The Higgs Boson and the Early Universe

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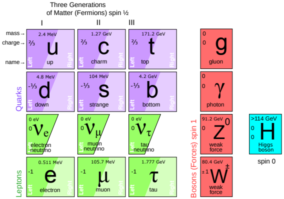
Outline

1. Introduction: Standard Model and the Universe
2. Inflation
   - Observations and simplest realization
   - How to use Higgs for inflation
3. Vacuum stability and particle masses
   - Experimental situation
   - What can happen?
4. Quantum corrections and theoretical problems
5. Conclusions

Lesson from LHC so far – Standard Model is good



- SM works in all laboratory/collider experiments (electroweak, strong)
- LHC 2012 – final piece of the model discovered – Higgs boson
  - Mass measured ~ 125 GeV – weak coupling!
    Perturbative and predictive for high energies
- Add gravity
  - get cosmology
  - get Planck scale $M_{Pl} \sim 1.22 \times 10^{19}$ GeV as the highest energy to worry about

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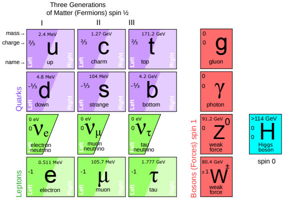

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Einstein gravity

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Things not explained by SM

Experimental observations: Cosmology

- Dark Matter
- Baryon asymmetry of the Universe
- Inflation

Laboratory

- Neutrino oscillations

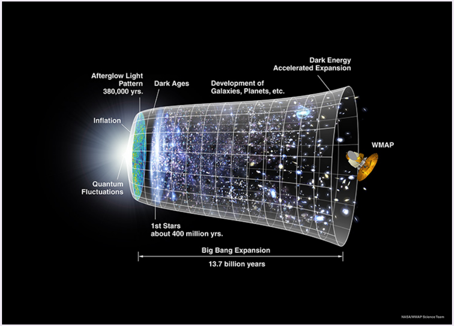
Explain everything except inflation – sterile neutrino
[Asaka, Blanchet, Shaposhnikov'05, Asaka, Shaposhnikov'05]

ΛCDM cosmology – describes the Universe

The Universe is

- Hot (I mean 2.73° K photons now)
- Expanding
- Extremely uniform (on large scales)

How did it all start?



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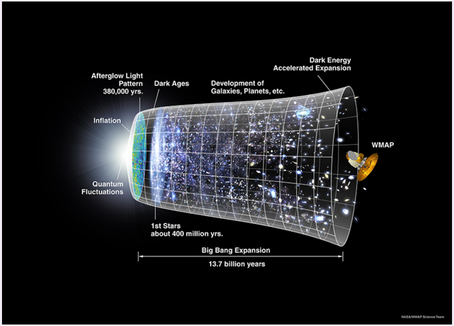
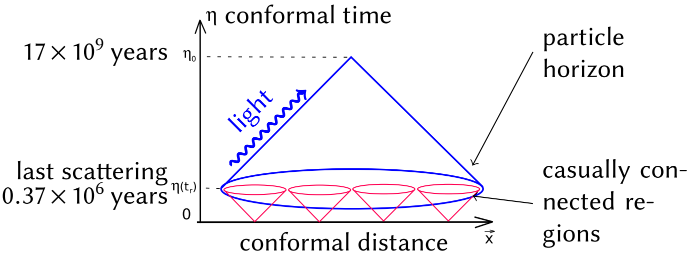


Problem – how all this happened?

Variations of initial conditions problem

- Singularity problem
- Flatness problem
- Entropy problem
- Horizon problem
- Primordial perturbations problem

Horizon problem



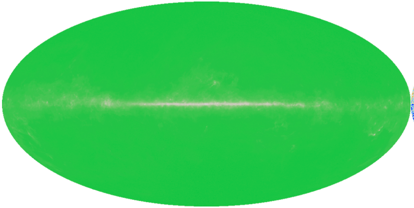
Observed Universe contained

2000 casually disconnected regions on CMB sky

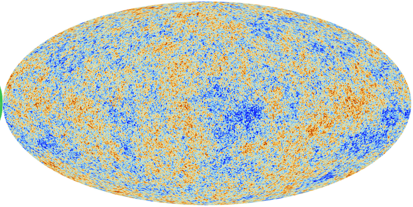
Why they are so similar?

