Basic Questions of High Energy Physics

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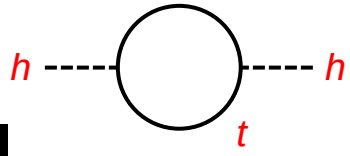
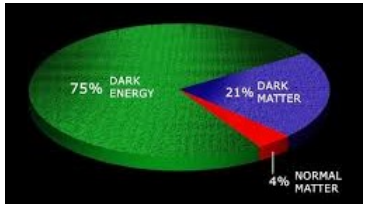
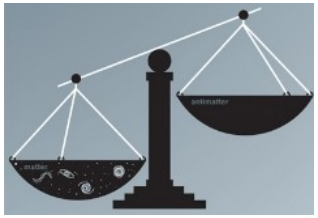
– Electroweak “naturalness”



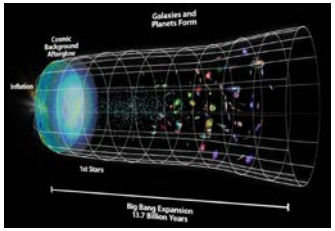
– Dark Matter



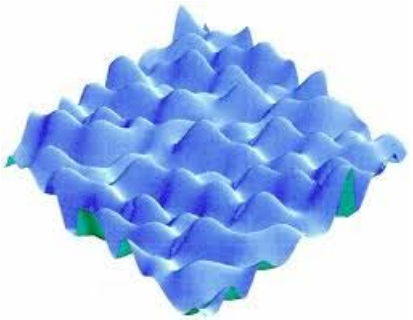
– Baryogenesis



– Inflation

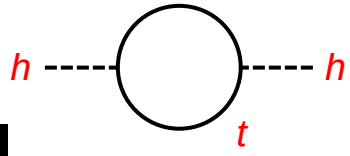


– Multiverse / Landscape



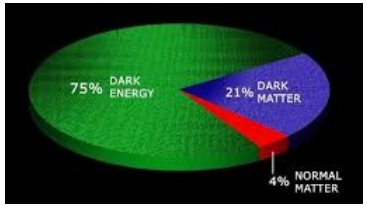
– Quantum gravity

– Electroweak “naturalness”



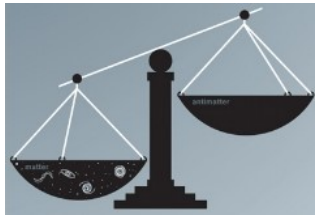
Composite Higgs

– Dark Matter



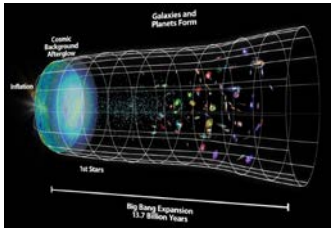
Higgs portal

– Baryogenesis



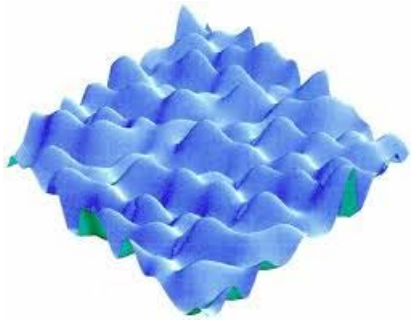
Electroweak baryogenesis

– Inflation



Higgs inflation

– Multiverse / Landscape



– Quantum gravity

Stability of the EWSB vacuum

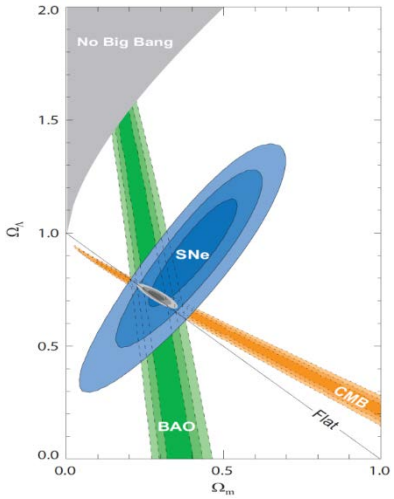
… The Higgs *could* be relevant for any of these!

