VACUUM STABILITY AND THE HIGGS BOSON

Lattice 2013

August 2nd, Mainz

J.R.Espinosa
ICREA, IFAE
Barcelona

ICREA Institució Catalana de Recerca i Estudis Avançats

IFAE

VACUUM STABILITY AND THE HIGGS BOSON

- Status after first LHC run
  Higgs discovered, no trace of BSM...
- $M_h \simeq 125$ GeV ⇨ EW vacuum unstable
- Several implications of this instability
- Lattice analyses?
- Conclusions.

REFERENCES

EARLY WORK ON VACUUM INSTABILITY

I. Krive, A. Linde '76

N. Krasnikov '78

L. Maiani, G. Parisi, R. Petronzio '78 + N. Cabibbo '79

H. Politzer, S. Wolfram '79

P. Hung '79

A. Linde '80

M. Lindner '86 + M. Sher, H. Zaglauer '89

+ ... many more

REFERENCES

RECENT PRECISION STUDIES

... +

M. Holthausen, K.S. Lim, M. Lindner [ph/1112.2415]

J. Elias-Miró, JRE, G.F. Giudice, G. Isidori, A. Riotto, A. Strumia [ph/1112.3022]

F. Bezrukov, M.Y. Kalmykov, B.A. Kniehl, M. Shaposhnikov [ph/1205.2893]

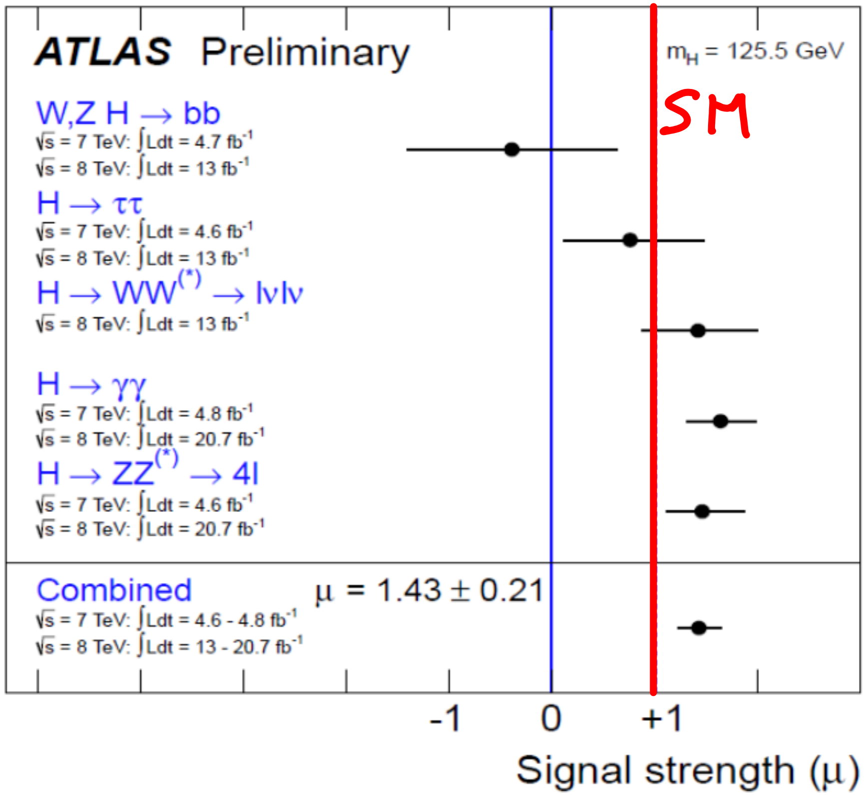
G. Degrassi, S. Di Vita, J. Elias-Miró, JRE, G.F. Giudice, G. Isidori, A. Strumia [ph/1205.6497]

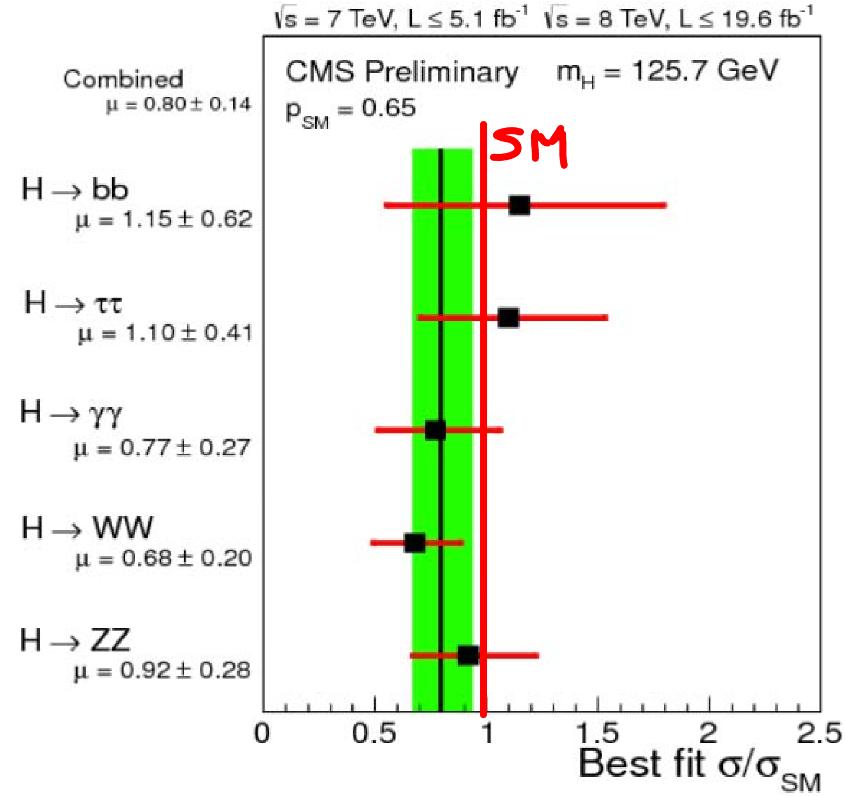
S. Alekhin, A. Djouadi, S. Moch [ph/1207.0980]

D. Buttazzo, G. Degrassi, P. Giardino, G. Giudice, F. Sala, A. Salvio, A. Strumia [ph/1307.3536]

BSM STATUS

- Higgs discovered, close to SM-like





Mh/GeV = 125.5 + 0.2 (stat) + 0.5/-0.6 (syst) ATLAS
Mh/GeV = 125.7 + 0.3 (stat) + 0.3 (syst) CMS

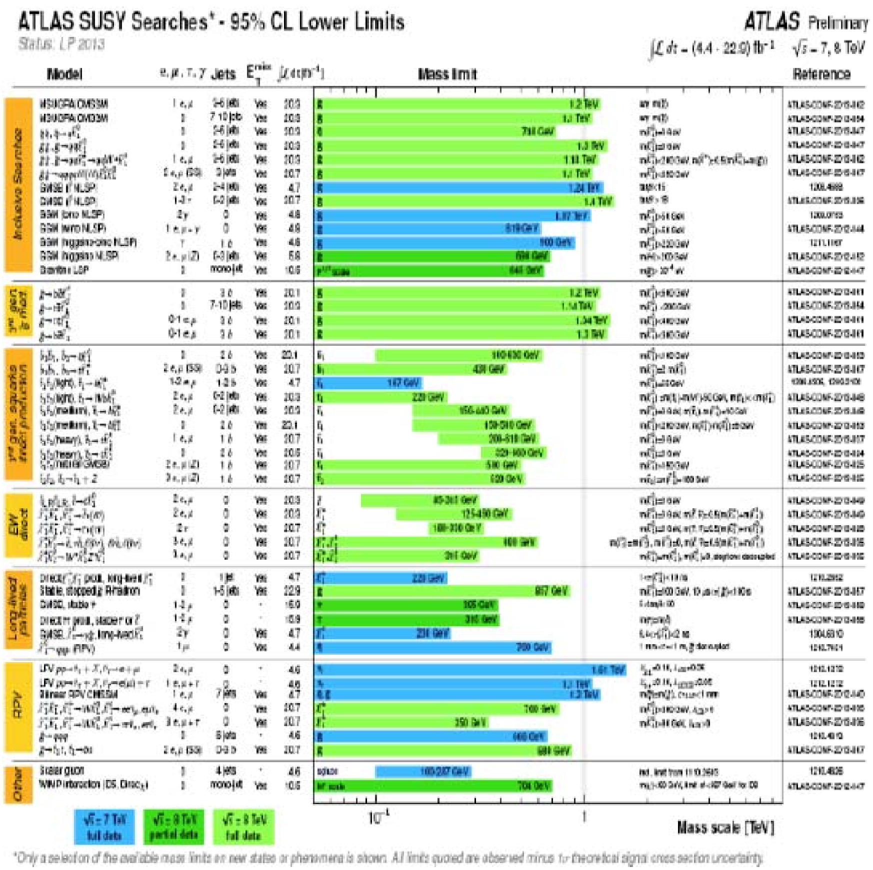
→ Lucia Masetti's talk

BSM STATUS

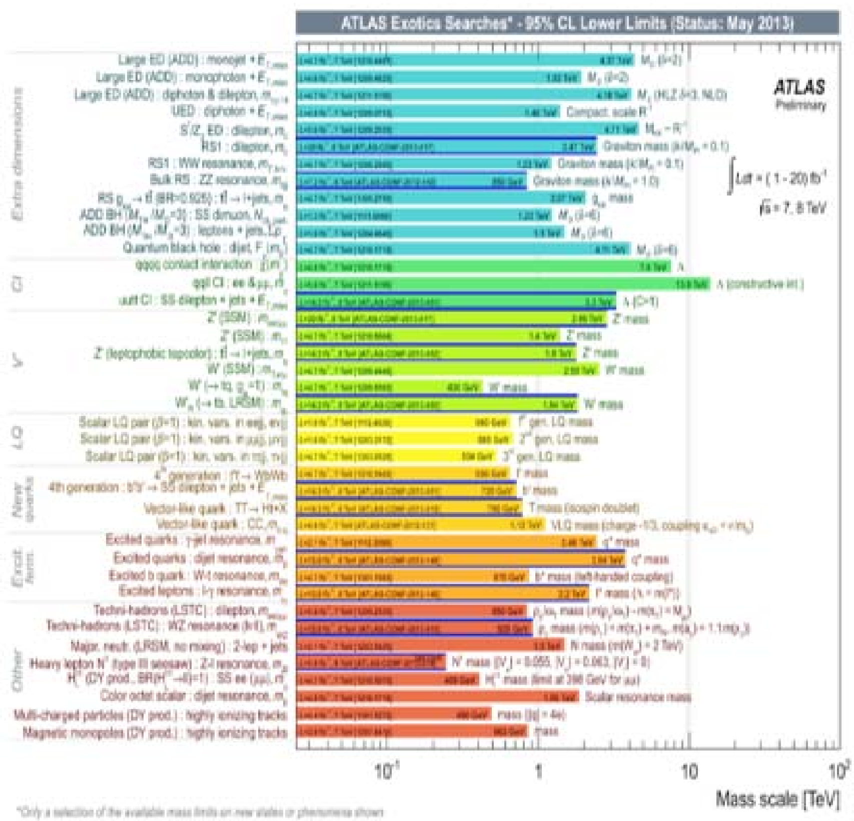
- No trace of BSM so far ⇨ $\Lambda >$ few TeV ?

