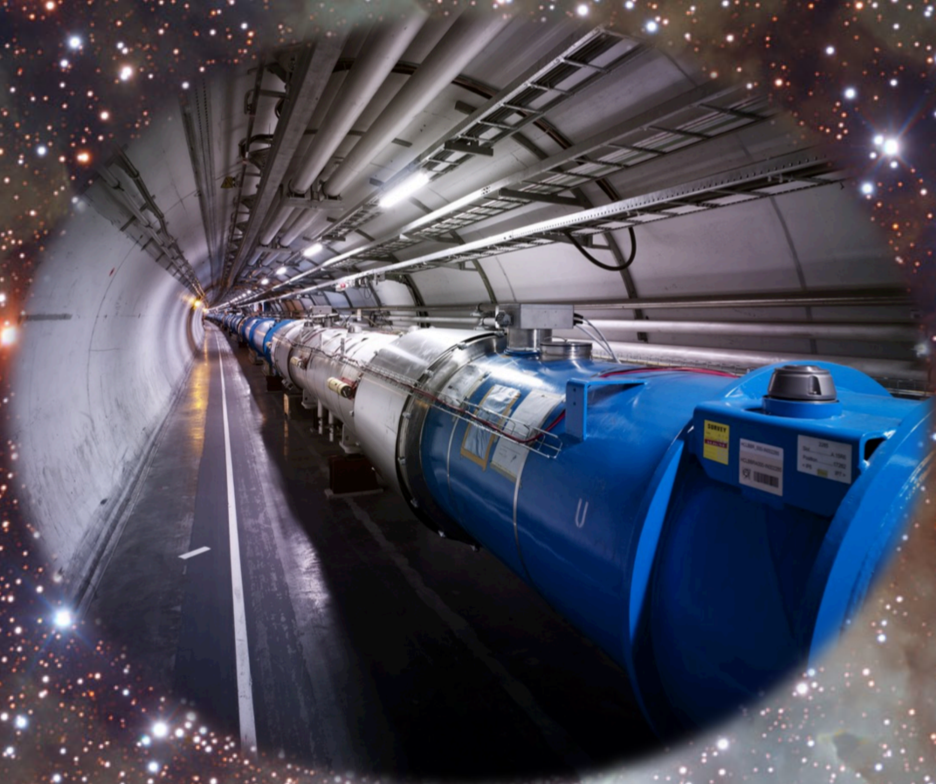
The LHC & the universe

G.F. Giudice

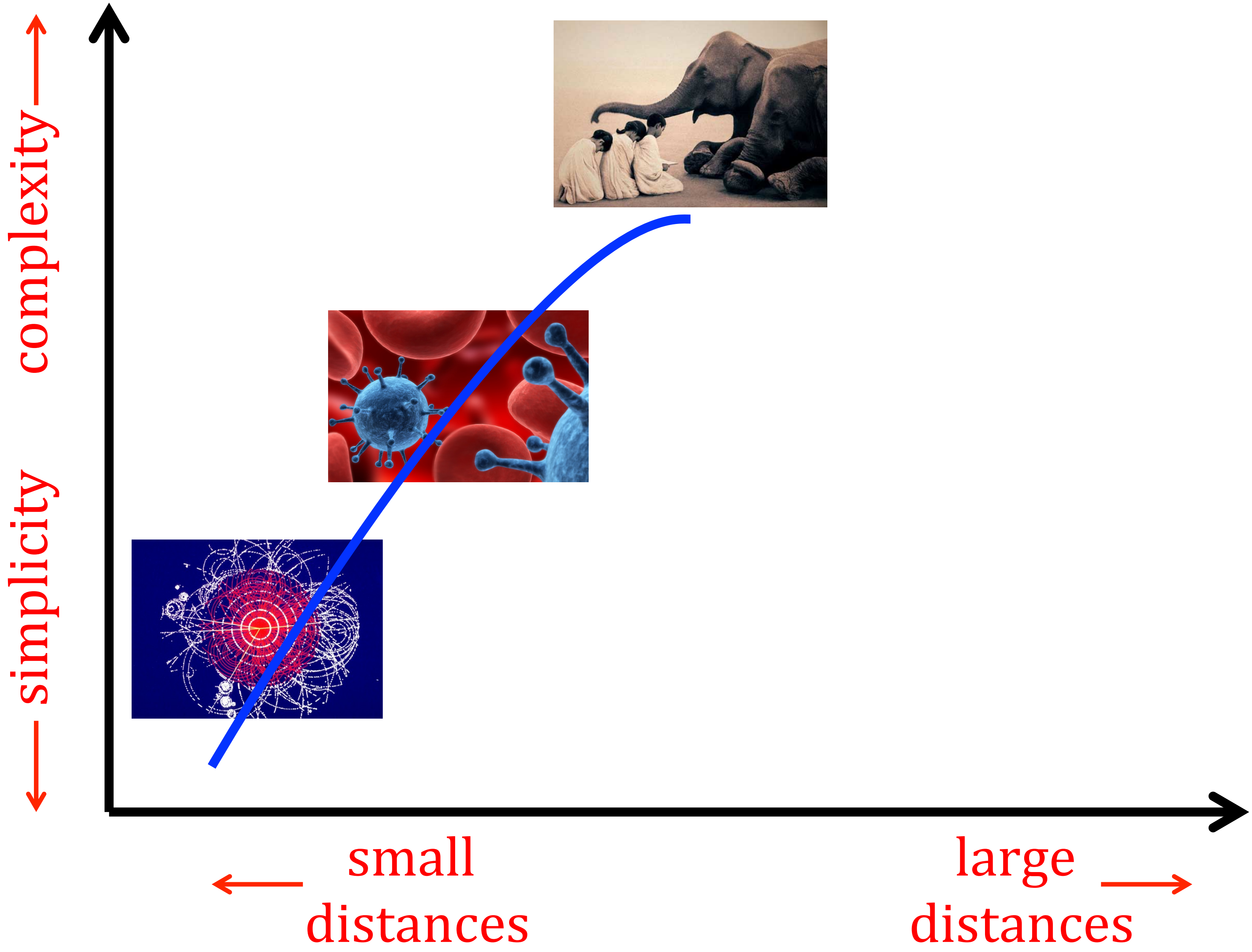
28th Texas Symposium on Relativistic Astrophysics

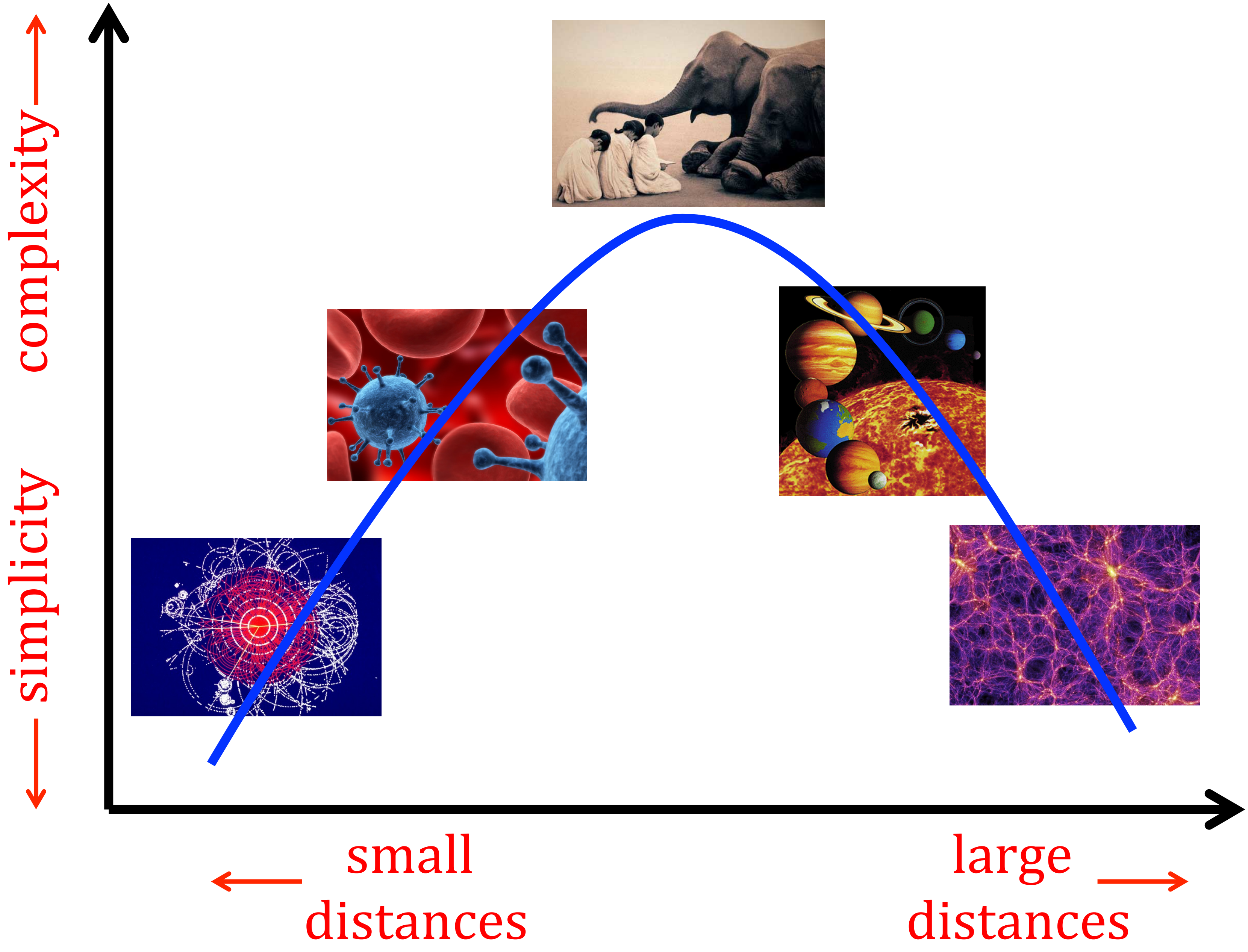
Geneva, 16 December 2015

The connection between the micro & macro cosm is one of the most astounding achievements of modern physics