Shocking news in 1998

Supernova cosmology project; Supernova search team

Expansion of the Universe is accelerating!

$$\Lambda \neq 0 \, !$$



Particle Data Group (2010)

Observationally,

$$\rho_\Lambda \sim (10^{-3}\ \text{eV})^4$$

Its smallness is already hard to understand

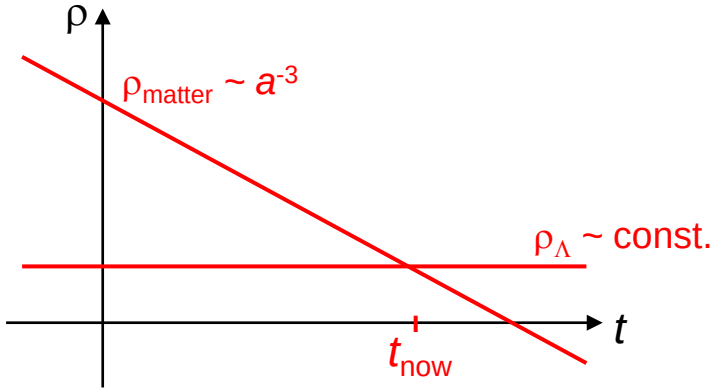
… natural size of $\rho_\Lambda \equiv \Lambda^2 M_{Pl}^2 \sim M_{Pl}^4$ (at the very least ~ TeV^4)

… Naïve estimate is $O(10^{120})$ too large

Moreover

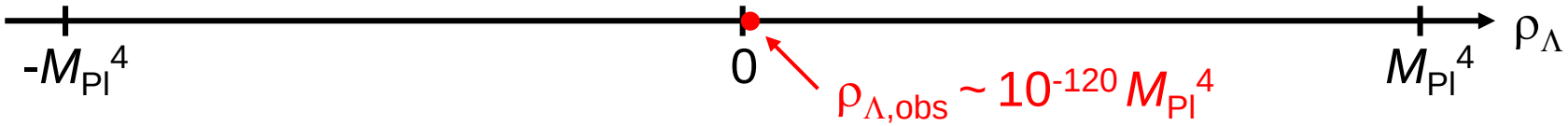
$$\rho_\Lambda \sim \rho_{matter}$$

— Why now?



Nonzero value completely changes the view!

Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



Unnatural (Note: $\rho_\Lambda = 0$ is NOT special from theoretical point of view)

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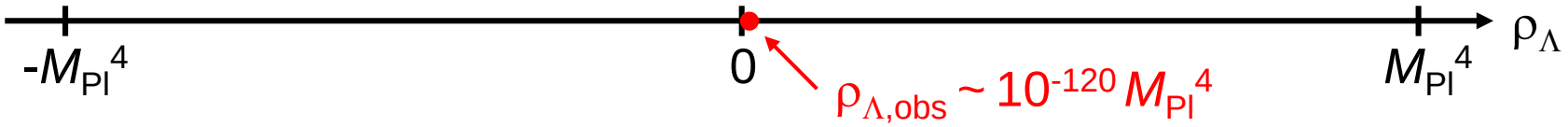
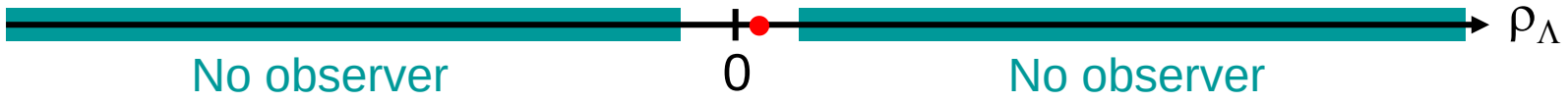


Unnatural (Note: $\rho_\Lambda = 0$ is NOT special from theoretical point of view)

⟹ Wait!

Is it really unnatural to *observe* this value?



