Interpreting the "Higgs-mass oracle"

Gino Isidori
[*INFN, Frascati & CERN*]

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- Introduction
- Consistency with the e.w. precision tests
- Stability and metastability bounds
- The running of λ
- High-scale matching & SUSY
- Conclusions

Introduction [*Ibis redibis...*]

Before the Higgs discovery there were strong hopes that knowing m_h we would have gained a clear clues about the nature of physics beyond the SM, especially in the context of SUSY

These hopes were justified, and indeed m_h *could have* given us unambiguous answers...

<u>Introduction</u> [*Ibis redibis...*]

Before the Higgs discovery there were strong hopes that knowing m_h we would have gained a clear clues about the nature of physics beyond the SM, especially in the context of SUSY

<u>These hopes were justified</u>, and indeed m_h *could have* given us unambiguous answers...

…however, the measured value resembles very much the typical “sibylline answer” of the ancient oracles.

Such as

Ibis redibis non morieris in bello

→ *You will go, be back, and not die in the battle*

→ *You will go, not be back, and die in the battle*

Introduction [*Ibis redibis...*]

Before the Higgs discovery there were strong hopes that knowing m_h we would have gained a clear clues about the nature of physics beyond the SM, especially in the context of SUSY

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…however, the measured value resembles very much the typical "sibylline answer" of the ancient oracles.

As I will illustrate in this talk, it is hard to conceive a more intricate/ambiguous situation concerning possible UV extensions of the SM than the one we have after the LHC8 results:

- m_h = 125 – 126 GeV
- no evidences of physics beyond the SM @ LHC8

Consistency with the e.w. precision tests

The Higgs mechanism is the most economical & simple choice to achieve the spontaneous symmetry breaking of both gauge and flavor symmetries that we observe in nature.

$$\mathscr{L}_{\text{higgs}} = D\phi^{+} D\phi - V(\phi) - Y^{ij}\, \psi_L^{\ i}\, \psi_R^{\ j}\, \phi$$

$$V(\phi) = -\,\mu^2\, \phi^{+}\phi + \lambda(\phi^{+}\phi)^2$$

Before the start of the LHC only the ground state determined by $V(\phi)$ (*and the corresponding Goldstone boson structure*) was tested with good accuracy:

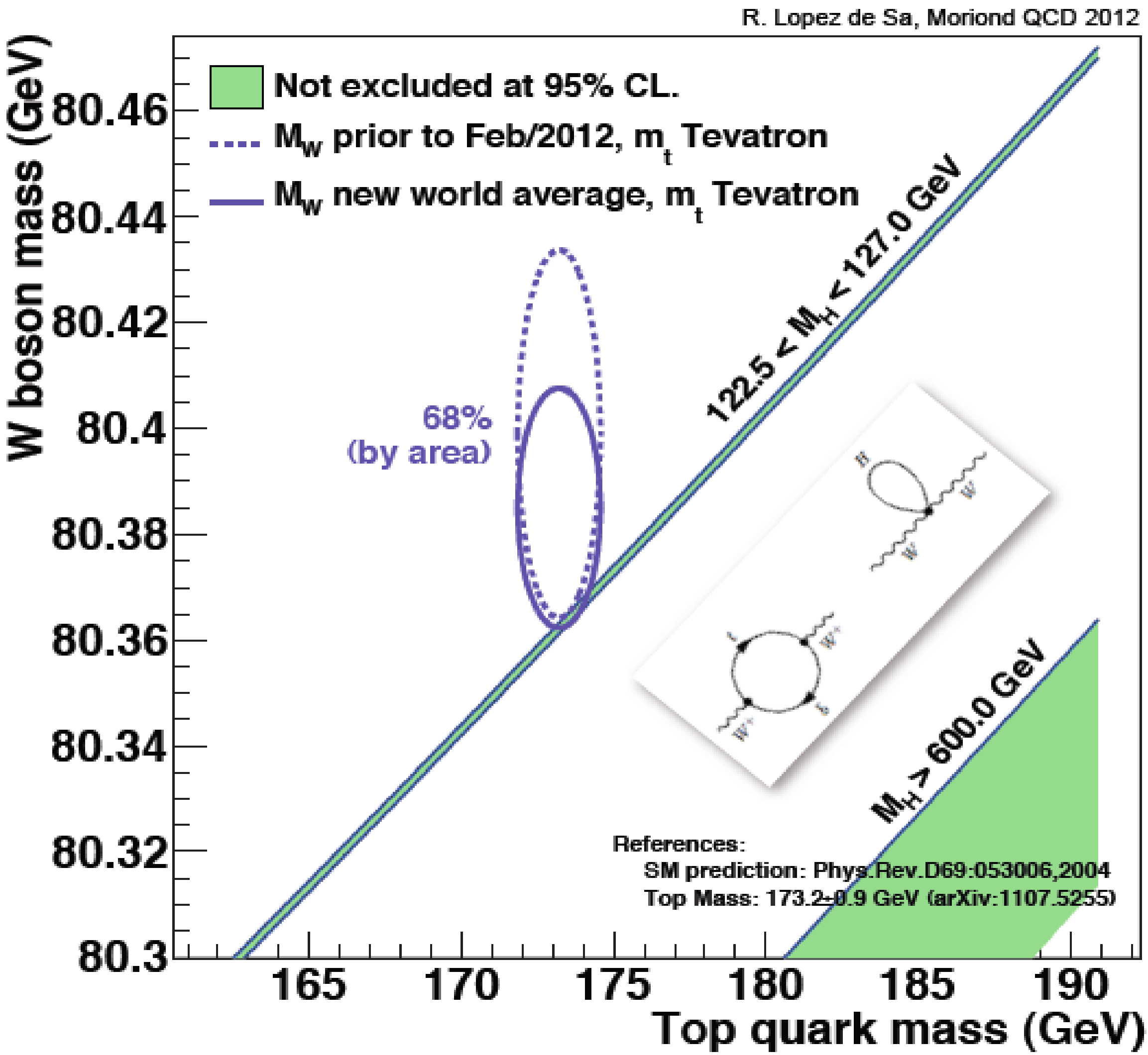
$$v = \langle \phi^{+}\phi \rangle^{1/2} \sim 246 \text{ GeV} \quad [\ m_W = \tfrac{1}{2}\, g\, v\ ]$$

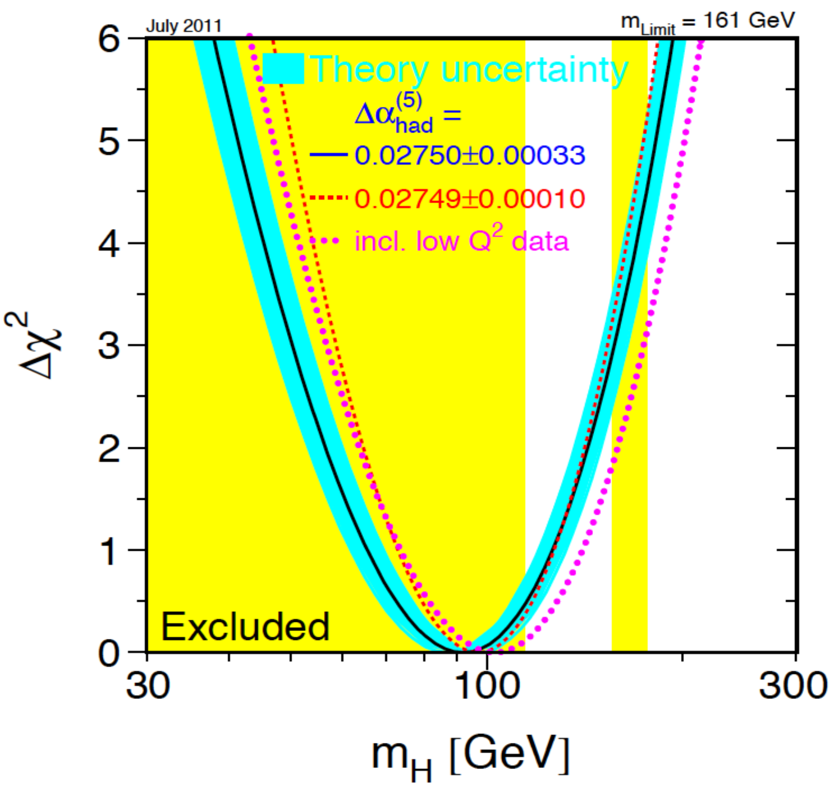
The situation has substantially changed with the measurement of the Higgs boson mass, that has allowed us to precisely (and separately) fix both μ^2 & λ:

$$\lambda_{(\text{tree})} = \tfrac{1}{2}\, m_h^{\ 2} / v^2 \approx 0.13 \qquad\qquad \mu^2_{\ (\text{tree})} = \tfrac{1}{2}\, m_h^{\ 2}$$

Consistency with the e.w. precision tests

Actually some information about the Higgs mass was already present in the e.w. precision tests (*assuming the validity of the SM up to high scales*):





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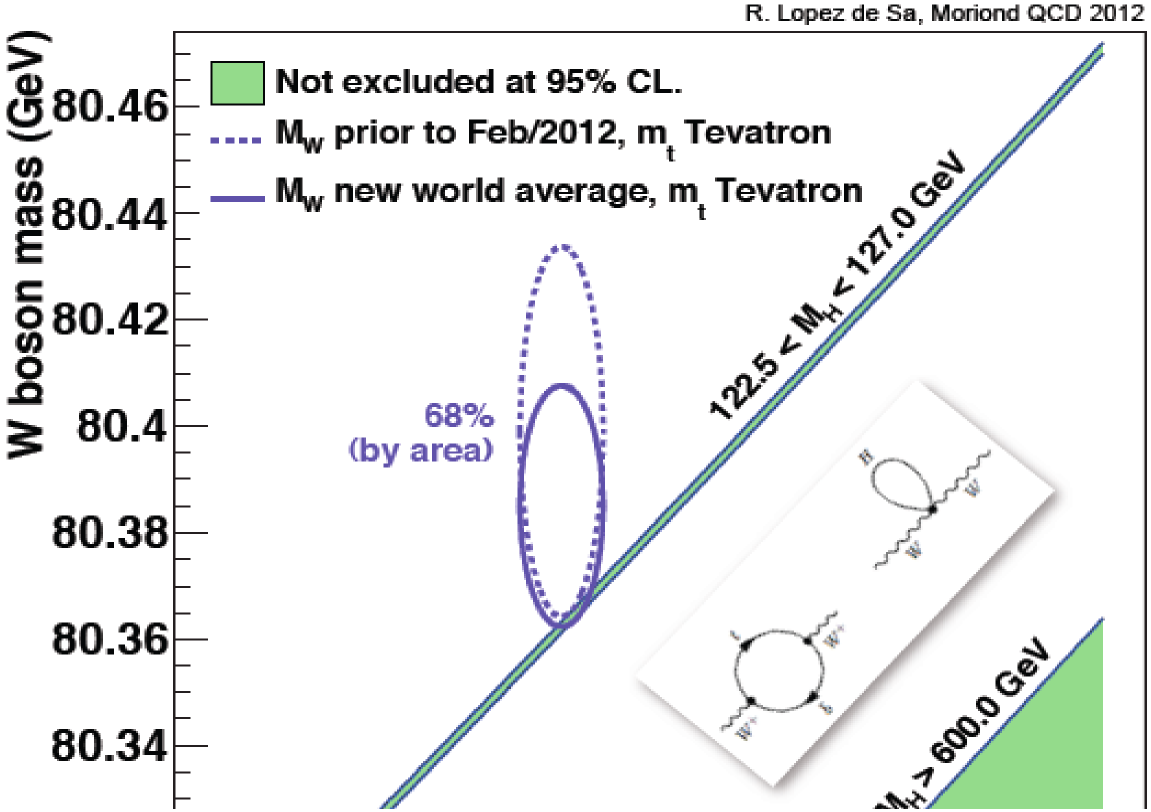

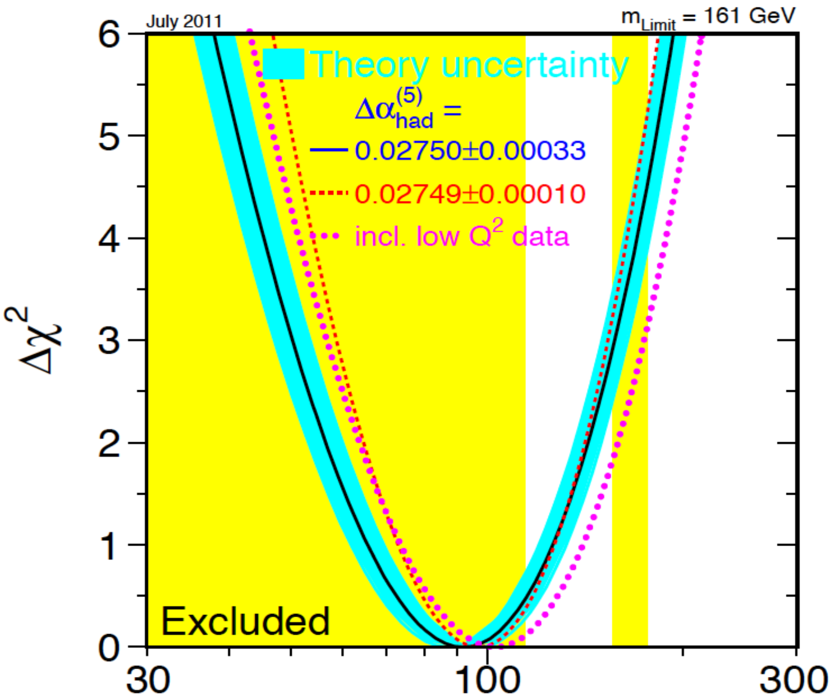

Message n.1: The observation of the physical Higgs boson with m_h well consistent with the (indirect) prediction of the e.w. precision tests is a *great success of the SM.*

