Observational phenomena on black hole with dark matter dress

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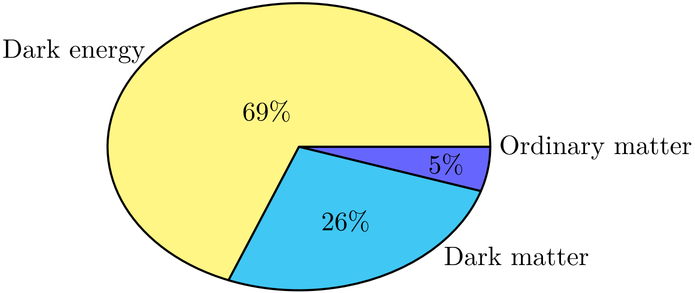
K. Kadota, J. H. Kim, P. Ko, XYY [2306.10828] PRD 109, 015022 (2024)
R.-G. Cai, T. Chen, S.-J. Wang, XYY [2210.02078] JCAP 03 (2023) 043
R.-G. Cai, Y.-C. Ding, XYY, Y.-F. Zhou [2007.11804] JCAP 03 (2021) 057

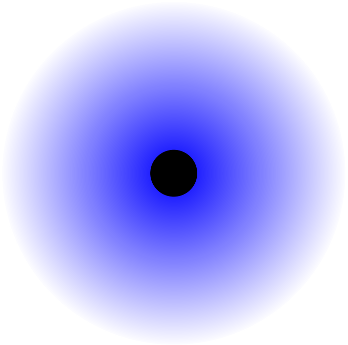


Particle dark matter + Black hole ⇒

Characteristic phenomena ⇐

⇓

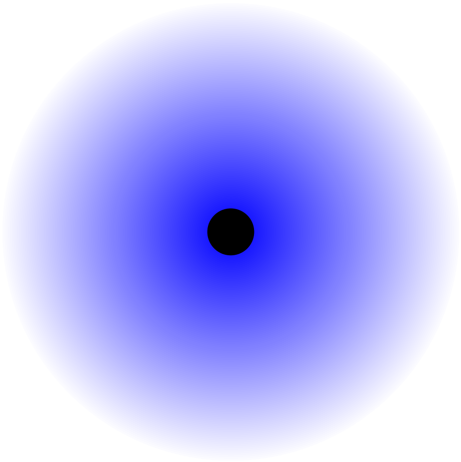
Nature of dark matter



Gravitational waves

K. Kadota, J. H. Kim, P. Ko, XYY [2306.10828] PRD 109, 015022 (2024)

- 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.

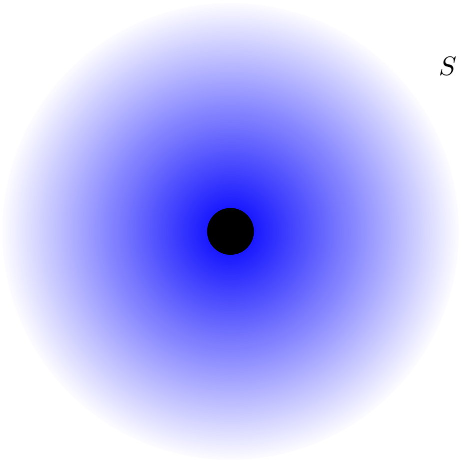


Black hole + Cold dark matter

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

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

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



Black hole + Self-interacting dark matter

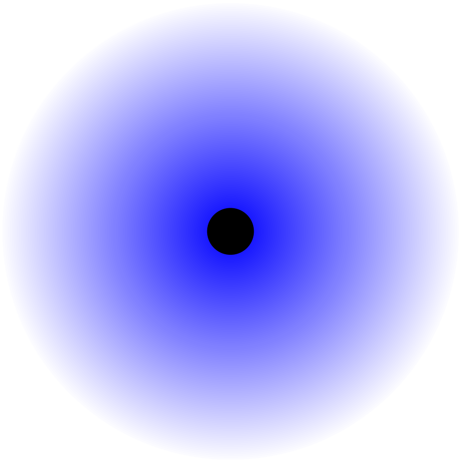
$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{m^2}{2}\phi^2 - \frac{\lambda}{4}\phi^4\right]$$

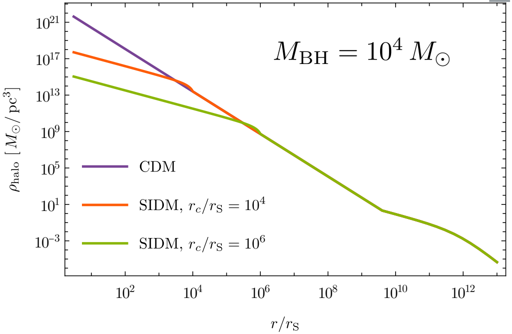
$$\lambda > 0, \quad \text{repulsive interaction}$$

