Baryogenesis and inflaton hunting at the LHC

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done in collaboration with:
Y. Cado, B. von Harling, E. Masso (2020-2022)

- The Standard Model of Particle Physics is a well defined (effective) theory valid up to the Planck scale and consistent with all present experimental data (LEP, Tevatron, LHC,…).

- However, there are some phenomena the SM cannot cope with, and which require the presence of New (BSM) Physics.

- These phenomena have to do more with Cosmology and Gravity than with Particle Physics.

- Baryogenesis
- Cosmological inflation
- Dark Matter
- Dark Energy

- Cosmology + Particle Physics
- Gravity + Particle Physics

In this talk I will concentrate in these issues

Contents

- Inflation and Higgs potential
- Baryogenesis by helical magnetic fields at inflation
- The model
-     Inflation
-     Gauge field production
-     Baryogenesis
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- Conclusions

Inflation and Higgs potential

- The SM Higgs potential has an instability at $h = h_I \simeq 10^{10} - 10^{11}$ GeV

- During inflation at N=# e-folds the probability of Higgs oscillation at the value h is

$$P(h, N) \simeq e^{-\frac{1}{2}\frac{h^2}{\langle h^2 \rangle}}, \quad \langle h^2 \rangle = \frac{H^2 N}{4\pi^2}$$

Espinosa et al. 1505.04825

- Condition to not find the Higgs away from its EW vacuum $P(h_I, N) < e^{-3N} \quad \Rightarrow \quad H < \sqrt{2/3}\frac{\pi}{N}h_I \simeq 0.04 h_I$ greatly constraining the inflationary model to low scale inflation

- High scale inflation requires Higgs potential stabilization

- Cosmological inflation is usually realized by an extra singlet scalar field ϕ: the inflaton

- We will associate the inflaton with the Higgs stabilizing field through the coupling $\mu\,\phi\,h^2$ which will constrain the value of μ and the inflaton mass $m_\phi < \mathcal{Q}_I$

- The inflaton, if coupled to the Chern-Simons density $\phi Y^{\mu\nu}\tilde{Y}_{\mu\nu}$ can trigger an explosive production of helical hypermagnetic fields

- Helical fields, if they survive till the EW phase transition, can generate the baryon asymmetry of the universe

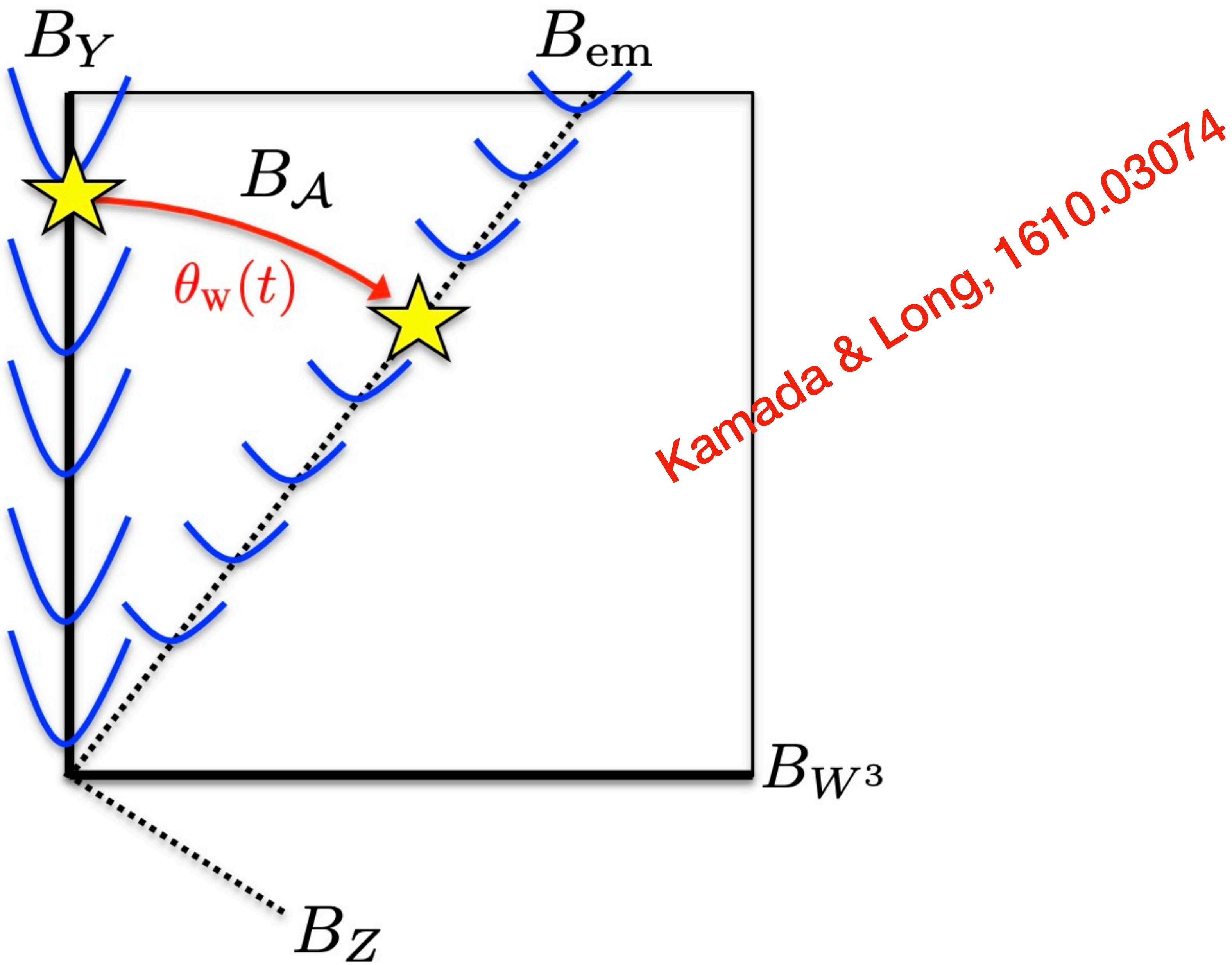
Baryogenesis by helical magnetic fields at inflation

- If the inflaton is coupled to the hypercharge Chern-Simons density it can generate helical magnetic fields B_Y with helicity $\mathscr{H}_Y$

- Due to the chiral anomaly the generation of helicity is accompanied by the generation of chiral fermion $f_{L,R}$ with particle-antiparticle asymmetry

$$\Delta Q_B = \Delta Q_L = N_g \left(\Delta N_{CS} - \frac{g_Y^2}{16\pi^2} \Delta \mathscr{H}_Y \right)$$

During the EWPT from unbroken to broken electroweak symmetry: $\mathscr{H}_Y \to \mathscr{H}_{EM}$



Now W_μ^a get thermal mass and the weak angle $\theta_W = \theta_W(T)$

- $\mathscr{H}_Y$ contributes to $\Delta(B+L)$, but $\mathscr{H}_{EM}$ does not

- The B_Y is not fully converted to B_{EM} at the EWPT, $T_{EWPT} \simeq 160$ GeV, and still remains when EW sphalerons freeze out at $T = T_{fo} \simeq 130$ GeV

- Therefore the source term from $\mathscr{H}_Y$ remains active while the washout of EW sphalerons goes out of equilibrium

$$\eta_B \simeq \frac{17}{1184\,\pi^2}(g_Y^2 + g_W^2)\frac{\mathscr{H}_Y T_{\rm rh}}{M_{\rm Pl}^2 H_{\rm inf}^2}\left[\frac{f_{\theta_W}}{\gamma_{W\rm sph}}\frac{H}{T}\right] \quad @\ T = 135\ GeV$$

$$\gamma_{W\rm sph} \simeq \exp\left(-147.7 + 107.9\,\frac{T}{130\,\rm GeV}\right)$$

Crossover lattice calculation

$$5.6 \times 10^{-4} < f_{\theta_w} \equiv -\sin(2\theta_W)\,d\theta_W/d\log T < 0.32$$

The model

The model is defined by the Lagrangian

$$\mathscr{L}_J = -\frac{M_p^2}{2}R - \frac{g}{2}\phi^2 R + \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \phi)^2 - U(\phi, h) - \frac{\phi}{4f_\phi}Y^{\mu\nu}\tilde{Y}_{\mu\nu}$$

