Probing Inflationary Reheating with Dark Matter

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Light Dark World 2026
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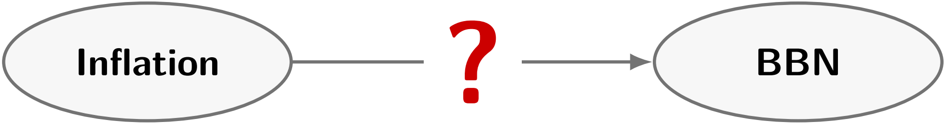
Question

Inflation exponentially dilutes everything.

Cold and empty

Hot thermal bath

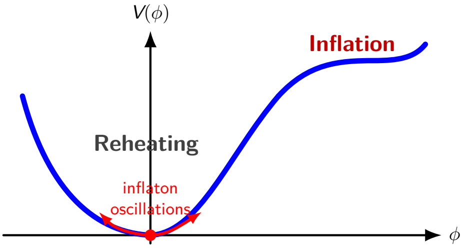


$T_{\rm end} \simeq 0$

$T_{\rm BBN} \sim {\rm MeV}$

How did the Universe become hot again?

Reheating: How it works?



- Couplings

$$\lambda\,\phi^2 h^2, \qquad \mu\,\phi h^2, \qquad y\,\phi\bar{\psi}\psi$$

- Oscillating ϕ

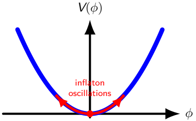
$$\Longrightarrow \text{ particle production } \Longrightarrow \text{ interactions } \Longrightarrow \text{ thermal bath}$$

- Rich phenomena with nonperturbative features

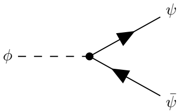
[Dolgov, Kirilova '89] [Traschen, Brandenberger '90] [Shtanov, Traschen, Brandenberger '94] [Kofman, Linde, Starobinsky '94]...

Evolution of the Reheating Background

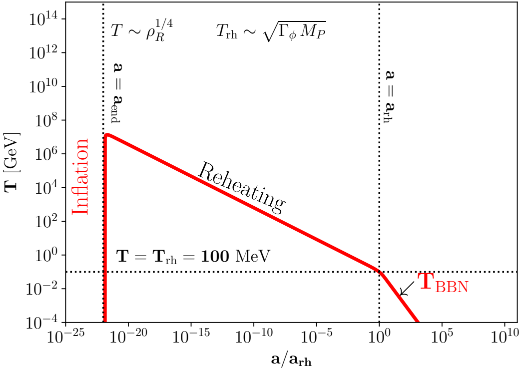
$$V(\phi) \simeq \frac{1}{2} m_\phi^2 \phi^2$$



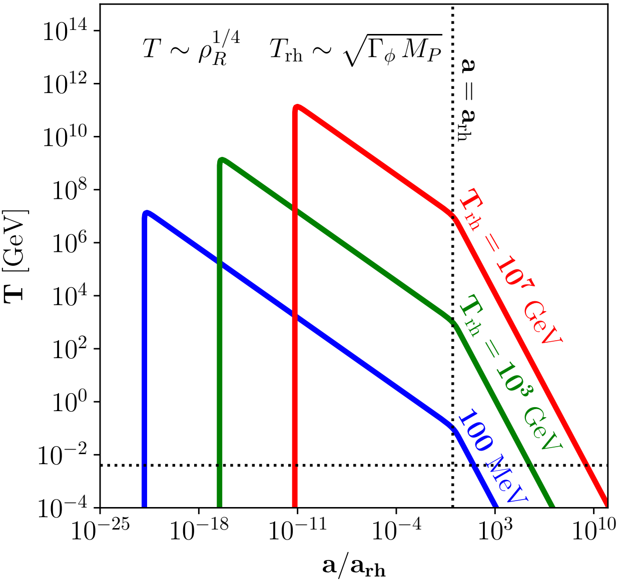
$$\Gamma_\phi \simeq \frac{y^2 m_\phi}{8\pi}$$



$$\dot{\rho}_R + 4H\rho_R = \Gamma_\phi \rho_\phi$$



Evolution of Background for different $T_{\rm rh}$



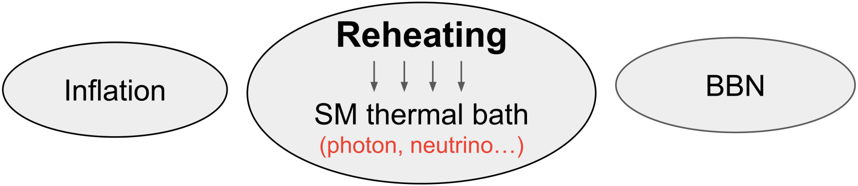
Reheating: Why Is It Important?

