The 9th PIRE - GEMADARC Collaboration Meeting

Search for Boosted keV–MeV Light Dark Matter Particles from Evaporating Primordial Black Holes at CDEX-10

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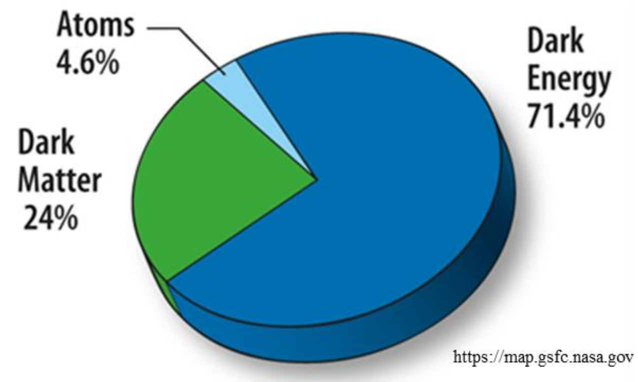
Outline

1.1 Dark Matter

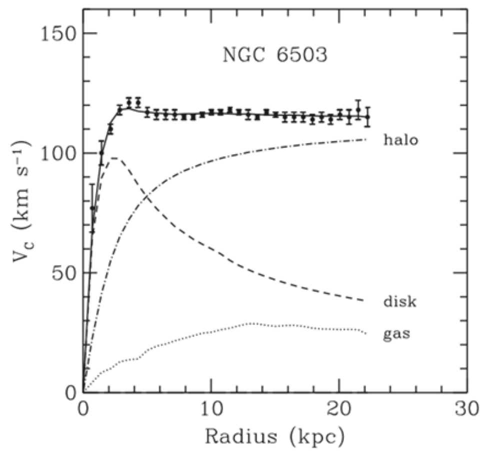
Dark Matter (DM): an indispensable part of the standard cosmological model.

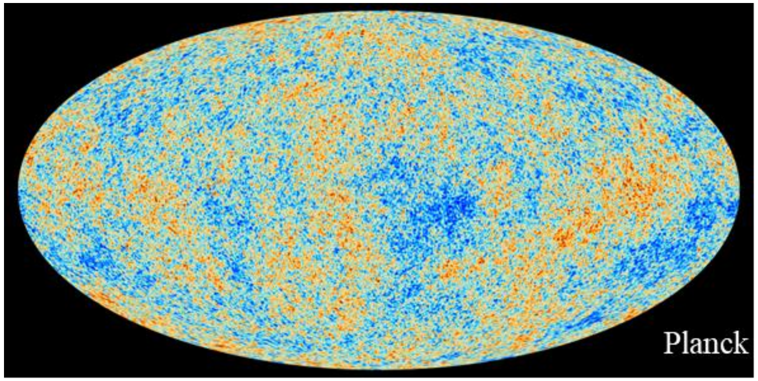


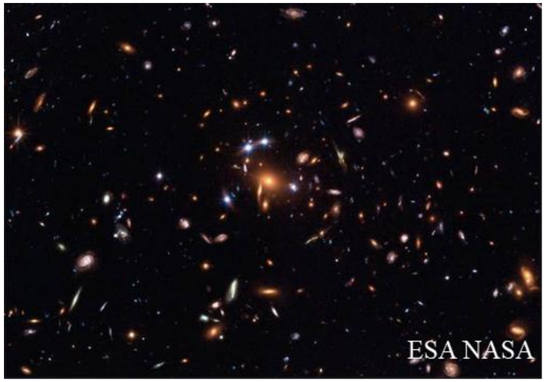
Convincing evidences:

1. Galactic rotation,
2. Bullet Nebula,
3. CMB,
4. Gravitational lens,

……

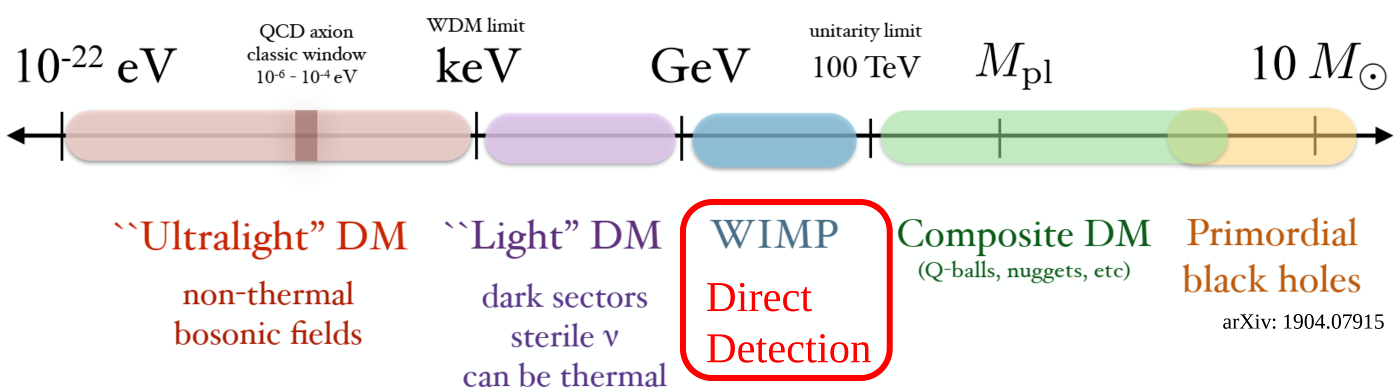






1.2 Dark Matter Direct Detection

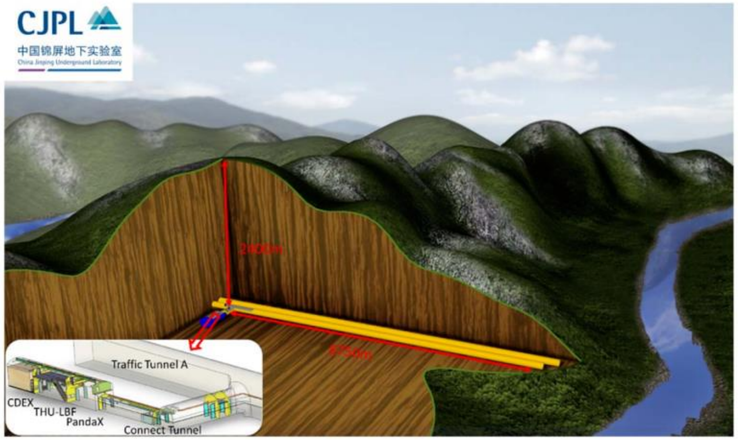
Experiment	Target	Signal	Laboratory
XENON	LXe	Ionization + Scintillation	Gran Sasso
DarkSide	LAr	Ionization + Scintillation	Gran Sasso
KIMS	CsI(Tl)	Scintillation	Y2L
CRESST	$CaWo_4$	Phonon + Scintillation	Gran Sasso
EDELWEISS	Ge	Ionization + Phonon	Modane
PandaX	LXe	Ionization + Scintillation	CJPL
CDEX	Ge	Ionization	CJPL

