COSMOLOGICAL SIGNATURES OF THE SM VACUUM INSTABILITY

J.R.Espinosa
IFT-UAM/CSIC
Madrid

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Hot topics in Modern Cosmology
Spontaneous Workshop XIII

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~~
19

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

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

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

CONTEXT, 2019

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

⇓

$\Lambda \sim$ few TeV

CONTENTEXT, 2019 / THIS TALK

- Higgs discovered, close to SM-like

+

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

+

- Disregarding naturalness

⇓

$\Lambda \sim M_{Pl}$?

SM EXTRAPOLATION

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

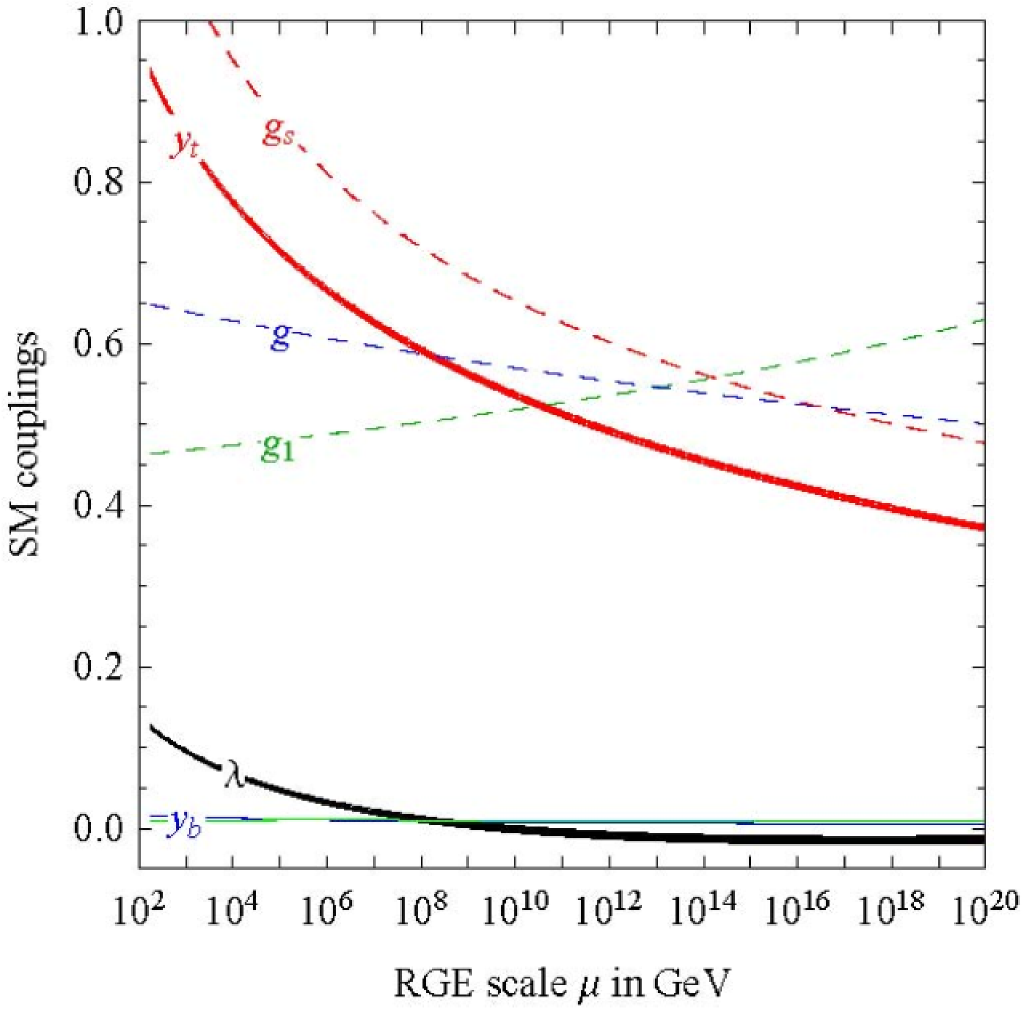
Assume Higgs has SM props.

no BSM Physics

All SM parameters known

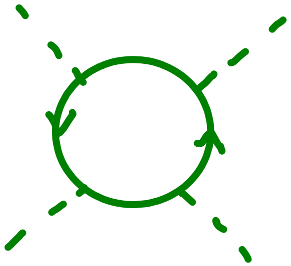
$M_h \Rightarrow \lambda(EW)$

Weakly coupled up to M_{Pl}

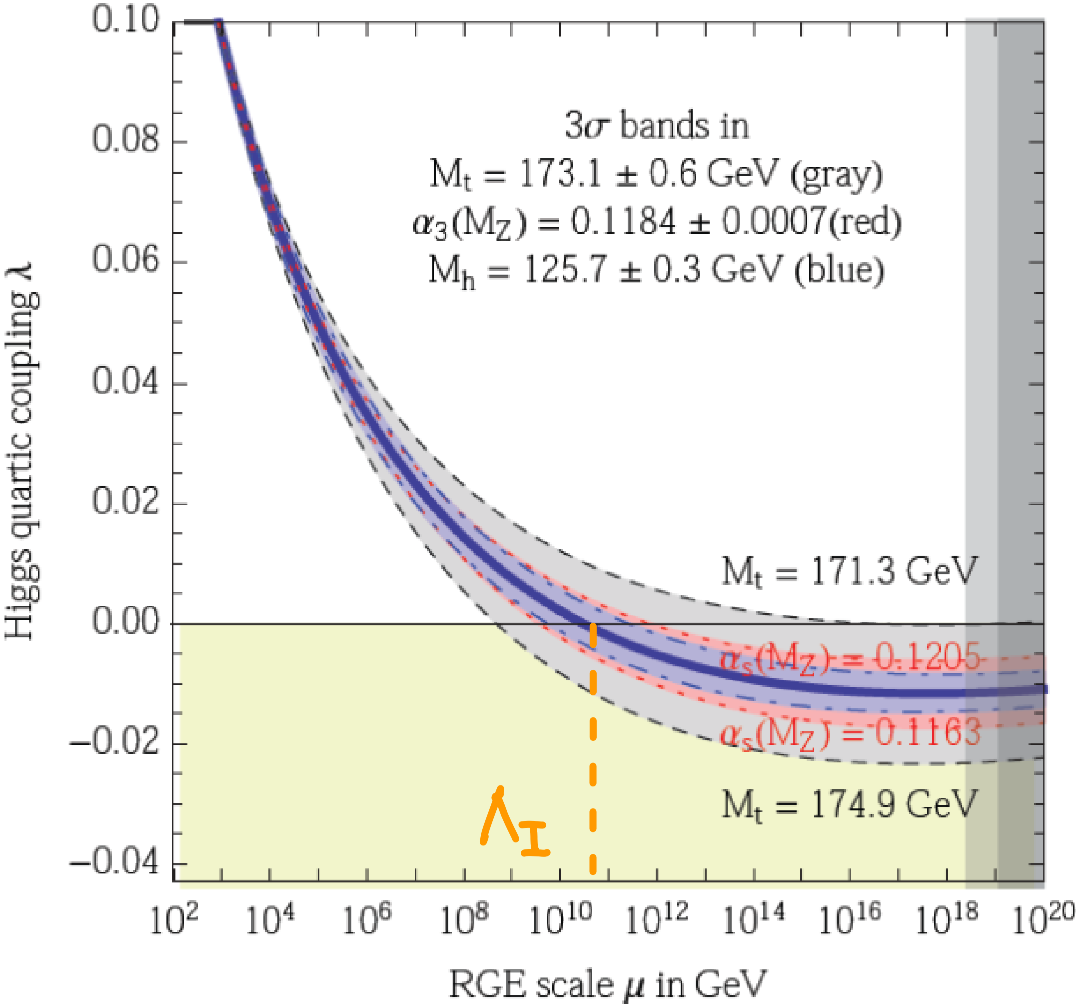


UV EXTRAPOLATED λ

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



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

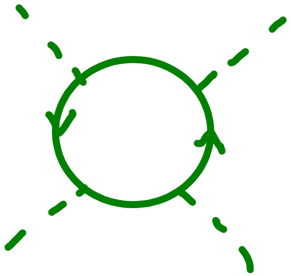


Degrassi et al '12, Buttazzo et al '13

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

VACUUM INSTABILITY

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

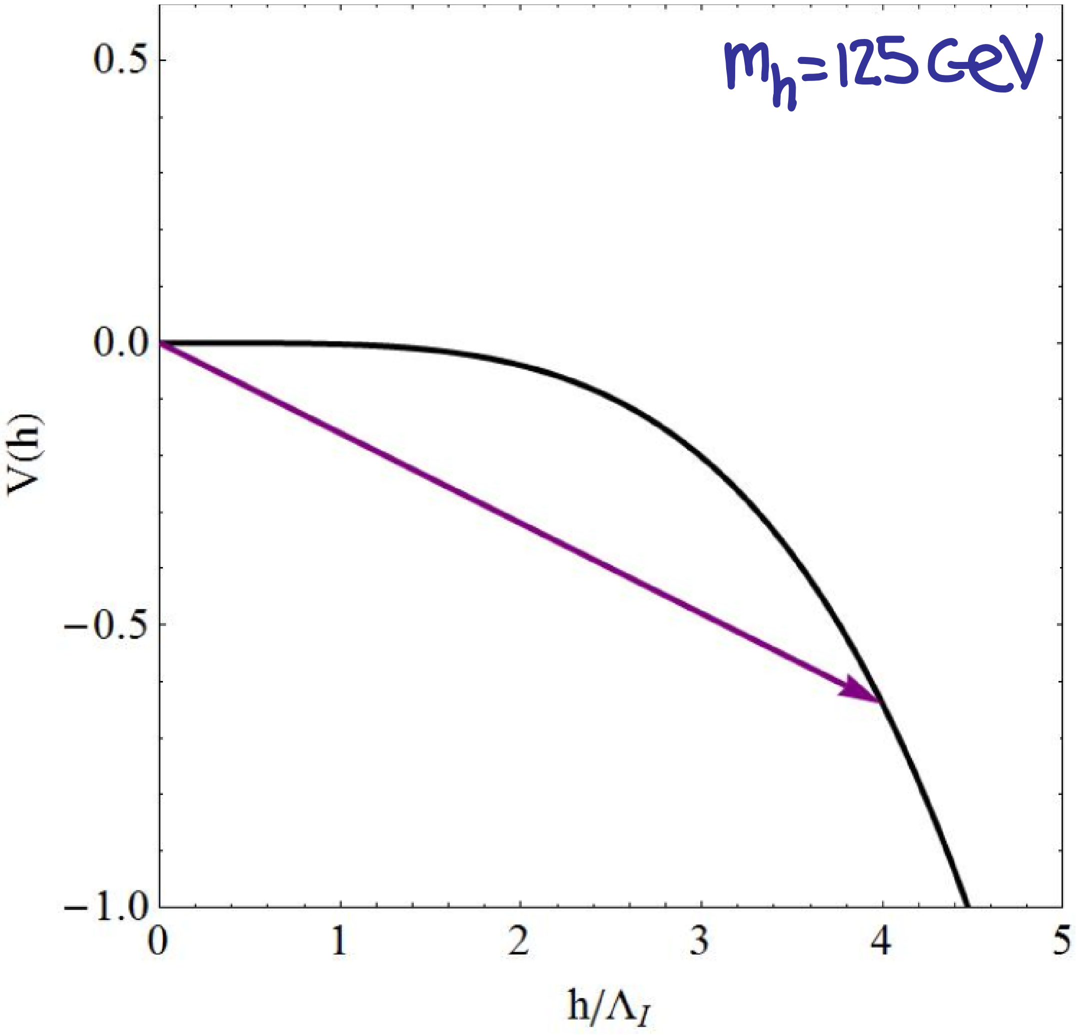


$\lambda < 0$ at $\Lambda_I \sim 10^{11}$ GeV

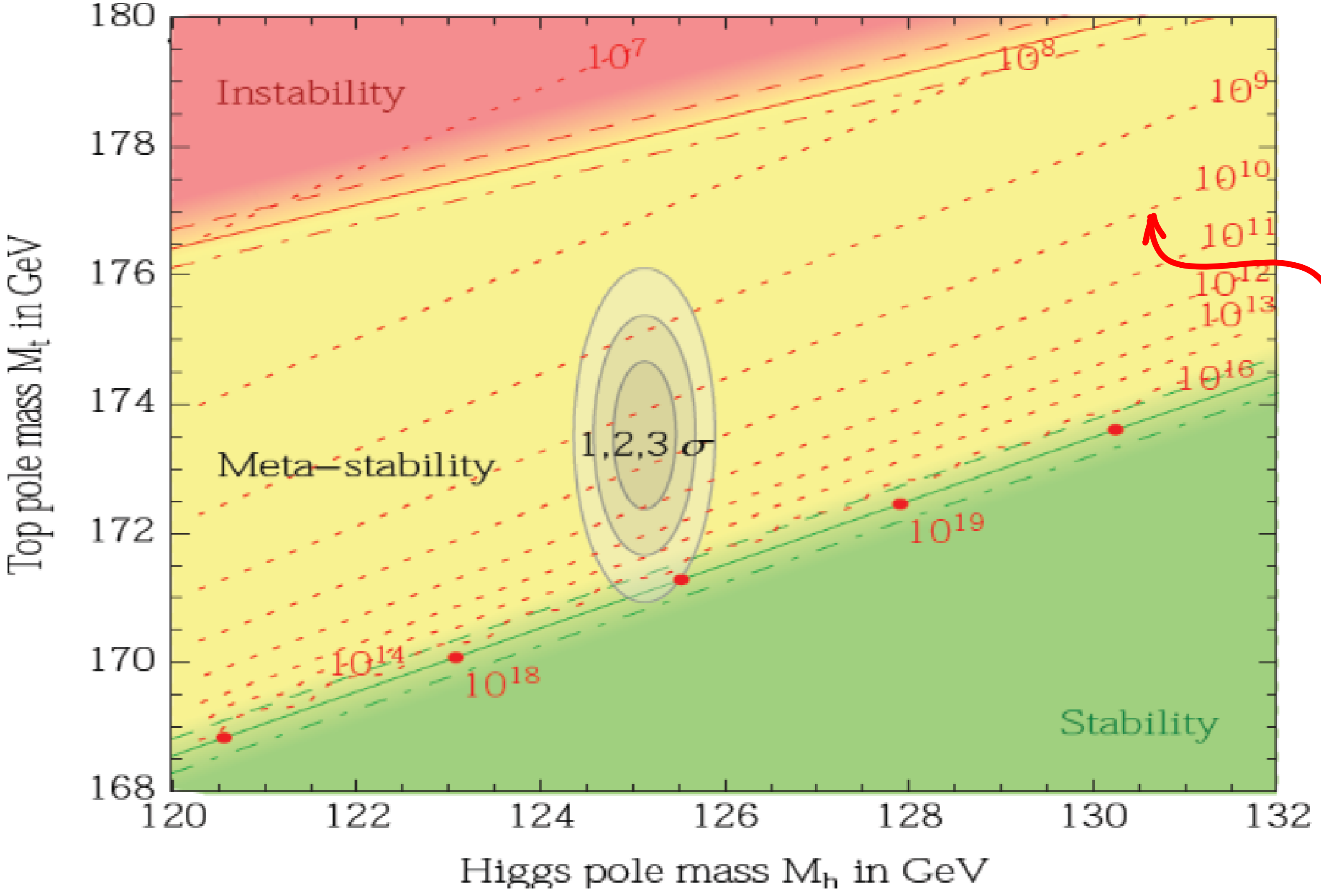
⇓

Higgs potential instability

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



HIGGS NEAR-CRITICALITY



Buttazzo et al '13

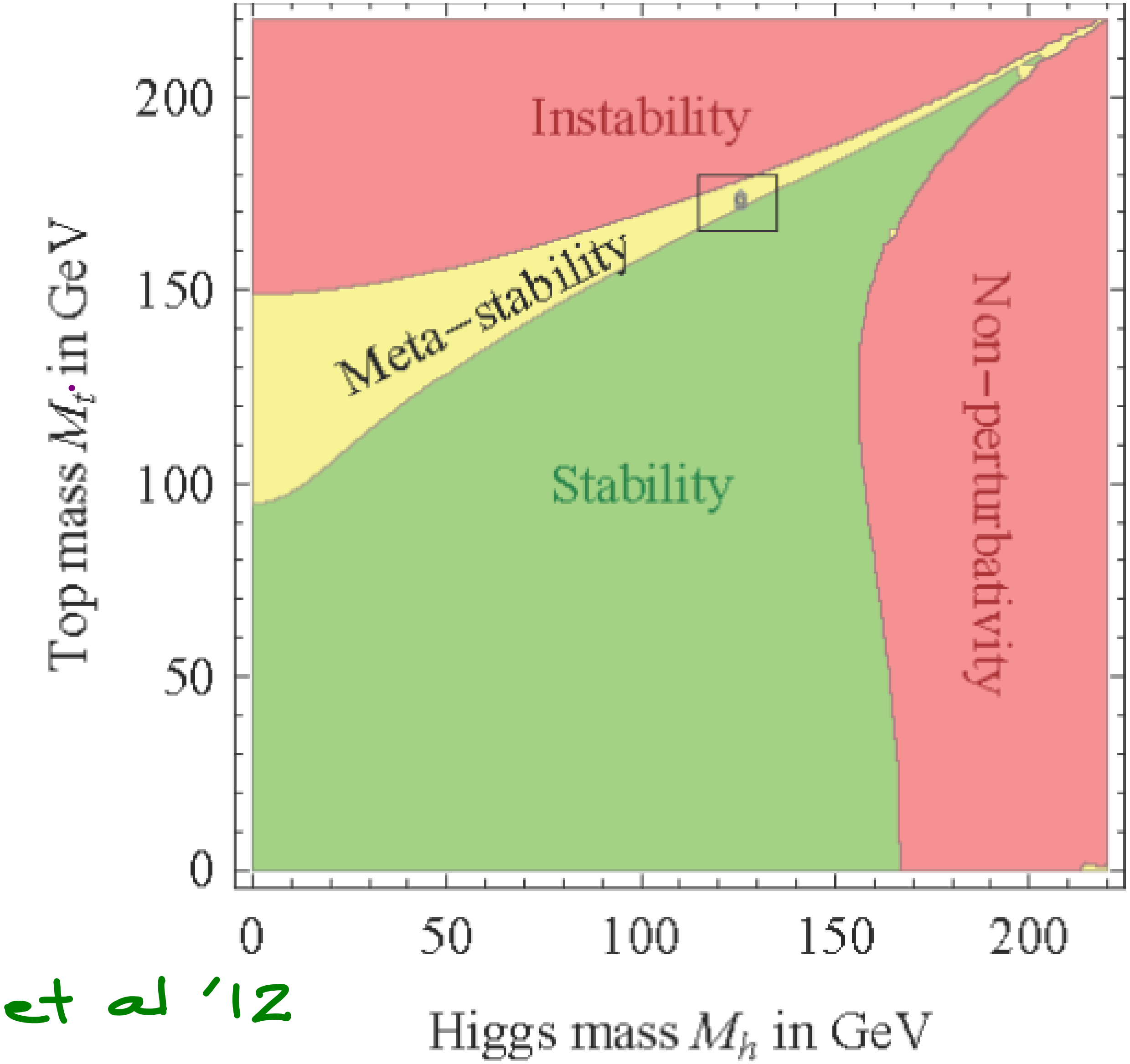
Λ_I (GeV)

$M_h = 125,15 \pm 0.24$ 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? $H_I \lesssim \frac{\Lambda_I}{10}\sqrt{\frac{N_e}{60}}$ But ways out

4. Decay right after inflation

   Interplay with $\xi|H|^2R$ / $c|H|^2\phi^2$

   Parametric/tachyonic resonant Higgs production.

