Probing Reheating with Graviton Bremsstrahlung

Yong Xu, MITP (JGU Mainz)

AstroParticle Symposium 2024
Paris-Saclay University, Nov 27

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence PRISMA+

Question

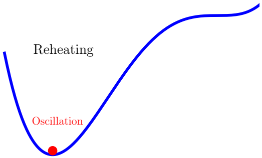
Inflation dilutes everything expotentially

- After inflation: the Universe is cold
- However, Big Bang Nucleosynthesis needs a Thermal background

$T_{\text{end}} \sim 0$ $T_{\text{BBN}} \sim \text{MeV}$

Reheating

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



- Basic ingredients:
  - Couplings $\mu\,\phi h^2$, $y\,\phi\bar{\psi}\psi$
  - Oscillating ϕ $\Longrightarrow$ particles production $\Longrightarrow$ interaction $\Longrightarrow$ thermal bath

    $\Longrightarrow$ define temperature
  - Complex with non-perturbative phenomena [Dolgov, Kirilova '89] [Traschen, Brandenberger '90] [Kofman, Linde, Starobinsky '97]...

Reheating

Inflaton Oscillations and Post-Inflationary Reheating

Marcos A.G. Garcia (Madrid, IFT and Madrid, Autonoma U.), Kunio Kaneta (Korea Inst. Advanced Study, Seoul), Yann Mambrini (IJCLab, Orsay), Keith A. Olive (Minnesota U., Theor. Phys. Inst. and Minnesota U.)
Dec 19, 2020

39 pages
Published in: *JCAP* 04 (2021) 012
Published: Apr 7, 2021
e-Print: 2012.10756 [hep-ph]
DOI: 10.1088/1475-7516/2021/04/012
Report number: UMN-TH-4006/20, FTPI-MINN-20/37, IFT-UAM/CSIC-20-185, KIAS-P20071
View in: HAL Science Ouverte, AMS MathSciNet, ADS Abstract Service

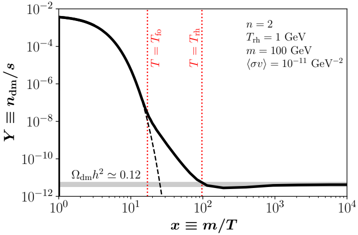
- Talks on different aspects of (p)reheating by N. Bernal, S. Clery, M. Garcia, M. Gross, K. Kaneta, D. Maity, J. Trankle

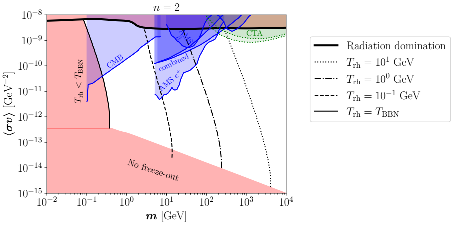
Temperature is important: WIMP

- Freeze-out in standard case (radiation phase after reheating) $T_{\text{fo}} < T_{\text{rh}} \implies$

$$Y \sim \frac{1}{\langle \sigma v \rangle} \implies \langle \sigma v \rangle \sim 10^{-9}\,\text{GeV}^{-2} \impliedby \text{too large, ruled out!}$$

- Freeze-out during reheating with $T_{\text{fo}} > T_{\text{rh}} \implies$ **much smaller** $\langle \sigma v \rangle \implies$ evade experimental constraints

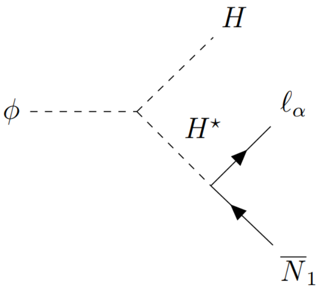


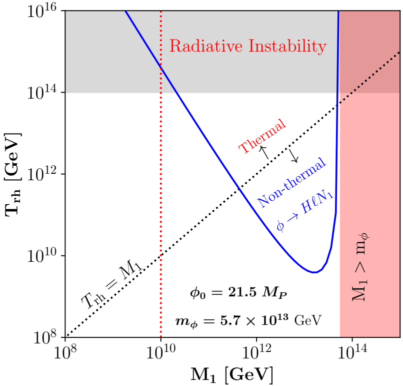


[Bernal, **YX** 2209.07546]

