

# ***The Higgs boson in Cosmology***



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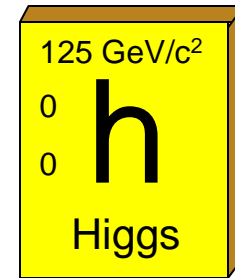
# *Outline*

- The Higgs was discovered at CERN in 2012
- It is the only fundamental scalar known
- = Relativistic ether gives mass to particles
- Its mass hints at a fundamental symmetry
- RGE equations leads to massless @ GUT
- Non-minimal coupling of Higgs to gravity
- Higgs drives inflation at GUT scale
- Breaking of scale invariance: the dilaton
- Higgs-Dilaton Inflation: predictions ( $n_s, w$ )
- Future surveys LSS and CMB experiments

# Three Generations of Matter (Fermions)

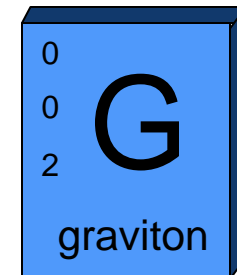
## *Is the Standard Model of Particle Physics complete?*

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> Z boson
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> W boson



scalar

vector



tensor

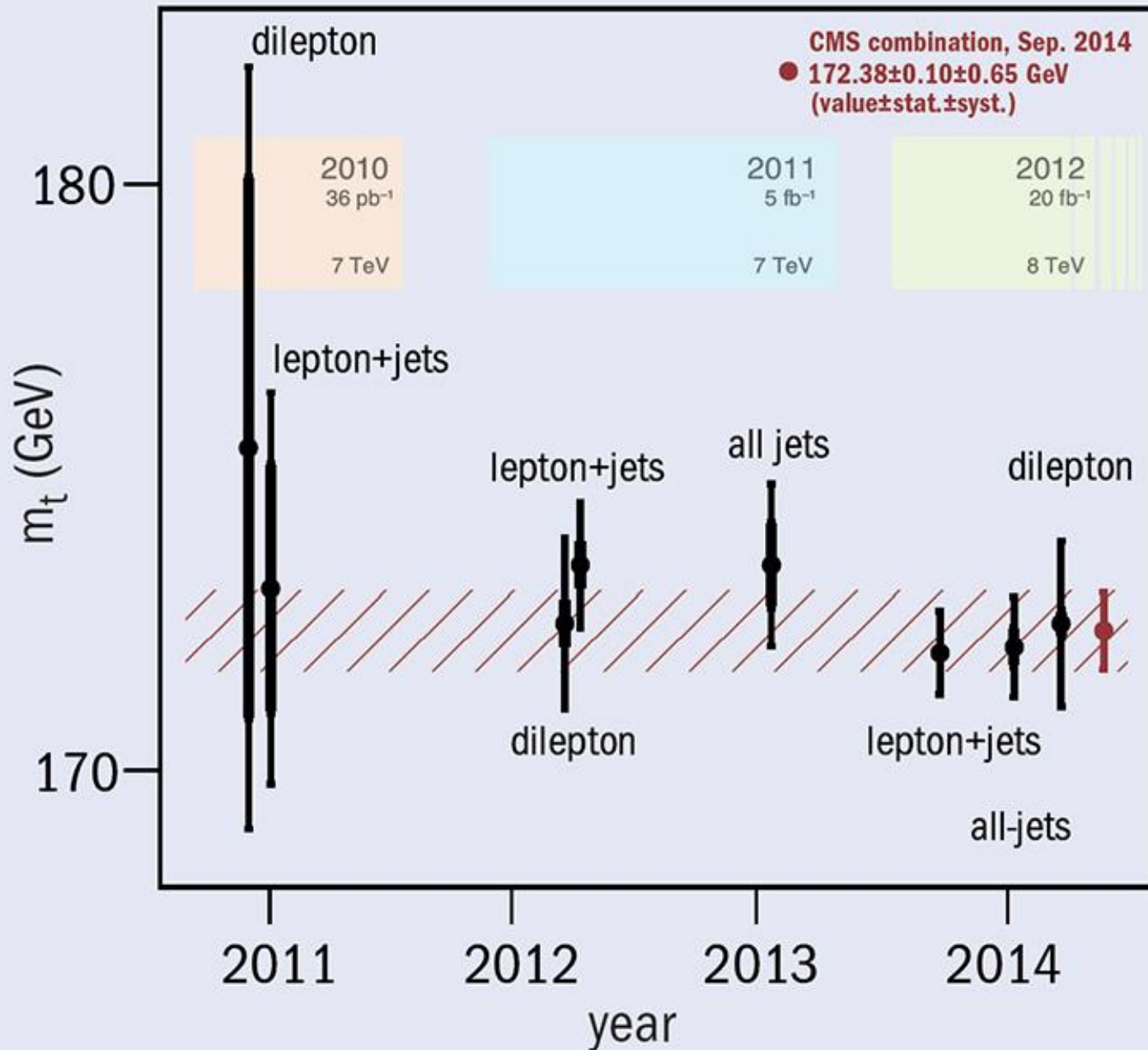


Gauge Bosons





# Top mass determination



## Beyond SM searches

Model	$\ell, \gamma$	Jets	$T_{miss}$	CP	Mass limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	$M_D$ 4.37 TeV
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	$M_S$ 5.2 TeV
	ADD QBH $\rightarrow \ell q$	$1e, \mu$	1 j	–	20.3	$M_{th}$ 5.2 TeV
	ADD QBH	–	2 j	–	20.3	$M_{th}$ 5.82 TeV
	ADD BH high $N_{trk}$	$2\mu$ (SS)	–	–	20.3	$M_{th}$ 5.7 TeV
	ADD BH high $\sum p_T$	$\geq 1e, \mu$	$\geq 2j$	–	20.3	$M_{th}$ 6.2 TeV
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	–	–	20.3	$G_{KK}$ mass 2.68 TeV
	RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$	$2e, \mu$	–	Yes	4.7	$G_{KK}$ mass 1.23 TeV
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell\ell qq$	$2e, \mu$	2 j / 1 J	–	20.3	$G_{KK}$ mass 730 GeV
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	$G_{KK}$ mass 590-710 GeV
Gauge bosons	Bulk RS $g_{KK} \rightarrow t\bar{t}$	$1e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	14.3	$g_{KK}$ mass 2.0 TeV
	$S^1/Z_2$ ED	$2e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV
	UED	$2\gamma$	–	Yes	4.8	Compact. scale $R^{-1}$ 1.41 TeV
	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	–	–	20.3	$Z'$ mass 2.9 TeV
	SSM $Z' \rightarrow \tau\tau$	$2\tau$	–	–	19.5	$Z'$ mass 1.9 TeV
	SSM $W' \rightarrow \ell\nu$	$1e, \mu$	–	Yes	20.3	$W'$ mass 3.28 TeV
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3e, \mu$	–	Yes	20.3	$W'$ mass 1.52 TeV
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	$2e, \mu$	2 j / 1 J	–	20.3	$W'$ mass 1.59 TeV
	LRSB $W'_R \rightarrow t\bar{b}$	$1e, \mu$	2 b, 0-1 j	Yes	14.3	$W'$ mass 1.84 TeV
	LRSB $W'_R \rightarrow t\bar{b}$	$0e, \mu$	$\geq 1b, 1J$	–	20.3	$W'$ mass 1.77 TeV
CI	CI $qqqq$	–	2 j	–	4.8	$\Lambda$ 7.6 TeV
	CI $qq\ell\ell$	$2e, \mu$	–	–	20.3	$\Lambda$ 21.6 TeV
	CI $uutt$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	14.3	$\Lambda$ 3.3 TeV
DM	EFT D5 operator (Dirac)	$0e, \mu$	1-2 j	Yes	10.5	$M_*$ 731 GeV
	EFT D9 operator (Dirac)	$0e, \mu$	1 J, $\leq 1j$	Yes	20.3	$M_*$ 2.4 TeV
LQ	Scalar LQ 1 <sup>st</sup> gen	$2e$	$\geq 2j$	–	1.0	LQ mass 660 GeV
	Scalar LQ 2 <sup>nd</sup> gen	$2\mu$	$\geq 2j$	–	1.0	LQ mass 685 GeV
	Scalar LQ 3 <sup>rd</sup> gen	$1e, \mu, 1\tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV
Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 4j$	Yes	14.3	T mass 790 GeV
	Vector-like quark $TT \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	14.3	T mass 670 GeV
	Vector-like quark $TT \rightarrow Zt + X$	$2/\geq 3e, \mu$	$\geq 2/\geq 1b$	–	20.3	T mass 735 GeV
	Vector-like quark $BB \rightarrow Zb + X$	$2/\geq 3e, \mu$	$\geq 2/\geq 1b$	–	20.3	B mass 755 GeV
	Vector-like quark $BB \rightarrow Wt + X$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	14.3	B mass 720 GeV
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1\gamma$	1 j	–	20.3	$q^*$ mass 3.5 TeV
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	$q^*$ mass 4.09 TeV
	Excited quark $b^* \rightarrow Wt$	1 or $2e, \mu$	1 b, 2 j or 1 j	Yes	4.7	$b^*$ mass 870 GeV
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	–	–	13.0	$\ell^*$ mass 2.2 TeV
Other	LSTC $a_T \rightarrow W\gamma$	$1e, \mu, 1\gamma$	–	Yes	20.3	$a_T$ mass 960 GeV
	LRSB Majorana $\nu$	$2e, \mu$	2 j	–	2.1	$N^0$ mass 1.5 TeV
	Type III Seesaw	$2e, \mu$	–	–	5.8	$N^\pm$ mass 245 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV

# *Standard Model parameters*

Buttazzo, Degrandi, Giardino, Giudice, Sala, Salvio, Strumia (2014)

$M_W = 80.384 \pm 0.014 \text{ GeV}$  Pole mass of the  $W$  boson

$M_Z = 91.1876 \pm 0.0021 \text{ GeV}$  Pole mass of the  $Z$  boson

$M_h = 125.15 \pm 0.24 \text{ GeV}$  Pole mass of the higgs

$M_t = 173.34 \pm 0.76 \pm 0.3 \text{ GeV}$  Pole mass of the top quark

$(\sqrt{2}G_\mu)^{-1/2} = 246.21971 \pm 0.00006 \text{ GeV}$  Fermi constant for  $\mu$  decay