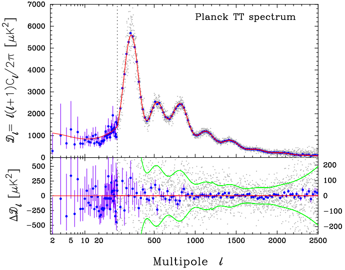
CMB – shape of primordial density perturbations

CMB sky $T = 2.725°$ K



CMB sky in detail $\delta T/T \sim 10^{-5}$





Primordial perturbations

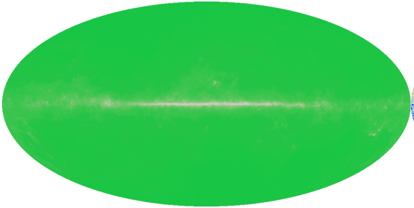
nearly (but not exactly!) scale invariant

$$\mathcal{P}_\mathcal{R}(k) = A_\mathcal{R}\left(\frac{k}{k_*}\right)^{n_s-1}$$

with spectral index $n_s \sim 0.96$

CMB – shape of primordial density perturbations

CMB sky $T = 2.725^\circ$ K



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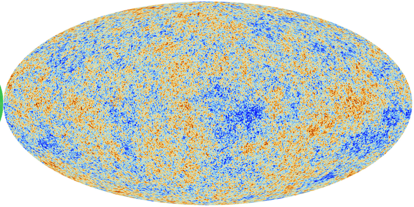
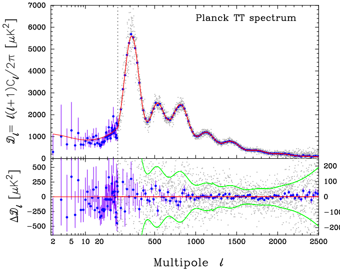
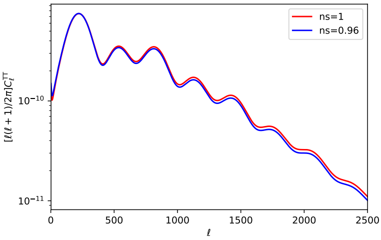




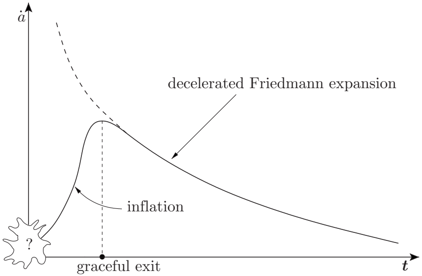
Primordial perturbations

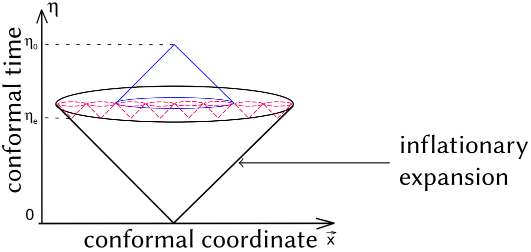


Inflation – accelerated expansion

$$\frac{l_i}{l_c} \sim \frac{\dot{a}_i}{\dot{a}_0}$$

Inflation is a stage of accelerated expansion of the Universe when gravity acts as a repulsive force



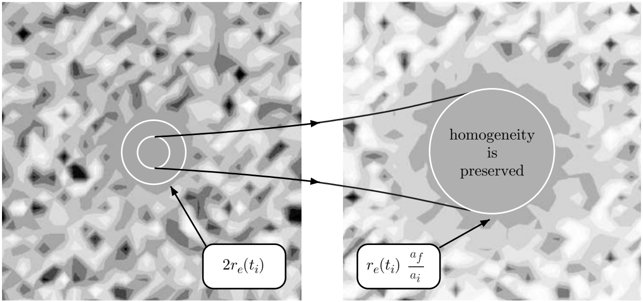


Small homogeneous patch is expanded to the whole observed Universe

In the accelerated Universe *event horizon* (region of the Universe that can be in principle affected by an event) exists

$$r_e(t) = a(t)\int_t^{t_{\max}} \frac{dt}{a} = a(t)\int_{a(t)}^{a_{\max}} \frac{da}{\dot{a}a}$$

converges for growing $\dot{a}$



Accelerated expansion – vacuum energy?

