# Dark radiation constraints on hidden gauge-axion system

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# § Introduction

- Standard Big Bang cosmology
  - Cosmic Expansion
  - Light elements
  - CMB

  - Problems
    - Horizon problem, …

- Inflationary cosmology

# § Inflationary cosmology

- Inflation [Guth (1981), Sato (1981)]
  - – Solving problems
    - Horizon problem, …
- Generating density perturbation from quantum fluctuation [Guth and Pi (1982), Hawking (1982)]
- Generating tensor perturbations

# §§ Tensor perturbation

- Generating tensor perturbations from quantum fluctuation [Starobinsky (1979)]
- Generating tensor perturbations sourced by other fields (sourced GW)
  - In variants of chromo natural inflation [Adshead and Wyman (2012)]
  - Pseudo scalar (“axion”) and hidden SU(2) gauge theory [Dimastrogiovanni et al (2012)]
  - Fluctuations of the vector potential $\delta A$ generate tensor perturbation $h_{ij}$ [Fujita et al (2018)]

# § Model

- Lagrangian [Dimastrogiovanni et al (2012)]

$$\mathcal{L} = \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\lambda}{4f}\chi F_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{L}_\phi$$

$$U(\chi) = \mu^4\left(1 + \cos\left(\frac{\chi}{f}\right)\right)$$

- Inflaton $\phi$
- Axion $\chi$
- Hidden SU(2) gauge field $A$ with the gauge coupling constant $g$

# Background solutions

- Inflaton domination during inflation
- Non-trivial gauge potential solution in FRW
  [Adshead and Wyman (2012)]
  $$A_0^a = 0, A_i^a = a(t)Q(t)\delta_i^a$$
- Energy and pressure of the gauge field
  $$\rho_A = \frac{3}{2}\left[\left(\dot{Q} + HQ\right)^2 + g^2 Q^4\right],$$
  $$p_A = \frac{1}{2}\left[\left(\dot{Q} + HQ\right)^2 + g^2 Q^4\right]$$
- Some "slow roll" parameters
  $$\epsilon_i = \frac{\rho_i + p_i}{2M_P^2 H^2}, \qquad \epsilon_H = -\frac{\dot{H}}{H^2} = \sum_i \epsilon_i$$

# Background solutions

- EOM for axion and gauge field

$$\ddot{\chi} + 3H\dot{\chi} + U_\chi + \frac{3g\lambda}{f} Q^2\left(\dot{Q} + HQ\right) = 0,$$

$$\ddot{Q} + 3H\dot{Q} + \left(\dot{H} + 2H^2\right)Q + 2g^2Q^3 - \frac{g\lambda}{f}\dot{\chi}Q^2 = 0,$$

- Under the strong coupling condition during inflation [Dimastrogiovanni and Peloso (2013)]

$$\left(\frac{\lambda Q}{f}\right)^2 \gg \frac{3}{{m_Q}^2}, \quad \left(\frac{\lambda Q}{f}\right)^2 \gg 2,$$

where $m_Q = {}^{gQ}/_{H}$

# Background solutions

- EOM for axion and gauge field

$$\ddot{\chi} + 3H\dot{\chi} + U_\chi + \frac{3g\lambda}{f} Q^2 (\dot{Q} + HQ) = 0,$$

$$\ddot{Q} + 3H\dot{Q} + (\dot{H} + 2H^2) Q + 2g^2 Q^3 - \frac{g\lambda}{f} \dot{\chi} Q^2 = 0,$$

- Gauge field and axion trapped at the min.

$$Q_{\rm min}(\chi) = \left( -\frac{f U_{,\chi}}{3g\lambda H} \right)^{1/3}$$

$$\frac{1}{Hf}\dot{\chi} = \frac{2}{\lambda} \left( m_{Q,{\rm min}}(\chi) + \frac{1}{m_{Q,{\rm min}}(\chi)} \right)$$

