LIVING DANGEROUSLY :

THE METASTABILITY OF THE EW VACUUM

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IFAE Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA

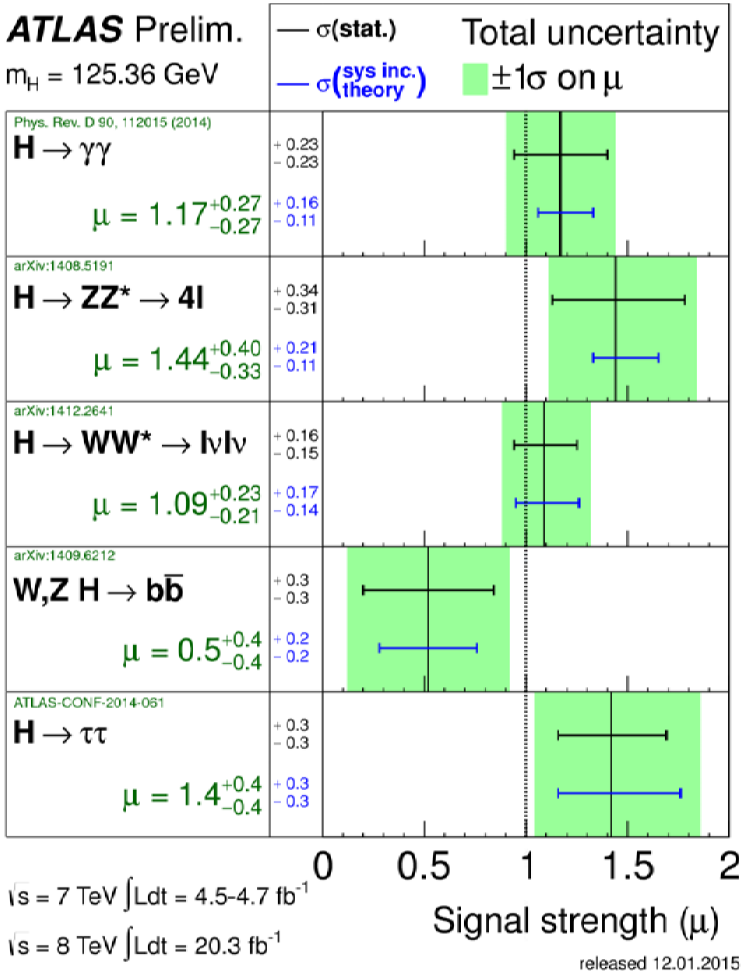
icrea
Institució Catalana de Recerca i Estudis Avançats

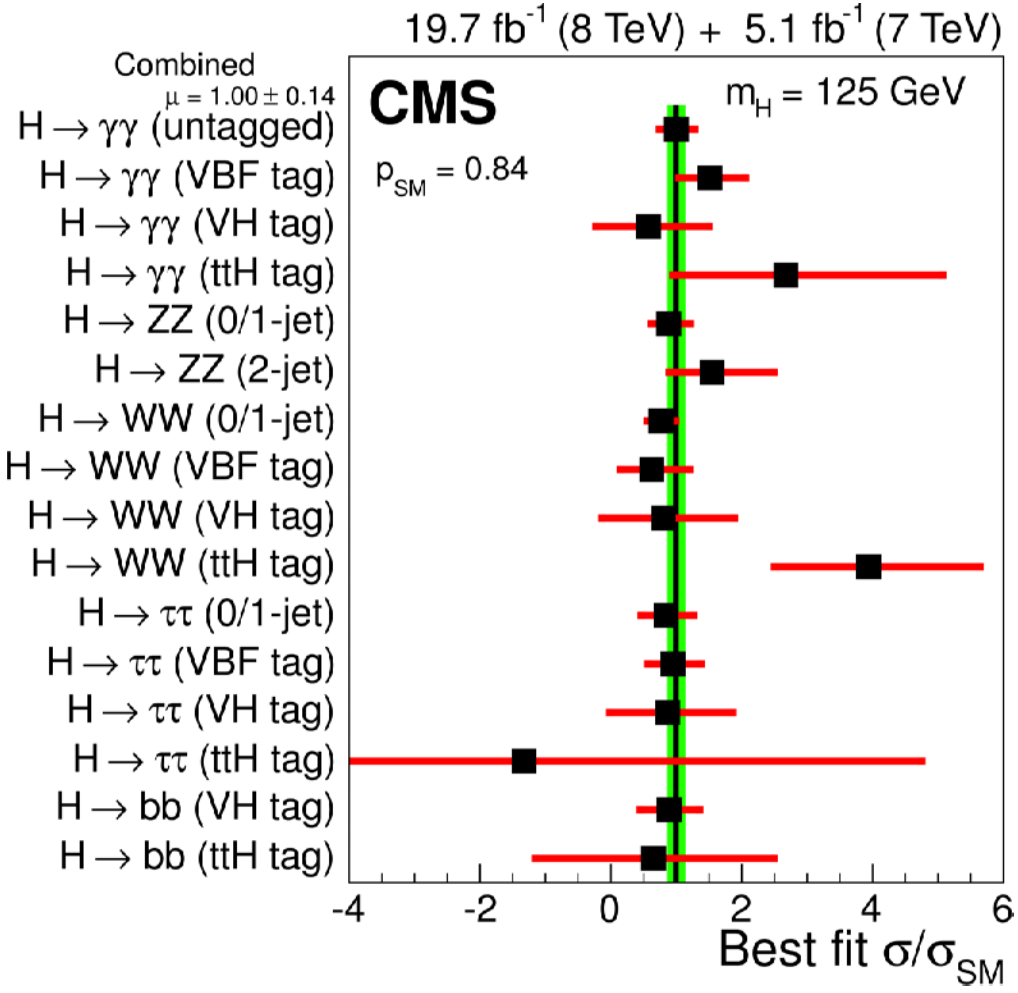
OUTLINE

- Context: Status after first LHC run
  Higgs discovered, no trace of other particles
- $M_h \simeq 125$ GeV ⇨ EW vacuum unstable
- Several implications of this instability
  - physics beyond the Standard Model (BSM)
  - Cosmology
  - Quantum gravity on dS space

SM STATUS

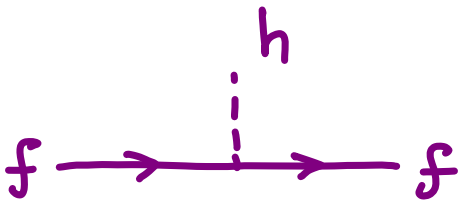
- Higgs discovered, close to SM-like

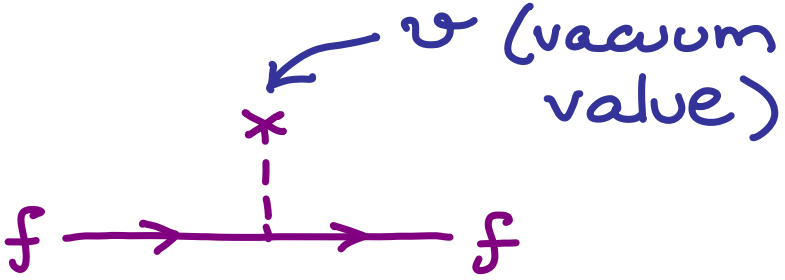


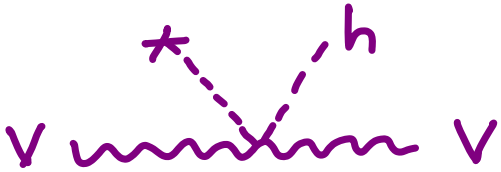


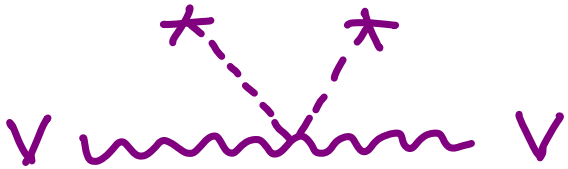
Mh/GeV = 125.09 + 0.21 (stat) + 0.11 (syst) ATLAS+CMS

- SM prediction





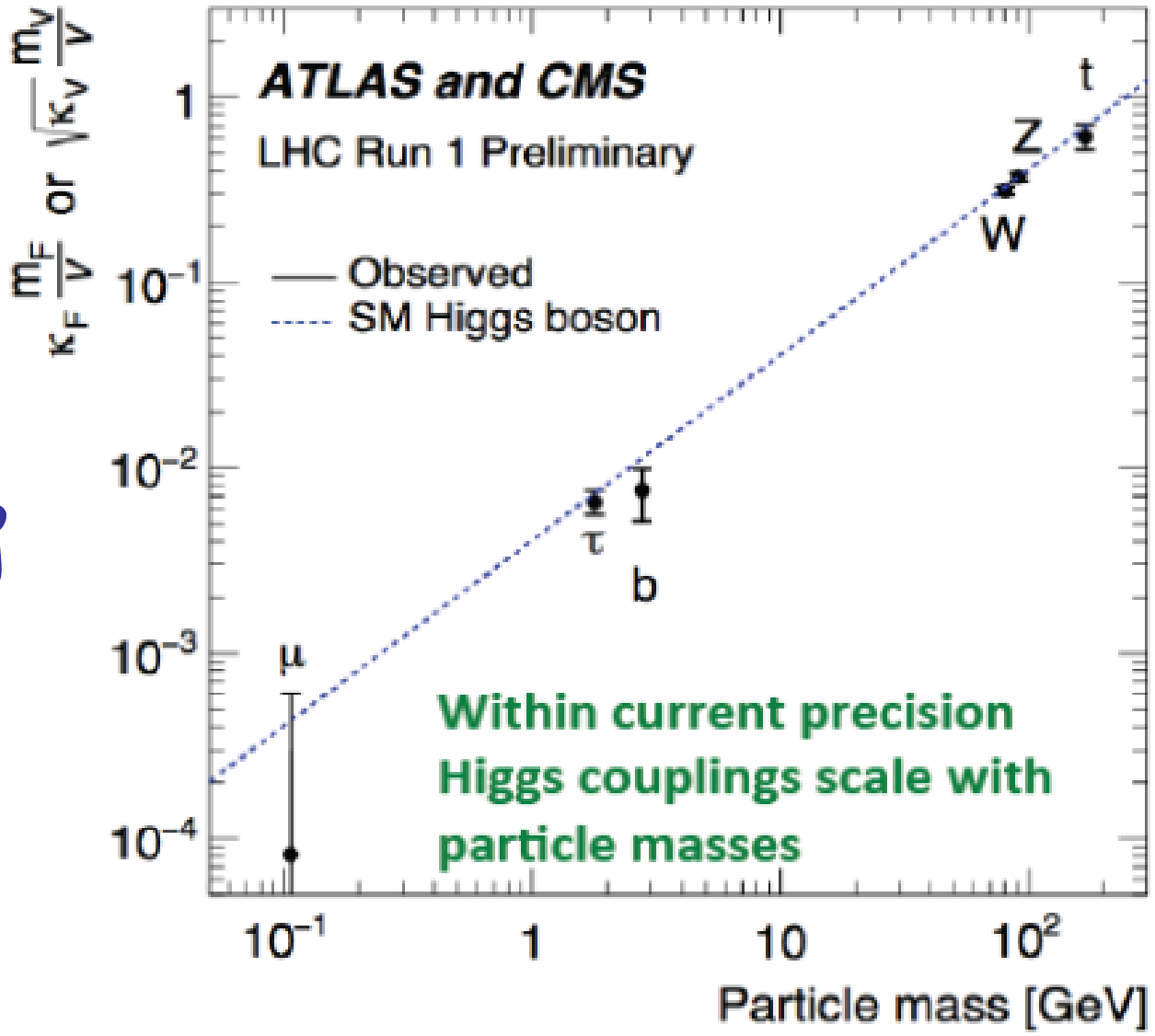




h-couplings $\propto$ particle masses

- Higgs discovered, close to SM-like

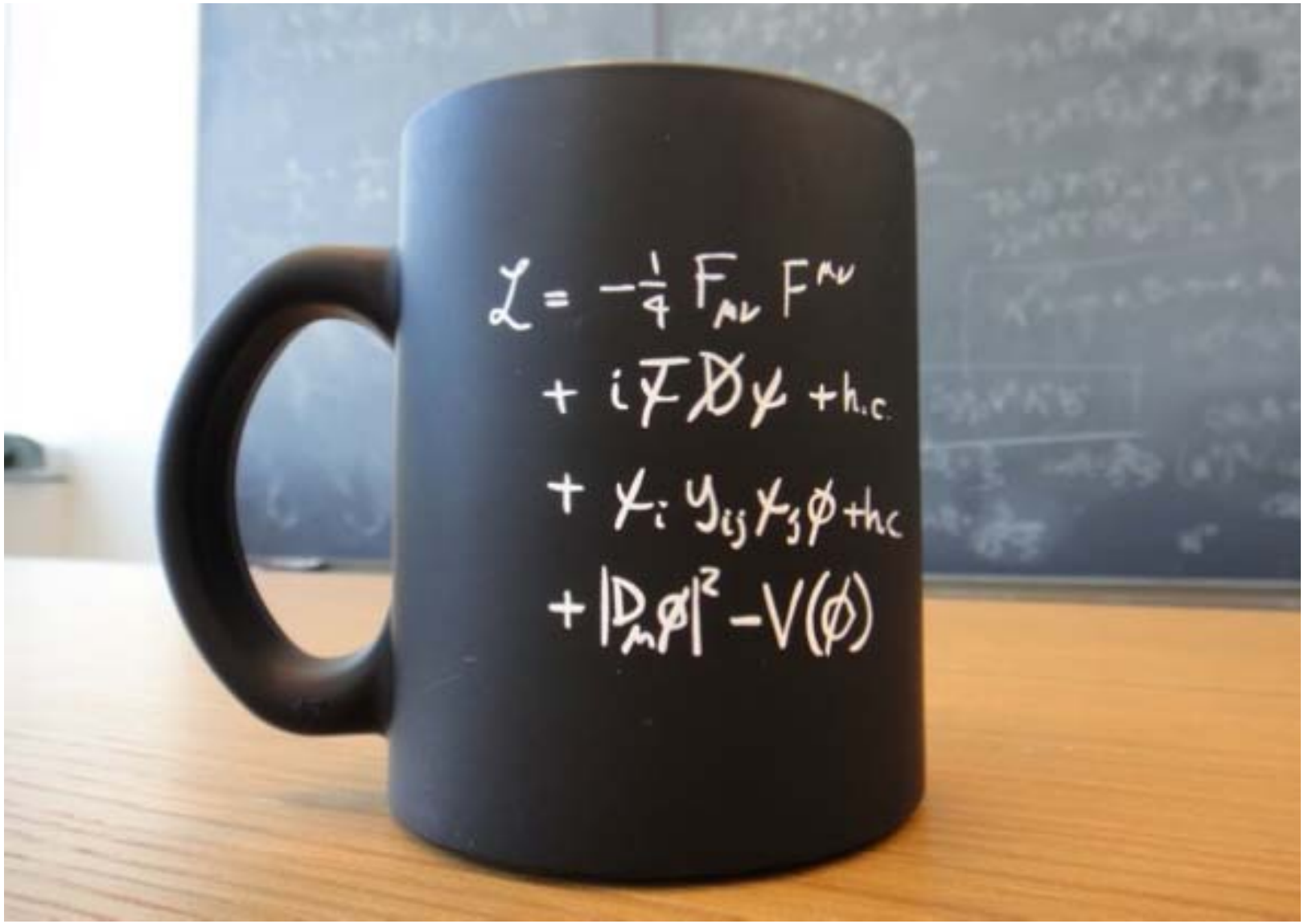
Higgs coupling



- Higgs discovered, close to SM-like

"Take a look at this everyone - it just could be the signature we've been looking for!"

STANDARD MODEL COMPLETE



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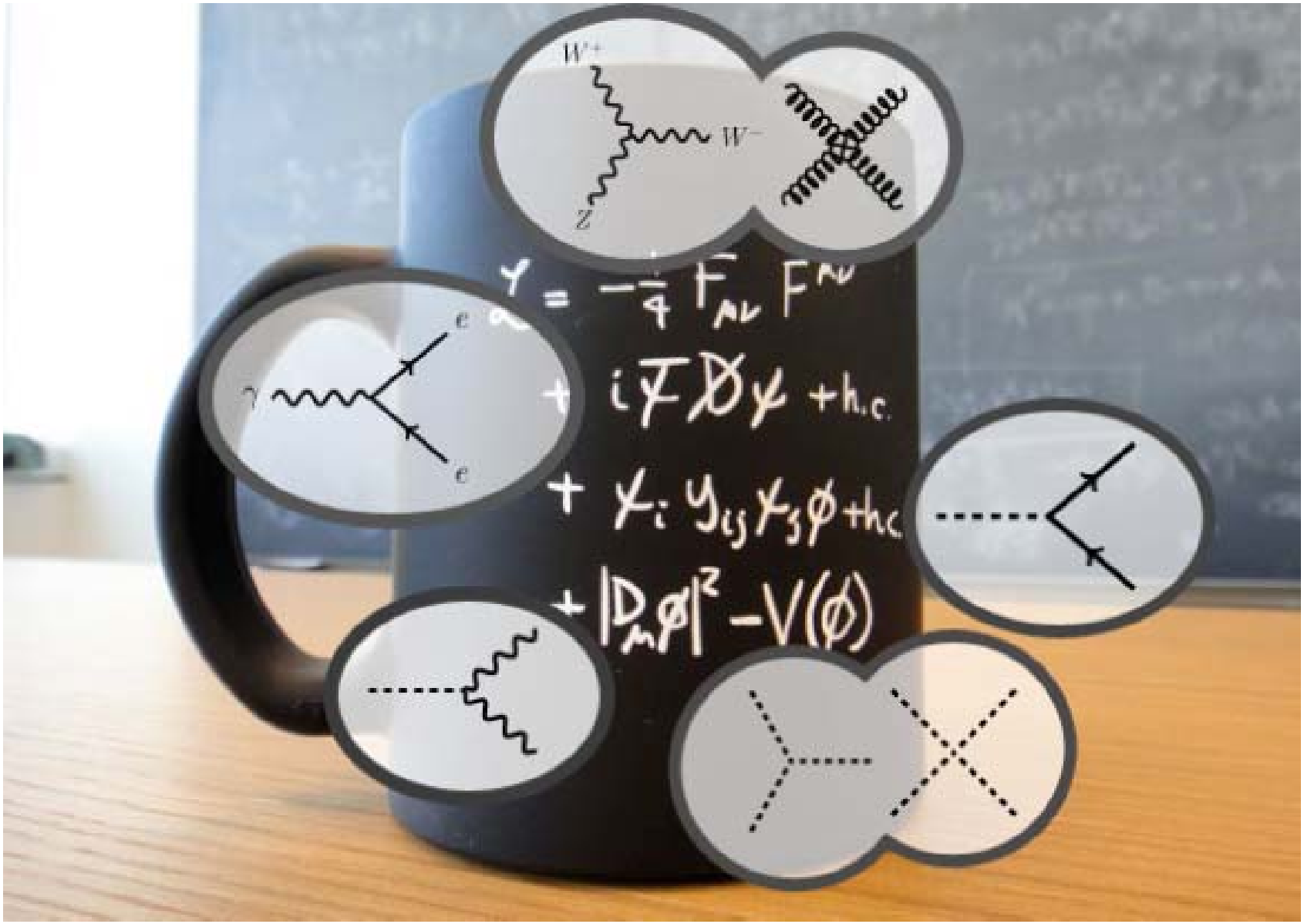

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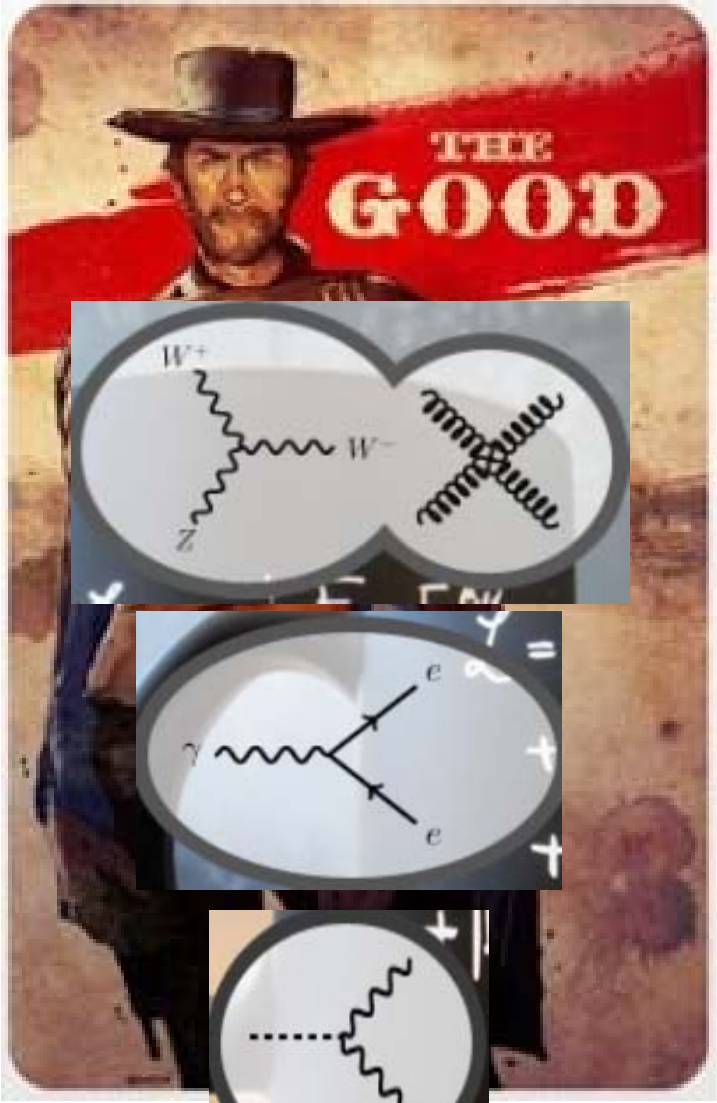

