The 7th KMI International Symposium on
"Quest for the Origin of Particles and the Universe" (KMI2026)
2026.11.10

Indirect Search of Dark Matter and its Implications

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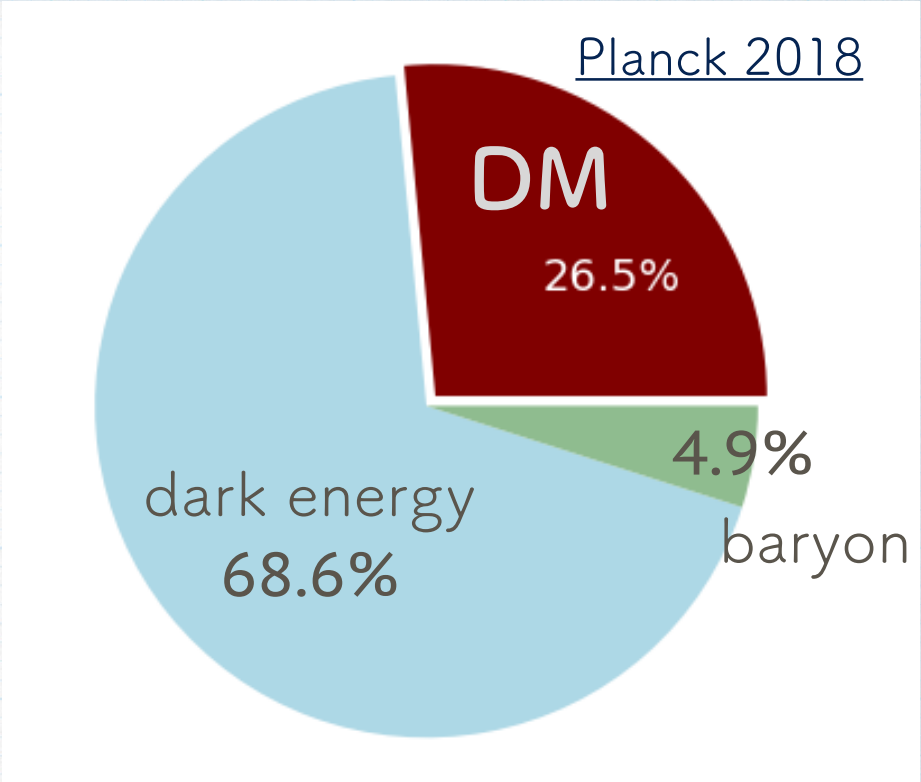
Contents:

1. basics concepts
2. further possibilities
3. connections to related fields
4. our understanding and future

1. basic concepts

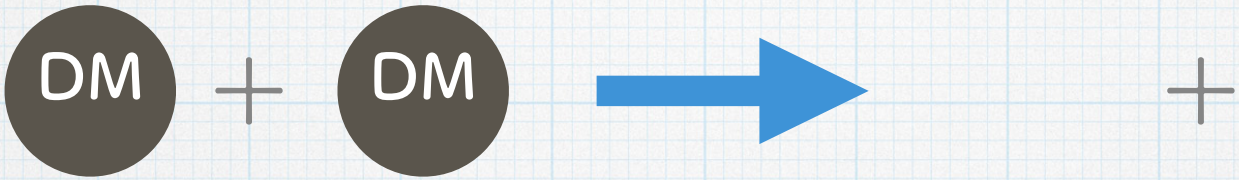
Indirect search:

- **basic idea:**
  Looking for signatures of DM interactions in astronomical/ astrophysical/ cosmological observables
- **advantages**
  - in alignment with original motivation for DM
  - plenty of DM in the Universe
  - wide coverage in mass/energy scale

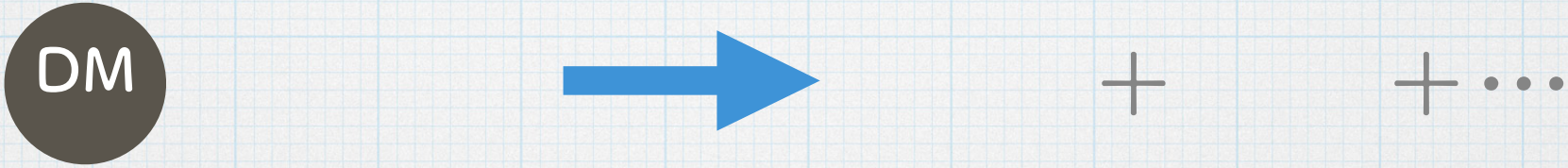


patterns:

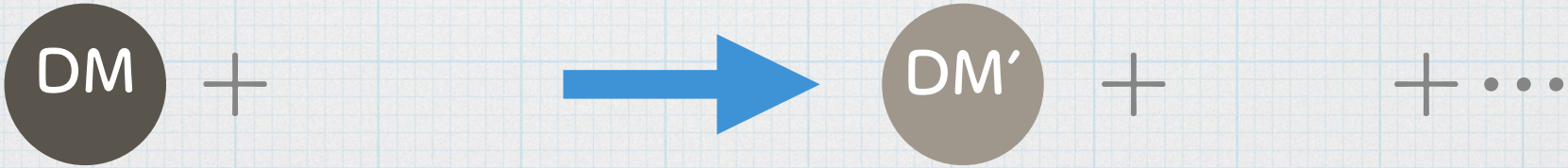
- annihilation:



- decay:



- conversion



general procedure

- annihilation:

$$\phi_i = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_\chi^2}\int_{E_{\rm th}}^{m_\chi} b_f \frac{dN_{i,f}}{dE}dE \cdot \int_{\Delta\Omega} d\Omega \int_{l.o.s} ds \rho_\chi^2$$

- decay:

$$\phi_i = \frac{1}{4\pi\tau}\frac{1}{m_\chi}\int_{E_{\rm th}}^{m_\chi} b_f \frac{dN_{i,f}}{dE}dE \cdot \int_{\Delta\Omega} d\Omega \int_{l.o.s} ds \rho_\chi$$

- conversion: e.g. ALP-photon conversion

$$F_{\rm obs}(E_\gamma) = \left[1 - \frac{\mathscr{A}}{1+(\epsilon/E)^2}\right] F_0, \quad \epsilon = \frac{m_a^2}{2g_{a\gamma}B}, \quad F_0 = kE_\gamma^{-\Gamma}$$

general procedure

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astrophysical knowledge required

construction of strategy

- **probe**

  γ-ray, neutrino, cosmic ray, gravitational wave

- **region**

  Sun, astrophysical objects, dwarf satellite, Galactic Center, galaxy clusters, isotropic emission,…

- **time interval**

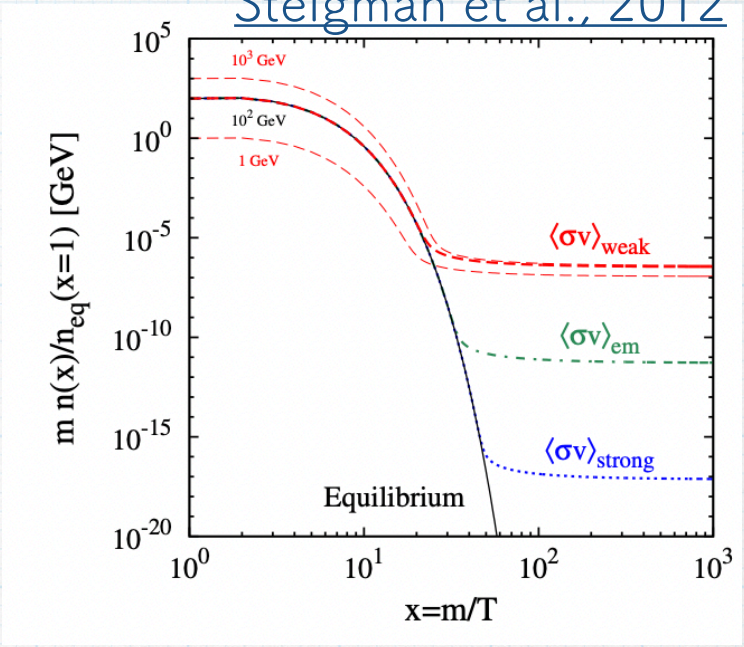
  static, transient

benchmark: WIMP

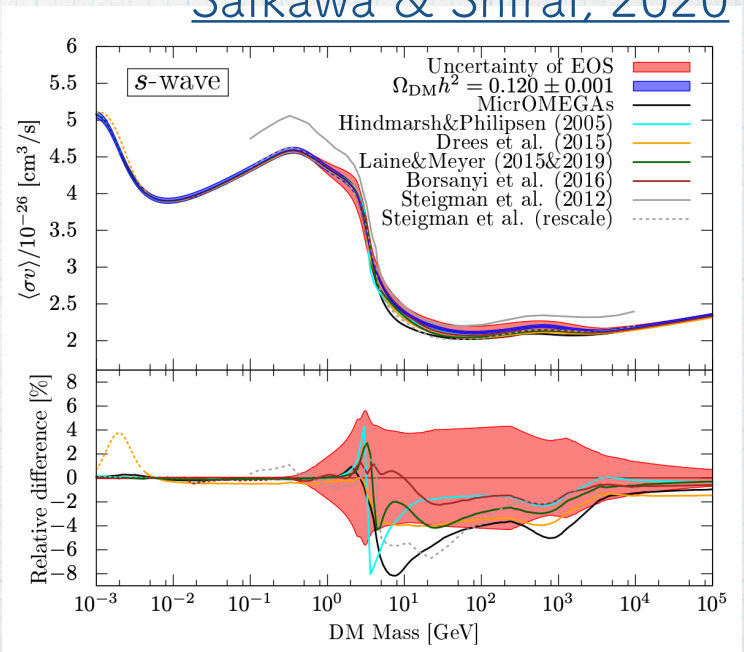
- the mass $m_{\mathrm{DM}} \sim \mathcal{O}(\mathrm{GeV}) - \mathcal{O}(\mathrm{TeV})$
- freeze-out scenario to achieve the relic abundance $\Omega_{\mathrm{DM}}h^2 \sim 0.12$
- the annihilation cross-section $\langle \sigma v \rangle \sim \mathcal{O}(10^{-26}\mathrm{cm}^3 s^{-1})$
- DM + DM ↔ SM + SM

looking for annihilation signal

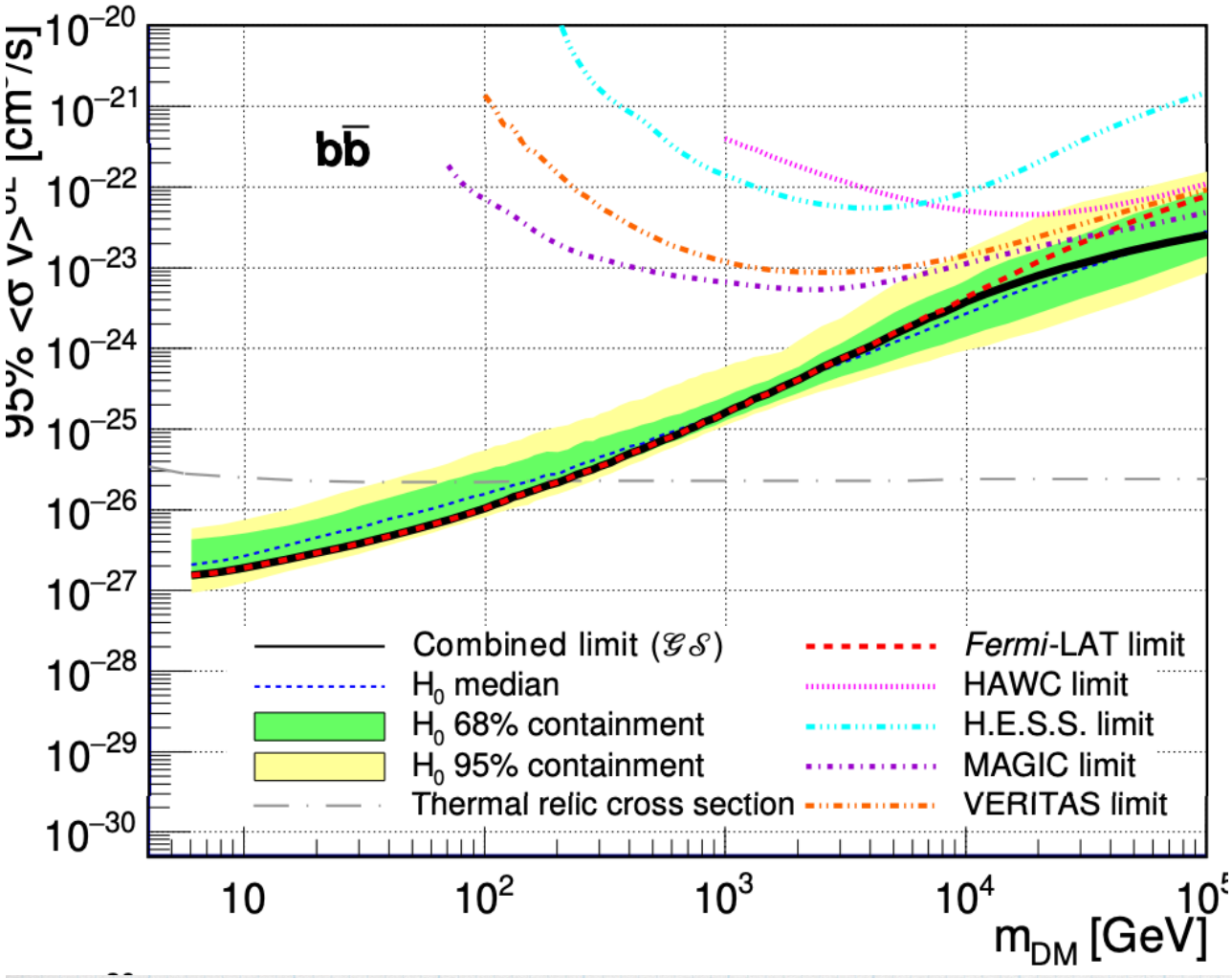
Steigman et al., 2012



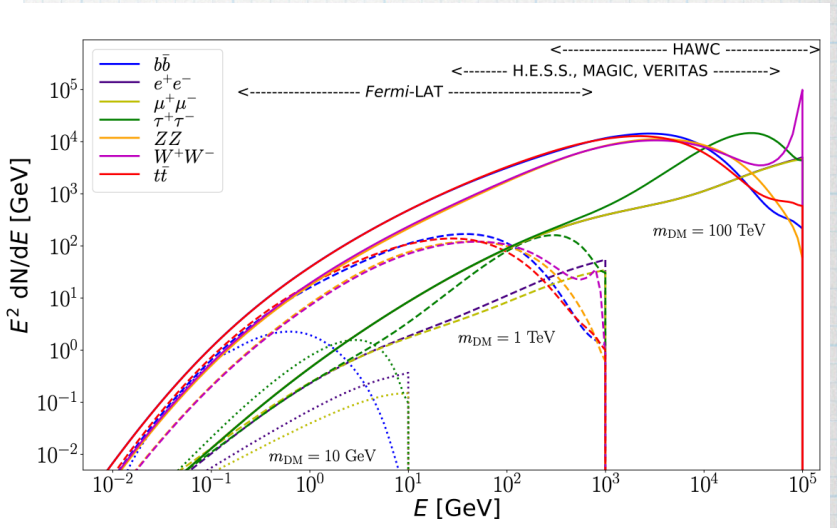
Saikawa & Shirai, 2020



γ-ray (dwarf spheroidal galaxies)