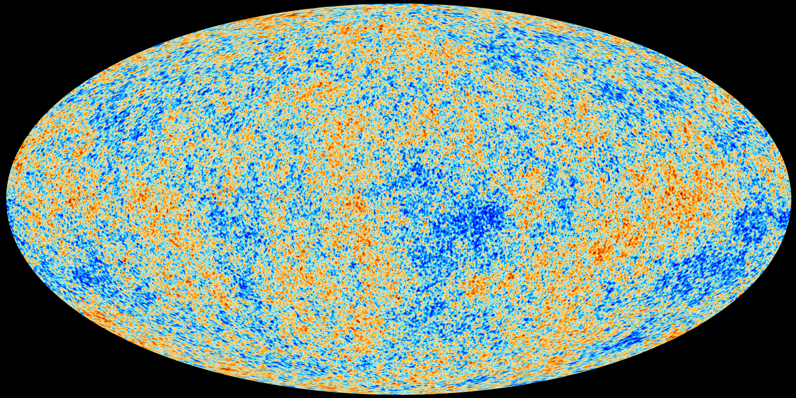
Nature's fundamental laws become apparent only at small distances


complexity
simplicity
small
distances
large
distances

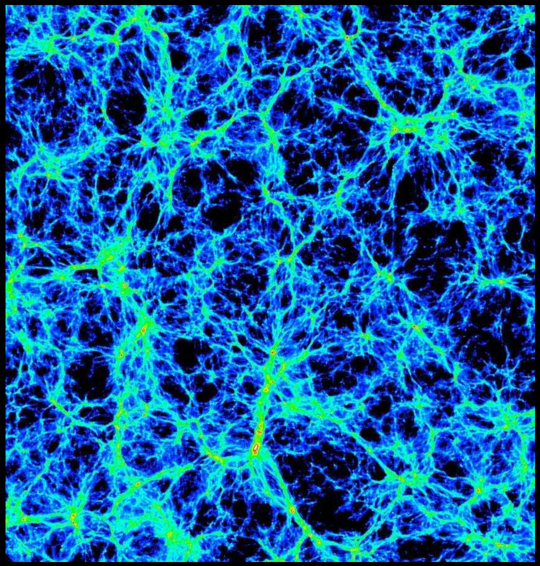

complexity
simplicity
small
distances
large
distances

The micro/macro connection is not just a qualitative feature

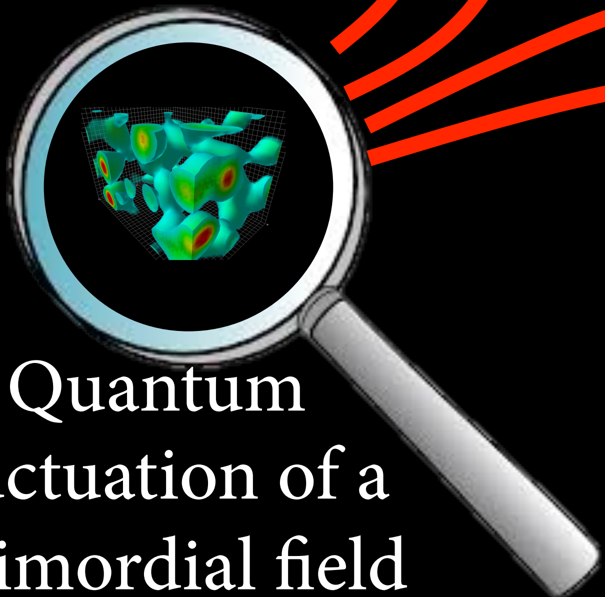
Best example:
inflation



CMB anisotropy



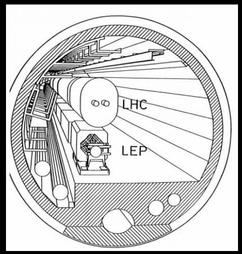
Large scale structures



Quantum fluctuation of a primordial field

LHC: timeline

21 Mar 1984
First LHC studies



16 Dec 1994
LHC approved

10 Sep 2008
LHC starts

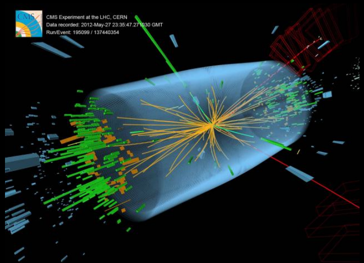
19 Sep 2008
LHC incident

20 Nov 2009
LHC restarts

30 Mar 2010
First collisions
at 7 TeV

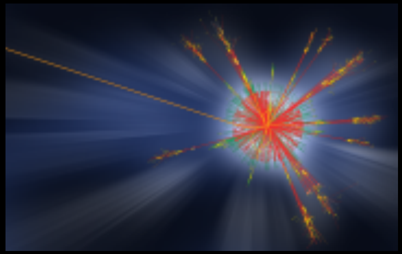
30 Oct 2011
End of *pp* run
(5 fb^{-1})

5 Apr 2012
First collisions
at 8 TeV



4 Jul 2012
Higgs discovery

19 Jan 2013
End of *pp* run
(20 fb^{-1})



03 Jun 2015
First collisions
at 13 TeV

04 Nov 2015
End of *pp* run
(4 fb^{-1})

The last brick of the SM building,
... but a special brick...

The success of the SM rests on the gauge principle

- elegant
- robust
- predictive

Higgs interactions: first known example of non-gauge fundamental forces?

The origin of all SM problems

$$L = \left(h_{ij} \bar{\psi}_i \psi_j H + \text{h.c.} \right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{CC}^4$$

