



GW Signatures of Reheating After Warm Axion Inflation

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[2503.01228, JCAP07(2025)002]

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[on-going]



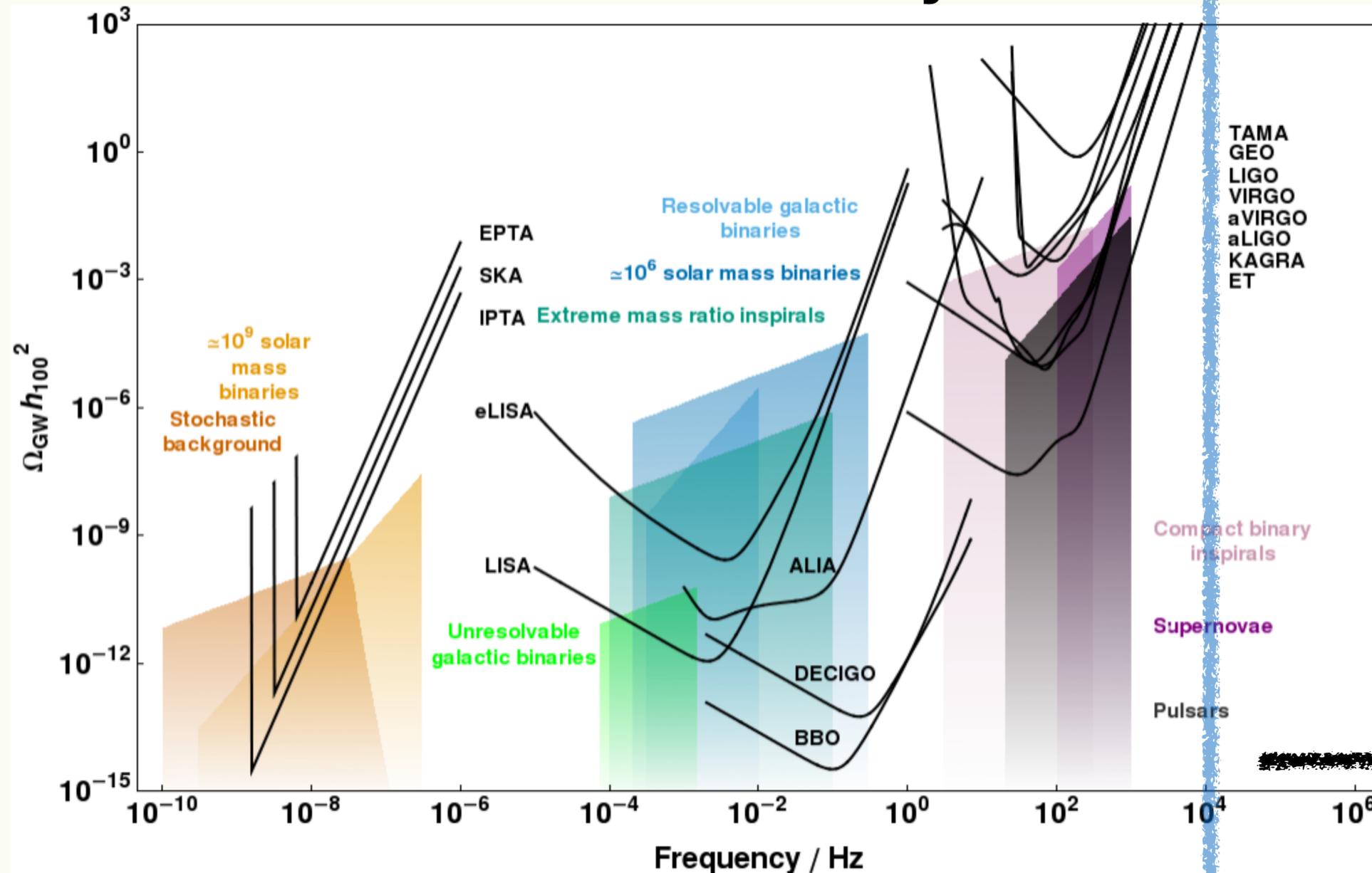
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S O K E N D A I