Consistency with the e.w. precision tests

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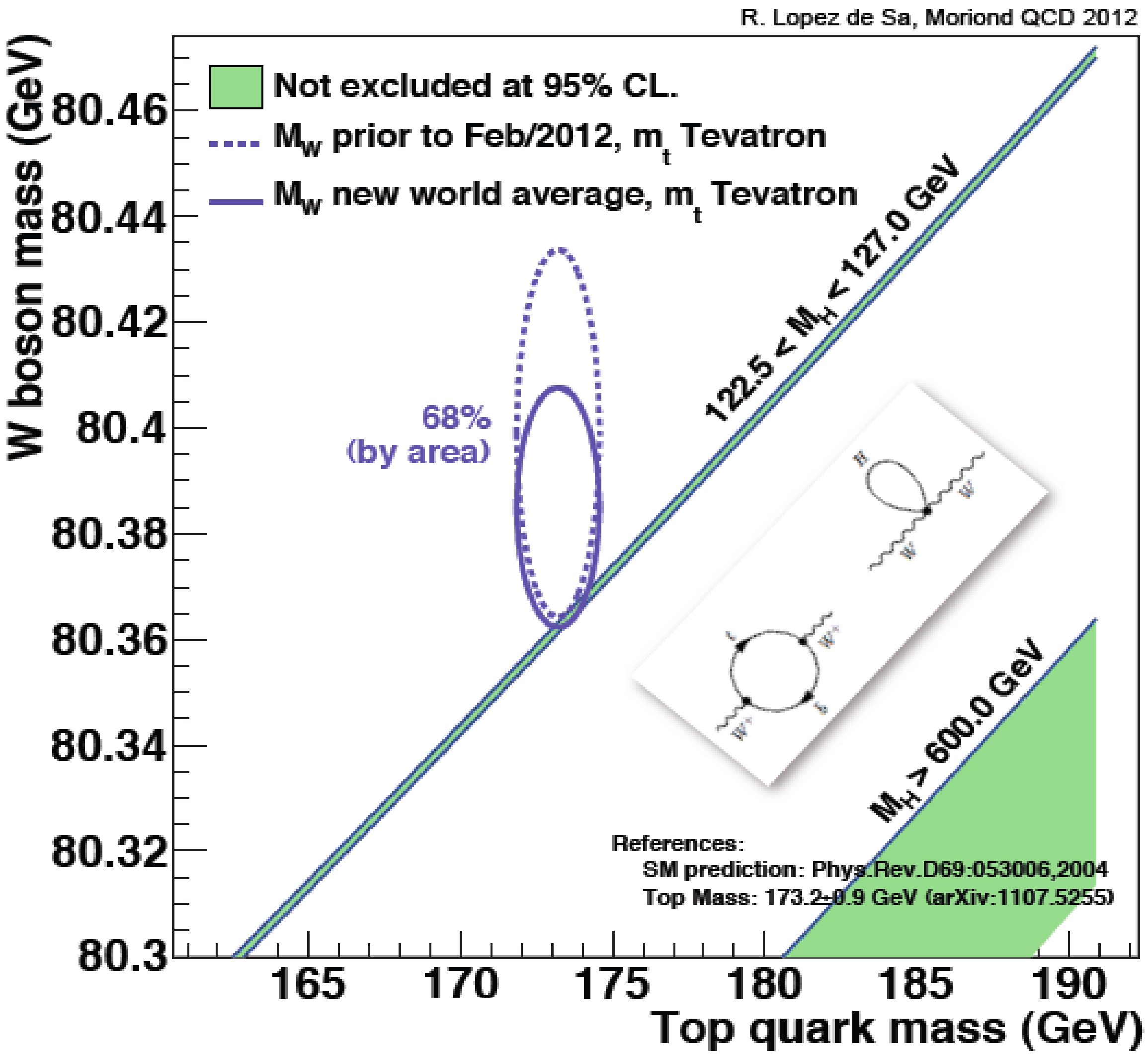


direct $m_h \neq$ indirect m_h

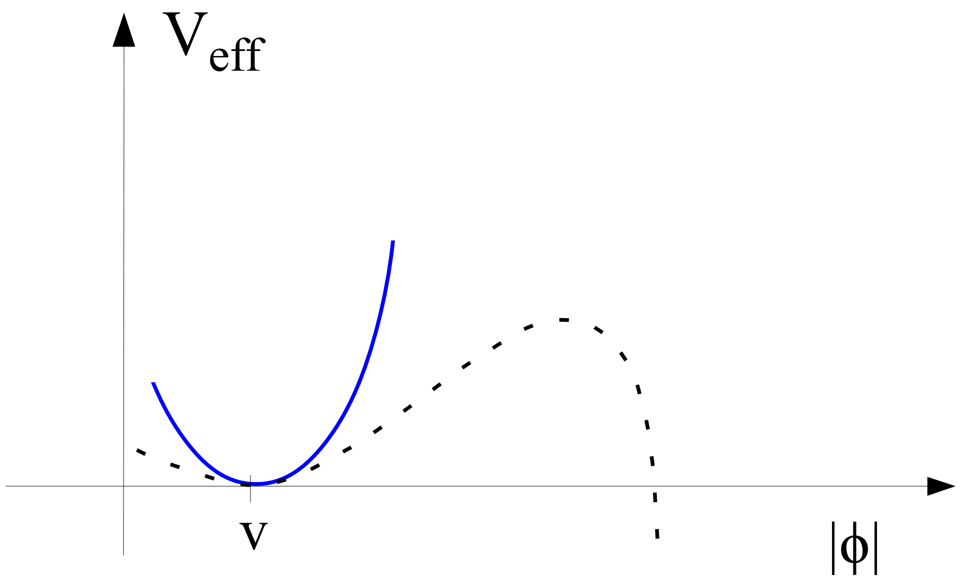
unambiguous indication

NP close to the TeV scale

The opposite is not necessarily true, but it indicates that (up to conspiracies) the theory has a *minimal* & *weakly coupled* structure around the TeV scale, as in the SM.

Stability and metastability bounds

A completely independent (and unambiguous) indication for NP could have been obtained by the high-energy behavior of the Higgs potential



Stability and metastability bounds

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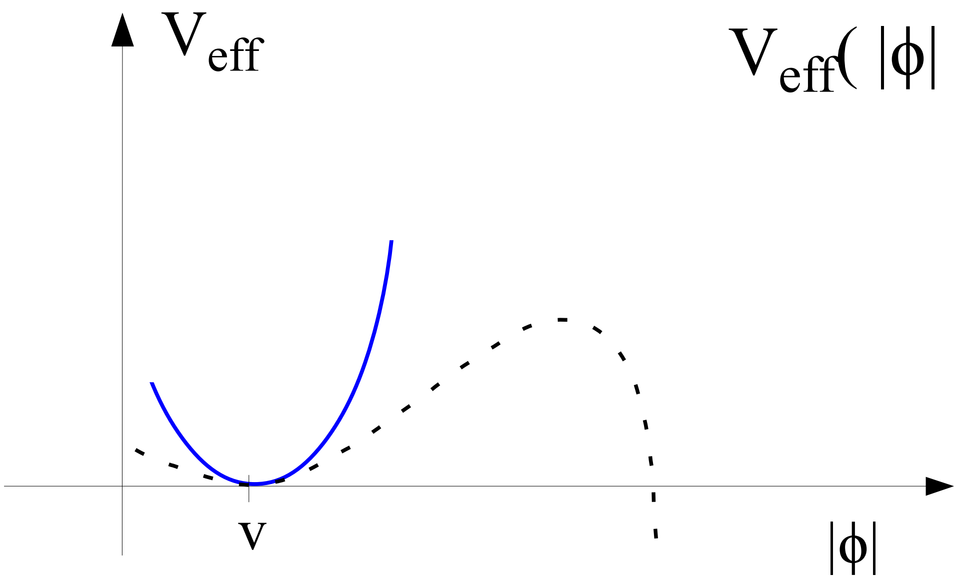
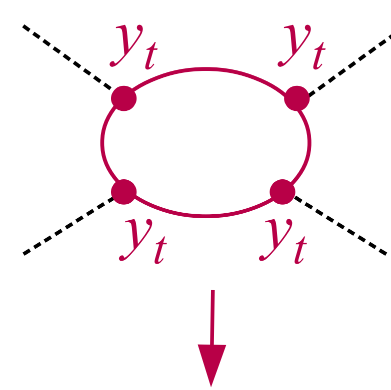
At large field values:

$$V_{eff}(\,|\phi| \gg v\,) \approx \lambda(|\phi|) \times |\phi|^4 + O(v^2|\phi|^2)$$



$$\lambda(v) \propto \frac{m_h^2}{v^2}$$

$$y_t(v) \propto \frac{m_t}{v}$$



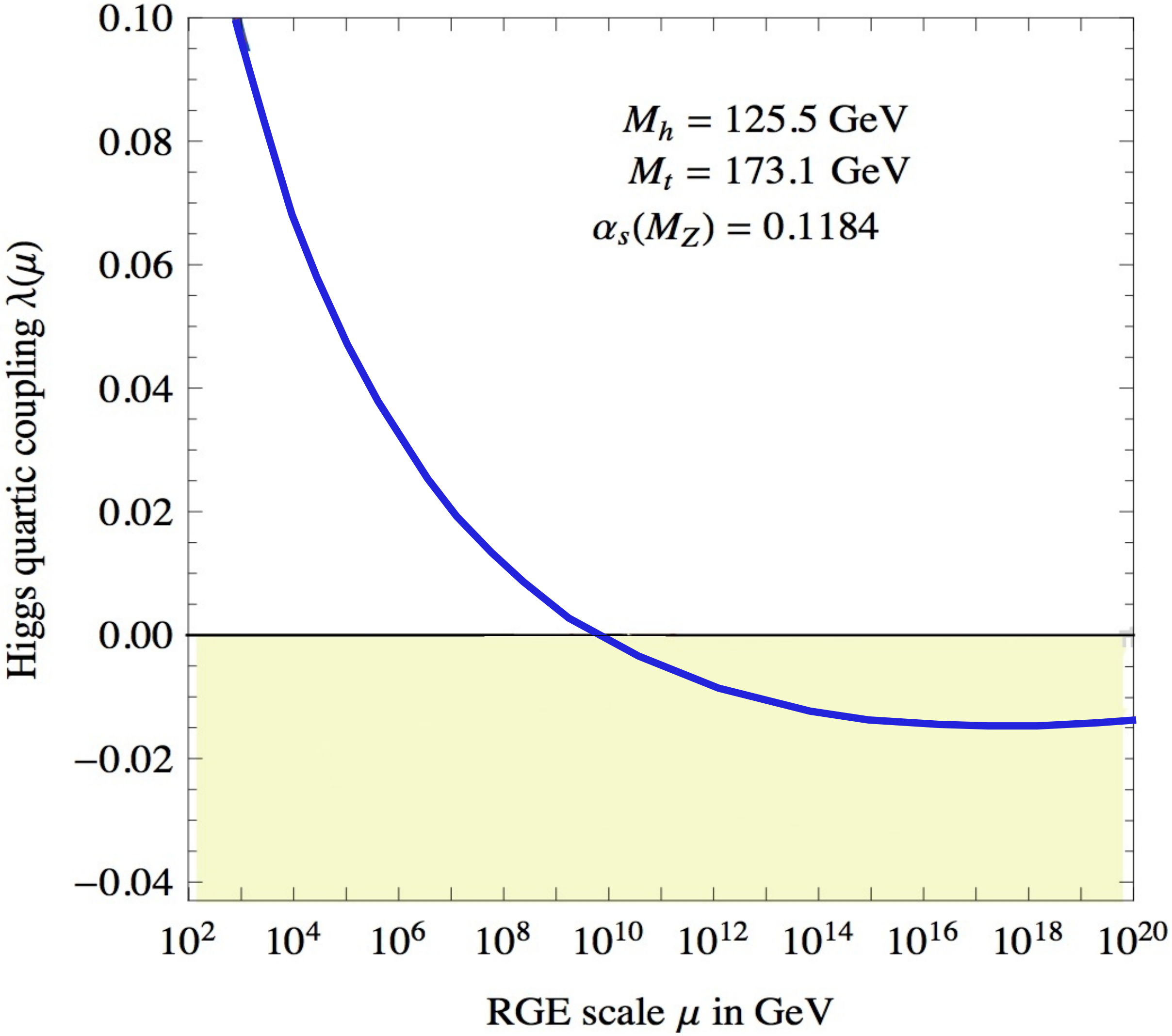
decreasing λ
at large energies

A too-light m_h could imply an
unstable Higgs potential → need for NP

Cabibbo, Maiani, Parisi, Petronzio, '79;
Hung '79; Lindner 86; Sher '89; ....

Stability and metastability bounds

This is indeed what happens for $m_h \approx 125$ GeV and $m_t \approx 173$ GeV !



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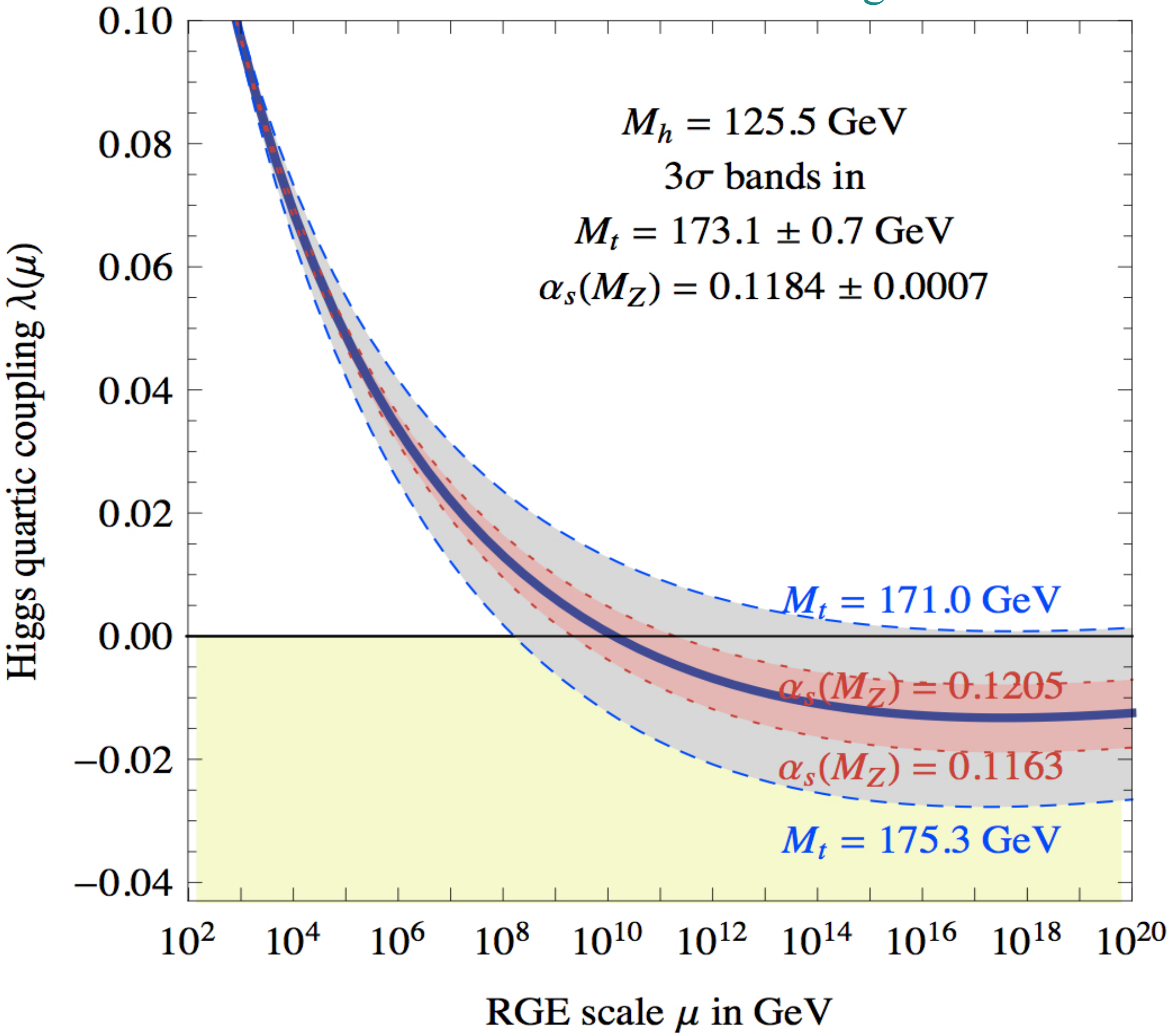
Degrassi *et al.* '12



...however, unfortunately this is not enough to unambiguously claim the need of NP:

- The present error on m_t does not allow us to exclude at more than 3σ that $\lambda > 0$ up to M_{Planck}

- Even for the central values of m_h and m_t, the Higgs potential remains sufficiently metastable

Stability and metastability bounds

The metastability condition: even if the potential has a second deeper minimum, the model is consistent with observations (= no need for NP) if the lifetime of the (unstable) e.w. minimum is longer than the age of the Universe

The e.w. minimum is destabilized by:

Quantum fluctuations (at T=0)

computable in a model-independent way

Thermal fluctuations

the probability depends on the thermal history of the universe & competes with the quantum tunneling only for very high T

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Most conservative bound

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The quantum tunneling occurs via bubble formation in the homogeneous background of the false (e.w.) minimum ["bounce" field configurations]

$$\text{Probability} \sim e^{-S_0[\phi_{bounce}]} \sim e^{-\frac{8\pi^2}{3|\lambda|}}$$

▶ *Stability and metastability bounds*

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computable in a model-independent way

⬇

Most conservative bound

Thermal fluctuations

result from full one-loop action, *assuming no further destabilization from Planck-scale dynamics* [→ talk by Branchina]

$$p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(1/R)|} + \begin{matrix}\text{tiny}\\ \text{higher-order}\\ \text{terms}\end{matrix} \right]$$

G.I., Ridolfi, Strumia '01

The tunneling is dominated by "bounces" of size R, such that λ(1/R) reaches its minimum value: λ can become negative, provided it remains small in magnitude.

