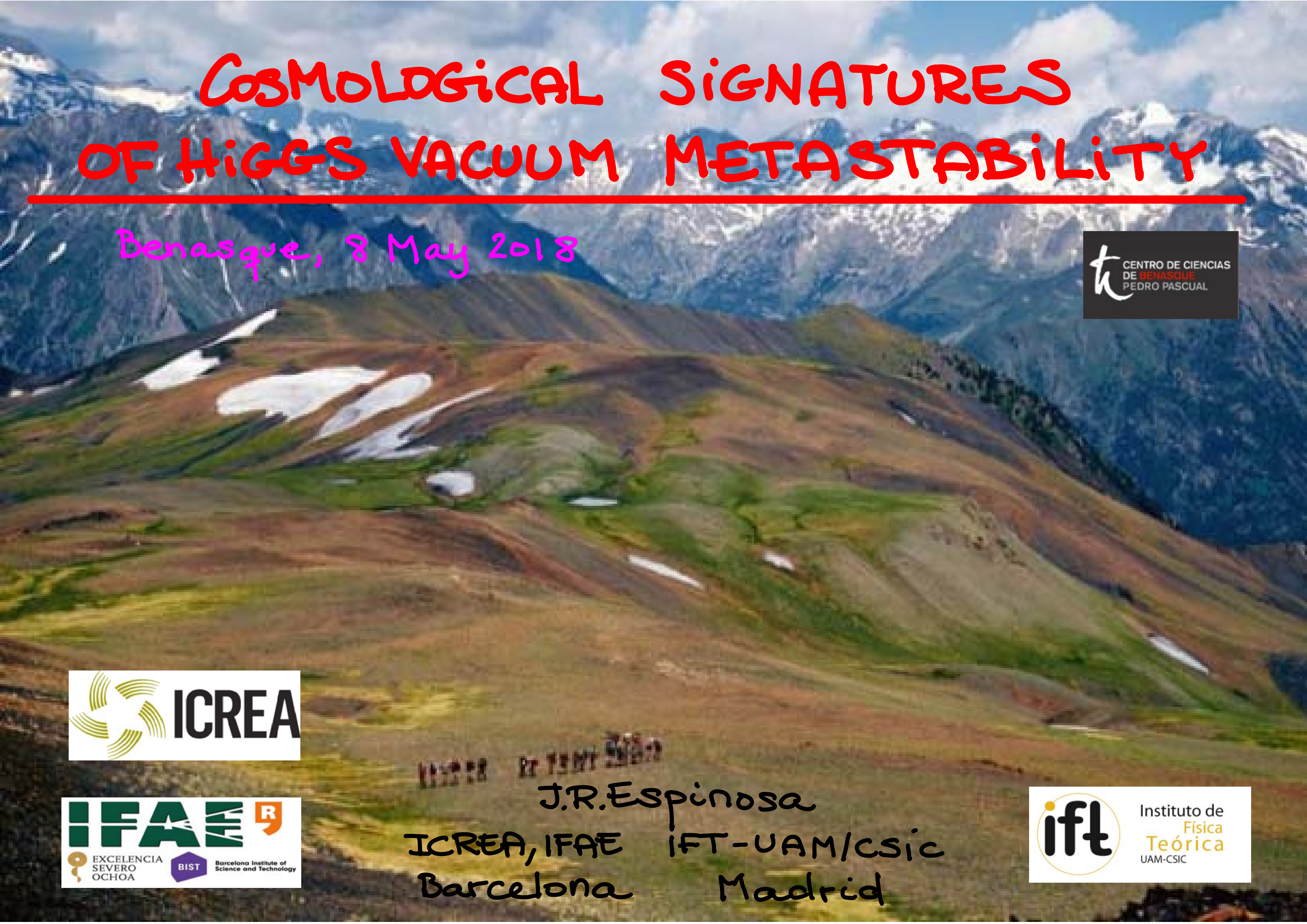

COSMOLOGICAL SIGNATURES OF HIGGS VACUUM METASTABILITY

Benasque, 8 May 2018

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

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COSMOLOGICAL PROBES OF THE UV END OF THE SM

Benasque, 8 May 2018

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OUTLINE

- ★ Context.
  SM extrapolated to UV
- ★ EW Vacuum Metastability
  Higgs near-criticality
- ★ Cosmological implications
- ★ Signatures of the instability:
  - ● Primordial Black Holes as Dark Matter
  - ● Gravitational Waves

CONTEXT, 20~~12~~, ~~13~~, ~~14~~, ~~15~~, ~~16~~, ~~17~~, 18

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

$$V = \frac{1}{2}\underbrace{m^2}_{\sim \frac{1}{(4\pi)^2}\Lambda^2} h^2 + \frac{1}{4}\lambda h^4 \quad \Rightarrow \quad \langle h \rangle^2 \sim \frac{m^2}{\lambda} \sim \text{EW}$$

CONTEXT, 2018

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

⇓

$\Lambda \sim$ few TeV

CONTEXT, 2018 / THIS TALK

- Higgs discovered, close to SM-like

+

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

+

- Disregarding naturalness

⇓

$\Lambda \sim M_{Pl}$?

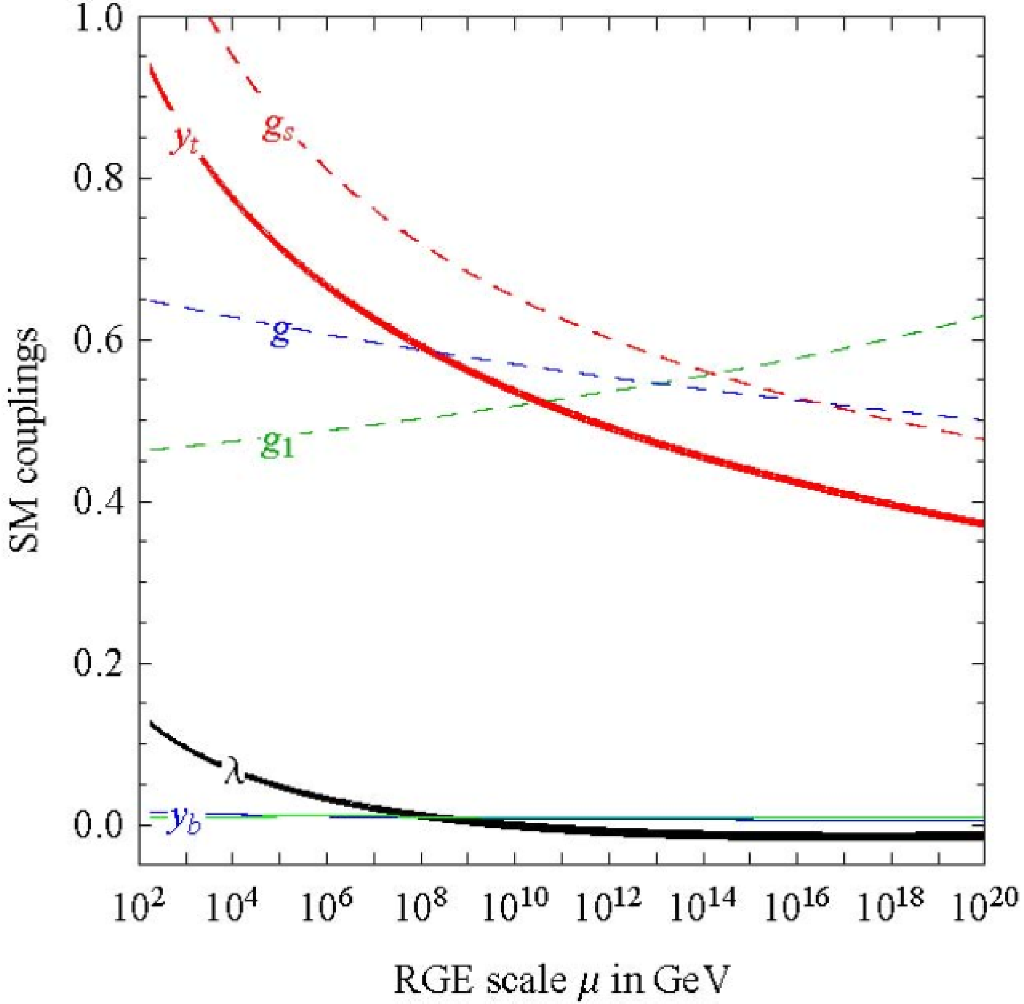
Non trivial possibility: can extrapolate SM to M_{Pl}

SM EXTRAPOLATION

Assume Higgs has SM props. and no BSM Physics

All SM parameters known

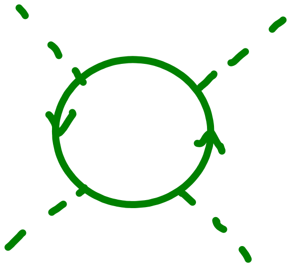
$M_h \Rightarrow \lambda(EW)$



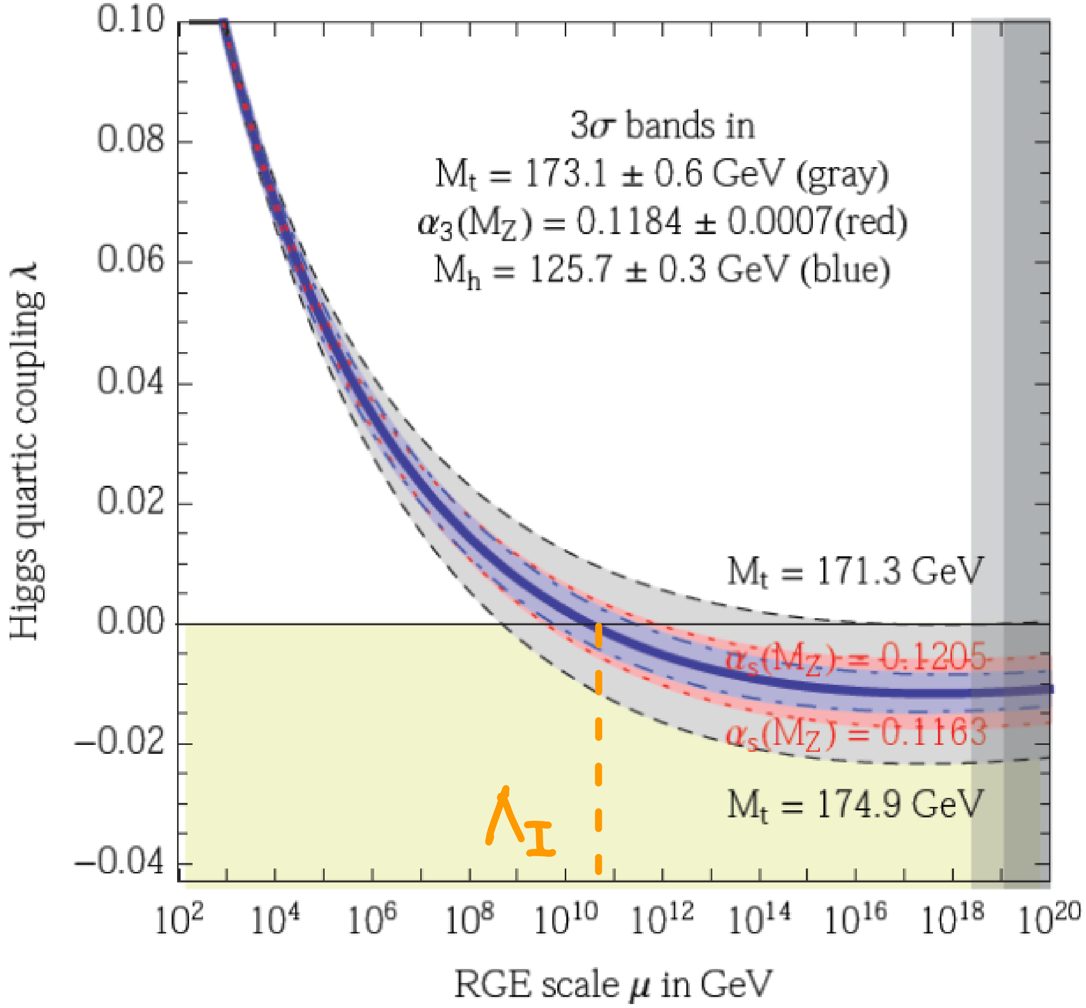
Weakly coupled up to M_{Pl}

UV EXTRAPOLATED λ

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



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

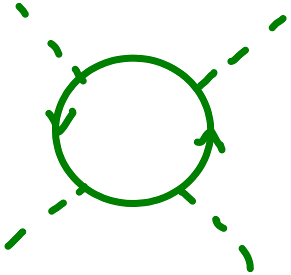


Degrassi et al '12 , Buttazzo et al '13

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

VACUUM INSTABILITY

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

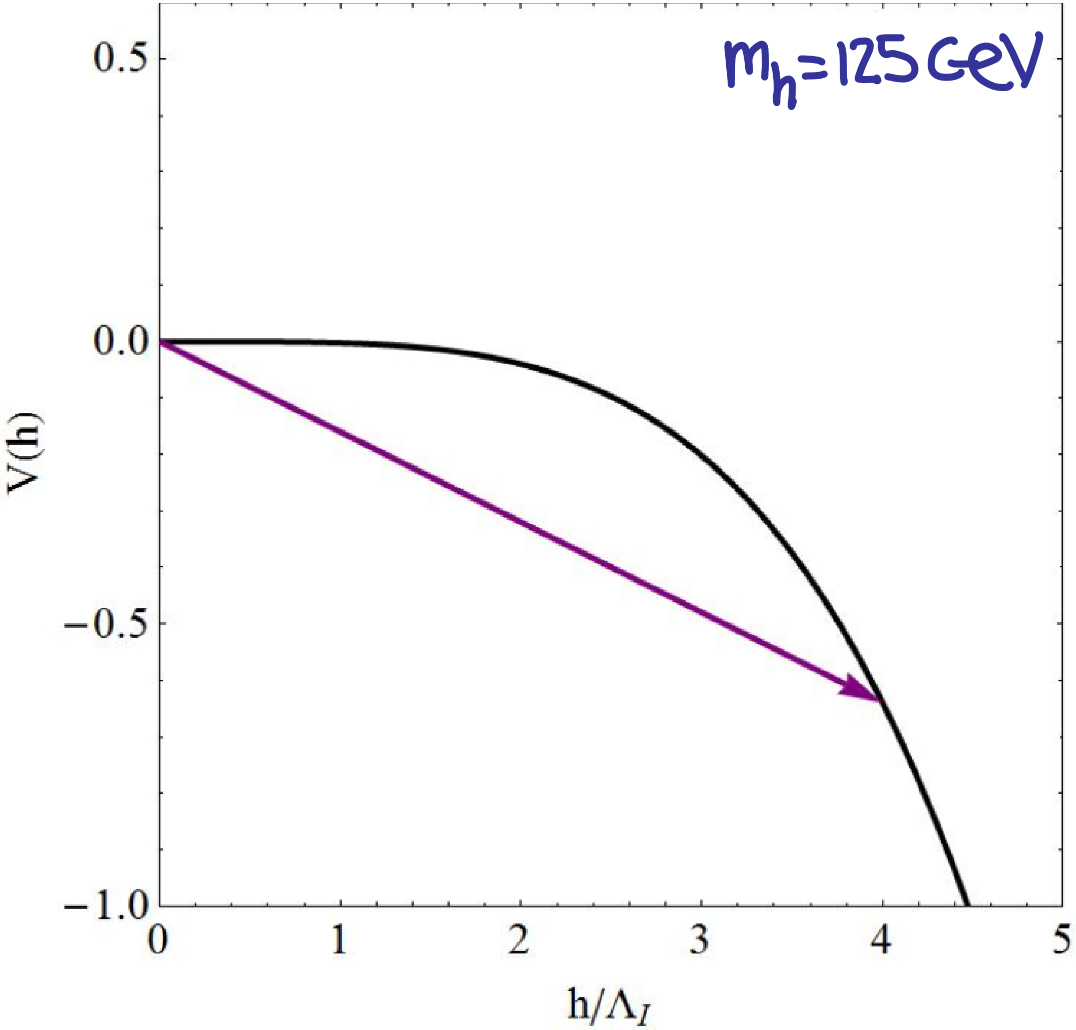


$\lambda < 0$ at $\Lambda_I \sim 10^{11}$ GeV

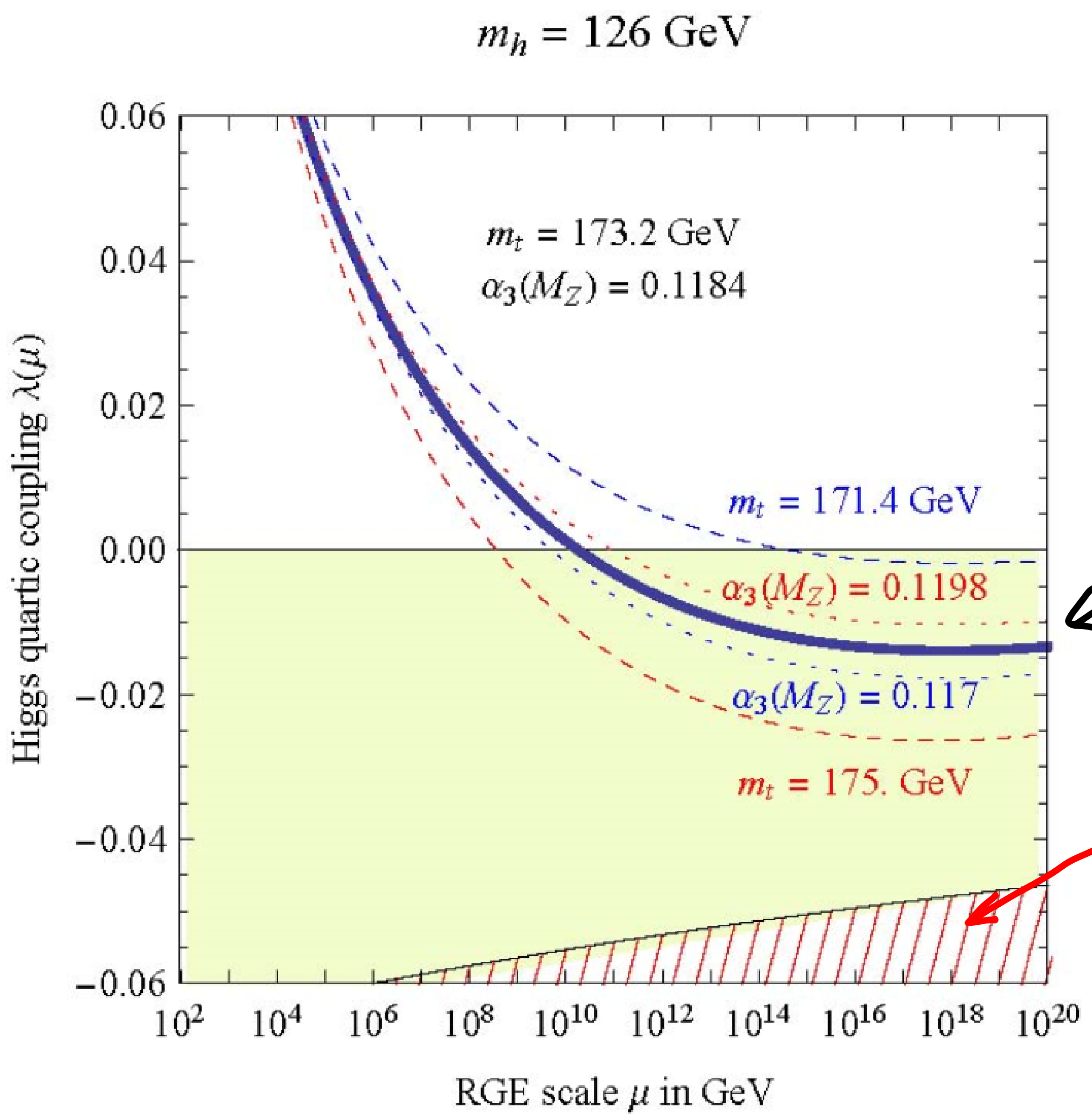
$\Downarrow$

Higgs potential instability

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



LIFE IN A METASTABLE VACUUM



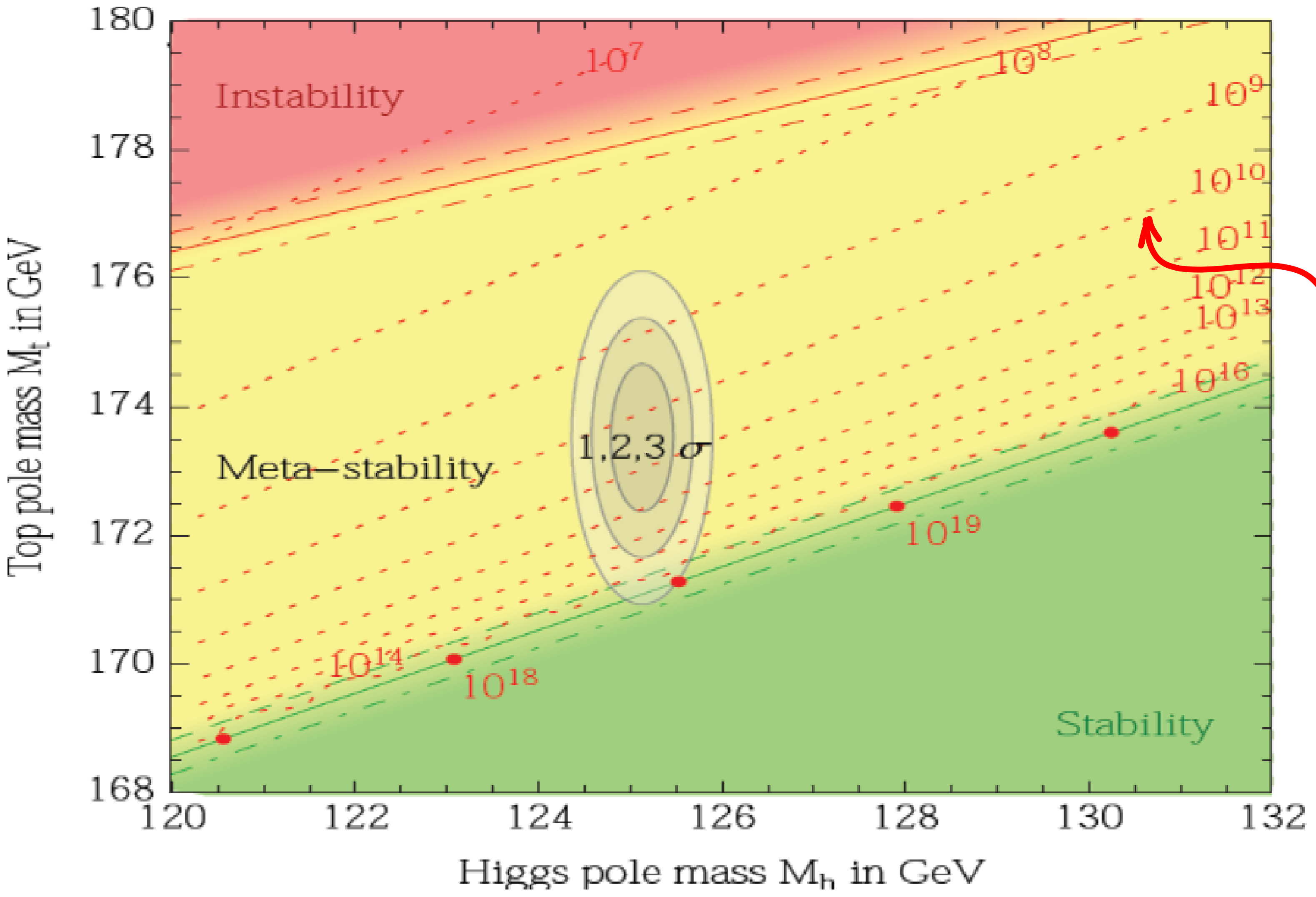
Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

Unstable vacuum

($M_h \downarrow$)

HIGGS NEAR-CRITICALITY



Buttazzo et al '13

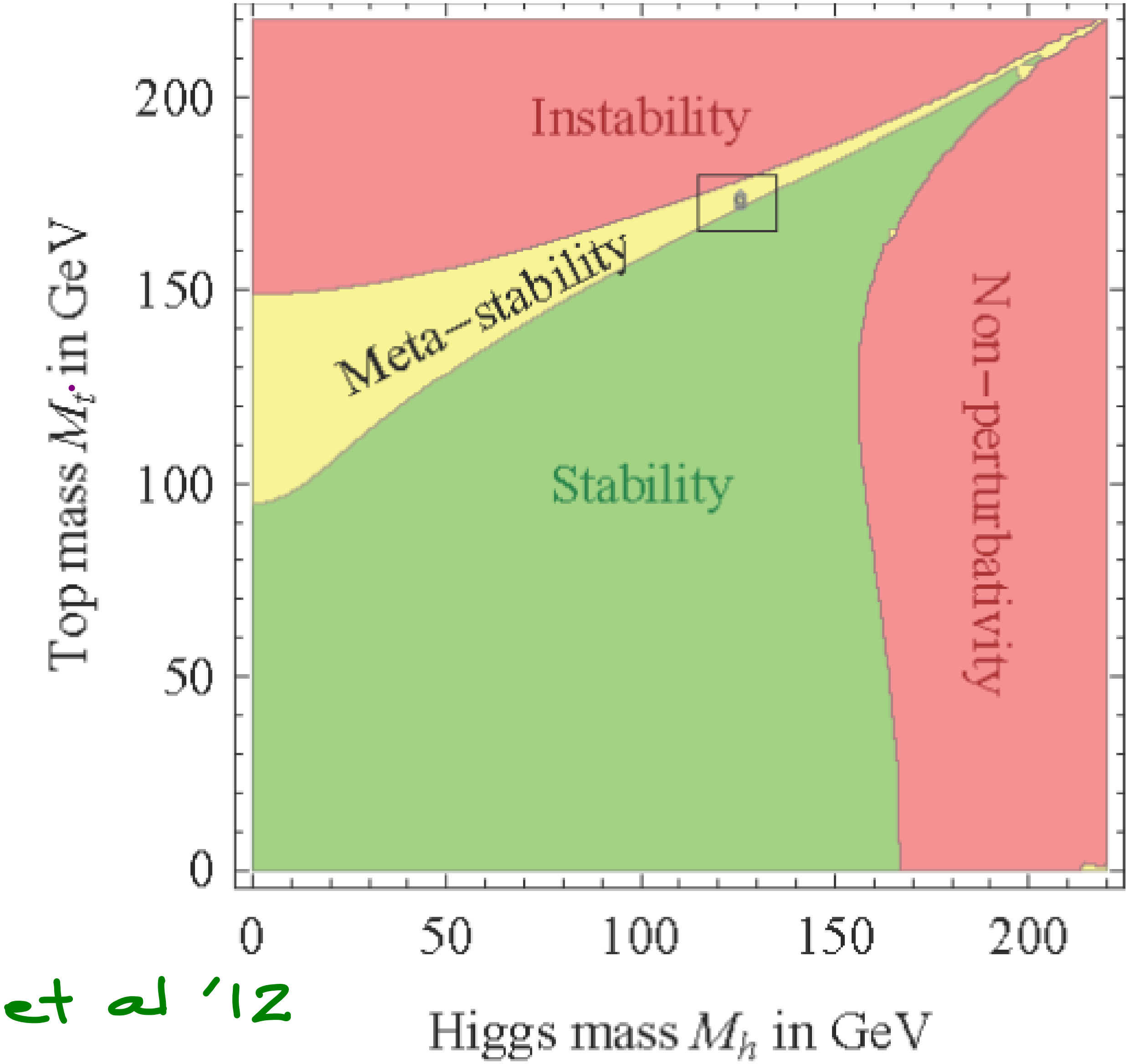
Λ_I (GeV)

$M_h = 125.15 \pm 0.24$ GeV

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

(back-up slides)

HIGGS NEAR-CRITICALITY



Degrassi et al '12

COSMOLOGICAL IMPLICATIONS

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

   Interplay with $\xi|H|^2R$, Parametric/tachyonic resonant Higgs production.

