IPARCOS
INSTITUTO DE FÍSICA
DE PARTÍCULAS Y DEL COSMOS
IPARCOS WORKSHOP
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Indirect dark matter searches in the gamma-ray band

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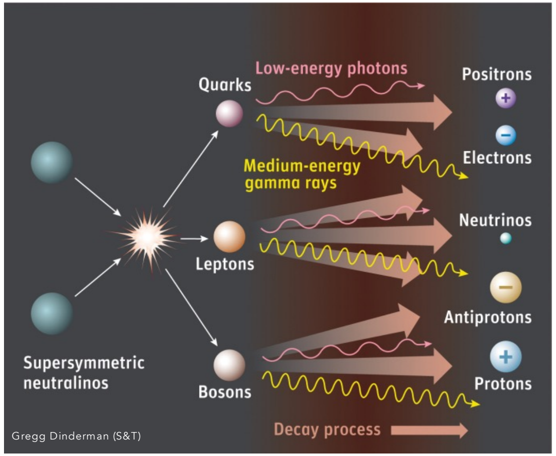
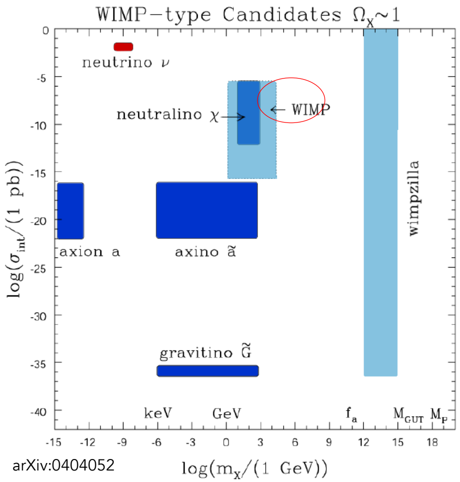
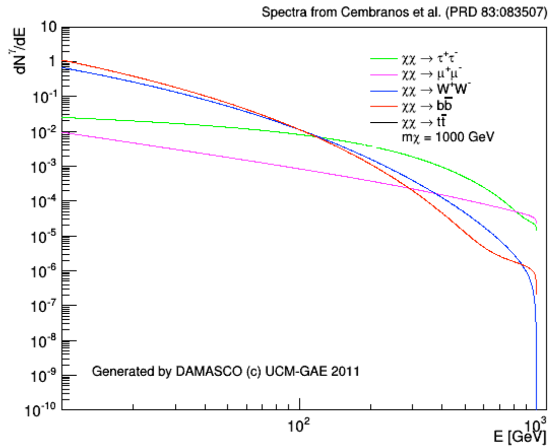
GAE

Background image:
Via Lactea Project
Diemand et al 2008

- Basis: Detection of DM annihilation or decay products (SM particles)
- In most cases, entangled with CR and subdominant
- WIMPs with masses > 100 GeV are good DM particle candidates
- Photons are privileged messengers
    - No deflection by B-fields, trace back to source
    - Observation of astrophysical targets
    - Characteristic spectral shape: identification







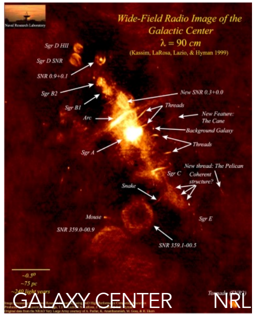
Expected spectrum from annihilating DM

$$\frac{d\Phi}{dE} = \boxed{J(\Delta\Omega)} \times \boxed{\frac{d\Phi^{PP}}{dE}} = \boxed{\int_{l.o.s,V} \rho^2_{DM}(l)\, d\Omega\, dl} \times \boxed{\frac{1}{4\pi} \frac{\langle \sigma_{ann} v \rangle}{2 m^2_{DM}} \sum_i B_i \frac{dN^\gamma_i}{dE}}$$