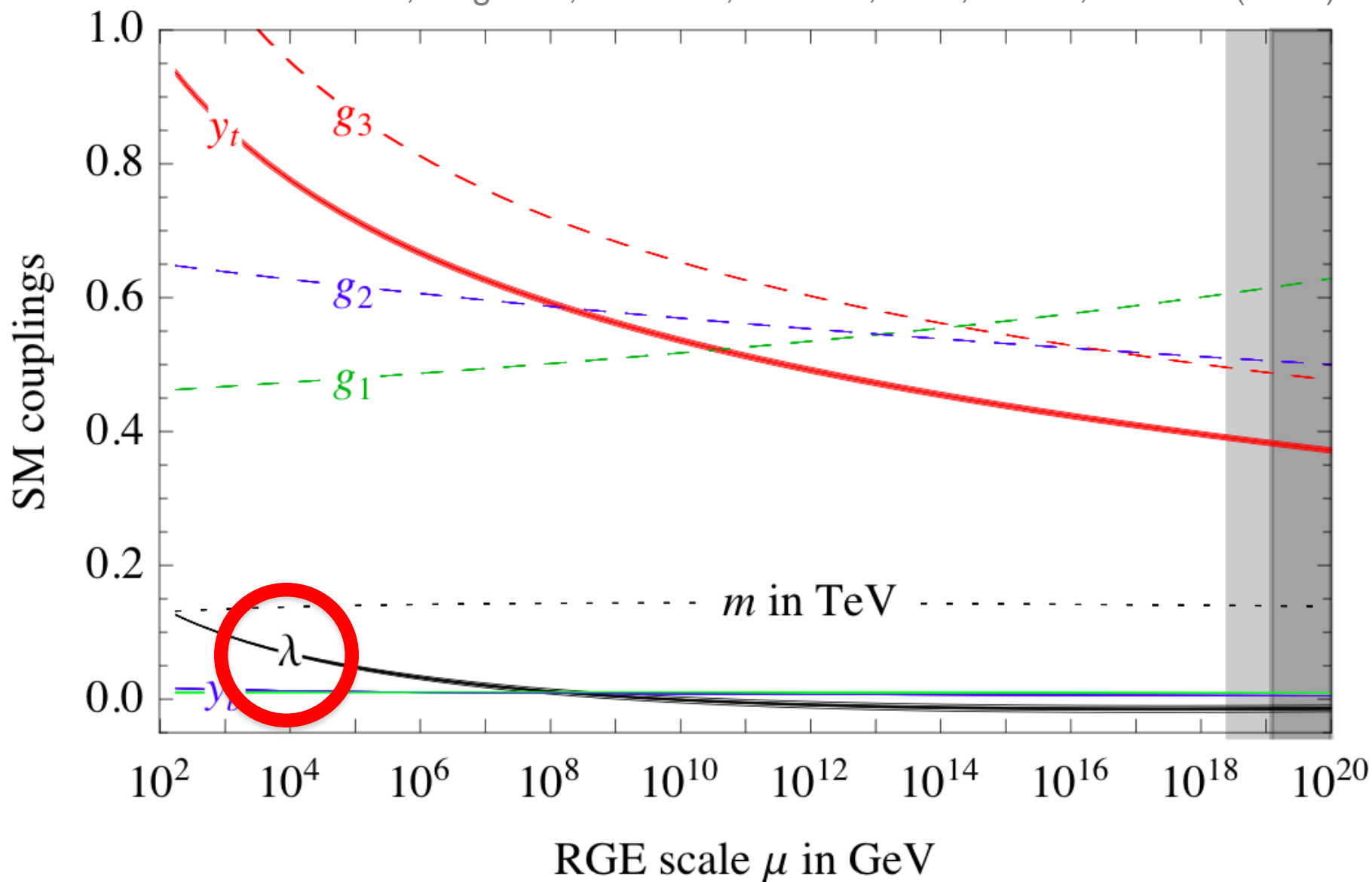
$\alpha_3(M_Z) = 0.1184 \pm 0.0007$   $\overline{\text{MS}}$  gauge  $\text{SU}(3)_c$  coupling (

## *Non-minimal coupling of Higgs to gravity*

$$S_J = \int d^4x \sqrt{-g} \left[ -\frac{M_{\text{Pl}}^2}{2} \left( 1 + \frac{2\xi H^\dagger H}{M_{\text{Pl}}^2} \right) \mathcal{R} + (\partial_\mu H)^\dagger (\partial^\mu H) - V \right]$$

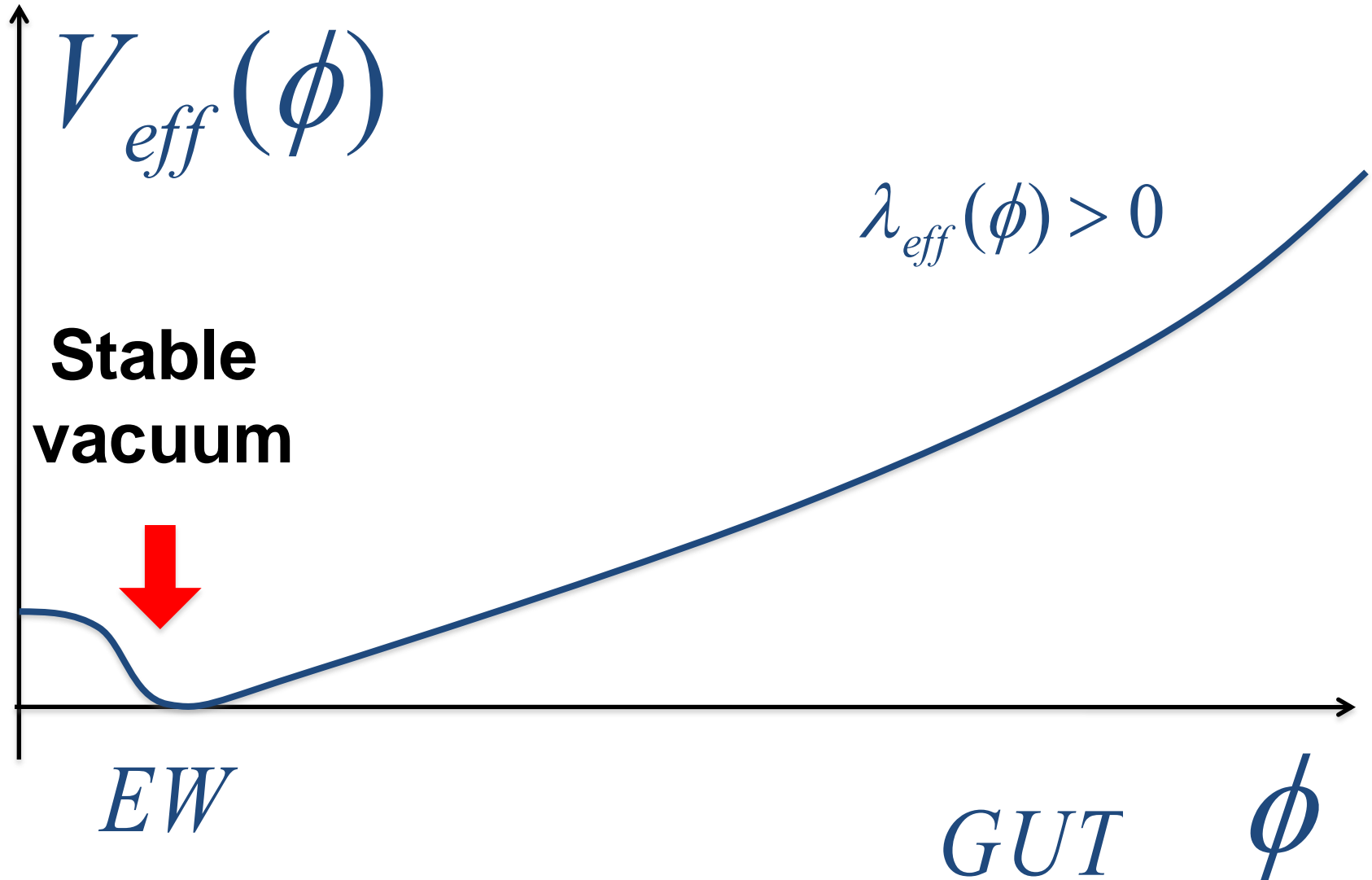
# *2-loop RGE running*

Buttazzo, Degrandi, Giardino, Giudice, Sala, Salvio, Strumia (2014)

