Dark Matter Searches using Indirect Detection techniques

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Introduction

- **Indirect dark matter (DM) searches**
  - Probes the DM regions that provide its gravitational evidence, ie “the places from which the problem came from”
  - Looks for signals that can only be attributed to DM annihilation or decay because of their spectral and/or spatial features
  - Signals can be searched for in the whole electromagnetic spectrum. cosmic rays (charged particles) and neutrinos

- **Disclaimers**
  - In this talk DM ↔ WIMP
  - I can’t cover every experiments/results, sorry if I miss yours

Indirect dark matter searches

- **Annihilation or decay of DM particle(s) in SM particles (primary channels)**
- **Then hadronization, decay, and radiation processes**

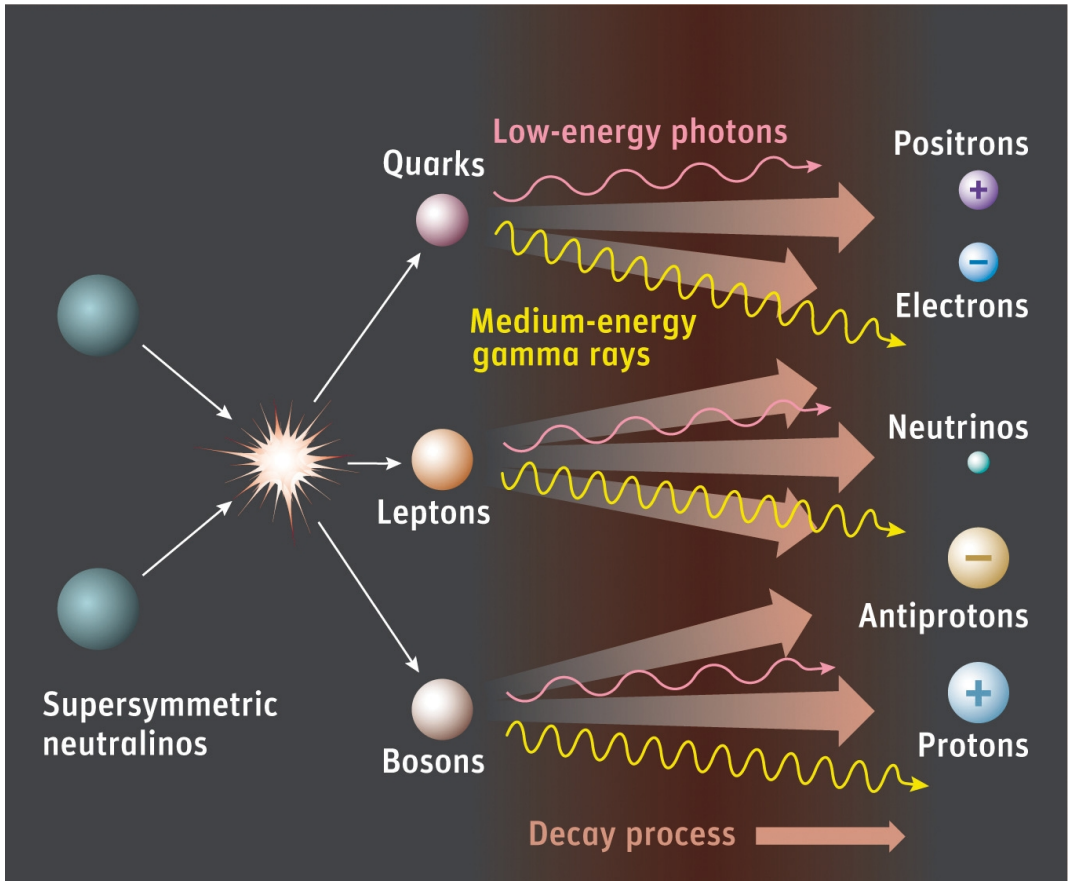
  → final states:

  photons

  electrons/positrons

  protons/antiprotons

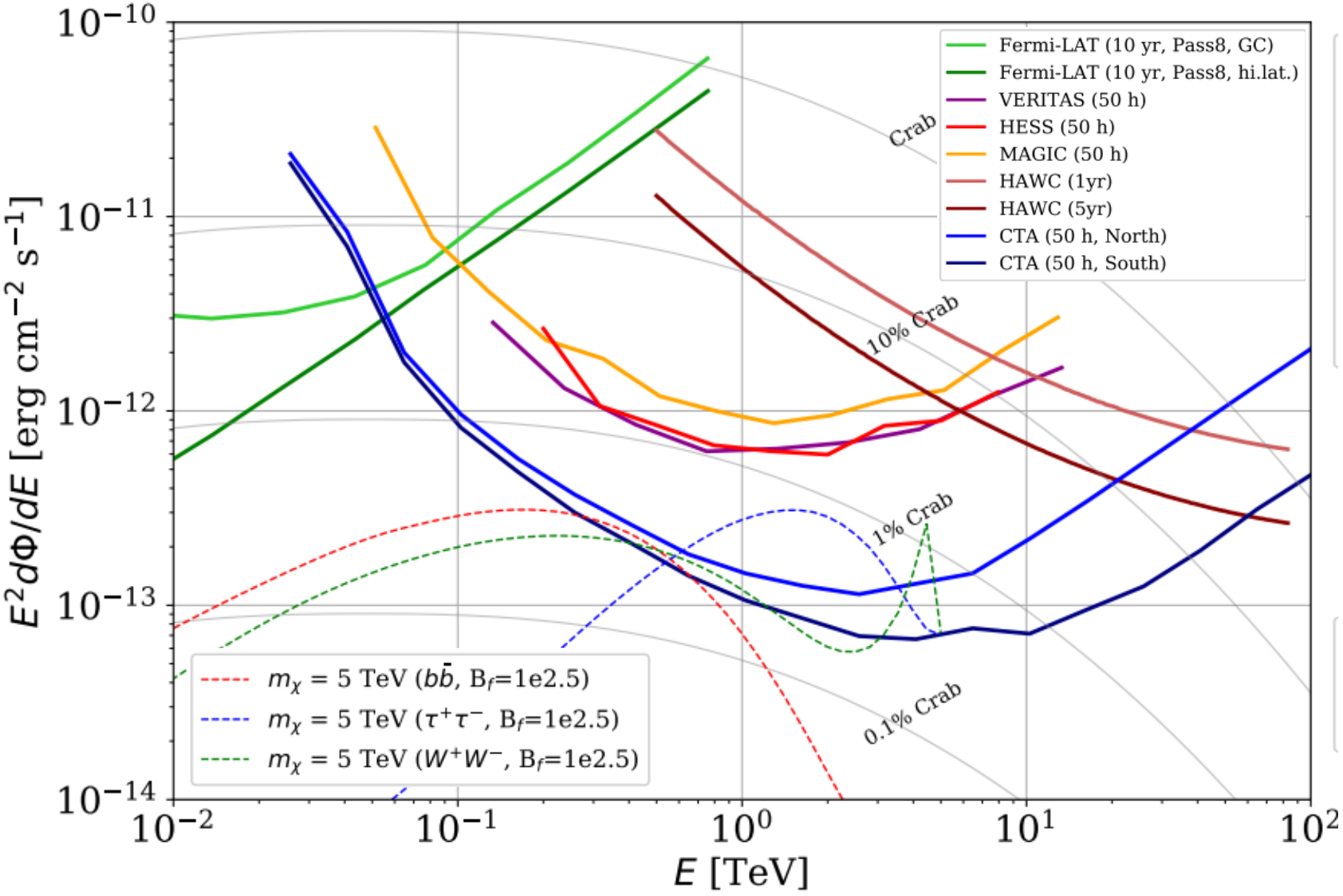
  neutrinos
- **Spectral features allow to determine mass and cross-section/lifetime**
- **Electrically neutral messengers don’t get deflected**



Many type of detectors

- **Photons**
  - Fermi-LAT, DAMPE
  - H.E.S.S., MAGIC, VERITAS
  - HAWC, LHAASO
- **Neutrinos**
  - IceCube, ANTARES, KM3NeT...
- **Electrons/positrons**
  - AMS-02, CALET, DAMPE, Fermi-LAT...
- **Protons/antiprotons**
  - AMS-02, CALET, DAMPE, Fermi-LAT, GRAPES-III, CREAM...

Sensitivity of gamma-ray detectors



Expected flux

- In the case of dark matter **annihilation**:

$$\frac{\Phi_{\rm ann}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m_{\rm DM}^2} \left.\frac{{\rm d}N}{{\rm d}E}\right|_{E=(1+z)E_\gamma} \times e^{-\tau(z,E_\gamma)} \times \underbrace{(1+z)^3 \int_0^{\Delta\Omega}\int_{\rm l.o.s.} \rho(l,\Omega)^2\, {\rm d}l\, {\rm d}\Omega}_{=: J_{\rm ann}}$$

- In the case of dark matter **decay**:

$$\frac{\Phi_{\rm decay}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi\, t_{\rm DM}\, m_{\rm DM}} \left.\frac{{\rm d}N}{{\rm d}E}\right|_{E=(1+z)E_\gamma} \times e^{-\tau(z,E_\gamma)} \times \underbrace{\int_0^{\Delta\Omega}\int_{\rm l.o.s.} \rho(l,\Omega)\, {\rm d}l\, {\rm d}\Omega}_{=: J_{\rm dec}}$$

Expected flux

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Parameters of interests

Expected flux

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- In the case of dark matter **decay**:

$$\frac{\Phi_{\rm decay}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi\, t_{\rm DM} m_{\rm DM}} \frac{{\rm d}N}{{\rm d}E}\bigg|_{E=(1+z)E_\gamma} \times e^{-\tau(z,E_\gamma)} \times \underbrace{\int_0^{\Delta\Omega}\int_{\rm l.o.s.} \rho(l,\Omega)\,{\rm d}l\,{\rm d}\Omega}_{=: J_{\rm dec}}$$

Inputs to the analysis

Expected flux

- In the case of dark matter **annihilation**:

$$\frac{\Phi_{\rm ann}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m_{\rm DM}^2} \left.\frac{{\rm d}N}{{\rm d}E}\right|_{E=(1+z)E_\gamma} \times e^{-\tau(z,E_\gamma)} \times (1+z)^3 \underbrace{\int_0^{\Delta\Omega}\int_{\rm l.o.s.} \rho(l,\Omega)^2\, {\rm d}l\, {\rm d}\Omega}_{=: J_{\rm ann}}$$

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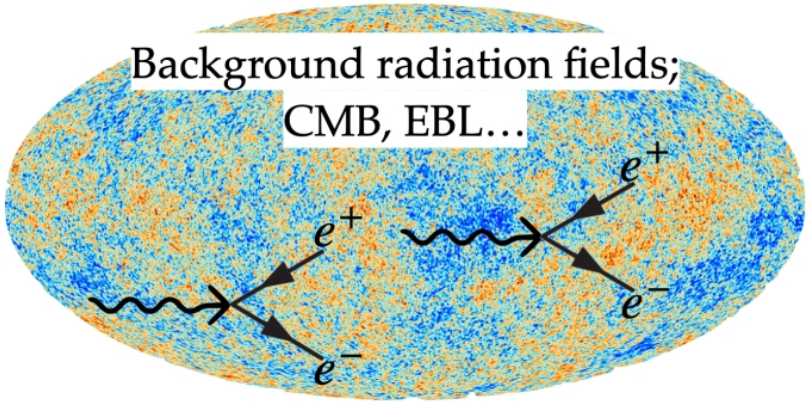


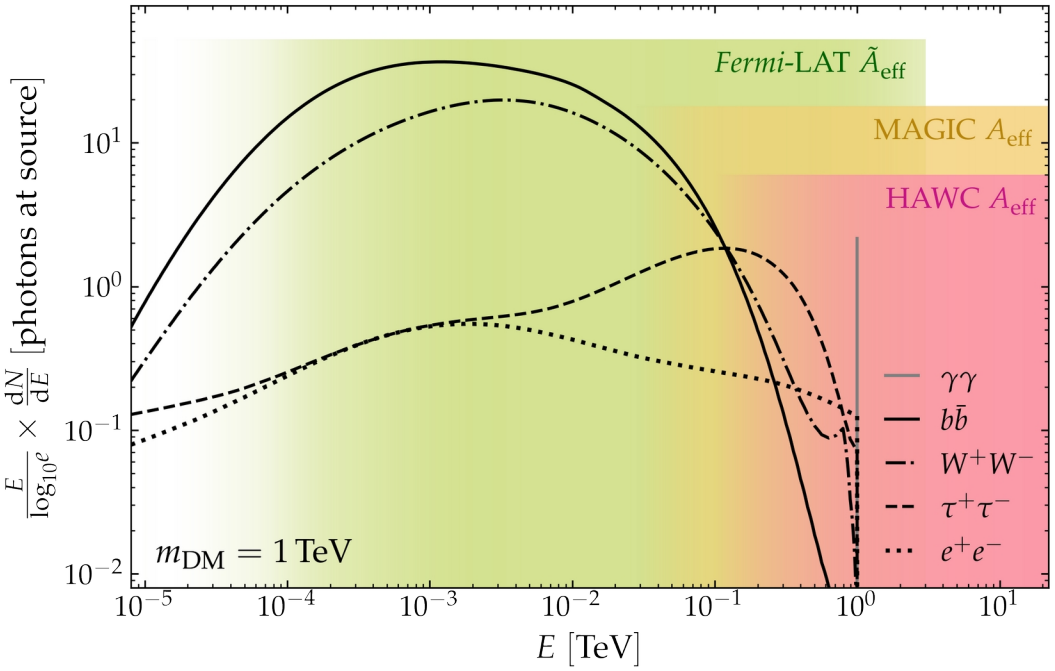
→ Ignored most of the time as we usually observe targets at z~0

Expected flux

$$\frac{\Phi_{\rm ann}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m^2_{\rm DM}} \frac{{\rm d}N}{{\rm d}E} \int_0^{\Delta\Omega} \int_{\rm l.o.s.} \rho(l,\Omega)^2\, {\rm d}l\, {\rm d}\Omega$$