SIGNATURES ?

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

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

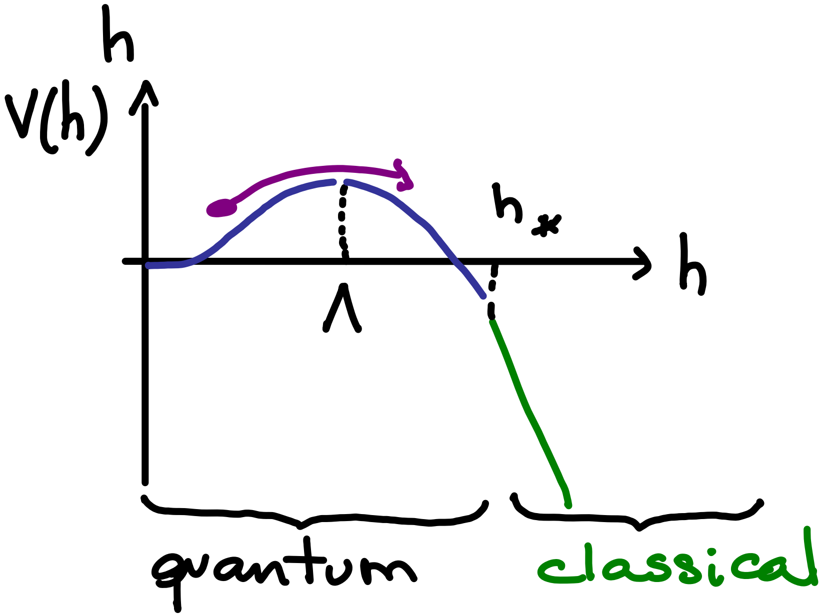
J.R.E, Racco, Riotto '17

Higgs can probe instability during inflation

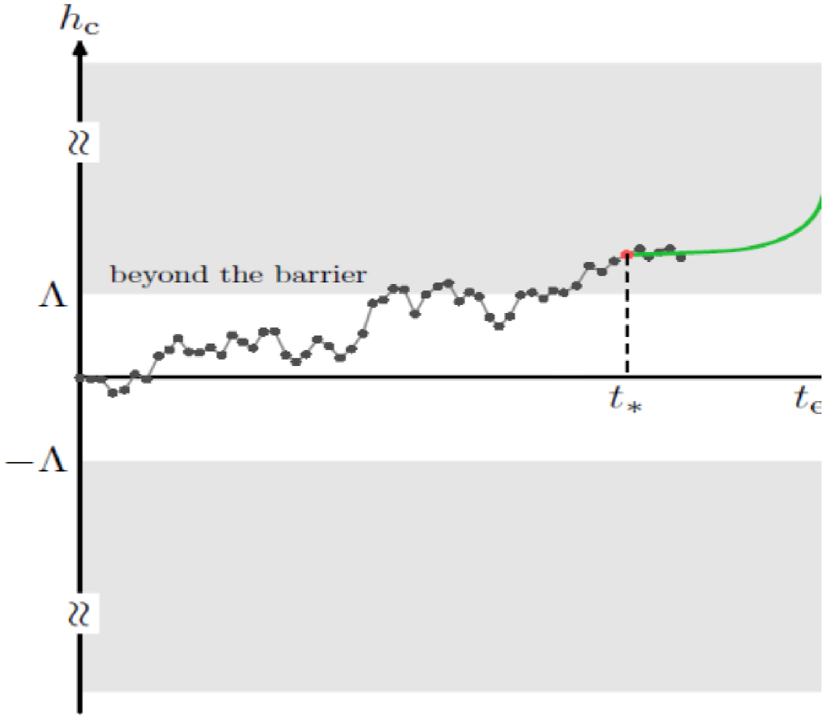
$H_I \gtrsim \Lambda_I$ say $H_I = 10^{12}$ GeV

Classical vs. quantum competition:

Δh in $\Delta t \sim 1/H_I$: $(\Delta h)_{clas} \simeq \frac{V'}{3H_I^2} \leftrightarrow (\Delta h)_{quant} \simeq \frac{H_I}{2\pi}$



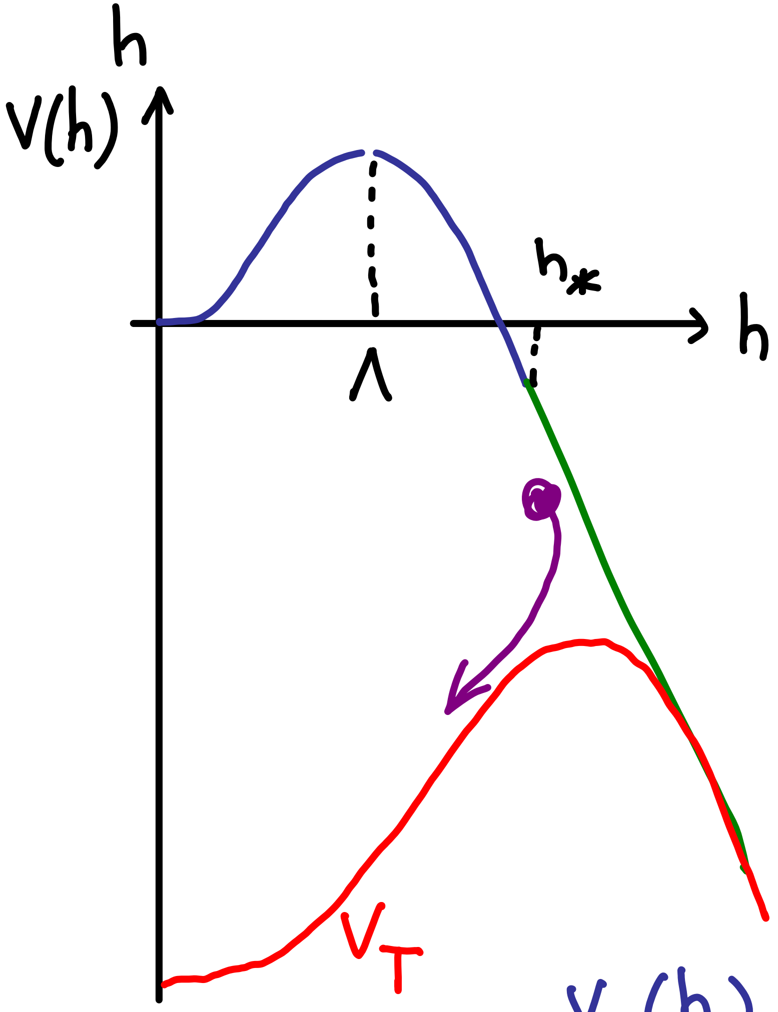
$h_* \sim H_I/|\lambda|^{1/3}$



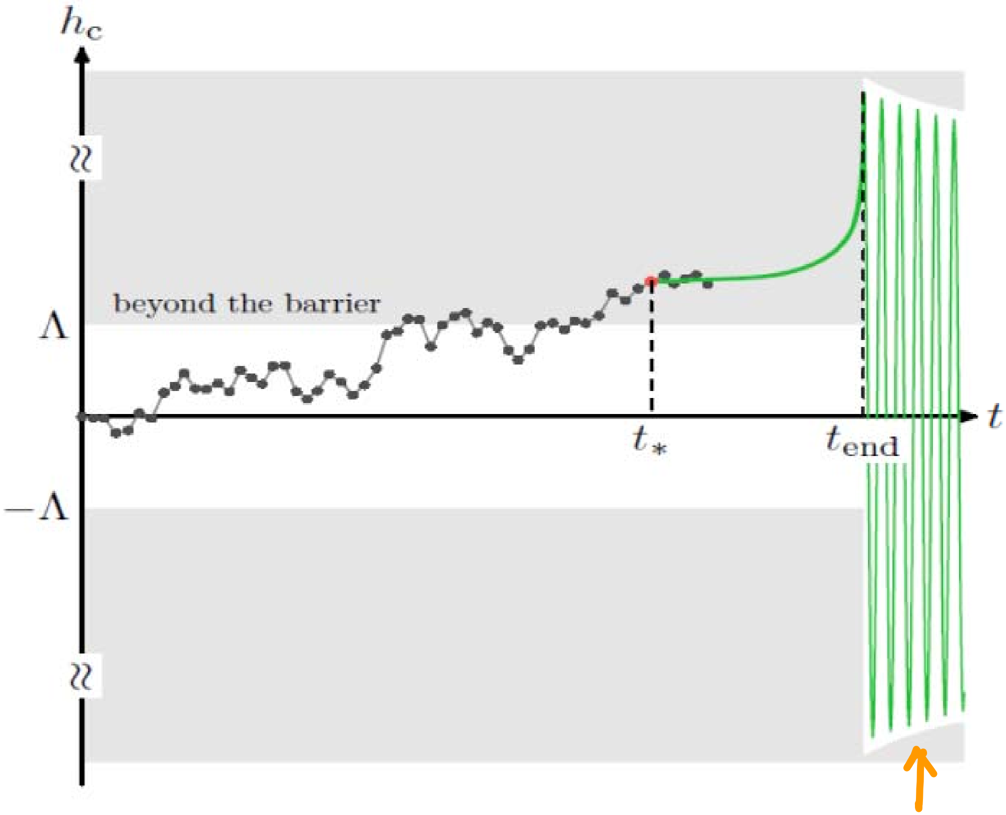
THERMAL RESCUE

J.R.E, Racco, Riotto '17

An efficient reheating saves the day.



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



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 fluctuation modes:

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

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

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

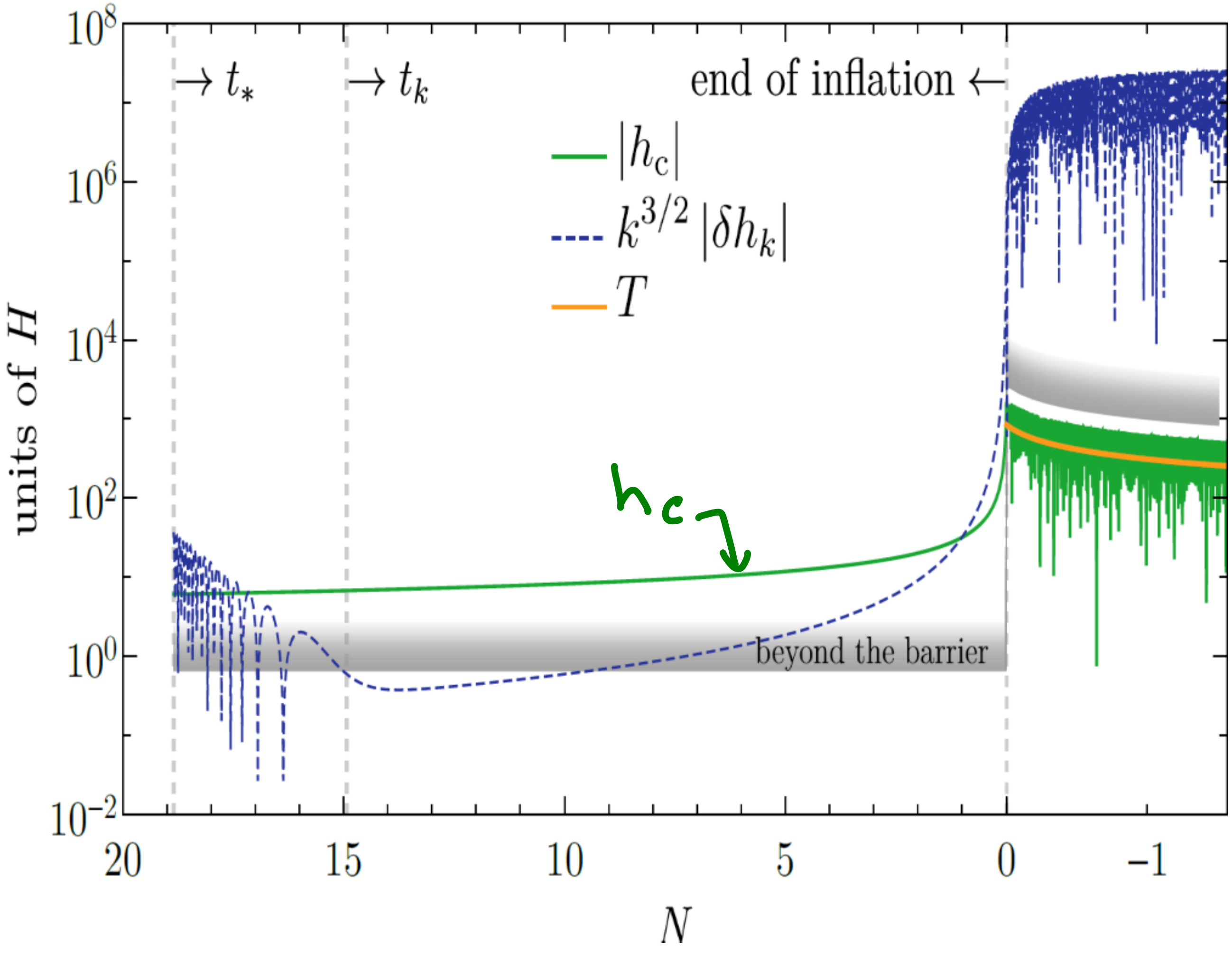
Super-Hubble modes $(k < Ha)$: grow with $V'' < 0$

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

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

GROWTH OF FLUCTUATIONS

J.R.E, Racco, Riotto '17

Gauge-invariant measure of perturbations :

Comoving curvature perturbation

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

inflaton usual one,
responsible for CMB
perturbations

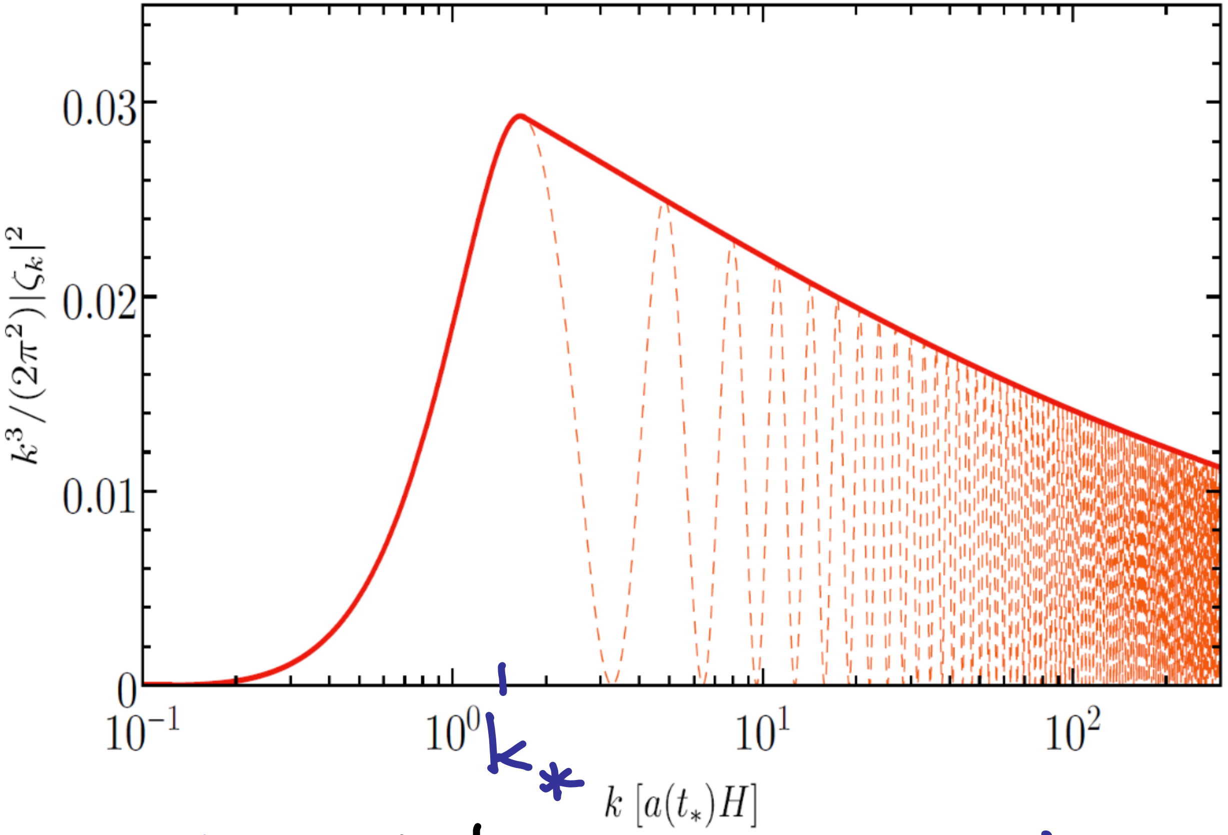
from Higgs,
dominant
at the end of
inflation

