The Higgs boson in Cosmology

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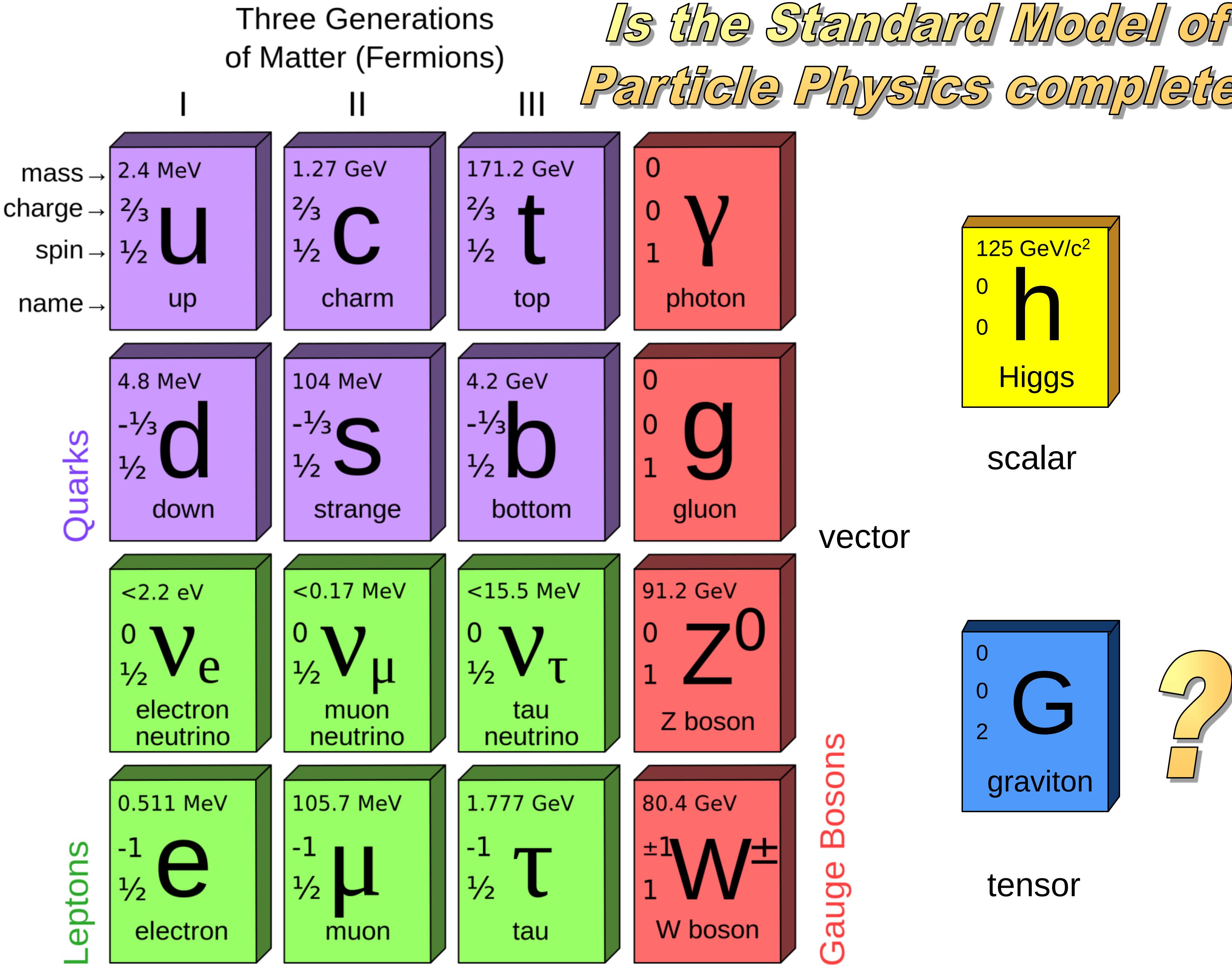
Outline

- 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

Is the Standard Model of Particle Physics complete?



Standard Model Higgs boson

Giardino, Kannike, Masina, Raidal, Strumia (2014)

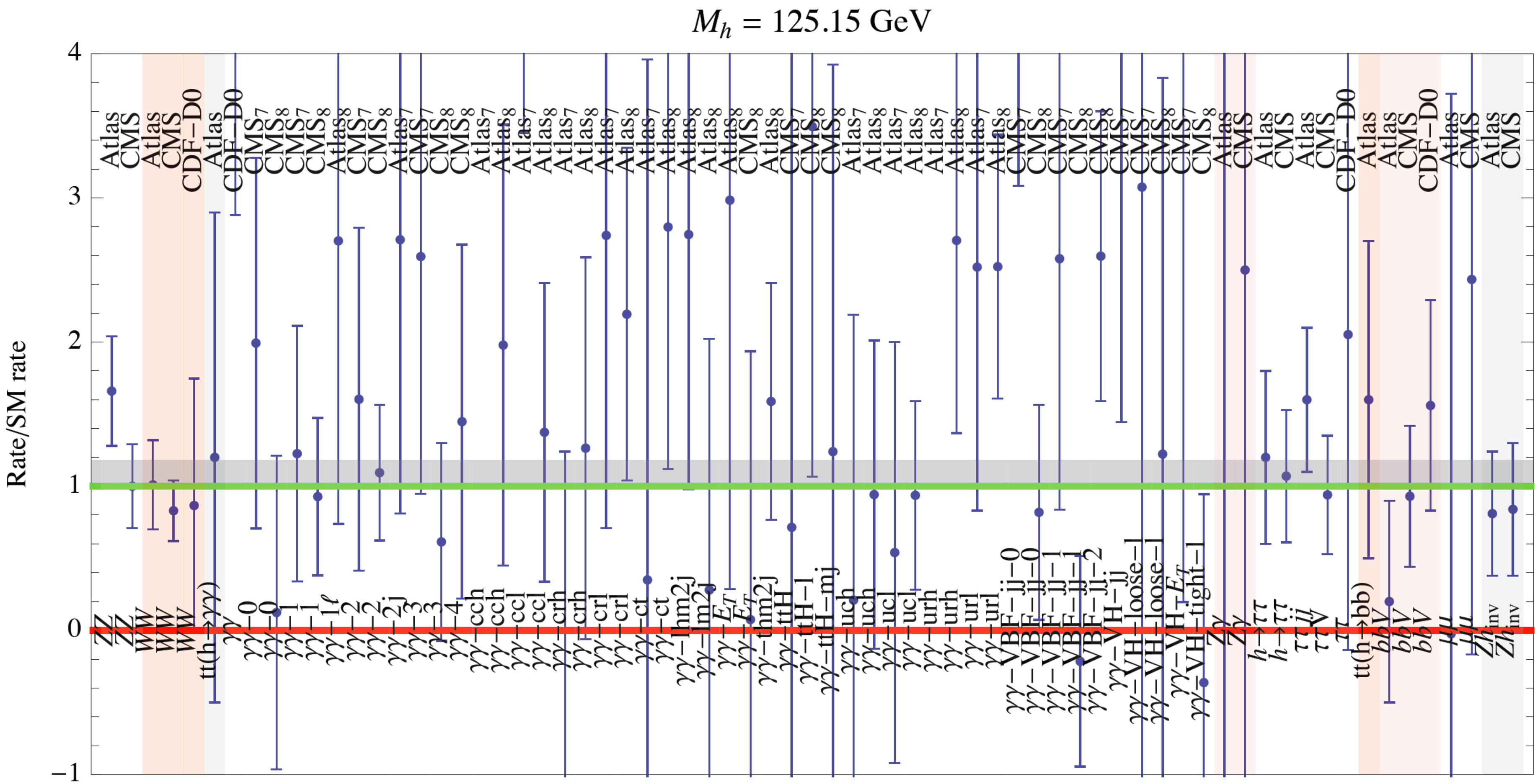
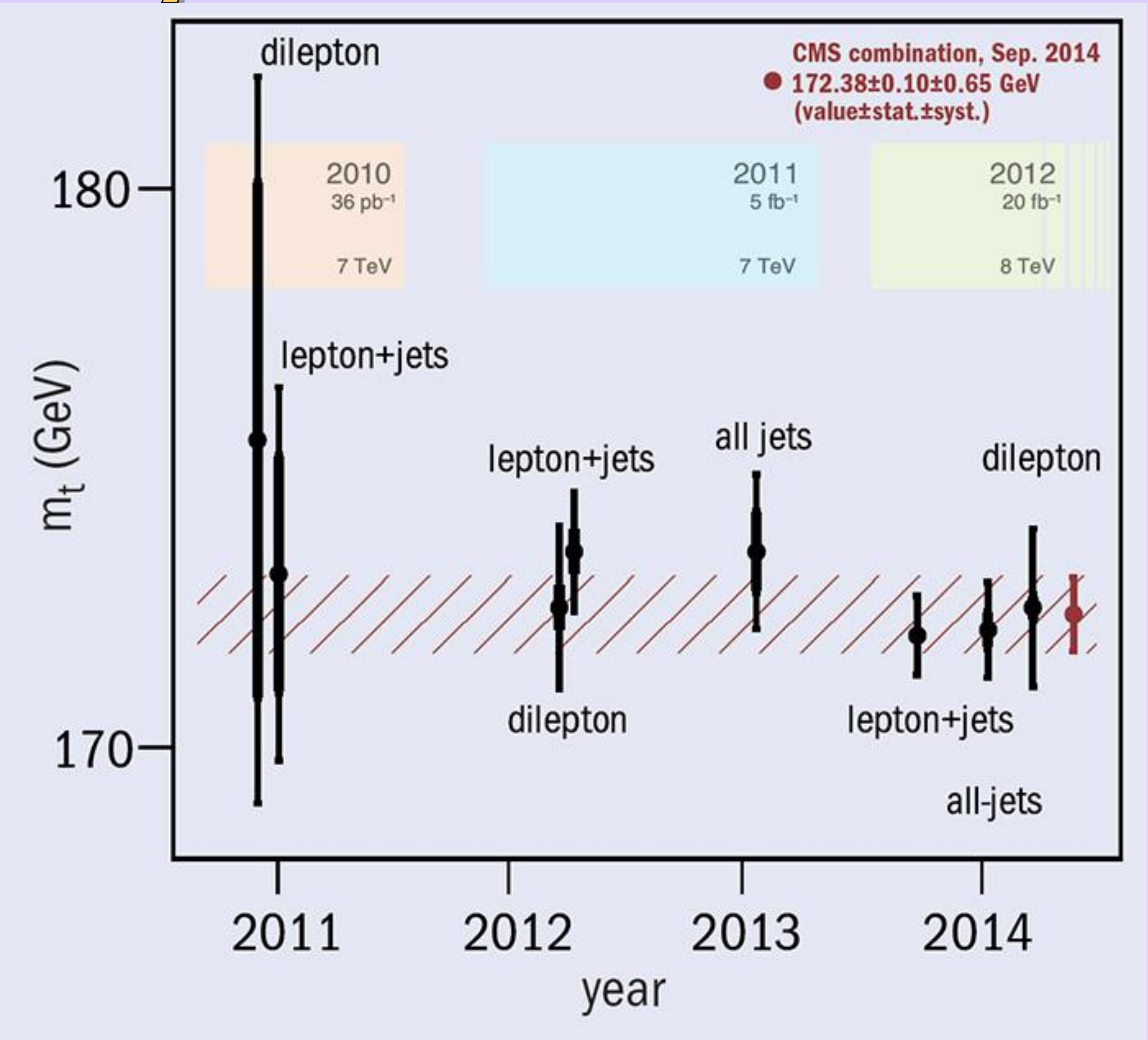
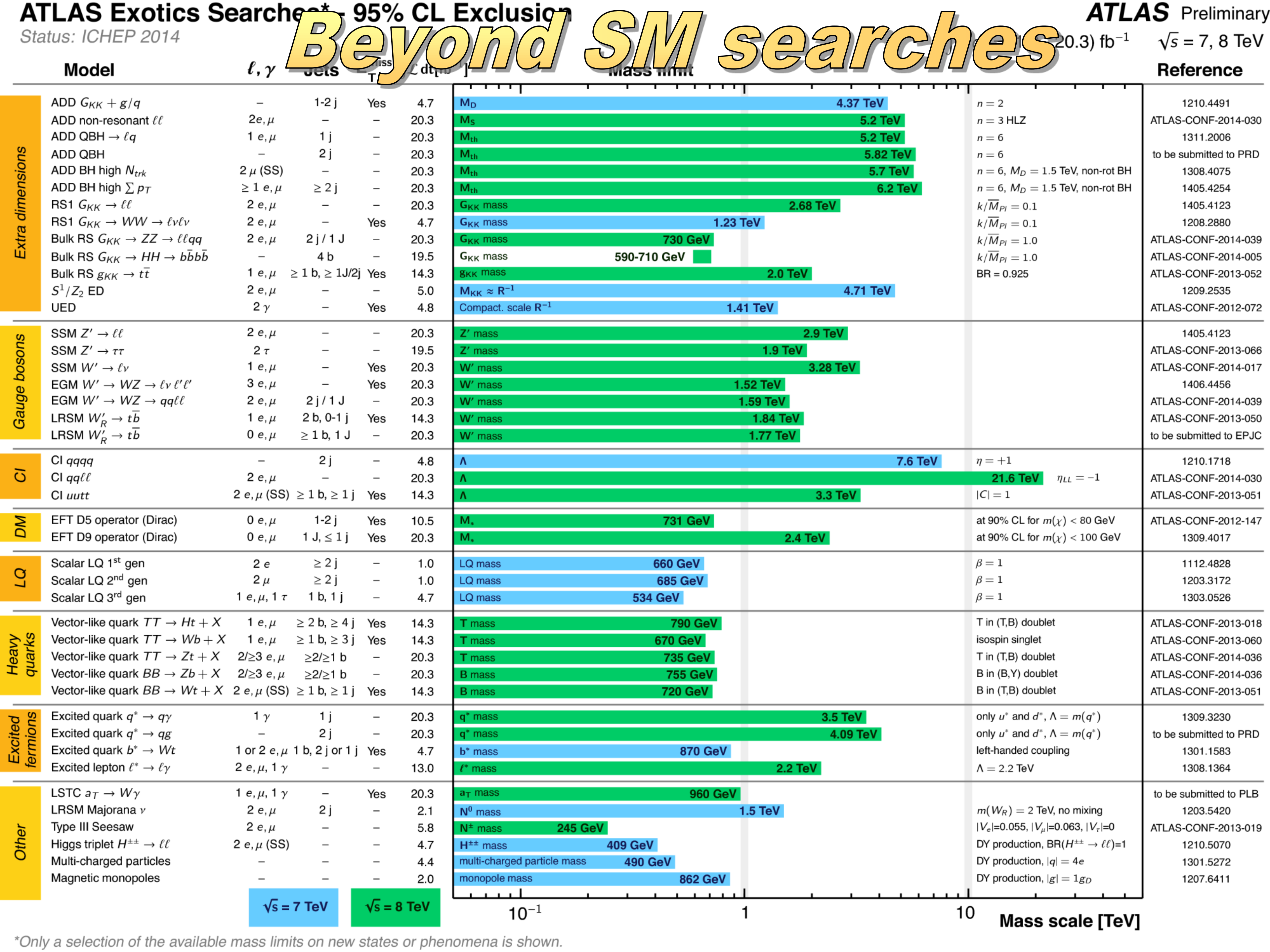


