# Improved Constraints on Dark Matter Annihilations around Primordial Black Holes

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arXiv: 2209.07541
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# Primordial Black Holes (PBH)

- Early universe leads to the formation of primordial black holes (Y. B. Zel'dovich and I. D. Novikov (1967), S. Hawking (1971), B. J. Carr and S. Hawking (1974), B. J. Carr (1975)). The hypothesis is that the gravitational collapse of the density fluctuations produced in the early universe results into the formation of PBHs.
- There are rich literaure discussing alternative scenarios for formation of PBHs.
- Note: PBHs are formed in the early universe and therefore can avoid constraints from big bang nucleosynthesis (BBN). Unlike astrophysical black holes who are born from death of a star (baryons), and therefore are subject to BBN constraint.
- Formation of 'particle DM' halos around the PBHs may lead to observable gamma-ray signals as a result of dark matter self annihilations. (**Mack et al. 2007; Ricotti et al. 2007, 08; Ricotti & Gould 2009; Scott & Sivertsson 2009**)

# PBH and Particle Dark Matter

The current observations suggest for $f_{\rm PBH} \neq 1$; one good possibility is that the DM is comprised of both the PBH and particle dark matter ($\chi$).

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm PBH} + \Omega_\chi}.$$

Thermal WIMP cross-section expansion:

$$\langle \sigma v \rangle = \sigma_s + \frac{3}{2} x^{-1} \sigma_p + \frac{15}{8} x^{-2} \sigma_d + \cdots ,$$

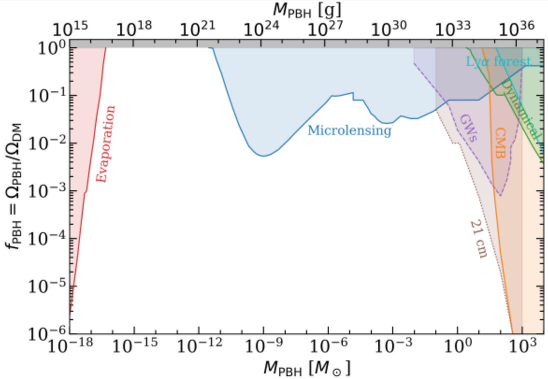
$x = m_\chi / T$ is the scaled temperature.

- s-wave: $\sigma_s \neq 0$. For $f_{\rm PBH} \to 0$, $\Omega_\chi h^2 = 0.12$, $\sigma_s \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$.
- p-wave: $\sigma_p$ is the leading term, $\langle \sigma v \rangle \propto v^2$.
- d-wave: $\sigma_d$ is the leading term, $\langle \sigma v \rangle \propto v^4$.

# The s-wave: Black holes and WIMPs can't coexist

- "Primordial Black Holes as Dark Matter: Almost All or Almost Nothing", Lacki & Beacom (2010).
- "WIMPs and stellar-mass primordial black holes are incompatible", Adamek et al. (2019): For DM mass $10 - 10^3$ GeV, $f_{\rm PBH} \lesssim 10^{-9}$.
- "Black Holes and WIMPs: All or Nothing or Something Else", Carr et al. (2020), arXiv: 2011.01930v4.

# Present limits on PBH abundance




Villanueva-Domingo et al. (2103.12087)

# Dark Matter density profile around PBH

$$\rho(\tilde{r}) = \frac{8}{\tilde{r}} \int_0^\infty d\beta_i \beta_i \int_0^\infty d\tilde{r}_i \tilde{r}_i \rho_i(\tilde{r}_i) f(\beta_i, \tilde{r}_i) \left(\frac{1}{\tilde{r}_i} - \beta_i^2\right)^{3/2} \int_{\sqrt{\mathcal{Y}_m}\Theta(\mathcal{Y}_m - 0)}^{1} \frac{dy}{\sqrt{y^2 - \mathcal{Y}_m}}$$

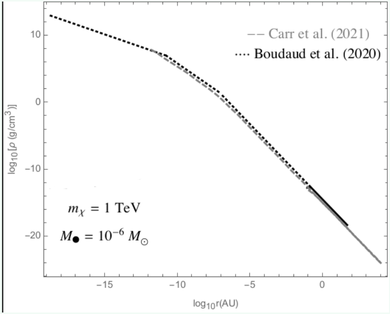
$f(\beta_i, \tilde{r}_i)$ is the fraction of dark matter particles with velocities between $\beta_i$ and $\beta_i + \mathrm{d}\beta_i$ given by

$$4\pi\beta_i^2 \mathrm{d}\beta_i f(\beta_i, \tilde{r}_i) = \frac{4\pi\beta_i^2}{(2\pi\sigma_i^2)^{3/2}} \exp\left(-\frac{\beta_i^2}{2\sigma_i^2}\right) \mathrm{d}\beta_i$$

$$\mathcal{Y}_m = 1 + \frac{\tilde{r}^2}{\tilde{r}_i^2}\left[\frac{1}{\beta_i^2}\left(\frac{1}{\tilde{r}_i} - \frac{1}{\tilde{r}}\right) - 1\right], \qquad \tilde{r} = r/r_{\mathrm{Sch}}, \qquad r_{\mathrm{Sch}} = 2GM_\bullet/c^2.$$