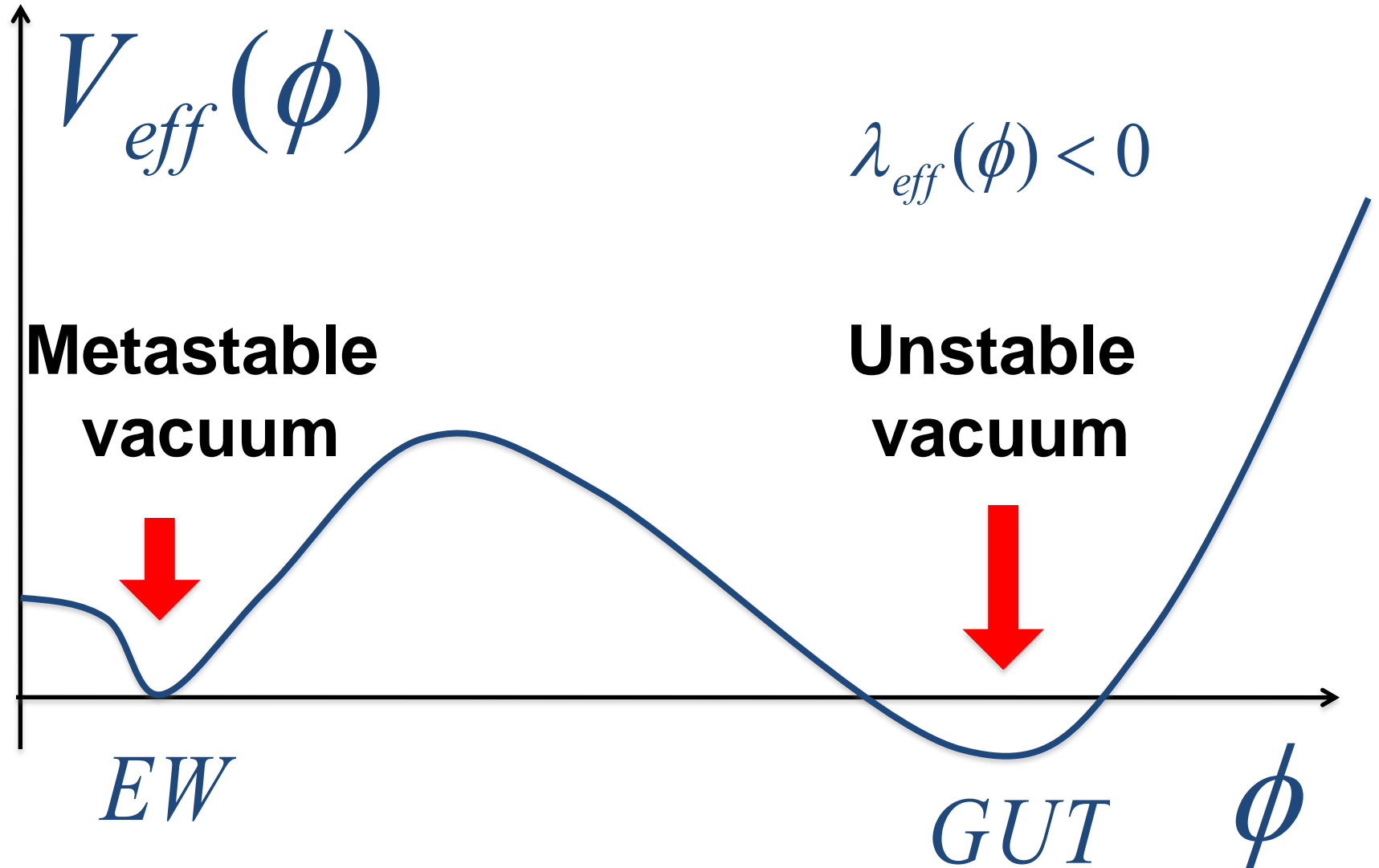


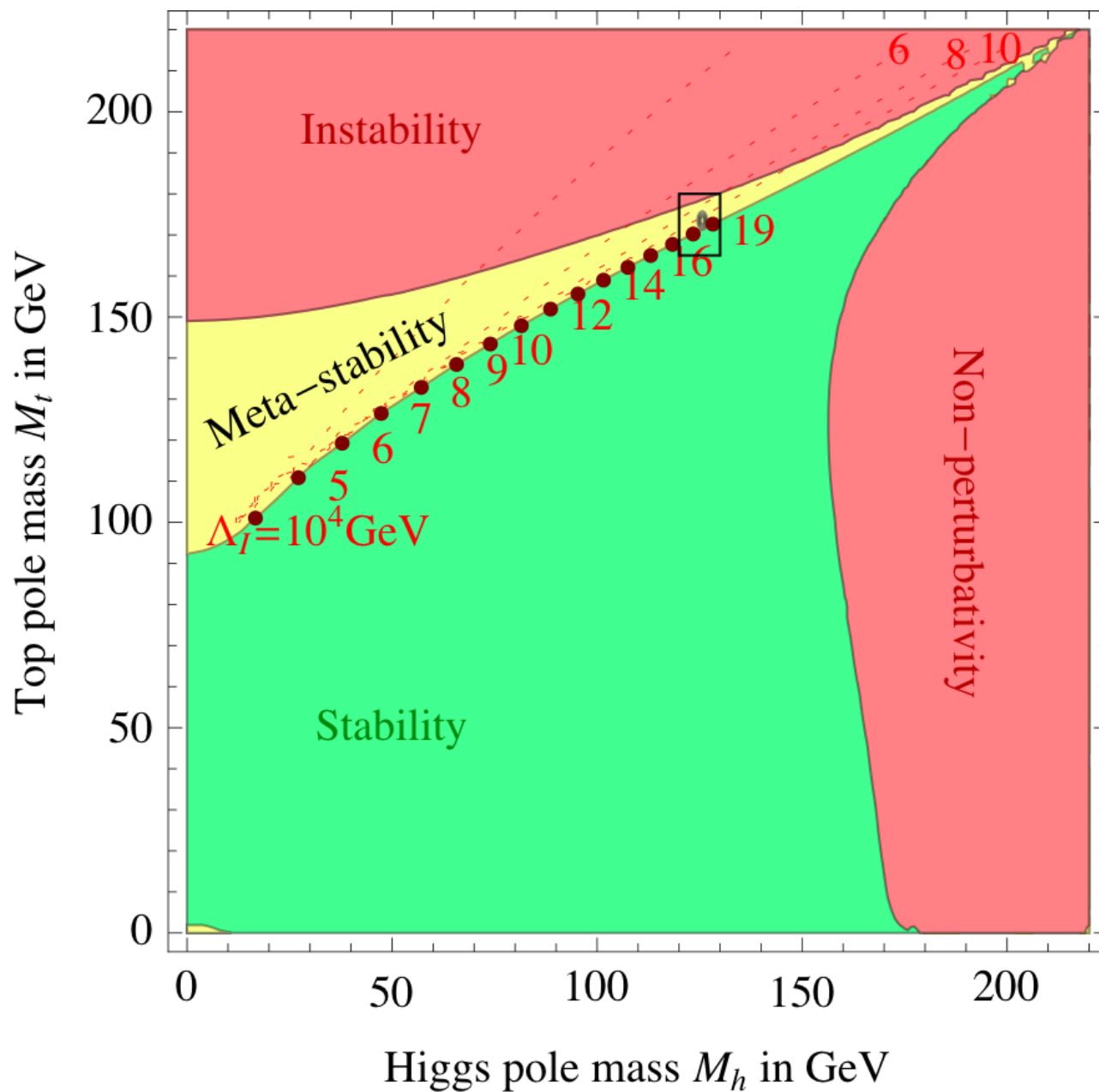


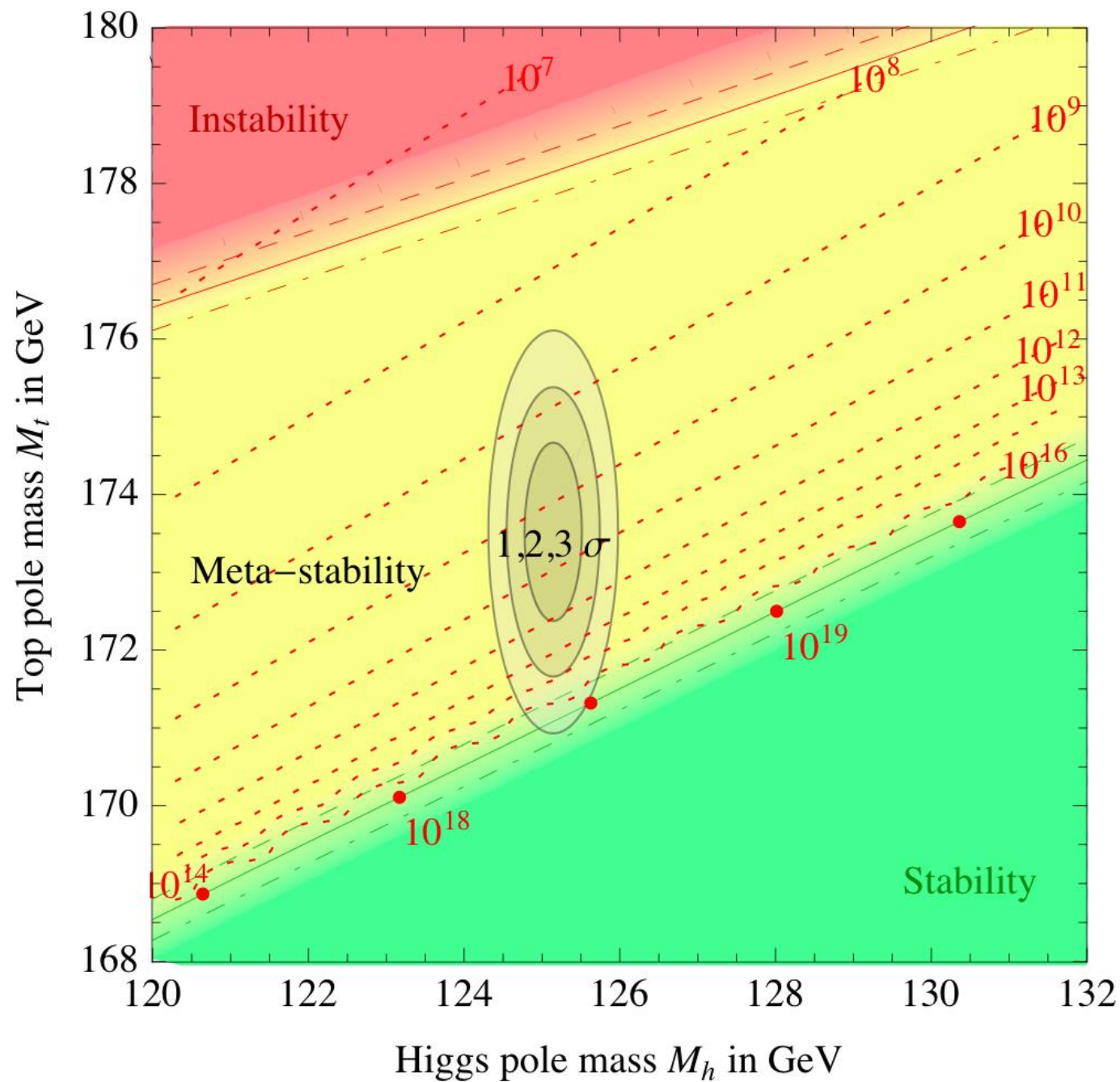
# *Higgs effective potential*



# *Higgs effective potential*

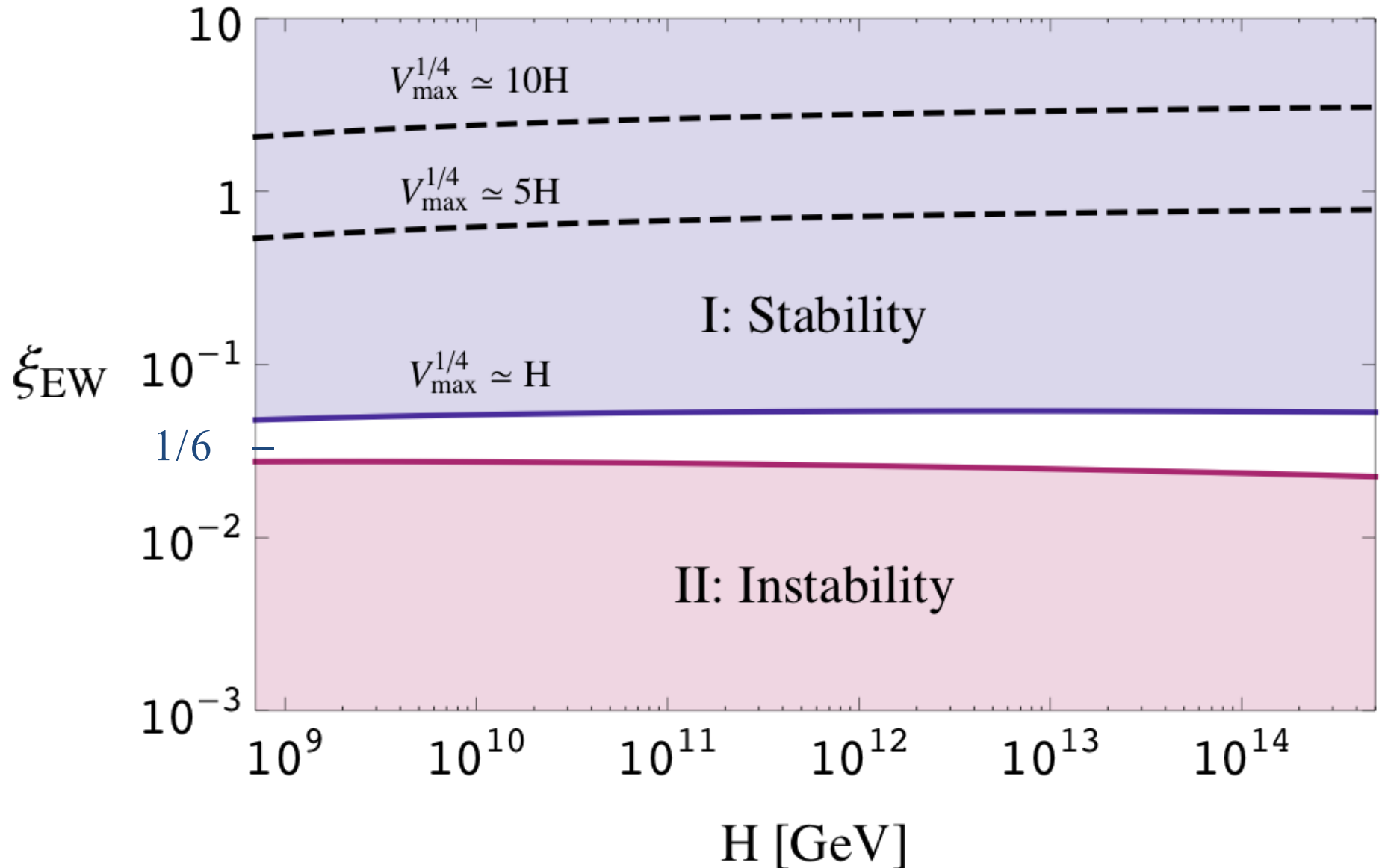






# *Non-minimal coupling of Higgs to gravity*

Herranen, Markkanen, Nurmi, Rajantie (2014)





