3rd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes

Dark matter searches with gamma rays

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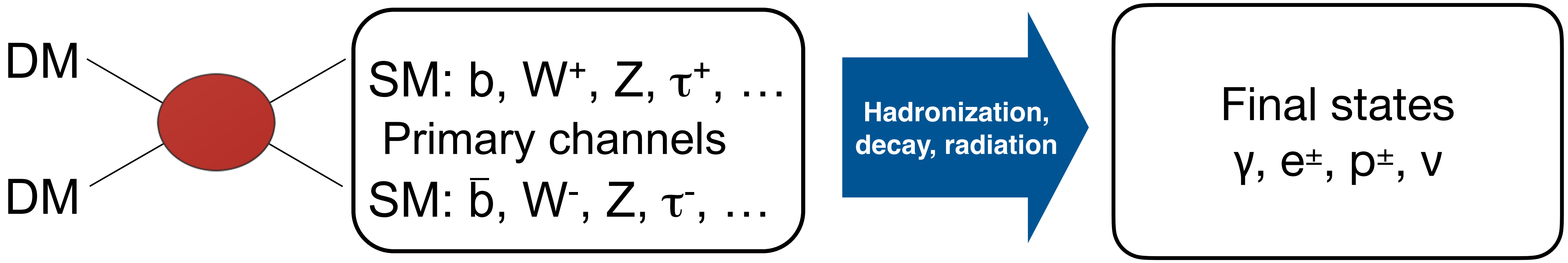
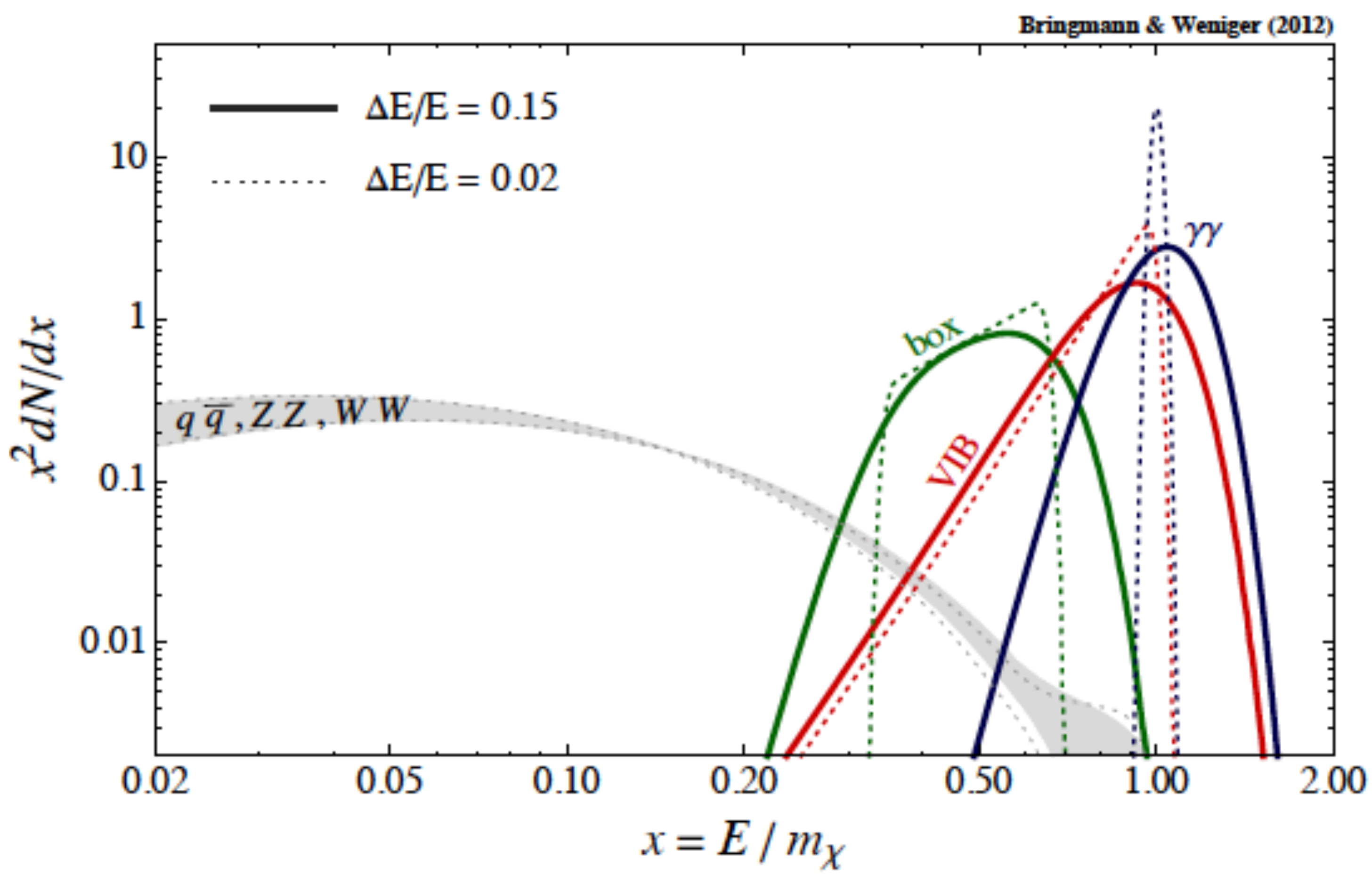
Gamma-ray indirect DM searches



- **Characteristic spectral features**:
  - Separation from background
  - Measure basic physical properties: mass, cross-section / lifetime
- **Gamma rays or neutrinos do not suffer from propagation effects**:
  - Can determine DM abundance and distribution in the Universe
- **Gamma rays easier to detect compared to neutrinos**
  - Different sensitive to different channels

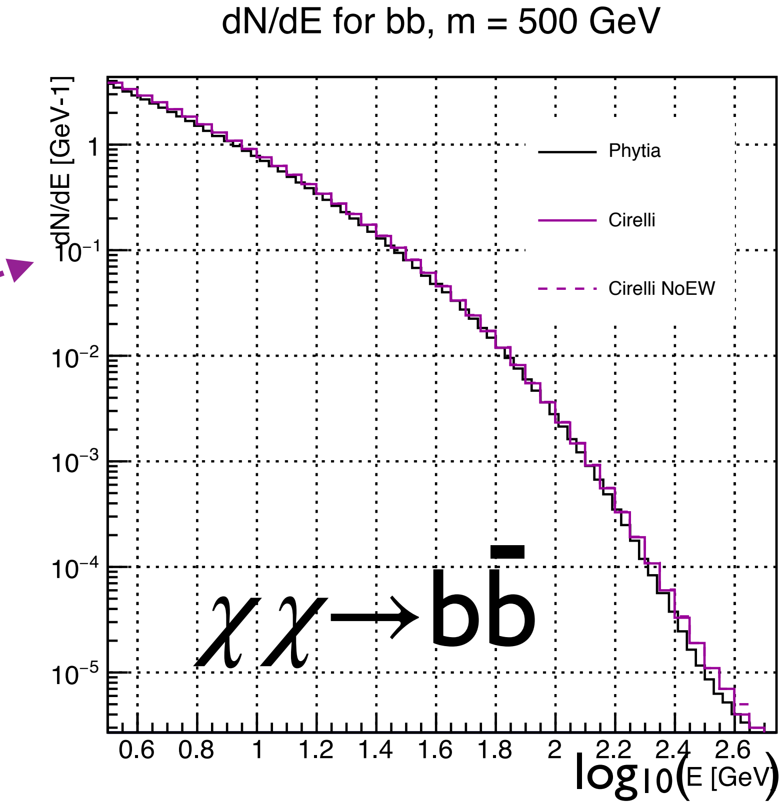


Gamma-ray fluxes

★ Expected **differential gamma-ray flux**:

$$\frac{d\Phi}{dE}(\Delta\Omega) = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle\, J(\Delta\Omega)}{2m_{\rm DM}^2}\,\frac{dN}{dE}$$

