Mesures indirectes en astroparticules

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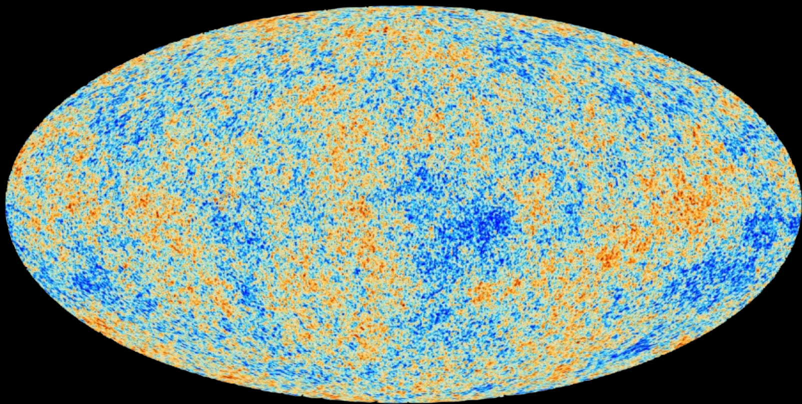
Journée SFP 2024: Lumière sur la Matière Noire

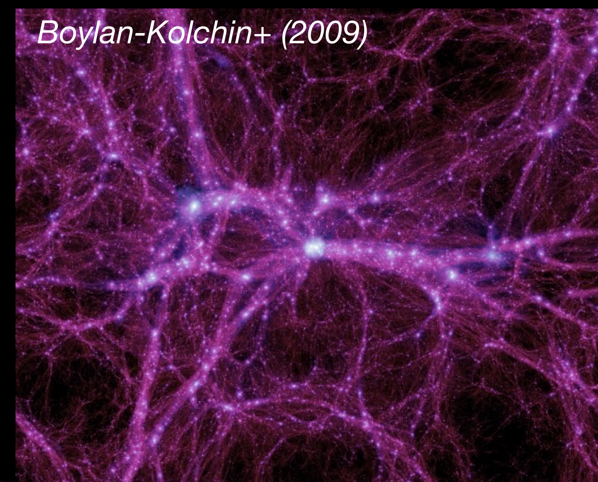
21 mars 2024, LPNHE, Jussieu

Dark Matter : what we know



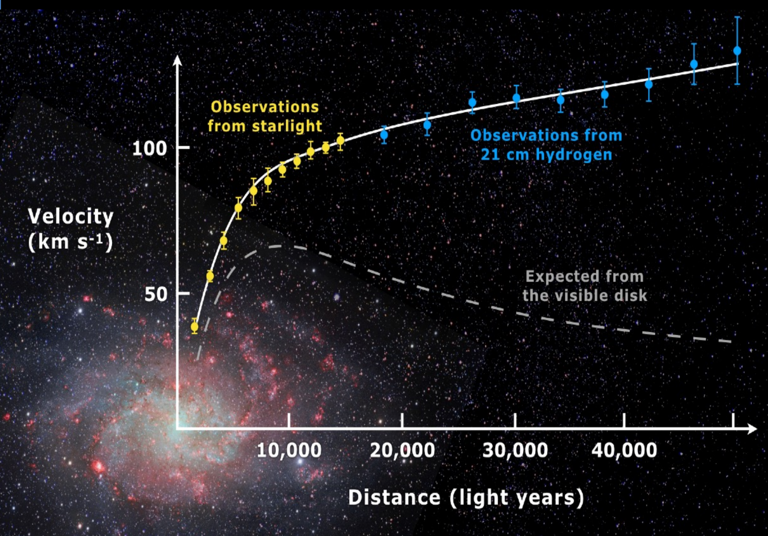
- **68% dark energy**
- **5% baryons**
- **27% dark matter (cold, collisionless)**

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



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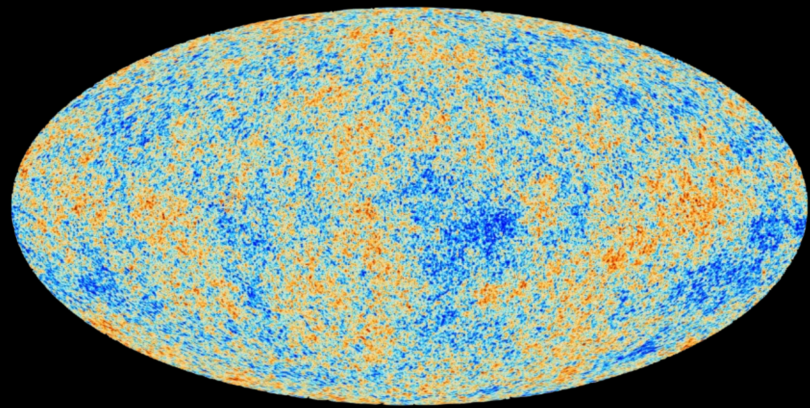

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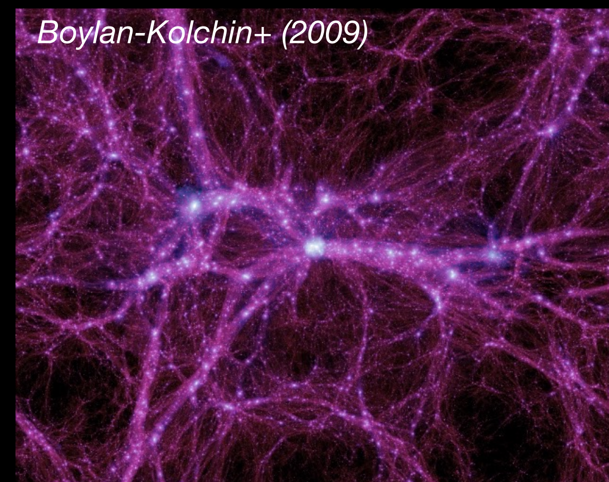


Dark matter density perturbations grow and become nonlinear
→ study structure formation with N-body simulations

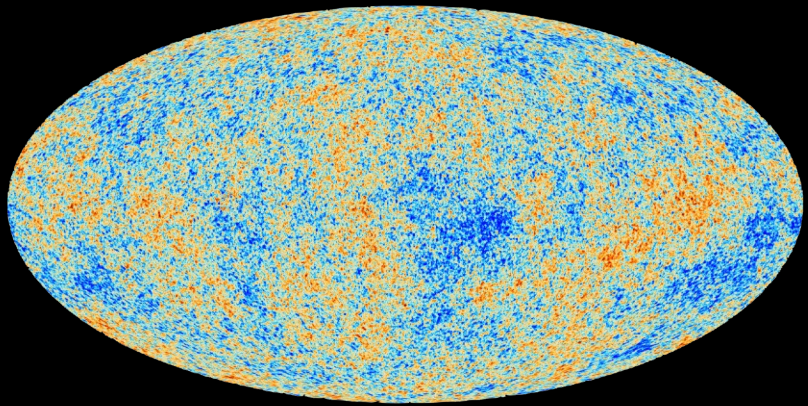
Dark matter forms self-gravitating halos that host galaxies

~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**

No good particle dark matter candidates within the Standard Model

Dark Matter : what we don't know



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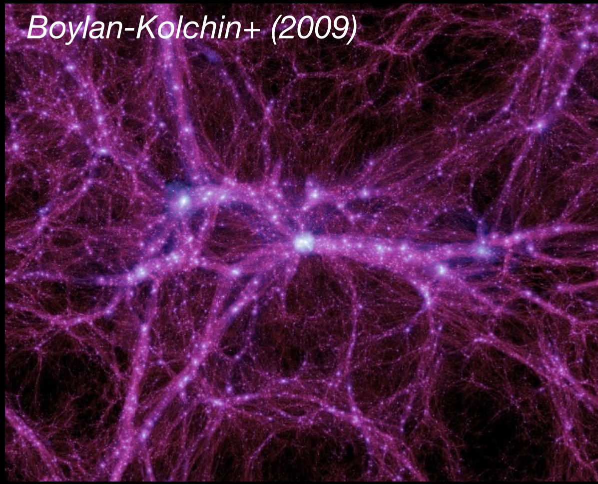


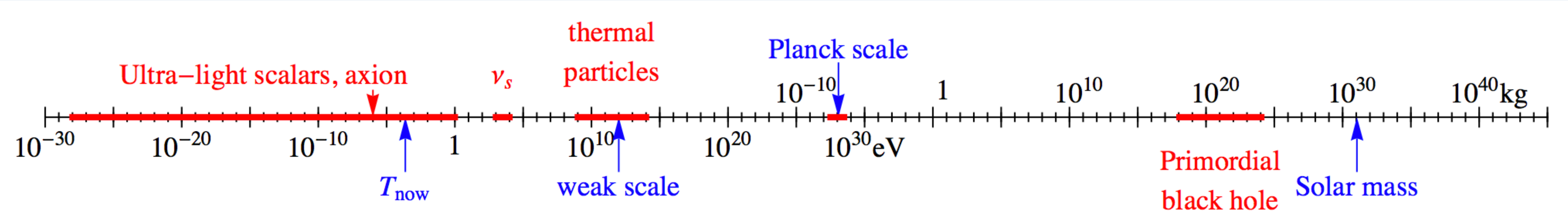
Dark matter density perturbations grow and become nonlinear
→ study structure formation with N-body simulations

Dark matter forms self-gravitating halos that host galaxies

Still a non-exhaustive list of open questions :

- **Is there cosmic evidence to go beyond the cold and collisionless paradigm ?**
- **Is DM wave-like or particle-like? Is it at all a particle (e.g. primordial black holes) ?**
- **Does dark matter have important self-interactions ?**
- **Whether it's absolutely stable, or decays slowly over time**
- **…**

The landscape of Dark Matter

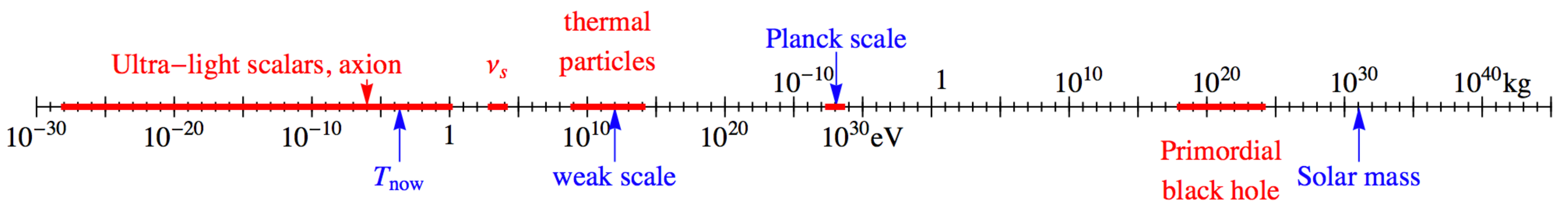


- **Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales**

- **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**

The landscape of Dark Matter



- **Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales**
- **The classfication of dark matter candidates is largely based on the particle physics features of the underlying models**
- **An alternative approach is to shift focus toward exploring wide ranges of the possible phenomena in an effort to understand how well existing experimental searches cover the space of possibilities, and eventually how new experimental opportunities provide sensitivity to regions of theory-space that are not captured by the current programs**

Astroparticle messengers

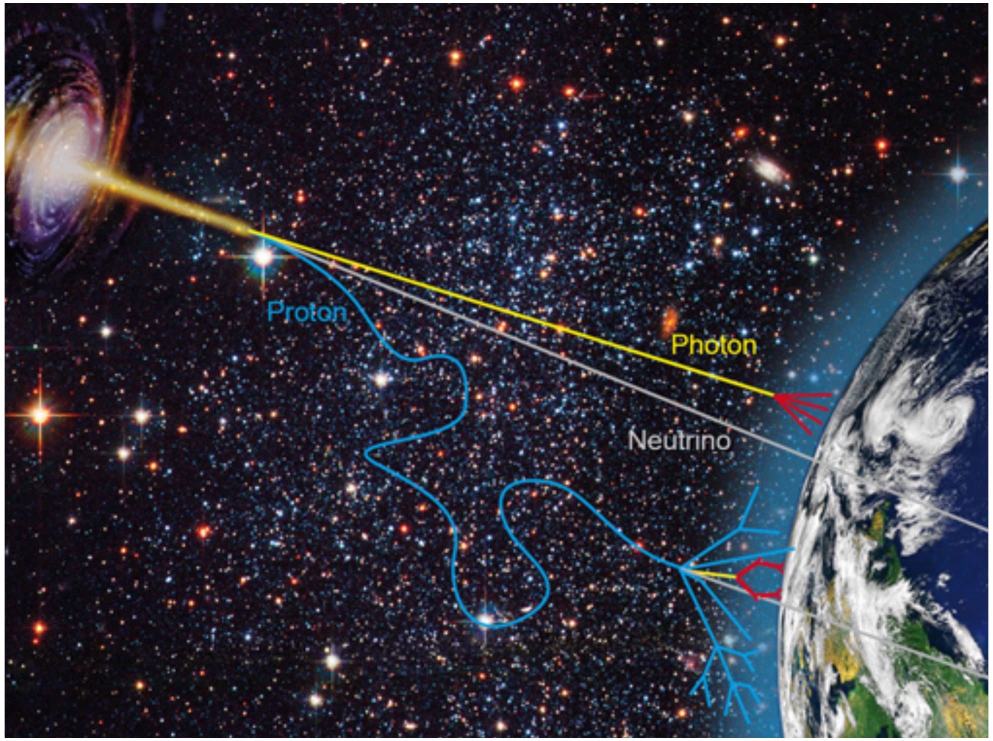
Neutral messengers – γ and ν

- Point to their sources : directional information
  → mapping of acceleration /propagation/production sites

- Can reveal the abundance and distribution of DM
  - need to account for absorption at extragalactic scale for gamma rays

  → 2D (occasionally 3D) information on source distribution - very valuable for separating signal from background

- Characteristic DM spectral features may be present in the spectrum



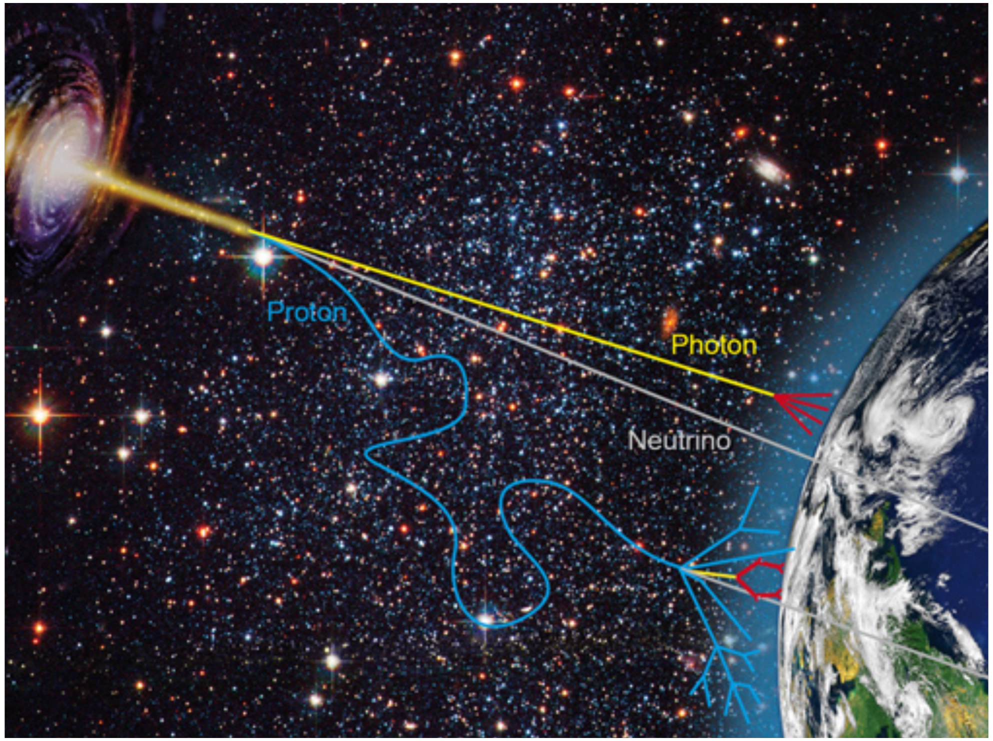
Identification of DM is possible
→ the gamma-ray/neutrino distribution in the sky can tell us the DM density distribution
→ the gamma-ray/neutrino spectrum can tells us the reaction process and DM mass

Astroparticle messengers

Neutral messengers – γ and ν

Charged messengers – p, $e^{\pm}$, …

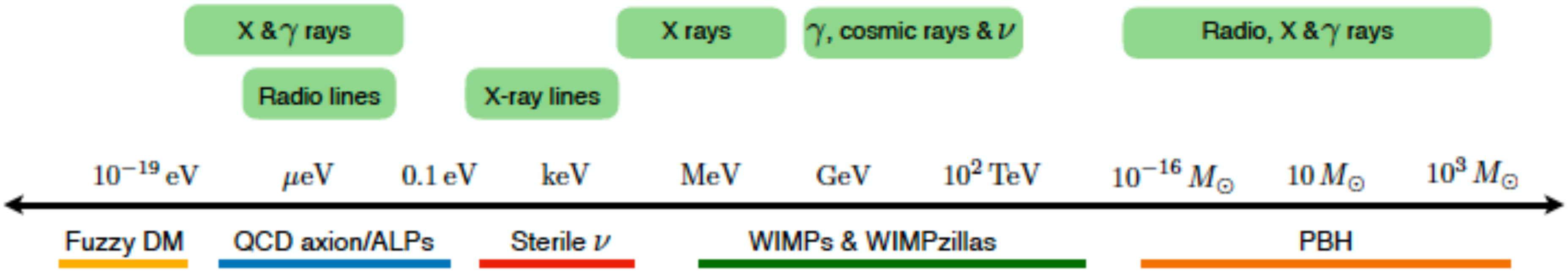
- Charged particles are affected by Galactic magnetic fields - trajectories do not point back toward sources
- CRs can lose energy rapidly, so even on sub-Galactic scales, their spectrum changes with distance from the source
- Makes signal/background separation more difficult, unless expected background is small



High energy anti-matter particles are rare enough that an excess can shine noticeably above backgrounds

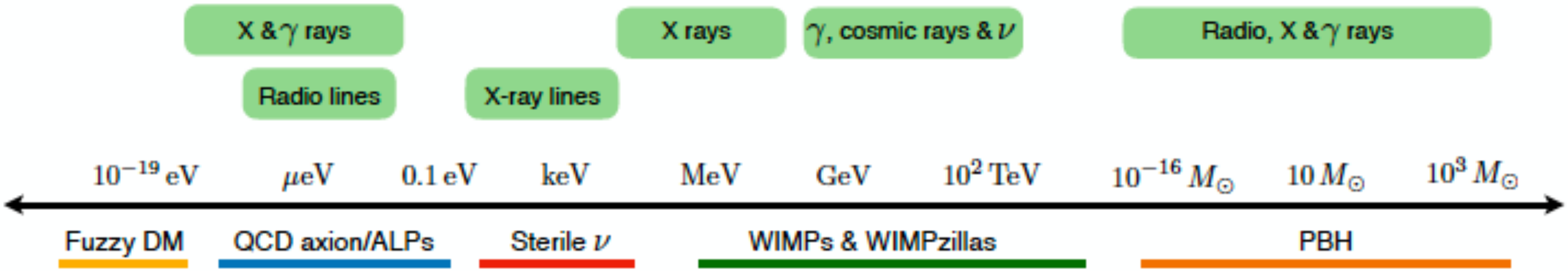
Astroparticle messengers

EuCAPT White Paper, arXiv:2110.10074



Astroparticle messengers and experiments

EuCAPT White Paper, arXiv:2110.10074



Particle dark matter emission

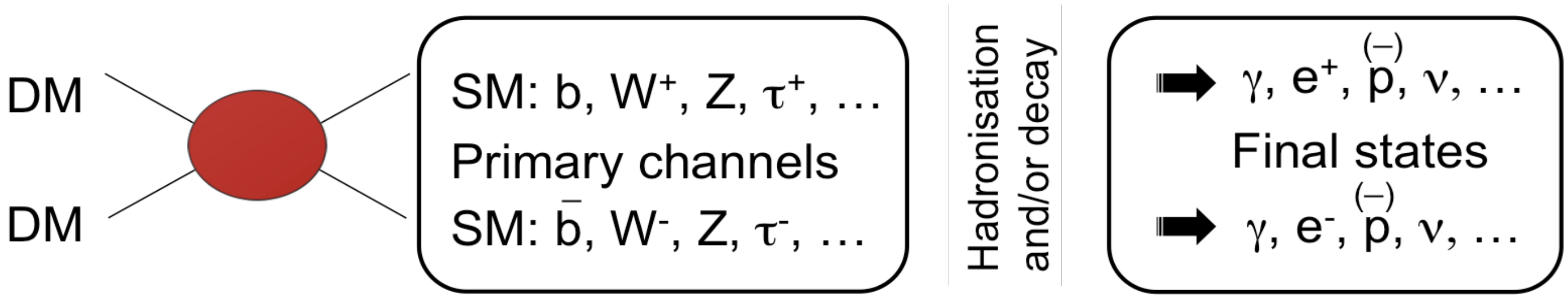
$$\text{DM (DM)} \rightarrow \text{SM SM}$$

