Gravitational Waves from Reheating: Messengers of the Pre-BBN Universe

XU, Yong 徐勇 (MITP & University of Mainz)

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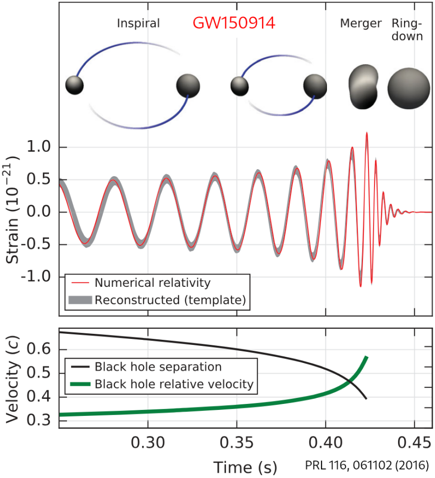
李政道研究所，上海交通大学
Tsung-Dao Lee Institute, Shanghai Jiao Tong University

Observations of GWs from Binary Black Hole Merger



GW150914, GW151226, GW170817, GW190521, GW20011, GW230529...
$\Longrightarrow$ Triumph of General Relativity and new era of GW astronomy!

The early Universe...

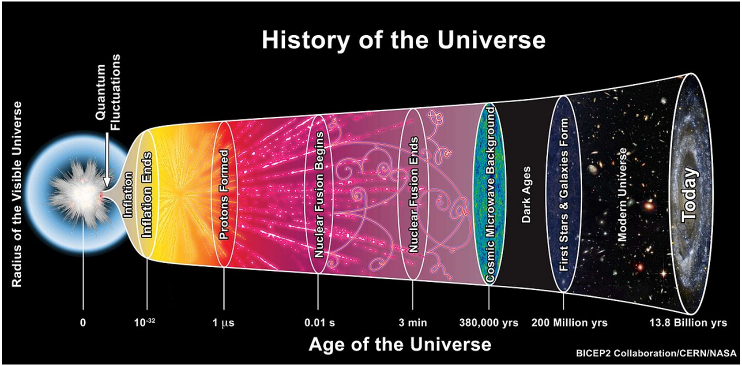
hosts a variety of GW sources.

This talk: the unavoidable GWs in inflationary cosmology

1. Overview of **recent advances** in gravitational waves (GWs) from reheating

2. Demonstrate how this **GW** background can **probe the physics before BBN**

History of the Universe



History of the Universe: several key events

- $t \sim 10^{-6}$ s : **QCD deconfinement transition** with $T \sim 150\,\text{MeV}$

  quark gluon soup $\Rightarrow p, n$

- $t \sim 1\,\text{s} - 200$ s: **Big Bang Nucleosynthesis** with MeV $\gtrsim T \gtrsim 50\,\text{keV}$

$$
\begin{aligned}
\mathrm{p} + \mathrm{n} &\longrightarrow {}^2\mathrm{H} + \gamma \\
\mathrm{p} + {}^2\mathrm{H} &\longrightarrow {}^3\mathrm{He} + \gamma \\
{}^2\mathrm{H} + {}^2\mathrm{H} &\longrightarrow {}^3\mathrm{He} + \mathrm{n} \\
{}^2\mathrm{H} + {}^2\mathrm{H} &\longrightarrow {}^3\mathrm{H} + \mathrm{p} \\
{}^3\mathrm{He} + {}^2\mathrm{H} &\longrightarrow {}^4\mathrm{He} + \mathrm{p} \\
{}^3\mathrm{H} + {}^2\mathrm{H} &\longrightarrow {}^4\mathrm{He} + \mathrm{n}
\end{aligned}
$$

- $t \sim 380\text{kyrs}$: **Recombination** $\Rightarrow$ neutral atom with $T \sim 0.3\text{eV}$

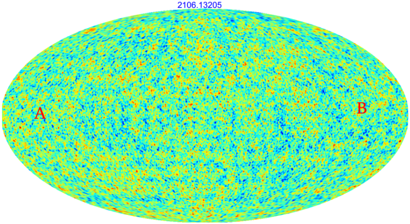
$$e^- + p^+ \rightarrow H + \gamma$$

Cosmic Microwave Background (CMB)

- **Before** recombination

$$e^- + \gamma \leftrightarrow e^- + \gamma$$

- **After** recombination: γ became free $\Longrightarrow$ CMB

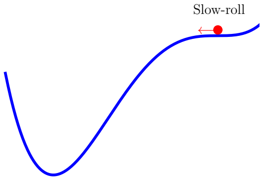


- Questions:
  1. **Why** looks so **homogeneous**?

     Universe so big $\Rightarrow$ causaly disconnected $\Rightarrow$ Horizon problem

  2. What is the **origin of the tiny inhomogeneities**?

Cosmic Inflation



- Cosmic inflation **(exponential expansion)**

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho(\phi)}{3\,M_P^2} \Rightarrow H = \sqrt{\frac{V(\phi)}{3\,M_P^2}} \Rightarrow a = e^{H\cdot t} \sim e^{60} \Rightarrow \textbf{small to BIG}$$

e.g. Polynomial Inflation $V(\phi) = d\left[\phi^4 - 8/3\phi_0\,(1-\beta)\,\phi^3 + 2\phi_0^2\phi^2\right]$ [Drees, **YX** 2104.03977, 2209.07545]

- Quantum fluctuation of ϕ

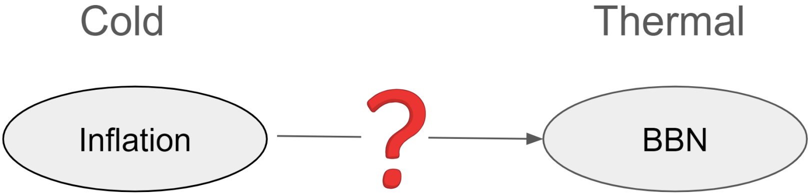
$$\delta\phi \Rightarrow \text{CMB inhomogeneities and seeds for structure}$$

which also sources GW $\delta\phi \implies \delta g_{\mu\nu}$

Question

Inflation dilutes everything expotentially

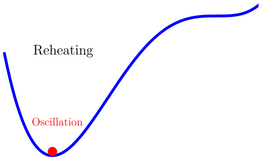
- After inflation: the Universe is cold and empty
- However, Big Bang Nucleosynthesis needs a Thermal background



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

Reheating

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



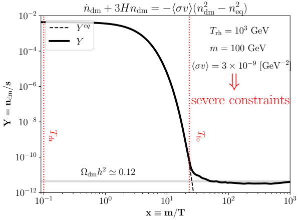
- Basic ingredients:
  - Couplings $\mu\,\phi h^2$, $y\,\phi\bar{\psi}\psi$
  - Oscillating ϕ $\Longrightarrow$ particles production $\Longrightarrow$ interaction $\Longrightarrow$ SM thermal bath $\Longrightarrow$ define temperature
  - Can be complex with non-perturbative phenomena

[Dolgov, Kirilova '89] [Traschen, Brandenberger '90] [Kofman, Linde, Starobinsky '97]... [Garcia, Kaneta, Mambrini, Olive '20]...

