Bugaboo black holes

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The talk in brief (I)

- Our vacuum is unstable
  - EW vacuum in SM is apparently false

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

  - vacuum lifetime $\ggg$ Universe age
- Black Hole can induce vacuum decay
  - BH evaporates, $T \propto M_{\mathrm{Pl}}^2/M_{\mathrm{BH}}$
  - tiny BH has higher temperature
  - BH reaching $T \sim E_{\mathrm{crit}}$ induces tunneling via bubble production

P.Burda, R.Gregory, I.Moss (2015,2015,2016)

The talk in brief (II)

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

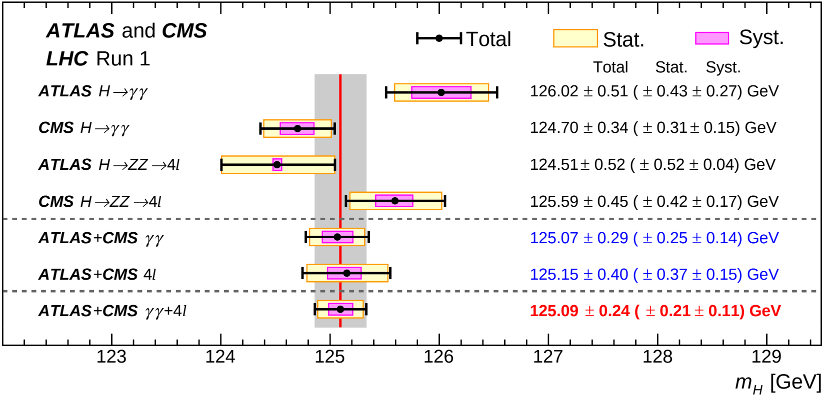
- if so, Bugaboo black holes ruin many models of early Universe
  - Inflation often ends with a dust-like stage
  - $\delta\rho/\rho \propto a(t)$ and may $\to \delta\rho/\rho \sim 1$
  - BH birth is an extremely rare event
  - BH quickly evaporates reaching $T \sim E_{\text{crit}}$
  - then it produces a bubble of the true vacuum
  - which by now covers the entire visible Universe

Outline

Outline

EW Higgs boson mass

1503.07589

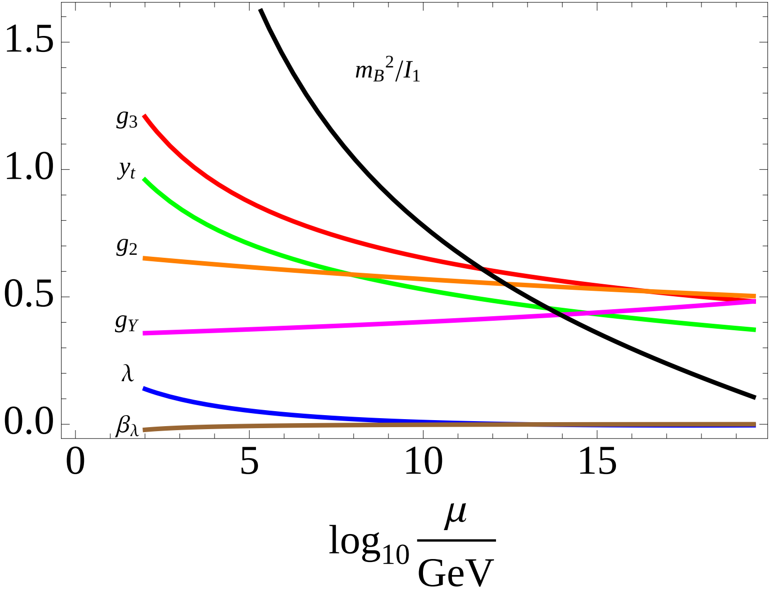


$$V = \frac{\lambda}{2}\left(\mathscr{H}^\dagger \mathscr{H} - \frac{v^2}{2}\right) \quad \longrightarrow \quad m_h = \sqrt{\lambda}\, v\,, \quad m_t = Y_t \frac{v}{\sqrt{2}}$$

