INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

53° Course: THE FUTURE OF OUR PHYSICS INCLUDING NEW FRONTIERS

Erice, 24 June – 3 July 2015

VACUUM STABILITY AND NEW PHYSICS

1

Emanuele Messina

University of Catania
INFN Sez. di Catania

References:

V. Branchina, E. Messina, Phys. Rev. Lett. 111, 241801 (2013) (arXiv:1307.5193);

V. Branchina, arXiv:1405.7864, Moriond 2014;

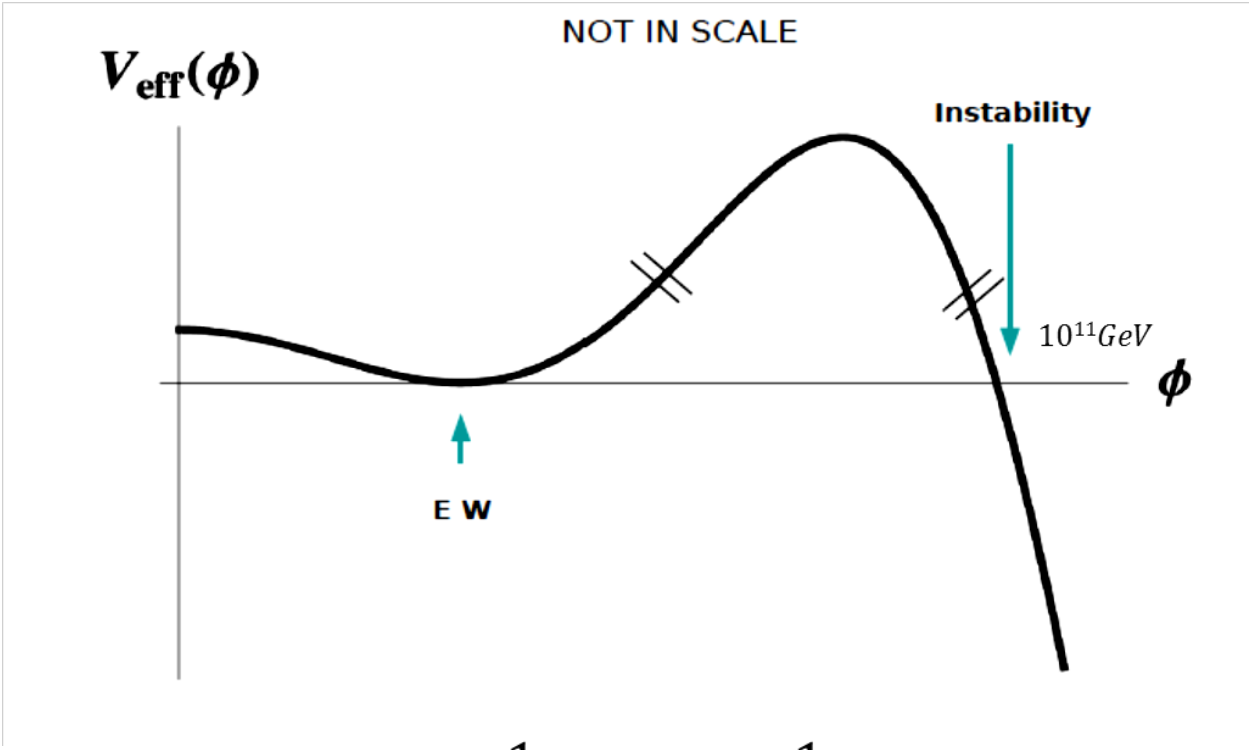
V. Branchina, E. Messina, A. Platania, JHEP 1409 (2014) 182 (arXiv:1407.4112);

V. Branchina, E. Messina, M. Sher, Phys. Rev.D91 (2015) 1, 013003 (arXiv:1408.5302);

V. Branchina, E. Messina, in preparation;

INSTABILITY

- The experimental results agree with the Standard Model predictions
- No sign of New Physics… → SM valid up to M_P ?



