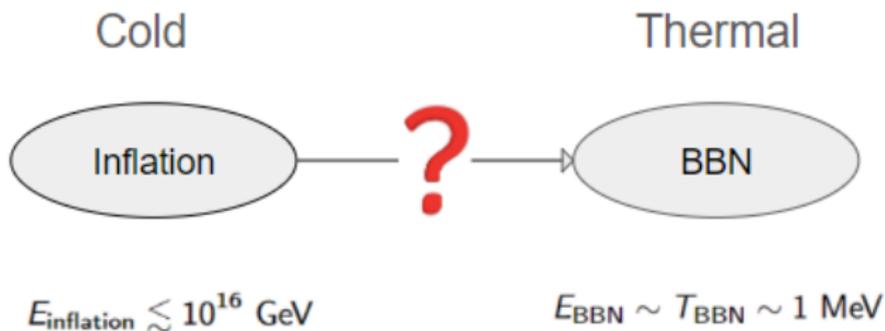


Observations

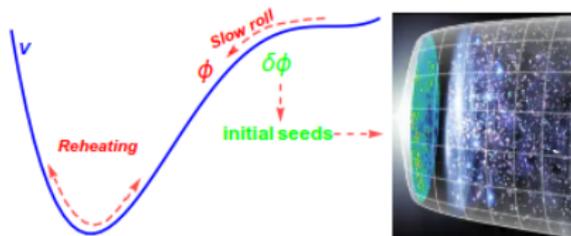
- Our Universe is flat and isotropic on large scales. Why?
 - Inflation driven by **vacuum** energy $E_{\text{inflation}}$
 - **But empty and cold at the end of inflation??** [Guth 1979]
- Big Bang Nucleosynthesis needs a **Thermal** background



Reheating

- A theory describing how inflaton ϕ energy \Rightarrow thermal background

[Kofman, Linde, Starobinsky 1997]



- Basic ingredients:
 - Couplings e.g. $\mu \phi h^2$, $\lambda \phi^2 h^2$, $y \phi \bar{N} N \Rightarrow$ Higgs and RHNs
 - Oscillating inflaton \Rightarrow violation of adiabaticity \Rightarrow particles production \Rightarrow interactions \Rightarrow thermal background
 - Can be complex with non-perturbative phenomena
- **Background temperature is important:**

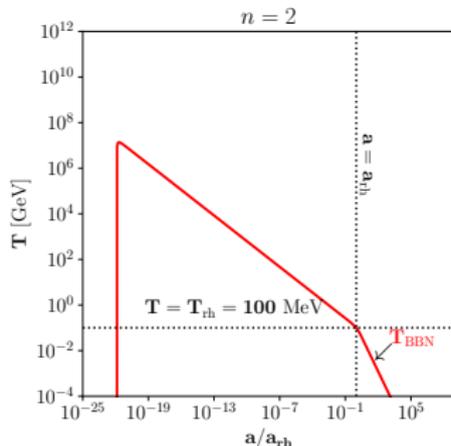
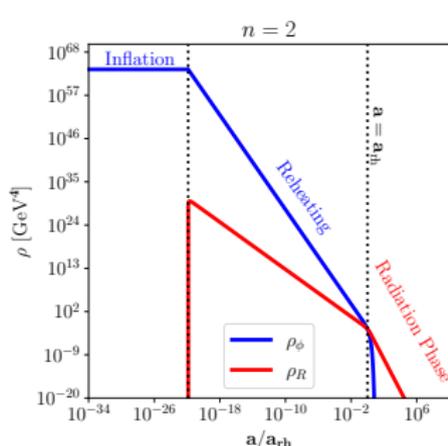
DM production, Baryogenesis, Phase Transition, GW...

