Gravity Waves from Preheating

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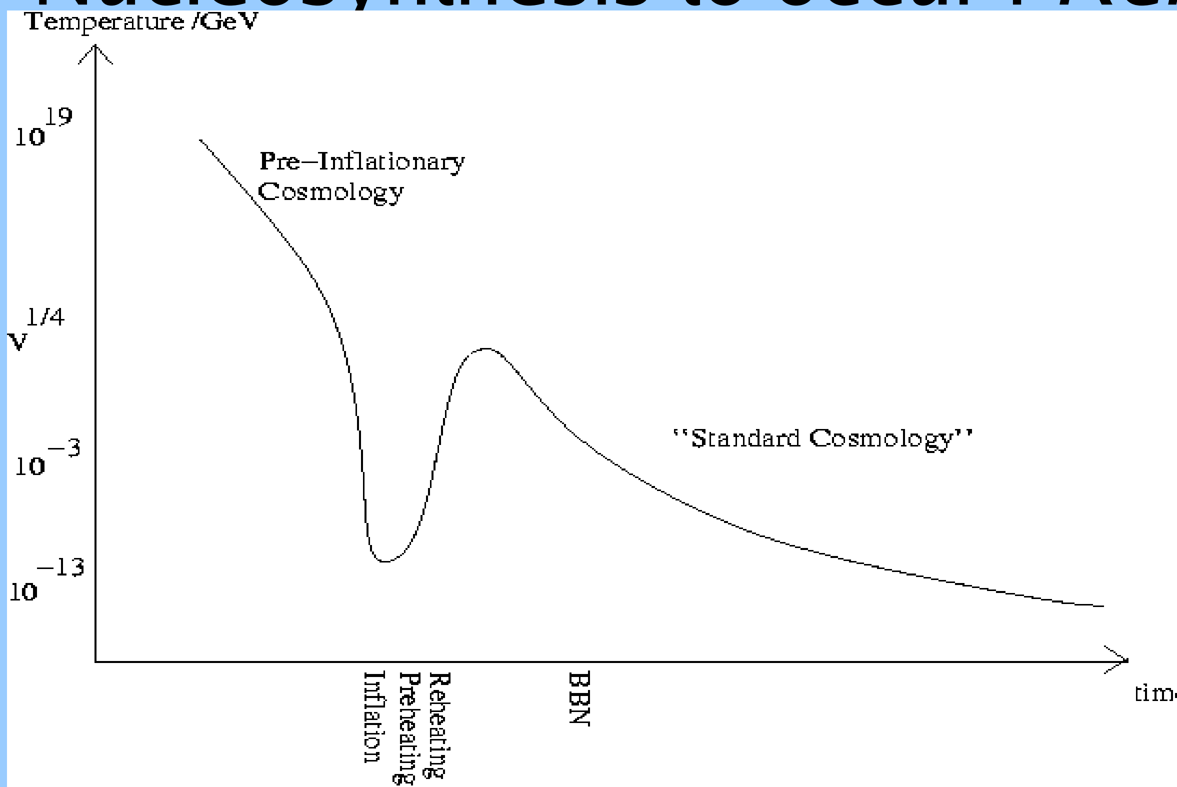
End of Inflation : Reheating

- At the bottom of potential, the Inflaton ϕ undergoes coherent oscillation and decays.
- Decay products must thermalize for Big Bang Nucleosynthesis to occur : *Reheating*.



Reheat Temperature : $T_{reheat} < V^{1/4}$

Inflation without Reheating doesn't solve cosmological problems!

Preheating

- Reheating is very model dependent : decay product, decay channels/couplings etc.
- Coherent oscillation of Inflaton : *parametric resonance* ("Preheating").
  Linde,Kofman,Starobinsky (1994)
  Traschen, Brandenberger (1993)
- Consider decay into massless scalar particles :

$$m_P^2 \frac{R}{2} - \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2} g^2 \phi^2 \chi^{2\text{right}}$$
$$S = \int dx^4 \sqrt{g}\, ¿$$

$$\chi_k '' + [A(k) - 2q \cos(2m_{eff}\, t)] m_{eff}^2 \chi_k = 0$$

$$A(k) = \frac{k^2}{m_{eff}^2 a^2} + 2q \qquad q = g^2 \frac{|\phi^2|}{4 m_{eff}^2}$$ *resonance parameter*

Harmonic oscillator with periodic forcing function!