$$M_t = 173.34\ GeV\ (\pm 0.76\ GeV)$$
$$M_H = 125.09\ GeV\ (\pm\ 0.3\ GeV)$$

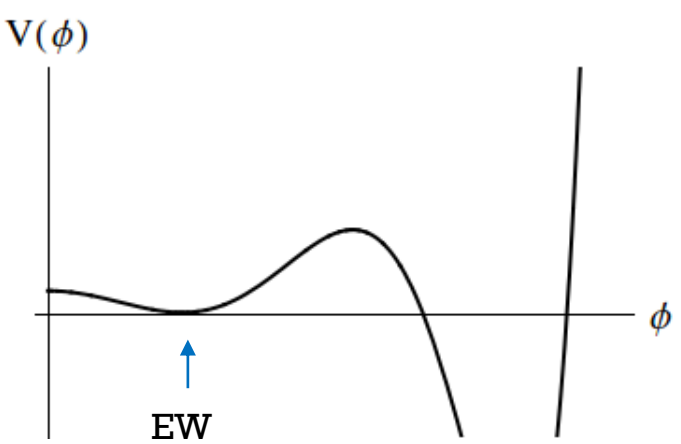
Φ : Higgs Field

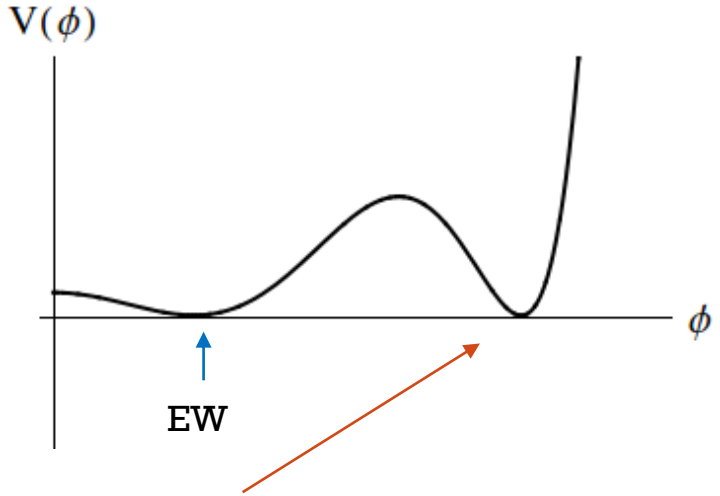
V_{eff} : Effective Potential

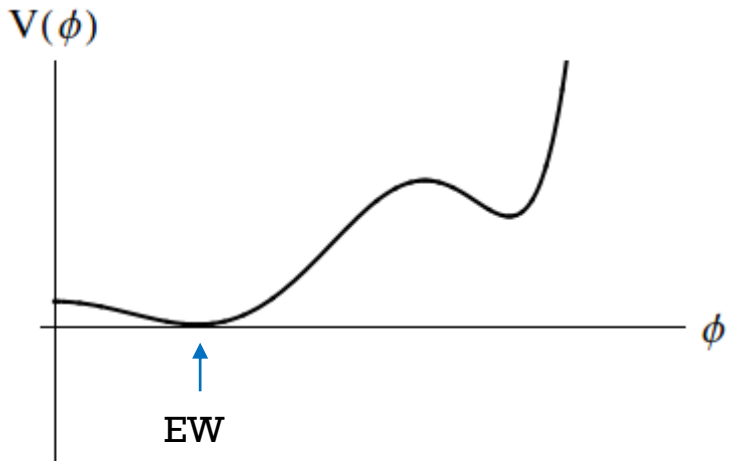
$$V_{eff}(\Phi) = \frac{1}{2}m^2\Phi^2 + \frac{1}{4}\lambda(\Phi)\Phi^4$$

SM interactions only

$\lambda(\Phi)<0$ The vacuum is unstable !!