1 **Thermal history**	2 **Expansion history**	3 **Relic production**
$T_{\rm max} > T_{\rm rh}$	$H_{\rm RH} \neq H_{\rm RD}$	$\dot{n}_\chi + 3Hn_\chi = \gamma_{\rm source}(T)$

$$\boxed{\Omega_\chi = \Omega_\chi\left[T(t), H, \gamma_{\rm source}(T)\right]}$$

Reheating $\Longrightarrow$ uncertainties for experimental predictions and exclusion limits!

How Can We Probe Reheating?



Weakly coupled particles
$\Longrightarrow$ **reheating messengers**

Three Reheating Messengers

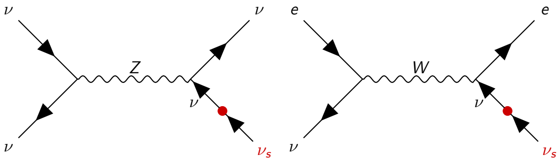
Dark matter can preserve information

$\boxed{\text{Sterile neutrino DM}}$ $\boxed{\text{WIMP DM}}$ $\boxed{\text{Axion DM}}$

Three windows into reheating

[For alternative scenarios, see e.g. the talk by Rafa Lopez on dark photon.]

Sterile Neutrino Production: Oscillation



- Production $\nu_\alpha \to \nu_s$

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_s(p,t) = \Gamma_\alpha \frac{1}{4}\sin^2(2\theta_m)\left[f_\alpha(1-f_s) - f_s(1-f_\alpha)\right]$$

[Barbieri, Dolgov '90; Kainulainen '90; Dodelson, Widrow '94; Shi, Fuller '99; Abazajian, Fuller, Patel '01; Asaka, Blanchet, Shaposhnikov '05,...]

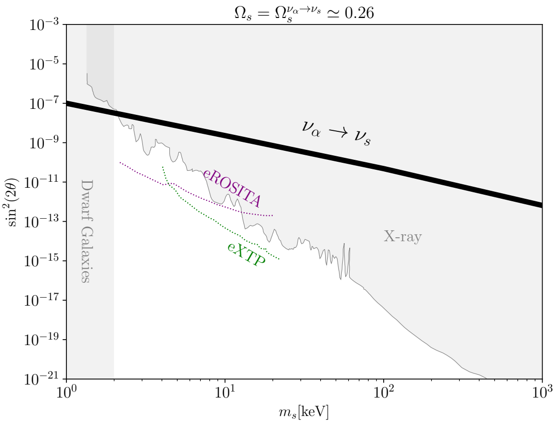
- Γ_α: $2 \to 2$ scattering rate; can be enhanced with neutrino self interaction.

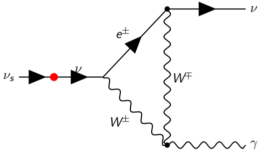
[Gouvêa, Sen,Tangarife, Zhang '19]