Jordan frame

$$U(\phi, h) = U_{\rm SM}(h) + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\lambda_{\phi h}\phi^2 h^2 + \frac{1}{4}\lambda_\phi \phi^4 - \sqrt{\frac{\delta_\lambda}{2}}\, m\phi\, h^2$$

$$U_{\rm SM}(h) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_0 h^4, \quad \lambda \equiv \lambda_0 - \delta_\lambda$$

$$\beta_{\lambda_{\phi h}} \propto \lambda_{\phi h}$$

$m < \mathscr{Q}_I$ To stabilize SM potential

$$\beta_{\lambda_\phi} \propto 8\lambda_{\phi h}^2 + 18\lambda_\phi^2$$

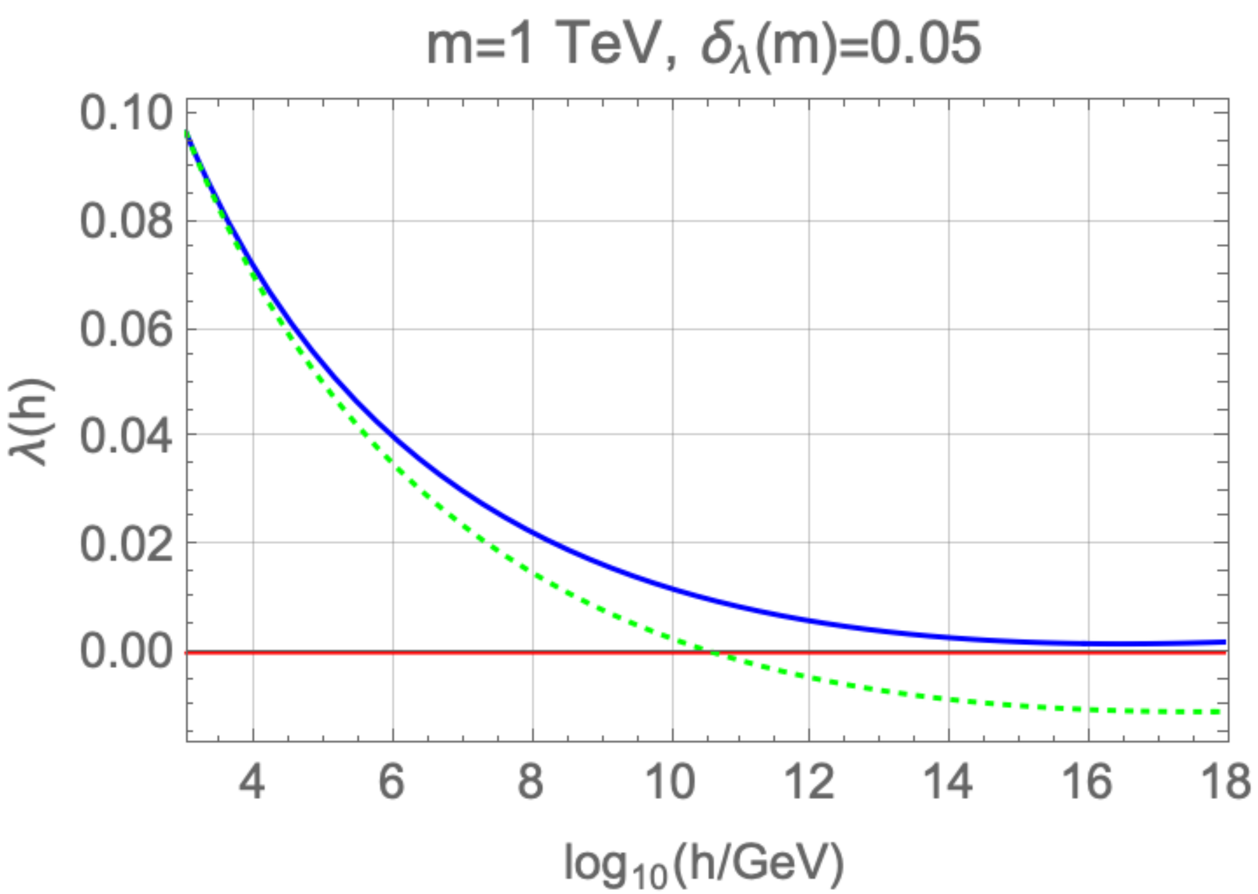
$\lambda_\phi \ll 1, \quad \lambda_{\phi h} = 0$ Stable under radiative corrections

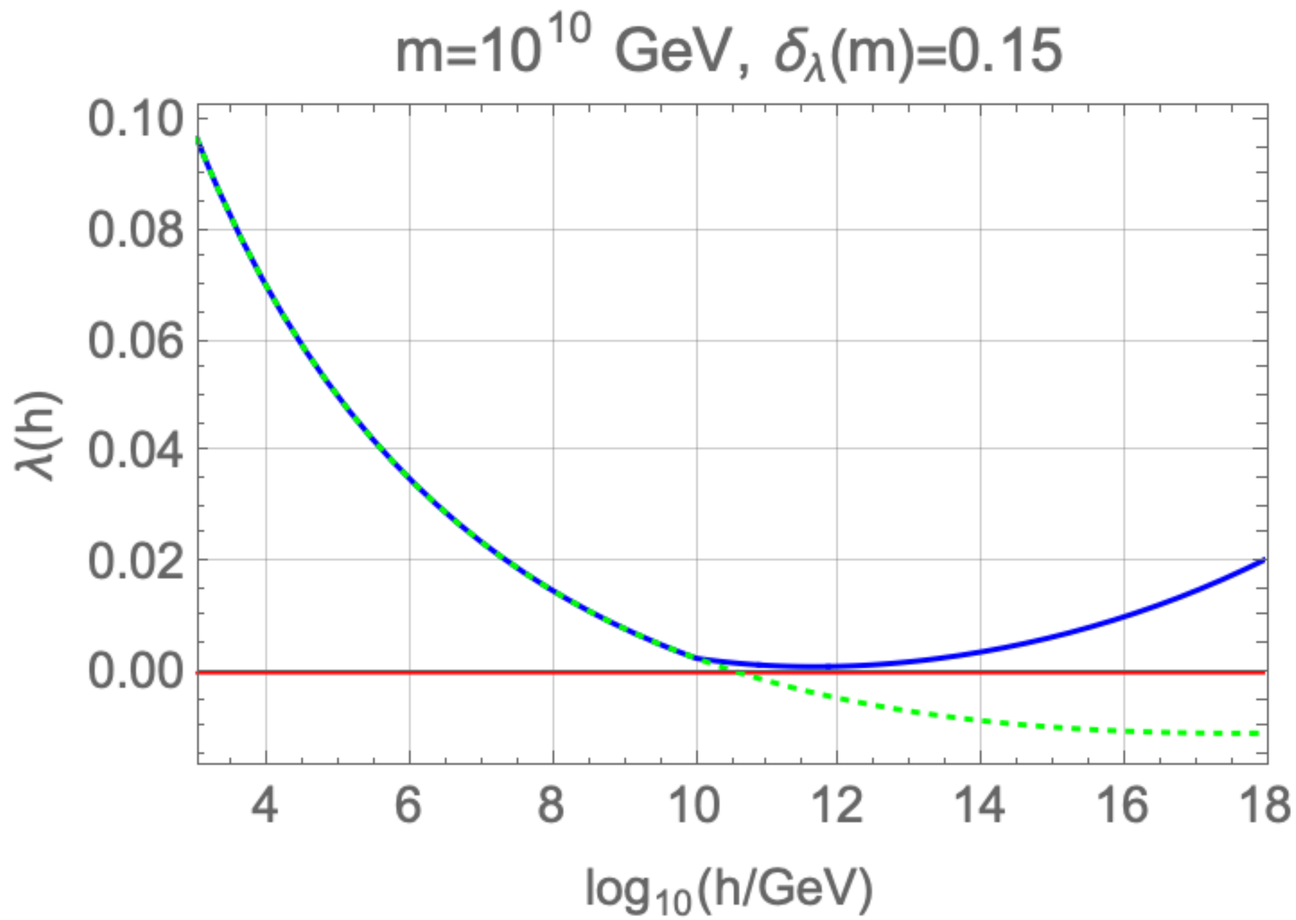
To cope with A_s CMB normalization

Then δ_λ triggers a modification of the SM **RGE** and can then stabilize the SM potential

J. Barbon et al., 1501.02231

$$\Delta\beta_\lambda = \frac{1}{2\pi^2}\delta_\lambda(3\lambda + \delta_\lambda)$$

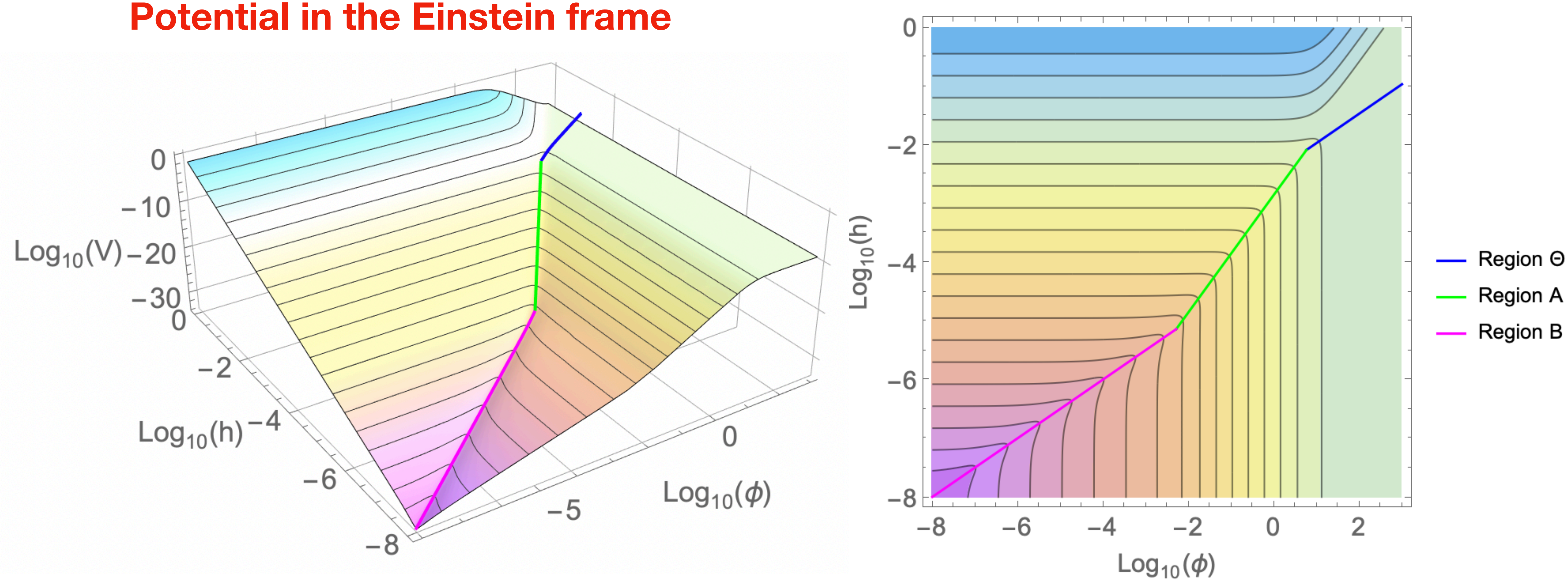




The Einstein frame is obtained by the Weyl transformation on the metric $g_{\mu\nu} \to \Theta\ g_{\mu\nu}$

