Primordial black holes from 5th forces

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based on

F. Bezrukov, M. Pauly, J.Rubio, JCAP 1802 (2018) no.02, 040

L. Amendola, J. Rubio, C. Wetterich arXiv:1711.09915 (to appear in PRD RC)

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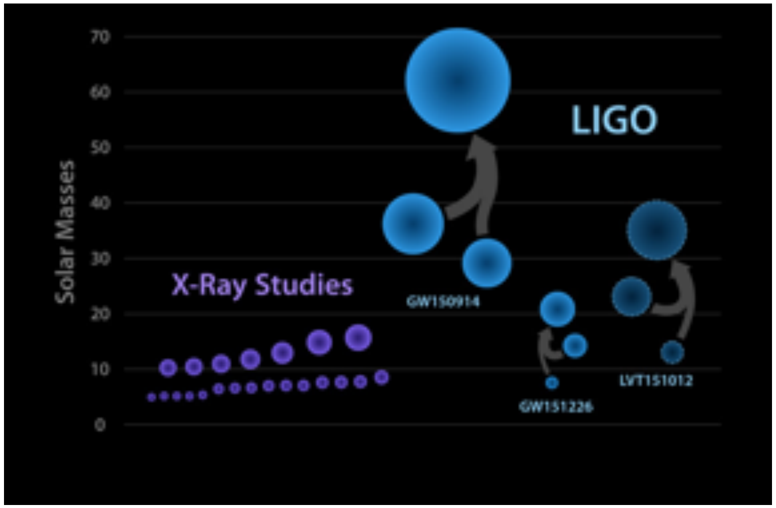
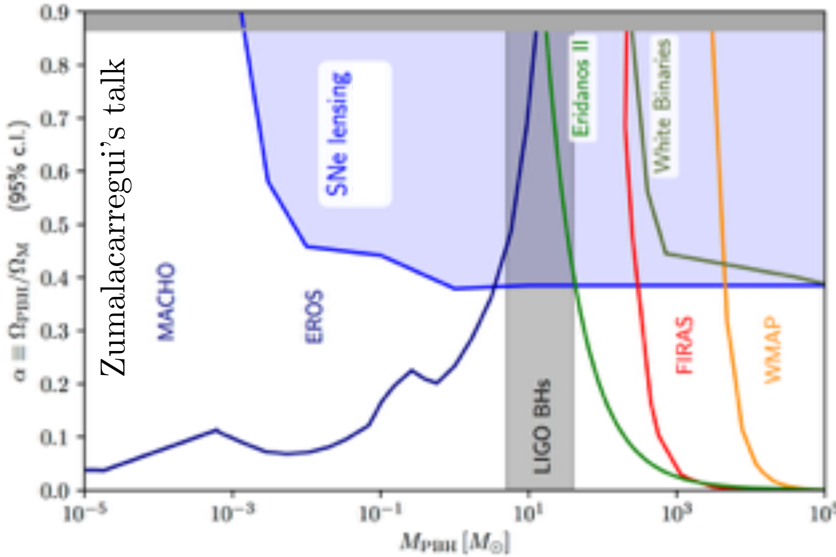
The revival of a rather old idea

LIGO observation of $\mathcal{O}(10)\ M_\odot$

Dark Matter candidate





Whether or not DM is primarily made out of PBHs, it is interesting to know if any of the BHs LIGO detected are primordial