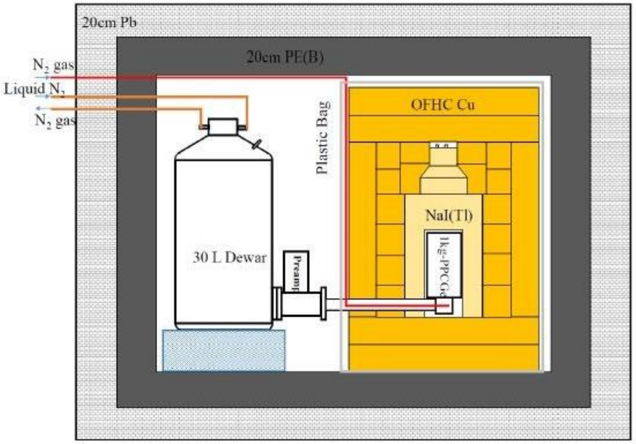


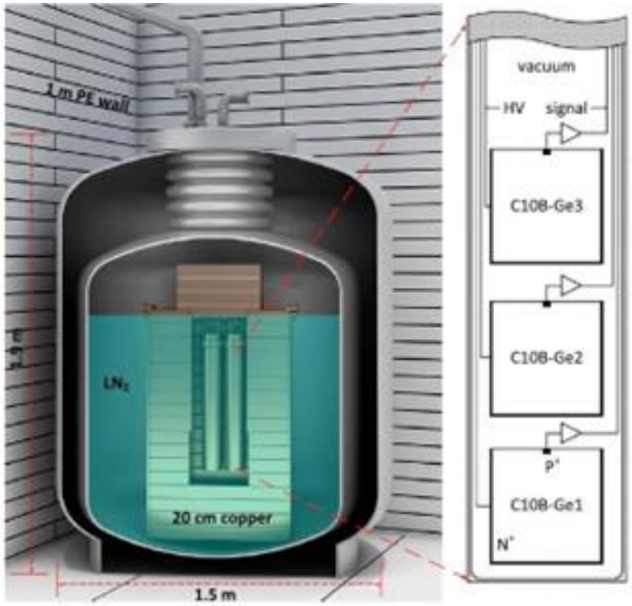
arXiv: 1904.07915

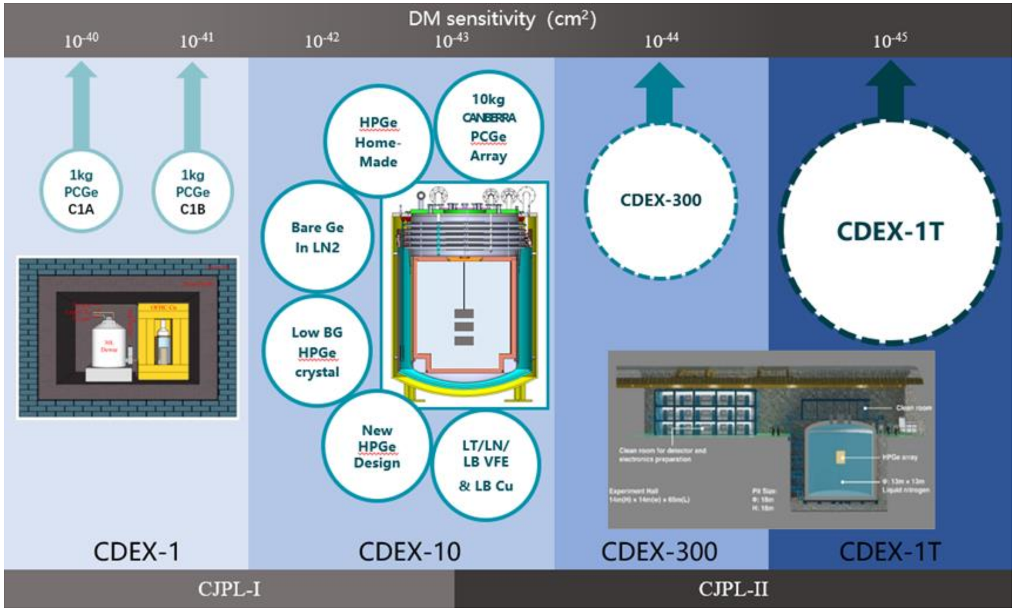
1.3 CDEX (China Dark Matter Experiment)

中国暗物质实验
China Dark matter EXperiment







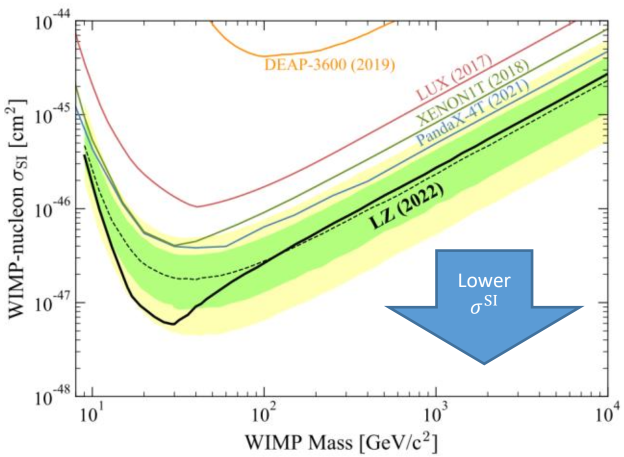


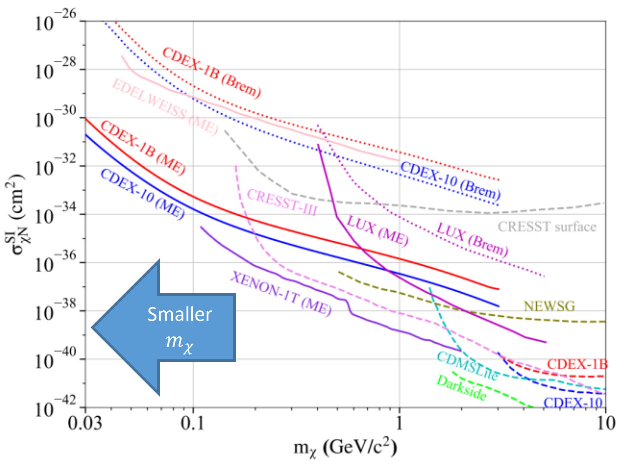
Outline

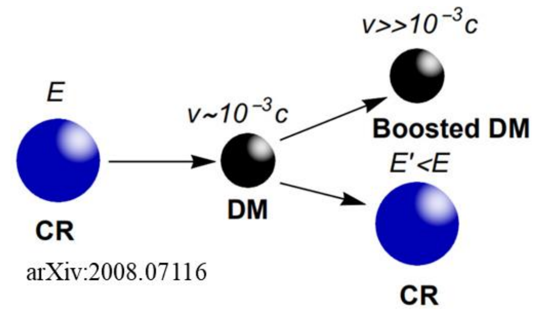
2.1 Boosted Dark Matter

No definite signal has been found in the direct or indirect DM search!

Light dark matter particle: χ







Lower cross section σ_χ? → Lower background? Larger detector?

Lower DM mass m_χ? → Lower threshold? Higher recoil energy?

How?