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

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

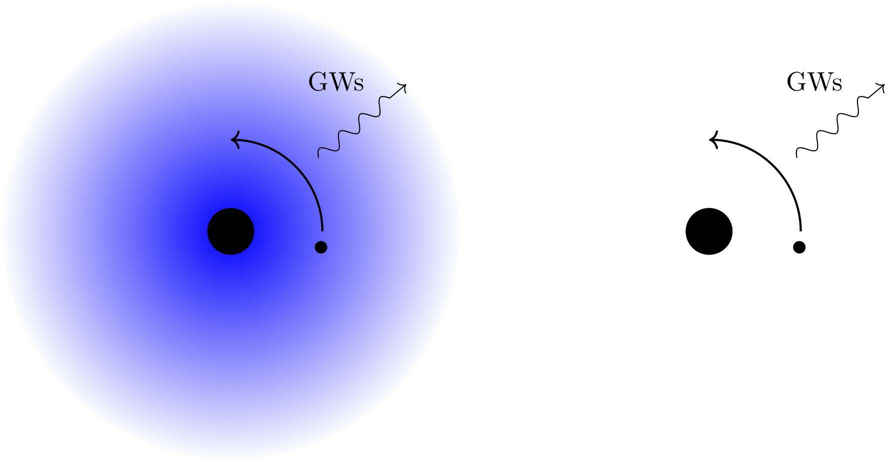
$$\rho_{\text{halo}}(r) = \begin{cases} \rho_{\text{soliton}}(r), & r_{\min} \leq r < r_c \\ \rho_{\text{spike}}(r), & r_c \leq r < r_{\text{sp}} \\ \rho_{\text{NFW}}(r), & r_{\text{sp}} \leq r \end{cases}$$





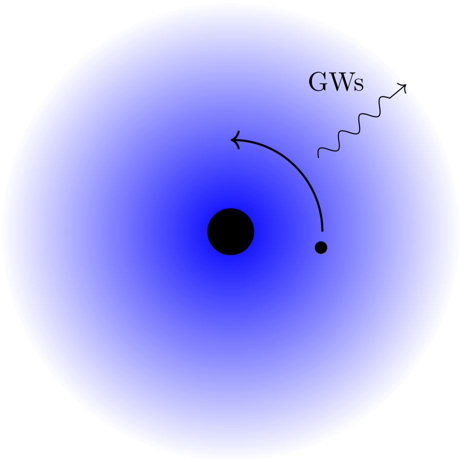
Black hole + Self-interacting dark matter

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



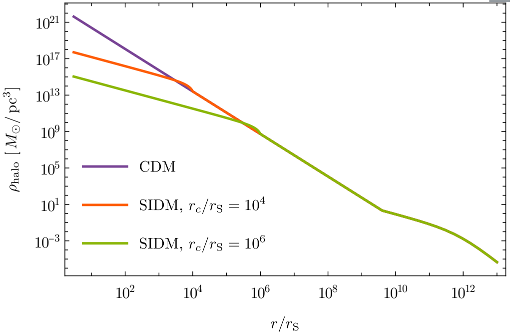
- Dynamical friction
- Accretion

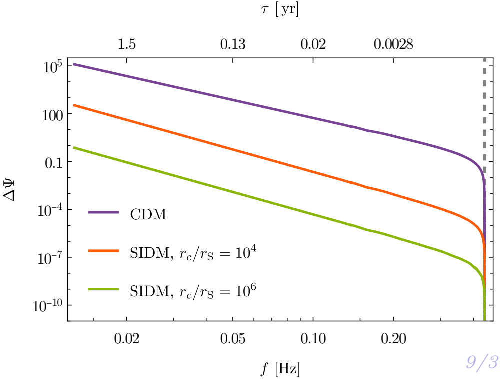
$\Rightarrow$ Dephasing of GWs: $\Delta\Psi = \Psi(\text{vacuum}) - \Psi(\text{with DM halo})$



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

LISA





Fisher information matrix:

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

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

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

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

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:

