Dark matter searches with MAGIC: a short history

Daniel Kerszberg (IFAE-BIST)

La Palma

20 MAGIC

Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

Dark matter searches w
a short histor

Daniel Kerszberg (IFAE-BI

La Palma

Short summary: 1st decade

2004: no signal

2005: no signal

2006: no signal

2007: no signal

2008: no signal

NO SIGNAL FOUND

2009: no signal

2010: no signal

2011: no signal

2012: no signal

2013: no signal

Short summary: 2nd decade

2014: no signal

2015: no signal

2016: no signal

2017: no signal

2018: no signal

NO SIGNAL FOUND

2019: no signal

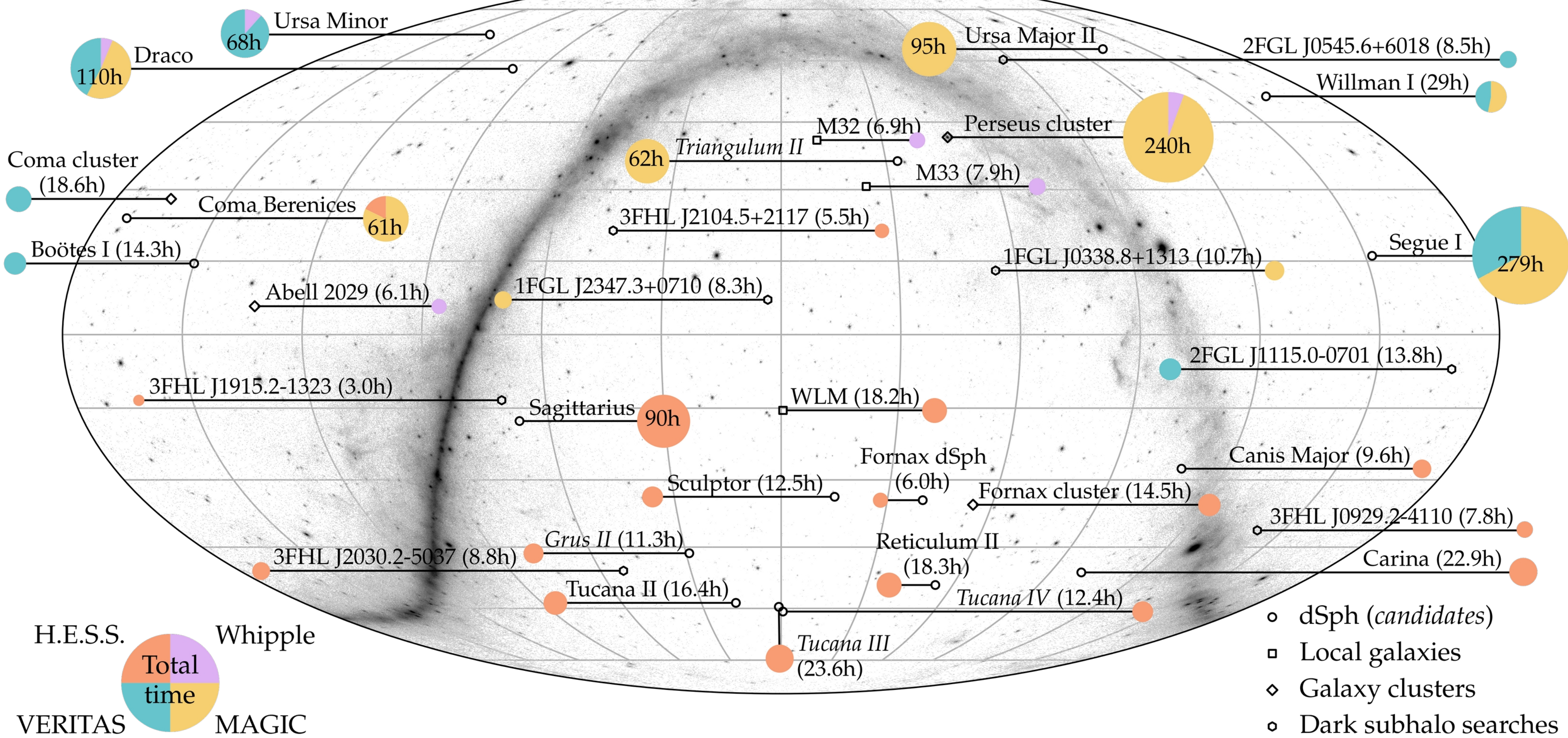
2020: no signal

2021: no signal

2022: no signal

2023: no signal

Observed targets



+

Intermediate Mass Black Holes: Doro et al. (ICRC 2007)

Milky Way Halo: Ninci et al. (ICRC 2019)

Galactic Center: PRL 130 061002

Expected flux

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

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

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

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

Expected flux

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

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

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

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

Parameters of interests

Expected flux

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

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

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

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

Inputs to the analysis

Expected flux

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

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

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

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

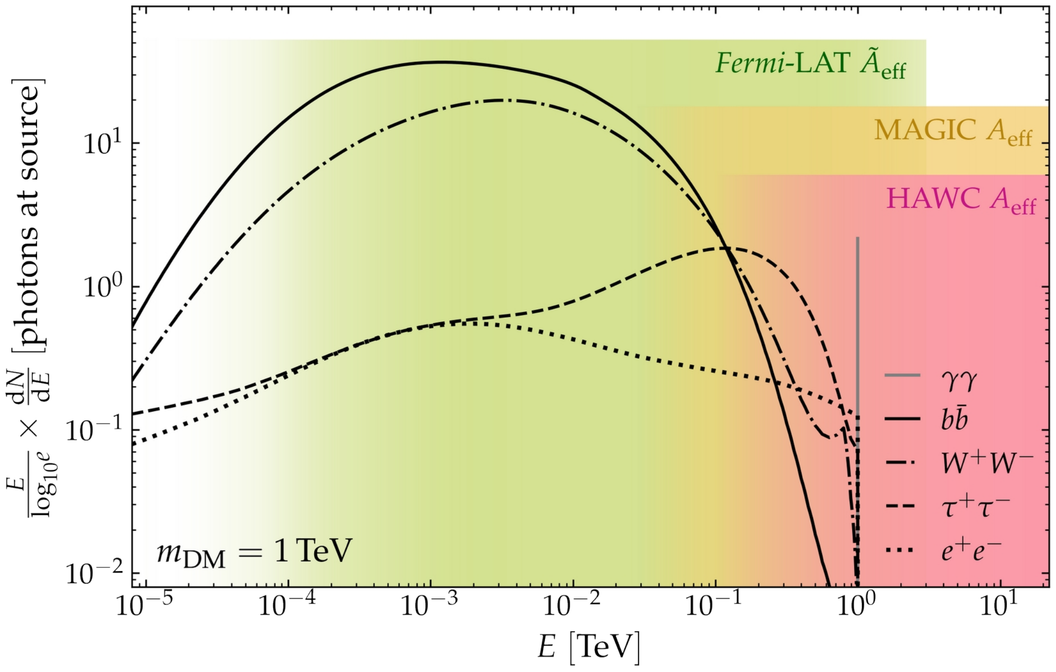
Ignored in >99% of the case as we usually observe targets at z~0