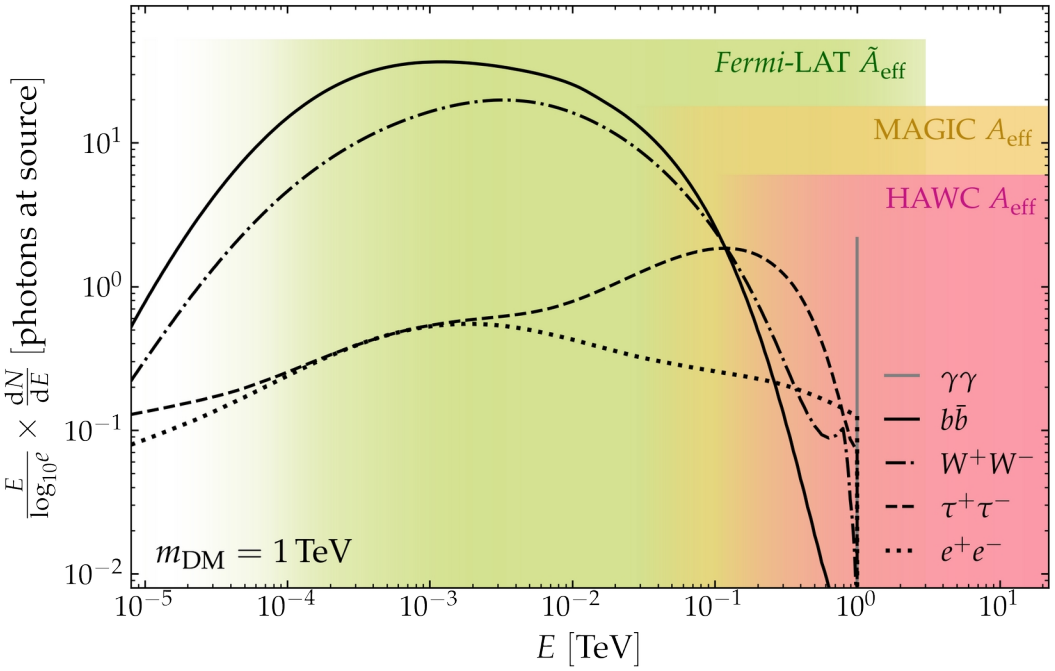
Expected flux

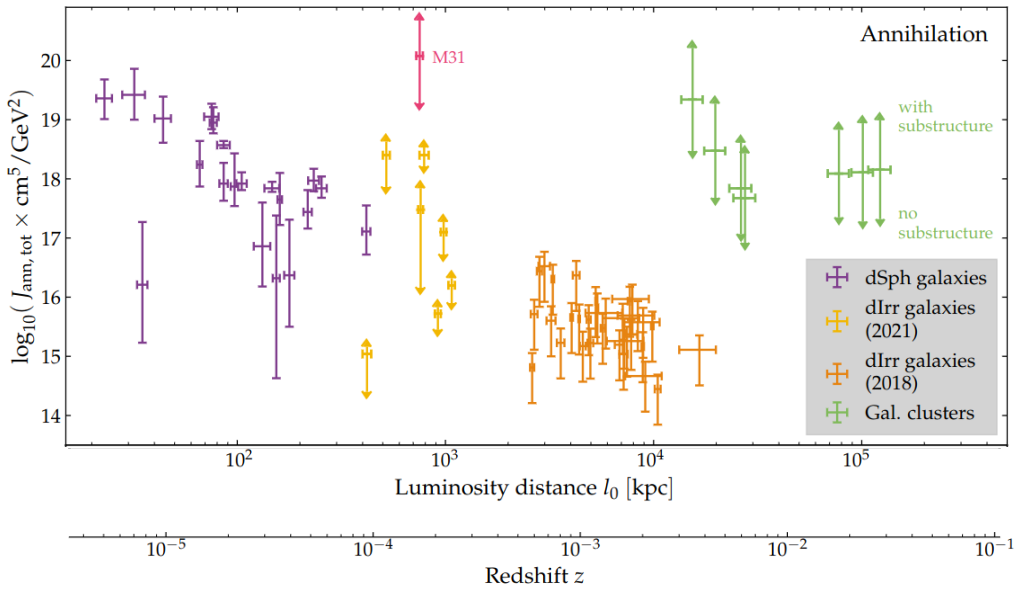
$$\frac{\Phi_{\rm ann}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m_{\rm DM}^2} \frac{{\rm d}N}{{\rm d}E} \int_0^{\Delta\Omega} \int_{\rm l.o.s.} \rho(l,\Omega)^2 \, {\rm d}l \, {\rm d}\Omega$$



Expected flux

$$\frac{\Phi_{\rm ann}}{{\rm d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m_{\rm DM}^2} \frac{{\rm d}N}{{\rm d}E} \int_{\Delta\Omega} \int_{0}^{\text{l.o.s.}} \rho(l,\Omega)^2 \, {\rm d}l \, {\rm d}\Omega$$

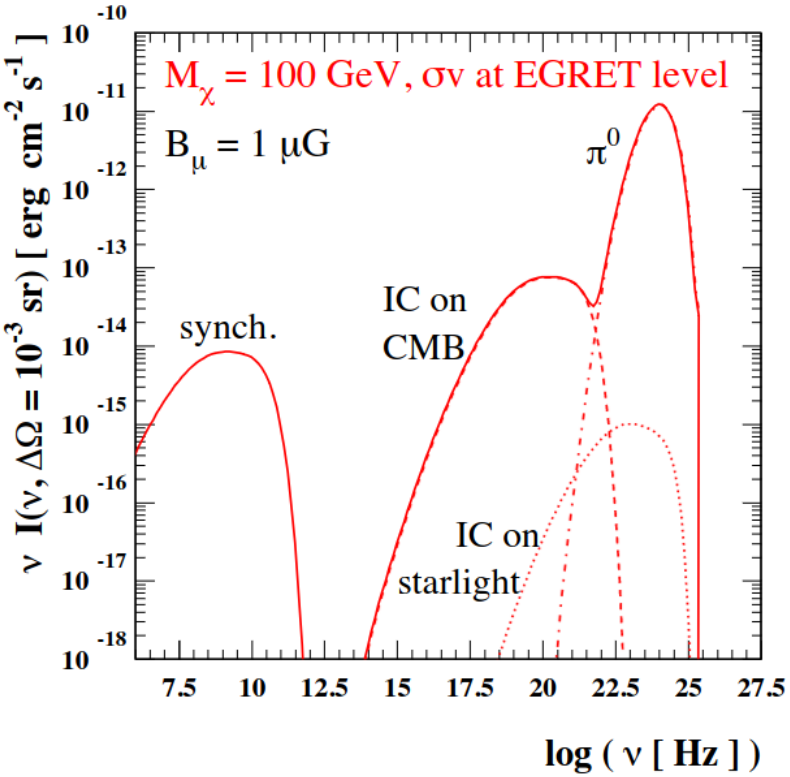


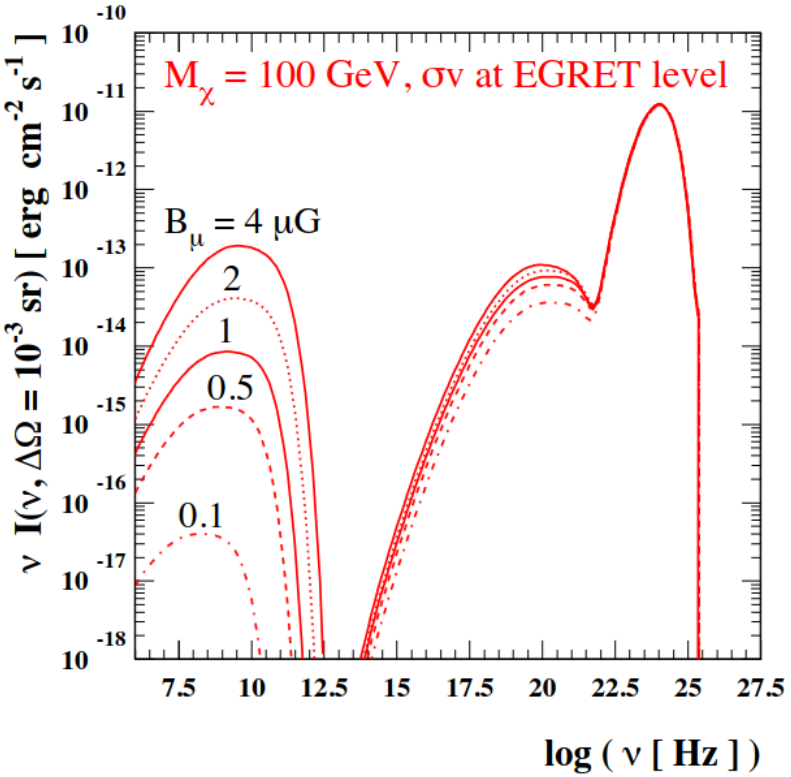


Expected flux: the case of low energy (radio) photons

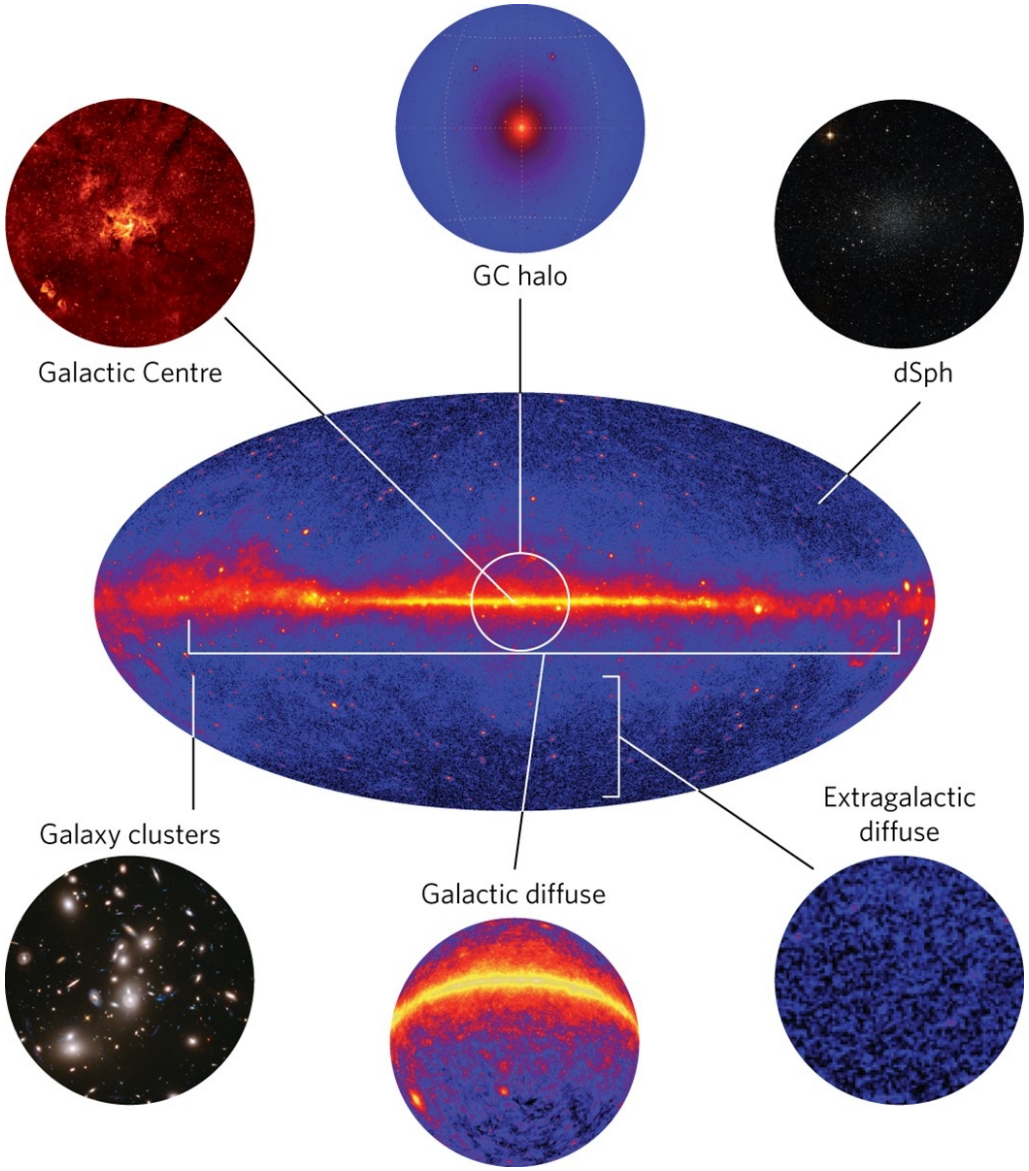
- **Electron/positron population in the GeV-TeV range → photon emission in the MHz-GHz range in presence of ~uG magnetic fields**

$$\frac{\partial n_e}{\partial t} = \nabla\left[D\nabla n_e\right] + \frac{\partial}{\partial E}\left[b_e(E)n_e\right] + Q_e(E,r)$$

