Minimal Production of Prompt Gravitational Waves during Reheating

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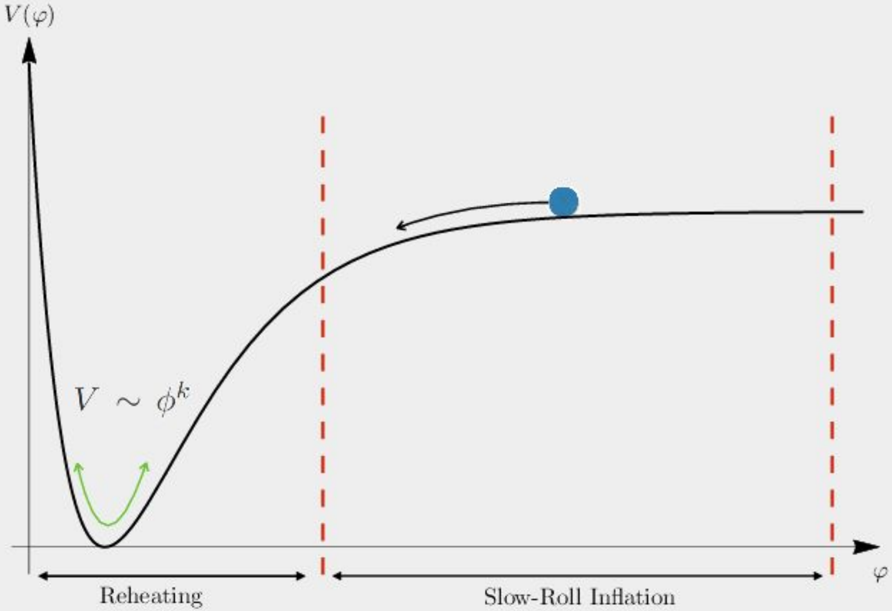


After inflation, the inflaton oscillates around the minimum, $V(\phi) \sim \phi^k$, producing particles and *reheating* the universe.

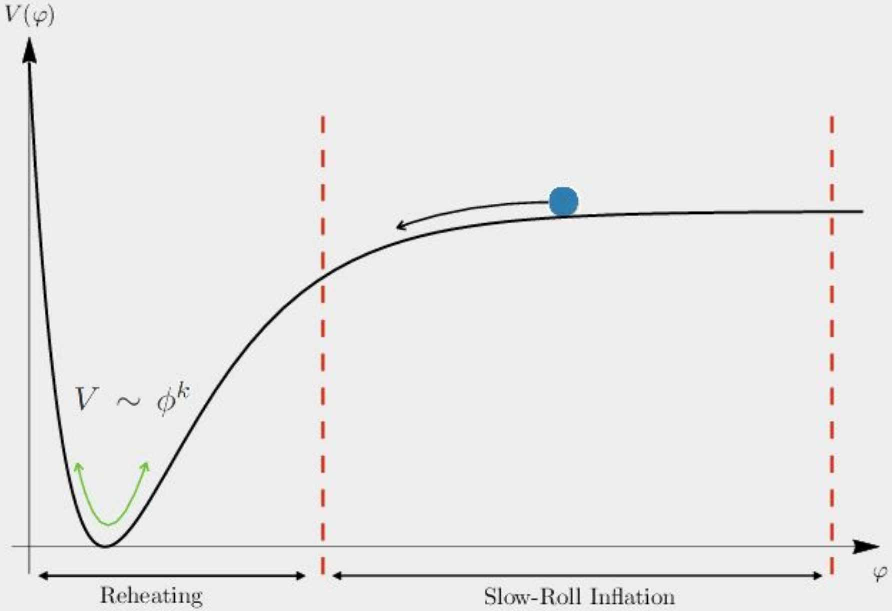
This approximation (value of k), depends on the inflation model.

Different inflation models usually give close predictions (n_s, r, ...)

PROBLEMS

1) Degeneracy in the predictions of many inflationary models

2) Reheating is difficult to test experimentally



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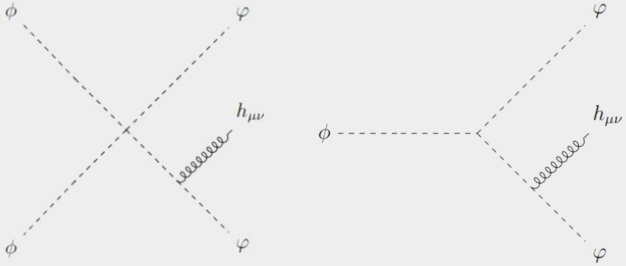
OUR QUESTIONS

1) How to distinguish different inflationary models (different k's)?
2) Any useful probe of reheating?

