Stellar evolution constrains primordial black holes as dark matter candidates

M.S. Pshirkov\textsuperscript{1,2}, F. Capela\textsuperscript{3}, P.G. Tinyakov\textsuperscript{4}

\textsuperscript{1}Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetsky prospekt 13, 119992, Moscow, Russia
\textsuperscript{2}Institute for Nuclear Research of the Russian Academy of Sciences, 117312, Moscow, Russia
\textsuperscript{3}DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge, CB30WA, United Kingdom
\textsuperscript{4}Université Libre de Bruxelles, Service de Physique Théorique, CP225, 1050, Brussels, Belgium
PBHs as Dark Matter candidate

• Could be a viable alternative to particle dark matter

<table>
<thead>
<tr>
<th>PROS</th>
<th>CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Don’t need to alter extremely well-tested SM</td>
<td>• Very difficult to form ➔ very special density perturbation spectrum in the very Early Universe</td>
</tr>
<tr>
<td>• Very cold and collisionless* (*advantage at the moment)</td>
<td>• Extremely small cross-section: $\sigma \approx 10^{-56} ,(m/1g)^2 , \text{cm}^2$</td>
</tr>
<tr>
<td>• Dark</td>
<td></td>
</tr>
<tr>
<td>• Extremely small cross-section: $\sigma \approx 10^{-56} ,(m/1g)^2 , \text{cm}^2$</td>
<td></td>
</tr>
</tbody>
</table>
PBHs: their mass spectrum

• No specific mass scale (except, maybe, $M_{Pl} = 10^{-5}$ g)
• Due to the Hawking evaporation we could get rid of all PBH with $m < 10^{15}$ g

$$t_H = \frac{5120 \pi G^2 M_{BH}^3}{\hbar c^4} = 10^{64} \left( \frac{M}{M_{\text{Sun}}} \right)^3 \text{ years}$$

• At higher masses PBH could contribute to DM considerably

- $10^{17}$ g
- $10^{26}$ g

$\gamma$-rays from evaporation

? microlensing, CMB distortions, galactic disc survival, wide binaries, etc.

• $10^{17}$-$10^{26}$ g window remains mostly unconstrained
Closing the gap

- As stated above, PBHs are exceedingly small: 
  \[ r_{BH} = 10^{-8} \left( \frac{M_{BH}}{10^{20} \text{ g}} \right) \text{ cm} \]
- Could considerably interact only with extremely dense matter

- The best candidate – neutron stars (NSs) with \( \rho \sim 10^{15} \text{ g/cm}^3 \).

- If a PBH *somehow* get captured by a NS, the latter one would be destroyed in a very short time, less than \( 10^6 \) years – thus simple observations of NS could be constraining.
How to get PBH inside NS?

- There are two similar ways:
  A. Simple capture by NS itself
  B. multi-staged
    I. Formation of DM mini-halo during the star-formation process
    II. Capture of DM from that mini-halo
    III. Sinking of DM closer to the central regions of the star
    IV. Supernova explosion/NS formation. The NS would inherit some fraction of DM. That would result in constraints on fraction of PBH in DM.

- We will mostly discuss the second option.
DM mini-halo

- GMC ($M=10^5 M_\odot$, $\rho \sim 500 \text{ cm}^{-3}$) fragmenting into much smaller and denser prestellar cores ($M \sim M_\odot$, $\rho \sim 10^6 \text{ cm}^{-3}$)
- Some tiny fraction of the DM is gravitationally bound to PC:

$$\rho_{DM,\text{bound}} = \rho_{DM} \frac{4\pi}{3} \left( \frac{3|\phi_0|}{\pi v^2} \right)^{3/2}$$

- Effect $\sim$velocity dispersion$^{-3}$, $\sim$DM concentration $\Rightarrow$ interested in regions with high abundance of slow-moving DM
- The best candidate would be globular clusters of primordial origin – could form already at $z=10-12$
- The DM density could be as high as $10^4 \text{ GeV/cm}^{-3}$ in the very beginning, $v \sim 7 \text{ km/s}$.
- The effect is easily rescalable.
DM mini-halo. Adiabatic contraction

- Prestellar core undergoes process of contraction

- DM follows the gravitational pull and concentrates in the deepening gravitational well