High Frequency Gravitational Wave background

Gravitational-wave sensitivity curves

[C.J. Moore+1408.0740]

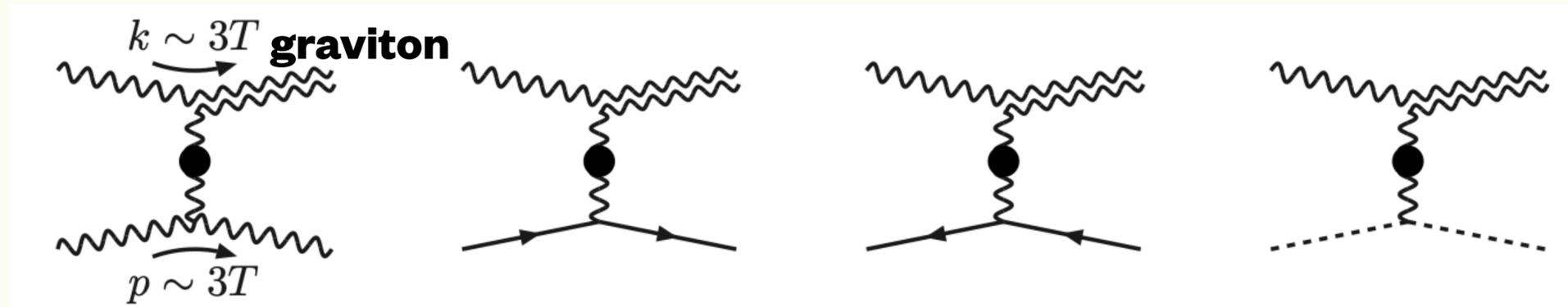


- No known astrophysical GW above 10^4 Hz
- High frequency GW are strong prove of cosmological origin !

High Frequency GW →

Perturbative Graviton production

(1) Thermal Gravitational Waves [Ghiglieri+1504.02569, Bernal+2410.21385]



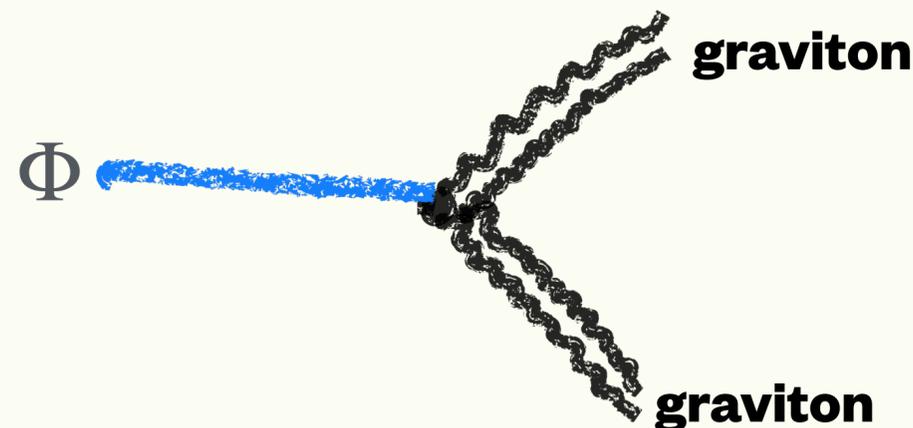
$$\mathcal{L}_{\text{GW}} = \frac{h_{\mu\nu}}{M_{\text{pl}}} T^{\mu\nu}$$

For $k, p \sim \pi T$

higher dim op

The spectrum depends on the reheating temperature, but its shape is almost blackbody peak at $f_{\text{peak}} = 80\text{GHz} \sim T_0$

(2) Scalar field decay to gravitons [Y.Ema+2112.12774, Landini+2501.09794]



Other example **annihilation, Bremsstrahlung**

[Ema+1502.02475, 2006.09972, Nakayama+1810.04975]

Scalar Field Decay Into Graviton

Question [Y.Ema+2112.12774, Landini+2501.09794]

Does Scalar Φ decay into graviton?

$$\mathcal{L} \sim c_1 \Phi R + c_2 \Phi R^2 + c_3 \Phi R_{\mu\nu} R^{\mu\nu} + c_4 \Phi R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$

$$\sim \phi(\partial h)^2$$

move to Einstein frame! $g_{\mu\nu} \rightarrow f(\Phi)g_{\mu\nu}$

$R = R_{\mu\nu} = 0$ for on-shell graviton in vacuum.

