Beyond Higgs inflation and dark matter

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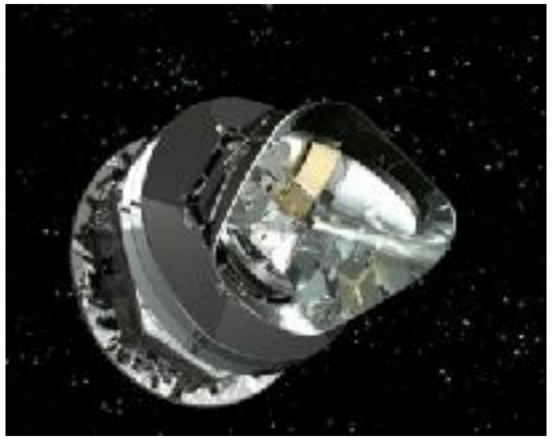
2019 Joint Workshop of FKPPL & TYL/FJPPL

Seogwipo KAL hotel, Jeju Island, May 9, 2019.

Finding New Physics: From Earth to Sky



- New Physics for Higgs and Hierarchy Problem: supersymmetry, warped extra dimension, clockwork mechanism, etc.
- New Physics for Dark Matter: WIMP, FIMP, SIMP, new production mechanisms and detections.
- New Physics for Flavor Physics: fermion masses/mixing, flavor puzzles from rare decays, magnetic/electric dipole moments.

FNES Collaboration

French team

Yann Mambrini
(LPT, Orsay)

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Korean team

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Published work: Vector SIMP dark matter, JHEP 1710, 162.

(collaboration with H. Murayama, E. Kuflik, Y. Hochberg)

Submitted: Vector SIMP dark matter with approximate custodial symmetry, 1904.04109 [hep-ph].

Workshops and Visits

Korea: funded by BK21+, NRF

KIAS Research Station, 16-19 Oct, 2016

KIAS Workshop, 24-28 Oct, 2016

Chung-Ang University, 28 Oct - 2 Nov, 2017

France: funded by FKPPL

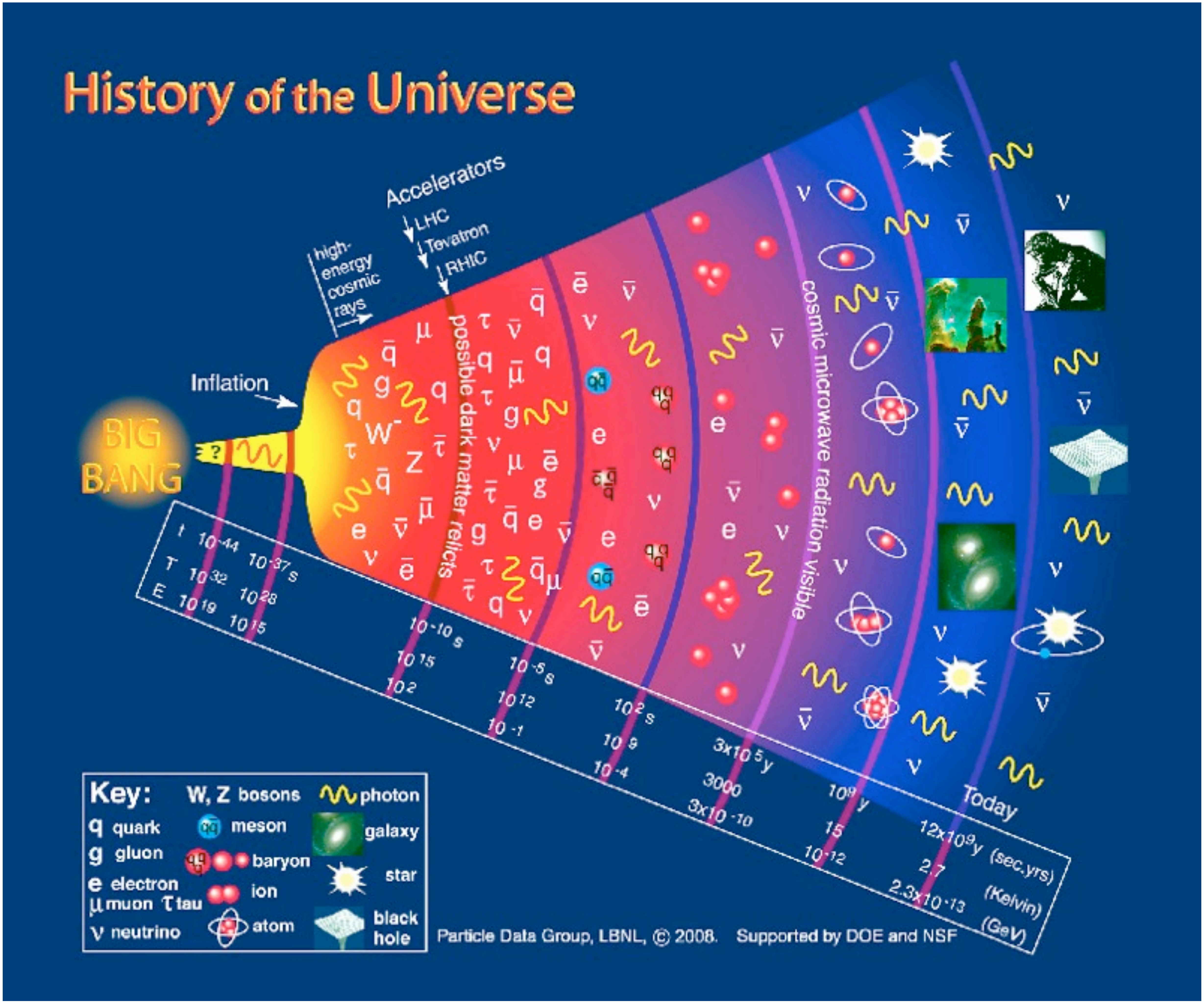
LPT, Orsay, 29-31 Jan, 2017

Dark Side of Universe, Annecy,
25-29 June, 2018

Astroparticle Symposium, Saclay,
28 Oct - 8 Nov, 2019

Outline

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


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
µ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008.
Supported by DOE and NSF

Instability of Higgs vacuum

- Quantum fluctuations change Higgs potential.

$$V = -\mu^2|H|^2 + \lambda|H|^4$$

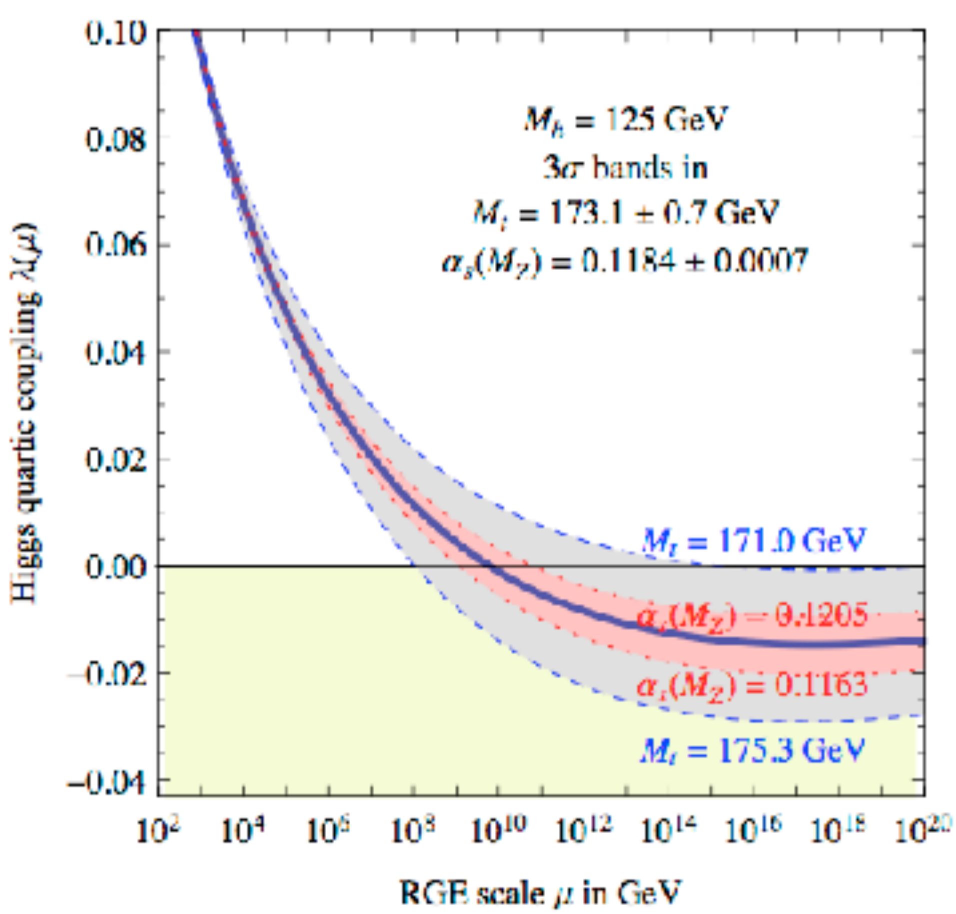
$$m_H \ll M_P \sim 10^{18}\,\mathrm{GeV}/c^2;$$

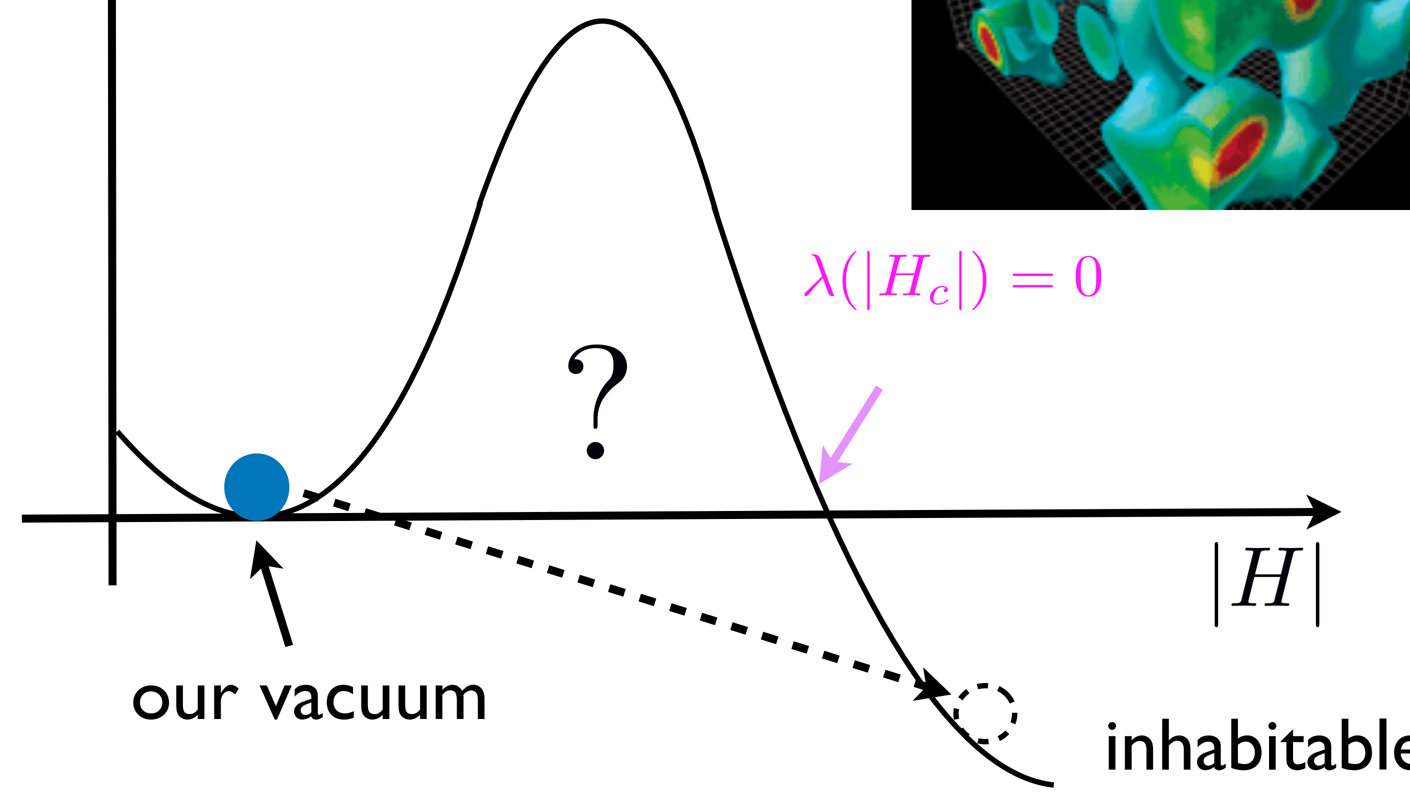
$$\lambda(v) = \frac{m_H^2}{2v^2} = 0.13$$

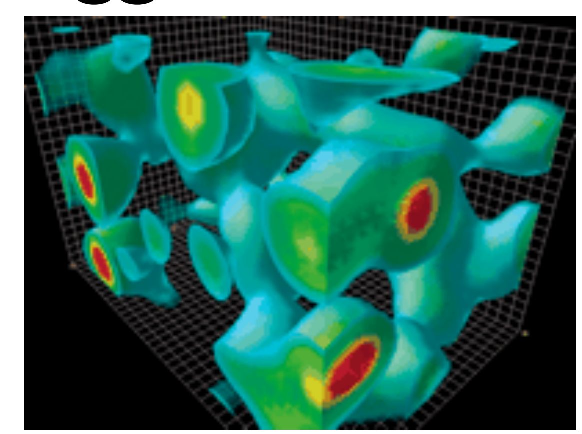
$$\lambda(\mu) \approx \lambda(v) - \frac{3}{8\pi^2}\, y_t^4(v) \ln\left(\frac{\mu}{v}\right)$$

