Inflaton as
a decaying dark matter

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Motivation & Introduction

Higgs inflation with non-minimal coupling requires large non-minimal coupling for successful inflation. $\xi \sim \mathcal{O}(10^4)$

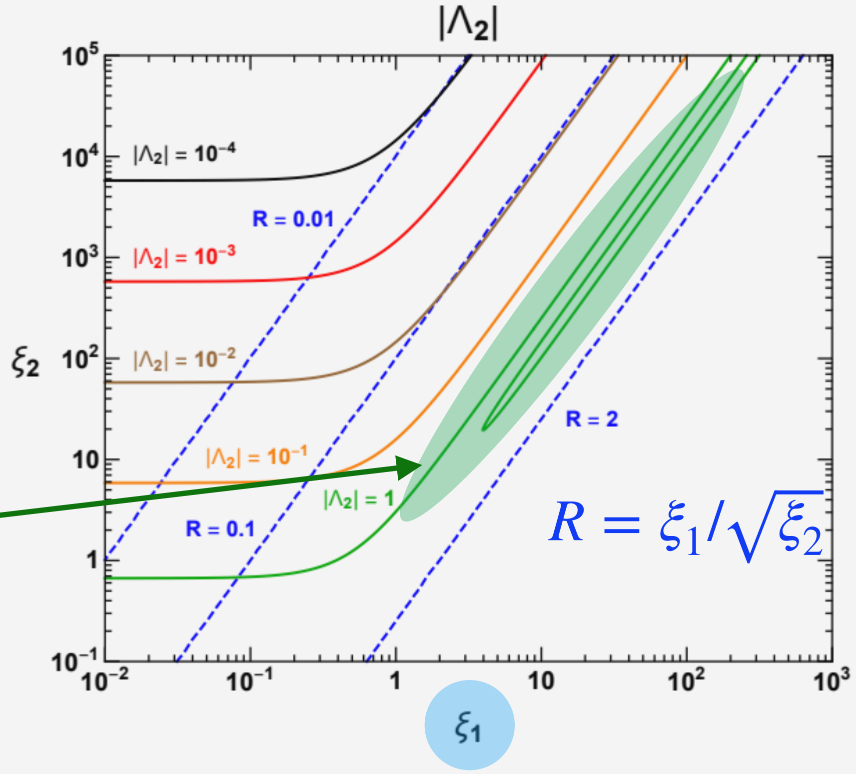
But large non-minimal coupling makes unitarity problem. $\Lambda_{\text{cut-off}} < \frac{E_k}{\xi} \sim \frac{M_p}{\xi}$

Introduce a linear non-minimal coupling in sigma model [H. M. Lee (2018)]

Soo-Min Choi's talk

$$\frac{\mathscr{L}}{\sqrt{-g}} \supset -\frac{1}{2}(1+\xi_1\sigma+\xi_2\sigma^2+2\xi_H|H|^2)R$$

$$\xi_1 \sim \sqrt{\xi_2} \Longrightarrow \Lambda_{\text{cut-off}} \sim M_p$$



If this σ can be a dark matter?

Model of inflation

Lagrangian in the Jordan frame

$$\frac{\mathscr{L}}{\sqrt{-g}} = -\frac{1}{2}\Omega(\sigma, H)R + \frac{1}{2}(\partial_\mu \sigma)^2 + |D_\mu H|^2 - V(\sigma, H)$$

Let $M_p = 1$

$$-\frac{1}{4g^2}V_{\mu\nu}V^{\mu\nu} + \bar{\psi} i \gamma^\mu \left(D_\mu + \frac{1}{2}\omega_\mu^{ab}\sigma_{ab}\right)\psi - (yH\bar{\psi}_L\psi_R + \mathrm{h.c.})$$

Z2 symmetry breaking

$$\Omega(\sigma, H) = 1 + \xi_1 \sigma + \xi_2 \sigma^2 + 2\xi_H |H|^2$$

linear non-minimal coupling

$$V(\sigma, H) = V_0 + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{4}\lambda_\sigma \sigma^4 + \frac{1}{2}\lambda_{\sigma H}\sigma^2|H|^2 + m_H^2 + \lambda_H |H|^4$$

Model of inflation

Choosing $H^T = (0,\ \phi)/\sqrt{2}$ and performing metric rescaling $g_{\mu\nu} = g^E_{\mu\nu}/\Omega$

