# Higgs Near-Criticality

Higgs Couplings 2017
Heidelberg
7/11/17

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# OUTLINE

- ★ Context.
  SM extrapolated to UV
- ★ EW Vacuum Metastability
  Higgs near-criticality
- ★ Interplay with BSM
- ★ Planckian effects ?
- ★ Cosmological implications

# CONTEXT, 20~~12~~, ~~13~~, ~~14~~, ~~15~~, ~~16~~, 17

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

$$V = \frac{1}{2} m^2 h^2 + \frac{1}{4} \lambda h^4 \Rightarrow \langle h \rangle^2 \sim \frac{m^2}{\lambda} \sim \text{EW}$$

$$m^2 \sim \frac{1}{(4\pi)^2} \Lambda^2$$

# CONTEXT, 2017

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

⇩

$\Lambda \sim$ few TeV

## CONTEXT, 2017 / THIS TALK

- Higgs discovered, close to SM-like

+

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

+

- Disregarding naturalness

⇩

$\Lambda \sim M_{Pl}$ ?

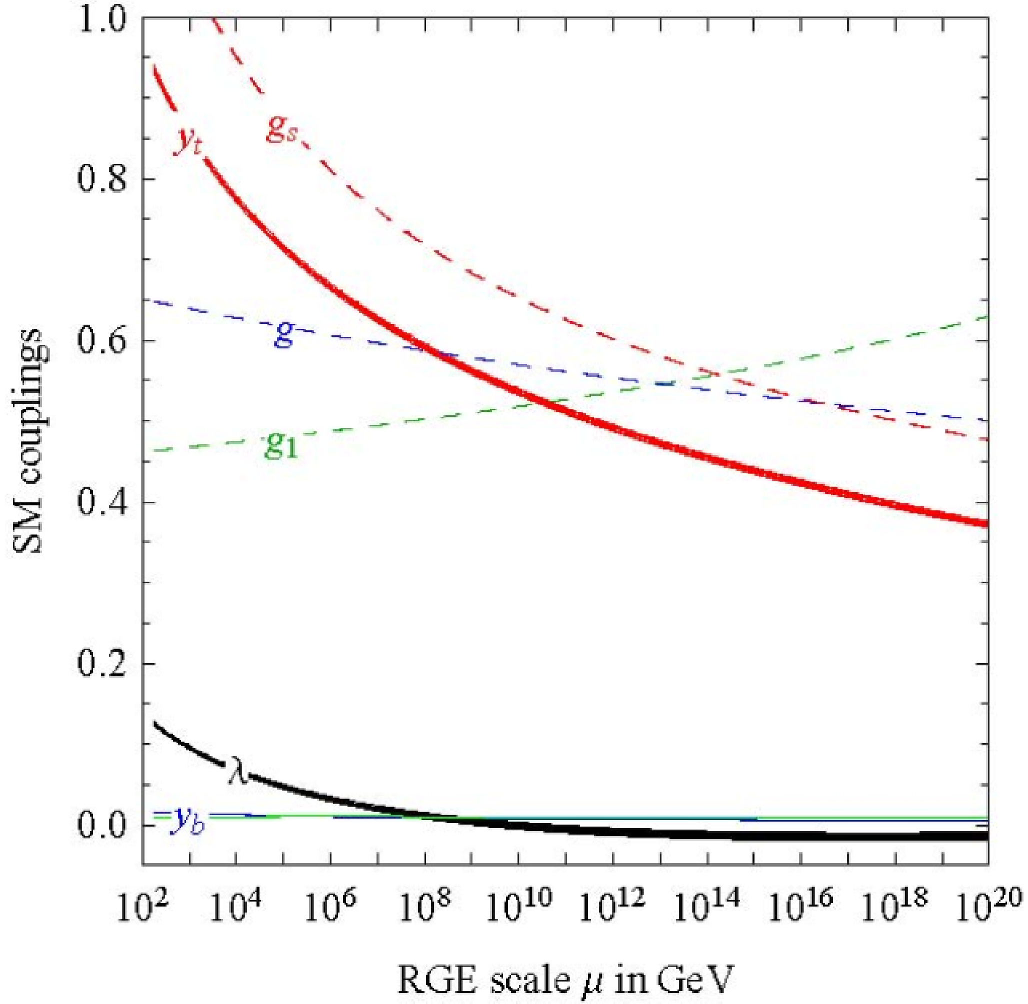
Non trivial possibility: can extrapolate SM to $M_{Pl}$

# SM EXTRAPOLATION

Assume Higgs has SM props. and no BSM Physics

All SM parameters known

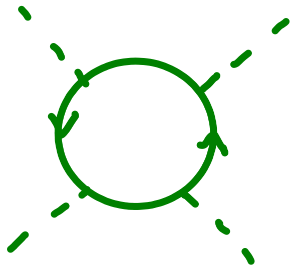
$M_h \Rightarrow \lambda(EW)$



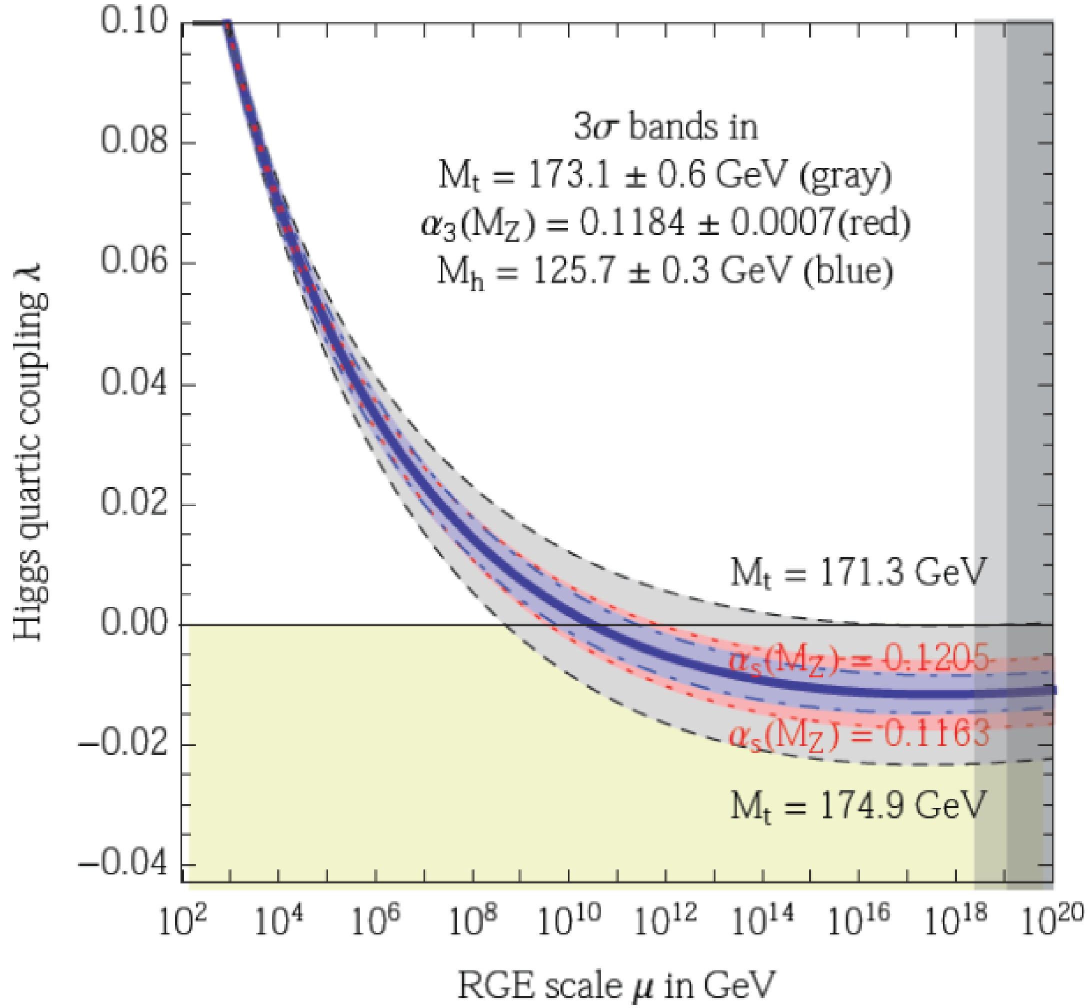

Weakly coupled up to $M_{Pl}$

# UV EXTRAPOLATED $\lambda$

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



$\lambda < 0$ at $\Lambda_I \sim 10^{11}$ GeV

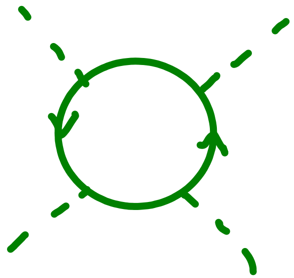



Degrassi et al '12, Buttazzo et al '13

(+ Bezrukov et al '12, Bednyakov et al '15)

# VACUUM INSTABILITY

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

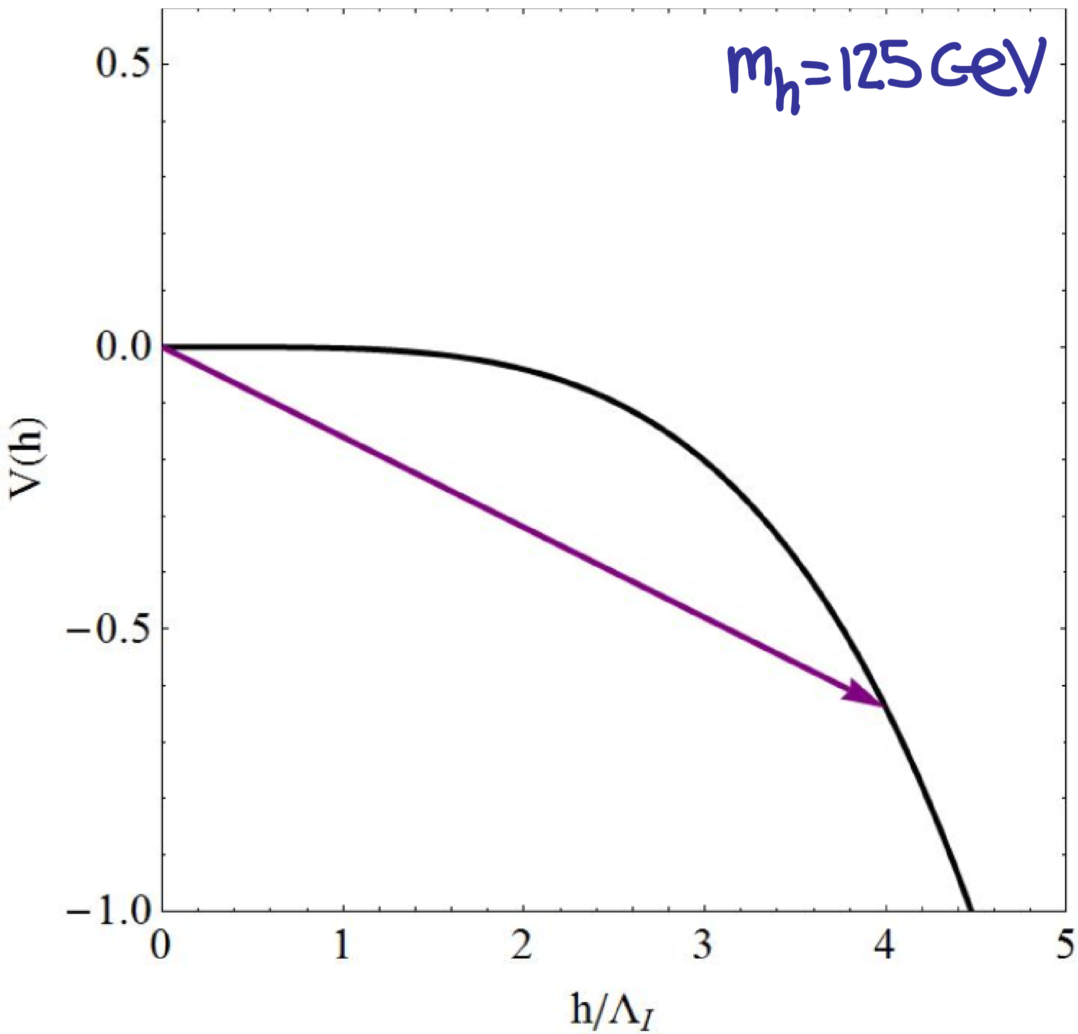


$\lambda < 0$ at $\Lambda_I \sim 10^{11}$ GeV

⇓

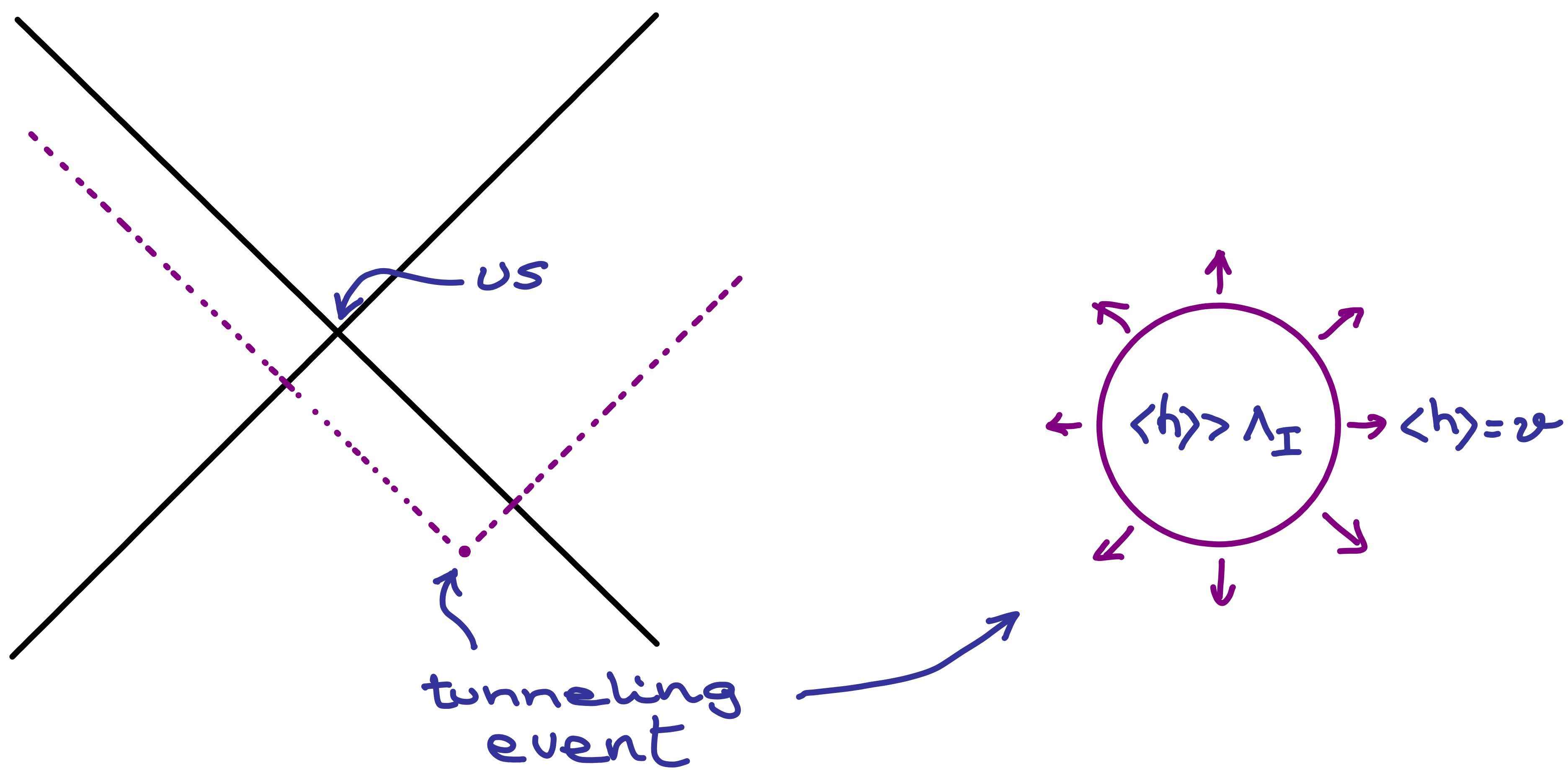
Higgs potential instability

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



# LIFE IN A METASTABLE VACUUM

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



# LIFE IN A METASTABLE VACUUM

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

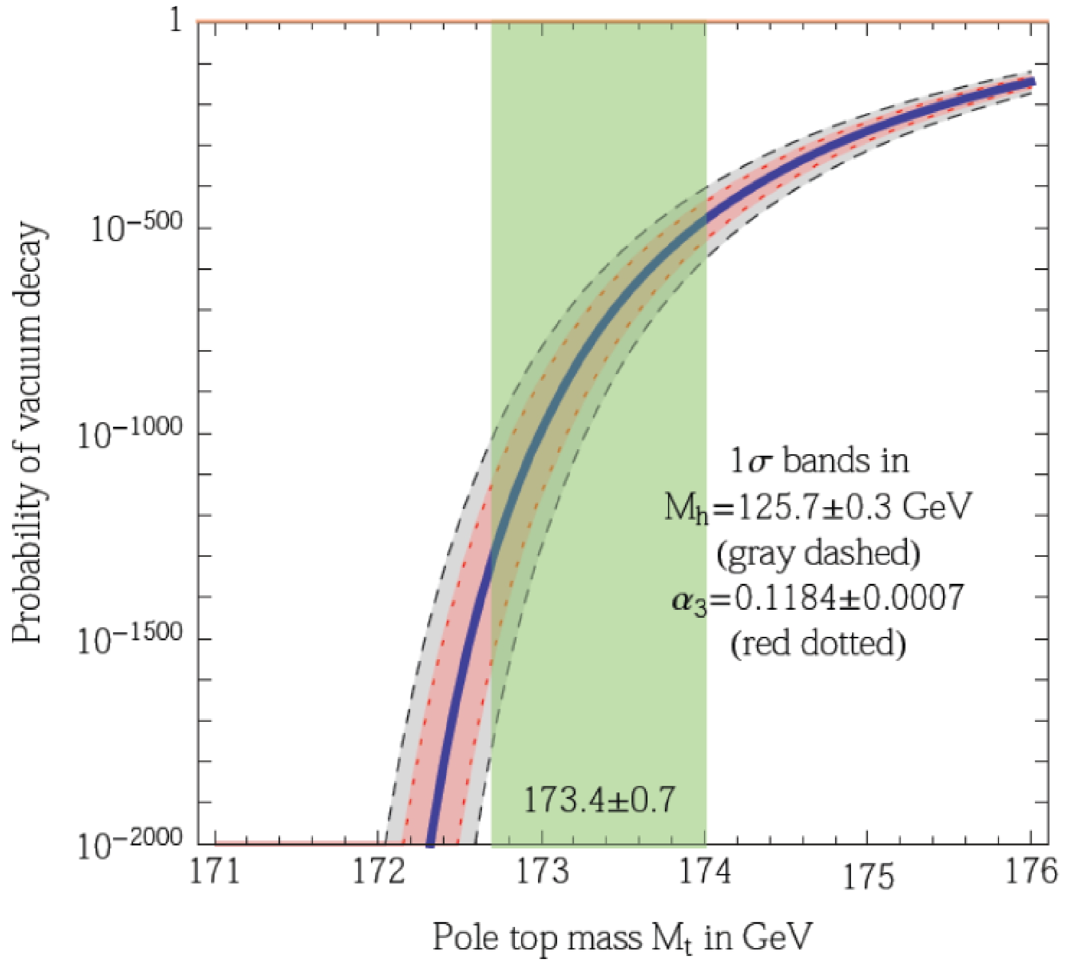
$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|\lambda|/0.01}\right]$$