⚠: Physics should not change under field redefinitions.

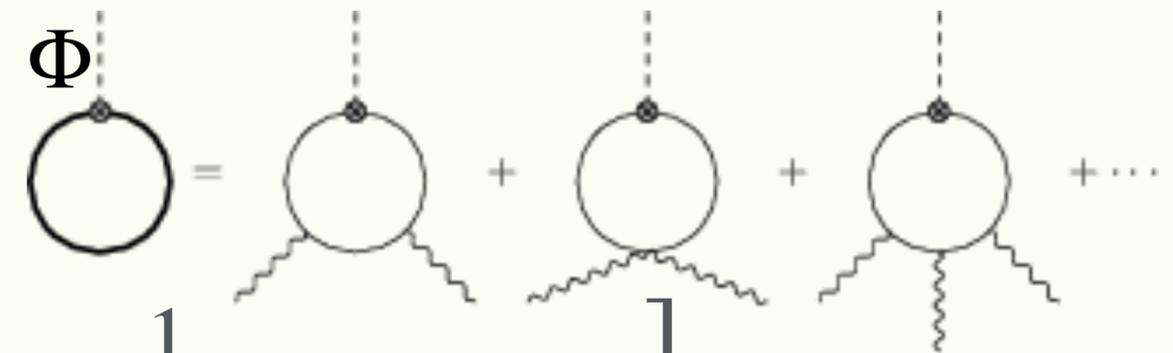
$c_4 \Phi R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$ give rise to decay into graviton.

Scalar Field Decay Into Graviton

[Y.Ema+2112.12774]

- The operator appears after integrating out heavy field χ

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} (m_\chi^2 + \lambda \Phi) \chi^2 \right]$$



$$\rightarrow \mathcal{L}_{\Phi hh} = \frac{\lambda}{32\pi^2} \frac{\Phi}{m_\chi^2} \left[-\frac{1}{72} R^2 + \frac{1}{180} R_{\mu\nu} R^{\mu\nu} + \frac{1}{180} R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} \right]$$

Decouple scale depends on Φ

Beta Function $\beta_{\mathcal{O}}$ for each curvature invariant

- Scalar can decay into graviton pair !**

Visible gravitational wave may be produced!

$$\Gamma(\Phi \rightarrow hh) = \frac{c_4^2 m_\Phi^7}{4\pi M_{\text{pl}}^4} \quad \text{w/ } c_4 = -\frac{\lambda}{32\pi^2} \frac{1}{180} \frac{1}{m_\eta^2}$$

Reheating after Axion Inflation with SU(N) gauge

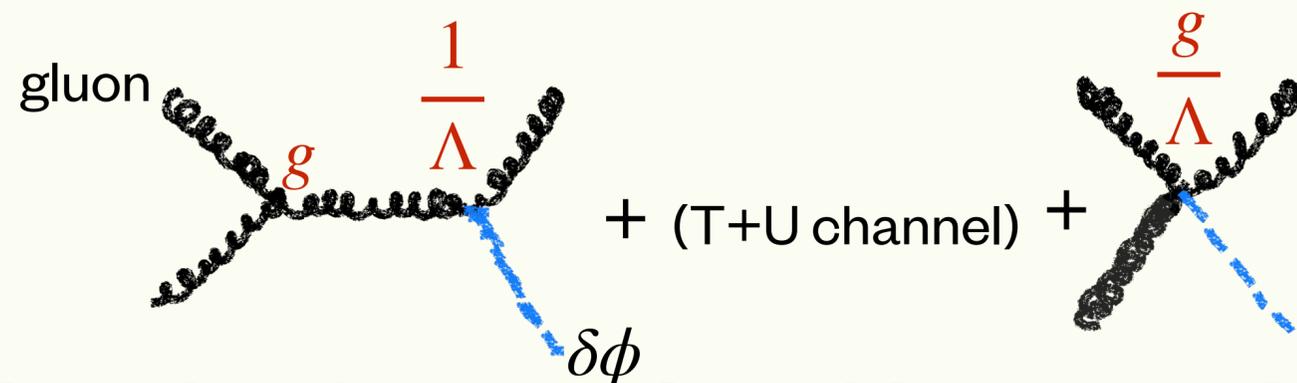
[T.Fujita, K.Mukaida, TT,2503.01228]



