Welcome to our Session!
New Constraints on Primordial Black Holes as Dark Matter

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work in particular with
Bernard Carr
Katherine Freese
Jens Jasche
Pavel Naselsky
Tommy Ohlsson
Glenn Starkman
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

To form smaller black holes we need higher density

Compare to cosmological density

Formation at early times; primordial black holes (PBHs)

Masses of primordial black holes:

$$M(t = 10^{-23} \, \text{s}) = 10^{15} \, \text{g}, \quad M(t = 10^{-6} \, \text{s}) = M_\odot$$
PBH Formation Mechanisms

⭐ Formation of primordial black holes
Formation of primordial black holes by cosmic string loops

http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html
PBH Formation Mechanisms

★ Formation of primordial black holes by
  ★ Cosmic string loops
  ★ Bubble collisions

http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html
Formation of primordial black holes by

- Cosmic string loops
- Bubble collisions
- Pressure reduction
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More in Chris' talk
Formation of primordial black holes by

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Formation of primordial black holes by

- Cosmic string loops
- Bubble collisions
- Pressure reduction
- Large density perturbations

Simple estimate: [Carr 1975]

\[ R > R_J \quad \Rightarrow \quad \delta_H > \omega \] , \quad \text{for} \quad \rho = \omega \rho

scale of the over density

Jeans length
**Probe a huge range of scales:**

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Field</th>
<th>Examples</th>
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</thead>
<tbody>
<tr>
<td>$M \sim 10^{-5} \text{g}$</td>
<td>Quantum Gravity</td>
<td>Planck relics, Extra dimensions and higher-dimensional black holes, …</td>
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<tr>
<td>$M \lesssim 10^{15} \text{g}$</td>
<td>Early Universe</td>
<td>Baryogenesis, Nucleosynthesis, Reionisation, …</td>
</tr>
<tr>
<td>$M \sim 10^{15} \text{g}$</td>
<td>High-Energy Physics</td>
<td>Cosmological and galactic gamma-rays, …</td>
</tr>
<tr>
<td>$M \gtrsim 10^{15} \text{g}$</td>
<td>Gravity</td>
<td>Critical phenomena, Cold dark matter, Dynamical effects, Lensing effects, Gravitational waves, Black holes in galactic nuclei, …</td>
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</table>
Consider an example of primordial black holes constituting all of the dark matter:

- Mass range: $10^{20}$ g
- Size: $10^{-8}$ cm
- Number in our Galaxy: $10^{25}$
- Distance: 10 AU
\[ \propto \Omega_{\text{PBH}} \left|_{\text{form}} \right. \]

\[ \beta' \]

\[ \text{Note that} \]

\[ \rho_{\text{rad}} \propto a^{-4} \]

\[ \rho_{\text{PBH}} \propto a^{-3} \]

and hence

\[ \Omega_{\text{PBH}} \propto a \]
If PBHs do not constitute the entirety of the dark matter, the latter must necessarily contain something else.

One possibility: a combined scenario, e.g. DM = PBHs + Particles

Let us now study WIMP annihilations in PBH halos:

- The annihilation rate $\Gamma \propto n^2$.
- Halo profile does matter; enhancement of $\Gamma$ in density spikes.
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★ 1) We derive the density profile of the captured WIMPs

\[ m_\chi = 100 \text{ GeV} \]

- $\rho_{\text{c}}$ vs. $r/r_g$
  - $M_{\text{PBH}}/M_\odot$
    - $10^{-2}$
    - $10^{-5}$
    - $10^{-12}$
    - $10^{-18}$

[Boucenna, FK, Ohlsson, Visinelli 2018]
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1) We derive the density profile of the captured WIMPs, 
2) calculate the annihilation rate

$$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

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- The annihilation rate \( \Gamma \propto n^2 \).

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[Graph showing the density profile of captured WIMPs with annotations for EG, F, NS, K, ML, E, and W.]

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Primordial black holes are very interesting!

- They are unique probes of their formation scenarios.

- If PBHs do not constitute the entirety of the dark matter, the latter must necessarily contain something else, with combined dark-matter scenarios (PBHs + WIMPs) are amongst the most plausible ones.

- These scenarios (also those with sterile neutrinos) have distinct signatures and might be falsified or confirmed in the near future.