It is natural to observe $\rho_{\Lambda,obs}$,

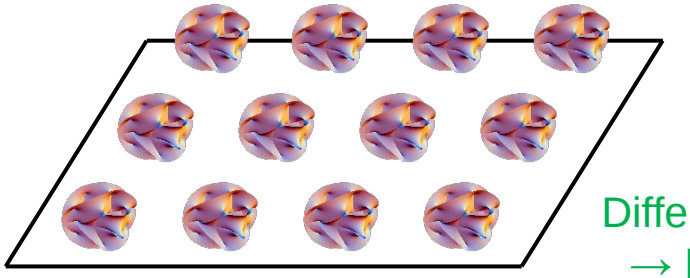
as long as different values of ρ_Λ are "sampled"

Weinberg ('87); also Banks, Linde, …

Theory also suggests:

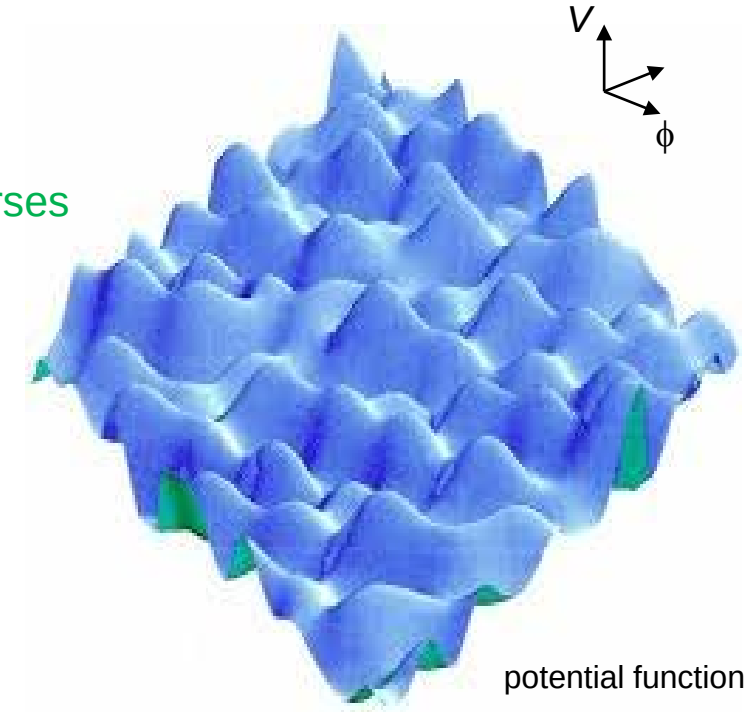
- String theory

  … existence of extra dimensions



https://commons.wikimedia.org/wiki/File:Calabi-Yau-alternate.png

Different solutions
→ Different universes



potential function

http://journalofcosmology.com/Multiverse9.html

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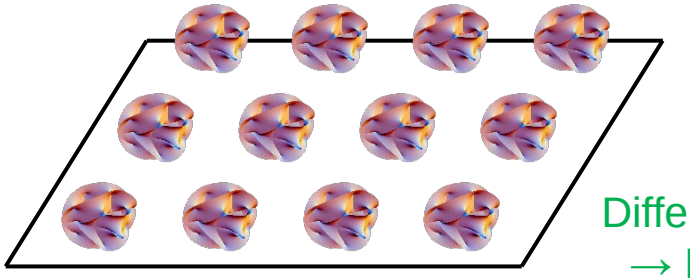

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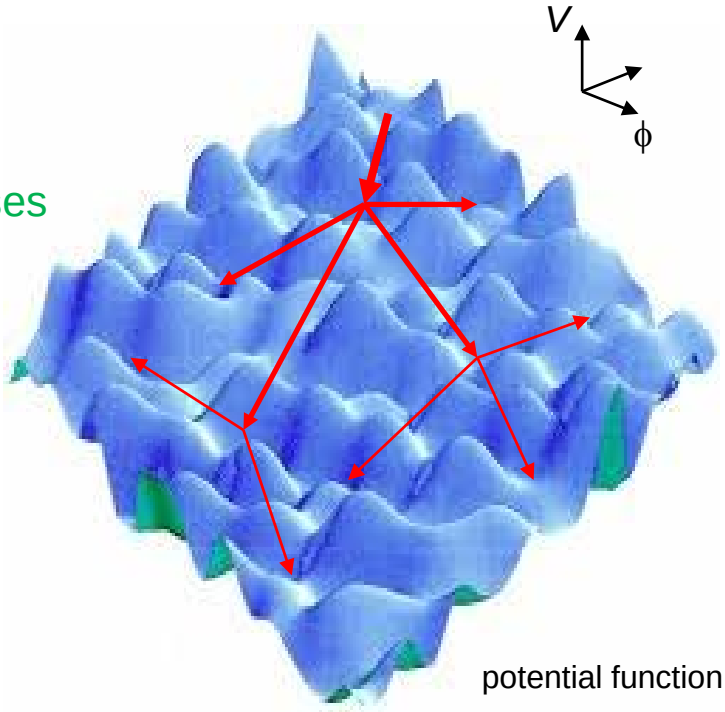

