Light Dark Matter from PBH evaporation and its detection

李佟
南开大学

based on arXiv: 2108.05608, 2203.14443, 22xx.xxxxx

in collaboration with Wei Chao (Beijing normal U.), Jiajun Liao (Zhongshan U.) and Rui-Jia Zhang (Nankai U.)

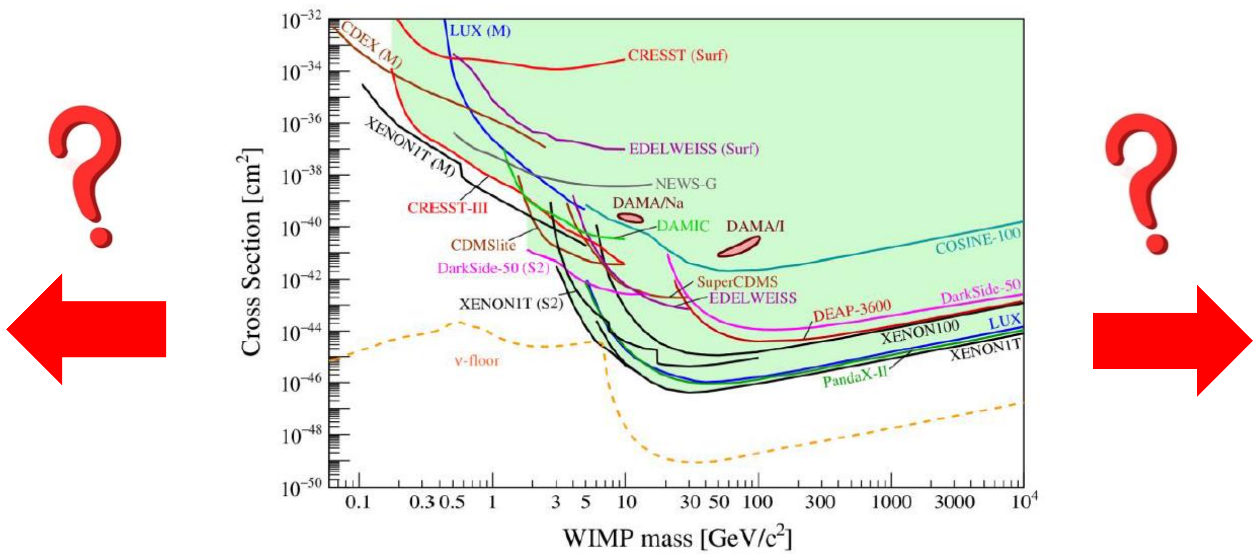
第三届粒子物理前沿研讨会，2022.7.21-26

Outline

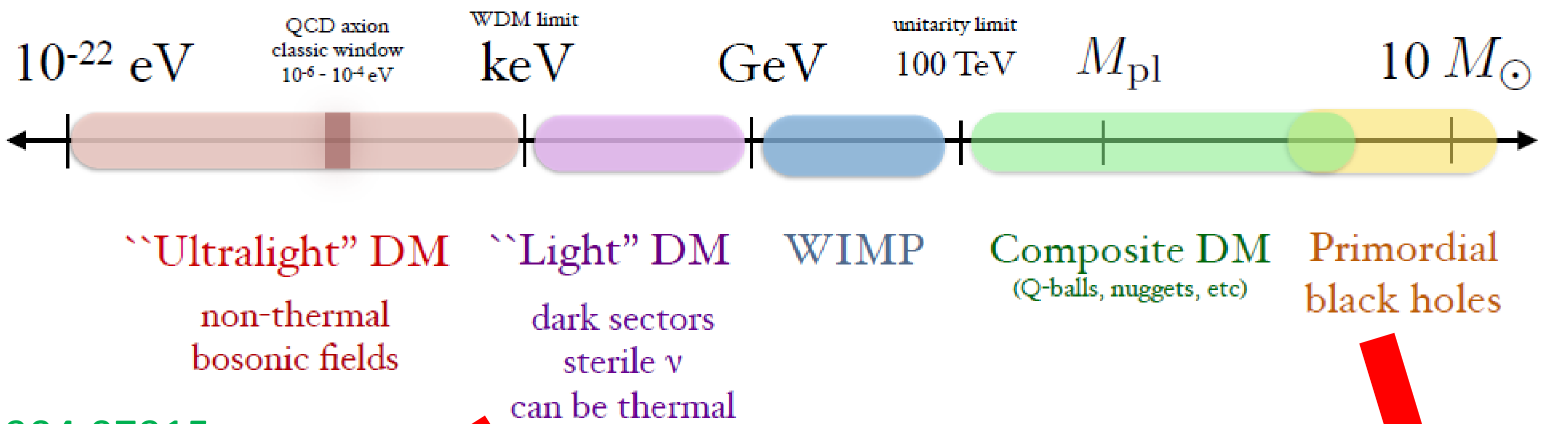
- Motivation
- Light DM from PBH evaporation
- Detection through electron targets
- Summary

