Classical scale invariance, Physical Naturalness, stability of scales and inflation

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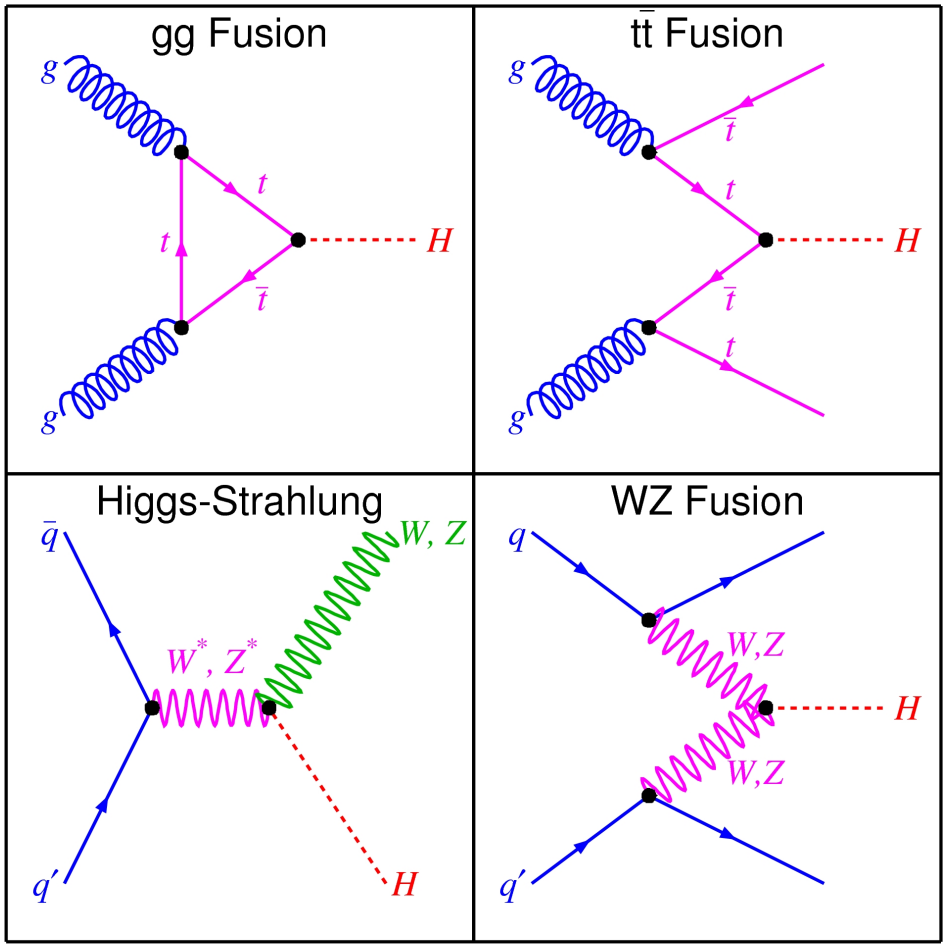
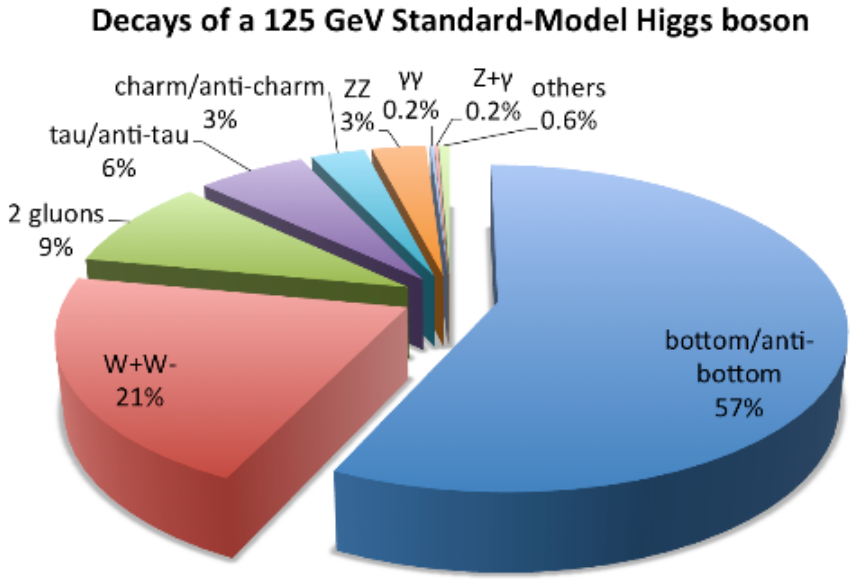
Outline

