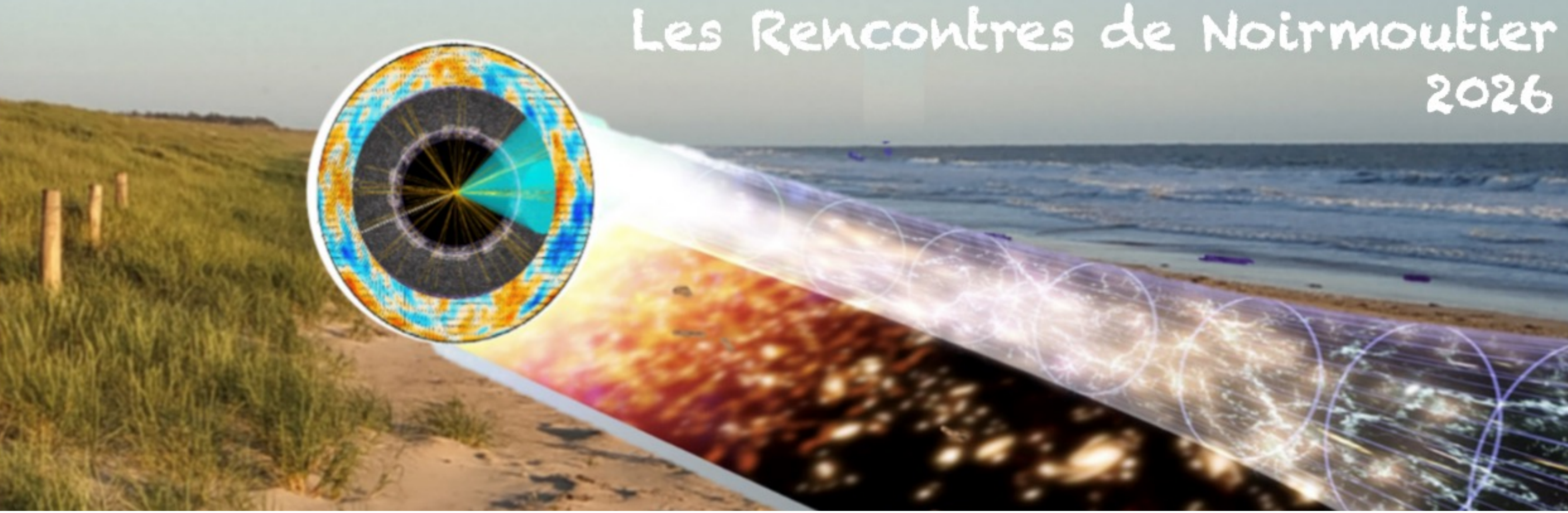
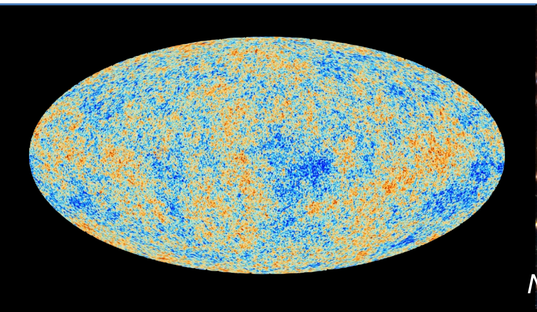
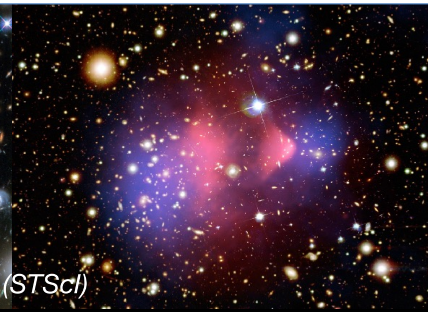


High-energy astrophysical searches of dark matter

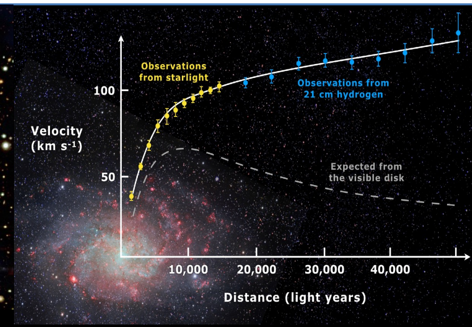
Emmanuel Moulin
CEA Saclay, Irfu, Université Paris-Saclay, France

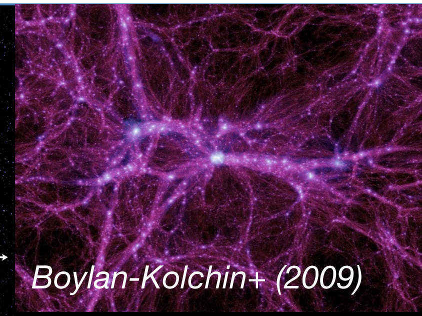
Standard model cosmology and Dark Matter



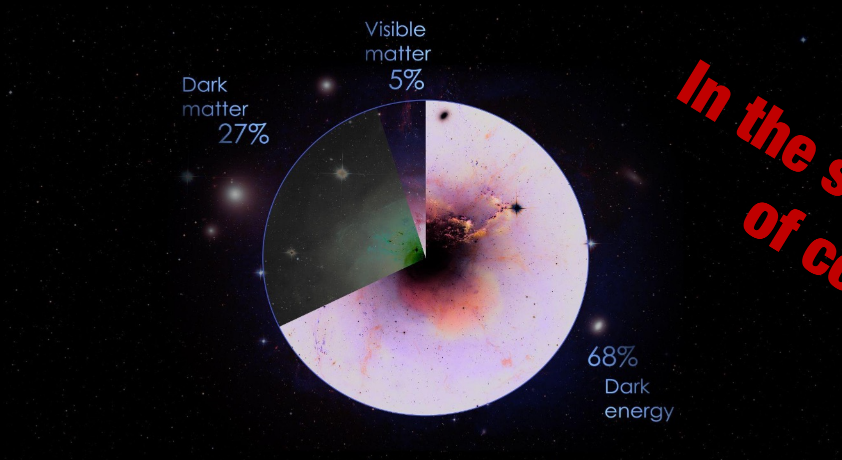


NASA, ESA, J. Lotz and HFF Team (STScI)





Boylan-Kolchin+ (2009)

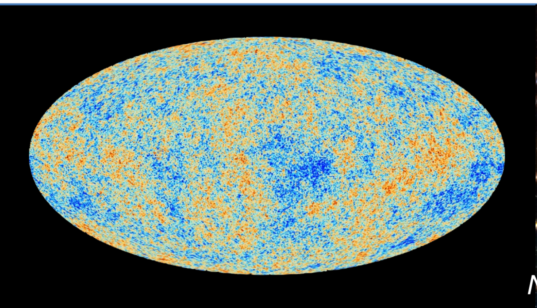


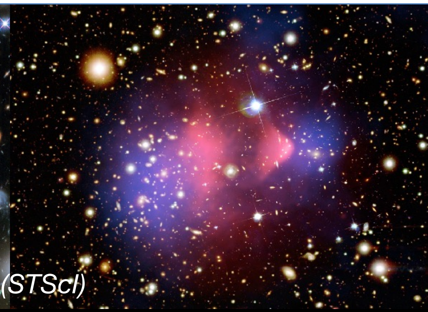
In the standard model of cosmology

Dark matter density perturbations grow and become nonlinear
→ study structure formation with N-body simulations

Dark matter forms self-gravitating halos that host galaxies

Standard model cosmology and Dark Matter





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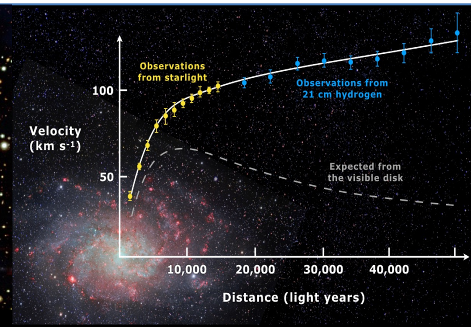

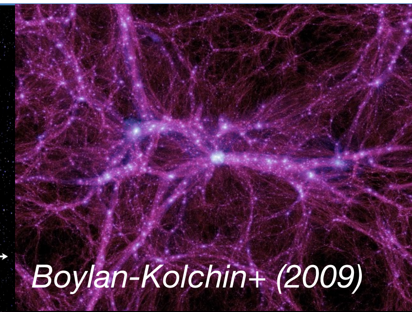

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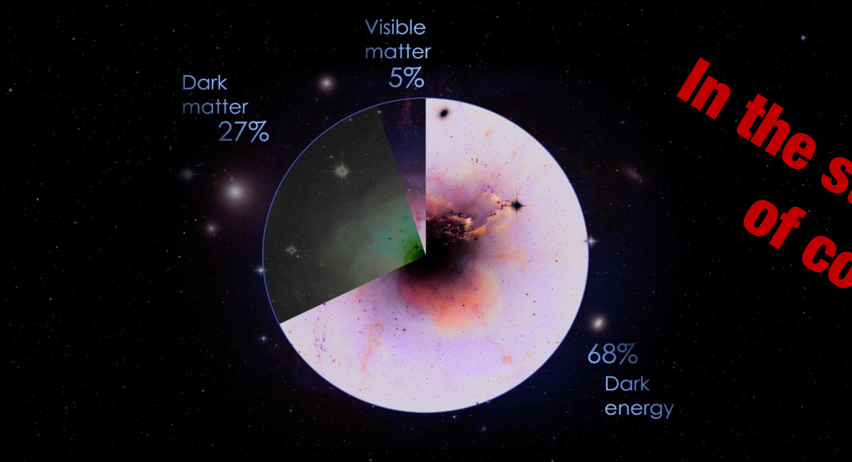


In the standard model of cosmology

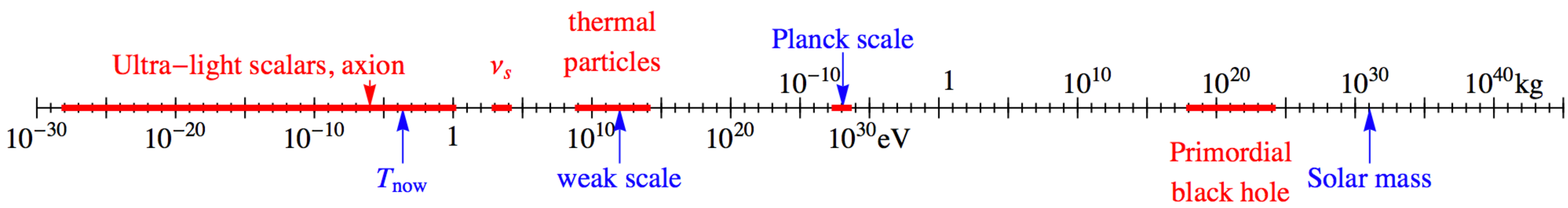
Dark matter density perturbations grow and become nonlinear → study structure formation with N-body simulations

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

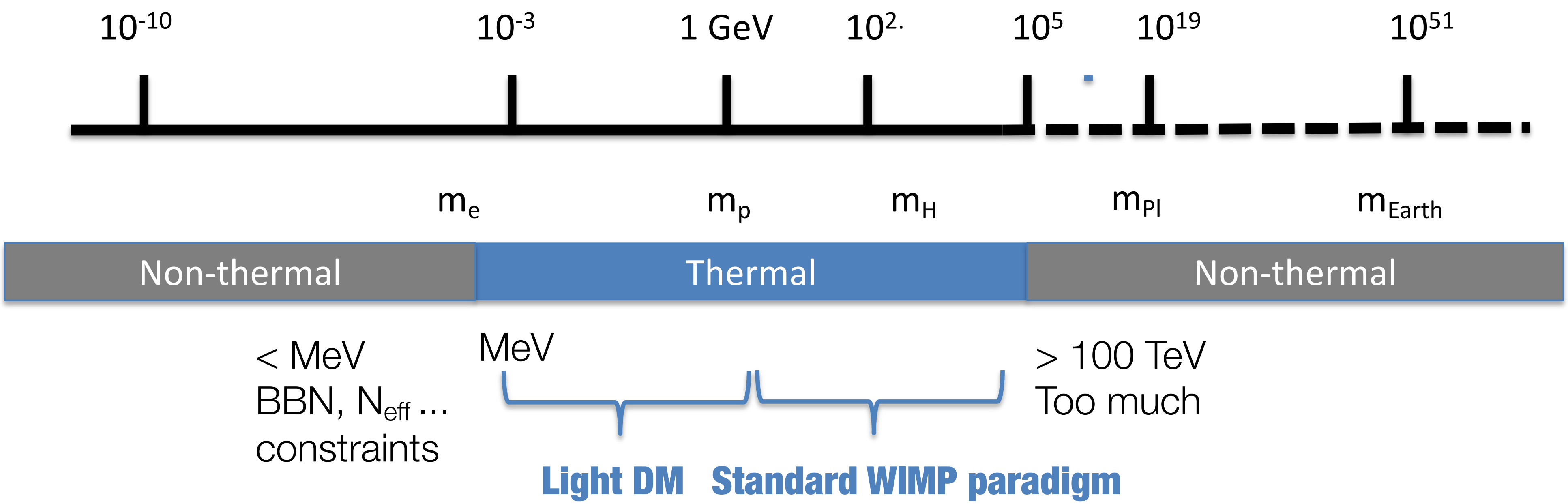


- Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales

- 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

DM as a relic from the Early Universe



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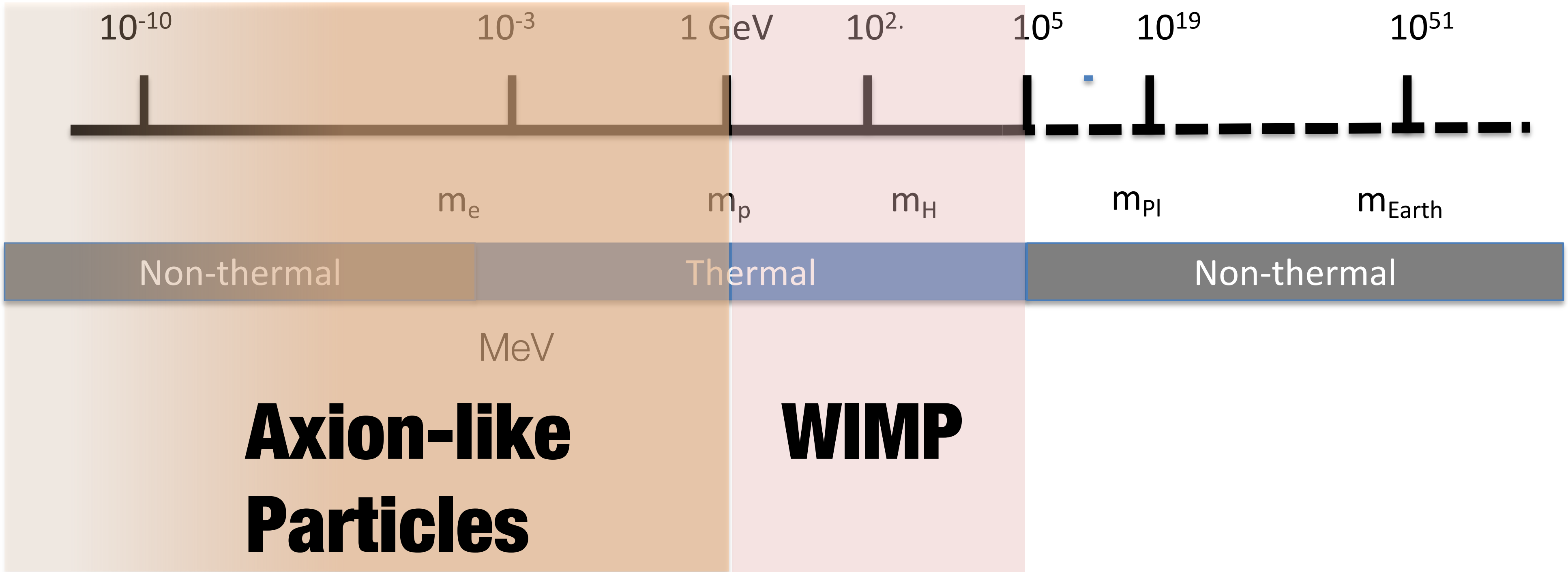
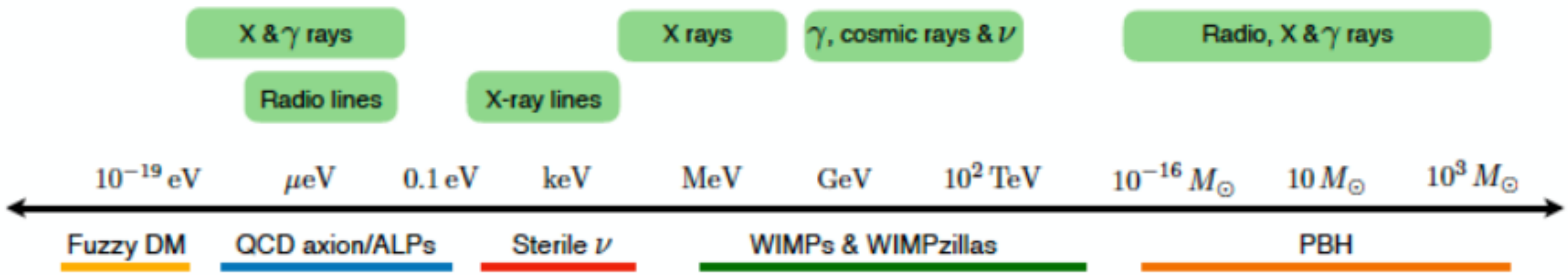