Motivation

- No doubt dark matter exists, but its constitution and nature still unknown
- As no conclusive evidence of WIMP dark matter in direct detection (up to now), we are motivated to consider alternative DM candidates in both theoretical and experimental aspects.



- DM could span an enormous mass range



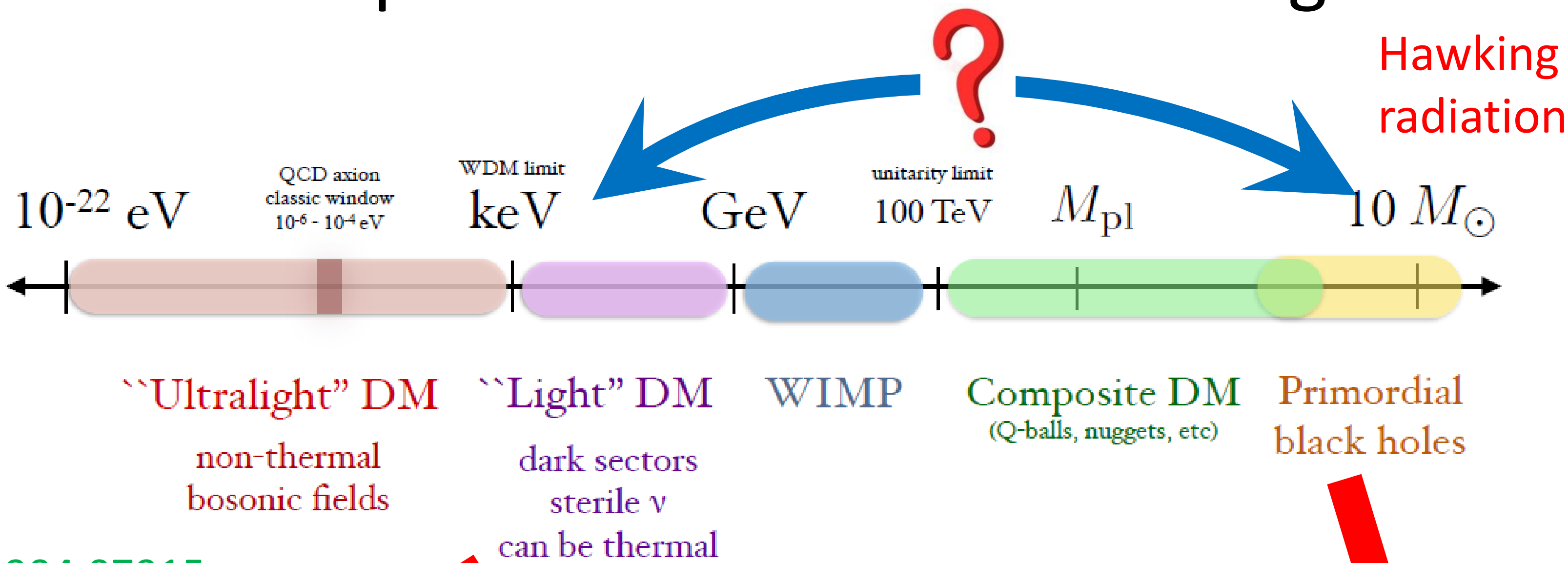
T. Lin, 1904.07915

$E_r \sim \frac{2\mu^2}{m_N} v^2$: below the threshold

1. lowering energy threshold by lighter nucleus (Ge, Ar, Si, He, etc.)
2. DM-electron ionization (direct DM-electron and Migdal effect)
3. boosted DM (cosmic ray, annihilation, etc.)