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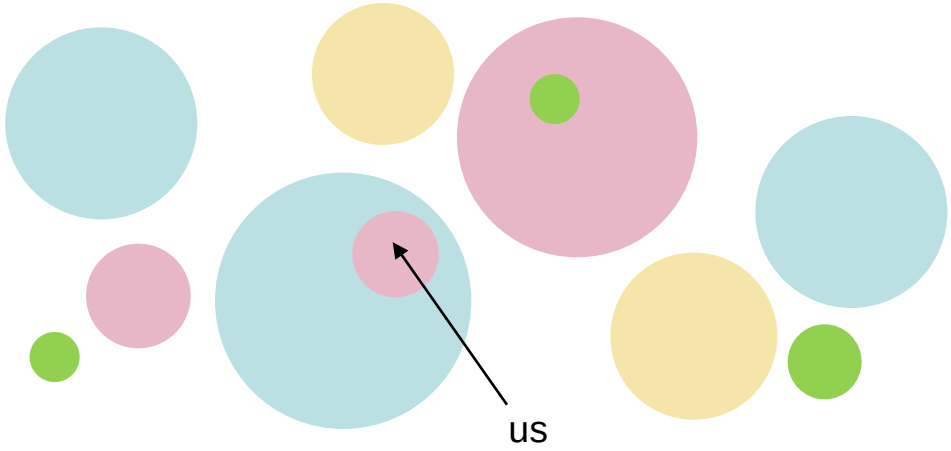
- Inflation

  … eternal to the future



… keep forming new “bubbles”

Typicality of our universe

Anthropic consideration in the landscape changes our thinking.

Weak scale affects environment Agrawal, Barr, Donoghue, Seckel ('97)

ex. Stability of complex nuclei

For fixed Yukawa couplings,

no complex nuclei for $v > 2\,v_{\rm obs}$ Damour, Donoghue ('07)

It is possible that $v_{\rm obs}$ arises as a result of environmental selection.

Does this mean that the Higgs *must* be extremely finely-tuned?

— No!

The scale of new physics is determined by statistics. … Typicality!

$$d\mathscr{N} \sim f(\Lambda)\,\frac{v^2}{\Lambda^2}\,d\Lambda \qquad f(\Lambda) \sim \Lambda^{p\text{-}1}$$

For $p < 2$, conventional naturalness results, but for $p > 2$, Λ prefers to be large.

Whether we see new physics or not depends on the probability distribution.

Composite Higgs

Georgi, Kaplan ('84); …; Kaplan ('91); …;
Contino, Y.N., Pomarol ('03); Agashe, Contino, Pomarol ('04); …

Strongly interacting sector:

$$G \rightarrow H$$

pseudo Nambu-Goldstone boson ≈ SM Higgs

The properties of the Higgs boson are affected.

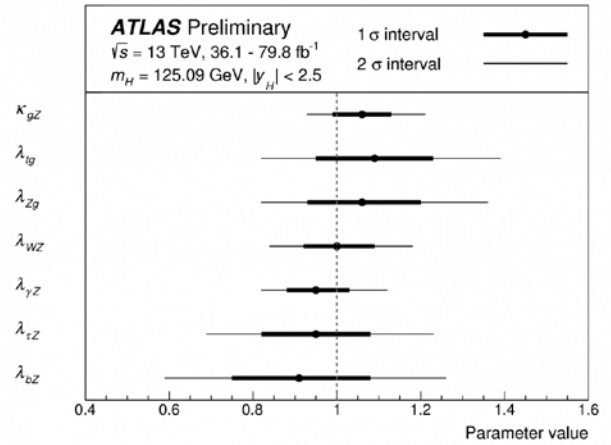
$$O_W = i\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \qquad O_B = i\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$O_{HW} = i(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad O_{HB} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

Giudice, Grojean, Pomarol, Rattazzi ('07)

Relevant quantities:

- Electroweak precision parameters (*Zbb̄*, *S*, *T*, etc.)
- Higgs couplings to gauge bosons and fermions
- Higgs self coupling