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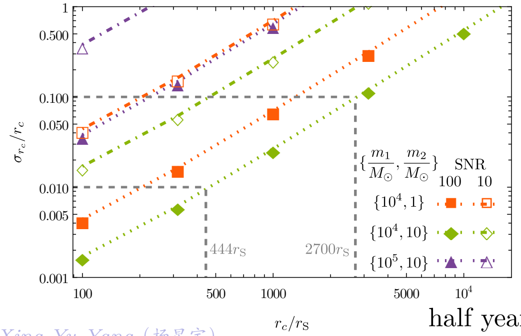

half year, LISA

Fisher information matrix:

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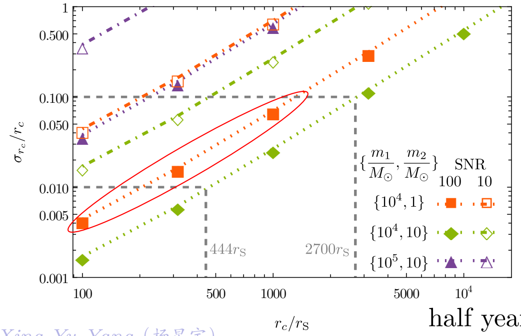
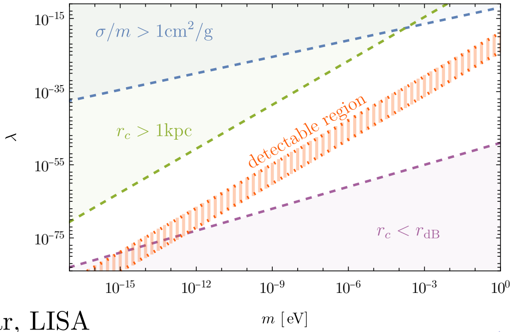


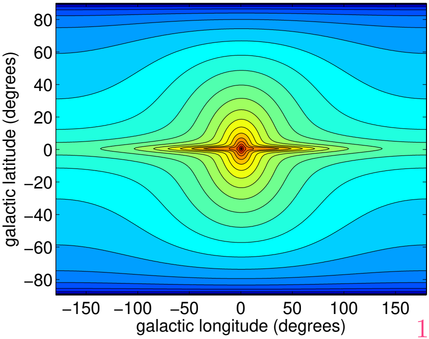


half year, LISA

Gamma ray

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

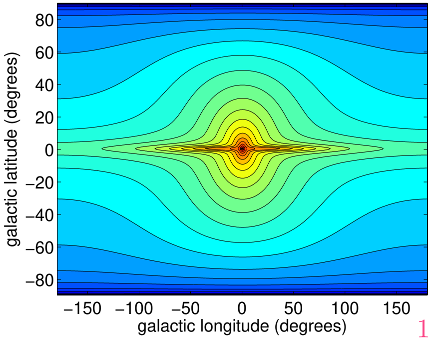
511 keV γ-ray intensity distribution



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

511 keV γ-ray intensity distribution



1201.0997

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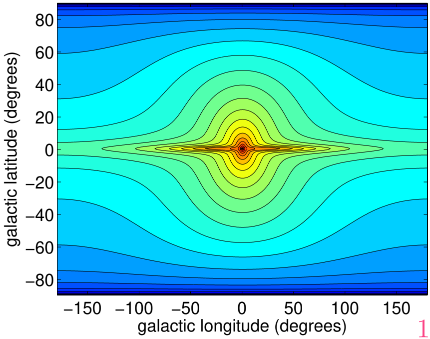
    - ⋆ DM

511 keV γ-ray intensity distribution



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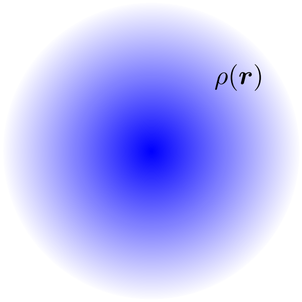
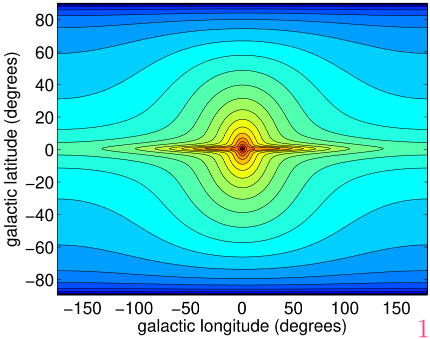


- Scattering-like DM
  - $\chi + \chi \to e^+ + \cdots$
  - $I(l,b) \sim \rho^2(\boldsymbol{r})$
- Decaying-like DM
  - $\chi \to e^+ + \cdots$
  - $I(l,b) \sim \rho(\boldsymbol{r})$