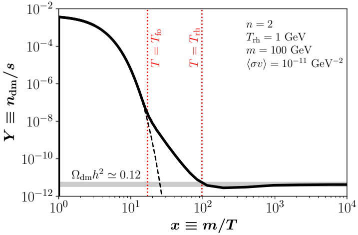
[Drees, **YX** '21]...[Barman, Bernal **YX** '24]...

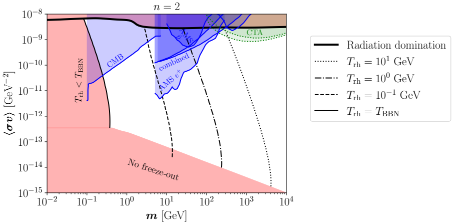
Temperature is important: WIMP Freeze-out

- Freeze-out after reheating $T_{\rm fo} < T_{\rm rh} \implies$



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

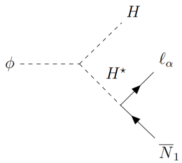


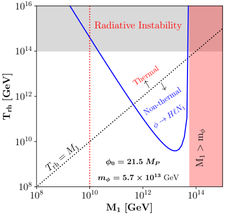


[Bernal, **YX** 2209.07546]

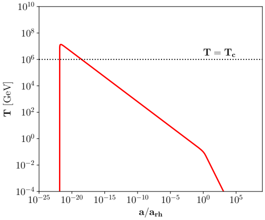
Temperature during reheating is important:

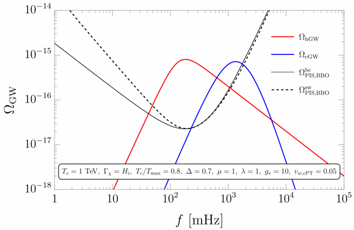
- New source of **Leptogenesis** [Drees, **YX** 2401.02485]





- Double peaked GW from **Phase Transition** [Buen-Abad, Chang, Hook 2305.09712]

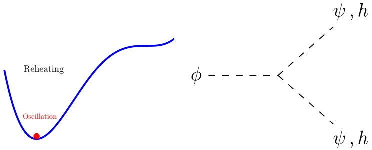




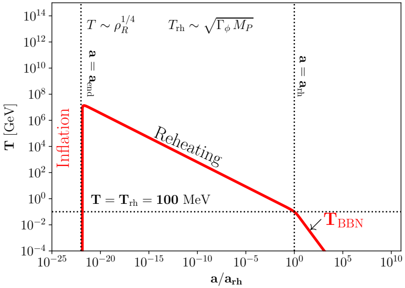
But, what controls the evolution of temperature?

Evolution of Background

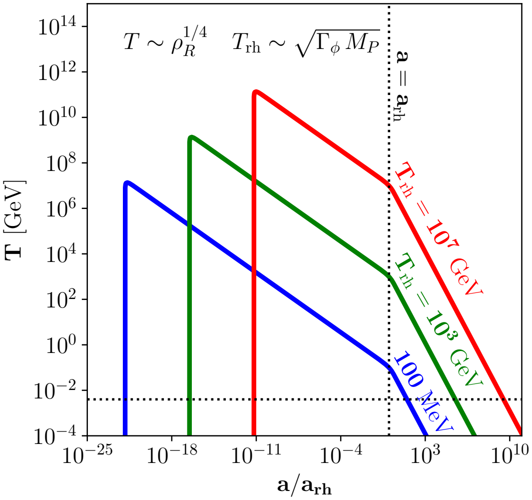
- Shape inflaton potential $V(\phi) \sim m_\phi^2 \phi^2$
- Couplings $\mu\,\phi h^2$, $y\,\phi\bar{\psi}\psi \implies \Gamma_\phi \sim \mu^2/m_\phi\,, y^2 m_\phi$



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

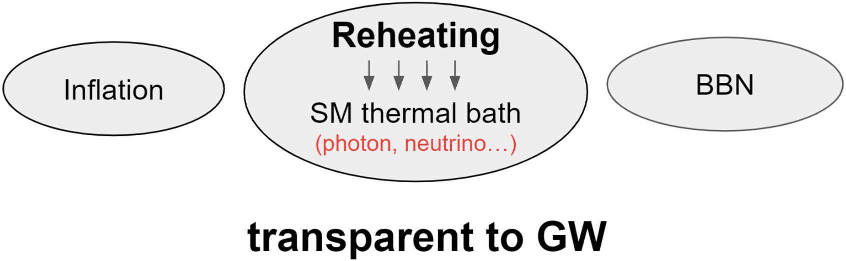


Evolution of Background for different $T_{\rm rh}$



[YX 2308.15322 Phys. Rev. D 108, 083536]

How To Probe Reheating?



- Probing Reheating with GWs! $\Leftarrow$ direct messengers

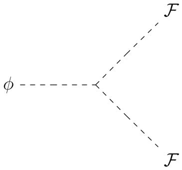
Goal of the rest part of this talk

1. Overview of **recent advances** on GWs from reheating

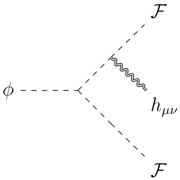
2. Demonstrate how the resulting GW spectrum can **probe reheating**

Graviton Bremsstrahlung during Reheating

- If, reheating: $\phi \mathcal{F} \mathcal{F}$ radiation production from ϕ decay



- Then, graviton production



gravitons emission $\Longrightarrow$ propagation $\Longrightarrow$ stochastic GW Background

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

GR as a Low Energy EFT

- Einstein-Hilbert action:

$$S_{\text{EH}} = \int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}R\right)$$

- Recall the definition: $R^{\lambda}_{\mu\nu\kappa} \sim \partial_\nu \Gamma^{\lambda}_{\nu\kappa} + ..$ and $\Gamma^{\lambda}_{\mu\nu} \sim g^{\lambda\rho}\partial_\nu g_{\rho\mu}$
$\implies R \sim \partial g \partial g$