- The process takes much longer than the free-fall time $t_{ff} \sim (G\rho)^{-1/2}$, so certain adiabatic invariants are conserved:
  - Angular momentum (central field)
    - $\int pdq = ET$

- That allows us to perform simulations: inject 30 millions test particles and evolve their orbits in the gravitational field of the gradually increasing central mass. Finally, we get some cuspy distribution $\rho(r) \sim r^{1.5}$
DM mini-halo. Adiabatic contraction

- Most of the particles reside on the very elongated orbits: there are much more particles that ever come within some $r$, than there within $r$ at any given moment.
- Enhancement factor is around $2 \times 10^3$ for $r=R_\odot$
- This could be a very large reservoir for DM – if we could only capture it effectively. Now everything is defined by DM-nucleon interactions
- From now on we would stick to one particular candidate – PBHs.
Capture of PBHs from mini-halo

• The capture proceeds in two stages:
  1. PBH spends most of its time outside the star, losing small fraction of its energy at each subsequent passage via dynamical friction

\[
t \sim 4 \times 10^2 \tau \sim \frac{100 \pi R_*^{5/2} v_{\text{esc}}^2}{Gm_{\text{BH}} \sqrt{GM_* \ln \Lambda}} \sim 2 \times 10^8 \text{ yrs} \left( \frac{10^{22} \text{ g}}{m_{\text{BH}}} \right)
\]

2. when the PBH is fully inside the star it starts to gradually lose energy and sink to the centre. The duration of this stage is considerably shorter

• If in the lifetime of the star \( N_{\text{BH}} \geq 1 \) PBHs of mass \( m_{\text{BH}} \) would sink to the centre, we would have some constraints:

\[
\frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \leq \frac{1}{N_{\text{BH}}}
\]
Constraints
Conclusions

• Mere observations of compact objects in regions with high DM density could considerably constrain PBH as the main DM constituent

• Observations of NSs in dwarf spheroidals would constrain PBHs in a broad $10^{20}-10^{24}$ g range

• If some old GCs are of primordial origin that would effectively rule out PBHs in $10^{16}-10^{25}$ g range ($\Omega_{\text{PBH}} \sim 1$), thus completely closing the last remaining possible window.
THANK YOU!
<table>
<thead>
<tr>
<th>$M_*/M_\odot$</th>
<th>$\rho_{\text{PSC}}$, GeV cm$^{-3}$</th>
<th>$M_{\text{bound}}$, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2 \times 10^1$</td>
<td>$4.4 \times 10^{19}$</td>
</tr>
<tr>
<td>2</td>
<td>$5.2 \times 10^1$</td>
<td>$2.5 \times 10^{20}$</td>
</tr>
<tr>
<td>3</td>
<td>$9.2 \times 10^1$</td>
<td>$7.2 \times 10^{20}$</td>
</tr>
<tr>
<td>4</td>
<td>$1.4 \times 10^2$</td>
<td>$1.5 \times 10^{21}$</td>
</tr>
<tr>
<td>5</td>
<td>$1.9 \times 10^2$</td>
<td>$2.6 \times 10^{21}$</td>
</tr>
<tr>
<td>6</td>
<td>$2.4 \times 10^2$</td>
<td>$4.2 \times 10^{21}$</td>
</tr>
<tr>
<td>7</td>
<td>$3 \times 10^2$</td>
<td>$6.2 \times 10^{21}$</td>
</tr>
<tr>
<td>8</td>
<td>$3.6 \times 10^2$</td>
<td>$8.7 \times 10^{21}$</td>
</tr>
<tr>
<td>10</td>
<td>$5 \times 10^2$</td>
<td>$1.6 \times 10^{22}$</td>
</tr>
<tr>
<td>12</td>
<td>$6.4 \times 10^2$</td>
<td>$2.4 \times 10^{22}$</td>
</tr>
<tr>
<td>15</td>
<td>$8.7 \times 10^2$</td>
<td>$4.3 \times 10^{22}$</td>
</tr>
</tbody>
</table>
Supplementary

\[ \rho_{\text{dm}} = 4 \cdot 10^2 \text{ GeVcm}^{-3} \]

\[ \rho_{\text{dm}} = 2 \cdot 10^3 \text{ GeVcm}^{-3} \]

\[ \rho_{\text{dm}} = 10^4 \text{ GeVcm}^{-3} \]