Stability and metastability bounds

The metastability condition: even if the potential has a second deeper minimum, the model is consistent with observations (= no need for NP) if the lifetime of the (unstable) e.w. minimum is longer than the age of the Universe

The e.w. minimum is destabilized by:

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the probability depends on the thermal history of the universe & competes with the quantum tunneling only for very high T

⬇

The tunneling is favored by the kinetic energy, but this effect is compensated by the appearance of an effective T-dependent positive mass: $m^2_{eff}(T) \sim g^2(T)\, T^2$

→ again tunneling needs non-trivial field configurations

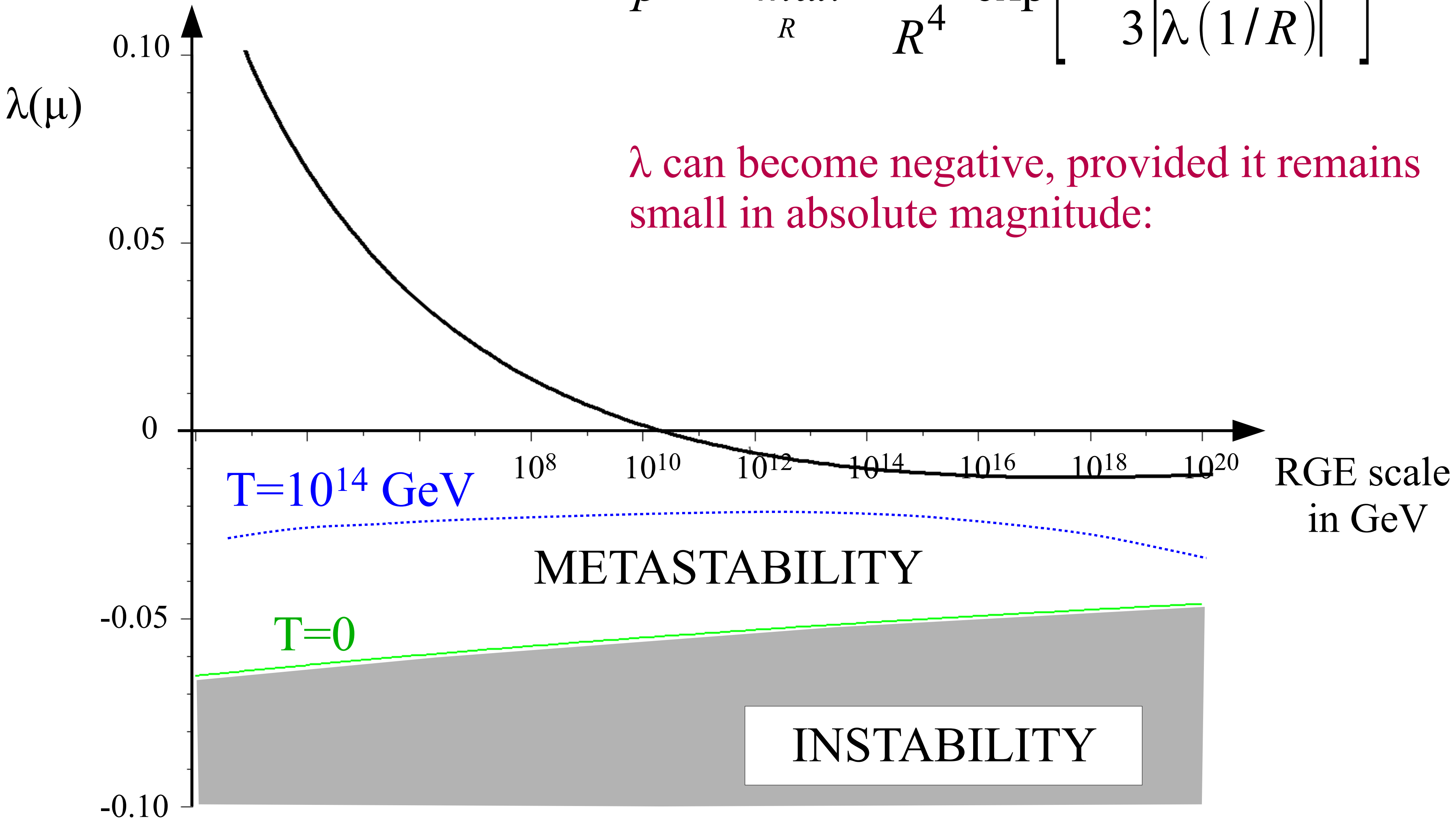
→ also in this case λ can become negative, provided it remains sufficiently small in magnitude.

Stability and metastability bounds

The metastability condition

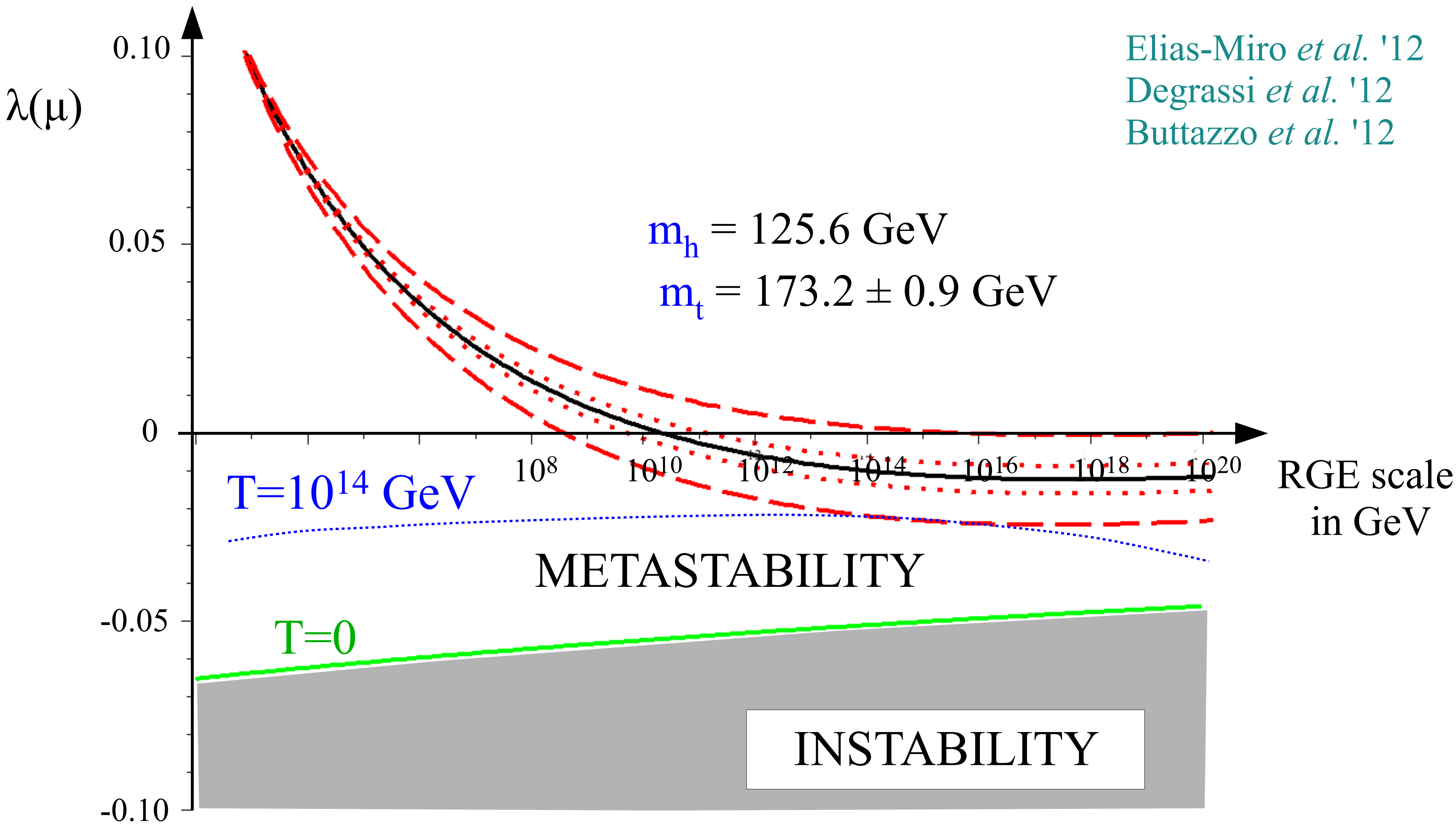
$$p \approx \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3\left|\lambda(1/R)\right|}\right]$$

λ can become negative, provided it remains small in absolute magnitude:



Stability and metastability bounds

Message n.2: For $m_h \approx$ 125-126 GeV and the present central value of m_{top}, the SM vacuum is unstable but sufficiently long-lived, compared to the age of the Universe



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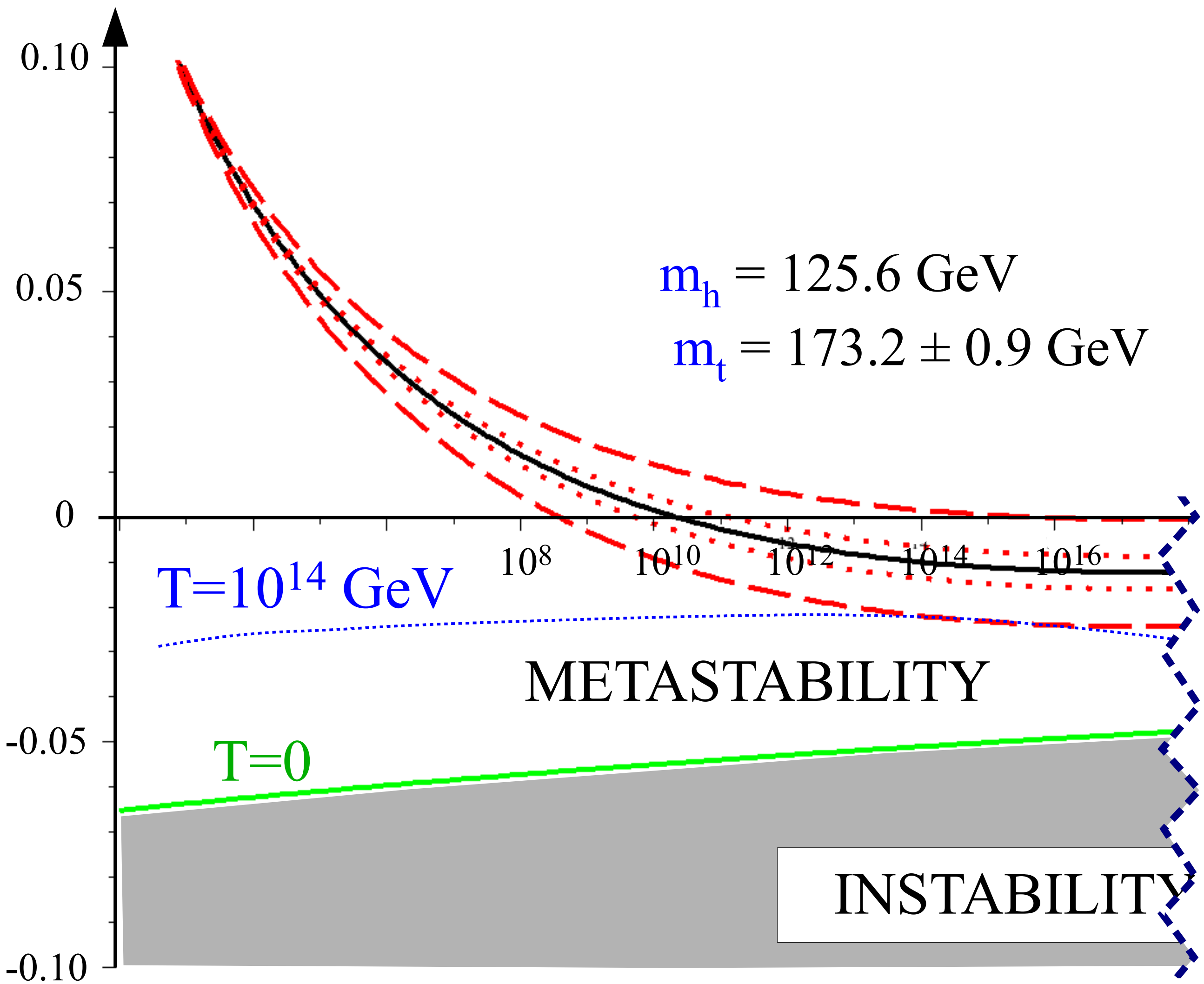


Elias-Miro *et al.* '12
Degrassi *et al.* '12
Buttazzo *et al.* '12

N.B.: we cannot trust the estimate of the tunneling rate too close to M_{Pl}

Stability and metastability bounds

Message n.2: The SM vacuum is unstable but sufficiently long-lived, compared to the age of the Universe → No need of NP below M_{Pl} to stabilize the SM vacuum

$\lambda(\mu)$ cross the metastability limit at a scale $\mu_0 << M_{Planck}$

↓ *unambiguous indication*

NP around/below μ_0

N.B.: Also in this case the opposite is NOT true.

Moreover, we cannot say anything about possible destabilization of the e.w. vacuum by Planck-scale dynamics [New "vacuum decay channels" could easily "open-up" at M_{Planck} → talk by Branchina].

▶ *The running of λ*

The running of λ

How "precise" is the estimate of the evolution of λ
(and the corresponding conclusion that the SM potential is unstable)?

A complete NNLO analysis has recently become possible:

- Two-loop potential — Ford, Jack, Jones '92, '01
- Three-loop beta functions — Mihaila, Salomon, Steinhauser '12; Chetyrkin, Zoller, '12
- Two-loop threshold corrections in relating $\lambda(v)$ to the Higgs mass:

$$\lambda(\mu) = \frac{G_F\, m_h^2}{\sqrt{2}} + \Delta\lambda(\mu)$$

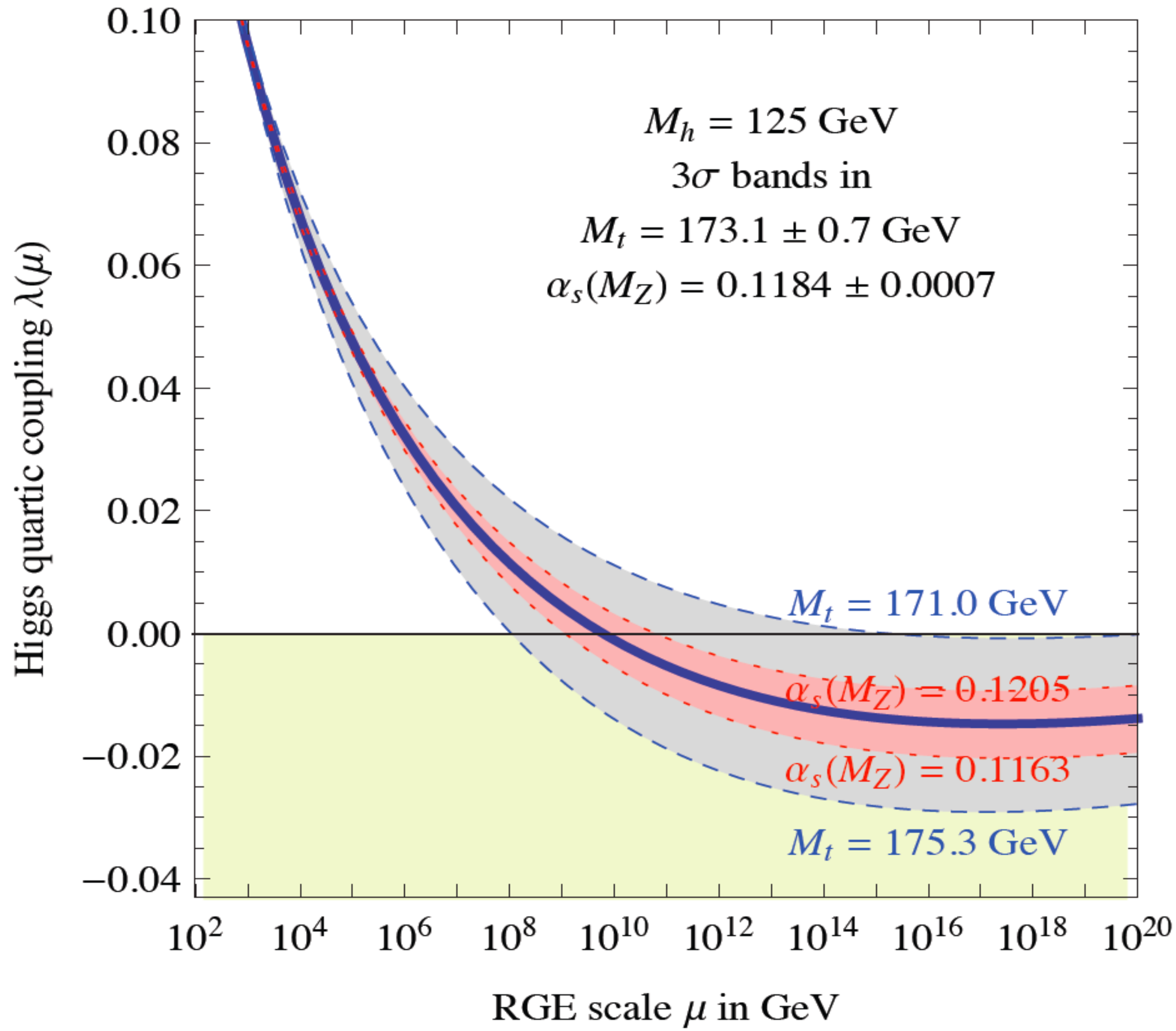
(*dominant uncertainty*)

Yukawa×QCD	Bezrukov *et al.* '12
Yukawa×QCD Yuk.×Yuk.	Degrassi *et al.* '12
Full 2-loop	Buttazzo *et al.* '13

The running of λ

Given the fast running of λ close to the e.w. scale, the dominant uncertainty comes from threshold (non-log enhanced) corrections at the electroweak scale (or in the precise evaluation of the initial condition).