- Self interaction → **thermalization** $\Gamma_{\text{th}} \sim N^2 \alpha^2 T$
- Confined at low T

- **Tachyonic Instability?** ← Magnetic mass $m_M \sim Ng^2 T$ [M.Laine+0906.4450]
- **Thermal dissipation ?** ← $\delta\phi$ production from thermal bath.

[A.Salvio+1310.6982, K.Bouzoud+2404.06113]



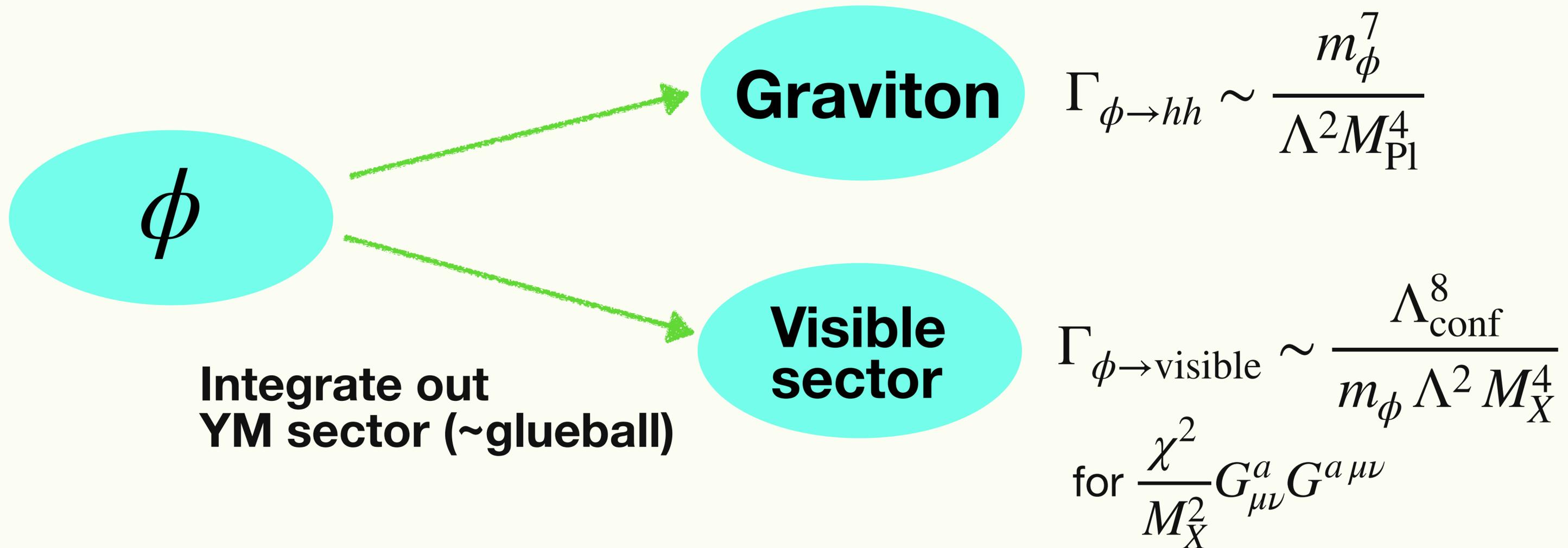
$$\Gamma_{\delta\phi} \sim (N^2 - 1)N \frac{\alpha T^3}{\Lambda^2}$$

Reheating is completed by perturbative decay of inflaton! (or may be glueball)

Implication of this system: Graviton Production

[K.Mukaida, TT ,ongoing]

