Unitary inflaton as dark matter and radiation

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Based on: HML, Phys. Rev. D78, 015020 (2018);
S. Choi, Y. Kang, HML, K. Yamashita, arXiv: 1902.03781[hep-ph].

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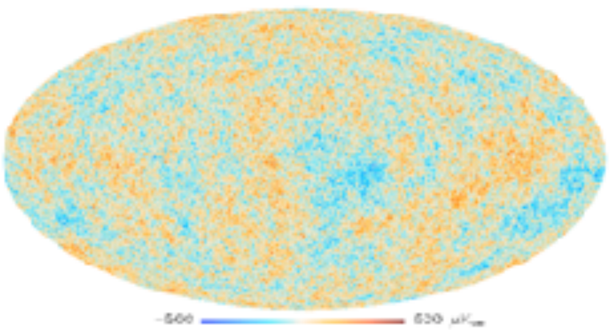
Outline

- Higgs inflation and beyond
- General sigma inflation
- Inflaton as dark matter
- Conclusions

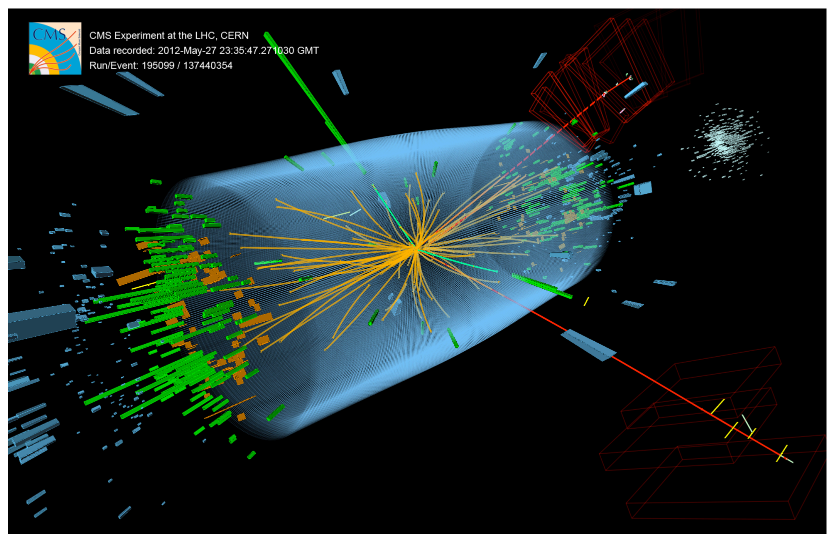
Particle physics in cosmology



Cosmic Microwave Background

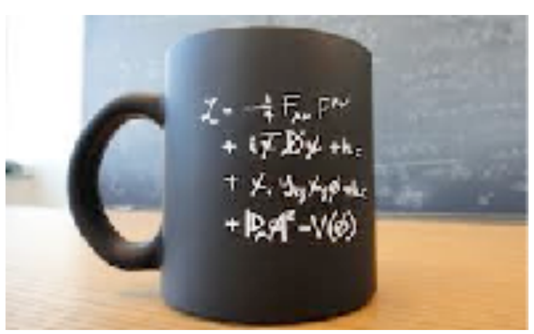
"Slow-roll inflation"

$m_I \ll H$

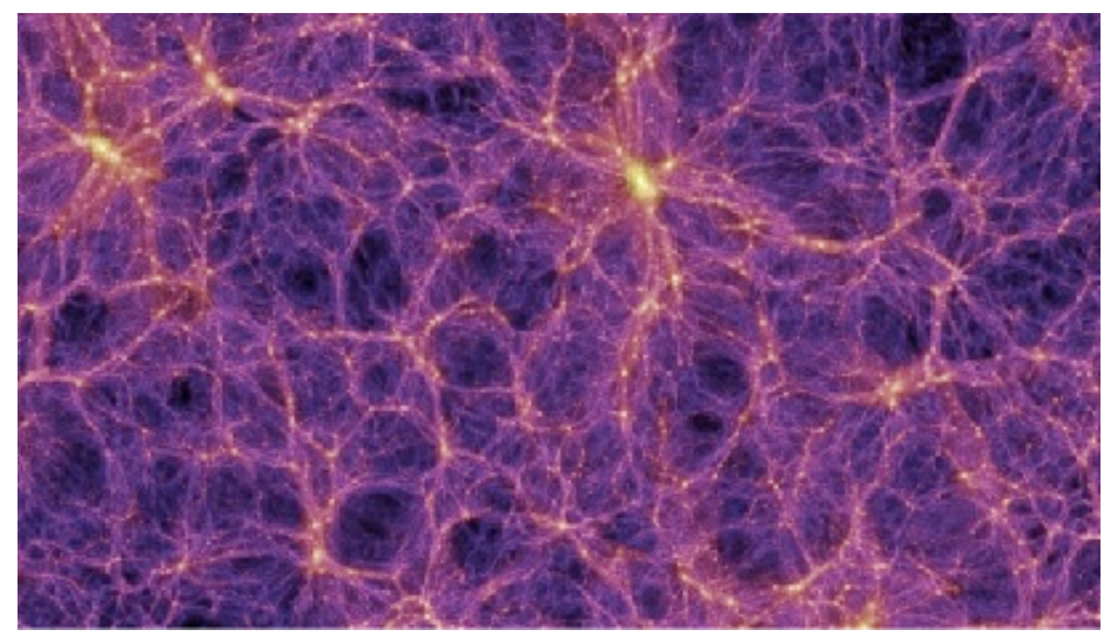


Mass generation

"Higgs boson" $m_H \ll M_P$



$?$

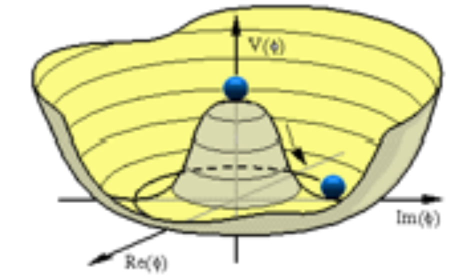


What are the origins of inflation, symmetry breaking, and dark matter?

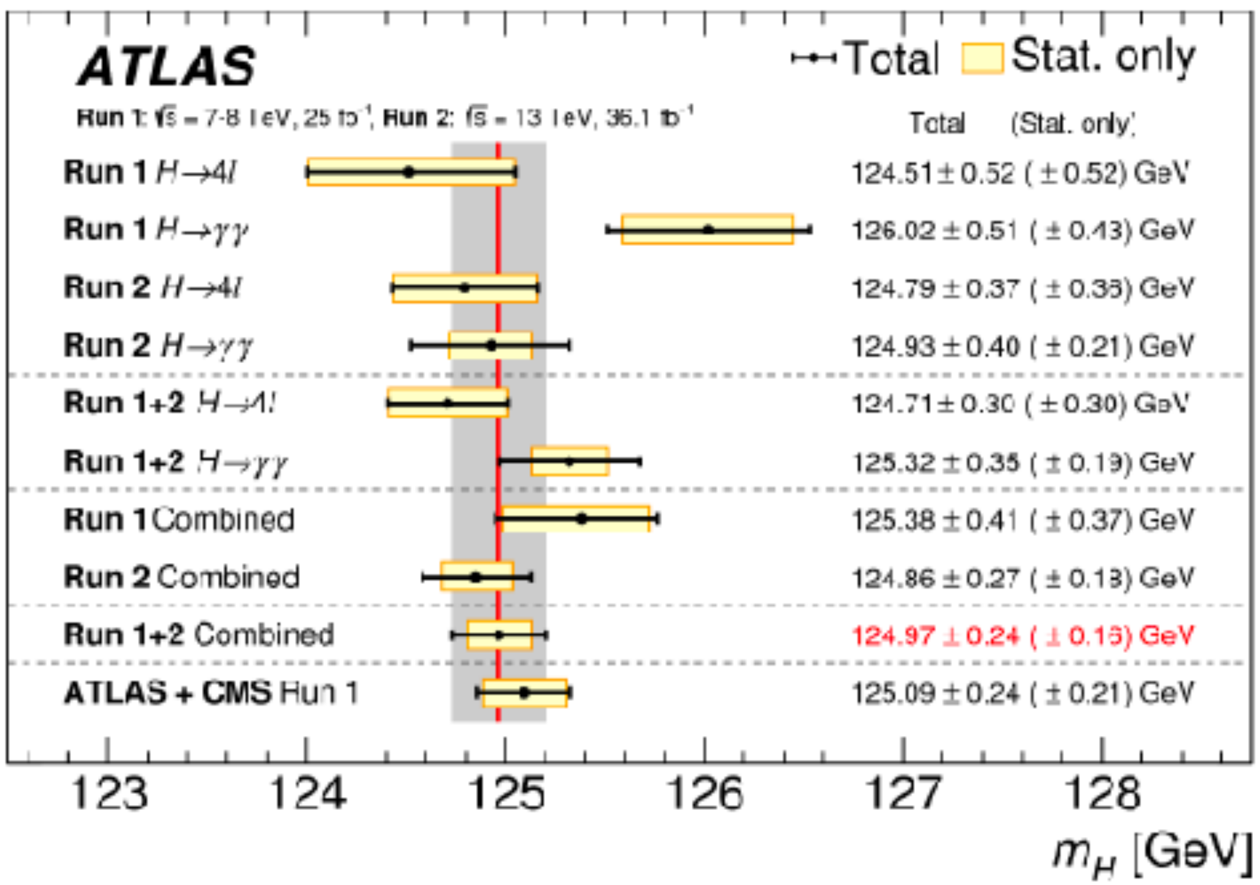
Large-scale structure

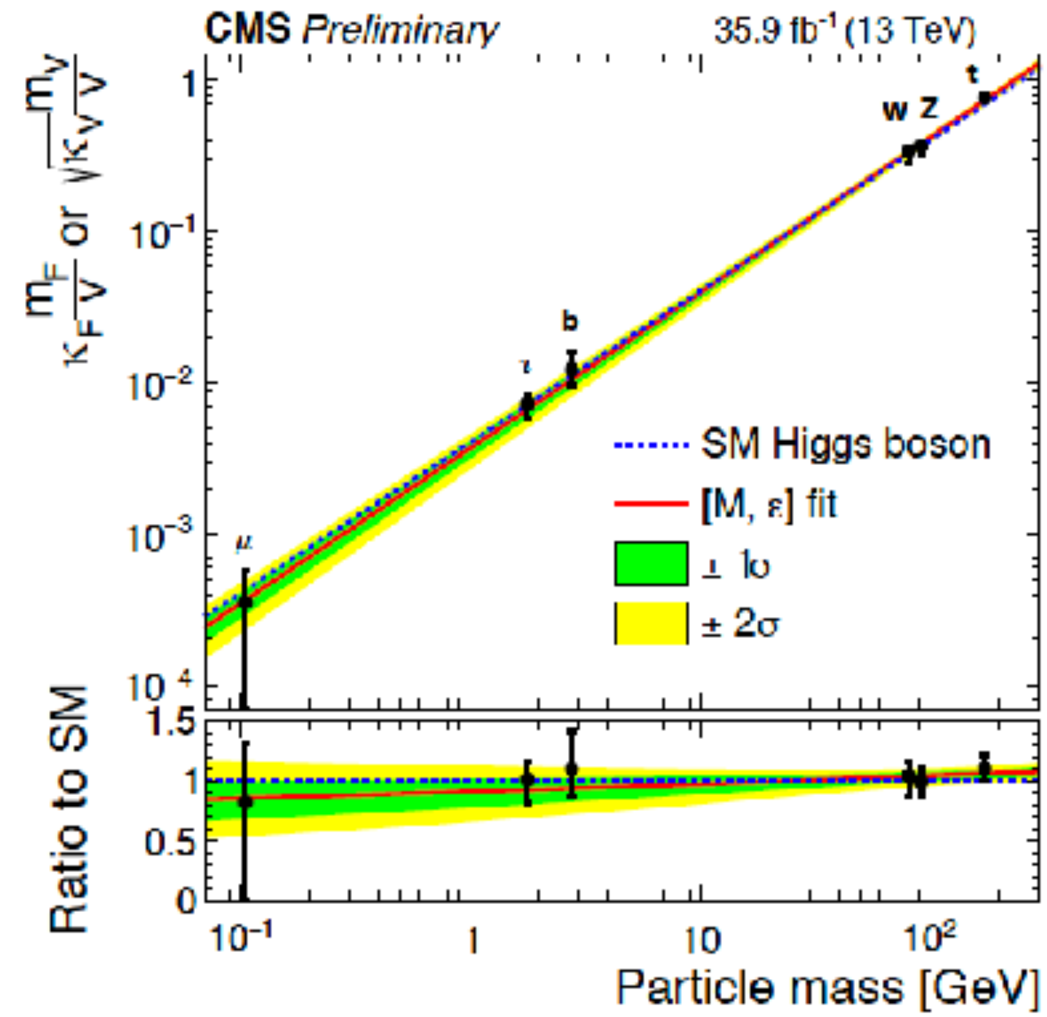
"Dark matter" $\tau_X > 10^{16}\,\mathrm{sec}$

Higgs boson at LHC



- 125GeV Higgs boson is (close to) a fundamental scalar particle, consistent with Higgs couplings predicted in SM.





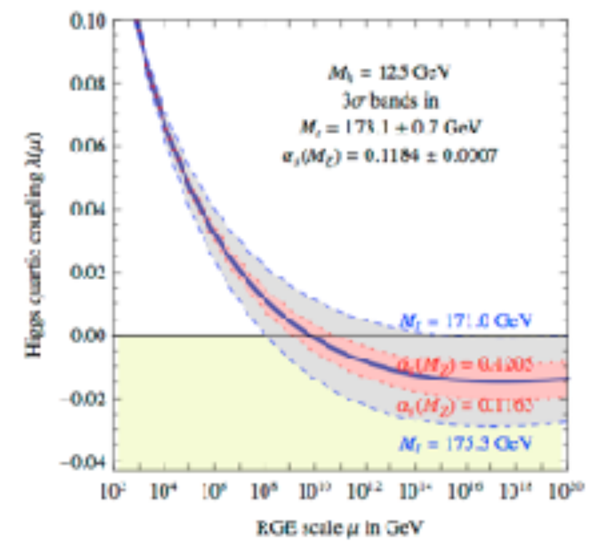
- Higgs precision is important at HL-LHC and future colliders.
- Is Higgs boson the last piece of the puzzles?

July 5, 2012 | World News | RayKrebs

Higgs Boson May Be Key to Understanding Dark Matter & New Physics?

Discovered Higgs boson has a key to open the door to new symmetries and interactions beyond the SM.

Knocking on Higgs's door

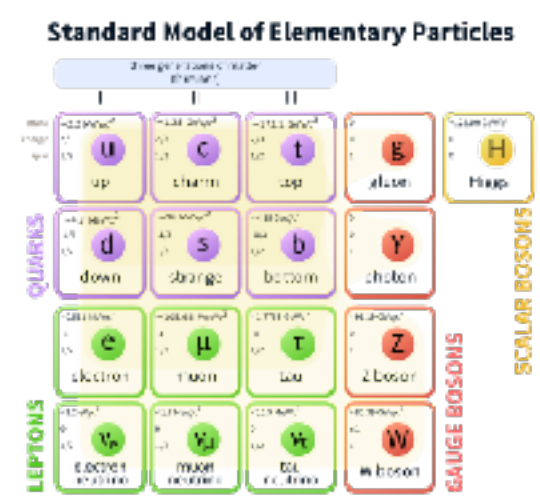


✔ Hierarchy problem, vacuum instability

$$V = m_H^2 |H|^2 + \lambda |H|^4$$

$$m_H^2 = m_{H,0}^2 - \frac{\kappa^2}{16\pi^2} M_{\text{heavy}}^2 \sim (100\,\text{GeV})^2, \;\; \lambda_H > 0$$

✔ Electroweak symmetry breaking $m_H^2 < 0?$

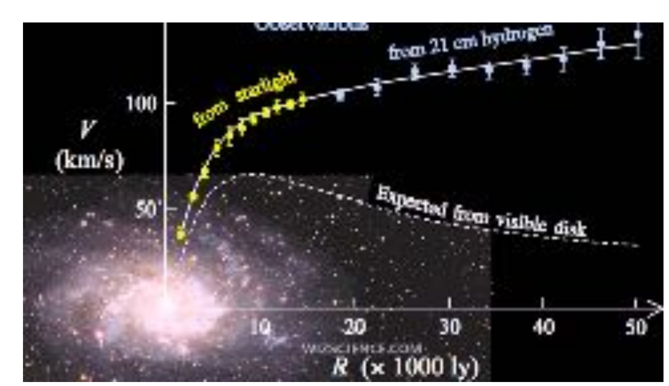


✔ Flavor puzzles, baryogenesis

$$H_1 Q_i U_j^c + H_2 Q_i D_j^c + \cdots$$ More Higgs?

