Observational phenomena on black hole with dark matter dress

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KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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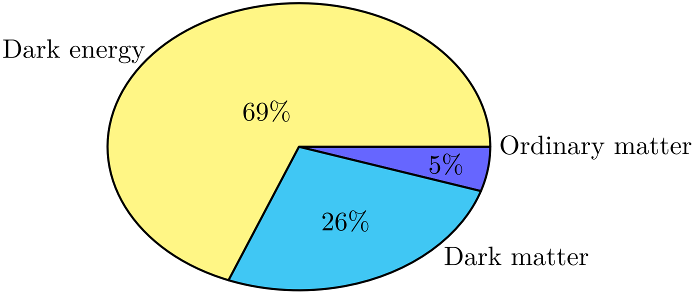
K. Kadota, J. H. Kim, P. Ko, XYY [2306.10828]
R.-G. Cai, T. Chen, S.-J. Wang, XYY [2210.02078] JCAP 03 (2023) 043
R.-G. Cai, Y.-C. Ding, XYY, Y.-F. Zhou [2007.11804] JCAP 03 (2021) 057

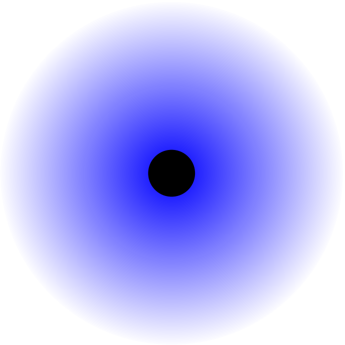


Black hole + Dark matter $\Rightarrow$

Characteristic phenomena $\Leftarrow$

$\Downarrow$

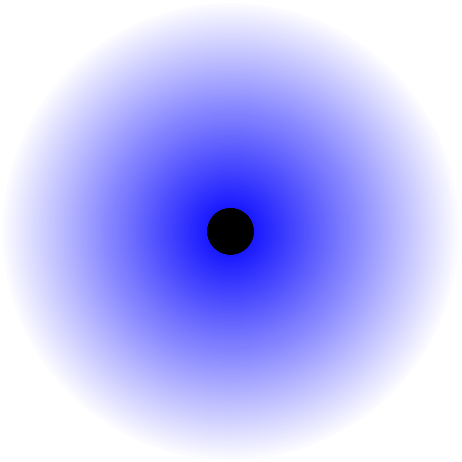
Nature of dark matter



Gravitational waves

K. Kadota, J. H. Kim, P. Ko, XYY [2306.10828]

- ΛCDM is an extremely successful model for the large scale structure of the Universe, corresponding to distances greater than $\mathcal{O}$(Mpc) today.
- On small scales, there are several discrepancies between CDM predictions and observations.
  - Core–cusp problem
  - Diversity problem
  - Missing satellites problem
  - Too-big-to-fail problem
- Self-interacting dark matter is proposed as a promising alternative to collisionless CDM.
  - Solving problems of CDM model.
  - Many dark matter models can give strong self-interaction.

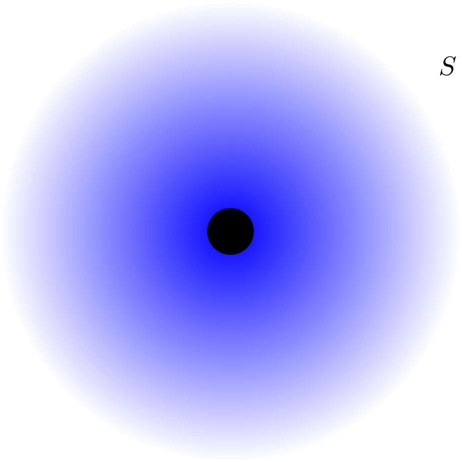


Black hole + Cold dark matter

- Spike halo:
  the adiabatic growth of a black hole creates a high density dark matter region.

$$\rho_{\text{halo}}(r) = \begin{cases} \rho_{\text{spike}}(r), & r_{\text{min}} \le r < r_{\text{sp}} \\ \rho_{\text{NFW}}(r), & r_{\text{sp}} \le r \end{cases}$$

$$\rho_{\text{spike}}(r) = \rho_{\text{sp}} \left(\frac{r_{\text{sp}}}{r} \right)^{\gamma_{\text{sp}}}, \gamma_{\text{sp}} = 7/3$$



$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{m^2}{2} \phi^2 - \frac{\lambda}{4} \phi^4 \right]$$

