Dark matter around primordial black holes

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The 7th International Conference on Particle Physics and Astrophysics
October 22-25, 2024, National Research Nuclear University “MEPhI”

Primordial black holes (PBHs)

The principal possibility of the primordial black holes (PBHs) formation in the early universe:

- *Zeldovich, Y.B.; Novikov, I.D. The Hypothesis of Cores Retarded during Expansion and the Hot Cosmological Model. Sov. Astron.* **10***, 602 (1967). [Astron. Zh.* **43***, 758 (1966).]*
- *Hawking S., "Gravitationally collapsed objects of very low mass", Mon. Not. R. Astron. Soc.* **152***, 75 (1971).*

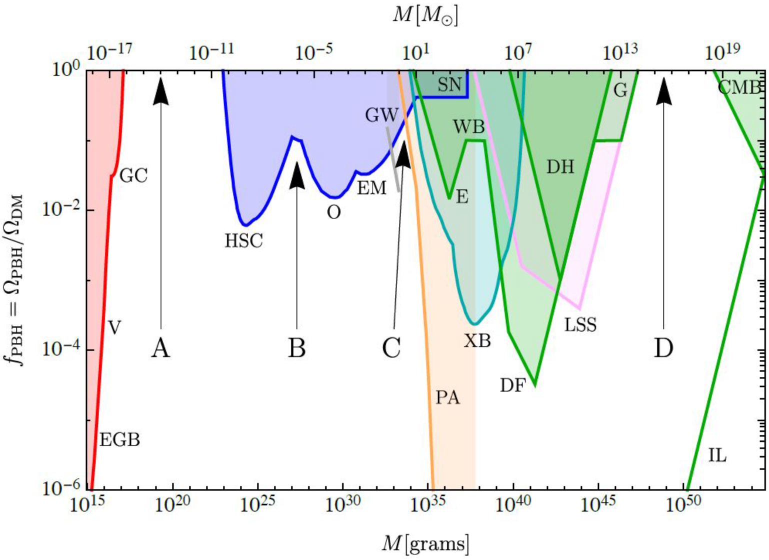
Possible mechanisms

- collapses of adiabatic density perturbations *(Carr, Hawking 1974)*, *(Carr 1975)*
- early dust-like stages *(Khlopov, Polnarev 1980)*, *(Zabotin, Naselskii, Polnarev 1987)*
- collapses of domain walls *(Berezin, Kuzmin, Tkachev 1983)*, *(Khlopov, Konoplich, Rubin, Sakharov 1998)*, *(Khlopov, Rubin, Sakharov 2005)*
- baryon charge fluctuations *(Dolgov, Silk 1993), (Dolgov, 2018)*
- collapses of cosmic strings loops *(Hawking, 1989)* or cusps *(Jenkin, Sakellariadou 2020)*

Possible observational signatures

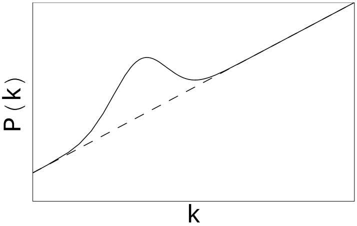
- gamma-ray bursts from evaporating PBHs
- PBHs as dark matter
- gas accretion on PBHs and x-ray radiation
- PBHs in galactic nuclei
- It is possible that some of the LIGO/Virgo events are explained by the merge of PBHs *(Nakamura, Sasaki, Tanaka, Thorne 1997)*, *(Sasaki et al. 2016)*, *(Dolgov, Postnov 2020)*

Constraints



(Carr, Kuhnel, arXiv:2110.02821)

The value of density perturbations that are necessary for the formation of a PBH can be achieved due to the presence of features in the inflationary potential *(Starobinsky 1992)*, *(Ivanov, Naselsky, Novikov 1994)*, as well as in inflationary models with several scalar fields *(Yokoyama 1995)*.