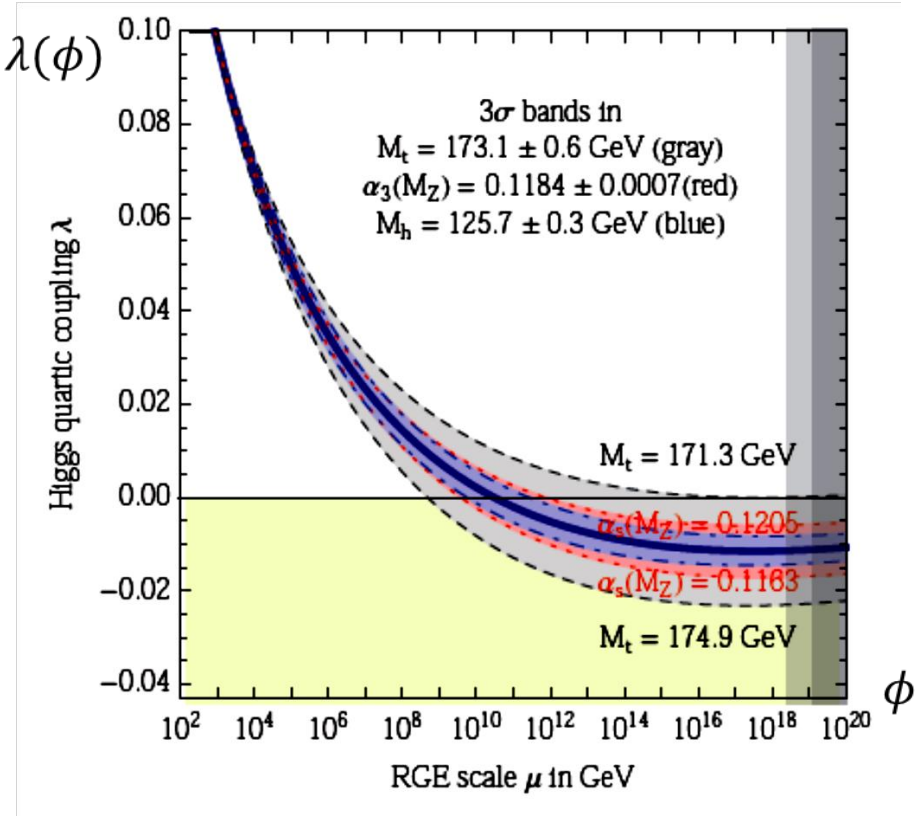




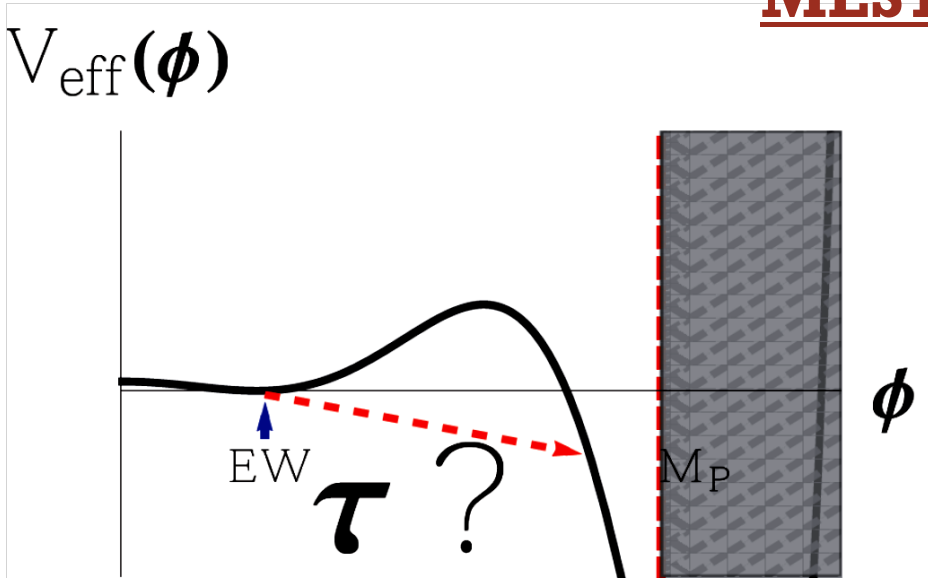
CRITICAL CONDITION

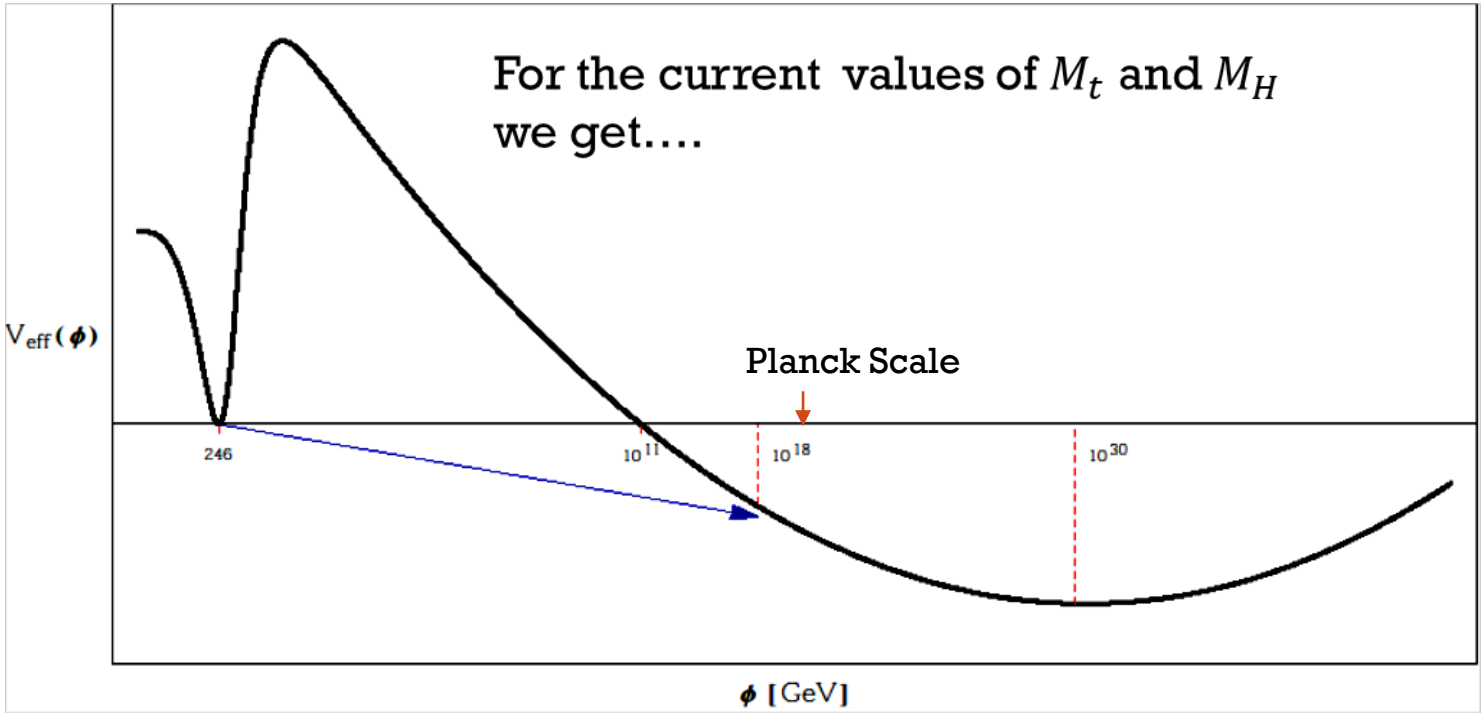
$$V_{eff}(\phi) \sim \frac{\lambda(\phi)}{4}\phi^4$$ *(SM interactions only)*

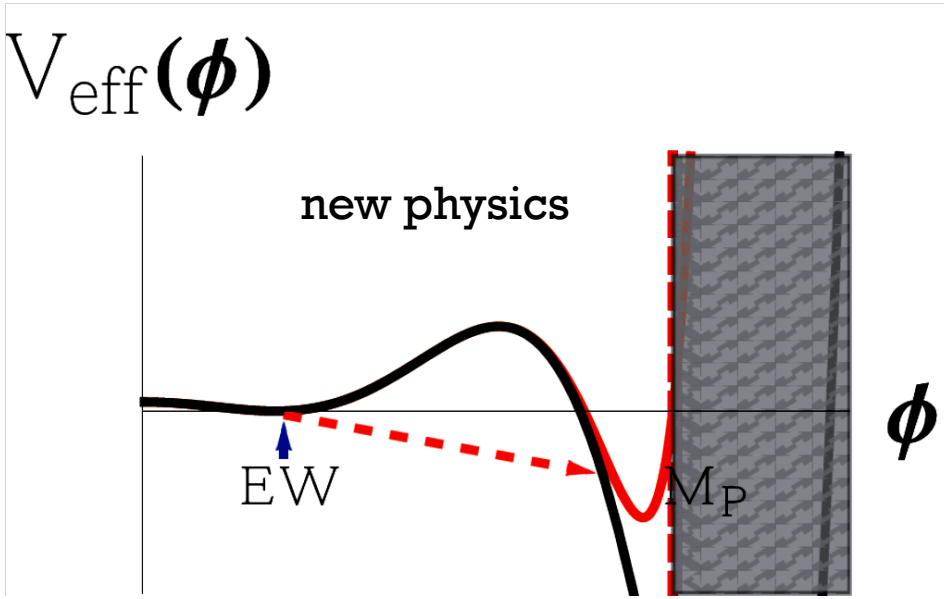
$V_{eff}(\phi) < V_{eff}(EW)$	for some ϕ	'UNSTABLE'
$V_{eff}(\phi) = V_{eff}(EW)$		CRITICAL LINE
$V_{eff}(\phi) > V_{eff}(EW)$	for all ϕ	STABLE