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

SPECTRUM

J.R.E, Racco, Riotto '17

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

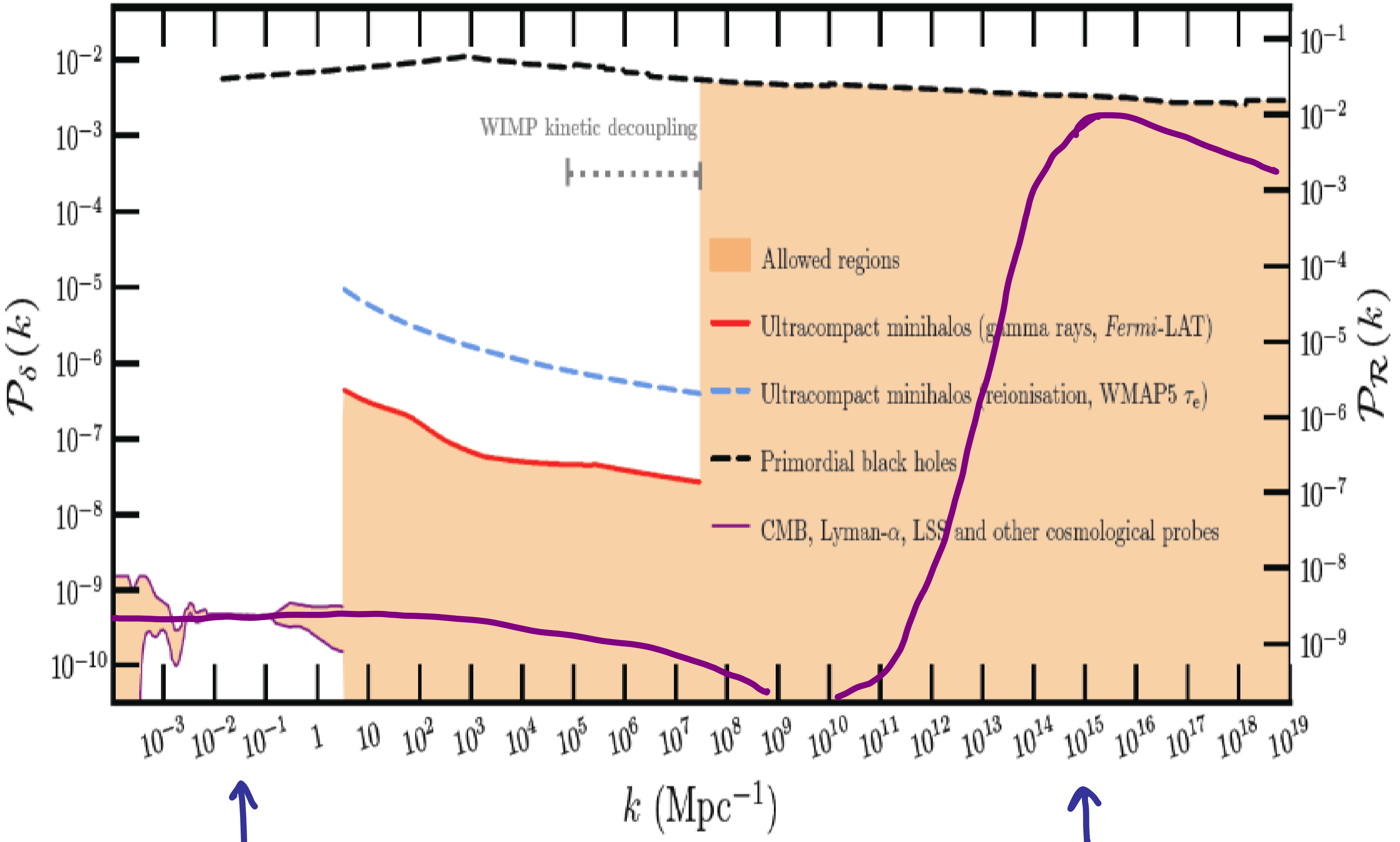


k_* determined by t_*

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

RELEVANT SCALES

Bringmann, Scott, Akrami '13



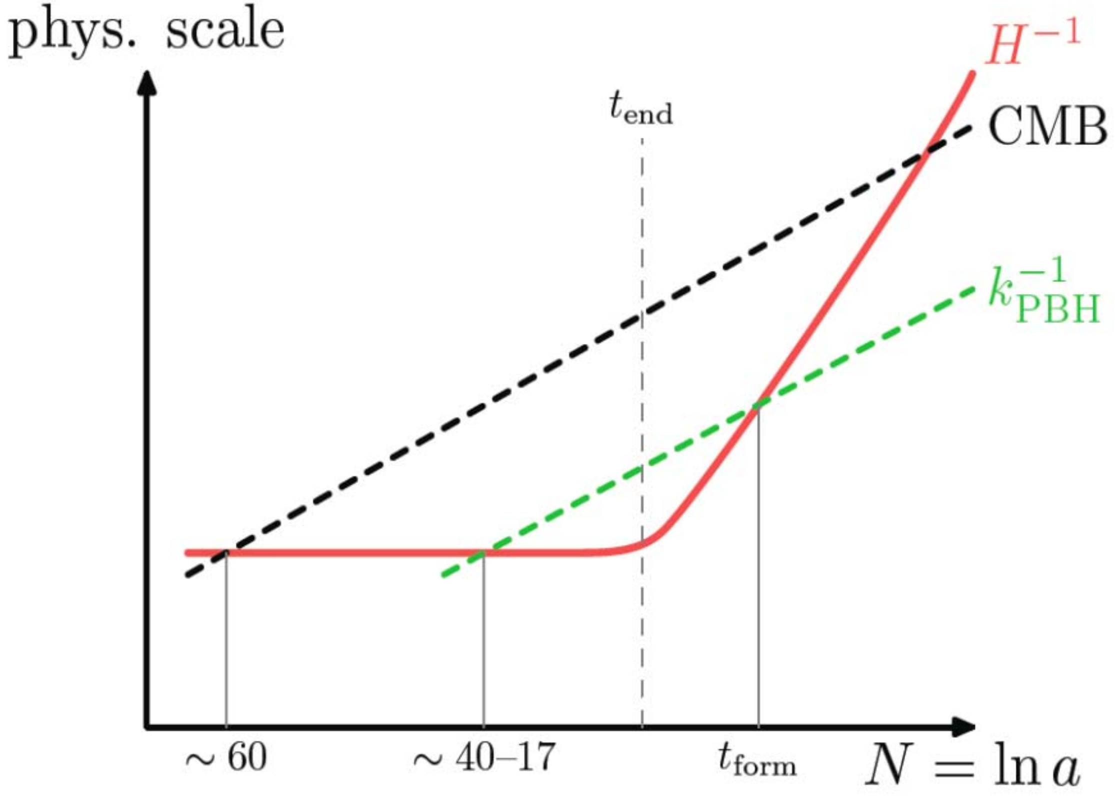
↑ CMB

↑ Higgs fluctuations

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

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

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 $(\sigma_\Delta \lesssim 0.05)$

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

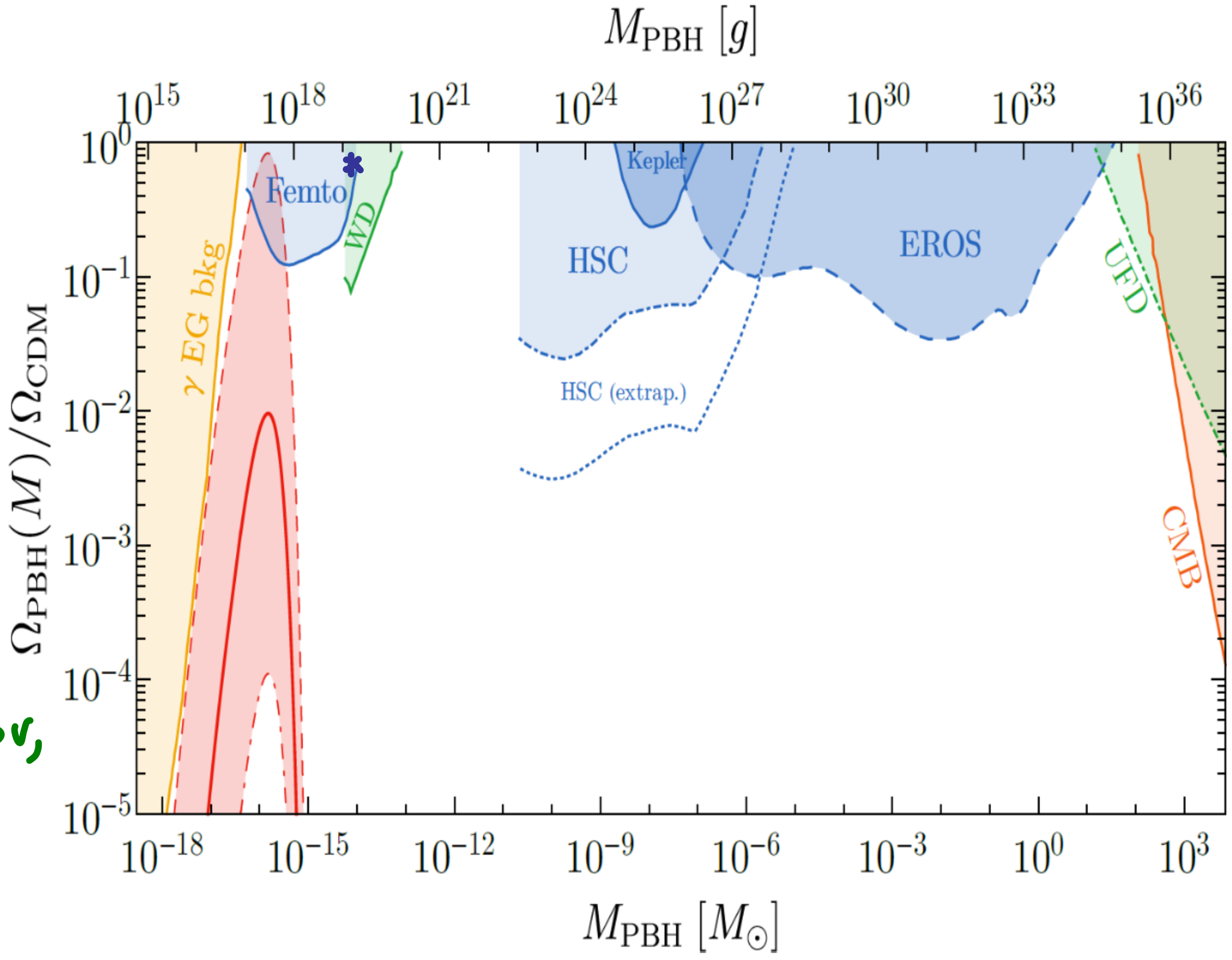
$$\frac{\Omega_{PBH}(M)}{\Omega_{CDM}} = \frac{\beta(M)}{1.6\times10^{-16}} \left(\frac{\gamma}{0.2}\right)^{3/2} \left(\frac{g_*}{106.75}\right)^{-1/4} \left(\frac{M}{10^{-15}M_\odot}\right)^{-1/2}$$

PBHs FROM HIGGS PERTURBATIONS

J.R.E, Racco, Riotto '17

PBH mass spectrum $m_h = 125.09$ GeV, $m_t = 172$ GeV

These PBHs might be (all) Dark Matter



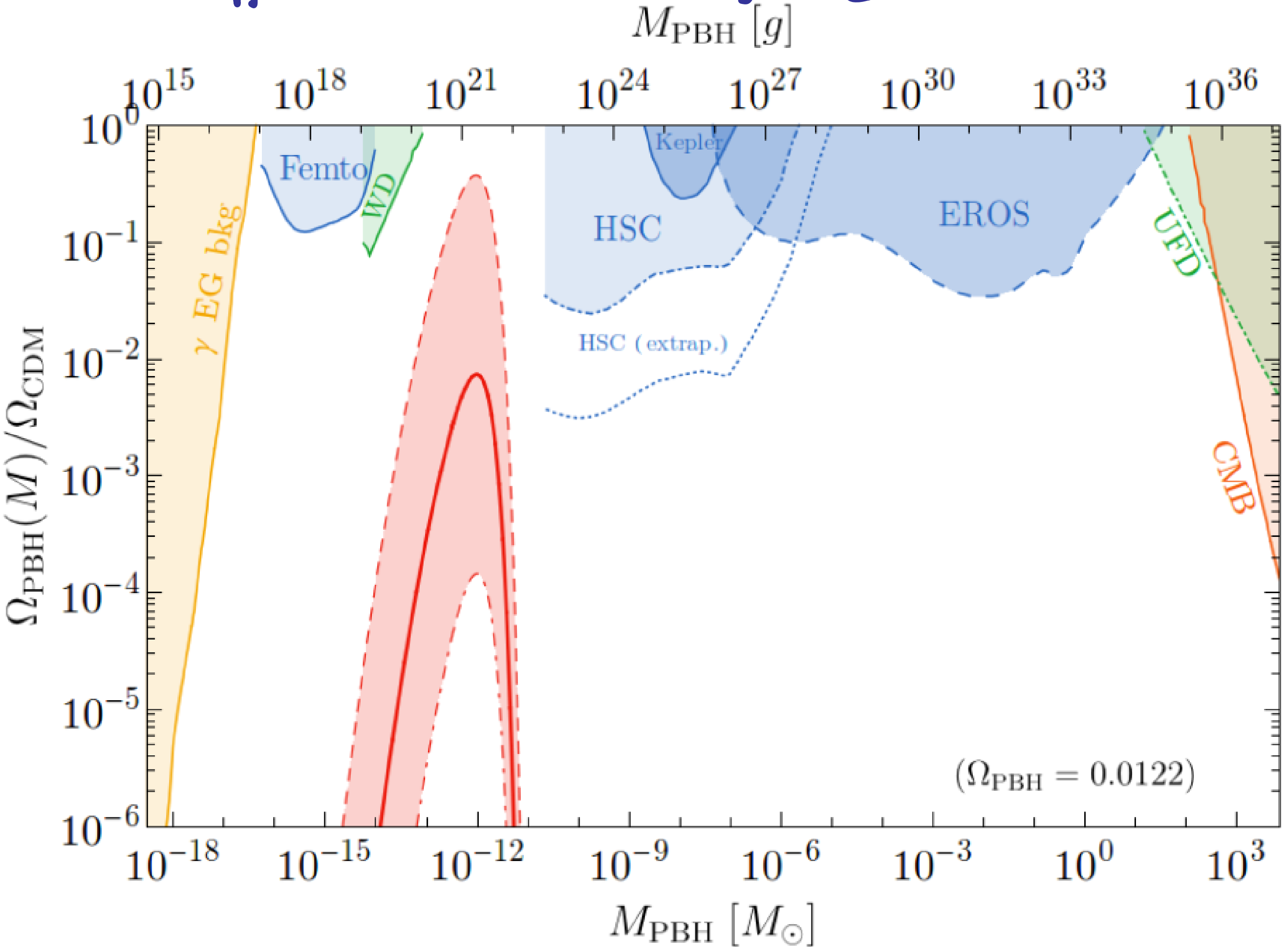
* Femtolensing bound not there

Katz, Kopp, Sibiryakov, Xue '18

PBHs FROM HiGGS PERTURBATIONS

J.R.E, Racco, Riotto '17

PBH mass spectrum $m_h = 125.33$ GeV, $m_t = 170.47$ GeV



These PBHs might be (all) Dark Matter

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

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

(~ a few in our solar system)

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

FINE-TUNING ISSUES

Back-up slides...

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.