$$\delta_{\rm H} \sim M_{\rm Pl}^{-3} V^{3/2}/(dV/d\phi)$$

$\delta_{\rm H}$ rises if $dV(\phi)/d\phi \to 0$

Kinetic decoupling

Mass of DM

$$t_{\rm H} \simeq \frac{GM_{\rm H}}{c^3} = 2.6 \times 10^{-13} \left(\frac{M_{\rm BH}}{10^{-8} M_{\odot}} \right) \text{ s.}$$

Temperature of the kinetic decoupling of neutralinos with masses $m \simeq 70$ GeV

$$T_d \simeq 27 \left(\frac{m}{70 \text{ GeV}} \right)^{1/4} \left(\frac{\tilde{M}}{0.2 \text{ TeV}} \right) \left(\frac{g_*}{10} \right)^{1/8} \text{MeV}$$

which occurs at a time

$$t_d \simeq 10^{-3} \left(\frac{m}{70 \text{ GeV}} \right)^{-1/2} \left(\frac{\tilde{M}}{0.2 \text{ TeV}} \right)^{-2} \left(\frac{g_*}{10} \right)^{-3/4} \text{s,}$$

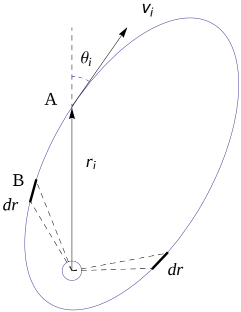
where $\tilde{M}$ is the supersymmetry parameter

If $M_{\rm BH} < 40 M_{\odot}$, then the kinetic decoupling of neutralinos occurs after the PBH formation.

Formation of density spike

Velocity distribution of DM far from PBH

$$f(\vec{v})d^3v = m^{3/2}(2\pi kT)^{-3/2}e^{-\frac{mv^2}{2kT}}d^3v$$



$$E < 0, \quad r_{\rm min} = a(1-e) \le r \le r_{\rm max} = a(1+e)$$

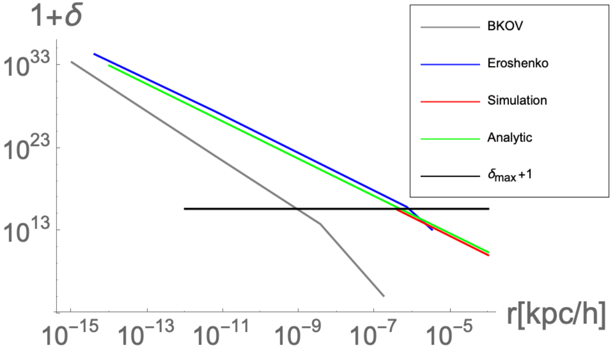
$$\rho(r)4\pi r^2 dr = \int 4\pi r_i^2 dr_i \rho_i(r_i) \int d^3v f(v) \frac{2(dt/dr)}{T_{\rm orb}} dr,$$

where the derivative dt/dr is found from the equation of motion

Density profile in spike

If one neglects the contribution of thermal velocities to the total energy of the particles, then

$$\rho(r) \simeq (\rho_{\rm eq}/2) t_{\rm eq}^{3/2} (2GM)^{3/4} r^{-9/4}$$



(Adamek, Byrnes, Gosenca, Hotchkiss 2019)

Common constraints on the PBHs and DM

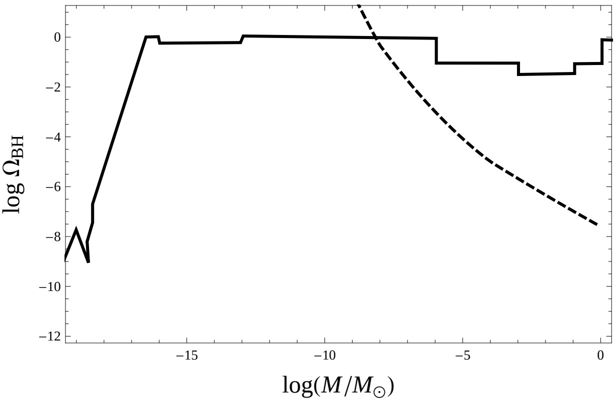


Figure: The solid curve indicates the known upper bounds on the cosmological PBH density parameter $\Omega_{\rm BH}$ from Carr et al. (2010). The dashed curve indicates the constraints based on the DM particle annihilation effect obtained here.