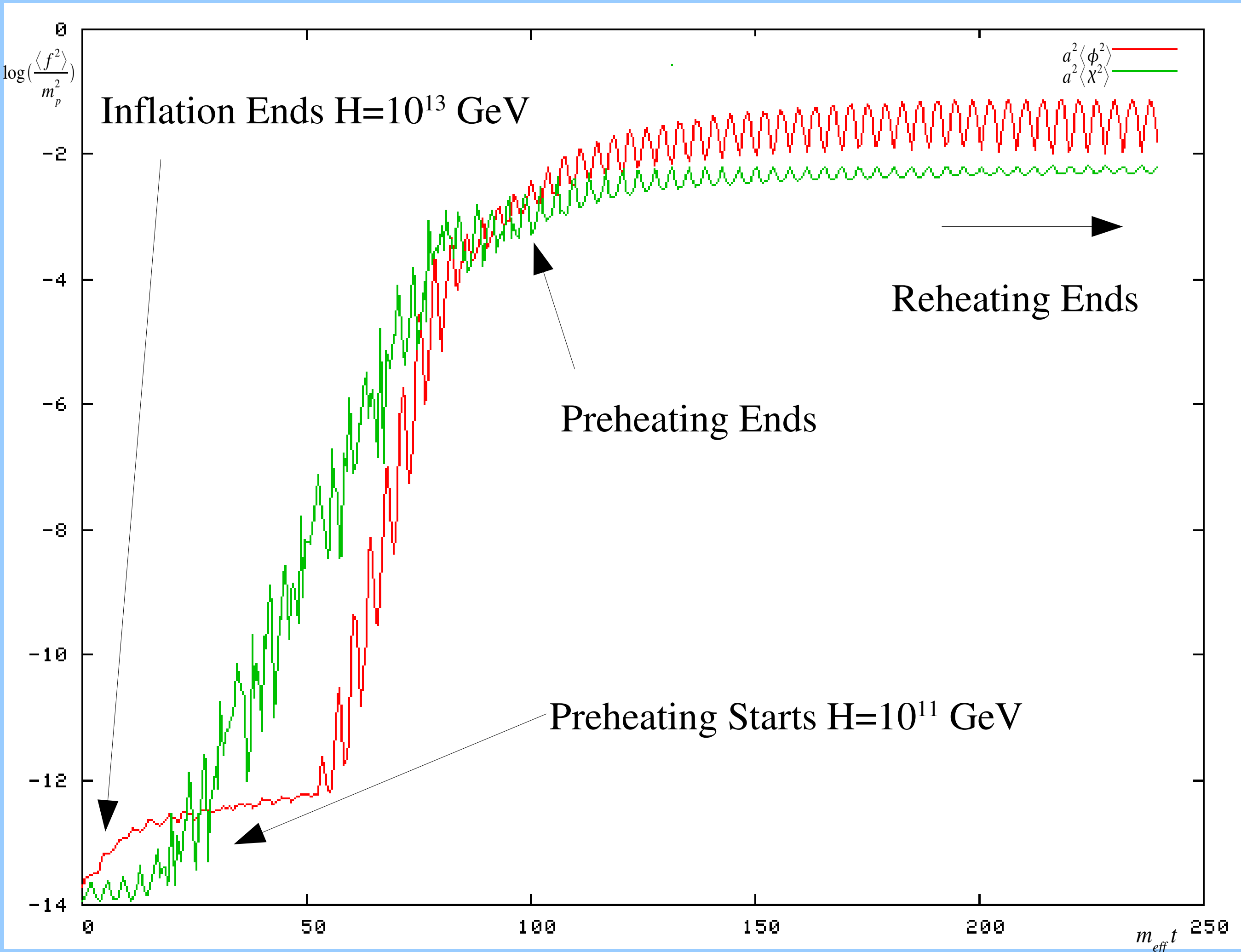
Preheating Features

- As long as the Inflaton is coupled to some field, preheating is likely to occur.
- Preheating selectively excite long wavelength modes : *non-thermal*.
- Very efficient and very short : most energy is dumped into these modes within a Hubble time.