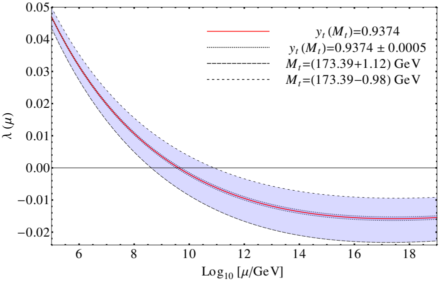
$$\frac{d\lambda}{d\log\mu} = +\#\lambda^2 - \#Y_t^4 \quad \longleftarrow \quad \lambda(m_h)\,, \quad Y_t(m_t)$$

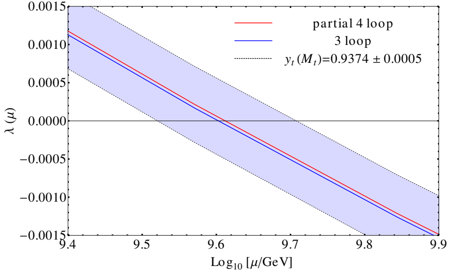
Running of the SM couplings

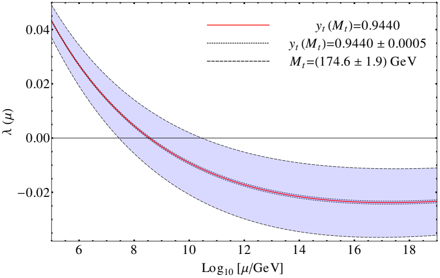
1305.7055



Critical point: selfcoupling becomes negative



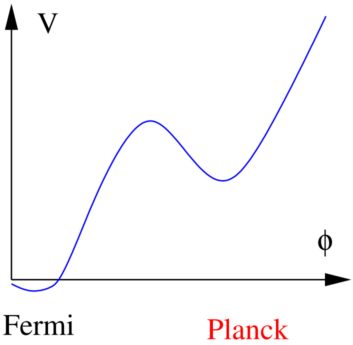


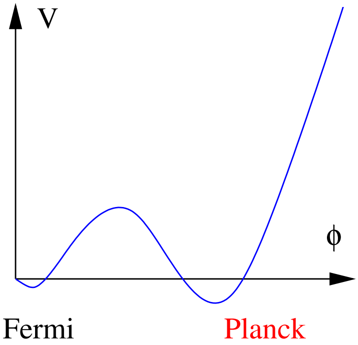


- present central values ($\alpha_s(M_Z)$, m_t, m_h) imply change of sign(λ)
- main uncertainty is due to extraction: $m_t \to Y_t(m_t)$

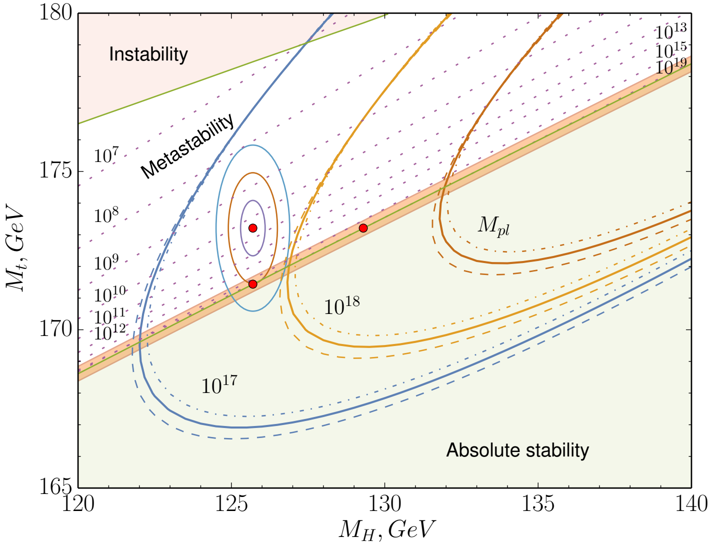
K.Chetyrkin, M.Zoller (2016)

EW Higgs potential with quantum corrections

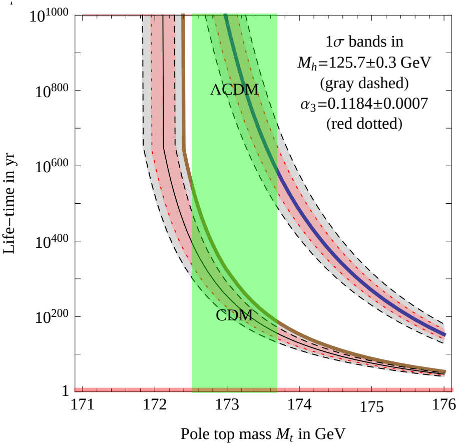


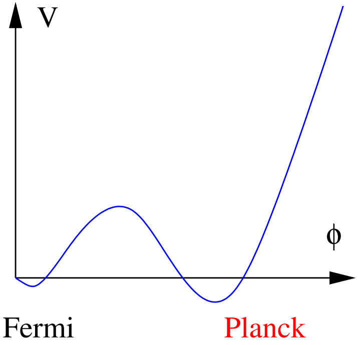


Apparently we leave in a false vacuum. . . A.Bednyakov et al (2015)