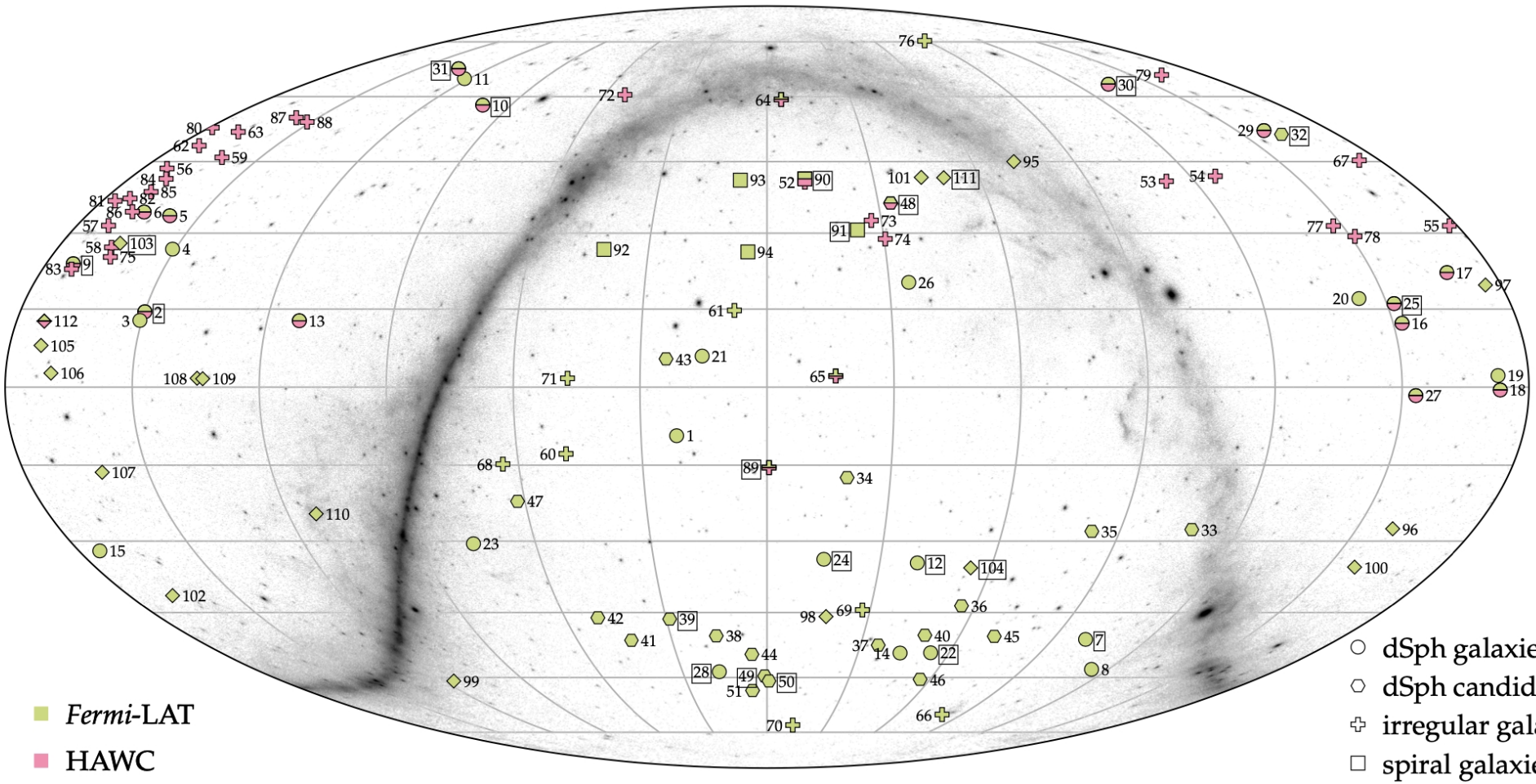




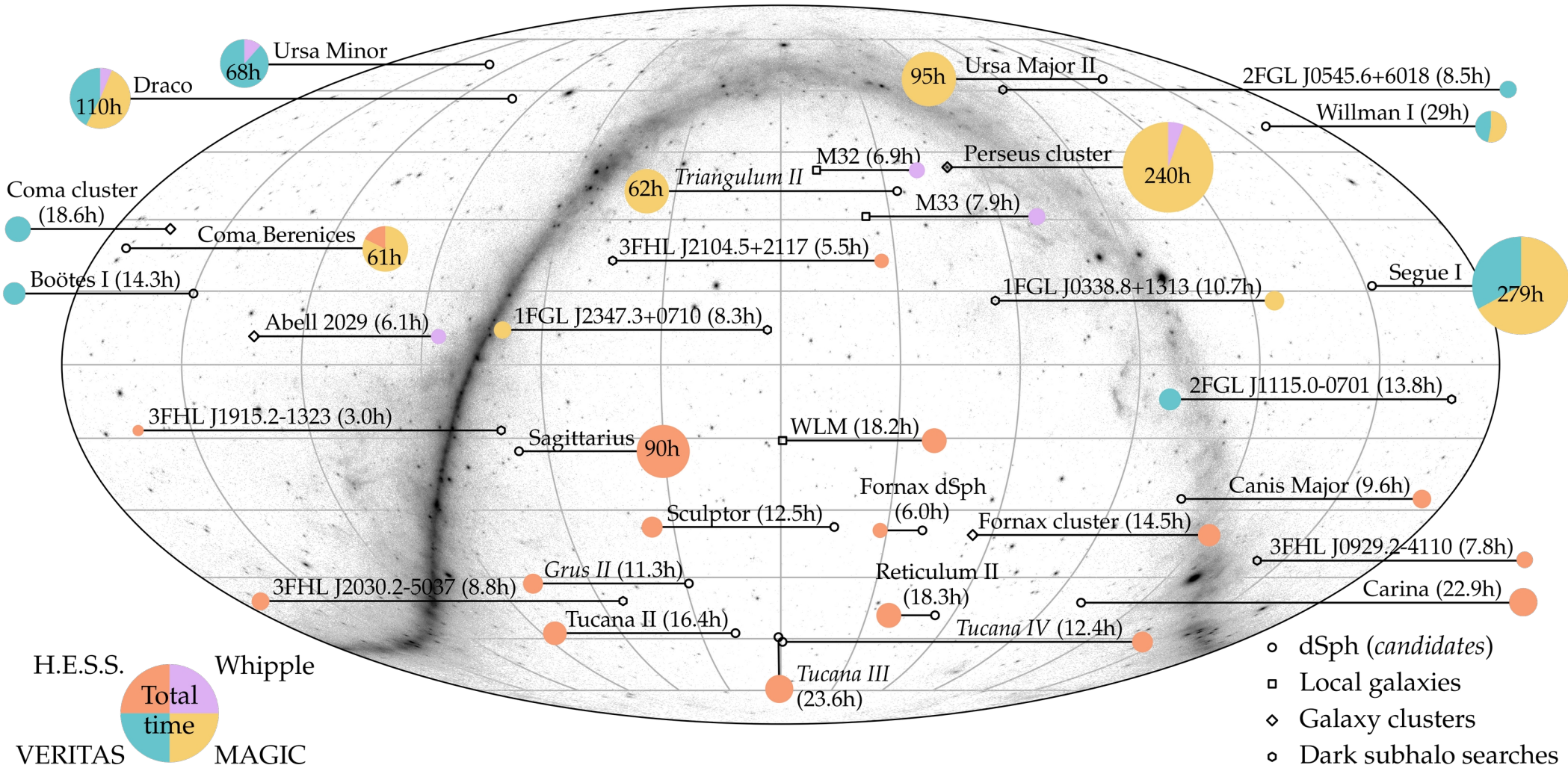
Various types of targets



Targets: Fermi-LAT and HAWC

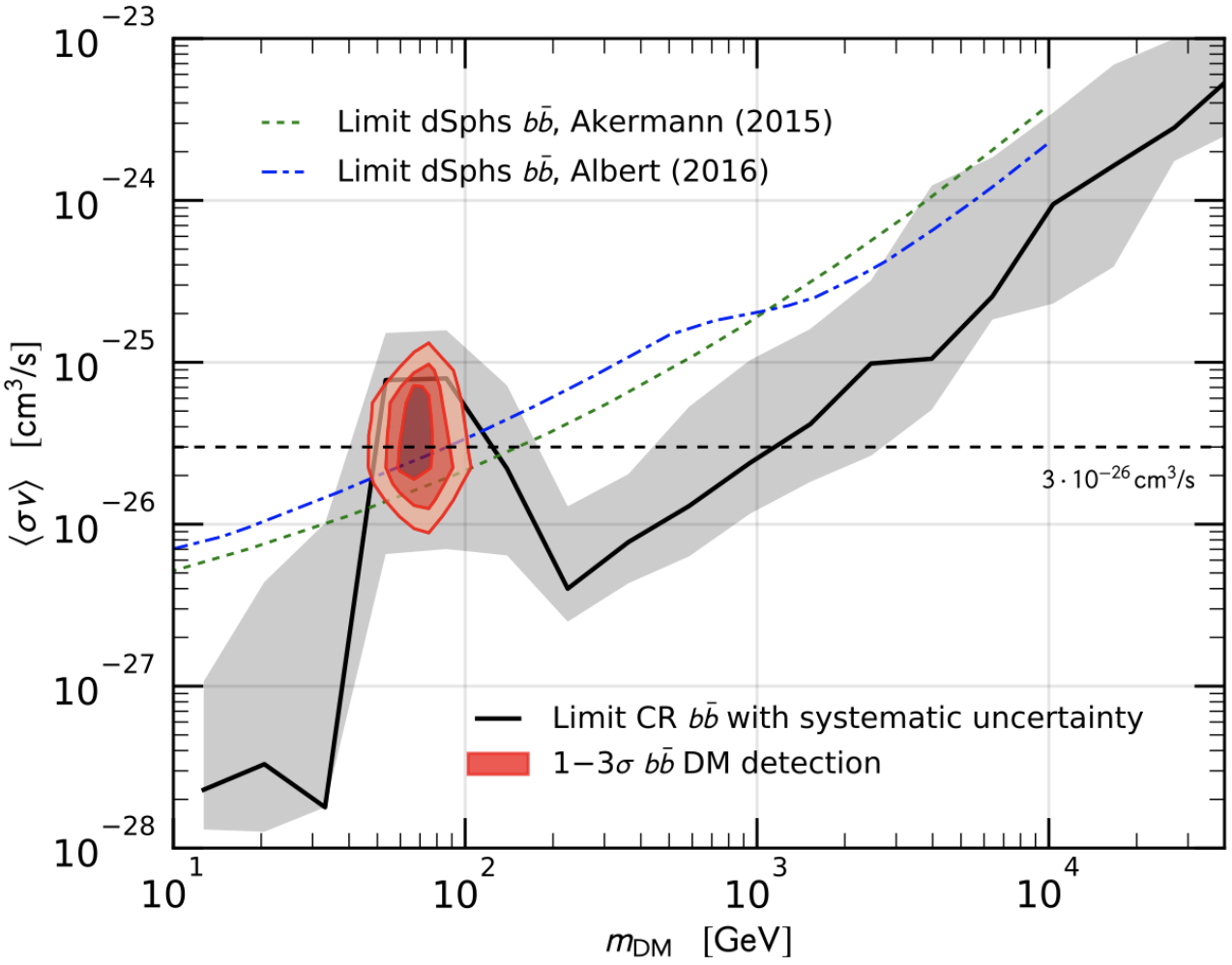


Targets: IACTs



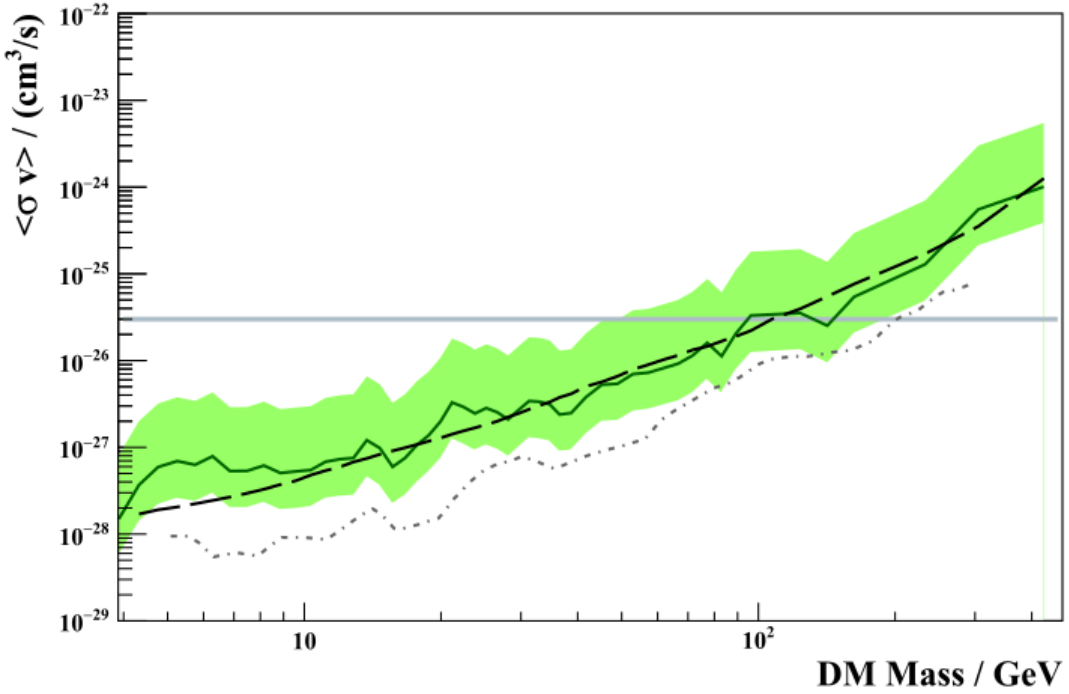
Diffuse spectrum (I)

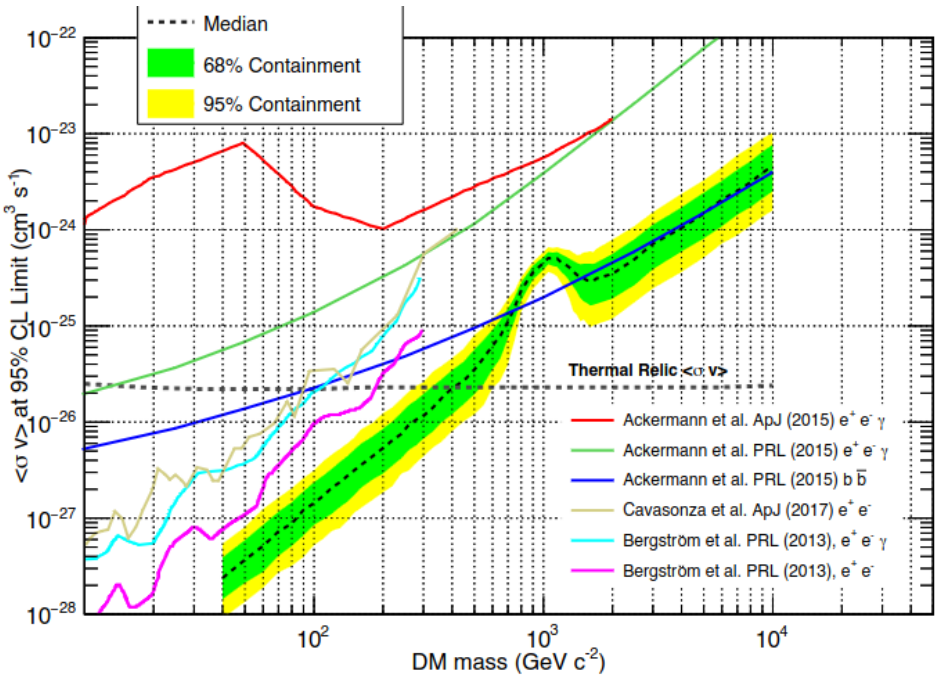
- **Antiprotons**



Diffuse spectrum (II)

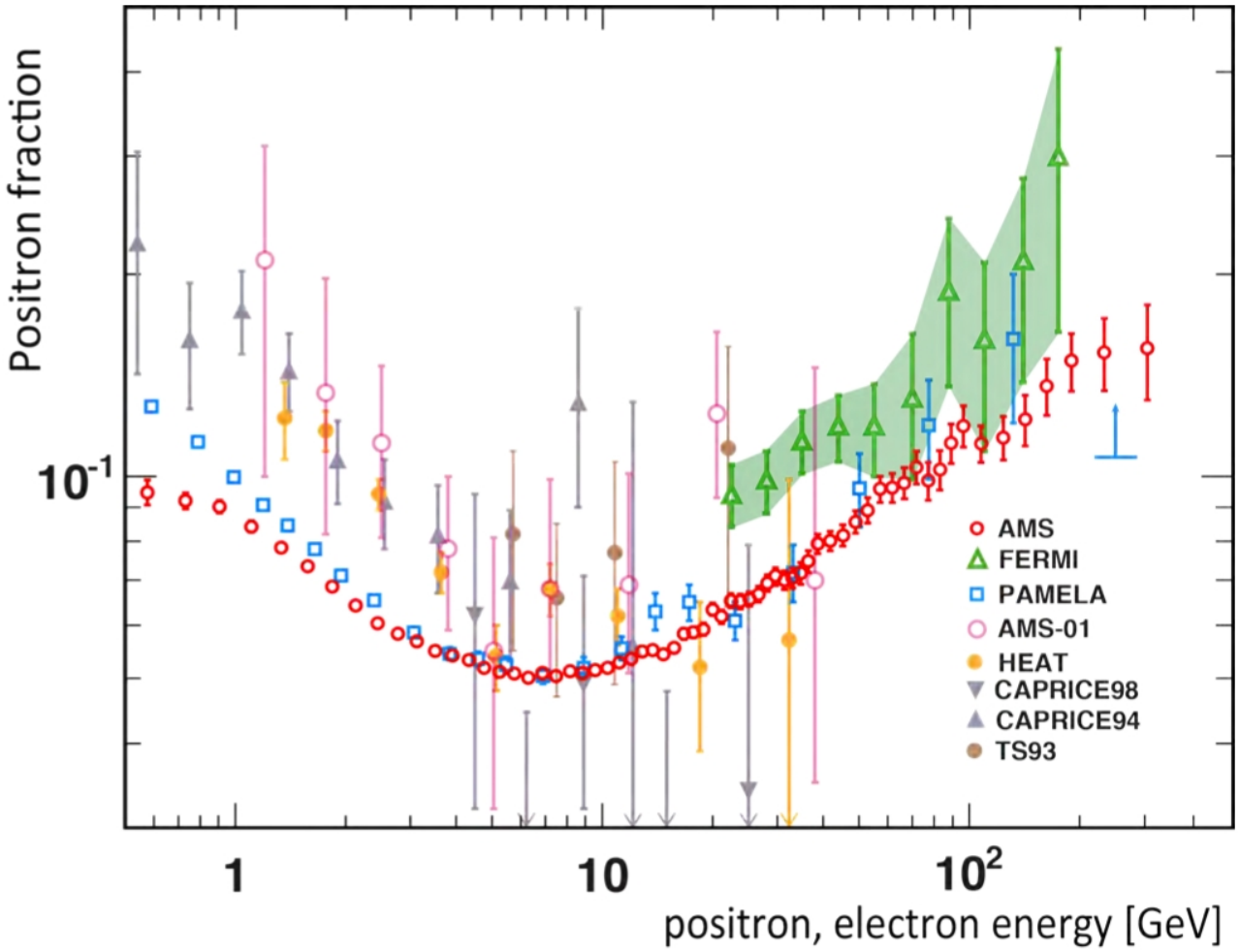
- **Electrons + positrons**





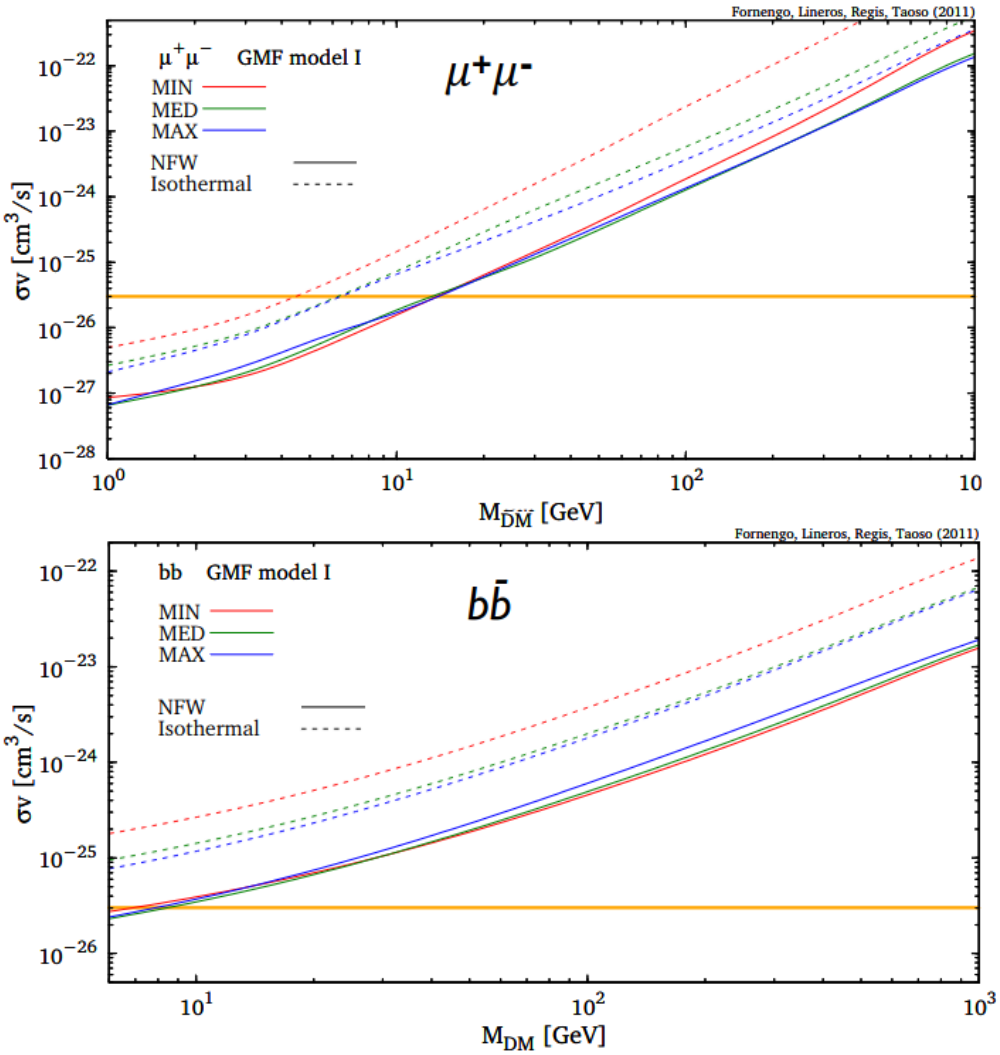
Diffuse spectrum (III)