Preheating Features

1. Very short but very efficient.
2. Very non-linear, inhomogeneities are large : *classical stochastic gravity waves!*

Can we see them? *Amplitude* and *frequency* today?



What frequency today?

- Given a physical mode *k* during preheating with Hubble parameter *H*, the corresponding physical wavelength *today* is

$$l_0 \approx 0.5 \frac{\sqrt{m_p H}}{k} cm$$

Larger *H*, universe expands *more* => longer wavelength today

Wavelength is inverse to wave vector amplitude

For the longest excitable wavelength $k = H$, then

$$l_0 \approx 0.5 \sqrt{\frac{m_p}{H}} cm = 10^4 \sim 10^5 cm \text{ for } H \approx 10^6 \sim 10^7 GeV \text{ if } V^{1/4} \approx 10^{15} GeV$$

$$\Rightarrow f \approx 10^5 \sim 10^6 Hz$$

Point : If *V* is lower, then quantum grav waves amplitude is reduced. But here the classical grav waves peak location is reddened : pushing it towards the next generation observatories.

Amplitude of Gravitational Waves

- An analytical estimate (Khlebnikov + Tkachev, 1997)

oscillation scale

Inflation scale

$$\Omega_{gw} h^2 = \frac{h^2}{\rho_{total}} \frac{d\rho_{gw}}{d\ln\omega} \approx 10^{-4} \frac{\bar{m}^2}{g^2} \frac{1}{m_p^2} \frac{k}{H}$$

compare : $\Omega_{gw,inf} = 10^{-4} \frac{H^2}{m_p^2}$

Fixing $g^2 \approx 10^{-6}$ we get :

Chaotic: $\bar{m} \approx H$ $\quad H_{inf} = 10^{13} GeV \Rightarrow \Omega_{gw} h^2 \approx 10^{-12}\ at\ f = 10^7\ Hz \quad (\Omega_{gw,inf} = 10^{-16})$