EW vacuum is false, but very long-lived



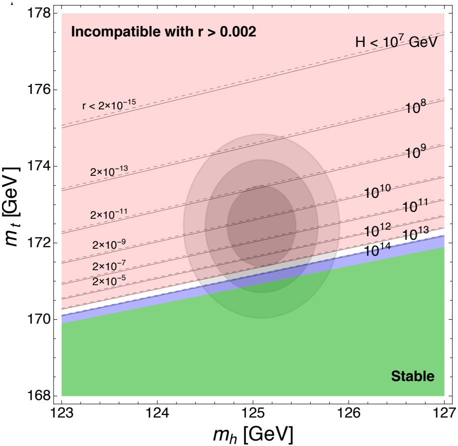


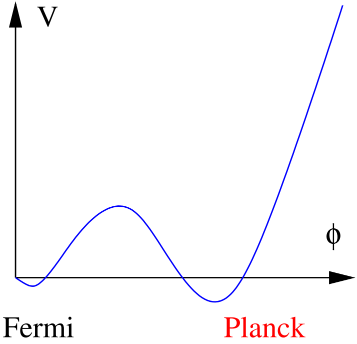
D.Buttazzo et al (2013)

Tunneling rate
to the Planck vacuum
is exponentially suppressed

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

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





1607.00381

This observation

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

Further limits on inflationary models

- Instability constrains inflation, $H \lesssim \ldots 10^9 \ldots 10^{13}\,\text{GeV}$
- BH-danger constrains the subsequent preheating stage

Outline

Further limits on inflationary models

- Imagine a BH in equilibrium with thermal bath

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

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

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

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

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

- It looks like a thermal jump over the potential barrier

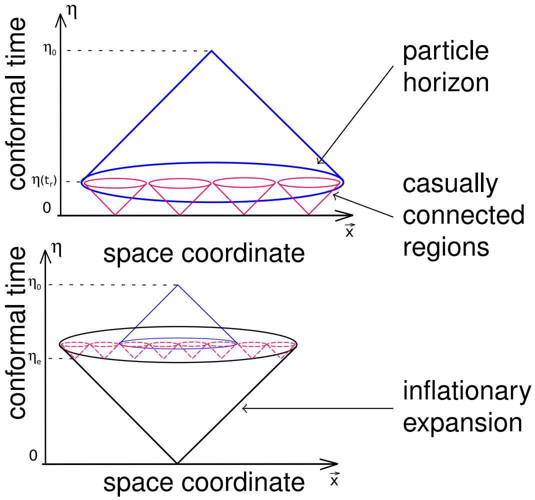
$$P \sim 1 \quad \text{at} \quad T_{\mathrm{BH}} \sim h_{crit}$$

Take it as it is

Outline

Inflationary solution of Hot Big Bang problems

- no initial singularity in dS space
- all scales grow exponentially, including the radius of the 3-sphere
  the Universe becomes exponentially flat
- any two particles are at exponentially large distances
  no heavy relics
  no traces of previous epochs!
- no particles in post-inflationary Universe
  to solve entropy problem we need post-inflationary reheating