MESTABILITY SCENARIO





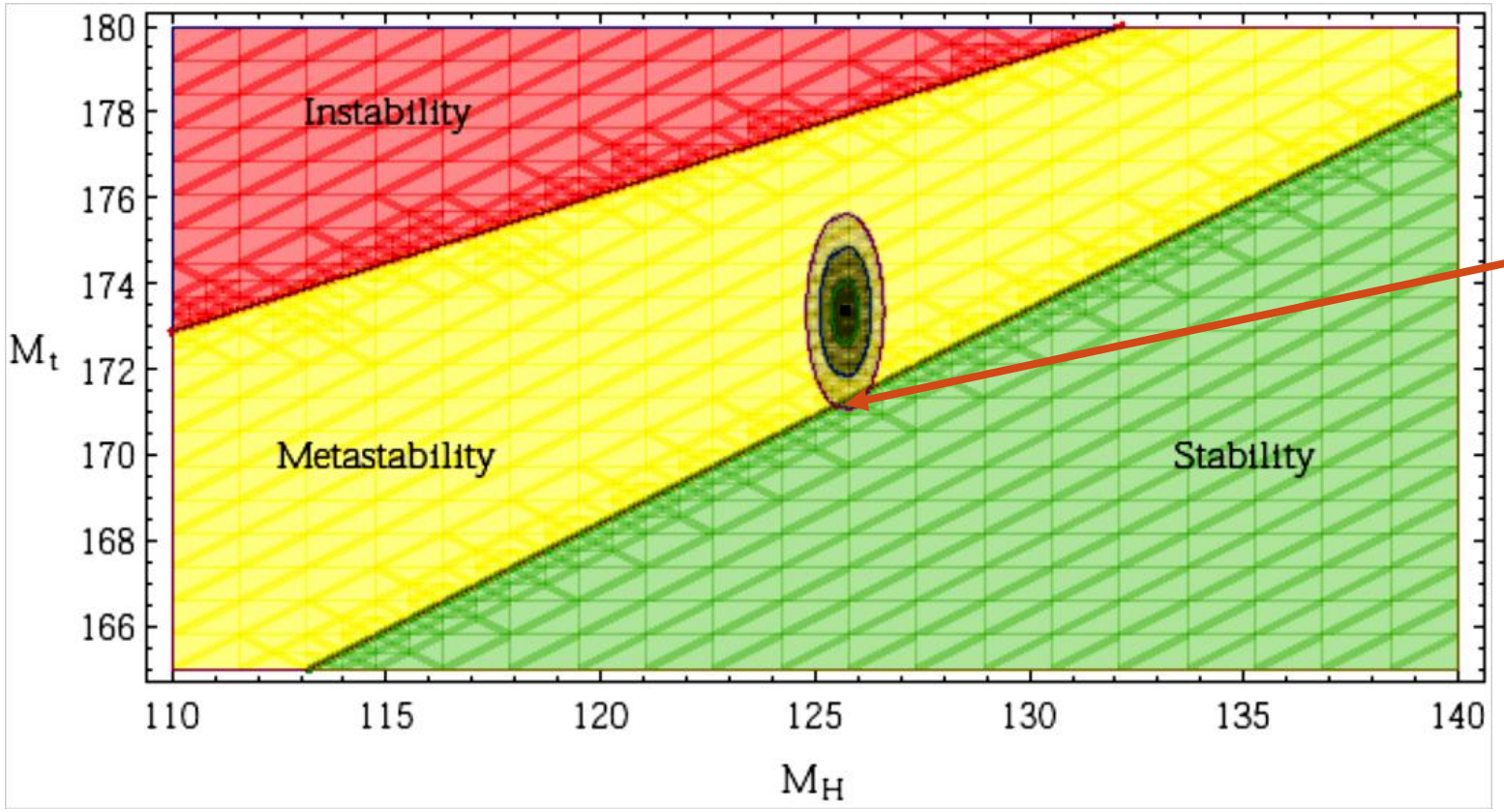


$\tau > T_U$	METASTABLE
$\tau = T_U$	CRITICAL LINE
$\tau < T_U$	UNSTABLE (tout-court)

τ : tunneling time

T_U : age of the Universe (10^{10} yr)

STABILITY DIAGRAM



M_t PRECISION MEASUREMENTS ?

STABILITY

$V_{eff}(\phi) > V_{eff}(EW)$

MESTABILITY

$V_{eff}(\phi) < V_{eff}(EW)$ but $\tau > T_U$

INSTABILITY

$\tau < T_U$

ASSUMPTION: NEW PHYSICS AT HIGH ENERGY SCALES CAN NOT HAVE AN IMPACT ON THE EW VACUUM STABILITY. (?)

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, JHEP 1312 (2013) 089.

COMPUTATION OF τ

$$V(\phi) \sim \frac{\lambda}{4}\phi^4$$

NEGLECTING NEW PHYSICS…

Euclidean equation of motion with O(4) symmetry $\left(r = \sqrt{x_\mu x_\mu}\right)$

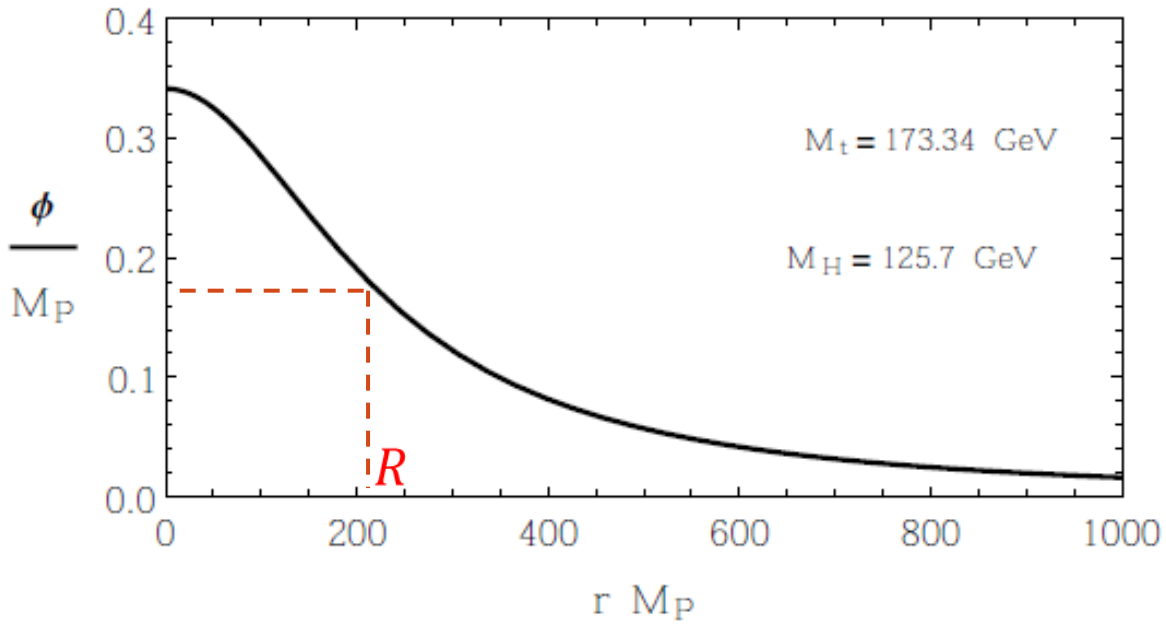
$$\frac{d^2\phi}{dr^2} + \frac{3}{r}\frac{d\phi}{dr} - \frac{dV}{d\phi} = 0$$