- Expansion

$$g_{\mu\nu} = \eta_{\mu\nu} + \left(h_{\mu\nu}\frac{2}{M_P}\right) \Leftarrow \begin{cases} (\cdots) & \text{pert. in linearized GR} \\ h_{\mu\nu} & \text{a dynamical field in field theory} \end{cases}$$

- Effective terms in the action

$$S_{\text{EH}} \supset \int d^4x M_P^2\left(\partial h \partial h + \frac{h}{M_P}\partial h \partial h + \frac{h^2}{M_P^2}\partial h \partial h + \ldots\right)$$

[**A. Zee** Quantum Field Theory in a Nutshell: Second Edition]

GR as a Low Energy EFT: including matter fields

- The action

$$S \supset \int d^4x\sqrt{-g}(\mathcal{L}_{\mathrm{EH}} + \mathcal{L}_\phi + \mathcal{L}_{int.})$$

- Inflaton sector

$$\mathcal{L}_\phi = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)$$

- Interaction part

$$\mathcal{L}_{int.} \supset \mu\phi|\varphi|^2 + y\phi\bar{\psi}\psi$$

- Use the expansion

$$g_{\mu\nu} = \eta_{\mu\nu} + \left(h_{\mu\nu}\frac{2}{M_P}\right)$$

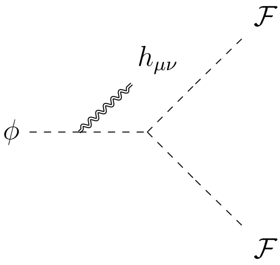
- Gravitational vertex

$$\boxed{\sqrt{-g}\mathcal{L} \supset -\frac{1}{M_P}\cdot h_{\mu\nu}\cdot \sum_{\phi,\psi,\varphi} T^{\mu\nu}}$$

e.g. $T^{\mu\nu}_\phi = \partial^\mu\phi\partial^\nu\phi - \frac{1}{2}\eta^{\mu\nu}(\partial^\alpha\phi\partial_\alpha\phi - m^2_\phi\phi^2)$

Graviton Production: Example with $\mathcal{F} = \varphi$

- For $\phi(\ell) \to \mathcal{F}(p)\mathcal{F}(q)h_{\mu\nu}(\omega)$



- Matrix element:

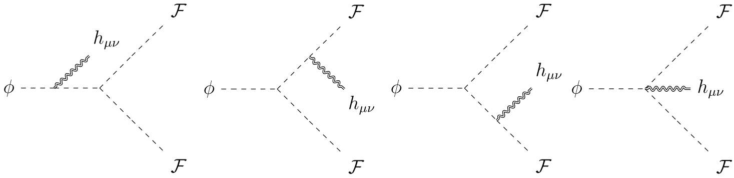
$$i\mathcal{M}_1 = (i\mu) \times \frac{i}{(\ell-\omega)^2 - m_\phi^2} \times \frac{-i}{M_P}\left[2\ell_\mu(\ell-\omega)_\nu - \eta_{\mu\nu}(\ell\cdot(\ell-\omega) - m_\phi^2)\right]\epsilon^{\mu\nu\star}$$

$$= -i\frac{\mu}{M_P}\frac{\ell_\mu\ell_\nu}{\ell\cdot\omega}$$

where $\omega^2 = m_g^2 = 0$

Graviton Production: Example with $\mathcal{F} = \varphi$

- For $\phi(\ell) \to \mathcal{F}(p)\mathcal{F}(q)h_{\mu\nu}(\omega)$



- Diagram 1:

$$i\mathcal{M}_1 = -i\frac{\mu}{M_P}\frac{\ell_\mu \ell_\nu}{\ell \cdot \omega}\epsilon^{\mu\nu\star} \to 0$$

- Diagram 2:

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

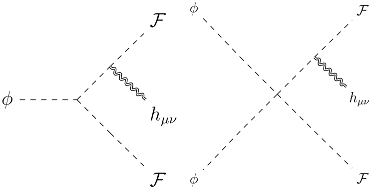
- Diagram 3:

$$i\mathcal{M}_3 = i\frac{\mu}{M_P}\frac{q_\mu q_\nu}{q \cdot \omega}\epsilon^{\mu\nu\star}$$

- Diagram 4:

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

Graviton Production Rate



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

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

[Nakayama, Tang 1810.04975] [Barman, Bernal, **YX**, Zapata 2301.11345] [Barman, Bernal, **YX**, Zapata 2305.16388] [Bernal, Cléry, Mambrini, **YX** 2311.12694]

Formalism for GW Spectrum

- GW spectrum ($k = 2\pi f$)

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\,\frac{d\rho_h}{d\ln k} = 8\pi^2 g_h\,\frac{f^4}{\rho_c}\,f_h$$

where

$$n_h = g_h \int \frac{d^3k}{(2\pi)^3}\, f_h\,, \quad \rho_h = g_h \int \frac{k\, d^3k}{(2\pi)^3}\, f_h \quad \Longrightarrow \quad \frac{d\rho_h}{dk} = g_h \frac{4\pi\, k^3}{(2\pi)^3}\, f_h$$

- The target: the graviton phase space distribution function f_h

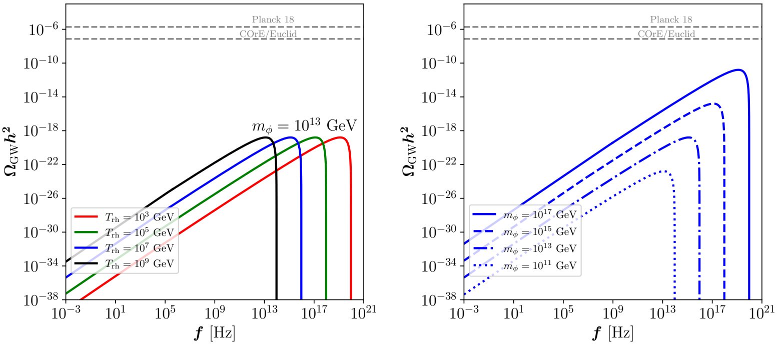
$$\left[\frac{\partial}{\partial t} - H(a)\, k\, \frac{\partial}{\partial k}\right] f_h(t,\ k) = \mathcal{C}_h(a,\ k)$$

$$\mathcal{C}_h = \frac{g_{n+m}}{2k}\int \left(\prod_{i=1}^{n+m} d\Pi_i\right) f_1 \cdots f_n\, |\overline{\mathcal{M}}|^2\, (2\pi)^4 \delta^{(4)}\left(\sum_{i=1}^{n} p_i - \sum_{j=n+1}^{n+m} p_j\right)$$

for $X_1 + X_2 + \cdots + X_n \to X_{n+1} + X_{n+2} + \cdots + X_{n+m} + h$

Bremsstrahlung GWs

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

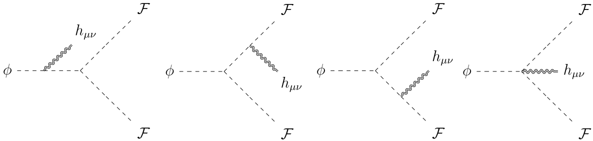


- Peak frequency: $f_{\rm peak} \simeq \frac{m_\phi}{2} \frac{1}{2\pi} \frac{a_{\rm rh}}{a_0} \simeq 10^{10} \left(\frac{m_\phi}{10^{13}\ \text{GeV}}\right) \left(\frac{10^{13}\ \text{GeV}}{T_{\rm rh}}\right)$ Hz
- At the peak: $\Omega_{\rm GW} \propto \left(\frac{m_\phi}{10^{13}\ \text{GeV}}\right)^2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