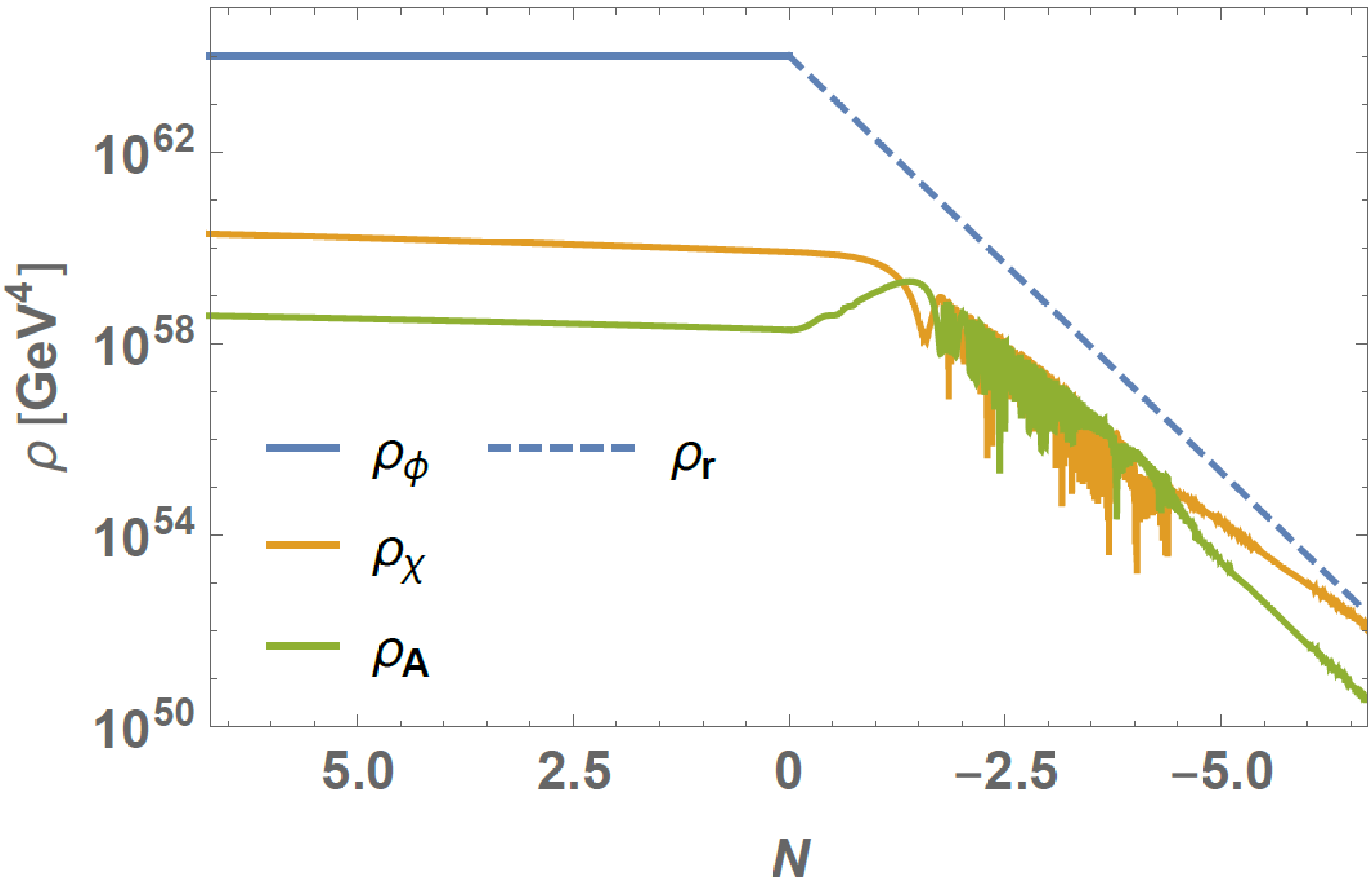
# Background solutions

- When the strong coupling condition violates, axion and hidden gauge start to oscillate and $\rho \propto a^{-3}$.
- Axion decays into gauge boson $H \cong \Gamma_\chi = \frac{3m_\chi^3\lambda^2}{64\pi f^2}$
- When it violates?