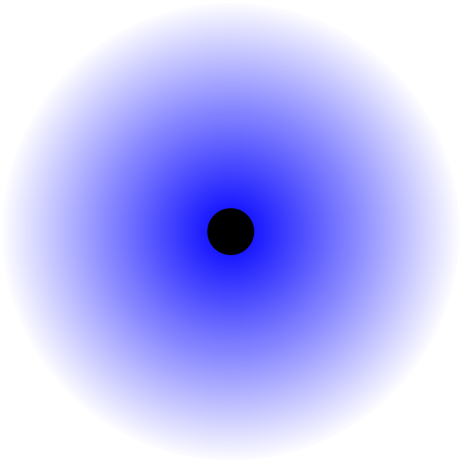
$\lambda > 0$, repulsive interaction

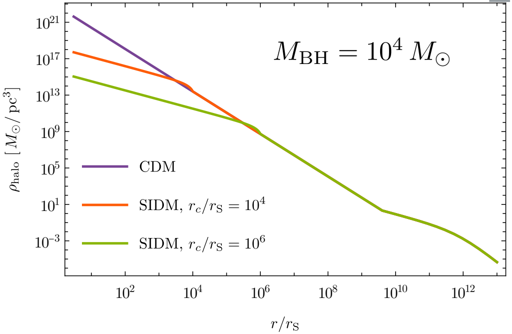
$$\rho_{\rm soliton}(r) = \rho_{\rm sin} \frac{\sin(r/r_c)}{r/r_c} + \rho_{\rm cos} \frac{\cos(r/r_c)}{r/r_c}$$

$$r_c \equiv \sqrt{\frac{3\lambda}{16\pi G m^4}}$$

Black hole + Self-interacting dark matter

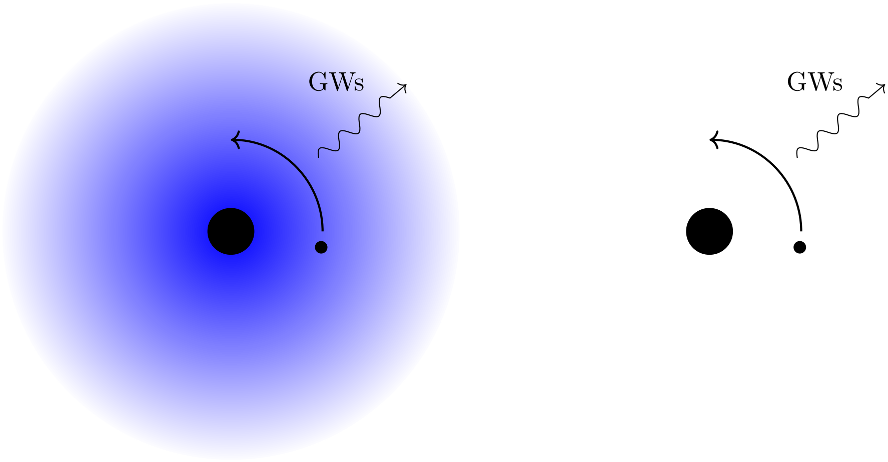
$$\rho_{\rm halo}(r) = \begin{cases} \rho_{\rm soliton}(r), & r_{\rm min} \leq r < r_c \\ \rho_{\rm spike}(r), & r_c \leq r < r_{\rm sp} \\ \rho_{\rm NFW}(r), & r_{\rm sp} \leq r \end{cases}$$





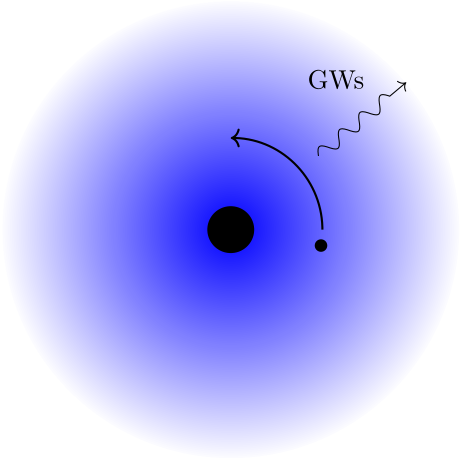
Black hole + Self-interacting dark matter

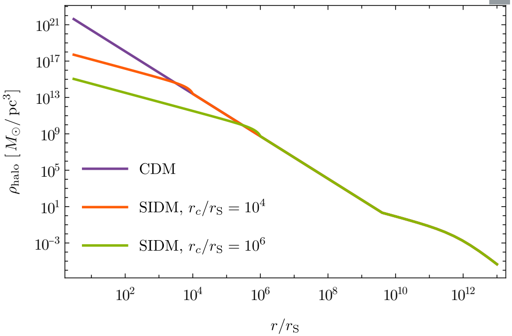
$$\rho_{\rm halo}(r) = \begin{cases} \rho_{\rm soliton}(r), & r_{\rm min} \le r < r_c \\ \rho_{\rm spike}(r), & r_c \le r < r_{\rm sp} \\ \rho_{\rm NFW}(r), & r_{\rm sp} \le r \end{cases}$$



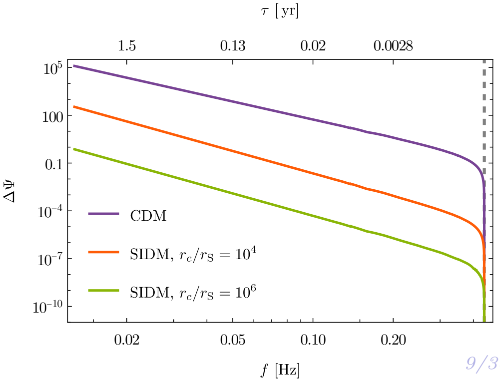
- Dynamical friction
- Accretion

$\Rightarrow$ Dephasing of GWs: $\Delta\Psi = \Psi(\text{vacuum}) - \Psi(\text{with DM halo})$





$$m_1 = 10^4\,M_\odot, m_2 = 1\,M_\odot$$



LISA

Fisher information matrix:

$$\Gamma_{ij} = \left(\frac{\partial \boldsymbol{d}(f)}{\partial \theta_i}, \frac{\partial \boldsymbol{d}(f)}{\partial \theta_j} \right)_{\boldsymbol{\theta}=\hat{\boldsymbol{\theta}}}$$

