Planck scale black hole dark matter from Higgs inflation

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Motivation

- Primordial black holes: a dark matter candidate
- Higgs inflation: an attractive model of cosmic inflation
- PBHs from Higgs inflation?

Higgs inflation

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\left(M^2 + \xi h^2\right)R + \frac{1}{2}g^{\mu\nu}\partial_\mu h\partial_\nu h - \frac{\lambda}{4}h^4\right]$$

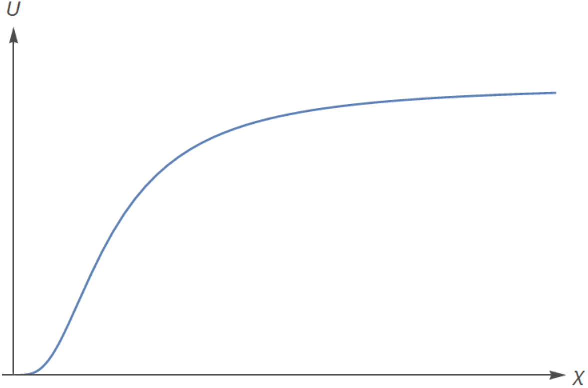
- First studied for SM Higgs in [0710.3755]
- Standard procedure: Weyl transformation

$$g_{E\mu\nu} = g_{\mu\nu}\left(1 + \frac{\xi h^2}{M^2}\right), \quad \frac{dh}{d\chi} = \frac{1 + \xi h^2}{\sqrt{1 + \xi h^2 + 6\xi^2 h^2}}$$

$$S_E = \int d^4x\sqrt{-g_E}\left[-\frac{1}{2}M^2 R_E + \frac{1}{2}g_{E\mu\nu}\partial^\mu\chi\partial^\nu\chi - U(\chi)\right]$$

Higgs inflation

- Einstein frame potential:



$$U = \frac{\lambda}{4} F^4[h(\chi)]\,, \qquad F(h) \equiv \frac{h}{\sqrt{1+\xi h^2}} \approx \frac{1}{\sqrt{\xi}} \left(1 - e^{-\sqrt{2/3}\chi}\right)^{1/2}$$

Higgs inflation

- CMB predictions fit the observations:

$$A_s = \frac{\lambda N^2}{72\pi^2\xi^2}\,,$$

$$n_s = 1 - \frac{2}{N}\,, \quad r = \frac{12}{N^2}$$

- For $N \sim 50$, $\xi = 800\sqrt{\lambda}N$:

$$n_s \approx 0.96\,, \quad r \approx 4.8 \times 10^{-3}$$

Quantum corrections

- Model non-renormalizable
  - Jordan frame: non-renormalizable gravity
  - Einstein frame: non-polynomial tree-level potential V
- Use effective field theory approach
  - Only include leading corrections in flat-potential limit
  - Use known results from "Chiral SM"

Quantum corrections

- Potential: $U = U_{tree} + U_{1-\mathrm{loop}}$,

$$U_{1-\mathrm{loop}} = \frac{6m_W^4}{64\pi^2}\left(\ln\frac{m_W^2}{\mu^2} - \frac{5}{6}\right) + \frac{3m_Z^4}{64\pi^2}\left(\ln\frac{m_Z^2}{\mu^2} - \frac{5}{6}\right) - \frac{3m_t^4}{16\pi^2}\left(\ln\frac{m_t^2}{\mu^2} - \frac{3}{2}\right)$$

$$m_W^2 = \frac{g^2F^2}{4}\,, \qquad m_Z^2 = \frac{(g^2+g'^2)F^2}{4}\,, \qquad m_t^2 = \frac{y_t^2F^2}{2}$$

Quantum corrections

- Running:

$$16\pi^2\beta_\lambda = -6y_t^4 + \frac{3}{8}\left(2g^4 + \left[g^2 + g'^2\right]^2\right),$$

$$16\pi^2\beta_{y_t} = y_t\left(\frac{9}{2}y_t^2 - \frac{9}{4}g^2 - \frac{17}{12}g'^2 - 8g_s^2\right),$$

$$16\pi^2\beta_g = -\frac{19}{6}g^3, \quad 16\pi^2\beta_{g'} = \frac{41}{6}g'^3, \quad 16\pi^2\beta_{g_s} = -7g_s^3$$

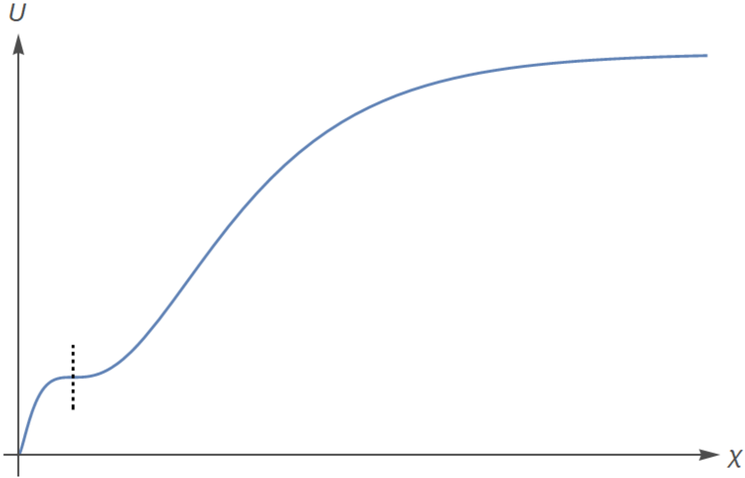
- Renormalization scale $\mu \sim \gamma F$ to minimize logarithm terms

Connection to accelerator physics

- $h \ll 1/\xi$: Standard Model
- $h \gg 1/\sqrt{\xi}$: Chiral Standard Model
- $1/\sqrt{\xi} \ll h \ll 1/\xi$: Corrections out of control!

