CTAO

LST sub-Array Inauguration

La Palma, 15 October 2026



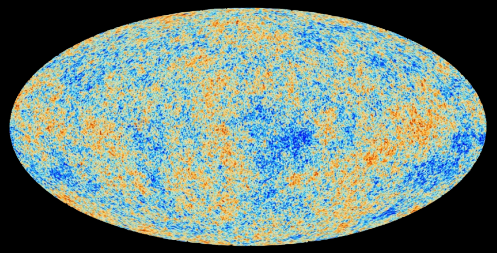
Dark Matter Study with CTAO and Underground

Emmanuel Moulin

CEA Saclay, Irfu, Université Paris-Saclay, France



Standard model cosmology and Dark Matter



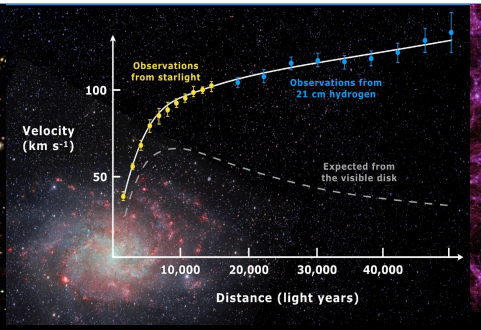
Cosmic Microwave Background



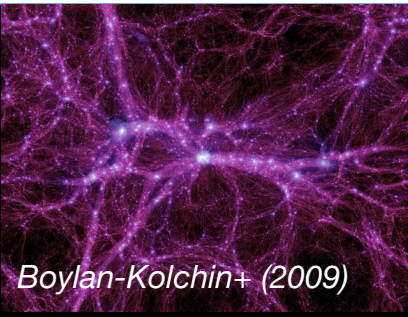
Gravitational Lensing



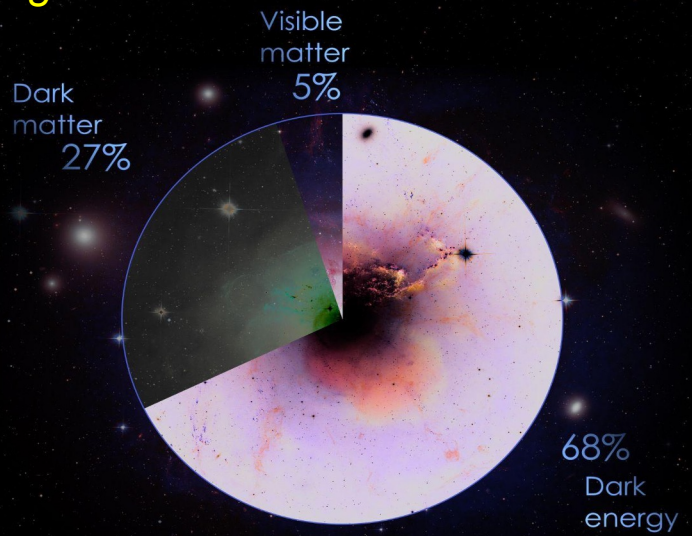
Colliding, galaxy clusters



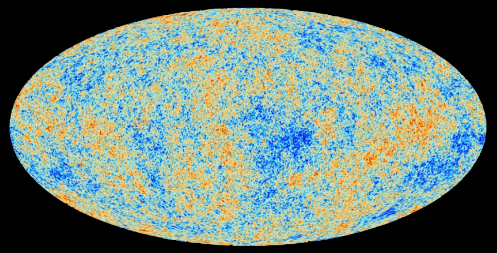
Galaxy rotation curve



Simulations of structure formation



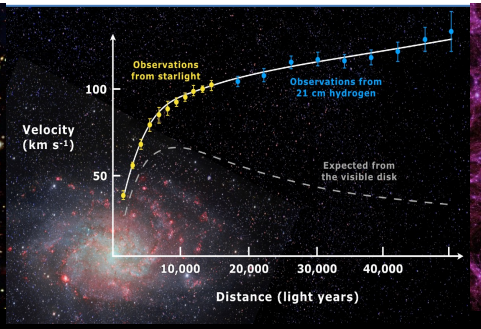
Standard model cosmology and Dark Matter

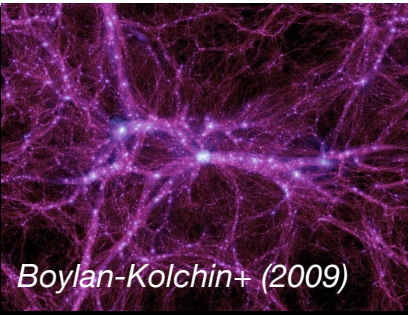




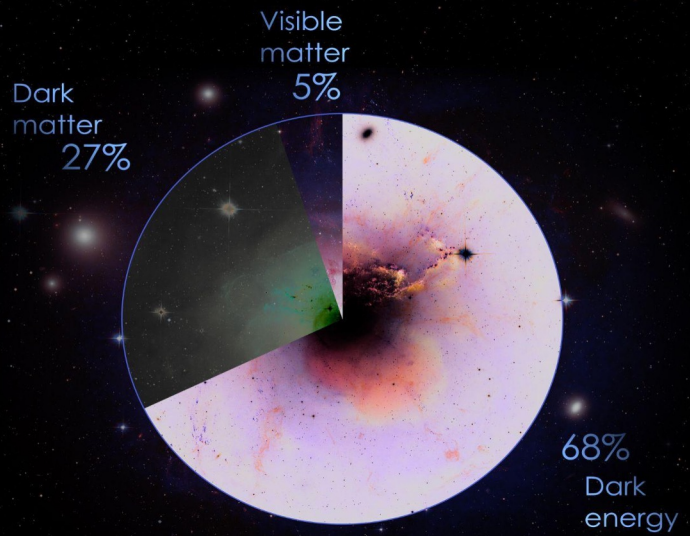
NASA, ESA, J. Lotz and HFF Team (STScI)







Boylan-Kolchin+ (2009)



- *Dark matter density perturbations grow and become nonlinear*

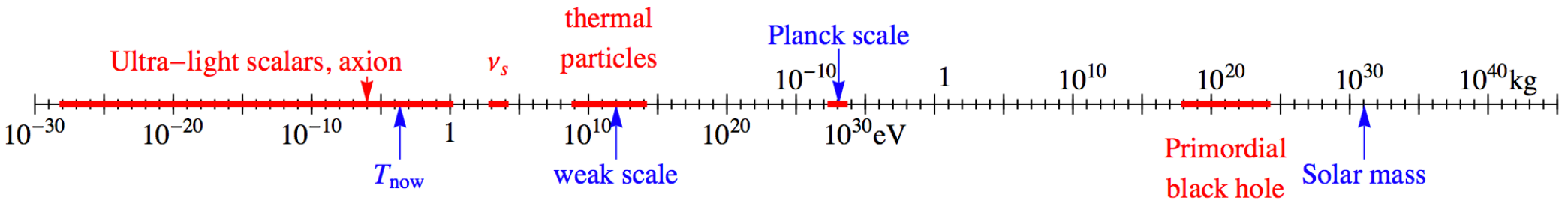
→ study structure formation with N-body simulations

- *Dark matter forms self-gravitating halos that host galaxies*

80% of the matter in the universe

- **neutral particle**
- **cold or not too warm**
- **very feebly interacting**
- **stable or very long lived**
- **possibly a relic from the early universe**

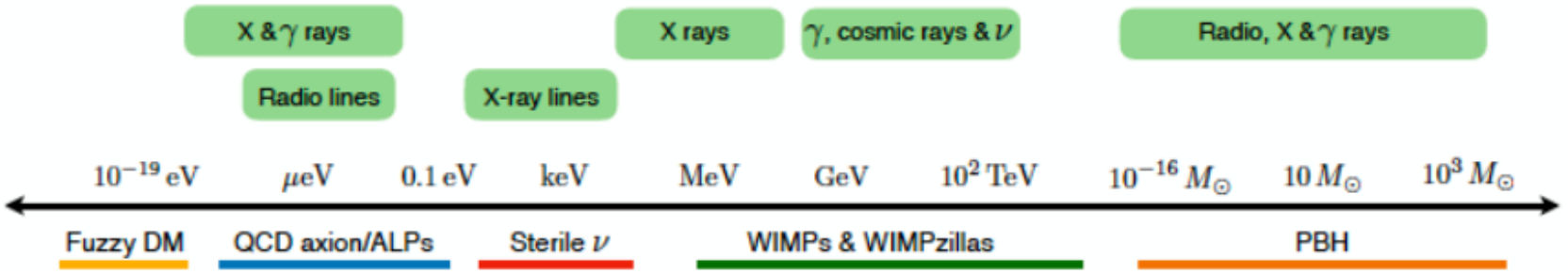
The landscape of Dark Matter

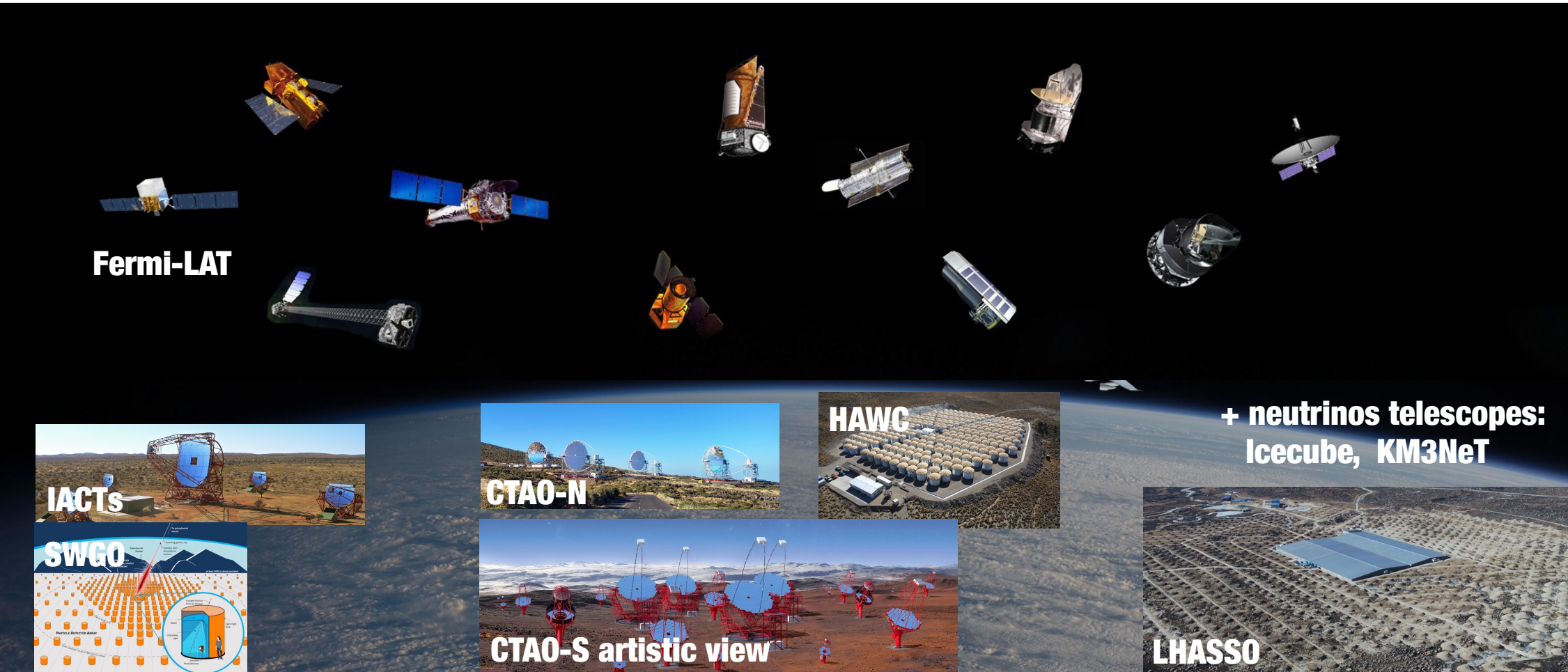


- *Wide spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales*
- *Cosmic experiments seek to detect and measure dark matter in its natural habitat: the halo of our Galaxy, the halos of distant galaxies, and the large-scale structure of the Universe*
- *Cosmic observables can establish that a given discovery is, in fact, associated with the dark matter in the Universe*

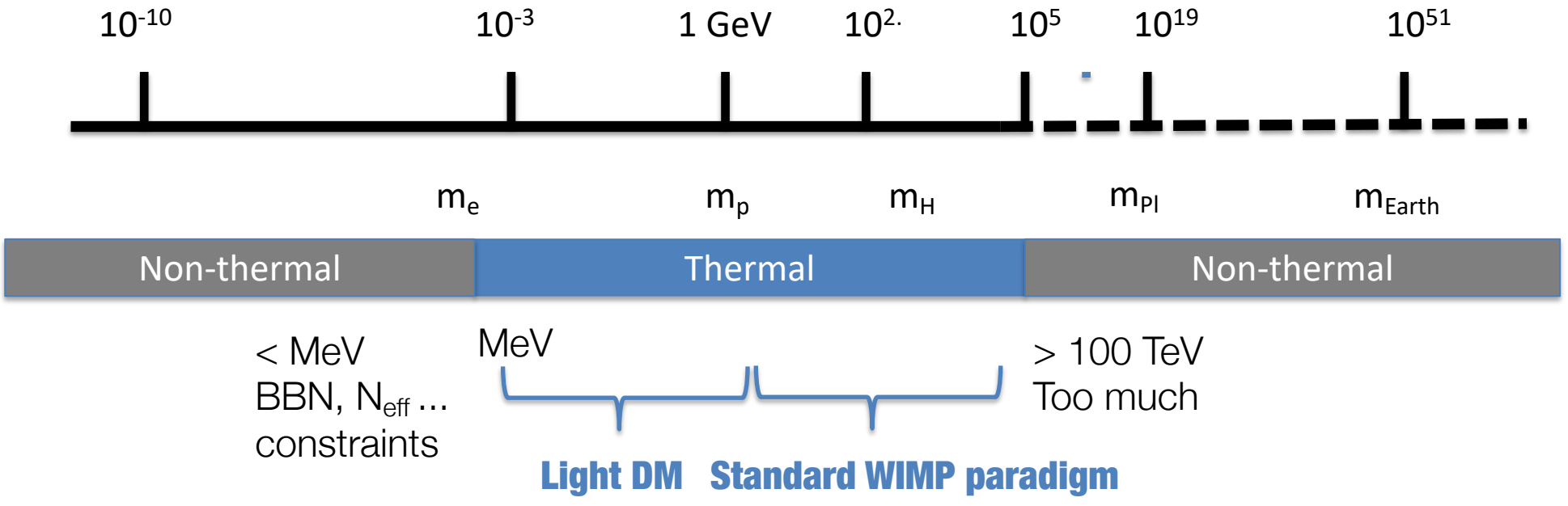
Astroparticle messengers and Instruments

EuCAPT White Paper, arXiv:2110.10074

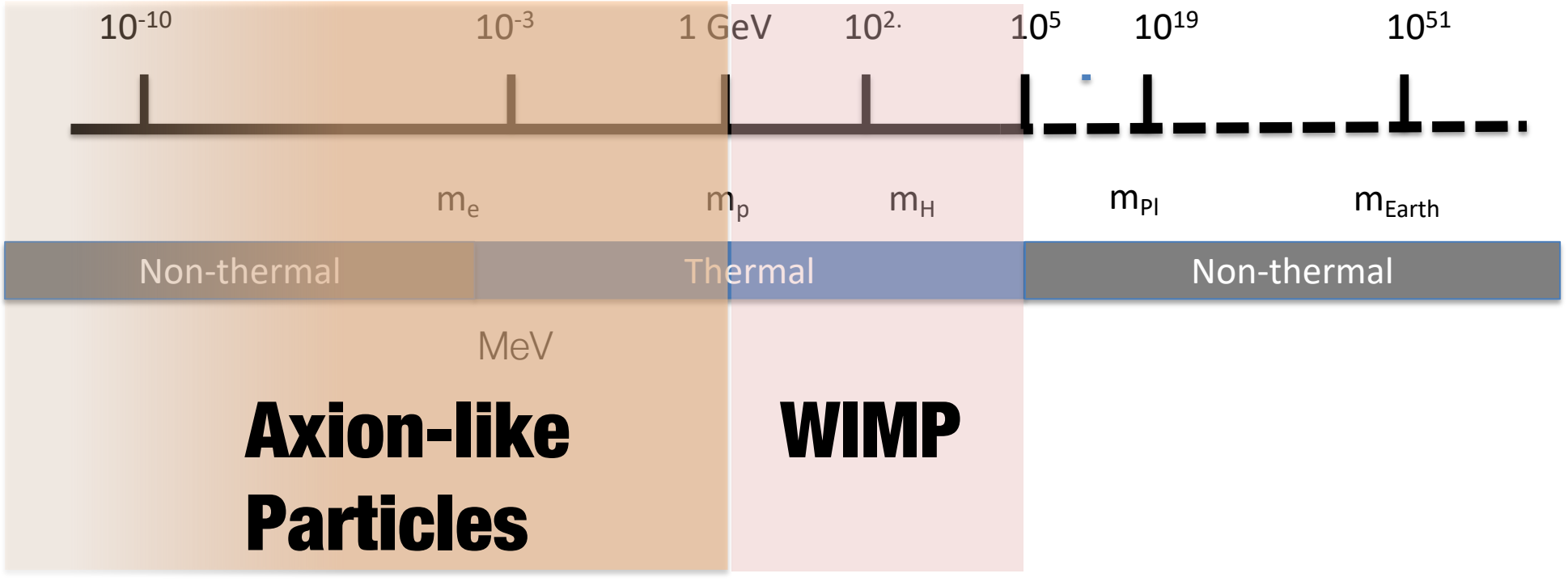




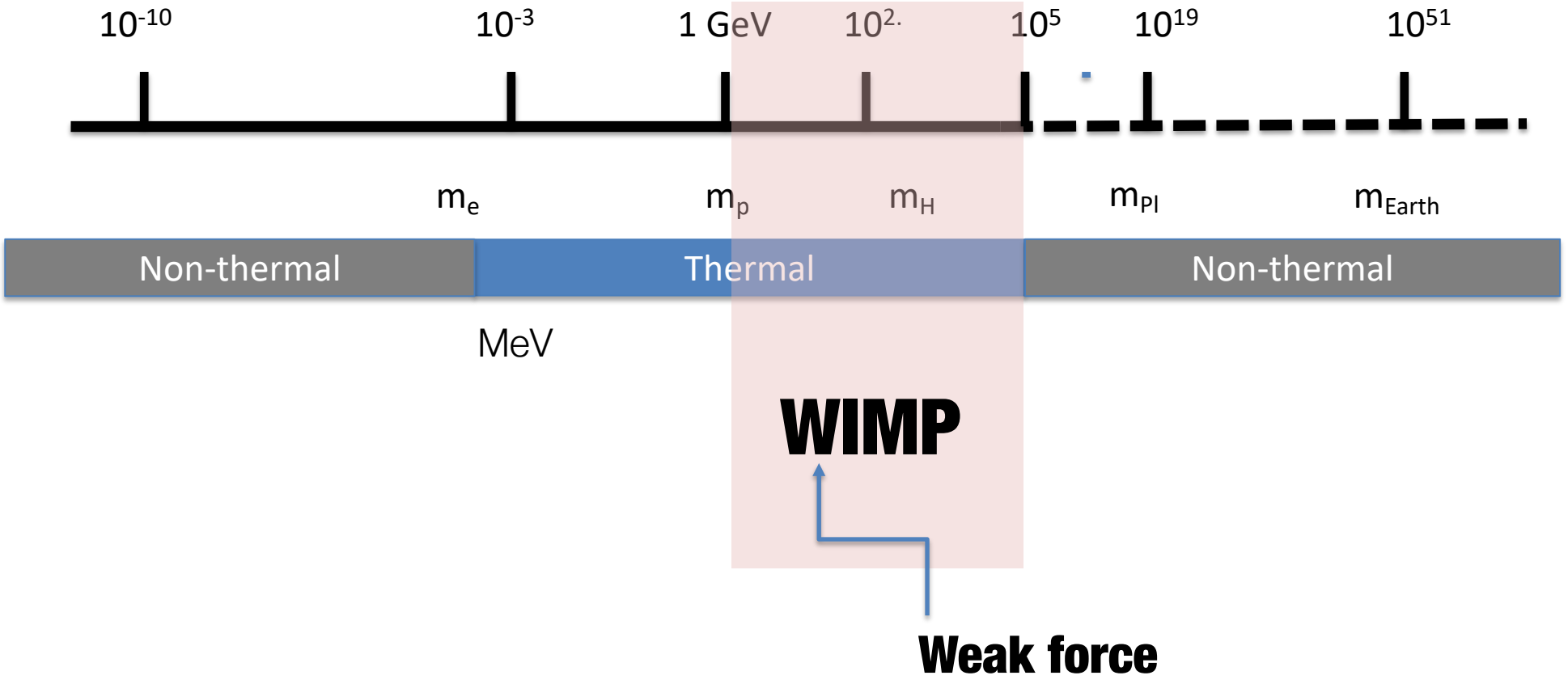
DM as a relic from the Early Universe



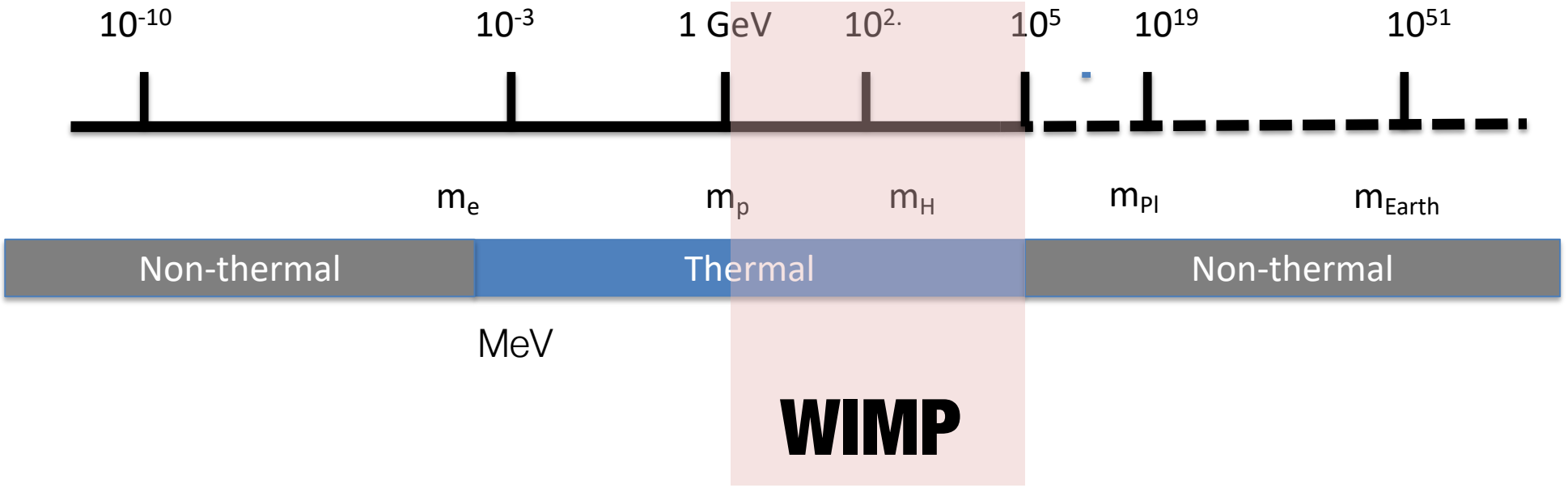
DM as a relic from the Early Universe



DM as a thermal relic from the Early Universe



DM as a thermal relic from the Early Universe



- The weak interaction mass scale and ordinary gauge couplings give right relic DM density