One observable for two purposes: Gravitational Waves

GW can be emitted from inflaton decay/annihilation channels (Bremsstrahlung)



...

see 2310.12023, 2301.11345, 2311.12694, ...

But we also have GWs *directly* from the inflaton condensate ... !

WK, G. Choi, K. A. Olive [2402.04310]

The *minimal* production from the *minimal* coupling

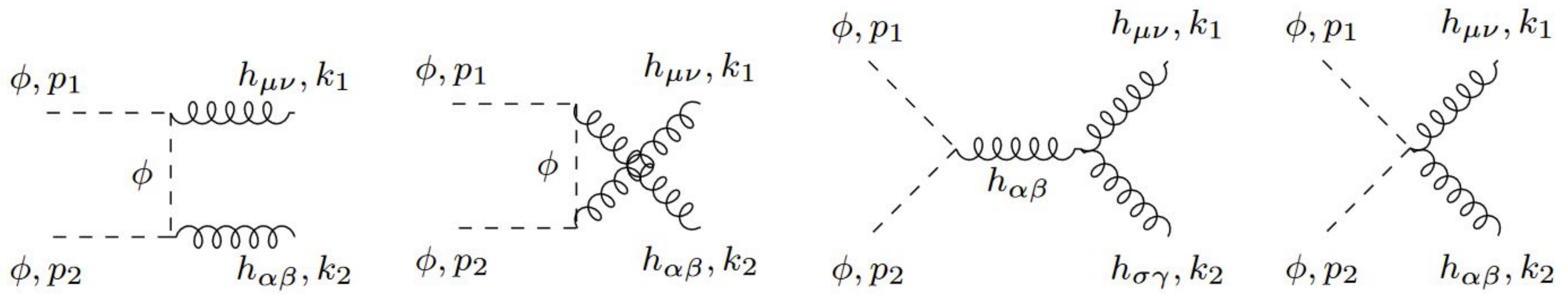
$$S = \int d^4x\sqrt{-g}\left(2\kappa^{-2}R + \frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi - V(\phi)\right)$$

Einstein-Hilbert action

scalar (inflaton) action

Expand the metric around flat space … $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu} + \cdots$

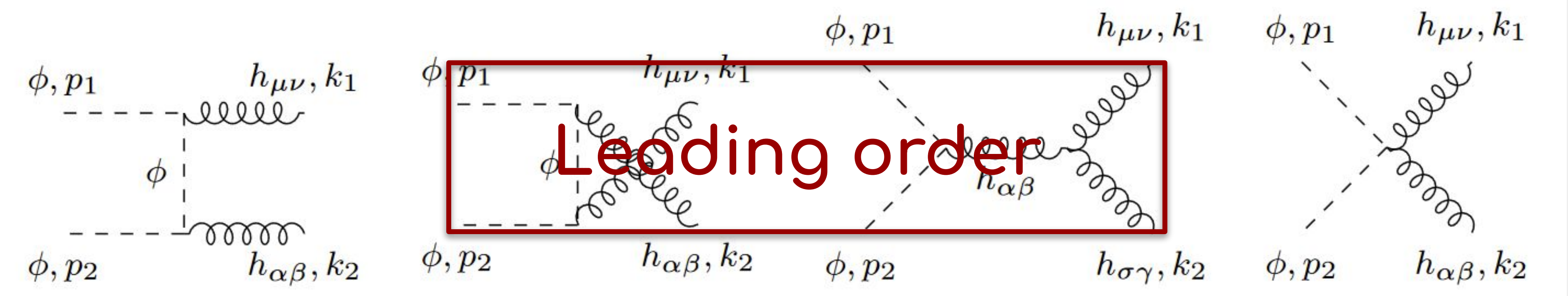
We get the inflaton-graviton couplings …



The *minimal* production from the *minimal* coupling

Once we assume minimal coupling to gravity, these processes are *inevitable*!