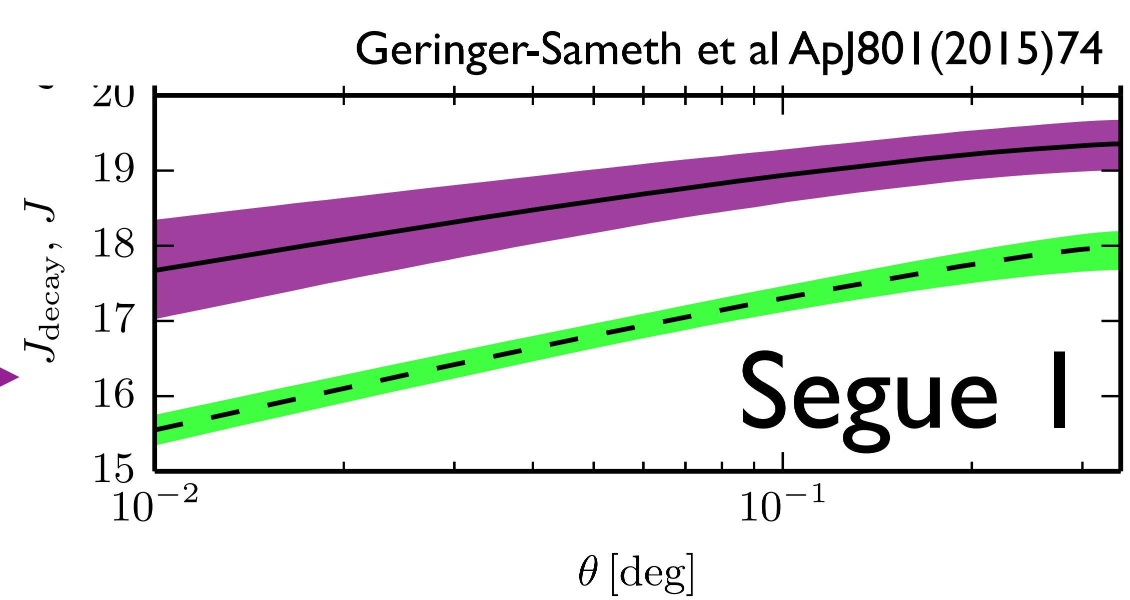
Pythia



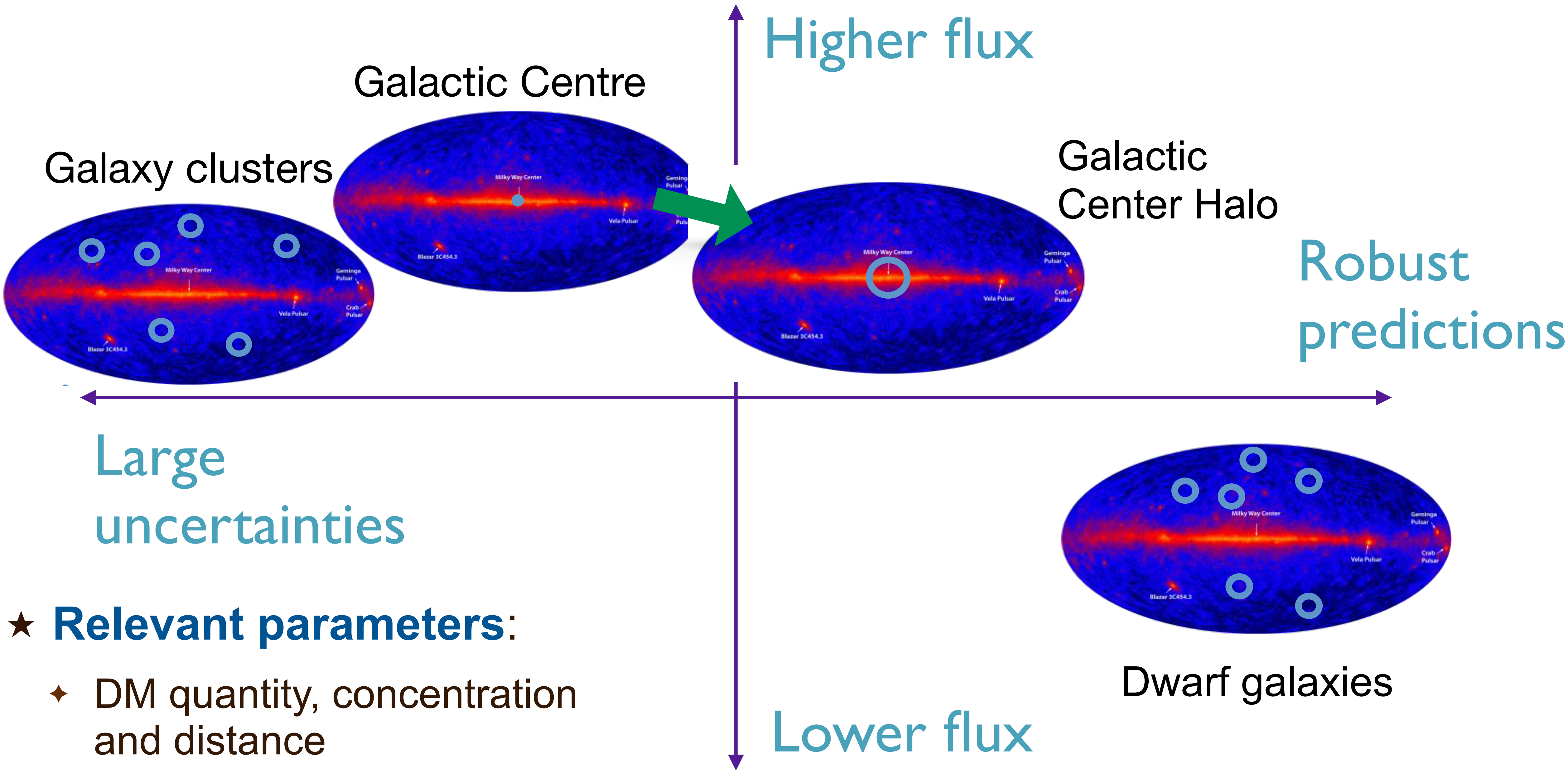
★ The **astrophysical** or **J-factor** depends on the DM distribution:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} dl\, \rho^2(l,\Omega)$$

Fit to stellar surface density and velocity dispersion profiles



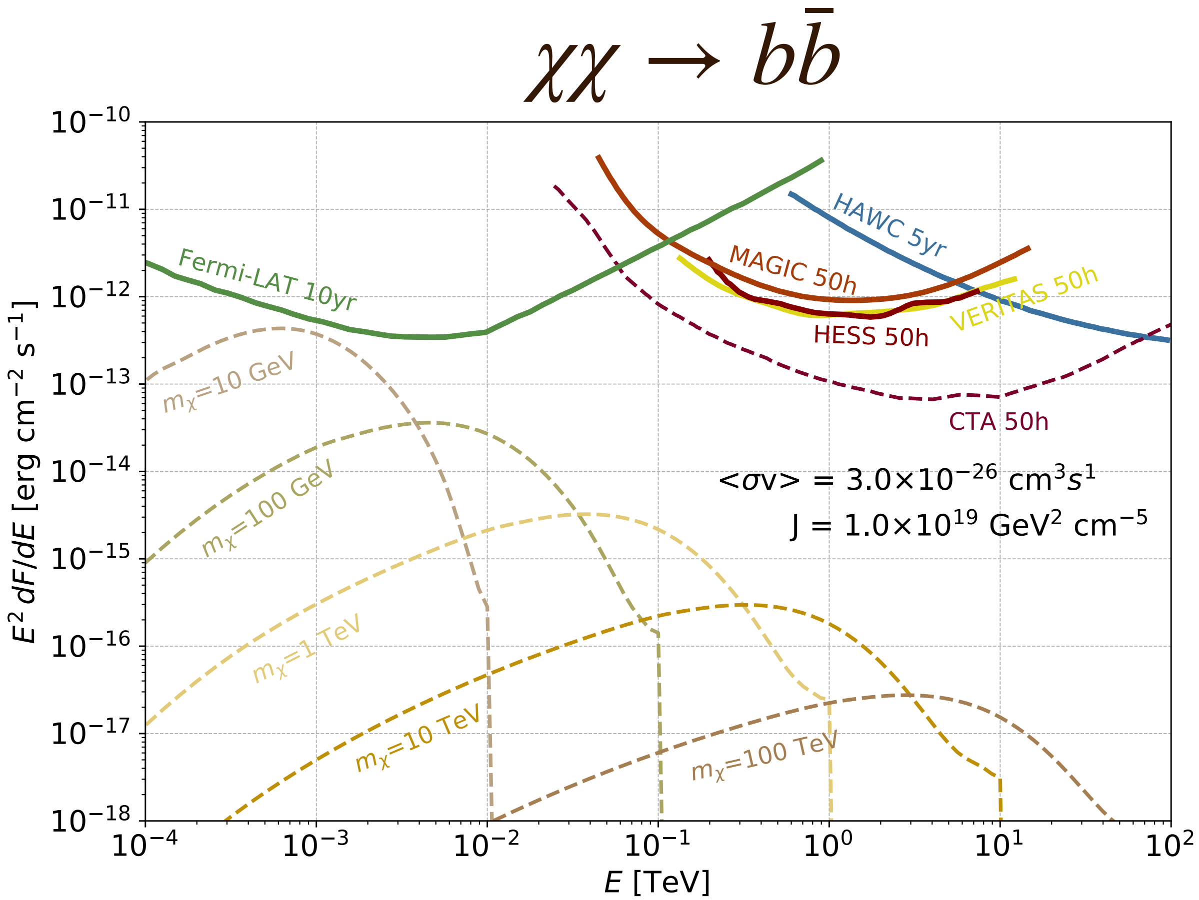
Targets for gamma-ray DM searches



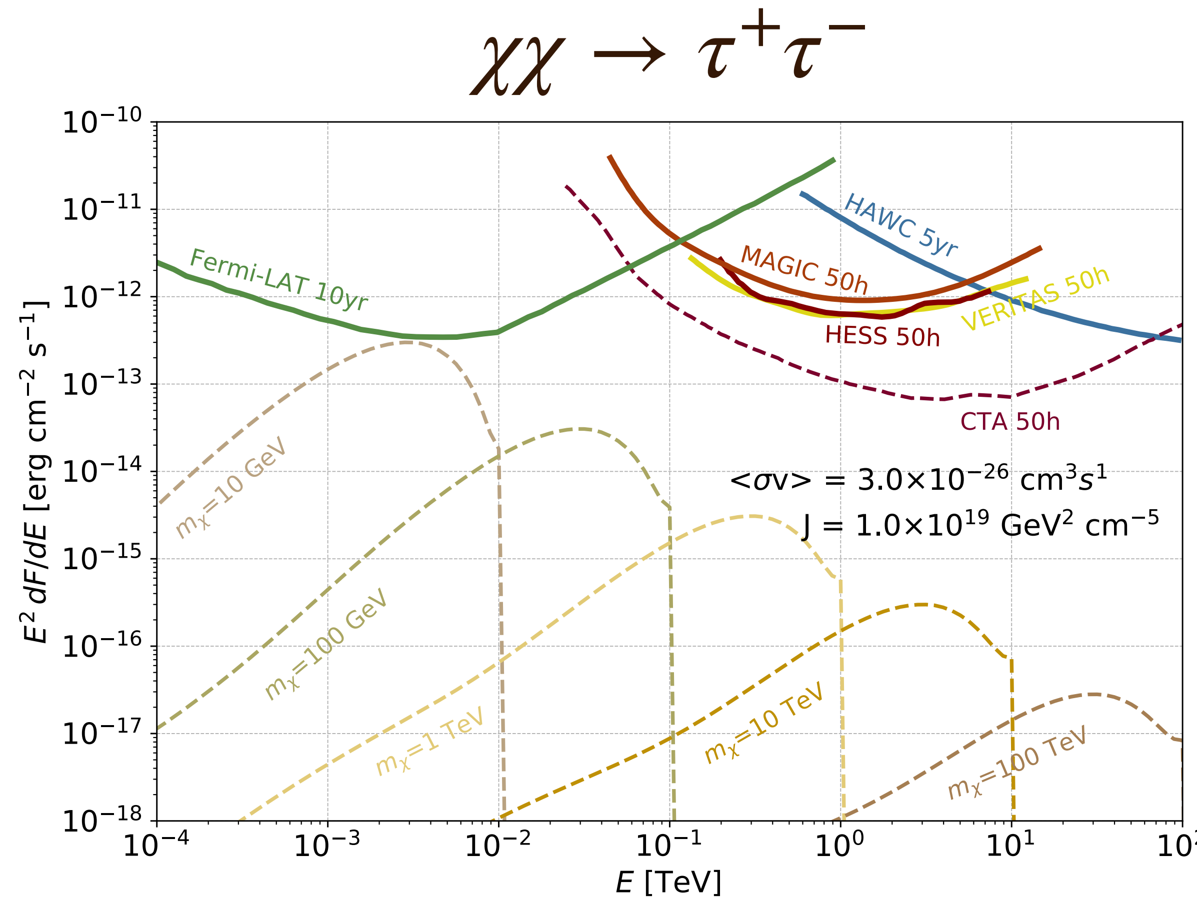
★ **Relevant parameters**:

- DM quantity, concentration and distance
- Uncertainties
- Astrophysical background

Sensitivity to gamma-ray DM searches



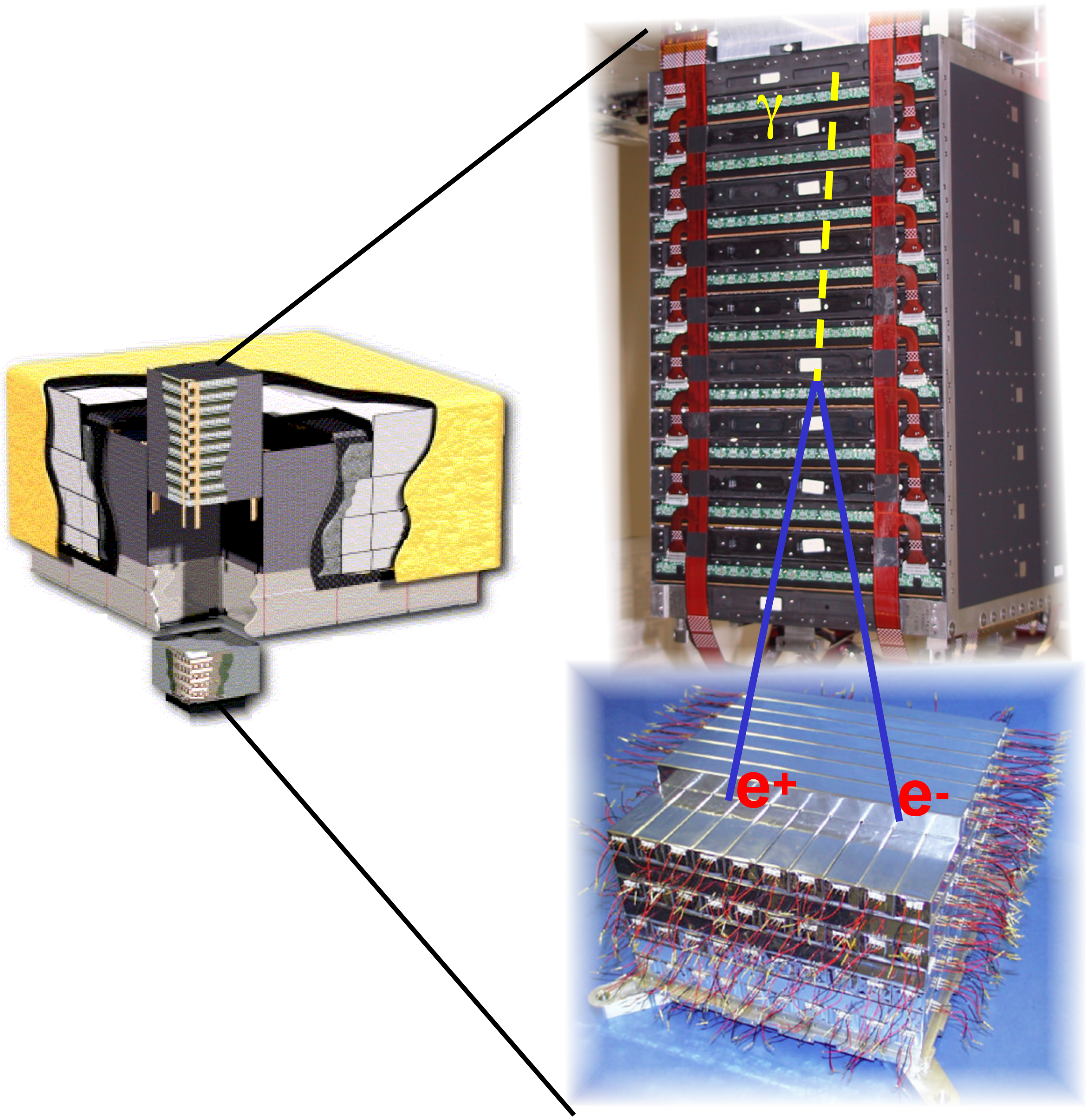
Rico, Galaxies 8(2020)25



- ★ **Gamma-ray continuum spectra** peak at energies ~m_χ/30-m_χ/3
- ★ For m_χ ~ [10 GeV, 100 TeV], the **most relevant instruments** are:
  - Fermi-LAT
  - Cherenkov telescopes: MAGIC, VERITAS, HESS, CTA (future)
  - Water Cherenkov detectors: HAWC, LAAHSO, SWGO (future)

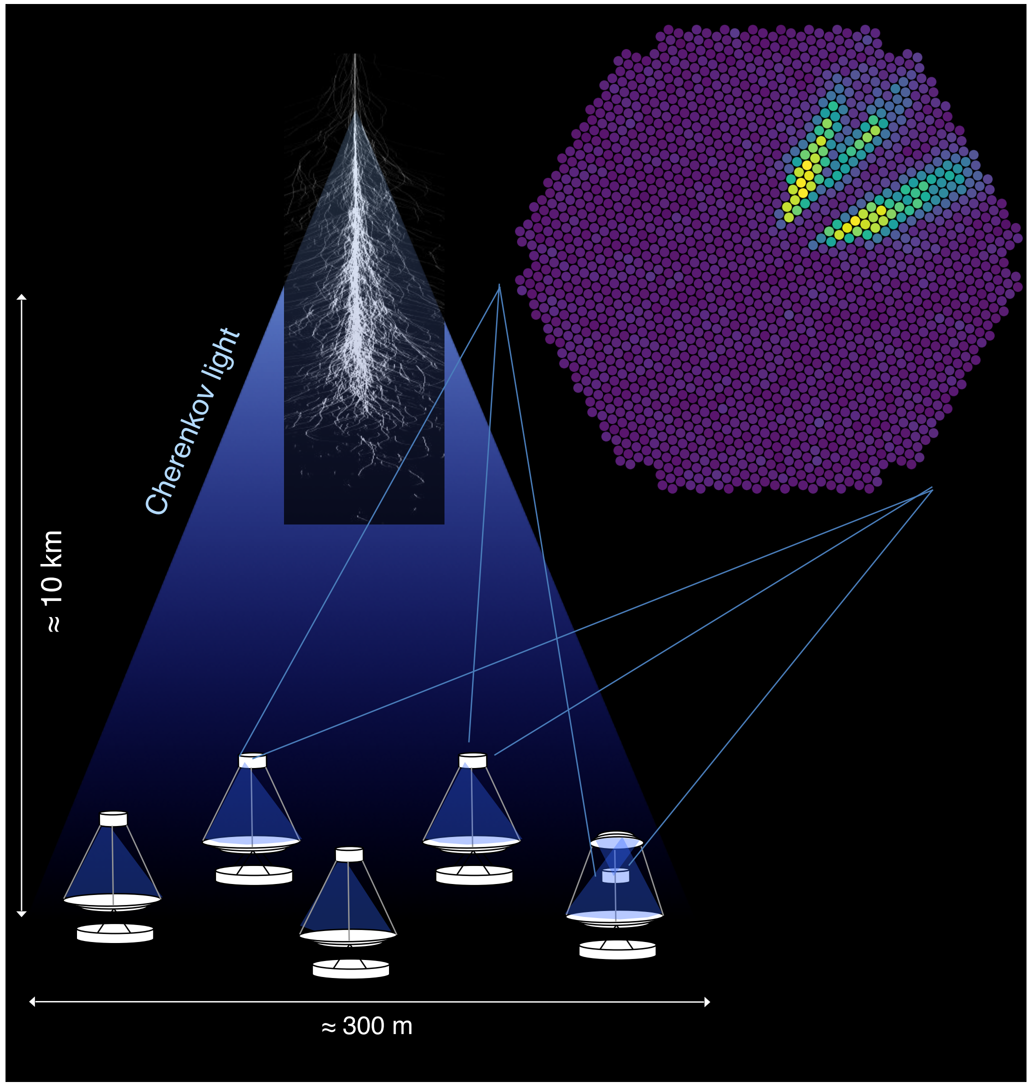
Fermi Large Area Telescope

- **Space-borne telescope**:
  - Operating since August 2008
  - Anti-coincidence shield + tracker + calorimeter
- Almost **background free**
- **Energy range** 100 MeV - 300 GeV
- **Energy resolution**: 10-15%
- **Angular resolution**: ~1º(0.1º) @ 1 (100) GeV
- **Field of view**: 2.4 sr (1/5 of sky)
- **Full sky survey** every 2 orbits (~3 hours)
- **~100% duty cycle**



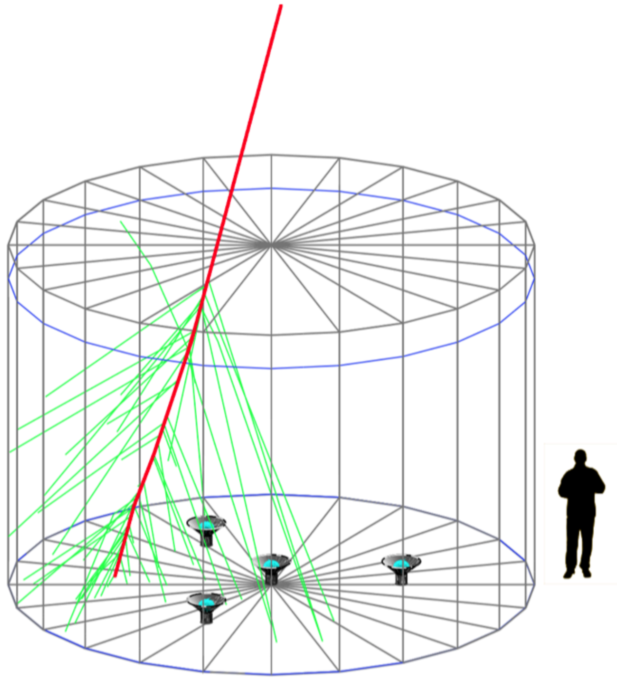
Cherenkov telescopes

- ★ **Gamma-ray flux** drops exponentially with energy
  → for E>100 GeV large collection areas needed
  → Cherenkov telescopes (MAGIC, VERITAS, HESS since 2000's + CTA in the [near] future)
- ★ **Intense CR background**
  → Imaging technique
- ★ **Energy range** ~100 GeV - ~100 TeV
- ★ **Energy resolution** 10-15%
- ★ **Angular resolution** ~0.1º at 1 TeV
- ★ **Field of view** 3-5º
- ★ **Duty cycle**: ~10%
- ★ **Pointed observations**, systematic scans of limited regions
- ★ **Several telescopes** for better performance