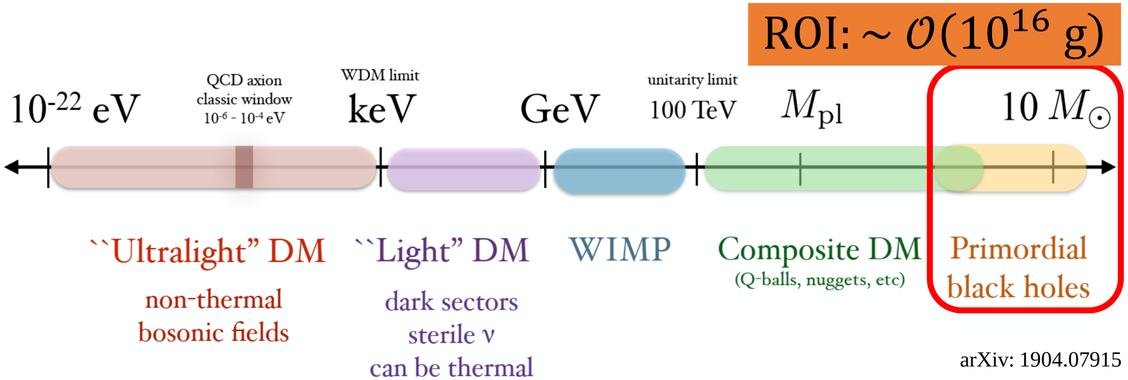
χ boosted by cosmic rays (PROSPECT, PandaX-II and CDEX-10), neutrinos, …

χ boosted via solar reflection

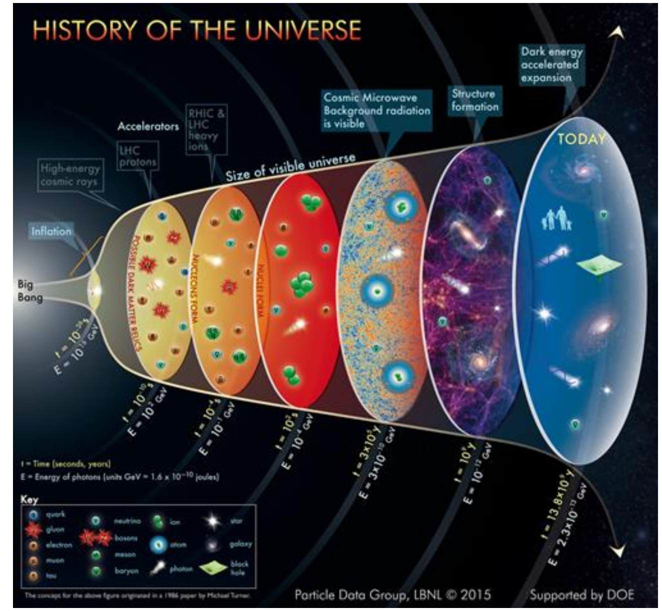
χ from evaporating Primordial Black Holes (PBHs)

2.2 Primordial Black Hole (PBH)

PBH, one of the DM candidates



arXiv: 1904.07915



Two waves of interest in PBH:

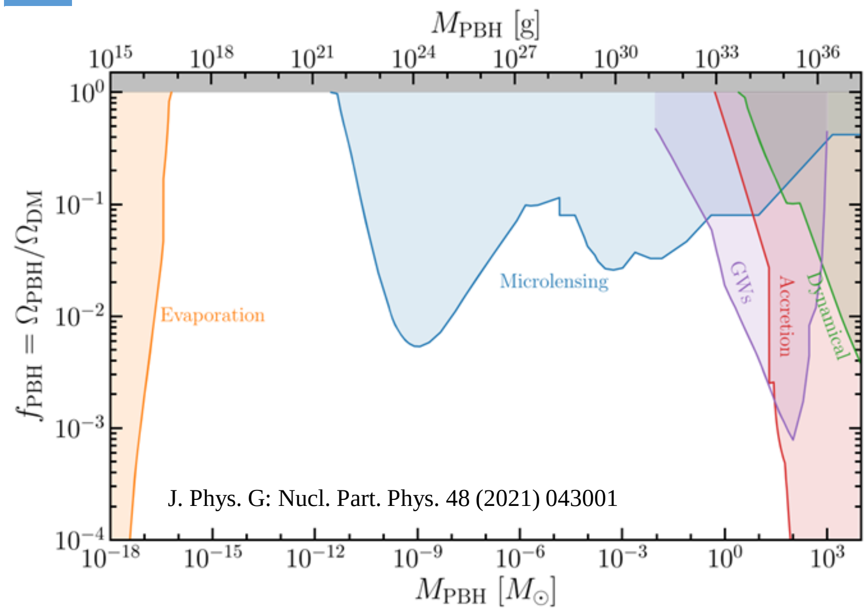
1997, MACHO, $0.5M_\odot$ compact objects excess in the Large Magellanic Cloud microlensing!

2016, LIGO-Virgo: gravitational waves (GW) from mergers of $\sim 10M_\odot$ black holes. These black holes could be primordial rather than astrophysical.

$$\mathrm{ROI}: \sim \mathcal{O}(10^{16}\ \mathrm{g}) \Rightarrow M_{PBH} \sim \frac{c^3 t}{G} \sim 10^{15}\left(\frac{t}{10^{-23}\ \mathrm{s}}\right)\ \mathrm{g} \Rightarrow t \sim 10^{-22}\ \mathrm{s}$$

Formation: gravitational collapse from density fluctuations in the early Universe

2.3 Constraints on PBH



Constraints on evaporating PBHs:

a. Big Bang Nucleosynthesis (BBN)

b. Cosmic Microwave Background (CMB)

c. Extragalactic and Galactic γ-ray backgrounds

d. Extragalactic and Galactic cosmic rays

e. PBH explosions

f. More speculative effects

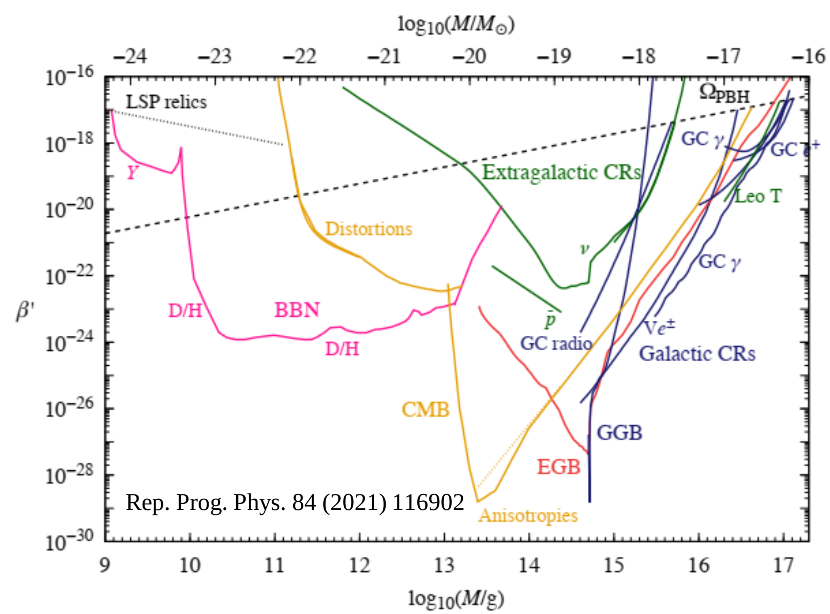
$M_{PBH} \sim 10^{16}$ g ($M_{Halley} \sim 10^{18}$ g)

COMPTEL: Galactic γ-ray backgrounds

Voyager-1: $e^{\pm}$

EDGES: 21 cm

JUNO, SuperK: ν



2.4 Hawking Radiation

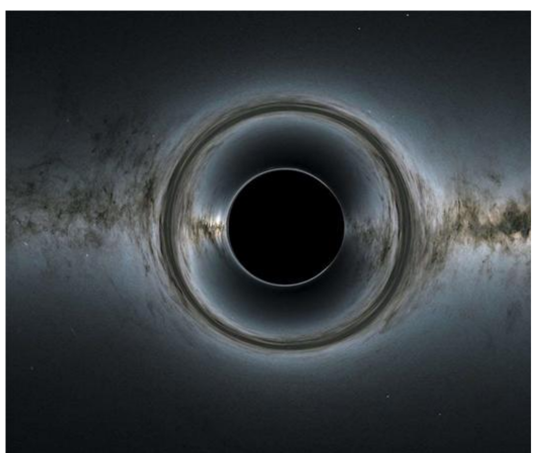
Hawking Radiation: Stephen Hawking, Quantum Field Theory + General Relativity, BHs Emit radiation as black bodies and lose their masses, reaching the Planck mass.