PBH from inflation

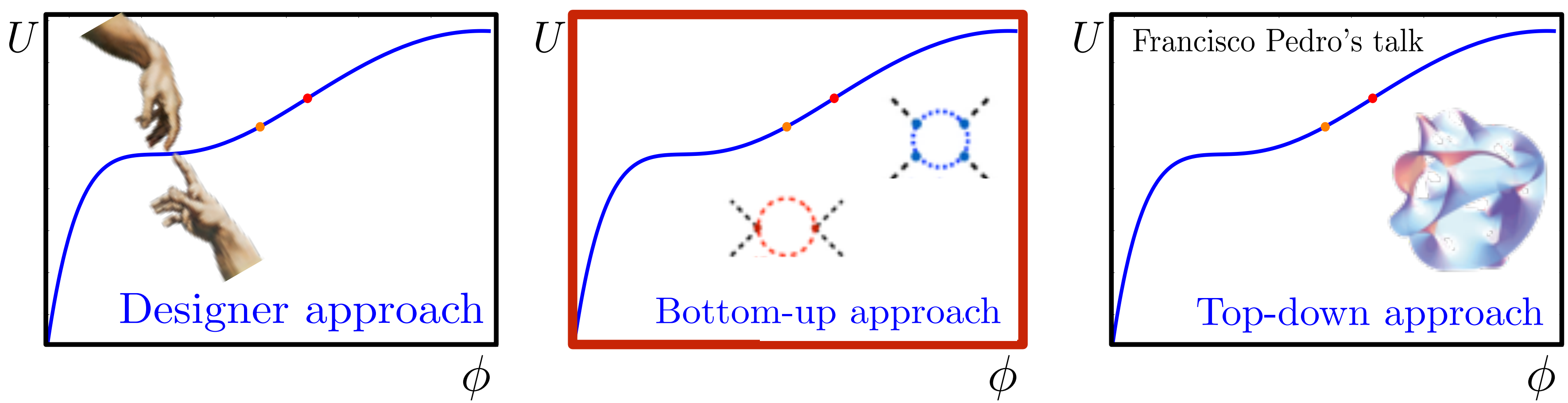
Most PBH production mechanisms are based on the generation of a non-trivial power spectrum during inflation

$$\mathcal{P}_{\mathcal{R}} \sim \frac{H^2}{\epsilon}$$

ultra slow-roll

During radiation domination an initially large ($\delta \sim 0.5$) density perturbation can collapse to form a PBH with mass of order of the horizon mass

Requires highly fine-tuned potentials
to generate the right enhancement at the right scales!



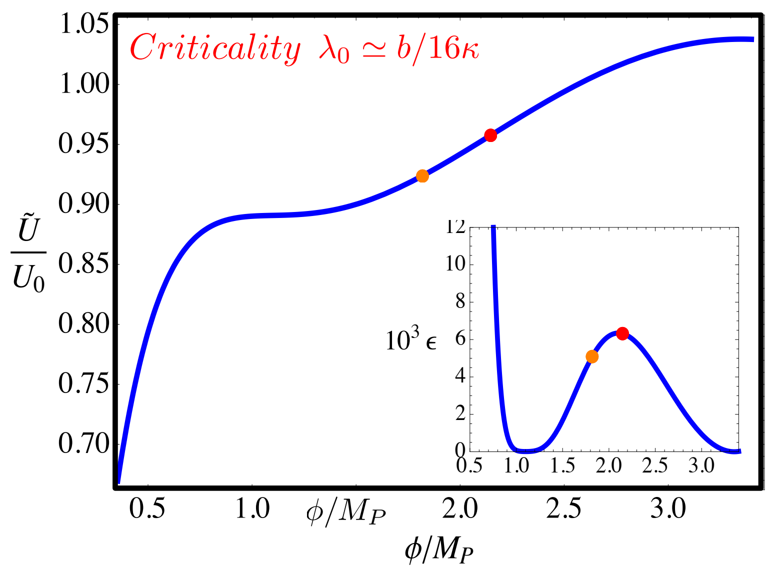
To generate PBH the spectrum should be enhanced by 7 orders of magnitude!

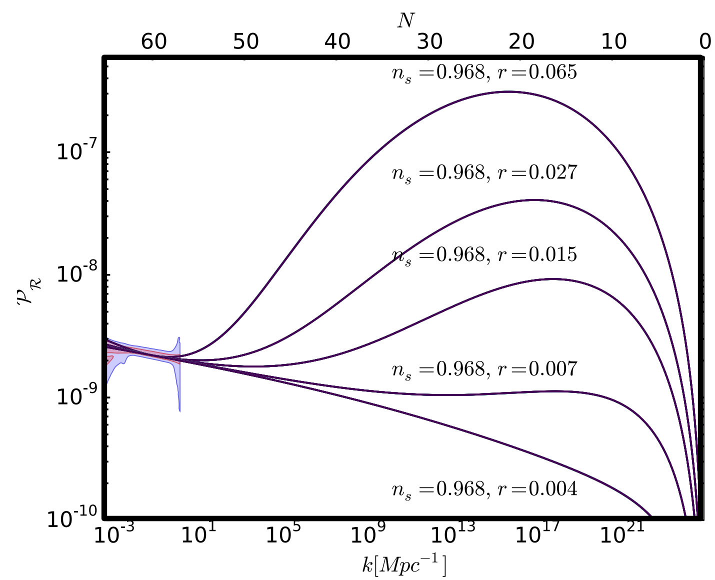
Higgs inflation

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2 + \xi_h h^2}{2} R - \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}(h^2 - v_{EW}^2)^2$$