Figure 1: *Measured Higgs boson rates at ATLAS, CMS, CDF, D0 and their average (horizontal gray band at ±1σ). Here 0 (red line) corresponds to no Higgs boson, 1 (green line) to the SM Higgs boson (including the latest data point, which describes the invisible Higgs rate).*

Top mass determination



Beyond SM searches



Standard Model parameters

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

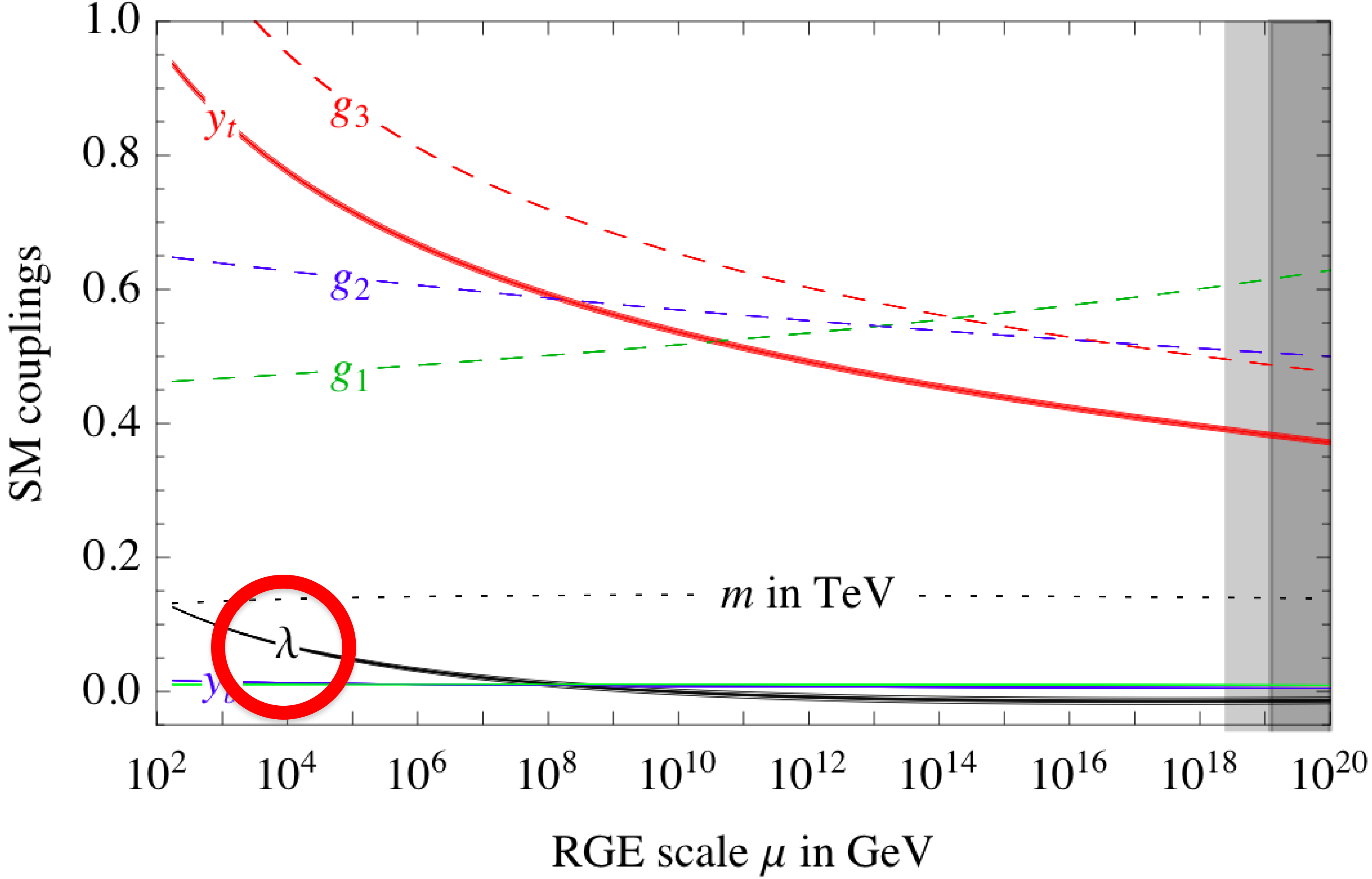
M_W	$=$	80.384 ± 0.014 GeV	Pole mass of the W boson
M_Z	$=$	91.1876 ± 0.0021 GeV	Pole mass of the Z boson
M_h	$=$	125.15 ± 0.24 GeV	Pole mass of the higgs
M_t	$=$	$173.34 \pm 0.76 \pm 0.3$ GeV	Pole mass of the top quark
$(\sqrt{2}G_\mu)^{-1/2}$	$=$	246.21971 ± 0.00006 GeV	Fermi constant for μ decay
$\alpha_3(M_Z)$	$=$	0.1184 ± 0.0007	$\overline{\text{MS}}$ gauge $\text{SU}(3)_c$ coupling (

Non-minimal coupling of Higgs to gravity

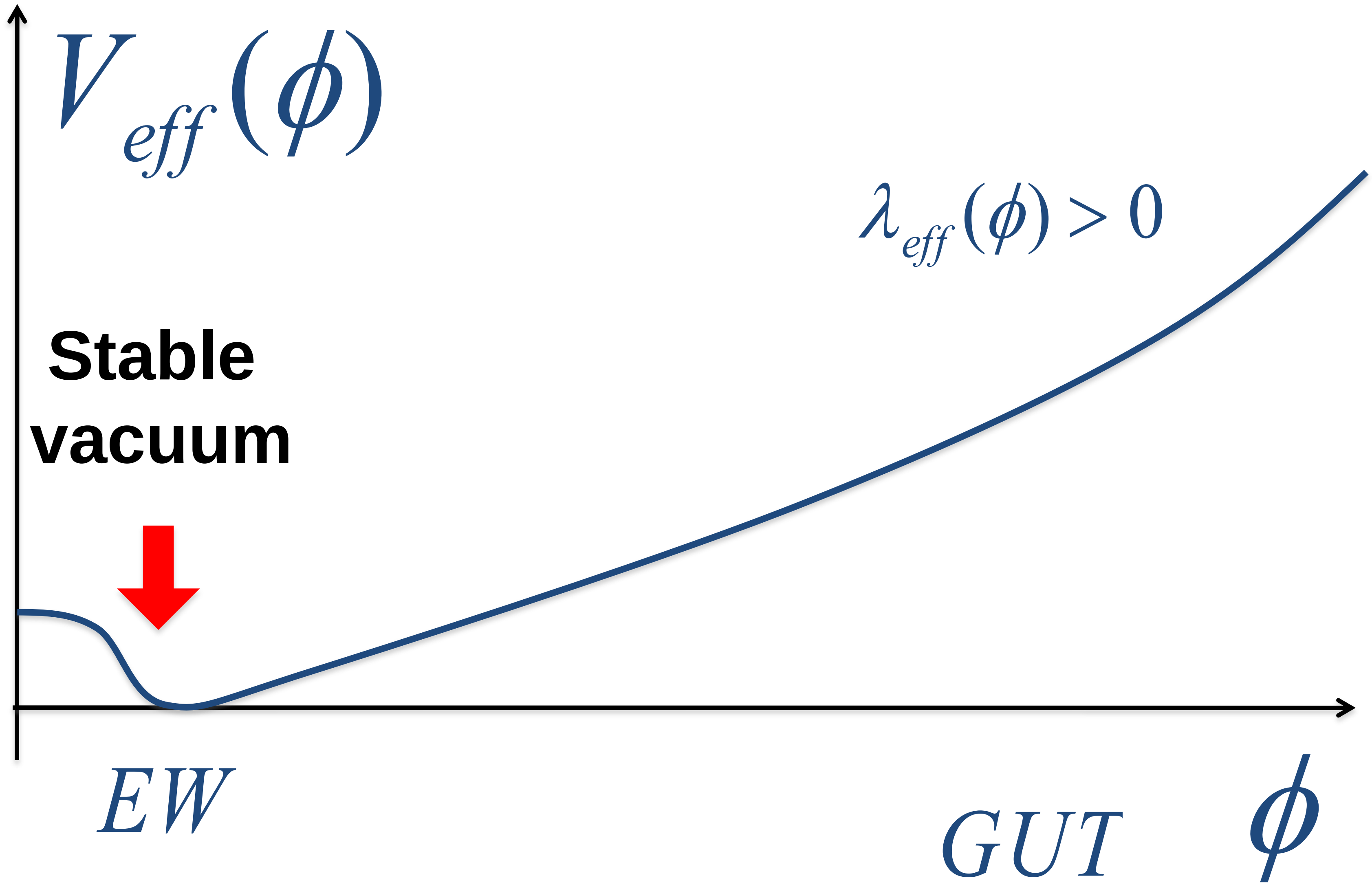
$$S_J = \int d^4x \sqrt{-g} \left[-\frac{M_{\text{Pl}}^2}{2} \left(1 + \frac{2\xi H^\dagger H}{M_{\text{Pl}}^2} \right) \mathcal{R} + (\partial_\mu H)^\dagger (\partial^\mu H) - V \right]$$

