Electroweak metastability and Higgs Inflation

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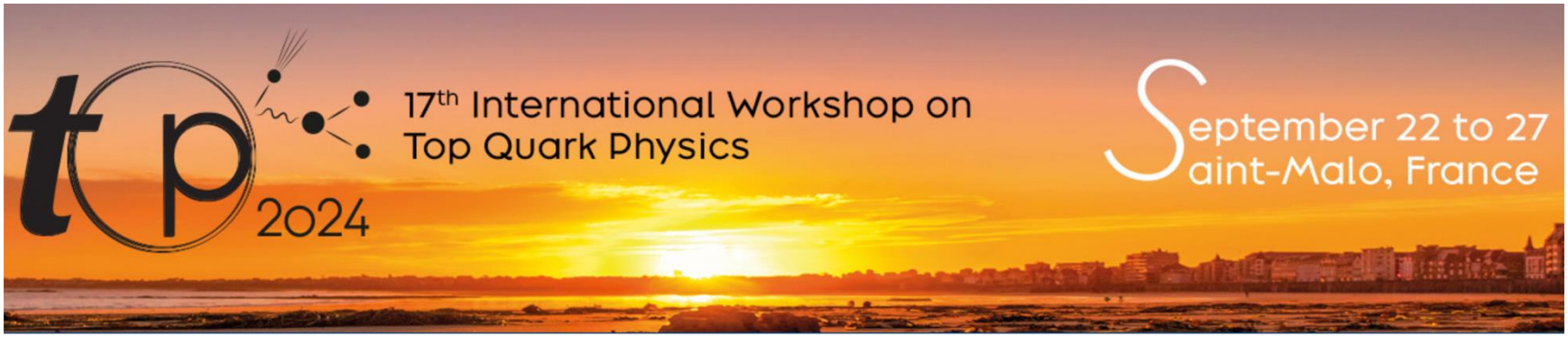


PLAN

1) Review of stability/metastability of the Higgs potential in the SM

→ focus on the shape of the SM Higgs potential around “criticality”

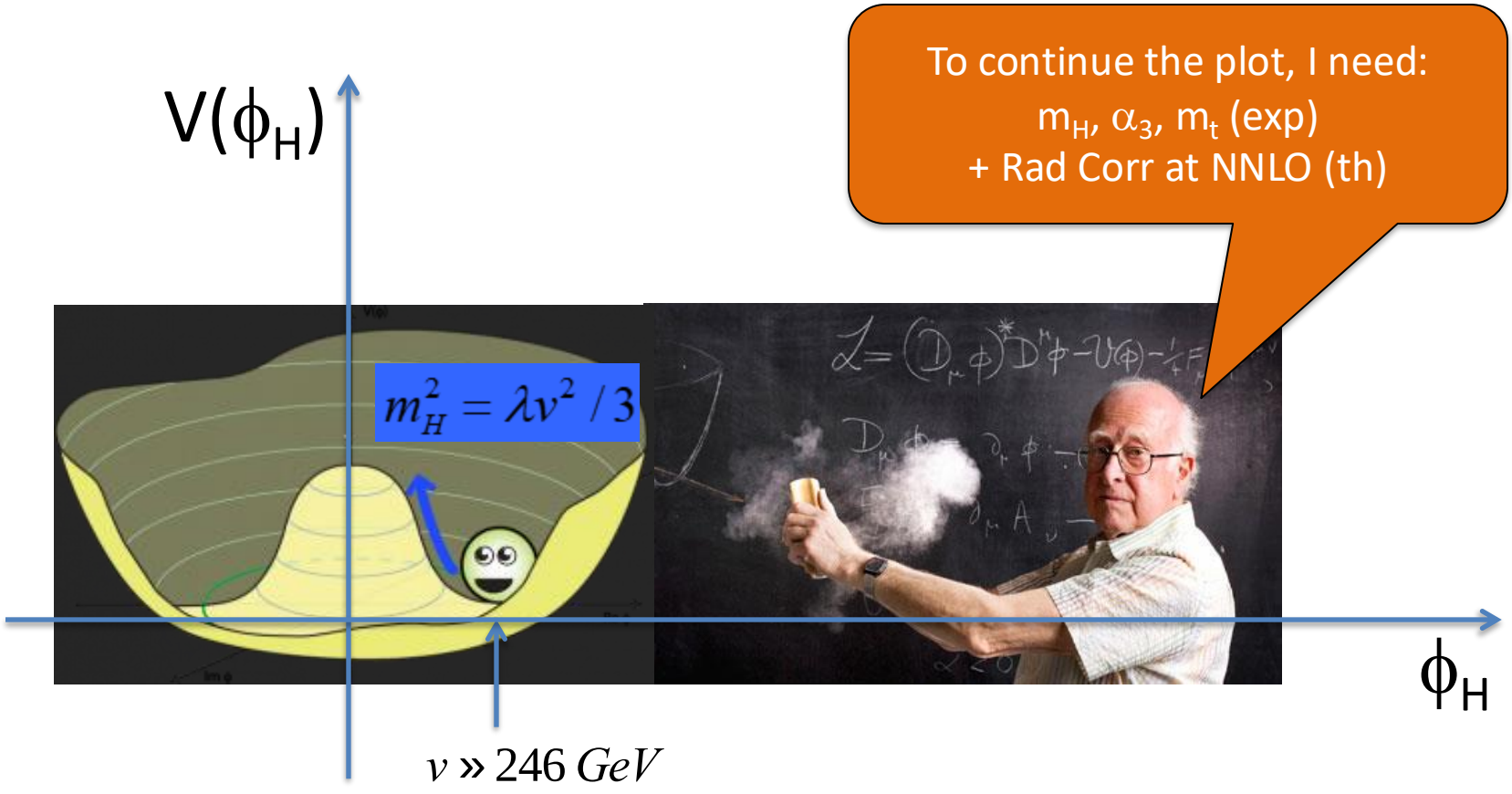
2) Review of inflation and why BSM physics is needed

3) Higgs inflation, i.e. adding a non-minimal coupling to gravity

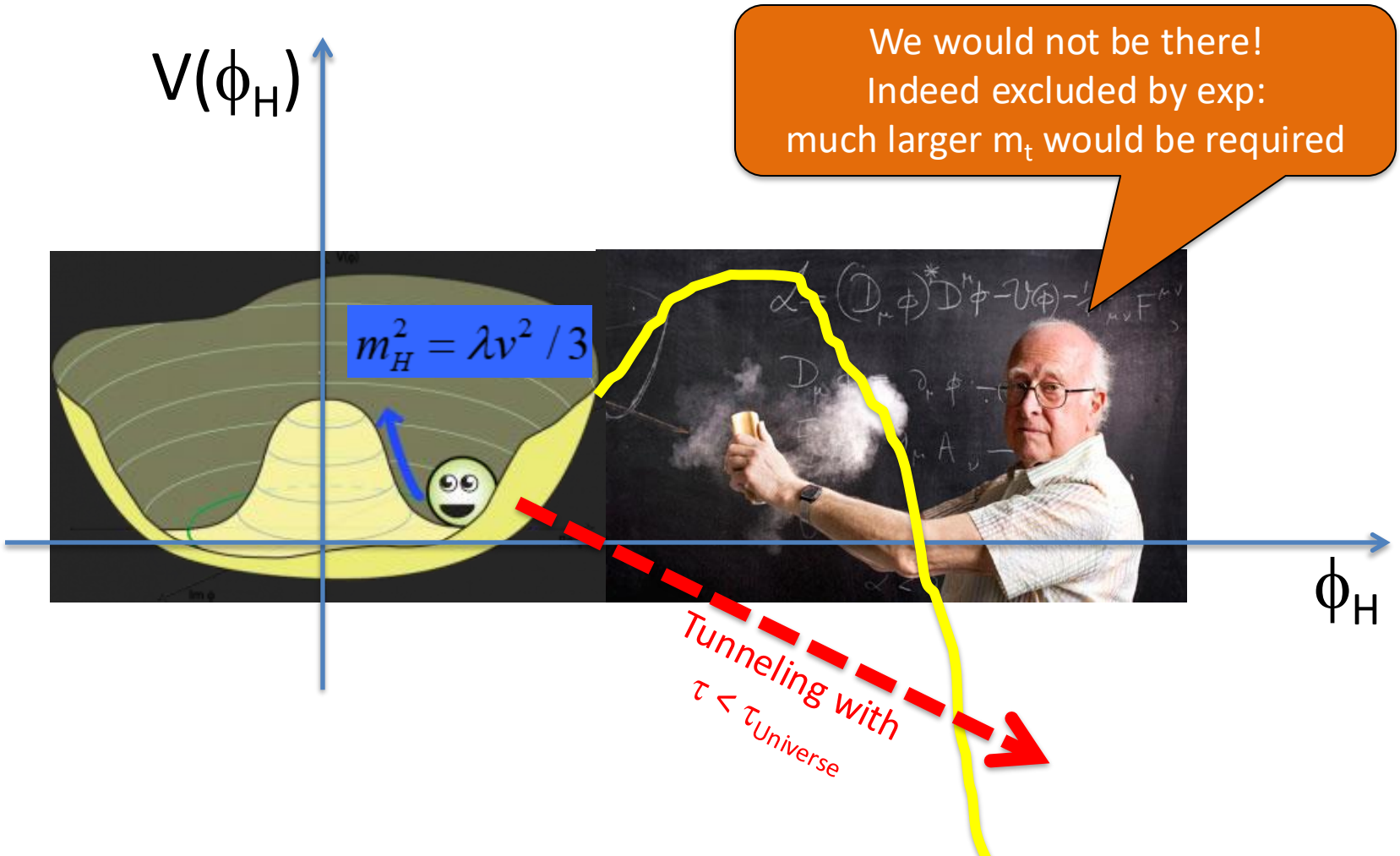
→ works also for some metastable configurations! [Masina Quiros 2403.02461]