1. During inflation
   - Rapid dilution
2. At the end of inflation
   - Possible dark radiation

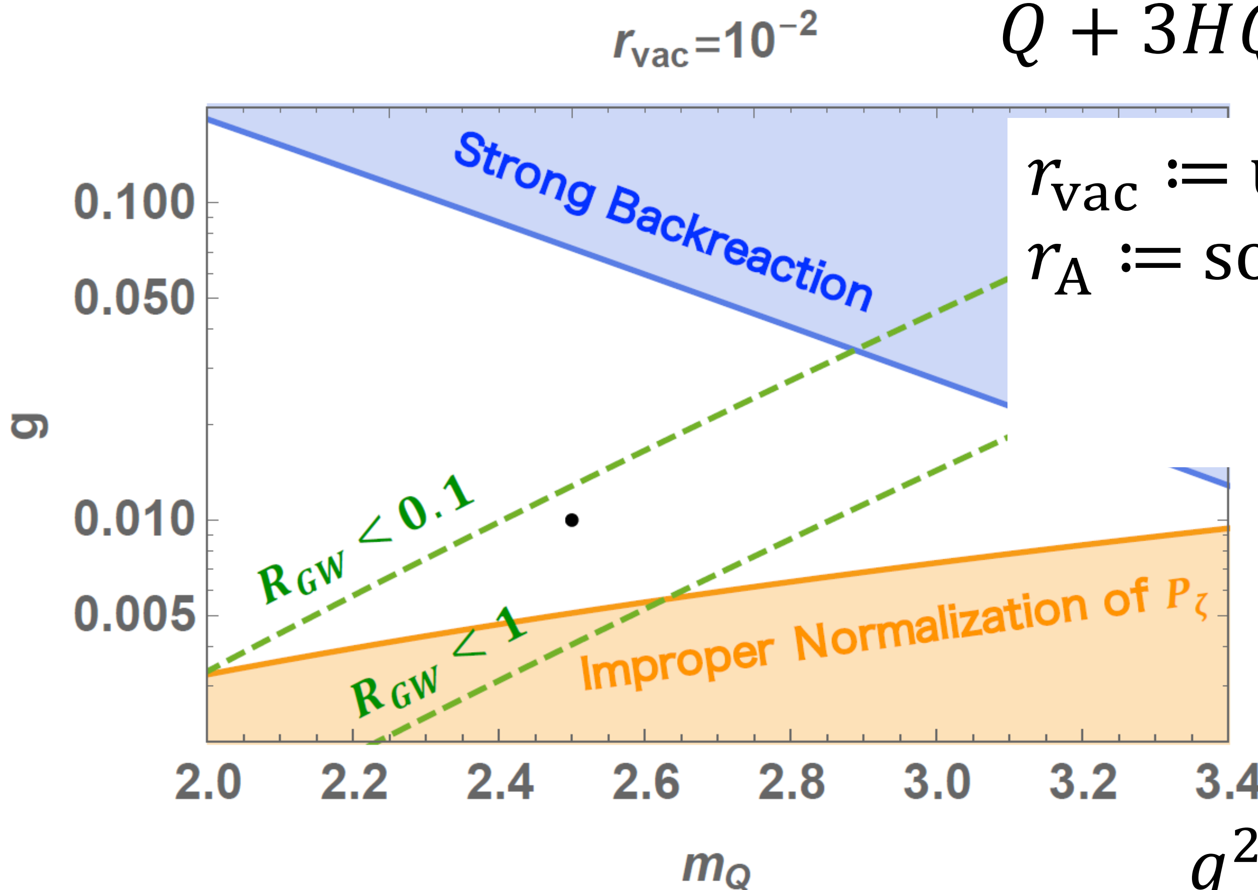
# Evolution

- Energy densities



# Constraints for successful inflation

[Papageorgiou et al (2019)]