→ Lucia Masetti's talk

"TSUNAMI" EXCLUSION PLOTS



SUSY



EXOTICS

BSM STATUS

- Higgs discovered, close to SM-like

+

- No trace of BSM so far ⇨ $\Lambda >$ few TeV ?

+

- Holding on to naturalness

⇩

$\Lambda \sim$ few TeV

BSM STATUS / THIS TALK

- Higgs discovered, close to SM-like

+

- No trace of BSM so far ⇒ $\Lambda \gg$ few TeV ?

+

- Disregarding naturalness

⇓

$\Lambda \sim M_{Pl}$?

$M_H \sim 125$ GeV. Implications for Stability

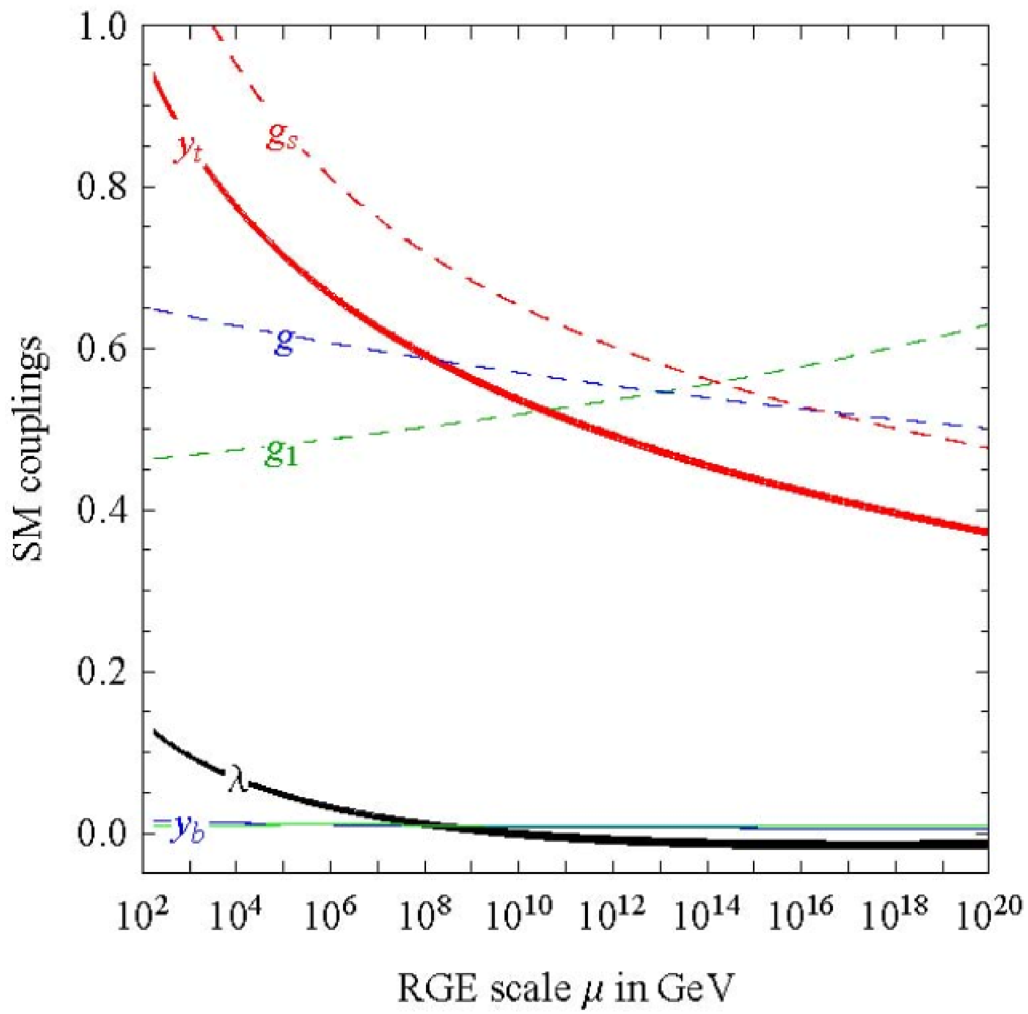
Assume Higgs has SM props. and no BSM Physics

All SM parameters known

$$M_h \Rightarrow \lambda(EW)$$

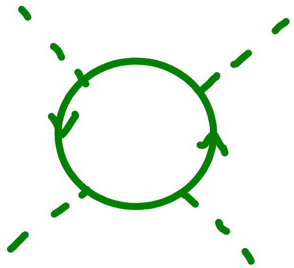
Forgetting naturalness, can the pure SM be valid up to M_{Pl}?

