Gravitational Waves from Graviton Bremsstrahlung during Reheating

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Gravitational Waves

Gravitational waves from:

* Binary neutron star
* Binary black hole
* Neutron star – black hole binary

* Phase transitions ← Talks by G. Arcadi & P. di Bari
* Topological defects
* Primordial black holes
* Preheating
* **Reheating** ← **this talk**

Gravitons

Gravitons → massless spin-2 particles

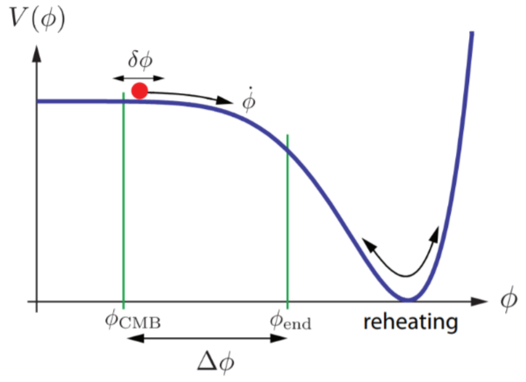
* Perturbations of the metric $$g_{\mu\nu} \simeq \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu}$$

* Graviton – matter interaction $$\sqrt{-g}\,\mathcal{L} \supset -\frac{1}{M_P} h_{\mu\nu} T^{\mu\nu}$$

* Graviton emission
  suppressed by $1/M_P^2$ → large $T^{\mu\nu}$ → reheating!

Inflationary Reheating

Reheating:
Transition from an *inflaton* to a *SM-radiation* dominated universe



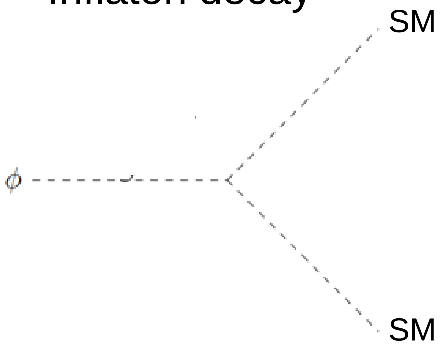
* Inflaton decays or annihilation

* Inflaton potential during reheating

* Possible non-perturbative effects: Preheating
  - fermions: Fermi blocking
  - scalars: quartic couplings avoid tachyonic instabilities
  → preheating not efficient in this setup