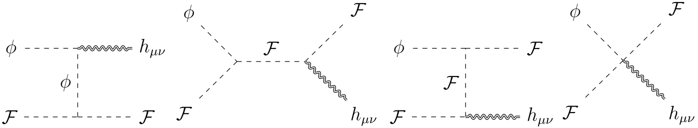
[**YX**, 2407.03256 JHEP 10 (2024) 174]

Inflaton Scattering and Decay

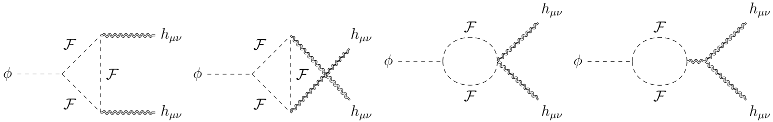
- So far: $\phi \to \mathcal{F}\mathcal{F} h_{\mu\nu}$



- Inflaton scattering with decay product $\Gamma_g^{2\to 2} \sim \Gamma_g^{1\to 3} \times \left(\frac{T}{m_\phi}\right)$



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

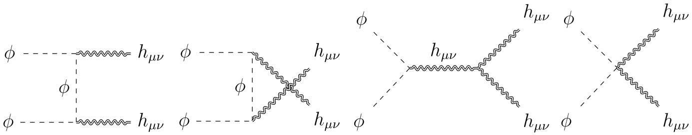


$$\Gamma_g^{1\to 2} \propto m_\phi^3 \, \mu^2 / M_P^4$$

[YX, 2407.03256 JHEP 10 (2024) 174]

Pure Inflaton Scattering

- Inflaton Inflaton

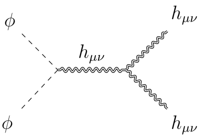


$$\Gamma_g^{2\to 2} = \frac{\rho_\phi}{m_\phi}\frac{m_\phi^2}{32\pi\, M_P^4} = \frac{\rho_\phi\, m_\phi}{32\pi\, M_P^4}$$

[Choi, Ke, Olive, 2402.04310] [Bernal, Xu, Wu, **YX** 2503.10756]

- **Computationally challenging** with $\mathcal{O}(10^6)$ terms to contract using traditionally Feynman diagram method with double gravitons (spin-2)

Triple Graviton Vertex



$$
\begin{aligned}
\tau^{\mu\nu}_{\alpha\beta,\gamma\delta}(k,q) \;=\;& \frac{i\kappa}{2}\Big\{ \big(I_{\alpha\beta,\gamma\delta} - \frac{1}{2}\eta_{\alpha\beta}\eta_{\gamma\delta}\big)\Big[k^\mu k^\nu + (k-q)^\mu (k-q)^\nu + q^\mu q^\nu - \frac{3}{2}\eta^{\mu\nu} q^2\Big] \\
+\;& 2q_\lambda q_\sigma \left[I^{\lambda\sigma,}{}_{\alpha\beta} I^{\mu\nu,}{}_{\gamma\delta} + I^{\lambda\sigma,}{}_{\gamma\delta} I^{\mu\nu,}{}_{\alpha\beta} - I^{\lambda\mu,}{}_{\alpha\beta} I^{\sigma\nu,}{}_{\gamma\delta} - I^{\sigma\nu,}{}_{\alpha\beta} I^{\lambda\mu,}{}_{\gamma\delta}\right] \\
+\;& [q_\lambda q^\mu (\eta_{\alpha\beta} I^{\lambda\nu,}{}_{\gamma\delta} + \eta_{\gamma\delta} I^{\lambda\nu,}{}_{\alpha\beta}) + q_\lambda q^\nu (\eta_{\alpha\beta} I^{\lambda\mu,}{}_{\gamma\delta} + \eta_{\gamma\delta} I^{\lambda\mu,}{}_{\alpha\beta}) \\
-\;& q^2 (\eta_{\alpha\beta} I^{\mu\nu,}{}_{\gamma\delta} + \eta_{\gamma\delta} I^{\mu\nu,}{}_{\alpha\beta}) - \eta^{\mu\nu} q^\lambda q^\sigma (\eta_{\alpha\beta} I_{\gamma\delta,\lambda\sigma} + \eta_{\gamma\delta} I_{\alpha\beta,\lambda\sigma})] \\
+\;& [2q^\lambda (I^{\sigma\nu,}{}_{\alpha\beta} I_{\gamma\delta,\lambda\sigma} (k-q)^\mu + I^{\sigma\mu,}{}_{\alpha\beta} I_{\gamma\delta,\lambda\sigma} (k-q)^\nu \\
-\;& I^{\sigma\nu,}{}_{\gamma\delta} I_{\alpha\beta,\lambda\sigma} k^\mu - I^{\sigma\mu,}{}_{\gamma\delta} I_{\alpha\beta,\lambda\sigma} k^\nu) \\
+\;& q^2 (I^{\sigma\mu,}{}_{\alpha\beta} I_{\gamma\delta,\sigma}{}^{\nu} + I_{\alpha\beta,\sigma}{}^{\nu} I^{\sigma\mu,}{}_{\gamma\delta}) + \eta^{\mu\nu} q^\lambda q_\sigma (I_{\alpha\beta,\lambda\rho} I^{\rho\sigma,}{}_{\gamma\delta} + I_{\gamma\delta,\lambda\rho} I^{\rho\sigma,}{}_{\alpha\beta})] \\
+\;& [(k^2 + (k-q)^2) \left(I^{\sigma\mu,}{}_{\alpha\beta} I_{\gamma\delta,\sigma}{}^{\nu} + I^{\sigma\nu,}{}_{\alpha\beta} I_{\gamma\delta,\sigma}{}^{\mu} - \frac{1}{2}\eta^{\mu\nu} P_{\alpha\beta,\gamma\delta} \right) \\
-\;& (k^2 \eta_{\gamma\delta} I^{\mu\nu,}{}_{\alpha\beta} + (k-q)^2 \eta_{\alpha\beta} I^{\mu\nu,}{}_{\gamma\delta})]\Big\} \qquad \text{gr-qc/0607045} \qquad (81)
\end{aligned}
$$

$\Longrightarrow$ lengthy and tedious...

