Probing Reheating with Graviton Bremsstrahlung

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2301.11345 2305.16388 2311.12694

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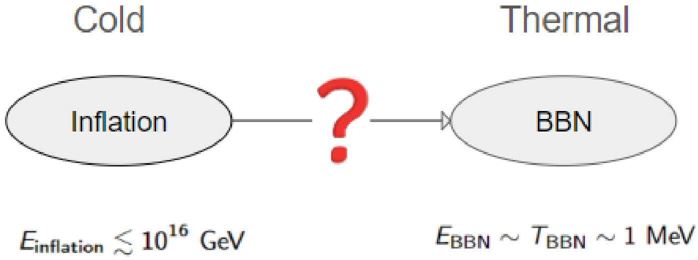
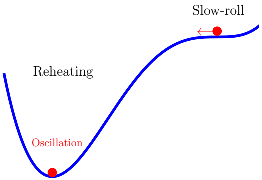
Observations

- Universe is flat and istropic at large scale $\Longrightarrow$ flatness and horizon problems
  - Need inflation, which is driven by vacuum energy $E_{\text{inflation}}$
  - After inflation: the Univerese is empty and cold
- Big Bang Nucleosynthesis needs a Thermal background



Reheating

- A theory describing how inflaton ϕ energy $\Longrightarrow$ thermal background



- Basic ingredients:
  - Couplings $\mu\,\phi h^2$, $\lambda\,\phi^2 h^2$, $y\,\phi\bar{\psi}\psi$
  - Oscillating ϕ $\Longrightarrow$ particles production $\Longrightarrow$ interaction $\Longrightarrow$ thermal bath
  - Complex with non-perturbative phenomena [talks by Piani, Loayza, Marschall]
- Reheating $\Longrightarrow$ thermal background. **Temperature is important**:

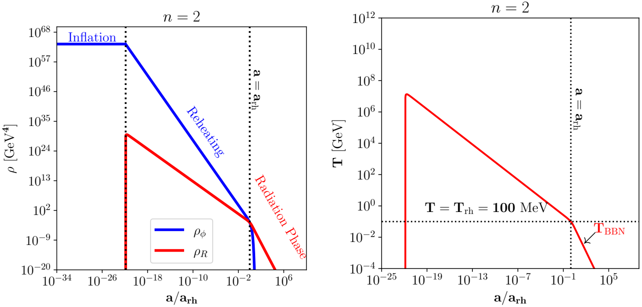
DM production, Baryogenesis, Phase Transition, GW...

Evolution of Background

- Shape of inflaton potential around minimum $V(\phi) \sim \phi^n$
- Couplings $\mu\,\phi h^2$, $y\,\phi\bar{\psi}\psi \implies \Gamma_\phi$

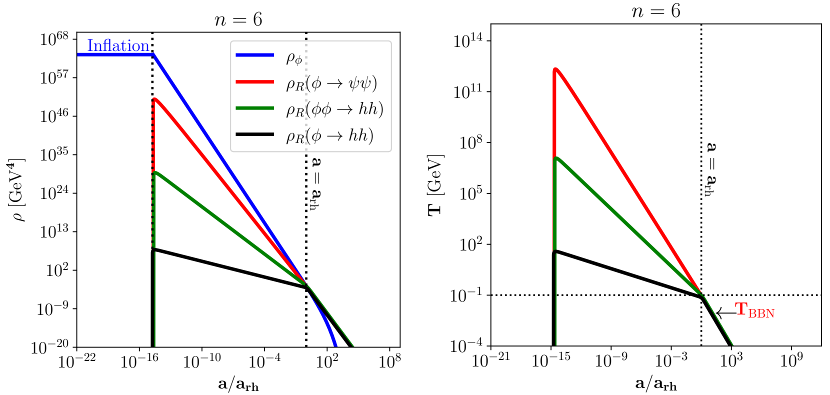
$$\frac{d\rho_\phi}{dt} + 3(1+w)H\,\rho_\phi = -(1+w)\Gamma_\phi\,\rho_\phi$$

$$\frac{d\rho_R}{dt} + 4H\,\rho_R = +(1+w)\Gamma_\phi\,\rho_\phi$$



[YX 2308.15322]