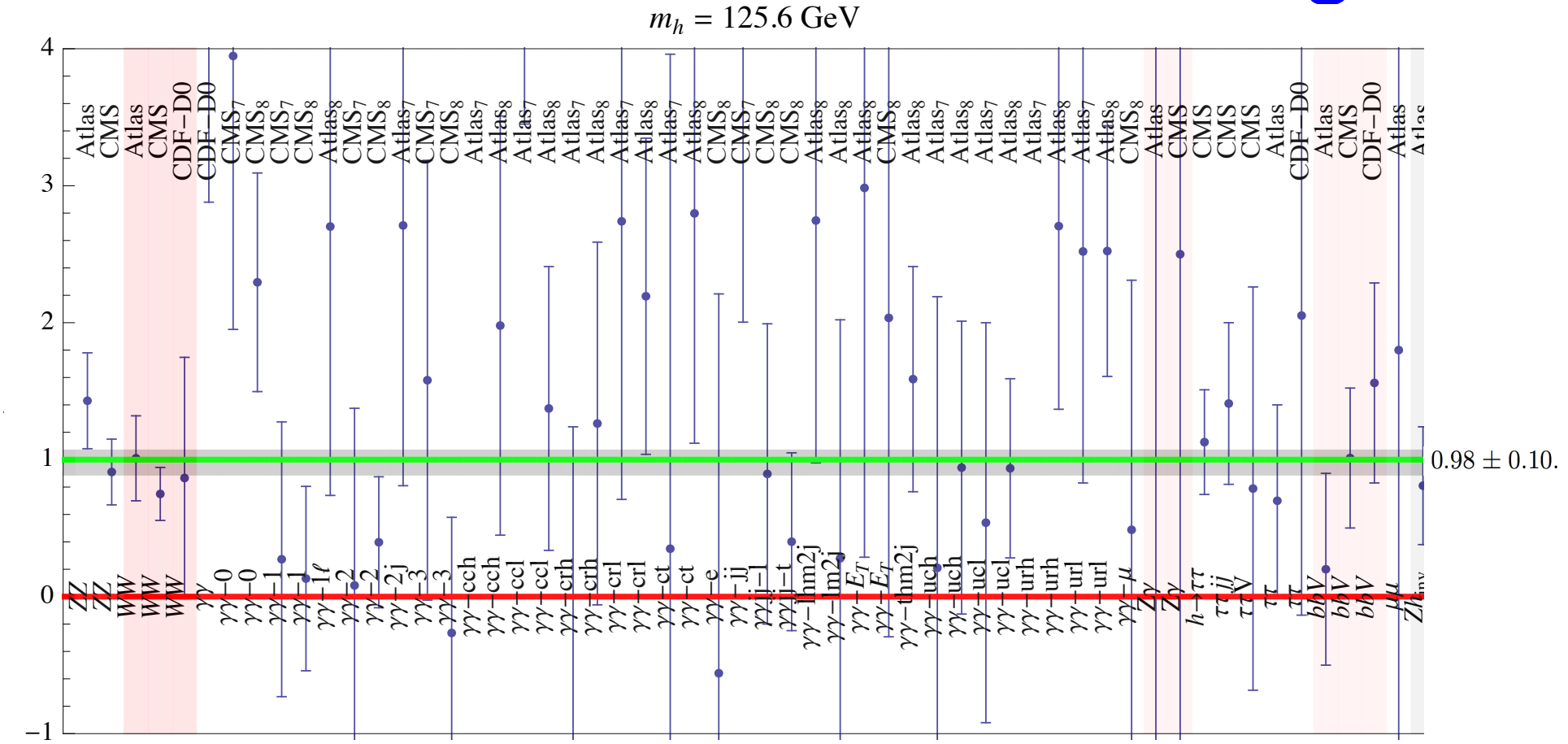
- Recall that physics is experimental science
- Physical Naturalness as a tool to discriminate between NP models – what do we learn?
- BICEP2, inflation and classical scale invariance