$\boldsymbol{\theta} = \{r_c; m_1, m_2, D_L, \iota, \chi, \vartheta, \varphi, \phi_{\mathrm{ISCO}}, t_{\mathrm{ISCO}}\}$

$$\boldsymbol{d}(f) = \left[\frac{\tilde{h}_1(f)}{\sqrt{S_1(f)}}, \frac{\tilde{h}_2(f)}{\sqrt{S_2(f)}}, \ldots, \frac{\tilde{h}_N(f)}{\sqrt{S_N(f)}} \right]^{\mathrm{T}}$$

$$\sigma_{\theta_i} = \sqrt{\Sigma_{ii}} \quad , \quad \boldsymbol{\Sigma} = \boldsymbol{\Gamma}^{-1}$$

The point of the Fisher matrix formalism is to **predict how well the experiment will be able to constrain the model parameters before doing the experiment.**

Fisher information matrix:

$$\Gamma_{ij} = \left(\frac{\partial \boldsymbol{d}(f)}{\partial \theta_i}, \frac{\partial \boldsymbol{d}(f)}{\partial \theta_j} \right)_{\boldsymbol{\theta}=\hat{\boldsymbol{\theta}}}$$

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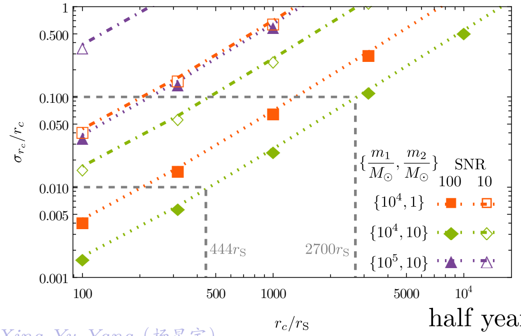


half year, LISA

Fisher information matrix:

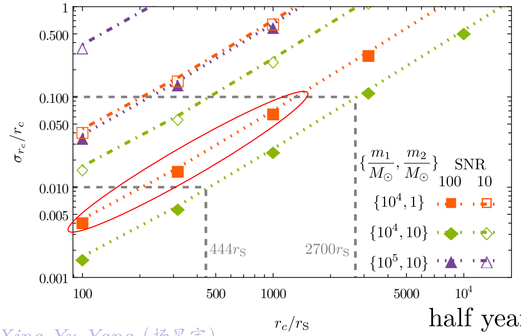
$$\Gamma_{ij} = \left(\frac{\partial \boldsymbol{d}(f)}{\partial \theta_i}, \frac{\partial \boldsymbol{d}(f)}{\partial \theta_j} \right)_{\boldsymbol{\theta}=\hat{\boldsymbol{\theta}}}$$

$$\boldsymbol{\theta} = \{ {\color{red} r_c}; m_1, m_2, D_L, \iota, \chi, \vartheta, \varphi, \phi_{\rm ISCO}, t_{\rm ISCO} \}$$

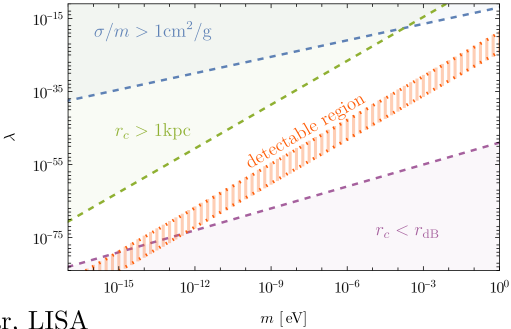
$$\boldsymbol{d}(f) = \left[\frac{\tilde{h}_1(f)}{\sqrt{S_1(f)}}, \frac{\tilde{h}_2(f)}{\sqrt{S_2(f)}}, \ldots, \frac{\tilde{h}_N(f)}{\sqrt{S_N(f)}} \right]^{\rm T}$$

$$\sigma_{\theta_i} = \sqrt{\Sigma_{ii}} \quad , \quad \boldsymbol{\Sigma} = \boldsymbol{\Gamma}^{-1}$$