4) Conclusions and perspectives

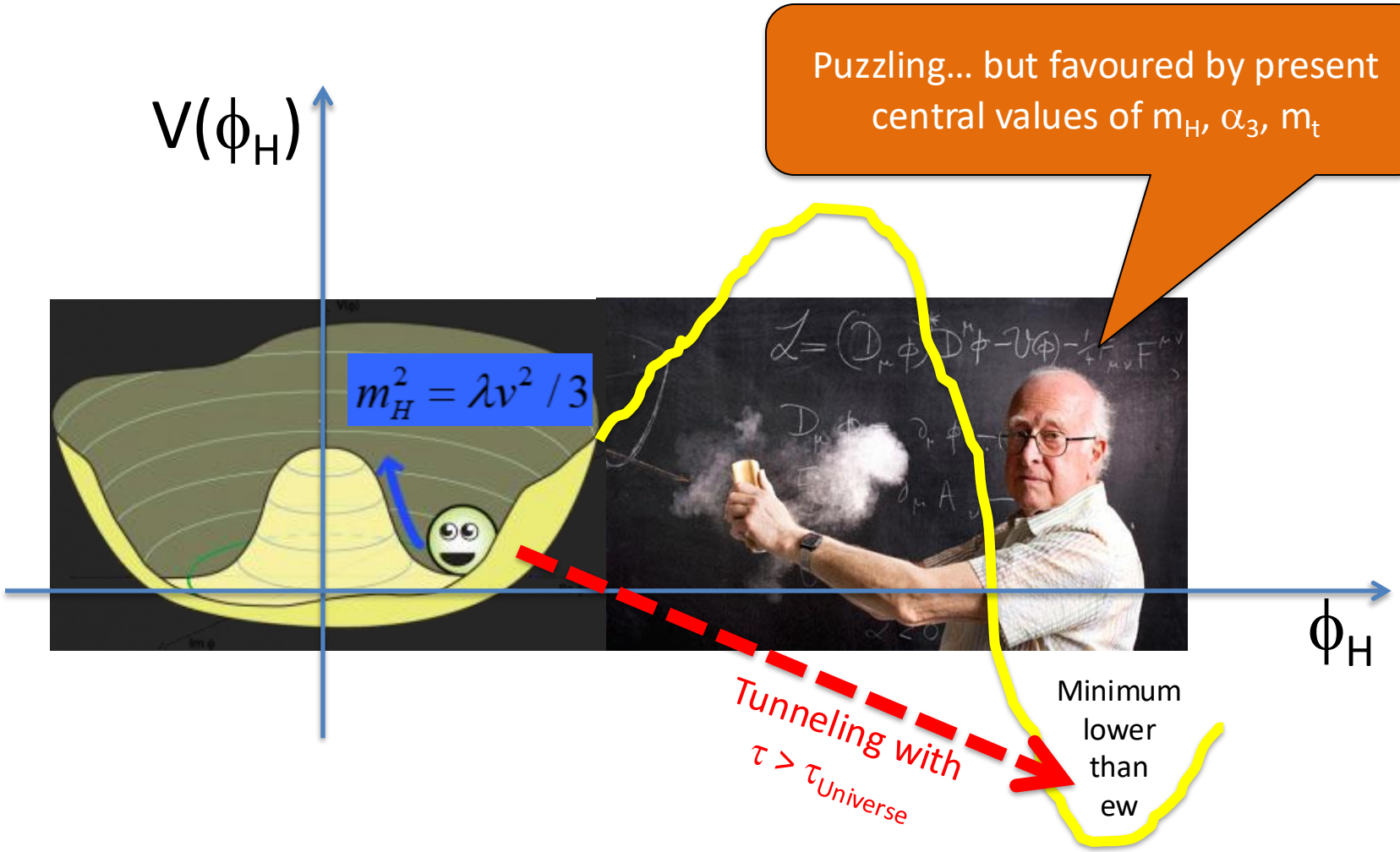
Consider the Higgs doublet $H = (0, (\phi_H + v)/\sqrt{2})$ and the SM Higgs effective potential



Scenario 1: INSTABILITY

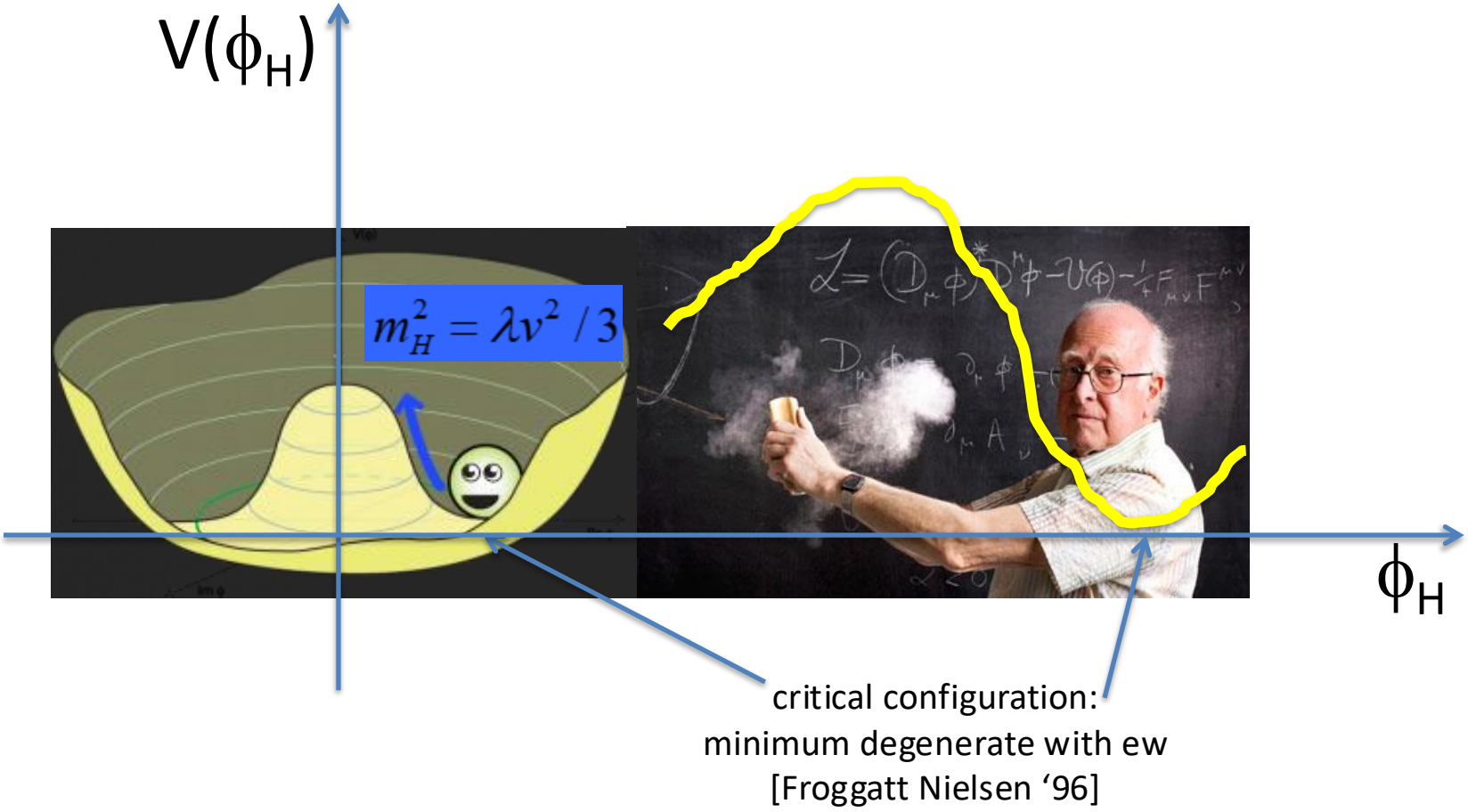


Scenario 2: METASTABILITY



Scenario 3: STABILITY

… Lowering m_t



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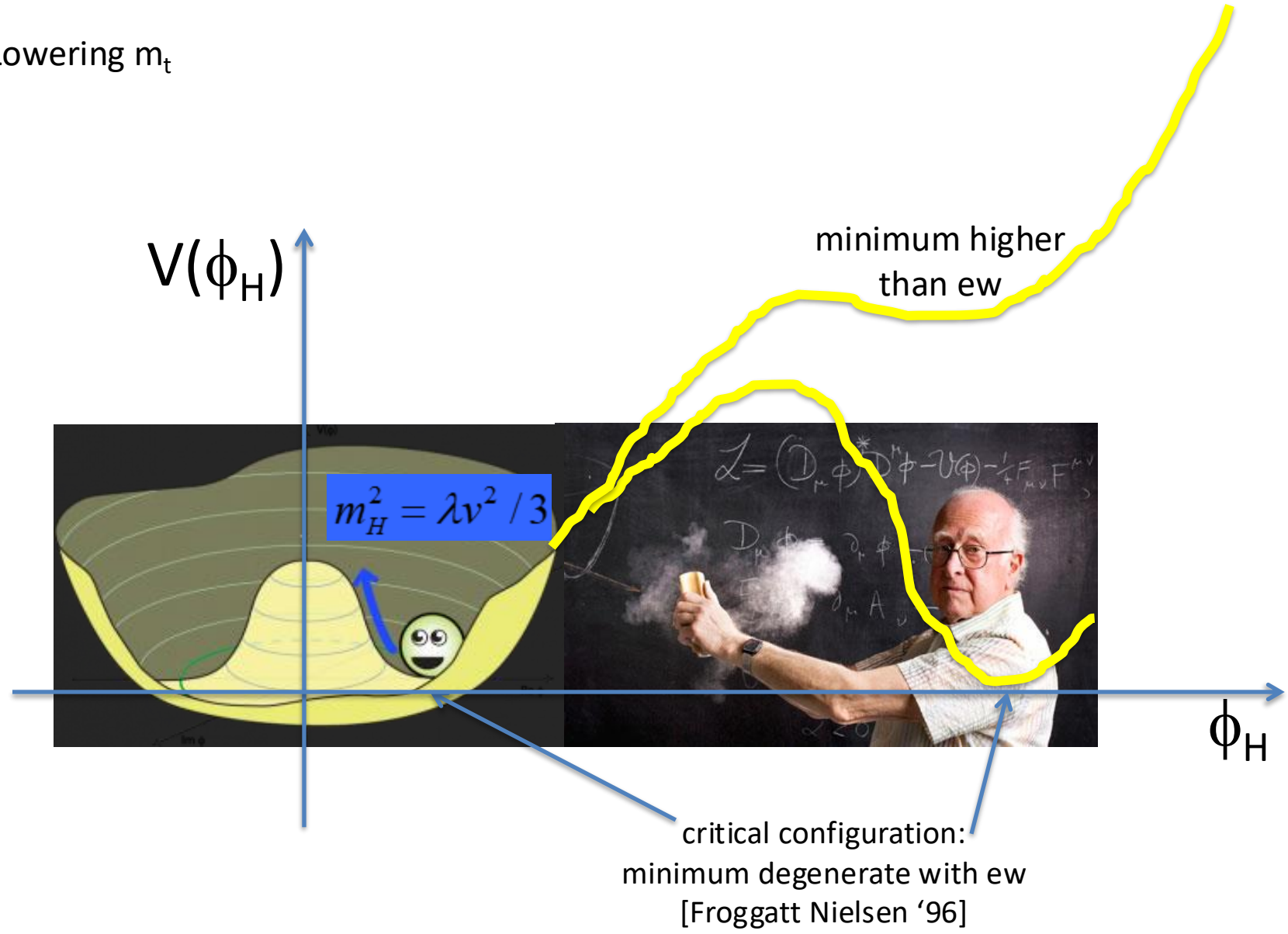