Astroparticle messengers and Instruments

EuCAPT White Paper, arXiv:2110.10074



Astroparticle messengers and Instruments

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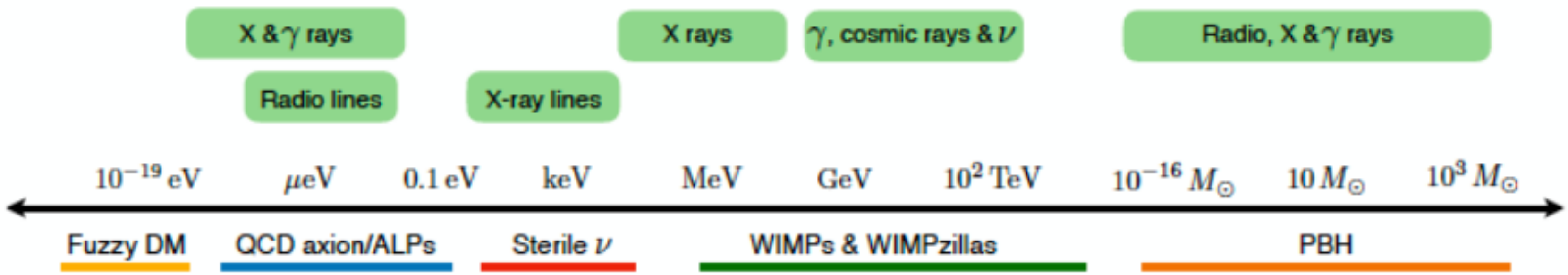
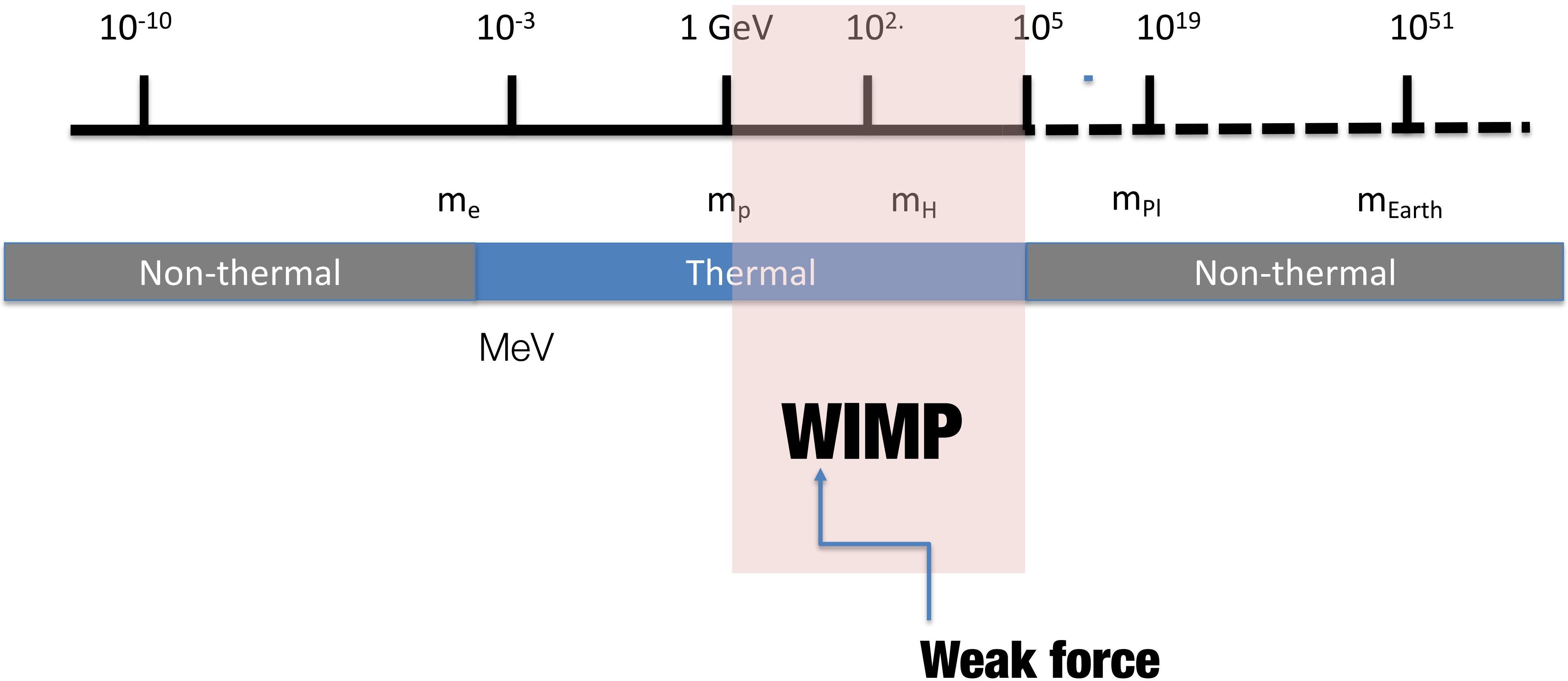
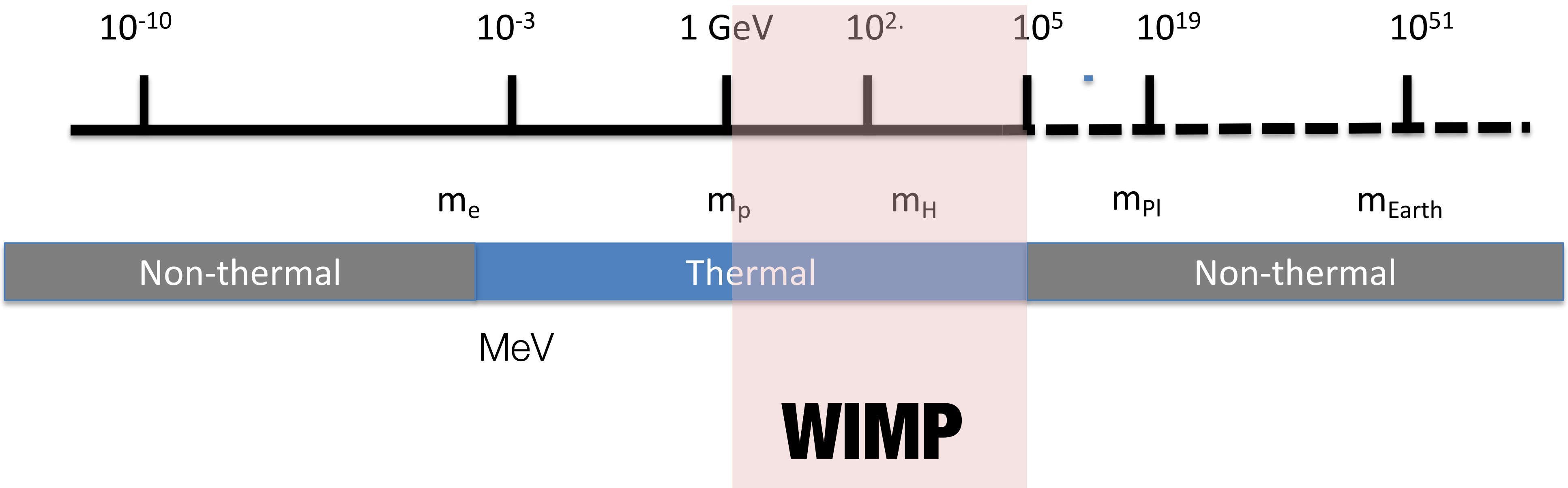


DM as a thermal relic from the Early Universe



DM as a thermal relic from the Early Universe



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

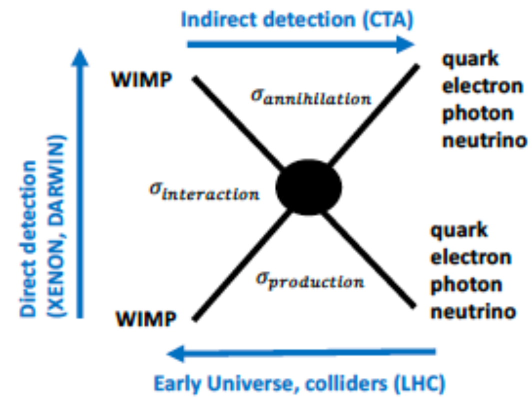
$$\Omega_{\rm DM} h^2 = \frac{3 \times 10^{-27}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle_{\rm W} \sim \frac{\alpha^2}{m^2_{\rm WIMP}} \sim 3 \times 10^{-26} \mathrm{cm^3 s^{-1}}$$

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

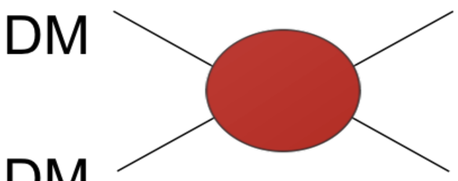
→ **Provides benchmark for indirect detection: thermally-produced WIMPs**

How to look for WIMPs ?



$$\text{DM (DM)} \rightarrow \text{SM SM}$$

- N = 1 : decay, N=2 : annihilation
- Annhilation/Decay at almost rest : $E_{CM} \simeq$ signal energy
- For self-conjugated dark matter annihilation

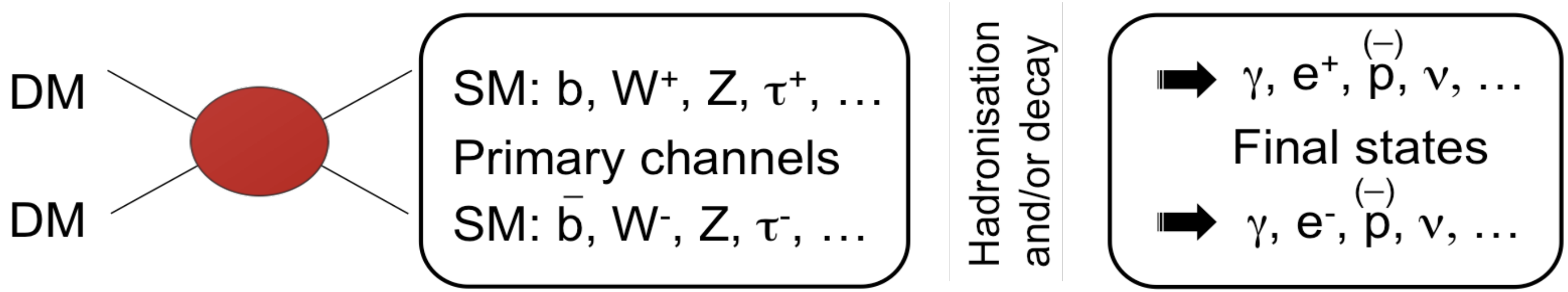


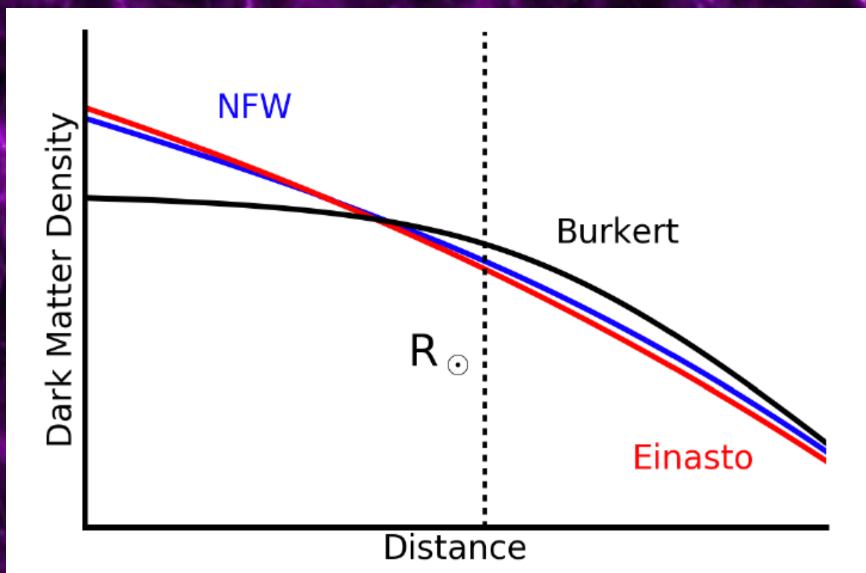
SM: b, W^+, Z, τ^+, …
Primary channels
SM: $\bar{b}$, W^-, Z, τ^-, …

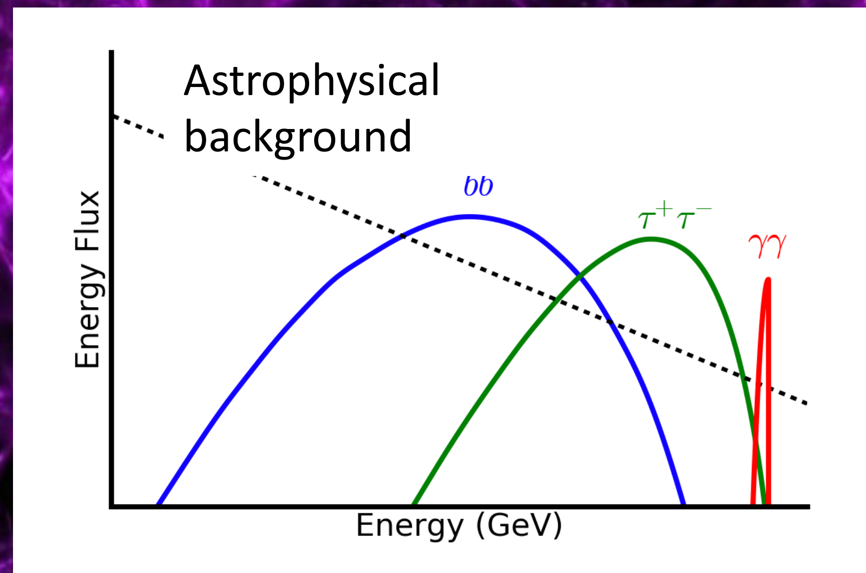
Hadronisation and/or decay

➡ γ, e^+, $\overset{(-)}{p}$, ν, …
Final states
➡ γ, e^-, $\overset{(-)}{p}$, ν, …

How to look for WIMPs ?