Weakly coupled up to M_{Pl}



VACUUM INSTABILITY

$$\frac{d\lambda}{d\ln Q} \sim -\frac{h_t^4}{16\pi^2}$$

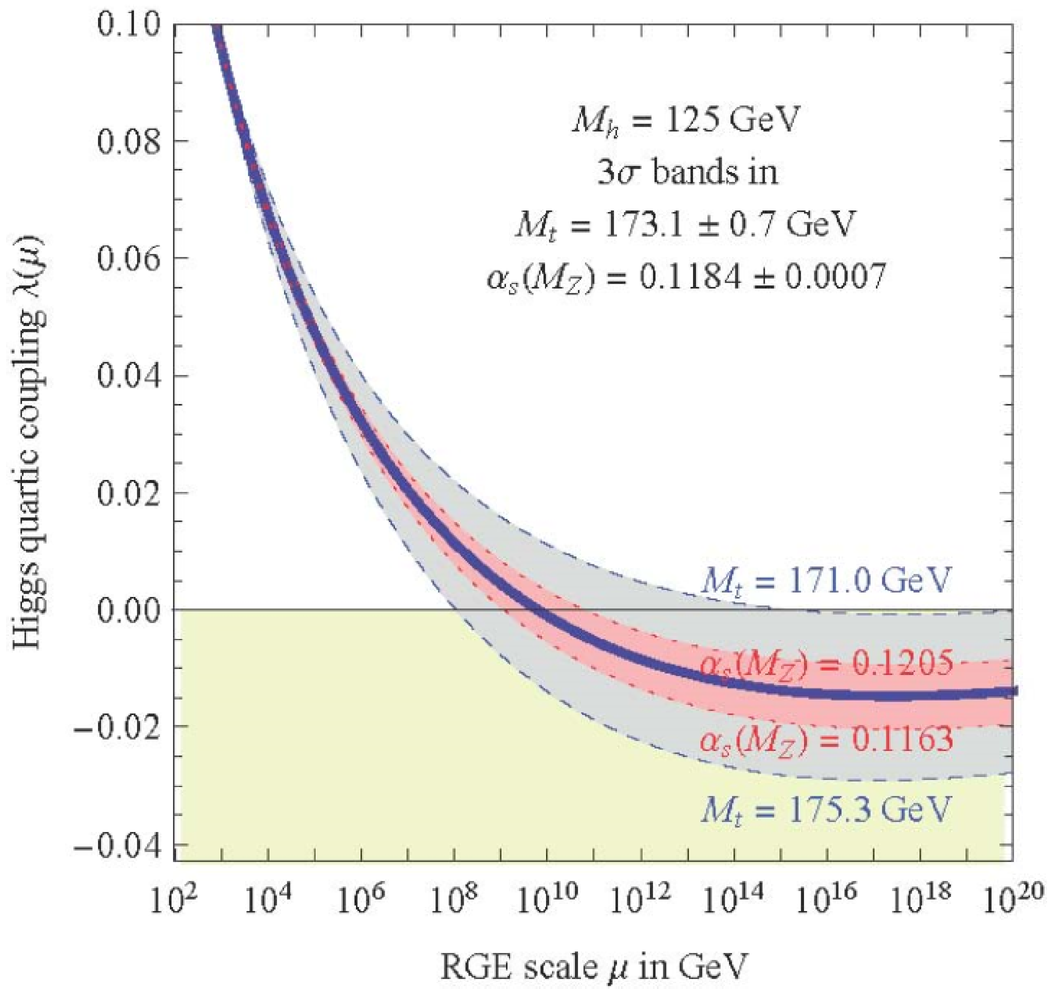


$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

$\Downarrow$

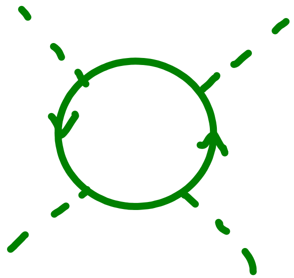
Higgs potential instability

$$V(\phi \gg M_t) \simeq \frac{1}{4}\lambda(Q \simeq h)\, h^4$$



VACUUM INSTABILITY

$$\frac{d\lambda}{d\ln Q} \sim -\frac{h_t^4}{16\pi^2}$$

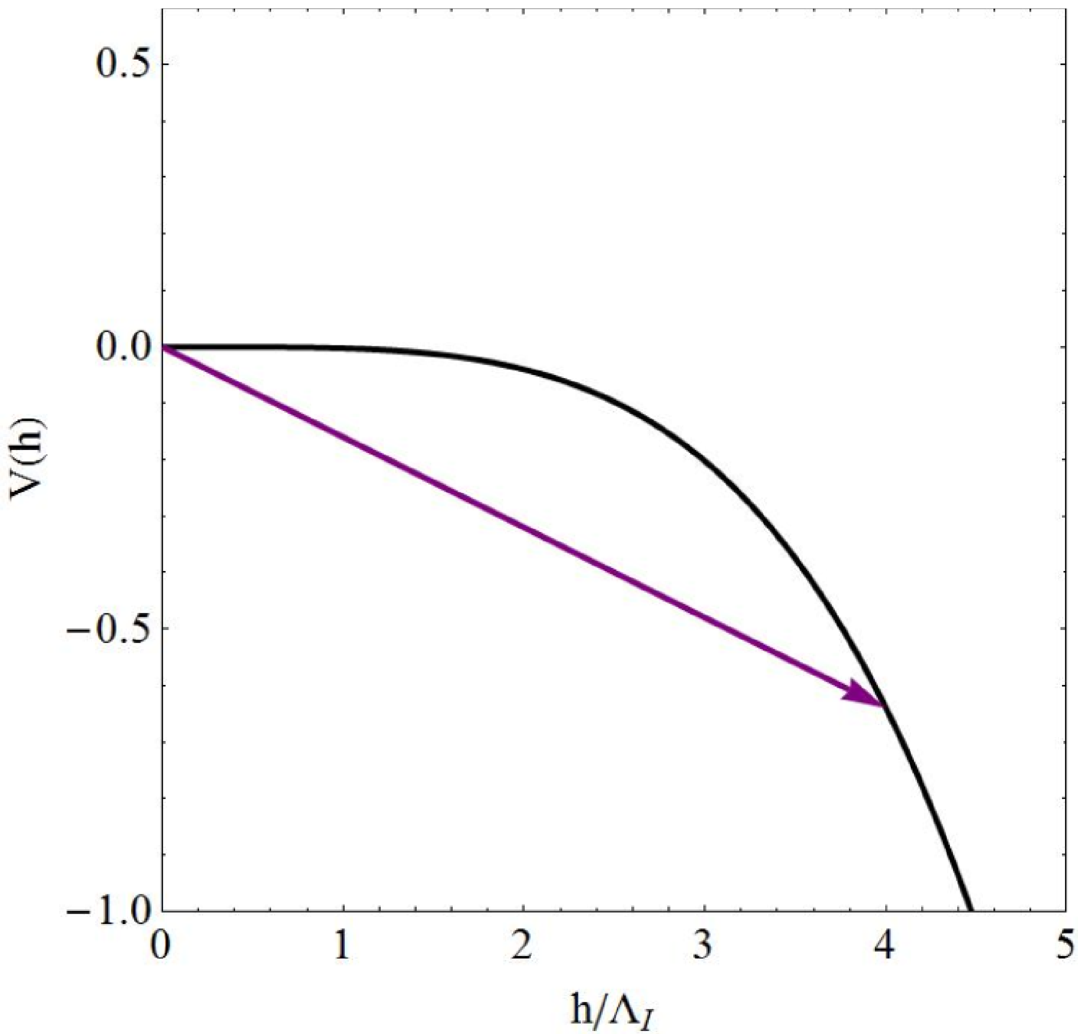


$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

⇓

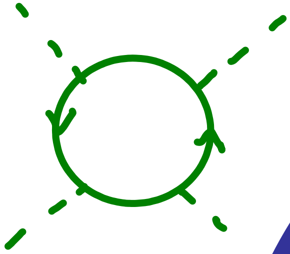
Higgs potential instability

$$V(\phi \gg M_t) \simeq \frac{1}{4}\lambda(Q \simeq h)\, h^4$$



VACUUM INSTABILITY

$$\frac{d\lambda}{d\ln Q} \sim -\frac{h_t^4}{16\pi^2}$$

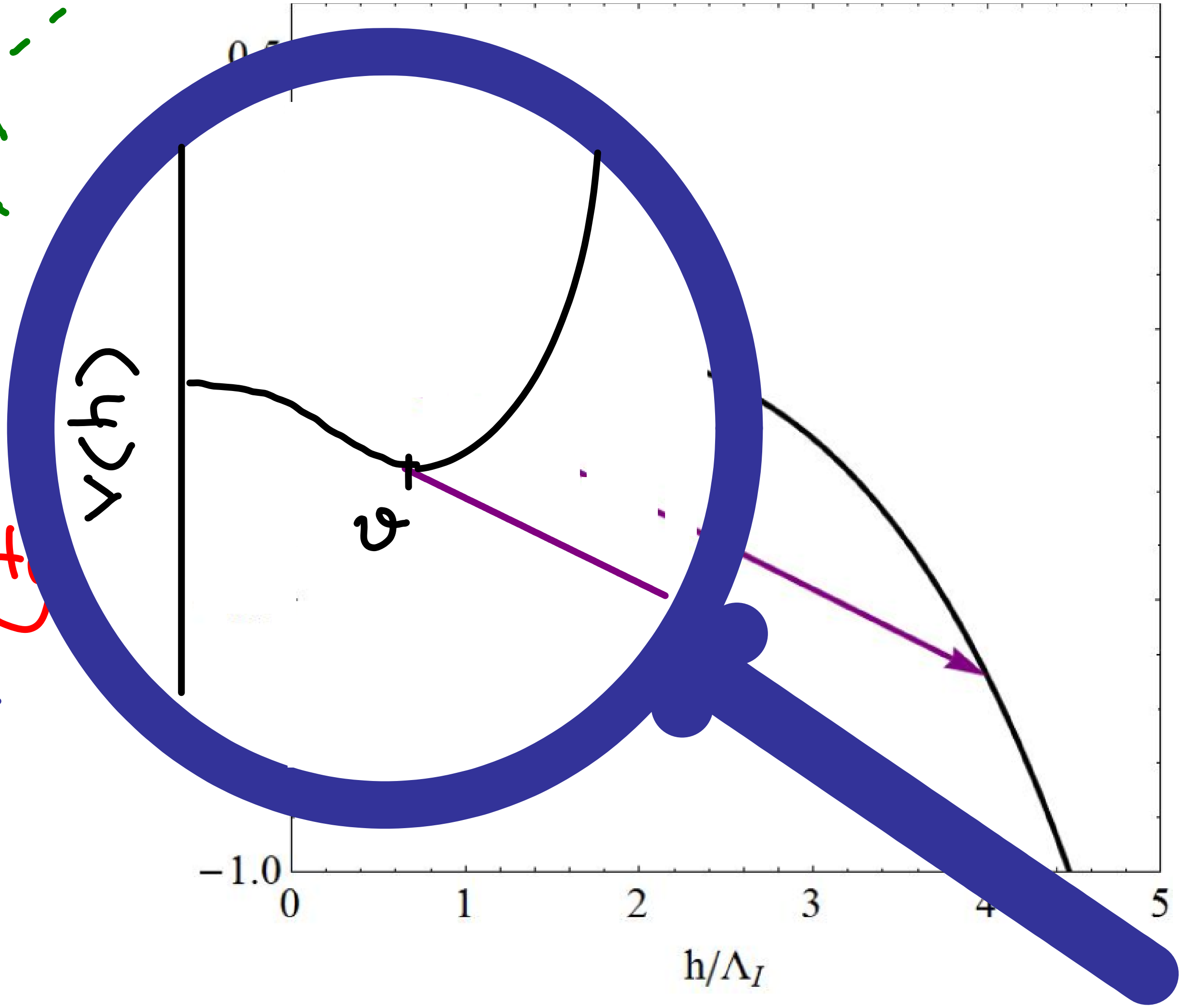


$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