Alternative Methods

- Bogoliubov formalism:

$$h''(k) + \omega_k^2 h(k) = 0 \quad \text{with} \quad \omega_k^2 \sim k^2 - a''(\tau)/a(\tau)$$

$$n_k^{\text{in}} = \langle \text{in}|a_k^\dagger a_k|\text{in}\rangle = 0 \implies n_k^{\text{out}} = \langle \text{in}|b_k^\dagger b_k|\text{in}\rangle = |\beta_k|^2 \neq 0$$

- Techniques from scattering amplitude (double-copy)

$$\mathcal{M}^{\text{graviton}} \sim \mathcal{A}^{\text{YM}} \times \mathcal{A}^{\text{YM}}$$

[projects in progress]

Gravitational Waves and Scattering Amplitudes

Snowmass White Paper: Gravitational Waves and Scattering Amplitudes

Alessandra Buonanno,[1,2] **Mohammed Khalil,**[1,2] **Donal O'Connell,**[3] **Radu Roiban,**[4] **Mikhail P. Solon,**[5] **Mao Zeng**[3]

[1] *Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam, 14476, Germany*

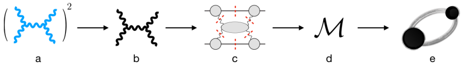
[2] *Department of Physics, University of Maryland, College Park, MD 20742, USA*

[3] *Higgs Centre for Theoretical Physics, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh, EH9 3FD, UK*

[4] *Department of Physics, Pennsylvania State University, University Park, PA 16802, USA*

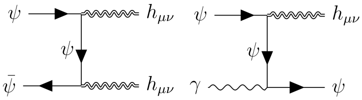
[5] *Mani L. Bhaumik Institute for Theoretical Physics, University of California at Los Angeles, Los Angeles, CA 90095, USA*

Abstract: We review recent progress and future prospects for harnessing powerful tools from theoretical high-energy physics, such as scattering amplitudes and effective field theory, to develop a precise and systematically improvable framework for calculating gravitational-wave signals from binary systems composed of black holes and/or neutron stars. This effort aims to provide state-of-the-art predictions that will enable high-precision measurements at future gravitational-wave detectors. In turn, applying the tools of quantum field theory in this new arena will uncover theoretical structures that can transform our understanding of basic phenomena and lead to new tools that will further the cycle of innovation. While still in a nascent stage, this research direction has already derived new analytic results in general relativity, and promises to advance the development of highly accurate waveform models for ever more sensitive detectors.



Pure Thermal Scattering

- Graviton from thermal particles scattering



- A single graviton production dominates

$$|\overline{\mathcal{M}}_{\gamma\psi\to h\psi}|^2 = \frac{g^2}{4M_P^2}\frac{u^2+s^2}{t}$$

divergent when $t = (p_1 - p_3)^2 = -2E_1E_3(1-\cos\theta) \to 0$ **(need regulator)**

- Graviton production rate

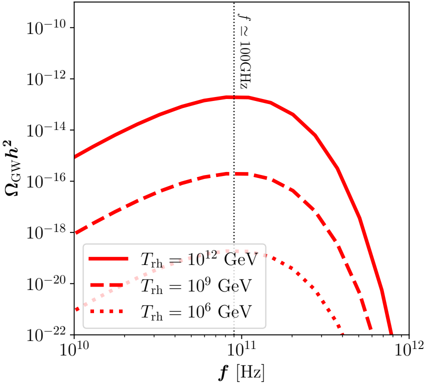
$$\Gamma_g \sim g^2 \frac{T^3}{M_P^2} e^{-k/T}$$

- Graviton energy: $E_g \sim T \implies E_0(\text{now}) = T \times \frac{a}{a_0} \sim T_{\text{CMB}} \sim \mathcal{O}(100)\text{GHz}$

[Ghiglieri, Laine 1504.02569] [Ghiglieri, Jackson, Laine, Zhu, 2004.11392] [Ringwald, Schütte-Engel, Tamarit 2011.04731]...
[Bernal,**YX** 2410.21385] [**YX**, 2412.21137] [Xu, **YX**, Yin, Zhu 2505.08868]

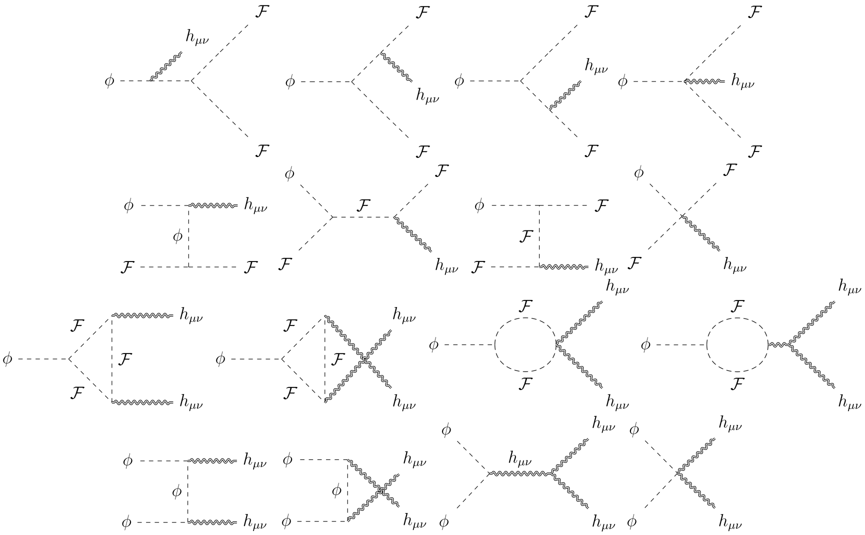
Thermal GW from the Standard Model

$$\Omega_{\mathsf{GW}} h^2 \simeq 8.6 \cdot 10^{-11} \left(\frac{T_{\mathsf{rh}}}{10^{14}\ \mathsf{GeV}} \right) \left(\frac{f}{10^{11}\ \mathsf{Hz}} \right)^3 \hat{\eta}(f)$$