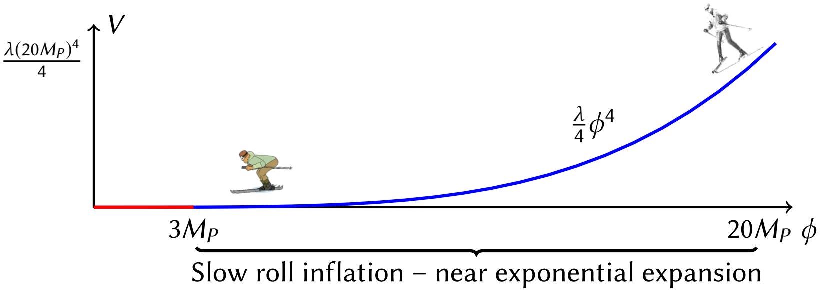
How to realize inflation?

- Vacuum energy is ok for present day accelerated expansion
  - cosmological constant Λ
  - exponential expansion $a \propto \exp(Ht)$ – acceleration
- But: it lasts forever!
- Should stop this expansion somehow after inflation…

Chaotic inflation–a scalar field

gives also primordial perturbations!

$$\mathcal{H}^2 \simeq \frac{1}{3M_P^2}\left(V(\phi)+\dot{\phi}^2/2\right), \qquad \ddot{\phi}+3\mathcal{H}\dot{\phi}+V'(\phi)=0$$



Field quantum fluctuations – primordial perturbations

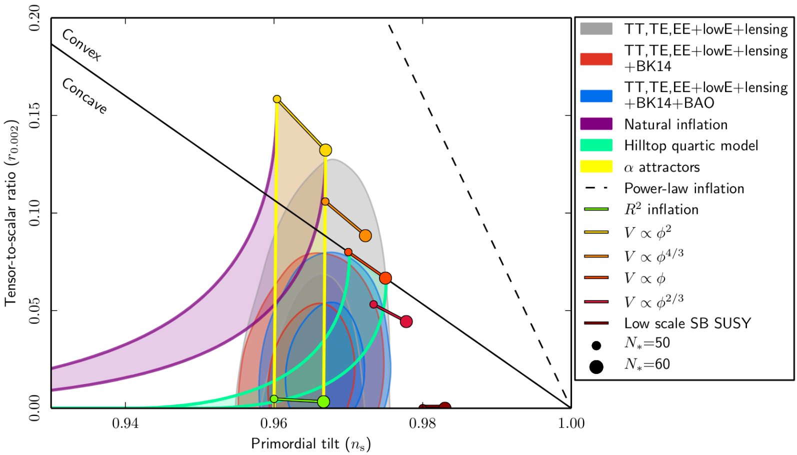
$\delta T/T \sim 10^{-5}$ requires:

quartic coupling: $\lambda \sim 10^{-13}$ (or mass: $m \sim 10^{13}$ GeV)

Where to get such a super weakly coupled field?

CMB observations favour flat potentials

PLANCK 2018



- Tensor modes (primordial gravity waves) $\propto V$
- primordial density perturbations $\propto V^{3/2}/V'$

Non-minimal coupling to gravity solves the problem

Quite an old idea

For a scalar field coupling to the Ricci curvature is possible (actually *required* by renormalization)

- [A.Zee'78, L.Smolin'79, B.Spokoiny'84]
- [D.Salopek J.Bond J.Bardeen'89]

Scalar part of the (Jordan frame) action

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \xi \frac{h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}$$

- h is the Higgs field; $M_P \equiv \frac{1}{\sqrt{8\pi G_N}} = 2.4 \times 10^{18}$GeV
- SM higgs vev $v \ll M_P/\sqrt{\xi}$ – can be neglected in the early Universe
- At $h \gg M_P/\sqrt{\xi}$ *all* masses are proportional to h – scale invariant spectrum!