- For Inflaton domination

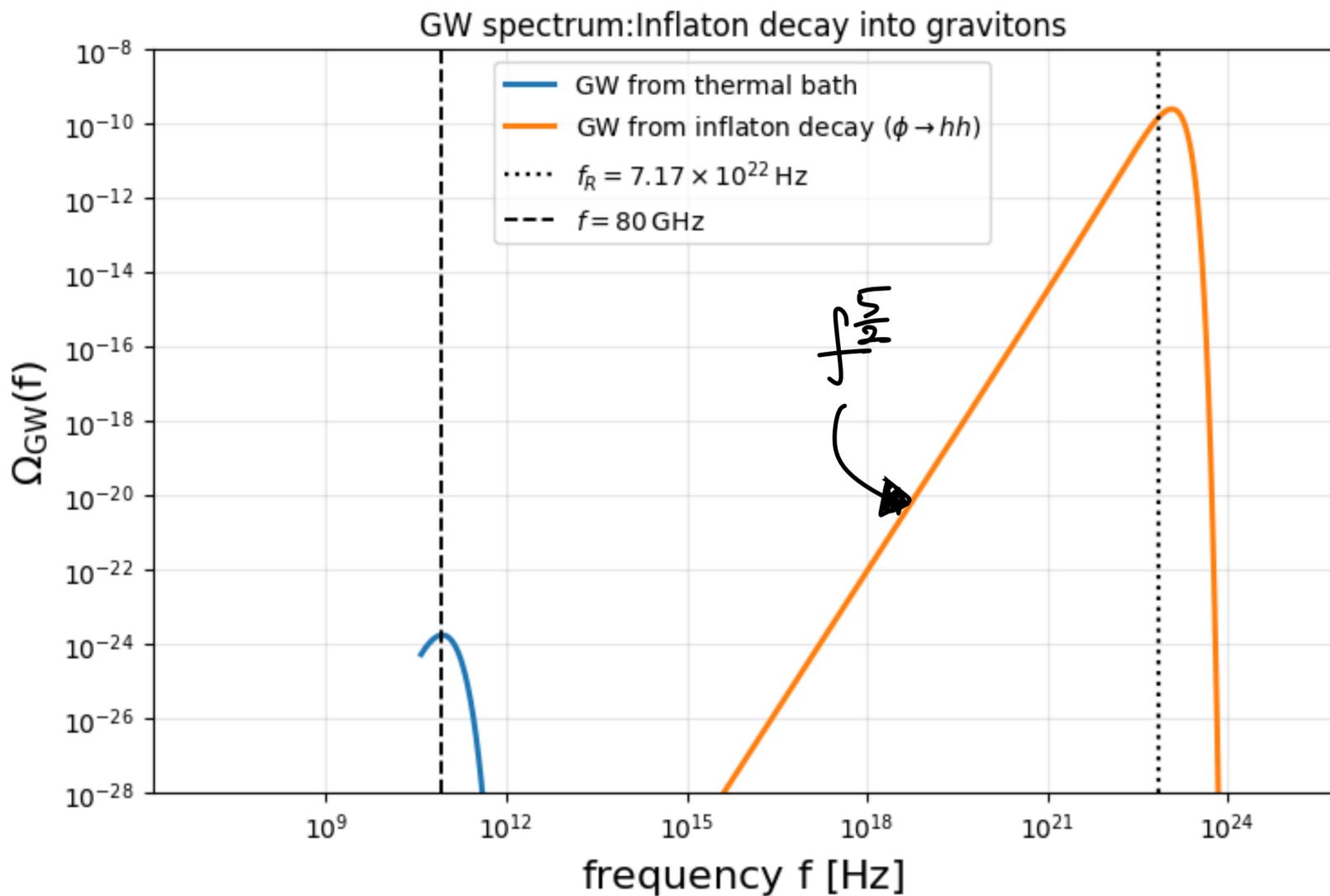


Same argument can be applied to the glueball-dominated case, since the heavier glueballs can be integrated out.