Then, Lagrangian in Einstein frame is

$$\frac{\mathscr{L}_E}{\sqrt{-g}} = -\frac{1}{2}R_E + \frac{1}{2\Omega}(\partial_\mu\sigma)^2 + \frac{3}{4}(\partial_\mu \ln\Omega)^2 + \frac{1}{2\Omega}\left((\partial_\mu\phi)^2 + \delta_V m_{V,0}\frac{\phi^2}{v^2}V_\mu V^\mu\right) - V_E(\sigma, H)$$

$$\underbrace{-\frac{1}{4g^2}V_{\mu\nu}V^{\mu\nu} + \bar{f}i\gamma^\mu\left(D_\mu + \frac{1}{2}\omega_\mu^{ab}\sigma_{ab}\right)f}_{\text{do not couple to inflaton}} - \frac{1}{\Omega^{1/2}}\frac{m_{f,0}}{v}\phi\bar{f}f$$

where $\delta_V = 1(2)$ for $V = Z(W)$ and $V_E = \dfrac{1}{\Omega^2}V$

Model of inflation

Taking $\sigma, \phi \ll 1$ near vacuum

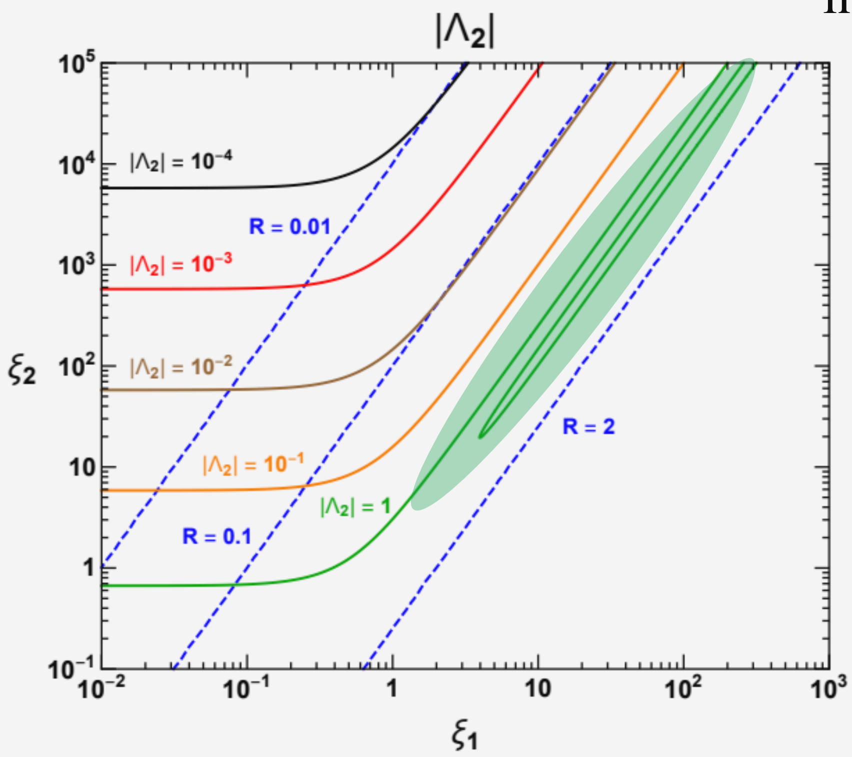
$$\mathscr{L}_{\text{kin},0} \approx \frac{1}{2}(1+\frac{3}{2}\xi_1^2)(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \phi)^2$$

→

Canonical sigma field

$$\chi = (1+\frac{3}{2}\xi_1^2)^{1/2}\sigma$$

$$\mathscr{L}_{\text{int}} = -\frac{1}{\Lambda_1}\chi(\partial_\mu \chi)^2 + \frac{1}{\Lambda_2^2}\chi^2(\partial_\mu \chi)^2 + \cdots$$



where $$|\Lambda_2| \equiv \frac{\sqrt{2}(1+\frac{3}{2}\xi_1^2)}{|\xi_1^2(1+\frac{9}{2}\xi_1^2) - \xi_2(1+15\xi_1^2 - 6\xi_2)|^{1/2}}$$

$\xi_1 \sim \sqrt{\xi_2}$ → $|\Lambda_2| \sim M_p$

ξ_1 has a crucial role to solve unitarity problem!

Inflaton decay

Taking $\sigma, \phi \ll 1$ near vacuum [Ibarra et al (2016)]

$$\mathcal{L}_{\rm int} \approx \xi_1 \sigma \Big[-\frac{1}{2}(\partial_\mu \phi)^2 + 2V + \frac{1}{2} m_{f,0} \frac{\phi}{v} \bar{f} f - \frac{1}{2} \delta_V m_{V,0}^2 \frac{\phi^2}{v^2} V_\mu V^\mu \Big]$$

$$\approx \boxed{\frac{1}{2} \frac{\xi_1}{\sqrt{1+\frac{3}{2}\xi_1^2}} \frac{\chi}{M_p} T^\mu_\mu}$$

$$V \approx V_0 + \frac{1}{2} m_\chi^2 \chi^2 + \frac{1}{4}\lambda_\chi \chi^4 + \frac{1}{4}\lambda_{\chi H}\chi^2\phi^2 + \frac{1}{2} m_H^2 \phi^2 + \frac{1}{4}\lambda_H \phi^4$$