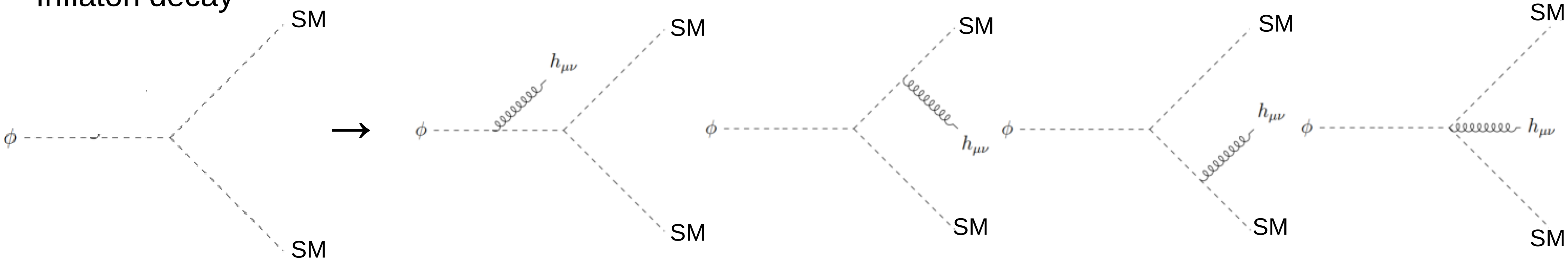
GWs from Graviton Bremsstrahlung

Reheating
Inflaton decay



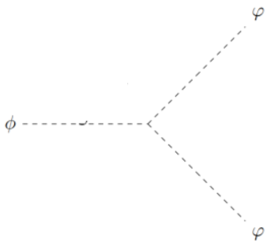
GWs from Graviton Bremsstrahlung

Reheating
Inflaton decay

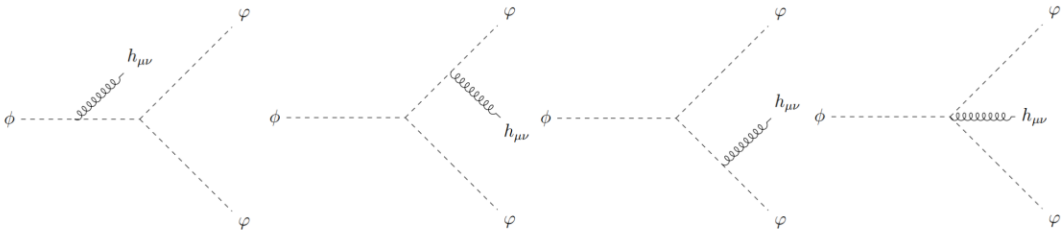


GWs from Graviton Bremsstrahlung

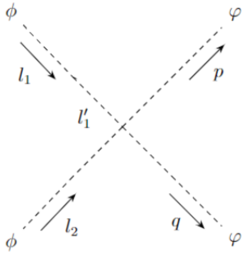
Inflaton decay



→



Inflaton annihilation



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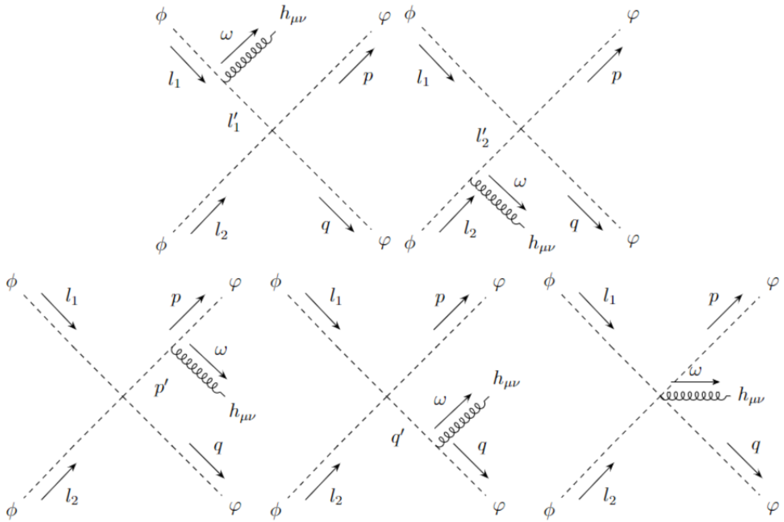
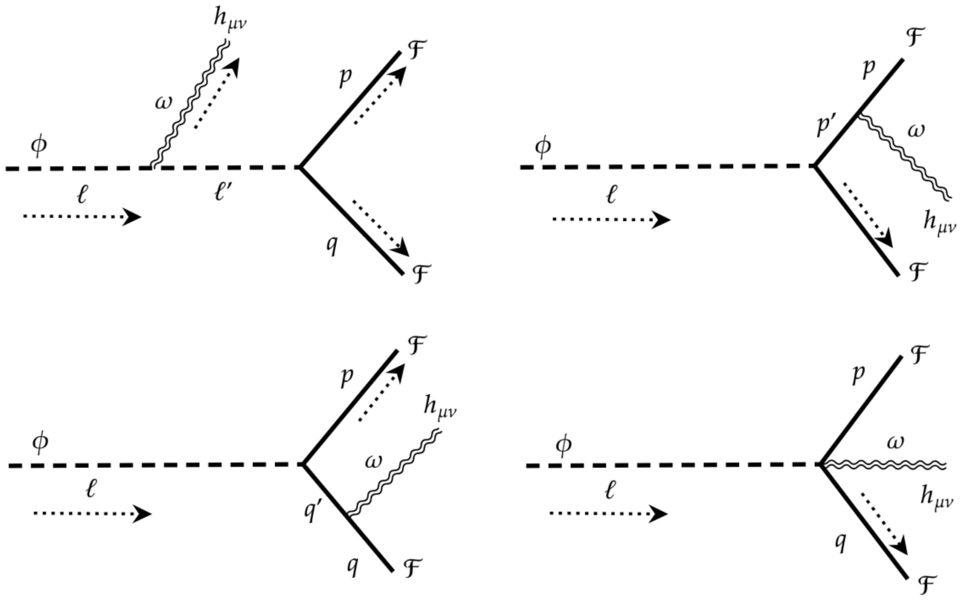