1. highly constrained by astrophysical observations
2. PBHs can make up DM density, but not 100%
3. Stochastic GW background would help to detect PBHs

- DM could span an enormous mass range



T. Lin, 1904.07915

$E_r \sim \frac{2\mu^2}{m_N} v^2$: below the threshold

1. lowering energy threshold by lighter nucleus (Ge, Ar, Si, He, etc.)
2. DM-electron ionization (direct DM-electron and Migdal effect)
3. boosted DM (cosmic ray, annihilation, etc.)

1. highly constrained by astrophysical observations
2. PBHs can make up DM density, but not 100%
3. Stochastic GW background would help to detect PBHs

PBHs and their evaporation

- For the first time, Zeldovich & Novikov discussed PBH in 1967, but their conclusion on the existence of PBHs was negative (but wrong). Sov. Astron. 10, 602 (1967)
- In 1974, Carr and Hawking showed that a black hole formed from local collapse would not grow as fast as the horizon. Mon. Not. R. astron. Soc. 168, 399 (1974)
- The "smallness" of PBHs promotes Hawking to raise his famous discovery that black holes radiate thermally with a temperature T_{PBH} and evaporate on Nature 248, 30 (1974)

$$k_{\rm B} T_{\rm PBH} = \frac{\hbar c^3}{8\pi G_N M_{\rm PBH}} \simeq 1.06 \left[\frac{10^{16}{\rm g}}{M_{\rm PBH}}\right] {\rm MeV} \qquad \tau(M) \approx \frac{\hbar\, c^4}{G^2 M^3} \approx 10^{64} \left(\frac{M}{M_\odot}\right)^3 {\rm yr}$$

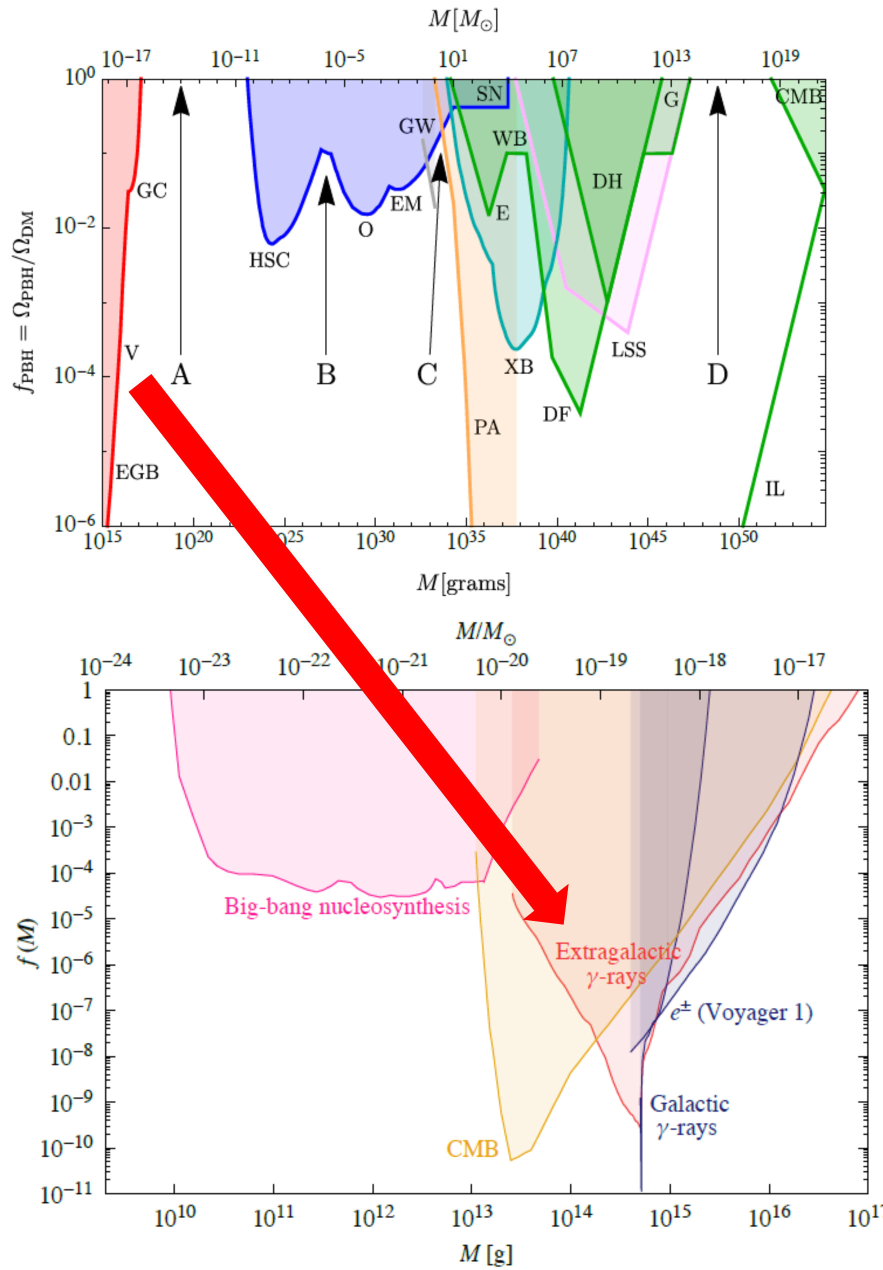
- PBHs lighter than $\sim 10^{14}$ g would have evaporated by now.