- Peak temperature with $\sin^2(2\theta_m)$ reaching maximum

$$T_{\rm peak} \simeq 130\,(m_s/{\rm keV})^{1/3}\,{\rm MeV}$$

Sterile Neutrino DM After reheating: Oscillation



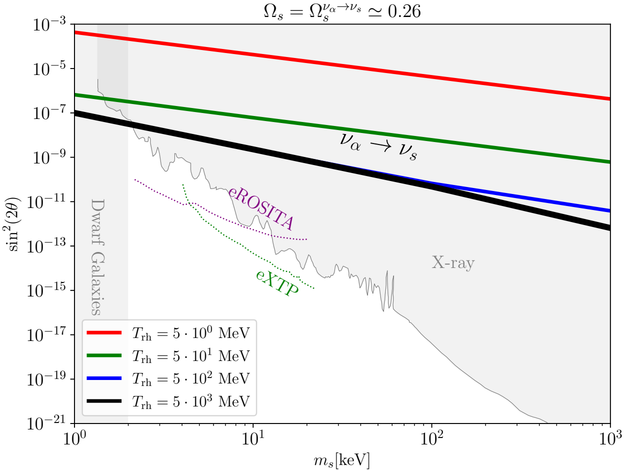


$$\Gamma_{\nu_s \to \nu\gamma} \propto \alpha G_F^2 \sin^2(2\theta)\, m_s^5$$

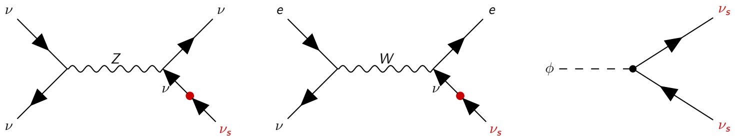
Sterile Neutrino DM During Reheating: Oscillation

- Modify the background

$$\left(\frac{\partial}{\partial t} - H\, p \frac{\partial}{\partial p}\right) f_s(p,t) = \mathcal{C}_{\nu_\alpha \to \nu_s}$$



Sterile Neutrino Production during Reheating: Decay



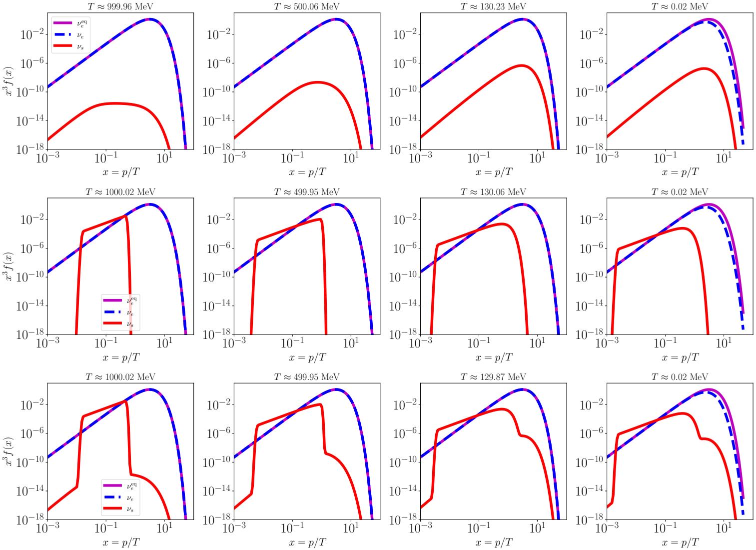
- Modify the production source

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_s(p,t) = \mathcal{C}_{\nu_\alpha \to \nu_s} + \mathcal{C}_{\phi \to \nu_s \nu_s}(p)$$

$$\mathcal{C}_{\nu_\alpha \to \nu_s} = \Gamma_\alpha \frac{1}{4} \sin^2(2\theta_m) \left[f_\alpha(1-f_s) - f_s(1-f_\alpha)\right]$$

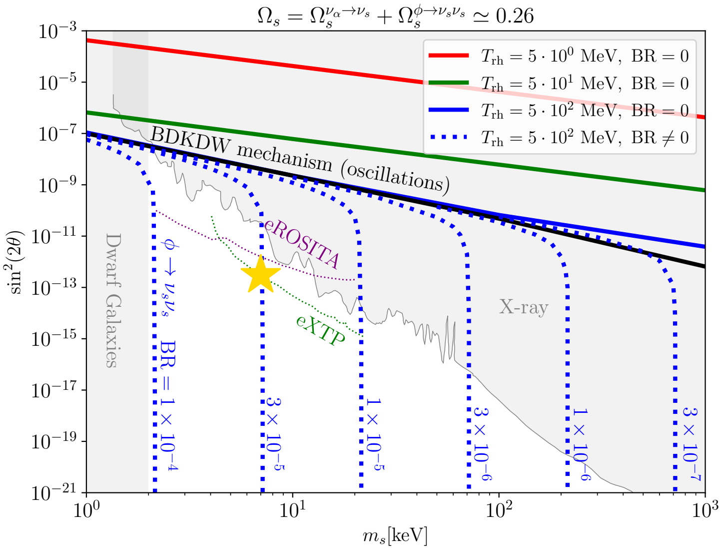
$$\mathcal{C}_{\phi \to \nu_s \nu_s}(p) = \frac{8\pi^2 \, n_\phi \, \Gamma_\phi \, \mathrm{BR}(\phi \to \nu_s \nu_s)}{m_\phi^2} \delta\left(p - \frac{m_\phi}{2}\right)$$

