Electroweak vacuum in cosmological context

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Conference on Quantum Field Theory and High Energy Physics
Hotel “Yubileinaya”,
Yaroslavl’, Russia, 02.07.2017

Consequences for cosmology

We observe Higgs boson of mass $m_h > 100\,\text{GeV}$ and nothing else...

- Gauge hierarchy problem
- Electroweak transition is a crossover

Particular value of $m_h \approx 125\ \text{GeV}$

- is either an amazing fine-tuning or is a hint of unification with gravity
- constrains inflationary dynamics, $V \sim (10^{16}\,\text{GeV})^4$
- In particular, Higgs-inflation does not work

NB: we have no direct observables for $T \gg 1\,\text{MeV}$

Electroweak transition might help with baryogenesis

Sakharov's condition of a successful baryogenesis

- B-violation
- C-, CP-violation
- departure from thermal equilibrium

I order phase transition
due to bubble percollation

would happen for $m_h \lesssim 40$ GeV

Minimal extension with one real scalar

$$\Delta V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{HS} S^2 H^\dagger H$$

- EW phase transition of the strongly I order
- Gravitational waves production by the new phase bubbles

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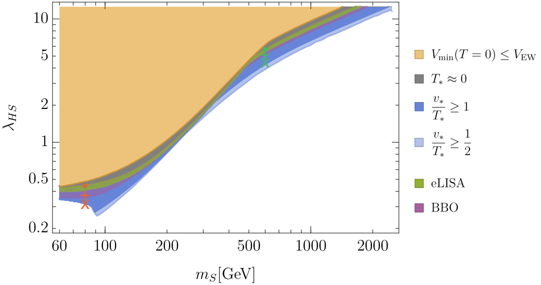
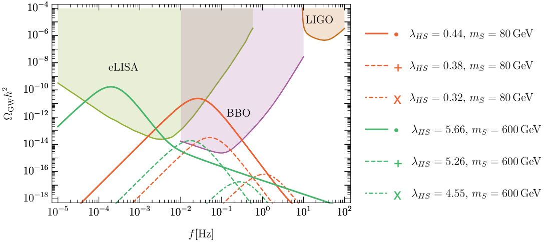
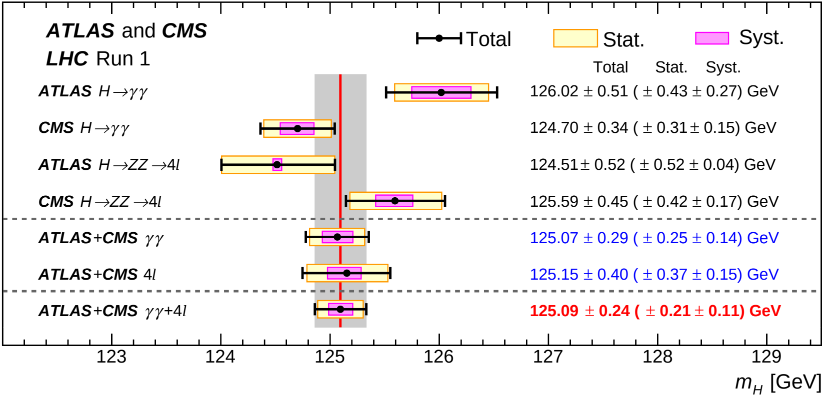




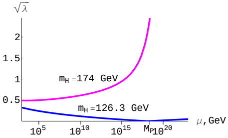
EW Higgs boson mass

1503.07589



$$V = \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \longrightarrow m_h = \sqrt{\lambda}\,v\,,\;\; m_t = Y_t\frac{v}{\sqrt{2}}$$

$$\frac{d\lambda}{d\log\mu} = +\#\lambda^2 - \#Y_t^4 \longleftarrow \lambda(m_h)\,,\;\; Y_t(m_t)$$