- More examples: see talk by N. Bernal

Temperature is important: Leptogenesis



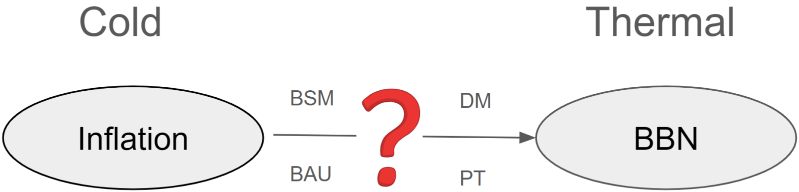


- $T_{rh} > M_1 \implies$ **thermal leptogenesis**
- $T_{rh} < M_1 \implies$ **non-thermal leptogenesis** $\phi \to H\ell N$

[Drees, **YX** 2401.02485]

We have learned

- Knowing the background temperature or physics before BBN is important!



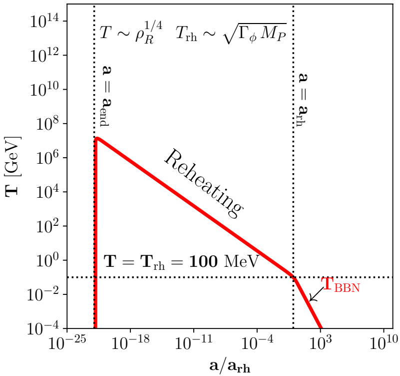
$T_{\text{end}} \sim 0$ $\qquad\qquad$ $T_{\text{BBN}} \sim \text{MeV}$

- But, what are the dynamics controlling the background evolution?

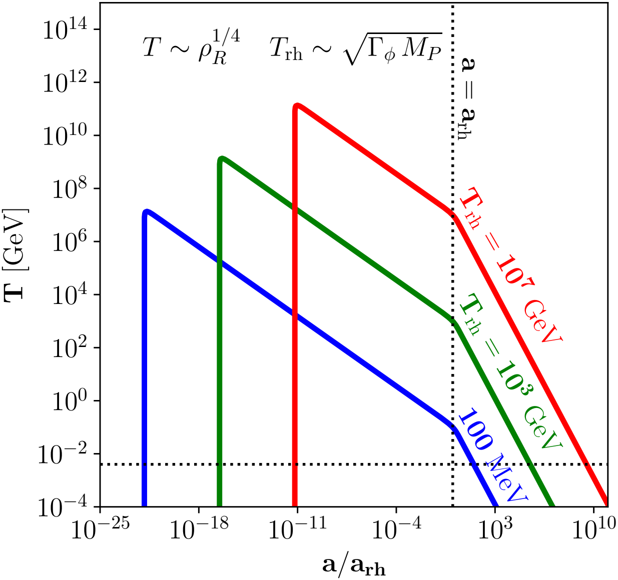
Evolution of Background

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

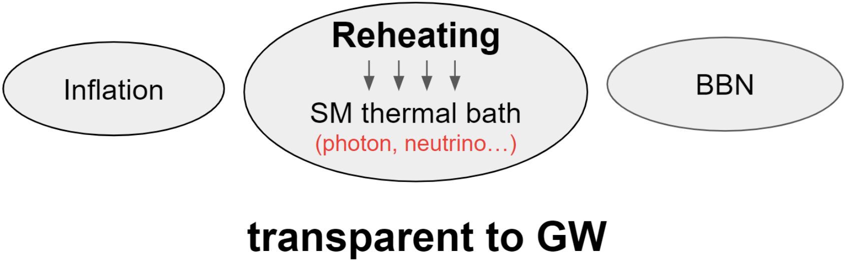
$$\frac{d\rho_\phi}{dt} + 3H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi; \quad \frac{d\rho_R}{dt} + 4H\,\rho_R = +\Gamma_\phi\,\rho_\phi$$



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



How To Probe Reheating?



- Probing Reheating with GWs!