Einstein frame

$$U(\phi) = \frac{\lambda(\phi) M_P^4}{4\xi_h^2}\left(1 - e^{-\frac{\sqrt{2/3}\phi}{M_P}}\right)^2 \quad \text{with} \quad \lambda(\phi) = \lambda_0 + b \log^2\left(\frac{\sqrt{\xi} F(\phi)}{\kappa M_P}\right)$$





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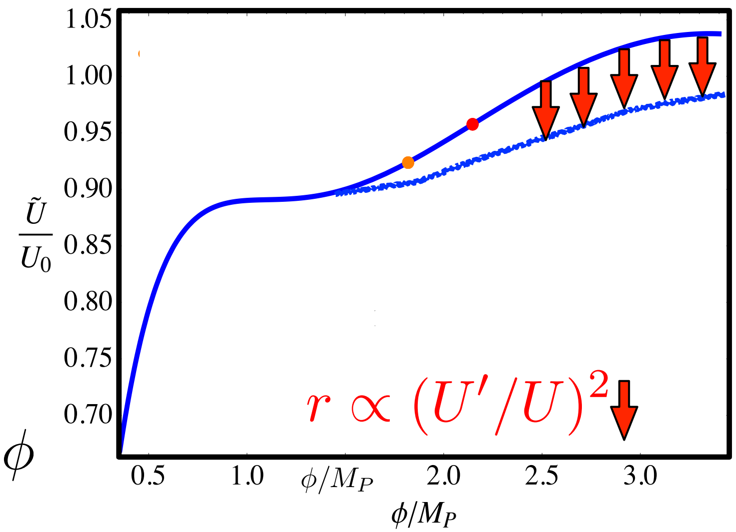
Larger peaks would be in conflict with CMB data

The ξ running trick

$$U(\phi) = \frac{\lambda(\phi) M_P^4}{4\xi_h^2}\left(1 - e^{-\frac{\sqrt{2/3}\phi}{M_P}}\right)^2$$

$$\xi_h = \xi_0 + b_\xi \log(\phi/\mu)$$

Softens the potential growth at large ϕ



PBH proposals

$$b_\xi \sim \mathcal{O}(10^{+2})!!$$

J. M. Ezquiaga, J. Garcia-Bellido, E. Ruiz Morales, Phys.Lett. B776 (2018) 345-349

G. Ballesteros, M. Taoso, Phys.Rev. D97 (2018) no.2, 023501

Standard Model

$$b_\xi \sim \pm\frac{g^2}{16\pi^2}\xi_h \sim \mathcal{O}(10^{-2})$$

F. Bezrukov, M. Pauly, J.Rubio, JCAP 1802 (2018) no.02, 040

PBH generation requires unrealistic running

An alternative paradigm

Long-range attractive interaction stronger than gravity

Ingredients

1. A scalar field with a mass smaller than the Hubble rate in some cosmological epoch after the end of inflation
2. Neutral particles(s) not involving (repulsive) interactions and being stable on the relevant time scales.

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \mathcal{L}_R - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + i\bar{\psi}\left(\gamma^\mu\nabla_\mu - m(\phi)\right)\psi\right]$$

Even the Higgs field could do the job!

Perfect fluid description

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = \frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi}$$

$$\dot{\rho}_\psi + 3H\,(\rho_\psi + p_\psi) = -\frac{\beta}{M_P}(\rho_\psi - 3p_\psi)\,\dot{\phi}$$

The coupling β measures the dependence of the mass on the field

$$\beta(\phi) = -M_P \frac{\partial \ln m(\phi)}{\partial \phi}$$

Note that β can be rather large. For a renormalizable interaction

$$m(\phi)\bar{\psi}\psi = m_0\bar{\psi}\psi + g\phi\bar{\psi}\psi \quad \Rightarrow \quad \beta(\phi) = -g\,M_P/m(\phi)$$

A small coupling g can be largely overwhelmed by the ratio $M_P/m(\phi)$

Growth of fluctuations

$$\delta_\psi'' + \left(1+\frac{\mathcal{H}'}{\mathcal{H}} - \frac{\beta\phi'}{M_P}\right)\delta_\psi' - \frac{3}{2}\left(Y\Omega_\psi\delta_\psi + \Omega_R\delta_R\right) = 0$$

