Vacuum (meta?)stability, Higgs inflation and physics beyond the Standard Model

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Summary of the LHC findings

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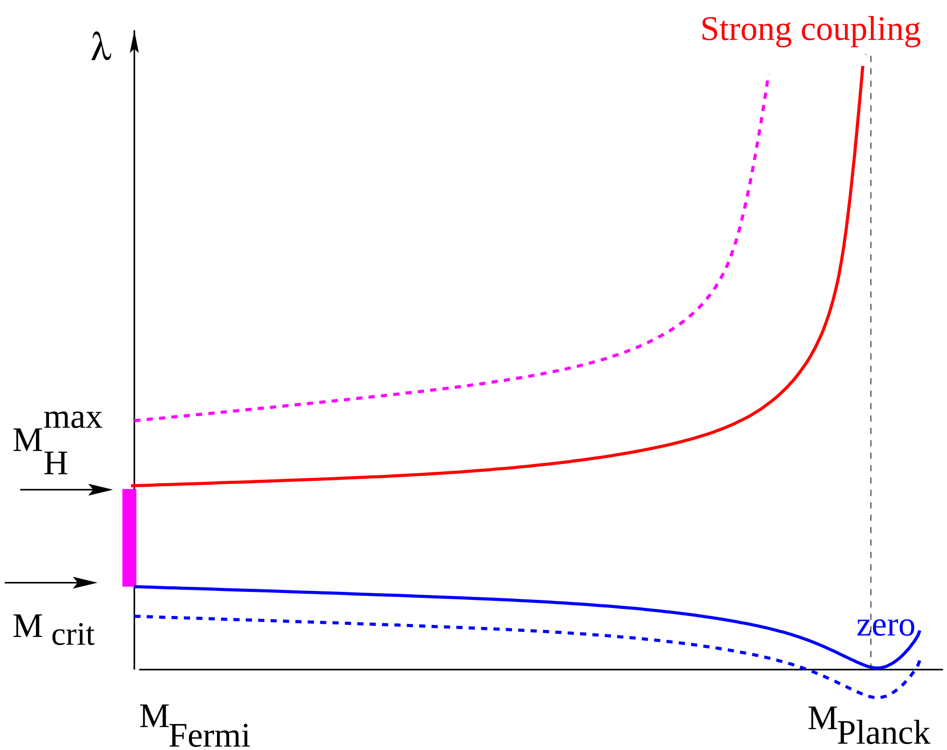
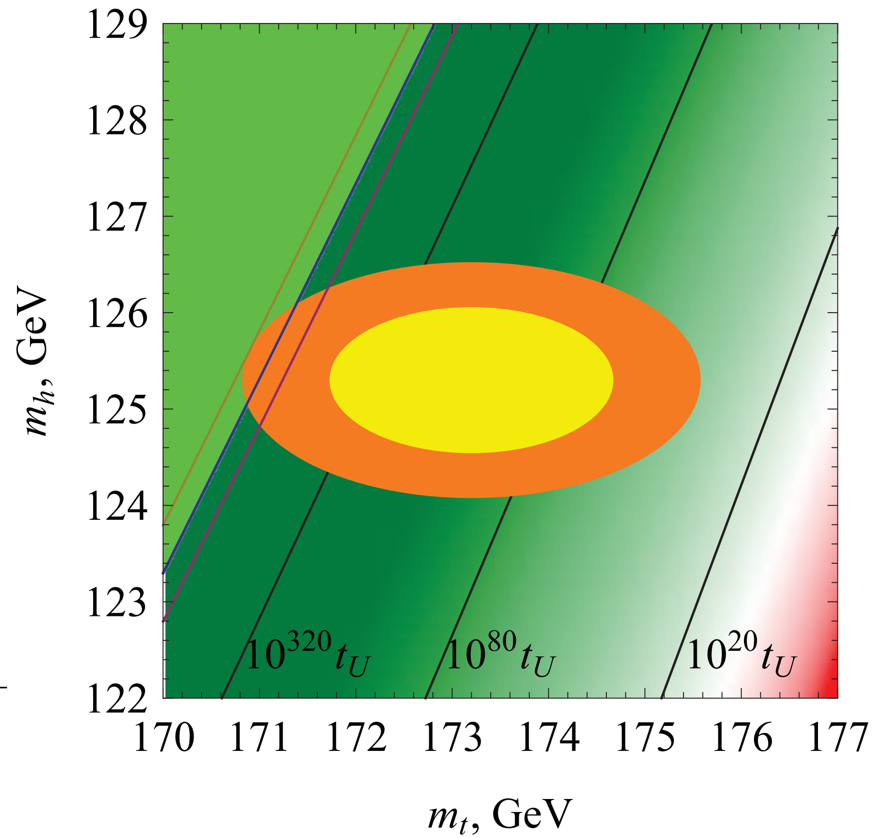
- The Standard Model in now complete: the last particle - Higgs boson, predicted by the SM, has been found
- No deviations from the SM have been observed
- The masses of the top quark and of the Higgs boson, the Nature has chosen, make the SM a self-consistent effective field theory all the way up to the Planck scale
  114 GeV $< m_H <$ 175 GeV

Behaviour of the scalar self-coupling

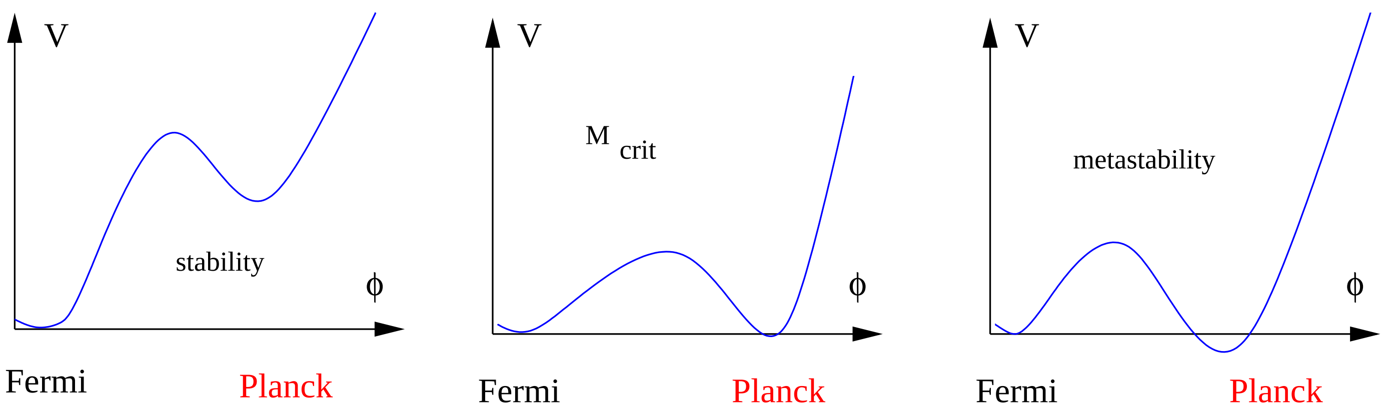


vacuum lifetime



Vacuum (meta?)stability

Important fact: The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM vacuum* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety values for M_H and M_t *** (09'):