Stability of Higgs vacuum

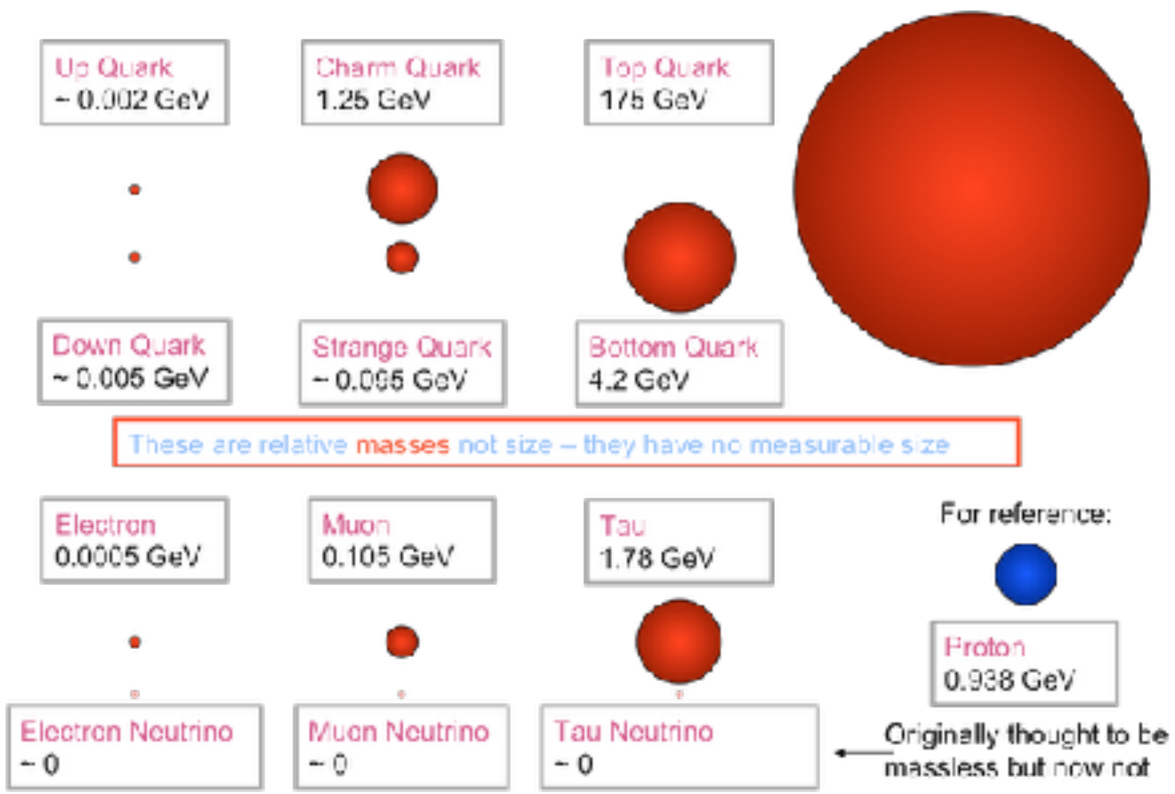
[HML et al, 2012]

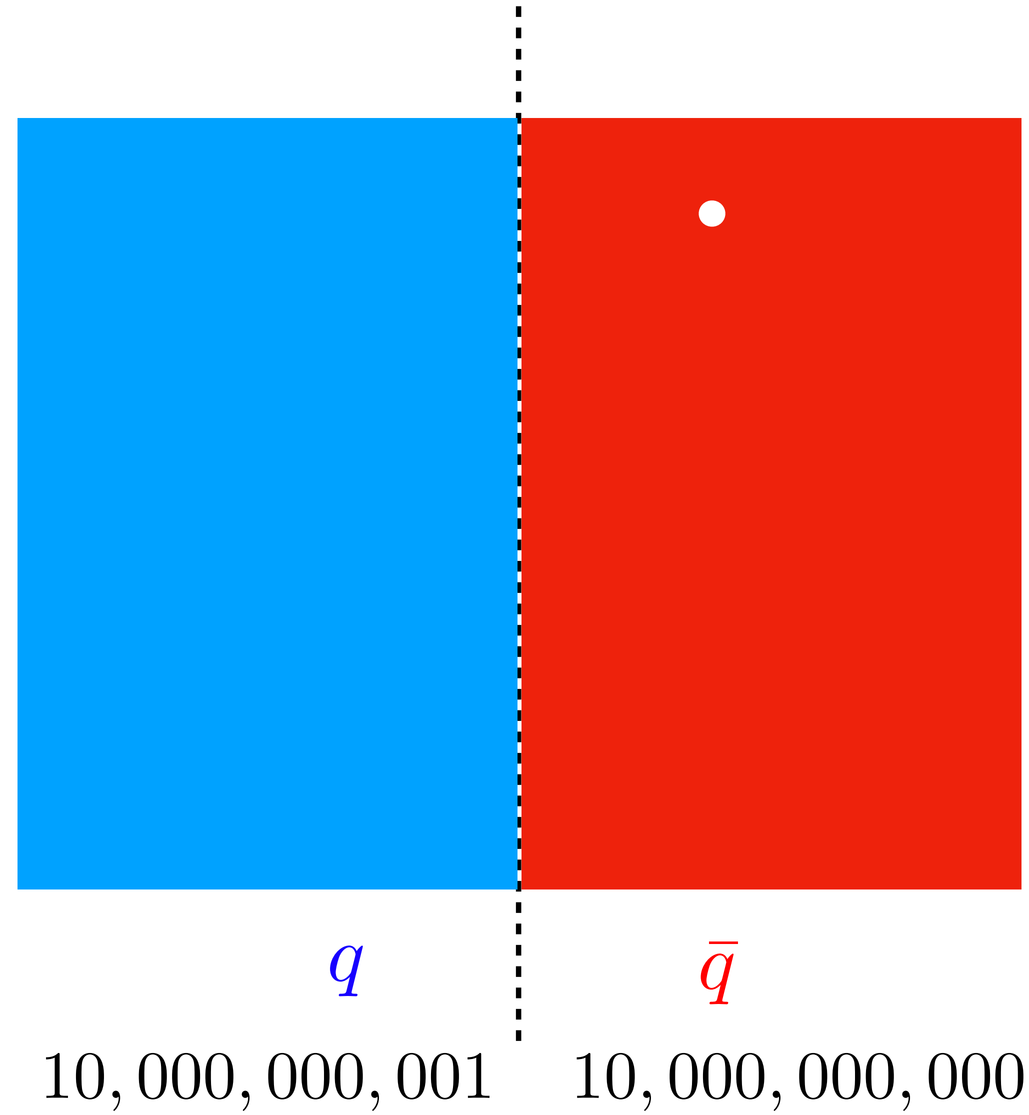






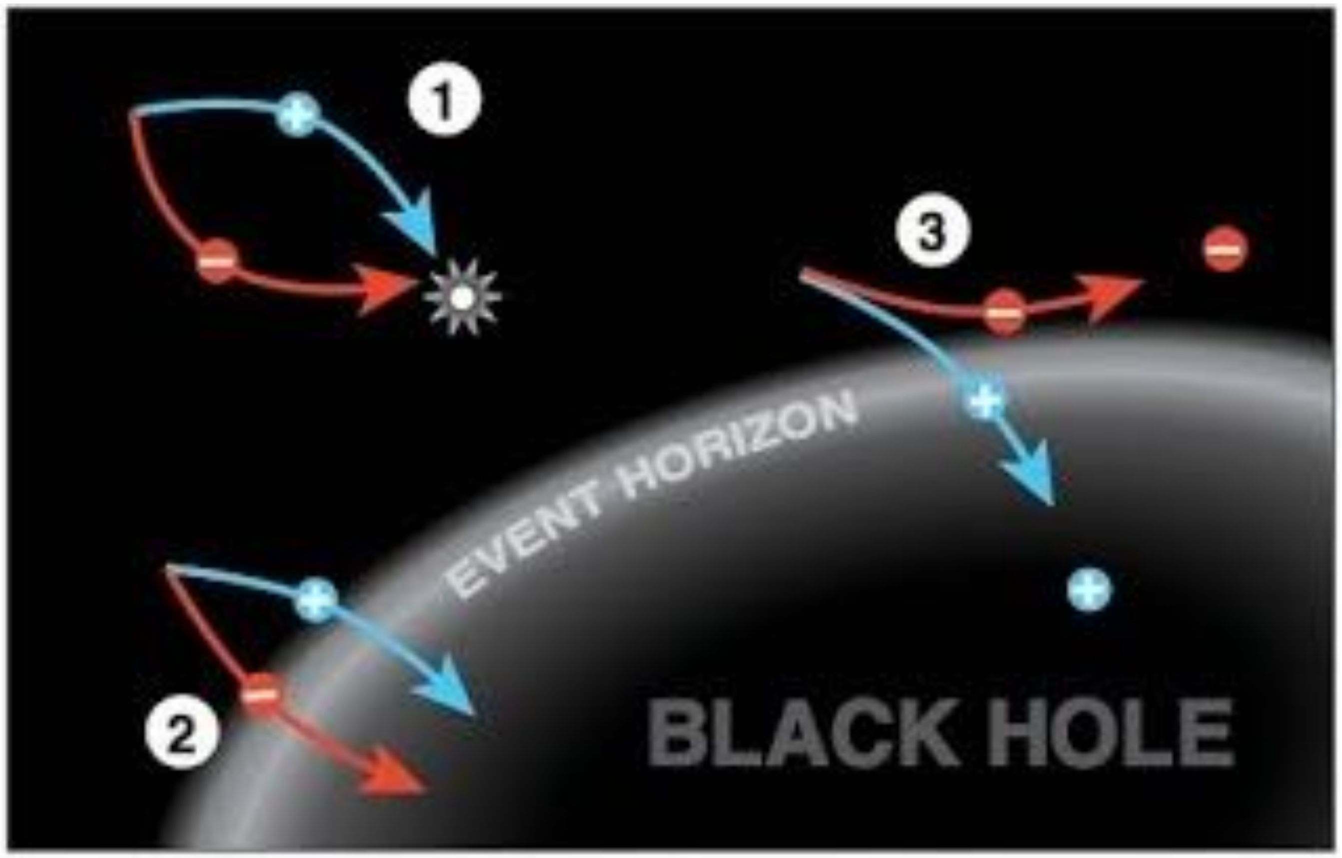
Flavor puzzles





- Quark and lepton masses? Origin of neutrino masses? $m_e/m_t \sim 10^{-6}, \; \Delta m_\nu^2 \sim 10^{-3}\text{eV}^2$
- Origin of matter asymmetry? $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (5.8 - 6.6) \times 10^{-10}$

Gravity and Big Bang



Cosmic refugees. Virtual particles that escape destruction near a black hole (case 3) create detectable radiation but can't carry information.

Path integral for gravity:

$$\int dg\, d\psi_{\rm SM}\, e^{i \int d^4x \sqrt{-g} \mathcal{L}_{\rm tot}},$$

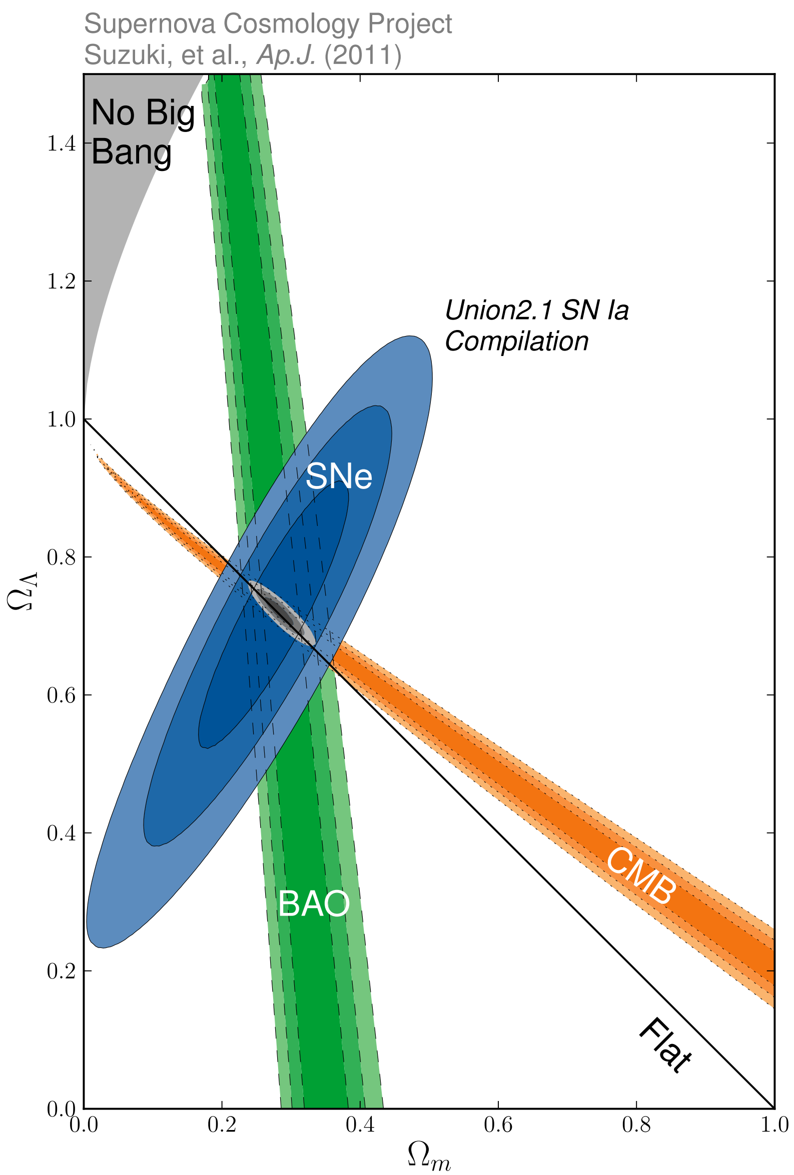
$$\mathcal{L}_{\rm tot} = \frac{1}{16\pi G} R - \Lambda + \mathcal{L}_{\rm SM}$$