GWs from Graviton Bremsstrahlung



Matrix elements

$$i\mathcal{M}_1 = \frac{-i\,\mu}{M_P}\,\frac{l_\mu\, l_\nu\, \epsilon_i^{\star\mu\nu}}{M\, E_\omega} = 0$$

$$i\mathcal{M}_2 = \frac{i\,\mu}{M_P}\,\frac{p_\mu\, p_\nu\, \epsilon_j^{\star\mu\nu}}{p\cdot\omega}\,,$$

$$i\mathcal{M}_3 = \frac{i\,\mu}{M_P}\,\frac{q_\mu\, q_\nu\, \epsilon_k^{\star\mu\nu}}{M\, E_\omega - p\,\cdot\omega}$$

$$i\mathcal{M}_4 \propto \eta_{\mu\nu}\epsilon^{\mu\nu} = 0\,,$$

Decay Widths

* Inflaton 2-body decay $\Gamma^{\text{2-body}} \simeq \frac{2\,M}{16\,\pi} \left(\frac{\mu}{M}\right)^2$

* Inflaton 3-body decay

$$\frac{d\Gamma^{\text{3-body}}}{dE_\omega} \simeq \frac{2}{64\,\pi^3} \left(\frac{\mu}{M_P}\right)^2 \frac{(2x-1)^2}{4x}$$

$$x = E_\omega / M$$

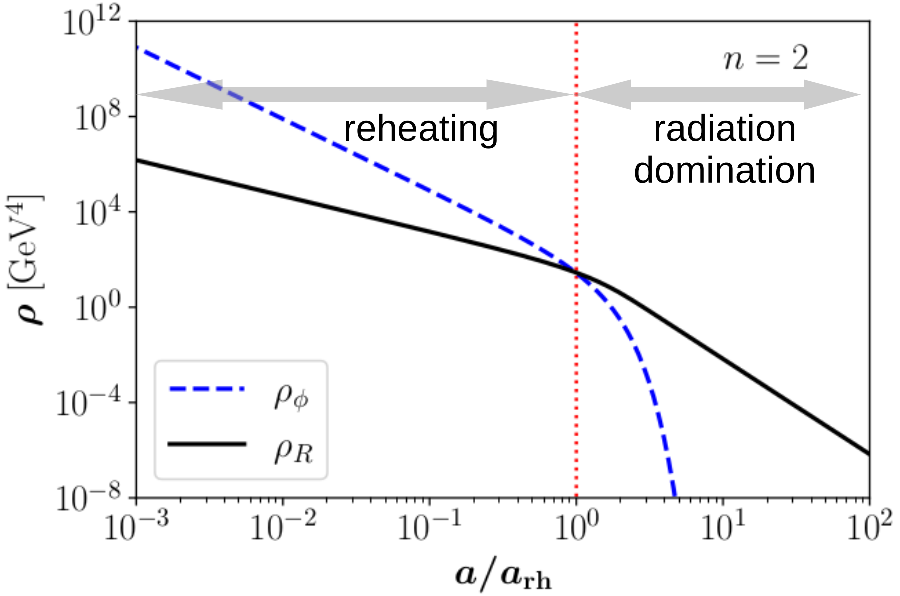
* $x < ½$ → graviton carries at most $M/2$

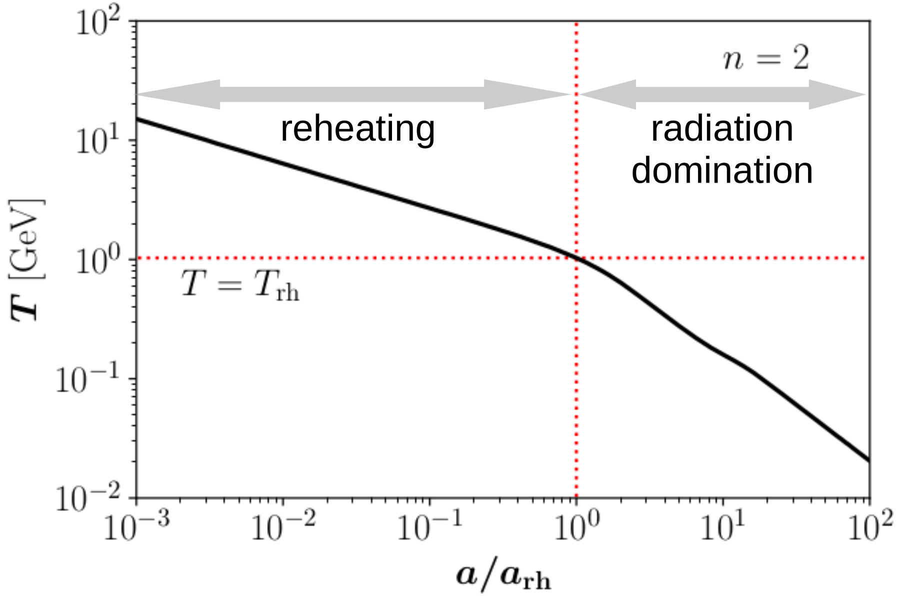
* IR divergence at $x \to 0$
  need vertex and self-energy 1-loop corrections