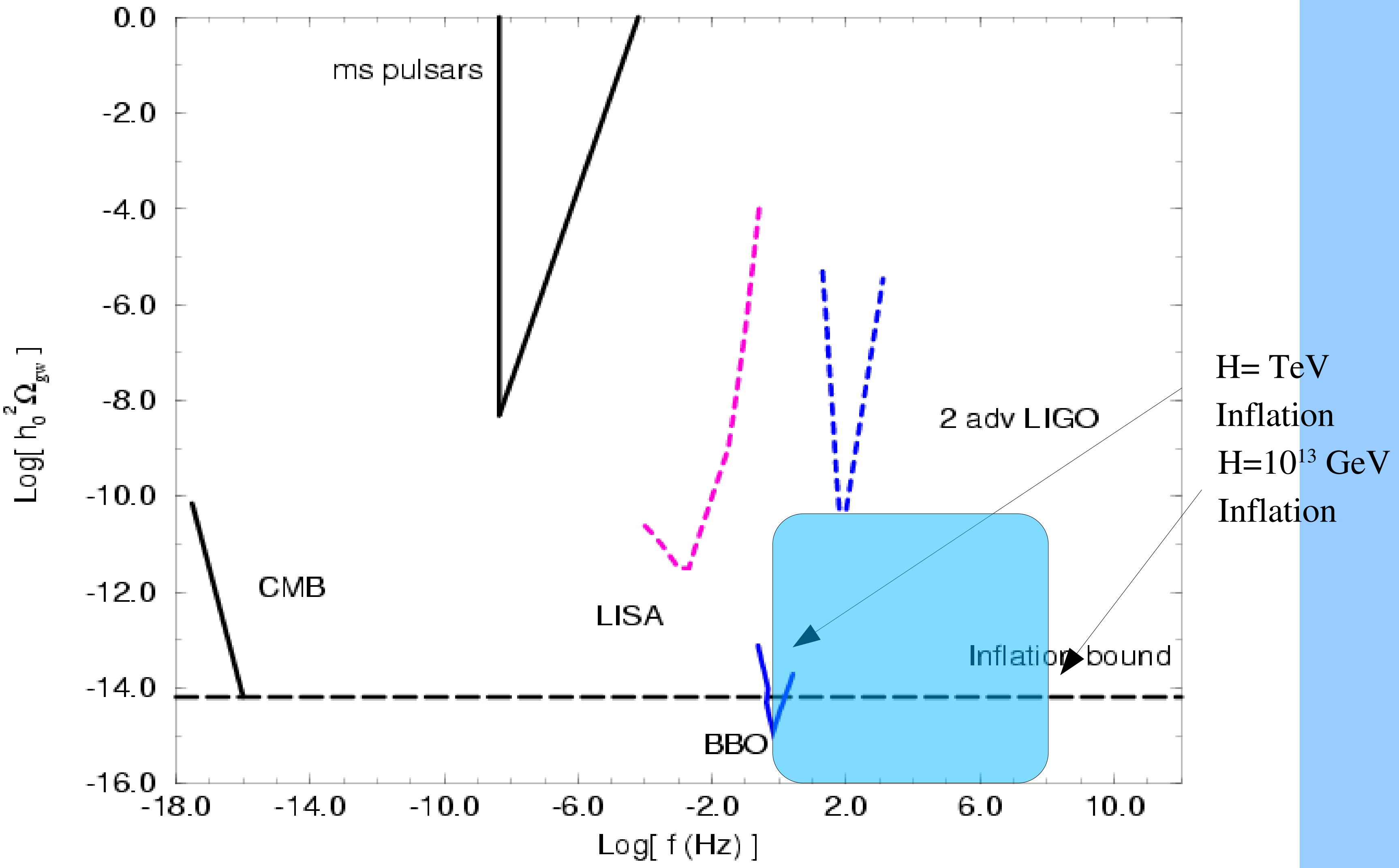
Hybrid: $\bar{m} \approx 10^6 H$ $\quad H_{inf} = 10^2 TeV \Rightarrow \Omega_{gw} h^2 \approx 10^{-10}\ at\ f = 10^2\ Hz \quad (\Omega_{gw,inf} = 10^{-32})$

(Garcia-Bellido, 1998)

- **Good : Low Inflation Scale, Large Oscillation Scale!**

What can we see?

Based on Maggiore (2000)



Primordial vs Preheat Grav. Waves

Primordial	**Preheating**
Quantum Source	Classical Source
Scale Invariant	Peaked near observable range
Low H : Low amplitude	Low H : redder peak
Probes Inflation scale	Probes oscillation scale
Amplitude lower bound small $\Omega_{gw,\,inf} h^2 < 10^{-14}$	Amplitude probably large $\Omega_{gw} h^2 \approx 10^{-13} \sim 10^{-10}$