$${\color{red} r_c \equiv \sqrt{\frac{3\lambda}{16\pi G m^4}}}$$



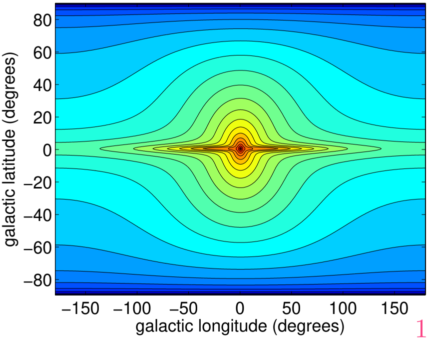
half year, LISA



Gamma ray

R.-G. Cai, Y.-C. Ding, XYY, Y.-F. Zhou [2007.11804] JCAP 03 (2021) 057

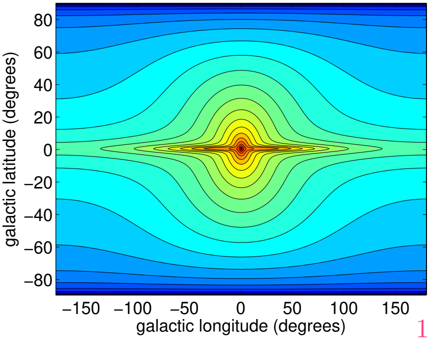
511 keV γ-ray intensity distribution



1201.0997

- 511 keV γ-ray excess
  - $\gamma \leftarrow e^+ + e^-$
  - puzzling morphology: flux ratio of bulge-to-disk $\sim O(1)$
  - ? origin of low-energy e^+ in bulge
    - $*$ astrophysical explanation: low-mass X-ray binaries, neutron star mergers, ...
    - $\star$ DM

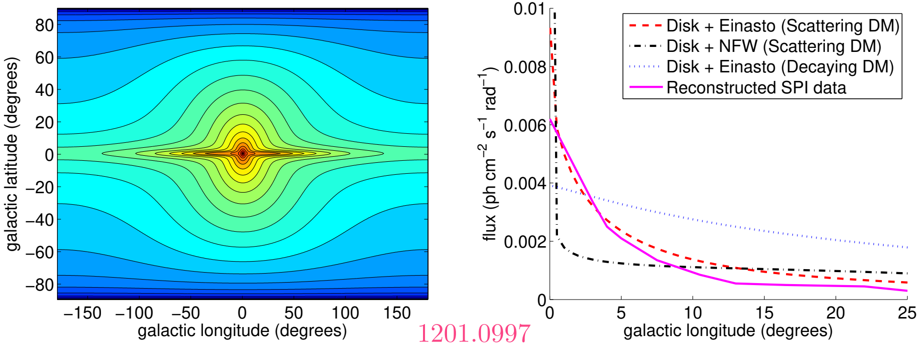
511 keV γ-ray intensity distribution



1201.0997

- Scattering-like DM
  - $\chi + \chi \to e^{+} + \cdots$
  - $I(l,b) \sim \rho^{2}(\boldsymbol{r})$
- Decaying-like DM
  - $\chi \to e^{+} + \cdots$
  - $I(l,b) \sim \rho(\boldsymbol{r})$

511 keV γ-ray intensity distribution

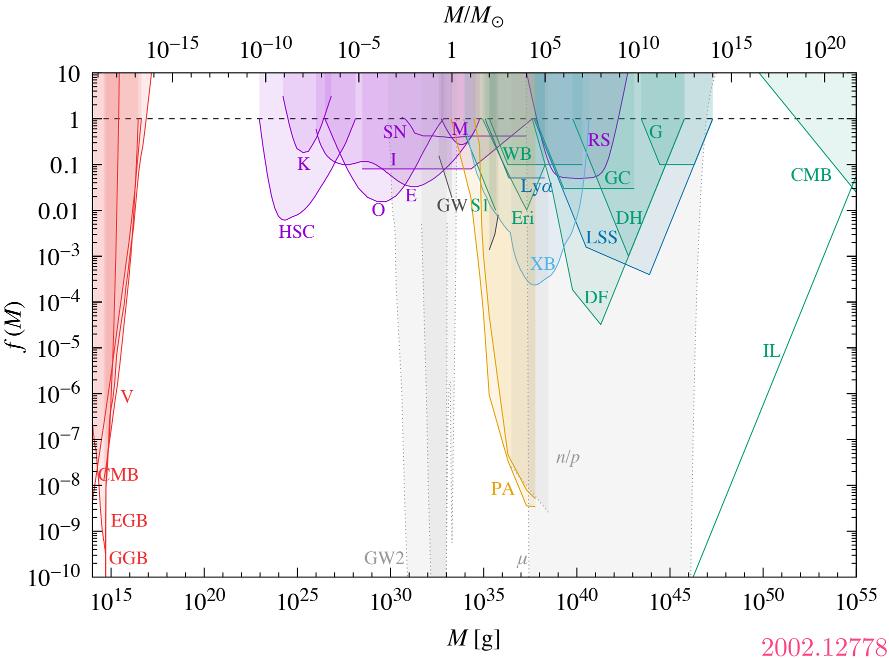


1201.0997

- Scattering-like DM
  - $\chi + \chi \to e^+ + \cdots$
  - $I(l,b) \sim \rho^2(\boldsymbol{r})$
- Decaying-like DM
  - $\chi \to e^+ + \cdots$
  - $I(l,b) \sim \rho(\boldsymbol{r})$