$$\Theta(\phi) = \left(1 + \frac{g\phi^2}{M_p^2}\right)^{-1}$$

Potential in the Einstein frame

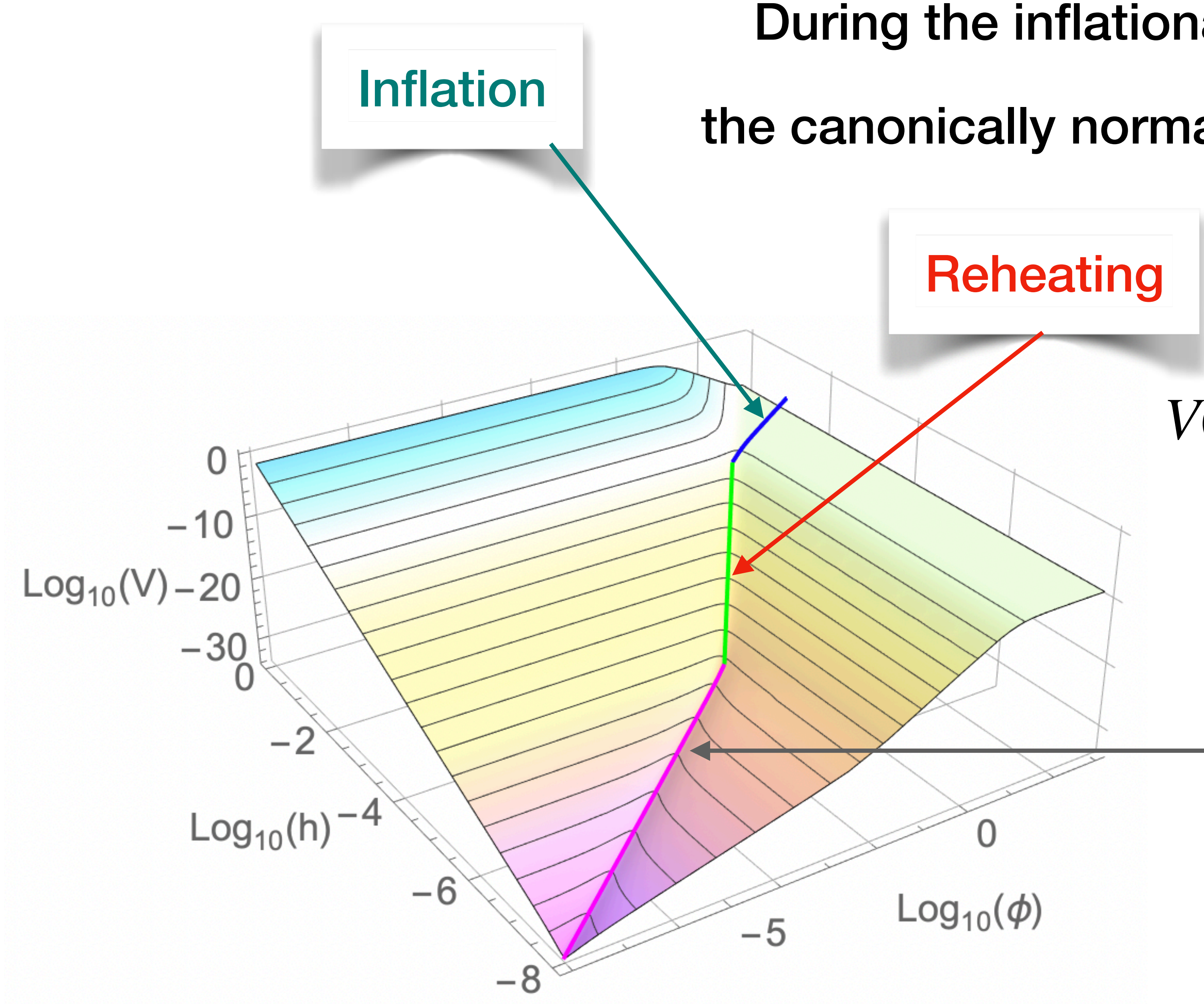


$$m = 10^{10}\ \text{GeV}, \quad \delta_\lambda = 0.15, \quad \lambda_\phi = 10^{-12}, \quad g = 0.01$$

Along the contour lines $h \ll \phi$

Inflation

During the inflationary regime $\left(g\phi^2 > M_p^2\right)$, in terms of the canonically normalized field $\phi \to \chi$ the inflaton potential