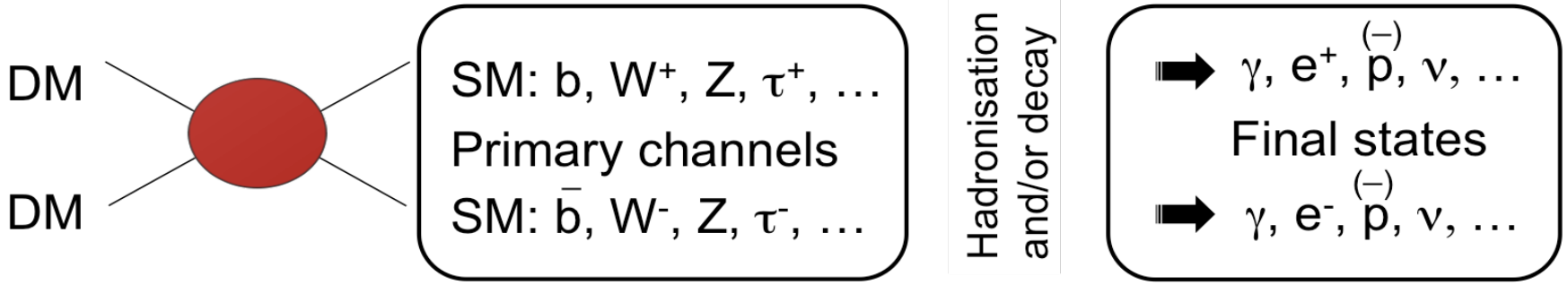
$$\Omega_{\rm DM}h^2 = \frac{3\times10^{-27}\ {\rm cm^3 s^{-1}}}{\langle\sigma v\rangle}$$

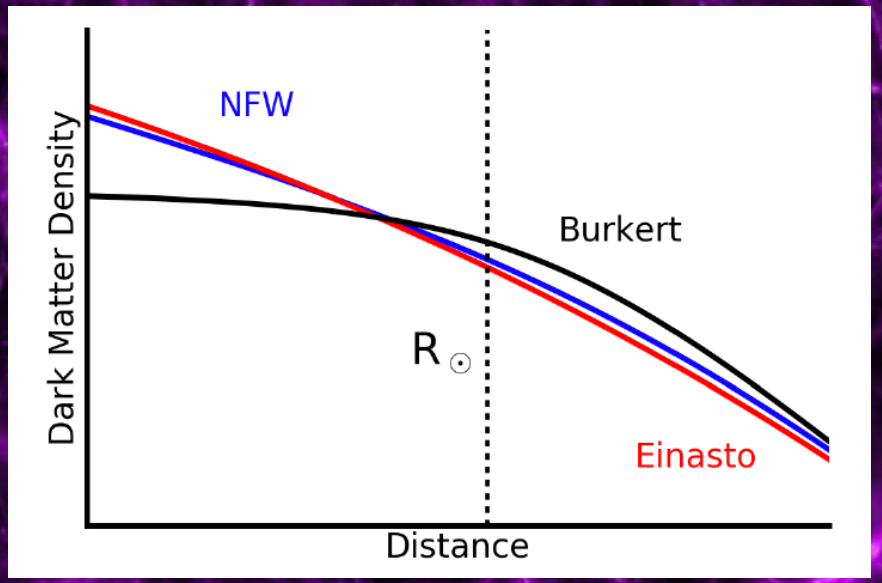
$$\langle\sigma v\rangle_{\rm W} \sim \frac{\alpha^2}{m^2_{\rm WIMP}} \sim 3\times10^{-26}{\rm cm^3 s^{-1}}$$

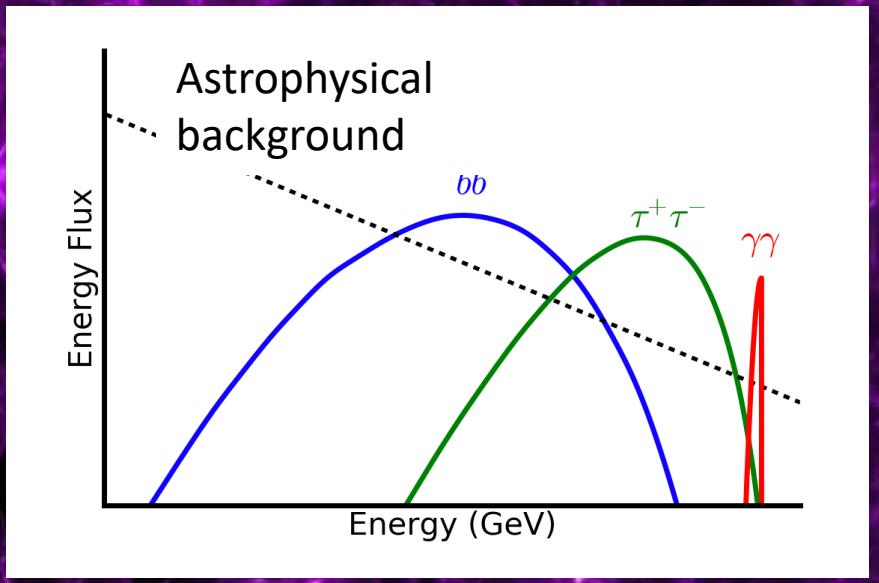
- GeV-TeV mass scale makes them **Cold Dark Matter**

→ **Provides benchmark for indirect detection: thermally-produced WIMPs**

Astrophysical searches for WIMPs





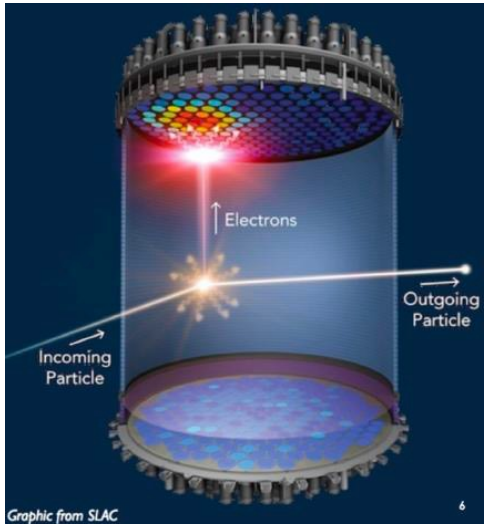


J-factor

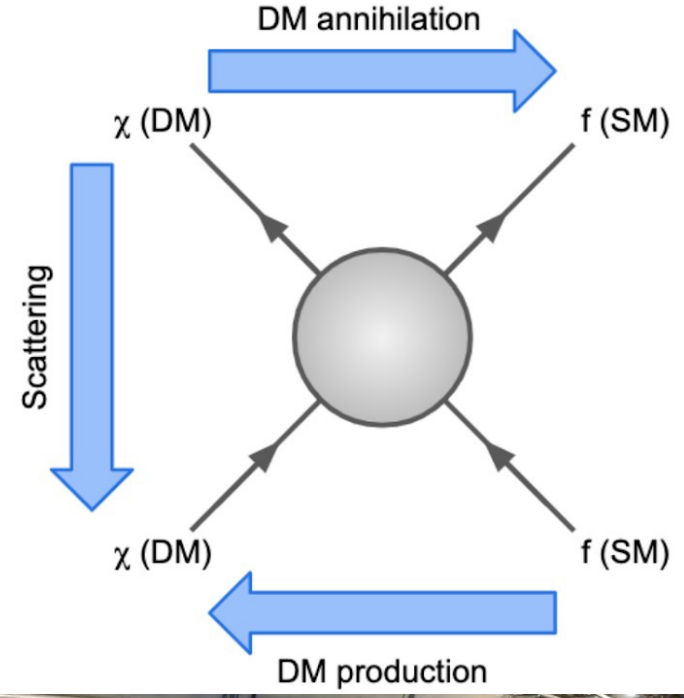
For self-conjugated DM annihilation:

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r[s])ds$$

Complementarity between the different approaches : Direct, Indirect and Collider experiments



XENONnT, LZ, Panda-X, …





+ WDC HAWC, LHAASO,…

Neutrino telescopes: IceCube, KM3Net, …



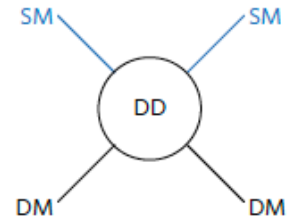
SuperCDMS, …

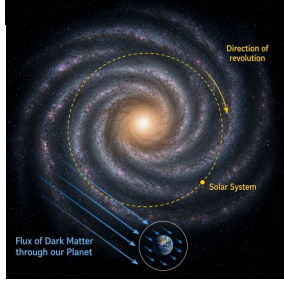


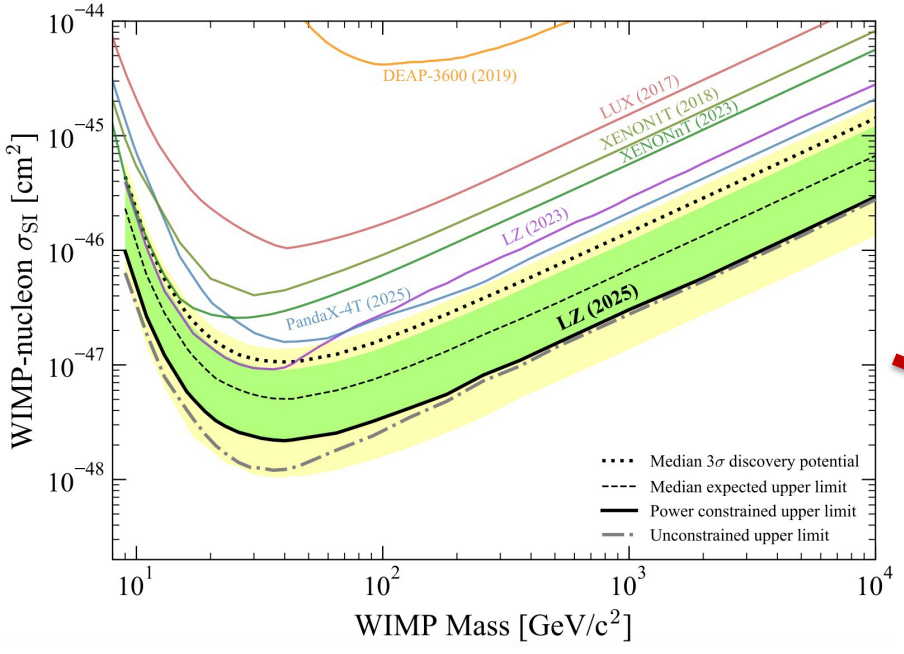


+AMS, DAMPE,…

Dark matter search underground

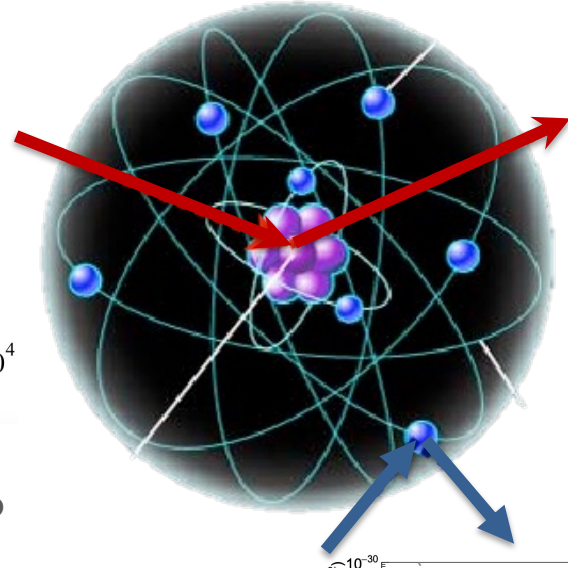


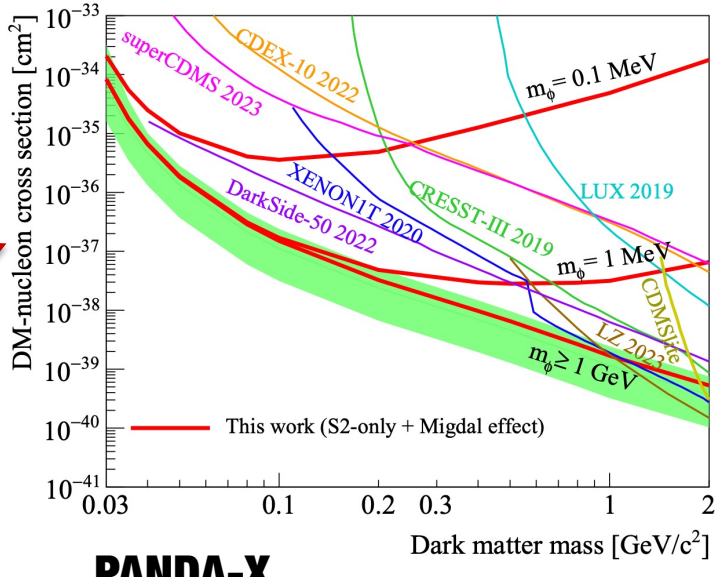




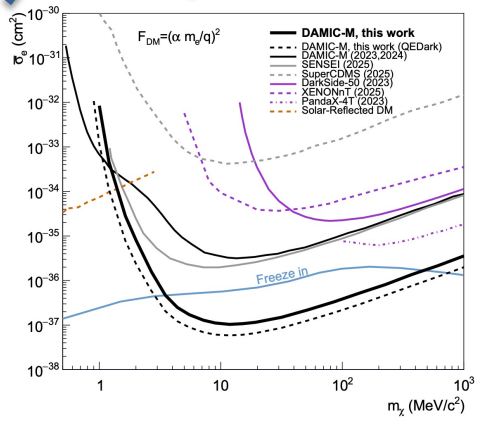
LUX-ZEPLIN

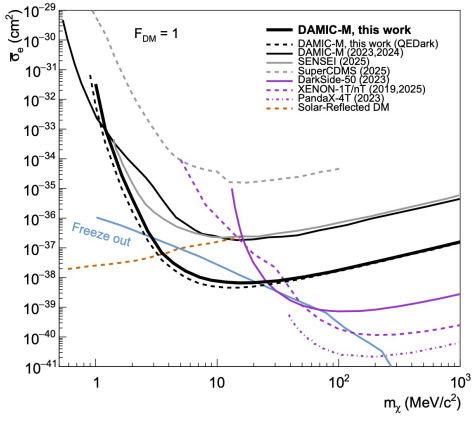
- 2.2x10^{-48} cm^2 for 40 GeV/c^2 WIMP





PANDA-X





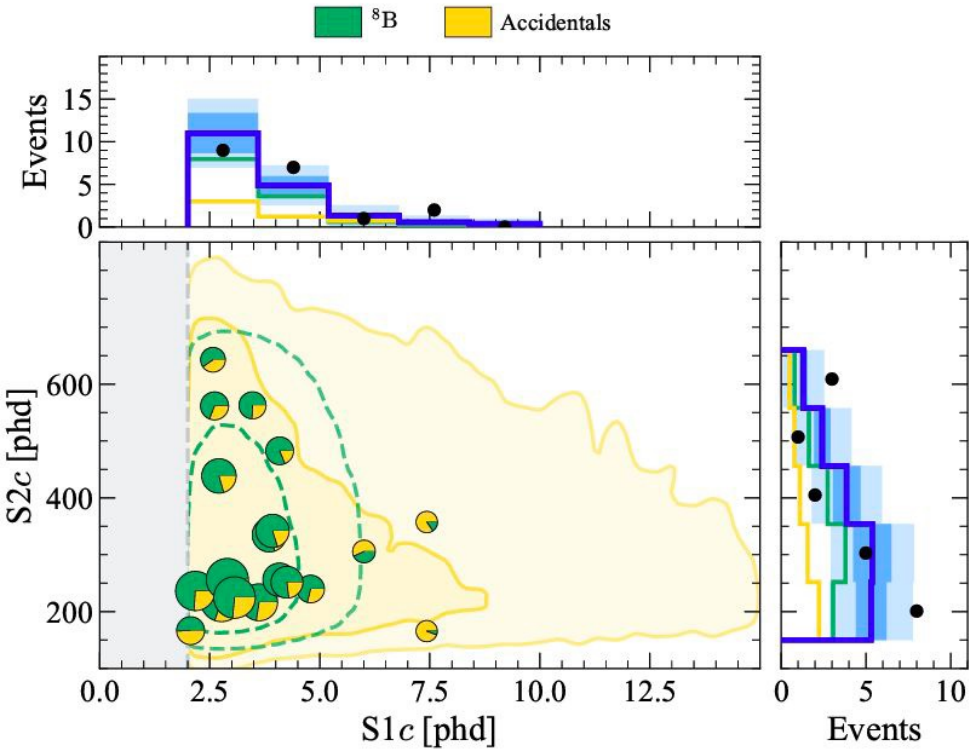
DAMIC-M

- **Strong constraints on the scattering cross section on nucleons and electrons in the 10-100 GeV mass scale**
- **Lighter (<100 MeV) DM being probed from electronic recoil searches**

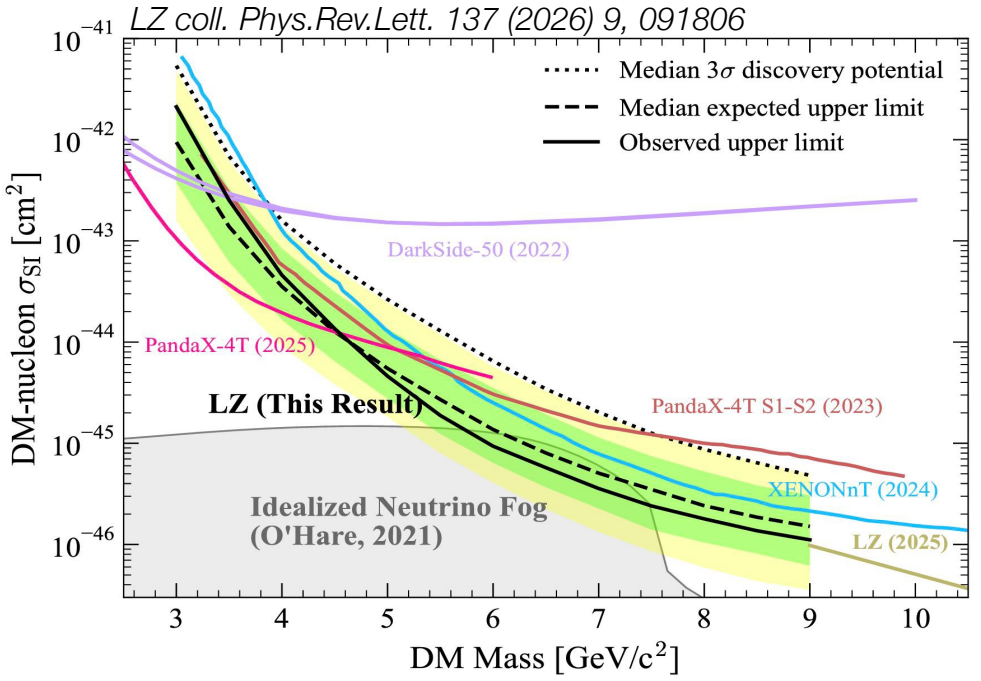
Low dark matter mass searches

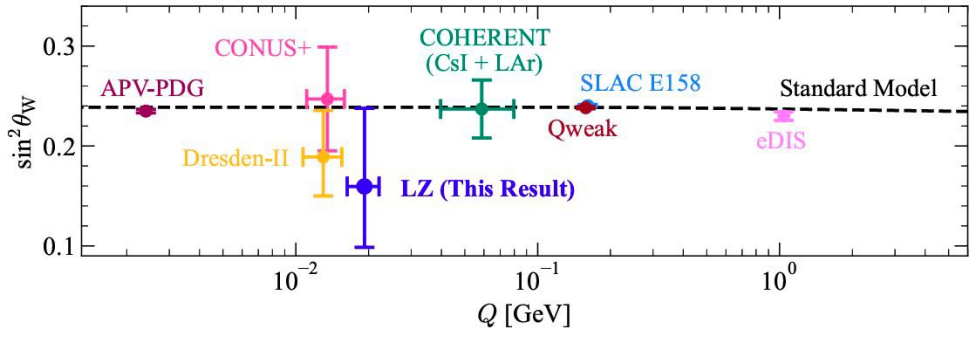
^{8}B CEνNS measurement

- Coherent Elastic Neutrino-Nucleus Scattering
- Predicted in 1974
- Detection of the scattering of neutrinos from the Sun in 2025