Key concepts: ρ_{DM}, distance, background

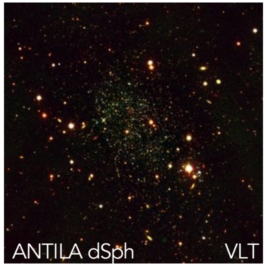
Galactic Center & Halo

- High flux
- Background Issues



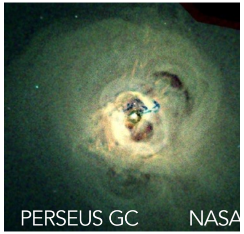
Dwarf Galaxies

- Large M/L
- No background
- Low flux



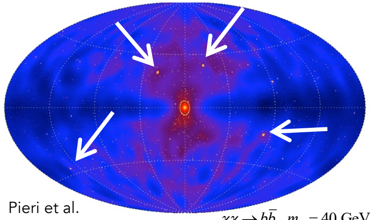
Galaxy Clusters

- Huge DM content
- Large distance
- High background



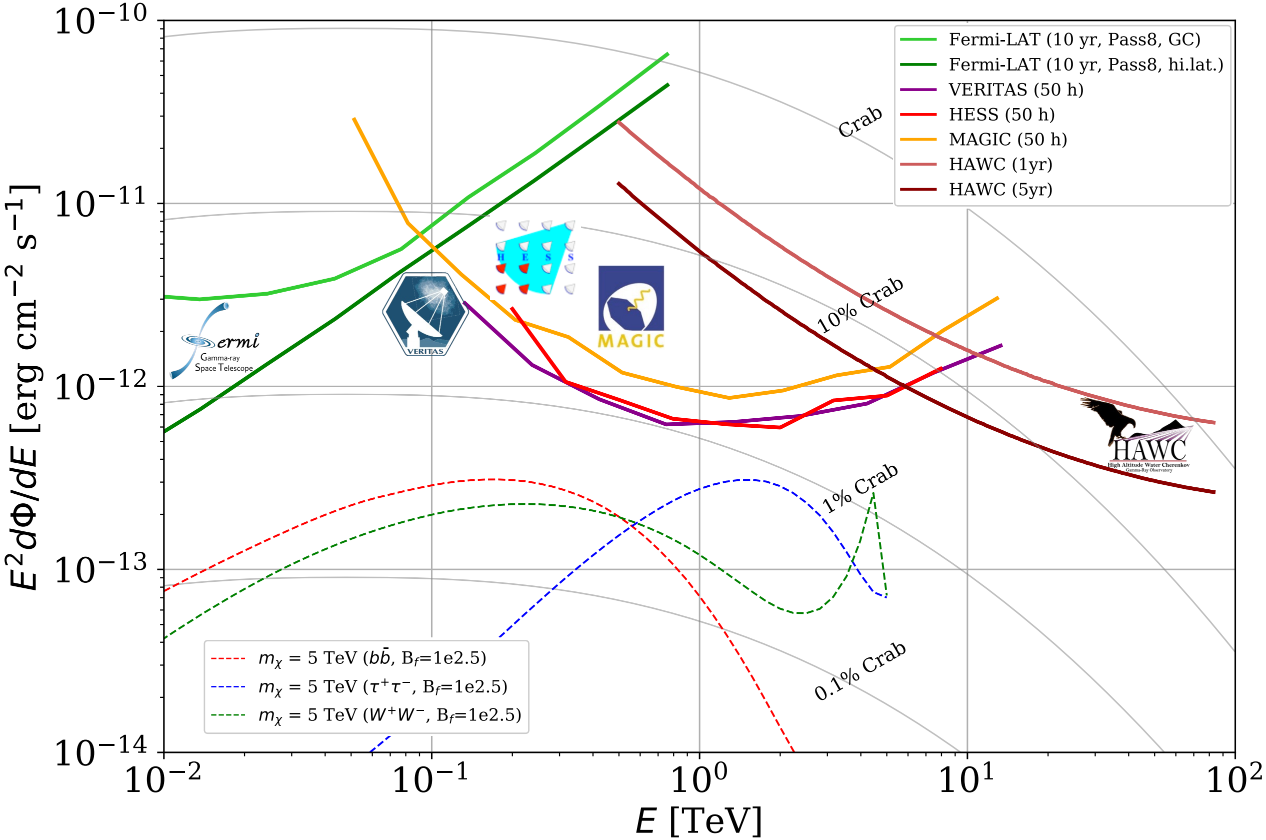
Unassociated HE Sources:

- DM Subhalos?