⇓

Higgs potential instability

$$V(\phi \gg M_t) \simeq \frac{1}{4}\lambda(Q \simeq h)\, h^4$$



LIFE IN A METASTABLE VACUUM

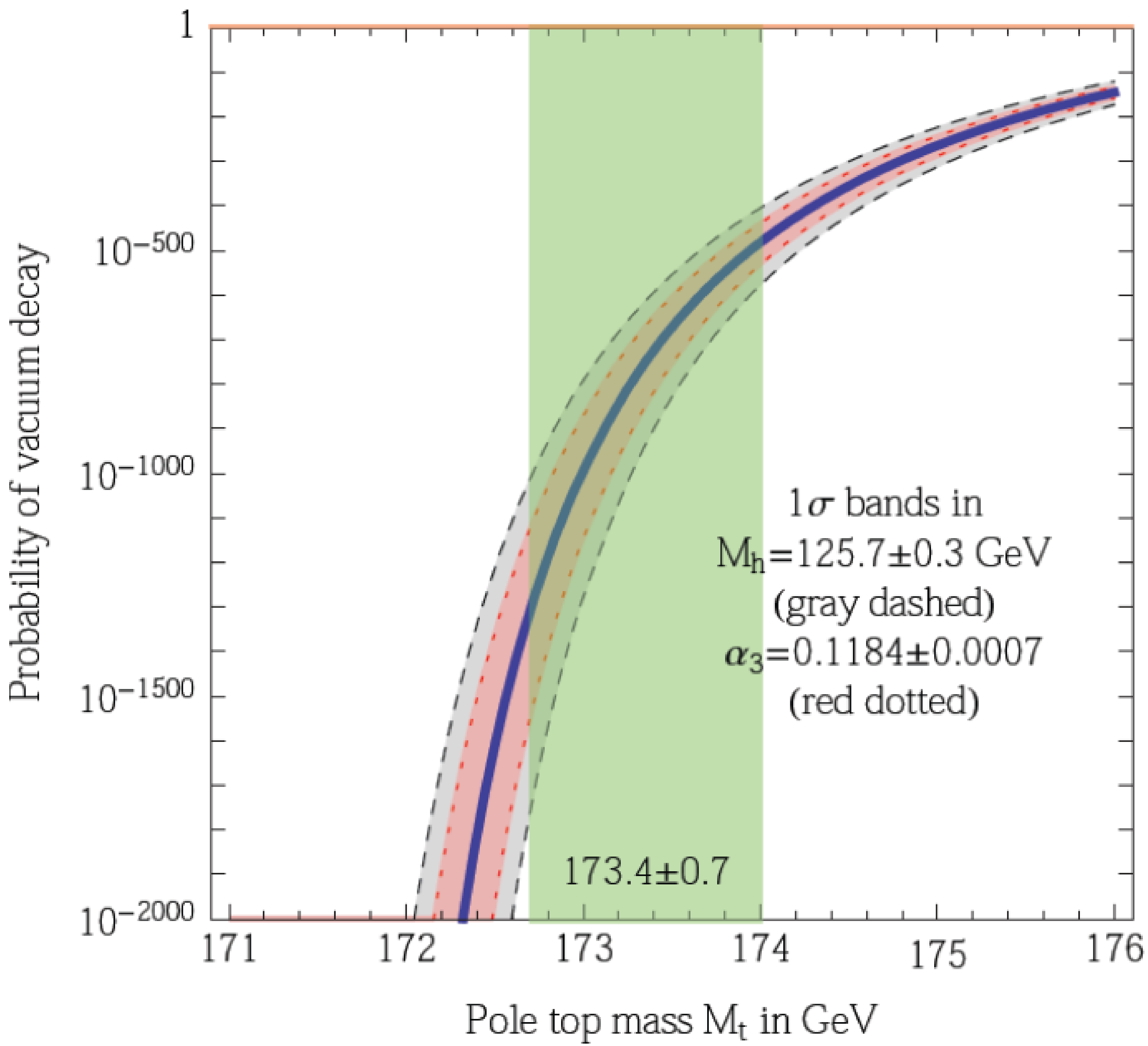
$$p = \text{Decay prob.} = \underbrace{\frac{\text{Decay rate}}{\Delta t \cdot \Delta V}}_{h^4 e^{-S_4}} \tau_U^4 \quad \text{with} \quad \tau_U^4 \sim \left(e^{140}/M_{Pl}\right)^4$$

$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|\lambda|/0.01}\right]$$

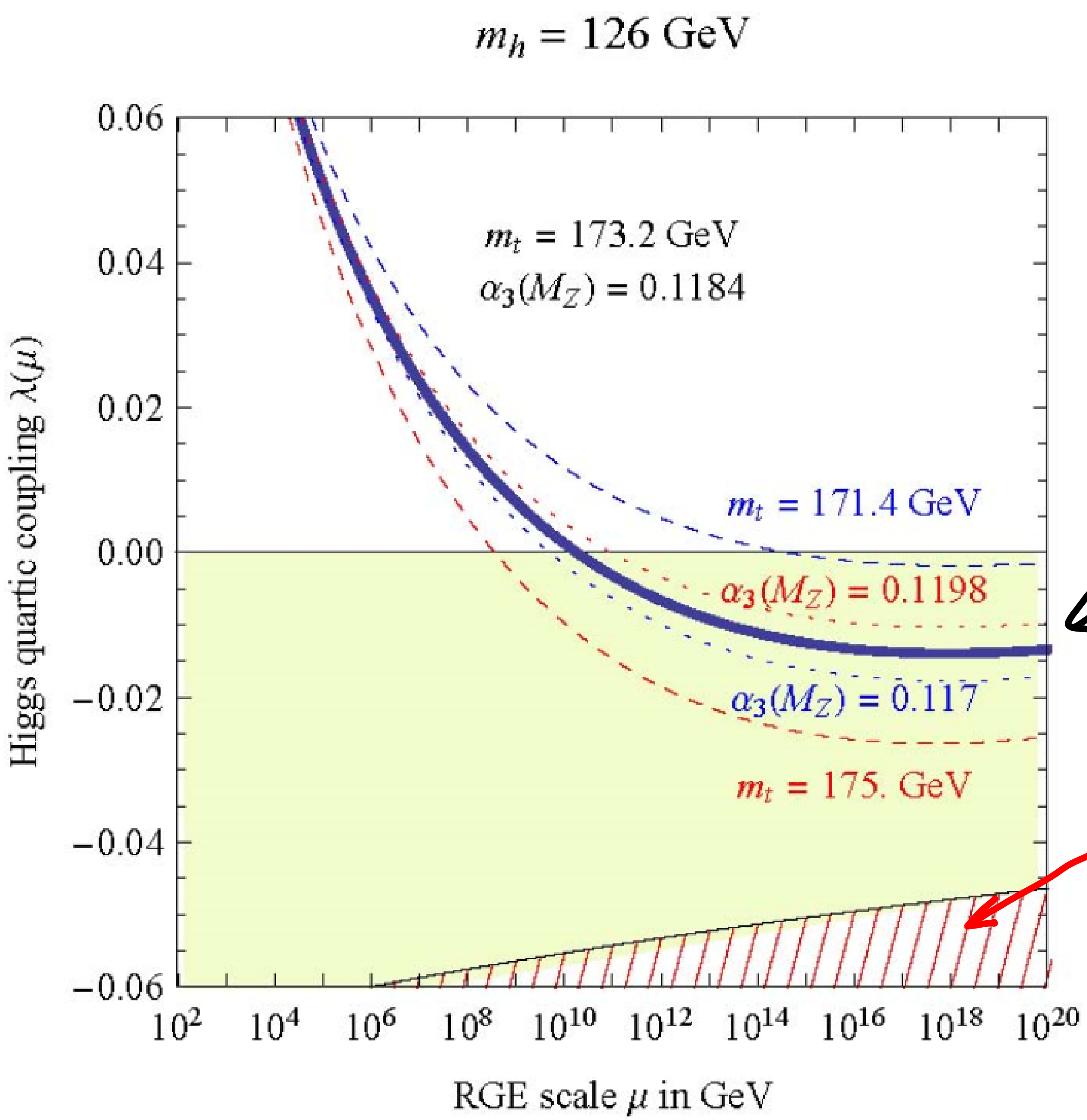
easily wins over τ_U^4

$p \lll 1$: Lifetime of EW vacuum much longer than τ_U

PROBABILITY OF VACUUM DECAY



LIFE IN A METASTABLE VACUUM

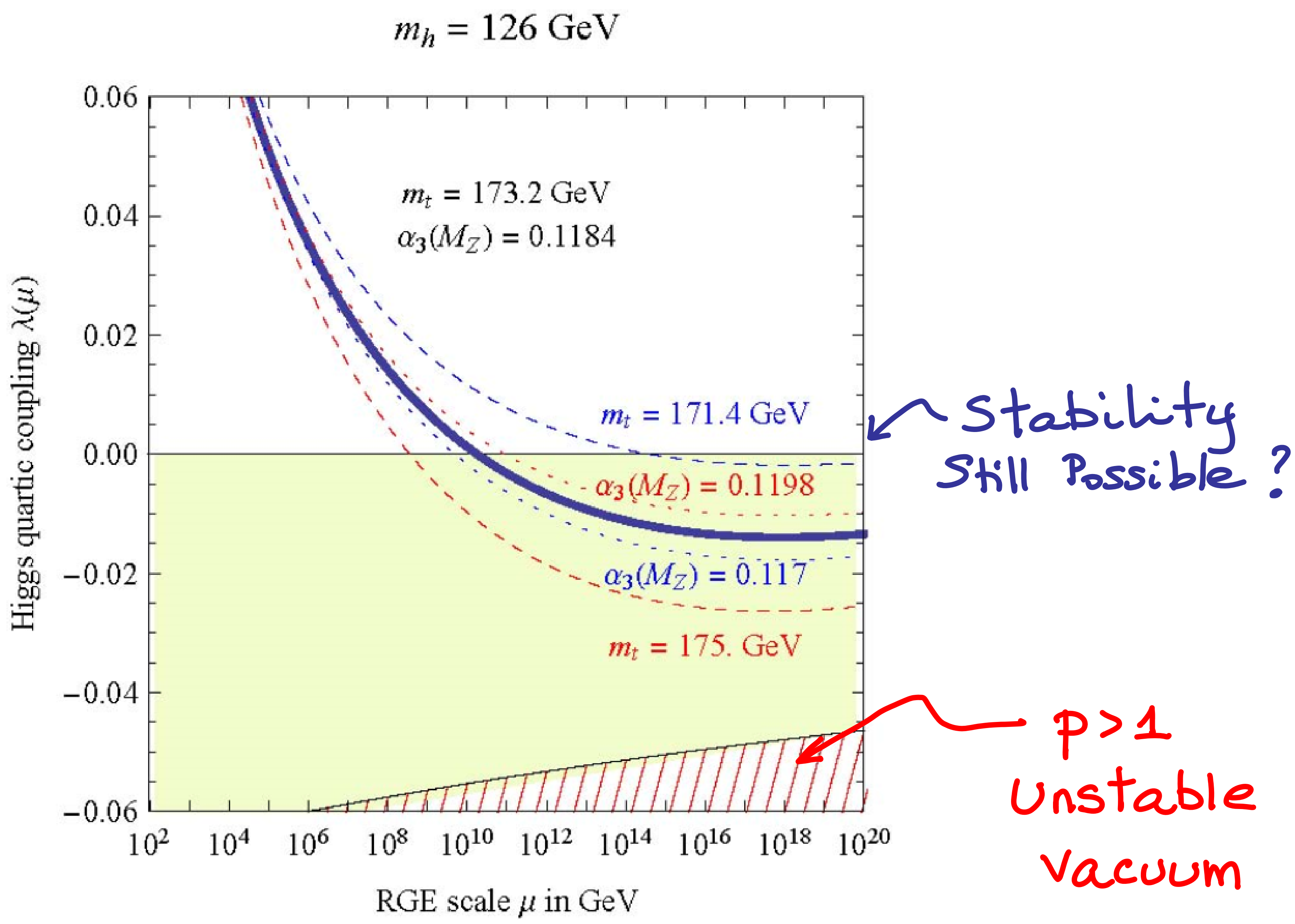


Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

$p > 1$
Unstable
Vacuum

LIFE IN A METASTABLE VACUUM



NNLO STABILITY BOUND

Lower bound on M_h for stability up to M_{Pl} :