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

Particle dark matter emission

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

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



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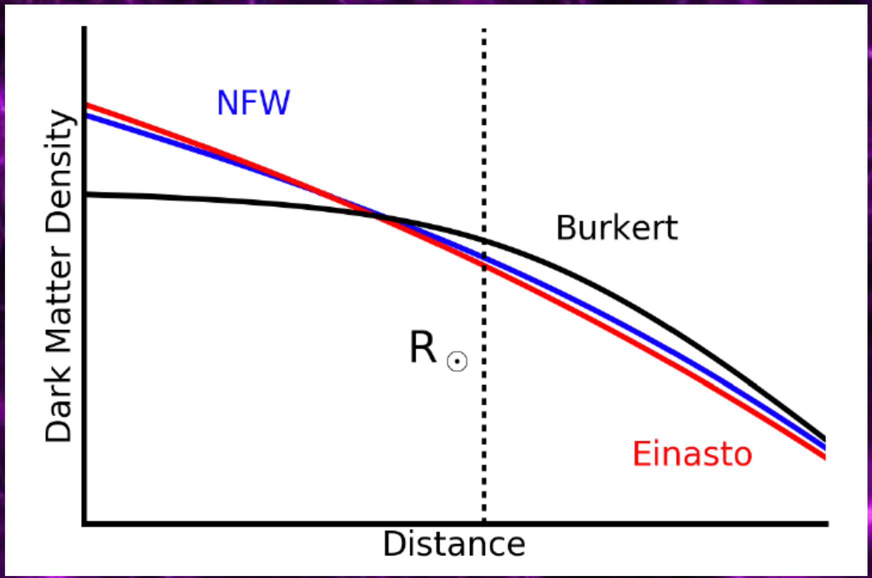
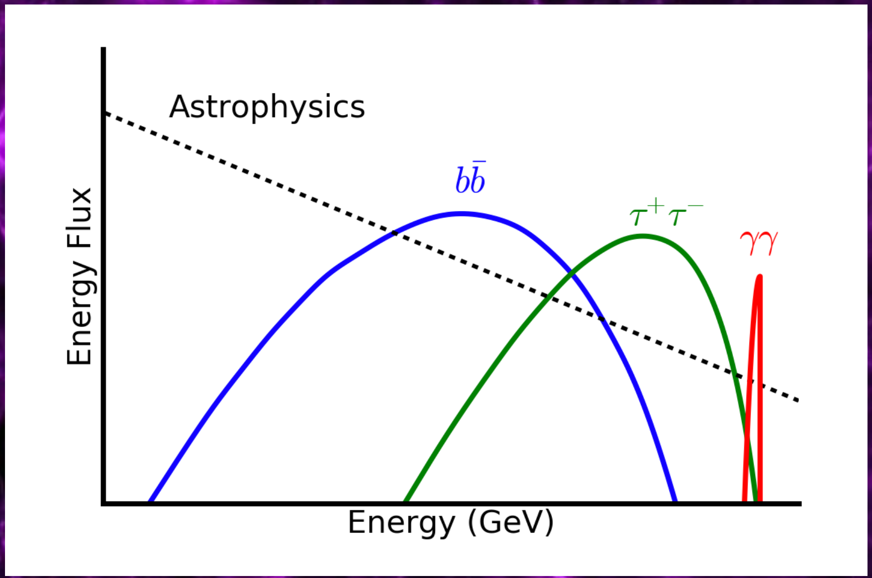
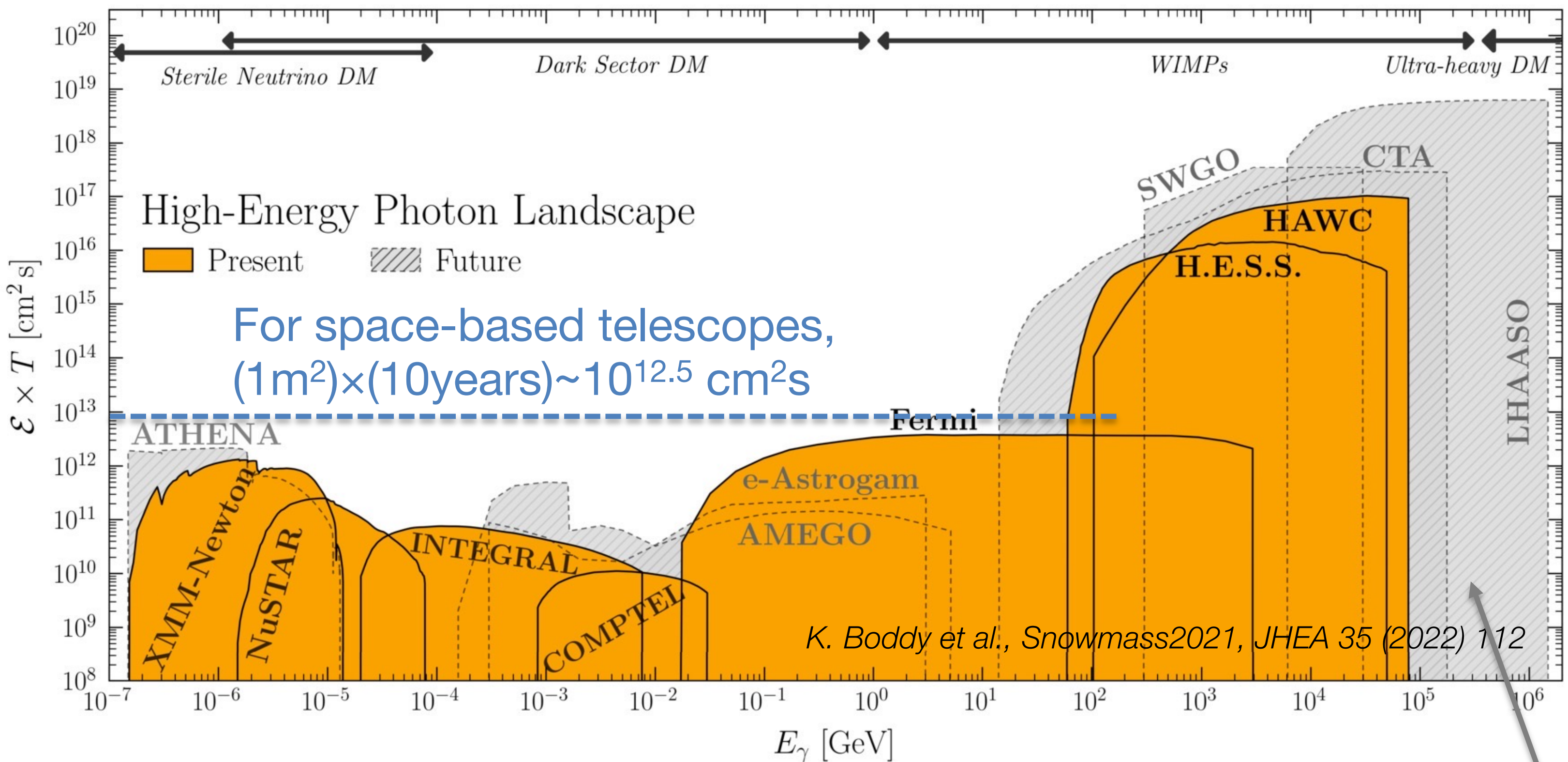




For annihilation: $$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r[s])ds$$

Exposure of x/γ-ray instruments for annihilating/decaying DM



ε : Effective area
T : Observation time

Nb of detected photons : $\propto \Phi \times \varepsilon \times T$

Disclaimer:
- one of the many ways to compare instruments
- for some DM searches, FoV or energy resolution can be critical as well

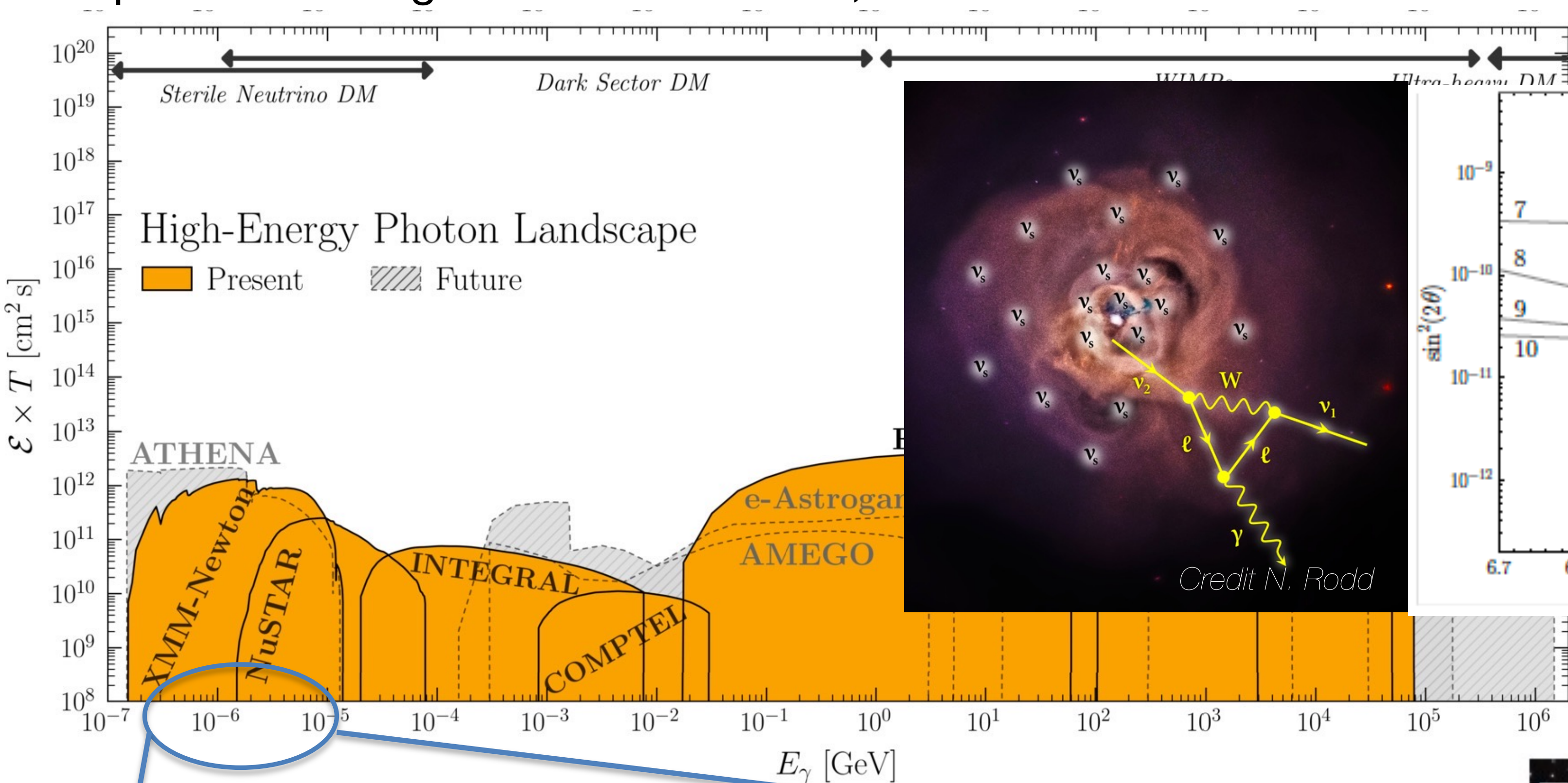
- **At keV–GeV energies, the expected observational progress is more modest at the level of exposure**
  - Important datasets with XMM, INTEGRAL, Fermi-LAT …
- **High Energies: significant improvement within ten years**

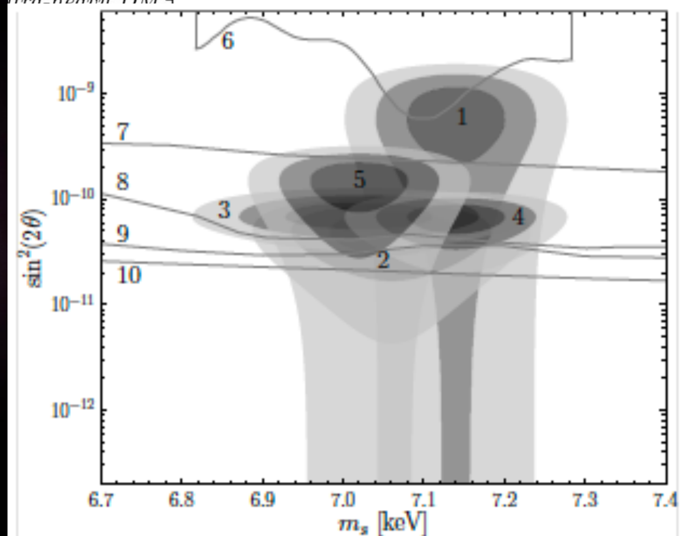
- PeV photons detected by LHASSO
- Also instruments searching for even higher energies, e.g., AUGER

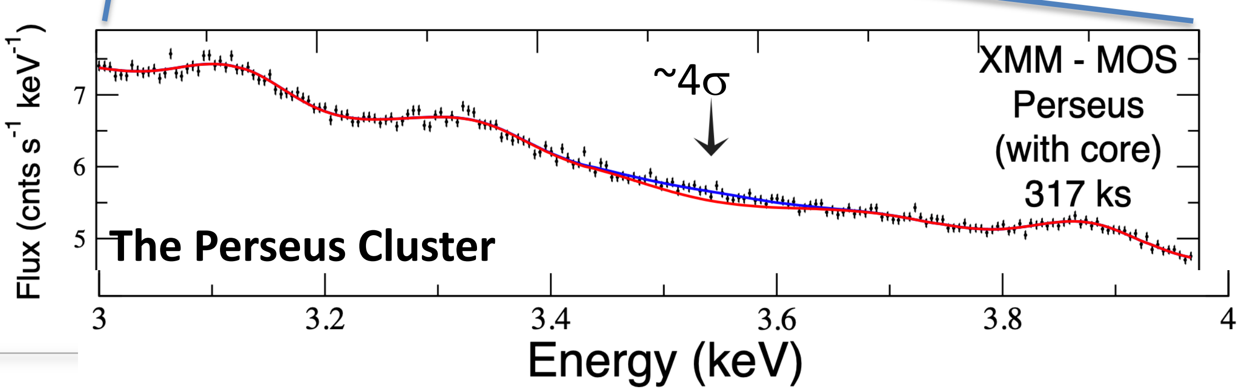
Sterile neutrino and the 3.5 keV line

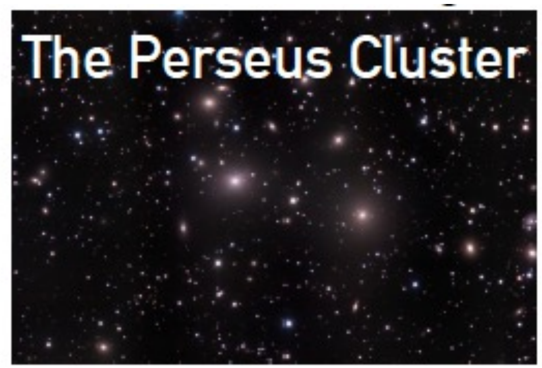
Important existing datasets with XMM, INTEGRAL