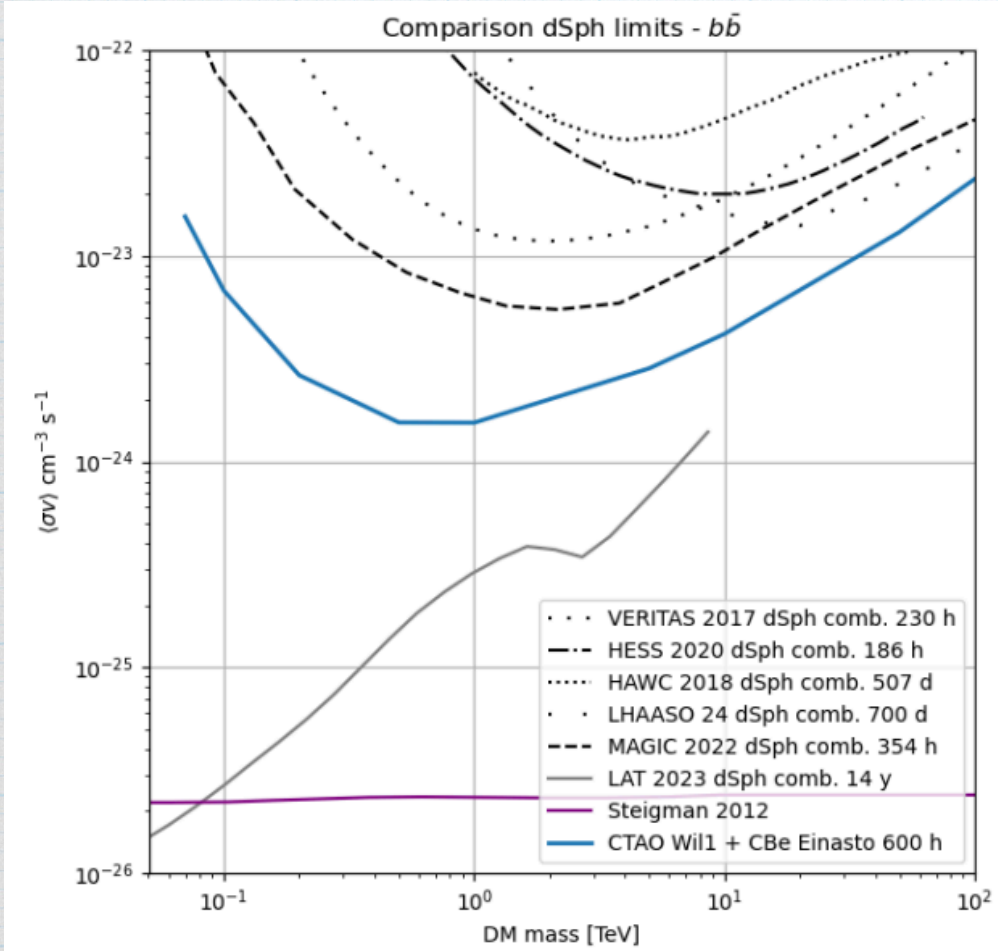
<u>The Fermi-LAT collaboration, the HAWC collaboration, the H.E.S.S. collaboration, the MAGIC collaboration and the VERITAS collaboration, 2026</u>

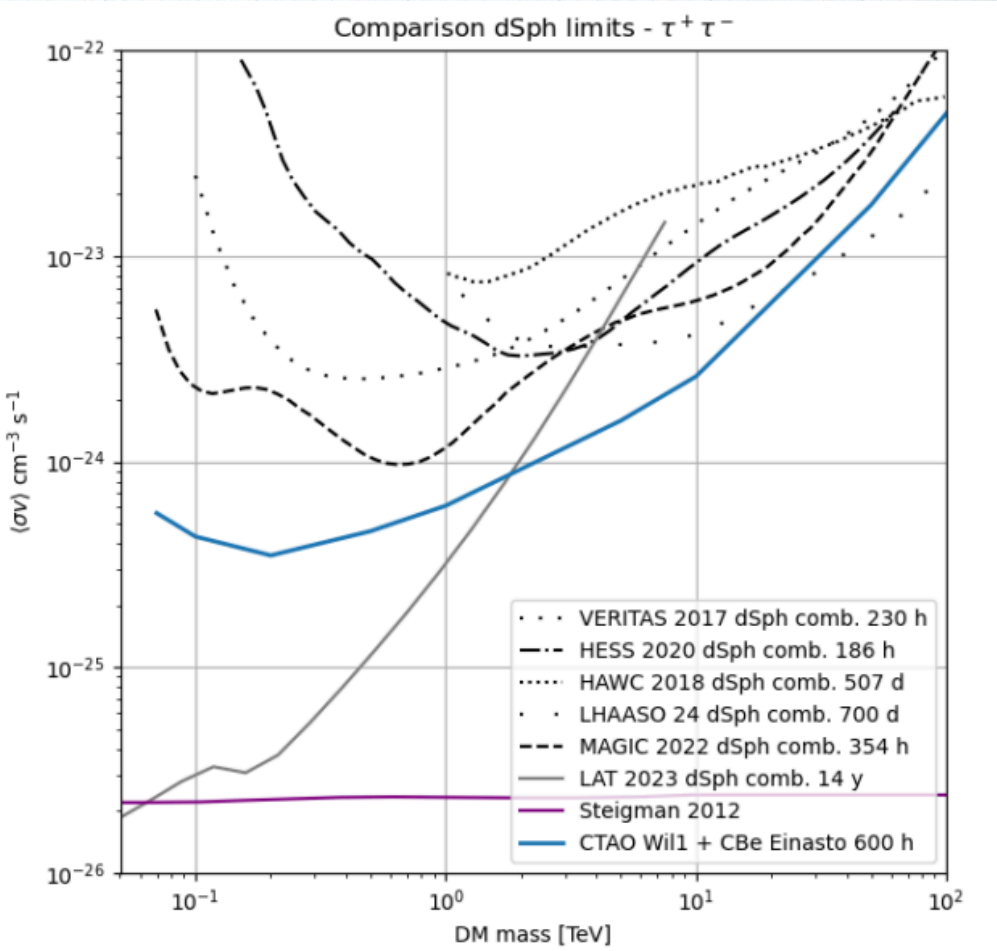


5 facilities, 20 dSphs combined (624h from IACT+Fermi-LAT+HAWC)

γ-ray (dwarf spheroidal galaxies)

CTAO collaboration, 2025

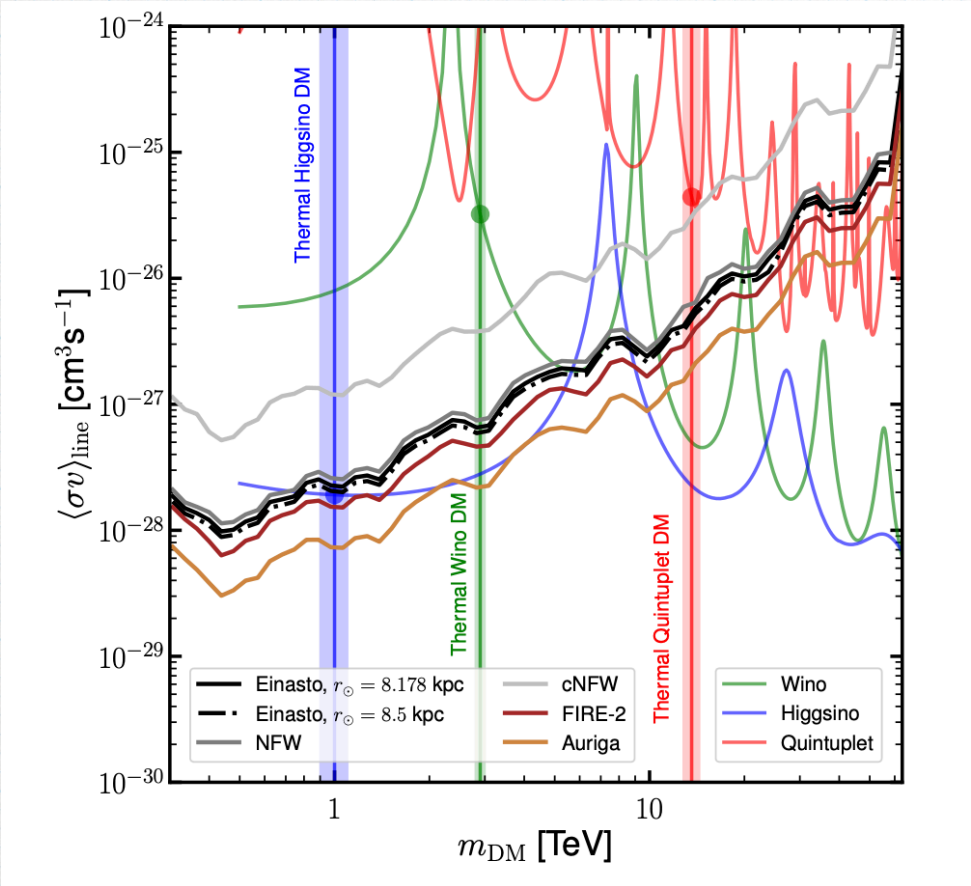




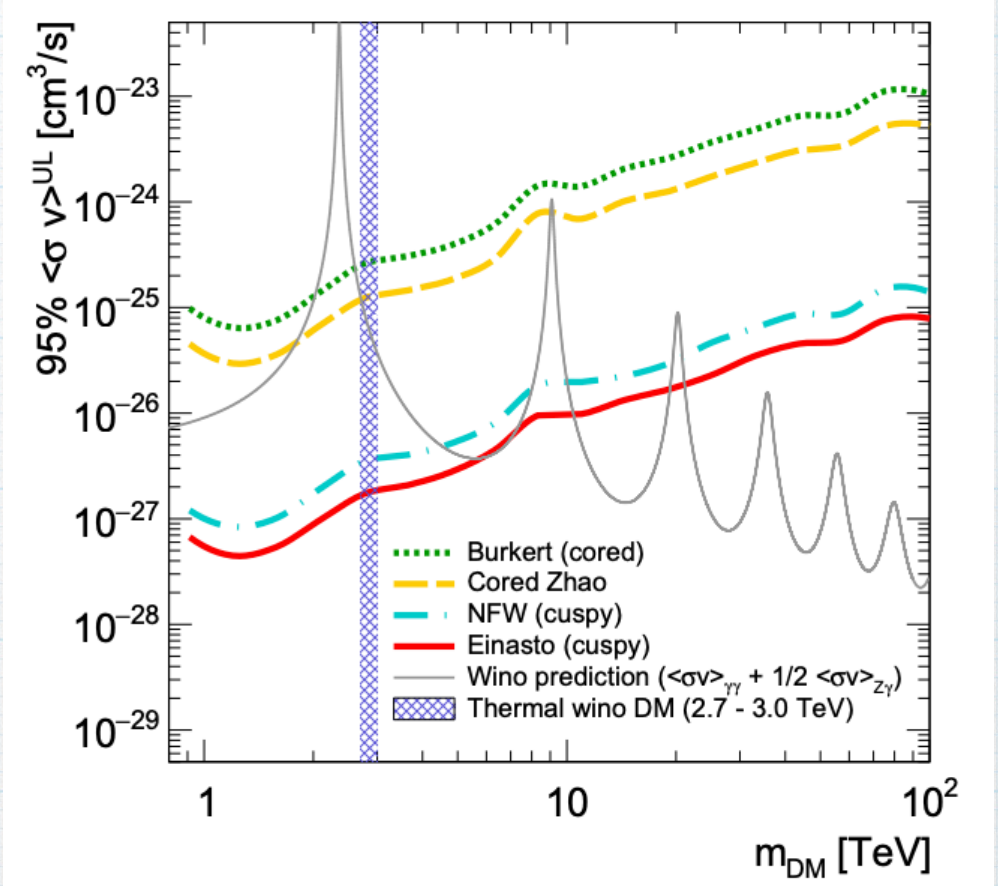
Prospects with Cherenkov Telescope Array Observatory

γ-ray (Galactic Center)

H.E.S.S. 2026



MAGIC 2022



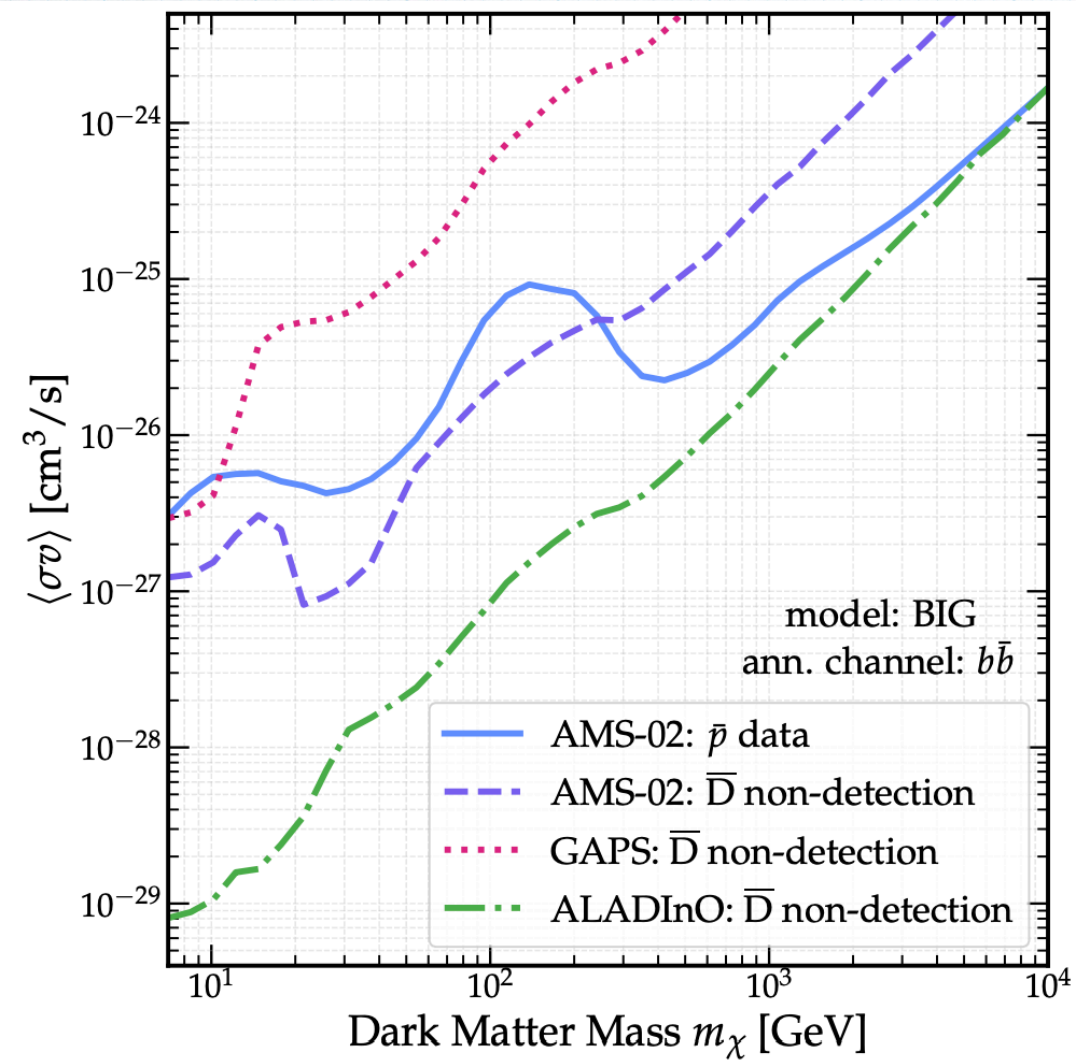
H.S.S.S. 546h

MAGIC 223h

monochromatic photon search → neutralino tests

cosmic-ray (anti-nucleon)