Backreaction by tensor pert. to bkg.

$$\ddot{Q} + 3H\dot{Q} + \cdots + \mathcal{T}_{\mathrm{BR}}^{Q} = 0$$

$r_{\mathrm{vac}}$ := usual t-s ratio

$r_{\mathrm{A}}$ := sourced GW-s ratio

$$R_{GW} := \frac{r_{\mathrm{A}}}{r_{\mathrm{vac}}}$$

Max = $^1/_4$

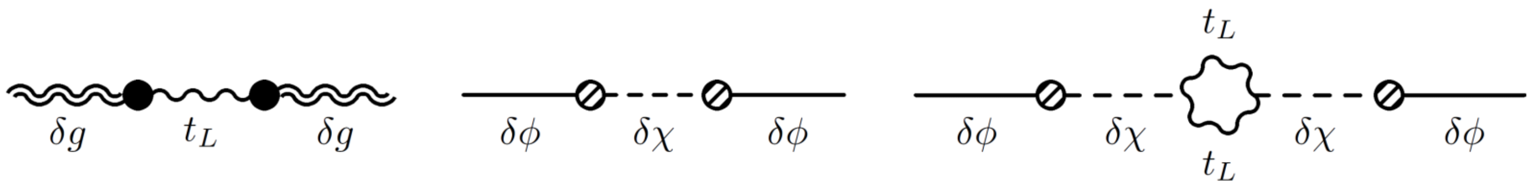
$$\mathcal{P}_\zeta \cong \frac{g^2}{8\pi^4 m_Q^4} \frac{\epsilon_B/\epsilon_\phi}{\left(1+\epsilon_B/\epsilon_\phi\right)^2}$$

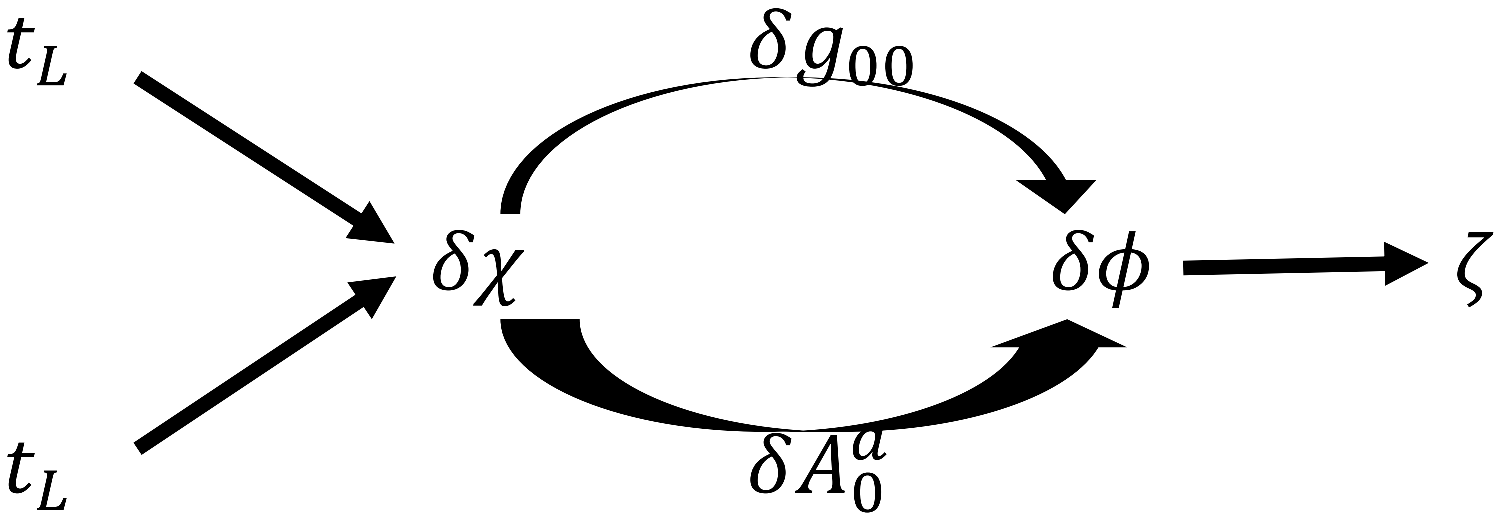
# Constraints from non-Gaussianity

- Non-linear interaction generate scalar perturbation from enhanced tensor perturbation.