2-loop RGE running

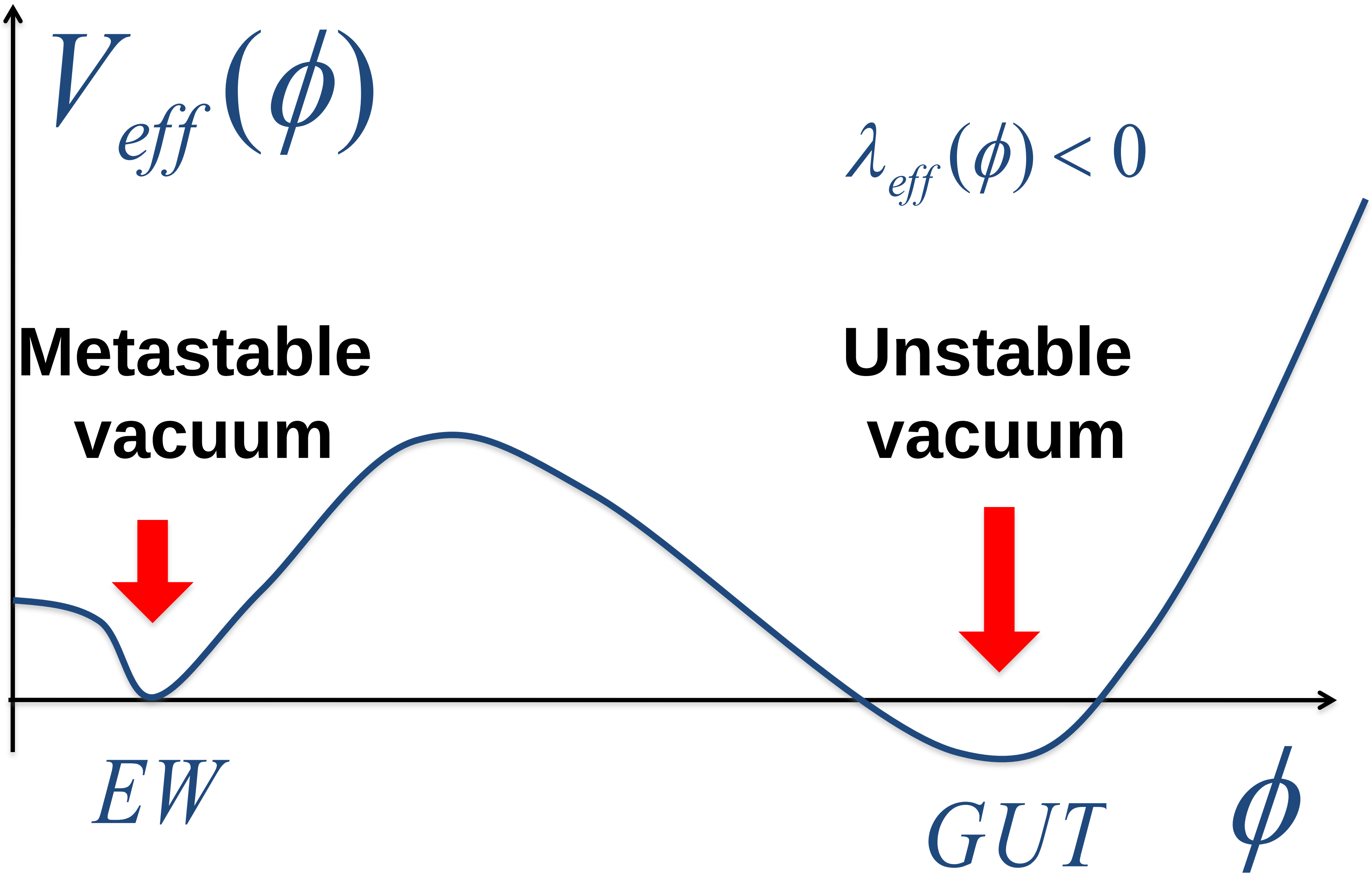
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)



