HIGGS-DILATON COSMOLOGY

Universality vs. Criticality

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

DISCRETE 2014
King's College
London

Drawing by Laura Pesce, *"Universi o multiversi"*

HIGGS INFLATION

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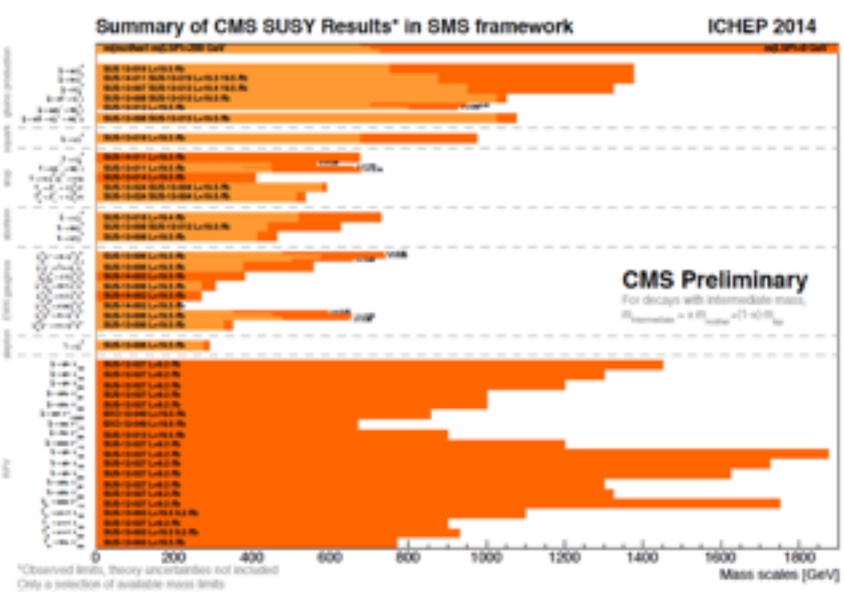
The era of scalars has begun

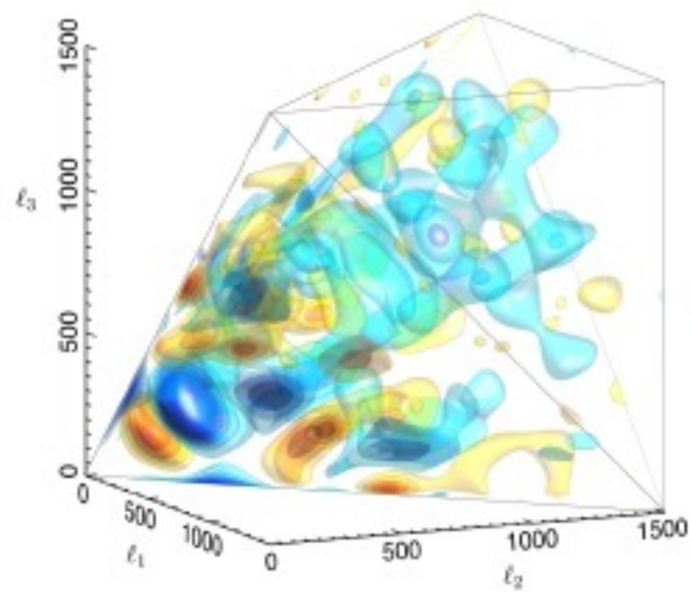
LHC

- "Clear evidence for a neutral boson with a mass of126 GeV"
- "Extensive search without any significant deviations from the SM so far"

PLANCK

- "Single field SR inflation has survived its most stringent
- "Small isocurvature contribution"
- "No evidence for primordial NG"





Higgs inflation: Jordan frame

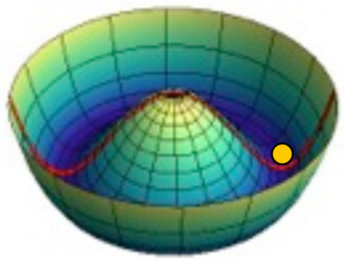
1. One field to rule them "all"

Identify the Higgs with the inflaton

"Frustra fit per plura quod potest fieri per pauciora". William of Ockham, Summa Totius Logicae

Scale invariance

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2 + \xi_h h^2}{2} R - \frac{1}{2}(\partial h)^2 - V(h)$$



2. Physicists' Nightmare Scenario

No new intermediate scales till "Planck" scale

Inflation easily studied in the Einstein frame

$$\tilde{g}_{\mu\nu} = \Omega^2(h) g_{\mu\nu} \qquad \Omega^2 = 1 + \frac{\xi_h h^2}{M_P^2}$$

Higgs inflation: Einstein frame

$$\frac{\tilde{\mathcal{L}}}{\sqrt{-\tilde{g}}} = \frac{M_P^2}{2}\tilde{R} - \frac{1}{2}\left(\frac{\Omega^2 + 6\xi_h^2 h^2/M_P^2}{\Omega^4}\right)\tilde{g}^{\mu\nu}\partial_\mu h\,\partial_\nu h - \frac{V(h)}{\Omega^4}$$

Redefining the field to make it canonic. normalized

$$\frac{\tilde{\mathcal{L}}}{\sqrt{-\tilde{g}}} = \frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - U(\phi)$$

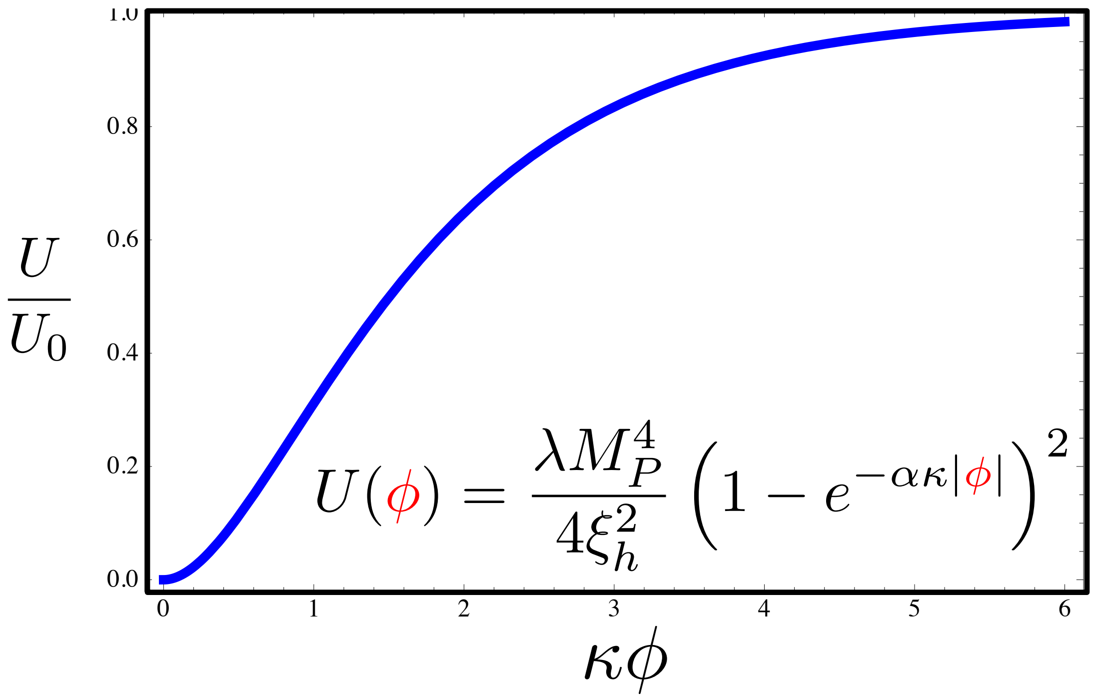
$$U(\phi) = \frac{\lambda}{4}\phi^4 \qquad \text{for} \quad h < \frac{M_P}{\sqrt{\xi_h}}$$

$$U(\phi) = \frac{\lambda M_P^4}{4\xi_h^2}\left(1 - e^{-\alpha\kappa|\phi|}\right)^2 \qquad \text{for} \quad h > \frac{M_P}{\sqrt{\xi_h}}$$