SIGNATURES ?

EW vacuum instability has a rich set of implications
(BSM models, cosmology : inflation, preheating, interplay with r, ...)

BUT

the mass scale of this physics is large

$$\Lambda_I \gtrsim 10^{10}\ \mathrm{GeV}$$

⇨ Difficult to test : no smoking-gun signature like proton decay...

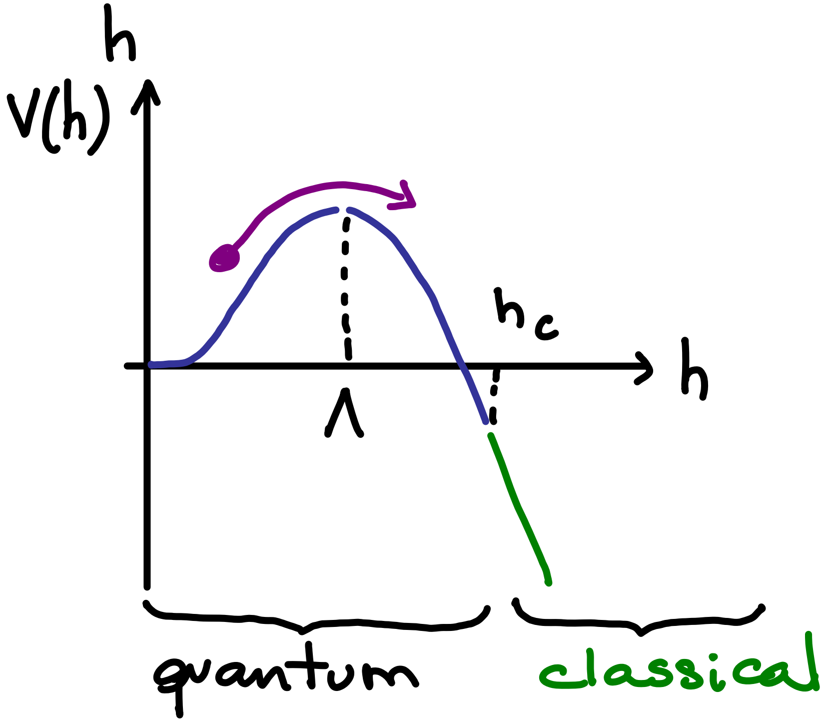
COSMOLOGICAL SIGNATURES. 1: PBHs as DM

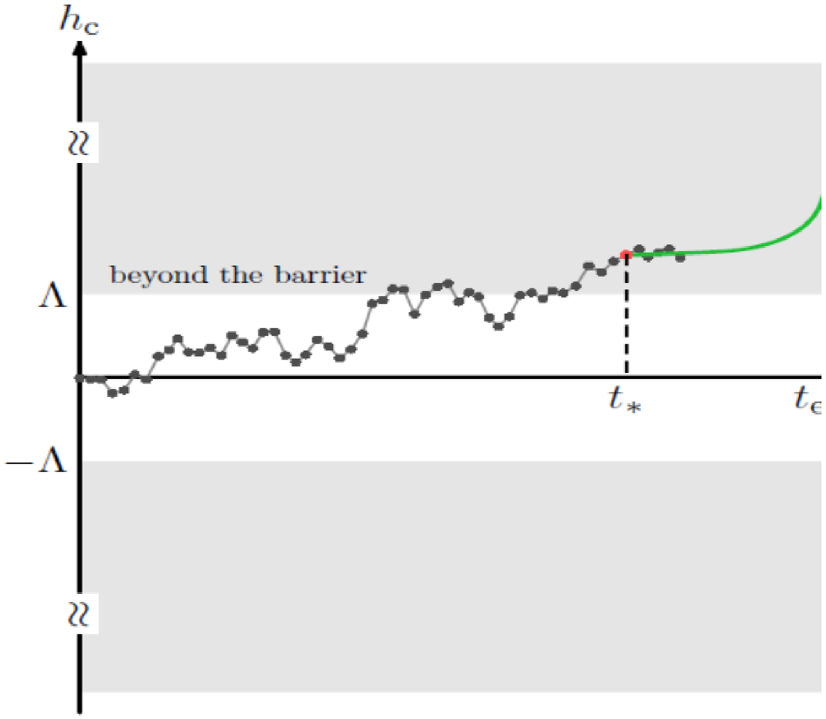
J.R.E, Racco, Riotto '17

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

Classical vs. quantum competition. Δh in $\Delta t \sim 1/H_I$:

$$(\Delta h)_{clas} \simeq \frac{V'}{3H_I^2} \leftrightarrow (\Delta h)_{quant} \simeq \frac{H_I}{2\pi}$$

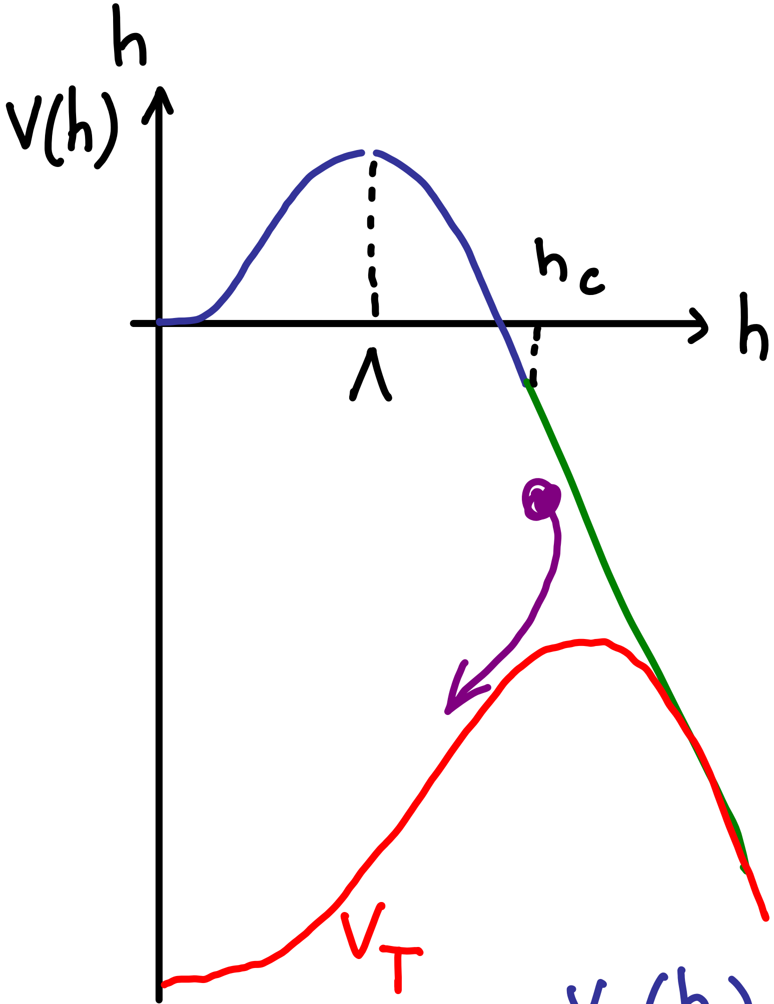


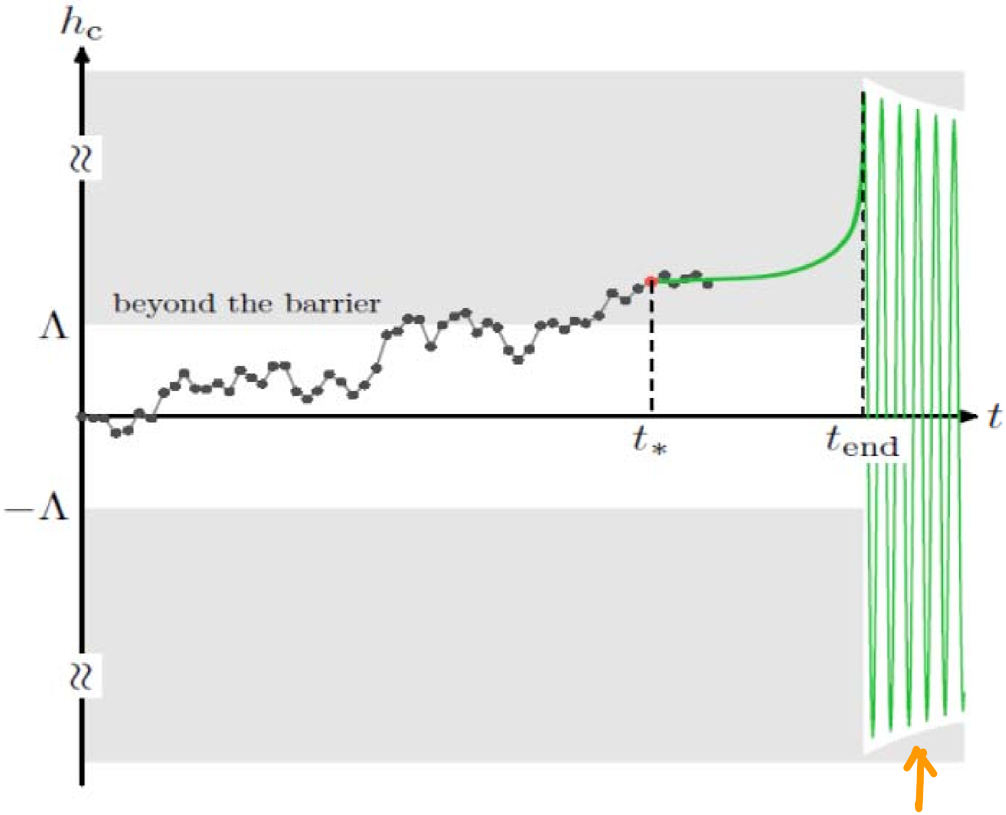


THERMAL RESCUE

J.R.E, Racco, Riotto '17

An efficient reheating saves the day.





$$V_T(h) \simeq \frac{1}{2}\kappa T^2 h_c^2$$

Thermal rescue

EVOLUTION OF HIGGS PERTURBATIONS

J.R.E, Racco, Riotto '17

After t_* :
$$\ddot{h}_c + 3H_I\dot{h}_c + V'(h_c) = 0$$

Higgs fluctuations:
$$\delta\ddot{h}_k + 3H_I\,\delta\dot{h}_k + \frac{k^2}{a^2}\delta h_k + V''(h_c)\,\delta h_k \simeq 0$$

Sub-Hubble modes $(k > Ha)$: oscillate and decrease

$|\delta h_k| \simeq \frac{H_I}{\sqrt{2k^3}}$ at Hubble crossing (at t_k)

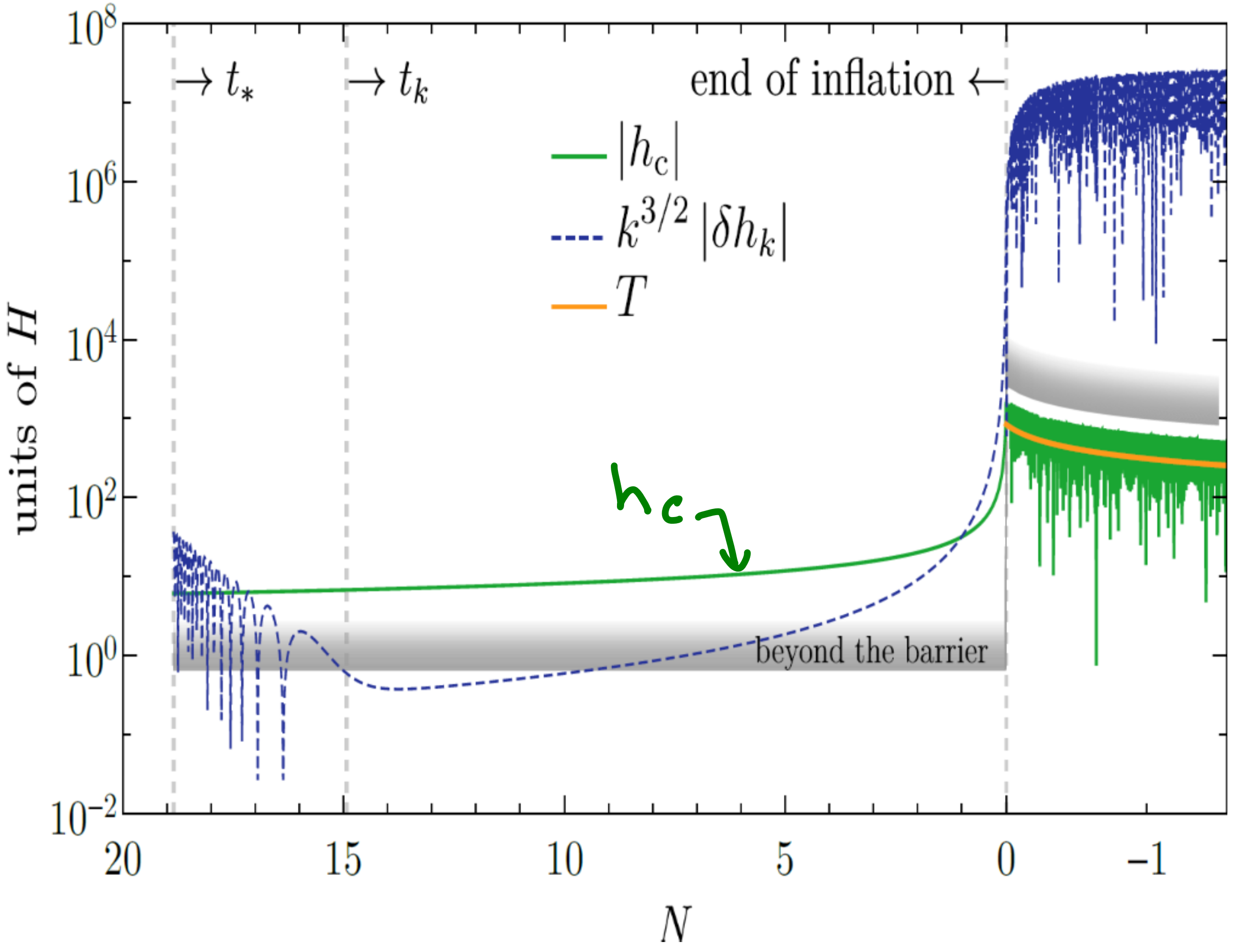
Super-Hubble modes $(k < Ha)$: grow with $V'' < 0$

$\delta h_k = c(k)\ \dot{h}_c(t)$ $\qquad$ $c(k) = \frac{H_I}{\sqrt{2k^3}\ \dot{h}_c(t_k)}$

GROWTH OF FLUCTUATIONS

J.R.E, Racco, Riotto '17

Making Higgs fluctuations grow significantly



Higgs fluctuations

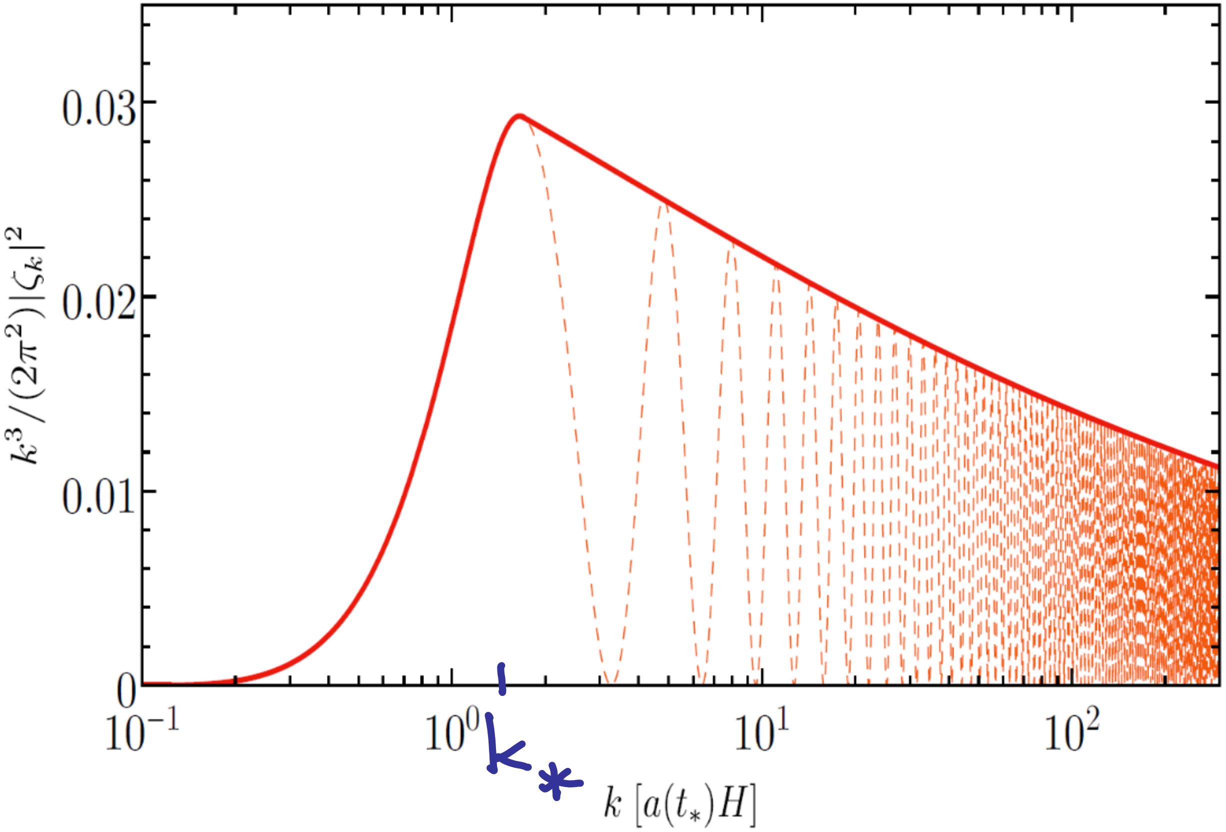
$k \sim 50\, a(t_*) H$

δh_k oscillate around minimum and decay quickly to radiation curvature perturbations

SPECTRUM

J.R.E, Racco, Riotto '17

Power spectrum $\mathcal{P}_\zeta = \frac{k^3}{2\pi^2}|\zeta_k|^2$



Can be quite large $\mathcal{P}_\zeta \sim 10^{-2}$ at the peak

k_* determined by t_*

GROWTH OF FLUCTUATIONS

J.R.E, Racco, Riotto '17

Gauge-invariant measure of perturbations :

Comoving curvature perturbation

$$\zeta = H_I \frac{\delta\rho}{\dot\rho} = \zeta_\phi \frac{\dot\rho_\phi}{\dot\rho} + H_I \frac{\delta\rho_h}{\dot\rho}$$

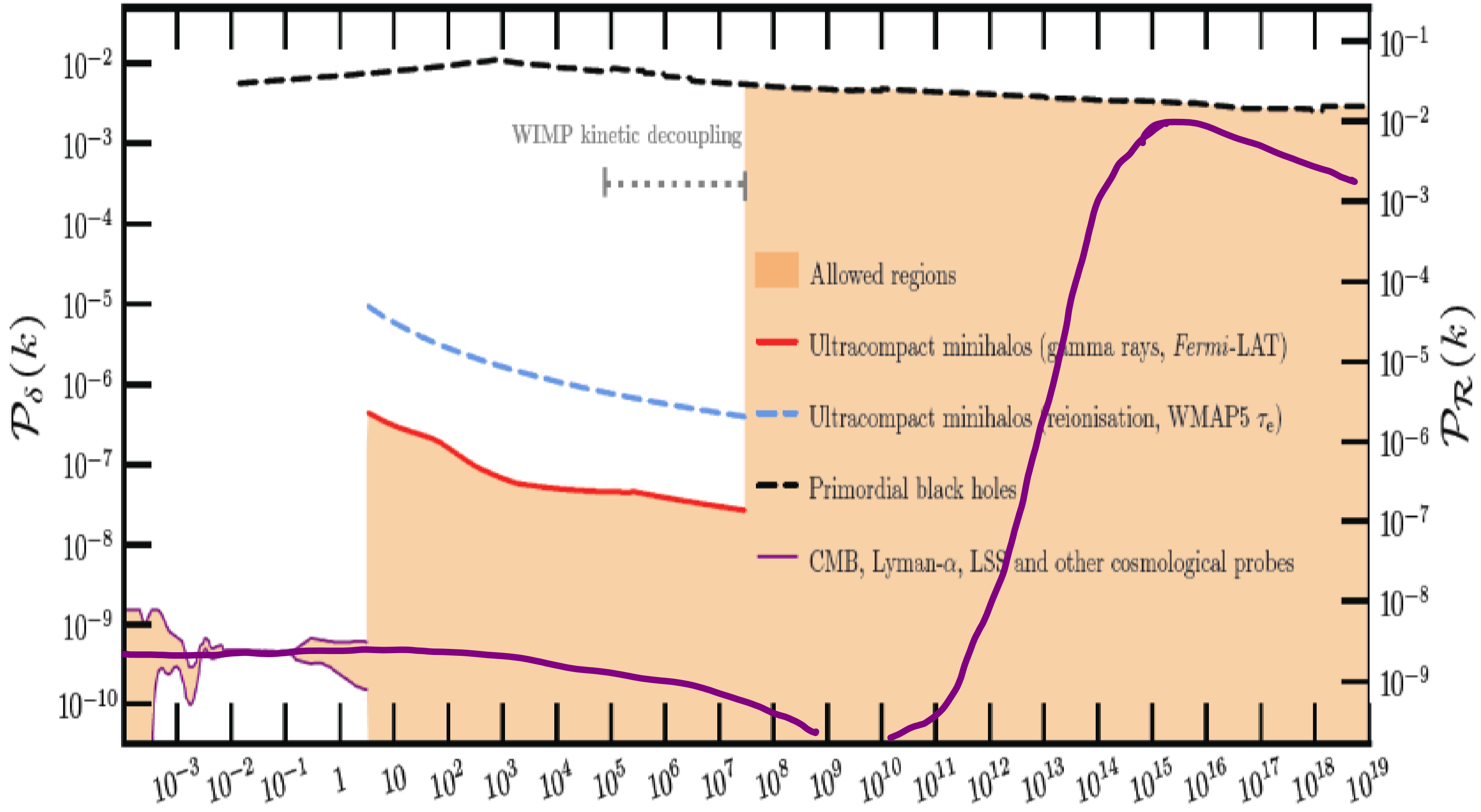
usual one,
responsible for CMB
perturbations

from Higgs,
dominant
at the end of
inflation

$$(k \ll aH): \quad \zeta_h \simeq \frac{H_I^2}{\sqrt{2k^3}\,\dot h_c(t_k)}$$

RELEVANT SCALES

Bringmann, Scott, Akrami '13



↑ CMB

↑ Higgs fluctuations

PRIMORDIAL BLACK HOLES

Zeldovich, Novikov '67 Hawking '71

Generated during early Universe evolution.

Mass range below star collapse is possible.

PBHs are collisionless, stable*, non-relativistic

these PBHs act as cold dark matter

Moderate deviations from homogeneity can lead to PBH production from radiation.

$\delta\rho/\rho \sim 1$, if horizon size, quite close to Schwarzschild radius

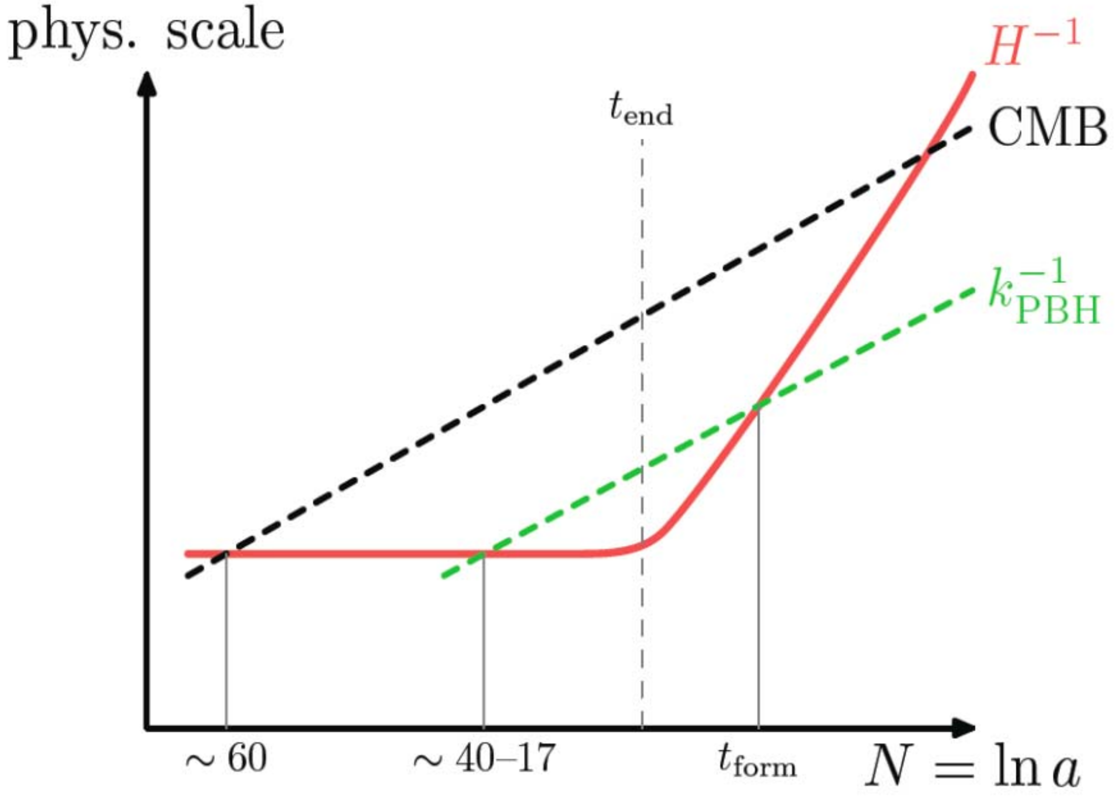
---

* If not too light

PBHs FROM HiGGS PERTURBATIONS

J.R.E, Racco, Riotto '17

Higgs fluctuations can seed large curvature perturbations, that collapse into PBHS when they reenter the horizon during radiation era



PBHs FROM HiGGS PERTURBATIONS

J.R.E, Racco, Riotto '17

Collapse into a PBH requires an overfluctuation

$$\Delta(\vec{x}) = \frac{4}{9}\frac{1}{a^2 H_I^2}\nabla^2 \zeta(\vec{x}) \geq 0.45$$

leading to

$$\frac{1}{H} = \frac{1}{H_I} e^{2N}$$

$$M_{PBH} = \gamma \cdot \underbrace{\frac{4\pi}{3}\rho H^{-3}}_{\text{mass in Hubble sphere}} \simeq \gamma \frac{M_{Pl}^2}{H_I} e^{2N}$$

efficiency factor ~0.2

e-folds till inflation ends

For $H_I \sim 10^{12}$ GeV

$$M_{PBH} = M_\odot e^{2(N-36)}$$

PBH ABUNDANCE

J.R.E, Racco, Riotto '17

How likely is $\Delta \gtrsim 0.45$?