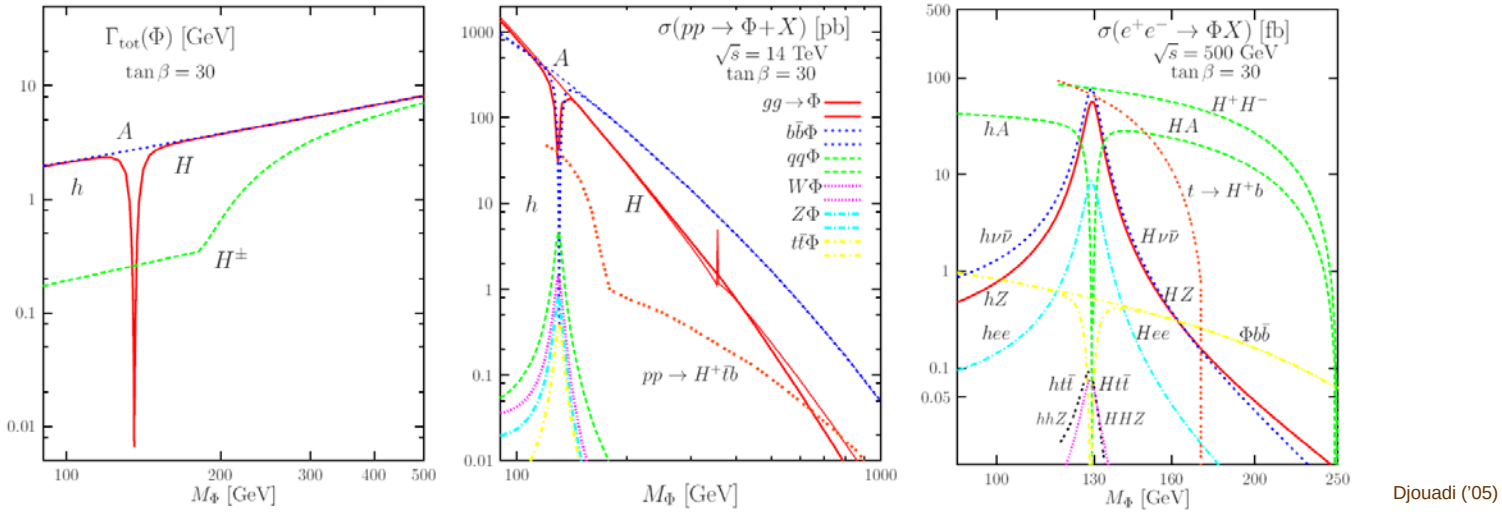
If any effect is seen, we expect a "large" new physics sector at higher energies.

Other Higgs bosons

There may be multiple Higgs bosons.

Example: Supersymmetric models, Non-supersymmetric two Higgs-doublet models, …

MSSM:



Djouadi ('05)

… different masses, different cross sections, different decay modes

With discovery of these Higgs bosons, we expect larger new physics nearby.

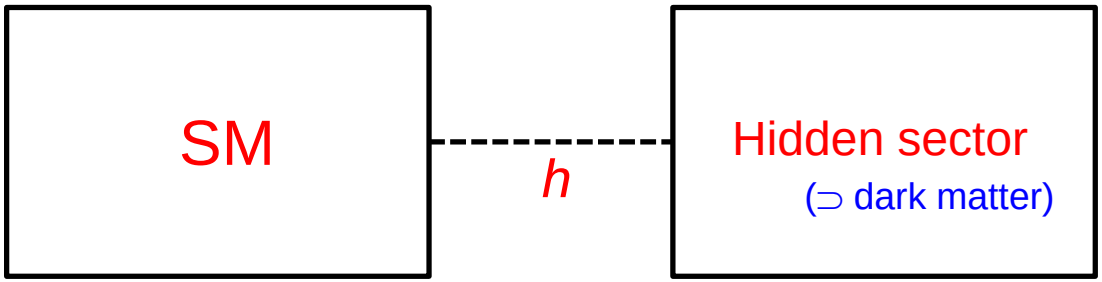
Note: The discovery of a new Higgs boson *without* other physics
→ a *real* challenge for the concept of typicality / naturalness

… One of the most unexpected (interesting) scenarios

Higgs portal

Binoth, van der Bij ('97); ...;
Schabinger, Wells ('05); ...; Patt, Wilczek ('06); ...