✔ Dark matter

$$\lambda_{HS} |H|^2 S^2$$ WIMP, FIMP, SIMP, …

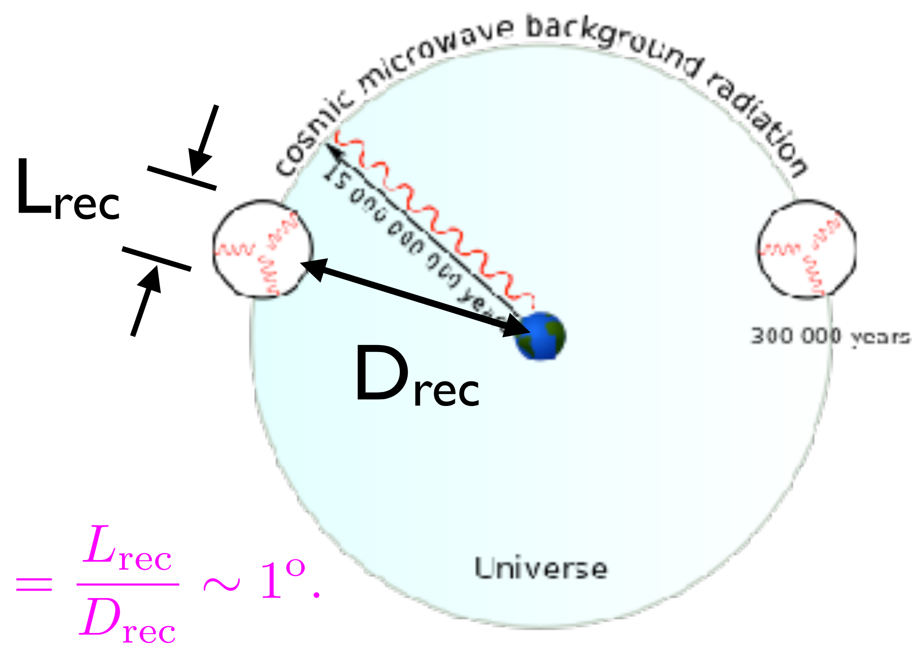


✔ Inflation

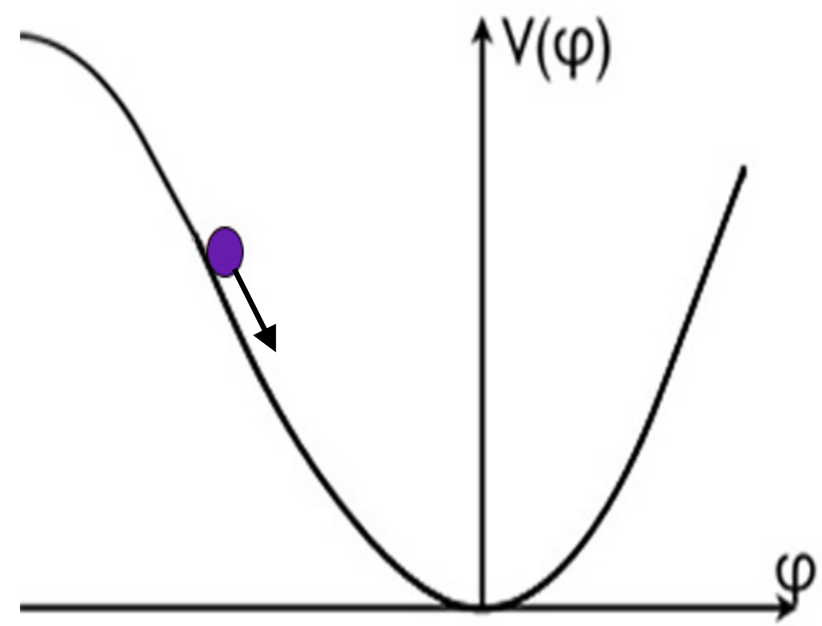
$$\xi |H|^2 \mathcal{R}$$ Higgs inflation?

Cosmic inflation

- Exponential expansion with a scalar field “inflaton” explains the initial conditions for Big Bang Cosmology.



$\theta = \frac{L_{\rm rec}}{D_{\rm rec}} \sim 1^{\rm o}.$



$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

Causally connected
at recombination

Number of efoldings:

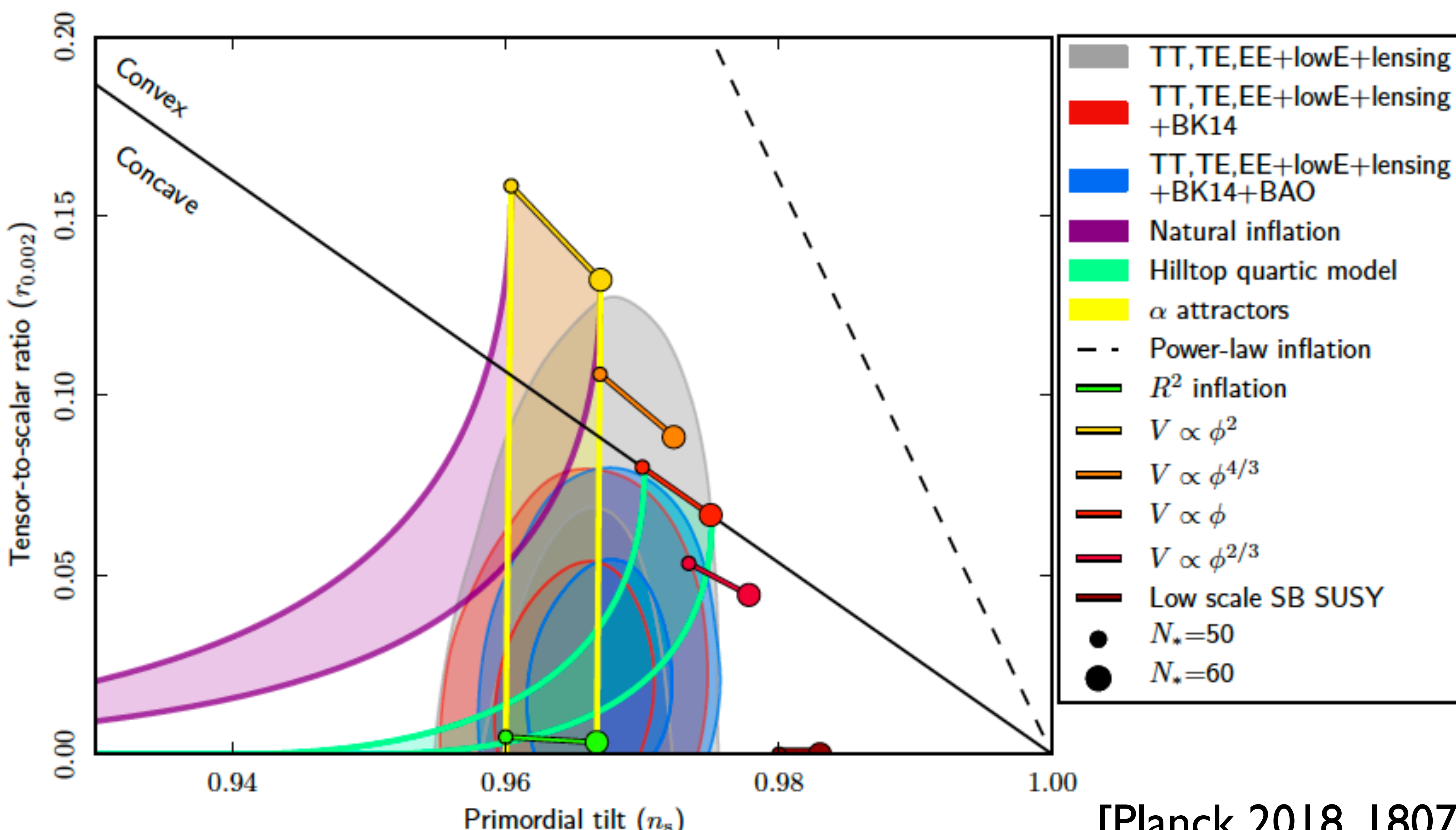
How uniform CMB 1 in 10^4 ?

$$N = \int_{t_i}^{t_f} H dt = 60$$

- Slow-roll inflation is confirmed by CMB anisotropies.

$$n_s = 1 - 6\epsilon + 2\eta, \quad r = 16\epsilon, \quad \epsilon \sim \frac{(V')^2}{V^2} \ll 1, \quad \eta \sim \frac{V''}{V} \ll 1.$$

Planck data

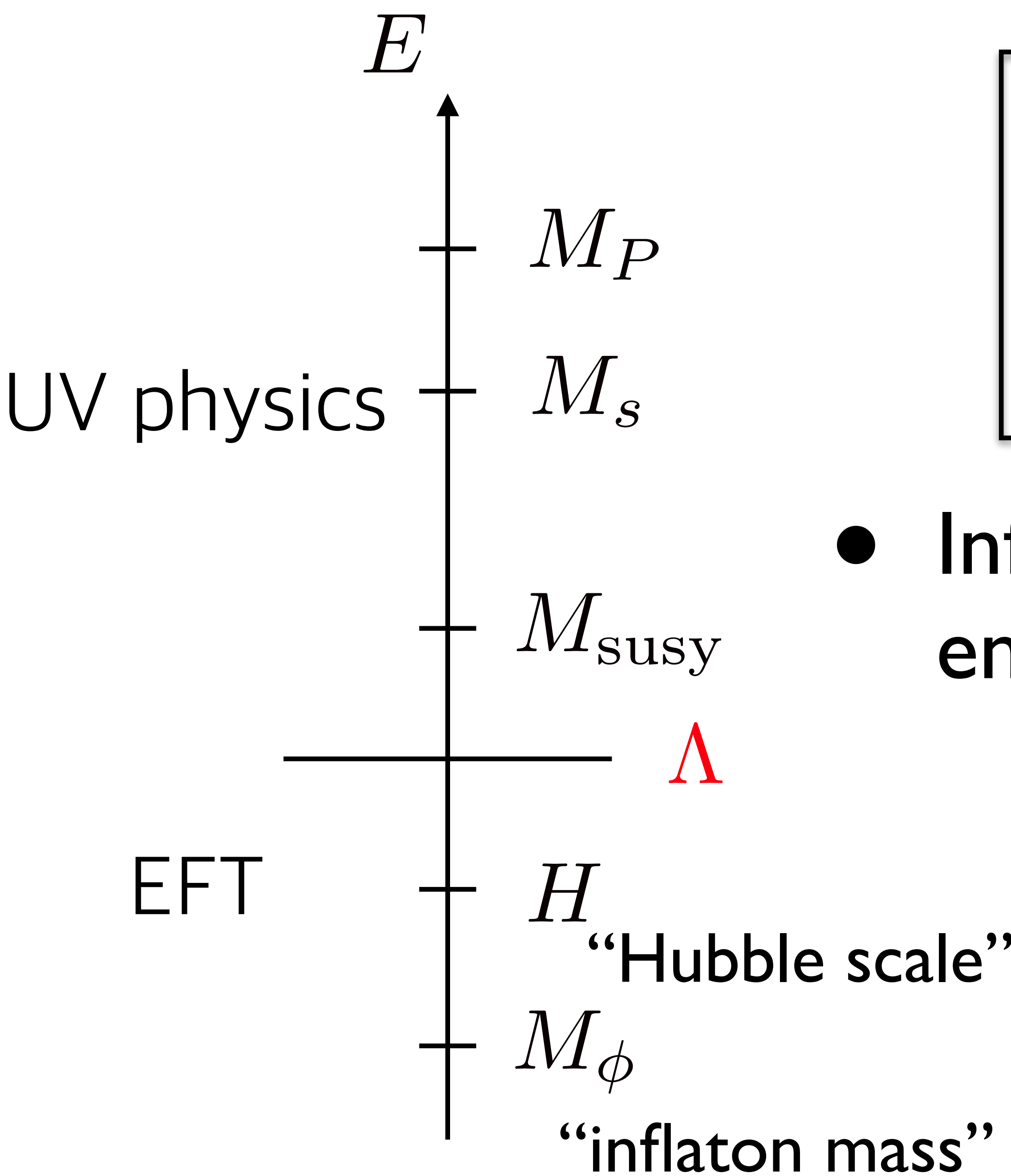


[Planck 2018, 180706211]

$n_s = 0.9659 \pm 0.0041$ $\quad$ $r_{0.002} < 0.10$ (95 % CL, *Planck* TT+lowE+lensing)

$n_s = 0.9653 \pm 0.0041$ $\quad$ $r_{0.002} < 0.064$ (95 % CL, *Planck* TT,TE,EE +lowE+lensing+BK14) .

Inflation as EFT



$$\epsilon \sim \frac{(V')^2}{V^2} \ll 1, \quad \eta \sim \frac{V''}{V} \ll 1.$$

$\Rightarrow$ $$M_\phi \ll H \sim \sqrt{V} \ll \Lambda$$

- Inflation is Effective field theory valid at energies much below UV cutoff.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{3}B\phi^3 - \frac{1}{4}\lambda\phi^4$$

$$-\sum_{n=1}^{\infty} \frac{c_n \phi^{n+4}}{\Lambda^n}.$$

- What controls UV physics (or unitarity) for entire range of inflaton fields?

Questions

- What is inflaton?

  axion, dilaton, moduli, wilson-line, Higgs boson, ….

- How is inflaton potential flat enough?

  shift, scale, supersymmetry, gauge, ….

- How does it interact with the rest? ⇒ Reheating

  effects on CMB? distinguishable?
  testable at colliders? dark matter? baryogengesis?

- In this talk, we consider the possibility of Higgs inflation, its UV completion and implications.

Higgs = inflaton?

- Minimally coupled Higgs boson:

$$\mathcal{L} = \sqrt{-g}\Big(\frac{1}{2}\mathcal{R} - |D_\mu H|^2 - \lambda_H |H|^4 - m_H^2 |H|^2 - V_0\Big)$$

$\lambda_H |H|^4$ inflation: $\lambda_H \sim 10^{-12}$

$m_H^2 |H|^2$ inflation: $m_H^2 \sim (10^{13}\,\mathrm{GeV})^2$

But, $m_h = \sqrt{2\lambda_H}\, v = 125\,\mathrm{GeV}$ ⇨ $\lambda_H = 0.13$

$$v = \sqrt{-\frac{m_H^2}{\lambda_H}} = 246\,\mathrm{GeV}$$ ⇨ $m_H^2 = -(98\,\mathrm{GeV})^2$

cf. inflection point: small running quartic coupling.

$$\lambda_H(h) = \lambda(\mu_c) + \frac{g_{\rm SM}^4}{(16\pi^2)^2}\ln\Big(\frac{h}{\mu_c}\Big), \quad \lambda(\mu_c) \ll 1, \quad \mu_c \sim M_P.$$

⇨ Too small number of efoldings.