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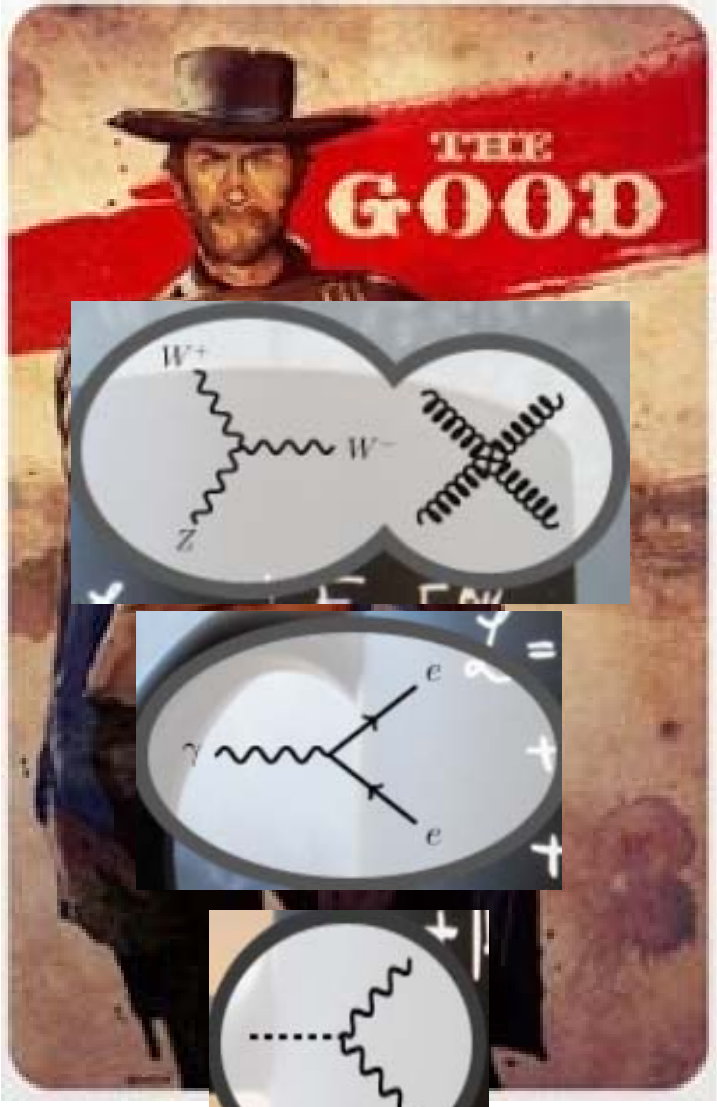

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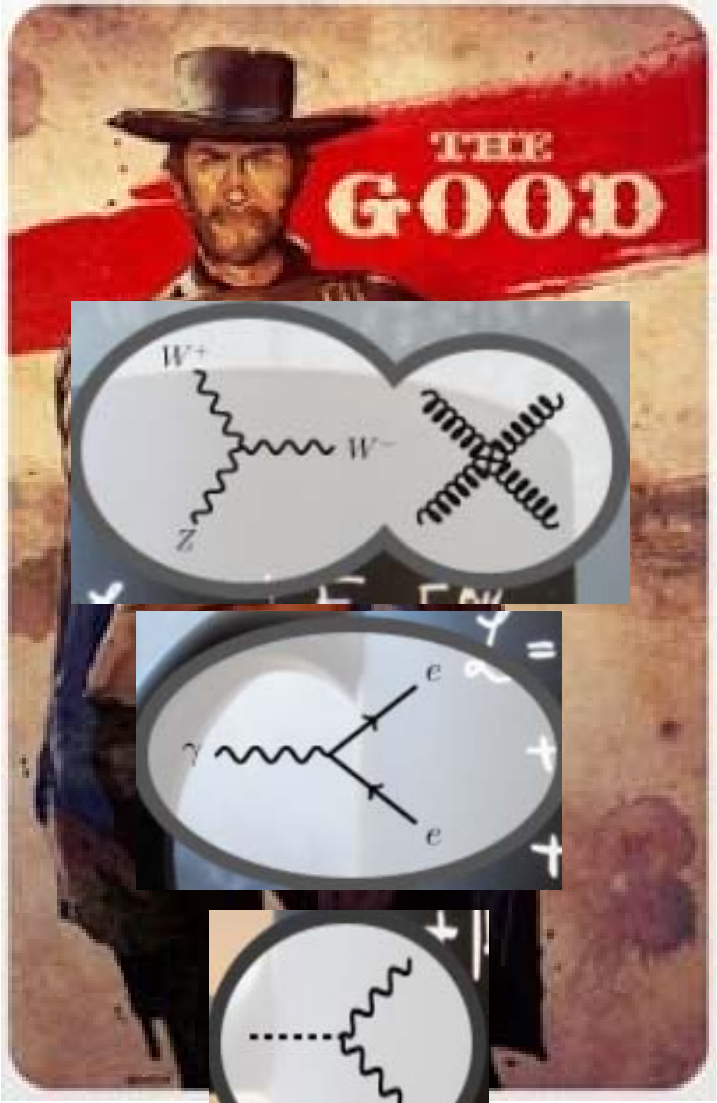
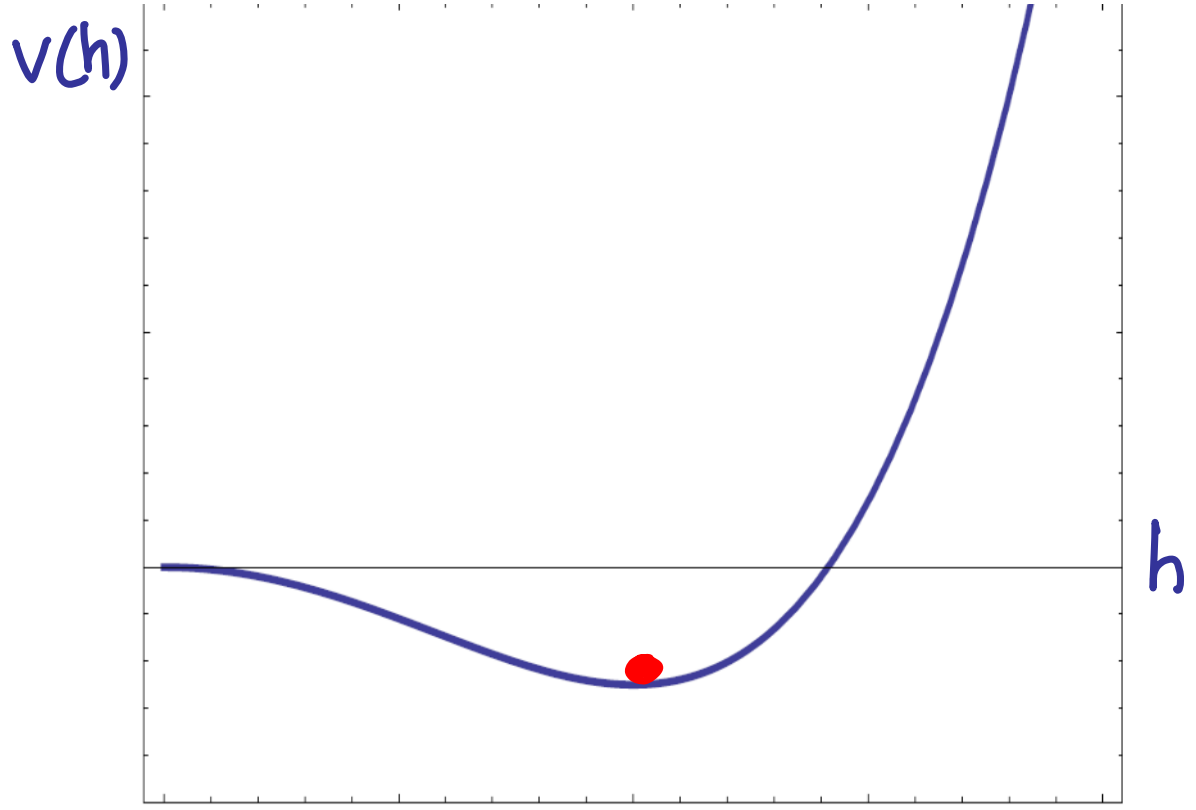


HIGGS : KEYSTONE & TROUBLEMAKER

Higgs potential

$$V(h) = \Lambda^4 - \frac{1}{2} m^2 h^2 + \frac{1}{4} \lambda h^4$$



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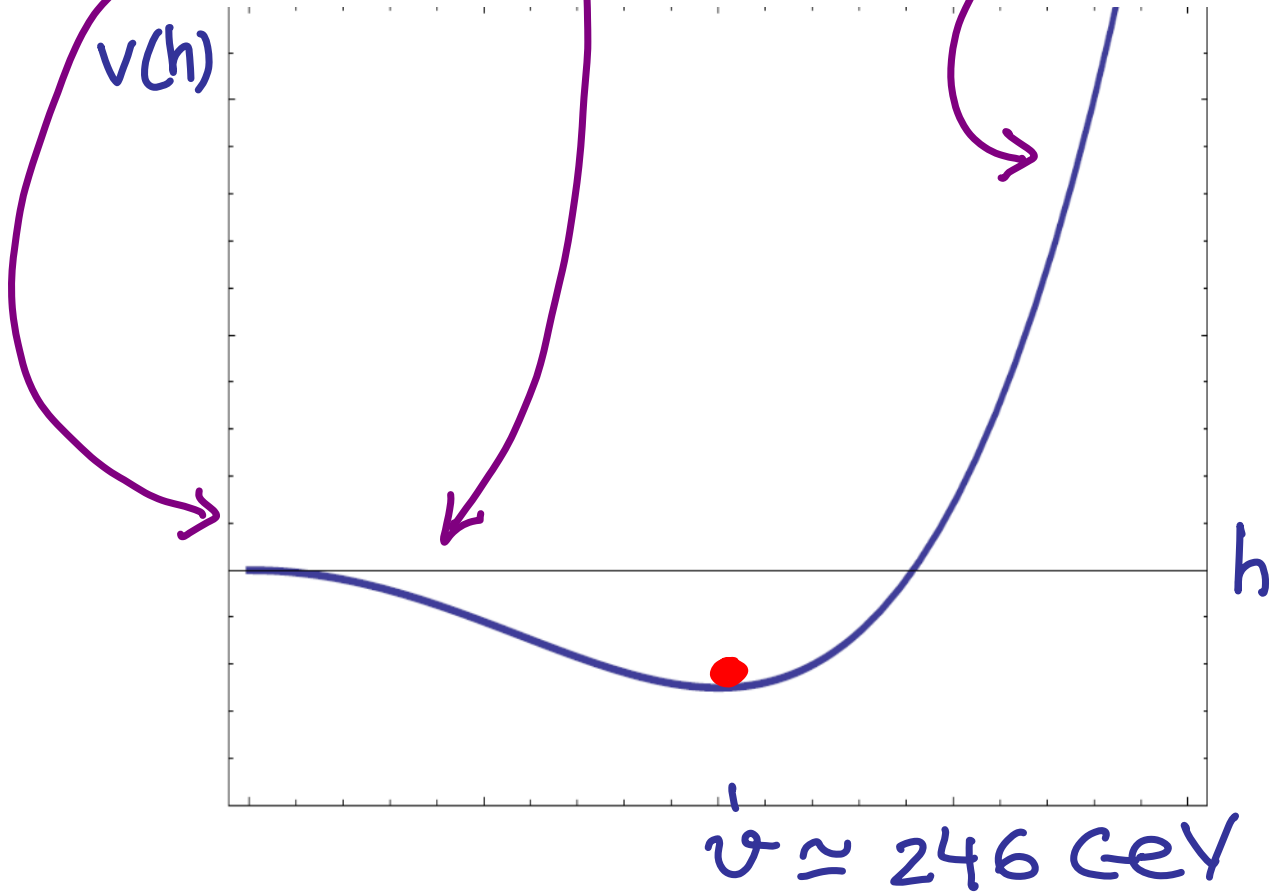

EW SCALE

$$v^2 = \frac{m^2}{\lambda}$$

HIGGS : KEYSTONE & TROUBLEMAKER

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this colloquium

HIGGS : KEYSTONE & TROUBLEMAKER

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Cosmological Constant $\rho_{vac} \sim (10^{-3} eV)^4$

Size ??

Must understand quantum gravity, important at $M_{Pl} \sim 10^{19} GeV$

$\Rightarrow \Lambda^4 \sim (10^{19} GeV)^4$ natural value

HIGGS : KEYSTONE & TROUBLEMAKER

Higgs potential

$$V(h) = \Lambda^4 - \frac{1}{2} m^2 h^2 + \frac{1}{4} \lambda h^4$$

mass term size ?

Quantum corrections make it sensitive to high mass scales, like $M_{Pl} \sim 10^{19}$ GeV, while we measure

$m \sim 100$ GeV. Not natural !

HIGGS : KEYSTONE & TROUBLEMAKER

Higgs potential

$$V(h) = \Lambda^4 - \frac{1}{2} m^2 h^2 + \frac{1}{4} \lambda h^4$$

mass term size ?

Solutions to this naturalness puzzle invdve

Beyond the Standard Model (BSM)

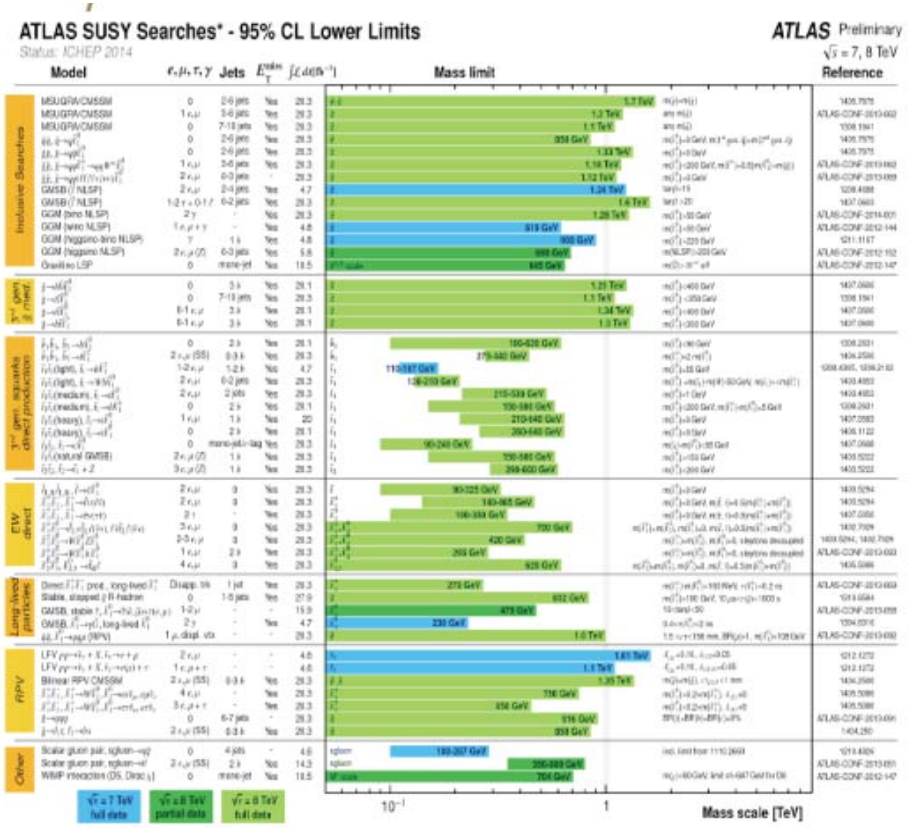
particles at $\Lambda \sim$ TeV scale

on the reach of the LHC

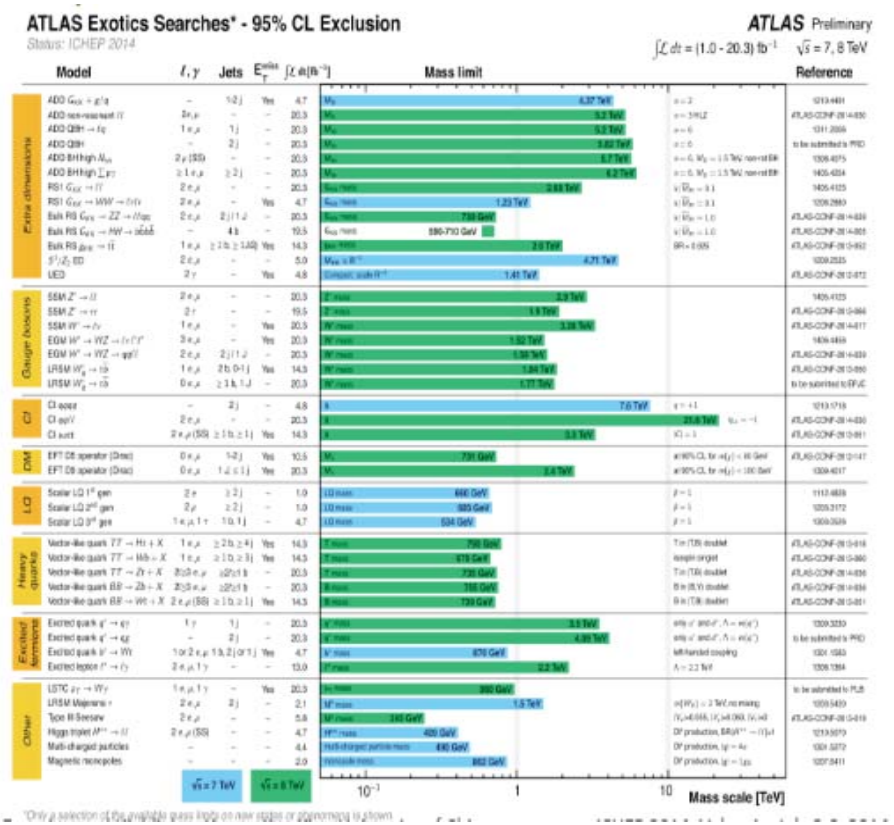
BSM STATUS

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

"TSUNAMI" EXCLUSION PLOTS



Supersymmetry



EXOTICS

BSM STATUS

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

BSM STATUS

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

⇓

$\Lambda \sim$ few TeV

BSM STATUS / THIS TALK

- Higgs discovered, close to SM-like

+

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

+

- Disregarding naturalness

⇓

$\Lambda \sim M_{Pl}$?

SM EXTRAPOLATION

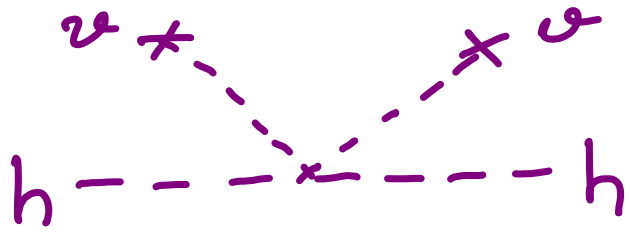
Can the SM be valid up to M_{Pl}?

All SM parameters known

3 fundamental forces $\{g_1, g_2, g_3\}$

Fermion masses $y_f v$ $\{y_f\}$

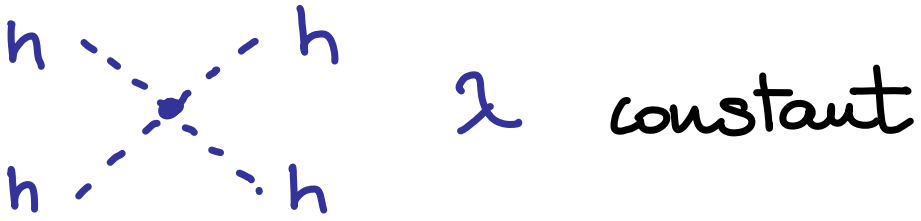
Last parameter: $M_h \Rightarrow \lambda(EW)$



All measured at the EW scale

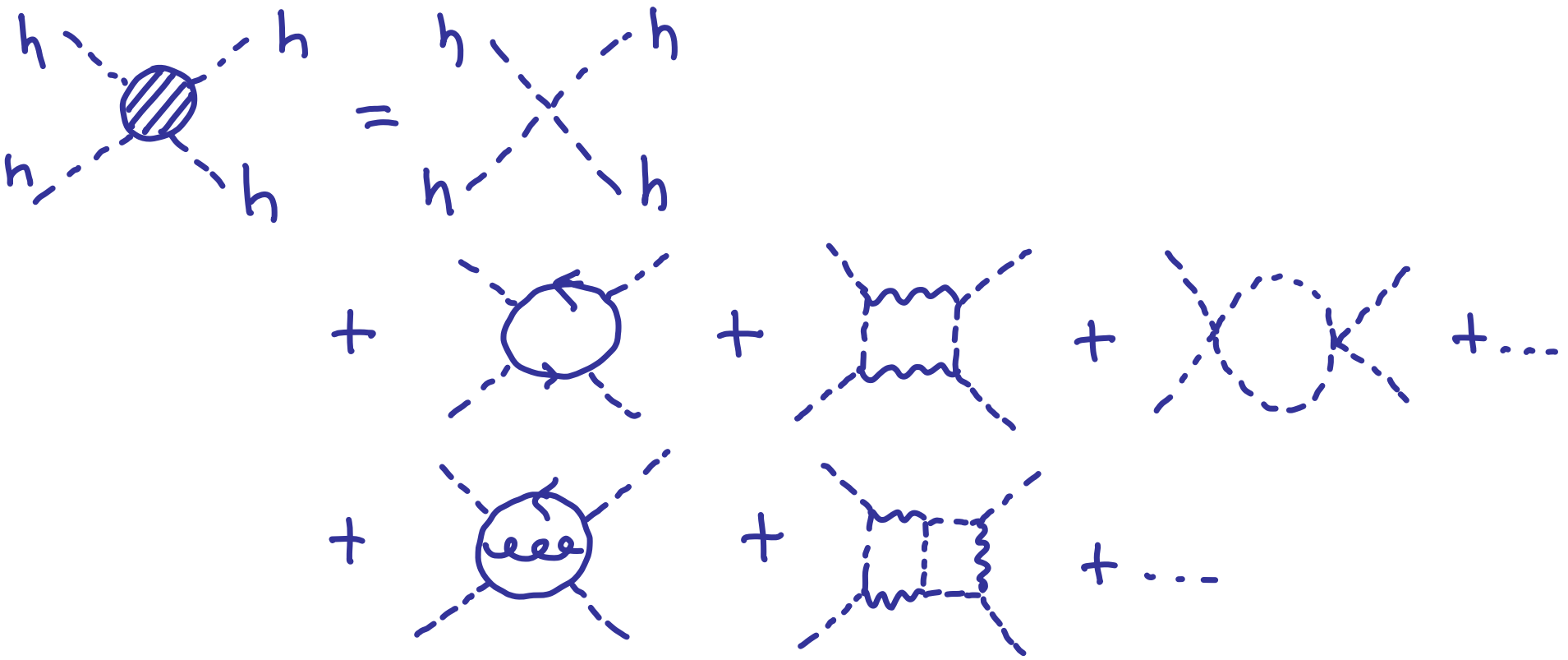
COUPLING CONSTANTS ARE NOT CONSTANT

In classical Field Theory:



COUPLING CONSTANTS ARE NOT CONSTANT

In Quantum Field Theory:

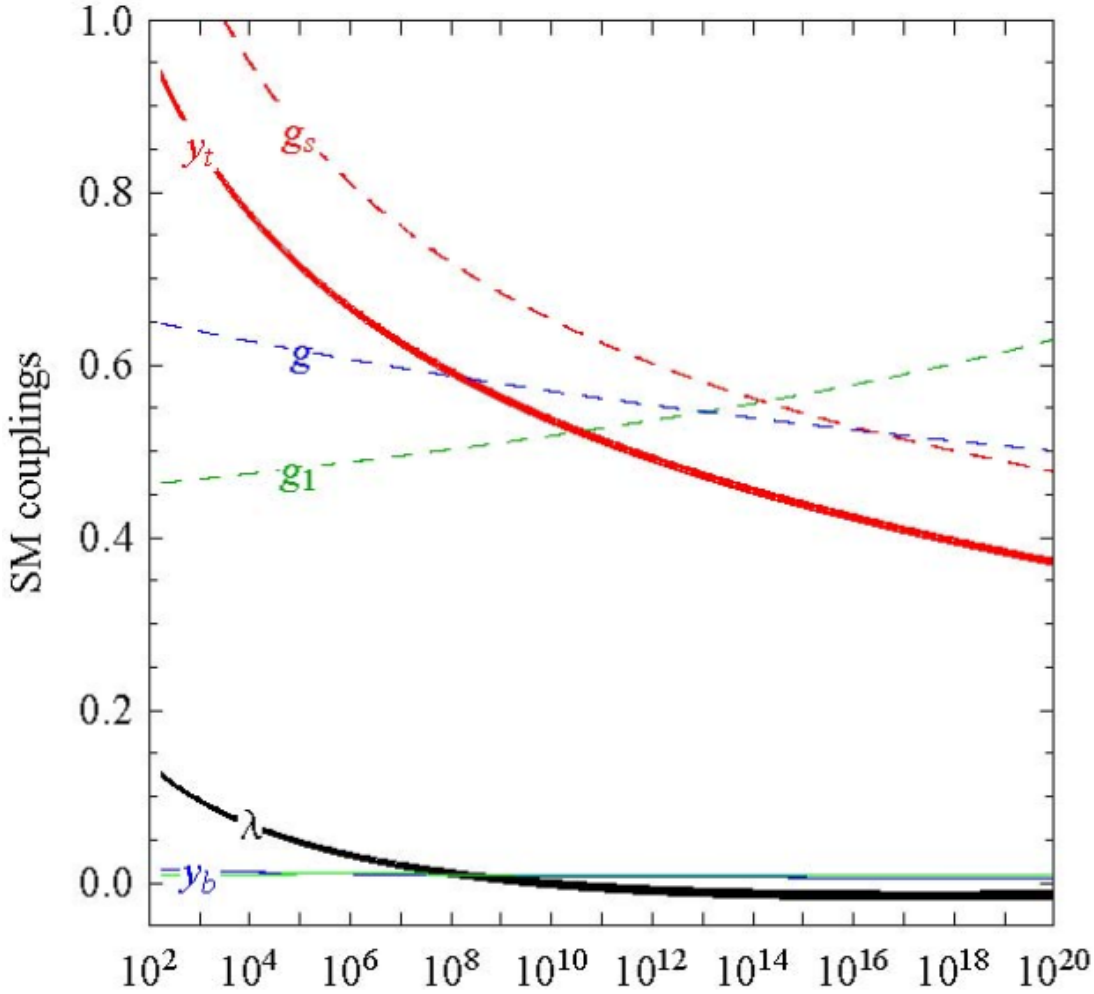


λ depends on ratios of masses and scattering E

λ "runs" with the energy scale $\beta_\lambda \equiv \frac{d\lambda}{d\log E}$

SM EXTRAPOLATION

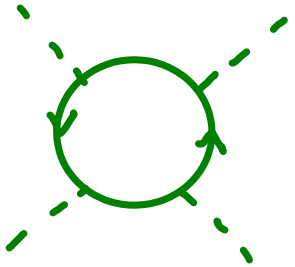
Can the SM be valid up to M_{Pl}?



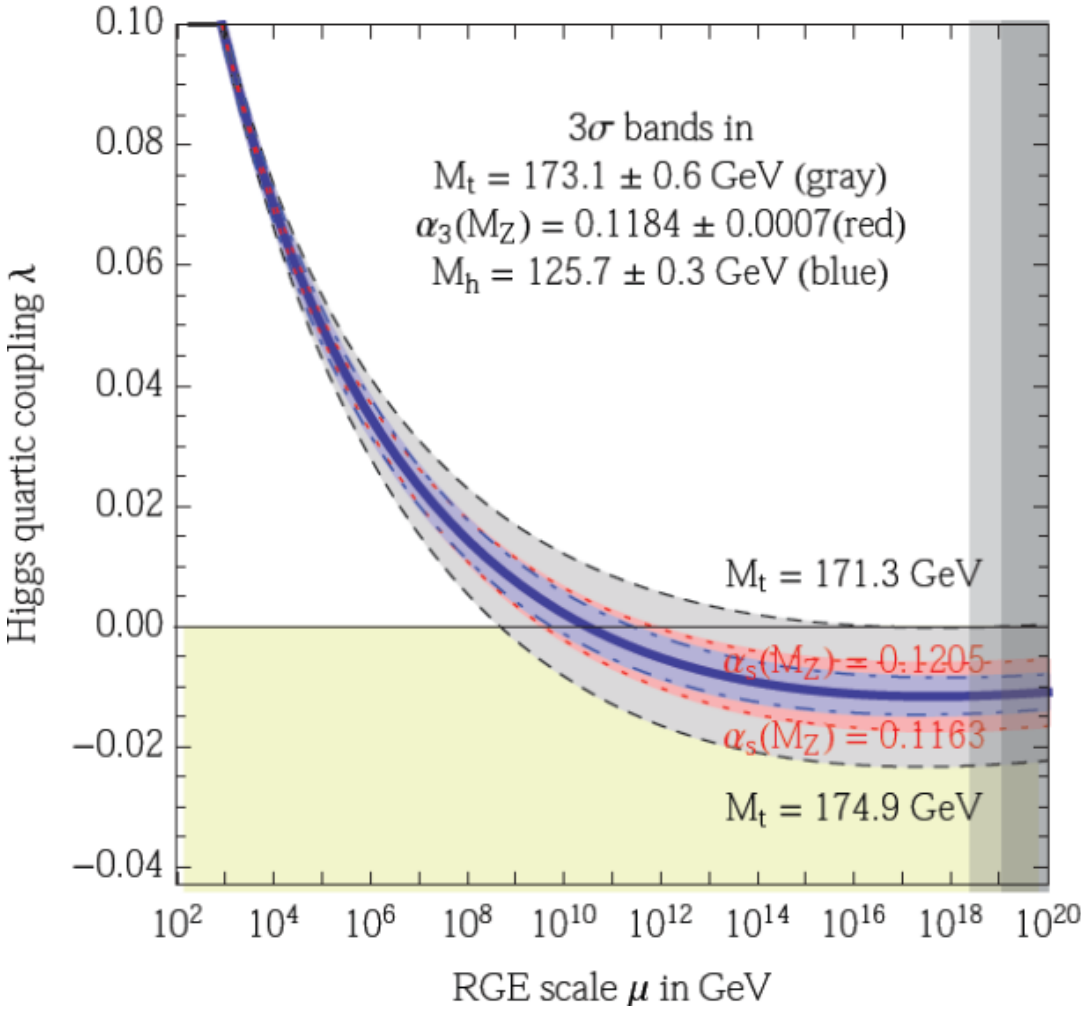
Weakly coupled up to M_{Pl}

VACUUM INSTABILITY

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



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



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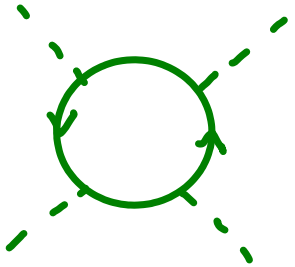

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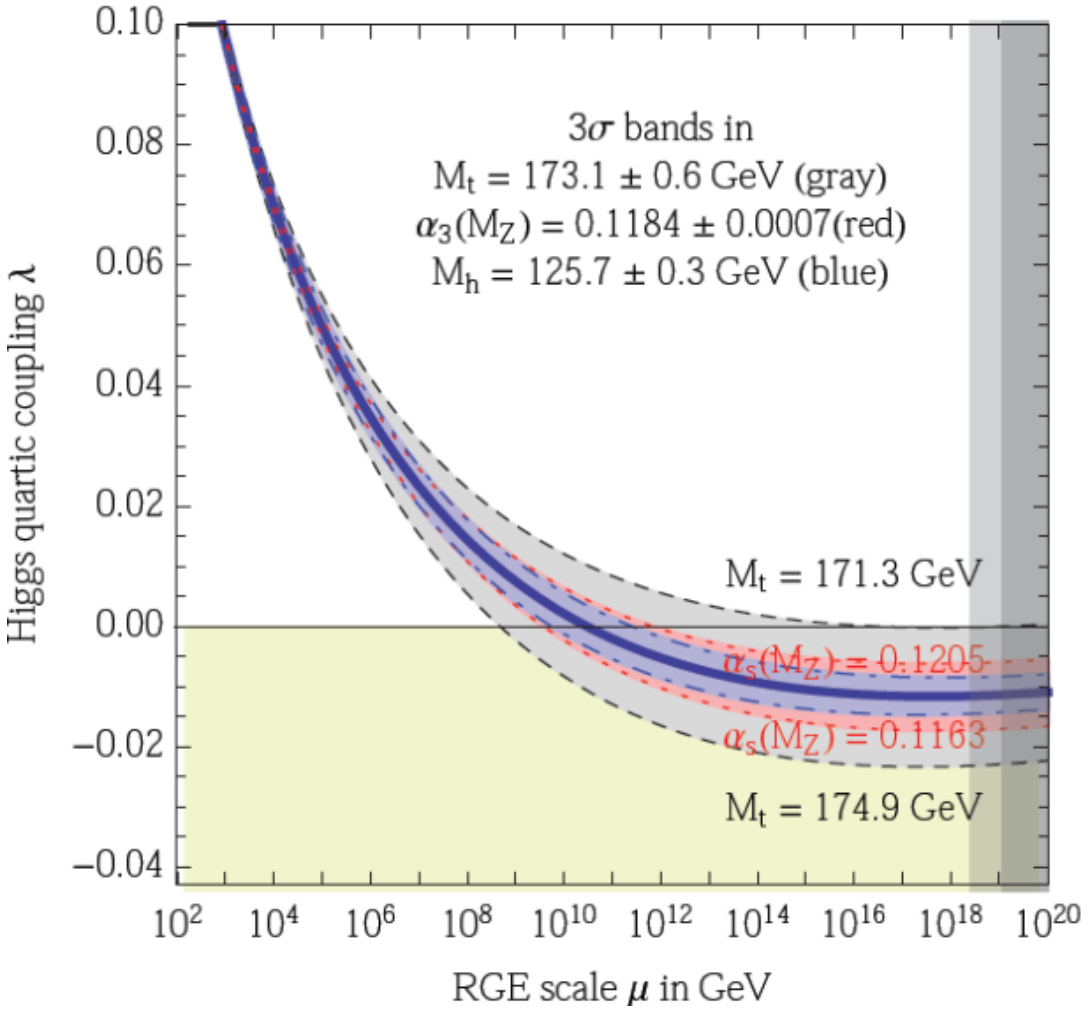
Higgs potential instability

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



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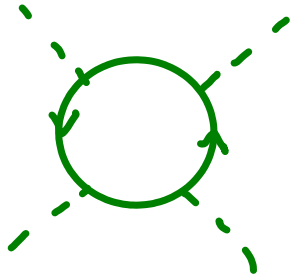

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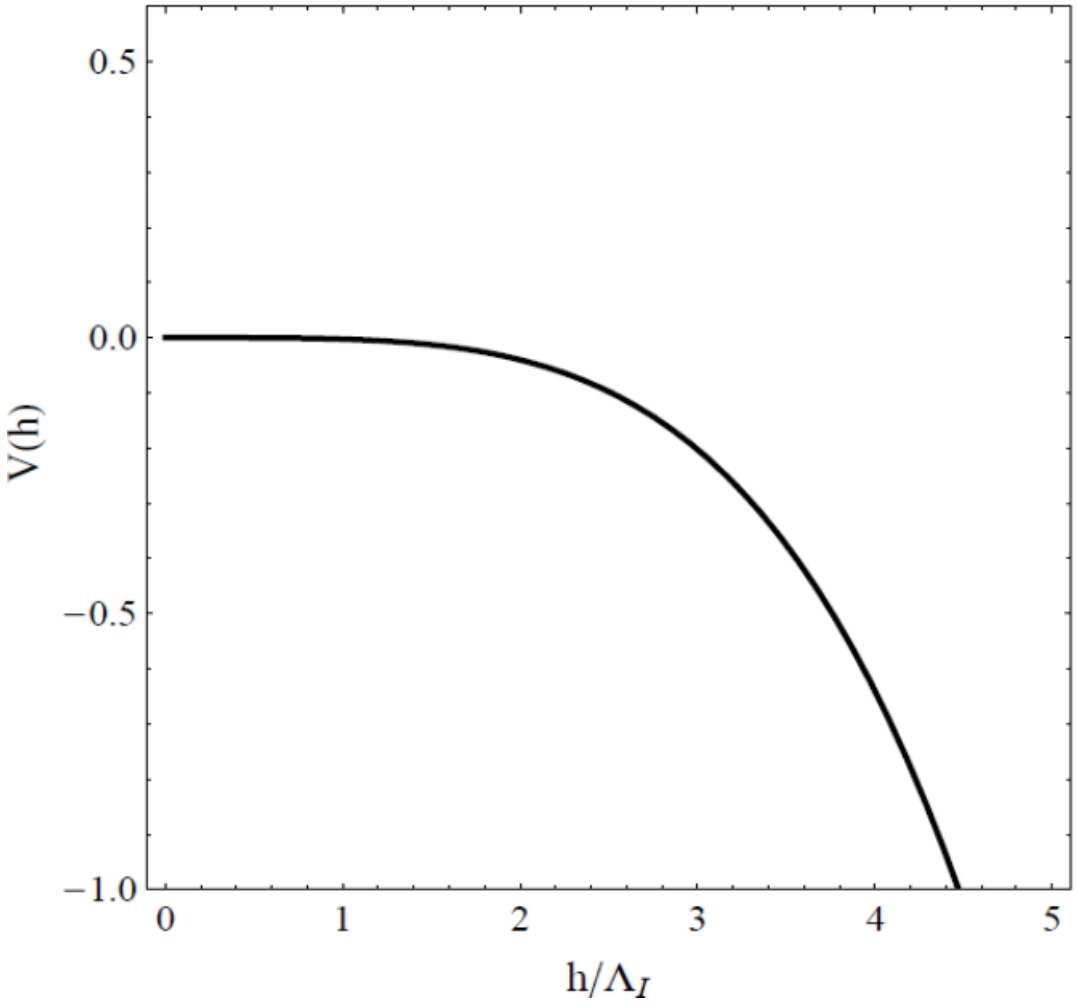

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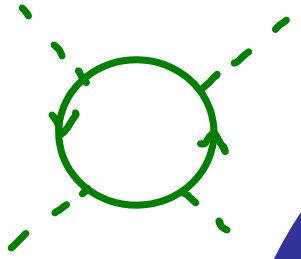

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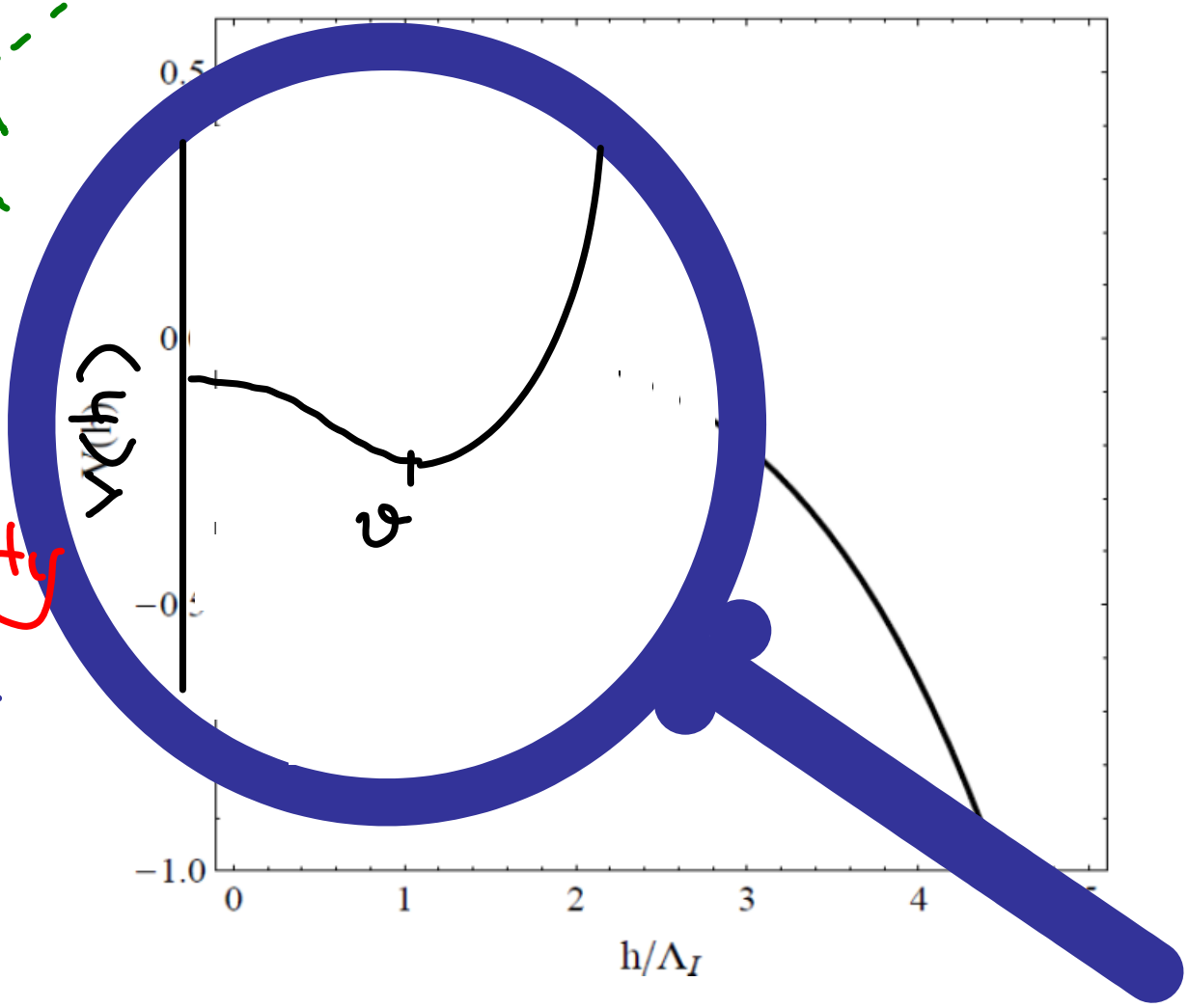

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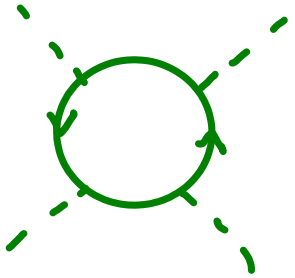