Evolution of Phase Space Distribution for Neutrino



[Cline, **YX** 2601.03346; https://github.com/yongxuDM/Sterile-Neutrino]

Probing Reheating with Sterile Neutrino DM



[Cline, **YX** 2601.03346]

WIMP Freeze-Out: After vs. During Reheating

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\rm eq}^2\right)$$

Freeze-out after reheating

$$T_{\rm fo} < T_{\rm rh} \Longrightarrow Y_\chi \propto \frac{1}{\langle\sigma v\rangle}$$

$$\langle\sigma v\rangle \sim 10^{-9}~{\rm GeV}^{-2}$$

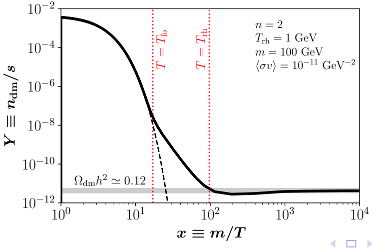
Strong constraints

Freeze-out during reheating

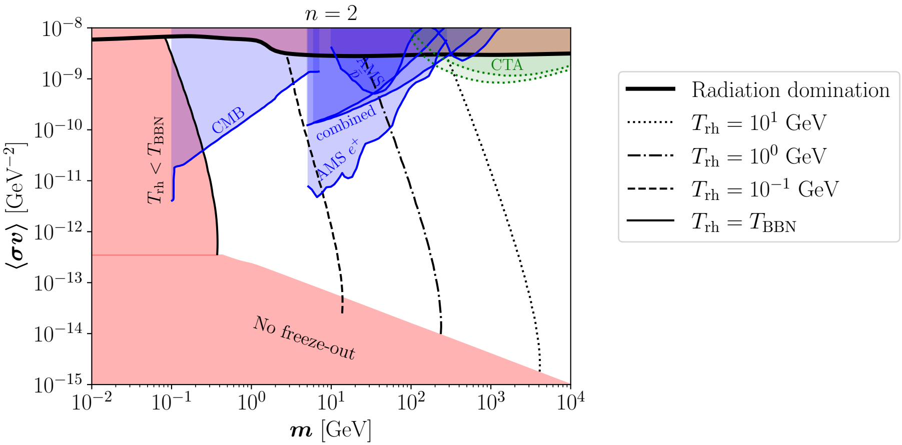
$$T_{\rm fo} > T_{\rm rh} \Longrightarrow Y_\chi \downarrow \text{(entropy dilution)}$$

$$\langle\sigma v\rangle \ll 10^{-9}~{\rm GeV}^{-2}$$

Constraints can be evaded



Probing Reheating with WIMP DM

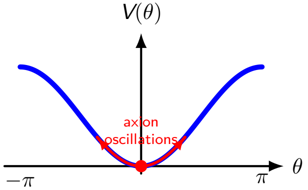


[Bernal, **YX** 2209.07546]

Axion Production during Reheating

$$V(\theta) = m_a^2 f_a^2 (1 - \cos\theta), \qquad \theta = \frac{a}{f_a}, \qquad \ddot{\theta} + 3H\dot{\theta} + m_a^2 \sin\theta = 0.$$

$H \gg m_a \implies \theta \simeq \theta_i$ frozen



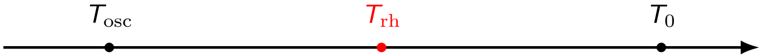
$$\boxed{H(T_{\rm osc}) \simeq m_a}$$

Axion oscillations begin

$$\rho_a(T_{\rm osc}) \simeq \frac{1}{2} m_a^2(T_{\rm osc}) f_a^2 \theta_i^2$$

Does $T_{\rm osc}$ occur before or after reheating?