From $\mathcal{P}_\zeta$ get the variance σ_Δ^2 $\quad (\sigma_\Delta \lesssim 0.05)$

The mass fraction ending up in PBH is

$$\beta(M) = \int_{\Delta_c}^{\infty} \frac{d\Delta}{\sqrt{2\pi}\,\sigma_\Delta}\, e^{-\Delta^2/2\sigma_\Delta^2} \simeq \frac{\sigma_\Delta}{\Delta_c \sqrt{2\pi}}\, e^{-\Delta_c^2/2\sigma_\Delta^2}$$

Evolving this

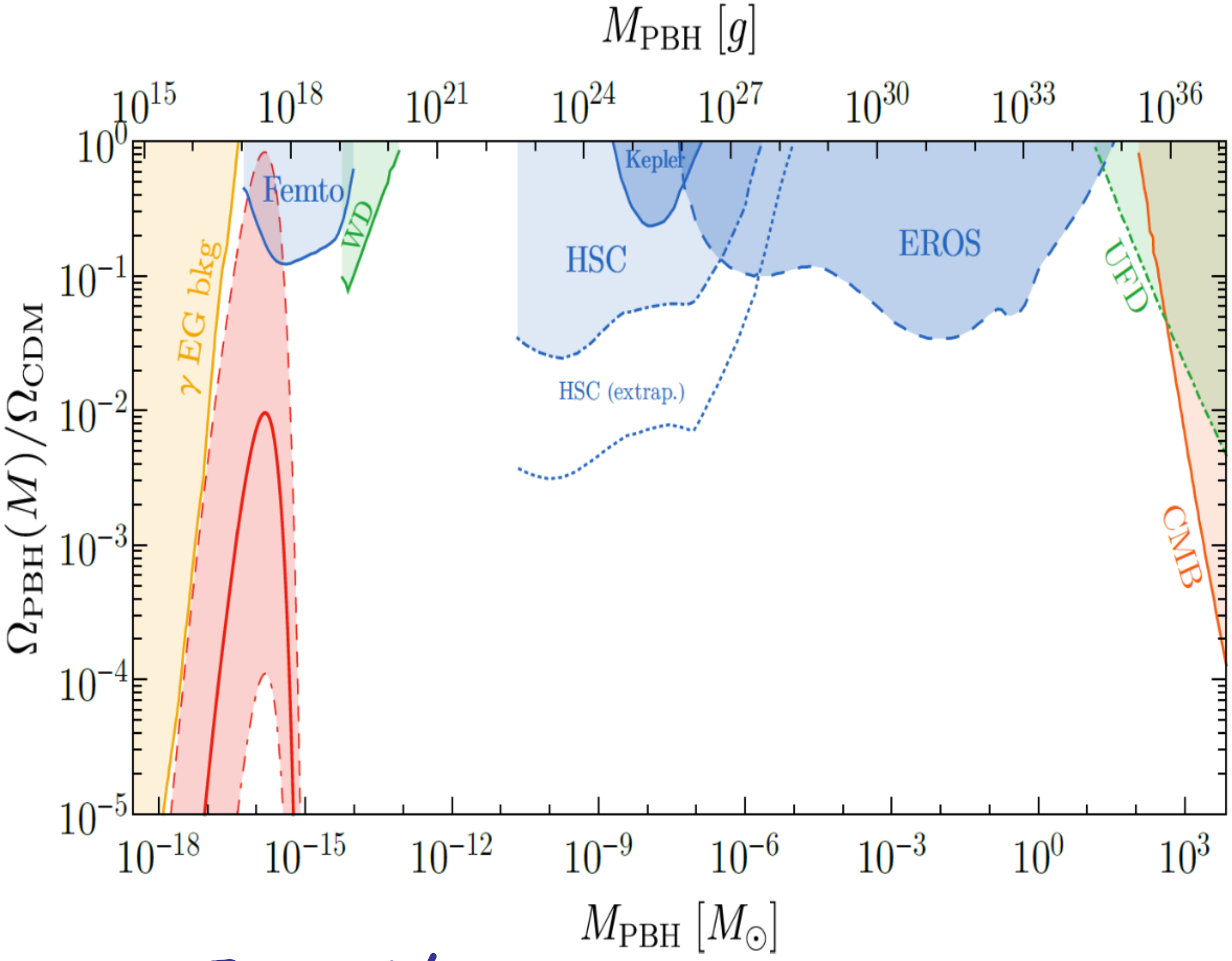
$$\frac{\Omega_{PBH}(M)}{\Omega_{CDM}} = \frac{\beta(M)}{1.6\times 10^{-16}} \left(\frac{\gamma}{0.2}\right)^{3/2} \left(\frac{g_*}{106.75}\right)^{-1/4} \left(\frac{M}{10^{-15} M_\odot}\right)^{-1/2}$$

PBHs FROM HiGGS PERTURBATIONS

J.R.E, Racco, Riotto '17

PBH mass spectrum

These PBHs might be (all) Dark Matter



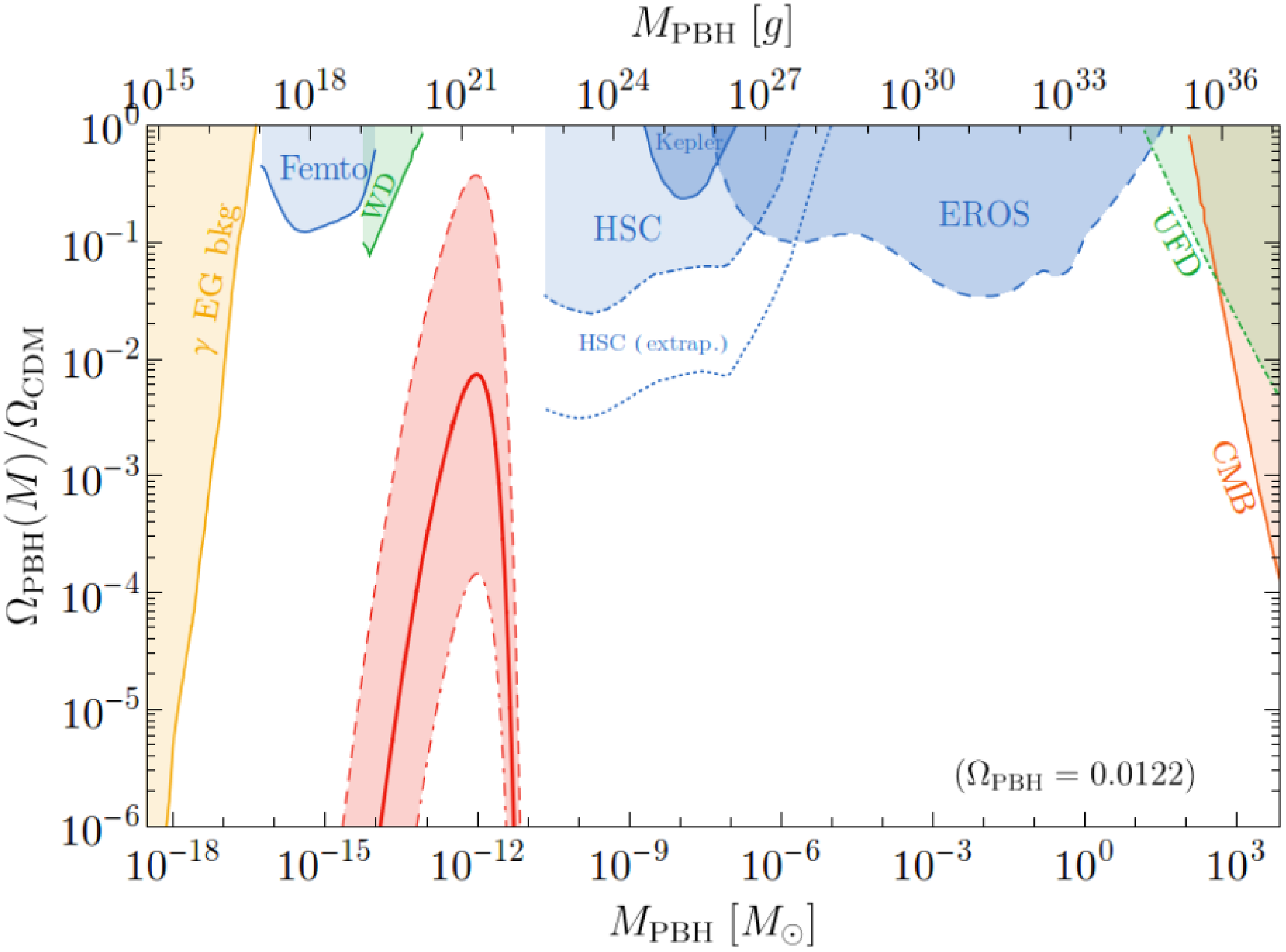
$m_h = 125.09$ GeV $\quad m_t = 172$ GeV

PBHs FROM HiGGS PERTURBATiONS

J.R.E, Racco, Riotto '17

PBH mass spectrum

These PBHs might be (all) Dark Matter



$m_h = 125.33$ GeV $\quad m_t = 170.47$ GeV

PBH PROPERTiES

J.R.E, Racco, Riotto '17

For $N \simeq 17$ one gets

$$M_{PBH} \simeq 10^{-16} M_{\odot}$$ (~ asteroid)

$$R_{PBH} \simeq 10^{-13}\ m$$ (subatomic size)

Assuming they give all DM

$$\rho_{DM} \sim 0.3\ GeV/cm^3 \Rightarrow \Delta x \sim 10^{12}\ m$$

(~ a few in our solar system)

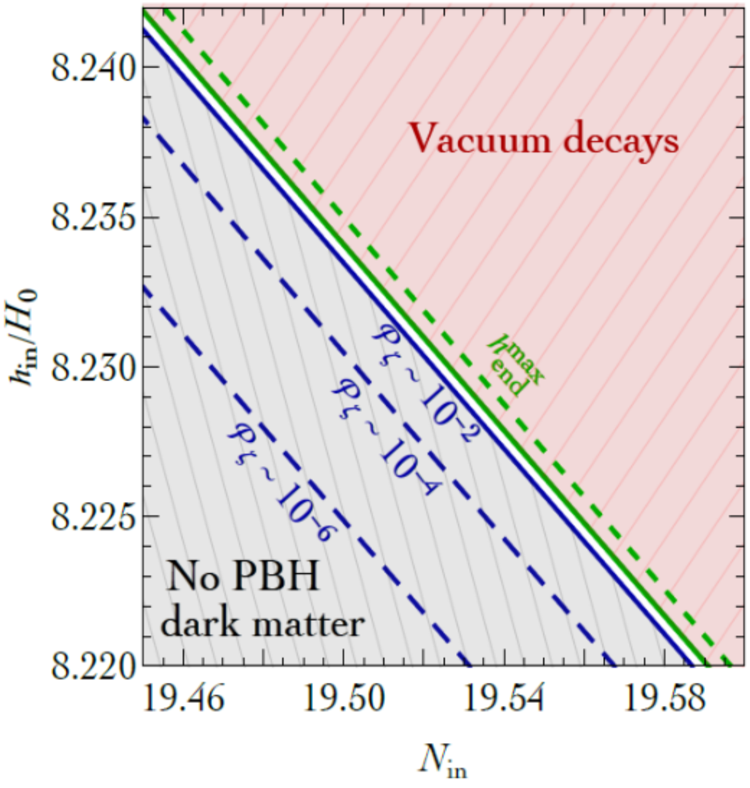
$$N_{Galaxy} \sim 10^{27}$$

FINE-TUNING ISSUES

J.R.E, Racco, Riotto '17

Scenario clearly tuned (eg, end of inflation right on time to save h_c).

Anthropic explanation Only way to get DM in SM, which is needed for large scale structure.



Strumia, Urbano et al '18

$$\delta\left(\frac{h_*}{H_I}\right) \sim \frac{1}{2\pi} \Rightarrow$$

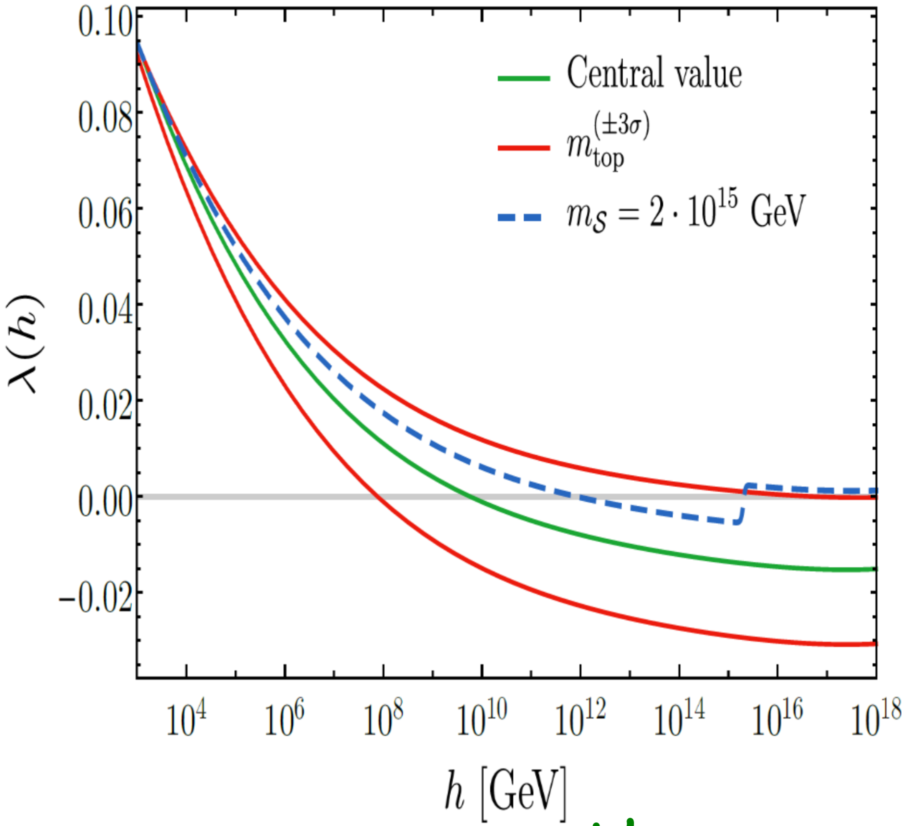
too small PBH abundance or vacuum decay

STABILIZATION HELPS

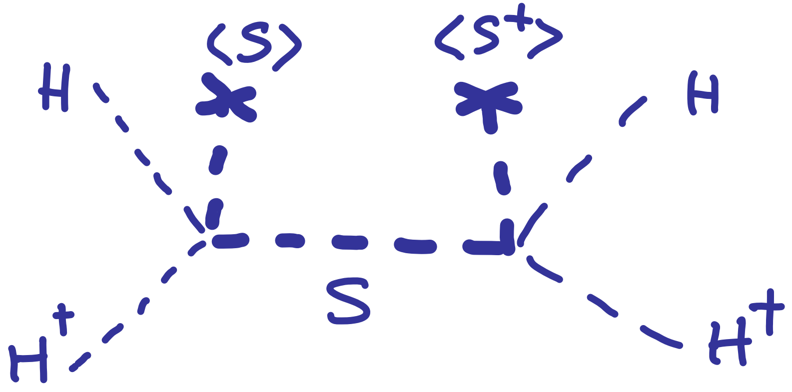
J.R.E., Racco, Riotto '18

Invoke tree-level threshold effect in λ to stabilize V

Singlet field S coupled to h



Elias-Miró et al '12

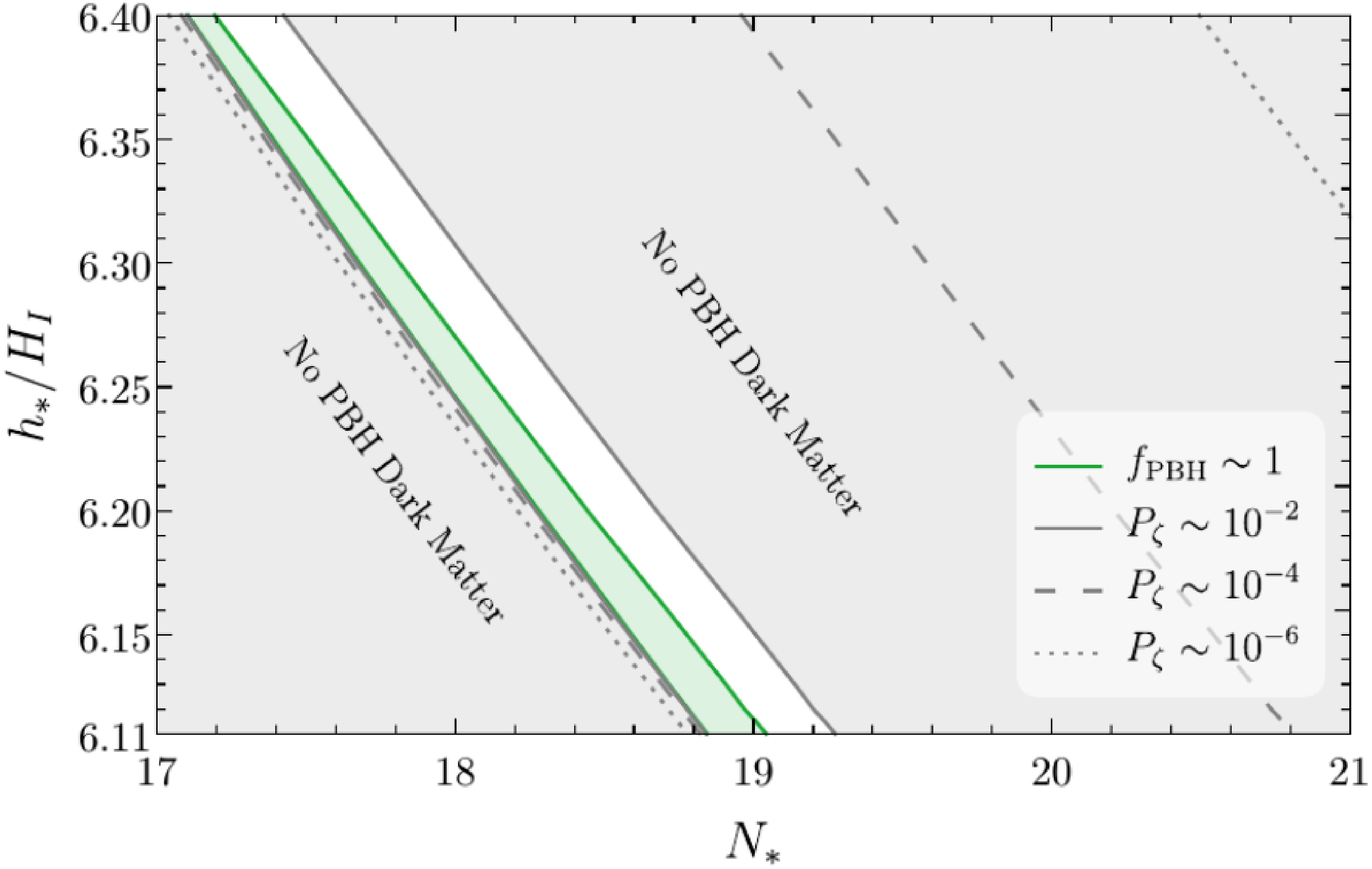


Non-SM minimum at $\sim 10^{15}$ GeV

Thermally rescued after inflation

STABILIZATION HELPS

J.R.E, Racco, Riotto '18



$\frac{1}{2\pi}$

No death by AdS

COSMOLOGICAL SIGNATURES. 2: GWs

J.R.E, Racco, Riotto '18

Besides the primordial tensor spectrum from inflation

⇨ Scalar-induced GW at 2nd-order in perturbations

$$ds^2 = -a^2(1+2\Phi)\,d\eta^2 + a^2\left[(1-2\psi)\delta_{ij} + \frac{1}{2}h_{ij}\right]dx^i dx^j$$

$(\psi = 2\zeta/3)$ scalar ↑ ↖ tensor

Einstein ⇨ $$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\,\mathcal{T}_{ij}^{lm}\,S_{lm}$$

projector ↗ ↖ source

$\sim \partial^2\psi^2$

Expect $$\mathcal{P}_\zeta \xrightarrow[\text{Gen. Relat.}]{} \mathcal{P}_h \sim \mathcal{P}_\zeta^2$$

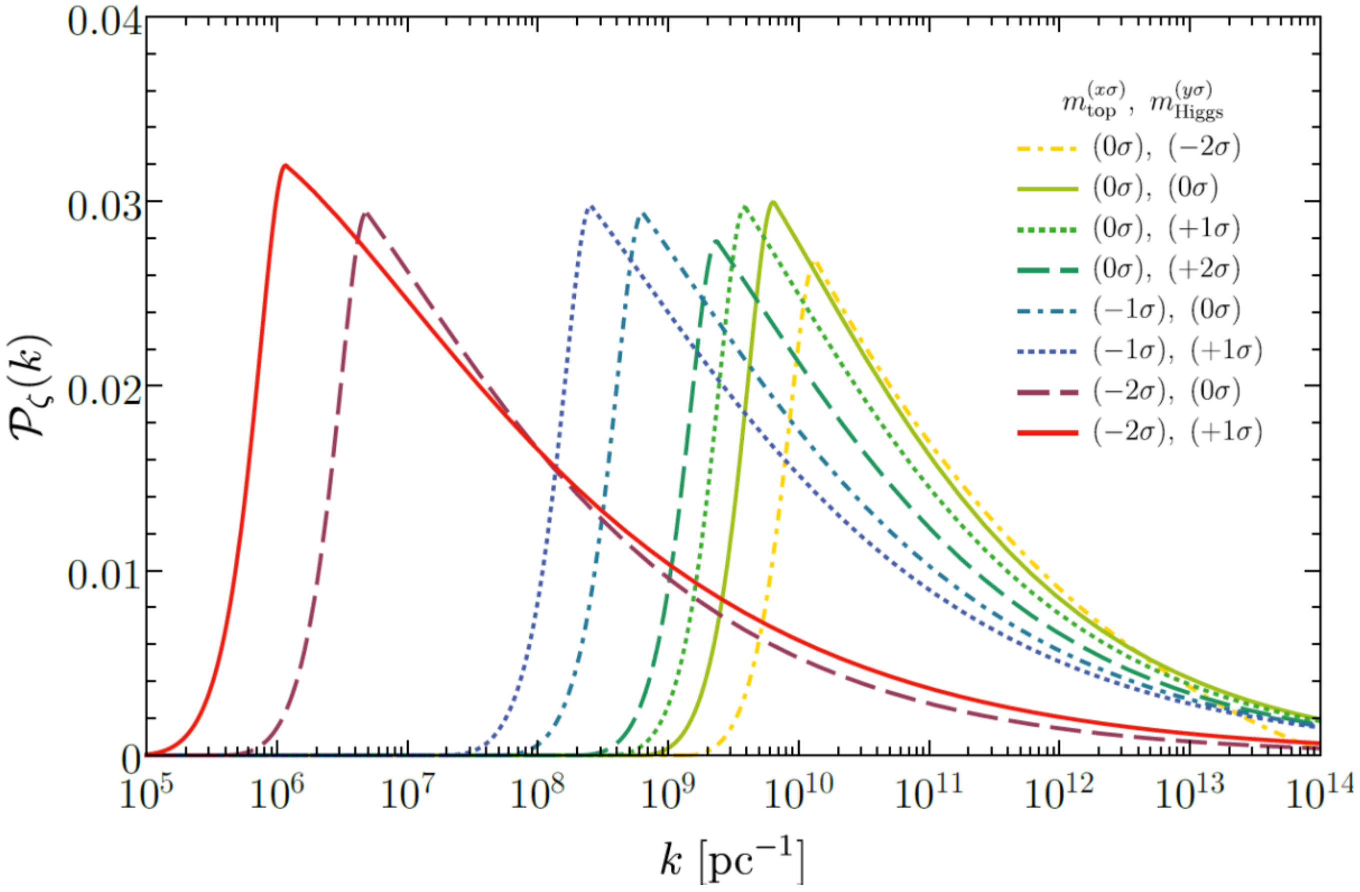
Potentially observable if $\mathcal{P}_\zeta$ sizeable.