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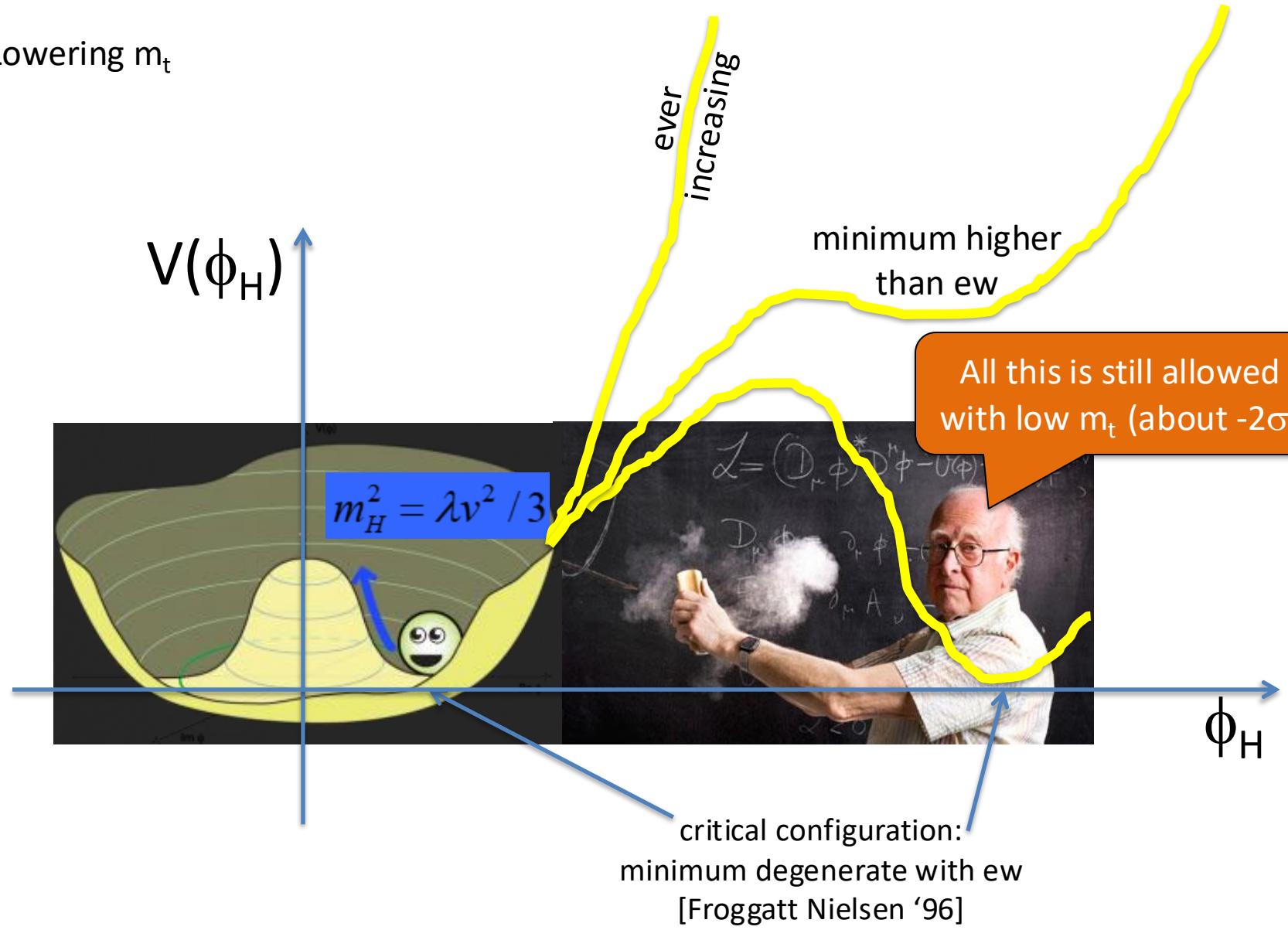
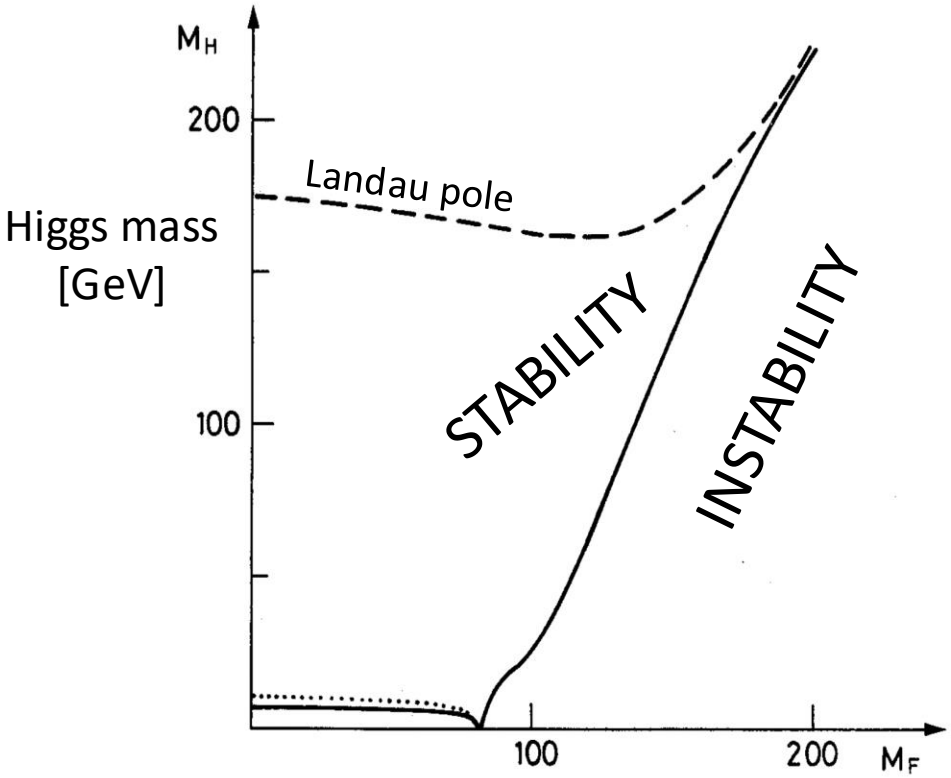
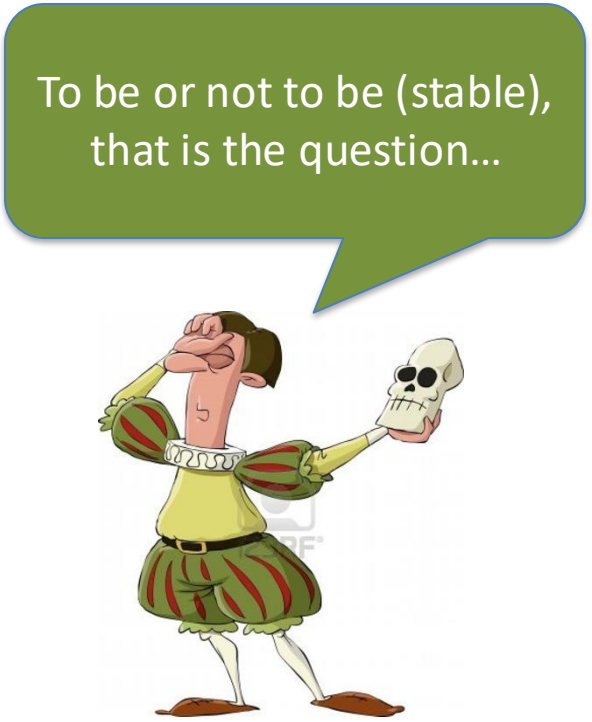


The program of discriminating the scenarios started in fall 70s [Cabibbo…]
(after top prediction in '73, but much before its discovery in '95!)