- **Positron fraction**



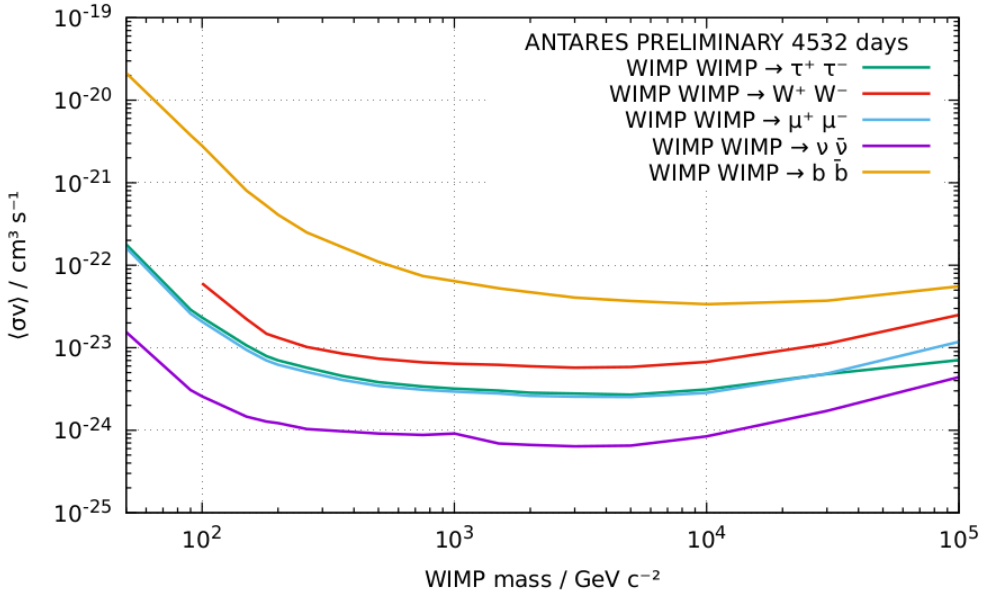
Galactic Center (I)

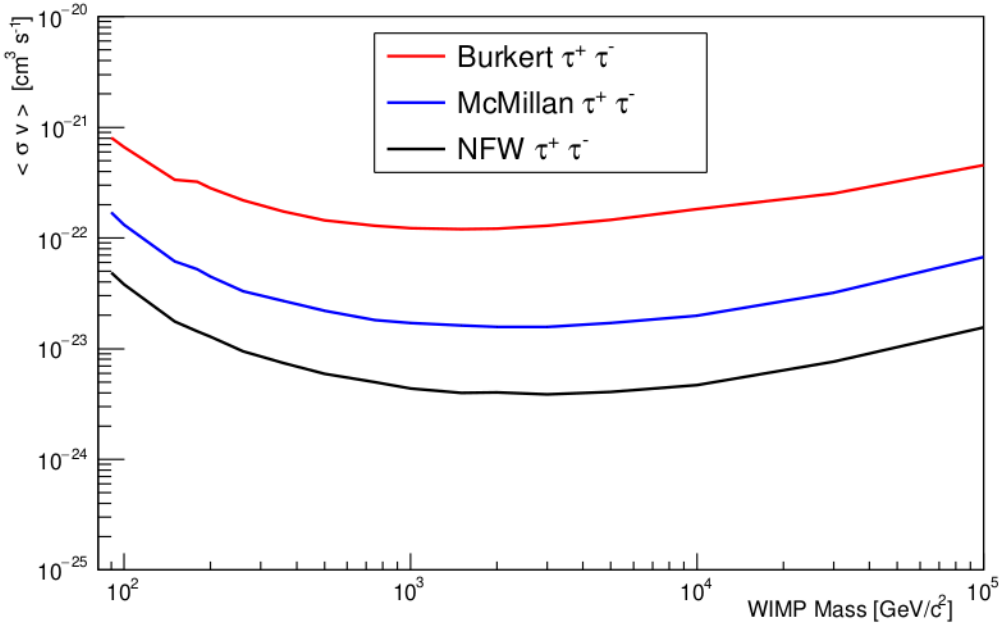
- **Low energy (radio) photons**



Galactic Center (II)

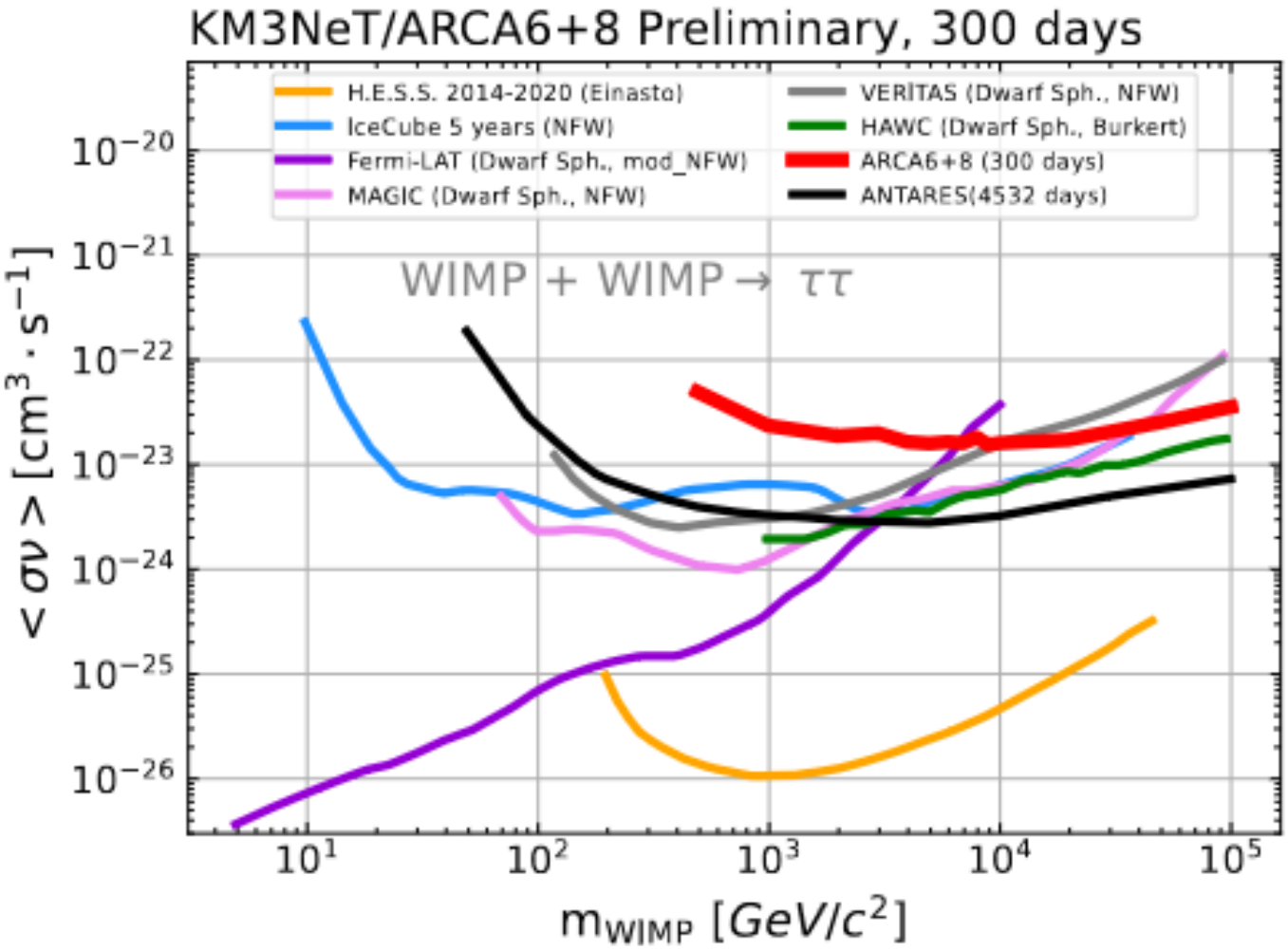
- **Neutrinos with ANTARES**





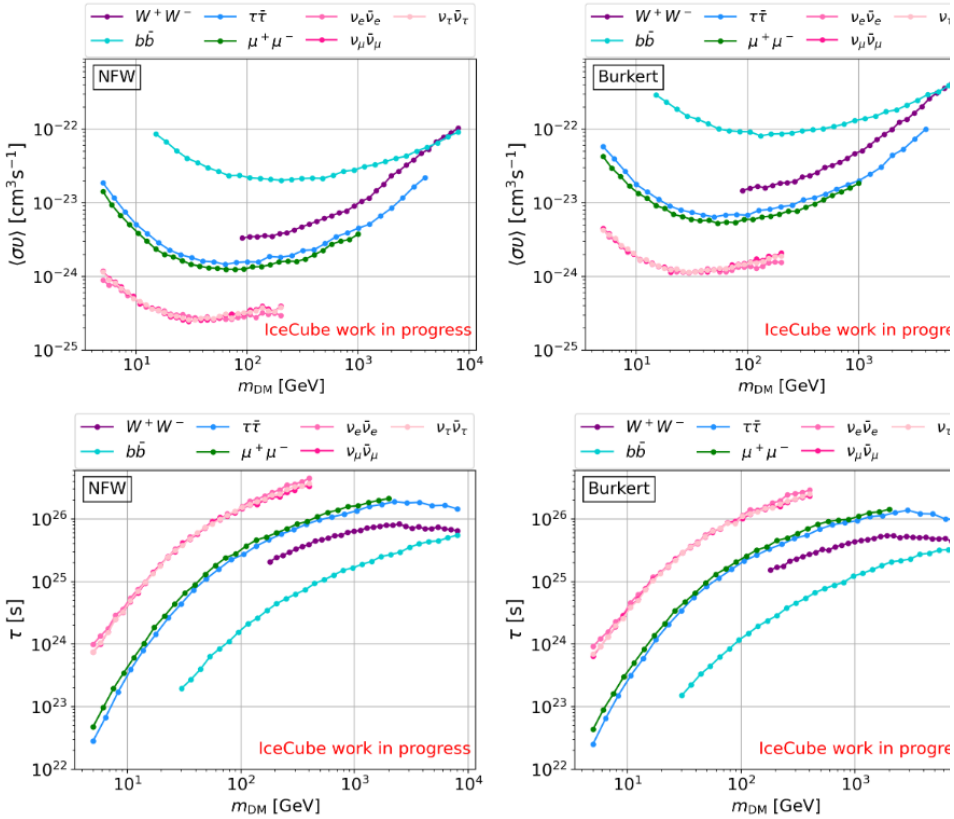
Galactic Center (III)

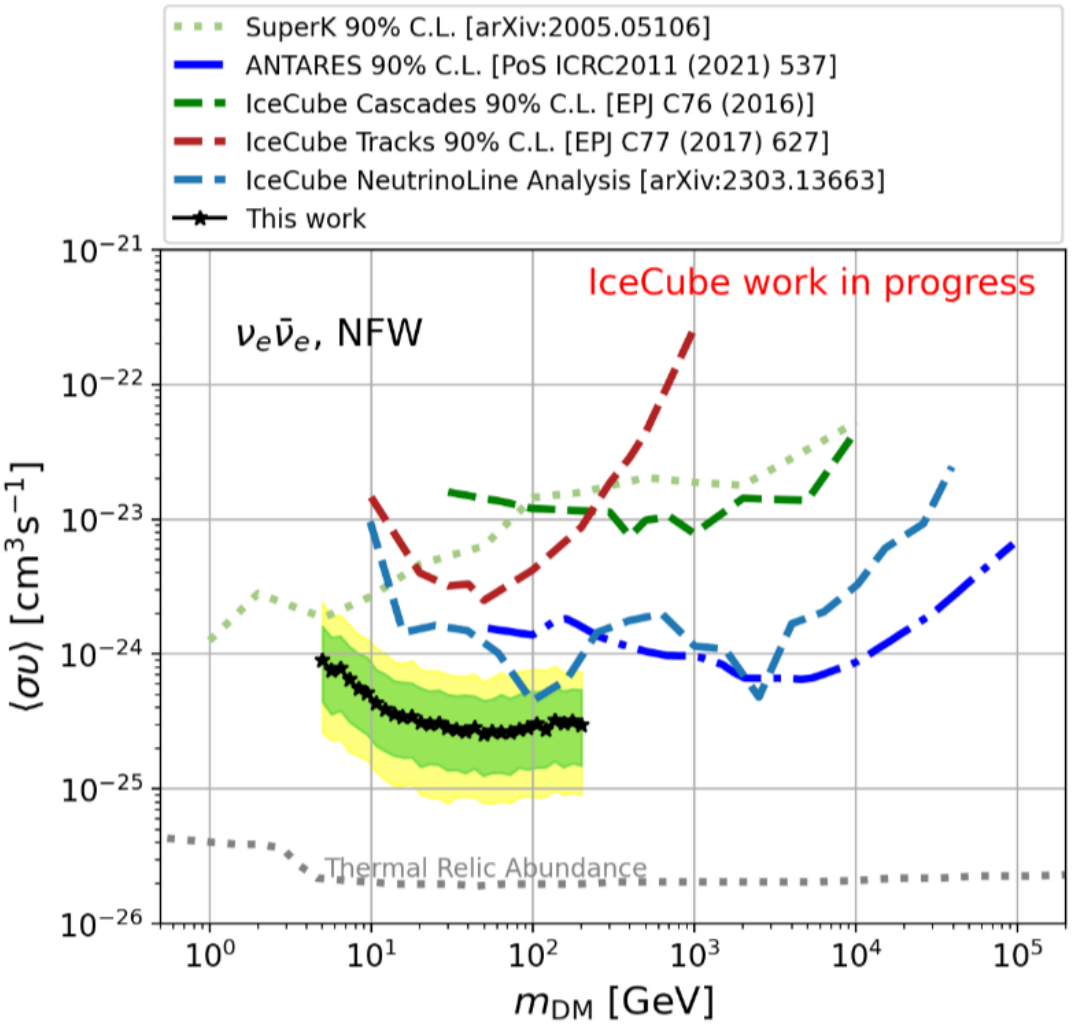
- **Neutrinos with KM3NeT/ARCA**



Galactic Center (IV)