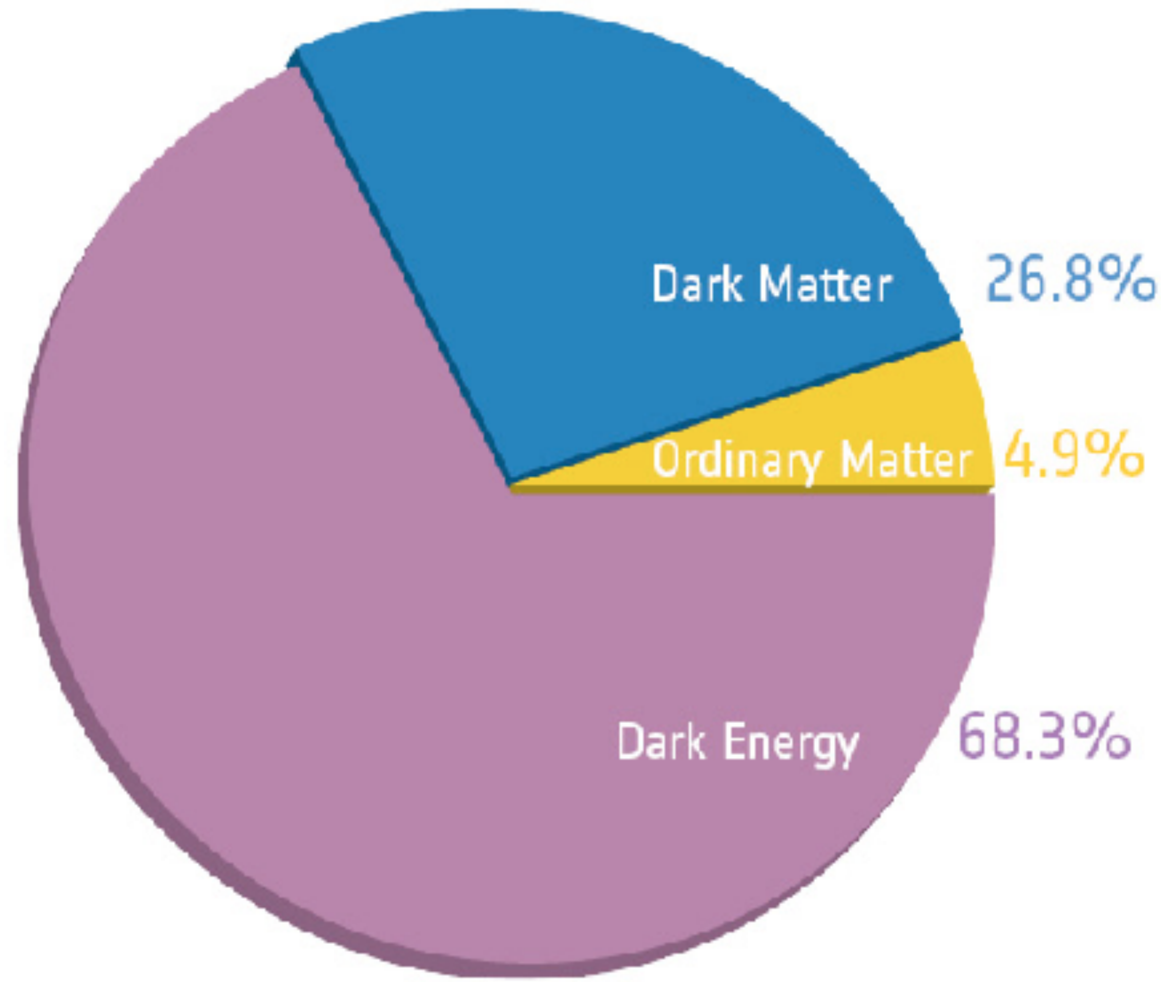
$$M_P^2 = \frac{1}{8\pi G},$$

$$\Lambda = 10^{-122} M_P^4 \ll M_P^4.$$

- Quantum mechanical description of gravity?
- Origin of initial conditions for Big Bang?
- Origin of Planck mass & Cosmological constant?

Dark matter and energy

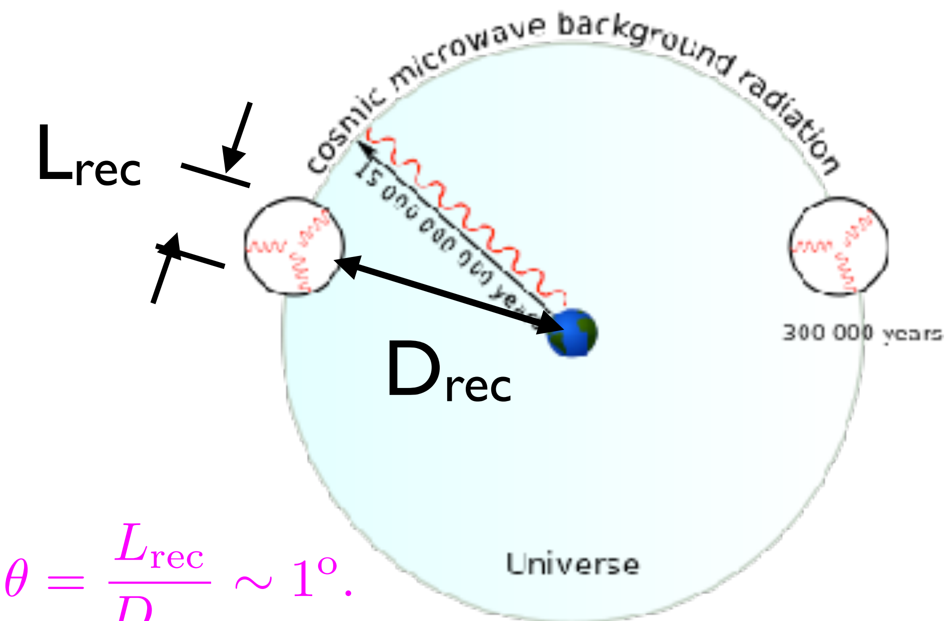




- Observed Universe is composed of 5% atoms and 95% of dark matter and dark energy.
- Origin of dark matter and dark energy?

Cosmic inflation

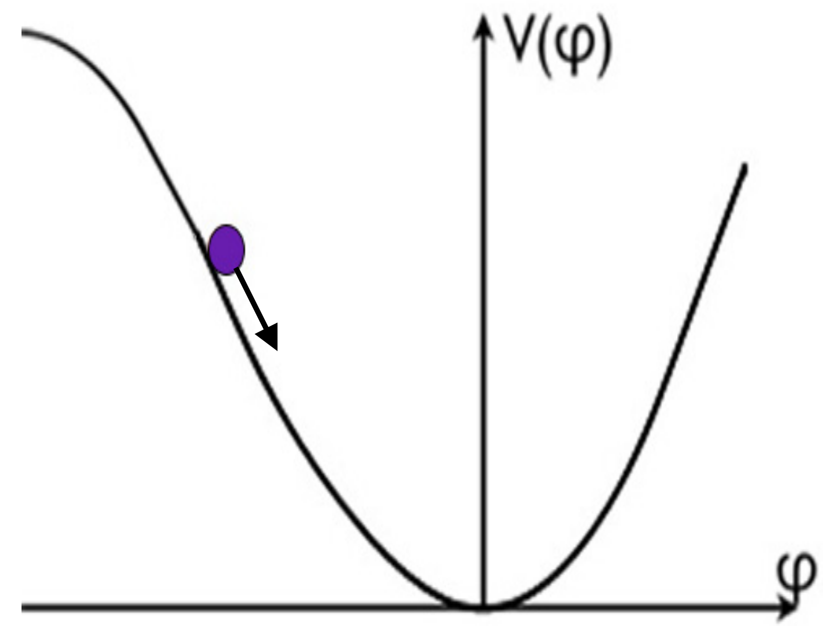
- Early varying vacuum energy with "inflaton" makes the expansion possible at all and sets the initial conditions.



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

Causally connected
at recombination

How uniform CMB 1 in 10^4 ?



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

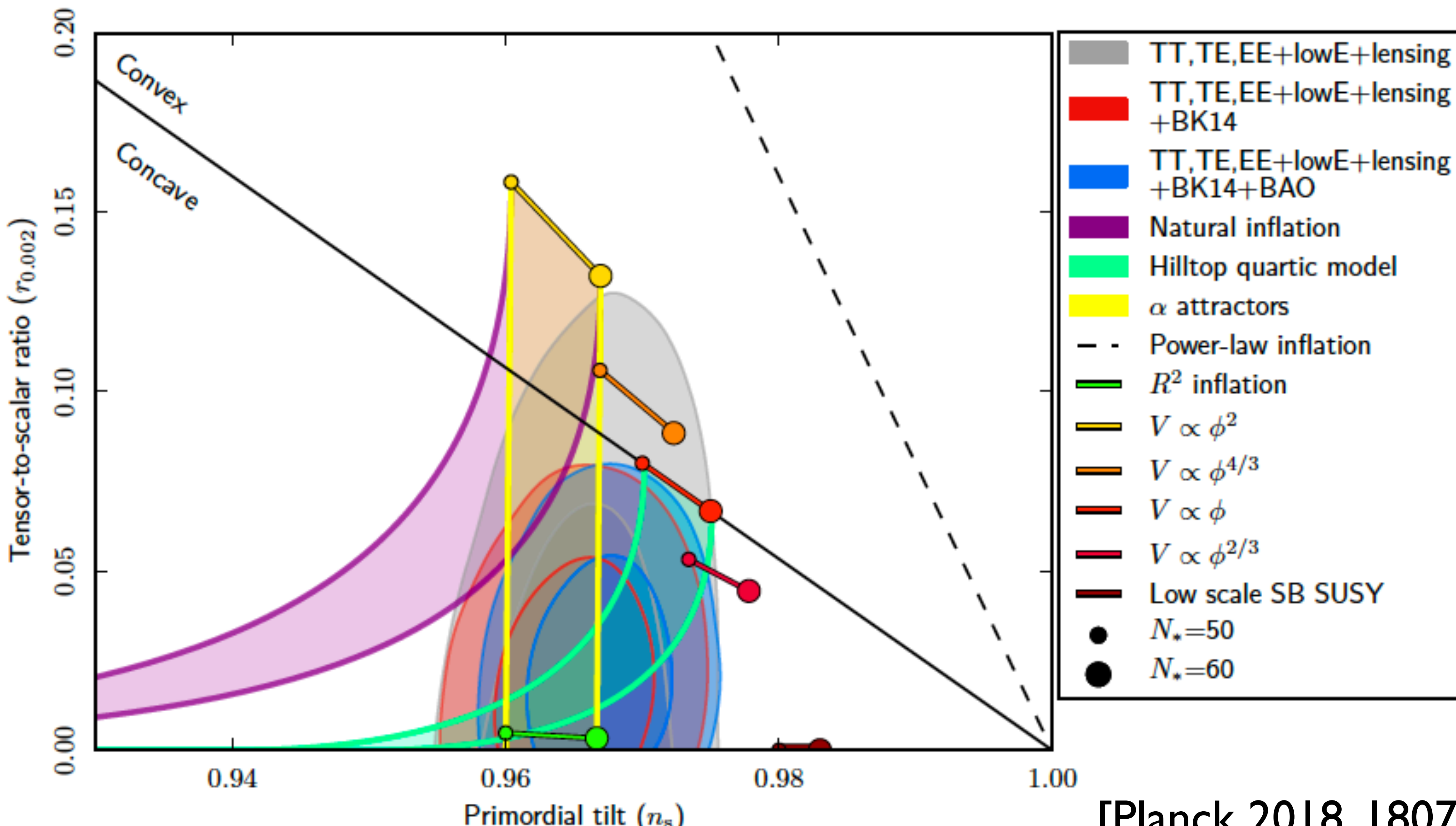
Number of efoldings:

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

- Slow-roll inflation is constrained by CMB anisotropies.

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

Planck data

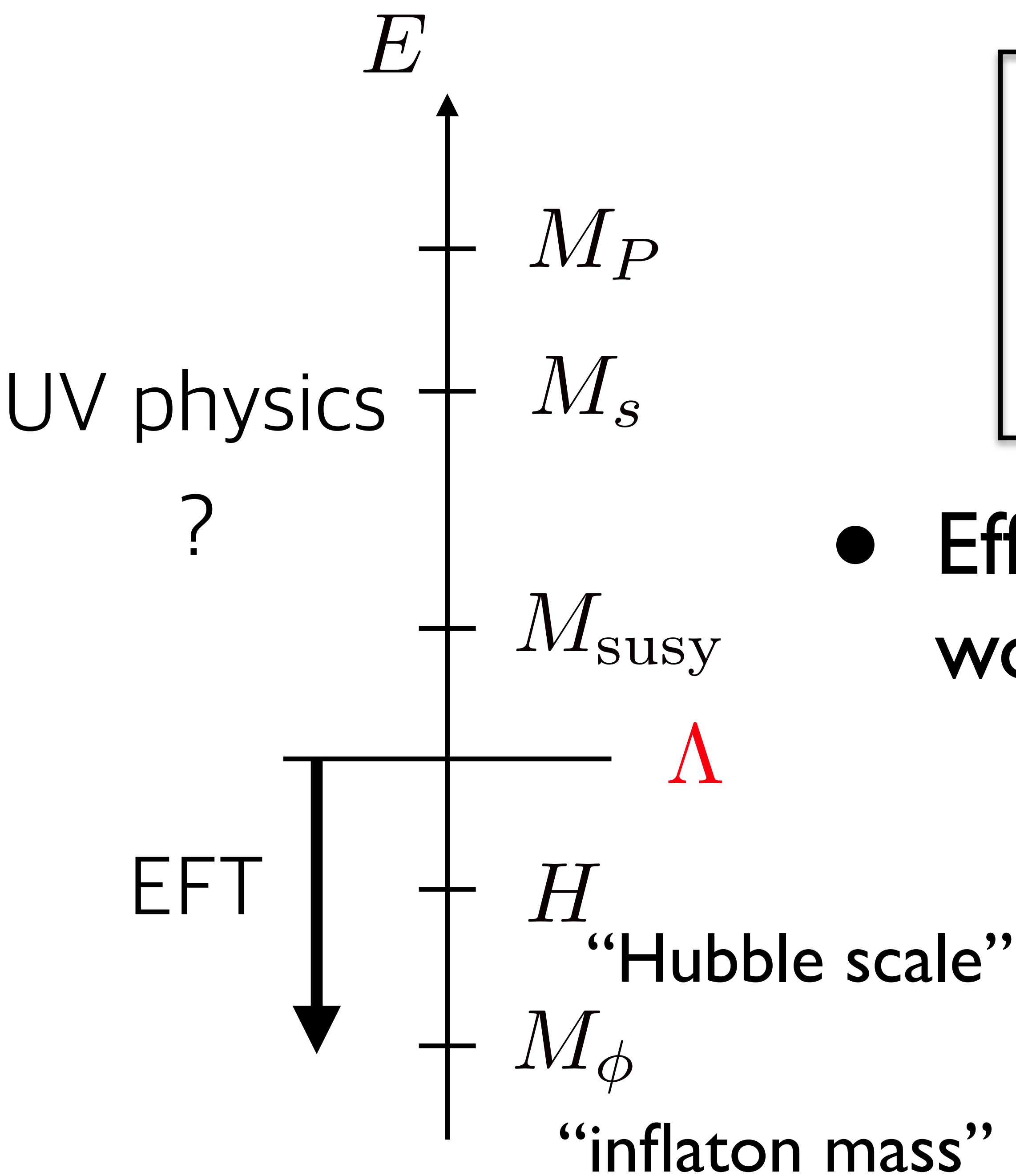


[Planck 2018, 180706211]

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

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

Inflation as EFT



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

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

- Effective field theory for inflation must work in a well-defined energy window.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{3} B\phi^3 - \frac{1}{4}\lambda\phi^4 - \sum_{n=1}^{\infty} \frac{c_n \phi^{n+4}}{\Lambda^n}.$$

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

Higgs inflation

[Bezrukov, Shaposhnikov (2007)]

- Bottom-up approach: Higgs boson as inflaton.

