Indirect detection of dark matter

HEPAP-DAS 2023
SAHA Institute of Nuclear Physics

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https://apod.nasa.gov/apod/ap200724.html

Syllabus

- Dark matter paradigm and searches (Day 1)
- Indirect searches with gamma rays (Day 2)
- Data analysis: specific methodologies (Day 3)

Credit: NASA, HST, Webb

Syllabus: Day 2

- Indirect dark matter searches with gamma rays
  - Estimation of expected fluxes
    - Astrophysical factor
    - Particle Physics factor
  - Targets
    - Galactic Center
    - Dwarf Spheroidal Galaxies
    - Subhalos
    - Galaxy clusters

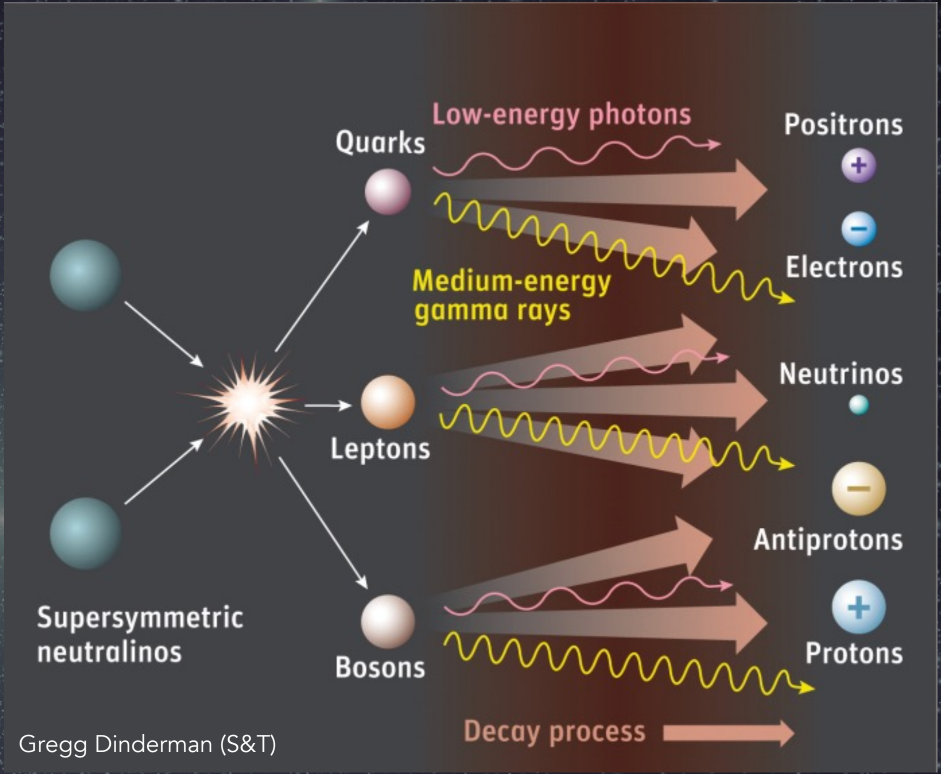
Credit: NASA, HST, Webb

Indirect detection:

- Basis: Detection of DM annihilation or decay products (SM particles)

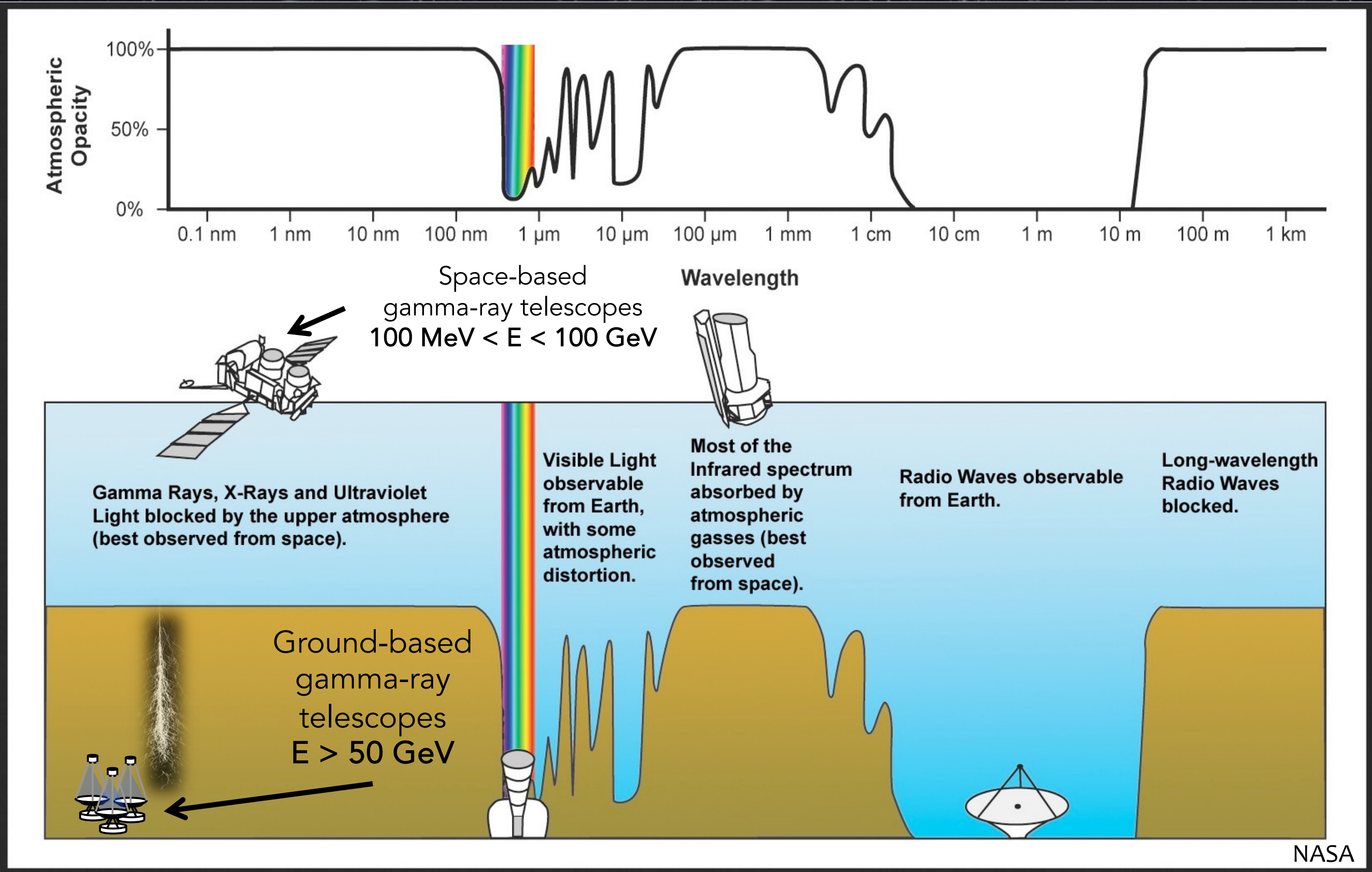
- In most cases, entangled with cosmic rays and subdominant

- Photons are privileged messengers
  - No deflection by B-fields
  - Trace back to source
  - Astrophysical targets

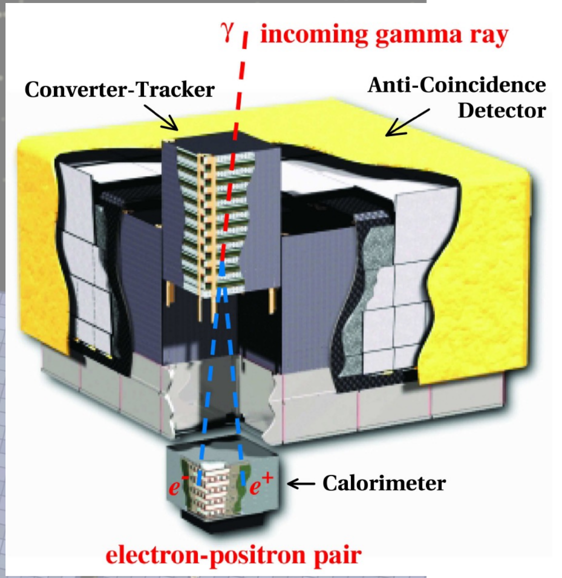


Gregg Dinderman (S&T)

Indirect Dark Matter Searches: Detectors



- Fermi-GST
  - Fermi-LAT and Fermi-GBM
- Fermi-LAT
  - Precision Si-strip tracker
  - Hodoscopic CsI calorimeter
  - Energy range: 20 MeV - 300 GeV
  - Large FoV ~2.4 sr
  - Full sky coverage every two orbits (~3h)
  - Collection area: ~1m²



fermi.gsfc.nasa.gov

Indirect Dark Matter Searches: Detectors

MAGIC

- Two telescope array
- La Palma Island (Spain)
    - 2200 m a.s.l.
- Reflectors: 2 x 17 m Ø
- Cameras: 3.5° FoV
    - 1039 PMT
- Energy
    - Threshold: 50 GeV
    - Resolution: 15%
- Angular resolution ~ 0.07°
- Sensitivity ~0.8 % C.U.
- Light Carbon Fiber struc.

VERITAS

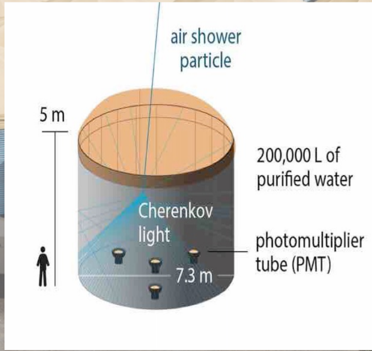
- Four telescope array
- Tucson (USA)
    - 1268 m a.s.l.
- Reflectors: 4 x 12 m Ø
- Cameras: 3.5° FoV
    - 499 PMT
- Energy
    - Threshold: 100 GeV
    - Resolution: 15%
- Angular resolution ~ 0.1°
- Sensitivity ~0.7 % C.U.

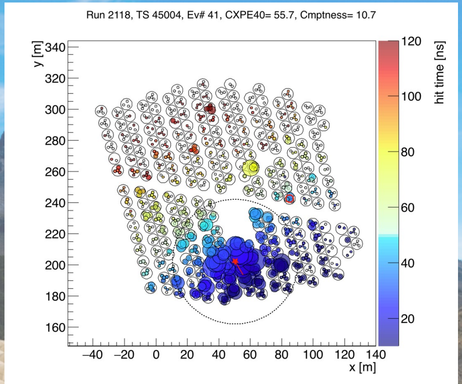
H.E.S.S.

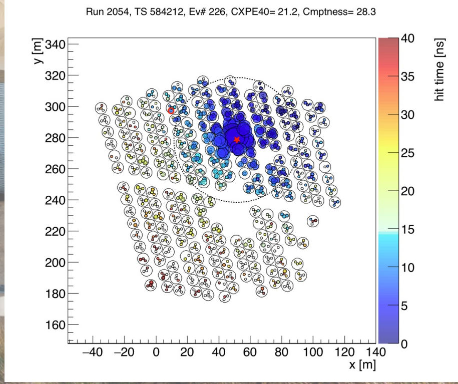
- 4+1 telescope array
- Namibia
    - 1800 m a.s.l.
- Reflectors:
    - 4 x 13 m Ø
    - 1 x 28 m Ø
- Cameras:
    - 4 x 960 PMT, 5° FoV
    - 1 x 2048 PMT, 3.2° FoV
- Energy
    - Threshold: 100 GeV
    - Resolution: 15%
- Angular resolution ~ 0.08°
- Sensitivity ~0.7 % C.U.

High Altitude Water Cherenkov gamma-ray Observatory

- 4100 m asl, Sierra Negra, Mexico
- Large FoV (15% sky)
- Covers 2/3 sky in 24h
- 90% duty cycle
- 300 4.5m x 7.3m tanks (4 PMTs)
- Energy range: 0.5 TeV – 100 TeV

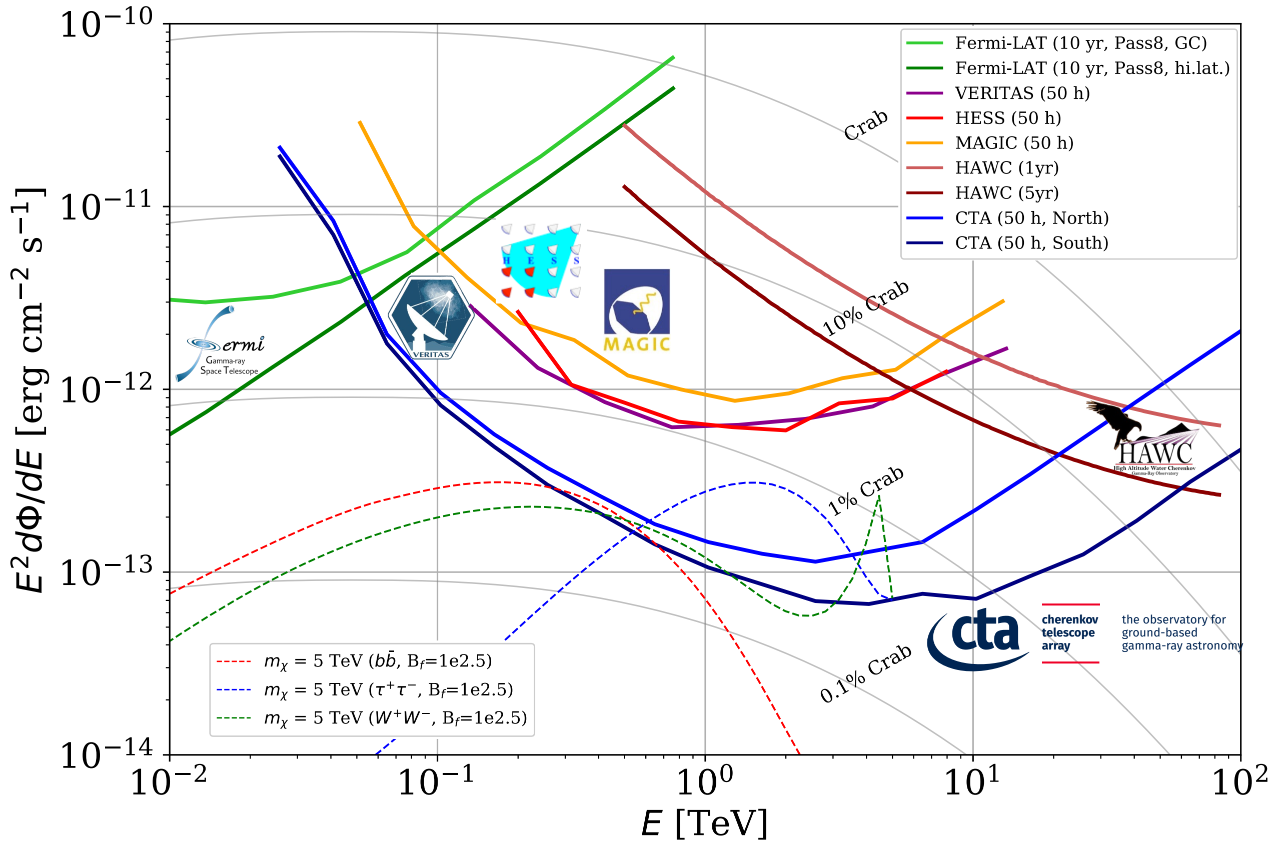






www.hawc-observatory.org

Indirect Dark Matter Searches: Detectors



Annihilation (DM DM → SM SM → secondary γ)