# 2-loop RGE running

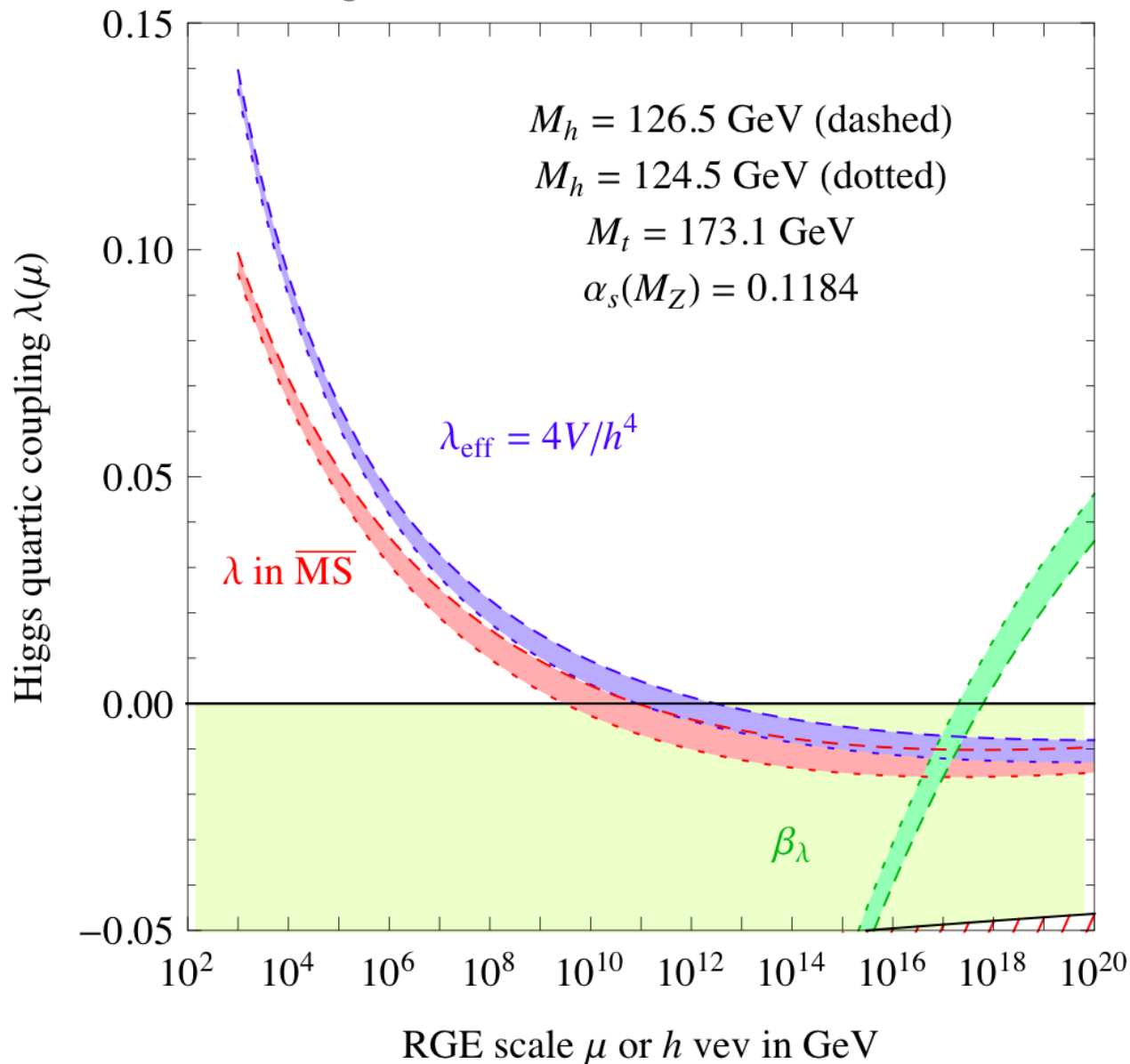
Allison (2014)

$$\begin{aligned}\beta_\lambda = & \frac{1}{(4\pi)^2} \left[ (6 + 18s^2) \lambda^2 - 6y_t^4 + \frac{3}{8} (2g^4 + (g^2 + g'^2)^2) + (-9g^2 - 3g'^2 + 12y_t^2) \lambda \right] \\ & + \frac{1}{(4\pi)^4} \left[ \frac{1}{48} ((912 + 3s) g^6 - (290 - s) g^4 g'^2 - (560 - s) g^2 g'^4 - (380 - s) g'^6) \right. \\ & + (38 - 8s) y_t^6 - y_t^4 \left( \frac{8}{3} g'^2 + 32g_s^2 + (12 - 117s + 108s^2) \lambda \right) \\ & + \lambda \left( -\frac{1}{8} (181 + 54s - 162s^2) g^4 + \frac{1}{4} (3 - 18s + 54s^2) g^2 g'^2 + \frac{1}{24} (90 + 377s + 162s^2) g'^4 \right. \\ & + (27 + 54s + 27s^2) g^2 \lambda + (9 + 18s + 9s^2) g'^2 \lambda - (48 + 288s - 324s^2 + 624s^3 - 324s^4) \lambda^2 \Big) \\ & \left. + y_t^2 \left( -\frac{9}{4} g^4 + \frac{21}{2} g^2 g'^2 - \frac{19}{4} g'^4 + \lambda \left( \frac{45}{2} g^2 + \frac{85}{6} g'^2 + 80g_s^2 - (36 + 108s^2) \lambda \right) \right) \right].\end{aligned}$$

$$\begin{aligned}\beta_\xi = & \frac{1}{(4\pi)^2} \left( \xi + \frac{1}{6} \right) \left[ -\frac{3}{2} g'^2 - \frac{9}{2} g^2 + 6y_t^2 + (6 + 6s) \lambda \right] \\ & + \frac{1}{(4\pi)^4} \left( \xi + \frac{1}{6} \right) \left[ \left( -\frac{199}{16} + \frac{27}{8} s \right) g^4 + \left( -\frac{3}{8} + \frac{9}{4} s \right) g^2 g'^2 + \left( \frac{3}{2} + \frac{485}{48} s \right) g'^4 \right. \\ & + \left( \frac{45}{4} g^2 + \frac{85}{12} g'^2 + 40g_s^2 \right) y_t^2 + \left( 18 - \frac{63}{2} s \right) y_t^4 + (36g^2 + 12g'^2 - 36y_t^2) (1 + s) \lambda \\ & \left. + (-108 + 126s - 144s^2 + 66s^3) \lambda^2 \right].\end{aligned}\tag{4}$$

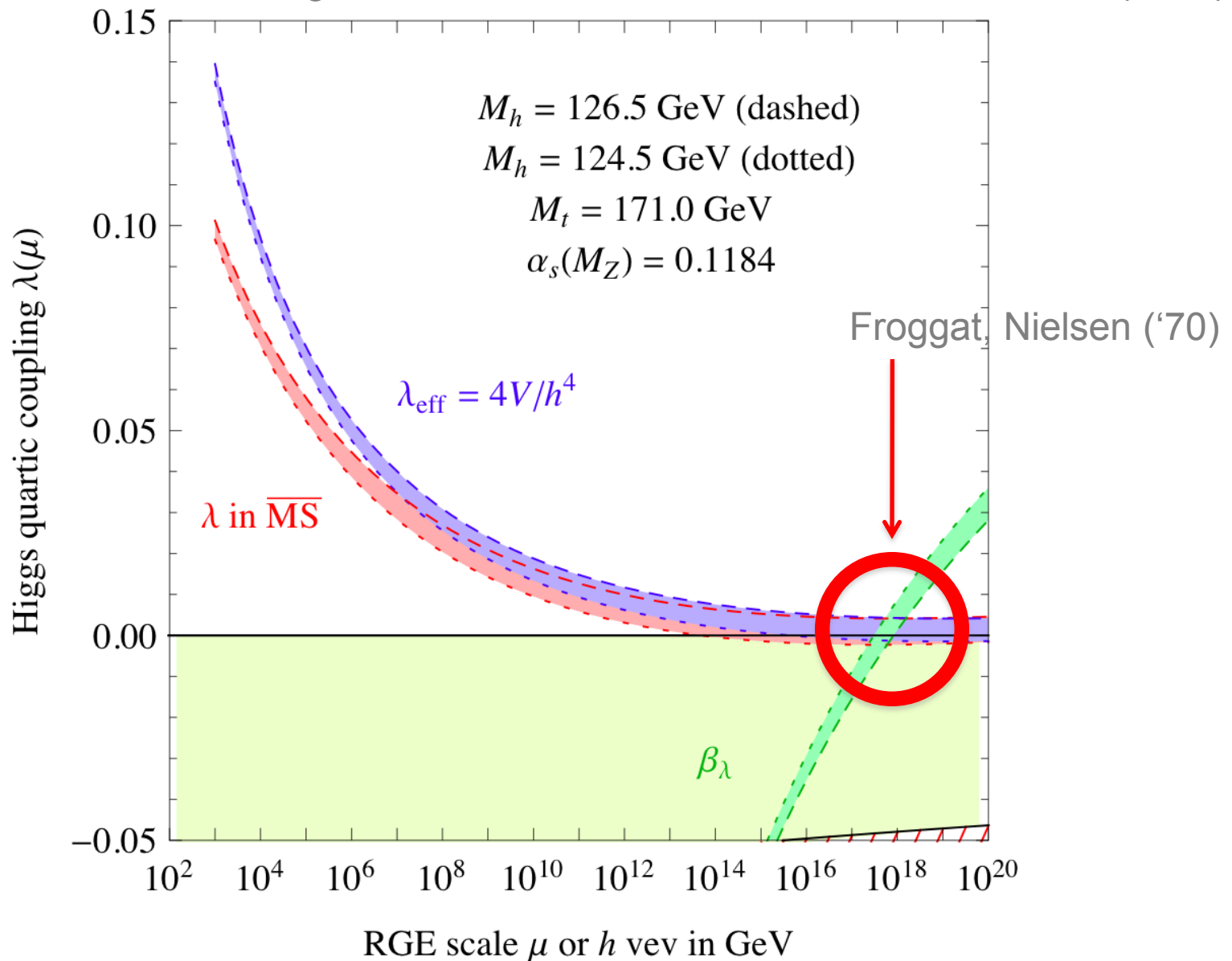
# Non-minimal coupling of Higgs to gravity

Buttazzo, Degrandi, Giardino, Giudice, Sala, Salvio, Strumia (2014)

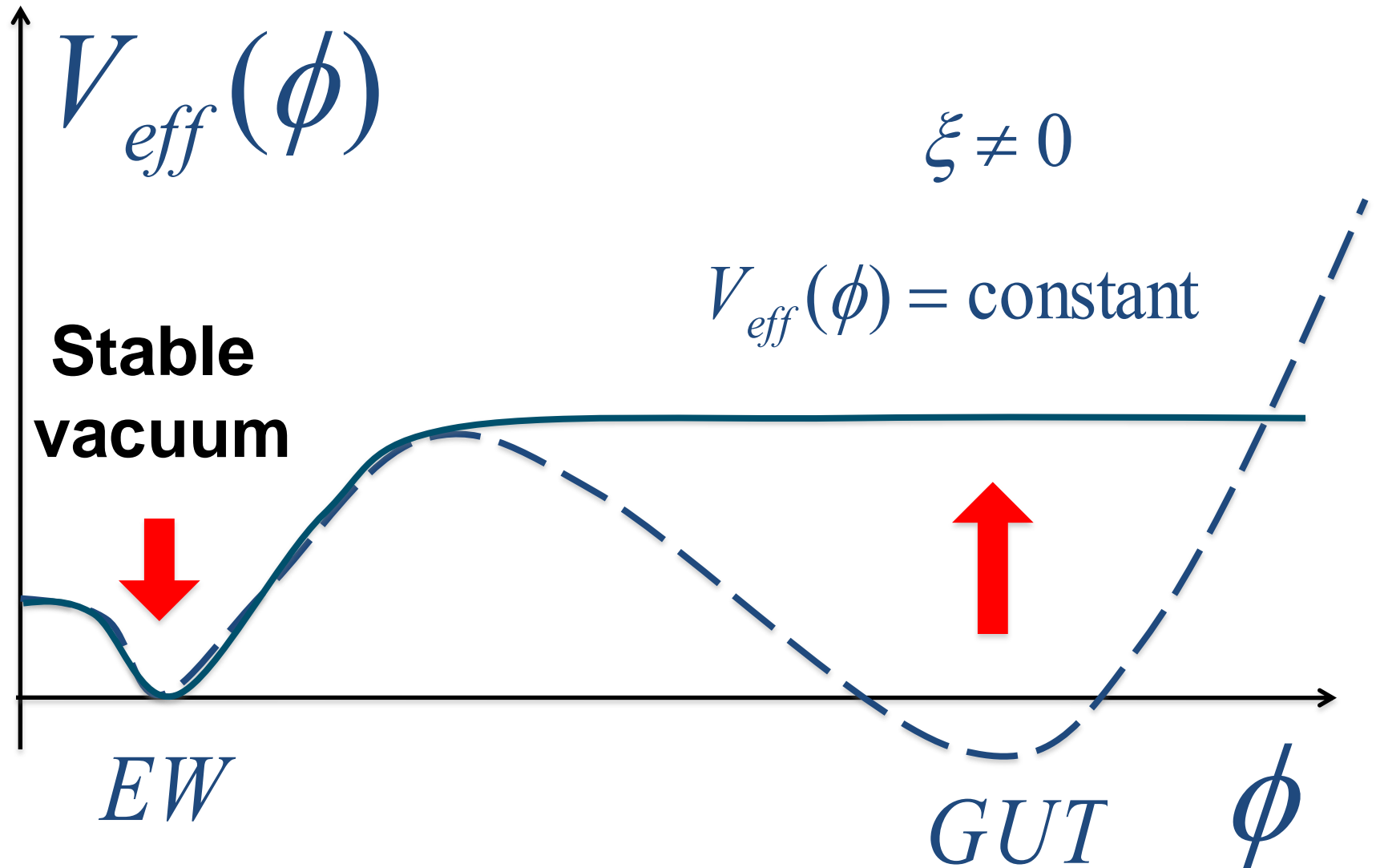


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Buttazzo, Degrandi, Giardino, Giudice, Sala, Salvio, Strumia (2014)