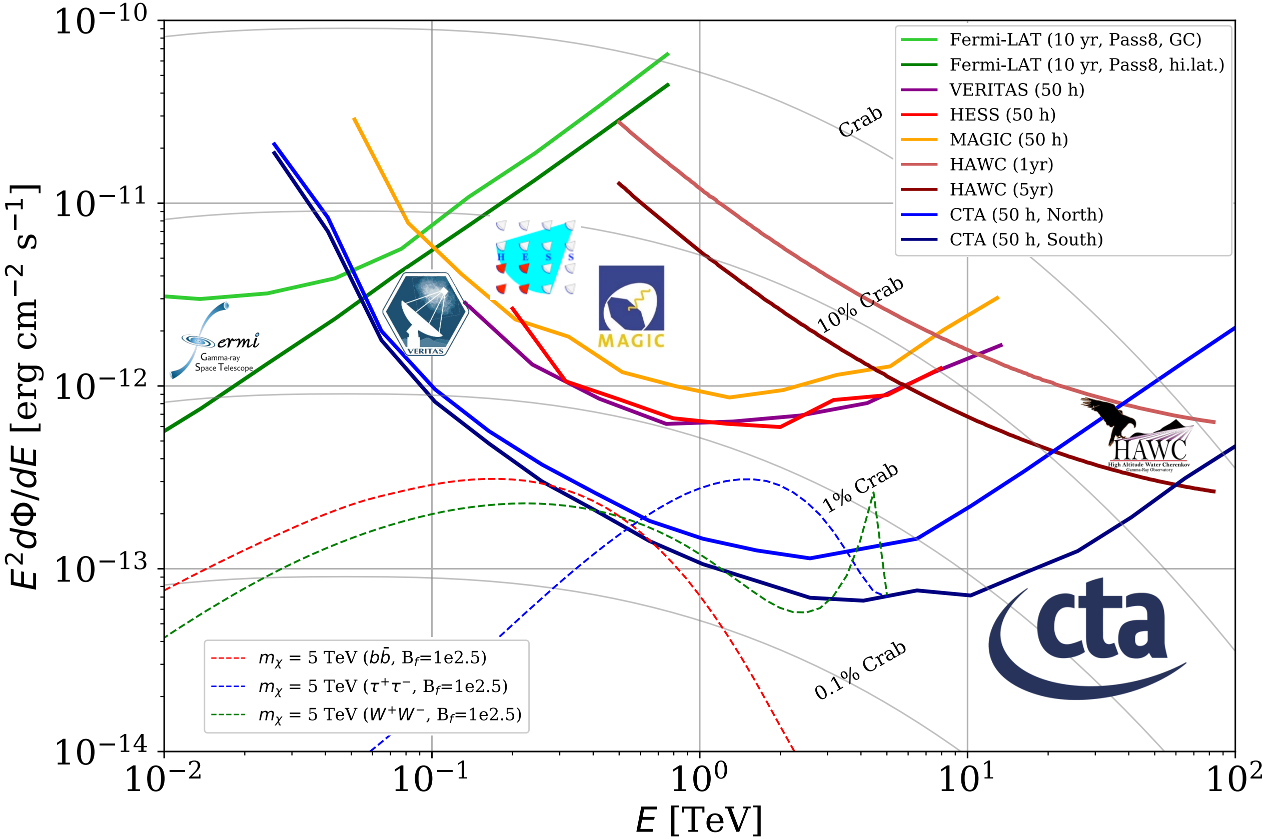


Pieri et al.
PRD 83:0235, 2008

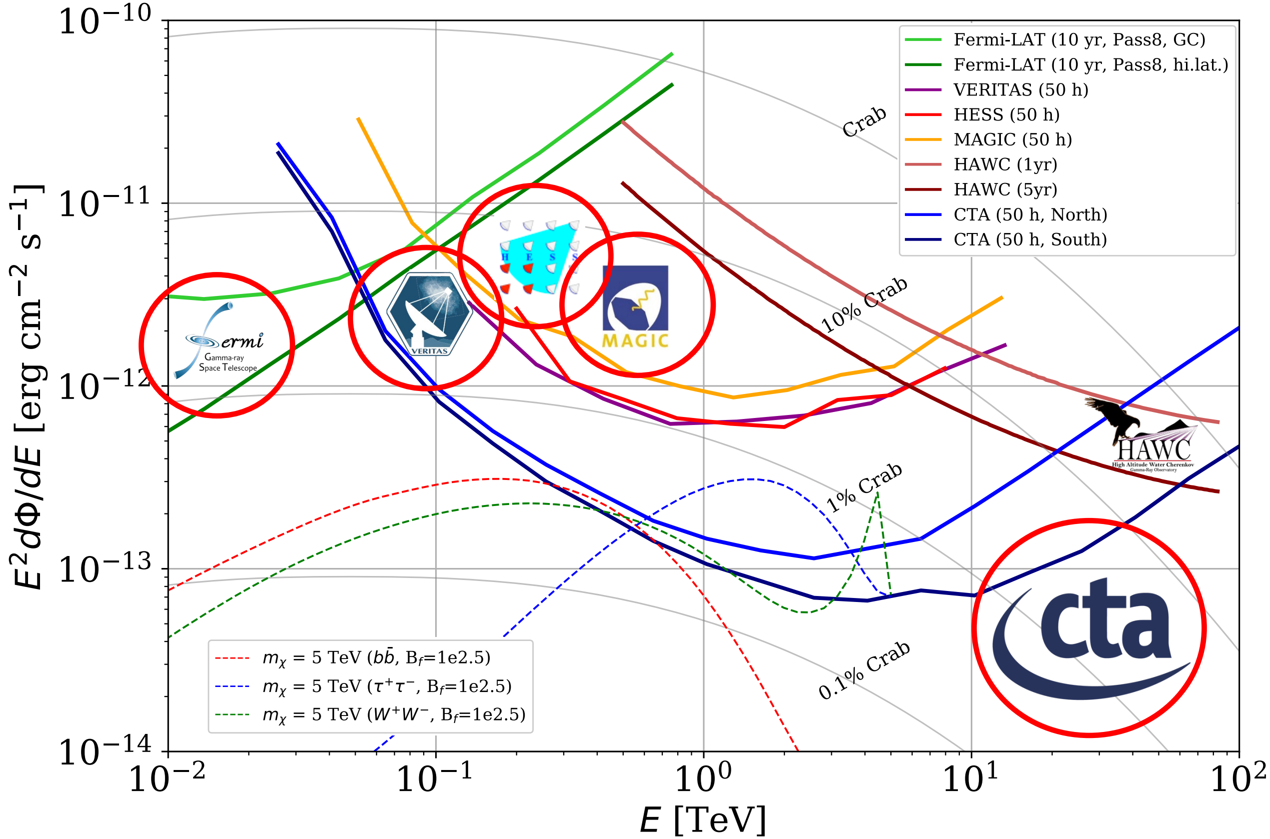
Sensitivity of current-generation γ-ray telescopes



Sensitivity of CTA: the next-generation γ-ray observatory