Chaotic inflation at large fields: graceful exit

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

If $V(\phi)$ dominates by chance

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

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

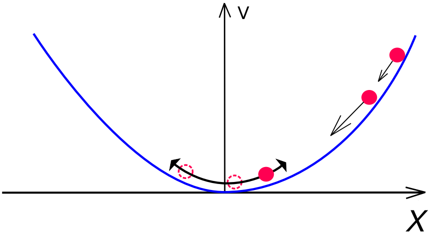
$$V \simeq \text{const}$$

"slow roll" solution

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

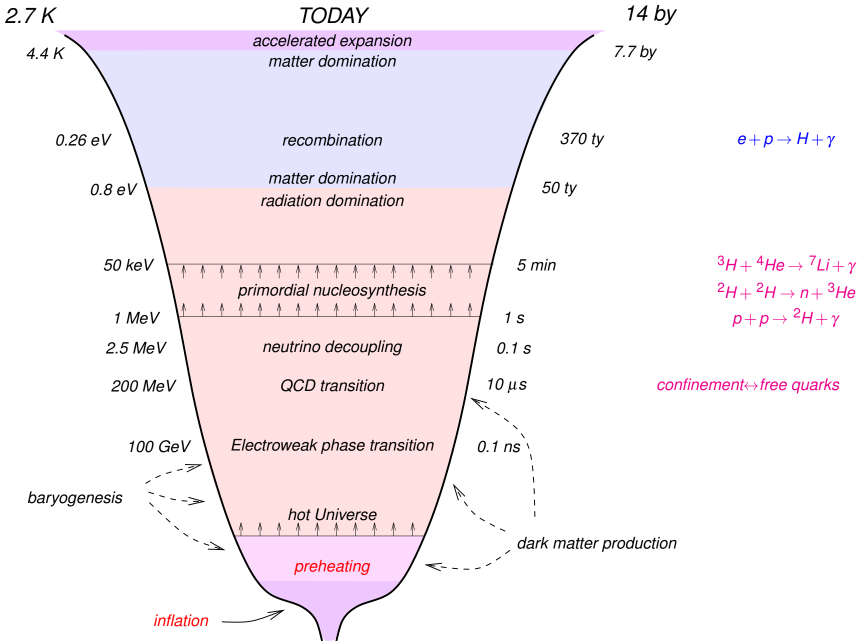
valid while slow roll conditions

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



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



2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.8 eV
50 ty
radiation domination
50 keV
5 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
preheating
inflation

Unexpected bonus: generation of perturbations

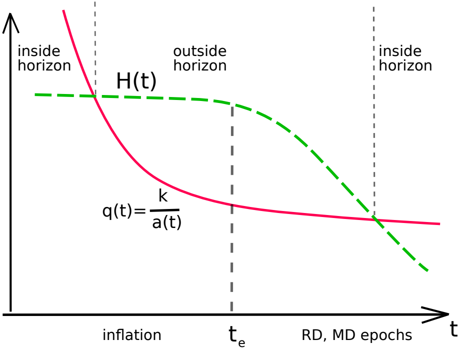
Quantum fluctuations of wavelength λ of a free massless field φ (inflaton and gravitons !!)
have 3-momenta $q \simeq 1/\lambda$ and an amplitudes of $\delta\varphi_\lambda \simeq q$

Evolution at inflation

- inside horizon: $q > H$
  $q \propto 1/a \Rightarrow$ $\delta\varphi_\lambda \propto q \propto 1/a$

- outside horison: $q < H$
  $q \propto a \Rightarrow$ $\delta\varphi_\lambda = \text{const} = H_{infl}/2\pi$!!!

- got "classical" fluctuations:
  $$\delta\varphi_\lambda = \delta\varphi_\lambda^{quantum} \times e^{N_e}$$



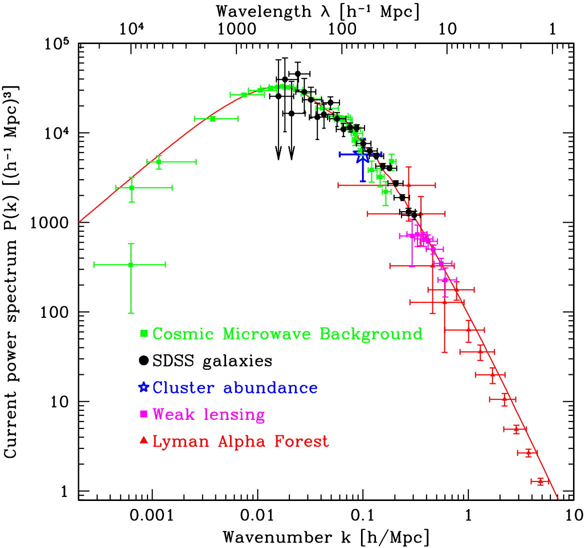
scalar modes $\delta\phi_\lambda \sim H_{infl}$

tensor modes $\delta g_{\mu\nu} \sim h \sim H_{infl}/M_{Pl}$

Later at normal stage

$H \propto 1/t$, $q/H \nearrow$, modes "enter horizon"

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 till 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