Stefanuto et al., 2026



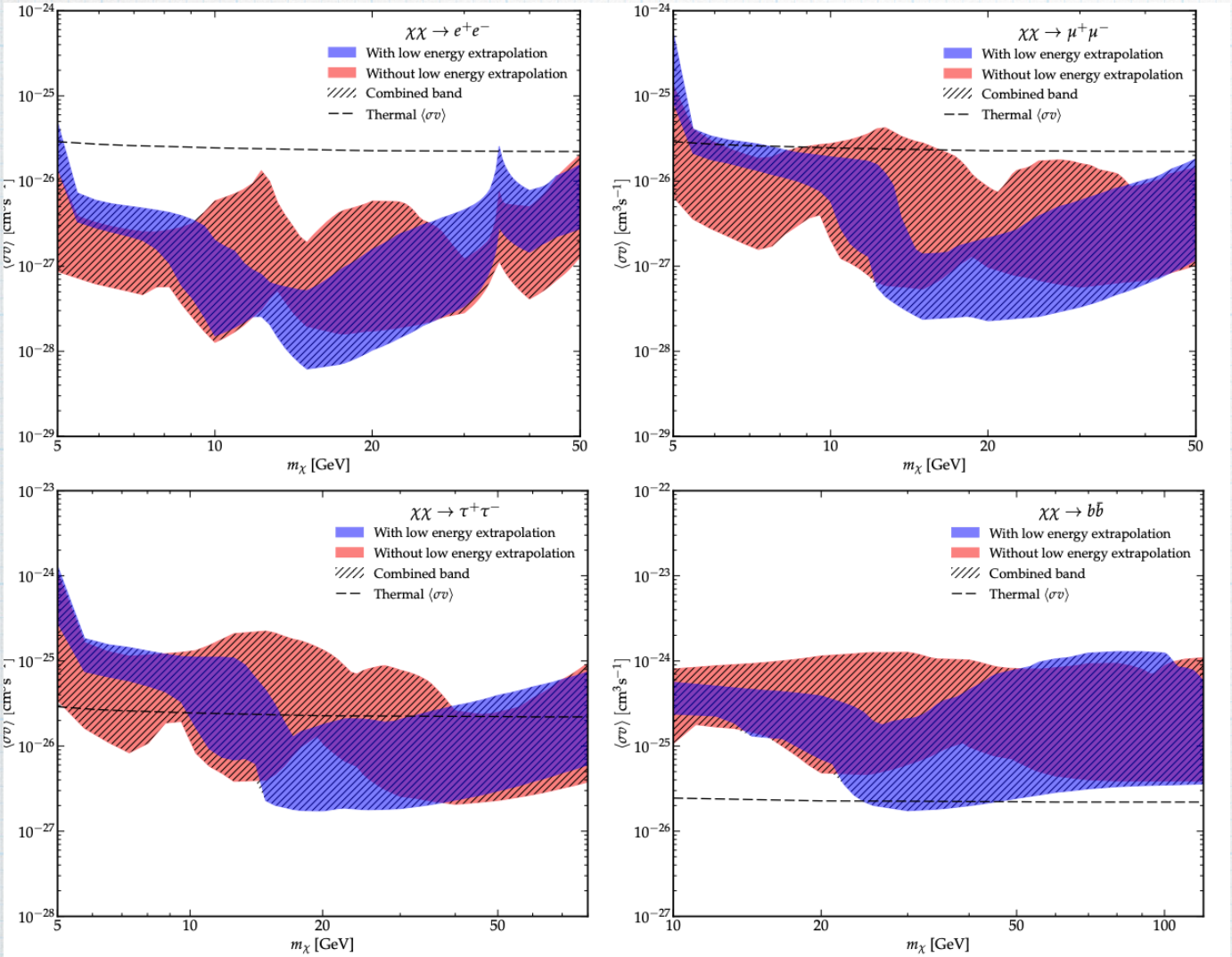
primary from DM annihilation
+ secondary contribution

- primary model
- coalescence model
- propagation
- solar modulation

AMS-02 $\bar{p}$ data (7years) & $\bar{p}$ & $\bar{D}$ prospects

cosmic-ray (electron-positron)

Krommydas & Cholis, 2022

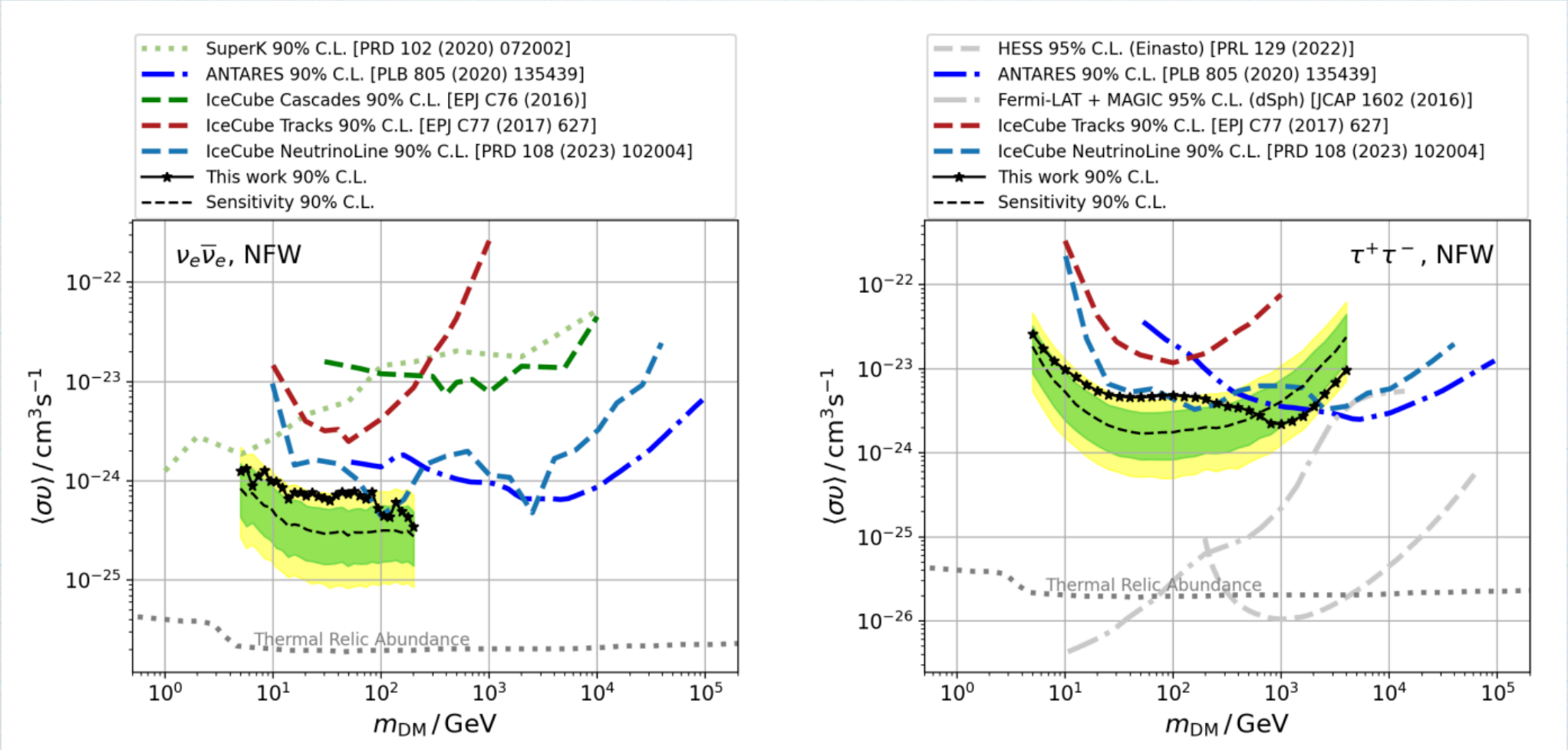


- primary from DM annihilation + secondary contribution
- primary model
- propagation
- astrophysical background
- solar modulation

AMS-02 $e^- + e^+$ data (7years)

neutrino (Galactic Center)

IceCube collaboration, 2025

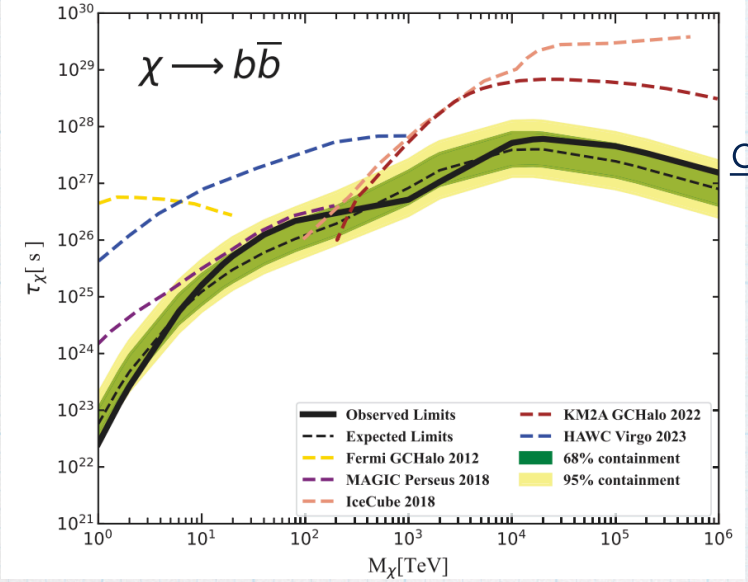


IceCube DeepCore ν, 10years

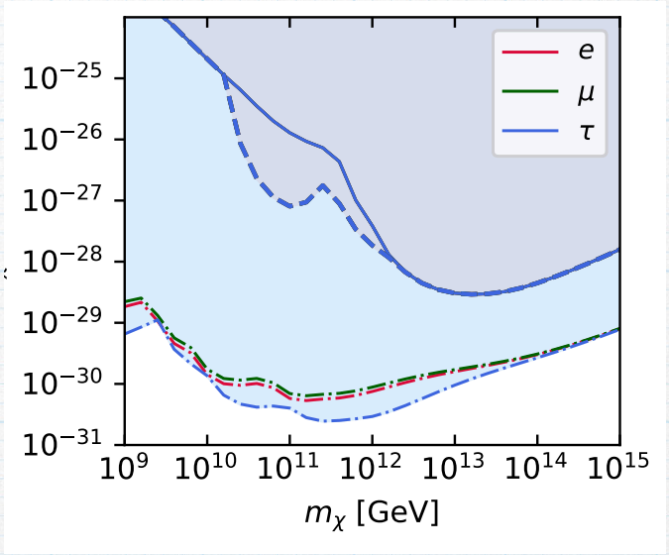
more about target models…

- decaying DM
- axion & axion-like particles (ALPs)
- sterile neutrinos
- primordial black holes (PBHs)
- …