J-factor

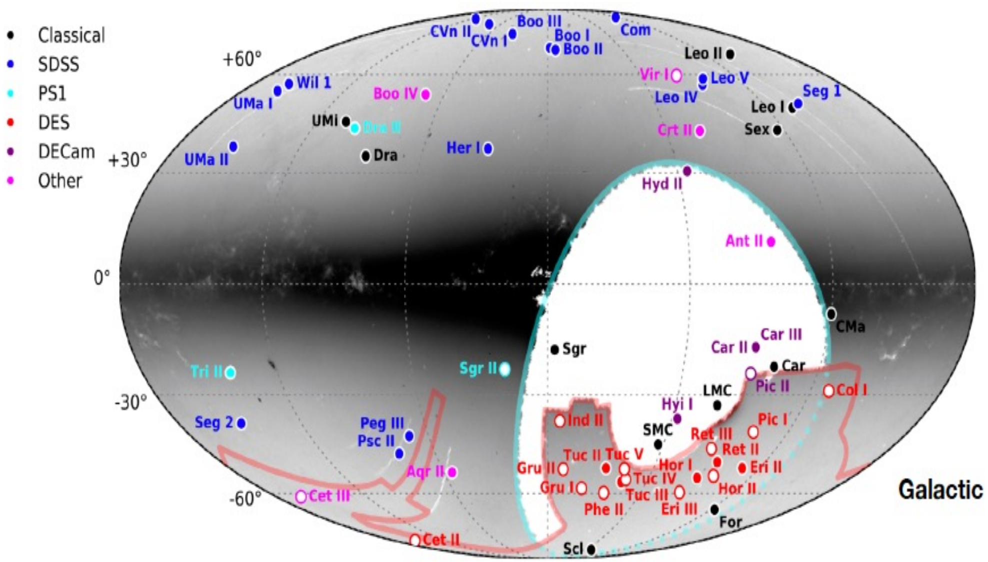
For self-conjugated DM annihilation:

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

Dwarf galaxies observations with GeV-TeV gamma rays

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

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



10 years 1038 days

	Fermi-LAT	HAWC	H.E.S.S., MAGIC, VERITAS						
Source name	Exposure (10^{11} s cm^2)	$\lvert\Delta\phi\rvert$ (°)	IACTs	Zenith (°)	Time exposure (h)	Energy range (TeV)	θ_{sig} (°)	τ	S (σ)
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0	0.10–41	0.17	8.6	−1.0
Canes Venatici I	2.9	14.6	–	–	–	–	–	–	–
Canes Venatici II	2.9	15.3	–	–	–	–	–	–	–
Carina	3.1	–	H.E.S.S.	27 – 46	23.7	0.31–70	0.10	18.0	−0.3
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4	0.55–70	0.10	14.4	−0.4
			MAGIC	5–37	49.5	0.06–10	0.17	1.0	0.8
Draco	3.8	38.1	MAGIC	29–45	52.1	0.07–10	0.22	1.0	−0.7
			VERITAS	25 – 40	49.8	0.12–70	0.17	9.0	−1.0
Fornax	2.7	–	H.E.S.S.	11 – 25	6.8	0.23–70	0.10	45.5	−1.5
Hercules	2.8	6.3	–	–	–	–	–	–	–
Leo I	2.5	6.7	–	–	–	–	–	–	–
Leo II	2.6	3.1	–	–	–	–	–	–	–
Leo IV	2.4	19.5	–	–	–	–	–	–	–
Leo V	2.4	–	–	–	–	–	–	–	–
Leo T	2.6	–	–	–	–	–	–	–	–
Sculptor	2.7	–	H.E.S.S.	10 – 46	11.8	0.20–70	0.10	19.8	−2.2
Segue 1	2.5	2.9	MAGIC	13 – 37	158.0	0.06–10	0.12	1.0	−0.5
			VERITAS	15 – 35	92.0	0.08–50	0.17	7.6	0.7
Segue 2	2.7	–	–	–	–	–	–	–	–
Sextans	2.4	20.6	–	–	–	–	–	–	–
Ursa Major I	3.4	32.9	–	–	–	–	–	–	–
Ursa Major II	4.0	44.1	MAGIC	35 – 45	94.8	0.12–10	0.30	1.0	−2.1
Ursa Minor	4.1	–	VERITAS	35 – 45	60.4	0.16 – 93	0.17	8.4	−0.1

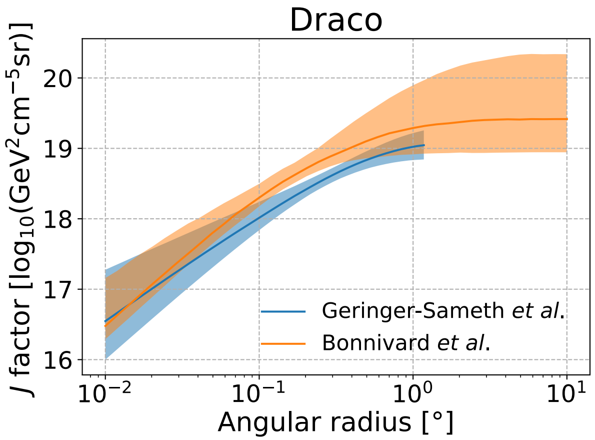
Joint analysis

- of observations of five instruments
- at the likelihood level

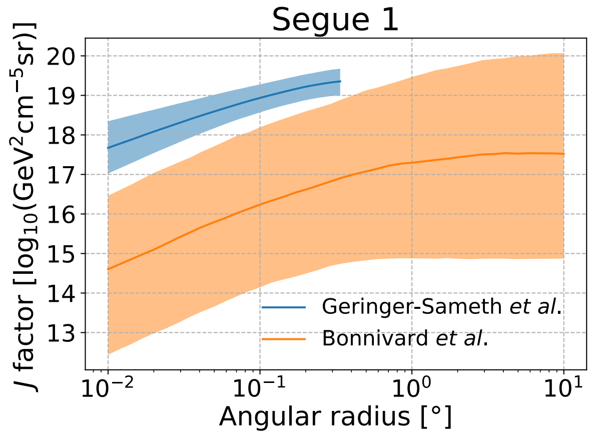
No positive signal for any dSph individually or altogether → upper limits to cross-section

Combined limits from GeV-TeV gamma rays

Classical



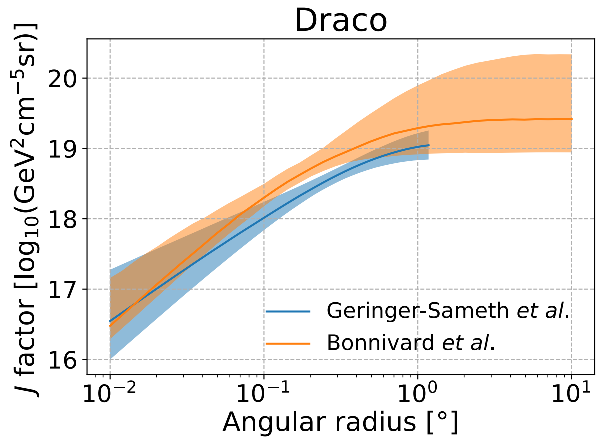
Ultra-faint



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	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

Combined limits from GeV-TeV gamma rays

Classical



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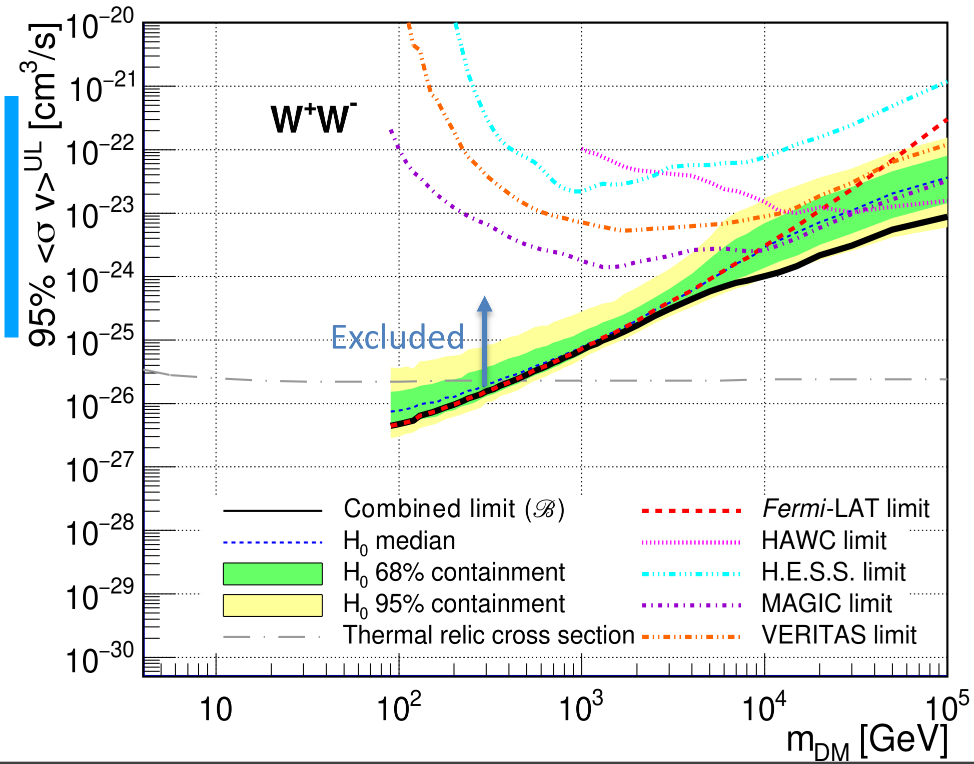


~600 authors, 120 institutions
JCAP 03 (2026) 035

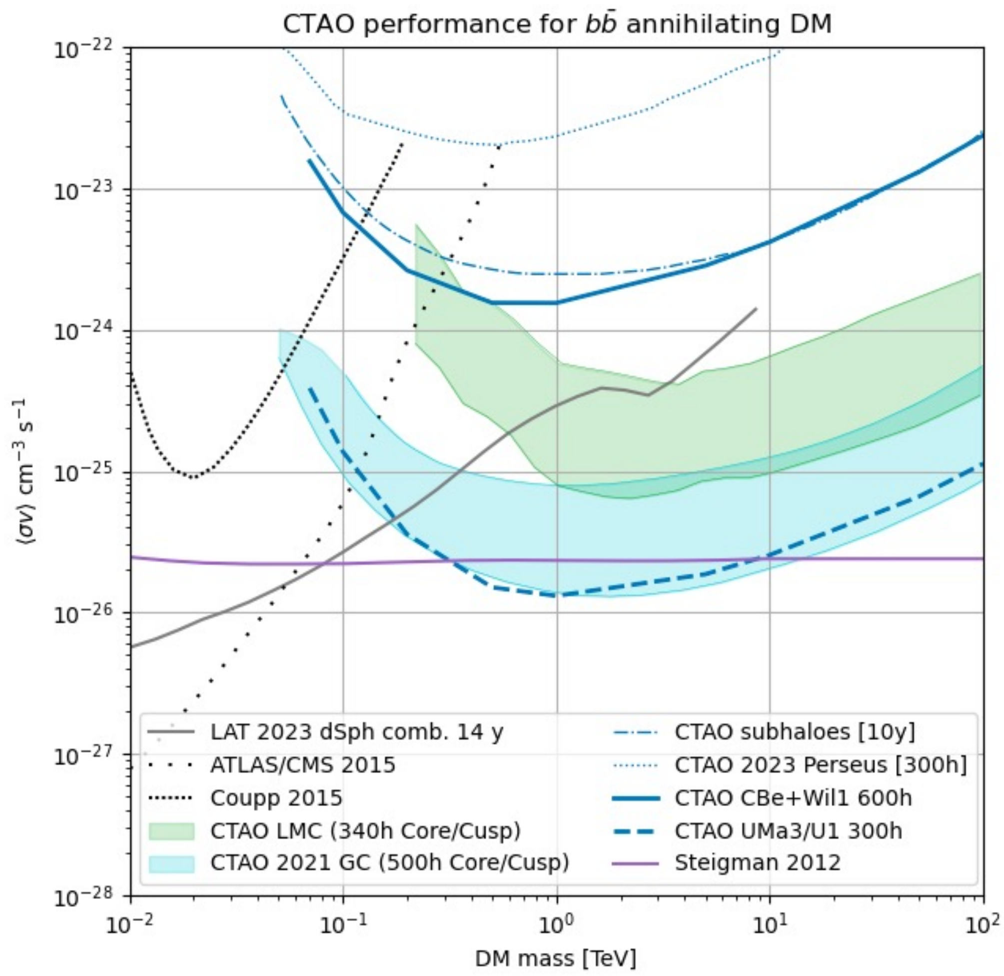
- More constraining limits: factor 2-3 improvement wrt best limits in the overlapping region
- More robust limits: independent uncertainties tend to balance
- Uncertainty from J-factor determination dominates: effect gauged using two independent computations

Forecast sensitivity with CTAO

Alpha configuration

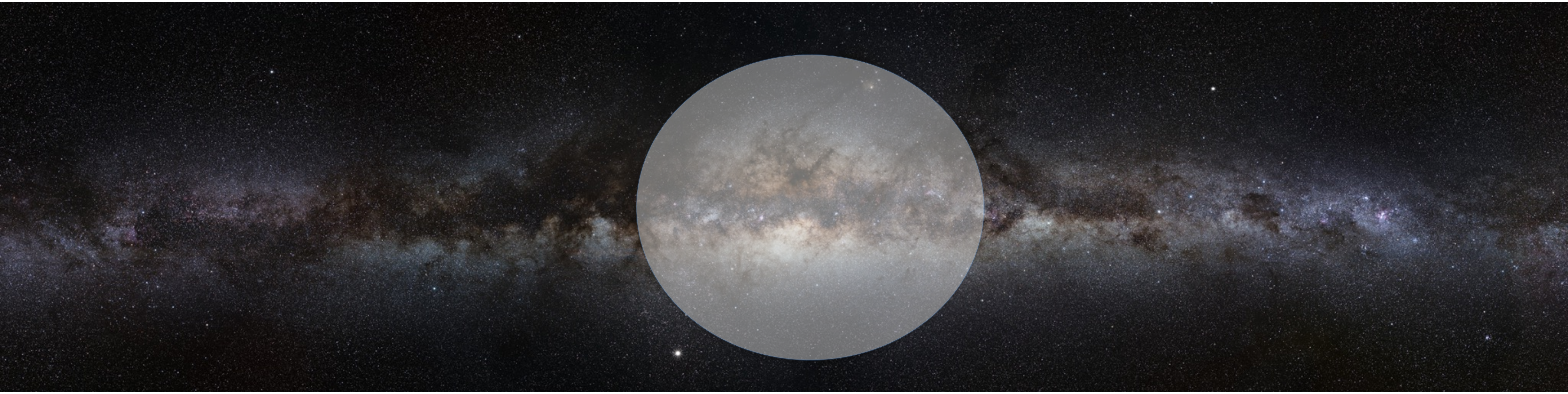
- Northern site, La Palma: 4 LSTs, 9 MSTs
- Southern site, Chile : 14 MSTs, 37 SSTs

- More than an order of magnitude uncertainties on the astrophysical factors exist, likely more for the faintest dSphs
- Limitations from the absence of stellar proper motions, potential tidal diruption from the MW, contamination from foreground stars, non-spherical symmetry of the halo, …
- Large observation program requested : about 600 hours for dSphs