511 keV γ-ray intensity distribution



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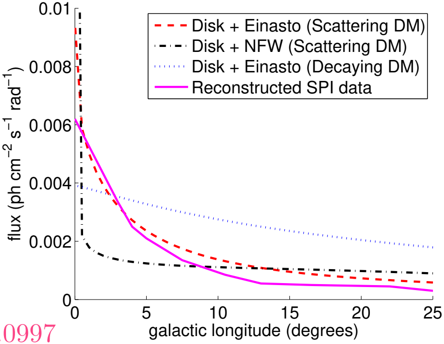

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  - $\chi \to e^+ + \cdots$
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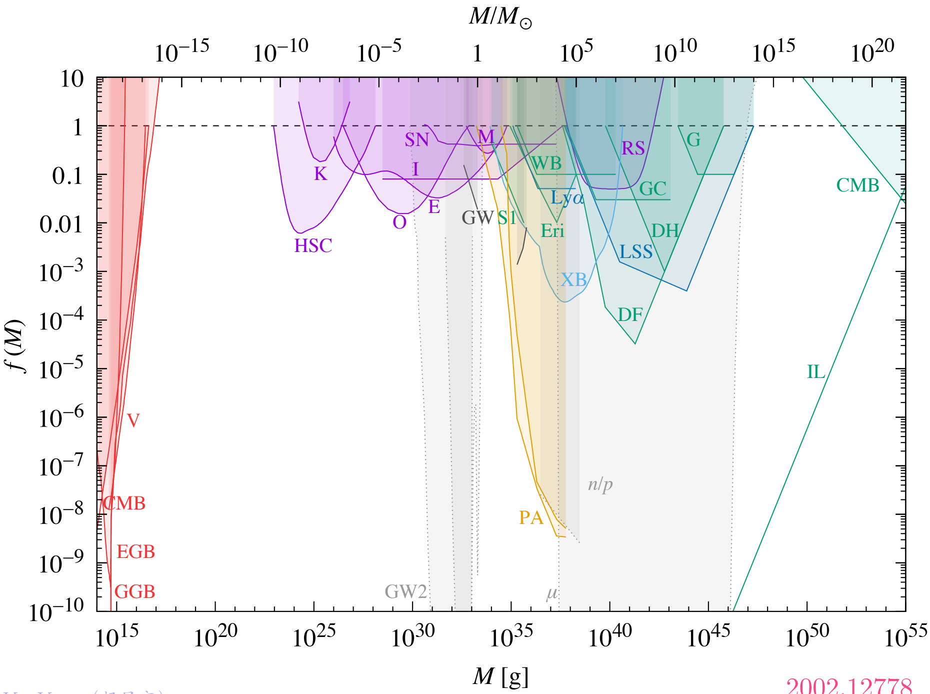
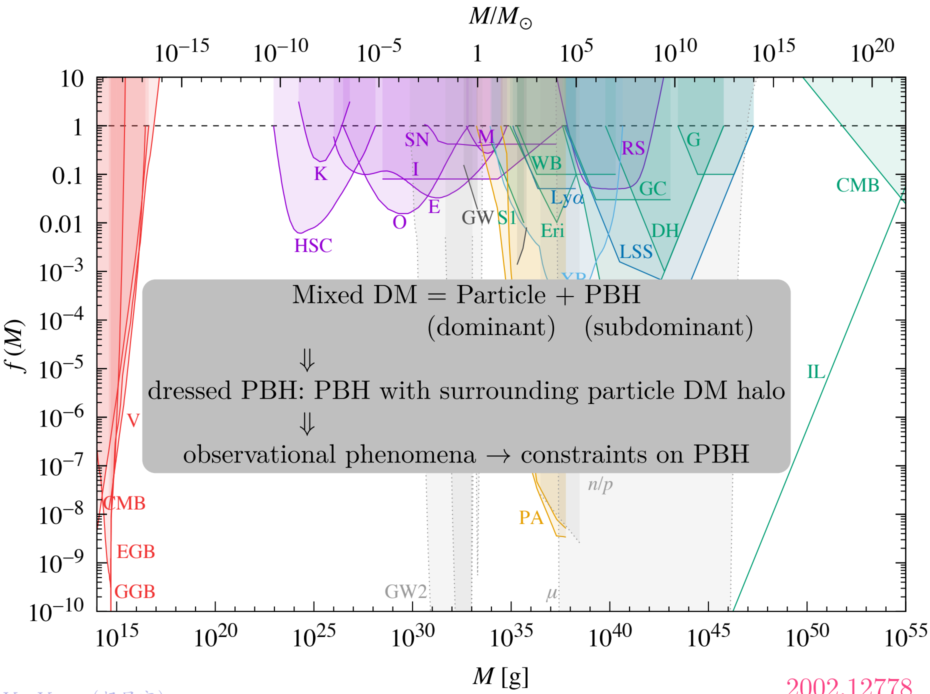
gives upper bound