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

Decay (DM → γ γ , DM → SM SM → secondary γ)

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

Galaxies 2022, 10, 92

Estimation of expected gamma-ray fluxes

Annihilation (DM DM → SM SM → secondary γ)

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

Decay (DM → γ γ , DM → SM SM → secondary γ)

$$\frac{\Phi_{\text{decay}}}{\mathrm{d}E_\gamma}(E_\gamma, \Delta\Omega) = \underbrace{\frac{1}{4\pi\, t_{\text{DM}}\, m_{\text{DM}}} \frac{\mathrm{d}N}{\mathrm{d}E}}_{\text{Particle Physics factor}} \underbrace{\int_0^{\Delta\Omega} \int_{\text{l.o.s.}} \rho(l, \Omega) \, \mathrm{d}l \, \mathrm{d}\Omega}_{\text{Astrophysical factor}} .$$

Local volume, DM mass below few TeV: attenuation not relevant

Galaxies 2022, 10, 92

Estimation of expected gamma-ray fluxes

Particle Physics factor

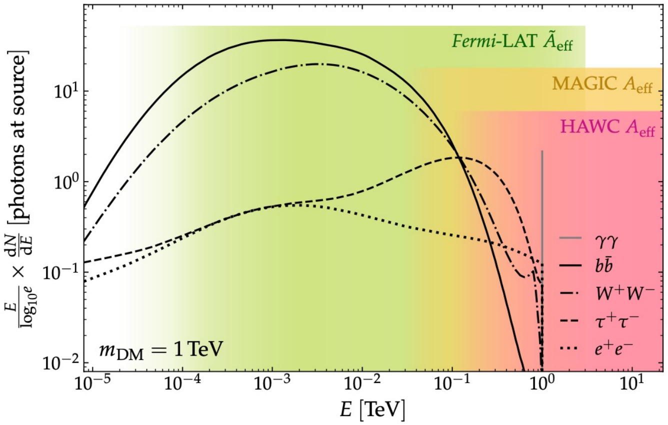
Photon yield

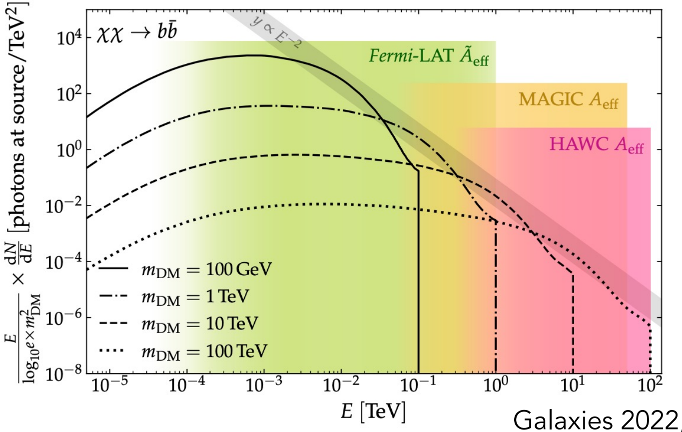
Ann. $\dfrac{\langle \sigma v \rangle}{8\pi\, m_{\mathrm{DM}}^2} \boxed{\dfrac{\mathrm{d}N}{\mathrm{d}E}}$

Dec. $\dfrac{1}{4\pi\, t_{\mathrm{DM}}\, m_{\mathrm{DM}}} \boxed{\dfrac{\mathrm{d}N}{\mathrm{d}E}}$

$$\frac{dN}{dE} = \sum_i B_i \left.\frac{dN}{dE}\right|_i$$

i: annihilation /decay channel
B_i: branching ratio of channel i





Galaxies 2022, 10, 92

Particle Physics factor

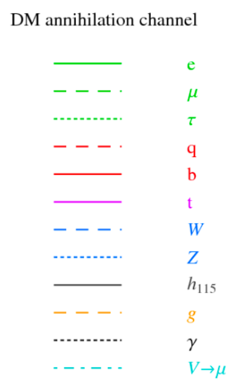
$$\frac{dN}{dE} = \sum_i B_i \boxed{\left.\frac{dN}{dE}\right|_i}$$

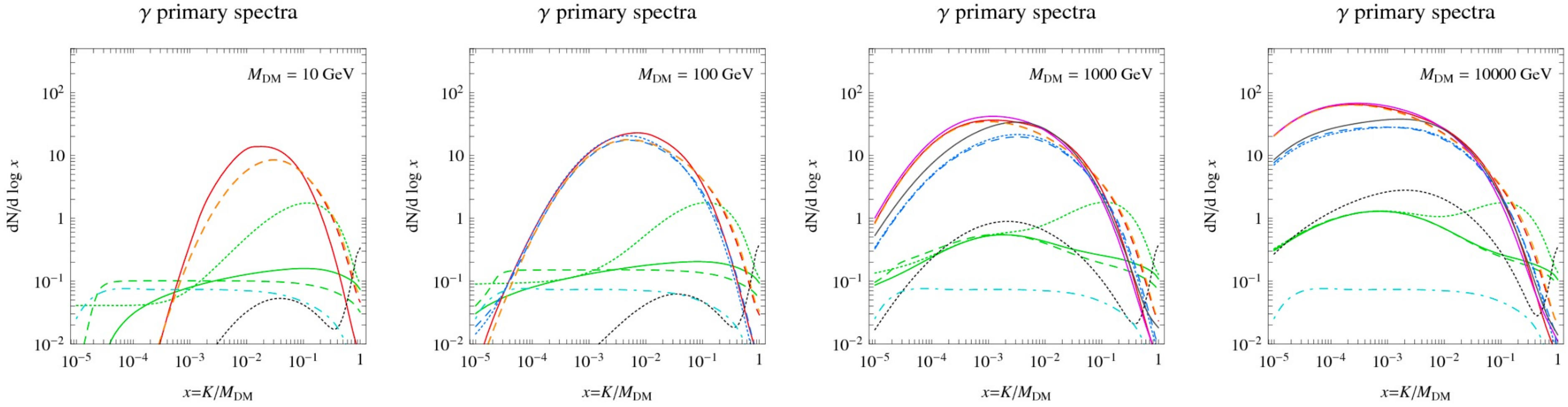
JCAP03(2011)051

PPPC 4 DM ID: a poor particle physicist cookbook for dark matter indirect detection

Photon yields from simulations (Pythia, Herwig)

http://www.marcocirelli.net/PPPC4DMID.html





Estimation of expected gamma-ray fluxes

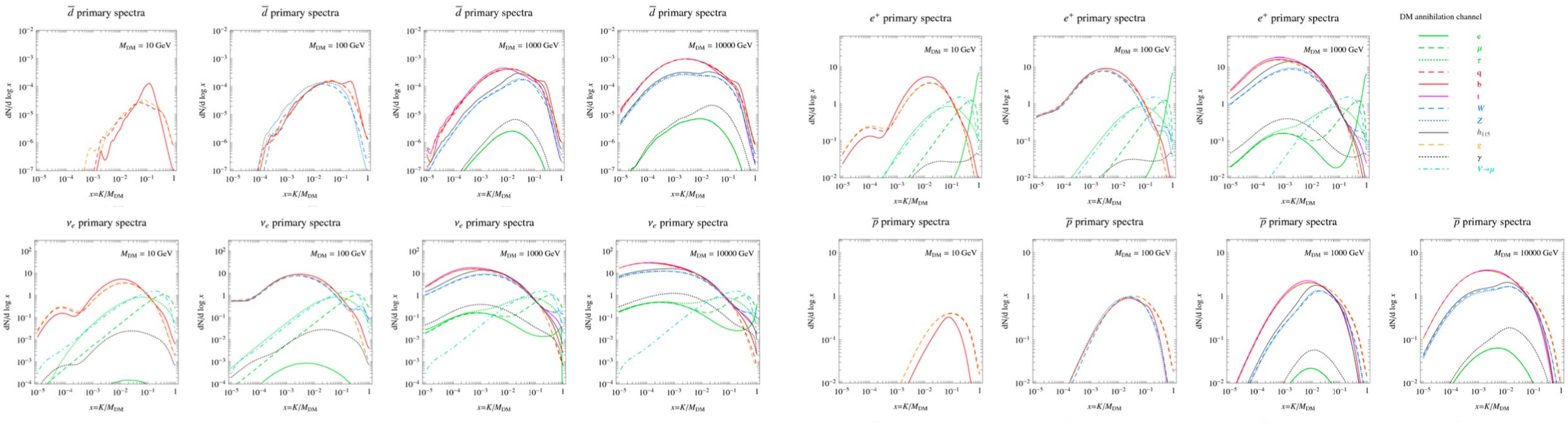
Particle Physics factor

$$\frac{dN}{dE} = \sum_i B_i \boxed{\left.\frac{dN}{dE}\right|_i}$$

JCAP03(2011)051

PPPC 4 DM ID: way more than just photons! $e^{\pm}, \bar{p}, \bar{d}, \gamma, \overset{(-)}{\nu}_{e,\mu,\tau}$ at production

Including propagation in the Galaxy for charged particles

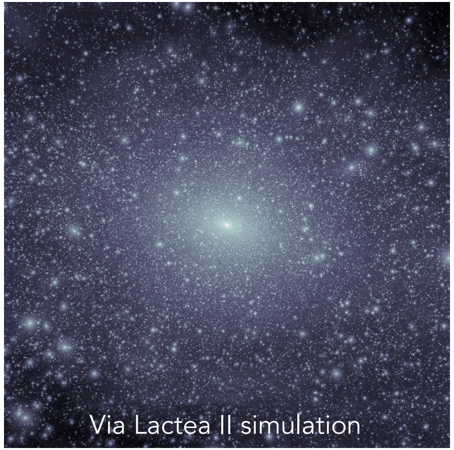


Astrophysical factor

Ann. $$\int_{0}^{\Delta\Omega}\int_{\text{l.o.s.}} \rho(l,\Omega)^2\, dl\, d\Omega \,.$$

Dec. $$\int_{0}^{\Delta\Omega}\int_{\text{l.o.s.}} \rho(l,\Omega)\, dl\, d\Omega \,.$$

N-body DM simulations



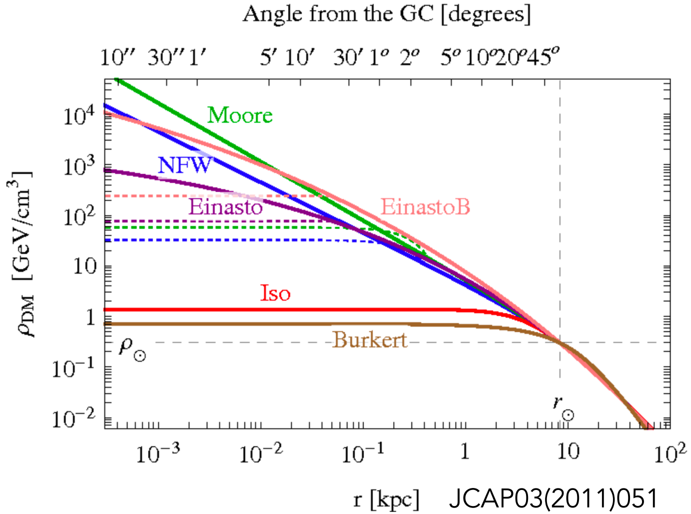
$$\text{NFW}: \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$



JCAP03(2011)051

Estimation of expected gamma-ray fluxes

Astrophysical factor

clumpy.gitlab.io

Ann. $$\int_0^{\Delta\Omega}\int_{\mathrm{l.o.s.}} \rho(l,\Omega)^2 \, \mathrm{d}l \, \mathrm{d}\Omega \; .$$

Dec. $$\int_0^{\Delta\Omega}\int_{\mathrm{l.o.s.}} \rho(l,\Omega) \, \mathrm{d}l \, \mathrm{d}\Omega \; .$$

A code for γ-ray and ν signals from dark matter structures

We hope you will enjoy using **CLUMPY** whether you are:

- *an experimental astroparticle physicist* looking for *J*-factors or synthetic 2D γ-ray or ν skymaps from dark matter decay or annihilation, to calculate your instrumental sensitivity or to use in model/template analyses;
- *a theoretical astroparticle physicist* wishing to explore the γ-ray or ν flux in the Galaxy, dSphs, or galaxy clusters for your preferred particle physics model;
- *an astrophysicist* working on the DM content of dSphs and wishing to perform a Jeans analysis on your kinematic data;
- *a cosmologist* wishing to compute halo mass functions for any cosmology, redshift, and overdensity definition Δ.

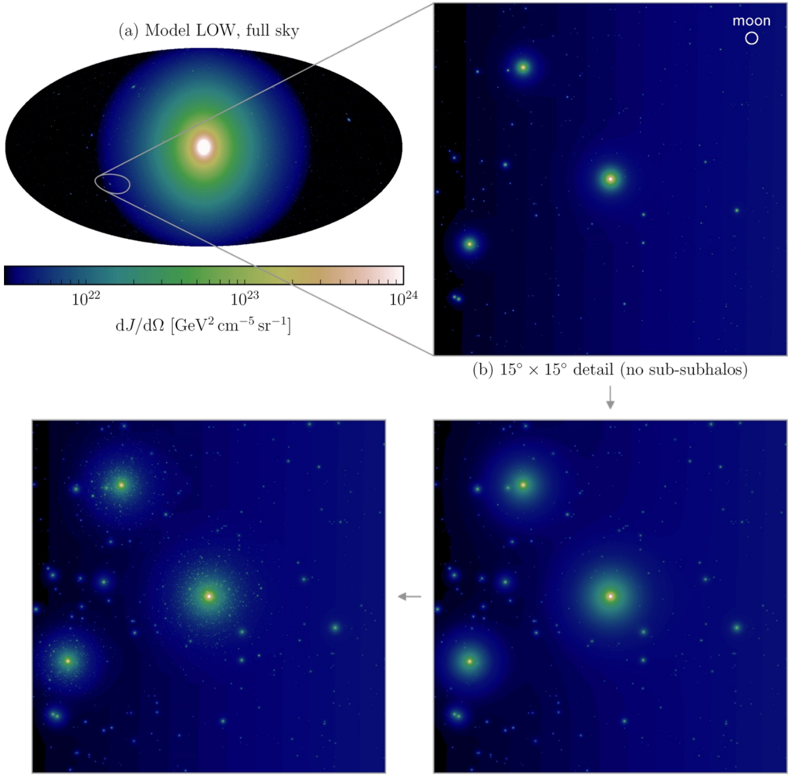
Estimation of expected gamma-ray fluxes

Astrophysical factor

clumpy.gitlab.io

Ann. $$\int_{0}^{\Delta\Omega}\int_{\text{l.o.s.}} \rho(l,\Omega)^2 \, dl \, d\Omega \; .$$

Dec. $$\int_{0}^{\Delta\Omega}\int_{\text{l.o.s.}} \rho(l,\Omega) \, dl \, d\Omega \; .$$



(b) 15° × 15° detail (no sub-subhalos)

(d) Sub-subhalos, partially resolved

(c) Sub-subhalos, unresolved (model VAR5)

