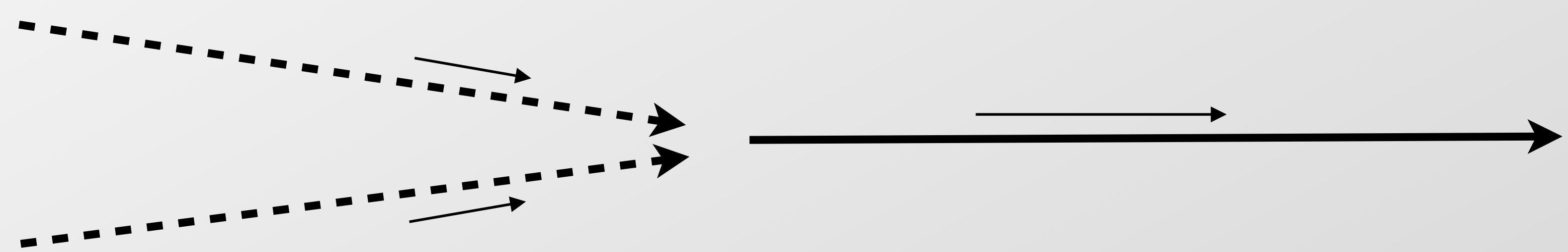
$$A_R \propto \exp\left\{\frac{\pi}{2}\frac{\dot{\phi}}{f\,H}\right\}$$

…and the energy of the electromagnetic field sources gravitational waves….

A_L and A_R have different amplitudes

$$<h_L h_L> \neq <h_R h_R>$$

Physics: in the limit of small transverse momentum two RH photons cannot create a LH graviton



Parity violating gravitational waves

$$\mathcal{P}_R(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9 \times 10^{-7}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\mathcal{P}_L(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2 \times 10^{-9}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

"standard" parity-invariant part

parity-violation!

$$\xi \equiv \frac{\dot{\phi}}{2\,f\,H} \gtrsim 1$$

(see Angelo's talk)

