Primordial Black Holes as Silver Bullets for WIMPS

arXiv:1905.01238

Adam Coogan

With Gianfranco Bertone, Daniele Gaggero, Bradley Kavanagh, Christoph Weniger

TeVPA, 3 December 2019
What are Primordial Black Holes?

PBHs constrain compact DM structures such as primordial black holes or ultracompact DM miniholes. In view of this, and given that we have seen how different mass scales influence the limits, we expect the projected exclusion curves to also move upwards by a factor of 4. This is similar in shape to the ones for PBHs if the PBH mass is understood as the "equivalent black hole mass".

In computing our projected limits, we have assumed the redshift of all GRBs in the sample to be around 1. This assumption is similar to the one used for PBHs, with an uncertainty of around 200%. We moreover need to take into account the fact that the DM number density scales inversely with mass, hence we expect the projected exclusion curves to also move upwards by a factor of 4. This is similar to the one used for PBHs, with an uncertainty of around 200%.

Future femtolensing sensitivity to primordial black holes compared to other probes. In particular, we compare our projected limits (blue dashed contours) to limits based on extragalactic microlensing searches by Subaru HSC and OGLE. Figure 6 shows the comparison between the limits obtained with femtolensing and those obtained with other probes. The Subaru HSC limits are cut off at masses below that mass, the geometric optics approximation employed in ref. [13]. In computing our projected limits, we have assumed the redshift of all GRBs in the sample to be 1. This assumption is similar to the one used for PBHs, with an uncertainty of around 200%.
Primordial Black Holes (PBHs) form in the early Universe (\(t < 10^{-3} \text{ s}\)) from large over-densities of the CDM density. We have taken the limits shown here from the compilation in ref. [Carr and Hawking, MNRAS 168 (1974); Carr, Astrophys. J. 201, 1 (1975)].

Figure 6: Future femtolensing sensitivity to primordial black holes compared to other probes. In computing our projected limits, we have assumed the redshift of all GRBs in the sample to be \(z = 1\), from the non-destruction of white dwarfs (WD) and from CMB anisotropies due to PBH evaporation. We moreover need to take into account the fact that the DM number density in globular clusters is estimated. We have used the photoionization-bandpass (BAND) model for the GRB spectrum, and we have assumed a 5% systematic uncertainty, uncorrelated between energy bins.

The Subaru HSC limits are cut off at masses below that mass, the geometric optics approximation employed in ref. [S. Hawking, Mon. Not. R. Astron. Soc. 152, 75 (1971)]. (Stronger CMB limits are obtained if more aggressive assumptions on the PBH mass is understood as the “equivalent black hole mass” because of the third dependence on controversial assumptions about accretion by PBHs are adopted.) The Subaru HSC limits are cut off at masses below that mass, the geometric optics approximation employed in ref. [S. Hawking, Mon. Not. R. Astron. Soc. 152, 75 (1971)]. (Stronger CMB limits are obtained if more aggressive assumptions on the PBH mass is understood as the “equivalent black hole mass” because of the third dependence on controversial assumptions about accretion by PBHs are adopted.)

Note: The diagram shows the projected femtolensing exclusion limits on PBHs, compared to limits based on extragalactic microlensing (OGLE) and from microlensing searches by Subaru HSC. The limits are shown for PBH masses ranging from \(10^{-18}\) to \(10^{-6}\) solar masses, with the exclusion limits more stringent for lower masses. The limits are compared to constraints from other probes, including the CMB, and the diagram highlights the potential of femtolensing to constrain compact DM structures such as PBHs or ultracompact DM minihalos.
What are Primordial Black Holes?

To summarize, we have critically investigated the potential of gravitational femtolensing to constrain compact DM structures such as primordial black holes or ultracompact DM minihalos. In view of this, and given that we have seen how differences in the mass distributions of PBHs and UCMHs are adopted to be similar in shape to the ones for PBHs if the PBH mass is understood as the "equivalent black hole mass".

Future femtolensing sensitivity to primordial black holes compared to other probes. In particular, we compare our projected limits (blue dashed contours) to limits based on extragalactic microlensing searches by Subaru HSC, from the non-destruction of white dwarfs, 

Future femtolensing sensitivity to primordial black holes compared to other probes. In particular, we compare our projected limits (blue dashed contours) to limits based on extragalactic microlensing searches by Subaru HSC, from the non-destruction of white dwarfs, and from CMB anisotropies due to PBH evaporation.