Expected flux

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

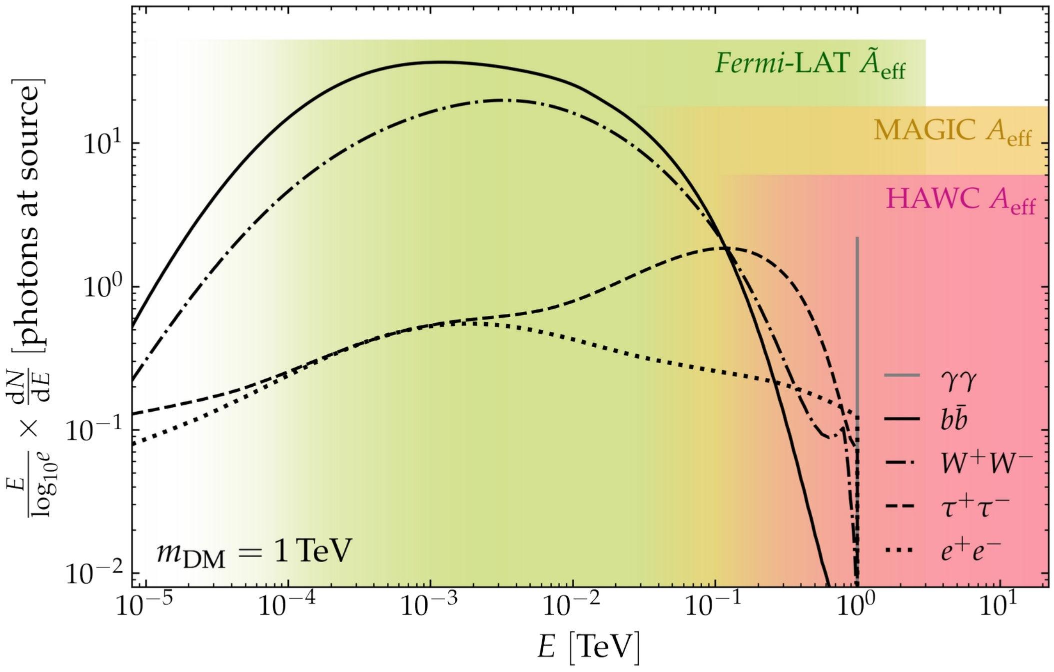
Expected flux

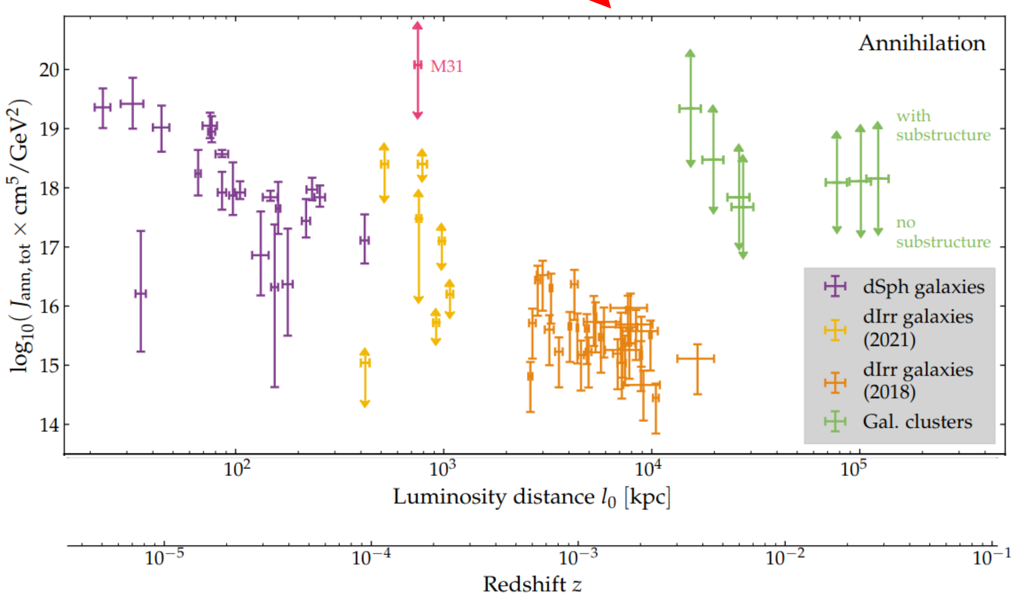
$$\frac{\Phi_{\text{ann}}}{\mathrm{d}E_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle \sigma v \rangle}{8\pi\, m_{\text{DM}}^2} \frac{\mathrm{d}N}{\mathrm{d}E} \int_0^{\Delta\Omega} \int_{\text{l.o.s.}} \rho(l,\Omega)^2 \,\mathrm{d}l\, \mathrm{d}\Omega$$



