Higgs-Dilaton inflation and LSS surveys

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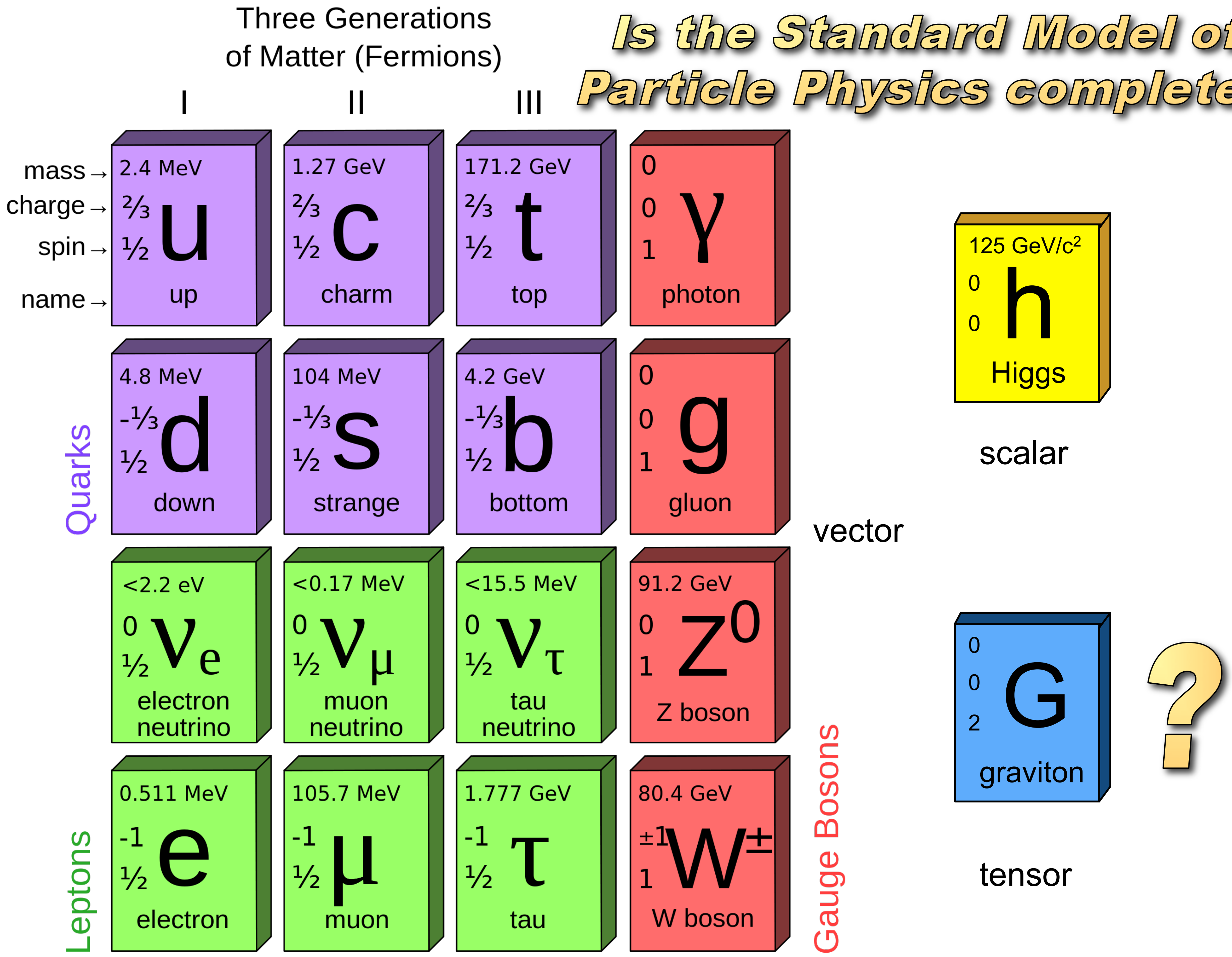
Outline

- 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 parameters

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

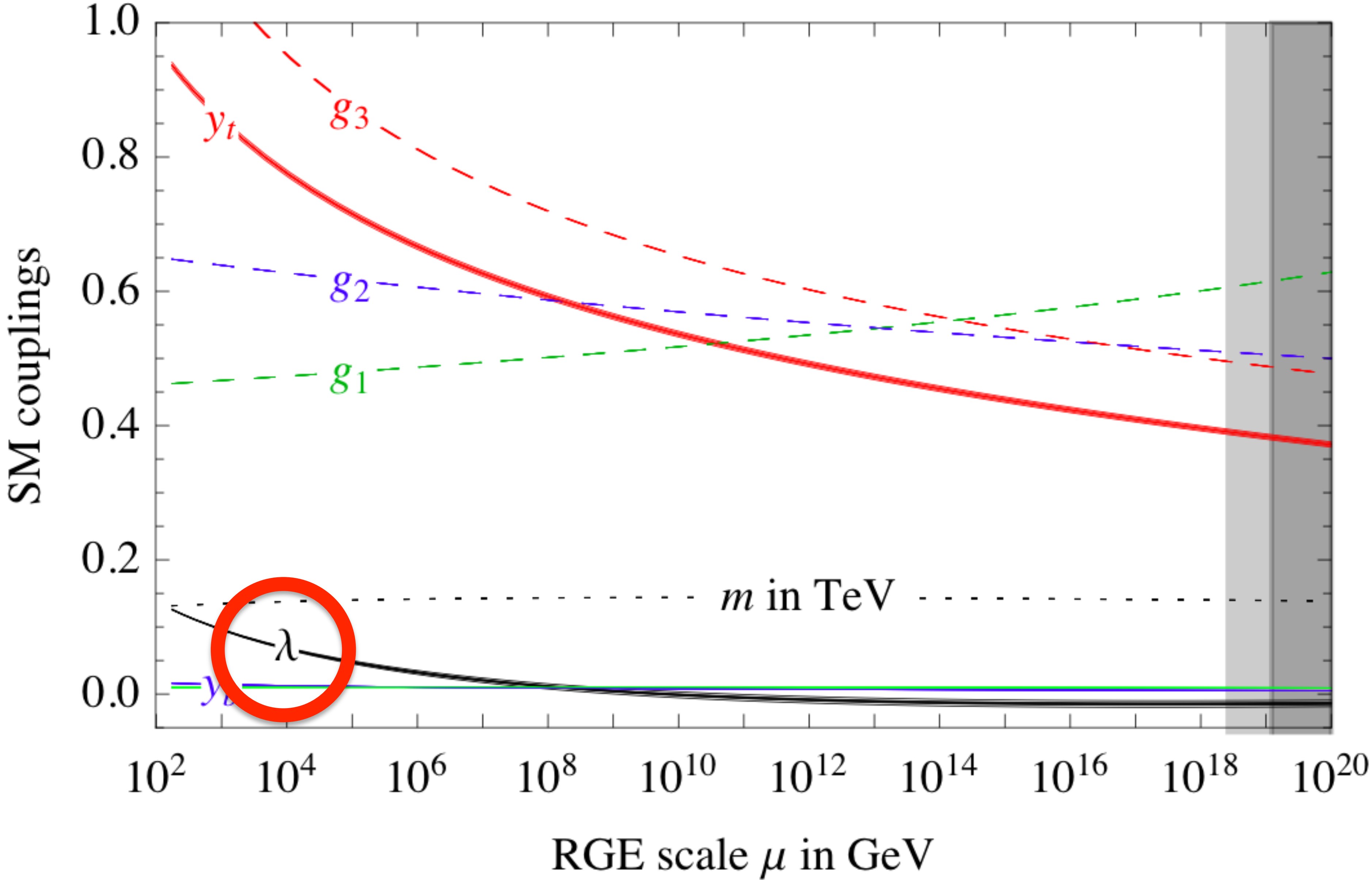
M_W	$=$	80.384 ± 0.014 GeV	Pole mass of the W boson
M_Z	$=$	91.1876 ± 0.0021 GeV	Pole mass of the Z boson
M_h	$=$	125.15 ± 0.24 GeV	Pole mass of the higgs
M_t	$=$	$173.34 \pm 0.76 \pm 0.3$ GeV	Pole mass of the top quark
$(\sqrt{2}G_\mu)^{-1/2}$	$=$	246.21971 ± 0.00006 GeV	Fermi constant for μ decay
$\alpha_3(M_Z)$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

Non-minimal coupling of Higgs to gravity

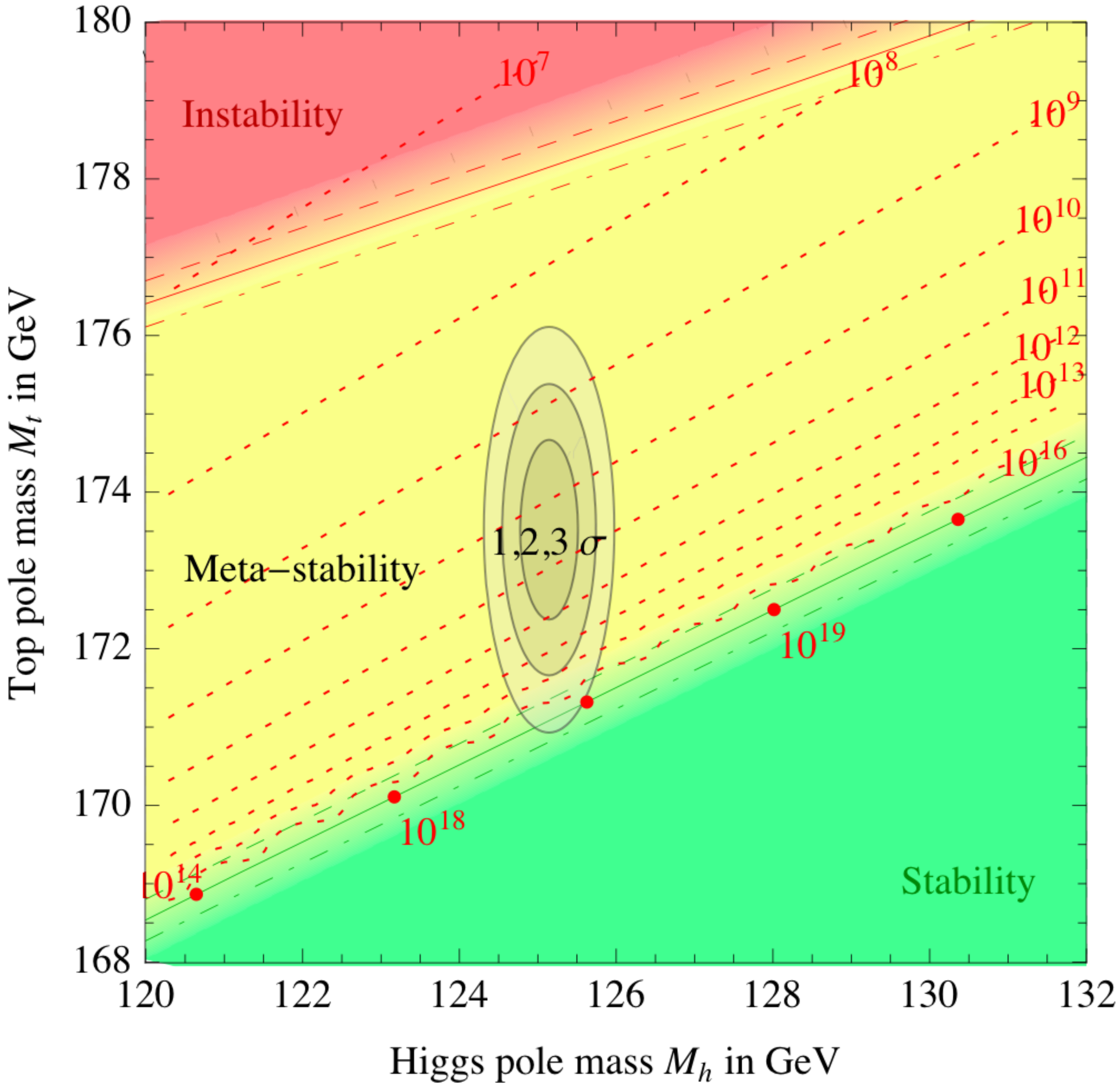
$$S_J = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2}{2}\left(1+\frac{2\xi H^\dagger H}{M_{\rm Pl}^2}\right)\mathcal{R} + (\partial_\mu H)^\dagger(\partial^\mu H) - V\right]$$