[Papageorgiou et al (2019)]

enhanced GW　　linear order negligible　　Nonlinear scalar sourced by $t_L$



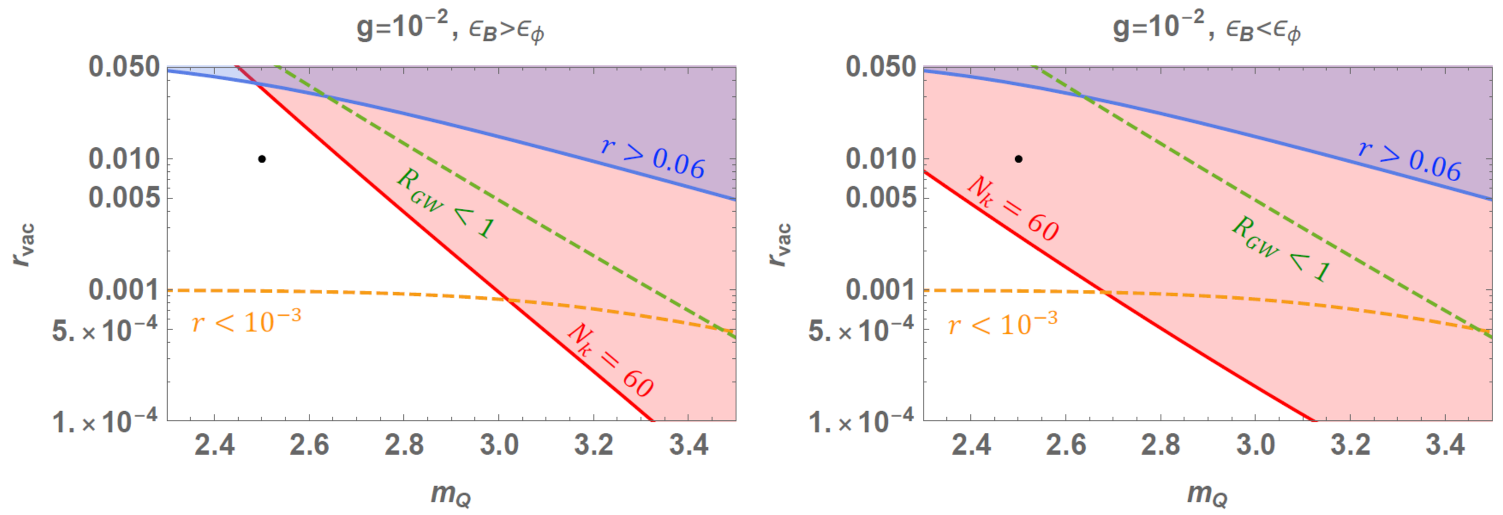
# Constraints from non-Gaussianity

- The constraint $f_{\rm NL}^{\rm equil} \leq O(100)$ is converted as

[Papageorgiou et al (2019)]

$$\frac{\text{NLinear in } \mathcal{P}_\phi}{\text{Linear in } \mathcal{P}_\phi} \cong \frac{5 \times 10^{-12}}{\left(1+\epsilon_B/\epsilon_\phi\right)^2} m_Q^{11} e^{7m_Q} N_k^2 r_{\rm vac}^2 < 0.1$$