Running of the SM couplings

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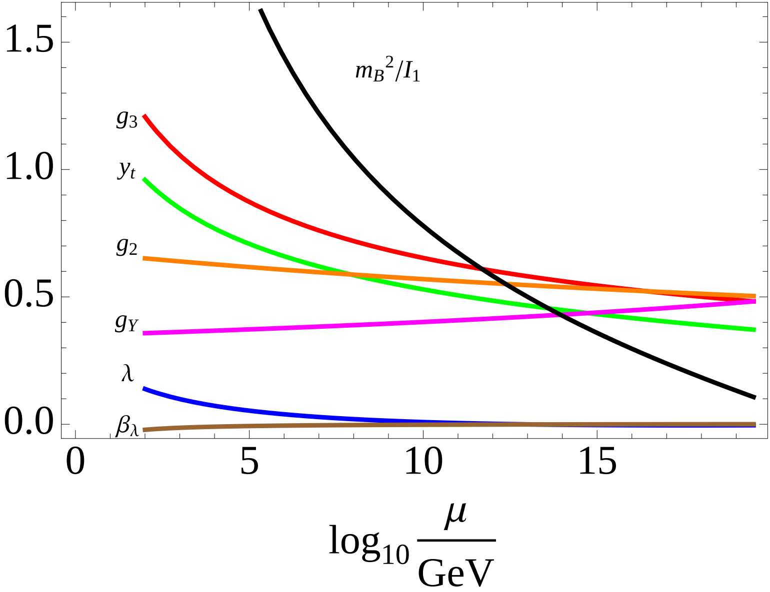
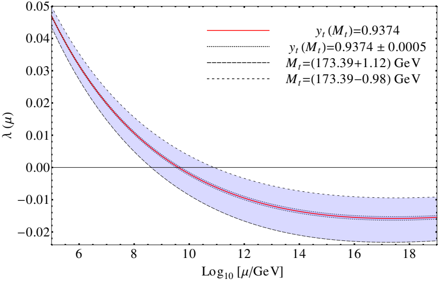
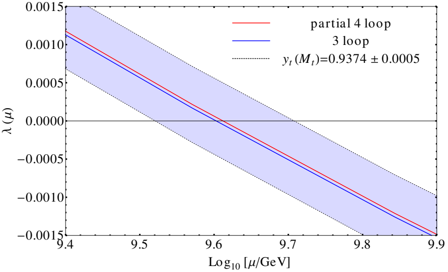
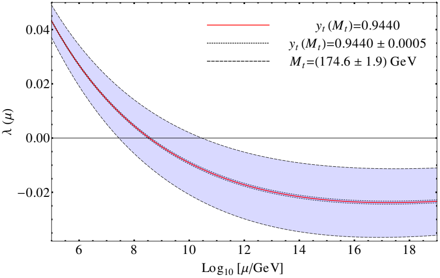


Critical point: selfcoupling becomes negative



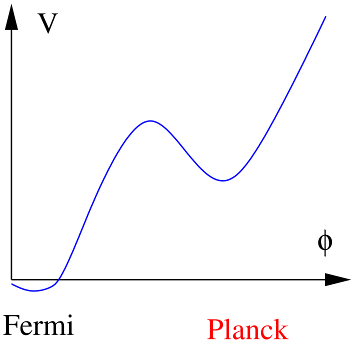


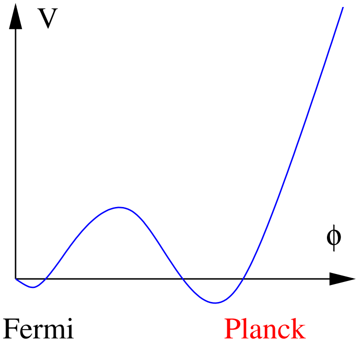


- present central values $(\alpha_s(M_Z), m_t, m_h)$ imply change of sign(λ)
- main uncertainty is due to extraction: $m_t \to Y_t(m_t)$
  RGE-calculations are precise enough

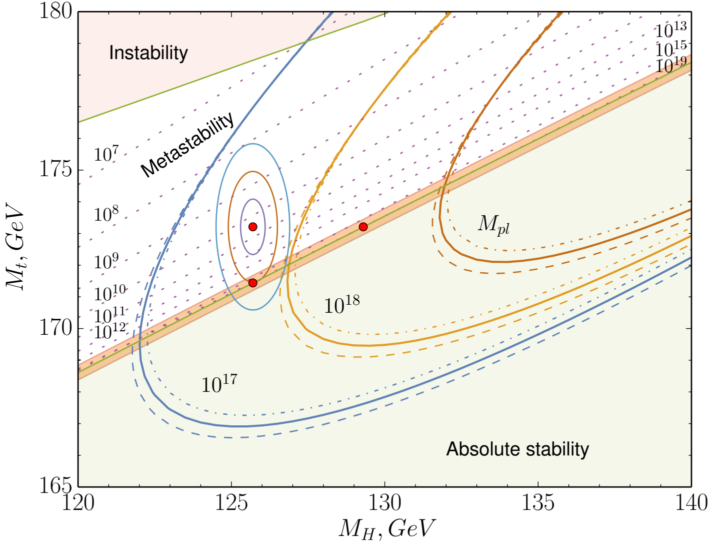
K.Chetyrkin, M.Zoller (2016)