2-loop RGE running

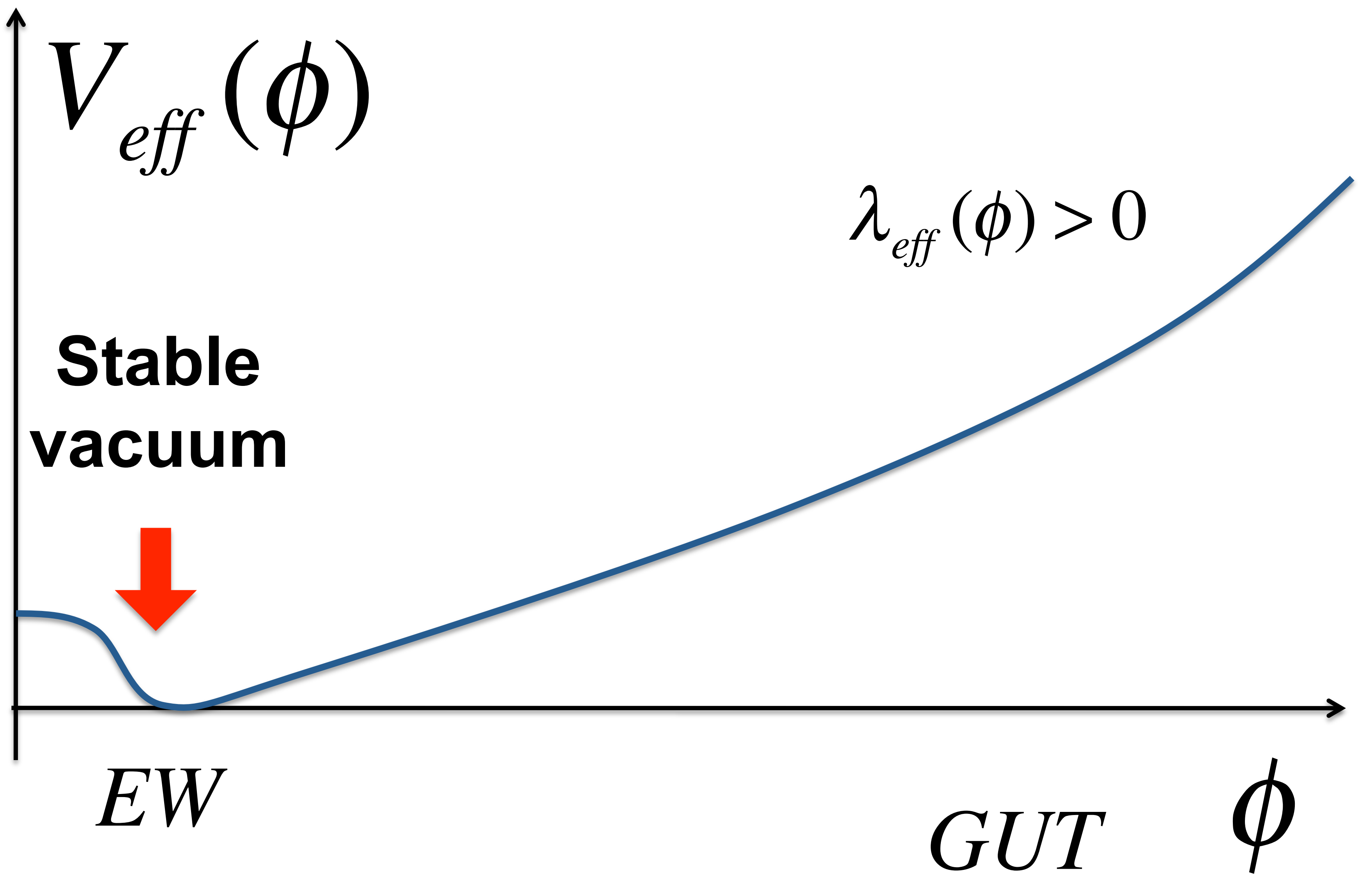
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)



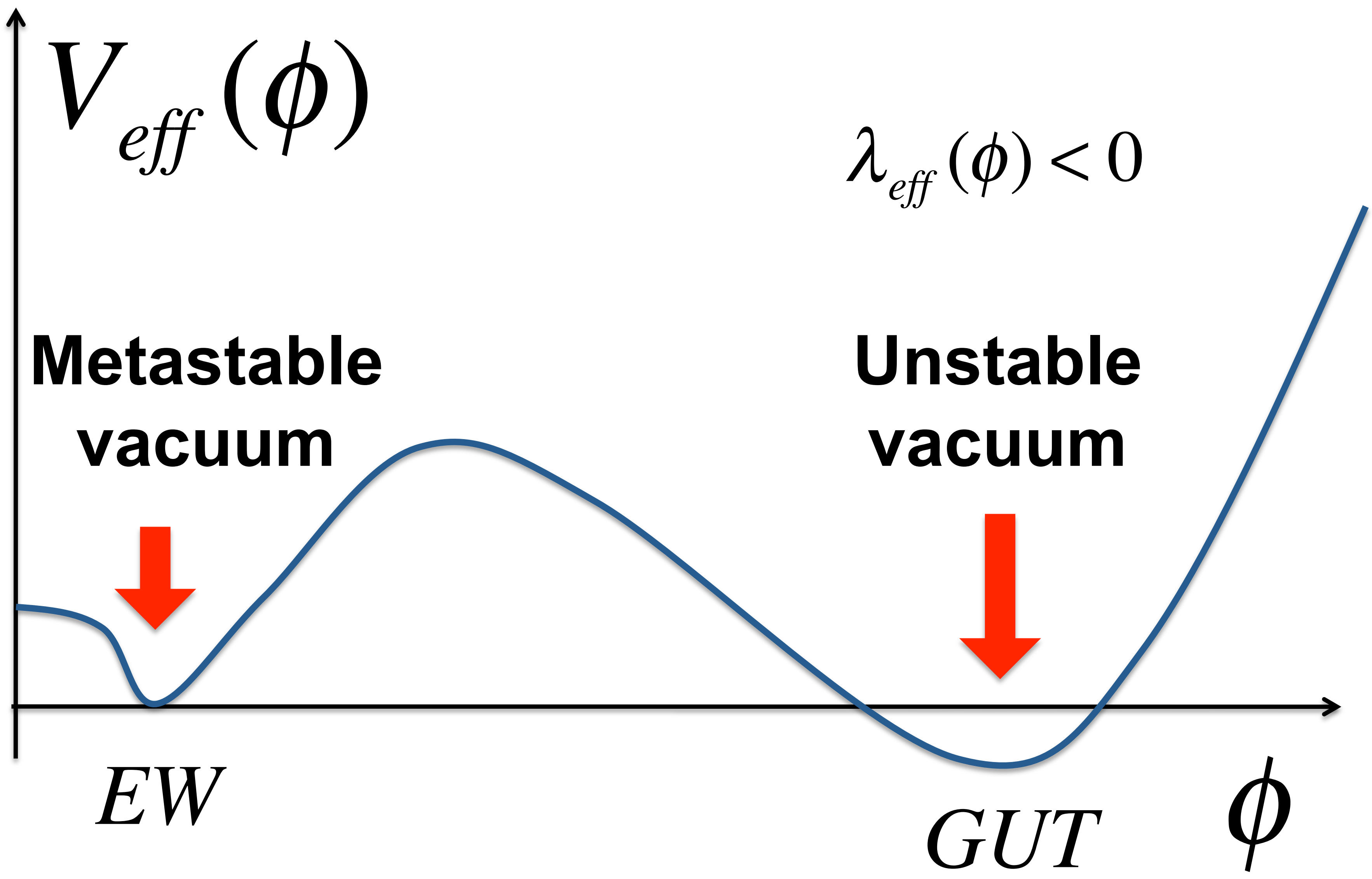
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)