Evolution of Background

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

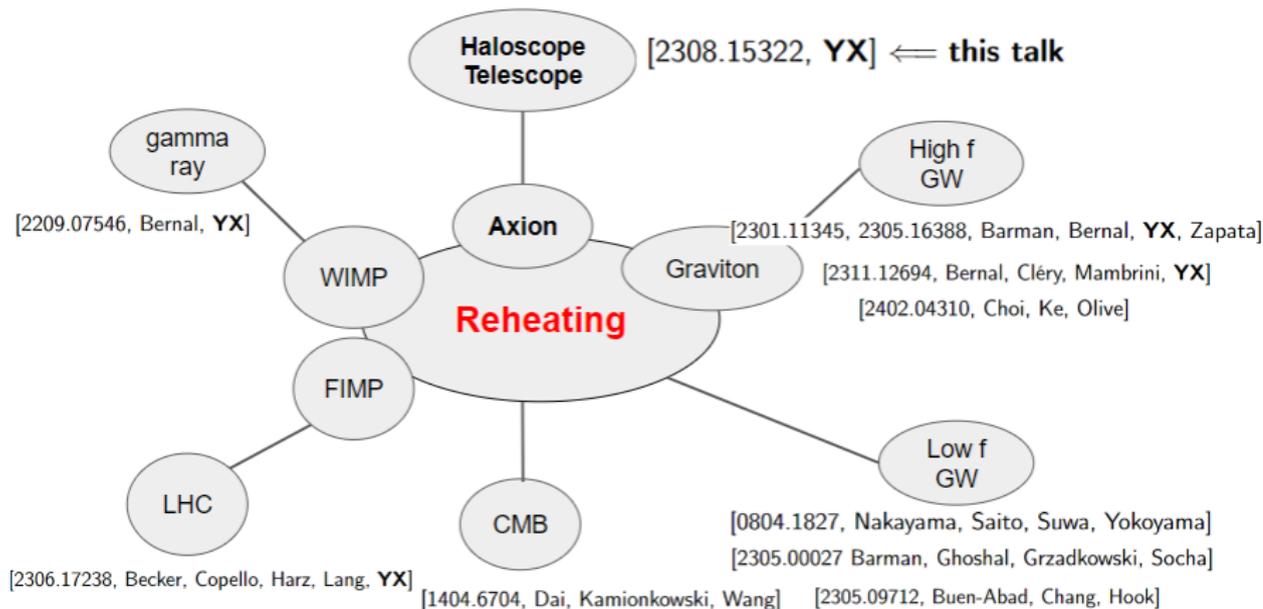
$$\frac{d\rho_\phi}{dt} + 3(1+w)H\rho_\phi = -(1+w)\Gamma\rho_\phi$$