CHARYBDIS (2003) and *BlackMax* (2008): compute the spectrum of particles generated by the evaporation of higher-dimensional BHs in a LHC-like detector.

PYTHIA， *HERWIG* and *Hazma*: particle physics codes compute the secondary spectra

A distribution of BHs in the universe？ Analytical approximations…

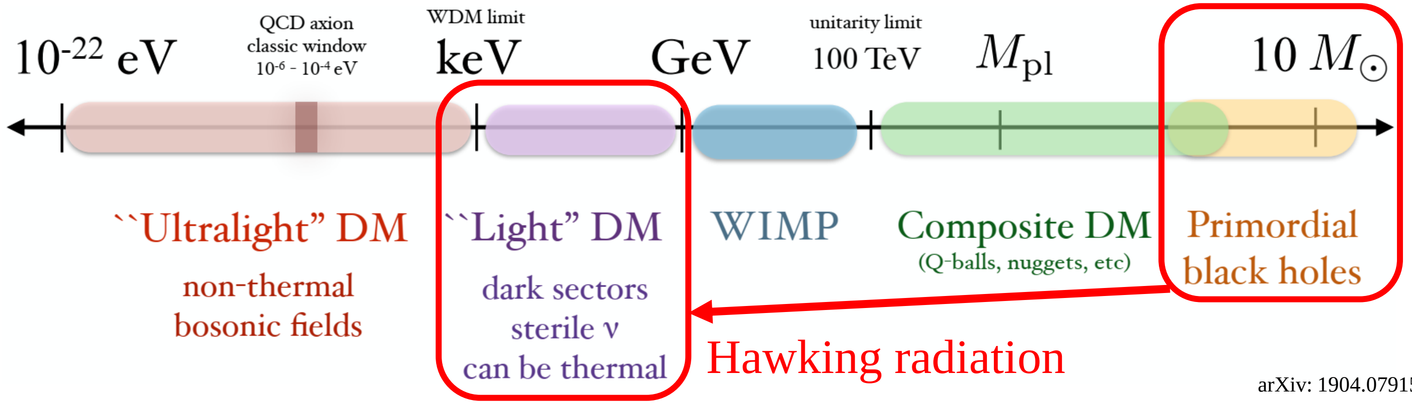
May 2019, *BlackHawk v1* released. Oct 2021, *BlackHawk v2*: BSM have been added!



HR
- SM: γ, ν, ...
- BSM: χ, Axion, ALP

2.5 Motivation

ROI: $\sim \mathcal{O}(10^{-18}\, M_{\odot})$



In BSM particle detection:

A novel boosted source

For Hawking radiation searching:

A novel direct searching object

Jan 2022, Calabrese et al., XENON-1T, PBH→χ→N.

May 2022, Calabrese et al., XENON-1T, Super-K, PBH→χ→e.

Sep 2022, Li et al., XENON-1T, Super-K, PBH→χ→e.

Axion(-like): Super-K, Hyper-K (2022); e-ASTROGAM, AMEGO (2023).

Outline

PART ONE **Dark Matter and Experiments**

PART TWO **Motivation**

PART THREE **Expected Energy Spectra**

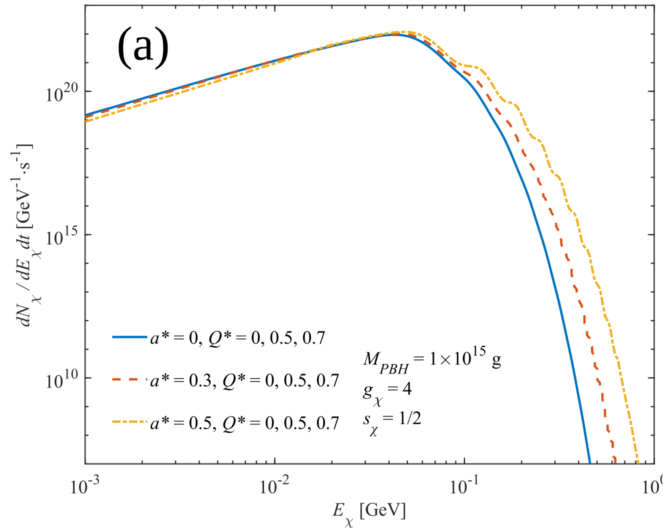
PART FOUR **Constraint Results**

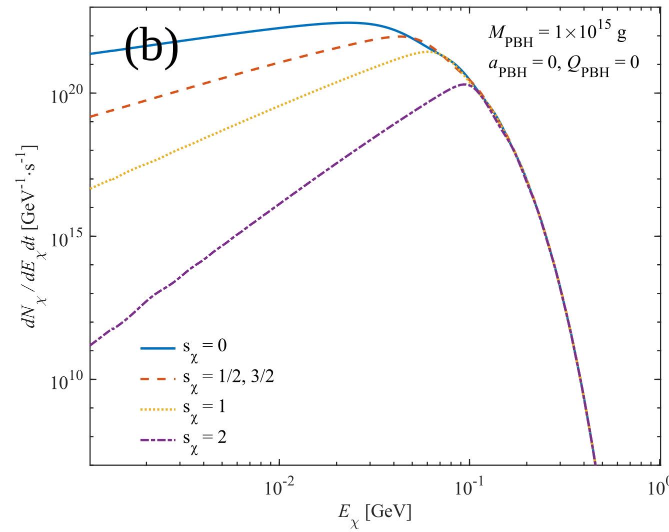
3.1 χ Spectra from Evaporating PBHs

Hawking temperature: $T_{PBH} = \frac{\hbar c^3}{8\pi G M_{PBH} k_B}$ (1)

Public code: *Blackhawk-v2.1*

Emission Rate: $\frac{d^2 N_\chi}{dE_\chi dt} = \frac{g_\chi}{2\pi} \frac{\Gamma_\chi(E_\chi, M_{PBH})}{exp(E_\chi / k_B M_{PBH}) + 1}$ (2)