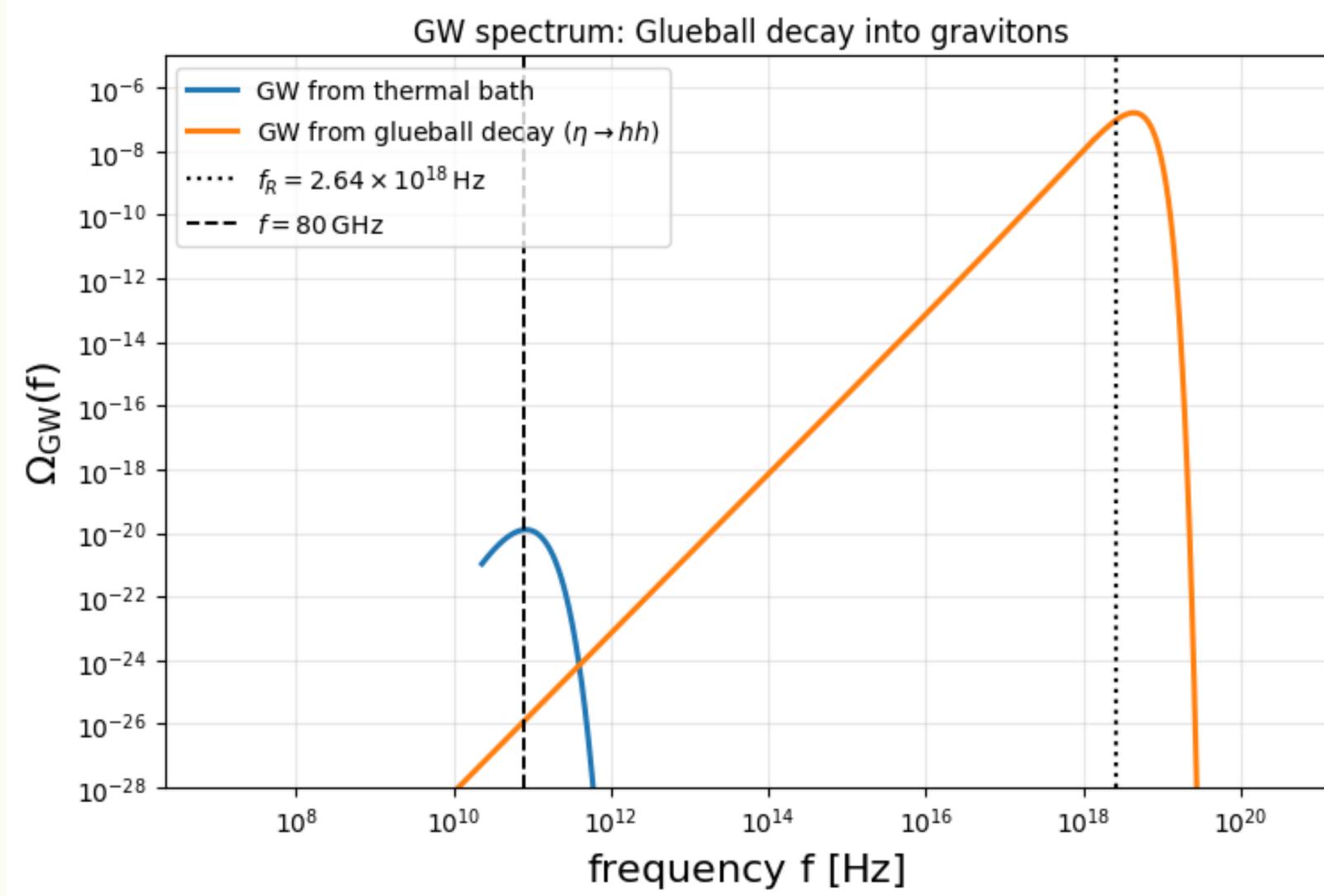
GW spectrum

$$m_\phi = 10^{13} \text{ GeV}, M_X = 8 \times 10^{17} \text{ GeV}, \theta_{\text{YM}} = 1$$

[K.Mukaida, TT ,ongoing]