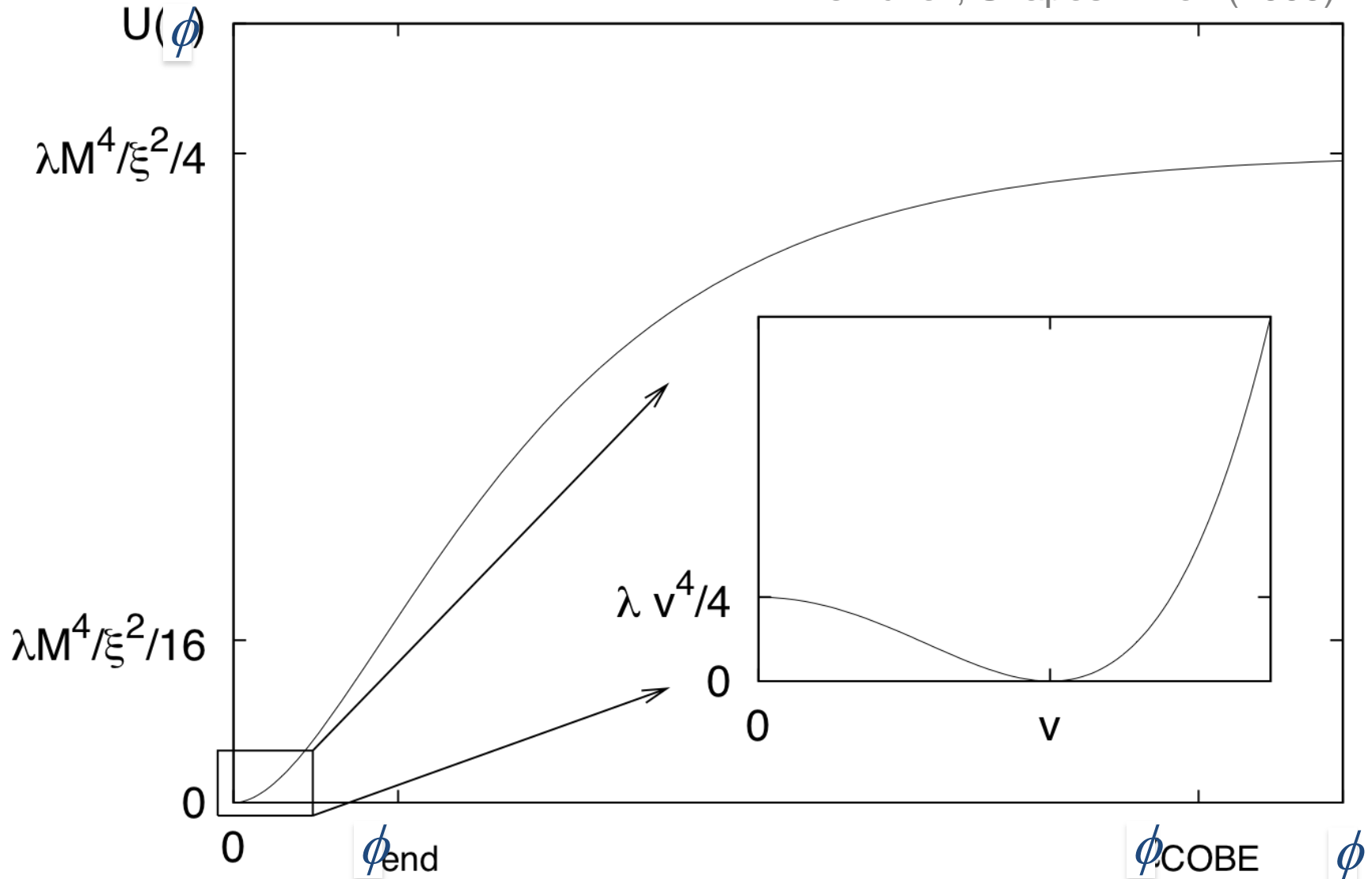


# *Higgs effective potential*



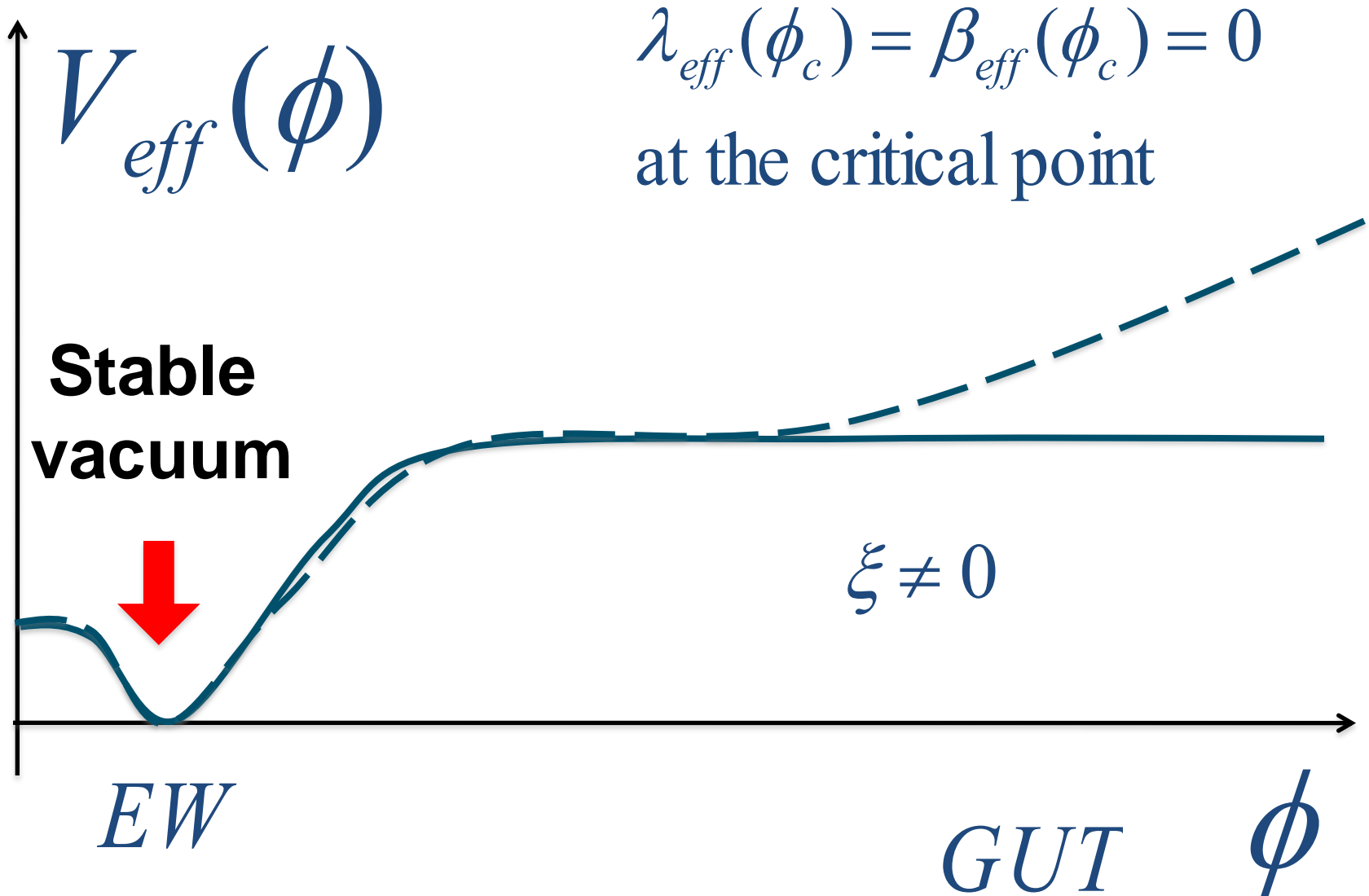
# *Higgs=Inflaton Potential*

Salopek, Bond, Bardeen (1989)  
Bezrukov, Shaposhnikov (2009)



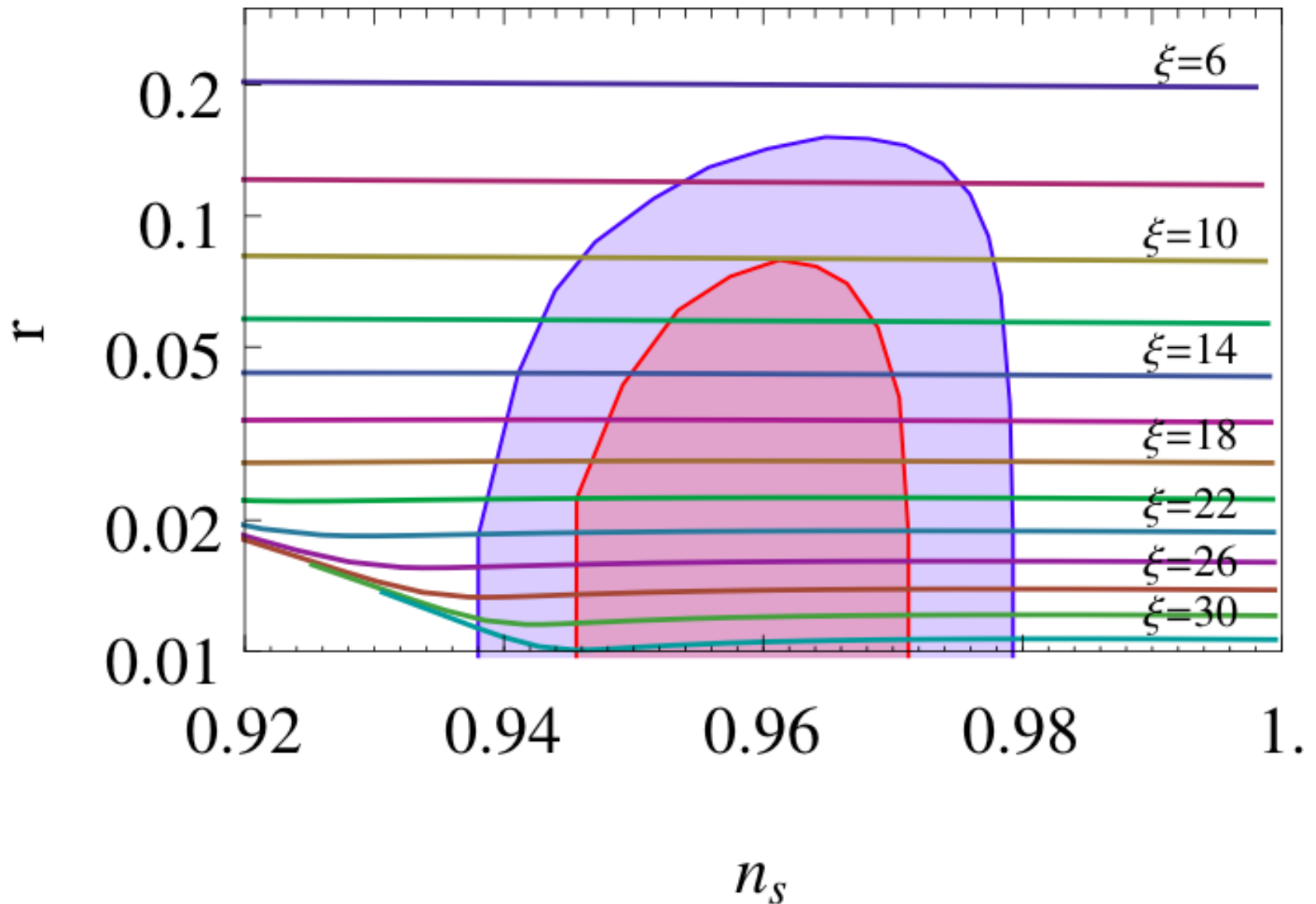


# *Higgs effective potential*



# *Higgs inflation at the critical point*

Bezrukov, Shaposhnikov (2014)