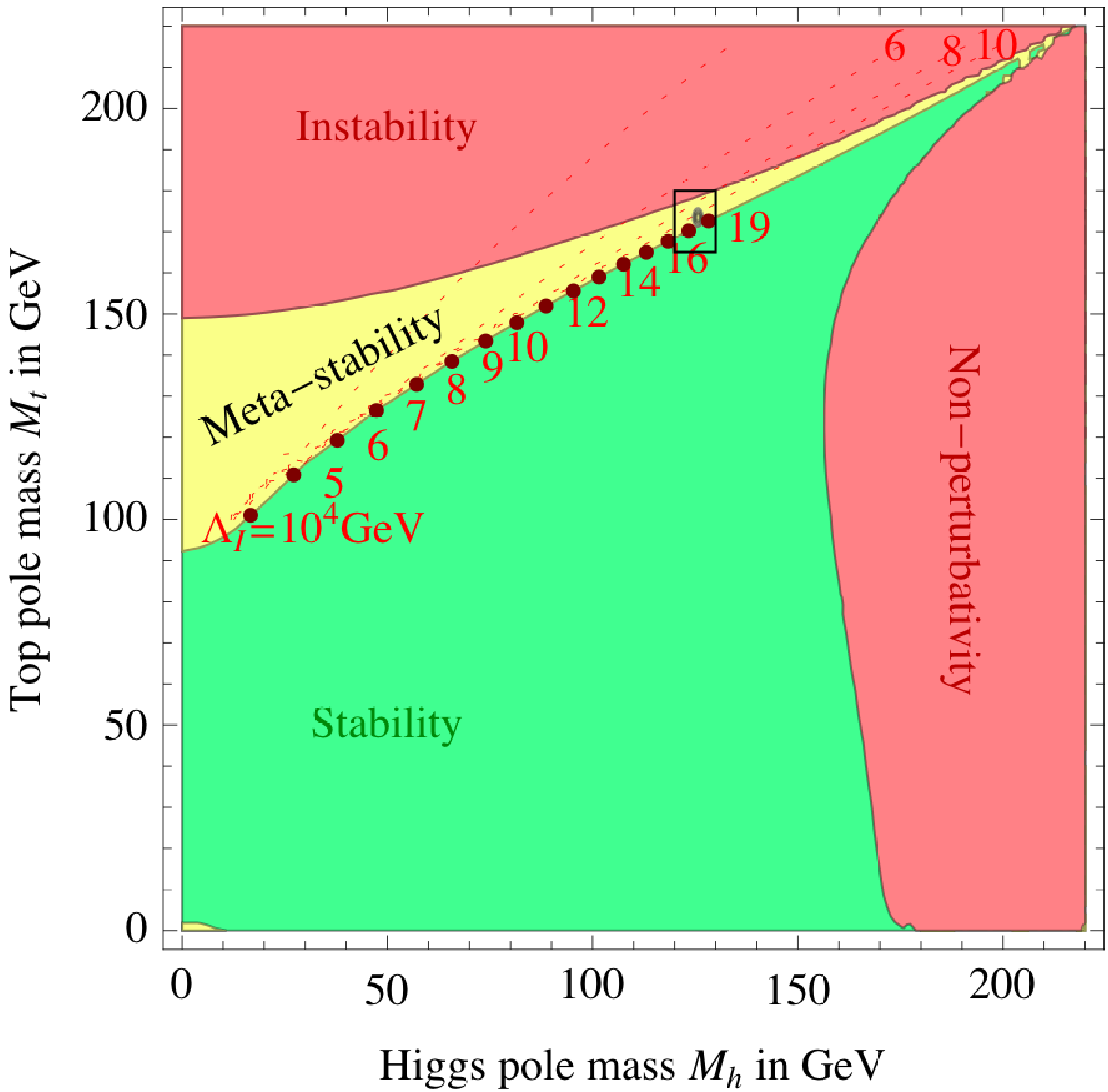
Higgs effective potential



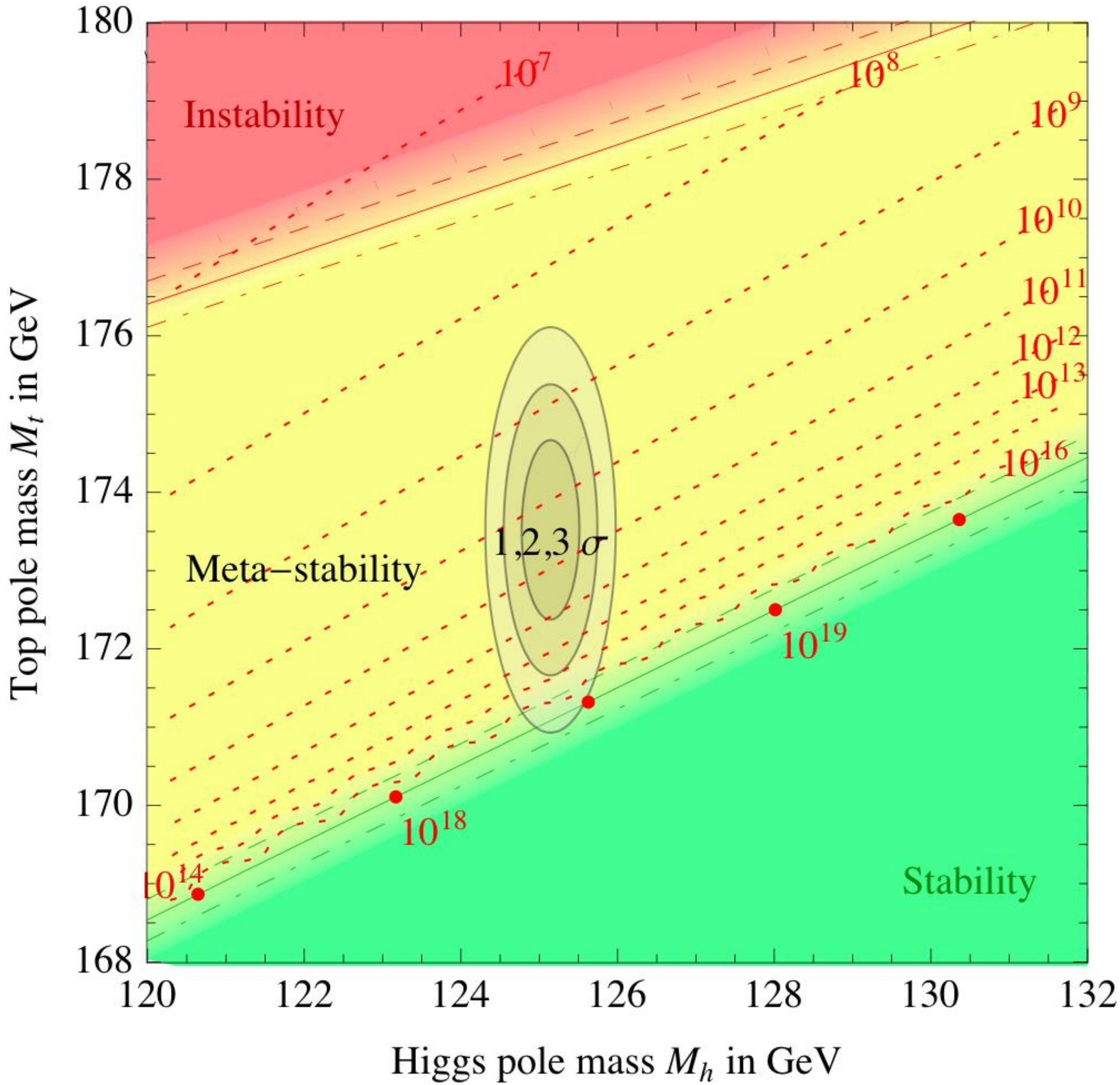
Higgs effective potential



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

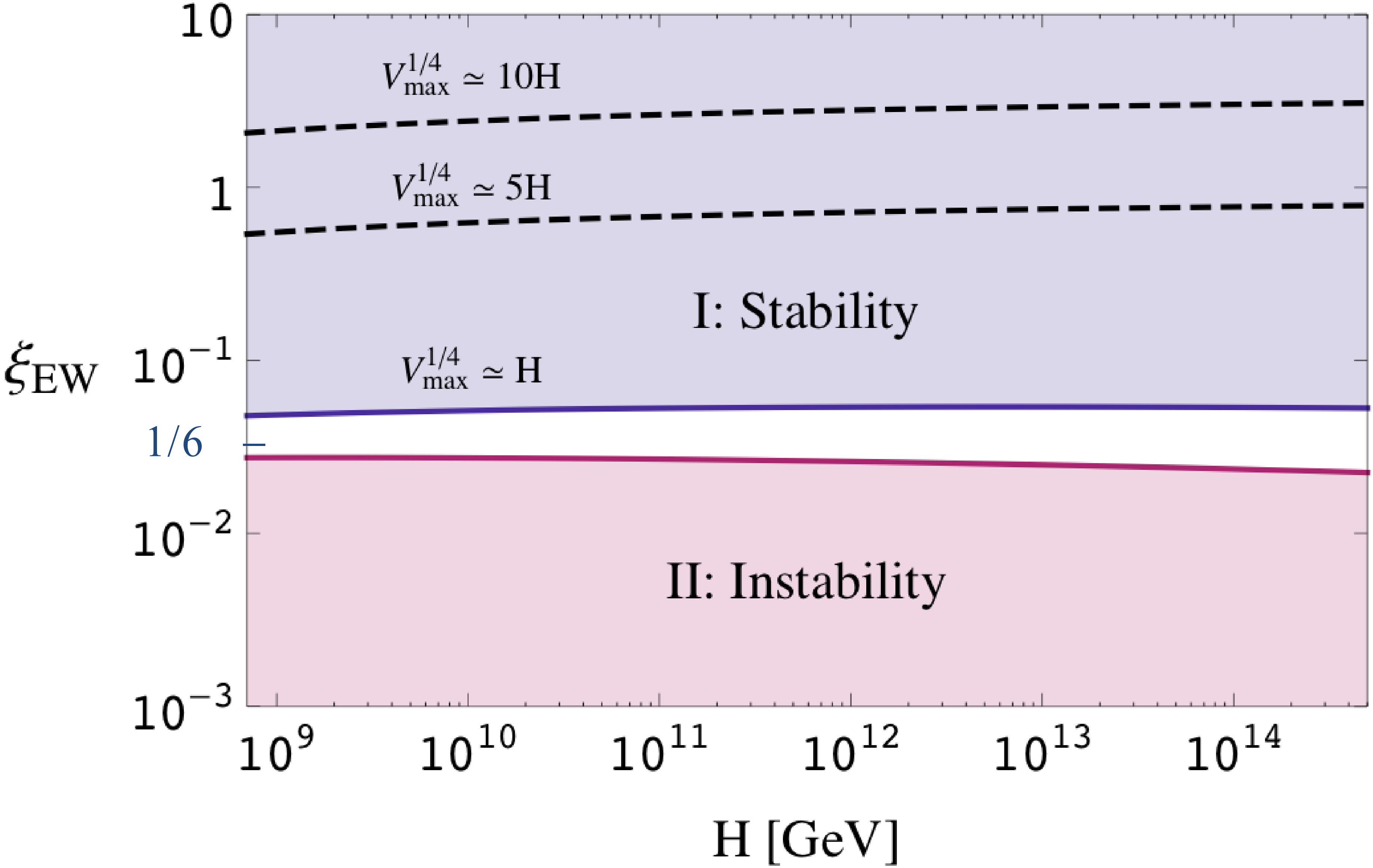


Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)



Non-minimal coupling of Higgs to gravity

Herranen, Markkanen, Nurmi, Rajantie (2014)



2-loop RGE running

Allison (2014)

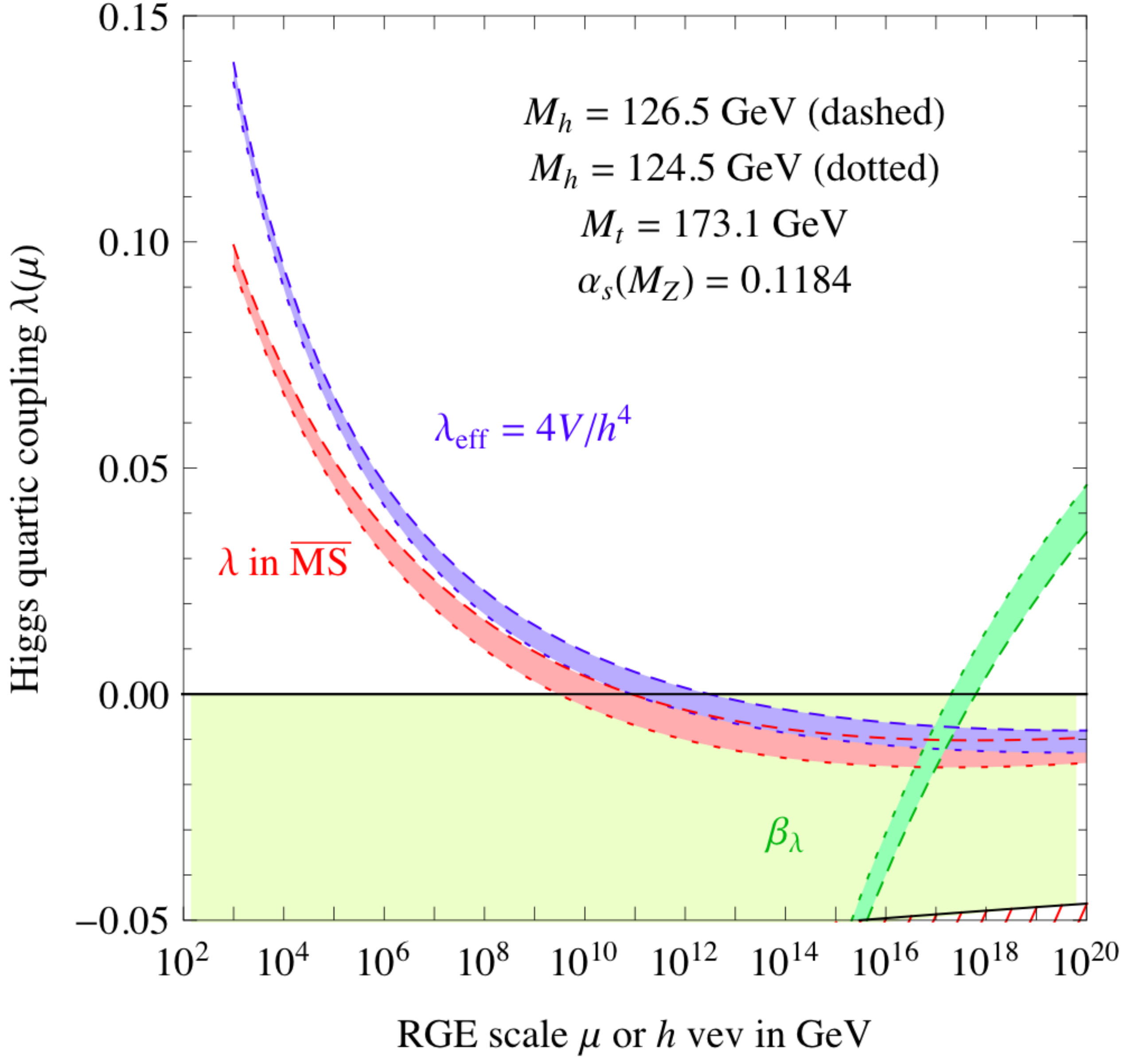
$$\beta_\lambda = \frac{1}{(4\pi)^2}\left[\left(6+18s^2\right)\lambda^2 - 6y_t^4 + \frac{3}{8}\left(2g^4 + \left(g^2+g'^2\right)^2\right) + \left(-9g^2 - 3g'^2 + 12y_t^2\right)\lambda\right]$$
$$+ \frac{1}{(4\pi)^4}\left[\frac{1}{48}\left(\left(912+3s\right)g^6 - \left(290-s\right)g^4g'^2 - \left(560-s\right)g^2g'^4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