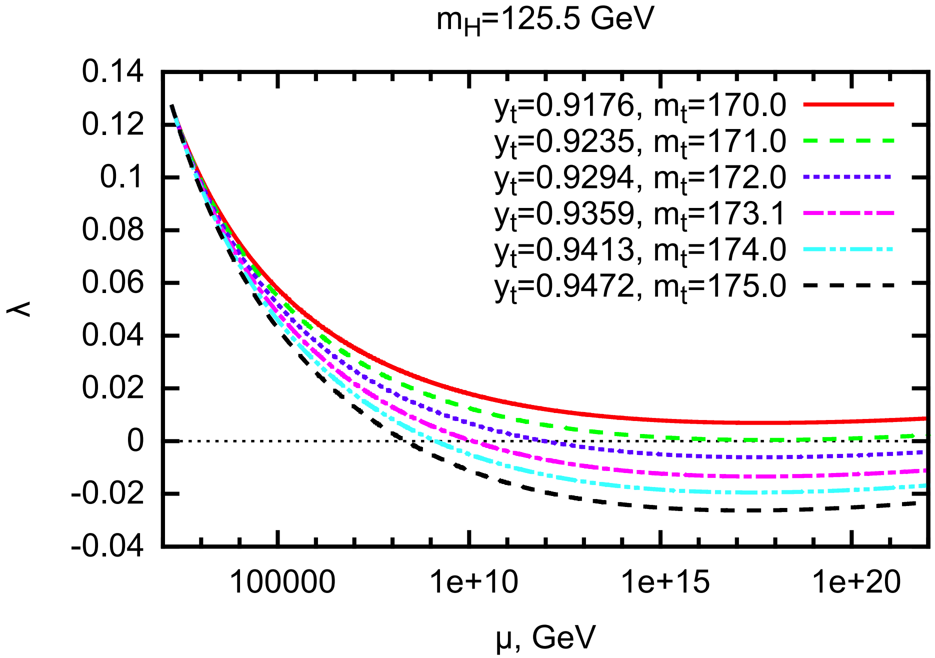


* Froggatt, Nielsen

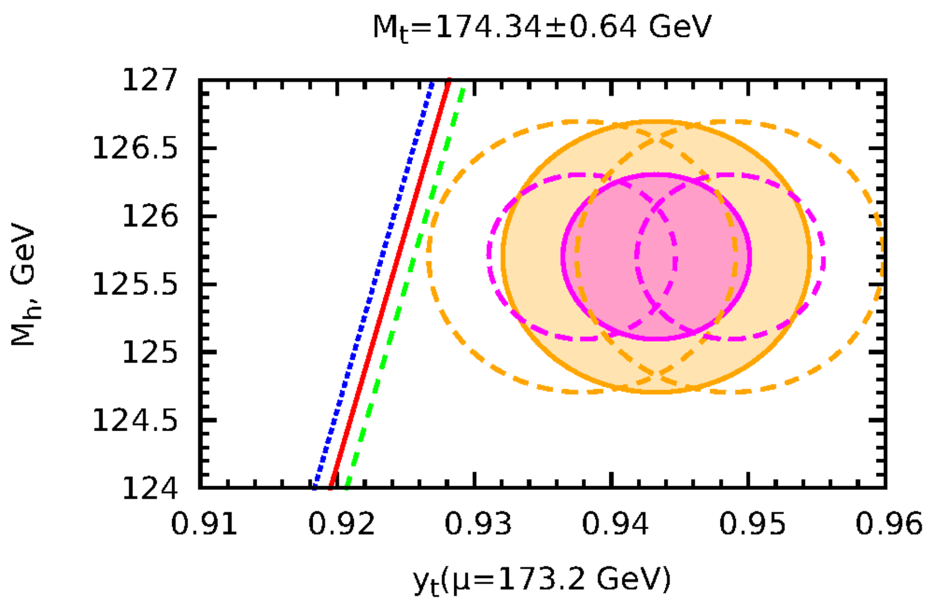
** Bezrukov, MS

De Simone, Hertzberg, Wilczek

*** Wetterich, MS

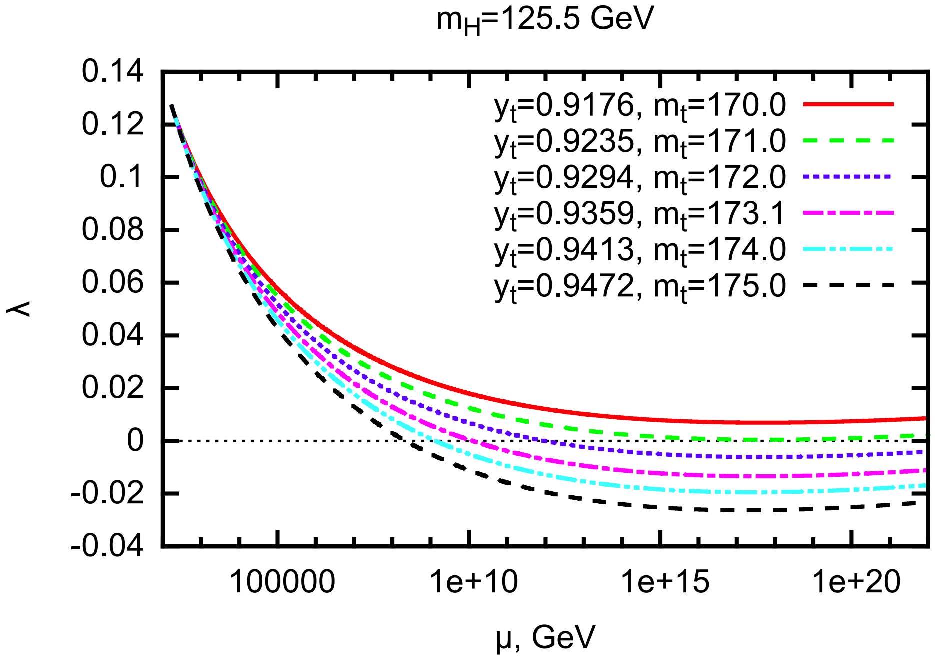


Absolute stability

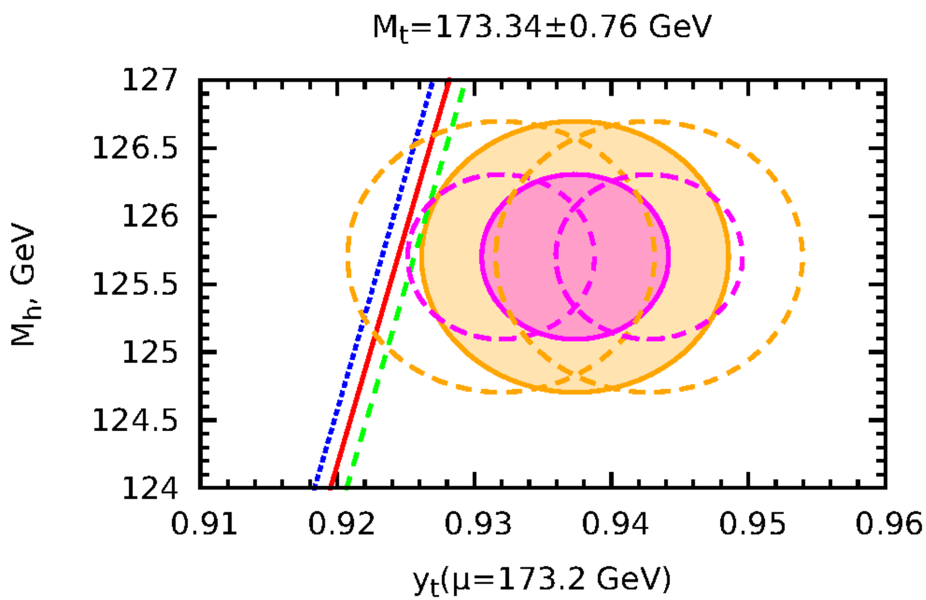


Metastability

TEVATRON 2014: $m_t = \mathbf{174.34 \pm 0.37 \pm 0.52\ GeV}$

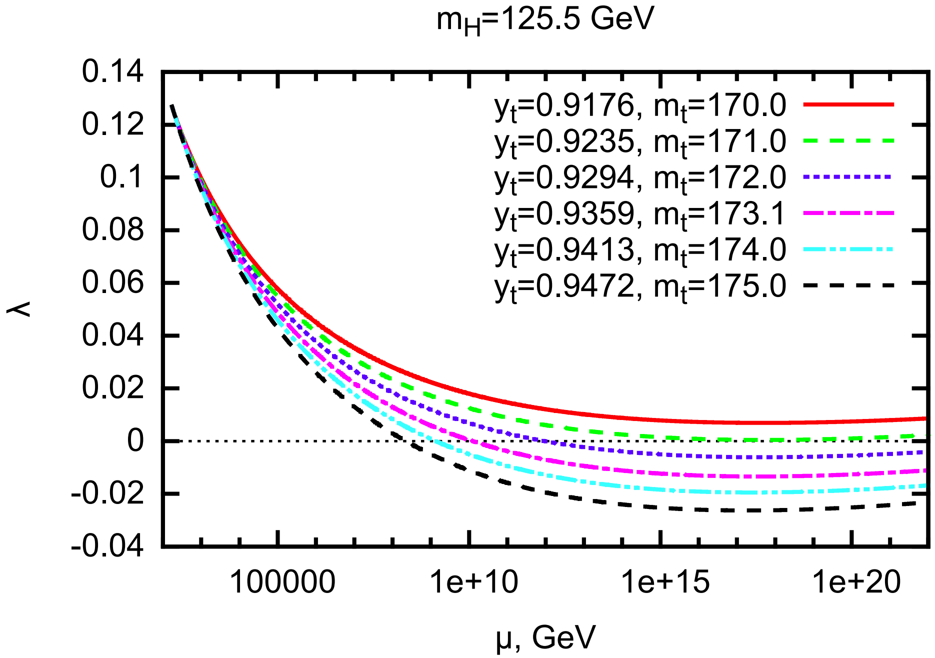


Absolute stability

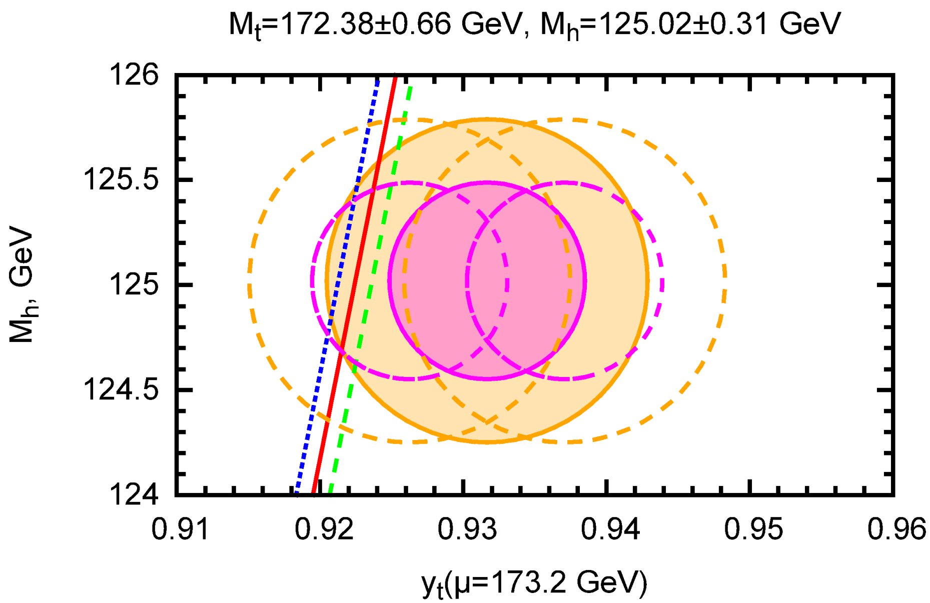


Metastability

PDG 2014: $m_t = \mathbf{173.34 \pm 0.27 \pm 0.71\ GeV}$



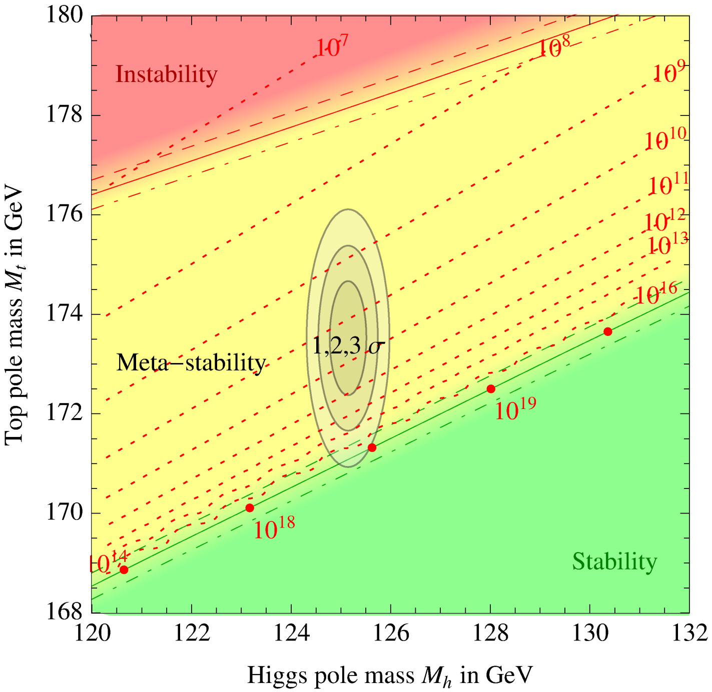
Absolute stability



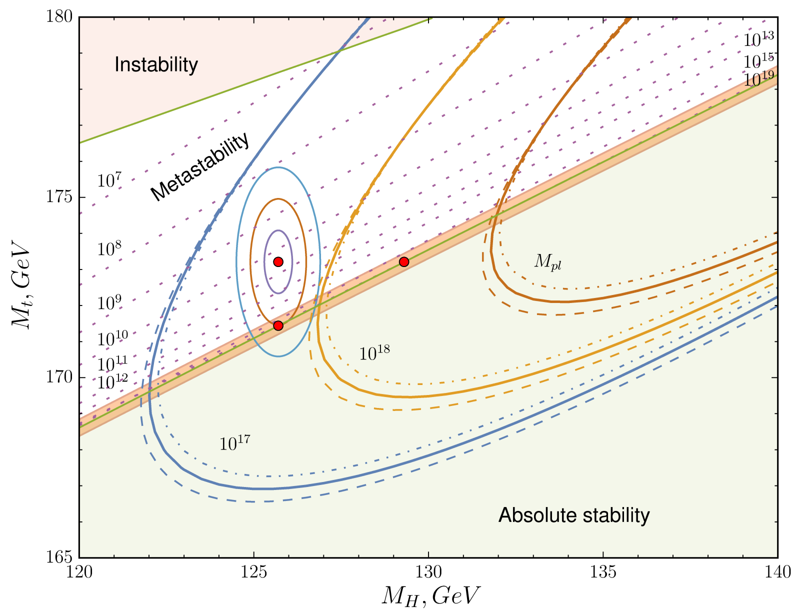
Metastability

CMS 2014: $m_t = 172.38 \pm 0.10 \pm 0.65$ GeV

Buttazzo et al, '13, '14



Bednyakov et al, '15

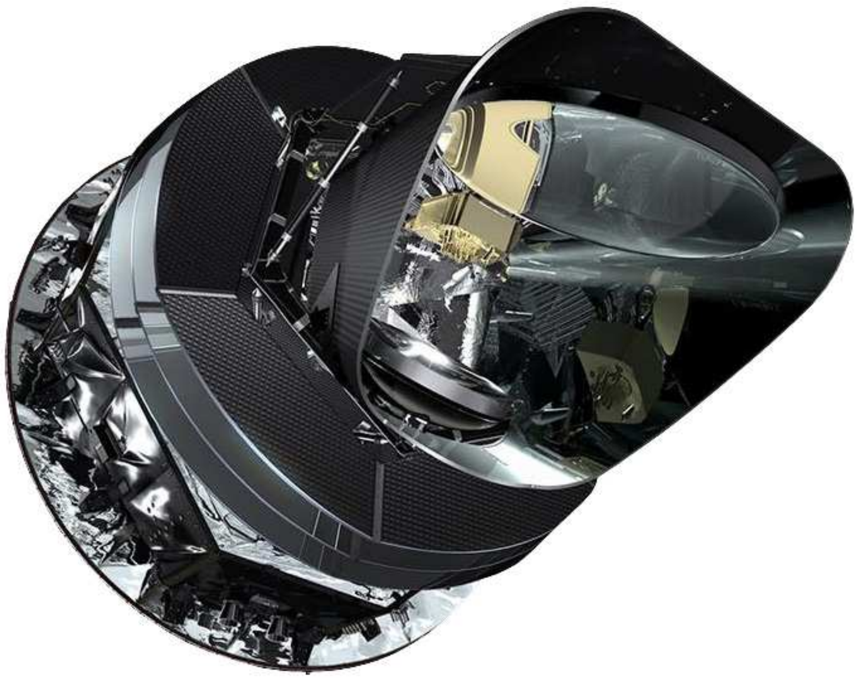


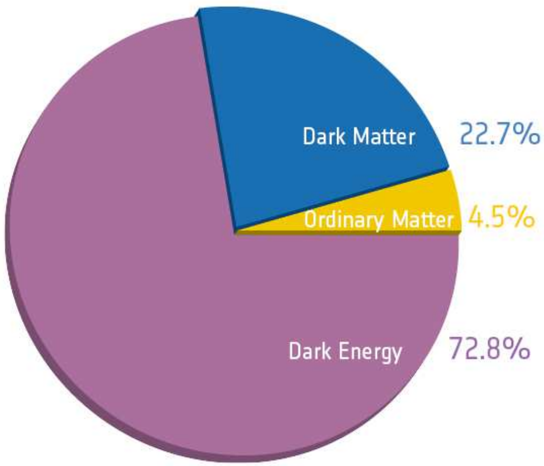
Vacuum is unstable at $\mathbf{2.8\sigma}$

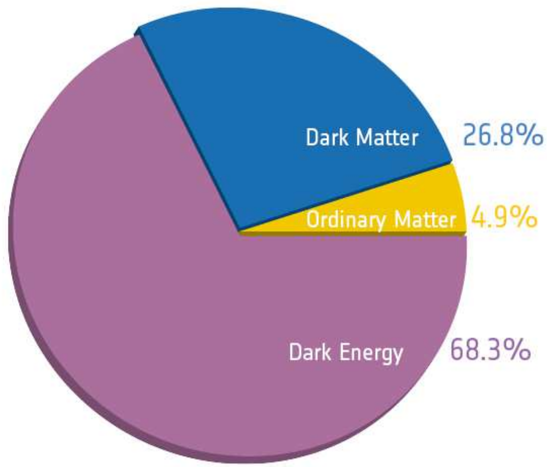
Vacuum is unstable at $\mathbf{1.3\sigma}$

Main uncertainty: top Yukawa coupling, relation between the MC mass and the top Yukawa coupling allows for ± 1 GeV in M_{top}. Alekhin et al, Frixione et al.

Planck results

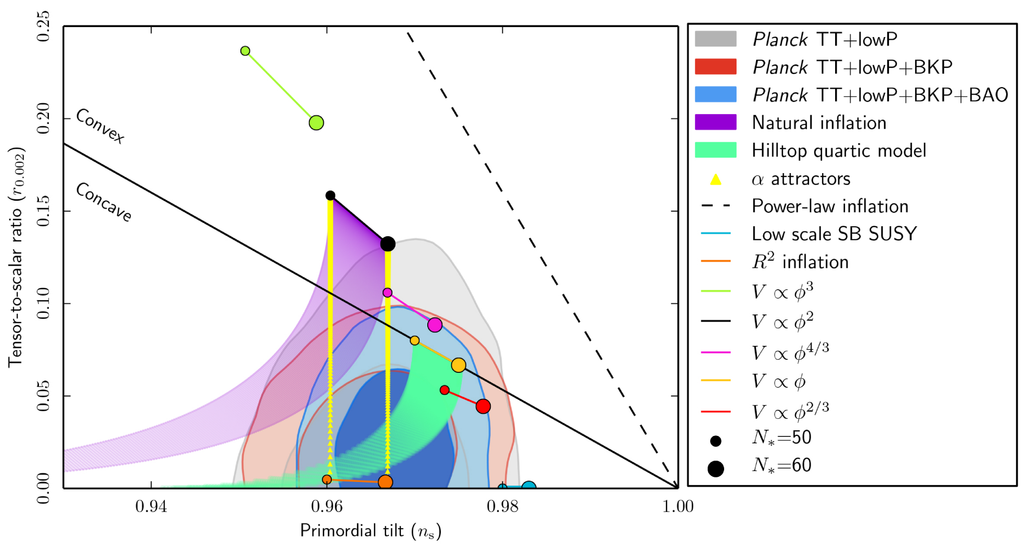






Before Planck

After Planck



The message from Planck: The Standard ΛCDM model is in a very good agreement with the data

- No primordial non-Gaussianities are observed
- One-field inflationary models agree well with Planck
- No physics beyond Standard ΛCDM is observed

Observational evidence for BSM physics