LHC discovered the Higgs boson





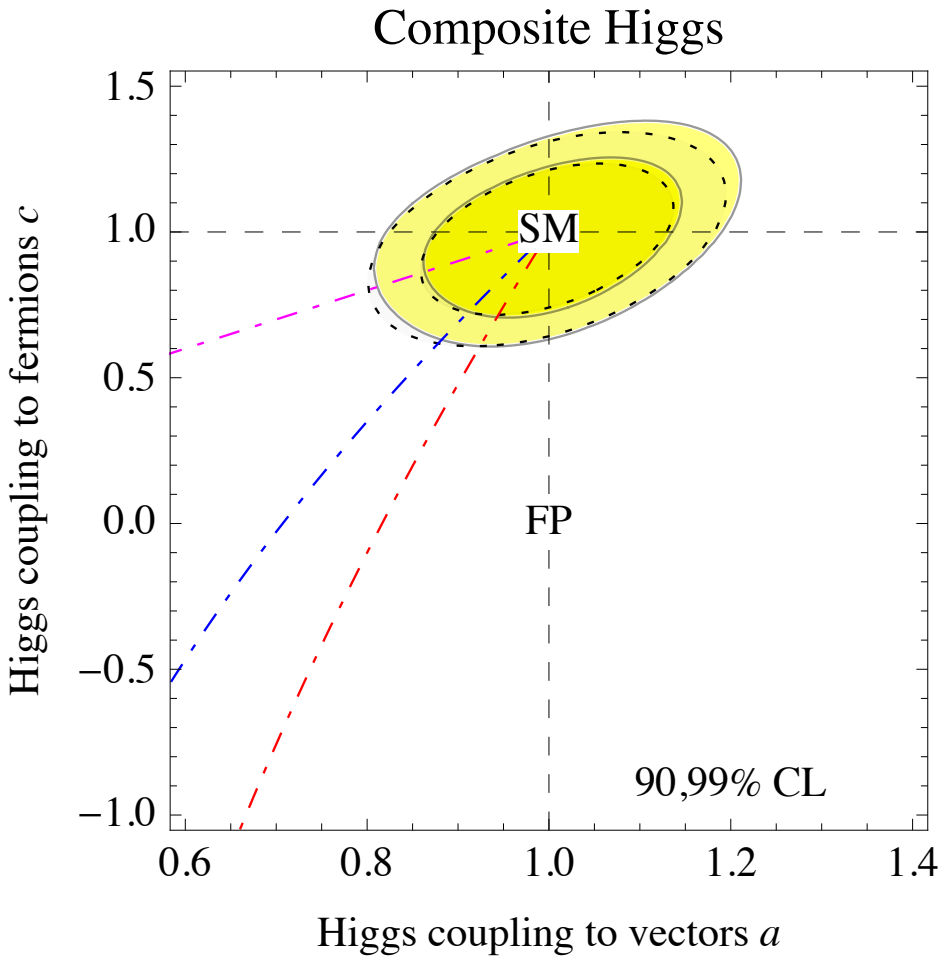
All LHC + Tevatron data - 10σ signal



P. Giardino, K. Kannike, I. Masina, M. Raidal, A. Strumia, arXiv:1303.3570

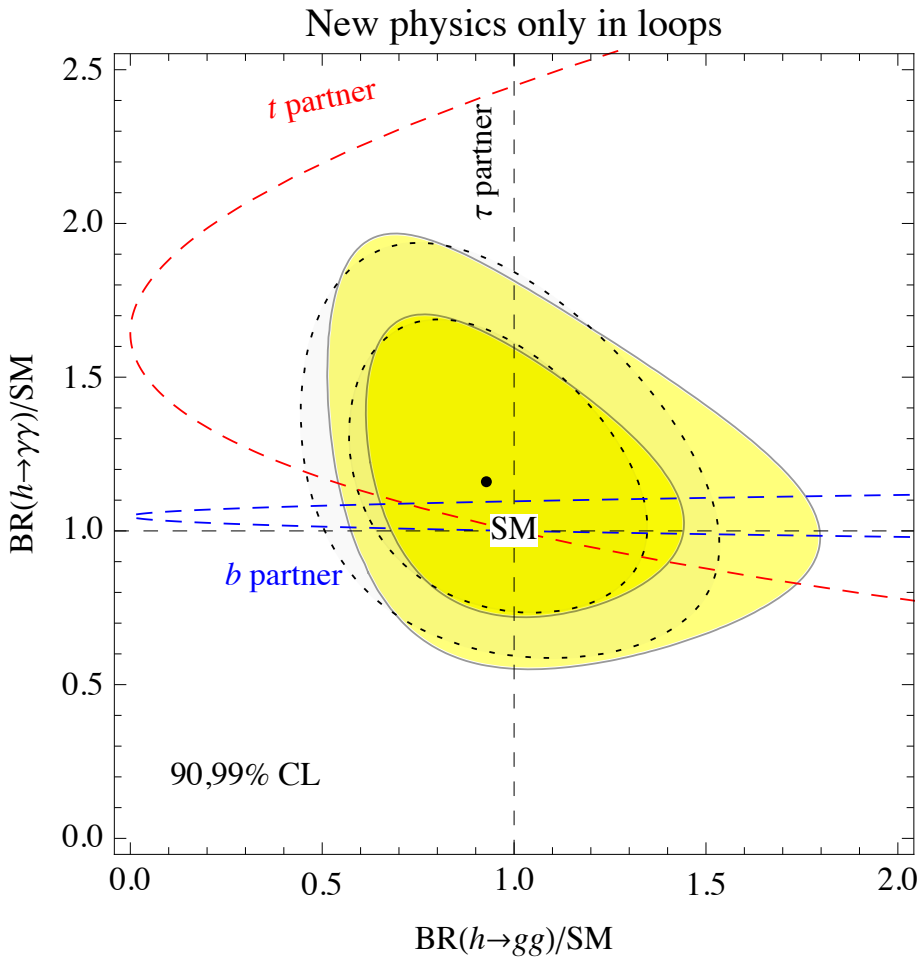
Tests of Higgs couplings

$$r_t = r_b = r_\tau = r_\mu = c, \qquad r_W = r_Z = a.$$



New physics enters only in loops

$$r_t = r_b = r_\tau = r_\mu = r_W = r_Z = 1, \qquad \frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = r_g^2, \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = r_\gamma^2$$



EW scale elementary scalars exist in Nature!

At the same time ….

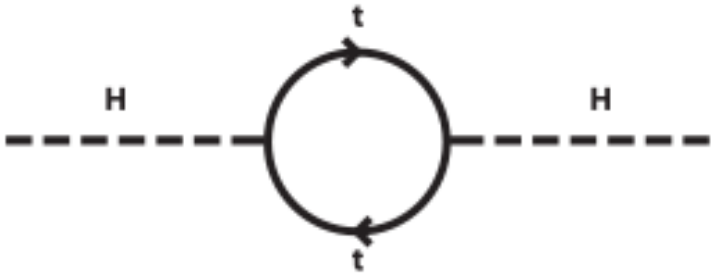
- LHC:
  - No SUSY
  - No signals of compositness, no resonances
  - No extra dimensions
  - No unexpected results
- Precision physics and flavour physics:
  - No new sources of flavour and CP violation
  - No higher dim. operators below 10-100 TeV

This is exactly opposite to the expectations by naturalness:

- All scalar masses must be at cutoff scale …
- … unless there exists a stabilizing mechanism at EW scale
- … or Nature is fine tuned

Where this wisdom is coming from?

Renormalization of scalar mass



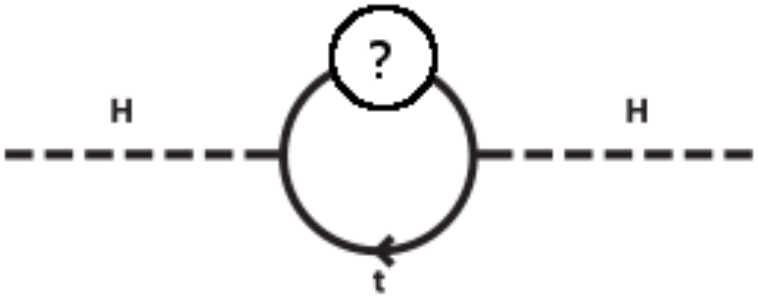
M_H=?

- Two points of view:
  - In cut-off dependent regularization schemes, scalar mass should get Λ^2 contribution
  - In dimensional regularization, there is no scale and therefore no such contribution
- Physics must not depend on math tool one uses to regularize divergent integrals!

  (Fine tuning of non-physical bare parameters does not measure physical naturalness)

The previous question is not well formulated

- IF there exists threshold of physical particles with mass M that couple to the scalar,



$$M_H^2 \propto M^2 \log(\Lambda/M)$$

- Scalar masses are naturally as large as the threshold mass scale
- Naturalness is a real, physical principle for NP

"Physical Naturalness"

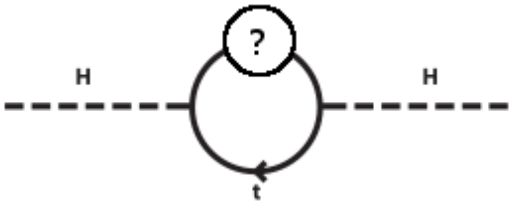
The hierarchy problem is properly named:
it is not the "quadratic divergence problem”

It concerns the physical hierarchy of
physical particles

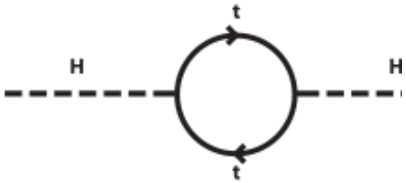
Last 40 years or so physicists have invented reasons to associate the cut-off scale Λ in cut-off regularization with a physical threshold

There is/has been lot of confusion

- Recently Skiba&Schmaltz claimed that $M_H^2 \propto \Lambda^2$ comes from breaking of quantum scale invariance
  - IF this breaking introduces particle threshold with $M^2 \propto \Lambda^2$, this is physical



  - However, they also claim that running in asymptotically free theory creates power-divergences
  - E.g., in massless QCD with massless scalar



the scalar mass is divergent! Cannot be physical!

The SM as an Effective Field Theory

- The Wilsonian view of renormalization:
  - Low scale EFT operators are generated by integrating out degrees of freedom of the UV theory at a cut-off scale Λ
  - Scalar mass parameters should be of order the cut-off scale $M \approx \Lambda$
  - Marginal couplings (Yukawas, gauge couplings, Higgs quartic) run logarithmically
  - Non-renormalizable operators are suppressed by powers of E/Λ

Wilsonian predictions for physics

- If the SM is an effective theory, we expect:
  - There can be no elementary scalars below the cutoff-scale
  - There should be evidence for dimension 5 and higher operators, if the cutoff-scale is not too high
  - Alternatively, there must be stabilizing mechanism - SUSY

- Otherwise theory is unnatural – accept anthropic fine tuning!

Clearly the LHC is telling us that the above reasoning does not work

- I am not telling that the Wilsonian picture of renormalization is wrong. QFT is OK!