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

2002.12778



Mixed DM = Particle + PBH

(dominant) (subdominant)

$\Downarrow$

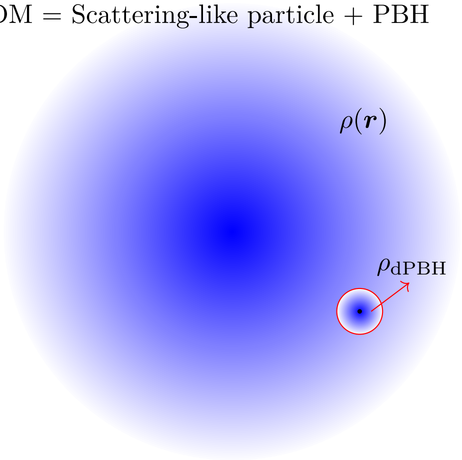
dressed PBH: PBH with surrounding particle DM halo

$\Downarrow$

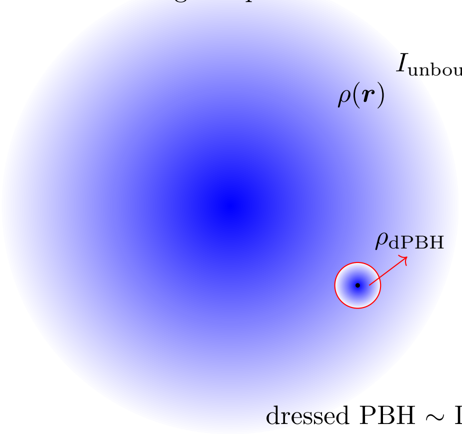
observational phenomena $\rightarrow$ constraints on PBH

2002.12778

DM = Scattering-like particle + PBH



DM = Scattering-like particle + PBH



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

Scattering-like

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

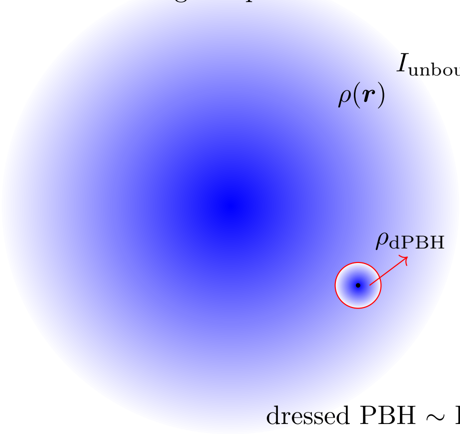
Decaying-like

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

dressed PBH $\sim$ Decaying-like DM

(which is upper bounded)

DM = Scattering-like particle + PBH



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

Scattering-like

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

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

Decaying-like

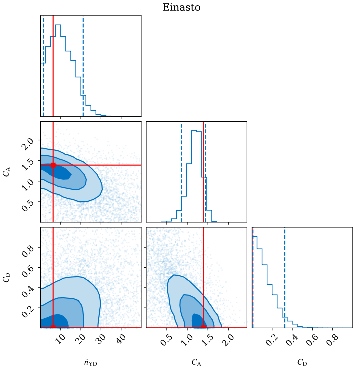
dressed PBH $\sim$ Decaying-like DM (which is upper bounded)

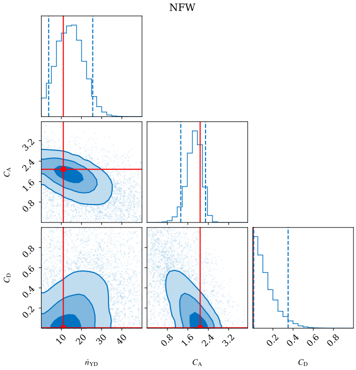
$$\frac{f_{\rm PBH}}{(1-f_{\rm PBH})^2} = \frac{2M_{\rm PBH}}{\int dr^3 \rho_{\rm dPBH}^2}\frac{C_{\rm D}}{C_{\rm A}}.$$