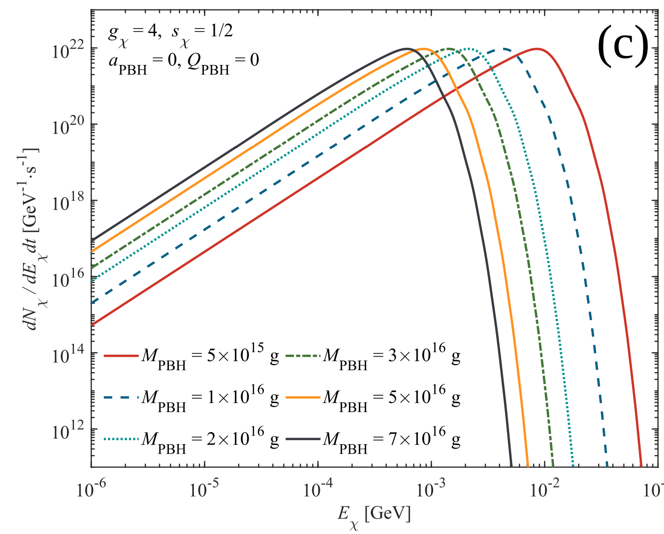
(a) PBHs with larger spins have harder spectra

(b) Fermion χ with different spins, the same spectra

χ: Dirac fermion, degrees of freedom $g_\chi = 4$

PBH: chargeless and spinless

(c) Larger M_{PBH}, softer spectrum



3.2 χ Flux Reaching Earth

$$\frac{d^2\phi_\chi}{dT_\chi d\Omega} = \frac{d^2\phi_\chi^{MW}}{dT_\chi d\Omega} + \frac{d^2\phi_\chi^{EG}}{dT_\chi d\Omega} \quad (3)$$

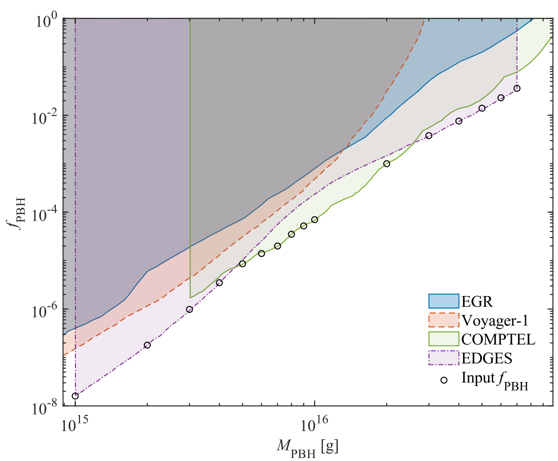
$$\frac{d^2\phi_\chi^{MW}}{dT_\chi d} = \frac{1}{4\pi}\frac{f_{PBH}}{M_{PBH}}\int\frac{d\Omega_s}{4\pi}\int dl\rho_{MW}^{\mathrm{NFW}}[r(s,\phi)]\frac{d^2N_\chi}{dT_\chi dt} \quad (4)$$

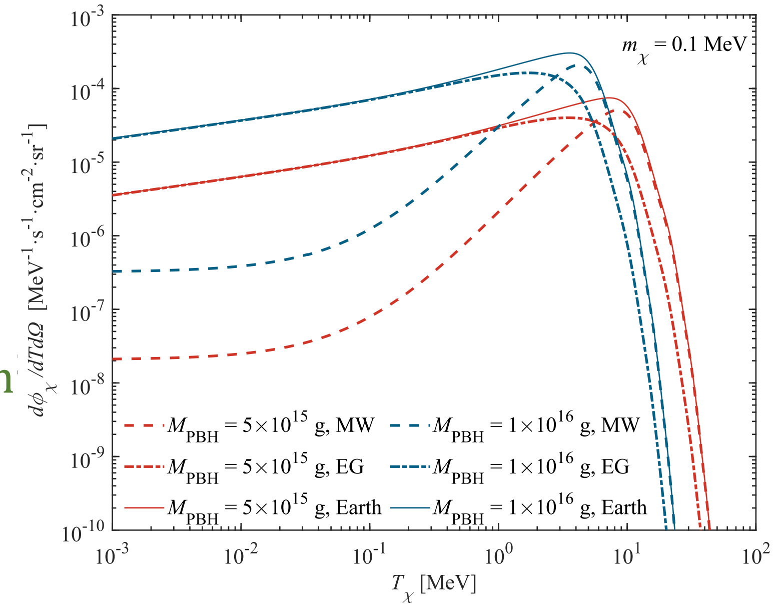
Navarro-Frenk-White DM Profile, $\rho_\chi = 0.4$ GeV/cm

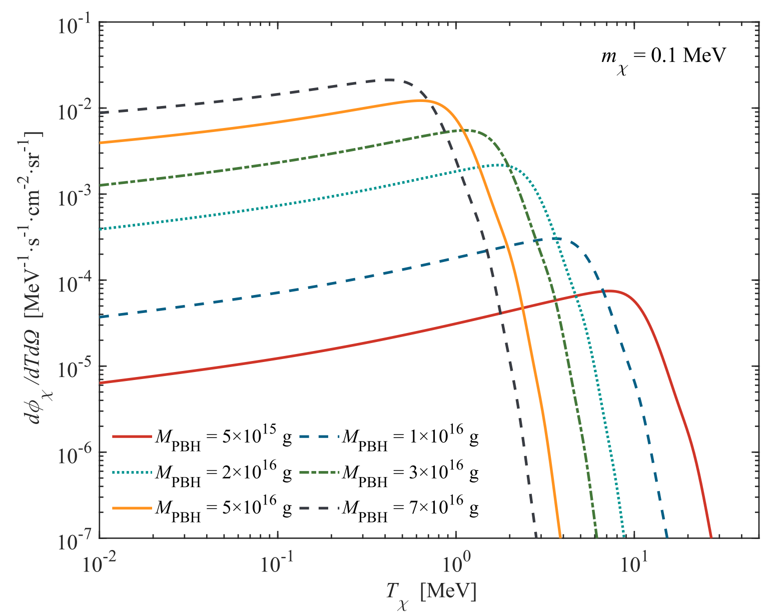
$$\frac{d^2\phi_\chi^{EG}}{dT_\chi d\Omega} = \frac{f_{PBH}\rho_{DM}}{4\pi M_{PBH}}\int dt[1+z(t)]\frac{d^2N_\chi}{dT_\chi dt} \quad (5)$$

$\rho_{DM} = 2.35 \times 10^{-30}$ g/cm^3,

t: the time of matter-radiation equality → now。







3.3 Earth Attenuation

Ballistic-Trajectory Approximation (BTA)

$$T_d(T_0) = \frac{2m_\chi T_0}{2m_\chi e^\tau - T_0(1+e^\tau)} \quad (6)$$

where, $\tau = d/l$, $d = 2400$ m。

$$l = \left[\sum_N n_N \sigma_{\chi N} \frac{2m_N m_\chi}{(m_N+m_\chi)^2}\right]^{-1} \quad (7)$$

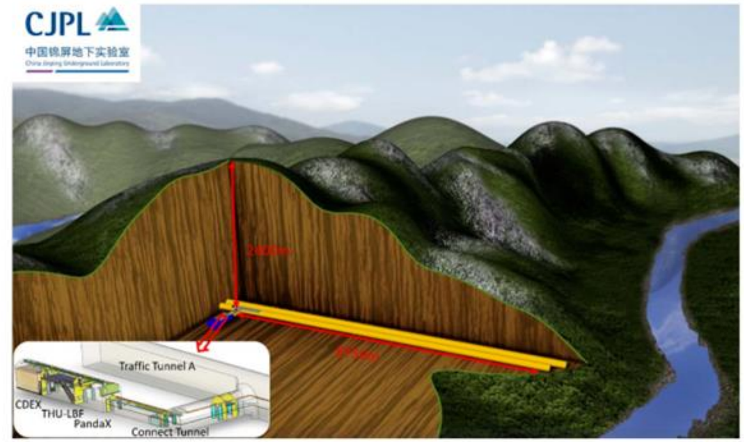
The rocks parameters:

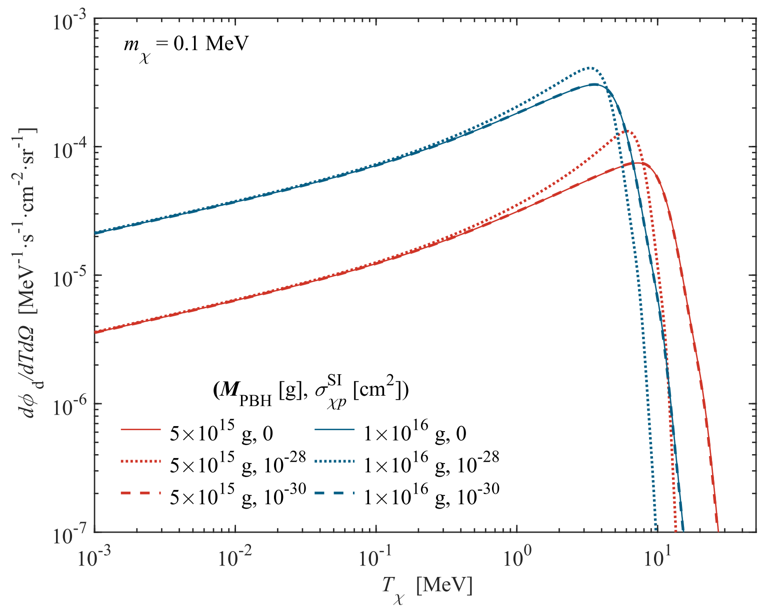
[Phys. Rev. D 105, 052005 (2022)].

$$\sigma_{\chi N} = \sigma_{\chi p}^{\mathrm{SI}} A_N^2 \left[\frac{m_N(m_\chi+m_p)}{m_p(m_\chi+m_N)}\right]^2 \quad (8)$$

The χ flux arriving at the CJPL:

$$\frac{d^2\phi_\chi^d}{dT_d d\Omega} \approx \frac{4m_\chi^2 e^\tau}{(2m_\chi+T_d-T_d e^\tau)^2}\left(\frac{d^2\phi_\chi}{dT_0 d\Omega}\right) \quad (9)$$





3.4 Nuclear Recoil Spectra

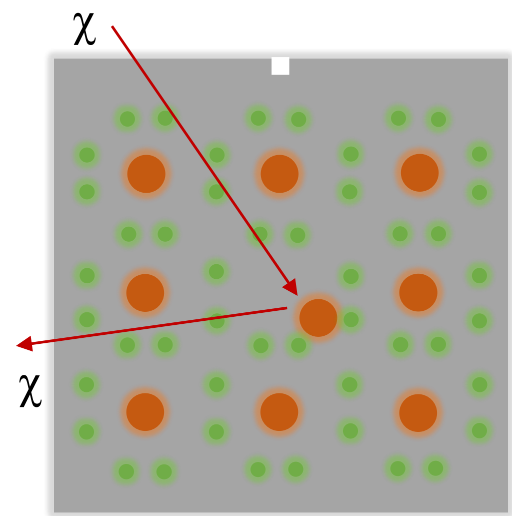
The differential nuclear recoil event rate:

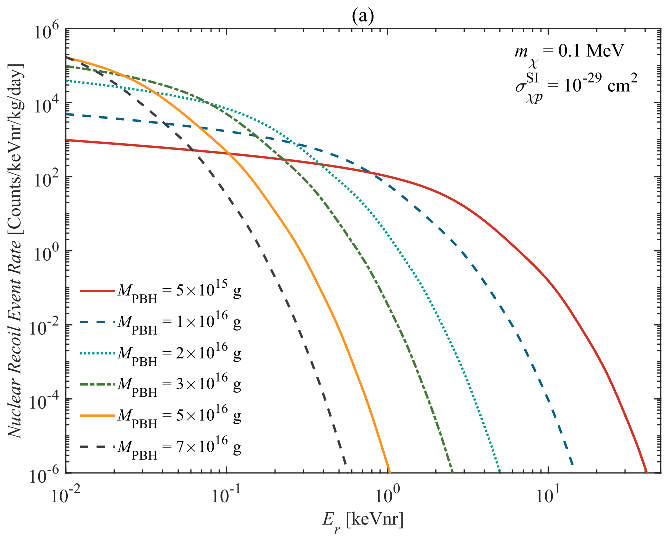
$$\frac{dR}{dE_r}(E_r) = \sigma_{\chi Ge} N_{Ge} \int dT_d d\Omega \, \frac{d^2\phi_\chi^d}{dT_d d\Omega} \frac{\Theta(E_r^{max} - E_r)}{E_r^{max}} \quad (10)$$

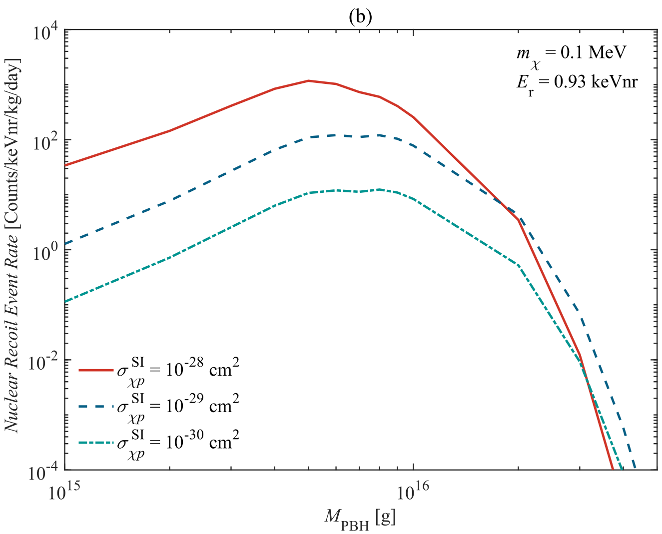
$$\sigma_{\chi Ge} = F^2(E_r)\sigma_{\chi p}^{\rm SI} A_{Ge}^2 \left[\frac{m_{Ge}(m_\chi + m_p)}{m_p(m_\chi + m_{Ge})}\right]^2 \quad (11)$$

$F(E_r)$ is Helm form factor,

$$E_r^{max} = \frac{T_d^2 + 2m_\chi T_d}{T_d + (m_\chi + m_{Ge})^2/(2m_{Ge})} \quad (12)$$







