Planck scale black hole dark matter from Higgs inflation

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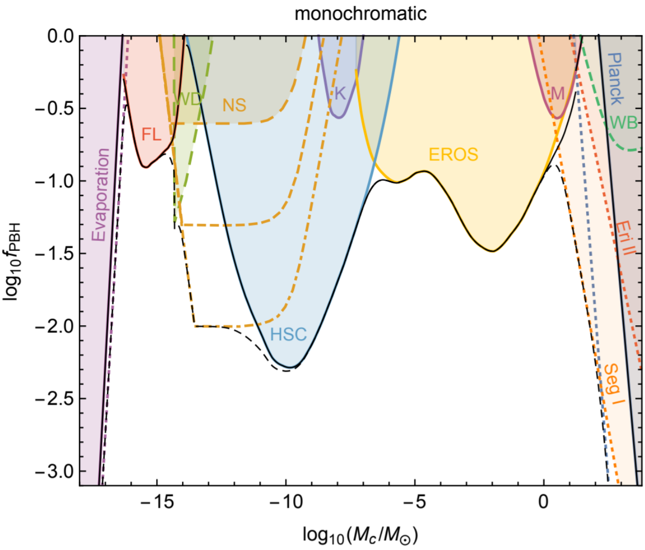
JCAP 1901 038, arXiv [1810.12608]

In collaboration with Syksy Räsänen

Primordial black holes (PBHs)

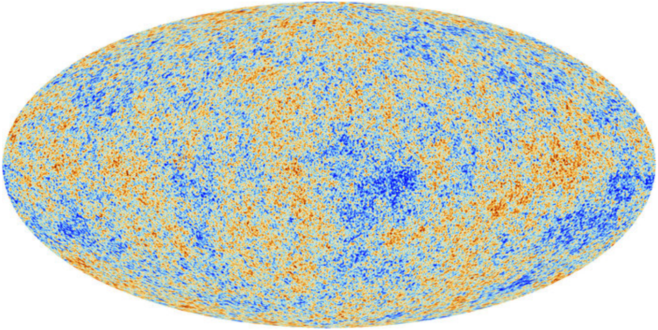
- Black holes formed in the early universe
- Dark matter candidate
- Observable by GW detectors?

PBHs as dark matter [1705.05567]



Origin of PBHs

- A possible origin: primordial density perturbations from cosmic inflation



PBHs from inflation

- PBHs from perturbations at scale k
- PBH mass:

$$M_{\mathrm{PBH}} = \gamma \frac{4\pi}{3} R^3 \rho \propto k^{-2}$$

- PBH abundance:

$$\Omega_{\mathrm{PBH\,eq}} = 5 \frac{\sqrt{2\mathcal{P}_{\mathcal{R}}(k)}}{\sqrt{\pi}\zeta_c} e^{-\frac{\zeta_c^2}{2\mathcal{P}_{\mathcal{R}}(k)} + \log\frac{k}{k_*}}$$

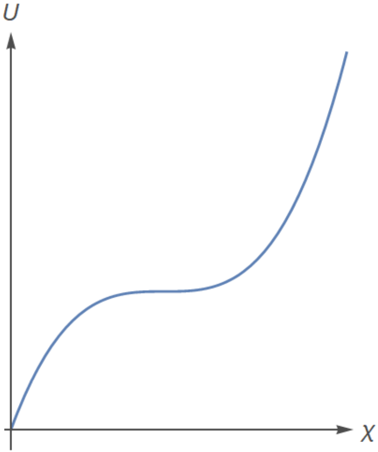
- Need $\mathcal{P}_{\mathcal{R}}(k) \gtrsim 10^{-4}$.