Diagram



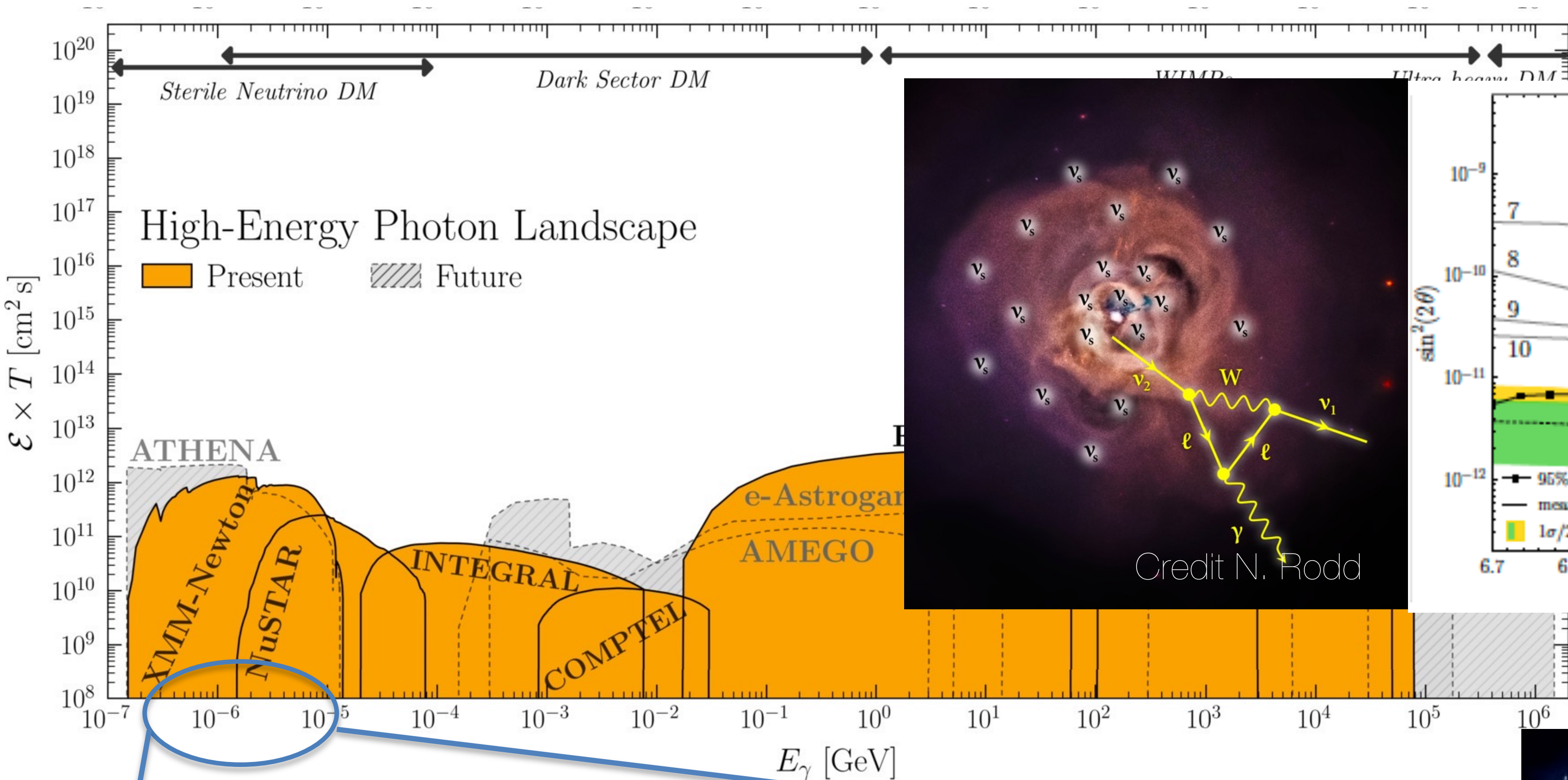


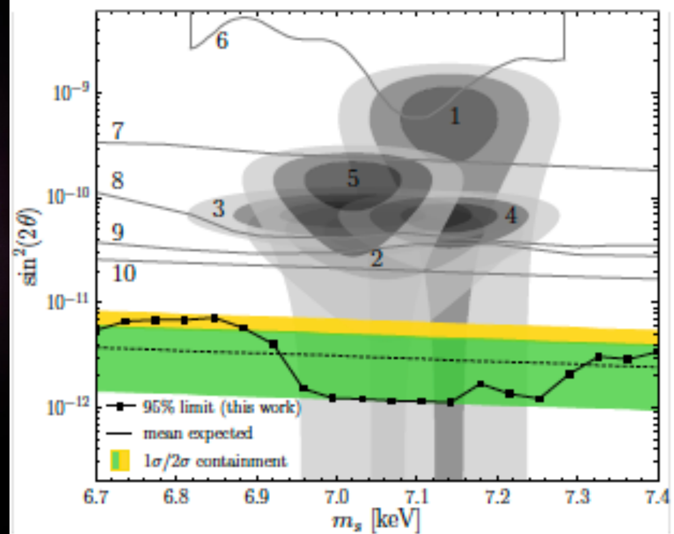


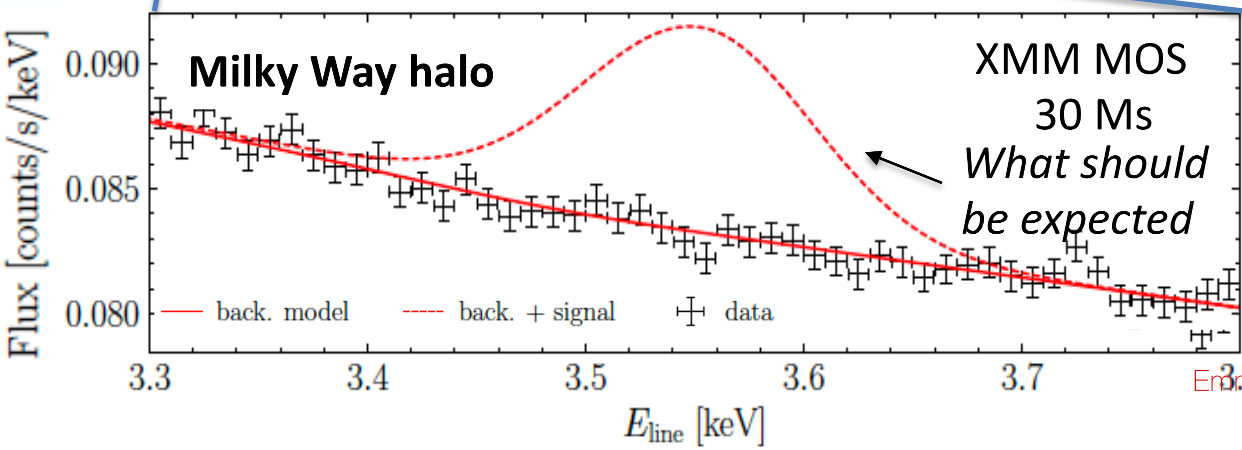


Sterile neutrino and the 3.5 keV line

Diagram







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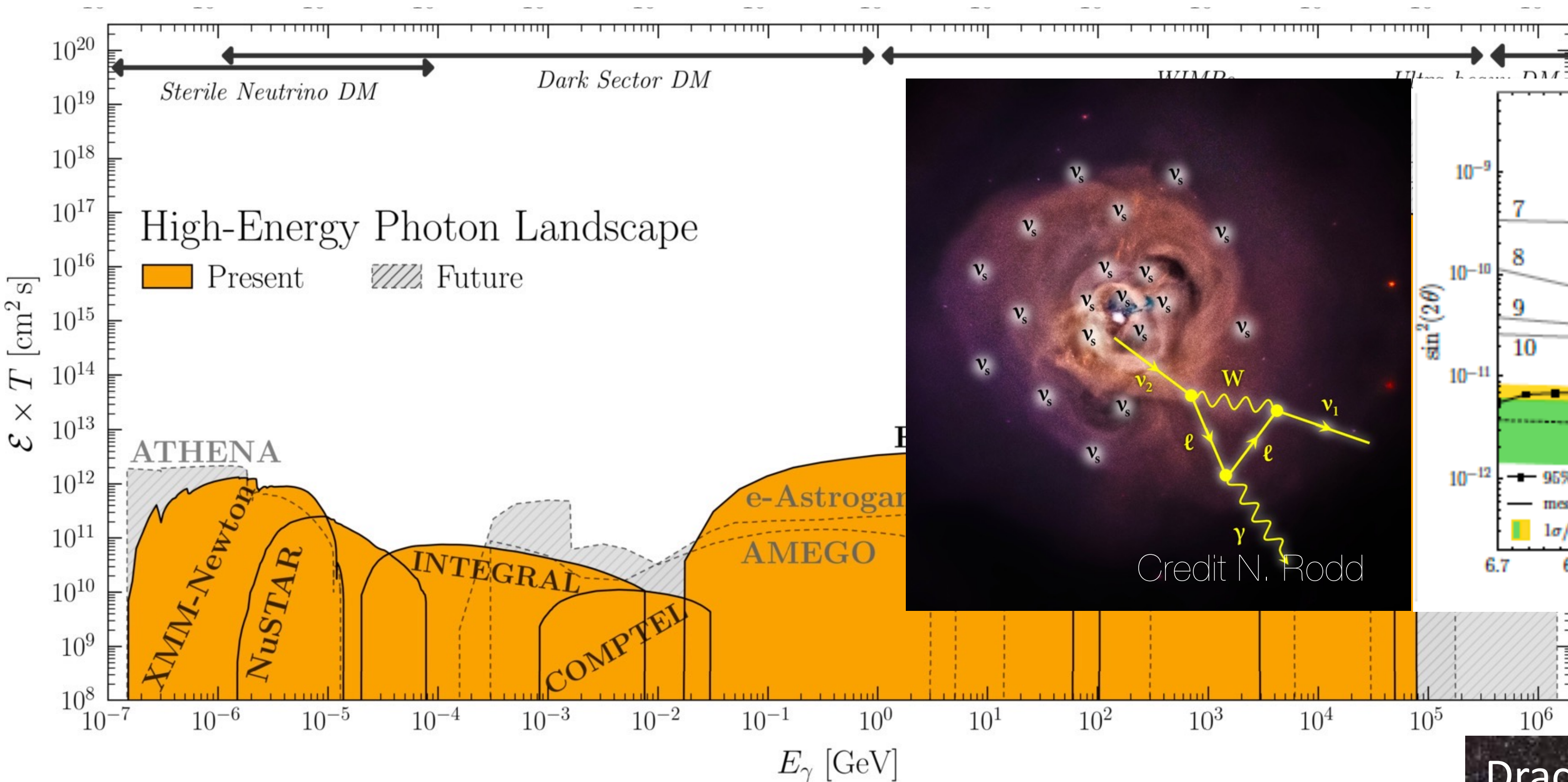
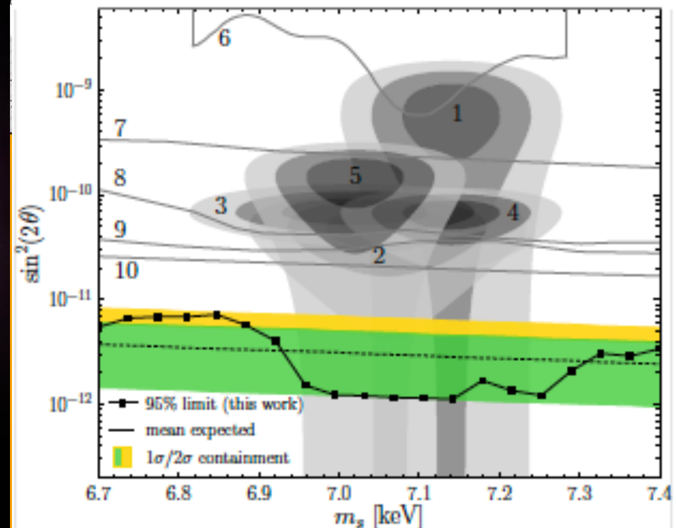


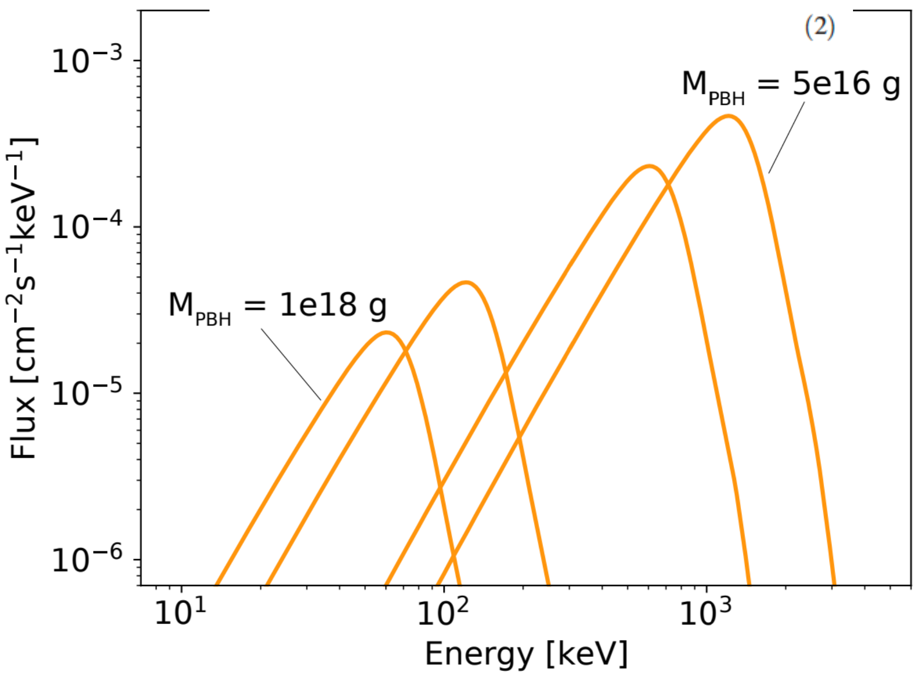


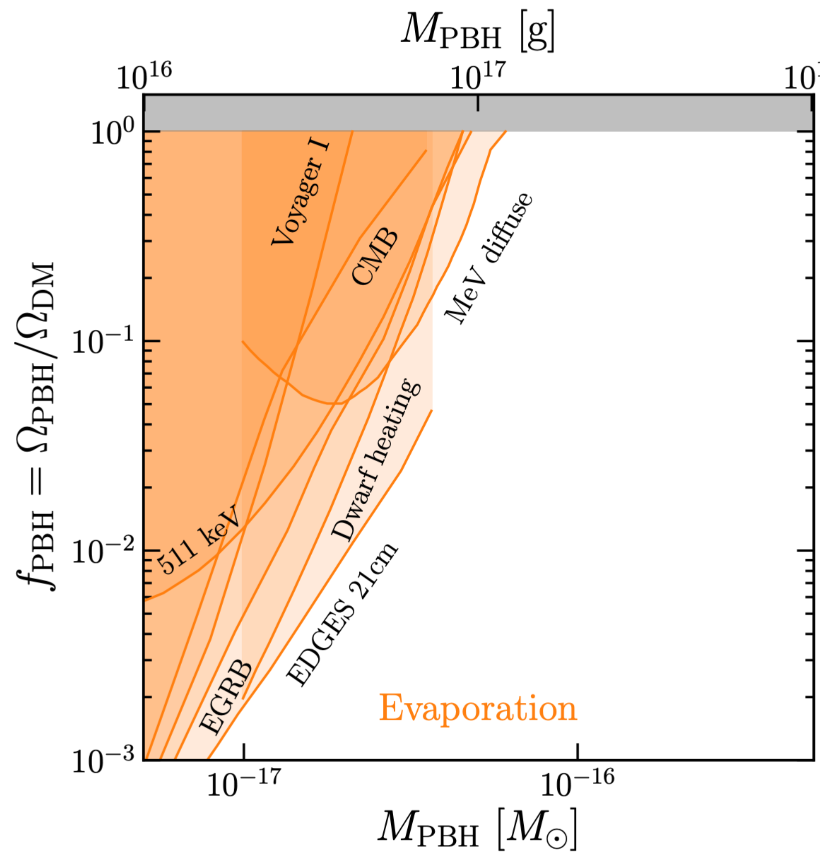
- 1.6 Msec XMM-Newton observations of the dwarf spheroidal galaxy Draco exluded also a 3.5 keV DM line
- Line seen in galaxy clusters plausible from background mismodeling

PBH searches with keV/MeV photons

- Continuum of x-ray / gamma-ray from via Hawking radiation
  → almost-black (grey) body emission

$$\frac{d^2\Phi_\gamma}{dE_\gamma}(\Delta\Omega) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\mathrm{LOS}} ds \frac{f_{\mathrm{pbh}}\rho_{\mathrm{DM}}(r(s,d,\theta))}{M_{\mathrm{pbh}}}\frac{d^2N_\gamma}{dE_\gamma dt}. \quad (2)$$



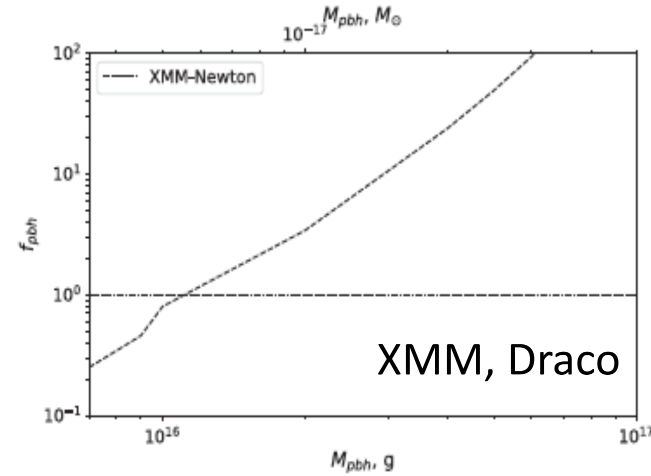


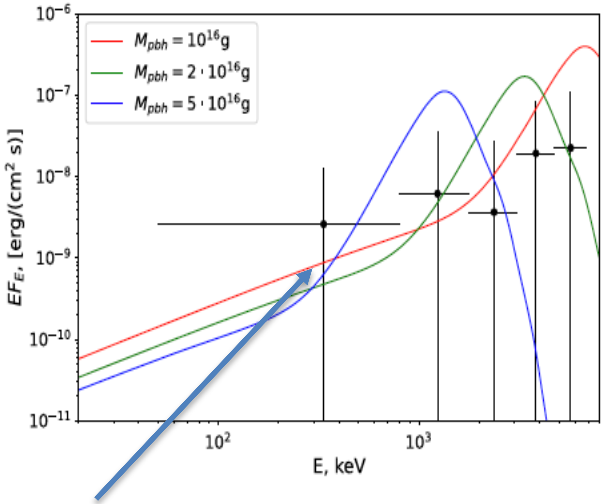
Green and Kavanagh J. Phys. G 48 (2021) 4, 043001

- Unconstrained mass range ~10^{17}-10^{22} g, the so-called asteroid mass gap where f_{PBH} can be 1

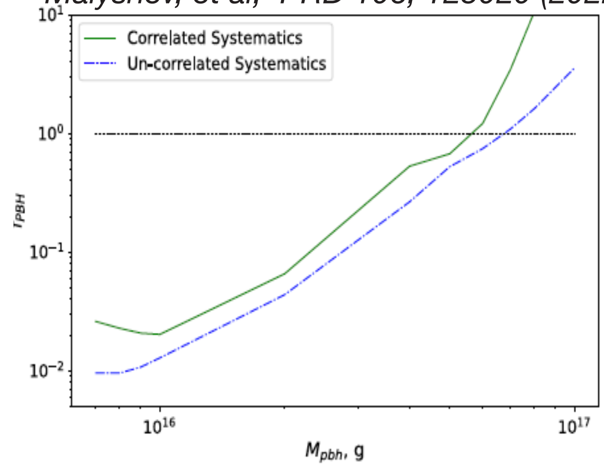
PBH searches with keV/MeV photons

- ~3 Ms XMM observations of Draco
- **MeV Galactic diffuse emission**
  - INTEGRAL SPI observations of the inner Milky Way between 2002/11 and 2021/10



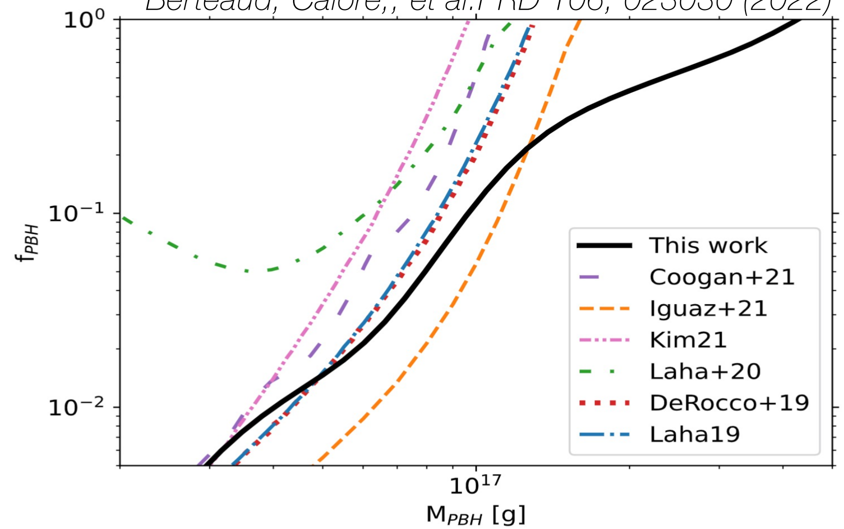


Malyshev, et al, PRD 106, 123020 (2022)



- Backgound template modelling appraoch
  - ICS of electrons off the interstellar radiation field
  - unresolved sources
  - nuclear lines, …

Berteaud, Calore,, et al.PRD 106, 023030 (2022)

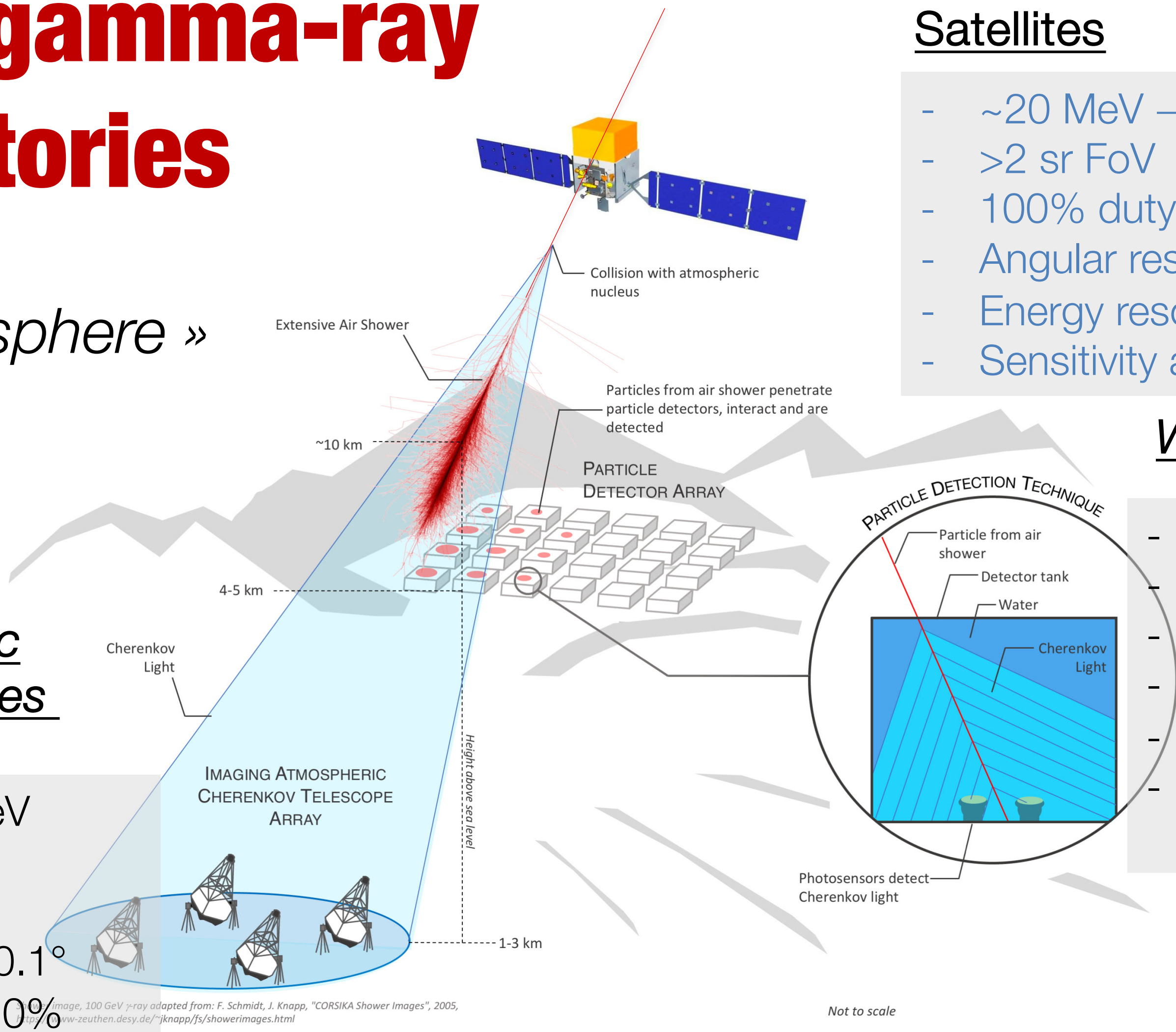


Residual INTERGAL/SPI background from ON/OFF observartion pairing to minimize the effects of the time-dependent background variability

$$\frac{d^2\Phi_\gamma}{dE_\gamma dt} = \frac{f_{\rm pbh}}{4\pi M_{\rm pbh}} \frac{d^2N_\gamma}{dE_\gamma dt} \sum_{\rm i} (D_{\rm ON,i} - \alpha_i D_{\rm OFF,i})$$

HE/VHE gamma-ray observatories

« Blocked by the atmosphere »



Satellites

- ~20 MeV → 300 GeV
- >2 sr FoV
- 100% duty cycle
- Angular resolution 0.15-3.5°
- Energy resolution ~10%
- Sensitivity a few % Crab flux