SCALAR POWER SPECTRUM

J.R.E, Racco, Riotto '18

$\mathcal{P}_\zeta$ is $m_{h,t}$ sensitive

$m_h = 125.09 \pm 0.24$ GeV $m_t = 172.47 \pm 0.5$ GeV

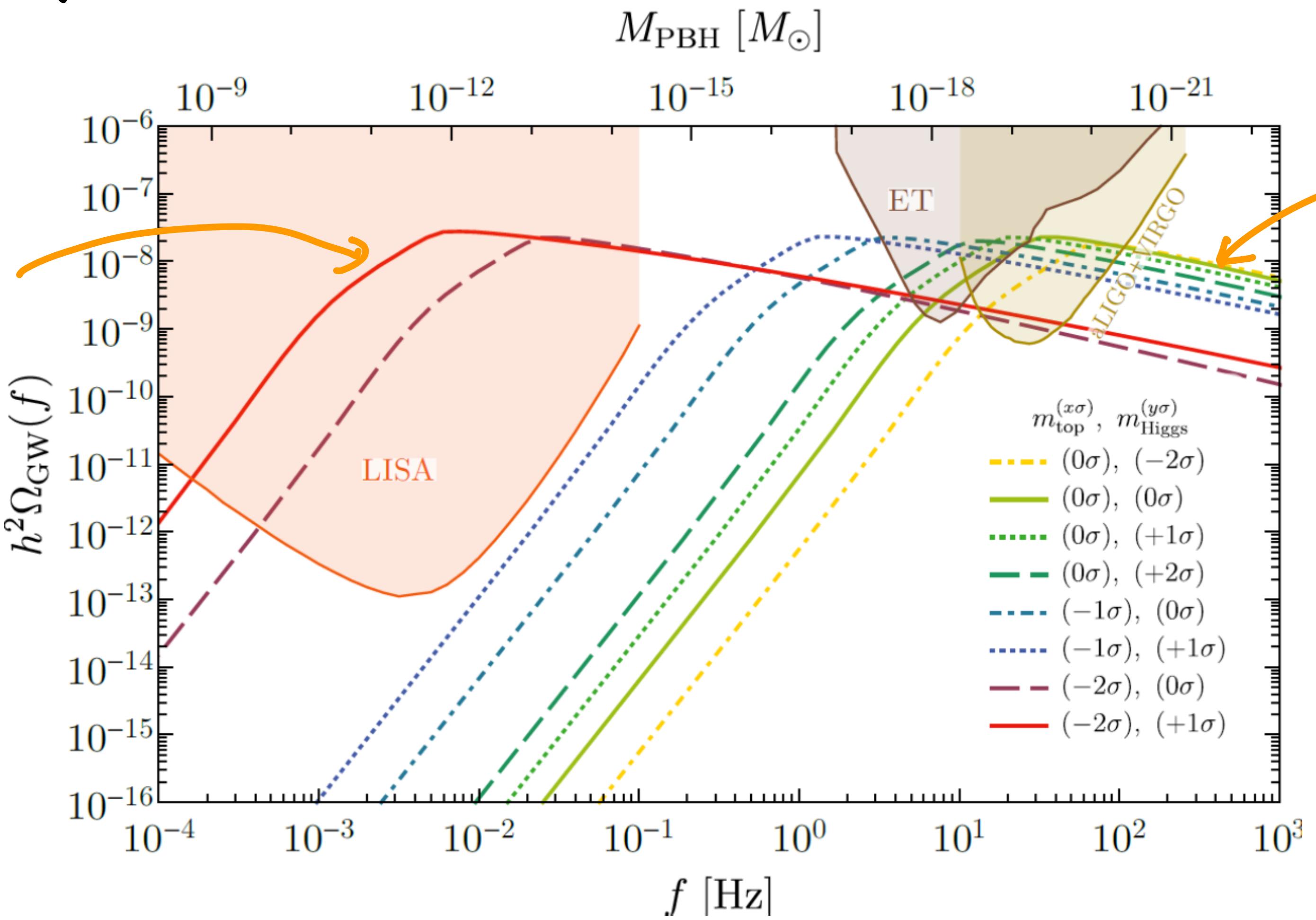


$\Lambda_I \uparrow \longleftrightarrow \Lambda_I \downarrow$

GW SPECTRUM

J.R.E, Racco, Riotto '18

GW Spectrum on the reach of future experiments



$n_T \simeq 3$

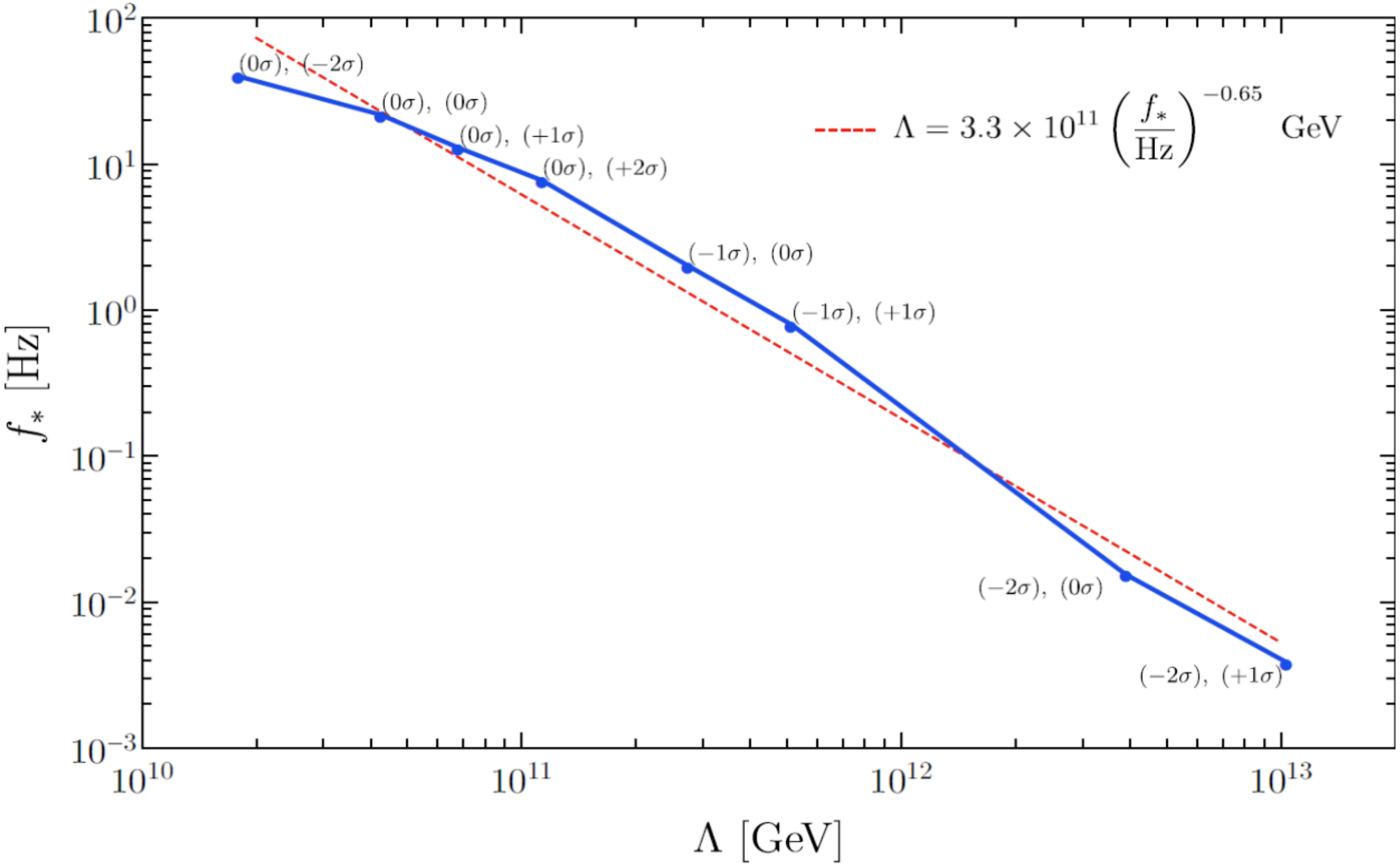
$n_T \simeq -0.6$

$$\Omega_{GW}(f) \simeq 3\times10^{-8}\,(f/f_*)^{n_T}$$

"HEARiNG" THE INSTABiLiTY SCALE

J.R.E, Racco, Riotto '18

Peak f_* $m_{h,t}$ sensitive ⇨ Λ_I sensitive



$$\Lambda_I = 3.3 \times 10^{11}\,\mathrm{GeV} \left(\frac{f_*}{Hz}\right)^{-0.6}$$

BISPECTRUM

J.R.E, Racco, Riotto '18

Bi-spectrum (3-point h_{ij} correlator) is another observable of interest for LISA, as it would allow to discriminate GW mechanisms.

$$\langle h^r(\eta,\vec{k}_1)\, h^s(\eta,\vec{k}_2)\, h^t(\eta,\vec{k}_3)\rangle = (2\pi)^3\, \delta(\vec{k}_1+\vec{k}_2+\vec{k}_3)\, B_h^{rst}(\vec{k}_i)$$

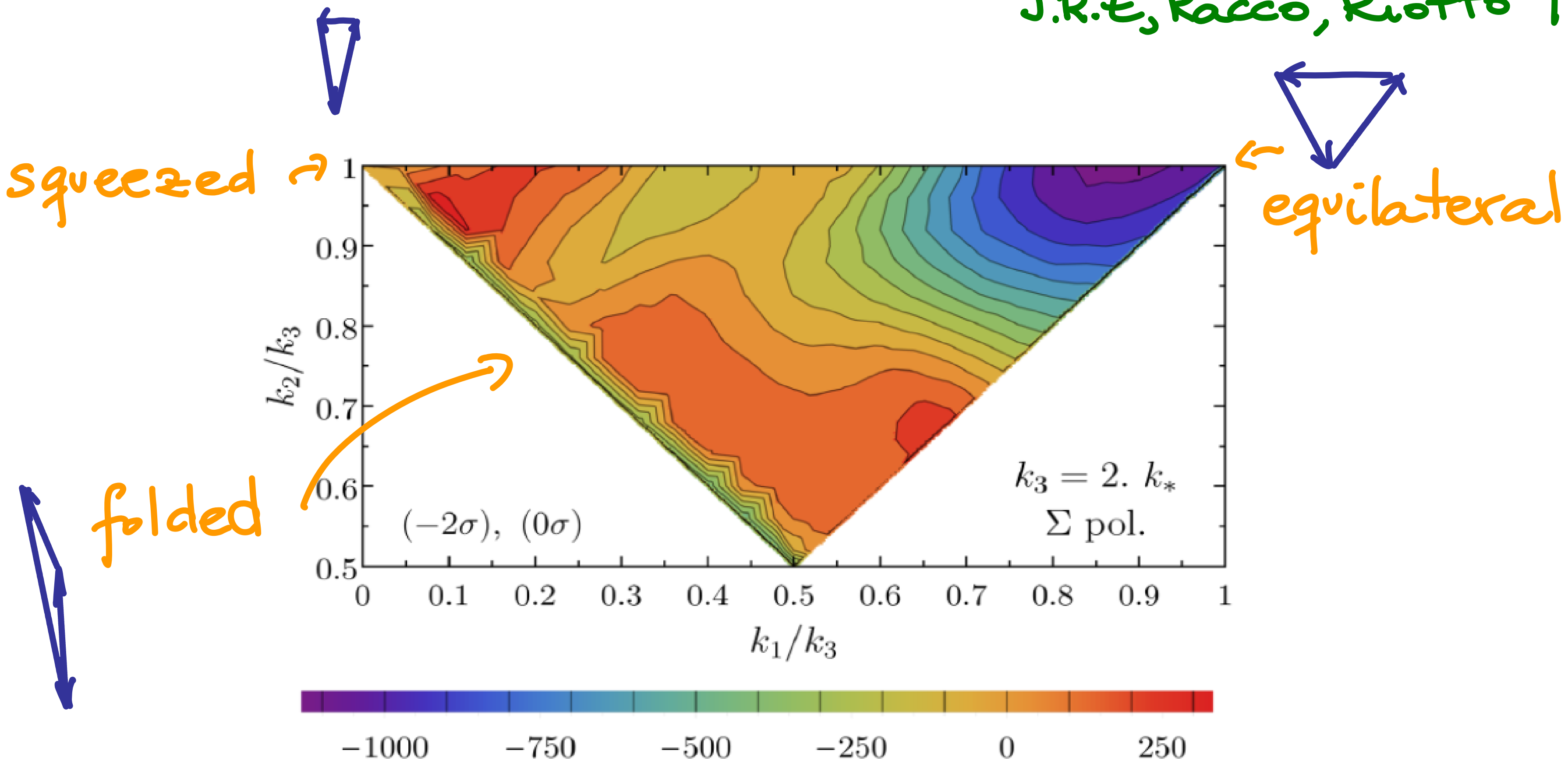
where r,s,t = polarizations $(+,\times)$ of the Fourier modes:

$$h_{ij}(\eta,\vec{x}) = \int \frac{d^3k}{(2\pi)^3}\left[h^{(+)}_{\vec{k}}(\eta)\, e^{(+)}_{ij}(\vec{k}) + h^{(\times)}_{k}(\eta)\, e^{(\times)}_{ij}(\vec{k})\right]$$

polarization tensors

BISPECTRUM

J.R.E, Racco, Riotto '18

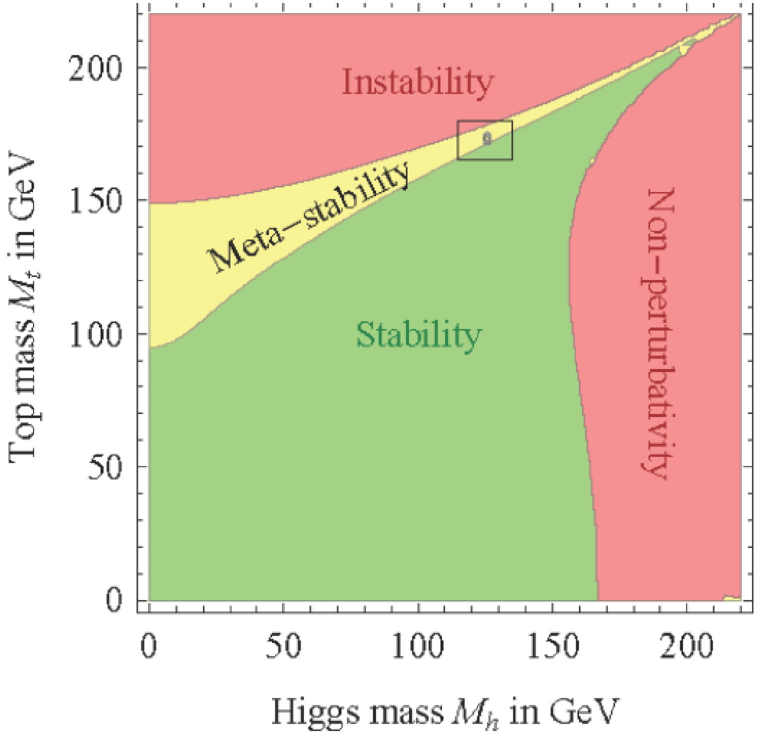


$$S_h^{rst}(\vec{k}_1,\vec{k}_2,\vec{k}_3) = \frac{k_1^2 k_2^2 k_3^2 \; B_h^{rst}(\vec{k}_1,\vec{k}_2,\vec{k}_3)}{\sqrt{\mathcal{P}_h(k_1)\,\mathcal{P}_h(k_2)\,\mathcal{P}_h(k_3)}} \qquad (k_1 \le k_2 \le k_3)$$

useful to characterize the GW background.

CONCLUSIONS

Higgs near-criticality



- ★ Intriguing. (~ GUT hint)
  Deep meaning?

- ★ Has a rich set of cosmological implications

  (inflation, preheating, interplay with r, ...)

- ★ Difficult to test (no smoking-gun signature like proton decay...)

CONCLUSIONS

Possible signatures
From Higgs fluctuations
enhanced if instability
region is probed

★ PBHs as DM

Requires tuning (anthropics? / ruled out?)

Ways-out for mechanism if $V(h)$ stabilized

★ GW background from scalar perturbations

Potentially observable: near instability!

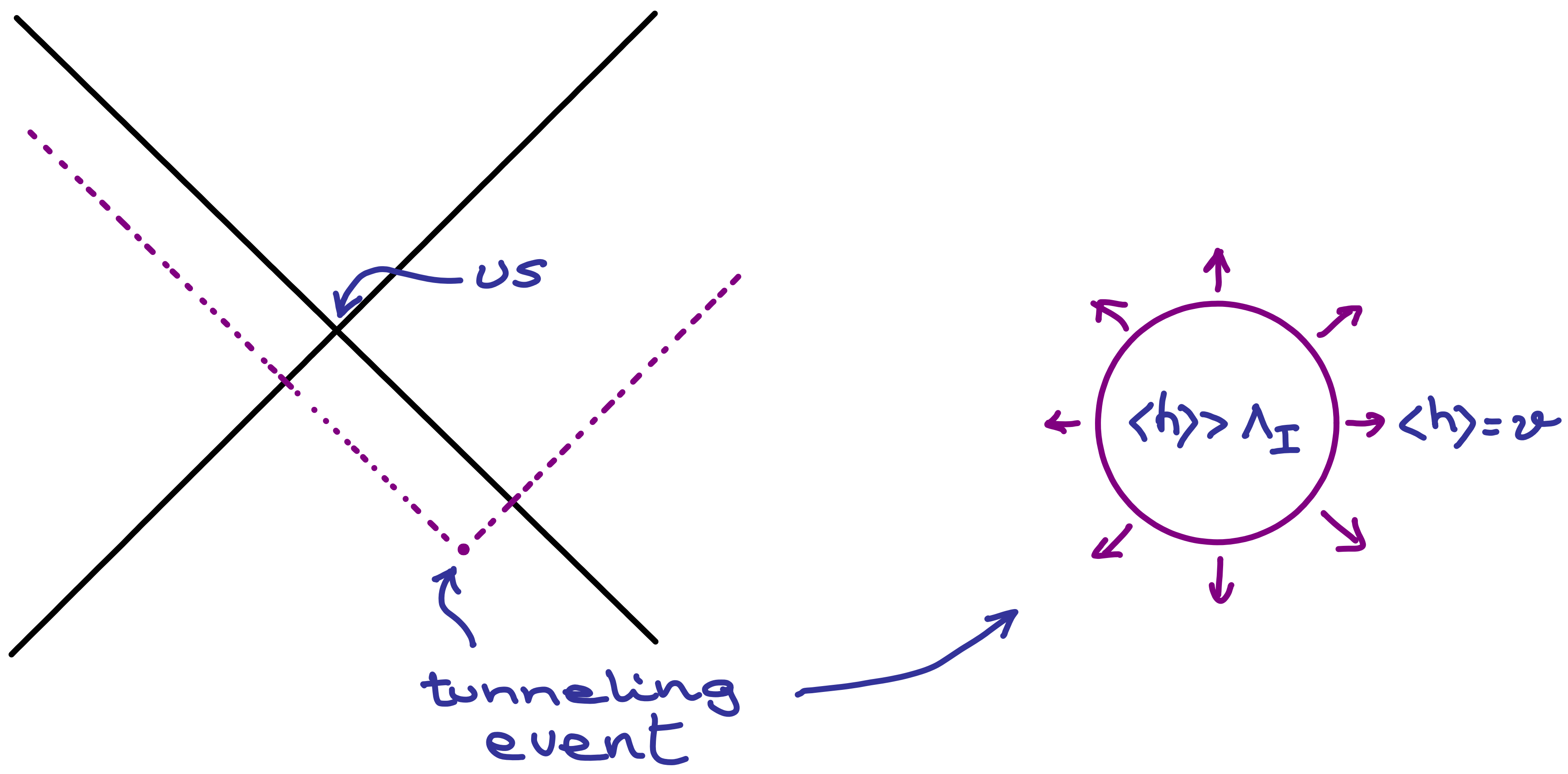
★ Collider - DM - GW link to check consistency.

Cosmological observables are great UV probes!

BACK-UP SLIDES

LIFE IN A METASTABLE VACUUM

$$p = \text{Decay prob.} = \frac{\text{Decay rate}}{\Delta t \cdot \Delta V}\, \tau_U^4 \quad \text{with} \quad \tau_U^4 \sim e^{560}/M_{Pl}^4$$



LIFE IN A METASTABLE VACUUM

$$p = \text{Decay prob.} = \underbrace{\frac{\text{Decay rate}}{\Delta t \cdot \Delta V}}_{h^4 e^{-S_4}} \tau_U^4 \quad \text{with } \tau_U^4 \sim e^{560}/M_{Pl}^4$$

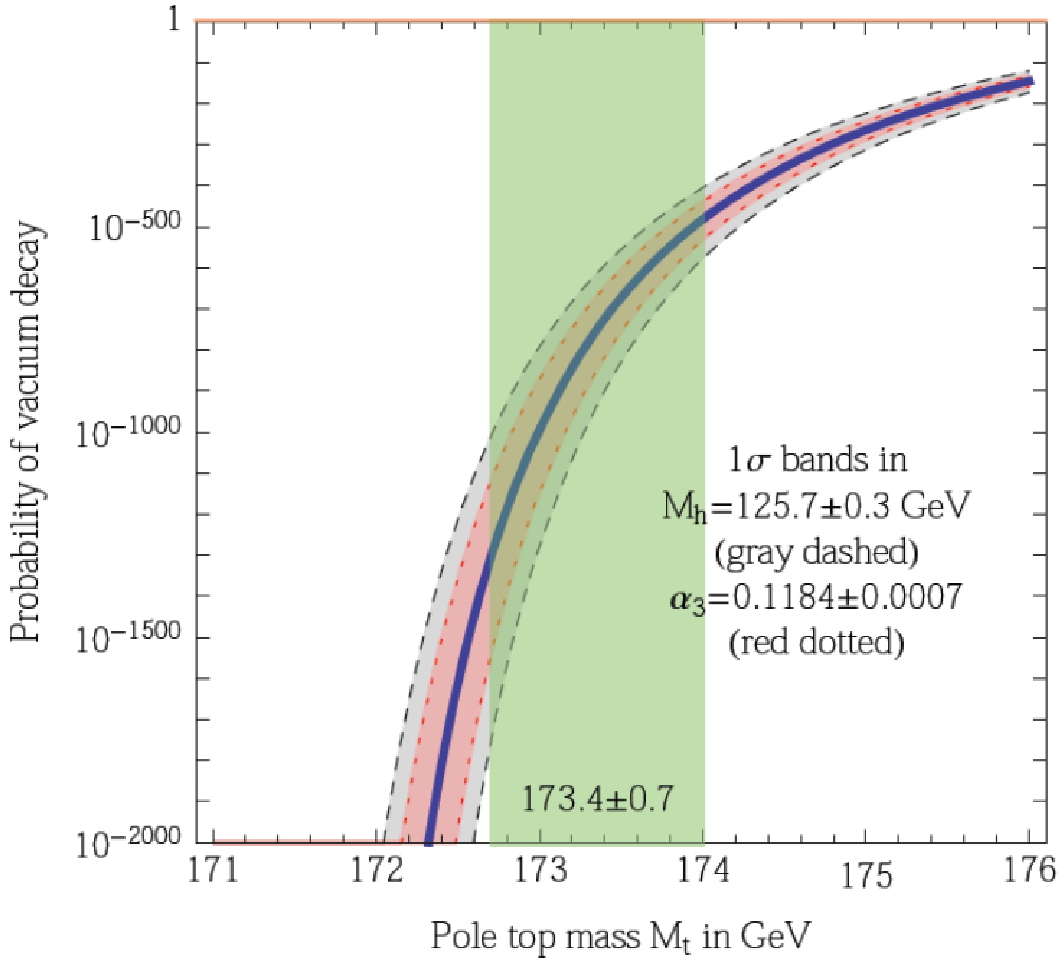
$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|\lambda|/0.01}\right]$$

(Isidori, Ridolfi, Strumia '01)

easily wins over τ_U^4

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

PROBABILITY OF VACUUM DECAY



Buttazzo et al '13

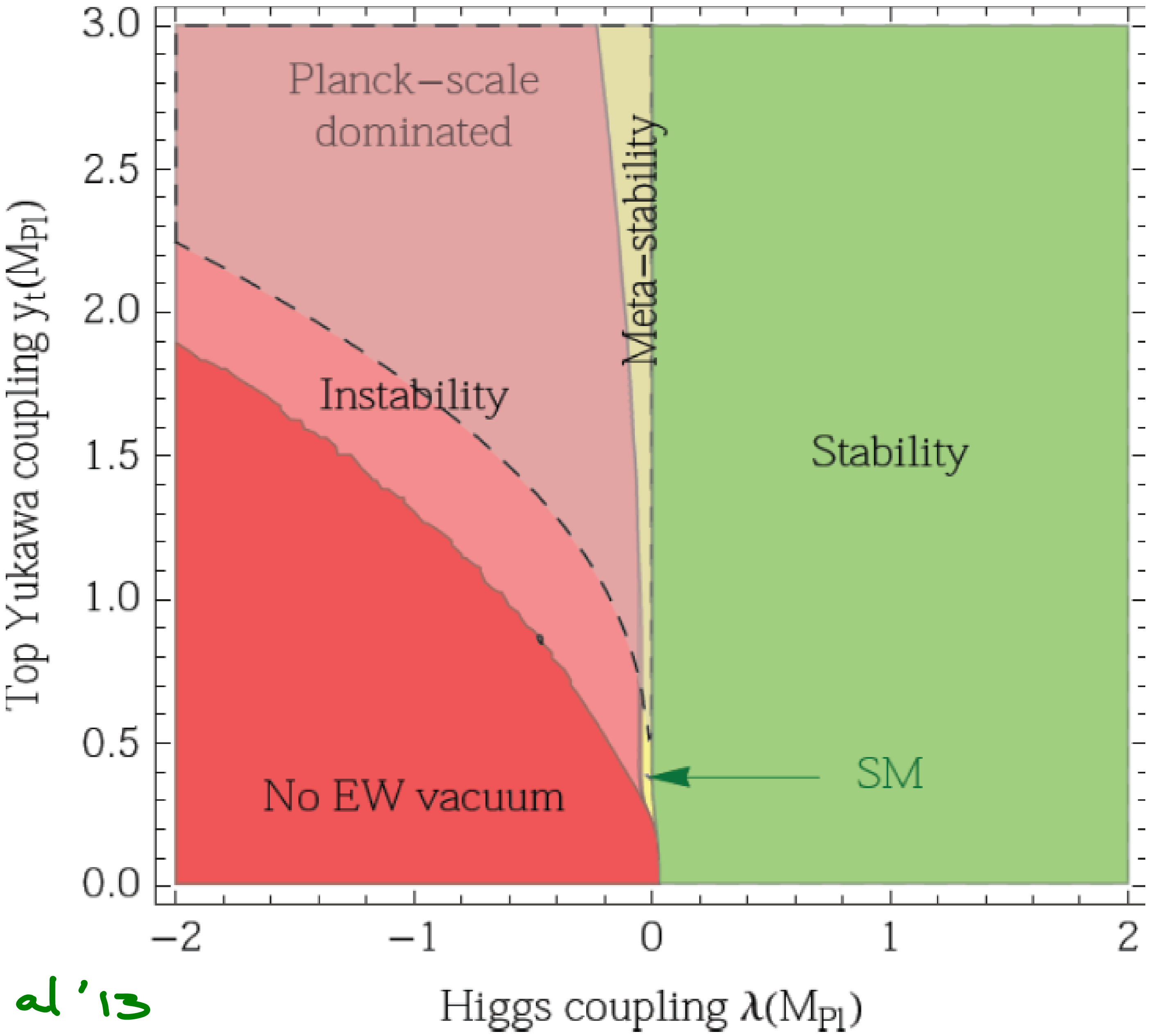
(+ Andreassen, Frost, Schwartz '17 + Chigusa, Moroi, Shoji '17'18)