(Isidori, Ridolfi, Strumia '01)

easily wins over $\tau_U^4$

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

# PROBABILITY OF VACUUM DECAY




Buttazzo et al '13

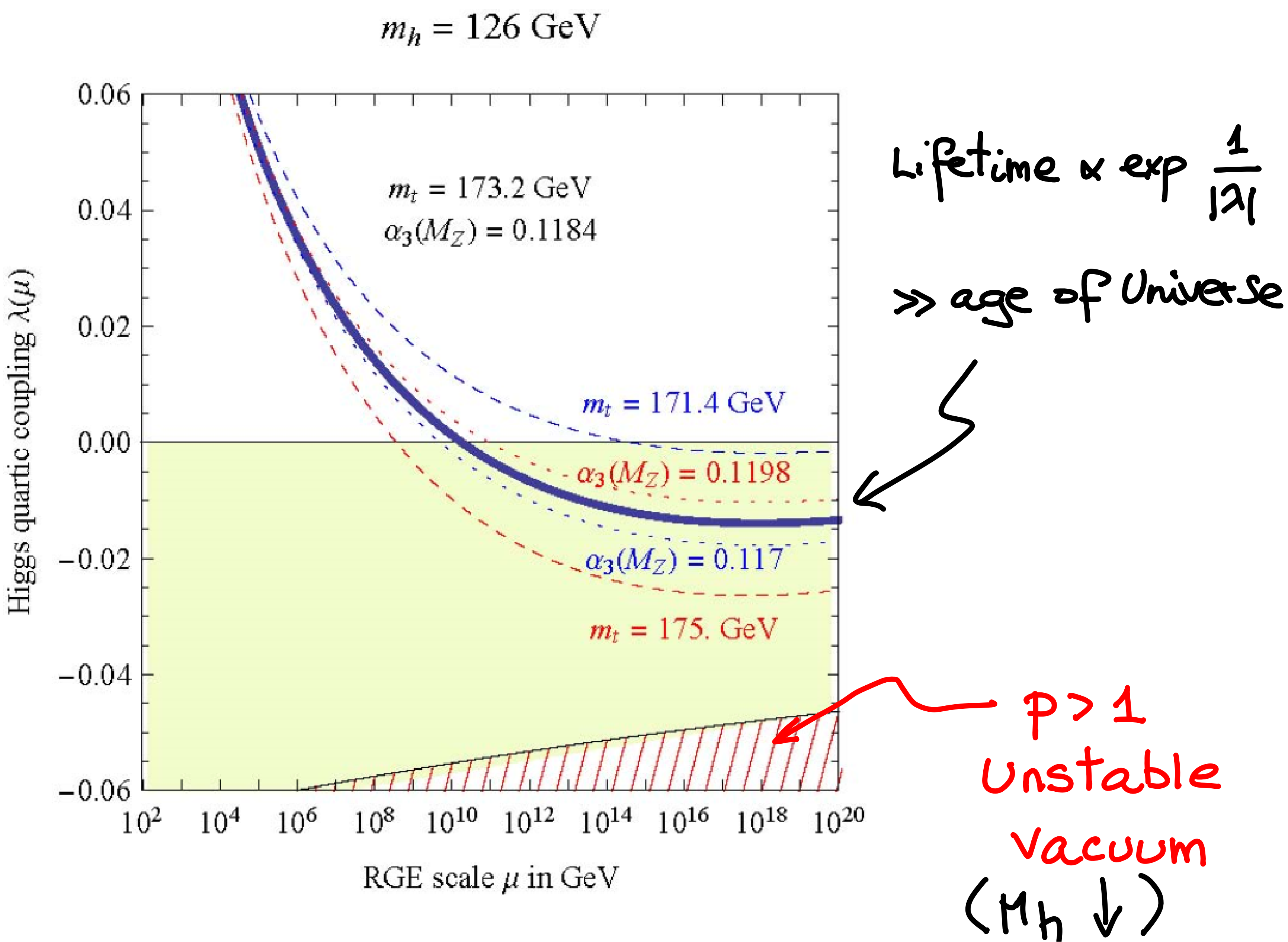
(+ Andreassen, Frost, Schwartz '17, + Chigusa, Moroi, Shoji '17)

# PROBABILITY OF VACUUM DECAY

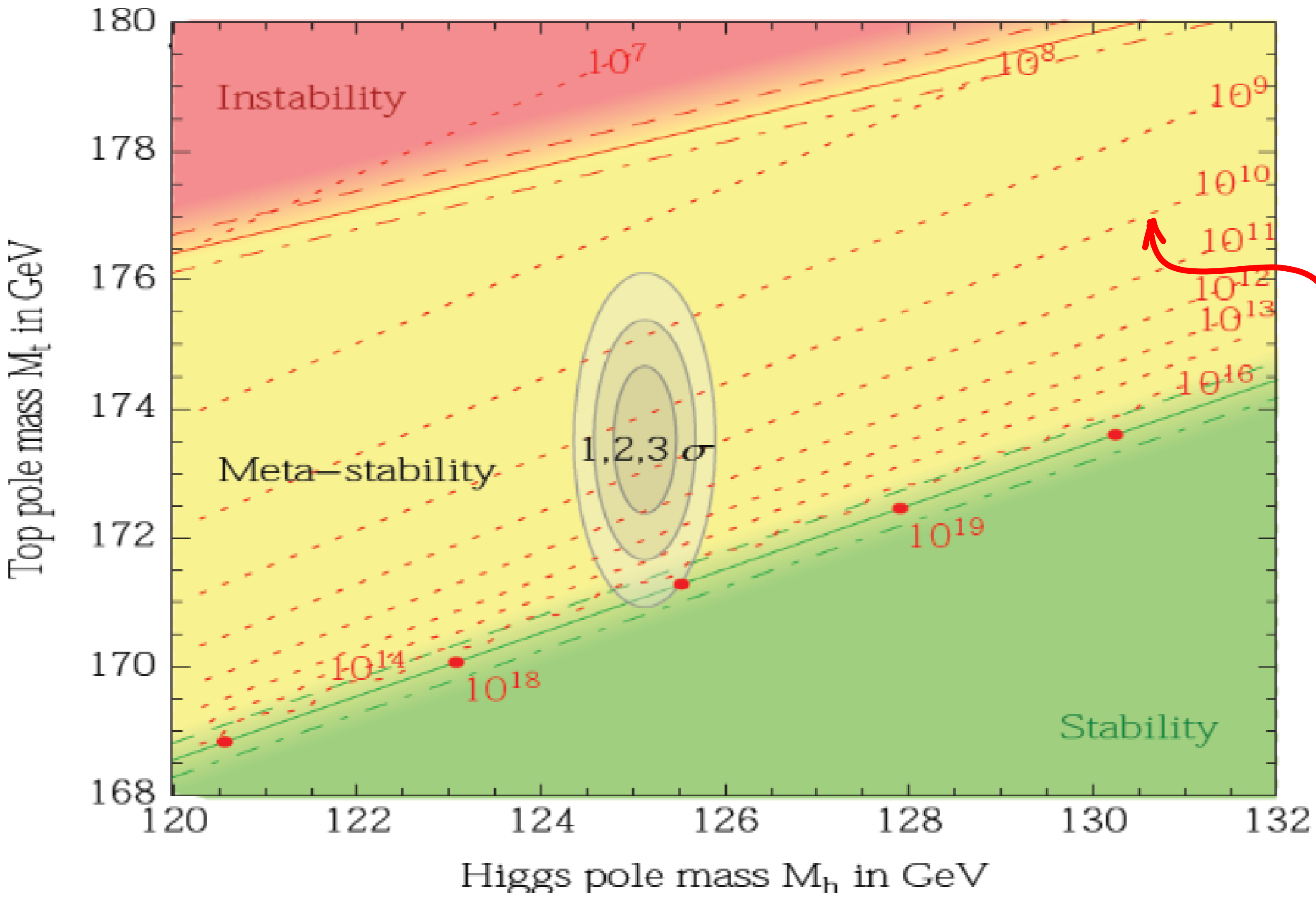
Q: Is BSM below $M_{Pl}$ required to cure the metastability of the EW vacuum?

A: No!

# LIFE IN A METASTABLE VACUUM



# HIGGS NEAR-CRITICALITY




Buttazzo et al '13

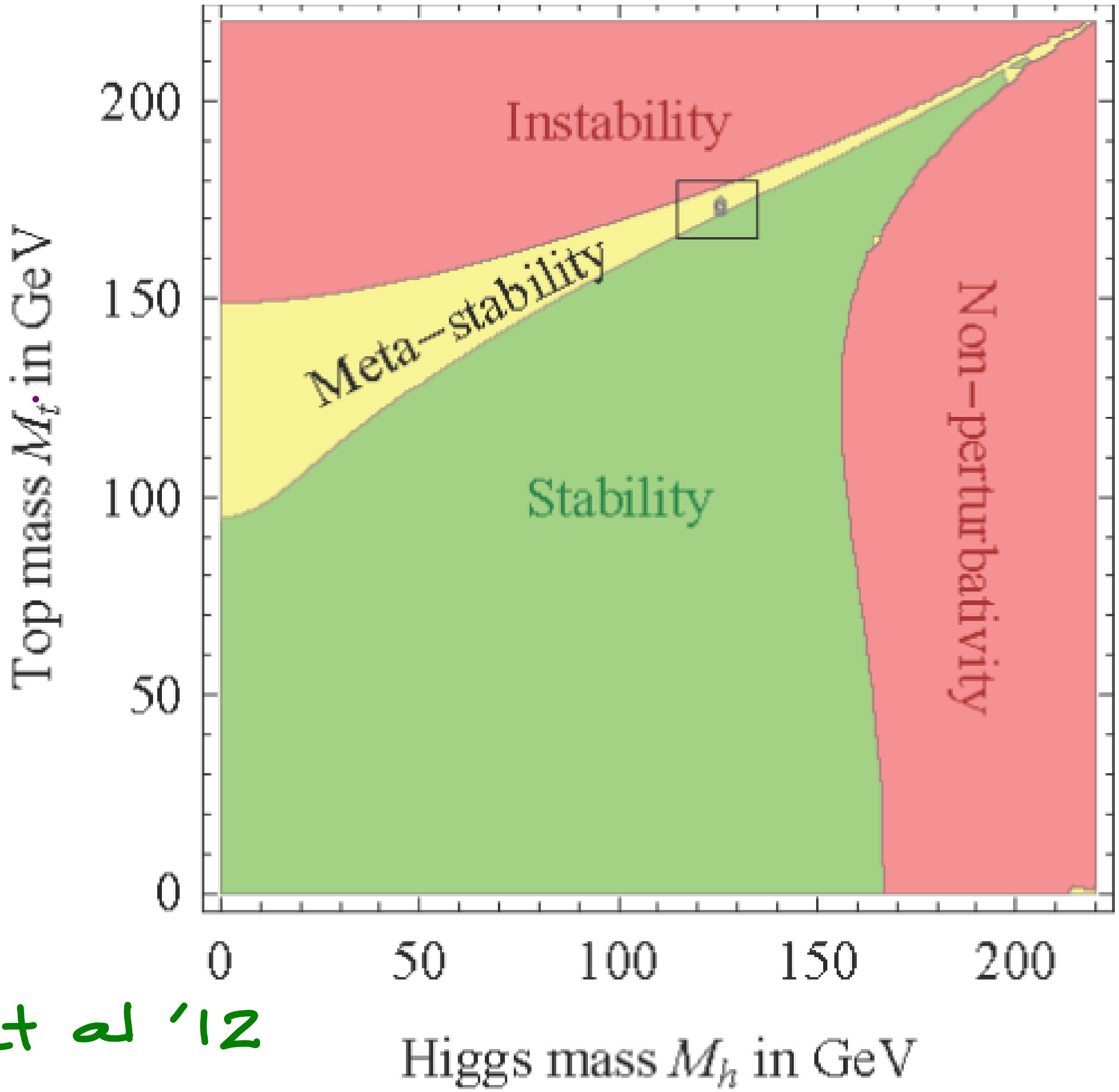
$\Lambda_I$ (GeV)

$M_h = 125.15 \pm 0.24$ GeV

$M_t = 173.34 \pm 0.76 \pm 0.3$ GeV

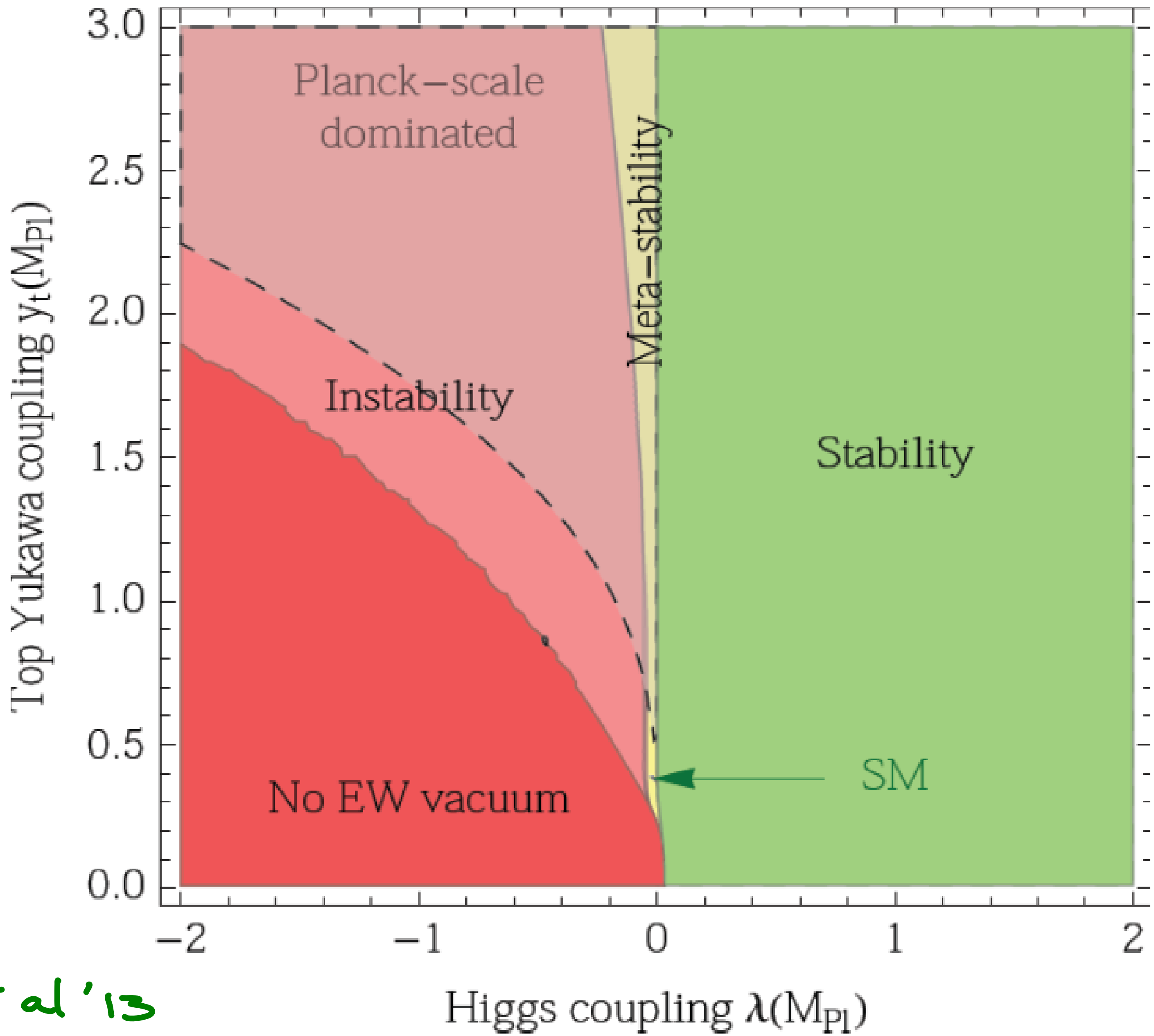
(back-up slides)

# HIGGS NEAR-CRITICALITY




Degrassi et al '12

# LIVING AT THE EDGE



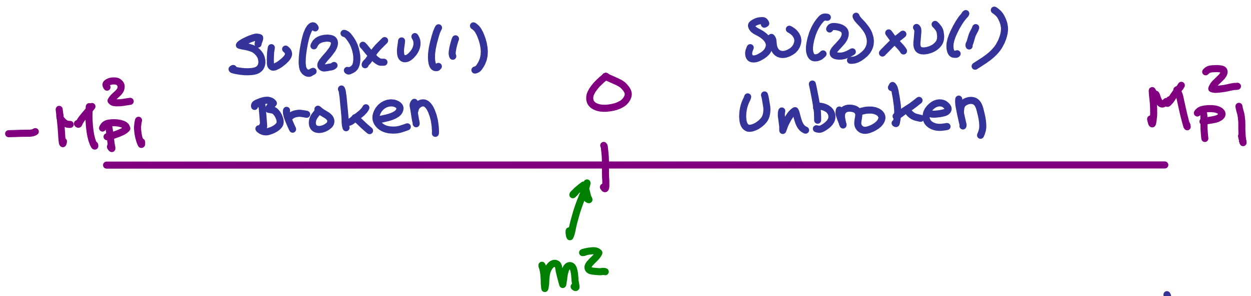

Buttazzo et al '13

# 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...

- Neutrino masses
- Matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Inflation

# 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 (and SUSY!) |

# BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

| | Example |
|---|---|
| IRRELEVANT | See-saw neutrinos $M_R \lesssim 10^{13}\,\mathrm{GeV}$ |
| MAKE IT WORSE | See-saw neutrinos $M_R \gtrsim 10^{13}\,\mathrm{GeV}$ |
| 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