Water Cherenkov Detectors

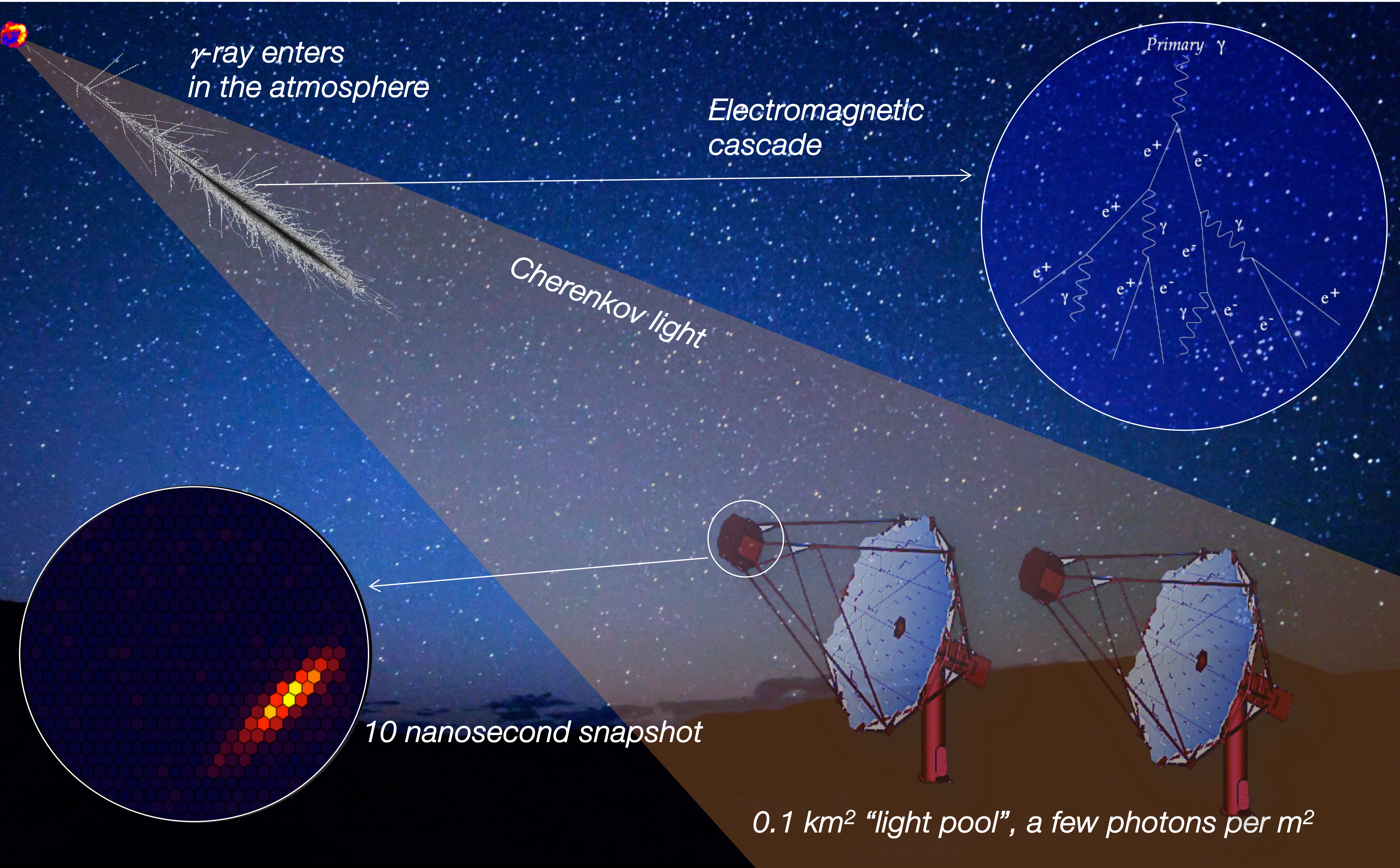
- ~100 GeV → 1 PeV
- 90% duty cycle
- ~sr FoV
- angular resolution 0.2 - 0.8°
- energy resolution ~50%
- sensitivity 5-10% Crab flux

Imaging Atmospheric Cherenkov Telescopes

- ~30 GeV → ~100 TeV
- Small FoV : ~ 5°
- Duty-cycle: 10-15%
- Angular resolution <0.1°
- Energy resolution ~10%
- sensitivity 1% Crab flux

- **IACT can provide detailed morphologies of limited region of the sky**
- **Satellites/WCD are very powerful to scan large regions**

Imaging Atmospheric Cherenkov technique



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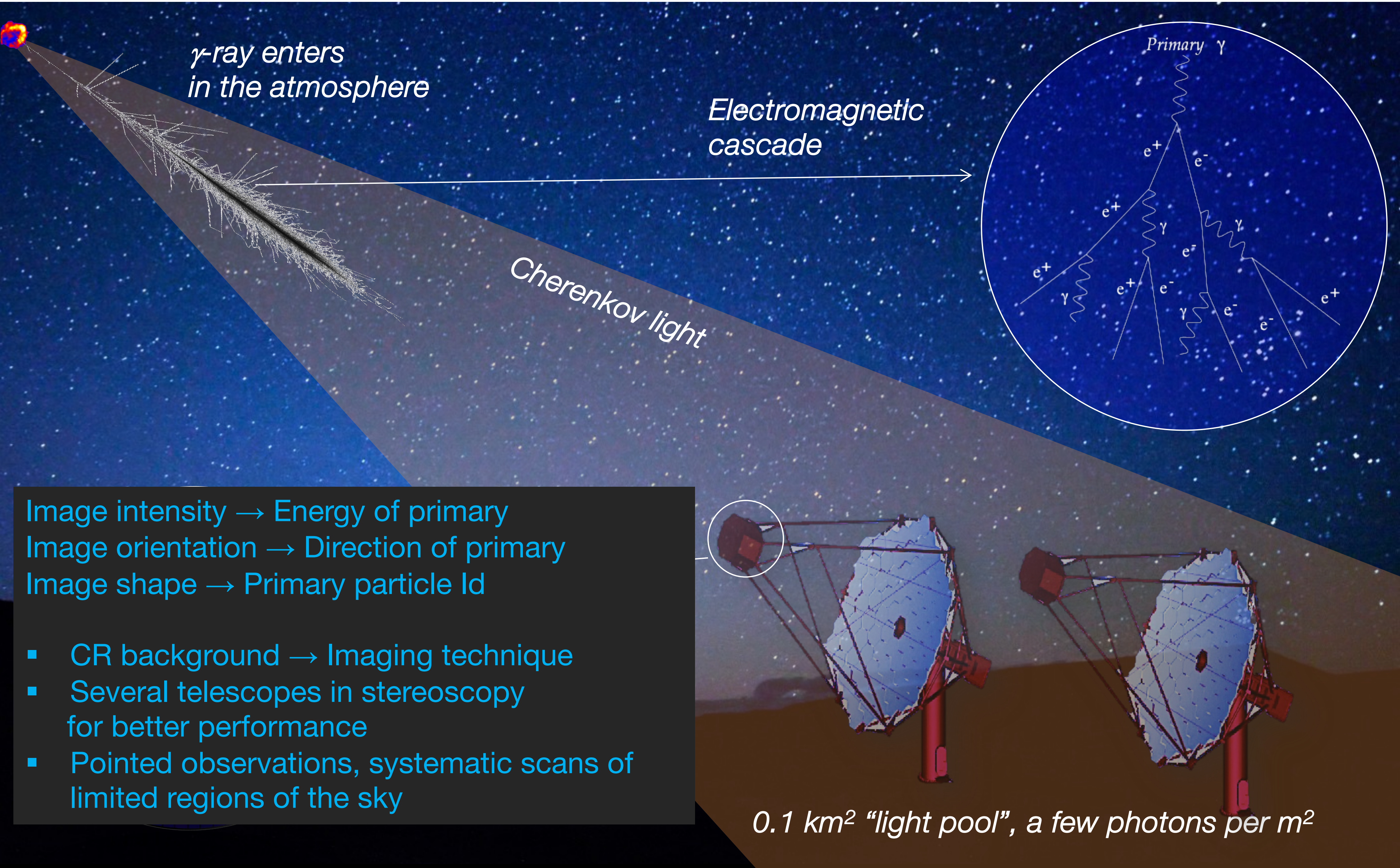
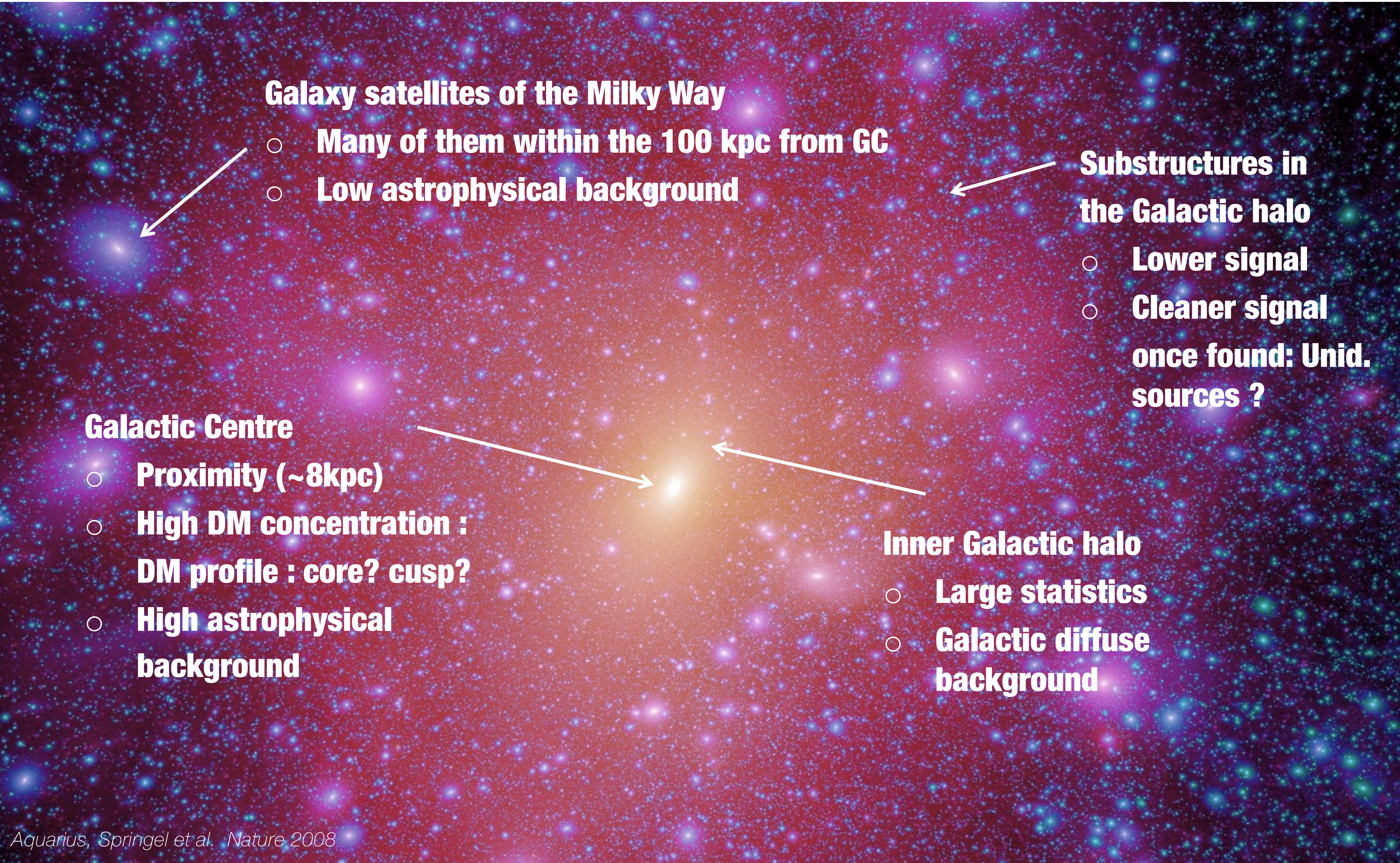


Image intensity → Energy of primary
Image orientation → Direction of primary
Image shape → Primary particle Id

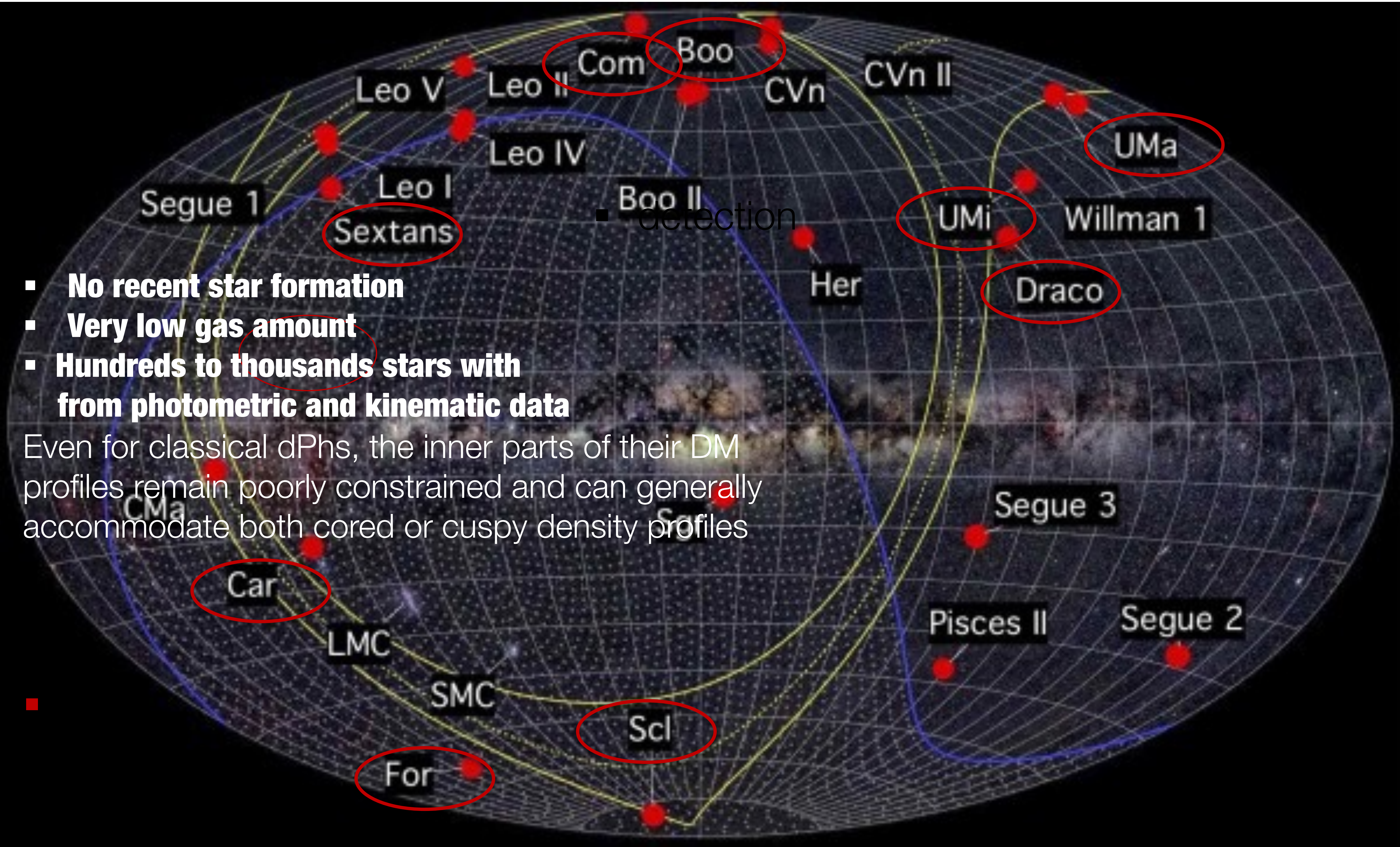
- CR background → Imaging technique
- Several telescopes in stereoscopy for better performance
- Pointed observations, systematic scans of limited regions of the sky

Targets and strategies at galactic scale



Aquarius, Springel et al. Nature 2008

Classical dwarf spheroidal galaxies



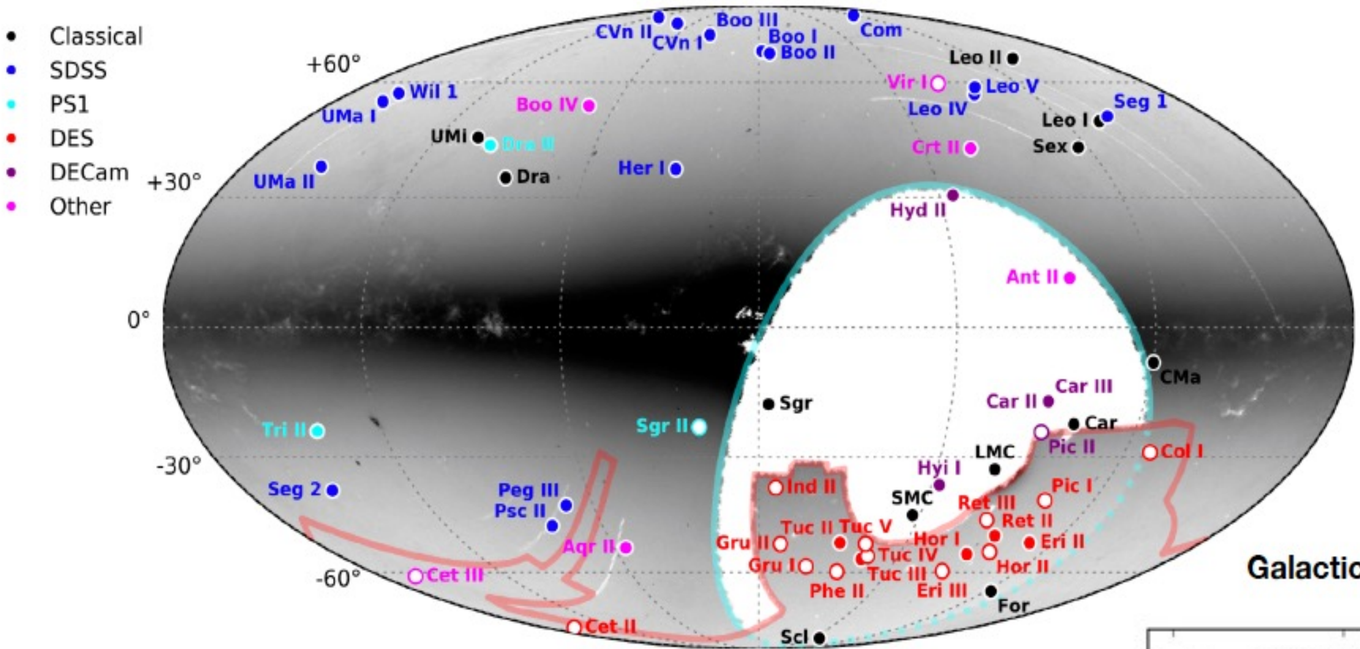
- detection

- **No recent star formation**
- **Very low gas amount**
- **Hundreds to thousands stars with from photometric and kinematic data**

Even for classical dPhs, the inner parts of their DM profiles remain poorly constrained and can generally accommodate both cored or cuspy density profiles

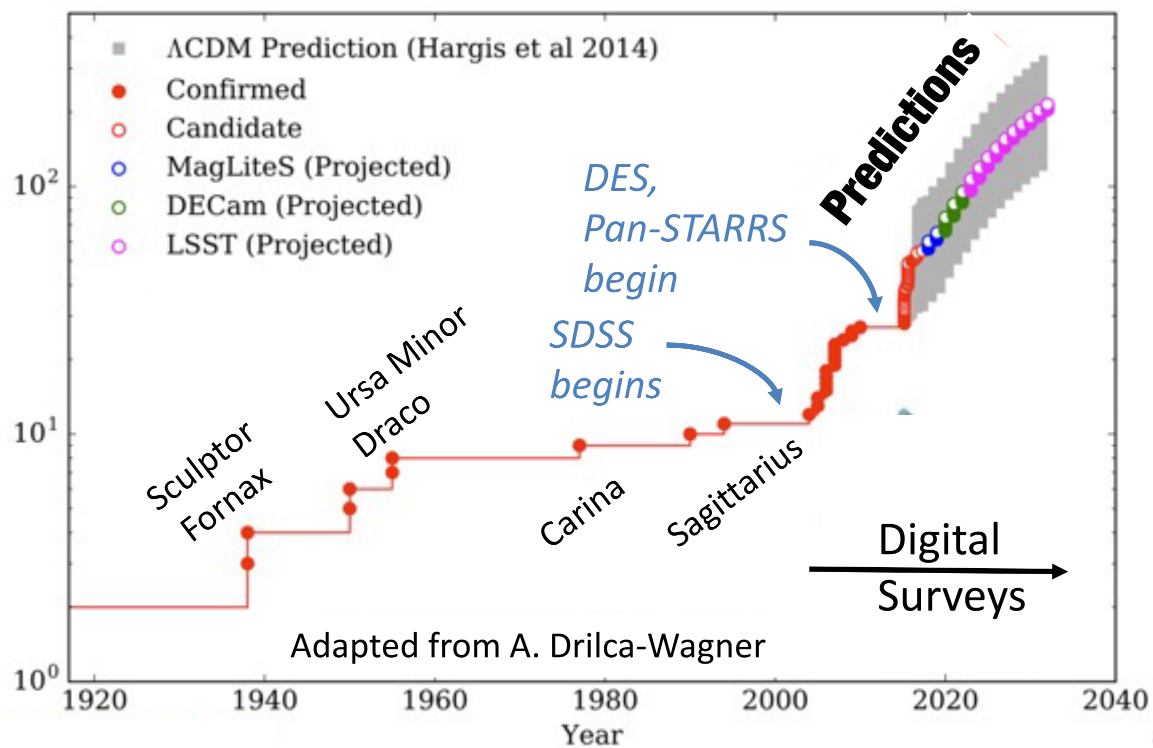
-

A growing number of known targets



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

- More to be discovered in the future thanks to improvements in telescope technologies and performances, e.g., the ''Vera C. Rubin'' Observatory



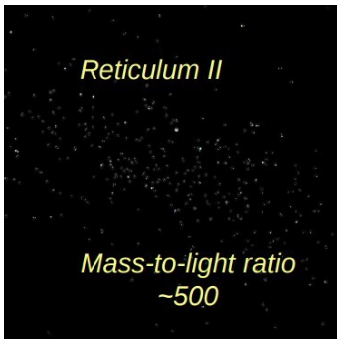
Dark Matter profiles in dSphs

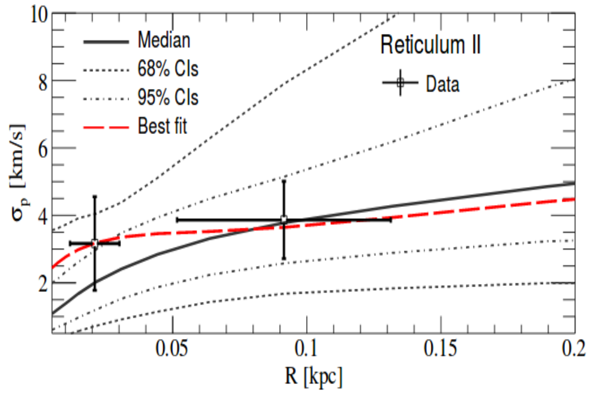
- **Modelling of the DM distribution**
  - Pressure-supported systems
  - Stars of kinematic tracers of the gravitational potential