PROBABILITY OF VACUUM DECAY

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

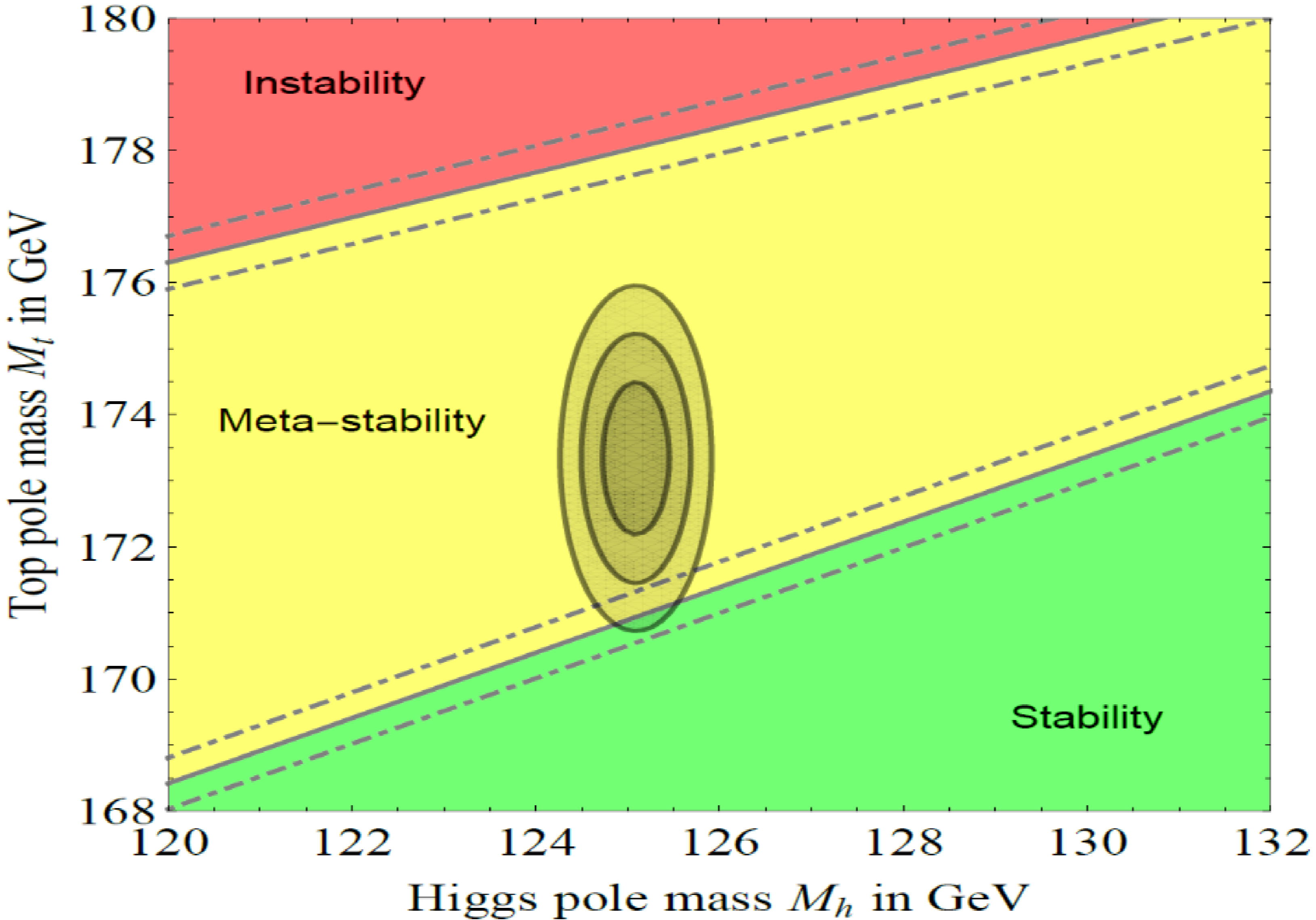
A: No!

LIVING AT THE EDGE



Buttazzo et al '13

TOP MASS AND STABILITY



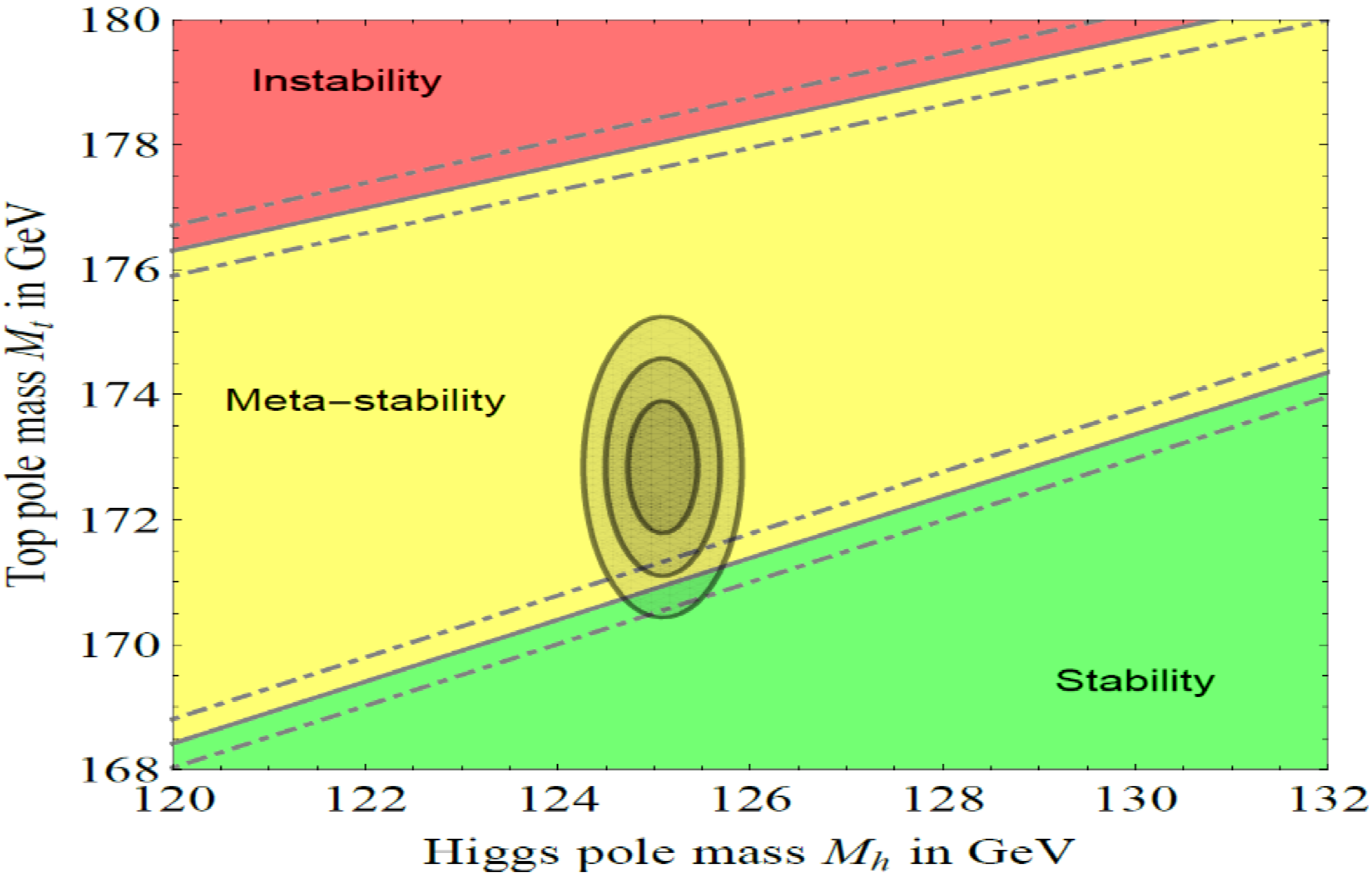
$\alpha_s = 0.1181 \pm 0.0011$

$M_h = 125.09 \pm 0.24$ GeV

World Average '14

$M_t = 173.34 \pm 0.76$ GeV

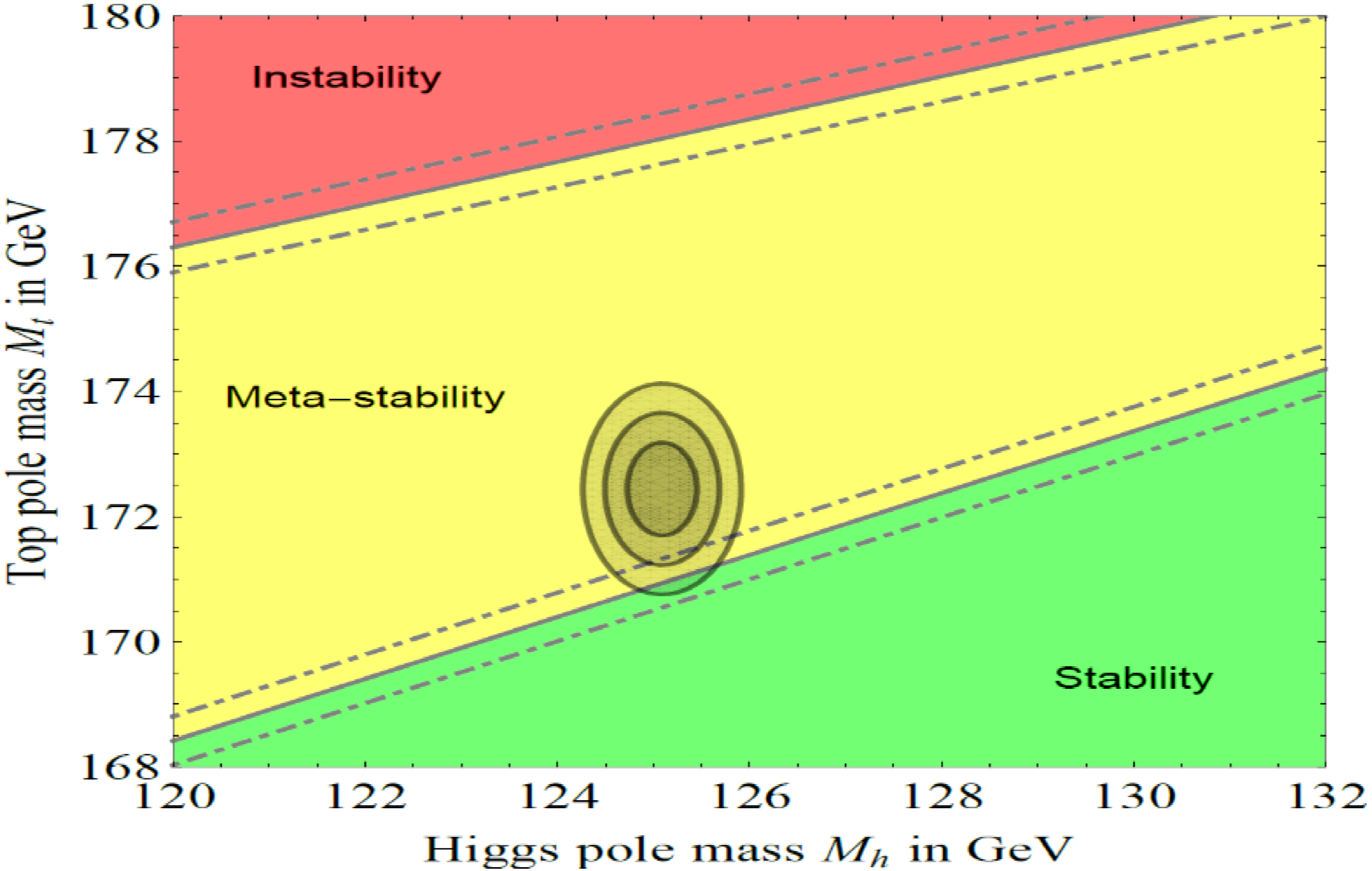
TOP MASS AND STABILITY



ATLAS'16

$M_t = 172.84 \pm 0.70$ GeV

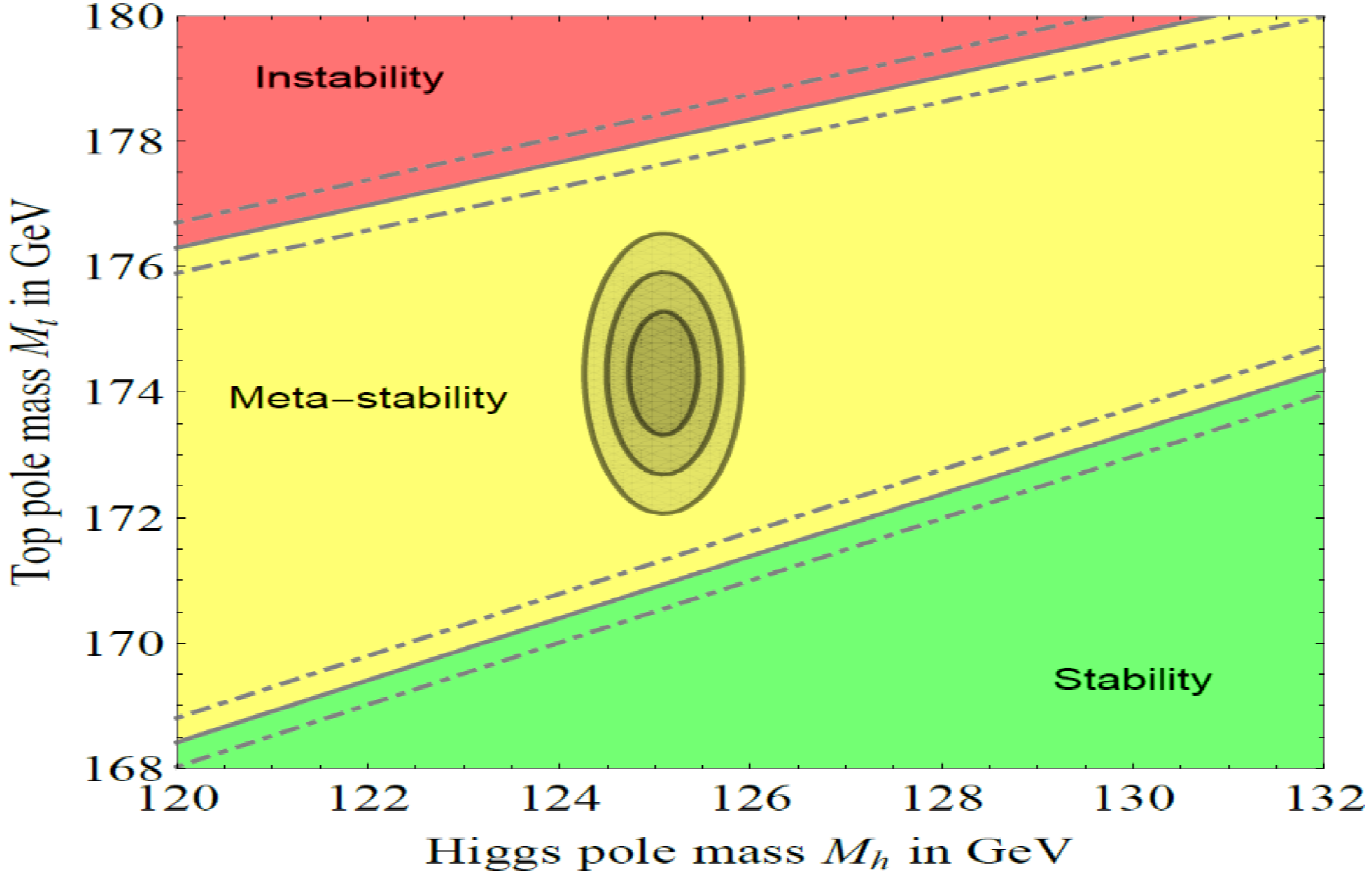
TOP MASS AND STABILITY



CMS '16

$M_t = 172.44 \pm 0.49$ GeV

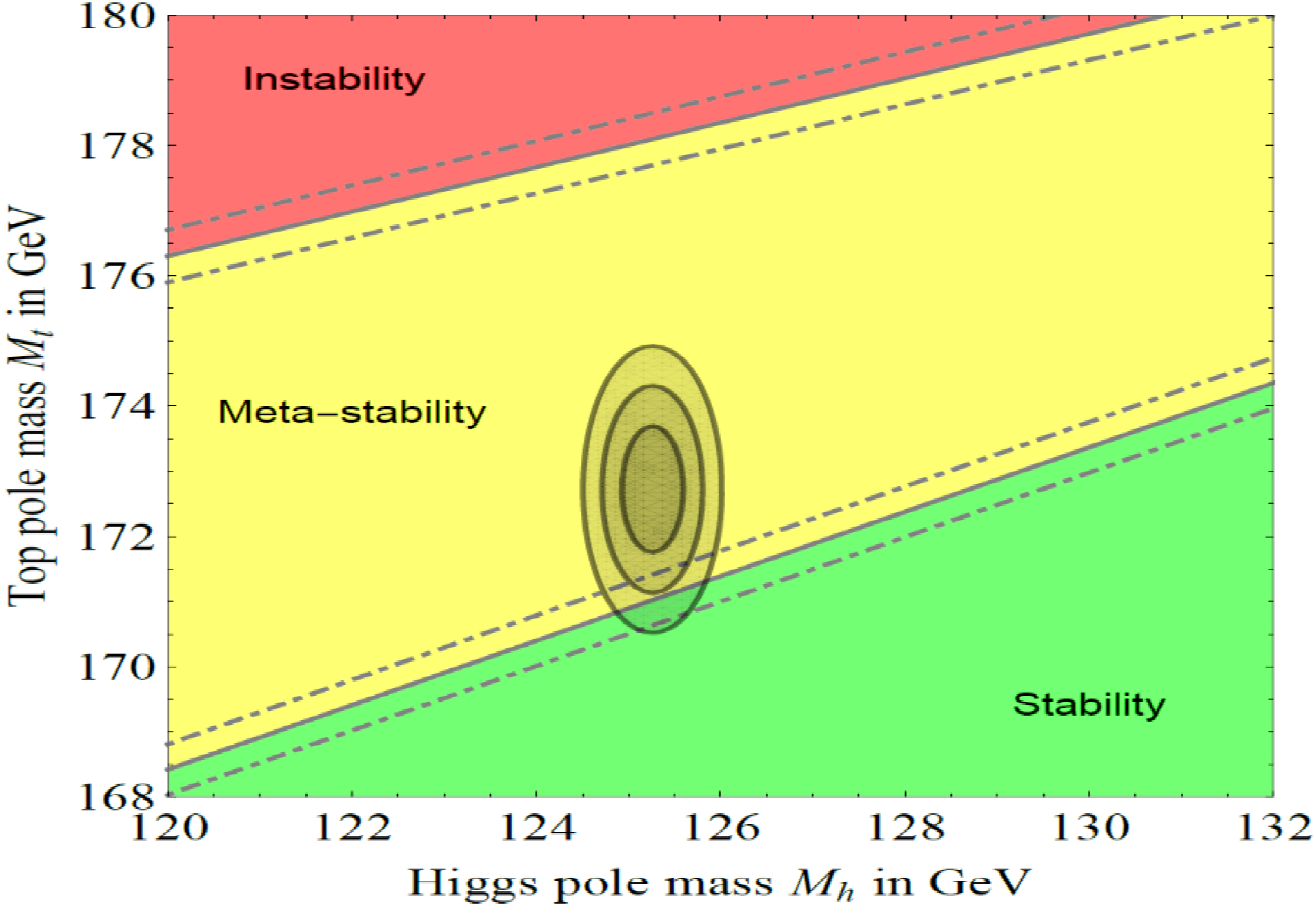
TOP MASS AND STABILITY



Tevatron Comb. '16

$M_t = 174.30 \pm 0.65\,\text{GeV}$

TOP MASS AND STABILITY



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

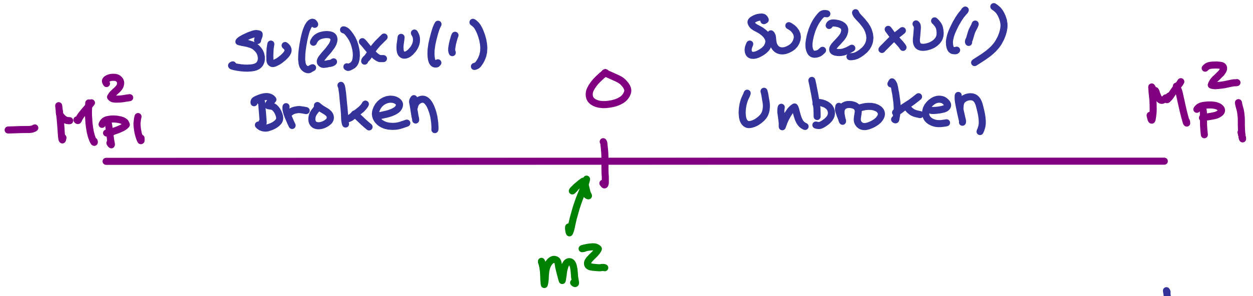
LHC + Tevatron comb. $M_t = 172.72 \pm 0.64$ GeV

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

Not tied to TeV scale in principle.

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

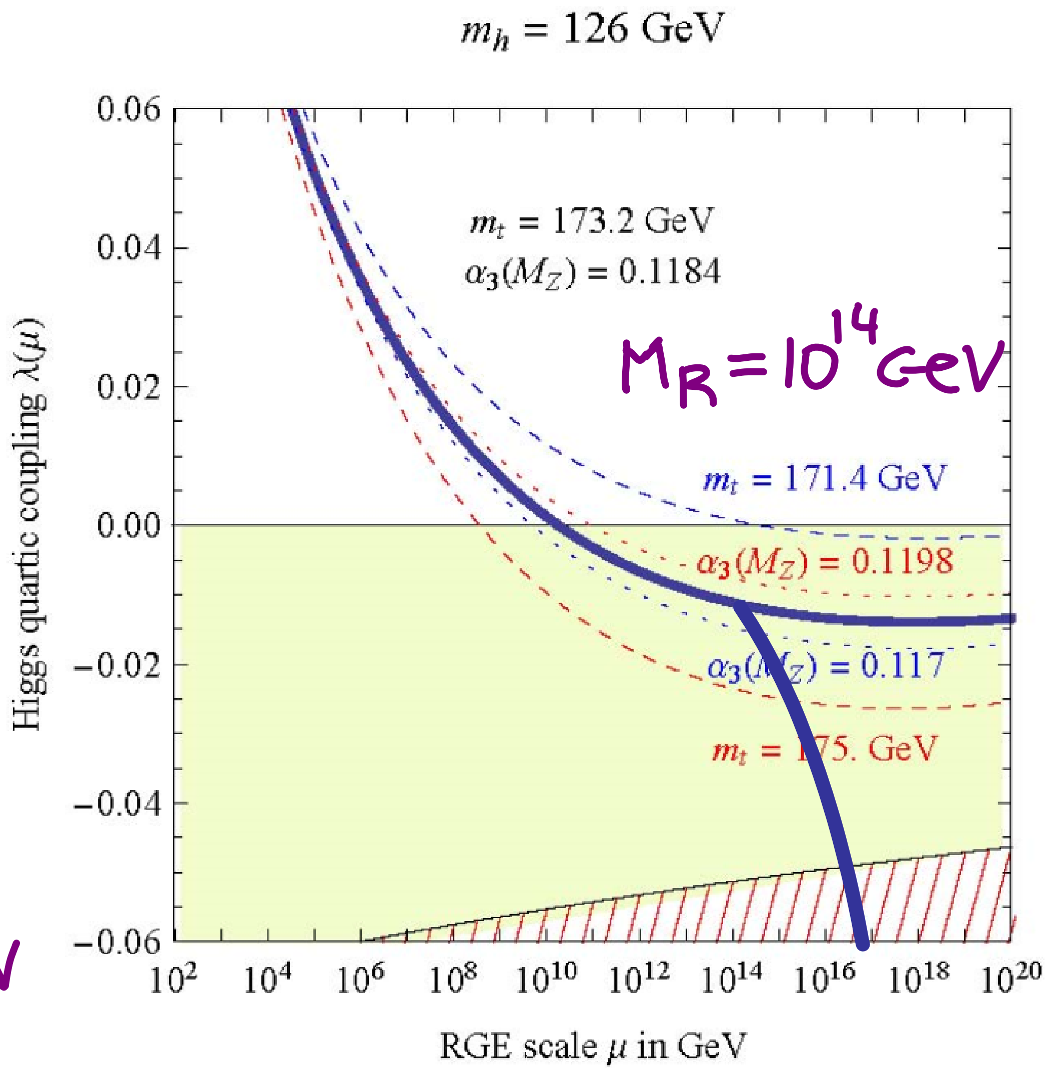
- See-saw neutrinos: Impact on $\beta_\lambda \supset -y_\nu^4/(16\pi^2)$ *