All the non-linearities moved to the scalar sector

A sufficiently flat potential

Scale invariance becomes shift symmetry



$$\frac{\lambda}{\xi_h^2} \sim 10^{-11}$$

COBE

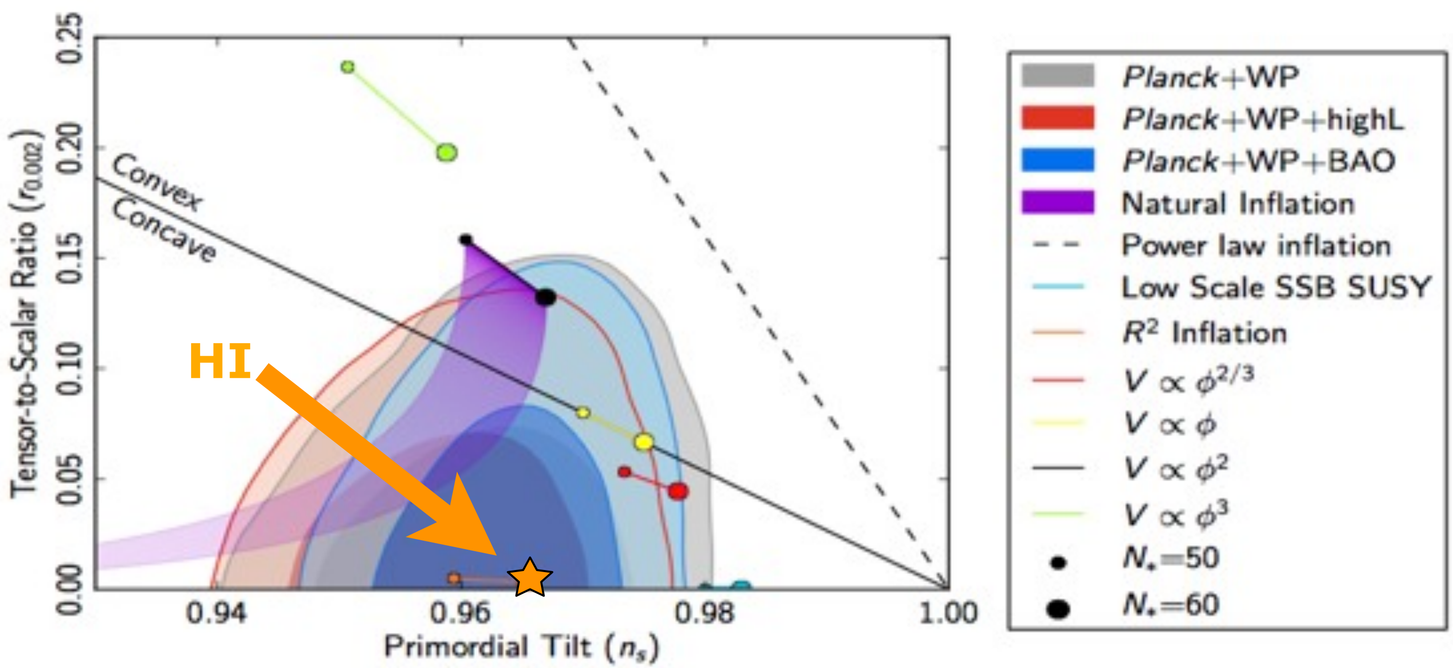
Only λ/ξ_h^2 is important

The primordial spectra

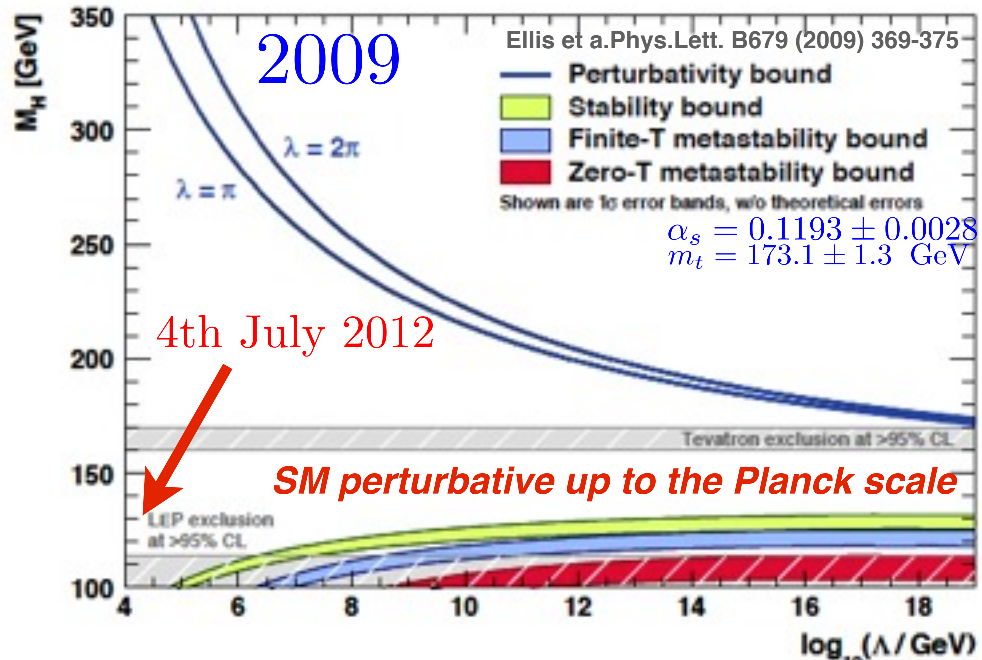
Scalar pert. $\mathcal{P}_S(k) = \mathcal{A}_s \left(\frac{k}{k^*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k^*) + \frac{1}{6}\beta_s (\ln(k/k^*))^2 + \ldots}$

Tensor pert. $\mathcal{P}_T(k) = \mathcal{A}_t \left(\frac{k}{k^*}\right)^{n_t + \frac{1}{2}\alpha_t \ln(k/k^*) + \ldots}$

$$n_s \equiv 1 + \frac{d \ln \mathcal{P}_s}{d \ln k} \qquad r(k) \equiv \frac{\mathcal{P}_T(k)}{\mathcal{P}_s(k)} \qquad \alpha_s \equiv \frac{d n_s}{d \ln k} \qquad \beta_s \equiv \frac{d^2 n_s}{d \ln k^2}$$



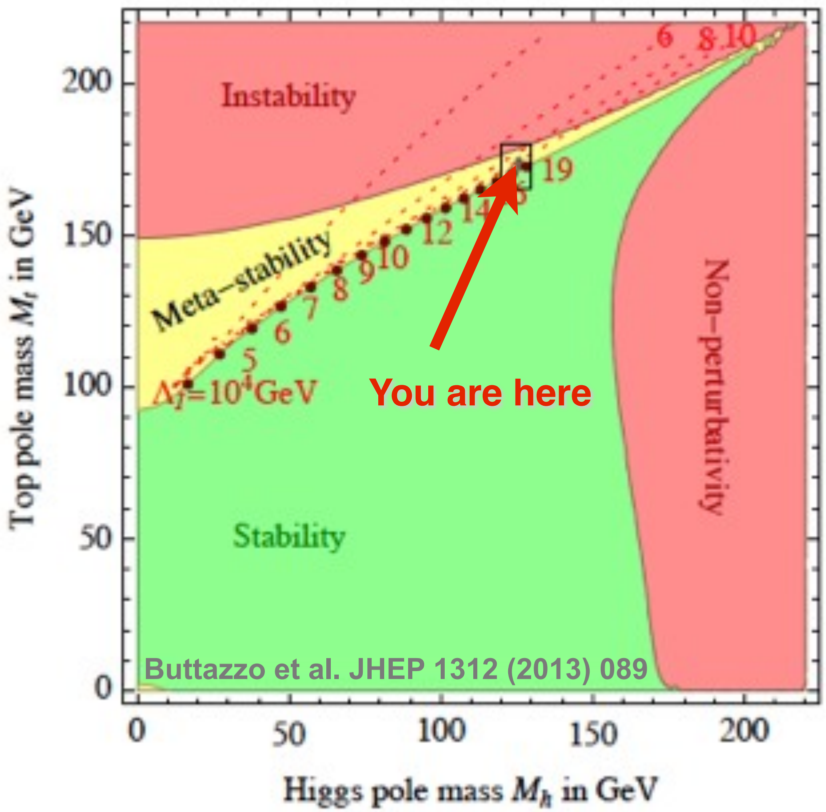
The Higgs is like Odysseus between Scylla and Charybdis