Background-only model rejected with 4.5σ significance (expected 6.7σ)



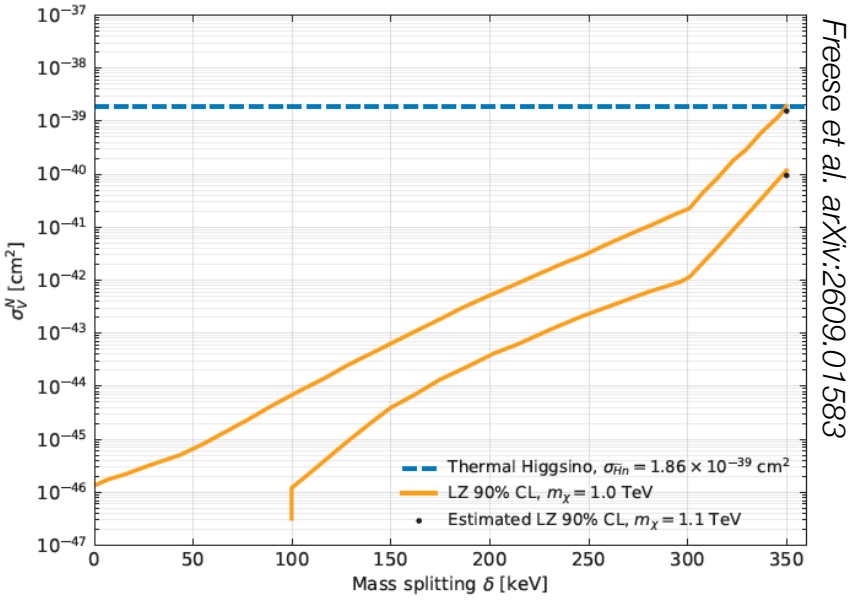


- Measure weak-mixing angle ($\sin^2\theta_W$) at low momentum transfer (Q), consistent with SM

LZ recoil event at 248 keV

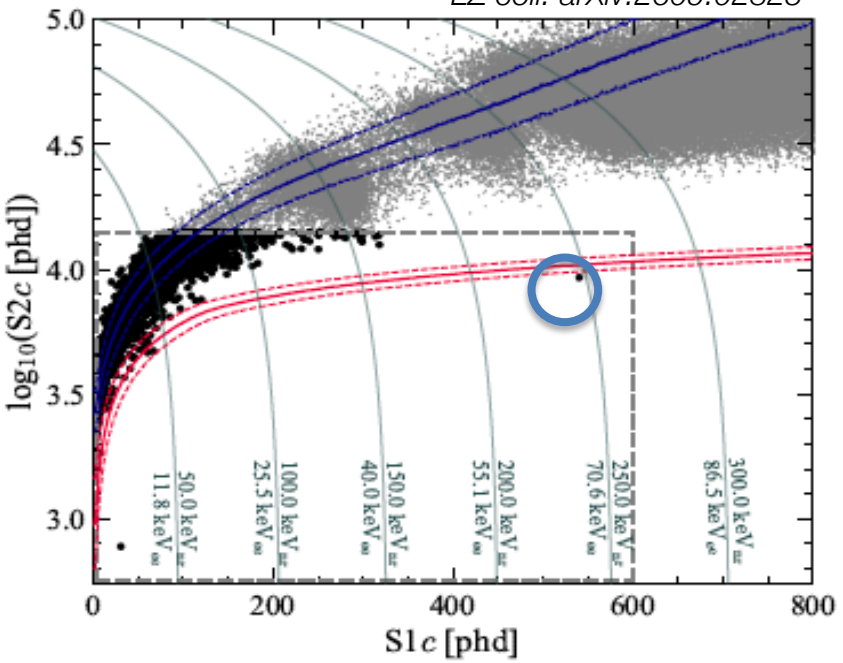
- Nuclear recoil of 248 +/- 23 (stat) +/- 23 (syst) keV in a region where background expectation is low
- Several rare background processes and detector effects studied in detail

A nearly pure Higgsino naturally realizes inelastic DM for a Higgsino mass ~1 TeV and a mass splitting ~350 keV

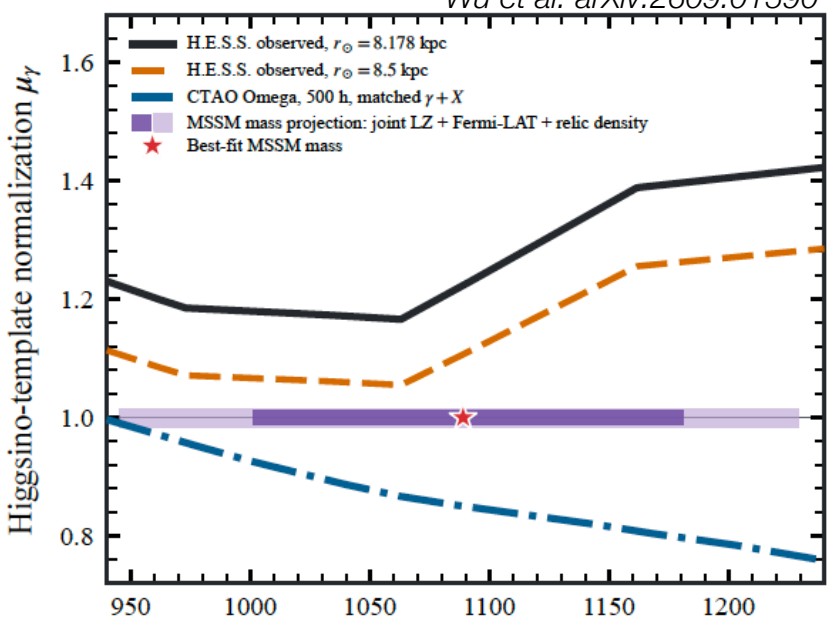


Freese et al. arXiv:2609.01583

LZ coll. arXiv:2609.02823



Wu et al. arXiv:2609.01590

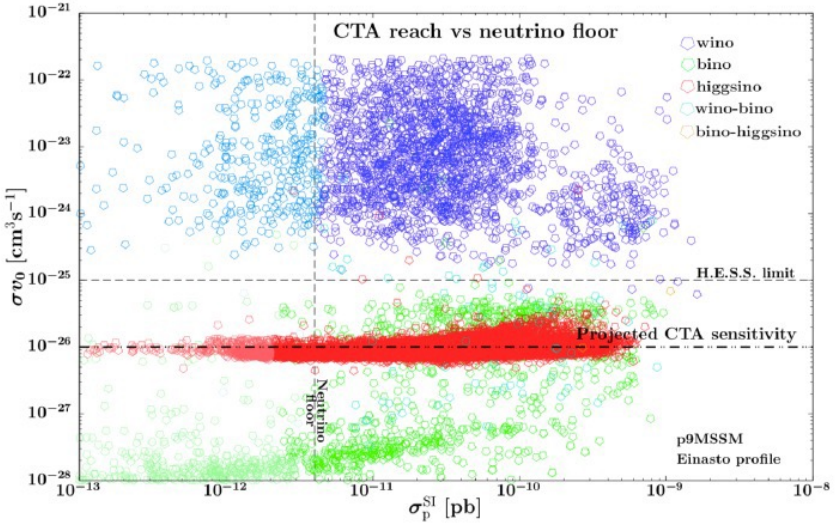


- **Caveat:** constraints from Higgsino annihilation from capture in the Sun *e.g.,Pospelov et al. arXiv:2609.02775*
- Lots of enthusiasm in the community... Stay tuned

Wino and Higgsino indirect detection

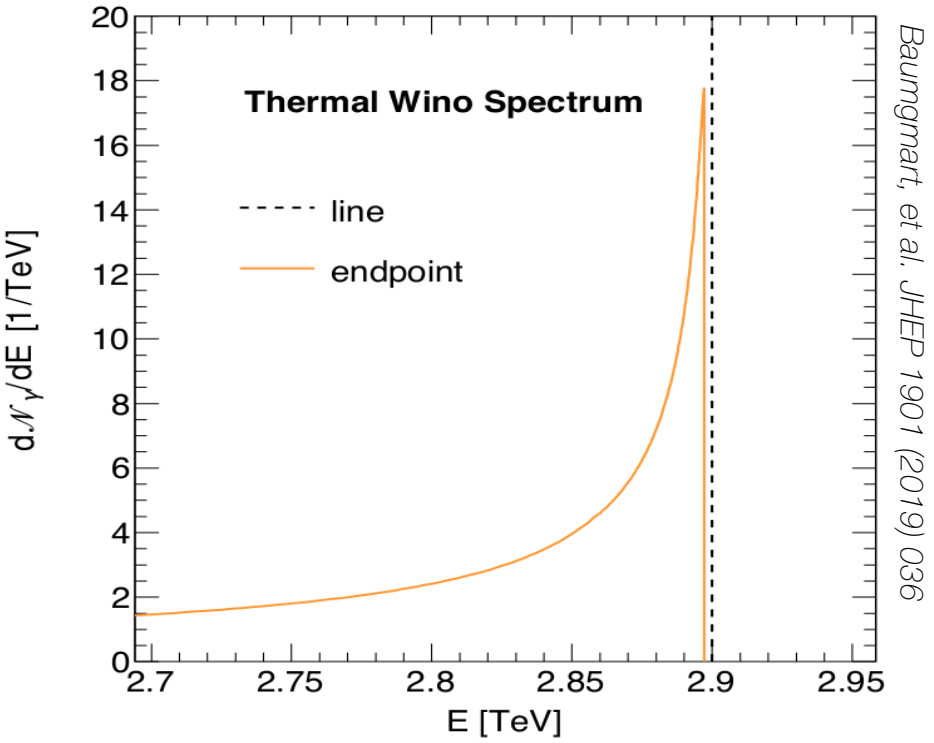
- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!

Hryczuk, EM, et al., JHEP 1910 (2019) 043



TeV-scale dark matter : Wino and Higgsino

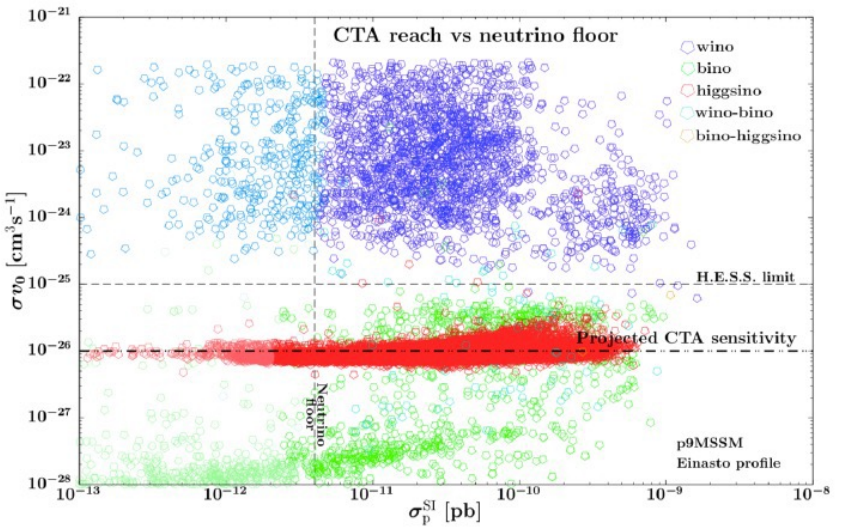
- **Wino/Higgsino show prominent gamma-ray line feature in the annihilation spectra**
  - a very “clean” annihilation channel
  - no astrophysical lines expected

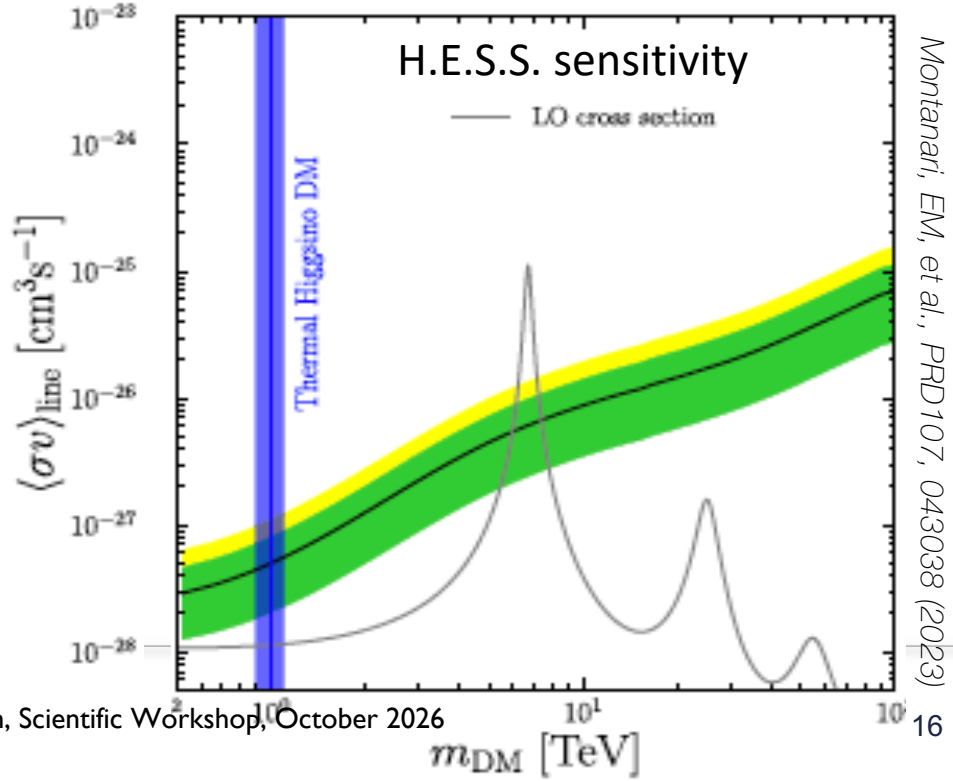


Strong Constraints on thermal Wino DM

e.g, Rinchiuso, Rodd, EM, et al., PRD 98, 123014 (2018)

Hryczuk, EM, et al., JHEP 1910 (2019) 043

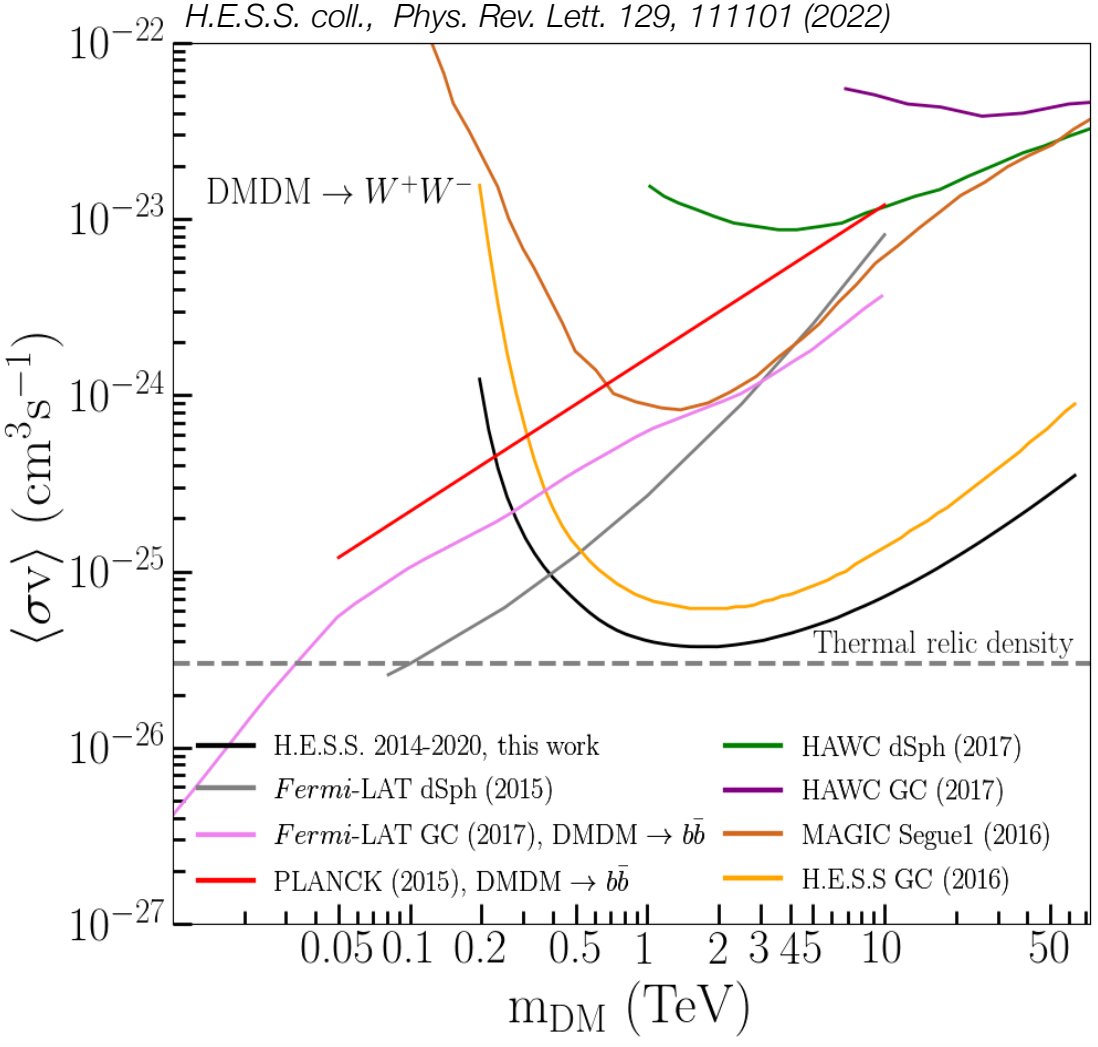




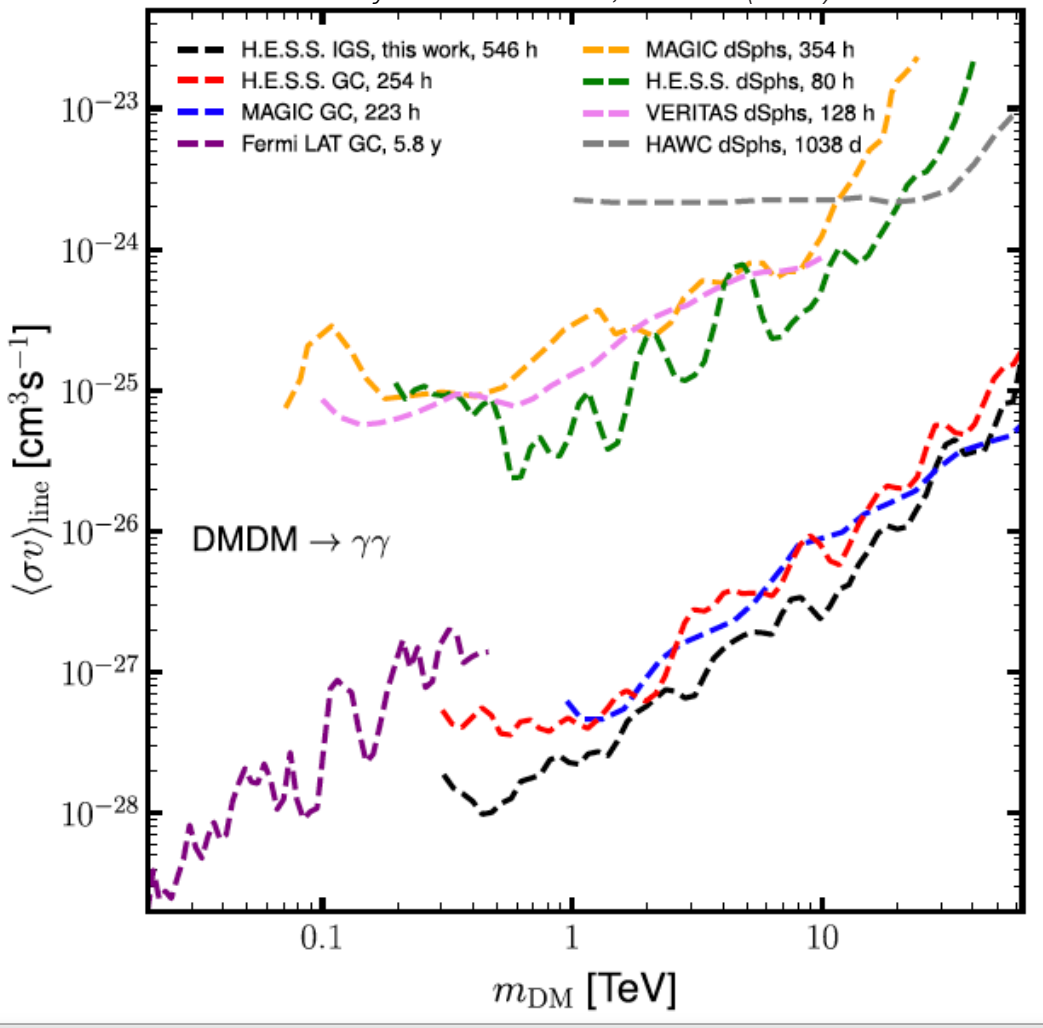
TeV-scale dark matter constraints

Current IACTs are reaching the required sensitivity probe thermal WIMPs

H.E.S.S. coll., Phys. Rev. Lett. 129, 111101 (2022)