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

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

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

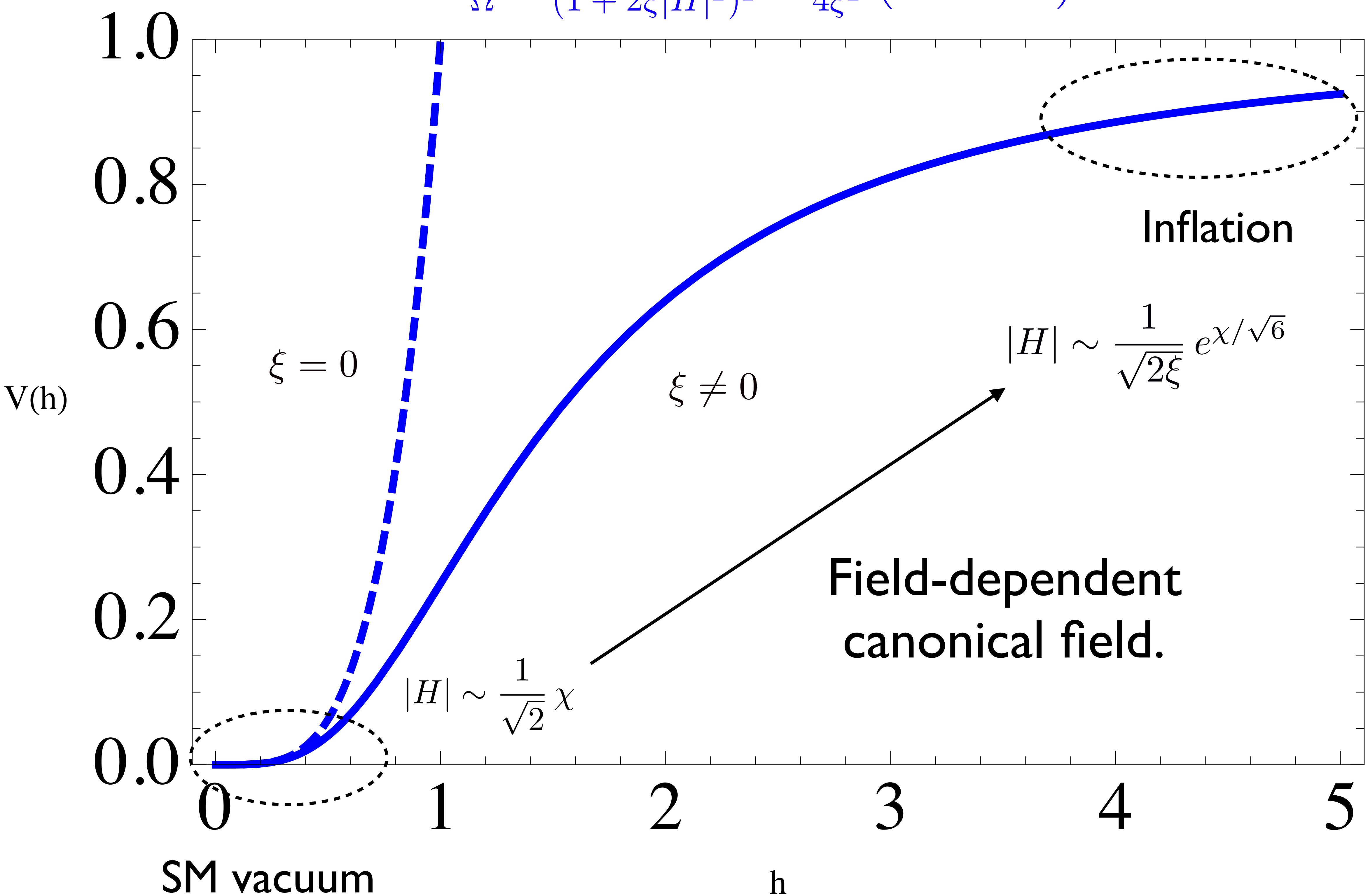
Adding a non-minimal coupling makes inflation work!

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

✔ $n_s = 1 - \frac{2}{N} = 0.966, \quad r = \frac{12}{N^2} = 0.0033$ "Perfect for Planck data"

Higgs inflation

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



Higgs inflation as EFT

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

- Higgs self-interactions

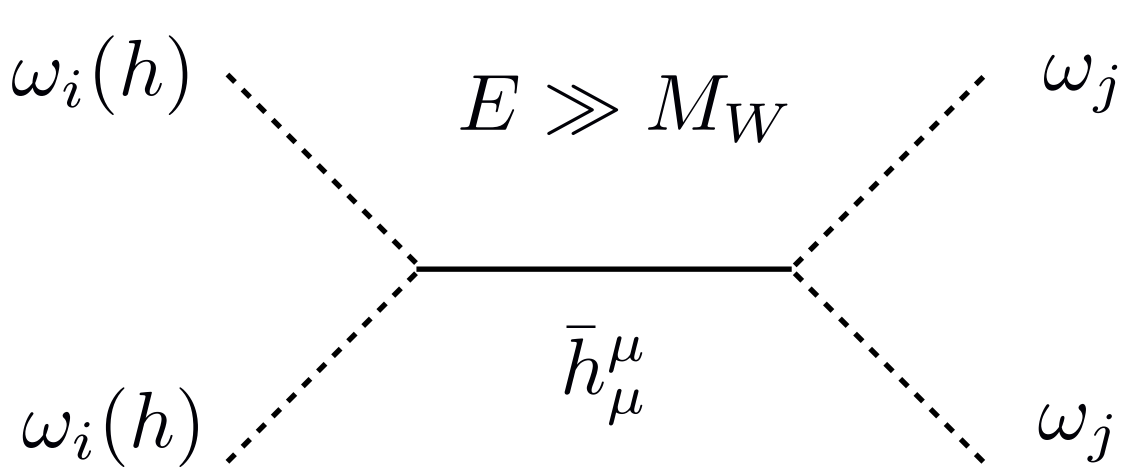
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -\omega_2(x) - i\omega_1(x) \\ \varphi(x) + h(x) + i\omega_3(x) \end{pmatrix}, \quad g_{\mu\nu}(x) = \hat{g}_{\mu\nu}(x) + \frac{h_{\mu\nu}(x)}{M_P}.$$

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

cf. Einstein frame:

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

- Effective field theory breaks down too early.



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

Unitarity bound ~ Hubble scale,

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

Beyond Higgs inflation

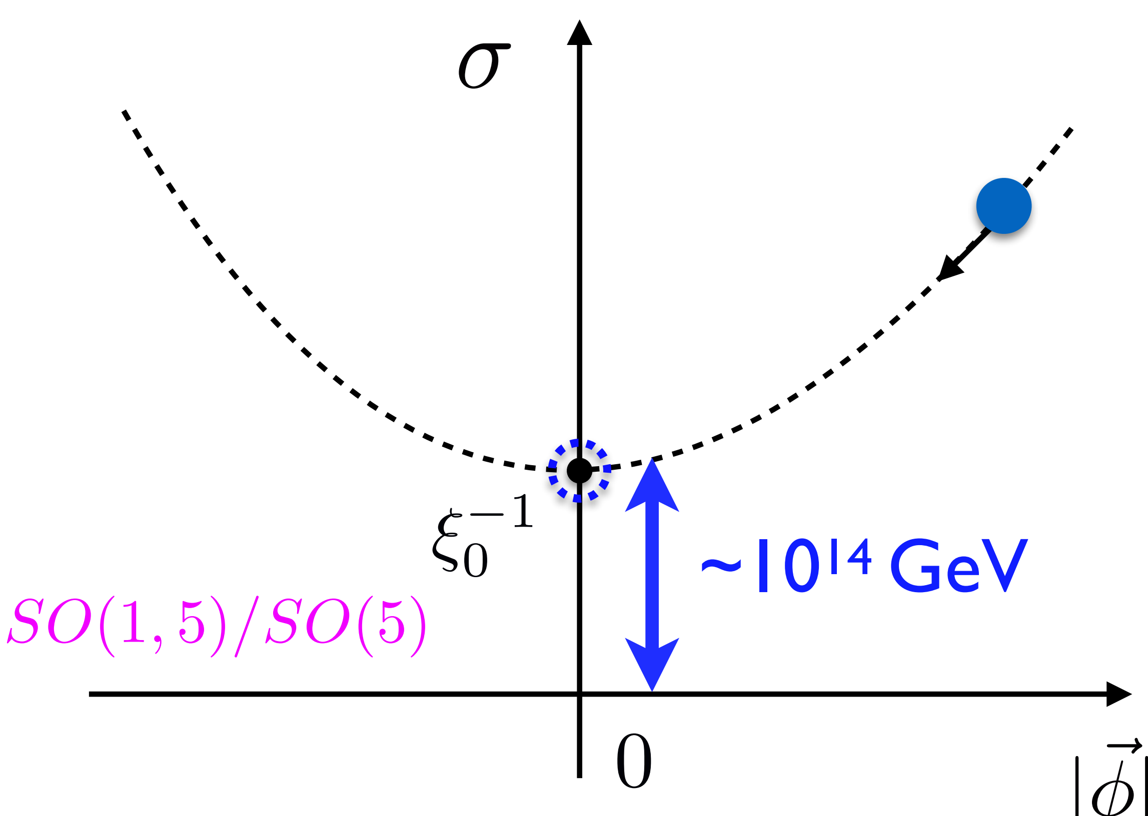
"Induced gravity" $\mathcal{L}_J = \sqrt{-g}\left[\underline{\xi_0\sigma^2\mathcal{R}} - \frac{1}{2}(\partial_\mu\sigma)^2 - \lambda\left(\sigma^2 - \vec{\phi}^2 - \xi_0^{-1}\right)^2\right]$

Planck mass is induced by loops: [Zee, Smolin (1979)]

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

⇒ Higgs inflation just as EFT: $\mathcal{L}_{\rm eff} = \sqrt{-g}(1+\xi_0\vec{\phi}^2)\mathcal{R}$

Higgs moves together with sigma field in hyperboloid!



[Giudice, HML (2010)]

1) SO(4)=>SO(1,5)/SO(5)

2) Higgs inflation-like.

3) Sigma field is very heavy.

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

Scalars dual to Starobinsky

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

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

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

Hubbard-Stratonovich transf.

- Starobinsky model as a UV completion?

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

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

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

$$\xi\hat{\sigma}^2 = 1 + \xi_H h^2 + \xi\sigma^2$$

"belongs to sigma-field models"

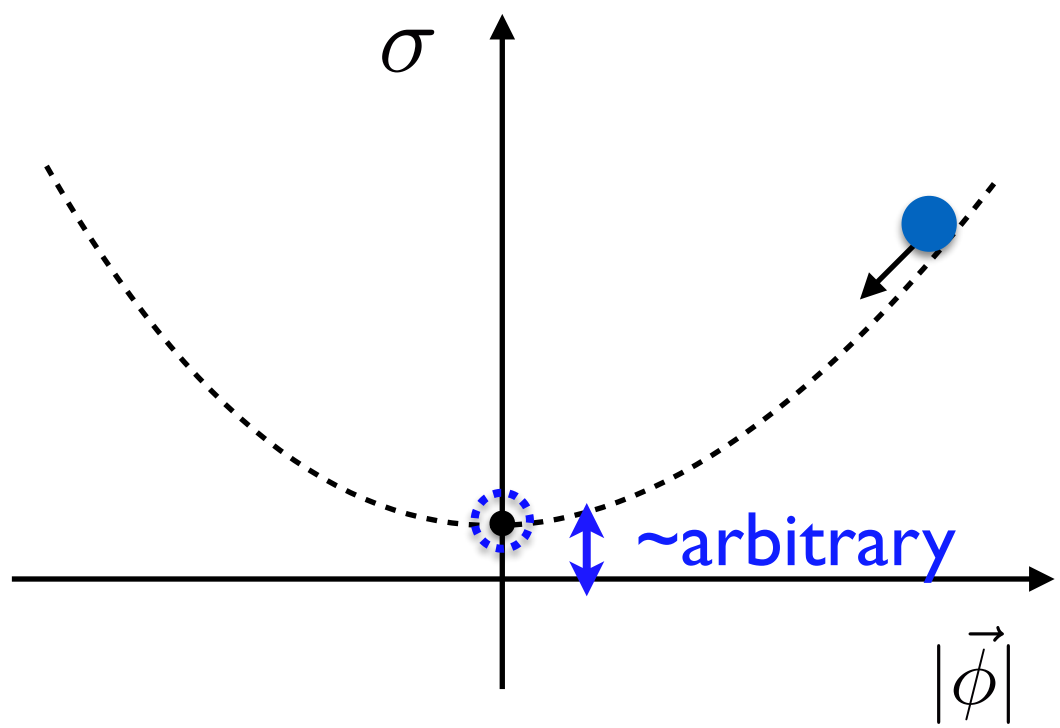
General sigma inflation

Generalize sigma models with linear non-minimal coupling.

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

[HML (2018)]

Stable gravity:	$\xi_1^2 < 4\xi_0$
Unitarity:	$\xi_1 \sim \sqrt{\xi_0}$



Large sigma-graviton mixing:

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

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

→

1) Sigma interactions are suppressed.
2) Sigma mass parameters can be arbitrarily small.