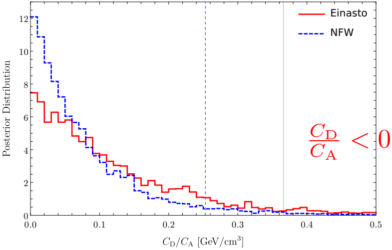
- Morphology of 511 keV gamma-ray observations $\Rightarrow$ upper bound on $C_{\rm D}/C_{\rm A}$
- Theoretical calculation $\Rightarrow$ $\rho_{\rm dPBH}$

Fit to INTEGRAL/SPI data

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



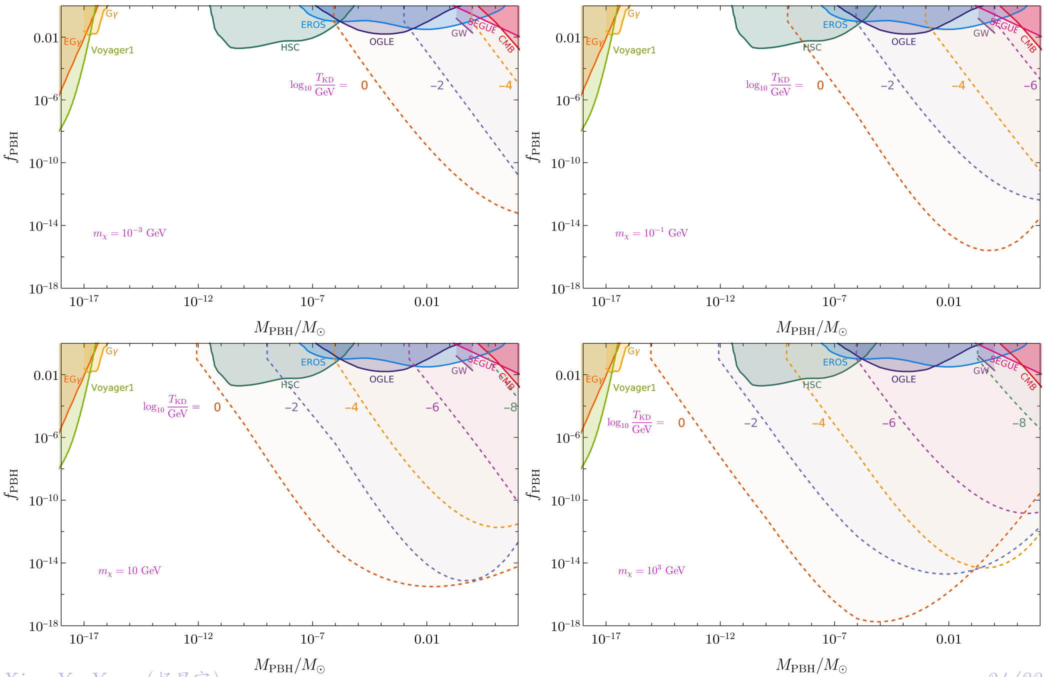




$$\frac{C_D}{C_A} < 0.37 \ \text{GeV}/\text{cm}^3$$

95% upper bound

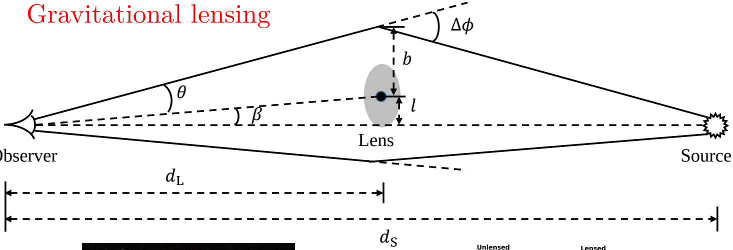
$$\frac{f_{\rm PBH}}{(1-f_{\rm PBH})^2} = \frac{2M_{\rm PBH}}{\int dr^3 \rho^2_{\rm dPBH}} \frac{C_{\rm D}}{C_{\rm A}} < \frac{3M_{\rm PBH}}{2\pi\rho^2_{\rm max} r_c^3} \times 0.37 \ \ {\rm GeV/\ cm^3}$$