Expected flux

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

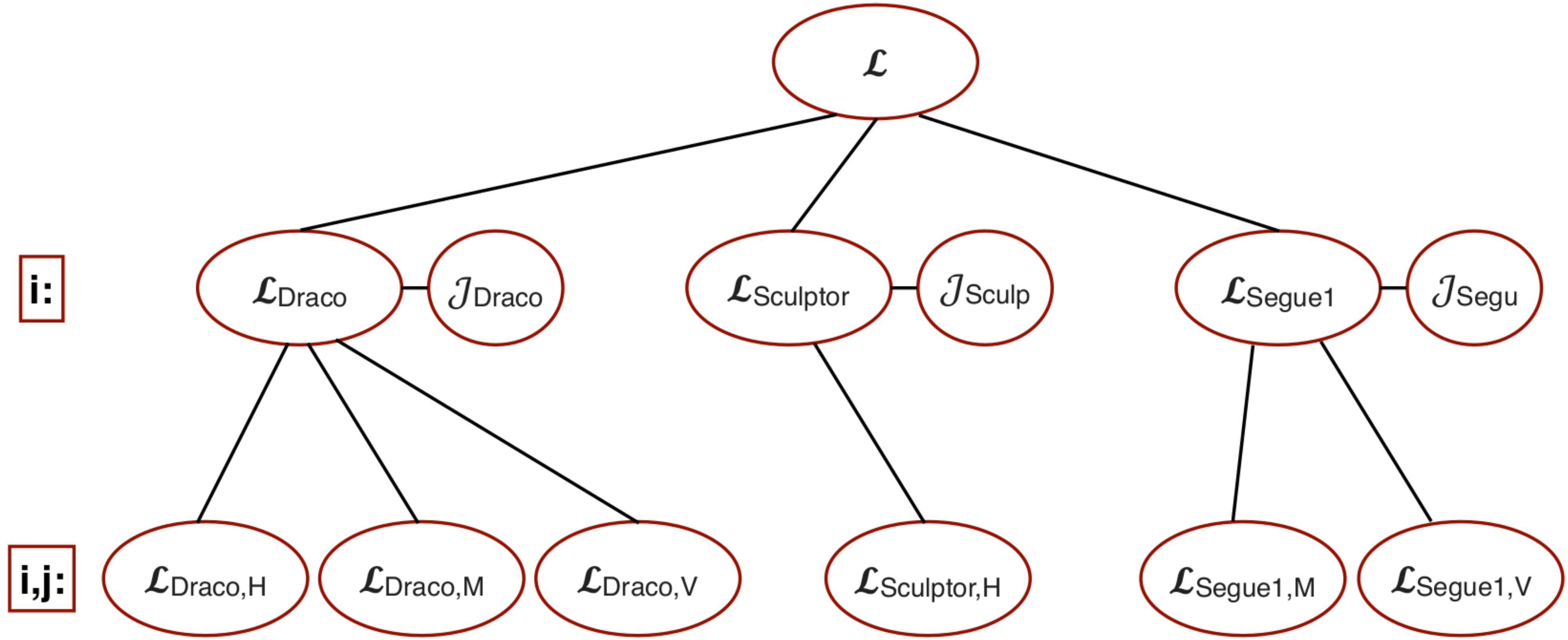




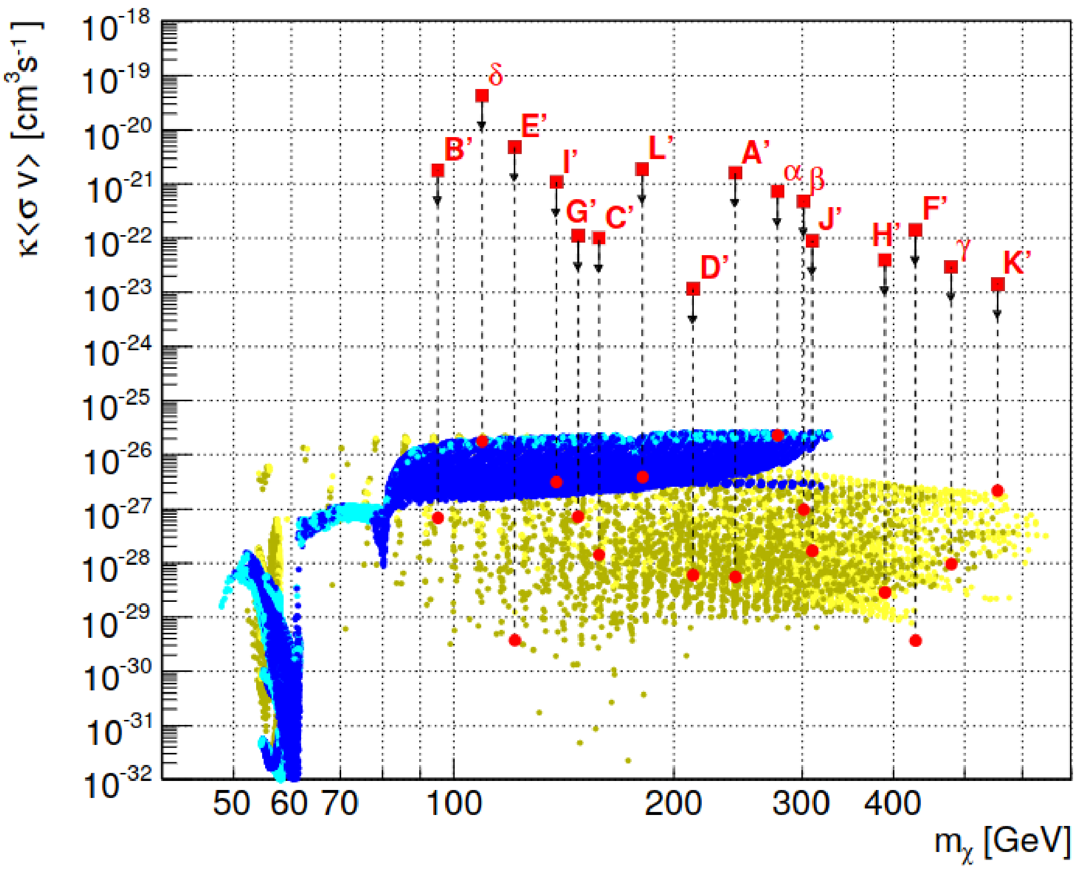
State of the art analysis

The combined likelihood:

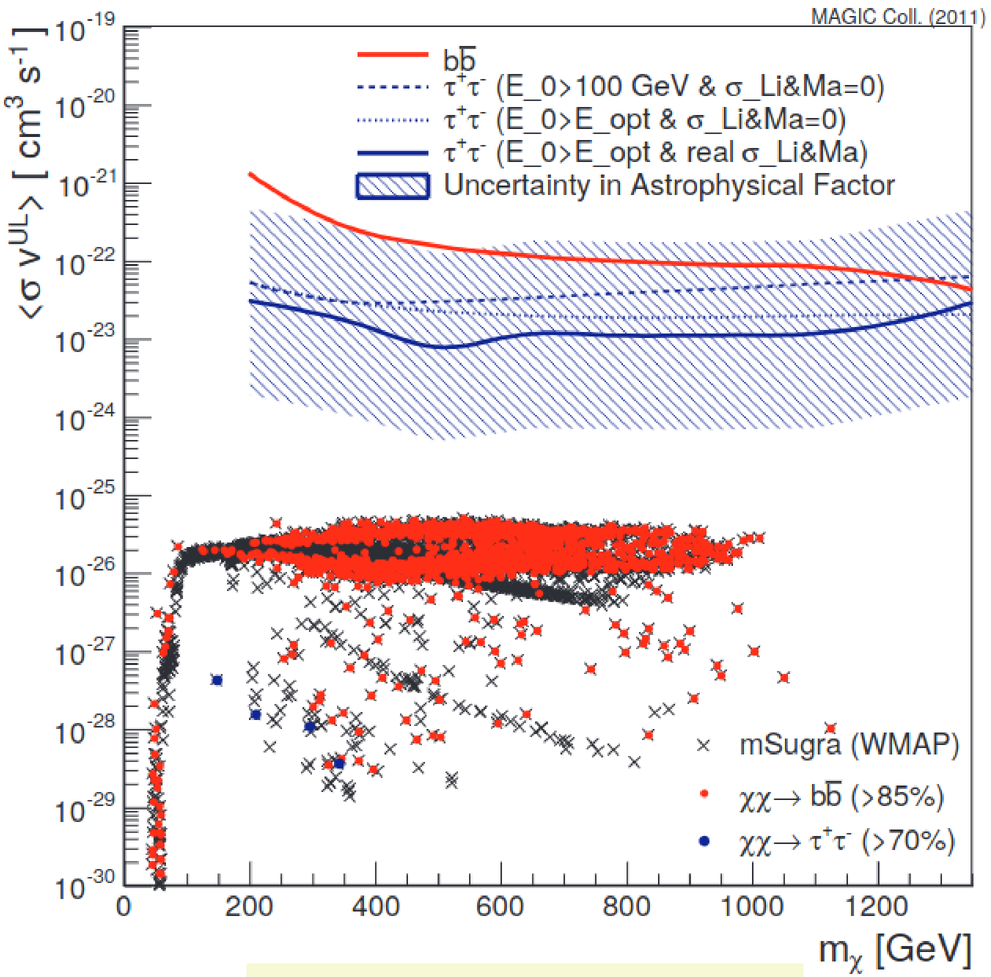
$$\mathcal{L}\left(\langle\sigma v\rangle;\boldsymbol{\nu}\mid\boldsymbol{\mathcal{D}}_{\mathrm{dSphs}}\right)=\prod_{l=1}^{N_{\mathrm{dSphs}}}\mathcal{L}_{\mathrm{dSph},l}\left(\langle\sigma v\rangle;J_l,\boldsymbol{\nu_l}\mid\boldsymbol{\mathcal{D}_{l,\mathrm{measured}}}\right)\times\mathcal{J}_l\left(J_l\mid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