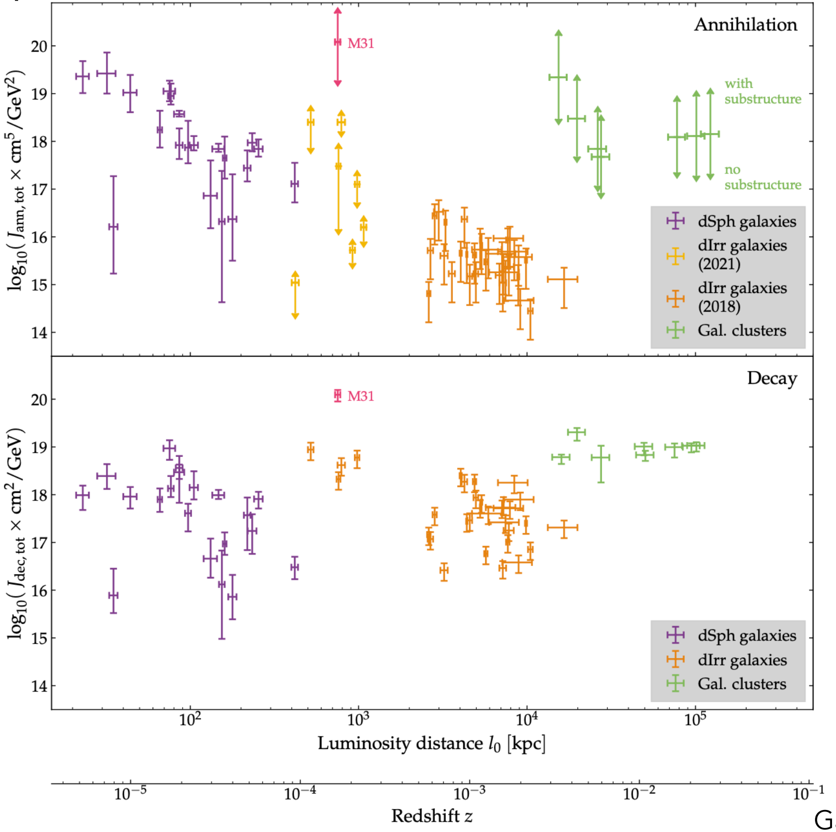
Hütten (2017, PhD thesis)

Astrophysical factor

clumpy.gitlab.io

Ann. $$\int_0^{\Delta\Omega}\int_{\text{l.o.s.}} \rho(l,\Omega)^2\, dl\, d\Omega\ .$$

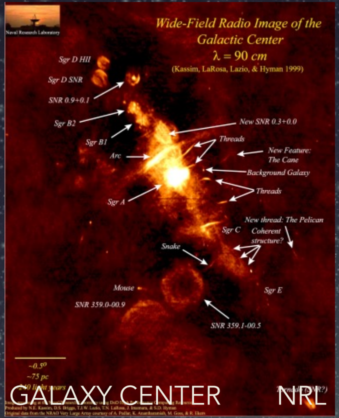
Dec. $$\int_0^{\Delta\Omega}\int_{\text{l.o.s.}} \rho(l,\Omega)\, dl\, d\Omega\ .$$



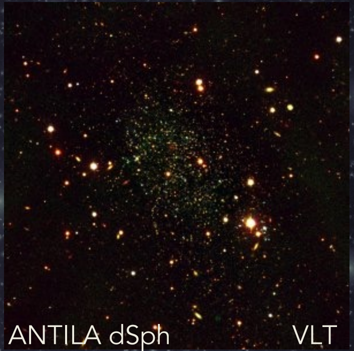
Galaxies 2022, 10, 92

Targets

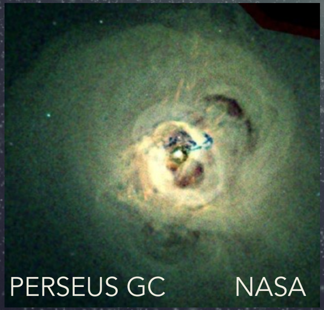
- Galactic Center
- High flux
- Huge background



- Dwarf Galaxies
- Large M/L
- No background
- Low flux

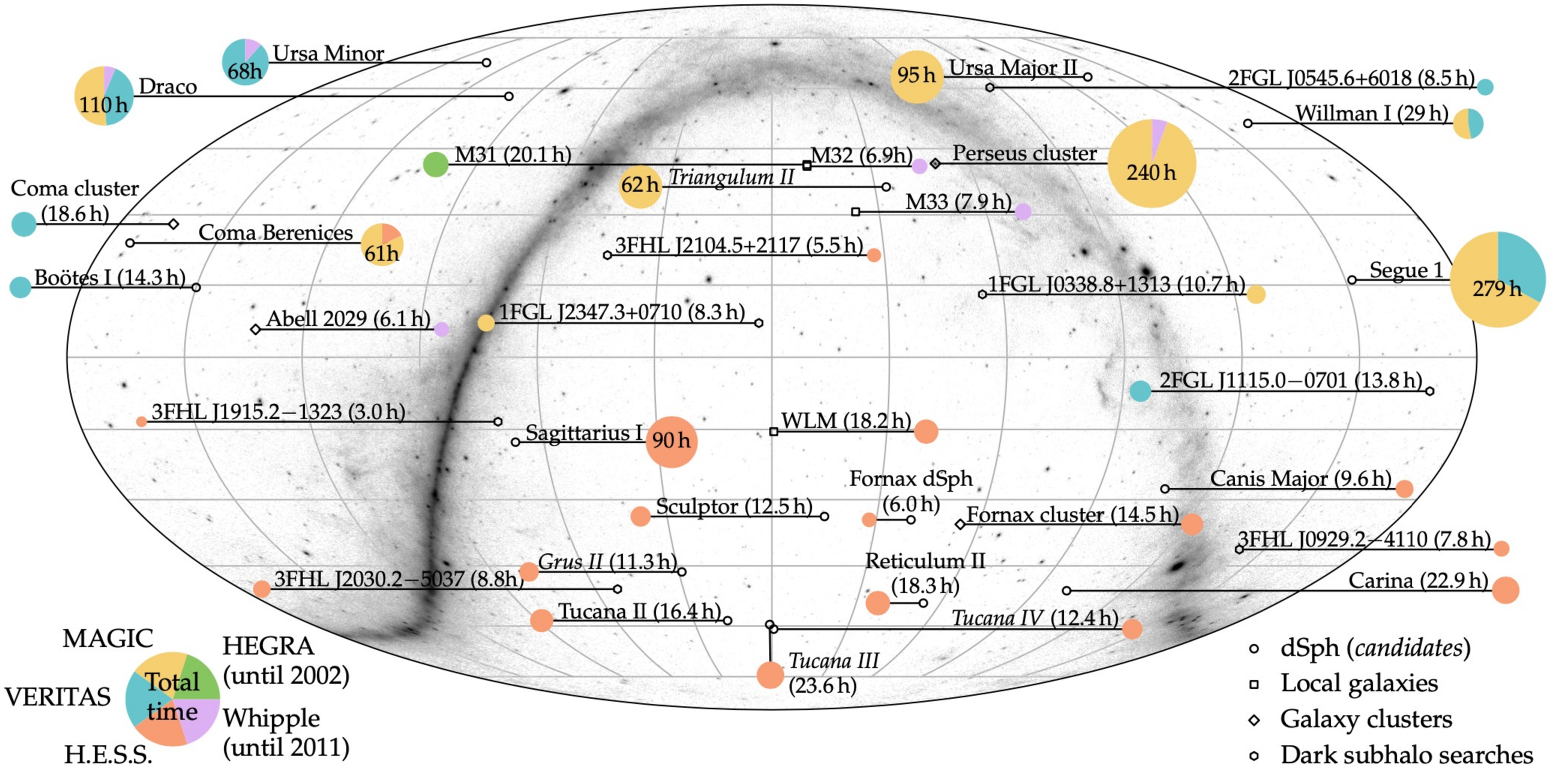


- Galaxy Clusters
- Huge DM content
- Large distance
- High background



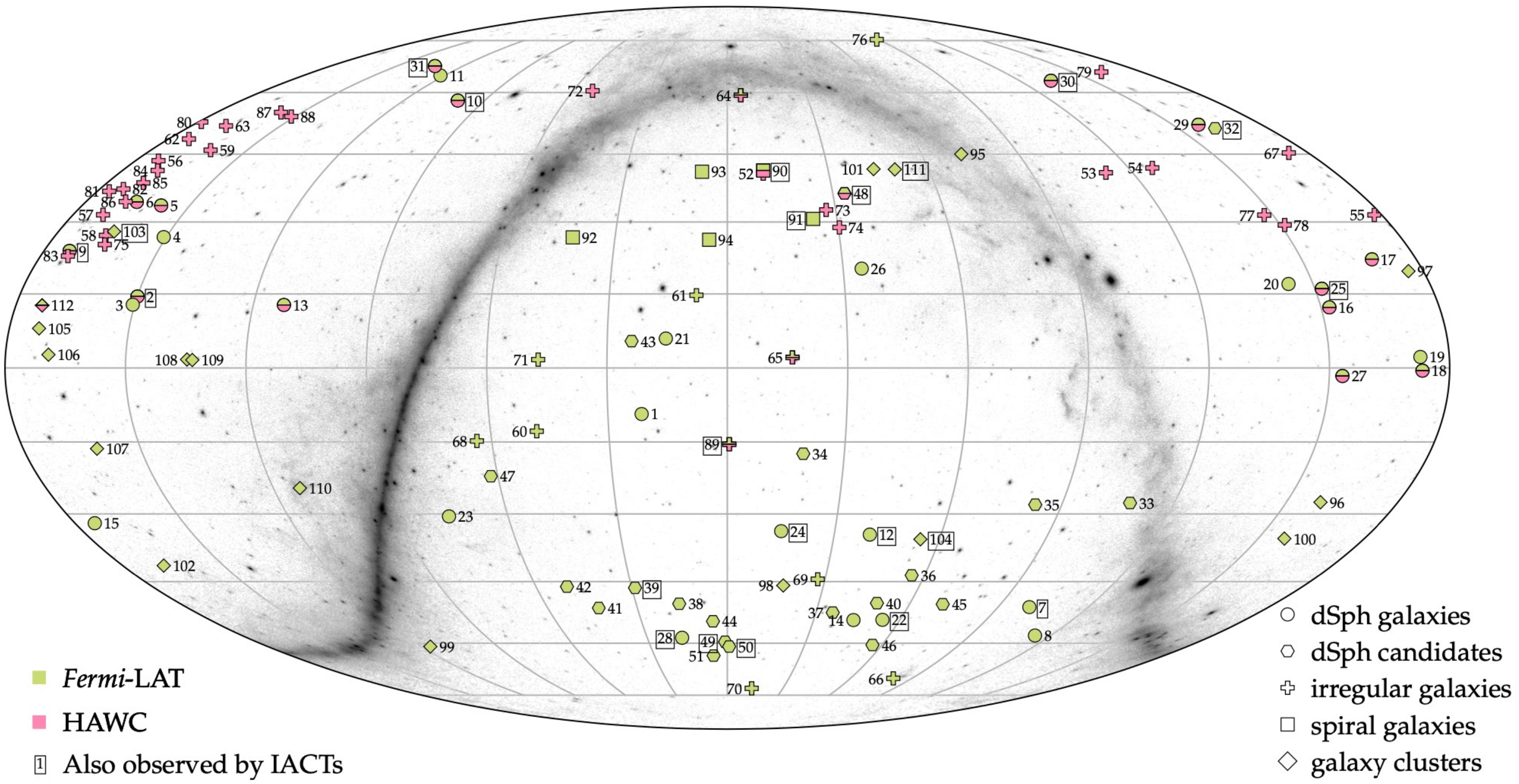
- *DM subhalos*
- *Irregular dSph*
- *Spiral galaxies*
- *…*

Targets: IACTs



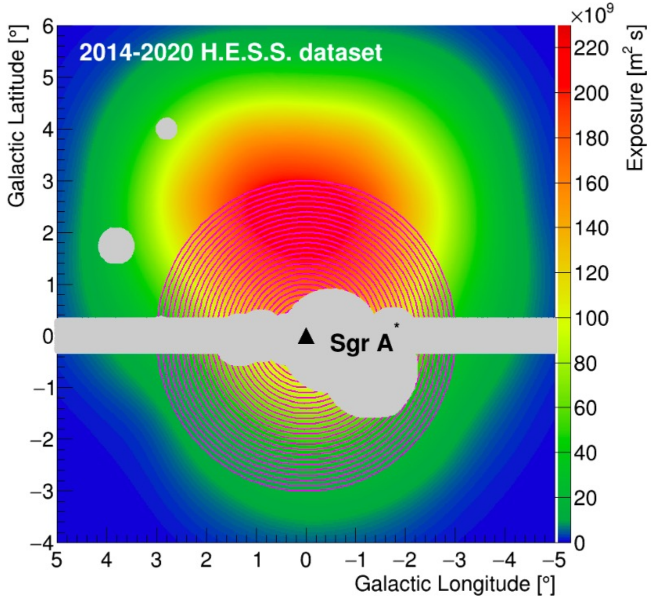
Galaxies 2022, 10, 92

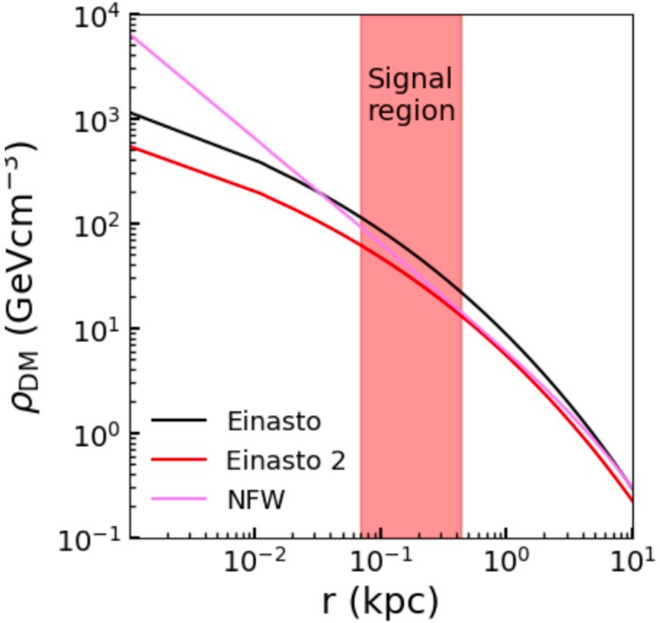
Targets: Fermi-LAT



Galaxies 2022, 10, 92

H.E.S.S. Inner Galaxy Survey





$$\rho_{\mathrm{E}}(r) = \rho_{\mathrm{s}} \exp\left[-\frac{2}{\alpha_{\mathrm{s}}}\left(\left(\frac{r}{r_{\mathrm{s}}}\right)^{\alpha_{\mathrm{s}}} - 1\right)\right]$$