State-of-the-art NNLO calculation:

- 2-loop V_{eff} (Ford, Jack, Jones [ph/0111190])
- 3-loop RGEs (..., Chetyrkin, Zoller [ph/1205.2892], Bednyakov, Pikelner, Velizhanin [ph/1212.6829])
- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$
  (..., Shaposhnikov et al [ph/1205.2893],
  , Degrassi et al [ph/1205.6497],
  , Buttazzo et al [ph/1307.3536])

NNLO STABILITY BOUND

For stability up to M_{Pl} :

$$M_h\,[\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t(\mathrm{GeV}) - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{th}$$

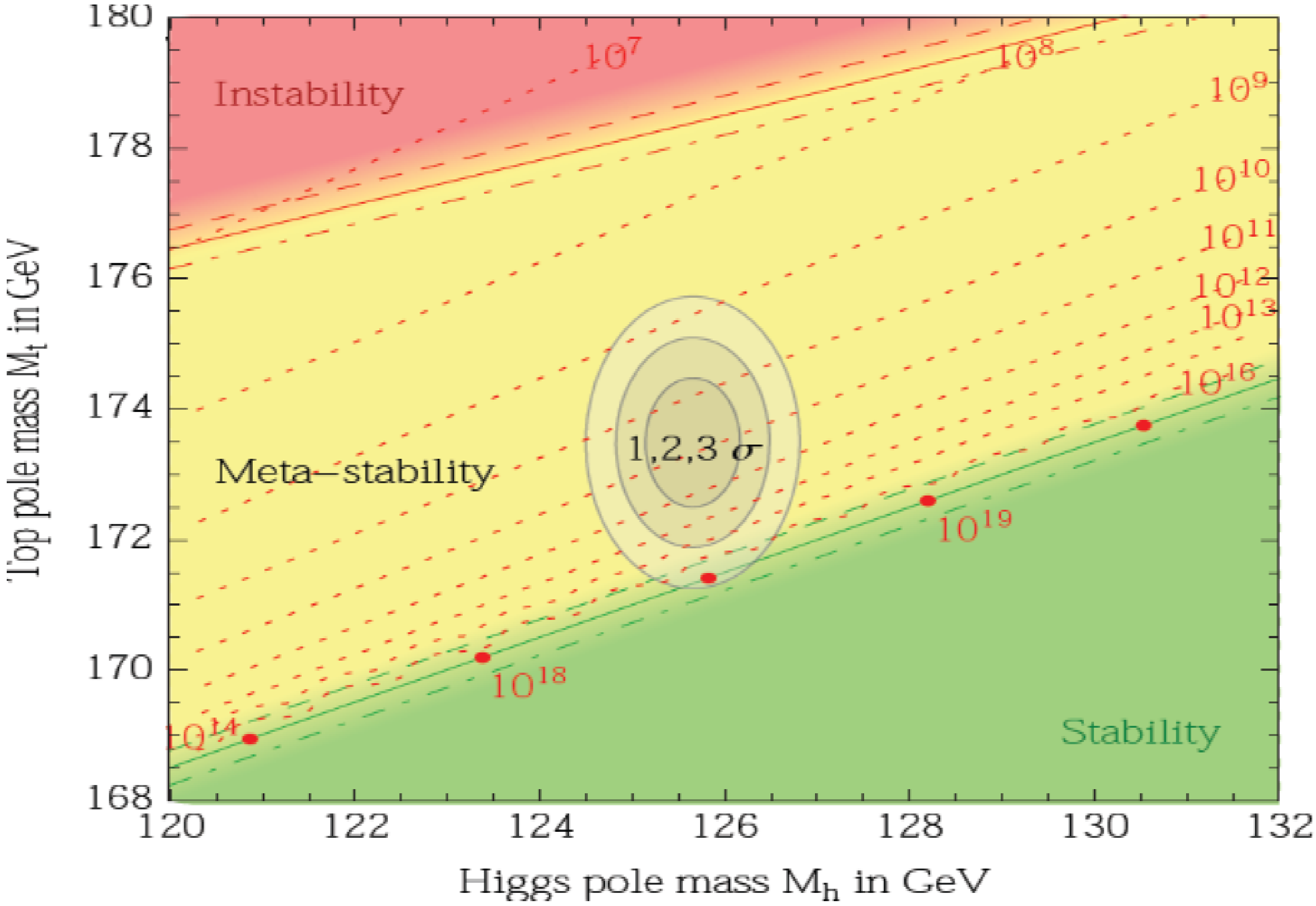
Degrassi et al '12

$$M_h\,[\mathrm{GeV}] > 129.6 + 2\left(\frac{M_t(\mathrm{GeV}) - 173.35}{1}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{th}$$