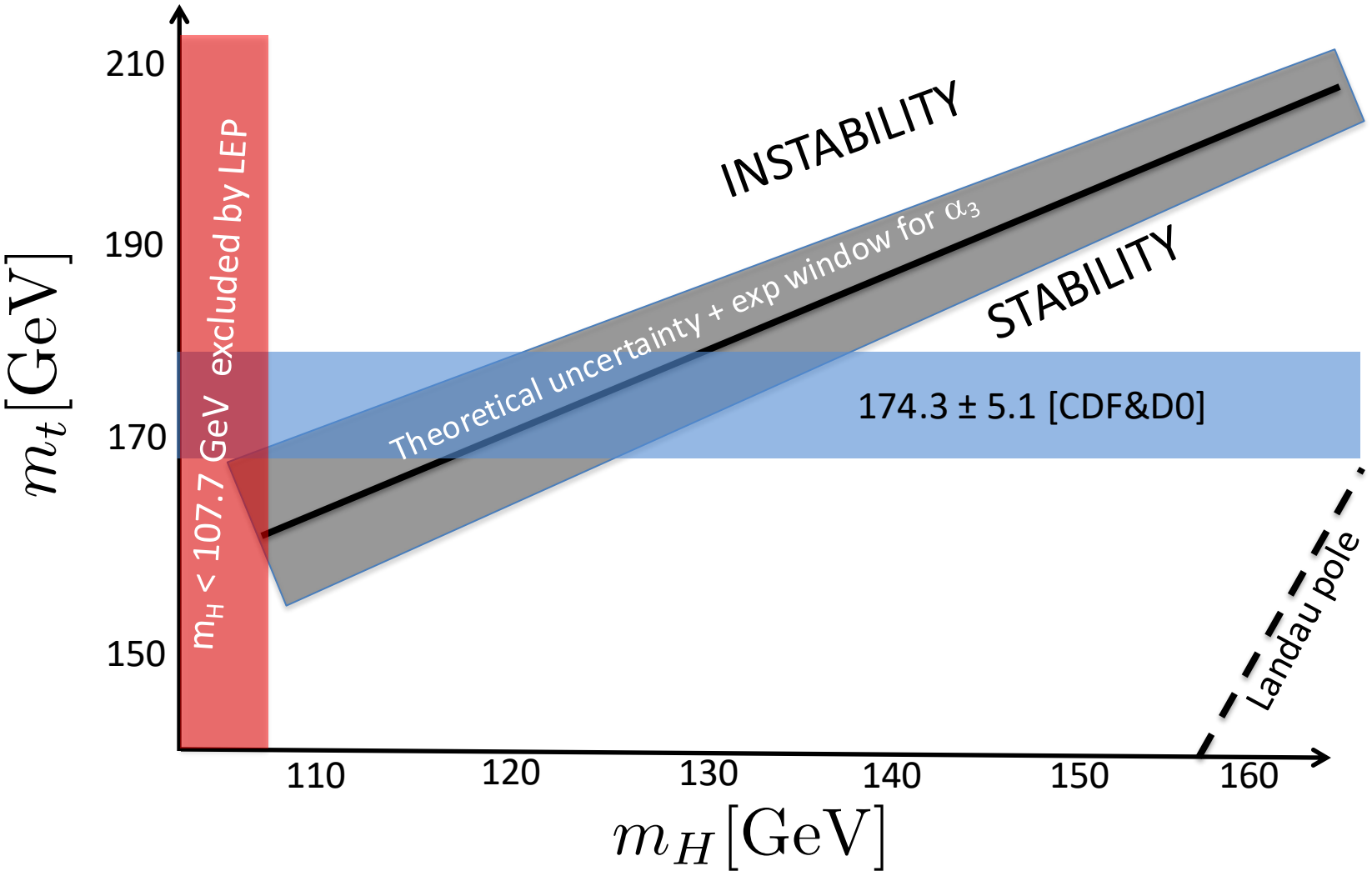
Plot from:
Cabibbo Maiani Parisi Petronzio *Nucl.Phys.B* 158 (1979) 295





How the program evolved: **PDG 2000**

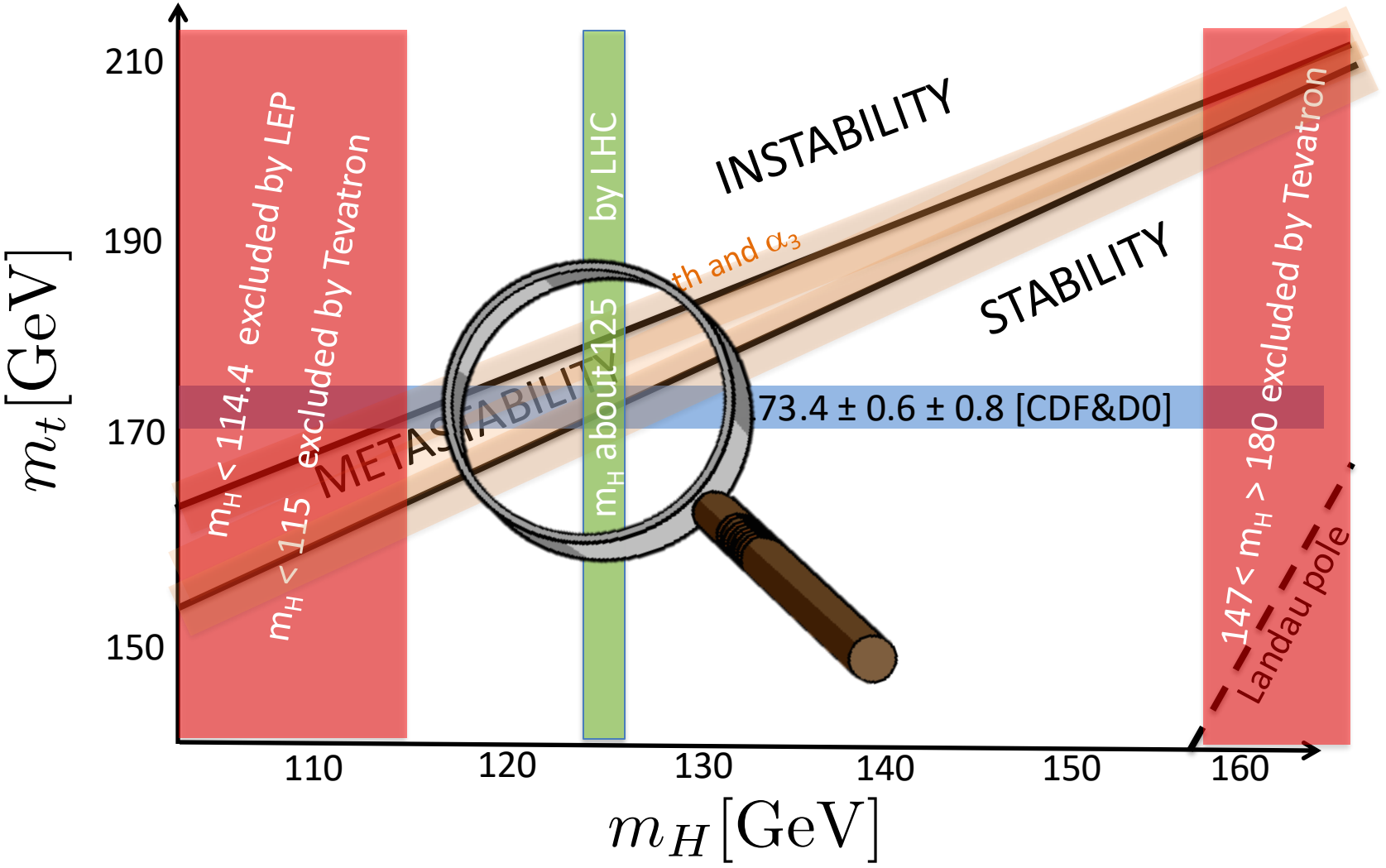
[Casas Espinosa Quiros, Hambye Riesselman, …]



Isidori Ridolfi Strumia hep-ph/0104016 differentiated metastability/instability

How the program evolved: **PDG 2012**

calculation was performed at NLO

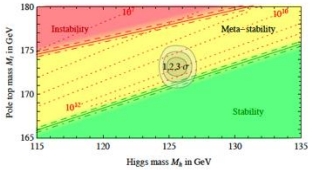


Huge activity followed to improve exp data and push theoretical calculation at NNLO

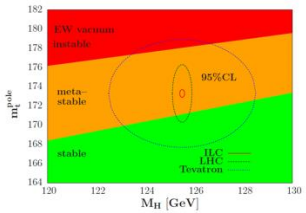
Many groups at work, essentially agreening: here just a selection of few plots and refs

time

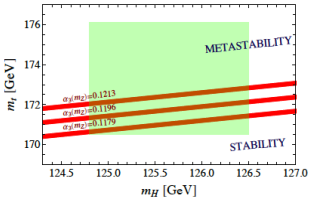
FIRST NNLO by Degrassi et al, arXiv:1205.6497