Some early results

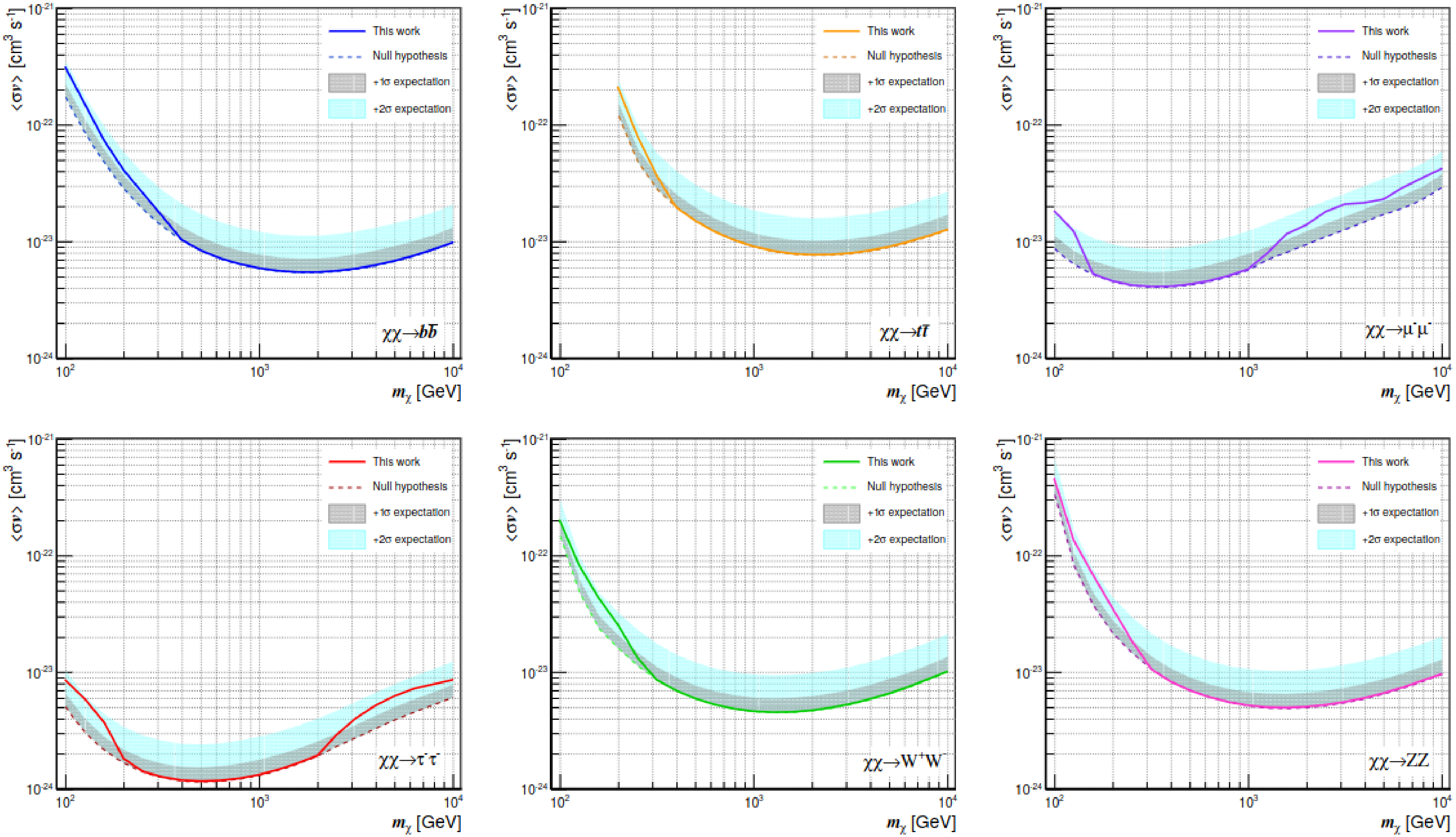


~8h of mono obs. of Draco Annihilation ApJ 679:428–431 (2008)



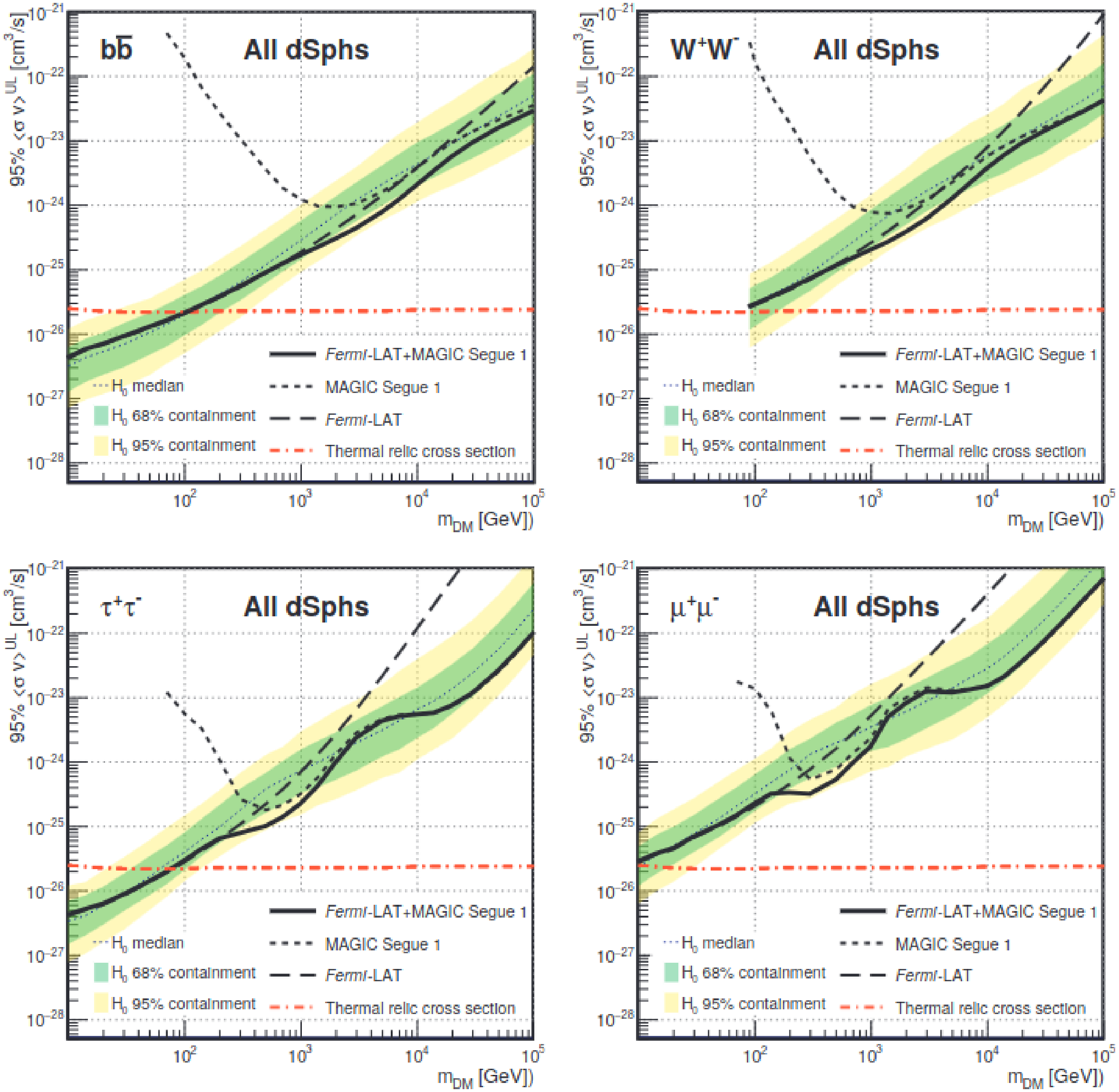
~29h of mono obs. of Segue 1 Annihilation JCAP 1106:035 (2011)

The first stereo result



~158h of stereo obs. of Segue 1
Annihilation
JCAP 1402:008 (2014)