# BSM IMPLICATIONS

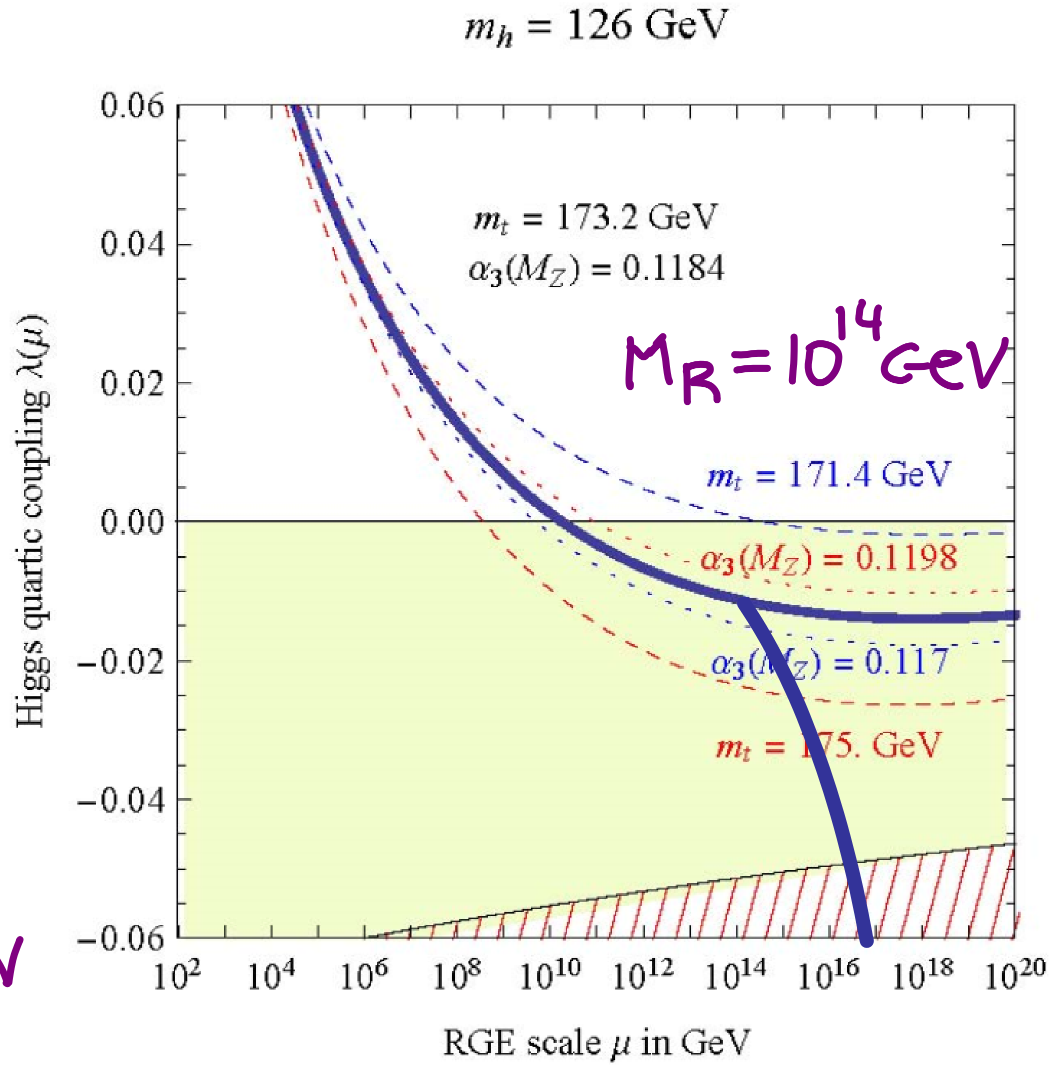
- See-saw neutrinos: Impact on $\beta_\lambda \supset - y_\nu^4/(16\pi^2)$ *

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

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

Adds to the top destabilizing effect

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

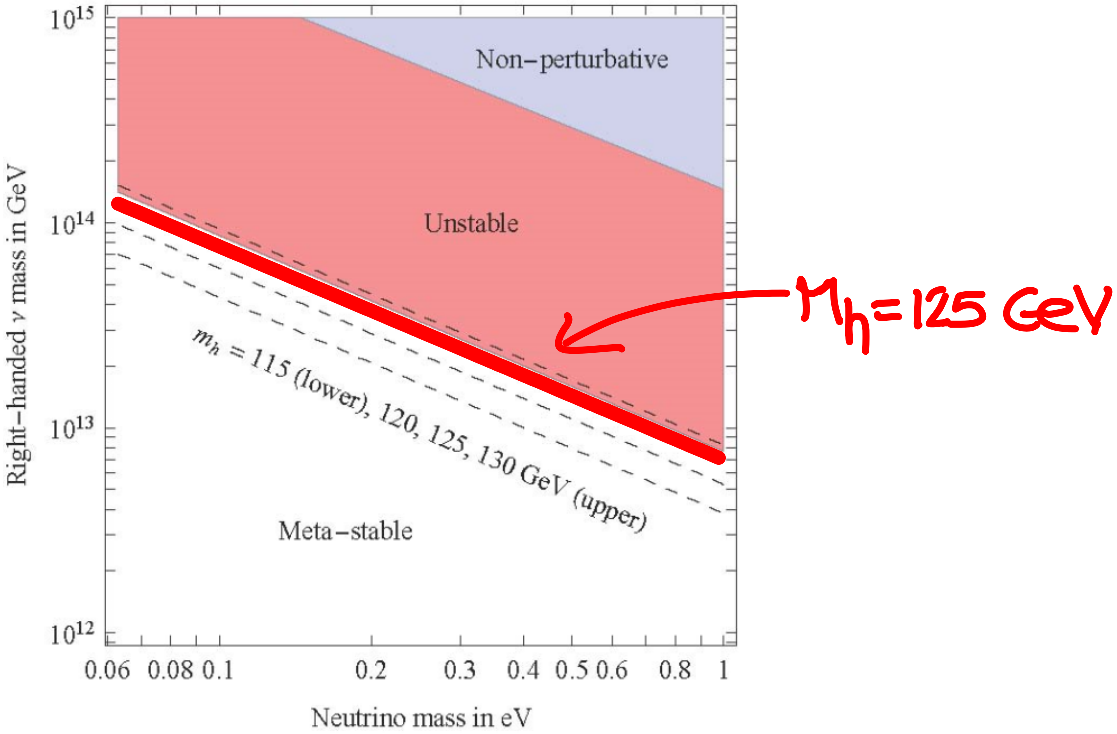



Elias-Miro et al. '11

# BSM IMPLICATIONS

- See-saw neutrinos : Bound on $M_{\nu_R}$

$M_R$




$m_\nu$

Elias-Miro et al '11

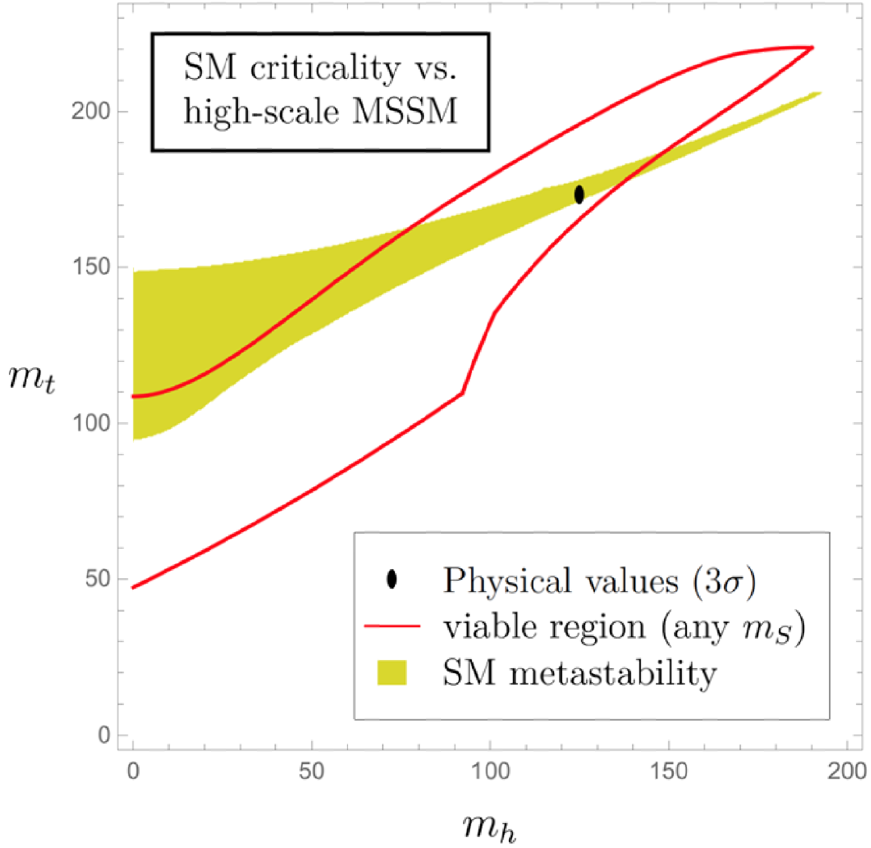
Useful to bound additional sources of instability.

# SM vs HIGH SCALE MSSM

Isidori, Pattori '17

MSSM

- Natural Non-split spectrum
- $m_S \lesssim 10^6$ GeV
- unification
- Radiative EWSB




⇨ Compatible with measured $(m_h, m_t)$

Less intriguing/remarkable than near-criticality...

# PLANCKIAN EFFECTS ?

Analysis relies on SM as effective QFT valid below $M_{Pl} \simeq 1.2 \times 10^{19}\,\mathrm{GeV}$

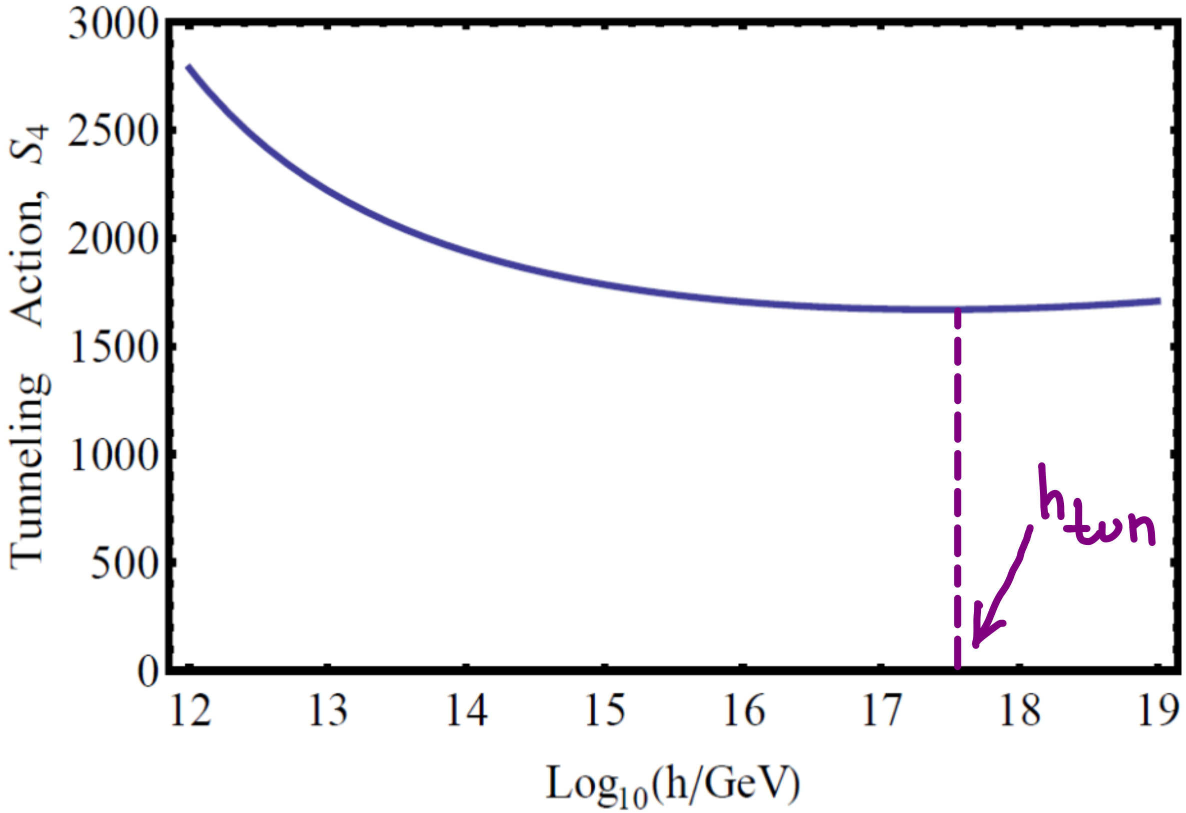
Field values or energy densities never become $\sim M_{Pl}^{(4)}$

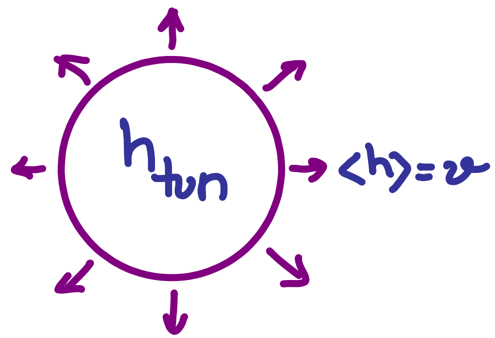
# TUNNELING BUBBLE

Remember: tunneling action $S_4 \simeq \frac{8\pi^2}{3|\lambda(h)|}$

⇨ Tunneling dominated by field value $h_{tun}$ where $|\lambda(h)|$ maximal

Arnold '89



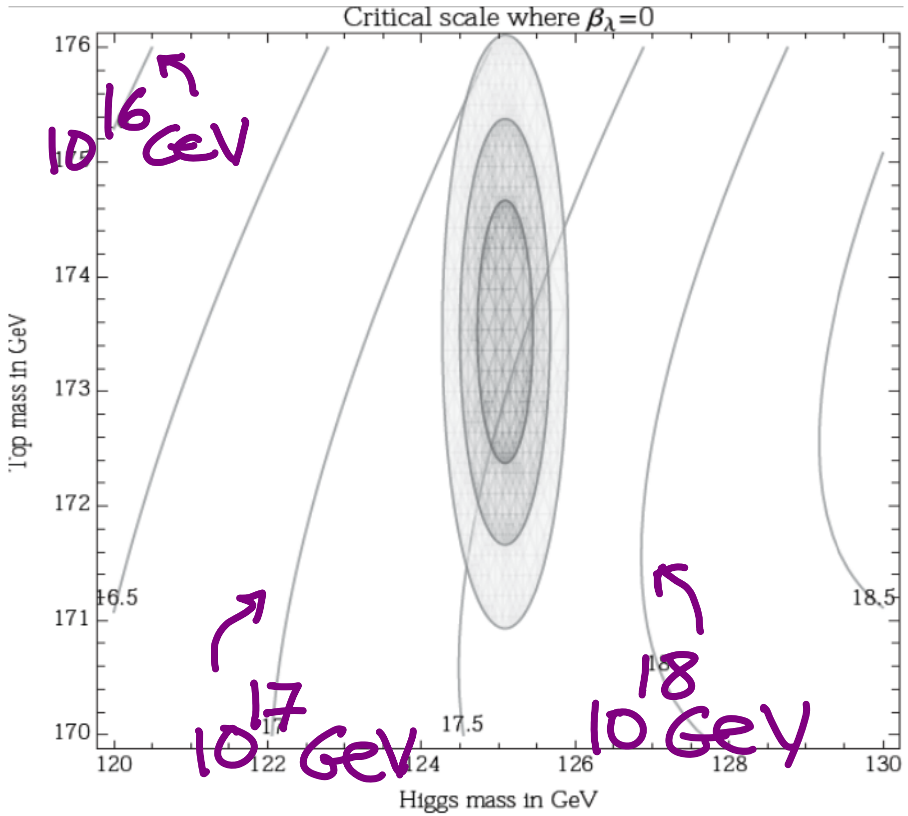




Although $h_{tun} \gg \Lambda_I$

Still, $h_{tun} < M_{Pl}$

# TUNNELING BUBBLE

However, $h_{tun}$ is not so far from $M_{Pl} = 1.2 \times 10^{19}$ GeV




A. Strumia

Tunneling might be sensitive to Planckian effects.

Gravitational (Coleman-De Luccia) corrections are included and small Isidori et al'08, Salvio et al'16

# PLANCKIAN EFFECTS ?

Analysis relies on SM as effective QFT valid below

$$M_{Pl} \simeq 1.2 \times 10^{19}\,\text{GeV}$$

Field values or energy densities never become $\sim M_{Pl}^{(4)}$

- What happens to $V(h)$ beyond $M_{Pl}$ ?

  No one knows. Most likely not describable by a QFT.

- Can gravitational physics have effects below $M_{Pl}$ ?

  This can be studied in $h/M_{Pl}$ expansion.

  (Analysis of non-ren ops & stability: Eichhorn et al'15)

# PLANCKIAN EFFECTS ?

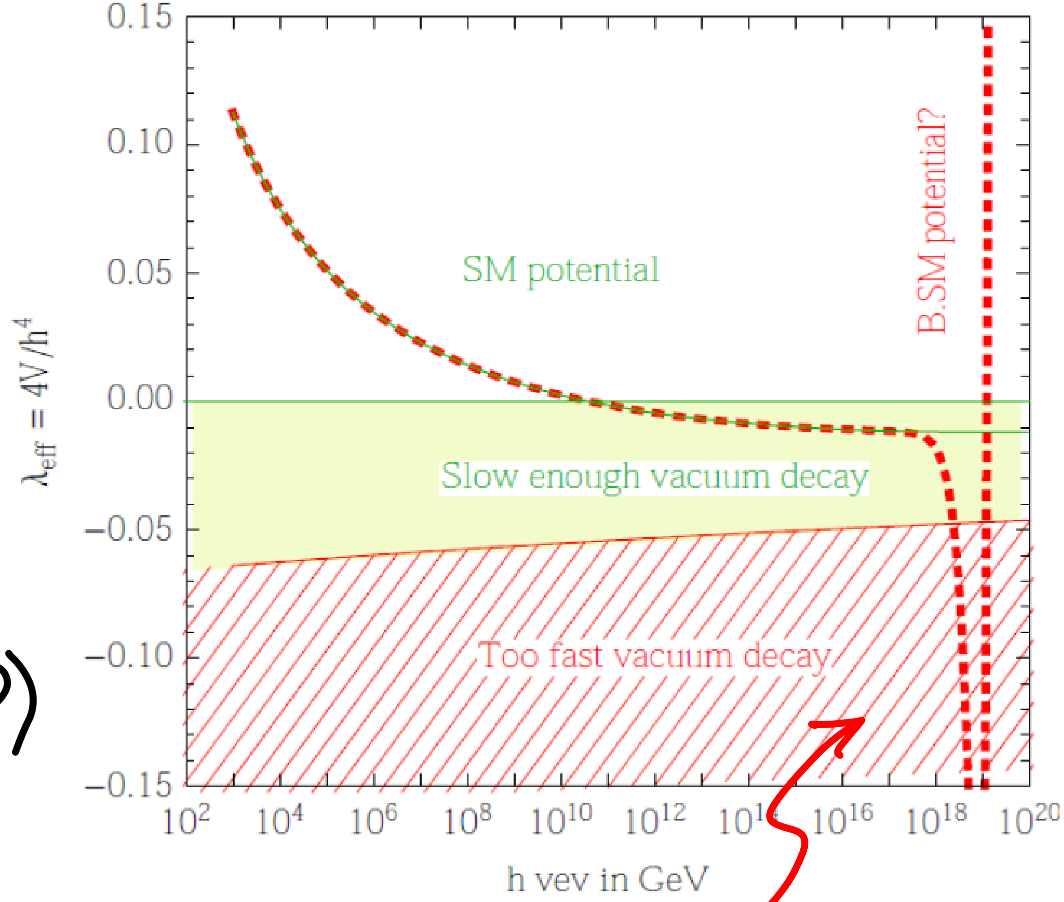
Branchina et al.