[FB, Shaposhnikov'08]

Conformal transformation – nice way to calculate

It is possible to get rid of the non-minimal coupling by the conformal transformation (change of variables)

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\,, \qquad \Omega^2 \equiv 1 + \frac{\xi h^2}{M_P^2}$$

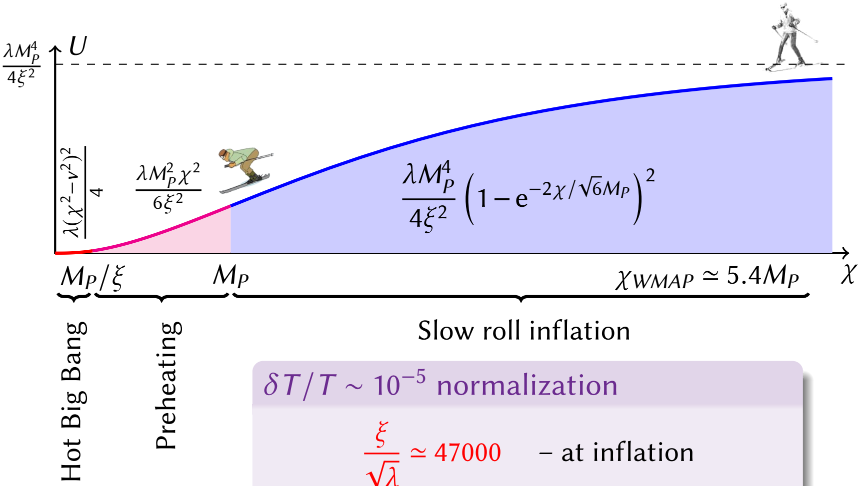
Redefinition of the Higgs field to get canonical kinetic term

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}} \quad \Longrightarrow \quad \begin{cases} h \simeq \chi & \text{for } h < M_P/\xi \\ \Omega^2 \simeq \exp\left(\frac{2\chi}{\sqrt{6}M_P}\right) & \text{for } h > M_P/\xi \end{cases}$$

Resulting action (Einstein frame action)

$$S_E = \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - \frac{\lambda}{4}\frac{h(\chi)^4}{\Omega(\chi)^4} \right\}$$

Potential – different stages of the Universe



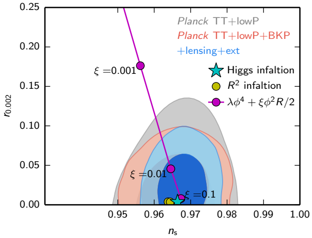
$\delta T/T \sim 10^{-5}$ normalization

$$\frac{\xi}{\sqrt{\lambda}} \simeq 47000 \quad \text{– at inflation}$$

Small λ is traded for large ξ

CMB parameters are predicted

Exactly as preferred by observations



spectral index	$n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2}$	$\simeq 0.97$
tensor/scalar ratio	$r \simeq \frac{192}{(4N+3)^2}$	$\simeq 0.0033$

$$\delta T/T \sim 10^{-5} \quad \Longrightarrow \quad \frac{\xi}{\sqrt{\lambda}} \simeq 47000$$

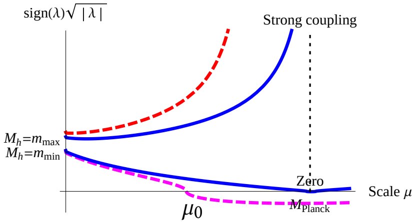
Why should we care about particle physics?

- What happens at the scales between Electroweak 200 GeV and Planck 10^{19} GeV?
- Is SM consistent at all energies?
- Do any problems appear?
- Are there quantum corrections to the inflationary dynamics?

Standard Model self-consistency and Radiative Corrections

- Higgs self coupling constant λ changes with energy due to radiative corrections.

$$(4\pi)^2 \frac{d\lambda}{d\log\mu} = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g_2^4 + (g_2^2 + g_1^2)^2) + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda$$



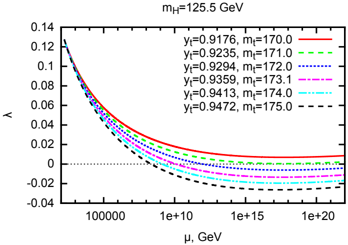
- Behaviour is determined by the masses of the Higgs boson $m_H = \sqrt{2\lambda}v$ and other heavy particles (top quark $m_t = y_t v/\sqrt{2}$)
- If Higgs is heavy $M_H > 170$ GeV – the model enters *strong coupling* at some low energy scale – new physics required.