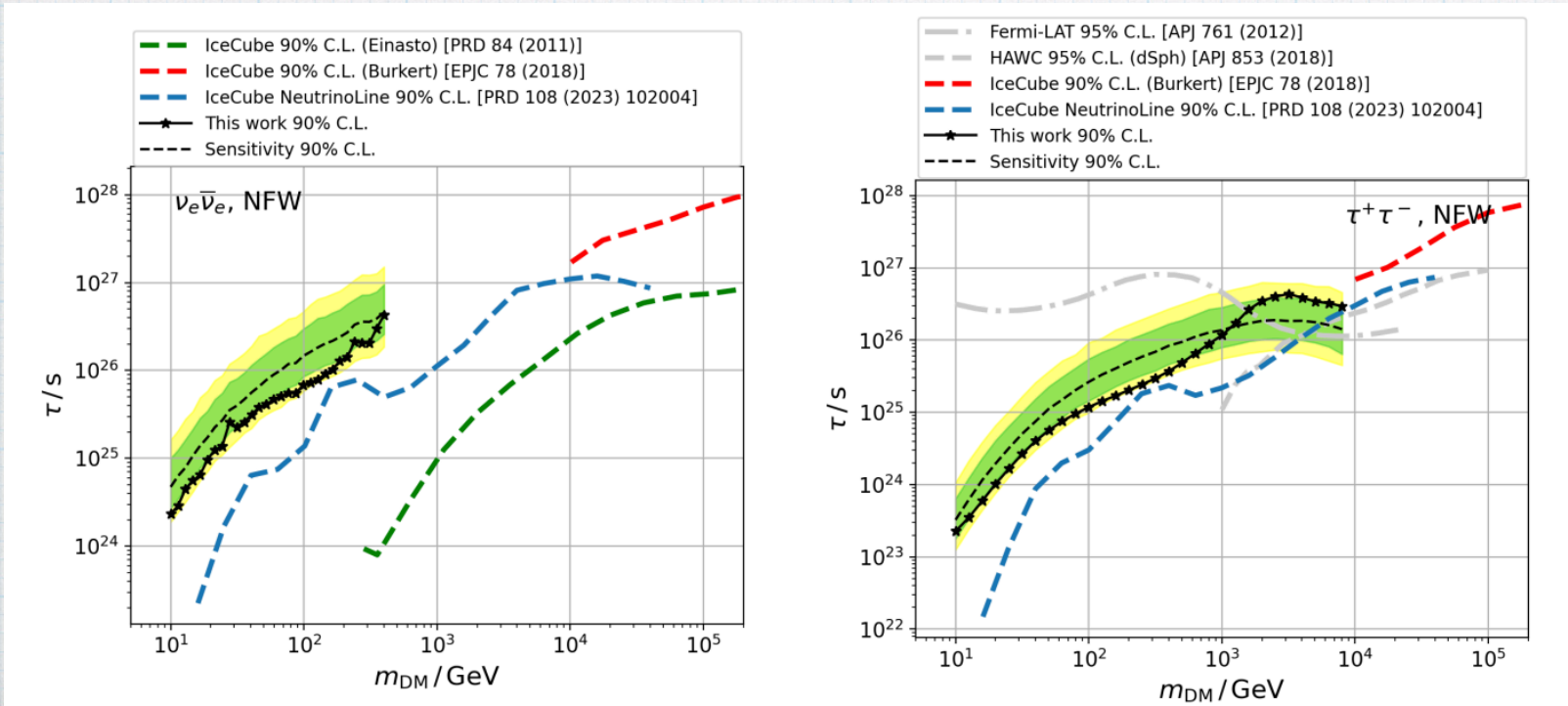
decaying DM



LHAASO collaboration, 2024

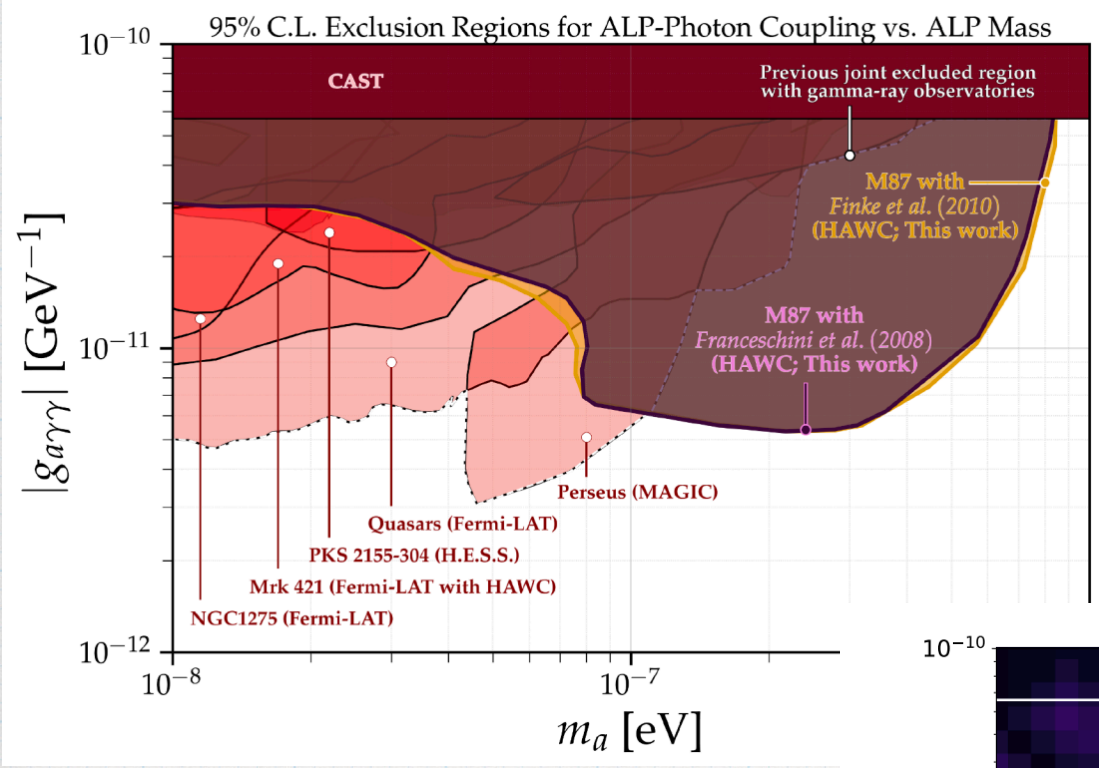


Das et al., 2023 $(p + \bar{p})$



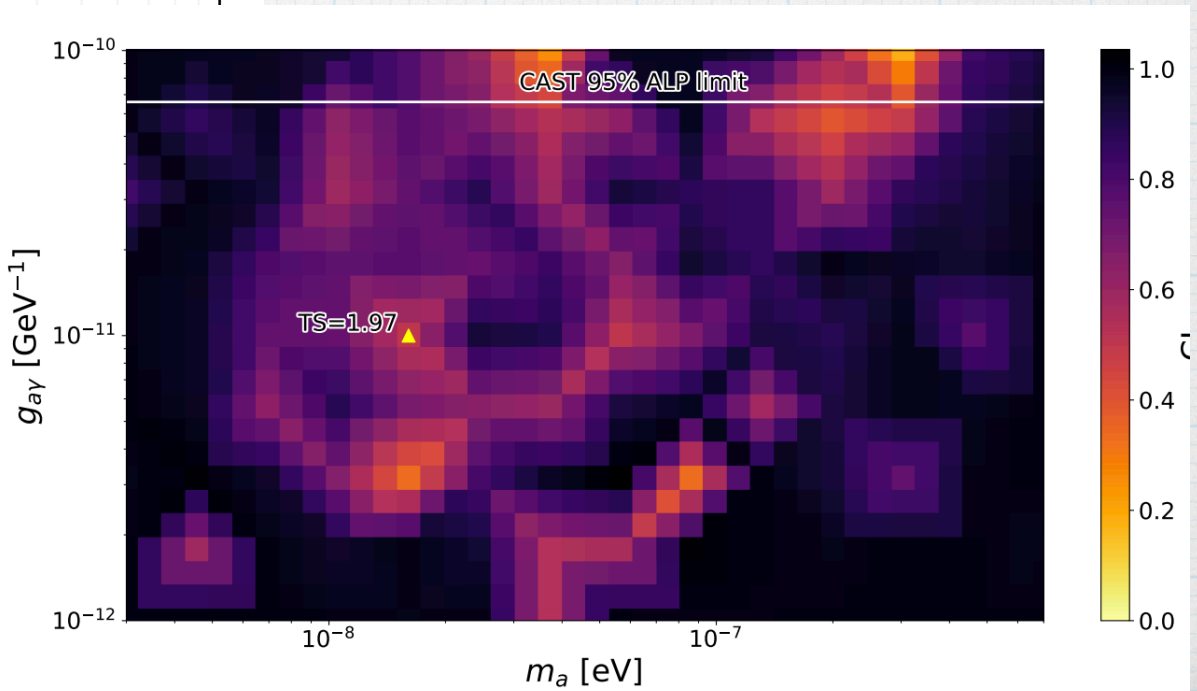
IceCube collaboration, 2025

axion-like particles



[HAWC, 2026]

M87, 7.5year

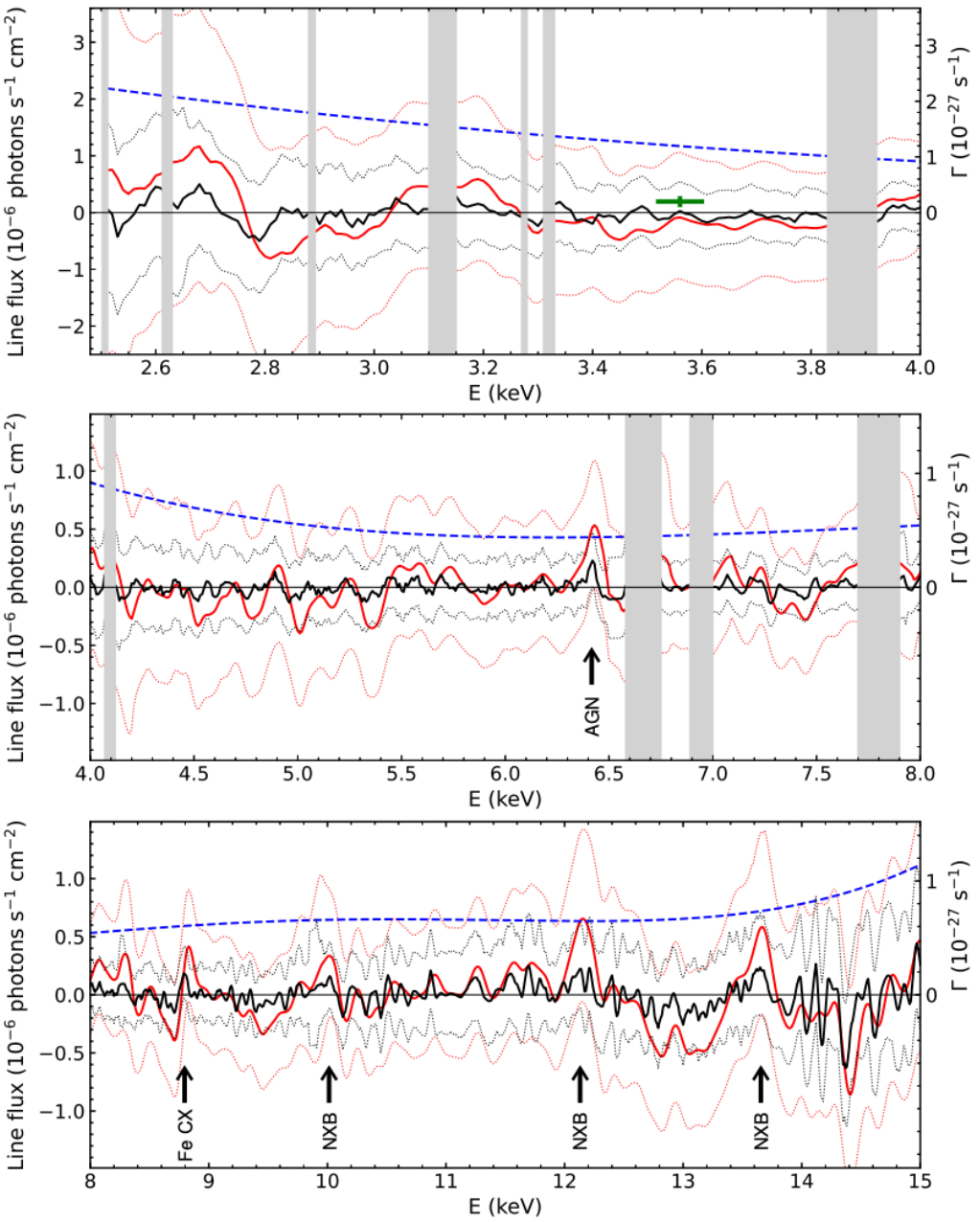


[VERITAS collaboration, 2025]

NGC1257 flare,

2.2h

sterile neutrino



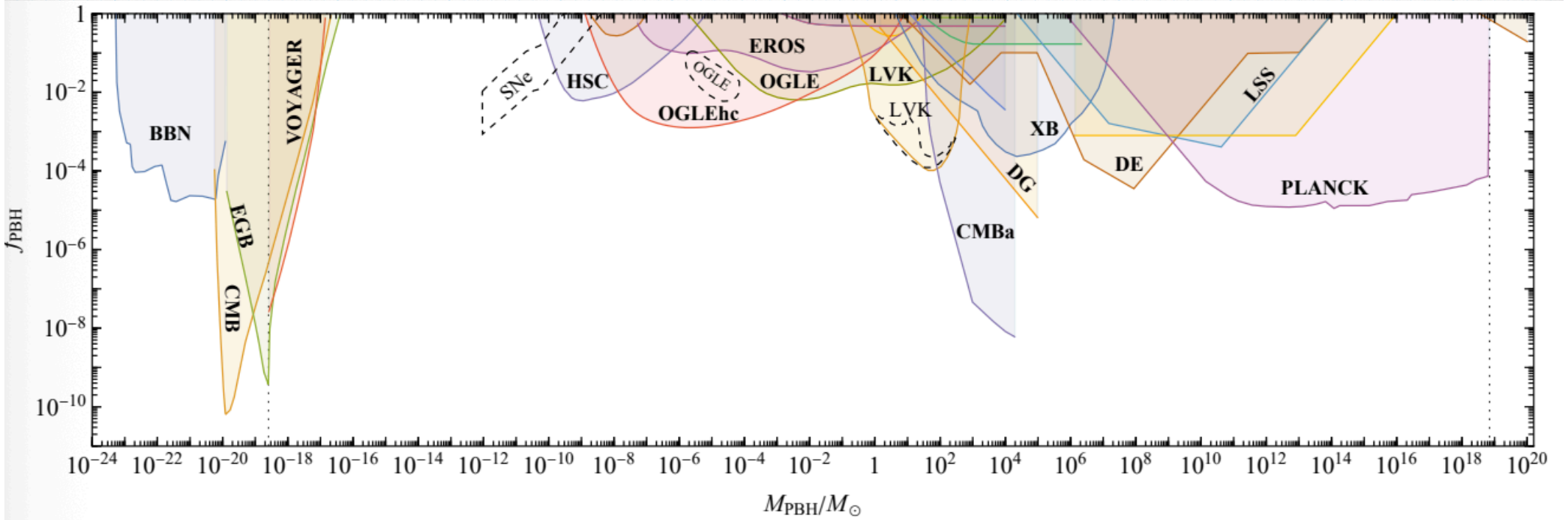
XRISM collaboration, 2025

10 galaxy cluster stacked,
3.748Ms total
Upper limits on 3.55keV
sterile ν decay rate

$\Gamma \sim 1.0 \times 10^{-27}/\mathrm{s}$

primordial black holes

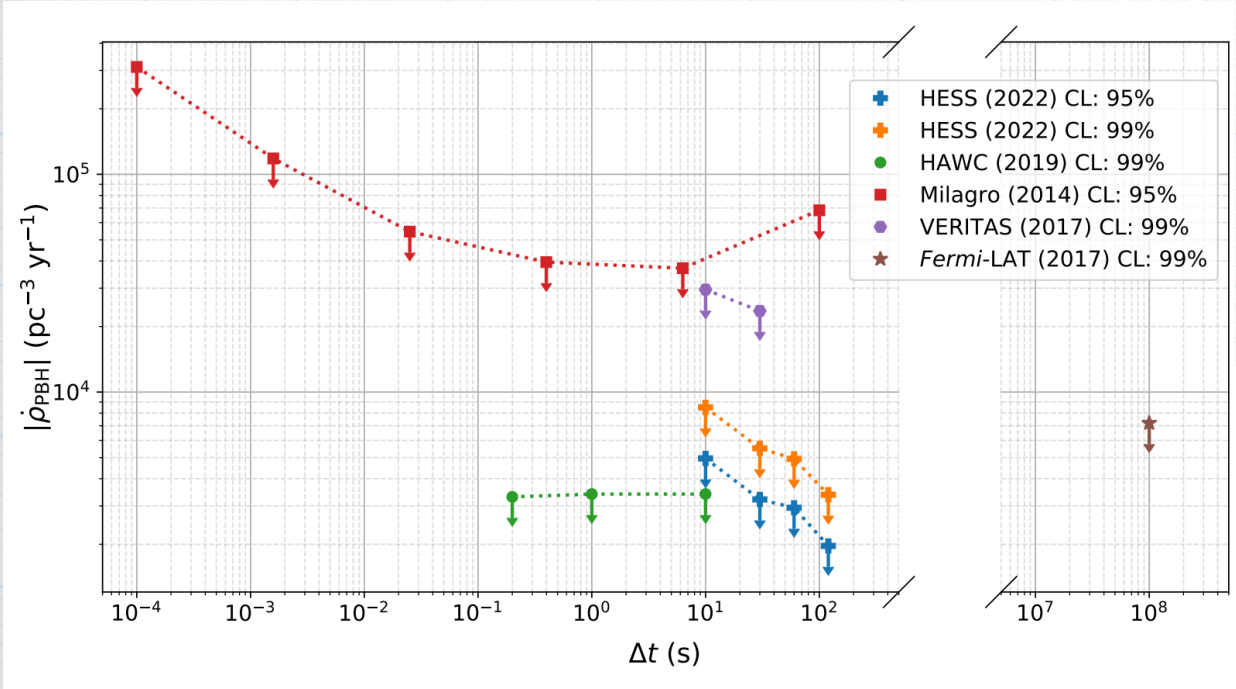
Carr et al., 2026



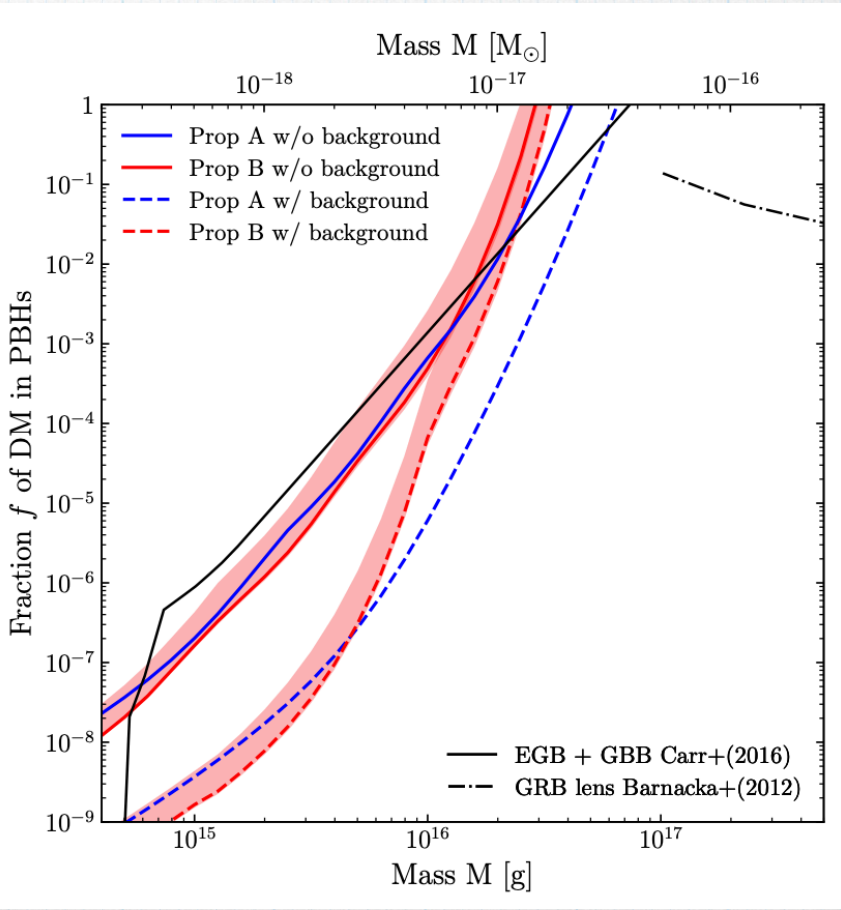
Two highlight:

- H.E.S.S. bursting PBH search
- Voyager constraint in 2018

primordial black holes



H.E.S.S. collaboration, 2023



Boudaud & Cirelli, 2018

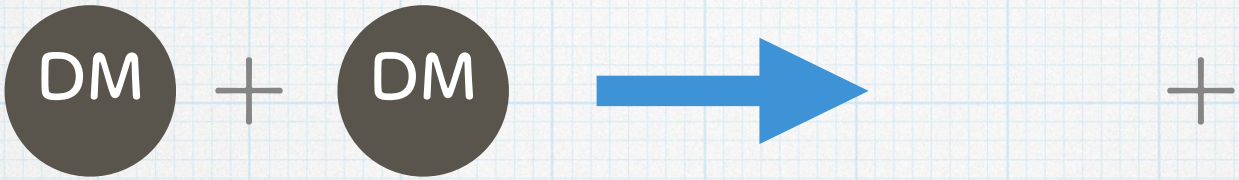
Two highlight:

- H.E.S.S. bursting PBH search
- Voyager constraint in 2018

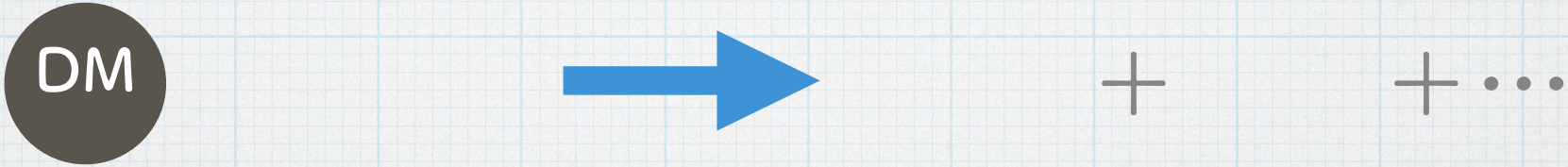
2. further possibilities

patterns:

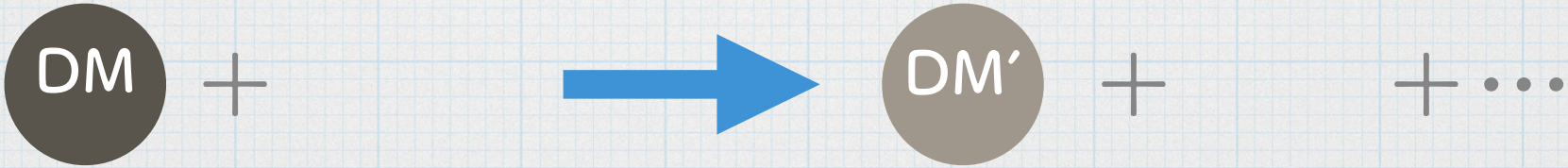
- annihilation:



- decay:



- conversion



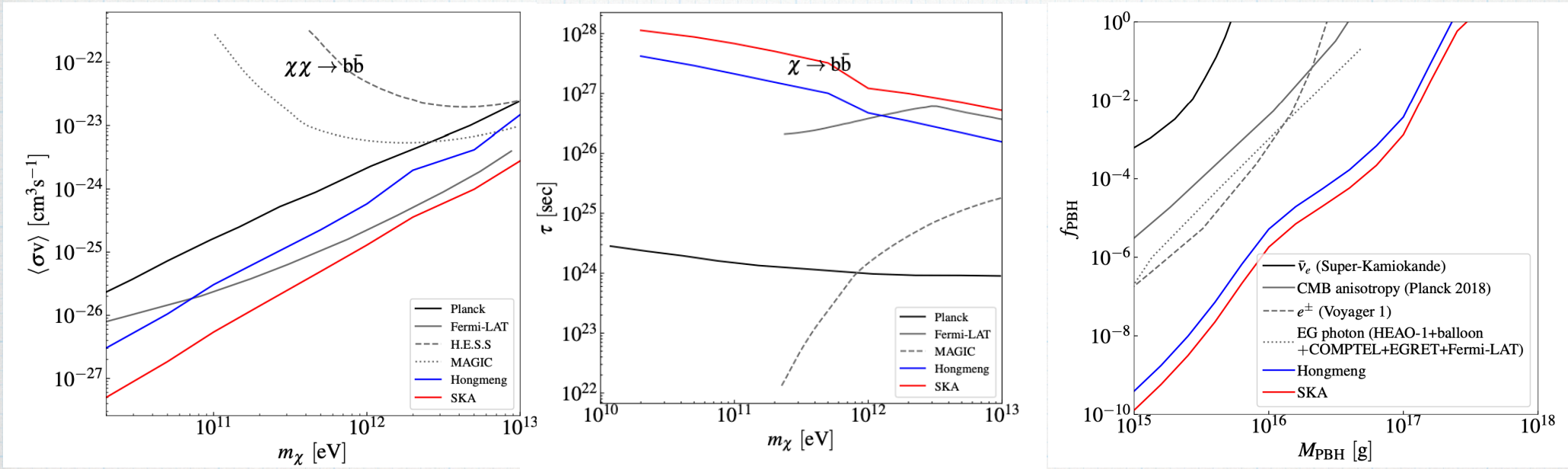
energy/momentum transfer

DM serves as energy/momentum injection/extracting source:

- energy injection
  → heating, excitation,…
- momentum transfer
  →boost,…
- energy extraction
  →cooling,…

injection to intergalactic medium

Zhao et al., 2025



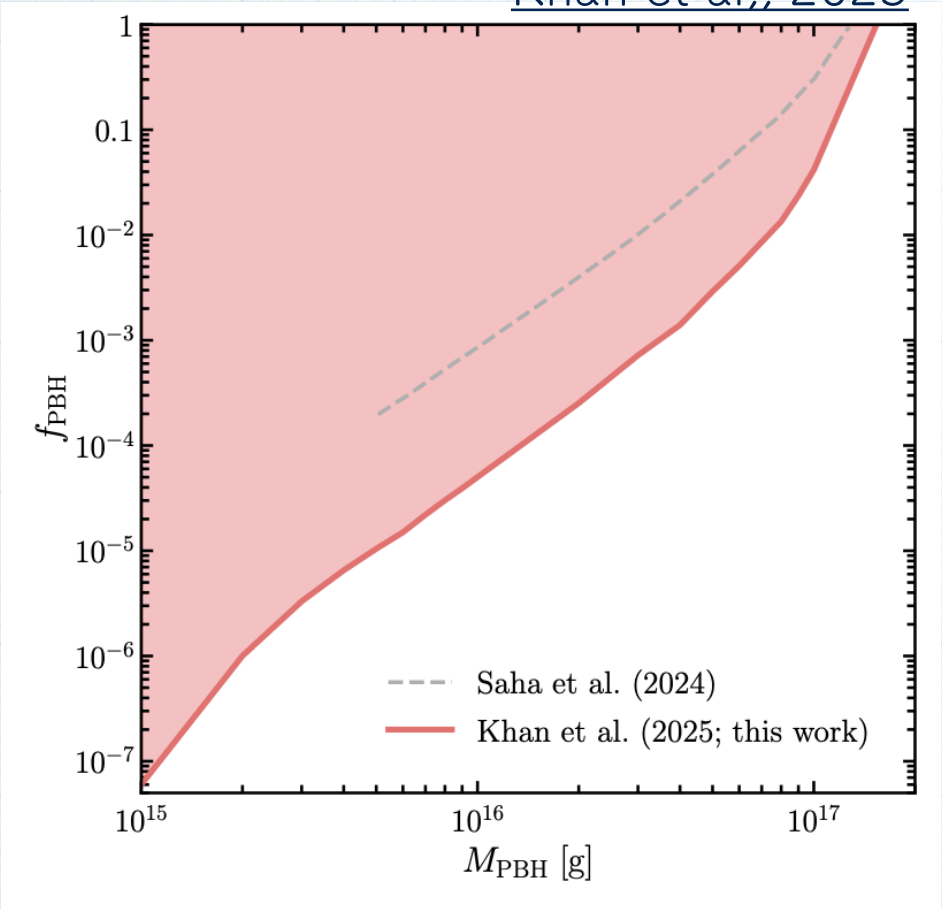
annihilation decaying PBH fraction

21cm power spectrum: prospects with SKA

integration time 10000h

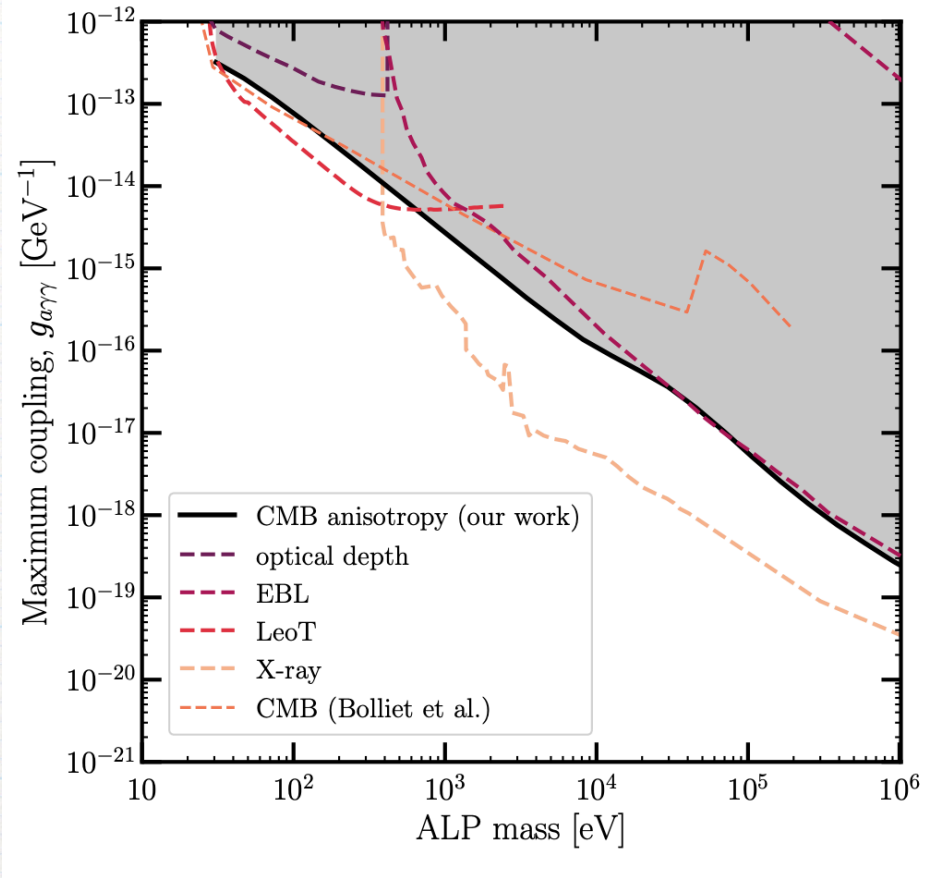
injection to intergalactic medium

Khan et al., 2025



PBH fraction
(Lyman-α spectra)

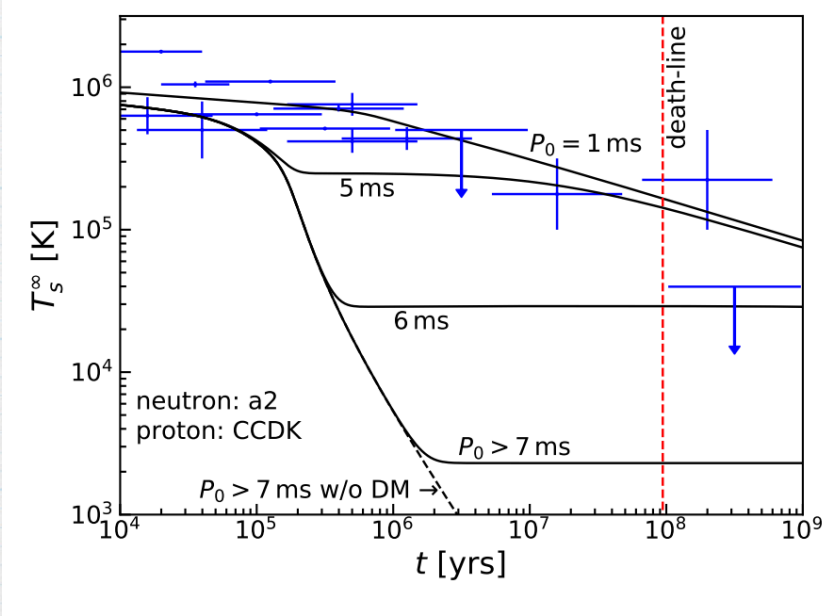
Liu et al., 2023



ALP coupling
(CMB spectral distortion)

injection to celestial body

Hamaguchi et al., 2019



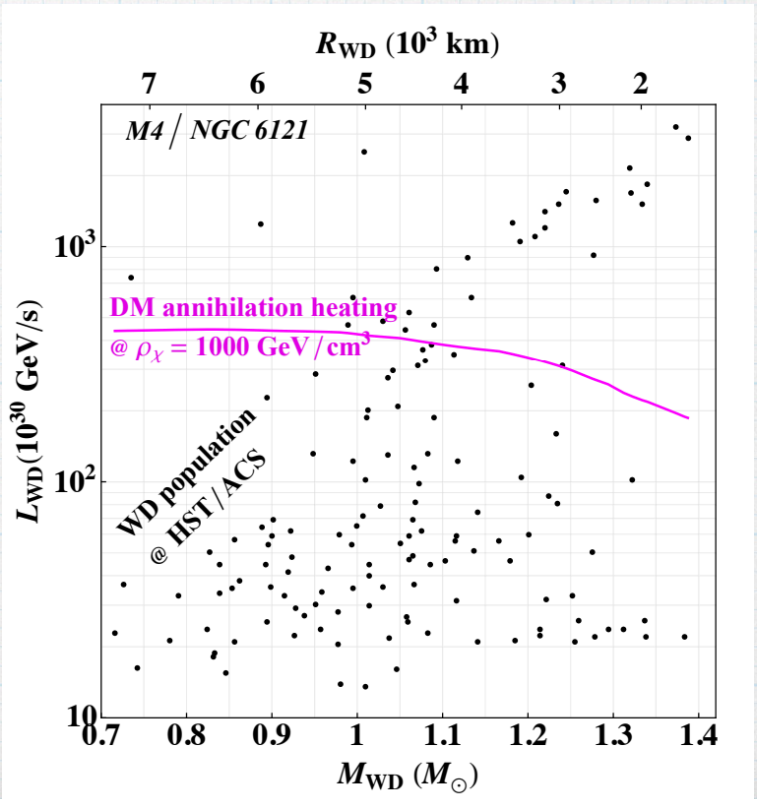
Neutron star heating

(see also Bell et al., 2023)