HAWC

- ★ **Altitude**: 4100m (Sierra Negra, Mexico)
- ★ **Since**: 2013 (partial) / 2015 (full detector)
- ★ **300 water Cherenkov detectors** covering 22000 m^2
- ★ **Highest energy range**: 300 GeV - 100 TeV
- ★ **Wide field of view**:
  - ✦ 15% sky field of view
  - ✦ 2/3 or sky scanned every day
- ★ **Duty cycle**: ~100%
- ★ **Angular resolution**:
  1° @ 1 TeV
  0.2° @ >30 TeV
- ★ **Relatively poor CR/gamma-ray separation,** much better by LHAASO thanks to muon detectors



Likelihood analysis

Total likelihood:

$$\mathcal{L}(\alpha;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{l=1}^{N_{\mathrm{dSph}}} \mathcal{L}_{\gamma}(\alpha\bar{J}_l;\boldsymbol{\mu}_l|\boldsymbol{\mathcal{D}}_{\gamma_l}) \cdot \mathcal{L}_J(\bar{J}_l|\boldsymbol{\mathcal{D}}_{J_l})$$

Likelihood per target:

$$\mathcal{L}_{\gamma}(\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_{\gamma}) = \prod_{k=1}^{N_{\mathrm{meas}}} \mathcal{L}_{\gamma,k}(\alpha\bar{J};\boldsymbol{\mu}_k|\boldsymbol{\mathcal{D}}_{\gamma,k})$$

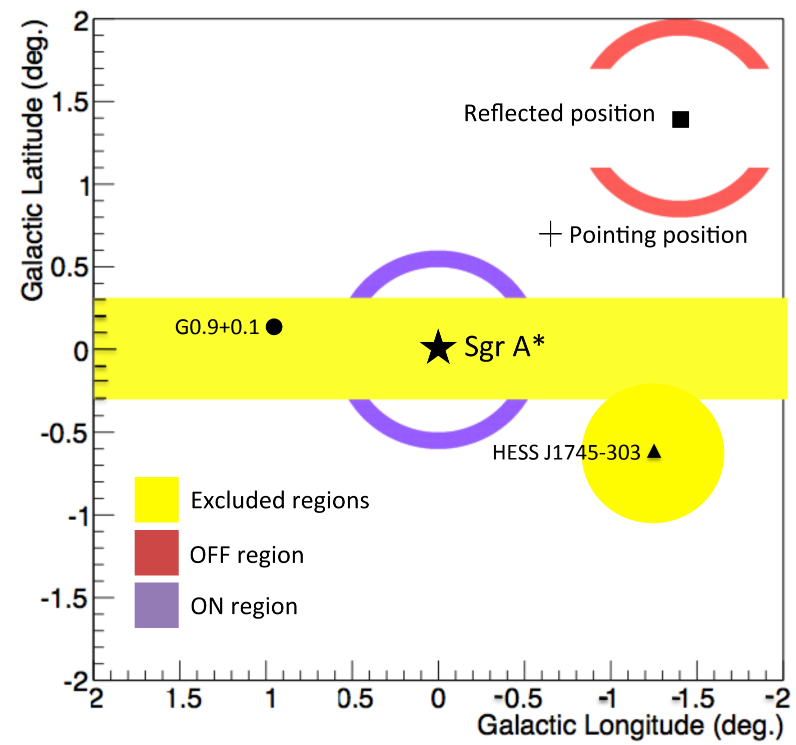
Likelihood per observations:

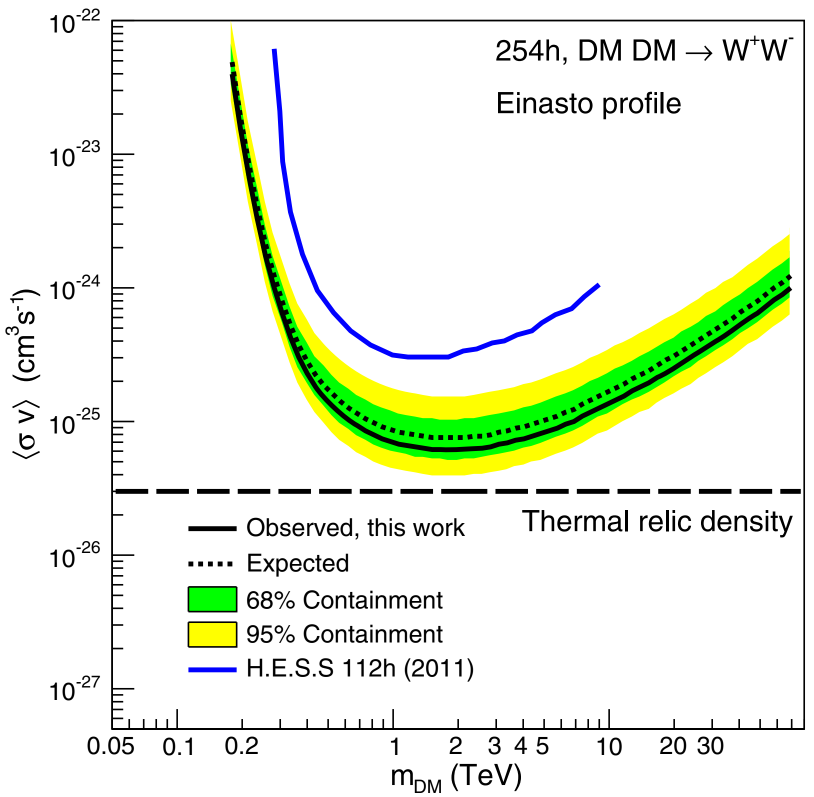
$$\mathcal{L}_{\gamma,k}(\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_{\gamma}) = \prod_{i=1}^{N_{E'}} \prod_{j=1}^{N_{\hat{p}'}} P\left(s_{ij}(\alpha\bar{J};\boldsymbol{\mu}) + b_{ij}(\boldsymbol{\mu})|N_{ij}\right) \cdot \mathcal{L}_{\mu}(\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_{\mu})$$

★ Different instruments basically differ in the relevant nuisance parameters $\boldsymbol{\mu}$ and their pdf

Galactic Center

- ★ **Highest J-factor from Earth** (~10^{21} GeV^2 cm^{-5}) → obvious target
- ★ **Observed by HESS** for 10 years (2004-2014), 254 hours
- ★ **Crowded central part and Galactic plane** excluded due to intense astrophysical background
- ★ **Improved analysis + deeper observations** → 4-5 times better sensitivity
- ★ **No signal detected** → upper limits $<\sigma v>\sim 10^{-25}$ cm^3 s^{-1} for $\chi\chi \rightarrow W^+W^-$