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

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

Adds to the top destabilizing effect

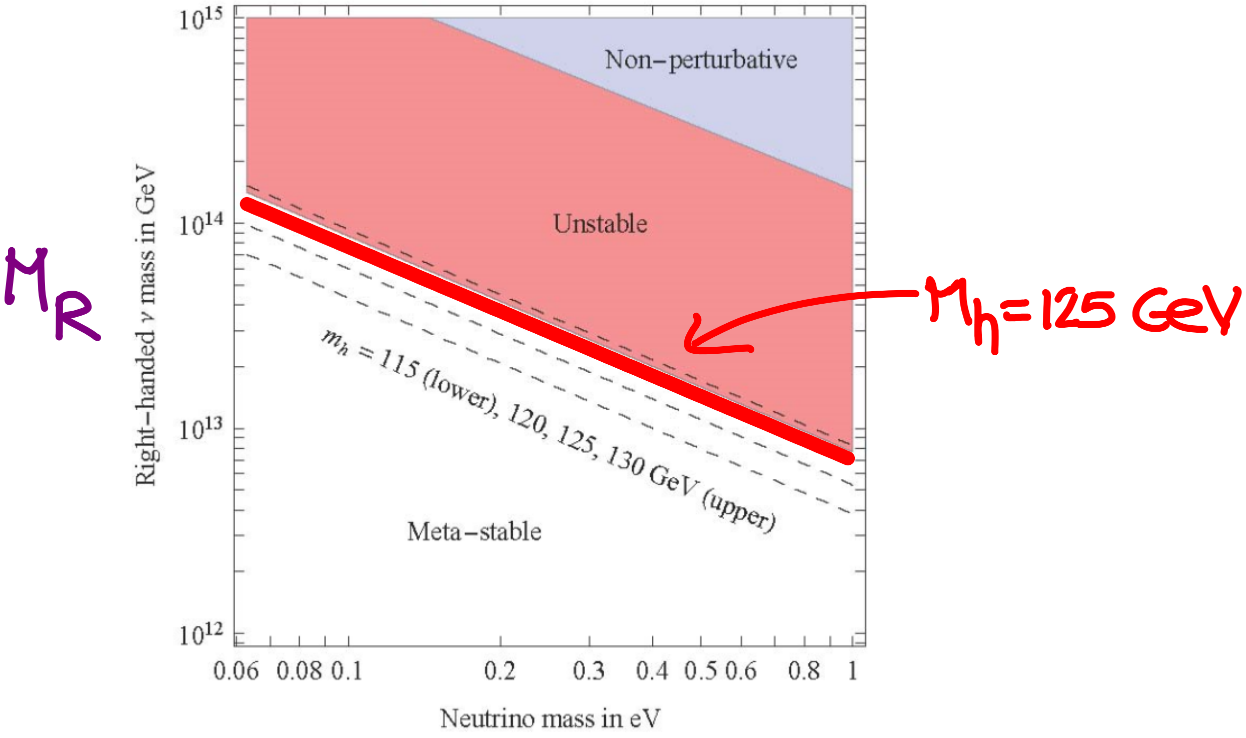
Important for $M_R \gtrsim 10^{13-14}$ GeV



Elias-Miro et al '11

BSM IMPLICATIONS

- See-saw neutrinos: Bound on M_{ν_R}



m_ν

Elias-Miro et al '11

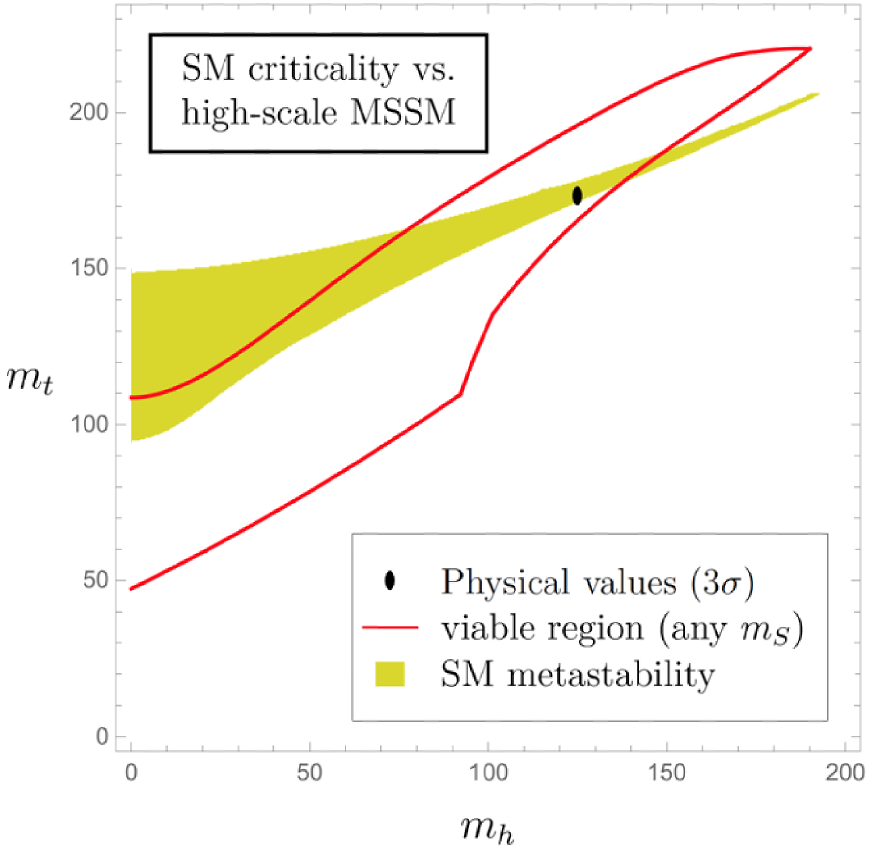
Useful to bound additional sources of instability.

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

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

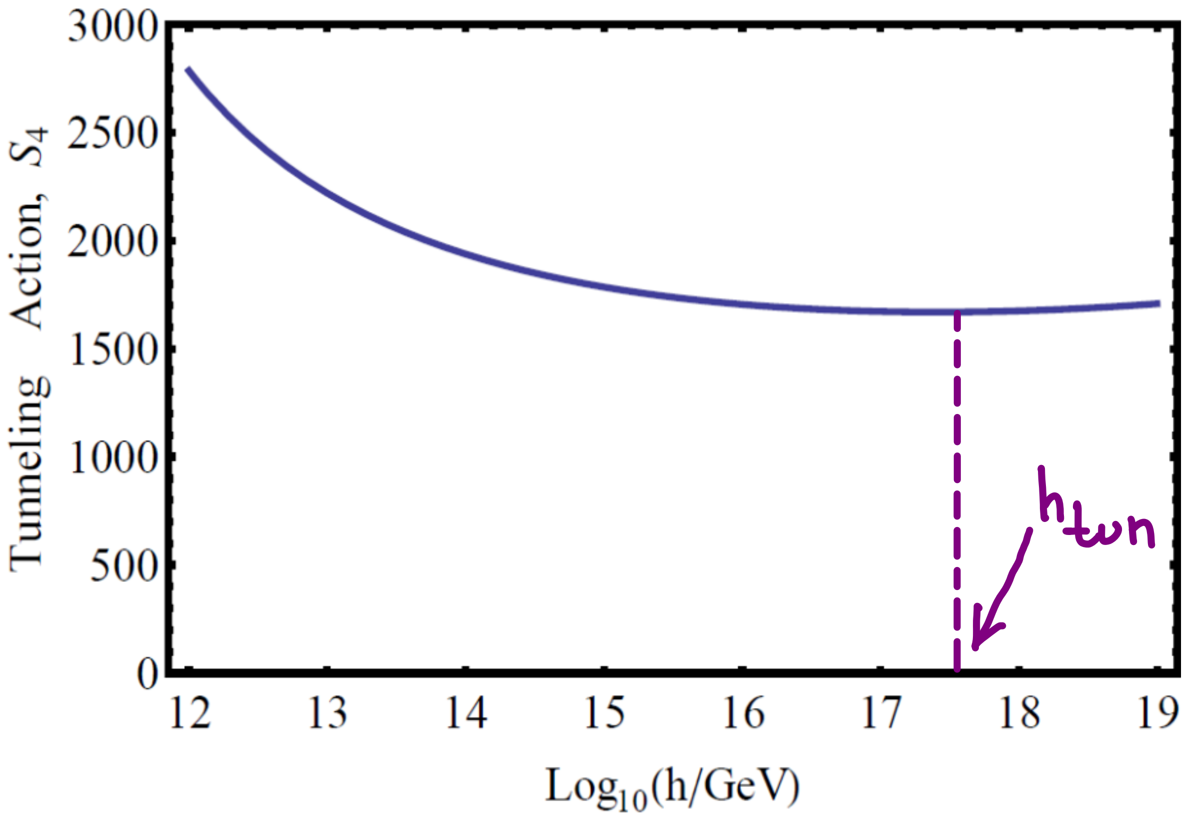
Field values or energy densities never become $\sim M_{Pl}^{(4)}$

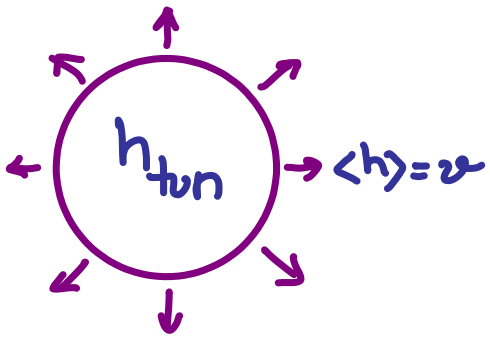
TUNNELING BUBBLE

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

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

Arnold '89



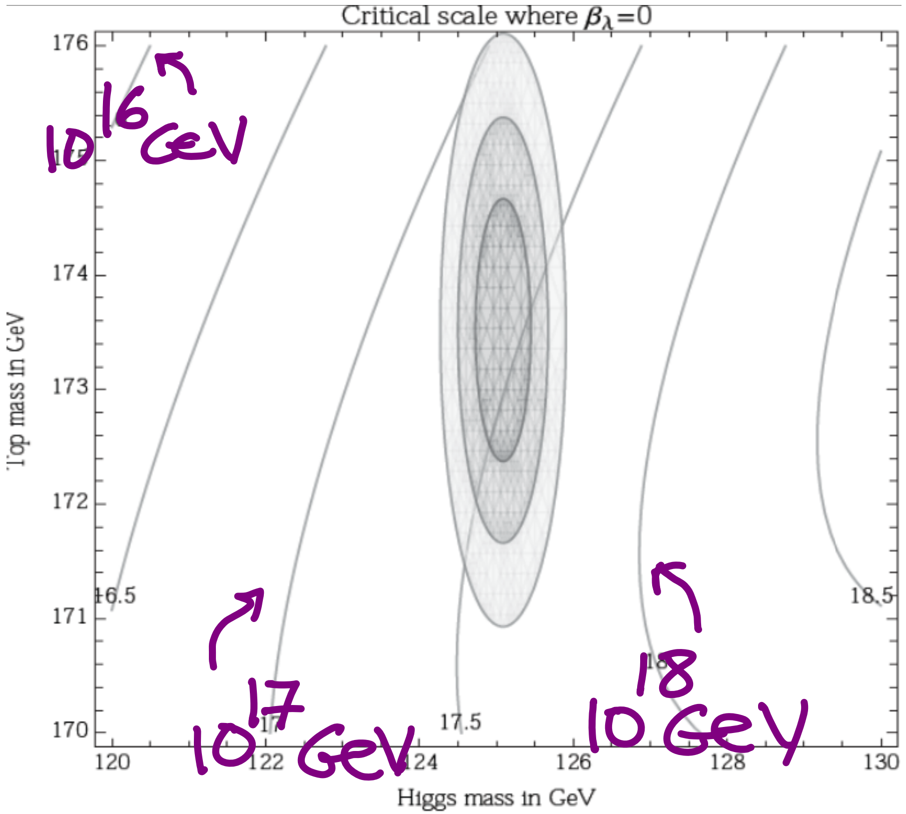


Although $h_{tun} \gg \Lambda_I$

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

TUNNELING BUBBLE

However, h_{tun} is not so far from $M_{Pl}=1.2\times10^{19}\,\text{GeV}$



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 ?

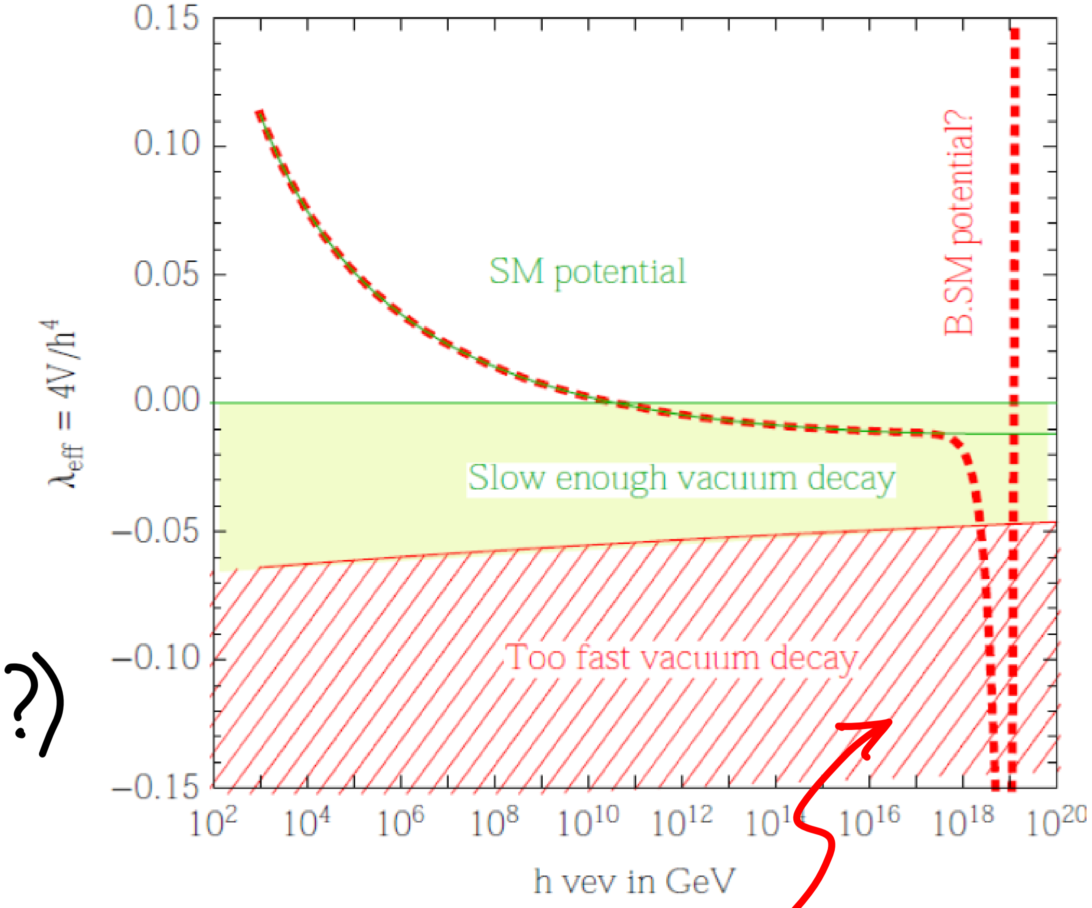
Branchina et al.

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

studied with

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

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)?

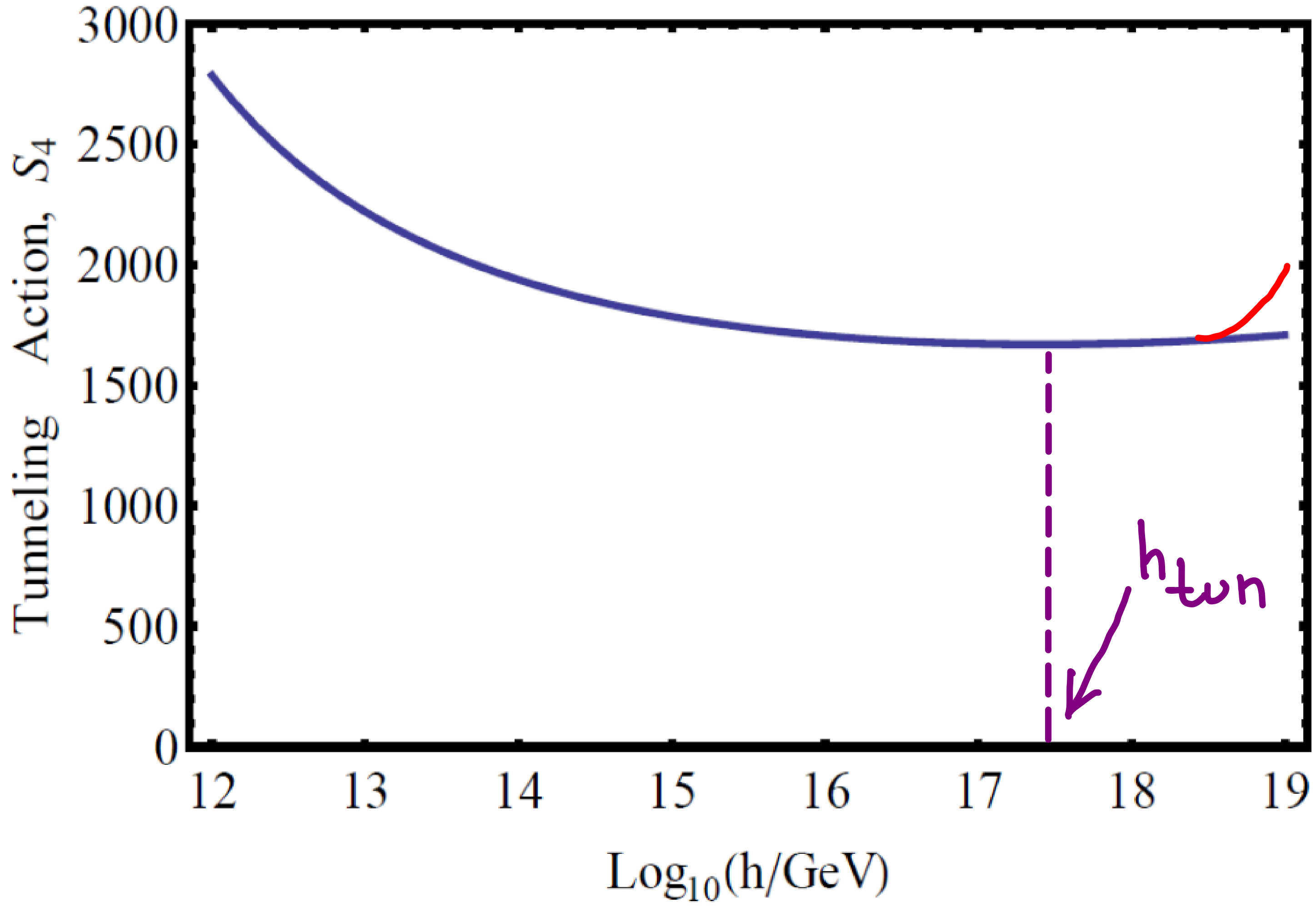
Q: Can M_P physics make the potential stable?

(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. $\lambda_6 > 0$

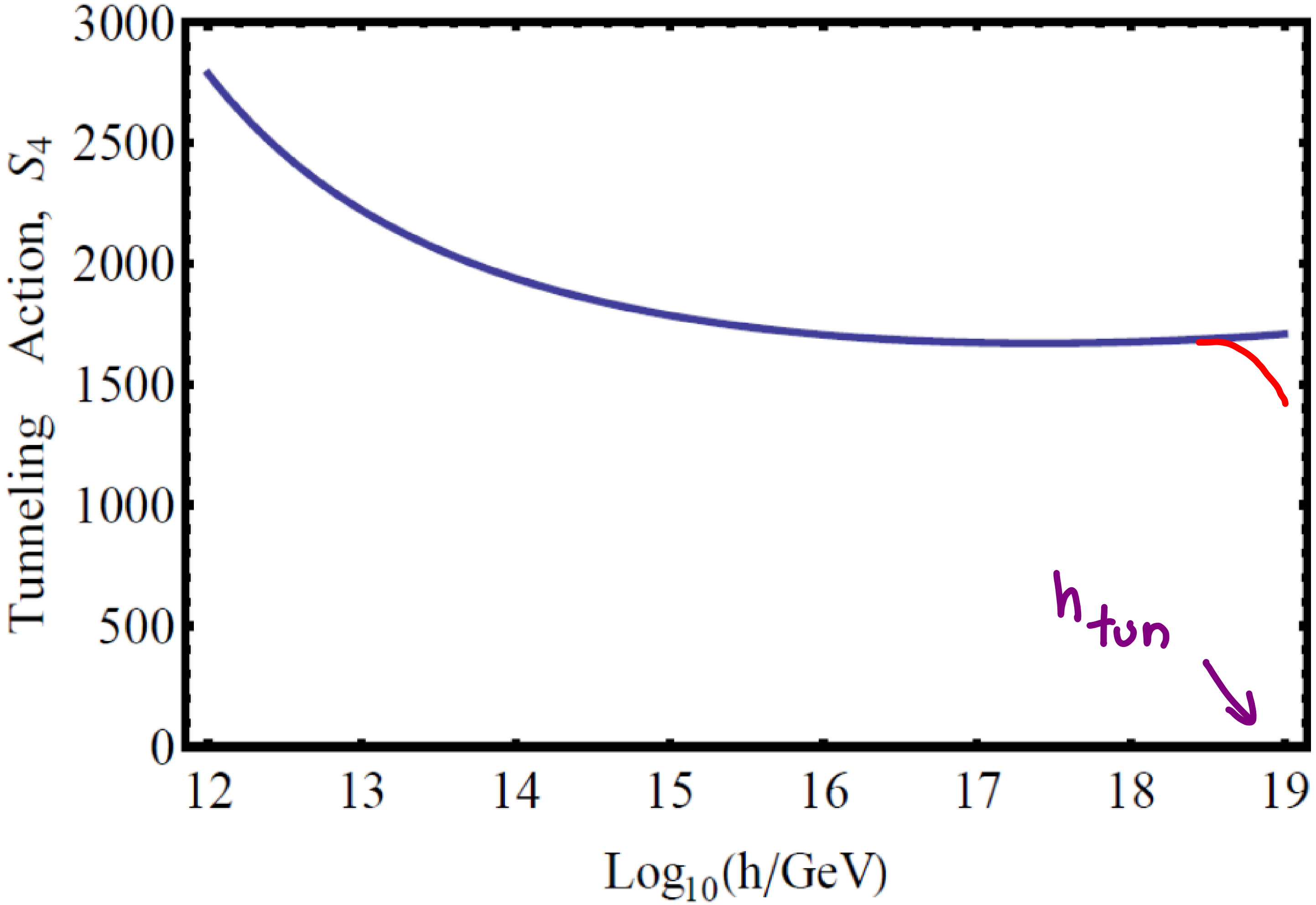


Tunneling action (and h_{tun}) unchanged

PLANCKIAN EFFECTS ON V(h)?

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.

PLANCKIAN EFFECTS ON $V(h)$?

Q: Can Planckian physics spoil criticality?

A1: Of course!

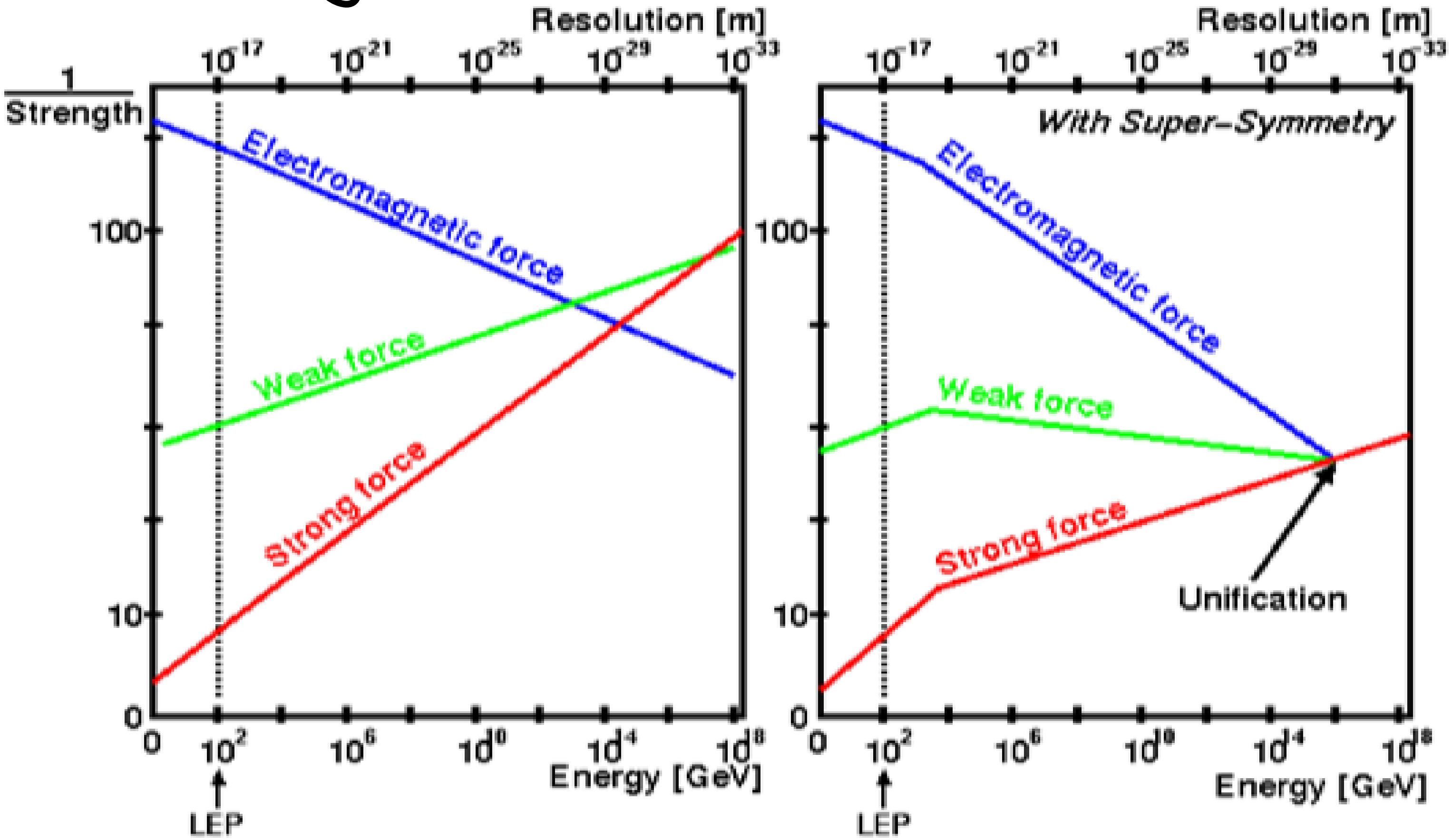
Even modest see-saw neutrinos could.

A2: That's the wrong question to ask!