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

(A

Non-minimal coupling of Higgs to gravity

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



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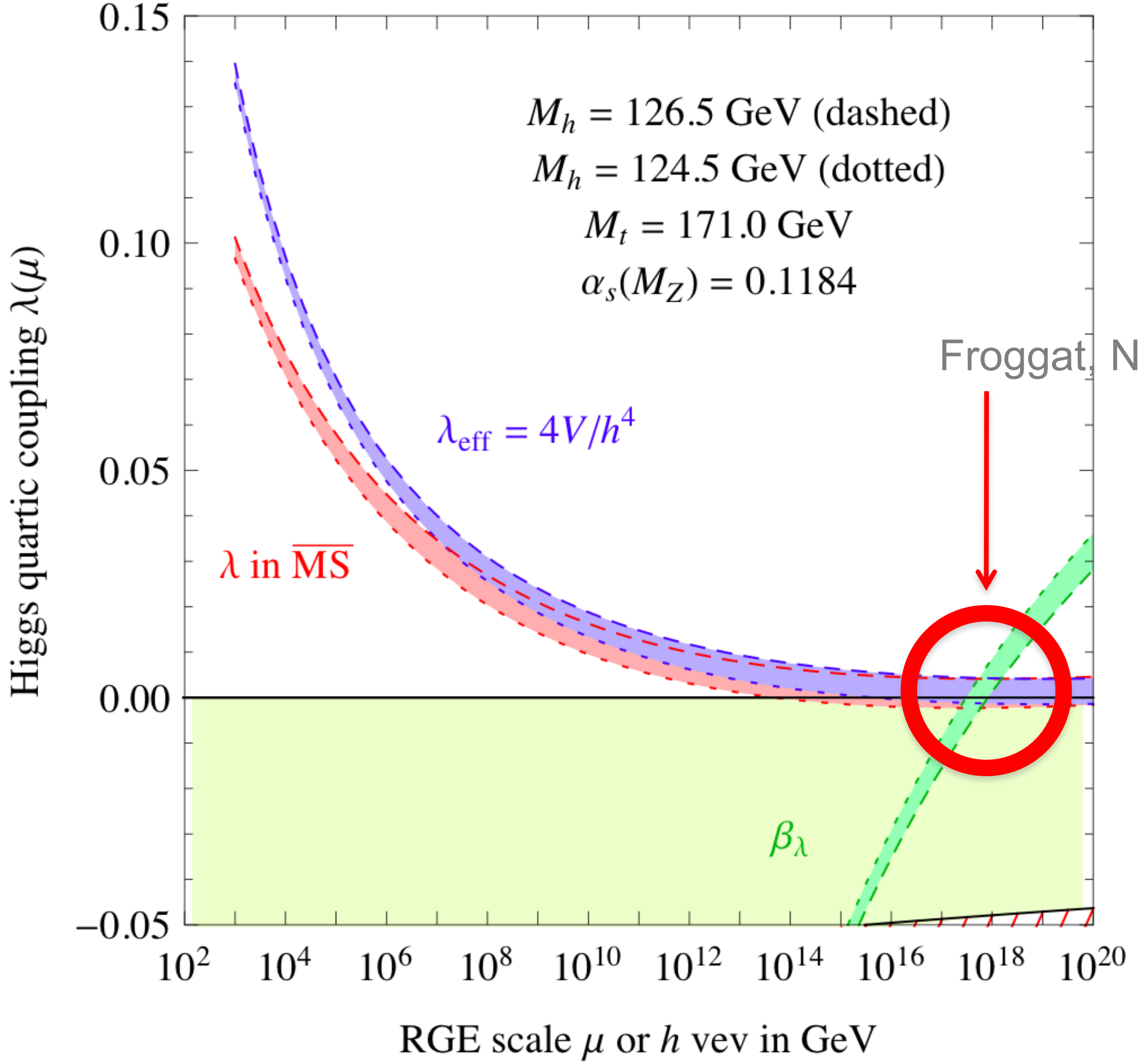
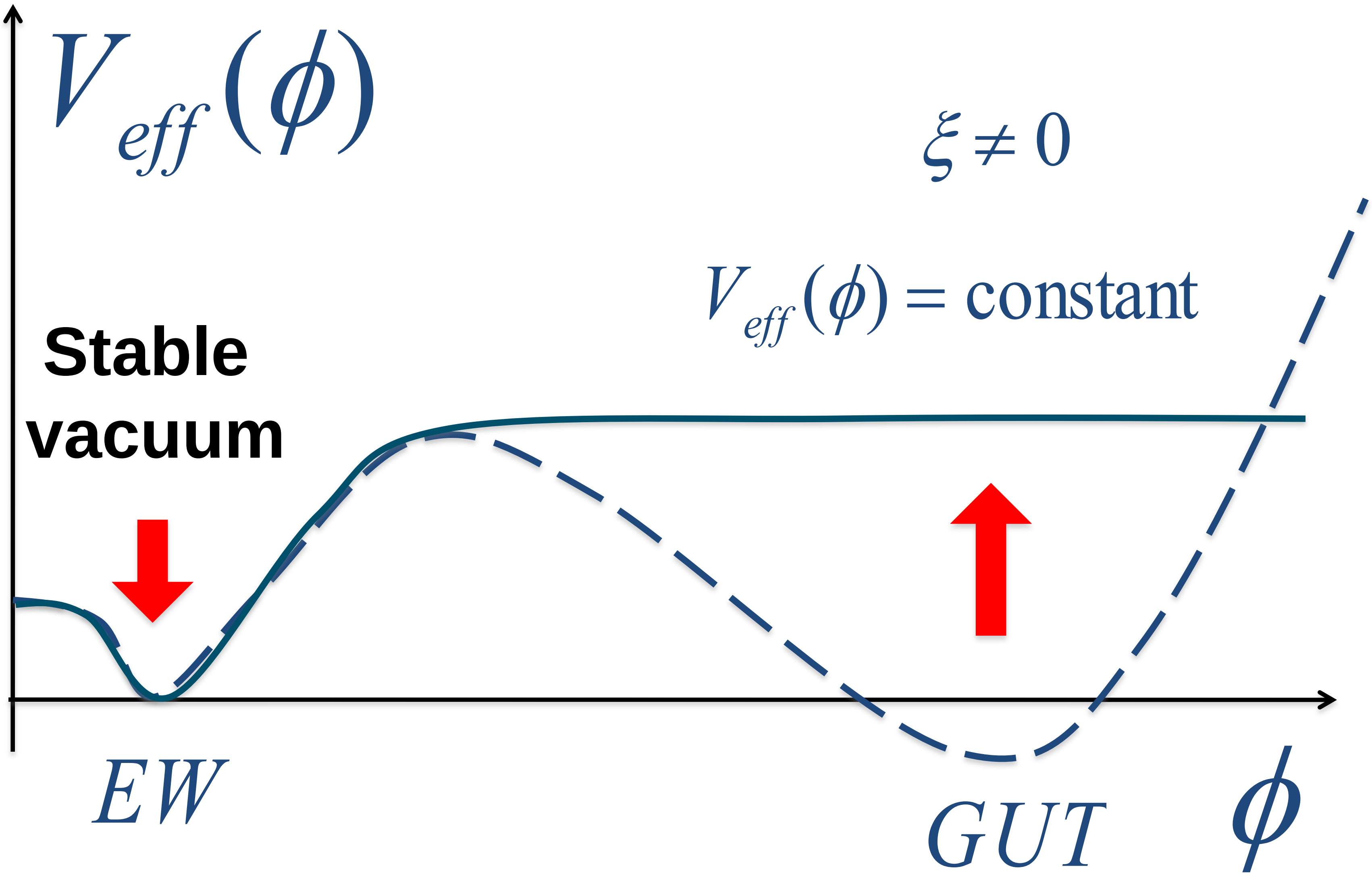
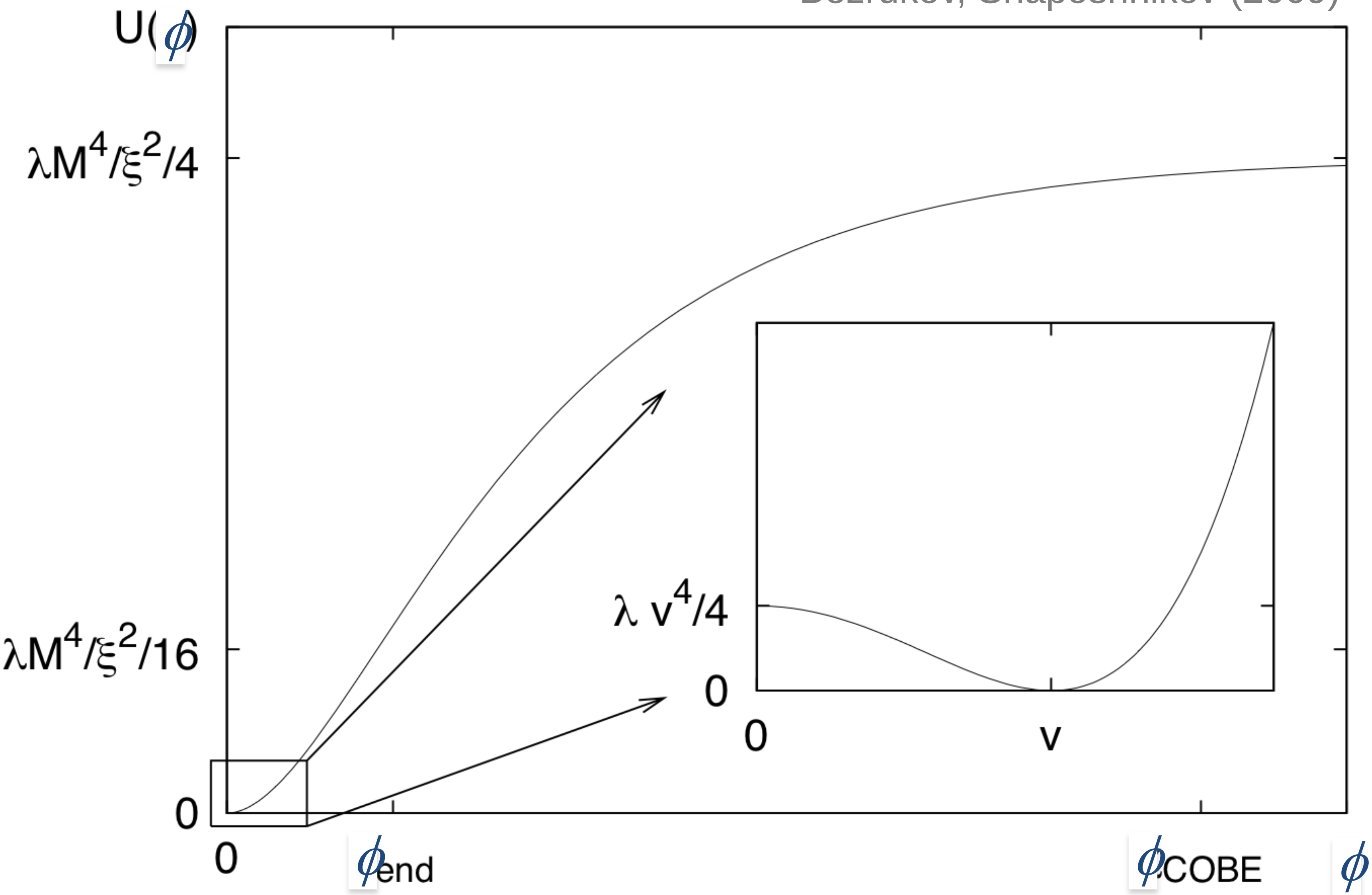


Higgs effective potential



Higgs=Inflaton Potential

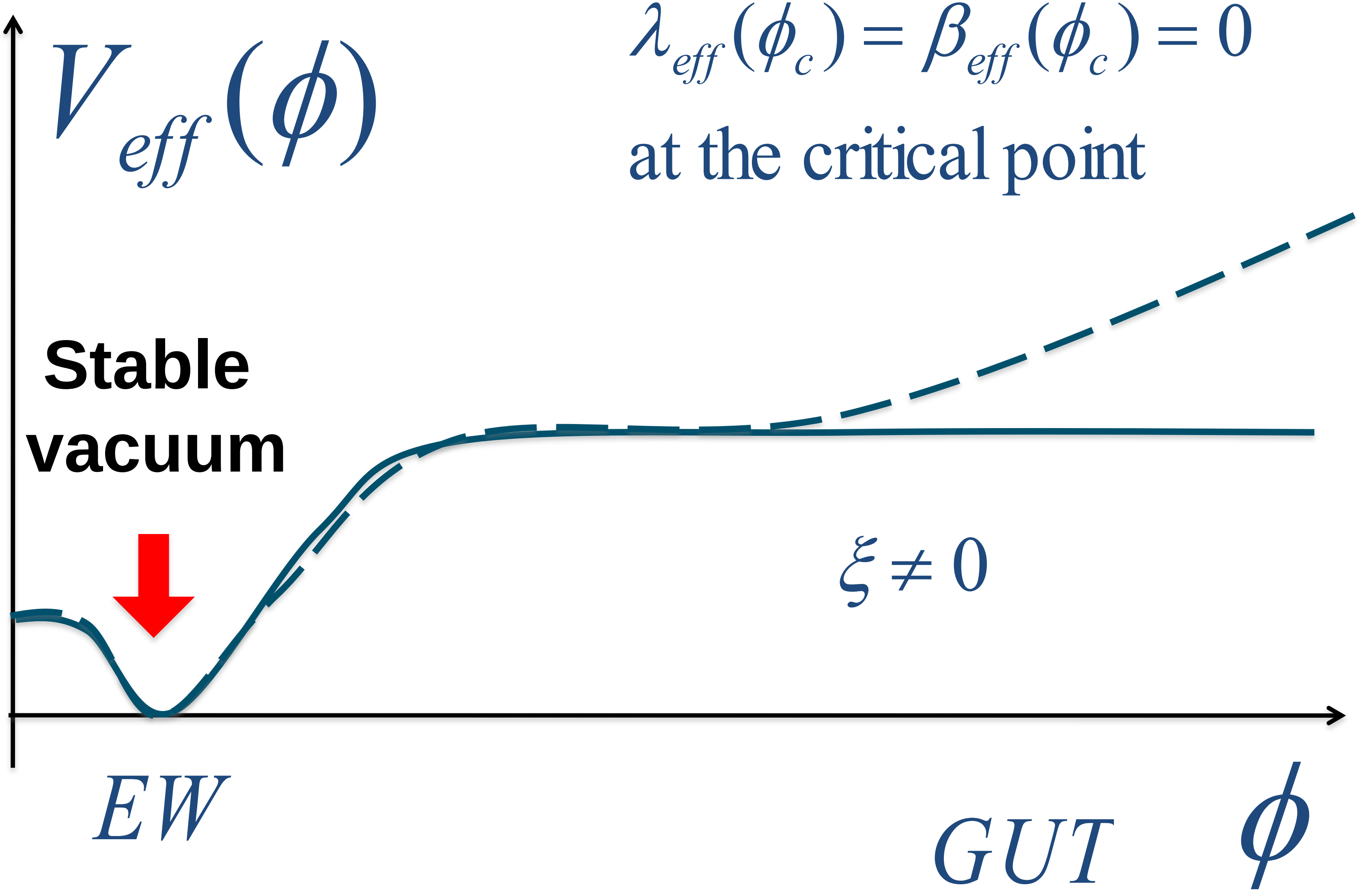
Salopek, Bond, Bardeen (1989)
Bezrukov, Shaposhnikov (2009)