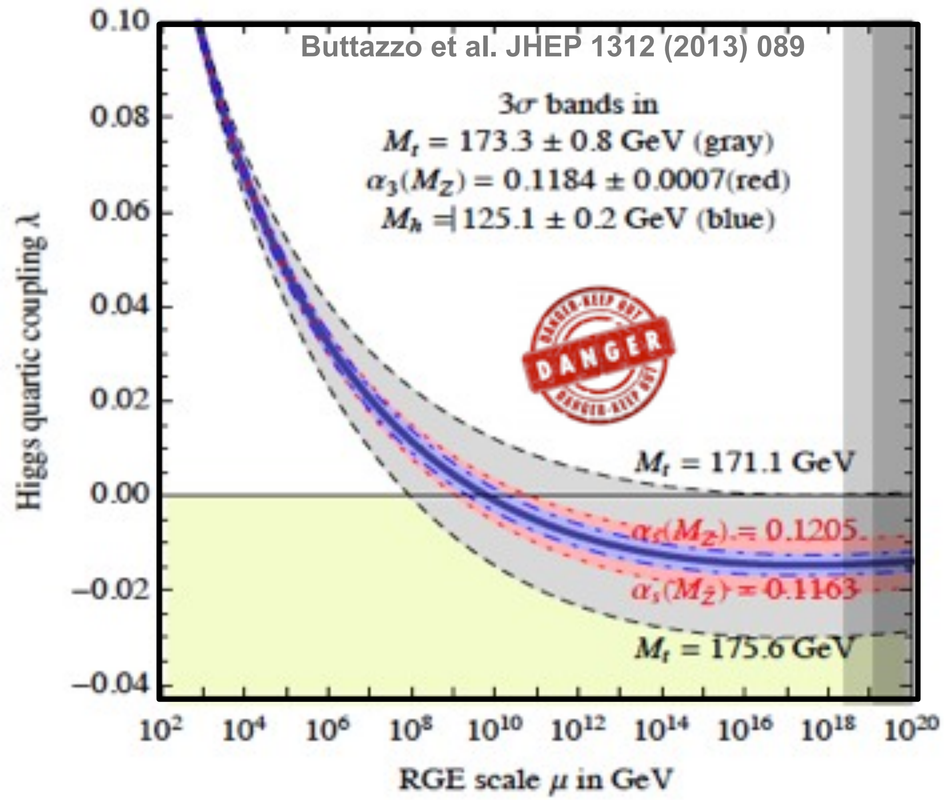


"incidit in scyllam cupiens vitare charybdim"

"he runs on Scylla, wishing to avoid Charybdis"

On the edge of stability





Non trivial interplay between top Yukawa and Higgs self-coupling....evil *Scylla* hidden in error bars

Stable or metaestable? An experimental rather than theoretical issue ...

Is there a reason for that? M. Lindner, M. Sher, and H. W. Zaglauer, Phys.Lett., B228, 139 (1989), C. Froggatt and H. B. Nielsen, Phys.Lett., B368,96 (1996), M. Shaposhnikov and C. Wetterich, Phys.Lett., B683, 196 (2010), M. Veltman, Acta Phys.Polon., B12, 437 (1981), B683, 196 (2010), M. Holthausen, K.S.Lim, M.Lindner and references therein....

Gravitational corrections? Lalak,Lewicki, Olszewki arXiv 14.02.3826, Branchina, Massina Phys.Rev.Lett. 111 (2013) 241801 etc...

Vacuum stability vs inflation ?

"If m_h and m_t are close to the measured central value, Higgs inflation is not possible and V_{eff} becomes negative much before M_P"

SM + gravity is non-renormalizable

1. Which is the sensitivity to higher dimensional operators?
2. Which are the renormalization group equations? Which is the relation between high and low energy parameters?

In the lack of UV completion the answer to these questions can be only based on the

SELF-CONSISTENCY OF PROCEDURE

1. Sensitivity to high dim. operators

Defining the cutoff from the theory itself by considering all possible reactions

- The energy at which perturbative unitarity in high-energy scattering processes is violated

1. Compute the quadratic lagrangian

$$\Phi(\mathbf{x},t) = \bar{\Phi}(t) + \delta\Phi(\mathbf{x},t) \rightarrow c_n \frac{\mathcal{O}_n(\delta\Phi)}{[\Lambda(\bar{\Phi})]^{n-4}}$$

⚠ **Background dependent!**

2. Get rid of the mixings in the quadratic action

3. Read out the cutoff from higher order oper.

Example $\phi = \bar{\phi} + \delta\phi \qquad g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$

1. Compute the quadratic lagrangian (Jordan F.)

$$\mathcal{L}^{(2)} = -\frac{M_P^2 + \xi\bar{\phi}^2}{8}\left(h^{\mu\nu}\Box h_{\mu\nu} + 2\partial_\nu h^{\mu\nu}\partial^\rho h_{\mu\rho} - 2\partial_\nu h^{\mu\nu}\partial_\mu h - h\Box h\right) + \frac{1}{2}(\partial_\mu\delta\phi)^2 + \xi\bar{\phi}\left(\Box h - \partial_\lambda\partial_\rho h^{\lambda\rho}\right)\delta\phi\,,$$

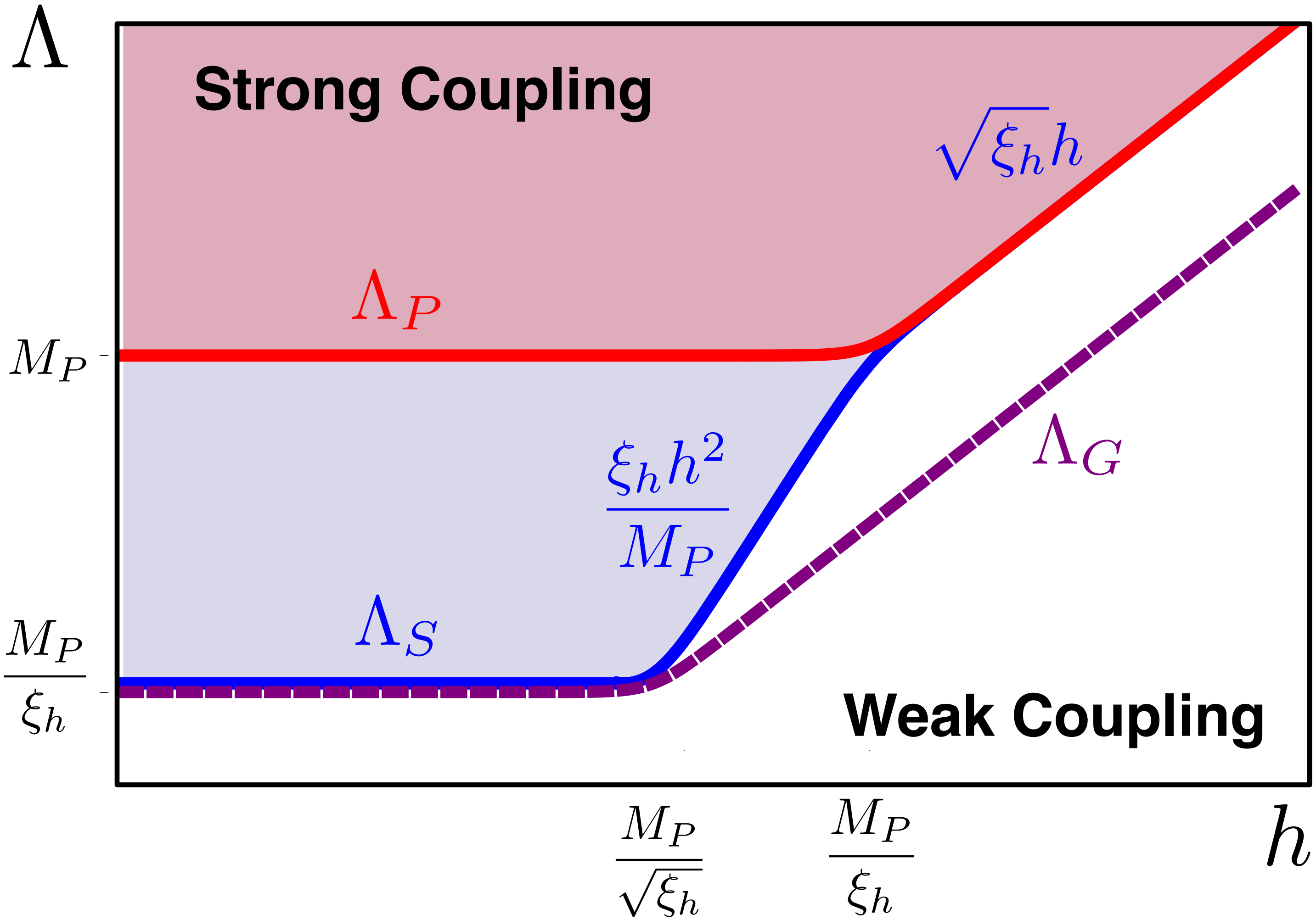
2. Get rid of the mixings in the quadratic action