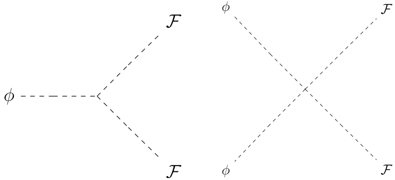
Goal of the rest part of this talk

1. Show **a simple and unavoidable source of GWs** via graviton Bremsstrahlung

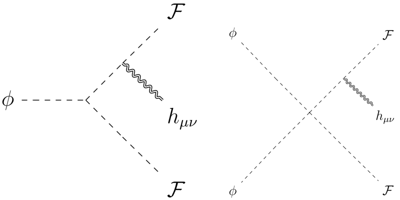
2. Demonstrate how such GW spectrum can help to **probe reheating**

Graviton Bremsstrahlung during Reheating

- If, reheating: $\phi\mathcal{F}\mathcal{F}$ (decay) or $\phi^2\mathcal{F}\mathcal{F}$ (annihilation)



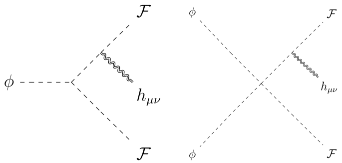
- Then, graviton production



gravitons emission $\Longrightarrow$ propagation $\Longrightarrow$ SGWB

[Nakayama, Tang 1810.04975]
[Huang, Yin 1905.08510]
[Barman, Bernal, **YX**, Zapata 2301.11345]
[Bernal, Cléry, Mambrini, **YX** 2311.12694]

Graviton Production Rate



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

- $x = \frac{E_g}{m_\phi}$: $x \to 0 \implies \frac{d\Gamma}{dE_g} \to \infty$ (soft divergence) [Weinberg '65] [Barker, Gupta and Kaskas '69]

[Nakayama, Tang 1810.04975]
[Barman, Bernal, **YX**, Zapata 2301.11345]
[Bernal, Cléry, Mambrini, **YX** 2311.12694]

GW Spectrum

- GW amplitude:

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

- Differential spectrum

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

$$\sim \text{(differential BR)} \times \text{(energy fraction)}$$

- Recall that

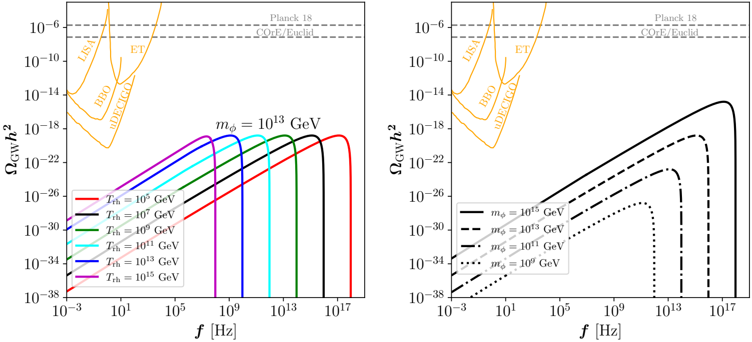
$$\frac{d\Gamma}{dE_g} \propto \frac{\mu^2}{M_P^2}\frac{m_\phi}{E_g} \quad \text{and} \quad \Gamma_\phi \propto \frac{\mu^2}{m_\phi}$$

- Expect

$$\Omega_{\mathsf{GW}} \sim \frac{d(\rho_{\mathsf{GW}}/\rho_R)}{d\ln E_g} \propto \frac{(E_g \times m_\phi)}{M_P^2}$$

Bremsstrahlung GWs

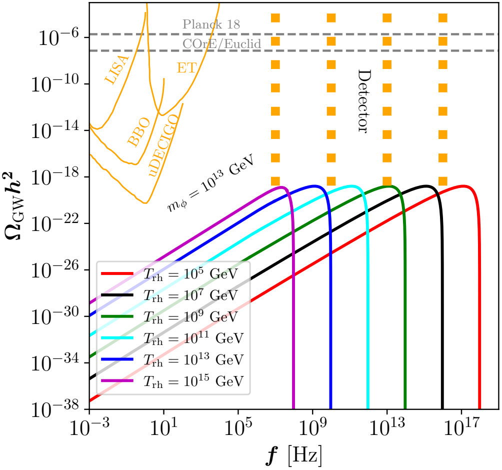
$$\Omega_{\mathrm{GW}} h^2 \sim 10^{-18} \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right) \left(\frac{T_{\mathrm{rh}}}{10^{13}\ \mathrm{GeV}}\right) \left(\frac{f}{10^{9}\ \mathrm{Hz}}\right)$$