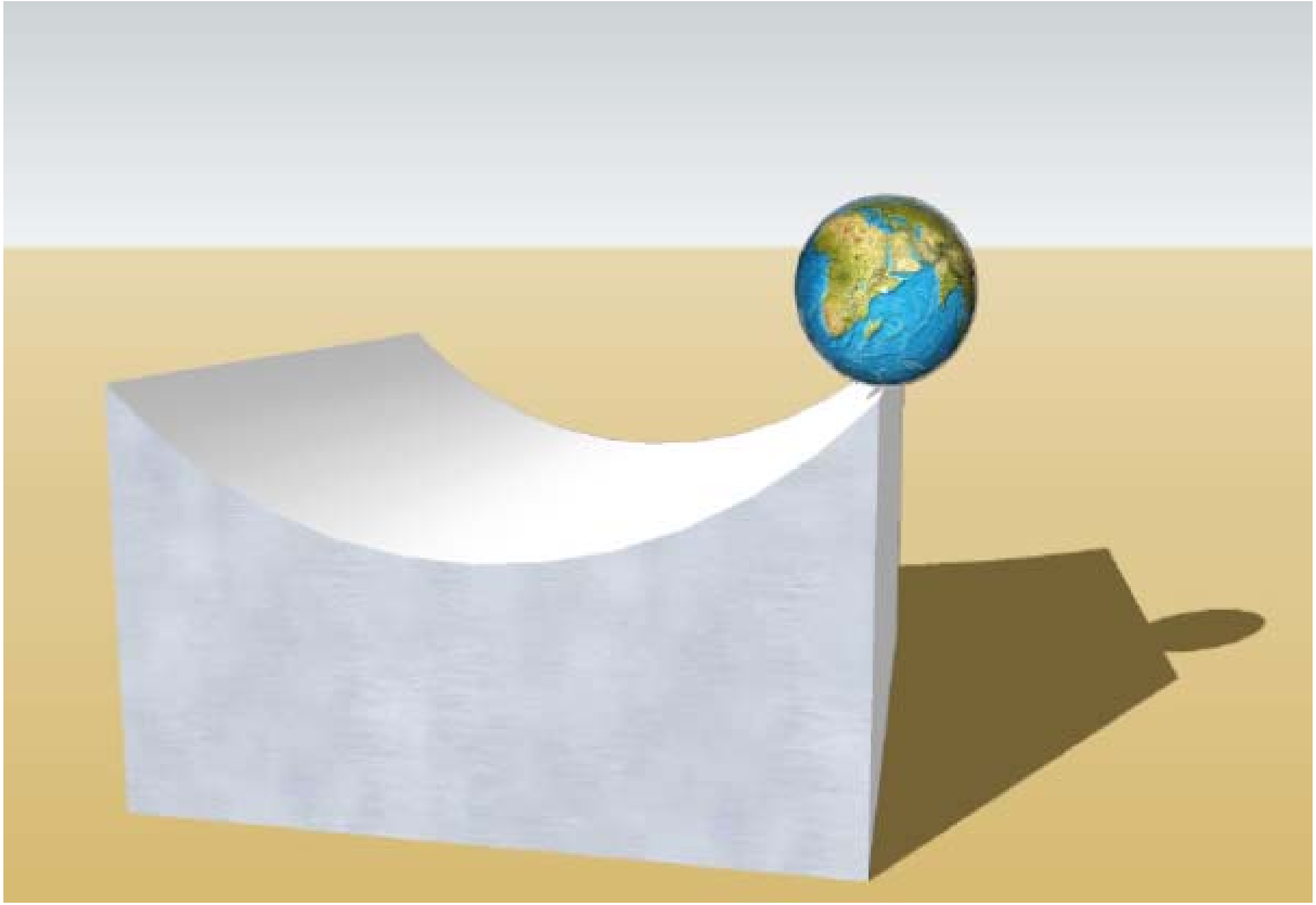
Buttazzo et al '13

Both reduced previous theory error by a factor 3

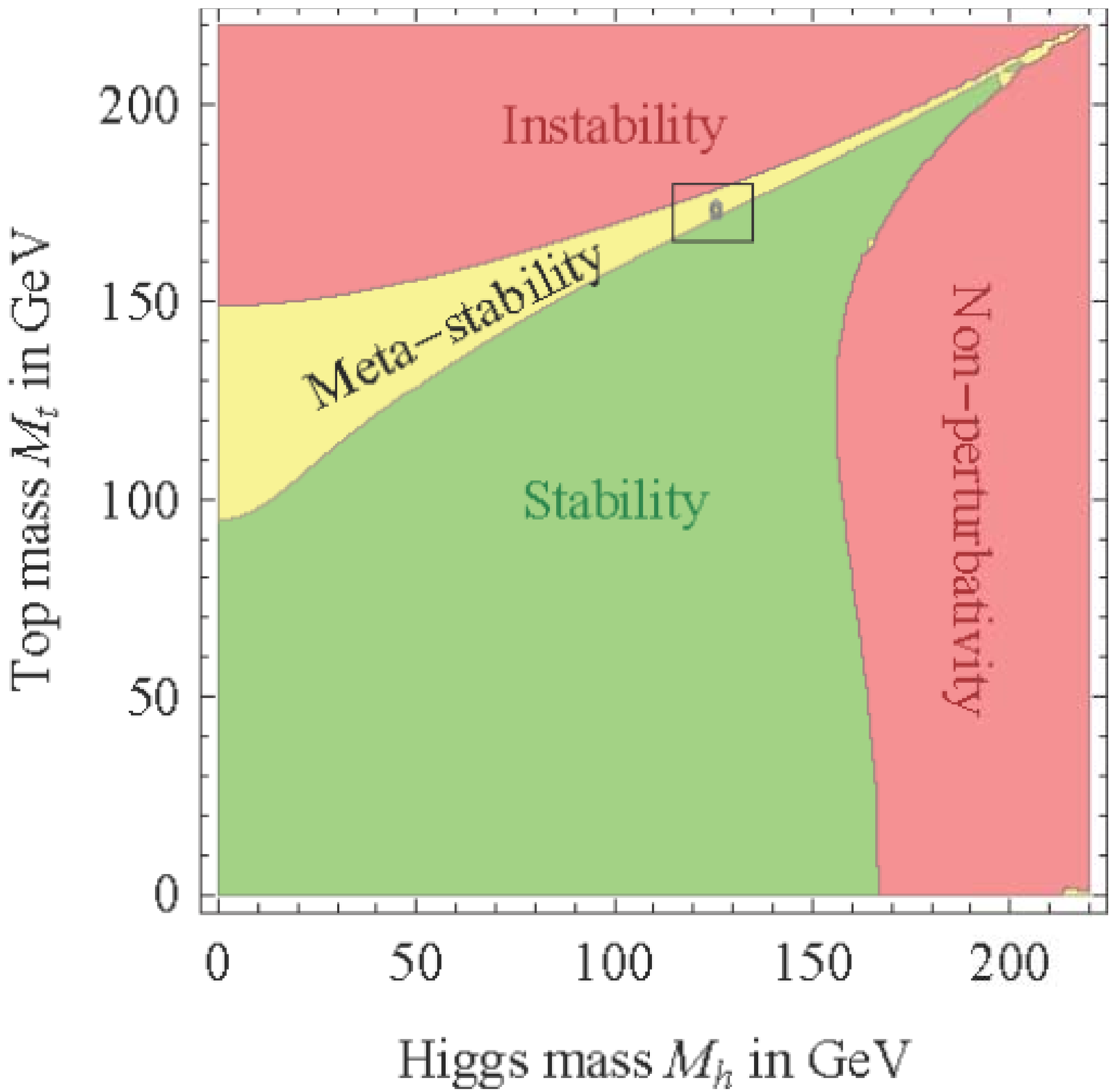
LIVING AT THE EDGE



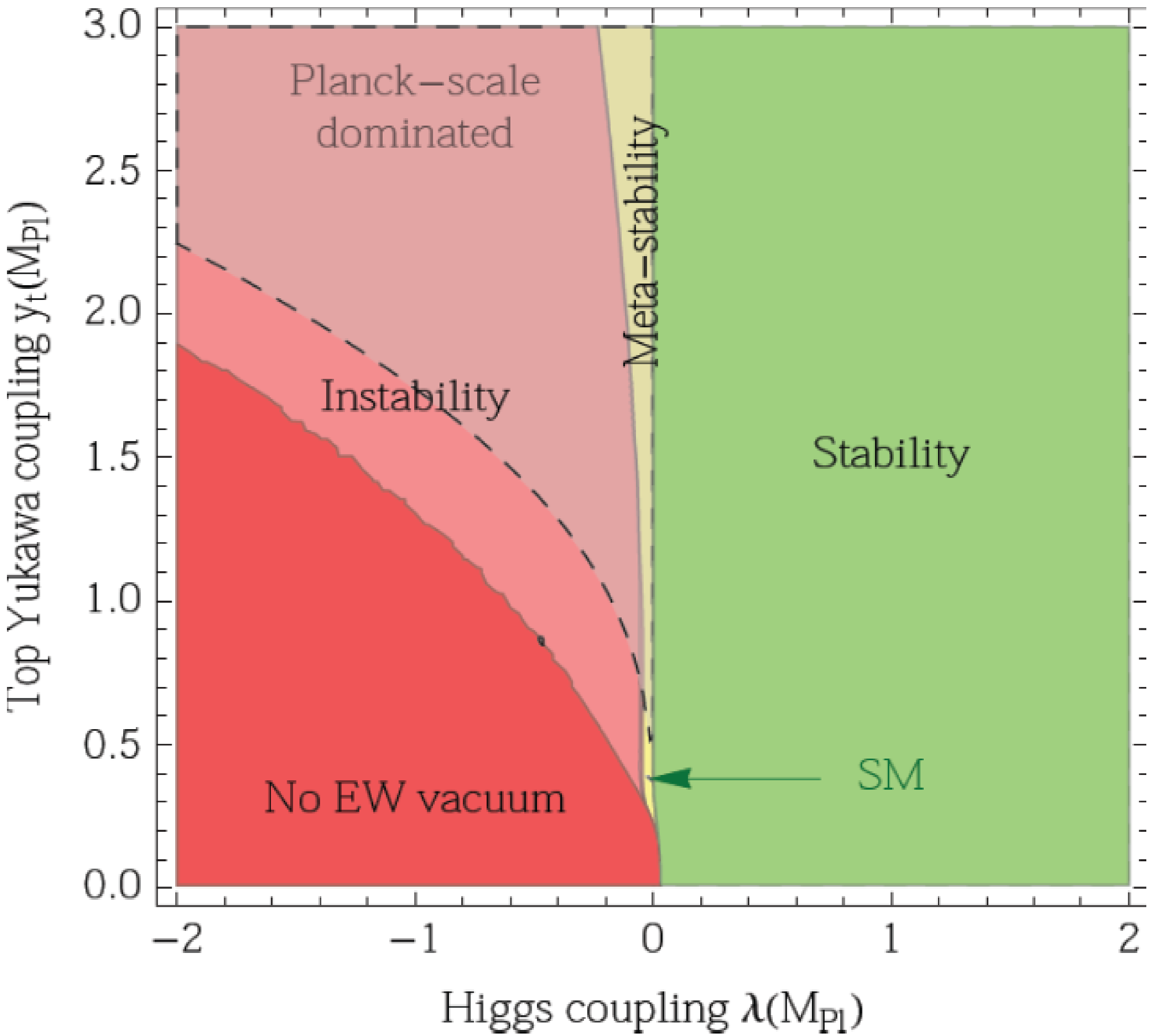
LIVING AT THE EDGE



LIVING AT THE EDGE



LIVING AT THE EDGE

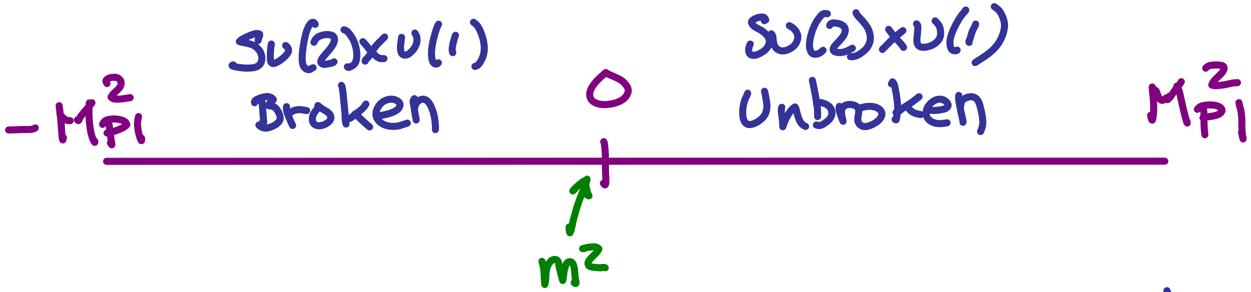


NEW KNOWLEDGE BRINGS NEW QUESTIONS

★ Why do we live near the critical boundary for stability?

$$\lambda(M_{Pl}) \simeq 0$$

★ Is this related to our living near the phase boundary $m^2/M_{Pl}^2 \simeq 0$?



★ Is the EW scale determined by Planck scale physics?

★ Or is this just a coincidence? BSM...

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

IRRELEVANT

MAKE IT WORSE

CURE IT

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

Example

IRRELEVANT

See-saw neutrinos

MAKE IT WORSE

CURE IT

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

Example

IRRELEVANT — See-saw neutrinos

MAKE IT WORSE — See-saw neutrinos

CURE IT

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

	Example
IRRELEVANT	See-saw neutrinos
MAKE IT WORSE	See-saw neutrinos
CURE IT	See-saw neutrinos

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

	Example
IRRELEVANT	See-saw neutrinos $M_R \lesssim 10^{13}\,\text{GeV}$
MAKE IT WORSE	See-saw neutrinos $M_R \gtrsim 10^{13}\,\text{GeV}$
CURE IT	See-saw neutrinos $M_R \sim \langle S \rangle$ & $\lambda_{HS} \lvert H\rvert^2 \lvert S\rvert^2$

Lebedev '12, Elias-Miro et al. '12

LATTICE STABILITY BOUNDS

All couplings are weak

⇒ the perturbative approach should be reliable.