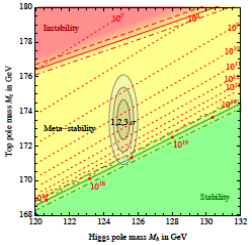
Alekhin et al, arXiv:1207.0980



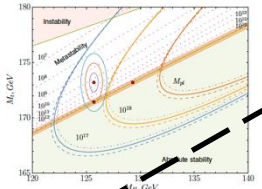
Masina, arXiv:1209.0393



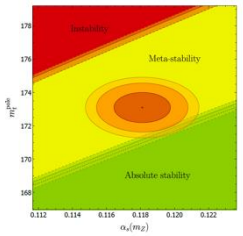
Buttazzo et al, arXiv:1307.3536



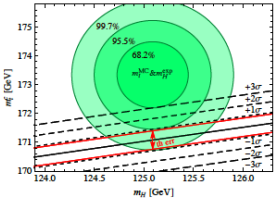
Bednyakhov et al, arXiv:1507.08833



Andreassen et al, arXiv:1707.08124



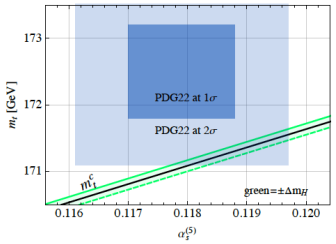
Masina, arXiv:1805.02160



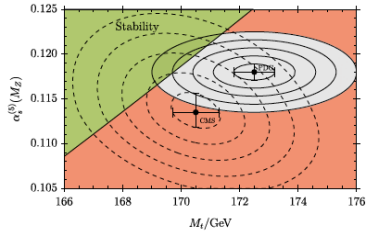
Franceschini et al, arXiv:2203.17197

m_H well known, trade for α_3-m_t plane

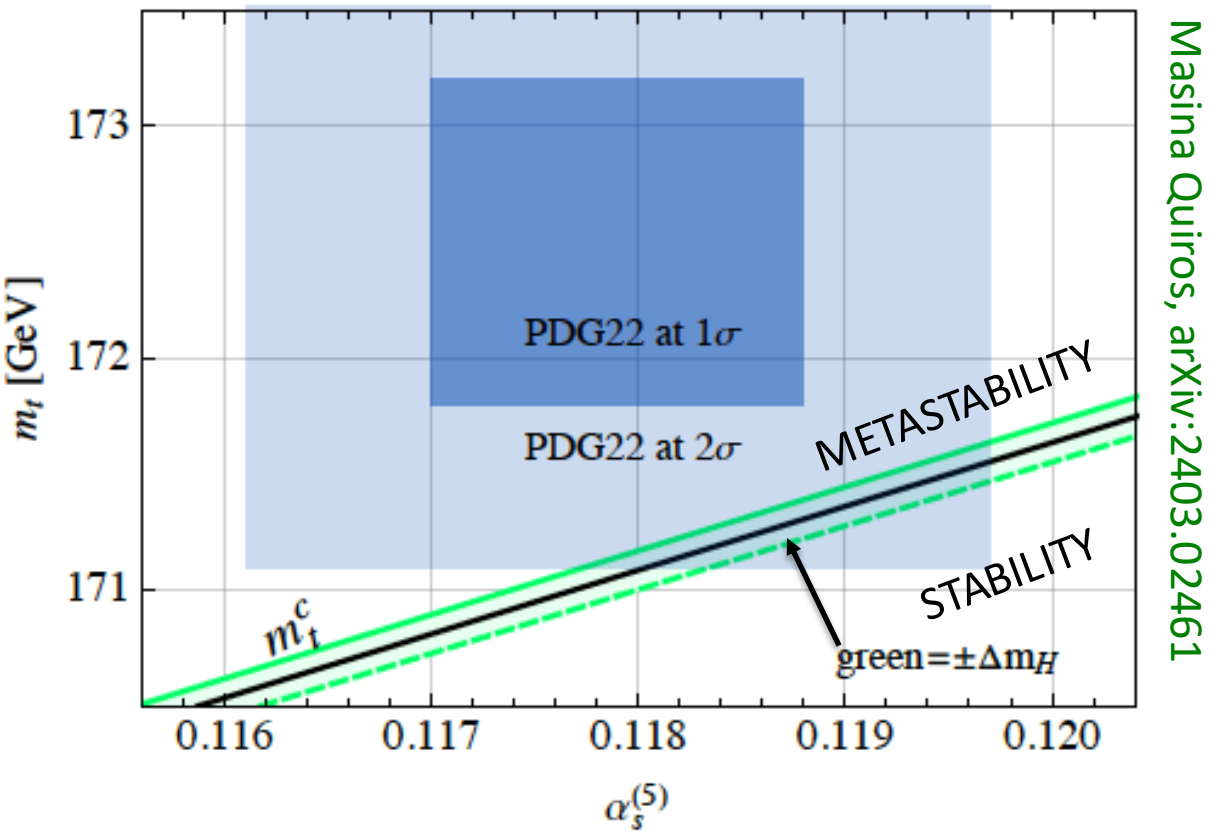
Masina Quiros, arXiv:2403.02461



Hiller et al, arXiv:2401.08811



From our most recent analysis [using PDG22 data]

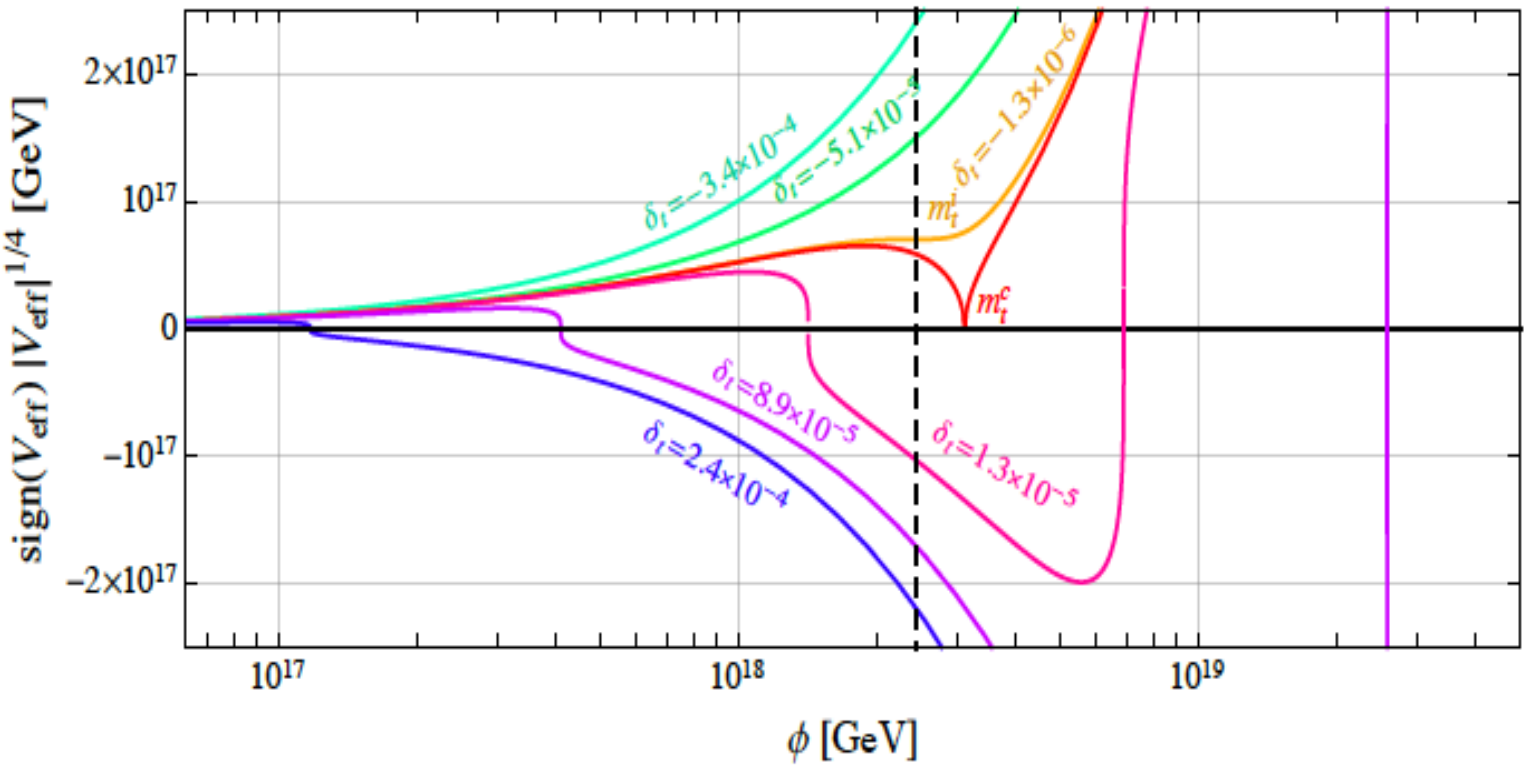


Prospects to discriminate metastability/stability discussed later in this mini-workshop

Focus on the shape of the Higgs potential around criticality (m_t^c ←→ 2 deg vacua)

$$m_t = m_t^c\,(1+\delta_t)$$

A fractional deviation $\delta_t=10^{-4}$ from m_t^c (i.e. ± 0.017 GeV from m_t) has a drastic effect!



Masina Quiros, arXiv:2403.02461

The Higgs is the ONLY elementary scalar found…
could it be involved in primordial inflation?

PLAN

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2) Review of inflation and why BSM physics is needed

3) Higgs inflation, i.e. adding a non-minimal coupling to gravity

→ works also for some metastable configurations! [Masina Quiros 2403.02461]

4) Conclusions and perspectives

Basic idea of inflation: introduce a homogeneous scalar «inflaton» field ϕ

if, for some reason, there has been a period in which the Hubble rate H was dominated by a positive nearly constant potential V(ϕ)

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = H(t)^2 \approx \frac{8\pi}{3}\frac{V(\phi)}{M_P^2} > 0$$

V acts as "dark energy"

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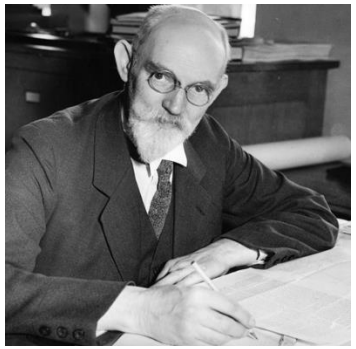

$$a(t) \propto e^{H\,t}$$

EXPONENTIAL EXPANSION
of the scale factor for an empty (no matter) de Sitter universe

Can explain:
flatness, isotropy and homogeneity, …

… but the inflationary period should end (after about N=60 efolds), leading also to matter production via (re)heating

Dynamics of the inflaton is of Klein-Gordon type (new inflation type)

typically negligible

$$\ddot{\phi} = -3H\dot{\phi} - V'(\phi)$$

Hubble damping

← like a ball rolling down a hill

Flat hill
→ slow-roll conditions

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 < 1 \qquad \eta = M_P^2\frac{V''}{V} < 1$$

leads to *nearly scale invariant* (k=aH) density perturbations (seeds for LSS formation)

See PDG22 reviews
for defs:

small

$$\Delta_R^2(k) = \Delta_R^2(k_*)\left(\frac{k}{k_*}\right)$$

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See PDG22 reviews
for defs and exp data:

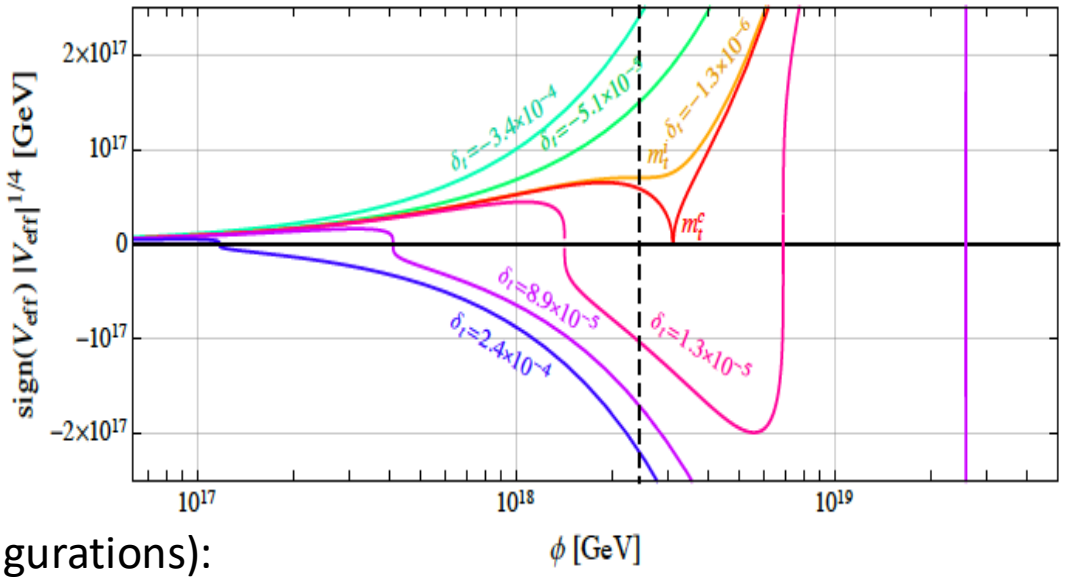
$$\Delta_R^2(k) = \Delta_R^2(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}$$

$n_s - 1$ = - 0.035 ± 0.005

$2.1\text{x}10^{-9} \cong \frac{2}{3\pi^2 r}\frac{V(\phi)}{M_P^4}$ where $r \approx 16\epsilon_* < 0.036$

Is it possible to exploit the SM Higgs potential for inflation?