Effective inflaton potential

Two field dynamics for inflation:
$$\begin{cases} e^{\frac{2}{\sqrt{6}}\chi} = \xi_1\sigma + \xi_2\sigma^2 + \xi_H\phi^2, \\ \tau = \dfrac{\phi}{\sigma}. \end{cases}$$

"vacua with stabilized field ratio"

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

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

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

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

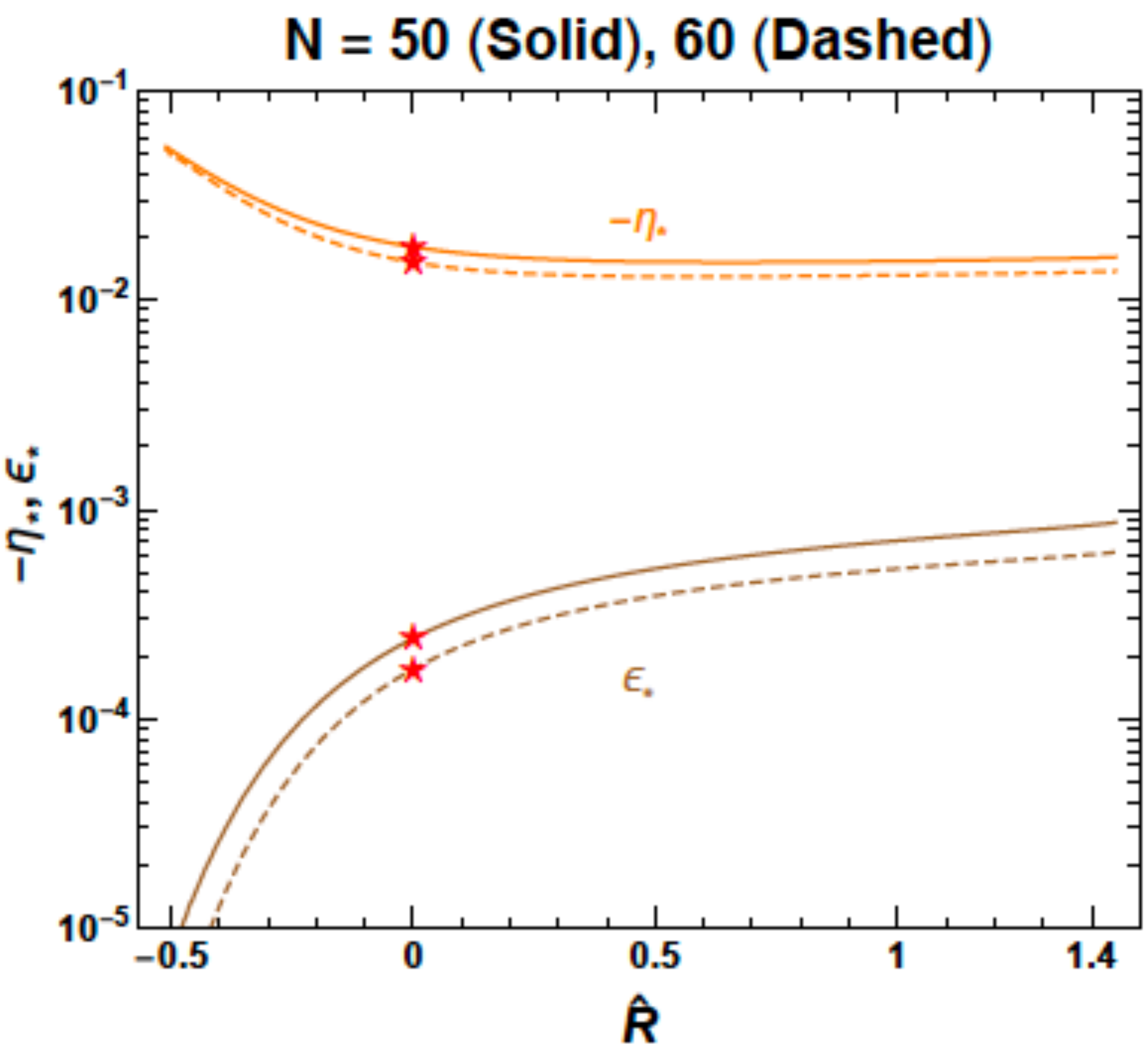
$\xi_2 \gg \xi_H = \mathcal{O}(1)$ assumed.

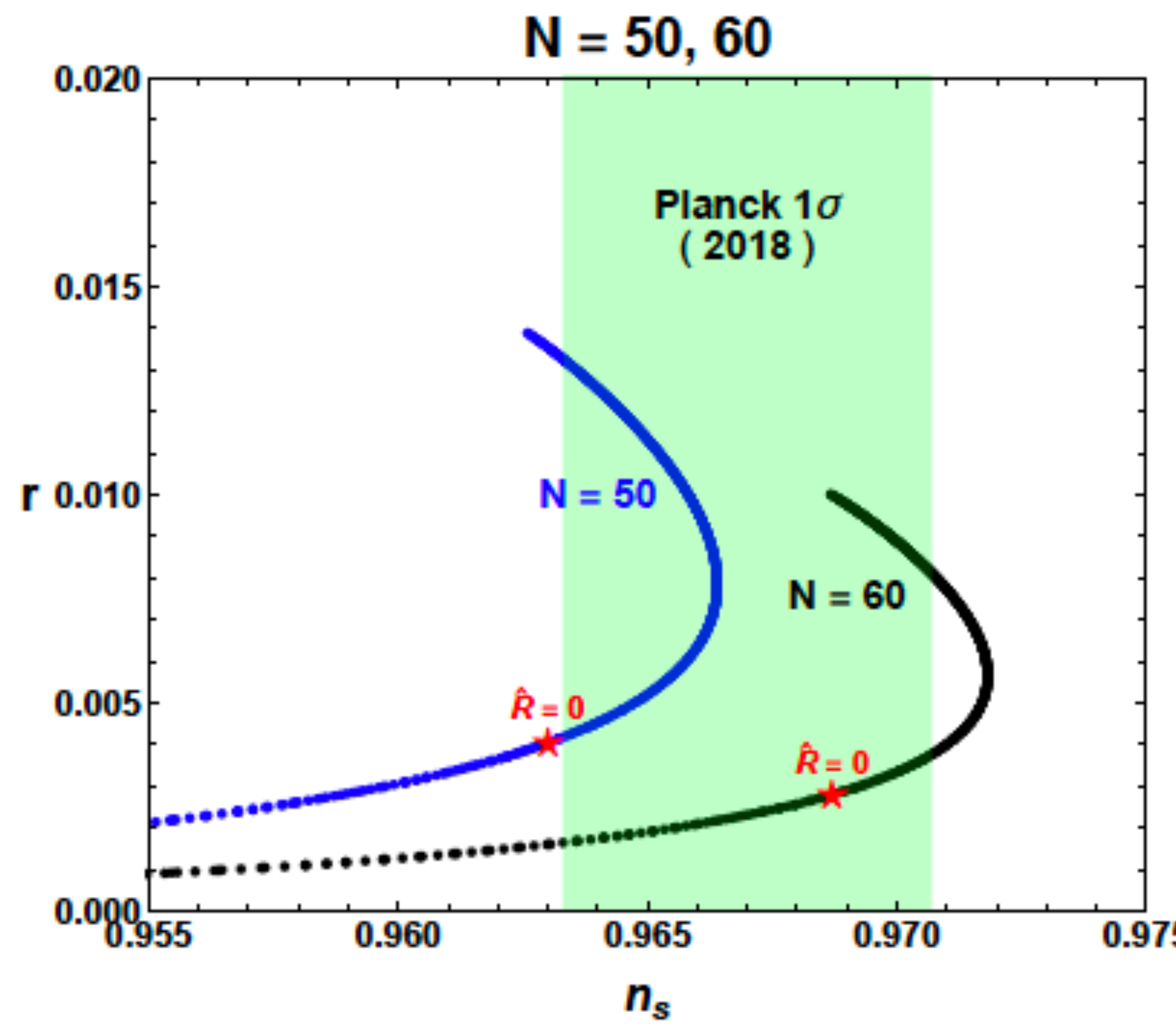
➡ $\chi \gg 1:$ **Higgs-sigma mixed or pure sigma inflation.**

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

Inflaton = radial component: $m_\tau \sim \sqrt{\xi_2 V_I} \gg m_\chi \sim \sqrt{|\eta| V_I}$

Tensor mode scales up!





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

★ Higgs inflation

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

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

Inflaton dark matter

Approximate Z_2 → **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 the trace of EM tensor:

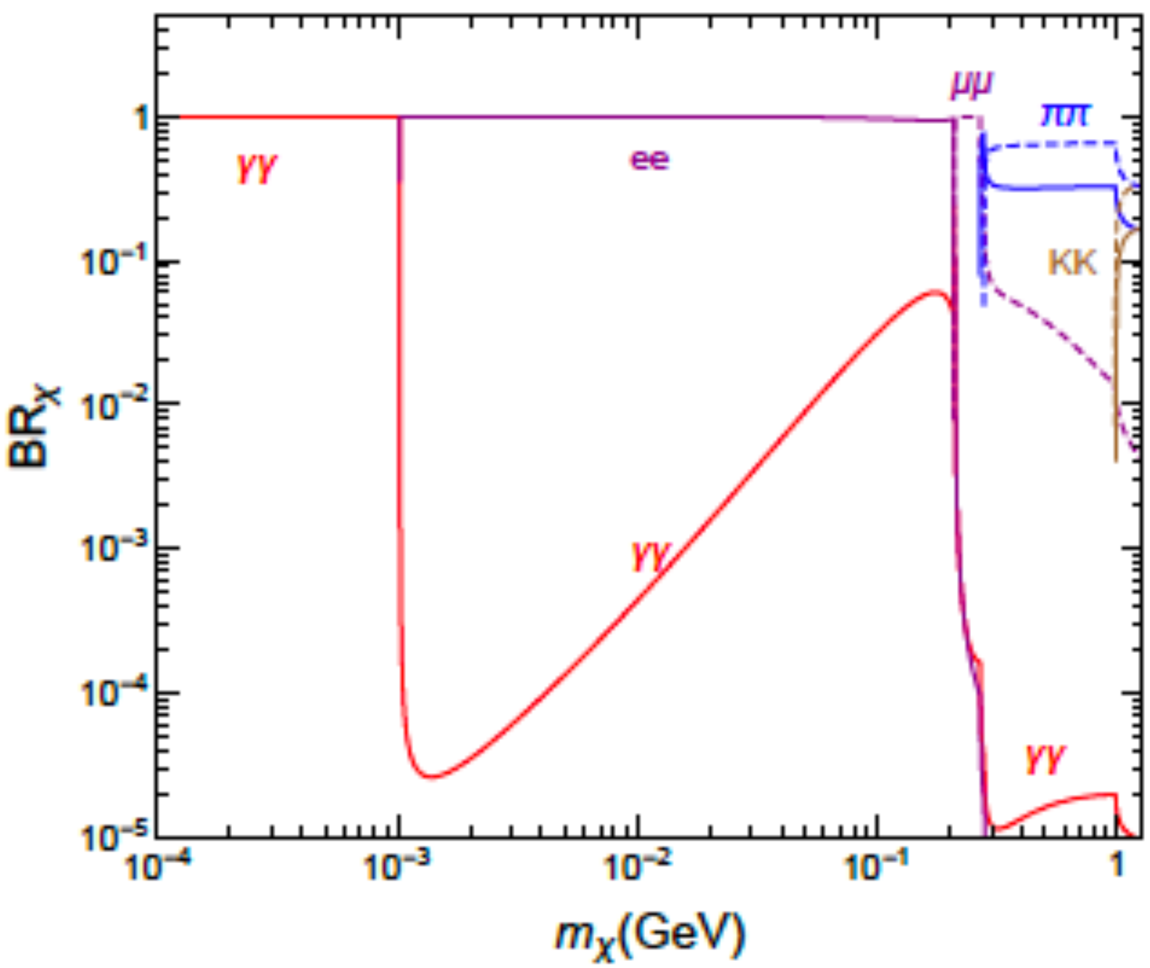
$$\mathcal{L}_\sigma=\frac{1}{2}\xi_1\sigma T^\mu_\mu\approx\frac{1}{2}\frac{\xi_1}{\sqrt{1+\frac{3}{2}\xi_1^2}}\frac{\chi}{M_P}T^\mu_\mu,$$

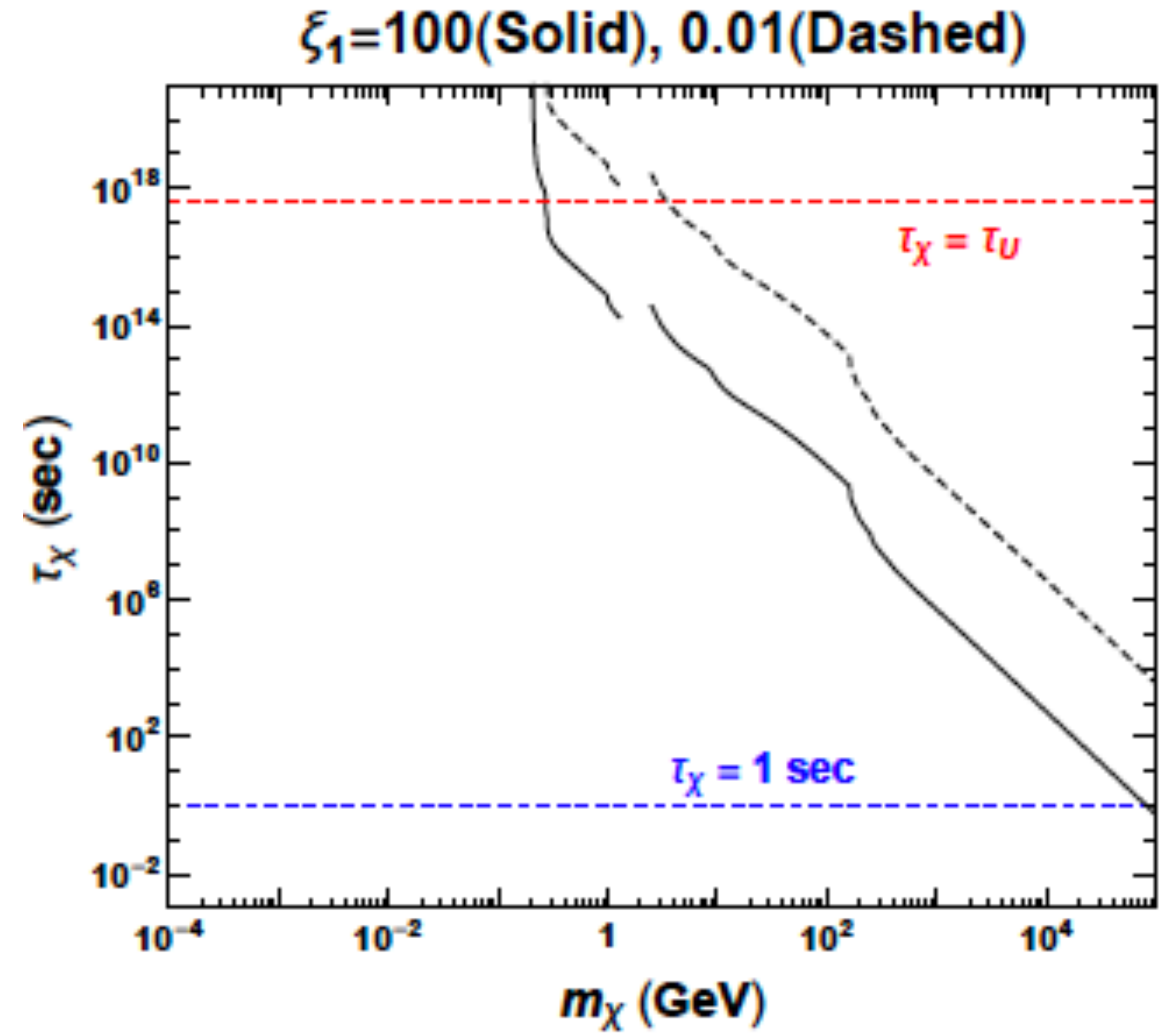
[Ibarra et al (2016); Choi, Kang, HML, Yamashita (2019)]