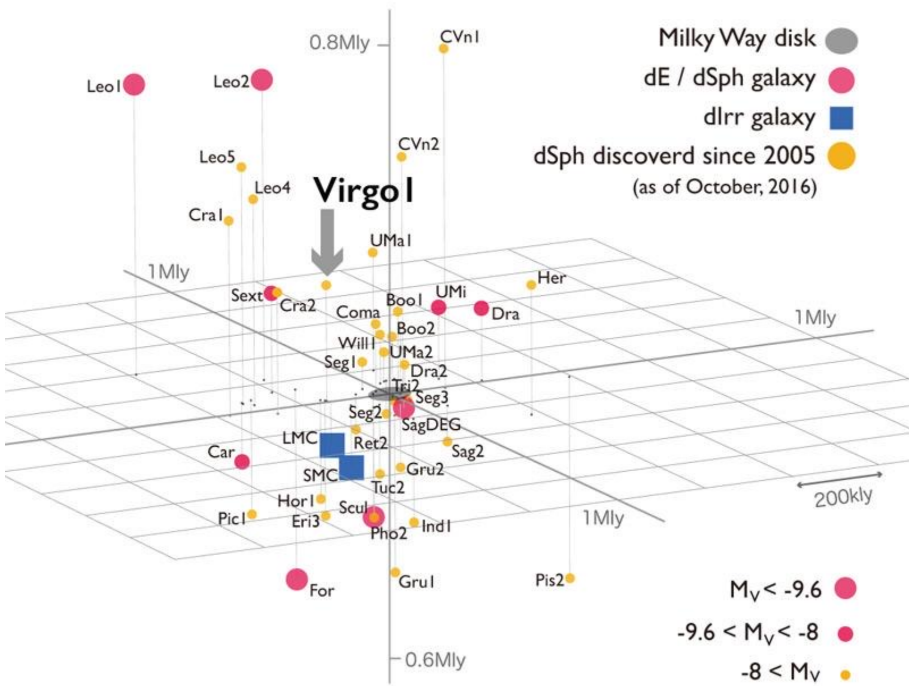
GAE involvement in γ-ray telescopes



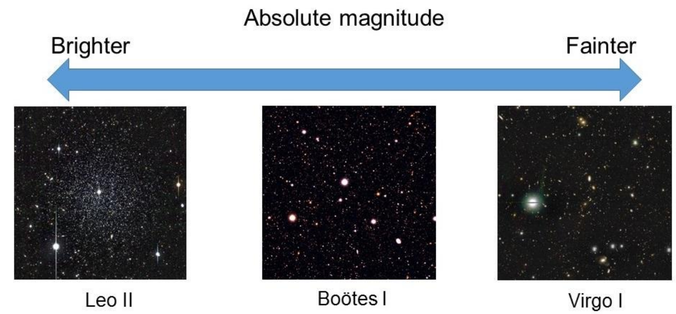
- What's NOT coming next: A comprehensive review of DM searches in the γ-ray band