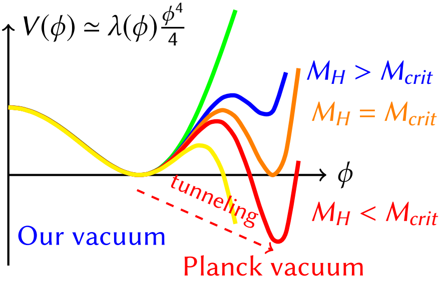
RG corrections change Higgs potential

Realistic Higgs mass options

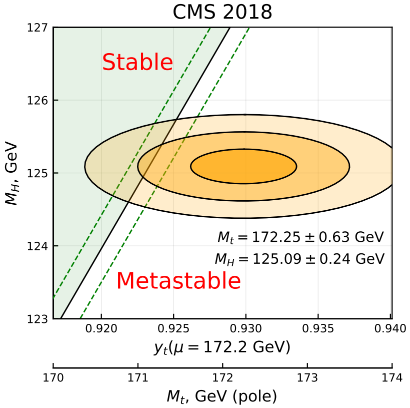
- For Higgs masses $M_H < M_{\text{critical}}$ coupling constant is negative above some scale μ_0.
- The Higgs potential may become negative!
  - Our world is not in the lowest energy state!
  - Problems at some scale $\mu_0 > 10^{10}$ GeV?

Higgs self-coupling evolution:





Experiment: we are in the critical case

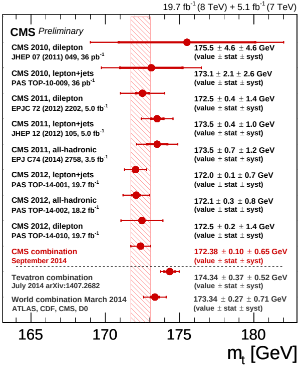


- Precision goal for y_t – better than 0.5%
- Higgs quartic self coupling – less relevant

FB, Kalmykov, Kniehl, Shaposhnikov'12; Buttazo et.al.'13, Bednyakov et.al.'15

Determination of top quark Yukawa

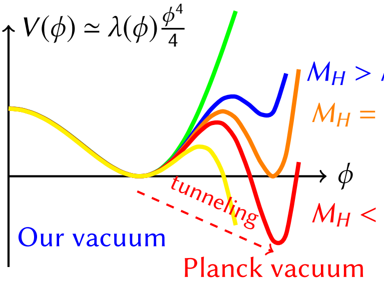
- Hard to determine mass in the events
- Hard to relate the "pole" (even worse for "Mont-Carlo") mass to the $\overline{\text{MS}}$ top quark Yukawa
  - NLO event generators
  - Electroweak corrections – important at the current precision goals!



- Build a lepton collider! FCC-ee! $\delta m_t \sim 100$ MeV
- Improve analysis on a hadron collider?

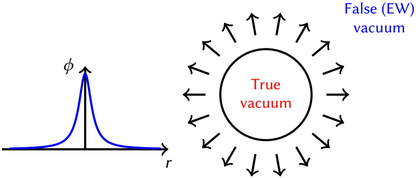
Options for Higgs potential

- Higher m_H, lower m_t
  - stable EW vacuum
  - Higgs inflation as in the first part of the talk
- Lower m_H, higher m_t
  - unstable EW vacuum?!
- Critical m_H for given m_t
  - Interesting coincidence:
    - $m_H \simeq 126$ GeV predicted
    - λ_{min} is at scale $\mu \sim M_P$



What to do if we are metastable?

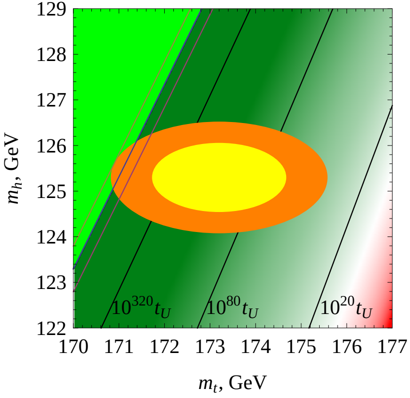
Vacuum decays by creating bubbles of true vacuum, which then expand very fast ($v \longrightarrow c$)



Tunneling suppression:

$$p_{\text{decay}} \propto \mathrm{e}^{-S_{\text{bounce}}} \sim \mathrm{e}^{-\frac{8\pi^8}{3\lambda(h)}}$$

Lifetime $\gg$ age of the Universe!