# *Mass hierarchy: Fermi - Planck scales*

- The **Standard Model** plus **Gravity** has 3 dimensional parameters:  **$G$ ,  $v$ ,  $\Lambda$**
- Could all scales have a **common origin**?
- **Minimal extension** of SM + GR with no dimensional parameter in the action:  
**Scale invariance** at the classical level
- S.I. maintained at the **quantum level**
- All scales induced by Spont. S.B. of S.I.
- **→** New scalar (singlet) d.o.f. = dilaton

# *Scale Invariance*

- Dilaton is **Goldstone Boson** of S.B. of S.I.
- Dilaton is exactly **massless**
- Dilaton only couples to Higgs (derivatively)
- It cannot be detected in LHC collisions
- Substitute GR for **Unimodular Gravity** w/ no dimensional parameter in the action.
- The integration constant gives non-trivial potential for dilaton: **thawing quintessence**
- Dilaton is the massless Dark Energy field

# *Higgs-dilaton inflation*

JGB, Rubio, Shaposhnikov, Zenhausern (2011)  
Shaposhnikov, Zenhausern (2009)

Lagrangian:

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2} (\xi_\chi \chi^2 + \xi_h h^2) R - \frac{1}{2} (\partial_\mu \chi)^2 - \frac{1}{2} (\partial_\mu h)^2 - V(h, \chi) - \Lambda_0 ,$$

Einstein-frame metric:  $\tilde{g}_{\mu\nu} = M_P^{-2} (\xi_\chi \chi^2 + \xi_h h^2) g_{\mu\nu}$

$$\frac{\mathcal{L}}{\sqrt{-\tilde{g}}} = M_P^2 \frac{\tilde{R}}{2} - \frac{1}{2} \tilde{K} - \tilde{U}(h, \chi)$$

$$\tilde{K}(\chi, h) = \kappa_{ij}^E \tilde{g}^{\mu\nu} \partial_\mu \Phi^i \partial_\nu \Phi^j , \quad \kappa_{ij}^E \equiv \frac{1}{\Omega^2} \left( \delta_{ij} + \frac{3}{2} M_P^2 \frac{\partial_i \Omega^2 \partial_j \Omega^2}{\Omega^2} \right)$$

$$\tilde{U}(\chi, h) \equiv \frac{U(\chi, h)}{\Omega^4} \equiv \frac{M_P^4}{(\xi_\chi \chi^2 + \xi_h h^2)^2} \left( \frac{\lambda}{4} \left( h^2 - \frac{\alpha}{\lambda} \chi^2 \right)^2 + \Lambda_0 \right)$$



# Higgs-dilaton potential

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

Noether current of scale invariance in E-frame:

$$\tilde{D}_\mu \tilde{J}^\mu = -\frac{\partial \tilde{V}_{\Lambda_0}}{\partial \phi^i} \Delta \phi^i = \frac{4\Lambda_0}{\Omega^4} \quad \eta = \frac{\xi_\chi}{\xi_h} \quad \text{and} \quad \varsigma = \frac{(1+6\xi_h)\xi_\chi}{(1+6\xi_\chi)\xi_h}$$

$$\tilde{J}^\mu = \tilde{g}^{\mu\nu} \frac{M_P^2}{2(\xi_\chi \chi^2 + \xi_h h^2)} \partial_\nu ((1+6\xi_\chi)\chi^2 + (1+6\xi_h)h^2)$$

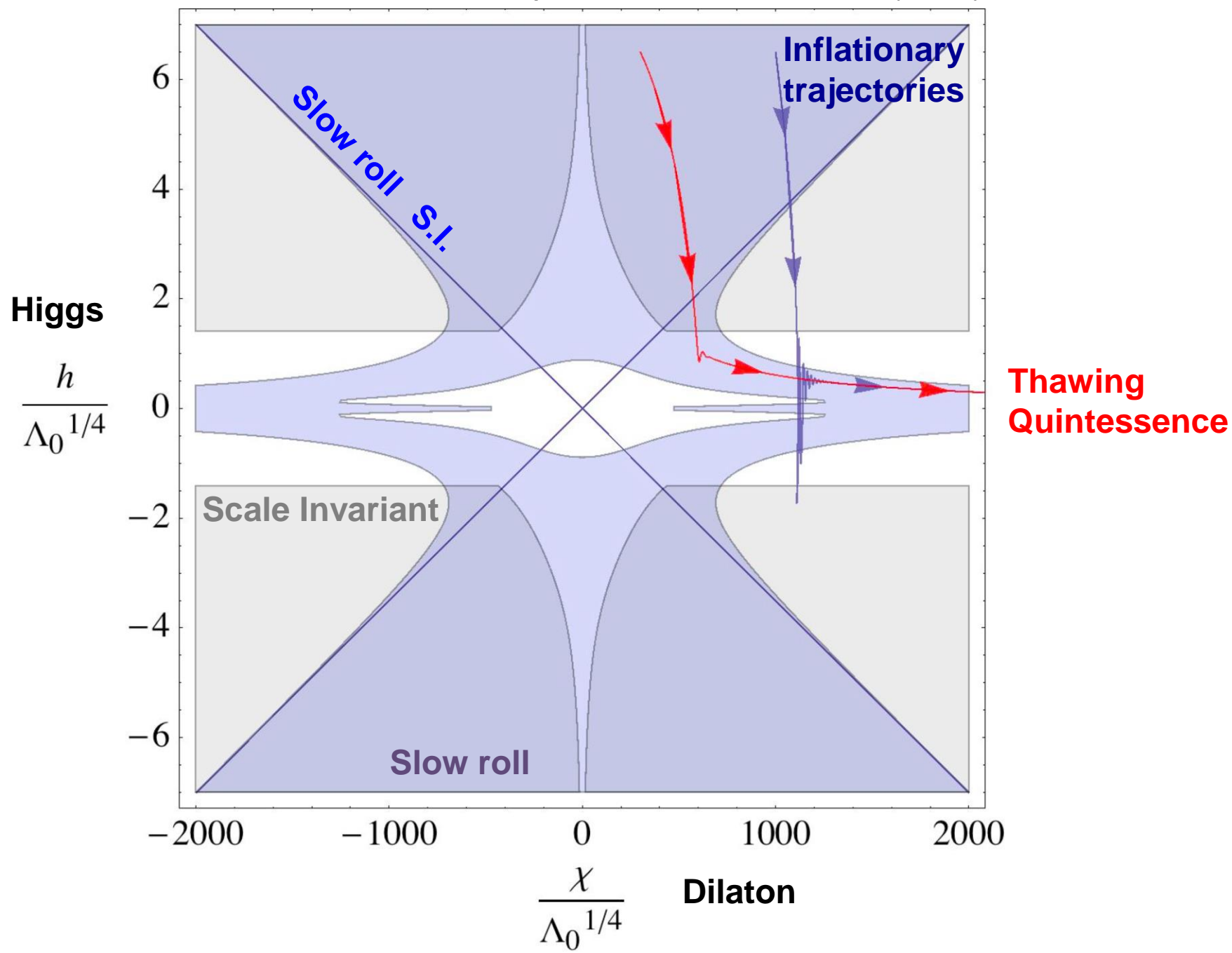
Field redefinition (radial and angular coordinates):

$$\rho = \frac{M_P}{2} \log \left[ \frac{(1+6\xi_\chi)\chi^2 + (1+6\xi_h)h^2}{M_P^2} \right], \quad \tan \theta = \sqrt{\frac{1+6\xi_h}{1+6\xi_\chi}} \frac{h}{\chi}$$
$$\tilde{K} = \left( \frac{1+6\xi_h}{\xi_h} \right) \frac{1}{\sin^2 \theta + \varsigma \cos^2 \theta} (\partial \rho)^2 + \frac{M_P^2 \varsigma}{\xi_\chi} \frac{\tan^2 \theta + \eta}{\cos^2 \theta (\tan^2 \theta + \varsigma)^2} (\partial \theta)^2,$$

Inflationary potential:

Quintessence potential:

$$\tilde{U}(\theta) = \frac{\lambda M_P^4}{4\xi_h^2} \left( \frac{\sin^2 \theta}{\sin^2 \theta + \varsigma \cos^2 \theta} \right)^2, \quad \tilde{U}_{\Lambda_0}(\rho, \theta) = \Lambda_0 \left( \frac{1+6\xi_h}{\xi_h} \right)^2 \frac{e^{-4\rho/M_P}}{(\sin^2 \theta + \varsigma \cos^2 \theta)^2}$$



# Predictions of Higgs-dilaton inflation

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

$$\begin{aligned}
 P_\zeta(k_0) &\simeq \frac{\lambda N^{*2}}{72\pi^2 \xi_h^2} \left( 1 + \frac{1}{3} (4\xi_\chi N^*)^2 + \dots \right), & \alpha_\zeta(k_0) &\simeq -\frac{1}{6}r(k_0) = \frac{4}{3}n_g(k_0), \\
 n_s(k_0) - 1 &\simeq -\frac{2}{N^*} \left( 1 + \frac{1}{3} (4\xi_\chi N^*)^2 + \dots \right), & n_s(k_0) &< 0.97 \simeq 1 - \frac{2}{N^*}, \\
 \alpha_\zeta(k_0) &\simeq -\frac{2}{N^{*2}} \left( 1 - \frac{1}{3} (4\xi_\chi N^*)^2 + \dots \right), & \alpha_\zeta(k_0) &> -0.0006 \simeq -\frac{2}{N^{*2}}, \\
 r(k_0) &\simeq \frac{12}{N^{*2}} \left( 1 - \frac{1}{3} (4\xi_\chi N^*)^2 + \dots \right), & r(k_0) &< 0.0033 \simeq \frac{12}{N^{*2}}
 \end{aligned}$$

$$\xi_\chi \lesssim 0.008 \quad \text{translates to} \quad \begin{cases} \alpha_\zeta(k_0) \lesssim -0.00015, \\ r(k_0) \gtrsim 0.0009 \end{cases}$$