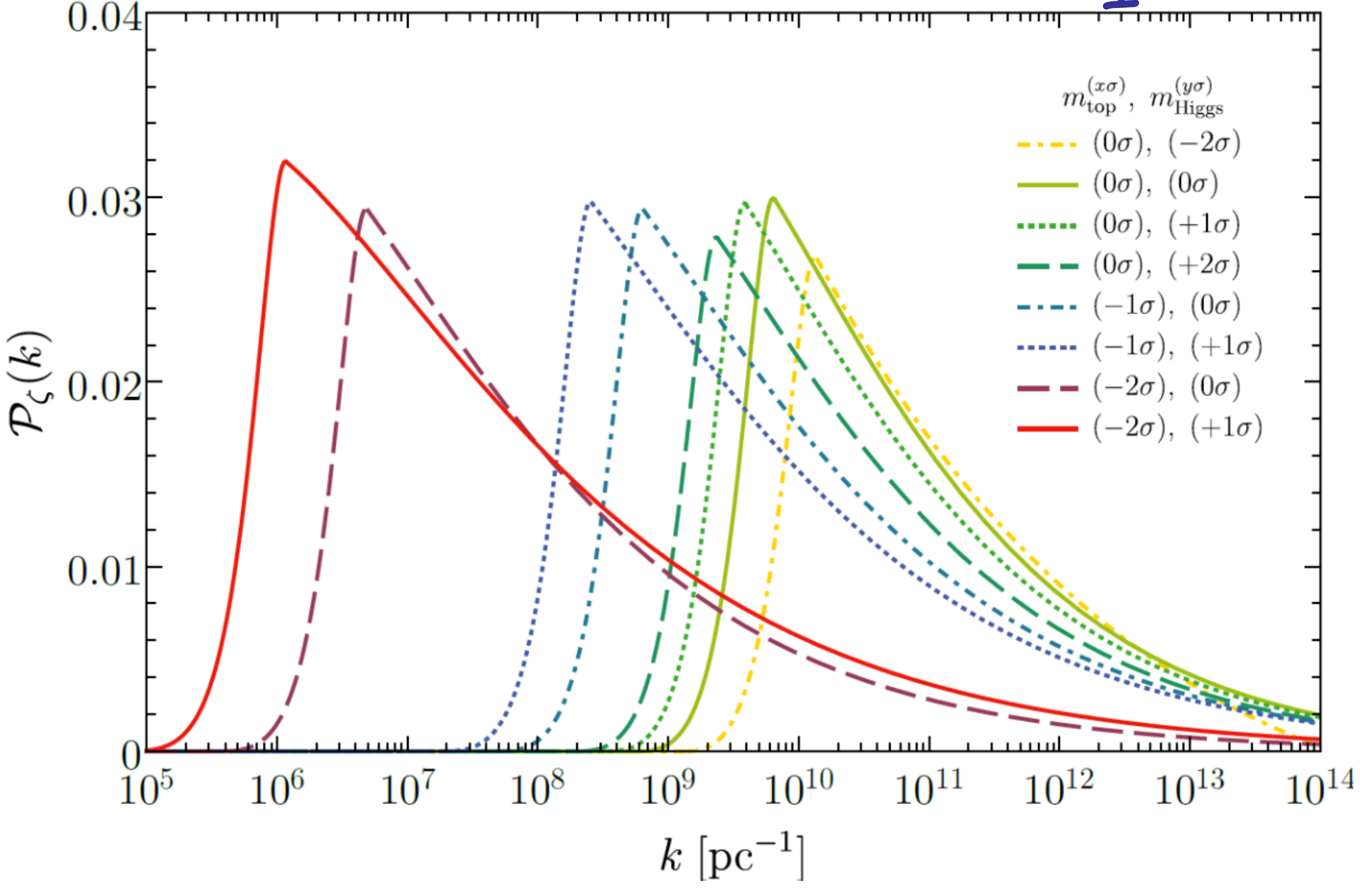
SCALAR POWER SPECTRUM

J.R.E, Racco, Riotto '18

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

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

$H_I = 10^{12}$ GeV

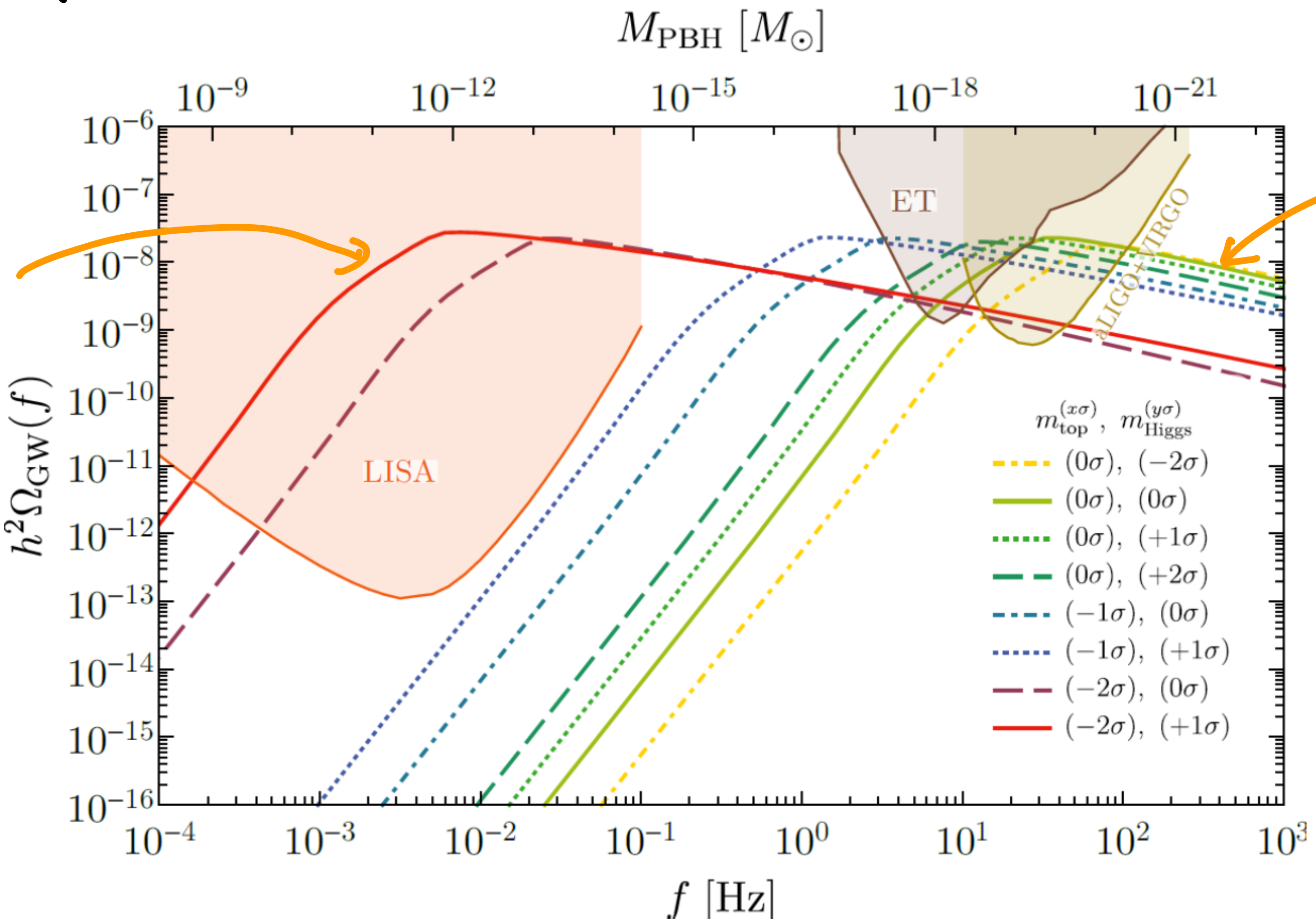


$\Lambda_I \uparrow \longleftrightarrow \Lambda_I \downarrow$

GW SPECTRUM

J.R.E, Racco, Riotto '18

GW Spectrum on the reach of future experiments



$n_T \simeq 3$

$n_T \simeq -0.6$

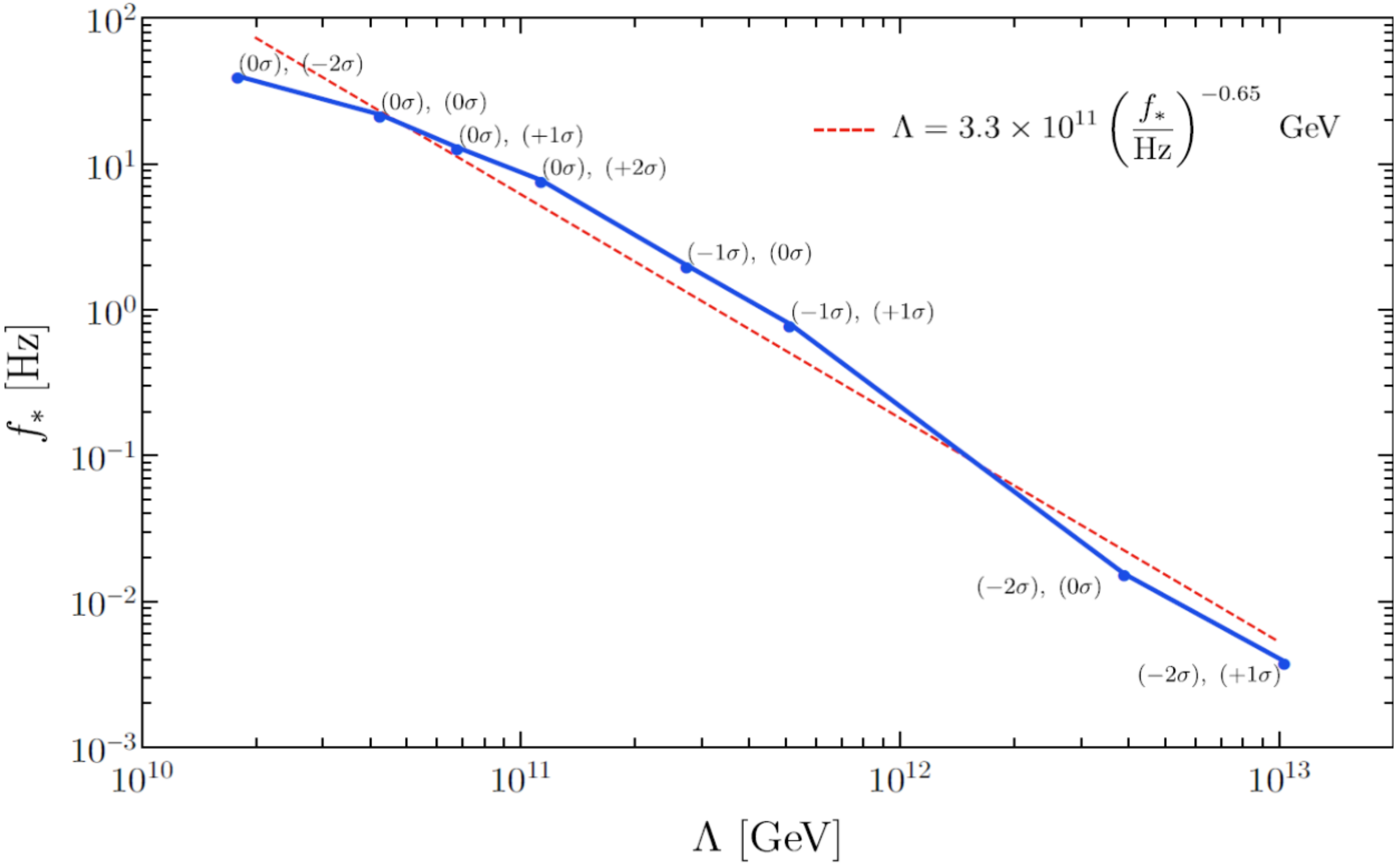
$$\Omega_{GW}(f) \simeq 3\times10^{-8}\,(f/f_*)^{n_T}$$

$$\Omega_{GW}^{\rm peak} \sim \Omega_{\rm rad}\,\mathcal{P}_\zeta^2$$

"HEARING" THE INSTABILITY SCALE

J.R.E, Racco, Riotto '18

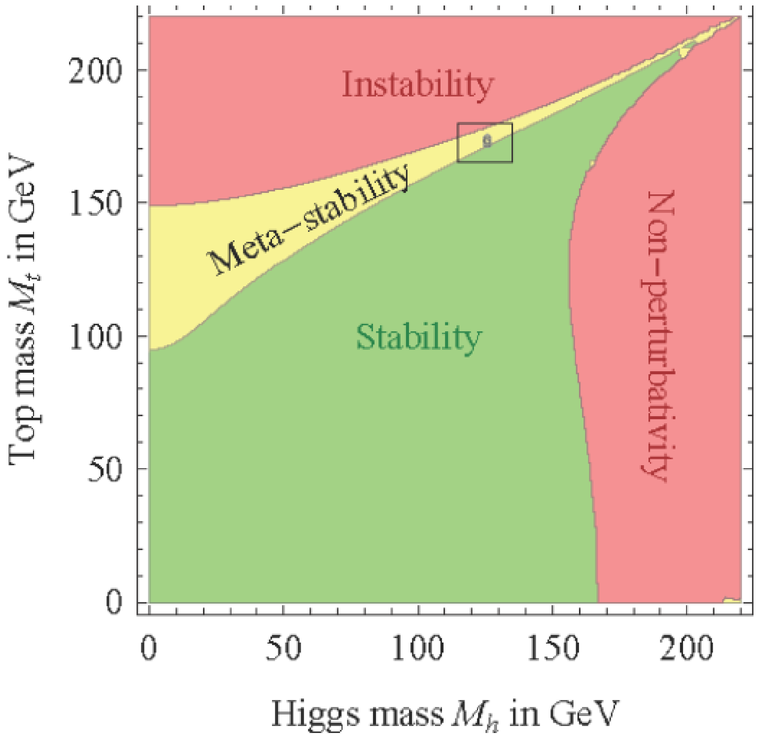
Peak f_* $m_{h,t}$ sensitive ⇨ Λ_I sensitive



$$\Lambda_I = 3.3\times10^{11}\,\mathrm{GeV}\left(\frac{f_*}{\mathrm{Hz}}\right)^{-0.6}$$

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 during inflation

★ PBHs as DM

Quite economical / requires tuning

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

FINE-TUNING ISSUES

J.R.E, Racco, Riotto '17

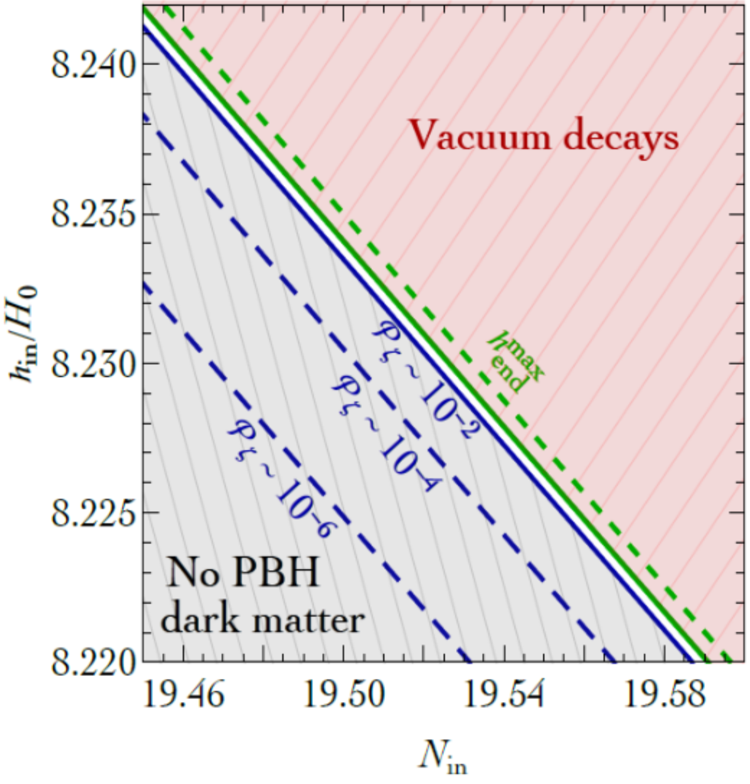
Scenario clearly tuned (eg, end of inflation right on time to save h_c).