From Bartolo et al 16

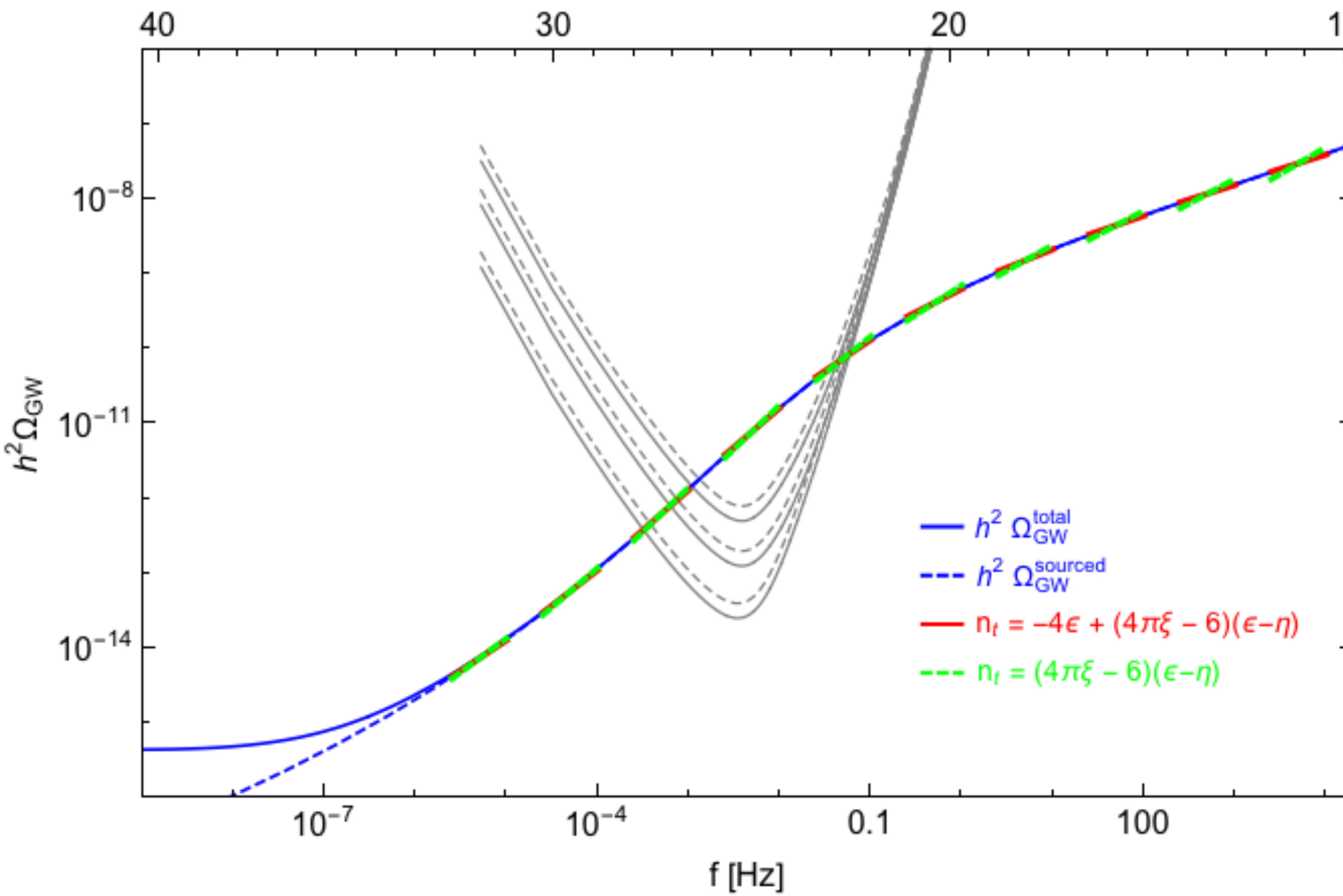


Figure 4. Spectrum of GWs today $h^2\Omega_{\rm GW}$ obtained from a numerical integration of the dynamical equations of motion (for a model of quadratic inflaton potential, with inflaton - gauge field coupling $f = M_{\rm Pl}/35$), versus the local parametrization $h^2\Omega_{\rm GW} \propto (f/f_*)^{n_T}$, evaluated at various pivot frequencies f_* and with the spectral tilt n_T obtained from successive approximations to the analytic expression (3.13).

Bispectrum of tensors

$$\langle h_R(\mathbf{k}_1)\, h_R(\mathbf{k}_2)\, h_R(\mathbf{k}_3)\rangle_{\rm equil} \simeq -5.7\times 10^{-10}\,\frac{H^6}{M_P^6}\,\frac{e^{6\pi\xi}}{\xi^9}\,\frac{\delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})}{k^6}\,,$$

$$\langle h_L(\mathbf{k}_1)\, h_R(\mathbf{k}_2)\, h_R(\mathbf{k}_3)\rangle_{\rm equil} \simeq -9.0\times 10^{-12}\,\frac{H^6}{M_P^6}\,\frac{e^{6\pi\xi}}{\xi^9}\,\frac{\delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})}{k^6}\,,$$

$$\langle h_L(\mathbf{k}_1)\, h_L(\mathbf{k}_2)\, h_R(\mathbf{k}_3)\rangle_{\rm equil} \simeq 1.9\times 10^{-15}\,\frac{H^6}{M_P^6}\,\frac{e^{6\pi\xi}}{\xi^9}\,\frac{\delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})}{k^6}\,,$$

$$\langle h_L(\mathbf{k}_1)\, h_L(\mathbf{k}_2)\, h_L(\mathbf{k}_3)\rangle_{\rm equil} \simeq -1.2\times 10^{-14}\,\frac{H^6}{M_P^6}\,\frac{e^{6\pi\xi}}{\xi^9}\,\frac{\delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})}{k^6}\,.$$

(Parity violating) (see Valerie's talk)

Large nongaussianities in tensors!

$$\langle hhh\rangle \simeq .1\, \langle hh\rangle^{3/2}$$

Other models?