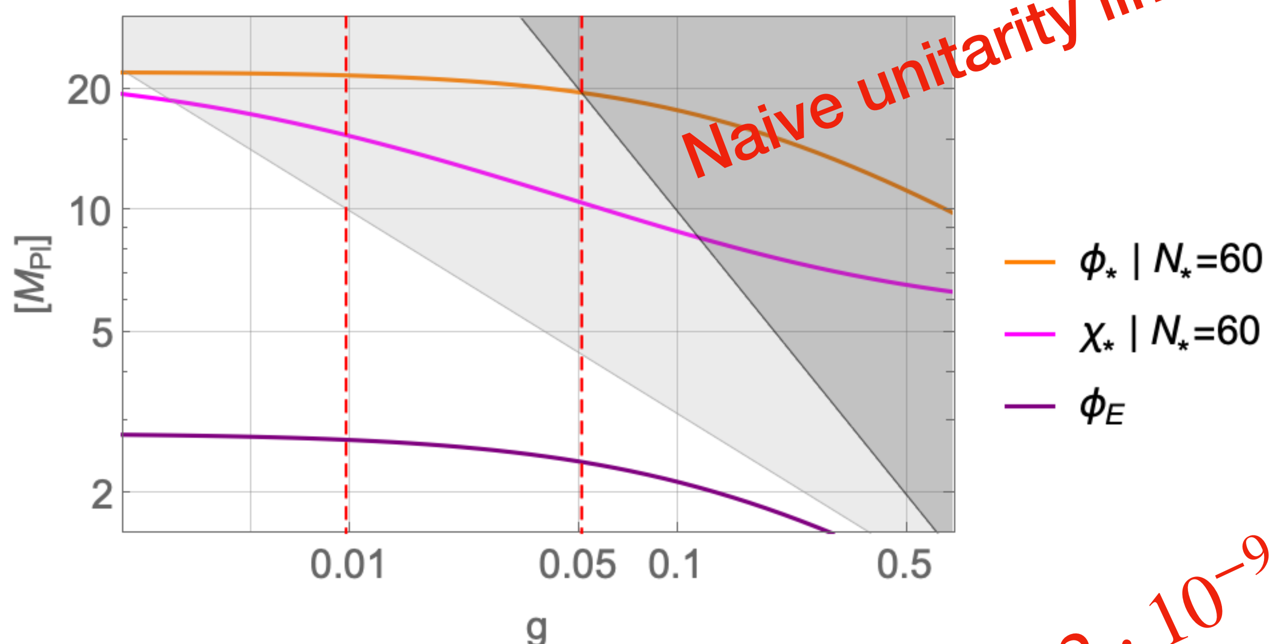


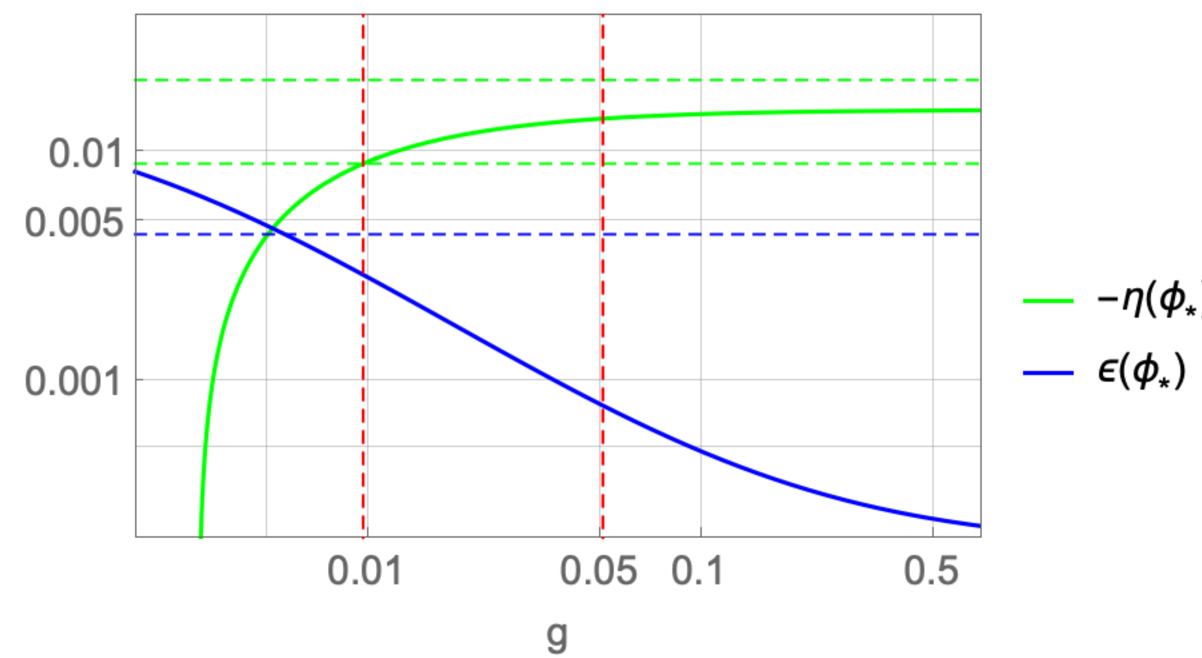
$$V(\chi) \simeq \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\chi}{M_p}}\right)^2, \quad \alpha = 1 + \frac{1}{6g}$$

We obtain the α-attractor models

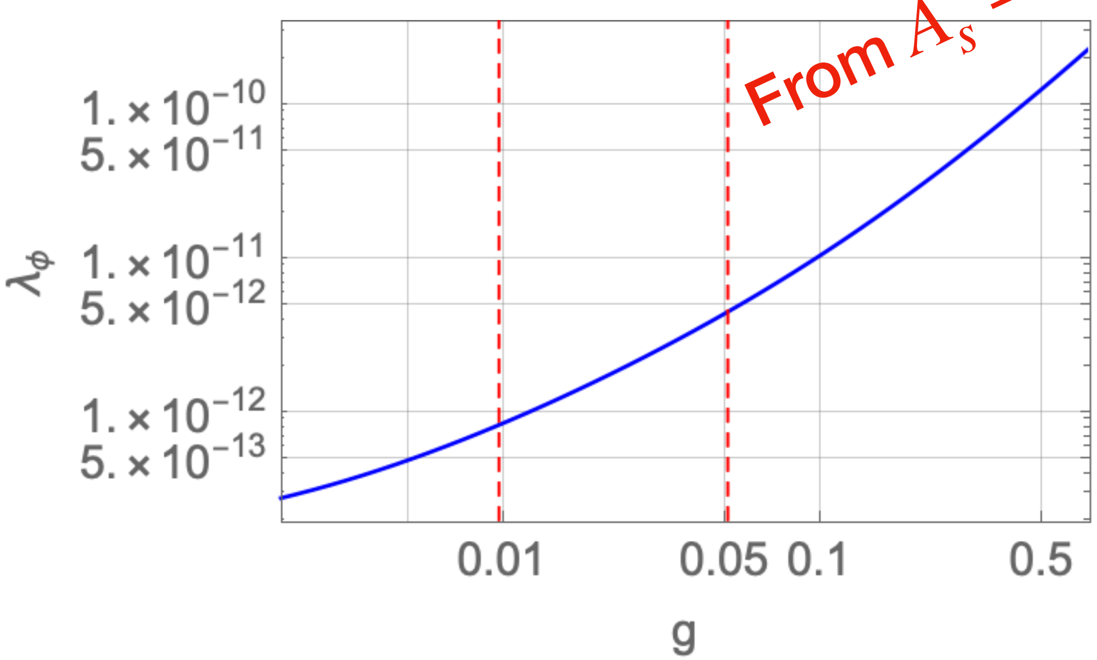
- Inflation is mainly driven by the field ϕ, but the Higgs h also participates in the inflation at a small rate. The predictions are

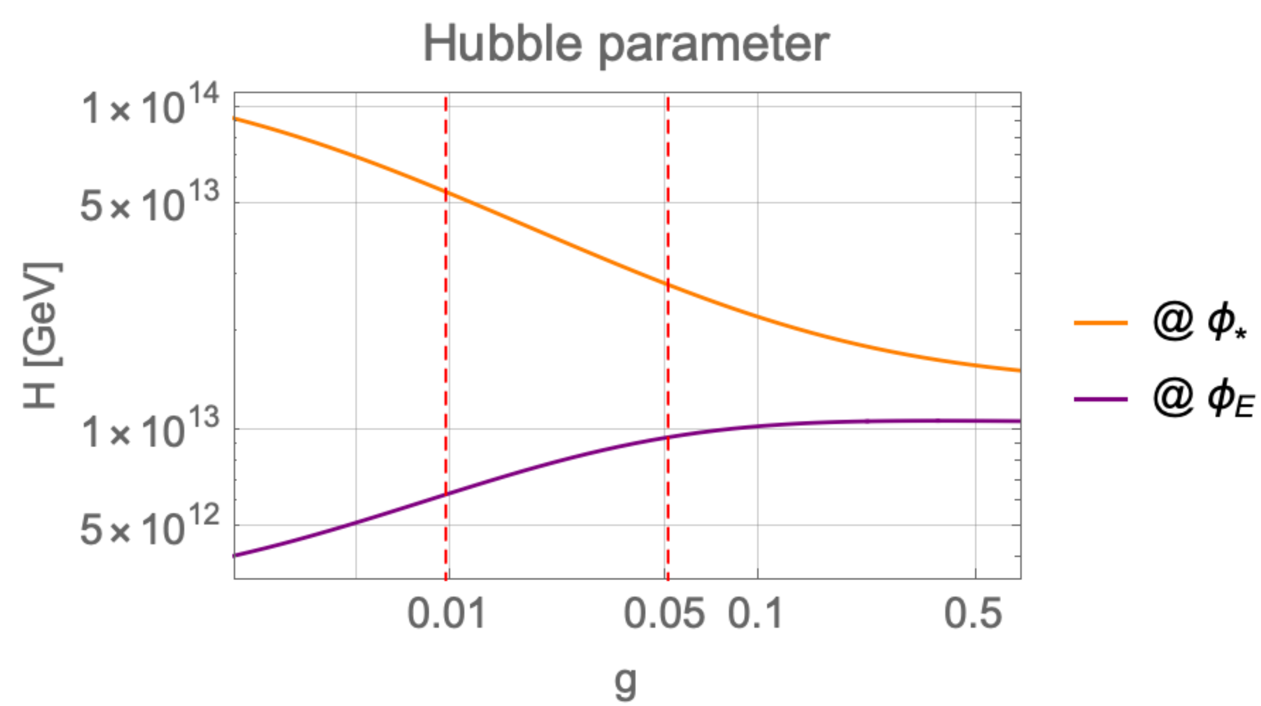
Naive unitarity limit $g\phi^2 < M_P^2$





From $A_s = 2.2 \cdot 10^{-9}$





- The model predictions are then

Limit $g \to \infty$

$$0.96448 \lesssim n_s \lesssim 0.96695 \qquad (0.96783)$$
$$-0.00063 \lesssim n_s' \lesssim -0.00019 \qquad (-0.00005)$$
$$0.0467 \gtrsim r \gtrsim 0.0124 \qquad (0.00296)$$

- In agreement with observations from Planck/Keck/BICEP

$$n_s = 0.9649 \pm 0.0042, \qquad n_s' = -0.0045 \pm 0.0067, \qquad r = 0.014^{+0.010}_{-0.011}$$

Scalar spectral index

Spectral index running

Tensor to scalar ratio

UV completion for CP-violation

- CP violation in the model is triggered by the Lagrangian

$$S_{\not{\mathscr{C}}\not{\mathscr{P}}} = -\int d^4x \, \frac{\phi}{4f_\phi} Y_{\mu\nu}\tilde{Y}^{\mu\nu}$$

- A simple UV completion generating such effective operator can be a massive (mass M) hypercharged vector-like fermion ψ with a CP-violating coupling to ϕ induced by the angle θ_λ

$$\mathscr{L} = -\bar{\psi}_L(M + |\lambda_\psi| e^{i\theta_\lambda}\phi)\psi_R + h.c. = -|\lambda_\psi|\phi \left|\cos\theta_\lambda\bar{\psi}\psi + \sin\theta_\lambda\bar{\psi}i\gamma_5\psi\right|$$

- The CP-even $\phi Y_{\mu\nu} Y^{\mu\nu}$, and CP odd $\phi Y_{\mu\nu} \tilde{Y}^{\mu\nu}$ couplings are generated by triangular loop diagrams where the fermion propagates in the loop and emit two gauge bosons Y^{μ} via the $\cos\theta_{\lambda}$ and $\sin\theta_{\lambda}$ couplings respectively