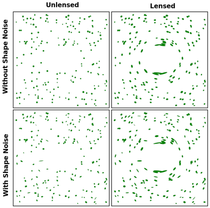
Gravitational lensing

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

Gravitational lensing

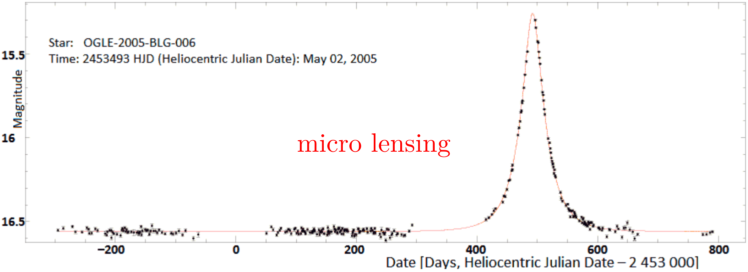


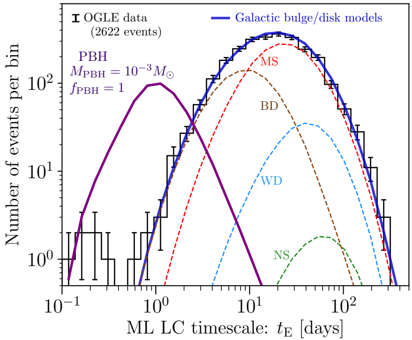
strong lensing

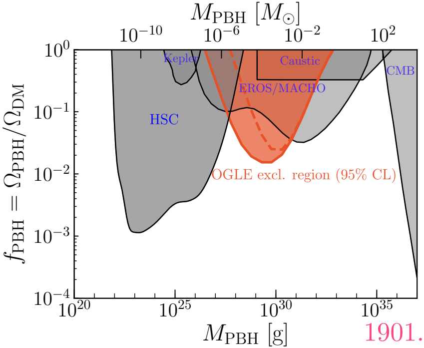


weak lensing

micro lensing





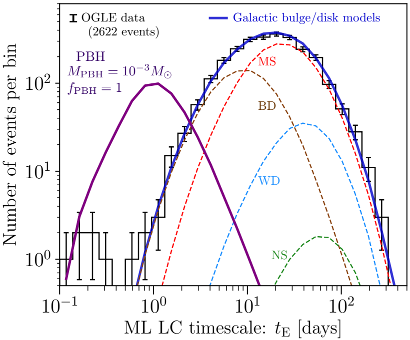


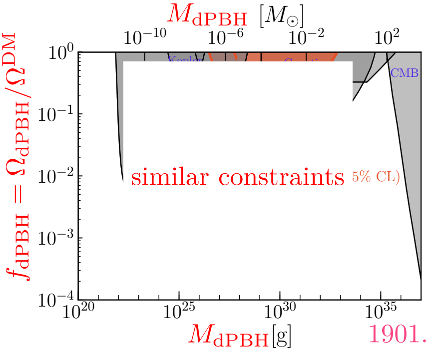
1901.07120

PBH as lens

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

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





1901.07120

dPBH as lens

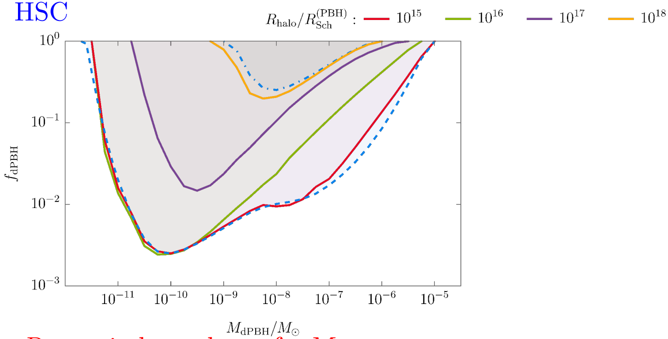
$$N_{\rm event}\ ({\rm Galactic}) + N_{\rm event}\ ({\rm dPBH}) \lesssim N_{\rm event}\ ({\rm Observed})$$

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

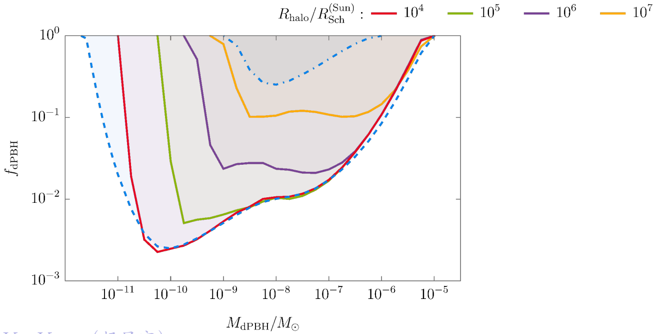
$$\uparrow\ M_{\rm PBH} + M_{\rm halo}$$