EW Higgs potential with quantum corrections

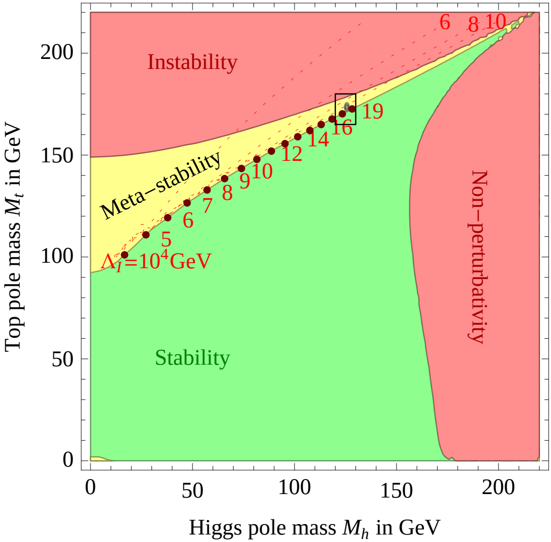




Apparently we leave in a false vacuum. . . A.Bednyakov et al (2015)



How weird to live with 125 GeV Higgs. . .



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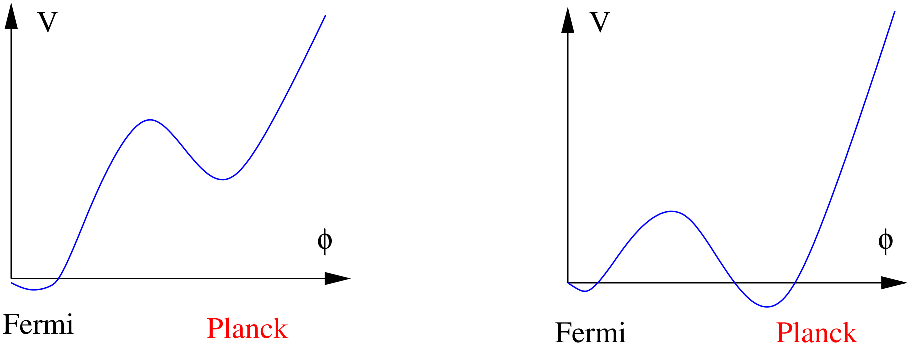
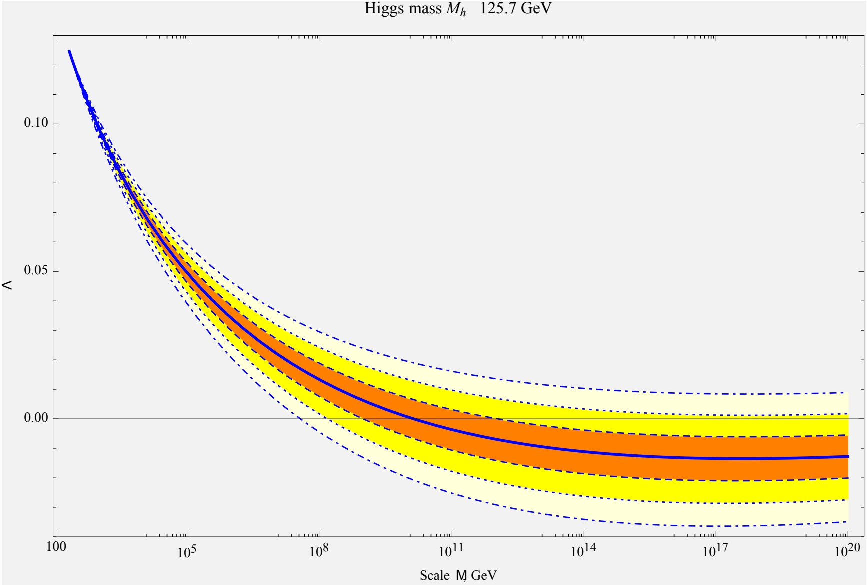
Multiple point principle: D.Bennett, H.Nielsen (1993), C.Froggatt, H.Nielsen (1995)



$$\Lambda \simeq 0 \Rightarrow V(\phi_{EW}) = V(\phi_{Planck}) = 0 \Rightarrow \lambda(\mu_{Planck}) = 0$$

$$\text{gravity scale} \Rightarrow V'(\phi_{EW}) = V'(\phi_{Planck}) = 0 \Rightarrow \frac{d\lambda(\mu)}{d\log\mu}(\mu_{Planck}) = 0$$

These gave $m_t \simeq 173$ GeV , $m_h \simeq 129$ GeV GUT concept?