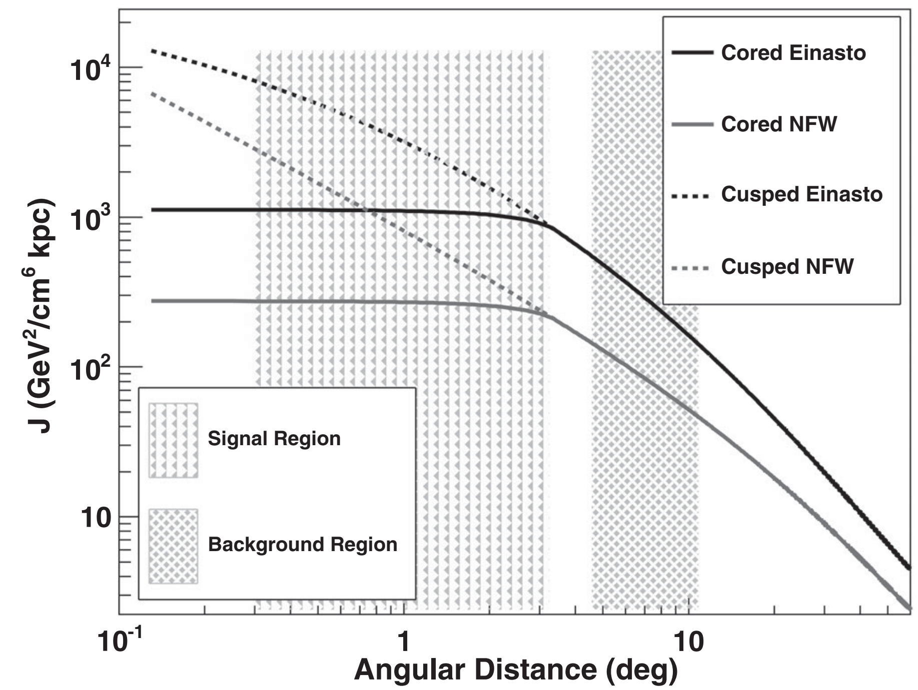


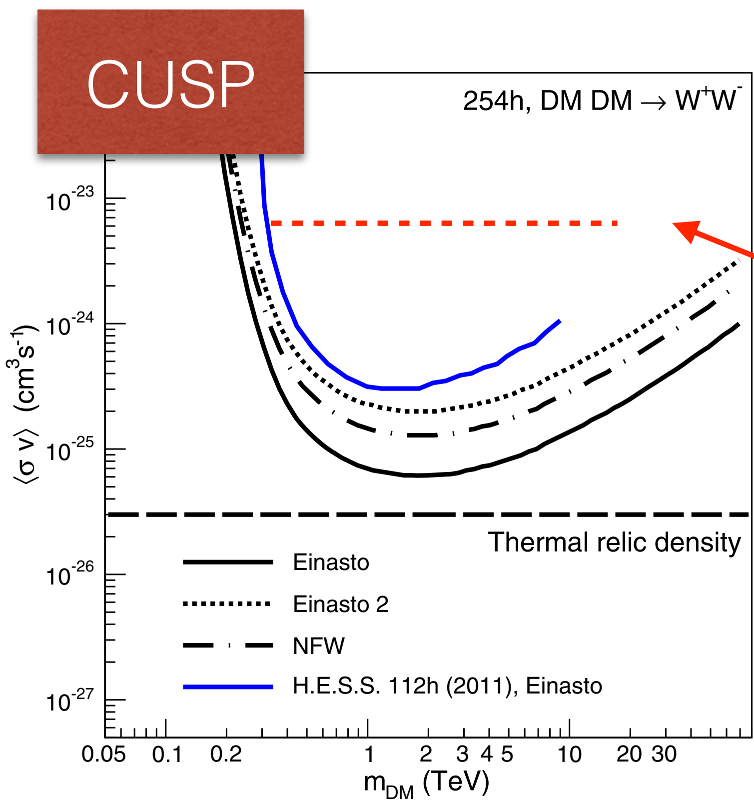


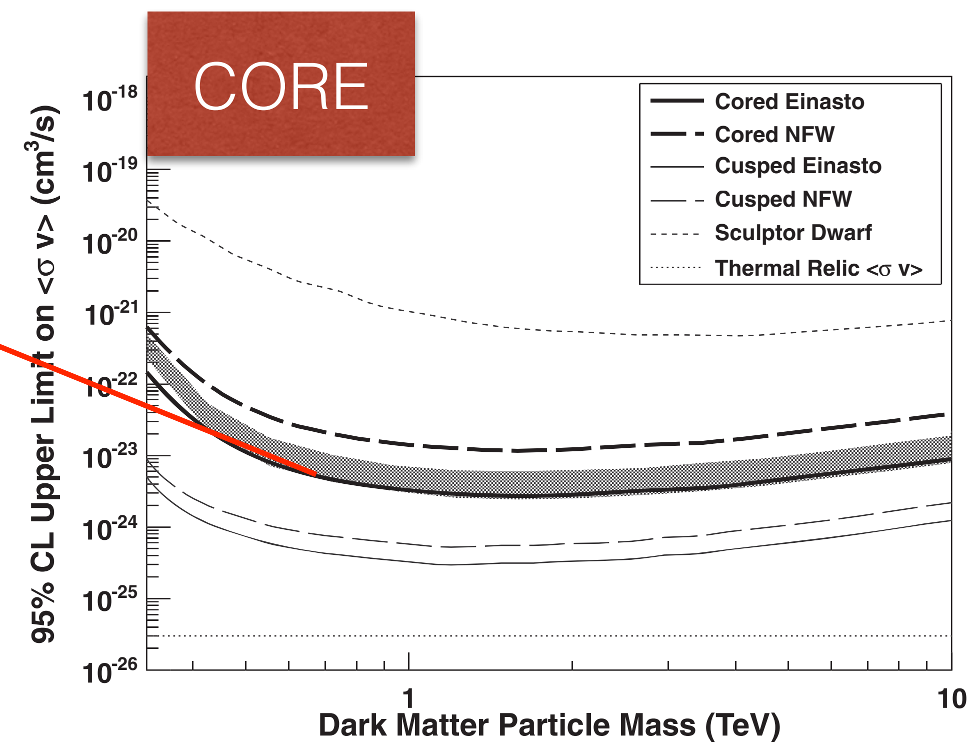
Abdallah et al. PRL117(2016)111301

Drawbacks of GC analysis

- ★ Sensitive to the **choice of DM density profile**
- ★ For very deep observations, both **statistical and systematic uncertainties on background estimation** become important (more complex analysis needed)