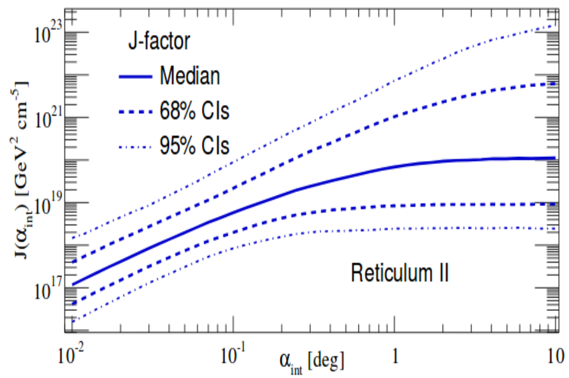
Jeans equation assuming equilibrium, non-rotating (and spherical) system

- Even for classical dPhs, the inner parts of their DM profiles remain poorly constrained and can generally accommodate both cored or cuspy density profiles

- The example for the ultra-faint dwarf spheroidal galaxy Reticulum II:



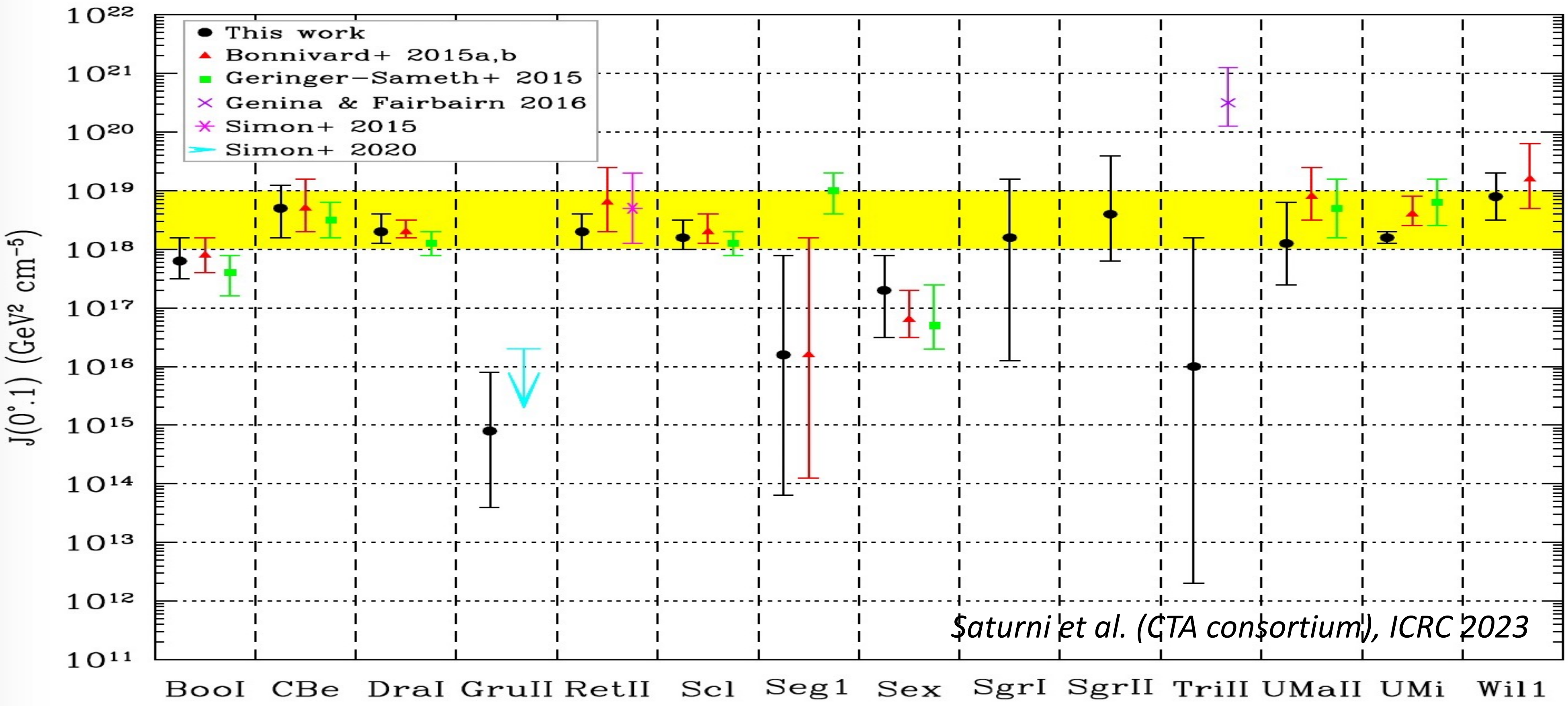




<u>Disclaimer </u>: Impact of triaxiality on halos, stellar membership probability, binary stars, tidal disruption, …

Comparison of J-factors

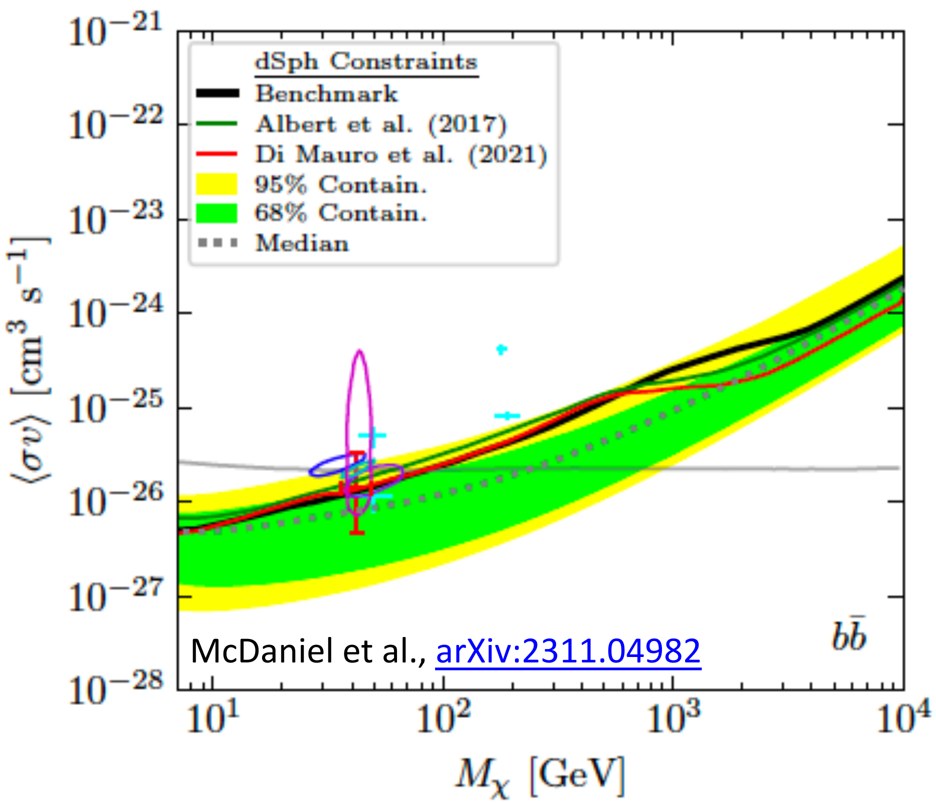
$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{\rm los} \rho^2(r(s,\theta)) {\rm d}s{\rm d}\Omega.$$



- Expected spread due to assumptions and/or choices on kinematic datasets, light and DM profiles, velocity anisotropy, stellar membership probability, triaxiality odf the halo, …

Constraints from dwarf galaxies

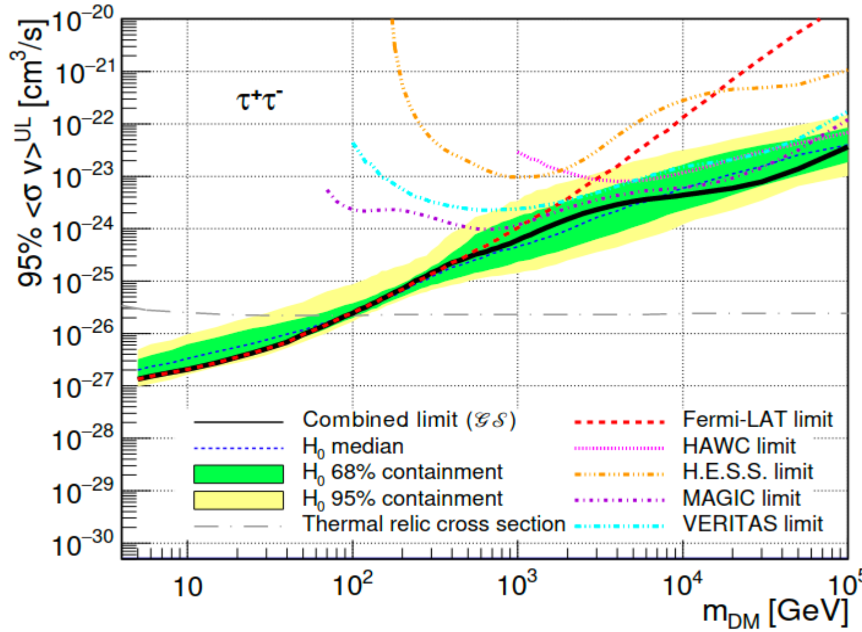
- **Fermi-LAT contraints**
  14-year dataset



- Thermal-relic annihilation cross section probed for masses up to 100 GeV

- **Joint effort to combine observations**

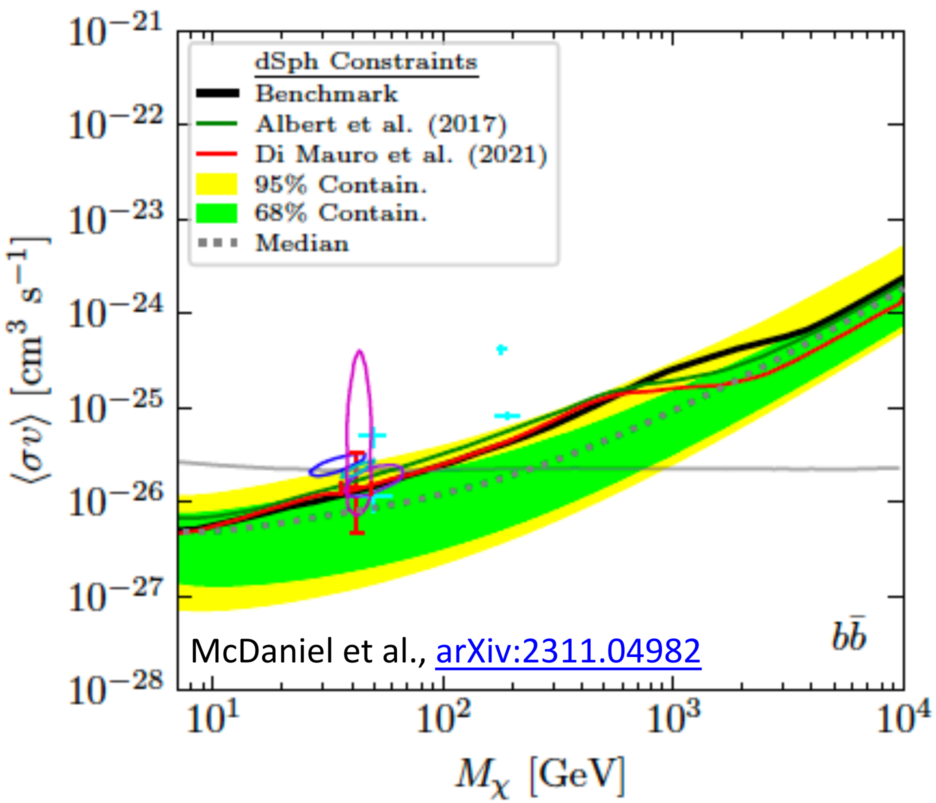
- This analysis framework allows us to perform multi-instrument and multi-target analysis
- Common elements :
  - Agreed model parameters
  - Sharable likelihood table formats
  - Joint likelihood test statistic



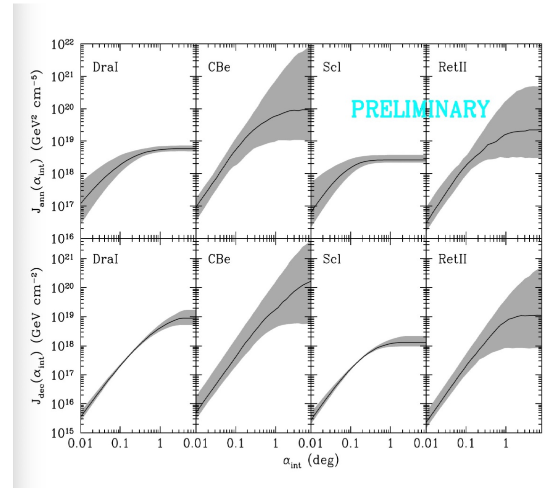
Kerszberg et al. ICRC 2023

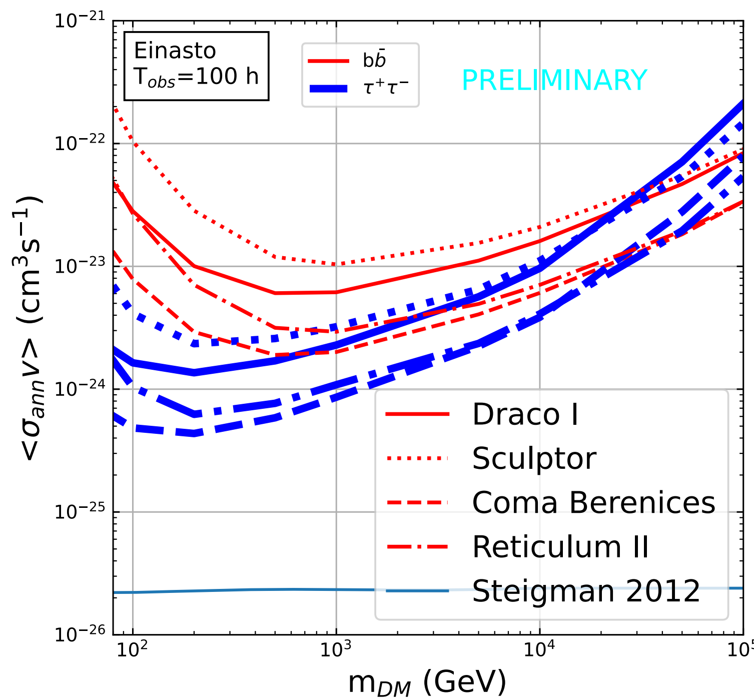
Constraints from dwarf galaxies and prospects

- **Fermi-LAT contraints 14-year dataset**



- **CTA sensitivity forecast**
  - selection according to:
    1. Distance(d<100pc)
    2. Culmination zenith angle (ZAmin < 30°)
  - 100h observations for each dSph assumed





Saturni et al. (CTA consortium), ICRC 2023

- For realistic observations time, CTA can reach cross sections of ~10^{-24} cm^{3}s^{-1} for masses above 1 TeV

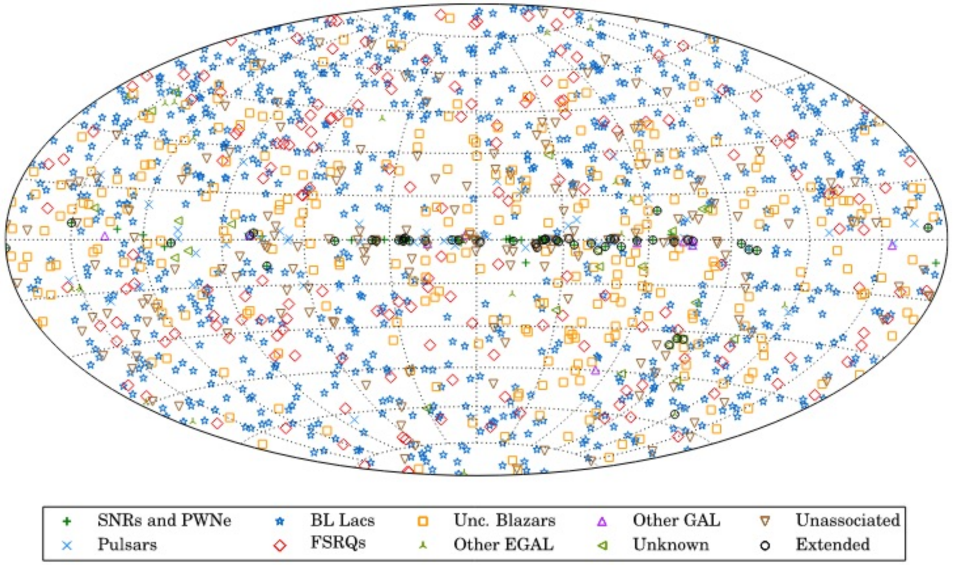
Dark matter substructures in Galactic halos ?

- **Dark Matter Subhalos**

1. **Assuming subhalos composed by WIMPs**
   → could shine in gamma-rays

2. **Fermi-LAT revealed a population of sources that lack association at other wavelenghts;**
   → these sources are classified as Unassociated
   → careful selection can tell us what the promosing DM subhalo candidates

- Lower signal than the GC region
- No other wavelengths counterpart
- No astrophyiscal background
- Location : selection through the catalog of (Hard) Fermi-LAT sources ?



Ajello et al., Astrophys. J. Suppl. 2017, 232, 18

200 unassociated over
1556 sources in the Fermi-LAT catalogue

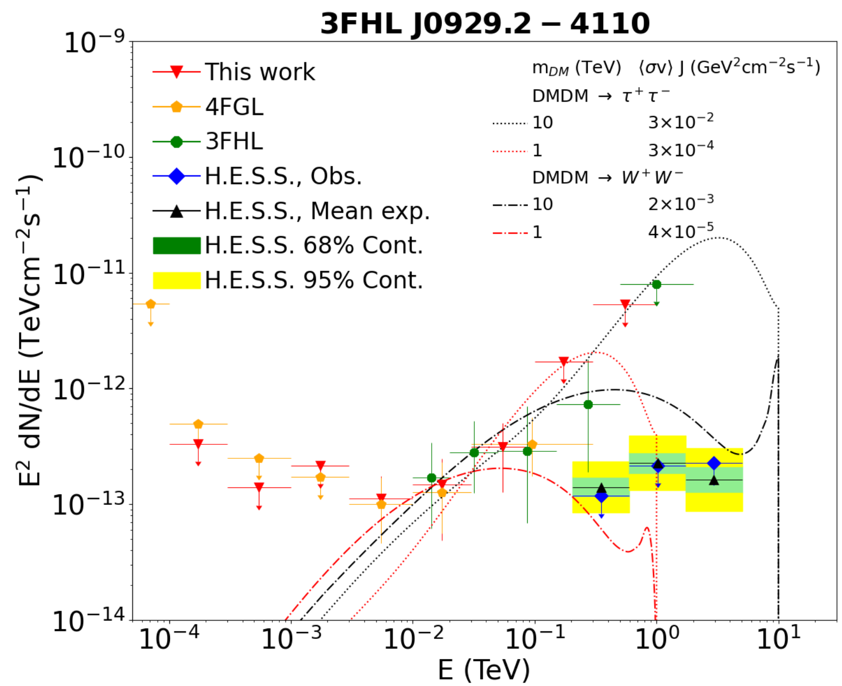
Dark matter substructures in Galactic halos ?

- **Dark Matter Subhalos**

1. **Assuming subhalos composed by WIMPs**
   → could shine in gamma-rays

2. **Fermi-LAT revealed a population of sources that lack association at other wavelenghts;**
   → these sources are classified as Unassociated
   → careful selection can tell us what the promosing DM subhalo candidates

- **Selection of the unassociated sources in the Third catalog of Hard Fermi-LAT sources (3FHL) to obtain the most promising UFOs for H.E.S.S. observations**



H.E.S.S. Coll. Astrophys.J., 918, 17 (2021)

Dark matter substructures in Galactic halos ?