Higgs effective potential

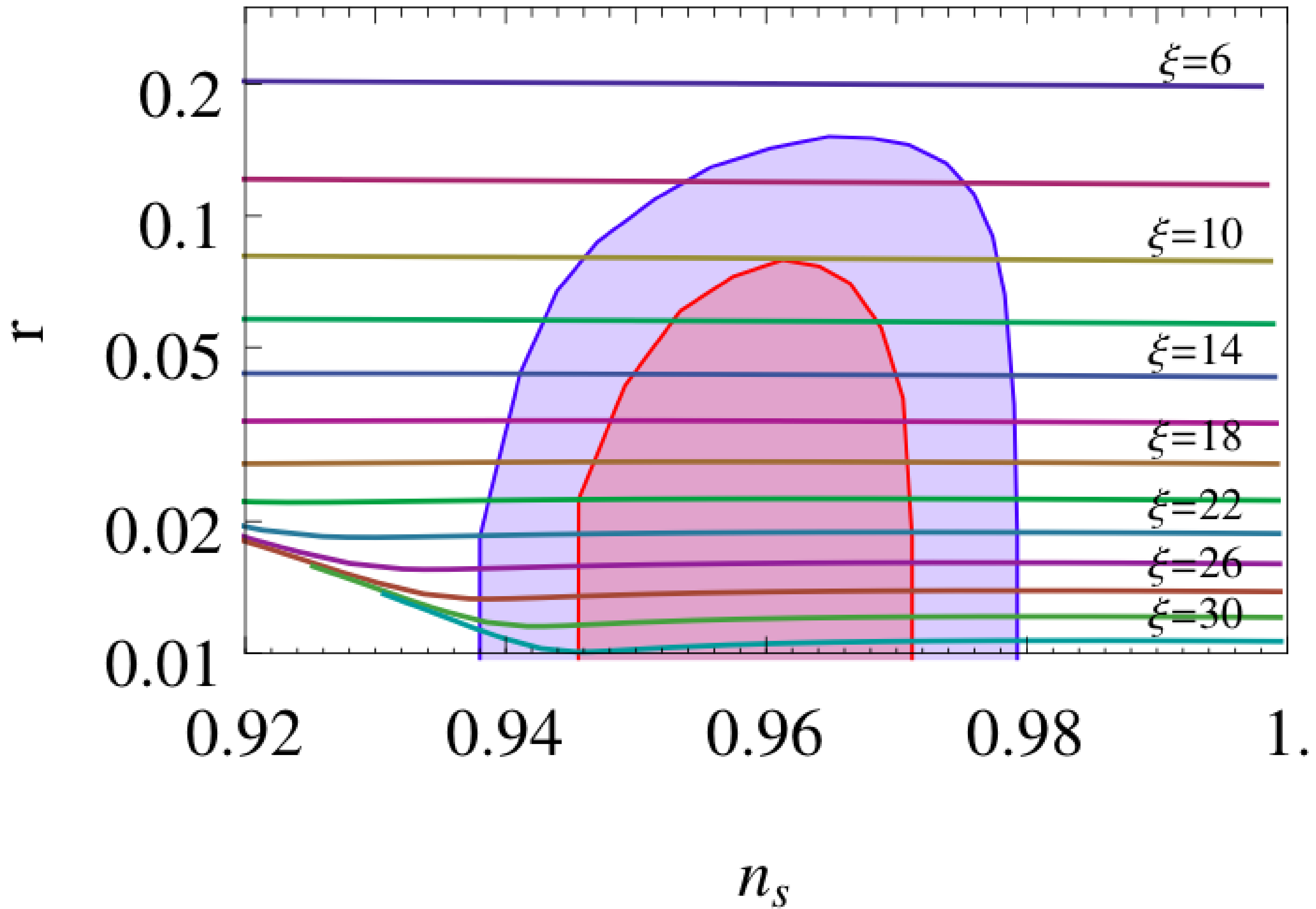
$$\lambda_{eff}(\phi_c) = \beta_{eff}(\phi_c) = 0$$

at the critical point



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, Λ
- 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:

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

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

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

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

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

Higgs-dilaton potential

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

Noether current of scale invariance in E-frame:

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

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

Field redefinition (radial and angular coordinates):

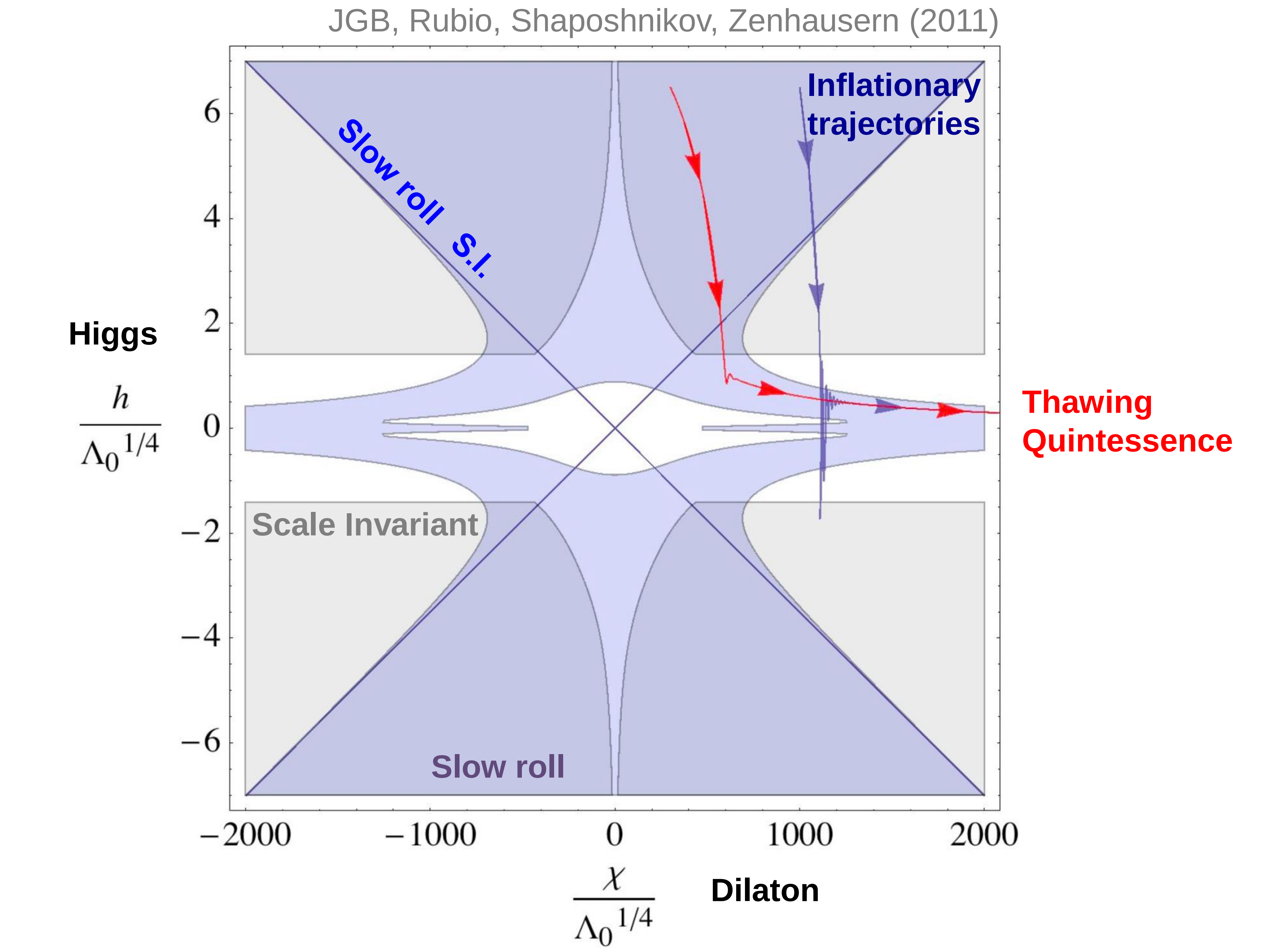
$$\rho = \frac{M_P}{2}\log\left[\frac{(1+6\xi_\chi)\chi^2 + (1+6\xi_h)h^2}{M_P^2}\right] , \quad \tan\theta = \sqrt{\frac{1+6\xi_h}{1+6\xi_\chi}}\,\frac{h}{\chi}$$

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

Inflationary potential:

Quintessence potential:

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


JGB, Rubio, Shaposhnikov, Zenhausern (2011)
Inflationary trajectories
Slow roll S.I.
Higgs
$\frac{h}{\Lambda_0^{1/4}}$
Thawing Quintessence
Scale Invariant
Slow roll
6
4
2
0
−2
−4
−6
−2000
−1000
0
1000
2000
$\frac{\chi}{\Lambda_0^{1/4}}$
Dilaton