Combining data with Fermi-LAT

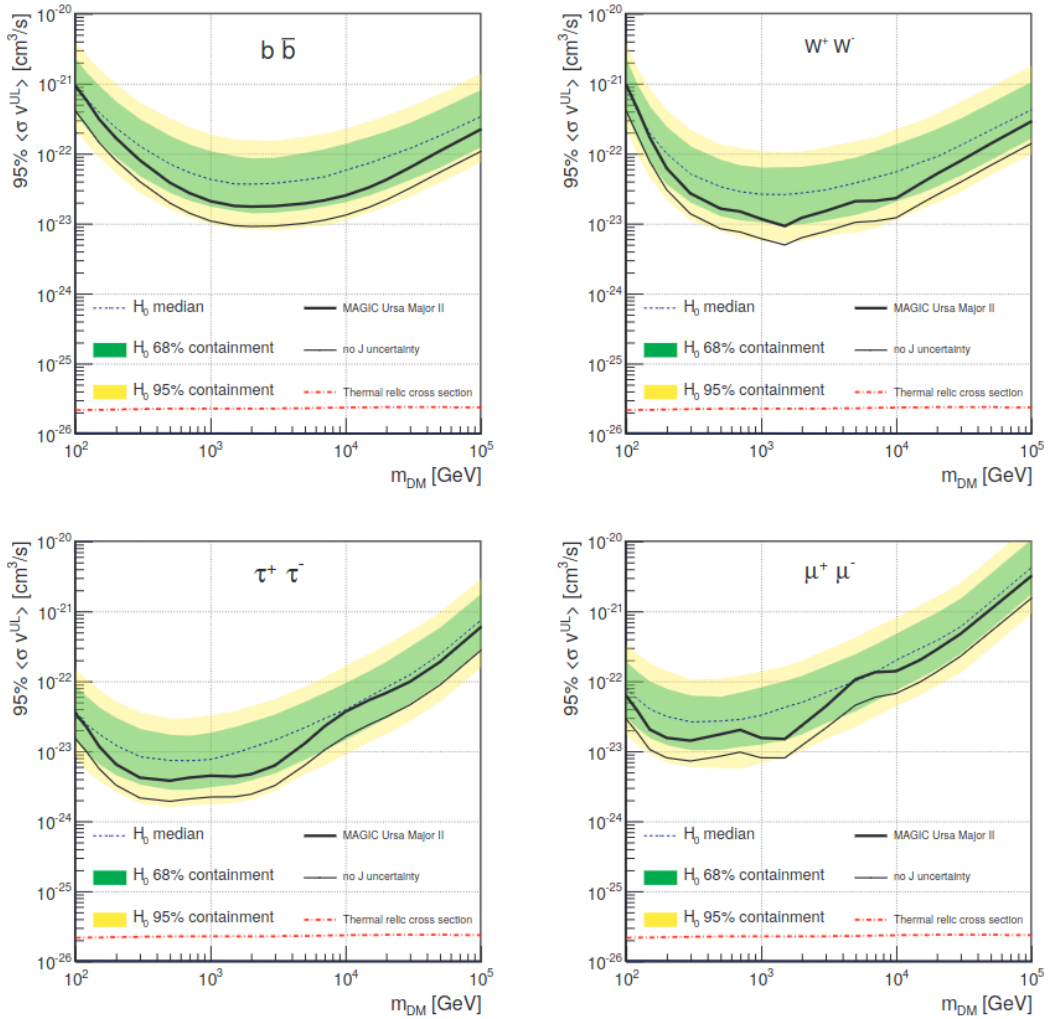


~158h of stereo obs. of Segue1 by MAGIC + 6 years of obs. of 15 dSphs by Fermi-LAT

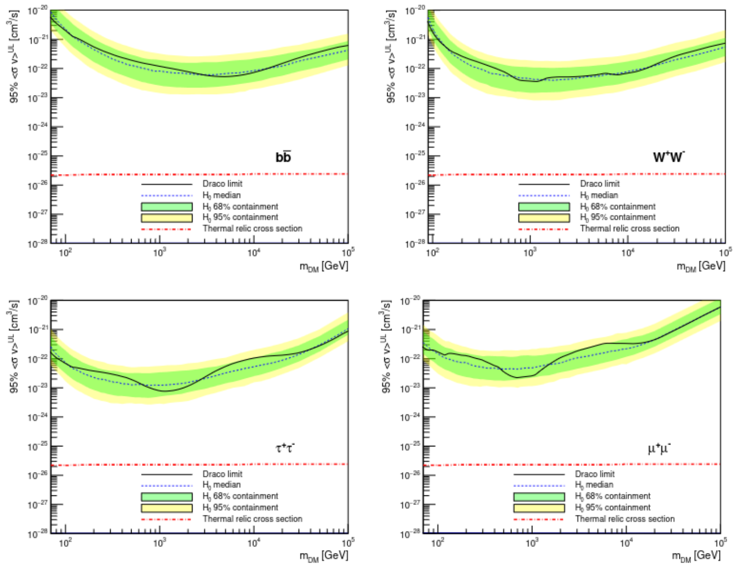
Annihilation

JCAP 1602:039 (2016)

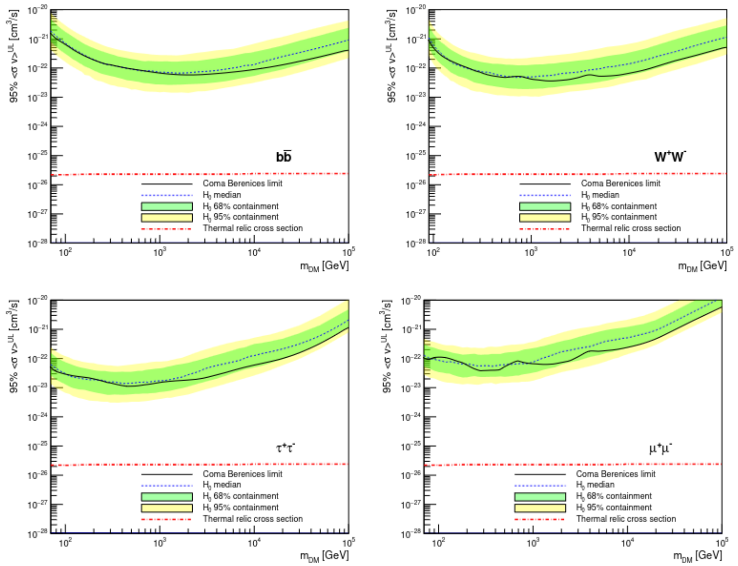
Expanding the pool of dSphs observed



~95h of stereo obs. of Ursa Major II
Annihilation
JCAP 1803:009 (2018)