Probing Reheating via Axion Experiments



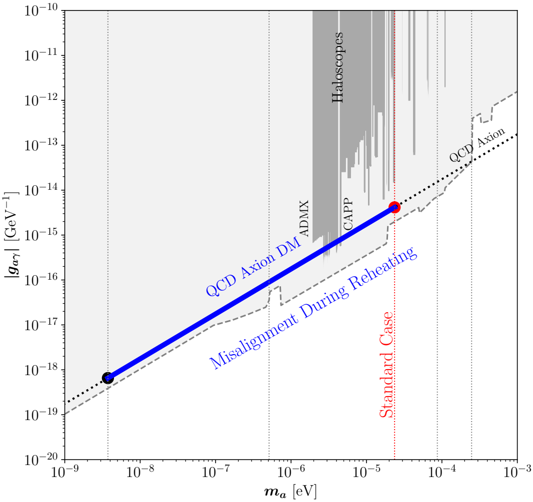
$$\rho_a(T_0) = \rho_a(T_{\rm osc})\,\frac{s(T_0)}{s(T_{\rm osc})}\,\frac{S(T_{\rm osc})}{S(T_{\rm rh})}$$

$$\boxed{\Omega_a(m_a, g_{a\gamma}, T_{\rm rh}) \simeq 0.26 \Longrightarrow \ \downarrow T_{\rm rh} \Longrightarrow \frac{S(T_{\rm osc})}{S(T_{\rm rh})}\downarrow \ \Longrightarrow f_a \uparrow \Longrightarrow m_a \downarrow}$$

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4}\, a\, F\tilde{F} = g_{a\gamma}\, a\, \vec{E}\cdot\vec{B} \sim \frac{a}{f_a}\,\vec{E}\cdot\vec{B}$$

Different reheating histories lead to different experimental targets

Probing Reheating with Axion DM



$$4\ \text{MeV} \lesssim T_{\text{rh}} \lesssim 1\ \text{GeV}$$

[YX 2308.15322]

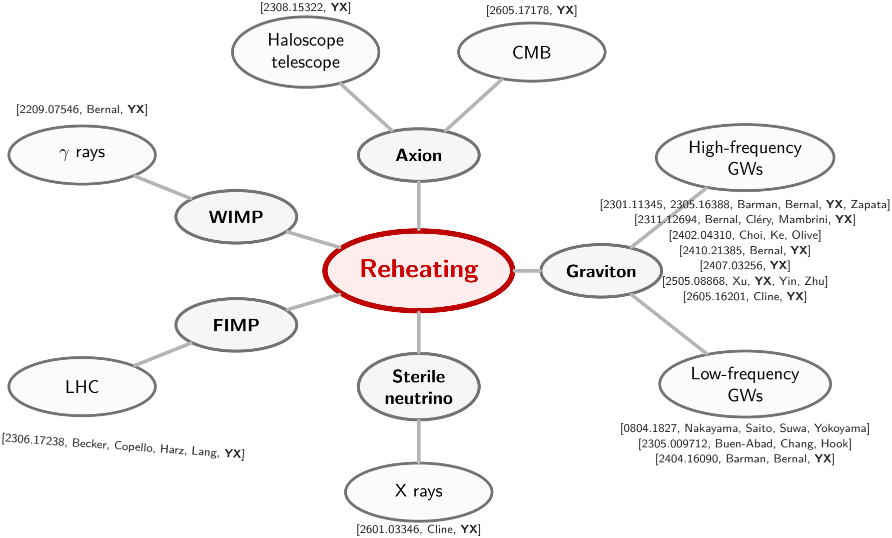
Summary

Inflation $\Longrightarrow$ **Reheating** $\Longrightarrow$ BBN

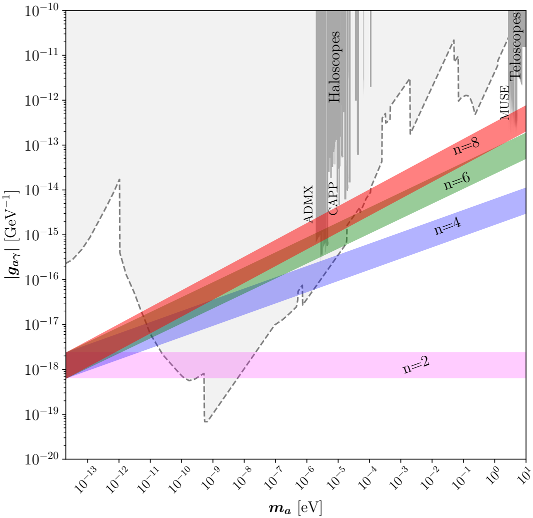
- Reheating determines the **thermal history** of the pre-BBN Universe.
- Reheating **strongly modifies DM production** and **shift experimental targets**.