Prototypical example of model leading particle production

Inflaton ϕ interacts with another scalar χ via

$$\mathcal{L}_{\rm int} = -\frac{g^2}{2}(\phi - \phi_0)^2\chi^2$$

When ϕ crosses ϕ_0, χ becomes temporarily massless and is cheap to produce

➽ ~ $\left(g\,\dot{\phi}_0\right)^{3/2} >> H^3$ quanta of χ per unit volume are produced

that can source the tensor modes

Unfortunately...

The effect is too small:

$$\begin{array}{c}\text{Height of feature}\\ \text{in GW spectrum}\end{array} \sim \begin{array}{c}\text{Height of standard}\\ \text{GW spectrum}\end{array} \times \left\{ 1 + \mathcal{O}\left(10^{-3}\right) \frac{H^2}{M_P^2} \left(\frac{g\,\dot{\phi}}{H^2}\right)^{3/2} \right\}$$

where the enhancement factor

$$\simeq 10^{-3}\, g^{3/2}\, \epsilon^{3/4}\, \left(H/M_P\right)^{1/2} \ll 1$$

Unfortunately...

The effect is too small.

Interpretation:
Nonrelativistic modes do not generate GWs

Can we check this?

Can we evade this conclusion?

Goolsby-Cole, LS 17

Symmetry restoration

produce massless scalars

$$V(\phi,\sigma) = V_0(\phi) + \frac{\mu}{2}(\phi - \phi_0)\sigma^2 + \frac{\lambda}{4}\sigma^4$$

inflaton $\varphi < \varphi_0 \Rightarrow \langle\sigma\rangle \neq 0$

inflaton $\varphi > \varphi_0 \Rightarrow \langle\sigma\rangle = 0$

…and the field σ determines mass of N auxiliary fields χ_i…

$$\mathcal{L}_\chi = -\frac{1}{2}\sum_{i=1}^{N} \partial_\mu \chi_i \, \partial^\mu \chi_i - \frac{h^2}{2}\sum_{i=1}^{N} \chi_i^2 \, \boldsymbol{\sigma}^2$$

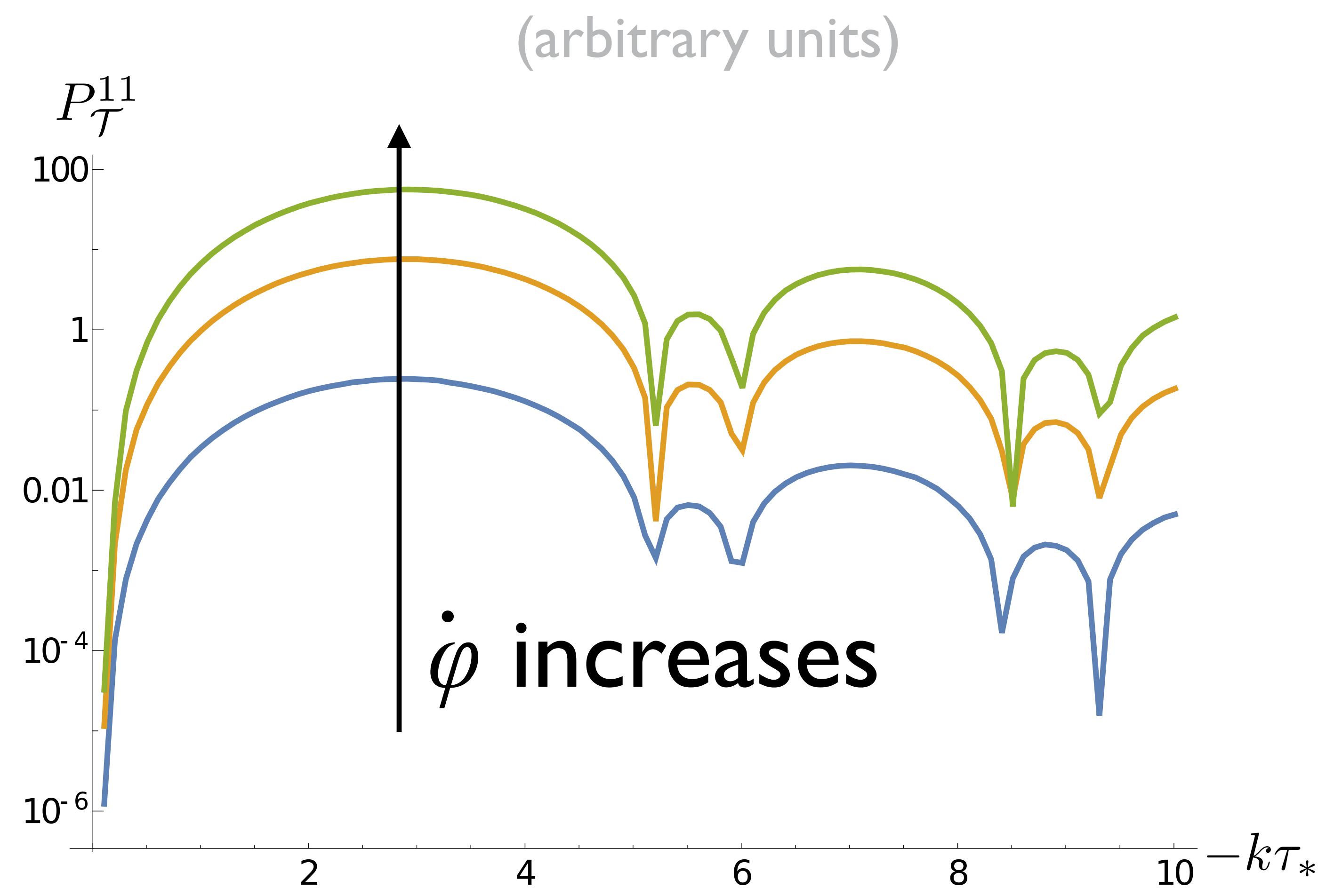
…that source GWs!