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- The Universe is asymmetric: it contains baryons, but there is no antimatter in amounts comparable with matter. This cannot be explained in the SM.
- The Universe expansion at present is accelerating. Is this simply a tiny cosmological constant or something more complicated?

How to reconcile the evidence for new physics without spoiling the success of the Standard Model and Standard ΛCDM?

Many suggestions, inspired by “naturalness”: how to protect the Higgs boson mass from large corrections coming from unification of the three forces

- Low energy supersymmetry: WIMP as a dark matter candidate, electroweak baryogenesis
- Composite Higgs boson
- Large extra dimensions

Generically, this requires the existence of many new particles at the reach of LHC.

Accelerated expansion of the Universe: Dynamical dark energy? Modification of gravity at very large scales? New super-light fields?

A proposal for minimal new physics:

Standard Model with non-minimal coupling of the Higgs field to gravitational Ricci scalar : Higgs inflation

+

3 right-handed neutrinos with masses in KeV-GeV region: neutrino masses, dark matter, and baryogenesis

+

cosmological constant: no clue why so small, but fits the data

Higgs inflation
near the critical line

Higgs Inflation, no loops

Higgs field in general must have non-minimal coupling to gravity:

$$S_G = \int d^4x \sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R \right\}$$

Jordan, Feynman, Brans, Dicke,...