$$\delta\phi = \sqrt{\frac{M_P^2 + \xi\bar{\phi}^2}{M_P^2 + \xi\bar{\phi}^2 + 6\xi^2\bar{\phi}^2}}\,\delta\hat{\phi}\,,$$

$$h_{\mu\nu} = \frac{1}{\sqrt{M_P^2 + \xi\bar{\phi}^2}}\,\hat{h}_{\mu\nu} - \frac{2\xi\bar{\phi}}{\sqrt{(M_P^2 + \xi\bar{\phi}^2)(M_P^2 + \xi\bar{\phi}^2 + 6\xi^2\bar{\phi}^2)}}\,\bar{g}_{\mu\nu}\,\delta\hat{\phi}$$

3. Read out the cutoff from higher order operat.

$$\frac{\xi\sqrt{M_P^2 + \xi\bar{\phi}^2}}{M_P^2 + \xi\bar{\phi}^2 + 6\xi^2\bar{\phi}^2}(\delta\hat{\phi})^2\Box\hat{h}$$



A consistent EFT : Cutoffs are parametrically larger than all the energy scales involved in the history of the Universe

2. Running of the couplings

Gauge bosons/fermions action invariant under conformal transformations except for the mass terms

$$\mathcal{L}_F = \frac{y_f}{\sqrt{2}} h \bar{\psi}\psi \quad \longrightarrow \quad \tilde{\mathcal{L}}_F = \frac{y_f}{\sqrt{2}} \frac{h}{\Omega} \bar{\psi}\psi \equiv \frac{y_f}{\sqrt{2}} F(\phi) \bar{\psi}\psi$$

Low energies

$$F = \phi$$

$$F'(0) = 1$$

$$\tilde{m}_{A,f} = m_{A,f}$$

USUAL SM

During inflation

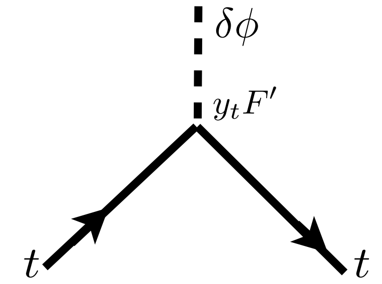
$$F = \frac{M_P}{\sqrt{\xi_h}} \left(1 - e^{-\alpha\kappa|\phi|}\right)^{1/2}$$

$$F'(\phi_0) = 0$$

$$\tilde{m}_{A,f} = \text{const.}$$

CHIRAL SM

$$\tilde{\mathcal{L}}_t(\phi + \delta\phi) = \frac{y_t}{\sqrt{2}} F(\phi + \delta\phi)\bar{\psi}_t\psi_t$$
$$= \frac{y_t}{\sqrt{2}} F(\phi)\bar{\psi}_t\psi_t + \frac{y_t}{\sqrt{2}} \frac{dF(\phi)}{d\phi} \delta\phi\bar{\psi}_t\psi_t + \ldots$$

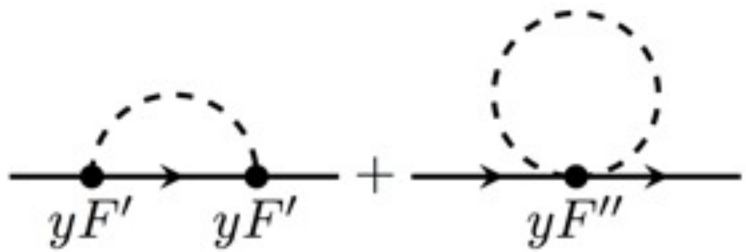


In a background field the coupling of the top to the Higgs pert. is proportional to F$'$.

At low energies	**At high energies**
$F = \phi \quad F'(0) = 1$	$F = const. \quad F'(\phi_0) = 0$

Consider the propagation of the top quark

Add counterterms to cancel divergencies



$$\delta\mathcal{L}_{\rm ct} \sim \left(\# \frac{y_t^3}{\bar{\epsilon}} + \delta y_{t1}\right) F'^2 F\bar{\psi}\psi + \left(\# \frac{y_t\lambda}{\bar{\epsilon}} + \delta y_{t2}\right) F''(F^4)''\bar{\psi}\psi;$$