3.5 Excepted Observed Spectra

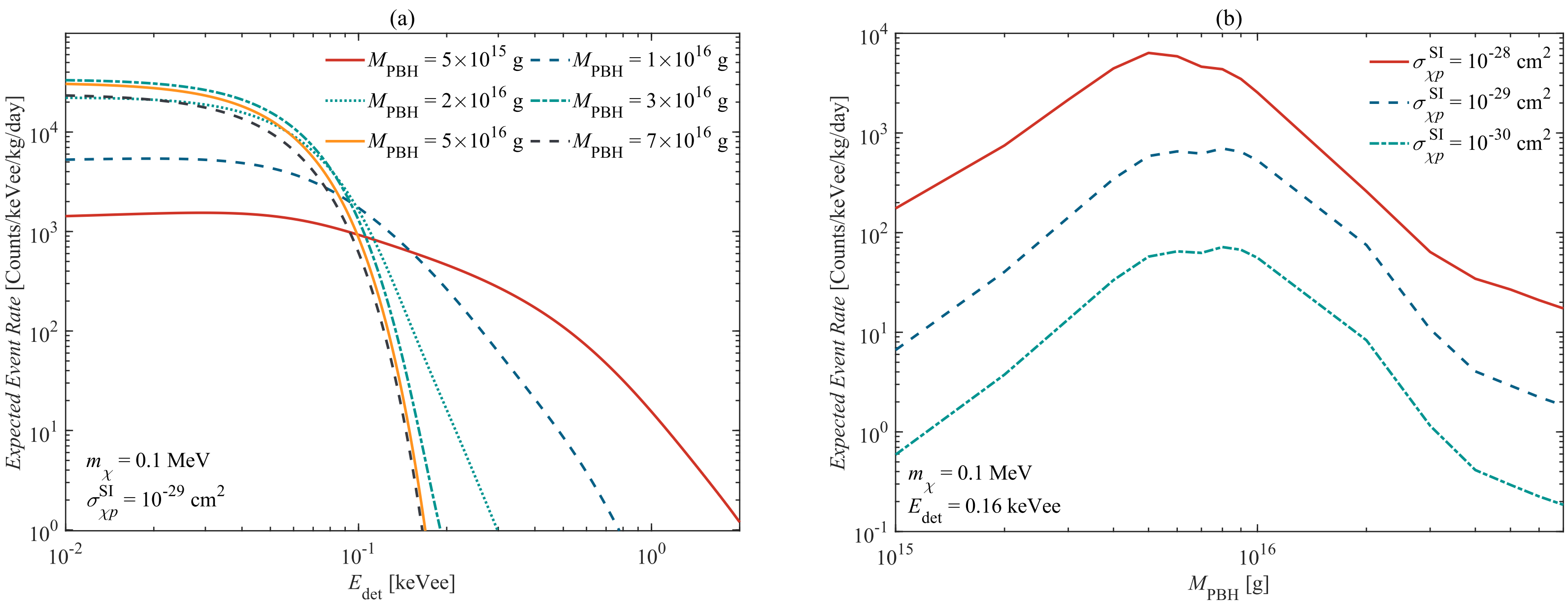
$E_{det} = f_{nr} \cdot E_r$

Quenching factor f_{nr}: Lindhard, $\kappa = 0.16$

The differential energy deposition event rate:

$$\frac{dR}{dE_{det}} = \frac{dR}{dE_r} \cdot \left(\frac{df_{nr}}{dE_r} \cdot E_r + f_{nr}\right)^{-1} \quad (13)$$

CDEX-10 Energy Resolution: $std = 35.8 + 16.6 \times E(\mathrm{keV})^{1/2}$ (eV).



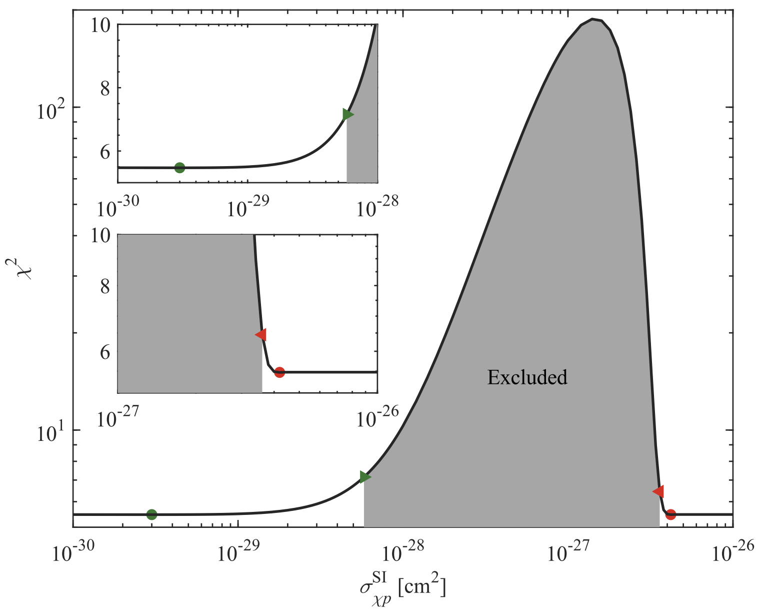
Outline

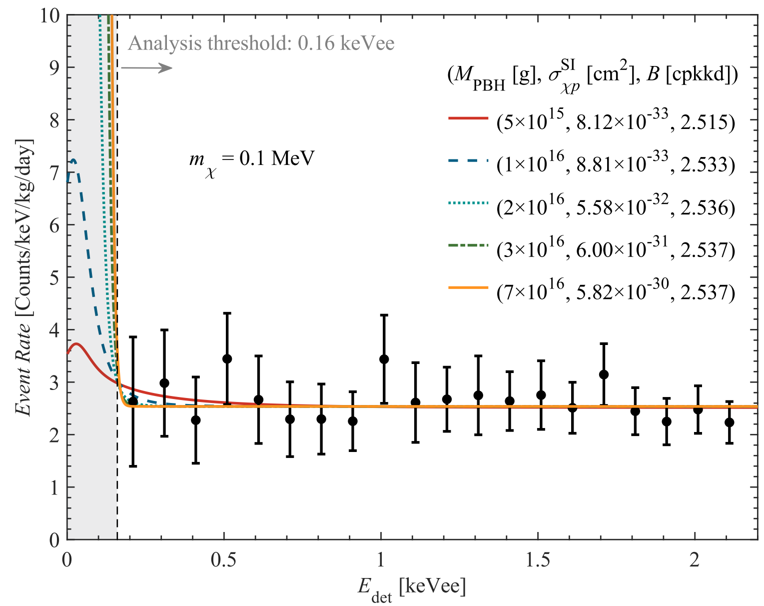
4.1 Spectra Comparison

$$\chi^2\left(M_{PBH}, f_{PBH}, m_\chi, \sigma_{\chi p}^{SI}\right) = \sum_i \frac{\left[n_i - B - S_i\left(M_{PBH}, f_{PBH}, m_\chi, \sigma_{\chi p}^{SI}\right)\right]^2}{\Delta_i^2} \quad (14)$$

Feldman-Cousins χ^2, One-side 90% C.L.