Predictions of Higgs-dilaton inflation

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

$$P_\zeta(k_0) \simeq \frac{\lambda N^{*2}}{72\pi^2\xi_h^2}\left(1+\frac{1}{3}(4\xi_\chi N^*)^2+\dots\right), \qquad \alpha_\zeta(k_0) \simeq -\tfrac{1}{6}r(k_0) = \tfrac{4}{3}n_g(k_0),$$

$$n_s(k_0)-1 \simeq -\frac{2}{N^*}\left(1+\frac{1}{3}(4\xi_\chi N^*)^2+\dots\right),$$

$$\alpha_\zeta(k_0) \simeq -\frac{2}{N^{*2}}\left(1-\frac{1}{3}(4\xi_\chi N^*)^2+\dots\right),$$

$$r(k_0) \simeq \frac{12}{N^{*2}}\left(1-\frac{1}{3}(4\xi_\chi N^*)^2+\dots\right),$$

$$n_s(k_0) < 0.97 \simeq 1-\frac{2}{N^*},$$

$$\alpha_\zeta(k_0) > -0.0006 \simeq -\frac{2}{N^{*2}},$$

$$r(k_0) < 0.0033 \simeq \frac{12}{N^{*2}}$$

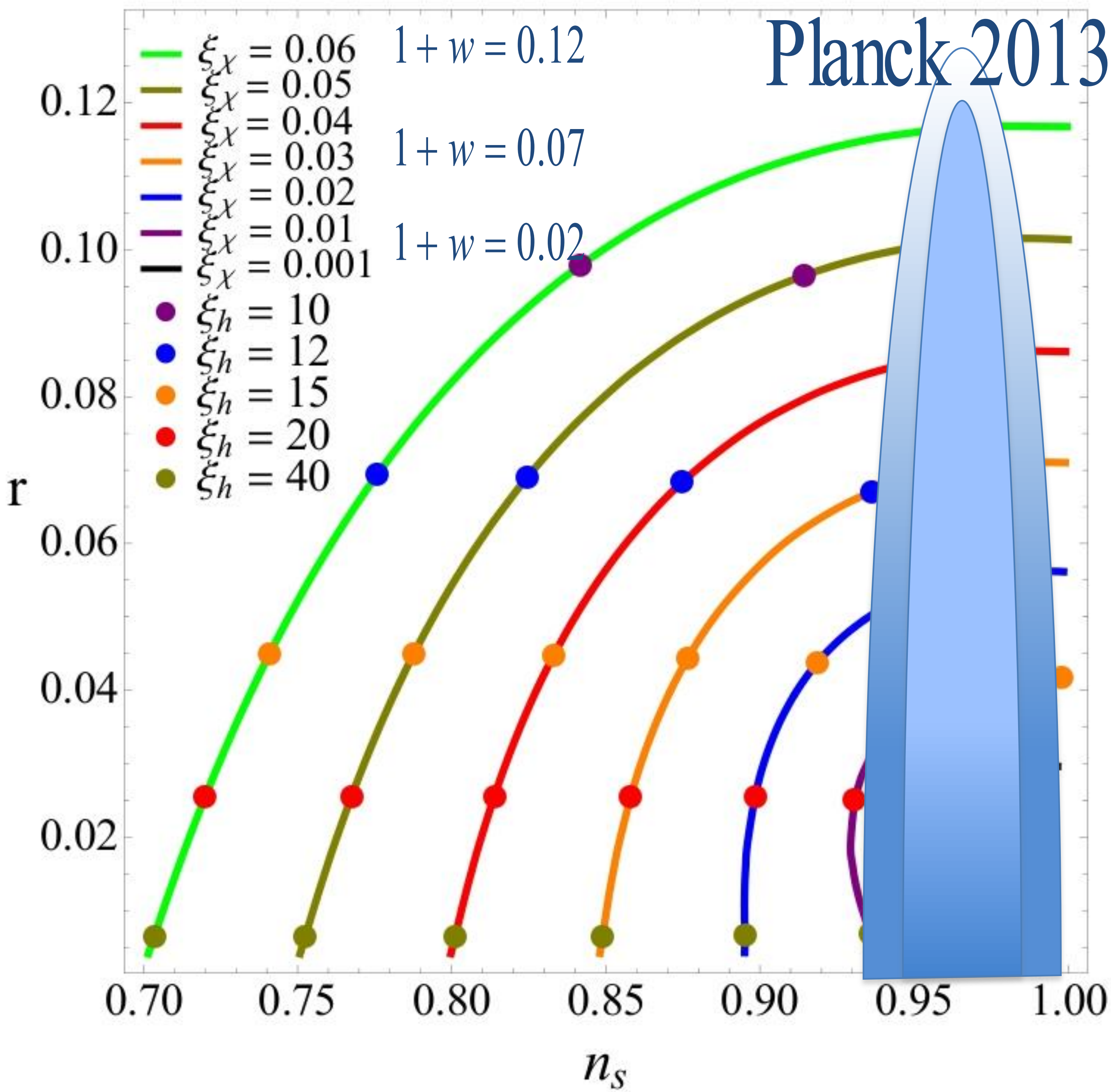
$\xi_\chi \lesssim 0.008$ translates to $\begin{cases}\alpha_\zeta(k_0) \lesssim -0.000\,15, \\ r(k_0) \gtrsim 0.0009\end{cases}$

reheating after inflation

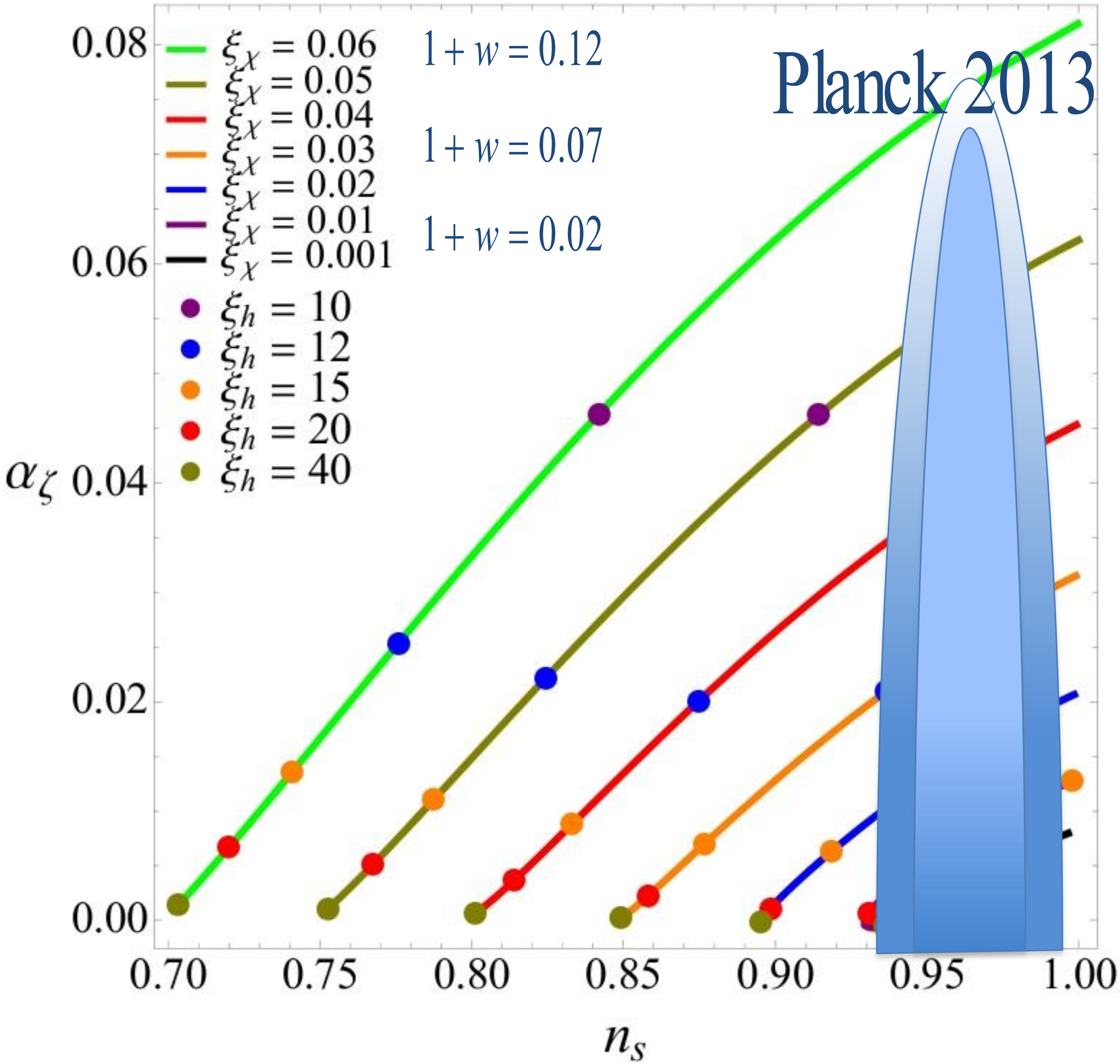
JGB, Rubio, Shaposhnikov (2012)

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

$$N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff} \qquad (g_0 = 106.75\,,\ g_{\rm f} = 10.75)$$



Planck 2013
$1+w=0.12$
$1+w=0.07$
$1+w=0.02$
$\xi_\chi = 0.06$
$\xi_\chi = 0.05$
$\xi_\chi = 0.04$
$\xi_\chi = 0.03$
$\xi_\chi = 0.02$
$\xi_\chi = 0.01$
$\xi_\chi = 0.001$
$\xi_h = 10$
$\xi_h = 12$
$\xi_h = 15$
$\xi_h = 20$
$\xi_h = 40$
r
0.12
0.10
0.08
0.06
0.04
0.02
0.70
0.75
0.80
0.85
0.90
0.95
1.00
n_s



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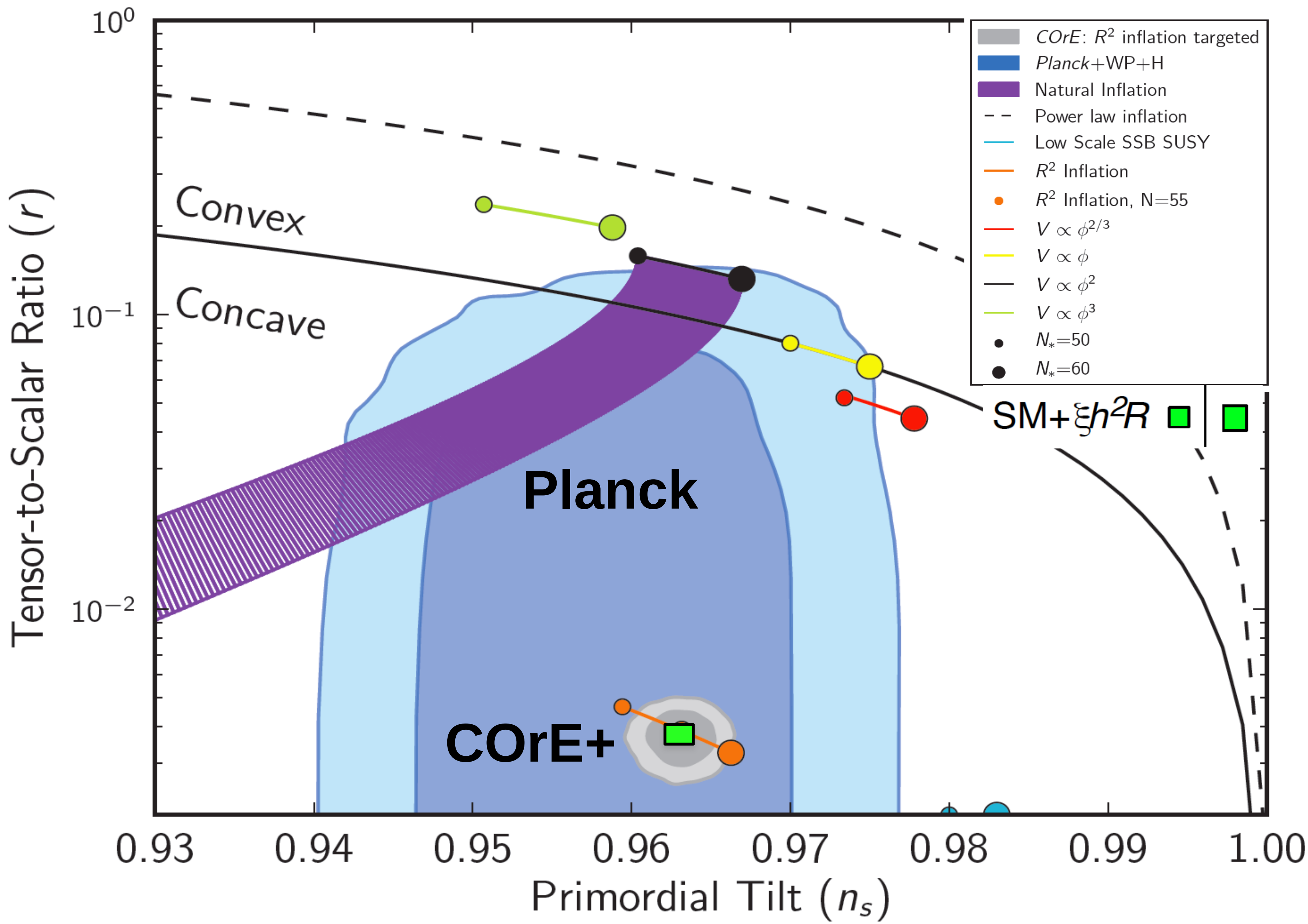
$\xi_\chi = 0.001$
$\xi_h = 10$
$\xi_h = 12$
$\xi_h = 15$
$\xi_h = 20$
$\xi_h = 40$
α_ζ
0.08
0.06
0.04
0.02
0.00
0.70
0.75
0.80
0.85
0.90
0.95
1.00
n_s