$N_k$ : e-fold of axion roll from CMB scale to its pot. min



# Dark radiation

- The energy densities at the recombination

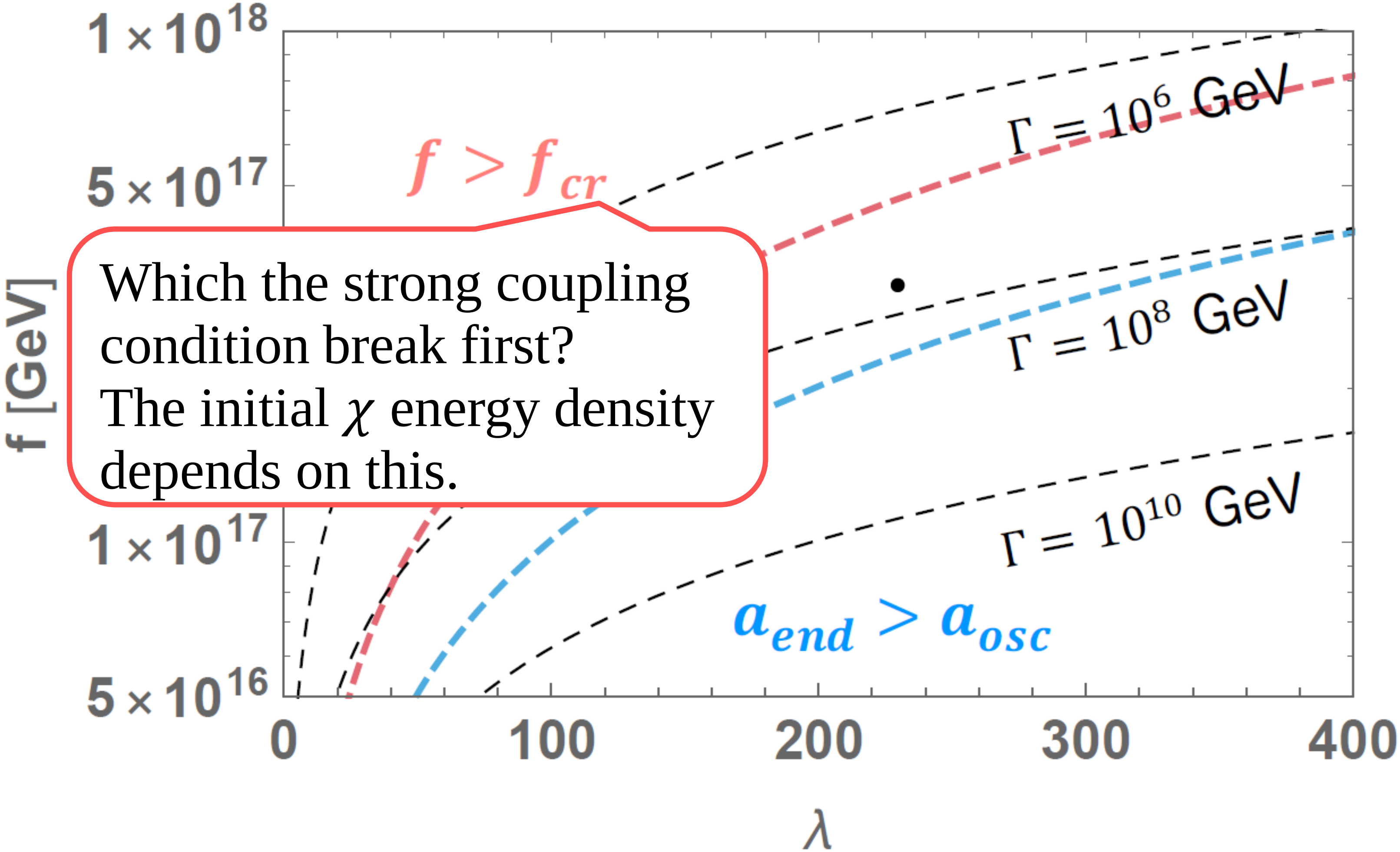
$$\rho_r = \rho_\gamma + \frac{7N_{\mathrm{eff}}^{\mathrm{SM}}}{4}\frac{\pi^2 T_\nu^4}{30\pi} + \rho_d$$

$$= \rho_\gamma + \left(N_{\mathrm{eff}}^{\mathrm{SM}} + \Delta N_{\mathrm{eff}}\right)\frac{7}{4}\frac{\pi^2 T_\nu^4}{30\pi}$$