While the smallness of λ (and the other couplings) at high energies imply that the 3-loop terms in the beta functions play a very minor role (useful to control the error).



▶ The running of λ

With the NNLO calculation we are able to derive a very precise relation between Higgs and top masses from vacuum stability:

Absolute stability: Degrassi *et al.* '12

$$M_h\ [\mathrm{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

Conservative th. error given the size of the shifts from NLO to NNLO:

$+\,0.6\,\mathrm{GeV}$ due to the QCD threshold corrections to λ

$+\,0.2\,\mathrm{GeV}$ due to the Yukawa threshold corrections to λ

$-\,0.2\,\mathrm{GeV}$ from RG equation at 3 loops

$-\,0.1\,\mathrm{GeV}$ from the effective potential at 2 loops.

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Reliability of this th. error estimate fully confirmed by complete 2-loop threshold corr.

Buttazzo *et al.* '13

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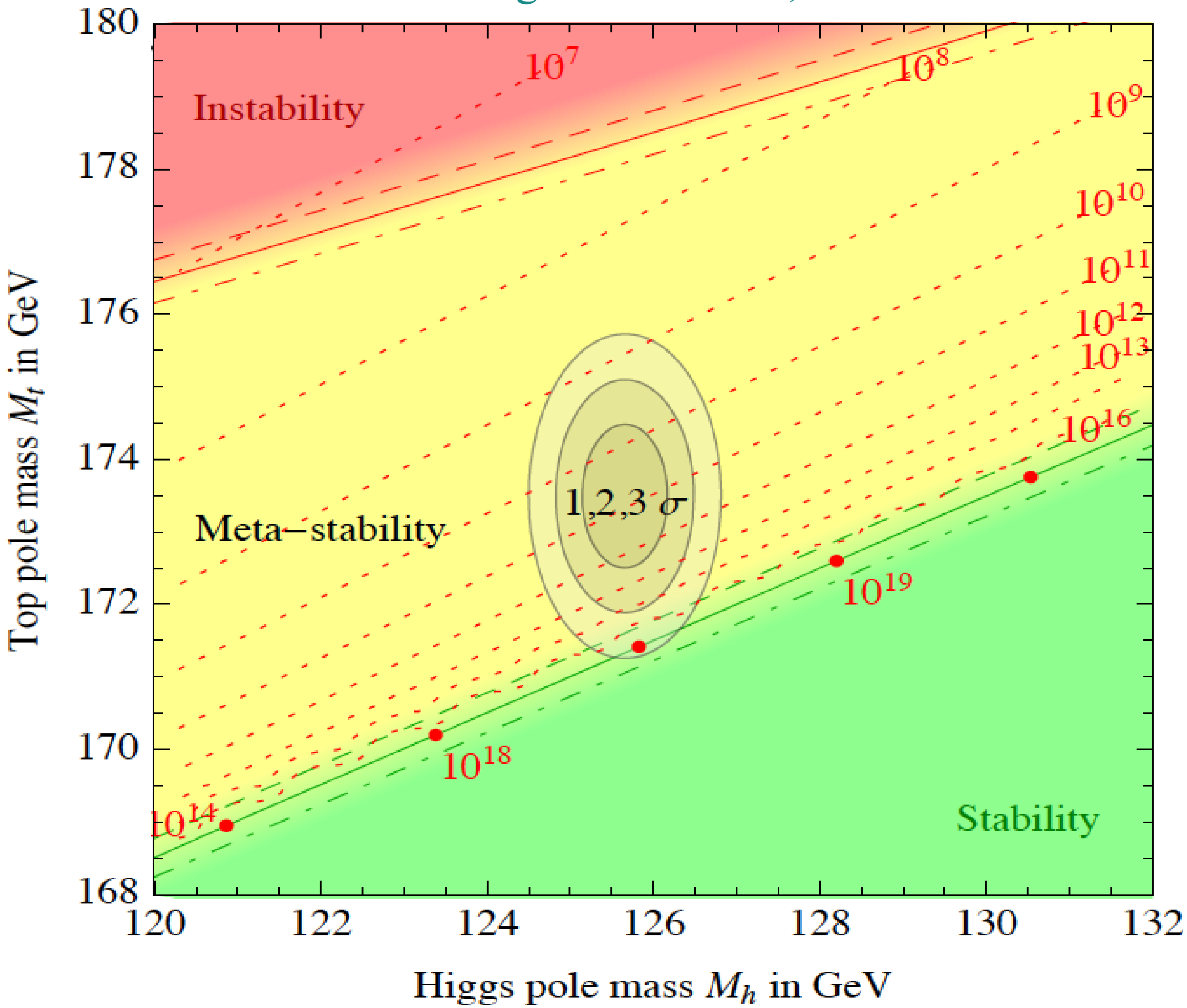

N.B.: This is not a standard "phase-diagram plot" [*we have not solved the model*...]

It denotes the stability/instability regions assuming no further destabilization from Planck-scale dynamics

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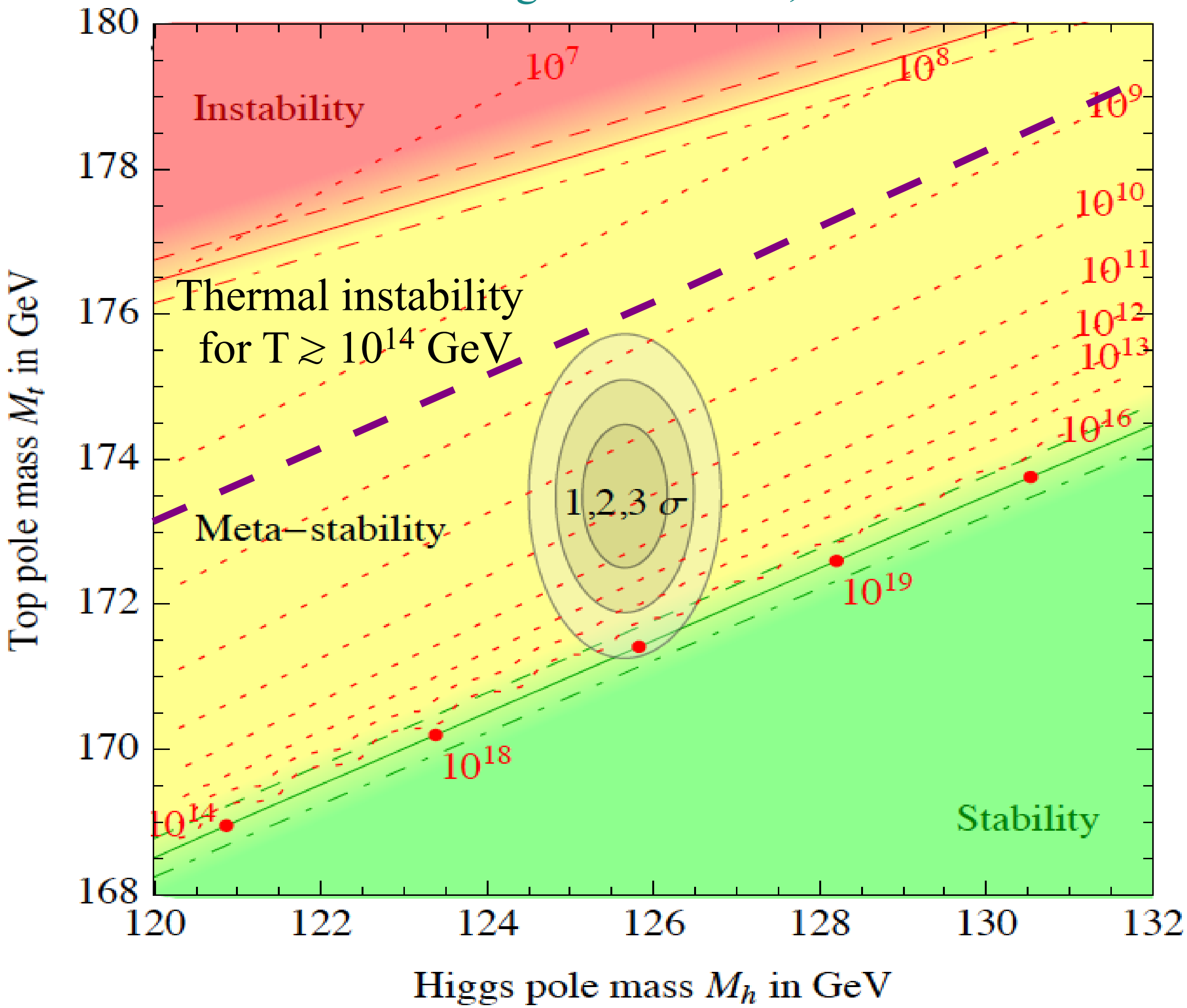

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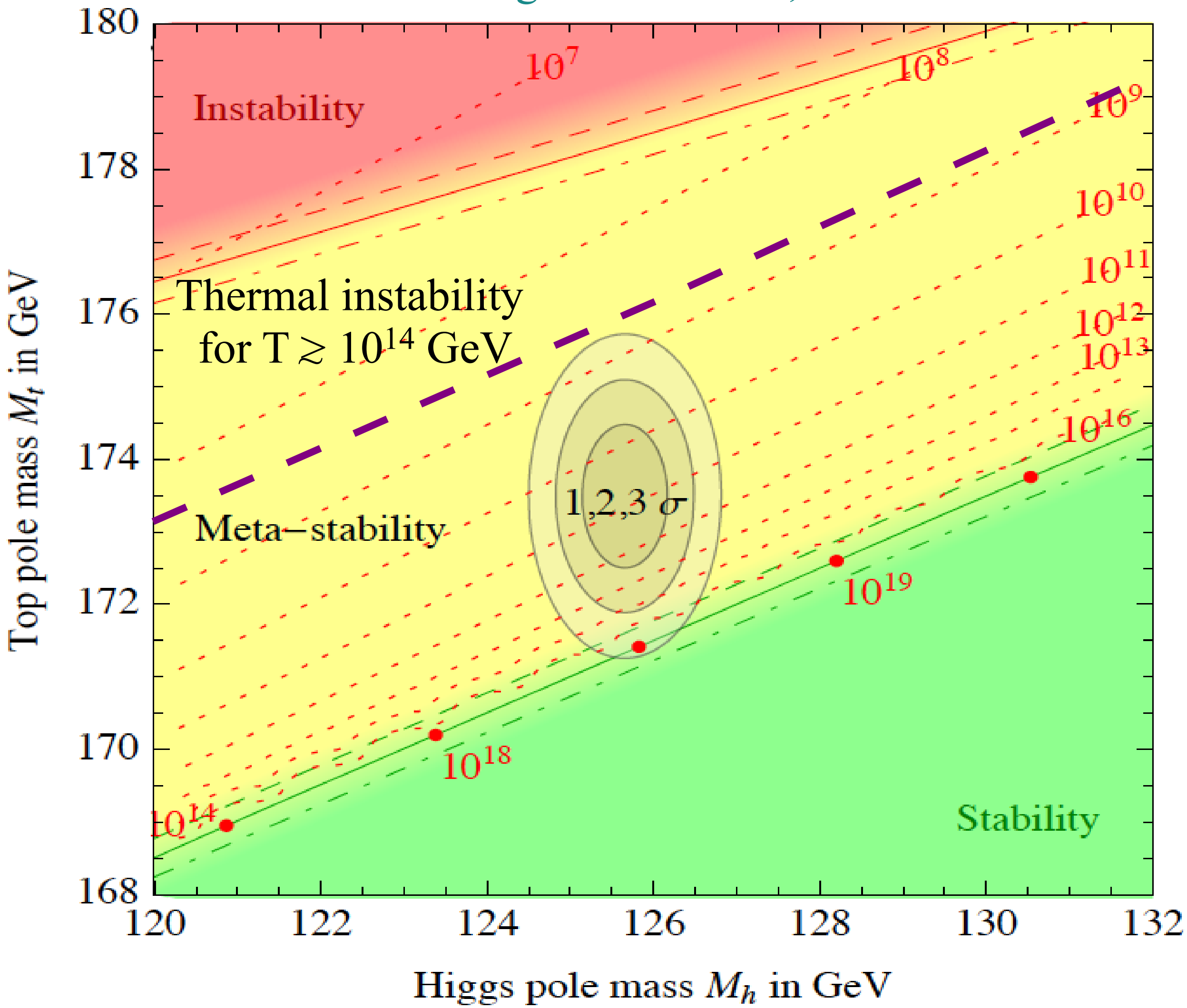


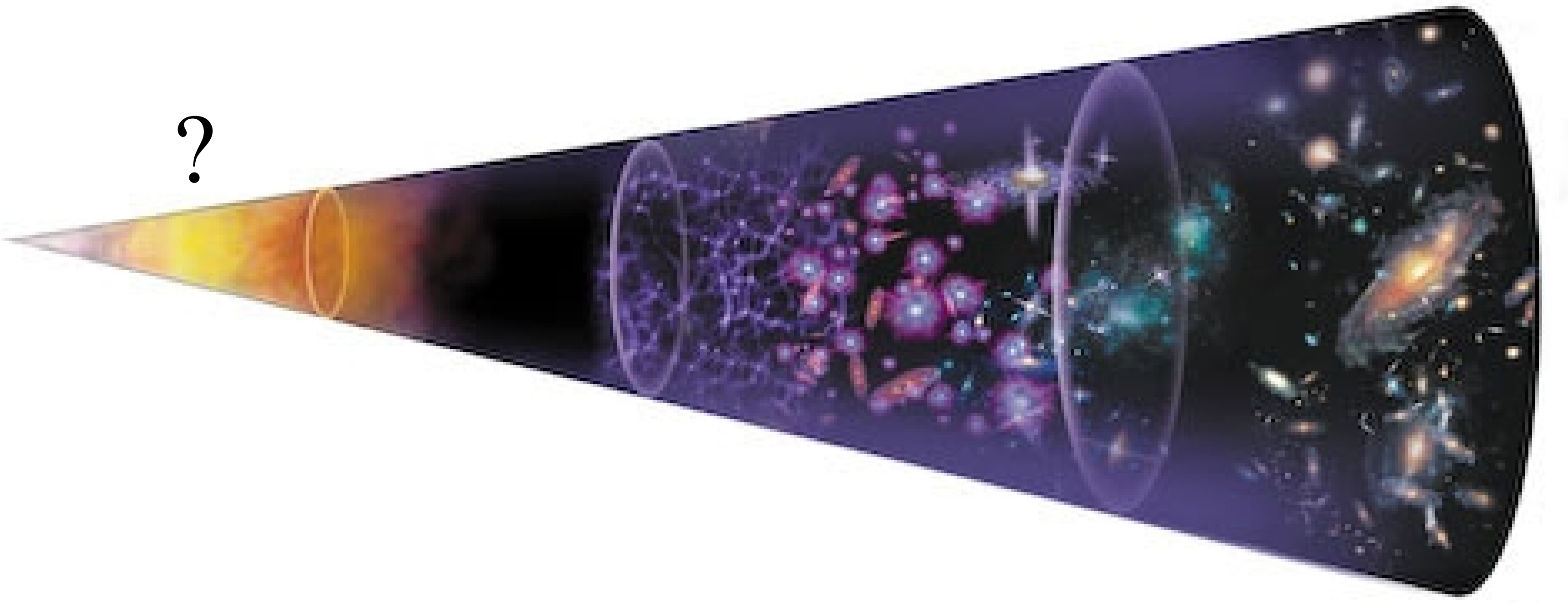
The error on m_h will soon go down → main uncertainty induced by the top mass.