- The corresponding loop diagrams are finite

- For maximal CP-violation, $\theta_{\lambda} = \pm\,\pi/2$ only the $\phi Y_{\mu\nu} \tilde{Y}^{\mu\nu}$ is generated such that

$$M \simeq \frac{|\lambda_{\psi}|\, g_Y^2}{4\pi^2} f_{\phi} \simeq 8 \cdot 10^{15}\ GeV\, |\lambda_{\psi}|\, (f_{\phi}/M_P)$$

Gauge field production

Equation of motion for gauge fields $\mathbf{A}$ in gauge $A_0 = 0, \quad \nabla \times \mathbf{A} = 0$

$$\left(\frac{\partial^2}{\partial \tau^2} - \nabla^2 - \frac{a\,\dot{\phi}}{f_\phi} \nabla \times \right) \mathbf{A} = \mathbf{J}, \quad \mathbf{J} = \sigma \mathbf{E} = -\sigma \frac{\partial \mathbf{A}}{\partial \tau}$$

Fermion current

Ohm's law

conductivity

Gauge field quantization

$$\mathbf{A}(\tau, \mathbf{x}) = \sum_{\lambda=\pm} \int \frac{d^3k}{(2\pi)^3} \left[\epsilon_\lambda(\mathbf{k})\, a_\lambda(\mathbf{k})\, A_\lambda(\tau, \mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{x}} + \mathrm{h.c.} \right]$$

$$\xi = -\frac{\dot{\phi}}{2Hf_\phi}$$

Equation of motion for A_λ, $\lambda = \pm$

$$A_\lambda'' + \sigma A_\lambda' + k\left(k + \lambda \frac{2\xi}{\tau} \right) A_\lambda = 0$$

Observable quantities are: $\rho_E = \frac{1}{2}\mathbf{E}^2, \quad \rho_B = \frac{1}{2}\mathbf{B}^2, \quad \mathscr{H}$ (helicity)

$$\rho_E \equiv \frac{1}{a^4}\int^{k_c} \mathrm{d}k\, \frac{k^2}{4\pi^2}\left(|A'_+|^2 + |A'_-|^2\right), \quad \rho_B \equiv \frac{1}{a^4}\int^{k_c} \mathrm{d}k\, \frac{k^4}{4\pi^2}\left(|A_+|^2 + |A_-|^2\right)$$

$$\mathscr{H} \equiv \lim_{V\to\infty}\frac{1}{V}\int_V \mathrm{d}^3x\, \frac{\langle \mathbf{A}\cdot\mathbf{B}\rangle}{a^3} = \frac{1}{a^3}\int^{k_c} \mathrm{d}k\, \frac{k^3}{2\pi^2}\left(|A_+|^2 - |A_-|^2\right)$$

For collinear E and B fields, one Dirac fermion with mass m charge Q the conductivity

$$\sigma = \frac{|eQ|^3}{6\pi^2}\frac{a}{H}\sqrt{2\rho_B}\,\coth\left(\pi\sqrt{\frac{\rho_B}{\rho_E}}\right)\exp\left\{-\frac{\pi m^2}{\sqrt{2\rho_E}\,|eQ|}\right\}$$

V. Domcke and K. Mukaida, 1806.08769

Collinearity can be checked by the angle θ

$$\cos\theta = -\frac{\langle \mathbf{E}\cdot\mathbf{B}\rangle}{2a^2\sqrt{\rho_E\rho_B}}$$

Condition $|\cos\theta| \simeq 1$ is verified a posteriori

No Schwinger effect: $\sigma = 0$

- At early time, when $|k\tau| \gg 2\xi$, the modes are in their BD vacuum

- When $|k\tau| \simeq 2\xi$, one of the modes develop both parametric and tachyonic instabilities leading to exponential growth while the other stay in the vacuum

- During the last e-folds of inflation, i.e. $|k\tau| \ll 2\xi$, the growing mode has solution:

$$A_\lambda \simeq \frac{1}{\sqrt{2k}} \left(\frac{k}{2\xi a_E H_E} \right)^{\frac{1}{4}} \exp \left\{ \pi\xi - 2\sqrt{\frac{2\xi k}{a_E H_E}} \right\}$$

All observables can be computed analytically

$$\rho_B \simeq \frac{315}{2^{18}} \frac{a_E^4 H_E^4}{\pi^2 \xi^5} \mathrm{e}^{2\pi\xi}, \quad \rho_E \simeq \frac{63}{2^{16}} \frac{a_E^4 H_E^4}{\pi^2 \xi^3} \mathrm{e}^{2\pi\xi}, \quad \mathscr{H} \simeq \frac{45}{2^{15}} \frac{a_E^3 H_E^3}{\pi^2 \xi^4} \mathrm{e}^{2\pi\xi}$$

Schwinger effect

- Fermion production takes energy from the gauge system and back reacts on gauge field production

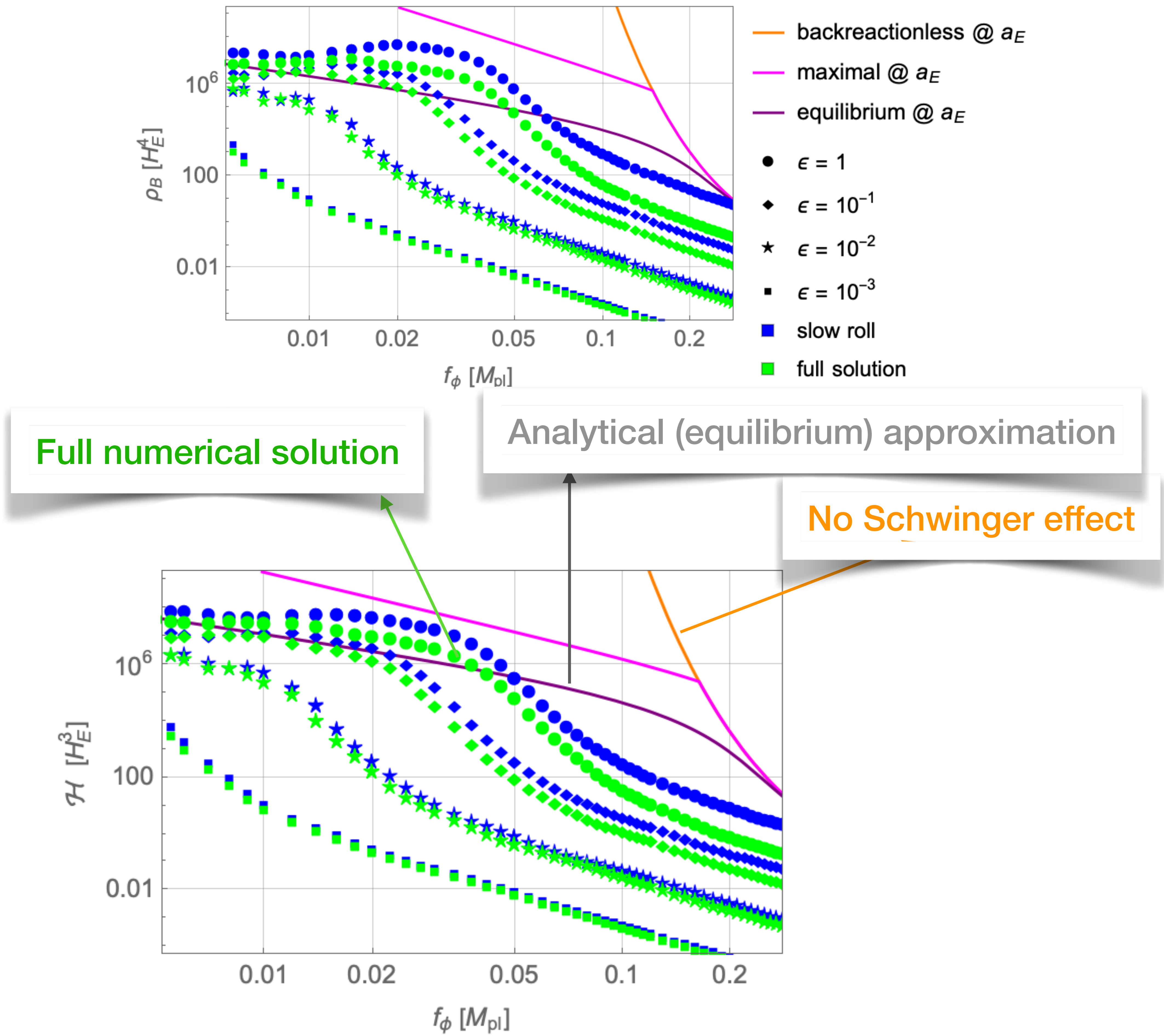
- The production of gauge fields is damped in the presence of the Schwinger effect

- Calculation are fully numerical. Only some analytical approximations are provided

- Light fermions contribute to conductivity according to the Higgs background value during inflation as $m_f^2 = \frac{Y_f^2}{2} h^2$

- It is difficult to avoid light fermions from first and second generations, with small Yukawa couplings $e, \mu, u, d, \ldots$, to contribute