Given V_{eff} >0 , would you need stability or even metastability would work?



Start from top to bottom
(from stable to metastable configurations):

→ ever increasing: too steep, no slow roll

→ inflection point: a bit of slow roll, but not for enough efolds
[see e.g. Isidori Rychkov Strumia Tetradis, 0712.0242]

→ Higgs trapped in shallow vacuum (old inflation type) + another field as inflaton:
leads to too large r [Masina, 1805.02160]

→ critical & → metastable configurations: do not work

Why shallow vacuum does not work:

[Masina, 1805.02160]

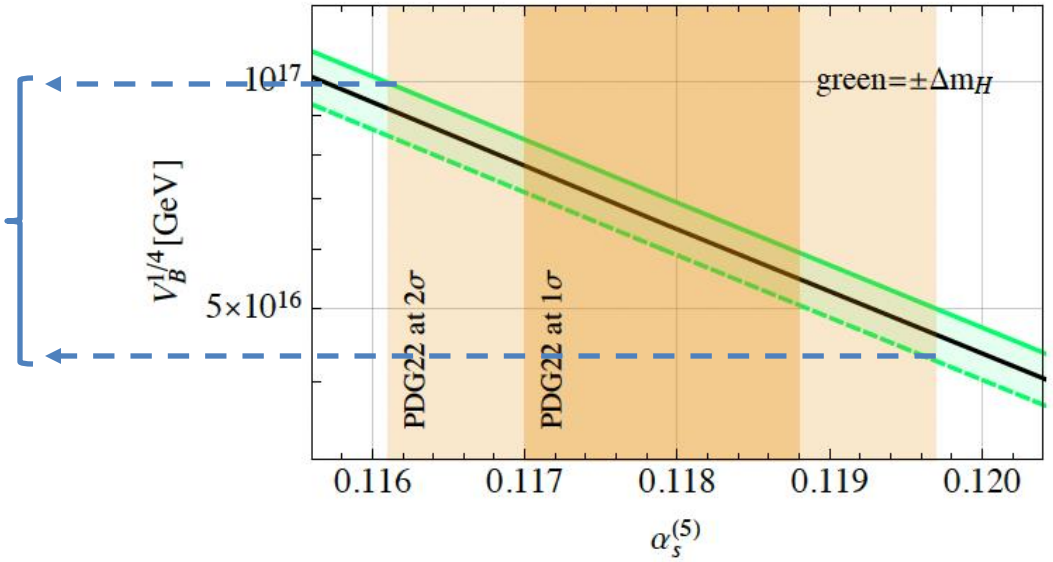
Call $V_B^{1/4}$ the height of the barrier between the ew and «high scale» minimum

$$\frac{V_B^{1/4}}{M_P} \approx \left(\frac{3\pi^2}{2} r \Delta_R^2\right)^{1/4} \approx 1.3 \times 10^{-2} r^{1/4}$$

exp lim on r<0.036 → $V_B^{1/4} < 2.5 \times 10^{16}\,\mathrm{GeV}$

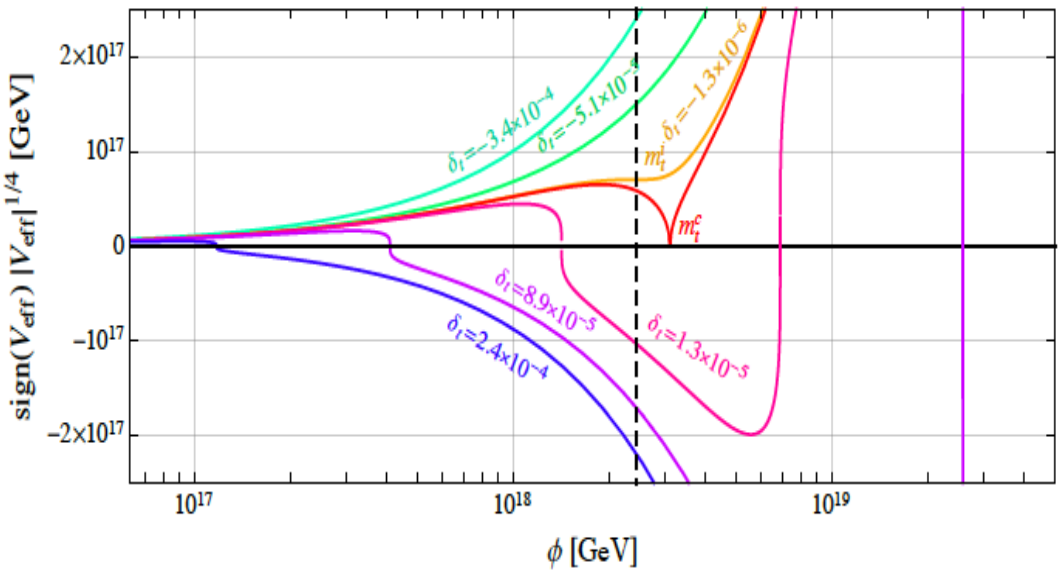
…too small wrt SM prediction!

SM prediction: 5×10^{16} - 10^{17}



Masina Quiros, arXiv:2403.02461

GENERAL LESSON:
need new physics BSM



For instance: something that «flattens» the Higgs potential at some ϕ,
so that the Higgs itself is the inflaton?

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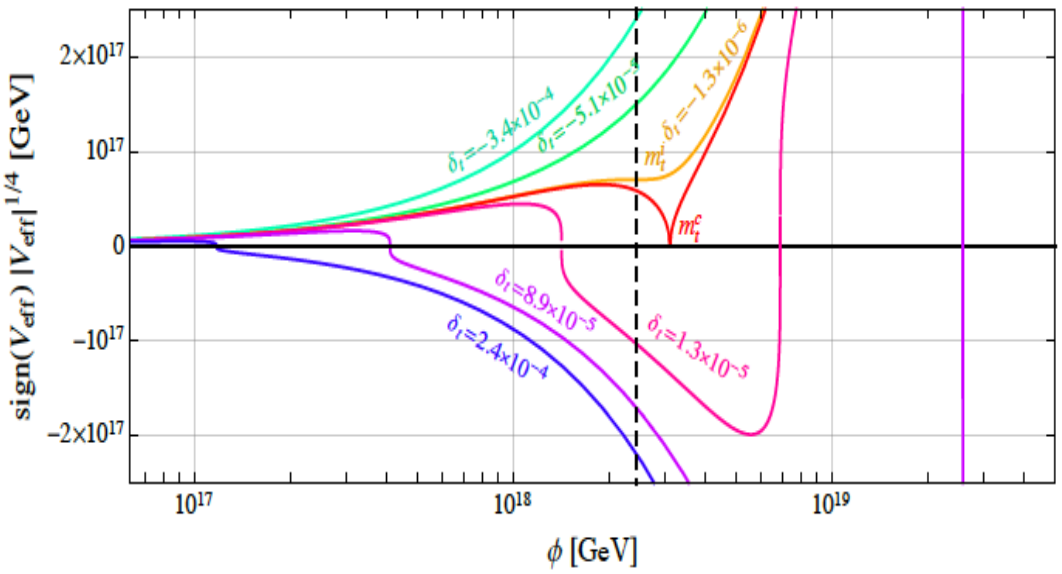

For instance: something that «flattens» the Higgs potential at some ϕ,
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Bezrukov and Shaposhnikov
[Phys. Lett. B659, 703 (2008), arXiv:0710.3755]


Considered stable configurations, and showed this happens
by adding a non-minimal coupling of the Higgs with gravity!

PLAN

1) Review of stability/metastability of the Higgs potential in the SM

→ focus on the shape of the SM Higgs potential around “criticality”

2) Review of inflation and why BSM physics is needed

3) Higgs inflation, i.e. adding a non-minimal coupling to gravity [NON TECHNICAL]

→ works also for some metastable configurations! [Masina Quiros 2403.02461]

4) Conclusions and perspectives

ξ=non-minimal coupling of Higgs with gravity

$1+\frac{\xi\phi^2}{M_P^2}$

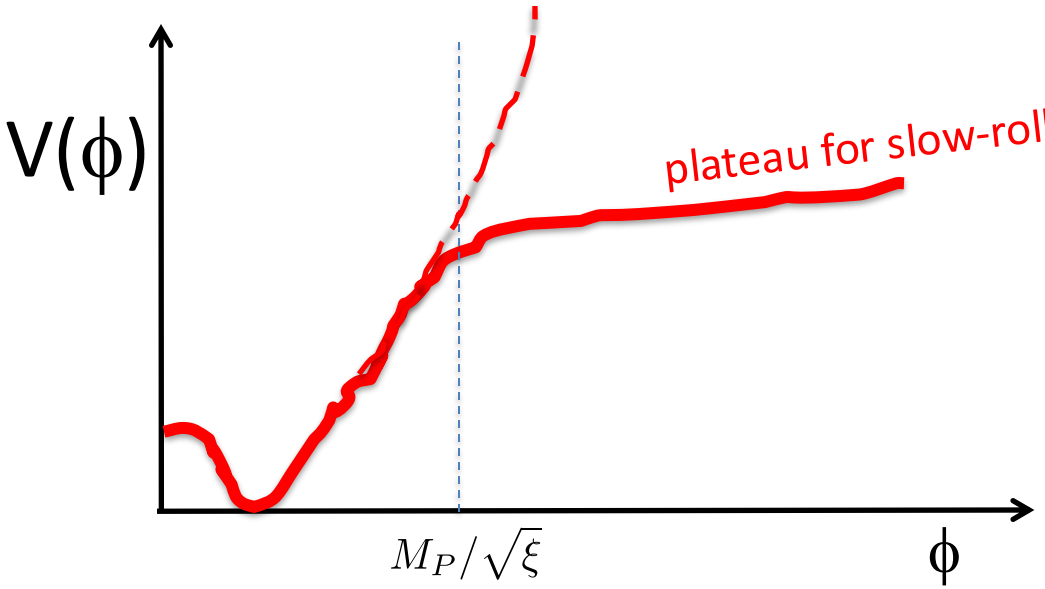
SM Higgs potential

$$S=\int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}f(\phi)R+\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi-V(\phi)\right)$$

upon conformal transformation to Einstein frame and redefinition of Higgs field to have canonical kinetic term

$$S_E=\int d^4x\sqrt{-\hat{g}}\left(-\frac{M^2}{2}\hat{R}+\frac{\partial_\mu\chi\partial^\mu\chi}{2}-V_E(\chi(h))\right)$$

$$\frac{\frac{\lambda}{4}\phi^4}{(1+\frac{\xi\phi^2}{M_P^2})^2}$$



Higgs potential flattened (also including NNLO) at $\phi > M_P/\sqrt{\xi}$

Metric formalism

predictions for N=60: $n_s-1=-2/N\approx-0.033$, $r=12/N^2\approx0.0033$ [as Starobinski inflation]