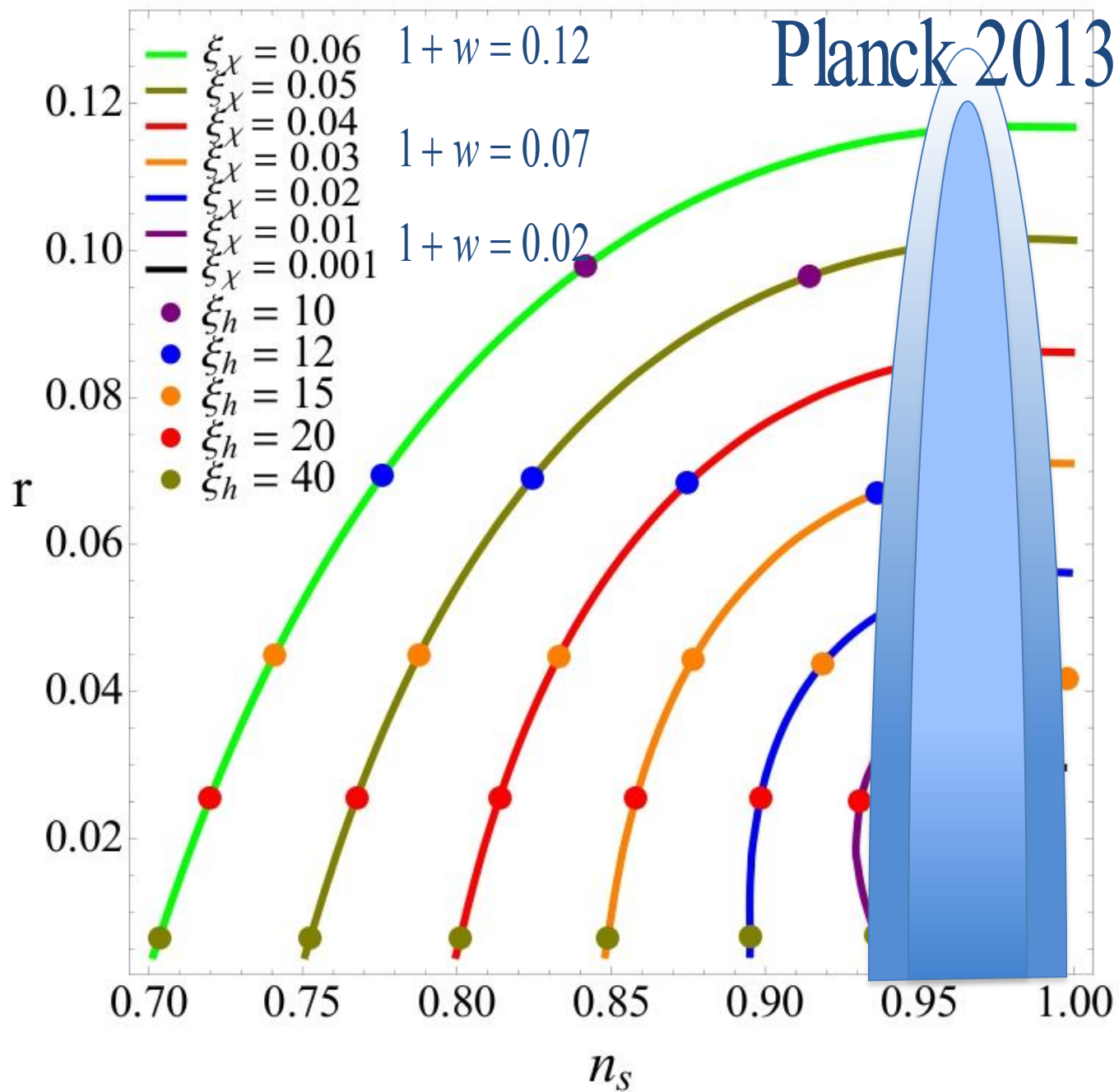
reheating after inflation

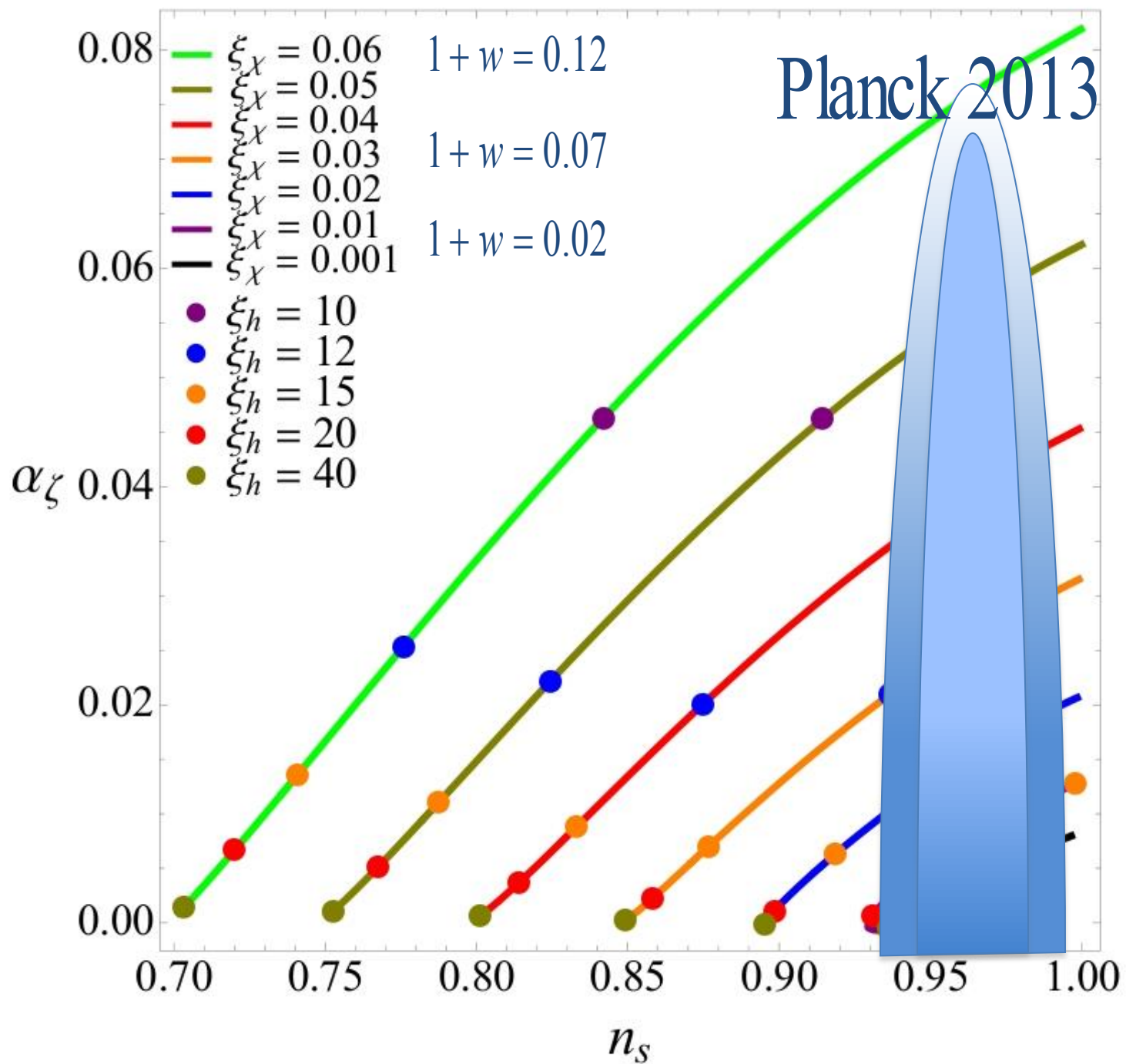
JGB, Rubio, Shaposhnikov (2012)

$$\Delta N_{\text{eff}} \equiv \left( \frac{\rho_\chi}{\rho_\nu} \right)_f = \frac{g_0}{g_\nu} \left( \frac{g_f}{g_0} \right)^{4/3} C \simeq 2.85 \times 10^{-7} \ll 1.$$

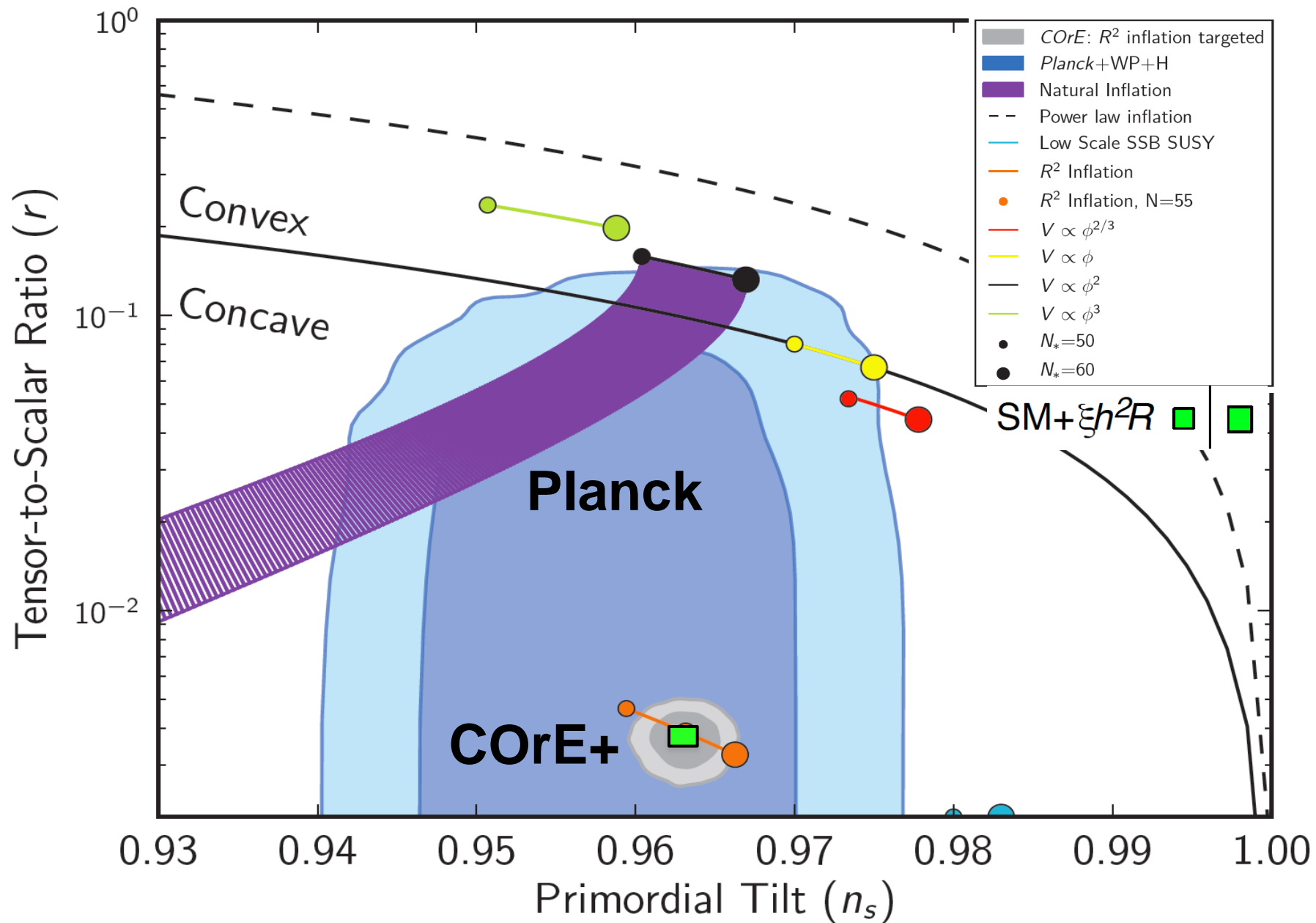
$$N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}$$