The m_t presently determined by ATLAS, CMS, Tevatron is not really the pole mass...

Hoang & Stewart, '07-'08
Alekhin, Djouadi, Moch '12,

… but nice convergence to the same m_t of several indep. measurements by CMS & ATLAS → small non-perturbative errors

▶ *High-scale matching and SUSY*



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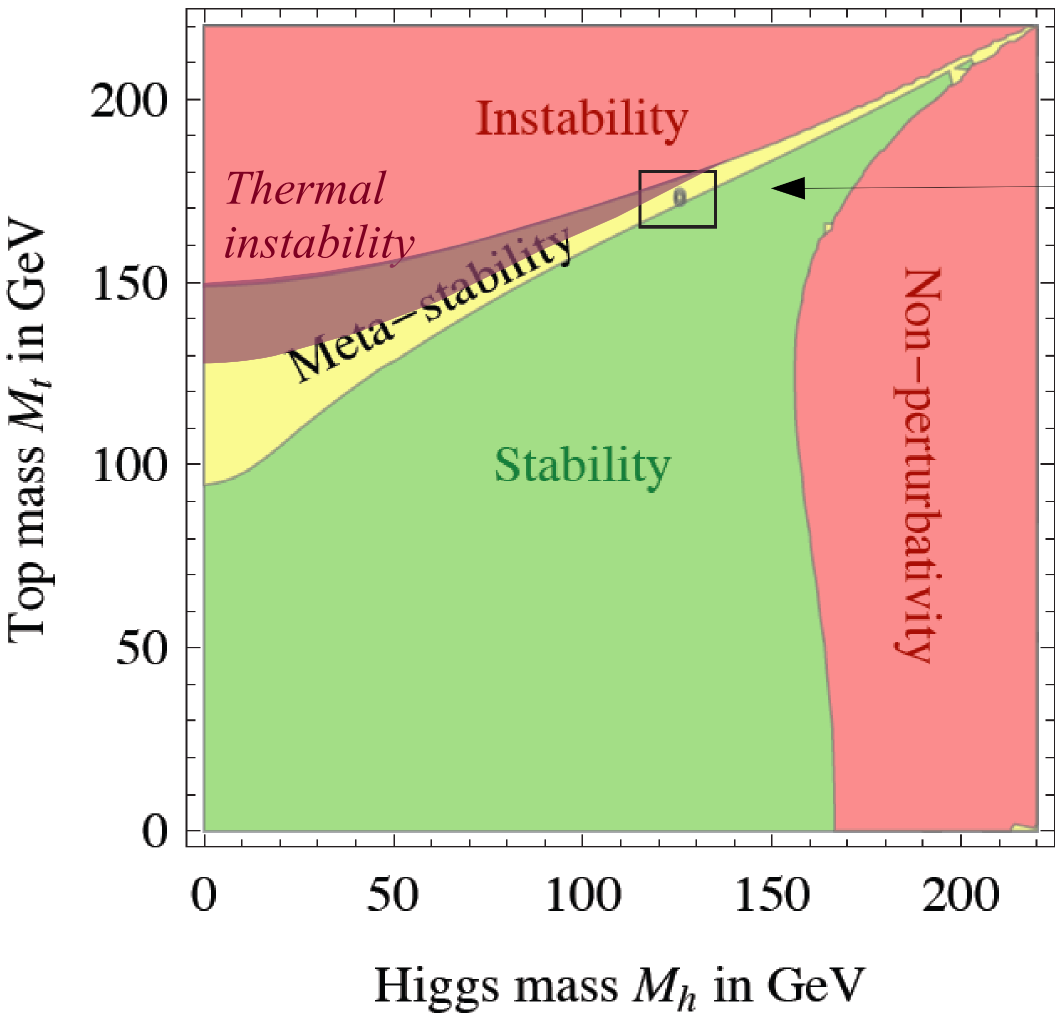
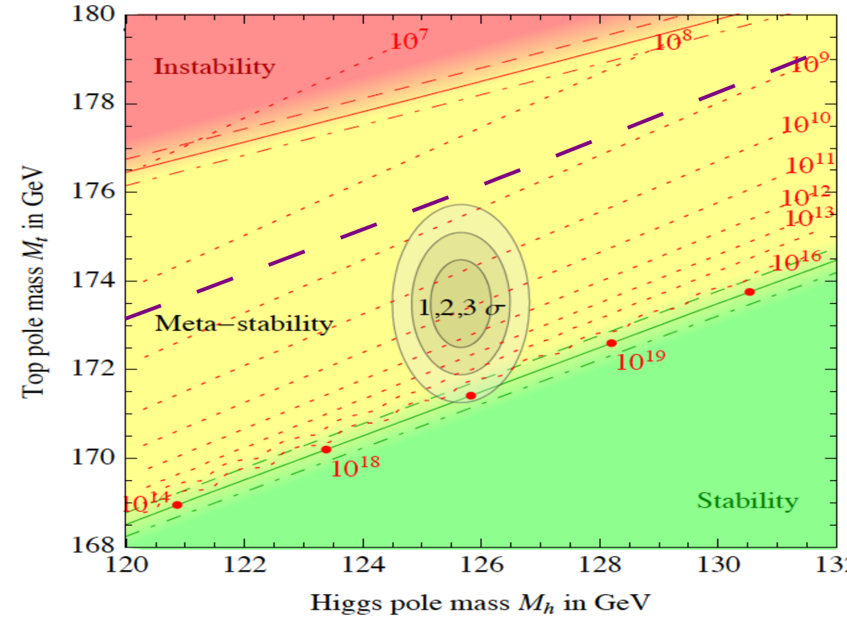




Looking at the plane from a more distant perspective, it appears more clearly that "we live" in a quite "peculiar" region...

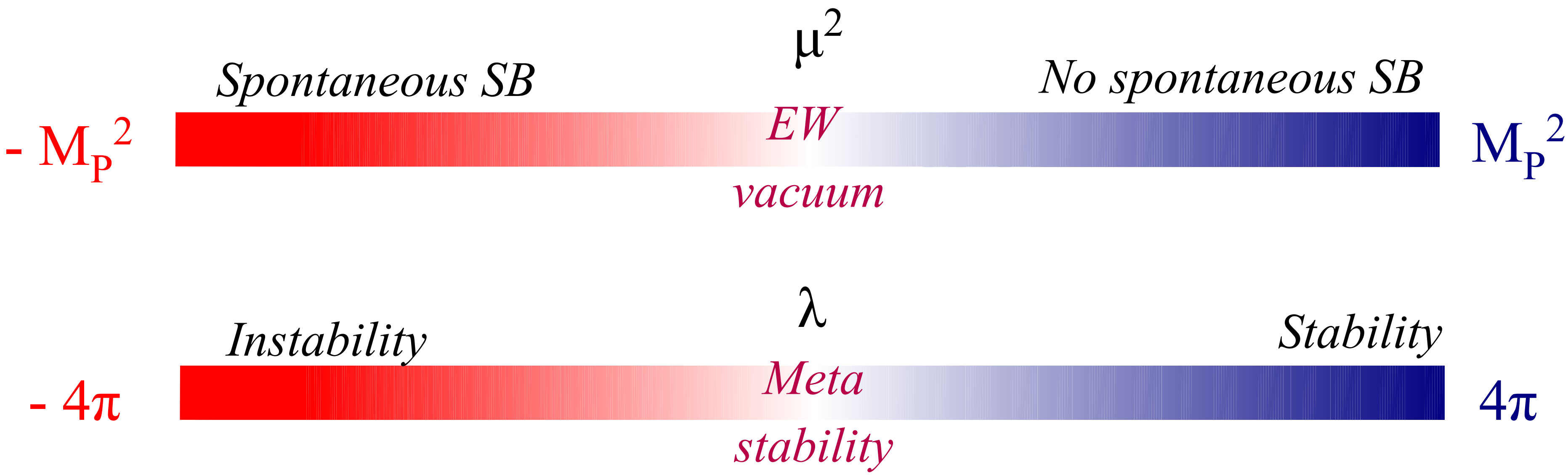
Froggatt, Nielsen, Takanishi, '01
Arkani-Hamed *et al.*, '08
Shaposhnikov, Wetterich, '10
+
many recent papers...

Moving m_t down by ~ 2 GeV, we reach the even more peculiar configuration where $\lambda(M_{pl})=0$

High-scale matching and SUSY

It seems that the Higgs potential is "doubly tuned" around two "critical values":

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2$$



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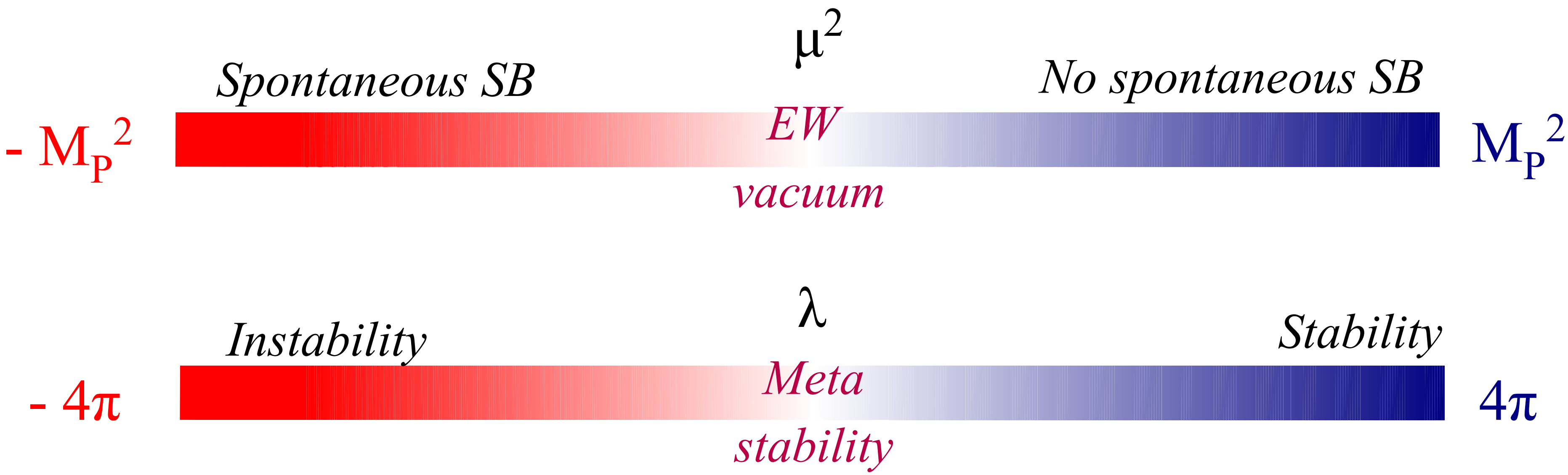


Possible support in favor of the "Multiverse" [→ talk by Hall]

Close analogy with the cosmological constant? Maybe...
More dependence about the assumptions on the "pressure" in parameter space.

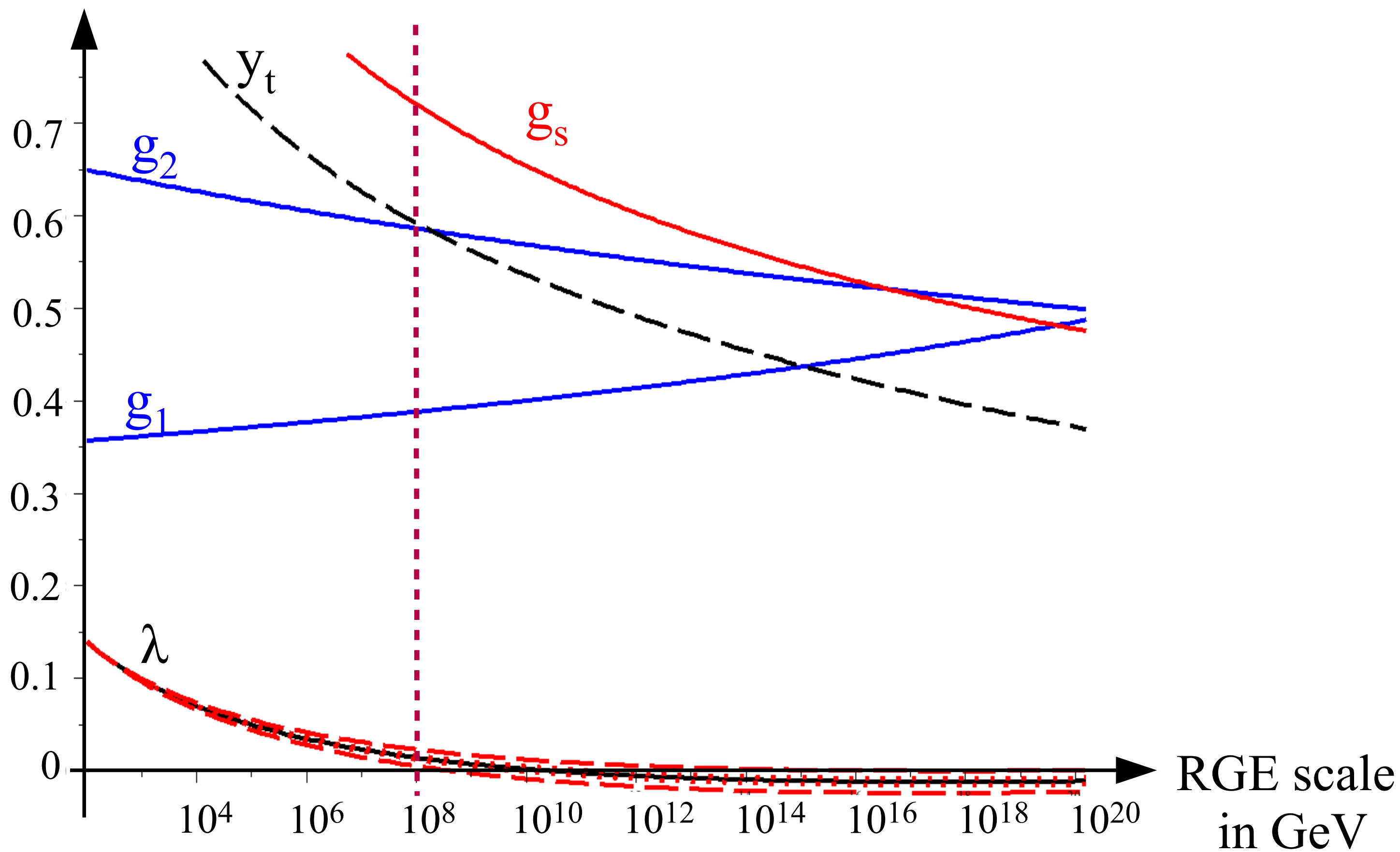
High-scale matching and SUSY

What's special about $\lambda(M_{pl})=0$?