Substituting r prediction in previous formula

pink line ← $$-2.5 \approx \log_{10}\left(\frac{3\pi^2 r\Delta_R^2}{2}\right)^{1/4} = \log_{10}\frac{V_i^{1/4}}{M_P}$$

→ $V_i^{1/4} \approx 7.6 \times 10^{15}$ GeV
hence pred for ξ

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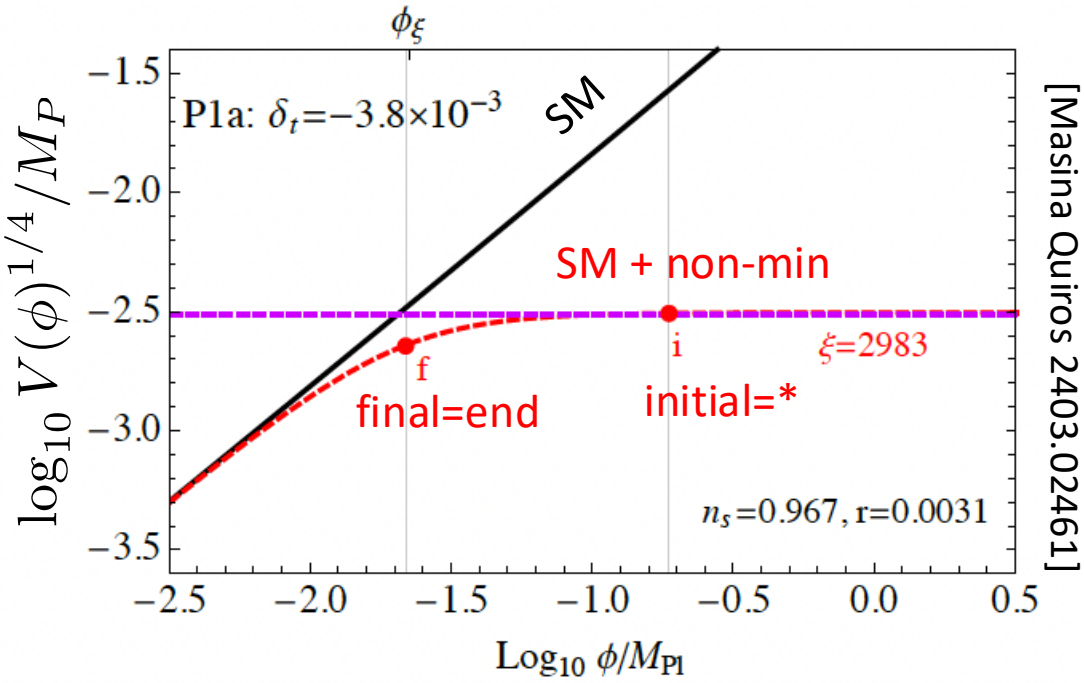
EVER INCREASING
(STABLE CONFIGURATIONS)
+ non-min coupling

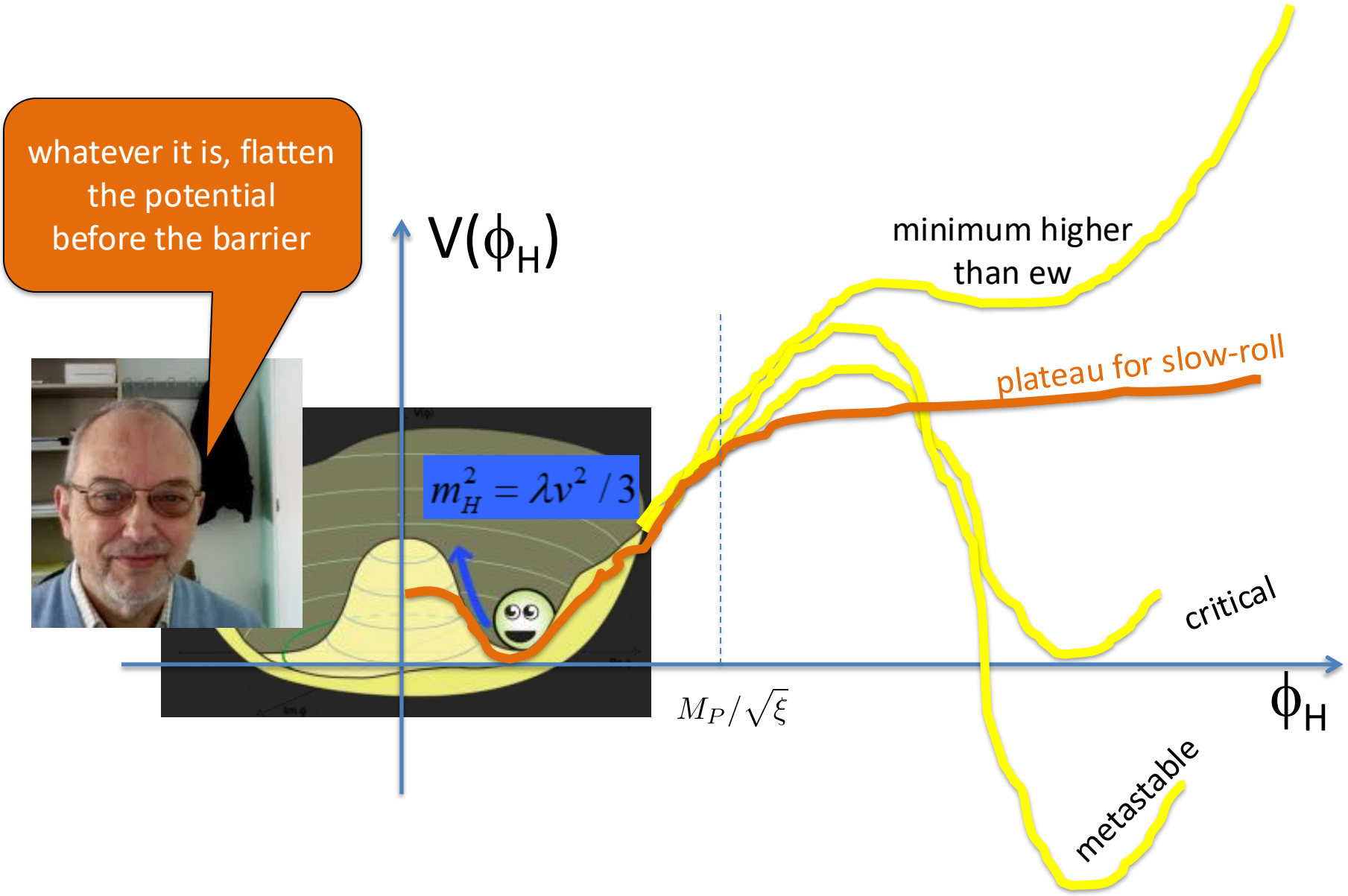
Well known that it works with large ξ=O(3000)



[Masina Quiros 2403.02461]

WHAT ABOUT OTHER CONFIGURATIONS + non-min?

[Masina Quiros 2403.02461]



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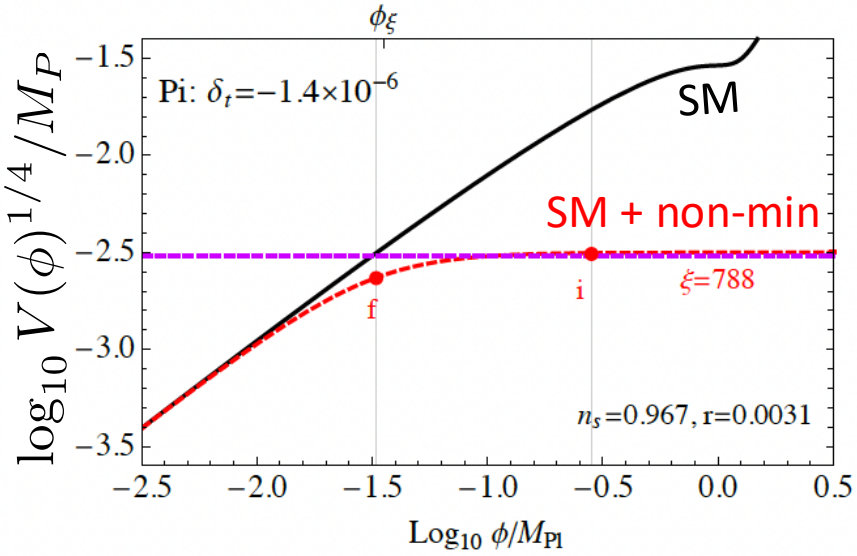
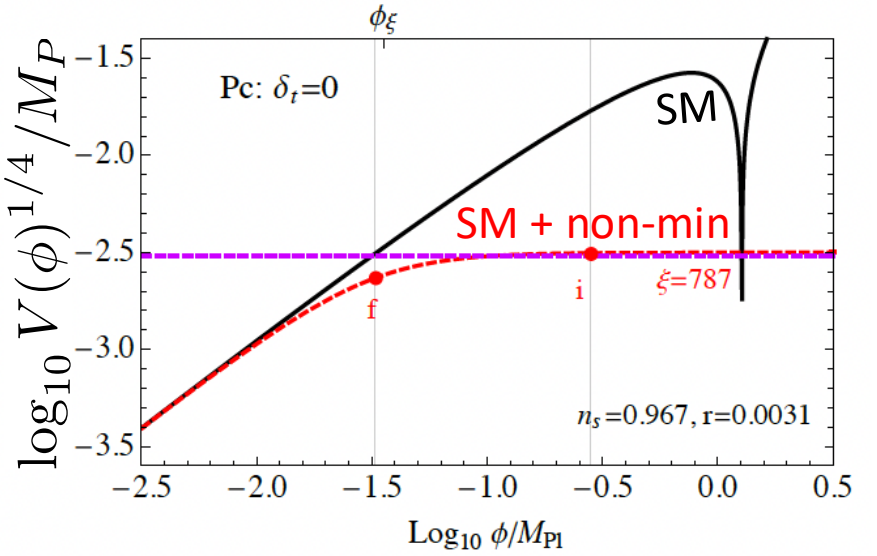
from INFLECTION POINT and SHALLOW MINUM to CRITICAL CONFIG + non-min