- PBHs as DM and the constraints on the fraction of DM in PBH: f_{PBH}

- PBHs $\sim 10^{15}\ g$ produce photon ~100 MeV and highly constrained by extragalactic gamma-ray background: $f(M) < 10^{-8}$

- difficult to detect their final phase at the present epoch

- recent concentrations to the PBHs heavier than $10^{15}\ g$, unaffected by Hawking radiation;
4 windows and GW detections



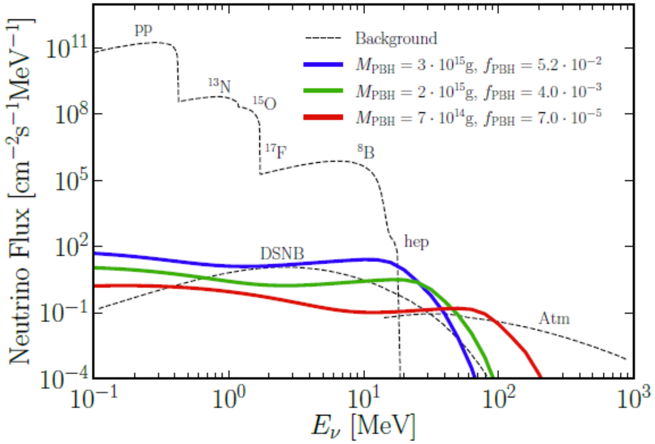
- The development of terrestrial facilities enables us to consider the detection and constraint on PBHs: neutrino experiments

  1912.01014, 2010.16053, 2106.02492, 2106.05013, 2110.00025, 2110.05637, 2108.05608, 2203.14979

- Smaller PBH masses give harder spectra of the emitted neutrinos peaked at $\sim 4.2\ T_{PBH}$ and maximized at $O(100)$ MeV (comparable to diffuse supernova neutrino background and atmospheric neutrinos)

- Such energetic neutrinos can boost light DM in the MW

  Wei Chao, TL, Jiajun Liao, 2108.05608



- Why not boosted DM itself? It is possible for $m_\chi < 1$ MeV

  with Wei Chao's private discussion

Light DM from PBH evaporation

- The PBHs emit Dirac DM with the number density

$$\frac{d^2N}{dEdt} = \frac{1}{2\pi}\frac{\Gamma(E, M_{PBH})}{\exp(E/k_B T_{PBH}) + 1}$$

Γ: greybody factor (describing the probability of DM χ escaping the PBH gravitational well)

- In principle, spinning PBHs would make the evaporation faster and the spectrum becomes harder. We ignore the spin of PBH.