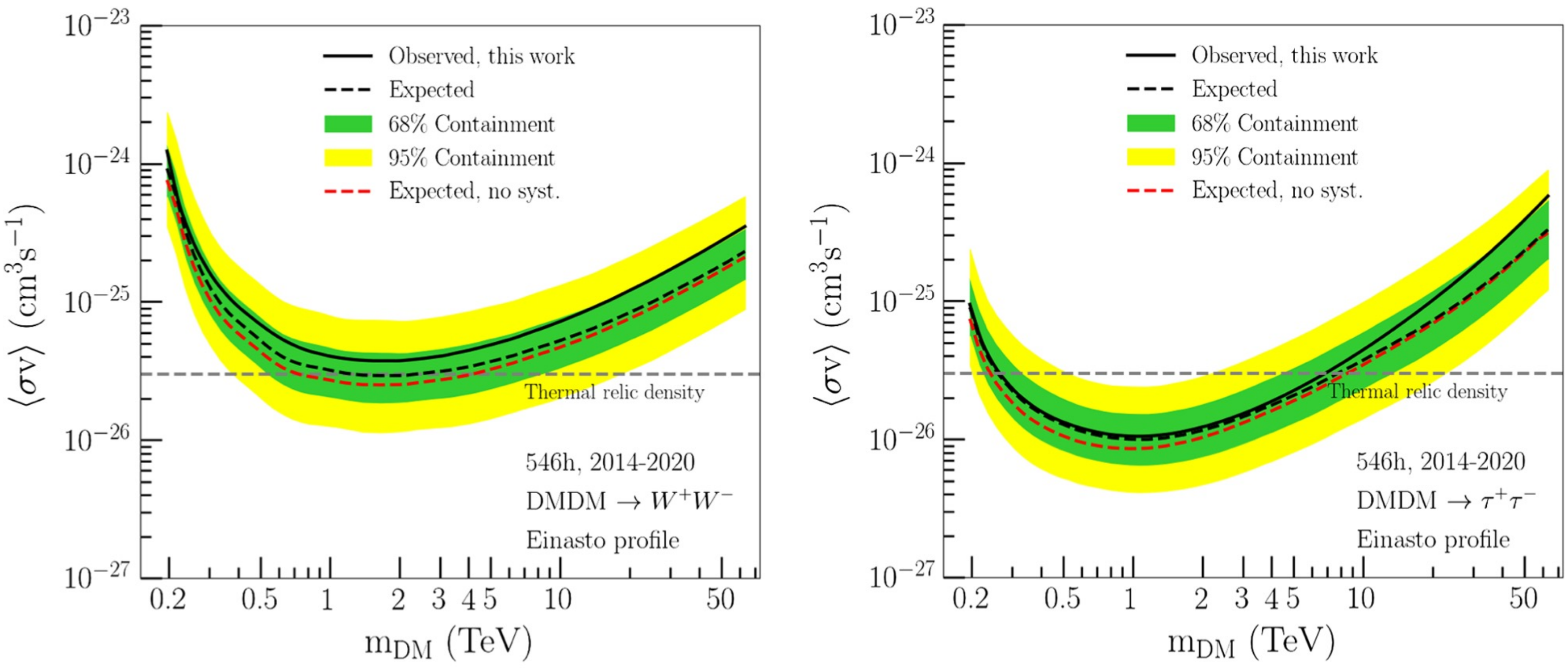
$$\rho_{\mathrm{NFW}}(r) = \rho_{\mathrm{s}}\left(\frac{r}{r_{\mathrm{s}}}\left(1+\frac{r}{r_{\mathrm{s}}}\right)^2\right)^{-1}$$

Profiles	Einasto	NFW	Einasto 2 [7]
ρ_{s} (GeVcm^{-3})	0.079	0.307	0.033
r_{s} (kpc)	20.0	21.0	28.4
α_{s}	0.17	/	0.17

Combined likelihood from 25 ROI

Phys. Rev. Lett. **129**, 111101 (2022)

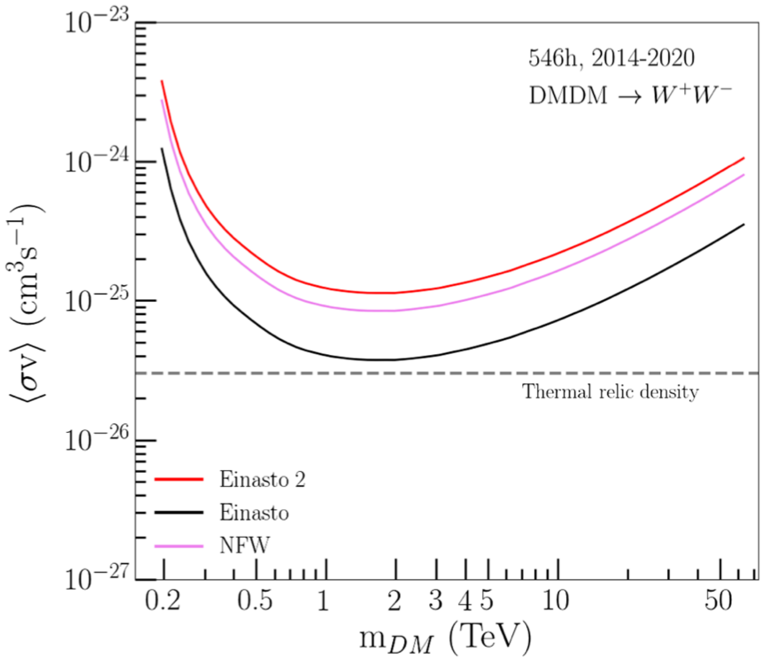
H.E.S.S. Inner Galaxy Survey

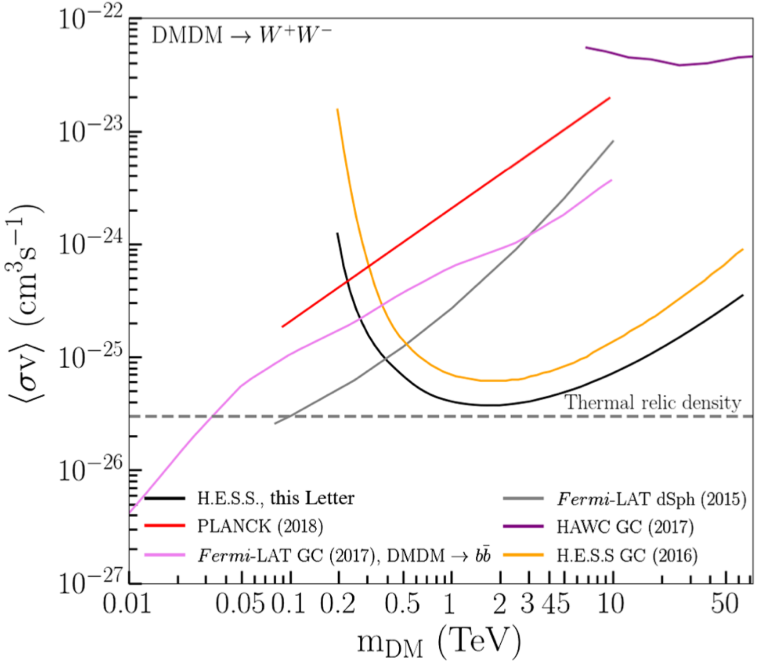


Most constraining limits to date in the TeV range

Phys. Rev. Lett. **129**, 111101 (2022)

H.E.S.S. Inner Galaxy Survey

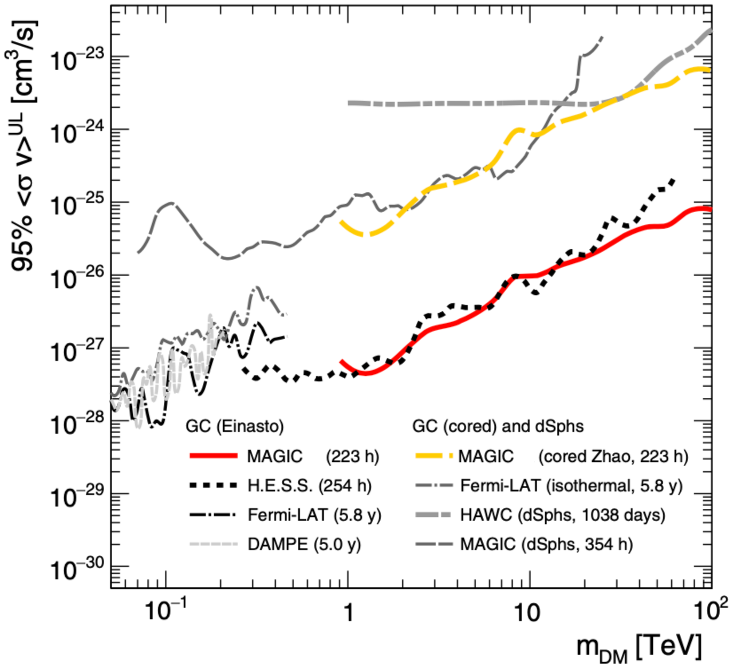


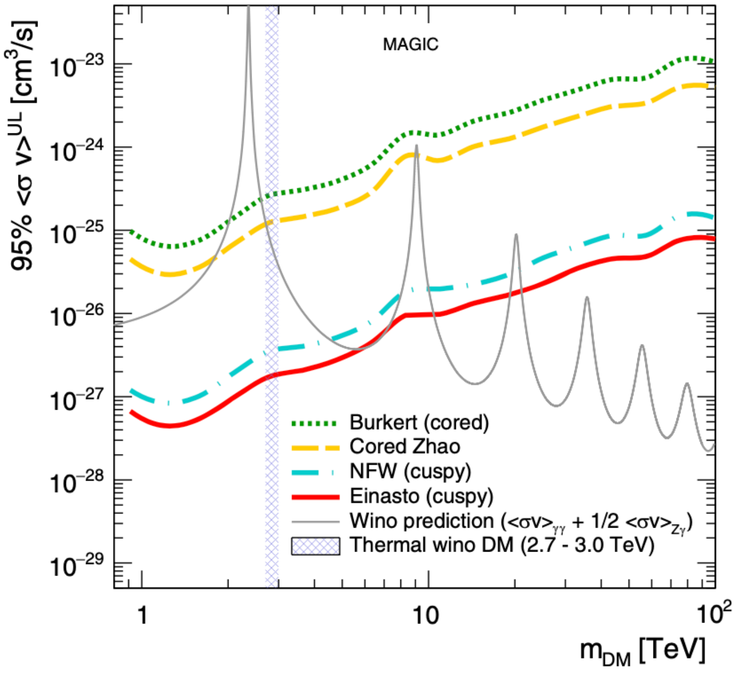


Very sensitive to selection of density profile

Phys. Rev. Lett. **129**, 111101 (2022)

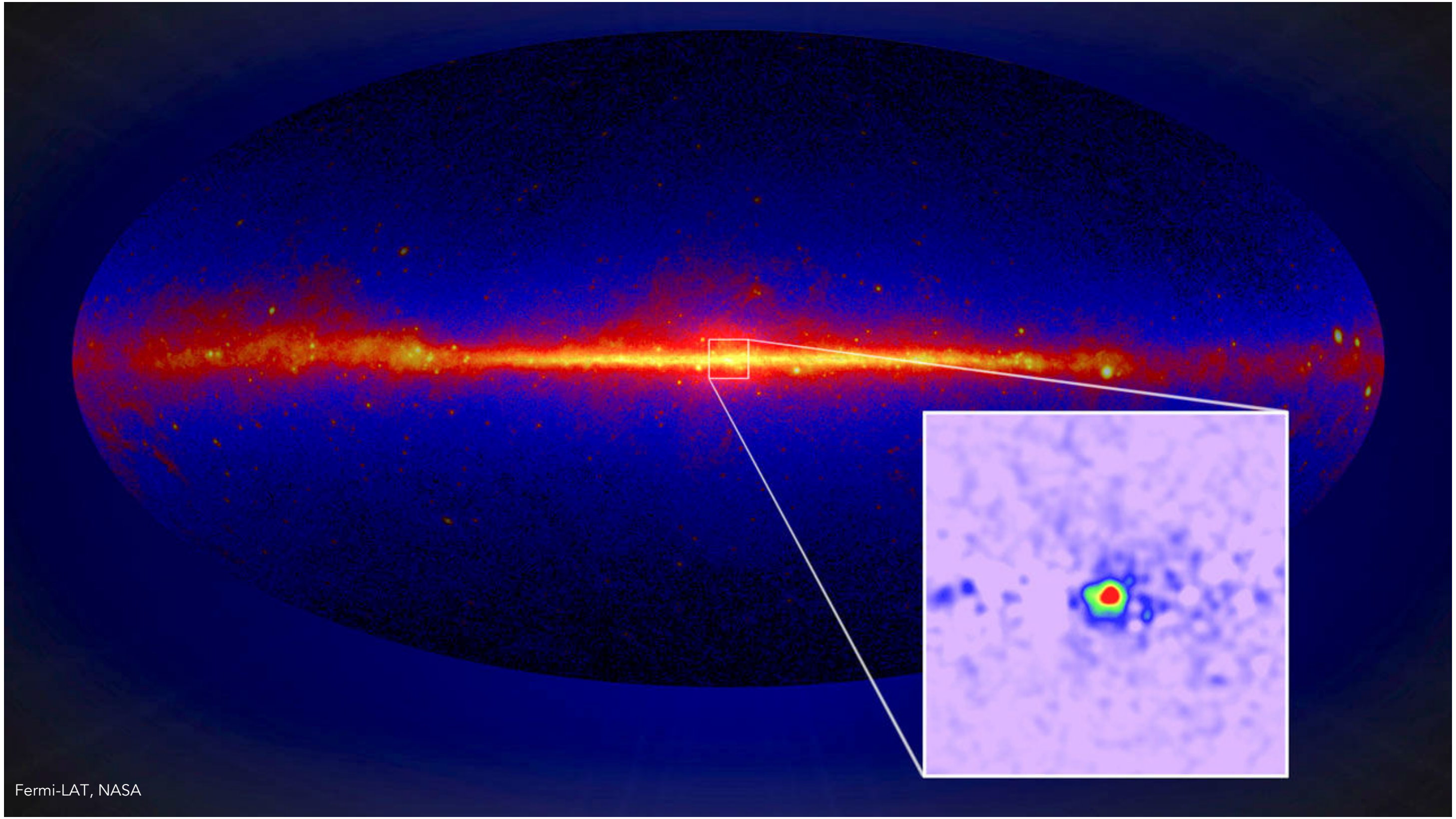
Search for spectral lines with MAGIC



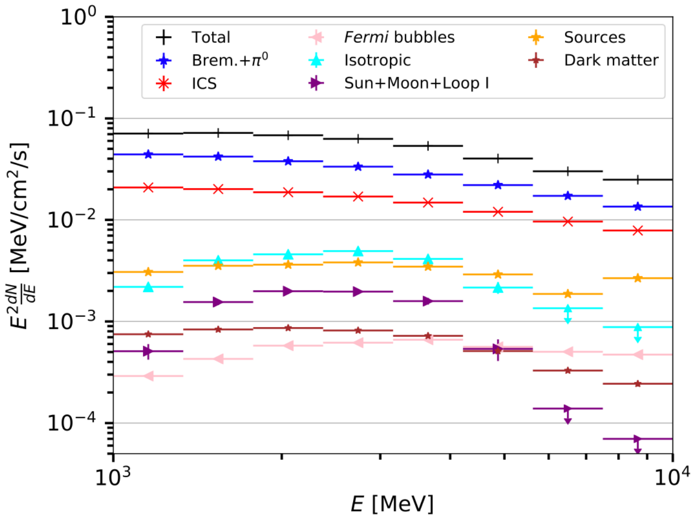


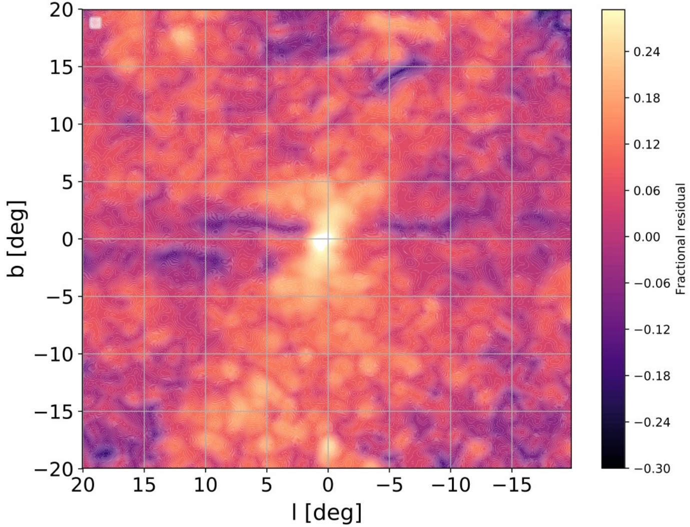
PRL 130, 061002 (2023)