PBHs from inflation

- Slow-roll: $\mathcal{P}_{\mathcal{R}}(k) = \left.\frac{V}{24\pi^2\epsilon_V}\right|_{k=aH}$
- Large for $\epsilon_V \to 0$

PBHs from inflation

- Need potential with a feature:



Ultra-slow roll

- Near feature:

$$\ddot{\phi} + 3H\dot{\phi} + \underbrace{V'(\phi)}_{\to 0} = 0$$

$$\Rightarrow \eta_H \equiv -\frac{\ddot{\phi}}{H\dot{\phi}} \to 3 > 1$$

- Slow-roll approximation broken! Need to calculate $\mathcal{P}_{\mathcal{R}}(k)$ numerically: solve

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

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

Higgs inflation

- Standard Model Higgs, coupled non-minimally to gravity, drives cosmic inflation

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

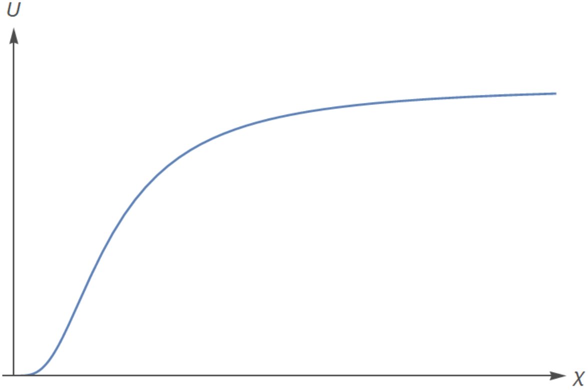
- Weyl transformation to Einstein frame:

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

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

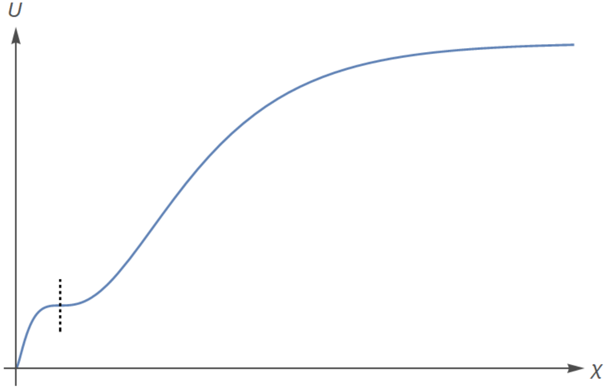
Higgs inflation

- Einstein frame potential:



- Compatible with Planck CMB results; in particular, $n_s = 0.9625 \pm 0.0048$ [1807.06211]

PBHs from a feature in the potential



- Feature from quantum corrections to effective potential

Quantum corrections

- Model is non-renormalizable
- At large field values, can use effective field theory: chiral SM
- Freedom in connecting this to electroweak scale physics (jumps in couplings)

Quantum corrections

- Quantum corrected potential with running couplings:

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

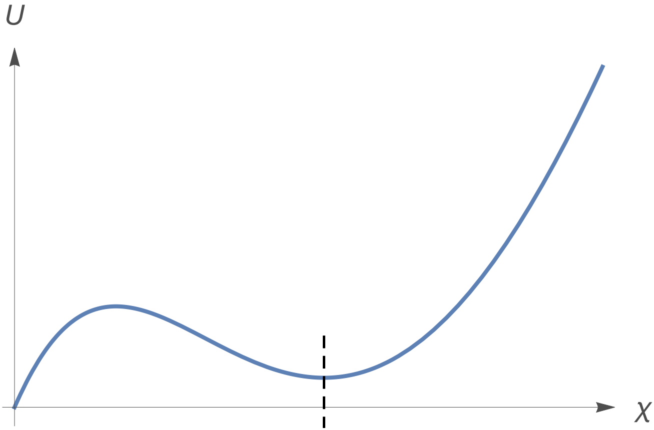
$$U_{tree} = \frac{\lambda}{4} F[h(\chi)]^4\,, \qquad F(h) \equiv \frac{h}{\sqrt{1+\xi h^2}}\,,$$

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

Quantum corrections

- Scan over all quantum-corrected potentials with a suitable feature
- Check PBH formation for them

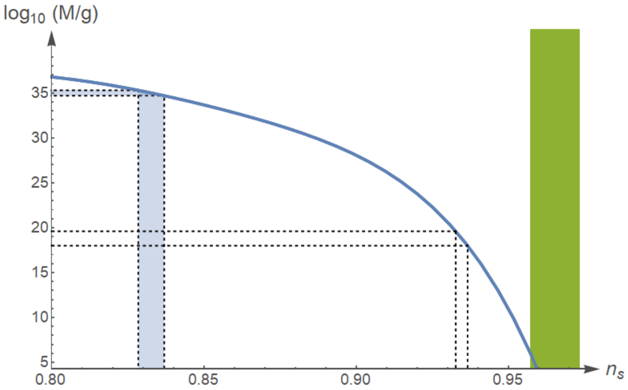
Results



- PBH abundance can be fine-tuned

Results

- PBH mass:



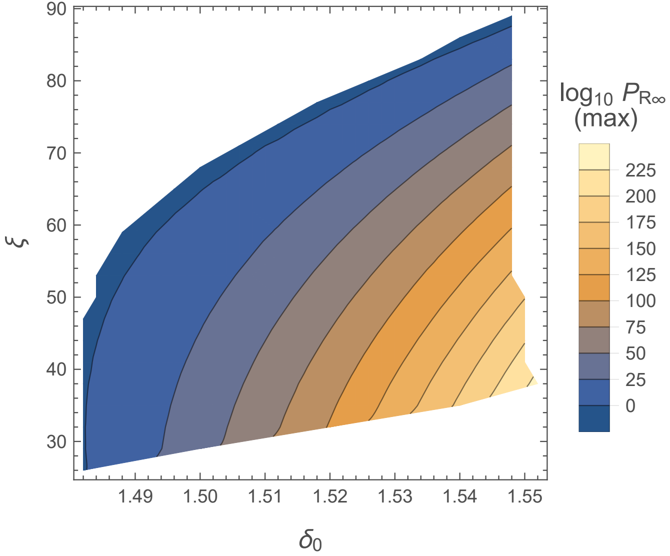
- Discrepancy between PBH limits and CMB measurements

Planck scale dark matter?

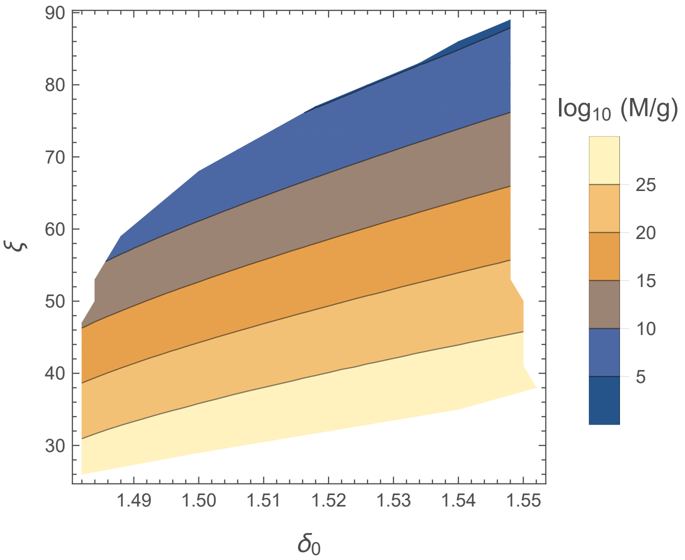
- In Higgs inflation, measured n_s is only compatible with small PBHs
- These evaporate quickly by Hawking radiation
- IF Planck mass relics left behind: these could constitute DM

Conclusions

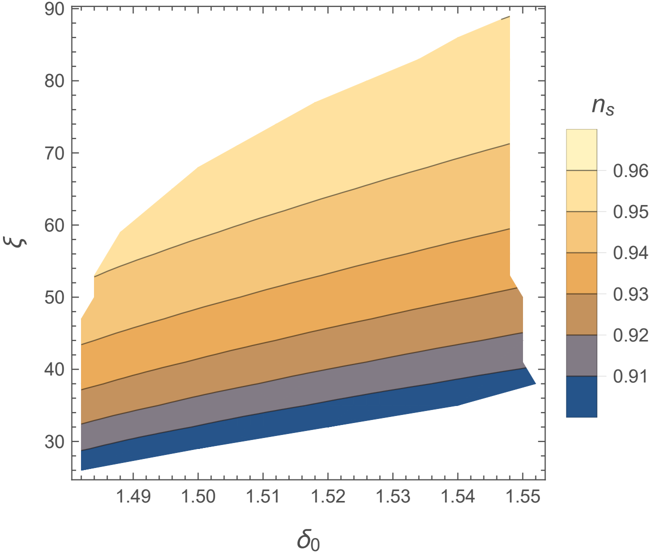
- PBHs can be produced abundantly in Higgs inflation
- Big black holes not compatible with CMB observations
- Planck mass relics as DM still possible