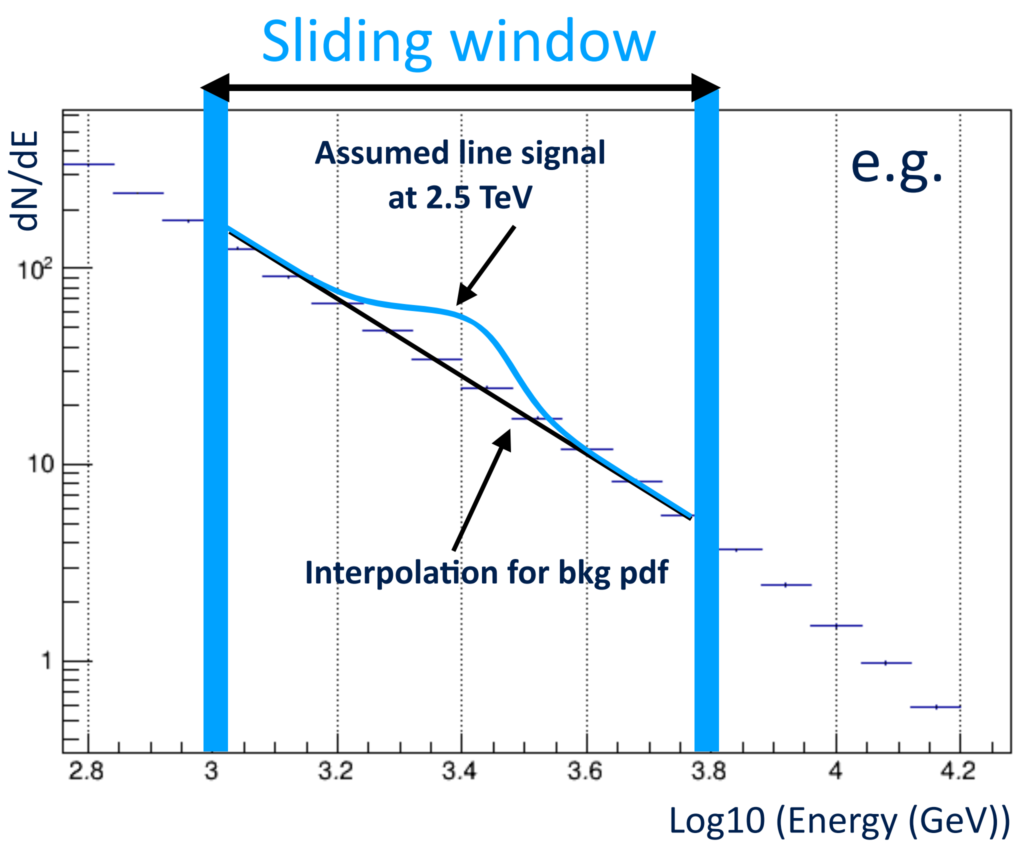


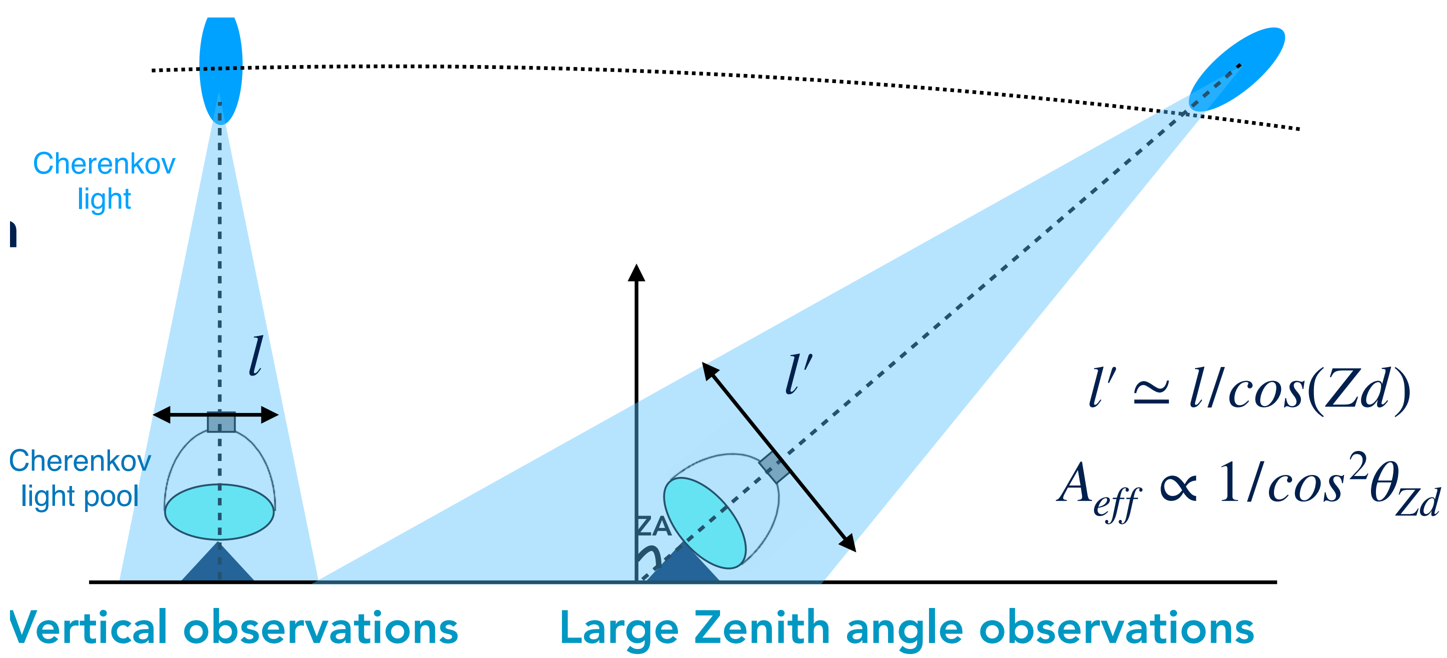


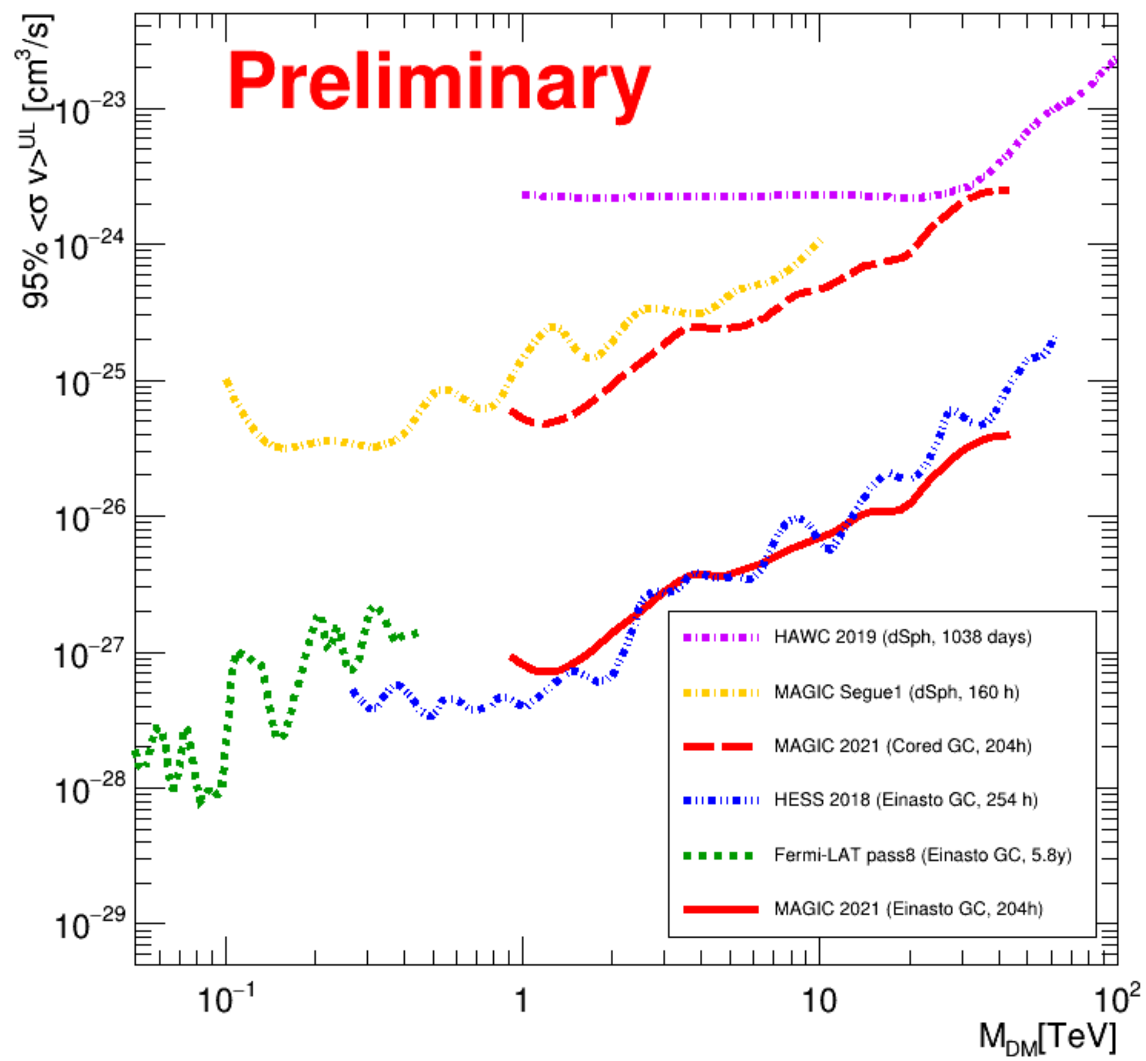


Abramowski et al. PRL114(2015)081301

Spectral lines



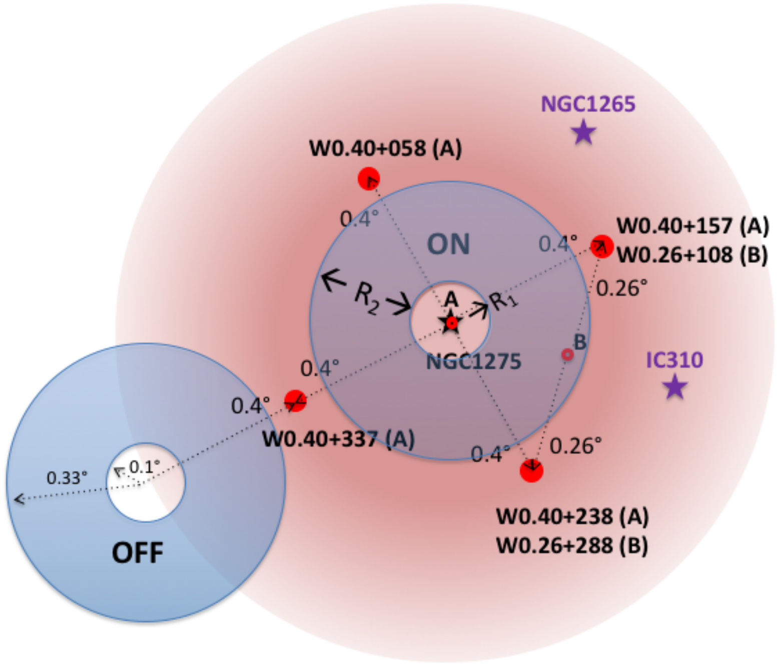


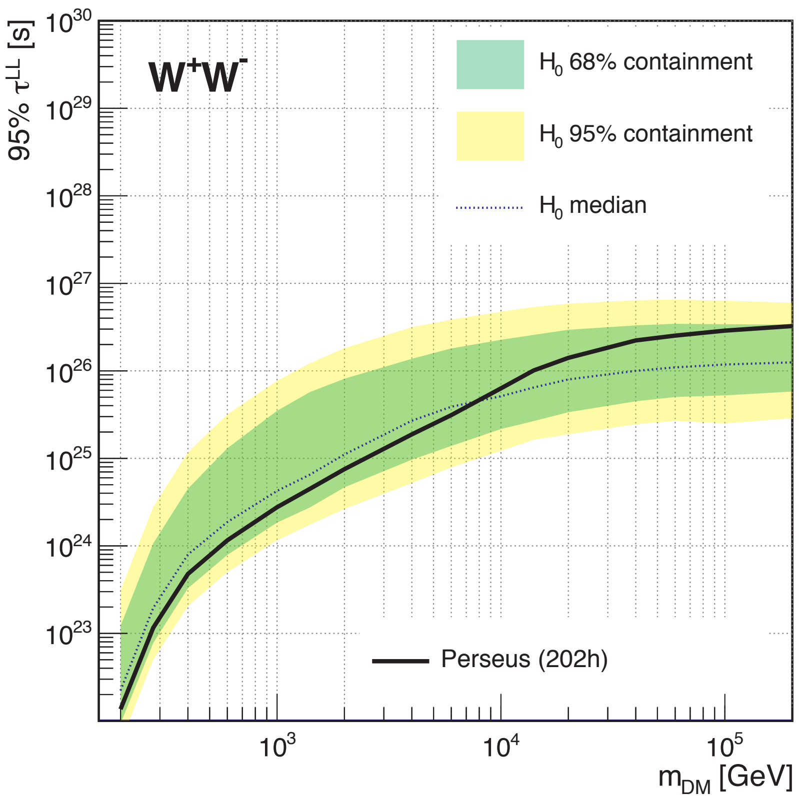


Inada et al.,PoS(ICRC2021)520

Galaxy clusters

- ★ **Contain substructure**
  → boost to DM annihilation signal (by factors 10-100)
  → big uncertainties due to extrapolation from simulations
- ★ **DM decay signal intensity** depends only on total mass (huge) and therefore can set strong and robust limits from galaxy clusters
- ★ **Extended sources** for IACTs
  → more difficult analysis
- ★ **Results from Perseus cluster**:
  - ✦ Very deep MAGIC observations (200 h),
  - ✦ Gamma-ray source (NGC1275) coinciding with center of DM halo
  - ✦ Signal “contamination” of background
  - ✦ **DM lifetime** > 10^{25} (10^{26}) s for 1 (10) TeV WIMPS