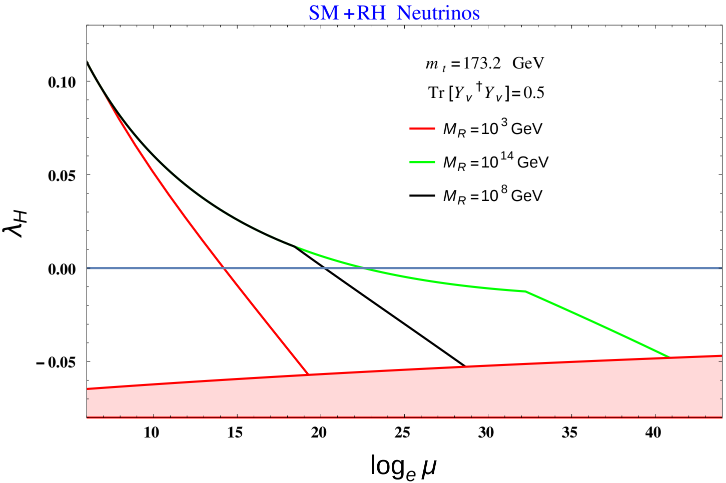


Higgs mass M_h 125.7 GeV
0.10
0.05
0.00
λ
100
10^5
10^8
10^{11}
10^{14}
10^{17}
10^{20}
Scale μ, GeV

1610.01421

- If a hint, it implies, similar to GUTs, a great desert…
  new physics (which must exist) is below/at EW scale
- If a coincidence, can it be changed?
  Yes, and in simple yet well-motivated models

Heavy sterile neutrinos act as top-quark



$$m_\nu = v^2\,\hat{Y}_\nu^T\,\hat{M}_N^{-1}\,\hat{Y}_\nu$$

$$\frac{d\lambda_H}{d\log\mu} \propto Y_\nu^\dagger Y_\nu$$

1706.04931

Additional scalars act as Higgs

Take minimal scalar DM model

$$V = V_{SM} + \frac{1}{2}\mu_\phi^2\phi^2 + \frac{1}{2}\lambda_{\phi H}\phi^2 H^\dagger H + \frac{1}{4!}\lambda_\phi\phi^4$$

$$m_{DM} = \sqrt{\mu_\phi^2 + \frac{1}{2}\lambda_{\phi H} v^2}$$

$$\Omega_{DM} \propto m_{DM} n_{DM} \propto \frac{1}{\sigma_{ann}} \propto \frac{m_{DM}^2}{\lambda_{\phi H}^2}$$

indirect:

$$\text{flux}(DM + DM \to SM) \propto n_{DM}^2 \sigma_{ann} \propto \frac{1}{\lambda_{\phi H}^2}$$

direct:

$$\Gamma(DM + A \to DM + A) \propto n_{DM}\sigma_{ann} \propto \frac{1}{m_{DM}}$$

Scalar DM really helps

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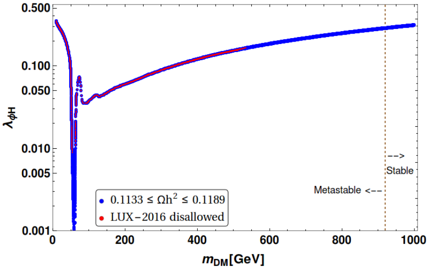
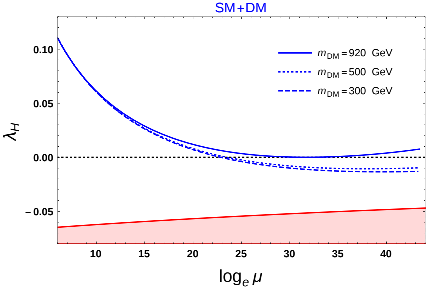
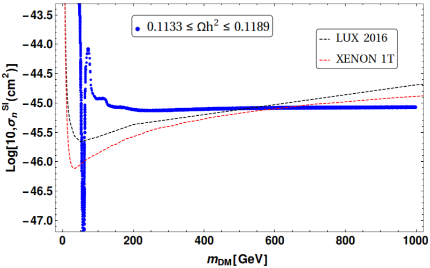
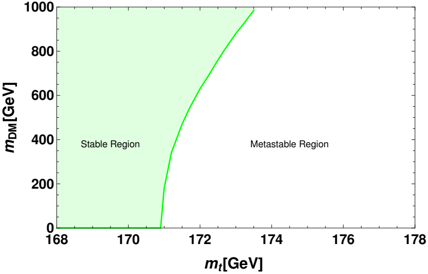