Boltzmann Equations: background

$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\Gamma^{2\text{-body}}\rho_\phi$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma^{2\text{-body}}\rho_\phi$$





Boltzmann Equations: GWs

$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\left(\left(\Gamma^{\text{2-body}} + \Gamma^{\text{3-body}}\right)\rho_\phi\right.$$

$\Longrightarrow$ fraction of energy to radiation

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma^{\text{2-body}}\rho_\phi + \int \frac{d\Gamma^{\text{3-body}}}{dE_\omega}\,\frac{M - E_\omega}{M}\,\rho_\phi\,dE_\omega$$

$$\frac{d\rho_{\rm GW}}{dt} + 4\,H\,\rho_{\rm GW} = +\int \frac{d\Gamma^{\text{3-body}}}{dE_\omega}\,\frac{E_\omega}{M}\,\rho_\phi\,dE_\omega$$

$\Longrightarrow$ fraction of energy to graviton

$$\frac{d(\rho_{\rm GW}/\rho_R)}{dE_\omega} \sim \left(\frac{d\Gamma^{\text{3-body}}}{dE_\omega}\,\frac{1}{\Gamma^{\text{2-body}}}\right) \times \left(\frac{E_\omega}{M}\right)$$

$\sim$ differential BR $\times$ energy fraction

GW Spectrum

* GW amplitude

$$\Omega_{GW}(f) = \Omega_\gamma^0 \frac{d(\rho_{GW}/\rho_R)}{d \ln f} \sim \mathcal{C}_{\Omega_{GW}} \left(\frac{T_{rh}}{5.5 \times 10^{15}\ \text{GeV}}\right) \left(\frac{M}{M_P}\right) \left(\frac{f}{10^{12}\ \text{Hz}}\right)$$