CTA consortium, MNRAS 544 (2025) 3, 2946

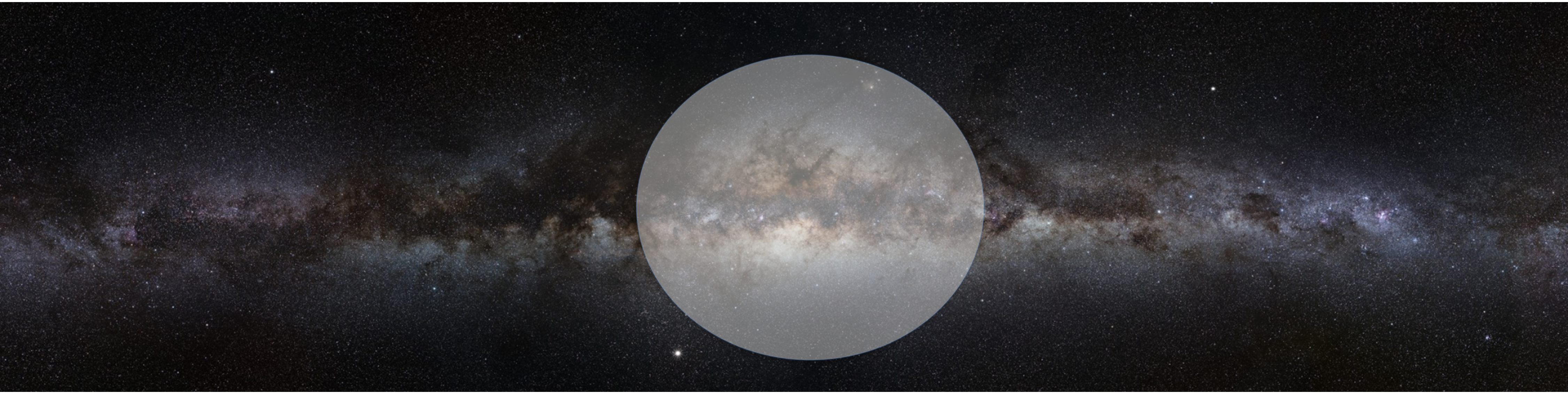
The inner halo of the Milky Way



- **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, …

The inner halo of the Milky Way



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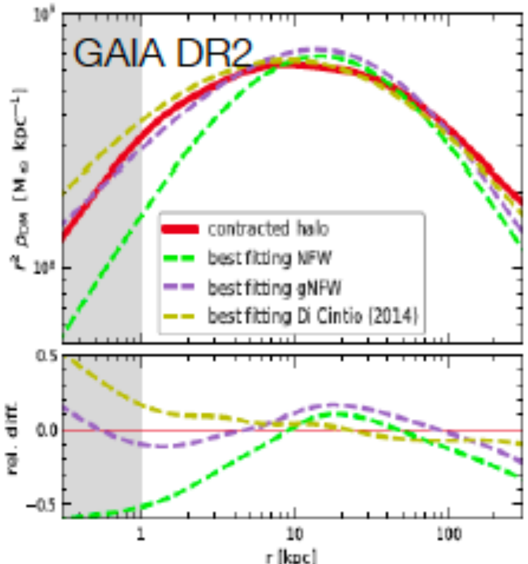
Caveat : DM distribution below~1kpc

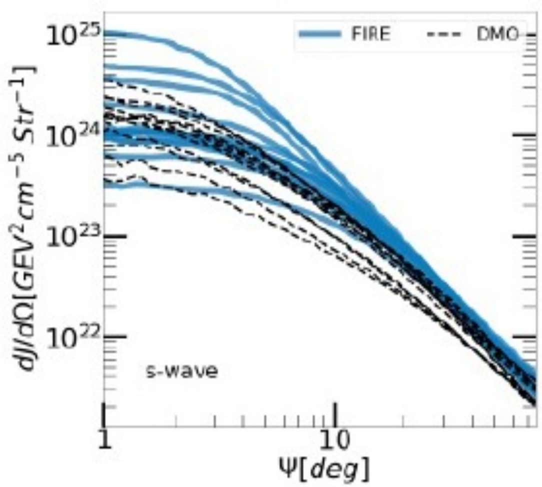
Mass modelling

Cautun et al. MNRAS 494, 4291 (2020)



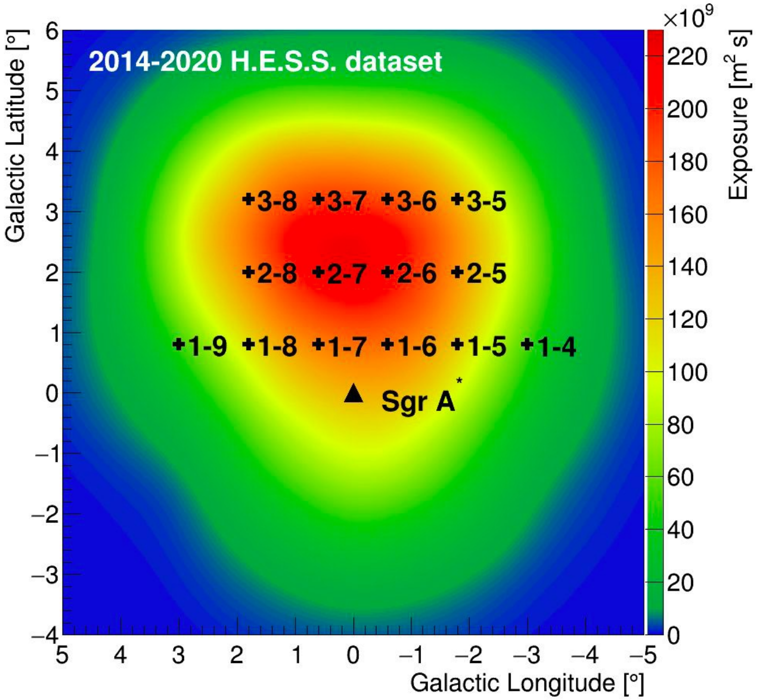
Hydrodynamical simulations

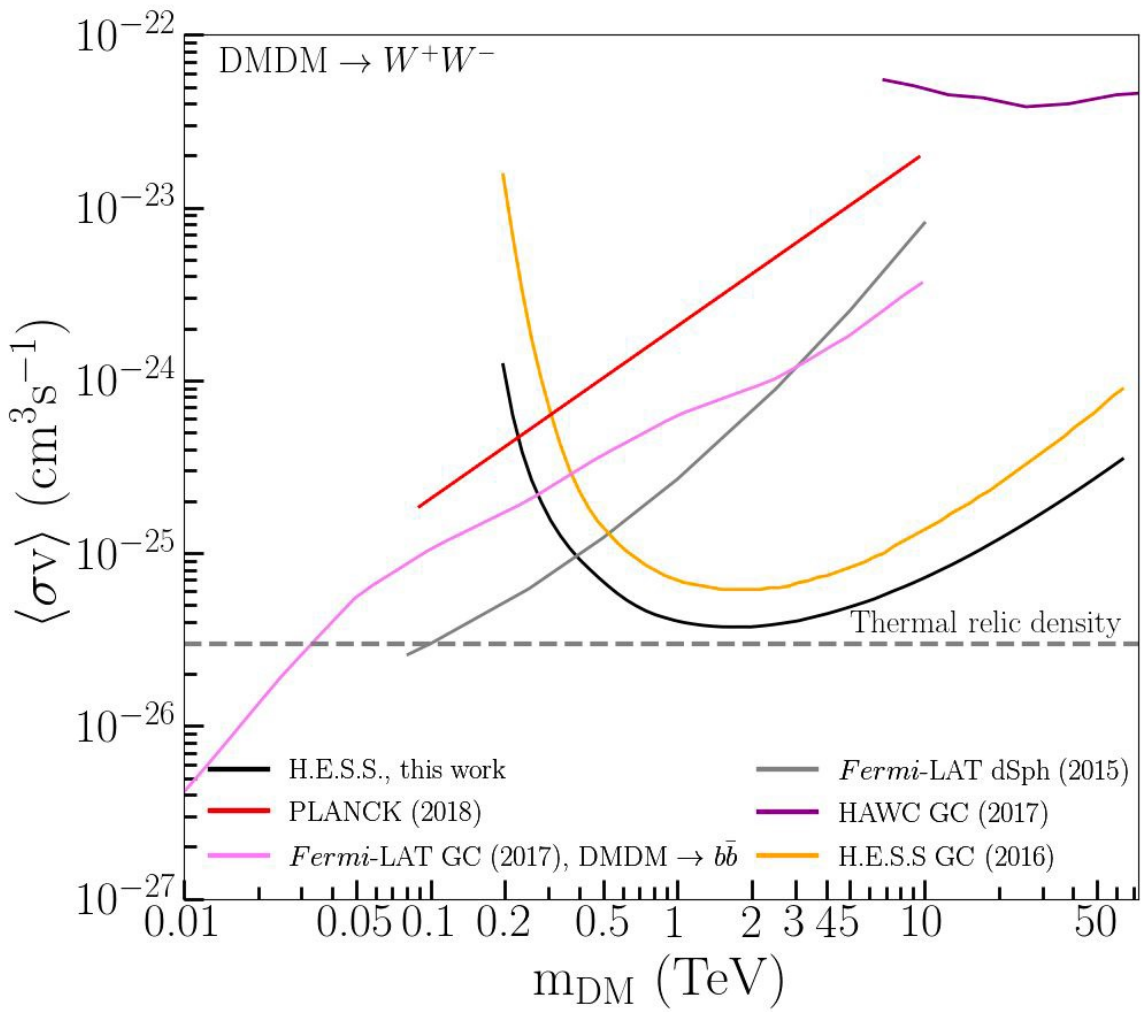
McKeown et al. MNRAS 513, 55 (2022)



Searches for continuum signals

- **Deep survey of the inner Galaxy (< 1kpc) going on with H.E.S.S.**

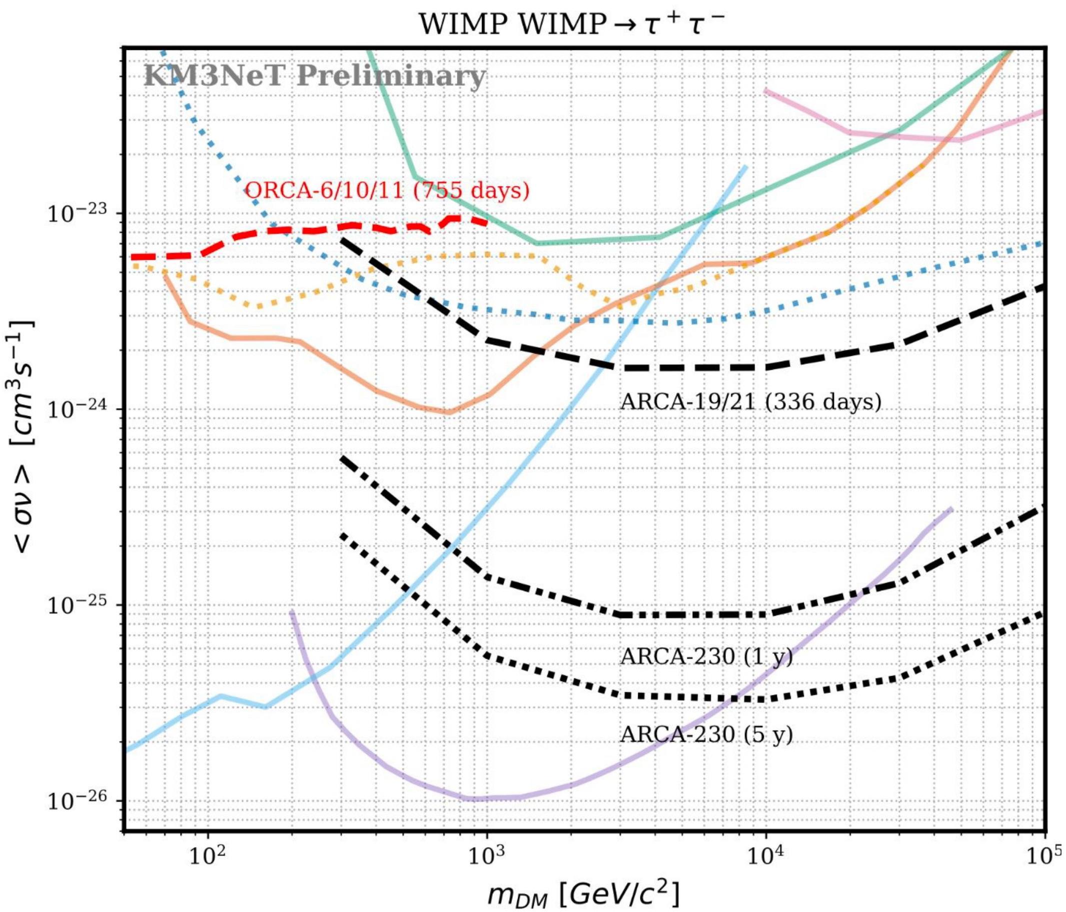


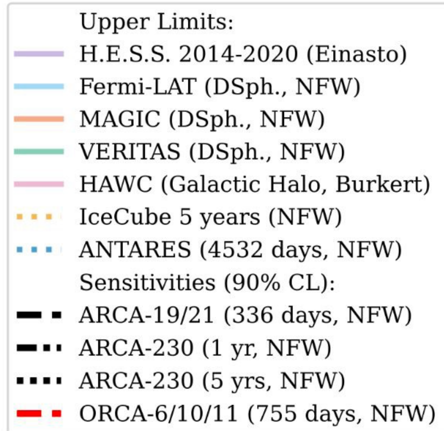


H.E.S.S. Collaboration,
Phys. Rev. Lett. 129, 111101 (2022)

- TeV window of opportunity for CTAO/SWGO

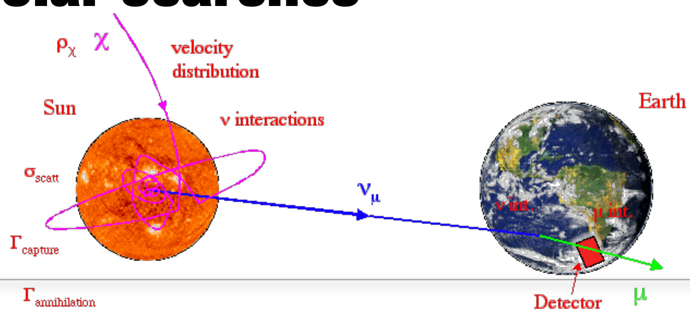
VHE neutrinos : KM3Net sensitivity and Icecube