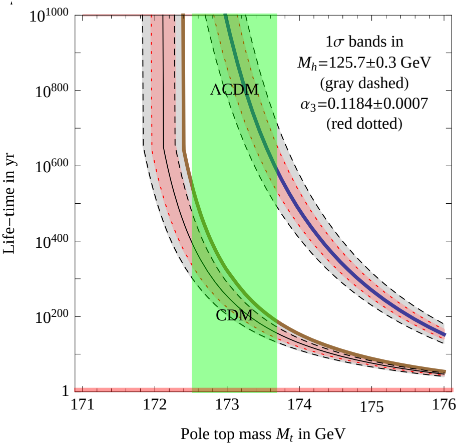


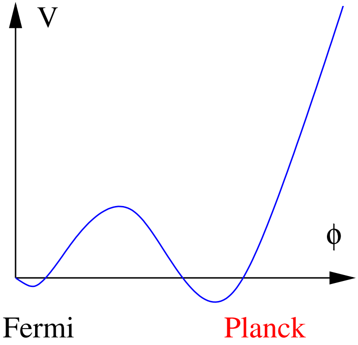


What does it mean for cosmology?

- Instability implies a finite lifetime of our EW-World
  a catastrophic event in the future
- The past was safe
  Specific cosmic evolution to avoid trapping in the Planck vacuum

EW vacuum is false, but very long-lived



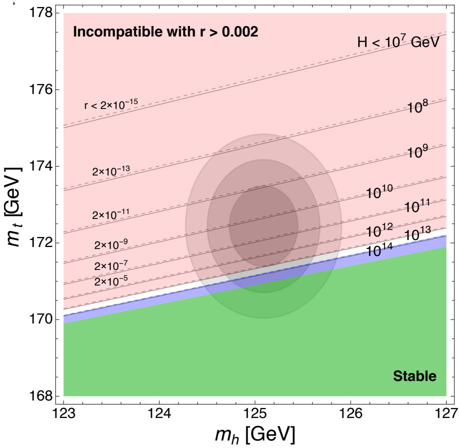


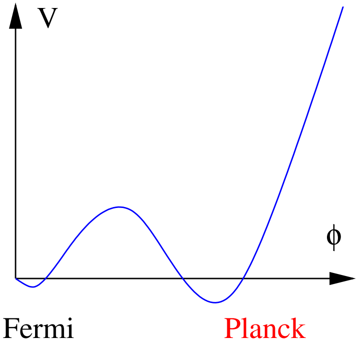
D.Buttazzo et al (2013)

$t_{\text{tunn}} > 10^{600}\,\text{y}$ vs $t_{\text{U}} = 10^{10}\,\text{y}$

Tunneling rate
to the Planck vacuum
is exponentially suppressed

All bosons fluctuate including the SM Higgs $\phi \sim \mathscr{H}/2\pi$





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$r = P_T/P_S\,,\;\; P_T \sim (\mathscr{H}/M_{Pl})^2$

This observation constrains inflation

$\mathscr{H} \lesssim 10^9 \ldots 10^{13}\,\text{GeV} \quad \text{at } 1\,\sigma$

Additional ingredients?. . . naturally

- Higgs-portal coupling to inflaton $\beta X^2 H^\dagger H$

  (the simplest and renormalizable way to reheat the Universe) at inflation

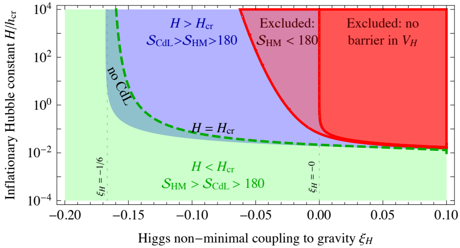
  $$\longrightarrow \beta M_{Pl}^2 H^\dagger H$$

  but $\beta \lll 1$ to avoid quantum corrections to the inflaton potential

- Non-minimal coupling to gravity $\xi R H^\dagger H$

  (emerges due to quantum corrections from matter fields) at inflation

  $$\longrightarrow \xi \mathscr{H}^2 H^\dagger H$$



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An exotic process w/o modification of the Higgs sector

- Take a generic large-field inflation
- After inflation, but before the reheating matter perturbation can grow and form small clumps
- A tiny fraction of them collapse further to small black holes
- It was argue in literature that evaporating BH induces tunneling process
- If true,
  this implies further limits on inflationary models and subsequent reheating mechanisms