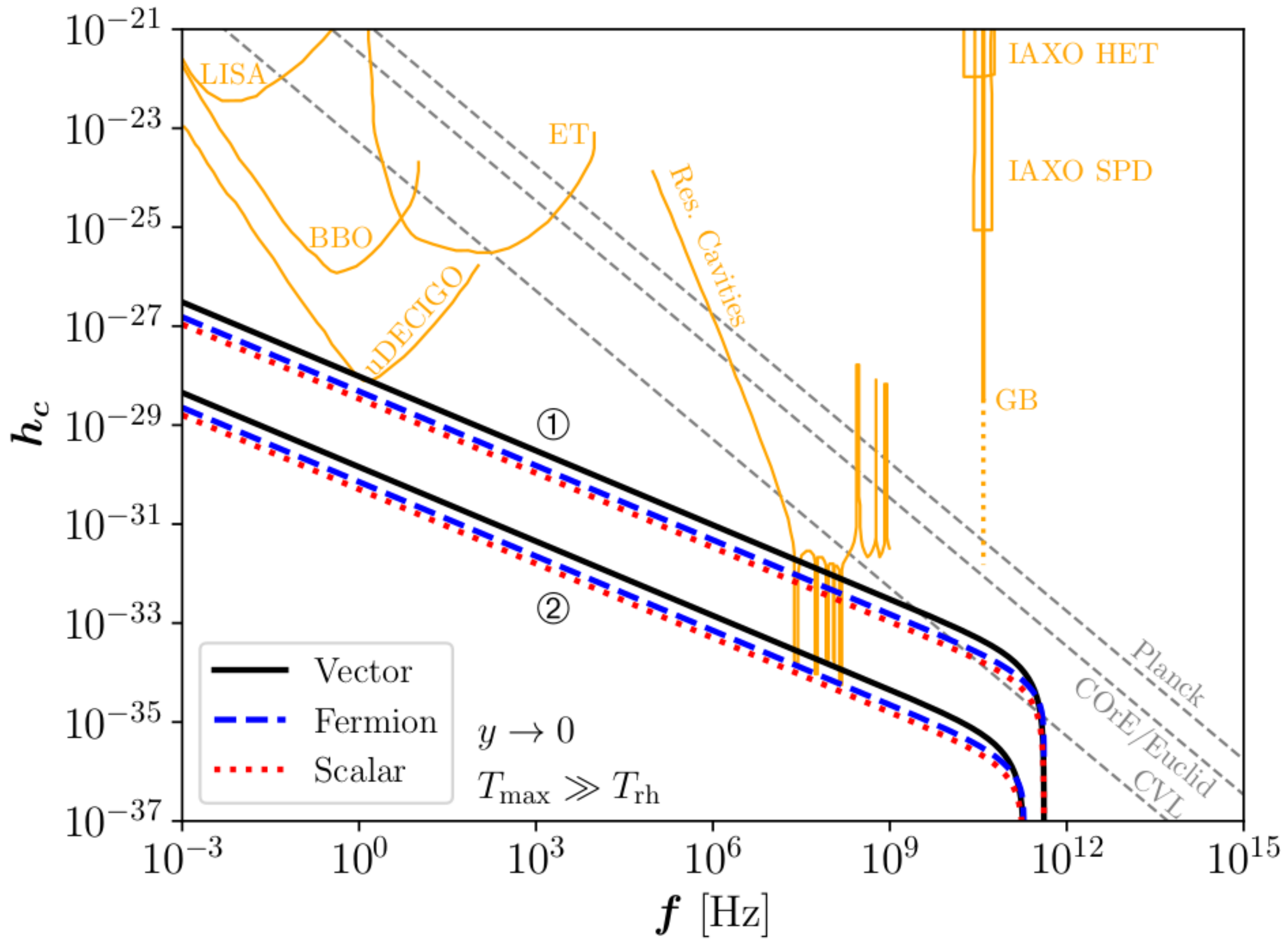
* Graviton energy and frequency

$$E_\omega = 2\pi f \frac{a_0}{a_{rh}} \sim 2\pi f \frac{T_{rh}}{T_0}$$

* Frequency: Upper bound

$$f \lesssim \frac{M}{4\pi} \frac{T_0}{T_{rh}} \sim 4.1 \times 10^{12} \left(\frac{M}{M_P}\right) \left(\frac{5.5 \times 10^{15}\ \text{GeV}}{T_{rh}}\right) \text{Hz}$$

GW Spectrum



Strain parameter

$$h_c(f) = 1/f \times \sqrt{3\,H_0^2\,\Omega_{\rm GW}(f)/2\pi^2}$$

① $M = M_P/10,\ T_{\rm rh} = 5.5 \cdot 10^{15}$ GeV;

② $M = M_P/10^3,\ T_{\rm rh} = M_P/(2 \cdot 10^4)$

Reheating in General Potential ϕ^n

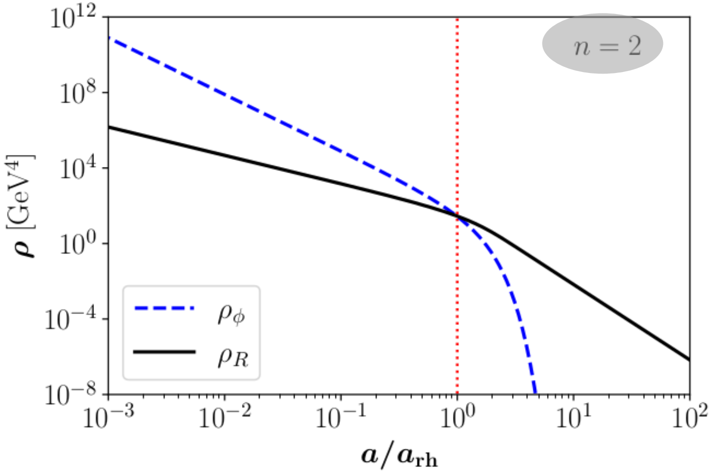
* So far $V(\phi) \sim \phi^2$ during reheating