Brown dwarf heating

(Acevedo et al.,2024)

Garani et al., 2023



White dwarf heating

(See also Bell et al., 2024)

Planet heating

(Blanco et al., 2025)

reaction in/around celestial body

- DM environment around the target body
- astrophysical environment inside/around the target body
- capture rate of DM
- modeling of reactions (scattering, annihilation, decay, BH formation,…) inside/around the body
- escape of the products after DM interaction from the body and propagation

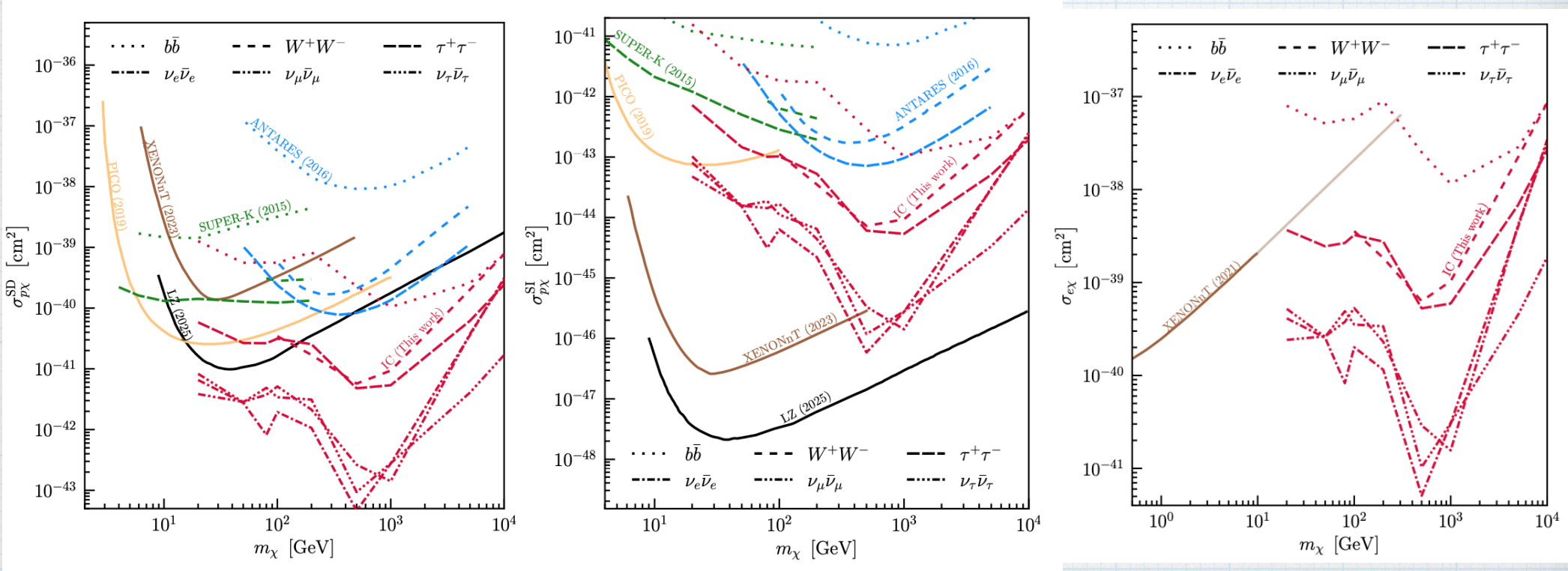
direct × indirect

with astrophysical and particle physics knowledge

Leane et al., 2023

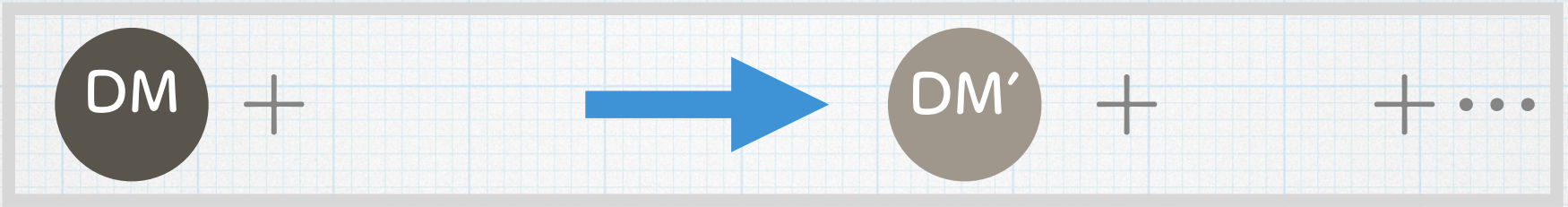
neutrino (solar accumulation)

IceCube collaboration, 2025

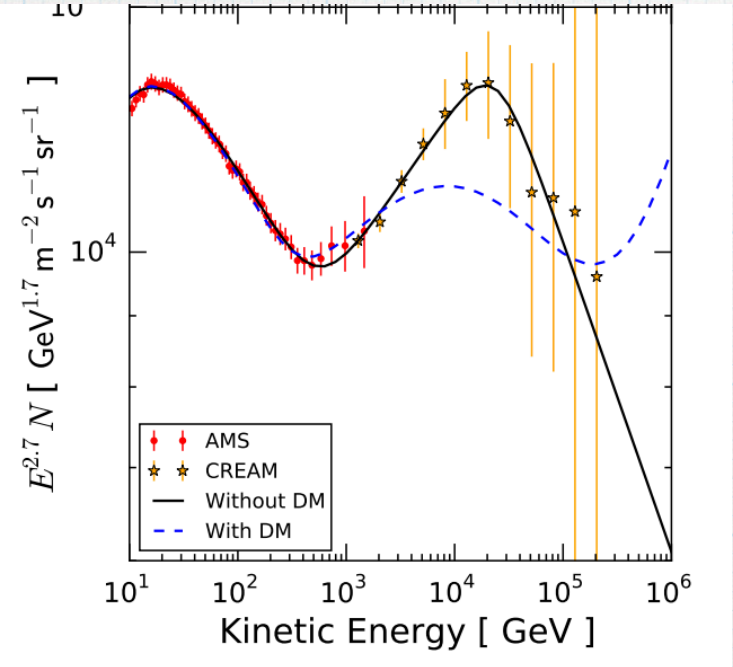


IceCube, Sun (10 years)

reverse direct detection

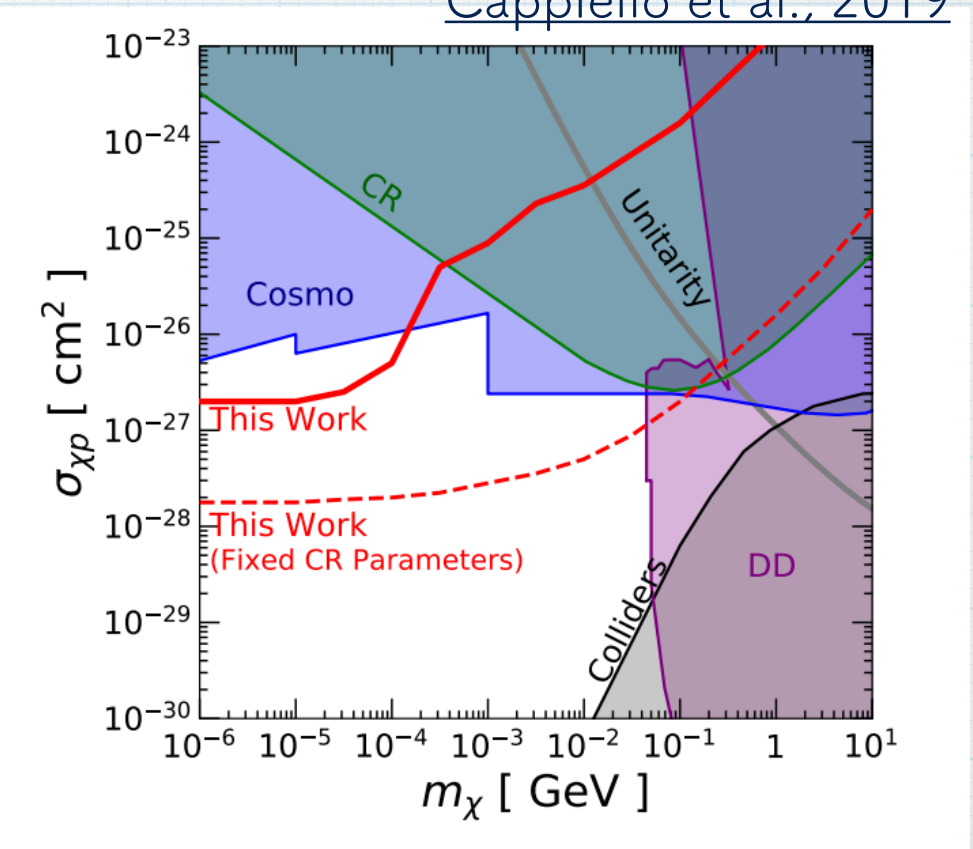


direct scattering in space

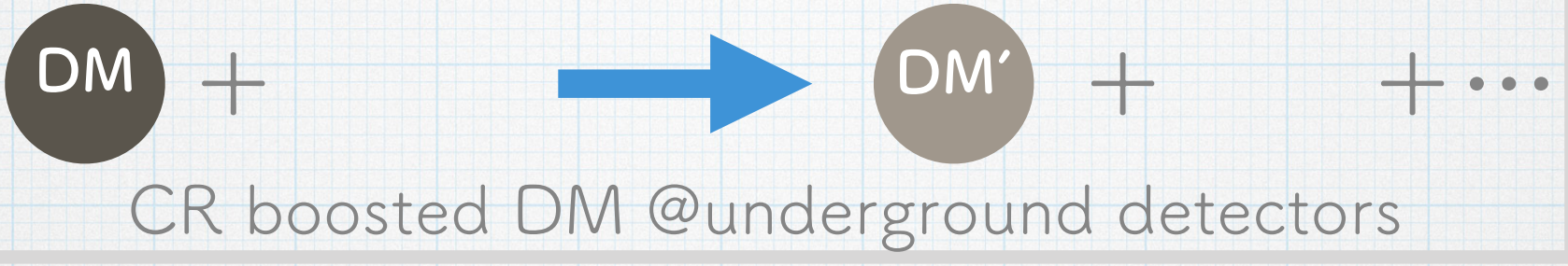


$m_\chi = 1\mathrm{keV}, \sigma_{\chi p} = 2.0 \times 10^{-27}\mathrm{cm}^2$

Cappiello et al., 2019



reverse direct detection



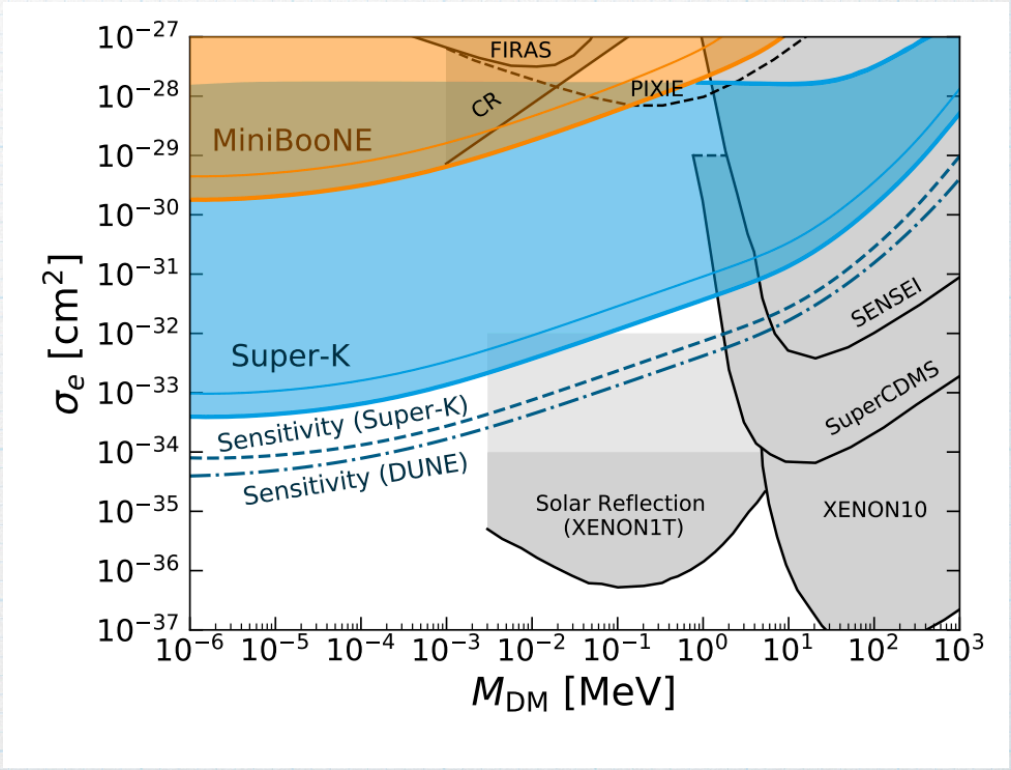
Ema et al., 2019

energy transfer (CR → DM)