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

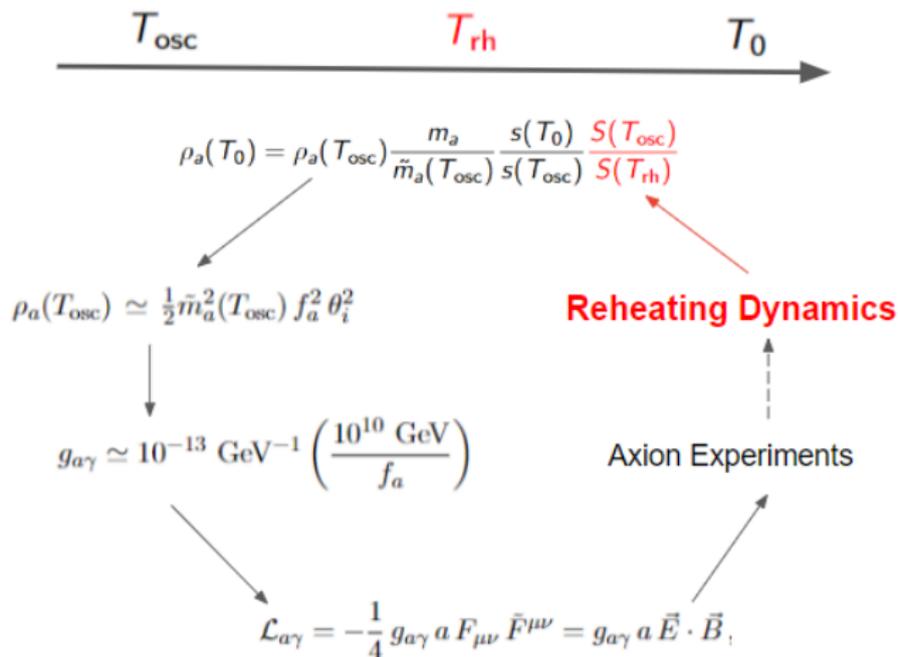


$$T \sim \rho_R^{1/4}$$

Probing Reheating

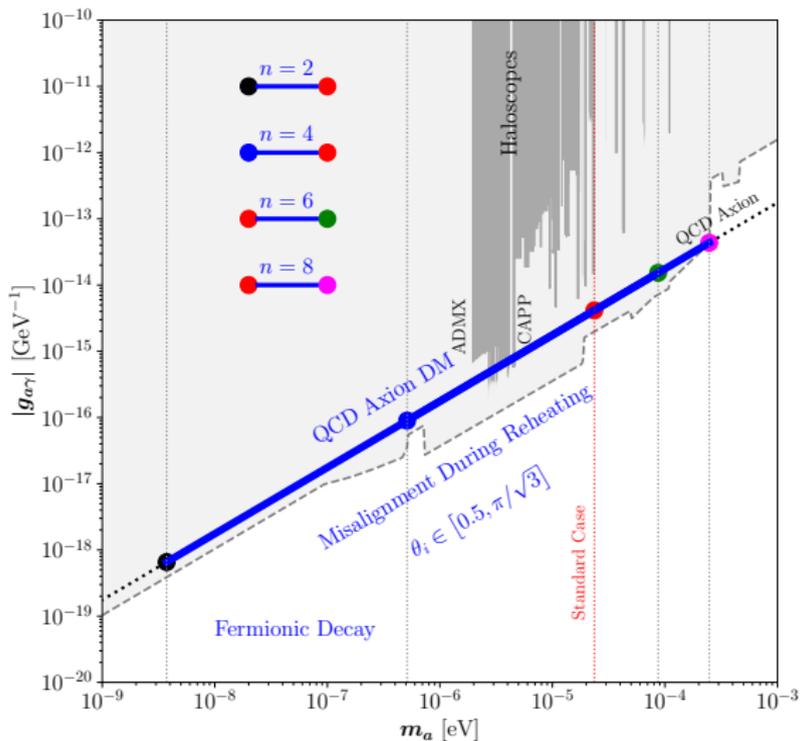


Probing Reheating via Axion experiments



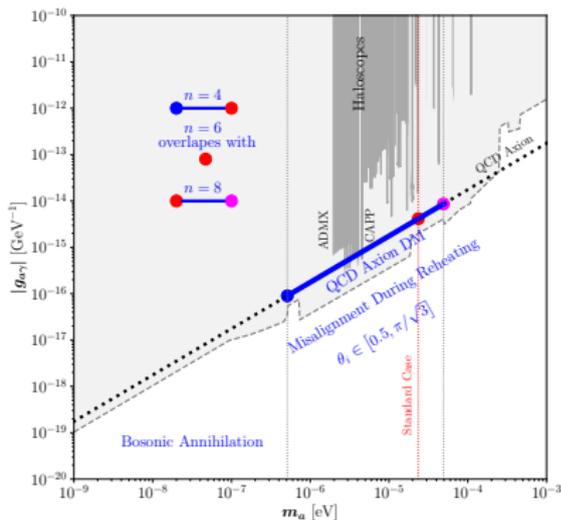
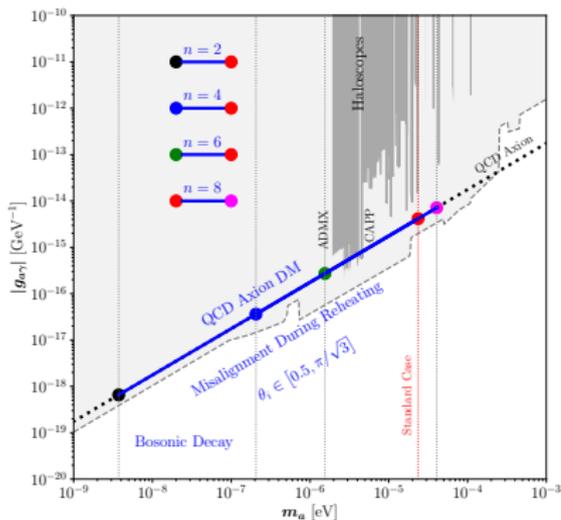
- **Reheating Dynamics:** n and $\Gamma \implies$ different $T \implies$ different $m_a \implies$ **experimental implications**