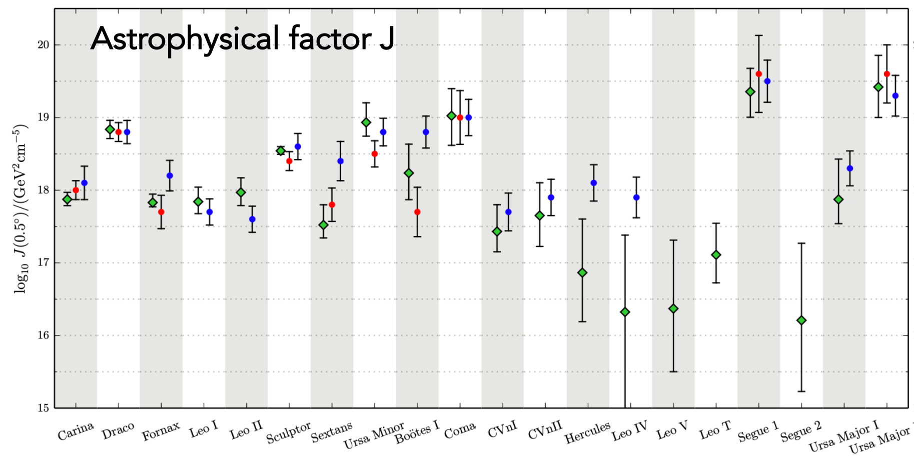
- What's coming next: Quick review of DM searches efforts **within GAE**

  - Searches in dSph with current-gen IACTs
  - Searches for DM subhalos with Fermi-LAT & IACTs
  - Combined searches in dSph with current-gen γ-ray telescopes
  - Prospects for DM searches with next-gen IACTs
  - Some projects for the future



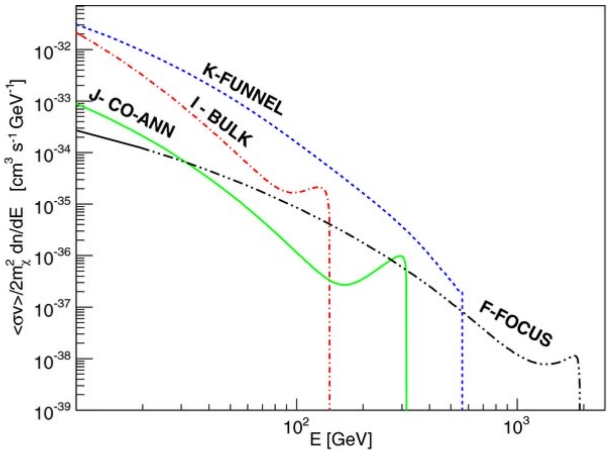
subarutelescope.org



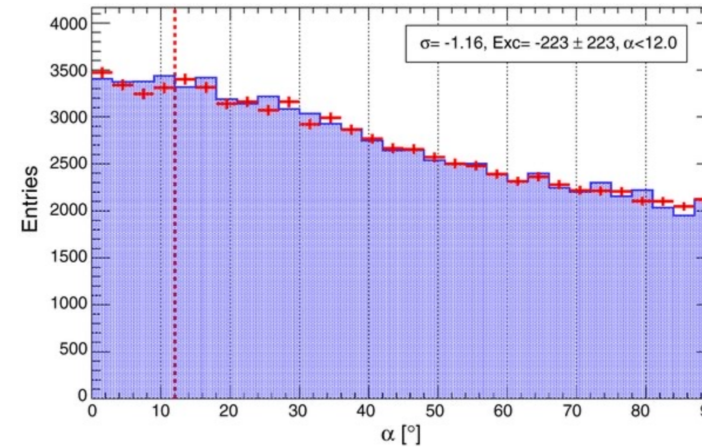


Geringer-Sameth *et al* 2015 *ApJ* **801** 74

- 15.5h observation, no signal
- Four mSUGRA benchmark models tested
- (Seems tidally disrupted, no longer good DM target)