BOUNCE SOLUTION FOR THE CENTRAL VALUES…

Infinite number of solutions of arbitrary size R (classical degeneracy)

$$\phi_b(r) = \sqrt{\frac{8}{|\lambda|}}\frac{R}{r^2 + R^2}$$

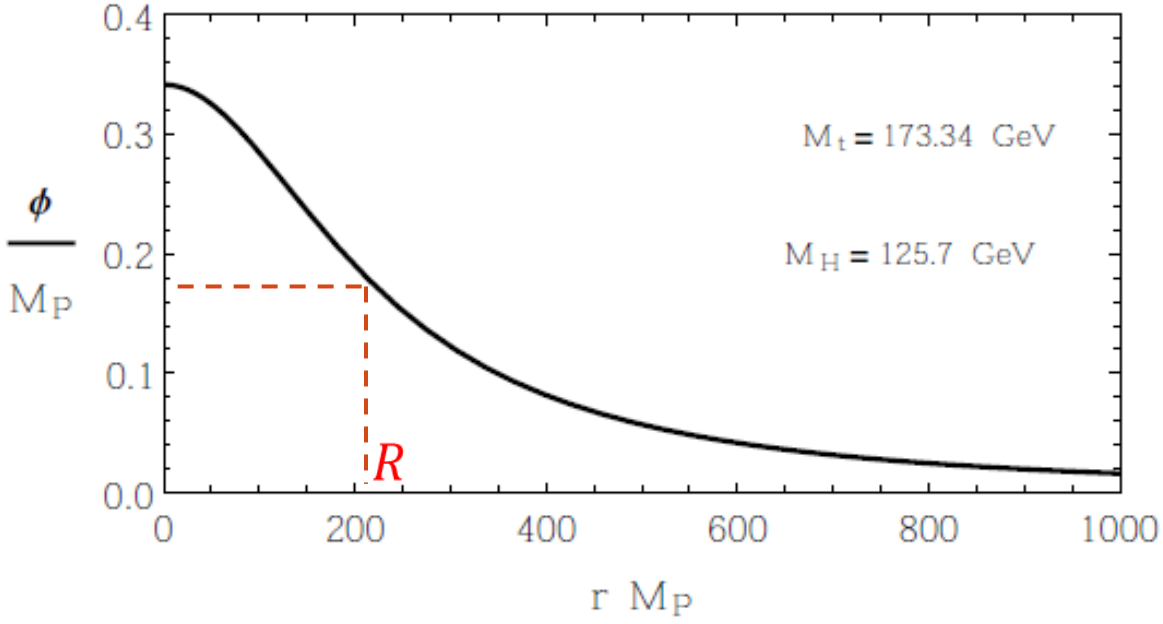
$$\tau \sim e^{S[\phi_b]} \times T_U$$



NEGLECTING NEW PHYSICS…

$$S[\phi_b] = \frac{8\pi^2}{3|\lambda|}$$

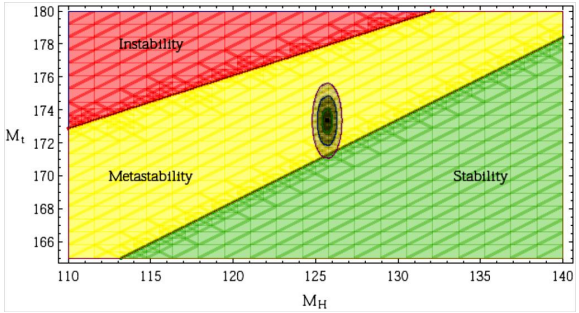
Classical degeneracy
broken by quantum fluctuations



$$\tau = \left[\frac{R_{max}^4}{T_U^4} e^{S[\phi_b]}\right] \times \left[e^{\Delta S}\right] \times T_U$$

R_{max} *FUNCTION OF SM PARAMETERS* (M_t, M_H)

$$\tau \sim 10^{655} T_U \quad \Rightarrow \quad \text{METASTABLE}$$



A TOY UV COMPLETION

High energy couplings

HEAVY FERMION: ψ

HEAVY SCALAR: S

$$V_0(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda_0}{4}\phi^4$$

$$\Delta V(\phi, S, \psi) = \frac{M_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4 + \frac{g_S}{4}\phi^2 S^2 + M_f\,\overline{\psi}\,\psi + \frac{g_S}{\sqrt{2}}\phi\overline{\psi}\,\psi$$

$M_f \sim 10^{17}\ GeV$

$M_S \sim 10^{18}\ GeV$

THRESHOLD SCALE

1 **Integrate out heavy d.o.f.**

$$V_{new}(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda_0}{4}\phi^4$$
$$+\frac{1}{64\pi^2}\left(M_S^2 + \frac{g_S}{2}\phi^2\right)^2\left[ln\left(\frac{M_S^2 + \frac{g_S}{2}\phi^2}{\mu^2}\right) - \frac{3}{2}\right]$$
$$-\frac{1}{16\pi^2}\left(M_f^2 + \frac{g_f^2}{2}\phi^2\right)^2\left[ln\left(\frac{M_f^2 + \frac{g_f^2}{2}\phi^2}{\mu^2}\right) - \frac{3}{2}\right]$$

2 **Impose threshold cond.**

$$m_H^2 = m^2 + \Delta m^2$$
$$\lambda_{SM} = \lambda_0 + \Delta\lambda$$

So that for $\phi < M_f$

$$V_{new}(\phi) \cong \frac{m_H^2}{2}\phi^2 + \frac{\lambda_{SM}}{4}\phi^4 + \ldots$$

3 **Get $U(\phi)$**

$$V_{new}(\phi) = \frac{m_H^2}{2}\phi^2 + \frac{\lambda_{SM}}{4}\phi^4 + U(\phi)$$