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

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

Long-lived inflaton





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

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

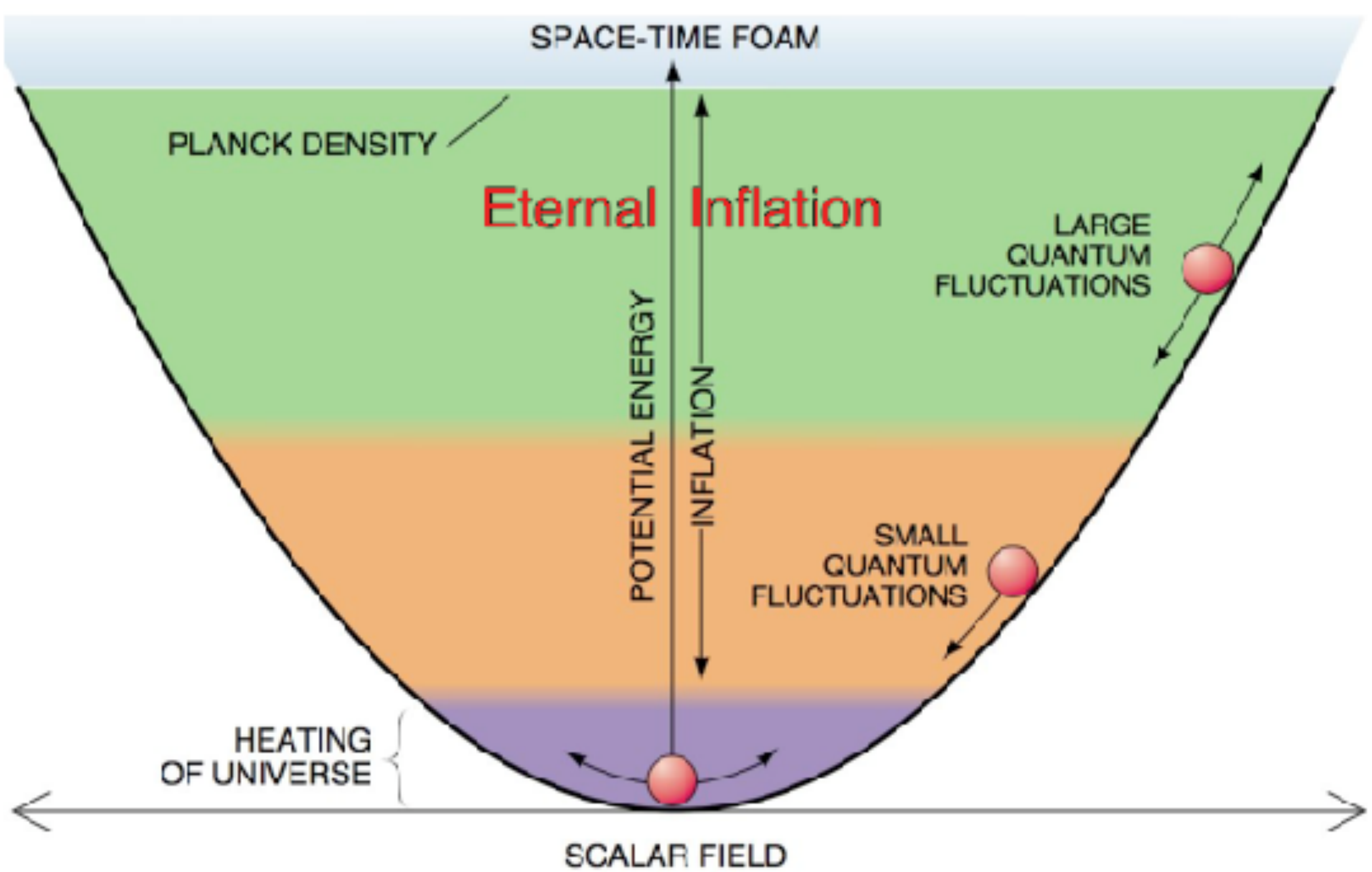
No CMB bound on inflaton for $m_\chi \lesssim 2\,\mathrm{MeV}.$

Reheating

- After inflation, the Universe is almost at zero temperature.

→ Reheating mechanism is required!

$$V(\phi) = \frac{m^2}{2}\phi^2$$

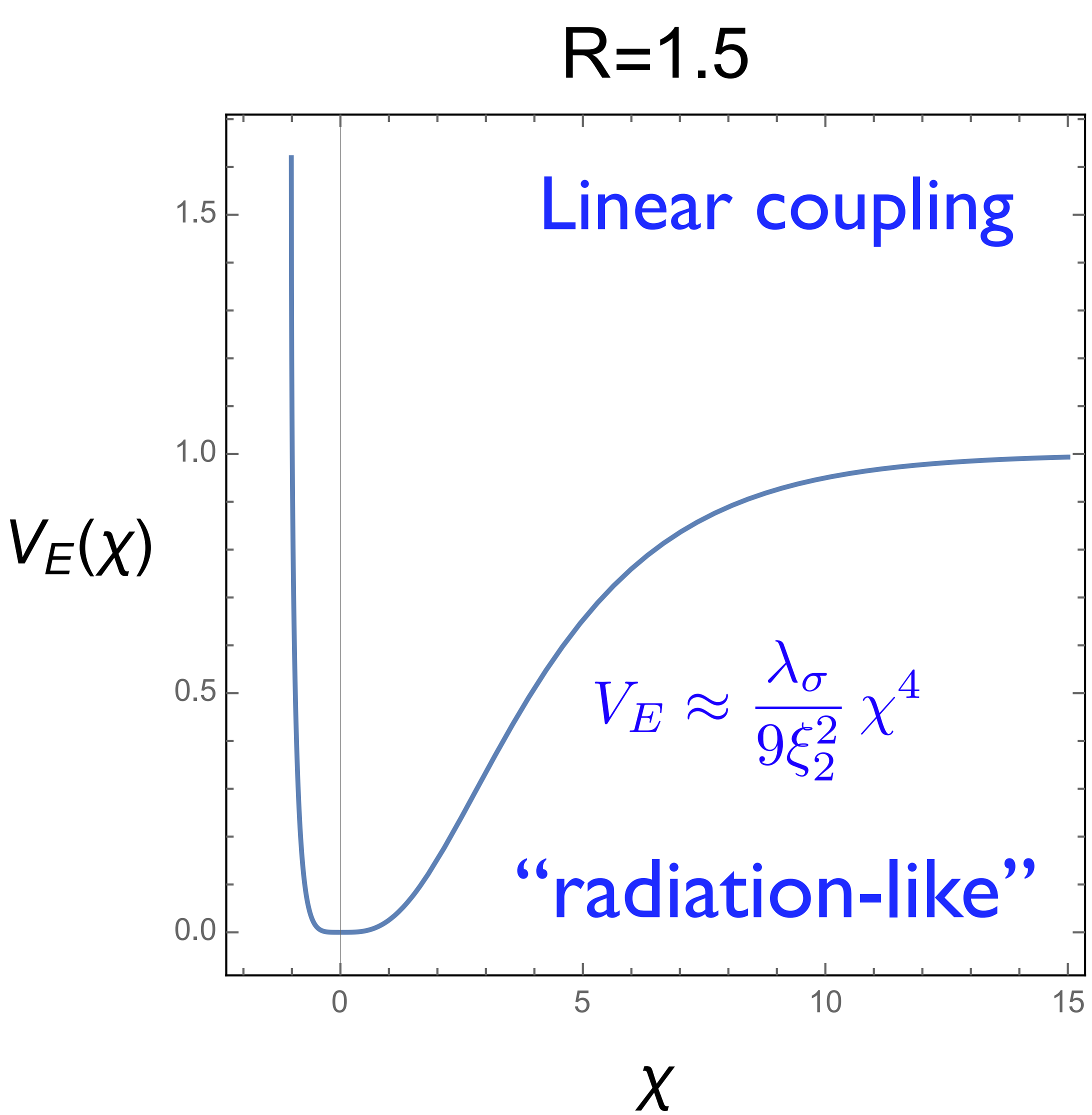


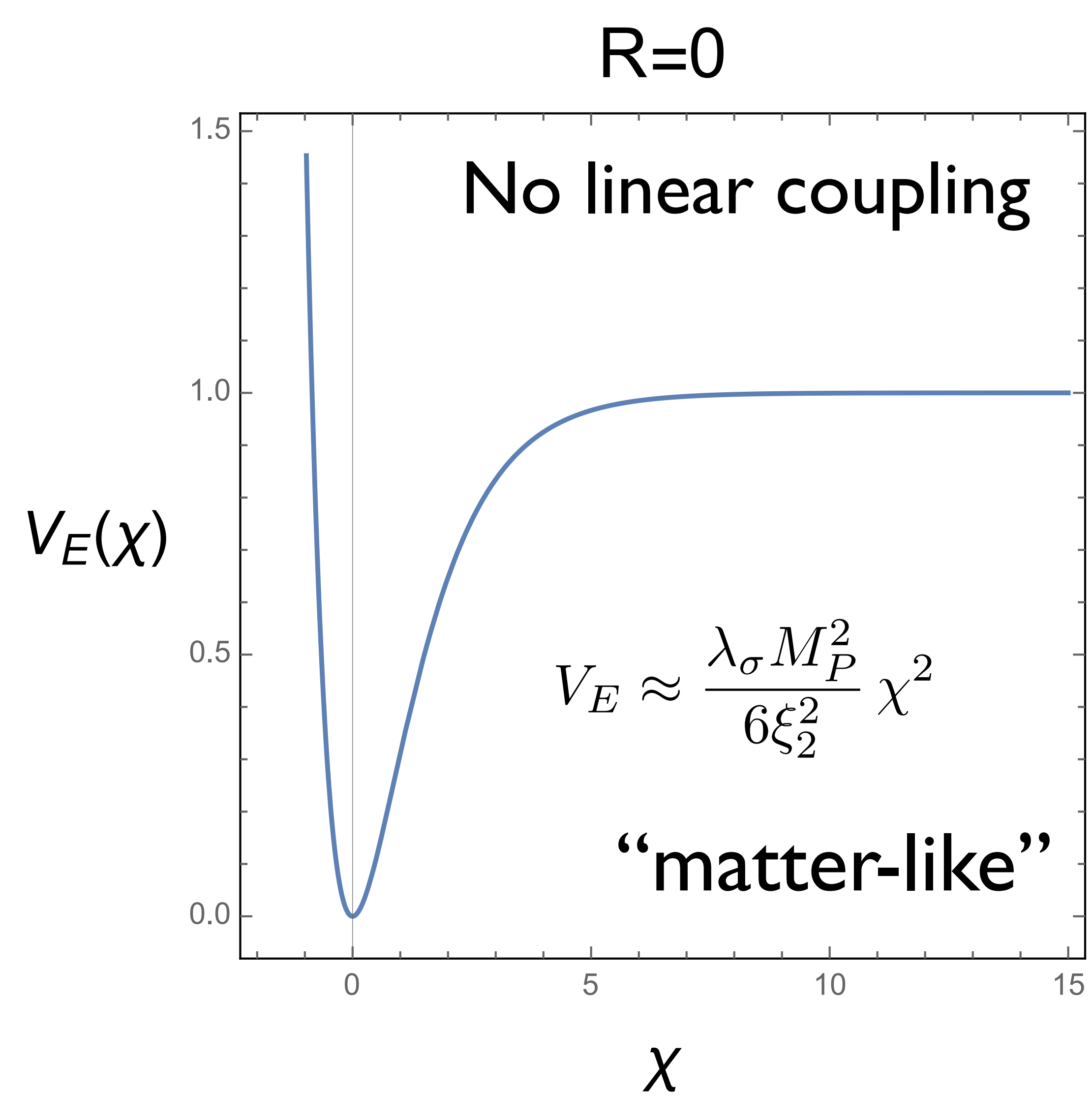
Reheating from sigma field

"Quartic potential" during reheating

$$\chi \approx \sqrt{\frac{3}{2}}\ln\Omega = \sqrt{\frac{3}{2}}\ln(1+\xi_1\sigma+\xi_2\sigma^2)$$ [Choi, Kang, HML, Yamashita (2019)]

$$\chi \lesssim 1: \qquad V_E \approx \frac{\lambda_\chi}{4}\chi^4, \qquad \lambda_\chi \equiv \frac{4\lambda_\sigma}{9\xi_2^2} = (5.3\times 10^{-10})R^{-4}\left(\frac{r}{0.01}\right)$$