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

Strumia, Urbano et al '18

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

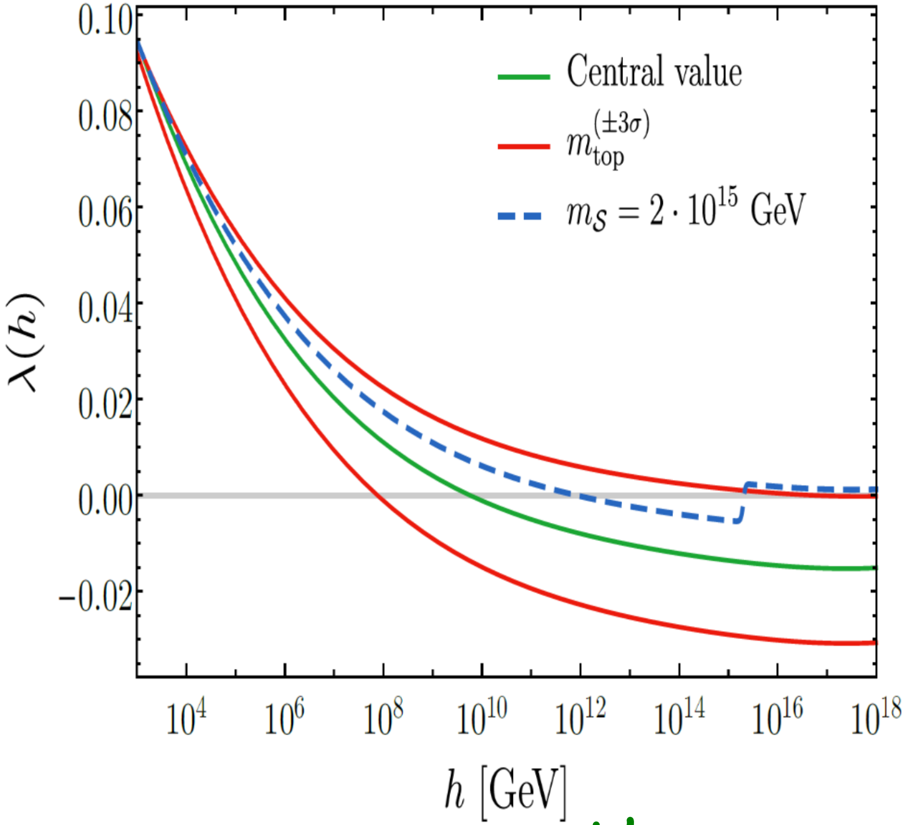
too small PBH abundance or vacuum decay



STABILIZATION HELPS

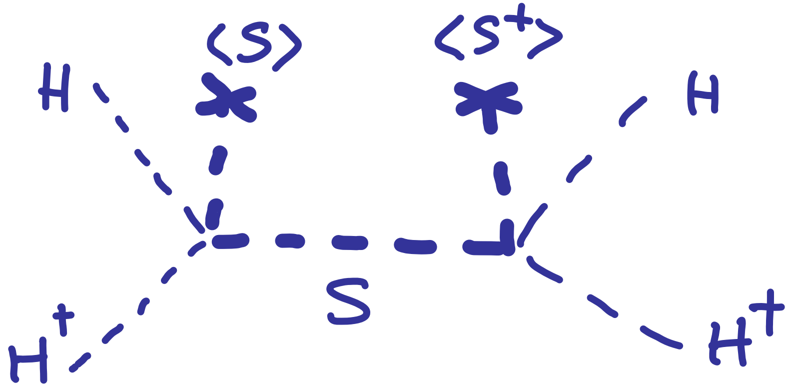
J.R.E, Racco, Riotto '18

Invoke tree-level threshold effect in λ to stabilize V



Elias-Miró et al'12

Singlet field S coupled to h

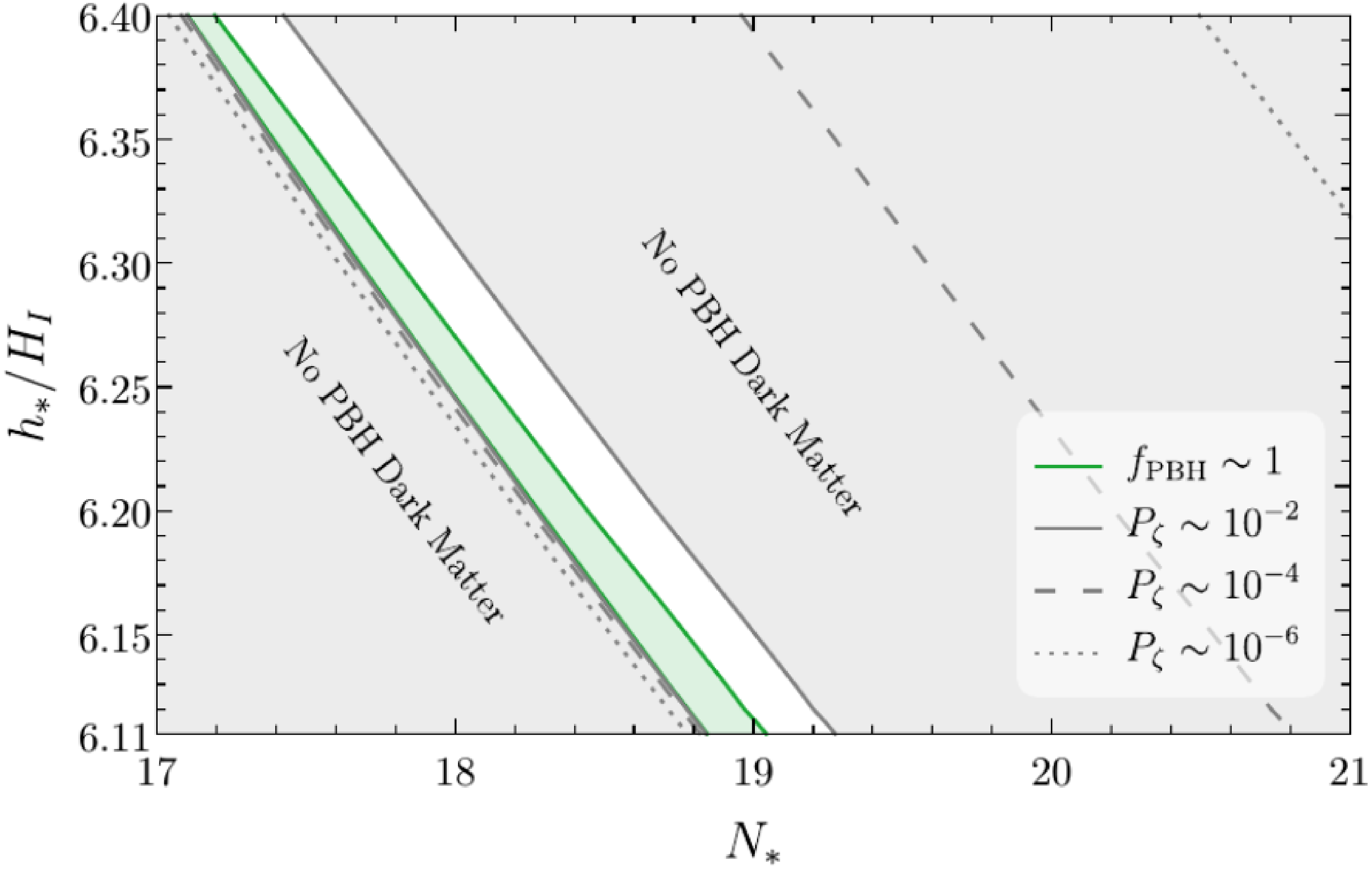


Non-SM minimum at $\sim 10^{15}$ GeV

Thermally rescued after inflation

STABILIZATION HELPS

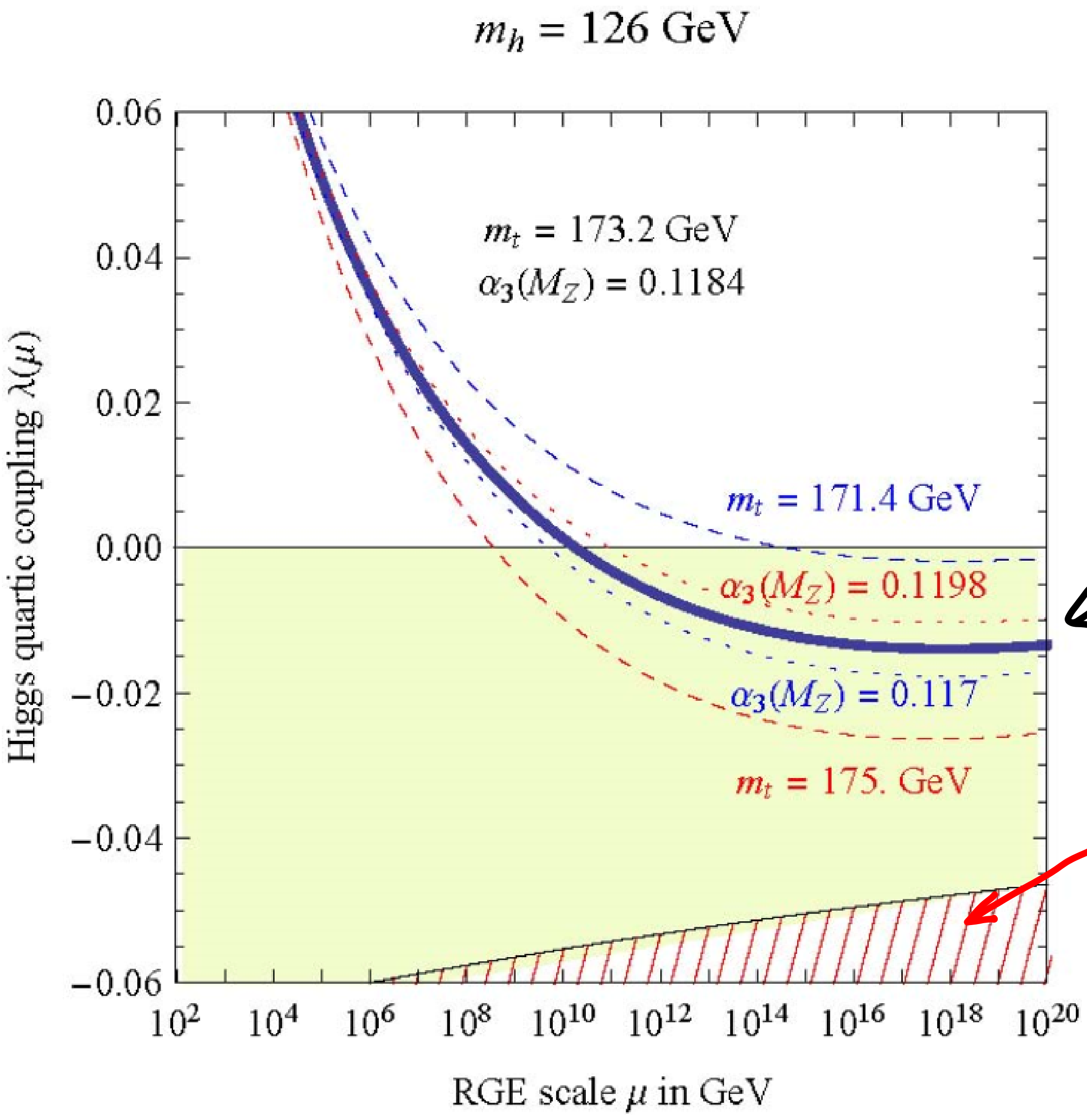
J.R.E, Racco, Riotto '18



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

No death by AdS

LIFE IN A METASTABLE VACUUM



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

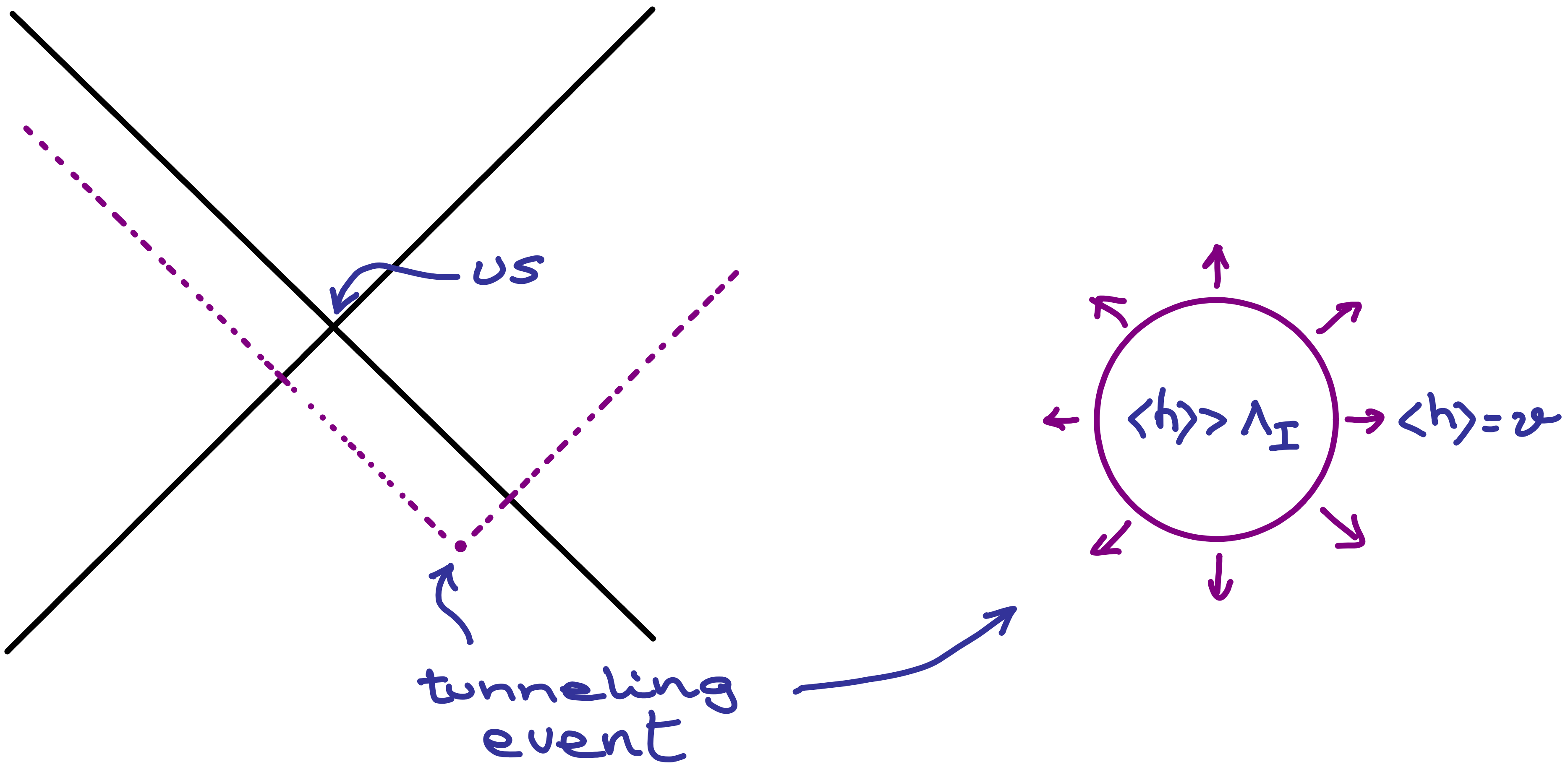
$\gg$ age of Universe

Unstable vacuum

$(M_h \downarrow)$

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

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

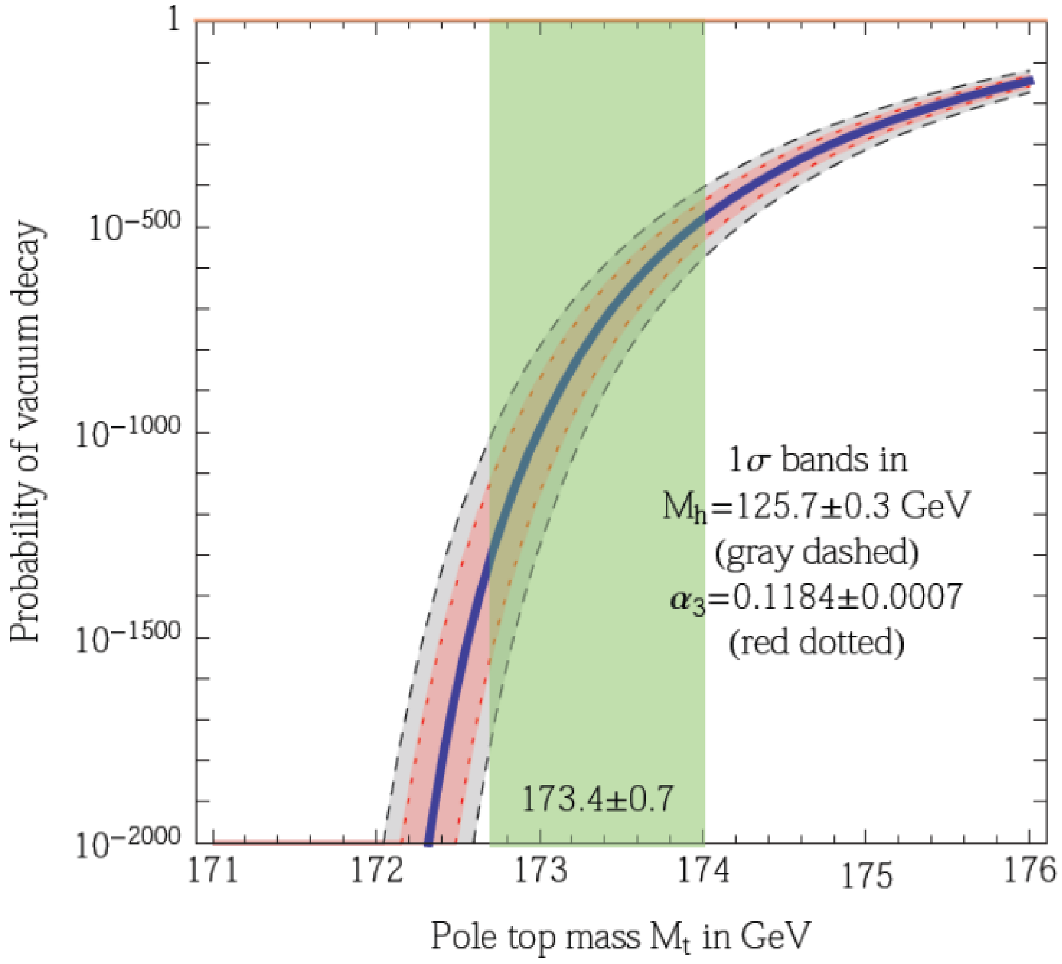
$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|\lambda|/0.01}\right]$$