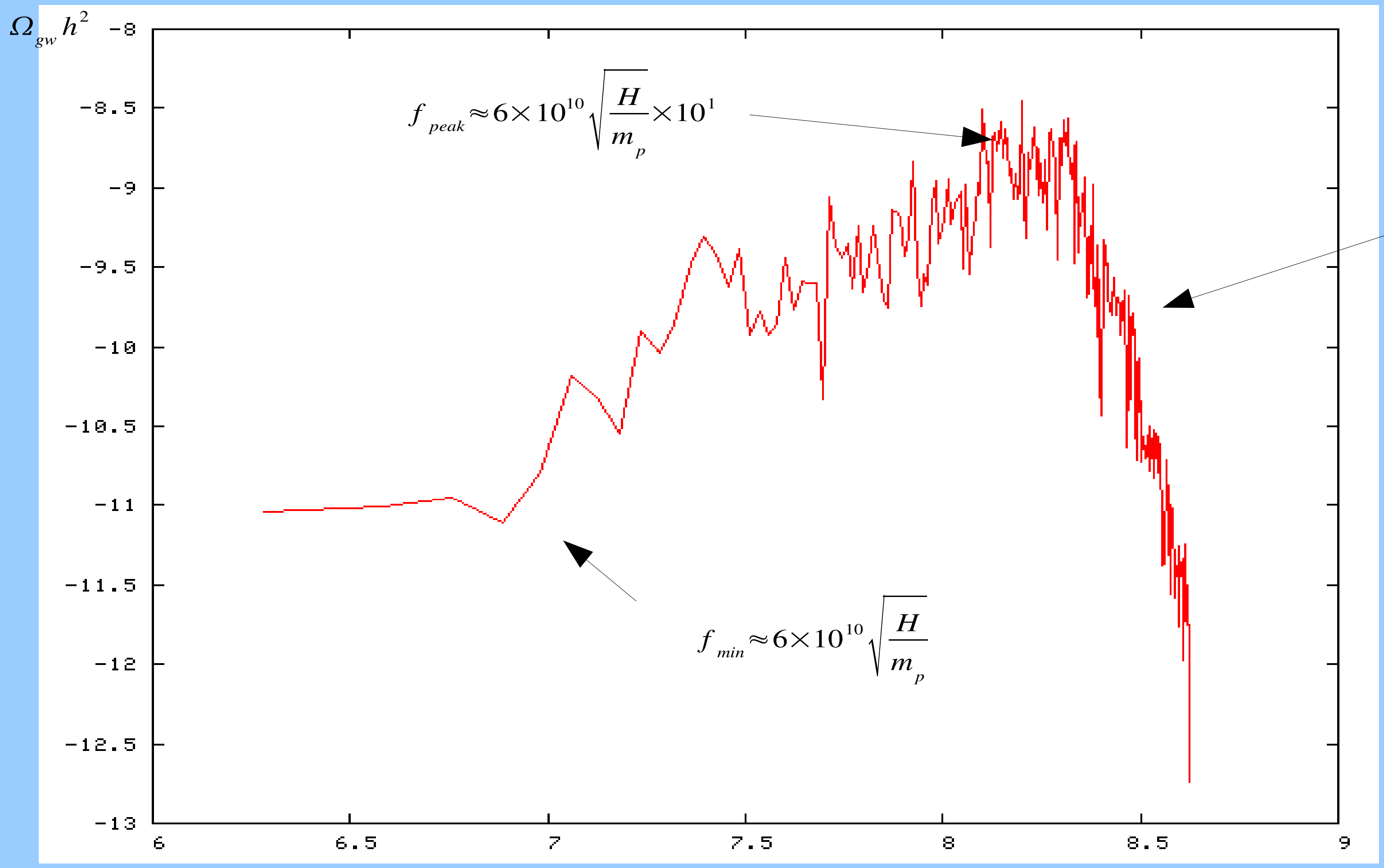
Numerical Simulations

- Lattice Simulation : LatticeEasy to evolve fields.(Tkachev and Felder).
- We extended the code to compute gravitational waves.
- Reproduced the simulation results of Tkachev and Khlebnikov (1997) for $\frac{\lambda}{4}\phi^4+g^2\phi^2\chi^2$
- New results for Chaotic Models $\frac{1}{2}m^2\phi^2+g^2\phi^2\chi^2$
- Hybrid Models (In progress)

Quartic Inflation

$$\frac{\lambda}{4}\phi^4+\frac{1}{2}g^2\phi^2\chi^2 \,,\, \lambda=10^{-14} \,,\, \frac{g^2}{\lambda}=120$$