- The DM flux is composed of the contributions of both the PBHs in the Milky Way and the extragalactic PBHs

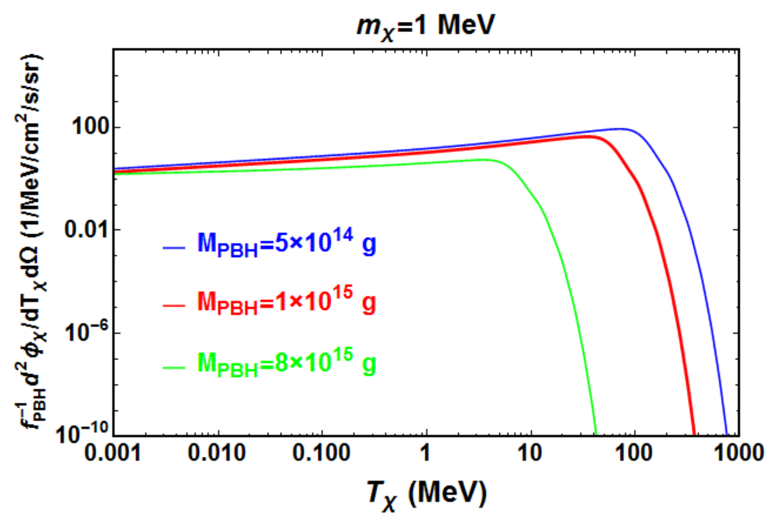
$$\frac{d^2\phi_\chi}{dT_\chi d\Omega} = \frac{d^2\phi_\chi^{\rm MW}}{dT_\chi d\Omega} + \frac{d^2\phi_\chi^{\rm EG}}{dT_\chi d\Omega}$$

MW: taking NFW DM profile

$$\frac{d^2\phi_\chi^{\rm MW}}{dT_\chi d\Omega} = \frac{f_{\rm PBH}}{4\pi M_{\rm PBH}} \frac{d^2 N_\chi}{dT_\chi dt} \int \frac{d\Omega_s}{4\pi} \int dl \rho_{\rm MW}[r(l,\psi)]$$

EG: energy redshifted

$$\frac{d^2\phi_\chi^{\rm EG}}{dT_\chi d\Omega} = \frac{f_{\rm PBH}\rho_{\rm DM}}{4\pi M_{\rm PBH}} \int_{t_{\rm min}}^{t_{\rm max}} dt[1+z(t)] \frac{d^2 N_\chi}{dT_\chi dt}$$



- Light DM produced from PBHs gains energies peaked at $O(10)\sim O(100)$ MeV and have ultra-relativistic velocities

Detection through electron targets (1810.10543)

Novel direct detection constraints on light dark matter

Torsten Bringmann[1] and Maxim Pospelov[2,3]

[1]*Department of Physics, University of Oslo, Box 1048, N-0371 Oslo, Norway*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
[3]*Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
(Dated: June 2018)

All attempts to directly detect particle dark matter (DM) scattering on nuclei suffer from the partial or total loss of sensitivity for DM masses in the GeV range or below. We derive novel constraints from the inevitable existence of a subdominant, but highly energetic, component of DM generated through collisions with cosmic rays. Subsequent scattering inside conventional DM detectors, as well as neutrino detectors sensitive to nuclear recoils, limits the DM-nucleon scattering cross section to be below $10^{-31}\,\mathrm{cm}^2$ for both spin-independent and spin-dependent scattering of light DM.

- Considering the earth attenuation, the actual DM flux reaching the detector is

$$\frac{d^2\phi_\chi^d}{dT_\chi^d d\Omega} \approx \frac{4m_\chi^2 e^\tau}{(2m_\chi + T_\chi^d - T_\chi^d e^\tau)^2} \frac{d^2\phi_\chi}{dT_\chi d\Omega}\bigg|_{T_\chi^0} \qquad \tau = z/\ell$$

ℓ: the mean free path of DM $\qquad \ell = \left[n_e^\oplus \sigma_{\chi e} \frac{2m_e m_\chi}{(m_e + m_\chi)^2} \right]^{-1}$

$T_\chi{}^0$: the initial energy

$$T_\chi^0(T_\chi^d) = \frac{2m_\chi T_\chi^d e^\tau}{2m_\chi + T_\chi^d - T_\chi^d e^\tau}$$

- Finally, the number of DM scattering per recoil energy of electron T_e

$$\frac{d^3 N_\chi}{dt d\Omega dT_e} = N_e \int dT_\chi^d \sigma_{\chi e} D_\chi^e(T_e, T_\chi^d) \frac{d^2\phi_\chi^d}{dT_\chi^d d\Omega}$$

DM transfers energy to the electron target assuming electrons at rest frame

$$D_\chi^e(T_e, T_\chi) = \frac{1}{T_e^{\max}(T_\chi)} \Theta(T_e^{\max}(T_\chi) - T_e)$$