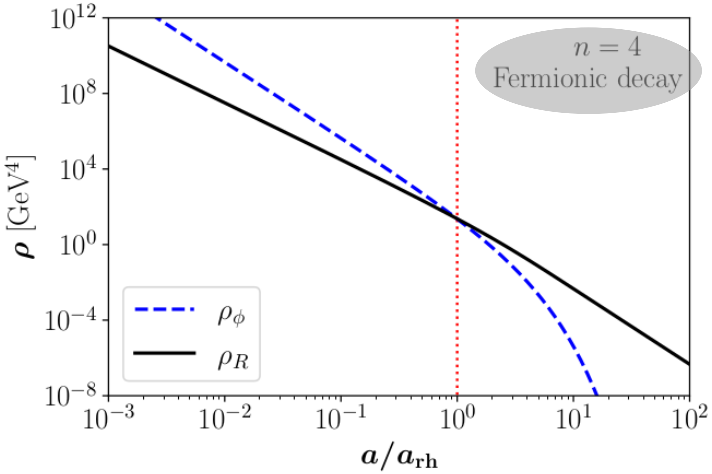
* General monomial potentials $V(\phi) \sim \phi^n$
* Inflaton mass $M^2 \sim V''(\phi)$ → becomes field dependent

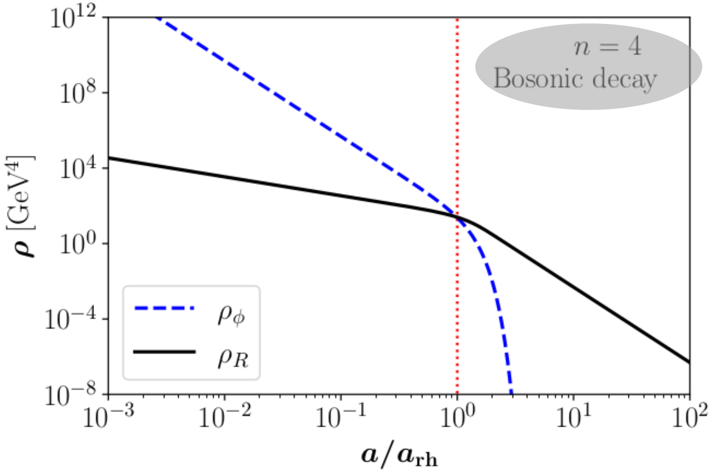
* Decay widths become filed dependent

$$\Gamma_{\rm bos} \sim \frac{\mu^2}{8\pi m_\phi} \qquad \Gamma_{\rm ferm} \sim \frac{y^2 m_\phi}{8\pi}$$