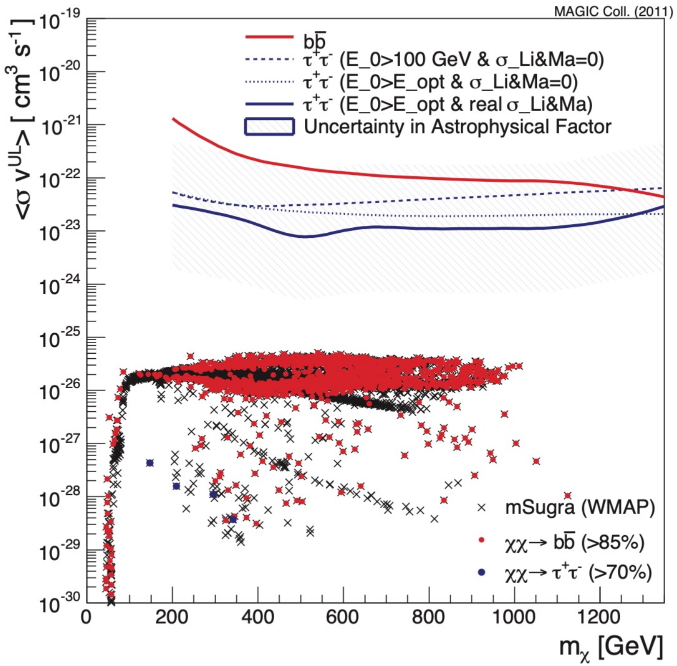
BM	$m_{1/2}$	m_0	tan β	A_0	sign(μ)	m_χ	$\langle \sigma v_{\chi\chi} \rangle$	Φ^{PP}(>100)
I'	350	181	35	0	+	141	3.62×10^{-27}	7.55×10^{-34}
J'	750	299	35	0	+	316	3.19×10^{-28}	1.23×10^{-34}
K'	1300	1001	46	0	−	565	2.59×10^{-26}	6.33×10^{-33}
F^*	7792	22100	24.1	17.7	+	1926	2.57×10^{-27}	5.98×10^{-34}

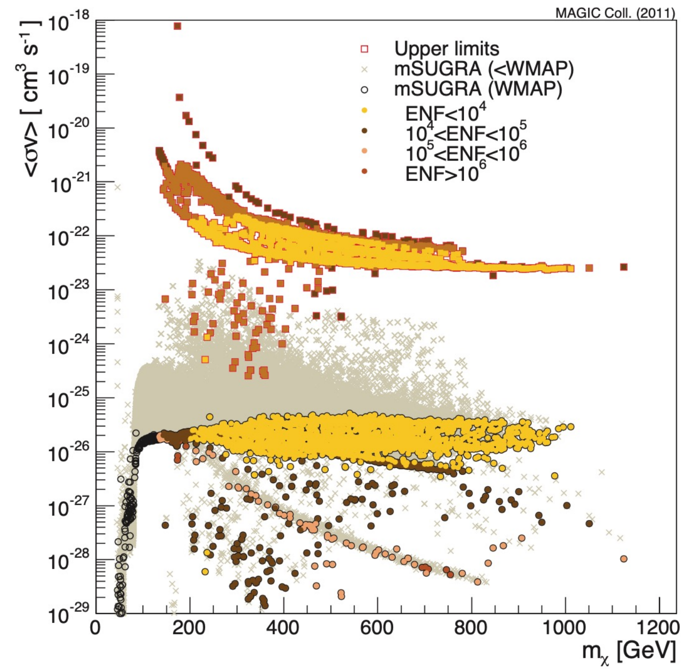


BM	Φ^{model}(>100 GeV)	Φ^{ul}(>100 GeV)	B^{ul}
I'	2.64×10^{-16}	9.87×10^{-12}	3.7×10^4
J'	4.29×10^{-17}	5.69×10^{-12}	1.3×10^5
K'	2.32×10^{-15}	6.83×10^{-12}	2.9×10^3
F^*	2.09×10^{-16}	7.13×10^{-12}	3.4×10^4

E. Aliu *et al* 2009 ApJ **697** 1299

- 43.2h observation, no signal
- mSUGRA scan tested



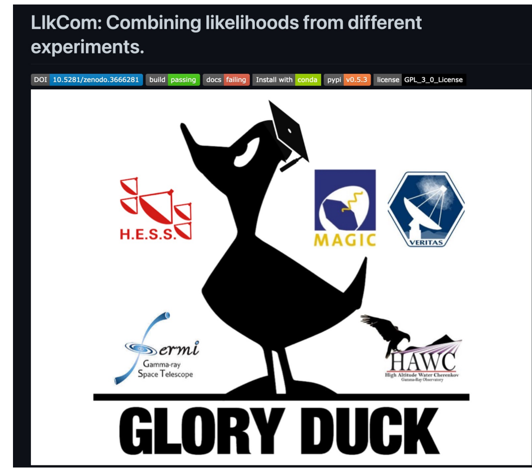


[Aleksić *et al* JCAP06(2011)035]