- Peak frequency: $f_{\mathrm{peak}} \simeq \frac{m_\phi}{2} \frac{1}{2\pi} \frac{a_{\mathrm{rh}}}{a_0} \simeq 10^{10} \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right) \left(\frac{10^{13}\ \mathrm{GeV}}{T_{\mathrm{rh}}}\right)$ Hz
- At the peak: $\Omega_{\mathrm{GW}} \propto \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right)^2$

[Barman, Bernal, **YX**, Zapata 2301.11345] [Bernal, Cléry, Mambrini, **YX** 2311.12694] [**YX**, 2407.03256]

Probing Reheating (m_ϕ and $T_{\rm rh}$) with Bremsstrahlung GWs

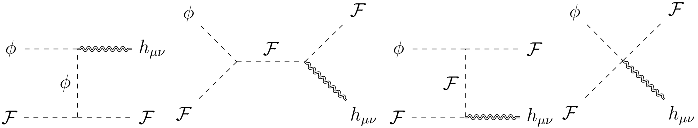


- If null signal at a frequency $\implies$ $m_\phi \gtrsim 10^{13}$ GeV with a specific $T_{\rm rh}$ ruled out

[YX, 2407.03256]

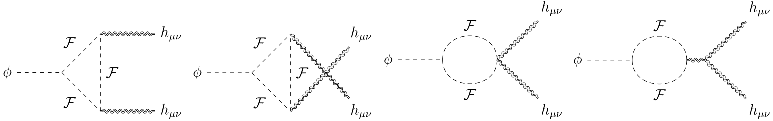
Inflaton Scattering and Decay

- Inflaton scattering with decay product



$$\Gamma_g^{2\to 2} \sim \Gamma_g^{1\to 3} \times \left(\frac{T}{m_\phi}\right)^n$$

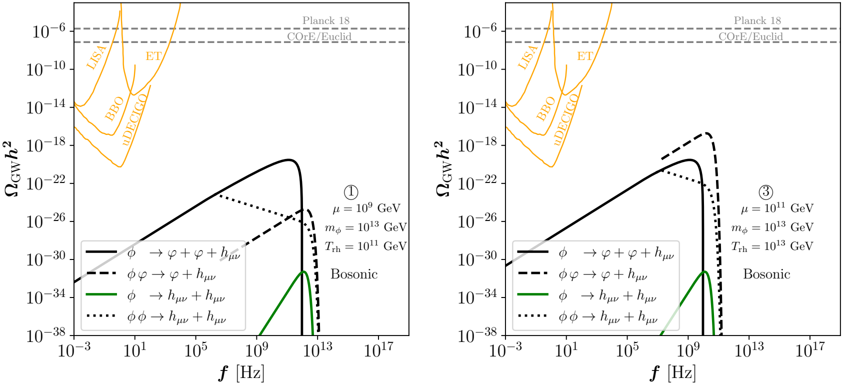
- Inflaton decays (possible only at 1–loop level) in Einstein-Hilbert framework



$$\Gamma_g^{1\to 2} \simeq \frac{3\, m_\phi^3\, \mu^2}{2048\, \pi^5 M_P^4}$$

[**YX**, 2407.03256]

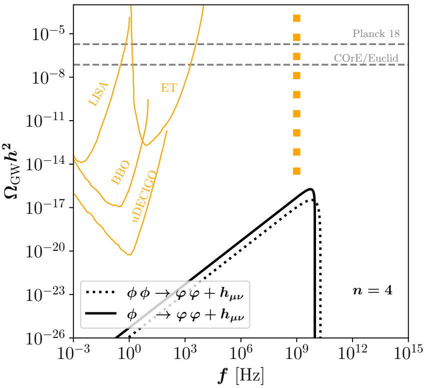
A Systematic Comparison



- Left $m_\phi \gg T_{\rm rh}$: $1 \to 3$ dominates
- Right $m_\phi \lesssim T_{\rm rh}$: $2 \to 2$ dominate