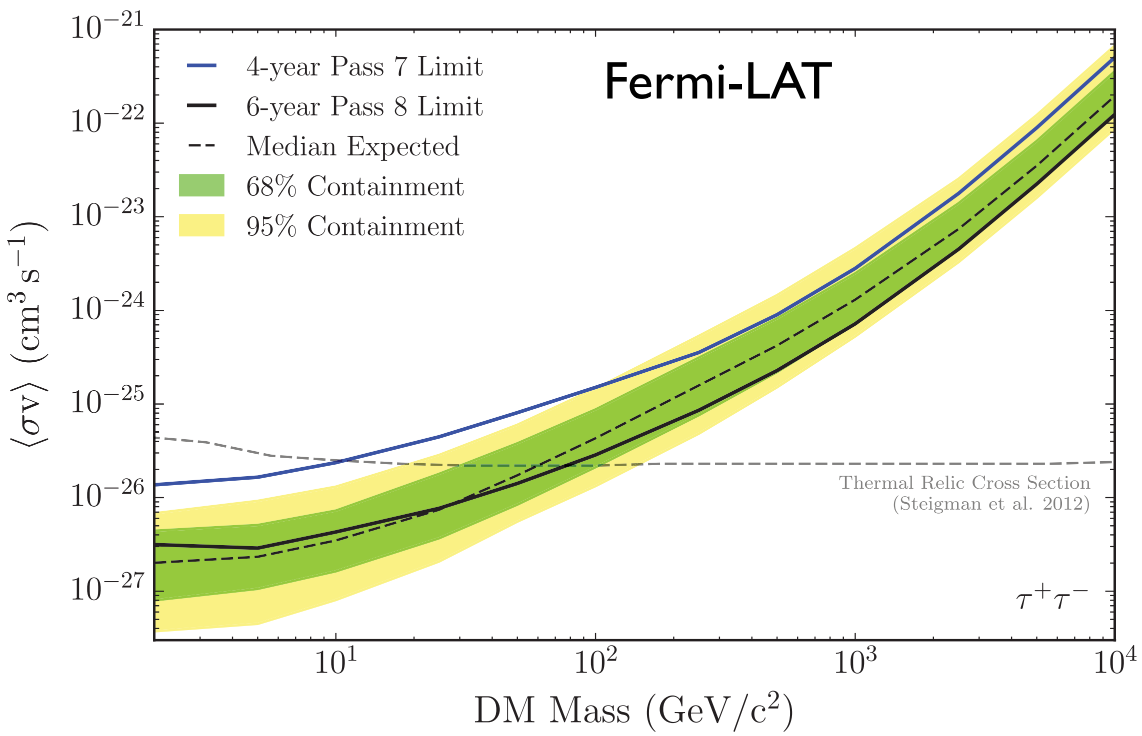


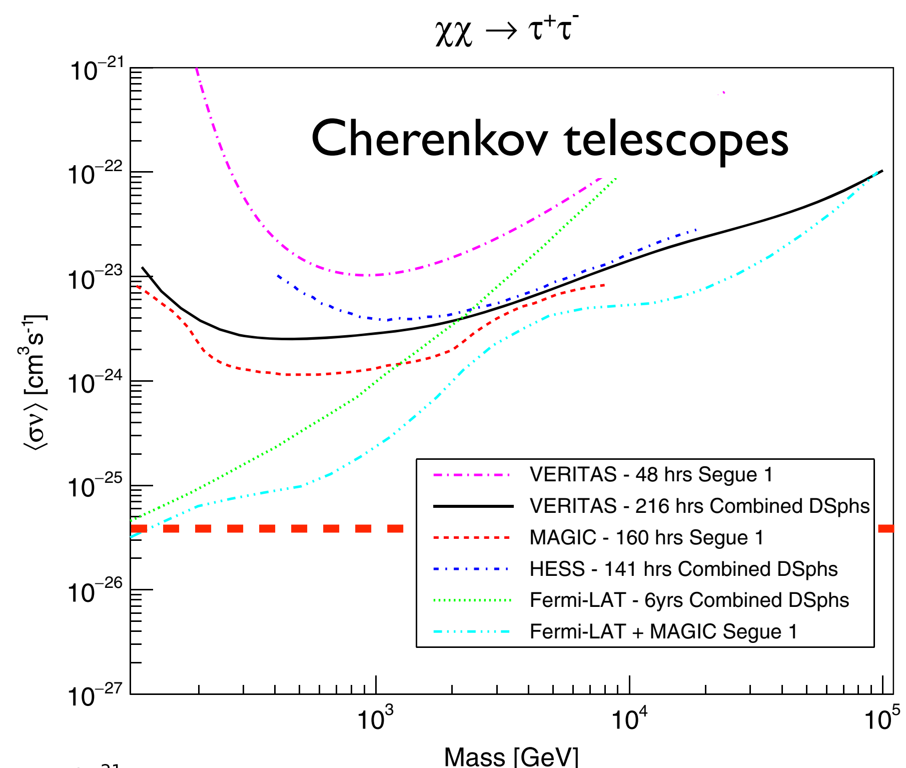


Acciari et al. PDU 22 (2018) 38

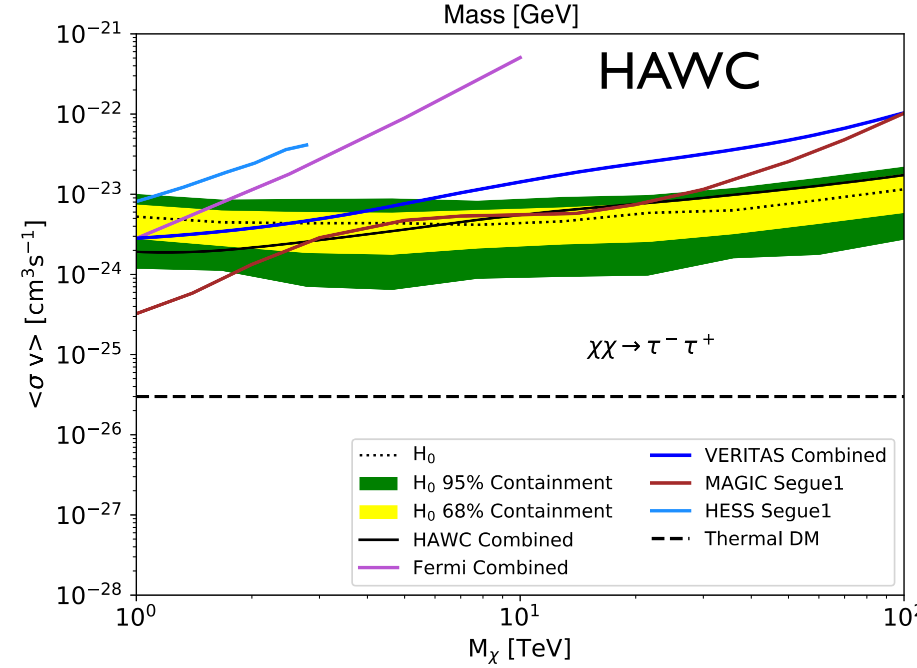
Dwarf spheroidal galaxies

Ackermann at al. PRD89(2014)042001





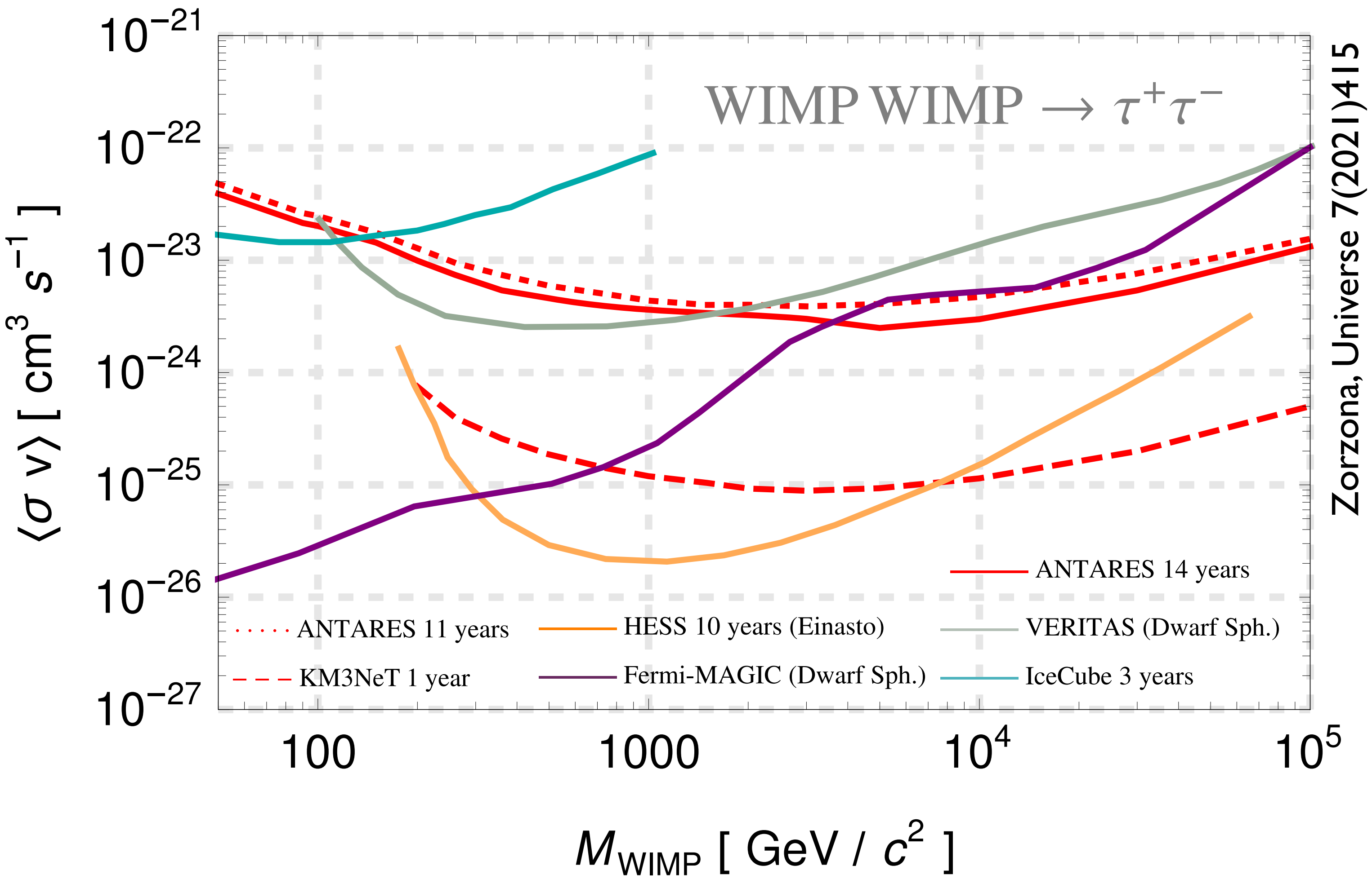
Archambault et al. PRD95(2017)082001



Albert et al. ApJ853(2018)154

- ★ **Most robust** astrophysical probe into nature of dark matter
- ★ **Limits below thermal relic cross section** by Fermi-LAT below ~100 GeV

Comparison with neutrinos



★ **Comparison between results sometimes difficult** due to different assumptions/conventions used during analysis

★ **Sensitivity improves** when considering all observations

→ Combined analysis!

Combination of results: MAGIC+Fermi-LAT

★ **Joint-likelihood** depending on one free parameter (proportional to gamma-ray intensity), one term per target:

$$\mathcal{L}(\langle\sigma v\rangle;\boldsymbol{\nu}\,|\,\boldsymbol{\mathcal{D}}) = \prod_{i=1}^{N_{\text{target}}} \mathcal{L}_i(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_i\,|\,\boldsymbol{\mathcal{D}}_i)\cdot\mathcal{J}(J_i\,|\,J_{\text{obs},i},\sigma_i)$$

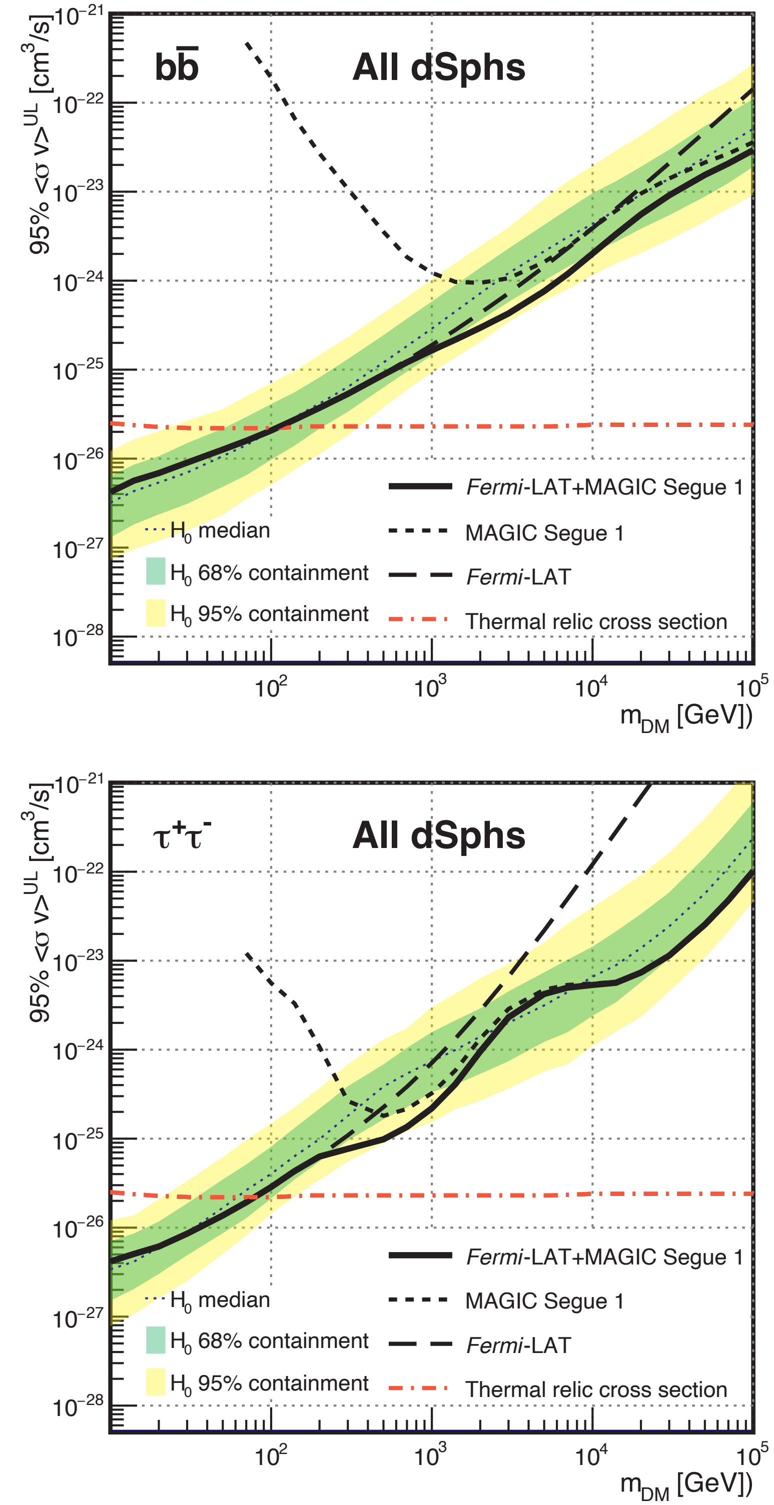
★ Can include **target-wise uncertainties on J-factor**

$$\mathcal{J}(J\,|\,J_{\text{obs}},\sigma) = \frac{1}{\ln(10)J_{\text{obs}}\sqrt{2\pi}\sigma}\times e^{-\left(\log_{10}(J)-\log_{10}(J_{\text{obs}})\right)^2/2\sigma^2}$$