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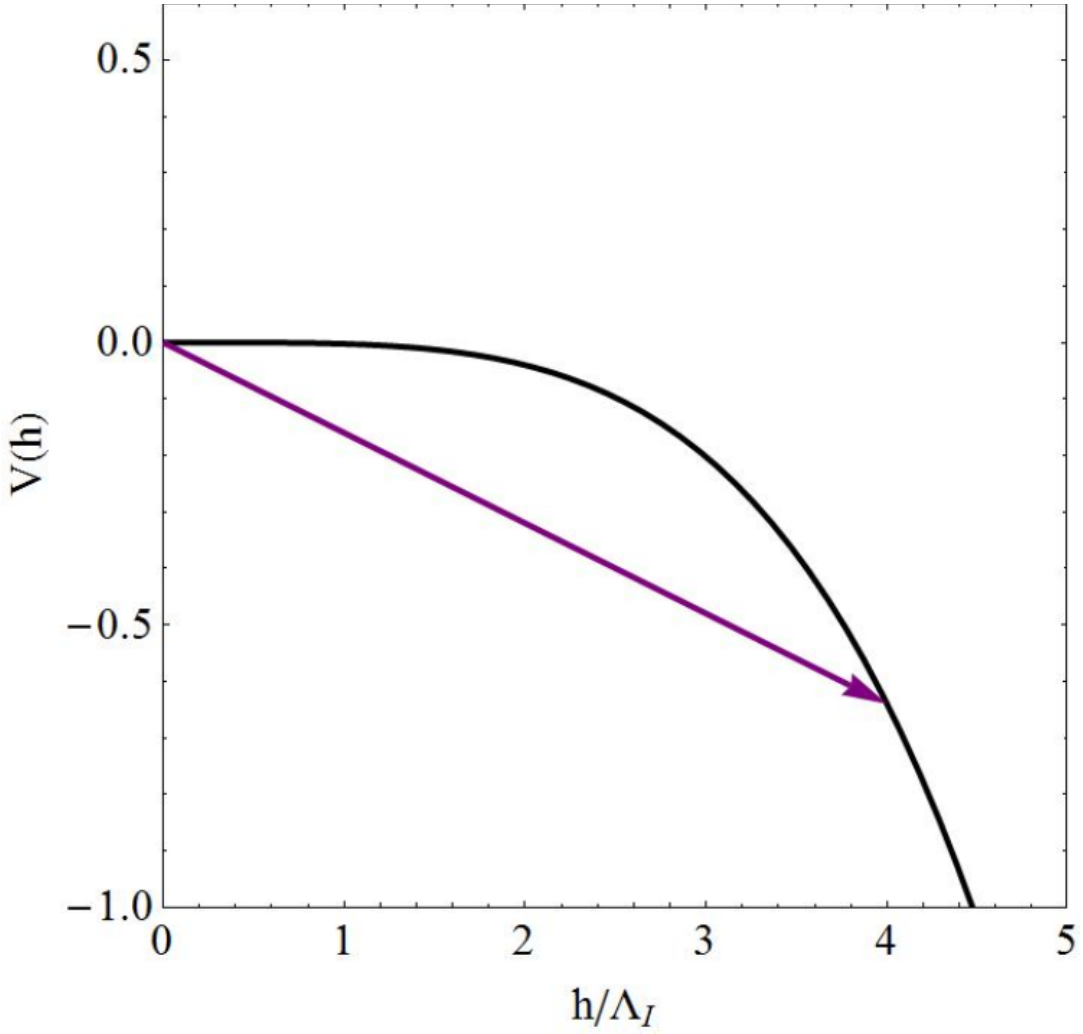
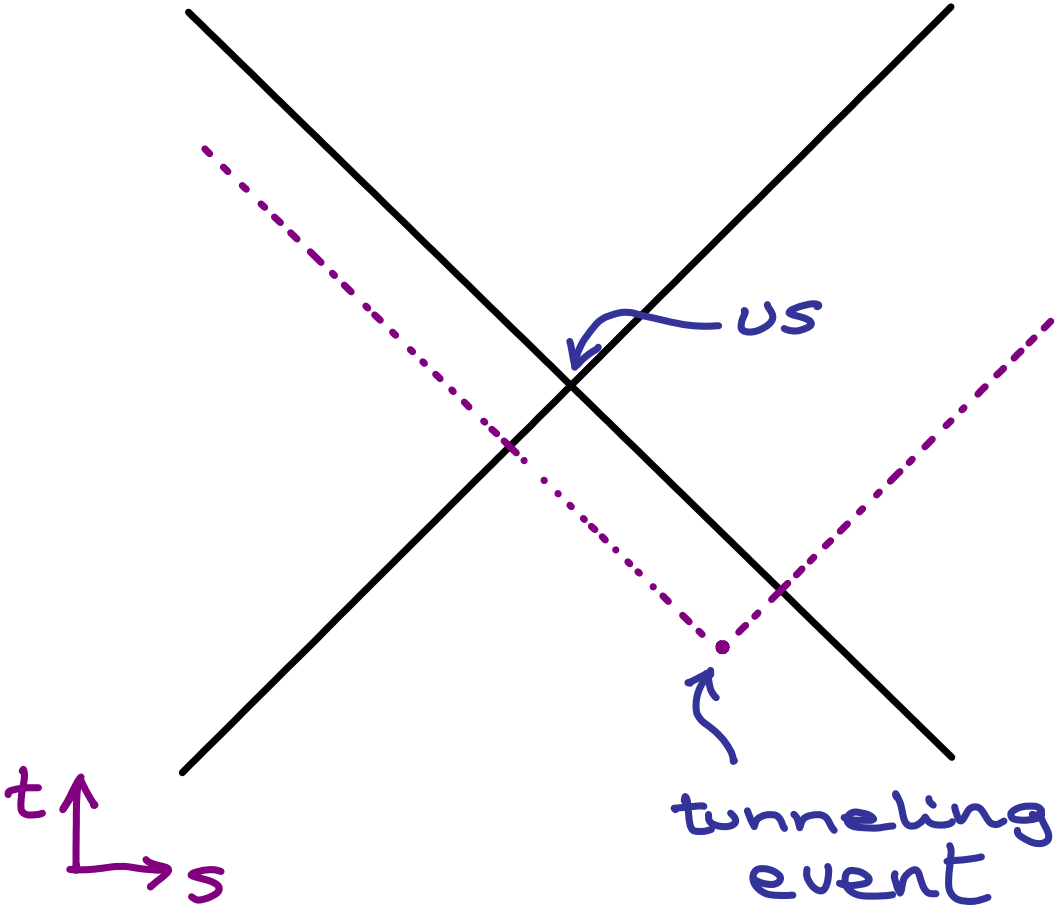
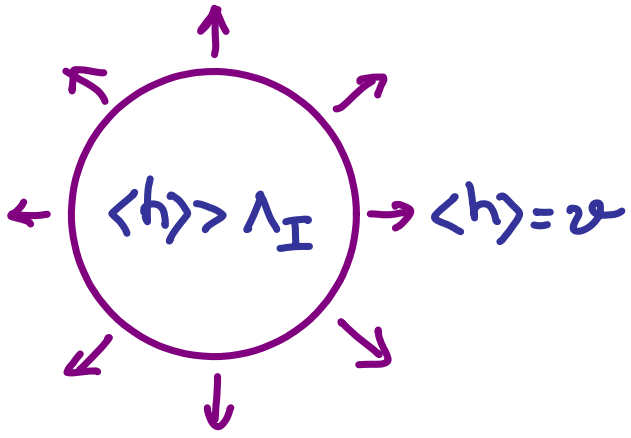


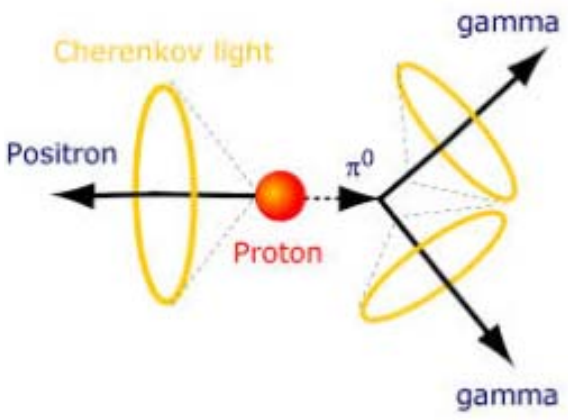
LIFE IN A METASTABLE VACUUM

Decay probability ?





VACUUM DECAY VS MATTER DECAY



Proton decay predicted in Grand Unification Theories with typical lifetime

$\tau \sim 10^{35}$ yr $\gg \tau_U \sim 10^{10}$ yr

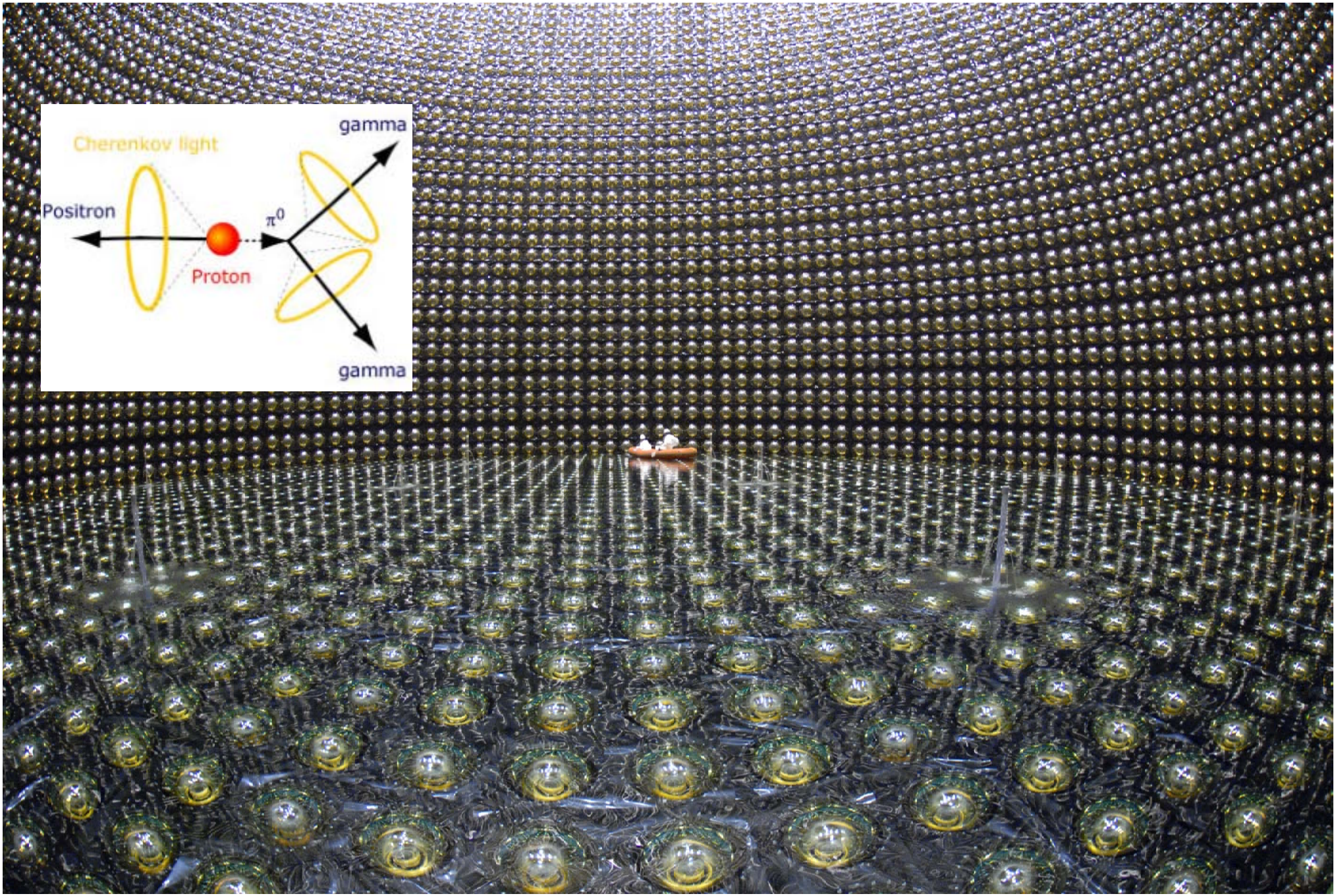
Searched for by looking at many protons during many years

Current limit

$$\tau > 10^{34} \text{ yr}$$

from Superkamiokande exp. (206 kton-yr. exposure)

VACUUM DECAY VS MATTER DECAY



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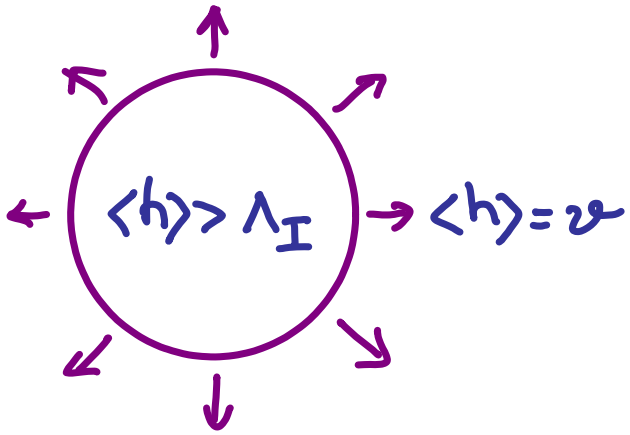
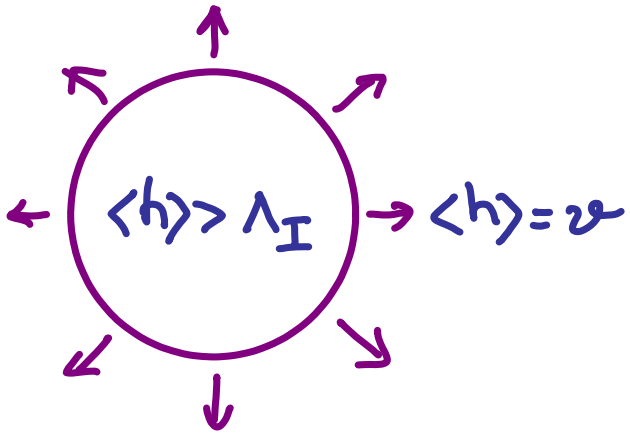


For vacuum decay we only have one universe...
but our "water tank" is huge : the whole universe

and the running time of the "experiment" is also huge : the age of the universe

VACUUM DECAY VS MATTER DECAY



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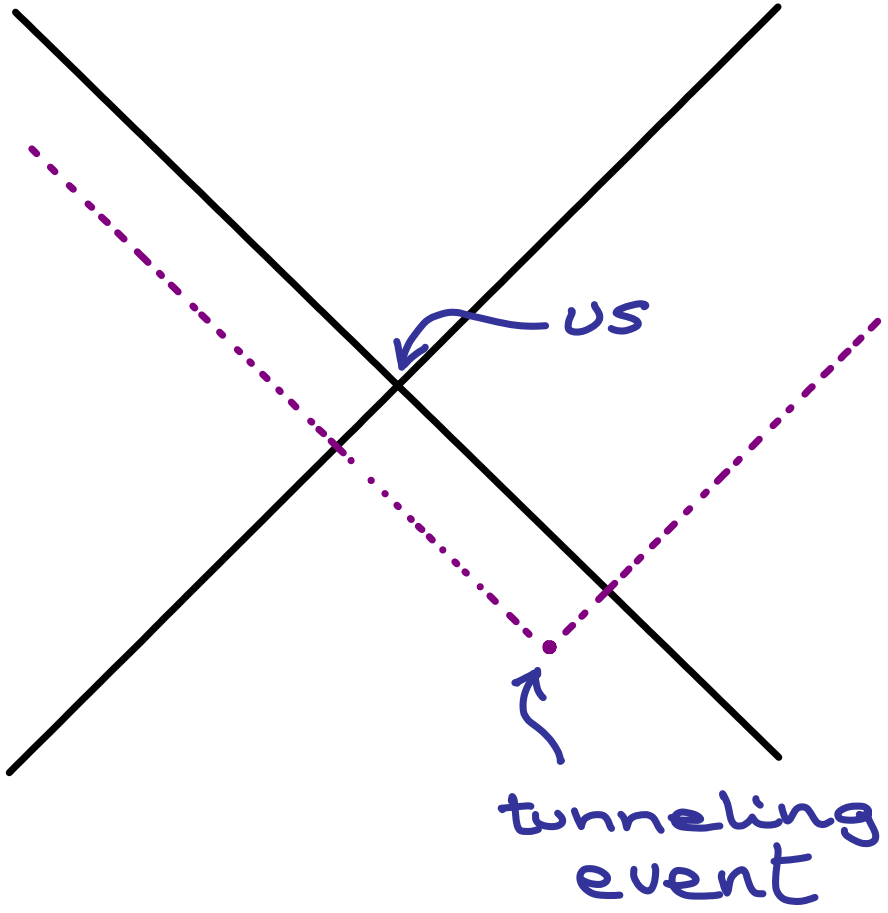
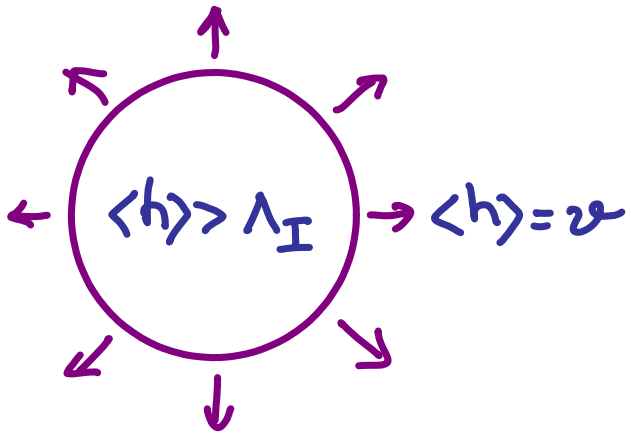
The largest (and cheapest!) experiment ever...

LIFE IN A METASTABLE VACUUM

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





LIFE IN A METASTABLE VACUUM

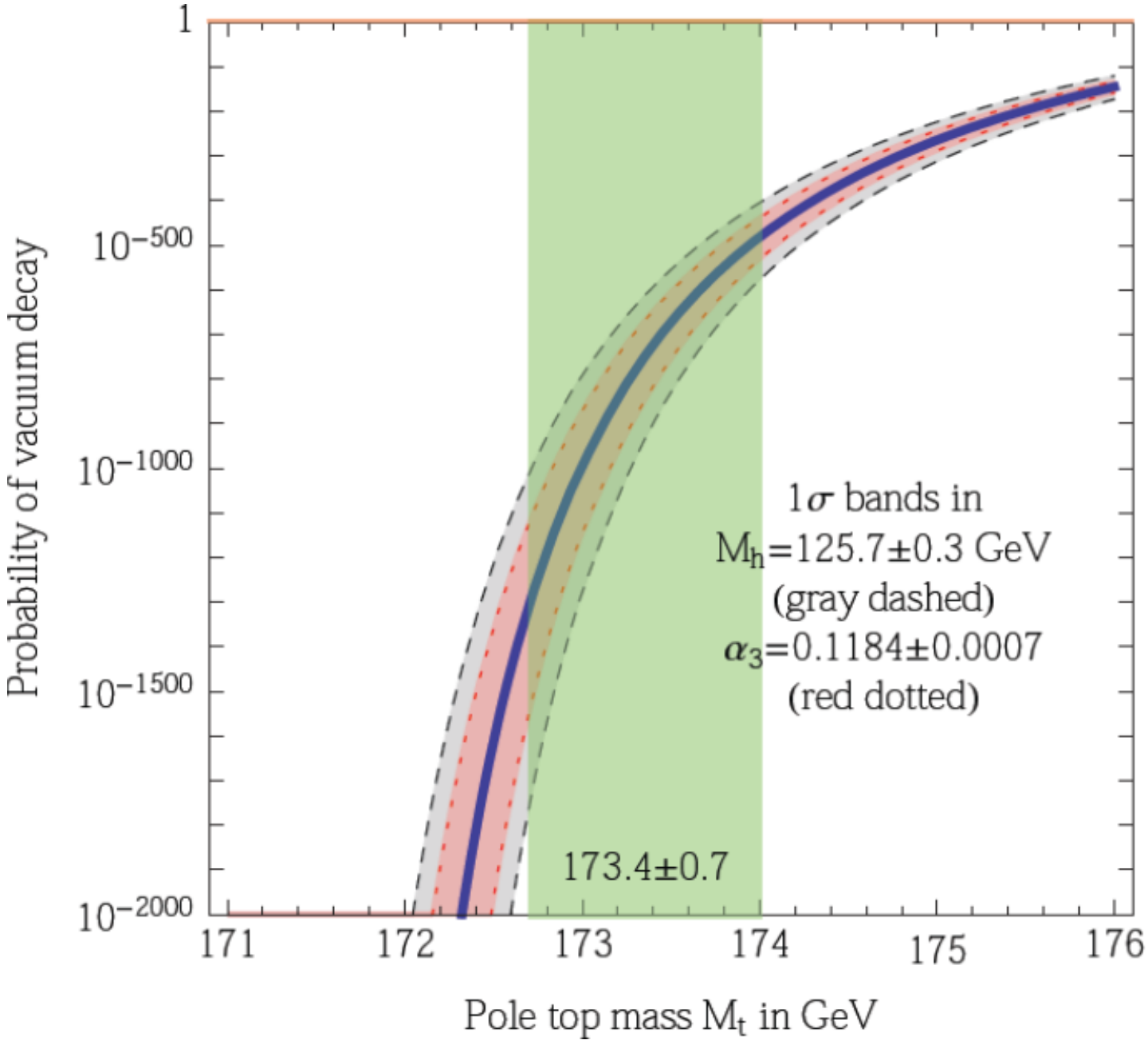
$$p = \text{Decay prob.} = \underbrace{\frac{\text{Decay rate}}{\Delta t \cdot \Delta V}}_{h^4 e^{-S_4}} \tau_U^4 \quad \text{with} \quad \tau_U^4 \sim \left(e^{140}/M_{Pl}\right)^4$$

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

easily wins over τ_U^4

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

PROBABILITY OF VACUUM DECAY

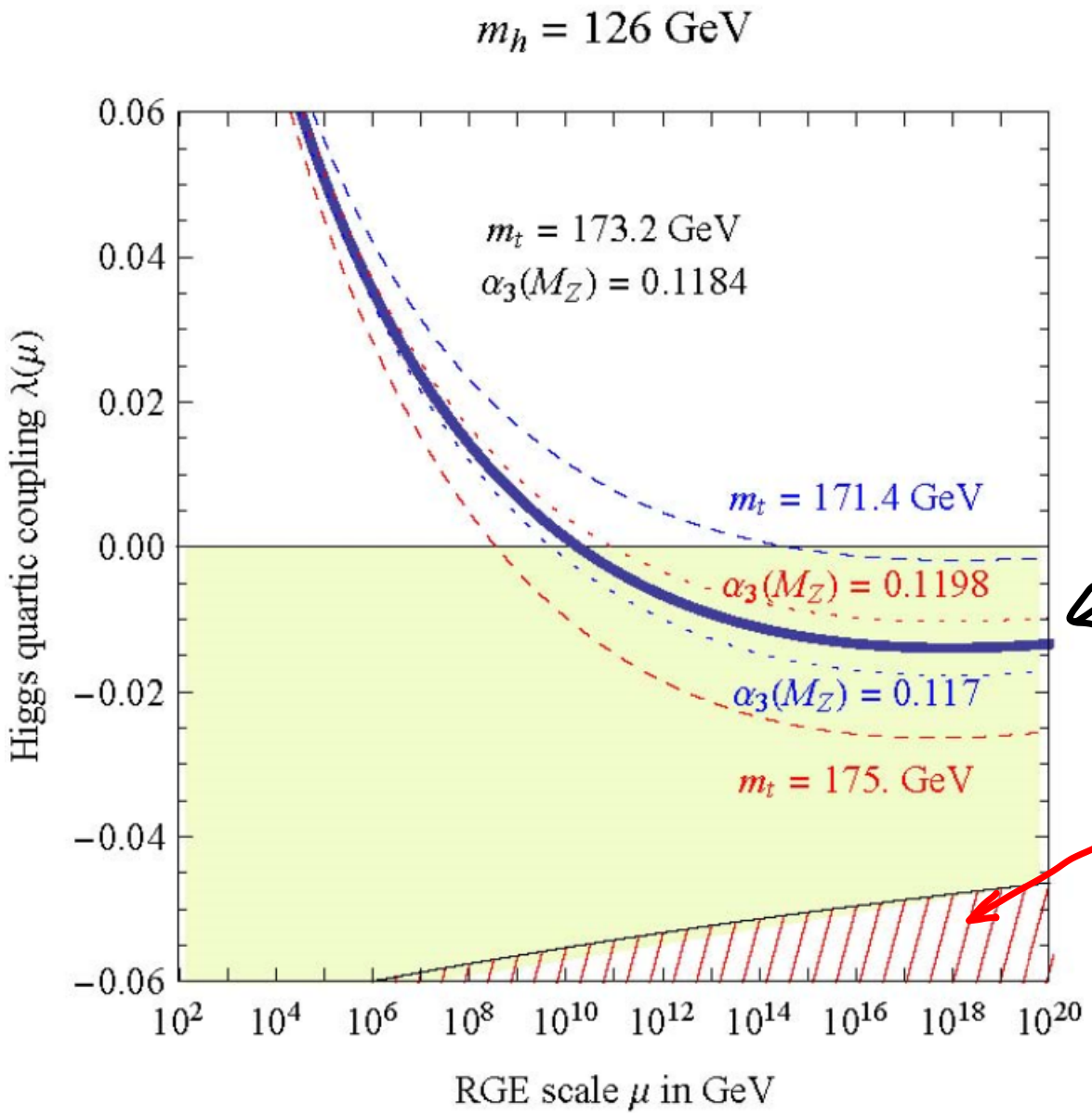


PROBABILITY OF VACUUM DECAY

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

A: No!