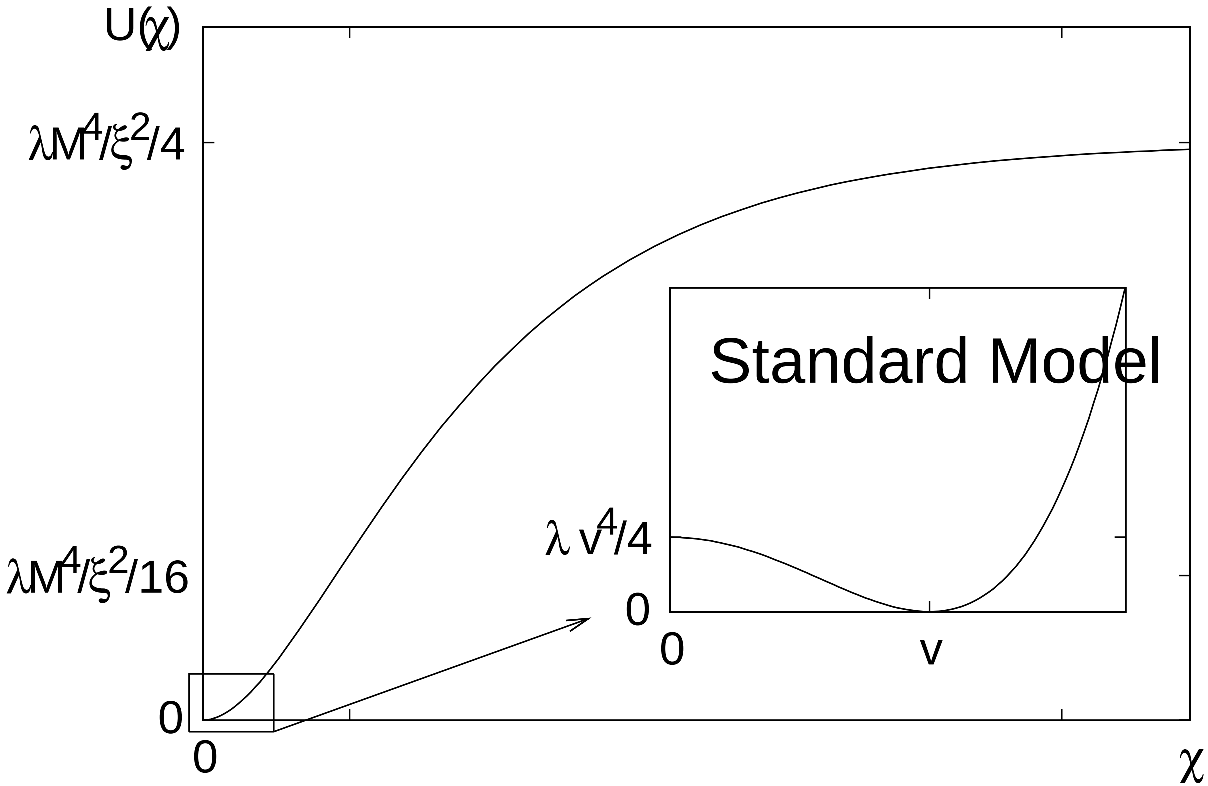
Consider large Higgs fields $h > M_P/\sqrt{\xi}$, which may have existed in the early Universe

The Higgs field not only gives particles their masses $\propto h$, but also determines the gravity interaction strength:

$M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h$

For $h > \frac{M_P}{\sqrt{\xi}}$ (classical) physics is the same (M_W/M_P^{eff} does not depend on h)!

Potential in Einstein frame



χ - canonically normalized scalar field in Einstein frame.

Potential for the Higgs field may be flat at large values of h: Linde chaotic inflation

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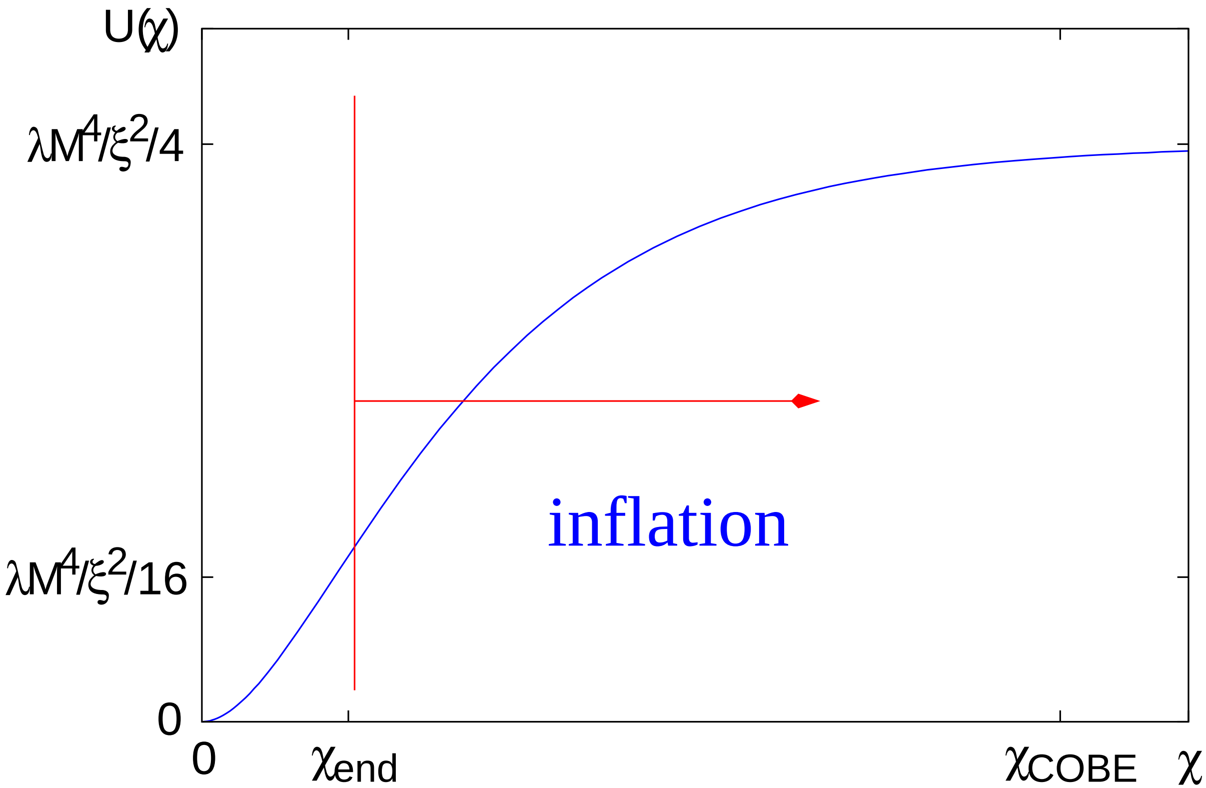
Inflation, Big Bang - all in the framework of the Standard Model

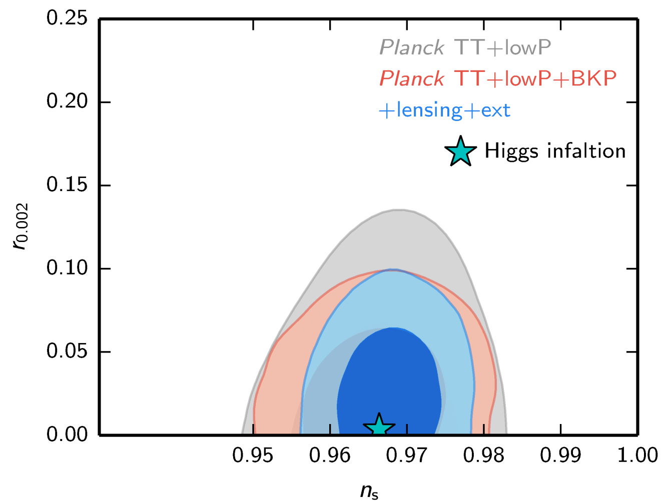
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

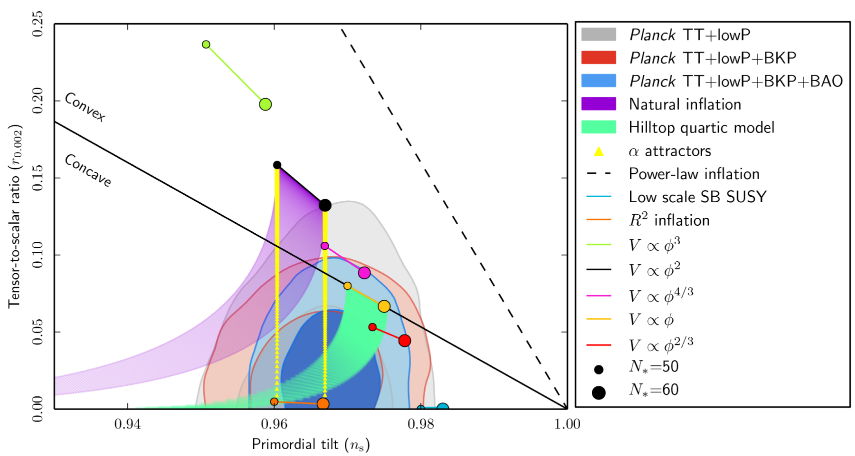


- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

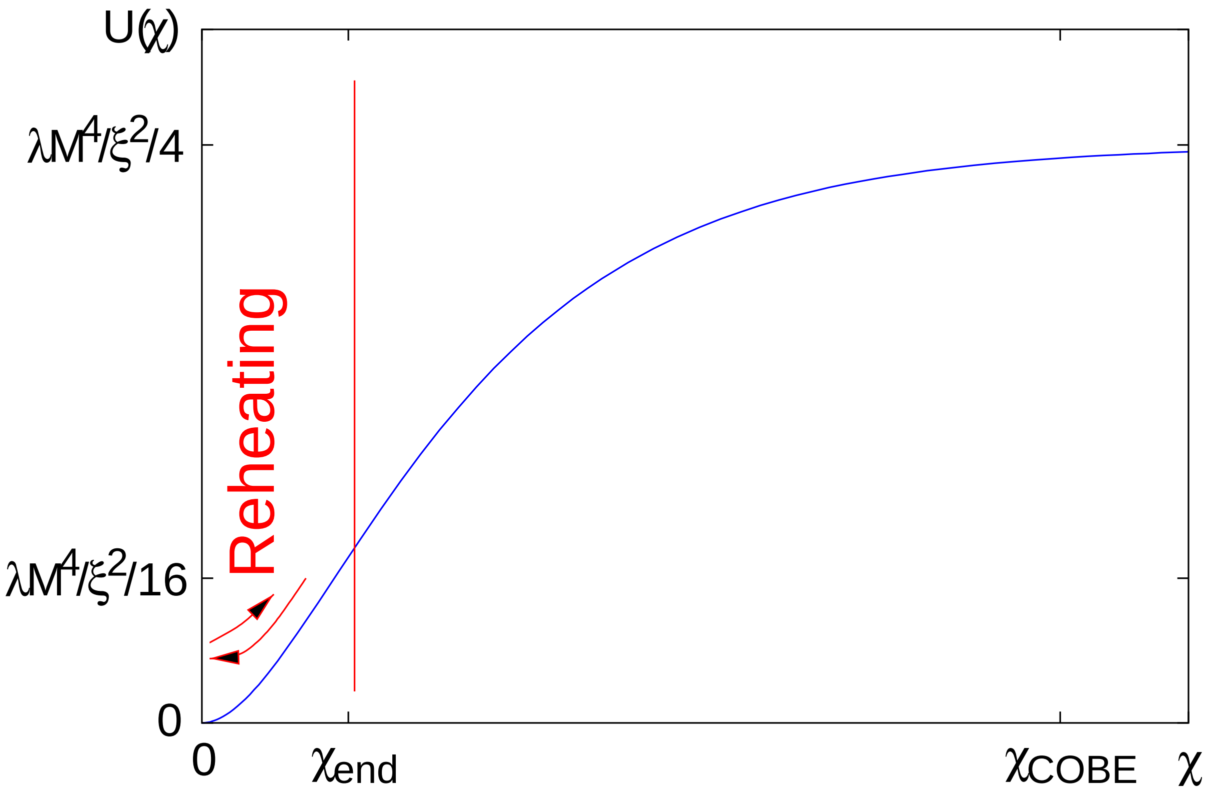
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

$$n_s = 0.97, \quad r = 0.003$$





Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- All particles of the Standard Model are produced
- Coherent Higgs field disappears
- The Universe is heated up to $T \propto M_P/\xi \sim 10^{14}$ GeV

Any theory of inflation is non-renormalisable, as it includes gravity!