PBH DM using femtolensing, we refrain from a more detailed sensitivity study for UCMHs. The Subaru HSC limits are cut off below that mass, the geometric optics approximation employed in ref. [Green & Liddle, astro-ph/9901268] is no longer valid. We thus shift to higher masses by a factor $4C_{\text{opt}}$ corresponding to a weakening of the limit by that factor.
Primordial black holes accumulate WIMP halos

High redshift

Low redshift
Thermal WIMP $\Rightarrow$ PBH constraint

In Fig. 3, we display density plots for the PBH fraction $f_{\text{PBH}}$ as a function of $m_x$ and $h v_i$ for the four above-mentioned values of $M_{\text{PBH}}$. The colored regions of these plots represent $f_{\text{PBH}}$ with the color scale indicating the value of $\log_{10} f_{\text{PBH}}$. White regions show areas in which the value of $f_{\text{PBH}} > 1$ and are therefore excluded. The hatched regions mark the areas of the WIMP parameter space that are excluded by the search of gamma rays from DM annihilation in dwarf satellite galaxies coming from the combined analysis of the Fermi and MAGIC telescopes [73] for the $b\bar{b}$ channel. This bound assumes that WIMPs account for the total DM of the Universe and is therefore only valid for $f_{\text{PBH}} \sim 1$, otherwise it should be properly rescaled for the considered value of $f_{\text{PBH}}$. We show it to illustrate the interplay between the WIMP indirect-detection bounds and $f_{\text{PBH}}$. Figure 4 provides the maximal value of $f_{\text{PBH}}$ for each WIMP parameter pair $m_x$ and $h v_i$. 

References:
- arXiv:1003.3466
- arXiv:1607.00612
- arXiv:1901.08528
- arXiv:1712.06383
PBH detection $\Rightarrow$ WIMP constraint
PBH detection $\Rightarrow$ WIMP constraint

1. Detection scenario: $M_{\text{PBH}}, N_{\text{PBH}}$
PBH detection $\Rightarrow$ WIMP constraint

1. Detection scenario: $M_{\text{PBH}}, N_{\text{PBH}}$

2. Infer PBH abundance $f_{\text{PBH}}$
PBH detection $\Rightarrow$ WIMP constraint

1. Detection scenario: $M_{PBH}, N_{PBH}$

2. Infer PBH abundance $f_{PBH}$

3. For WIMP model, constrain $\langle \sigma v \rangle$ with $\gamma$-ray observations
1. Detection scenarios
1. Detection scenarios

• *LIGO O3* detects $M_{\text{PBH}} = 0.5 \, M_\odot$ merger
1. Detection scenarios

- *LIGO O3* detects $M_{\text{PBH}} = 0.5 \, M_\odot$ merger
  - Why PBHs? $M_{\text{PBH}} < 1.4 \, M_\odot$ (Chandrasekhar limit)
1. Detection scenarios

- *LIGO O3* detects $M_{\text{PBH}} = 0.5 \, M_\odot$ merger
  - Why PBHs? $M_{\text{PBH}} < 1.4 \, M_\odot$ (Chandrasekhar limit)

- *Einstein Telescope* detects $z \geq 40$, $M_{\text{PBH}} = 10 \, M_\odot$ merger
1. Detection scenarios

- **LIGO O3** detects $M_{\text{PBH}} = 0.5 \ M_\odot$ merger
  - Why PBHs? $M_{\text{PBH}} < 1.4 \ M_\odot$ (Chandrasekhar limit)

- **Einstein Telescope** detects $z \geq 40$, $M_{\text{PBH}} = 10 \ M_\odot$ merger
  - Why PBHs? Astrophysical BHs form and merge at lower redshifts
1. Detection scenarios

- *LIGO O3* detects $M_{\text{PBH}} = 0.5 \, M_\odot$ merger
  - Why PBHs? $M_{\text{PBH}} < 1.4 \, M_\odot$ (Chandrasekhar limit)

- *Einstein Telescope* detects $z \geq 40$, $M_{\text{PBH}} = 10 \, M_\odot$ merger
  - Why PBHs? Astrophysical BHs form and merge at lower redshifts

$p(f_{\text{PBH}}|N_{\text{PBH}})$: depends on $\int dz$ (merger rate) $\times$ (sensitivity)
1. Detection scenarios
1. Detection scenarios