Higgs effective potential

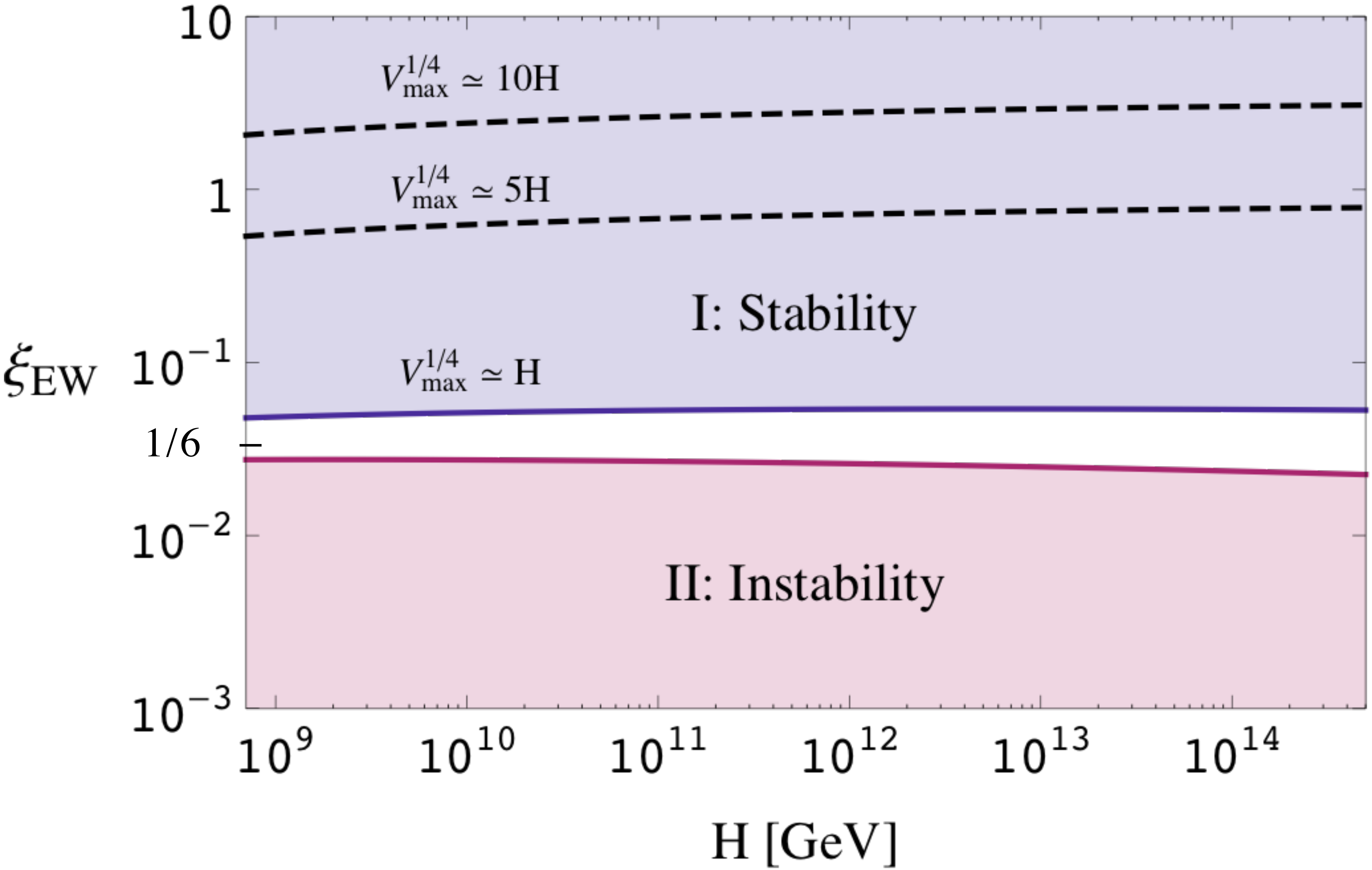


Higgs effective potential

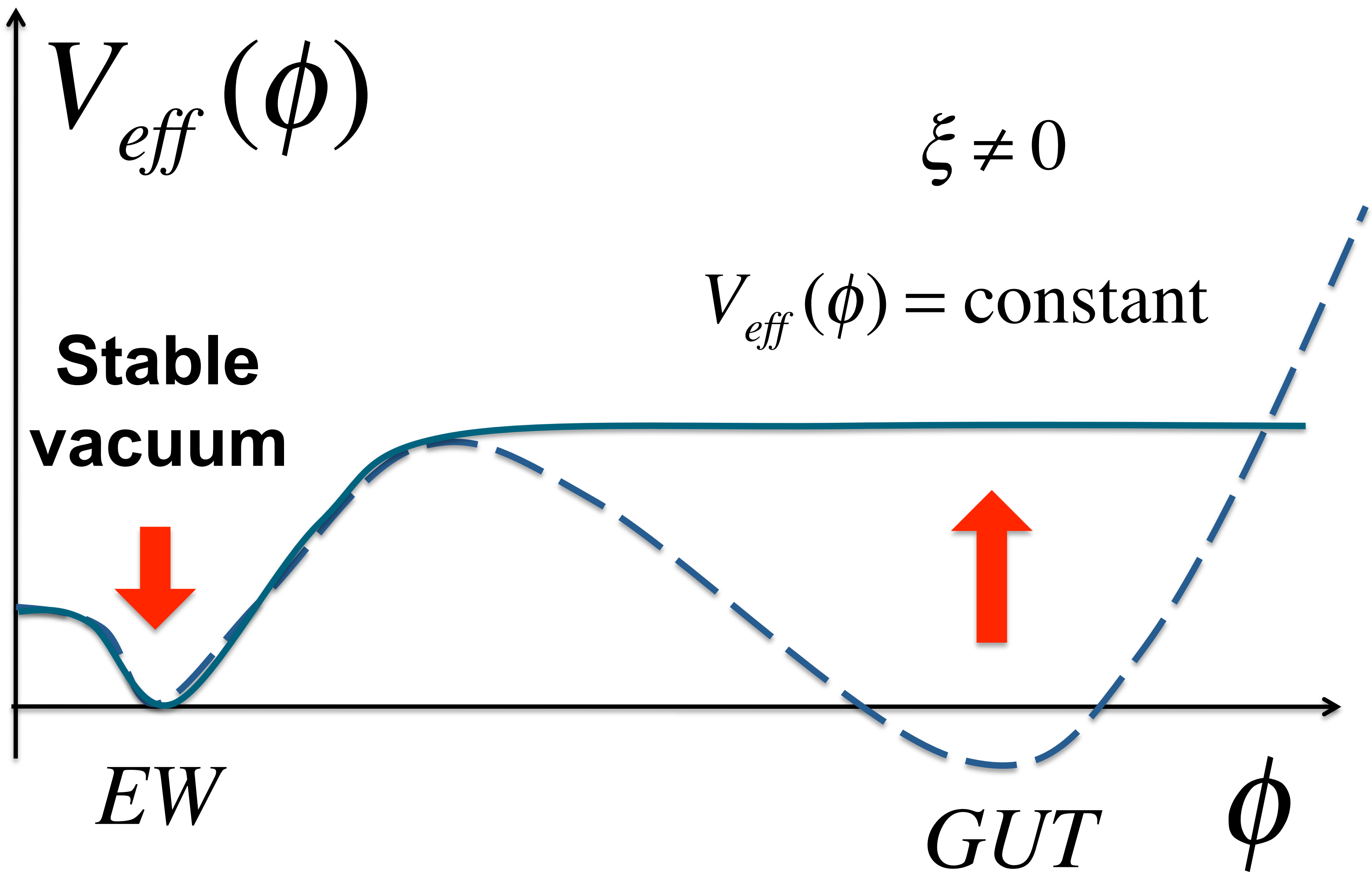


Non-minimal coupling of Higgs to gravity

Herranen, Markkanen, Nurmi, Rajantie (2014)

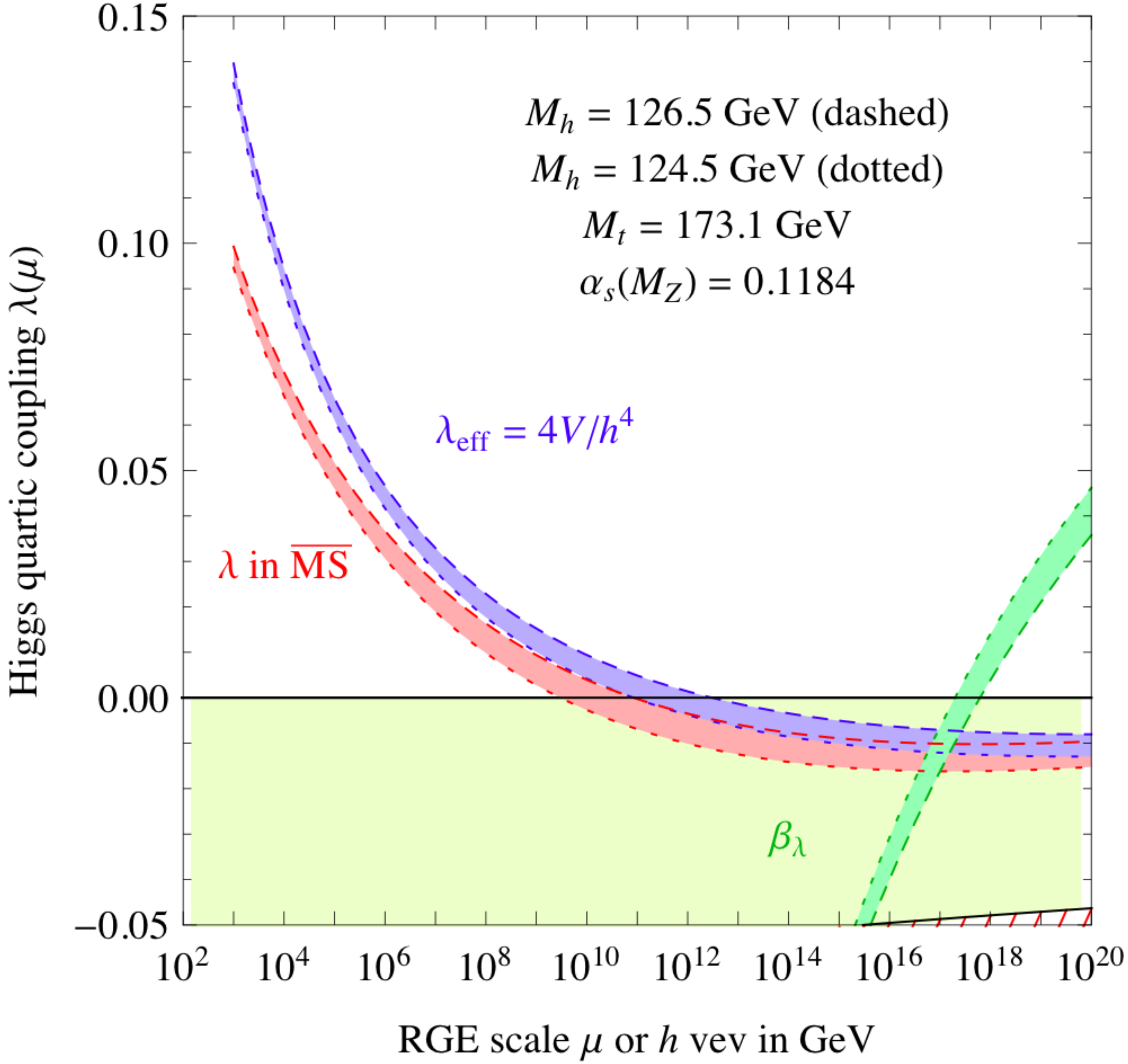


Higgs effective potential



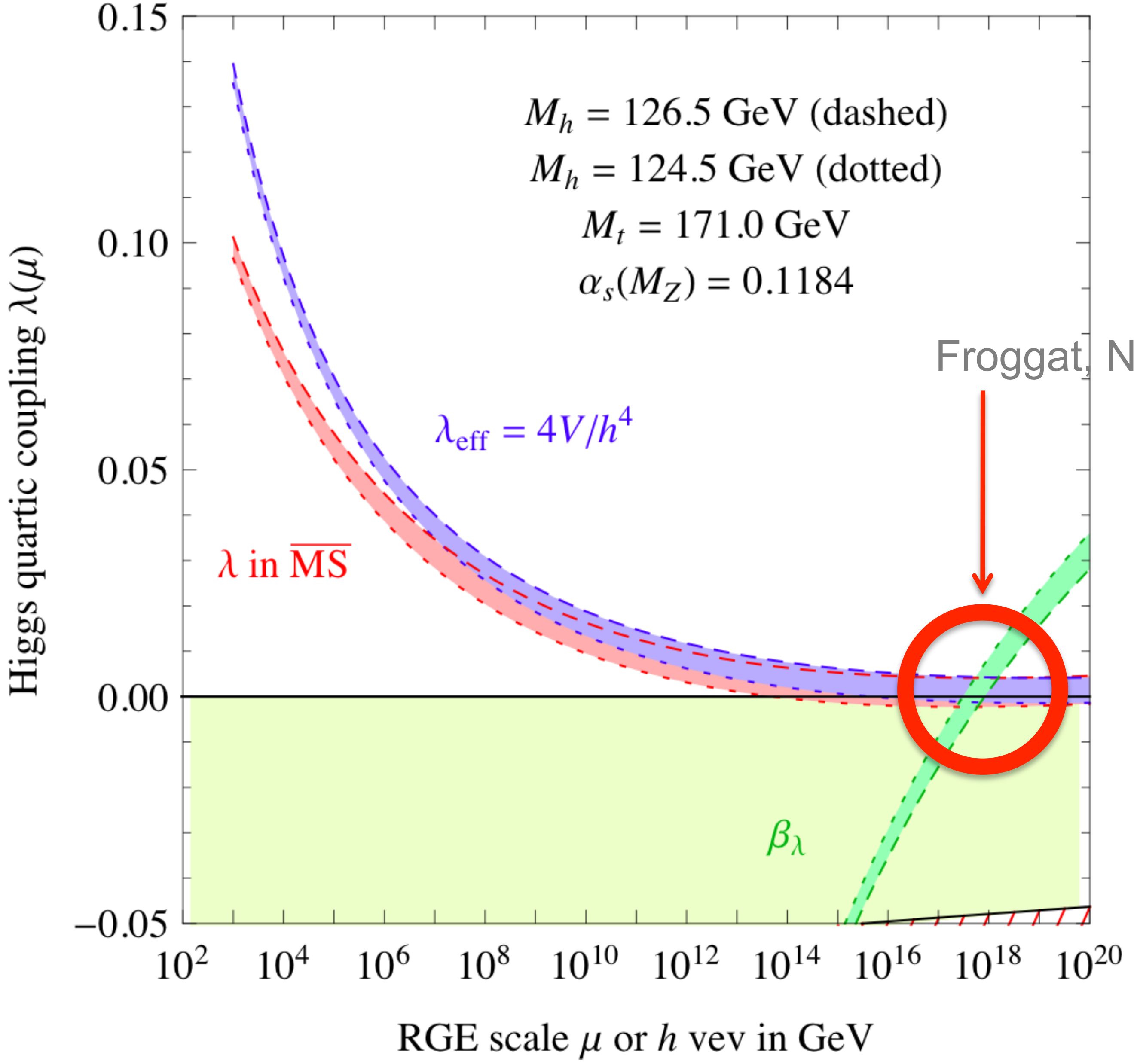
Non-minimal coupling of Higgs to gravity

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

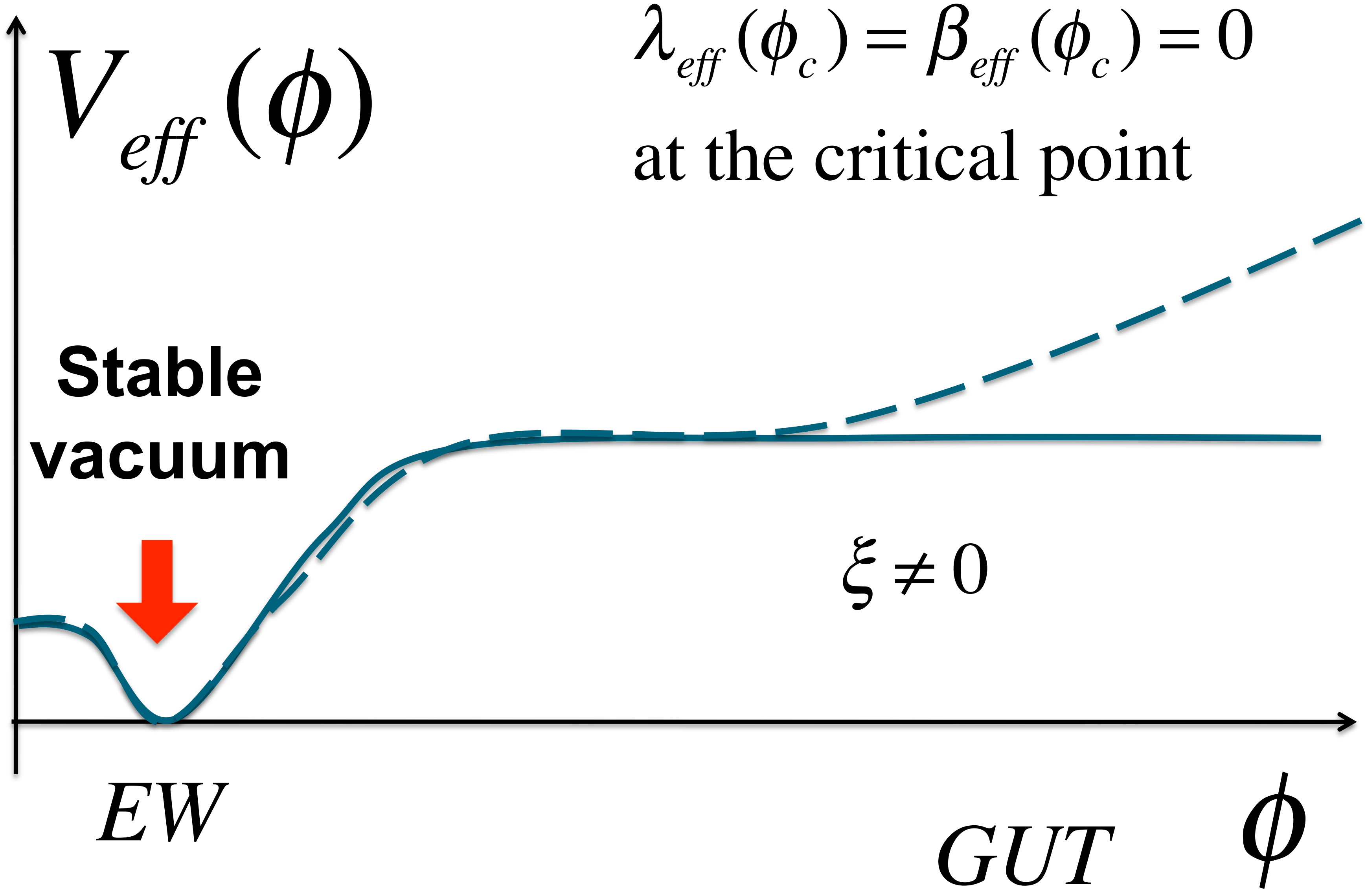


Non-minimal coupling of Higgs to gravity

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



Higgs effective potential



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:

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

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

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

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

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

Higgs-dilaton inflation

- Spontaneous breaking of S.I. gives:

  Graviton and dilaton massless, Higgs massive

$$\langle\chi\rangle = \chi_0 \qquad h_0^2 = \frac{\alpha}{\lambda}\chi_0^2$$

$$m_H^2 = 2\alpha M_P^2 \frac{(1+6\xi_\chi) + \frac{\alpha}{\lambda}(1+6\xi_h)}{(1+6\xi_\chi)\xi_\chi + \frac{\alpha}{\lambda}(1+6\xi_h)\xi_h}$$

- Higgs mass finetuning:

$$m_H^2 \lll M_P^2 = \xi_\chi \chi_0^2 + \xi_h h_0^2$$

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):

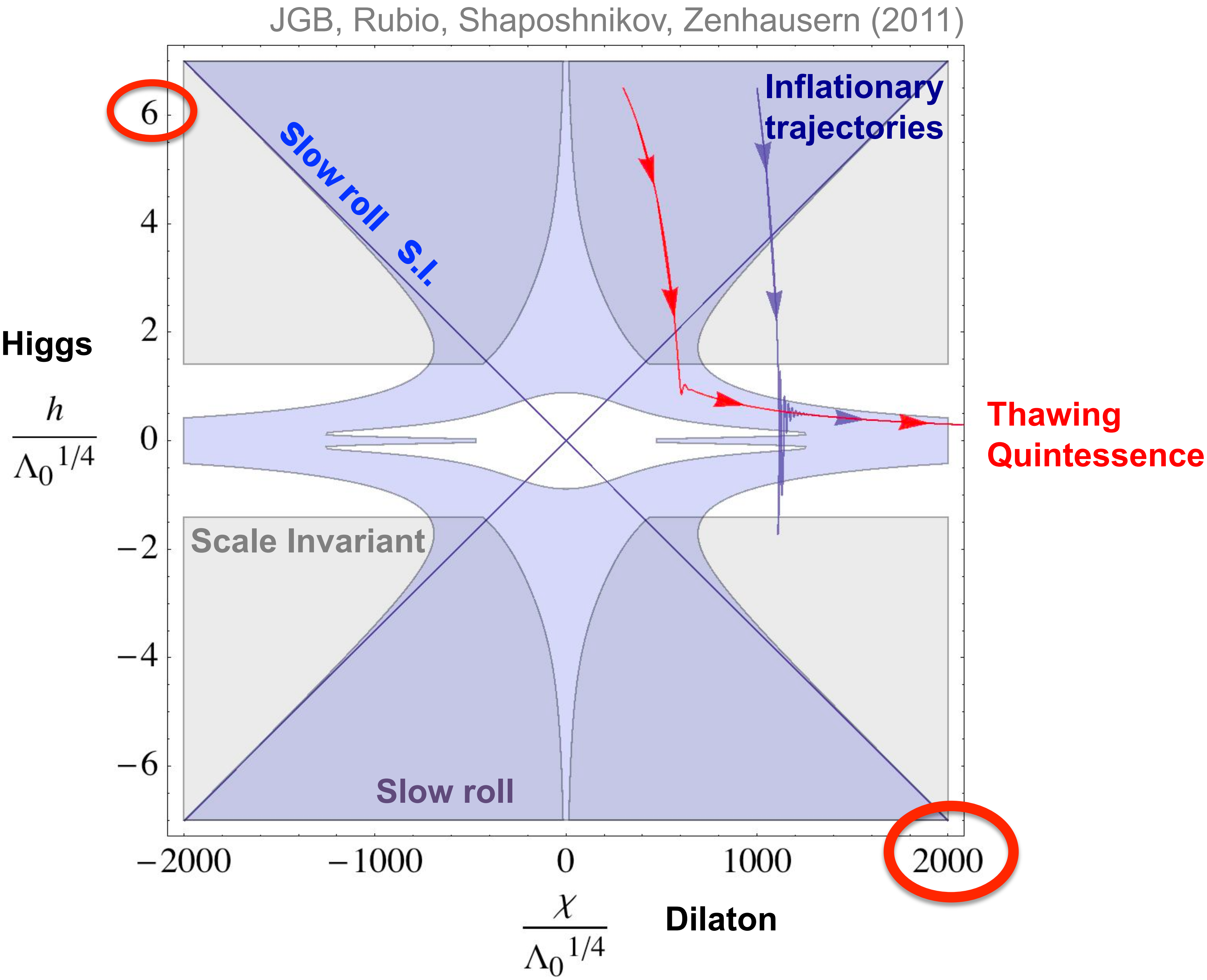
$$\rho = \frac{M_P}{2}\log\left[\frac{(1+6\xi_\chi)\chi^2+(1+6\xi_h)h^2}{M_P^2}\right], \quad \tan\theta = \sqrt{\frac{1+6\xi_h}{1+6\xi_\chi}}\frac{h}{\chi}$$

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

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)

$$P_\zeta(k_0) \simeq \frac{\lambda N^{*2}}{72\pi^2 \xi_h^2}\left(1 + \frac{1}{3}(4\xi_\chi N^*)^2 + \ldots\right),$$

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

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

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

$$\alpha_\zeta(k_0) \simeq -\tfrac{1}{6}r(k_0) = \tfrac{4}{3}n_g(k_0),$$

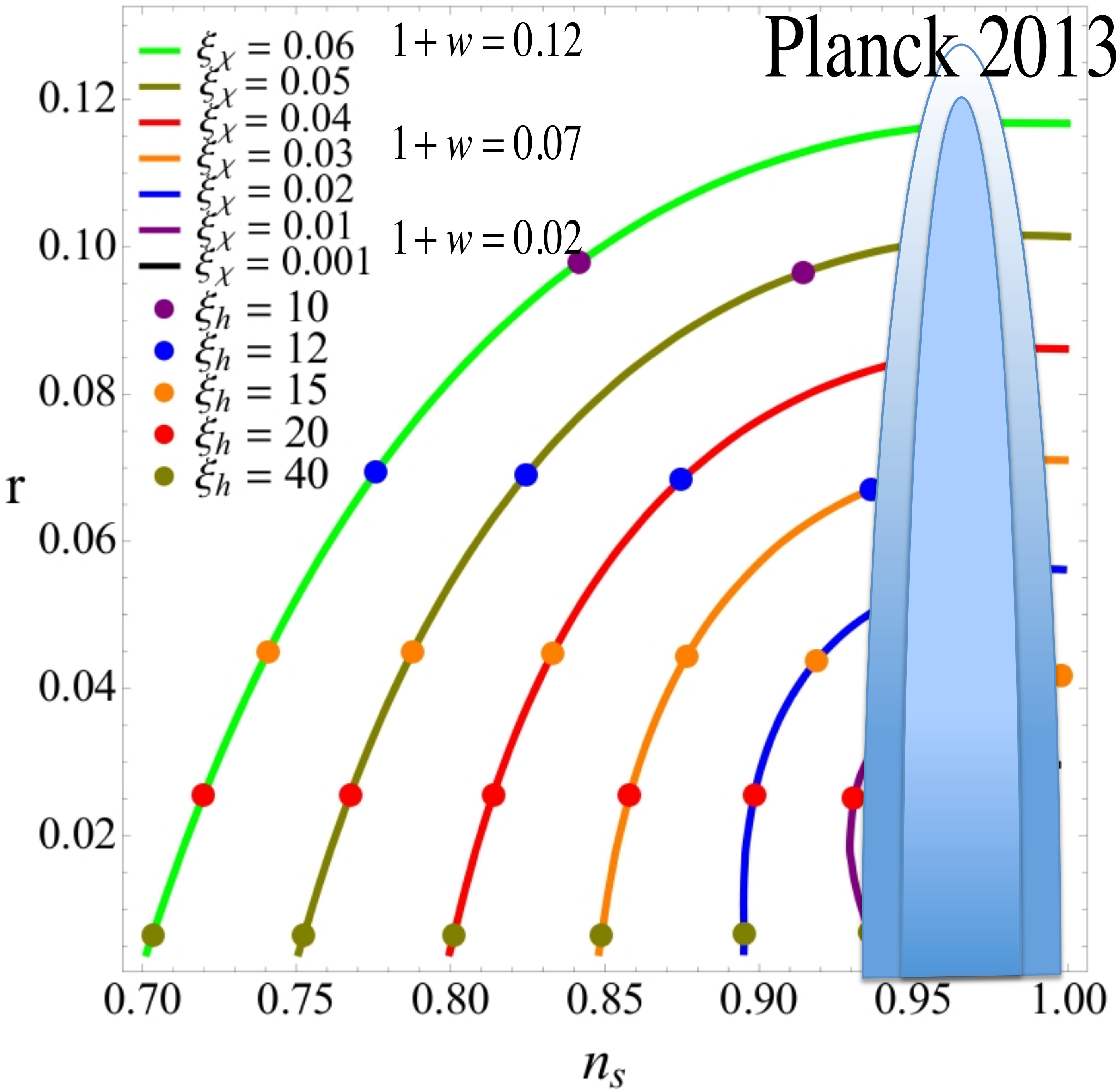
$$n_s(k_0) < 0.97 \simeq 1 - \frac{2}{N^*},$$