Evolution of Background

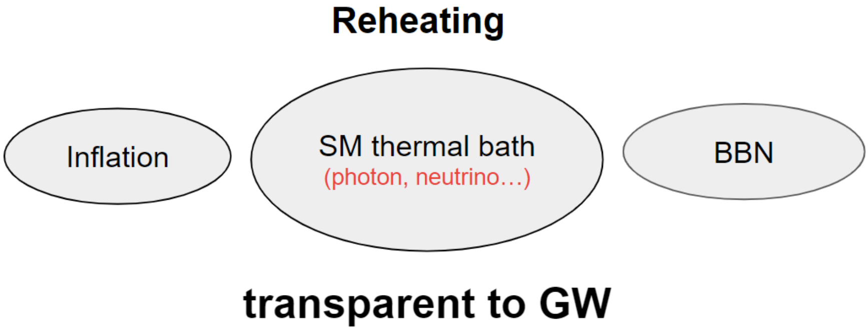


- Fermionic decay: $\Gamma_\phi \sim \frac{y^2 m_\phi}{8\pi}$ with $m_\phi \propto V'' \propto \phi^{n-2}$
- Annihilation: $\Gamma_\phi \sim \frac{\lambda^2 \rho_\phi}{16\pi\, m_\phi^3}$ Bosonic decay: $\Gamma_\phi \sim \frac{\mu^2}{8\pi\, m_\phi}$

n and **type inflaton-matter couplings** $\Longrightarrow$ background evolution

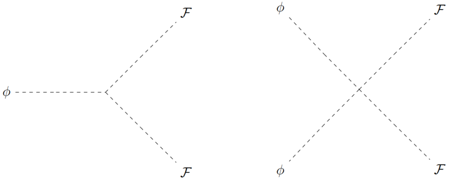
[YX 2308.15322]

How To Probe Reheating?

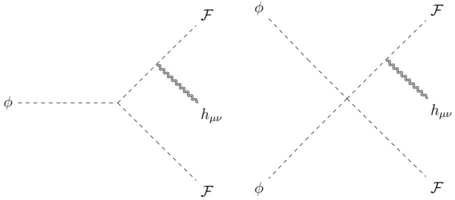


Graviton Bremsstrahlung during Reheating

- Reheating: via $\phi\mathcal{F}\mathcal{F}$ (decay) or $\phi^2\mathcal{F}\mathcal{F}$ (annihilation)

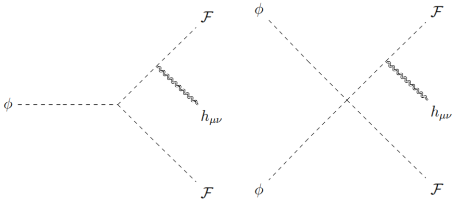


- Graviton Production: $T^{\mu\nu} g_{\mu\nu}$ with $g_{\mu\nu} \simeq \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu} \implies \frac{1}{M_P} T^{\mu\nu} h_{\mu\nu}$



gravitons emission $\implies$ propagation $\implies$ SGWB

[Nakayama, Tang 1810.04975]
[Bernal, Cléry, Mambrini, **YX** 2311.12694]



$$\frac{d\Gamma}{dE_g} \simeq \begin{cases} \frac{y^2}{64\pi^3}\left(\frac{m_\phi}{M_P}\right)^2 \frac{(1-2x)\left[2x(x-1)+1\right]}{x} & \text{fermionic decay} \\ \frac{1}{64\pi^3}\left(\frac{\mu}{M_P}\right)^2 \frac{(1-2x)^2}{x} & \text{bosonic decay} \\ \frac{\lambda^2}{8\pi^3}\,\frac{\rho_\phi}{m_\phi^2\, M_P^2}\,\frac{(1-x)^2}{x} & \text{bosonic annihilation} \end{cases}$$

- $x = \frac{E_g}{m_\phi}$; when $x \to 0 \implies$ soft divergence [Weinberg '65] [Barker, Gupta and Kaskas '69]

[Barman, Bernal, **YX**, Zapata 2301.11345]
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[Bernal, Cléry, Mambrini, **YX** 2311.12694]

GW Spectrum

- GW amplitude:

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f} = \Omega_\gamma^0 \frac{d(\rho_{\rm GW}/\rho_R)}{d\ln f}$$
$$\sim \Omega_\gamma^0 \frac{d(\rho_{\rm GW}/\rho_R)}{d\ln E_g}$$

- Differential spectrum

$$\frac{d(\rho_{\rm GW}/\rho_R)}{dE_g} \propto \left(\frac{d\Gamma}{dE_g}\frac{1}{\Gamma_\phi}\right) \times \left(\frac{E_g}{m_\phi}\right) \times \text{dilution}$$

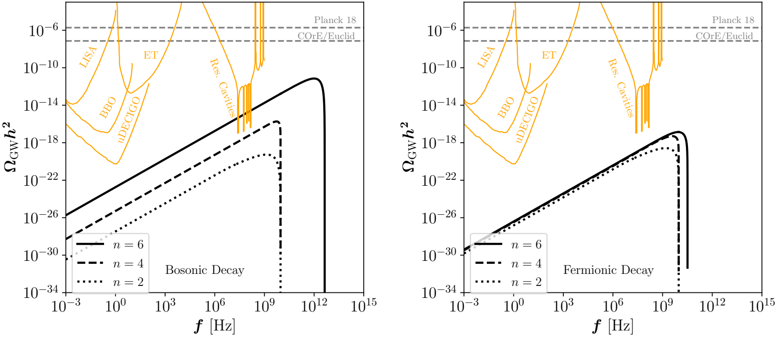
$$\sim \text{differential BR} \times \text{energy fraction} \times \text{dilution}$$