(Isidori, Ridolfi, Strumia '01)

easily wins over τ_U^4

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

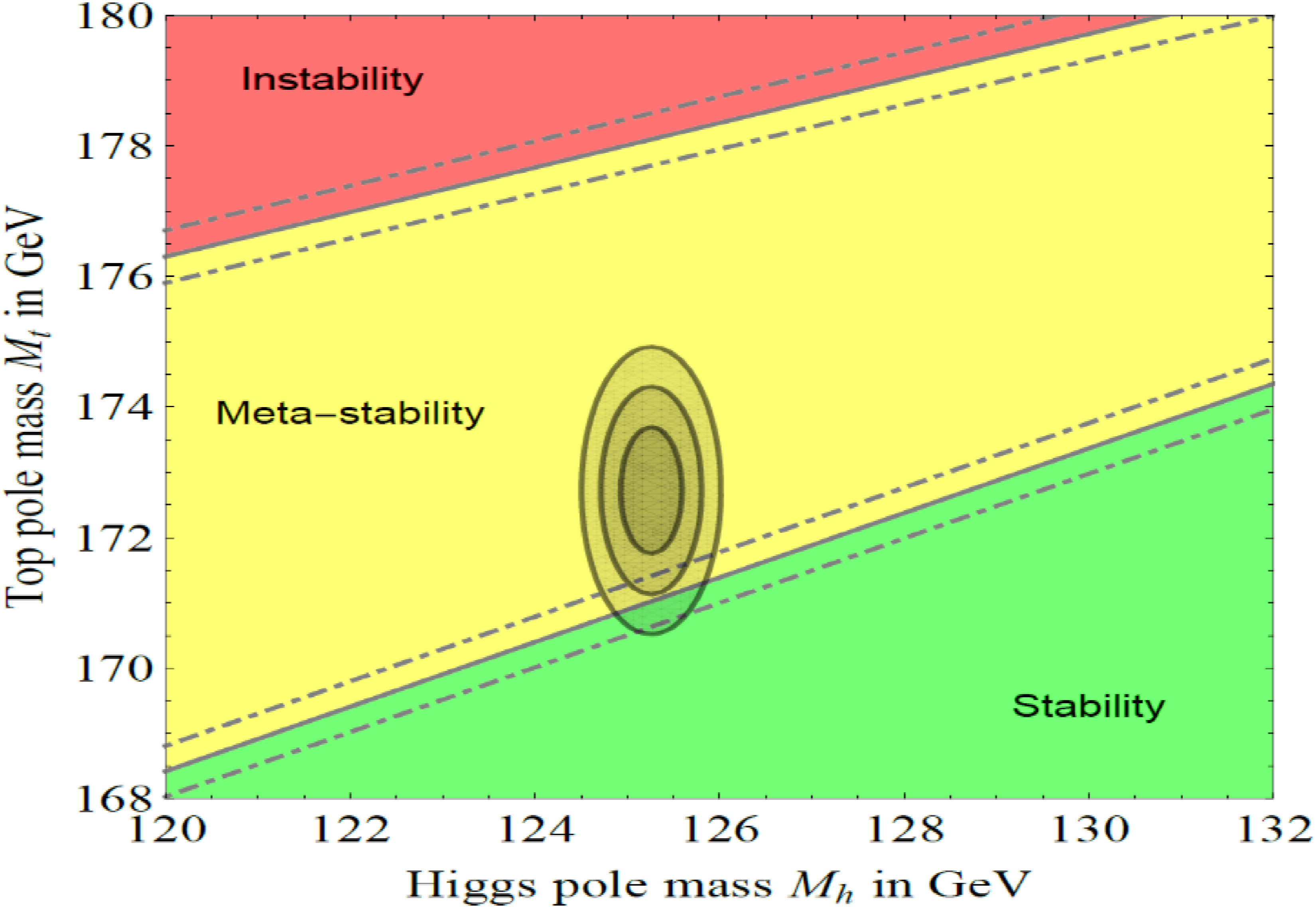
PROBABILITY OF VACUUM DECAY



Buttazzo et al '13

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

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

COSMOLOGICAL IMPLICATIONS

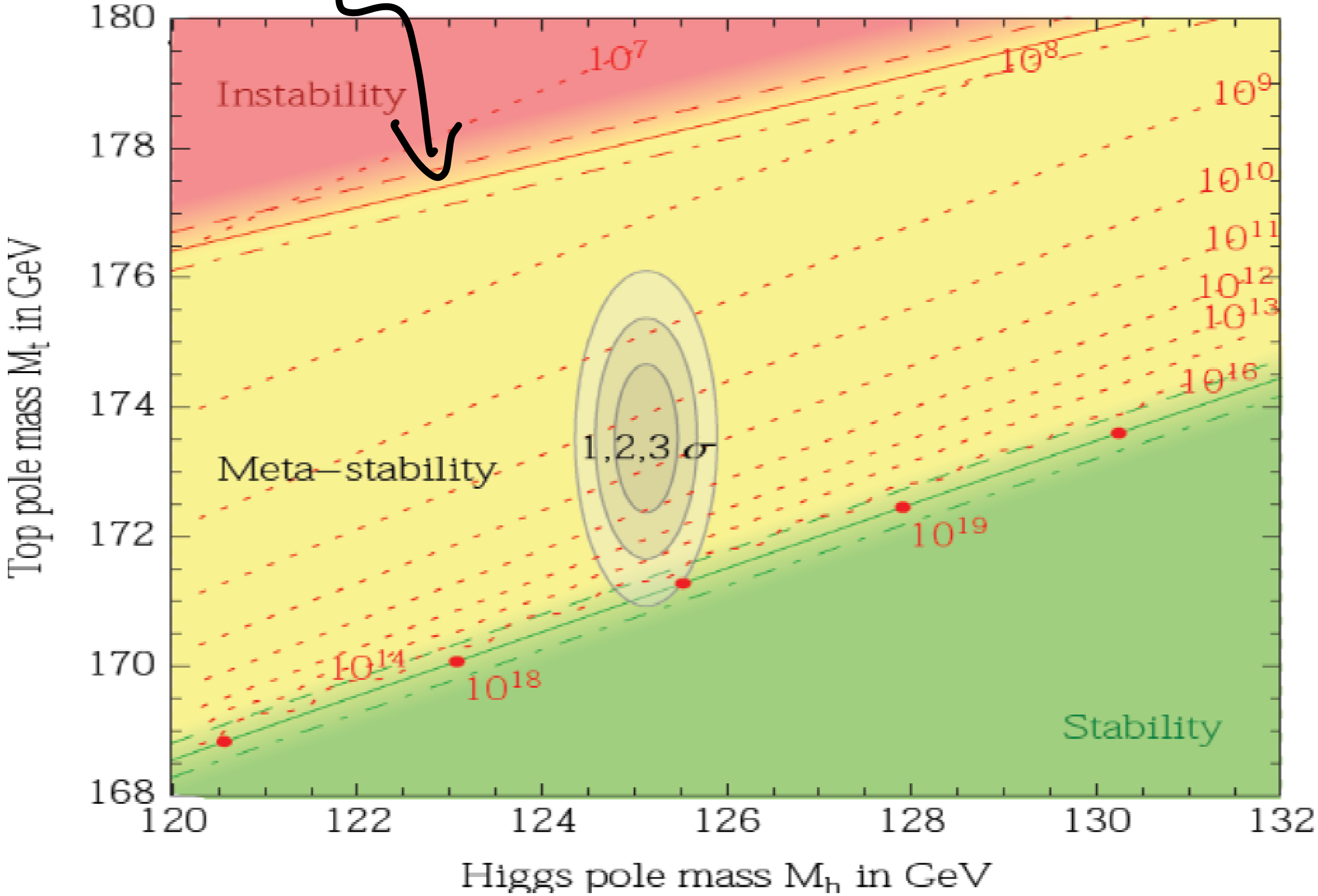
1. Decay by quantum tunneling

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

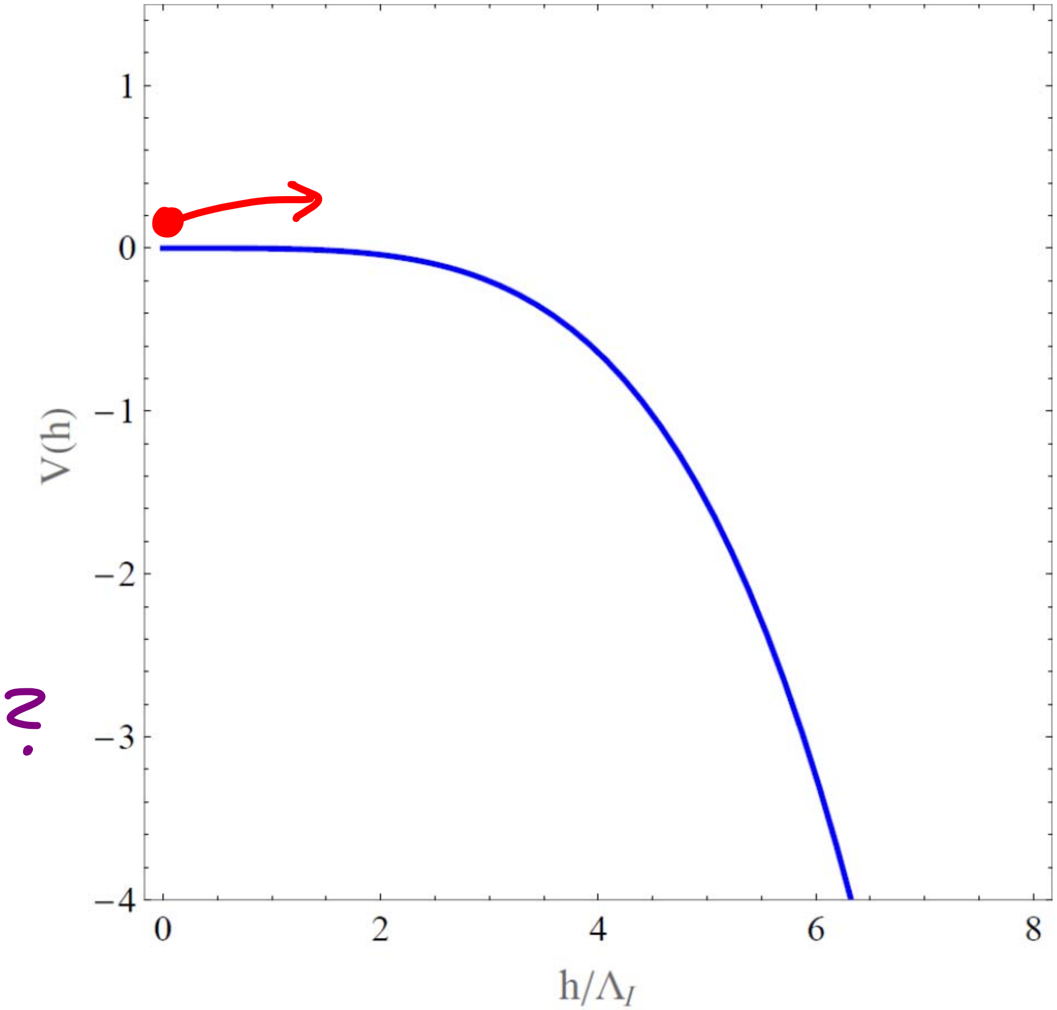
   But long lifetime

2. Decay by thermal fluctuations

I2. DECAY BY THERMAL FLUCTUATIONS

Thermal decay during the early Universe

Thermal excitations
over the barrier



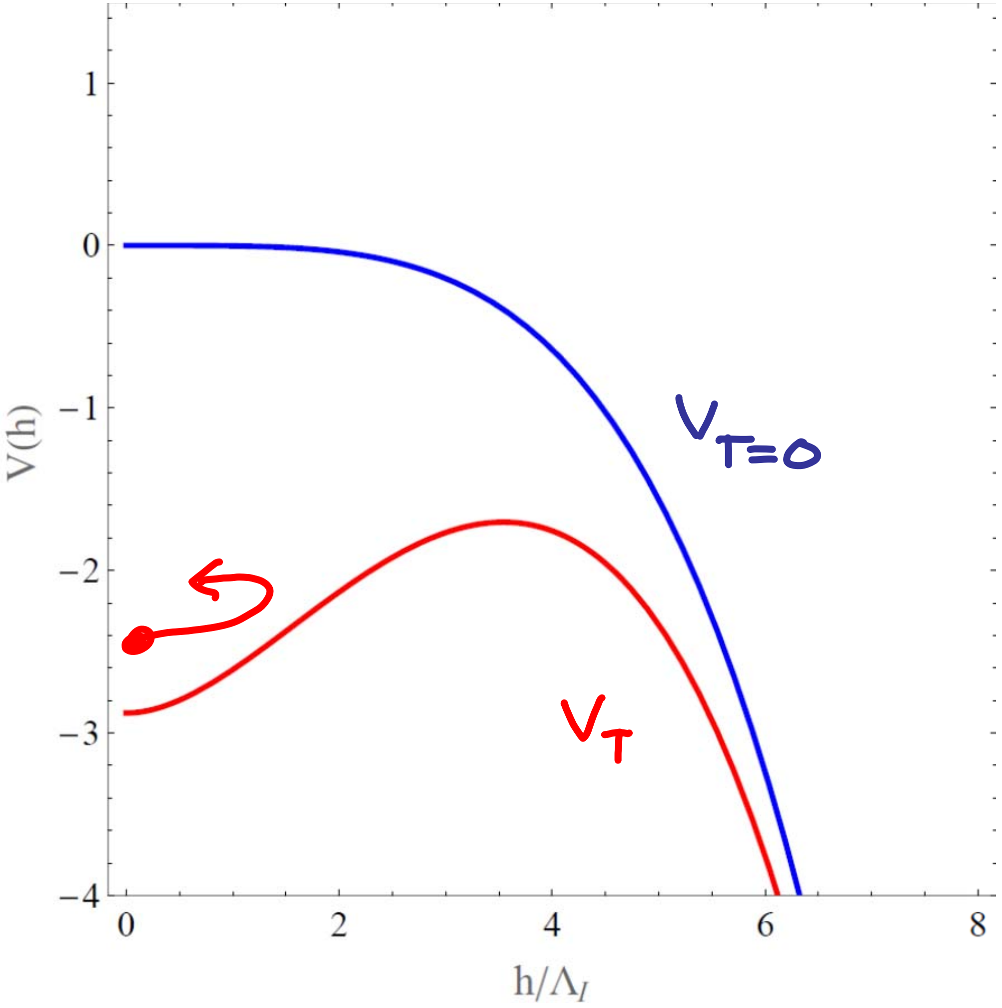
$$\sqrt{\langle h^2 \rangle} \sim T \gtrsim \Lambda_I$$

Upper bound on T_{RH} ?

DECAY BY THERMAL FLUCTUATIONS

Thermal decay during the early Universe

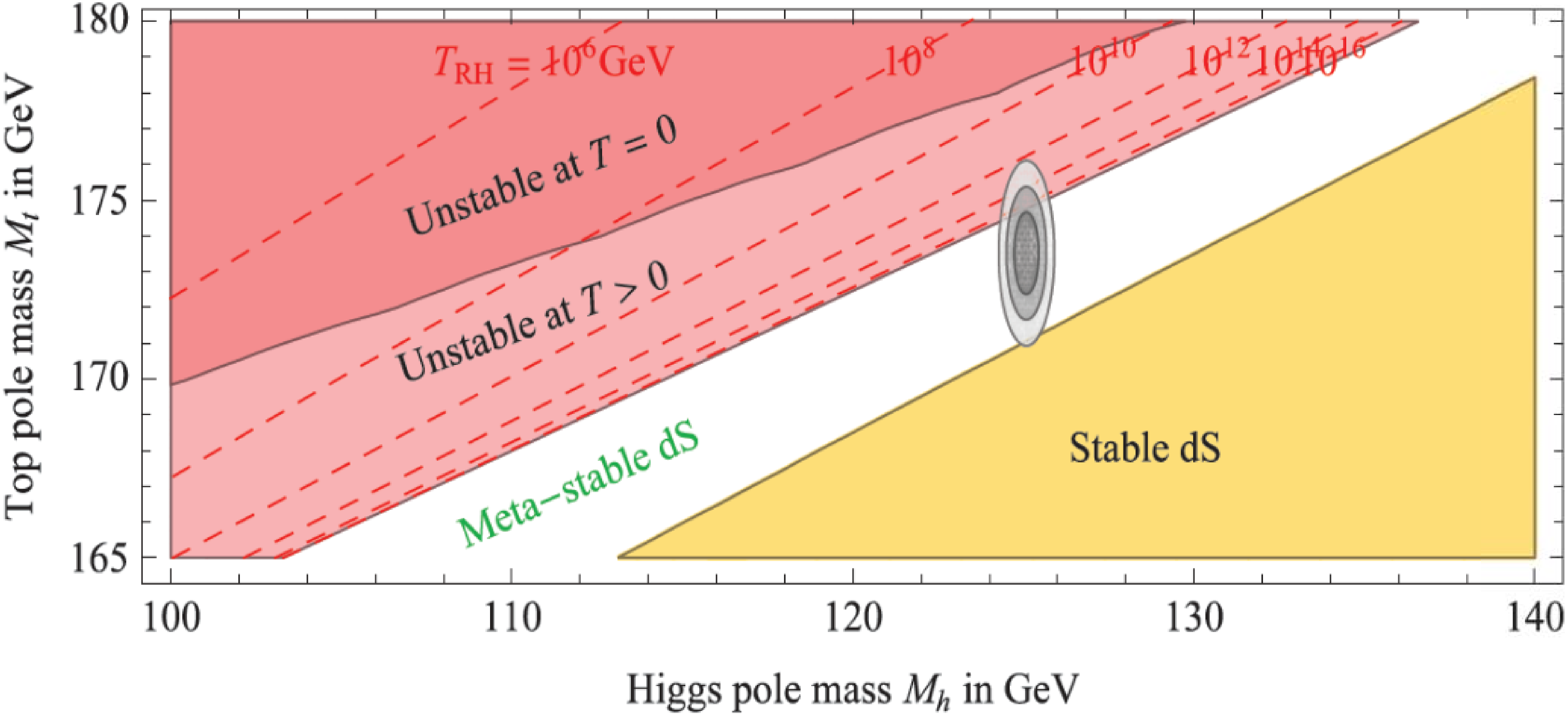
$\langle h^2 \rangle \sim T^2$



but thermal corrections tend to stabilize V(h)