Criticality ⟷ Gauge Coupling Unification

AN INTRIGUING HINT FROM LEP

Gauge coupling unification :

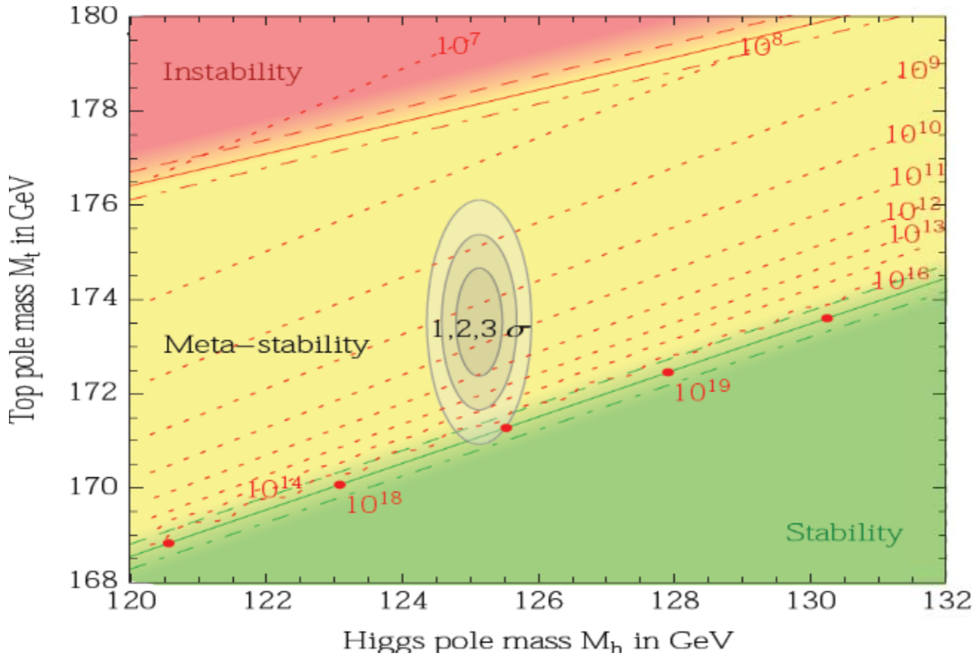


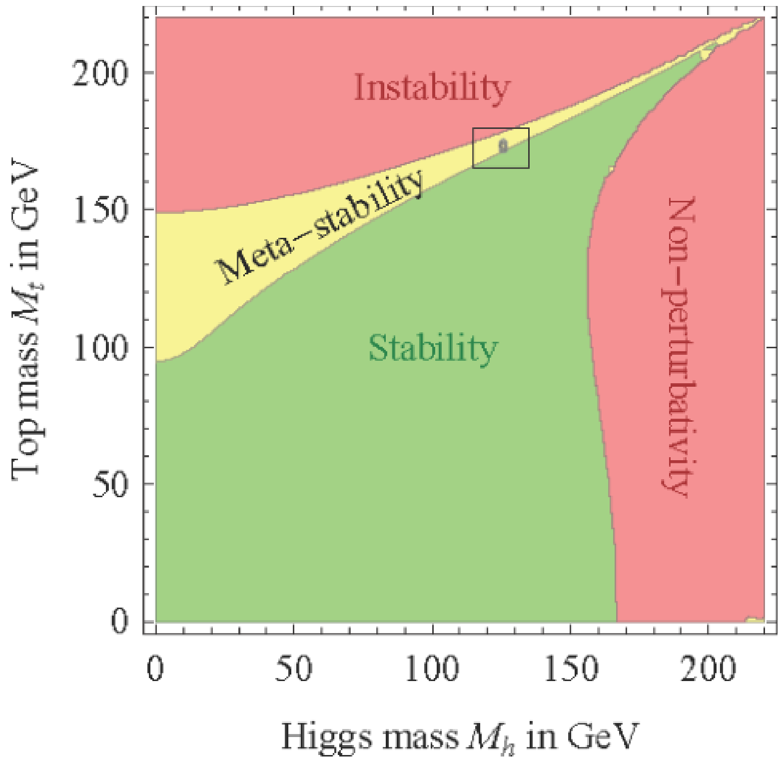
Many effects can upset it, including huge corrections from physics at the unification scale.

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

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:

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

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

Γ_{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 Λ 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 $[\text{Radius of critical bubble}]^{-1} \quad (\gg \Lambda_I)$

- Hubble rate during inflation for destabilization with some probability

COSMOLOGICAL IMPLICATIONS

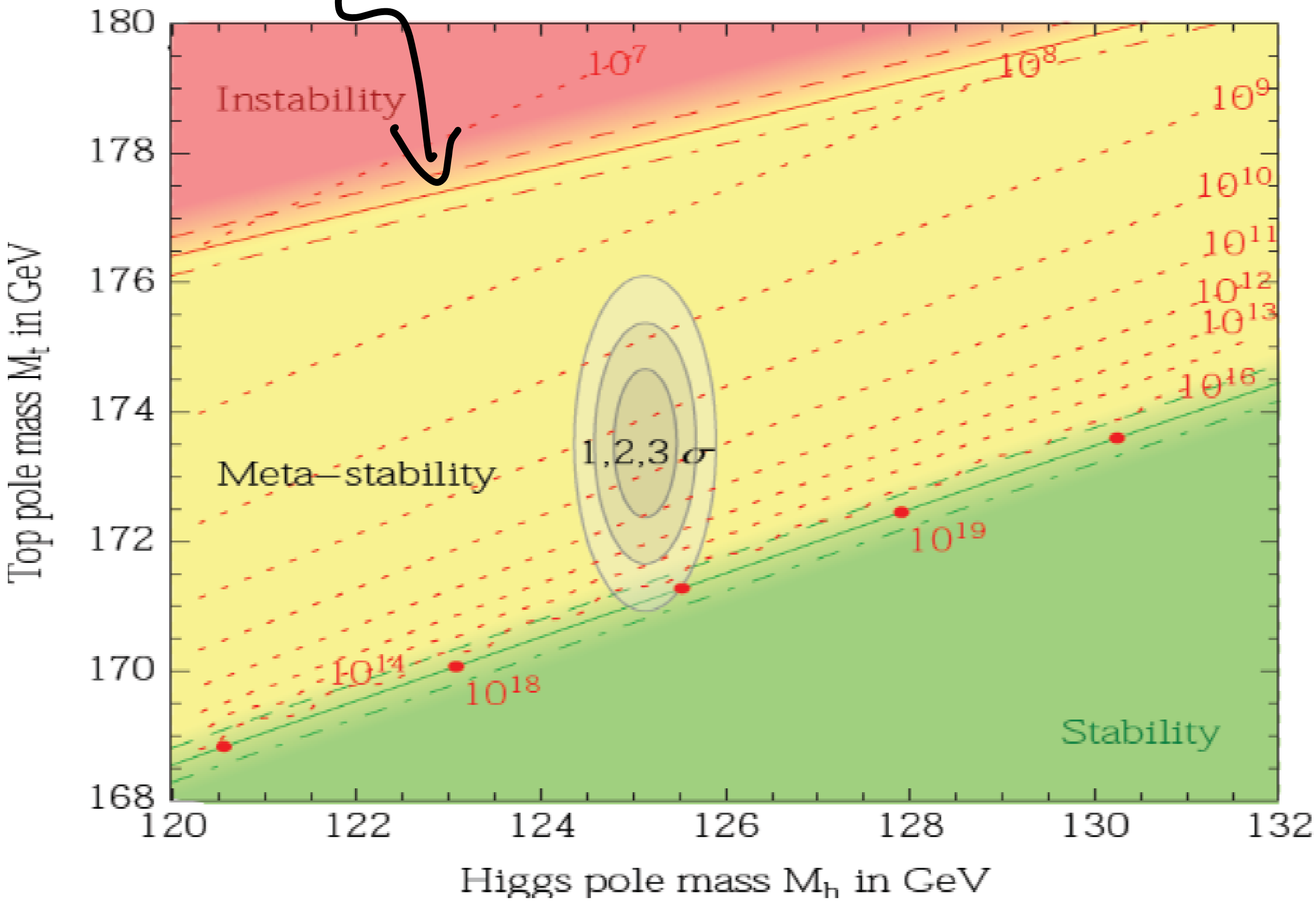
1. Decay by quantum tunneling

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

COSMOLOGICAL IMPLICATIONS

1. Decay by quantum tunneling

   But long lifetime

2. Decay by thermal fluctuations

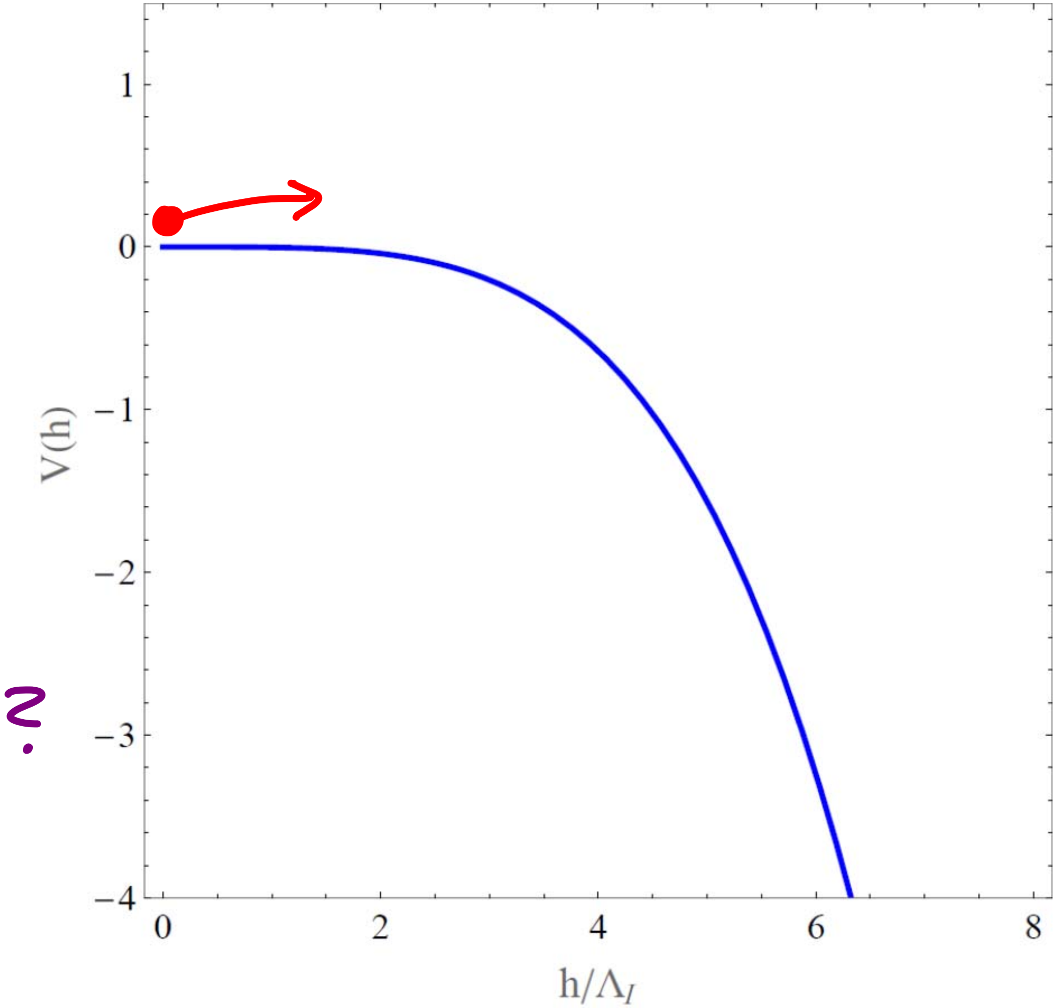
I2. DECAY BY THERMAL FLUCTUATIONS

Thermal decay during the early Universe

Thermal excitations over the barrier

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

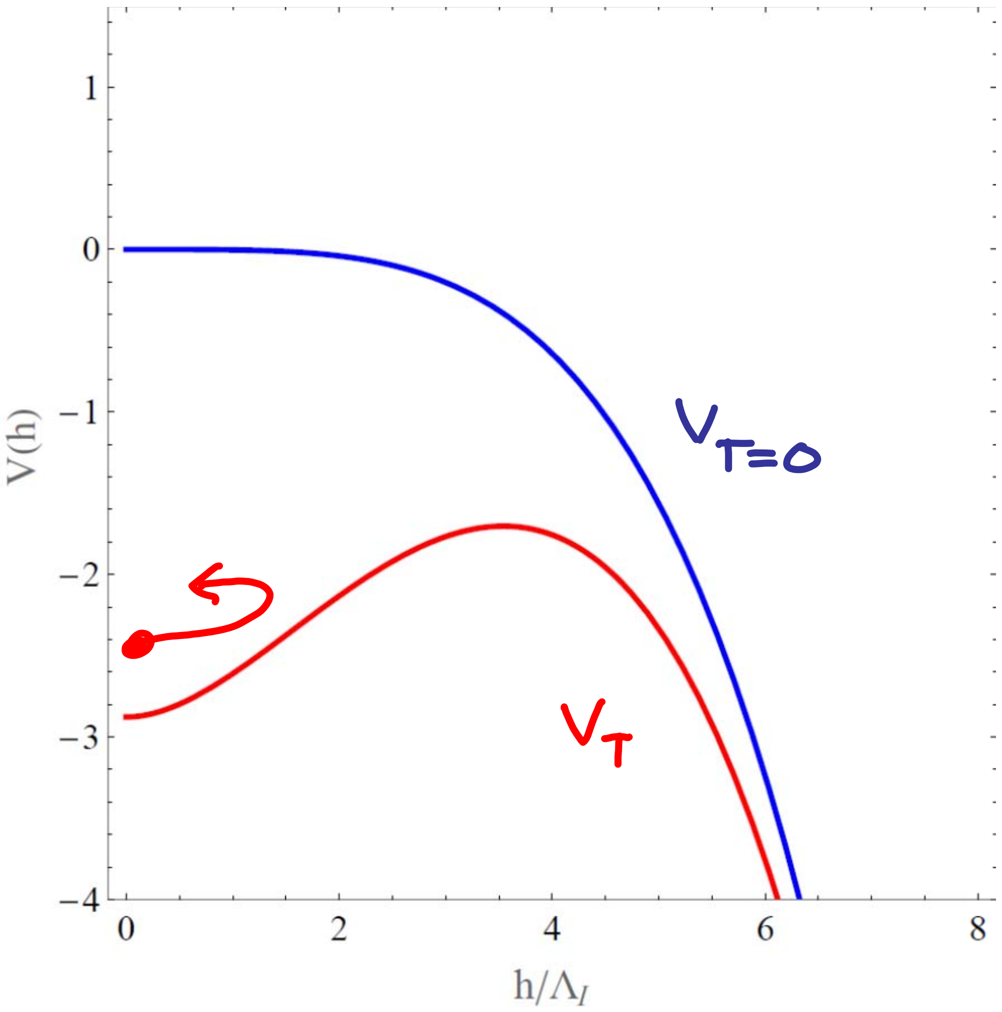
Upper bound on T_{RH} ?



DECAY BY THERMAL FLUCTUATIONS

Thermal decay during the early Universe

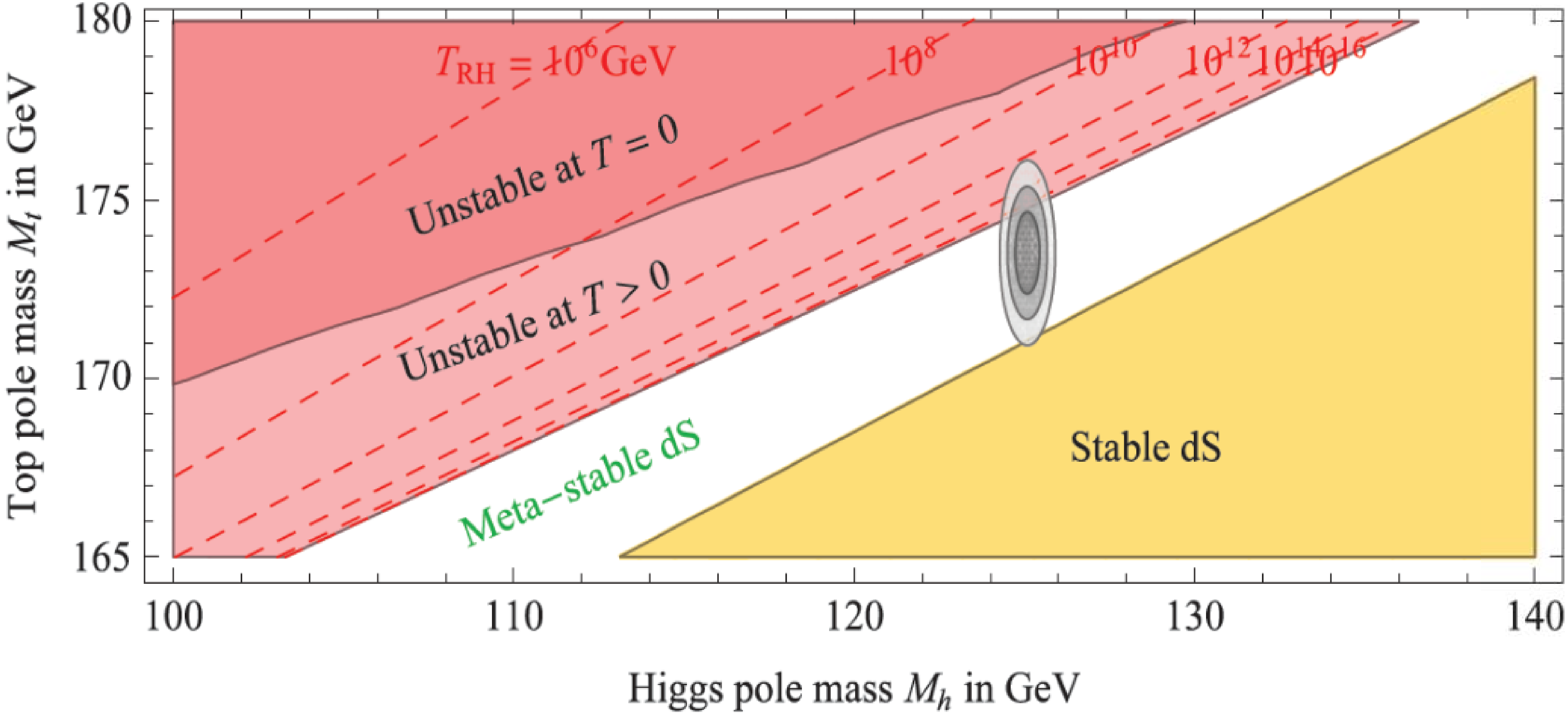
$\langle h^2 \rangle \sim T^2$



but thermal corrections tend to stabilize V(h)

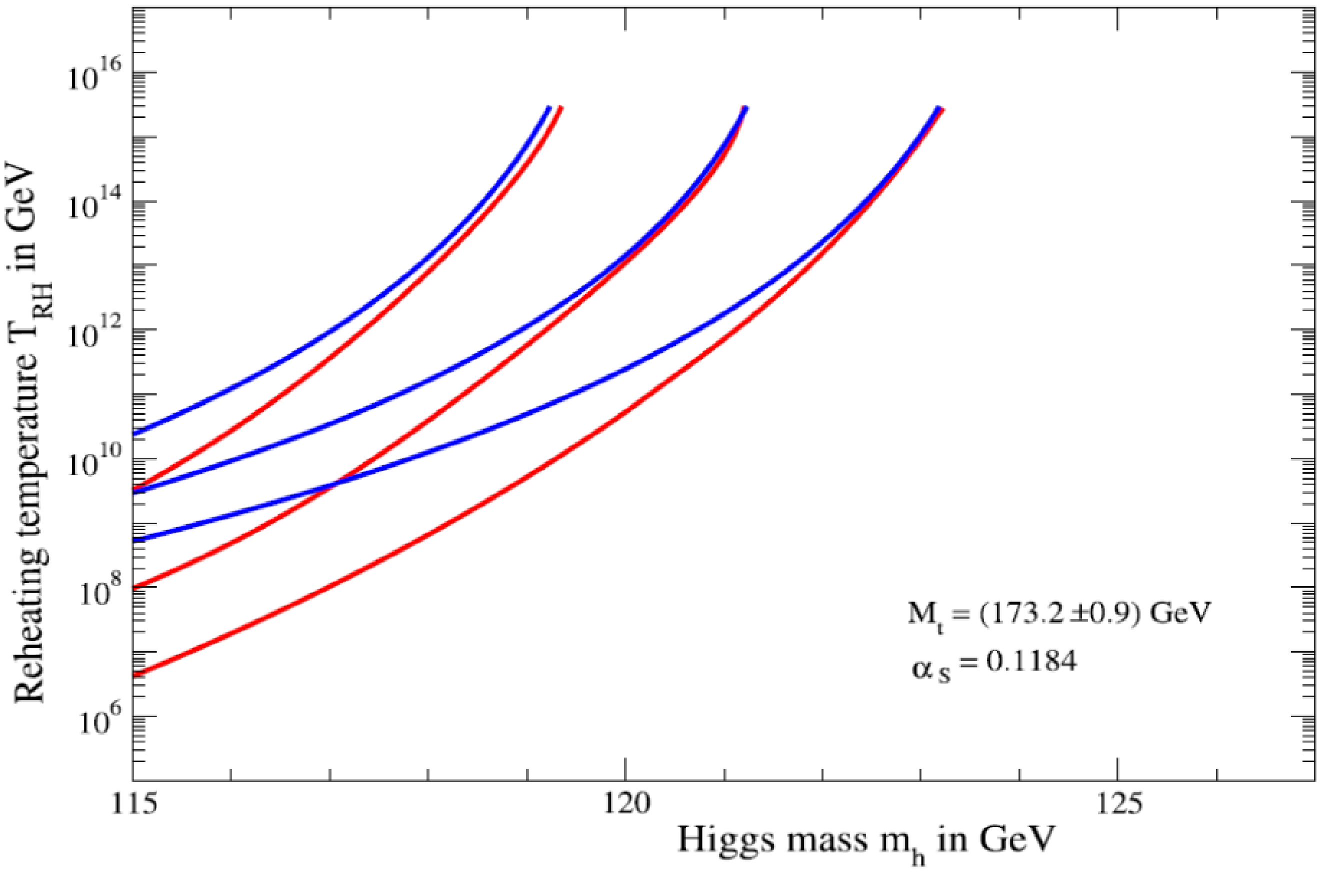
THERMAL VACUUM DECAY

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

(NO) BOUND ON T_{RH}



COSMOLOGICAL IMPLICATIONS

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**

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

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

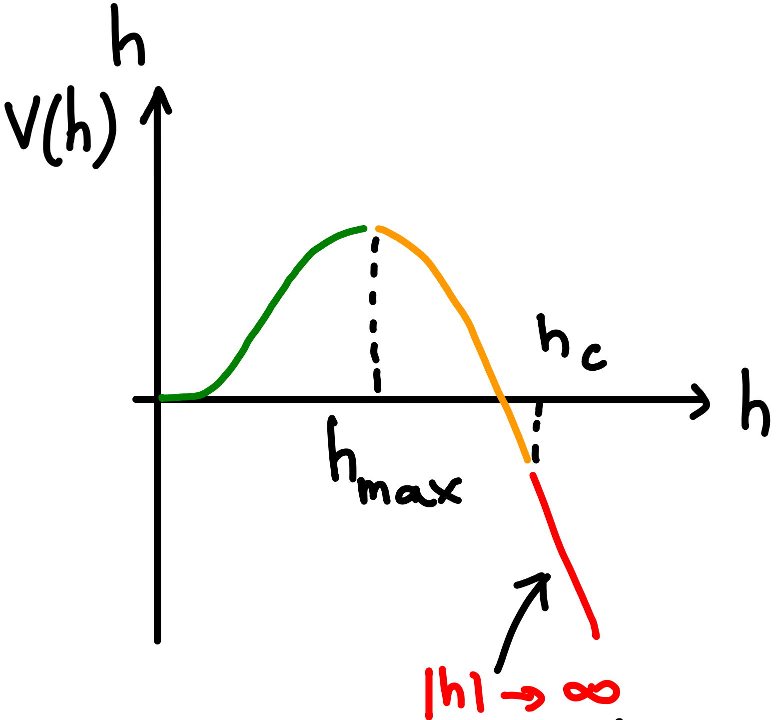
Upper bound on H_I ?