$Y \equiv 1 + 2\beta^2$ Combined strength of the fifth force and gravity

Scaling solution in the $\beta \gg 1$ limit

$$Y \approx 2\beta^2$$

$$\Omega_\psi = \frac{1}{3\beta^2} \qquad \Omega_R = 1 - \frac{1}{2\beta^2}$$

$$\Omega_\phi = \frac{1}{6\beta^2} \qquad \phi' = M_P/\beta$$

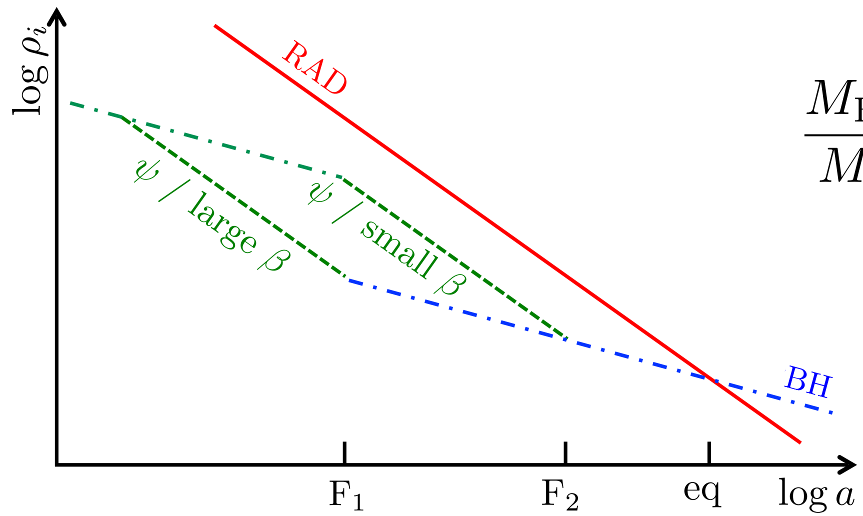
$$\delta_\psi'' - \delta_\psi' - \delta_\psi = 0 \quad \Rightarrow \quad \delta_\psi = \delta_{\psi,\mathrm{in}}\left(\frac{a}{a_{\mathrm{in}}}\right)^{\frac{1+\sqrt{5}}{2}}$$

The initial spectrum can be completely standard!

Black hole formation

Once formed PBH behave as NR matter

PBH remain stable even if the ψ particles outside them decay at a later stage



$$\frac{M_{\rm BH}}{M_\odot} = \frac{c}{3\beta^2}\left(\frac{H_{\rm eq}}{H_{\rm F}}\right)^2 = \frac{c}{27\beta^6\Omega^2_{\rm BH}(a_{\rm eq})}$$

with $\quad c \equiv \dfrac{M_{\rm eq}}{M_\odot} = 2.7\times 10^{17}$

Black hole dark matter?

$\Omega_{\rm BH}(a_{\rm eq}) = 1/2 \qquad\qquad M_{\rm max} \simeq \left(\dfrac{585}{\beta}\right)^6 M_\odot$

$\mathcal{O}(10)M_\odot$ PBH require a scalar field with mass $\lesssim 10^{-14}$ eV. Dark energy?

Conclusions

- ✓ Most PBH generation mechanisms require highly fine-tuned inflationary potentials
- ✓ They typically involve non-minimal coupling with unrealistic runnings

An alternative: PBH from 5th forces during RD

- ✓ Ingredients:
  1. Scalar field with a mass smaller than the Hubble rate
  2. Neutral particle(s) not involving (repulsive) interactions
  3. Attractive interaction stronger than gravity
- ✓ Advantages:
  1. Natural and ubiquitous ingredients of BSM extensions
  2. The initial power spectrum can be completely "standard"
- ✓ To be quantitative, a more refined analysis is needed:
  1. Reconsider spherical collapse in the presence of 5th force
  2. Determine critical density of collapse
  3. Account for merging & accretion effects
  4. Involved BSM scenarios may lead to non-monocromatic spectra

A plethora of scenarios

Scalar/Mediator field ϕ

Higgs field Seesaw scalar triplet	→	Early BH formation	→	Smaller PBH masses
Cosmon/quintessence field	→	Late BH formation	→	Larger PBH masses

Heavy particles ψ

Fermion (e.g seesaw heavy neutrino) Scalar	↔	stable (e.g. DM candidate) Decay after PBH formation