Note on Planck corrections

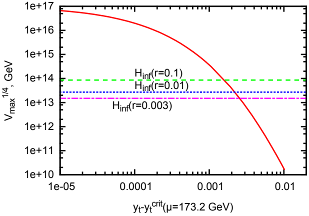
- Critical bubble size $\sim$ Planck scale
- Potential corrections $V_{\text{Planck}} = \pm \frac{\phi^n}{M_P^{n-4}}$ change lifetime!
  - Only + sign is allowed for Planck scale corrections!

Stability in Early Universe

As far as we are "safe" now (i.e. at low energies), what about Early Universe?
What happens with the Higgs boson at inflation?

Metastable vacuum during inflation *is* dangerous

- Let us suppose Higgs is not at all connected to inflationary physics (e.g. R^2 inflation)
- All fileds have vacuum fluctuation
- Typical momentum $k \sim H_{\mathrm{inf}}$ is of the order of Hubble scale
  - If typical momentum is greater than the potential barrier – SM vacuum would decay if



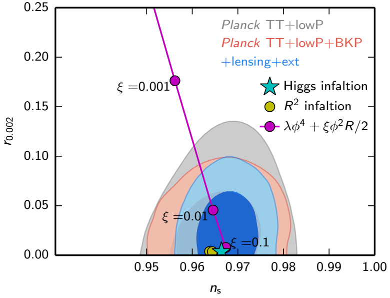
$$H_{\mathrm{inf}} > V_{\mathrm{max}}^{1/4}$$

Most probably, fluctuations at inflation lead to SM vacuum decay…

- Observation of any tensor-to-scalar ratio r by CMB polarization missions would mean great danger for metastable SM vacuum!

Measurement of primordial tensor modes determines scale of inflation

$$H_{\text{inf}} = \sqrt{\frac{V_{\text{infl}}}{3M_P^2}} \sim 8.6 \times 10^{13}\,\text{GeV}\left(\frac{r}{0.1}\right)^{1/2}$$



Does inflation contradict metastable EW vacuum?

Of course we do not know

- Higgs interacting with inflation can cure the problem. Examples
  - Higgs (ϕ)–inflaton (χ) interaction may stabilize the Higgs

$$L_{\text{int}} = -\alpha\phi^2\chi^2$$

  - Higgs-gravity *negative* non-minimal coupling stabilizes Higgs in de-Sitter (inflating) space

$$L_{\text{nm}} = \xi\phi^2 R$$

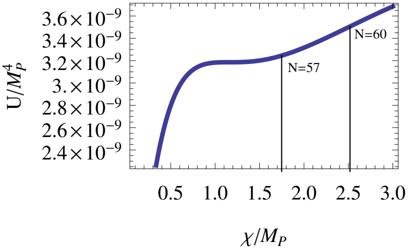
- New physics *below* μ_0 may remove Planck scale vacuum and make EW vacuum stable – many examples

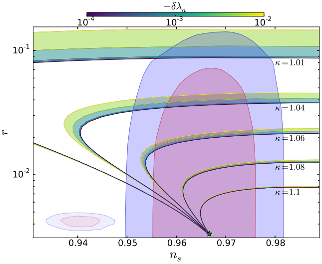
Near critical Higgs mass – critical HI

$$U_{\text{RG improved}}(\chi) = \frac{\lambda(\mu)}{4}\frac{M_P^4}{\xi^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$$

$1 \ggg \lambda_{min} > 0$

- Small $\xi \lesssim 10$ – λ vs. $\delta\lambda$ significant, gives "feature" in the potential
- Very flat potential – larg perturbations.
- different inflationary predictions – large r
- Production of primordial black holes – even Dark Matter
  - Solar mass? [Ezquiaga, Garcia-Bellido, et.al.'18]
  - Planck mass? [Rasanen, Tomberg'18]





Consistency

Up to now we neglected the quantum effects, assuming they do not spoil the story. Is this really the case?