Probe pre-BBN Universe with Dark Matter Experiments.

Probing Pre-BBN Universe: Synergy and Complementarity



Probing reheating with ALP DM



$\Longrightarrow$ probe the inflaton shape during oscillation $V \sim \phi^n$

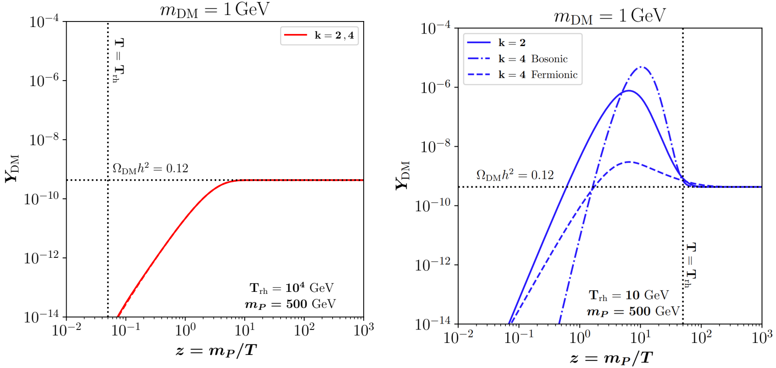
[YX 2308.15322]

FIMP from LLP decay

- DM freeze-in from a gauge charged parent particle decay

$$P \to \mathrm{DM} + f_{\mathrm{SM}}$$

- Left: after reheating ($T_{\mathrm{FI}} < T_{\mathrm{rh}}$)   Right: during reheating ($T_{\mathrm{FI}} > T_{\mathrm{rh}}$)



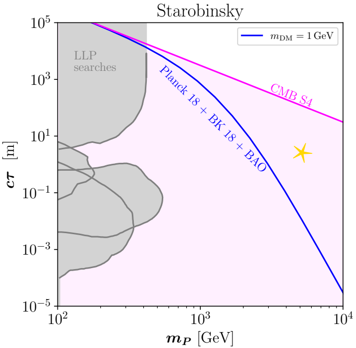
[Becker, Copello, Harz, Lang, **YX** 2306.17238]

Probing Reheating with FIMP

- DM freeze-in from a gauge charged parent particle decay

$$P \to \mathrm{DM} + f_{\mathrm{SM}}$$

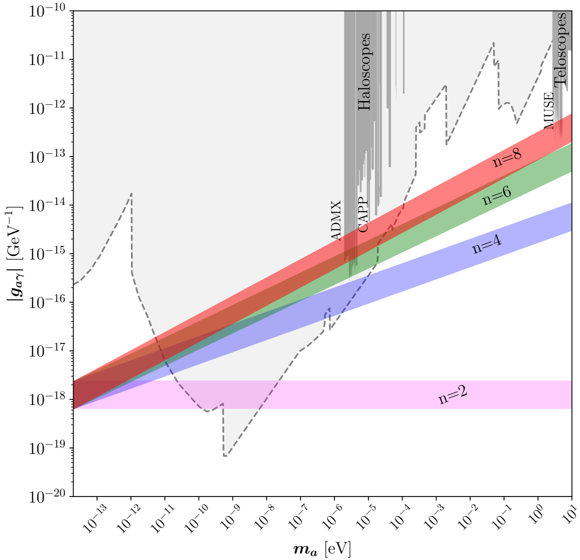
- $T_{\mathrm{FI}} < T_{\mathrm{rh}} \implies c\tau \sim m_P^{-2} \qquad T_{\mathrm{FI}} > T_{\mathrm{rh}} \implies c\tau \sim m_P^{-9}$



- In Starobinsky inflation with $m_{\mathrm{DM}} = 1\,\mathrm{GeV}$: if an event (e.g. yellow star) at collider $\implies$ $T_{\mathrm{rh}} \gg 180\mathrm{GeV}$!