How to account for this fact in general, and for the Higgs inflation in particular? Higher dimensional operators? Radiative corrections?

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(ii) Self-consistent approach to Higgs inflation: compute the onset of strong coupling Λ ("UV cutoff") by considering tree high energy scattering amplitudes Burgess, Lee, Trott ; Barbon and Espinosa in the Higgs-dependent background Bezrukov, Magnin, M.S., Sibiryakov; Ferrara, Kallosh, Linde, A. Marrani, Van Proeyen and add higher-dimensional operators suppressed by this cutoff.

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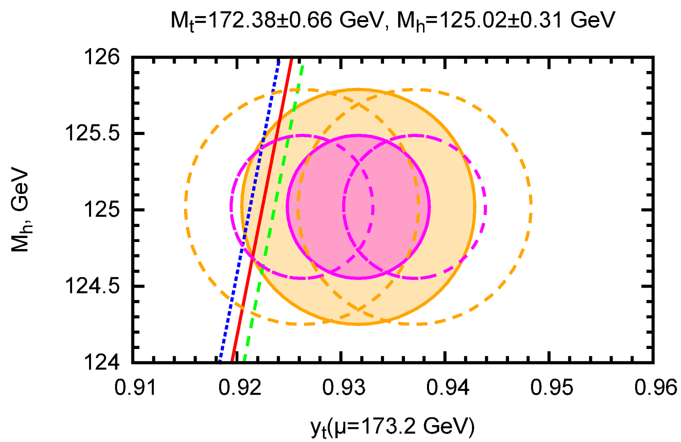
Radiative corrections, different approaches: Barvinsky, Kamenshchik, Starobinsky; Bezrukov, MS; De Simone, Hertzberg, Wilczek; George, Mooij, Postma,...

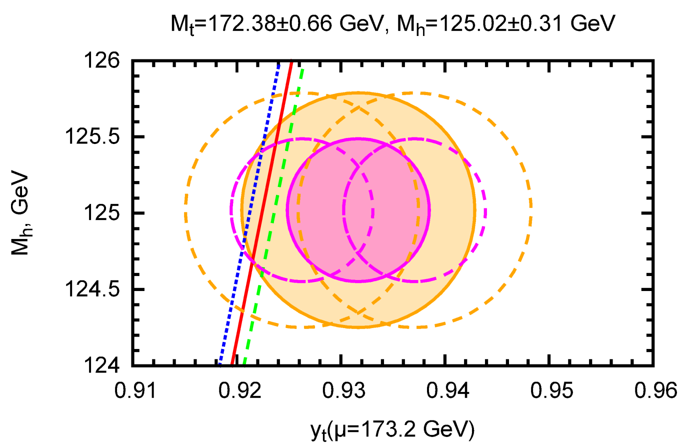
Higgs inflation: $y_t < y_t^{\rm crit}$



The same story as the Higgs inflation at the tree level.

Critical Higgs inflation: $y_t \approx y_t^{\rm crit}$

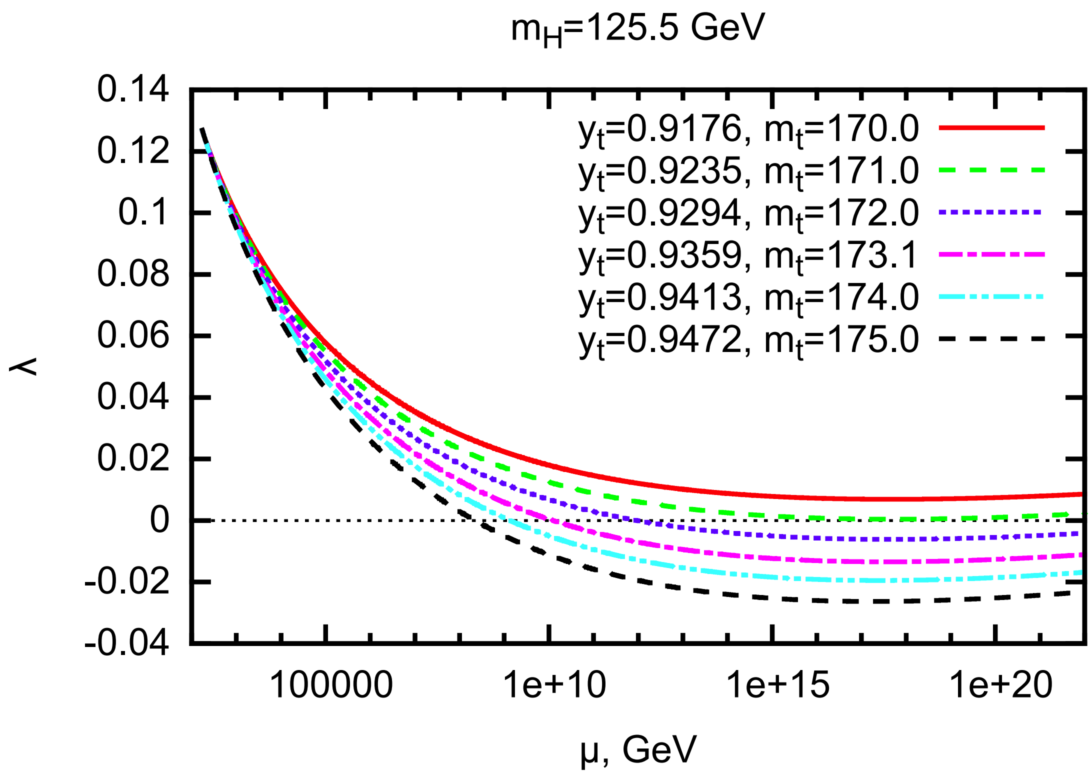
Extreme fine tuning of the Higgs and top quark masses



Bezrukov, MS

For y_t very close to $y_t^{\mathbf{crit}}$: critical Higgs inflation - tensor-to-scalar ratio can be large, $\xi \sim \mathbf{10}$

Behaviour of λ:



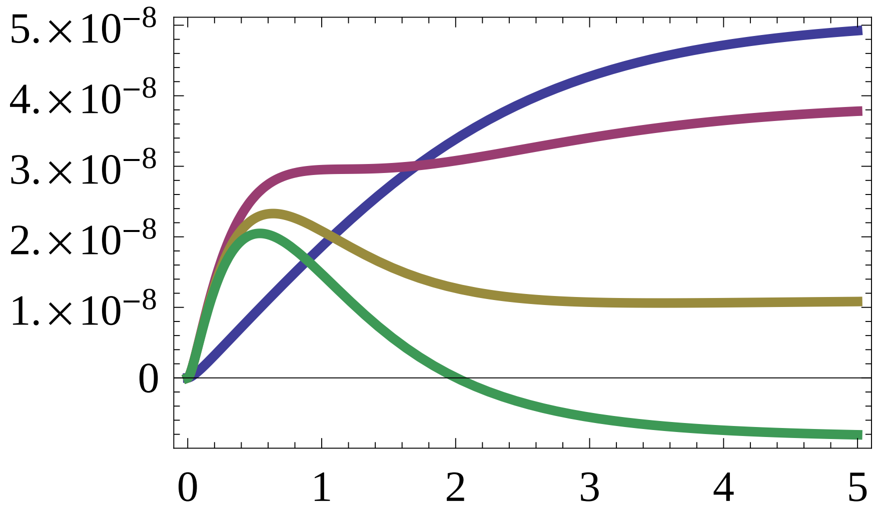
Effective potential

$$U(\chi) \simeq \frac{\lambda(z')}{4\xi^2}\bar{\mu}^4\,,\;\; z' = \frac{\bar{\mu}}{\kappa M_P},\;\; \bar{\mu}^2 = M_P^2\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)$$