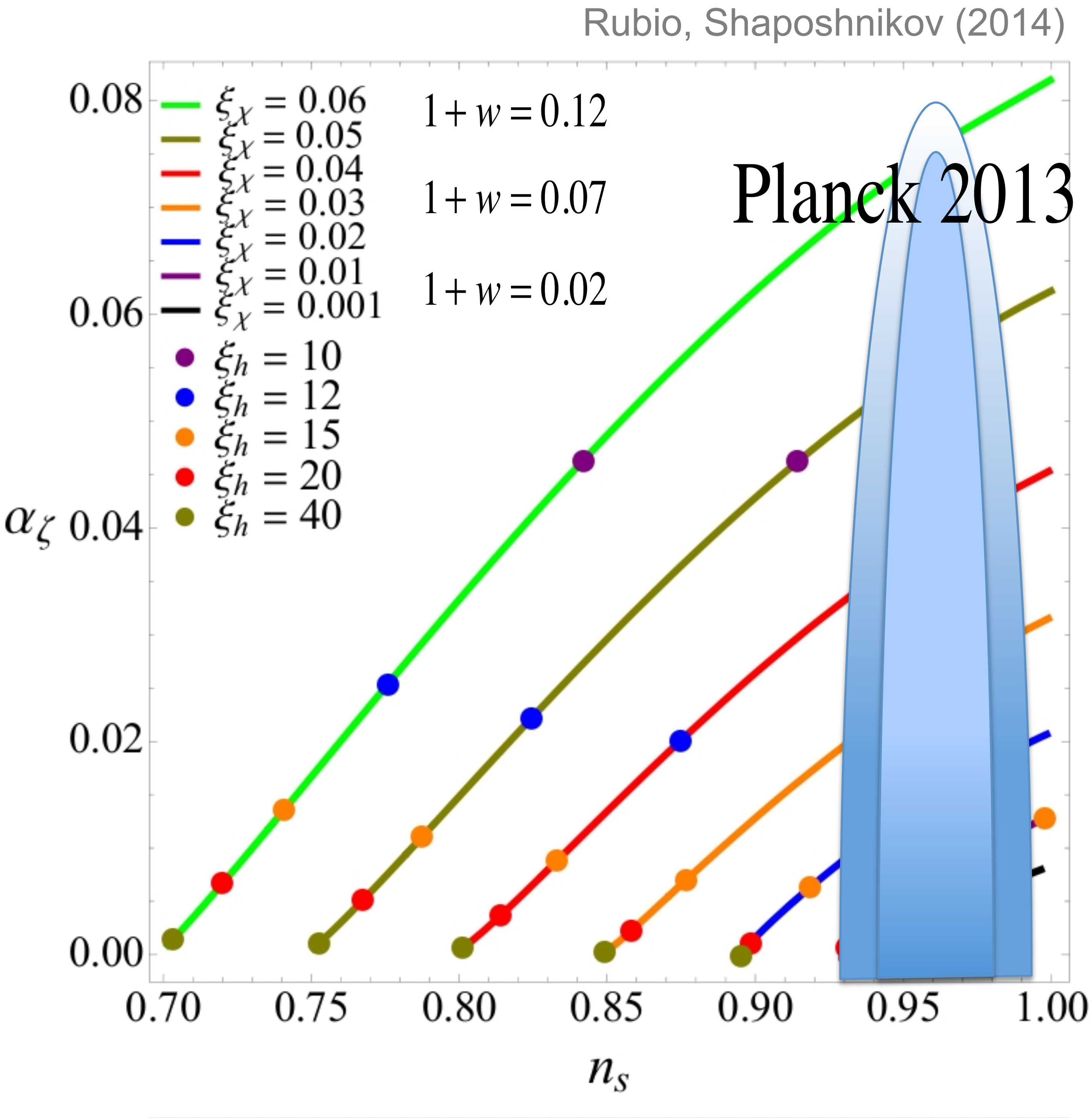
$$\alpha_\zeta(k_0) > -0.0006 \simeq -\frac{2}{N^{*2}},$$

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

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

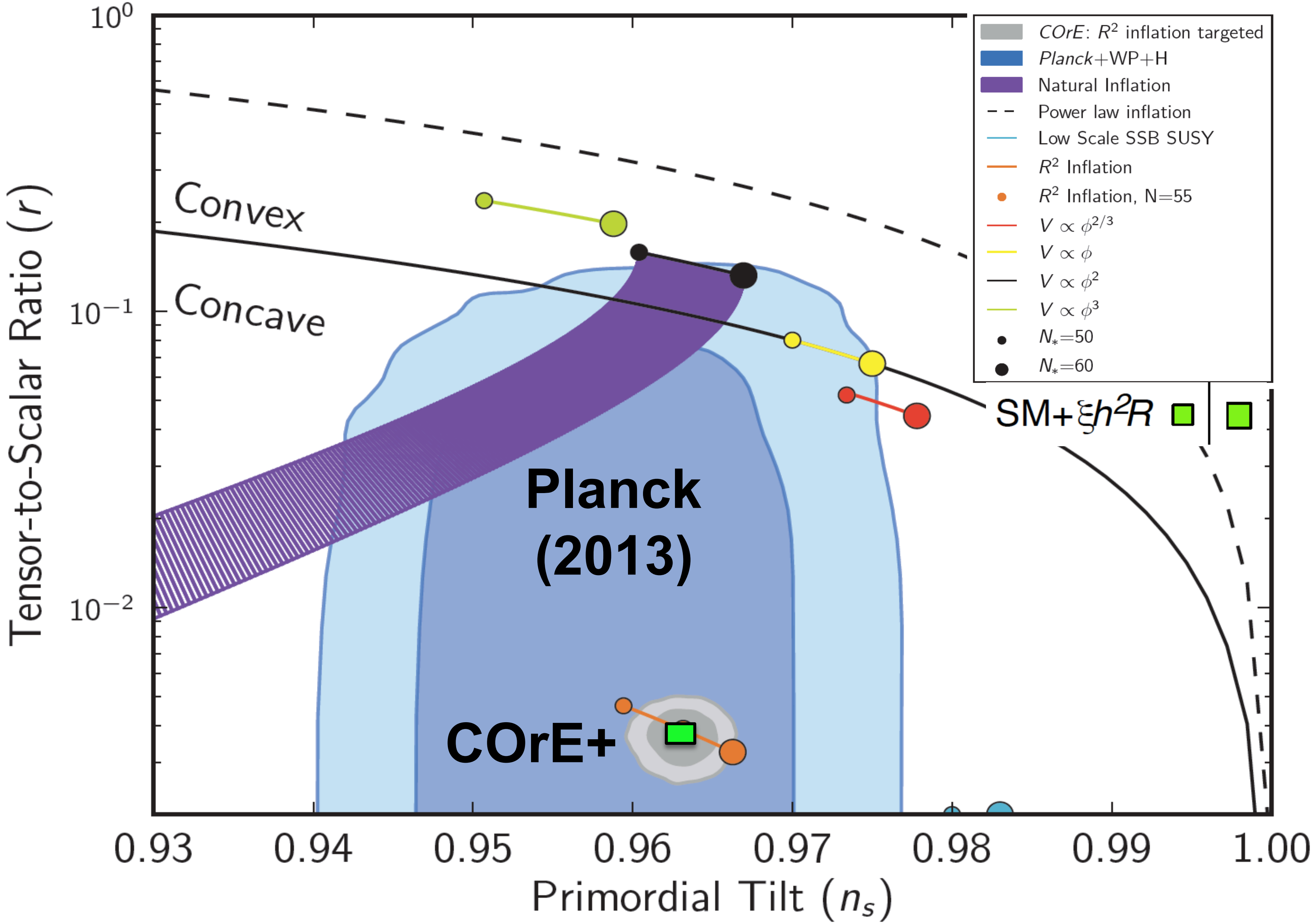
Rubio, Shaposhnikov (2014)


Planck 2013
$\xi_\chi = 0.06$
$\xi_\chi = 0.05$
$\xi_\chi = 0.04$
$\xi_\chi = 0.03$
$\xi_\chi = 0.02$
$\xi_\chi = 0.01$
$\xi_\chi = 0.001$
$\xi_h = 10$
$\xi_h = 12$
$\xi_h = 15$
$\xi_h = 20$
$\xi_h = 40$
$1+w=0.12$
$1+w=0.07$
$1+w=0.02$
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



Rubio, Shaposhnikov (2014)
$\xi_\chi = 0.06$
$\xi_\chi = 0.05$
$\xi_\chi = 0.04$
$\xi_\chi = 0.03$
$\xi_\chi = 0.02$
$\xi_\chi = 0.01$
$\xi_\chi = 0.001$
$\xi_h = 10$
$\xi_h = 12$
$\xi_h = 15$
$\xi_h = 20$
$\xi_h = 40$
$1 + w = 0.12$
$1 + w = 0.07$
$1 + w = 0.02$
Planck 2013
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)