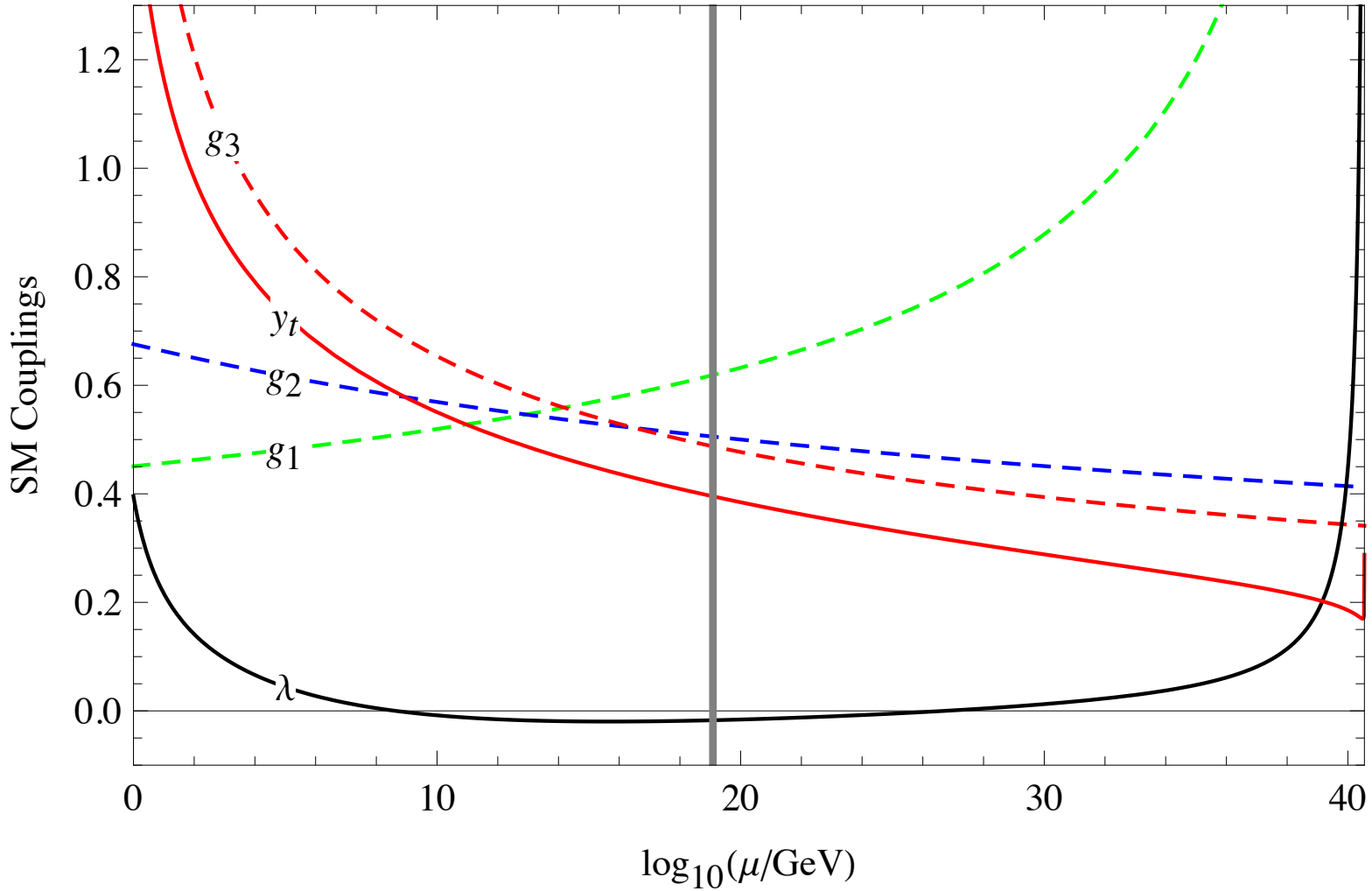
- I am telling that experiment teaches us that the SM is not EQFT in the Wilsonian sense

- The SM is not obtained from some UV theory by integrating out heavy particles (GUT is excluded) but is part of the UV theory itself

But the gravity exists!

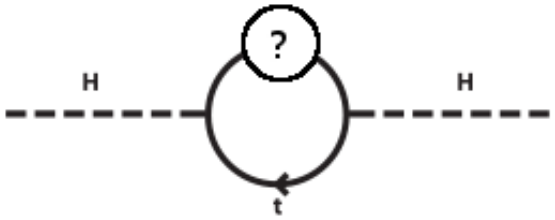
- The UV theory of renormalizable quantum gravity is not known
- There are two logical possibilities:
  - Gravity becomes strong at Planck scale MP, thus Higgs mass must be at MP (standard paradigm to motivate SUSY)
  - Gravity remains weakly coupled, like Agravity (new paradigm)
- It is difficult, if not impossible, to test the latter unless inflation provides us with new information

The SM couplings in the full validity range



But the Landau poles exist!

- QED is exp. most tested and theoretically best understood QFT. Is it really pathologically ill?
- It is not clear that Landau pole introduces a new threshold – just perturbation theory breaks down



- Lattice studies show that there is NO Landau pole below the lattice cut-off scale a

Landau poles and strong coupling

- There is nothing wrong with QED with non-perturbative coupling (loose tools to compute)
- Non-perturbative studies claim: photon decouples, interaction grows linearly and the theory remains unitary
- Log running of electric charge does not introduce the hierarchy problem, why should power running do?
- It is not clear that Landau pole is a problem at all

Next question Wilson addressed

- Why there are no operators of any arbitrary dimension? H^6, H^8, H^{123}, …

- Classical scale invariance is a fundamental law of Nature!

- Classical scale invariance does not solve the hierarchy problem if there is more than 1 scale

But there exist scales!