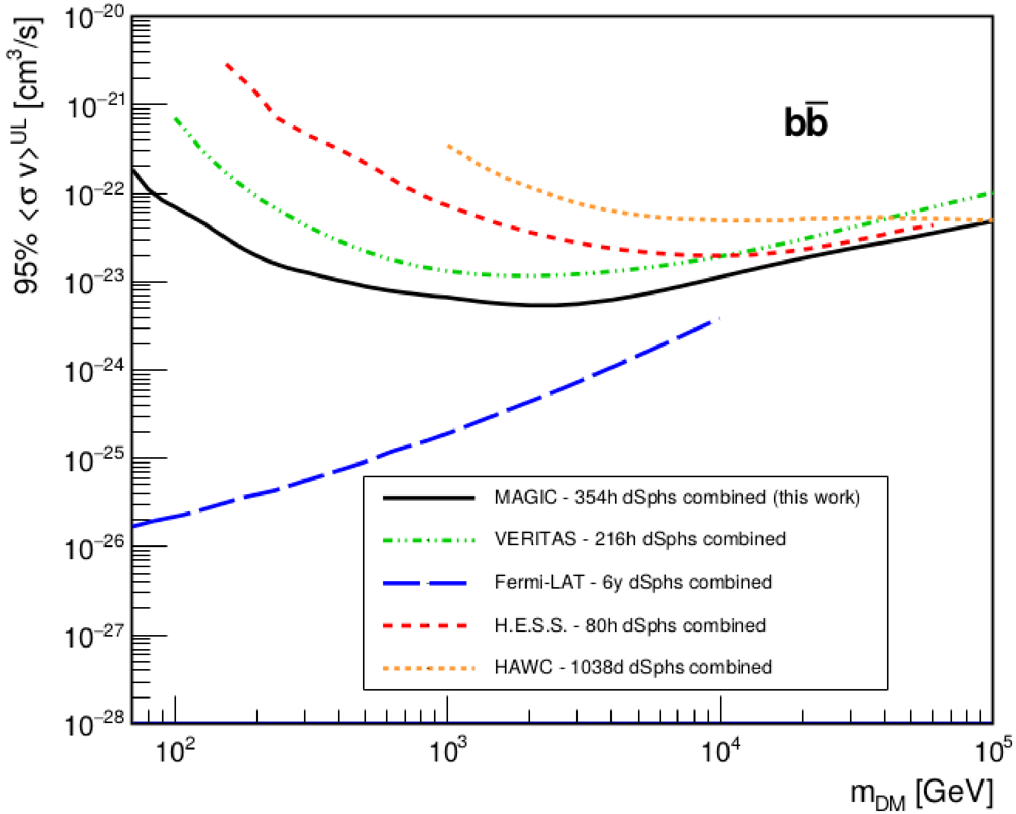


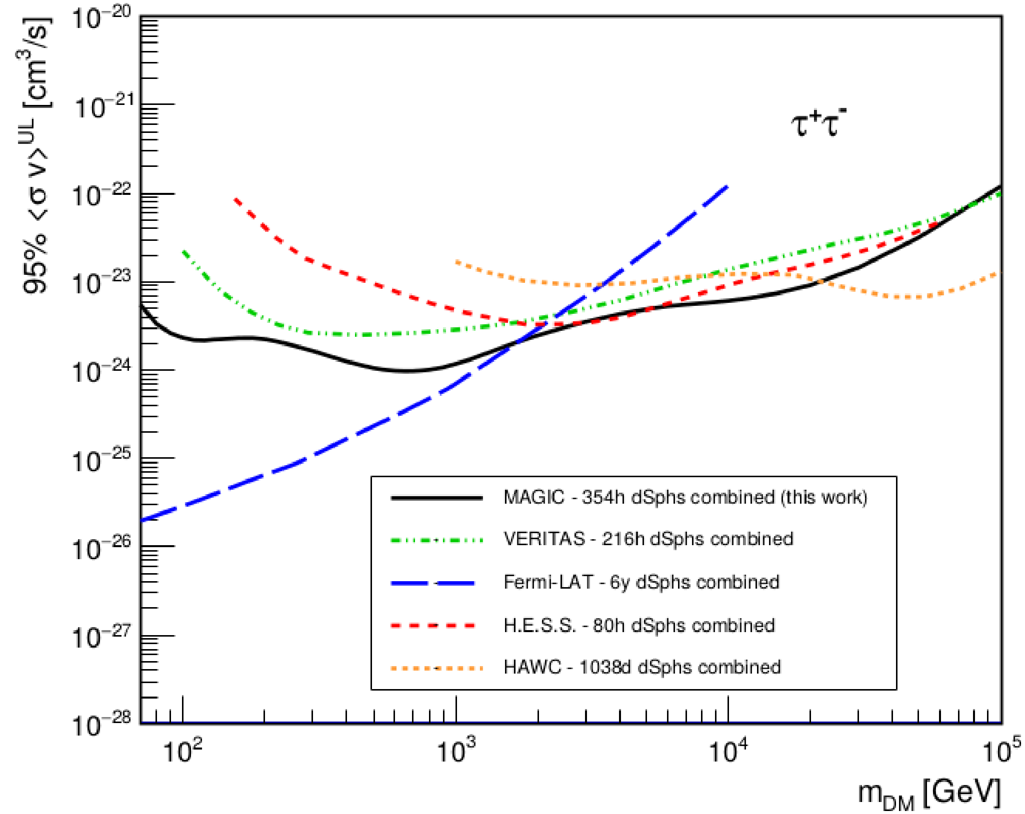
~52h of stereo obs. of Draco
Annihilation
PDU 35 100912 (2022)



~50h of stereo obs. of Coma
Annihilation
PDU 35 100912 (2022)

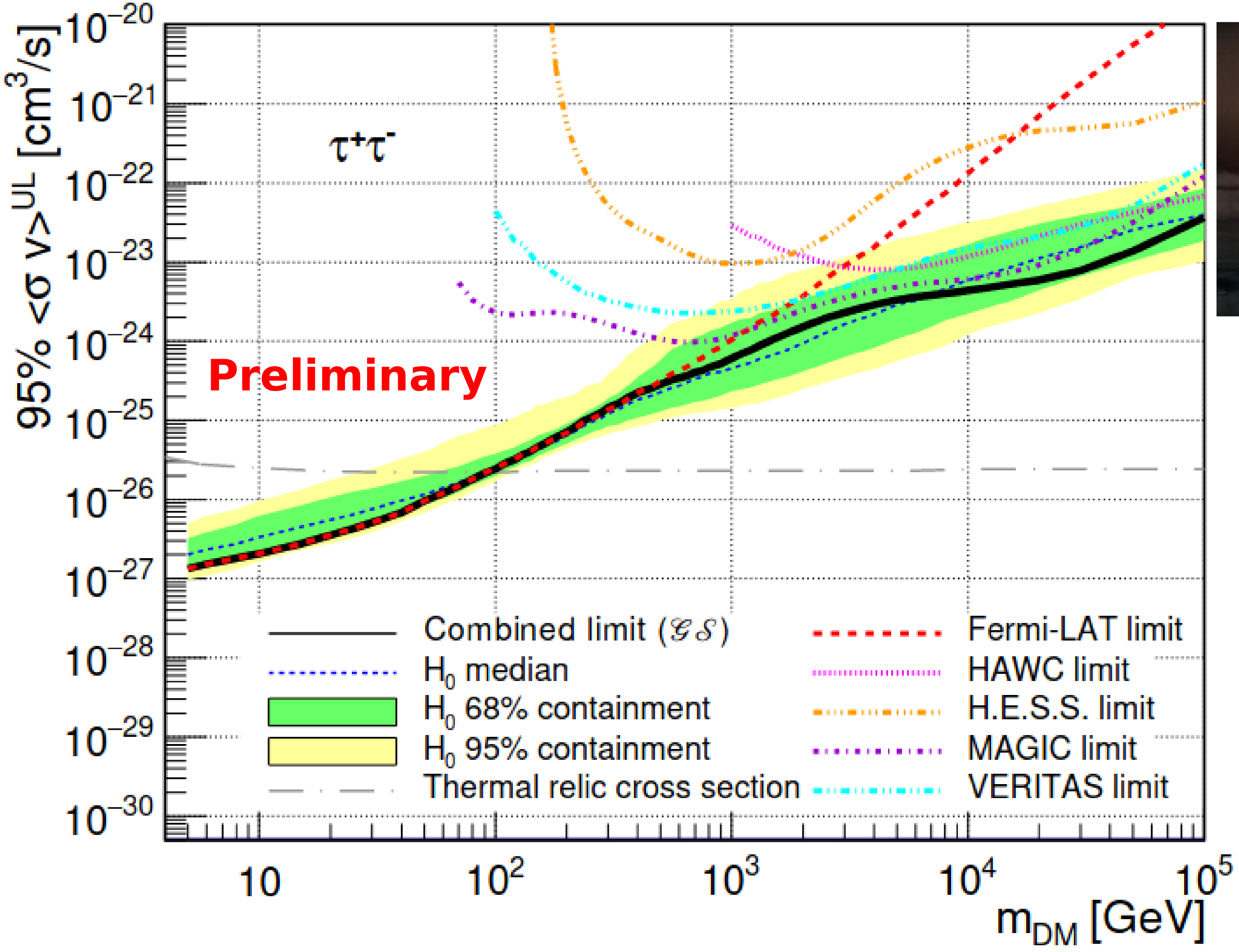
Combining MAGIC dSphs observations





~354h of stereo obs. of Segue 1, Ursa major II, Draco, and Coma Annihilation
PDU 35 100912 (2022)