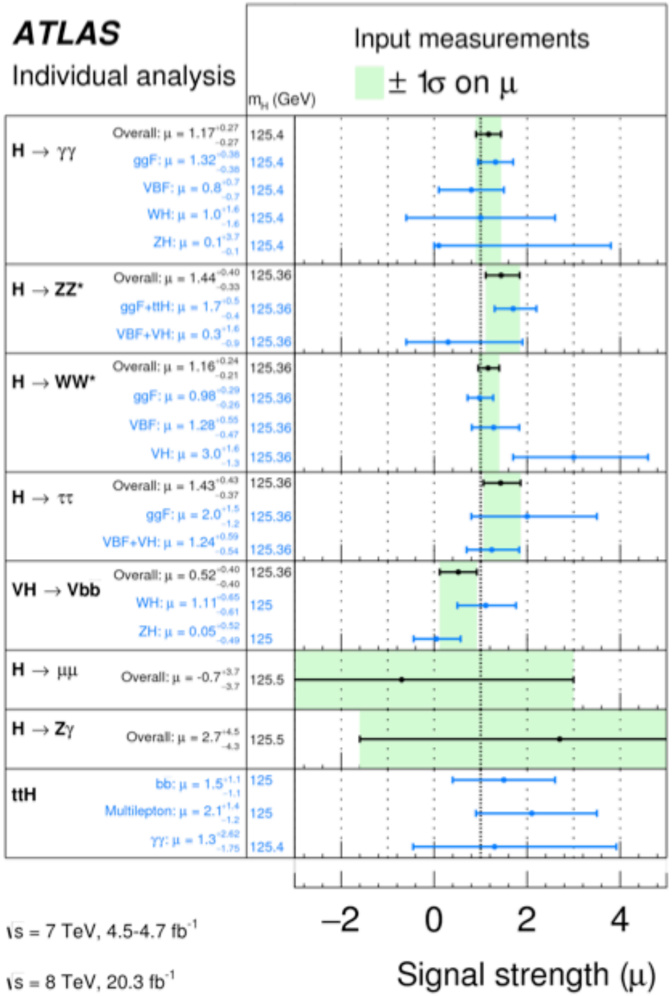
Flavor puzzle

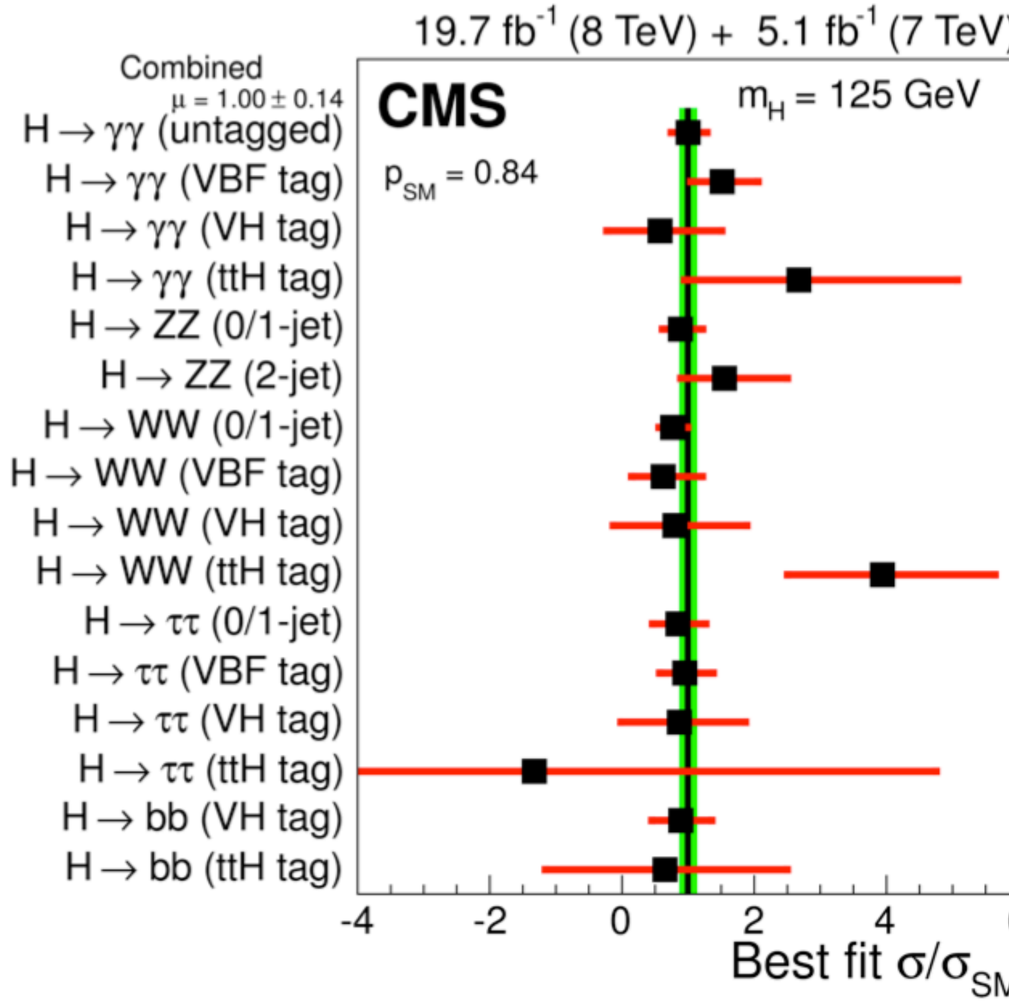
Stability of the potential

Hierarchy problem

Cosmological constant problem

Is the Higgs a fundamental scalar with non-gauge interactions?





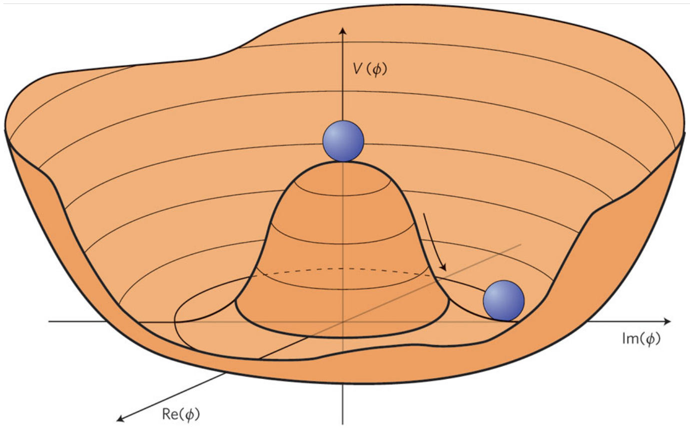
The Higgs is SM-like at the level of 20-40% accuracy

$$\Delta = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale } \; 4\pi f > \sqrt{\frac{20\%}{\Delta}} \;\; 7\text{ TeV}$$

Does new dynamics reinstate the gauge principle?
Is the Higgs truly fundamental? $\Rightarrow$ experiments!

If so, fuel for inflationary model-building
Scalar fields no longer tools for toy models

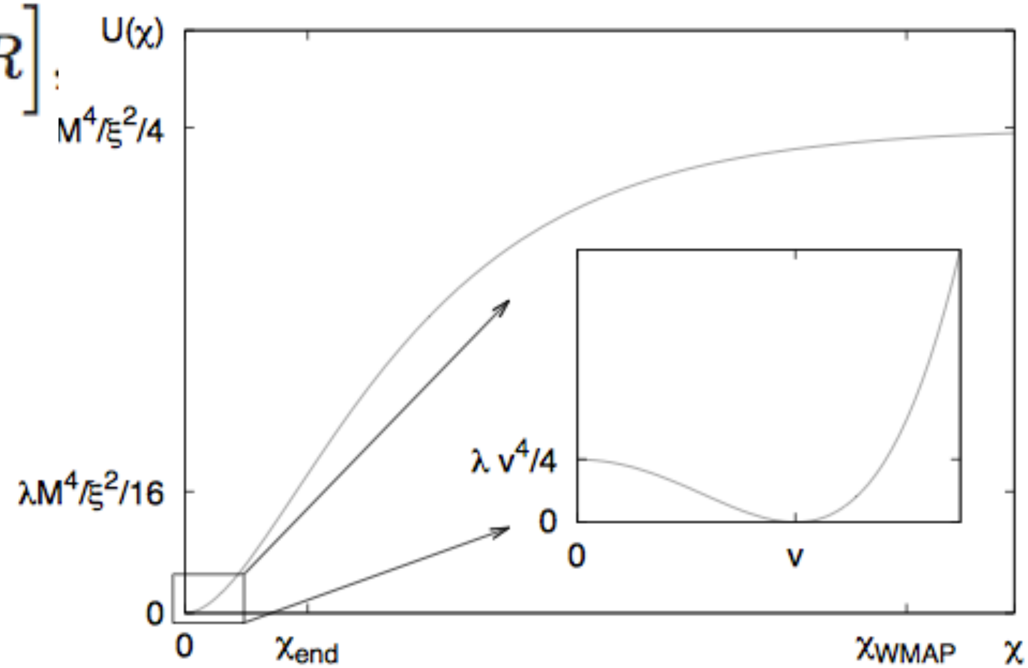
Extreme case: the Higgs as inflaton



needs large-field modification

Simplest example: Higgs-curvature term

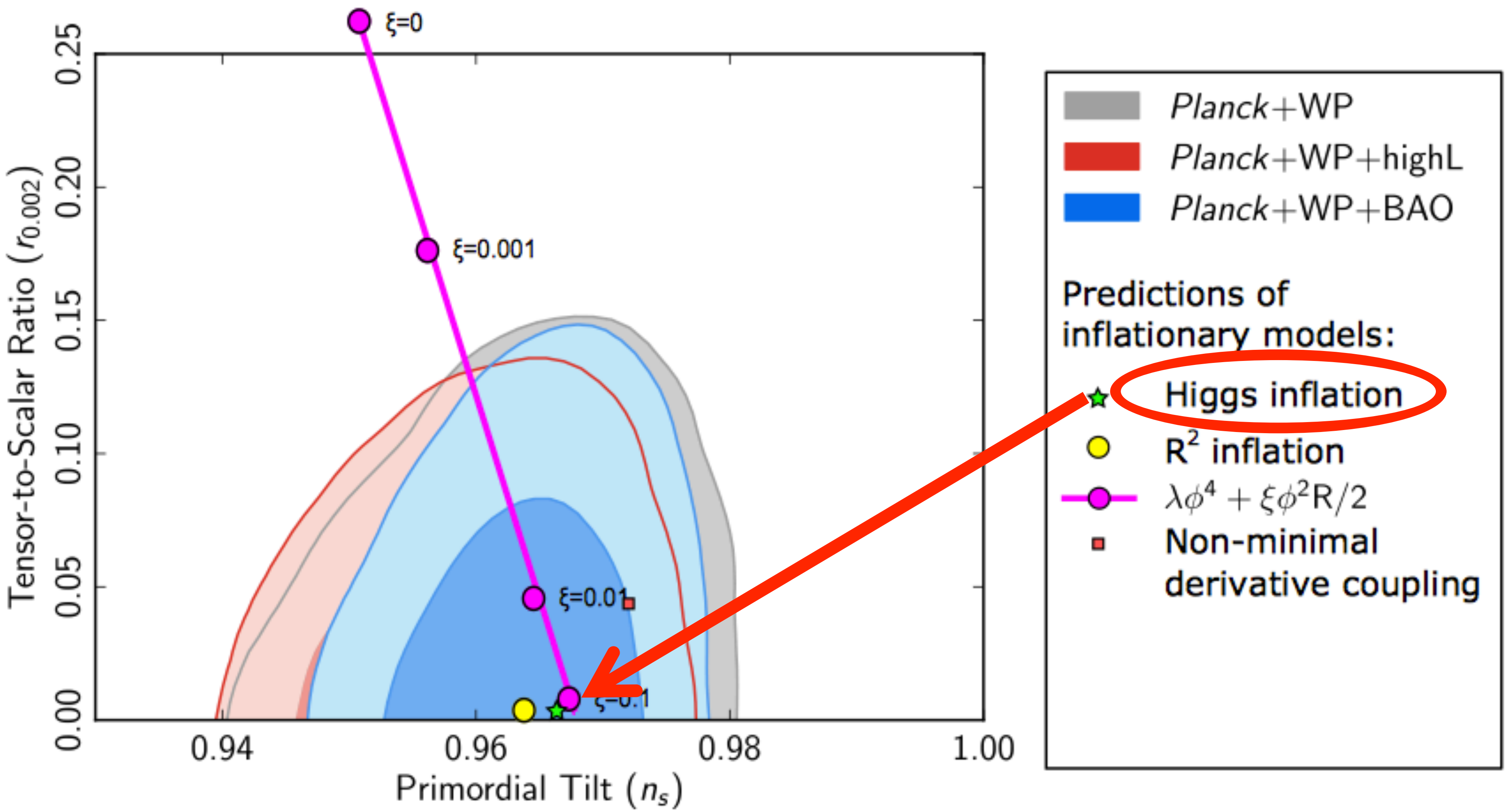
$$\delta S_{\rm NM} = \int d^4x\sqrt{-g}\Big[-\xi\Phi^\dagger\Phi R\Big],$$