Cut off scale today

Let us work in the Einstein frame

Change of variables: $\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2+(\xi+6\xi^2)h^2}}{M_P^2+\xi h^2}$ leads to the higher order terms in the potential (expanded in a power law series)

$$V(\chi) = \lambda\frac{h^4}{4\Omega^4} \simeq \lambda\frac{h^4}{4} \simeq \lambda\frac{\chi^4}{4} + \#\frac{\chi^6}{(M_P/\xi)^2} + \cdots$$

Unitarity is violated at tree level

in scattering processes (eg. $2 \longrightarrow 4$) with energy above the "cut-off"

$$E > \Lambda_0 \sim \frac{M_P}{\xi}$$

Hubble scale at inflation is $H \sim \lambda^{1/2}\frac{M_P}{\xi}$ – not much smaller than the today cut-off Λ_0 :(

[Burgess, Lee, Trott'09, Barbon, Espinosa'09, Hertzberg'10]

Threshold effects at M_P/ξ summarized by two new arbitrary constants $\delta\lambda$, δy_t

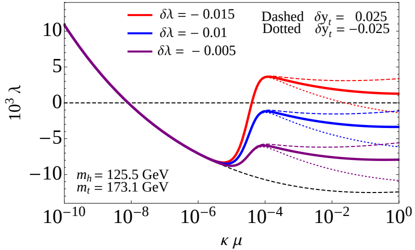
- Low and high scale coupling constants may be different

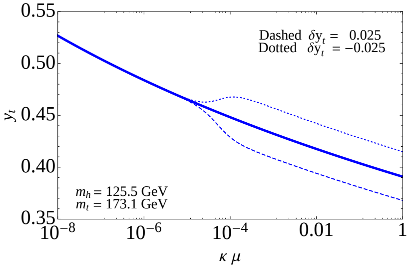
$$\lambda(\mu) \to \lambda(\mu) + \delta\lambda\left[\left(F'^2 + \tfrac{1}{3}F''F\right)^2 - 1\right]$$

$$y_t(\mu) \to y_t(\mu) + \delta y_t\left[F'^2 - 1\right]$$

Attempts to improve

- UV complete theories
- Scale invariant theories

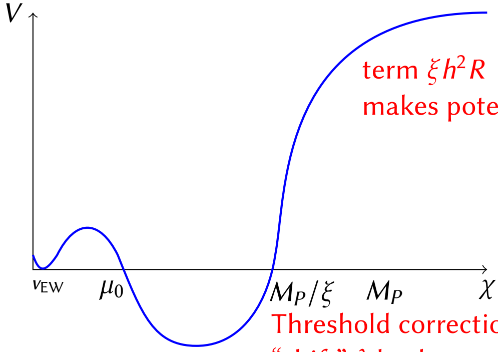




Higgs inflation and radiative corrections

Can be also used to “save” the metastable vacuum

$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R - \xi\frac{h^2}{2}R + g_{\mu\nu}\frac{\partial^\mu h\partial^\nu h}{2} - \frac{\lambda}{4}(h^2-v^2)^2\right\}$$



term $\xi h^2 R$
makes potential flat

Threshold corrections at scale M_P/ξ
“shift” λ back to positive values

[FB, Rubio, Shaposhnikov’14]

(Not really to scale)

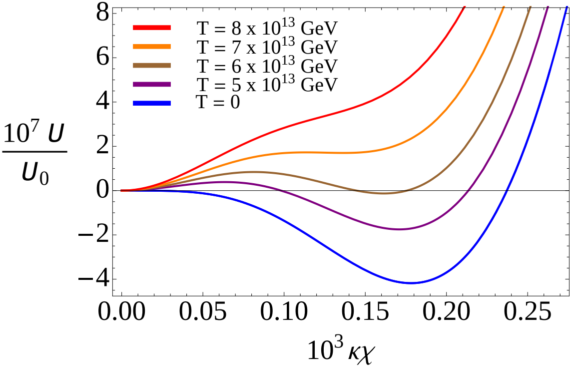
New physics *above* μ_0 may solve the problem

Requirements

- Minimum at Planck scale should be removed (but can remain near $\mu_0 \sim 10^{10}$ GeV)
- Reheating after inflation should be fast.