History of density spike study around PBHs

- Incompatibility of the model with a large number of PBHs with sufficiently large masses and annihilating DM, but density profile $\rho \propto r^{-3/2}$ was assumed *(Lacki, Beacom 2010)*
- Primordial black hole as a source of the boost factor *(Saito, Shirai 2011)*
- Basic equations describing the density profile: *(Saito, Matsumoto, Shirai, Yanagida 2011)*
- Annihilation of DM in density spikes *(Dong 2011)*
- Structure of the density spike, residual thermal velocities of DM particles *(Eroshenko 2016)*
- The calculation method has been significantly improved in *(Boucenna, Kuhnel, Ohlsson, Visinelli 2018)*
- Profile close to $\rho \propto r^{-9/4}$ was obtained by numerical modelling *(Adamek, Byrnes, Gosenca, Hotchkiss 2019)*
- The issue of compatibility of PBHs and annihilating DM with a wide range of possible parameters *(Carr, Kuhnel, Visinelli 2021)*
- Analytical expression $\rho \propto r^{-9/4}$ in the limit of zero thermal velocities *(Ireland 2024)*

Annihilation plateau

The maximum density of DM from the condition $\rho\langle\sigma_{\rm ann} v\rangle t_0/m \sim 1$ *(Berezinsky, Gurevich, Zybin 1992)*, *(Silk, Stebbins 1993)*. Central plateau with the constant DM density

$$\rho_{\rm max} \simeq \frac{m}{\langle\sigma_{\rm ann} v\rangle t_0} \sim 10^{-14} \left(\frac{m}{70\ \mathrm{GeV}}\right) \times \tag{1}$$

$$\times \quad \left(\frac{\langle\sigma_{\rm ann} v\rangle}{3 \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}}\right)^{-1} \left(\frac{t_0}{1.36 \times 10^{10}\ \mathrm{yrs}}\right)^{-1}\ \mathrm{g\ cm}^{-3},$$

where $\langle\sigma_{\rm ann} v\rangle$ is the annihilation cross section, t_0 is the age of the universe.

In the plateau region, the DM density should have fallen to the value of $\rho_{\rm max}$ by now.

However, this approach is not sufficient to calculate the structure of the transition region for elongated orbits.

Distribution of DM particles by orbital parameters $f = f(t, E, L^2)$ *(Vasiliev 2007)* !!!

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \vec{r}}\dot{\vec{r}} + \frac{\partial f}{\partial \vec{v}}\dot{\vec{v}} = -f\,\langle \sigma_{\rm ann} v\rangle n(t,r),$$

where $n(t,r) = \int f d^3v$

$$\frac{\partial f}{\partial \vec{r}}\dot{\vec{r}} + \frac{\partial f}{\partial \vec{v}}\dot{\vec{v}} = 0, \quad \frac{\partial f}{\partial t} = -f\,\langle \sigma_{\rm ann} v\rangle n(t,r).$$

$$(r,\vec{v}) \to (E,L) \quad n(t,r) = \int\limits_{E_{\rm min}} dE' \int\limits_{L_g} dL' \frac{4\pi L'}{r^2 v_r} f(t,E',L'^2),$$

where radial velocity $v_r(E',L') = 2^{1/2}\left(E' + GM/r - L'^2/2r^2\right)^{1/2}$

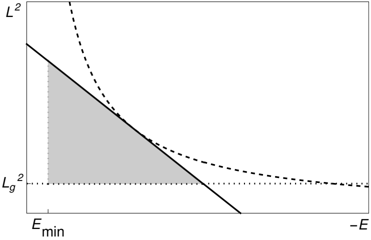


Figure: Lindblad diagram.