Bezrukov-Shaposhnikov

$$\xi \simeq 47\,000\sqrt{\lambda}, \qquad N \simeq 57.7$$

$$n_s \simeq 1 - 8\frac{4N+9}{(4N+3)^2} \simeq 0.967, \qquad r \simeq \frac{192}{(4N+3)^2} \simeq 0.0031,$$



Perturbative unitarity violated at M_P / ξ

New physics must appear at that scale

(we cannot trust the potential above the cutoff)

Next-to-simplest example: Higgs + 1 scalar

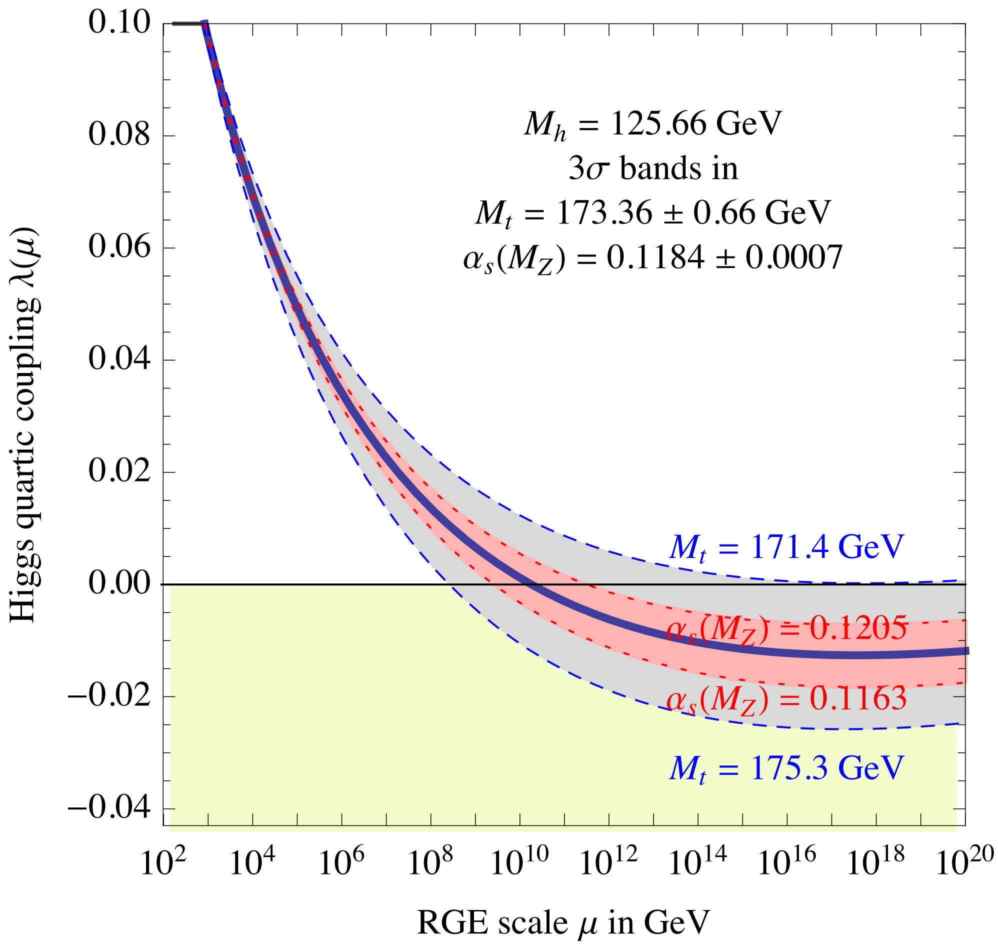
Giudice-Lee

Barbon-Casas-Elias-Espinosa

General lessons from UV-completed models

- Higgs may play a role in inflation, but it is unlikely to be the dominant source
- Inflationary predictions are fairly robust
- Except for special cases, observation of r can rule out the models

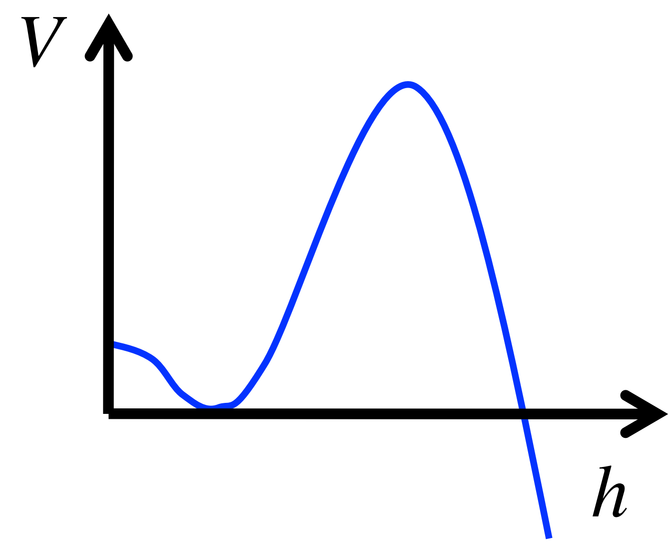
If SM + Higgs is the full story, new implications for cosmology