- The gauge preheating is jeopardized by the production of fermions



backreactionless @ a_E
maximal @ a_E
equilibrium @ a_E
ϵ = 1
ϵ = 10^{-1}
ϵ = 10^{-2}
ϵ = 10^{-3}
slow roll
full solution
ρ_B [H_E^4]
10^6
100
0.01
0.01
0.02
0.05
0.1
0.2
f_ϕ [$M_{\rm pl}$]
Full numerical solution
Analytical (equilibrium) approximation
No Schwinger effect
$\mathcal{H}$ [H_E^3]
10^6
100
0.01
0.01
0.02
0.05
0.1
0.2
f_ϕ [$M_{\rm pl}$]

Baryogenesis

- To achieve baryogenesis, helicity has to survive until the EWPT
- After reheating, gauge fields interact with the thermal plasma: described by magnetohydrodynamics (MHD) equations
- Magnetic *diffusion* leads to helicity decay, and magnetic *induction* to helicity conservation: they are controlled by the *magnetic Reynolds number* $\mathscr{R}_m$
- If $\mathscr{R}_m > 1$ *induction* leads and helicity is conserved

$$\mathscr{R}_m^{\mathrm{rh}} \approx 5.9 \cdot 10^{-6} \, \frac{\rho_{B_Y} \ell_{B_Y}^2}{H_E^2} \left(\frac{H_E}{10^{13}\,\mathrm{GeV}} \right) \left(\frac{T_{\mathrm{rh}}}{T_{\mathrm{rh}}^{\mathrm{ins}}} \right)^{\frac{2}{3}}$$

$$\ell_B = \frac{2\pi}{\rho_B} \int_0^{k_c} \mathrm{d}k \, \frac{k^3}{4\pi^2} \left(|A_+|^2 + |A_-|^2 \right)$$

Magnetic correlation length

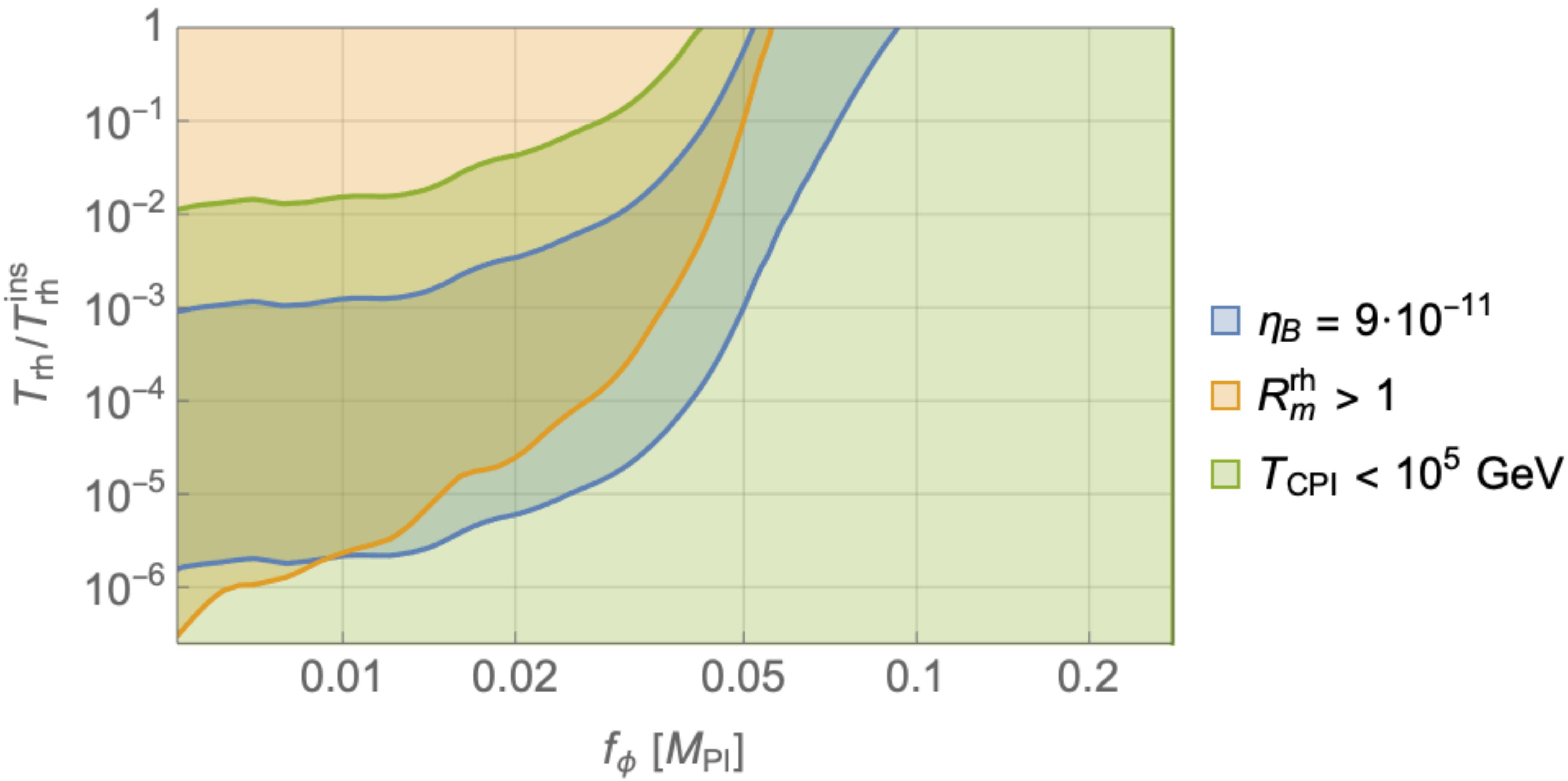
- When the symmetric phase is restored during reheating, *Chiral Plasma Instability (CPI)* is a phenomenon by which an asymmetry via chiral anomaly is generated and decays into a helicity with opposite sign: cancellation of the total helicity and no baryogenesis at the EWPT

- *CPI* can be avoided if the temperature at which it happens T_{CPI} is smaller than the temperature at which *the last* species (e_R) reaches equilibrium through its Yukawa coupling ($T_{CPI} \lesssim 10^5\ \mathrm{GeV}$) as sphalerons erase the fermion asymmetry

$$T_{\rm CPI}/\mathrm{GeV} \simeq 4 \cdot 10^{-7}\ \frac{\mathscr{H}_Y^2}{H_E^6} \left(\frac{H_E}{10^{13}\,\mathrm{GeV}}\right)^3 \left(\frac{T_{\rm rh}}{T_{\rm rh}^{\rm ins}}\right)^2 \lesssim 10^5$$

Baryogenesis region

$$T_{\rm rh}^{\rm ins} \simeq 2 \cdot 10^{15}\ \text{GeV}$$



$$f_\phi \lesssim 0.05\, M_P$$

Phenomenology

The naturalness problem

- The theory has two separated scales: the inflaton mass m and the Higgs mass m_h
- In the limit $\mu \equiv \sqrt{2\delta_\lambda}\, m \to 0$ there is an enhanced $\mathbb{Z}_2$ symmetry $\phi \to -\phi$ indicating that any value of μ, as small as it can be , is natural in the sense of ’t Hooft, as the symmetry is recovered
- One loop correction to the Higgs mass parameter μ_h^2

$$\Delta\mu_h^2 \simeq -\frac{\delta_\lambda}{8\pi^2} m^2 \log\frac{m^2}{m_h^2}$$

$$\left|\Delta\mu_h^2\right| \lesssim \mu_h^2 = m_h^2/2 \;\Rightarrow\; m \lesssim 1.2 \text{ TeV}$$

Higgs-inflaton mixing

The minimum equations $\mu_h^2 = \lambda v^2, \quad v_\phi = \sqrt{\frac{\delta_\lambda}{2}\frac{v^2}{m}}$

and the squared mass matrix at the minimum

$$\mathcal{M}^2 = \begin{pmatrix} 2(\lambda+\delta_\lambda)v^2 & -\sqrt{2\delta_\lambda}\, mv \\ -\sqrt{2\delta_\lambda}\, mv & m^2 \end{pmatrix}$$

lead to mass eigenstates $\tilde{h} = c_\alpha h + s_\alpha \phi, \quad \tilde{\phi} = c_\alpha \phi - s_\alpha h\,,$

with masses $$\frac{m^2_{\tilde{h},\tilde{\phi}}}{m^2} = \frac{1}{2} + (\lambda+\delta_\lambda)\frac{v^2}{m^2} \mp \sqrt{\frac{1}{4} - (\lambda-\delta_\lambda)\frac{v^2}{m^2} + (\lambda+\delta_\lambda)^2\frac{v^4}{m^4}}$$

and mixing angle $s_\alpha \simeq \sqrt{2\delta_\lambda}\frac{v}{m}, \quad m \gg v$

$$\mathcal{B}(\tilde{\phi} \to X\bar{X}) = \mathcal{B}(\tilde{h} \to X\bar{X}) \cdot s_\alpha^2\, \Gamma_{\tilde{h}}/\Gamma_{\tilde{\phi}}$$

$$\Gamma_{\tilde{\phi}} \simeq 2\delta_\lambda c_\alpha^2 \frac{m}{32\pi^2}, \quad \Gamma_{\tilde{h}} \simeq 4c_\alpha^2\ \mathrm{MeV}$$