Despite also the beta function vanishes, is not a true fixed point (other coupl. $\neq$ 0).

Maybe more interesting the overall smallness of λ compared to the other couplings.

At a scale $\Lambda \gtrsim 10^8$ GeV λ becomes of the same order of its typical e.w. quantum corrections: *hints of a radiatively generated coupling*?



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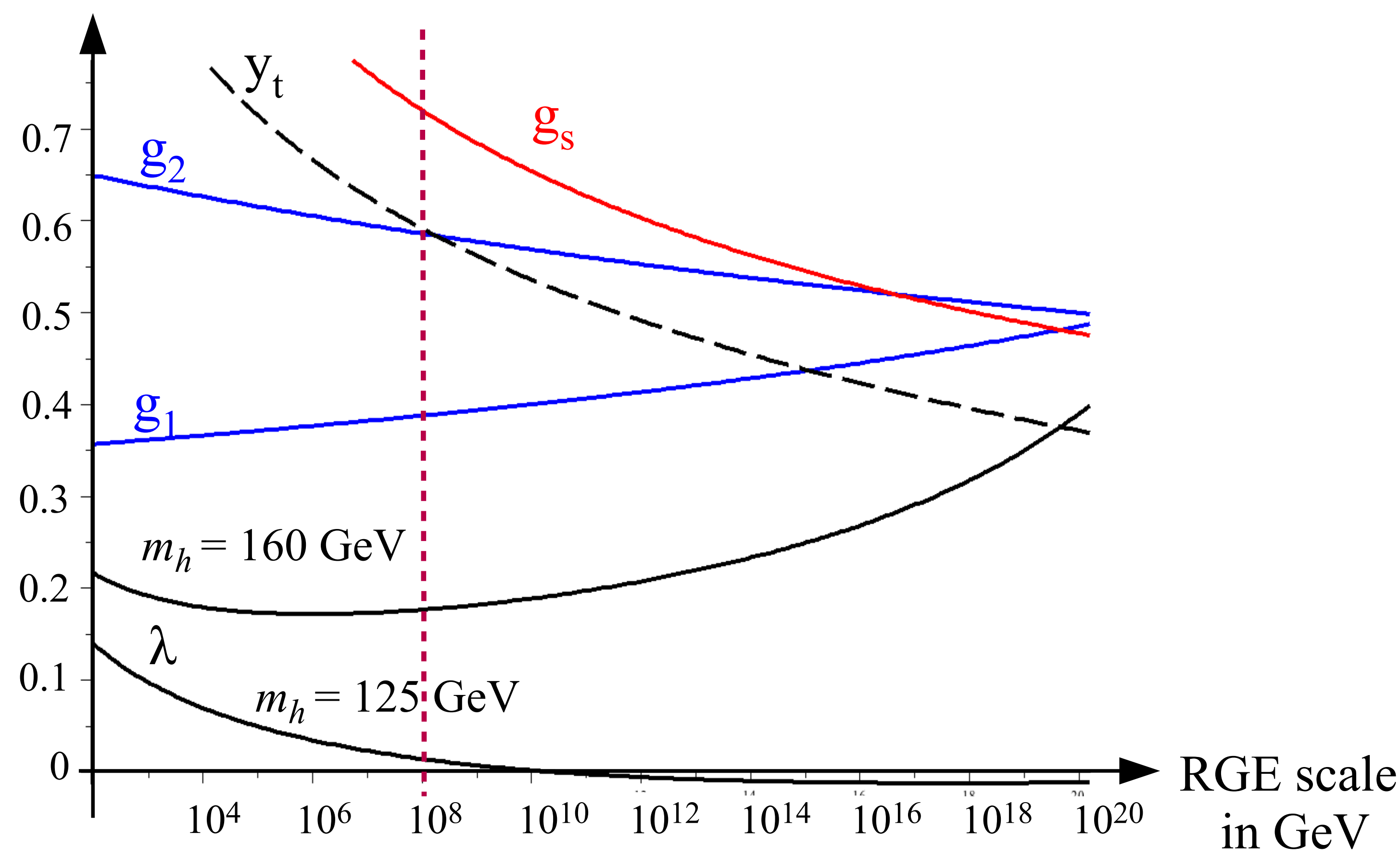

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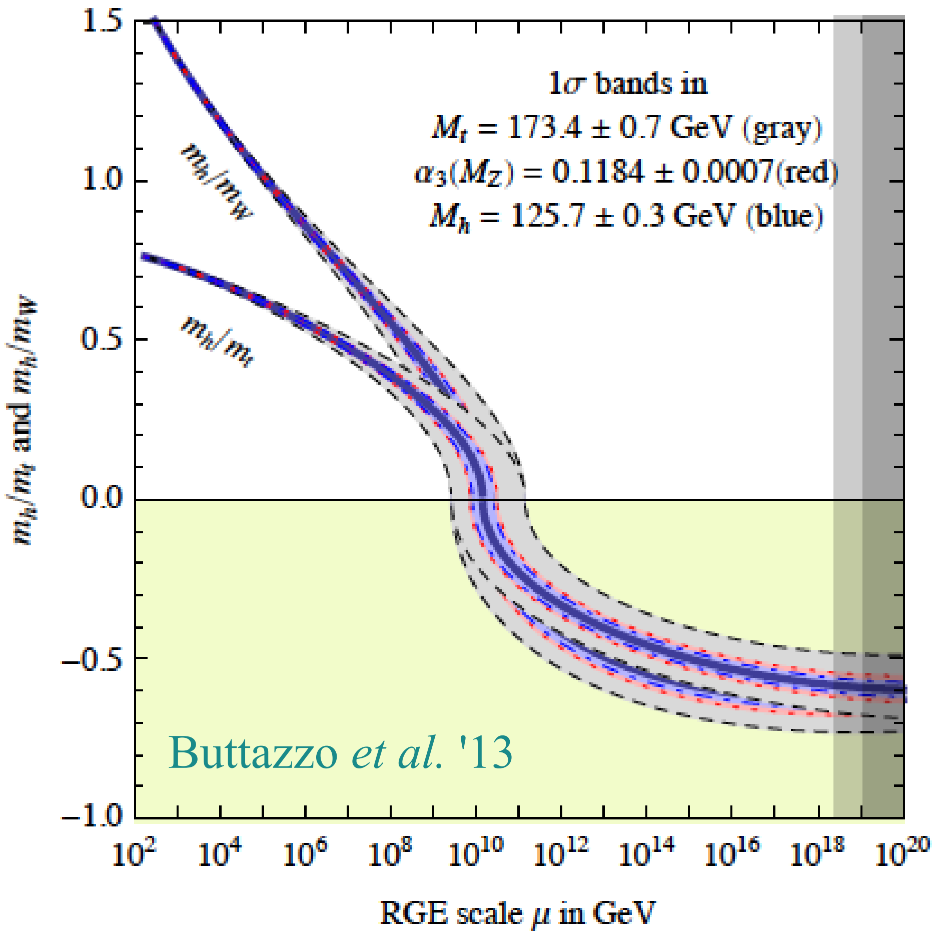
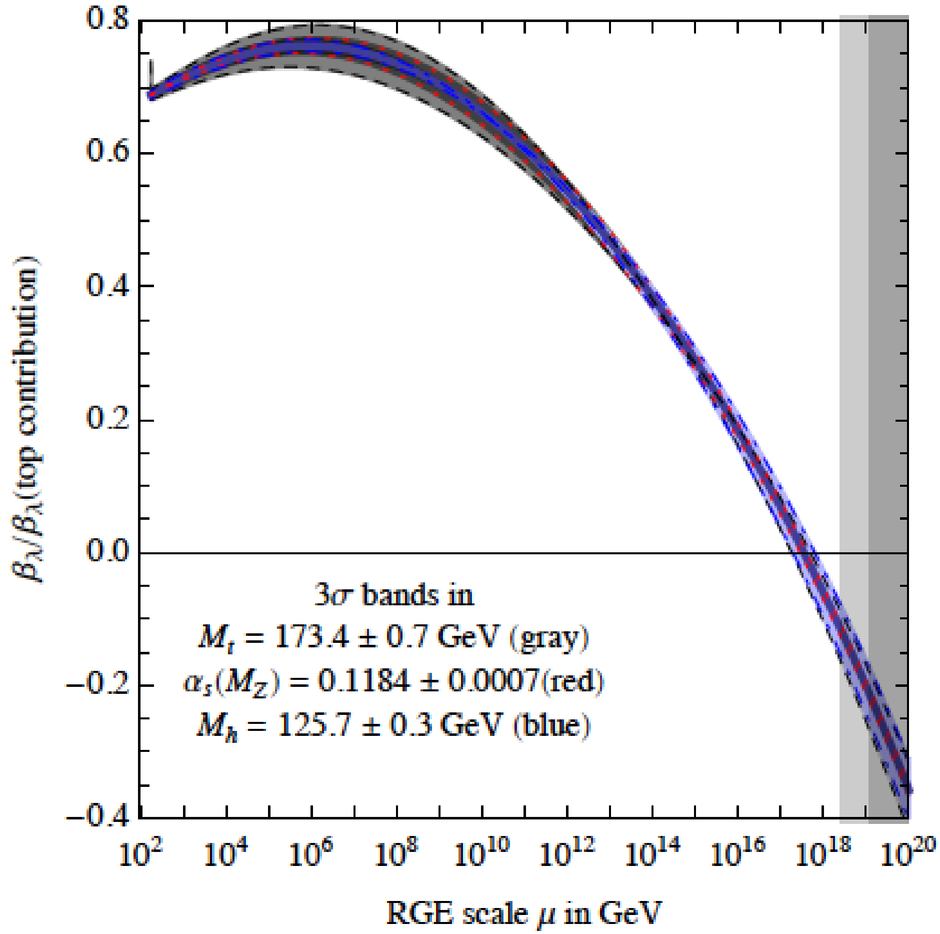




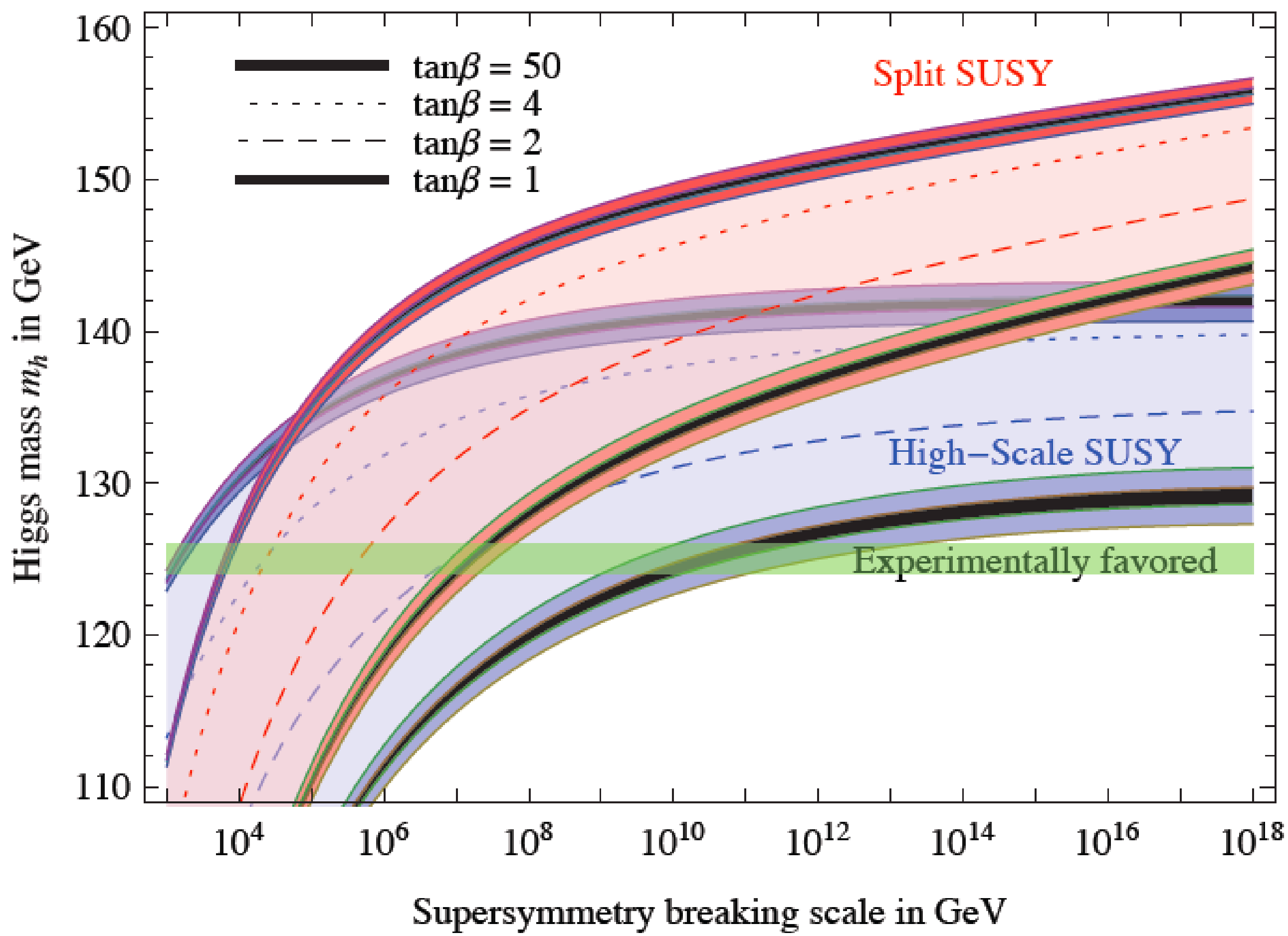
N.B.: using "natural units" the smallness of λ seems more "accidental"

High-scale matching and SUSY

The smallness of λ certainly fits well with the possibility of a high-scale matching with a weakly coupled theory, such as various versions of SUSY [*high-scale/split/mini-split*...]