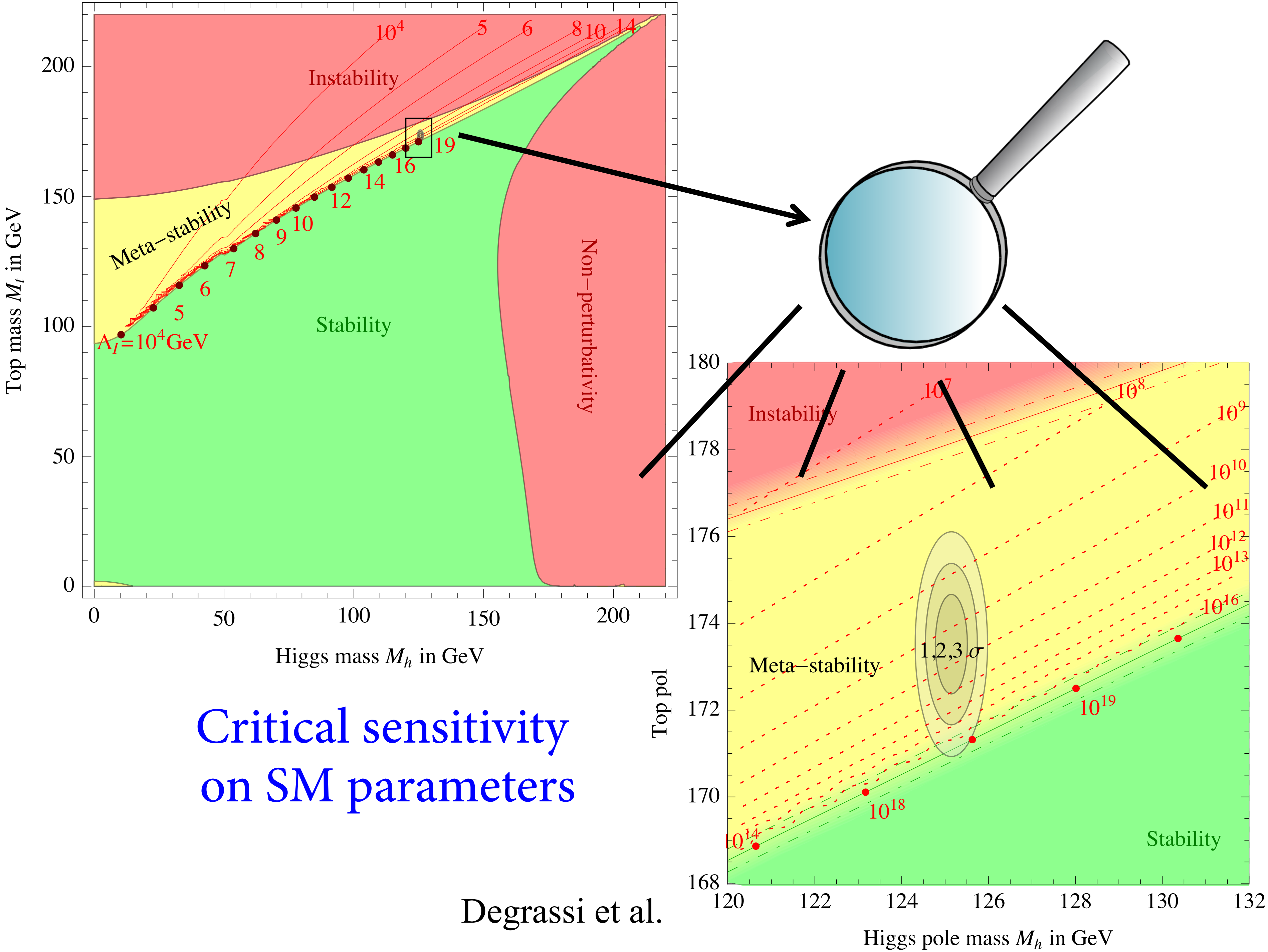


↑Higgs mass

↓Top quark mass

$$\frac{16\pi^2}{3}\,\mu\frac{d\lambda}{d\mu} = -2y_t^4 + 4y_t^2\lambda + 8\lambda^2 +$$



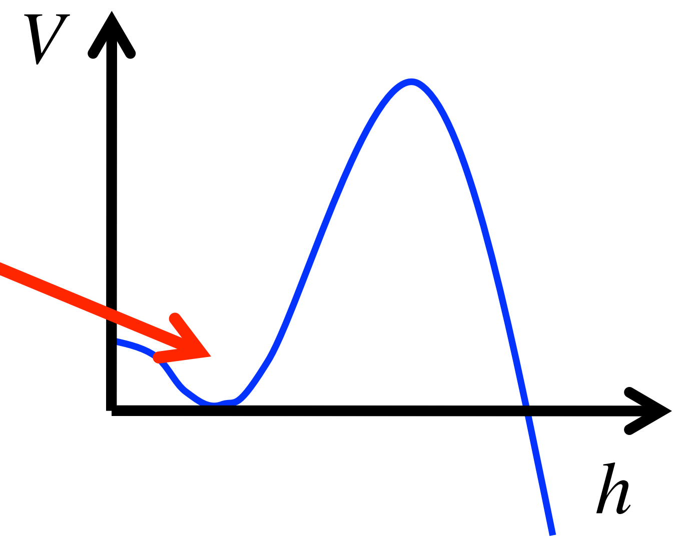


Critical sensitivity on SM parameters

Degrassi et al.

What does metastability imply for the early universe?

1) How did we end up here?

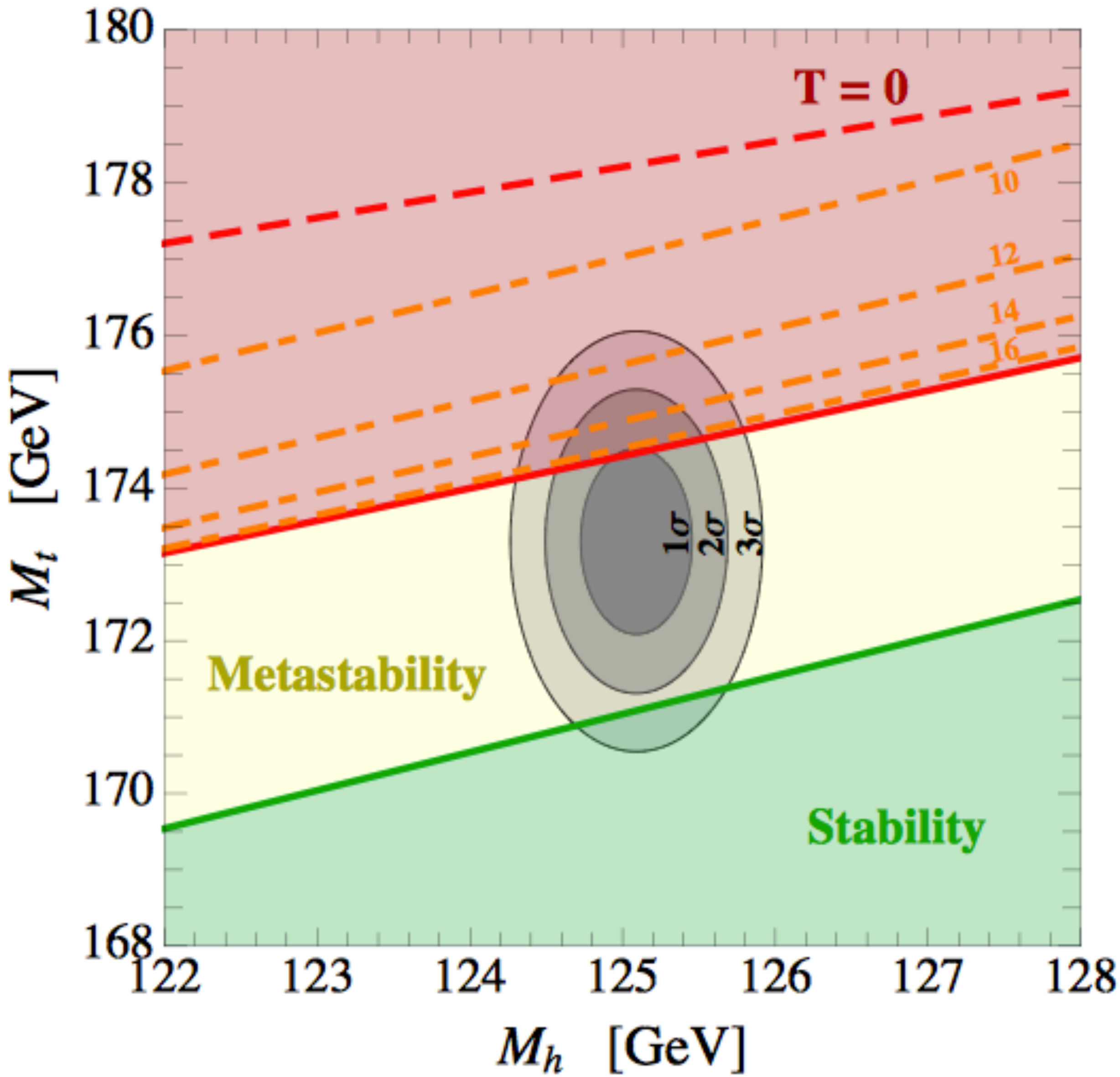


- Initial condition from pre-inflationary thermal phase
- Large $Rh^2 \approx H^2h^2$ stabilizing the origin
- Small coupling to inflaton (negligible Higgs contribution to energy density)

$$10^{-10} \leq \lambda_{h\phi} \leq 10^{-6}$$

Lebedev-Westphal

2) Why wasn't the vacuum destabilized by thermal effects?