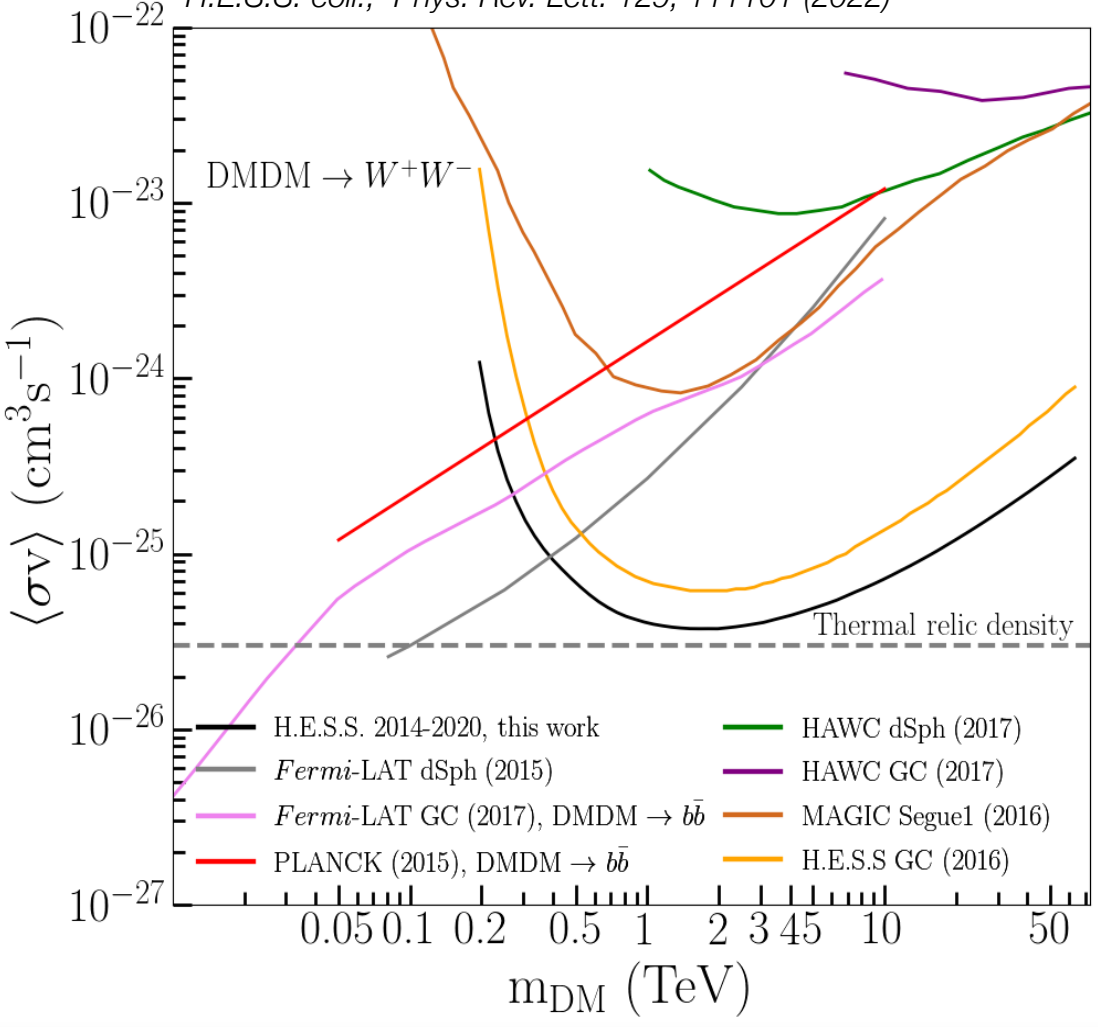
H.E.S.S. coll. Phys. Rev. Lett. 137, 091002 (2026)



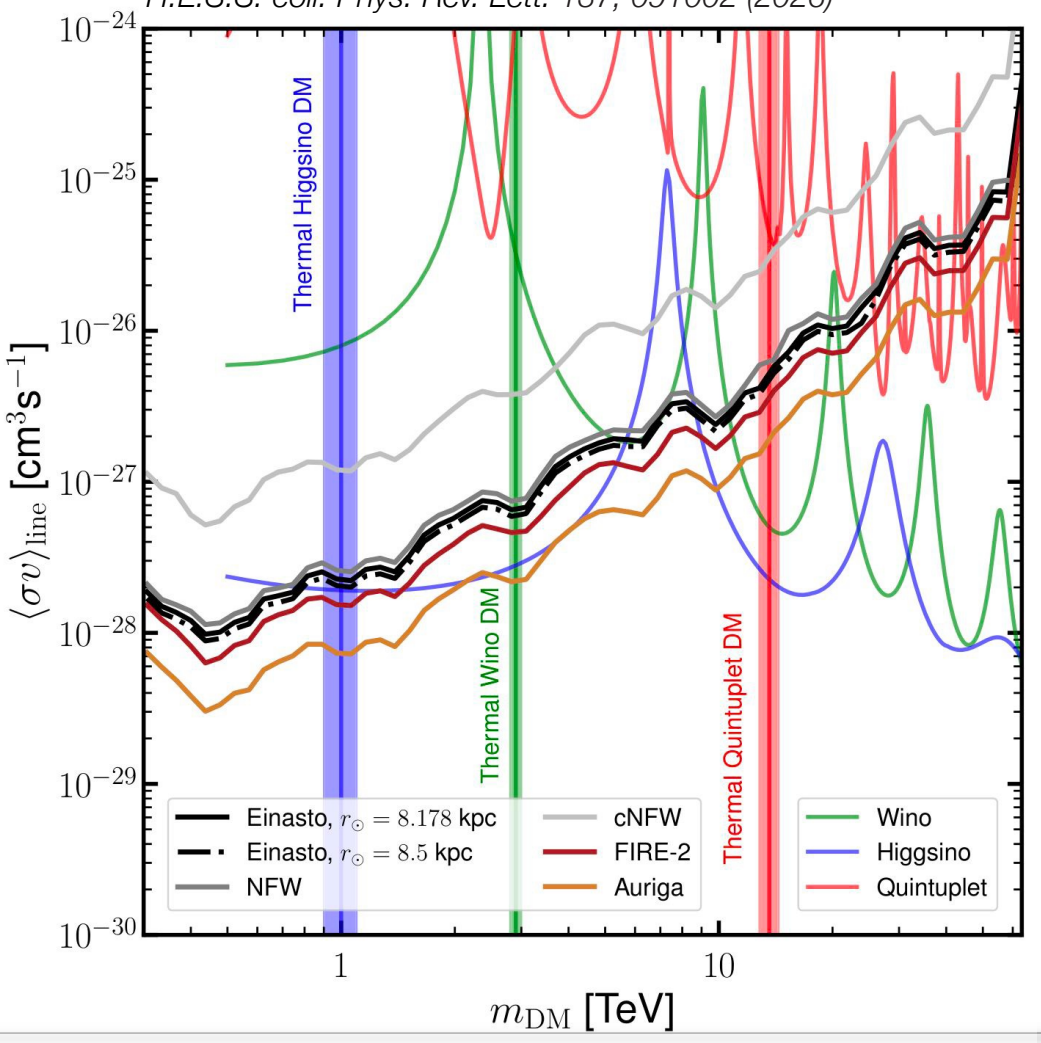
TeV-scale dark matter constraints

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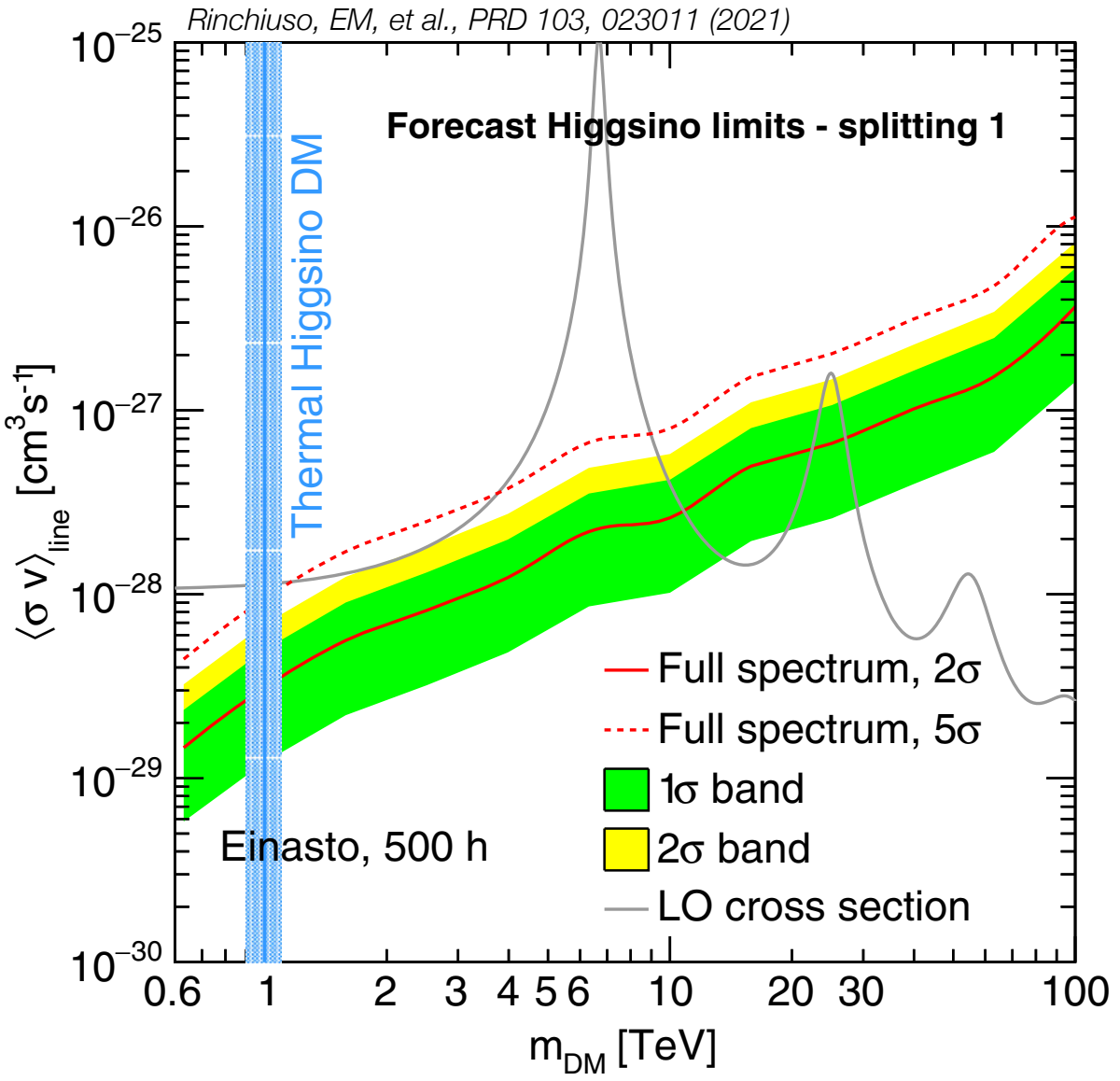
H.E.S.S. coll. Phys. Rev. Lett. 137, 091002 (2026)



Higgsino dark matter reach with CTAO ?

- Last remaining well-motivated WIMP benchmark model ?
- Likely invisible at direct detection
- Difficult even at FCC-hh

Capdevilla et al. JHEP 06 (2021) 133

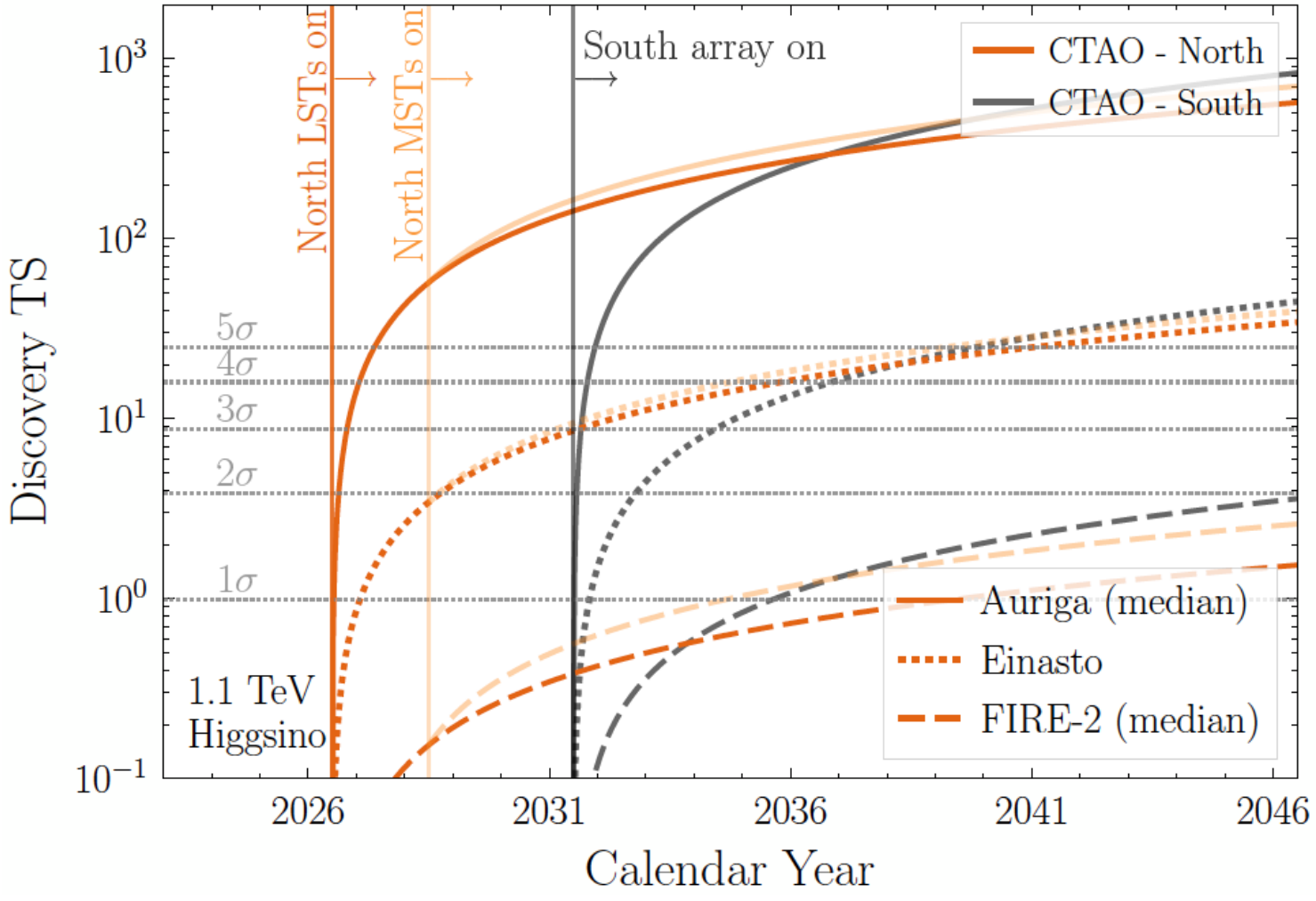


Higgsino dark matter reach with CTAO ?

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Capdevilla et al. JHEP 06 (2021) 133

Abe, Inada, EM, Rodd, Safdi, Xu, Phys. Rev. D 114, 023052 (2026)



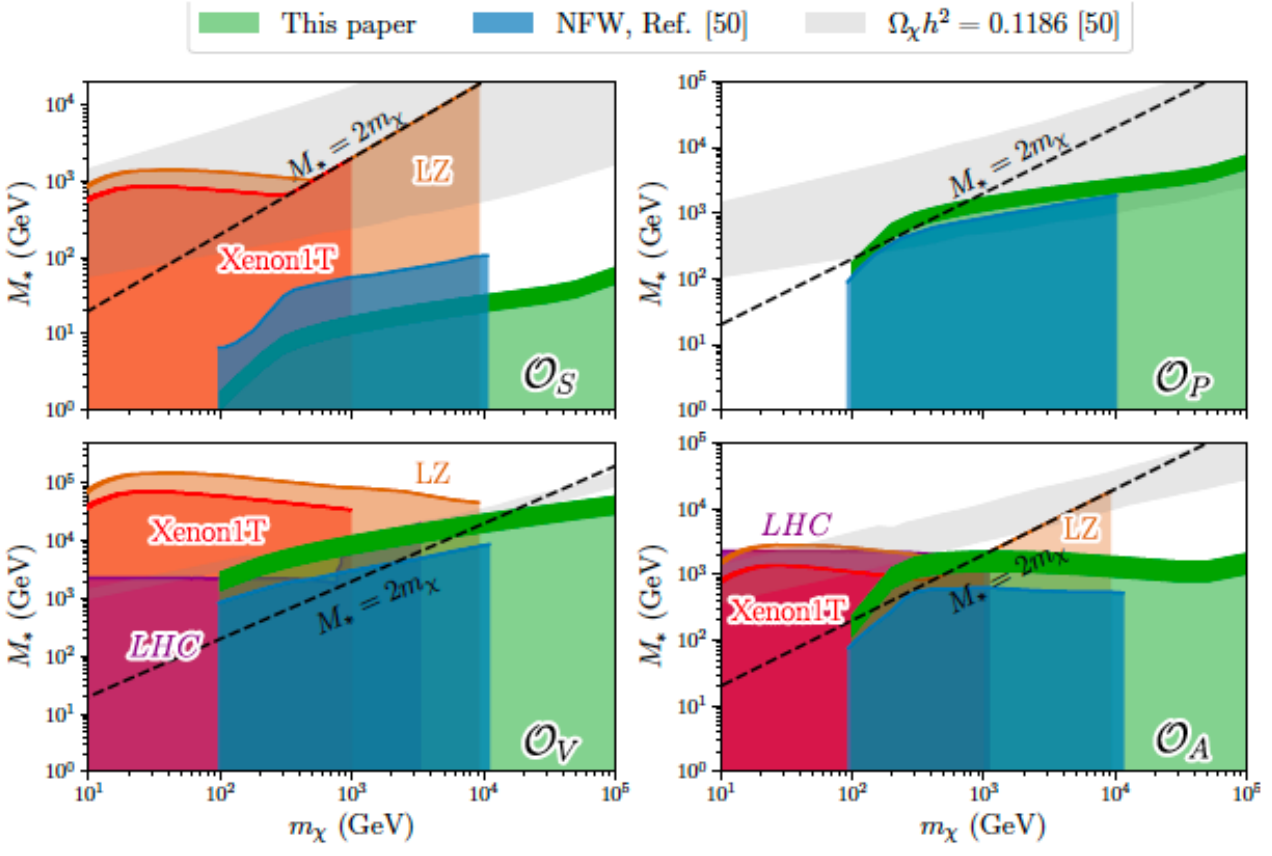
Synergy with collider and direct detection searches

- Direct comparison of results from multiple probes requires a concrete particle physics hypothesis
  → framework of effective field theory or simplified model approaches (some limitations still exist)

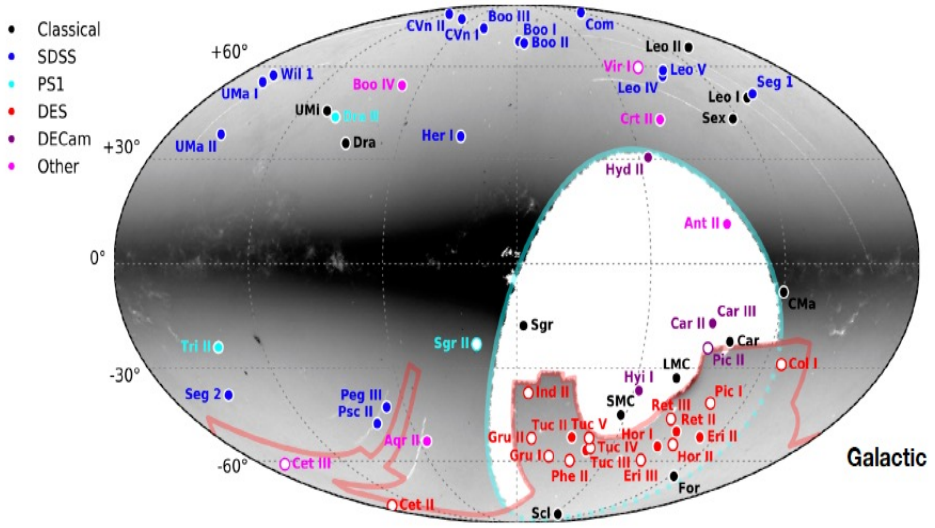
- For EFT approach: CTAO reach
  - mass scale M⋆
  - 4 operators: scalar, pseudo-scalar, vector, axial-vector