Khlebnikov + Tkachev 1997

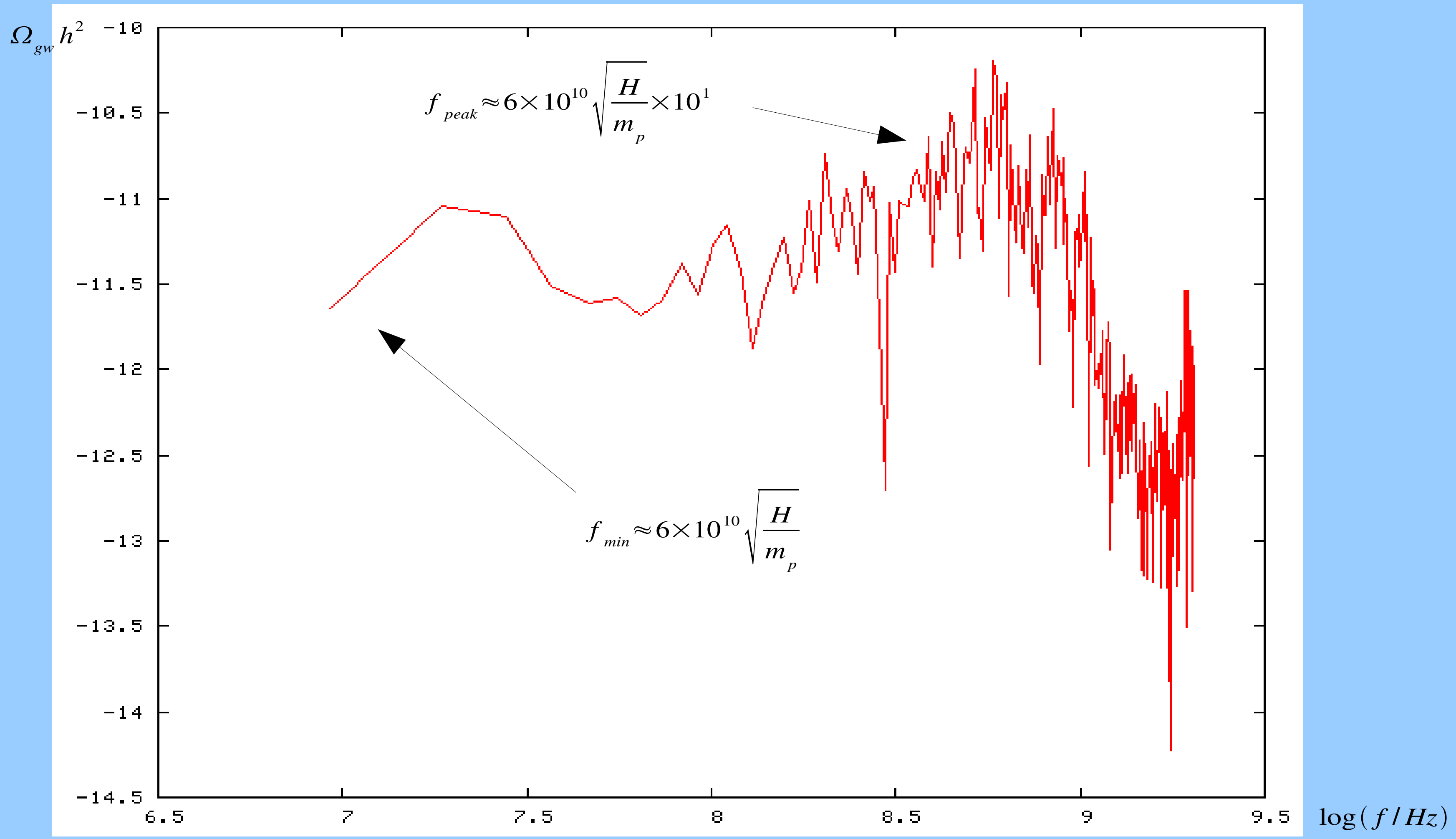


$\log(f\,/\,Hz)$

As k increases, $A(k)>q$, and we leave the resonance bands.

Chaotic Inflation

$$\frac{1}{2}m^2\phi^2+\frac{1}{2}g^2\phi^2\chi^2\ ,\ m\approx 10^{13}GeV\ ,\ g^2=10^{-6}$$



Summary

- Preheating/Reheating is a generic process.
- Large Inhomogeneities : gravitational wave production.
- Numerical Coincidence : peak wavelength is within range of future observatories
- Gravitational Wave amplitude 3 to 4 orders of magnitude more than primordial spectrum
- Low Inflation Scale : bad for observing primordial spectrum, but good for preheating spectrum!
- A new window into Inflation?

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