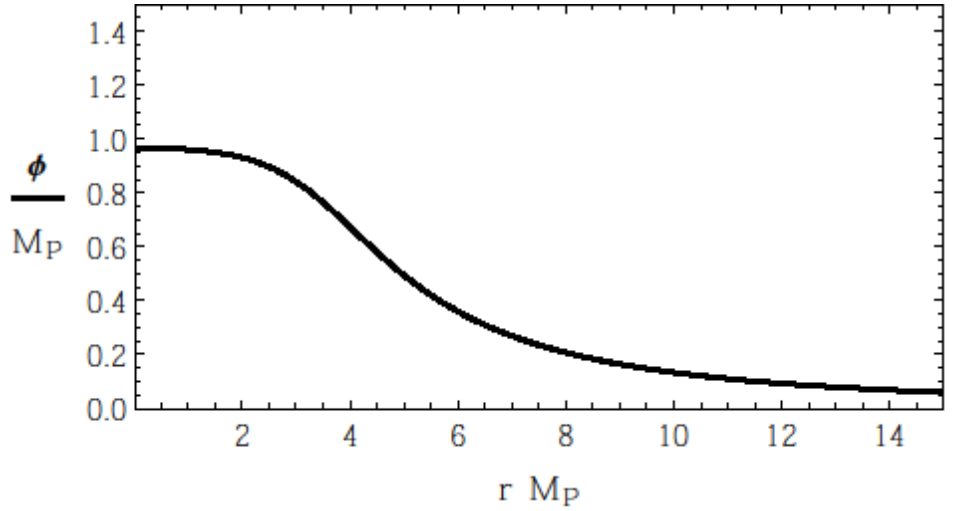
$$U(\phi) = \frac{\lambda_6}{6\,M_f^2}\phi^6 + \frac{\lambda_8}{8\,M_f^4}\phi^8 + \ldots$$

COMPUTATION OF τ

ADDING NEW PHYSICS (our approach)

$$V_{new}(\phi) = \frac{\lambda_{SM}}{4}\phi^4 + U(\phi)$$

$$\frac{d^2\phi}{dr^2} + \frac{3}{r}\frac{d\phi}{dr} - \frac{dV_{new}}{d\phi} = 0$$



NEW BOUNCE SOLUTION!!!!

ϕ_{new}^{b} ⟶ $\tau = \left[\frac{R_{new}^4}{T_U^4} e^{S_{new}[\phi_b^{new}]+\Delta S}\right] \times T_U$

SCALE INVARIANCE IS BROKEN !! ⟶ $R_{new} \sim 1/M_f$

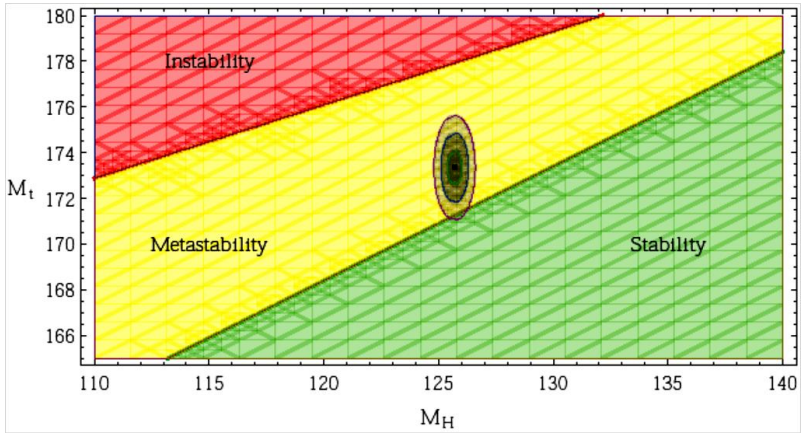
DEPENDS ON THE THRESHOLD SCALE

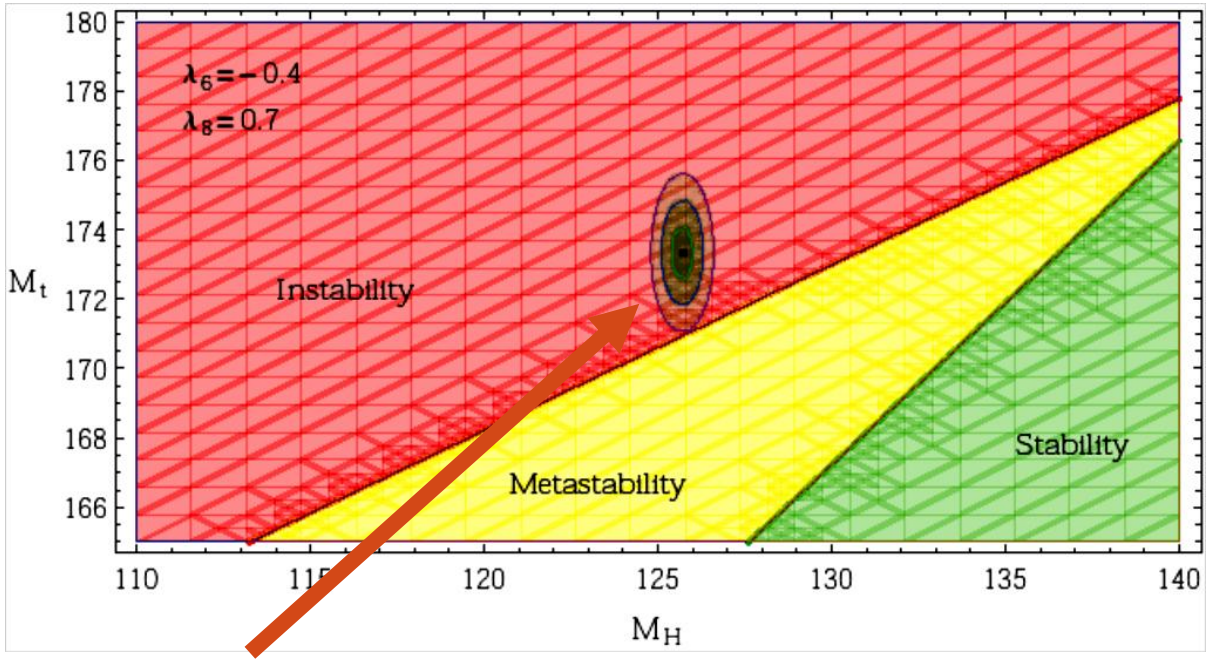
Neglecting the effects of New Physics ….

$$\tau \sim 10^{655} T_U$$

With new physics, for specific values of M_f, M_S, g_f and g_S.