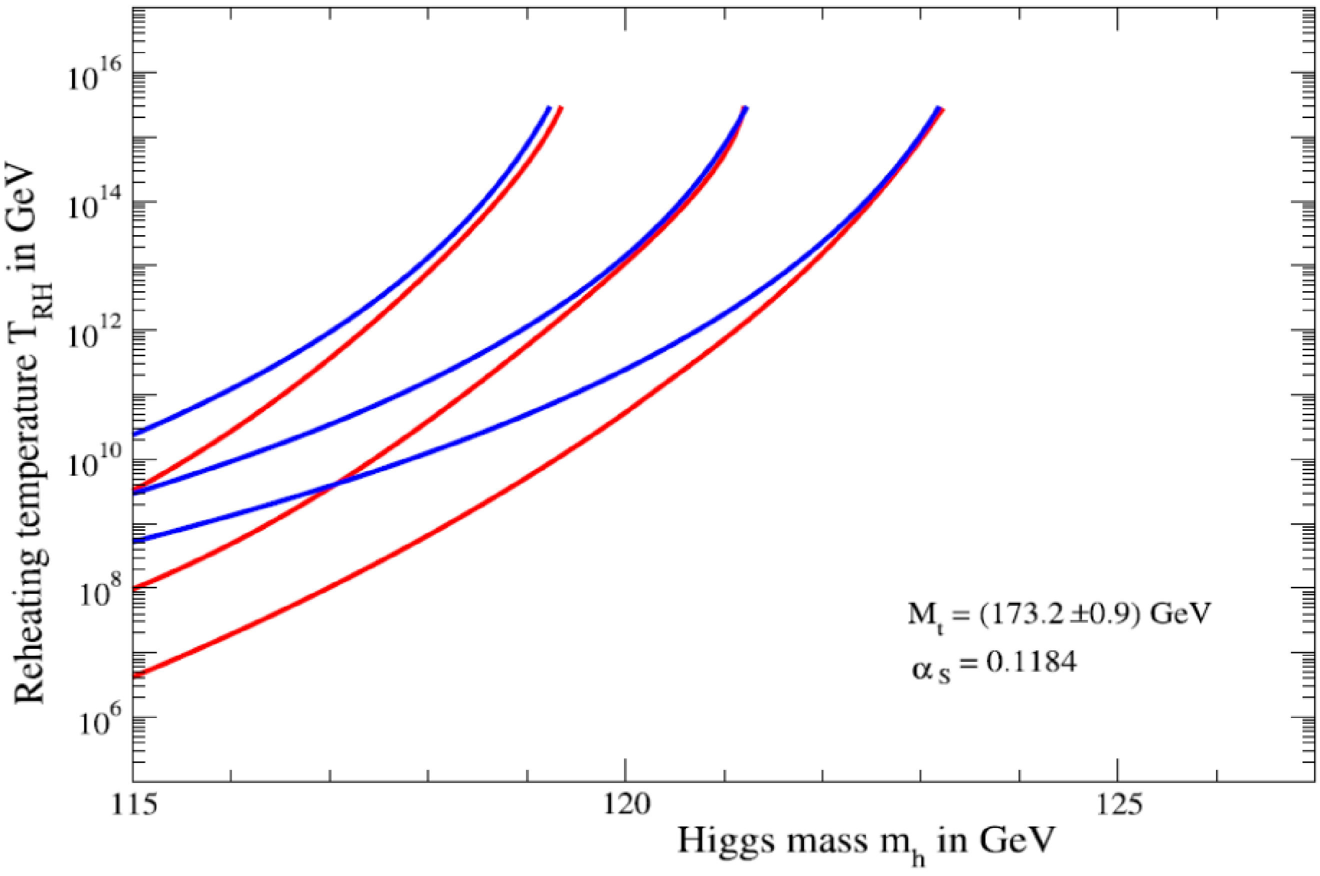
THERMAL VACUUM DECAY

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

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

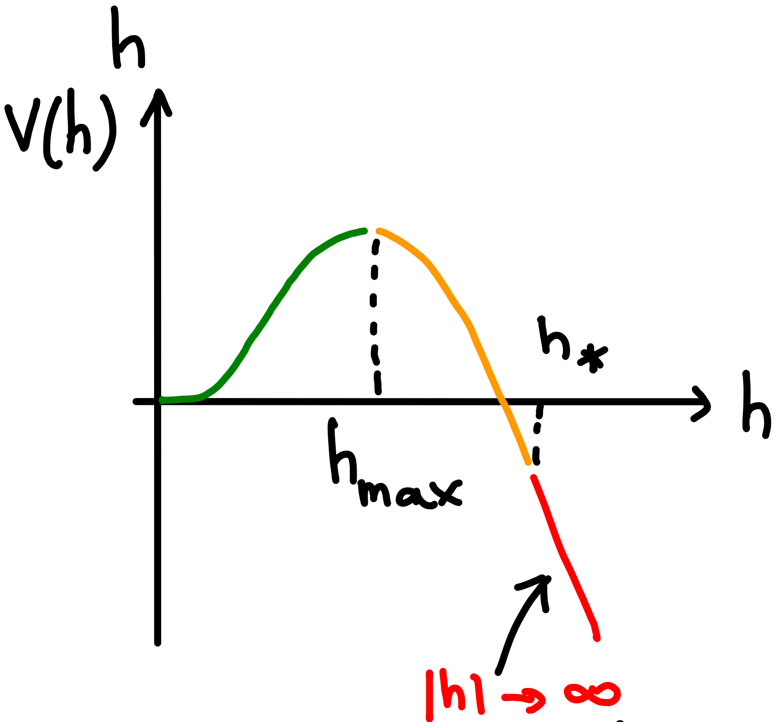
Upper bound on H_I ?

VACUUM DECAY DURING INFLATION

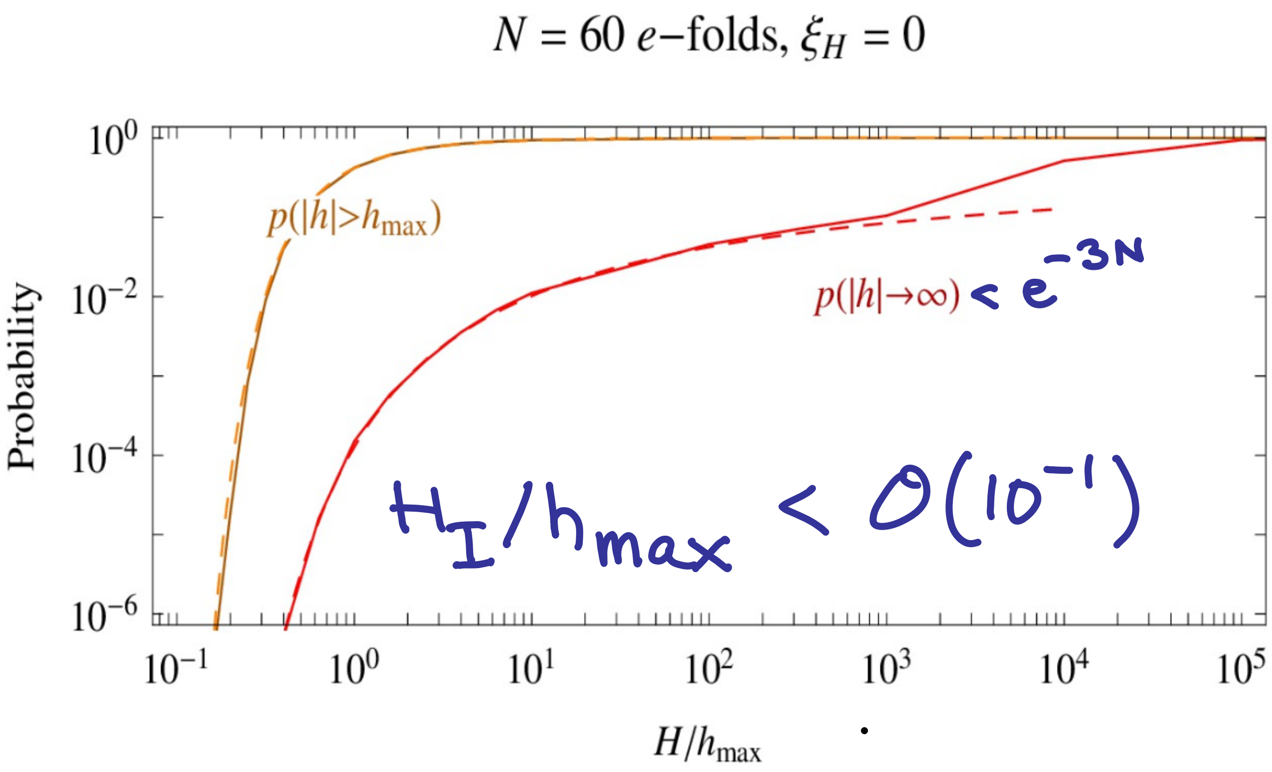
Classical vs. quantum competition. Δh in $\Delta t \sim 1/H_I$:

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

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



classical roll beats quantum fluctuations



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

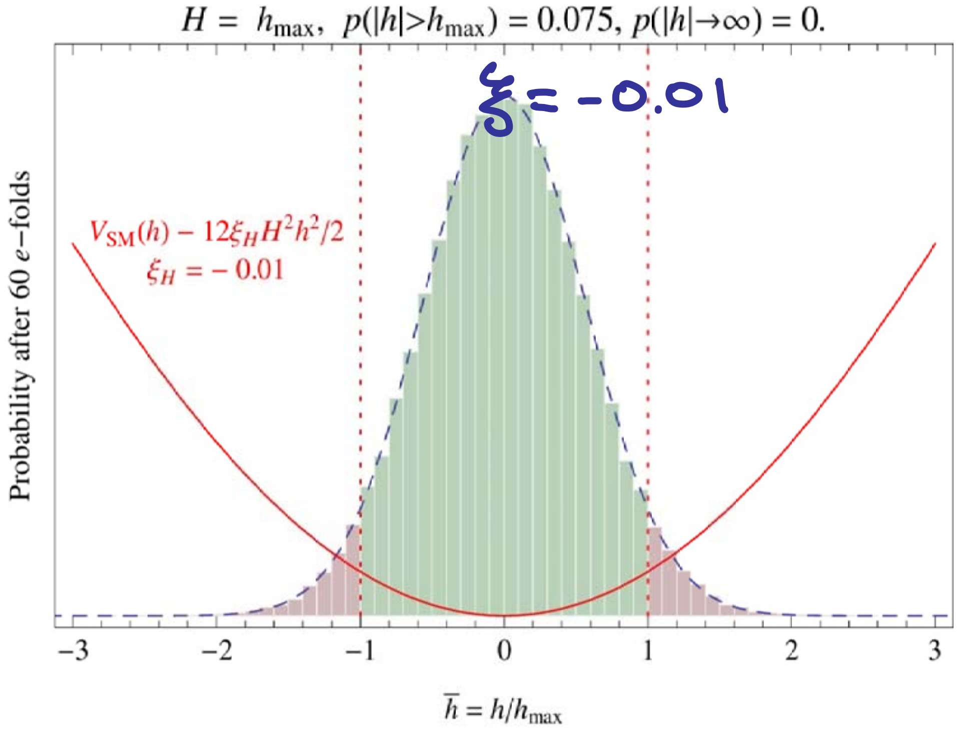
VACUUM DECAY DURING INFLATION ?

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

During inflation $R = -12 H_I^2$

$$\left.\begin{matrix} \delta\mathcal{L} = -\xi |H|^2 R \\ R = -12 H_I^2 \end{matrix}\right\} m_H^2 = -12\xi H_I^2$$