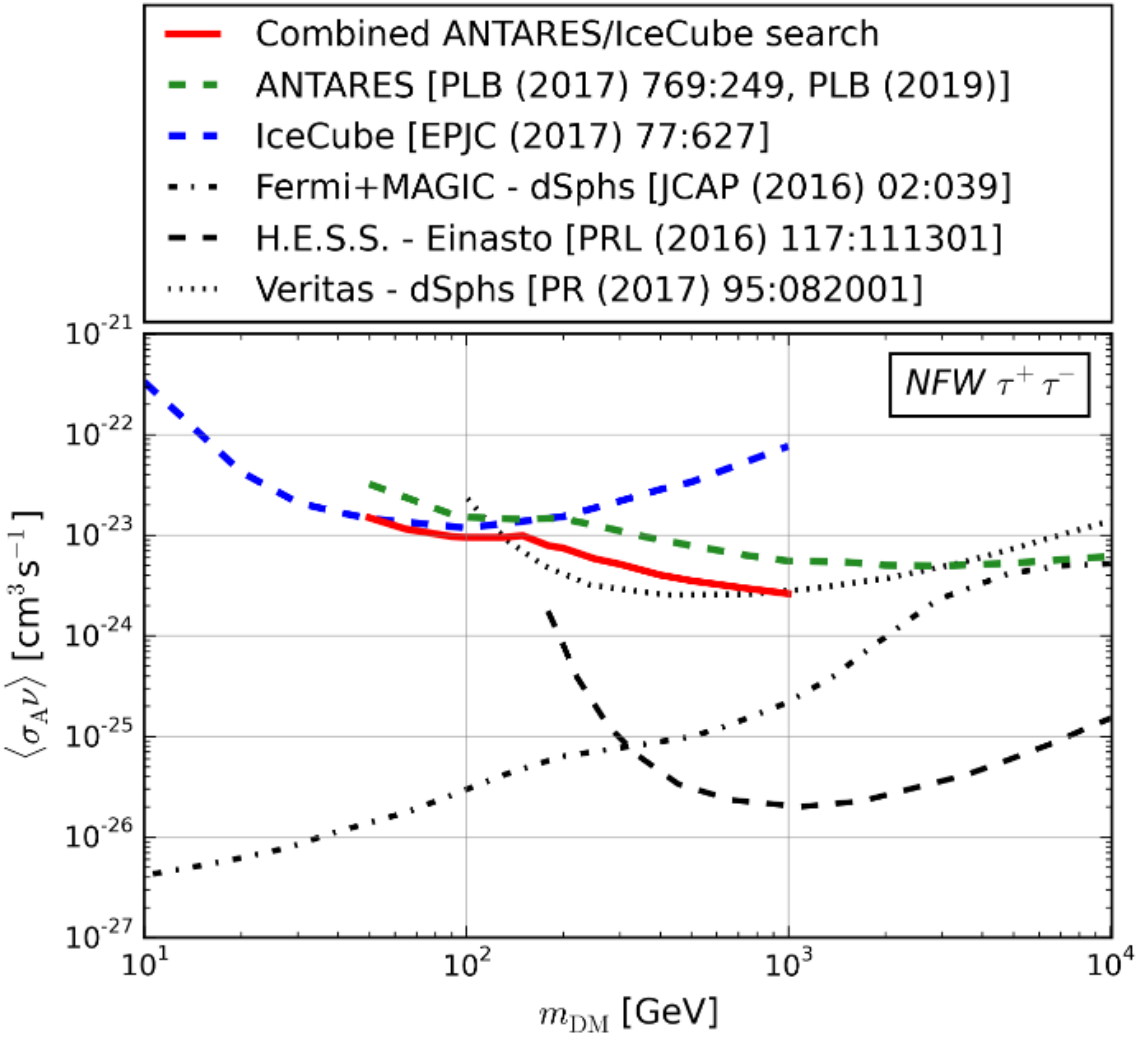
- **Neutrinos with IceCube**





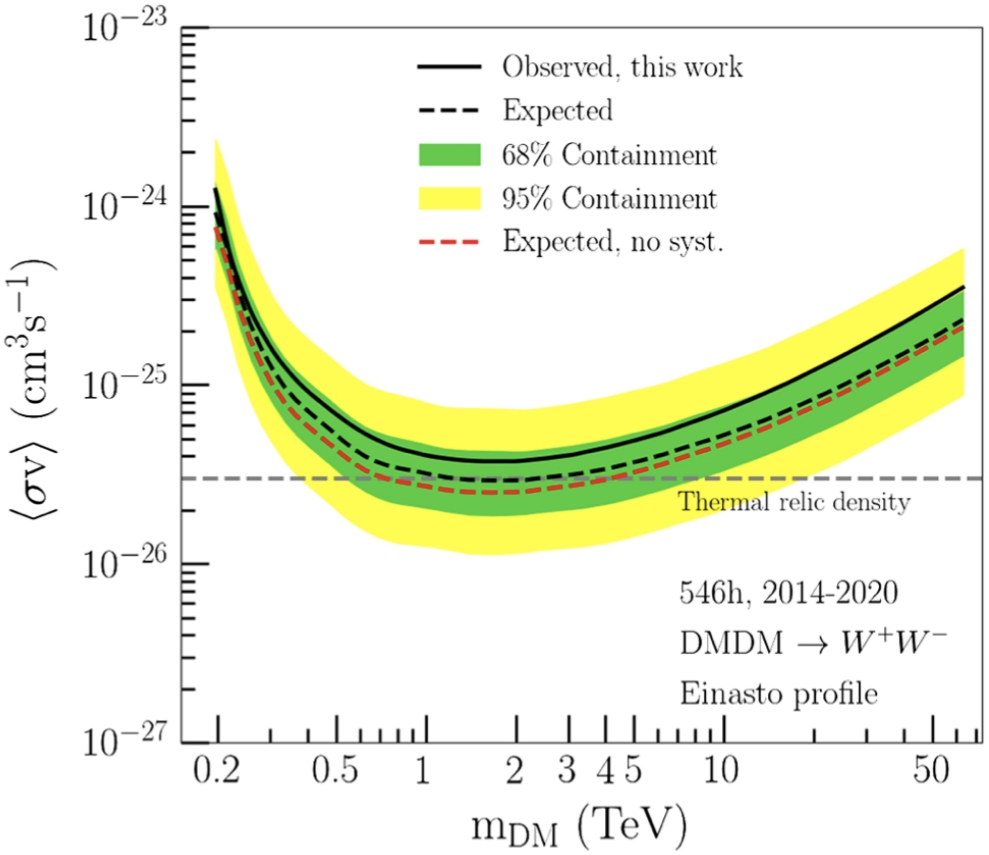
Galactic Center (V)

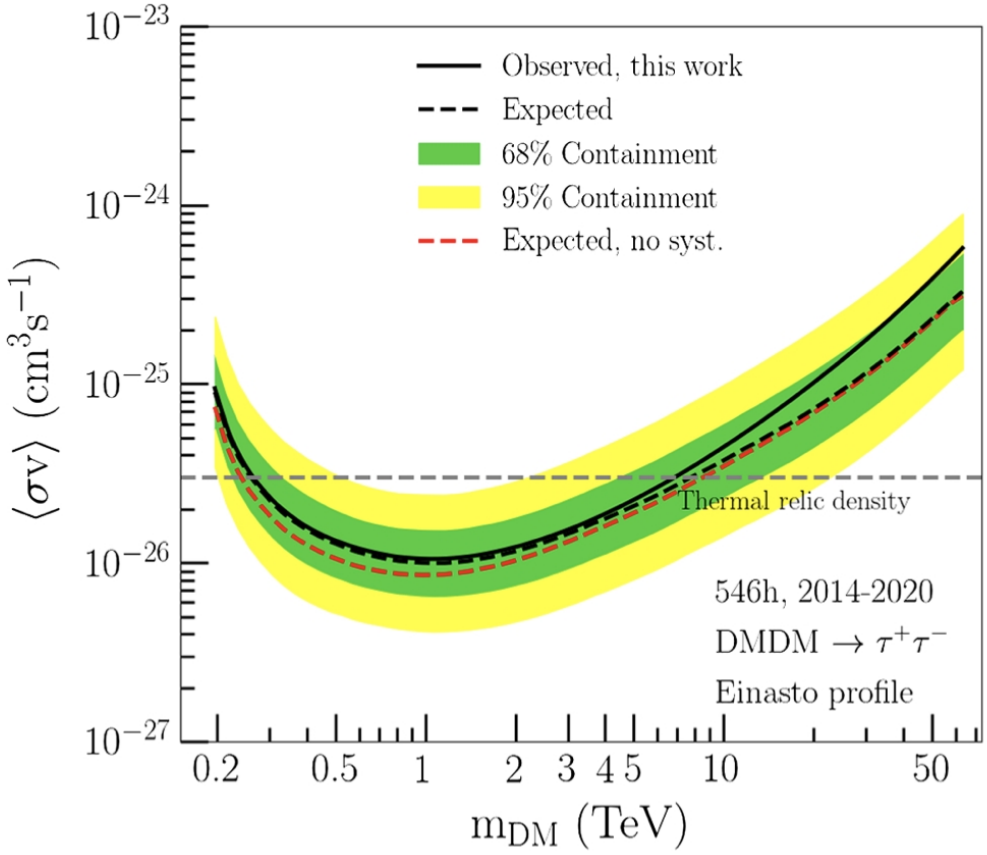
- **Combined ANTARES+IceCube search**



Galactic Center (VI)

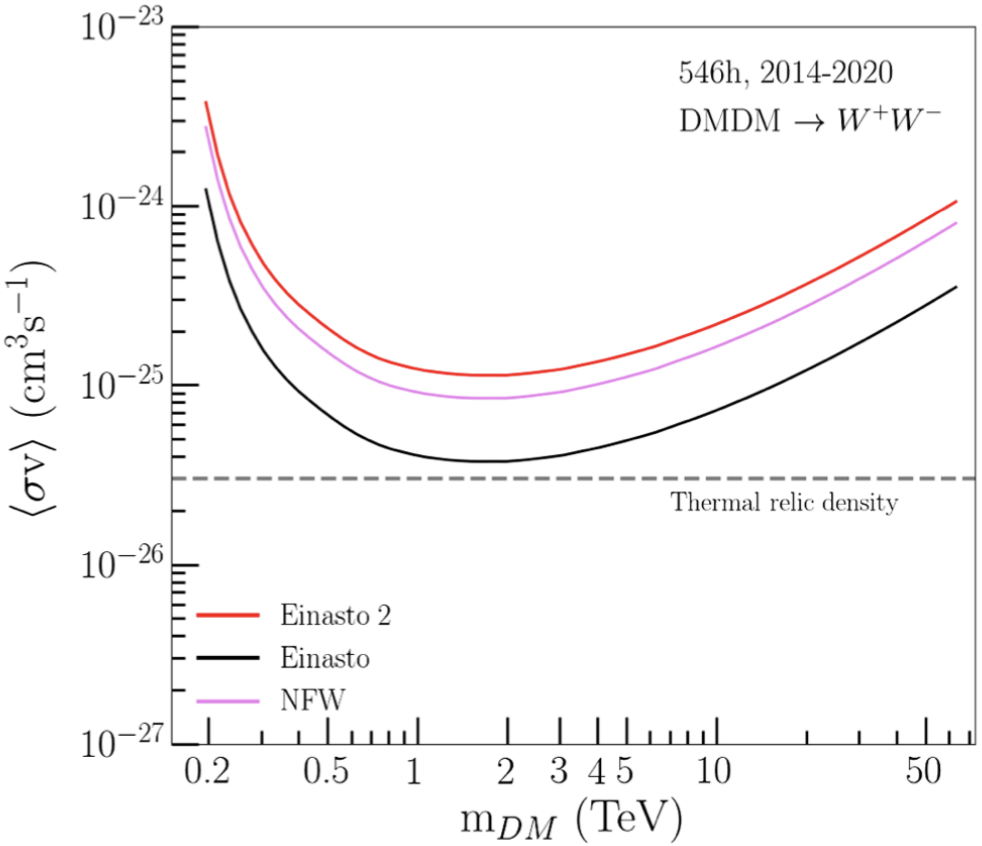
- **High energy (gamma rays) photons, H.E.S.S.**

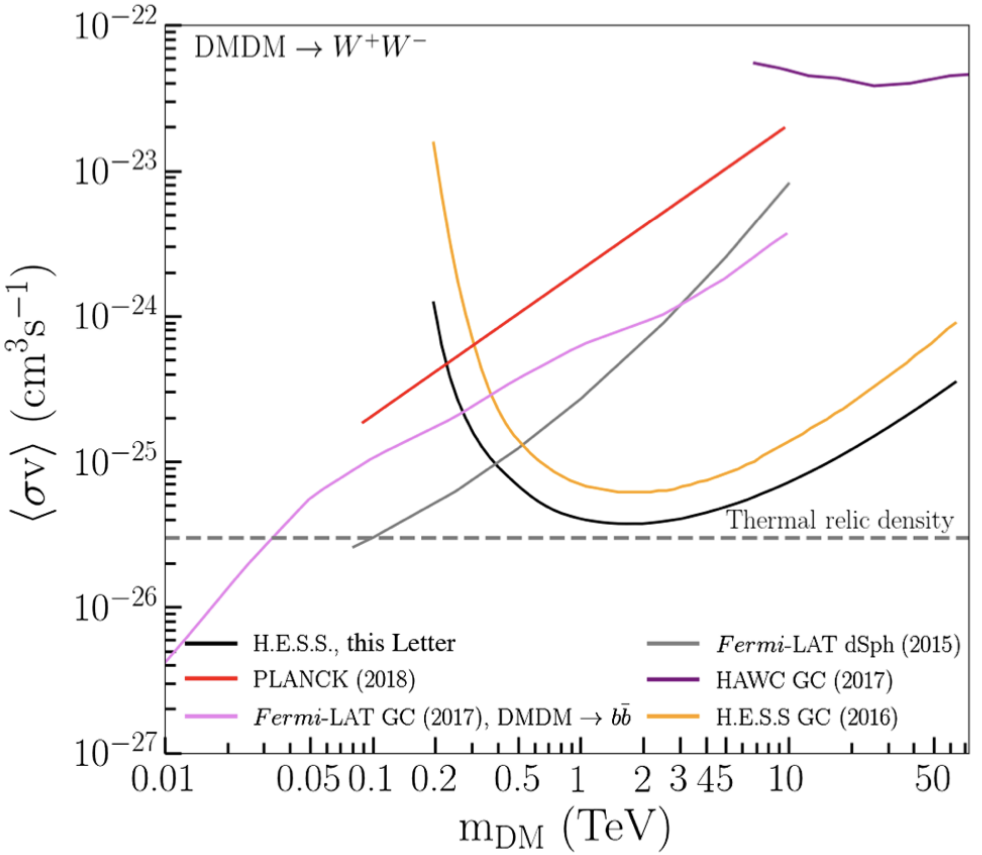




Galactic Center (VII)

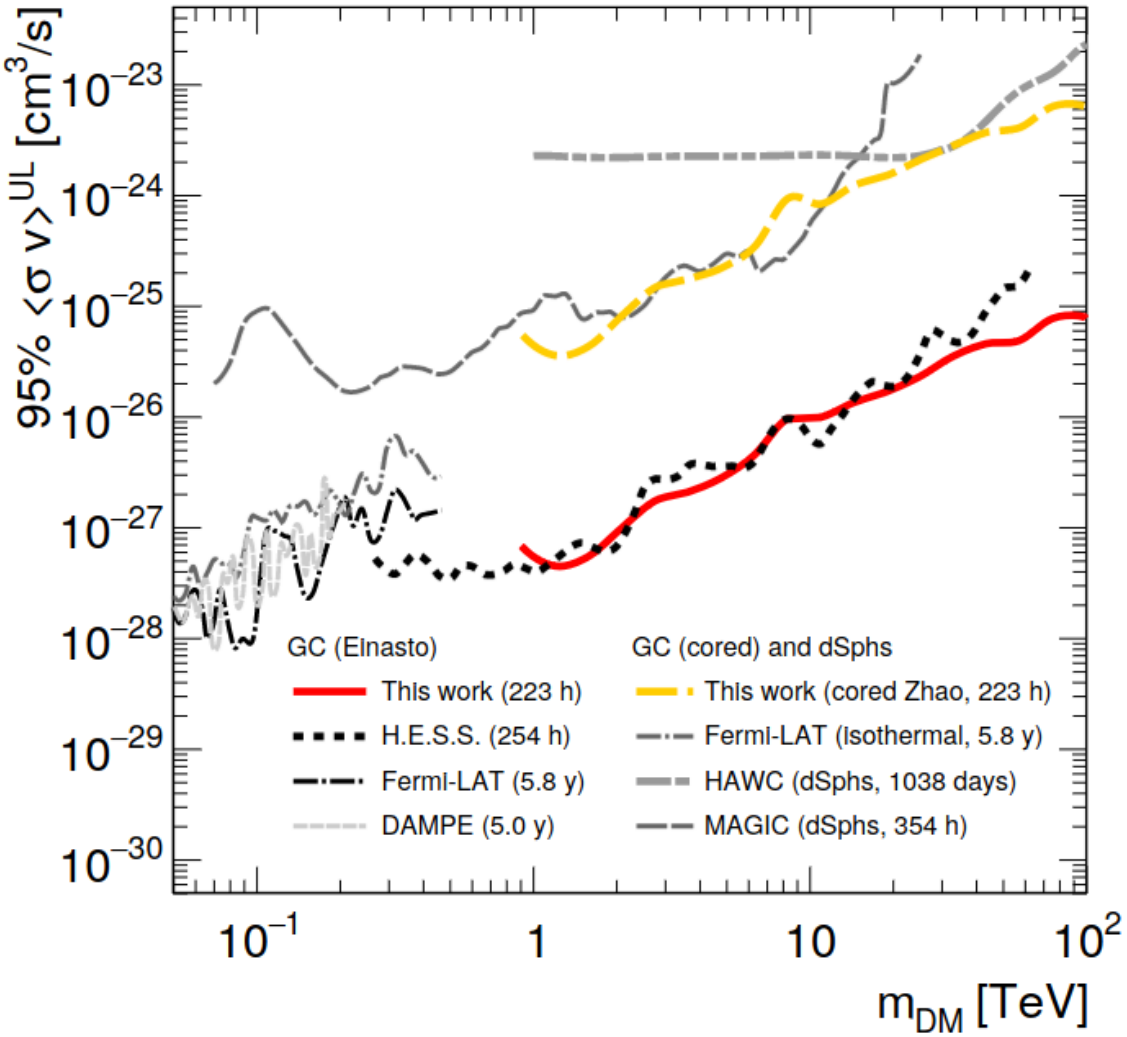
- **High energy (gamma rays) photons, H.E.S.S.**