$\delta_V = 1$ (2) for $V = Z$ (W)

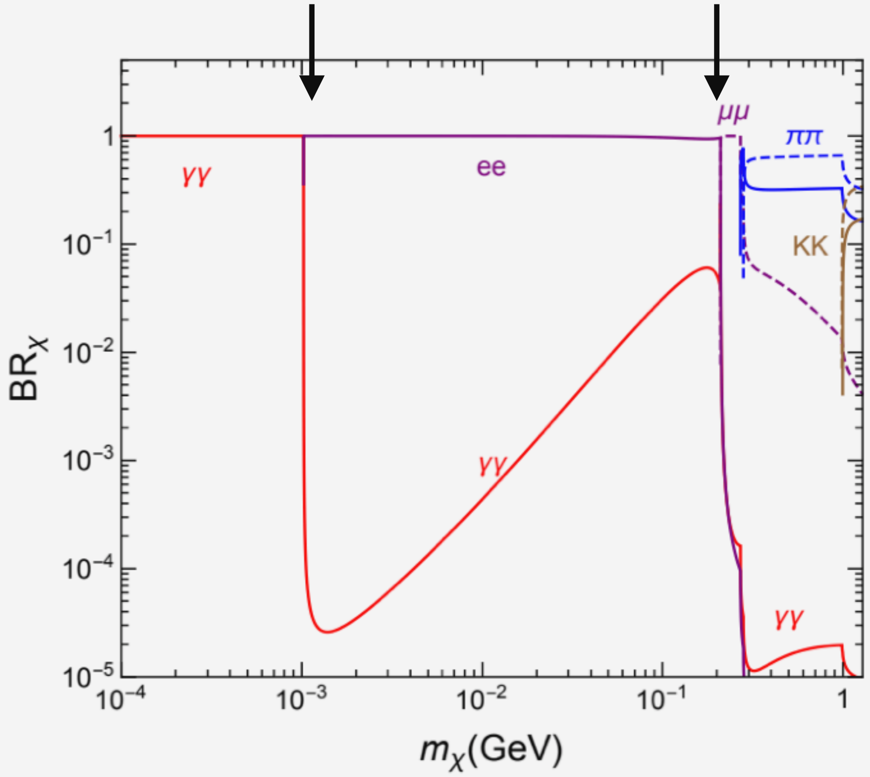
Inflaton decays to the SM through T^μ_μ only by linear coupling

Inflaton decay

Inflaton coupling to the SM :

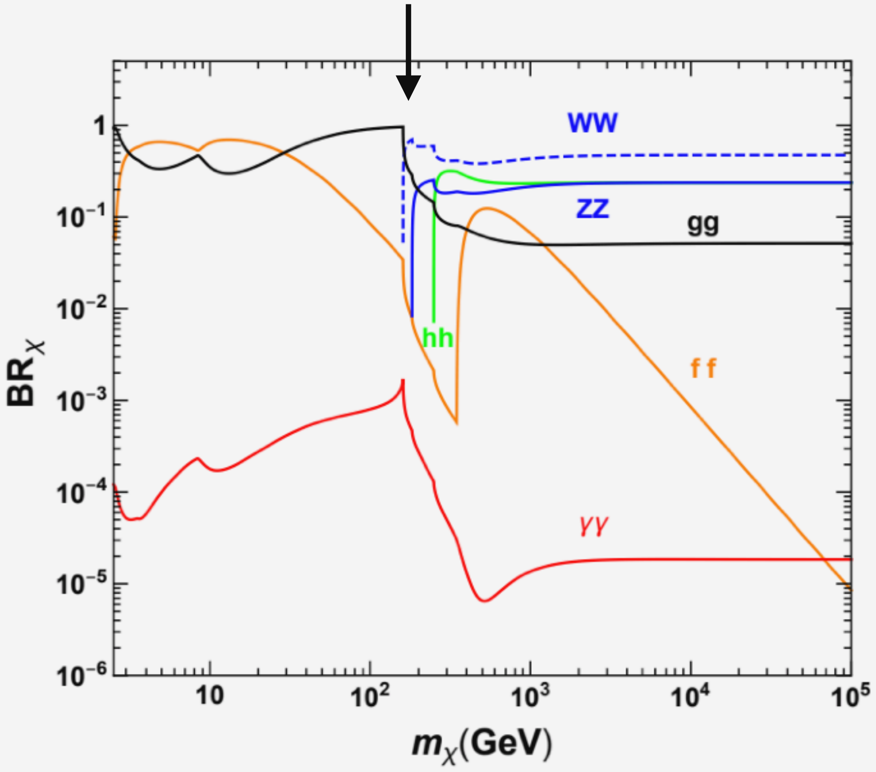
Higgs	tree level
fermion mass term	
gauge boson mass term	
massless gauge bosons	trace anomalies, threshold effects
mesons	chiral perturbation theory