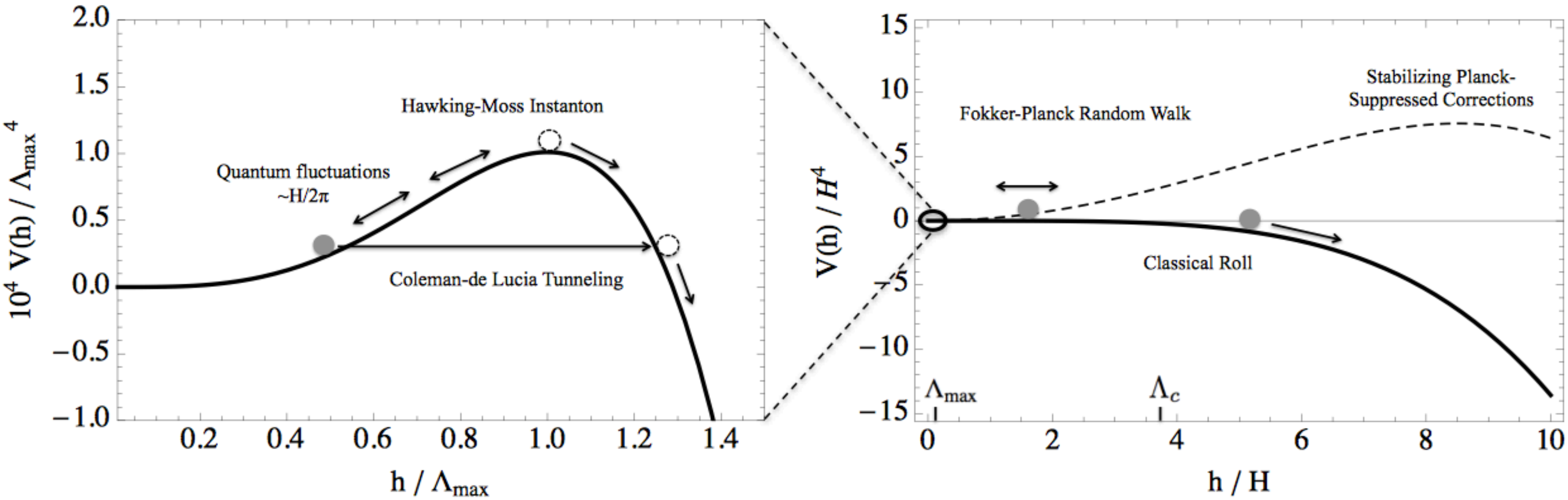


Delle Rose-Marzo-Urbano

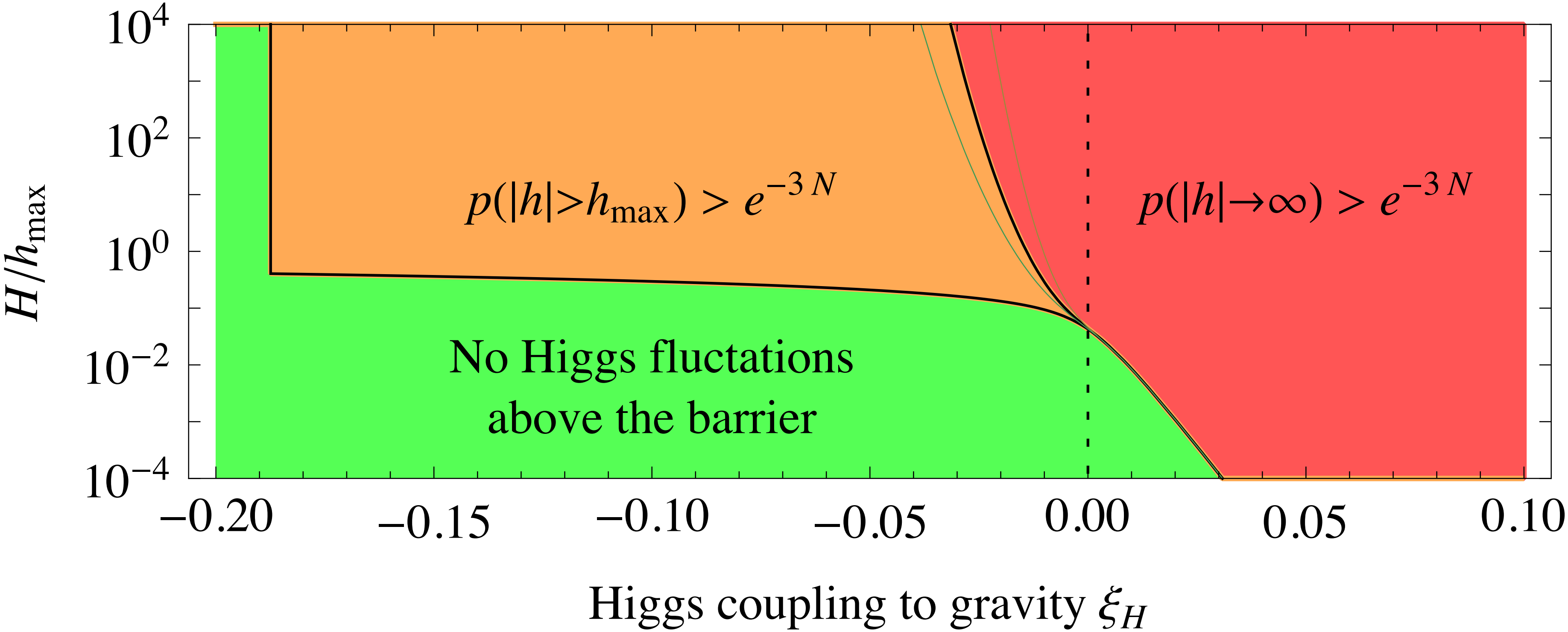
2) Why wasn't the vacuum destabilized during inflation?

Espinosa-Giudice-Riotto

$H << h_{\text{max}}$ $H >> h_{\text{max}}$



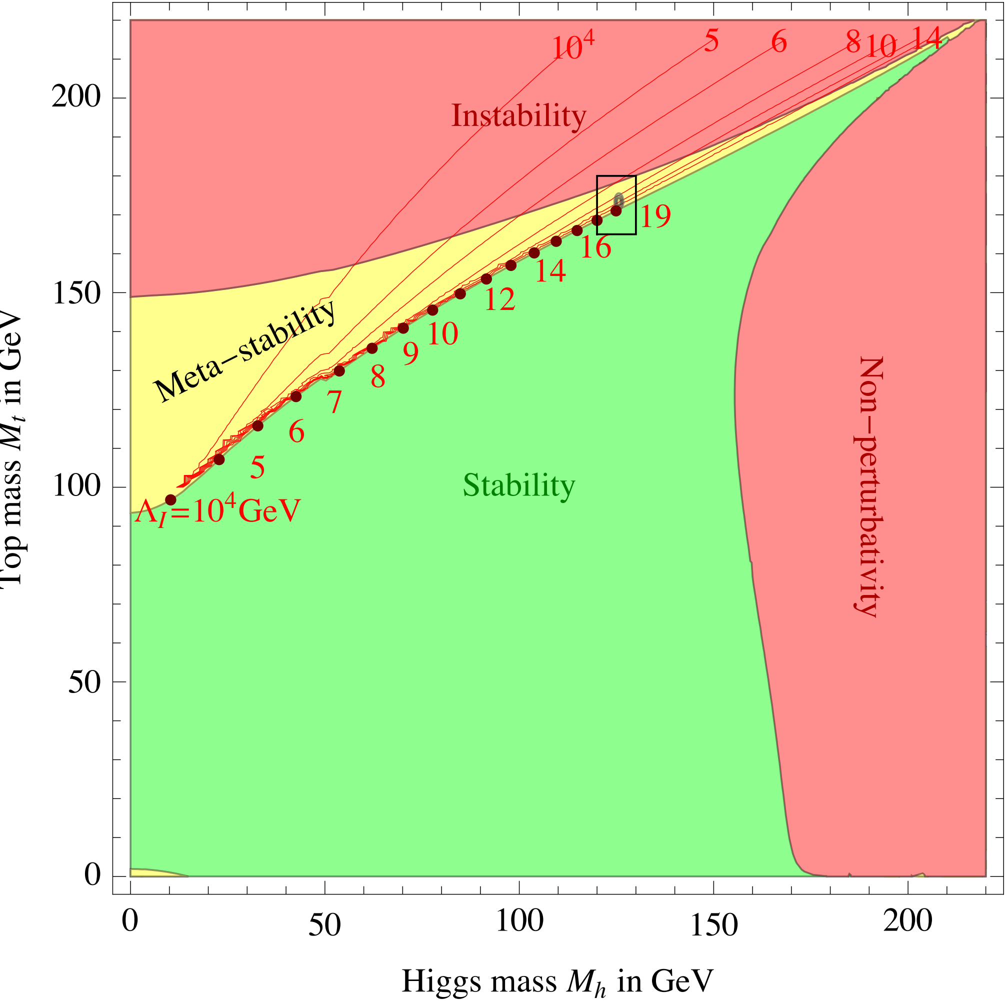
Hook et al.



Espinosa et al.

- Vacuum stability implies a constraint on Hubble during inflation
- Important if tensor modes are detected

$$H \approx 8\times10^{13}\ \text{GeV}\ (r/0.1)^{1/2}$$

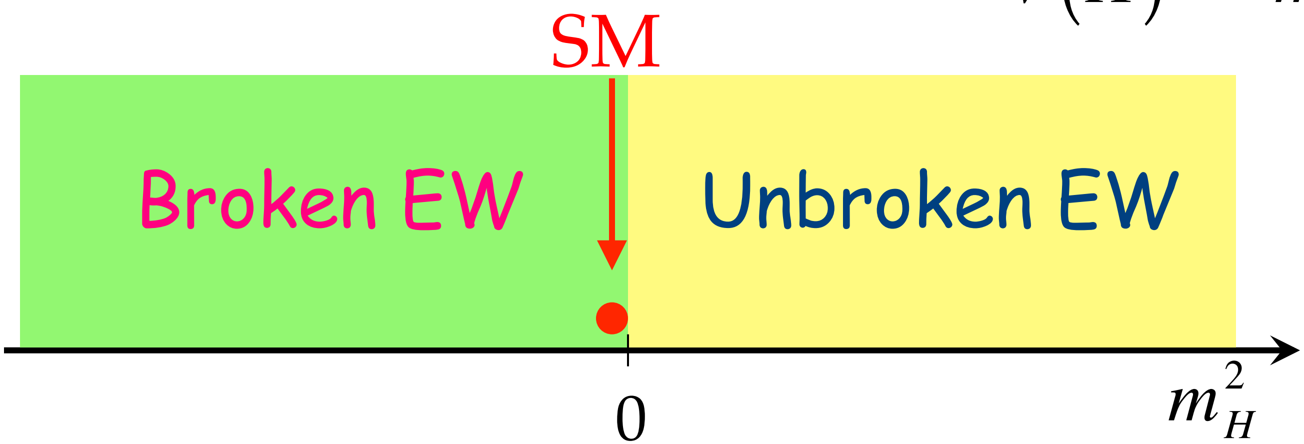


Is there a message in Higgs near-criticality?