- *Square Kilometer Array* detects radio emission from gas accretion by \(100 \, M_\odot\) galactic PBHs
1. Detection scenarios

- *Square Kilometer Array* detects radio emission from gas accretion by $100 \, M_{\odot}$ galactic PBHs
  
  - Requires complex, multiwavelength population analysis
1. Detection scenarios

- **Square Kilometer Array** detects radio emission from gas accretion by $100 \, M_\odot$ galactic PBHs

- Requires complex, multiwavelength population analysis

**Compute $p(f_{\text{PBH}}|N_{\text{PBH}})$ with Monte Carlo simulation**
2. Detection \(\rightarrow\) abundance

Number of observed PBH candidates, \(N_{PBH}\)

PBH fraction \(f_{PBH}\)

LIGO O3, \(M_{PBH} = 0.5 M_\odot\)

ET \((z \geq 40)\), \(M_{PBH} = 10 M_\odot\)

SKA, \(M_{PBH} = 100 M_\odot\)
3. Ann. rate around PBH

WIMP halo around 30 M⊙ PBH

\[ \delta_{\text{phy}} + 1 \]

\[ r_{\text{phy}} [\text{kpc/h}] \]

arXiv:1901.08528
3. Ann. rate around PBH

WIMP halo around 30 M\(\odot\) PBH

Analytic estimate:
\[ \rho(r) \propto r^{-9/4} \]
3. Ann. rate around PBH

WIMP halo around 30 M\(_\odot\) PBH

Density cutoff

Analytic estimate:
\[ \rho(r) \propto r^{-9/4} \]
3. Ann. rate around PBH

WIMP halo around 30 M⊙ PBH

Density cutoff

Analytic estimate: \( \rho(r) \propto r^{-9/4} \)

Can now compute gamma-ray flux from PBH’s halo
3. Point source $\gamma$-ray limits

**Constraint:** PBH halos as $\gamma$-ray *galactic point sources*
3. Point source $\gamma$-ray limits

**Constraint:** PBH halos as $\gamma$-ray *galactic point sources*

Monte Carlo procedure
3. Point source $\gamma$-ray limits

**Constraint:** PBH halos as $\gamma$-ray *galactic point sources*

**Monte Carlo procedure**
1. Place PBHs in Milky Way
3. Point source $\gamma$-ray limits

**Constraint:** PBH halos as $\gamma$-ray *galactic point sources*

**Monte Carlo procedure**
1. Place PBHs in Milky Way
2. Assess detectability
3. Point source γ-ray limits

**Constraint:** PBH halos as γ-ray galactic point sources

**Monte Carlo procedure**
1. Place PBHs in Milky Way
2. Assess detectability
3. Point source γ-ray limits

**Constraint:** PBH halos as γ-ray *galactic point sources*

**Monte Carlo procedure**
1. Place PBHs in Milky Way
2. Assess detectability
3. Point source $\gamma$-ray limits

**Constraint:** PBH halos as $\gamma$-ray *galactic point sources*

**Monte Carlo procedure**
1. Place PBHs in Milky Way
2. Assess detectability
3. **Limit:** require $N_{p.s.} < 19$
3. Point source $\gamma$-ray limits

**Constraint:** PBH halos as $\gamma$-ray galactic point sources

**Monte Carlo procedure**
1. Place PBHs in Milky Way
2. Assess detectability
3. **Limit:** require $N_{p.s.} < 19$

Number of 3FGL unassociated sources compatible with DM annihilation
3. Extragalactic $\gamma$-ray limits

**Constraint:** diffuse $\gamma$ rays from *extragalactic* PBH halos
3. Extragalactic γ-ray limits

Constraint: diffuse γ rays from extragalactic PBH halos
3. Extragalactic γ-ray limits

**Constraint:** diffuse γ rays from *extragalactic* PBH halos

**Ingredients:**
3. Extragalactic γ-ray limits

**Constraint:** diffuse γ rays from *extragalactic* PBH halos

**Ingredients:**
- *Ann. rate* in PBH halo
3. Extragalactic γ-ray limits

**Constraint:** diffuse γ rays from *extragalactic* PBH halos

**Ingredients:**
- *Ann. rate in PBH halo*
- *Cosmological PBH density*
3. Extragalactic γ-ray limits

**Constraint:** diffuse γ rays from extragalactic PBH halos

**Ingredients:**
- Ann. rate in PBH halo
- Cosmological PBH density
- Attenuation
3. Extragalactic γ-ray limits

**Constraint:** diffuse γ rays from *extragalactic* PBH halos

**Ingredients:**
- Ann. rate in PBH halo
- Cosmological PBH density
- Attenuation
- Redshifting
3. Extragalactic \( \gamma \)-ray limits