ee threshold **$\mu\mu$ threshold**



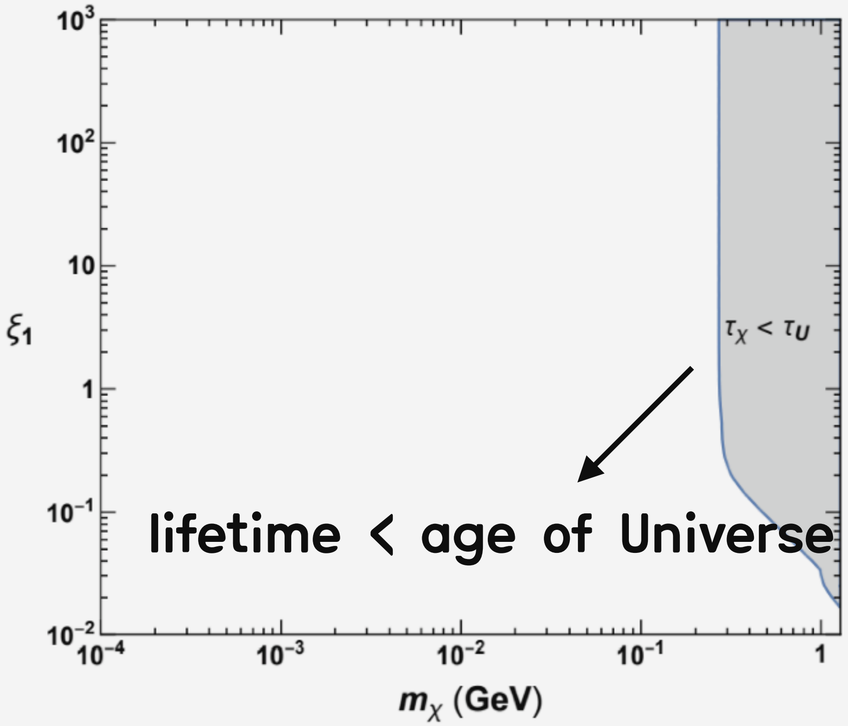
light inflaton decay $m_\chi < m_c$

WW threshold



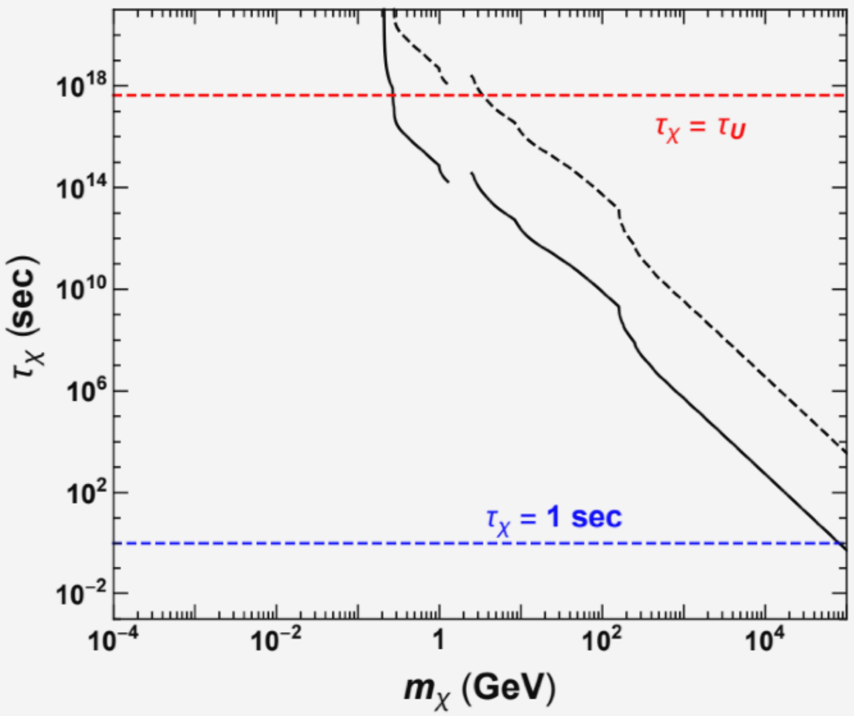
Heavy inflaton decay $m_\chi > 2.5\text{GeV}$

Inflaton as dark matter



lifetime < age of Universe

ξ_1=100(Solid), 0.01(Dashed)