1810.10543
1811.00520

N_e: total number of free electrons in targets

$\sigma_{\chi e}$: DM-electron scattering total cross section

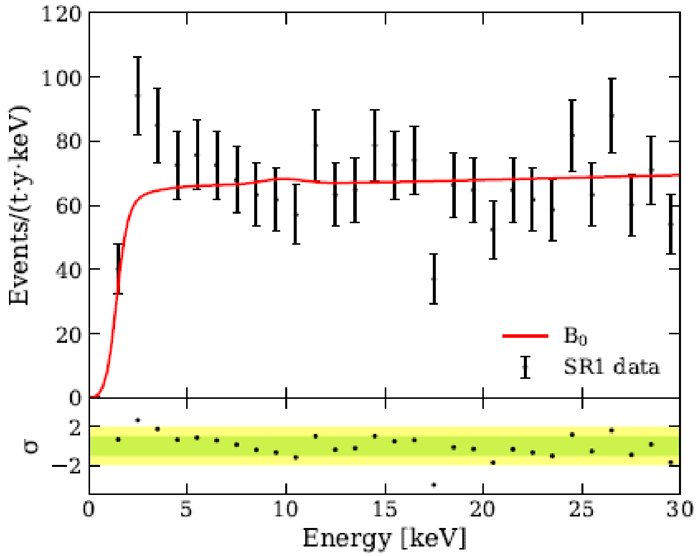
- Super-K has performed the search of boosted DM for $T_e > 100$ MeV   Super-K, 1711.05278

	100 MeV$< E_{vis} <$ 1.33 GeV			1.33 GeV $< E_{vis} <$ 20 GeV			$E_{vis} >$ 20 GeV		
	Data	ν-MC	ϵ_{sig}(0.5 GeV)	Data	ν-MC	ϵ_{sig}(5 GeV)	Data	ν-MC	ϵ_{sig}(50 GeV)
FCFV	15206	14858.1	97.7%	4908	5109.7	93.8%	118	107.5	84.9%
& single ring	11367	10997.4	95.8%	2868	3161.8	93.3%	71	68.2	82.2%
& e-like	5655	5571.5	94.7%	1514	1644.2	93.0%	71	68.1	82.2%
& 0 decay-e	5049	5013.8	94.7%	1065	1207.2	93.0%	13	15.7	82.2%
& 0 neutrons	4042	3992.9	93.0%	658	772.6	91.3%	3	7.4	81.1%

- We take the total measured number of events in the first energy bin, and place a conservative bound on the PBHBDM by using

$$\epsilon \times N_\chi < N_{\rm SK}$$

- Xenon1T and prospect (20 ton·yr)



Xenon1T, 2006.09721

- We place 2σ bound based on a chi2

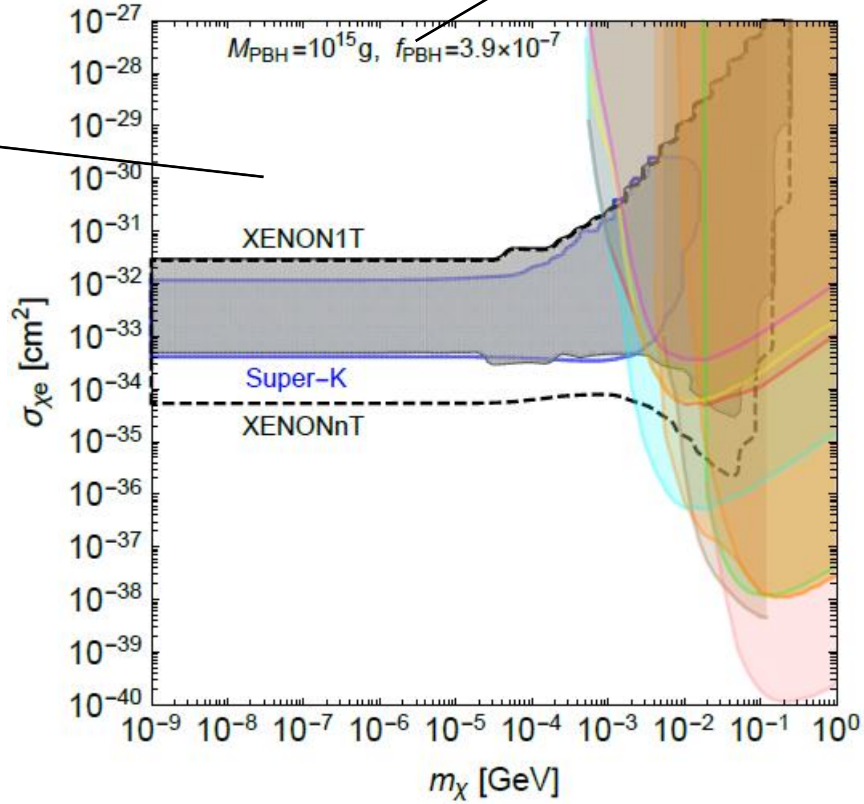
$$\chi^2 = \sum_i \frac{\left[\left(\frac{dR_{\chi+B_0}}{dT_{\rm rec}}\right)_i - \left(\frac{dR_{obs}}{dT_{\rm rec}}\right)_i\right]^2}{\sigma_i^2}$$