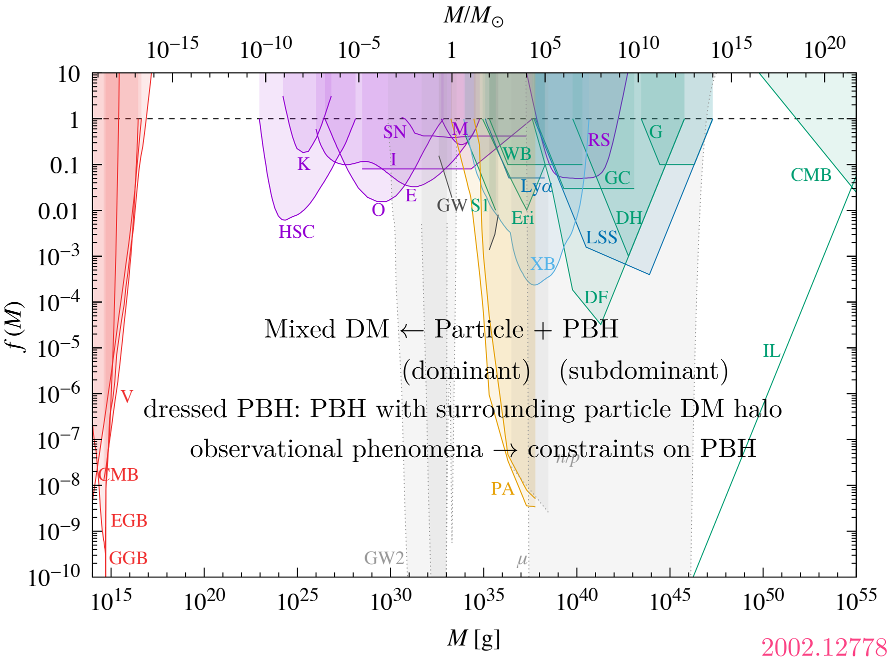
gives upper bound

Mixed DM = Scattering-like DM + Decaying-like DM



$M/M_\odot$
10^{-15} 10^{-10} 10^{-5} 1 10^{5} 10^{10} 10^{15} 10^{20}
$f(M)$
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
V
CMB
EGB
GGB
HSC
K
SN
I
O
E
M
GW
S1
WB
Lyα
Eri
RS
GC
G
DH
LSS
XB
DF
CMB
IL
GW2
PA
n/p
μ
10^{15} 10^{20} 10^{25} 10^{30} 10^{35} 10^{40} 10^{45} 10^{50} 10^{55}
M [g]

2002.12778



Mixed DM ← Particle + PBH

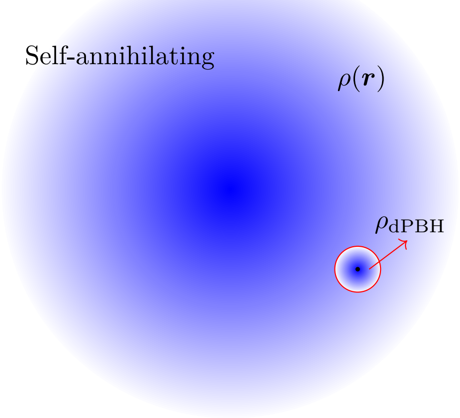
(dominant) (subdominant)

dressed PBH: PBH with surrounding particle DM halo

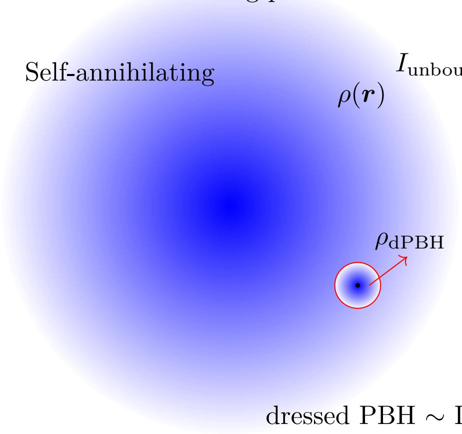
observational phenomena → constraints on PBH

2002.12778

DM = Self-annihilating particles + PBHs



DM = Self-annihilating particles + PBHs



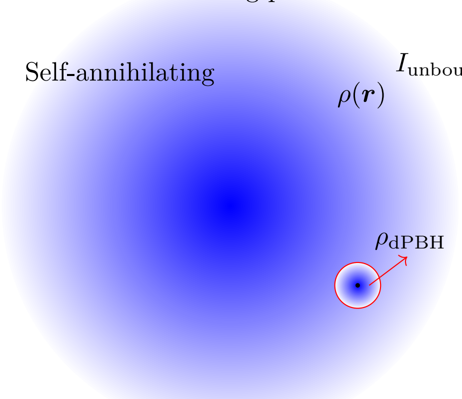
$$I_{\rm unbounded}(l,b) \propto \int_{\rm l.o.s} \frac{1}{2} \underbrace{\frac{\langle \sigma v\rangle}{m_\chi^2}(1-f_{\rm PBH})^2}_{C_{\rm A}} \rho^2(\boldsymbol{r})\, ds$$

$$I_{\rm dPBH}(l,b) \propto \int_{\rm l.o.s} \underbrace{\frac{\Gamma_{\rm PBH}}{M_{\rm PBH}} f_{\rm PBH}}_{C_{\rm D}} \rho(\boldsymbol{r})\, ds$$