[Masina Quiros 2403.02461]

They all work with ξ about 800

Metric formalism

predictions for N=60: $n_s-1=-2/N\approx-0.033$, $r=12/N^2\approx0.0033$

Substituting r prediction in previous formula

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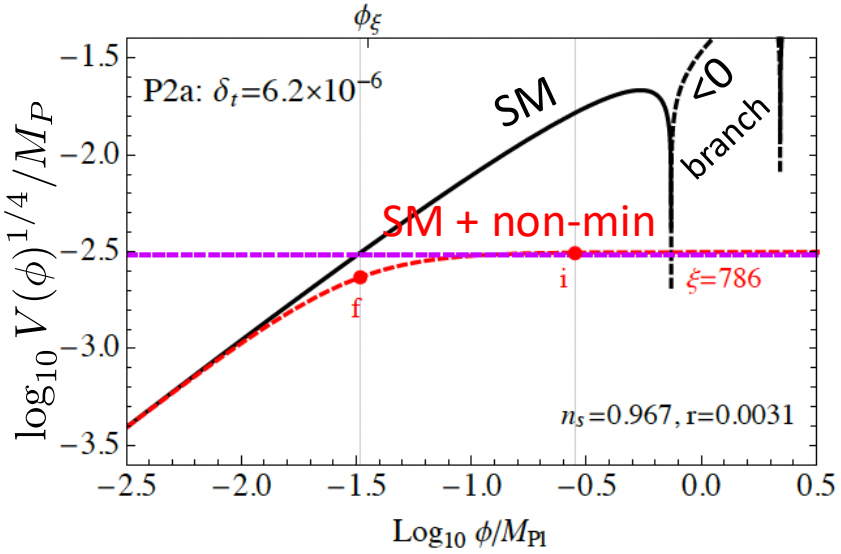
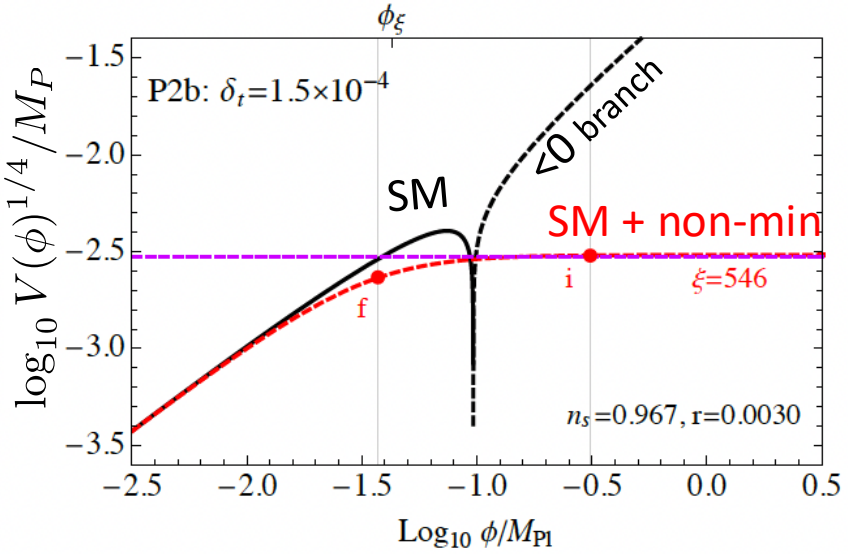
METASTABLE CONFIGURATIONS + non-min

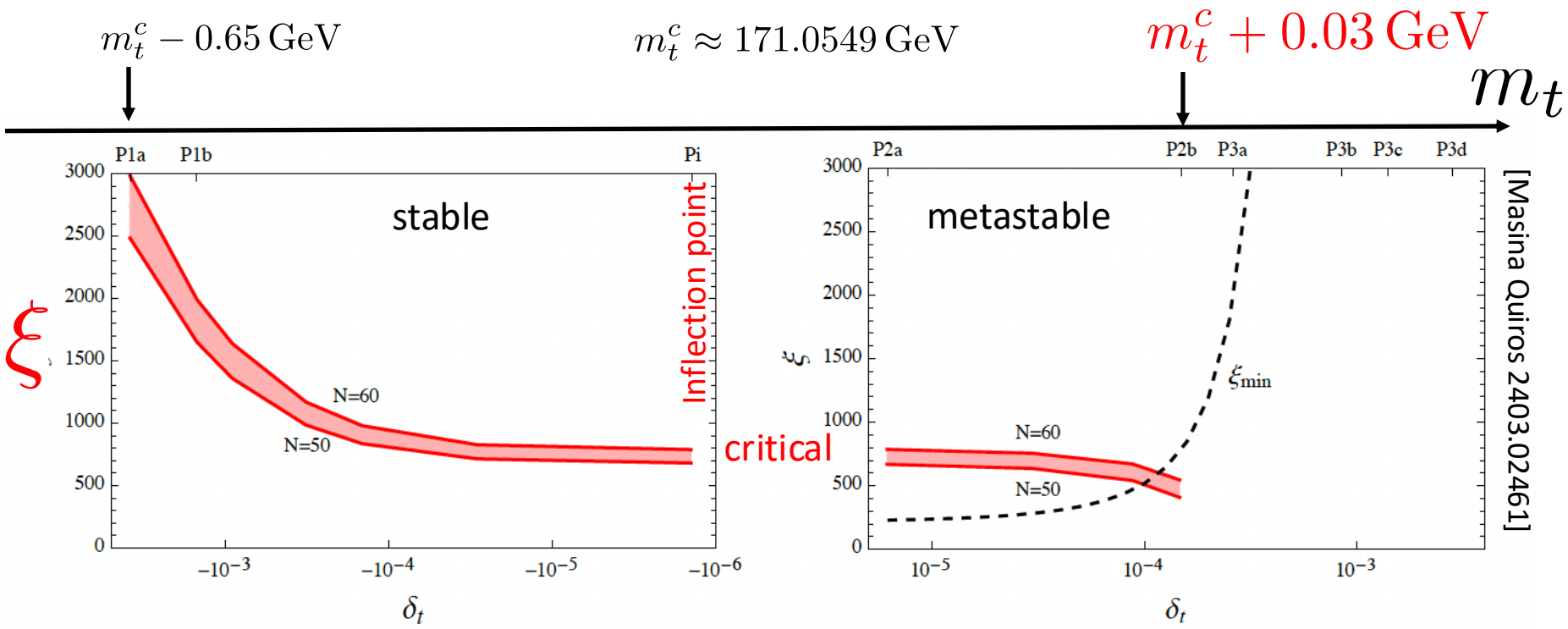




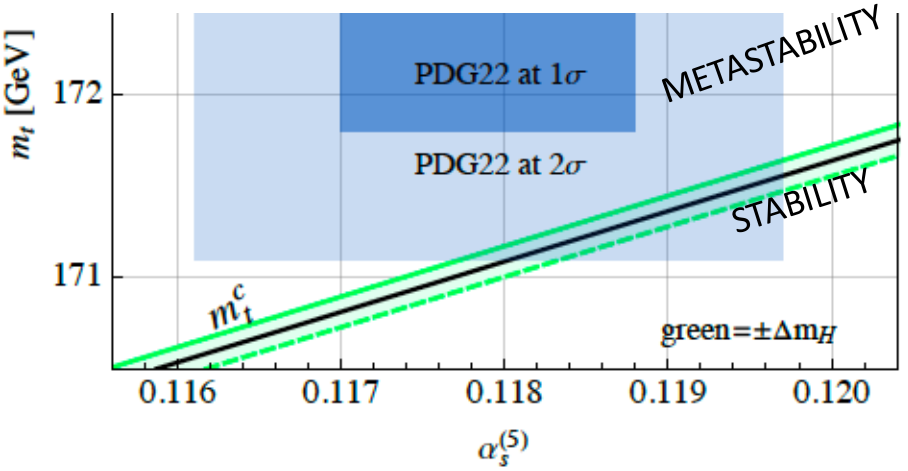
[Masina Quiros 2403.02461]

ξ down to 550 … but stops working when the barrier gets below than pink line

RESULTS for central m_H and α_3



→ Higgs inflation allowed also in a very small (nearly invisible) portion of the metastable region



NO ROSES WITHOUT A THORN…

1) The issue of UNITARITY

Calculation reliable during inflation as now there is agreement that the cutoff Λ at $\phi > M_P/\sqrt{\xi}$ satisfies

$$M_P/\sqrt{\xi} \sim \Lambda > H_f \sim M_P/\xi$$

[Mikura Tada 2110.03925, Ito Khater Rasanen 2111.05621 Kharnanas et al 2203.09534]

→ calculation reliable even for reheating for $\xi<10^3$ [Sfakianakis et al 1810.01304]

2) Which FORMALISM?

Ongoing debate on how to couple matter to gravity:
Palatini (or else) formalism? [see e.g. Gialamas et al 2303.14148]

Palatini: same prediction for n_s=1-2/N, but a different one for r

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→ focus on the shape of the SM Higgs potential around “criticality”

2) Review of inflation and why BSM physics is needed

3) Higgs inflation, i.e. adding a non-minimal coupling to gravity

→ works also for some metastable configurations! [Masina Quiros 2403.02461]

4) Conclusions and perspectives

CONCLUSIONS: TAKE-HOME MESSAGES

1) Intriguing *coincidence* for the values of m_t , m_H and α_3
suggests Higgs potential might be close to *criticality*

2) Need BSM for inflation: conservative possibility is a
non-minimal coupling with gravity, so called *Higgs-inflation*

3) Higgs-inflation works even (better) for *slightly metastable* configurations:

→ up to $m_t = m_t^c + 0.03$ GeV

→ with smaller value of ξ , down to 500
(welcome to avoid unitary issues even at reheating)

PROSPECTS: TOP physicists, keep working hard!