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

Probing reheating with ALP DM

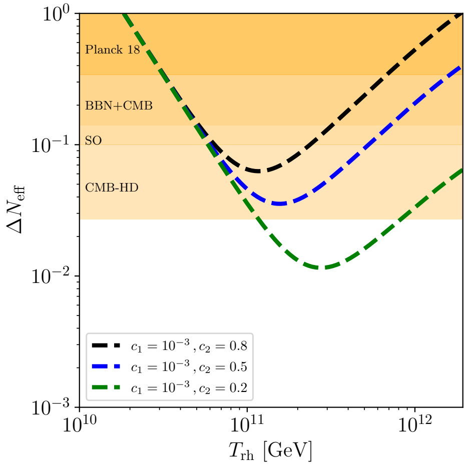


[YX 2308.15322]

Probing Reheating with Axion Dark Radiation

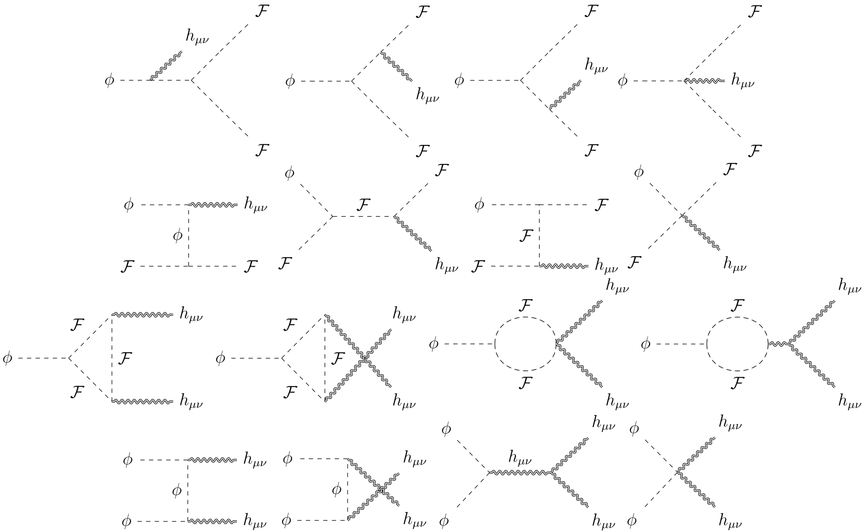
Inflaton-dependent axion kinetic term

$$\mathcal{L} \supset Z(\phi)(\partial a)^2/2, \qquad Z(\phi) = 1 + c_1\phi/\Lambda + c_2\phi^2/\Lambda^2 + \cdots$$



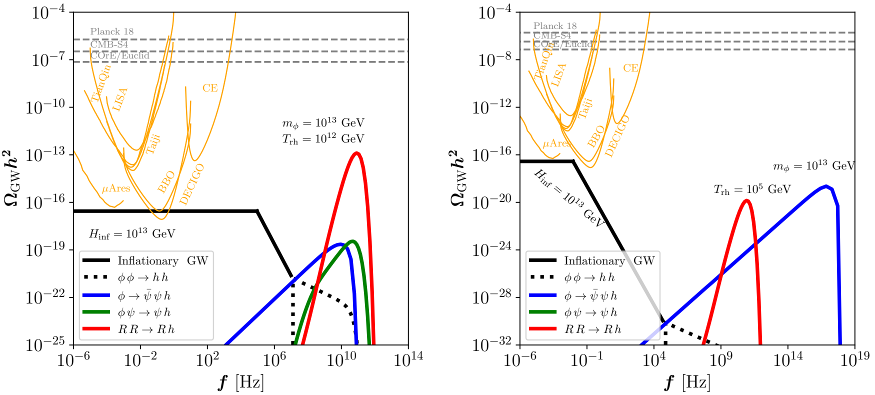
[YX 2605.17178]

Graviton production during reheating



+ thermal SM particle scatterings (many more diagrams...)

Probing Reheating with Graviton



- Bremstahlung GWs $\Longrightarrow$ **probe** m_ϕ
- Thermal GWs $\Longrightarrow$ **probe** $T_{\rm rh}$

[Xu, **YX**, Yin, Zhu 2505.08868]