LIFE IN A METASTABLE VACUUM

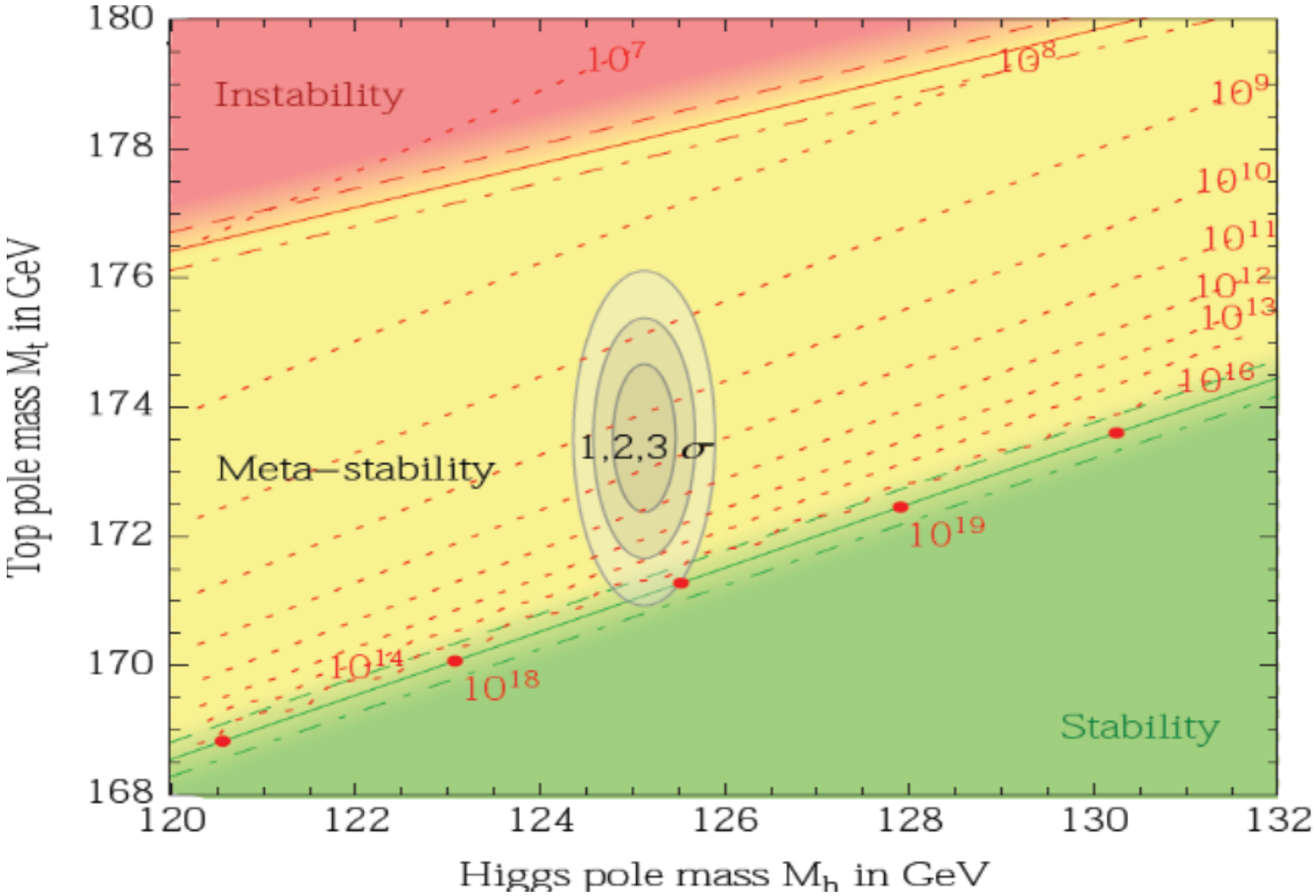


Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

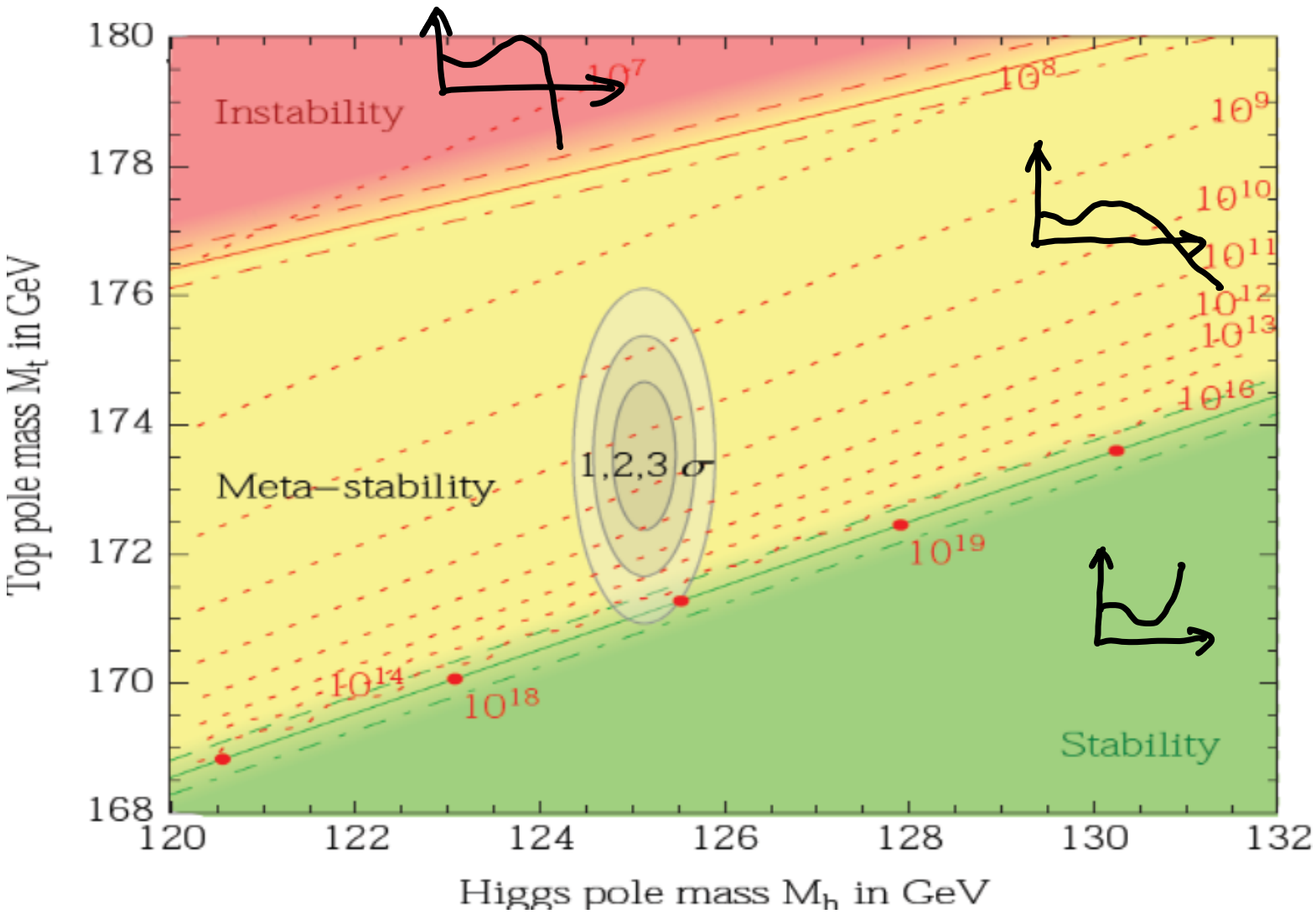
P > 1
Unstable
Vacuum
($M_h \downarrow$)

LIVING AT THE EDGE



$M_h = 125.13 \pm 0.23$ GeV $M_t = 173.34 \pm 0.76$ GeV

LIVING AT THE EDGE



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NNLO STABILITY BOUND

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

State-of-the-art NNLO calculation:

- 2-loop Veff (Ford, Jack, Jones [ph/0111190])

- 3-loop RGE β_i (..., Chetyrkin, Zoller [ph/1205.2892], Bednyakov, Pikelner, Velizhanin [ph/1212.6829])

- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$ (..., Shaposhnikov et al [ph/1205.2893], , Degrassi et al [ph/1205.6497], , Buttazzo et al [ph/1307.3536])

FROM LO TO NLO TO NNLO ...

$\#L$ $\alpha \equiv$ expansion parameter $(h_t^2/4\pi)^2$ $\log \equiv \log(h/m_t)$

0	α^0				
1	$\alpha\log$	α			
2	$\alpha^2\log^2$	$\alpha^2\log$	α^2		
⋮					
n	$\alpha^n\log^n$	$\alpha^n\log^{n-1}$	$\alpha^n\log^{n-2}$	....	α^n

FROM LO TO NLO TO NNLO ...

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⋮					
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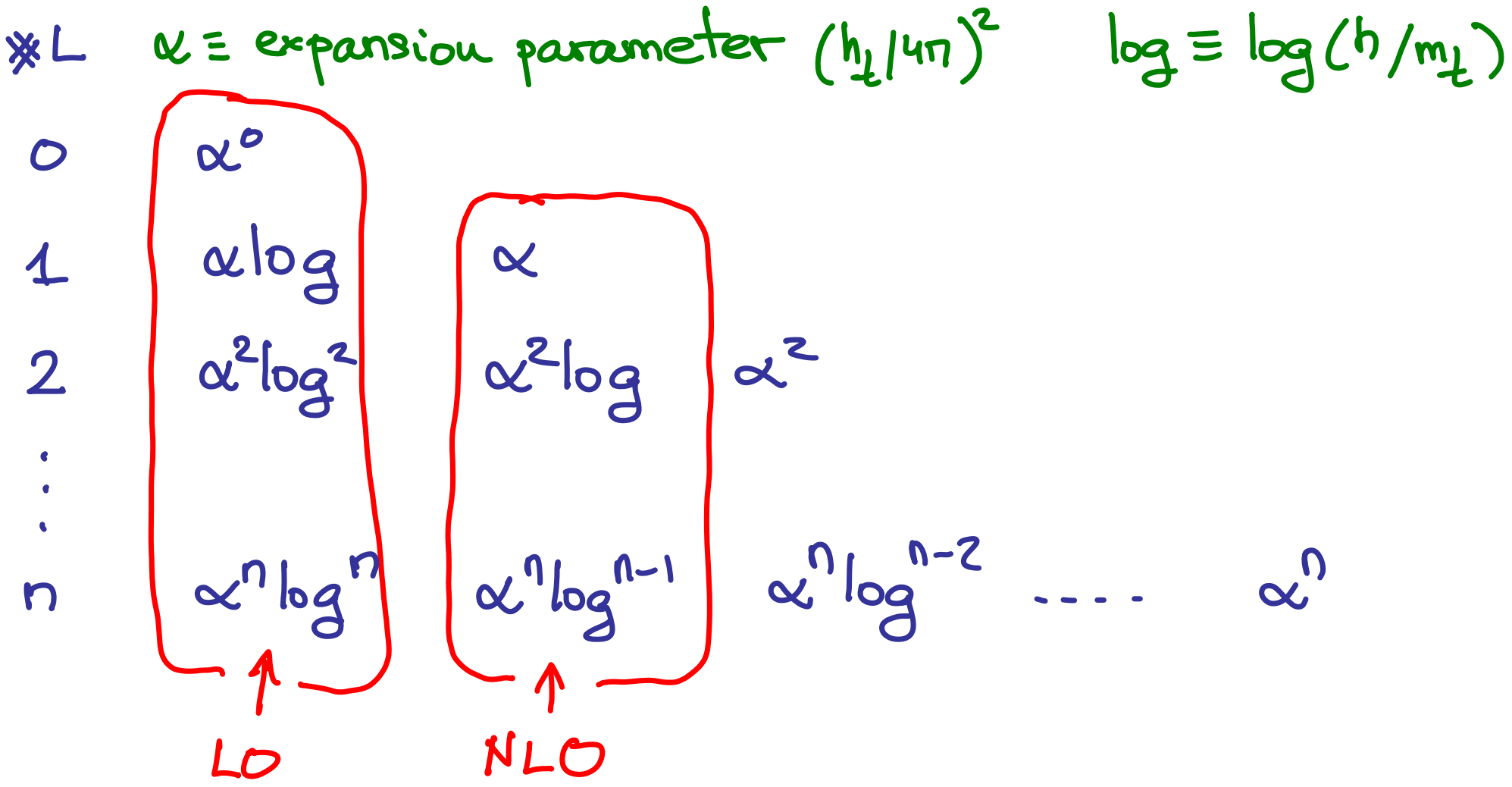
LO

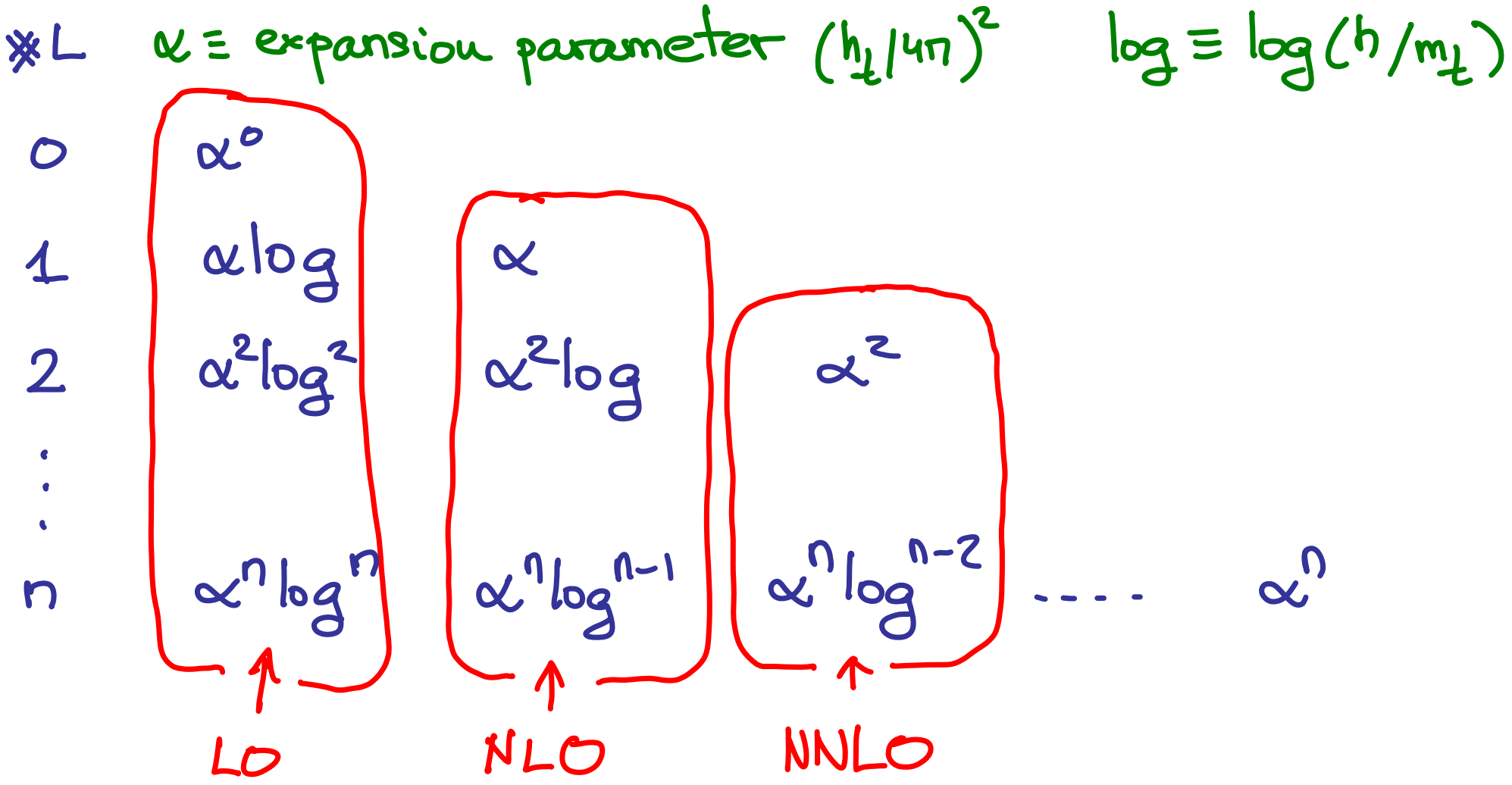
RG $\beta^{(1)}$ resums the whole series to all loops.

FROM LO TO NLO TO NNLO ...



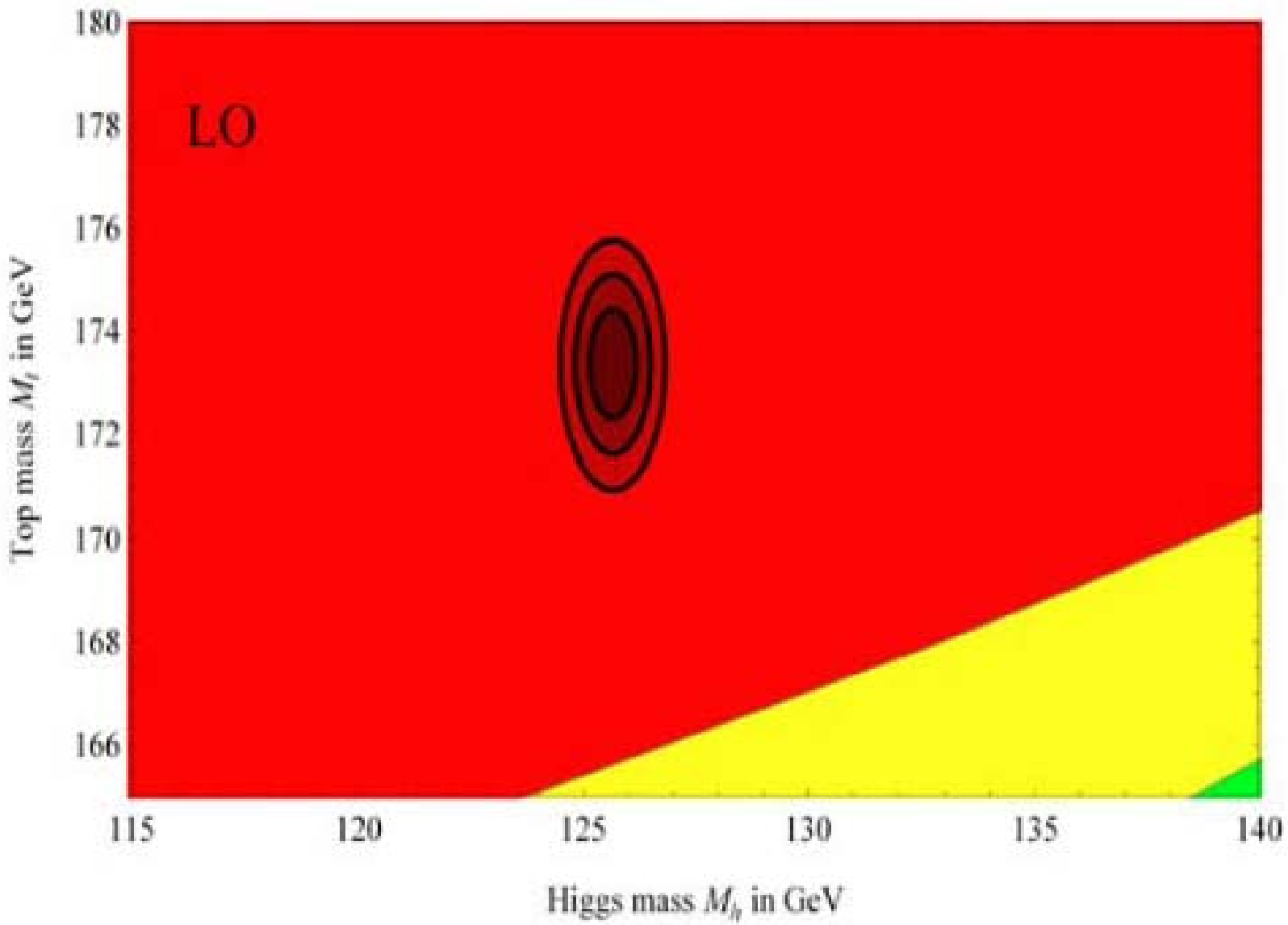
RG $\beta^{(z)}_{\vdots}$ resums the whole series to all loops.

FROM LO TO NLO TO NNLO ...

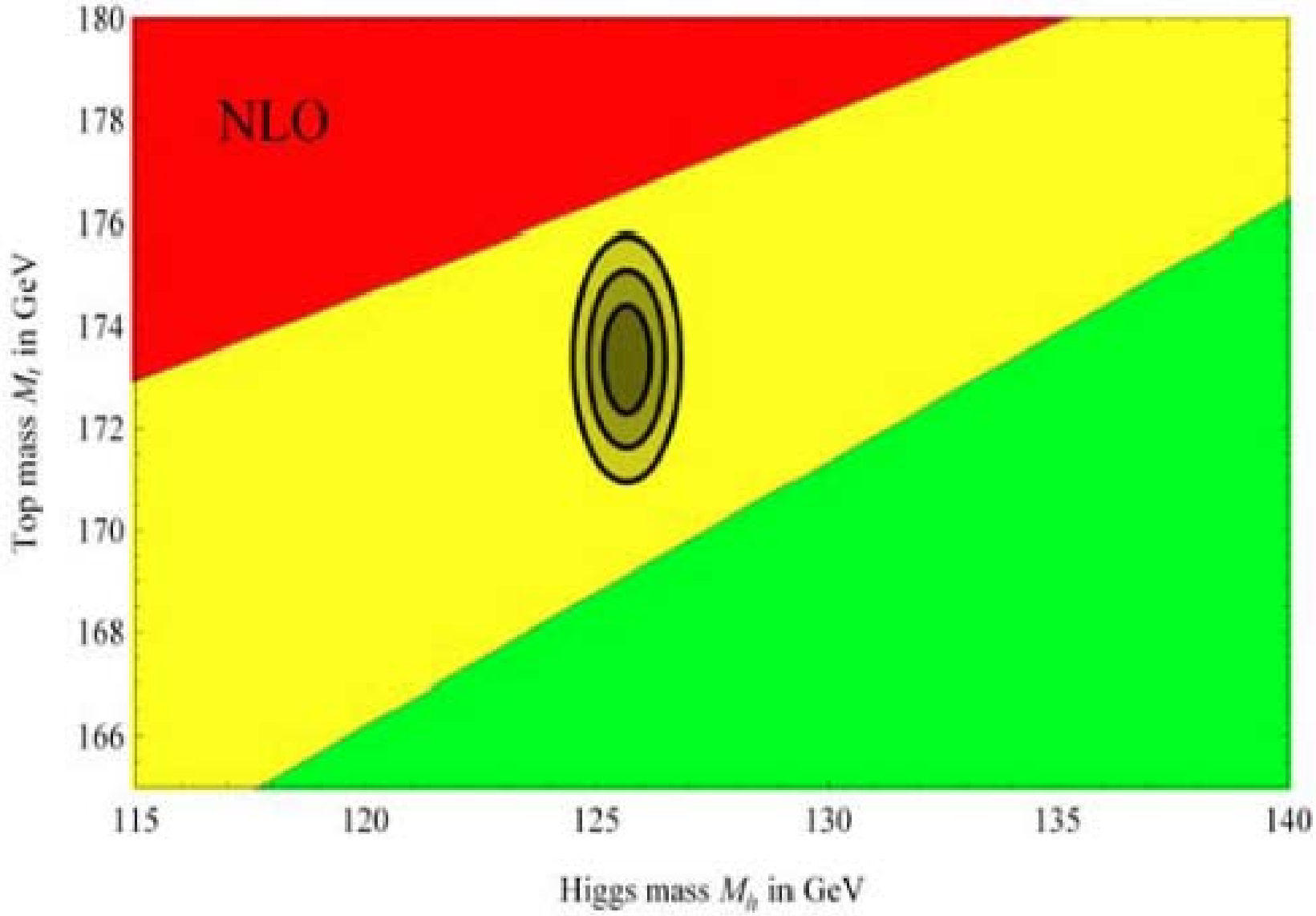


RG $\beta^{(3)}$ resums the whole series to all loops.