Further limits on inflationary models

- Imagine a BH in equilibrium with thermal bath

$$T_{\rm bath} = T_{\rm BH} \propto M_{\rm Pl}^2/M_{\rm BH}$$

- In thermal bath any field configuration is allowed, but Boltzman suppressed

$$P \propto e^{-E/T_{\rm BH}}$$

- P.Burda, R.Gregory, I.Moss (2015,2015,2016) performed a Euclidean calculation for a true vacuum bubble configuration with BH inside

$$P \propto e^{-E_B/T_{\rm BH}}$$

- It looks like a thermal jump over the potential barrier

$$P \sim 1 \quad \text{at} \quad T_{\rm BH} \sim h_{crit}$$

Take it as it is

Chaotic inflation at large fields: graceful exit

If $V(\phi)$ dominates by chance

Chaotic inflation, A.Linde (1983), A.Linde (1984)

$$\ddot{\phi} - \Delta\phi/a^2 + 3H\dot{\phi} + V'(\phi) = 0$$

for power-law potential at $\phi > M_{Pl}$

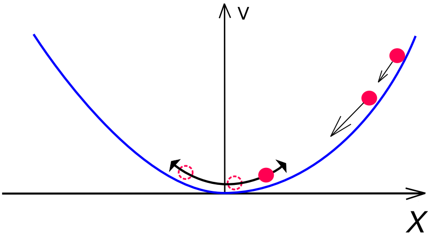
$$V \simeq \text{const}$$

"slow roll" solution

$$H^2 = \frac{8\pi}{3M_P^2} V(\phi)\,, \quad a(t) \propto e^{Ht}$$

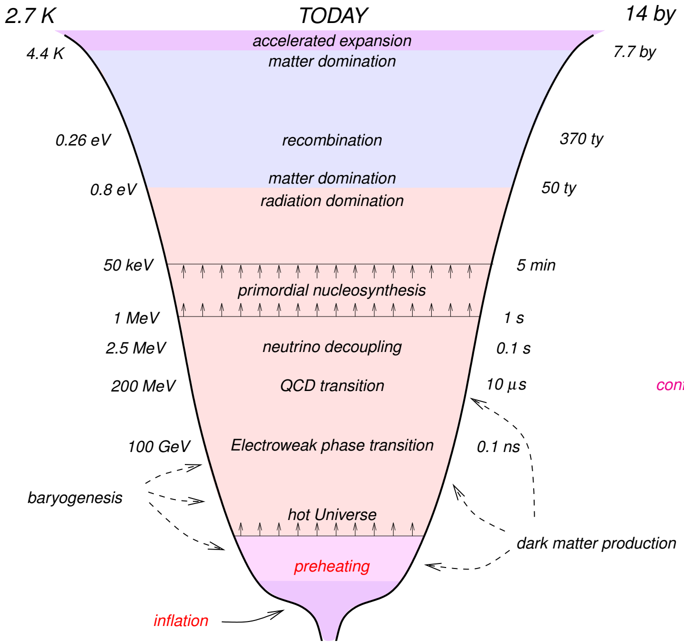
valid while slow roll conditions

$$M_P^2 \frac{V''}{V} \ll 1\,, \quad M_P^2 \frac{V'^2}{V^2} \ll 1$$



Later inflaton oscillates and Universe expands 'normally', $a(t)/t \to 0$

e.g. if $V(\phi) \propto \phi^2$ it looks like Matter-dominated stage



$e + p \to H + \gamma$

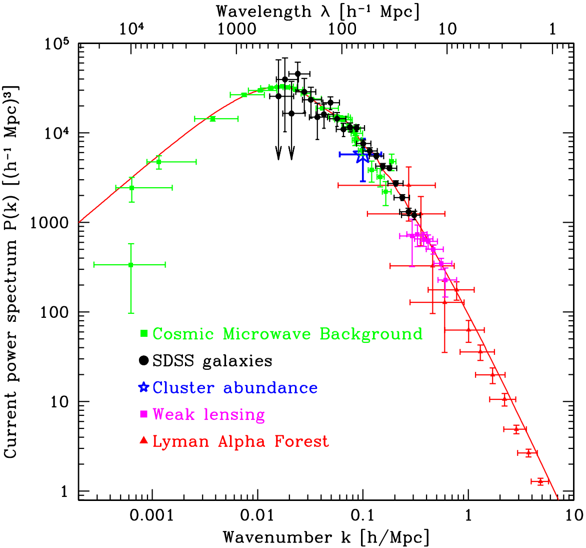
$^3H + {}^4He \to {}^7Li + \gamma$

$^2H + {}^2H \to n + {}^3He$

$p + p \to {}^2H + \gamma$

confinement↔free quarks

Observation of matter power spectrum



Observable range:

$$\frac{k_{max}}{k_{min}} \sim 10^5$$

$$\Delta N_e \simeq 10$$

Small scales we cannot describe:

for a long time in nonlinear regime

The natural choice: $V(\phi) \propto \phi^2$ is the simplest oscillator

- Universe expands as at Matter domination

$$H^2(t) = \frac{8\pi}{3} G\rho \propto \frac{1}{a^3(t)} ,$$

- subhorizon matter perturbation modes

$$a/k \simeq R(t) \ll 1/H(t)$$

grow linearly with scale factor $(\delta\rho/\rho)_k \propto a$ starting from

$$(\delta\rho/\rho)_{k,i} \equiv \delta_i \sim 10^{-4}$$

at the horizon crossing $R_* = 1/H_*$.