If inflaton = dark matter

light dark matter: $m_\chi < 2m_\pi = 270$ MeV

Thermal freeze-out $\langle \sigma v \rangle \approx \left(\frac{\alpha_{\mathrm{eff}}}{5 \times 10{-6}}\right)^2 \left(\frac{100 \text{ MeV}}{m_\chi}\right)^2$

requires enough $\lambda_{\chi H} \propto \frac{1}{\xi_1^2} \ll 1$

non-thermal production is needed

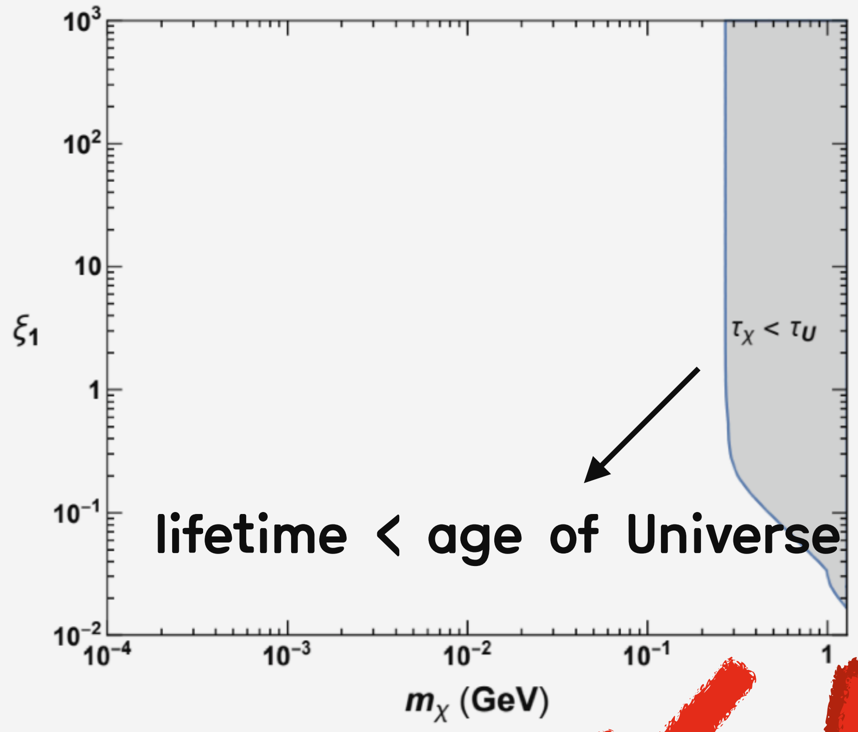
If inflaton ≠ dark matter

1) WIMP requires enough T_{RH}

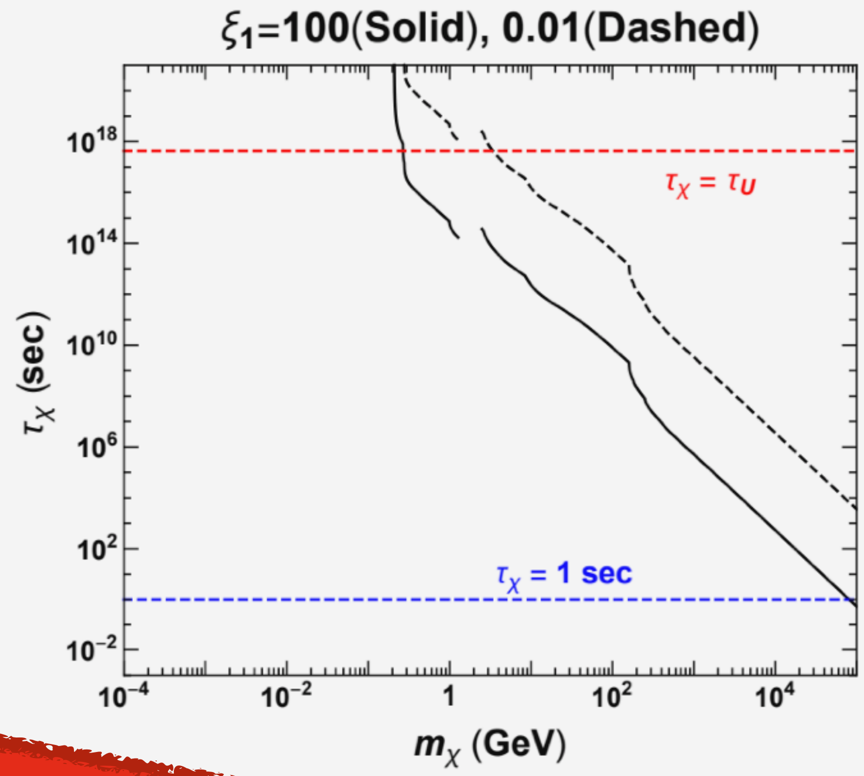
$$T_{\mathrm{RH}} \approx (4.4 \times 10^6 \text{ GeV})\left(\frac{\lambda_{\chi H}}{10^{-8}}\right)$$

2) inflaton decays to dark matter

Inflaton as dark matter



lifetime < age of Universe



minimal possibility of dark matter!