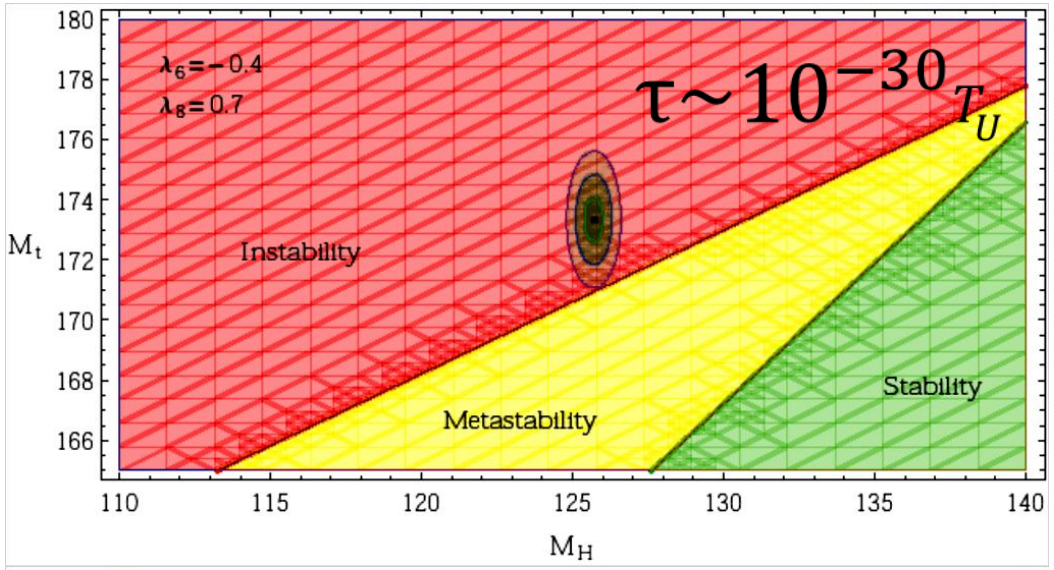
$$\tau \sim 10^{-30} T_U$$

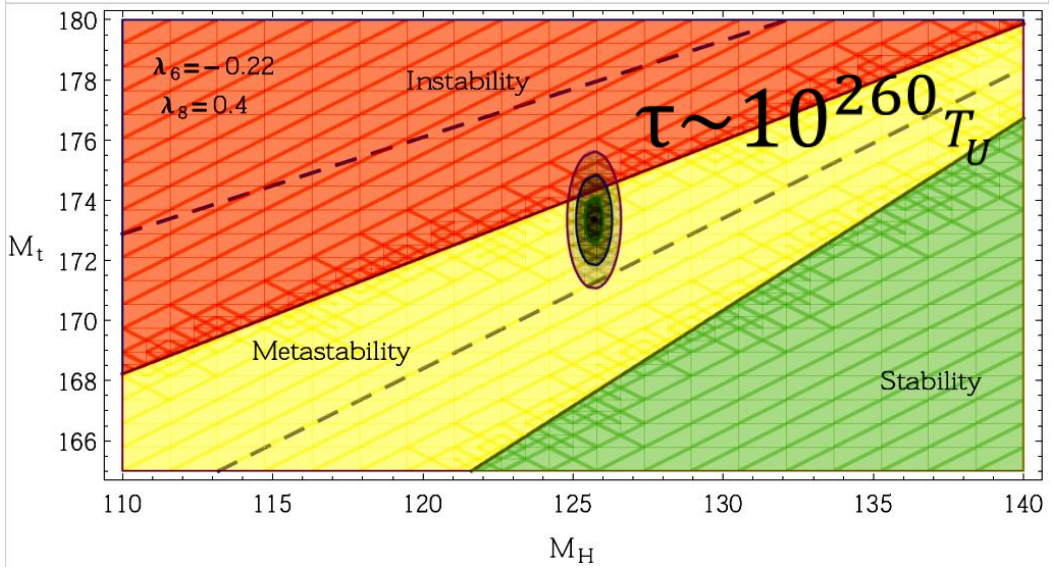




UNSTABLE !!! (not universal)

PRECISION MEASUREMENTS ON M_t

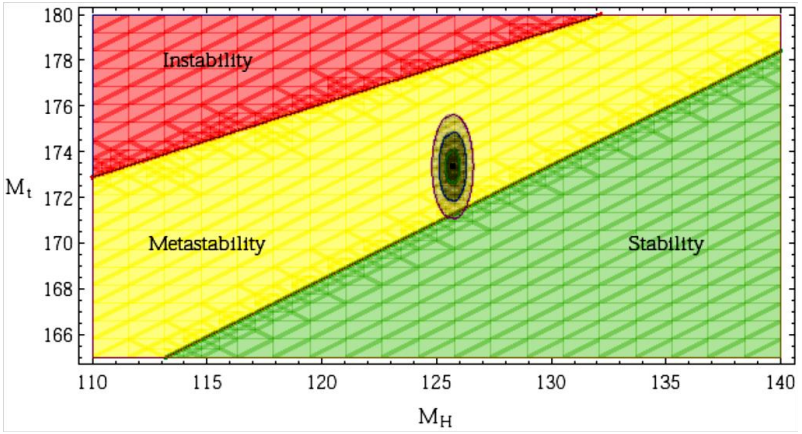




different values of M_f, M_S, g_f and g_S

ΔM_t ?

To be compared with $\tau \sim 10^{655}\, T_U$



1. Consider different Standard Model extensions

2. Precision measurement of M_t select the "good" theories providing a (meta)stable vacuum

SUMMARY AND PERSPECTIVES

- We computed the tunneling time of the EW vacuum by including the effects of New Physics at very high energies and showed that the electroweak vacuum lifetime strongly depends on the new physics interactions.

- More generally, we showed that *the Stability Phase Diagram* strongly depends on new physics at high energy scales.

- M_H *and* M_t , are not sufficients to determine *the stability condition for the EW vacuum*.