- Let DM stage be long enough to reach $(\delta\rho/\rho)_k \sim 1$
- a very small chance that sufficiently spherical and smooth overdensity of size R further collapses to BH of size $r_g = 2M/M_{\rm Pl}^2$

$$\mathscr{P}_{BH} \approx 2 \times 10^{-2} \left(\frac{r_g}{R}\right)^{13/2} \approx 2 \times 10^{-2}\, \delta_i^{13/2}$$

A.Polnarev, M.Khlopov (1980,1981,1982,1985)

The natural choice: $V(\phi) \propto \phi^2$ is the simplest oscillator

- There are $(HR)^{-3} \simeq \delta_i^{-3/2}$ clumps of size R inside the Hubble volume at turnaround. The probability to have a BH there

$$\mathscr{P}_{BH,hor} \approx 2 \times 10^{-22} \left(\frac{\delta_i}{10^{-4}}\right)^5$$

  is still very small

- However, present-day Universe has many such regions !

$$N_{hor} = \left(\frac{H}{H_0}\right)^3 \left(\frac{a}{a_0}\right)^3$$

- the largest possible black holes formed right before the reheating

$$H_{reh}^2 \sim G g_{*,reh} T_{reh}^4 / M_{\rm Pl}^2$$

- The probability to have a region *in the presently visible part of the Universe* where a black hole had been formed at the post-inflationary matter-dominated stage is NOT SMALL AT ALL

$$\mathscr{P}_{BH,0} = N_{hor} \times \mathscr{P}_{BH,hor} \simeq \left(\frac{T_{reh}}{3 \times 10^{-4}\,\text{GeV}}\right)^3 \times \left(\frac{\delta_i}{10^{-4}}\right)^5 .$$

All models with long preheating are excluded

$$\mathscr{P}_{BH,0} = N_{hor} \times \mathscr{P}_{BH,\,hor} \simeq \left(\frac{T_{reh}}{3 \times 10^{-4}\,\mathrm{GeV}} \right)^3 \times \left(\frac{\delta_i}{10^{-4}} \right)^5 .$$

Valid on the assumption that

- EW vacuum is metastable
- MD stage is long enough for perturbations to grow by a factor $\delta_i^{-1} \sim 10^4$
- produced BH are evaporated by present, that is $M_{BH} < 10^{14}$ g

e.g., R^2-model is excluded

What is still allowed ?

D.G., D.Levkov, A.Panin (2017)

- The smallest BH are formed by the perturbations entering the horizon right after inflation
  low-energy inflation

$$\rho_{inf} \lesssim \frac{3\,M_{Pl}^6}{32\pi M_c^2} \approx (2\times 10^9\,\text{GeV})^4, \quad \longrightarrow \quad H_{inf} \lesssim \text{ GeV}$$

  is safe from BH induced tunneling
- Models with high-energy inflation must quickly reheat the Universe

$$T_{reh} \gtrsim 5\times 10^{12}\,\text{GeV} \times \frac{\rho_{inf}^{1/4}}{10^{16}\,\text{GeV}} \times \left(\frac{\delta_i}{10^{-4}}\right)^{3/4}$$

  (may be stronger by an order of magnitude)

Further refinement

$$\mathscr{P}_{BH,0} = N_{hor} \times \mathscr{P}_{BH,hor} \simeq \left(\frac{T_{reh}}{3 \times 10^{-4}\,\mathrm{GeV}} \right)^3 \times \left(\frac{\delta_i}{10^{-4}} \right)^5 .$$

Even at $(\delta\rho/\rho)_k \sim 0.1$ some overdense region may by chance enter nonlinear regime