	ID	DD
$\mathcal{O}_S$	v^2	1
$\mathcal{O}_P$	1	$(\vec{s}_\chi \cdot \vec{q})\,(\vec{s}_N \cdot \vec{q})$
$\mathcal{O}_V$	1	1
$\mathcal{O}_A$	$m_q^2,\ v^2$	$\vec{s}_\chi \cdot \vec{s}_N$

Reis, Scaffadi, EM, White JCAP 02 (2026) 015



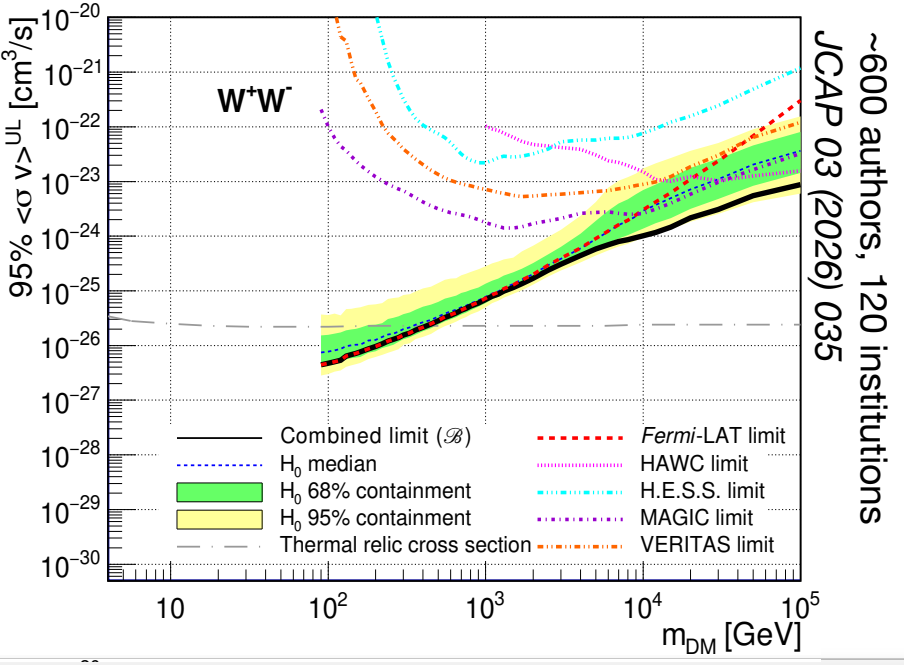
Dwarf galaxies observations



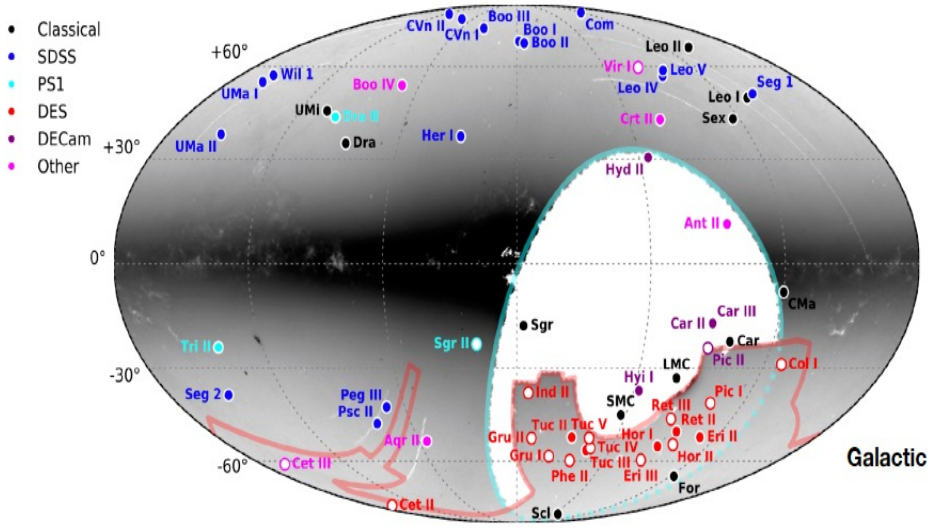
Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5}})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5}})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue 1	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue 2	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

- **No recent star formation**
- **Very low gas amount**

Census of Milky Way satellites including all dwarf galaxies spectroscopically confirmed as well as suspected ones



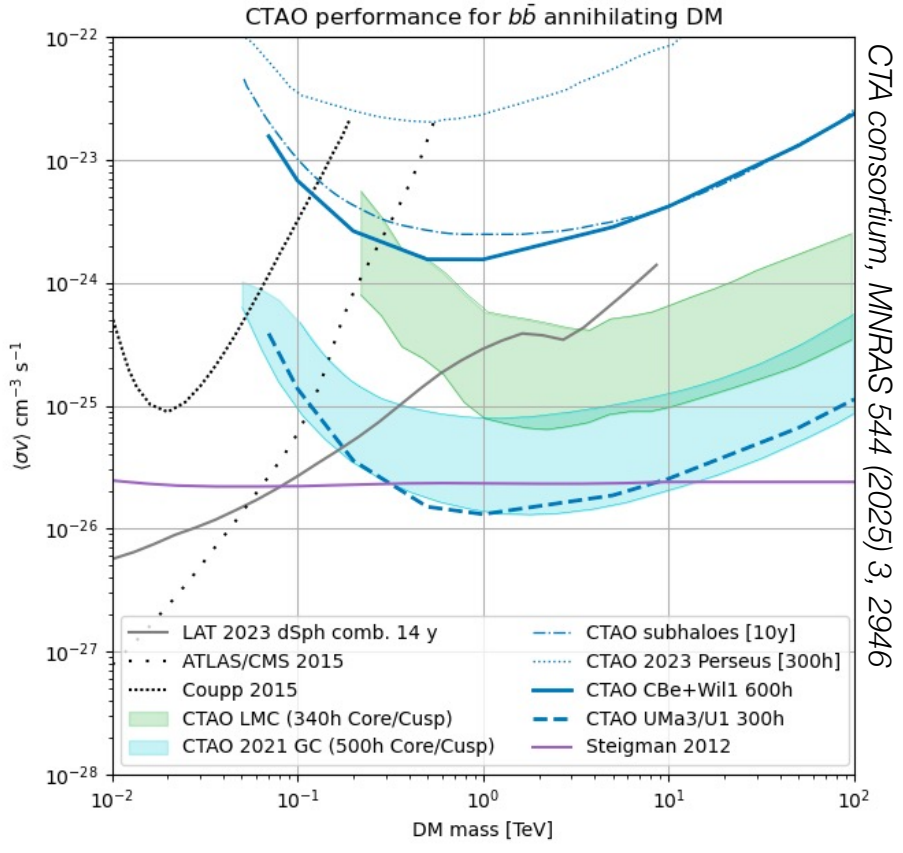
Dwarf galaxies observations



Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5}})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5}})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
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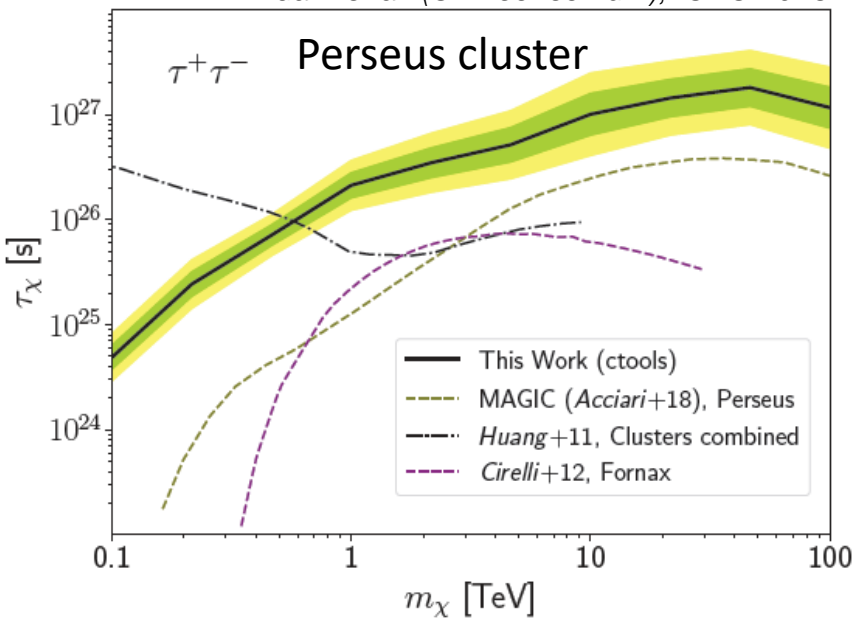


(Heavy) Decaying Dark Matter

- Decaying DM searches target regions of the sky where large volumes can be probed, *e.g.*, *galaxy clusters*

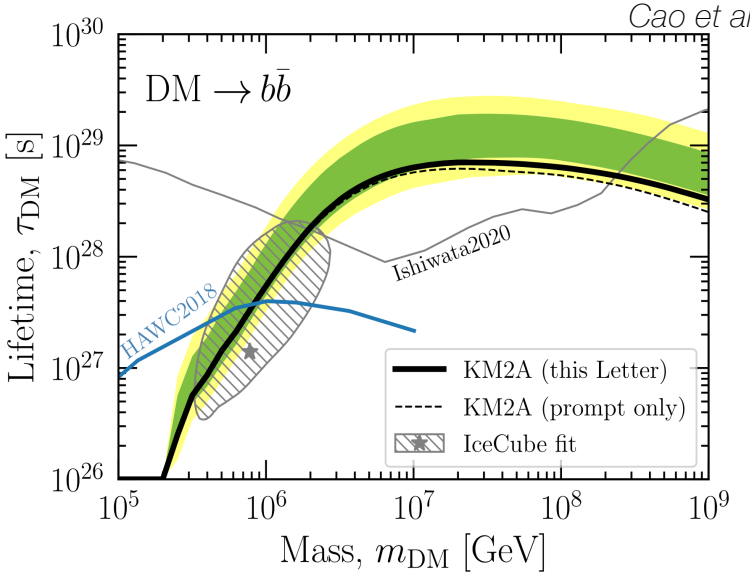
- **> PeV dark matter with wide FoV instruments**
  570 Days of LHAASO Observations
  → Strongest constraints on PeV DM

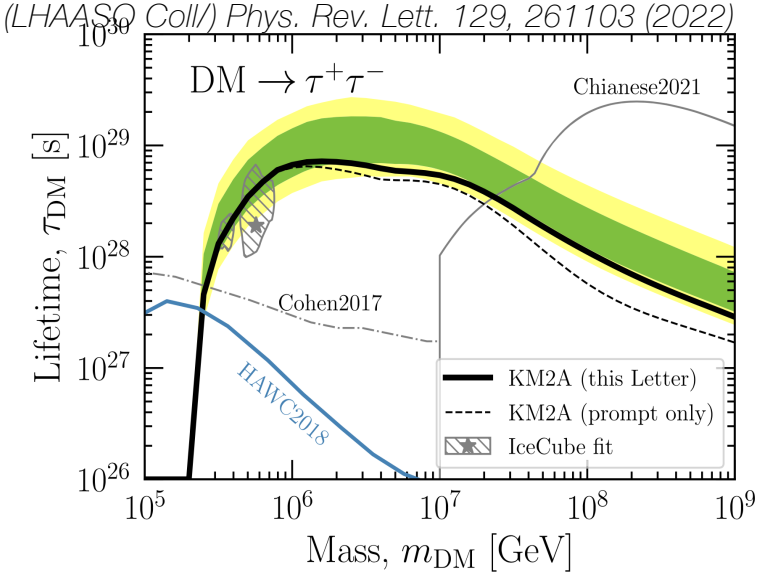
Adam et al. (CTA consortium), ICRC 2023



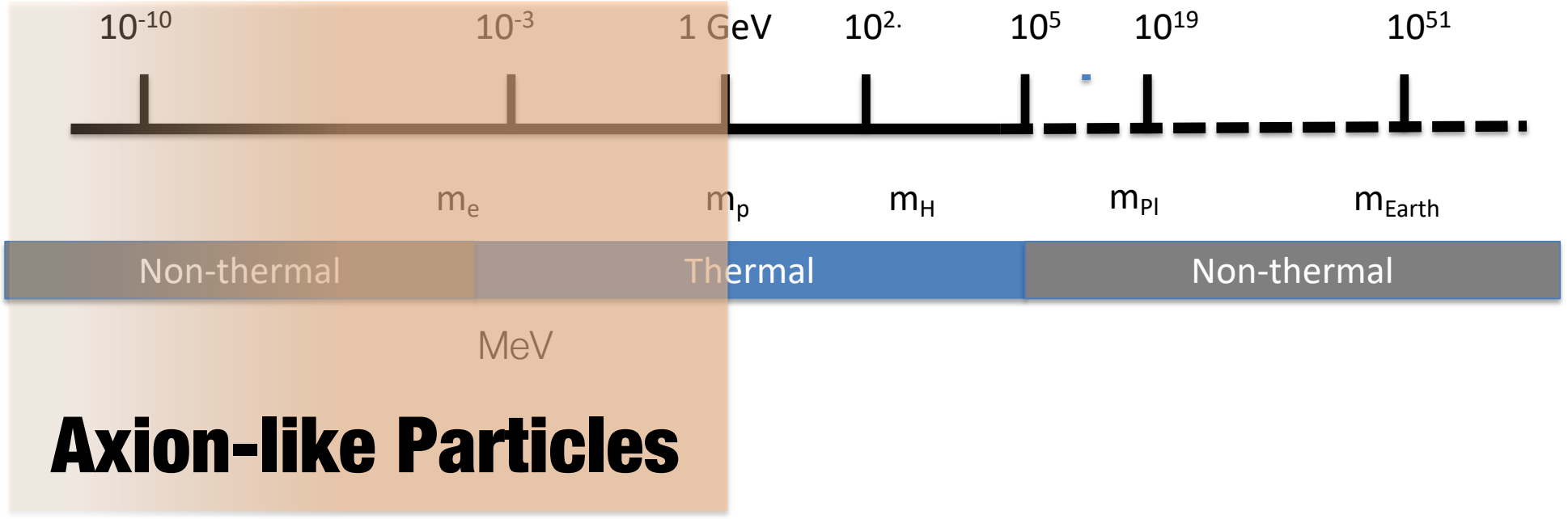


Cao et al. (LHAASO Coll/) Phys. Rev. Lett. 129, 261103 (2022)

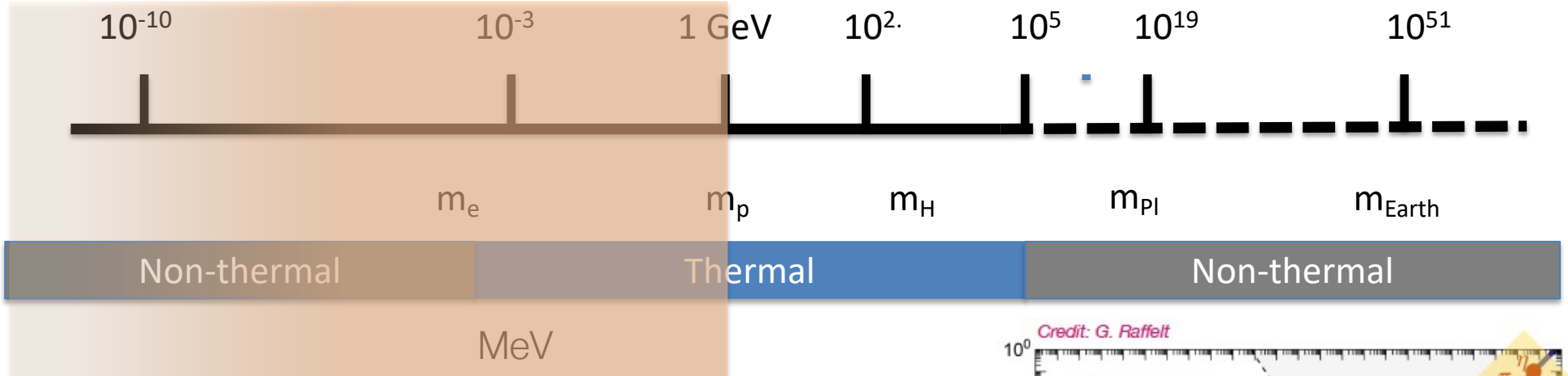




DM as a relic from the Early Universe



DM as a relic from the Early Universe



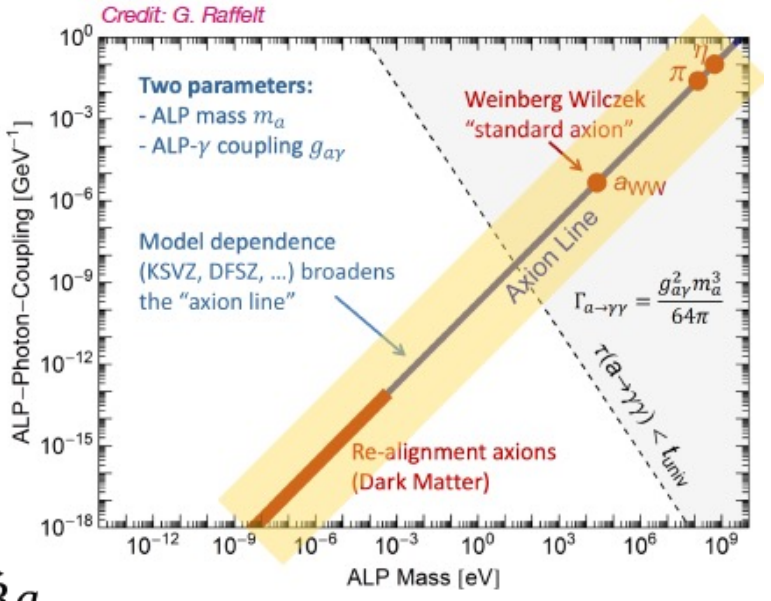
Axion-like Particles

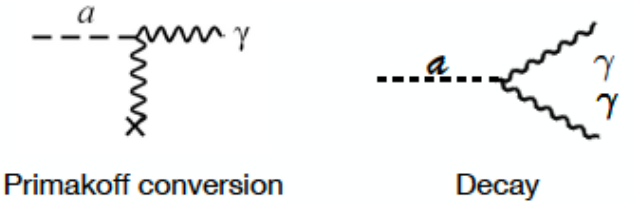
Axions

- Light pseudo-scalar particle
- Minimal coupling with gluons to solve the strong CP problem
- Viable cold dark matter candidate
- Induced coupling with photons: $\mathscr{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$

Axion-like particles

- As opposed to axions, mass and coupling constant are unrelated

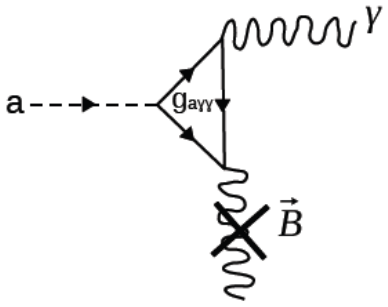




Primakoff conversion Decay

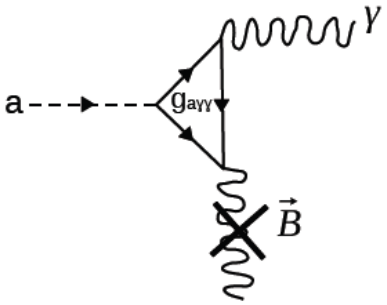
ALP searches with VHE gamma rays

- **In the presence of an external magnetic field**
  → possibility to have ALP-Photon oscillations
- The conversion probability $P_{a\gamma}$ is dependent on the magnetic field intensity and orientation as well as the scale of the magnetized region