- No direct way to connect low and high energy regimes. Parametrize this by effective "jumps" in λ and y_t

Fine-tuning: critical point



Critical point inflation

- Chance for production of primordial black holes
- Slow roll: perturbations amplified for $\epsilon_V \to 0$, since

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{V}{24\pi^2\epsilon_V}$$

Critical point inflation

- Near the critical point: slow-roll broken
- Instead, ultra slow roll (USR): $V' = 0$, so

$$\ddot{\chi} + 3H\dot{\chi} = 0$$

- Need to calculate perturbations numerically:

$$\mu_k'' + \left(k^2 - \frac{z''}{z}\right)\mu_k = 0\,, \qquad z \equiv a\frac{\dot{\chi}}{H}\,,$$

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2}\frac{|\mu_k|^2}{z^2}$$

PBH formation

- PBH fraction:

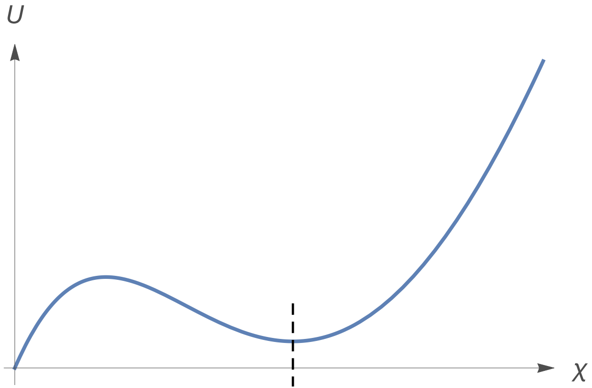
$$\Omega_{\mathrm{PBH\,eq}} \propto e^{-\frac{\zeta_c^2}{2\mathcal{P}_{\mathcal{R}}(k)}+\Delta N}$$

- To be significant, need $\mathcal{P}_{\mathcal{R}}(k) \gtrsim 10^{-4}$
- PBH mass:

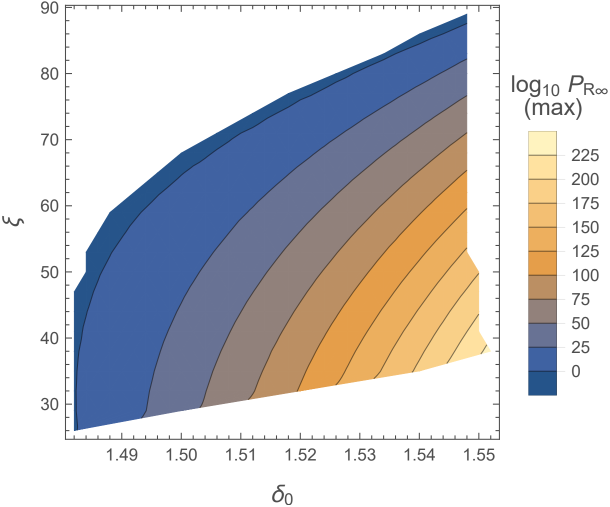
$$M_{\mathrm{PBH}} = \gamma \frac{4\pi}{3} H^{-3} \rho \approx 2 \times 10^{15} \times e^{-2\Delta N} M_{\odot}$$

PBH formation

- Most efficient production for a potential with a local minimum:

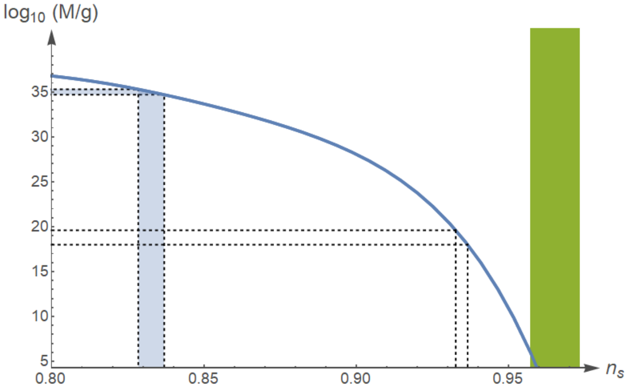


PBH formation: numerical scan



- Efficient PBH production!

PBH mass versus n_s

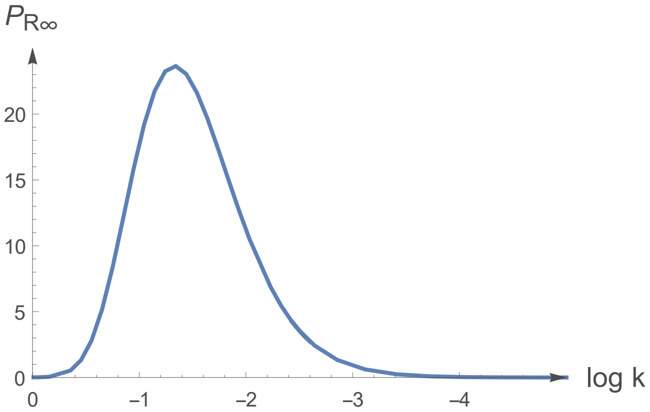


- Problem: need $M < 10^6$ g
- Evaporation by Hawking radiation!
- Planck mass relics?

Summary

- Higgs inflation can produce PBHs when quantum corrections are taken into account
- However, only very small PBHs are compatible with CMB observations
- These could evaporate into Planck mass relics and constitute all of dark matter

PBH numerics



PBH numerics