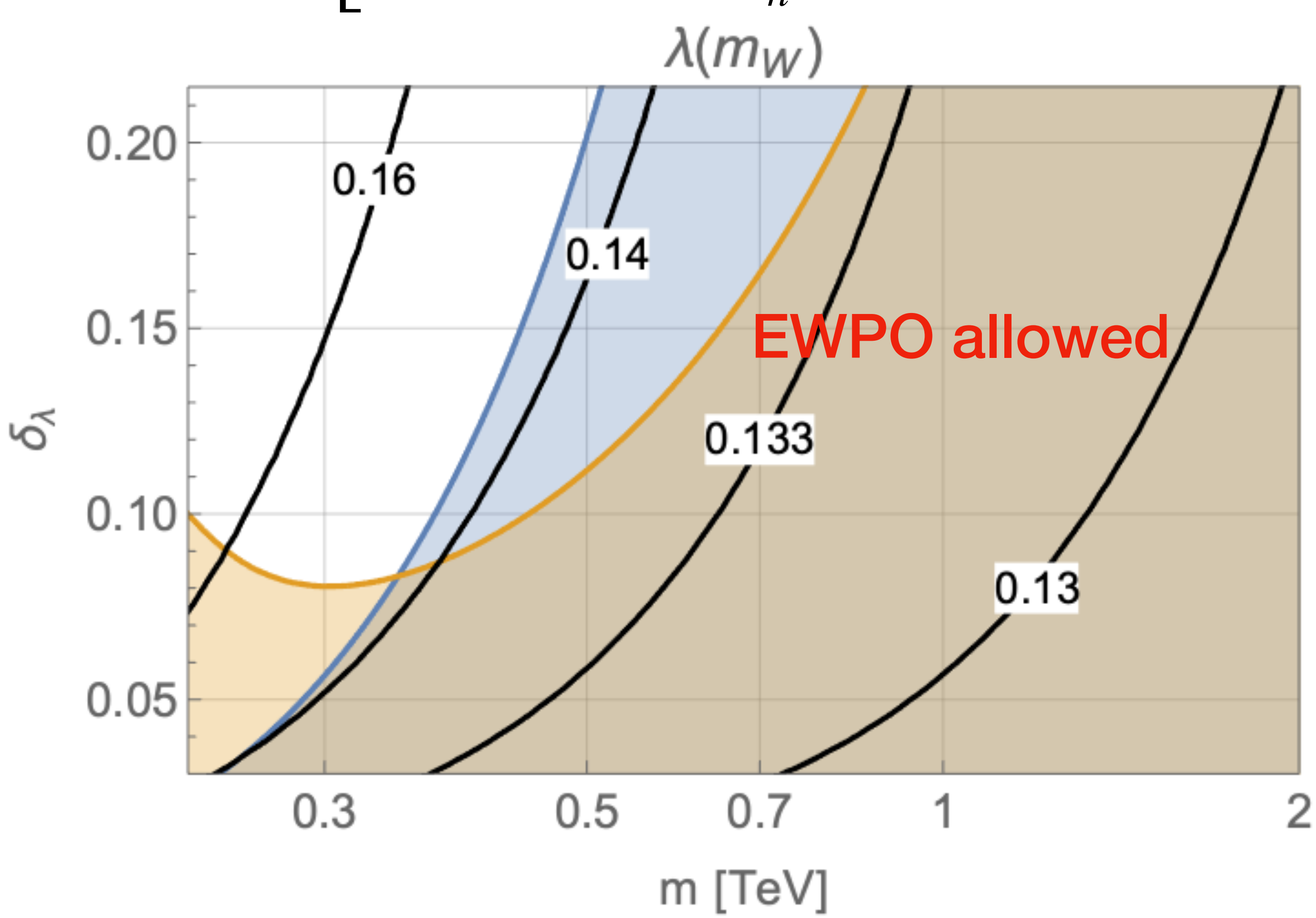
The inflaton decays into all SM particles

EW precision constraints

The doublet-singlet mixing can affect the EWPO through changes in the gauge boson propagators

$$\Delta T \simeq \frac{3}{16\pi}\frac{s_\alpha^2}{s_W^2}\left[\left(\frac{1}{c_W^2}\frac{m_{\tilde{h}}^2}{m_{\tilde{h}}^2 - m_Z^2}\log\frac{m_{\tilde{h}}^2}{m_Z^2} - \frac{m_{\tilde{h}}^2}{m_{\tilde{h}}^2 - m_W^2}\log\frac{m_{\tilde{h}}^2}{m_W^2}\right) - \left(m_{\tilde{h}} \to m_{\tilde{\phi}}\right)\right]$$

$$\Delta S = \frac{s_\alpha^2}{12\pi}\left[\frac{\hat{m}_{\tilde{h}}^6 - 9\hat{m}_{\tilde{h}}^4 + 3\hat{m}_{\tilde{h}}^2 + 5 + 12\hat{m}_{\tilde{h}}^2\log(\hat{m}_{\tilde{h}}^2)}{(\hat{m}_{\tilde{h}}^2 - 1)^3} - \left(\hat{m}_{\tilde{h}} \to \hat{m}_{\tilde{\phi}}\right)\right]$$



$$\hat{m}_i = m_i/m_Z$$

i) The Higgs signal strength

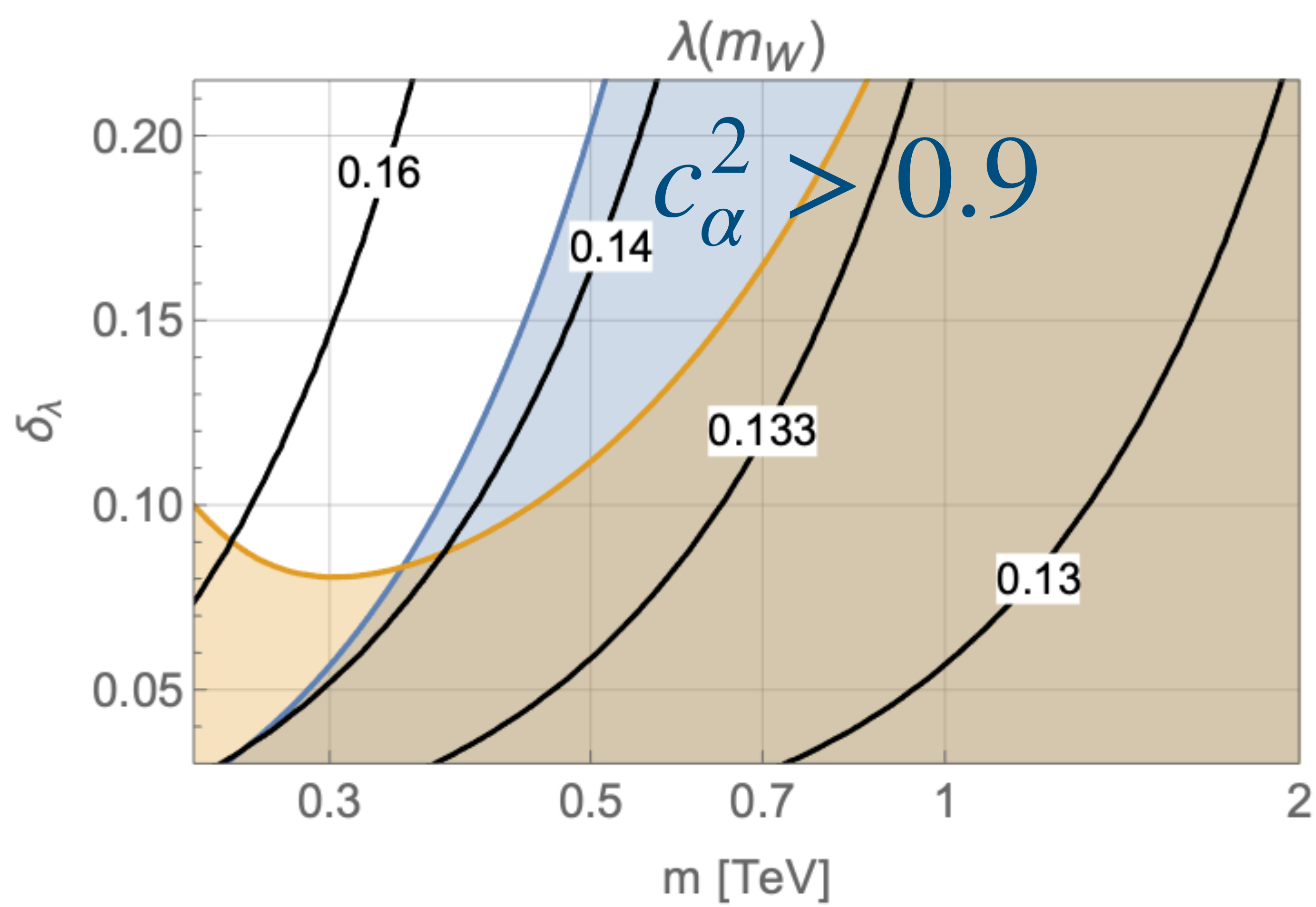
The coupling of the mass eigenstate $\tilde{h}$ to SM particles is suppressed with respect to the coupling of the weak state h by c_α

The signal strength modifier r_i^f for the process $i \to \tilde{h} \to f$ is

$$r_i^f = \frac{\sigma_i\,\mathscr{B}^f}{(\sigma_i)_{\rm SM}\,\mathscr{B}^f_{\rm SM}} \simeq c_\alpha^2$$