- Expect

$$\Omega_{\rm GW}(f) \propto f$$

[Barman, Bernal, **YX**, Zapata 2301.11345]

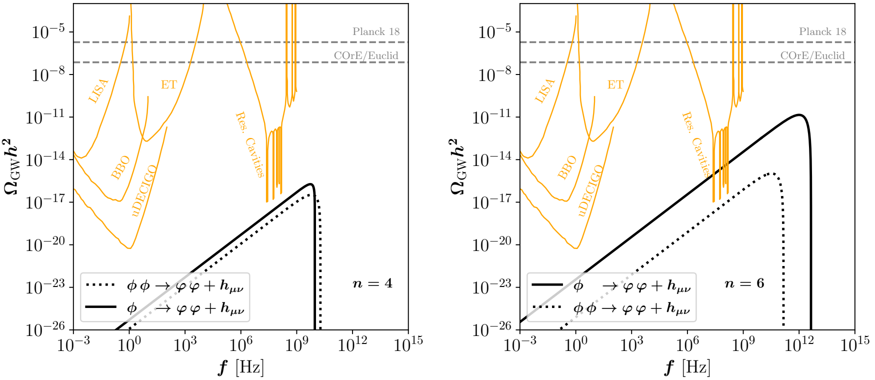
GW Spectrum: Bosonic decay vs Fermionic decay



- GW amplitude **lager in bosonic decay** for $n > 2$ with $V(\phi) \sim \phi^n$
- The distinction in GW $\Longrightarrow$ a novel channel to probe reheating

[Barman, Bernal, **YX**, Zapata 2301.11345]
[Barman, Bernal, **YX**, Zapata 2305.16388]

GW Spectrum: Bosonic Decay vs Bosonic Annhilation



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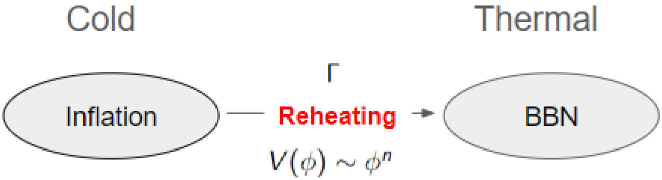
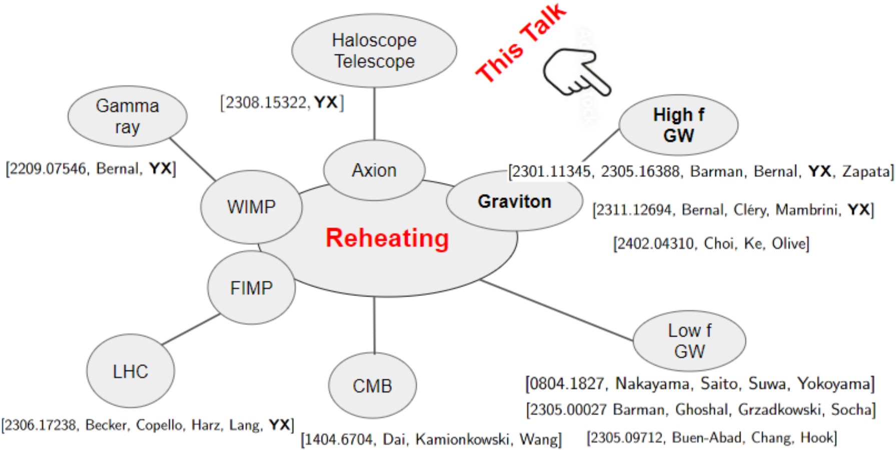
Summary



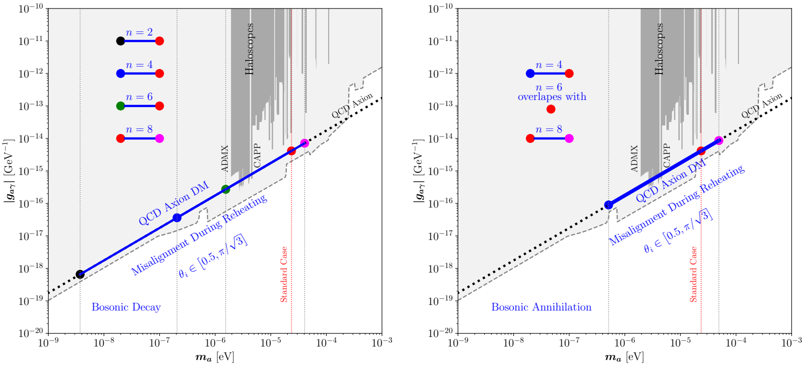
- Reheating explains Cold → Thermal
- The dynamics and background temperature evolution controlled by:
  1. **inflaton potential shape (n)**
  2. **type of inflaton-matter coupling (Γ)**
- There is an unavoidable SGWB from **Graviton Bremsstrahlung**
- Future GW experiments could potentially **probe reheating**

Probing Reheating: Astro-Cosmo-Collider Synergy



Thanks for your attention!