- Coincidence?
- Dynamical attractor? Self-organized criticality?
- Statistical explanation in the multiverse?
- Cosmological evolution of fundamental parameters?

Higgs naturalness as a "criticality" condition

$$V(H) = -m_H^2 |H|^2 + \lambda |H|^4$$

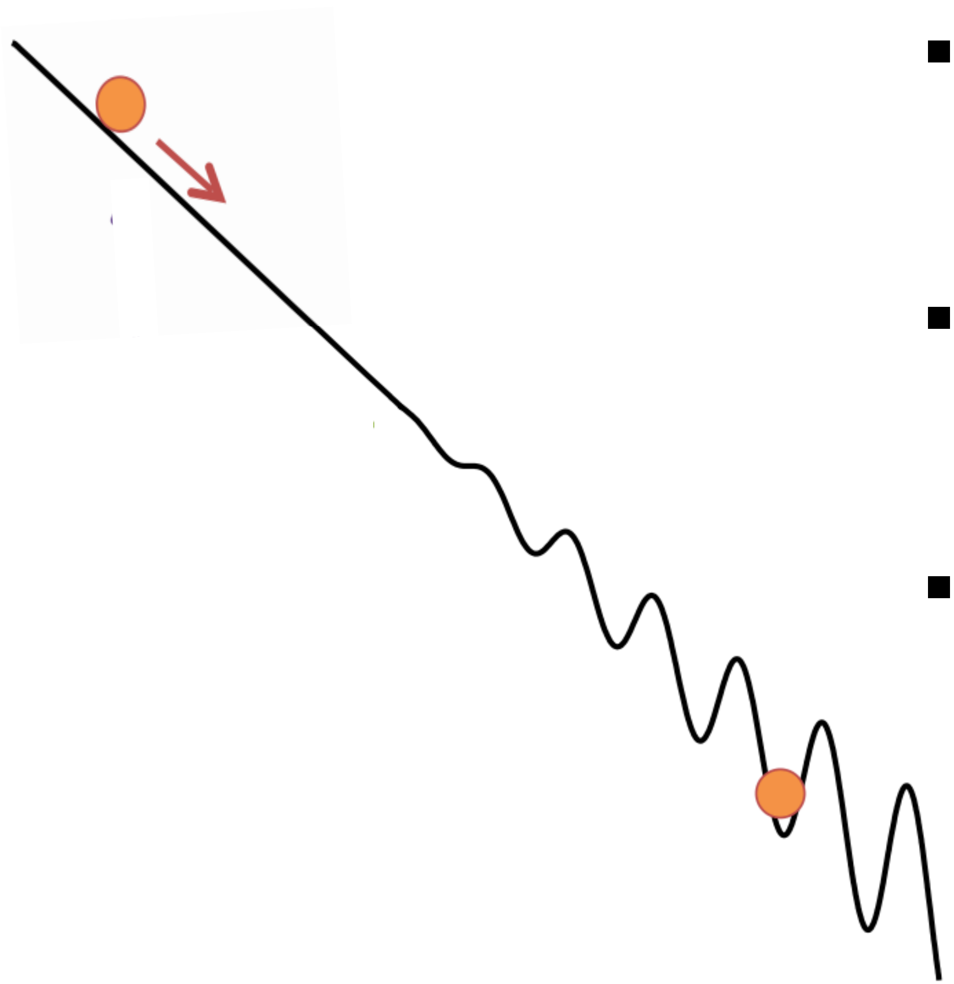


Why is nature so close to the critical line?

- Is $m_H^2 \approx 0$ special because of symmetry? (supersymmetry, Goldstone symmetry)
- Is $m_H^2 \approx 0$ special because of SOC?

An example of Higgs naturalness explained by SOC

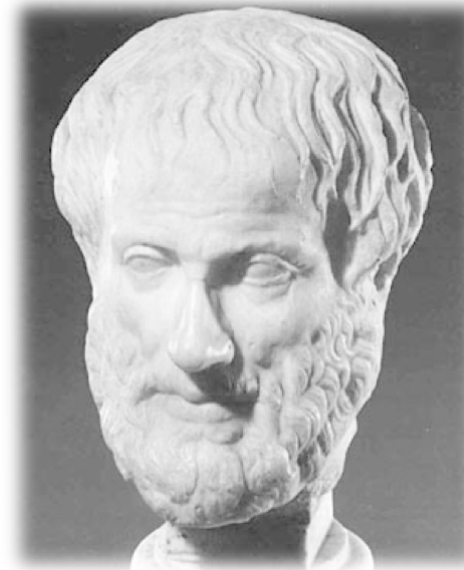
Graham-Kaplan-Rajendran

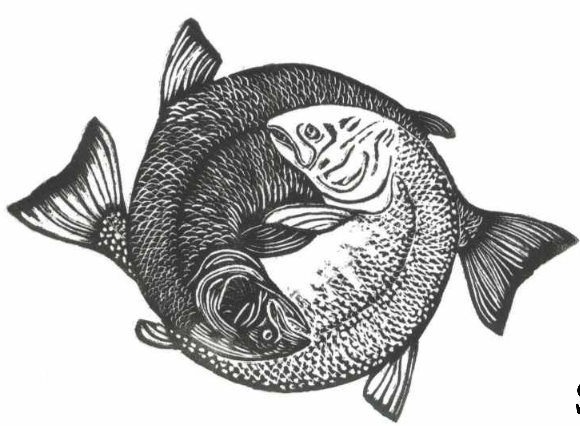


- The relaxion rolls down a shift-breaking potential
- The Higgs mass is scanned during the cosmological evolution
- Back-reaction from EW breaking

We are facing a fundamental issue that will influence the future strategy of particle physics and early cosmology

The SM is an EFT emerging from a more fundamental theory at the TeV scale





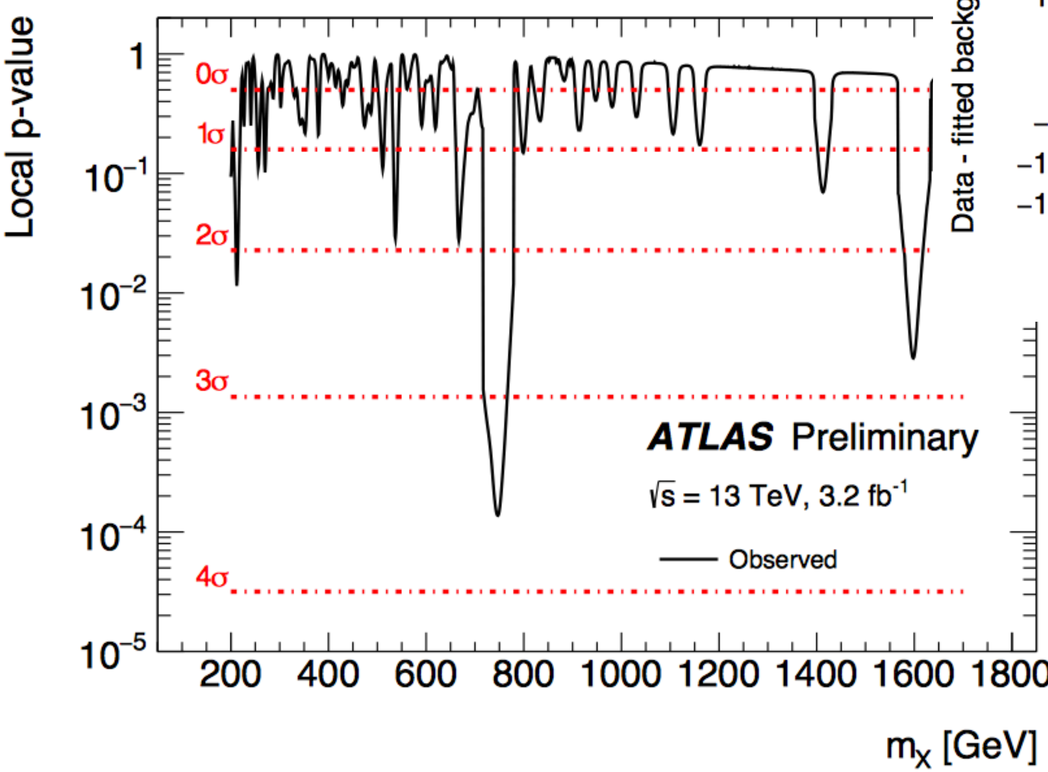
Higgs naturalness and the CC indicate a breakdown of EFT intuition (SOC, multiverse, cosmological selection of parameters, ...)