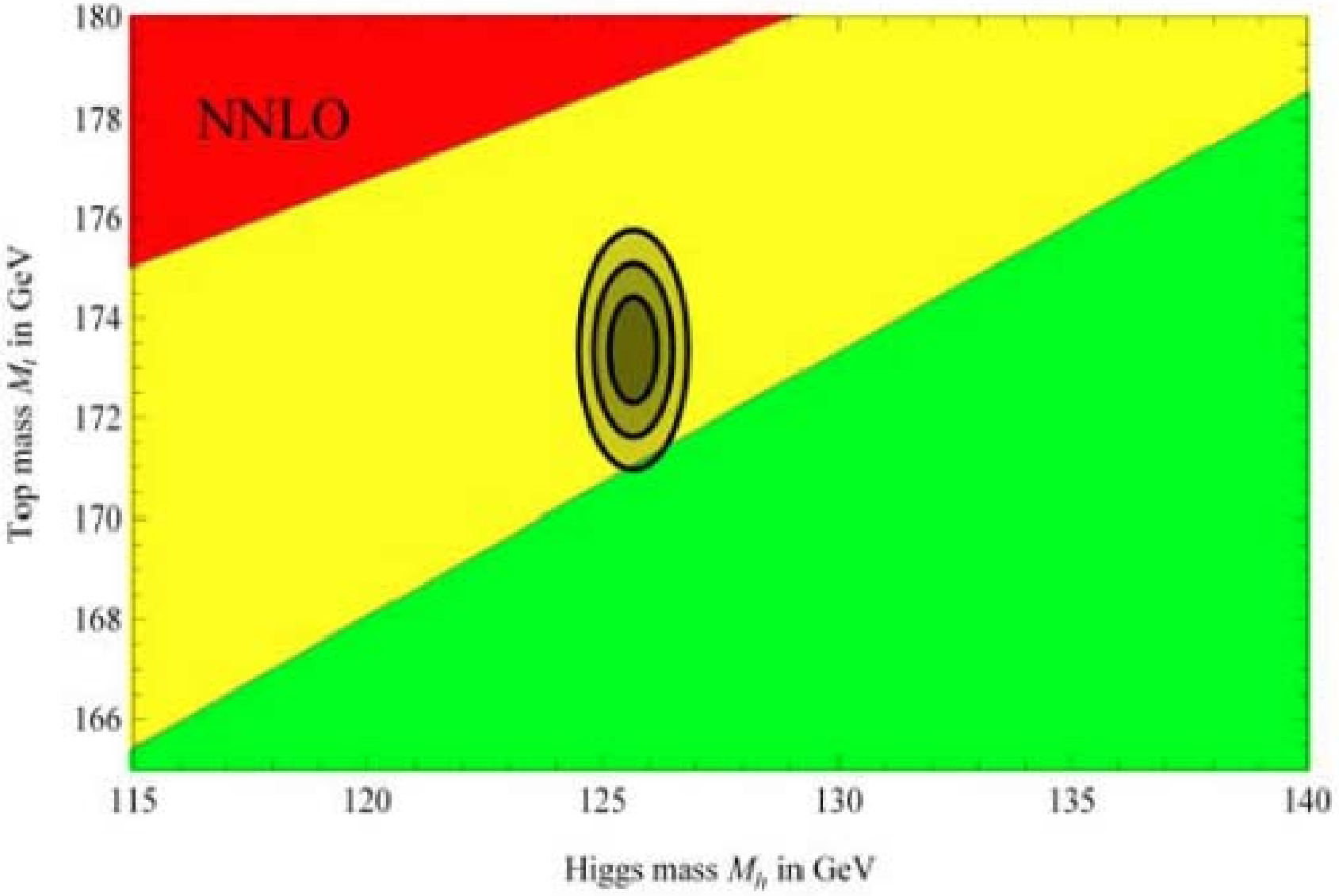
PROGRESS IN STABILITY CALCULATION



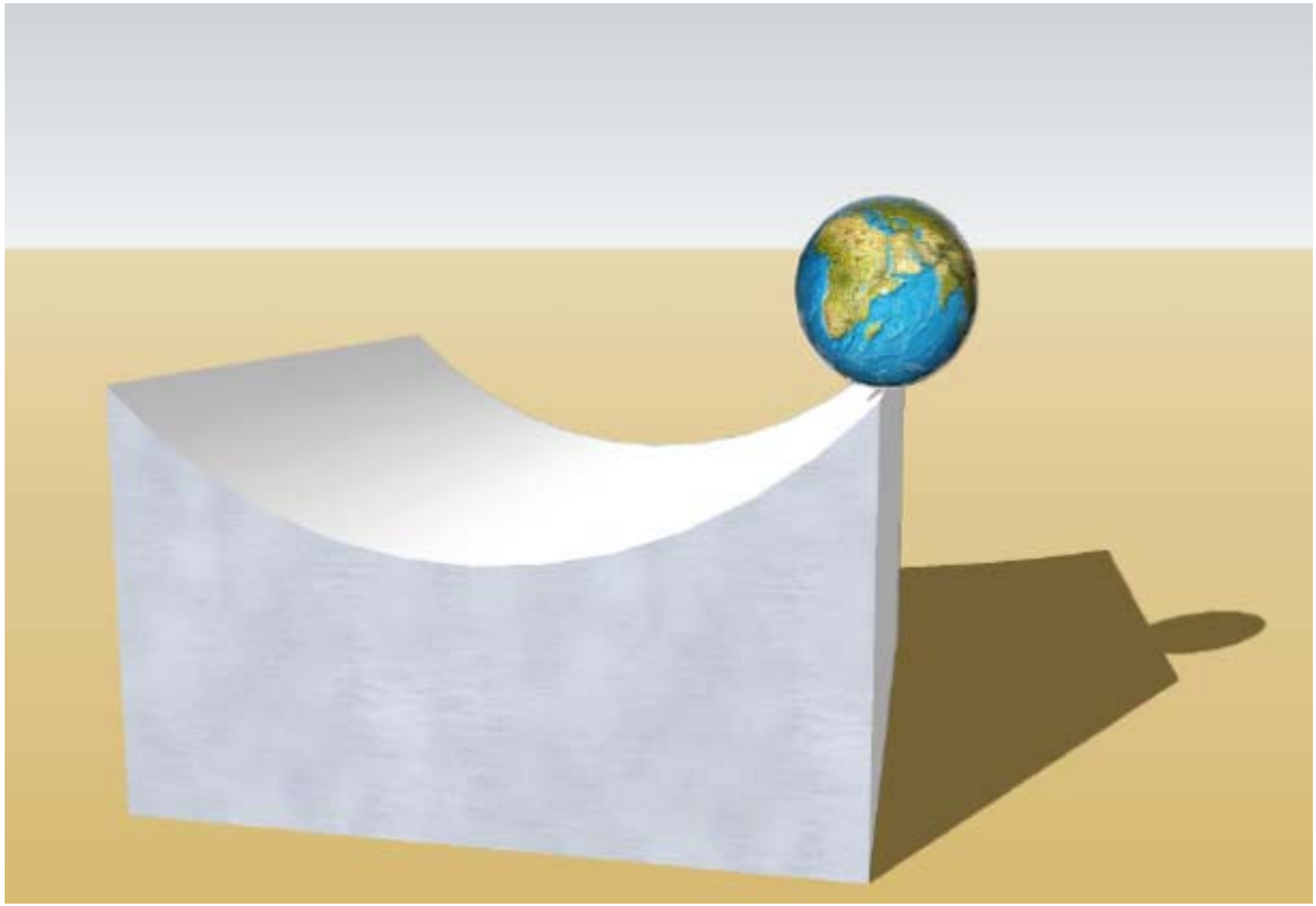
PROGRESS IN STABILITY CALCULATION



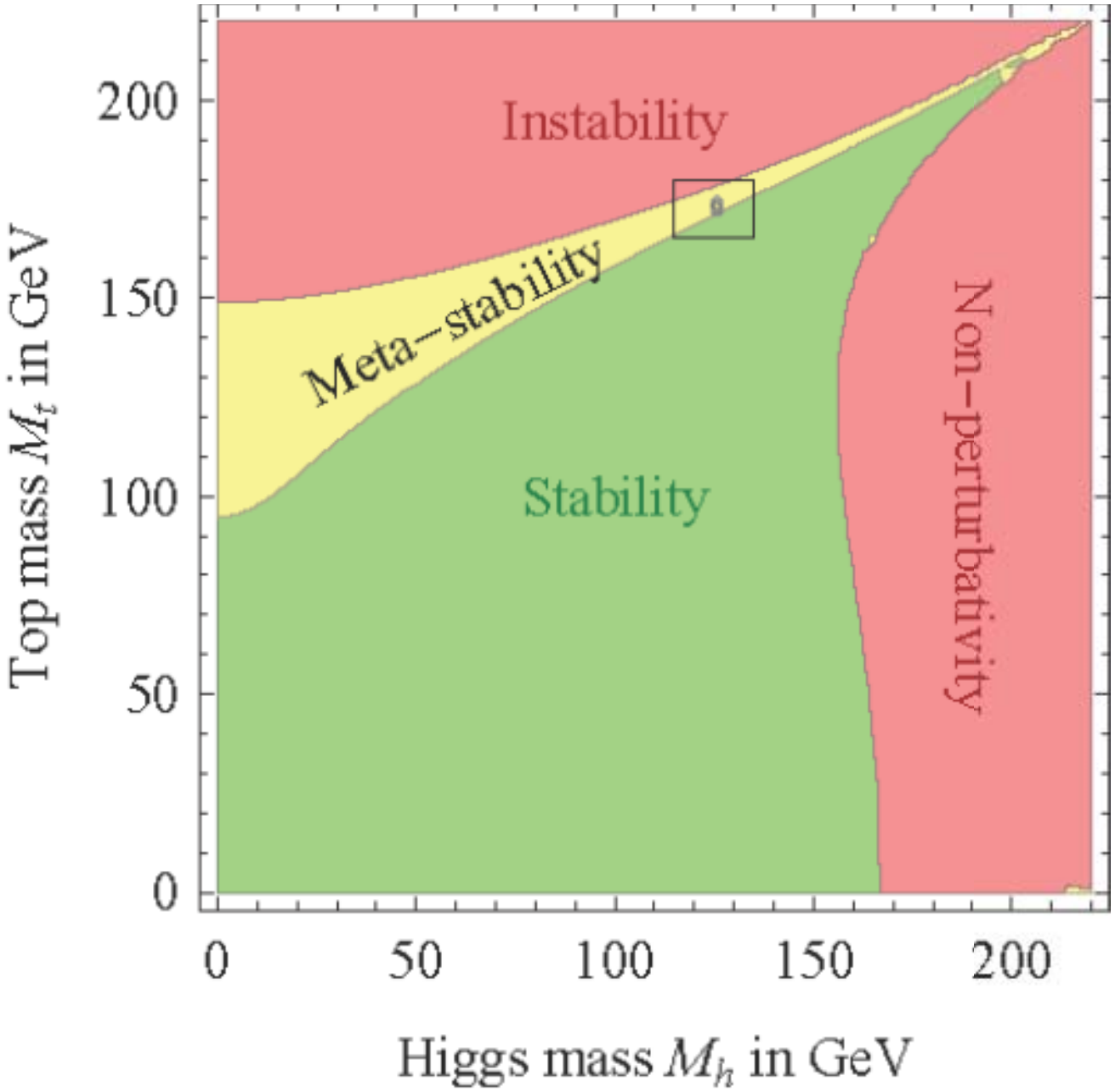
PROGRESS IN STABILITY CALCULATION



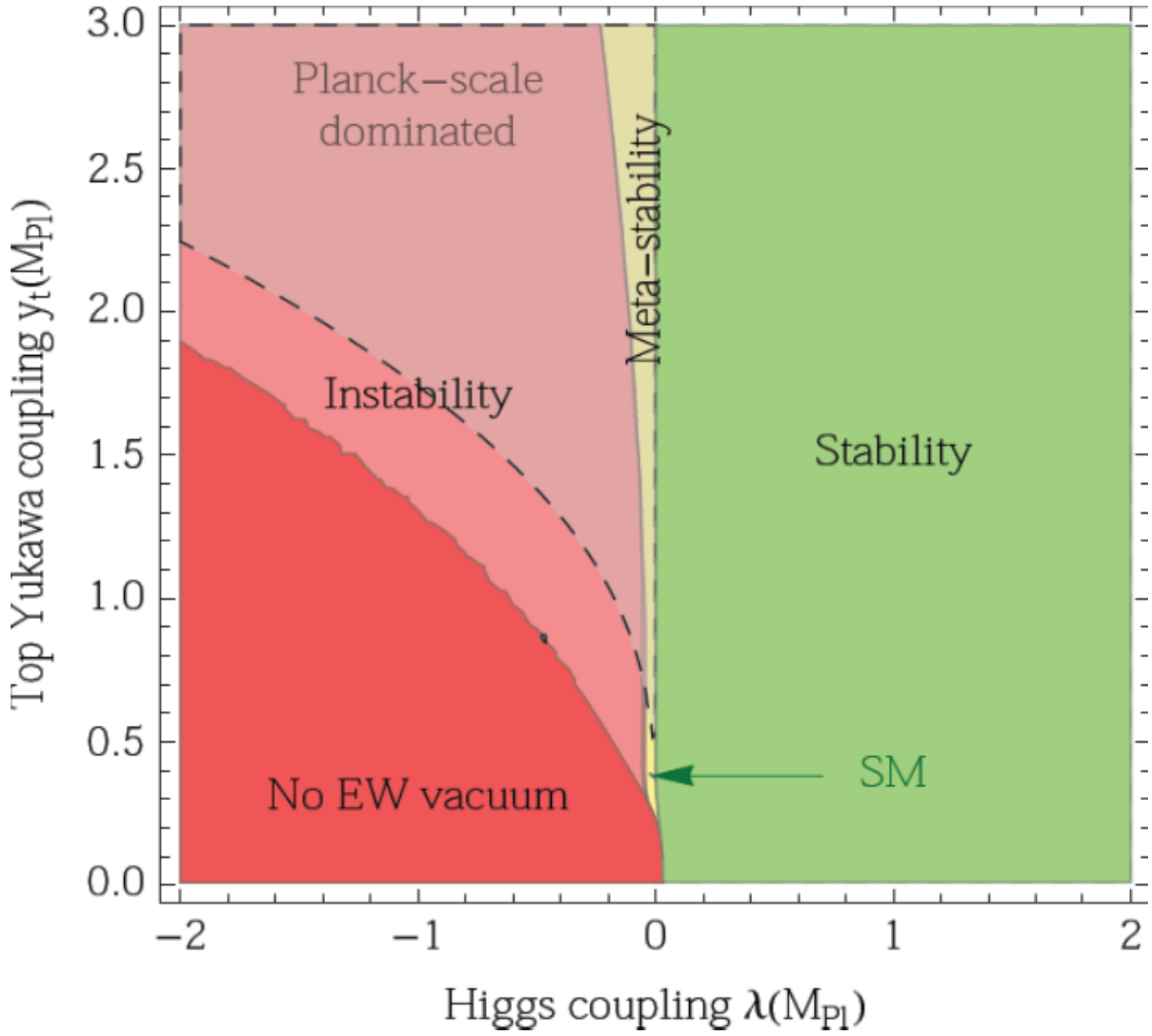
LIVING AT THE EDGE



LIVING AT THE EDGE



LIVING AT THE EDGE

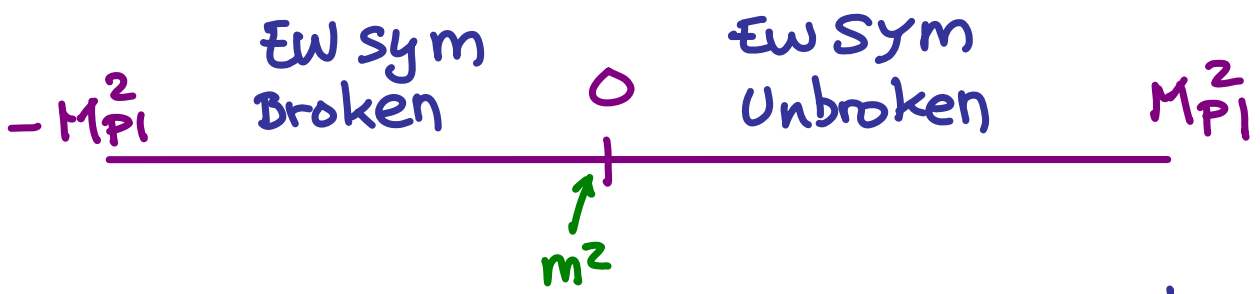


NEW KNOWLEDGE BRINGS NEW QUESTIONS

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

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

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



★ Is the EW scale determined by Planck scale physics?

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

BSM & STABILITY

Even without naturalness, BSM must exist...

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

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...

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Example

IRRELEVANT — See-saw neutrinos

MAKE IT WORSE

CURE IT

BSM & STABILITY

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

BSM & STABILITY

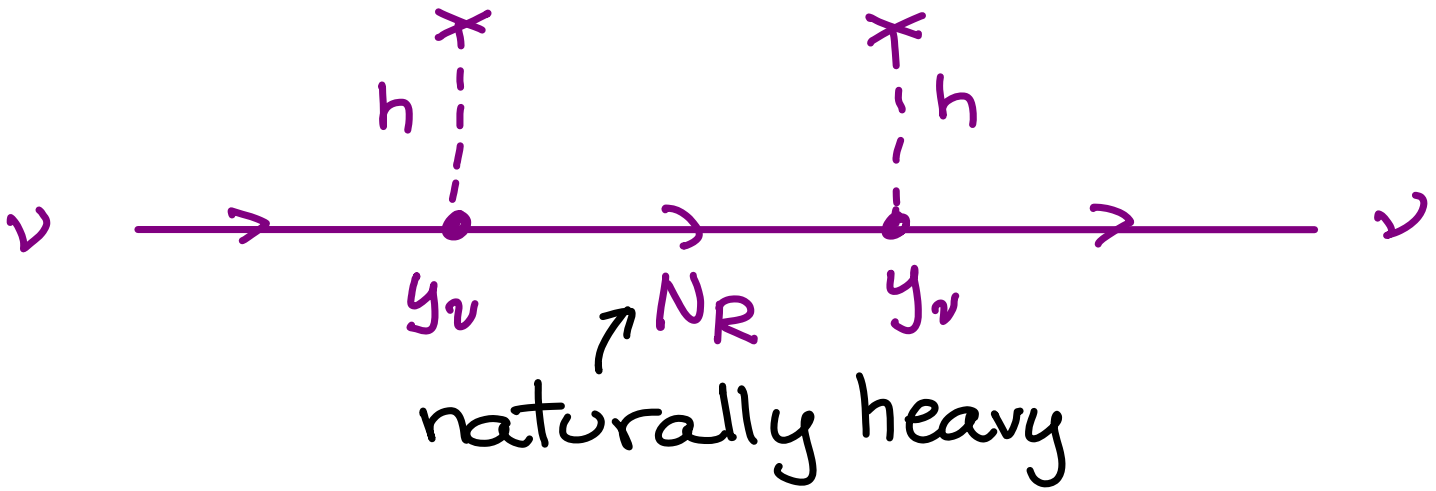
Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

	Example
IRRELEVANT	See-saw neutrinos
MAKE IT WORSE	See-saw neutrinos
CURE IT	See-saw neutrinos (& SUSY!)