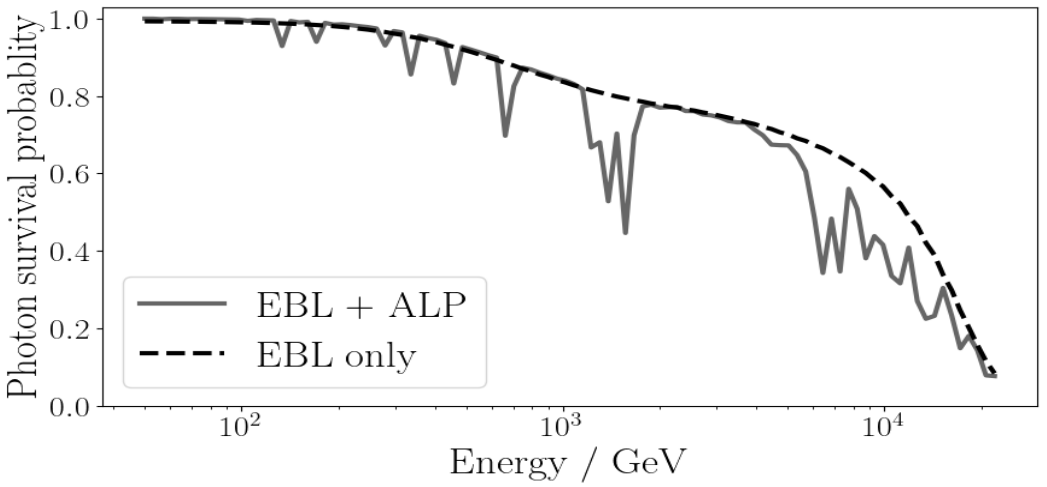


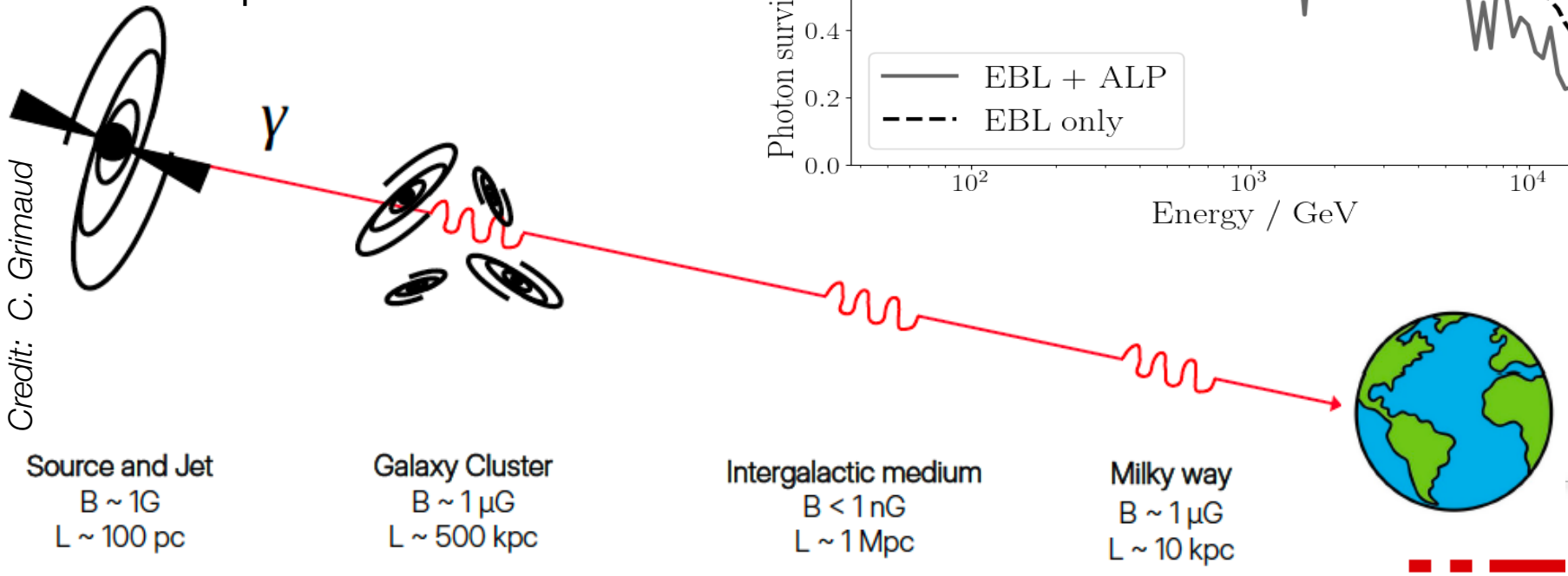
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- Wiggles: energy-dependent deviations from smooth GeV-TeV spectrum

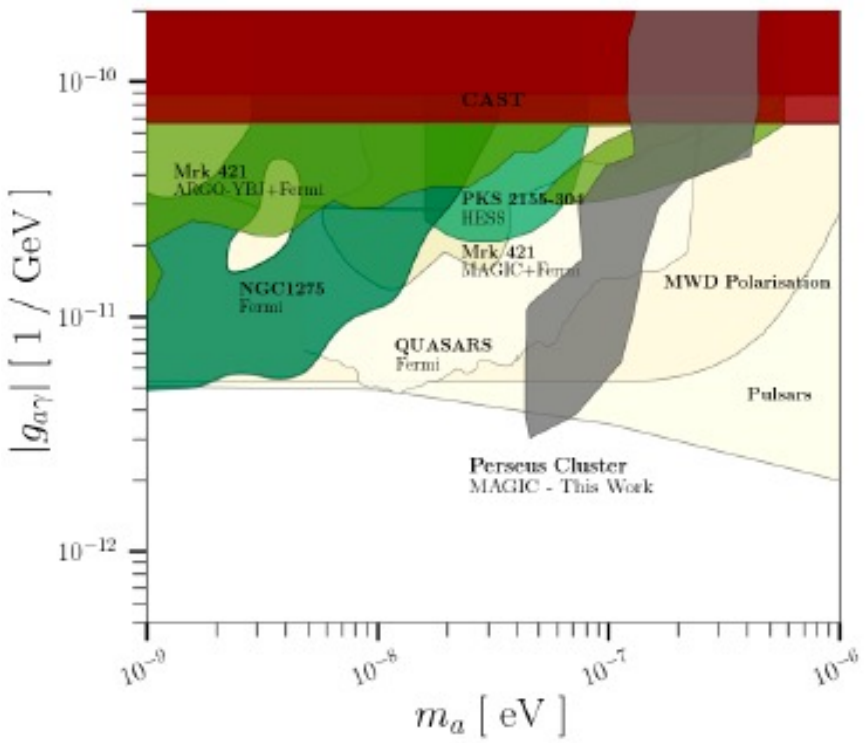




ALP searches with VHE gamma rays

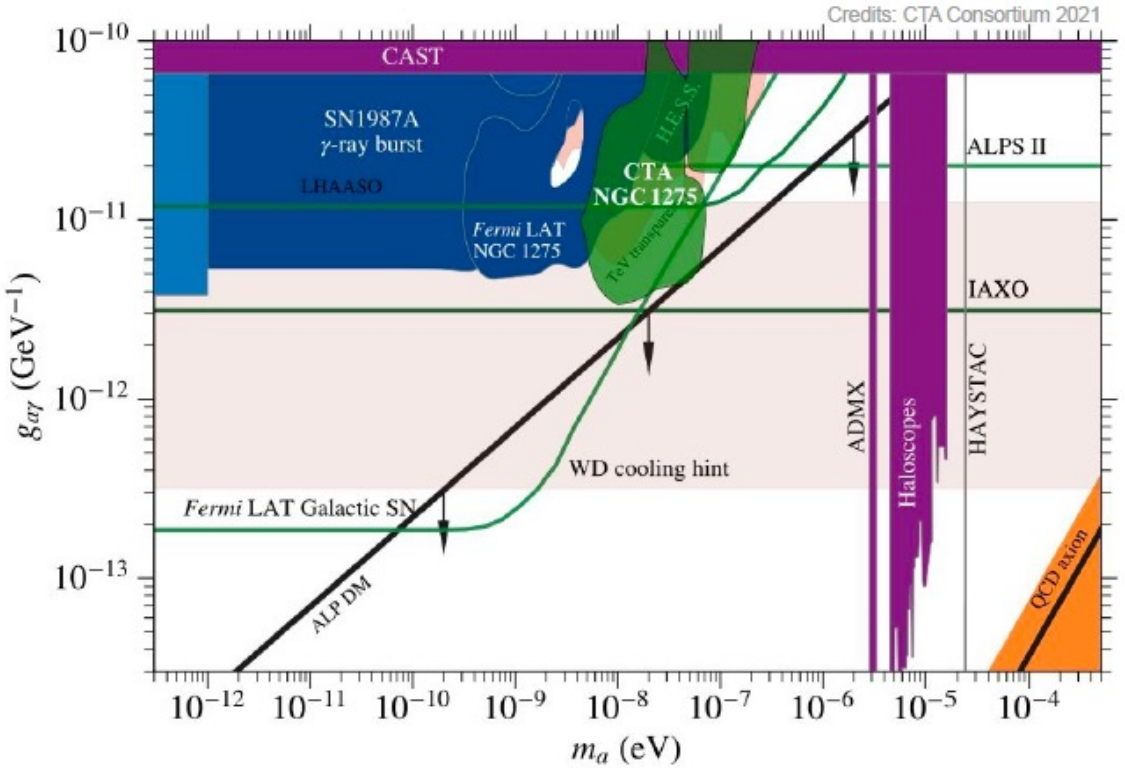
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Observations of Perseus cluster by MAGIC ~40 h



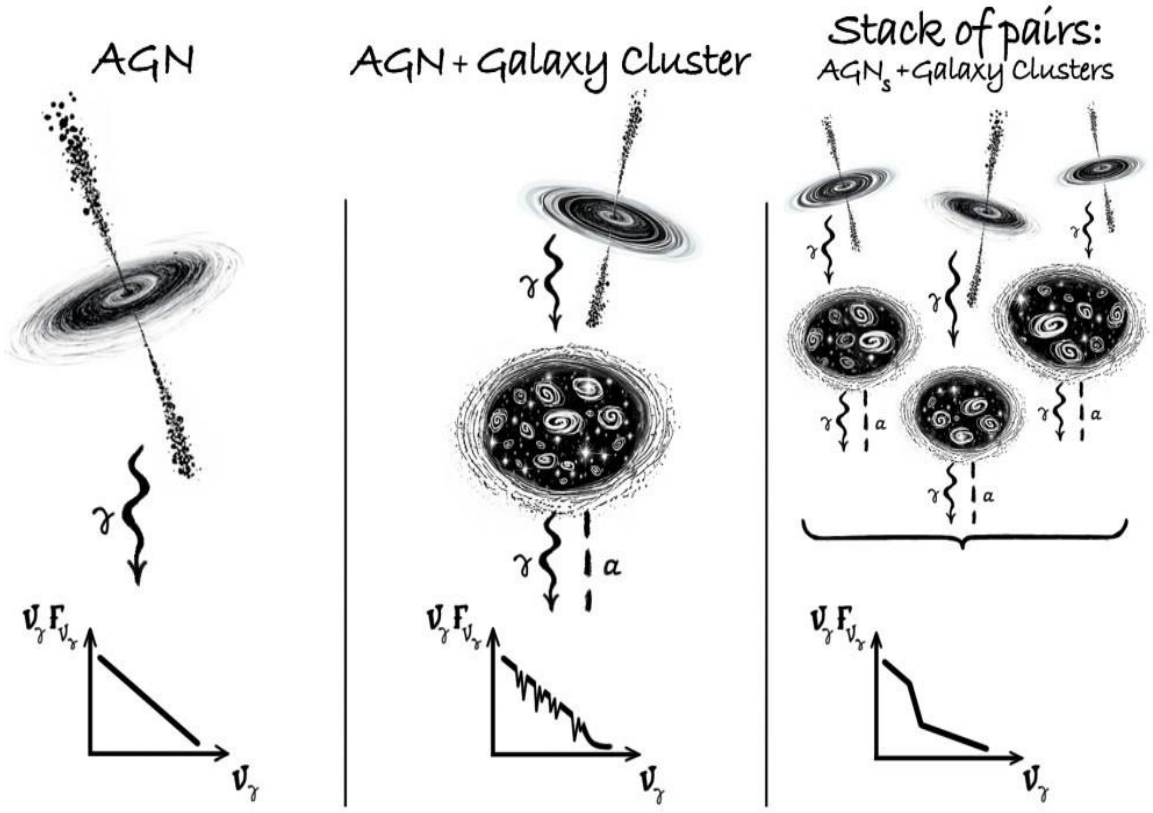
MAGIC Coll. Phys.Dark Univ. 44 (2024) 101425

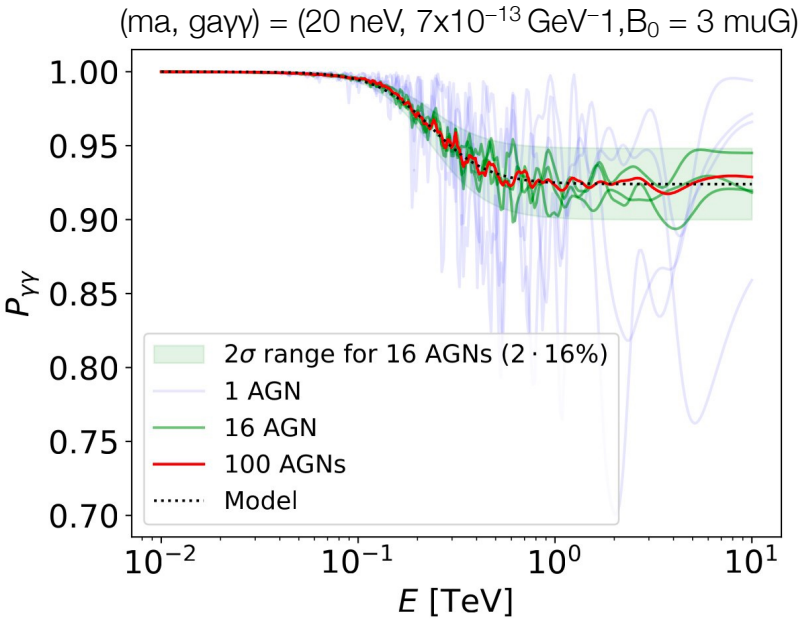
Prospects for CTA: Perseus cluster



Probing ALP with AGN-GalaxyCluster pairs

Caveat: for GC, no reliable measurement of the small-scale properties of the field (orientation, domain length) → need to marginalize over a large number of small-scale configuration of the magnetic field





- **Stacking analysis of multiple AGN-GC pairs**

→ gives a smooth predictable spectral imprint

Probing ALP with AGN-GalaxyCluster pairs

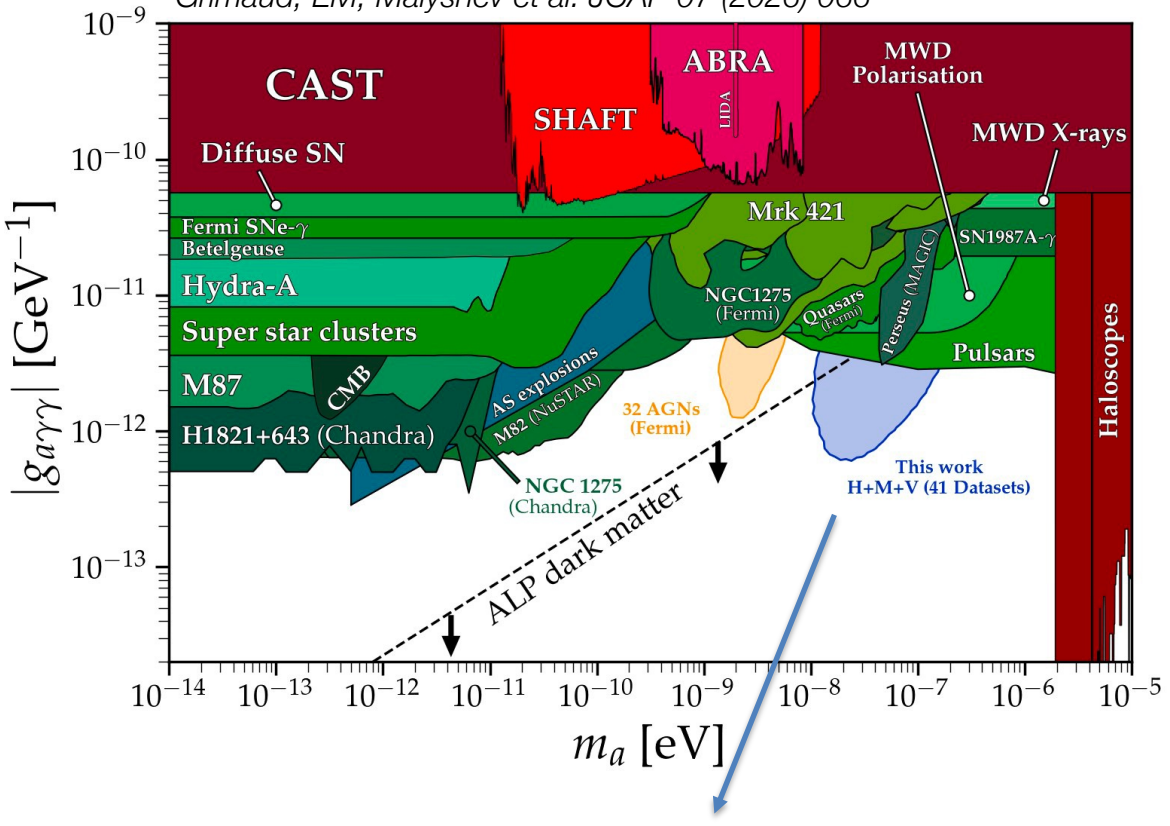
Caveat: for GC, no reliable measurement of the small-scale properties of the field (orientation, domain length) → need to marginalize over a large number of small-scale configuration of the magnetic field

AGN-GC selection

>10 GeV gamma-ray bright AGNs with SZ catalog (GC)
→ 16 AGN-GC pairs selected
→ 41 datasets from H.E.S.S., MAGIC and VERITAS

Fermi-LAT name	RA	Dec.	z
4FGL J0617.7-1715	94.43	-17.25	0.10
4FGL J0912.5+1556	138.14	15.93	0.21
4FGL J1058.4+0133	164.62	1.56	0.89
4FGL J1213.0+5129	183.26	51.48	0.80
4FGL J1303.0+2434	195.76	24.58	0.99
4FGL J1508.8+2708	227.20	27.14	0.27
4FGL J1615.6+4712	243.92	47.20	0.20
4FGL J2041.9-3735	310.48	-37.59	0.10
4FGL J2314.0+1445	348.51	14.75	0.16
4FGL J2321.9+2734	350.49	27.57	1.25
4FGL J2338.9+2124	354.74	21.40	0.29
4FGL J0654.4+4514	103.61	45.24	0.93
4FGL J1242.9+7315	190.75	73.26	0.08
4FGL J0319.8+4130	49.96	41.51	0.02
4FGL J1230.8+1223	187.71	12.39	0.00
4FGL J1144.9+1937	176.24	19.63	0.02

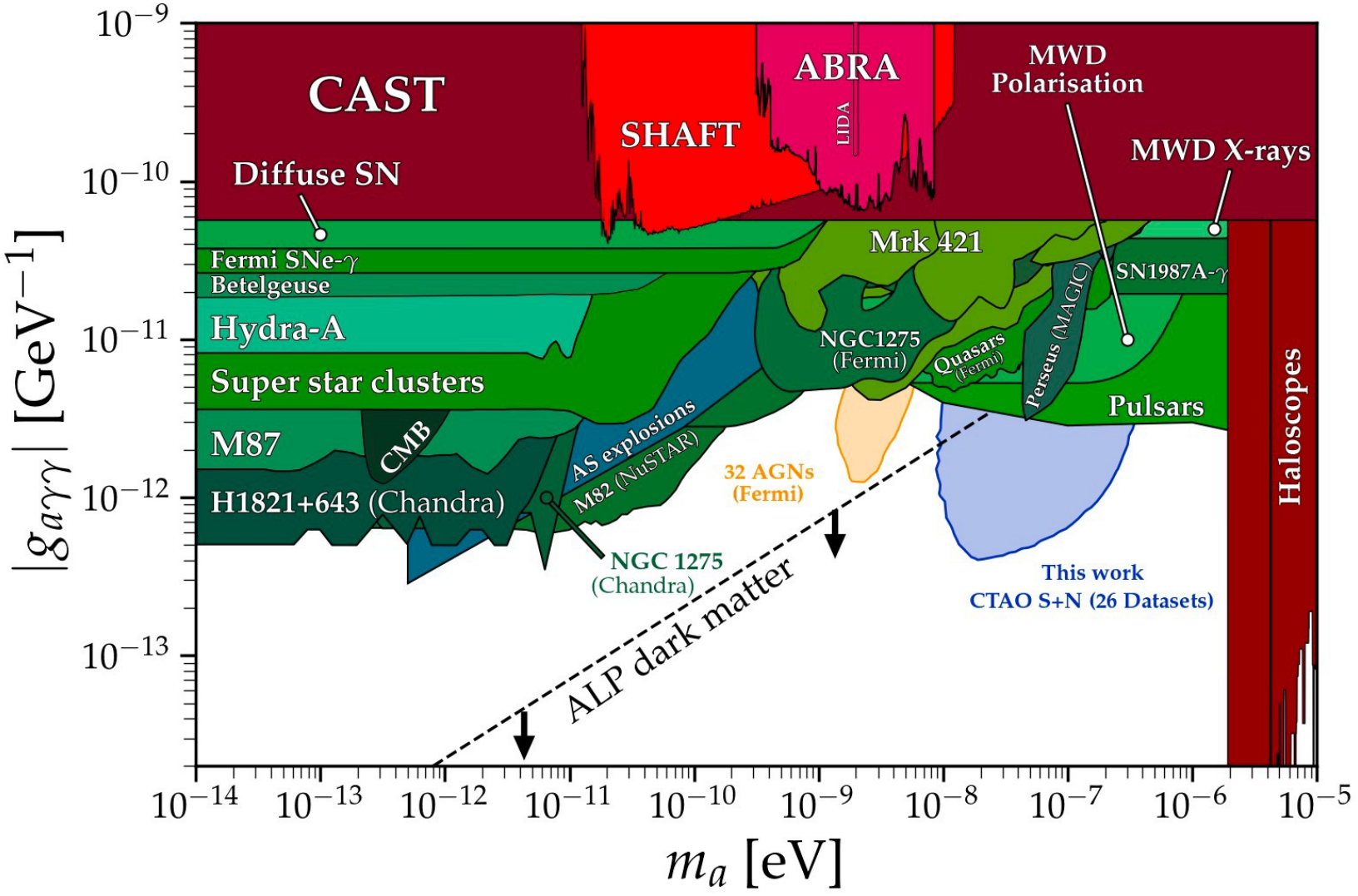
Grimaud, EM, Malyshev et al. JCAP 07 (2026) 066