Galactic center excess



Galactic center excess





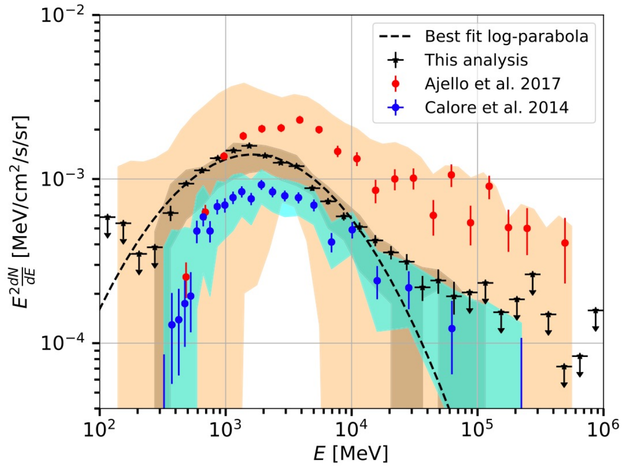
Model	N° comp.	List templates used for each component
1	17	5 rings for bremsstrahlung (Brem.) and π^0 emission, 3 for inverse Compton (CMB, SL. IR), 2 for low latitude bubbles, isotropic (ISO), 1 template for Loop I, the Sun, and the Moon (LoopMoonSun).
2	9	1 Brem., 1 π^0, 3 for inverse Compton (IC), 2 for low latitude bubbles, 1 ISO, 1 LoopMoonSun.
3	8	1 Brem. and π^0, 3 IC, 2 for low latitude bubbles, 1 ISO, 1 LoopMoonSun.
4	8	1 Brem., 1 for π^0, 3 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
5	8	2 for Brem. and π^0 divided into H1 and H2, 3 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
6	7	1 Brem., 1 for π^0, 1 for IC, 2 for bubbles, 1 ISO, 1 LoopMoonSun.
7	7	1 Brem. and π^0, 3 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
8	5	1 Brem. and π^0, 1 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
9	4	1 Brem. and π^0, 1 IC, 1 bubbles, 1 ISO and LoopMoonSun.
10	4	1 Brem. and π^0 and IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
11	1	1 unique template for all components.

Very detailed modeling of the region
Weighted likelihood analysis
Excess presence is robust

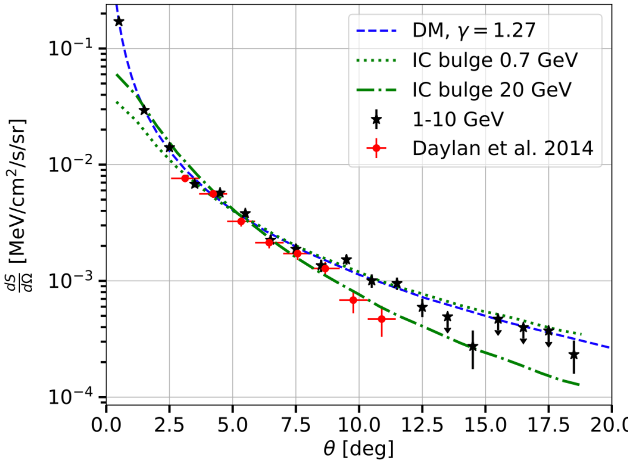
PRD 103, 063029 (2021)

Galactic center excess

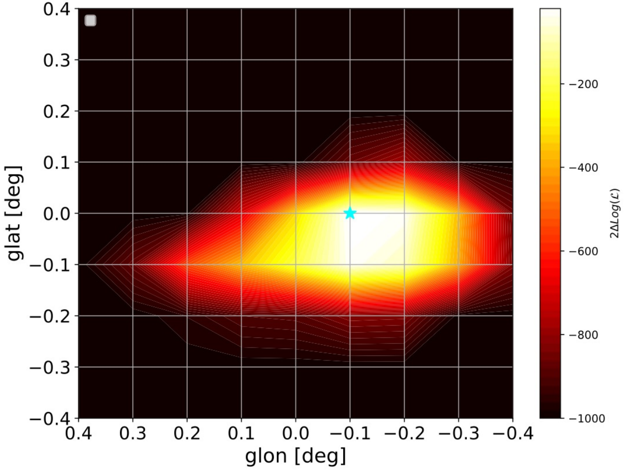
- GC is a very complex region of complex modeling: unresolved sources, distribution of CR density, etc.
- Dark matter annihilation? Unresolved population of MSPs?
- Origin of excess still under debate



SED well fitted by ~50 GeV DM (bb)

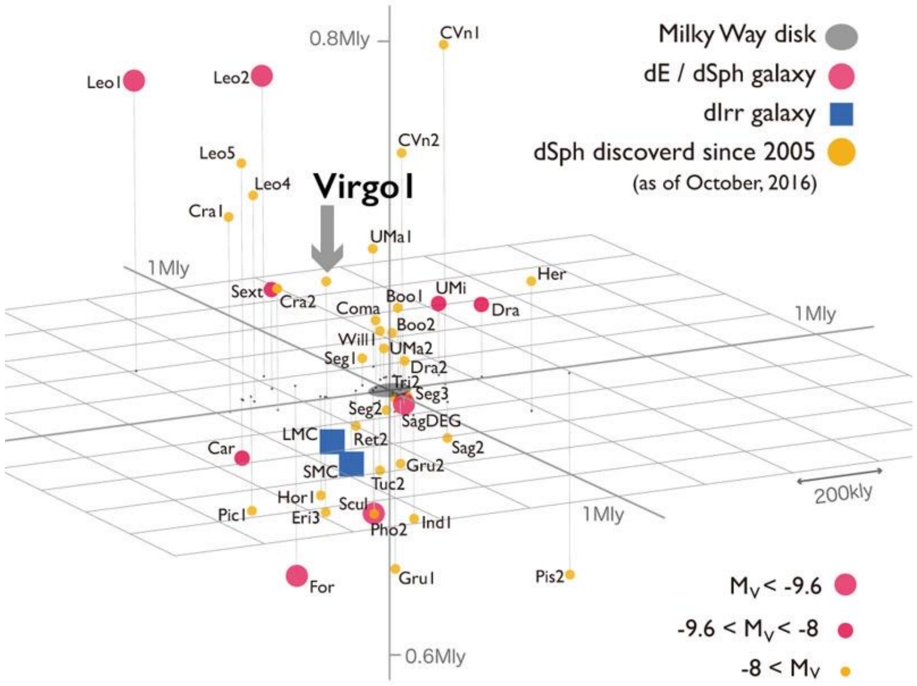


Spatial morphology: NFW compatible

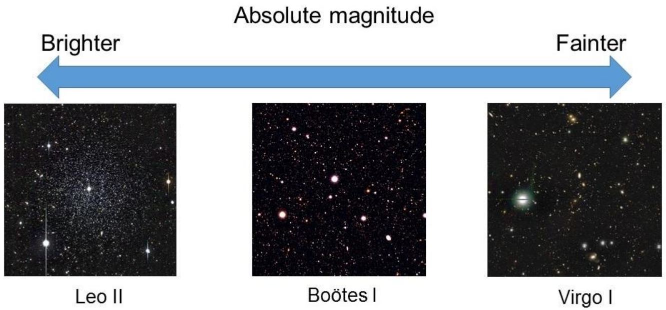


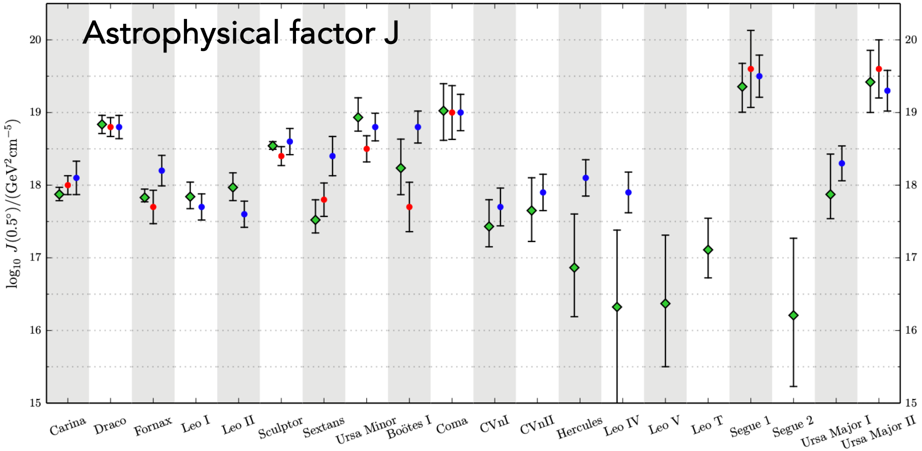
Compatible with spherical symmetry
Positionally compatible with Sgr A*

PRD 103, 063029 (2021)



subarutelescope.org

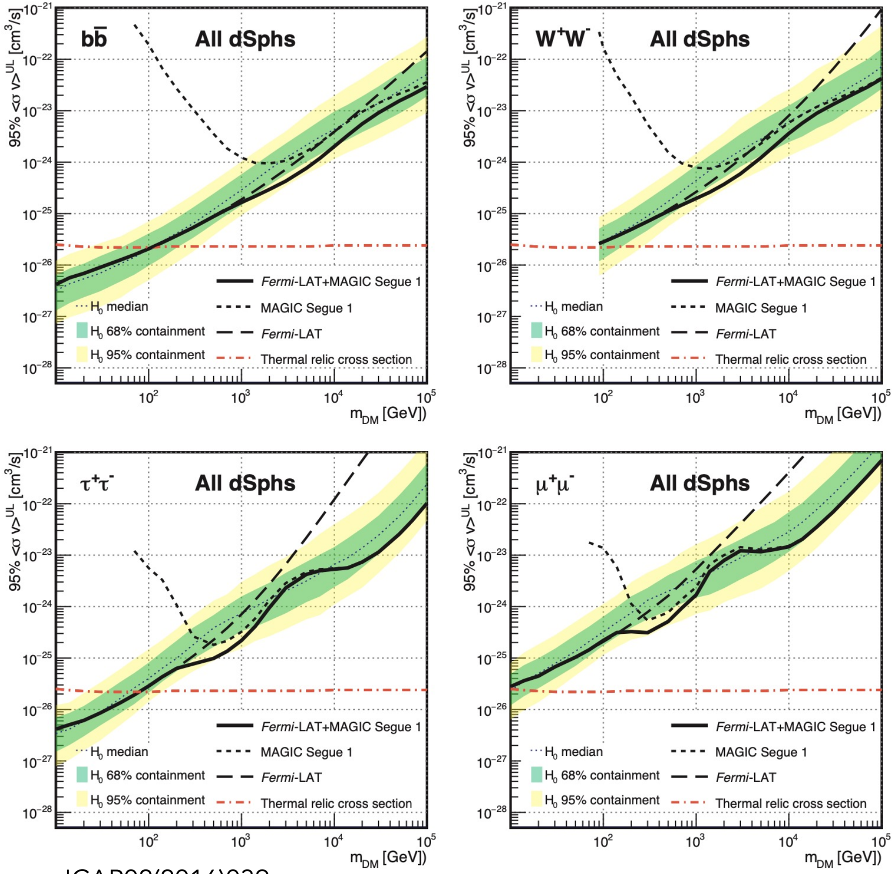




Geringer-Sameth *et al* 2015 *ApJ* **801** 74

Fermi-LAT + MAGIC

- First combined likelihood analysis in the gamma-ray band
- MAGIC: 160h Segue 1
- Fermi-LAT: 15 dSph



JCAP02(2016)039

Glory Duck

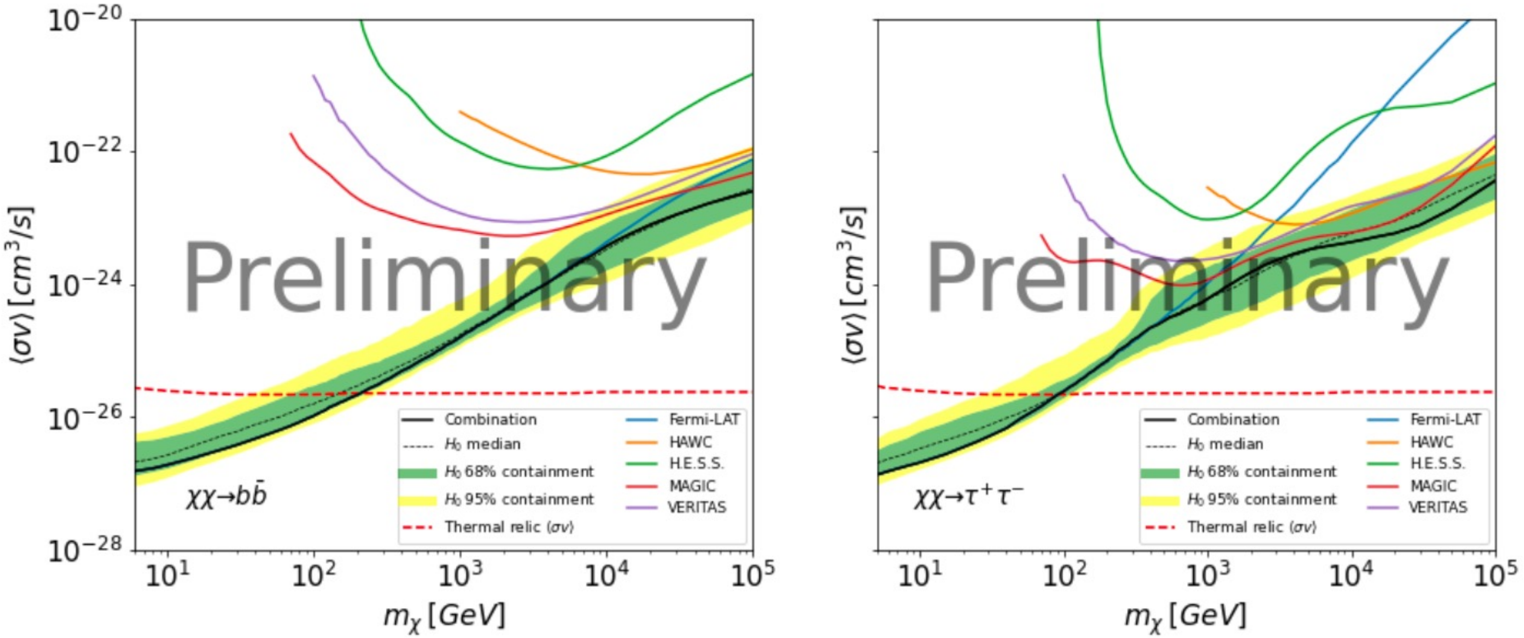
Source name	Experiments	Distance (kpc)	$\log_{10} J$ $\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr})$
Bootes I	*Fermi*-LAT, HAWC, VERITAS	66	$18.24^{+0.40}_{-0.37}$
Canes Venatici I	*Fermi*-LAT	218	$17.44^{+0.37}_{-0.28}$
Canes Venatici II	*Fermi*-LAT, HAWC	160	$17.65^{+0.45}_{-0.43}$
Carina	*Fermi*-LAT, H.E.S.S.	105	$17.92^{+0.19}_{-0.11}$
Coma Berenices	*Fermi*-LAT, HAWC, H.E.S.S., MAGIC	44	$19.02^{+0.37}_{-0.41}$
Draco	*Fermi*-LAT, HAWC, MAGIC, VERITAS	76	$19.05^{+0.22}_{-0.21}$
Fornax	*Fermi*-LAT, H.E.S.S.	147	$17.84^{+0.11}_{-0.06}$
Hercules	*Fermi*-LAT, HAWC	132	$16.86^{+0.74}_{-0.68}$
Leo I	*Fermi*-LAT, HAWC	254	$17.84^{+0.20}_{-0.16}$
Leo II	*Fermi*-LAT, HAWC	233	$17.97^{+0.20}_{-0.18}$
Leo IV	*Fermi*-LAT, HAWC	154	$16.32^{+1.06}_{-1.70}$
Leo T	*Fermi*-LAT	417	$17.11^{+0.44}_{-0.39}$
Leo V	*Fermi*-LAT	178	$16.37^{+0.94}_{-0.87}$
Sculptor	*Fermi*-LAT, H.E.S.S.	86	$18.57^{+0.07}_{-0.05}$
Segue I	*Fermi*-LAT, HAWC, MAGIC, VERITAS	23	$19.36^{+0.32}_{-0.35}$
Segue II	*Fermi*-LAT	35	$16.21^{+1.06}_{-0.98}$
Sextans	*Fermi*-LAT, HAWC	86	$17.92^{+0.35}_{-0.29}$
Ursa Major I	*Fermi*-LAT, HAWC	97	$17.87^{+0.56}_{-0.33}$
Ursa Major II	*Fermi*-LAT, HAWC, MAGIC	32	$19.42^{+0.44}_{-0.42}$
Ursa Minor	*Fermi*-LAT, VERITAS	76	$18.95^{+0.26}_{-0.18}$