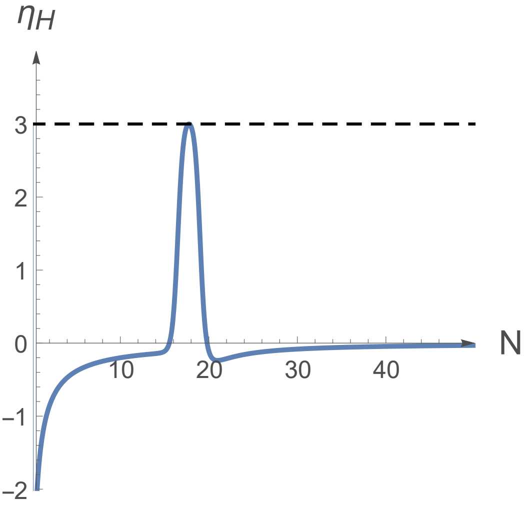


90
80
70
60
50
40
30
ξ
1.49
1.50
1.51
1.52
1.53
1.54
1.55
δ_0
$\log_{10} P_{R\infty}$ (max)
225
200
175
150
125
100
75
50
25
0

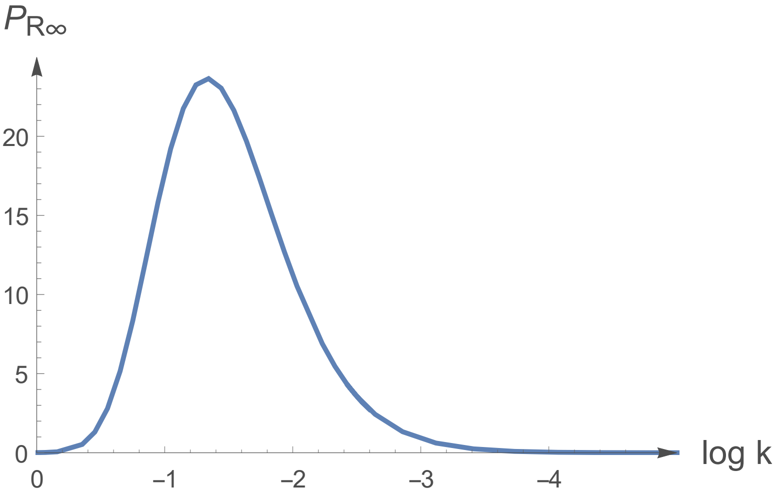


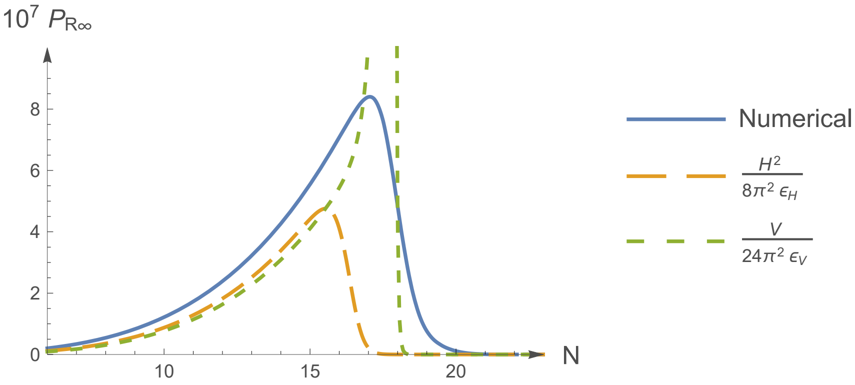
90
80
70
60
50
40
30
ξ
1.49
1.50
1.51
1.52
1.53
1.54
1.55
δ0
log10 (M/g)
25
20
15
10
5


90
80
70
60
50
40
30
1.49
1.50
1.51
1.52
1.53
1.54
1.55
ξ
δ_0
n_s
0.96
0.95
0.94
0.93
0.92
0.91



η_H
3
2
1
0
-1
-2
10
20
30
40
N


$P_{R\infty}$
20
15
10
5
0
0
−1
−2
−3
−4
log k



$10^7\ P_{R\infty}$
8
6
4
2
0
10
15
20
N
Numerical
$\frac{H^2}{8\pi^2\,\epsilon_H}$
$\frac{V}{24\pi^2\,\epsilon_V}$