Experimental Implications with Fermionic Reheating



$$g_{a\gamma} \propto \left(\frac{1}{f_a} \right) \propto m_a$$

Experimental Implications with Bosonic Reheating

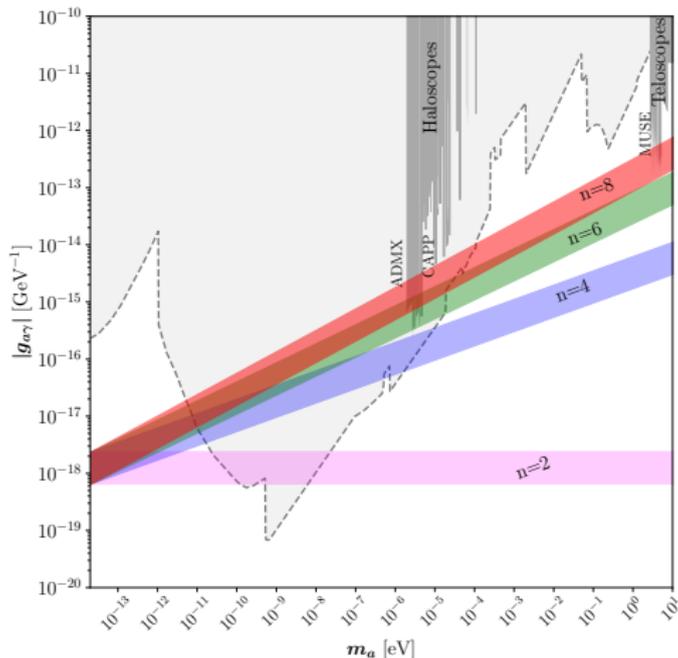


- Assume QCD axion makes up all DM. If a positive signal with

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

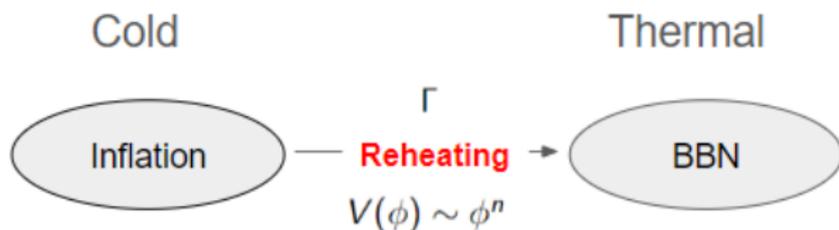
⇒ **bosonic annihilation less likely**

ALP



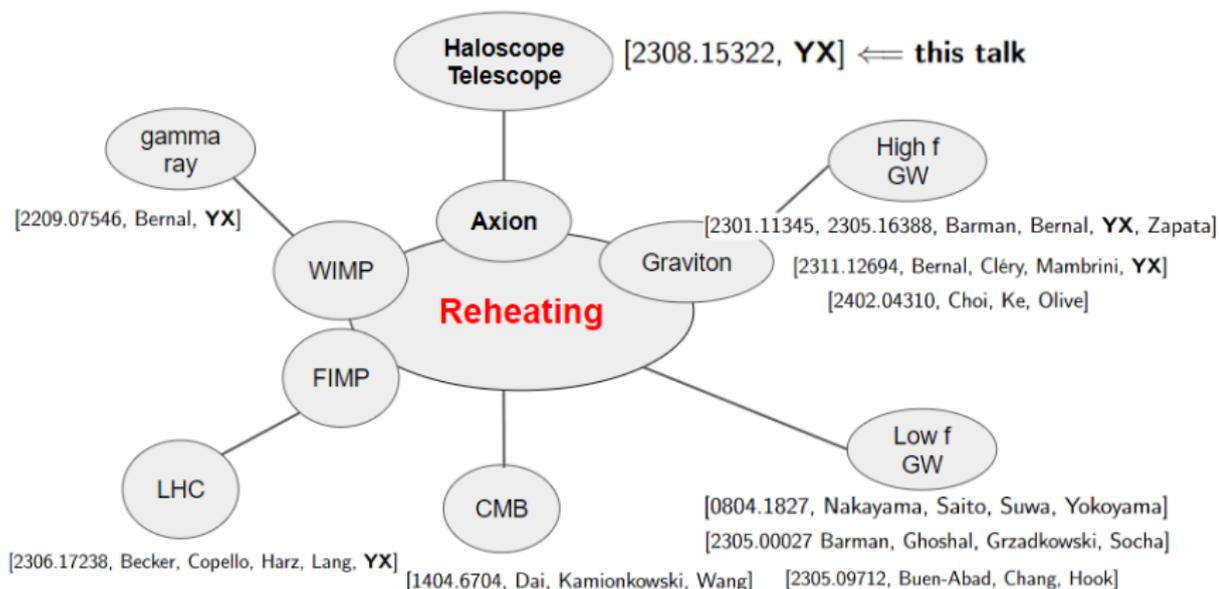
$$\Omega_a h^2 \simeq \left(\frac{\theta_i}{1.0}\right)^2 \left(\frac{f_a}{1.3 \times 10^{13} \times \exp(8.1/n) \text{ GeV}}\right)^2 \left(\frac{T_{\text{rh}}}{4 \text{ MeV}}\right)^{\frac{4-n}{n}} \left(\frac{m_a}{7.4 \times 10^{-11} \text{ eV}}\right)^{\frac{n-2}{n}}$$