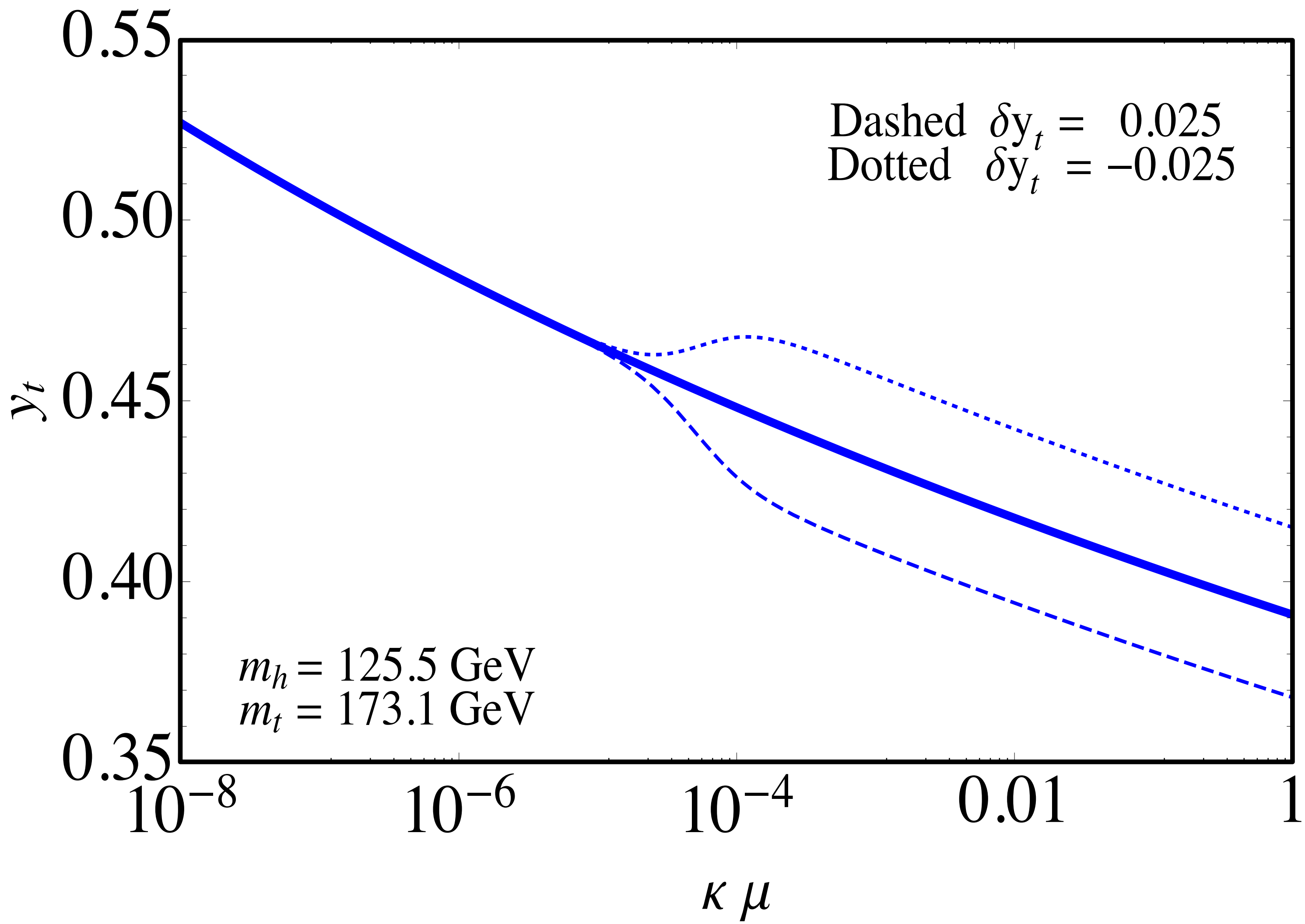
$\phi\psi\psi$ at small ϕ

At low energies

$F = \phi \quad F'(0) = 1$

At high energies

$F = const. \quad F'(\phi_0) = 0$

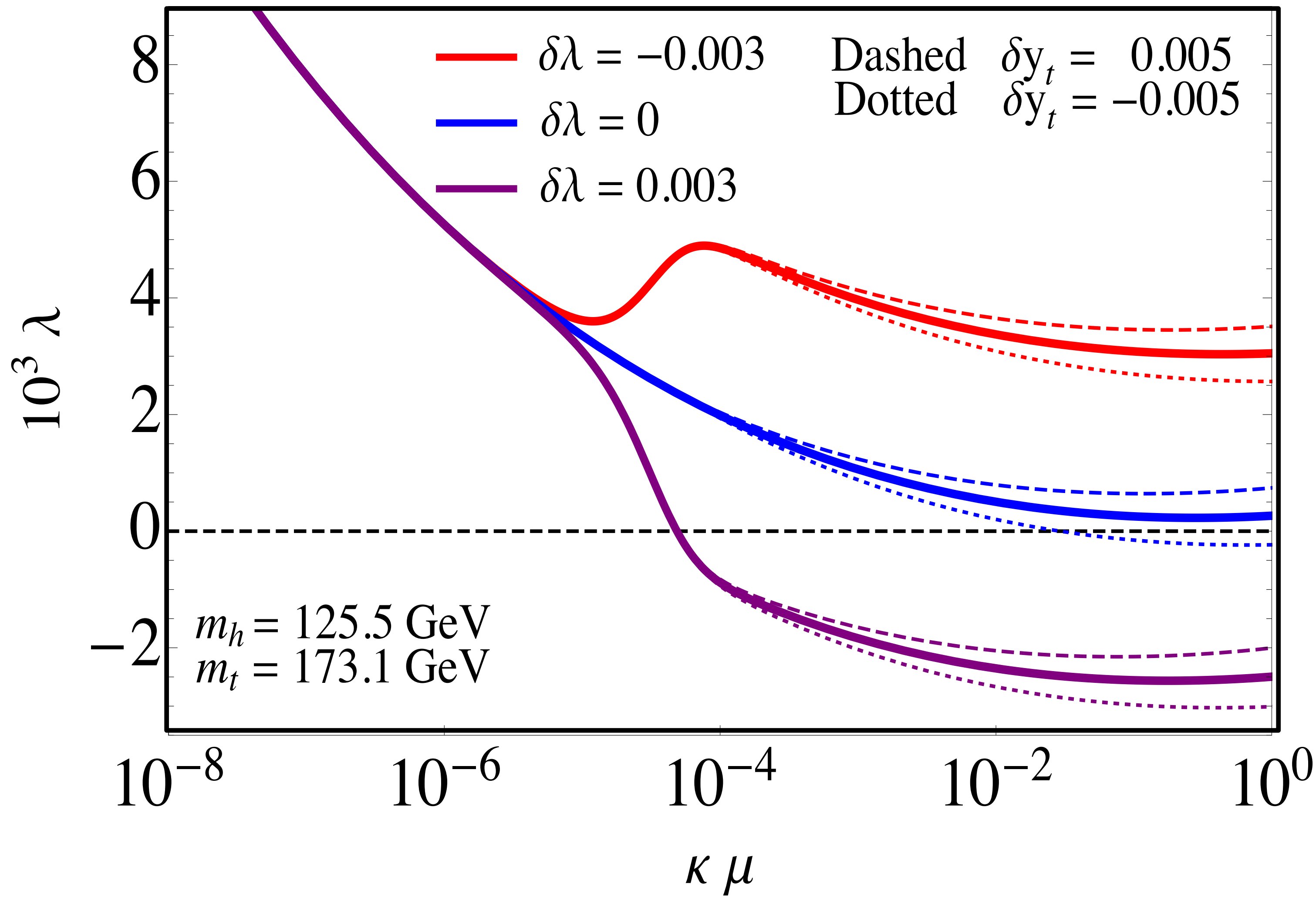


At low energies

$F = \phi \quad F'(0) = 1$

At high energies

$F = const. \quad F'(\phi_0) = 0$



1. **Run SM RGE** until the chiral SM ---> Jumps

2. The obtained values are used as the input of the **chiral phase**, whose **RG equations** are run until a given scale.

3. This scale is chosen to **minimize higher order corrections**

4. **RGE effective potential** at inflation is computed

$$U_{RGE}(\phi) = \frac{\lambda(\mu(\phi))M_P^4}{4\xi_h^2(\mu(\phi))}\left(1 - e^{-\alpha\kappa\phi}\right)^2$$

7. **Inflationary observables** are computed

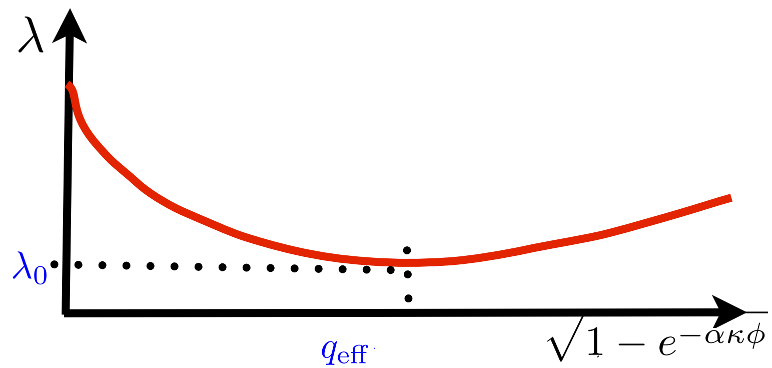
Lets look at the asymptotics

$$\lambda(\mu(\phi)) = \lambda_0 + b\log^2\left(\frac{\sqrt{1-e^{-\alpha\kappa\phi}}}{q_{\rm eff}}\right)$$

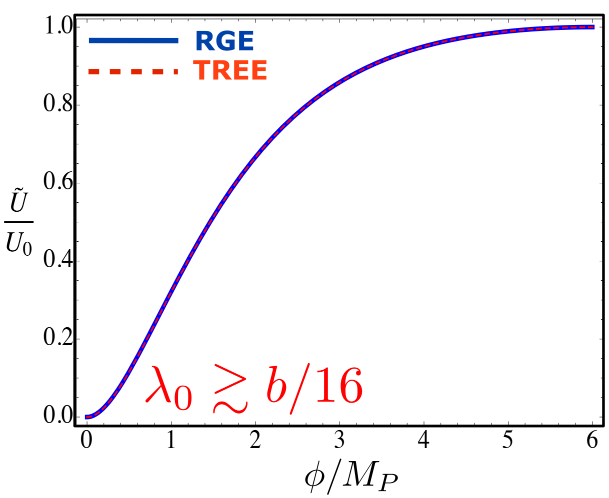
$$b \simeq 2.3\times 10^{-5}$$

$$\lambda_0 = \lambda_0(m_h^*, m_t^*) \ll 1$$

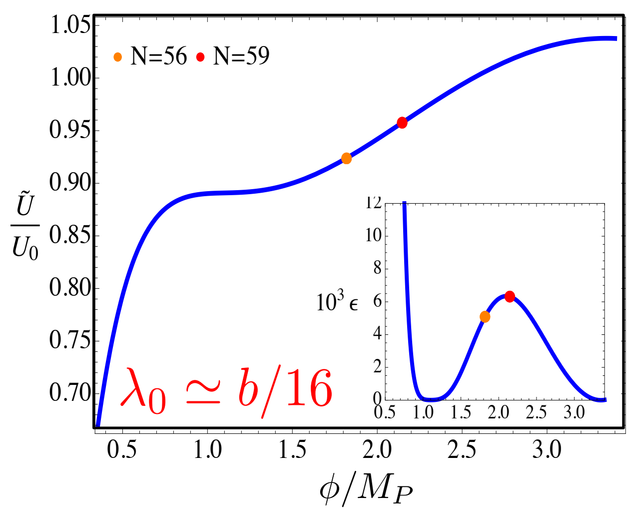
$$q_{\rm eff} = q_{\rm eff}(m_h^*, m_t^*) \sim \mathcal{O}(1)$$