Deeper obs. and updated results: [Aleksić *et al* JCAP02(2014)008]

Source name	Experiments	Distance (kpc)	$\log_{10} J$ $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
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
- LlkCom (T. Miener)

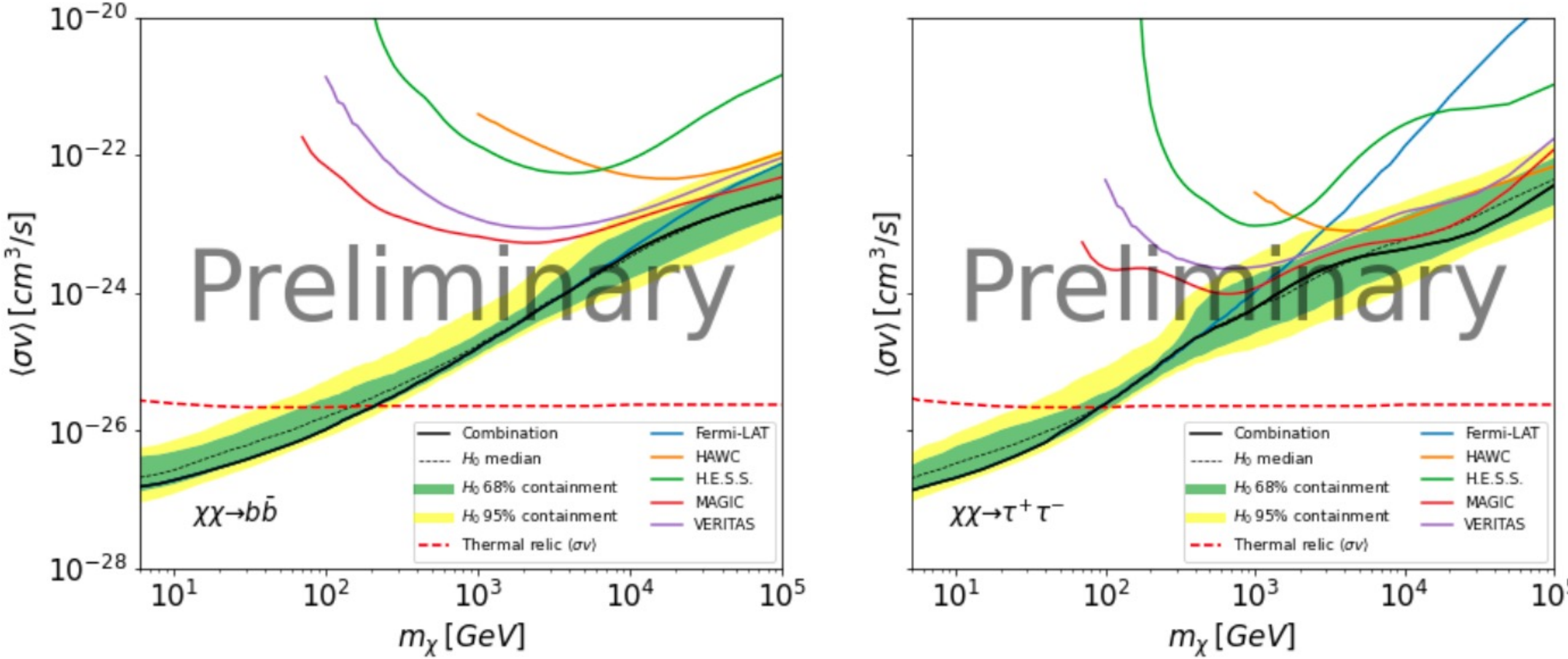


github.com/TjarkMiener/likelihood_combiner

Armand et al. PoS(ICRC21)

$$\mathcal{L}_{\rm bin}\left(\langle\sigma v\rangle; J, \boldsymbol{\mu} \mid \boldsymbol{\mathcal{D}}\right) = \mathcal{L}_{\rm bin}(\langle\sigma v\rangle; \{b_i\}_{i=1,\ldots,N_{\rm bins}}, J, \tau \mid \{N_{{\rm ON},i}, N_{{\rm OFF},i}\}_{i=1,\ldots,N_{\rm bins}})$$