Giudice & Strumia '11-'12

Arvanitaki, Craig, Dimopoulos, Villadoro, '12



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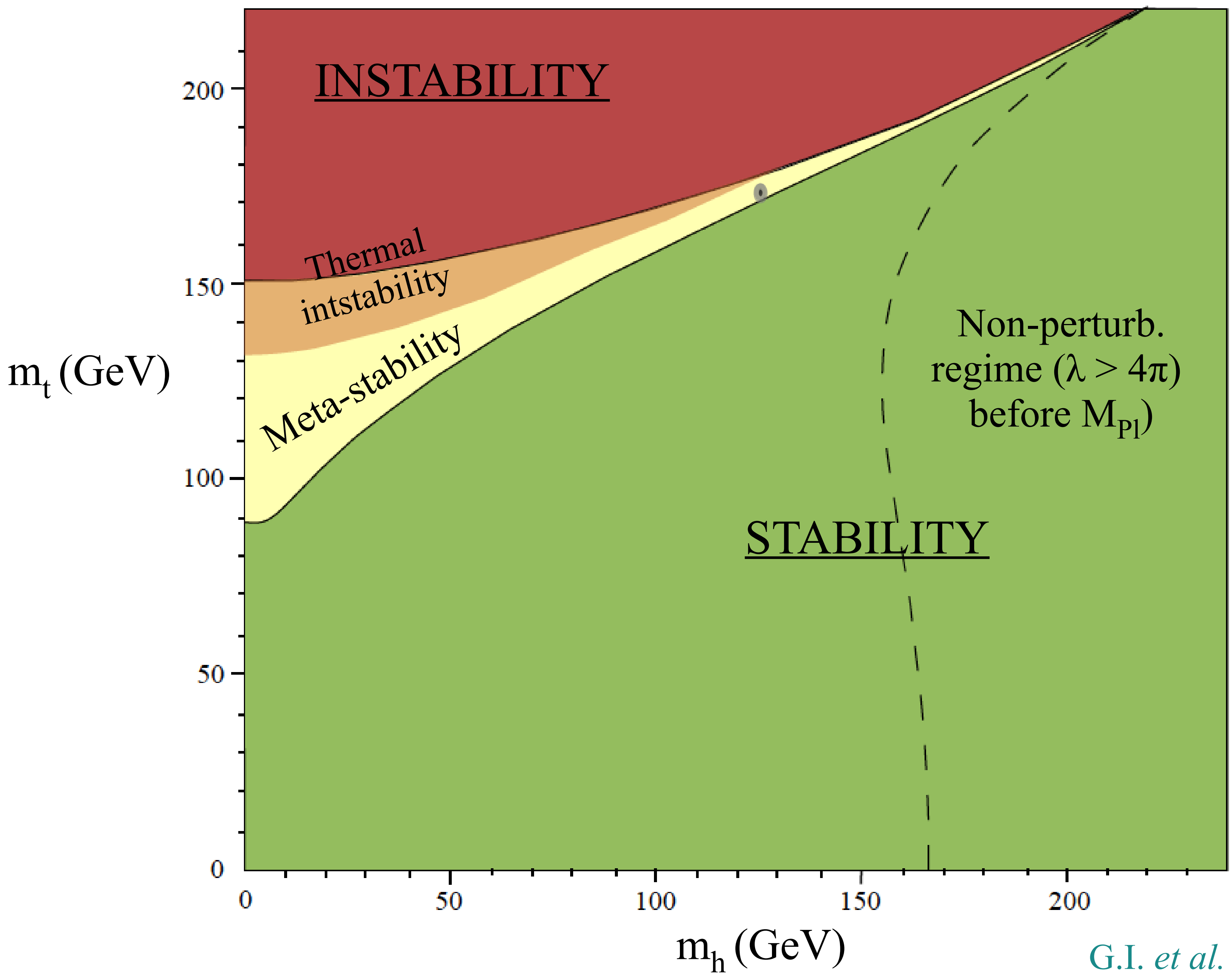
A closer look to the simplest case:
(unsplitted) high-scale SUSY → common SUSY mass M_S

To a good accuracy, the prediction for m_h is obtained imposing this UV matching condition,

$$\lambda(M_S) = \frac{1}{8}\left[g^2(M_S)+g'^2(M_S)\right]\cos(2\beta) + \frac{3}{16\pi^2}\, y_t(M_S)^4\, \widetilde{X}_t \qquad 0 < \widetilde{X}_t < 6$$

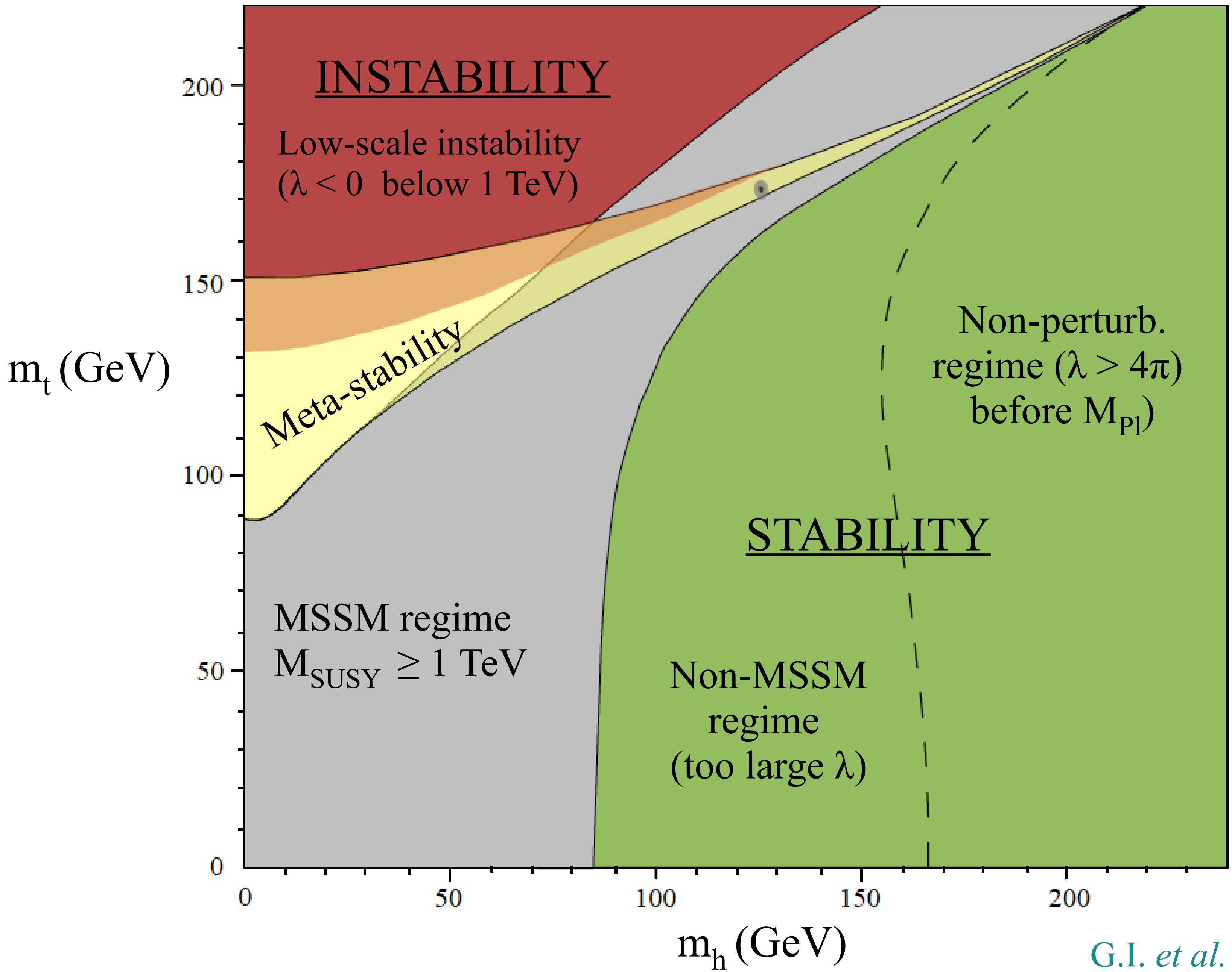
and running down to the e.w. scale using SM RGE

High-scale matching and SUSY



G.I. *et al.* - work in prog.

High-scale matching and SUSY



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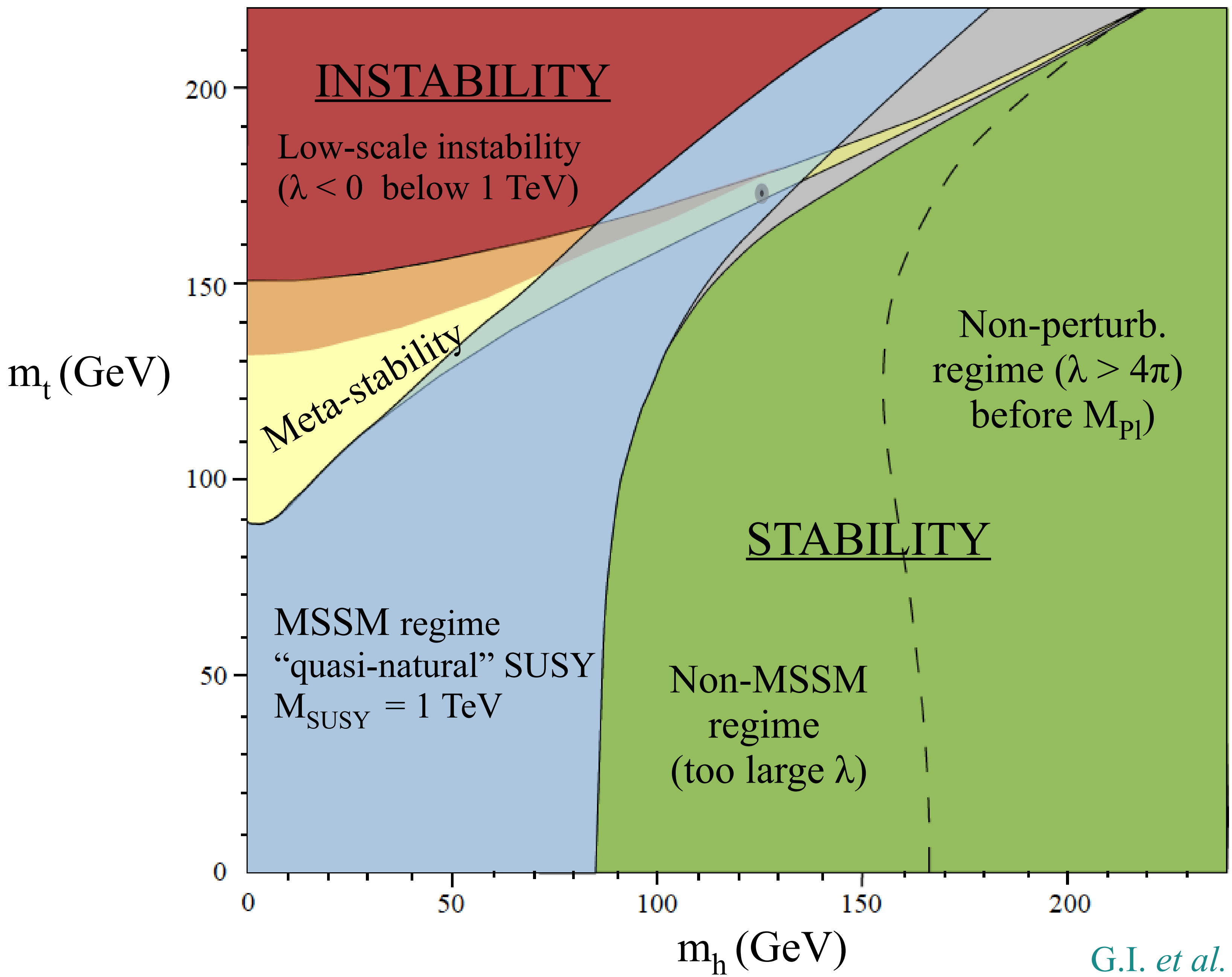

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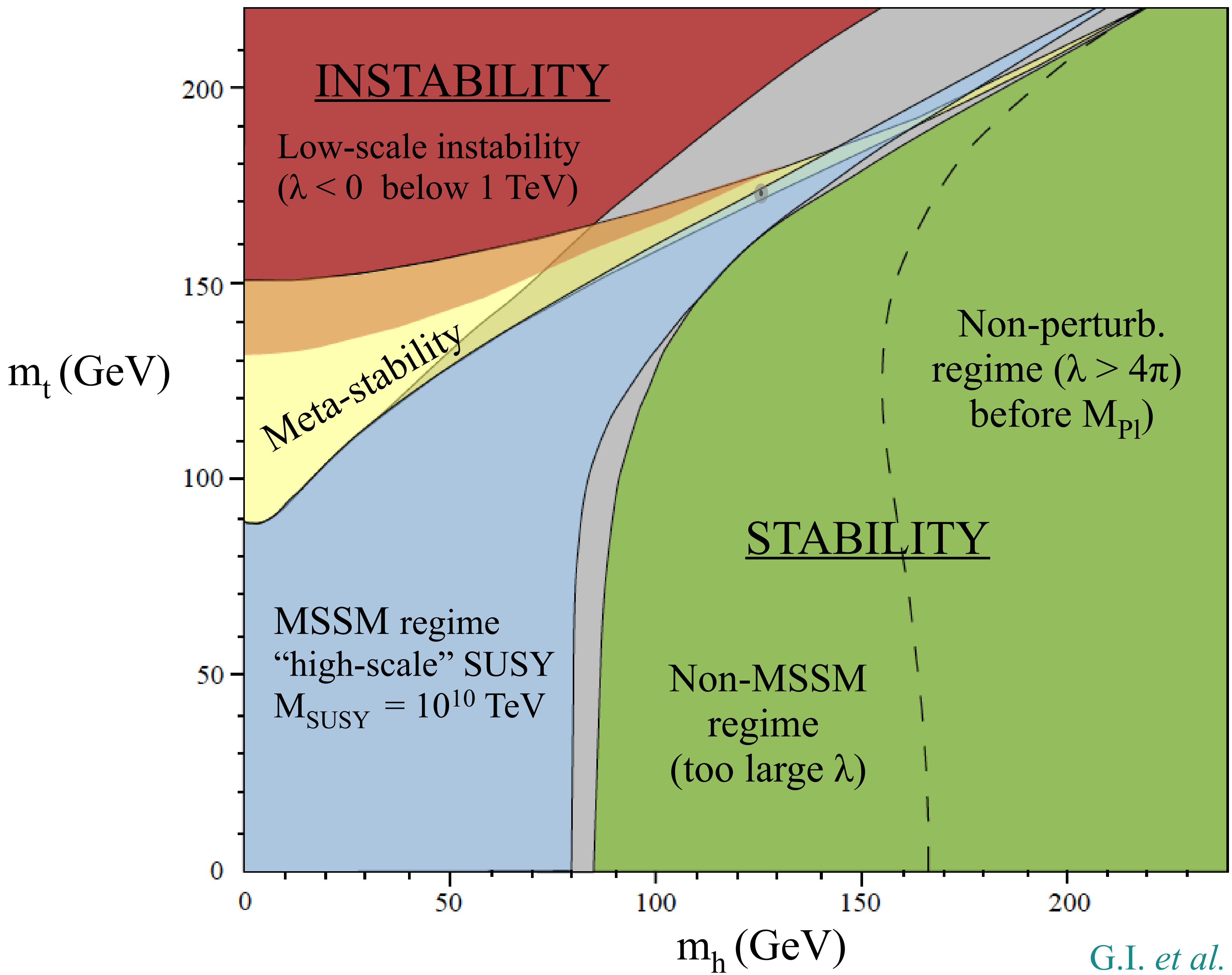

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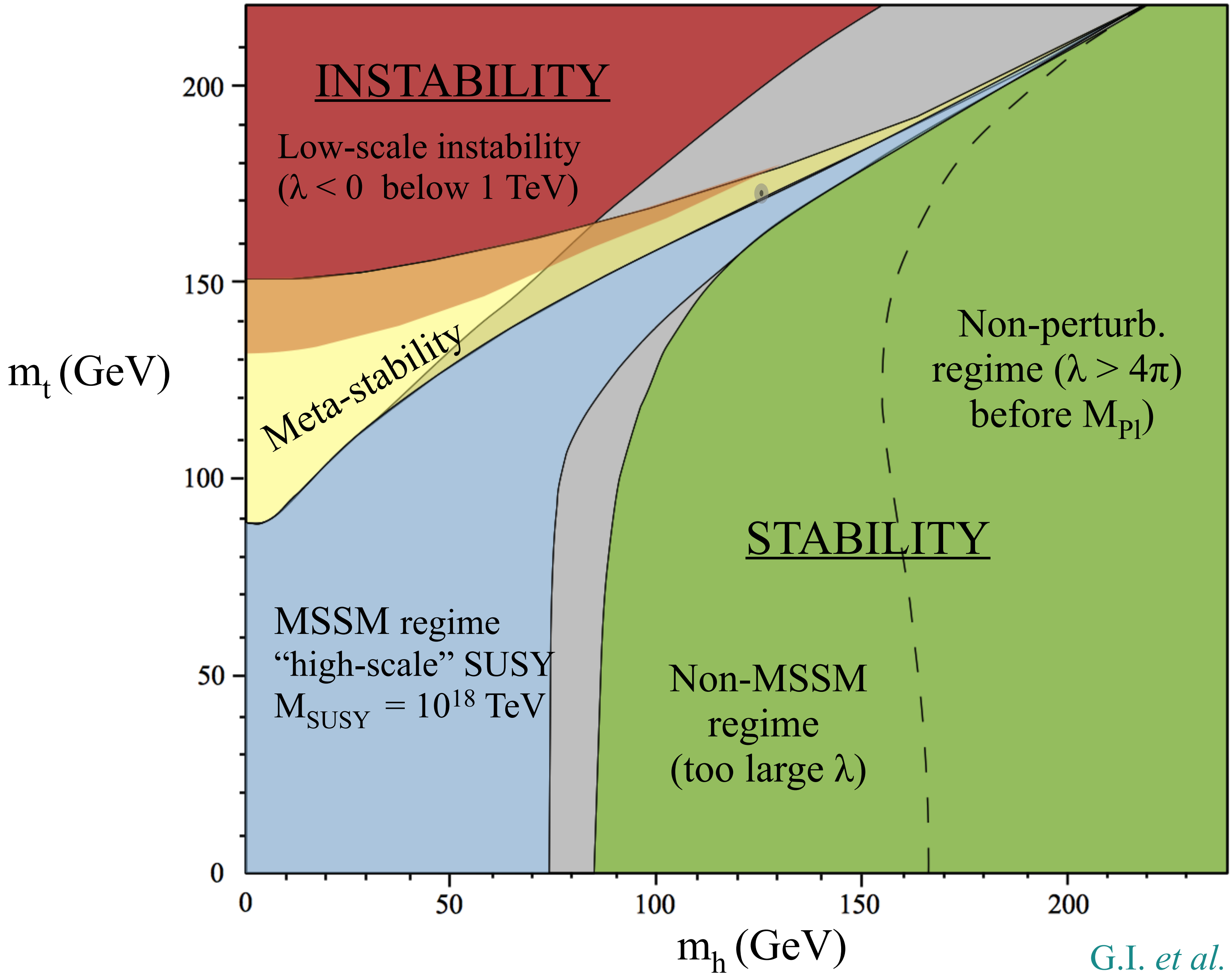