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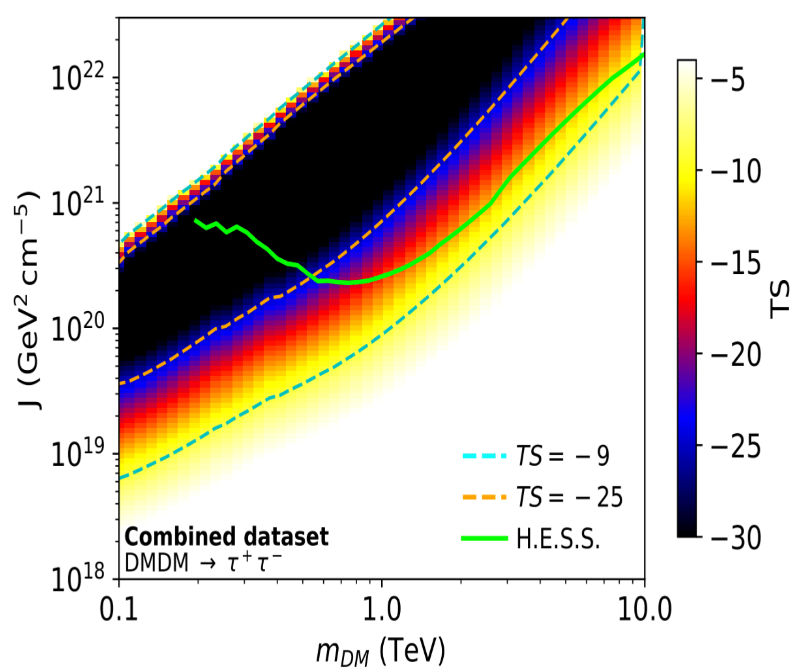
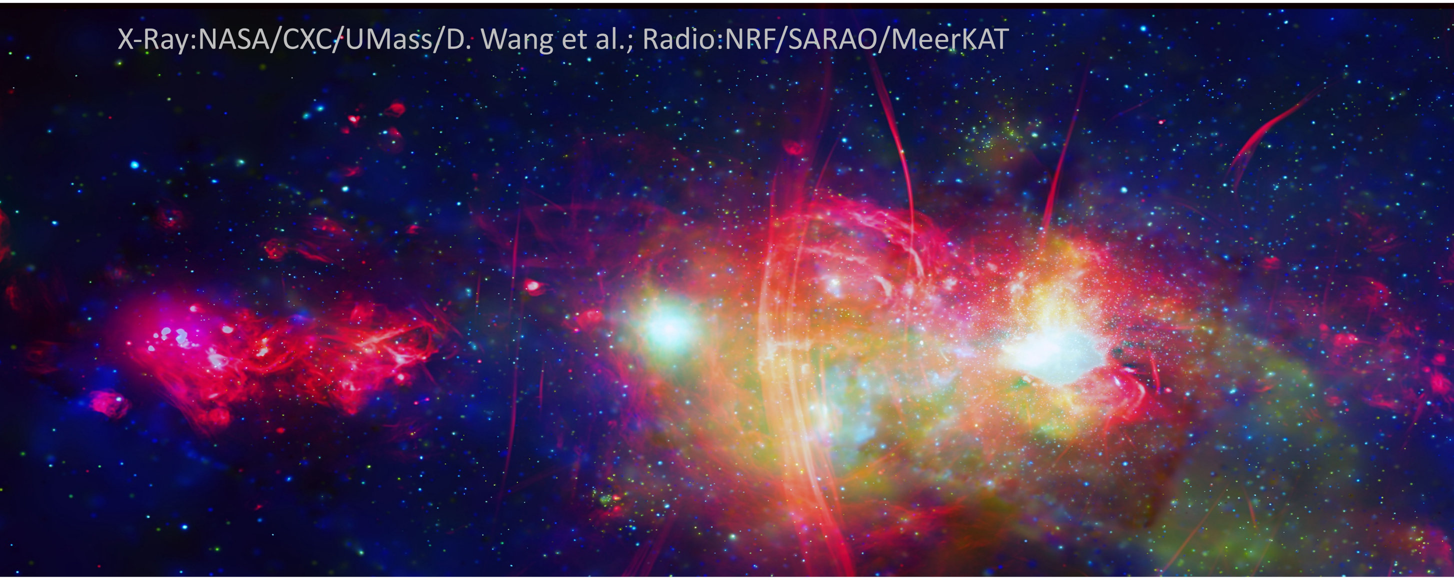
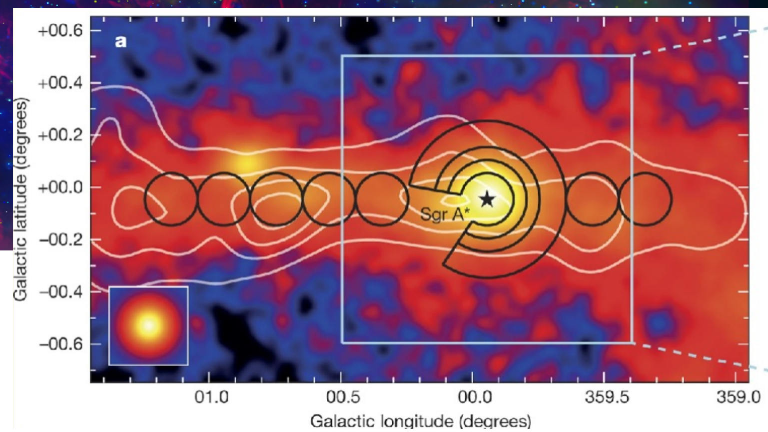


H.E.S.S. Coll. Astrophys.J., 918, 17 (2021)

Assuming thermally-produced WIMPs: → UFOs very unlikely DM subhalos

The Galactic Center

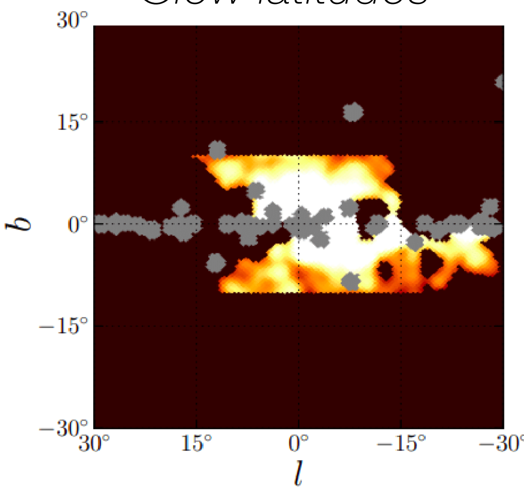




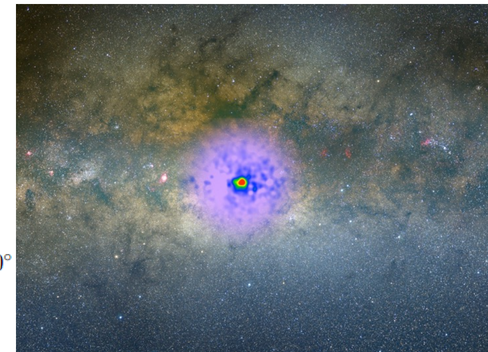
- A complex region at VHE: base of Fermi Bubbles, an hypothetical population of millisecond pulsars, …
  with extended structures beyond single fov and/or source confusion

- Expected to be the brightest sources of DM annihilations !

Fermi bubbles.
@low latitudes



The Galactic Centre Excess seen by Fermi-LAT



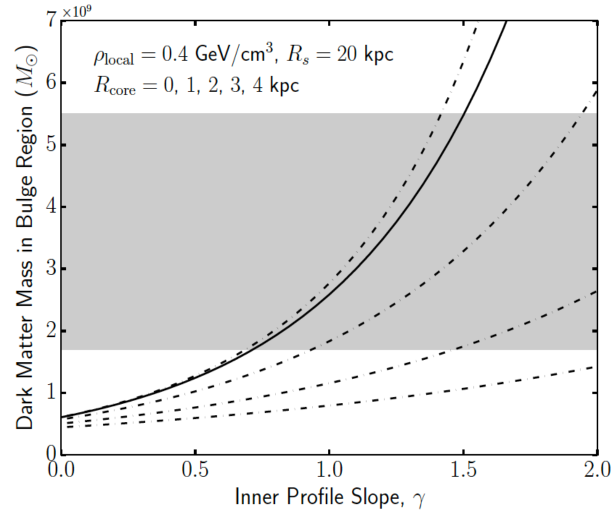
Dark Matter distribution in the inner Milky Way

- **Mass modelling using kinematic tracers (stars, gas, …)**
  - careful modeling of the baryonic component and has associated systematic uncertainties

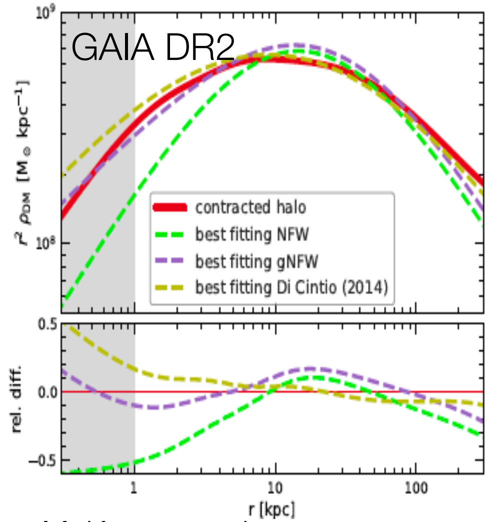
- **Hydrodynamical N-body simulations:**
  - Physics of baryons plays a crucial role at small scales
  - Baryonic feedback on the DM halo
    → large uncertainties
  - the resolution limit of simulations becomes also relevant

- DM distribution not firmly predicted from simulations nor constrained by observations

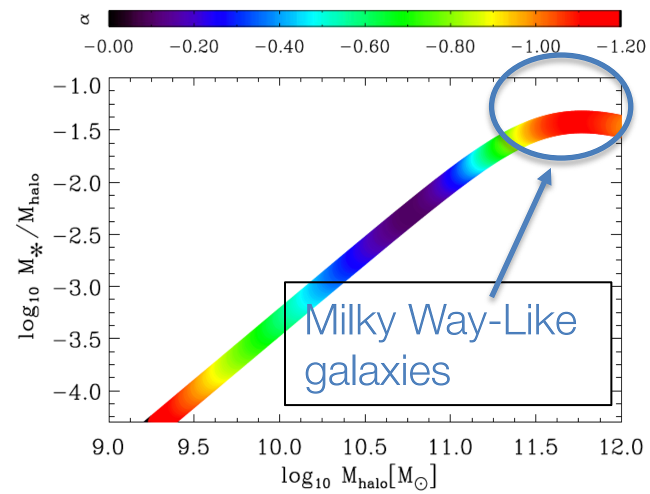
Portail et al. MNRAS 448, 713 (2015)



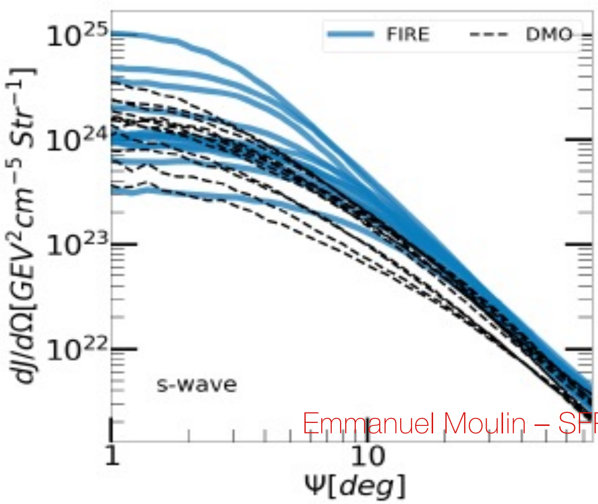
Cautun et al. MNRAS 494, 4291 (2020)



Di Cintio et al., MNRAS 437, 415 (2014)

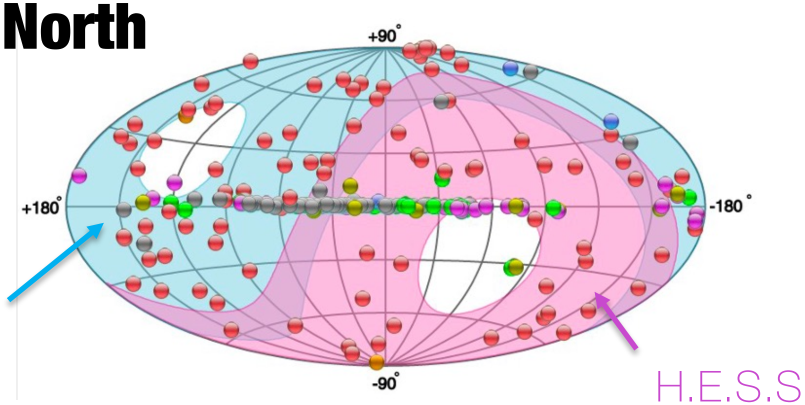


McKeown et al. MNRAS 513, 55 (2022)

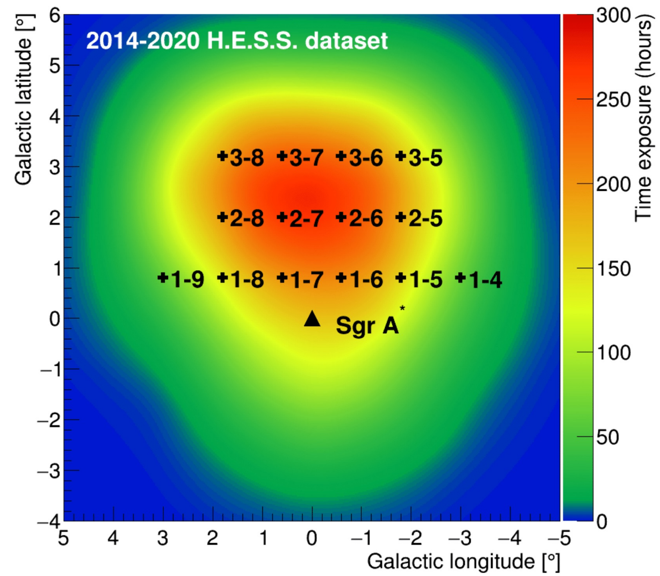


Galactic Centre observations by IACTs

- **Visibility from North and South Hemisphere**



Deep survey of the inner Galaxy going on with H.E.S.S.
- Negative latitude scan started

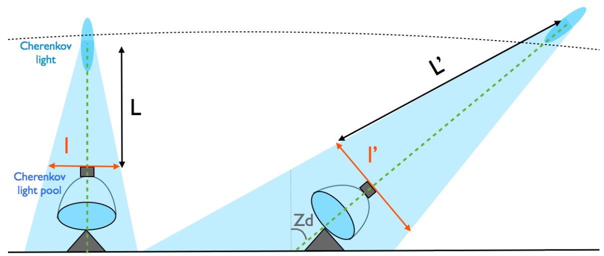


H.E.S.S. coll., Phys. Rev. Lett. 129, 111101 (2022)

- **O(100) hour datasets are being taken**

Searches currently still statistically dominated
→ continued benefit from more observations
e.g., *Montanari, EM, Rodd, PRD107, 043038 (2023)*

- **GC region can be observed by MAGIC, VERITAS, HAWC at high zenith angles**

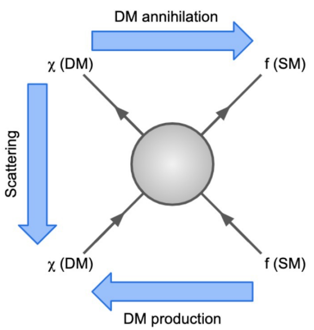


Credit. S. Abe

- a raise in the energy threshold
- effective area at higher energies increased up to an order of magnitude compared to low zenith angles
- Higher systematic uncertainties expected

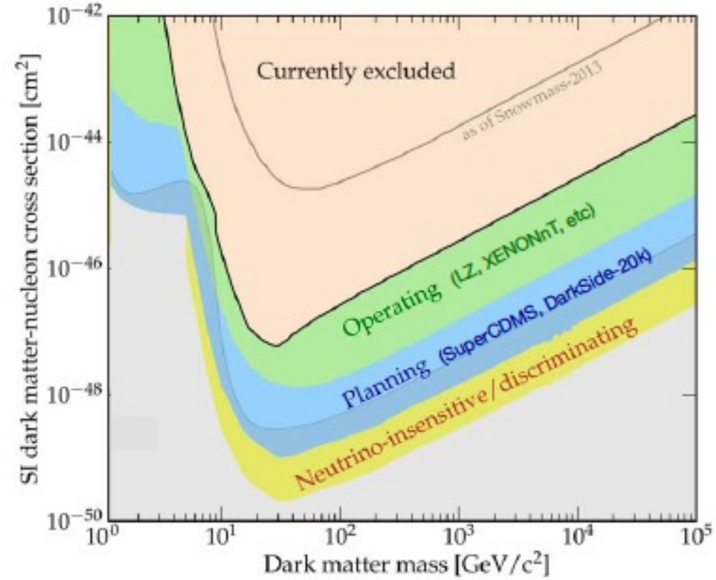
WIMP status

1 GeV – 100 TeV, electroweak couplings with SM



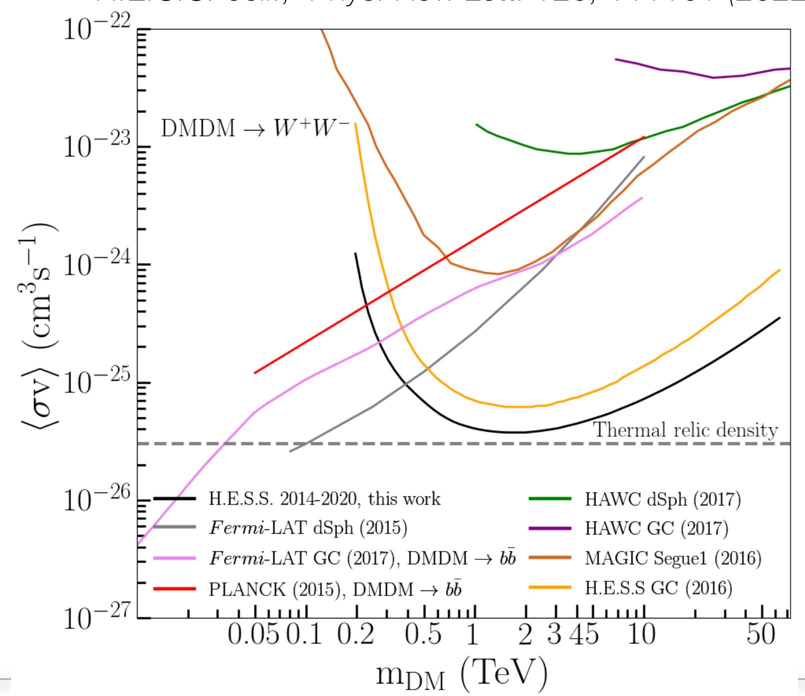
- **No detection (yet) of new weak-scale physics at the LHC**
- **No detection (yet) of WIMPs in direct dark matter searches**

2021 Snowmass Community Study
Chapter 5: Cosmic Frontier



- Strong constraints from direct searches probing cross sections as small as 10^{-47} cm^2 @ 30 GeV

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



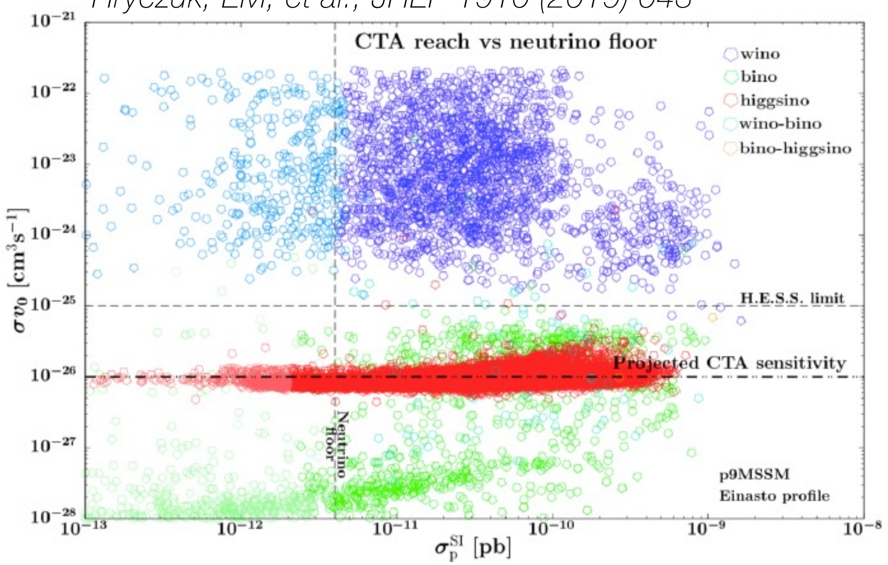
- Strong constraints from VHE gamma rays probing thermal relic TeV DM

- **Some of the simplest thermal WIMP scenarios, e.g., pure higgsinos and winos produce the measured DM abundance not yet detected**

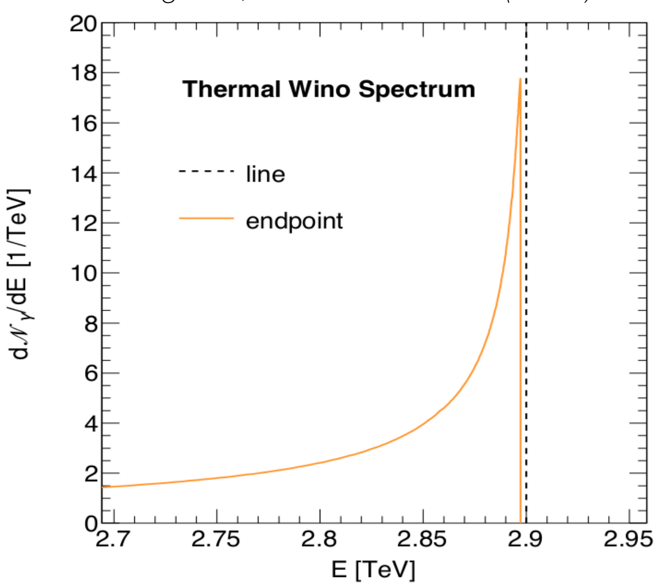
TeV DM models : Wino and Higgsino

- **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**

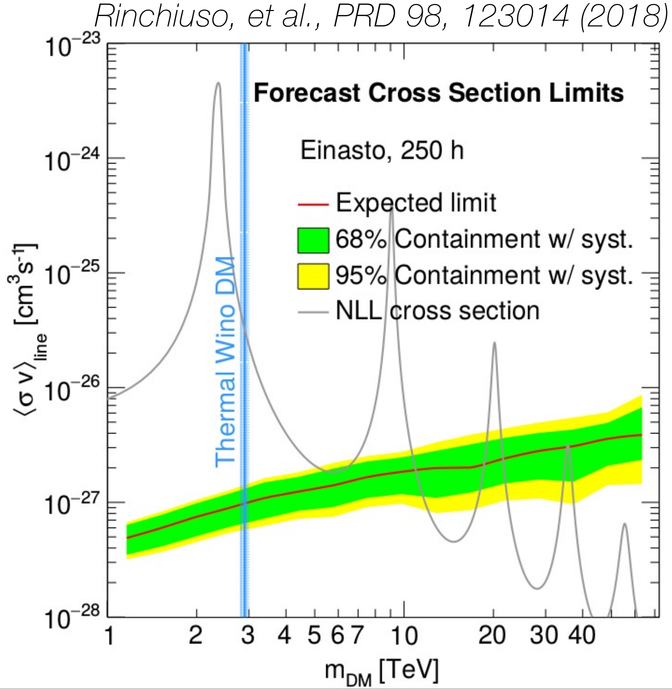
Hryczuk, EM, et al., JHEP 1910 (2019) 043