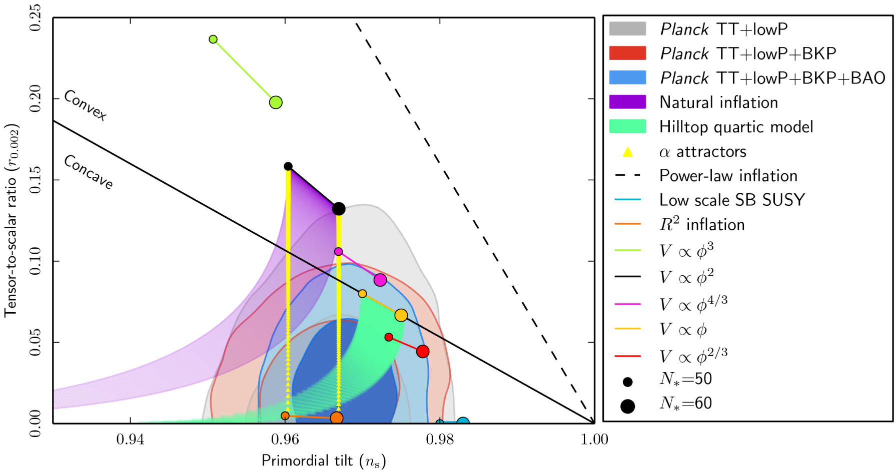
- Press–Schechter formalism for density contrast dispersion
- Assuming the spectrum remains flat at small scales

$$\mathscr{P}_{BH} \simeq 10^{-2} \times \delta_i \times \left(\frac{H_{reh}}{H_{inf}} \right)^{11/3} \exp\left(-\frac{\delta_c^2}{2\delta_i^2} \left(\frac{H_{reh}}{H_{inf}} \right)^{4/3} \right) .$$

- And place stronger limits,
  e.g. on the reheating temperature in models with high-energy inflation

$$T_{reh} \gtrsim 3 \times 10^{13}\,\mathrm{GeV} \times \frac{\rho_{inf}^{1/4}}{10^{16}\,\mathrm{GeV}} \times \left(\frac{\delta_i}{10^{-4}} \right)^{3/4} .$$

Planck 2015 favors flat inflaton potentials



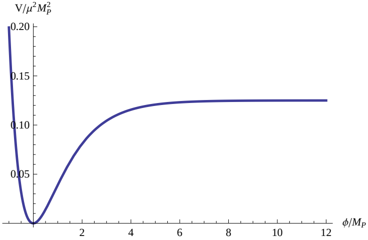
$$r = \frac{A_T}{A_S} \propto \frac{\dot{\phi}^2}{H^2 M_{Pl}^2} \propto \left(\frac{V'}{V}\right)^2 \ll 1$$

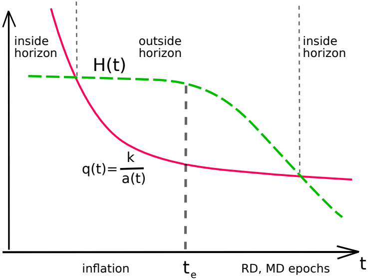
The power spectra of primordial perturbations

CMB anisotropy is measured at
$k/a_0 = 0.002/\text{Mpc}$

$$N = \frac{1}{3}\log\left(\frac{\pi^2}{30\sqrt{27}}\right) - \log\frac{(k/a_0)}{T_0 g_0^{1/3}} + \log\frac{V_*^{1/2}}{V_e^{1/4} M_P}$$

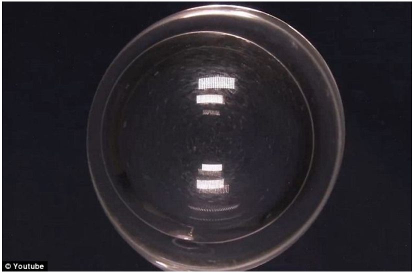
$$-\frac{1}{3}\log\frac{V_e^{1/4}}{10^{13}\,\text{GeV}} - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_{reh}}$$





Disclaimer: the BH-induced tunneling is questionable

the interpretation of the Euclidean solution is rather suspecious



For further study see

D.G., D.Levkov, A.Panin (2017)

D.Canko et al (2017)

K.Mukaida, M.Yamada (2017)

Conclusions

- Our vacuum is unstable *t*-quark mass is crucial !!
  - EW vacuum in SM is apparently false

$$E_{\text{EW}} = 100\,\text{GeV} \to 10^{11}\,\text{GeV} = E_{\text{crit}}$$

  - vacuum lifetime $\ggg$ Universe age
- if so (nothing else at LHC): no EW-baryogenesis, no Higgs-inflation
- very special value $m_h \approx 125\,\text{GeV}$
  may be a hint of unification with gravity

  then NP is at/below EW scale
- Inflation is strongly constrained

  and even more if BH induces the vacuum decay
- New Physics coupled to in Higgs sector can change everything !!