SEE-SAW NEUTRINOS

Very elegant mechanism to explain smallnes of neutrino masses



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

$\lesssim$ eV

10^2 GeV

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

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

OTHER IMPLICATIONS

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

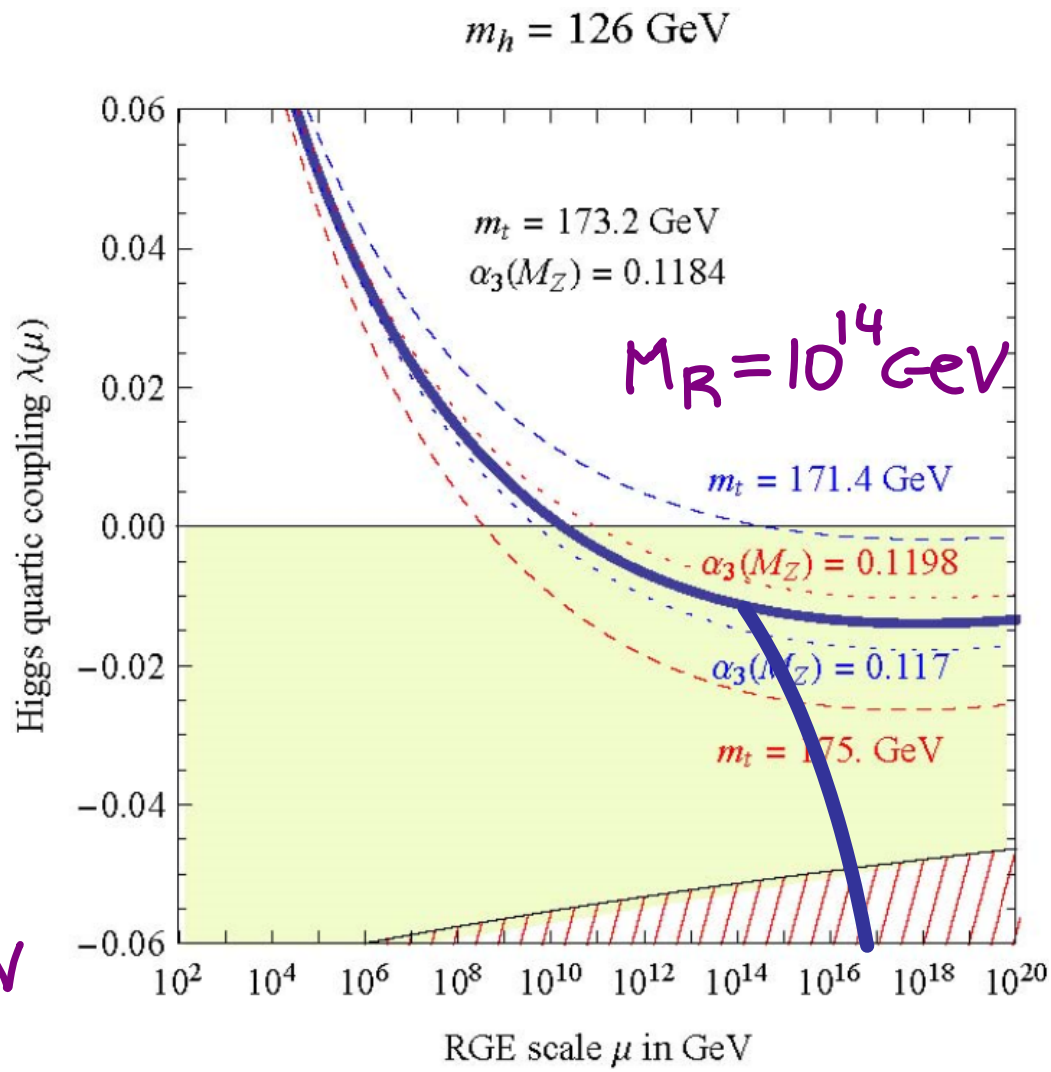
$$m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$

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

⇧

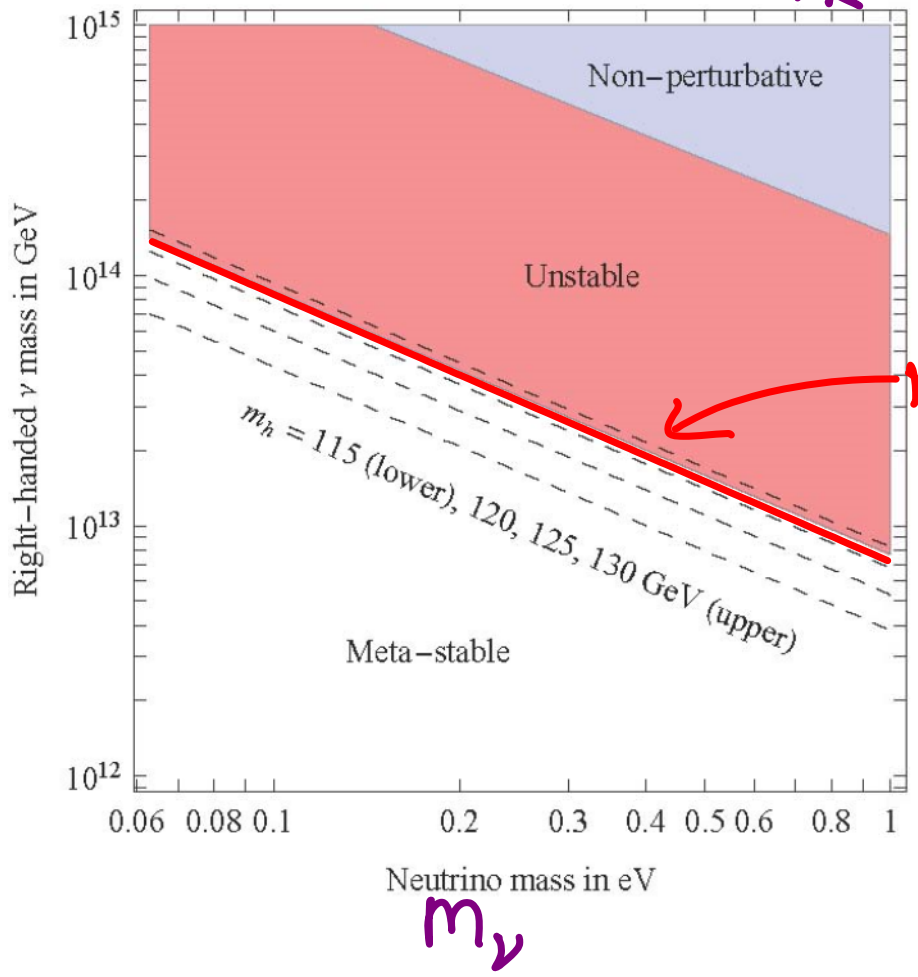
Adds to the top destabilizing effect

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



BSM IMPLICATIONS

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



M_R

M_h=125 GeV

m_ν

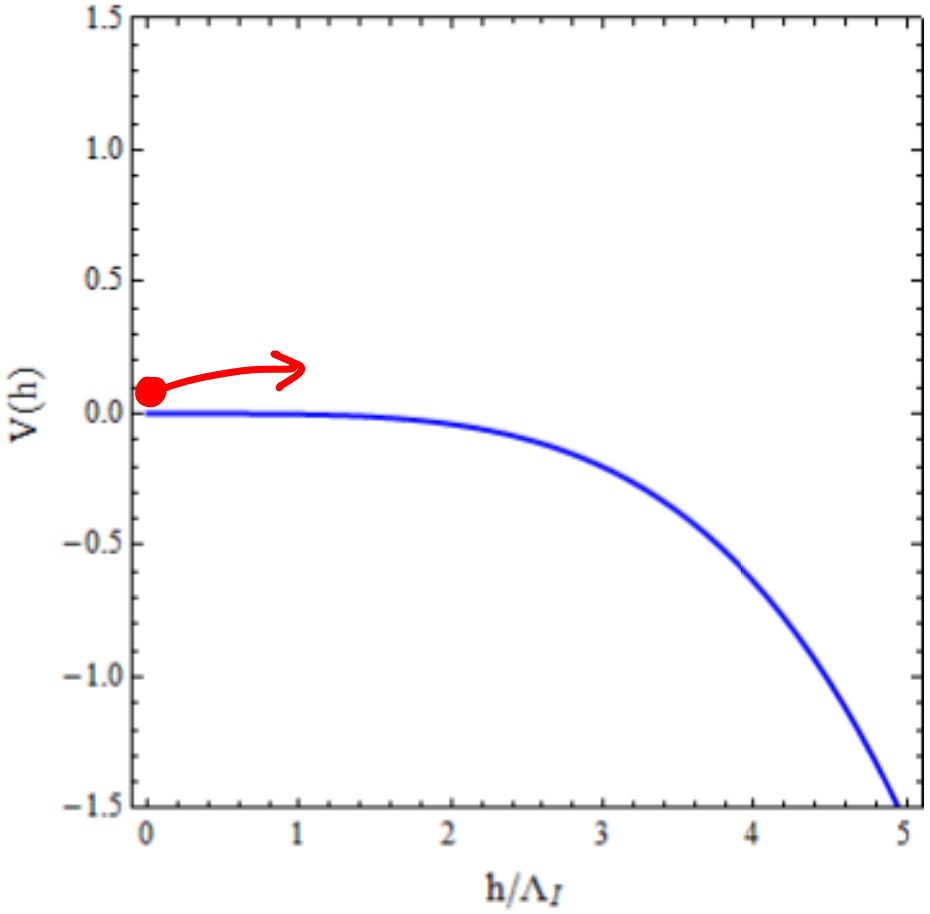
Useful to bound additional sources of instability.

INTERPLAY WITH COSMOLOGY (※1)

- Thermal decay during the early Universe

  Thermal fluctuations can induce vacuum decay

Bound on T_{RH} ?



INTERPLAY WITH COSMOLOGY

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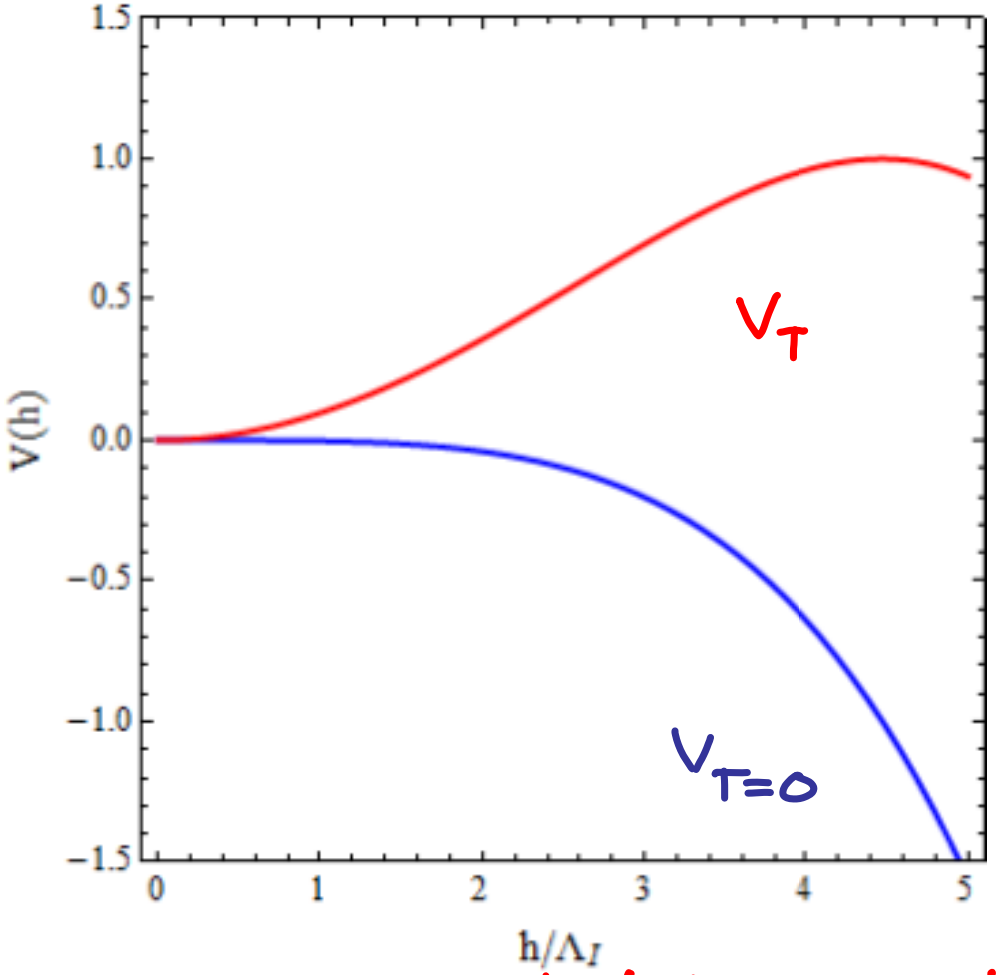


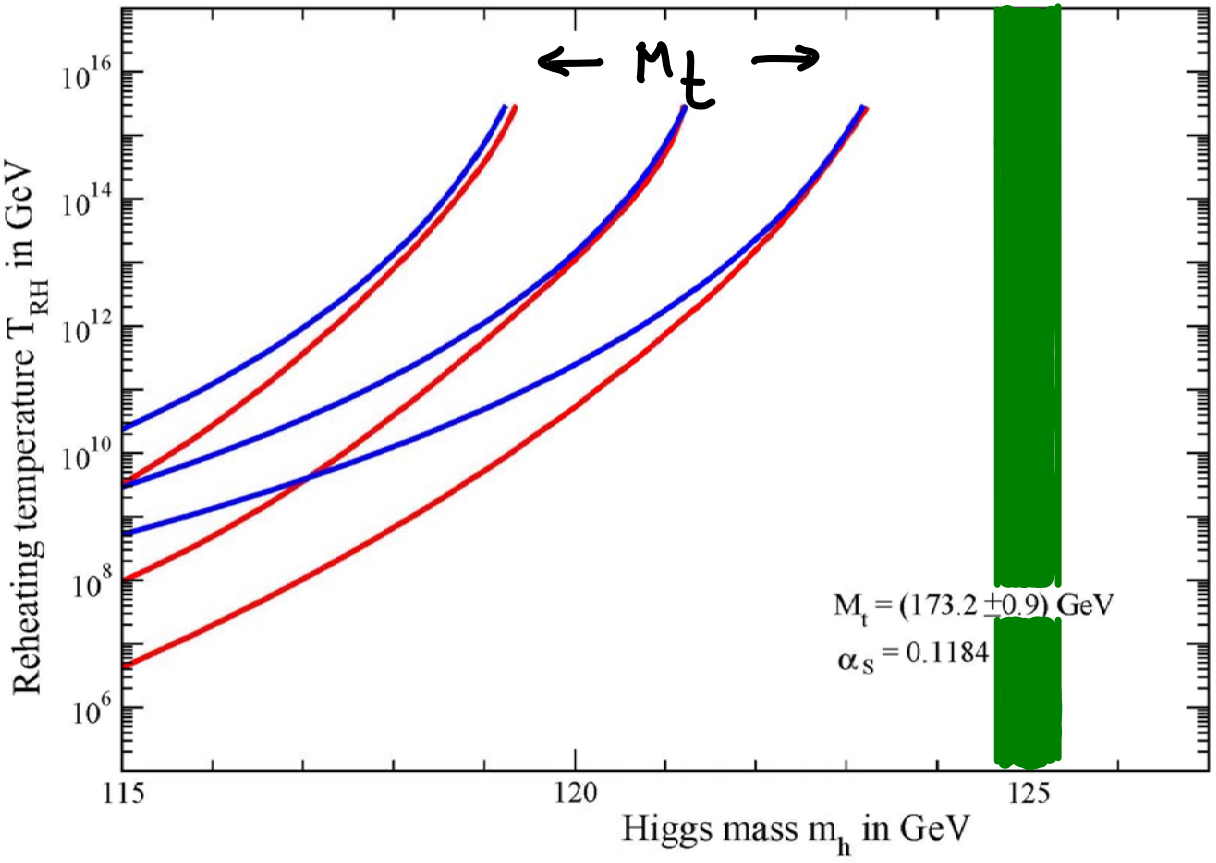
but Thermal corrections tend to stabilize V(h)

THERMAL VACUUM DECAY

Bound on T_{RH} ?

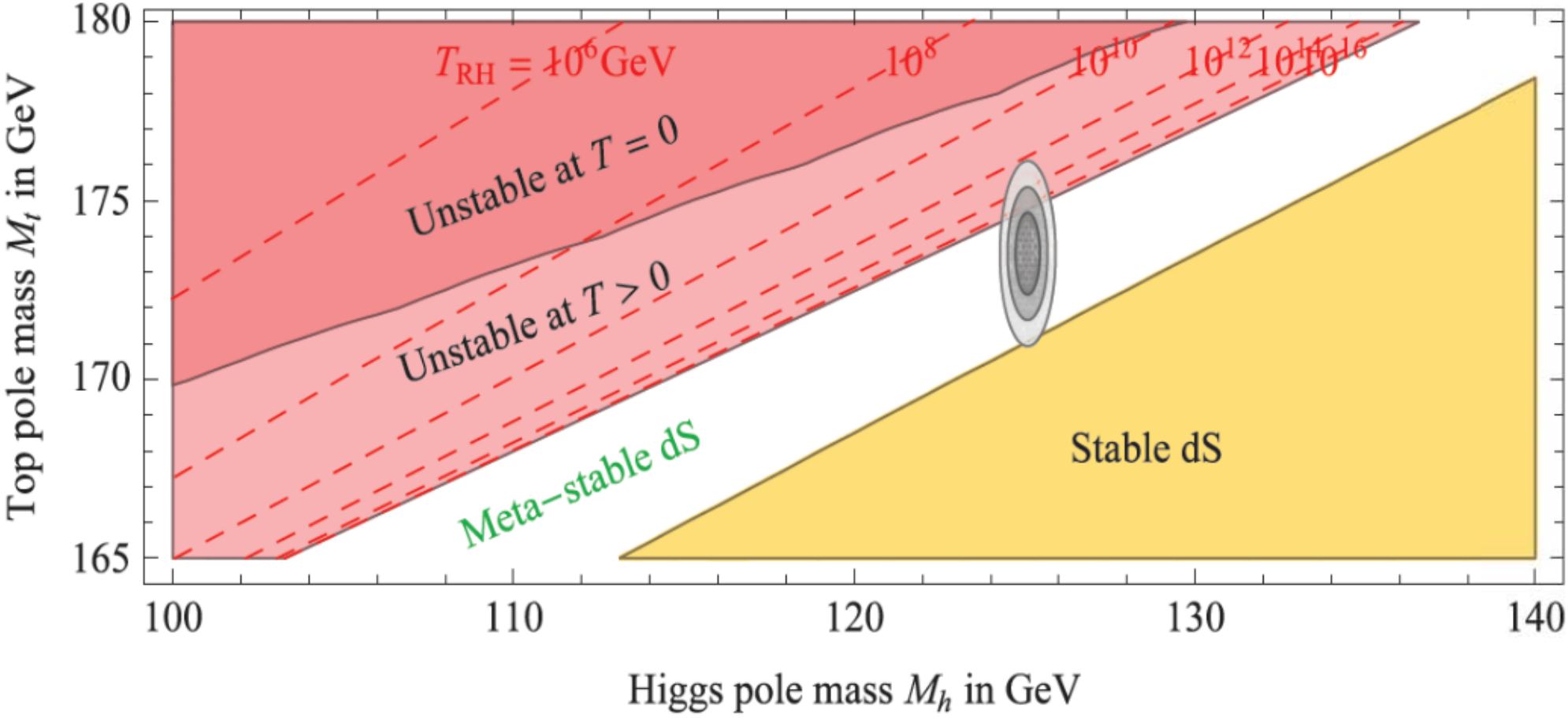
$H = 10^{14}$ GeV ——

Instant reheating ——



THERMAL VACUUM DECAY

Bound on T_{RH} ? Not for preferred M_h, M_t .



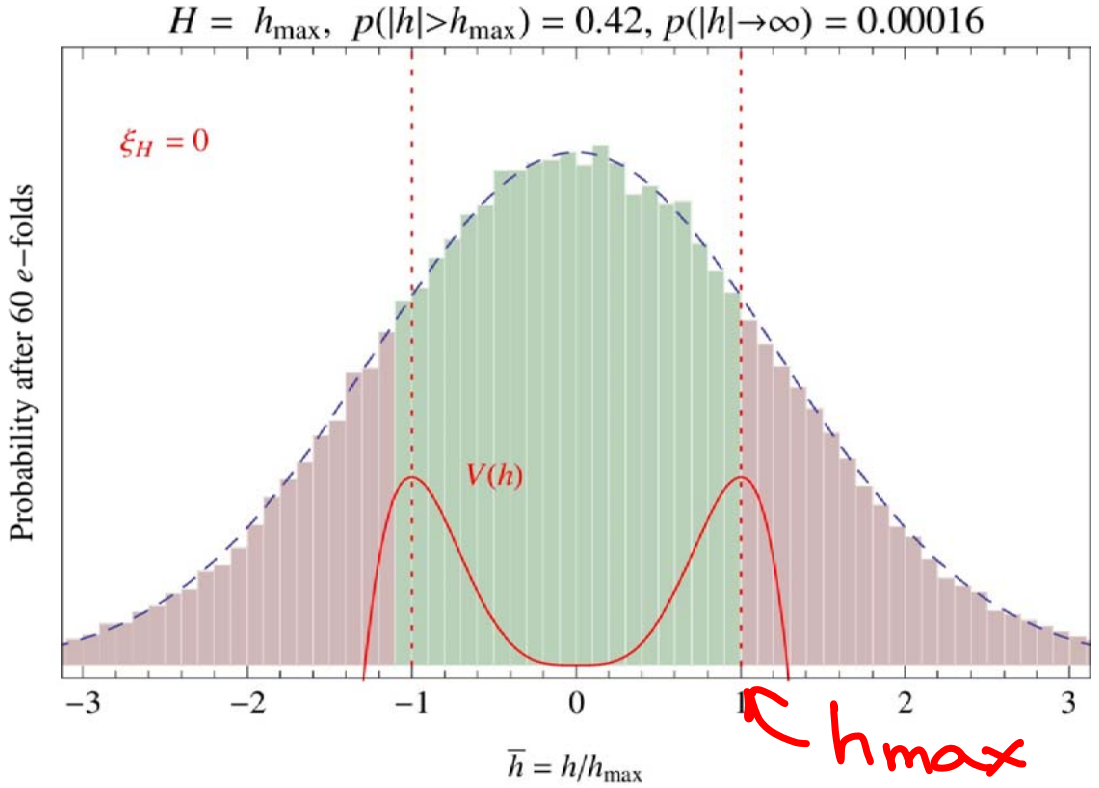
INTERPLAY WITH COSMOLOGY (#2)

- Vacuum decay during inflation

Inflation induces large fluctuations in light fields

Higgs random-walks with step $\sim H_I/2\pi$ per $\Delta t \sim H_I^{-1}$

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



INTERPLAY WITH COSMOLOGY (#2)

Can be used to put constraints on H_I

Typically

$$H_I < 10^{-2} h_{max} \sim 10^9 \text{ GeV}$$

Implications for the detectability of primordial gravitational waves which require a much larger H_I ($\sim 10^{15\text{-}16}$ GeV)

Precise bound depends on cosmological evolution and possible couplings of the Higgs to gravity or the inflaton field.

IMPLICATIONS FOR QUANTUM GRAVITY ON dS?

QUANTUM GRAVITY ON dS

Not clear if quantum gravity on a stable dS space ($V_{min}>0$) can be formulated consistently

- What are the observables ?