Summary



- **Reheating** explains Cold \rightarrow Thermal
- The dynamics and background temperature evolution controlled by:
 1. **inflaton potential shape (n)**
 2. **type of inflaton-matter coupling (Γ)**
- Future **axion experiments** could potentially **probe reheating**

Probing Reheating: Astro-Cosmo-Collider Synergy

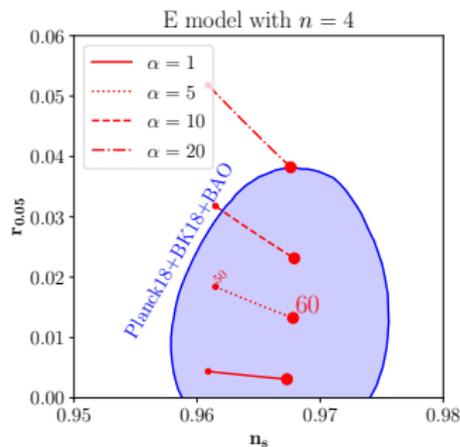
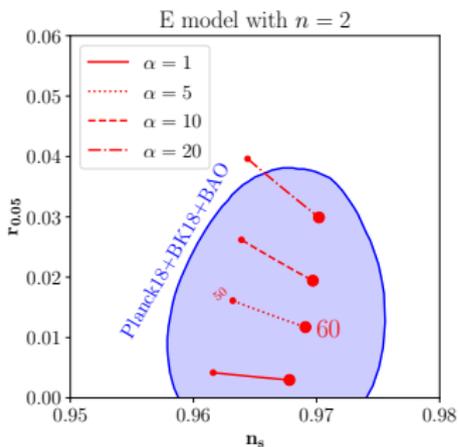


Thanks for your attention!

Alpha Attractor Inflation

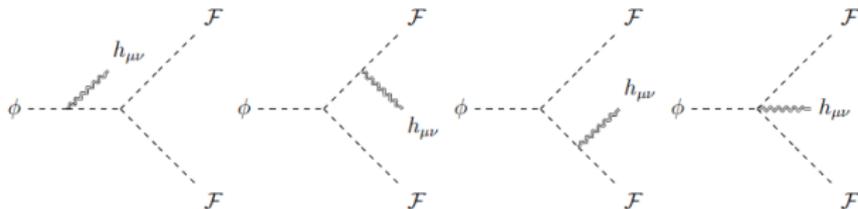
- The E model [Kallosh and Linde '13]

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



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

Probing Reheating with Graviton Bremsstrahlung and High Frequency GW



The GW spectrum [Barman, Bernal, YX, Zapata, 2301.11345]

$$\Omega_{\text{GW}}(f) \simeq \mathcal{O}(10^{-8}) \left(\frac{T_{\text{rh}}}{5.5 \times 10^{15} \text{ GeV}} \right) \left(\frac{m_\phi}{M_P} \right) \left(\frac{f}{10^{12} \text{ Hz}} \right)$$