**Constraint:** diffuse \( \gamma \) rays from *extragalactic* PBH halos

**Limit:** for each bin, require \( \phi \lesssim \phi_{\text{obs}} + 3 \Delta \phi_{\text{obs}} \)

**Ingredients:**

- *Ann. rate* in PBH halo
- *Cosmological* PBH density
- Attenuation
- Redshifting
3. Extragalactic $\gamma$-ray limits

**Constraint:** diffuse $\gamma$ rays from *extragalactic* PBH halos

**Limit:** for each bin, require $\phi \lesssim \phi_{\text{obs}} + 3 \Delta \phi_{\text{obs}}$

**Ingredients:**
- Ann. rate in PBH halo
- Cosmological PBH density
- Attenuation
- Redshifting

Robust constraint with few assumptions
PBH detection $\implies$ WIMP constraint
$0.5 \, M_\odot$ merger, LIGO O3

$\frac{f_\chi}{(\sigma v)_0} (\text{cm}^3/\text{s})$ vs. $m_\chi$ (GeV)

- Thermal relic
- Preferred region for MSSM7
- $N_{O3} = 1$
- $N_{O3} = 80$
- Unitarity
0.5 $M_\odot$ merger, LIGO O3

Thermal relic

Preferred region for MSSM7

$N_{O3} = 1$

Unitarity

$N_{O3} = 80$
$0.5 \, M_\odot$ merger, LIGO O3

Preferred region for MSSM7

Thermal relic

Unitarity

N_{O3} = 1

N_{O3} = 80

$f_\chi^4 (\sigma v)_0 \, (\text{cm}^3/\text{s})$

$m_\chi \, (\text{GeV})$
10 M⊙ z≥40 merger, Einstein Telescope

Thermal relic
Preferred region for scalar singlet model

\[ N_{ET} = 1 \]
\[ N_{ET} = 24000 \]

Unitarity
10 M⊙ z ≥ 40 merger, Einstein Telescope

<table>
<thead>
<tr>
<th>m(GeV)</th>
<th>n/cm³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

Thermal relic

Preferred region for scalar singlet model

$N_{ET} = 1$

$N_{ET} = 24000$

$f_\chi < 0.1$

Unitarity
100 $M_\odot$, radio detections at SKA

$N_{SKA} = 10$

$N_{SKA} = 80$

Thermal relic

Unitarity

Envelope of various BSM models
Envelope of various BSM models

100 M⊙, radio detections at SKA

Thermal relic

Ensemble of various BSM models

\[ f_x < 0.1 \]
Conclusion

The figure shows the thermal relic abundance $f_{\chi}^4(\sigma v)_0$ in units of $(\text{cm}^3/\text{s})$ as a function of the mass $m_\chi$ (GeV) for different values of $N_{ET}$ and $N_{SKA}$. The thermal relic line is indicated by the dashed horizontal line. The green and blue lines represent $N_{ET} = 1$ and $N_{ET} = 24000$, respectively, with $N_{SKA} = 10$ and $N_{SKA} = 80$. The orange line represents $N_{ET} = 80$, $N_{SKA} = 10$, and $N_{O3} = 1$, while the grey and dark grey shaded regions indicate the area between $N_{O3} = 1$ and $N_{O3} = 80$. The black diagonal line represents the unitarity condition. The leftmost boundary of the dark grey region corresponds to the $N_{ET} = 1$ curve, and the $N_{ET} = 24000$ curve is shifted to the left by a factor of $10^3$. The rightmost boundary of the grey shaded region corresponds to the $N_{ET} = 1$ curve, and the $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3$. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3. The $N_{ET} = 24000$ curve is shifted to the right by a factor of $10^3. The $N_{ET} = 24000$ curve is shifted to
Conclusion

- Even one PBH detection would rule out standard thermal WIMPs
Conclusion

• Even one PBH detection would rule out standard thermal WIMPs

• Also would constrain any BSM model with a WIMP, even if it’s under-abundant
Conclusion

- Even one PBH detection would rule out standard thermal WIMPs
- Also would constrain any BSM model with a WIMP, even if it’s under-abundant

Thank you!