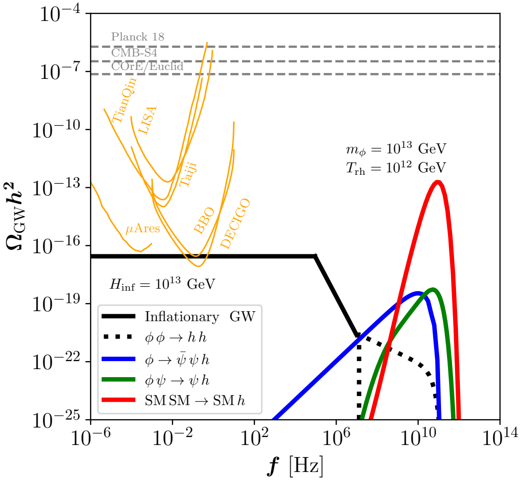
[**YX**, 2412.21137; Phys.Lett.B 865 (2025) 139483]

All Channels



$+$ thermal scatterings with SM

A Systematic Comparison



- Low f regime: inflationary GWs dominate $\Longrightarrow$ **probe** $H_{\rm inf}$
- High f regime: thermal GWs dominate (unless $m_\phi \gg T_{\rm rh}$) $\Longrightarrow$ **probe** $T_{\rm rh}$

Detection of Ultra-high Frequency Gravitational Waves

Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

Nancy Aggarwal (Northwestern U.), Odylio D. Aguiar (Sao Jose, INPE), Andreas Bauswein (Darmstadt, GSI), Giancarlo Cella (INFN, Pisa), Sebastian Clesse (Brussels U.)
Show All(25)

Nov 24, 2020

60 pages
Published in: *Living Rev.Rel.* 24 (2021) 1, 4
Published: Dec 6, 2021
e-Print: 2011.12414 [gr-qc]
DOI: 10.1007/s41114-021-00032-5
Report number: CERN-TH-2020-185, HIP-2020-28/TH, DESY 20-195, CERN-TH-2020-185, HIP-2020-28/TH, DESY 20-195
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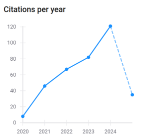

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

Nancy Aggarwal (Northwestern U.), Odylio D. Aguiar (Sao Jose, INPE), Diego Blas (Barcelona, IFAE and ICREA, Barcelona), Andreas Bauswein (Darmstadt, GSI), Giancarlo Cella (INFN, Pisa)
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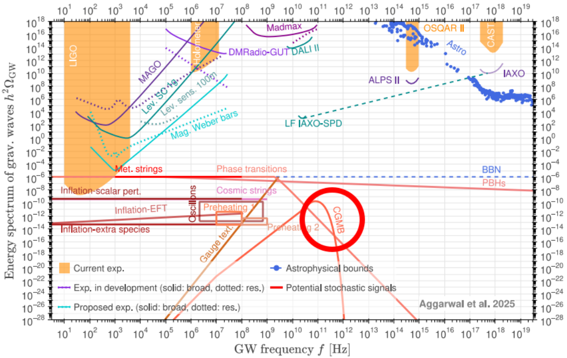
Jan 20, 2025

138 pages
e-Print: 2501.11723 [gr-qc]
Report number: CERN-TH-2025-014, DESY-25-007
View in: CERN Document Server, HAL Science Ouverte, ADS Abstract Service

2025



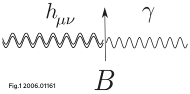
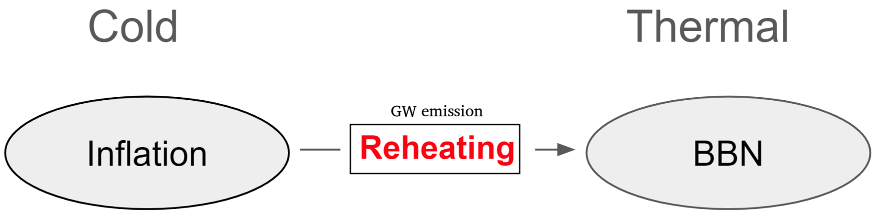


Fig.1 2006.01161

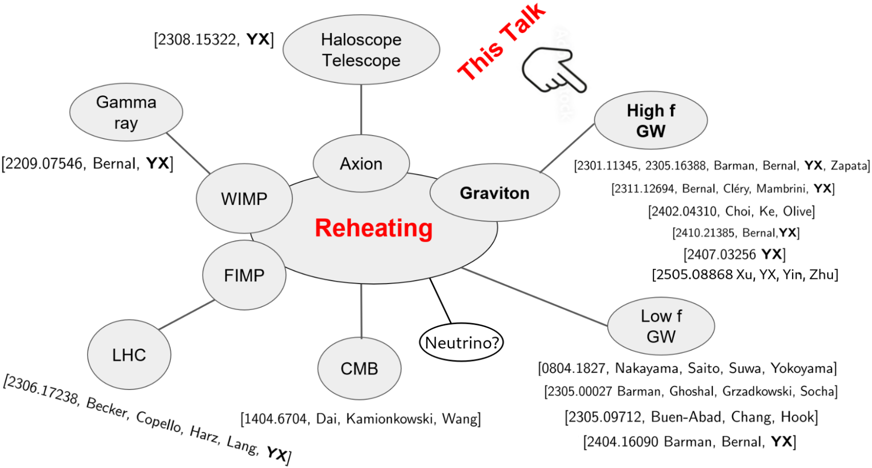
Summary



- Reheating explains Cold $\to$ Thermal (important for many BSM phenomena)
- Two important parameters $(m_\phi$ and $T_{\rm rh})$ and several **GW** sources
  1. $m_\phi \gg T_{\rm rh} \implies$ Non-Thermal Bremsstrahlung GWs dominate $\implies$ **probe** m_ϕ
  2. Large $T_{\rm rh} \implies$ Thermal GWs dominate $\implies$ **probe** $T_{\rm rh}$

$\implies$ GWs as messengers of pre-BBN universe!

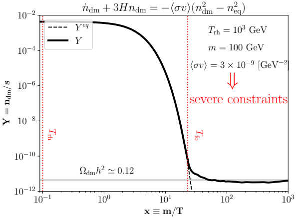
Probing Pre-BBN: Astro-Cosmo-Collider Synergy and Landscape of messengers



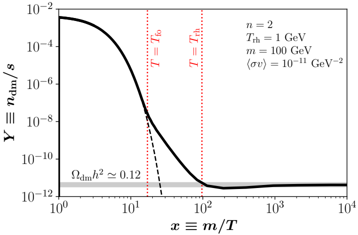
Thanks for your attention!