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Conclusions

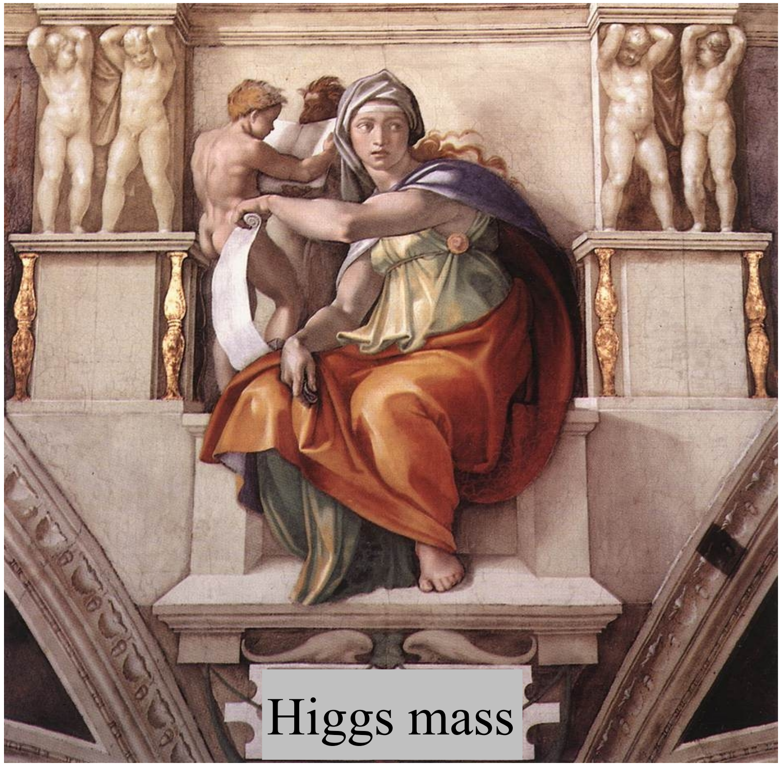
- A SM-like Higgs with $m_h \sim 125$ GeV does not allow us to derive model-independent conclusions about the scale of New Physics: the SM Higgs potential is unstable but sufficiently long-lived.

- Clear indication of a small λ at high energies: SUSY remains an excellent candidate as UV completion of the SM, but m_h alone leaves open a wide range of values for the SUSY breaking scale.

- The peculiar "doubly-critical" structure of the Higgs potential may be the indication some (*non-completely understood yet*) statistical phenomenon, as expected in the "Multiverse".

Conclusions

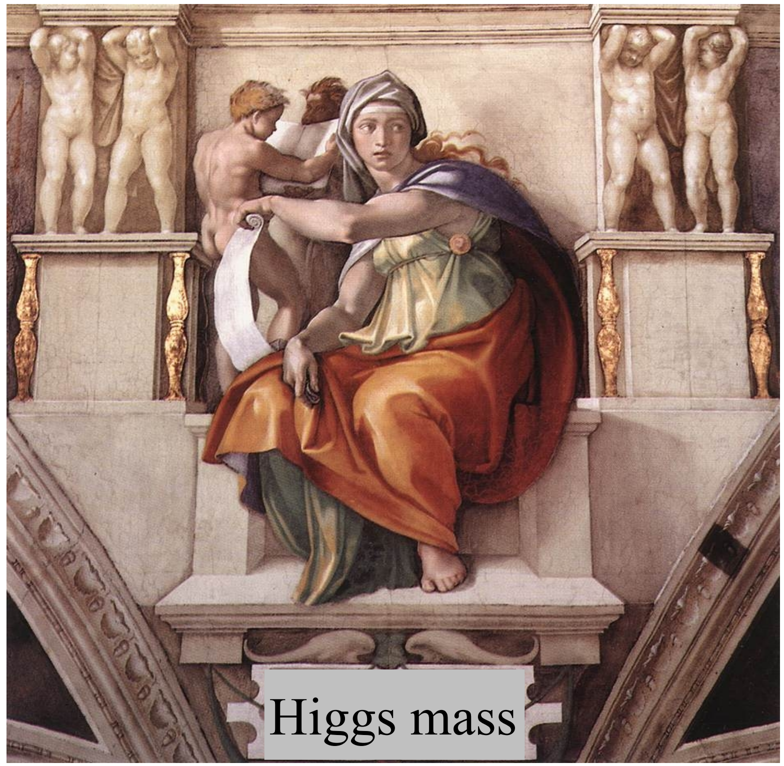
My understanding of the “Higgs-mass oracle”:



“ SM valid up to high scales No SUSY will show at LHC13 ”

▶ Conclusions

My understanding of the “Higgs-mass oracle”:

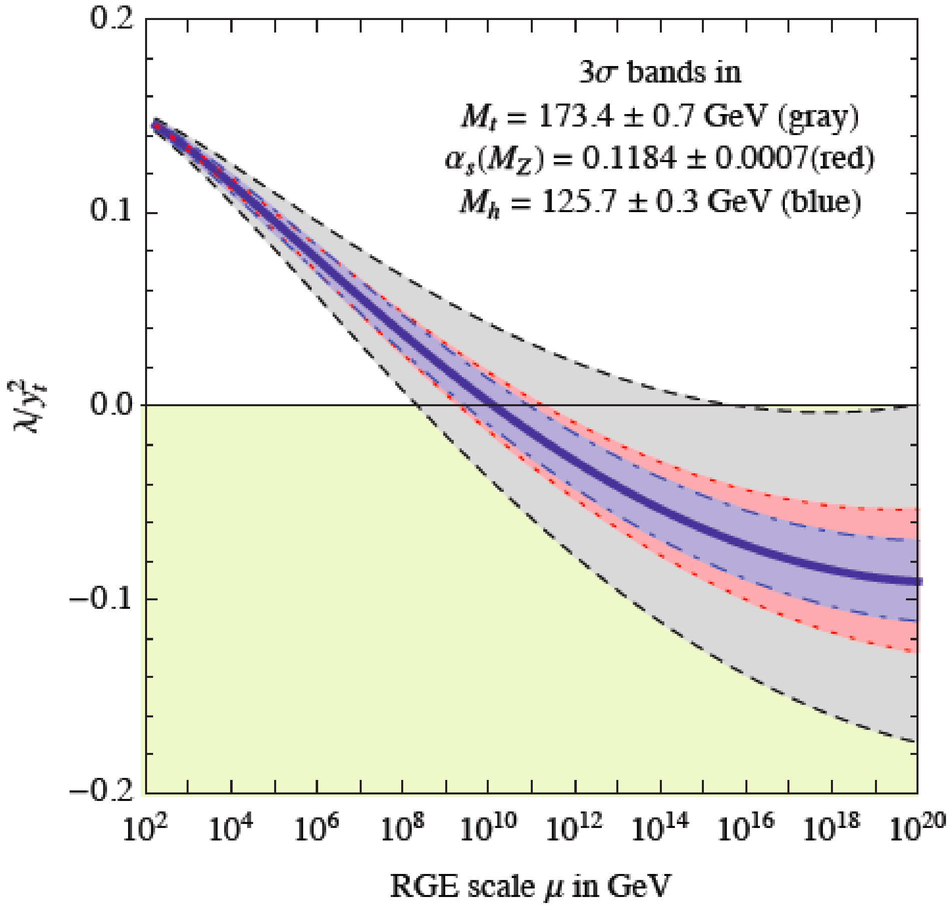


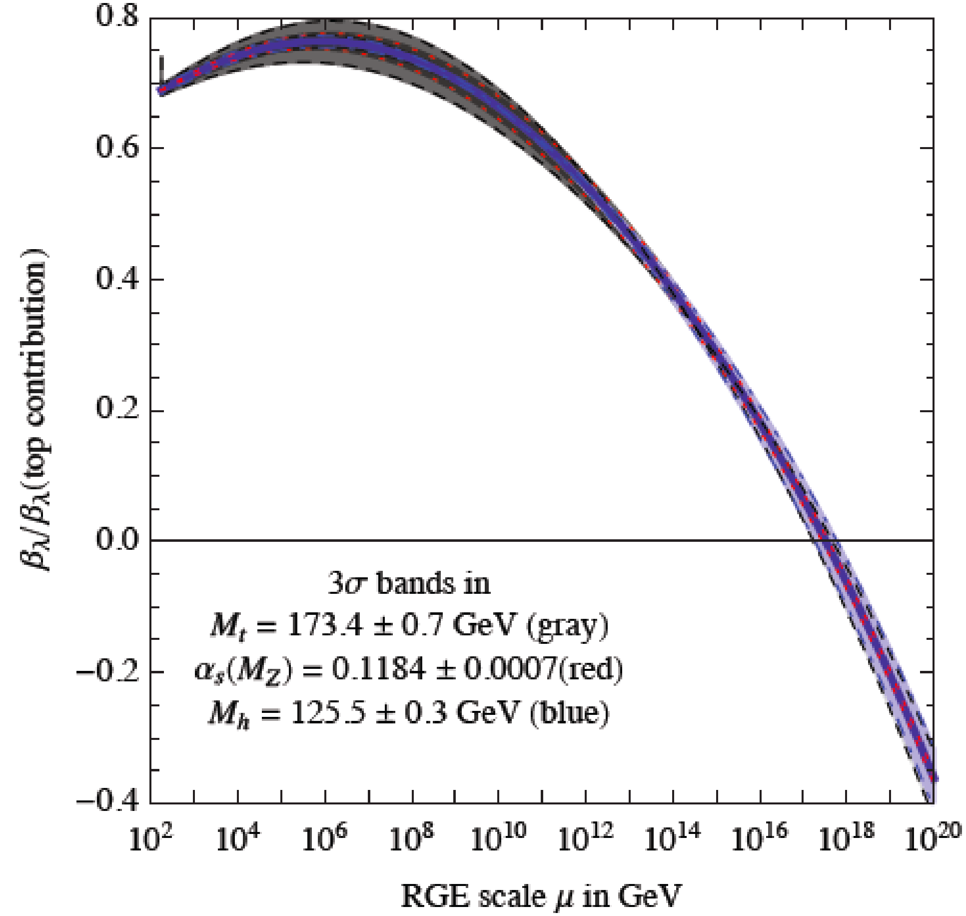
“ SM valid up to high scales No SUSY will show at LHC13 ”

SM valid up to high scales.
No SUSY will show at LHC13.

SM valid up to high scales?
No: SUSY will show at LHC13!

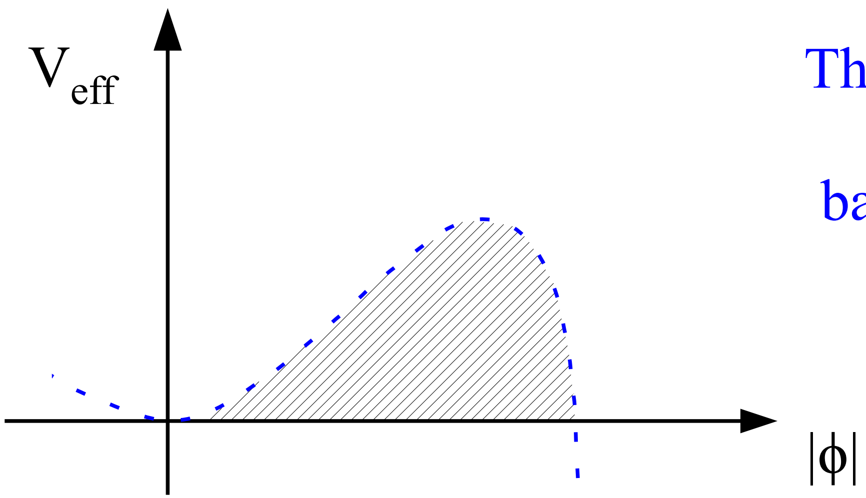

Backup





Rattazzi @ LHC-IT (Genova, 2013)

The quantum-tunneling rate:



The quantum tunneling occurs via bubble formation in the homogeneous background of the false (e.w.) minimum

Coleman '79

At the semi-classical level, the tunneling probability can be written as:

$$\boxed{p \approx K\, e^{-S_0[h]}}$$

Volume factor

$K \propto T_U^4$ not exactly calculable within the semi-classical approx.

Euclidean action

$$\int \frac{1}{2} (\partial_\mu h)^2 + V(h)$$

Bounce

solution of the e.o.m. that interpolates between the false and the true vacuum

N.B.: within a QFT (system with infinite d.o.f.) the tunneling is suppressed even in absence of a potential barrier (kinematic barrier due to the boundary conditions)

✯ *The quantum-tunneling rate:*

If we neglect the mass term, the tree-level Higgs potential is scale invariant & its bounces have a rather simple form:

$$h(r) = \left(\frac{2}{|\lambda|}\right)^{1/2} \frac{2R}{r^2+R^2}$$

$r = x_\mu x_\mu$ $O(4)$ invariant bounces minimize the action

$R =$ arbitrary scale parameter

$$\Downarrow$$

$$S_0[h] = \frac{8\pi^2}{3|\lambda|} \quad \Longrightarrow \quad p_{semicl.} \approx (T_U/R)^4\, e^{-8\pi^2/3|\lambda|}$$

If $|\lambda|$ remains sufficiently small, the tunneling rate can be very suppressed

N.B.: the tunneling rate is a pure non-perturbative phenomenon - cannot be computed to any finite order in "ordinary" perturbation theory [*wrong choice of the vacuum*]

✯ The quantum-tunneling rate:

To go beyond the semi-classical level we need to take into account the quantum fluctuations around the (non-constant) bounce solution

Callan, Coleman '79

Non-trivial problem which has been solved (semi-analytically) in the SM case:

G.I., Ridolfi, Strumia '01

⬇

- Quantum corrections break scale invariance
- The tunneling is dominated by bounces of size R, such that $\lambda(1/R)$ reaches its minimum value:

$$p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(\mu)|} - \Delta S(\mu R) \right]$$

μ independent

$\Delta S \approx 0$ if we set $\mu = 1/R$

✯ The quantum-tunneling rate:

To go beyond the semi-classical level we need to take into account the quantum fluctuations around the (non-constant) bounce solution Callan, Coleman '79

Non-trivial problem which has been solved (semi-analytically) in the SM case:

G.I., Ridolfi, Strumia '01

- Quantum corrections break scale invariance
- The tunneling is dominated by bounces of size R, such that λ(1/R) reaches its minimum value
- The critical R determine the reference scale of the volume pre-factor:

$$p \approx \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(1/R)|} \right]$$

The leading gravitational effects are also calculable when 1/R is not far from (but below) M_{pl}

G.I., Rychkov, Strumia, Tetradis '08

Buttazzo *et al.* '13:

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]	—

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