Primordial Black Holes as Dark Matter

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work in particular with
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Primordial Black Holes — Formation

★ Black-hole (BH) formation for $R < R_S$

★ Astrophysical: From $10^9 M_\odot$ down to $M_\odot$ but not lower.

★ Have a look at the density

$$\rho_S = 10^{18} \left( \frac{M}{M_\odot} \right)^{-2} \frac{g}{\text{cm}^3}$$

→ To form smaller black holes we need higher density

→ Compare to cosmological density

$$\rho_C = 10^6 \left( \frac{t}{\text{s}} \right)^{-2} \frac{g}{\text{cm}^3}$$

→ Formation at early times; primordial black holes (PBHs)

★ Masses of primordial black holes:

$$M(t = 10^{-45} \text{ s}) = M_{\text{Planck}},$$

$$M(t = 10^{-23} \text{ s}) = 10^{15} \text{ g}, \quad M(t = 10^{-6} \text{ s}) = M_\odot$$
**Formation** of primordial black holes by

- Cosmic string loops
- Bubble collisions
- Large density perturbations of inflationary origin

Simple estimate:

\[ R > R_J \quad \Rightarrow \quad \delta_H > \omega \quad , \quad \text{for} \quad \rho = \omega \rho \]
probe a huge range of scales:

- \( M \sim 10^{-5}\text{g} \) Quantum Gravity:
  Planck relics, Extra dimensions and higher-dimensional black holes, ...

- \( M \lesssim 10^{15}\text{g} \) Early Universe:
  Baryogenesis, Nucleosynthesis, Reionisation, ...

- \( M \sim 10^{15}\text{g} \) High-Energy Physics:
  Cosmological and galactic gamma-rays, ...

- \( M \gtrsim 10^{15}\text{g} \) Gravity:
  Critical phenomena, Cold dark matter, Lensing effects, Gravitational waves, Black holes in galactic nuclei, ...
Critical Collapse

★ Usually: Assume

\[ M_{BH} \propto M_H \]

horizon mass

★ Critical scaling:

[Choptuik '93]

\[ M_{BH} = k M_H (\delta - \delta_c)^\gamma \]
density contrast

★ Radiation domination:

\[ k \approx 3.3, \quad \delta_c \approx 0.45, \quad \gamma \approx 0.36 \]

[Miller et al. 2004]
How would this look for monochromatic mass function?

[Carr, FK, Sandstad 2016]
How would this look for monochromatic mass function?

It is simply impossible to get a monochromatic spectrum!

[Carr, FK, Sandstad 2016]
More Systematic Study

\[ \frac{df}{dM} = N \exp \left[ -\frac{(\log M - \log M_f)^2}{2 \sigma_f^2} \right] \]

[Green 2016]
We applied this to this constrain “curtain”:

![Graph showing extended mass spectra and constraints with labels for various mass categories like EG, F, WD, NS, ML, mLQ, PT, and K, along with logarithmic scales for mass (M/M⊙) and frequency (f). The graph is shaded to indicate regions of constraint, and references to FK, Freese 2017 are included.]
More Systematic Study — Results

Log$_{10} (f)$

Log$_{10}(M_f/M_\odot)$

[FK, Freese 2017]
It is crucial to re-derive the constraints for (the realistic(!) case) of extended mass functions!

$\log_{10}(f)$

$\log_{10}(M_f/M_\odot)$
Consider the simplest non-sphericity: An Ellipsoid
Non-Sphericity

\[
\delta_{ec} \approx 1 + \kappa \left( \frac{\sigma^2}{\delta_c^2} \right)^\gamma
\]

\[
\langle e \rangle = \frac{3 \sigma}{\sqrt{10\pi} \delta}, \quad \langle p \rangle = 0
\]

Simple estimate: As the collapse starts along shortest axis first, consider collapse of largest enclosed sphere (green curve):

\[
\frac{\delta_{ec}}{\delta_c} \approx (1 + 3e) = 1 + \frac{9}{\sqrt{10\pi}} \left( \frac{\sigma^2}{\delta_c^2} \right)^{1/2}
\]

[FK, Sandstad 2016]
★ Non-Sphericity

Non-Sphericity Effects

\[
\frac{\delta_{ec}}{\delta_{c}} \sim 1 + \kappa \left( \frac{\sigma^2}{\delta_c^2} \right)^\gamma
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Simple estimate: As the collapse starts along shortest axis first, consider collapse of largest enclosed sphere (green curve): 

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\frac{\delta_{ec}}{\delta_c} \sim (1 + 3e) = 1 + \frac{9}{\sqrt{10\pi}} \left( \frac{\sigma^2}{\delta_c^2} \right)^{1/2}
\]

Even slight non-sphericity reduces the abundance of PBHs significantly!
If PBHs constitute a significant fraction of the dark matter, at the center of our Galaxy one would have a very large number of PBH inspiralling into SgrA*.

Stochastic enhancement; Detection forecasts for LISA:

[FK, Freese, Starkman, Matas 2017]
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Stochastic enhancement; Detection forecasts for LISA:

LISA will be a splendid PBH dark-matter detection machine!*
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Stochastic enhancement; Detection forecasts for LISA:

LISA will be a splendid PBH dark-matter detection machine!*

*If there is a substantial fraction of macroscopic dark matter.

[FK, Freese, Starkman, Matas 2017]
Uncertainty due to non-sphericities and critical collapse:

AKRAMI, FK, SANDSTAD 2017

[Akrami, FK, Sandstad 2017]
Uncertainty due to non-sphericities and critical collapse:

The primordial power spectrum is essentially not constraint from current constraints on the PBH abundance!

[Akrami, FK, Sandstad 2017]
Conclusion

★ Primordial black holes are very interesting!

★ They are unique probes of their formation scenarios.

★ They could provide the entire dark matter.

★ A detailed understanding their formation is crucial.

★ Extended mass spectra require special care when comparing to constraints.

★ LISA might detect them!

★ Also, combined dark-matter scenarios (PBHs + WIMPs or sterile neutrinos) might be well constraint in the near future.