$$V = \frac{\lambda}{4} h^4 + \underbrace{\frac{\lambda_6}{6} \frac{h^6}{M_{Pl}^2} + \frac{\lambda_8}{8} \frac{h^8}{M_{Pl}^4}}_{\Delta V}$$

studied with

$\lambda_6 < 0 \qquad \lambda_8 > 0$

Tailored to create a minimum below $M_{Pl}$ (why?) by $\lambda_6 \leftrightarrow \lambda_8$ interplay




Potential made much more unstable

# PLANCKIAN EFFECTS ON $V(h)$ ?

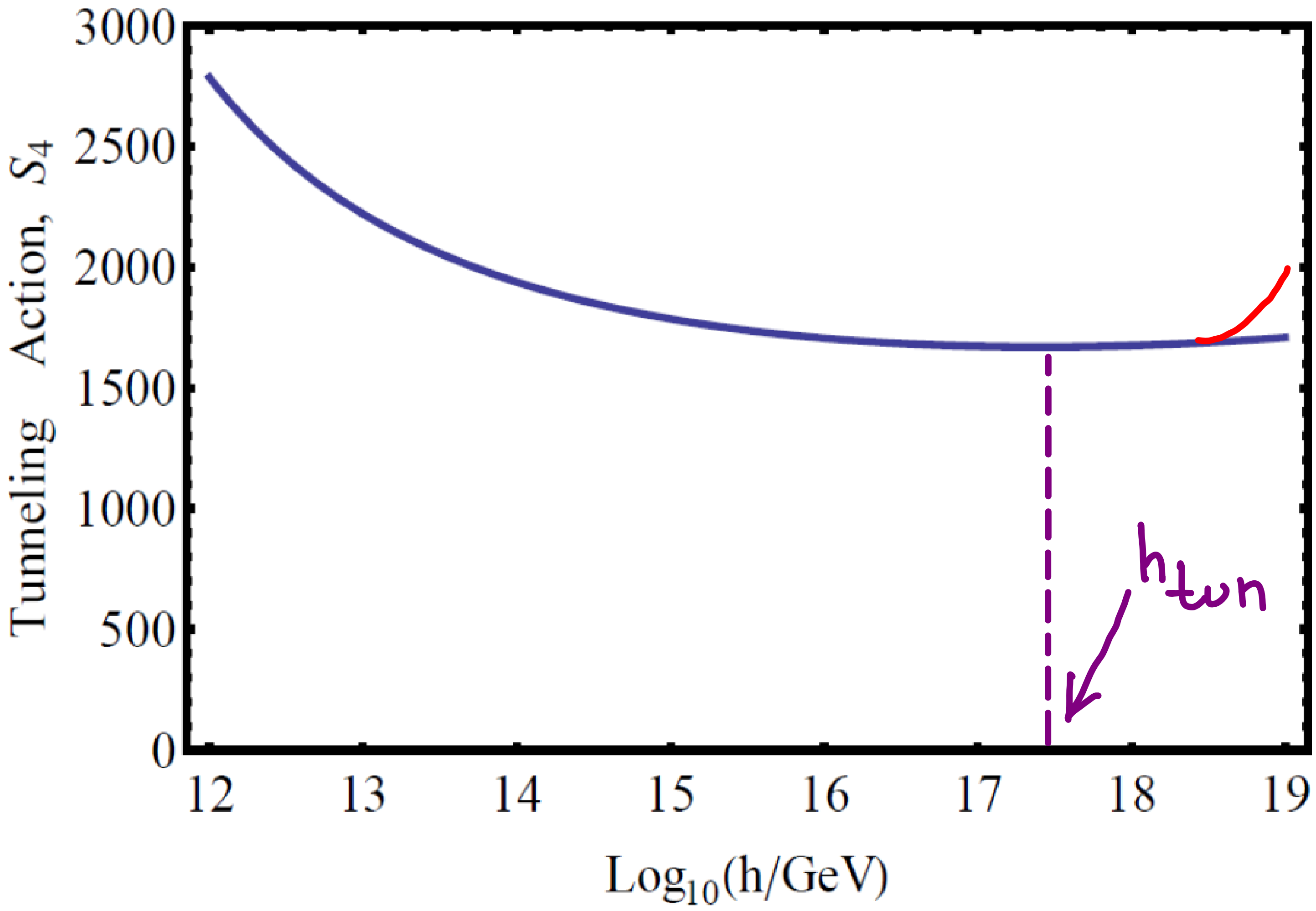
Q : Can $M_P$ physics make the potential stable ?

(eg. shifting the stability line towards the experimental values of $M_h$ & $M_t$ ? )

A : No.

# PLANCKIAN EFFECTS ON V(h)?

Effect on tunneling action $\Delta V > 0$ eg. $\lambda_6 > 0$




Tunneling action (and $h_{tun}$) unchanged

# PLANCKIAN EFFECTS ON V(h) ?

Q: Can Planckian physics spoil criticality?

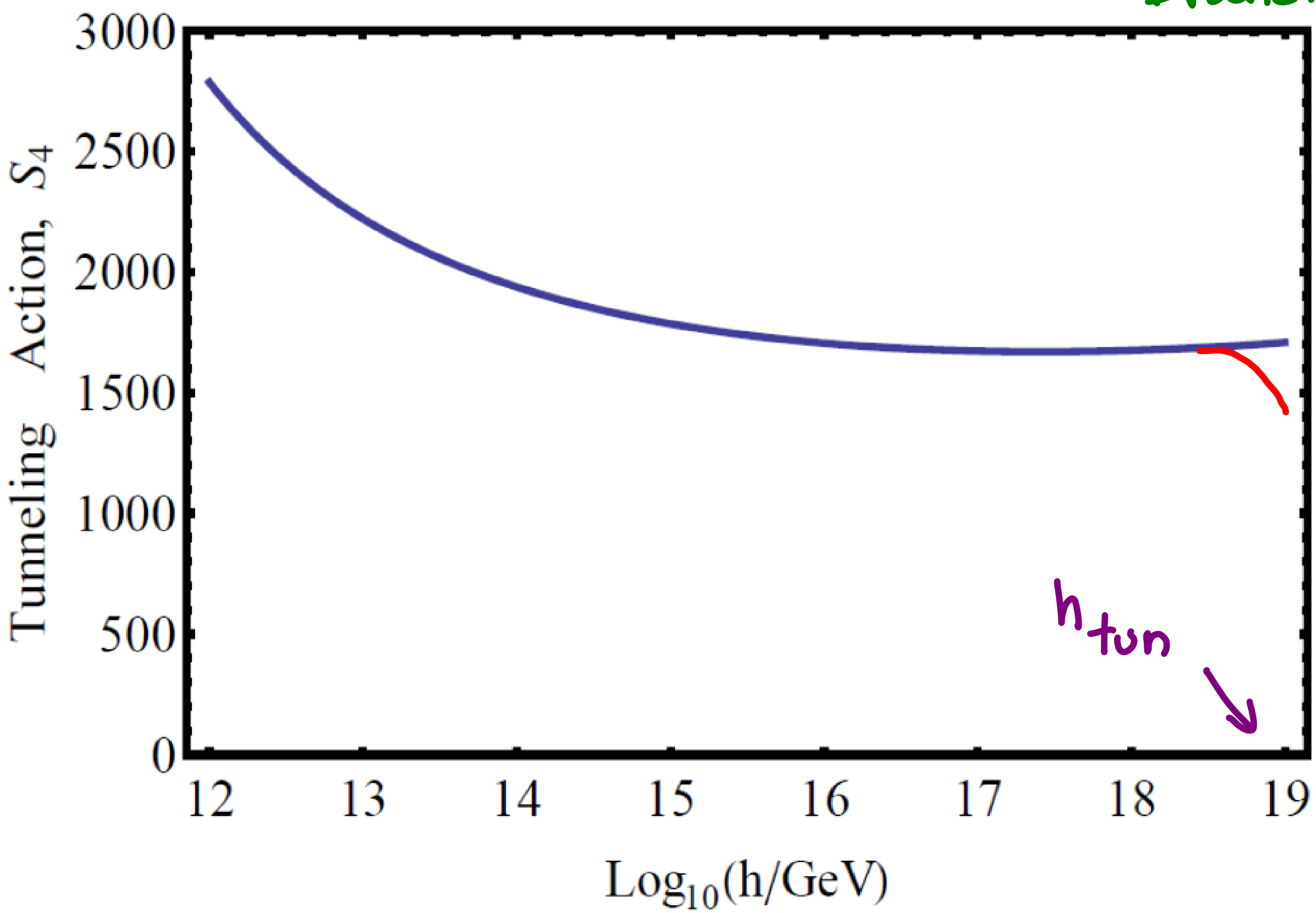
A1: Of course!

Even modest see-saw neutrinos could.

# PLANCKIAN EFFECTS ON V(h)?

Effect on tunneling action $\Delta V < 0$ $\lambda_6 < 0, \lambda_8 > 0$

Branchina et al.




Potential more unstable (unmotivated?)

# PLANCKIAN EFFECTS ON V(h)?

Q: Can Planckian physics spoil criticality?

A1: Of course!

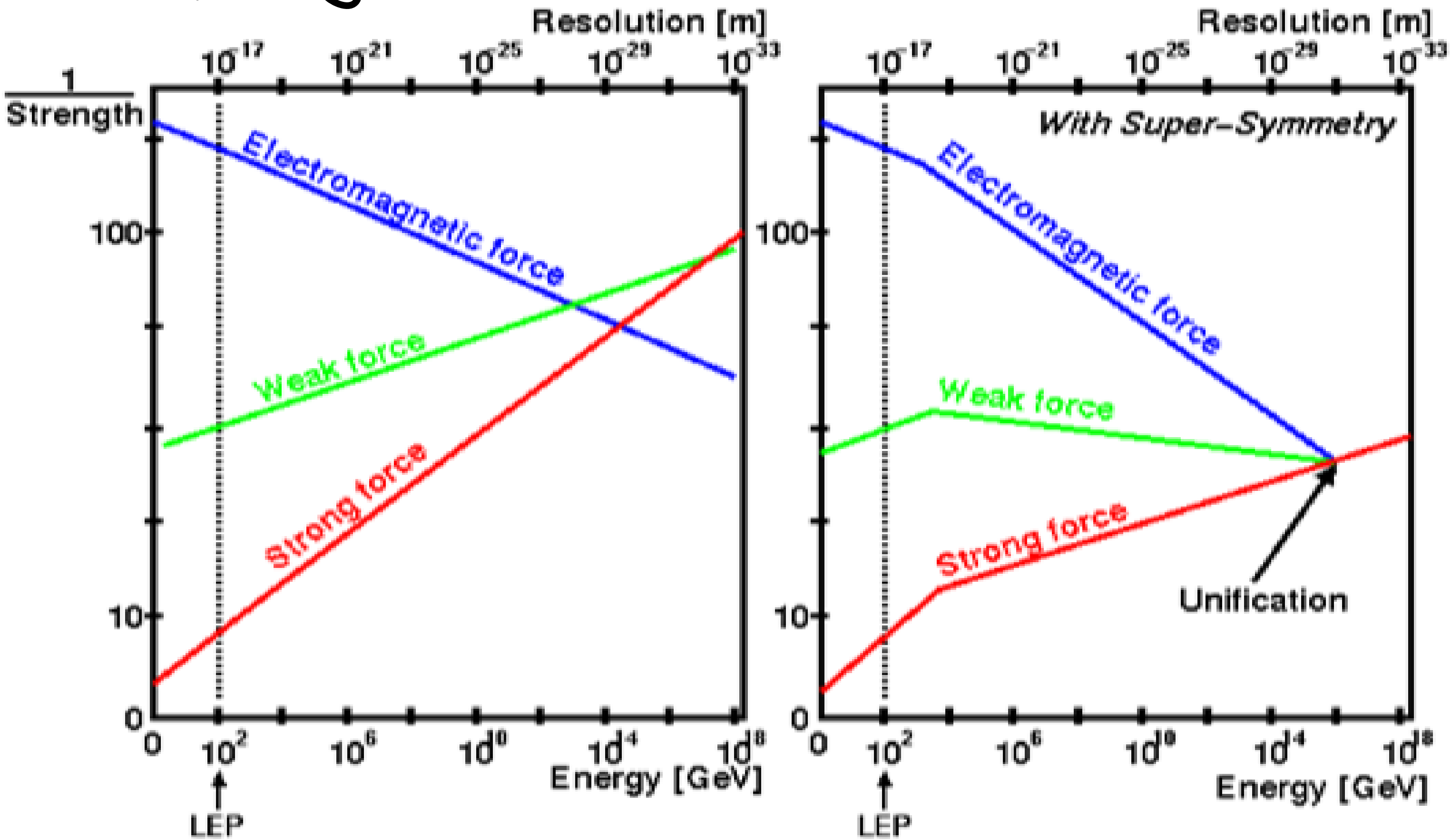
Even modest see-saw neutrinos could.

A2: That's the wrong question to ask!

Criticality $\longleftrightarrow$ Gauge Coupling Unification

# AN INTRIGUING HINT FROM LEP

Gauge coupling unification :

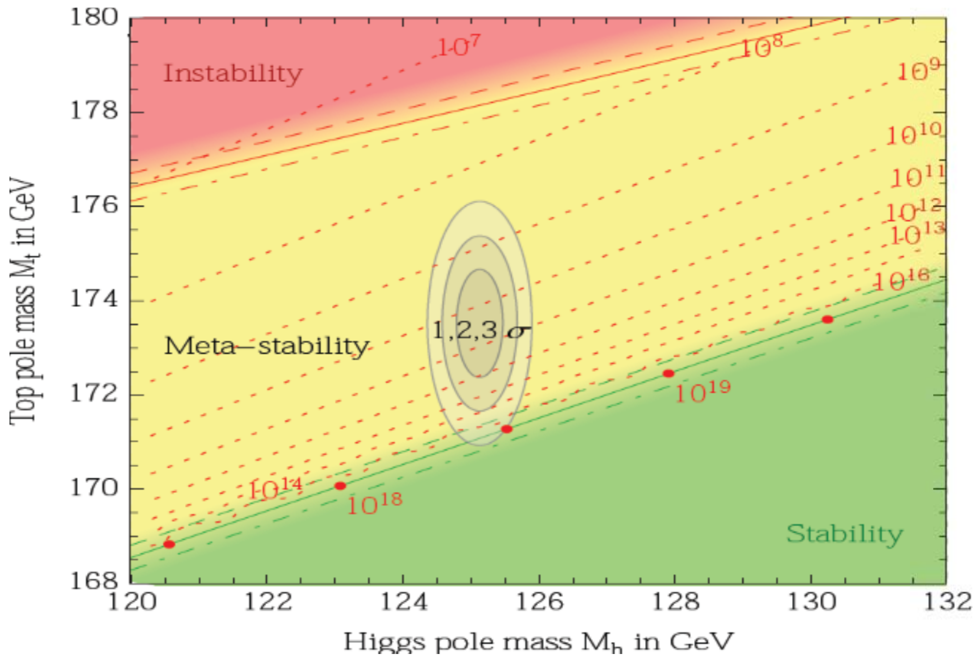


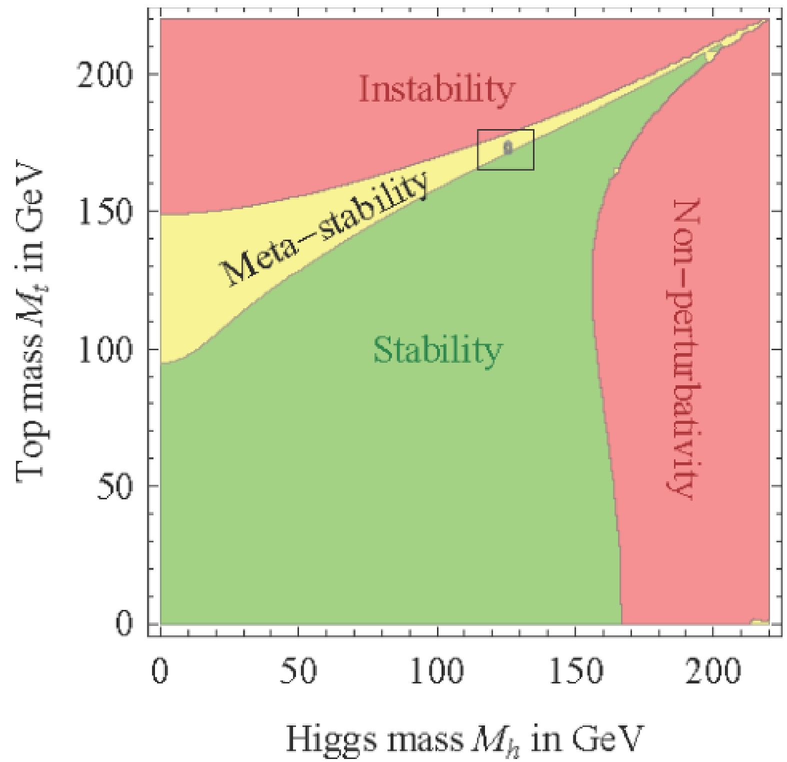

Many effects can upset it, including huge corrections from physics at the unification scale.

Yet, it might be telling us something important

# AN INTRIGUING HINT FROM LHC

Living close to the stability boundary:

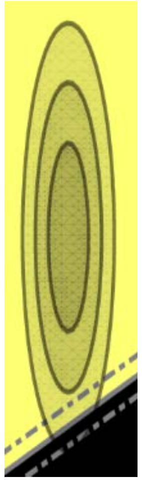



Many effects can upset it, including huge corrections from physics at the Planck scale.

Yet, it might be telling us something important

# Cosmological Implications



## I. Metastable vacuum

1. Decay by quantum tunneling

   But long lifetime

2. Decay by thermal fluctuations

   Bound on $T_{RH}$? Not for $(m_t, m_h)^{exp}$

3. Decay during inflation

   Bound on Hubble rate? $H_I \lesssim \Lambda_I/10$ But ways out

4. Decay right after inflation

   Rich physics. Interplay with $\xi |H|^2 R$

## II. Stable potential

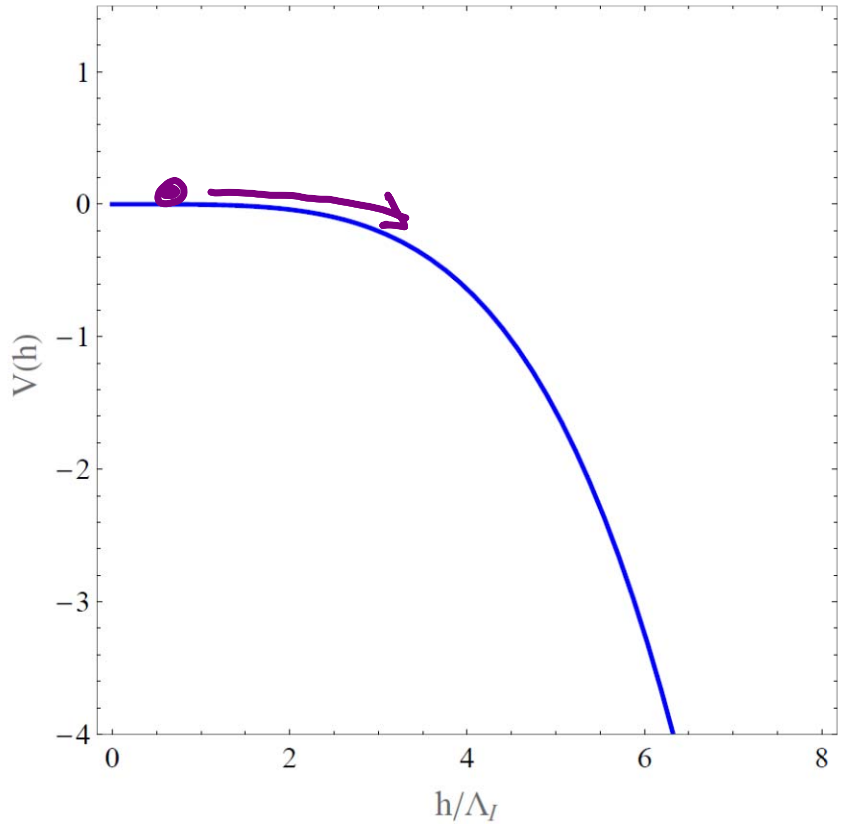
1. Higgs Inflation?