Combining Fermi-LAT, HAWC, H.E.S.S., MAGIC, VERITAS dSphs observations



M. Doro (MAGIC 15 years)

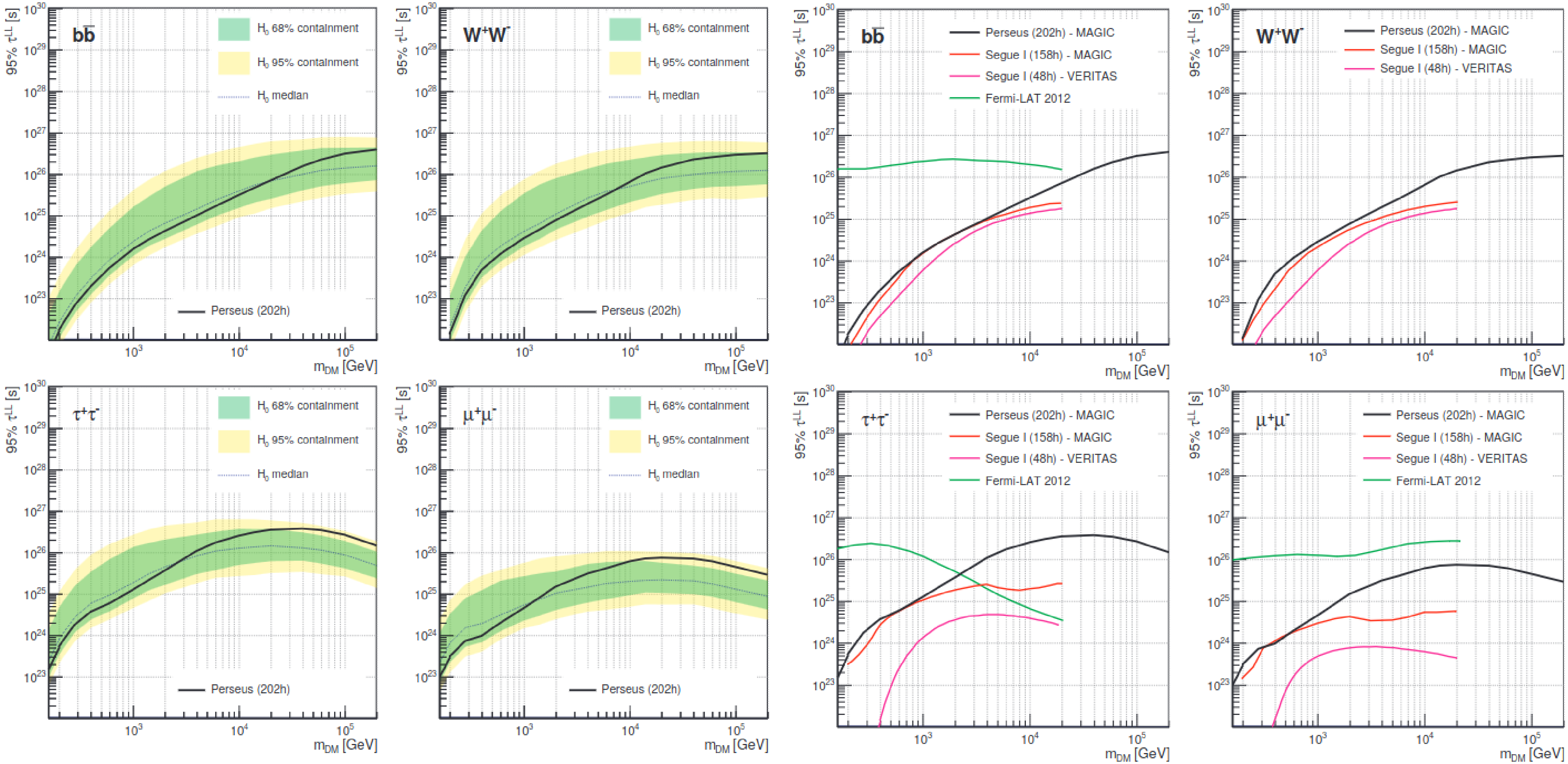
20 dSphs, 45 data sets, combining data from 5 gamma-ray experiments

Annihilation

PoS(ICRC2023)1426

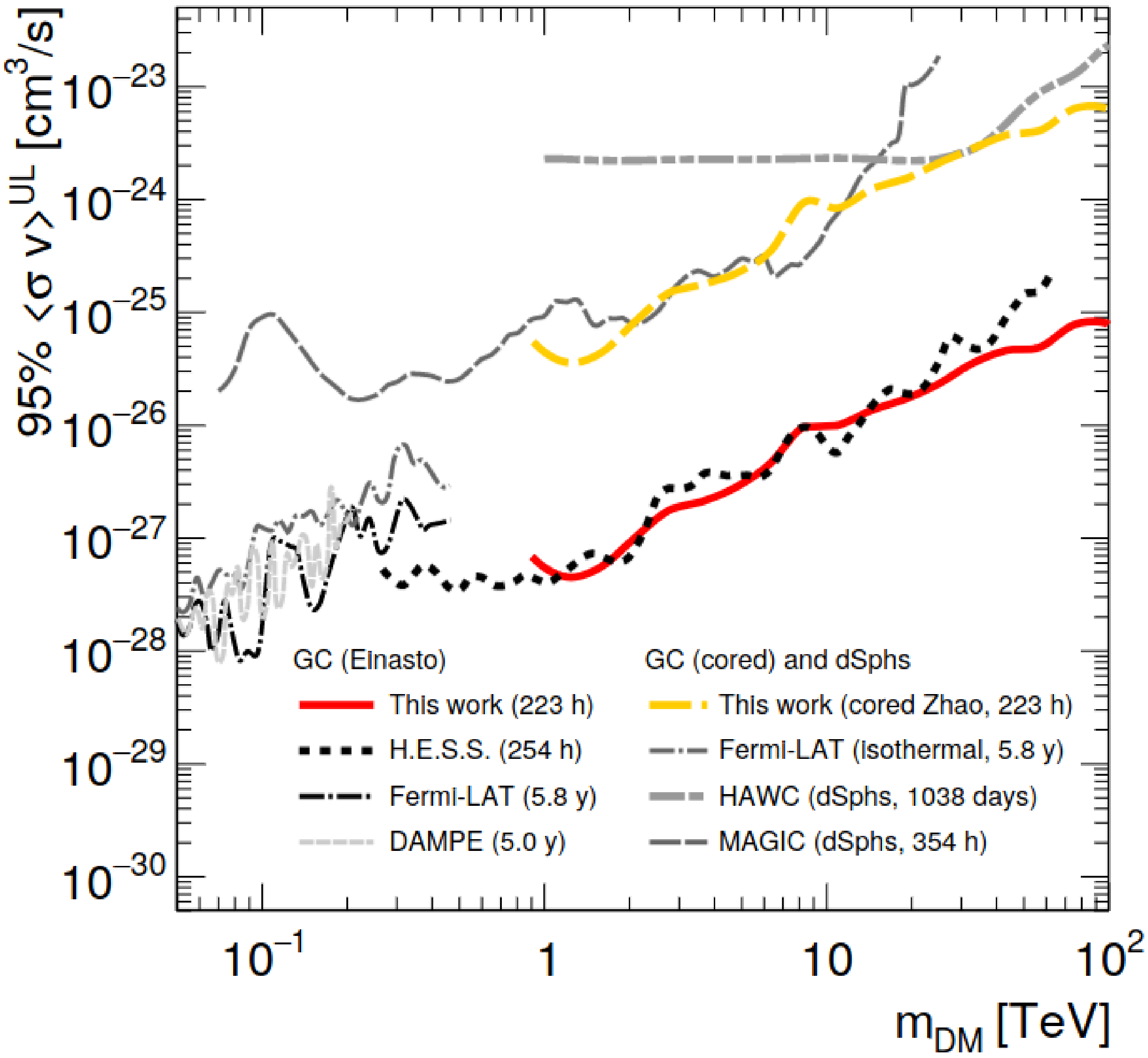
→ combined limit is up to a factor 2-3 more constraining