What has been done:

Lower bound on M_h associated with $\lambda(\Lambda) \to 0$

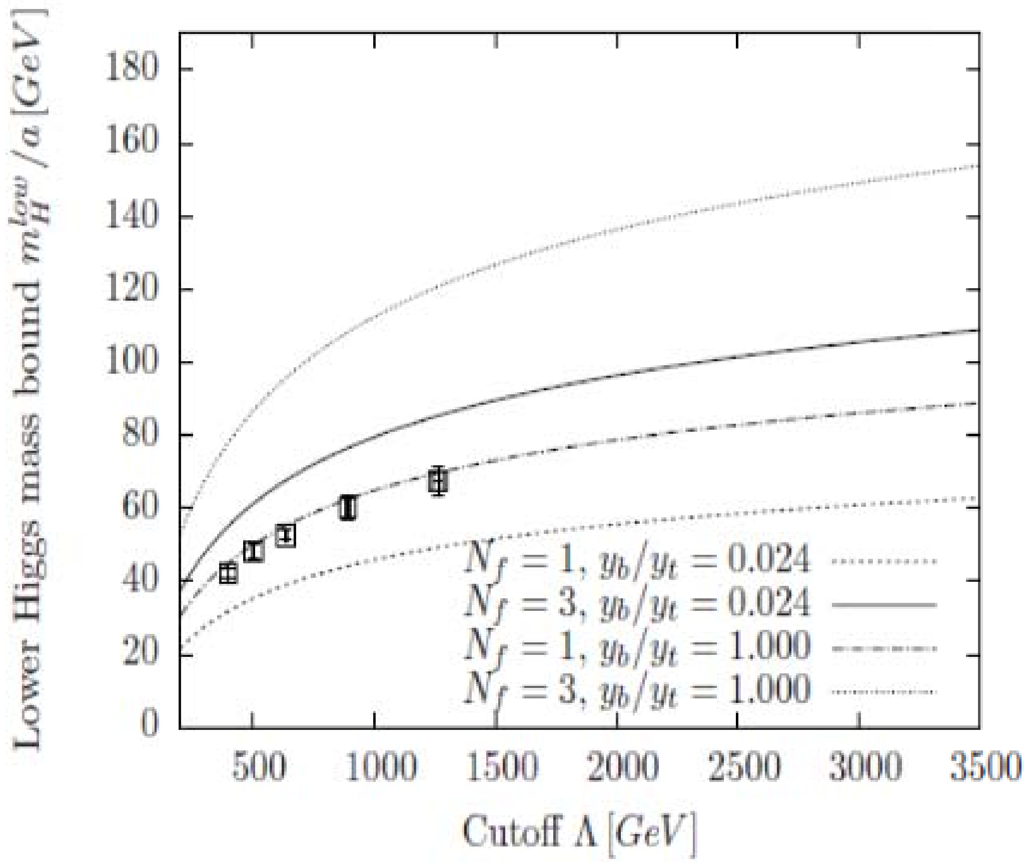
LATTICE STABILITY BOUNDS

State-of-the-art:

Chirally invariant Higgs-Yukawa model

Gerhold, Jansen '09

- $M_{h,stab}(\Lambda)$ from $\lambda(\Lambda)=0$ in lattice pert. theory.
- Xcheck with lattice simulation with $N_f=1$, $y_b/y_t=1$.
- Apply to realistic values $N_f=3$, $y_b/y_t=0.024$.
- Bound a bit higher than in cont. pert. approach (expected)



See also Fodor, Holland, Kuti, Nogradi, Schroeder '07

LATTICE STABILITY BOUNDS

What could be done next:

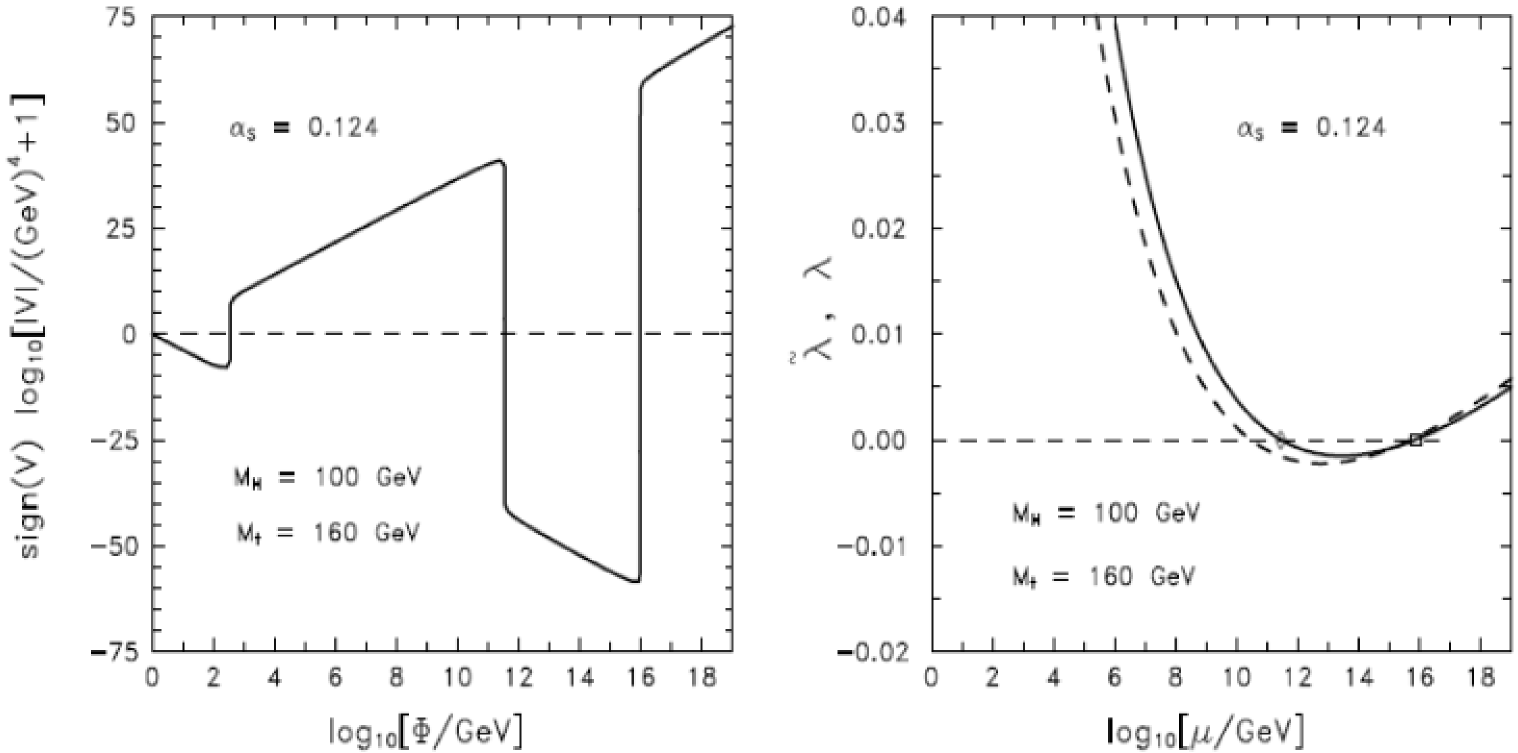
- Study the tunneling out of the EW vacuum.

That's truly non-perturbative!

But the need to have $\lambda(\Lambda) < 0$ is an obstacle to see the second vacuum in the lattice...

LATTICE STABILITY BOUNDS

In the SM, g_i couplings can compensate the destabilizing effect of h_t



$\lambda(\Lambda) > 0$

LATTICE STABILITY BOUNDS

What could be done next:

- Study the tunneling out of the EW vacuum.

Need some stabilization mechanism:

e.g. $\frac{\lambda}{\Lambda^2}|H|^6$, → Attila Nagy's talk on Monday

new scalar d.o.f.,...

- Interesting to study these mechanisms by their own sake.

CONCLUSIONS

We finally have data to explore the physics of electroweak symmetry breaking!

★ $M_h \simeq 125\,\text{GeV}$ ⇒ Unstable EW vacuum w/o BSM

Long-lived and intriguingly close to stability boundary

This instability has implications for cosmology, BSM, ...

★ Lattice studies ?

Tunneling and stabilization mechanisms

But, let's hope for natural BSM @ LHC14 !

To Honor Johannes Gutenberg

Slides handwritten on a tablet PC

TOP MASS CAVEATS

Have assumed

$$M_t = 173.1 \pm 0.7 \text{ GeV}$$

from Tevatron+LHC is the top pole mass.

Theoretically cleaner determination from $\sigma(t\bar{t})$ but larger error

$$M_t = 173.3 \pm 2.8 \text{ GeV}$$

would still allow for stability

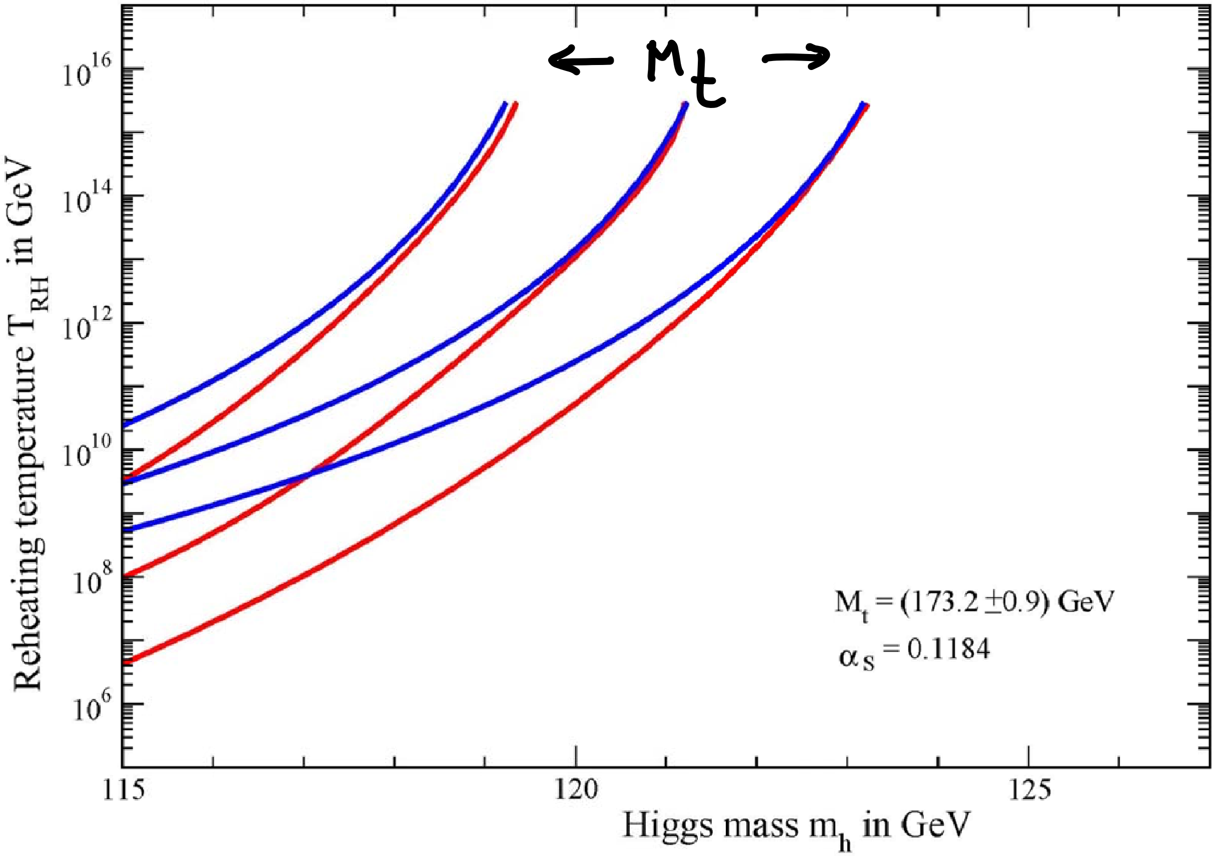
Alekhin, Djouadi, Moch'12

Too conservative given the good agreement...
and the expected size of $\Delta M_t \simeq \Lambda_{QCD}$

OTHER IMPLICATIONS

- Cosmology :

  Thermal fluctuations can induce vacuum decay



Bound on T_{RH} ?