Higgs inflation

[Bezrukov, Shaposhnikov (2007)]

- Add a non-minimal coupling for Higgs boson to the SM.

$$\mathcal{L} = \sqrt{-g}\Big(\frac{1}{2}\mathcal{R} + \boxed{\xi|H|^2\mathcal{R}} - |D_\mu H|^2 - \lambda_H(|H|^2 - v^2/2)^2\Big)$$

$$\Rightarrow \quad \mathcal{L}_E = \sqrt{-g_E}\Big(\frac{1}{2}\mathcal{R}(g_E) - \underline{\frac{3\xi^2}{\Omega^2}(\partial_\mu|H|^2)^2 - \frac{1}{\Omega}|D_\mu H|^2} - \frac{V}{\Omega^2}\Big)$$

$$g_{\mu\nu} = \Omega^{-1} g_{E,\mu\nu}, \quad \Omega = 1 + 2\xi|H|^2$$

Non-canonical kinetic terms

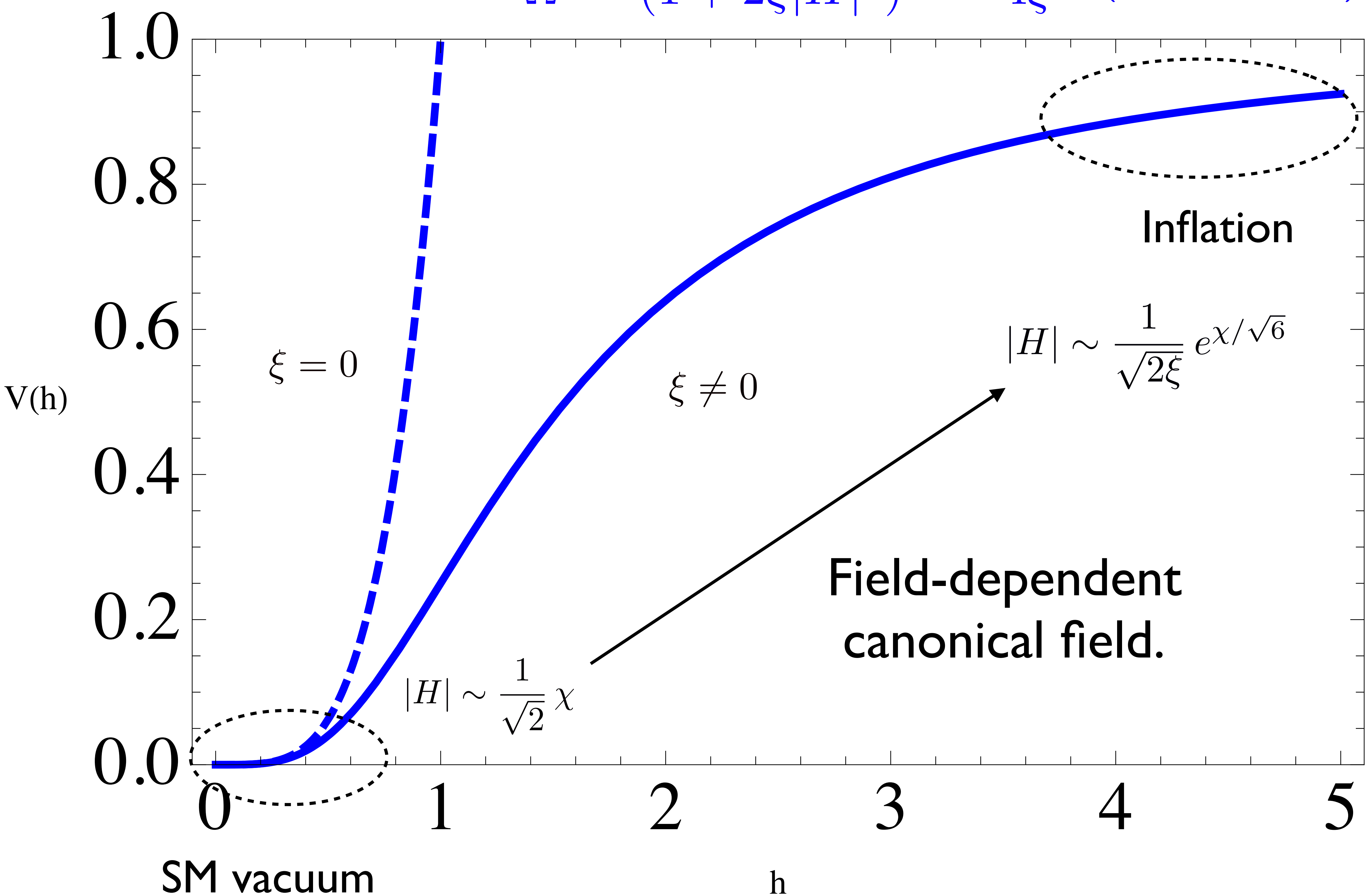
Higgs boson can drive cosmic inflation, with definite predictions.

✓ $\frac{\Delta T}{T} \sim 10^{-4} \Rightarrow \frac{\sqrt{\lambda_H}}{\xi} = 2\times 10^{-5}$ "Large non-minimal coupling"

✓ $n_s = 1 - \frac{2}{N} = 0.966, \quad r = \frac{12}{N^2} = 0.0033$ "Consistent with Planck data"

Higgs potential

$$\frac{V}{\Omega} = \frac{\lambda_H |H|^4}{(1+2\xi|H|^2)^2} \sim \frac{\lambda_H}{4\xi^2}\left(1 - e^{-\frac{2}{\sqrt{6}}\chi}\right)$$



Power counting for EFT

[Burgess, HML, Trott (2009)]

- Truncate the effective action in scalar-tensor gravity.

$$-\frac{\mathcal{L}_{\rm eff}}{\sqrt{-g}} = v^4 V(\theta) + \frac{M_p^2}{2} g^{\mu\nu}\Big[W(\theta)\, R_{\mu\nu} + G_{ij}(\theta)\,\partial_\mu\theta^i\partial_\nu\theta^j\Big]$$
$$+A(\theta)(\partial\theta)^4 + B(\theta)\,R^2 + C(\theta)\,R\,(\partial\theta)^2 + \frac{E(\theta)}{M^2}\,(\partial\theta)^6 + \frac{F(\theta)}{M^2}\,R^3 + \cdots .$$

- Identify interactions from field expansions in EFT.

$$\theta^i(x) = \vartheta^i(x) + \frac{\phi^i(x)}{M_p} \quad \text{and} \quad g_{\mu\nu}(x) = \hat{g}_{\mu\nu}(x) + \frac{h_{\mu\nu}(x)}{M_p}$$

- Validity of semi-classical approximation: $\dot{h}/h,\ H \ll M$

cutoff

$$\text{Quantum action}:\ \Gamma = \int d^4x \mathcal{L}_{\rm eff}(\text{background}) + \hbar\Delta\Gamma,$$

"power counting" in EFT : $\Delta\Gamma \ll \Gamma$

⇒ Effective interactions are constrained.

Trouble with large coupling

[Han, Willenbrock (2004); Burgess, HML, Trott (2009,2010); Barbon, Espinosa (2009); Hertzberg (2010)]

- Effective Higgs interactions

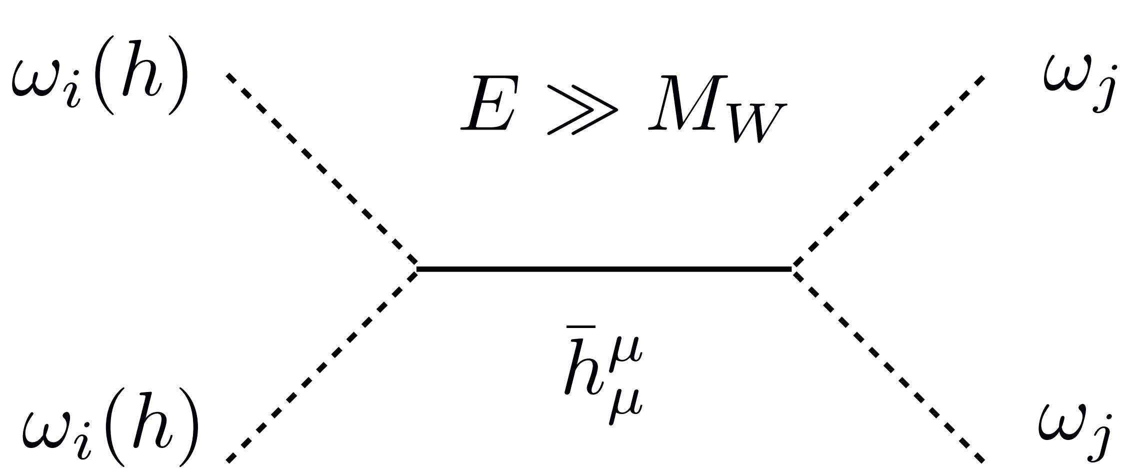
$$H=\frac{1}{\sqrt{2}}\begin{pmatrix} -\omega_2(x)-i\omega_1(x) \\ \varphi(x)+h(x)+i\omega_3(x)\end{pmatrix}, \quad g_{\mu\nu}(x)=\hat{g}_{\mu\nu}(x)+\frac{h_{\mu\nu}(x)}{M_P}.$$

$$\Rightarrow \quad \mathcal{L}_{\rm int}=\frac{1}{4}\left(\omega_1^2+\omega_2^2+\omega_3^2+(\varphi+h)^2\right)\boxed{\frac{\xi}{\Lambda}}\left(\Box\bar{h}^\mu_\mu+2\partial^\alpha\partial^\beta\bar{h}_{\alpha\beta}+\cdots\right).$$

cf. Einstein frame:

$$\mathcal{L}_{\rm eff}=\frac{2\xi}{M_P^2}|H|^2|D_\mu H|^2-\boxed{\frac{3\xi^2}{M_P^2}}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)+\frac{4\lambda_H\xi}{M_P^2}|H|^6+\cdots$$

- Perturbative unitarity is violated at small scales.



$$\mathcal{M}_{\omega_i\omega_i\to\omega_j\omega_j}\sim\frac{\xi^2E^2}{M_P^2},$$

Unitarity bound ~ Hubble scale,

$$E\lesssim\frac{M_P}{\xi} \quad \text{vs} \quad H_{\rm inf}\sim\frac{\sqrt{\lambda_H}M_P}{\xi}.$$

Saving Higgs inflation

[Giudice, HML (2010)]

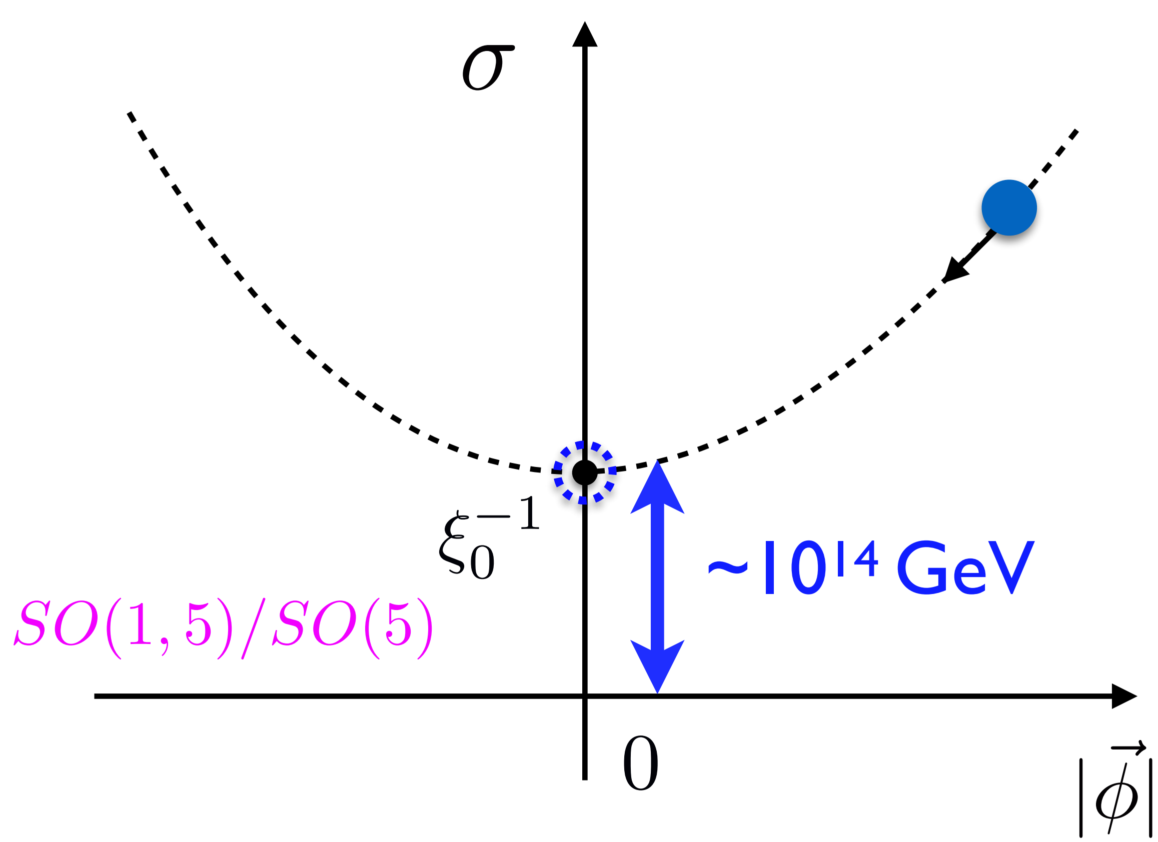
"Induced gravity" $\mathcal{L}_J = \sqrt{-g}\left[\xi_0\sigma^2\mathcal{R} - \frac{1}{2}(\partial_\mu\sigma)^2 - \lambda\left(\sigma^2 - \vec{\phi}^2 - \xi_0^{-1}\right)^2\right]$

$\int D\psi\, e^{iS(g,\psi)} = e^{i\int d^4x\sqrt{-g}(M_P^2\mathcal{R}+\cdots)}$ [Zee, Smolin (1979)]

Integrate out "sigma field": $\mathcal{L}_{\rm eff} = \sqrt{-g}(1+\xi_0\vec{\phi}^2)\mathcal{R}$

~Higgs inflation as EFT.

Full theory: Higgs moves in hyperbolic space!



The same predictions as in Higgs inflation.

Physical sigma mass is tied up to inflation scale.

$m_\sigma^2 = 4\lambda H^2 \sim (10^{13}\,{\rm GeV})^2$

Scalars dual to Starobinsky

- Starobinsky R^2 model is dual to a scalar-tensor theory.

[Starobinsky (1984); Giudice, HML (2014)]

$$\mathcal{L}=\sqrt{-g}\left(\frac{R}{2}+\xi^2R^2\right) \Longleftrightarrow \mathcal{L}=\sqrt{-g}\left(\frac{R}{2}+\frac{1}{2}\xi\sigma^2R-\frac{1}{16}\sigma^4\right)$$

Hubbard-Stratonovich transf.

- Starobinsky model as a UV completion?

[Y. Ema (2017); Gorbunov, Tokareva (2018)]

$$\mathcal{L}=\sqrt{-g}\left(\frac{1}{2}(1+\xi_H h^2+\underline{\xi\sigma^2})R-\frac{1}{2}(\partial_\mu h)^2-\underline{\frac{1}{16}}\sigma^4-V(h)\right)$$

$$\Rightarrow \mathcal{L}=\sqrt{-g}\left(\frac{1}{2}\xi\hat{\sigma}^2R-\frac{1}{2}(\partial_\mu h)^2-\frac{1}{16}\left(\hat{\sigma}^2-\frac{\xi_H}{\xi}h^2-\frac{1}{\xi}\right)^2-V(h)\right)$$

$\xi\hat{\sigma}^2=1+\xi_H h^2+\xi\sigma^2$: Equivalent to a sigma-field model.

Higher curvature terms such as R^3 would spoil unless suppressed.