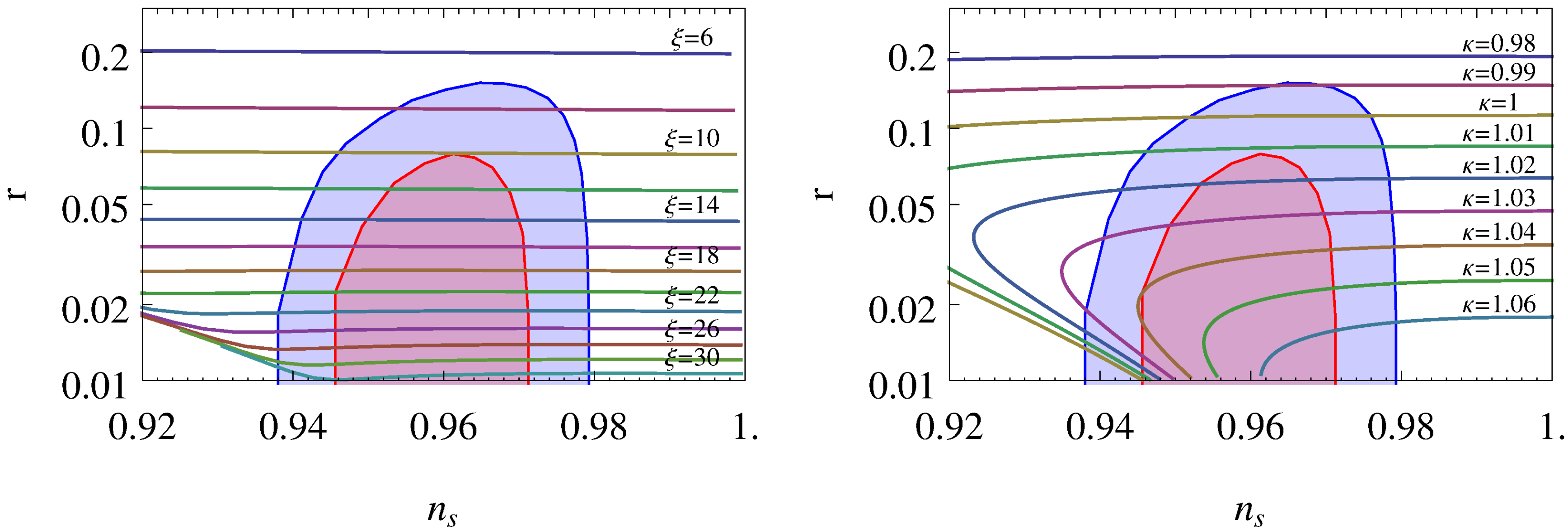
The parameter μ that optimises the convergence of the perturbation theory is related to $\bar{\mu}$ as

$$\mu^2 = \alpha^2\frac{y_t(\mu)^2}{2}\frac{\bar{\mu}^2}{\xi(\mu)}\,,\;\; \alpha \simeq 0.6$$

Behaviour of effective potential for $\lambda_0 \simeq b/16$:



The inflationary indexes

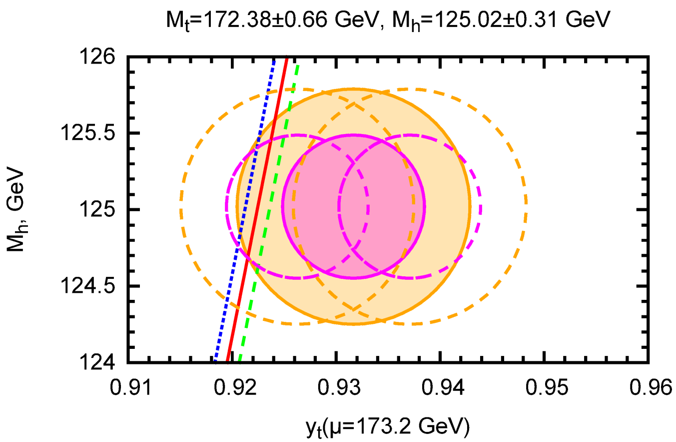


r can be large!

see also Hamada, Kawai, Oda and Park

Critical Higgs inflation only works if both Higgs and top quark masses are close to their experimental values.

Living beyond the edge: Higgs inflation and vacuum metastability, $y_t > y_t^{\rm crit}$



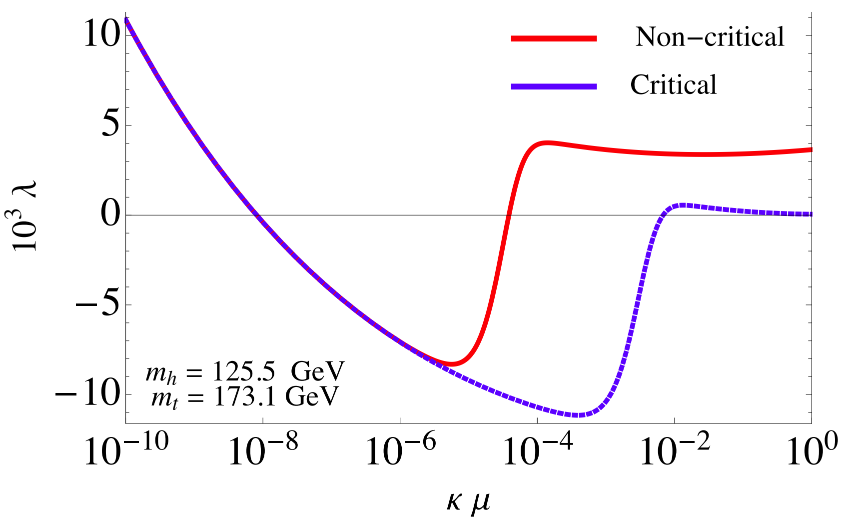
Bezrukov, Rubio, MS

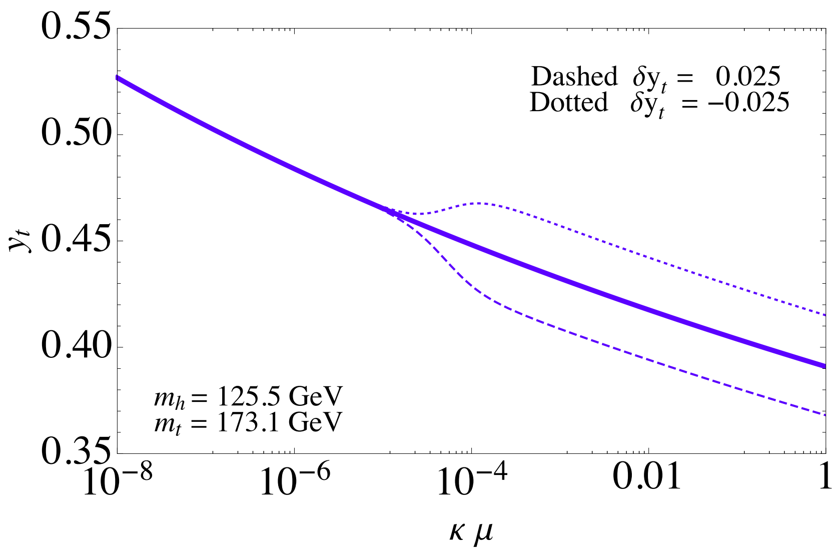
Renormalisation of the SM coupling constants at the scale M_P/ξ:

"jumps" of λ and y_t controlled by UV completion of the SM, which cannot be found from low-energy observables of the SM

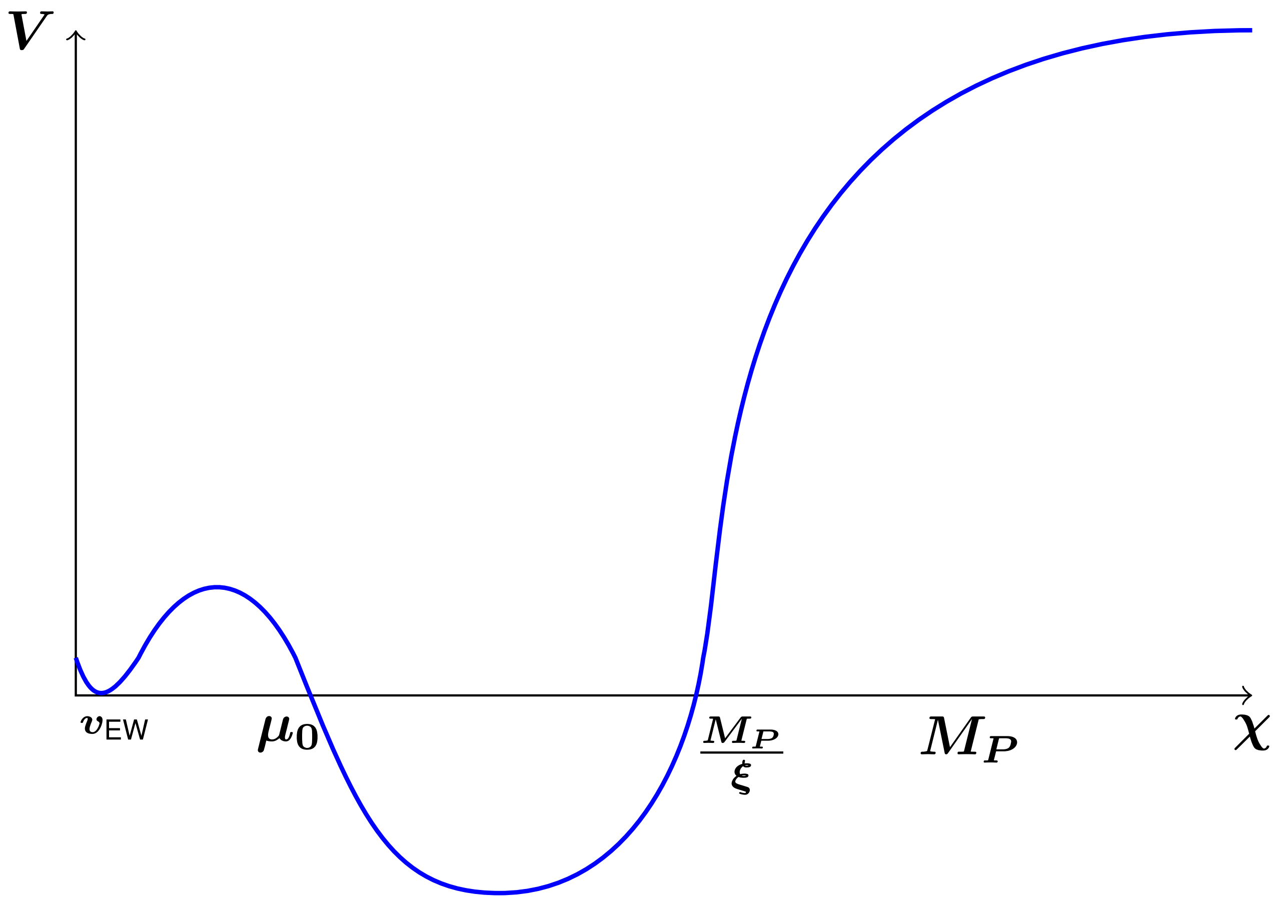
Bezrukov, Magnin, MS., Sibiryakov

$\lambda(M_P/\xi)$ is small due to cancellations between fermionic and bosonic loops: $\delta\lambda$ can be of the order of λ