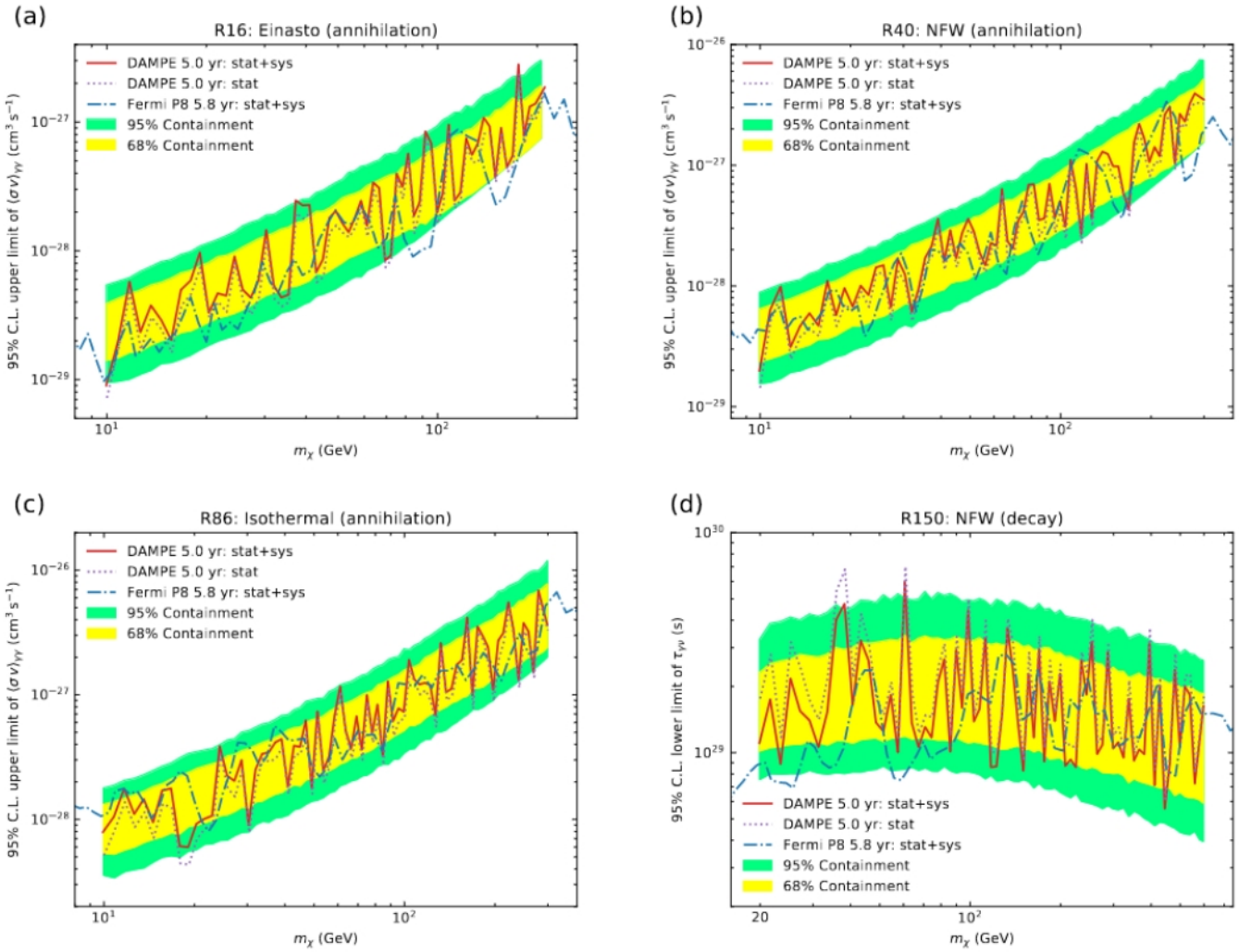
Galactic Center (VIII)

- **High energy (gamma rays) photons, MAGIC**



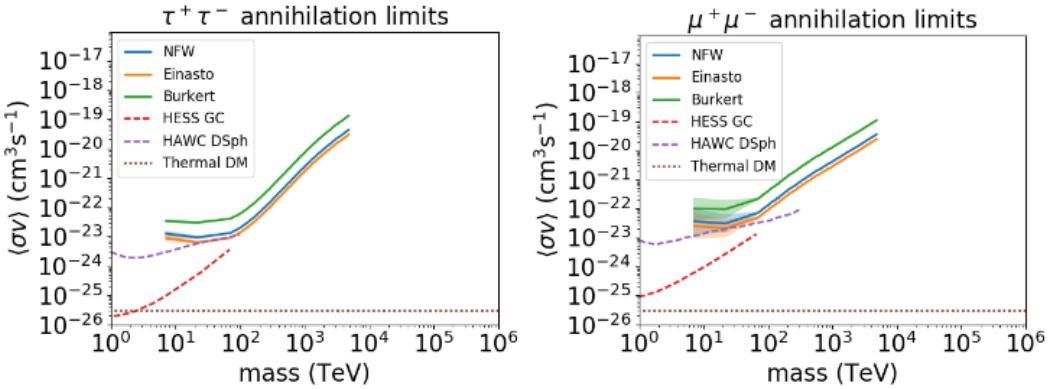
Galactic Center (IX)

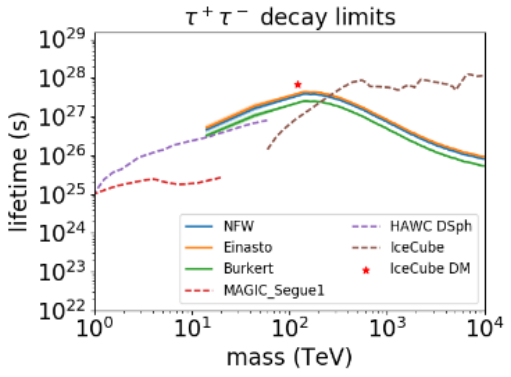
- **High energy (gamma rays) photons, DAMPE**

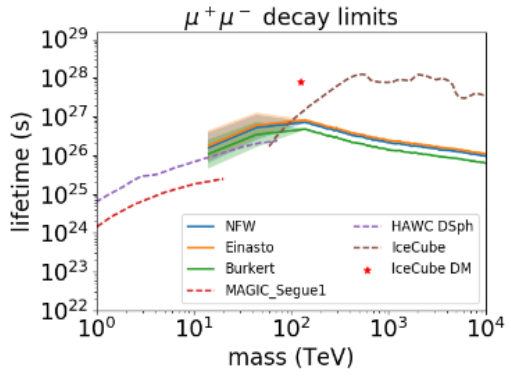


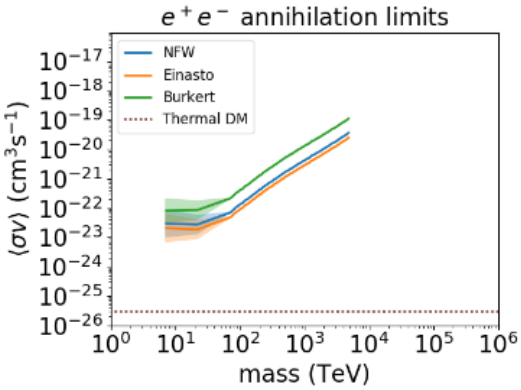
Galactic Center (X)

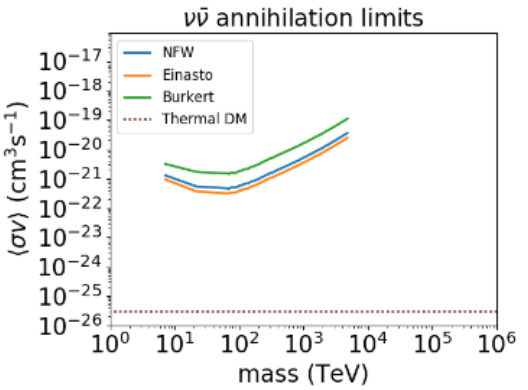
- **High energy (gamma rays) photons, HAWC**