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

HSC

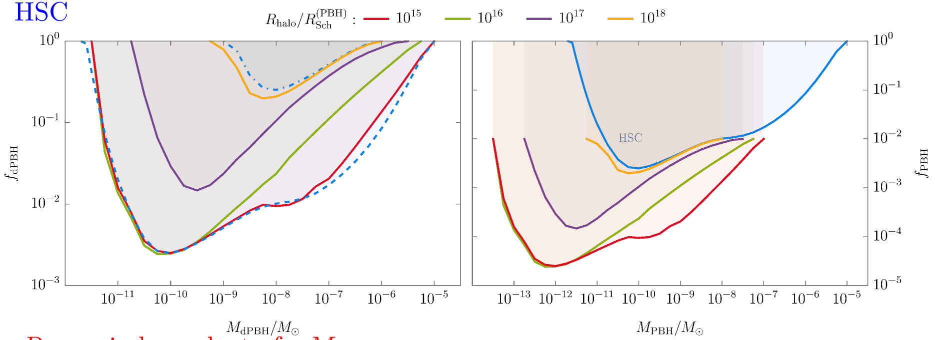


$R_{\rm halo}$ independent of $M_{\rm PBH}$

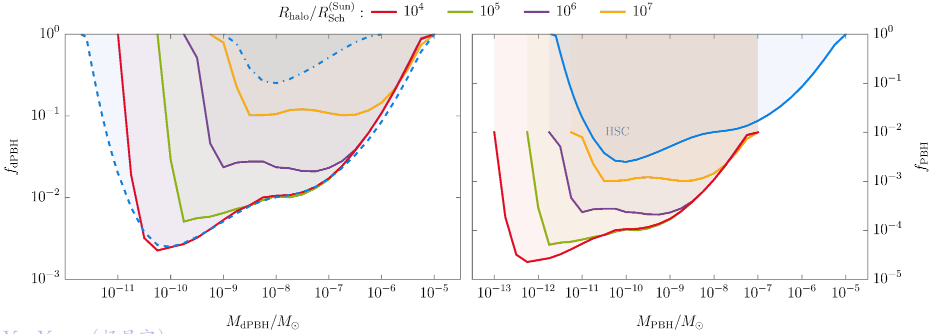


$R_{\rm halo} \propto M_{\rm PBH}$ $\quad M_{\rm halo} = 100 M_{\rm PBH}$,

HSC



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



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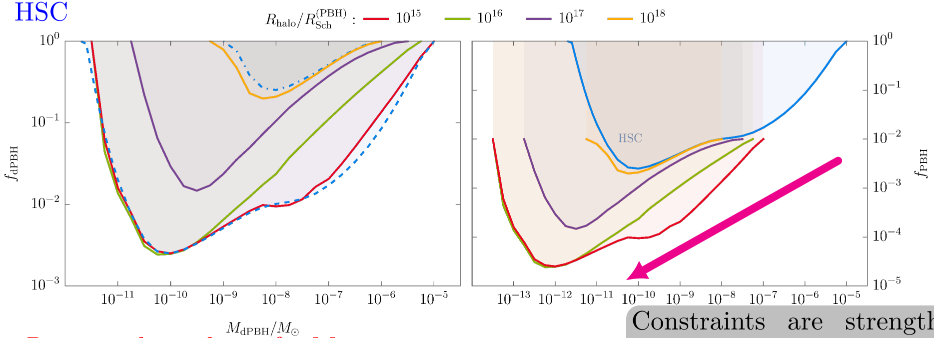
HSC



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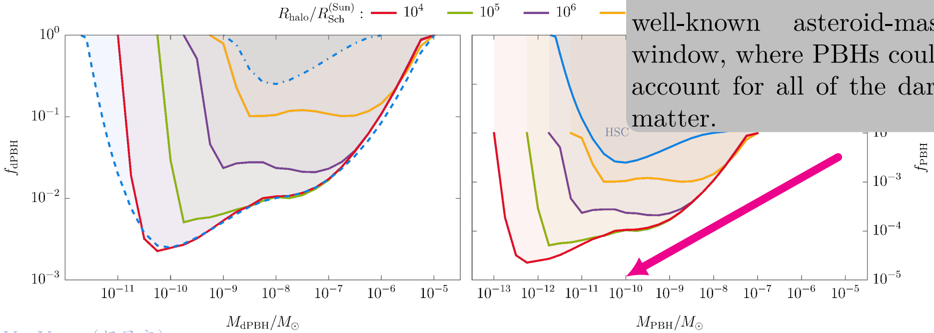

Constraints are strengthened and shift toward the well-known asteroid-mass window, where PBHs could account for all of the dark matter.

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.

- Taking the surrounding halo of PBHs into consideration, the constraints on PBH abundance from microlensing can be strengthened and can shift toward the well-known asteroid-mass window, where PBHs could account for all of the dark matter.