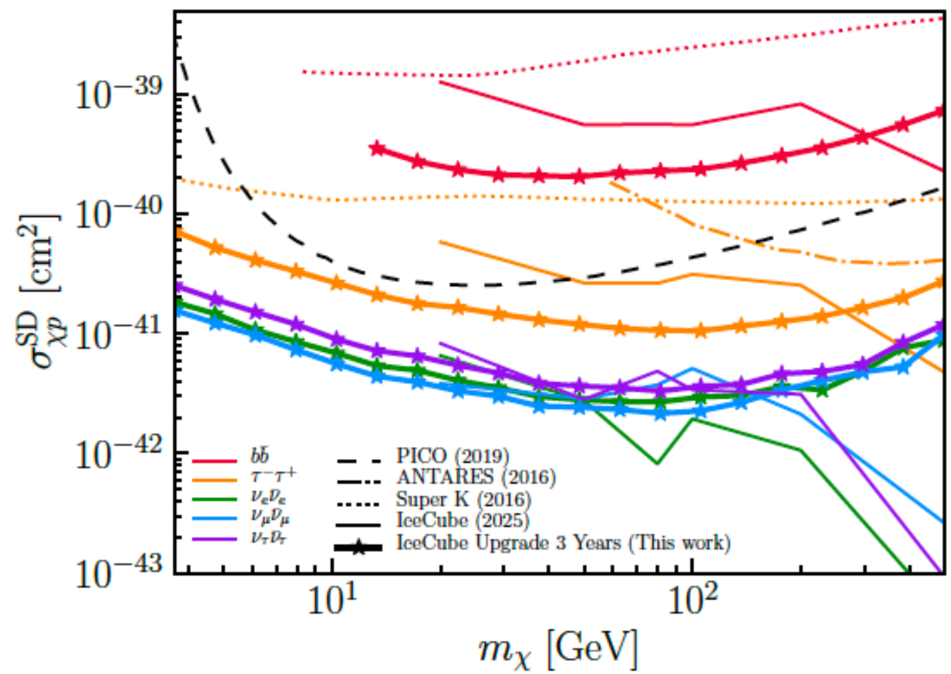




- **Galactic center forecast**

- **Solar searches**



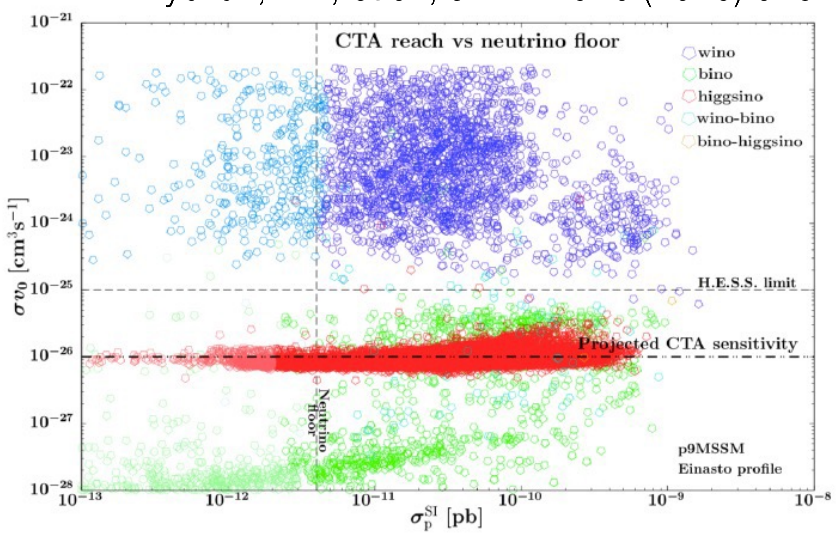


Icecube coll. arXiv:2605.06600v1

SU(2) WIMPs: Wino and Higgsino

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

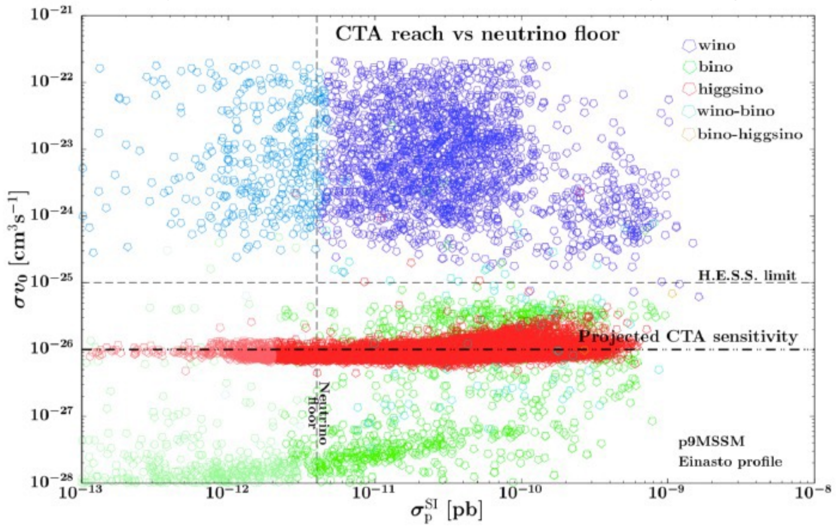


SU(2) WIMPs: Wino and Higgsino

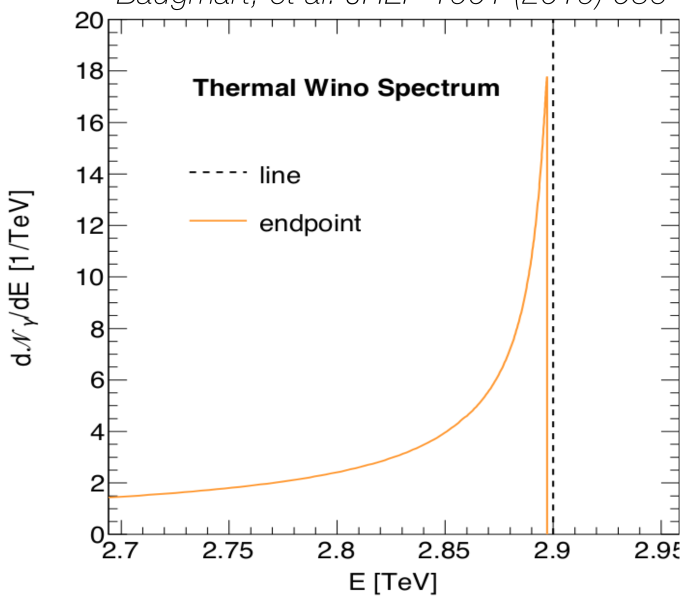
Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons

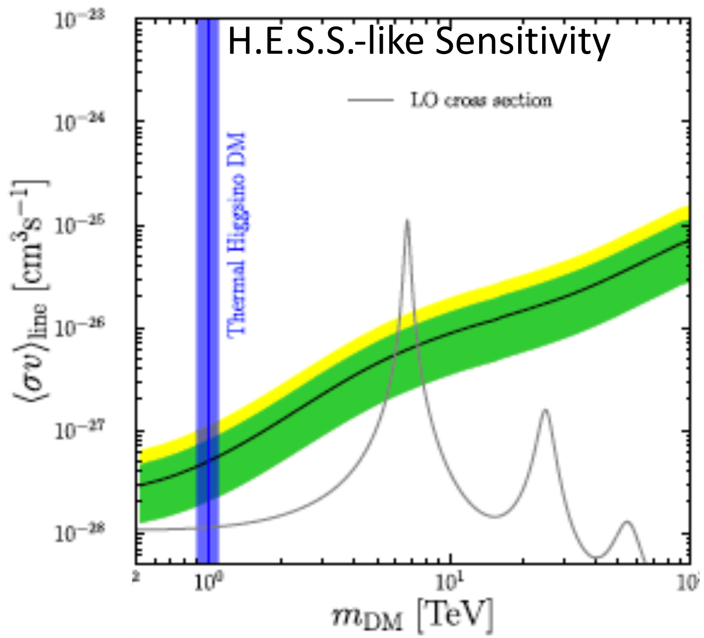
- Wino/Higgsino show prominent gamma ray line (-like) feature in the annihilation spectra

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



Baugmart, et al. JHEP 1901 (2019) 036





Montanari, EM, et al., PRD107, 043038 (2023)

Constraints on thermal Wino dark matter

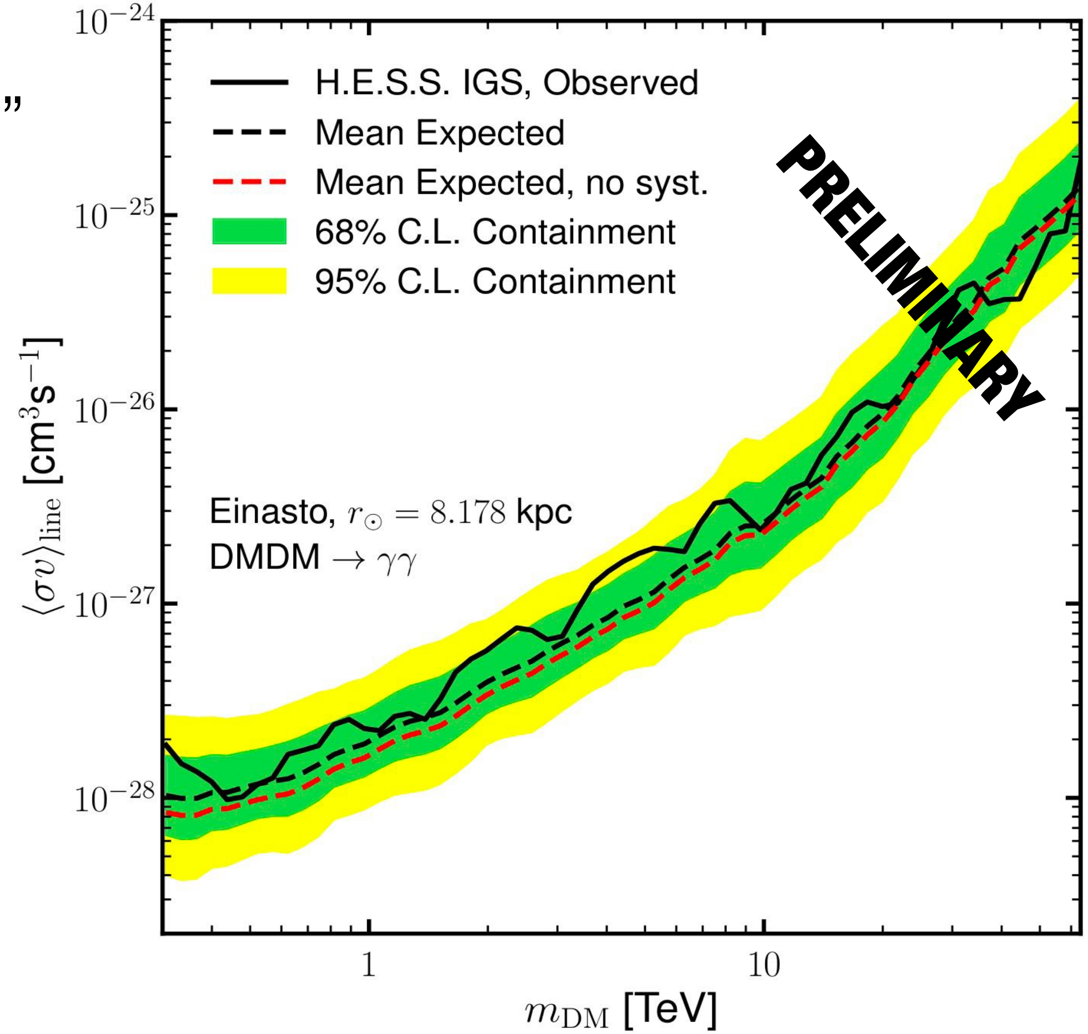
- DM cores up to several kpc excluded at ~2 TeV

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

Search for TeV gamma-ray line

- Gamma-ray line signal from ($\chi\chi\to\gamma\gamma$ or $\chi\chi\to\gamma Z$) is a very “clean” possible annihilation channel
- No astrophysical lines expected

→ Best prospect for a “smoking gun” indirect signal for DM



Search for TeV gamma-ray line

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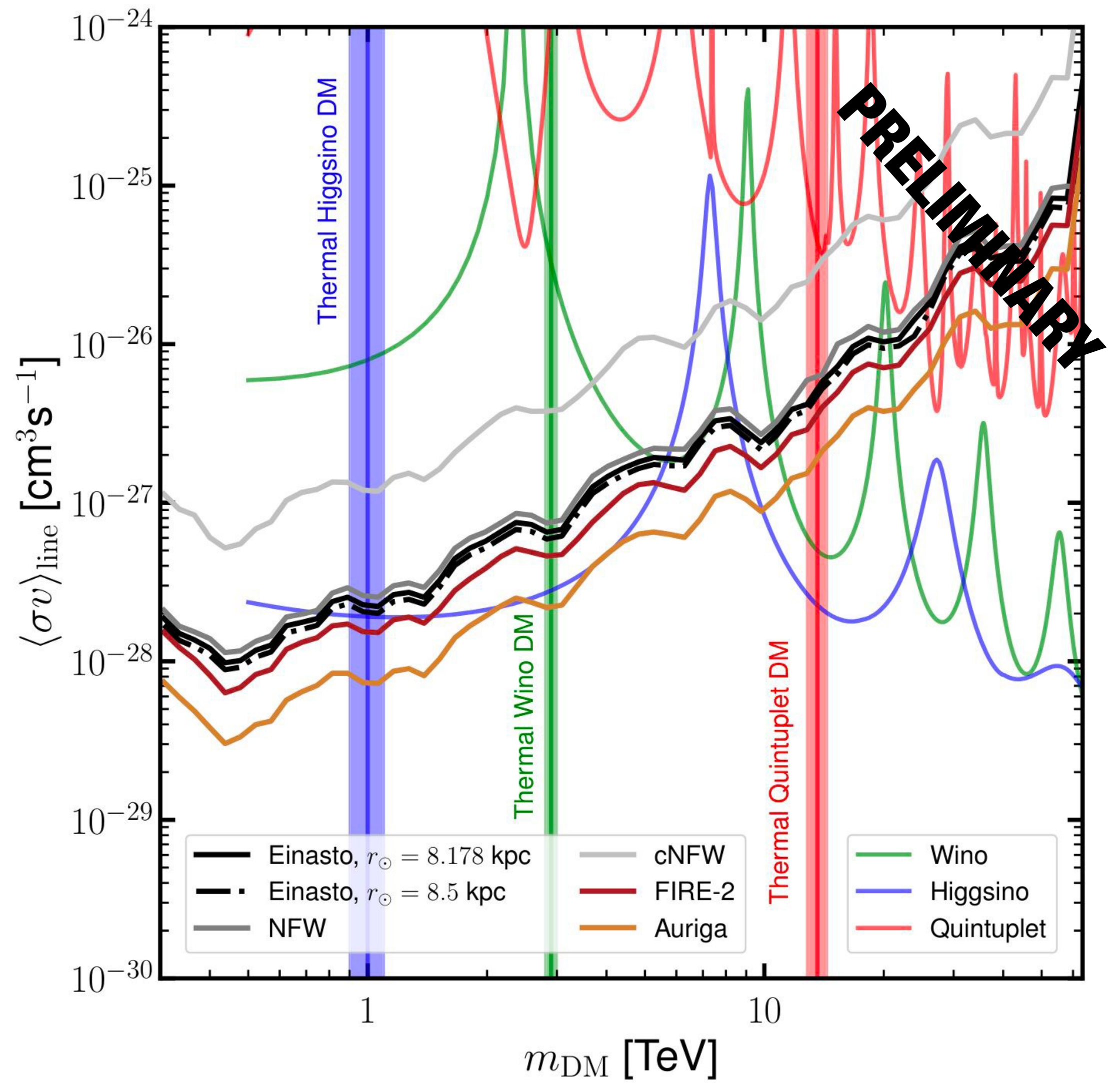
- No astrophysical lines expected

→ Best prospect for a "smoking gun" indirect signal for DM

- **Pure Wino, Higgsino, Quintuplet**
  - Actively searched at LHC
  - Thermal Wino/ Quintuplet excluded
  - Challenging thermal Higgsino for the first time

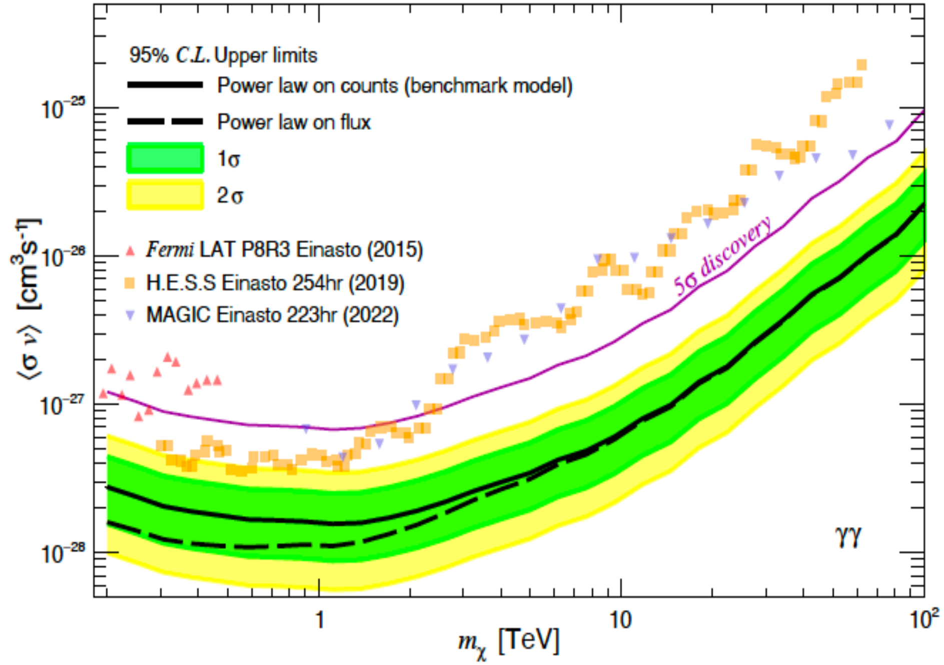


H.E.S.S. Collaboration, submitted (2026)

Gamma-ray line sensitivity reach with CTAO

Prospects with Galactic Center observations with CTAO

- A total of 500 hours of observation time with a roughly homogeneous exposure over the inner 4°
- A factor of 2-to-10 improvement compared to H.E.S.S./MAGIC