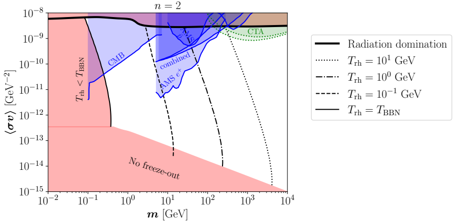
Temperature is important: WIMP Freeze-out

- Freeze-out after reheating $T_{\rm fo} < T_{\rm rh} \implies$



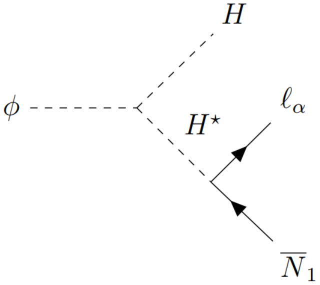
- Freeze-out during reheating with $T_{\rm fo} > T_{\rm rh} \implies$ **much smaller** $\langle\sigma v\rangle \implies$ evade experimental constraints

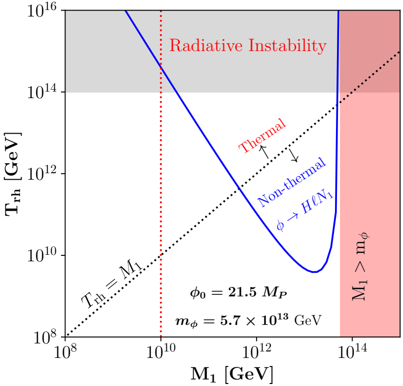




[Bernal, **YX** 2209.07546]

Temperature is important: Leptogenesis



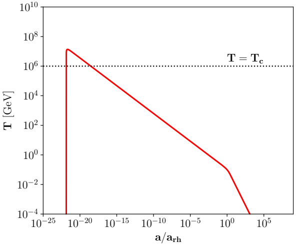


- $T_{rh} > M_1 \implies$ **thermal leptogenesis**
- $T_{rh} < M_1 \implies$ **non-thermal leptogenesis** $\phi \to H\ell N$

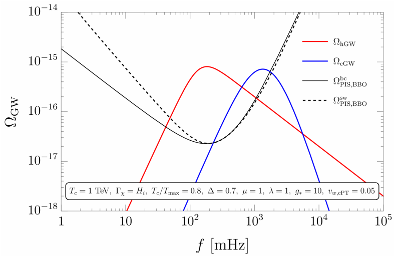
[Drees, **YX** 2401.02485]

Temperature is important: Phase Transition

- Possible to have $T_c < T_{\max}$

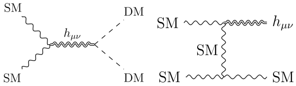


- Double PT $\Longrightarrow$ double peaked GW [Buen-Abad, Chang, Hook 2305.09712]

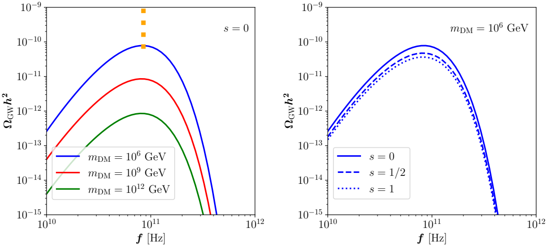


Probing Gravitational Dark Matter with Thermal GWs

- Minimal scenario: DM with pure gravity interaction
- GWs offers a new avenue: unavoidable cogenesis of DM and GW



$$\Omega_{\rm GW} h^2 \sim 8.6 \times 10^{-11} \left(\frac{\Omega_{\rm DM} h^2}{0.12}\right)^{1/3} \left(\frac{f}{10^{11}\ \text{Hz}}\right)^3 \left(\frac{\alpha_{\rm spin}}{3 \cdot 10^{-3}}\right)^{-1/3} \left(\frac{m_{\rm DM}}{10^9\ \text{GeV}}\right)^{-1/3}$$



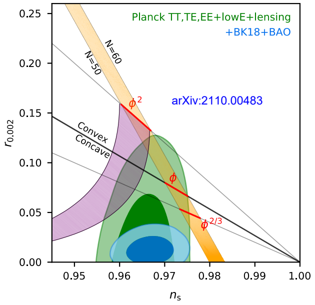
- Left frame: **Null signal** $\Omega_{\rm GW} h^2 \gtrsim 10^{-10} \implies$ **exclude** $m_{\rm DM} \lesssim 10^6$ **GeV**
- Right frame: Positive signal and enough resolution $\implies$ probe the spin!

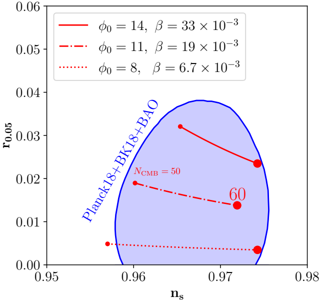
[**YX**, 2412.21137; Phys.Lett.B 865 (2025) 139483]

Polynomial Inflation

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

$$V(\phi) = b\phi^2 + c\phi^3 + d\phi^4 \sim d\left[\phi^4 - 8/3\phi_0\left(1-\beta\right)\phi^3 + 2\phi_0^2\phi^2\right]$$





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

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

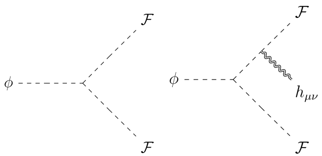
Bremsstrahlung GW Spectrum

- GW amplitude:

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

- Differential spectrum

$$\frac{d(\rho_{\mathrm{GW}}/\rho_R)}{dE_g} \propto \left(\frac{d\Gamma}{dE_g}\frac{1}{\Gamma_\phi}\right) \times \left(\frac{E_g}{m_\phi}\right) \sim (\text{differential BR}) \times (\text{energy fraction})$$



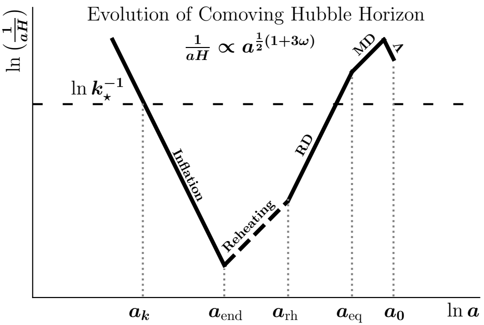
- Recall that

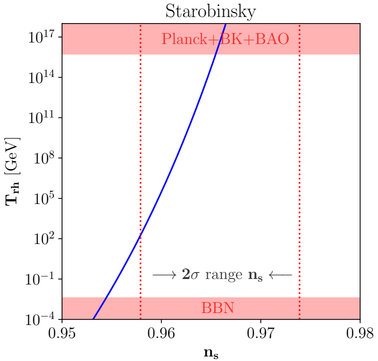
$$\Gamma_\phi \propto \frac{\mu^2}{m_\phi} \quad \text{and} \quad \frac{d\Gamma}{dE_g} \propto \frac{\mu^2}{M_P^2}\frac{m_\phi}{E_g}$$