Baumgmart, et al. JHEP 1901 (2019) 036



Rinchiuso, et al., PRD 98, 123014 (2018)



- Sensitivity to Thermal Wino dark matter
  → DM cores up to several kpc can be probed
  e.g, Rinchiuso et al., PRD 98, 123014 (2018)

TeV DM models : Wino and Higgsino

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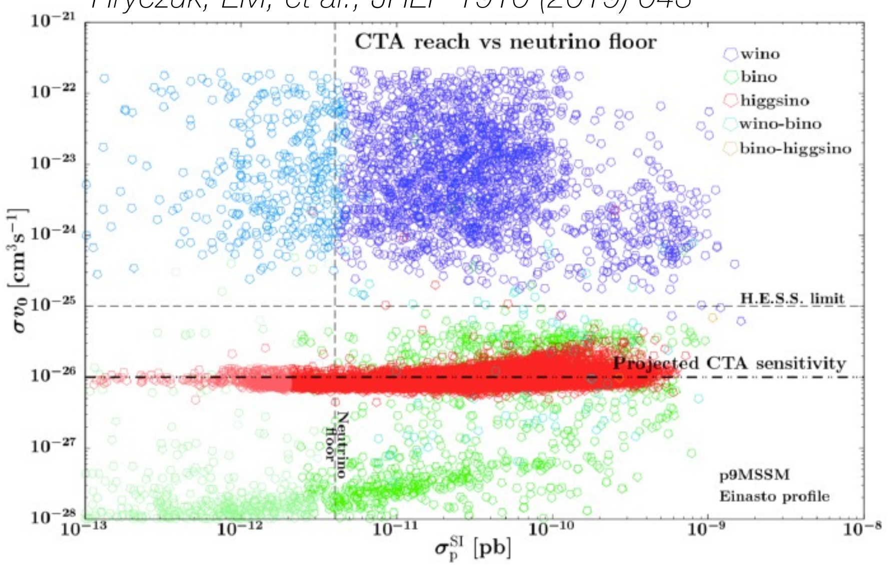

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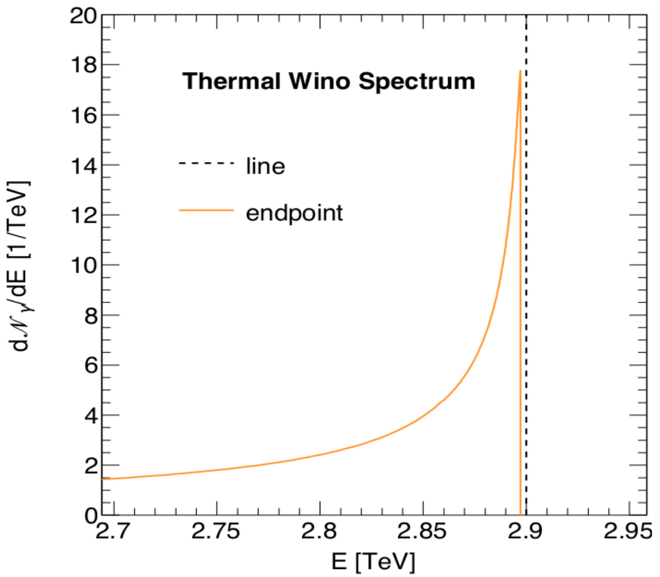
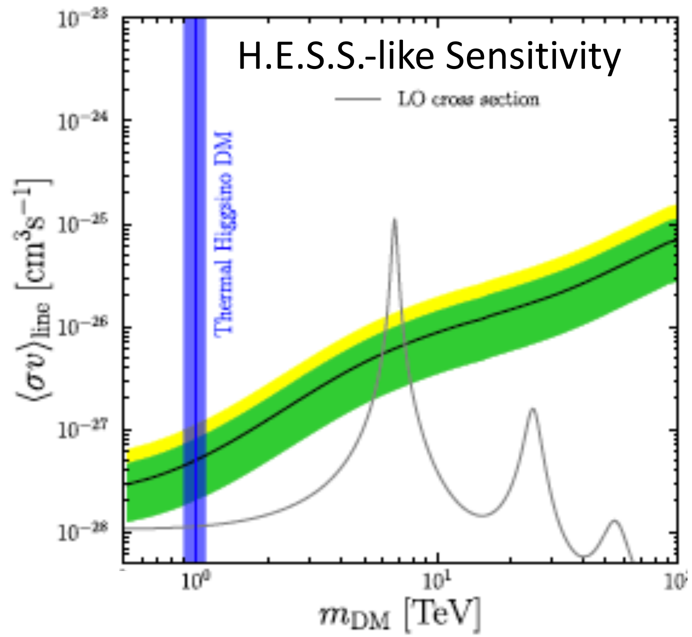




Montanari, et al., PRD107, 043038 (2023)

Strong constraints on Thermal Wino dark matter

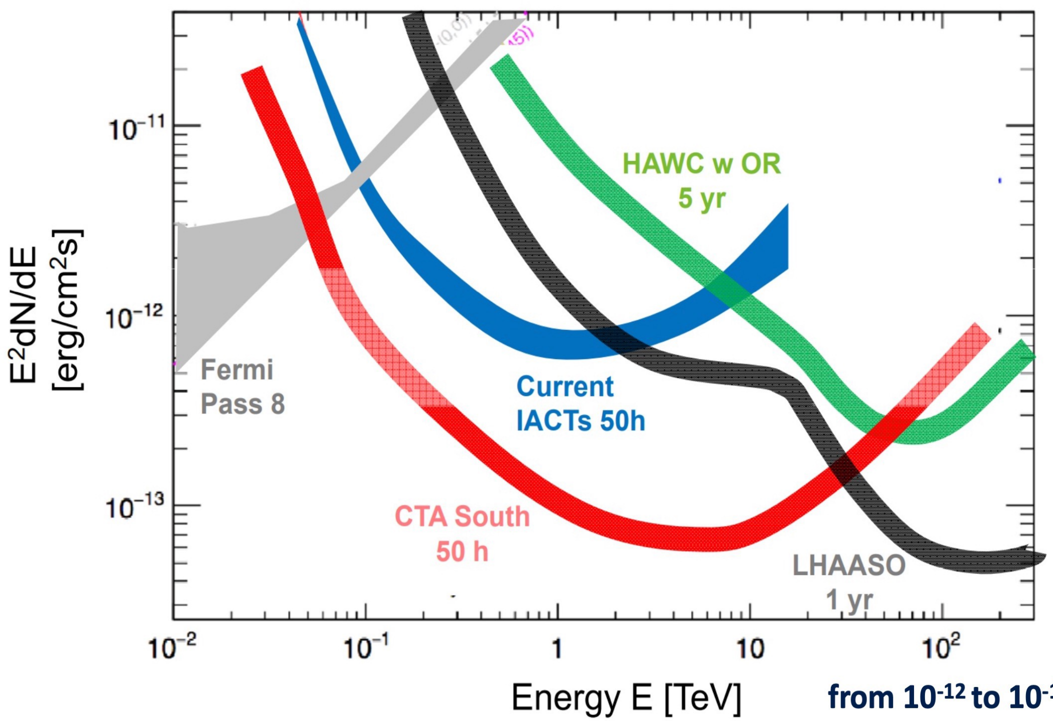
- DM cores up to several kpc excluded at ~2 TeV

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

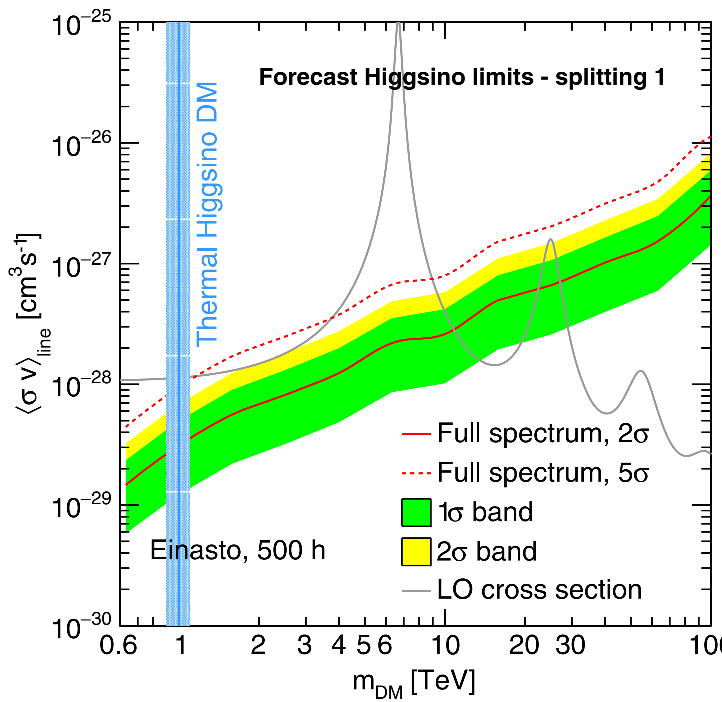
Wino and Higgsino : prospects with CTA

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

- **Higgsino sentivity forecast with CTA**



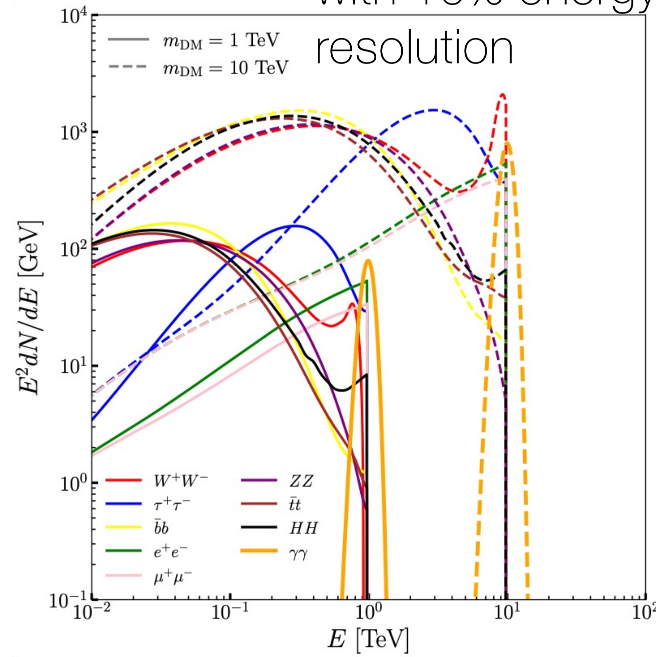
from 10^{-12} to 10^{-13} erg/cm^{2}s



Rinchiuso et al., Phys.Rev. D. 103, 023011 (2021)

Dark matter line searches

Line spectrum with 10% energy resolution



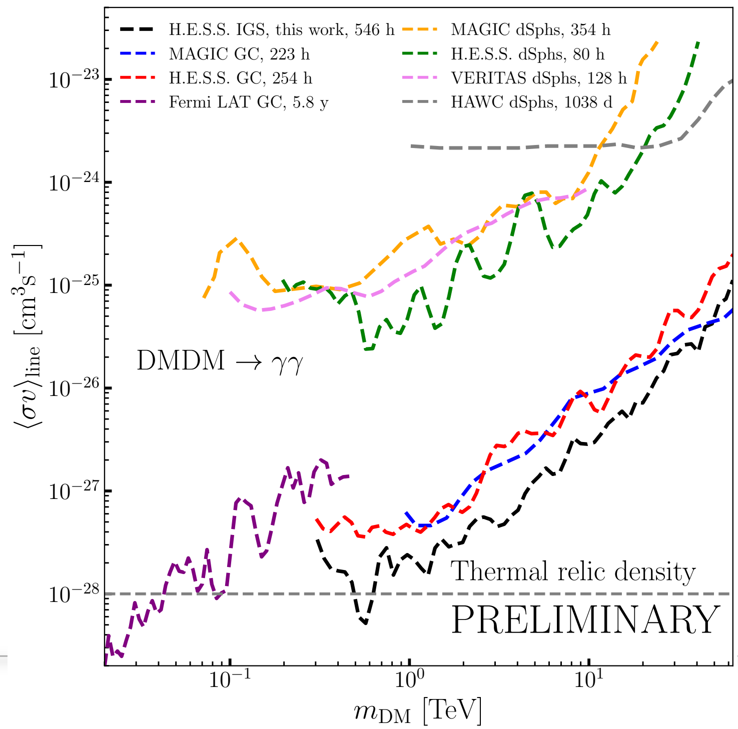
- Gamma-ray line signal from χχ→γγ or χχ→γZ is a very "clean" possible annihilation channel
- No astrophysical lines expected.

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

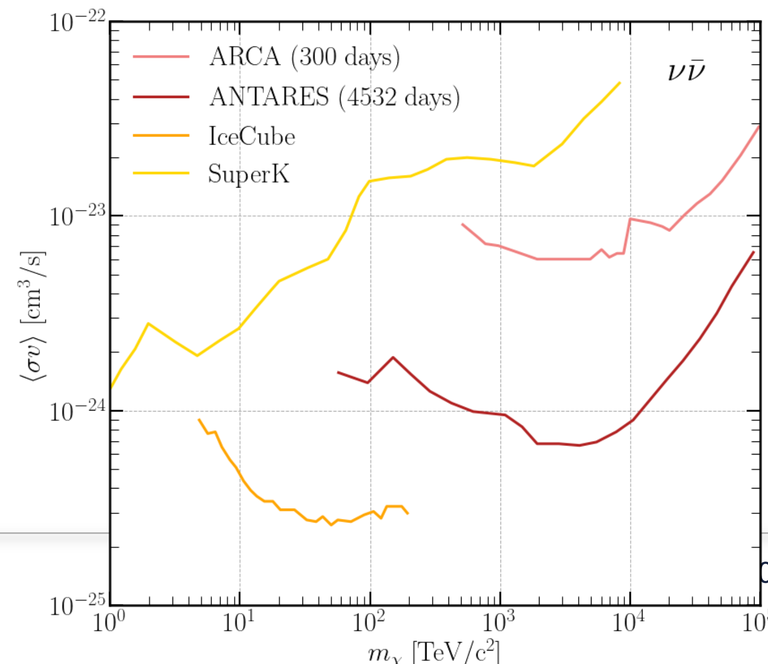
Stringent constraints :

- **from Fermi-LAT at sub-TeV**
- **IACTs at > TeV**

EM et al: (H.E.SS.S.. coll), ICRC2023



Neutrino line in the Galactic Center



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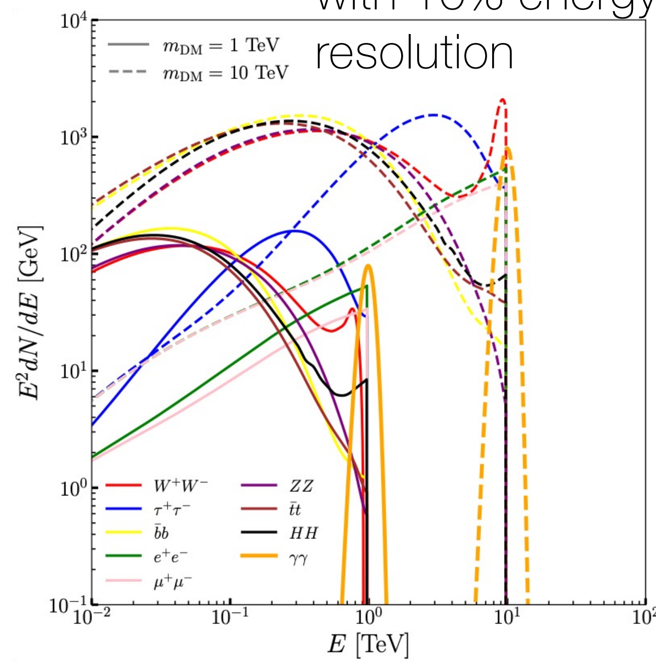
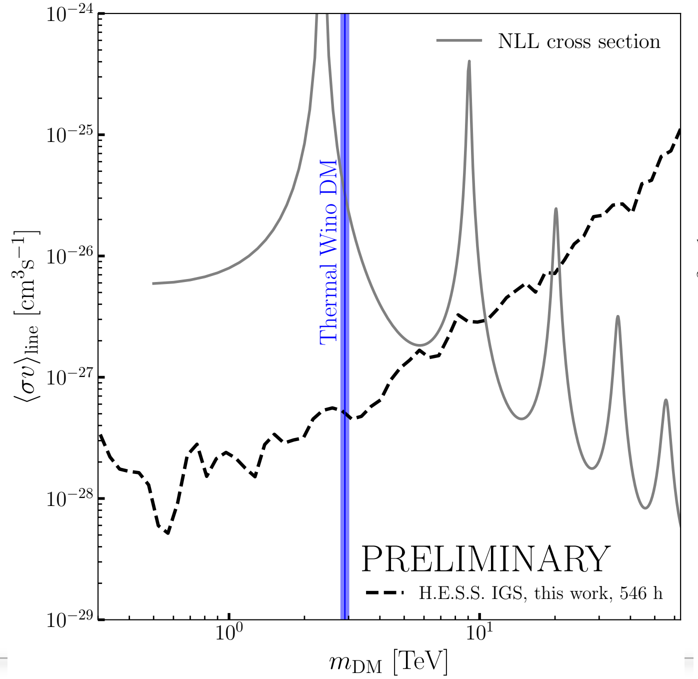
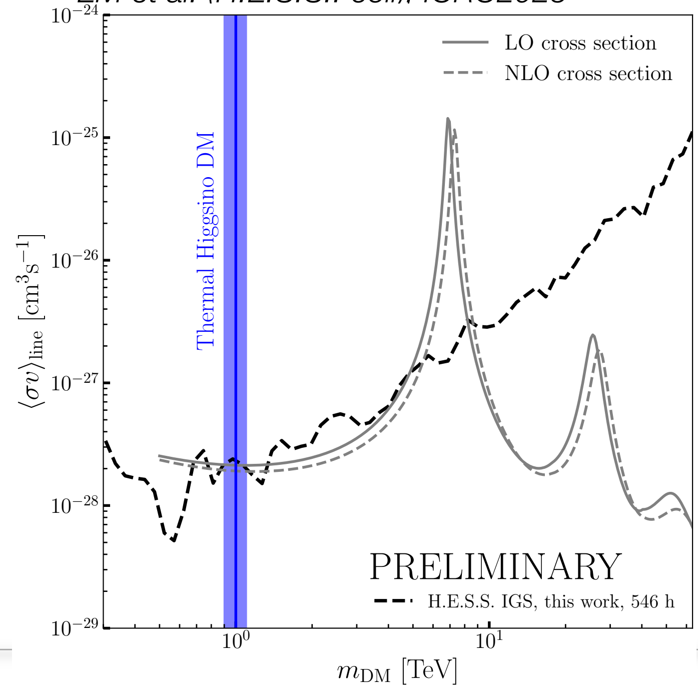