Sensitivity of combined mock observations of H.E.S.S, MAGIC and VERITAS

CTAO forecast sensitivity

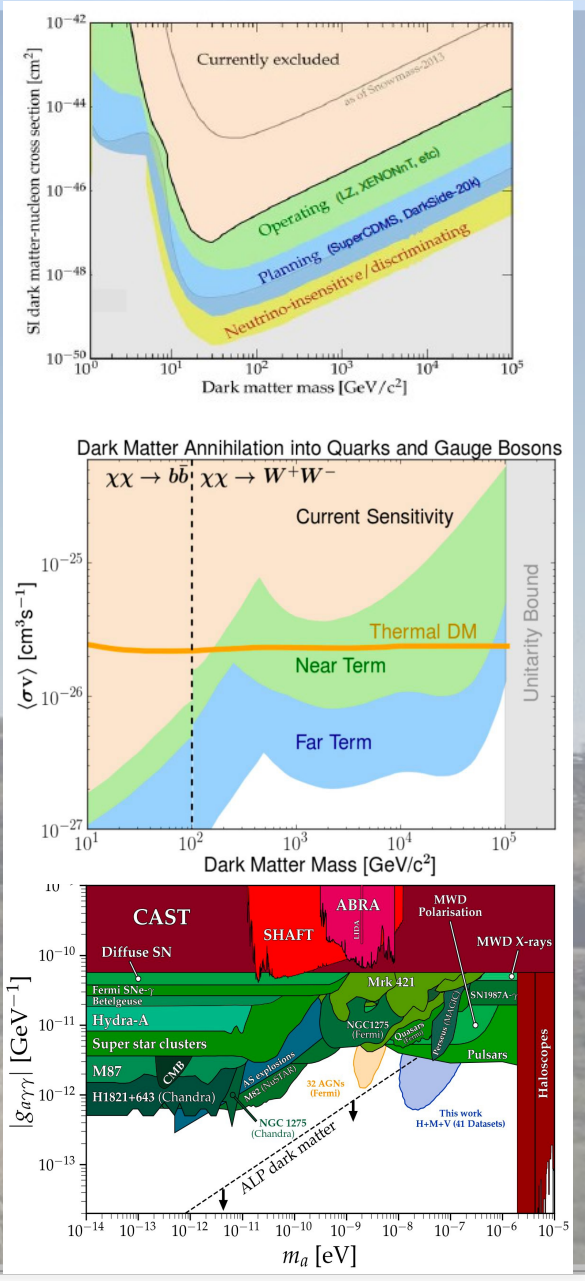
26 datasets :
CTAO N :
15 AGN-GC
CTAO S :
11 AGN-GC



This approach enables to probe the uncovered region in the 10-100 neV masse range where ALP can comprise all the DM in the Universe

Summary and outlook

- Maturing experiments & shrinking parameter spaces
- *WIMP paradigm* : diversified, trend towards minimal DM model searches
  - Last remaining well-motivated WIMP benchmark model probed ?
- *ALP* : sensitivity reach in the relevant parameter space
- Robust searches, chasing systematics, instead of interpreting « anomalies »
- Every major astrophysics discovery in the last decade came from combining multiple messengers
  → multimessenger probes of dark matter

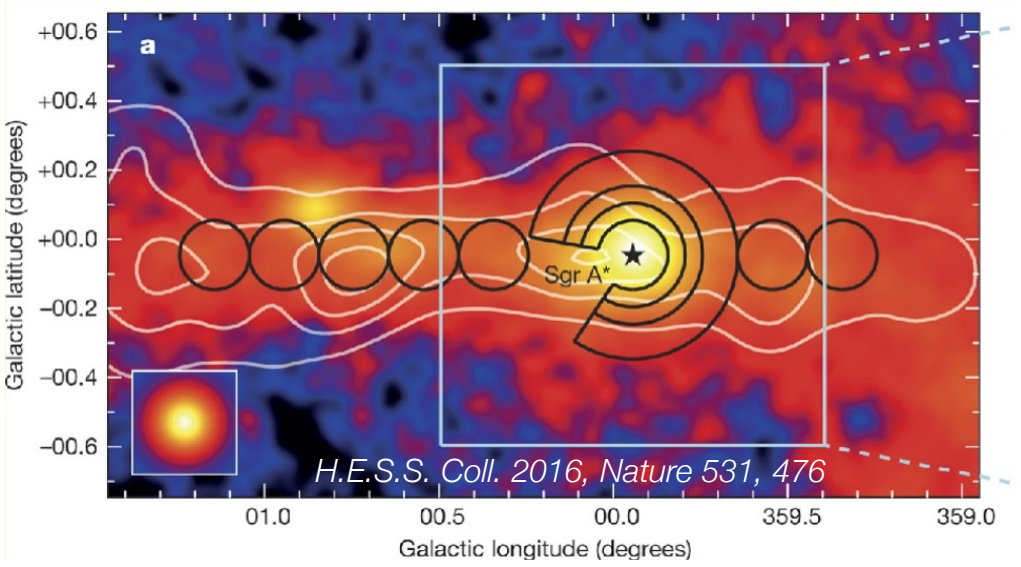


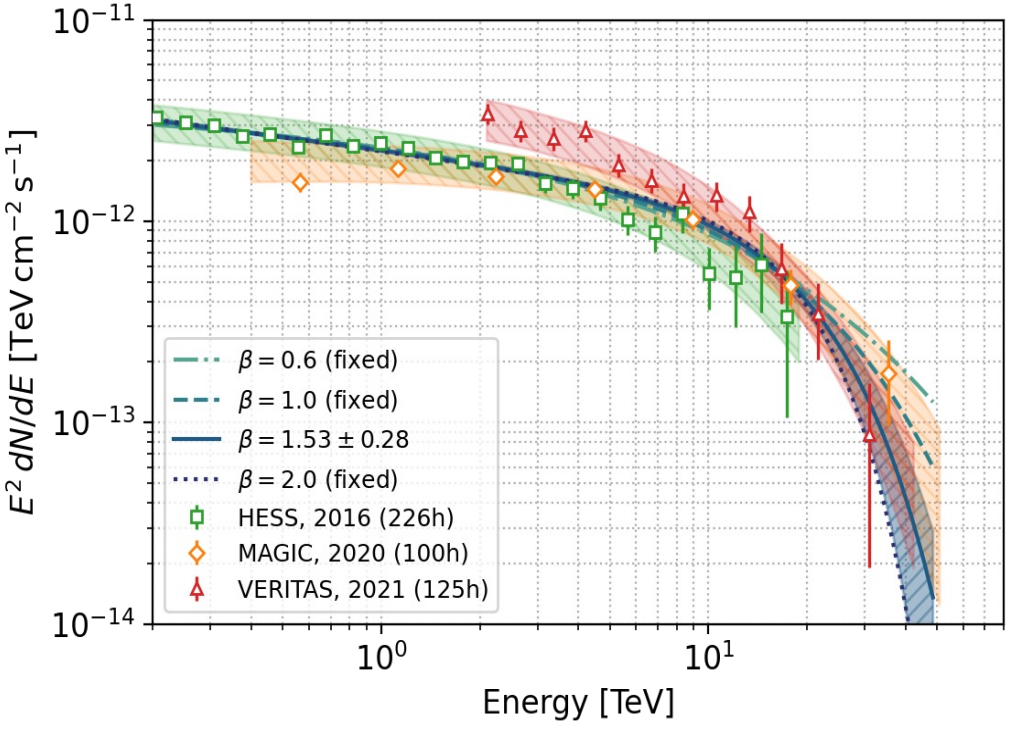
Back-up

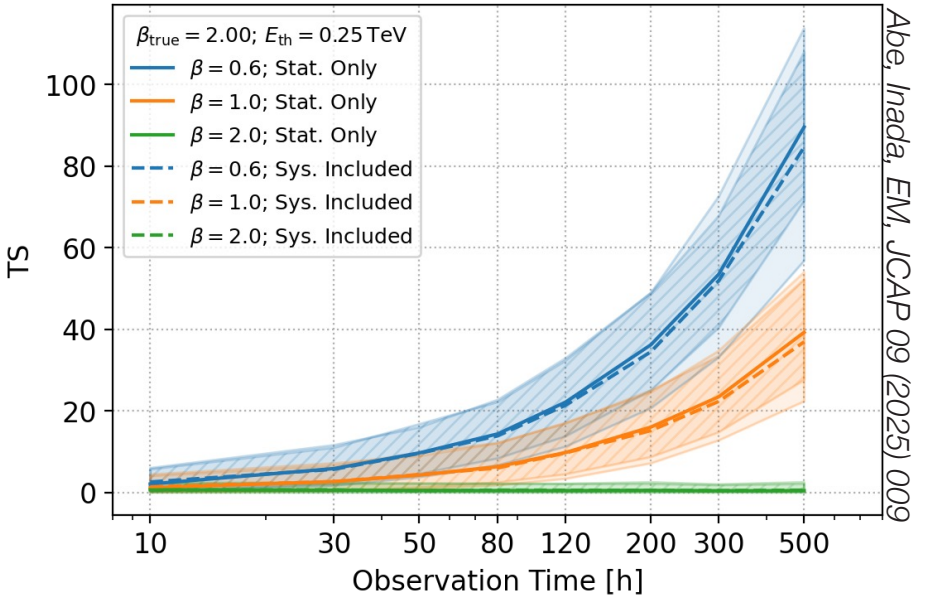
Nature of the central source HESS J1745-290 ?

- **Nature of the source ?** Sgr A*; a pulsar wind nebula G359.95-0.04, a spike of annihilating DM particles
  - no firm association so far
- Strong energy suppression at several TeV
  - well described by (super-)exponential cut-off power-law

$$\Phi(E) = \Phi_0 \times \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\Gamma} \times \exp\left(-\frac{E}{E_c}\right)^{\beta}$$

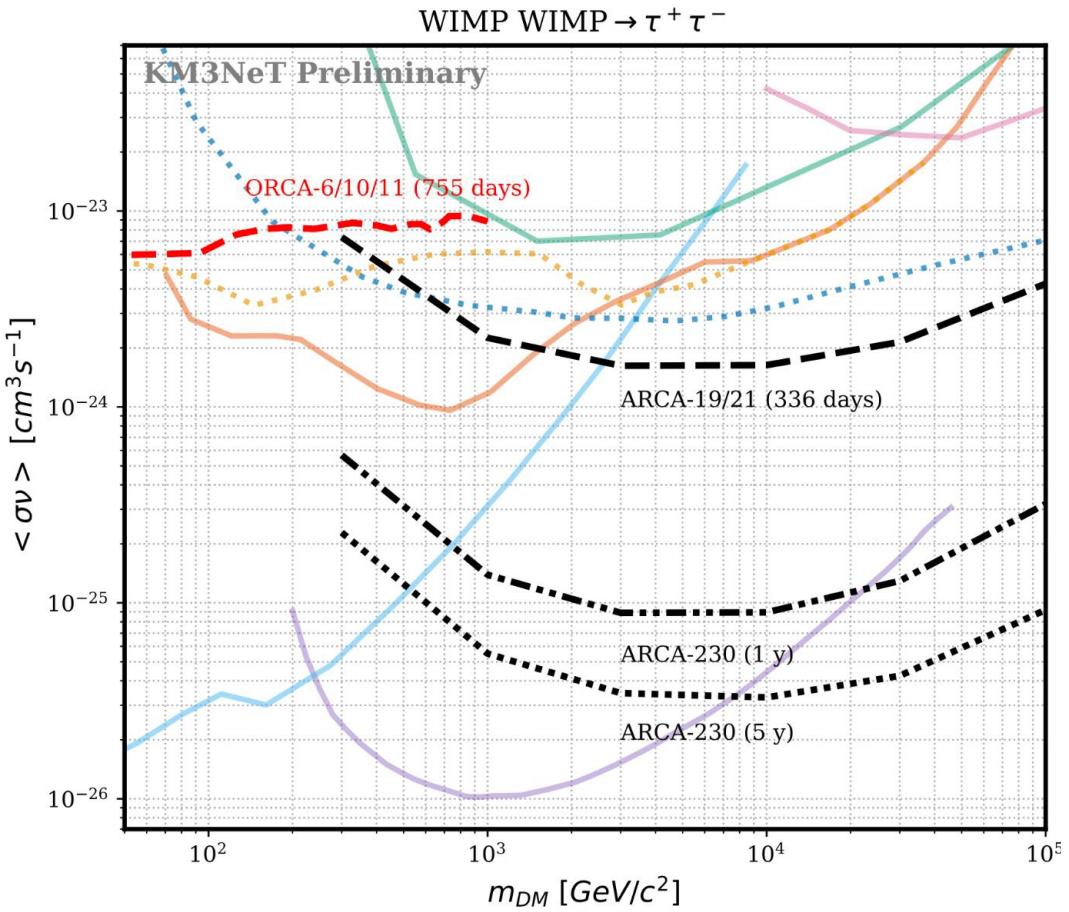


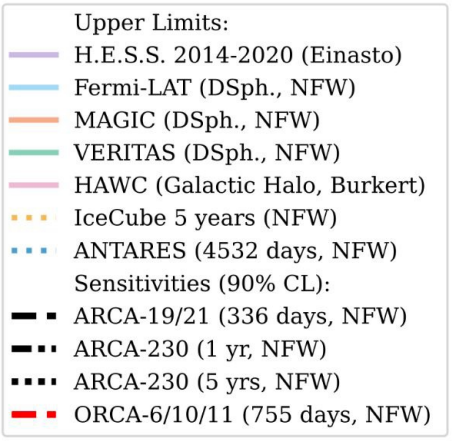




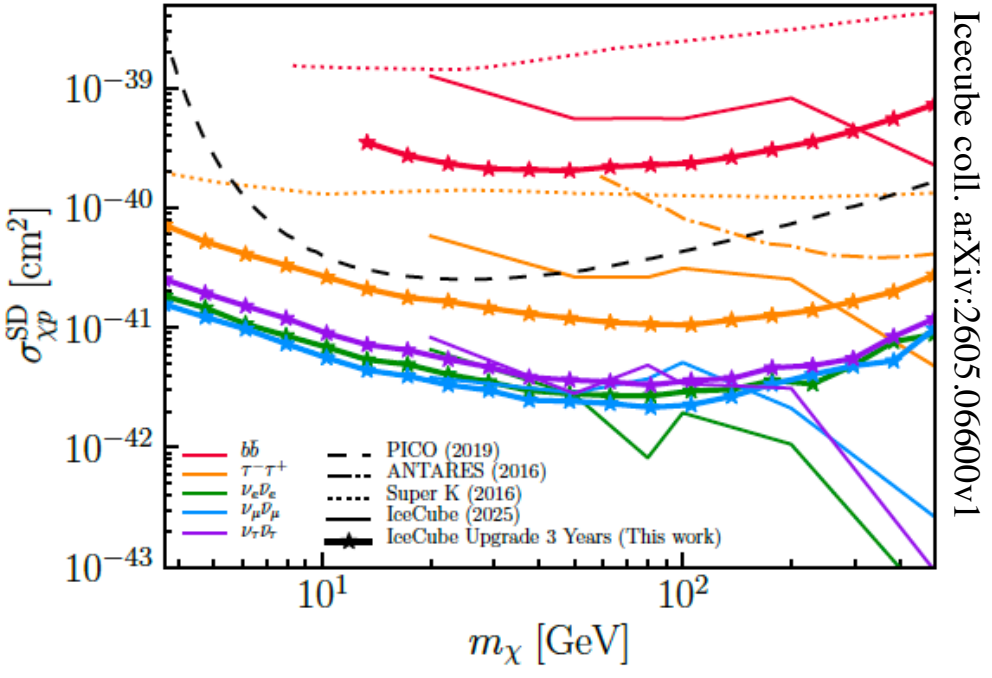
Models with β values differing by one or more from the true value can be distinguished with multi-year observations

VHE neutrinos : KM3Net sensitivity and Icecube



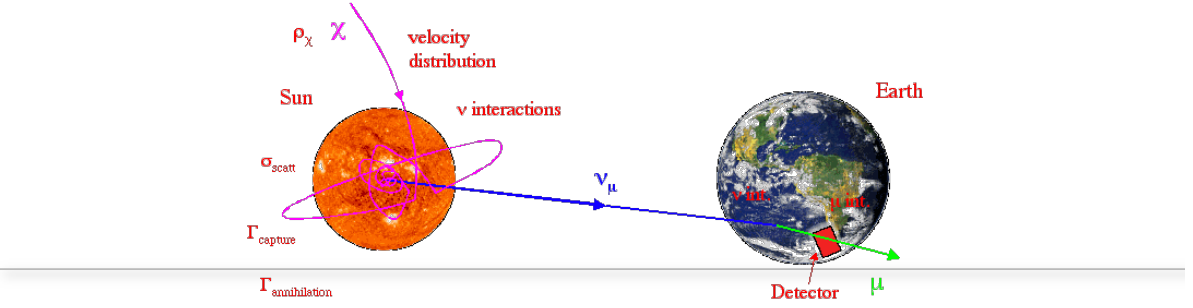


- **Galactic center frorecast**



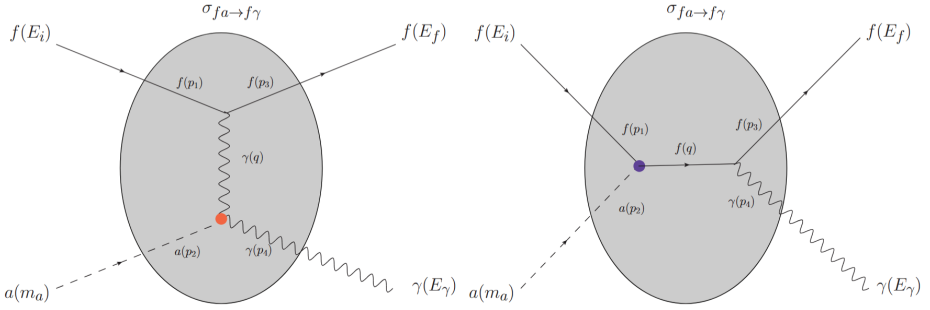
Icecube coll. arXiv:2605.06600v1

- **Solar searches**

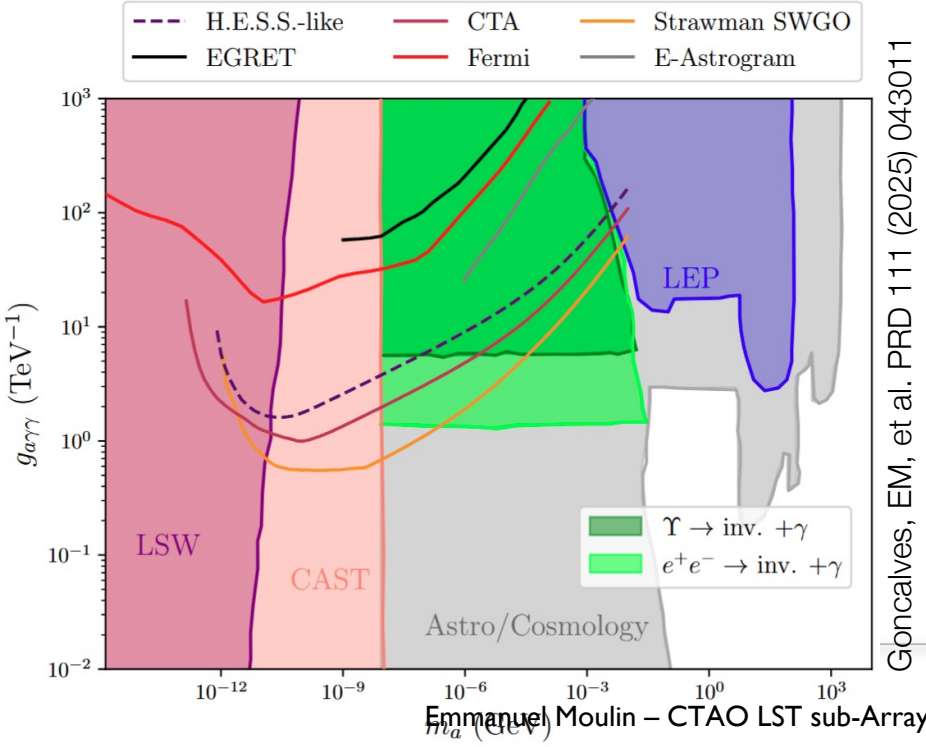


Probing ALPs from cosmic-ray scattering in the Milky Way dark matter halo

- VHE CR protons and electron interaction with ALPs
  - Inverse Primakoff and Inverse Compton scatterings
- For IP process:
  - CR protons :



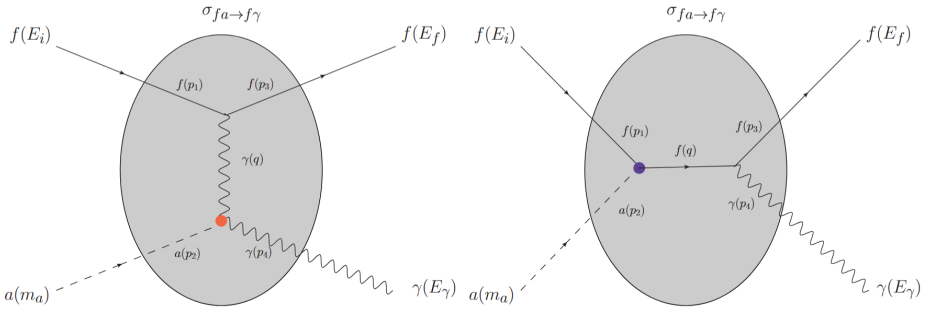
$$\frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} = \frac{1}{m_a} \times D(\Delta\Omega) \times \int_{E_p^{min}(E_\gamma)} dE_p \frac{d\Phi_p}{dE_p}(E_p) \cdot \frac{d\sigma_{p+a\to p+\gamma}}{dE_\gamma}(E_p, E_\gamma)$$