$$\Gamma_{\rm PBH} = \int dr^3 \frac{1}{2} \frac{\langle \sigma v\rangle}{m_\chi^2} \rho_{\rm dPBH}^2$$

dressed PBH $\sim$ Decaying-like DM

DM = Self-annihilating particles + PBHs



$$I_{\rm unbounded}(l,b) \propto \int_{\rm l.o.s} \frac{1}{2}\overbrace{\boxed{\frac{\langle\sigma v\rangle}{m_\chi^2}(1-f_{\rm PBH})^2}}^{C_{\rm A}}\rho^2(\boldsymbol{r})ds$$

$$I_{\rm dPBH}(l,b) \propto \int_{\rm l.o.s} \overbrace{\boxed{\frac{\Gamma_{\rm PBH}}{M_{\rm PBH}}f_{\rm PBH}}}^{C_{\rm D}}\rho(\boldsymbol{r})ds$$

$$\Gamma_{\rm PBH} = \int dr^3 \frac{1}{2}\frac{\langle\sigma v\rangle}{m_\chi^2}\rho_{\rm dPBH}^2$$

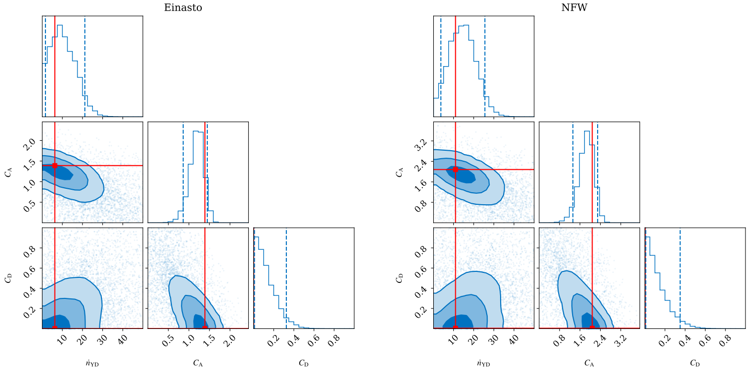
dressed PBH ∼ Decaying-like DM

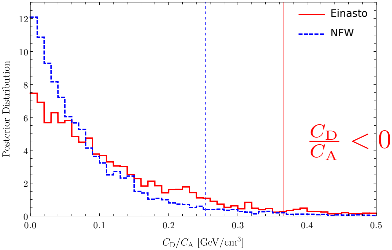
$$\frac{f_{\rm PBH}}{(1-f_{\rm PBH})^2} = \frac{2M_{\rm PBH}}{\int dr^3\rho_{\rm dPBH}^2}\frac{C_{\rm D}}{C_{\rm A}}.$$

- Morphology of 511 keV gamma-ray observations ⇒ upper bound on $C_{\rm D}/C_{\rm A}$
- Theoretical calculation ⇒ $\rho_{\rm dPBH}$

Fit to INTEGRAL/SPI data

$$I(l,b) = I_{\text{unbounded}}(l,b) + I_{\text{dPBH}}(l,b) + I_{\text{disk}}(l,b)$$