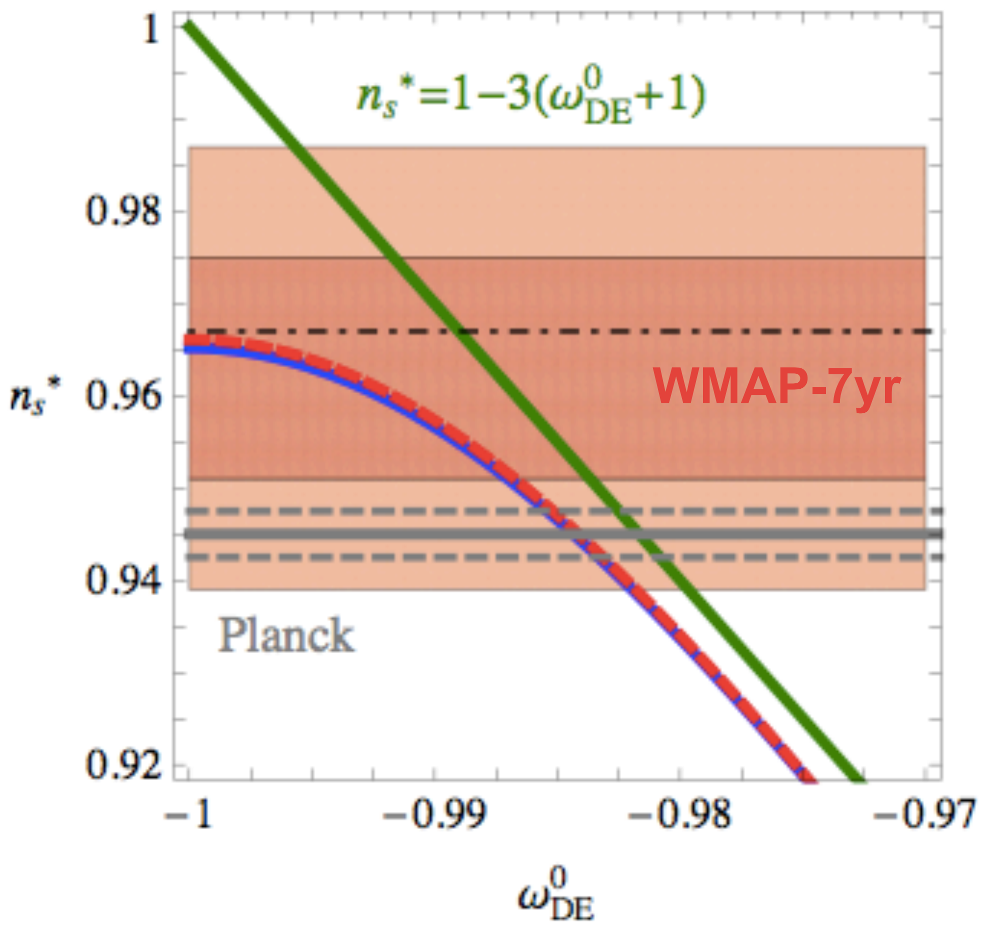
Consistency conditions

1st order ⟷ 0th order

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

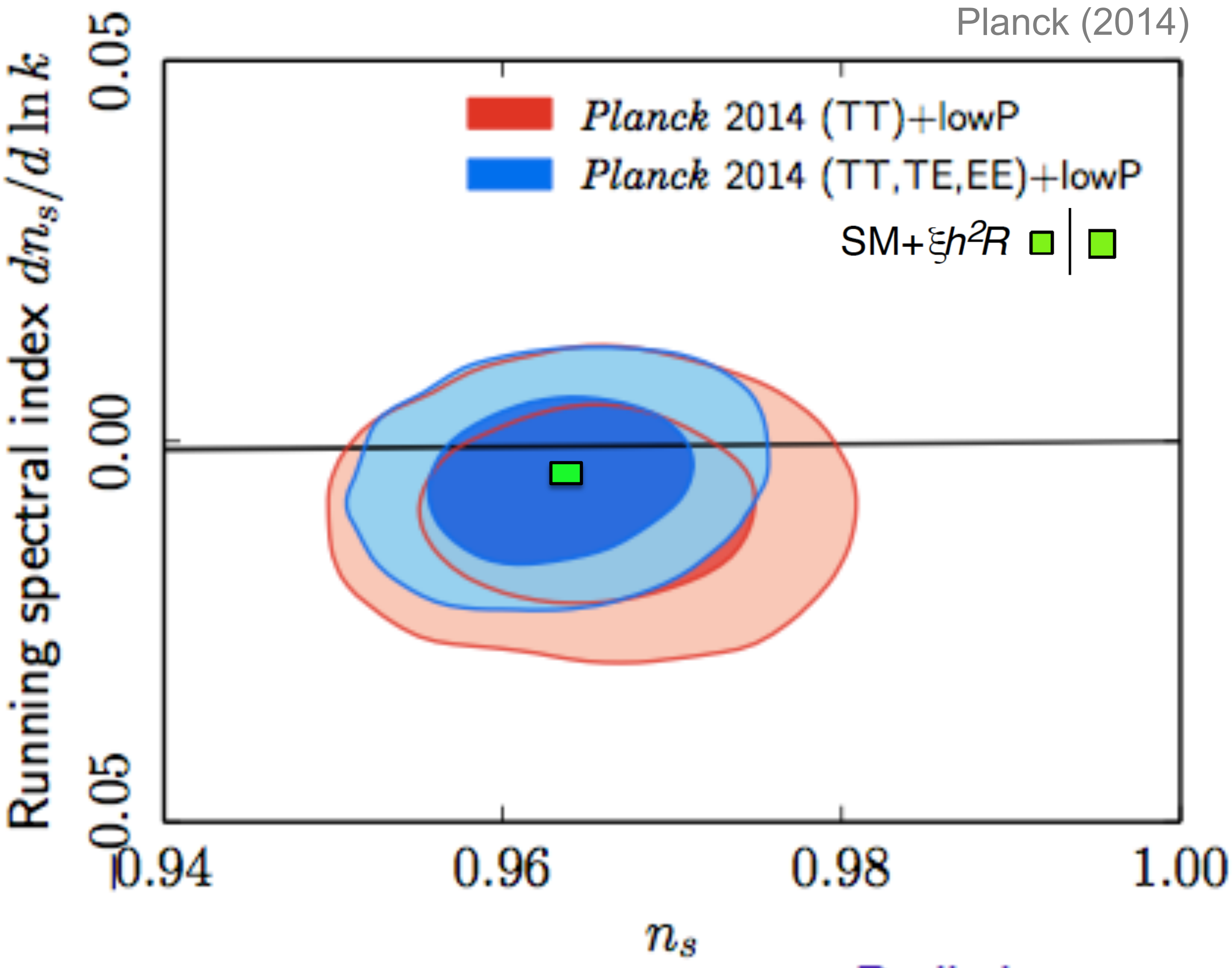
2nd order ⟷ 1st order

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



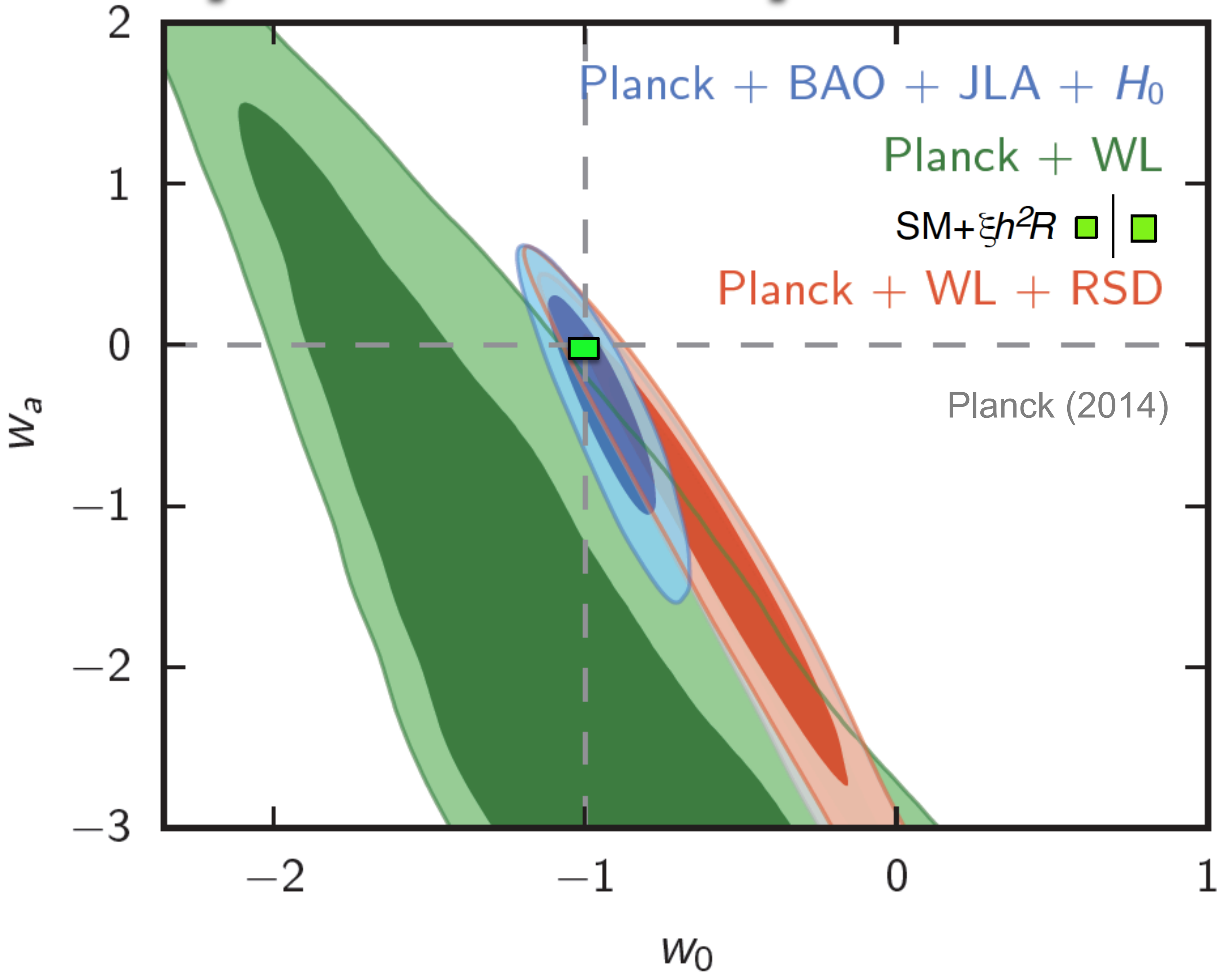
$$w_{DE}(a) = w_{DE}^0 + w_{DE}^a \ln(a/a_0)\,. \qquad \alpha_\zeta(k) \equiv \frac{dn_s}{d\ln k}$$

Spectral tilt – running tilt



Preliminary

Equation of state parameters



Combined Preheating in Higgs-Dilaton model

J. G.-B., D. G. Figueroa, J. Rubio

Phys.Rev.D79,063531(2009)

J. G.-B., J. Rubio, D. Zenhausern, M. Shaposhnikov

Phys.Rev.D84,123504(2011)

J. G.-B., J. Rubio, M. Shaposhnikov

Phys.Lett.B718,507(2012)

The SU(2)xU(1) Higgs-Dilaton model

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} + Tr[(D_\mu\Phi)^+ D^\mu\Phi] + \frac{1}{2}\xi\Phi^+\Phi R$$

$$+\frac{1}{2}(\partial_\mu\chi)^2 - V(\Phi,\chi)$$

$$-h\Phi\overline{\Psi}\Psi$$

$$D_\mu = \partial_\mu - \frac{i}{2}g_W A^a_\mu \tau_a - \frac{i}{2}g_Y B_\mu \tau_3$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_W \varepsilon^{abc} A^b_\mu A^c_\nu$$

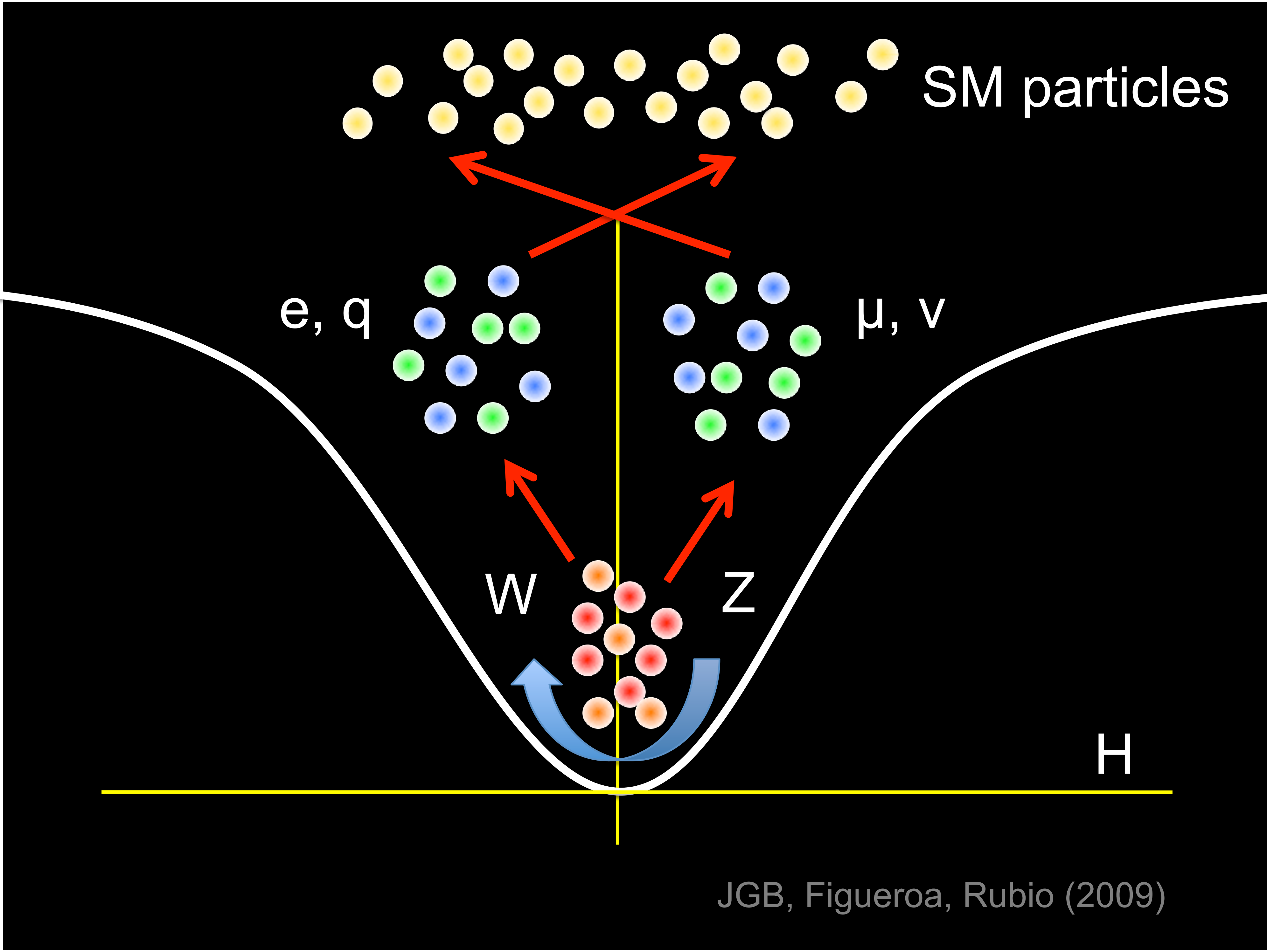
$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

$$Tr[\Phi^+\Phi] = \frac{1}{2}(\phi_0^2 + \phi^a\phi_a) \equiv \frac{1}{2}\phi^2$$

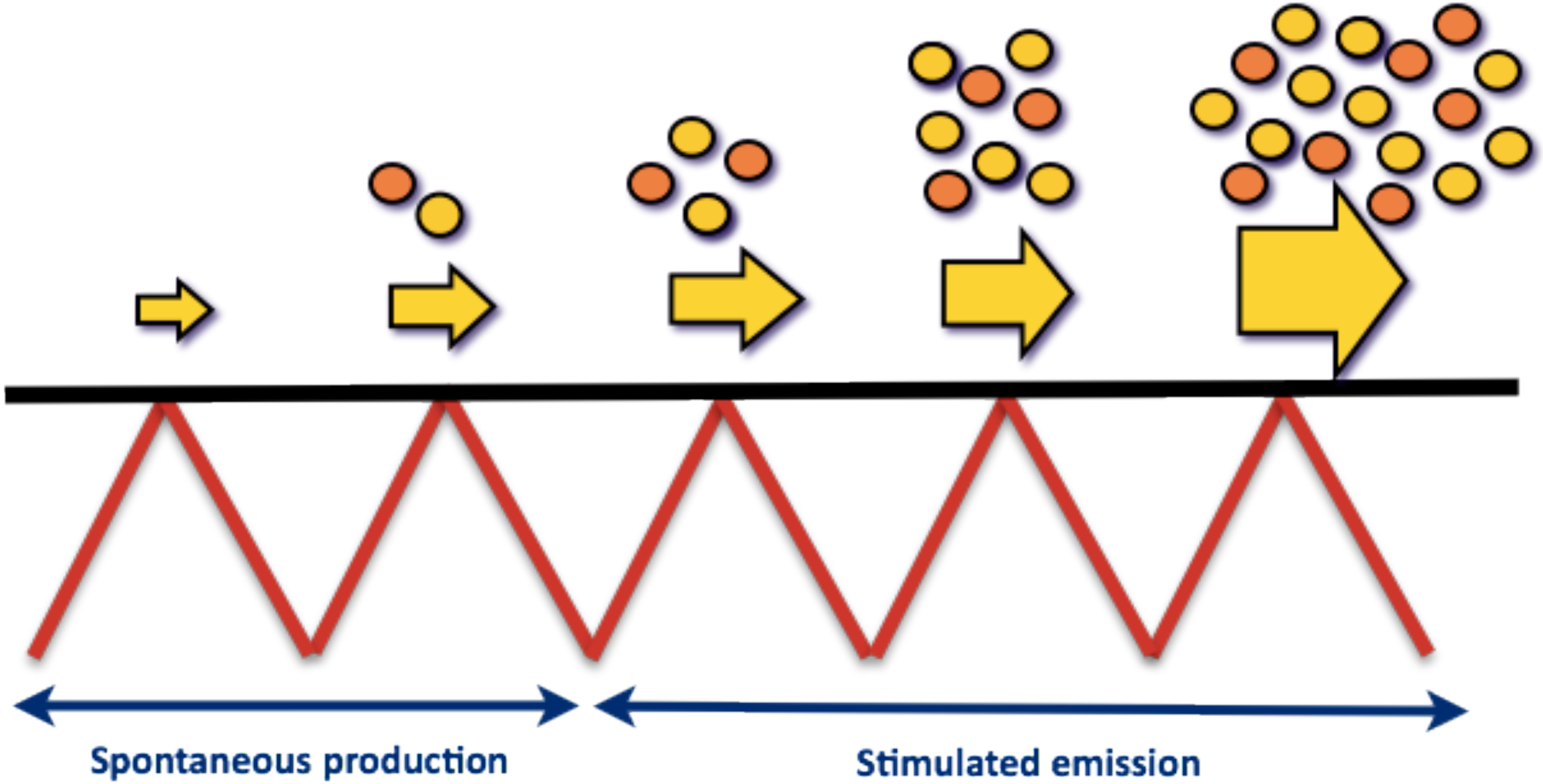
$$V(\phi,\chi) = \frac{\lambda}{4}(\phi^2 - \alpha\,\chi^2)^2 + \frac{\beta}{4}\chi^4$$