   Unitarity problem. No-go theorem?

# HIGGS → PBH → DM

J.R.E, Racco, Riotto '17

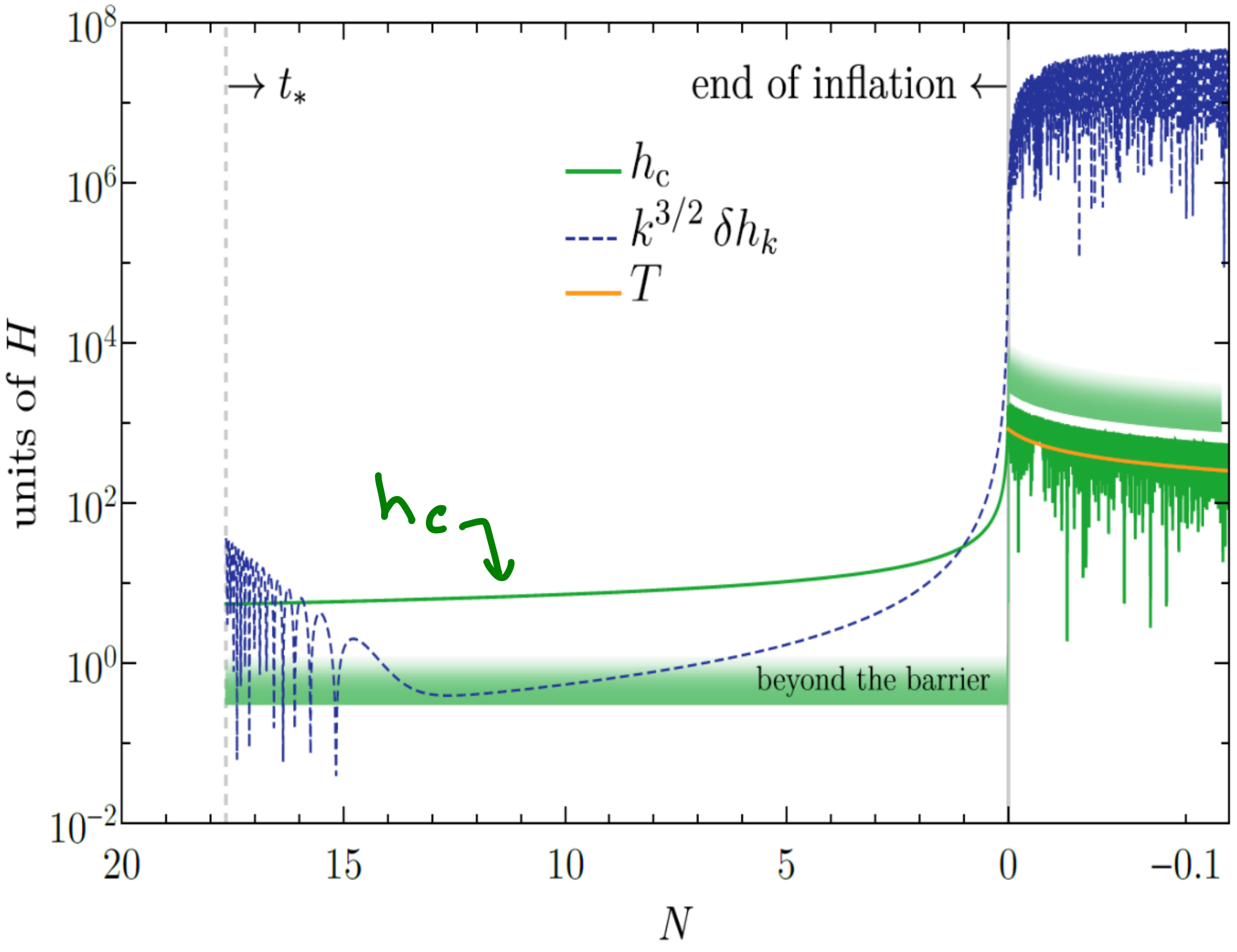
Higgs can probe instability during inflation ($H_I \gtrsim \Lambda_I$)



# HiGGS → PBH → DM

J.R.E, Racco, Riotto '17

Making Higgs fluctuations grow significantly

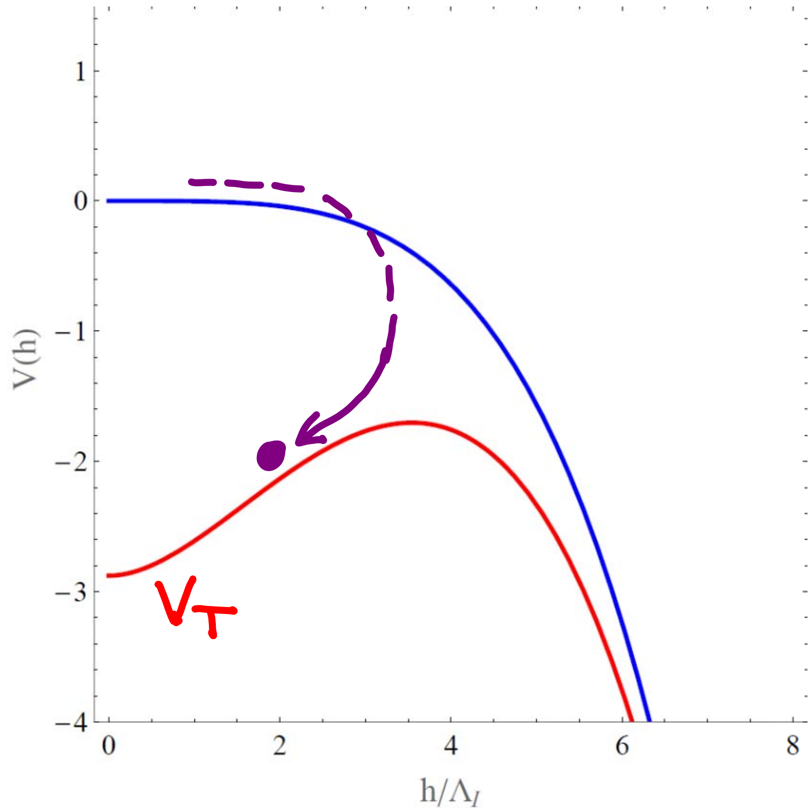



Higgs fluctuations

$k \sim 50\, a(t_*) H$

# HIGGS → PBH → DM

J.R.E, Racco, Riotto '17



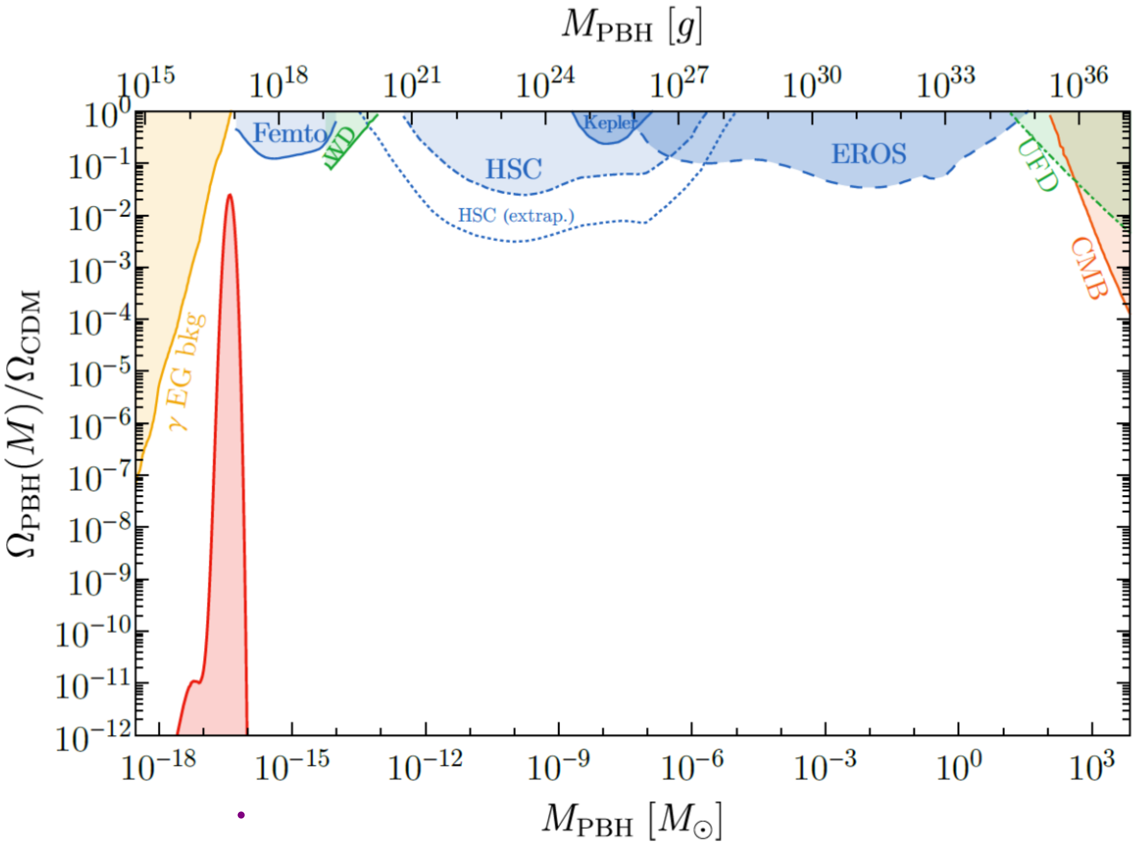

Provided the rolling Higgs is rescued by $T_{RH}$ after inflation ...

# HiGGS → PBH → DM

J.R.E, Racco, Riotto '17

These Higgs fluctuations can seed large curvature perturbations, that collapse into black holes when they reenter the horizon

These PBHs might be (all) Dark Matter



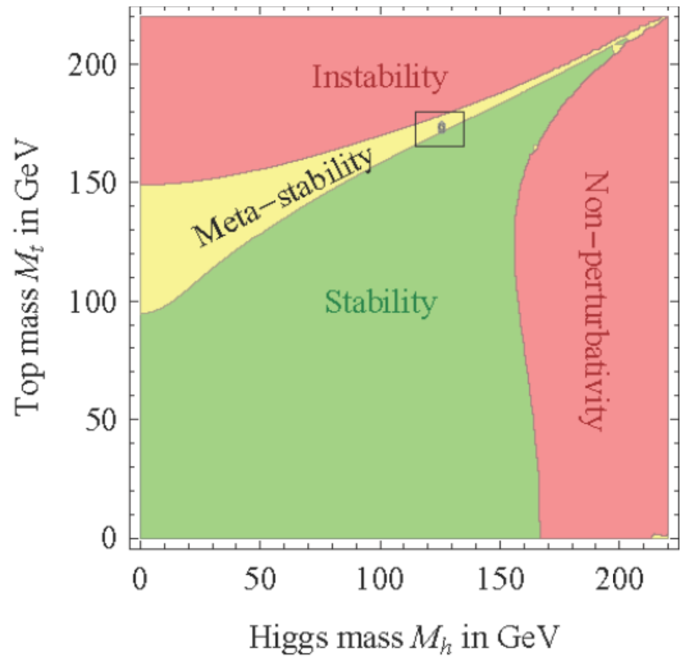
# CONCLUSIONS

Higgs near-criticality

★ Intriguing. (~ GUT hint)

Deep meaning?

★ Interplay with BSM can constrain models



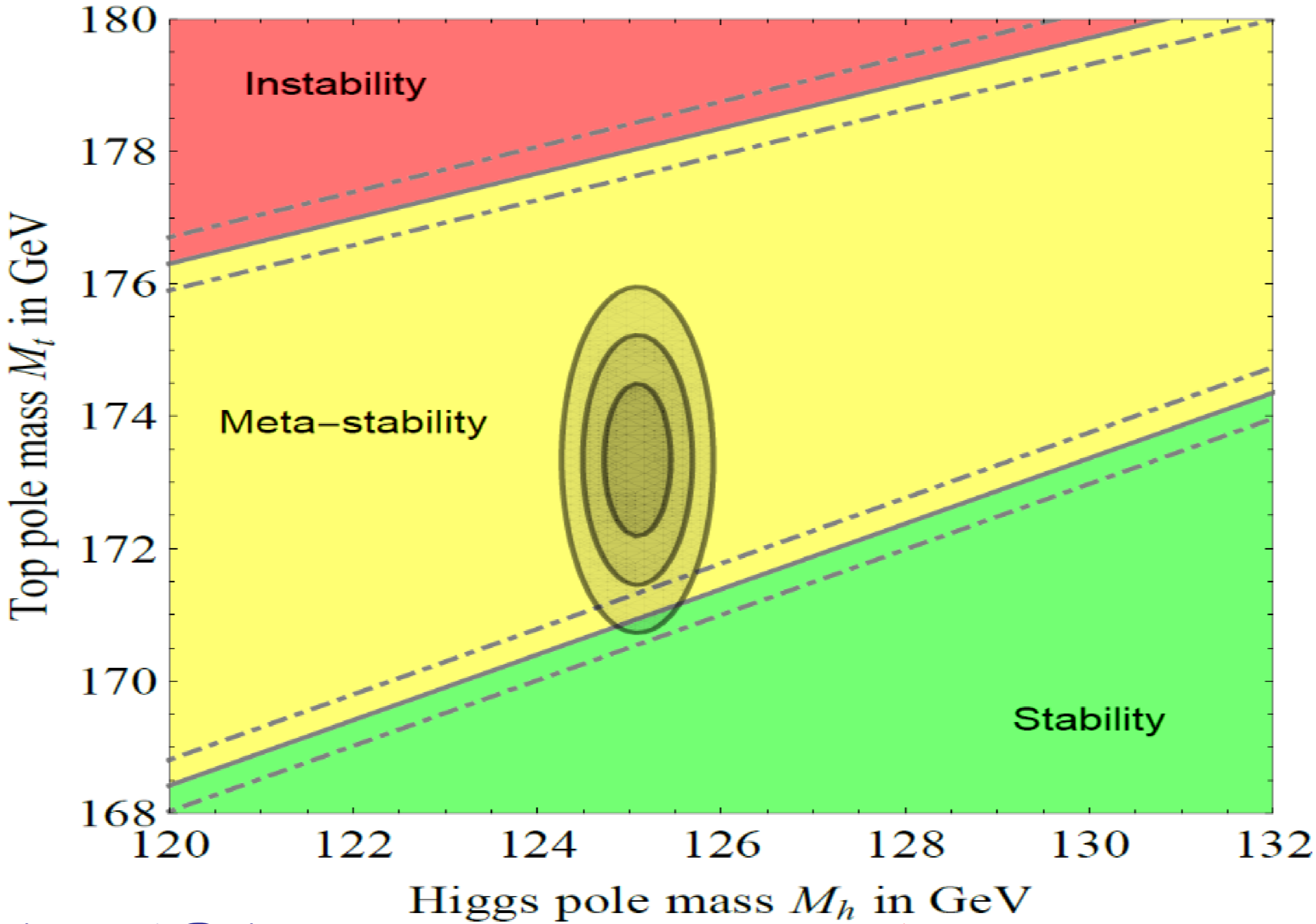

★ Planckian effects. Unknown. Small when calculable

★ Has a rich set of cosmological implications (inflation, preheating, interplay with r, ...)

★ Difficult to test (no smoking-gun signature like proton decay...) PBHs as DM?