They give the *minimal* amount of gravitational waves produced by inflaton during reheating



Leading order

Deriving the spectrum

Feynman diagrams → interaction rate $\Gamma_h(t)$ → solve Boltzmann equations

→ GW energy density → GW spectrum (redshifted to today)

$$\Omega_{\rm GW}h^2 = (d\rho_{\rm GW}/d\ln f)/(\rho_{c,0}h^{-2})$$

Encoding inflaton oscillation:

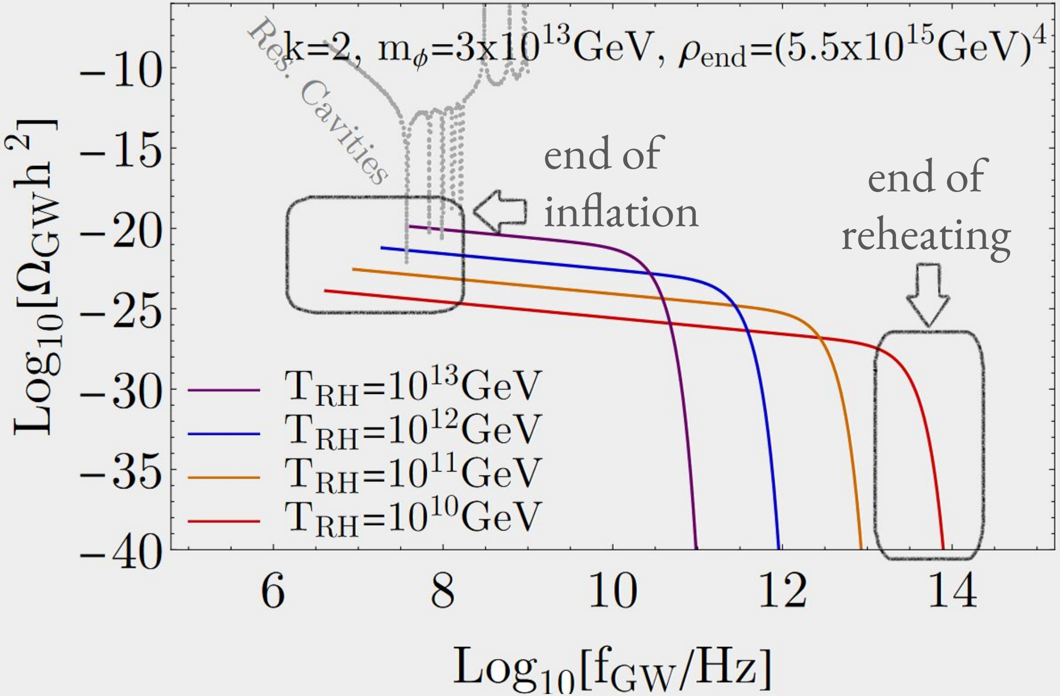
$$\phi(t) = \underset{\substack{\uparrow \\ \text{slowly varying} \\ \text{enveloppe}}}{\phi_0(t)} \cdot \mathcal{P}(t) \qquad \mathcal{P}(t) = \sum_{n=-\infty}^{\infty} \underset{\substack{\uparrow \\ \text{Fourier modes}}}{\mathcal{P}_n} e^{-in\omega t}$$