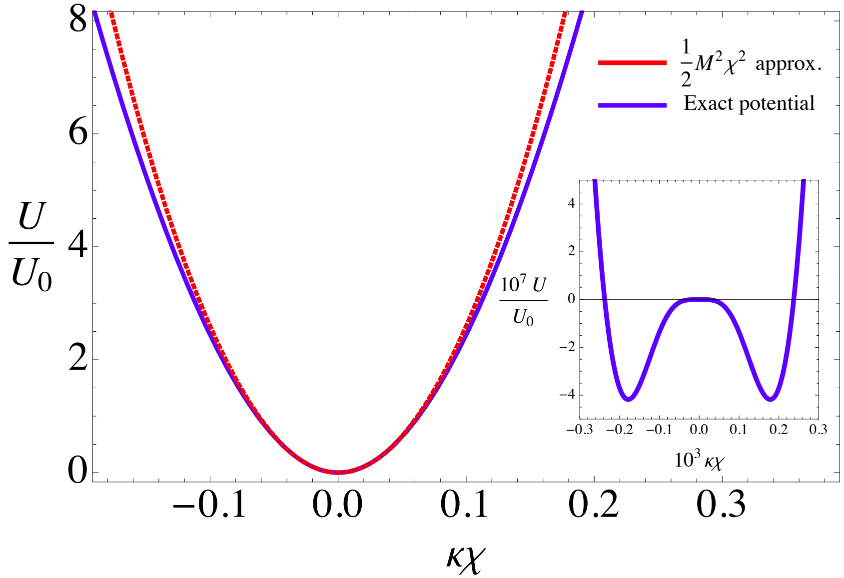


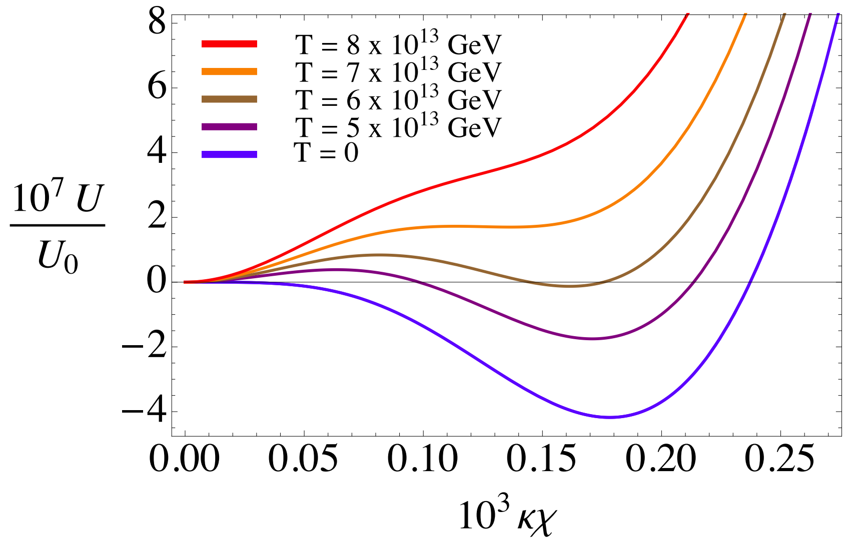


Higgs potential



Symmetry restoration

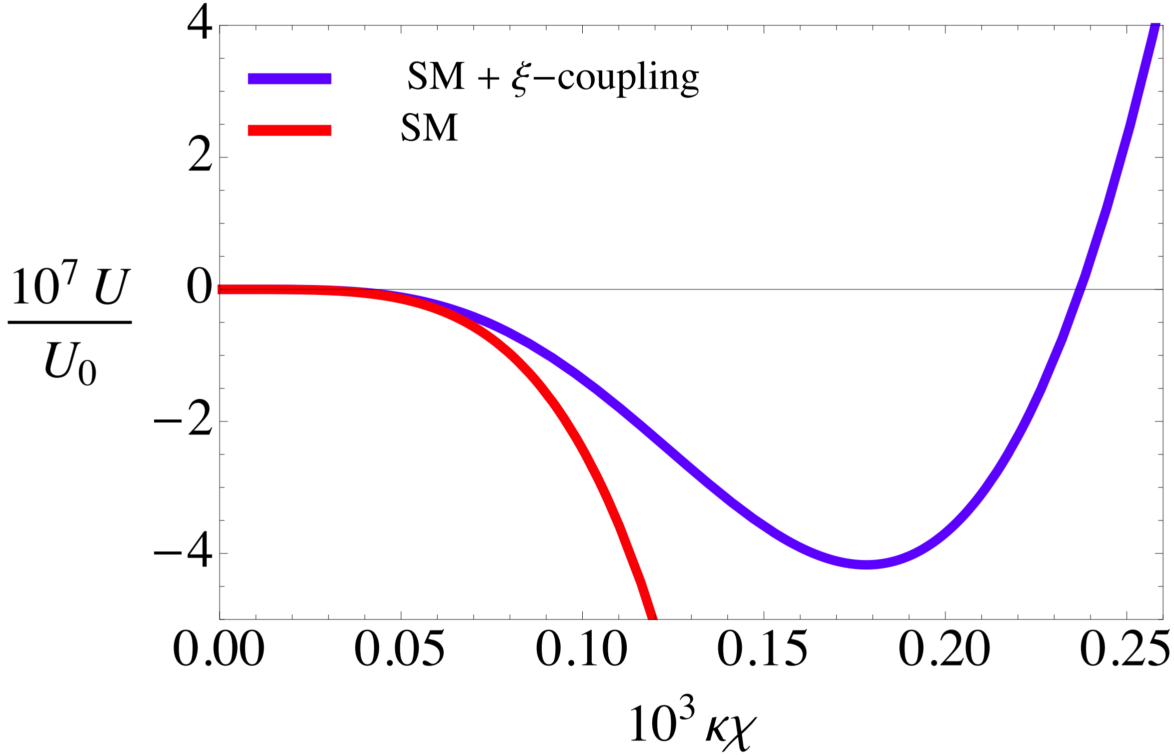




Reheating temperature $T_R \simeq 2 \times 10^{14}$ GeV $> T_+ \simeq 7 \times 10^{13}$ GeV, $T_c = 6 \times 10^{13}$ GeV

(Meta) stability of false vacuum

Computation for SM: Espinosa, Giudice, Riotto



Predictions for critical indexes n_s and r are the same as for non-crtitical Higgs inflation

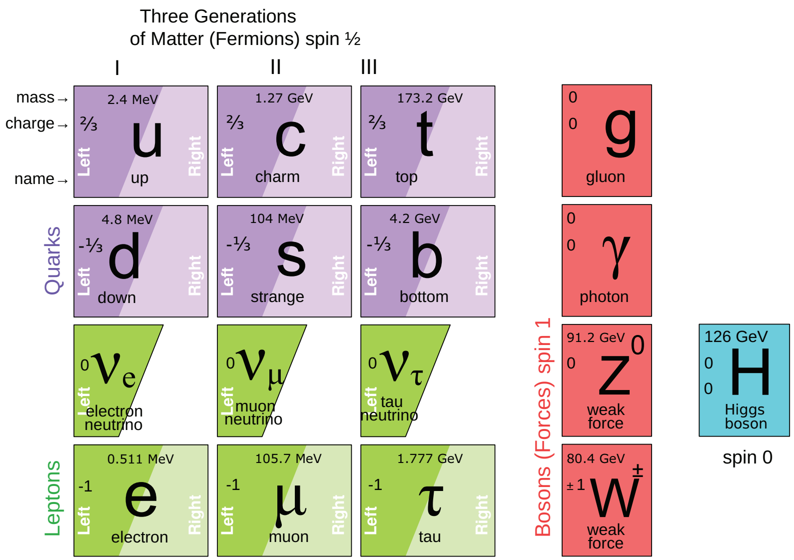
$$n_s = 0.97, \;\; r = 0.003$$

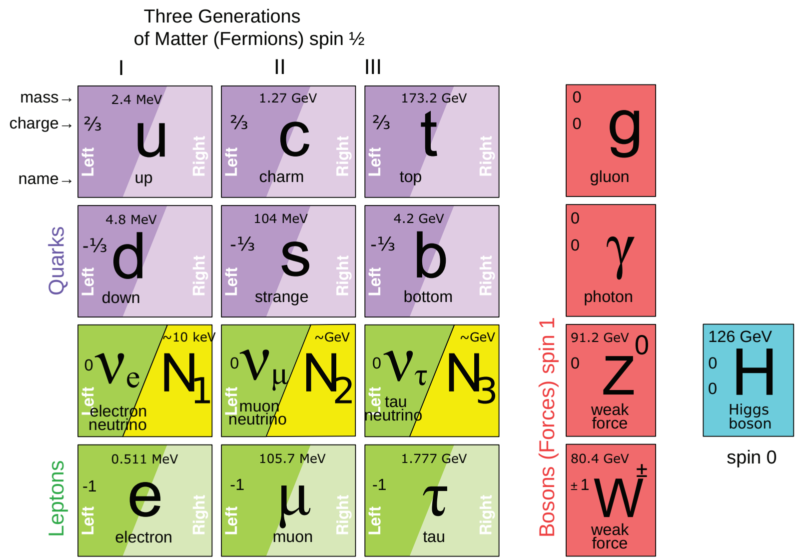
Critical Higgs inflation at $y_t > y_t^{\rm crit}$?

Critical Higgs inflation : small $\xi \sim 10$ - the depth of the large Higgs value vacuum is comparable with the energy stored in the Higgs after inflation: the required reheating temperature is too large, $T_+ \simeq 10^{16}$ GeV and cannot be achieved.