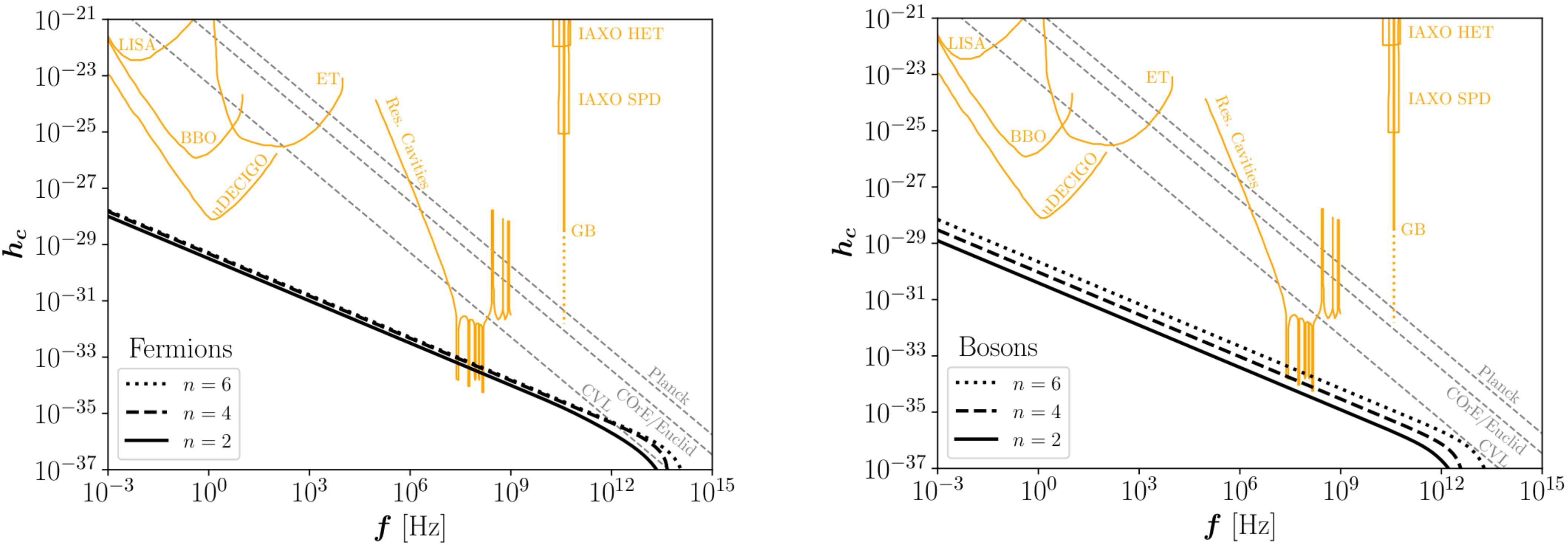
Reheating in General Potential ϕ^n







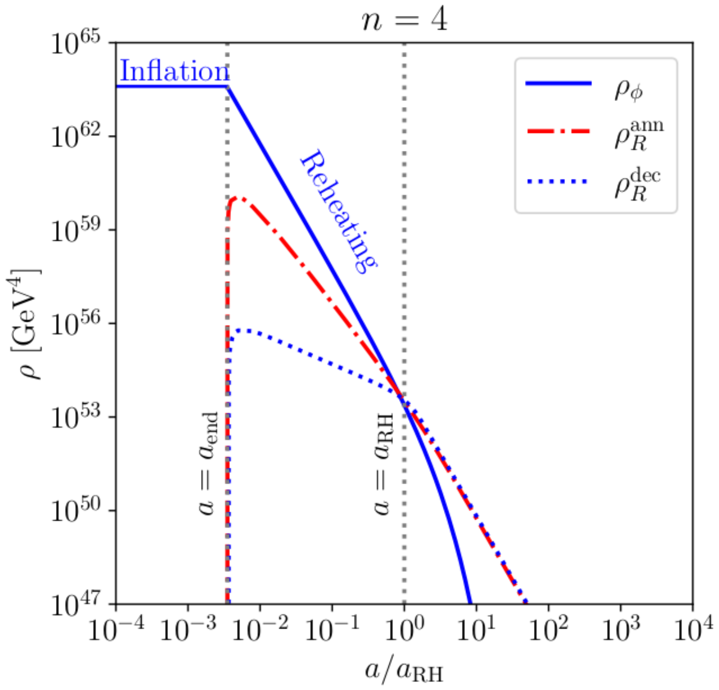
GW Spectrum in ϕ^n

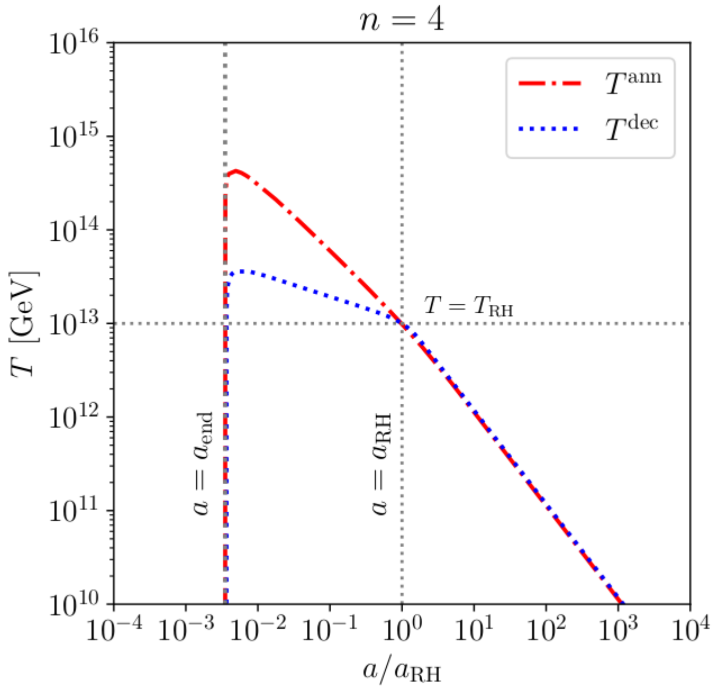


$M_{\rm rh} = 5 \times 10^{16}$ GeV, $T_{\rm rh} = 10^{13}$ GeV, and $T_{\max}/T_{\rm rh} = 10$