CDEX-10: $BKG \sim 2.5$ cpkkd, 205.4 kg · day





4.2 Constraints – $(m_\chi, \sigma_{\chi p}^{SI})$

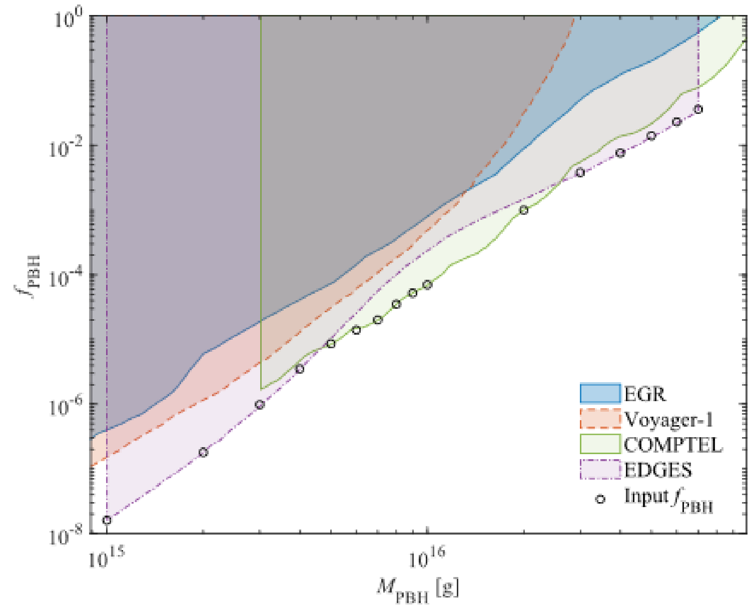
$\chi^2(M_{PBH}, f_{PBH}, m_\chi, \sigma_{\chi p}^{SI})$

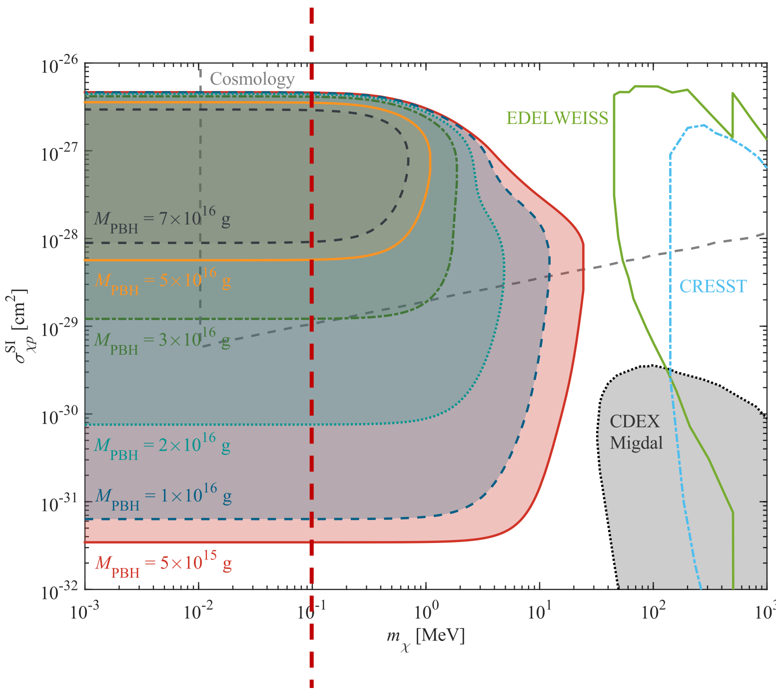
(M_{PBH}, f_{PBH}) from COMPTEL and EDGES

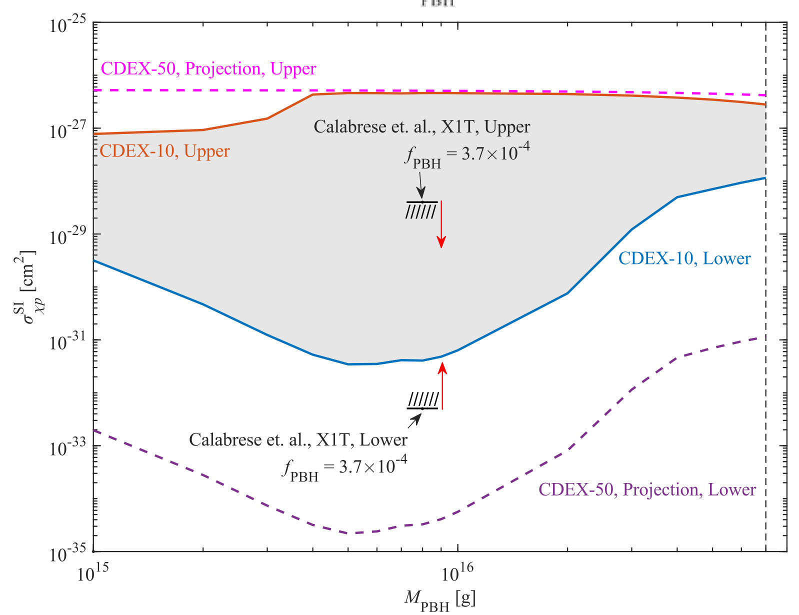
CDEX gives $(m_\chi, \sigma_{\chi p}^{SI})$ now

CDEX-10: 205.4 kg · day， $BKG \sim$ 2.5 cpkkd；

CDEX-50: 50 kg · yr , $BKG \sim$ 0.01 cpkkd。



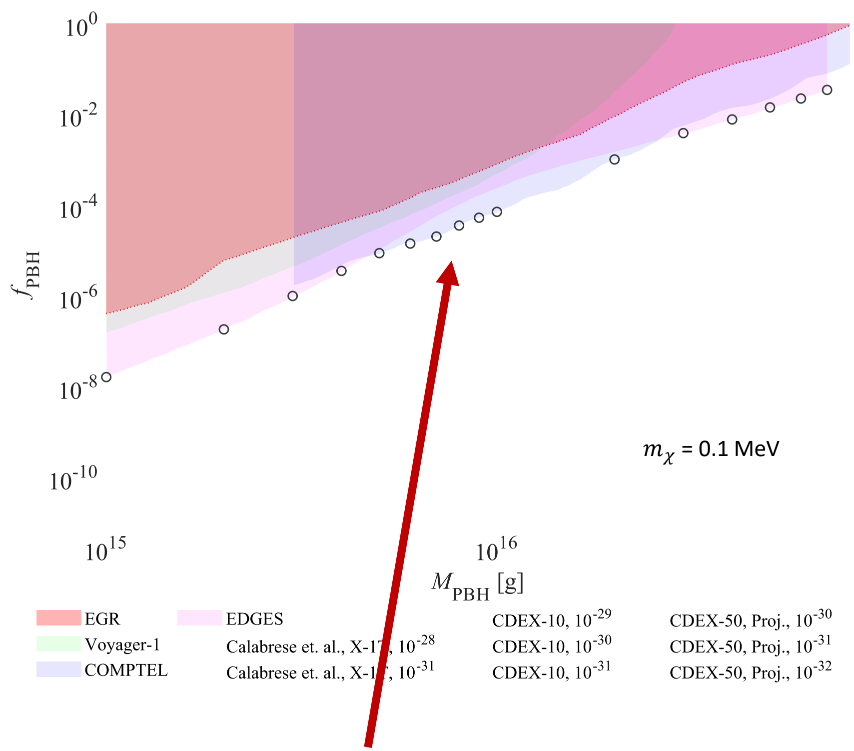




4.3 Constraints - (M_{PBH}, f_{PBH})

$\chi^2\left(M_{PBH}, f_{PBH}, m_\chi, \sigma_{\chi p}^{\text{SI}}\right)$

If $\left(m_\chi, \sigma_{\chi p}^{\text{SI}}\right)$ is known in the future, (M_{PBH}, f_{PBH}) will be limited.



CDEX-10 performs better at $M_{\rm PBH} \gtrsim 8 \times 10^{15}$ g.

CDEX-50, lower background and larger exposure: explore the larger PBH.

Thanks for your attention!

arXiv: 2211.07477

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