[YX, 2407.03256]

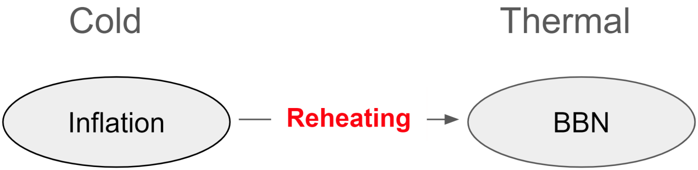
GW Spectrum: Bosonic Decay vs Bosonic Annhilation



Probing inflaton decay or annihilation

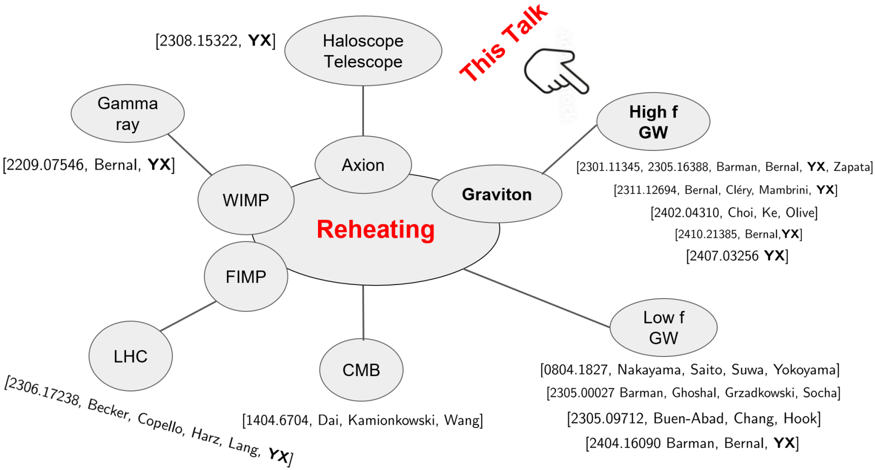
[Bernal, Cléry, Mambrini, **YX** 2311.12694]

Summary



- Reheating explains Cold → Thermal (important for many phenomena)
- Two important parameters
  1. m_ϕ
  2. T_{rh}
- Unavoidable SGWB from **Graviton Bremsstrahlung**, dominates if $m_\phi \gg T_{\text{rh}}$
- Future GW experiments could potentially **probe reheating**

Probing Physics before BBN: Astro-Cosmo-Collider Synergy

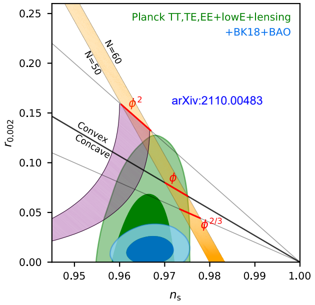


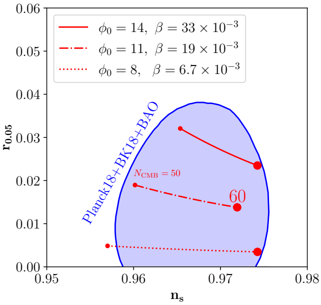
Thanks for your attention!

Polynomial Inflation

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

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





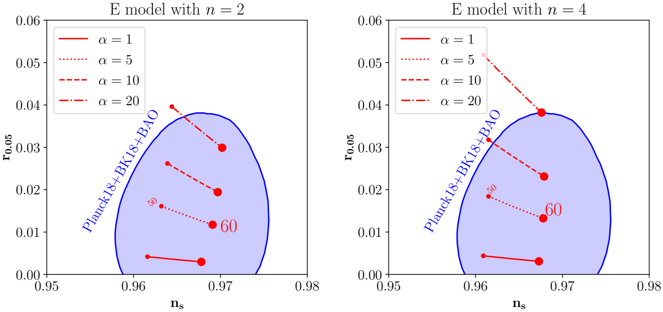
- During reheating: $V(\phi) \sim \phi^2$