VACUUM DECAY DURING INFLATION

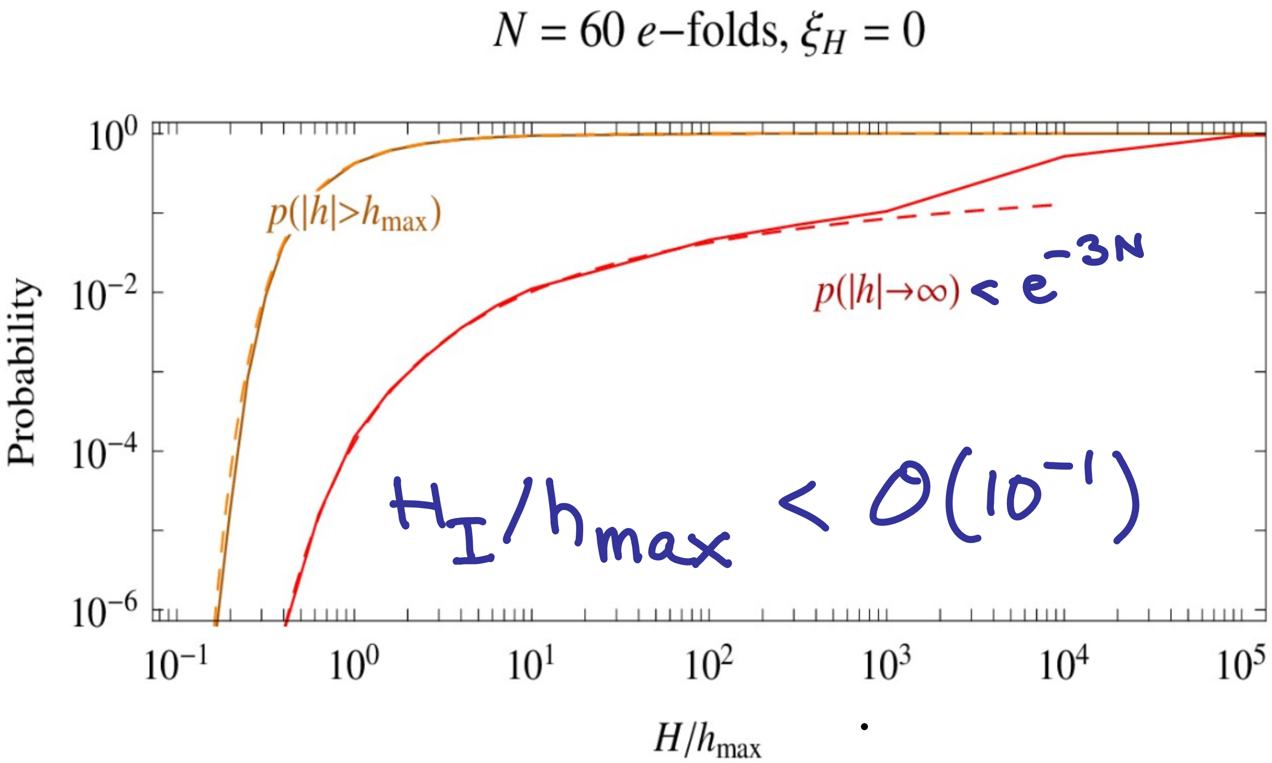
Classical vs. quantum competition. Δh in $\Delta t \sim 1/H_I$:

$$(\Delta h)_{\text{clas}} \simeq \frac{V'}{3H_I^2} \leftrightarrow (\Delta h)_{\text{quant}} \simeq \frac{H_I}{2\pi}$$

Equal $\Rightarrow$ $h_c \sim H_I/|\lambda|^{1/3}$



classical roll beats quantum fluctuations



$< e^{-3N}$

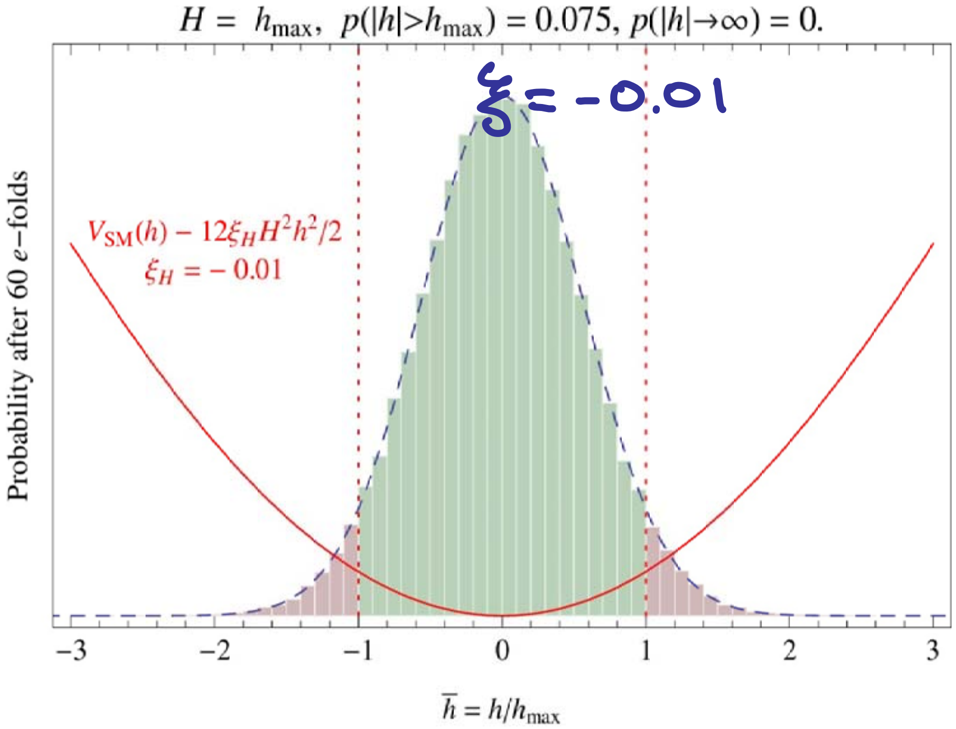
$H_I/h_{max} < \mathcal{O}(10^{-1})$

VACUUM DECAY DURING INFLATION ?

$$\left.\begin{array}{ll}\text{Simple way out} & \delta\mathcal{L} = -\xi |H|^2 R \\ \text{During inflation} & R = -12 H_I^2\end{array}\right\} m_H^2 = -12\xi H_I^2$$

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

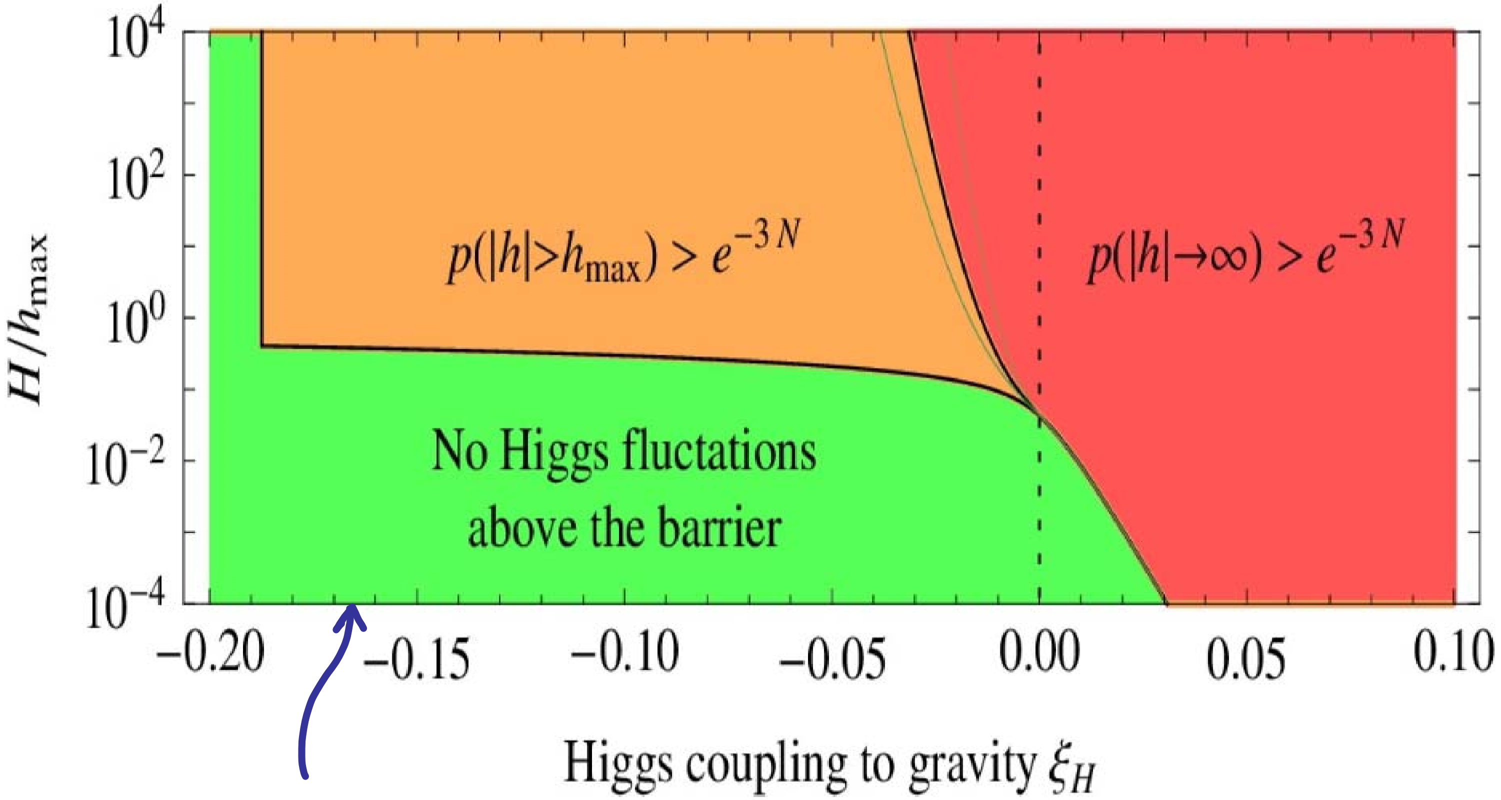
- For $\xi < -3/16$ Higgs fluctuations suppressed



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

VACUUM DECAY DURING INFLATION

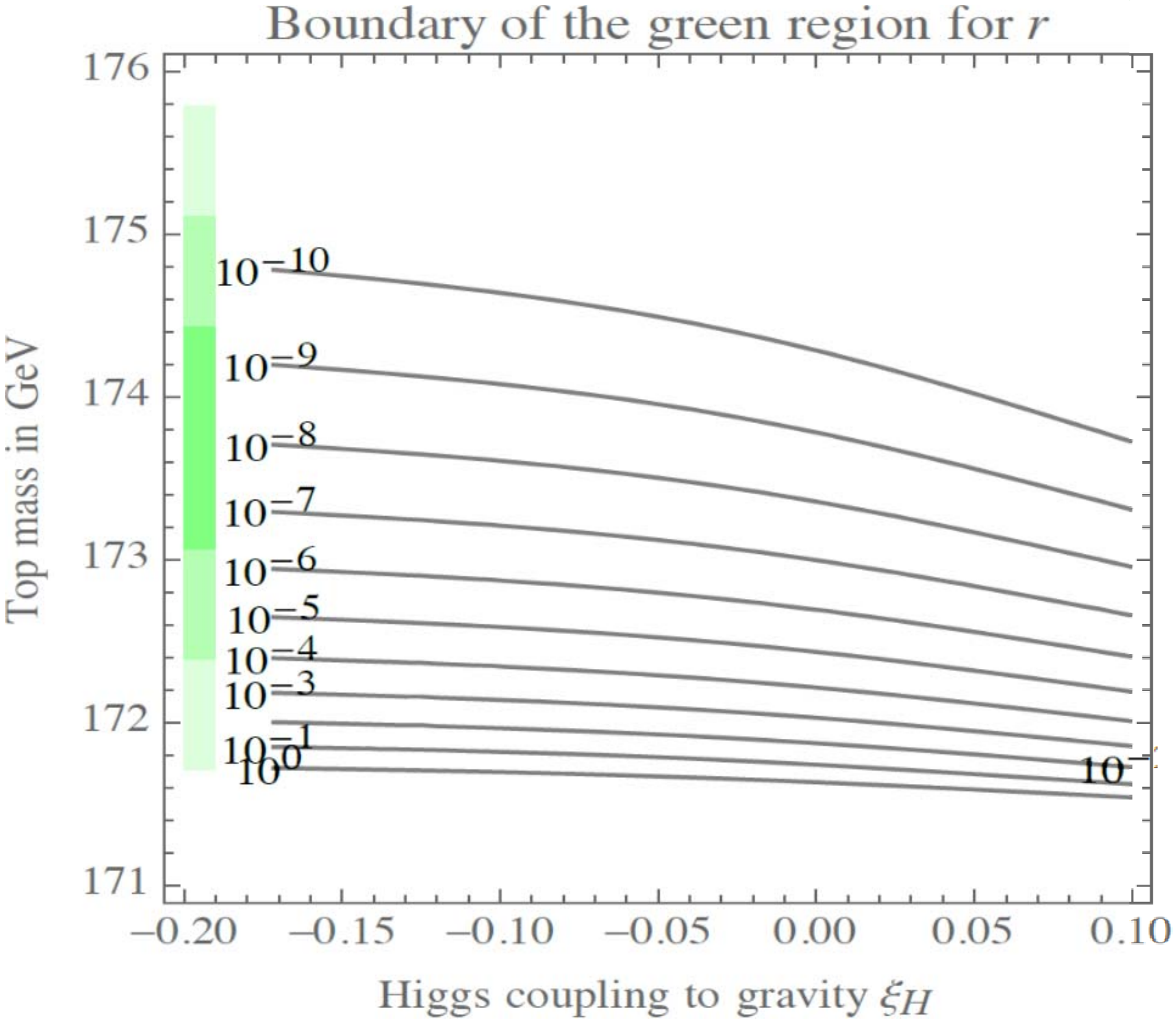
General picture for $\xi \neq 0$



$\xi_H = -1/6$ (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

COSMOLOGICAL IMPLICATIONS

1. Decay by quantum tunneling

   But long lifetime

2. Decay by thermal fluctuations

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

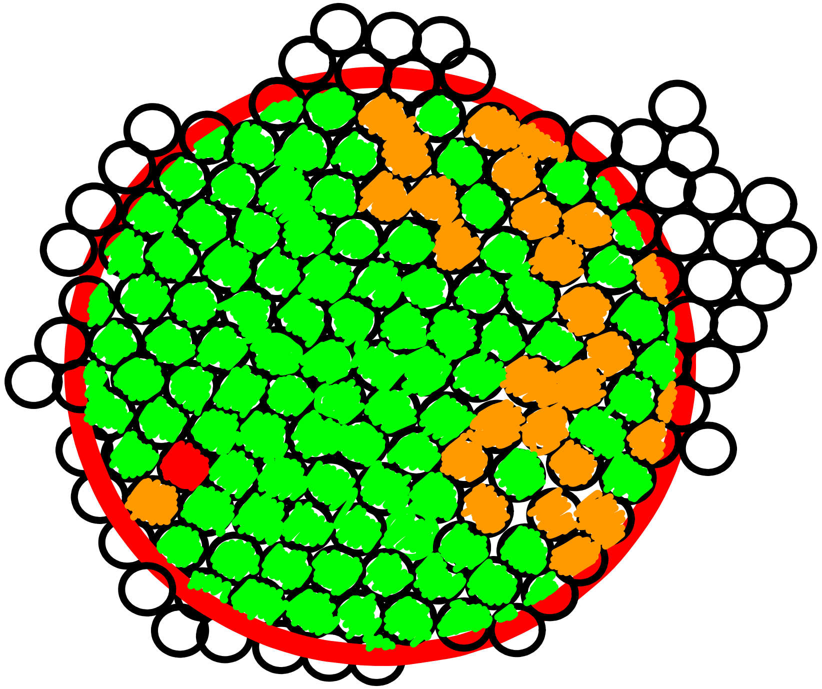
3. Decay during inflation

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

4. Decay right after inflation

14. VACUUM DECAY AFTER INFLATION

After inflation → pre-heating → reheating



e^{3N} $\frac{1}{H_I}$ patches

🟢 $h < h_{max}$ ⇨ Safe

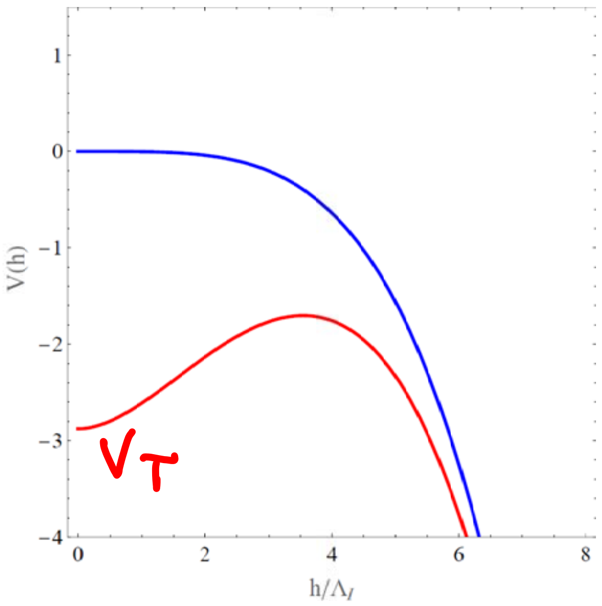
🟠 $h > h_{max}$ ⇨ Can be saved by thermal corrections to $V(h)$

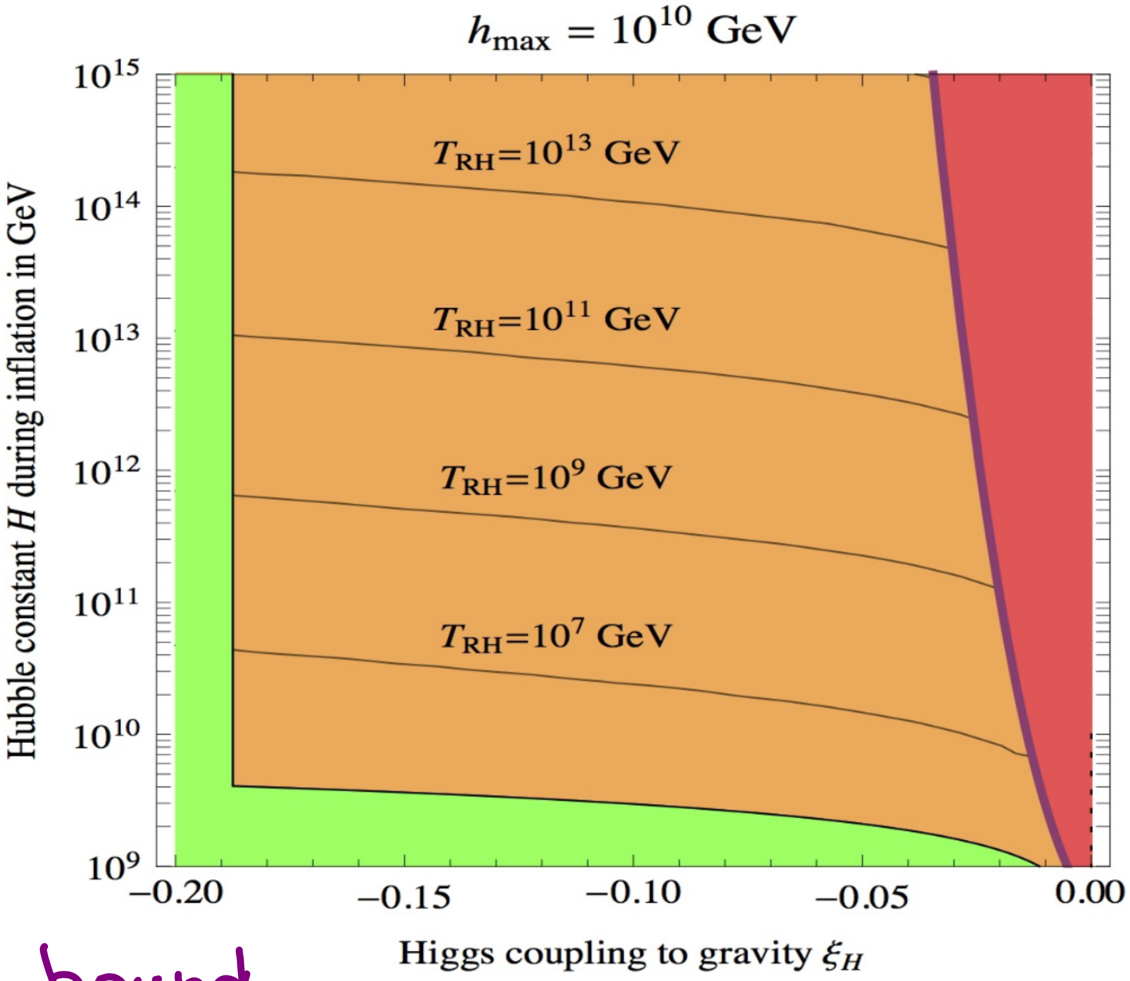
🔴 $h > h_c$ Deadly. In general they expand and eat all space.

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, Enquist et al'16, Postma et al'17
Lebedev et al'17.

Stabilizing terms during inflation

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

can be deadly during preheating

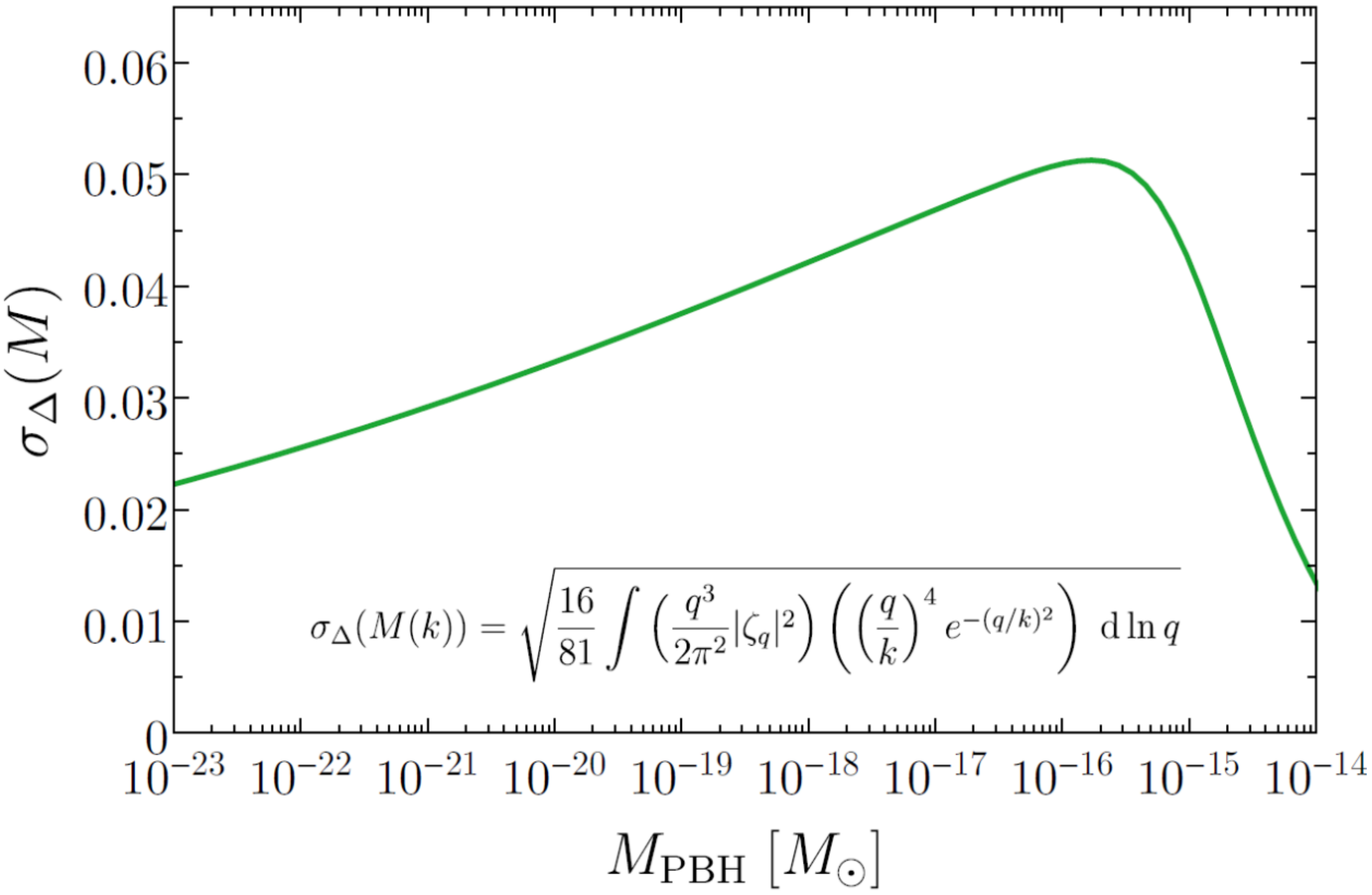
oscilating ϕ ⇨ tachyonic/oscilating m_H^2

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

⇨ Only a range of ξ or c might be allowed

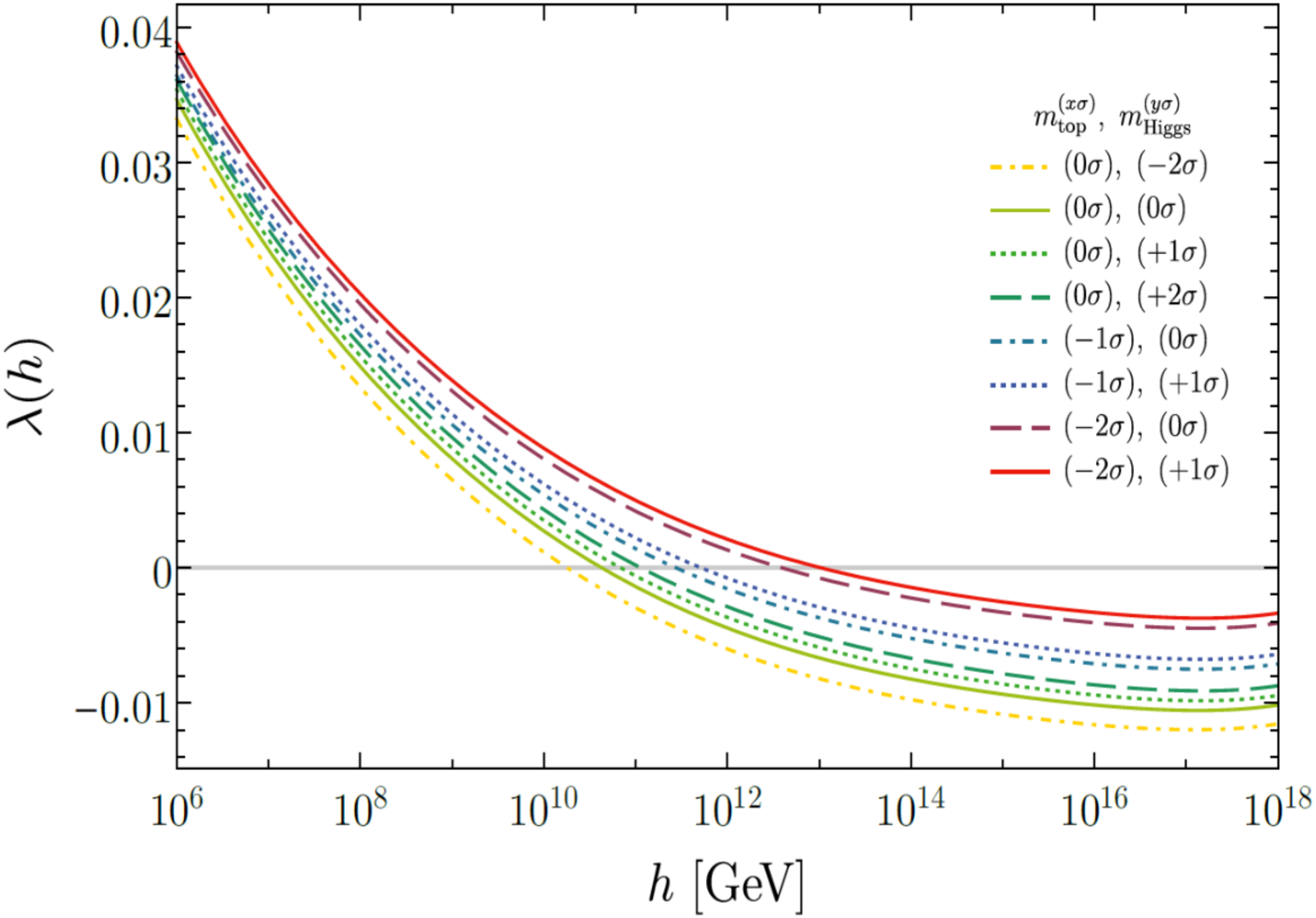
Surprises still possible...

Δ-VARIANCE



$$\sigma_\Delta(M(k)) = \sqrt{\frac{16}{81}\int\left(\frac{q^3}{2\pi^2}|\zeta_q|^2\right)\left(\left(\frac{q}{k}\right)^4 e^{-(q/k)^2}\right)\,\mathrm{d}\ln q}$$

NNLO λ-RUNNING



h_c, δh_k EVOLUTION – SM + SCALAR