Integrate along the orbit

$$\frac{\partial f(t,E,L)}{\partial t} = -\frac{2f\left\langle\sigma_{\rm ann}v\right\rangle}{T_{\rm orb}}\int\limits_{r_{\rm min}}^{r_{\rm max}} n(t,r)\frac{dr}{v_r},$$

where $r_{\rm min}$ and $r_{\rm max}$ are the roots of the equation $v_r = 0$,

$$T_{\rm orb} = \frac{\pi GM}{2^{1/2}|E|^{3/2}}$$

Initial distribution function

$$f(t, E, L^2) = \varkappa_1 \varepsilon^{1/4} e^{-l^2/l_m^2(\varepsilon)},$$

where

$$\varkappa_1 = \frac{\rho_d t_d^{1/2}}{2^{3/4}\pi^2 k_{\mathrm{B}} T_d (GMr^*)^{1/4}},$$

$$l_m^2(\varepsilon) = \varkappa_2 \varepsilon^{-1/2}, \quad \varkappa_2 = \frac{2^{5/2} k_{\mathrm{B}} T_d t_d}{m(GMr^*)^{1/2}}.$$

$\varkappa_1 = 4.6 \times 10^{-28}$, $\varkappa_2 = 4.5 \times 10^{-8}$ cm^{-6} s^3
Dimensionless units, $r^* = 0.1 r_{\mathrm{eq}}$, $x = r/r^*$, $\nu(x) = n(r) r^{*3}$,
$\phi = f(GMr^*)^{3/2}$, $\tau = t/t_0$

$$\rho(r) = 1.5 \times 10^{-19} \left(\frac{r}{r^*}\right)^{\gamma} \text{ g cm}^{-3},$$

where $\gamma \approx -2.37$. The density at $r \simeq r^*$ is about 2.4 times less than follows from the expression

$$\rho(r) \simeq 1.5\rho_d \left(\frac{r}{r_d}\right)^{-9/4},$$

obtained in *(Ireland 2024)* for the same radius. On the contrary, our expression at $r \simeq r^*$ is about 3.7 times larger than the expression

$$\rho(r) \simeq (\rho_{\rm eq}/2)t_{\rm eq}^{3/2}(2GM)^{3/4}r^{-9/4},$$

given in *(Adamek, Byrnes, Gosenca, Hotchkiss 2019)*

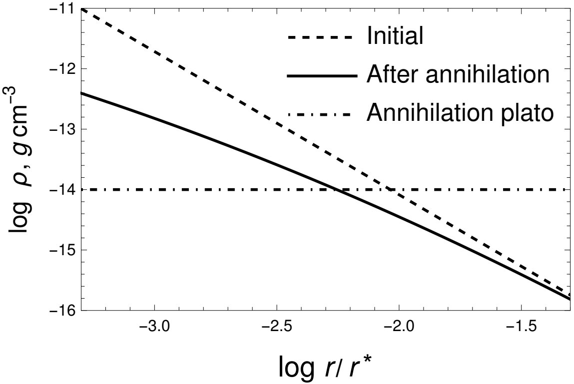


Figure: DM density at the spike around a PBH, taking into account particle annihilation (solid curve) in comparison with the initial density profile (dashed curve) and the "annihilation plateau" $\rho \sim 10^{-14}$ g cm^{-3} (dot-dashed curve). The exponent at the left is ≈ -0.7.

Conclusion

- At the cosmological stage of radiation dominance, dark matter density spikes should form around primordial black holes;
- In the case when dark matter particles are able to annihilate, the density in the central regions of the spikes decreases due to the elimination of particles;
- This effect leads to the modification of the central density profile;
- The orbits in spike around a primordial black hole are very elongated, and the angular momentum distribution has an exponential form;
- For such an initial distribution function, it is obtained that a cusp with the exponent ≈ -0.7 is formed in the central region, instead of an annihilation plateau;
- The presence of the cusp provides some correction to the rate of dark matter annihilation around primordial black holes.

Thank you for attention!