The Higgs field may play a role of connecting the SM to a hidden sector(s).



… affects the properties of the Higgs boson:

modification of the resonance shape, invisible decay channels, …

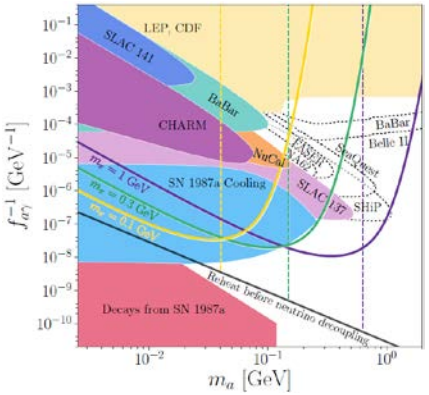
… provides a new window into a hidden / dark sector

A variant: axion (pseudo-scalar) portal

Y.N., Thaler ('08); ...; Hochberg, Kuflik, McGehee, Murayama, Schutz ('18); ...

A variety of probes possible:

beam dump and collider experiments, CMB, ...

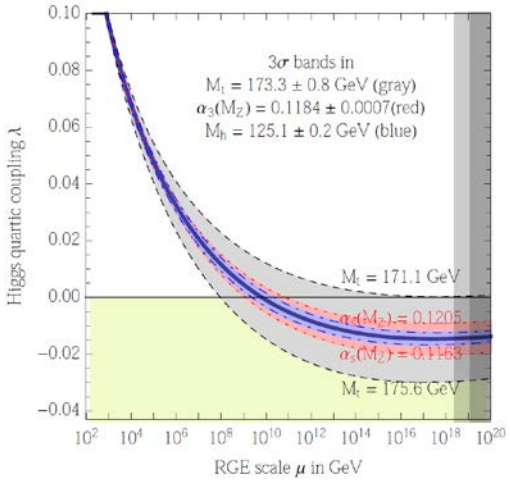


High energy properties

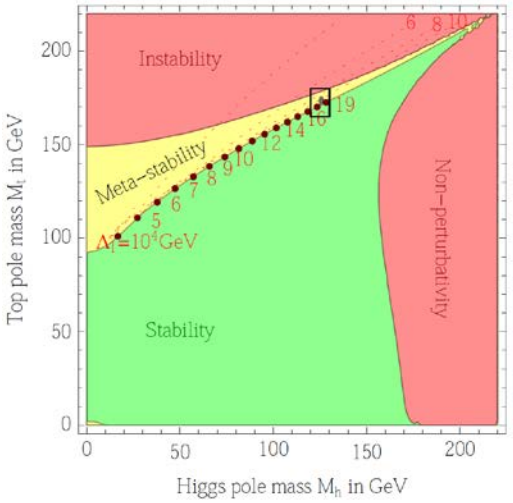
Physics may be Standard Model up to very high energies.

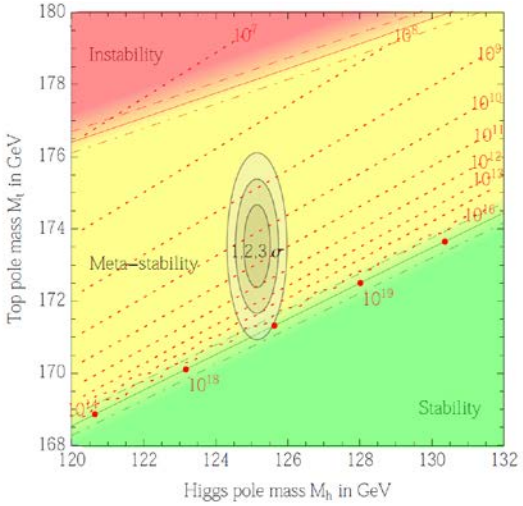
Precision measurements of the Higgs
and associated particles (top quark)

… may reveal fundamental aspects
of our universe through RG evolution.



Living dangerously in the multiverse?





… might be able to explore statistical properties of the string landscape.

Summary

- The Higgs field can be relevant
  to address many fundamental questions.

- Experimental windows are widely open.

… Let’s keep our fingers crossed!