- All IACTs + Fermi-LAT + HAWC
- 20 dSph
- Joint likelihood approach

Armand et al. PoS(ICRC21)

$$\mathcal{L}_{\text{bin}}\left(\langle\sigma v\rangle; J, \boldsymbol{\mu} \mid \boldsymbol{\mathcal{D}}\right) = \mathcal{L}_{\text{bin}}(\langle\sigma v\rangle; \{b_i\}_{i=1,\ldots,N_{\text{bins}}}, J, \tau \mid \{N_{\text{ON},i}, N_{\text{OFF},i}\}_{i=1,\ldots,N_{\text{bins}}})$$
$$= \prod_{i=1}^{N_{\text{bins}}} \left[\mathcal{P}(s_i(\langle\sigma v\rangle, J) + b_i \mid N_{\text{ON},i}) \cdot \mathcal{P}(\tau b_i \mid N_{\text{OFF},i})\right] \times \mathcal{T}(\tau \mid \tau_{\text{O}}, \sigma_\tau)$$

Glory Duck

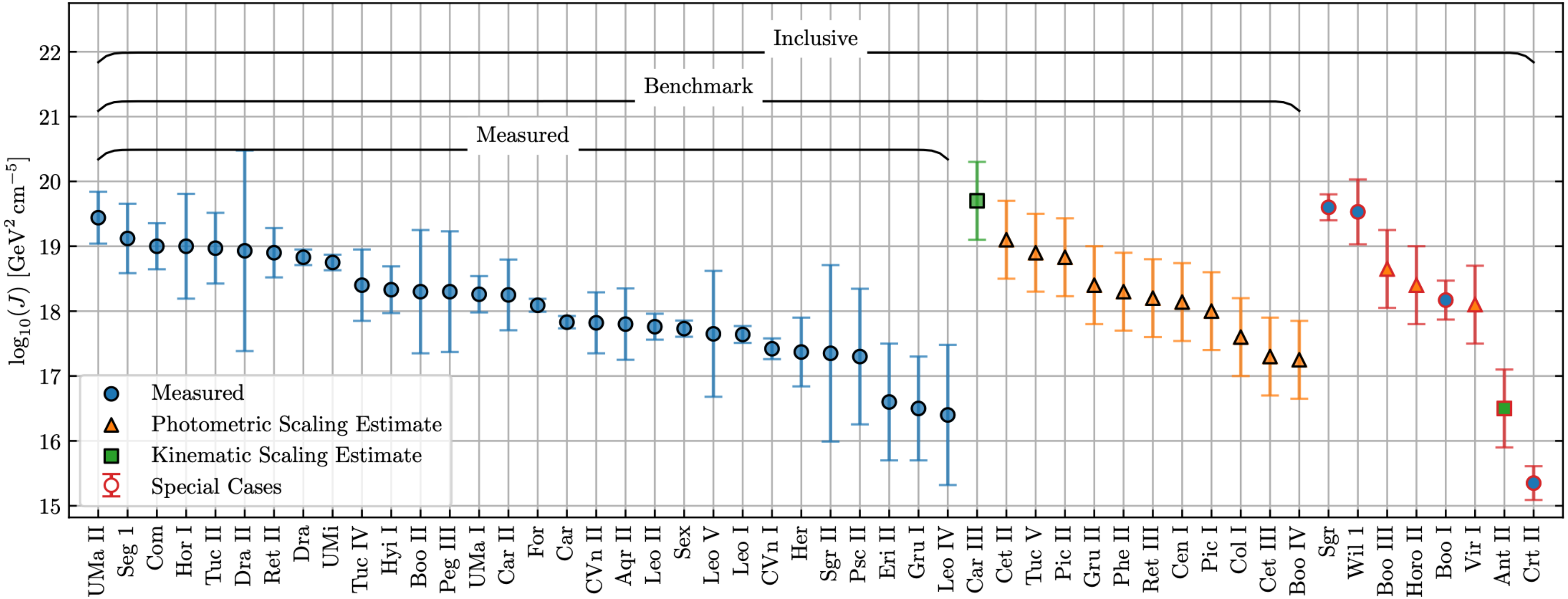


Armand et al. PoS(ICRC21)

- Widest range ever 5 GeV – 100 TeV
- Arguably most robust results up to date

Dwarf Spheroidal Galaxies

Fermi-LAT legacy analysis



14 years of data

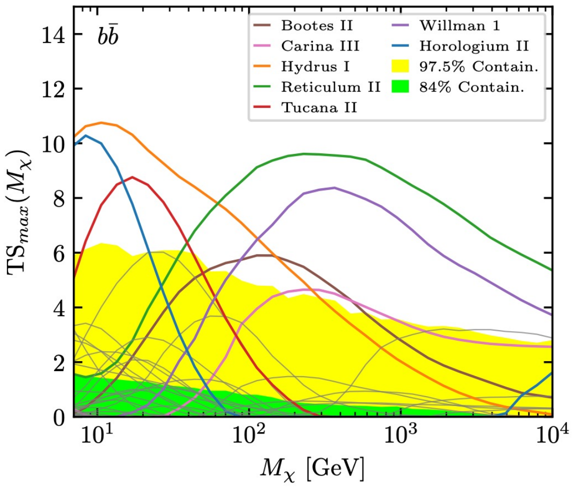
Updated census of dSph (50)

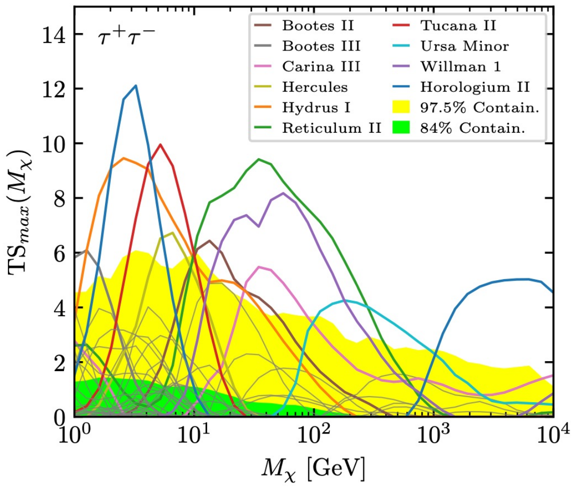
McDaniel et al. 2023
arXiv:2311.04982

Fermi-LAT legacy analysis

Individual dSph with > 2.0 σ

	M_χ [GeV]	$p_{\rm local}$	$p_{\rm global}$	$p_{\rm sample}$
		$b\bar{b}$		
Boötes II	228.5	1.3×10^{-2} $(2.2\,\sigma)$	8.1×10^{-2} $(1.4\,\sigma)$	0.97 $(-1.9\,\sigma)$
Carina III	366.5	2.1×10^{-2} $(2.0\,\sigma)$	1.1×10^{-1} $(1.2\,\sigma)$	0.99 $(-2.5\,\sigma)$
Horologium II	8.4	5.0×10^{-3} $(2.6\,\sigma)$	1.3×10^{-2} $(2.2\,\sigma)$	0.50 $(-0.0\,\sigma)$
Hydrus I	8.4	4.0×10^{-3} $(2.7\,\sigma)$	1.2×10^{-2} $(2.2\,\sigma)$	0.50 $(-0.0\,\sigma)$
Reticulum II	289.4	$<10^{-3}$ $(>3\,\sigma)$	1.6×10^{-2} $(2.1\,\sigma)$	0.57 $(-0.2\,\sigma)$
Tucana II	13.4	9.9×10^{-3} $(2.3\,\sigma)$	2.8×10^{-2} $(1.9\,\sigma)$	0.73 $(-0.6\,\sigma)$
Willman 1	228.5	2.0×10^{-3} $(2.9\,\sigma)$	3.3×10^{-2} $(1.8\,\sigma)$	0.76 $(-0.7\,\sigma)$
		$\tau^+\tau^-$		
Boötes II	13.4	1.6×10^{-2} $(2.1\,\sigma)$	5.9×10^{-2} $(1.6\,\sigma)$	0.97 $(-1.9\,\sigma)$
Carina III	43.8	1.2×10^{-2} $(2.3\,\sigma)$	8.3×10^{-2} $(1.4\,\sigma)$	0.99 $(-2.5\,\sigma)$
Horologium II	2.6	$<10^{-3}$ $(>3\,\sigma)$	7.9×10^{-3} $(2.4\,\sigma)$	0.36 $(0.4\,\sigma)$
Hydrus I	2.6	4.0×10^{-3} $(2.7\,\sigma)$	1.7×10^{-2} $(2.1\,\sigma)$	0.57 $(-0.2\,\sigma)$
Reticulum II	27.3	$<10^{-3}$ $(>3\,\sigma)$	2.2×10^{-2} $(2.0\,\sigma)$	0.68 $(-0.5\,\sigma)$
Tucana II	5.2	6.9×10^{-3} $(2.5\,\sigma)$	1.4×10^{-2} $(2.2\,\sigma)$	0.50 $(-0.0\,\sigma)$
Willman 1	43.8	$<10^{-3}$ $(>3\,\sigma)$	3.6×10^{-2} $(1.8\,\sigma)$	0.88 $(-1.2\,\sigma)$



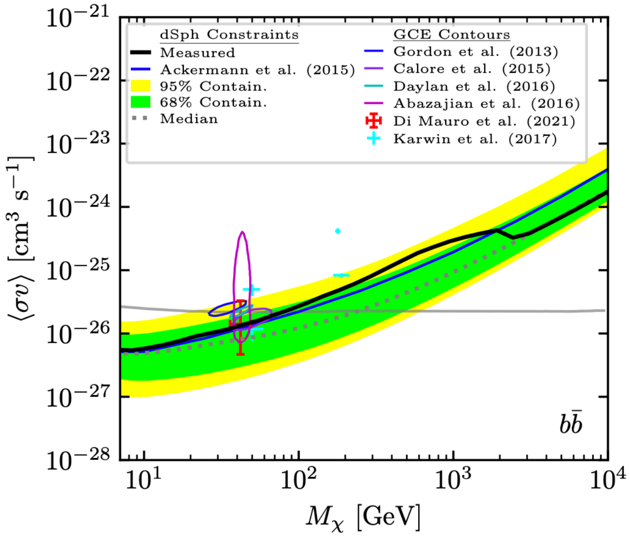


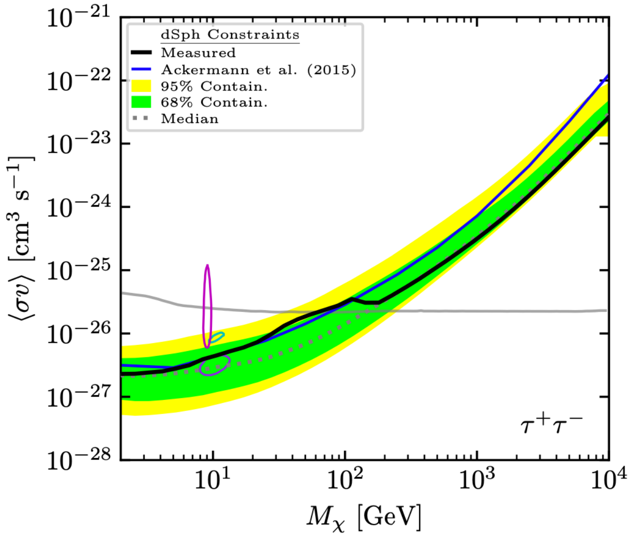
McDaniel et al. 2023
arXiv:2311.04982

Fermi-LAT legacy analysis

Whole sample

	$b\bar{b}$			$\tau^+\tau^-$		
	M_χ [GeV]	p_{local}	p_{global}	M_χ [GeV]	p_{local}	p_{global}
Measured	8.4	9.6×10^{-2} $(1.3\,\sigma)$	2.0×10^{-1} $(0.9\,\sigma)$	10.6	9.6×10^{-2} $(1.3\,\sigma)$	3.2×10^{-1} $(0.5\,\sigma)$
Benchmark	180.5	2.1×10^{-2} $(2.0\,\sigma)$	3.1×10^{-1} $(0.5\,\sigma)$	43.8	2.3×10^{-2} $(2.0\,\sigma)$	4.2×10^{-1} $(0.2\,\sigma)$
Inclusive	366.5	9.0×10^{-4} $(3.1\,\sigma)$	1.1×10^{-1} $(1.2\,\sigma)$	43.8	1.1×10^{-3} $(3.1\,\sigma)$	1.3×10^{-1} $(1.1\,\sigma)$





McDaniel et al. 2023
arXiv:2311.04982

Branon DM constraints with MAGIC

UED theory
SM: brane embedded in D = 4 +N spacetime
Branons: massive brane fluctuations