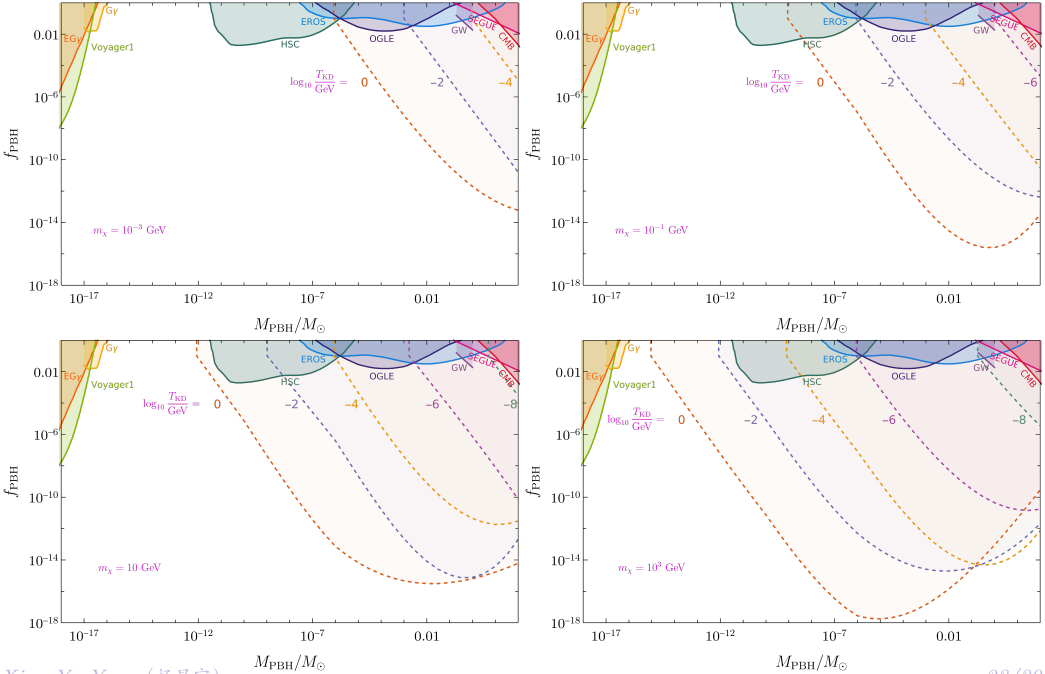




$\frac{C_D}{C_A} < 0.37\ \text{GeV/cm}^3$

95% upper bound

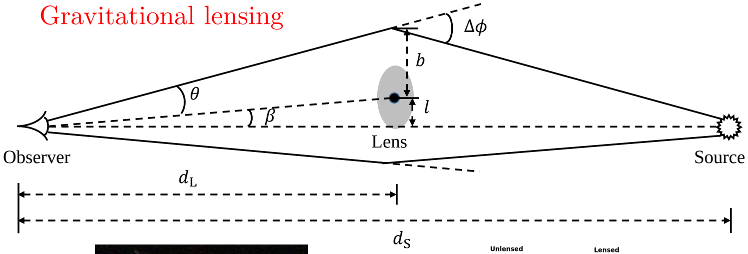
$$\frac{f_{\rm PBH}}{(1-f_{\rm PBH})^2} = \frac{2M_{\rm PBH}}{\int dr^3 \rho_{\rm dPBH}^2}\frac{C_{\rm D}}{C_{\rm A}} < \frac{3M_{\rm PBH}}{2\pi\rho_{\rm max}^2 r_c^3} \times 0.37\ \ {\rm GeV/\,cm^3}$$



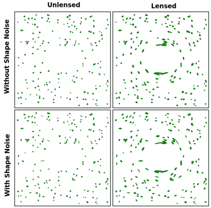
Gravitational lensing

R.-G. Cai, T. Chen, S.-J. Wang, XYY [2210.02078] JCAP 03 (2023) 043

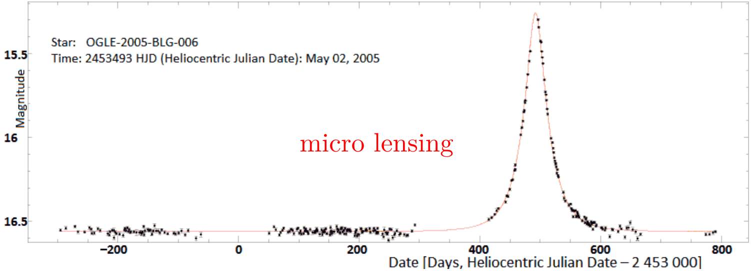
Gravitational lensing



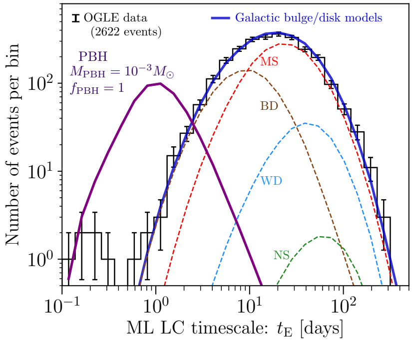
strong lensing

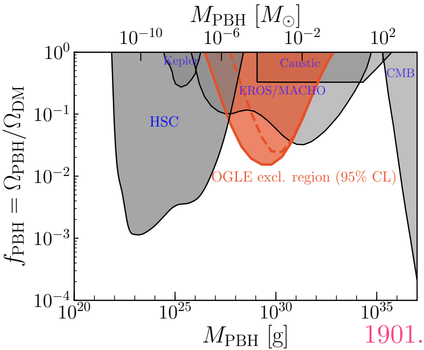


weak lensing



micro lensing



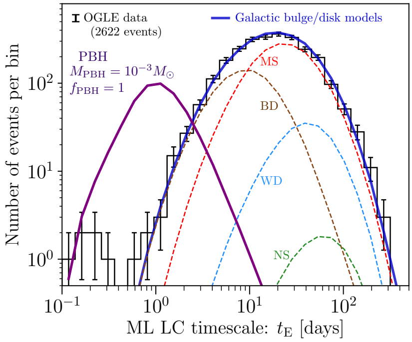


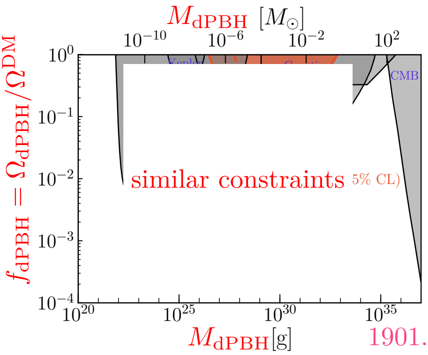
1901.07120

PBH as lens

$$N_{\rm event}\ (\text{Galactic}) + N_{\rm event}\ (\text{PBH}) \lesssim N_{\rm event}\ (\text{Observed})$$