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

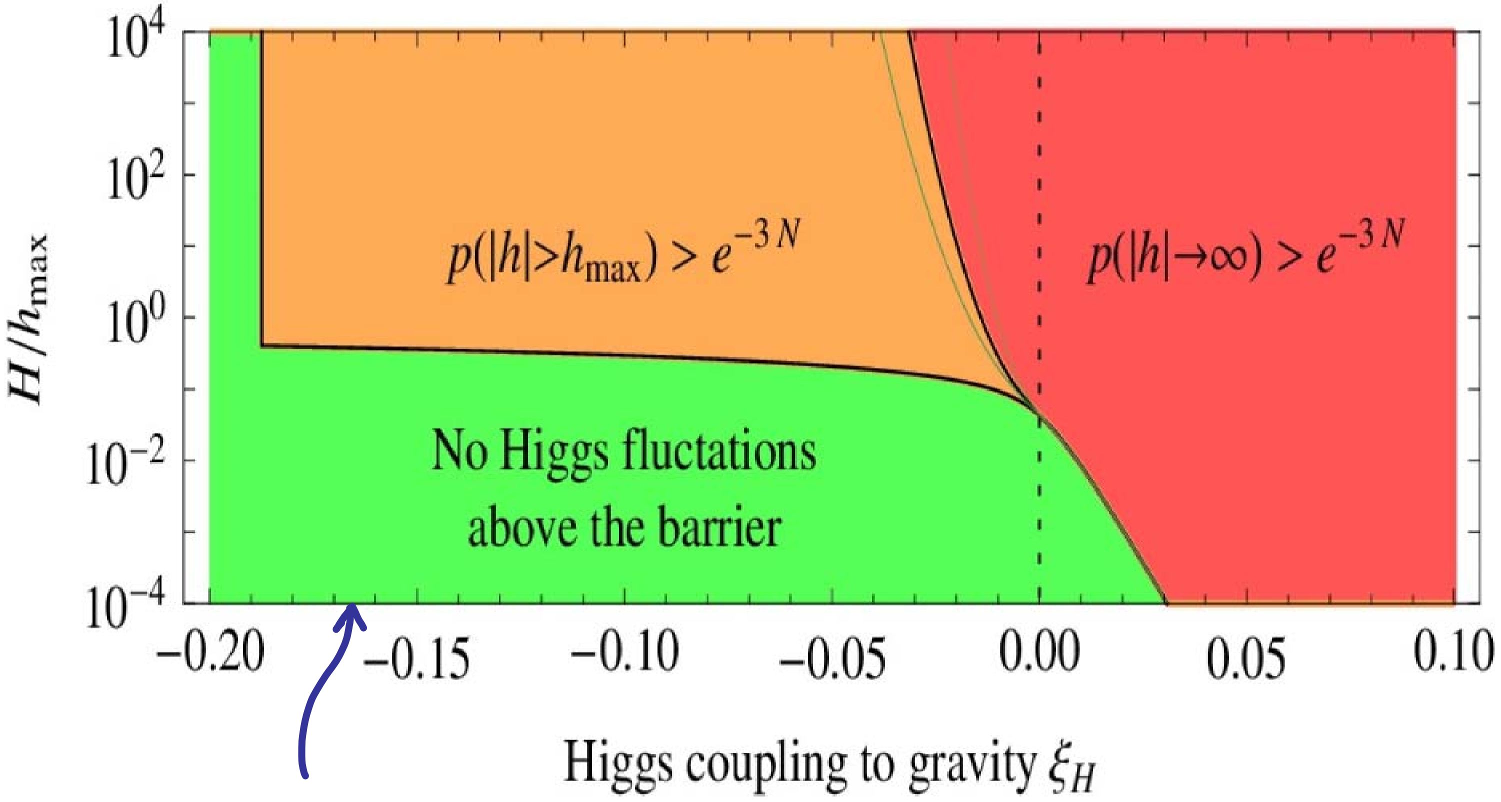


- For $\xi < -3/16$ Higgs fluctuations suppressed

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

VACUUM DECAY DURING INFLATION

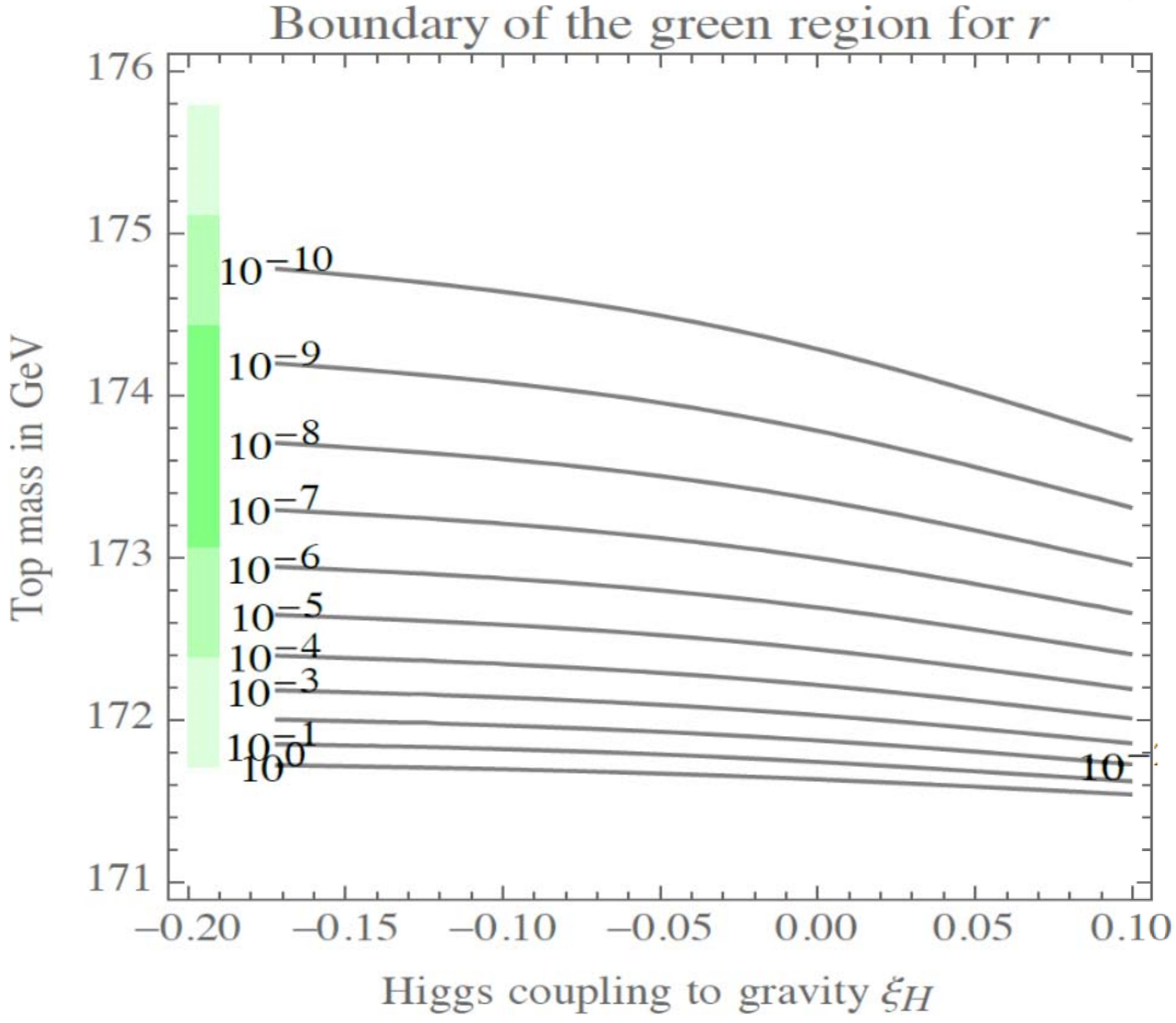
General picture for $\xi \neq 0$



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

BOUND ON H_I AS UPPER BOUND ON r

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


Boundary of the green region for r

A. Strumia

COSMOLOGICAL IMPLICATIONS

1. Decay by quantum tunneling

   But long lifetime

2. Decay by thermal fluctuations

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

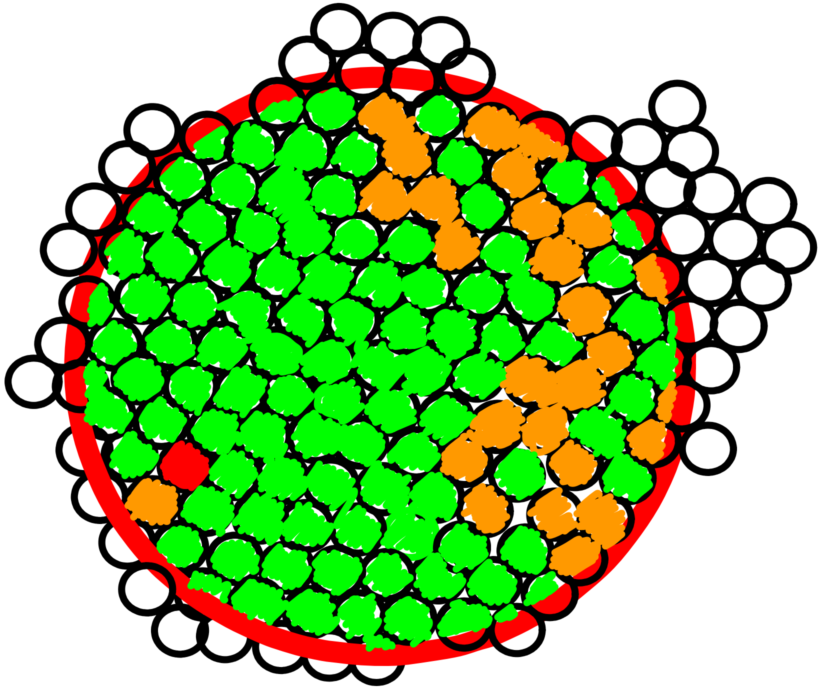
3. Decay during inflation

   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



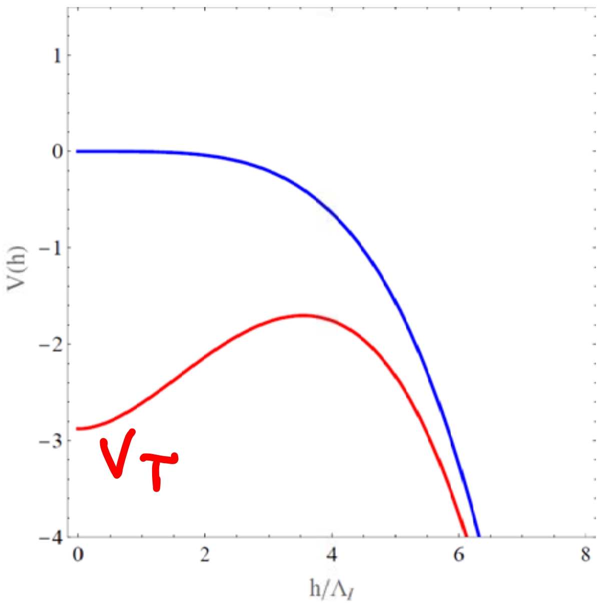
e^{3N} $\frac{1}{H_I}$ patches

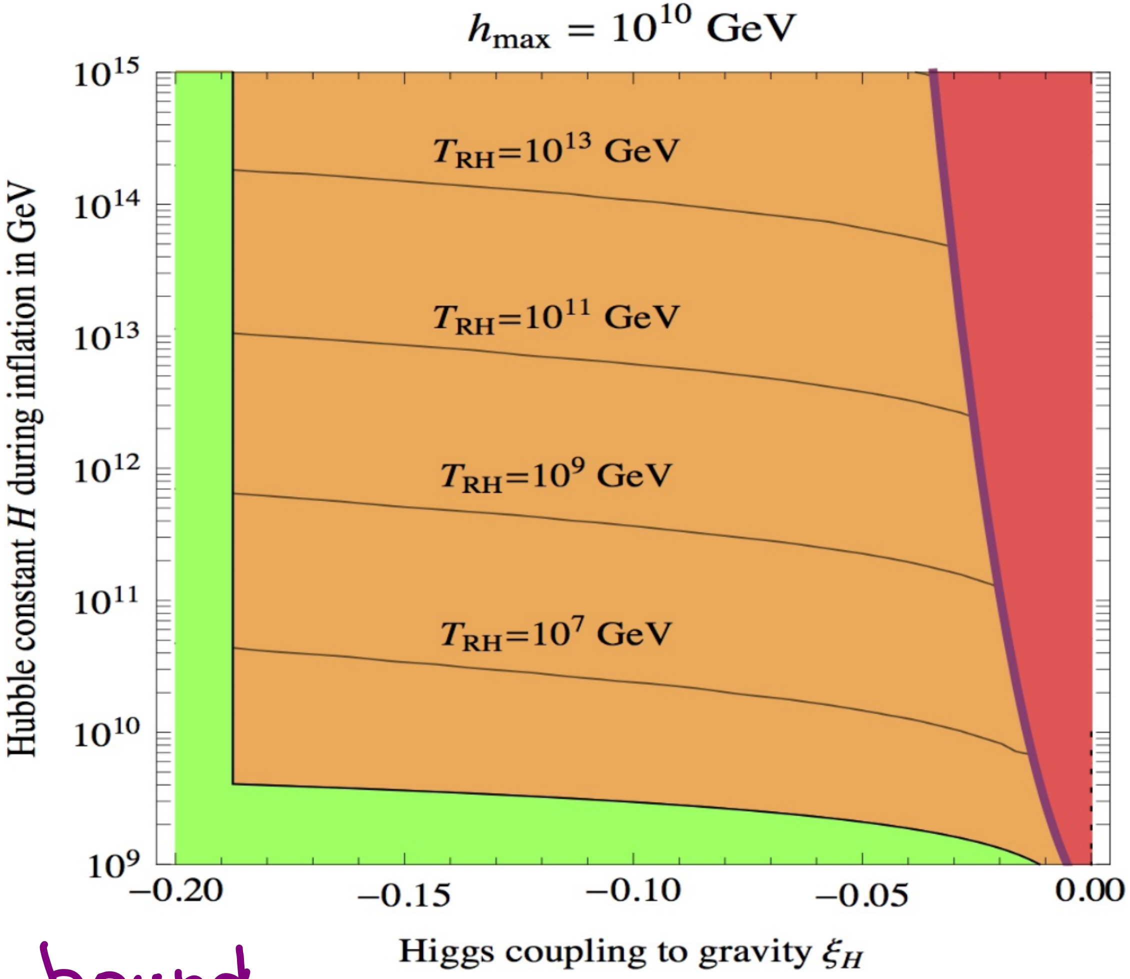
- 🟢 $h < h_{max}$ ⇨ Safe
- 🟠 $h > h_{max}$ ⇨ Can be saved by thermal corrections to $V(h)$
- 🔴 $h > h_c$ Deadly. In general they expand and eat all space.

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

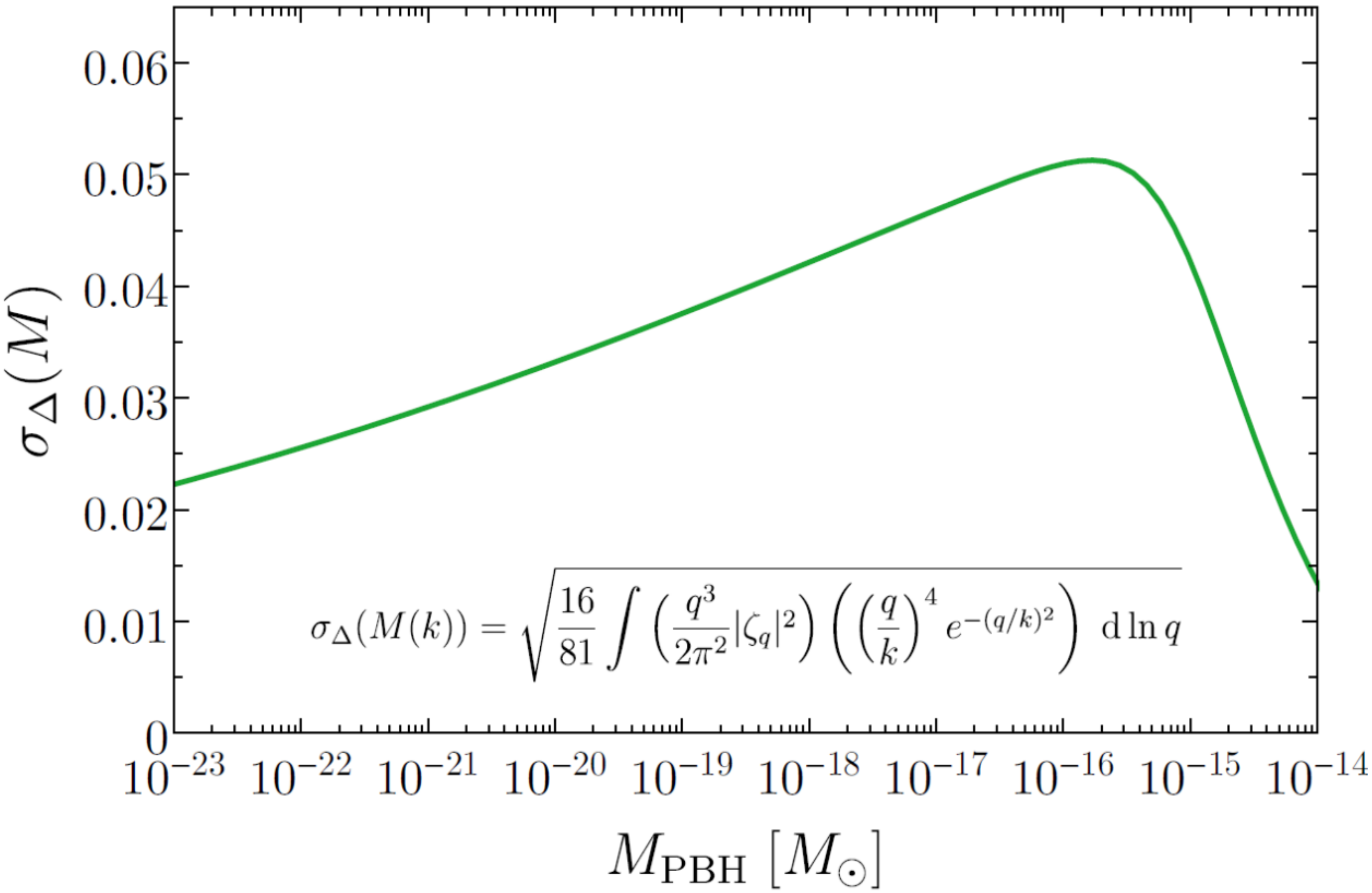
oscilating ϕ ⇨ tachyonic/oscilating m_H^2

⇨ 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

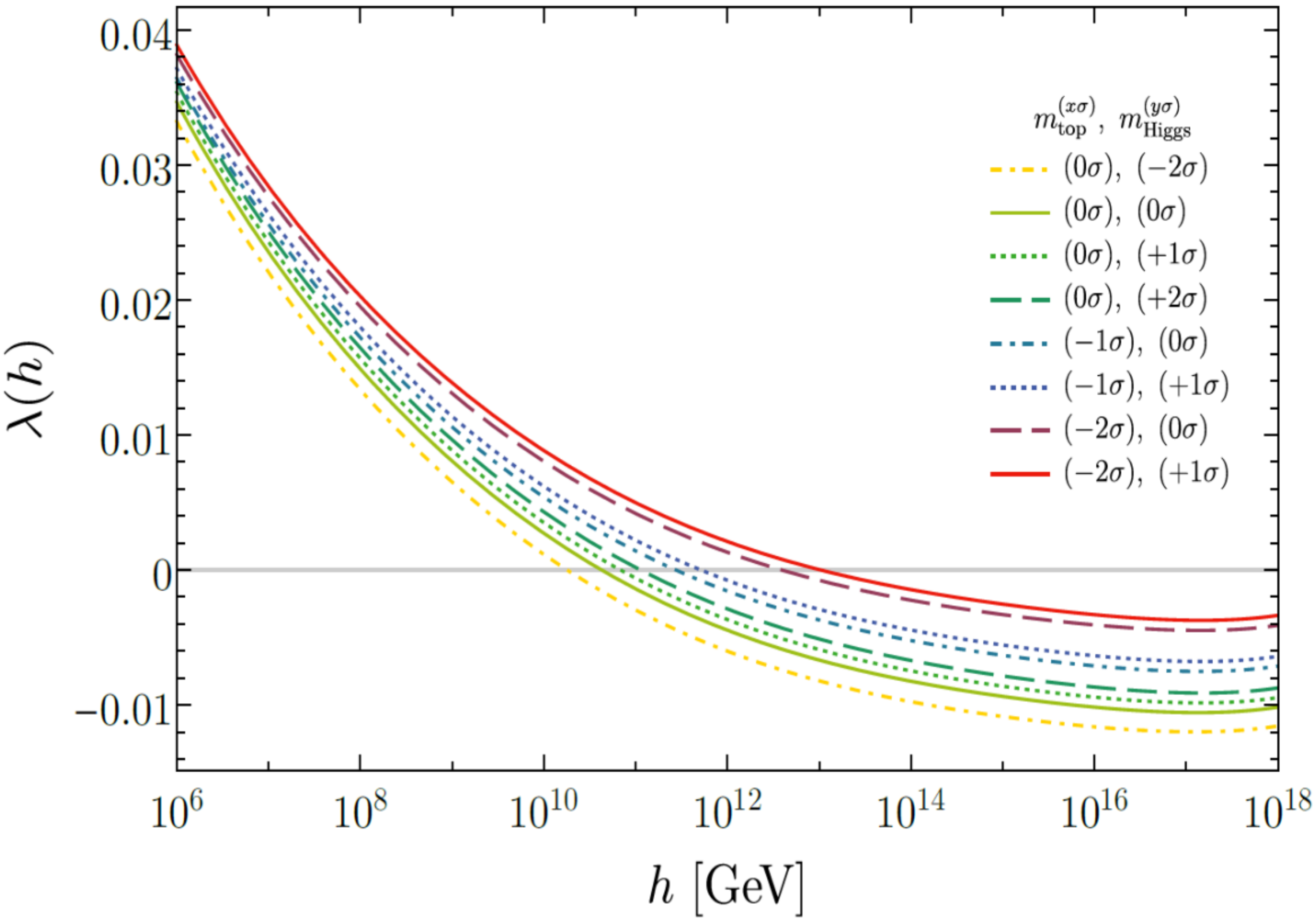
Surprises still possible...

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