+SM couplings


SM particles
e, q
μ, ν
W
Z
H
JGB, Figueroa, Rubio (2009)

Parametric resonance

$$n_k(j^+) = \mathcal{C}(x_j) + (2\mathcal{C}(x_j)+1)n_k(j^-) + 2\cos\theta_j\sqrt{\mathcal{C}(x_j)\,(\mathcal{C}(x_j)+1)}\sqrt{n_k(j^-)\,(n_k(j^-)+1)}$$

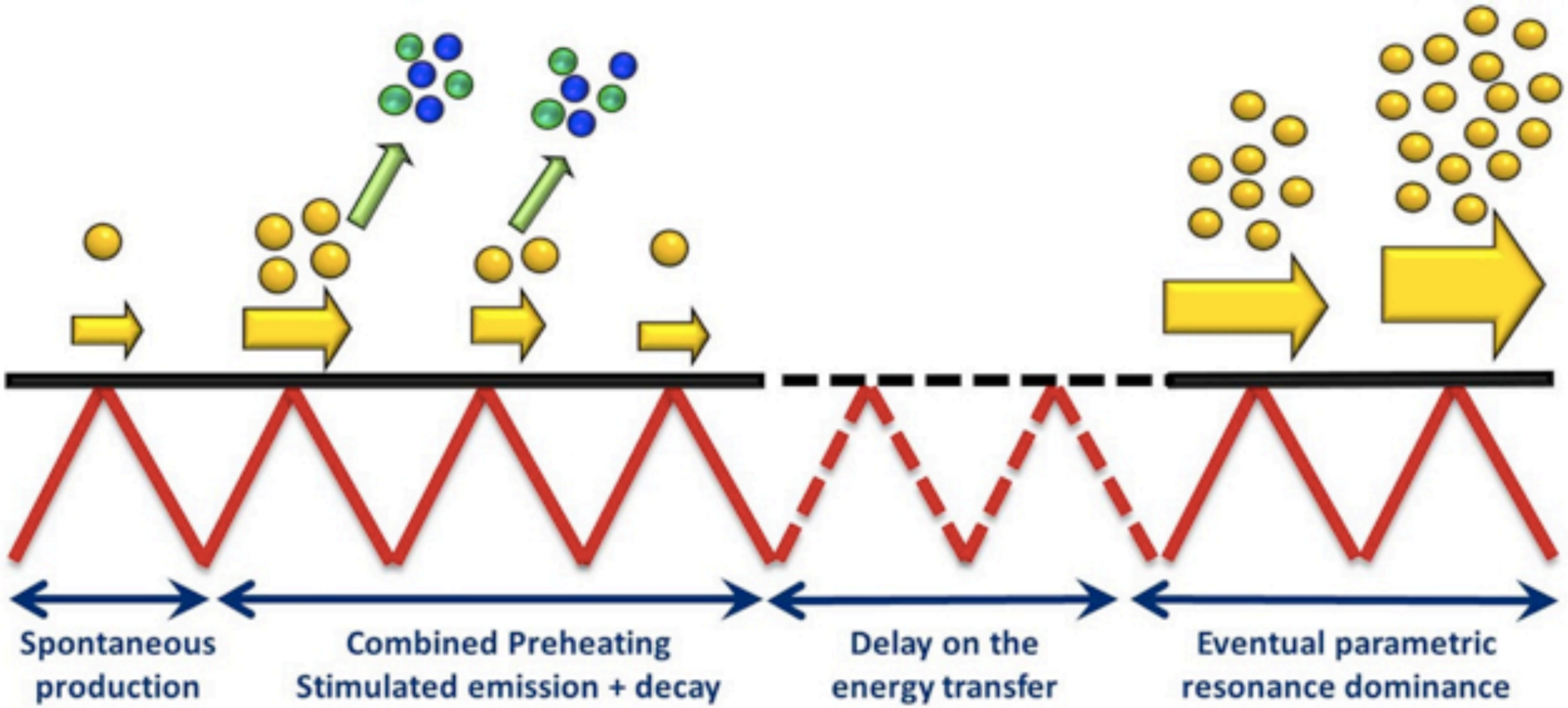


$$n_k(j^+) = n_k(j^-)e^{2\pi\mu_k(j)}$$

JGB, Figueroa, Rubio (2009)

Combined Preheating

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



General Formalism to be incorporated in any realistic theory of (p)reheating

JGB, Figueroa, Rubio (2009)

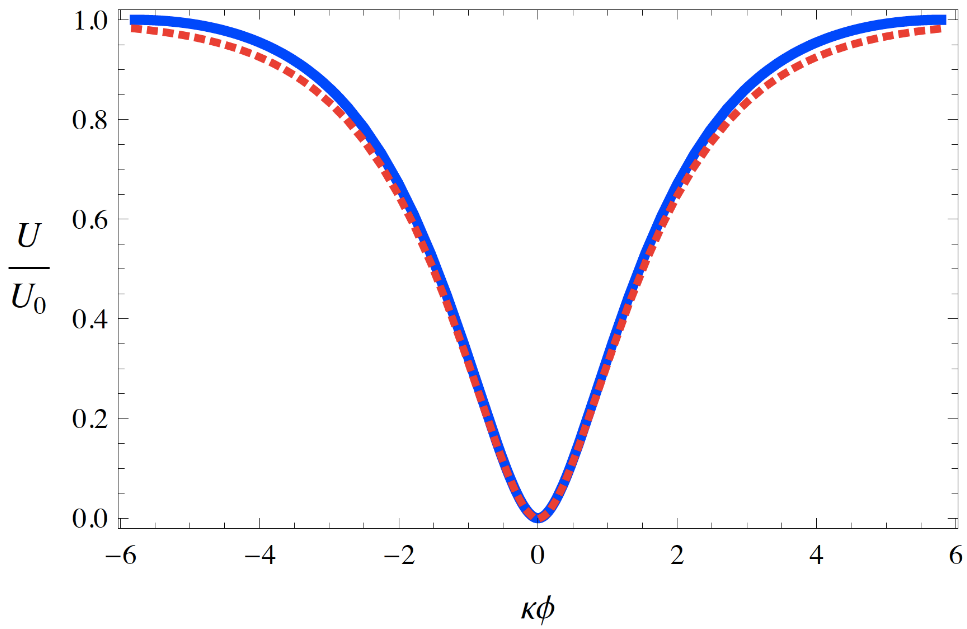
Dilaton prodution at preheating

JGB, Rubio, Shaposhnikov (2012)

$$\frac{\mathscr{L}}{\sqrt{-\tilde{g}}} = \frac{M_P^2}{2}\tilde{R} - \frac{e^{2b(\phi)}}{2}(\partial\rho)^2 - \frac{1}{2}(\partial\phi)^2 - \tilde{U}(\phi)$$

$$e^{2b(\phi)} \equiv \varsigma \cosh^2\left[a\kappa\left(\phi_0 - |\phi|\right)\right]$$

$$\tilde{U}(\phi) = \frac{\lambda M_P^4}{4\xi_h^2(1-\varsigma)^2}\left(1 - \varsigma\cosh^2[a\kappa\left(\phi_0 - |\phi|\right)]\right)^2$$



Dilaton prodution at preheating

JGB, Rubio, Shaposhnikov (2012)

dilaton perturbations $\delta\rho_k$ in Fourier space

$$\delta\ddot{\rho}_k + \left(3H + 2\dot{b}\right)\delta\dot{\rho}_k + \frac{k^2}{a^2}\delta\rho_k = 0\,, \qquad \frac{1}{a^3e^{2b}}\frac{d}{dt}\left(a^3e^{2b}\frac{d}{dt}\delta\rho_k\right) + \frac{k^2}{a^2}\delta\rho_k = 0$$

$$\delta\rho_k'' + \omega_k^2(\tau)\delta\rho_k = 0 \qquad \omega_k^2(\tau) = k^2a^4e^{4b}$$

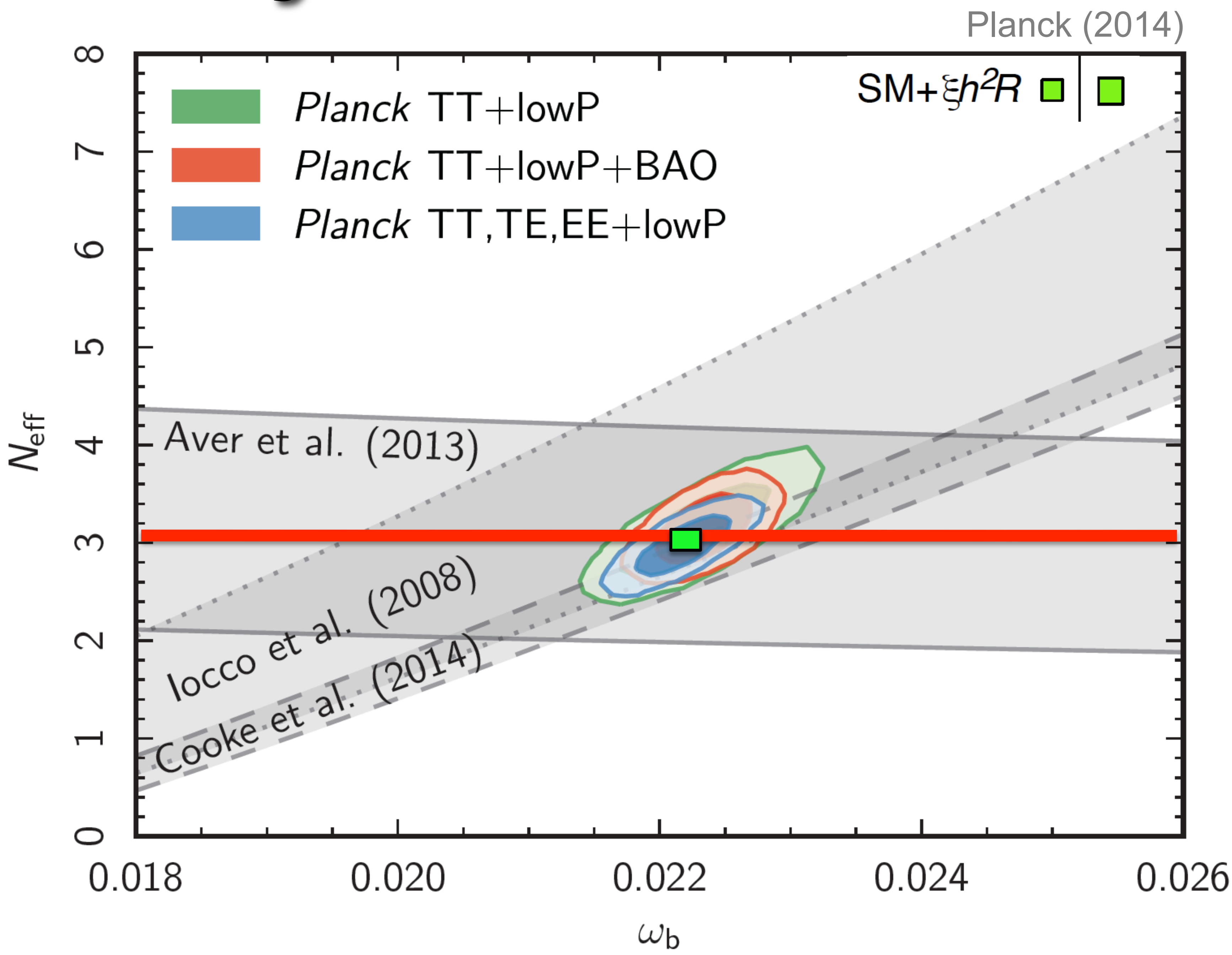
$$n_k + \frac{1}{2} = \frac{1}{2\omega_k}\left(|\delta\rho_k'|^2 + \omega_k^2|\delta\rho_k|^2\right) \qquad \rho_\chi = \frac{1}{2\pi^2}\int_0^\infty dk k^2\,\omega_k n_k$$

$$C \equiv \rho_\chi^0/\rho_{\rm SM}^0 \qquad g_0T_0^3a_0^3 = g_fT_f^3a_f^3 \qquad (g_0 = 106.75\,,\ g_{\rm f} = 10.75)$$

$$\rho_\nu = \frac{\pi^2}{30}g_\nu T_{\rm f}^4 \qquad N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$$

$$\Delta N_{\rm eff} \equiv \left(\frac{\rho_\chi}{\rho_\nu}\right)_{\rm f} = \frac{g_0}{g_\nu}\left(\frac{g_f}{g_0}\right)^{4/3} C \simeq \underline{2.85\times10^{-7}\ \ll 1.}$$