  Horizon obstruction to asymptotic quantities

- Local dS minima can't be stabilized by arbitrarily high/wide barriers

$$S_{cdL} \leq S_{dS}$$

S_{cdL}: tunneling action

S_{dS}: dS entropy $\sim (M_P/H)^2$

QUANTUM GRAVITY ON dS

- No stable dS vacua in string theory
- No classical compactification of 11D Supergravity to dS space

Yet, we are living in a dS phase of accelerated expansion with

$$\rho_{vac} \sim (10^{-3}\,eV)^4$$

NO QUANTUM GRAVITY ON dS

Let's suppose quantum gravity on dS does not make sense

No eternal inflation principle

or No dS vacuum can be stable

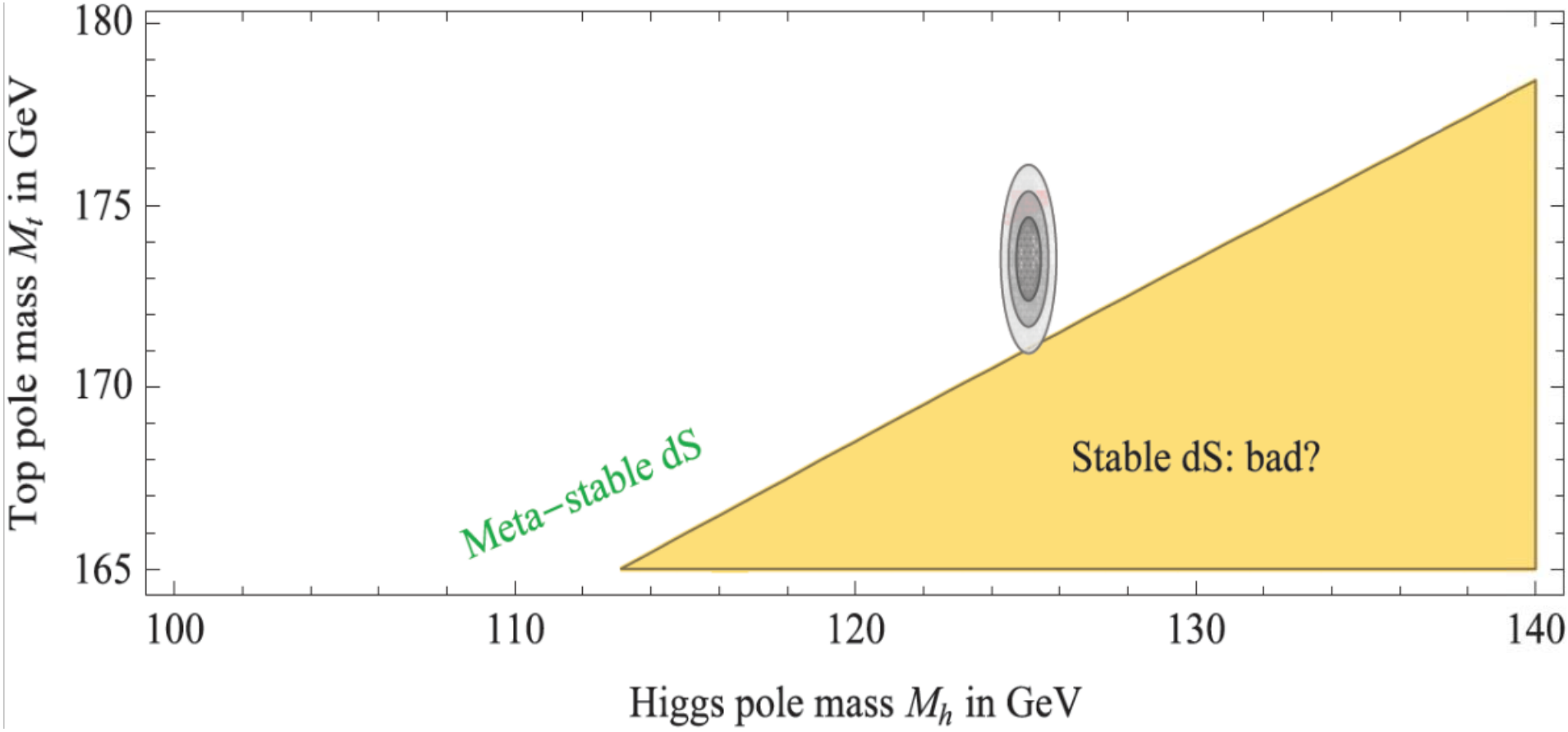
Way out: dS phase is limited in time

$\Gamma_{decay} \neq 0$

usually decay to some other vacua in a landscape.

NO QUANTUM GRAVITY ON dS

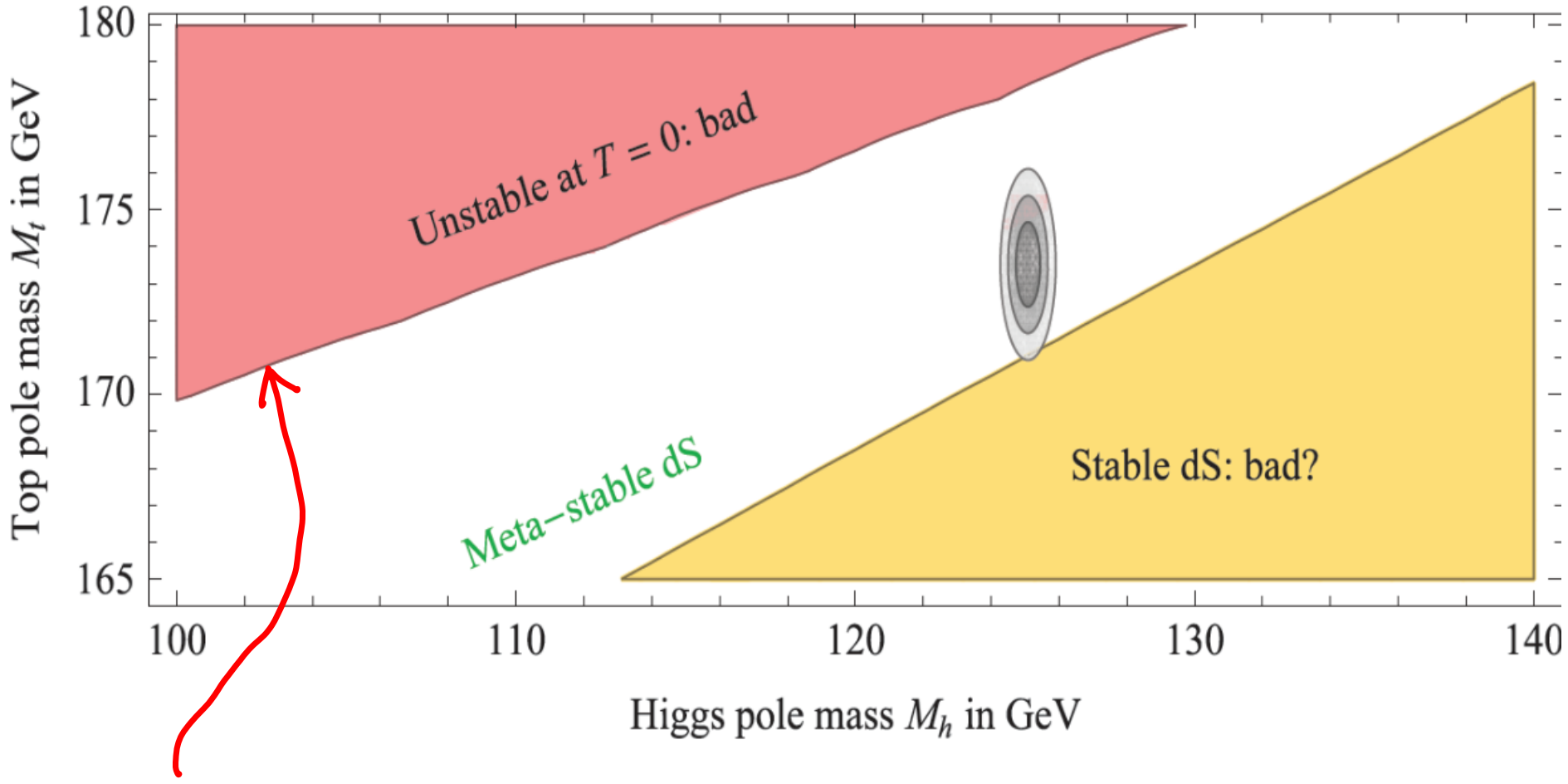
SM already offers this way out



Reason for living on the metastability region

NO QUANTUM GRAVITY ON dS

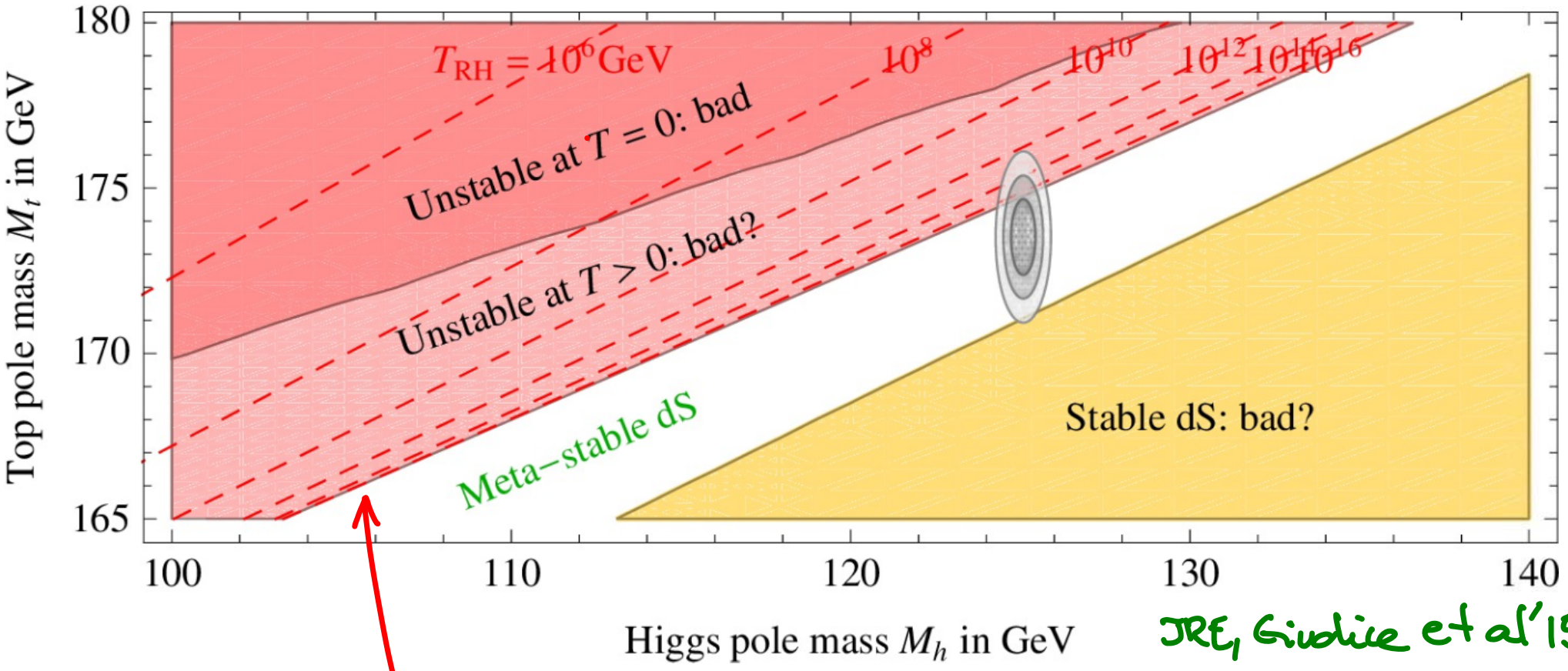
The metastability shouldn't be too strong :



$\tau_{decay} > \tau_U$

NO QUANTUM GRAVITY ON dS

Might need to survive also at high T :



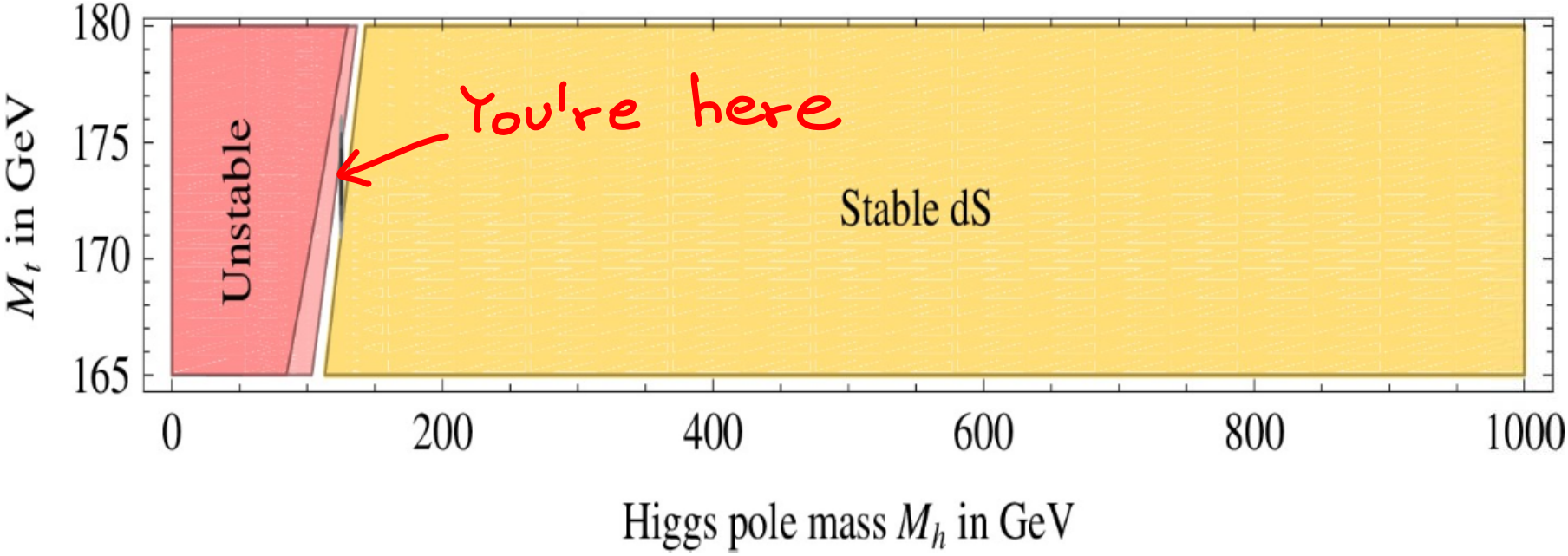
JRE, Giudice et al'15

Also forbidden if large T_{RH} is required
(eg in some solutions of the matter-antimatter pb.)

NO QUANTUM GRAVITY ON dS

SM already offers a way out

provided we live in a very special place:



CONCLUSIONS

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

★ $M_h \simeq 125$ GeV

⇨ Unstable EW vacuum in SM ($\Lambda_I \sim 10^{10}$ GeV)

EW vacuum is Long-lived and intriguingly close to stability boundary Deep meaning of this ?

This instability has implications for

BSM, Cosmology, Quantum gravity in dS, ...

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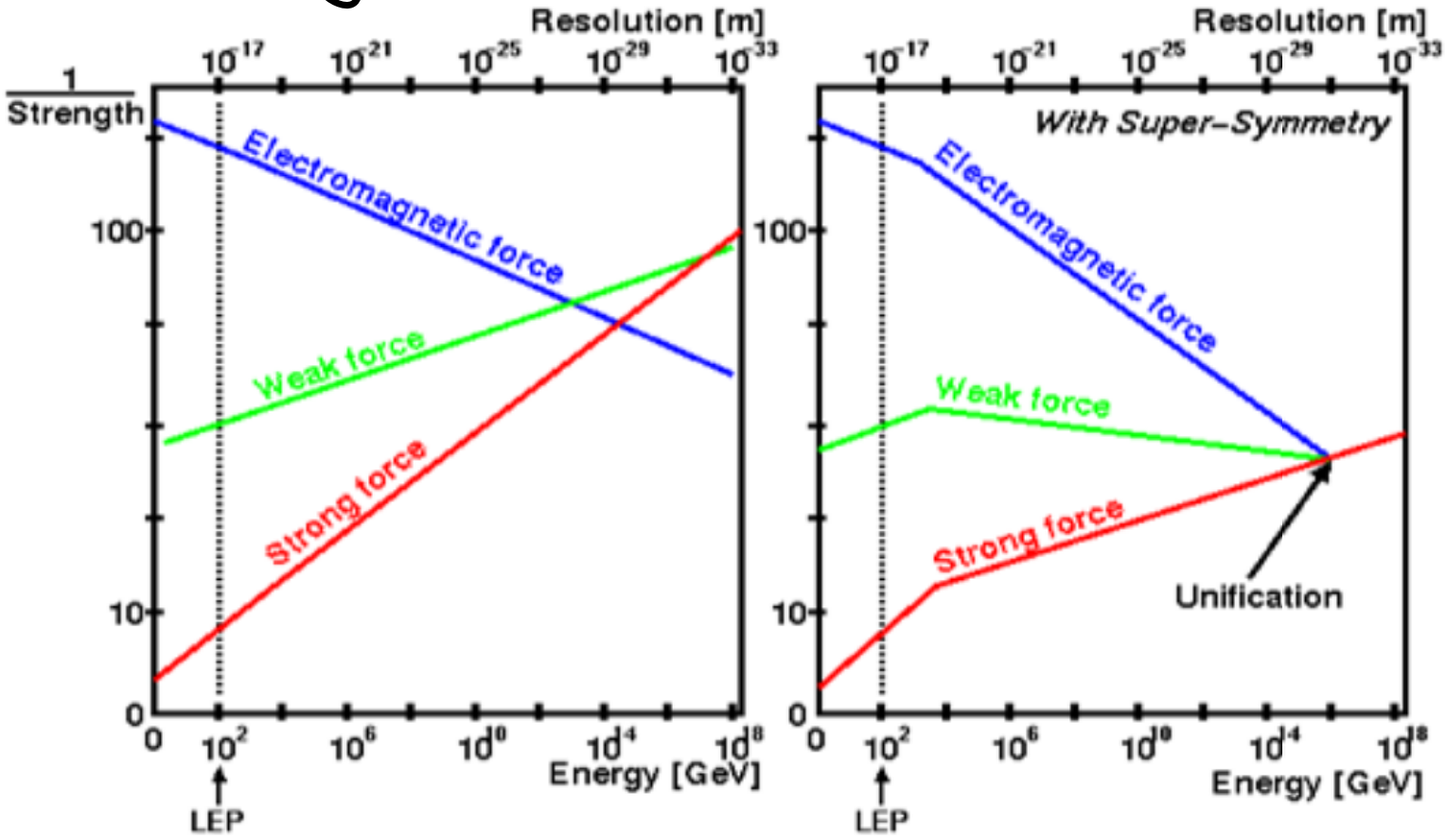
BSM, Cosmology, Quantum gravity in dS, ...

But let's hope for new physics at LHC-II !

BACK-UP SLIDES

AN INTRIGUING HINT FROM LEP

Gauge coupling unification :

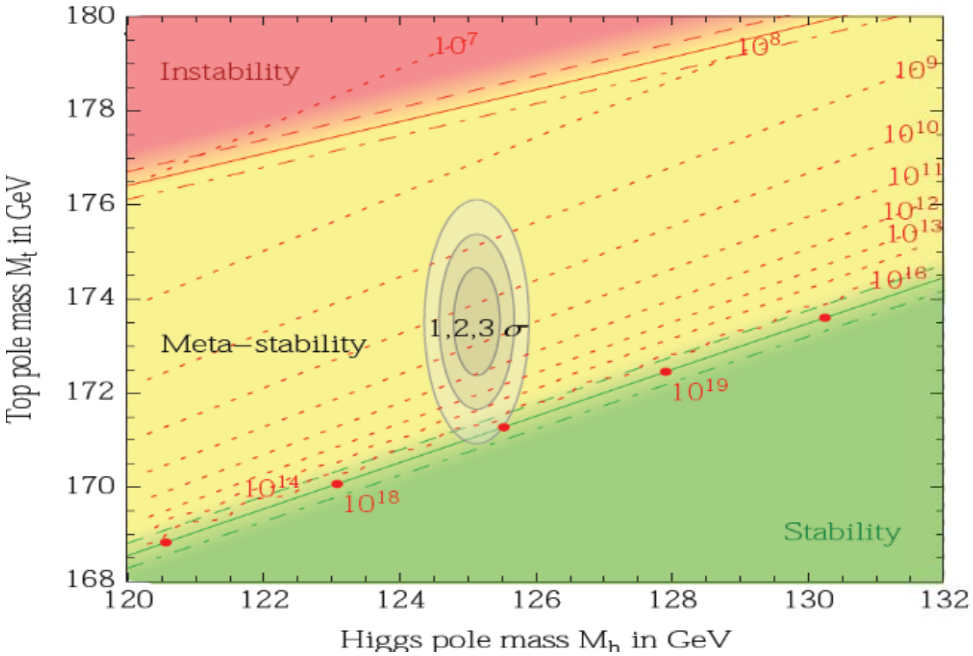


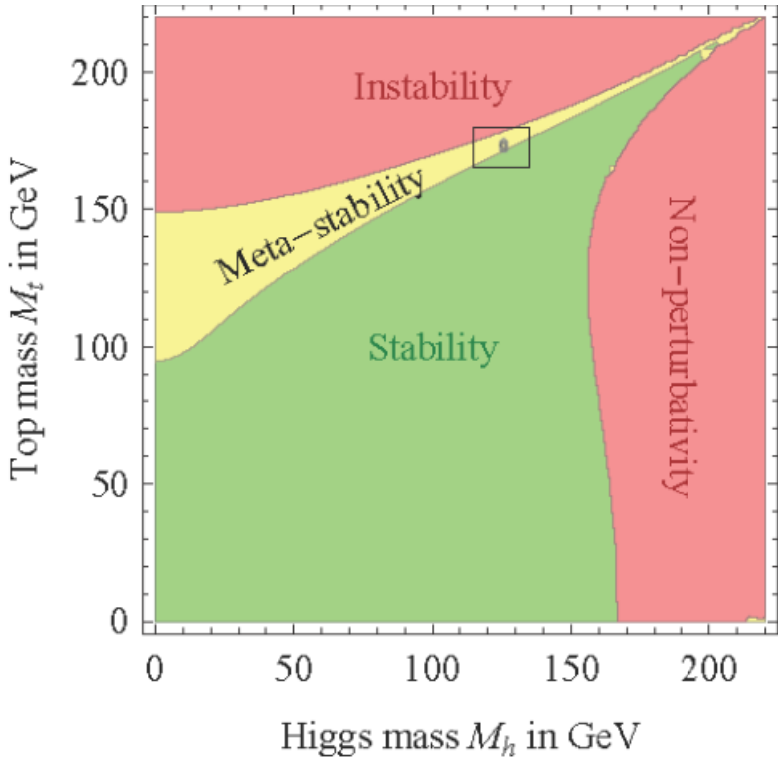
Many effects can upset it, including huge corrections from physics at the unification scale.

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