# BACK-UP SLIDES

# TOP MASS AND STABILITY



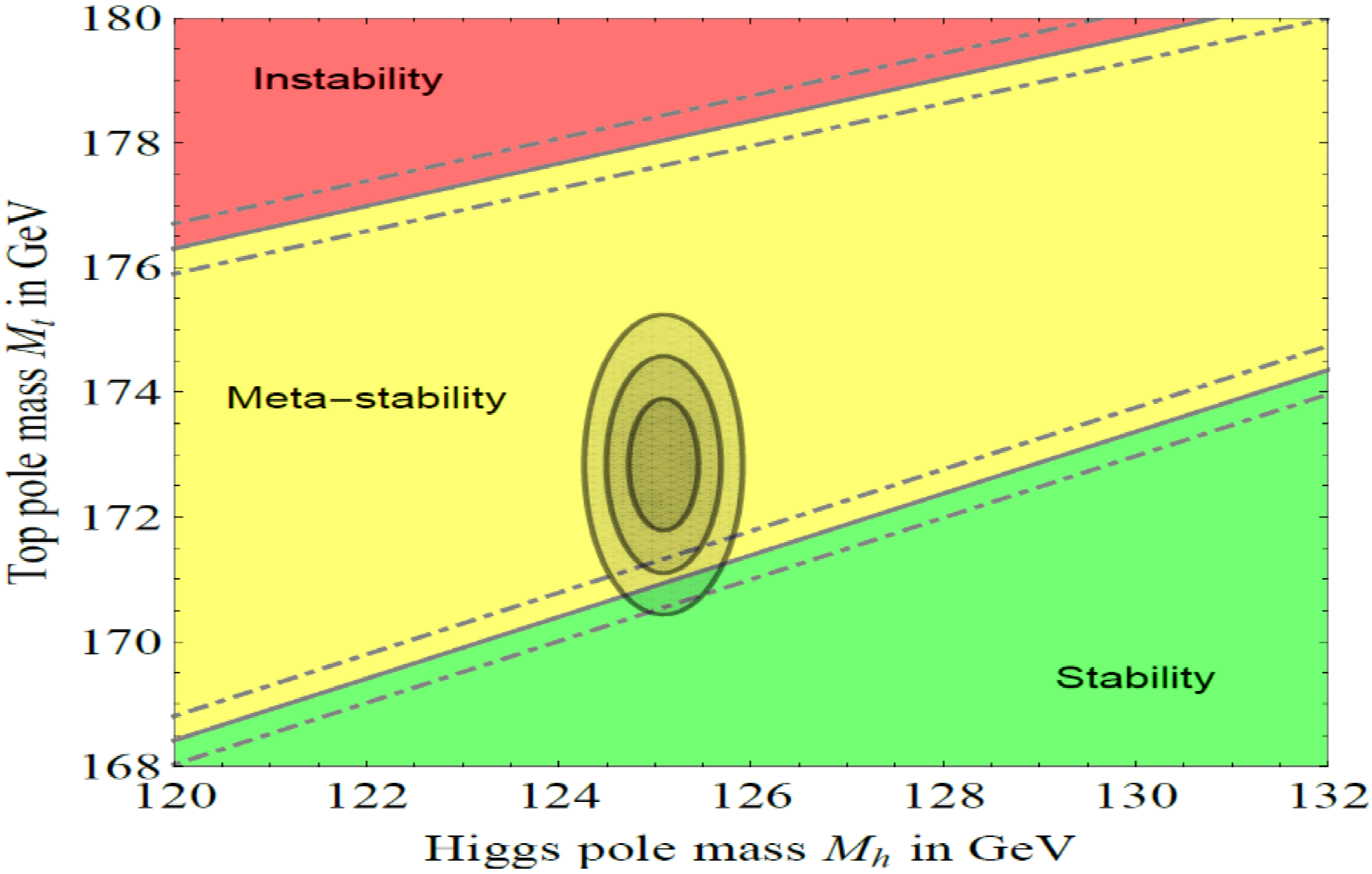

$\alpha_s = 0.1181 \pm 0.0011$

$M_h = 125.09 \pm 0.24$ GeV

World Average '14

$M_t = 173.34 \pm 0.76$ GeV

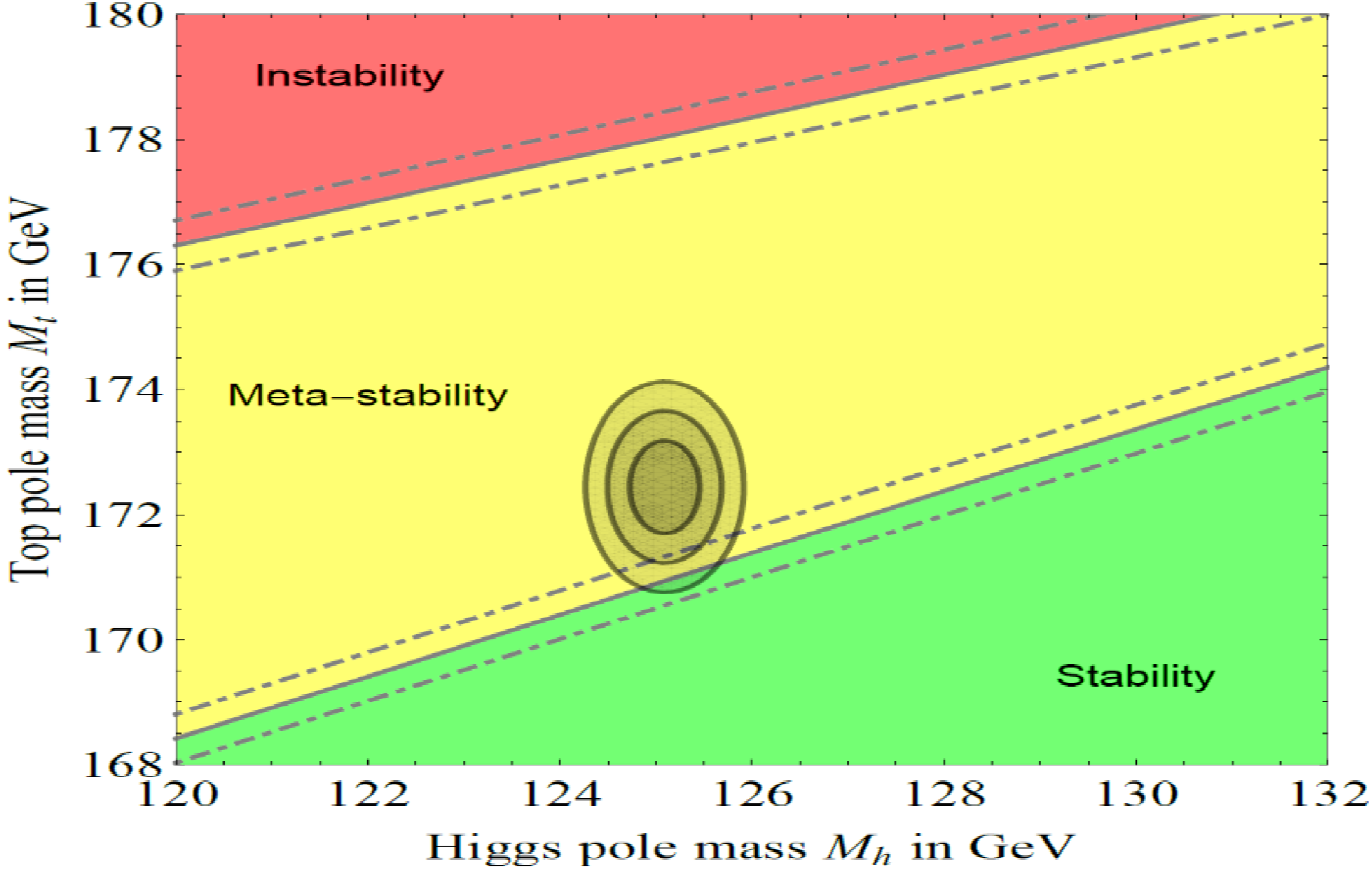
# TOP MASS AND STABILITY




ATLAS'16

$M_t = 172.84 \pm 0.70$ GeV

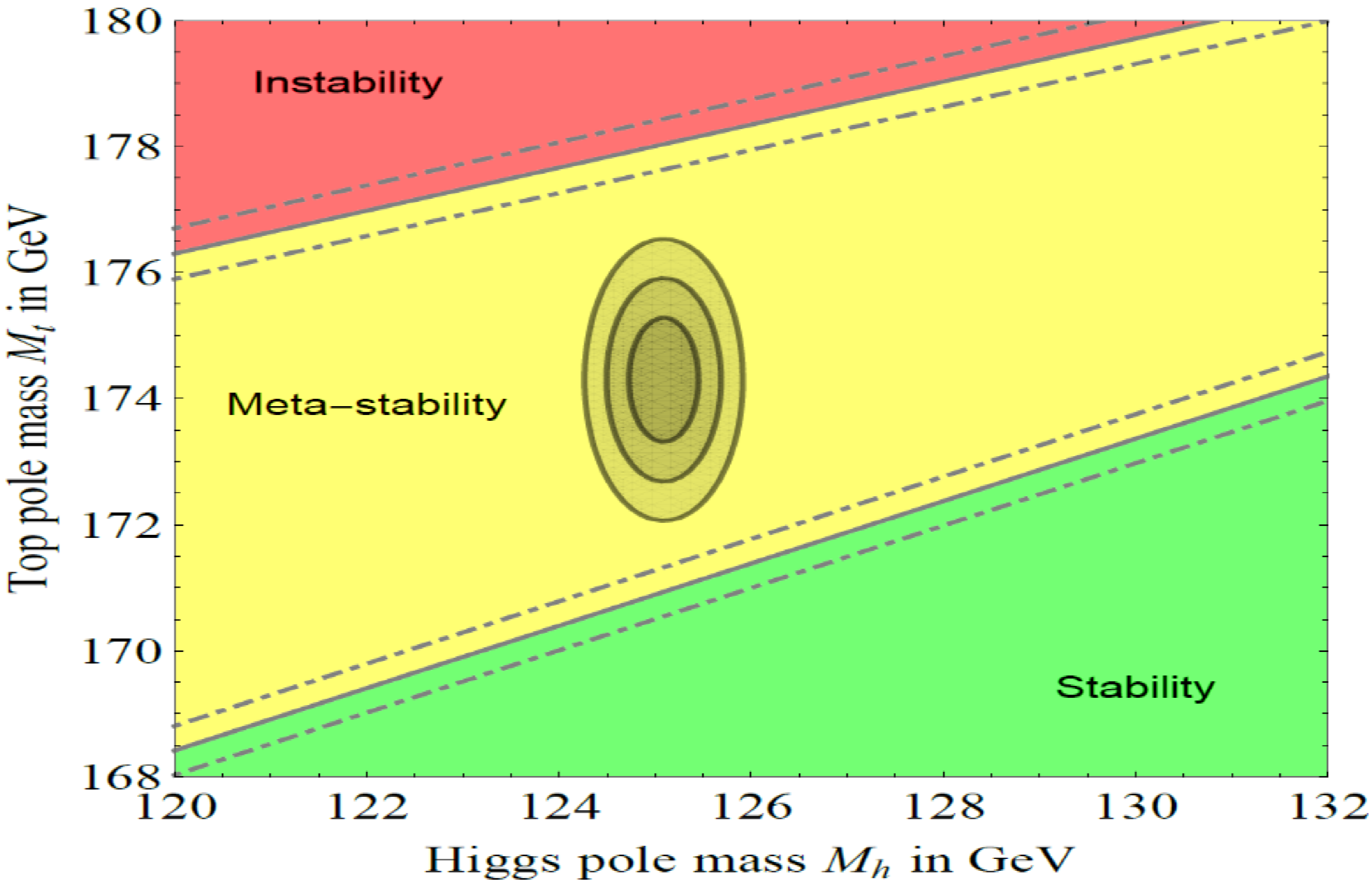
# TOP MASS AND STABILITY




CMS '16

$M_t = 172.44 \pm 0.49$ GeV

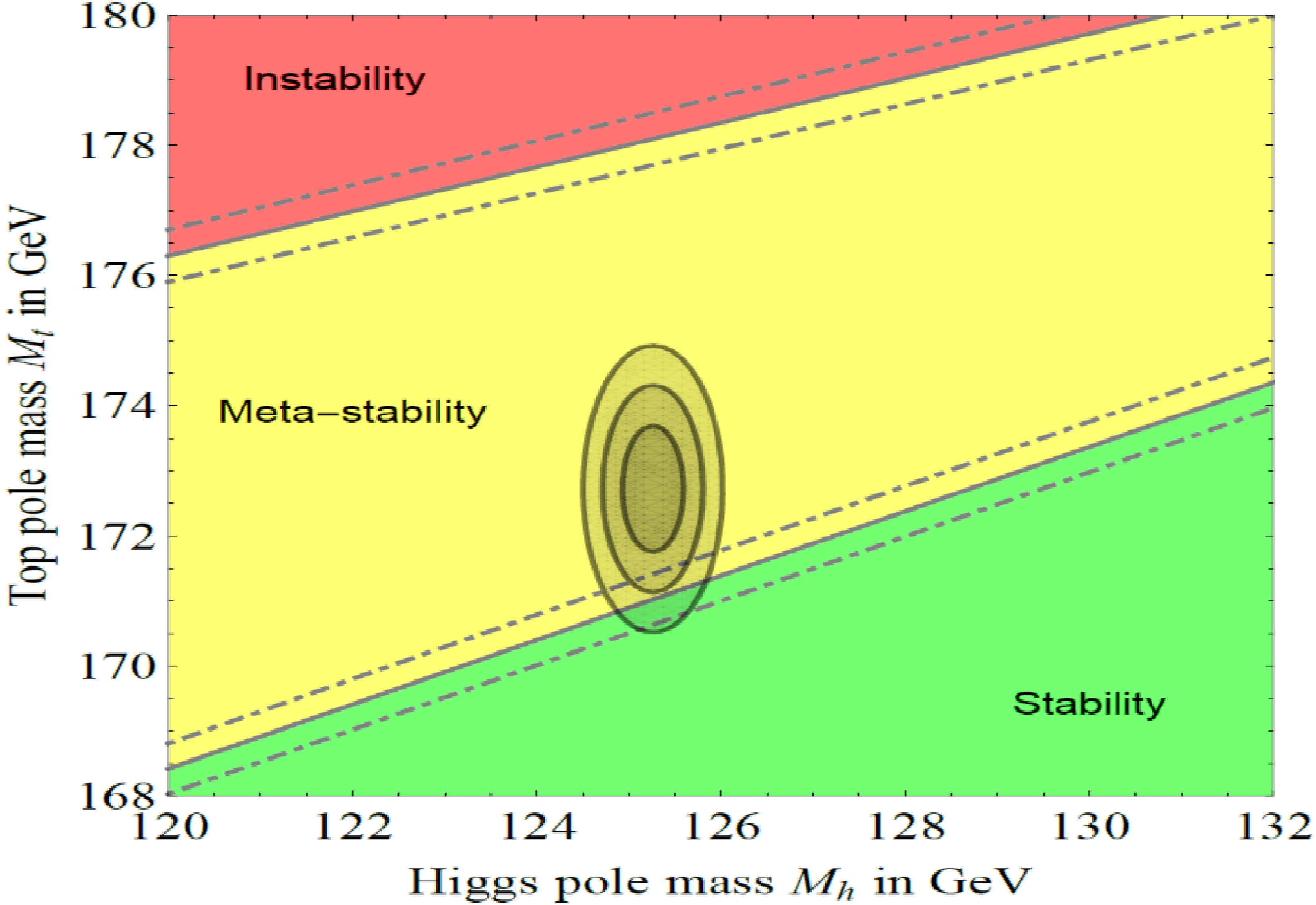
# TOP MASS AND STABILITY




Tevatron Comb. '16

$M_t = 174.30 \pm 0.65\,GeV$

# TOP MASS AND STABILITY



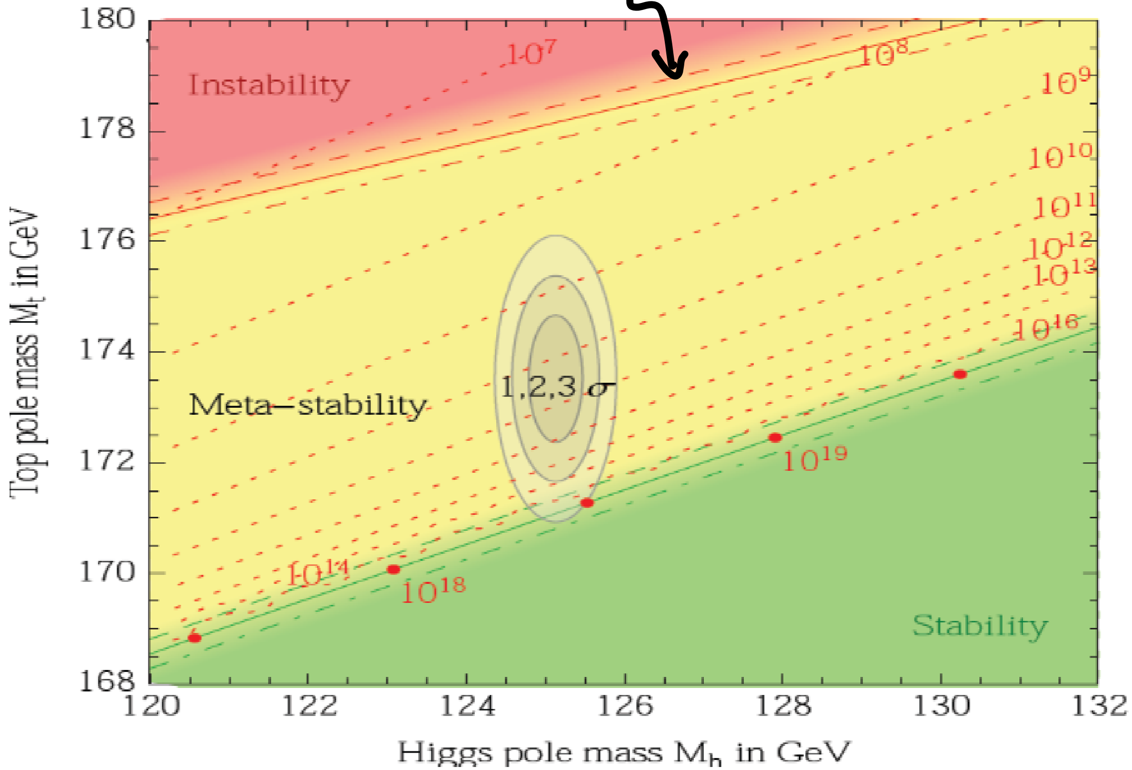

CMS $M_h = 125.26 \pm 0.20 \pm 0.08$ GeV

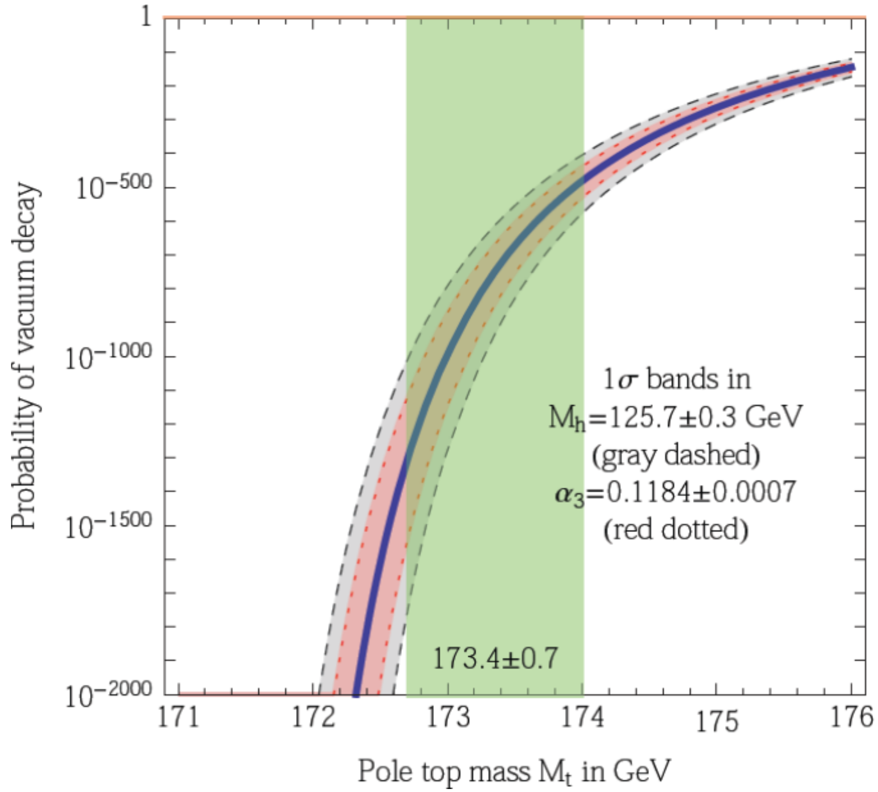
Erler, Moriond'17 LHC + Tevatron comb. $M_t = 172.72 \pm 0.64$ GeV

# I1. DECAY BY QUANTUM TUNNELING

Extremely long-lived metastable vacuum:

Safe below this line



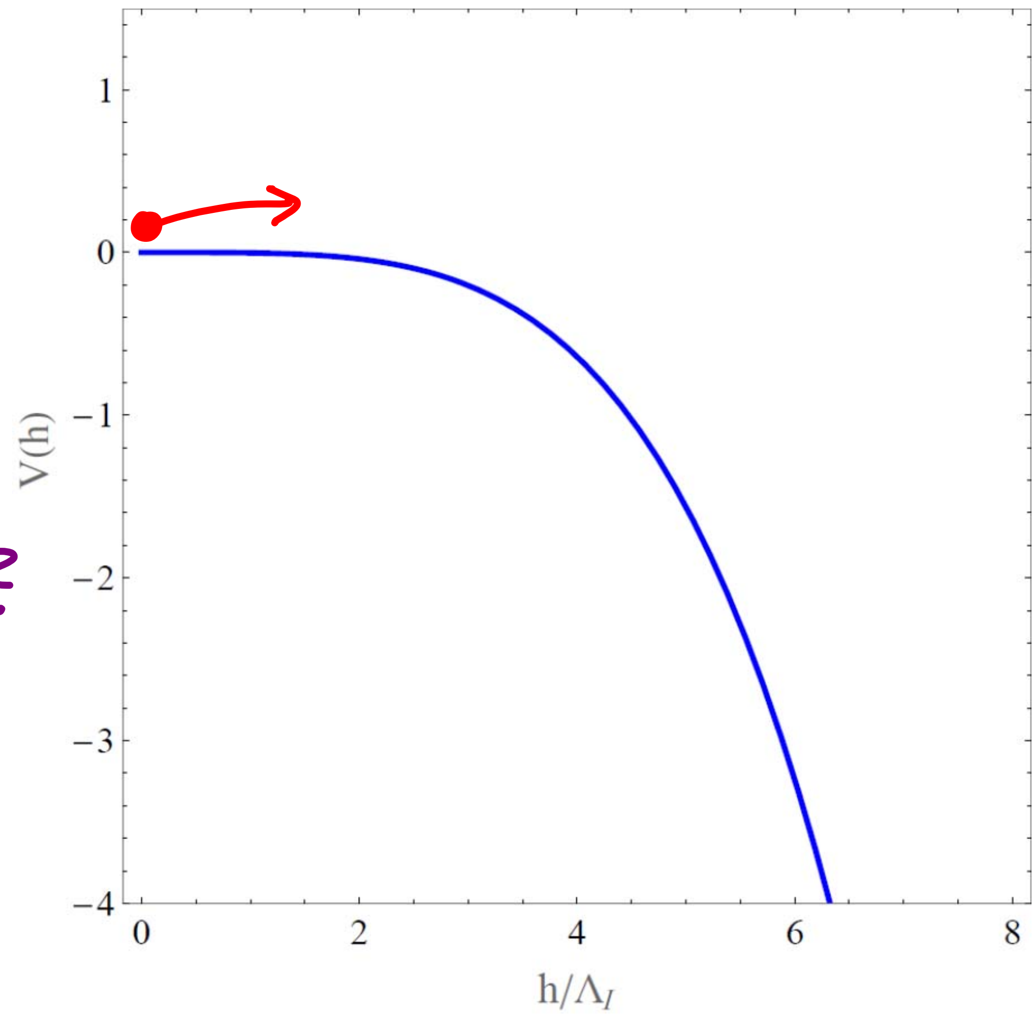

Buttazzo et al '13

⇨ No BSM needed to fix the instability

# I2. DECAY BY THERMAL FLUCTUATIONS

Thermal decay during the early Universe

$\sqrt{\langle h^2 \rangle} \sim T \gtrsim \Lambda_I$



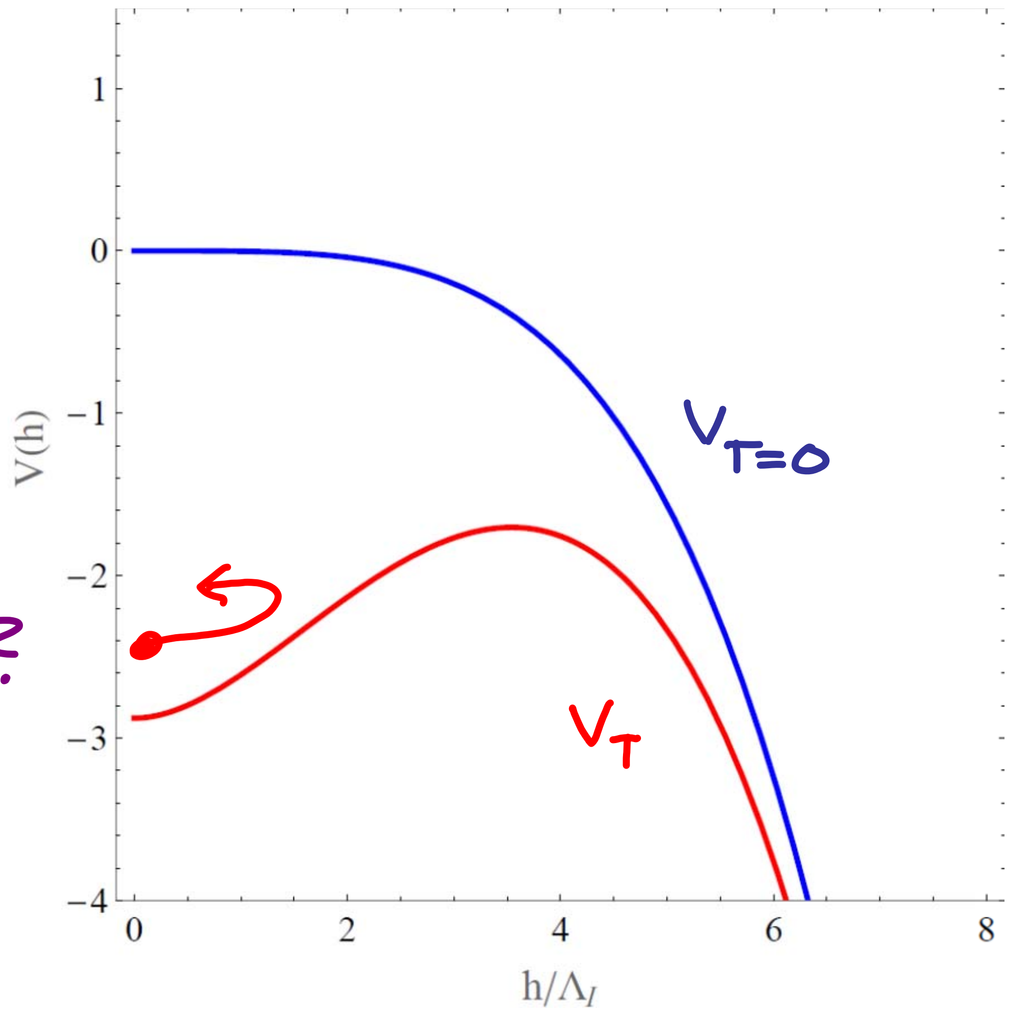

Upper bound on $T_{RH}$ ?

# DECAY BY THERMAL FLUCTUATIONS

Thermal decay during the early Universe

$\langle h^2 \rangle \sim T^2$

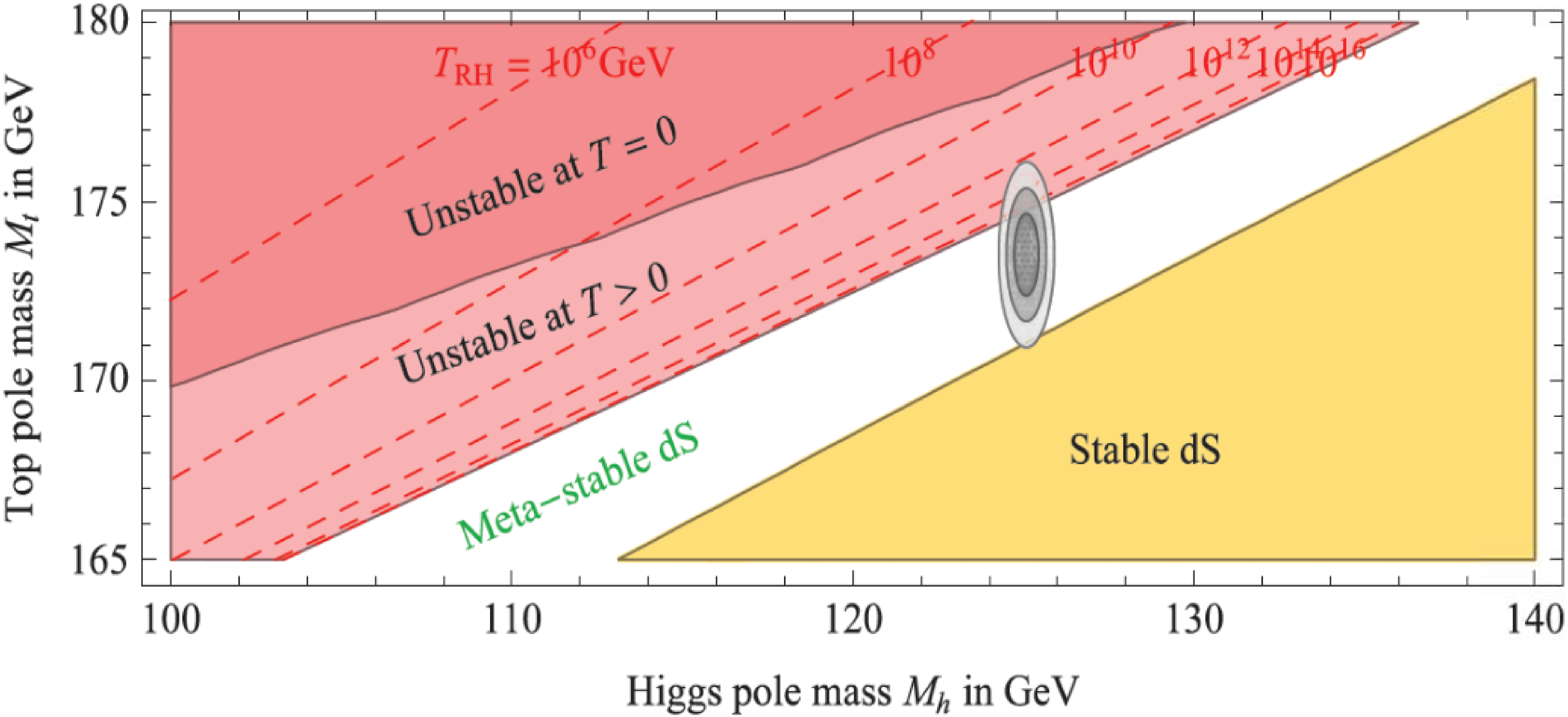
Upper bound on $T_{RH}$ ?




but thermal corrections tend to stabilize $V(h)$

# THERMAL VACUUM DECAY

Upper bound on $T_{RH}$ ? Not for preferred $M_h, M_t$ .




J.R.E, Giudice et al.'15  Urbano et al.'15  Salvio et al.'16

# I3. DECAY DURING INFLATION

JRE, Giudice, Riotto ... '07 '15, Fairbairn et al '14, Zurek et al '14 '15
Rajantie et al '14 , ...

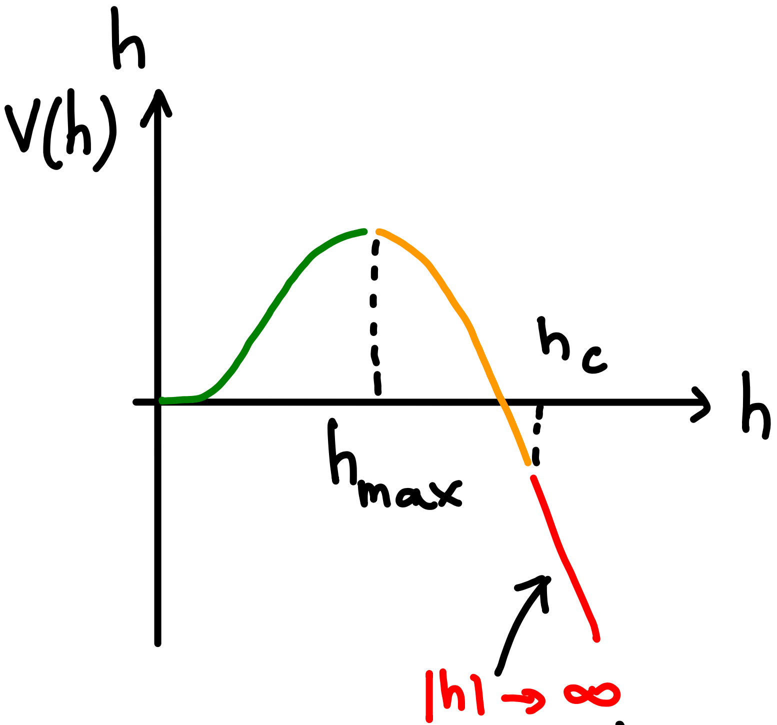
Boost by BICEP2 !

Inflation induces large fluctuations in light fields

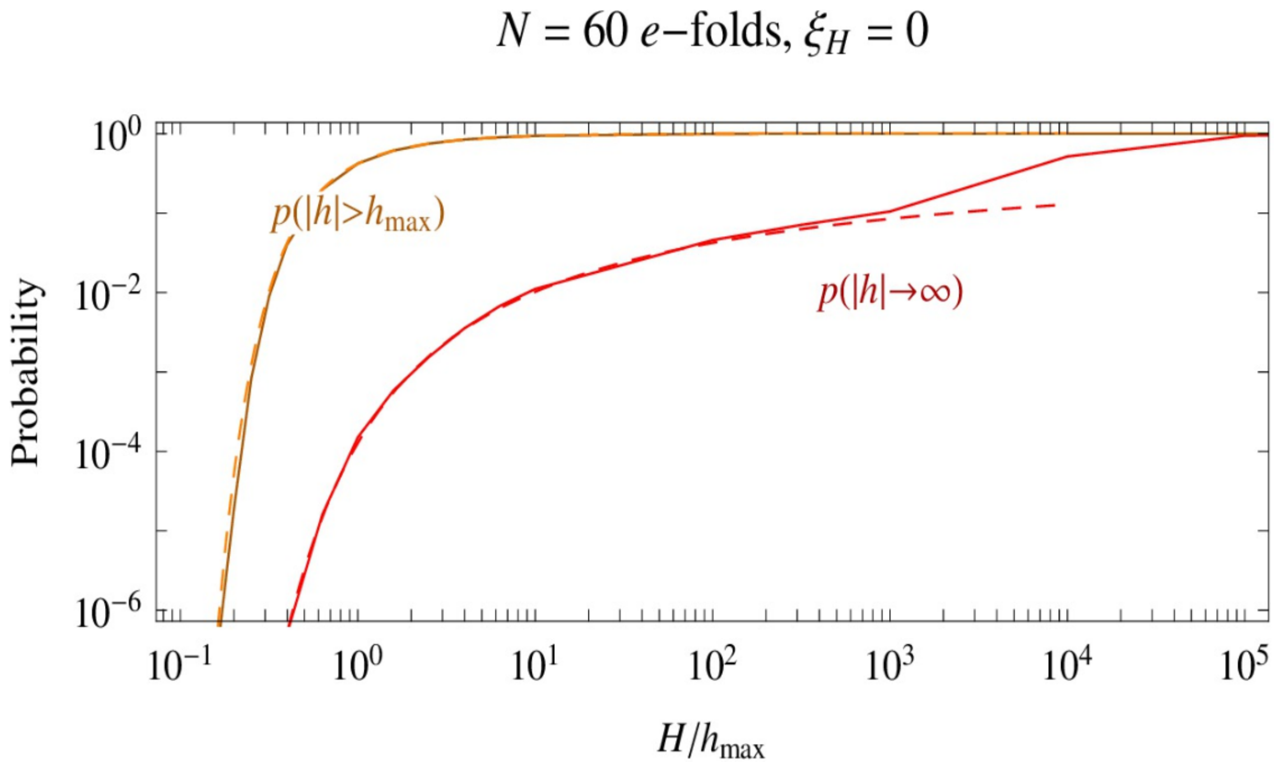
$$\sqrt{\langle h^2 \rangle} \sim \left(\frac{H_I}{2\pi}\right)\sqrt{N_e} > \Lambda_I \Rightarrow \text{Vacuum decay}$$

Upper bound on $H_I$ ?

# VACUUM DECAY DURING INFLATION




classical roll beats quantum fluctuations




$h_{max} \simeq 5 \times 10^{10}\ \text{GeV}$

$$(\Delta h)_{clas} \simeq \frac{V'}{H_I^2} = (\Delta h)_{quant} \simeq H_I \;\Rightarrow\; h_c \sim H_I/|\lambda|$$

# VACUUM DECAY DURING INFLATION ?

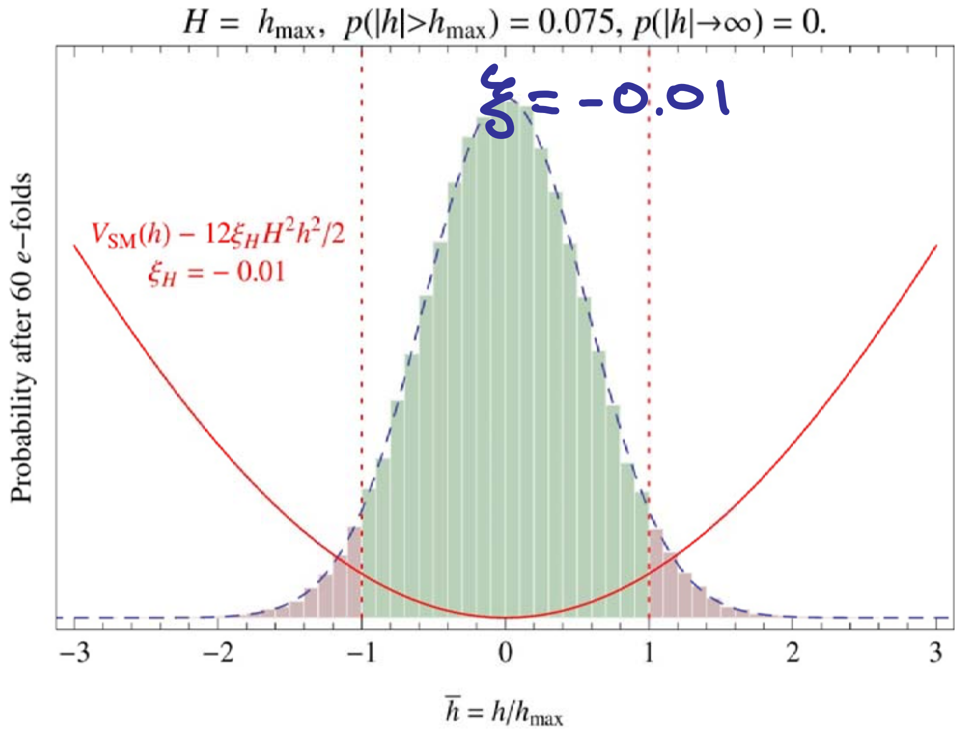
Simple way out $\delta\mathcal{L} = -\xi |H|^2 R$

During inflation $R = -12 H_I^2$

$\Big\}\ m_H^2 = -12\xi H_I^2$

- For $\xi < 0$, $\delta V(h) = \frac{1}{2}(-12\xi H_I^2) h^2$ can stabilize the potential