If inflaton = dark matter

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→ non-thermal production is needed

dark matter

1) WIMP requires enough $T_{\rm RH}$

$$T_{\rm RH} \approx (4.4\times10^6\ {\rm GeV})\left(\frac{\lambda_{\chi H}}{10^{-8}}\right)$$

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Dark matter production

through non-thermal production!

Dark matter relic abundance : $\Omega_\chi h^2 = \underbrace{(\Omega_\chi h^2)_{\rm FIMP}}_{1.} + \underbrace{(\Omega_\chi h^2)_{\rm RH}}_{2.}$

1. By Higgs decay at temp. $T \gtrsim m_h$ $\longrightarrow$ $\dot{n}_\chi + 3Hn_\chi = 2\left(\Gamma_{h\to\chi\chi}\, n_h^{\rm eq} - \Gamma_{\chi\chi\to h}\, n_\chi^2\right)$

$$(\Omega_\chi h^2)_{\rm FIMP} = 0.12 \left(\frac{100}{g_*(m_h)}\right)^{3/2} \left(\frac{\lambda_{\chi H}}{4.4\times 10^{-7}}\right)^2 \left(\frac{m_\chi}{1\,{\rm eV}}\right)$$

2. By inflaton condensate decay during reheating $\longrightarrow$ $(\Omega_\chi h^2)_{\rm RH} = \frac{\rho_\chi(a_{\rm eq})}{\rho_c/h^2}\left(\frac{a_{\rm eq}}{a_0}\right)^3$

$$\rho_\chi(a_{\rm eq}) = (6.75\times 10^{-38}\ {\rm GeV}^4)\lambda_\chi^{-1/4}\cdot {\rm BR}\cdot\left(\frac{m_\chi}{1\ {\rm eV}}\right) \quad \& \quad \boxed{{\rm BR} = \frac{\Gamma_{\chi_c\to\chi\chi}}{\Gamma_{\chi_c\to\chi\chi}+\Gamma_{\chi_c\to hh}}} = \frac{11.5\lambda_\chi^2}{11.5\lambda_\chi^2+\lambda_{\chi H}^2}$$

$$(\Omega_\chi h^2)_{\rm RH} = 0.12\left(\frac{1.4\times 10^{-8}}{\boxed{\lambda_{\chi H}}}\right)^2 R^{-7}\left(\frac{r}{0.01}\right)^{7/4}\left(\frac{m_\chi}{1\,{\rm eV}}\right)$$

$R = \xi_1/\sqrt{\xi_2}$, r : tensor to scalar ratio

Dark radiation

In the case with $T_{\rm NR} < T_{\rm BBN}$, dark matter is still relativistic during BBN

→ contribute to $\Delta N_{\rm eff}$

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right) g_* \cdot \frac{\rho_\chi(a_{\rm eq})}{\rho_R(a_{\rm eq})} \cdot \left(\frac{a_{\rm NR}}{a_{\rm eq}}\right)$$

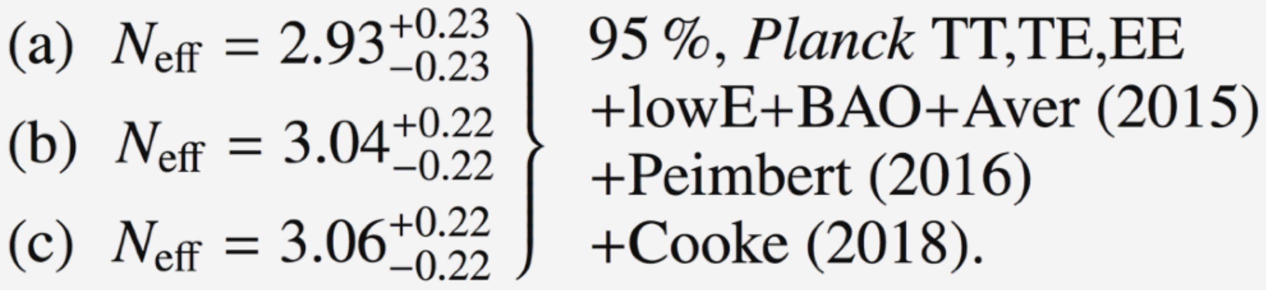
$$\leq 0.0944 R^{-1} \left(\frac{r}{0.01}\right)^{1/4} \left(\frac{1\ {\rm eV}}{m_\chi}\right)$$