- All scales in Nature are generated dynamically by quantum effects via dimensional transmutation

- The known mechanisms are
  - Strong QCD-like dynamics
  - Weakly coupled Coleman-Weinberg type dynamics

Lessons from the Physical Naturalness and classical scale invariance

Small couplings are natural

- Small scalar self-coupling (trivial fixed point) is natural
  - CMB tells us that inflaton self coupling is $<10^{-14}$
  - Higgs quartic can be vanishing at M_P
- Decoupling is natural

$$\lambda H^2 S^2$$

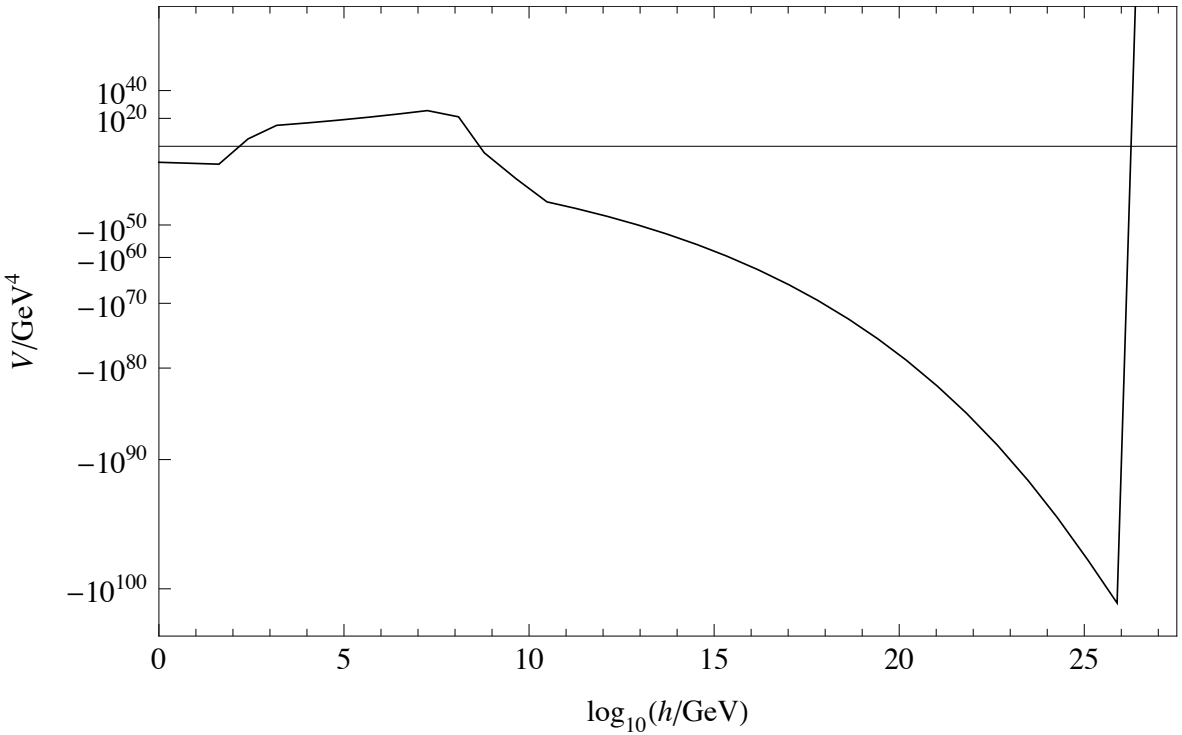
- $\lambda = 0$ in the portal increases symmetries, thus natural according to 't Hooft

Hierarchical scales can be stable and natural

- Scales are generated by logarithmic running of small couplings via CW mechanism
  - Large hierarchies are generated
  - Small portal couplings between the scales are natural, implying no large corrections from higher scales

The Standard Model revisited

The SM Higgs potential



- Lifetime of our metastable vac. is sufficient

- Why do not we live in the global minimum?

Such a SM Higgs potential is ph. unacceptable!

The most minimal scale invariant extension of the SM and DM

- Add one complex singlet S to the SM

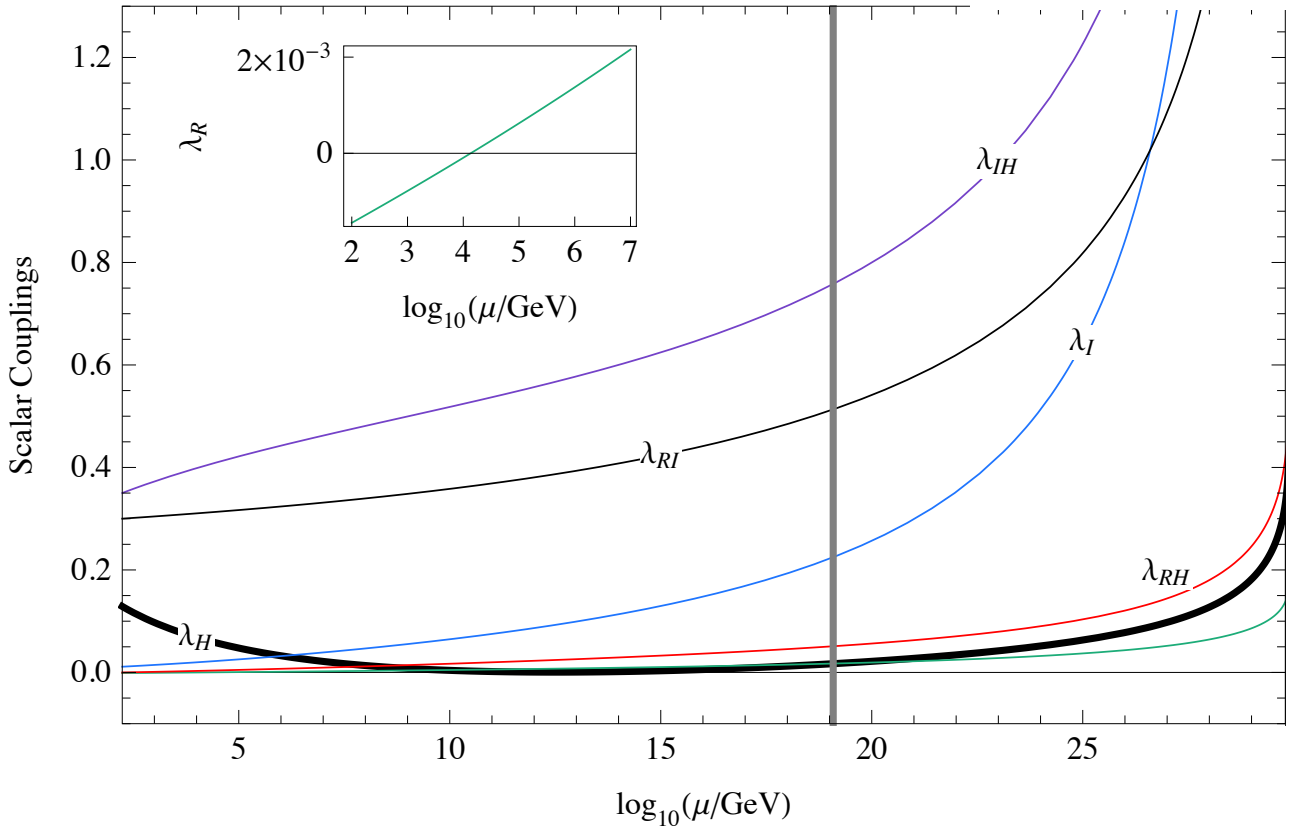
$$V = \lambda_H |H|^4 + \lambda_S |S|^4 + \frac{\lambda'_S}{2}\left[S^4 + (S^\dagger)^4\right] + \frac{\lambda''_S}{2}|S|^2\left[S^2 + (S^\dagger)^2\right] + \lambda_{SH}|S|^2|H|^2 + \frac{\lambda'_{SH}}{2}|H|^2\left[S^2 + (S^\dagger)^2\right].$$