- Our approach provide a validity test for possible UV completion of the SM at high energy scales.
  Any UV completion of SM at a certain threshold scale is allowed if it is stable or if $\tau > T_U$.

THANK YOU

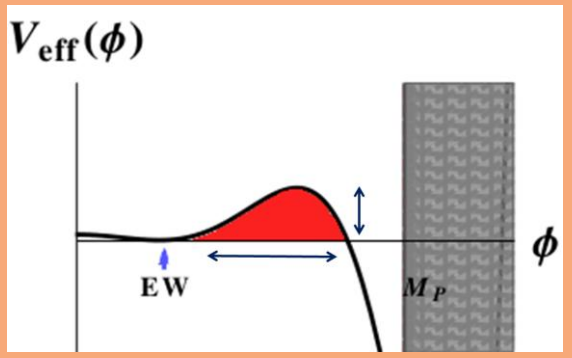
Backup - Slides

IN FAVOR OF UNIVERSALITY

COMMON (AND INCORRECT) ARGUMENTS …

- Extrapolation of the WKB results beyond Q.M.

→ only height and width of the barrier matter



- Instability Scale $\Lambda_I \sim 10^{11}\ GeV$ << Threshold Scale $M_P \sim 10^{19}\ GeV$

→ corrections to τ are suppressed as $\sim \left(\frac{\Lambda_I}{M_P}\right)^n$

BUT…

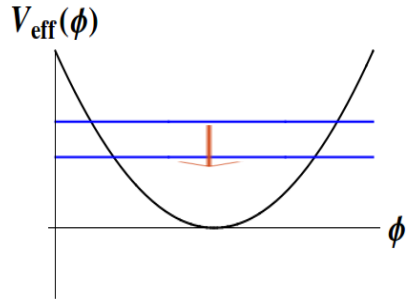
- QFT has an infinite number of d.o.f.

  The Potential Energy is

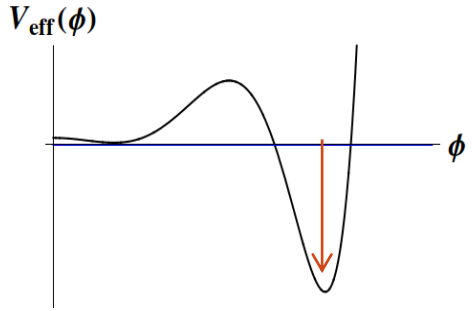
$$U = \int d^3x \left[\frac{1}{2} \left(\vec{\nabla} \phi(\vec{x}, t) \right)^2 + V(\phi(\vec{x}, t)) \right]$$

n. neighbour interactions

- Vacuum - decay is a non-perturbative phenomenon

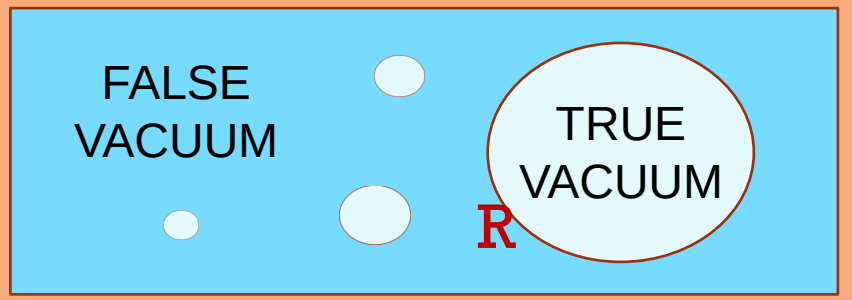


ES. HIGGS DECAY IS PERTURBATIVE



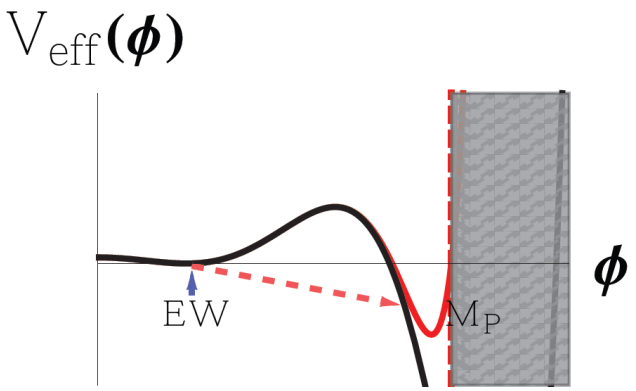
TUNNELING: NON - PERTURBATIVE

Tunneling in QFT like a Nucleation process



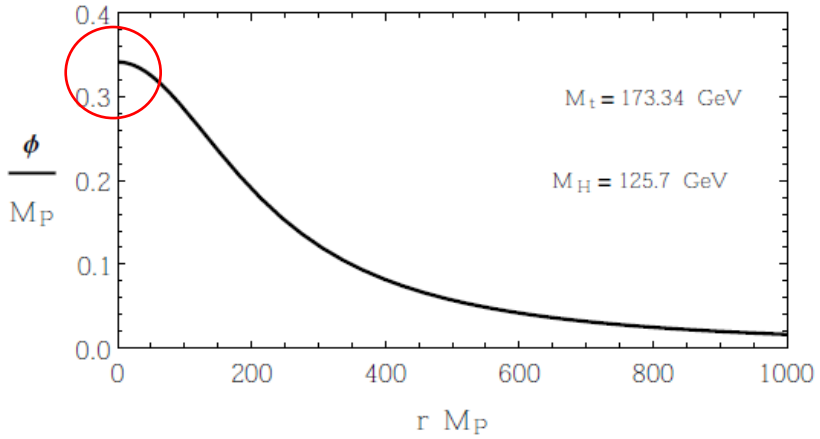
The transition amplitude is dominated by a non local configuration

WARNING 1: NEW PHYSICS IS NECESSARY (RESCUES THE POTENTIAL)



$$V_{new}(\phi) = \frac{\lambda}{4}\phi^4 + U(\phi)$$

WARNING 2: CENTER TOO CLOSE TO M_P



$$\Phi_b(r=0) \cong 0.35 M_P \quad \left(\Phi_b(r=0) \propto \frac{1}{R}\right)$$

$$V_{new}(\phi) = \frac{\lambda}{4}\phi^4 + U(\phi)$$