**Boudaud et al. (2021), arXiv: 2106.07480v2**

# Dark Matter density profile around PBH




$$\rho(r) \sim \begin{cases} r^{-3/4} & r < r_A \\ r^{-3/2} & r_A < r < r_B, \\ r^{-9/4} & r_B < r < r_C, \\ 0 & r > r_C \end{cases}$$

**Eroshenko et al. (2016), arXiv: 1607.00612v2**

**Boudaud et al. (2021), arXiv: 2106.07480v2**

**Carr et al. (2021), arXiv: 2011.01930v4**

# Effect of DM self-annihilation

The core density of the DM halo near the PBH will be affected by dark matter annihilations and, therefore, will deplete the high density core.

The annihilation rate is: $\Gamma_{\rm ann} \sim n_\chi \langle \sigma v \rangle$,

The annihilations results into a maximum core density

$$\rho_{\rm Max} \sim m_\chi n_\chi \sim \frac{m_\chi \Gamma_{\rm ann}}{\langle \sigma v \rangle} \sim \frac{m_\chi}{\langle \sigma v \rangle t_{\rm halo}}.$$

$t_{\rm halo} \sim 10^{10}$ years.
Expanded thermally averaged cross-section

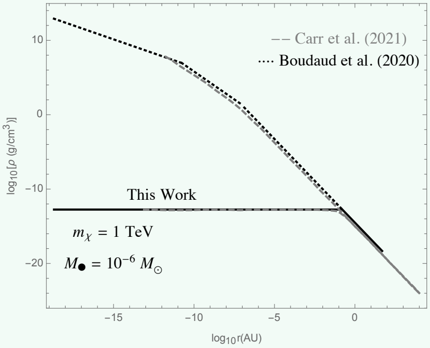
$$\langle \sigma v \rangle = \sigma_s + \sigma_p \frac{3}{2x} + \sigma_d \frac{15}{8x^2} + \cdots ,$$

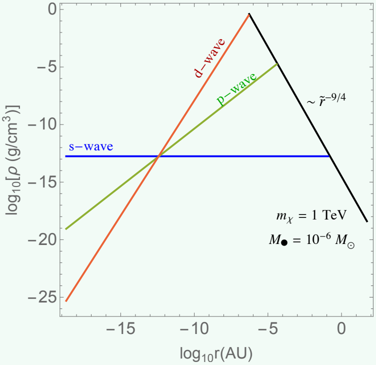
which can be velocity dependent.
The velocity changes radially as

$$v(r) \simeq \sqrt{GM_\bullet / r}.$$

# Effect of DM self-annihilation

In the s-wave scenario the core density is a constant profile. For velocity dependent cross-section the density core changes radially.

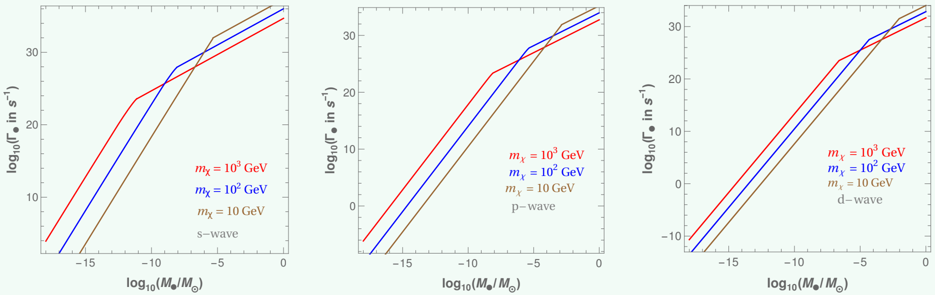


# DM Annihilation rate

The annihilation rate is calculated as

$$\Gamma_\bullet = \int dr \; r^2 \left( \frac{\rho(r)}{m_\chi} \right)^2 \langle \sigma v \rangle .$$



# Constraints on the Annihilation Rate

The extragalactic $\gamma$-ray flux provides with the strongest constraints,

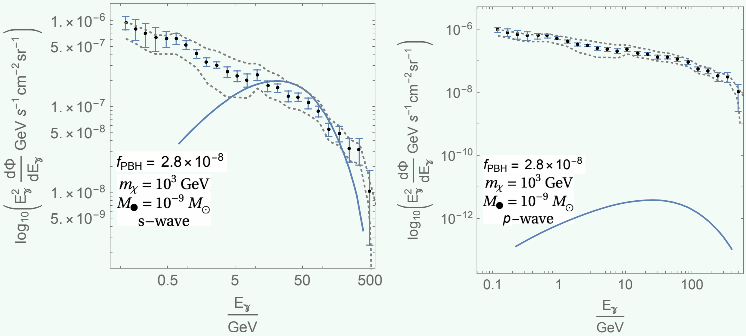
$$\left.\frac{d\Phi_\gamma}{dEd\Omega}\right|_{\mathrm{ExGal}} = \int_0^\infty dz \, \frac{n_{\mathrm{PBH}}}{8\pi H_0} \frac{\hat{\Gamma}_\bullet(z) e^{-\tau(z,E)}}{h(z)} \frac{dN_\gamma}{dE}; \qquad h(z) = H(z)/H_0$$