(instead of N scalars χ_i one can think e.g. of *SU(N)* gauge fields with σ= Higgs in adjoint representation)

$$\mathcal{L}_\chi \to -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu\, a} - \mathrm{Tr}\left\{(D_\mu \sigma)(D^\mu \sigma)^\dagger\right\}$$

depending on the pattern of symmetry breaking, many gauge fields can become massless

Induced tensor spectrum



Amplitude at peak

$$P_h = 2.5 \times 10^{-6}\, N\, \frac{H^4}{M_P^4}\, \frac{\Lambda_\chi^5}{H^5}$$

$$\Lambda_\chi^3 \equiv \frac{h^2\,\mu}{\lambda}\,\dot{\varphi}_*$$

After imposing many consistency constraints on the model…

…at interferometer scales (no CMB constraints):

$$\Omega_{\rm GW} h^2 \lesssim 10^{-12}\, N \left(\epsilon \,|\eta|\right)^{5/3}$$

(compare to LISA sensitivity $\sim 10^{-13}$)

For "natural" values of $\varepsilon \sim \eta \sim .1$, $N=1$, then $\Omega_{GW} \sim 10^{-15}$

…but can reach 10^{-13} without an extreme stretch of parameters…

Message from this work

- Fields that stay massless after production are indeed much more efficient sources of GWs
- Effect could be within LISA's reach, but with some stretch of parameters

Before concluding…

work in progress with Adshead, Pearce, Peloso and Mike Roberts,
follow up to work on scalar perturbations in same model

Large GWs from fermions?

Typically not an option, because of Pauli blocking… but…

$$\mathcal{L} = \bar{Y}\left[i\,\gamma^\mu\,\partial_\mu - m\,a - \frac{1}{f}\gamma^\mu\,\gamma^5\,\partial_\mu\phi\right]Y$$

(pseudoscalar inflaton φ, shift symmetric coupling to fermion Y)

Y has nonvanishing occupation number up to $k \sim \dot{\varphi}/f >> H$

Lots of fermions ⇒ Lots of GWs?

Conclusions

- Various mechanisms of particle creation during inflation $\Rightarrow$ extra sources of tensors
- Shift symmetric coupling to vector very successful with rich phenomenology
- Other options? Look more complicated, but worth studying