Fermions

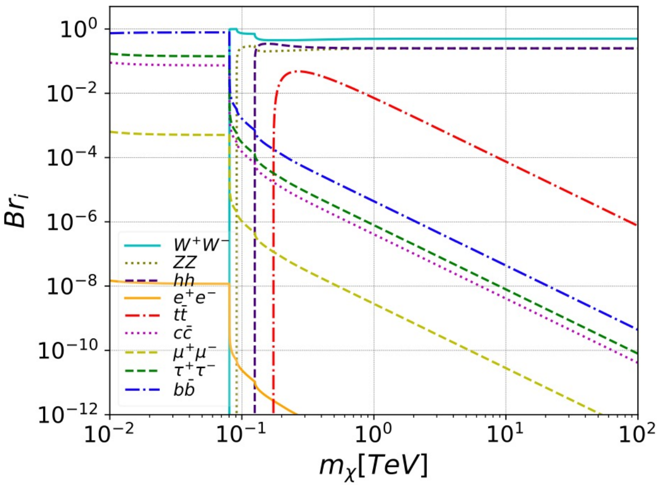
$$\langle \sigma_\psi v \rangle = \frac{m_\chi^2 m_\psi^2}{16\pi^2 f^8}\left(m_\chi^2 - m_\psi^2\right)\sqrt{1-\frac{m_\psi^2}{m_\chi^2}},$$

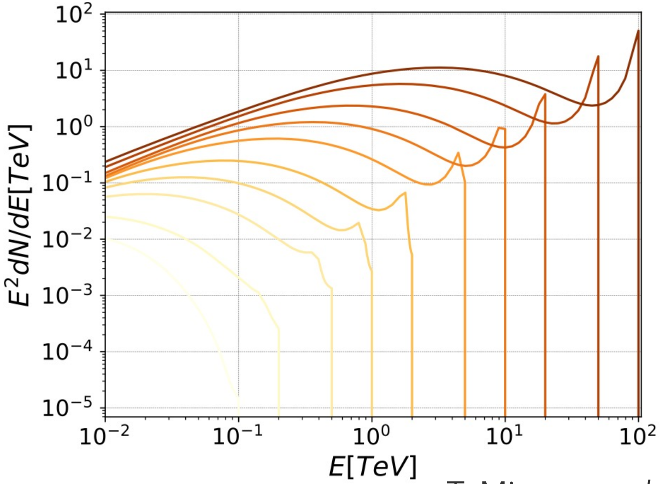
Massive gauge fields

$$\langle \sigma_{W,Z} v \rangle = \frac{m_\chi^2}{64\pi^2 f^8}\left(4m_\chi^4 - 4m_\chi^2 m_{W,Z}^2 + 3m_{W,Z}^4\right)\sqrt{1-\frac{m_{W,Z}^2}{m_\chi^2}},$$

Scalar fields

$$\langle \sigma_\Phi v \rangle = \frac{m_\chi^2}{32\pi^2 f^8}\left(2m_\chi^2 + m_\Phi^2\right)^2\sqrt{1-\frac{m_\Phi^2}{m_\chi^2}}.$$

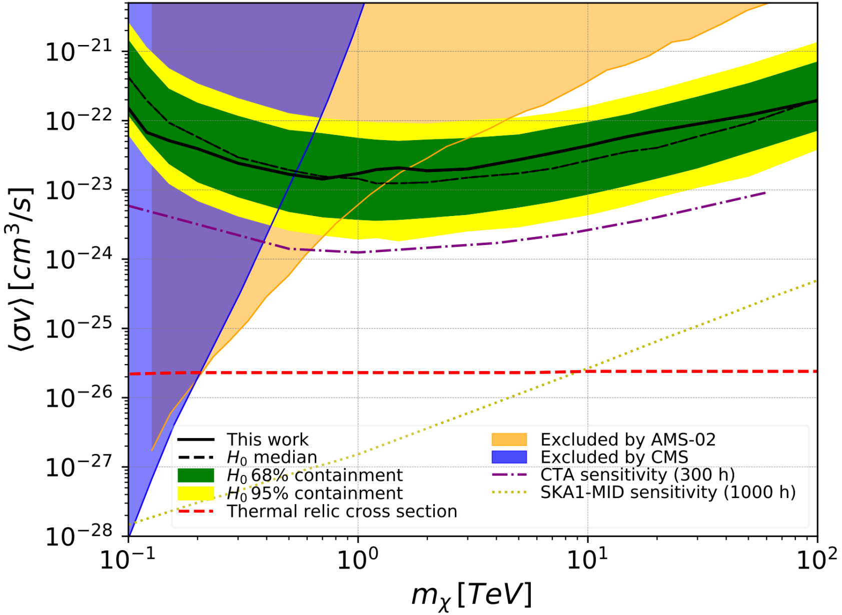


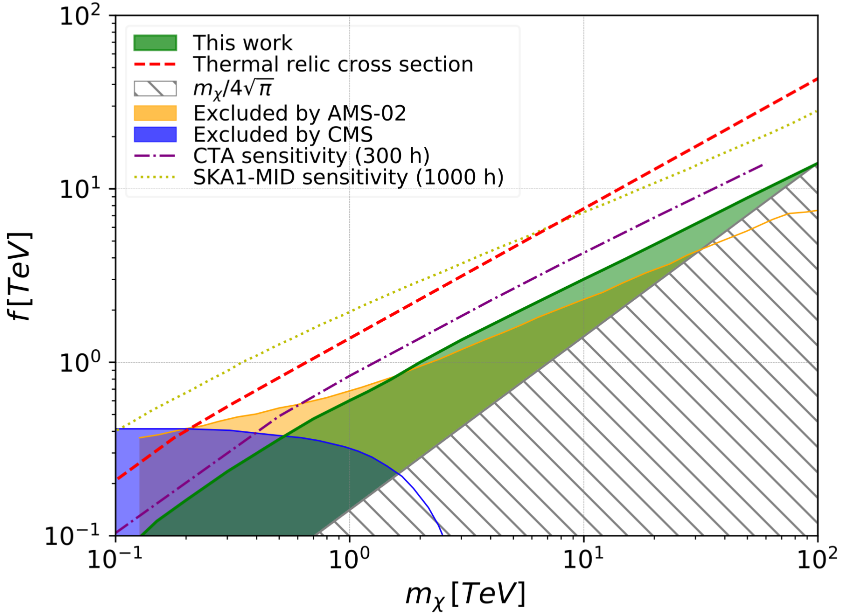


T. Miener *et al* JCAP05(2022)005

Branon DM constraints with MAGIC

MAGIC observations of Segue 1 (160 h)
Likelihood analysis

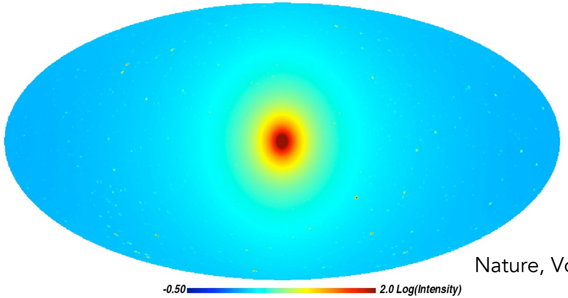




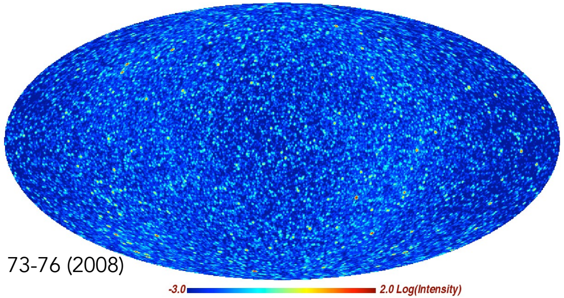
T. Miener *et al* JCAP05(2022)005

Dark Matter Subhalos

Main Halo + Diffuse SubH + Resolved SubH



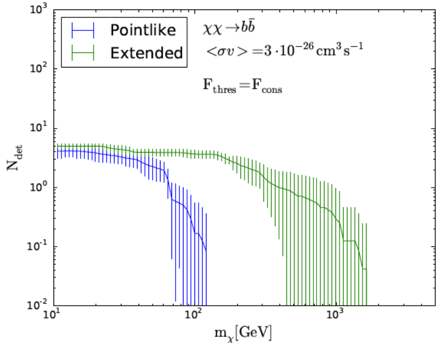
Resolved Subhalos



Nature, Vol456, Is7218, pp. 73-76 (2008)

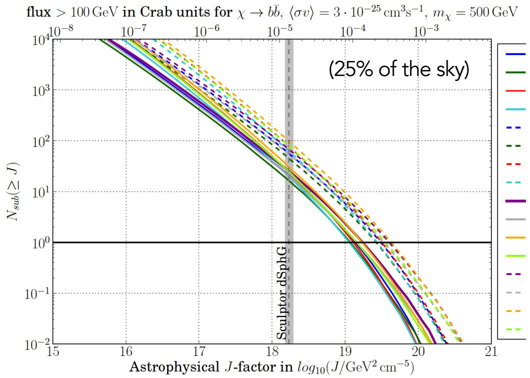
Estimates on the number of detectable subhalos:

Fermi-LAT

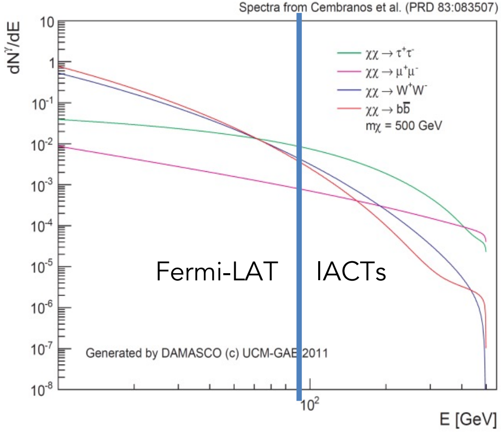


Schoonenberg et al. arXiv:1601.06781

IACT band

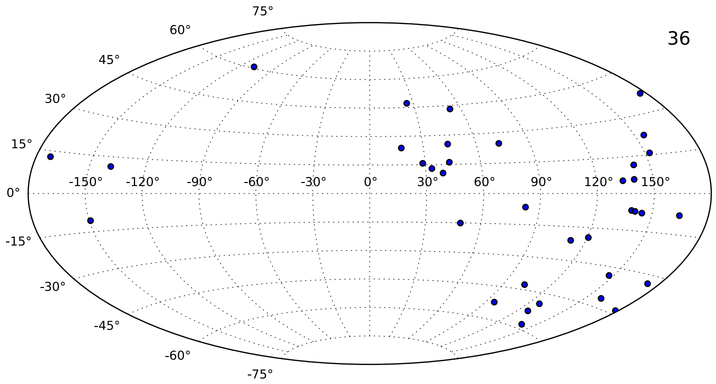


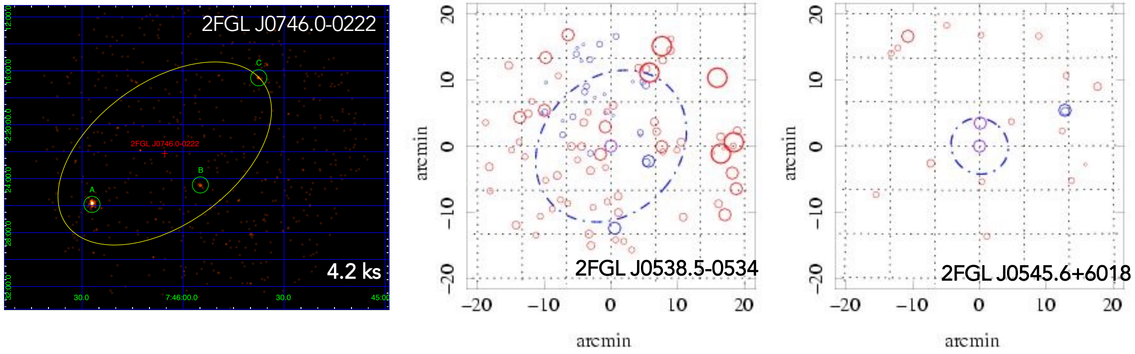
Hütten et al. arXiv:1508.03464



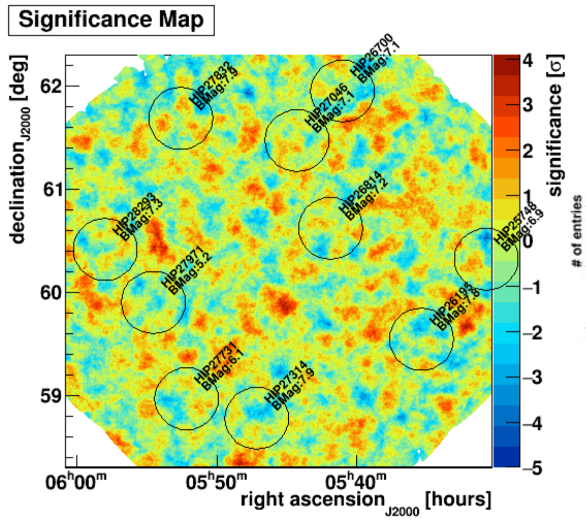
Selection criteria:

- Fermi-LAT catalogs
- Unassociated
- Galactic latitude > 5°
- No variability
- Observable by IACTs
- Affordable detectability
- >3σ in LAT >3 GeV
- No counterparts in catalogs
- No counterparts in Swift-XRT



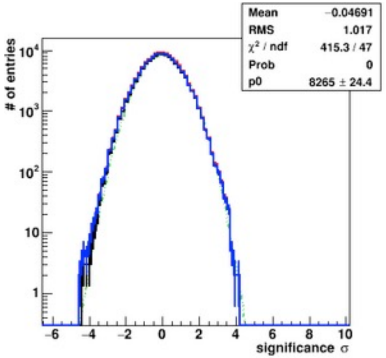


2FGL J0545.6+6018 Observations – VERITAS



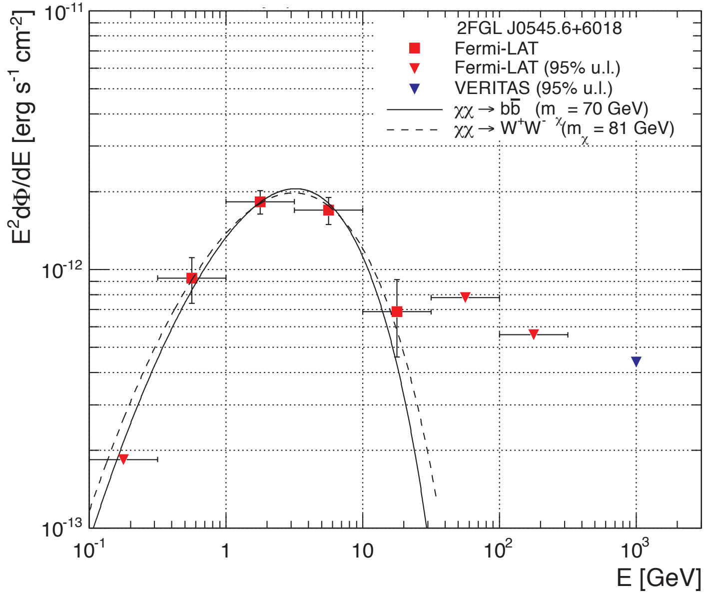
Exposure = **511 min**

Significance: **-0.7σ**



8.5h excellent quality data taken from 2013 to 2015

		Integral						Differential
		E>150 GeV		E>250 GeV		E>450 GeV		E_0 = 1 TeV
	c.l.	[$cm^{-2}s^{-1}$]	[C.U.]	[$cm^{-2}s^{-1}$]	[C.U.]	[$cm^{-2}s^{-1}$]	[C.U.]	[$TeV^{-1}cm^{-2}s^{-1}$]
2FGL J0545.6+6018	95%	1.95×10^{-12}	0.6%	0.95×10^{-12}	0.6%	0.16×10^{-12}	0.2%	1.88×10^{-13}
	99%	3.57×10^{-12}	1.0%	1.69×10^{-12}	1.0%	0.42×10^{-12}	0.6%	2.38×10^{-13}