Inflaton condensate

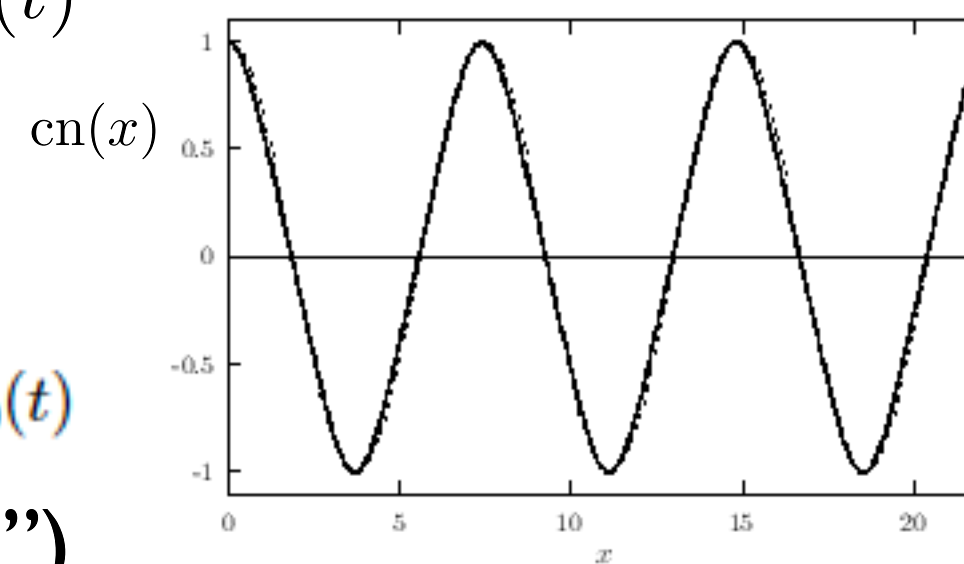
Inflaton condensate:

[P. Green et al, 1997; Tenkanen, 2016; Choi, Kang, HML, Yamashita (2019)]

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

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

$$\chi_0 = \chi_{\rm end}\sqrt{t_{\rm end}/t} \qquad \omega(t) = 0.85\lambda_\chi^{1/2}\chi_0(t)$$



1) Jacobi cosine form ("unharmonic")

2) Amplitude decreases due to expansion.

cf. matter-like: constant freq. $\chi_c(t) = \chi_0(t)\cos(mt), \quad H = \frac{2}{3t}.$

Particle production or decay from inflaton reheat!

"Preheating" (Particle production) — "Perturbative reheating" (decay)

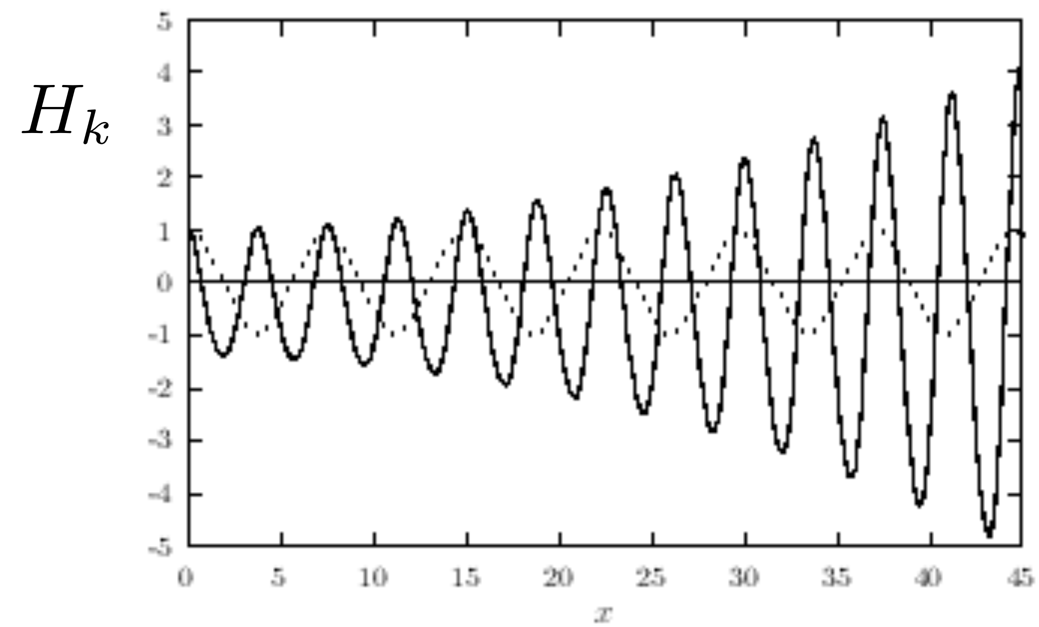
Preheating

Lame equations for Higgs perturbation

$H_k(t) = a(t)h_k(t)$:   [P. Green et al, 1997]

$$H_k'' + \left(\kappa^2 + \frac{\lambda_{\chi H}}{2\lambda_\chi}\,\mathrm{cn}^2\!\left(x, \frac{1}{\sqrt{2}}\right)\right) H_k = 0$$

$$\kappa^2 \equiv \frac{k^2}{\lambda_\chi \chi_0^2\, a(t)^2}$$ k: comoving momentum.



Growth of particle # with Higgs energy, $\omega_k^2 = \kappa^2 + \frac{\lambda_{\chi H}}{2\lambda_\chi}\,\mathrm{cn}^2\!\left(x, \frac{1}{\sqrt{2}}\right)$,

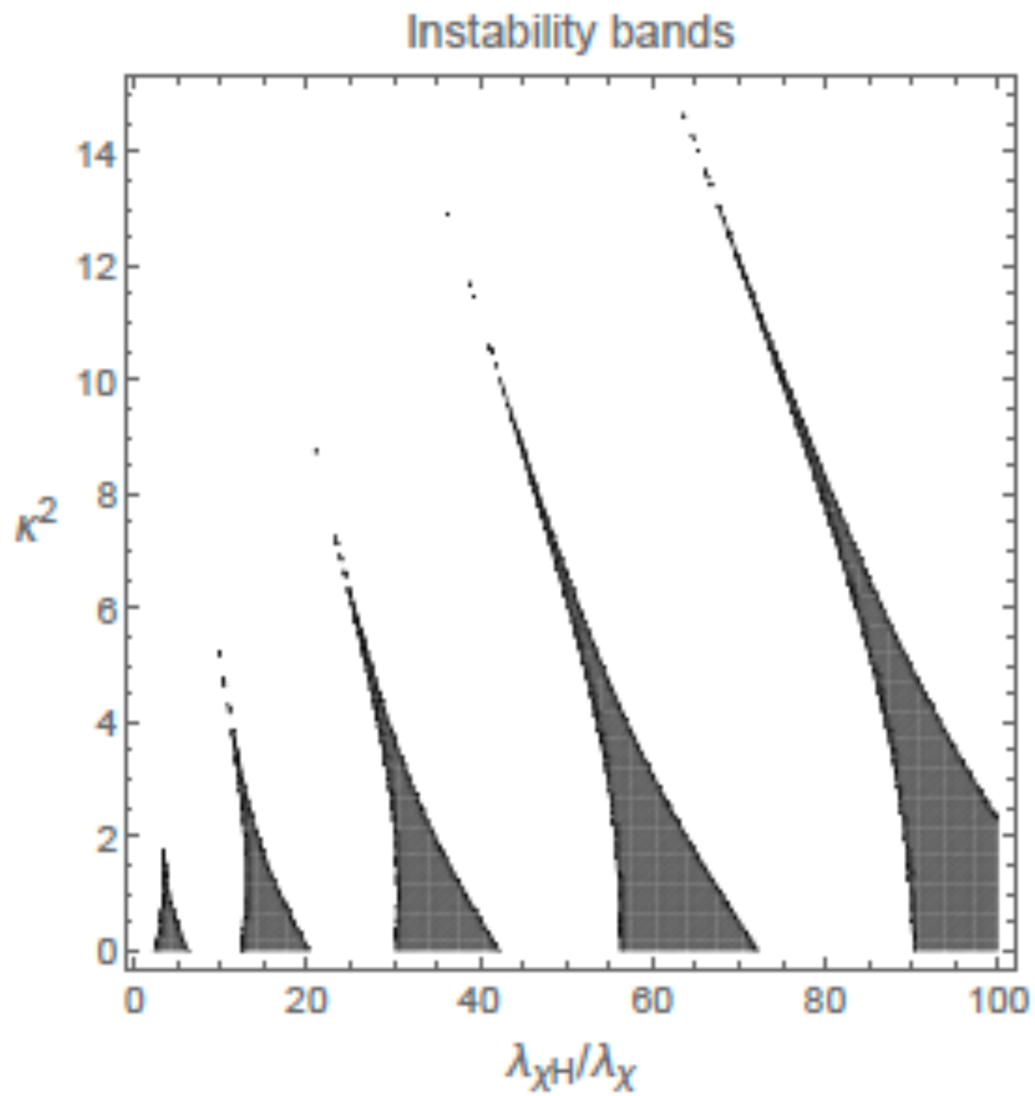
$$n_k = \frac{\omega_k}{2}\left(|H_k|^2 + \frac{|\dot{H}_k|^2}{\omega_k^2}\right) - \frac{1}{2} \Rightarrow n_k \sim e^{\mu_k x}, \quad x = (48\lambda_\chi)^{1/5}\sqrt{t}.$$

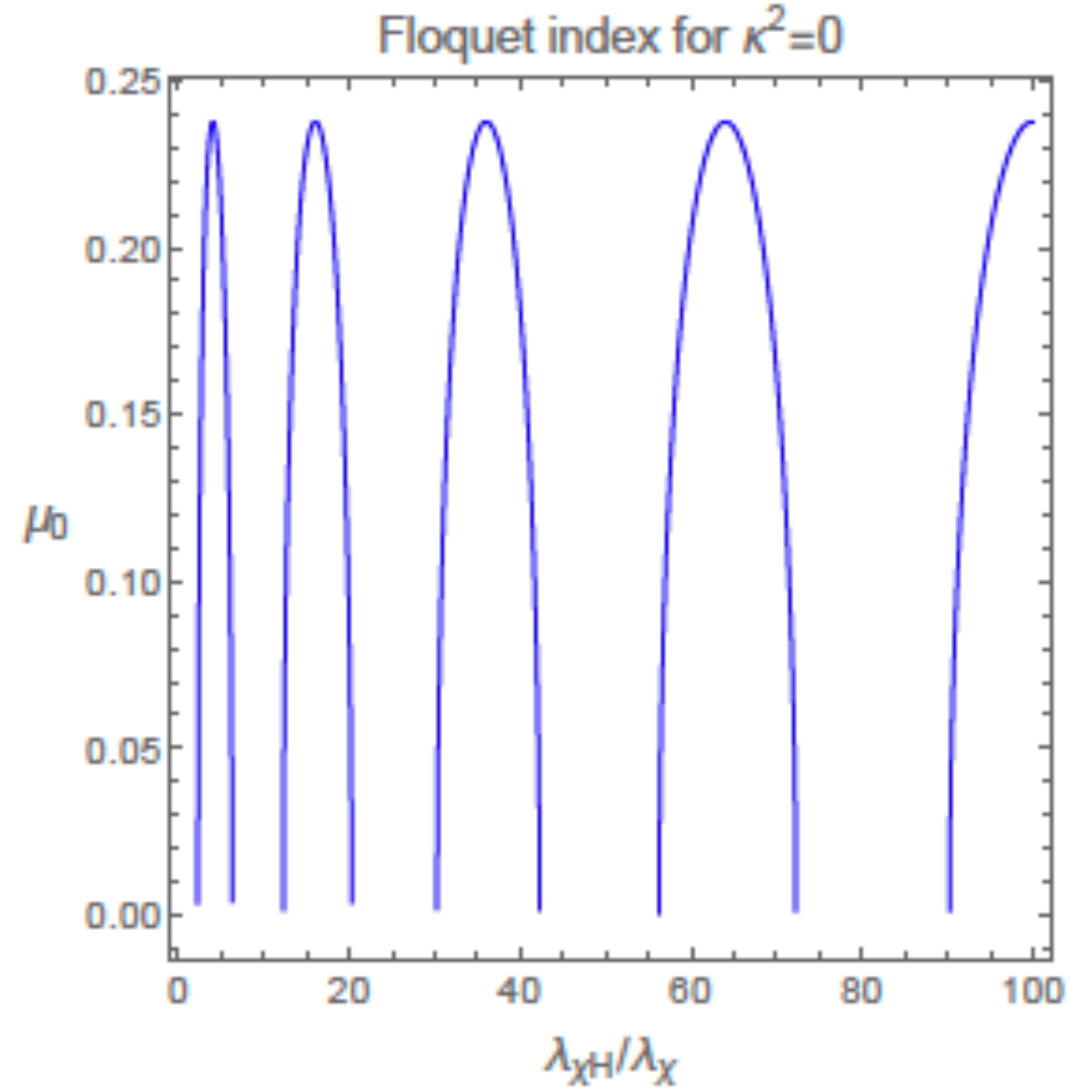
Preheating condition: $\frac{\dot{n}_k}{n_k} \sim 2\mu_k \dot{x} \gtrsim \Gamma_{\chi_c} \approx \Gamma_{\chi_c \to hh}$

$$\Rightarrow \quad \mu_k \gtrsim 2 \times 10^{-7} \left(\frac{\lambda_{\chi H}}{10^{-7}}\right)^2 \left(\frac{10^{-10}}{\lambda_\chi}\right)$$

[Choi, Kang, HML, Yamashita (2019v2, to appear)]

Preheating





Zero momentum: Broad resonance is efficient. High reheating!

Large momentum: Narrow resonance "Redshifted away"

Inefficient preheating → perturbative reheating!