$$(g_0 = 106.75, g_f = 10.75)$$





# Spectral tilt – tensor to scalar ratio





# Early Universe – Late Universe connection

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

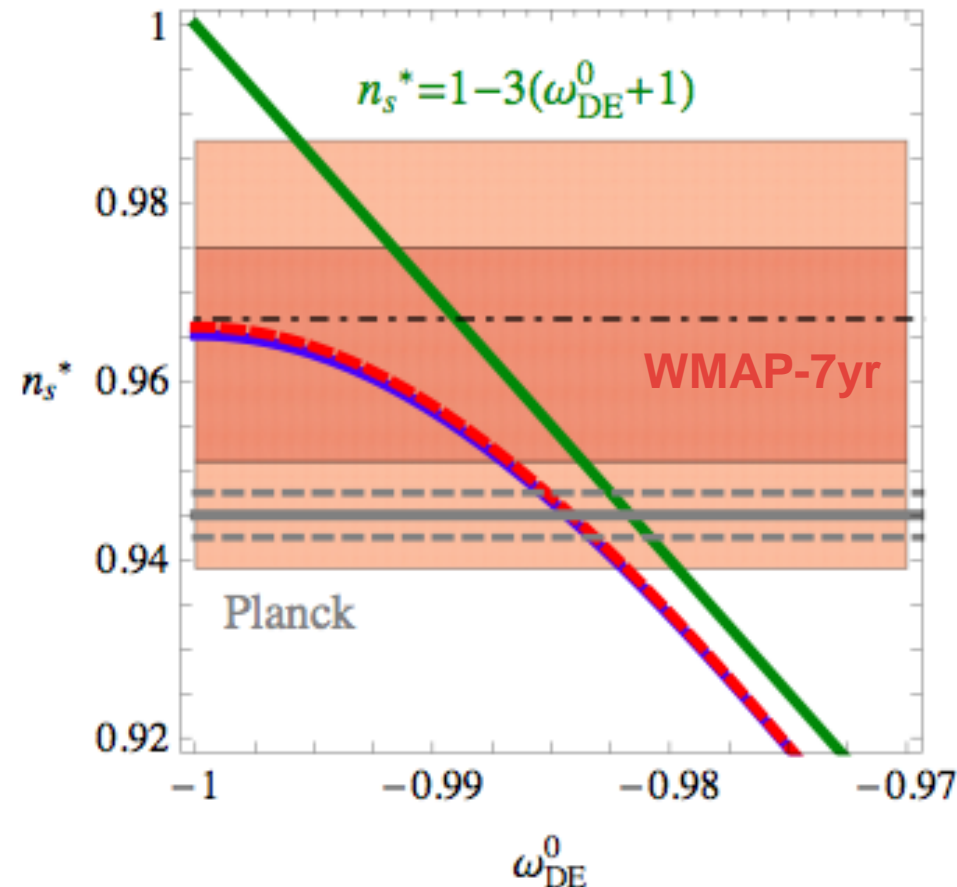
## Consistency conditions

1st order  $\longleftrightarrow$  0th order

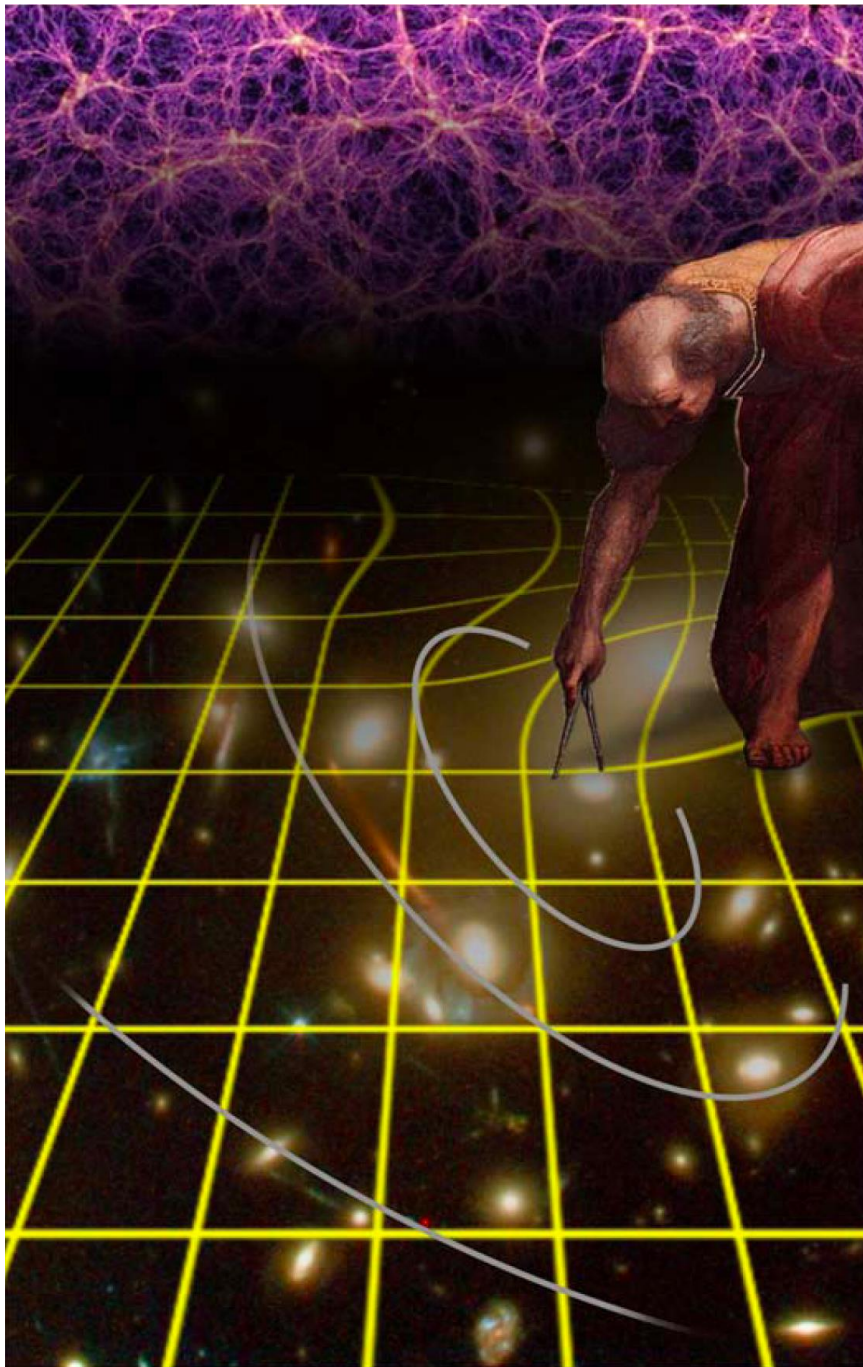
$$n_s^* - 1 \simeq -3(w_{DE}^0 + 1)$$

2nd order  $\longleftrightarrow$  1st order

$$\alpha_\zeta(k^*) \simeq 3w_{DE}^a$$



$$w_{DE}(a) = w_{DE}^0 + w_{DE}^a \ln(a/a_0). \quad \alpha_\zeta(k) \equiv \frac{dn_s}{d \ln k}$$



# ***EUCLID***

## **Spectroscopic survey**

100 million galaxies

15,000 sq. deg

$\Delta z_{\text{spec}} = 0.001 (1+z)$

8 bins  $z$  range [0.5,2.1]

Cost: 1B\$

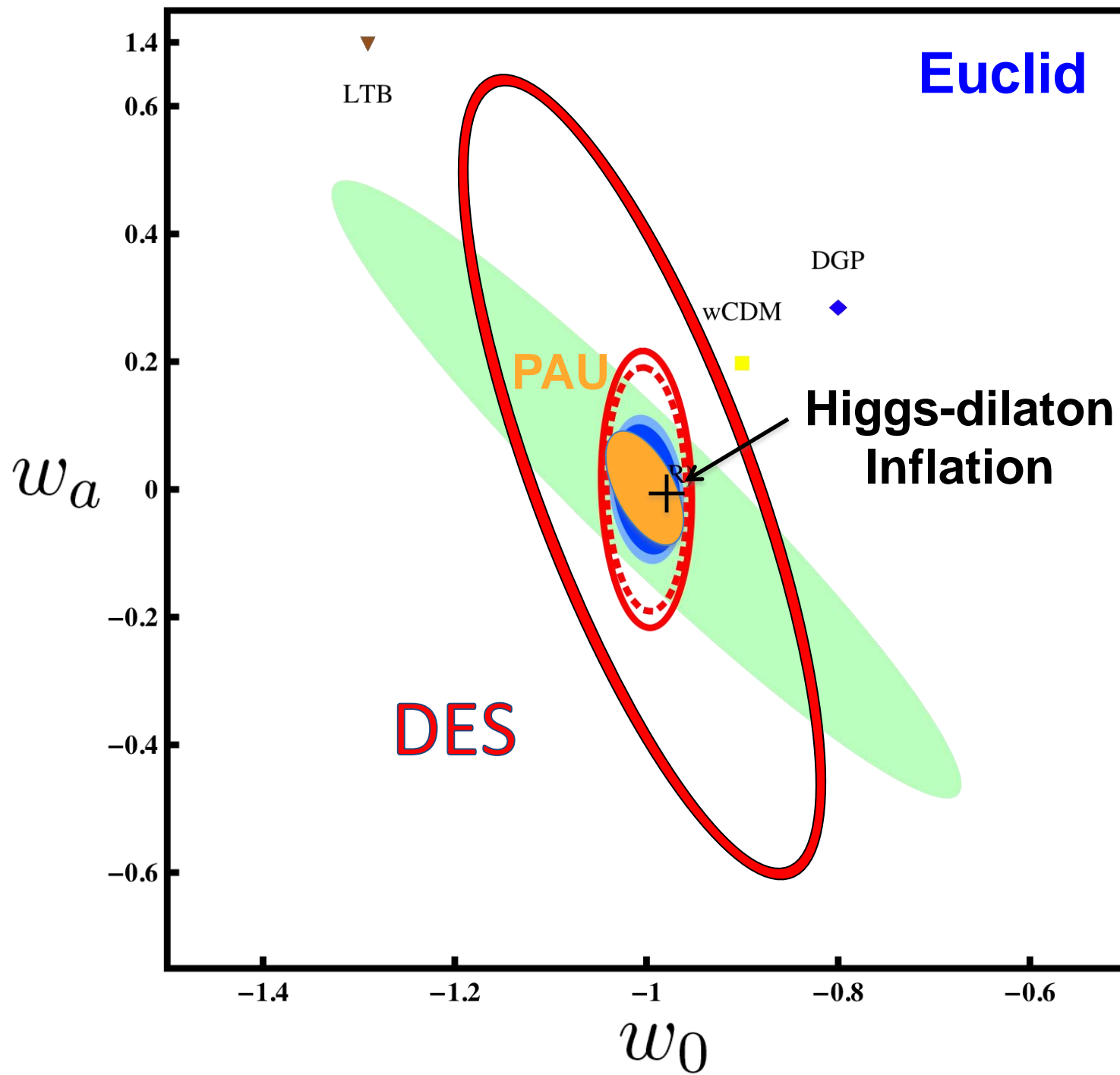
## **Imaging survey**

1000 million galaxies

15,000 deg sq.

$\Delta z_{\text{photo}} = 0.05 (1+z)$

5 bins  $z$  range [0.5,3.0]



# Conclusions

Particle Physics and Cosmology are intricately related and can be tested with next generation experiments.

- Higgs-dilaton inflation is natural extension of SM + GR (broken scale invariance)
- Precise CMB experiments: COrE+, etc.
- Deep galaxy surveys: DES, LSST, Euclid
- We may find a connection between Early and Late Universe:  $1-n_s = 3(1+w)$