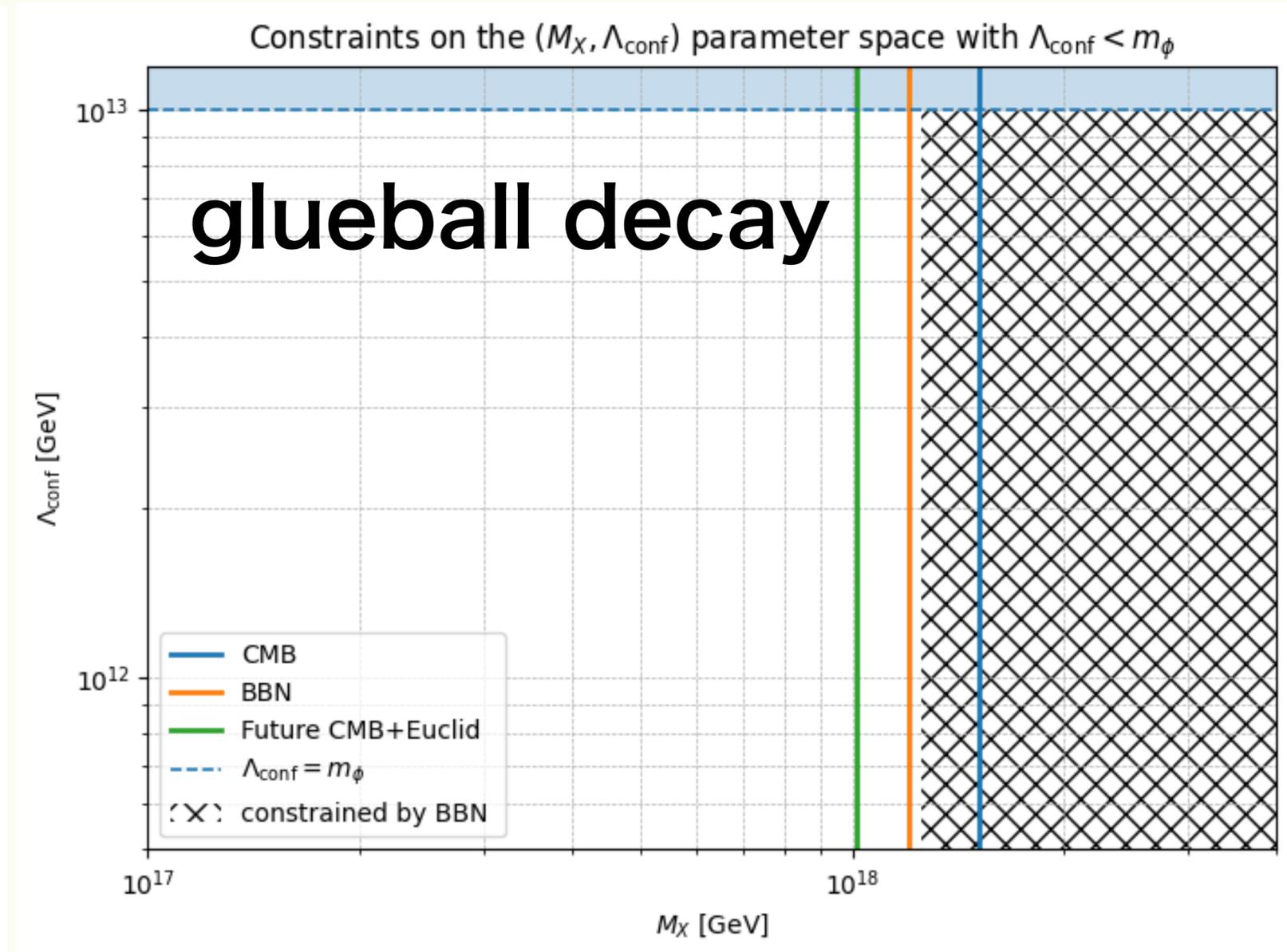
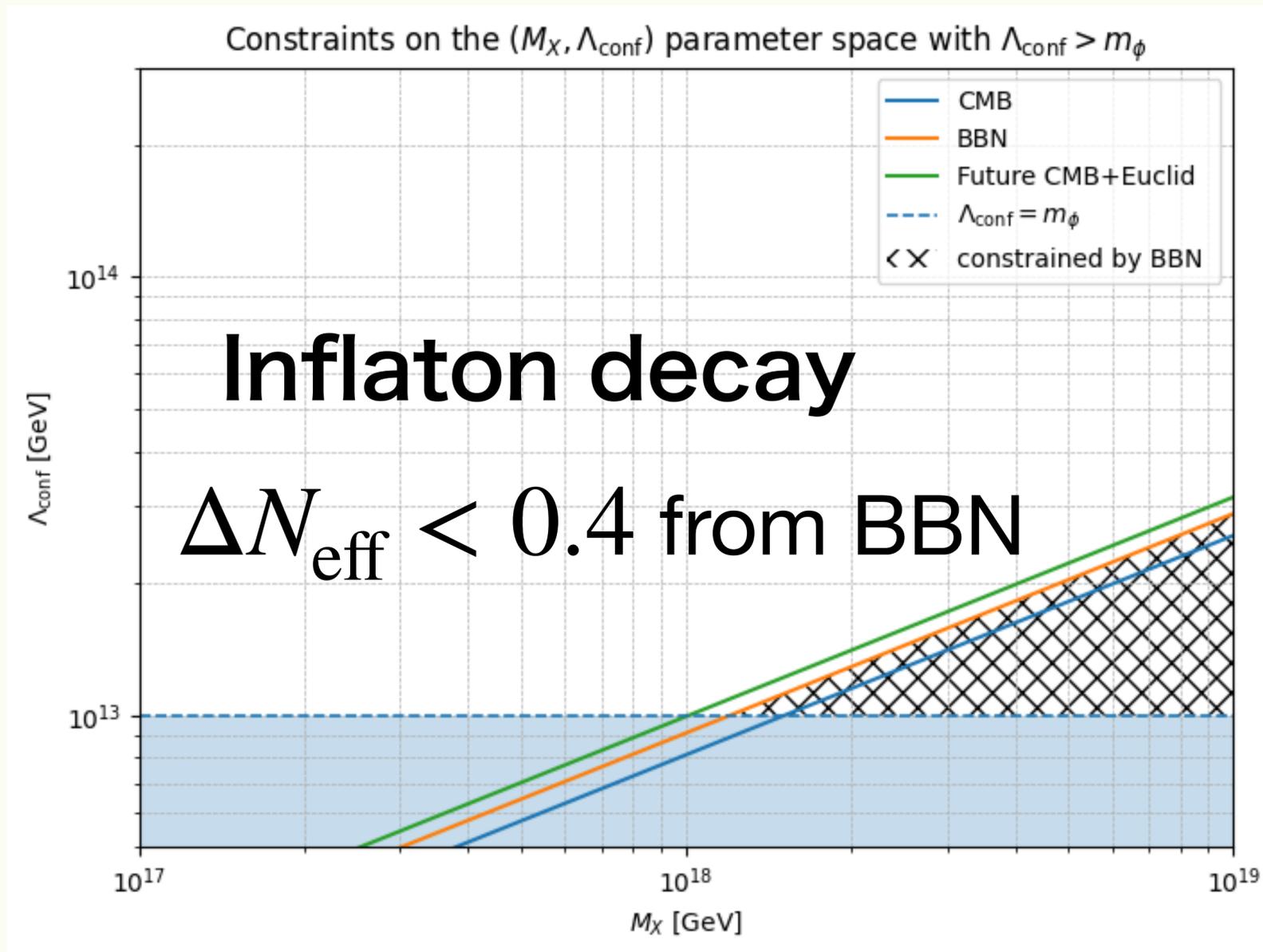
for $m_\phi < \Lambda_{\text{conf}} = 2 \times 10^{13} \text{ GeV}$



for $m_\phi > \Lambda_{\text{conf}} = 3 \times 10^{12} \text{ GeV}$

δN_{eff} contribution

[K.Mukaida, TT ,ongoing]



Suppressed coupling $M_X \geq 10^{18} \text{ GeV}$ between visible sector and the YM sector to be constrained by additional relativistic DOF δN_{eff}

Conclusion

We Study GW spectrum After Axion Inflation with SU(N) gauge

- Even if Axion Inflation, reheating is completed by perturbative decay.
- Heavier particles than inflaton (or glueball) may emerge during reheating.
- Integrating out its heavy particle leads perturbative decay into graviton!
- **A large GW signal is expected, which can be probed via δN_{eff} .**

Future Work ?

- $\Phi R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma}$ exists or not in our set up.
- Glueball EFT in the presence of θ_{YM} term.