No need for new physics at "low" ($< \mu_0$) scales!
Example: Higgs inflation with threshold corrections at M_p/ξ

After inflation symmetry is restored in preheating



- Thermal potential removes the high scale vacuum
- Universe cools down to EW vacuum
- We live in the metastable vacuum hoping not to decay too soon

Further note on variable choice:

We really need to know how quantum gravity works

- How do we interpret the gravity action:
  - Metric – $g_{\mu\nu}(x)$ is an independent field, Connection – $\Gamma^{\lambda}_{\mu\nu} \equiv \frac{g^{\lambda\rho}}{2}(g_{\rho\mu,\nu} + g_{\rho\nu,\mu} - g_{\mu\nu,\rho})$
  - Palatiny – $g_{\mu\nu}(x)$, $\Gamma^{\lambda}_{\mu\nu}(x)$ are independent fields
- Different *classical* dynamics if $\xi \neq 0$
  Can be seen as different transformation under $g_{\mu\nu} \longrightarrow \Omega(x) g_{\mu\nu}$

Rather different inflationary predictions!

Metric	Palatini
$R \longrightarrow \Omega^2 R + 6 g^{\mu\nu} \partial_\mu \ln\Omega \partial_\nu \ln\Omega$	$R \longrightarrow \Omega^2 R$
$\xi \sim 5 \times 10^4 \sqrt{\lambda}$ $r \sim 3.2 \times 10^{-3}$	$\xi \sim 1.5 \times 10^{10} \lambda$ $r \sim 3.5 \times 10^{-14} \lambda^{-1}$

e.g. Rasanen,Wahlman'17; Järv,Racioppi,Tenkanen'17

Conclusions

- There is a chance that we know the origins of the Universe!
- But we have yet to measure
  - top quark mass
  - Higgs boson mass
  - tensor-to-scalar ratio – CMB B-modes
  - …
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Conclusions

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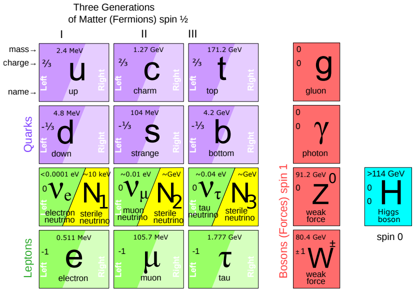
Possible: New physics only at low scales – νMSM



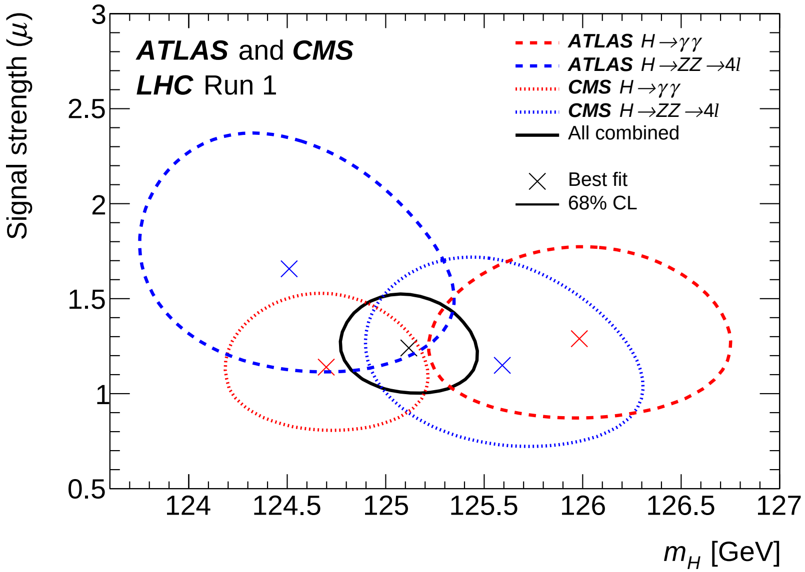
Role of sterile neutrinos

N_1 $M_1 \sim 1-50\text{keV}$: (Warm) Dark Matter,
Note: $M_1 = 7\text{keV}$ has been seen in X-rays?!

$N_{2,3}$ $M_{2,3} \sim$ several GeV:
Gives masses for active neutrinos, Baryogenesys

Asaka, Shaposhnikov'05; Asaka, Blanchet, Shaposhnikov'05

Higgs boson mass



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