Baryon content – N effective



How can we further test the HDI model?
We need deep and wide galaxy surveys

Four main probes

- Gravitational lensing
- Supernovae luminosities
- Galaxy cluster mass function & no. counts
- Baryon Acoustic Oscillations

DARK ENERGY
SURVEY

4m Blanco Telescope Cerro Tololo Chile

Dark Energy Survey

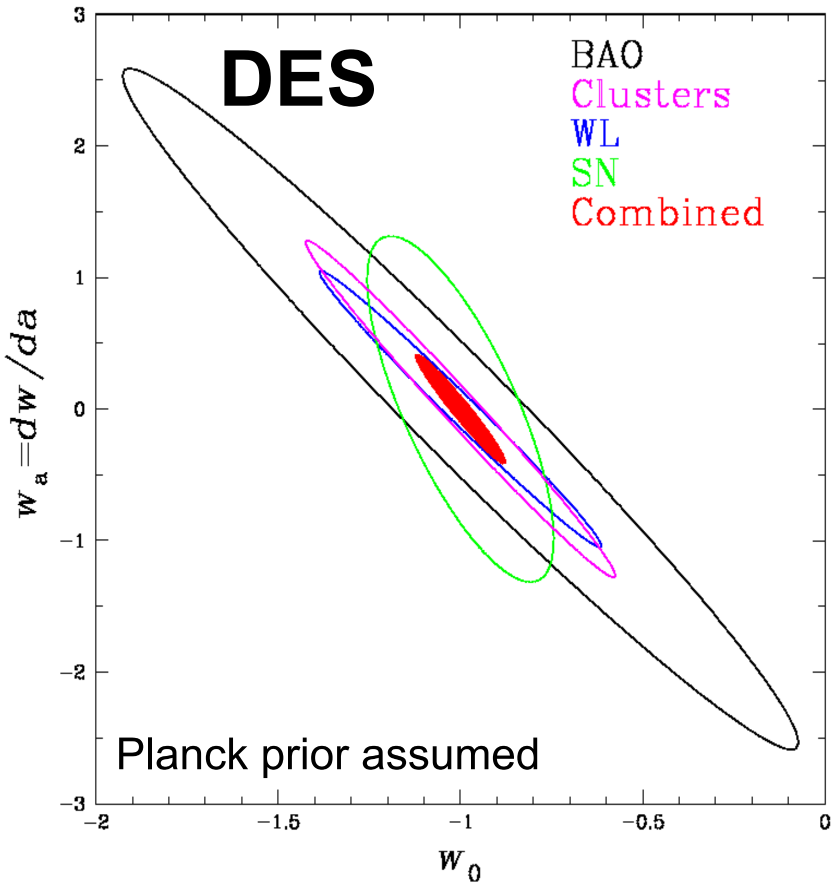
500 million galaxies
5000 deg sq.
$\Delta z_{photo} = 0.03\ (1+z)$
20 bins z range [0.2,1.5]

Cost: 100M$

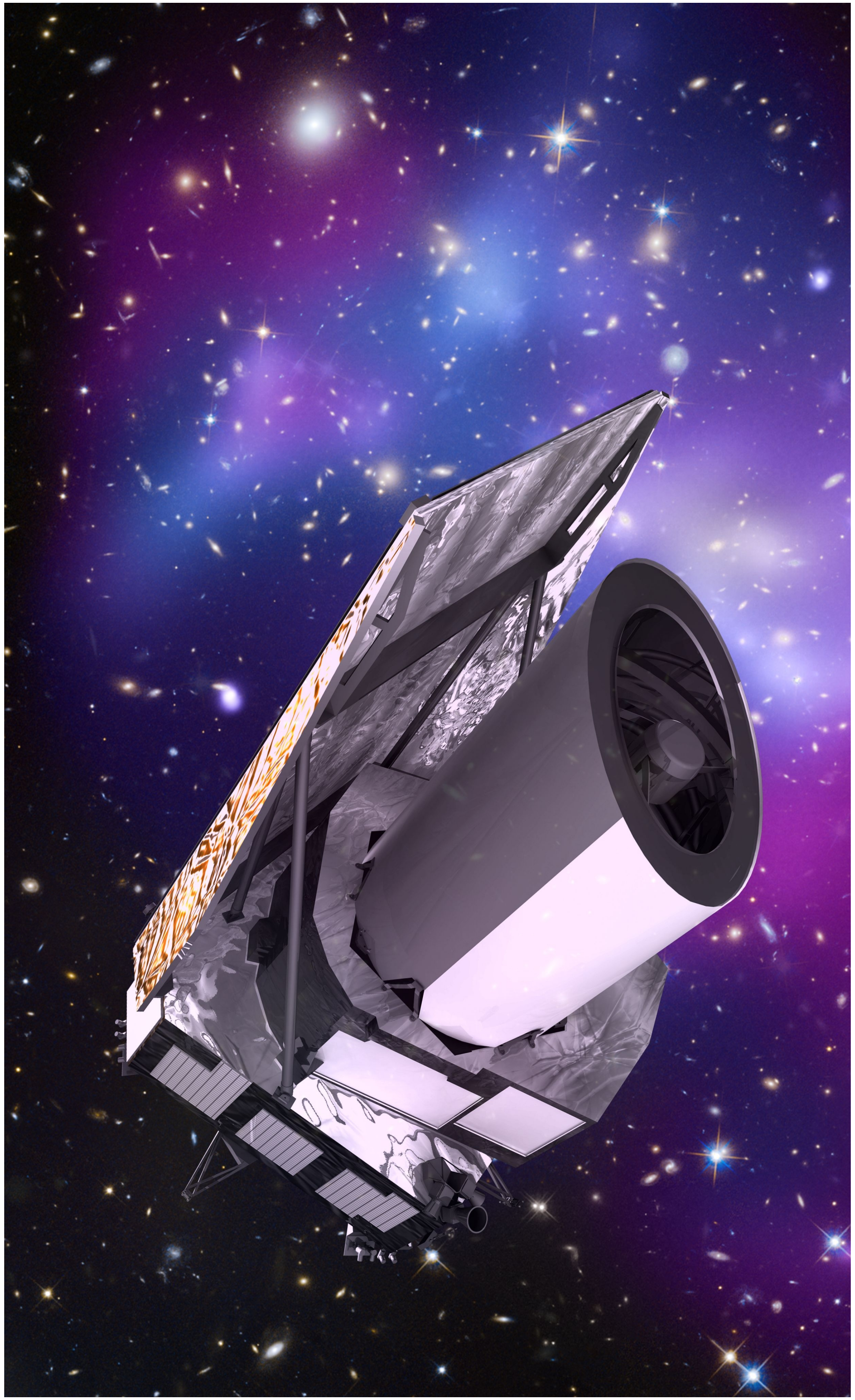
DES Science Reach

Four Probes of Dark Energy

- **Galaxy Clusters**
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry
- **Weak Lensing**
  - Shape measurements of 200 million galaxies
  - Sensitive to growth of structure and geometry
- **Baryon Acoustic Oscillations**
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- **Supernovae**
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry



Factor 3-5 improvement over Stage II DETF Figure of Merit



esa

EUCLID

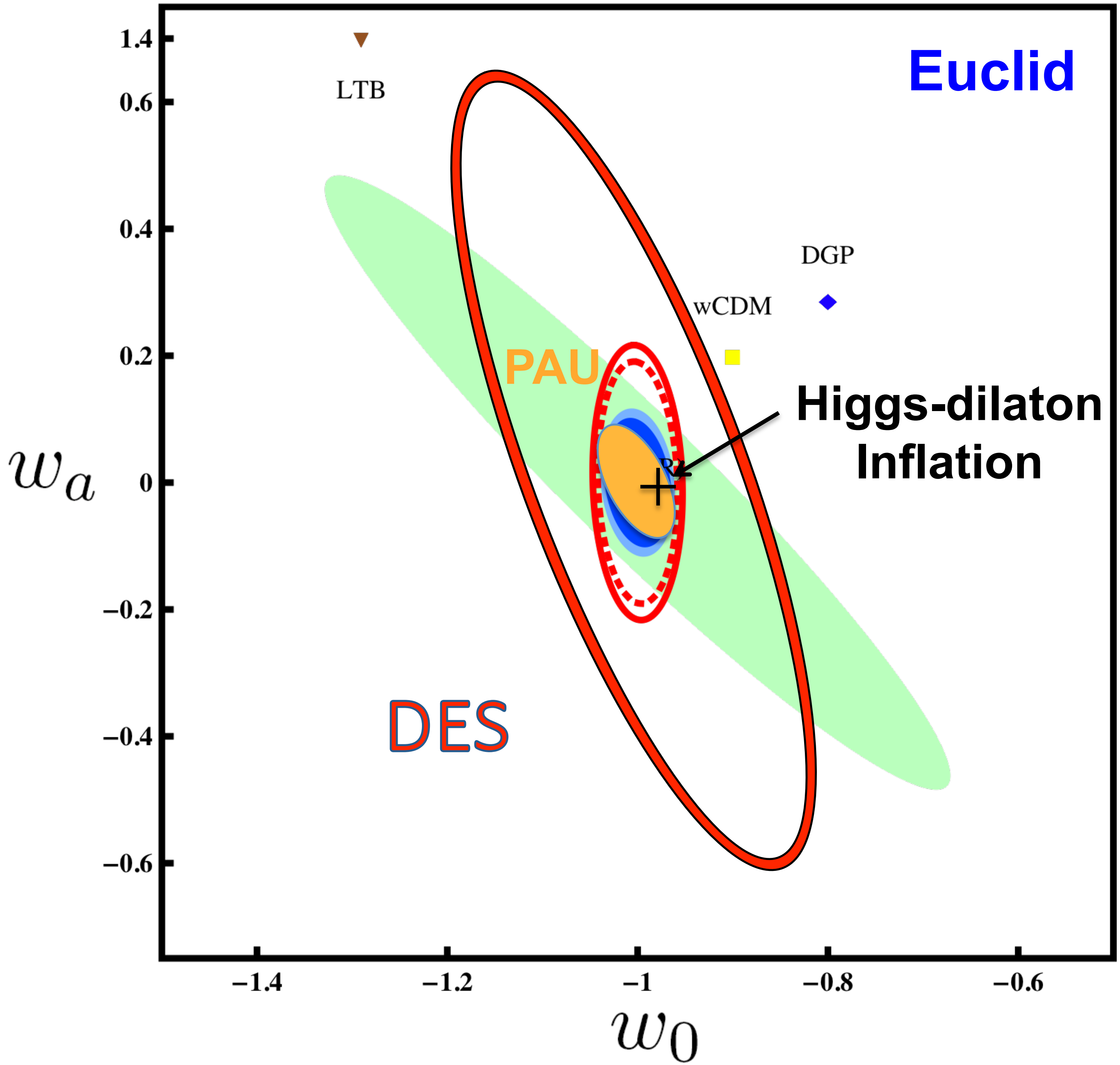
Spectroscopic survey

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

Cost: 1B$

Imaging survey

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



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

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: $1-n_s = 3(1+w)$