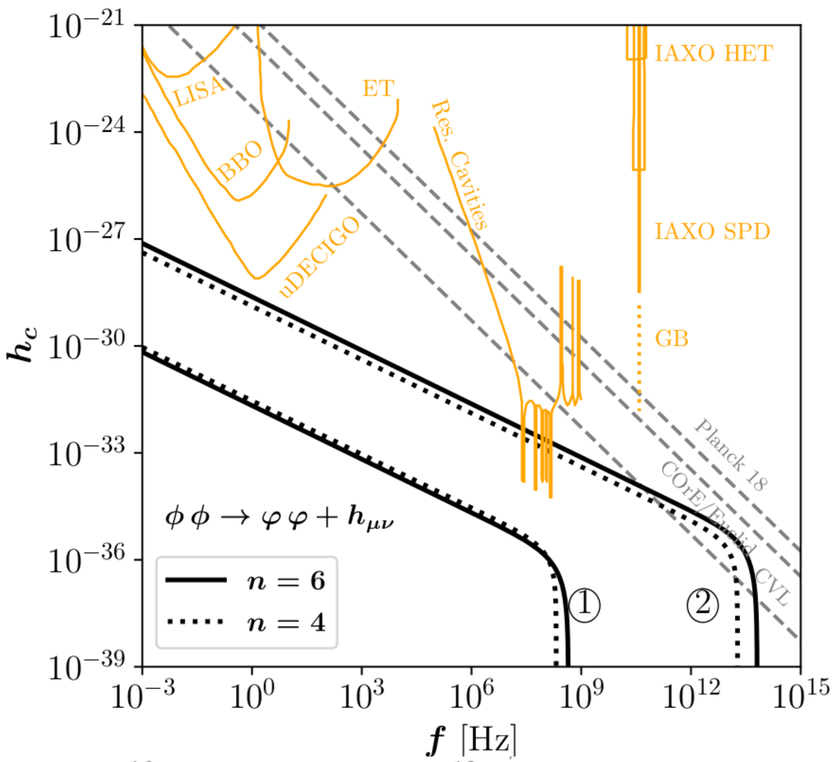
Reheating through Annihilations

* So far reheating through inflaton decays
  → inflaton annihilations are also viable





GW Spectrum for Annihilations



$m_\phi^{\rm RH} = 5 \times 10^{16}$ GeV, $T_{\rm RH} = 5 \times 10^{13}$ GeV and $T_{\max}/T_{\rm RH} = 4$

Conclusions & Outlook

- Reheating happens after cosmic inflation
- Irreducible GW background produced during cosmic reheating

  * reheating dynamics (inflaton potential)
  * inflaton dynamics (decay or annihilation)
  * inflaton – matter coupling
- Quadratic potentials: Very large M and T_{rh}
- Steeper potential: significant boost for bosonic reheating
  * not that large M and T_{rh}
- Decay & annihilation: Possible boost of GW spectrum
- **Reheating could be probed by graviton Bremsstrahlung**

Muchas gracias

Polarization Tensor

Massless gravitons have 2 polarizations

$$\begin{aligned} \epsilon^{i\,\mu\nu} &= \epsilon^{i\,\nu\mu} && \text{symmetric,} \\ \omega_\mu\, \epsilon^{i\,\mu\nu} &= 0 && \text{transverse,} \\ \eta_{\mu\nu}\, \epsilon^{i\,\mu\nu} &= 0 && \text{traceless,} \\ \epsilon^{i\,\mu\nu}\, \epsilon^{j\,\star}_{\mu\nu} &= \delta^{ij} && \text{orthonormal,} \end{aligned}$$

$$\sum_{\text{pol}} \epsilon^{\star\mu\nu} \epsilon^{\alpha\beta} = \frac{1}{2}\left(\hat{\eta}^{\mu\alpha}\hat{\eta}^{\nu\beta} + \hat{\eta}^{\mu\beta}\hat{\eta}^{\nu\alpha} - \hat{\eta}^{\mu\nu}\hat{\eta}^{\alpha\beta}\right)$$

$$\hat{\eta}_{\mu\nu} \equiv \eta_{\mu\nu} - \frac{\omega_\mu \bar{\omega}_\nu + \bar{\omega}_\mu \omega_\nu}{\omega \cdot \bar{\omega}}$$

where $\omega = (E_\omega, \vec{\omega})$ and $\bar{\omega} = (E_\omega, -\vec{\omega})$

Contribution to ΔN_{eff}