Spectral tilt – tensor to scalar ratio



Early Universe – Late Universe connection

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

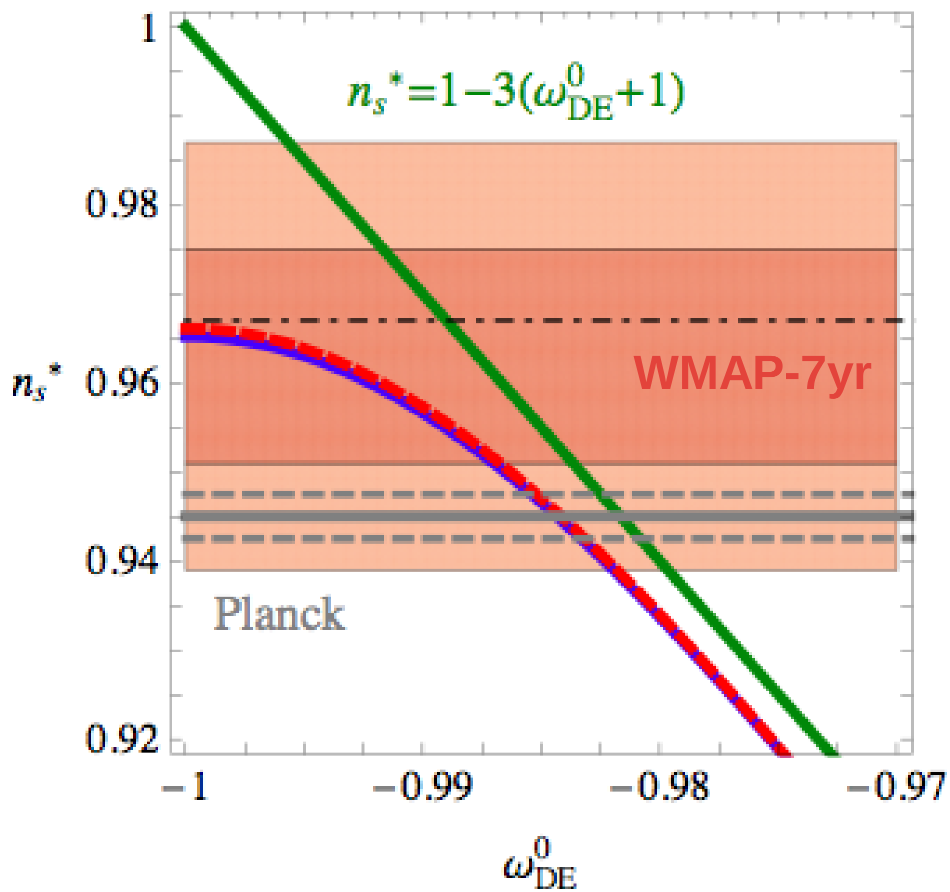
Consistency conditions

1st order ⟷ 0th order

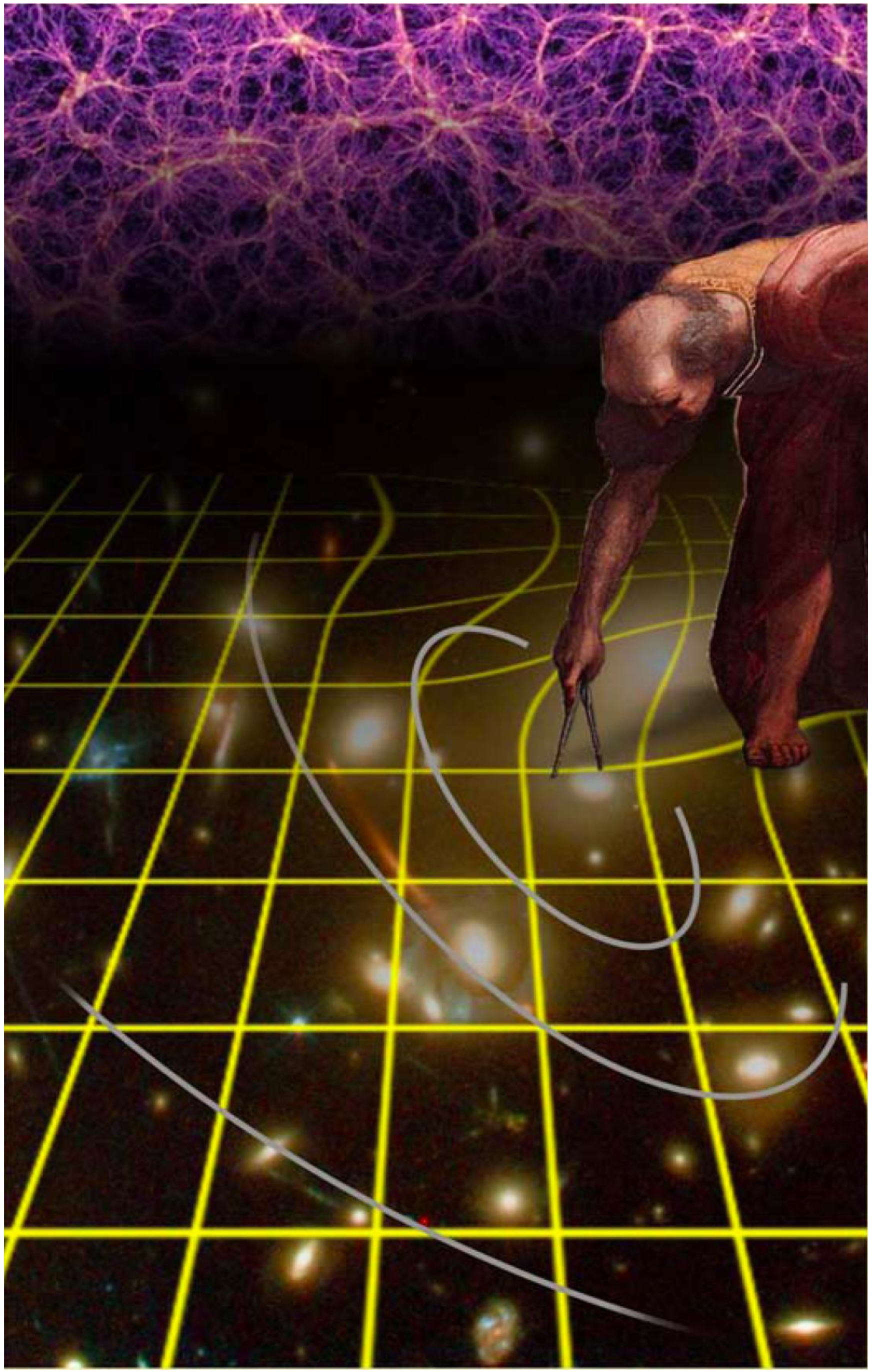
$$n_s^* - 1 \simeq -3(w_{DE}^0 + 1)$$

2nd order ⟷ 1st order

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



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



esa

EUCLID

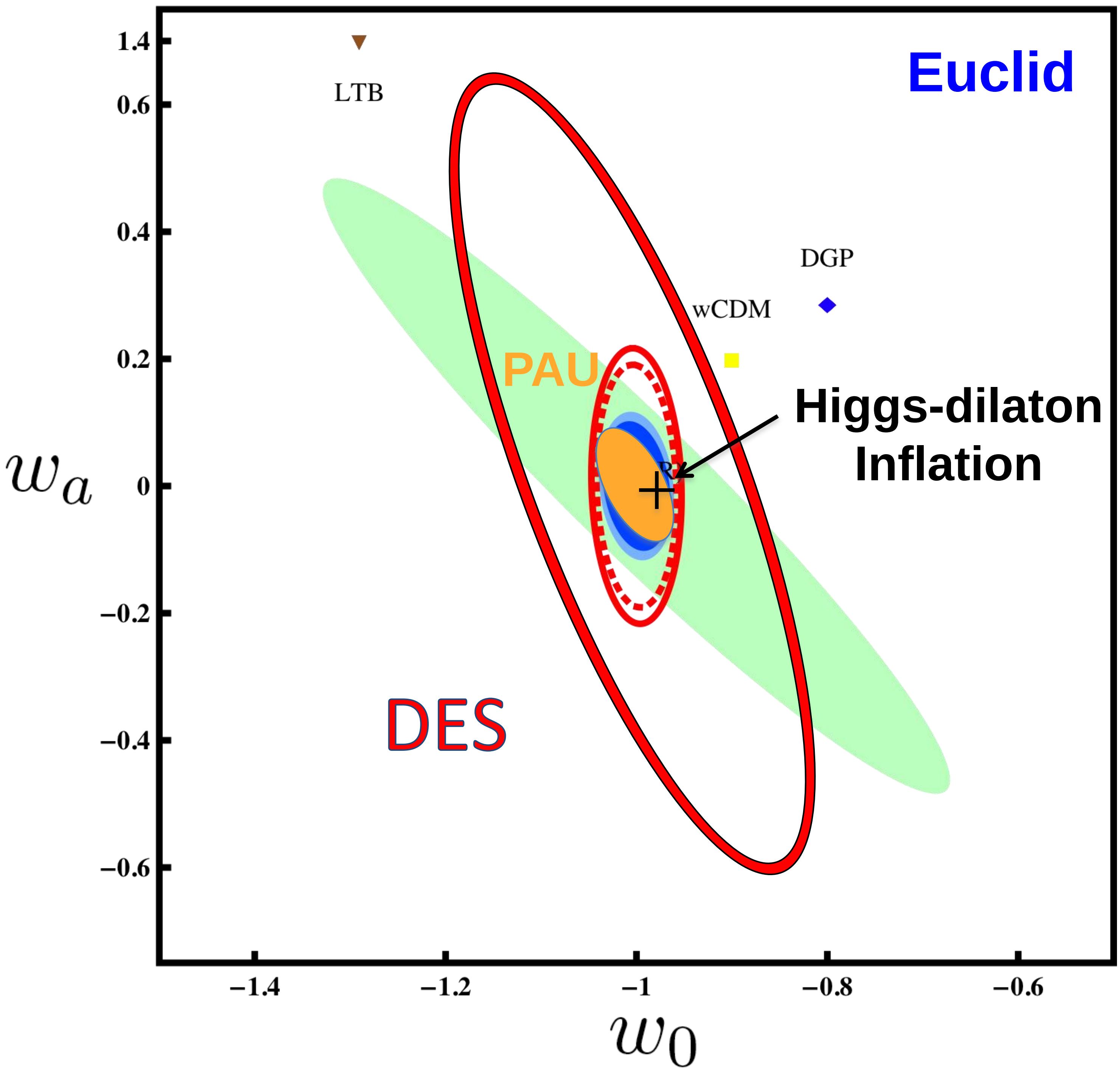
Spectroscopic survey

100 million galaxies
15,000 sq. deg
$\Delta z_{spec} = 0.001\ (1+z)$
8 bins z range [0.5,2.1]

Cost: 1B$

Imaging survey

1000 million galaxies
15,000 deg sq.
$\Delta z_{photo} = 0.05\ (1+z)$
5 bins z range [0.5,3.0]



Euclid
LTB
DGP
wCDM
PAU
Higgs-dilaton Inflation
DES
1.4
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−1.4
−1.2
−1
−0.8
−0.6
w_a
w_0

Conclusions

Particle Physics and Cosmology are intrincately 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: $1-n_s = 3(1+w)$