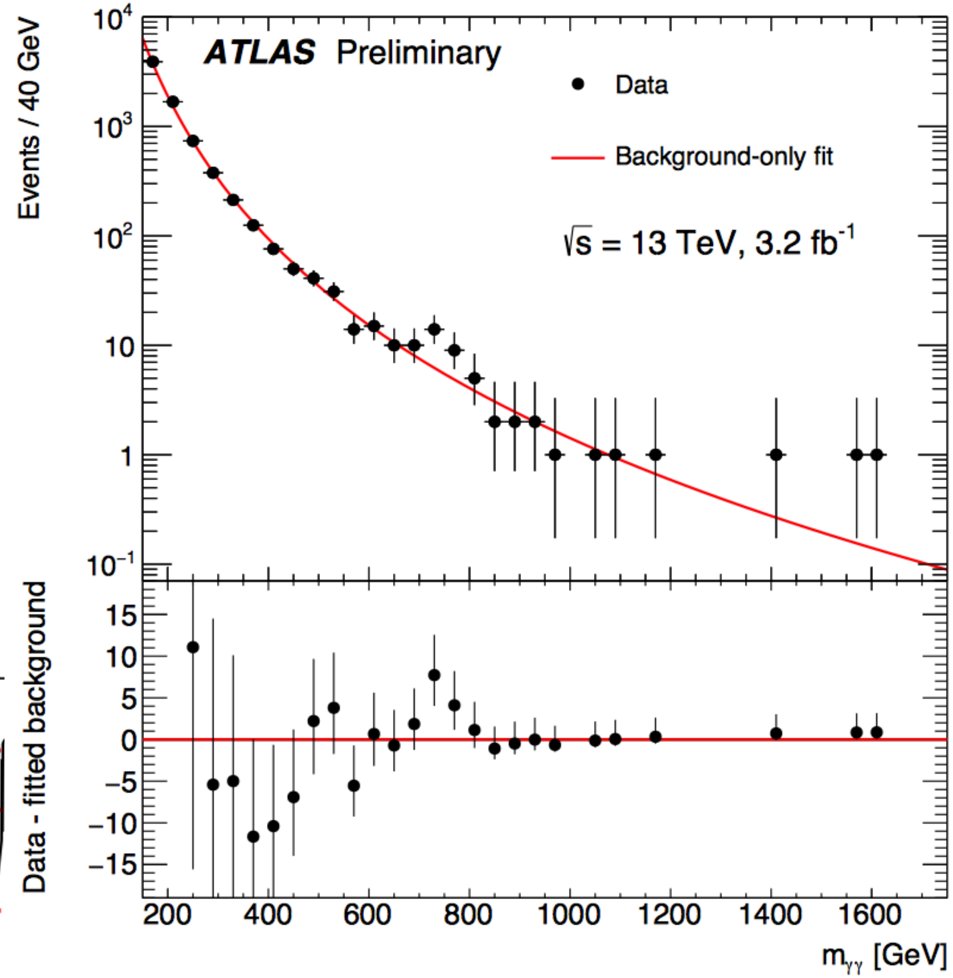
LHC: the future

From Apr 2016 to Nov 2018 $\rightarrow$ 100 fb^{-1} @ 13 TeV
LS2 until 2021
HL-LHC $\rightarrow$ 3000 fb^{-1}

A lot to be learned for cosmology:

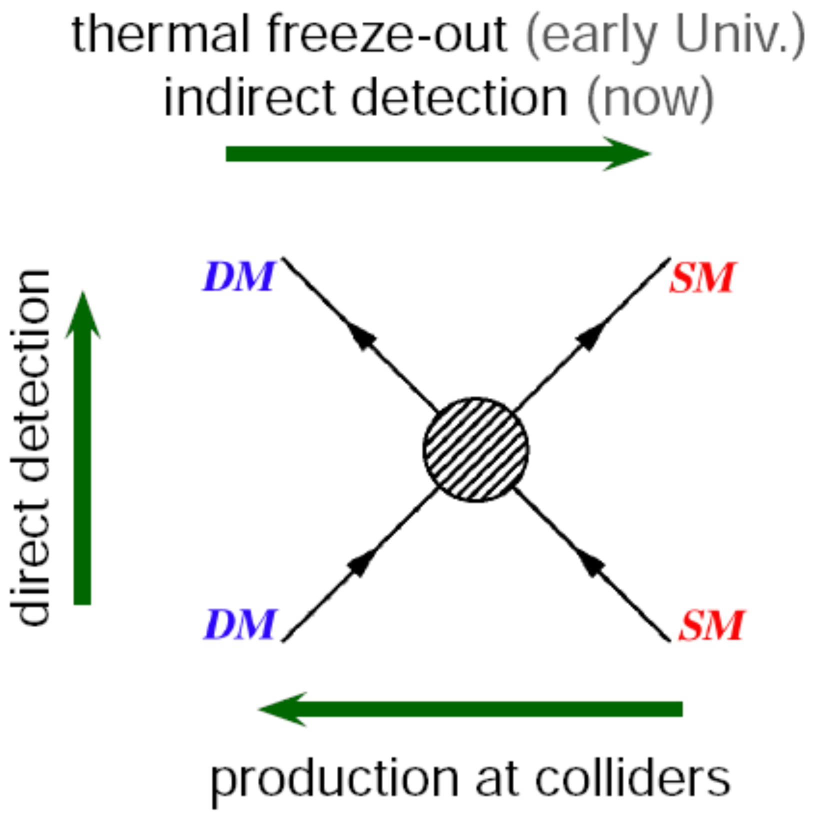
- Nature of the Higgs boson
- Higgs naturalness
- EW phase transition
- New physics?
- Dark matter?


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Observed
Local p-value
m_X [GeV]
0σ
1σ
2σ
3σ
4σ


ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb-1
Events / 40 GeV
Data - fitted background
m_γγ [GeV]

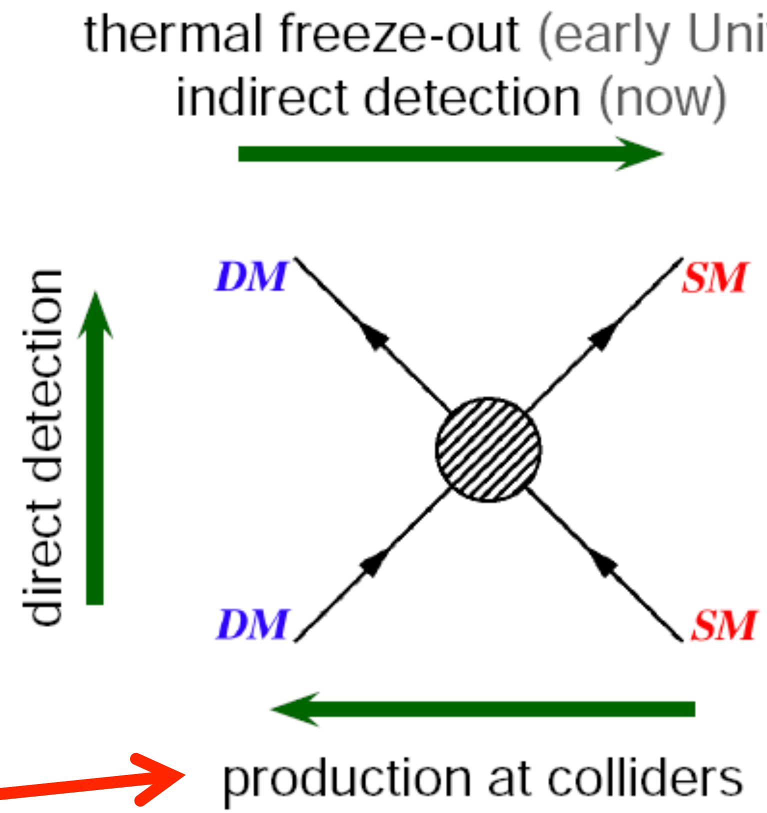
DM at the LHC

The standard lore...



DM at the LHC

The standard lore...



... is misleading

- Main signal comes from DM mediators
- EFT have limited use
- Searches are very model dependent

Conclusions

- Particle physics gives the tools for developing cosmology
- This is why the LHC is a formidable source of information for cosmology
- Lessons from Higgs: near-criticality, EW phase transition
- Naturalness has been challenged by LHC8. The answers from LHC13 will be critical for the strategy to go BSM, hence for cosmology
- The discovery of new physics can revolutionize our understanding of the microworld
- New information on the nature of dark matter