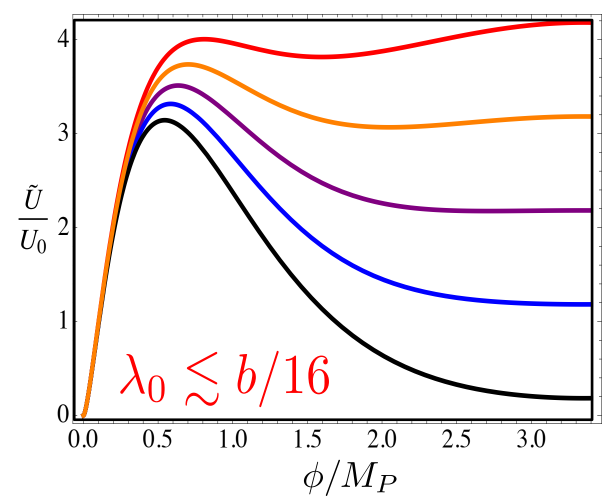
UNIVERSALITY



CRITICALITY



NO INFLATION



Universal regime

$$\lambda_0 \gtrsim b/16 \qquad \lambda(\mu(\phi)) = \lambda_0 + b \log^2\left(\frac{\sqrt{1-e^{-\alpha\kappa\phi}}}{q_{\rm eff}}\right)$$

Only λ_0/ξ_h^2 is important

For masses slightly above the critical Higgs mass *

$$m_h^* > m_{\rm crit} - 0.1 \log \frac{\xi}{1000} GeV$$

$$m_{\rm crit} = \left[129.1 + \frac{y_t(173.2\ {\rm GeV}) - 0.9361}{0.0058} \times 2.0\right] {\rm GeV}$$

Bezrukov et al. JHEP 1210 (2012) 140, Buttazzo et al. JHEP 1312 (2013) 089,

the predictions of the model are universal

$$n_s \simeq 0.97 \qquad r \simeq 0.003$$

Critical Regime

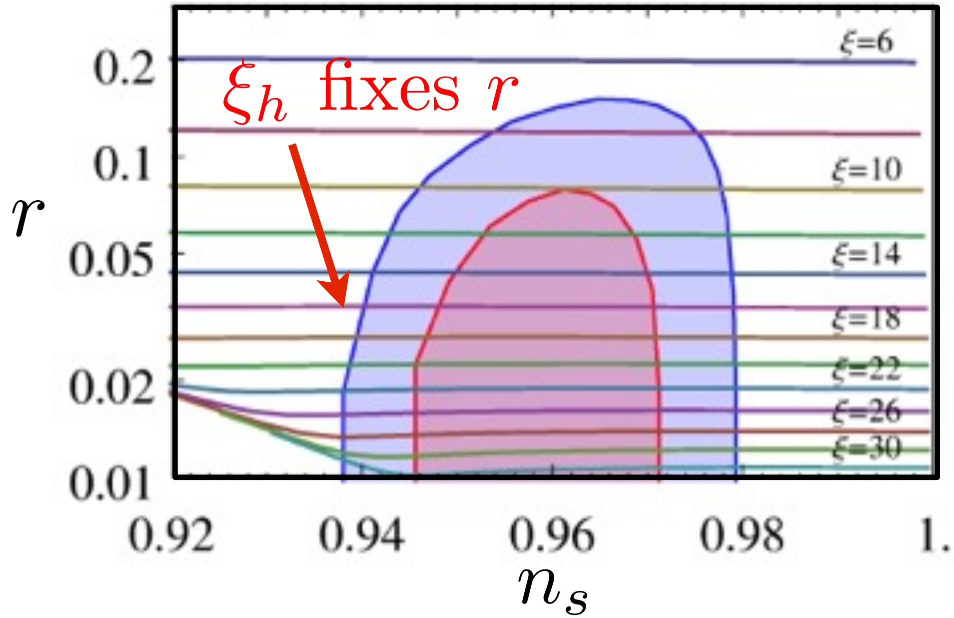
$$\lambda_0 \simeq b/16 \qquad \lambda(\mu(\phi)) = \lambda_0 + b\log^2\left(\frac{\sqrt{1-e^{-\alpha\kappa\phi}}}{q_{\text{eff}}}\right)$$

3 observational inputs for 3 unknown parameters

$\lambda_0 \longleftrightarrow A_s$

$\xi_h \longleftrightarrow r$

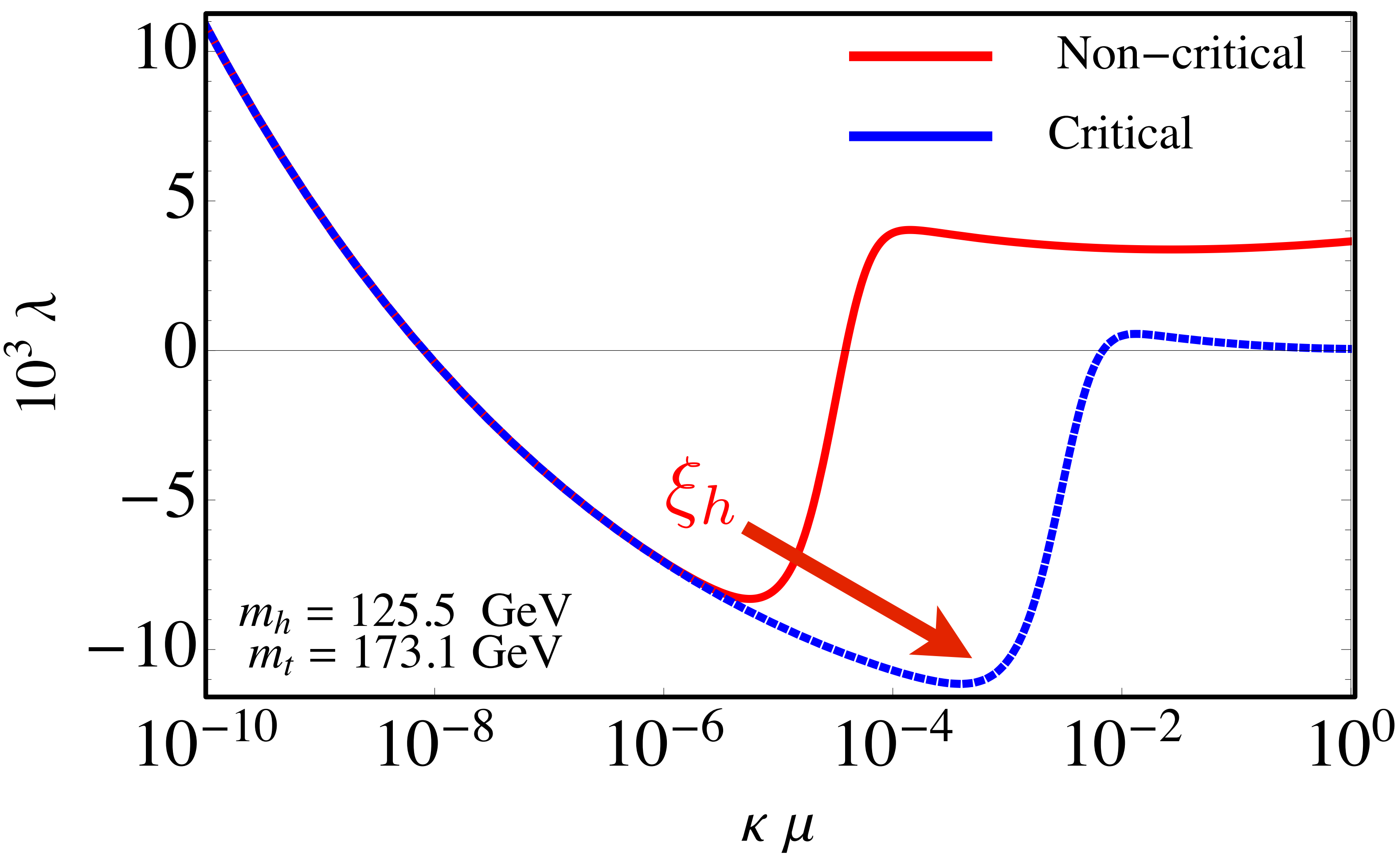
$q_{\text{eff}} \longleftrightarrow n_s$



No additional scales $\quad \dfrac{M_P}{\xi} \sim \dfrac{M_P}{\sqrt{\xi}} \sim M_P$


Living beyond the edge?