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

Alpha Attractor Inflation

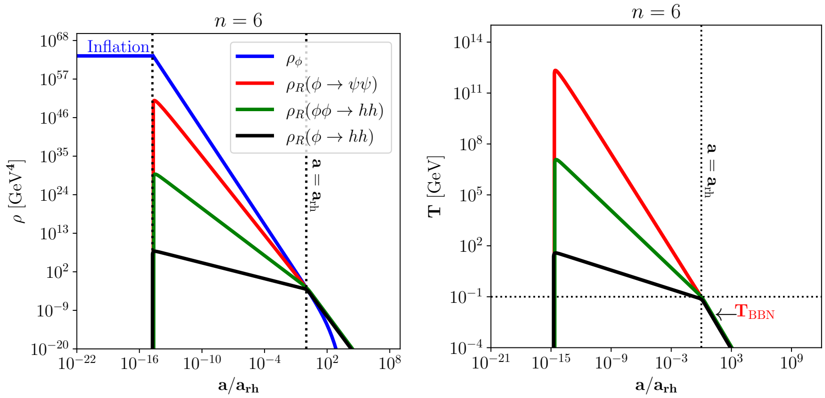
- The E model [Kallosh and Linde '13]

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



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

Evolution of Background for $n > 2$

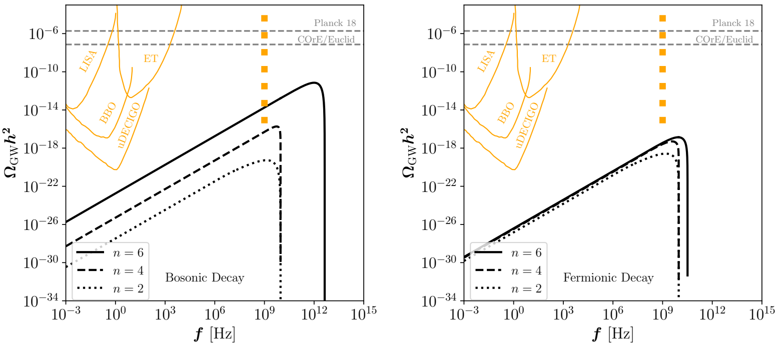


- Fermionic decay: $\Gamma_\phi \sim \frac{y^2 m_\phi}{8\pi}$ with $m_\phi \propto V'' \propto \phi^{n-2}$
- Annihilation: $\Gamma_\phi \sim \frac{\lambda^2 \rho_\phi}{16\pi\, m_\phi^3}$ Bosonic decay: $\Gamma_\phi \sim \frac{\mu^2}{8\pi\, m_\phi}$

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

[YX 2308.15322]

GW Spectrum: Bosonic decay vs Fermionic decay



- GW amplitude **lager in bosonic decay** for $n > 2$ with $V(\phi) \sim \phi^n$

$$\Omega_{\rm GW}(f) \propto \frac{d(\rho_{\rm GW}/\rho_R)}{d \ln f}$$

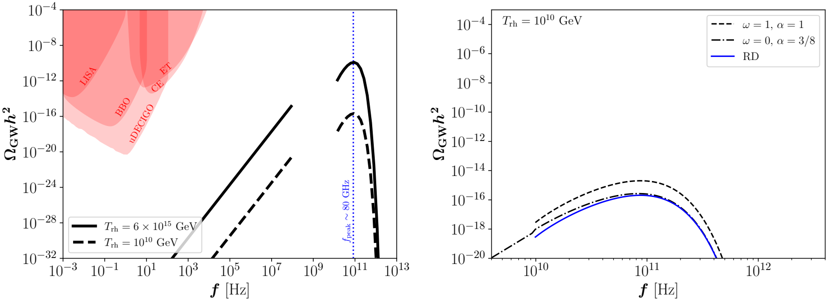
- The distinction in GW $\Longrightarrow$ a novel channel to probe the shape parameter n