$\uparrow$ — $f_{\rm PBH}, M_{\rm PBH}$





1901.07120

dPBH as lens

$$N_{\rm event}\ ({\rm Galactic}) + N_{\rm event}\ ({\rm dPBH}) \lesssim N_{\rm event}\ ({\rm Observed})$$

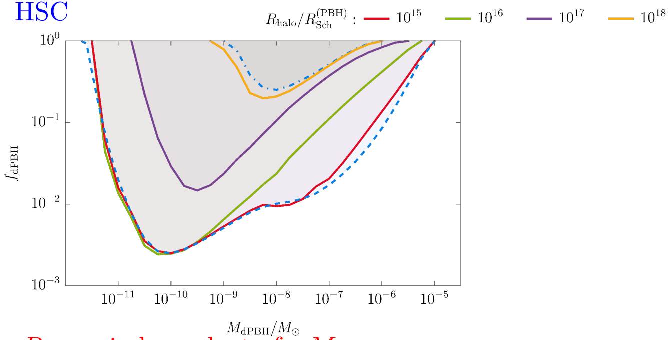
$$\uparrow\ f_{\rm dPBH}, M_{\rm dPBH}, R_{\rm halo}$$

$$\uparrow$$

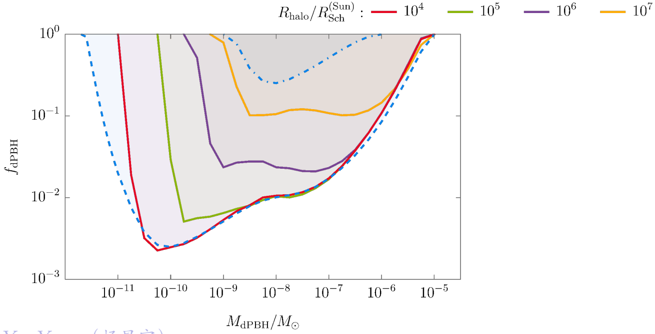
$$M_{\rm PBH} + M_{\rm halo}$$

$R_{\text{halo}} \propto M_{\text{PBH}}$ $M_{\text{halo}} = 100 M_{\text{PBH}}$,

HSC



R_{halo} independent of M_{PBH}



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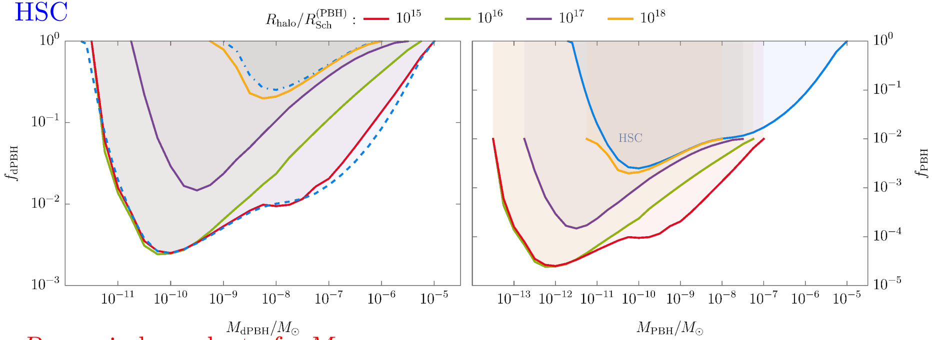
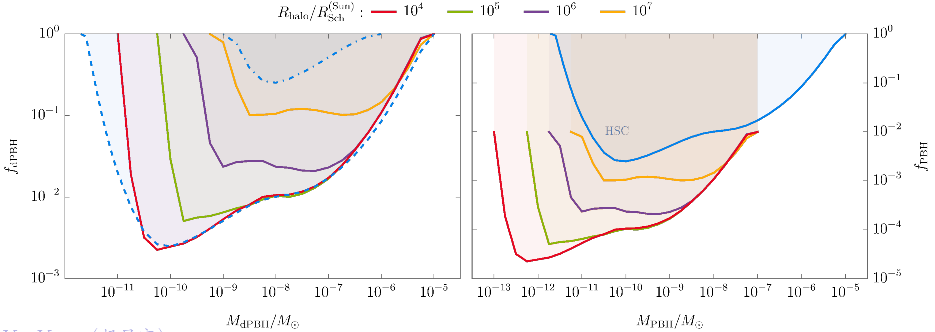
$R_{\rm halo} \propto M_{\rm PBH}$ $\quad M_{\rm halo} = 100 M_{\rm PBH}$,

HSC



$R_{\rm halo}$ independent of $M_{\rm PBH}$



Summary

- The accretion of dark matter around black holes could lead to the formation of surrounding halo, which can give characteristic observational phenomena. Such characteristic phenomena can be used to explore the nature of dark matter.

- The gravitational waves from intermediate mass ratio inspiral with surrounding halo can be probes on the self-interacting dark matter.

- The galactic 511 keV gamma-ray background has the potential to give much more stringent constraints on the fraction of PBHs in dark matter.

- By considering the surrounding halo of PBHs, we can strengthen the constraints on the abundance of PBHs. This approach also has the potential to shift the constraints towards the well-known asteroid-mass window, where PBHs could account for all of the dark matter.