- The SM vacuum stability is cured due to new bosonic contributions to the beta functions

$$16\pi^2\beta_{\lambda_H} = \frac{3}{8}(3g^4 + 2g^2g'^2 + g'^4) + \frac{1}{2}(\lambda_{RH}^2 + \lambda_{IH}^2) + 24\lambda_H^2 - 3\lambda_H(3g^2 + g'^2 - 4y_t^2) - 6y_t^4,$$

Dimensional transmutation without any additional gauge interaction

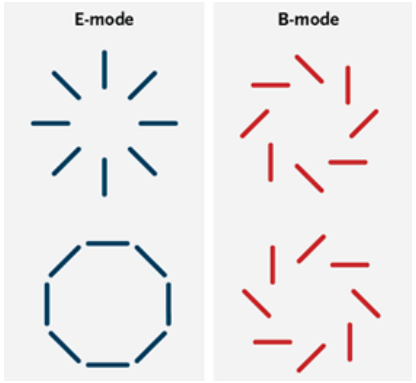
$$16\pi^2\beta_{\lambda_R} = 18\lambda_R^2 + 2\lambda_{RH}^2 + \frac{1}{2}\lambda_{RI}^2, \qquad v = v_R\sqrt{\frac{|\lambda_{RH}|}{2\lambda_H}},$$



The new BICEP2 on inflation support the classical scale invariance paradigm

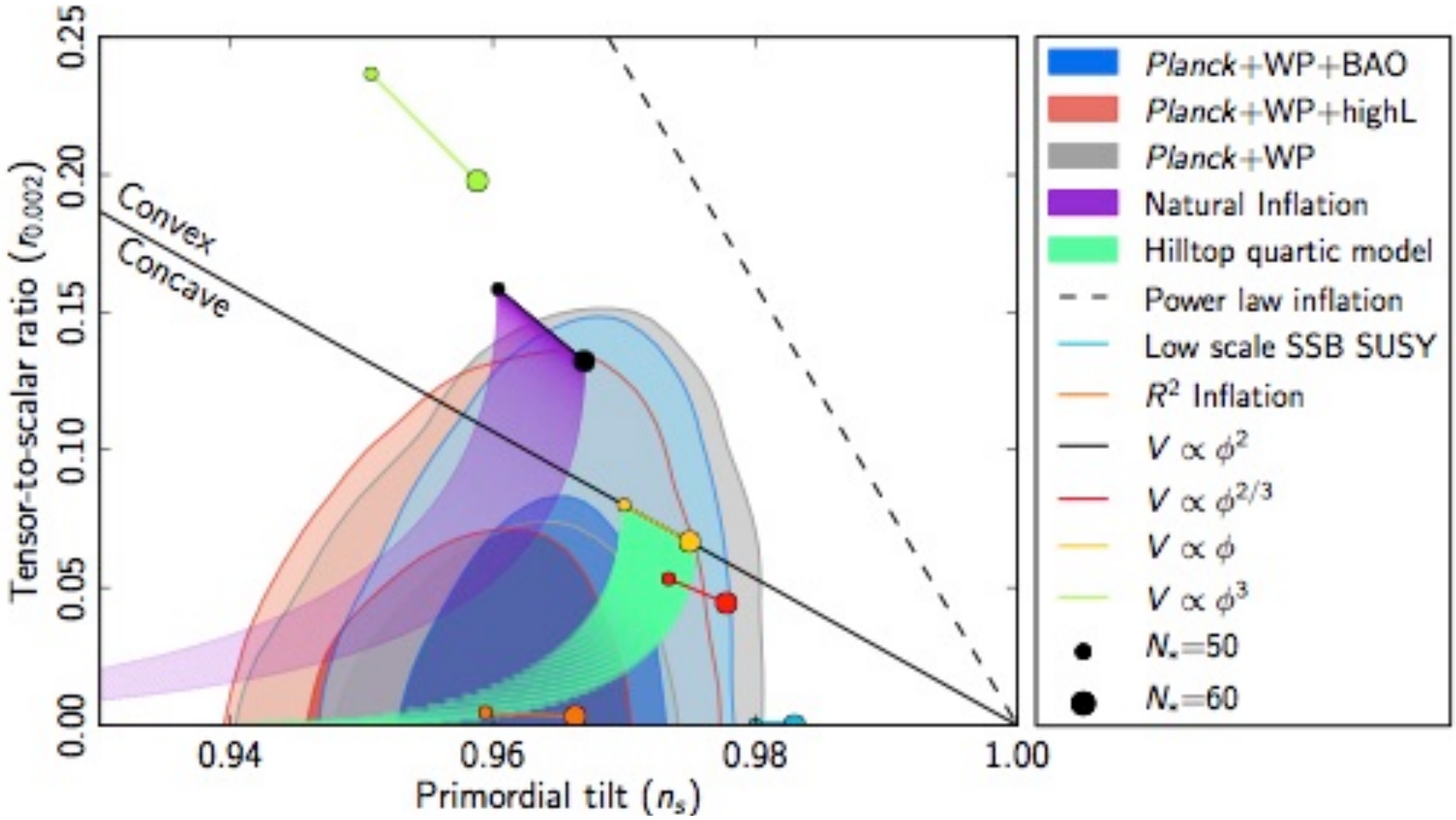
Quantum gravity discovered!