OTHER IMPLICATIONS

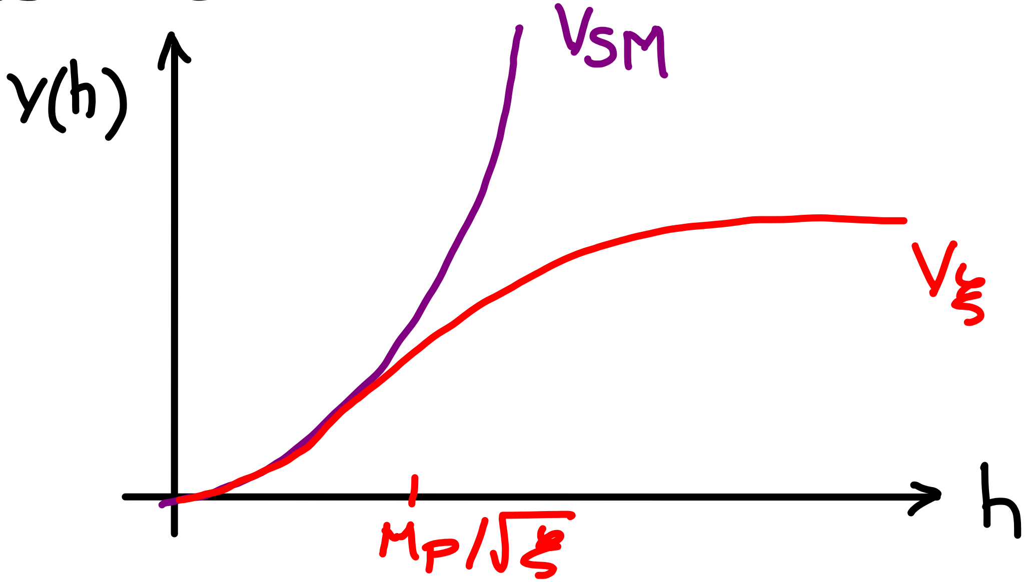
- Cosmology: Higgs inflation Bezrukov, Shaposhnikov '07

Higgs coupled to gravity as $\mathcal{L} \supset \int \sqrt{-g}\, \xi |H|^2 R$

coupling removed by $g_{\mu\nu} \to g_{\mu\nu} (1 + \xi h^2/M_P^2)^{-1}$

rescales the potential as

$$V(h) \Rightarrow \frac{V(h)}{(1+\xi h^2/M_P^2)^2}$$



Requires $\xi \sim 10^4$ to give the right spectrum of primordial fluctuations.

(MORE) TROUBLE FOR HIGGS INFLATION

※1 Effective theory with cutoff

$$\Lambda \sim \frac{M_P}{\xi} \ll \Lambda_{HI} \sim \frac{M_P}{\sqrt{\xi}}$$

Can't trust the plateau region

Burgess, Lee, Trott '09. Barbón, JRE '09

※2 Stability up to $\sim 10\,\Lambda_{HI}$ is a must.

Requires marginal values of M_h & M_t

INGREDIENTS NNLO STAB. BOUND

Renormalisation Group Equations

	LO 1 loop	NLO 2 loop	NNLO 3 loop	NNNLO 4 loop
g_3	full [50, 51]	$\mathcal{O}(\alpha_3^2)$ [52, 53] $\mathcal{O}(\alpha_3\alpha_{1,2})$ [58] full [60]	$\mathcal{O}(\alpha_3^3)$ [54, 55] $\mathcal{O}(\alpha_3^2\alpha_t)$ [59] full [61, 62]	$\mathcal{O}(\alpha_3^4)$ [56, 57]
$g_{1,2}$	full [50, 51]	full [60]	full [61, 62]	—
y_t	full [63]	$\mathcal{O}(\alpha_t^2, \alpha_3\alpha_t)$ [64] full [67]	full [65, 66]	—
λ, m^2	full [63]	full [68, 69]	full [70, 71]	—

Threshold corrections at the weak scale

	LO 0 loop	NLO 1 loop	NNLO 2 loop	NNNLO 3 loop
g_2	$2M_W/V$	full [72, 73]	Work in progress	—
g_Y	$2\sqrt{M_Z^2 - M_W^2}/V$	full [72, 73]	Work in progress	—
y_t	$\sqrt{2}M_t/V$	$\mathcal{O}(\alpha_3)$ [74] $\mathcal{O}(\alpha)$ [78]	$\mathcal{O}(\alpha_3^2, \alpha_3\alpha_{1,2})$ [33] full [This work]	$\mathcal{O}(\alpha_3^3)$ [75–77]
λ	$M_h^2/2V^2$	full [79]	for $g_{1,2} = 0$ [4] full [This work]	—
m^2	M_h^2	full [79]	full [This work]	—

OTHER IMPLICATIONS

- See-saw neutrinos: Impact on $\beta_\lambda \supset -y_\nu^4/(16\pi^2)$ *

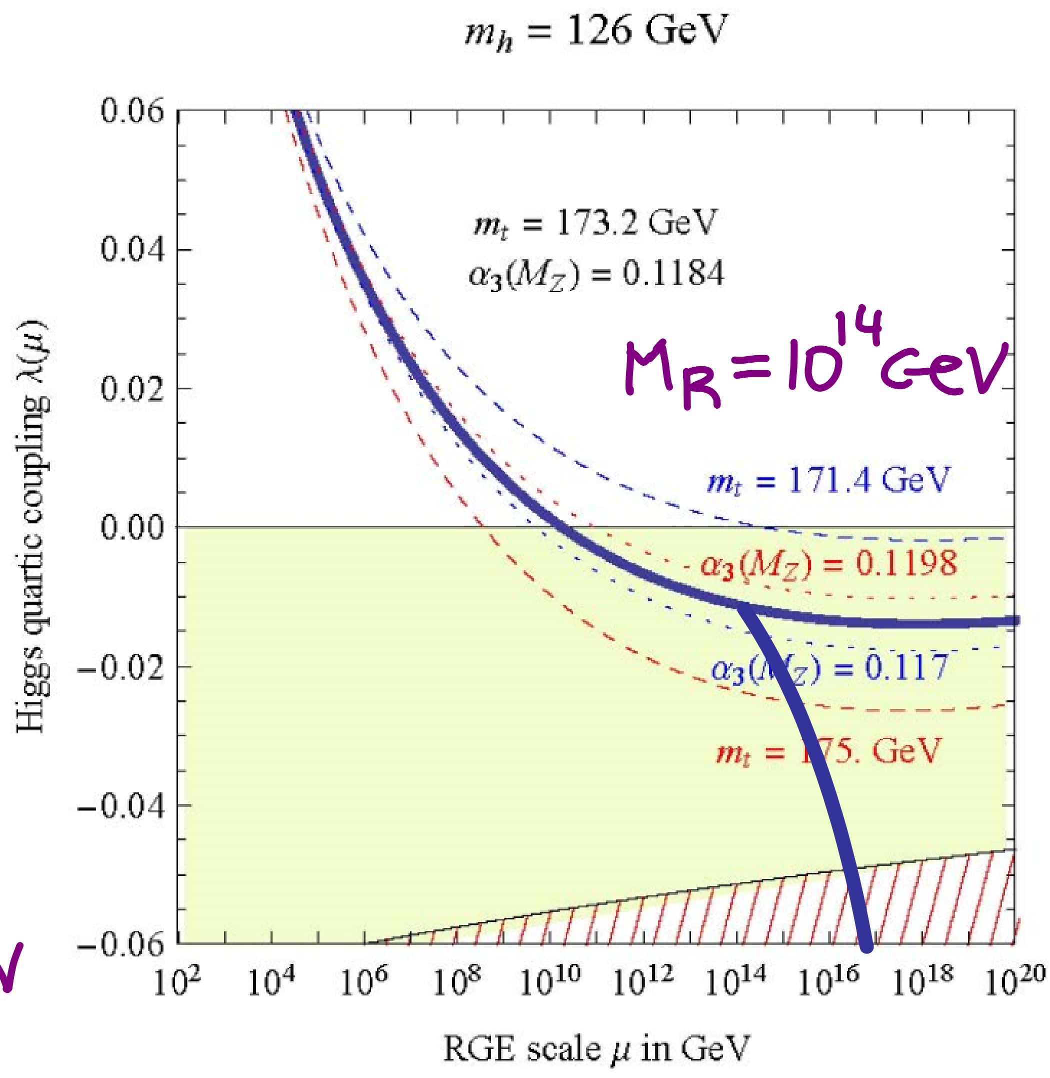
$$m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$

$M_R \uparrow \Rightarrow y_\nu \uparrow$

⇧

Adds to the top destabilizing effect

Important for $M_R \gtrsim 10^{13-14}$ GeV



OTHER IMPLICATIONS

- See-saw neutrinos: Bound on M_{ν_R}