H.E.S.S. constraints on Wino and Higgsino



EM et al. (H.E.S.S.. coll), ICRC2023



Probing the thermal Higgsino model for the first time

Dark matter line prospect

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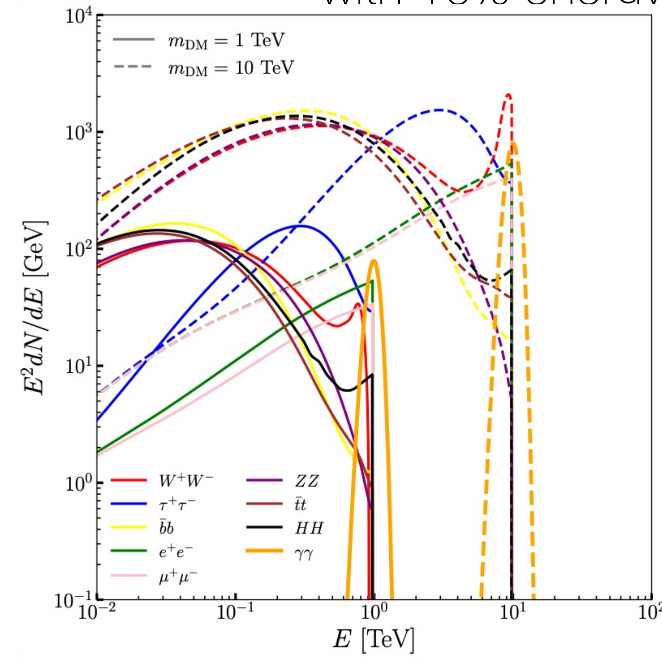
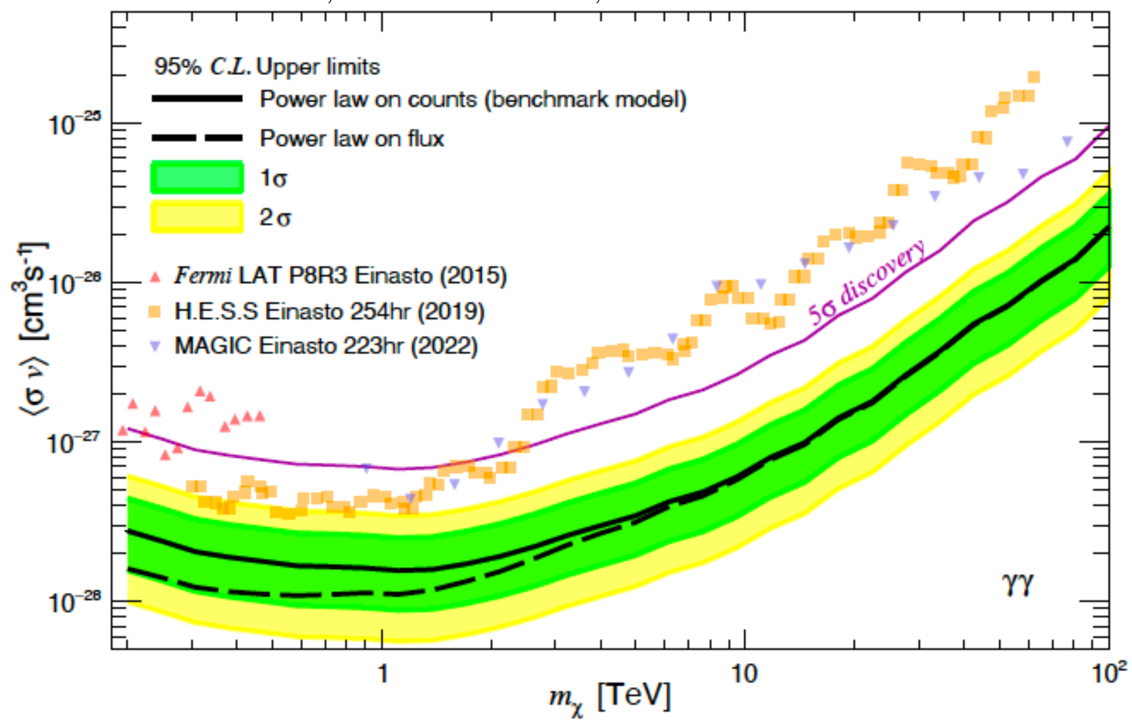
Line spectrum with 10% energy



Prospects with Galactic Center observations with CTA:

- 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 HESS/MAGIC

CTA consortium, arXiv:2403.04857, ICRC 2023



Heavy Decaying Dark Matter

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

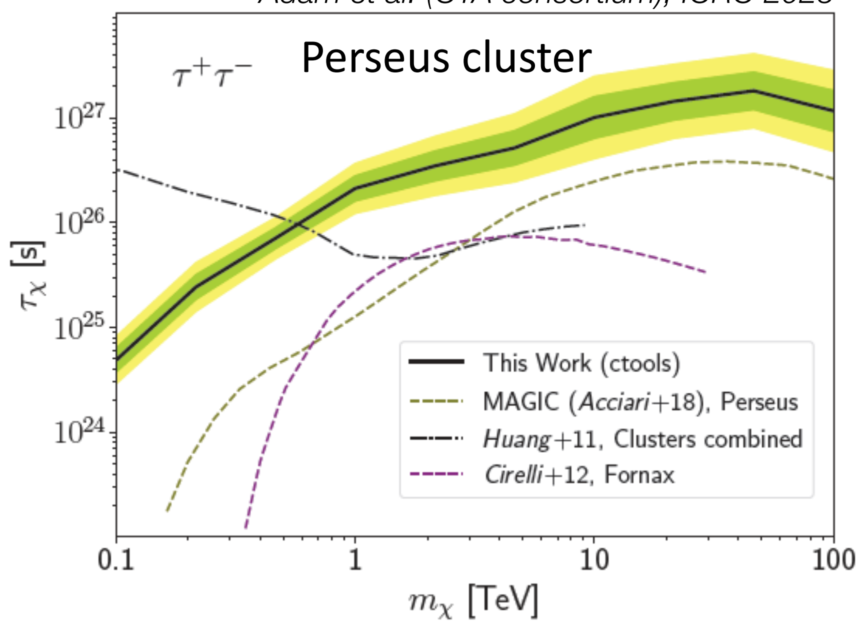
- **> PeV dark matter with wide FoV instruments**

  570 Days of LHAASO Observations

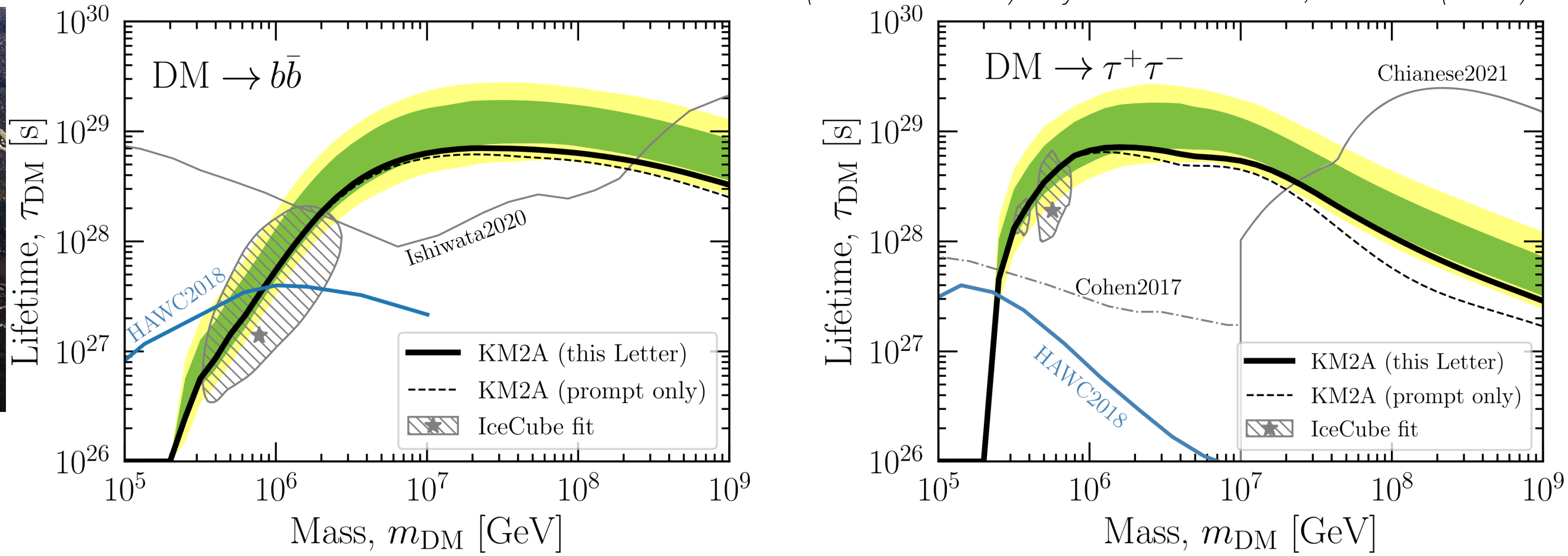
  ~ 15°<b<45°; 30°<l<60°: 0.27 sr

  → Strongest constraints on PeV DM

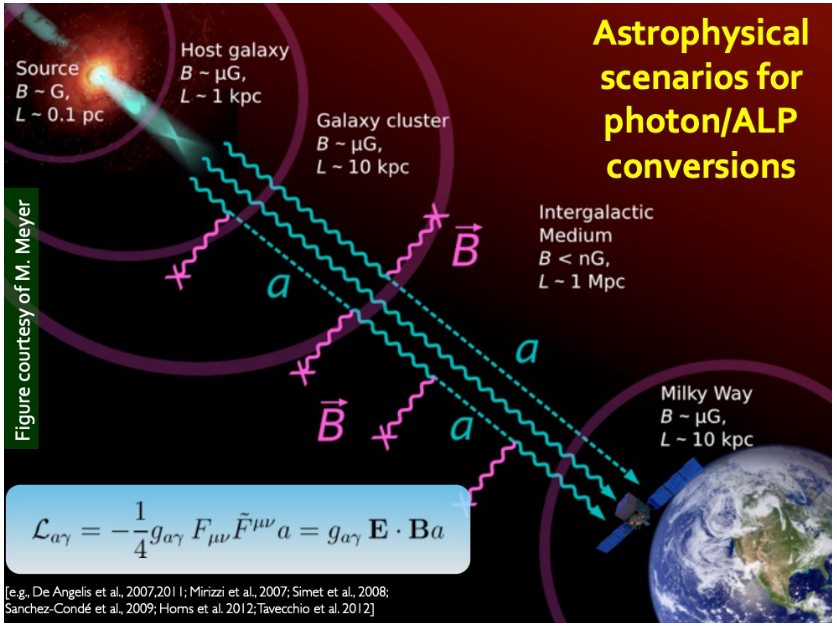
Adam et al. (CTA consortium), ICRC 2023



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

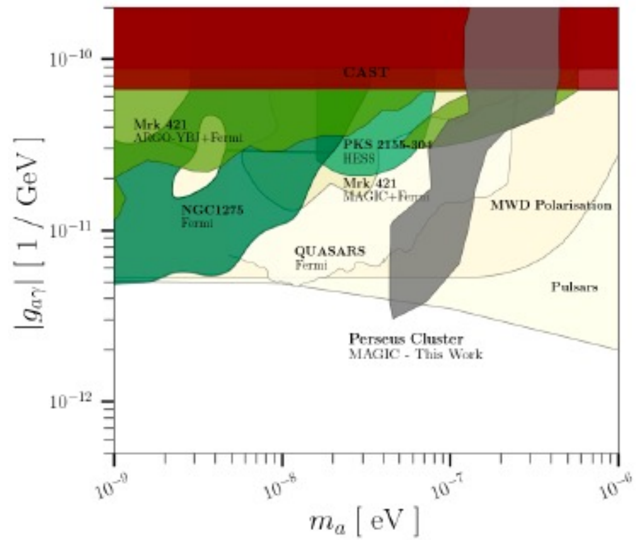


ALP searches with VHE gamma rays



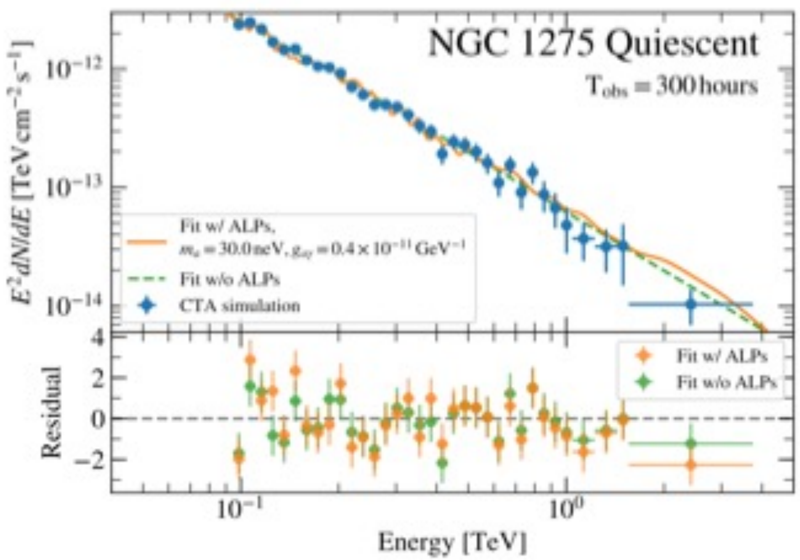
- Conversion in the cluster field
- photon-ALP conversion can leave imprints unique features in the spectra

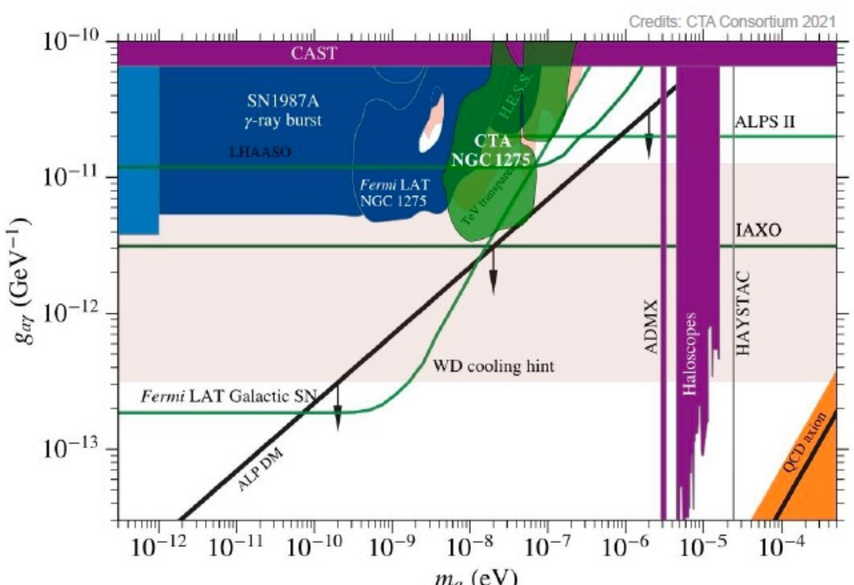
- **Observations of Perseus cluster by MAGIC ~40 h**



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

- **Prospects for CTA: Perseus cluster**

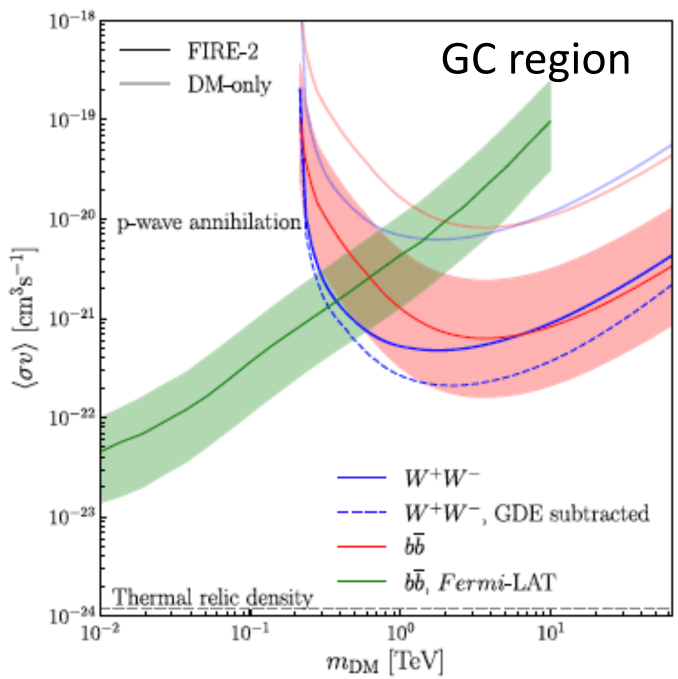


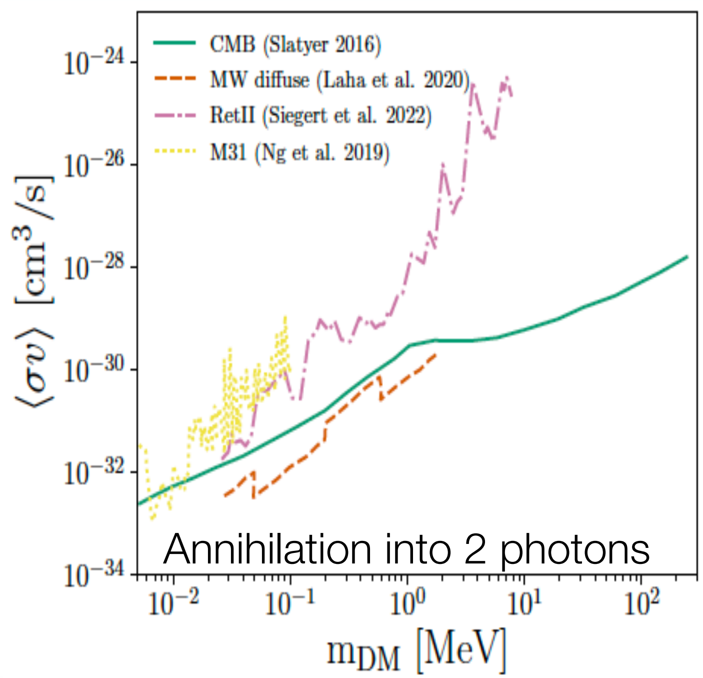


Alternatives to s-wave annihilations

- s-wave suppression appear in several DM models,
- for p-wave $\sigma v \propto (v/c)^2$
  - Hydrodynamical simualtions show enhanced DM velocity dispersion in the central region of Milky Way-sized galaxies compared to DM-only simulations
- In the sub-GeV mass range, current limits already generically rule out the simple thermal freeze-out scenario for s-wave annihilation

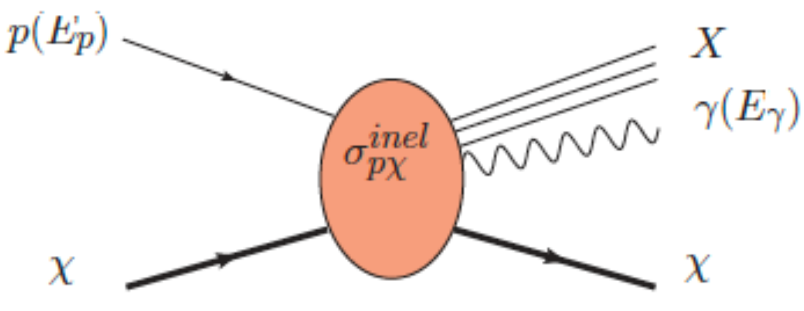
Montanari, et al. PRD 108, 083027 (2023)





Alternatives to annihilation/decay

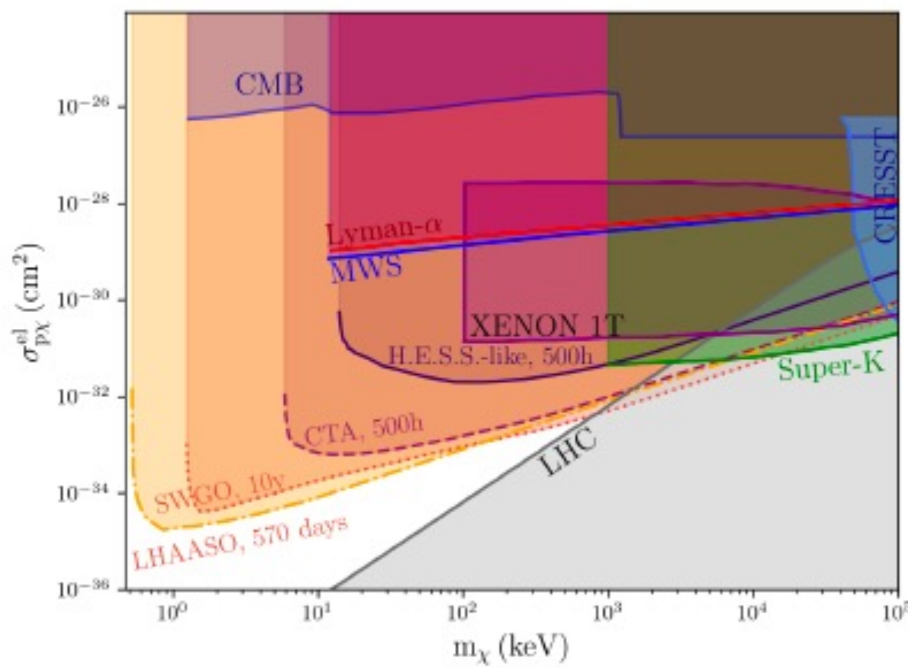
- **Cosmic particle interaction with dark matter**
  - interactions of dark matter with ordinary matter
  - astrophysical sources of high-energy neutrinos, electrons, protons as a particle beam
    - inelastic scattering:
      $\chi + p \rightarrow \chi + p +$ hadronic showers + γ-rays + neutrinos
  - GC harbors both high DM density and hadronic accelerator



In absence of specific underlying DM models:
the inelastic to the elastic cross section can be related such as $\sigma^{inel}_{p\chi} = 8/3\ \sigma^{el}_{p\chi}$

Broilo, et al. Phys. Rev. D 101 (2020) 074034

Reis, et al. arXiv:2403.09343



Summary and Outlook

- **TeV-scale dark matter allows a simple mechanism (thermal freezeout) to yield the observed abundance of dark matter**
  - Simple thermal relic scenario predicts benchmark cross-section that is not far below current detectability for indirect detection
- **A variety of complementary dark matter targets/environments are probed with photons from keV to PeV energies**
  - From Galatic scale to cosmological scales
- **Astroparticle messengers are sensitive to different dark matter models: WIMPs, Axions, Primordial black holes**
- **Multi-wavelength/messenger searches provide access to yet uncharted portions of the DM parameter space**