[Giudice, HML, unpublished]

General sigma inflation

General sigma inflation

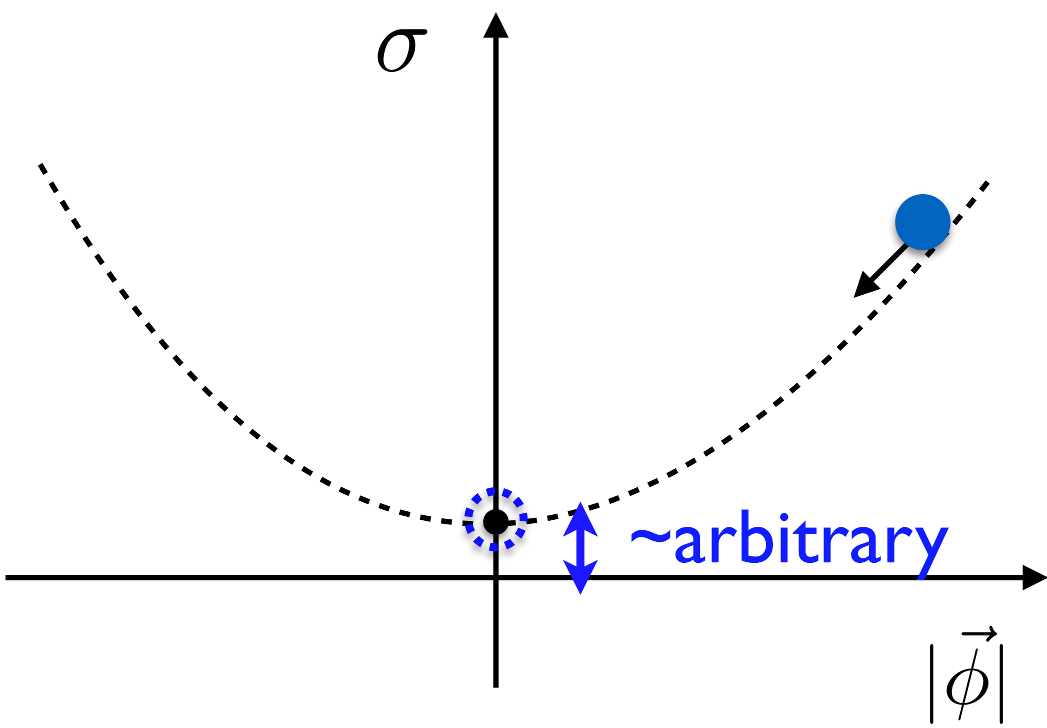
Introduce a linear non-minimal coupling in the sigma model.

$$\mathcal{L}_J = \sqrt{-g}\Big[-\frac{1}{2}\underbrace{(1+\xi_1\sigma+\xi_0\sigma^2)}_{=\Omega}\mathcal{R} + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}m_\sigma^2\sigma^2 - \lambda(\sigma^2-\vec{\phi}^2)^2 \Big]$$

[HML (2018)]

Stable gravity: $\xi_1^2 < 4\xi_0$

Unitarity up to Planck scale: $\xi_1 \sim \sqrt{\xi_0}$



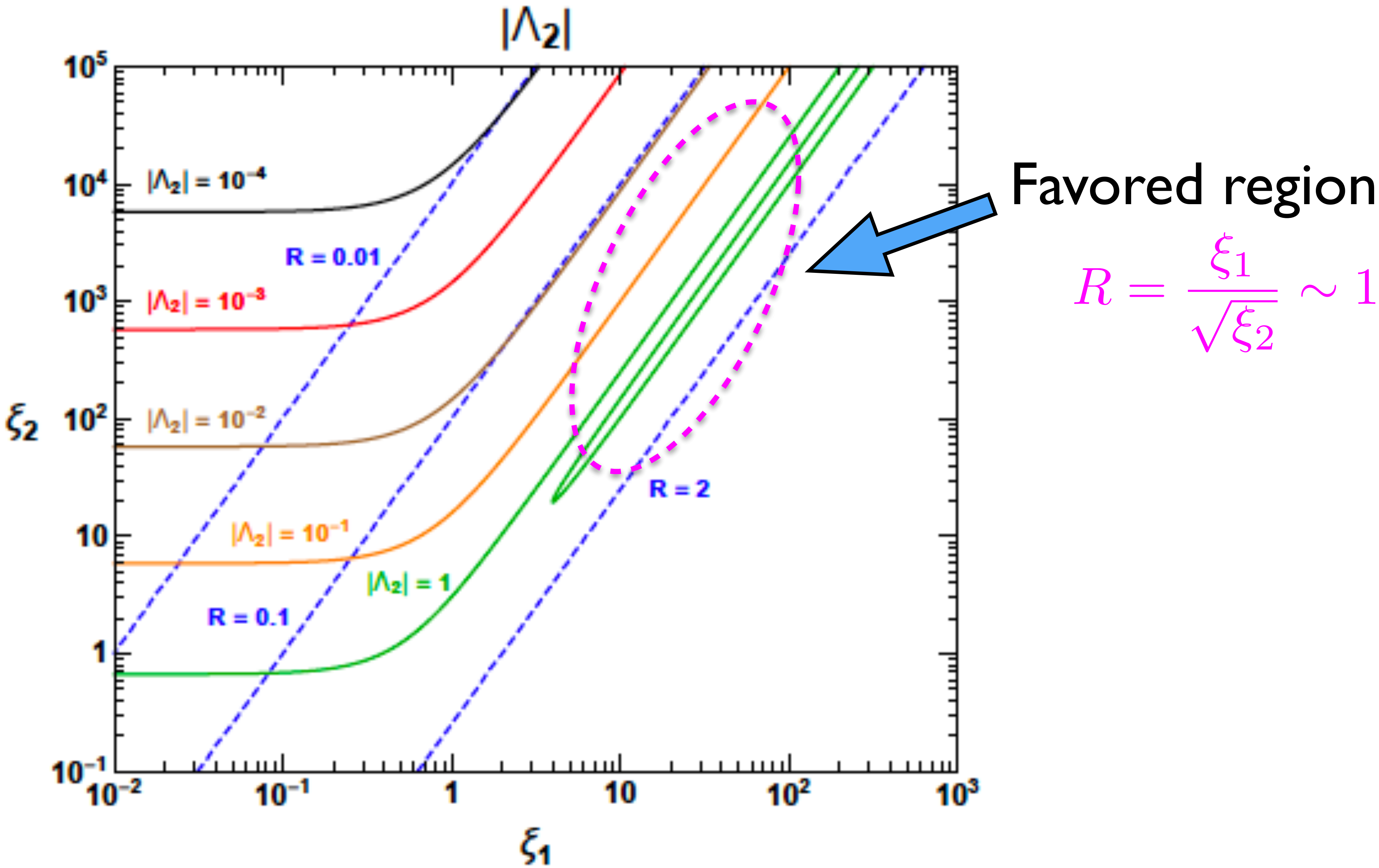
Large graviton mixing or kinetic term,

$$\mathcal{L}_J \supset -\frac{1}{2}\xi_1\sigma\delta\mathcal{R} = -\frac{1}{2}\xi_1\sigma\Box h + \cdots$$

$$\mathcal{L}_E \supset \frac{3}{4}\frac{\Omega'^2}{\Omega^2}(\partial_\mu\sigma)^2 = \frac{3}{4}\xi_1^2(\partial_\mu\sigma)^2 + \cdots$$

Suppressed interactions or large cutoff scale;
sigma mass can be arbitrarily small.

Λ_2 : Unitarity scale



Higgs EFT from sigma field

[HML (2018)]

Integrate out "sigma field" in general sigma models.

$$\mathcal{L}_J = \sqrt{-g}\left[(1+\xi_1\sigma+\xi_0\sigma^2)\mathcal{R} - \frac{1}{2}(\partial_\mu\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \lambda(\sigma^2 - a\vec{\phi}^2)^2\right]$$

$$\Rightarrow \quad \mathcal{L}_{\rm eff} = \sqrt{-g}\left[1+\xi_1\sqrt{a\vec{\phi}^2 - \frac{m_\sigma^2}{\lambda}} + a\xi_0\vec{\phi}^2\right]\mathcal{R}$$

$$\vec{\phi}^2 \gg |m_\sigma^2|/\lambda: \quad \mathcal{L}_{\rm eff} = \sqrt{-g}\left[1+\xi_1\sqrt{a\vec{\phi}^2} + a\xi_0\vec{\phi}^2\right]\mathcal{R}$$

Higgs inflation with non-analytic linear term.

$$\vec{\phi}^2 \ll |m_\sigma^2|/\lambda: \quad \mathcal{L}_{\rm eff} = \sqrt{-g}\left[(1+a\xi_0\vec{\phi}^2)\mathcal{R} - \lambda_{\rm eff}(\vec{\phi}^2)^2\right]$$

$\lambda_{\rm eff} = \lambda_\phi - a\lambda$: stabilize Higgs vacuum

"Higgs inflation in EFT"

Inflation dynamics

Take the most general Lagrangian for sigma field + Higgs:

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(1+\xi_1\sigma+\xi_2\sigma^2+\xi_H\phi^2)R+\frac{1}{2}(\partial_\mu\sigma)^2+\frac{1}{2}(\partial_\mu\phi)^2-V_J(\sigma,\phi),$$

$$V_J(\sigma,\phi)=\frac{1}{2}m_H^2\phi^2+\frac{1}{4}\lambda_H\phi^4+\frac{1}{2}m_\sigma^2\sigma^2-\mu\sigma\phi^2+\frac{1}{3}\alpha\sigma^3+\frac{1}{2}\lambda_{\sigma H}\sigma^2\phi^2+\frac{1}{4}\lambda_\sigma\sigma^4.$$

Two field dynamics for inflation: $\xi_1\sigma+\xi_2\sigma^2+\xi_H\phi^2 \gg 1$

$$\begin{aligned} e^{\frac{2}{\sqrt{6}}\chi} &= \xi_1\sigma+\xi_2\sigma^2+\xi_H\phi^2, \\ \tau &= \frac{\phi}{\sigma}. \end{aligned}$$

Scale-free limit:
mass terms irrelevant.

$$\Rightarrow \frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}R(g_E)+\frac{1}{2}(\partial_\mu\chi)^2+\frac{(\partial_\mu\tau)^2}{2\xi_2}-V_I(\tau)\left(1-2\hat{R}\,e^{-\frac{1}{\sqrt{6}}\chi}-2(1-\hat{R}^2)\,e^{-\frac{2}{\sqrt{6}}\chi}\right).$$

$$\hat{R}\equiv\frac{\xi_1}{(\xi_2+\xi_H\tau^2)^{1/2}}, \qquad V_I(\tau)\equiv\frac{\lambda_H\tau^4+\lambda_{\sigma H}\tau^2+\lambda_\sigma}{4(\xi_2+\xi_H\tau^2)^2}.$$

Inflation vacua

Stabilize tau field: $\xi_2 \gg \xi_H = \mathcal{O}(1)$ (no unitarity problem)

$$(1):\ \tau = \sqrt{-\frac{\lambda_{\sigma H}}{2\lambda_H}}\ :\ \lambda_H > 0\,,\ \lambda_{\sigma H} < 0\,, \qquad V_I = \frac{1}{4}\frac{\lambda_H\lambda_\sigma - \lambda_{\sigma H}^2/4}{\lambda_\sigma\xi_H^2 + \lambda_H\xi_2^2 - \lambda_{\sigma H}\xi_H\xi_2} \approx \boxed{\frac{1}{4\xi_2^2}\left(\lambda_\sigma - \frac{\lambda_{\sigma H}^2}{4\lambda_H}\right)},$$

$$(2):\ \tau = 0\ :\ \lambda_H > 0\,,\ \lambda_{\sigma H} > 0\,, \qquad V_I = \boxed{\frac{\lambda_\sigma}{4\xi_2^2}},$$

$$(3):\ \tau = \infty\ :\ \lambda_H < 0\,,\ \lambda_{\sigma H} < 0\,, \qquad V_I = \frac{\lambda_H}{4\xi_H^2},\ ✘$$

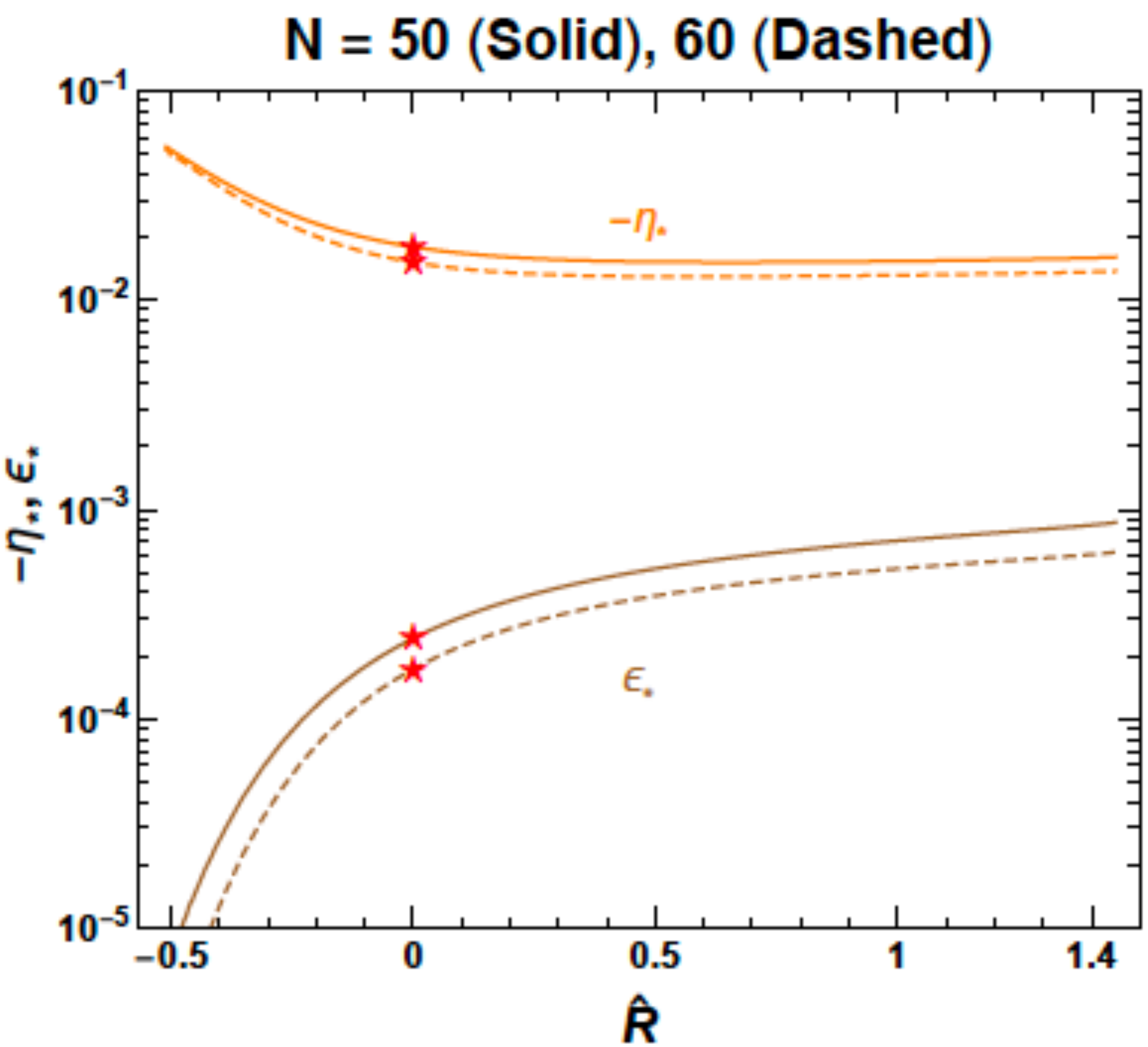
$$(4):\ \tau = 0, \infty\ :\ \lambda_H < 0\,,\ \lambda_{\sigma H} > 0 \qquad V_I = \boxed{\frac{\lambda_\sigma}{4\xi_2^2}} \ \text{or}\ \frac{\lambda_H}{4\xi_H^2},\ ✘$$