fast oscillatory part

for $k = 2$

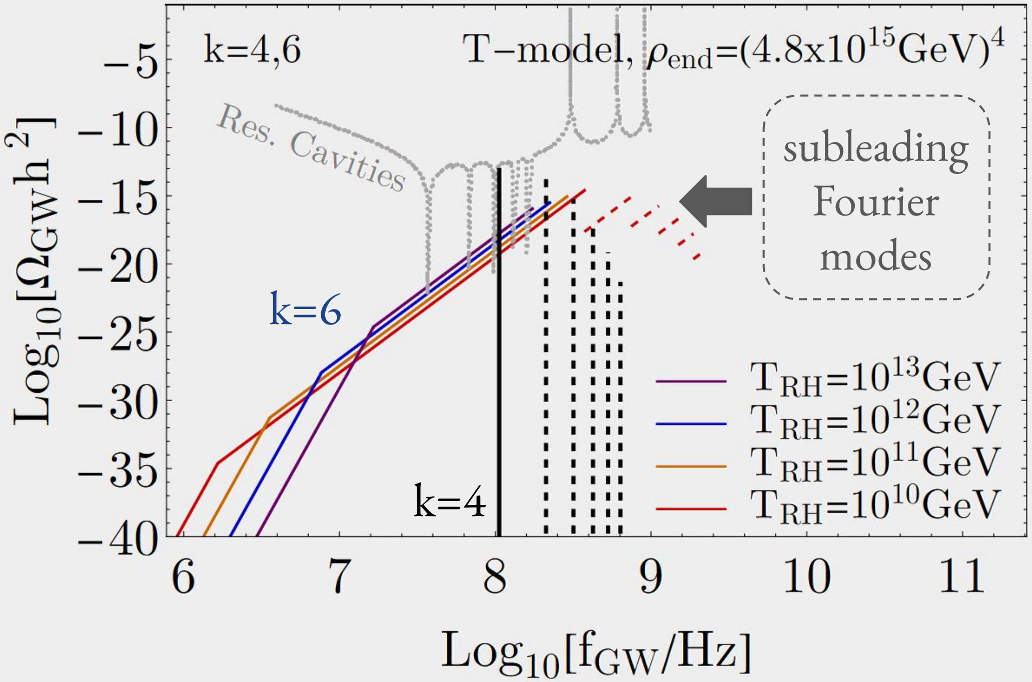
$\mathcal{P}_{n=\pm 1} = 1/2$

GW spectrum: fixed k=2, different reheating temperatures



- ♦ The production starts at the end of inflation (highest intensity)
- ♦ The production ceases at the end of reheating
- ♦ The cutoff is exponential

GW spectrum: k>2 and the discontinuous tail



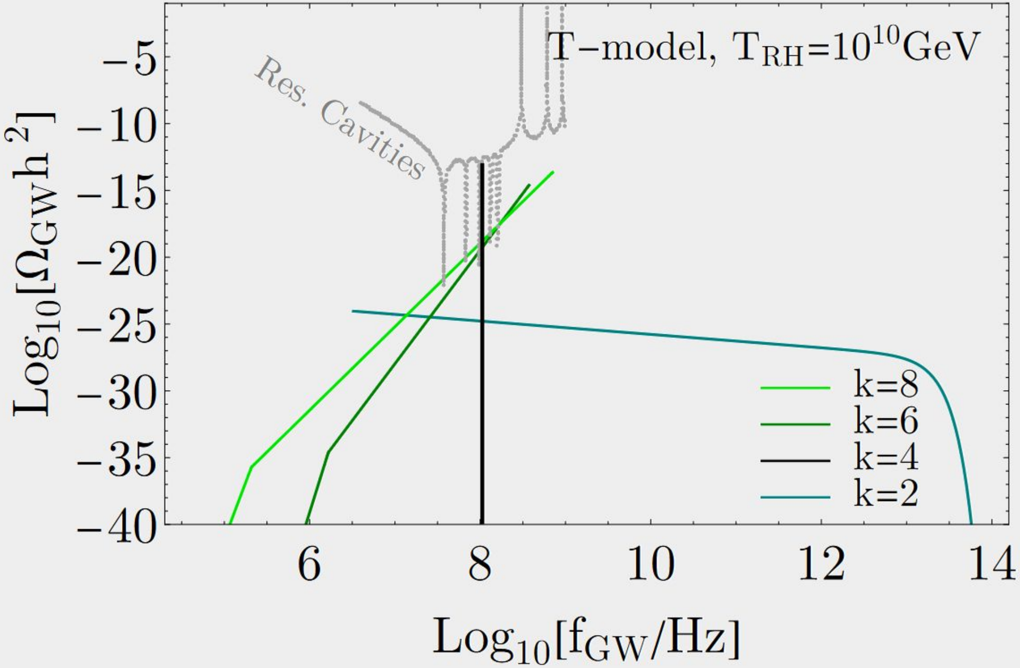
♦ For k>2, there is a discontinuous tail

♦ (special!) For k=4, the spectrum is an infinite series of *peaks*, with increasing frequency, decreasing intensity

♦ For k=4, the spectrum is independent of the reheating temperature

♦ The cutoff is *not* exponential

GW spectrum: comparison of different k’s



◆ The discontinuous tails are not displayed here

◆ The spectrum “rotates” clockwise for
larger and larger k

◆ The degeneracy of different k’s is clearly broken!

Conclusions

The production mechanism is inevitable, the GW production is minimal

What can we learn from the spectrum, once detected?

- The slope of the spectrum → value of k in $V(\boldsymbol{\phi}) \sim \boldsymbol{\phi}^k$
- The height of the signal → reheating temperature
- The width of the tail if k>2 → inflaton mass (direct measurement!)
- The shape of the cutoff → inflaton decay rate (reheating information)

Constructing high frequency GW detector is very challenging!