Dark matter from reheating

Reheating temperature: [Choi, Kang, HML, Yamashita (2019)]

$$\Gamma_{\chi_c\to\chi\chi} = 0.023\lambda_\chi^{3/2}\chi_0, \quad \Gamma_{\chi_c\to hh} = 0.002\lambda_{\chi H}^2\lambda_\chi^{-1/2}\chi_0. \qquad \mathrm{BR} = \frac{\Gamma_{\chi_c\to\chi\chi}}{\Gamma_{\chi_c\to\chi\chi}+\Gamma_{\chi_c\to hh}}$$

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

$$T_{\rm RH} = (4.4\times10^6\,\mathrm{GeV})\Big(\frac{100}{g_*(T_{\rm RH})}\Big)^{1/4}\Big(\frac{\lambda_{\chi H}}{10^{-8}}\Big)^2 R^3\,(1-\mathrm{BR})^{-3/4}\Big(\frac{r}{0.01}\Big)^{-3/4}$$

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

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

DM = Dark radiation

Dark matter relativistic at production: "Dark Radiation"

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

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

$T_{\rm NR} > T_{\rm BBN}$

before BBN

$$m_\chi > 7.8\,{\rm keV}$$

If DM remains relativistic during BBN,

Dark radiation:

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

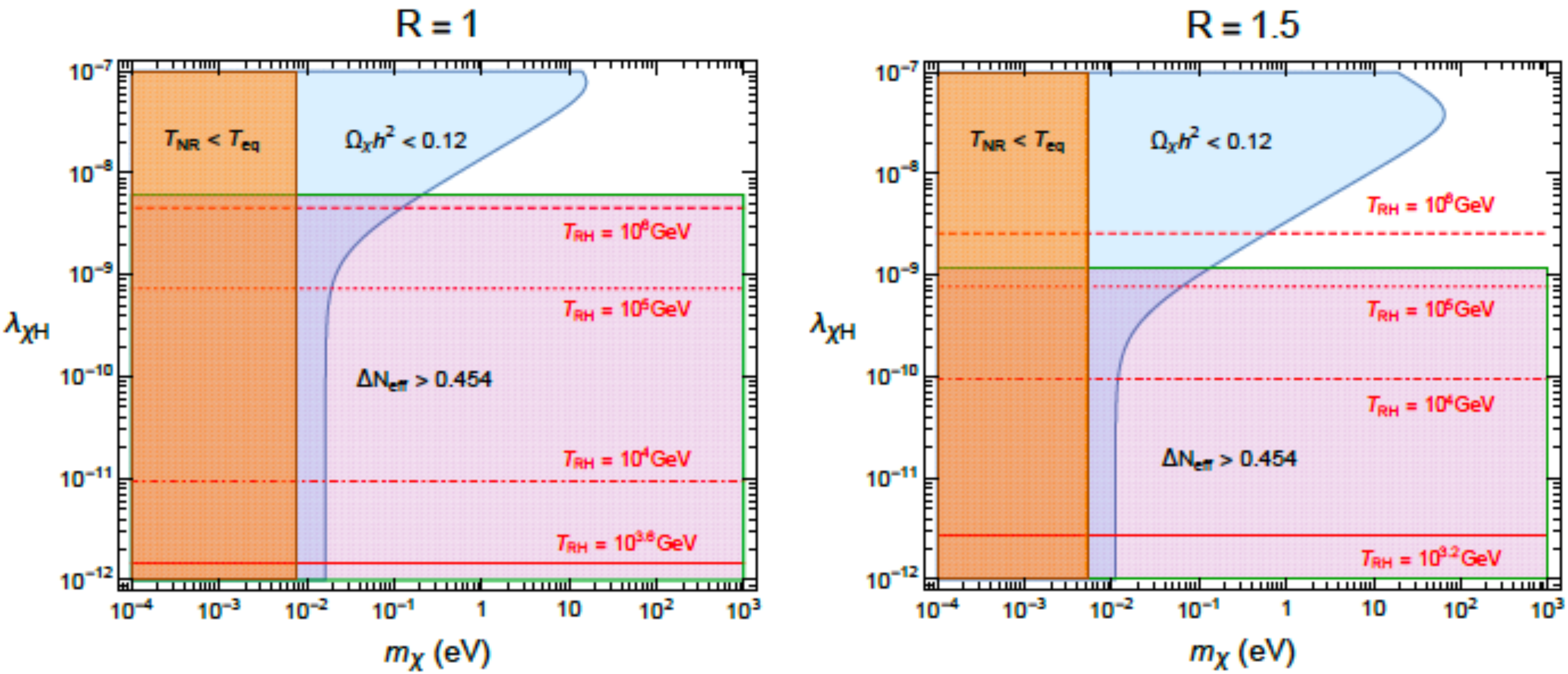
(a) $N_{\rm eff} = 2.93^{+0.23}_{-0.23}$
(b) $N_{\rm eff} = 3.04^{+0.22}_{-0.22}$
(c) $N_{\rm eff} = 3.06^{+0.22}_{-0.22}$

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

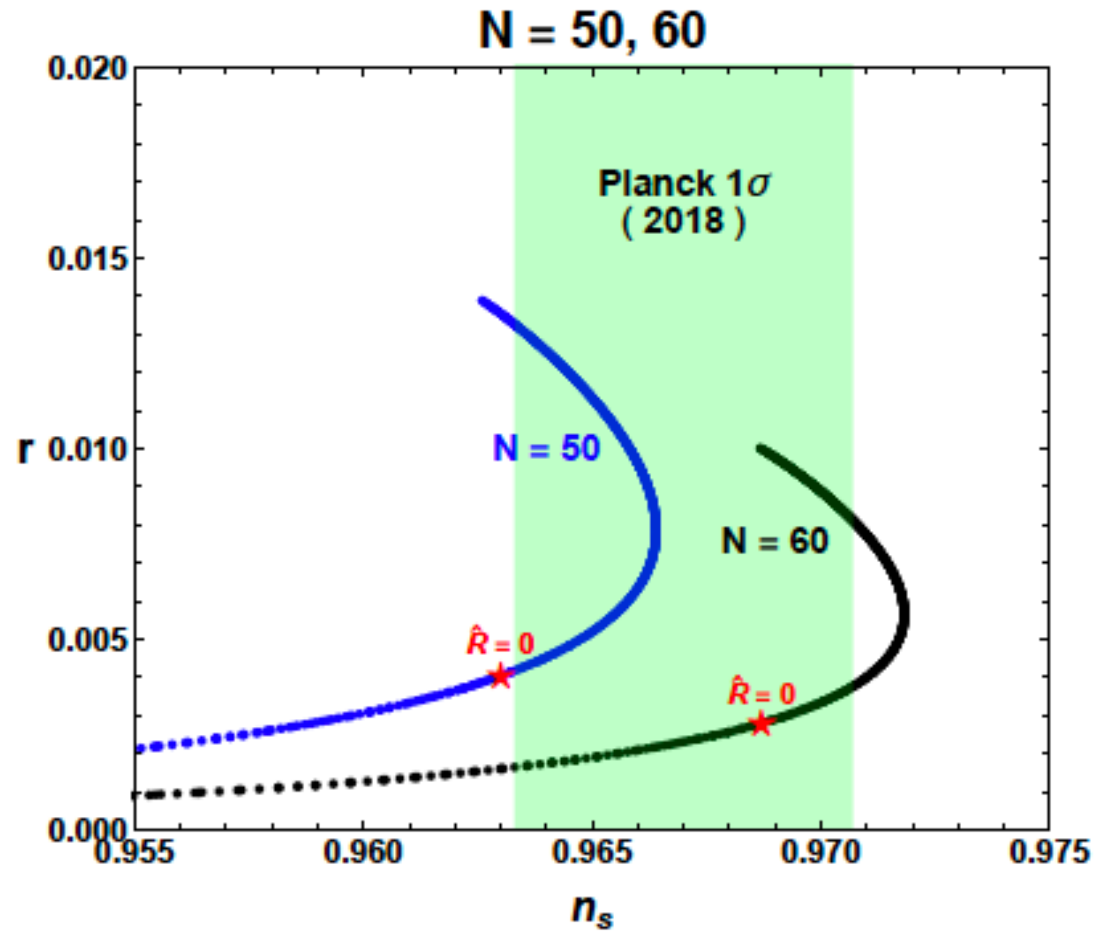
Inflaton dark matter

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

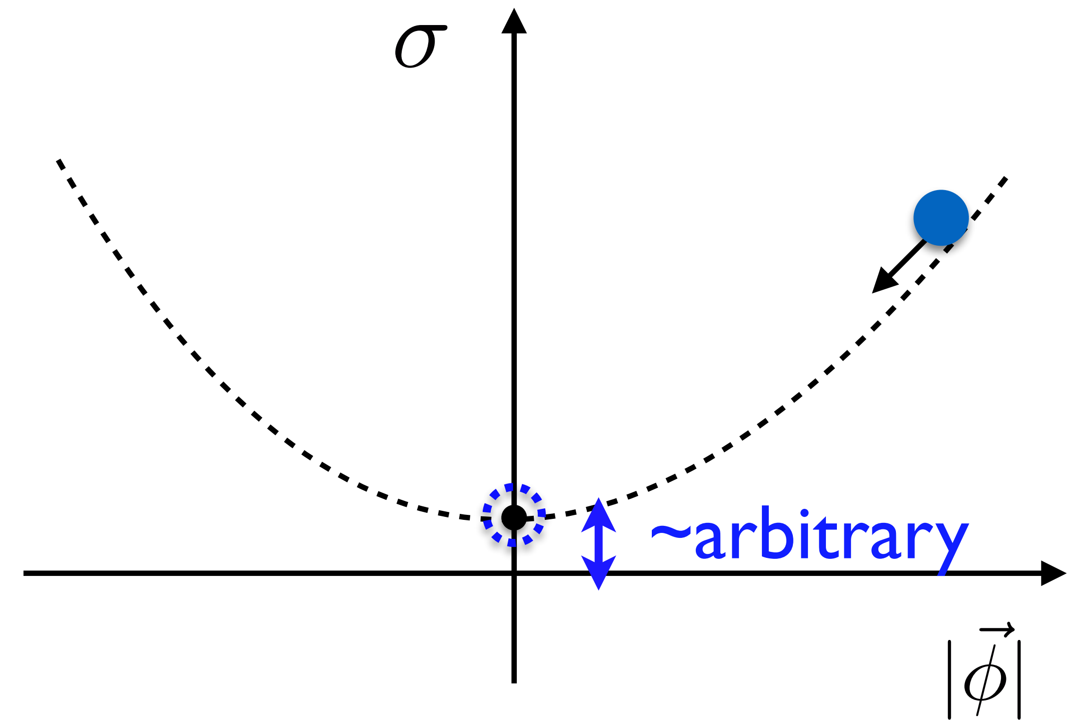


Blue: relic density, Purple: BBN, Orange: $T_{NR}<T_{eq}$

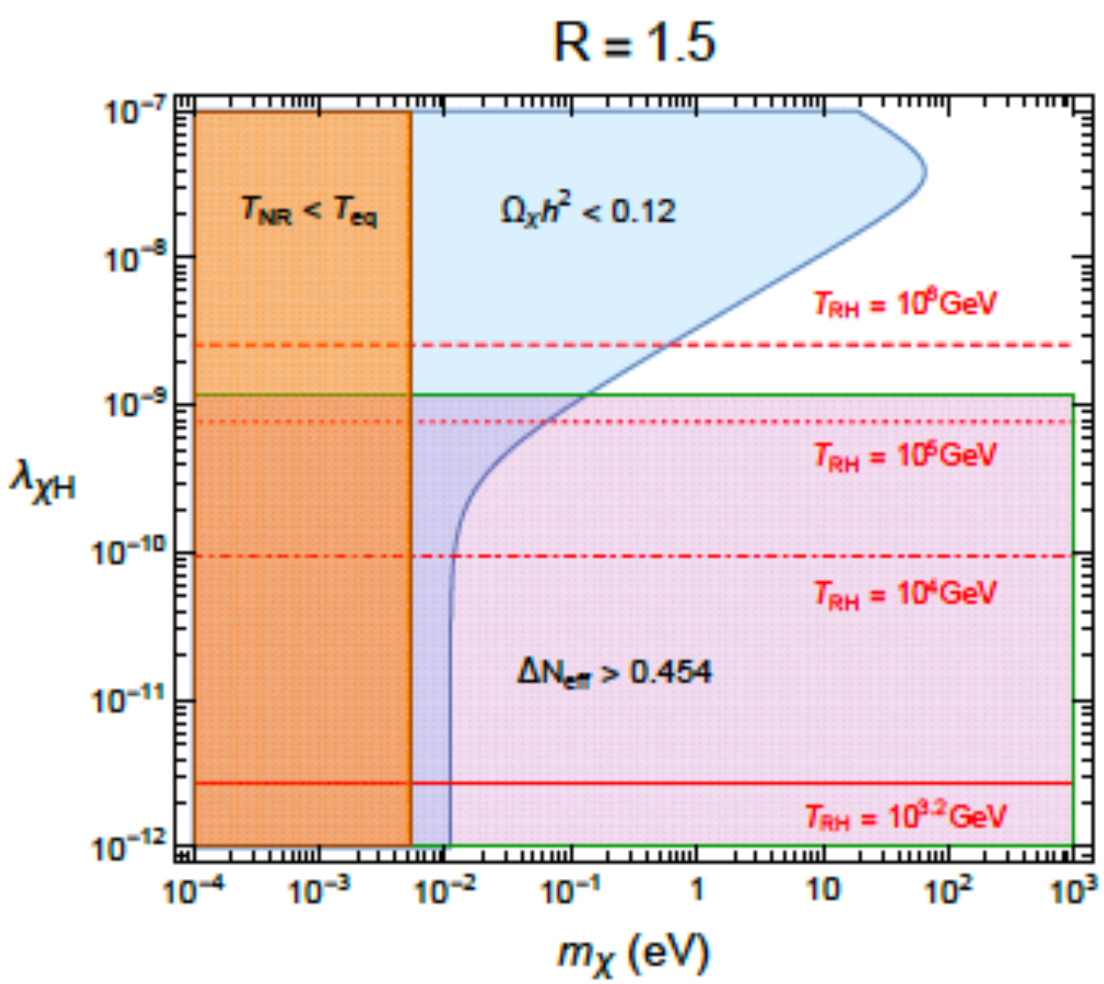
DM masses in the range of $0.1\,\mathrm{eV} \lesssim m_\chi \lesssim 100\,\mathrm{eV}$.



Inflation



Unitarity



Dark matter/radiation

Conclusions

- A general form of sigma models to unitarize Higgs inflation was proposed, covering various scalar-tensor theories valid below Planck scale.
- Large linear non-minimal coupling leads to sizable deviation in tensor mode up to r=0.01, novel reheating and small inflaton masses/parameters.
- Inflaton has suppressed couplings to the SM through the trace of energy-momentum tensor and small Higgs-portal coupling.
- Inflation is long-lived, becoming a viable candidate for decaying dark matter and dark radiation.