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

Thermal GWs during Reheating

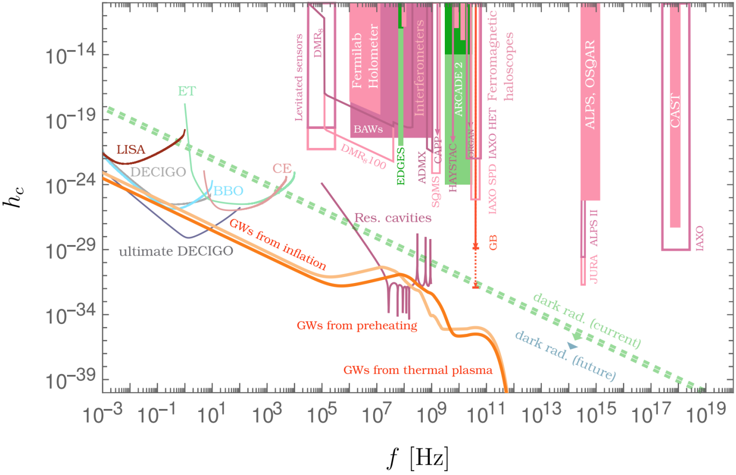
- Graviton from thermal plasma [Ghiglieri, Laine 1504.02569] [Ringwald, Schütte-Engel, Tamarit 2011.04731]

$$\Gamma_g \sim \frac{T^3}{M_P^2}$$



[Bernal, **YX** 2410.21385]

Ultra-high frequency GW Detection Prospect



$$h_c(f) \equiv \frac{H_0}{f}\sqrt{\frac{3}{2\pi^2}\,\Omega_{\mathsf{GW}}(f)} \simeq 1.26\times 10^{-18}\left(\frac{\mathrm{Hz}}{f}\right)\sqrt{h^2\,\Omega_{\mathsf{GW}}(f)}\,,$$

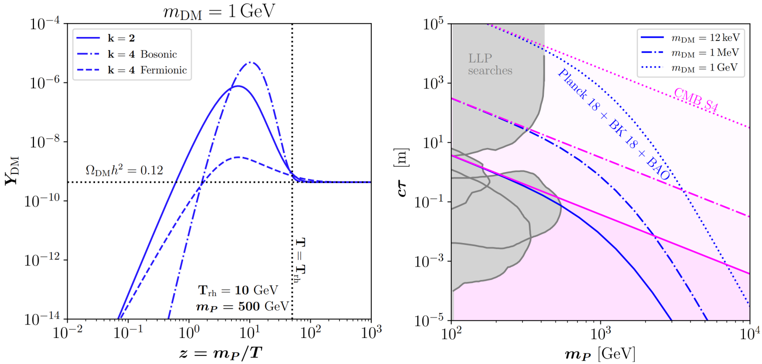
[Ringwald, Tamarit 2203.00621]

FIMP from LLP decay

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

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

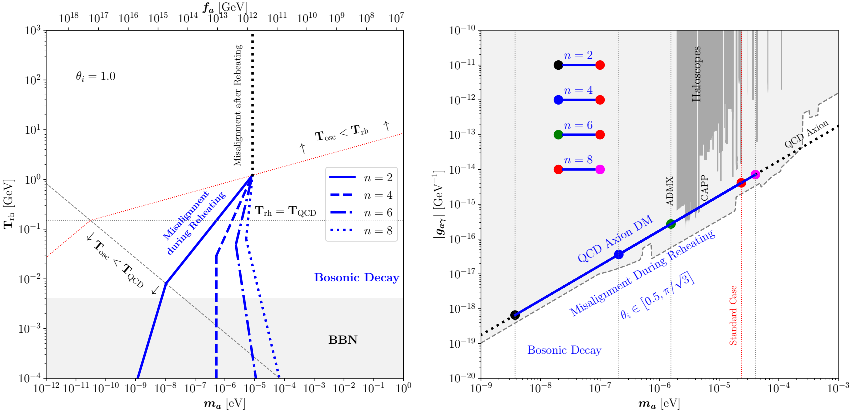
- $T_{\text{FI}} > T_{\text{rh}}$, freeze-in during reheating:



- Interesting interplay between collider searches and inflationary constraints!

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

Axion



[**YX** 2308.15322]