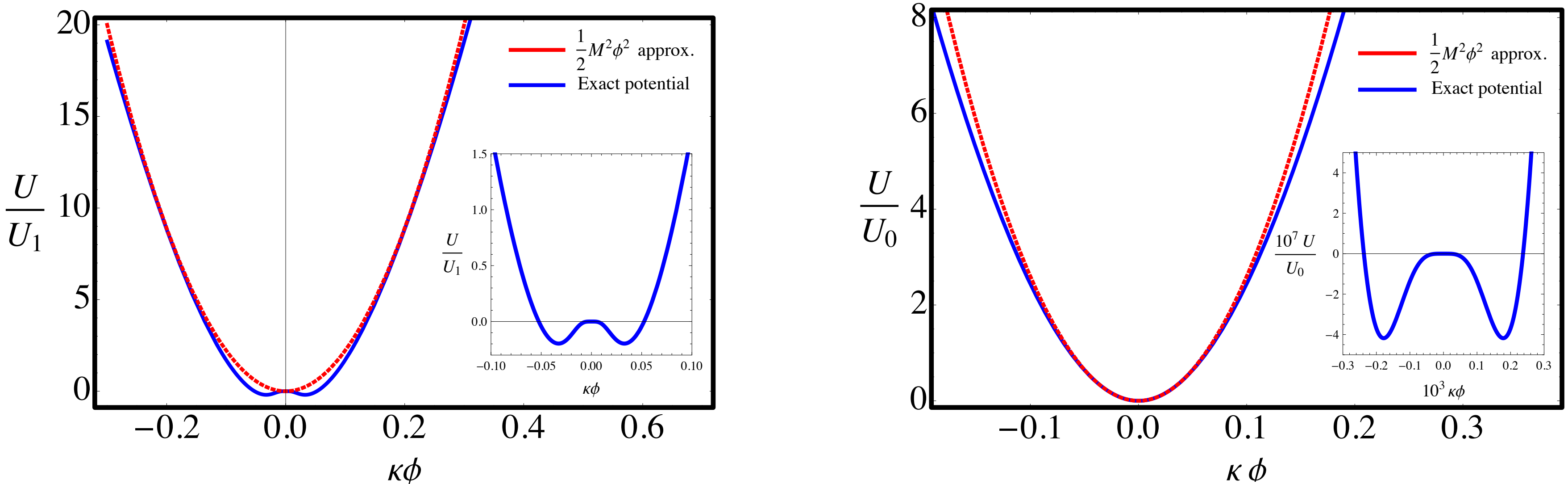
Restoring asymptotics

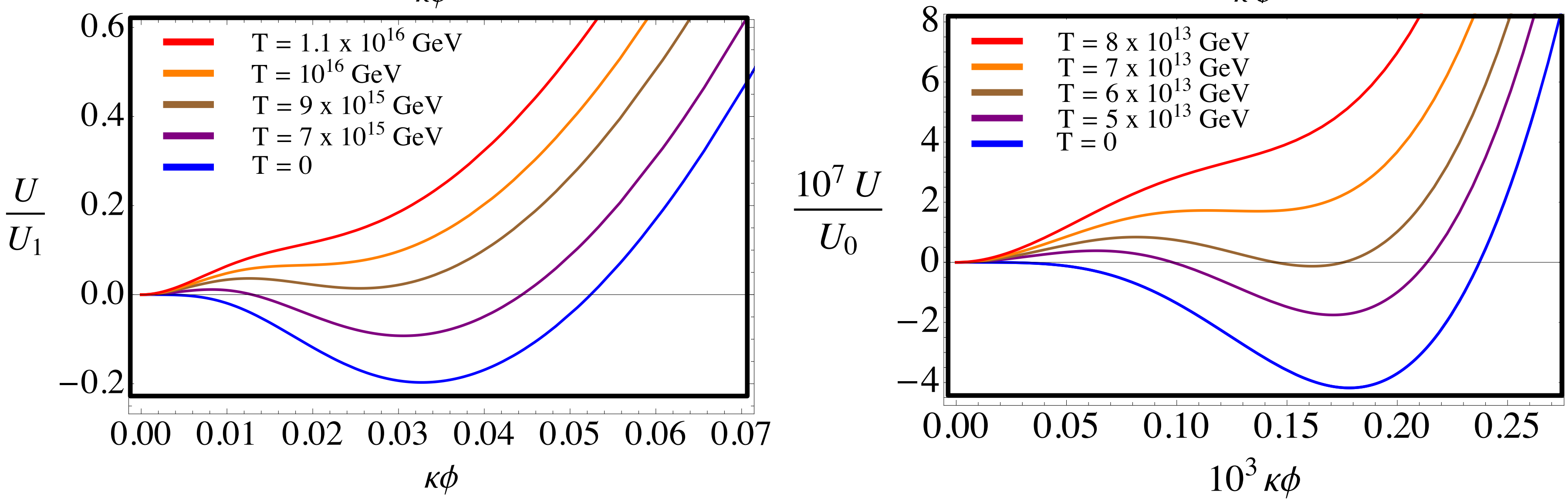


Thermal corrections

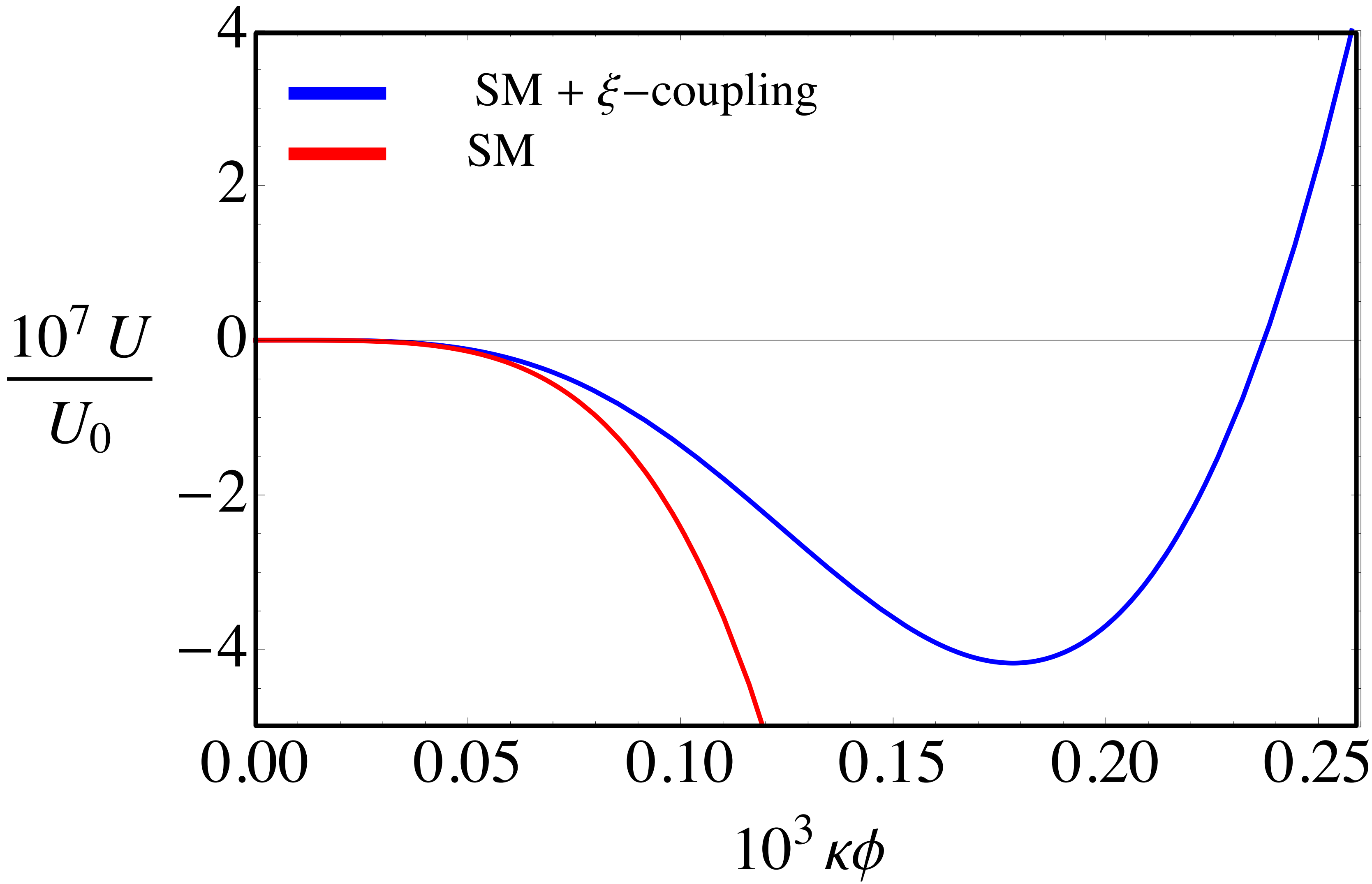
Critical case

Non-critical case





At low temperatures...