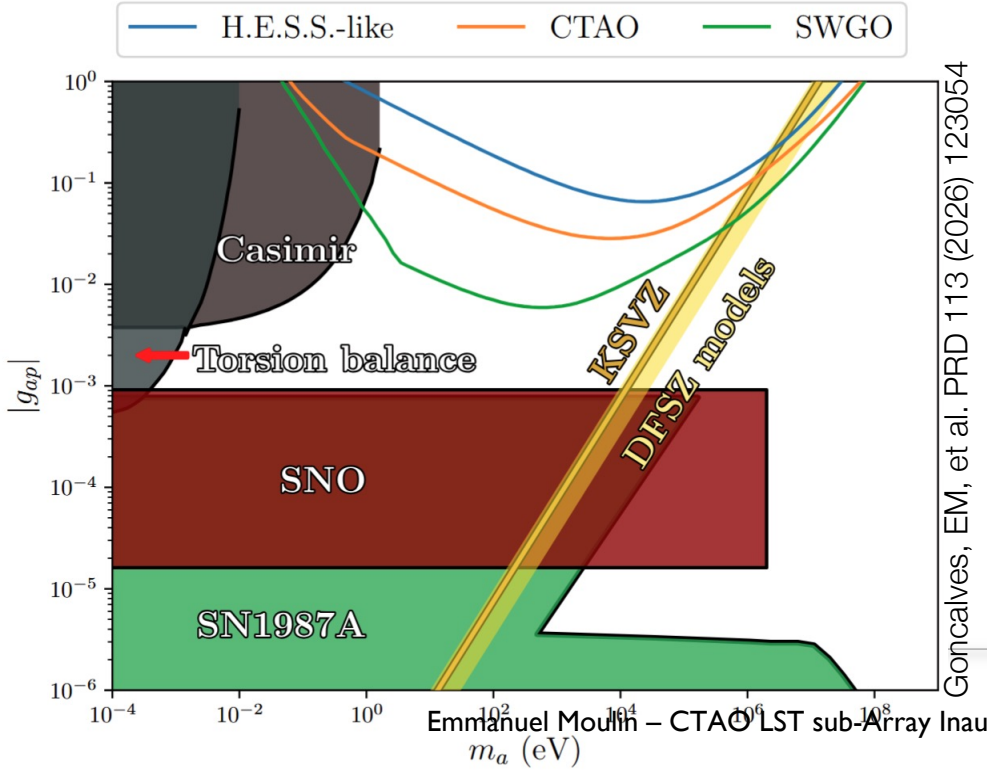
Goncalves, EM, et al. PRD 111 (2025) 043011

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  - CR protons:



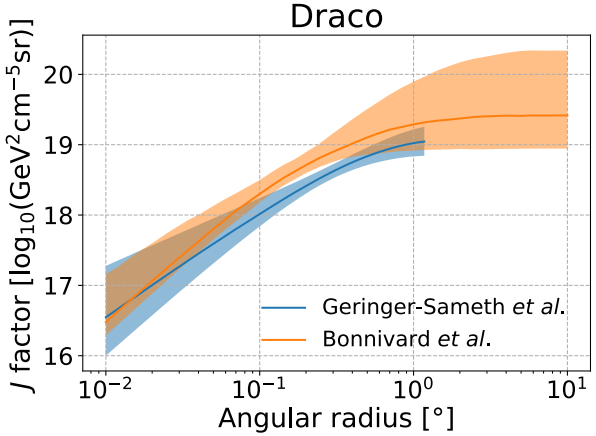
$$\frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} = \frac{1}{m_a} \times D(\Delta\Omega) \times \int_{E_p^{min}(E_\gamma)} dE_p \frac{d\Phi_p}{dE_p}(E_p) \cdot \frac{d\sigma_{p+a\to p+\gamma}}{dE_\gamma}(E_p, E_\gamma)$$



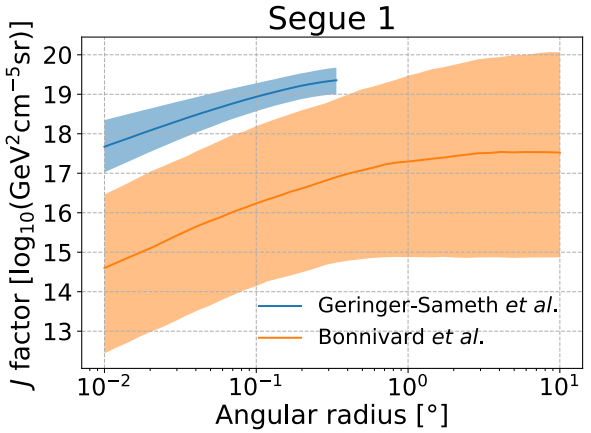
- Alternative approach sensitive in a region probed by different measurements
- Complementarity between different detection techniques
- Could probe ~MeV QCD axion models

Combined limits from GeV-TeV gamma rays

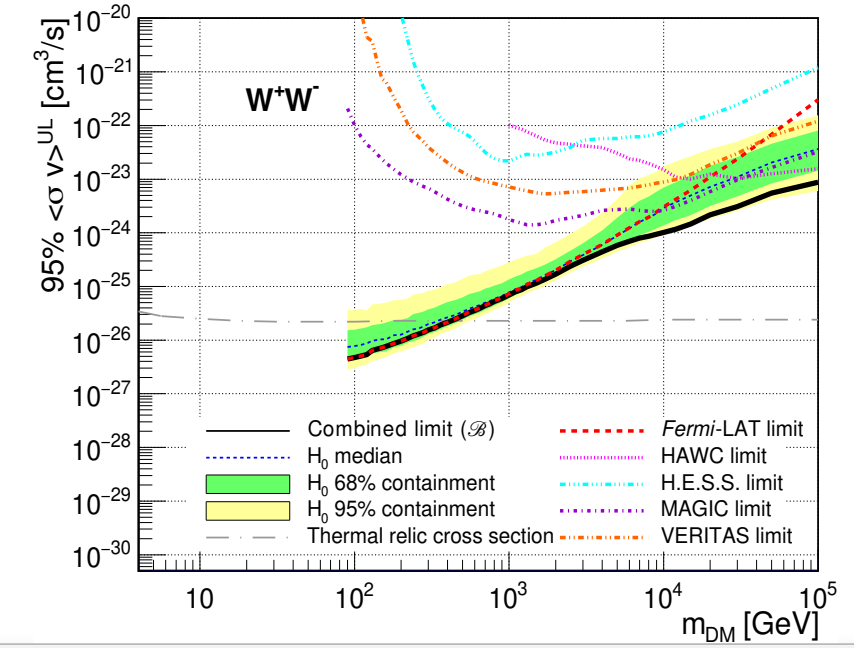
Classical



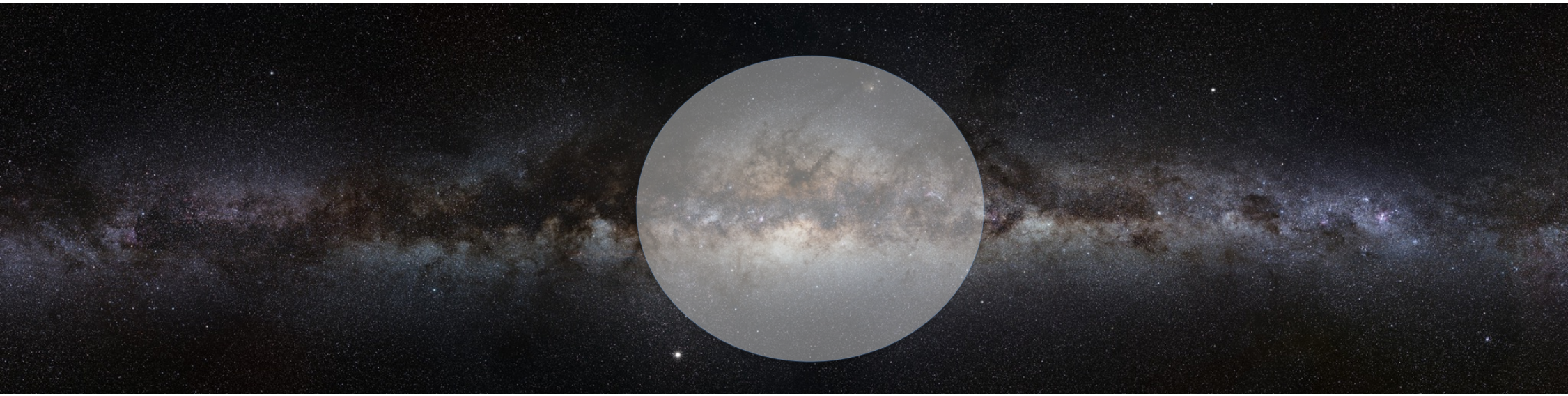
Ultra-faint



Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5}})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5}})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue 1	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue 2	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$



The inner halo of the Milky Way



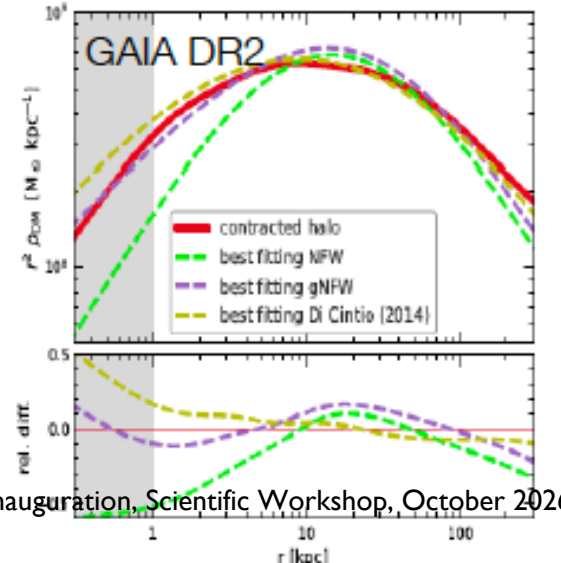
- **Expected to be the brightest sources of DM annihilations**

…but a complex region at VHE with challenging backgrounds: diffuse backgrounds, base of Fermi Bubbles, an hypothetical population of millisecond pulsars, …

Caveat : DM distribution below~1kpc

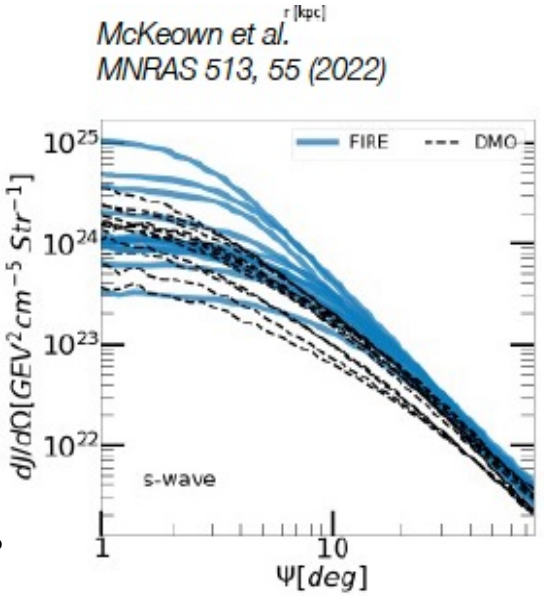
Mass modelling

Cautun et al.
MNRAS 494, 4291 (2020)



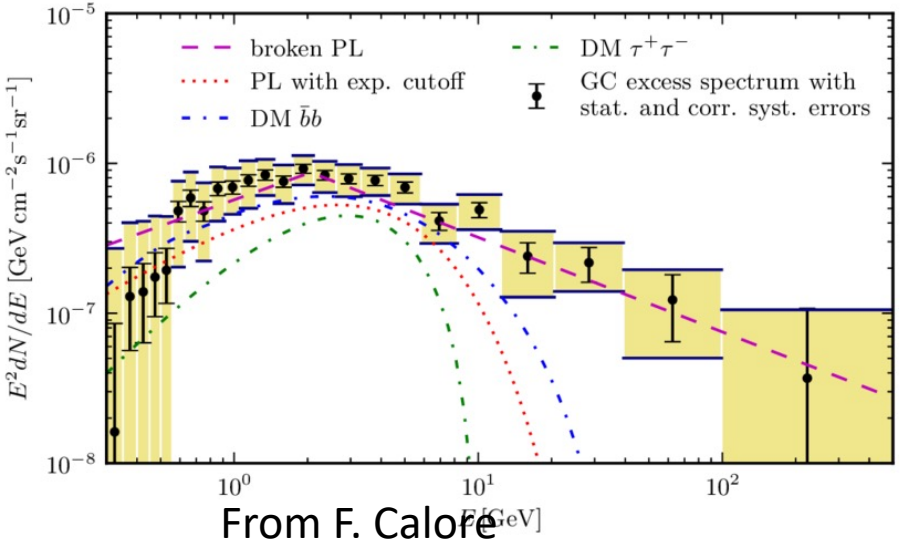
Hydrodynamical simulations

McKeown et al.
MNRAS 513, 55 (2022)

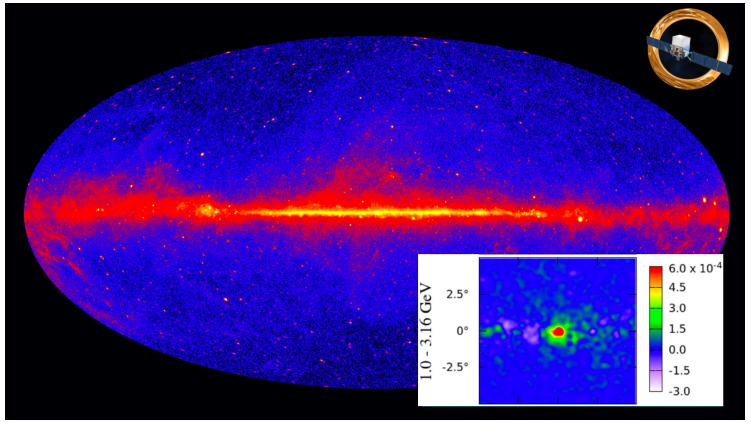


The Galactic Center Excess seen by Fermi-LAT

- Outstanding excess of GeV gamma rays at the Milky Way center, suggestive of WIMP of mass 40-50 GeV

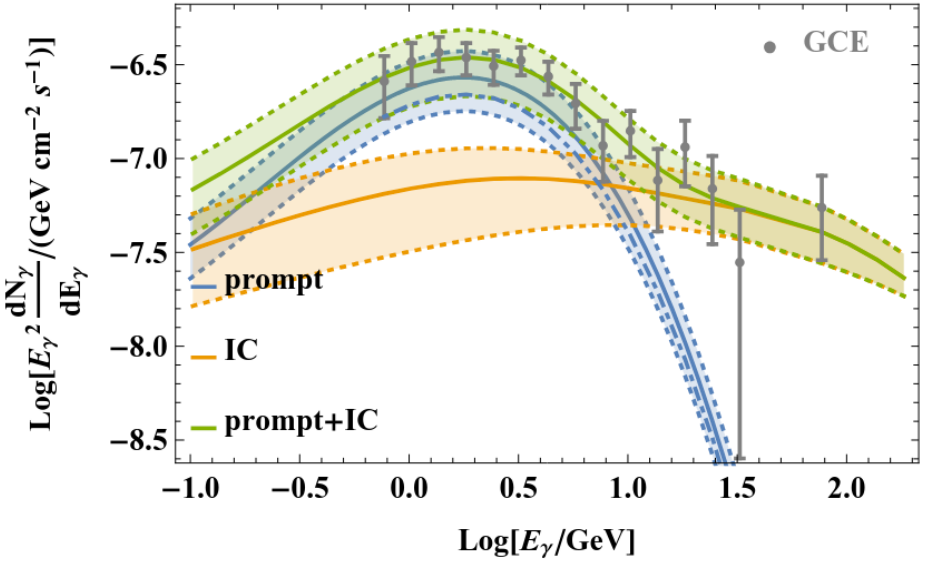


From F. Calore



Excess also by DAMPE (2025)

A. Gautam et al. Nat Astron. 6, 703 (2022)



- Interpretation is debated
  → recent morphological results support new astrophysics : unidentified population of millisecond pulsars ?

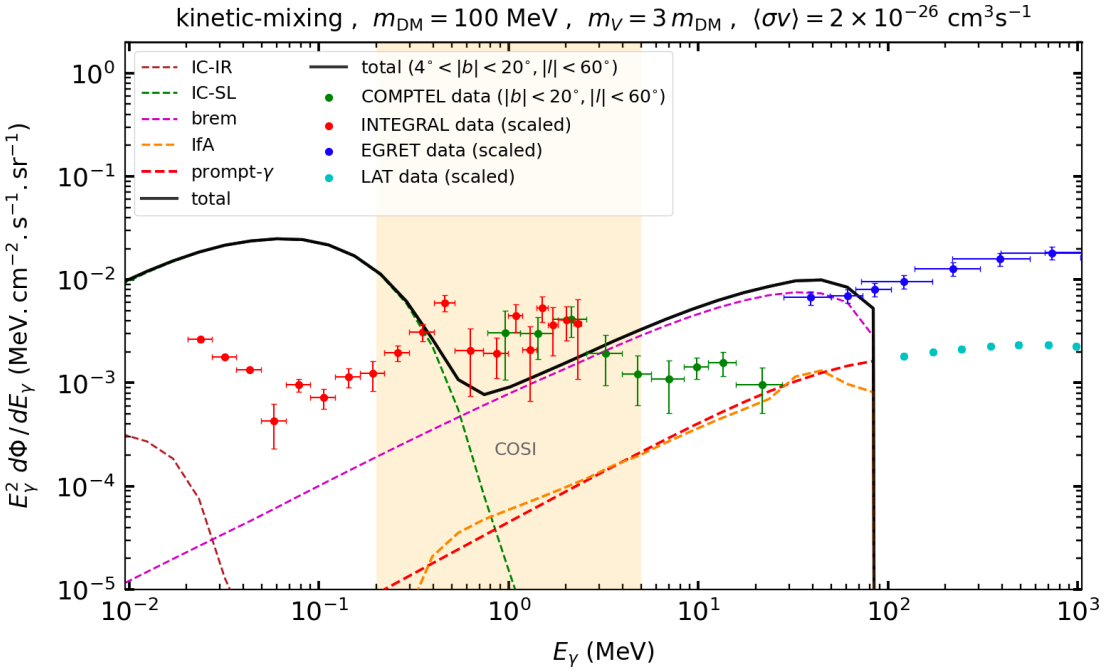
2512.16699: Discovery of two new millisecond pulsars towards the Galactic bulge

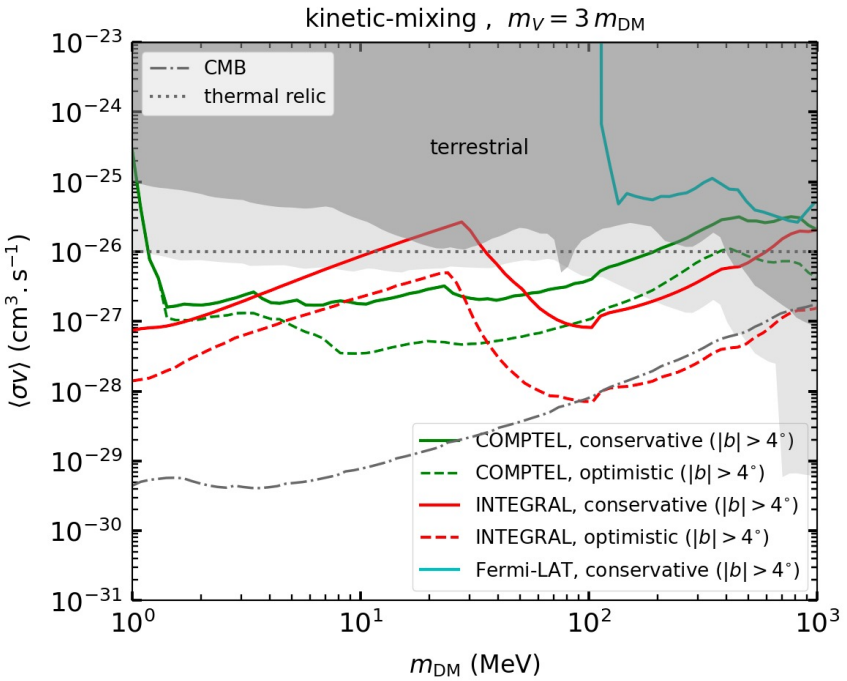
Sub-GeV DM searches

- DM can be composed of a light particle with a mass in the range MeV - GeV
  e.g., DM coupled to a new light gauge boson, hidden sector DM, etc.

- Prompt radiation+Secondary radiation: photon emissions via Inverse Compton scattering (ICS) , bremsstrahlung , In-flight annihilation (IfA) produced by DM induced e+/e-

Cirelli,et al. JCAP 01 (2026) 038 [2508.03819]





- Caveat: Background model, propagation effect