→ higher DM kinetic energy

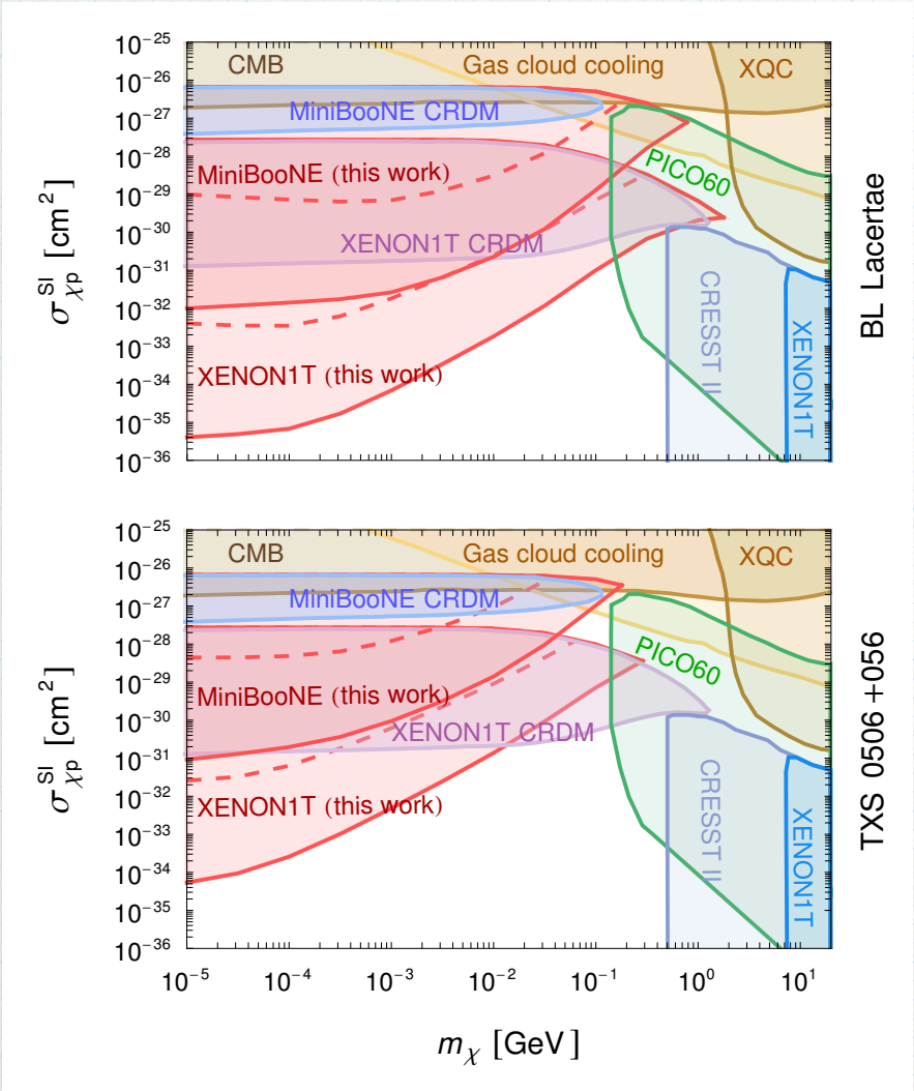
→ penetration power

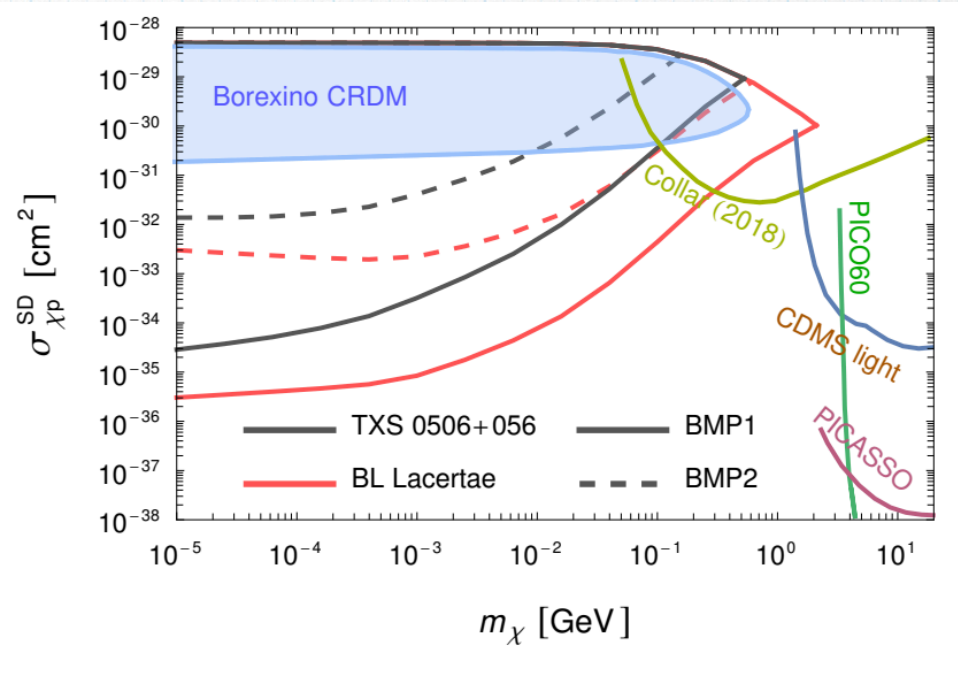
→ scattering @underground detector



e.g.) blazar boosted DM

Wang et al., 2021



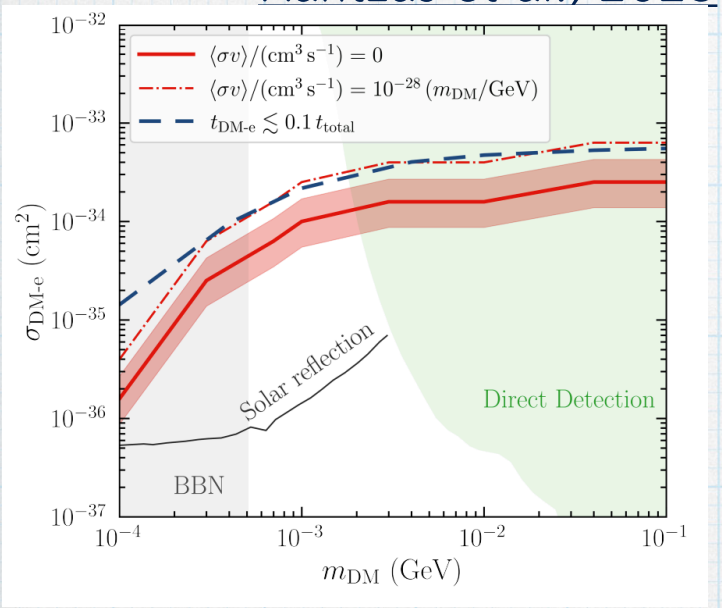


(see also Barllier et al., 2025)

- DM density spike around BH
- acceleration at AGN jet

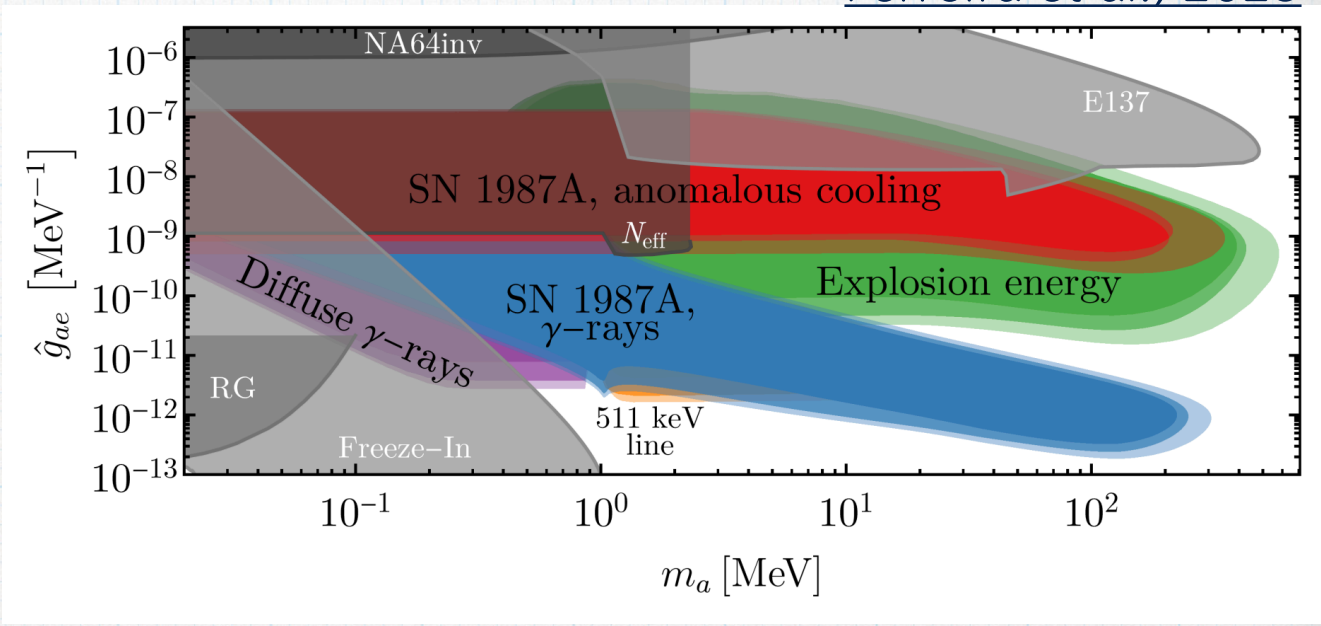
energy extraction

Kantzas et al., 2025



cooling of
astrophysical jet

Ferreira et al., 2025



cooling of SN
(and other effects)

many possibilities of direct × indirect

3. connections to related fields

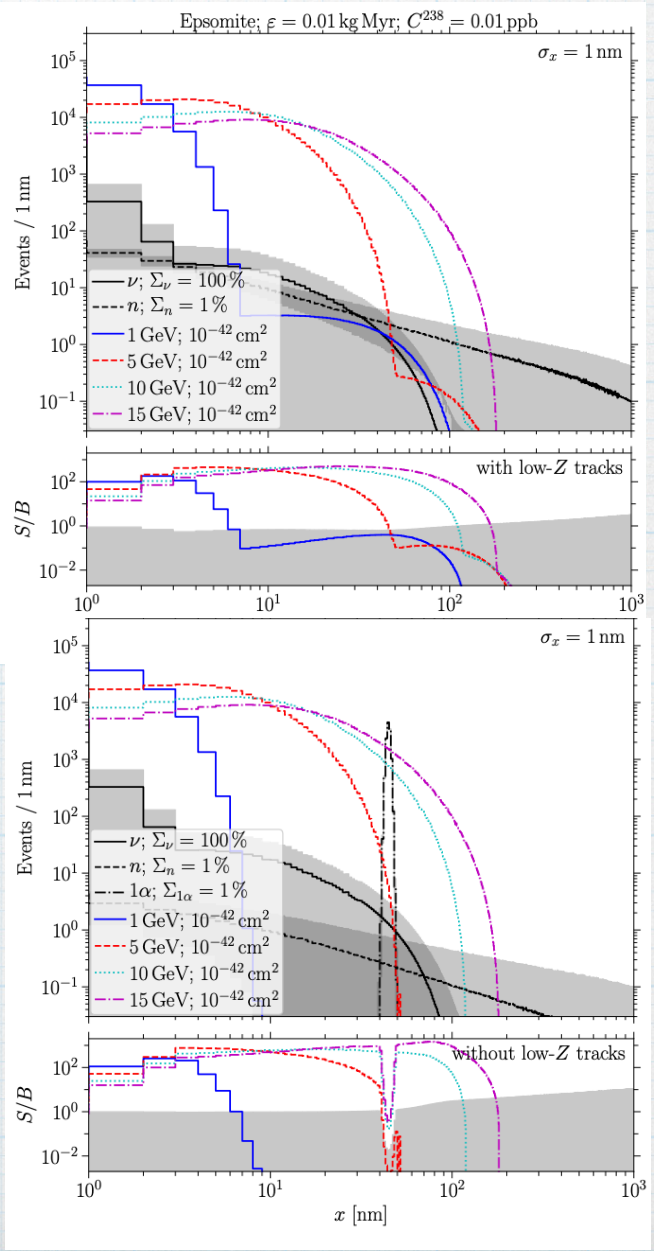
DM, cosmic-ray, ν detector

Drukier et al., 2018

paleo detector can be sensitive to …

- WIMP-like DM
- boosted DM
- heavy DM
- macroscopic DM
- past cosmic-ray events
- supernova ν
- atmospheric ν …

(Hirose et al., 2025)

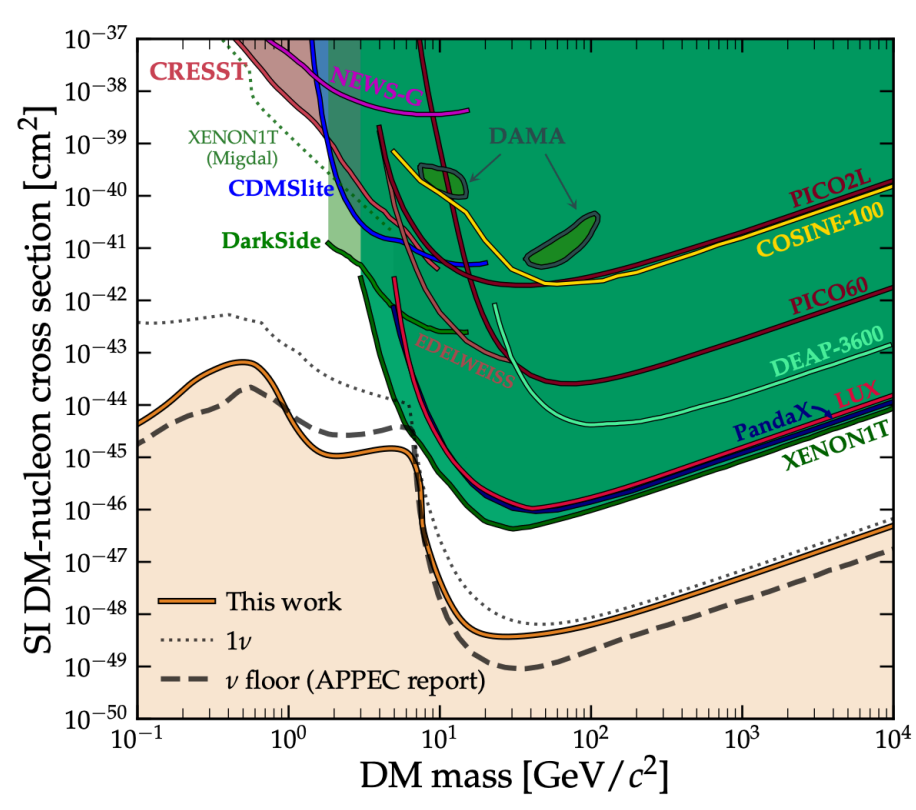


DM detector for neutrinos

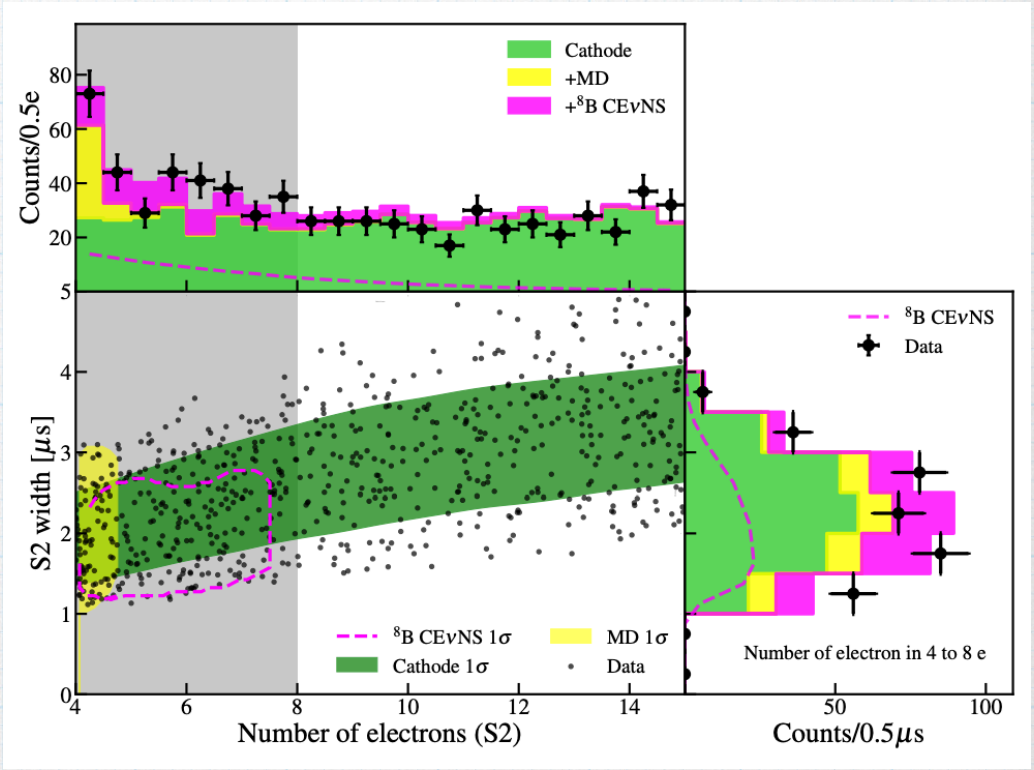
XENONnT & PandaX-4T reports

the CEvNS signal of solar ^{8}B neutrinos!