Neutrino masses, dark matter and baryon asymmetry

νMSM - the neutrino minimal Standard Model





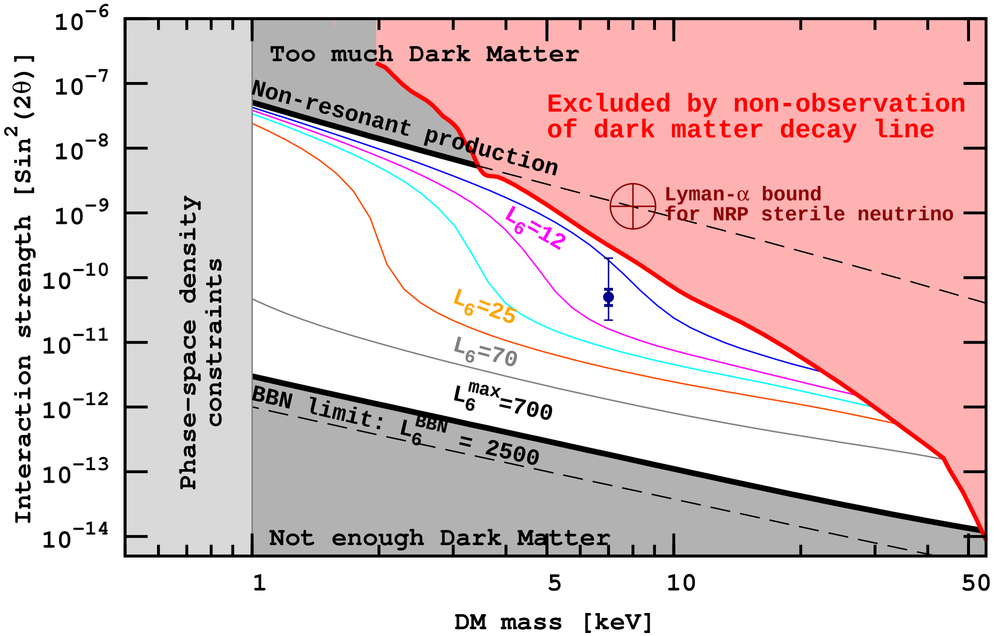
N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of N_2, N_3 with mass in 100 MeV – 80 GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe (BAU)

How to find DM HNL?

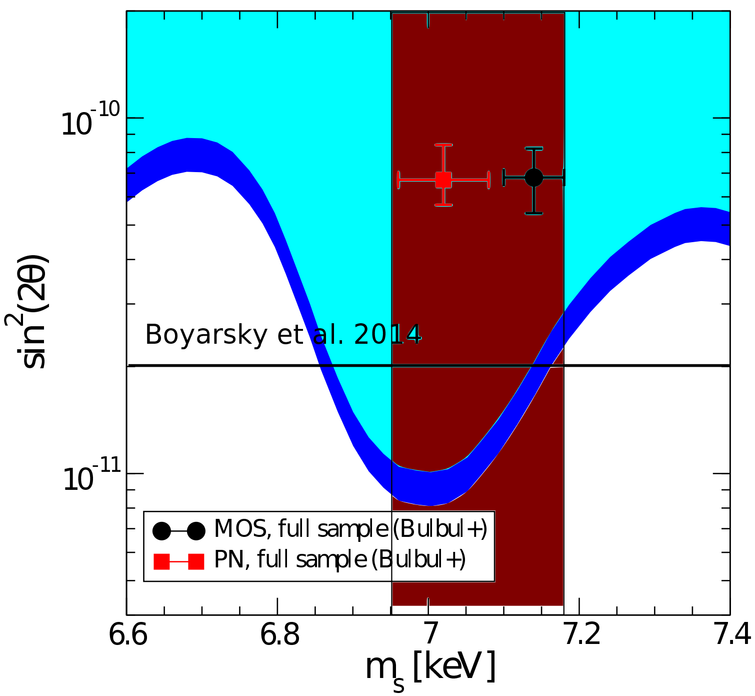
Strategy: Use X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line coming from decays $N \to \nu\gamma$



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul et al., e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky et al., e-Print: arXiv:1402.4119

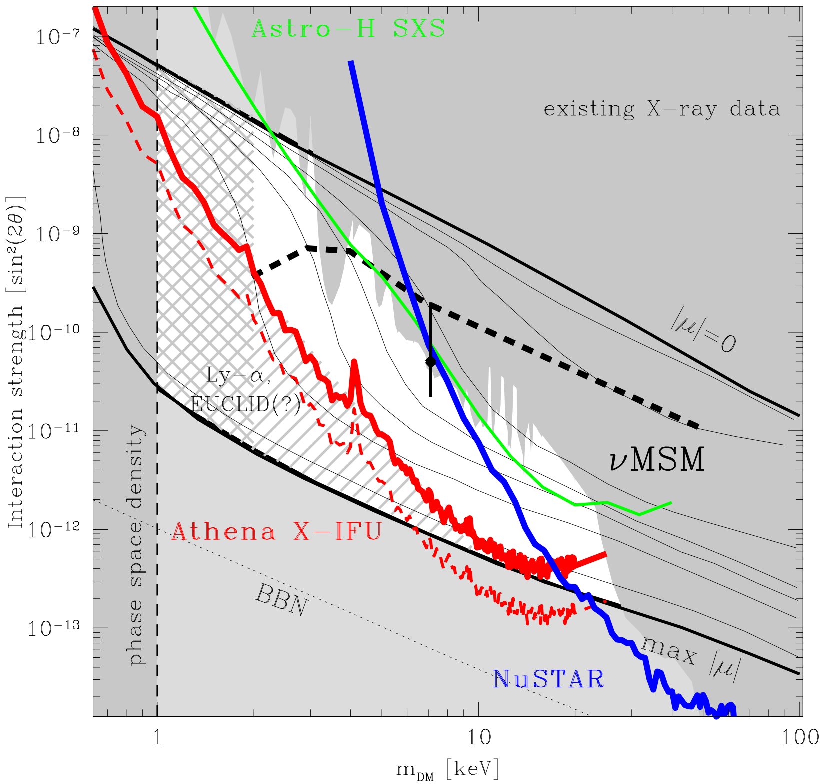
XMM observations of dwarf spheroidal galaxy Draco (1.6 Msec, PI Boyarsky)



From: Jeltema, Profumo, arXiv:1512.01239

- Statistical fluctuation?
- Non-DM origin of 3.5 keV line?
- Larger uncertainties in DM distribution?

Future projections



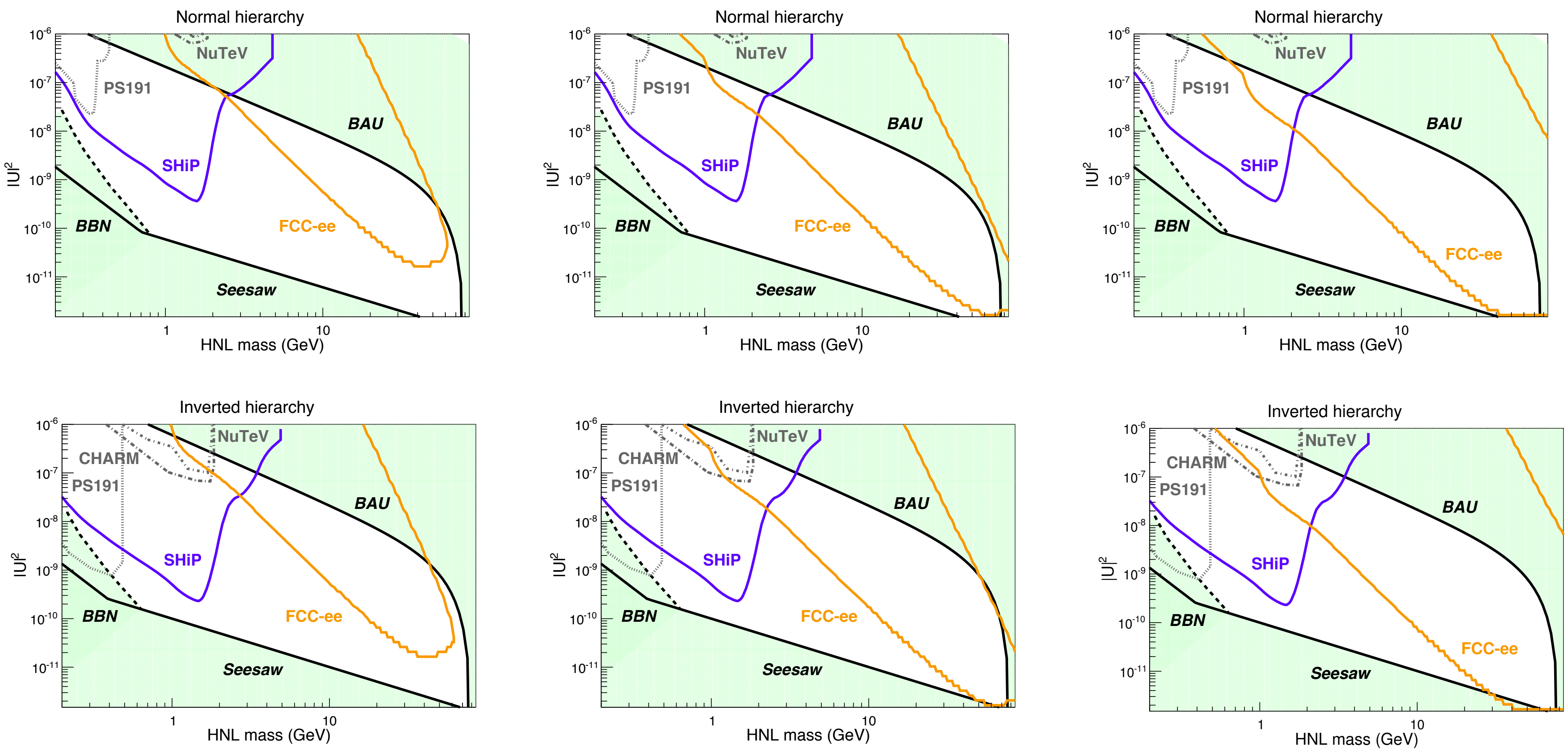
Parameter space of sterile neutrino DM in the νMSM, from arXiv:1509.02758, Neronov et al.

Red line - Athena (launch 2028). Left corner, shaded region "Lyman-alpha"/Euclid :

projection for future observations.

How to find HNL responsible for ν masses and BAU?

Strategy: search for decays of HNL such as $N \to \pi\mu$ with N created in fixed target experiments (new proposal at CERN SPS - SHiP) or with N created in Z-boson decays (new project FCC - ee)



Conclusions

- The SM is in a great shape and may be valid up to the Planck scale
- The Higgs inflation can take place both for absolutely stable and metastable vacuum, with universal predictions $n_s = 0.97, \; r = 0.003$ for a wide range of parameters
- For critical Higgs inflation corresponding to $y_t \approx y_t^{\rm crit}$ n_s and r can be substantially different from these values
- The BSM physics related to neutrino masses, dark matter and baryon asymmetry of the Universe can be light and can be searched at a number on new experiments (SHiP, FCC) and cosmic missions