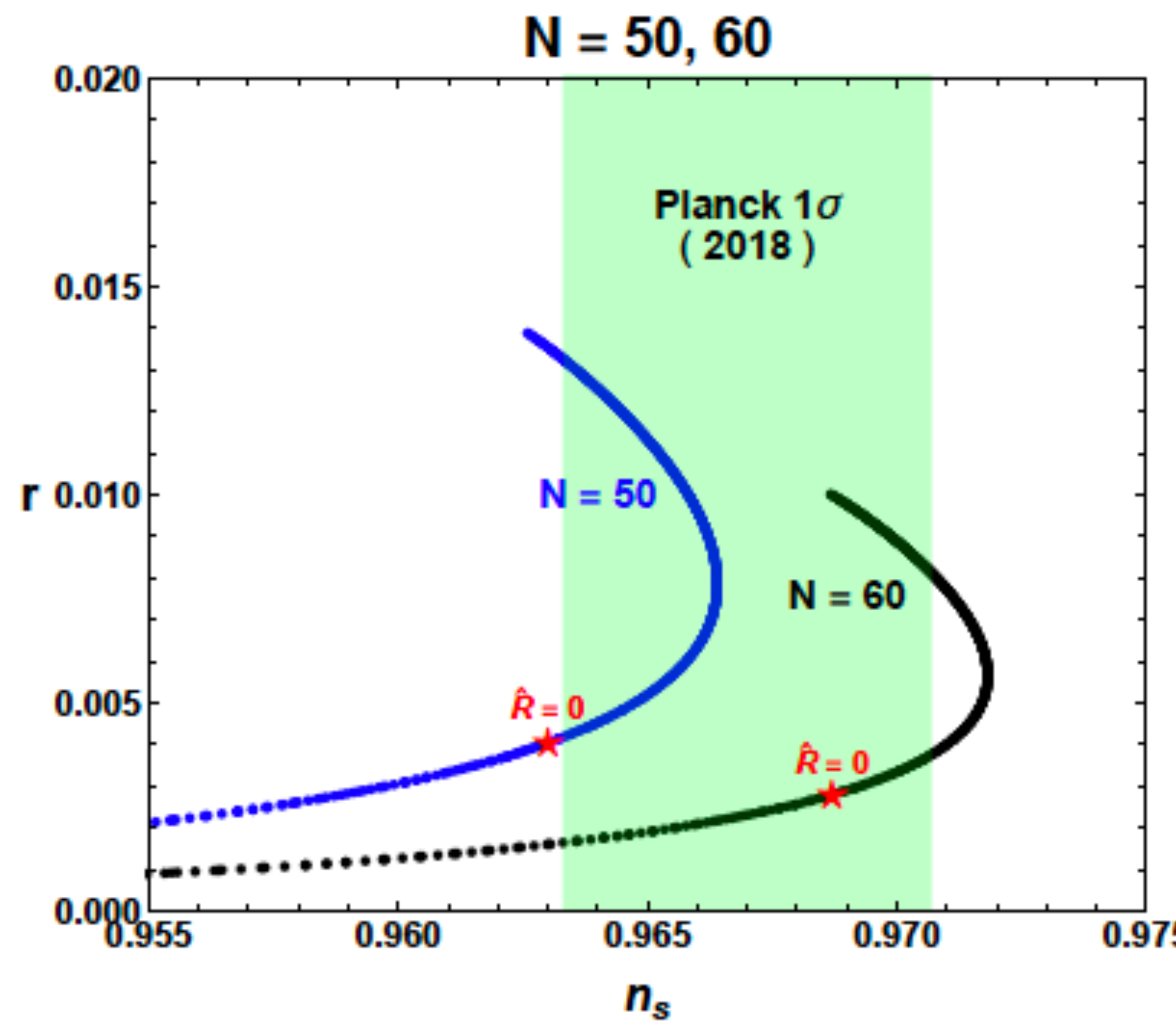
← Unstable Higgs vacuum

➡ Inflaton is Higgs-sigma mixed or pure sigma-field.

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}R(g_E) + \frac{1}{2}(\partial_\mu\chi)^2 - V_I(\tau)\left(1 - 2\hat{R}\,e^{-\frac{1}{\sqrt{6}}\chi} - 2(1-\hat{R}^2)\,e^{-\frac{2}{\sqrt{6}}\chi}\right).$$

Deviation from Higgs inflation





$$\hat{R} \equiv \xi_1/(\xi_2 + \xi_H \tau^2)^{1/2}$$

★ Higgs inflation

The higher unitarity scale, the more deviation up to r=0.01.

Tensor-to-scalar ratio testable at future CMB experiments.

Sigma field at low energy

[HML (2018)]

$\sigma, \phi \ll 1:$ $$\mathcal{L}_{\rm kin,0} = \frac{1}{2}\Big(1+\frac{3}{2}\xi_1^2\Big)(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \phi)^2.$$

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

Frame function: $$\Omega = 1 + \frac{\xi_1}{\sqrt{1+\frac{3}{2}\xi_1^2}}\chi + \frac{\xi_2}{1+\frac{3}{2}\xi_1^2}\chi^2 + \xi_H \phi^2.$$

$\xi_1 \sim \sqrt{\xi_2}$ → Unitarity cutoff below Planck scale.

Potential: $$V_E \approx \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}m_{\tilde\sigma}^2\tilde\sigma^2 - \tilde\mu\tilde\sigma\phi^2 + \frac{1}{3}\tilde\alpha\tilde\sigma^3 + \frac{1}{2}\lambda_{\tilde\sigma\phi}\tilde\sigma^2\phi^2 + \frac{1}{4}\lambda_{\tilde\sigma}\tilde\sigma^4$$

$$m_{\tilde\sigma}^2 = \Big(\frac{1}{1+\frac{3}{2}\xi_1^2}\Big)m_\sigma^2, \quad \tilde\mu = \Big(\frac{1}{1+\frac{3}{2}\xi_1^2}\Big)^{1/2}\mu, \quad \tilde\alpha = \Big(\frac{1}{1+\frac{3}{2}\xi_1^2}\Big)^{3/2}\alpha,$$

$$\lambda_{\tilde\sigma\phi} = \Big(\frac{1}{1+\frac{3}{2}\xi_1^2}\Big)\lambda_{\sigma\phi}, \quad \lambda_{\tilde\sigma} = \Big(\frac{1}{1+\frac{3}{2}\xi_1^2}\Big)^2\lambda_\sigma.$$

$\xi_1 \gg 1$ → Suppressed sigma couplings/masses.

Inflaton as dark matter

Inflaton dark matter

Approximate Z_2 symmetry ➡ **sigma inflaton = dark matter**

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

Z_2 symmetric in particle physics:

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

Z_2 broken in gravity: $\Omega(\sigma,H) = 1+\xi_1\sigma+\xi_2\sigma^2+2\xi_H|H|^2,$

Inflaton decays only by linear couplings to trace of EM tensor:

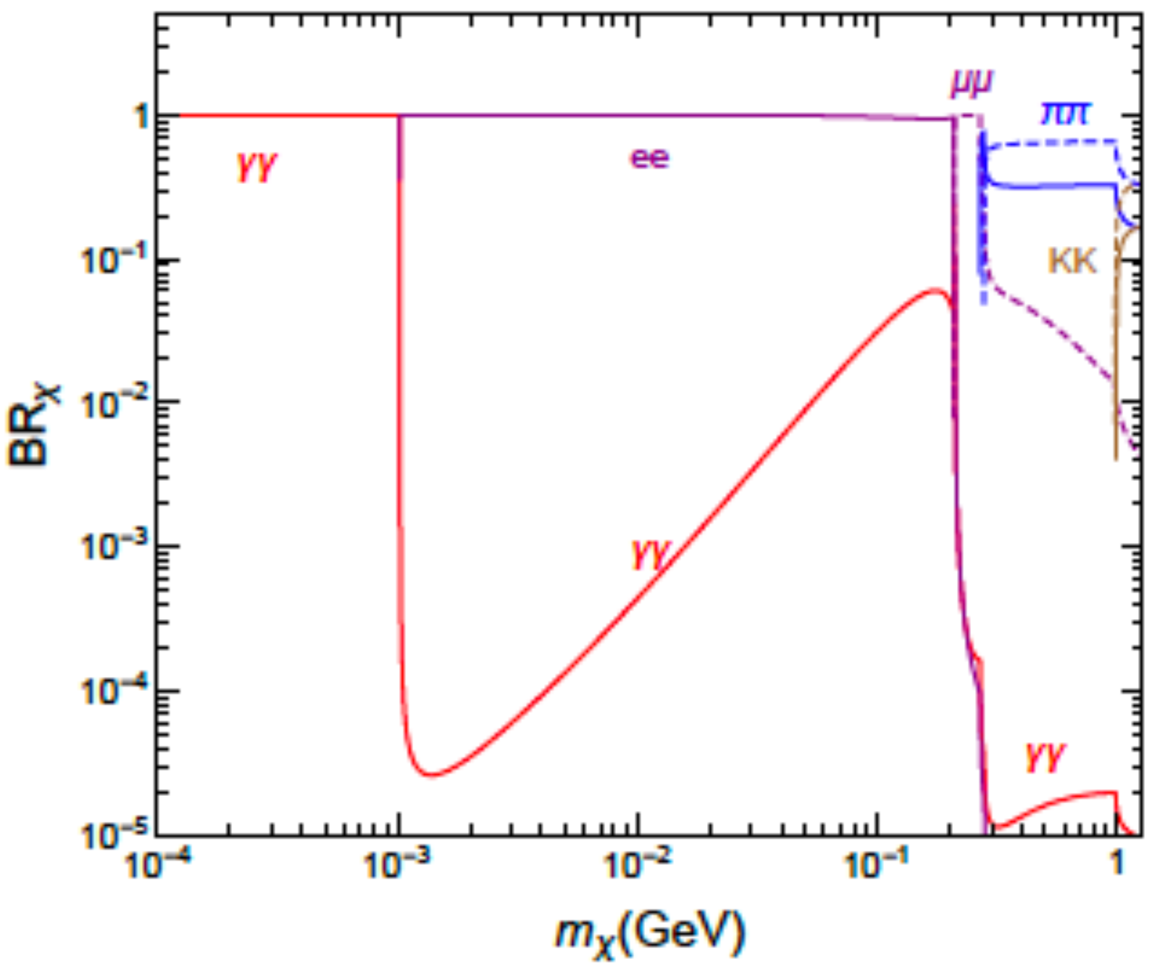
$$\mathcal{L}_\sigma=\frac{1}{2}\xi_1\sigma T^\mu_\mu\approx\frac{1}{2}\frac{\xi_1}{\sqrt{1+\frac{3}{2}\xi_1^2}}\frac{\chi}{M_P}T^\mu_\mu,$$

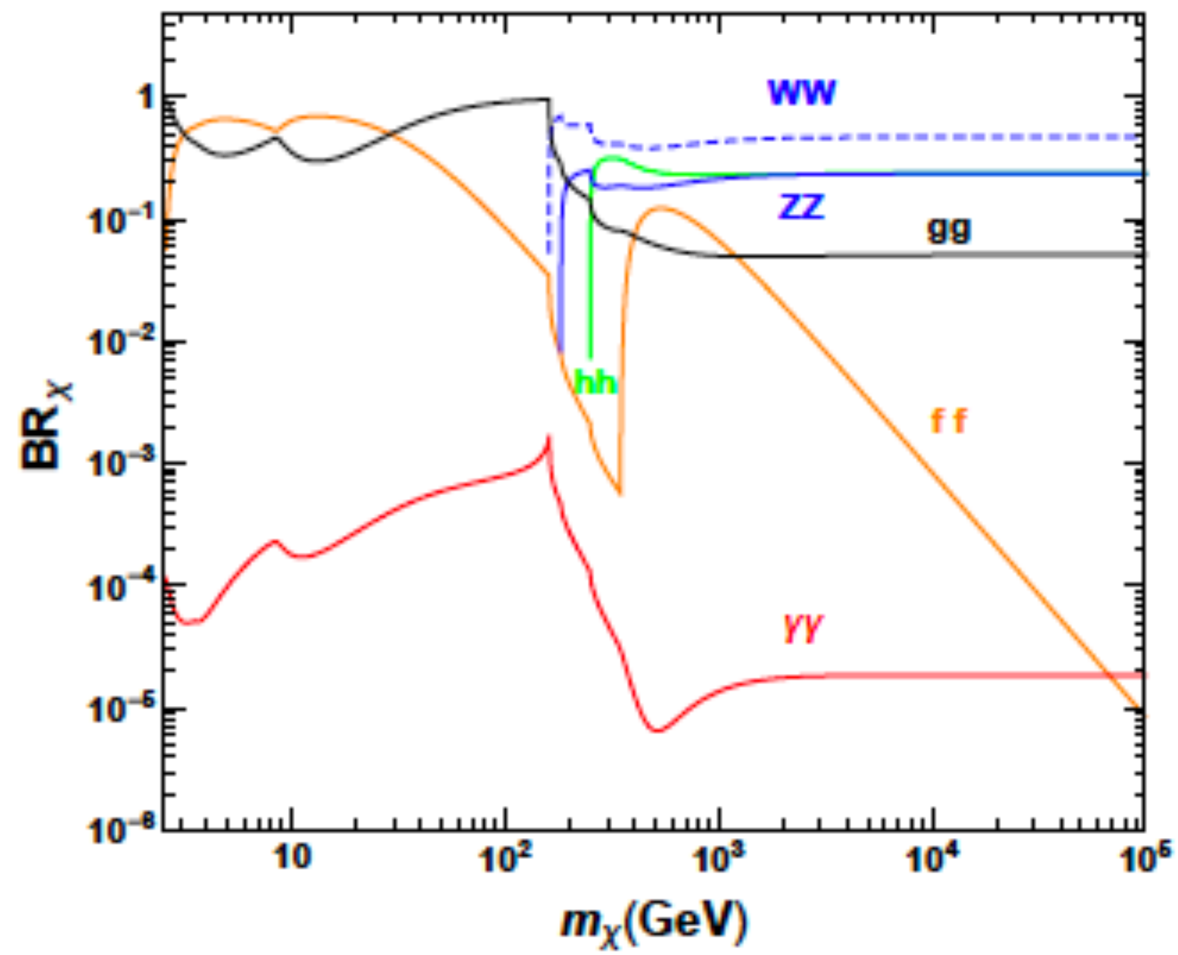
[Ibarra et al (2016); Choi, Kang, HML, Yamashita (2019)]

$$T^\mu_\mu=-(\partial_\mu\phi)^2+4V+\frac{m_f}{v}\phi\bar{f}f-\delta_V\frac{m_V^2}{v^2}\phi^2V_\mu V^\mu+\delta T^\mu_\mu,$$

Scale anomalies: $\delta T^\mu_\mu=\frac{\beta_S(\alpha_S)}{4\alpha_S}G^a_{\mu\nu}G^{a\mu\nu}+\frac{\beta_{\rm EM}(\alpha)}{4\alpha}F_{\mu\nu}F^{\mu\nu}+\cdots$ ➡ massless particles