Experimental data are

$$r = 1.11^{+0.09}_{-0.08} \quad \text{(ATLAS)}, \qquad r = 1.17 \pm 0.1 \quad \text{(CMS)}$$

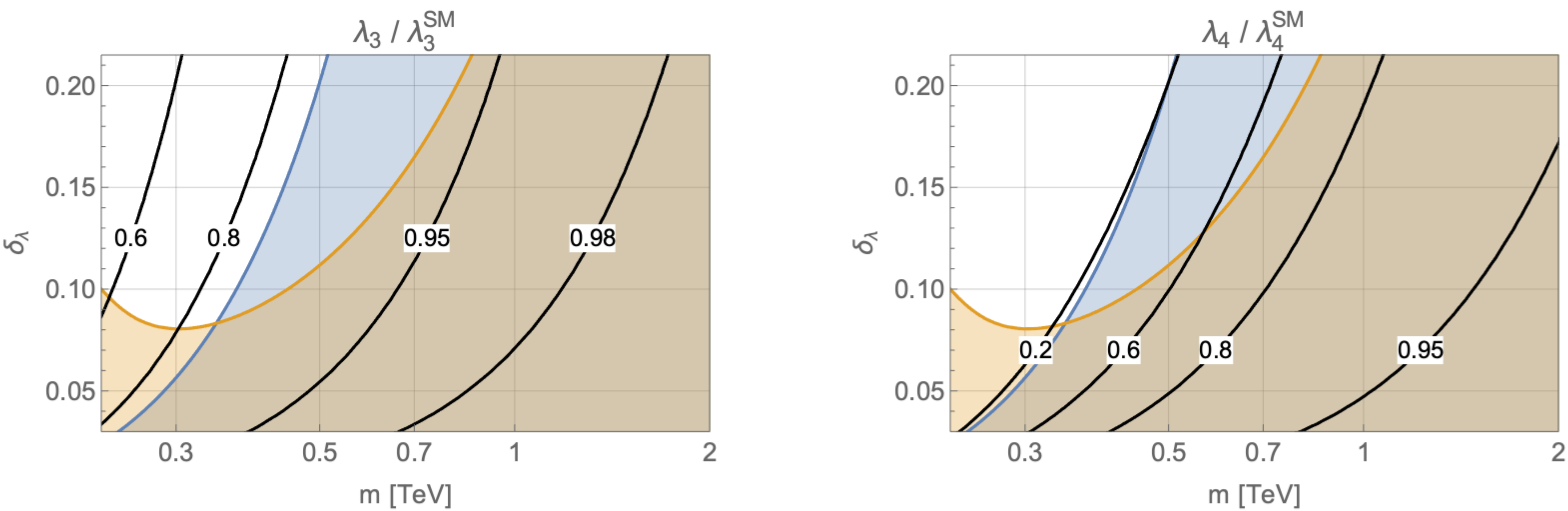


ii) Trilinear and quartic Higgs couplings

As the light state $\tilde{h}$ is identified with the SM Higgs, the trilinear λ_3 and quartic λ_4 couplings are modified with respect to the SM values

$$\lambda_3 = c_\alpha^3 v \left[\lambda + \delta_\lambda - t_\alpha \sqrt{\frac{\delta_\lambda}{2}} \frac{m}{v} \right]$$

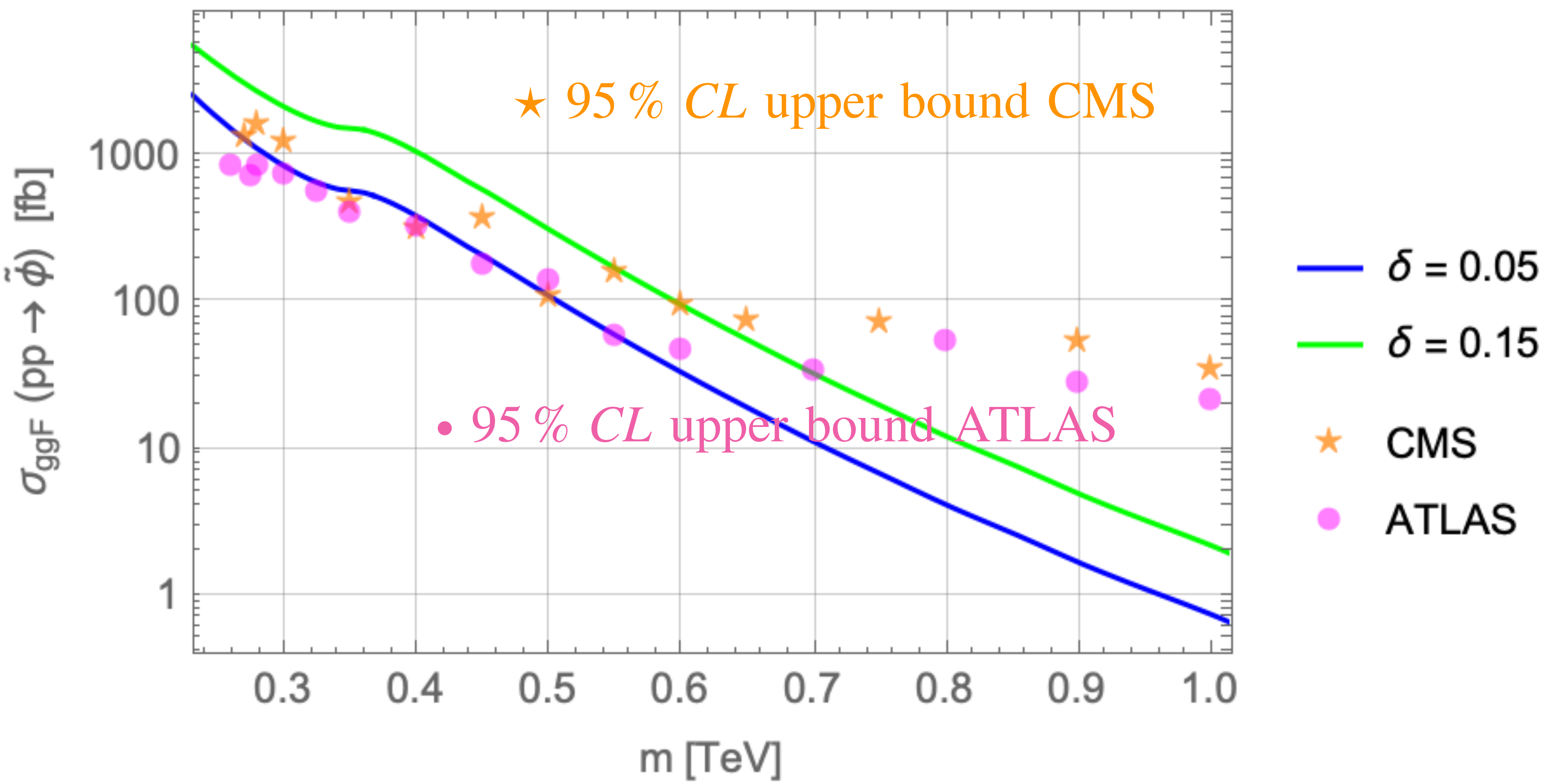
$$\lambda_4 = c_\alpha^4 \lambda + c_\alpha^2 (-c_\alpha^4 - 4 s_\alpha^4 + 4 c_\alpha^2 s_\alpha^2 + c_\alpha^2) \delta_\lambda - 6\sqrt{2\delta_\lambda}\, c_\alpha^3 s_\alpha (c_\alpha^2 - 2 s_\alpha^2)(\lambda + \delta_\lambda) \frac{v}{m} - 18 s_\alpha^2 c_\alpha^4 (\lambda + \delta_\lambda)^2 \frac{v^2}{m^2}$$



$$\lambda_3/\lambda_3^{SM} = 4.0^{+4.3}_{-4.1} \text{ (ATLAS)}, \quad \lambda_3/\lambda_3^{SM} = 0.6^{+6.3}_{-1.8} \text{ (CMS)}$$

iii) Inflaton production

The state $\tilde{\phi}$ can be produced at the LHC by the same mechanism of Higgs production with a x-section $\sigma(pp \to \tilde{\phi} + X) = s_\alpha^2 \, \sigma(pp \to H + X)$ where H is a mass m SM Higgs



$$m \gtrsim 0.55 \ (0.7) \ \text{TeV} @ 95\,\% \,\text{CL}, \quad \text{for } \delta_\lambda = 0.05 \ (0.15)$$

Conclusions

- We have considered an inflaton model with chaotic (quartic) potential, non-minimally coupled to gravity
- In the Einstein frame the potential is identified with α -attractor models
- If the inflaton mass $m \lesssim \mathcal{Q}_I \simeq 10^{11}$GeV, it can stabilize the SM vacuum at low scales
- The Higgs will participate to some extent in the process of inflation, making the link with Higgs Inflation models

- If the inflaton is coupled to the Chern-Simons density of the hypercharge, it can produce helical magnetic fields
- Fermion pair (Schwinger effect) production damps the gauge field production and prevents gauge preheating
- Even in the presence of fermion pair production there is room for baryogenesis
- Naturalness criteria imply that the inflaton mass should be in the TeV region
- In that case it will modify the trilinear and quartic SM couplings, and can be produced at the LHC and future colliders (a fascinating possibility!)