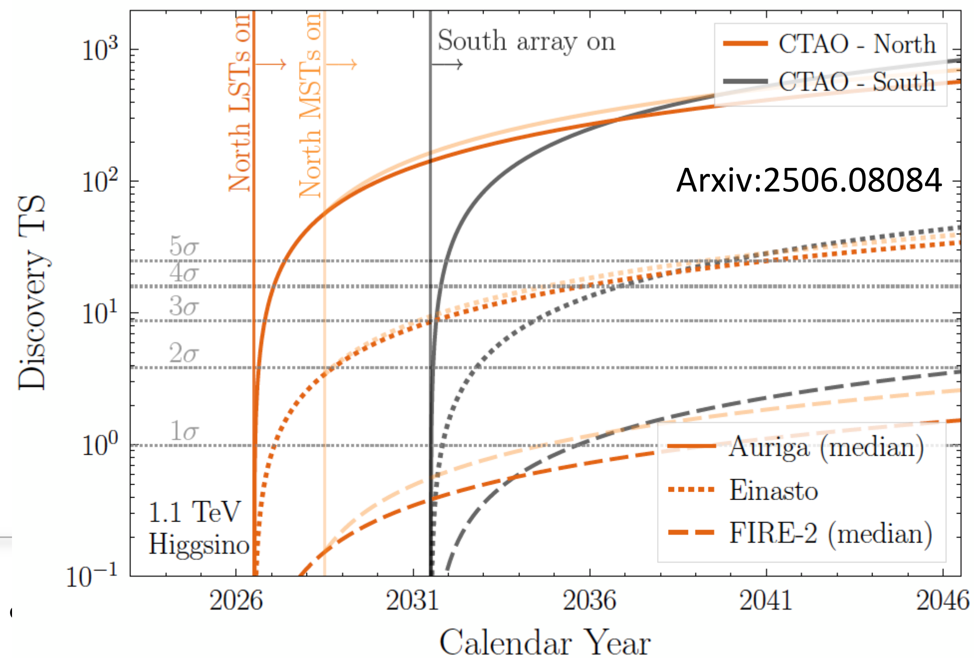


CTA Consortium, JCAP 07 (2024) 047

Higgsino dark matter

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

Capdevilla et al. JHEP 06 (2021) 133

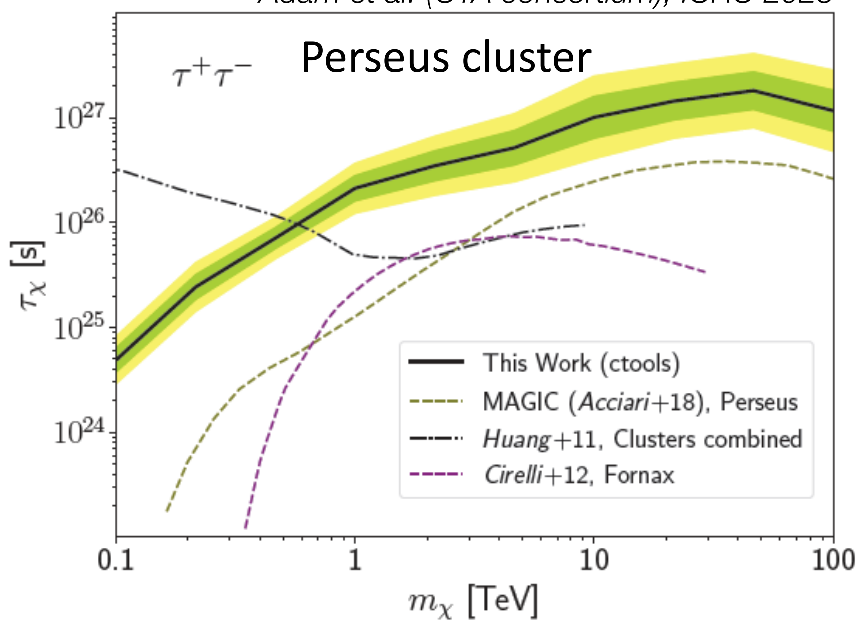


(Heavy) Decaying Dark Matter

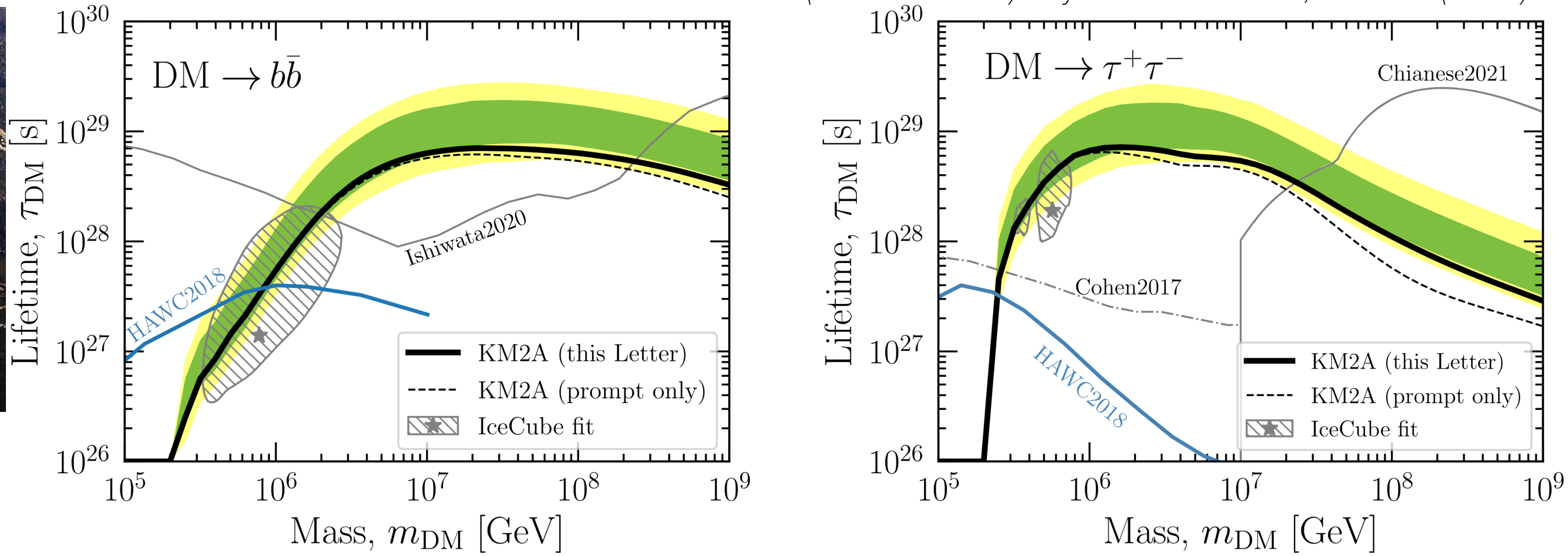
- Decaying DM searches target regions of the sky where large volumes can be probed, *e.g.*, *galaxy clusters*

- **> 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)



Synergy with collider and direct detection searches

- Individual experiments often present results on phenomenological quantities that are directly constrained by the relevant data (e.g., the annihilation or scattering rate)
- Direct comparison of results from multiple probes requires a concrete particle physics hypothesis
  → framework of effective field theory or simplified model approach
  (some limitations still exist)

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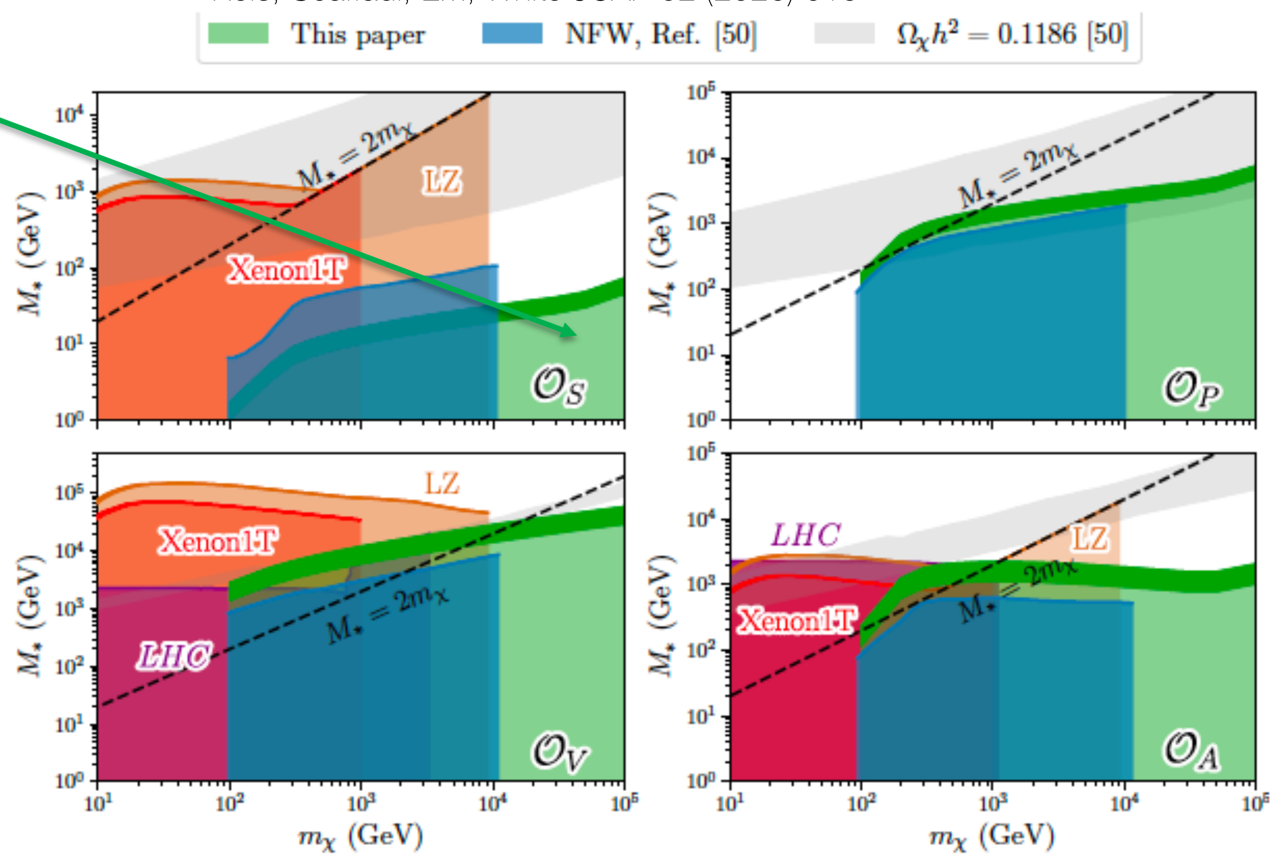
  → framework of effective field theory or simplified model approach
  (some limitations still exist)

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

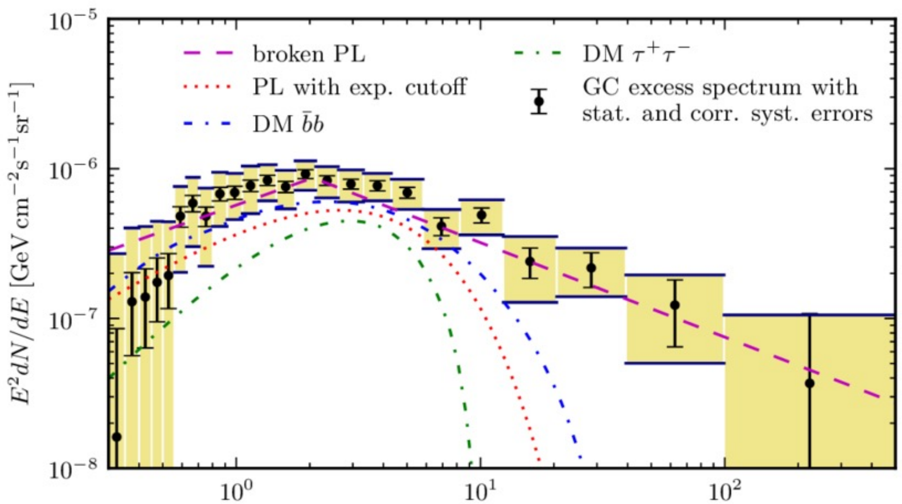
	ID	DD
$\mathcal{O}_S$	v^2	1
$\mathcal{O}_P$	1	$(\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$
$\mathcal{O}_V$	1	1
$\mathcal{O}_A$	m_q^2, v^2	$\vec{s}_\chi \cdot \vec{s}_N$

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

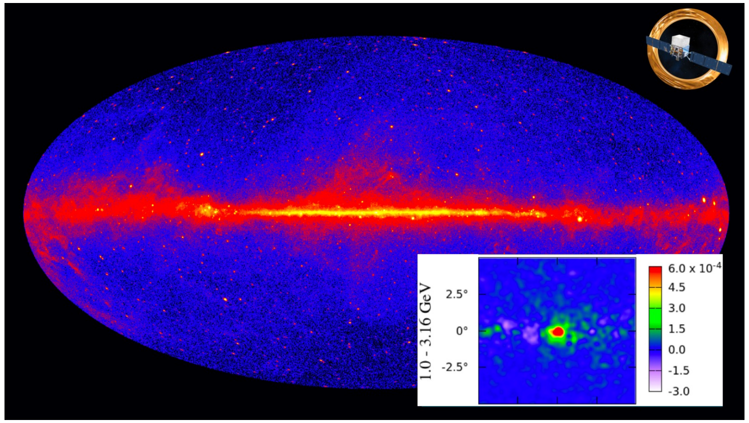


The Galactic Center Excess seen by Fermi-LAT

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

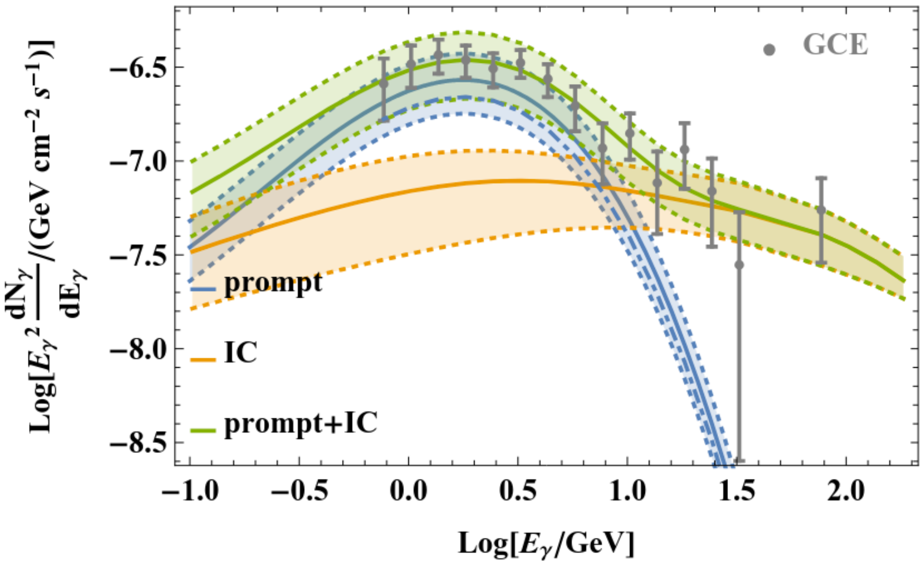


From F. Calore



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 ?