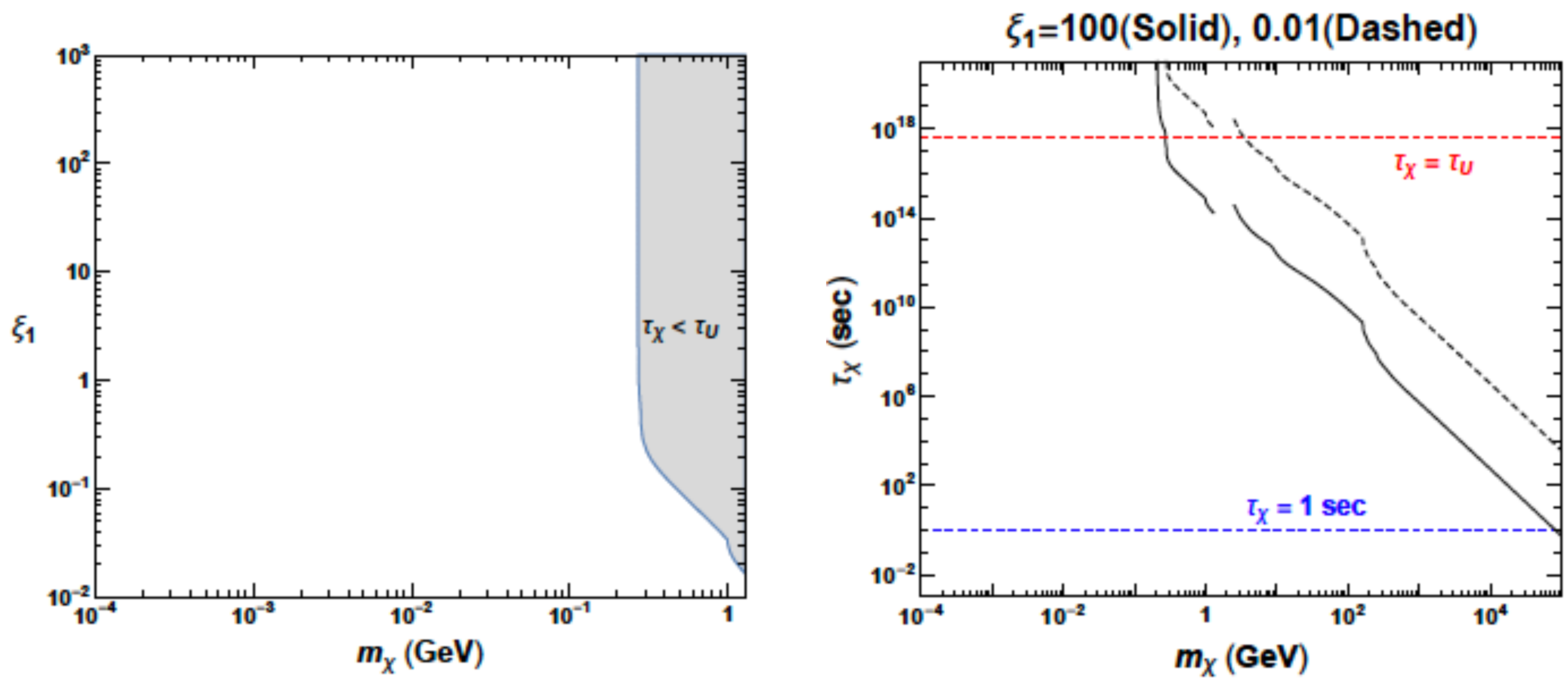
Inflaton decay rates





“light inflaton” “heavy inflaton”

Long-lived inflaton

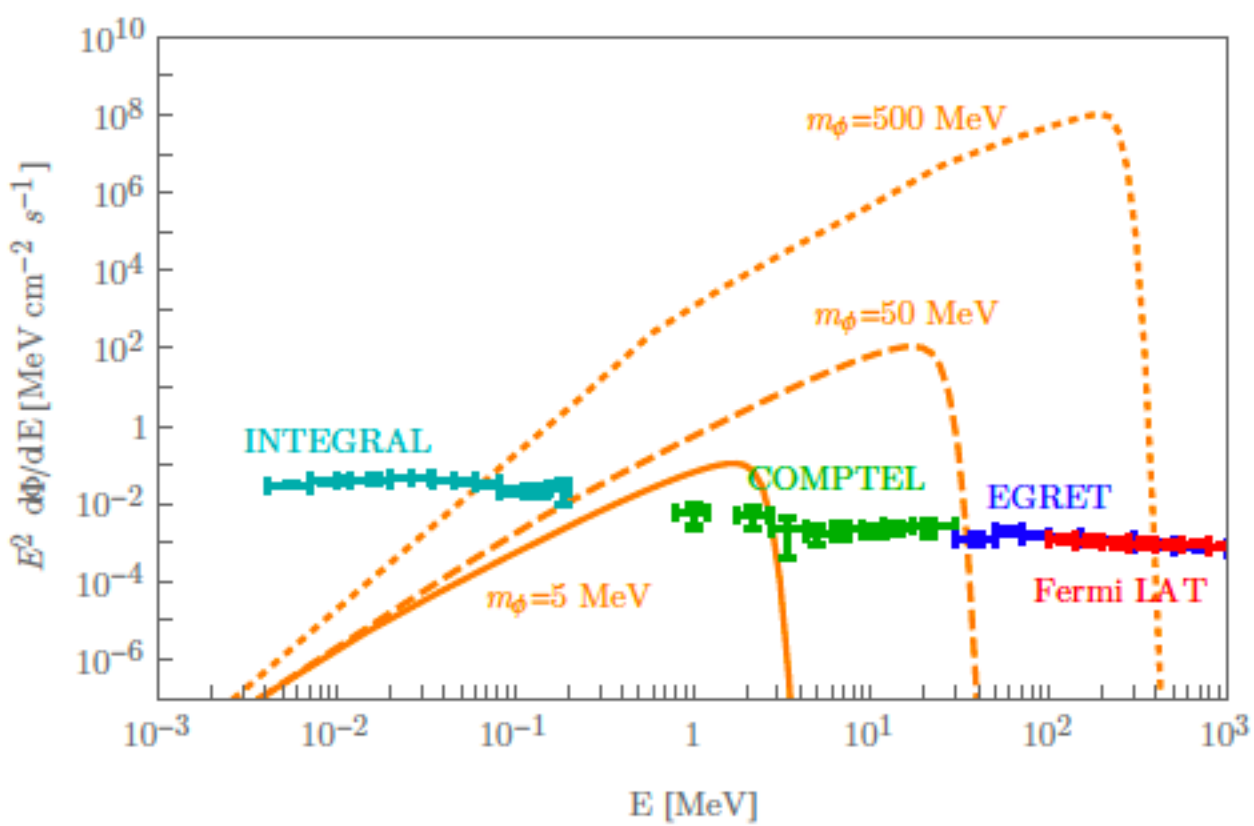


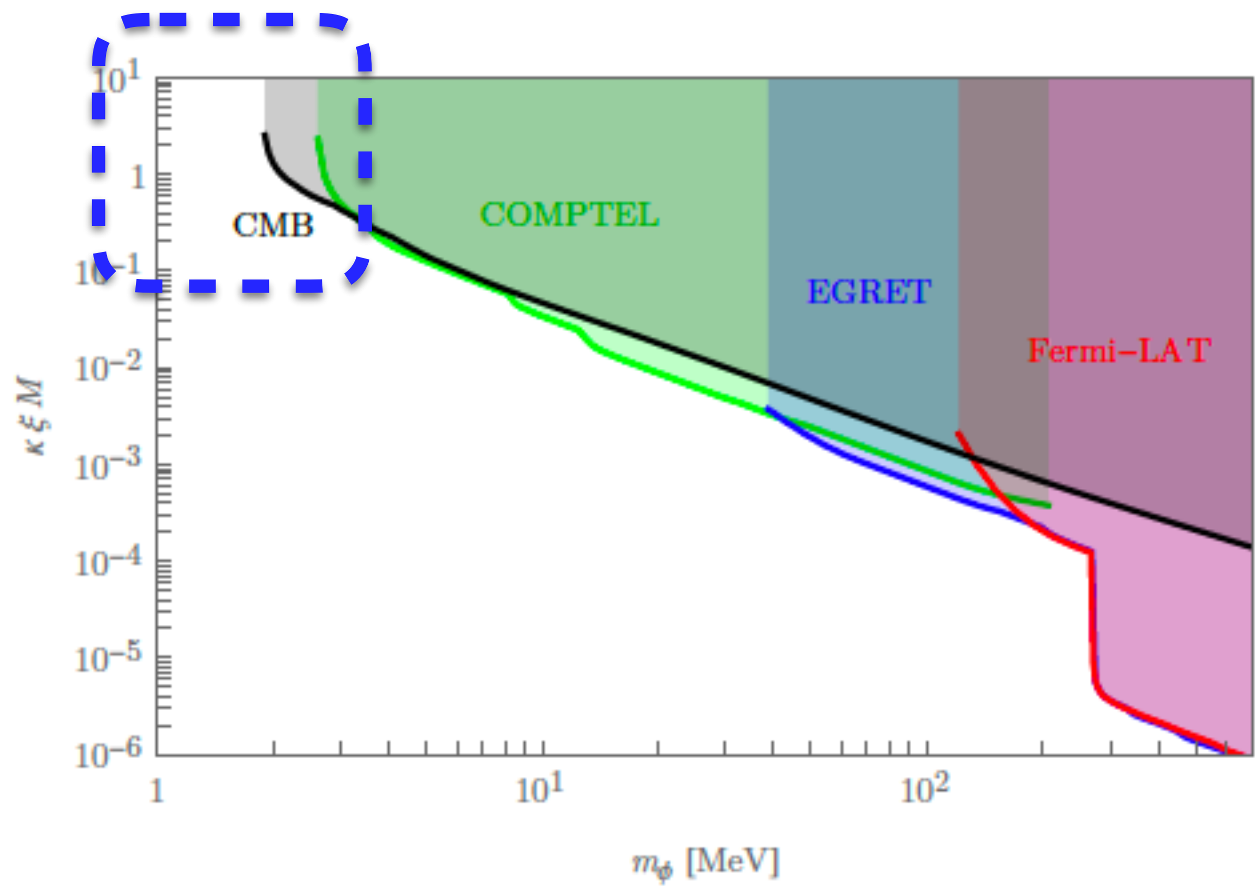
[Ibarra et al (2016, 2017); Choi, Kang, HML, Yamashita (2019)]

Inflaton can live longer than age of Universe for $m_\chi \lesssim 2m_\pi = 270\,\mathrm{MeV}.$

$m_\chi \lesssim 10^5\,\mathrm{GeV}:$ Inflaton long-lived up to 1sec.

Gamma-ray constraints





[Ibarra et al (2017)]

No CMB bound on inflaton for $m_\chi \lesssim 2\,\mathrm{MeV}$.

Inflaton during reheating

Reheating after pure sigma inflation: [Choi, Kang, HML, Yamashita (2019)]

$$\frac{d\chi}{d\sigma} = \sqrt{\frac{1}{\Omega}+\frac{3\Omega'^2}{2\Omega^2}} = \frac{1}{\Omega}\sqrt{1-\frac{\xi_1^2}{4\xi_2}+\xi_2(1+6\xi_2)\bar{\sigma}^2} \approx \sqrt{\frac{3}{2}}\frac{\Omega'}{\Omega}, \quad \bar{\sigma}=\sigma+\frac{\xi_1}{2\xi_2} \gtrsim \frac{1}{\xi_2}$$

$$\Rightarrow \chi \approx \sqrt{\frac{3}{2}}\ln\Omega = \sqrt{\frac{3}{2}}\ln(1+\xi_1\sigma+\xi_2\sigma^2)$$

: applicable from inflation to reheating

$$\chi \lesssim 1: \quad V_E = \frac{\lambda_\sigma}{4\Omega^2}\sigma^4$$

$$\approx \frac{\lambda_\sigma}{4\xi_2^2}\left[\left(1-\left(1-\frac{R^2}{4}\right)e^{-\frac{2}{\sqrt{6}}\chi}\right)^{1/2}-\frac{R}{2}e^{-\frac{1}{\sqrt{6}}\chi}\right]^4 \approx \frac{1}{4}\lambda_\chi\chi^4$$

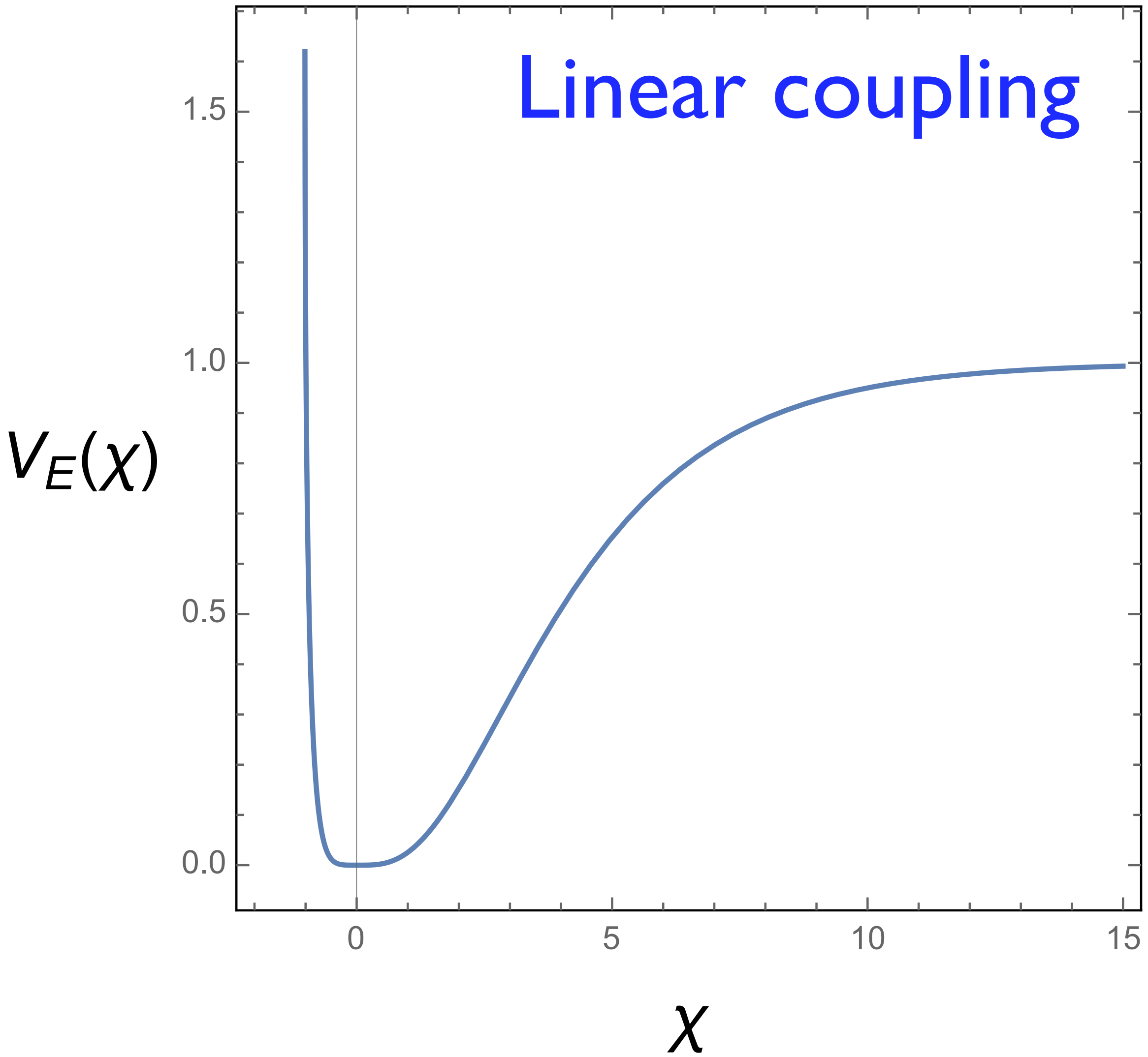
"Quartic potential" during reheating

CMB: $\frac{\lambda_\sigma}{\xi_2^2} = 1.2\times10^{-9}\left(\frac{r}{0.01}\right)$ $\Rightarrow$ $\lambda_\chi \equiv \frac{4\lambda_\sigma}{9\xi_2^2} = (5.3\times10^{-10})R^{-4}\left(\frac{r}{0.01}\right)$