Results

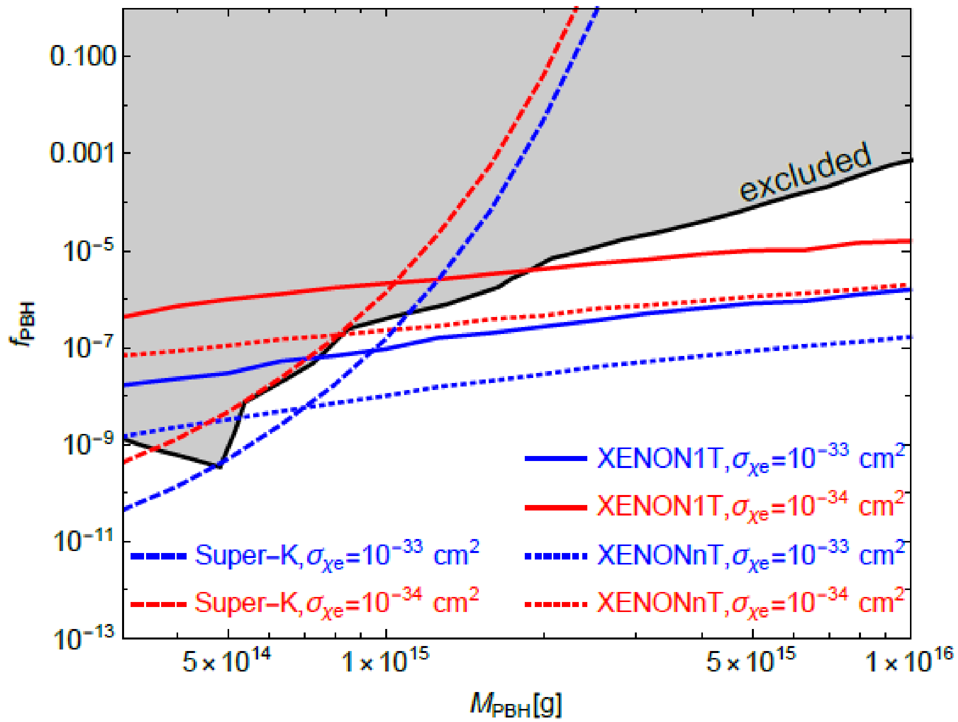
- Parameters: $M_{PBH}, f_{PBH}, m_\chi, \sigma_{\chi e}$

allowed by EG gamma-ray

$\sigma_{\chi e}$ too large to make BDM reach the detector



TL, Jiajun Liao, 2203.14443



TL, Jiajun Liao, 2203.14443

- The f_{PBH} bound can be improved by the terrestrial experiments
- The bounds from Super-K and Xenon1T are complementary

Summary

- The evaporation of PBHs provides a source of light boosted dark matter with energies peaked at $O(10){\sim}O(100)$ MeV.
- Such boosted dark matter can be searched at terrestrial facilities.
- The bounds on DM-electron scattering cross section and f_{PBH} can be improved.

Summary

- The evaporation of PBHs provides a source of light boosted dark matter with energies peaked at $O(10){\sim}O(100)$ MeV.
- Such boosted dark matter can be searched at terrestrial facilities.
- The bounds on DM-electron scattering cross section and f_{PBH} can be improved.

Thank you!