$\tau(z, E) \rightarrow$ Optical depth (Cirelli et al. [1012.4515])
$\frac{dN_\gamma}{dE} \rightarrow$ Energy distribution

$\hat{\Gamma}_\bullet(z)$ is redshift dependent annihilation rate; hence, $\hat{\Gamma}_\bullet(z=0) = \Gamma_\bullet$.
Turns out approximately we can parameterize $\hat{\Gamma}_\bullet(z) = \Gamma_\bullet h^x(z)$.

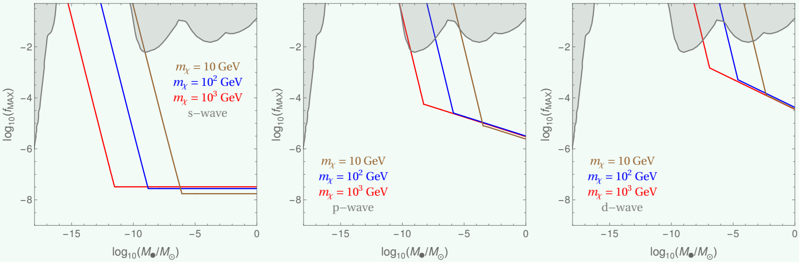
$$\hat{\Gamma}_\bullet^L \propto \begin{cases} 1 + \mathcal{O}(\log[h(z)]) & s-\mathrm{wave} \\ h^{2/5}(z) & p-\mathrm{wave} \\ h^{4/7}(z) & d-\mathrm{wave} \end{cases}, \qquad \hat{\Gamma}_\bullet^H \propto \begin{cases} h^{2/3}(z) & s-\mathrm{wave} \\ h^{10/13}(z) & p-\mathrm{wave} \\ h^{14/17}(z) & d-\mathrm{wave} \end{cases}.$$

# Extragalactic Differential Flux



# Limits on the Fractional Abundance $f_{PBH}$

Velocity dependent cross-section shows significant promises



# Mixed s- and p-wave

$$\langle \sigma v \rangle = \sigma_s + \sigma_p \frac{3}{2x} + \sigma_d \frac{15}{8x^2} + \cdots ,$$

'Pure p-wave': $\sigma_s = 0, \sigma_p \neq 0$.

'Mixed s- and p-wave': $\sigma_s \neq 0, \sigma_p \neq 0$, with the s-wave being suppressed by a factor $\mathcal{F}$.

loop factor suppression

$$\mathcal{F}_{\rm loop} \sim g^2/16\pi^2$$

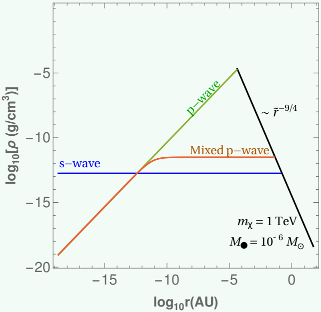
chirality flip

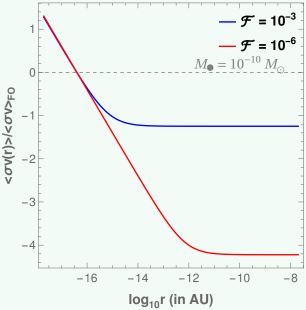
$$\mathcal{F}_{\rm chiral} \sim \left(\frac{m}{m_\chi}\right)^2$$

$$v(r) = \sqrt{\frac{G}{r}\left(M_\bullet + M_{\rm halo}(r)\right)}$$

# Mixed s- and p-wave

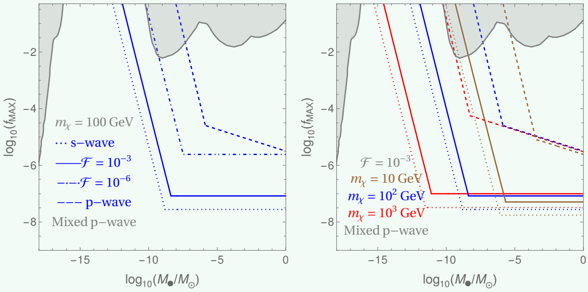
As the velocity varies radially the supressed s-wave dominates after a characteristic radius



# Mixed s- and p-wave

It shows that p-wave models with a supressed s-wave have limits close to s-wave models



## Conclusions

- The p-wave and d-wave case helps in amelioration of the bounds on $f_{\mathrm{PBH}}$, making those very interesting scenarios.
- Notably, the p-wave freeze-out scenario is very common in the Beyond Standard Model scenario.
- For p-wave and d-wave dark matter with non-zero s-wave contribution, we observe s-wave behavior beyond a characteristic radius.

# Thank You!