"small quartic coupling"

State of reheating

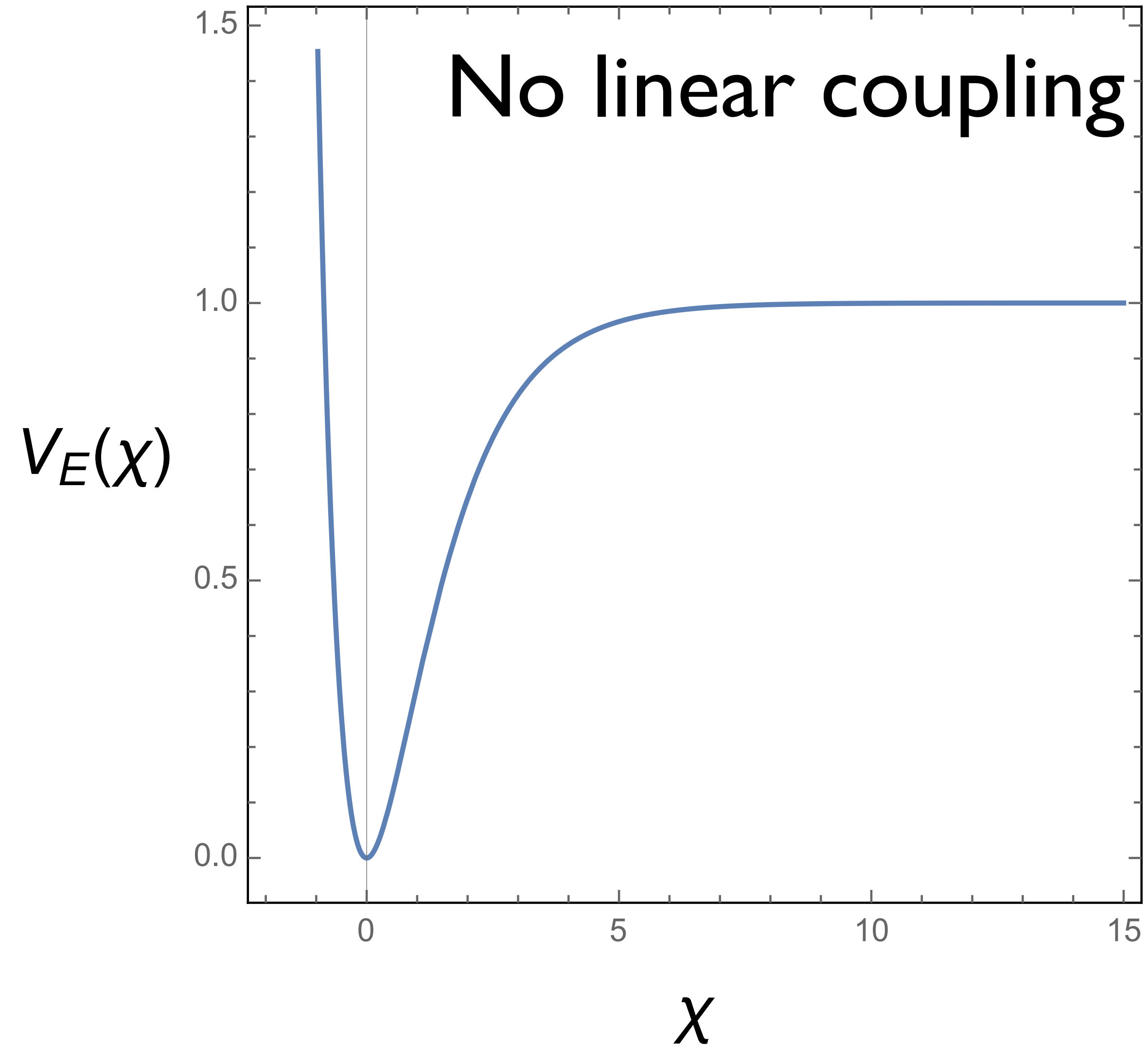
R=1.5



$$V_E \approx \frac{\lambda_\sigma}{9\xi_2^2}\,\chi^4$$

"radiation-like"

R=0



$$V_E \approx \frac{\lambda_\sigma M_P^2}{6\xi_2^2}\,\chi^2$$

"matter-like"

Inflaton condensate

[T. Tenkanen(2016); Almeida et al (2018); Choi, Kang, HML, Yamashita (2019)]

Inflaton condensate:

$$H^2 = \frac{\rho_{\chi_c}(t)}{3M_P^2} = \left(\frac{1}{2t}\right)^2, \quad \rho_{\chi_c} = \frac{1}{4}\lambda_\chi \chi_c^4(t)$$

$$\chi_c(t) = \chi_0(t)\,\mathrm{cn}\left(\omega(t)\,t, \frac{1}{\sqrt{2}}\right),$$

$$\chi_0 = \chi_{\rm end}\sqrt{t_{\rm end}/t}\,,$$

$$\omega(t) = 0.85\lambda_\chi^{1/2}\chi_0(t) \gg H.$$

Jacobi cosine ("unharmonic")

Background-dependent masses during reheating:

$$m_\chi^2 = 3\lambda_\chi\chi_c^2(t) + m_{\chi,0}^2\,,$$

$$m_h^2 = \frac{1}{2}\lambda_{\chi H}\chi_c^2(t) + m_{h,0}^2$$

Decay rates of inflaton condensate:

$$\Gamma_{\chi_c} = \Gamma_{\chi_c\to\chi\chi} + \Gamma_{\chi_c\to hh}\ ;$$

$$\Gamma_{\chi_c\to\chi\chi} = 0.023\lambda_\chi^{3/2}\chi_0,$$

$$\Gamma_{\chi_c\to hh} = 0.002\lambda_{\chi H}^2\lambda_\chi^{-1/2}\chi_0.$$

Reheating and dark matter

Reheating temperature:

$$\mathrm{BR} = \frac{\Gamma_{\chi_c\to\chi\chi}}{\Gamma_{\chi_c\to\chi\chi}+\Gamma_{\chi_c\to hh}} = \frac{11.5\lambda_\chi^2}{11.5\lambda_\chi^2+\lambda_{\chi H}^2}$$

$$\Gamma_{\chi_c} = \Gamma_{\chi_c\to hh}\cdot\left(\frac{1}{1-\mathrm{BR}}\right) \simeq H_{\rm dec} = \sqrt{\frac{\lambda_\chi}{12}}\,\frac{\chi_0^2(t_{\rm dec})}{M_P}\;; \qquad \frac{\pi^2 g_*(T_{\rm RH})}{30}T_{\rm RH}^4 = (1-\mathrm{BR})\cdot\rho_{\chi_c}(t_{\rm dec})$$

$$\begin{aligned} T_{\rm RH} &= 0.002\left(\frac{100}{g_*(T_{\rm RH})}\right)^{1/4}\lambda_{\chi H}^2\lambda_\chi^{-3/4}(1-\mathrm{BR})^{-3/4}M_P \\ &= (4.4\times 10^6\,\mathrm{GeV})\left(\frac{100}{g_*(T_{\rm RH})}\right)^{1/4}\left(\frac{\lambda_{\chi H}}{10^{-8}}\right)^2 R^3(1-\mathrm{BR})^{-3/4}\left(\frac{r}{0.01}\right)^{-3/4} \end{aligned}$$

Dark matter abundance: $\lambda_{\chi H}\sim\lambda_{\sigma H}/\xi_1^2\lesssim 10^{-7}$ out of equilibrium

$\Omega_\chi h^2 = (\Omega_\chi h^2)_{\rm FIMP} + (\Omega_\chi h^2)_{\rm RH}$: non-thermal production

Higgs decay: $(\Omega_\chi h^2)_{\rm FIMP} = 0.12\left(\frac{100}{g_*(m_h)}\right)^{3/2}\left(\frac{\lambda_{\chi H}}{4.4\times10^{-7}}\right)^2\left(\frac{m_\chi}{1\,\mathrm{eV}}\right)$

Inflaton decay: $(\Omega_\chi h^2)_{\rm RH} = 7.3\,R\left(\frac{r}{0.01}\right)^{-1/4}\cdot\mathrm{BR}\cdot\left(\frac{m_\chi}{1\,\mathrm{eV}}\right)$

Dark radiation from DM

Dark matter produced due to inflaton condensate remains relativistic until late times.

→ "Dark Radiation"

DM non-relativistic if $\frac{a_{\rm dec}}{a_{\rm NR}} \sim \frac{m_\chi}{k} \sim \frac{m_\chi}{\sqrt{3\lambda_\chi}\chi_0(t_{\rm dec})}$:

$$\frac{T_{\rm NR}}{T_{\rm eq}} = 0.77\lambda_\chi^{-1/4}\left(\frac{m_\chi}{1\,{\rm eV}}\right) = 160\,R\left(\frac{r}{0.01}\right)^{-1/4}\left(\frac{m_\chi}{1\,{\rm eV}}\right)$$

$T_{\rm NR} > T_{\rm BBN}$ → $m_\chi > 7.8\,{\rm keV}$

If DM remains relativistic during BBN,

Extra radiation:

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g_* \cdot \frac{\rho_\chi(a_{\rm eq})}{\rho_R(a_{\rm eq})} \cdot \left(\frac{a_{\rm NR}}{a_{\rm eq}}\right) \leq 0.0944\,R^{-1}\left(\frac{r}{0.01}\right)^{1/4}\left(\frac{1\,{\rm eV}}{m_\chi}\right)$$

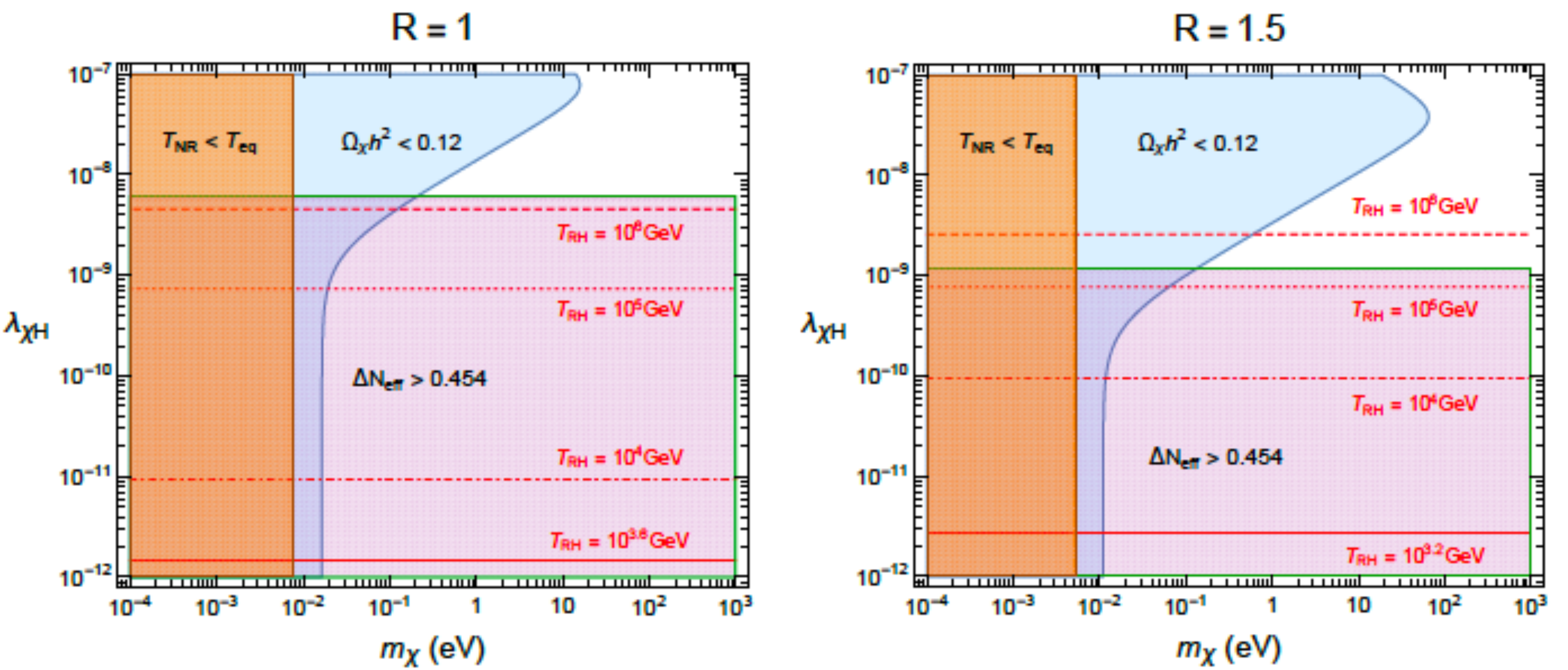
(a) $N_{\rm eff} = 2.93^{+0.23}_{-0.23}$
(b) $N_{\rm eff} = 3.04^{+0.22}_{-0.22}$
(c) $N_{\rm eff} = 3.06^{+0.22}_{-0.22}$

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

case c) $m_\chi \gtrsim 0.208(0.139)\,{\rm eV}$ within 2σ

Light inflaton DM

[Choi, Kang, HML, Yamashita (2019)]