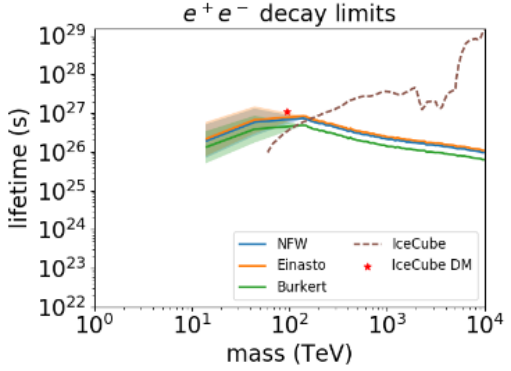


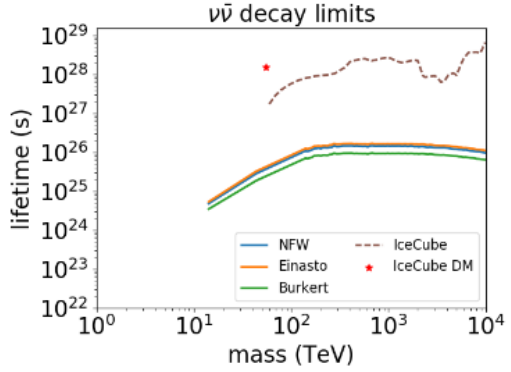






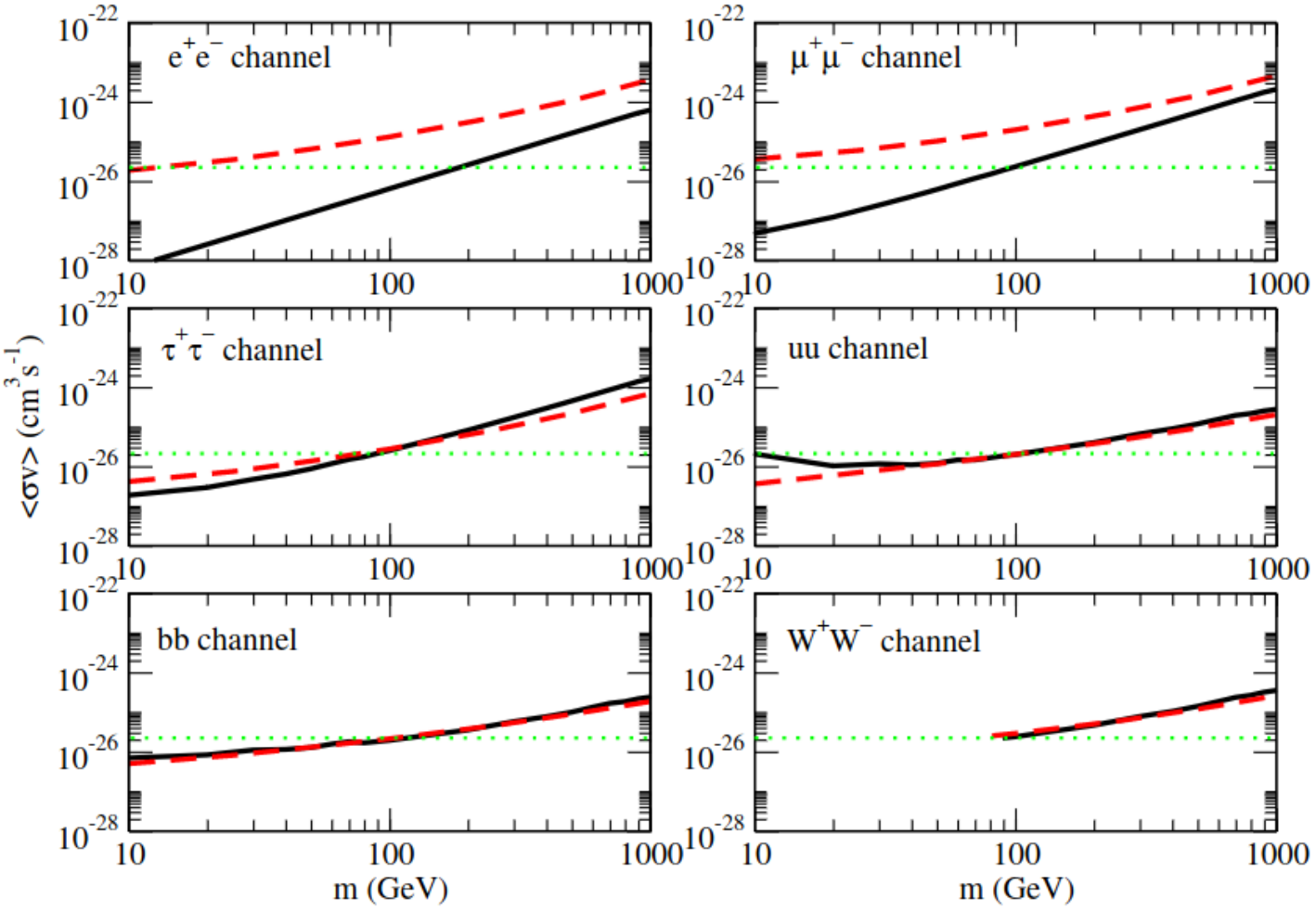






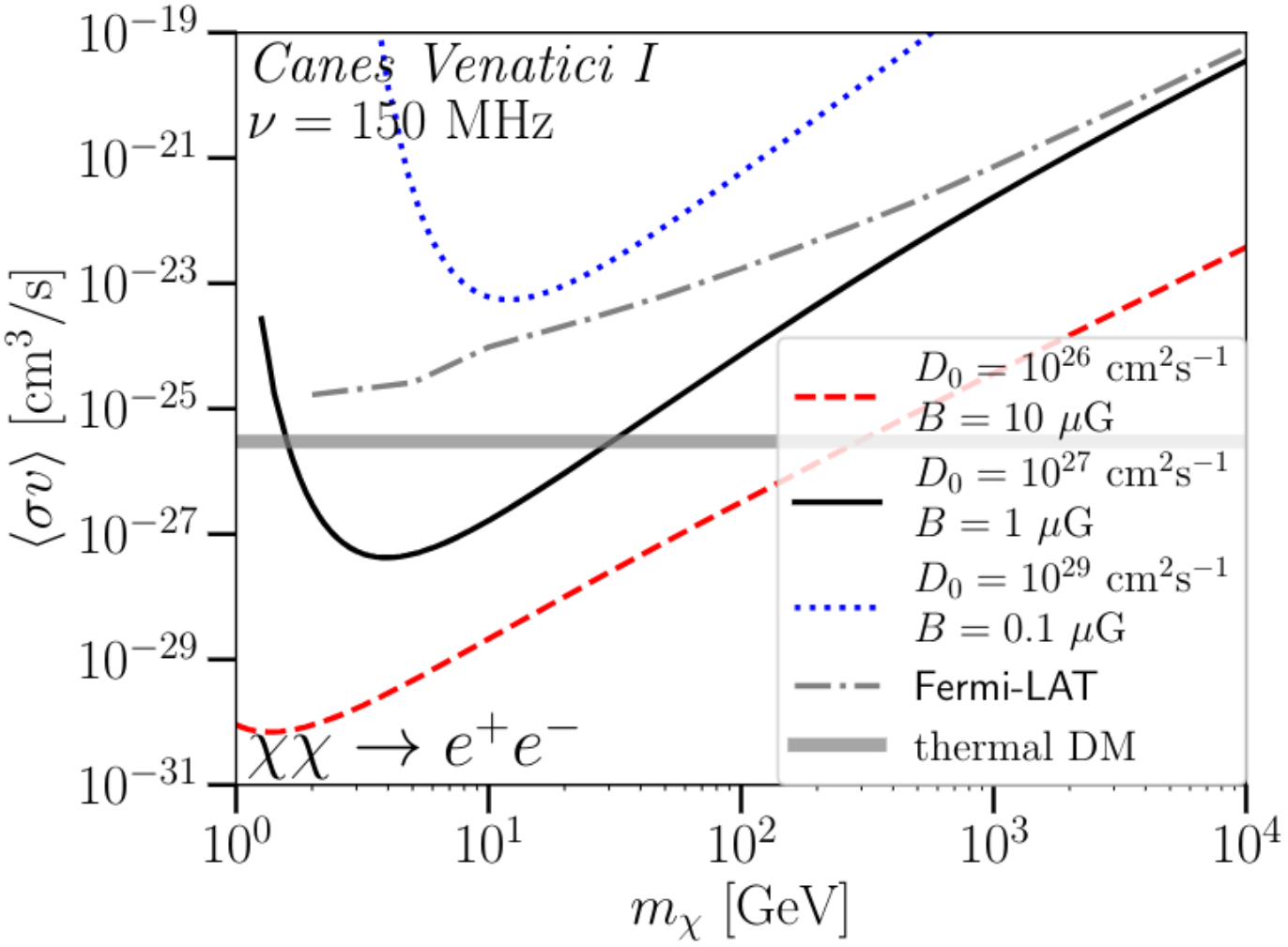
Galaxies: M31 (Andromeda)

- **Low energy (radio) photons with Westerbork Synthesis Radio Telescope data**



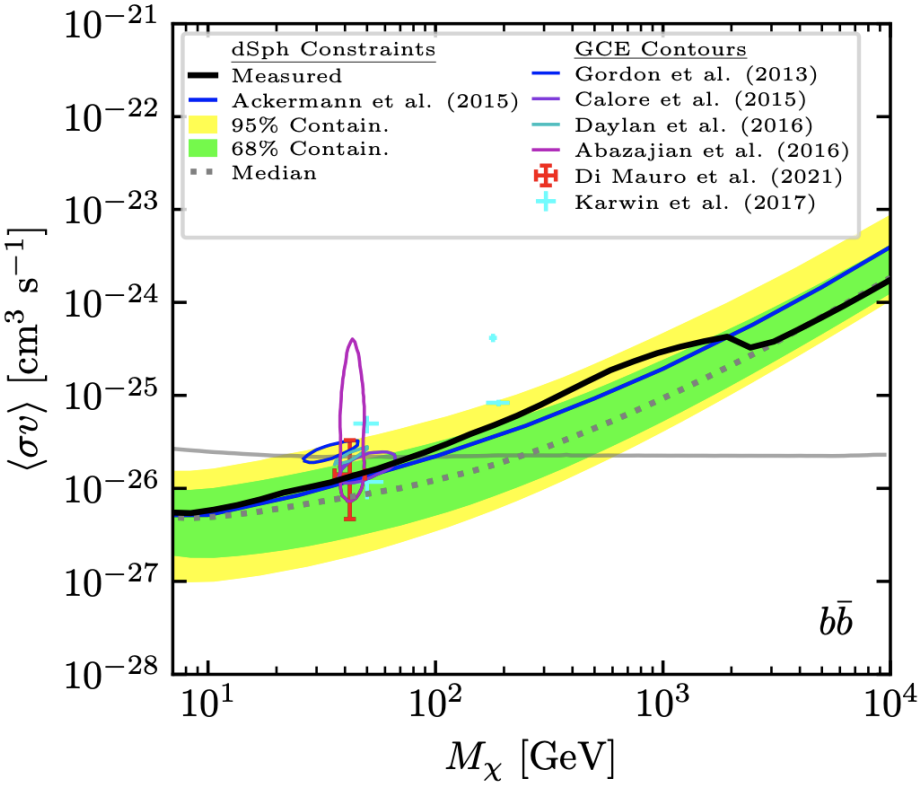
Dwarf spheroidal galaxies (I)

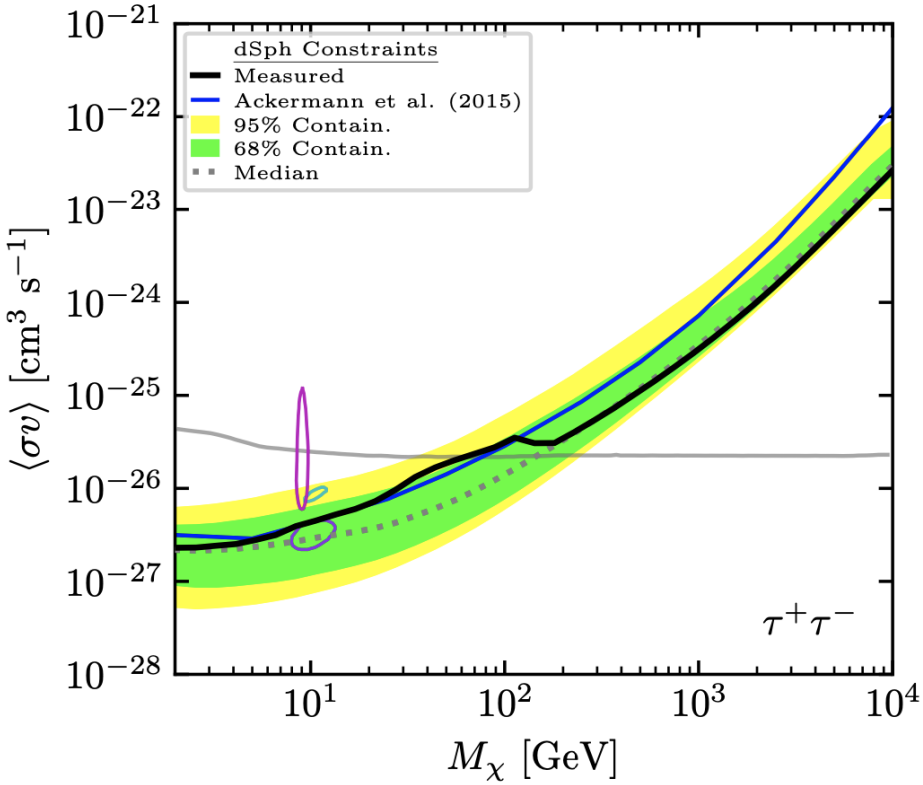
- **Low energy (radio) photons, Canes Venatici I (dSph) with LOFAR**



Dwarf spheroidal galaxies (II)

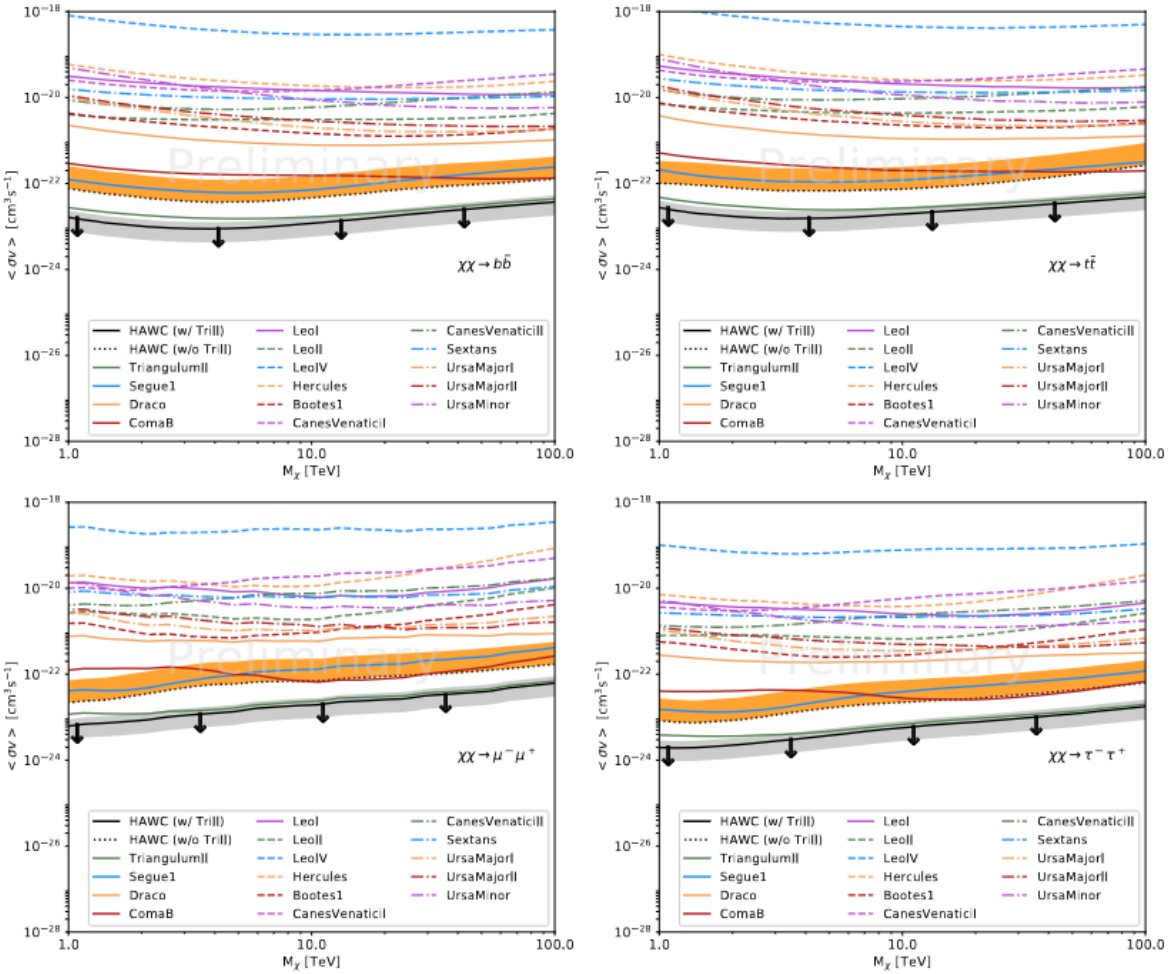
- **High energy (gamma rays) photons, Fermi-LAT**
  → 14 years of data, >30 dSphs





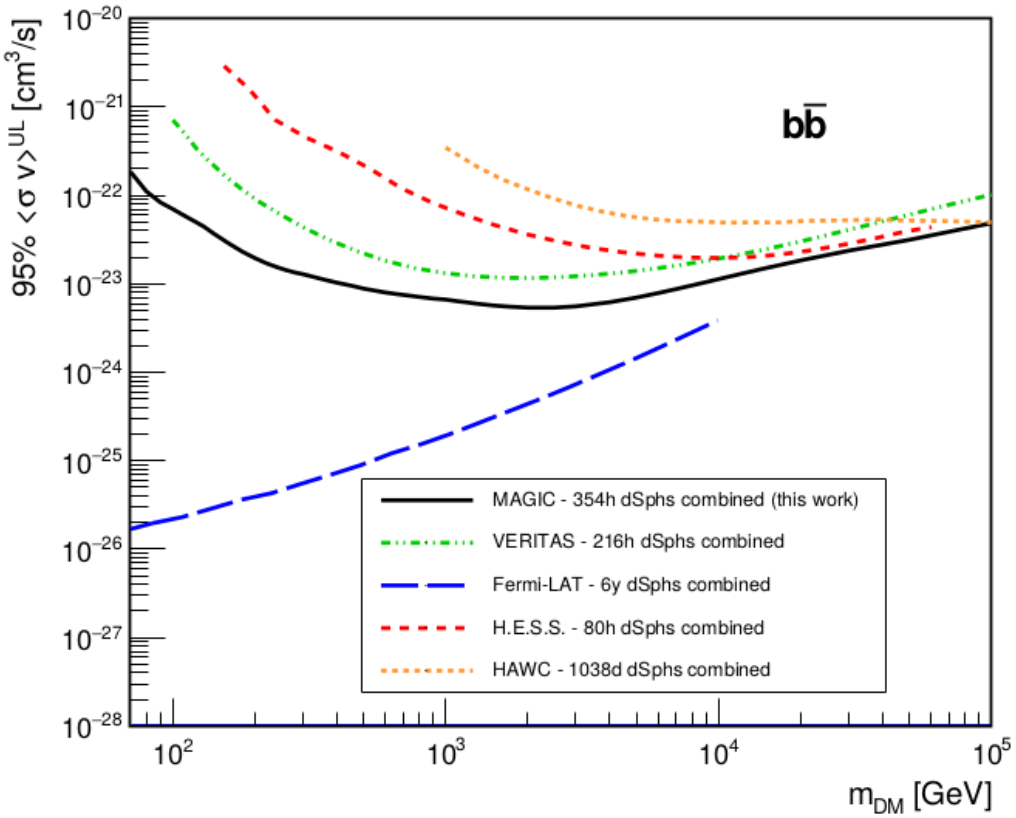
Dwarf spheroidal galaxies (III)

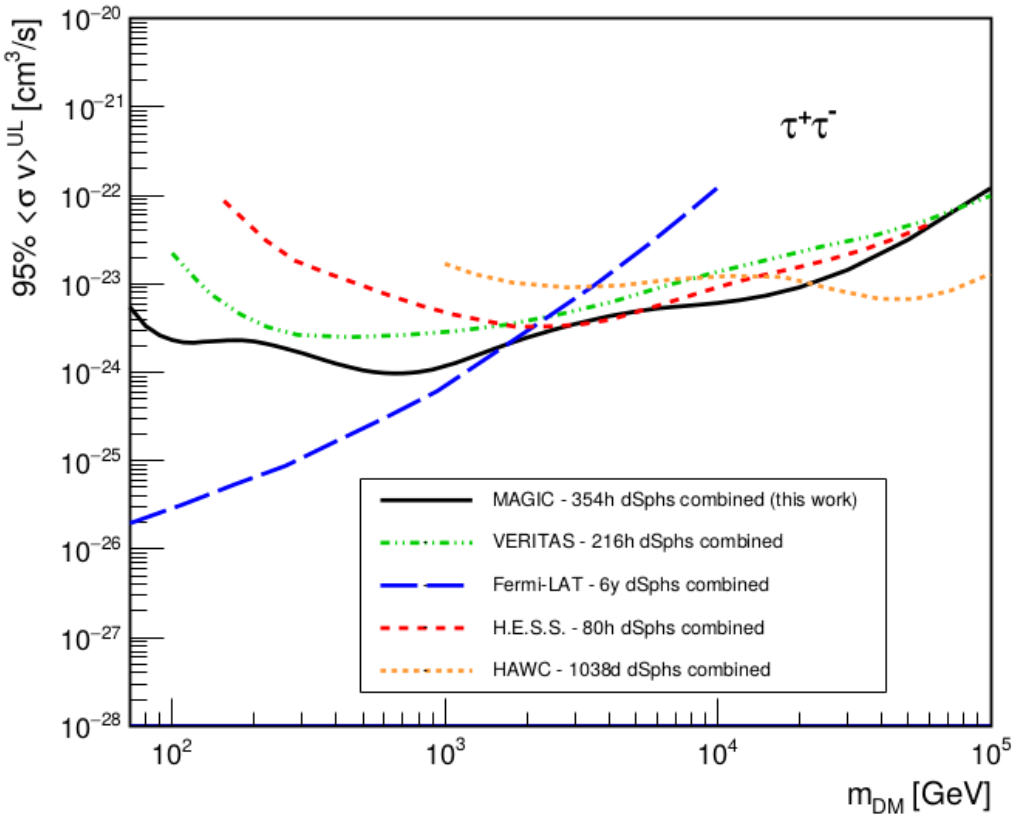
- **High energy (gamma rays) photons, HAWC**
  → 507 days of data, 15 dSphs