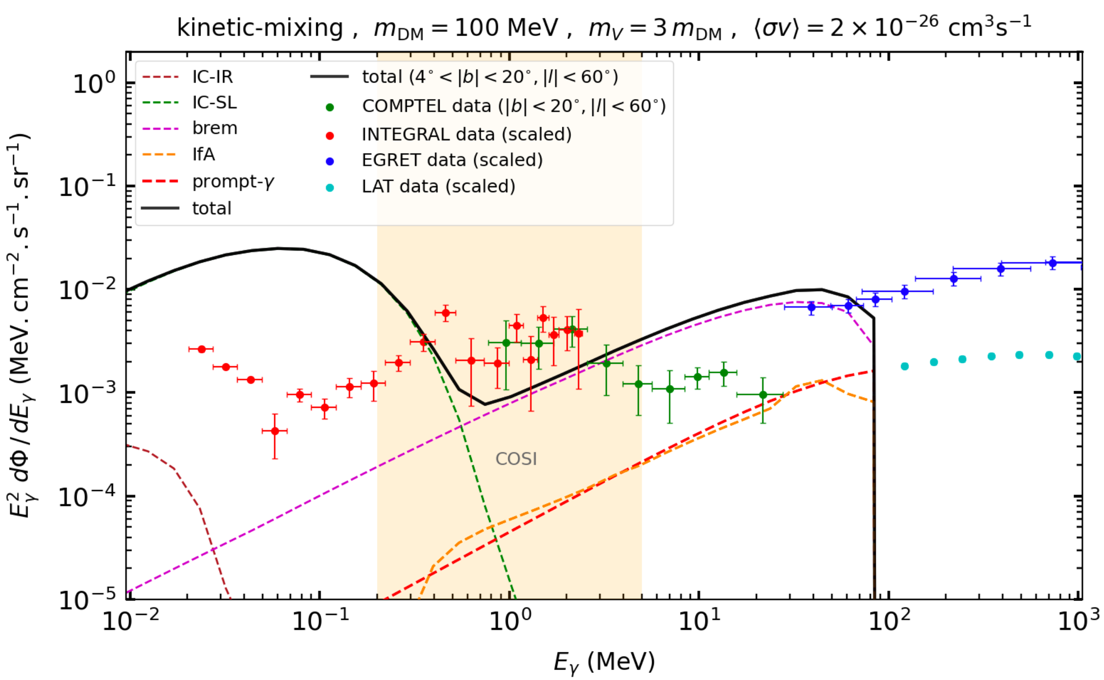
2512.16699: Discovery of two new millisecond pulsars towards the Galactic bulge

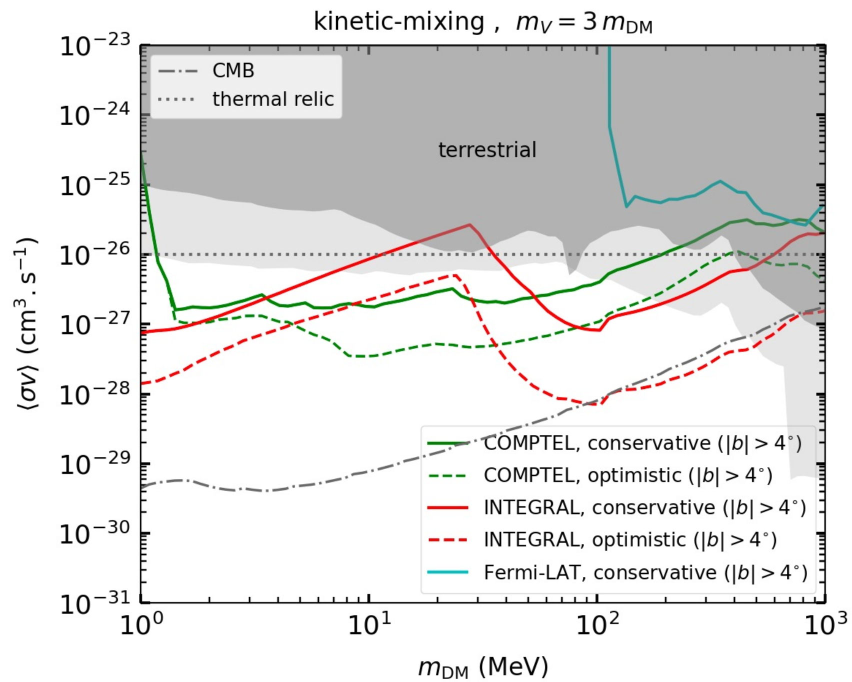
Sub-GeV DM searches

- 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-

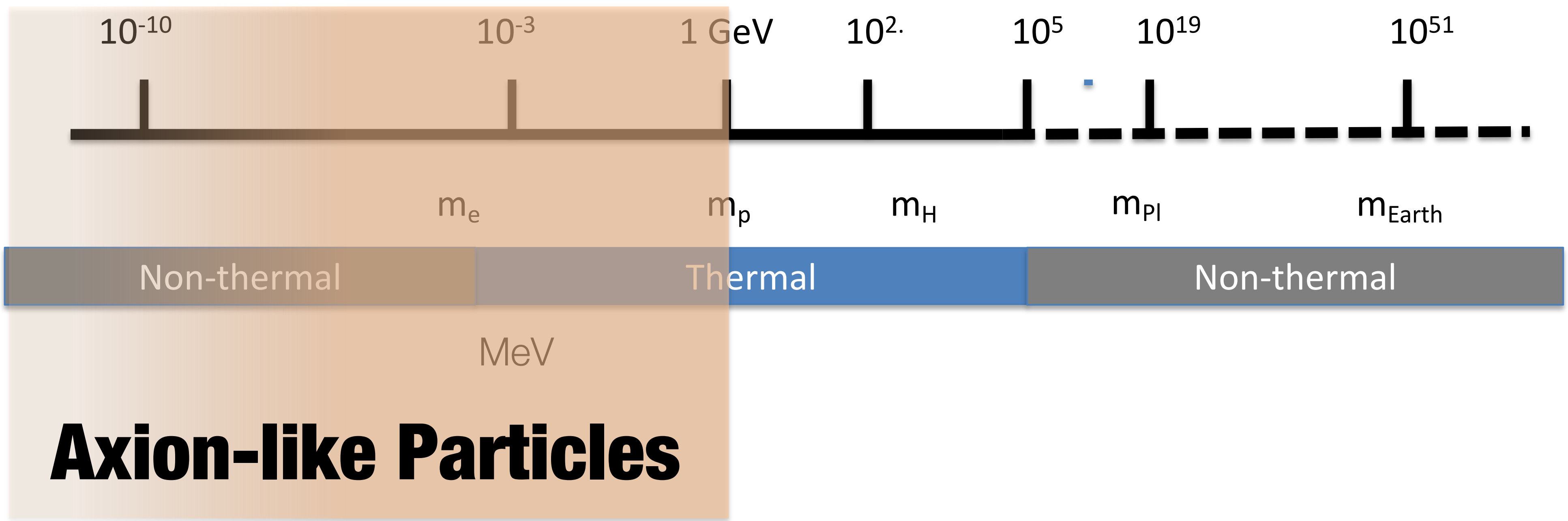
Cirelli,et al. JCAP 01 (2026) 038 [2508.03819]





- Caveat: Background model, propagation effect

DM as a relic from the Early Universe



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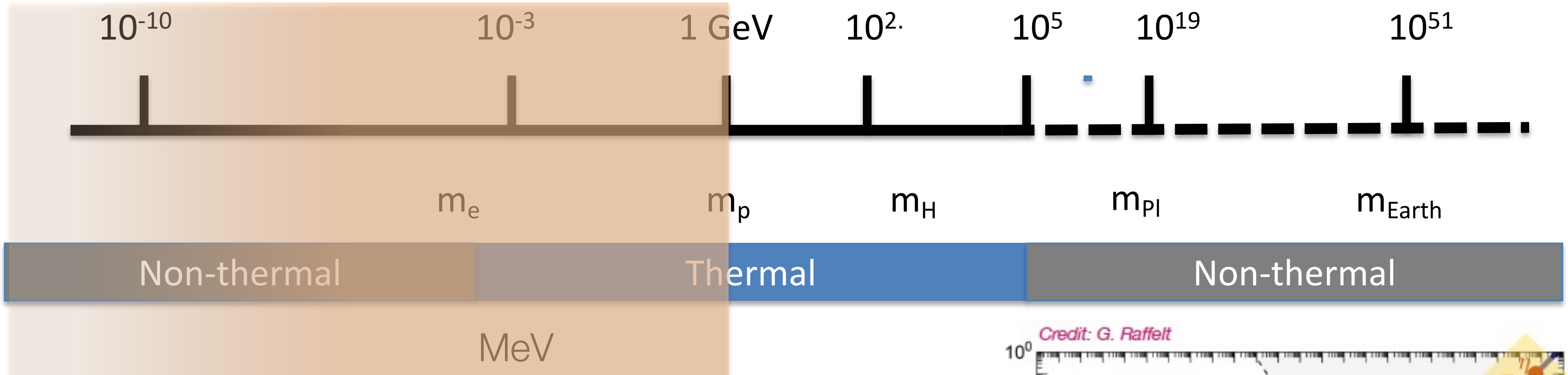


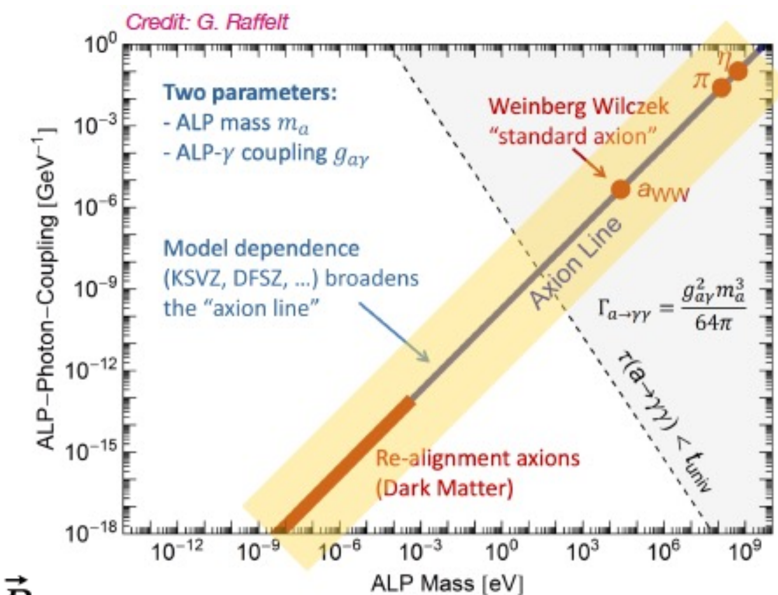
Axion-like Particles

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

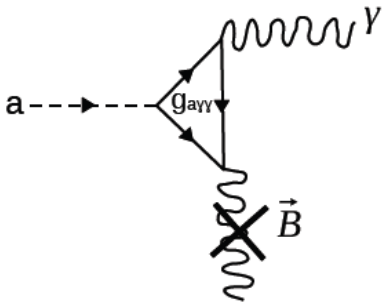


Primakoff conversion

Decay

ALP searches with VHE gamma rays

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



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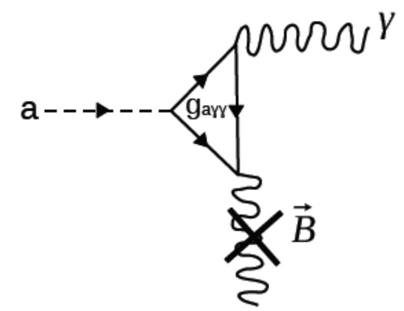
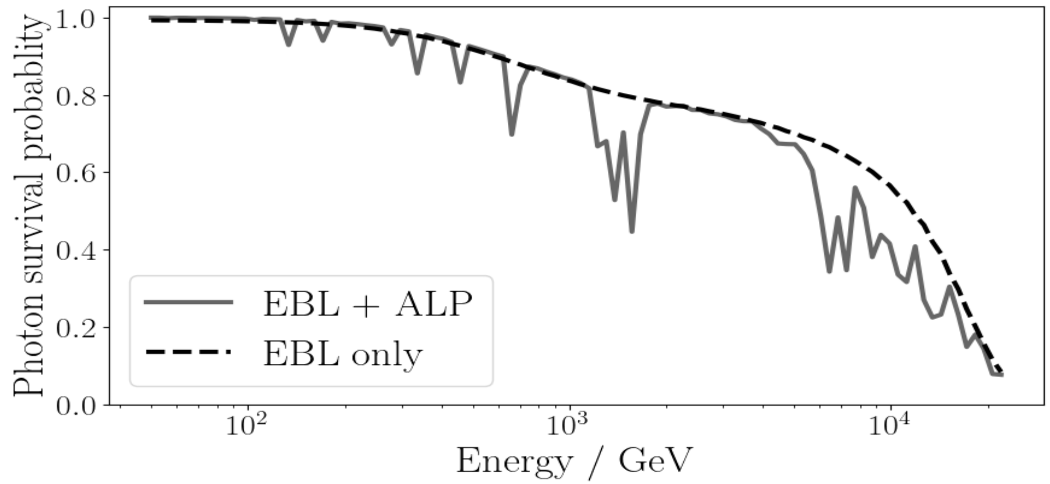
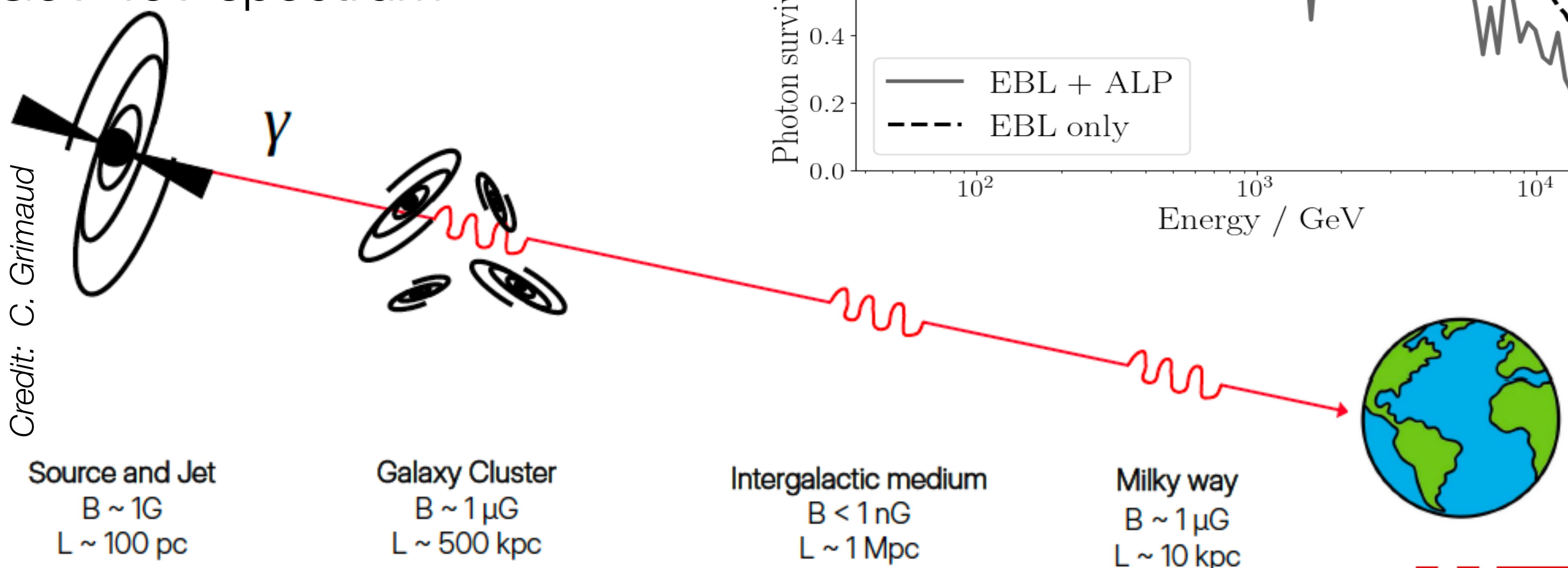