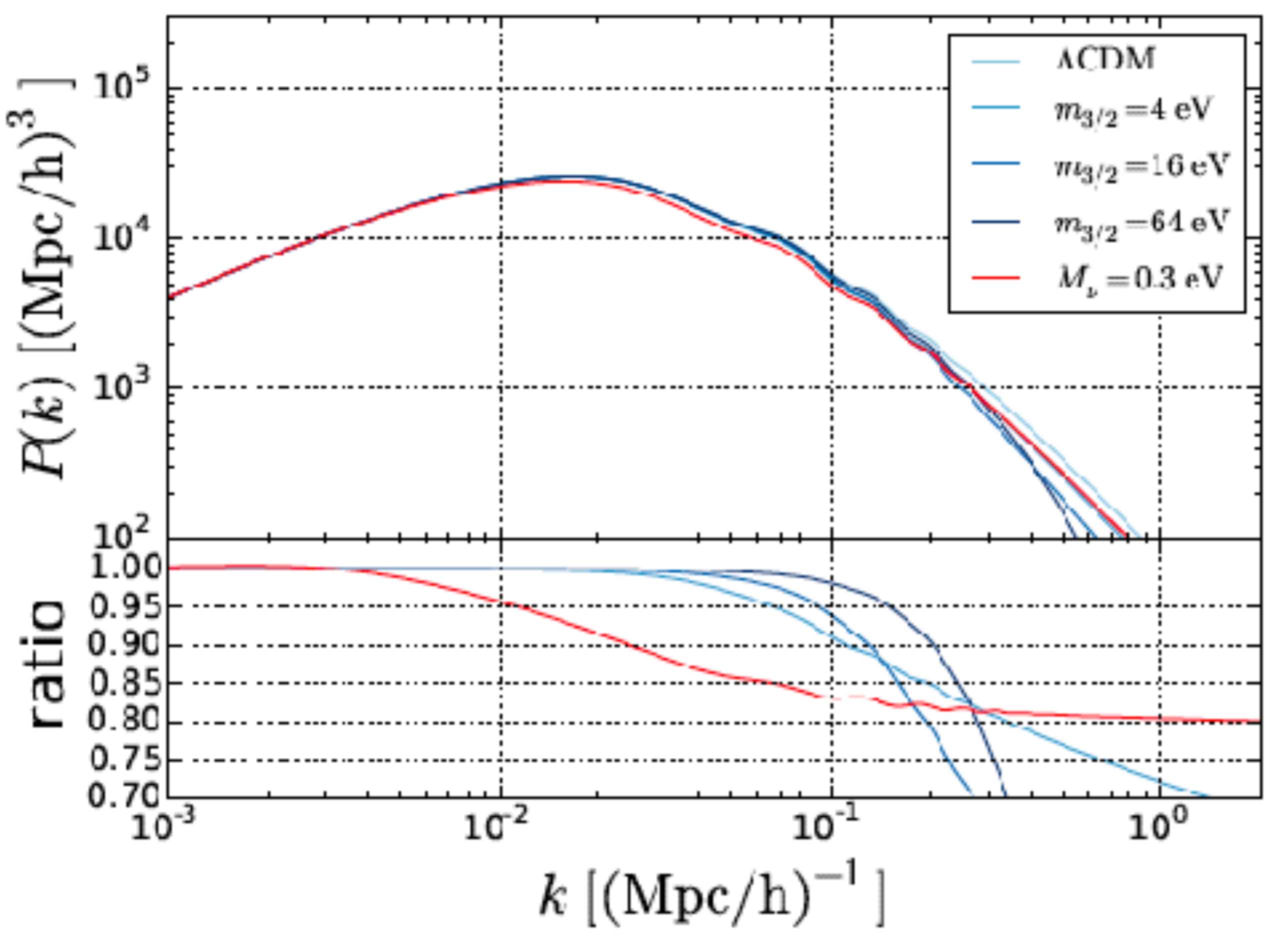


Blue: relic density, Purple: BBN, Orange: $T_{NR}<T_{eq}$

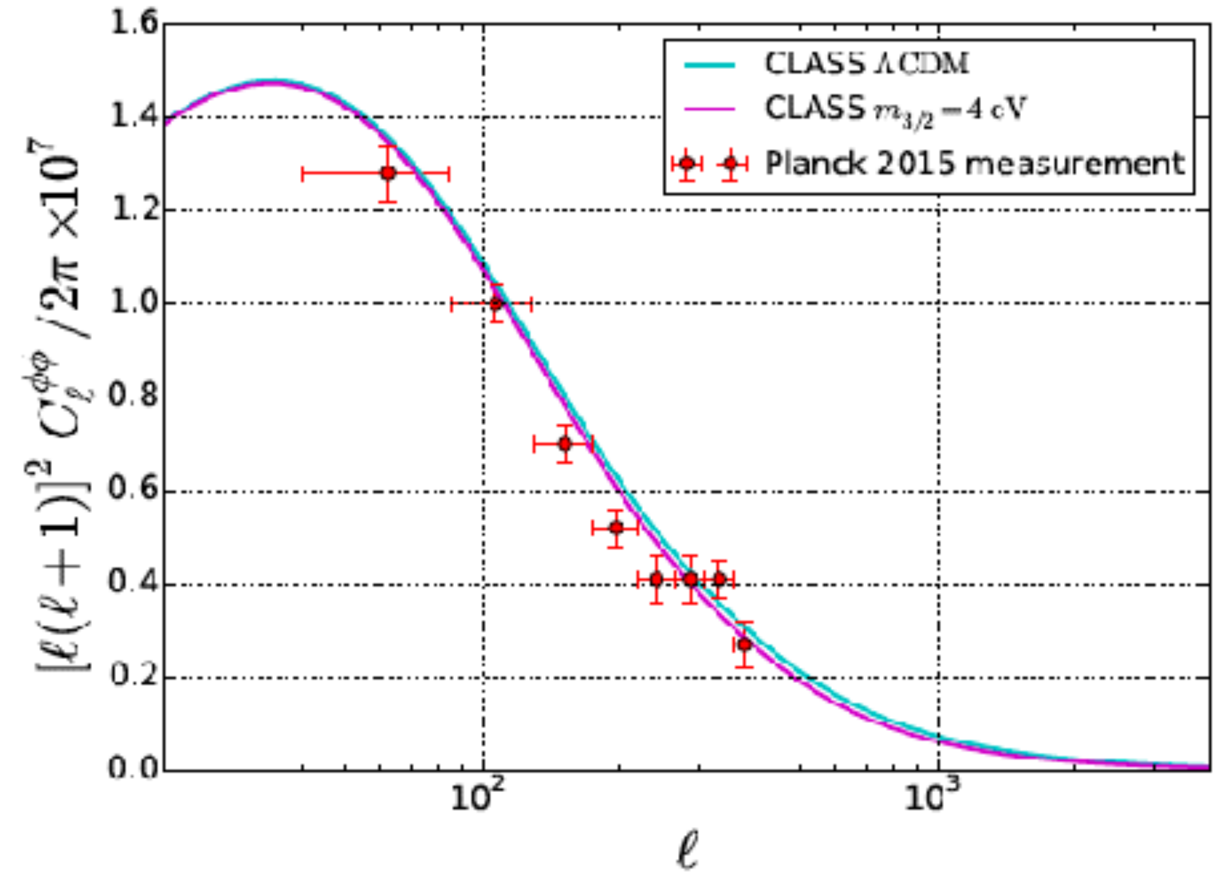
DM masses in the range of $0.1\,\mathrm{eV} \lesssim m_\chi \lesssim 100\,\mathrm{eV}.$

Bounds from large scales

Matter power spectrum



CMB lensing



[K. Osato et al (2016)]

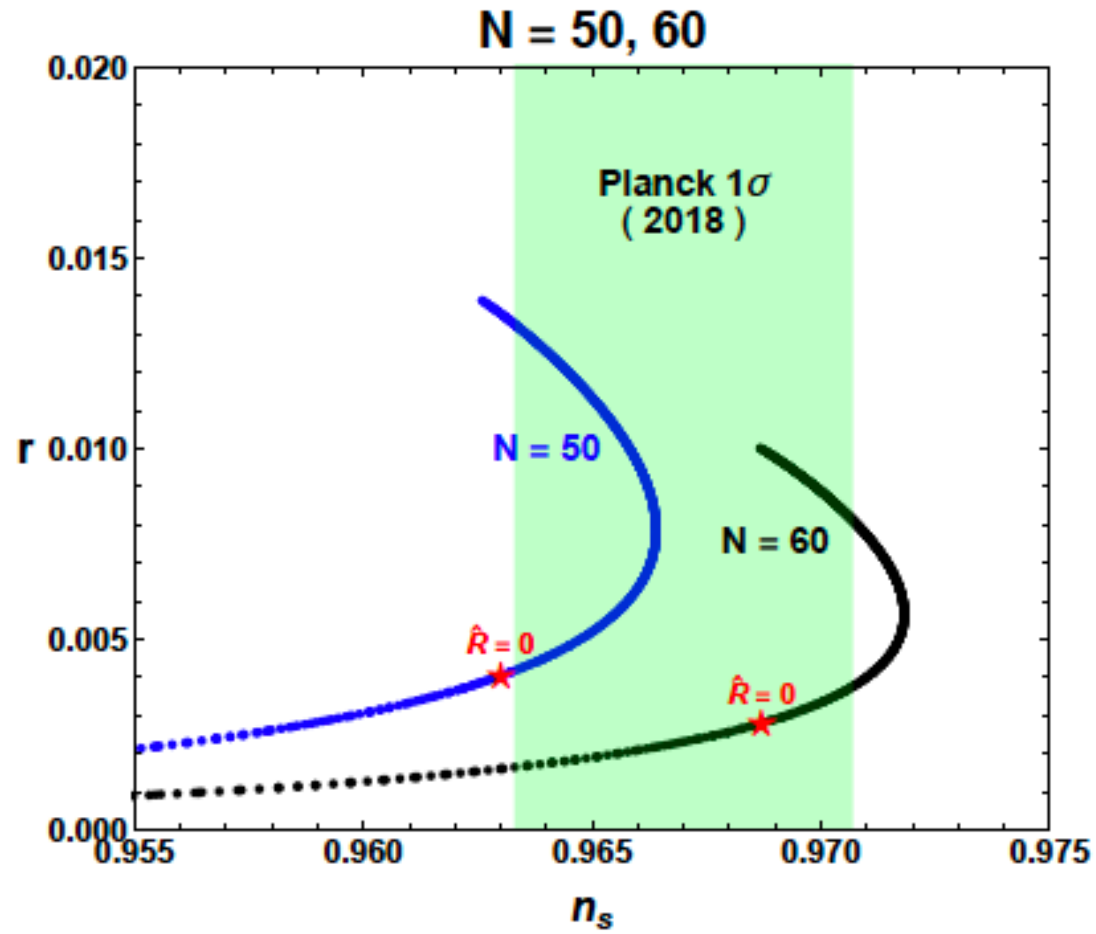
Suppression at small scales: $k_J = a\sqrt{\frac{4\pi G\rho_m}{\langle v^2\rangle}}\Big|_{a=a_{eq}} \simeq 0.86\ \mathrm{Mpc}^{-1}\left(\frac{m_{3/2}}{100\ \mathrm{eV}}\right)^{1/2}\left(\frac{g_{*s3/2}}{90}\right)^{5/6}$

$m_{\rm DM} < 16\,\mathrm{eV}$ (Lyman-α forest) [M.Viel et al (2005)]

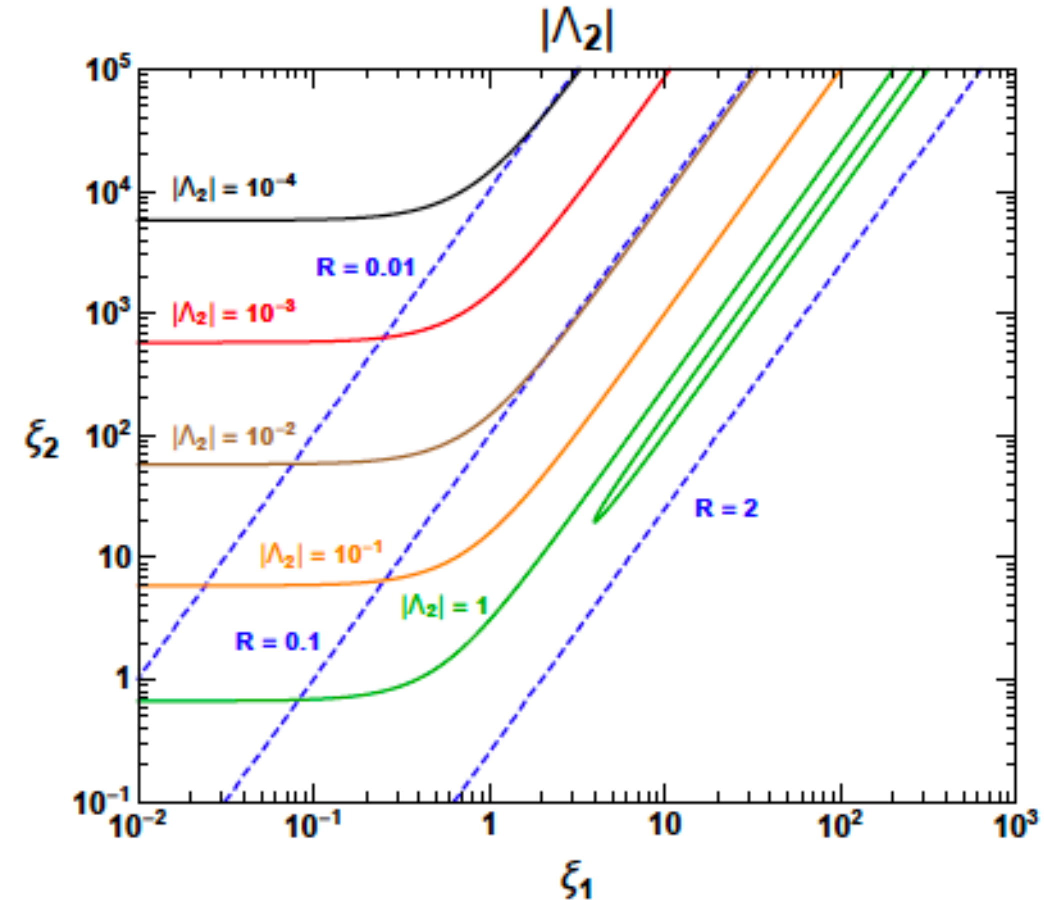
$m_{\rm DM} < 4.7\,\mathrm{eV}$ (CMB lensing) [K. Osato et al (2016)]

Conclusions

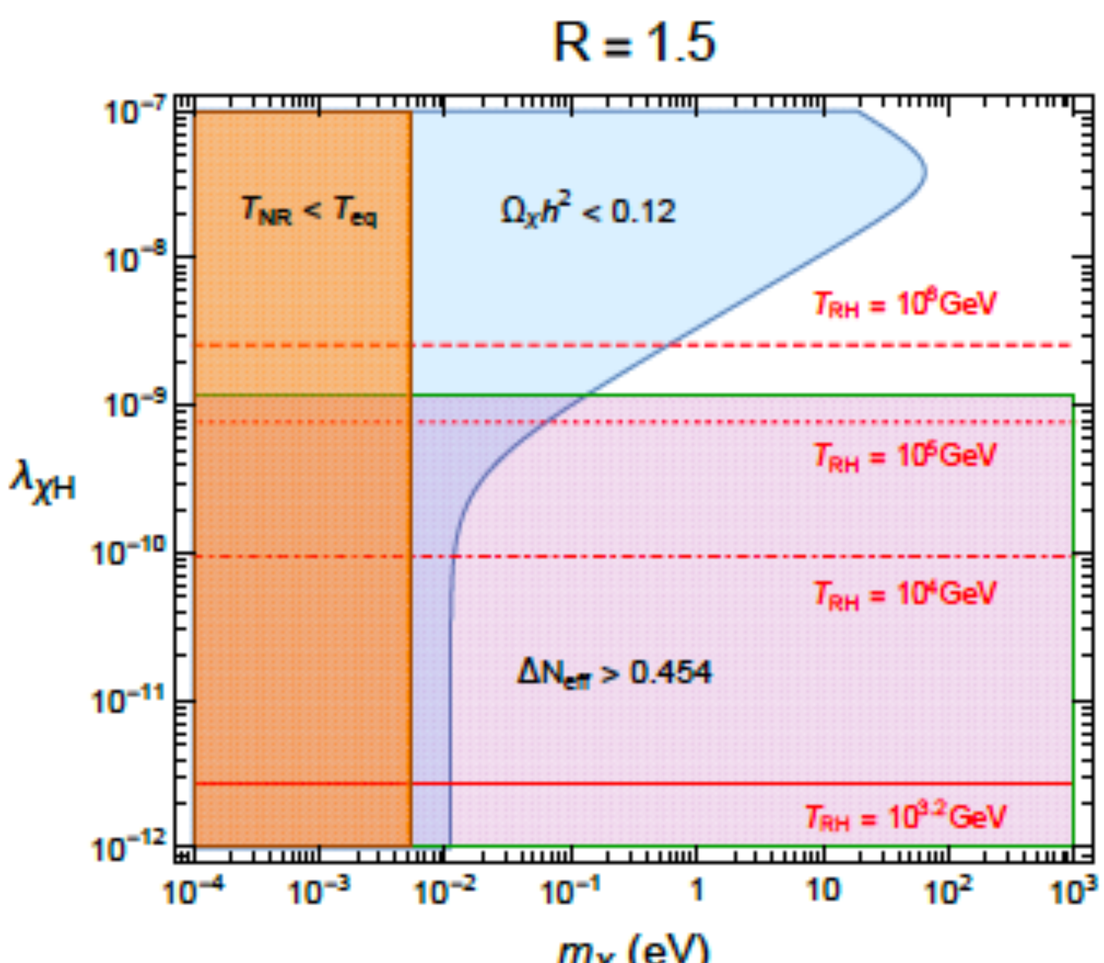
- We proposed a general form of sigma models to unitarize Higgs inflation.
- Large linear non-minimal coupling leads to sizable deviation in tensor mode up to r=0.01, novel reheating and small inflation masses/parameters.
- Inflation decays by gravity coupling, but it can be a viable candidate for light dark matter, being consistent with cosmological constraints.
- Light inflaton can also play roles for EW phase transition and Higgs production (work in progress).



Inflation



Unitarity



Dark matter/radiation