$R = \xi_1/\sqrt{\xi_2}$

r : tensor to scalar ratio

Consistent with (c) within 2σ, $m_\chi \gtrsim 0.208\ (0.139)\ {\rm eV}$ for $R = 1\ (1.5)$ and $r = 0.01$

Planck 2018



$$\left.\begin{array}{ll} \text{(a)} & N_{\rm eff} = 2.93^{+0.23}_{-0.23} \\ \text{(b)} & N_{\rm eff} = 3.04^{+0.22}_{-0.22} \\ \text{(c)} & N_{\rm eff} = 3.06^{+0.22}_{-0.22} \end{array}\right\}$$

95 %, *Planck* TT,TE,EE
+lowE+BAO+Aver (2015)
+Peimbert (2016)
+Cooke (2018).

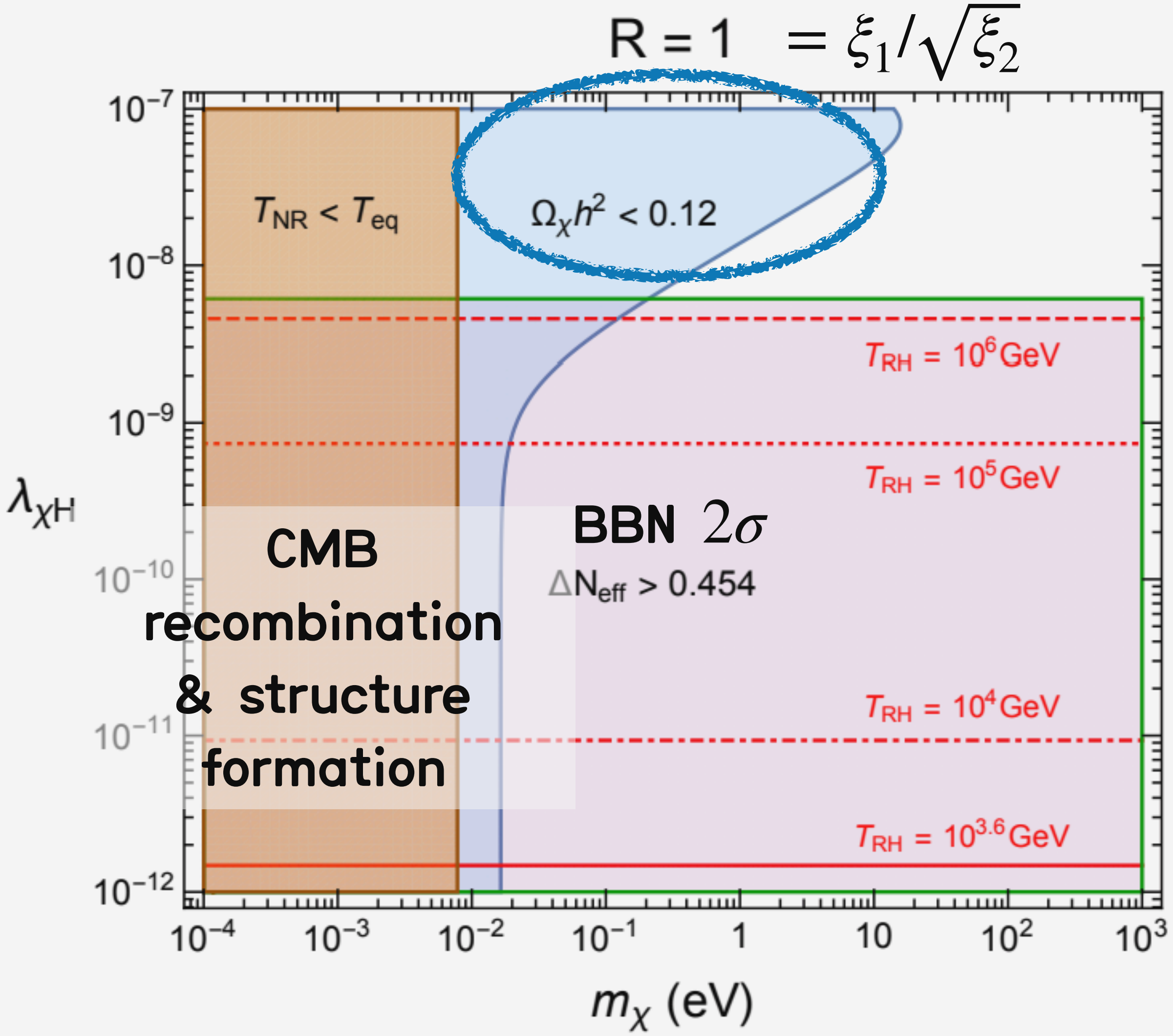
depending on deuterium fraction

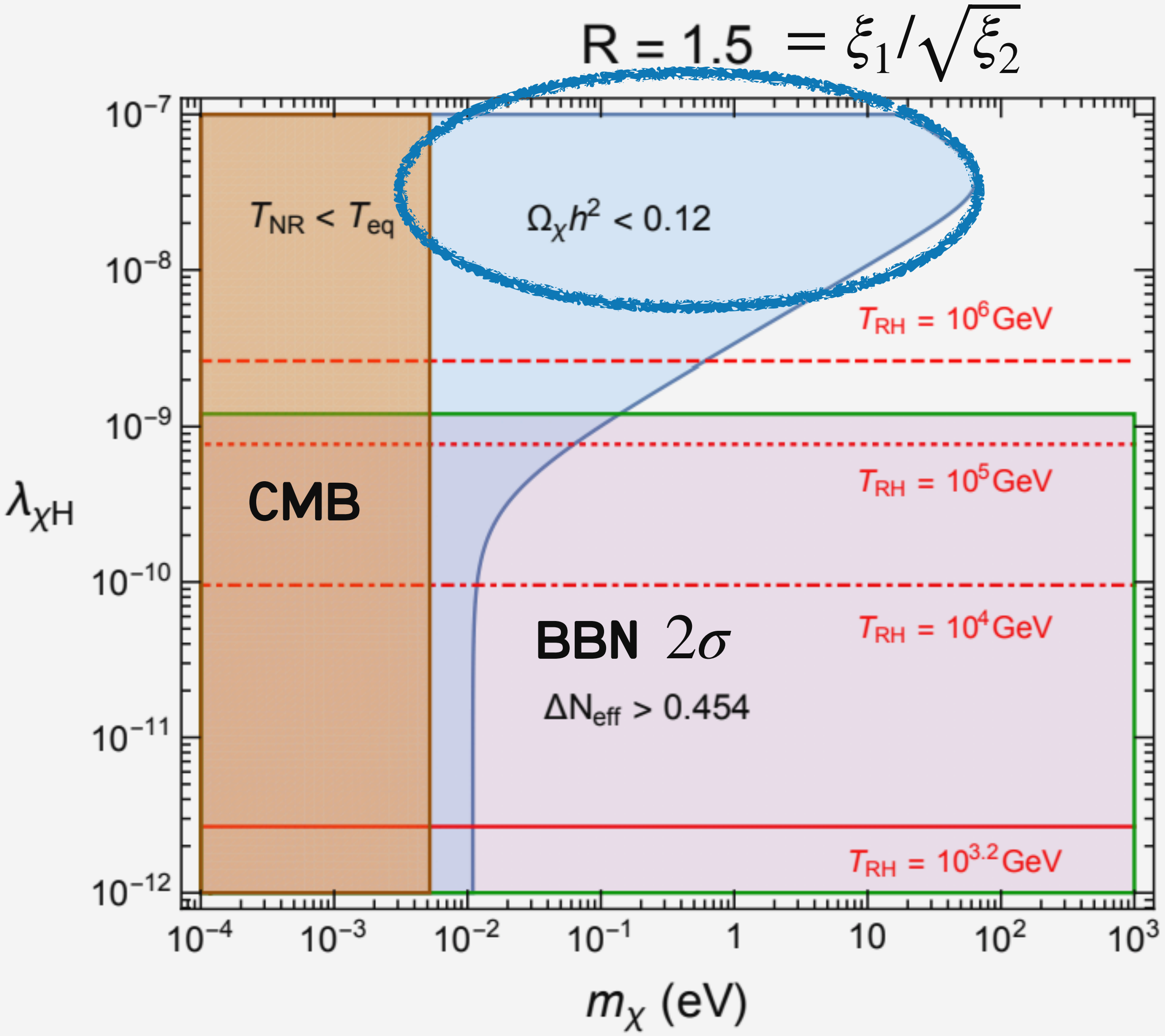
*Comments : If inflaton ≠ dark matter, lighter inflaton can be dark radiation

→ related to H_0 tension

[A. G. Riess et al (2019)] – 4.4 σ,
[K. C. Wong et al (2019)] – 5.3 σ, eariler papers w/ less σ
[M. Schmaltz et al (2015)]

Dark matter relic density





$$0.1 \text{ eV} \lesssim m_\chi \lesssim 100 \text{ eV}$$

Conclusion

Soo-Min Choi's talk

- Inflation model with linear & quadratic non-minimal coupling of sigma field
- Solve the unitarity problem through linear non-minimal coupling with large quadratic non-minimal coupling
- Inflaton = dark matter by non-thermal production (FIMP + Reheating)
- $m_{\rm DM}$ = 0.1 - 100 eV for BBN & CMB
- Higgs invisible decay, CMB, XENON10 → consistent enough.
  (CMB for γ-ray : constraints $m_\chi = 2$ MeV ~)