- Constraints on model parameters from $N_{\mathrm{eff}}$

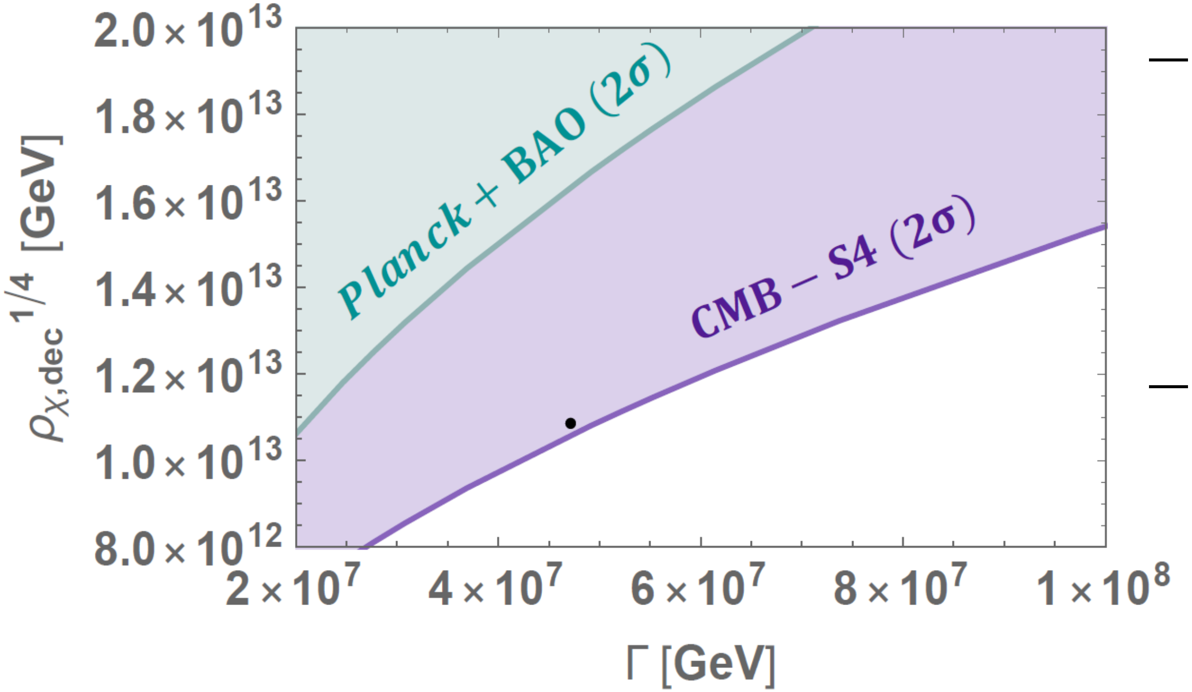
# Decay rate

- For $g = 10^{-2}, m_Q = 2.5, H_* = 2.4 \times 10^{13}$ GeV




Which the strong coupling condition break first?
The initial $\chi$ energy density depends on this.

# DR abundance




CMB-S4 prospect [Abazajian et al., (2019)]

$\Delta N_{\mathrm{eff}} < 0.03$

- A benchmark point
  - Parameters
    - $g = 10^{-2}, m_Q = 2.5, \lambda = 230, f = 3.2 \times 10^{17}$ GeV
  - Prediction
    - $r_{\mathrm{vac}} = 0.01$
    - $\mathcal{R}_{\mathrm{GW}} = 0.16$
    - $\Delta N_{\mathrm{eff}} = 0.066$
- Some region are testable.

# § Summary

- Hidden SU(2) gauge field and “axion”
  - Generation of tensor perturbations
  - “axion” decays into massless hidden gauge boson (DR)

- Non-negligible dark radiation can be produced.
  - Constraining the energy density and the decay rate
  - Future experiments will constrains more or detect DR.