- BICEP2 claims to measure primordial B-modes
  - Fluctuations of gravity
  - Gravitational lensing (excluded)
- Can also be induced by dust



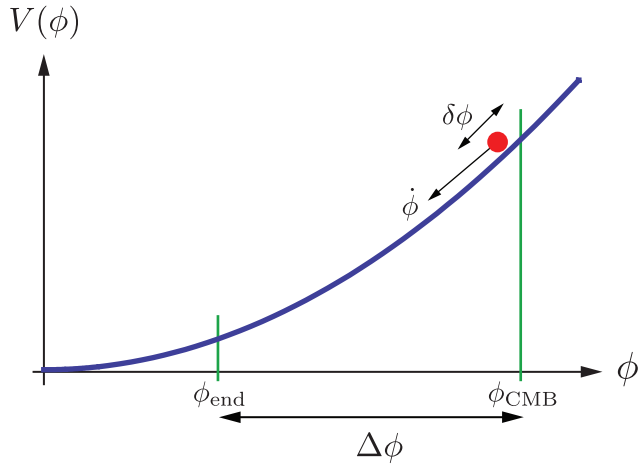
- Assuming the first, the measured tensor-to-scalar ratio r=0.2 implies the scale of inflation to be 10^{16}GeV
- This is our only realistic exp. test of quantum nature of gravity

Tension with Planck data



Implications for inflation and gravity?

- $V=(10^{16})^4$ GeV^4 is sub-Planckian – particle physics is under control
- But Lyth bound implies trans-Planckian field excursions

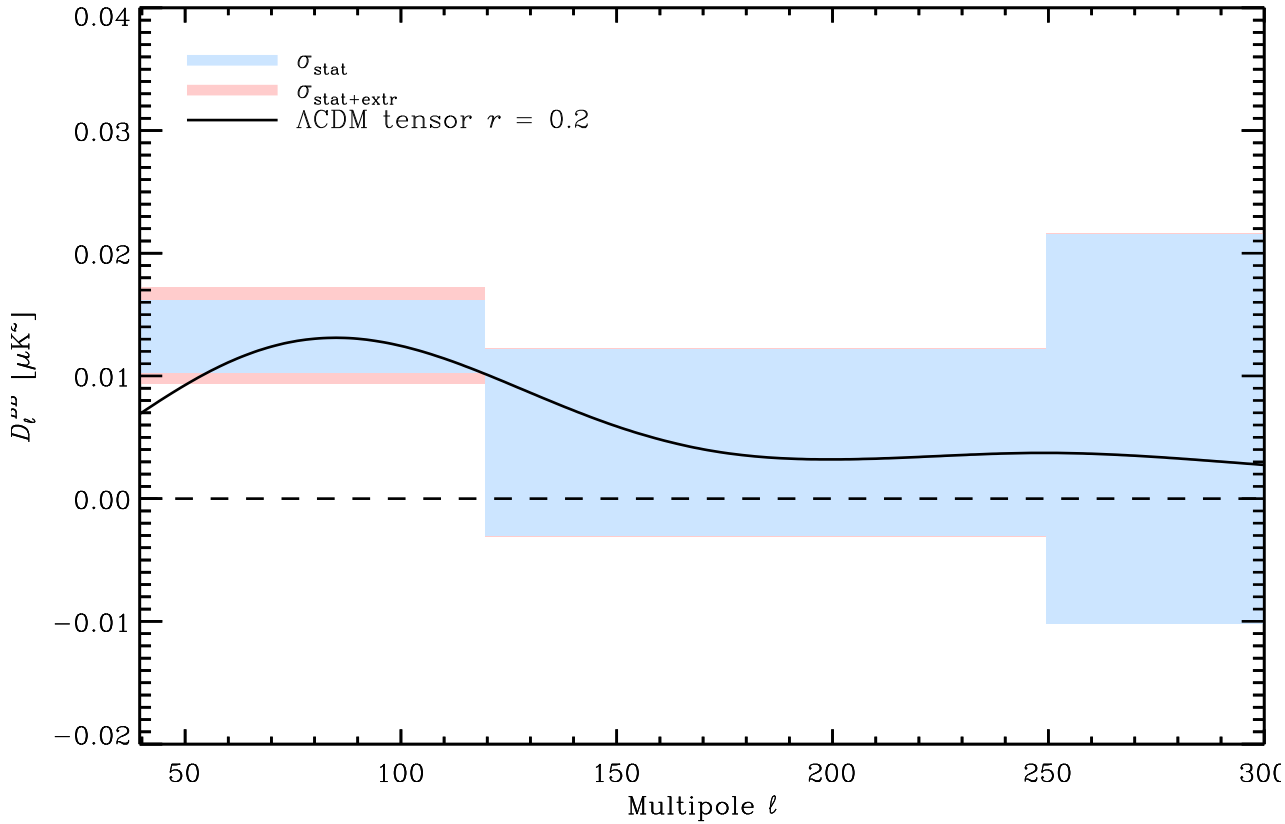


- What about operators like

φ^6, φ^{48}, φ^{234567} which all must be there according to standard paradigm?

- Inflation data shows no trans-Planckian operators!