★ For each target, **one term per instrument** having observed it:

$$\mathcal{L}_i(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_i\,|\,\boldsymbol{\mathcal{D}}_i) = \prod_{j=1}^{N_{\text{instrument}}} \mathcal{L}_{ij}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{ij}\,|\,\boldsymbol{\mathcal{D}}_{ij})$$

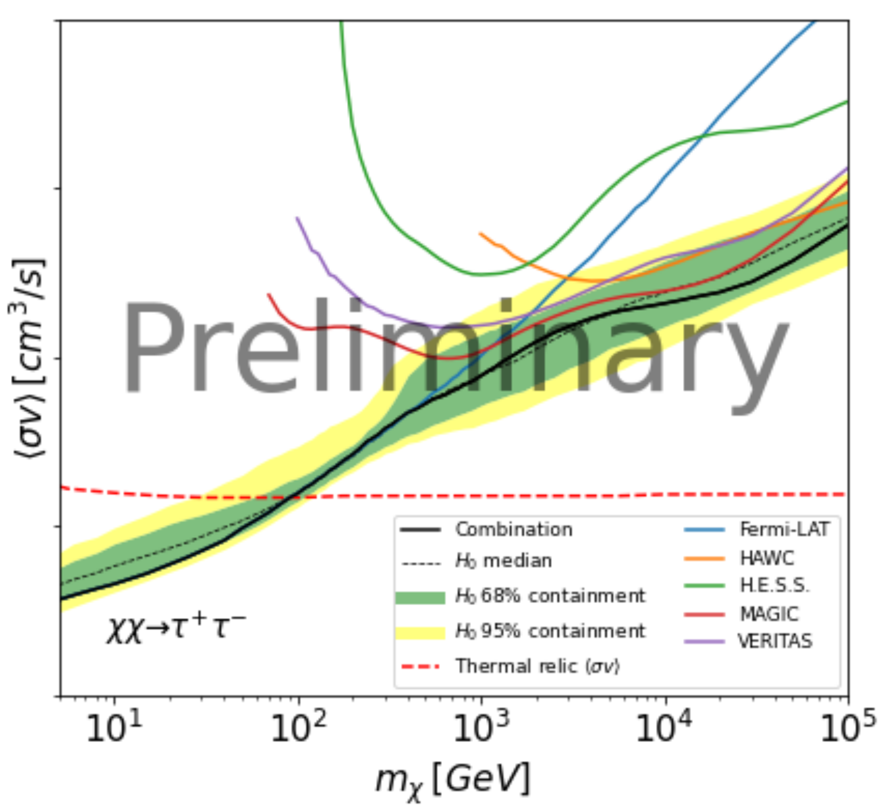
★ **Combined analysis** can be done by just sharing likelihood vales vs free parameter



Ahnen et al. JCAP1602(2016)039

Combined analysis: Glory Duck project

- ★ **Combine results** from all dSphs observed by Fermi, HESS, MAGIC, VERITAS and/or HAWC in their lifetime
- ★ All datasets analyzed using **common approach**:
  - ✦ Same DM density profiles
  - ✦ Same gamma-ray spectra from the same channels
  - ✦ Common treatment of common experimental uncertainties

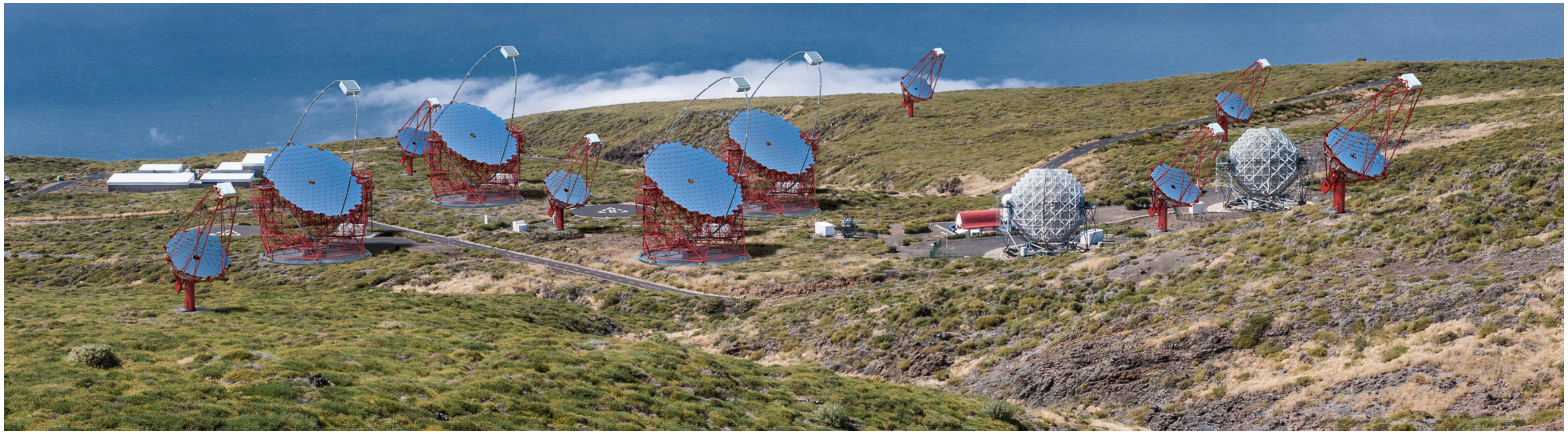


PoS ICRC2021 (2021) 528

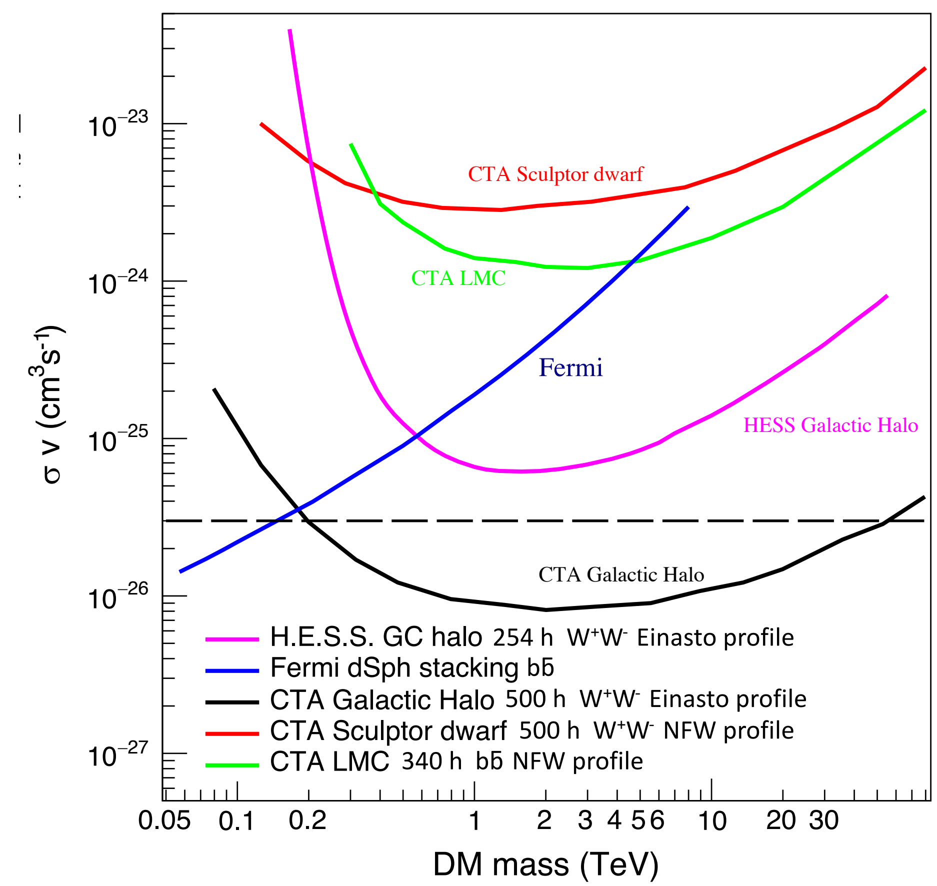
GLORY DUCK

dSph	Instrument[s]
Boötes I	VERITAS, HAWC, Fermi,
Canes Venatici I	HAWC, Fermi
Canes Venatici II	HAWC, Fermi
Carina	HESS, Fermi
Coma Berenices	MAGIC, HESS, HAWC, Fermi
Draco	MAGIC, VERITAS, HAWC,
Fornax	HESS, Fermi
Hercules	HAWC, Fermi
Leo I	HAWC, Fermi
Leo II	HAWC, Fermi
Leo IV	HAWC, Fermi
Leo T	Fermi
Leo V	Fermi
Sculptor	HESS, Fermi
Segue 1	MAGIC, VERITAS, HAWC,
Segue 2	Fermi
Sextans	HAWC, Fermi
Ursa Major I	HAWC, Fermi
Ursa Major II	MAGIC, HAWC, Fermi
Ursa Minor	VERITAS, Fermi

CTA



- ★ Two sites, telescopes of three different sizes
- ★ Alpha configuration:
  - ✦ North (La Palma): 4LST + 9 MST
  - ✦ South (Paranal): 14 MST + 37 SST
- ★ **Sensitive to the thermal relic density** for WIMP masses above ~200GeV



Acharya et al arXiv:1709.07997