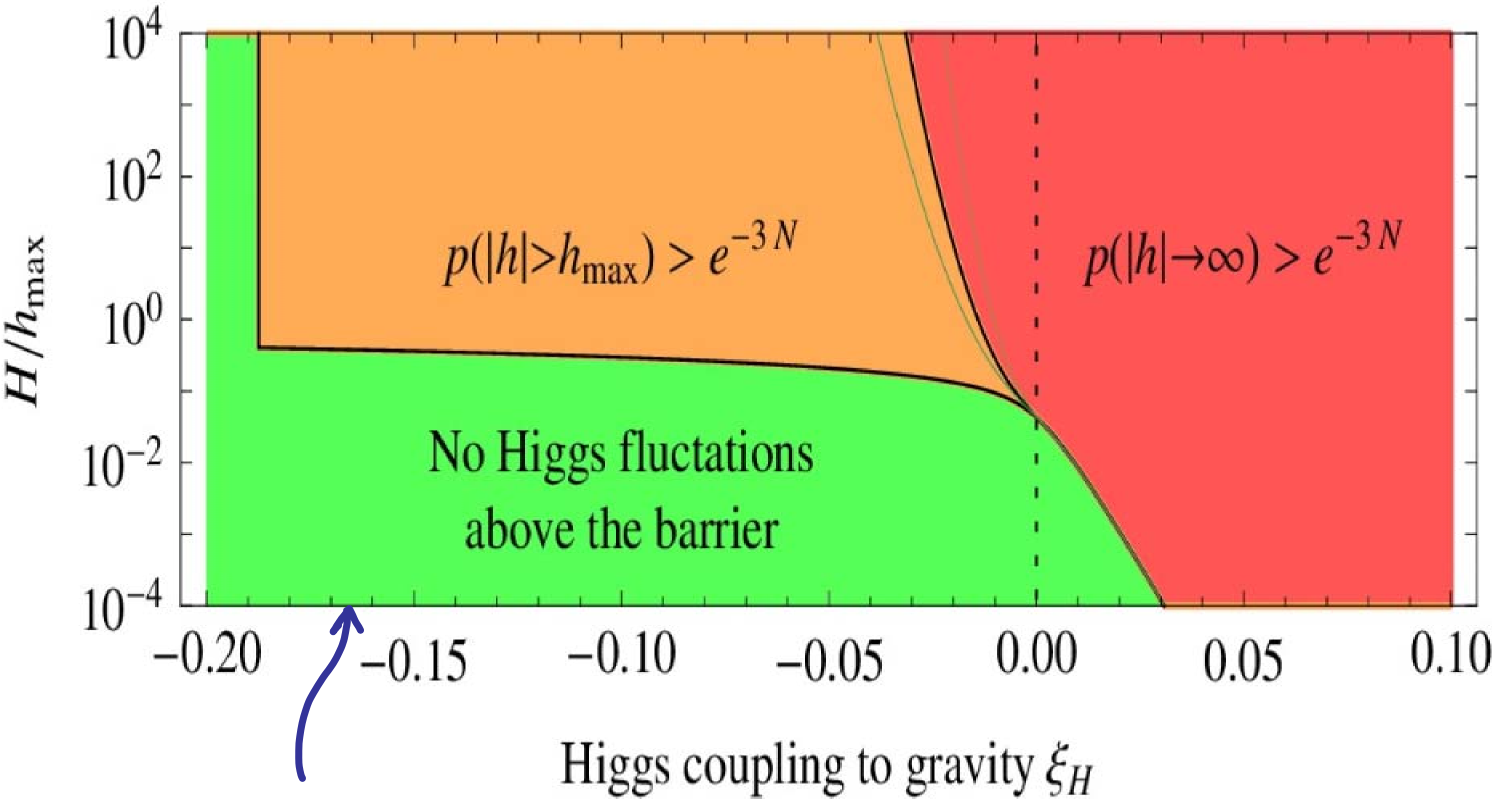
- For $\xi < -3/16$ Higgs fluctuations suppressed




Alternative: $\delta\mathcal{L} = -\frac{1}{2} c\,\phi^2 |H|^2$ ($\phi$ inflaton)

# VACUUM DECAY DURING INFLATION

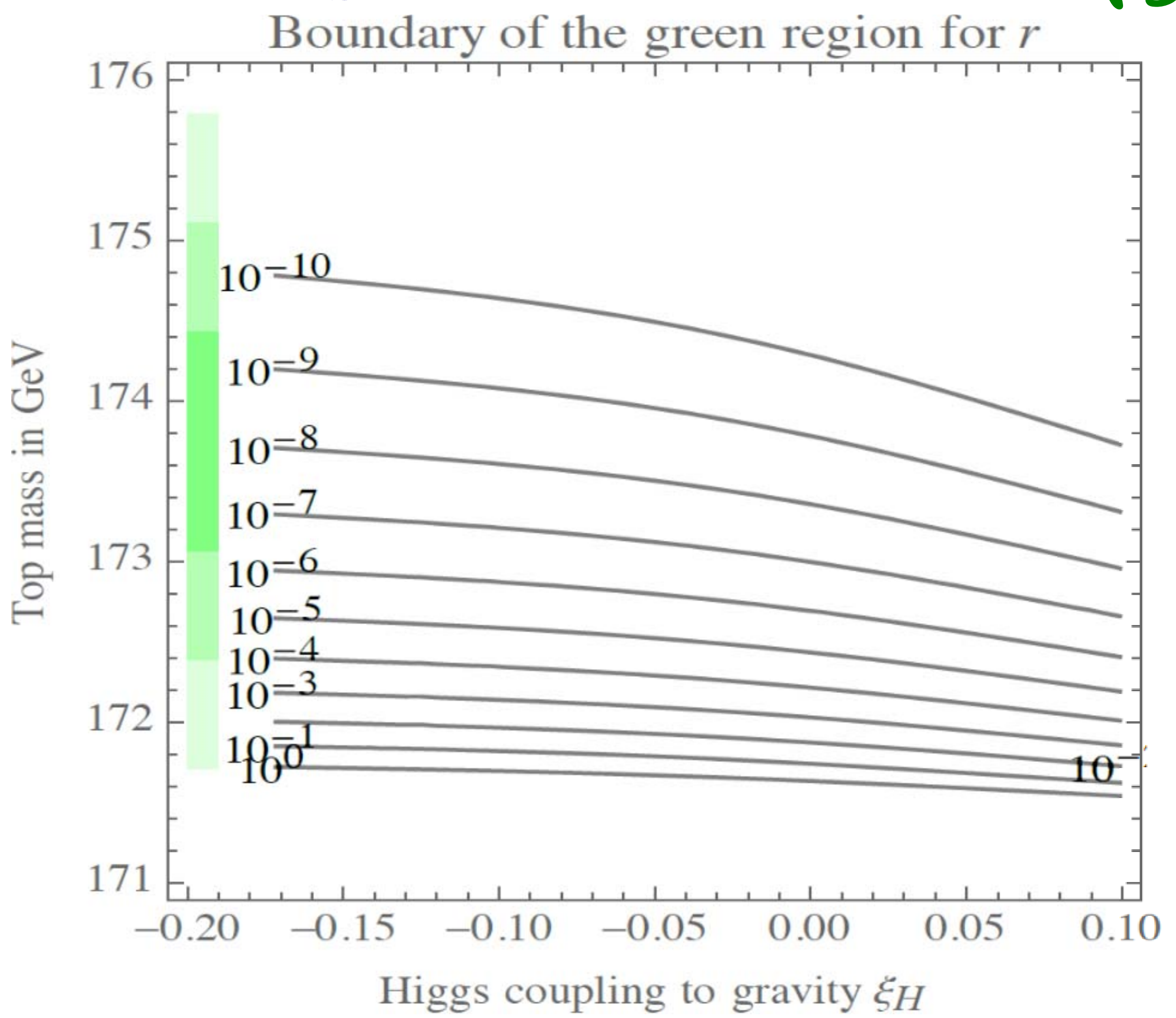
General picture for $\xi \neq 0$




$\xi_H = -1/6$ (conformal value)

# BOUND ON $H_I$ AS UPPER BOUND ON $r$

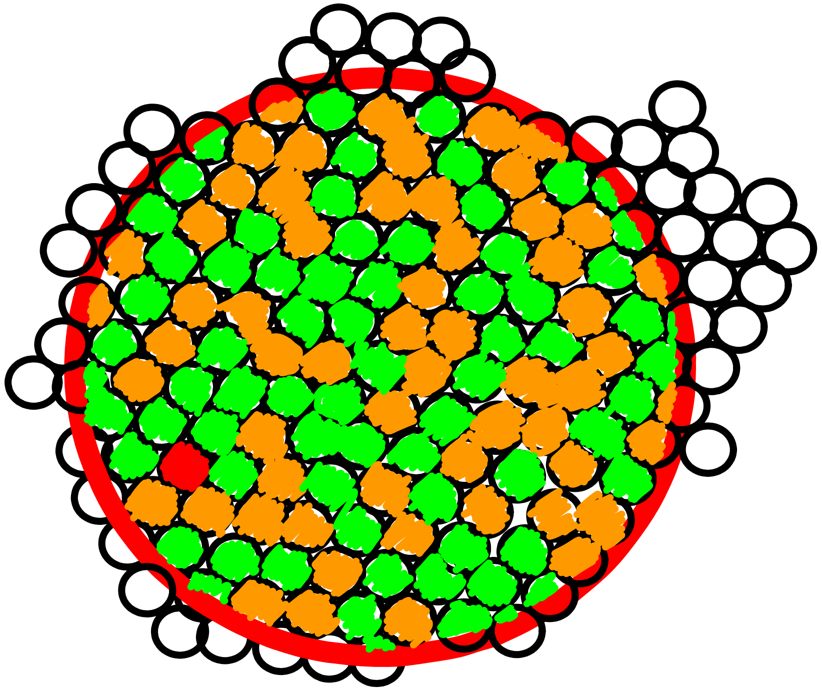
Remember $H_I \simeq 8 \times 10^{13}\,\text{GeV}\sqrt{\frac{r}{0.1}}$ ← tensor-to-scalar ratio




[A. Strumia, preliminary, based on JRE, Giudice et al.]

# 14. VACUUM DECAY AFTER INFLATION

After inflation → pre-heating → reheating



● $h < h_{max}$ ⇨ Safe

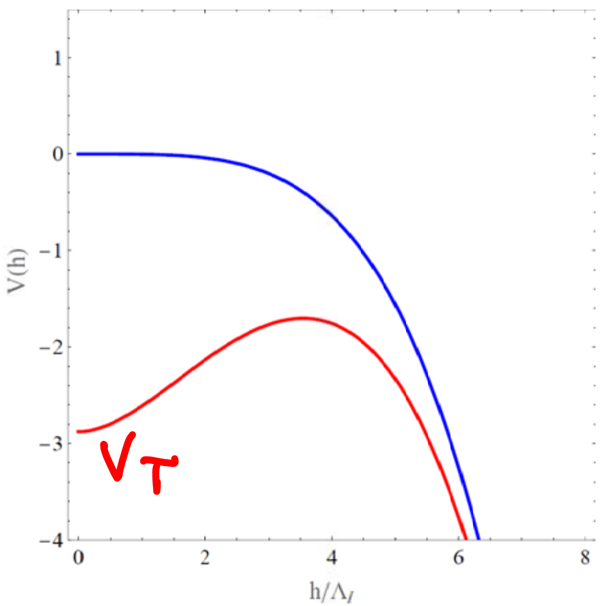
● $h > h_{max}$ ⇨ Can be saved by thermal corrections to $V(h)$

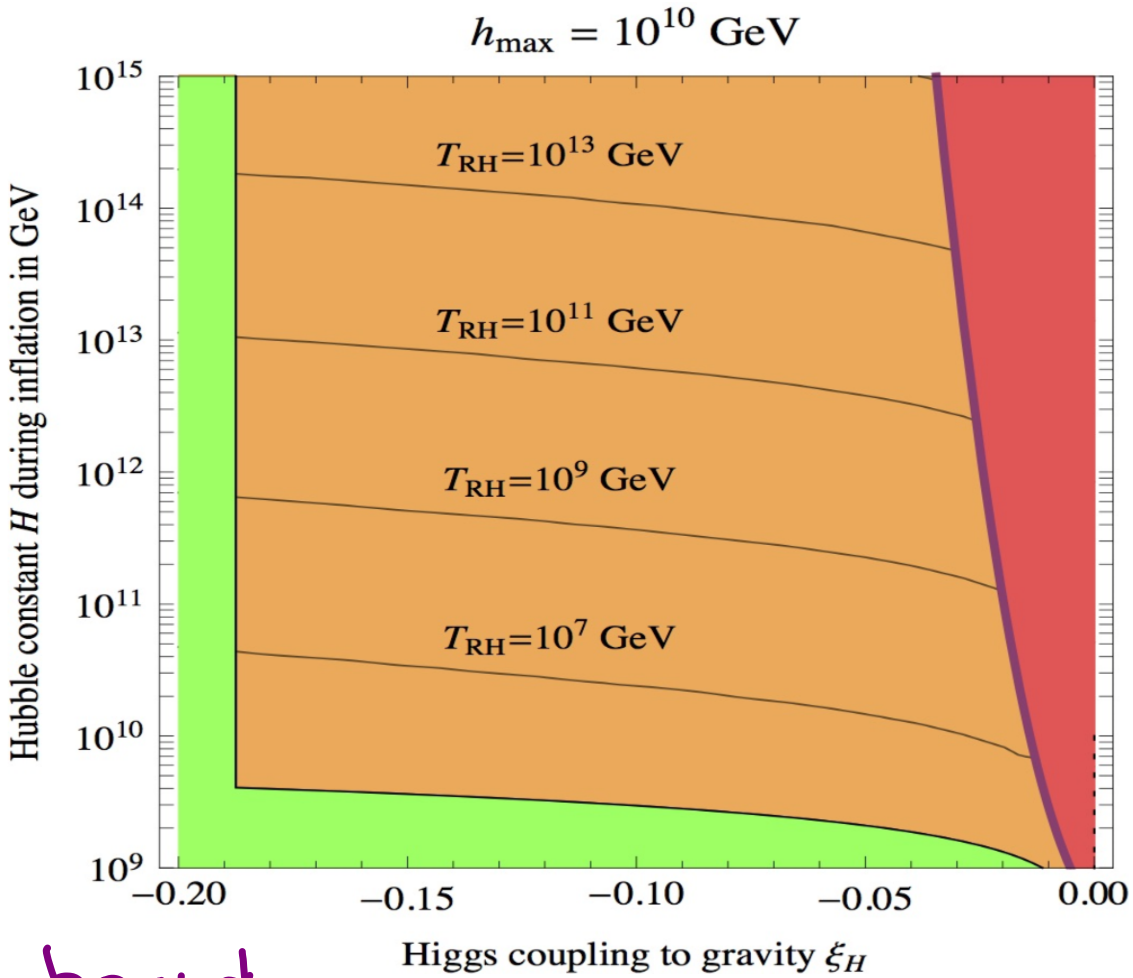
● $h > h_c$ Deadly. In general they expand and eat all space.

See JRE et al '15, Zurek et al '16 for the gory details...

# VACUUM DECAY AFTER INFLATION

- $h > h_{max}$ ⇨ can be saved by thermal corrections to $V(h)$




Allows to relax $H_I$ bound

# VACUUM DECAY AFTER INFLATION

Rajantie et al'15, Ema et al'16, Enqvist et al'16, Postma et al'17


Stabilizing terms during inflation

$$\delta\mathcal{L} \supset \xi |H|^2 R \;,\; \frac{c}{2}|H|^2\phi^2 \quad \leftarrow \text{inflaton}$$

can be deadly during preheating

oscillating $\phi$ $\Rightarrow$ tachyonic/oscillating $m_H^2$

$\Rightarrow$ tachyonic/parametric resonant production of Higgses : $\delta h^2 \sim H_I^2$ once again.

$\Rightarrow$ only a range of $\xi$ or $c$ might be allowed

Non trivial if both present Lebedev et al'17.

Surprises still possible...

# OTHER IMPLICATIONS

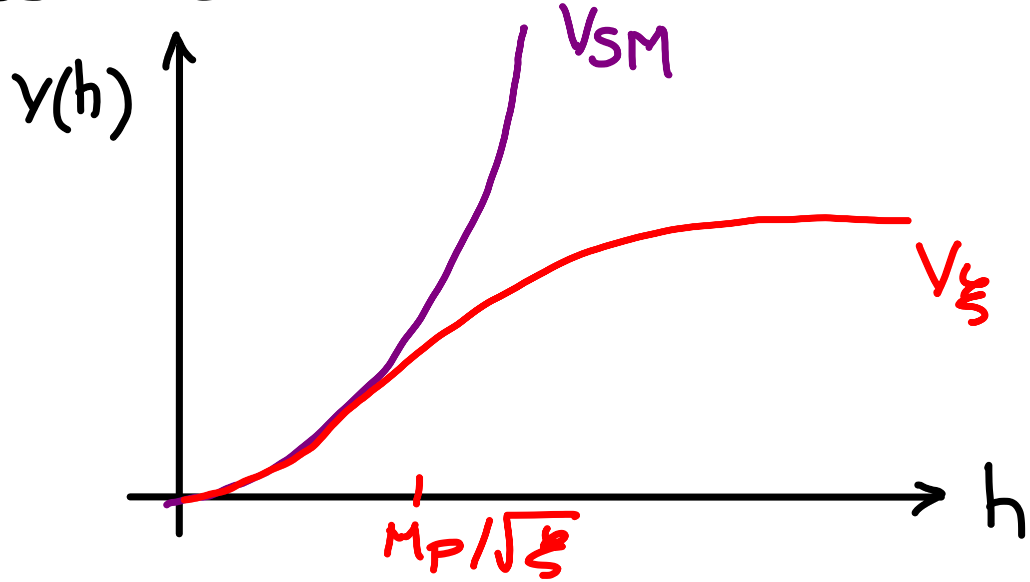
- Cosmology : Higgs inflation    Bezrukov, Shaposhnikov '07

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

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

rescales the potential as

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




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 et al. '09 '15

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

Requires marginal values of $M_h$ & $M_t$

※3 Additional scalar can solve ※1

But then that scalar plays inflaton role

Giudice, Lee '11 Barbón et al '15

# GAUGE DEPENDENCE OF V(h) ?

Old worry    Nielsen '75   Fukuda, Kugo '76

V(h) is gauge-dependent.

But if you calculate physical quantities you get gauge-independent answers:

$\Lambda_I$ Instability scale $(V(\Lambda_I)=0)$ is gauge-dep
Di Luzio, Mihaila '14

$M_h^c$ Higgs mass stability bound. is gauge-indep

$\Gamma_{decay}$ Vacuum decay rate is gauge-indep
Isidori, Ridolfi, Strumia '01

Gauge-dep is useful: it forces you to think what are the physical questions to ask!

# GAUGE DEPENDENCE OF V(h) ?

J.R.E, Garny, Konstandin, Riotto '16

Possible to extract gauge-independent scales related to the instability:

- Scale $\Lambda$ needed in $\delta V = \frac{1}{\Lambda^n} h^{4+n}$ to stabilize the potential

  $$\Lambda \simeq \Lambda_{\text{Landau Gauge}} \quad \text{for} \quad n \gg 1$$

- Scale [Radius of critical bubble]$^{-1}$ $(\gg \Lambda_I)$

- Hubble rate during inflation for destabilization with some probability