Planck published first dust data



The BICEP2 signal strength can be explained wit

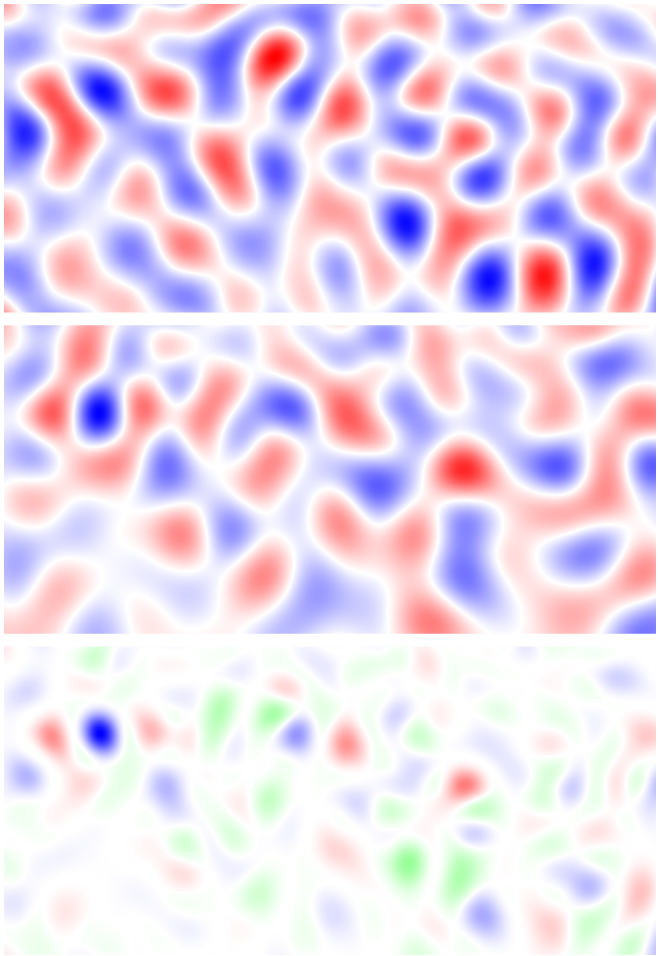
- r=0.2 and no dust
- R=0 and dust only

One needs to study correlations between the BICEP2 and dust maps

- Done by theorists
- Small but significant correlation found

- r=0.1±0.04

This analyses must be repeated by experiments



Classical scale invariance and CW inflation

- Assume that M_P and inflaton potential are induced by CW mechanism

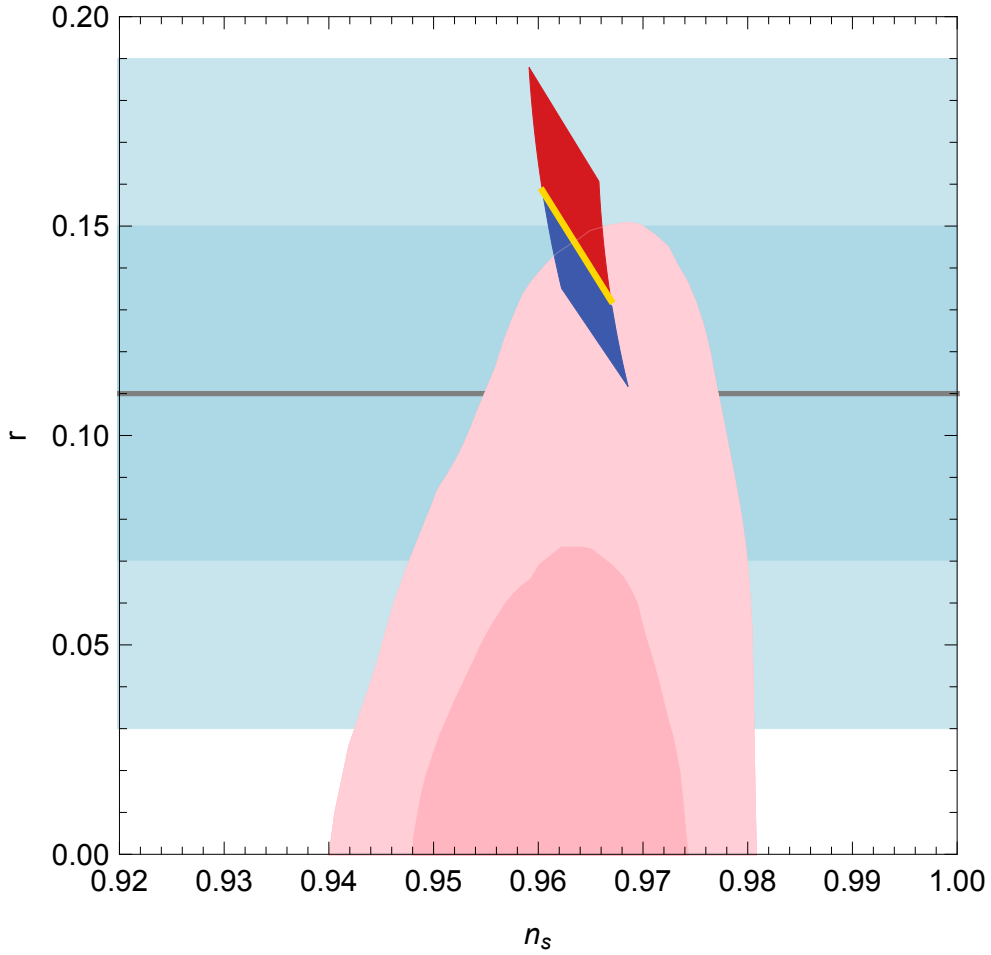
$$V = \frac{1}{4}\lambda_\phi(\phi)\phi^4, \qquad f(\phi)R \equiv \frac{\xi_\phi}{2}\phi^2 R \qquad v_\phi^2 = \frac{M_{\rm P}^2}{\xi_\phi}.$$

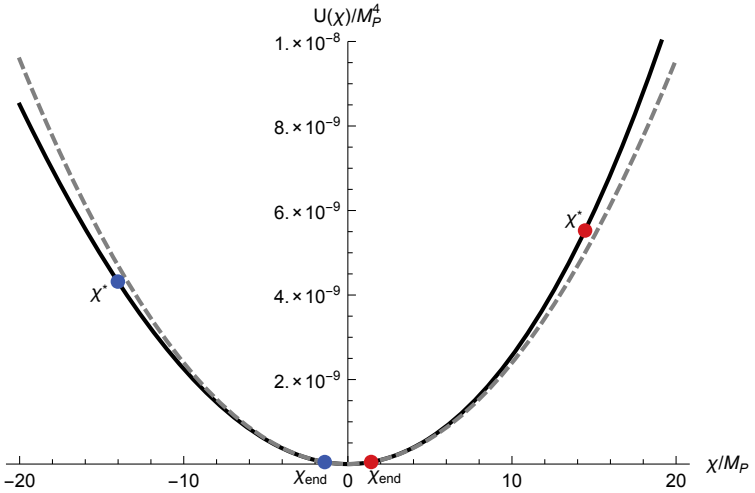
- Tune V(v)=0 to avoid CC
- The minimal model

$$\mathcal{L}_Y = y_\phi \phi \bar{N}^c N + y_\sigma \sigma \bar{N}^c N,$$
$$V = \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{4}\lambda_{\phi\sigma}\phi^2\sigma^2 + \frac{1}{4}\lambda_\sigma \sigma^4,$$

In Einstein frame $\qquad U(\phi) = \frac{1}{4}\lambda_\phi(\phi)\frac{M_{\rm P}^4}{\xi_\phi^2}.$

BICEP2 and Planck results indicate for classical scale invariance and CW inflation





If r=0.1 will be confirmed, this is clear evidence for dynamically generated Planck scale and for the classical scale invariance

My predictions

- For next week:
  - On Dec. 22 Planck polarization results will confirm LCDM
  - Tensions with other measurements will decrease
- For next 6 month:
  - r=0.1±0.05 will be obtained from correlated dust and BICEP2 maps
- For next 2-3 years:
  - No unexpected discovery from the LHC
  - Keck Array, BICEP3 etc will confirm r=0.1±0.02

Conclusions

- Naturalness is physical principle that can discriminate between different NP scenarios
- Lesson from the LHC: the SM seems to be part of UV theory of Nature rather than being merely a low-energy effective QFT a la Wilson (no GUT)
- In that case classical scale invariance is needed as a fundamental concept of Nature
- BICEP2 result supports CW inflation, dynamically generated M_P and classical scale invariance