Probing Reheating via Axion Experiments



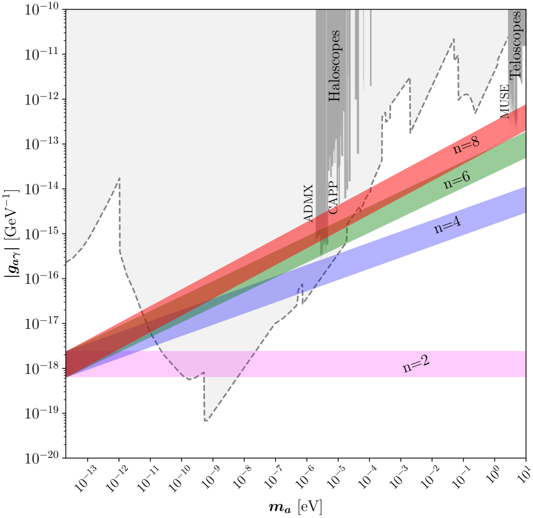
- Assume QCD axion makes up all DM. If a positive signal with

$$4 \cdot 10^{-9}\ \text{eV} \lesssim m_a \lesssim 5 \cdot 10^{-7}\ \text{eV}$$

$\implies$ **bosonic annihilation less likely**

[YX 2308.15322]

ALP



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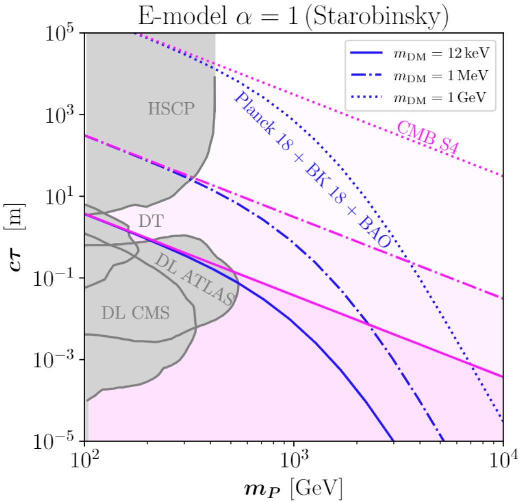
Probing Reheating with LLP Searches in the LHC

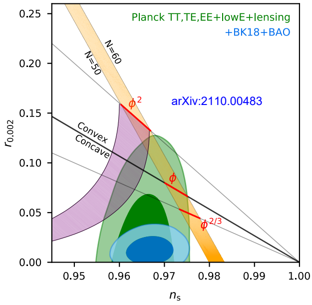


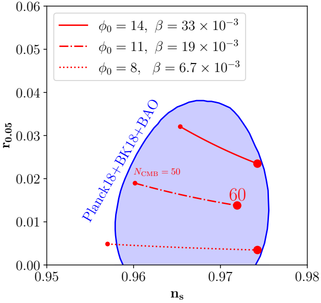
[Becker, Copello, Harz, Lang, **YX** 2306.17238]

Polynomial Inflation

- Monomial Chaotic Inflation $V(\phi) \sim \phi^p$ has been ruled out
- A General and Renormalizable Potential

$$V(\phi) \sim b\,\phi^2 + c\,\phi^3 + d\,\phi^4$$





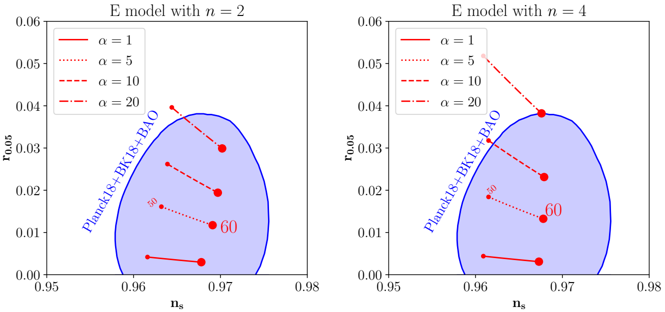
- During reheating: $V(\phi) \sim \phi^2$

[Drees, **YX** 2104.03977]
[Drees, **YX** 2209.07545]

Alpha Attractor Inflation

- The E model [Kallosh and Linde '13]

$$V(\phi) = \lambda M_P^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_P}}\right)^n$$



- During reheating, i.e . $\phi \ll M_P \implies V(\phi) \sim \phi^n$