O'Hare, 2021



PandaX collaboration, 2024

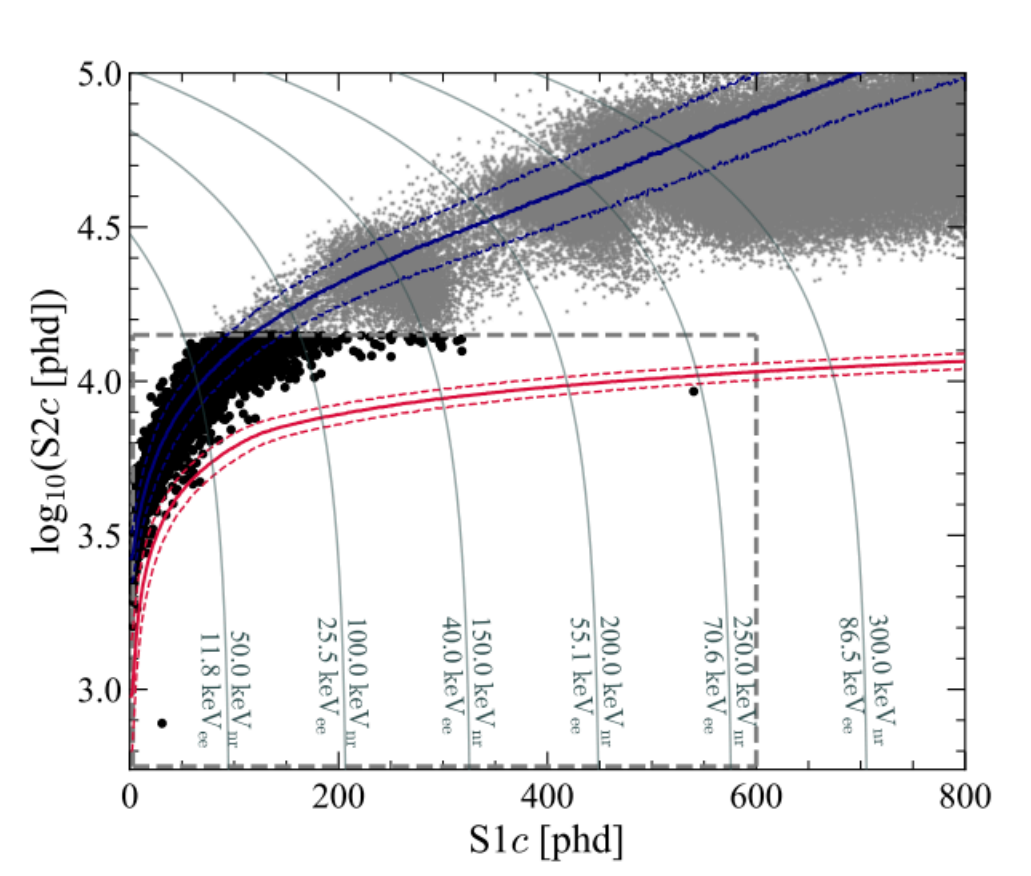


See also XENON collaboration, 2024

LZ excess:

Nuclear recoil at 248±23±23 keV?

LZ collaboration, 2026



To interpret with DM models..

- endothermic interaction
- exothermic interaction
- dependence of interaction on spin, momentum, ….
- boosted species
- modification in nuclear sector,
- …

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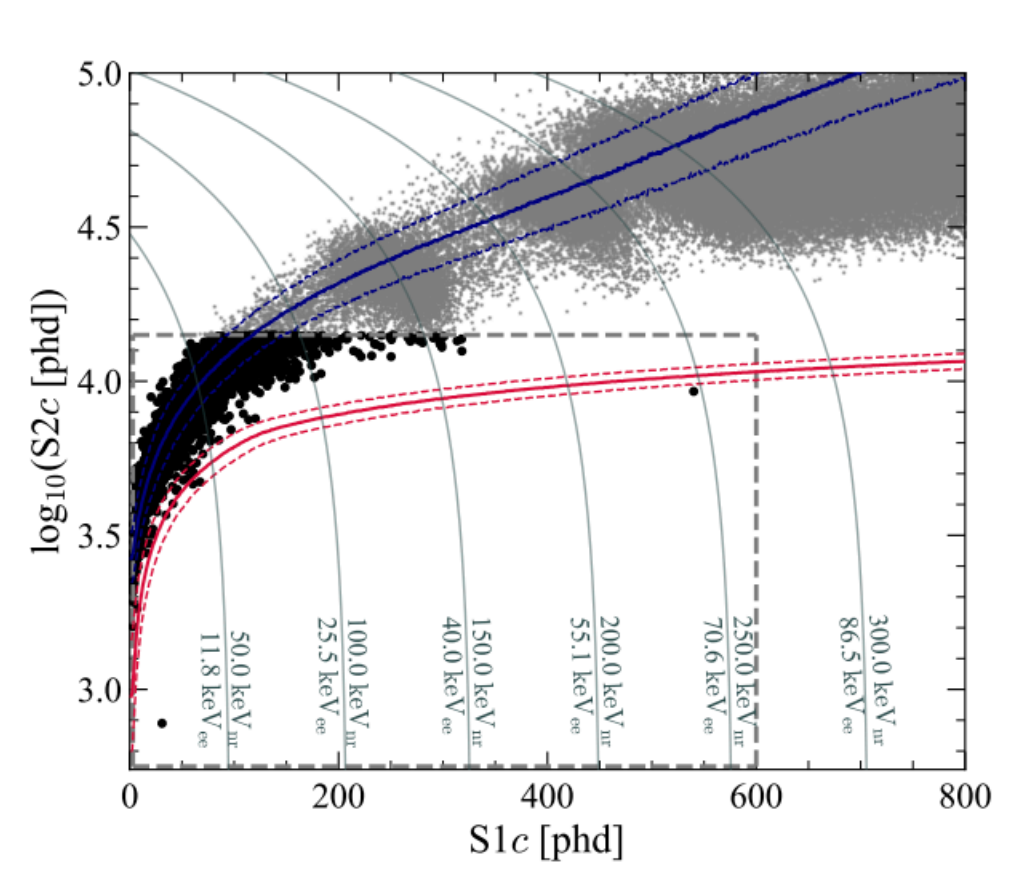

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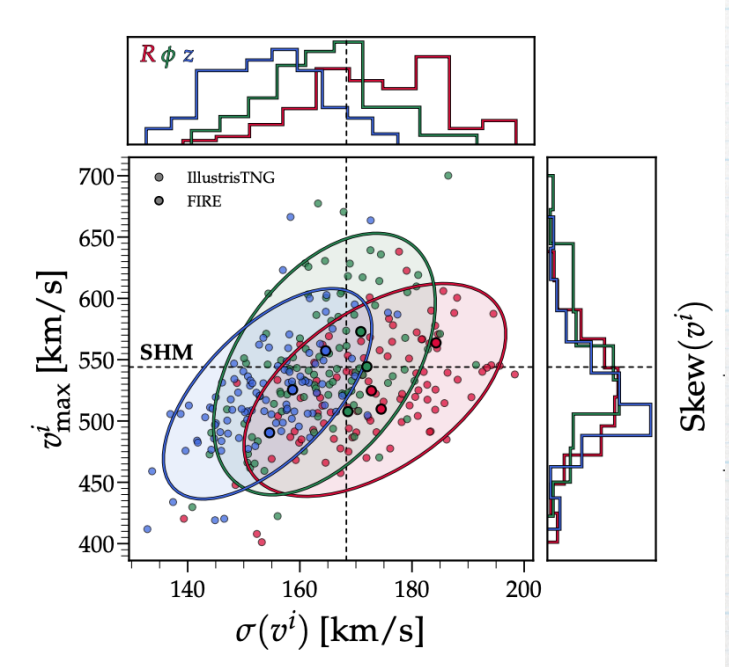
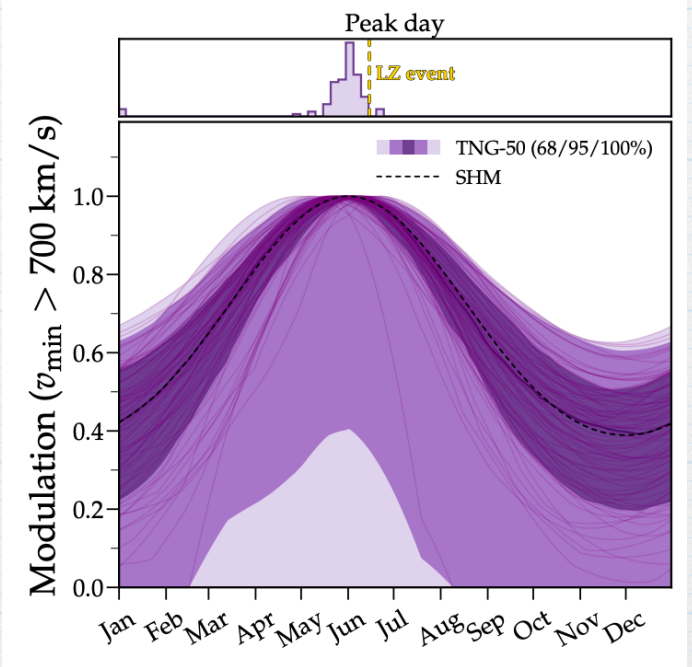
endothermic interaction

If high-velocity tail in DM distribution function …

- large momentum transfer leads to inelastic up-scattering
- favored region for model parameter ↔ halo models
- but need to be near the escape boundary





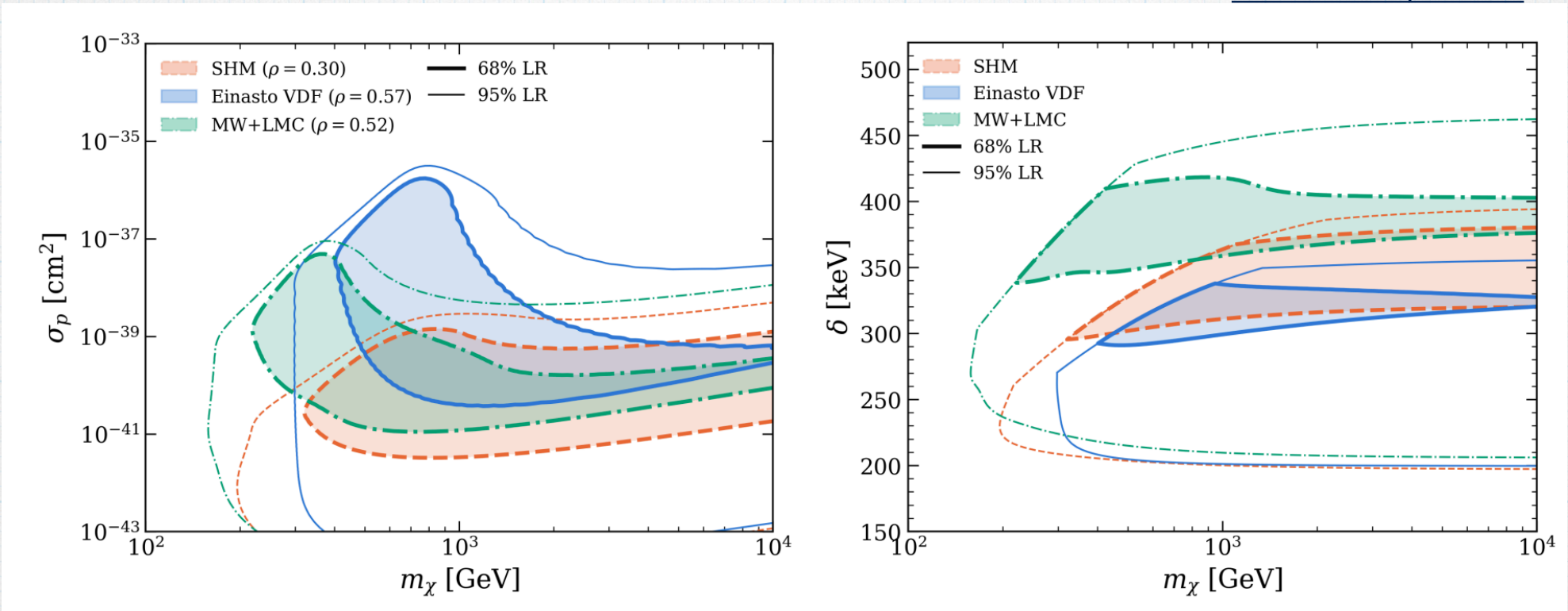
O'Hare, 2026

※if elastic, momentum-suppressed and/or spin-dependent non-relativistic interaction would be favored

endothermic interaction

origin of high-velocity tail: LMC perturbation?

Das et al., 2026

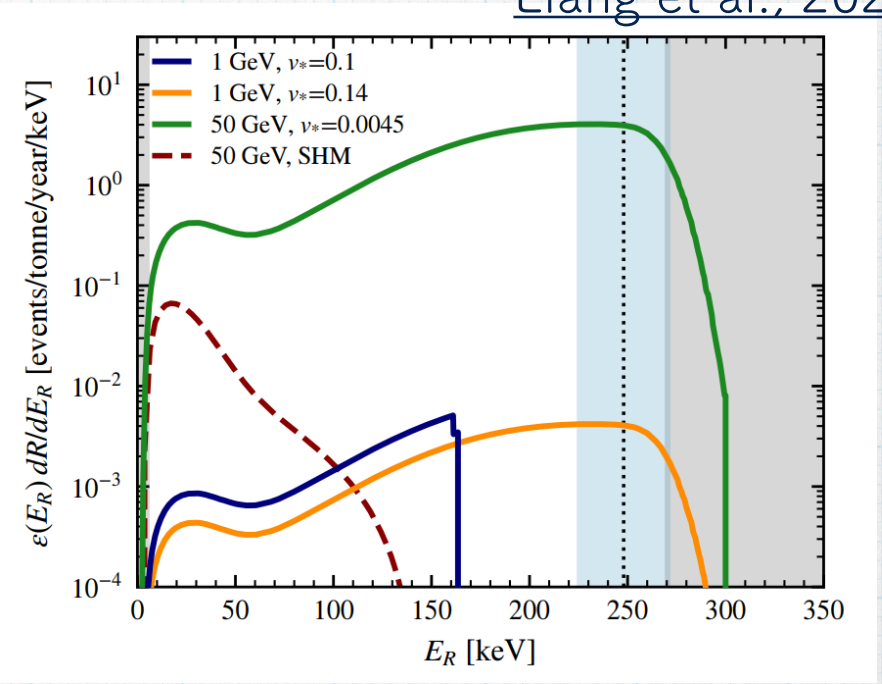


(See also Bozorgnia et al., 2026)

boosted species

presence of monochromatic energetic species?

Liang et al., 2026



- two-component models

  $\chi_2\chi_2 \rightarrow \chi_1\chi_1$

  (e.g. Mahapatatra & Paul 2026)
- composite models

  (e.g. Jung & Park 2026)
- emission from evaporation of primordial black holes (e.g. Kalita 2026)
- cosmic-ray or atmospheric ν boosts

  (e.g. Heikinheimo & Zimmermann 2026, Jeesun & Majumdar 2026, Brdar & Chattpadhyay 2026, Sierra et al 2026)

4. our understanding and future

our understanding

- Indirect searches can offer accesses to various DM candidates, covering ultralight to ultraheavy particles, as well as macroscopic models.

- WIMP DM models have been intensively probed. Constraints are approaching the canonical value at $m \lesssim \mathcal{O}(1)$TeV.

- Understandings of astrophysics and cosmological consistency are critically important for determining DM nature.

prospects

- Understandings of astrophysics and cosmology are being updated in amazing speed.
- Upgrades and new facilities are under construction, consideration, ⋯, which should enhance our accessibility.
- Many new ideas are now actively debated.
- The importance of synergy among various approaches and multiple usage of facilities should be increased.