Looking at galaxy clusters and decaying dark matter



~202h of stereo obs. of Perseus
Decay
PDU 22 38-47 (2018)

Looking at the Galactic Center

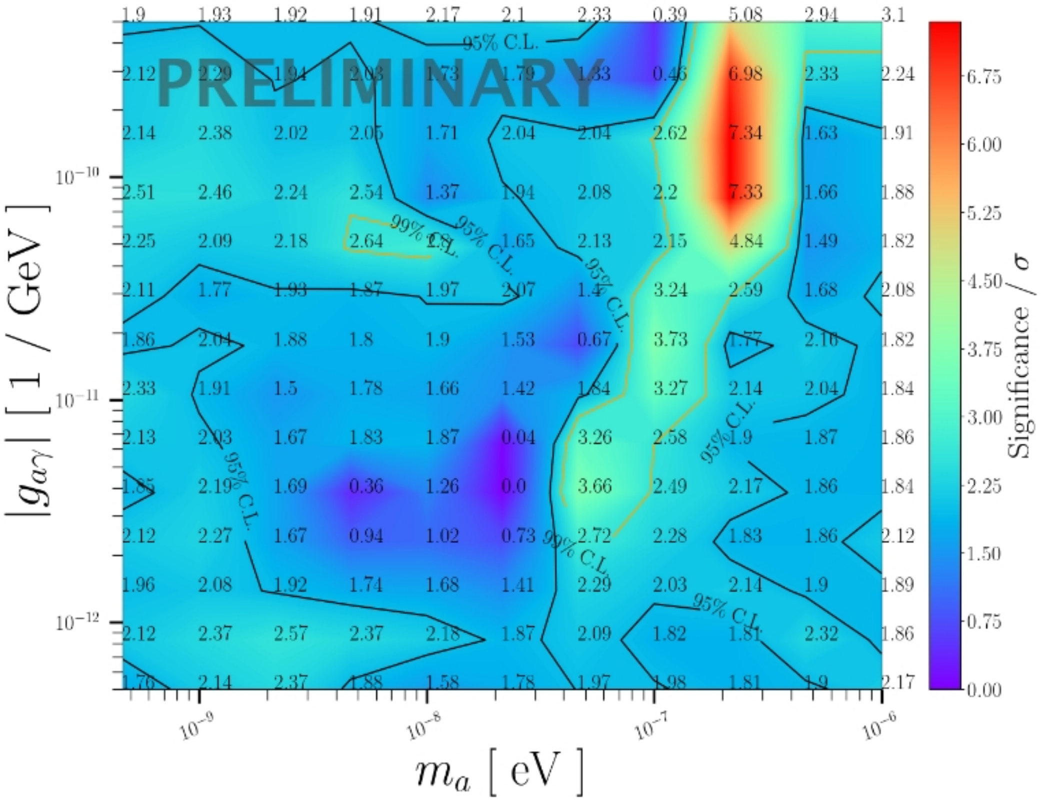


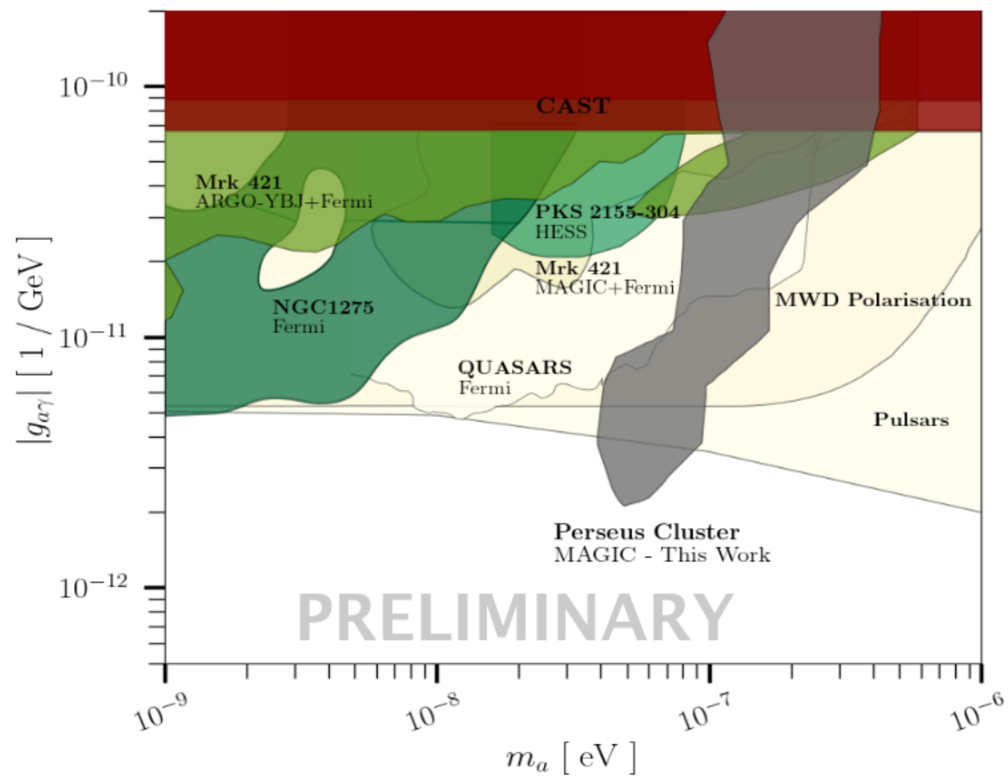
~223h of stereo obs. of the GC

Annihilation – line search

PRL 130 061002 (2023)

Exploring alternative models: Axion-Like Particles





~41h of stereo obs. of NGC 1275
Axion-like particle
PoS(ICRC2023)1442

- **Different class of dark matter candidates**
  - In presence of a magnetic field: possible conversion from an ALP to a gamma-ray and vice-versa → effect search for in AGN spectra

What's next?

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

  → more data, more systematic search, less bias

- **Combination with other wavelengths (e.g. radio) and other messengers (e.g. neutrinos, 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

- **Test of more specific DM models, possibly beyond 100 TeV**

  → find a suitable format to publicly release the data so that anyone can test any model against the best available data sets

What's next?

- **More of multi-instrument and multi-target analysis**
  → more data, more systematic search, less bias

- **Combination with other wavelengths (e.g. radio) and other messengers (e.g. neutrinos, 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

- **Test of more specific DM models, possibly beyond 100 TeV**
  → find a suitable format to publicly release the data

M. Doro et al, "Fundamental Physics Searches with IACTs", Advances in Very High Energy Astrophysics, World Scientific

J. Rico, "Gamma-Ray Dark Matter Searches in Milky Way Satellites — A Comparative Review of Data Analysis Methods and Current Results", Galaxies 8(1):25 (2020)

M. Hütten et al, "TeV Dark Matter Searches in the Extragalactic Gamma-ray Sky", Galaxies 10(5):92 (2022)