Life beyond the edge

Life beyond the edge

- ✓ The Higgs can make the Universe flat, homogeneous and isotropic
- ✓ A consistent EFT if the UV completion respects scale invariance

UNIVERSAL HI

$$r \simeq 0.003$$

$$\xi_h \sim \mathcal{O}(10^3)$$

CRITICAL HI

$$r \sim \mathcal{O}(0.1)$$

$$\xi_h \sim \mathcal{O}(10)$$

- ✓ The non-critical Higgs inflation scenario can be possible *even if our vacuum is metastable*
- ✓ The critical Higgs-inflation scenario *does require the stability of the vacuum all the way up till the inflationary scale*

2. Reliability of radiative corrections

Non-renormalizable -> Infinite number of counterterms

Respect scale invariance -> Dimensional regularization

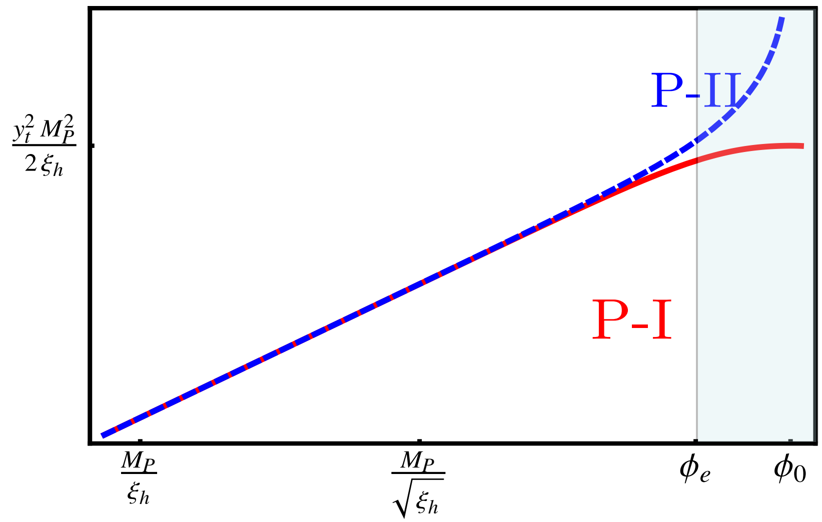
The choice of μ

In renormalizable theories, it is arbitrary and field-independent

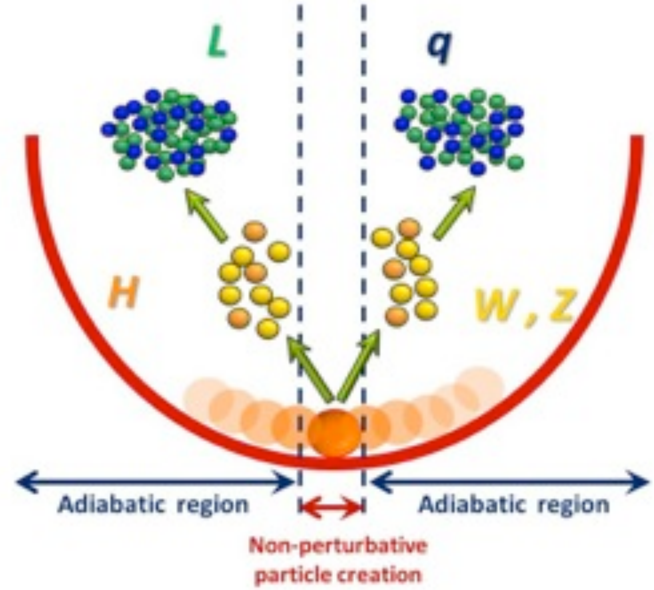
$$\lambda = \mu^{2\epsilon}\left(\lambda_R + \sum_n \frac{a_n}{\epsilon_n}\right)$$

We modify this prescription in our non-renormalizable theory

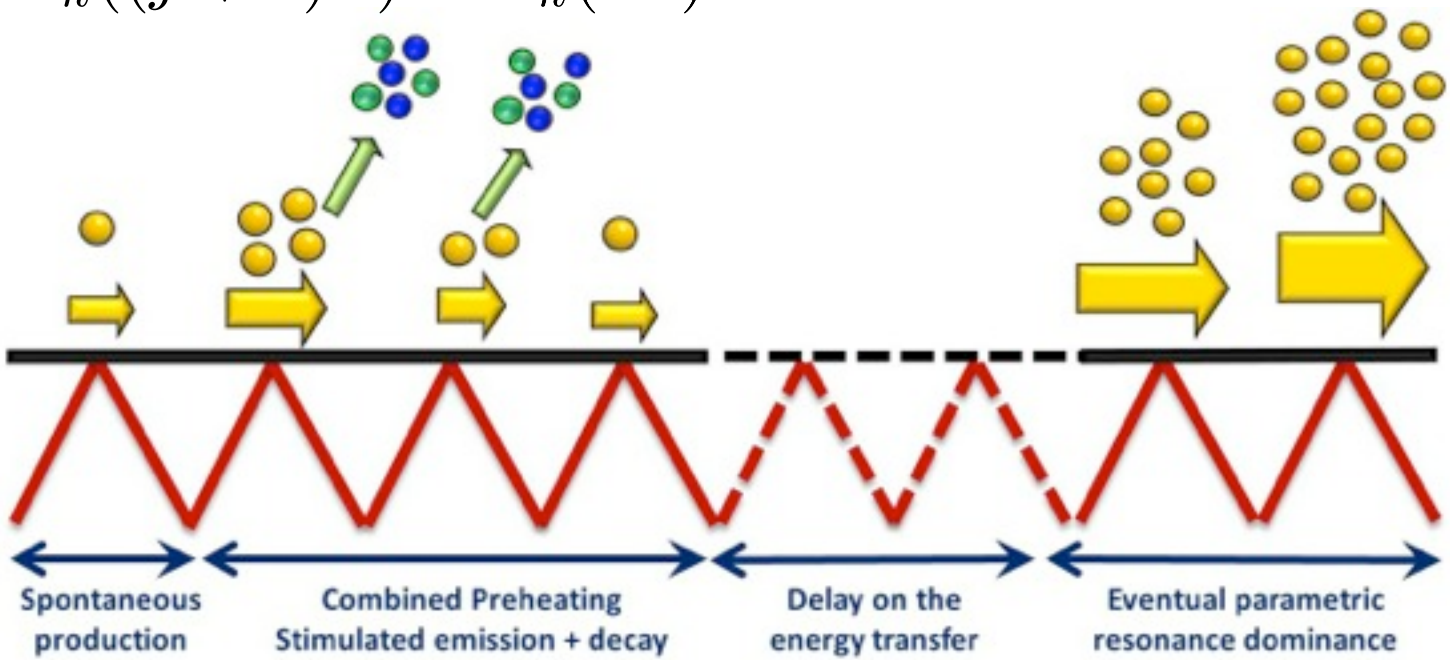
Jordan frame def.	
P-I	$M_P^2 + \xi_h h^2$
P-II	M_P^2



Combined Preheating



$$n_k((j+1)^+) = n_k(1^+)\, e^{-\gamma F_\Sigma(j)}\, e^{2\pi \sum_{i=1}^{j} \mu_k(i+1)}$$



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Critical case

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★ F. Bezrukov and M. Shaposhnikov arXiv:1403.6078.
★J. Rubio, M. Shaposhnikov Phys.Rev. D90 (2014) 027307