Dwarf spheroidal galaxies (IV)

- **High energy (gamma rays) photons, MAGIC**
  → 354h of data, 4 dSphs

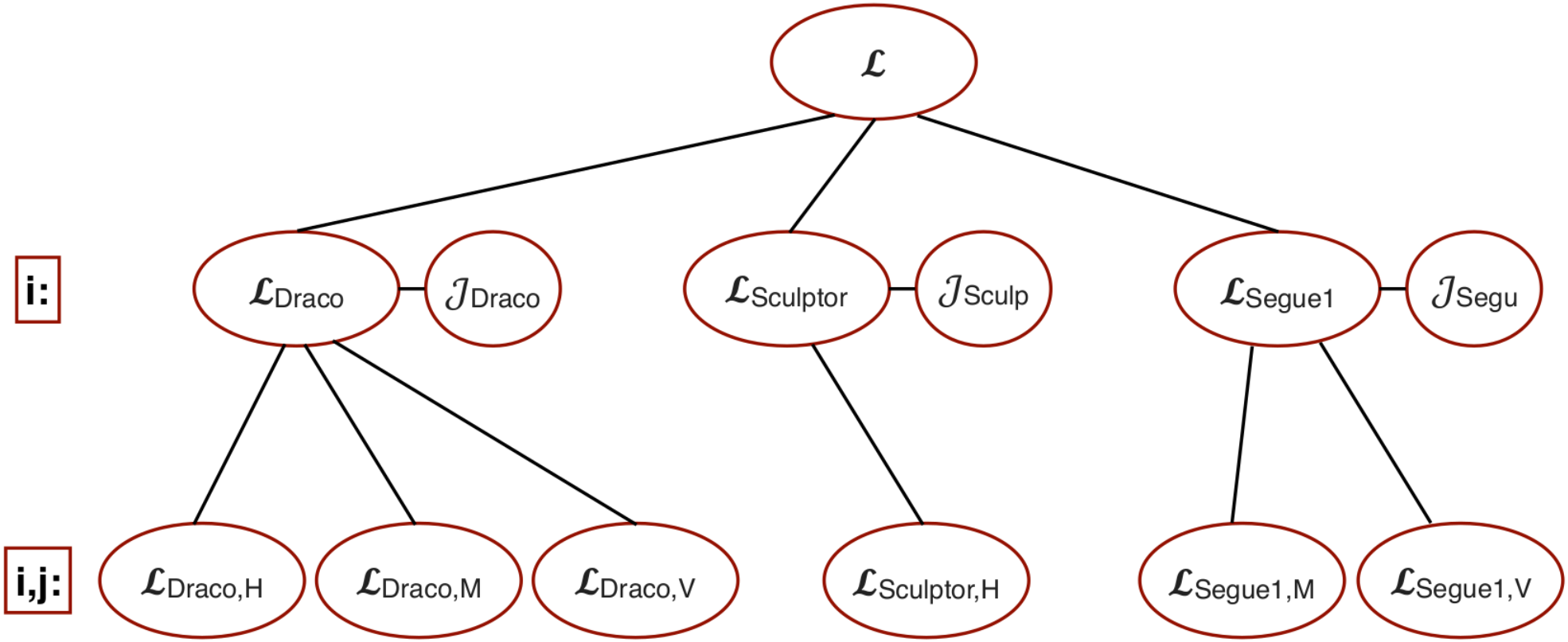




Combined likelihood analysis

The combined likelihood:

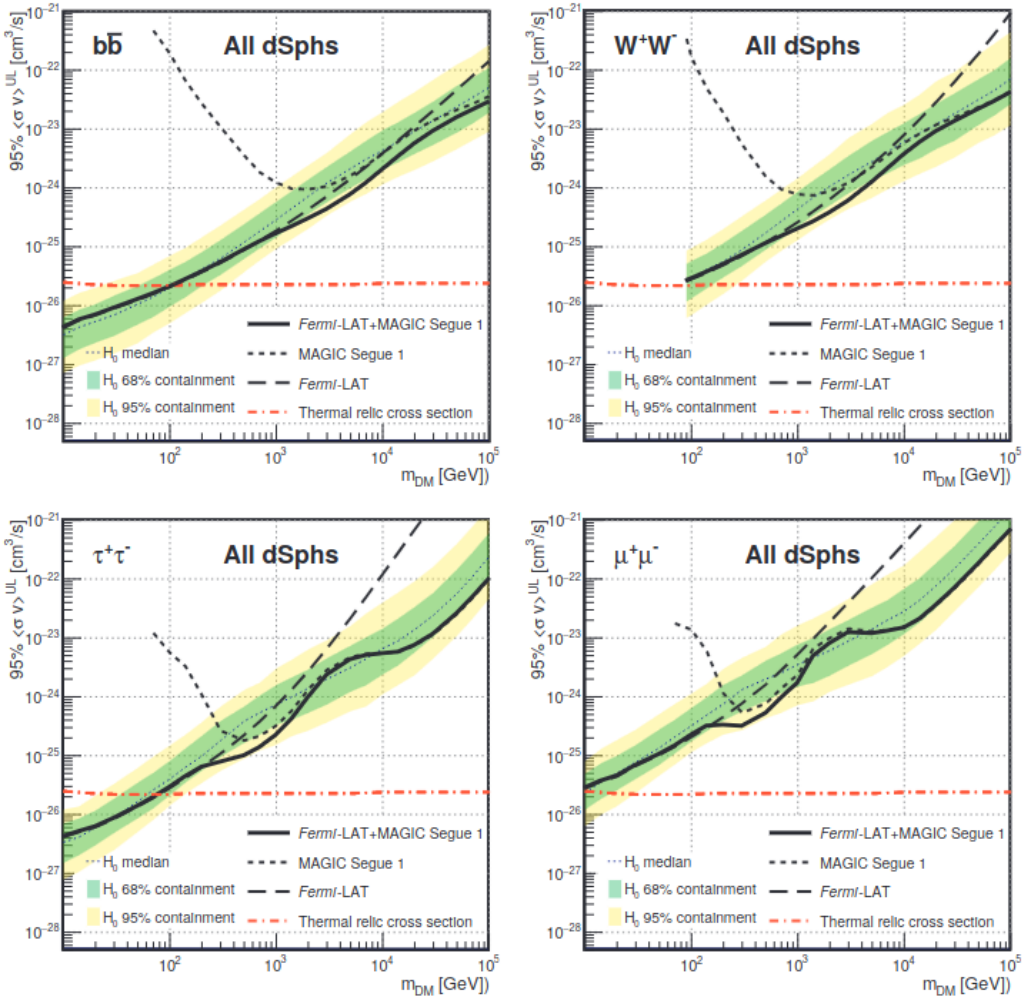
$$\mathcal{L}\left(\langle\sigma v\rangle; \boldsymbol{\nu} \mid \mathcal{D}_{\mathrm{dSphs}}\right) = \prod_{l=1}^{N_{\mathrm{dSphs}}} \mathcal{L}_{\mathrm{dSph},l}\left(\langle\sigma v\rangle; J_l, \boldsymbol{\nu_l} \mid \mathcal{D}_{\boldsymbol{l},\mathrm{measured}}\right) \times \mathcal{J}_l\left(J_l \mid J_{l,\mathrm{obs}}, \sigma_{\log J_l}\right)$$



Dwarf spheroidal galaxies (V)

- **High energy (gamma rays) photons**

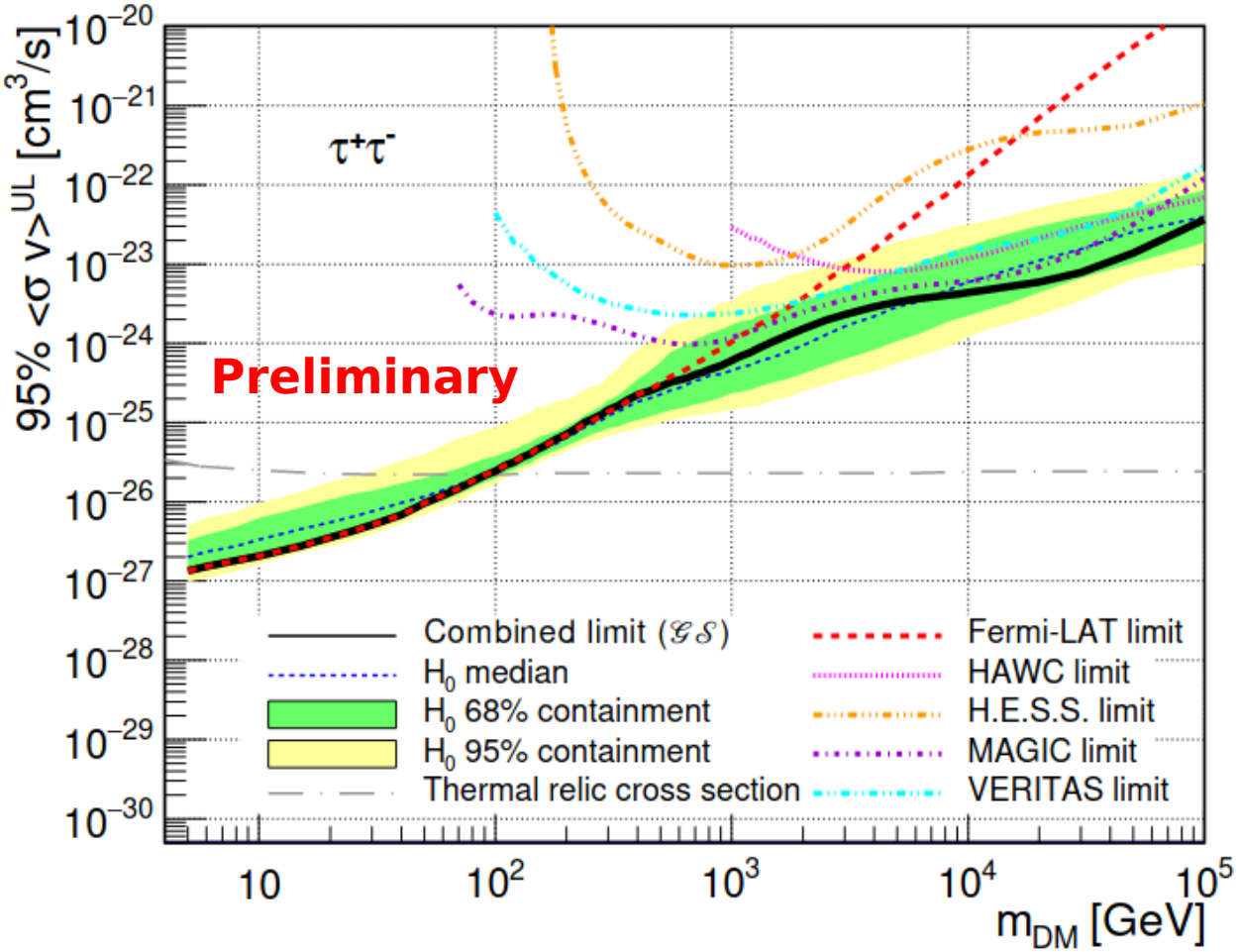
  → Fermi-LAT + MAGIC



Dwarf spheroidal galaxies (VI)

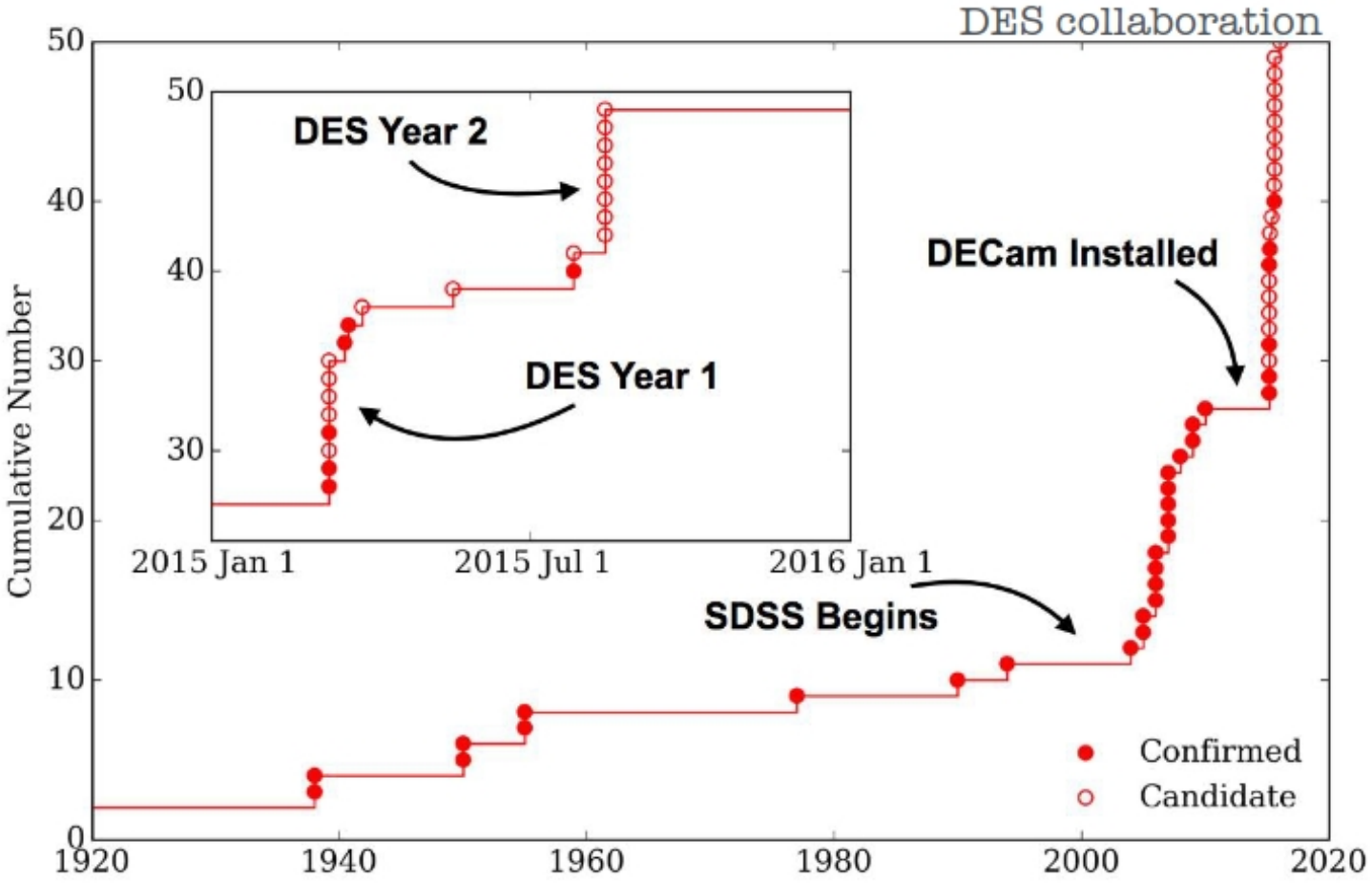
- **High energy (gamma rays) photons**

  → Fermi-LAT + HAWC + H.E.S.S. + MAGIC + VERITAS



Conclusion: what's next?

- **~ 50 dSphs discovered so far**
- **Future surveys, like LSST, will likely/hopefully find more dSphs**



Conclusion: what's next?

- **More sensitive instruments are and will come in the next years**

  → SKA, LHAASO, CTA

  → KM3NeT (ORCA & ARCA), IceCube-Gen2

  → HERD

- **More of multi-instrument and multi-target analysis**

  → more data, more systematic search, less bias

- **Combination between different wavelengths (e.g. radio and gamma) and other messengers (e.g. neutrinos, gamma rays, and maybe charged cosmic rays)**

  → more data, more channels, more harmonization/standardization of the analysis pipeline

- **Revision/update of the inputs to the analysis (J-factors, dN/dE)**

  → better evaluations of the systematics