- Wiggles: energy-dependent deviations from smooth GeV-TeV spectrum





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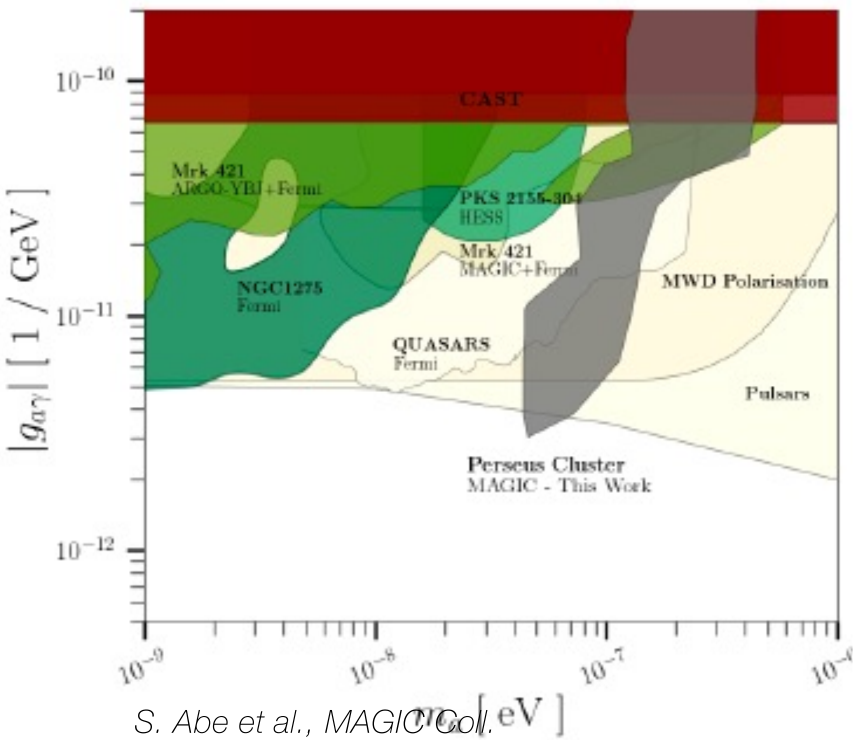
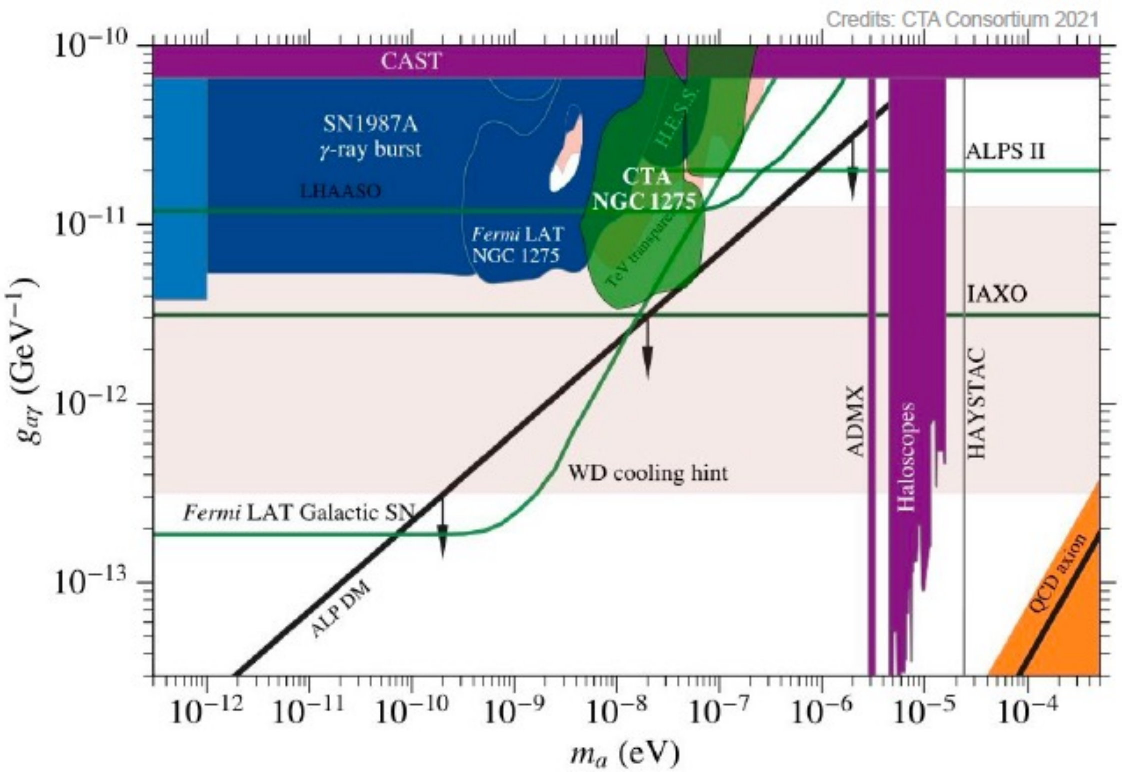
Observations of Perseus cluster by MAGIC ~40 h



S. Abe et al., MAGIC Coll.
Phys.Dark Univ. 44 (2024) 101425

Prospects for CTA: Perseus cluster



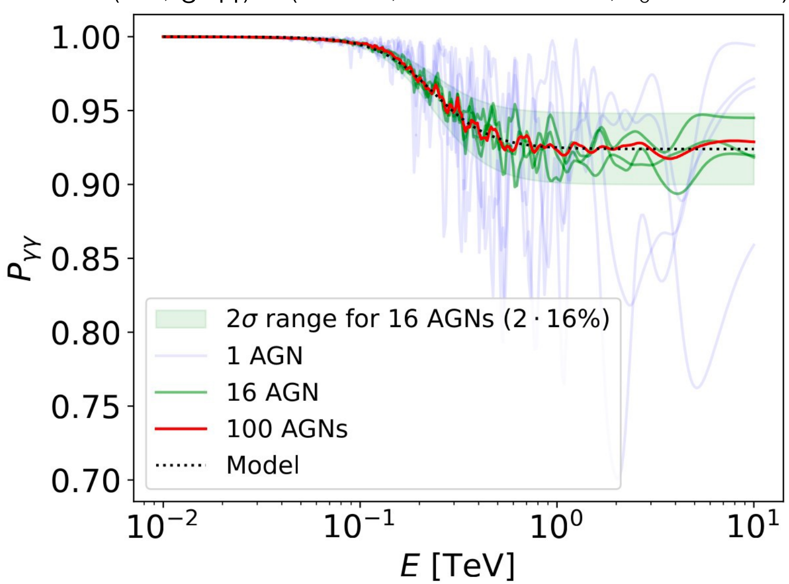
Probing ALP with AGN-GalaxyCluster pairs

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

(ma, gaγγ) = (20 neV, 7x10^{-13} GeV−1,B_0 = 3 muG)



Grimaud, EM, Malyshev et al. accepted JCAP (2026)

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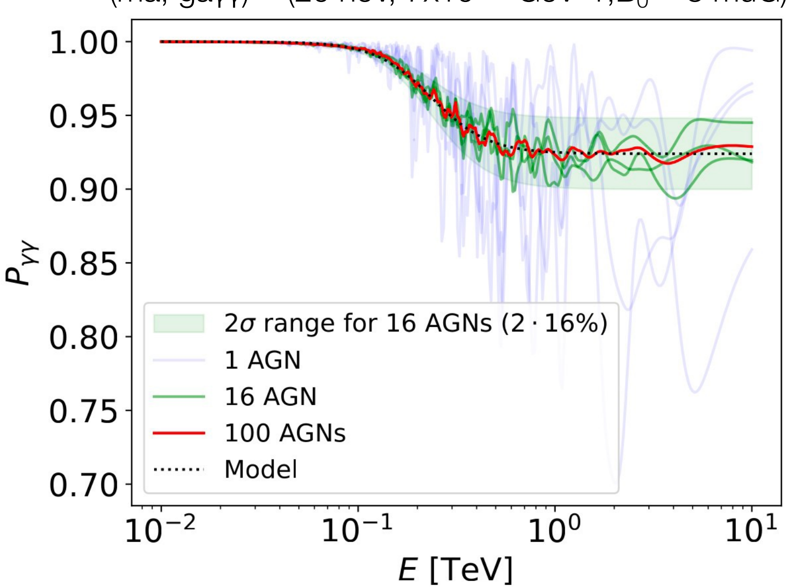
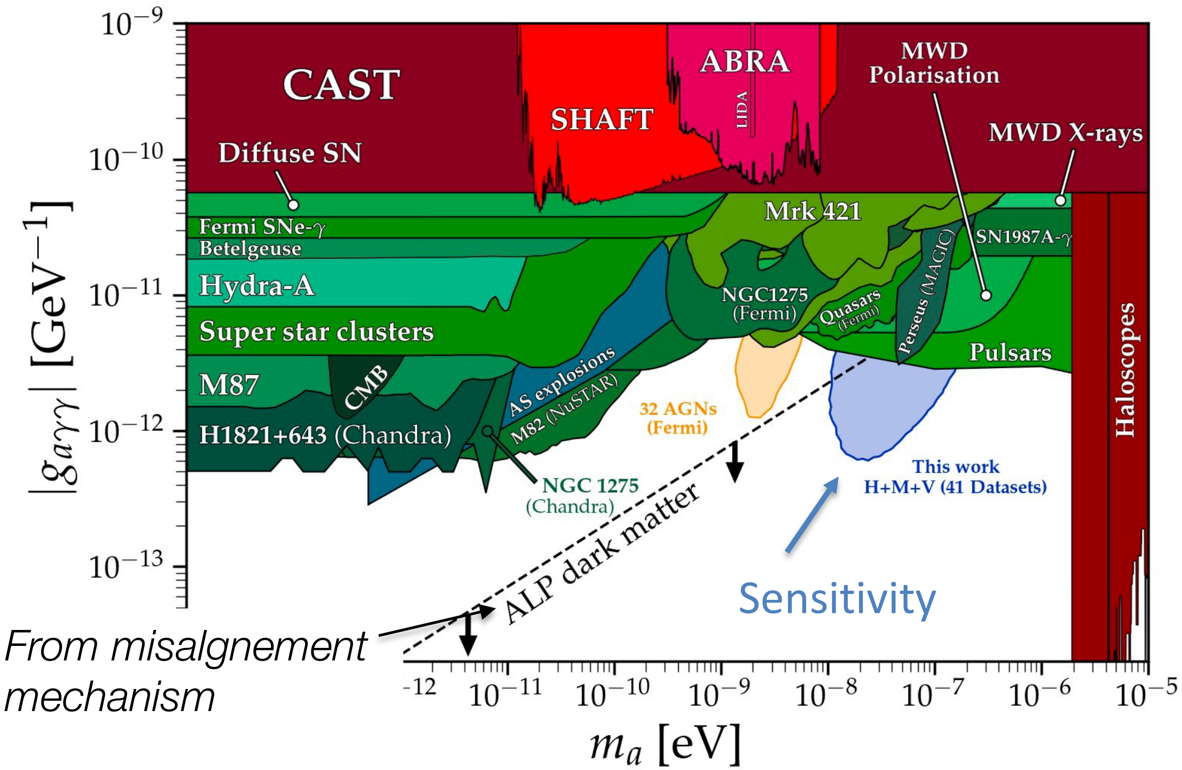


Grimaud, EM, Malyshev et al. accepted JCAP (2026)

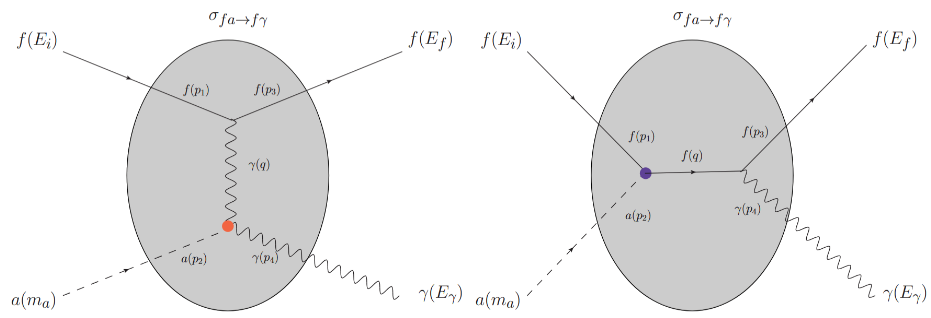
AGN-GC selection

>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



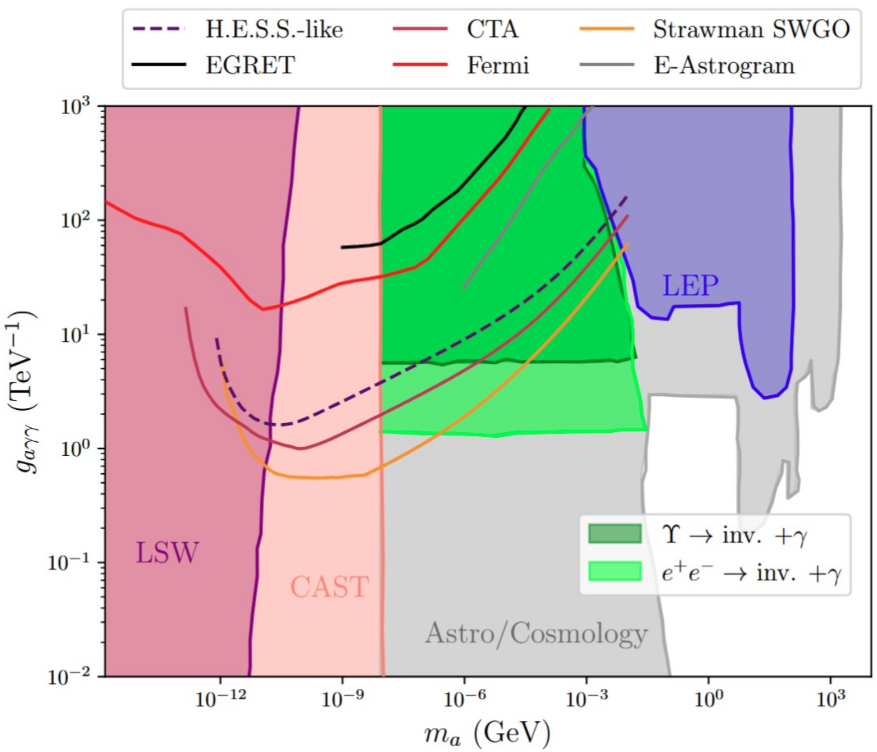
From misalgnement mechanism

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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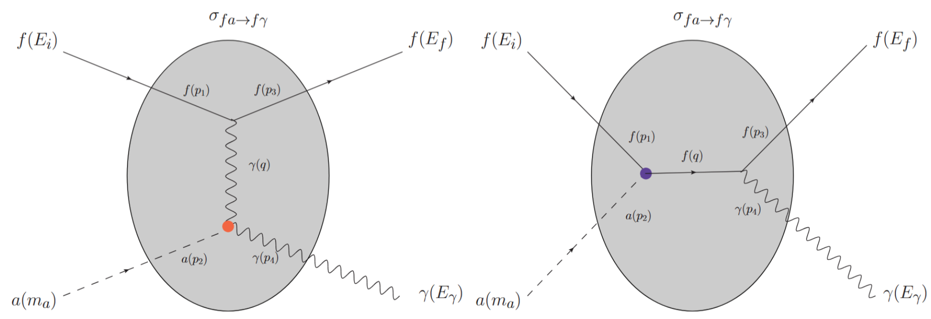

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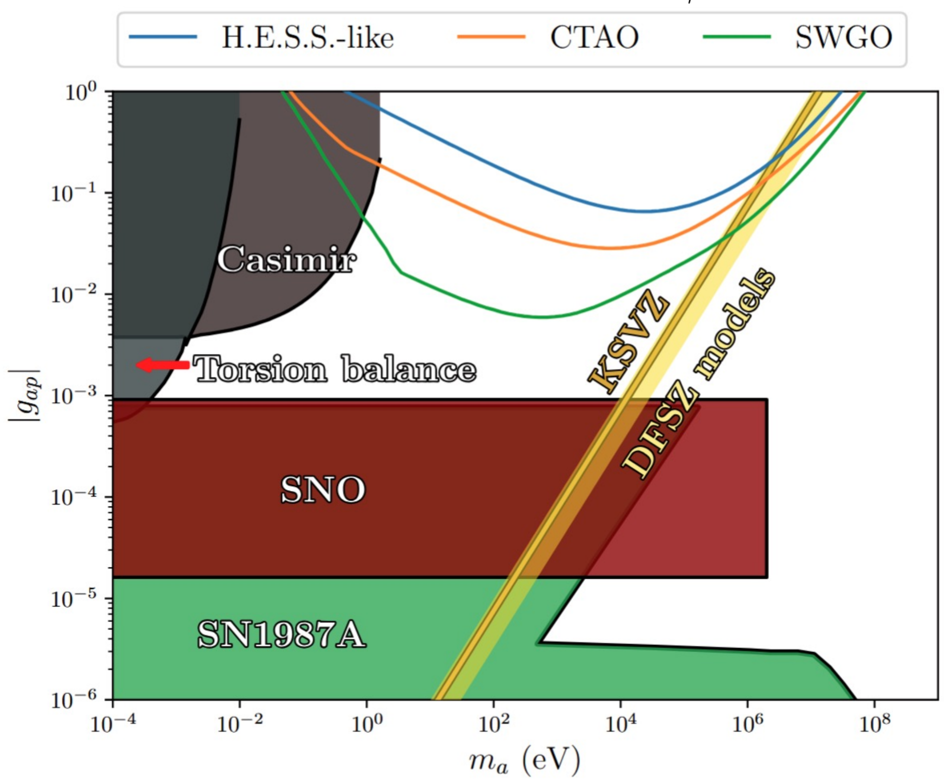

Goncalves, EM, et al. accepted PRD (2026)

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

Summary

- Maturing experiments & shrinking parameter spaces
- WIMP paradigm: diversified, trend towards minimal DM model searches
  - Last remaining well-motivated WIMP benchmark model probed ?
- ALP : sensitivity 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
  $\longrightarrow$ multimessenger probes of dark matter

Thanks for your attention