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

- 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

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

All models with long preheating are excluded

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

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 $M_{BH} < 10^{14}\,\text{g}$

Models with long preheating (e.g. R^2) are excluded

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

Consequently

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

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

  is safe from BH induced tunneling

- then low-temperature reheating is also preferable

$$T_{reh} \sim M_{\mathrm{Pl}}^{1/2} H_{reh}^{1/2} \lesssim 10^6\,\mathrm{GeV} \times \left(\frac{\delta_i}{10^{-4}} \right)^{3/4}$$

- Models with high-energy inflation must quickly reheat the Universe

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

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 density contrast dispersion

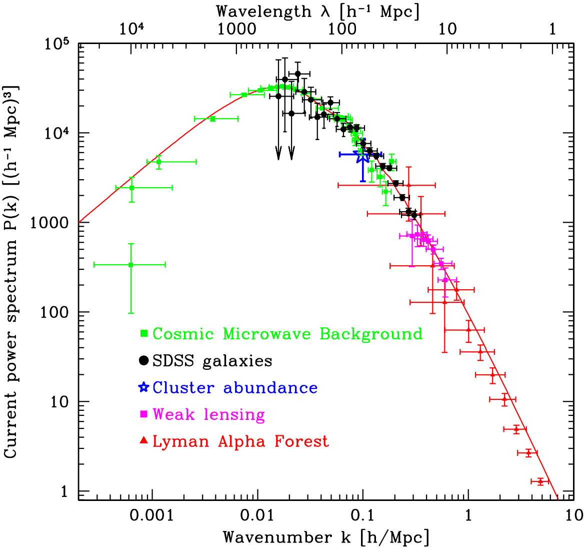
$$\langle\delta_R^2(t)\rangle \equiv \sigma_R^2(t) = \int_{Ha}^{k_{max}} \frac{dk}{k}\,\mathscr{P}(k,t) \times \frac{9j_1^2(Rk/a)}{(Rk/a)^2}\,,$$

allows to estimate the probability to form a nonlinear clump

$$\mathscr{P}_{clump} = \int_{\delta_c}^{\infty} \frac{d\delta}{\sqrt{2\pi}\sigma_R}\exp\left(-\frac{\delta^2}{2\sigma_R^2}\right) \approx \frac{\sigma_R}{\sqrt{2\pi}\,\delta_c}\exp\left(-\frac{\delta_c^2}{2\sigma_R^2}\right)$$

- Clumps must be sufficiently smooth (hard to estimate)
- The smallest BH are formed by the perturbations entering the horizon right after inflation... ? ... very model-dependent

Observation of matter power spectrum



Observable range:

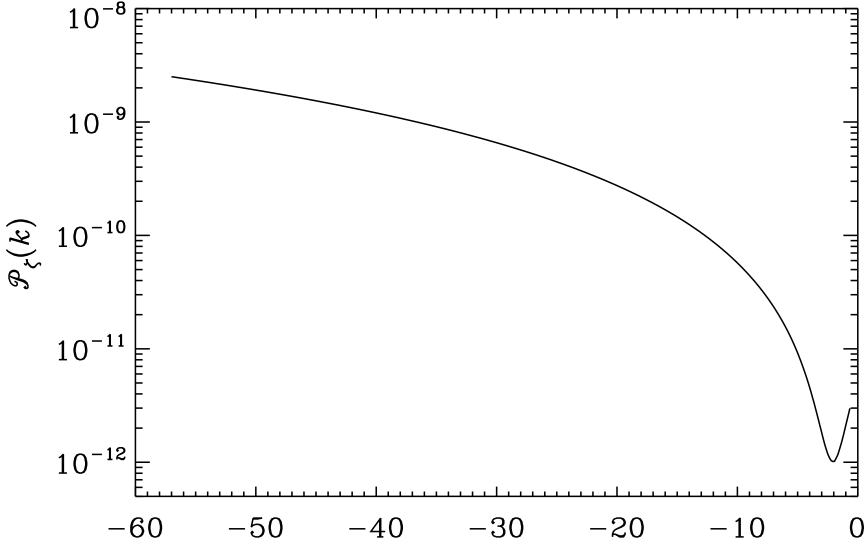
$$\frac{k_{max}}{k_{min}} \sim 10^5$$

$$\Delta N_e \simeq 10$$

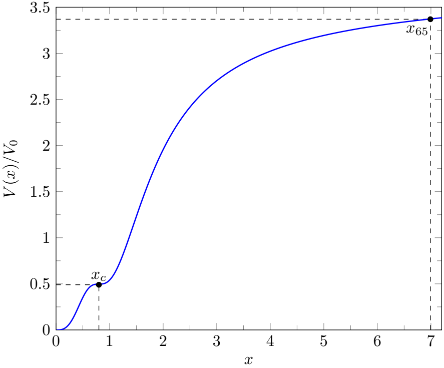
Small scales we cannot describe:

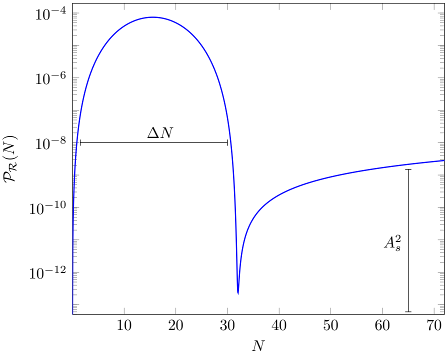
for a long time in nonlinear regime

Scalar perturbation spectrum in $m^2\phi^2$-inflation 1002.3278



Higgs-inflation with inflection point 1705.04861





Further refinement

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

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

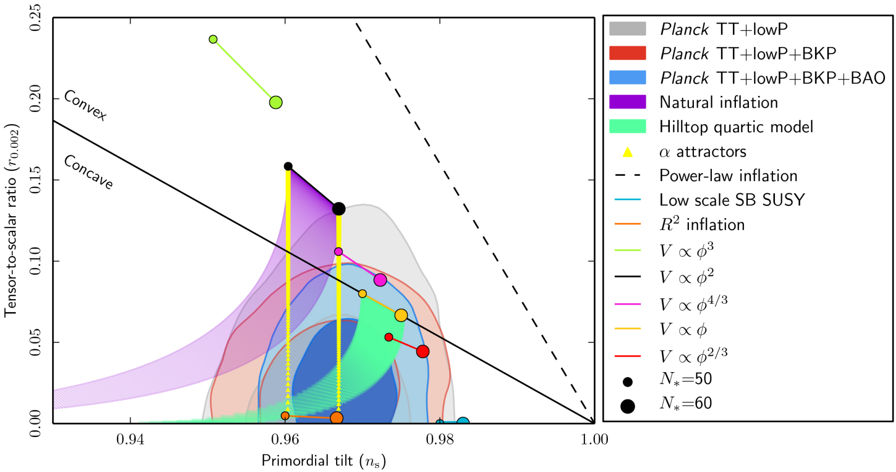
$$\mathscr{P}_{BH} \simeq 10^{-2} \times \sigma_{R,inf} \left(\frac{H_{reh}}{H_{inf}} \right)^{11/3} \exp\left(-\frac{\delta_c^2}{2\sigma_{R,inf}^2} \left(\frac{H_{reh}}{H_{inf}} \right)^{4/3} \right) .$$

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

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

Outline

Planck 2015 favors flat inflaton potentials



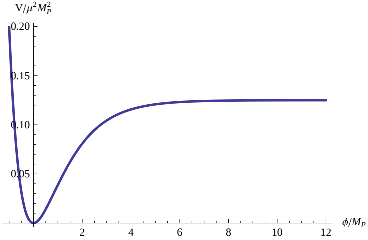
$$r = \frac{A_T}{A_S} \propto \frac{\dot{\phi}^2}{H^2 M_{Pl}^2} \propto \left(\frac{V'}{V}\right)^2 \ll 1$$

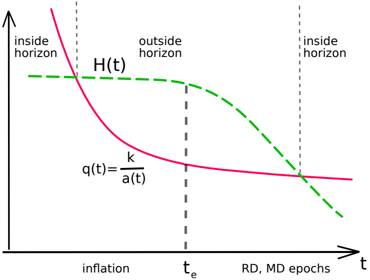
The power spectra of primordial perturbations

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

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

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





Conclusions

- A unique way to constrain the postinflationary reheating mechanism: inflaton coupling to the SM fields

  another example is GW from inflaton clumps
- many motivated model are excluded in this way e.g. R^2-inflation

  or e-folding number N is constrained
- EW vacuum is stable?,

  because of uncertainties... in m_t
- An evidence for New Physics in Higgs sector...?
- The claim that BH induce tunneling must be checked