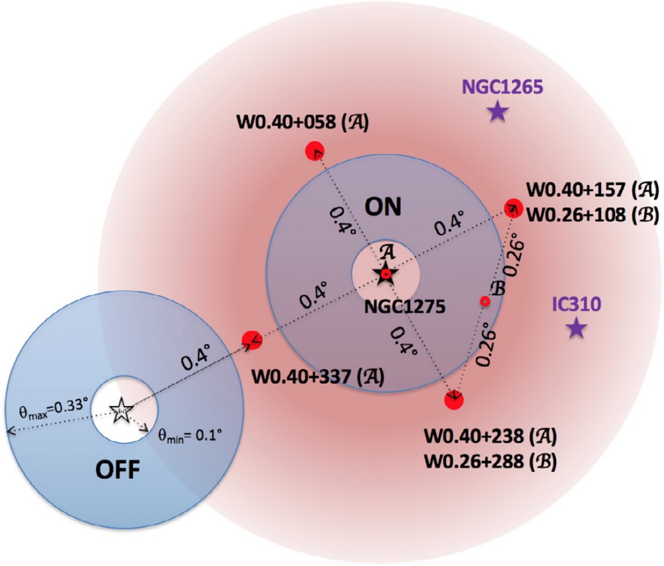
DN et al. PoS(ICRC2016)

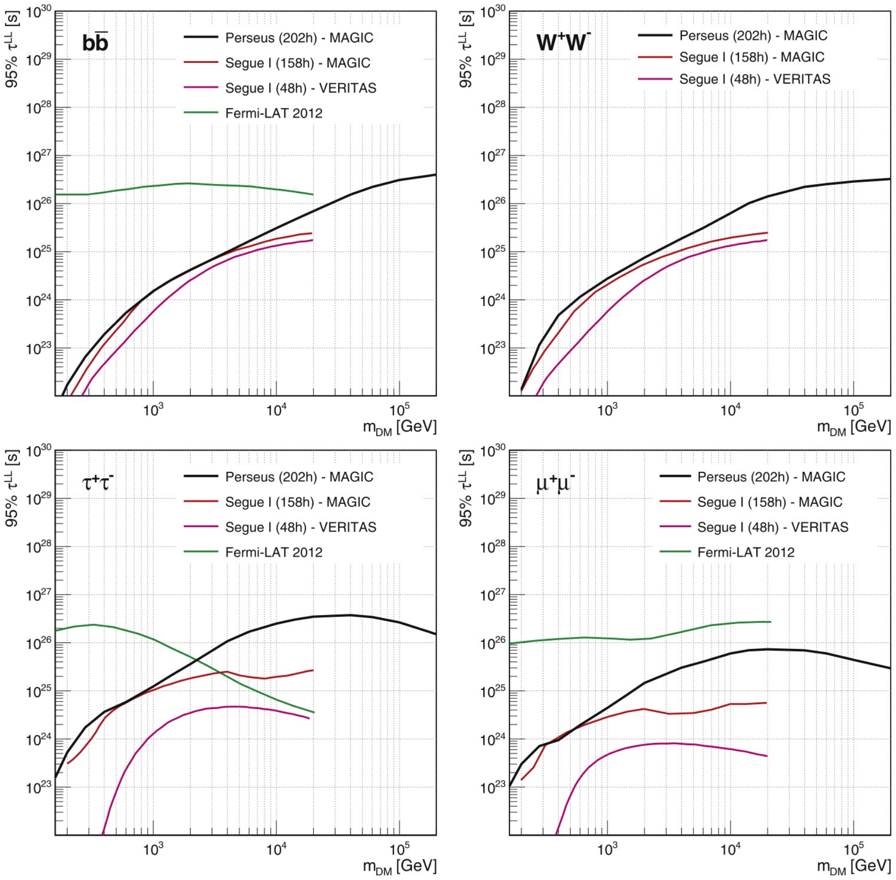
Channel	m_{WIMP} [GeV]	$\log_{10}(J)$ [$\log_{10}(GeV^2\ cm^{-5})$]	$\chi^2/d.o.f.$	$p-value$
$b\bar{b}$	70.4 ± 9.3	$20.7^{+0.1}_{-0.2}$	0.91	0.40
W^+W^-	80.8 ± 11.0	$20.8^{+0.2}_{-0.2}$	0.18	0.84
$\tau^+\tau^-$	18.0 ± 0.3	$20.2^{+0.1}_{-0.1}$	21.99	2.8×10^{-10}

- Assuming canonical
- Annihilation yield from Cembranos et al. 2011

Coma Cluster - MAGIC

Constraining decaying dark matter

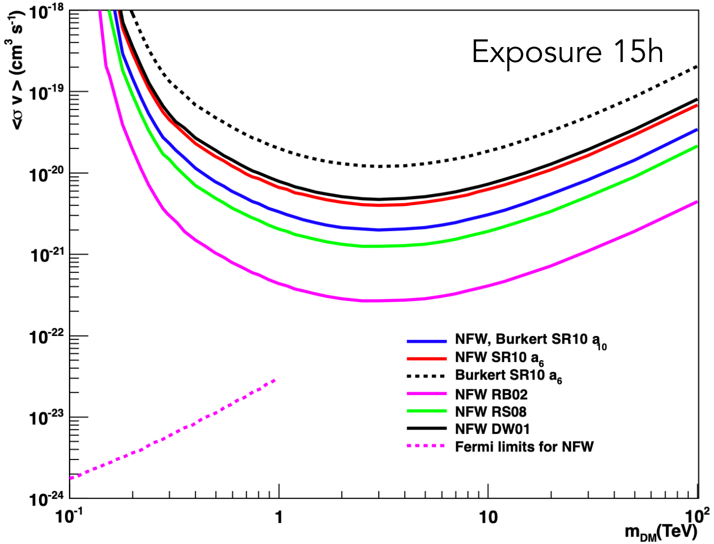




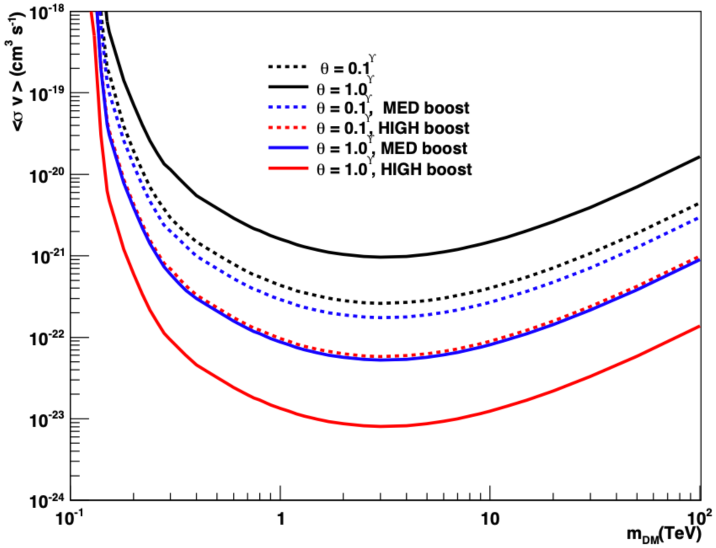
Physics of the Dark Universe 22 (2018) 38–47

Fornax Cluster – H.E.S.S.

Constraining annihilating dark matter

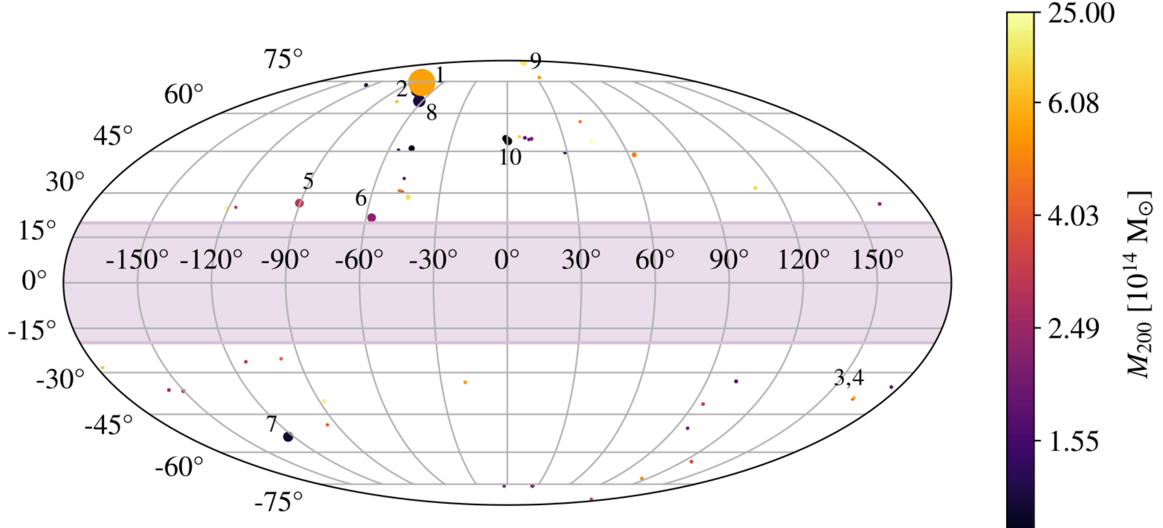


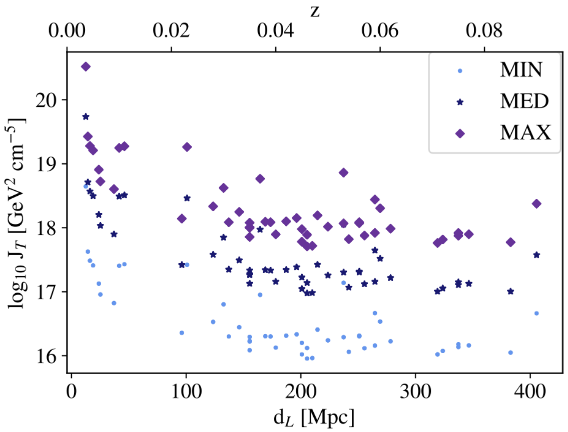
Including substructure

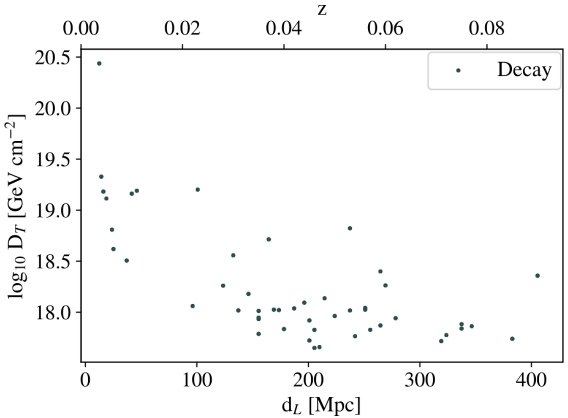


The Astrophysical Journal, 750, 123 (2012)

Galaxy clusters – Fermi-LAT





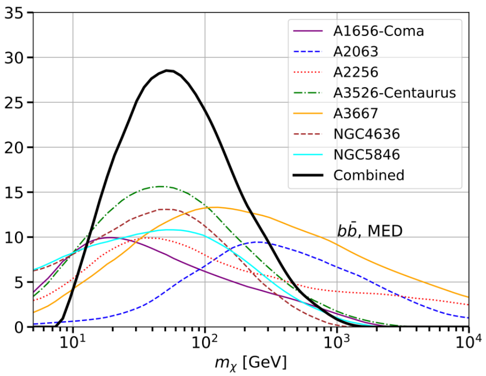


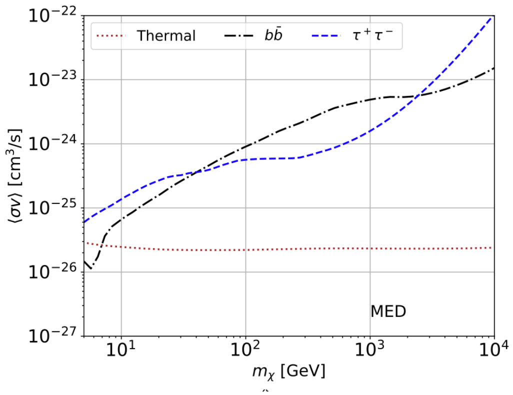
- 12 years of data, 49 clusters
- Three substructure scenarios

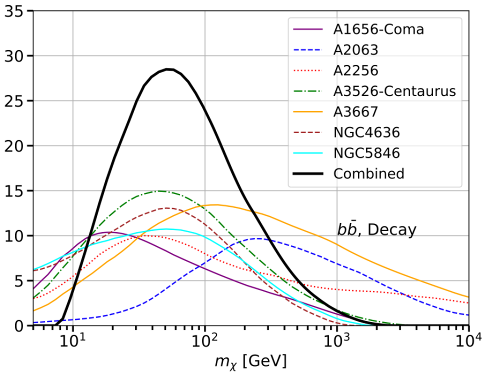
Dark Matter Subhalos

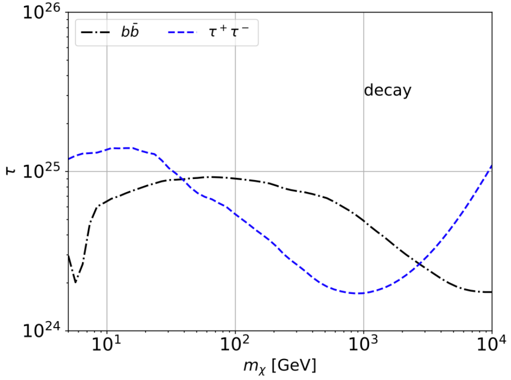
Galaxy clusters – Fermi-LAT

- 12 years of data, 49 clusters
- Three substructure scenarios
- No individual detection
- Sample above 5s for some channels but ruled out by dSph limits (most likely coming from CR interactions)









Data analysis: specific methodologies

Tomorrow

(*n.*) The best time to do everything you had planned for today.

PDG 2023

Further readings

TASI Lectures on the Particle Physics and Astrophysics of Dark Matter
https://arxiv.org/abs/2303.02169

TeV Dark Matter Searches in the Extragalactic Gamma-ray Sky
https://doi.org/10.3390/galaxies10050092

Les Houches Lectures on Indirect Detection of Dark Matter
https://arxiv.org/abs/2109.02696

TASI Lectures on Indirect Searches For Dark Matter
https://arxiv.org/abs/1812.02029

Particle Dark Matter: Observations, Models, and Searches
Bertone et al., Cambridge University Press (2010)

The Review of Particle Physics (2023)
https://pdg.lbl.gov

Credit: NASA, HST, Webb

Useful tools

Clumpy (Astrophysical factor)
https://clumpy.gitlab.io/CLUMPY

PPPC 4 DM (Particle Physics factor)
http://www.marcocirelli.net/PPPC4DMID.html

gLike (combined likelihood analysis)
https://github.com/javierrico/gLike

LlkCom (combined likelihood analysis)
https://github.com/TjarkMiener/likelihood_combiner

Credit: NASA, HST, Webb