- Expect

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

Matching reheating with inflationary predictions





$$\Longrightarrow \quad T_{\rm rh} = f(n_s, r)$$

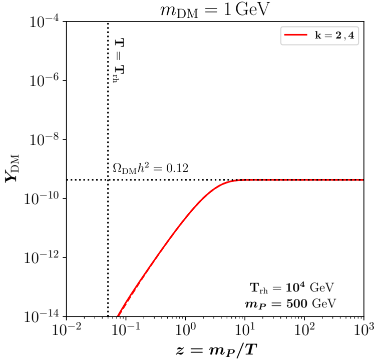
- Low bound on $T_{\rm rh}$ in Starobinsky inflaton: $T_{\rm rh} \simeq 180$ GeV

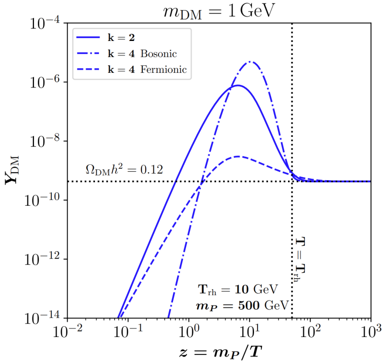
FIMP from LLP decay

- 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 ($T_{\mathrm{FI}} > T_{\mathrm{rh}}$)





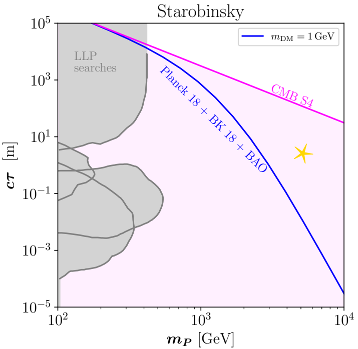
[Becker, Copello, Harz, Lang, **YX** 2306.17238]

FIMP from LLP decay

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

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

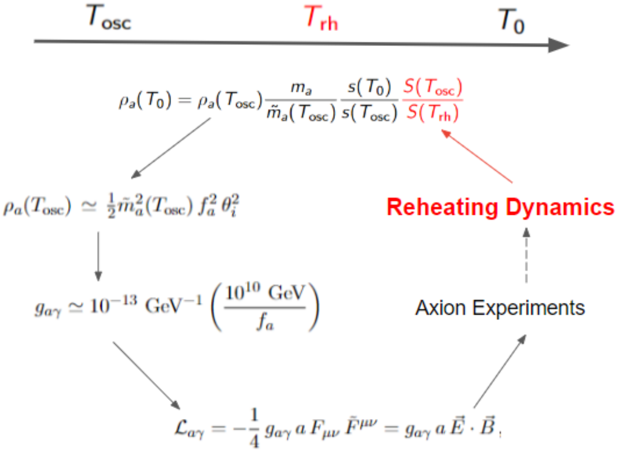
- $T_{\mathrm{FI}} < T_{\mathrm{rh}} \implies c\tau \sim m_P^{-2} \quad T_{\mathrm{FI}} > T_{\mathrm{rh}} \implies c\tau \sim m_P^{-9}$



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

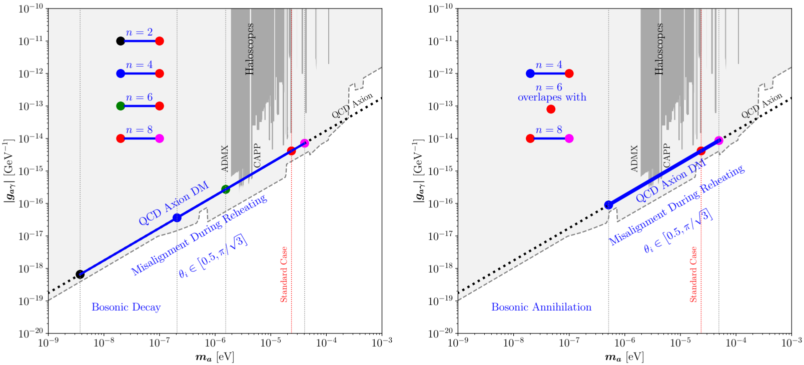
[Becker, Copello, Harz, Lang, **YX** 2306.17238]

Axion Production during reheating



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

Probing Reheating via Axion experiments: QCD Axion



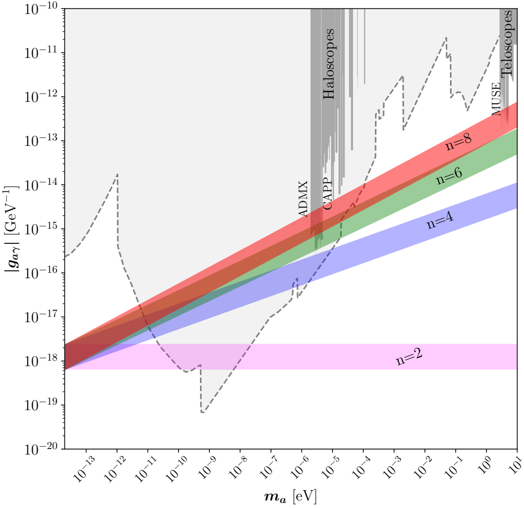
- Assume QCD axion makes up all DM. If a positive signal with

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

$\Longrightarrow$ **bosonic annihilation less likely**

[**YX** 2308.15322 Phys. Rev. D 108, 083536]

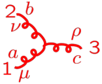
Probing Reheating via Axion experiments: ALP



[**YX** 2308.15322 Phys. Rev. D 108, 083536]

Double Copy

Yang-Mills gauge theory:

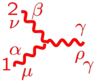


$$-gf^{abc}(\eta_{\mu\nu}(k_1 - k_2)_\rho + \text{cyclic})$$

$$\sim gf^{abc}\frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 31\rangle}$$

Only consistent vertices with correct dimensions

Einstein gravity:



$$i\kappa(\eta_{\mu\nu}(k_1 - k_2)_\rho + \text{cyclic})$$
$$\times\,(\eta_{\alpha\beta}(k_1 - k_2)_\gamma + \text{cyclic})$$

$$\sim i\kappa\left(\frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 31\rangle}\right)^2$$

"square" of Yang-Mills vertex.

$$\kappa^2 = 32\pi G$$