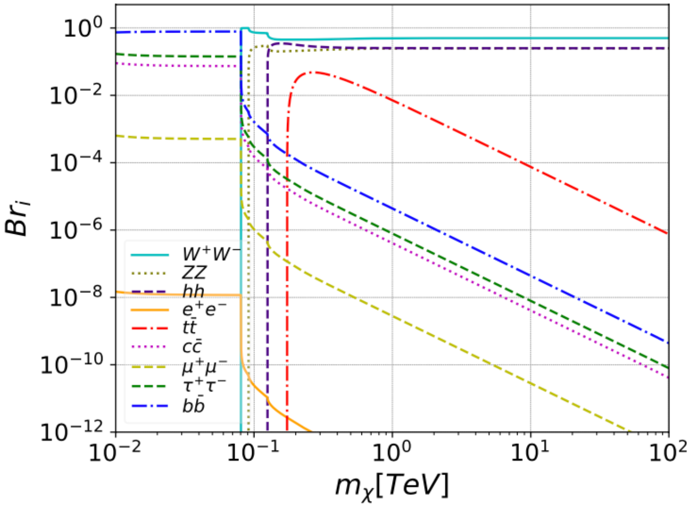
$$= \prod_{i=1}^{N_{\rm bins}} \left[\mathcal{P}(s_i(\langle\sigma v\rangle, J) + b_i \mid N_{{\rm ON},i}) \cdot \mathcal{P}(\tau b_i \mid N_{{\rm OFF},i})\right] \times \mathcal{T}(\tau \mid \tau_{\rm o}, \sigma_\tau)$$

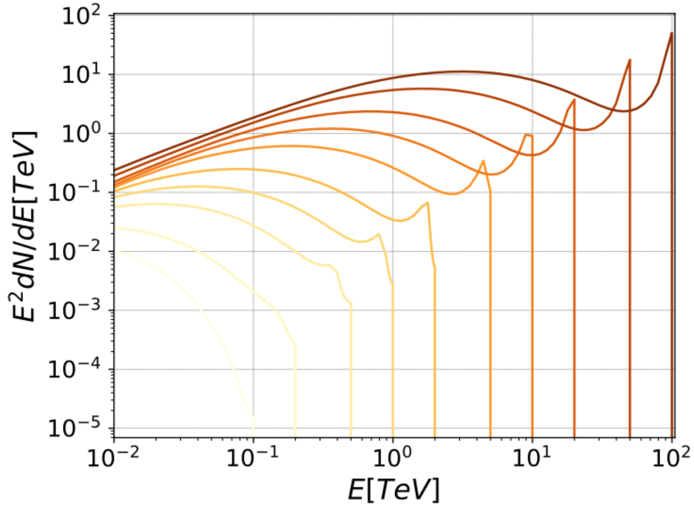


Armand et al. PoS(ICRC21)

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

Reanalysis of ~160h from Segue-1 observations by MAGIC
Branon DM model tested

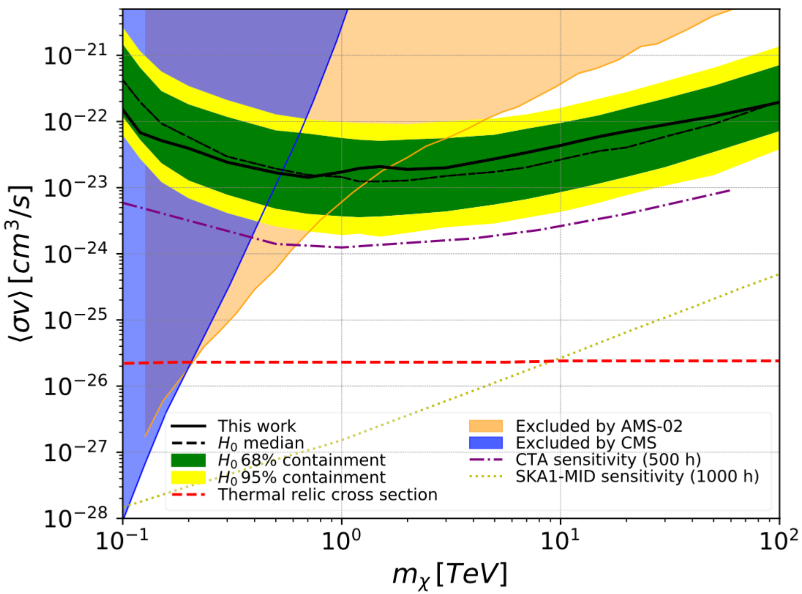


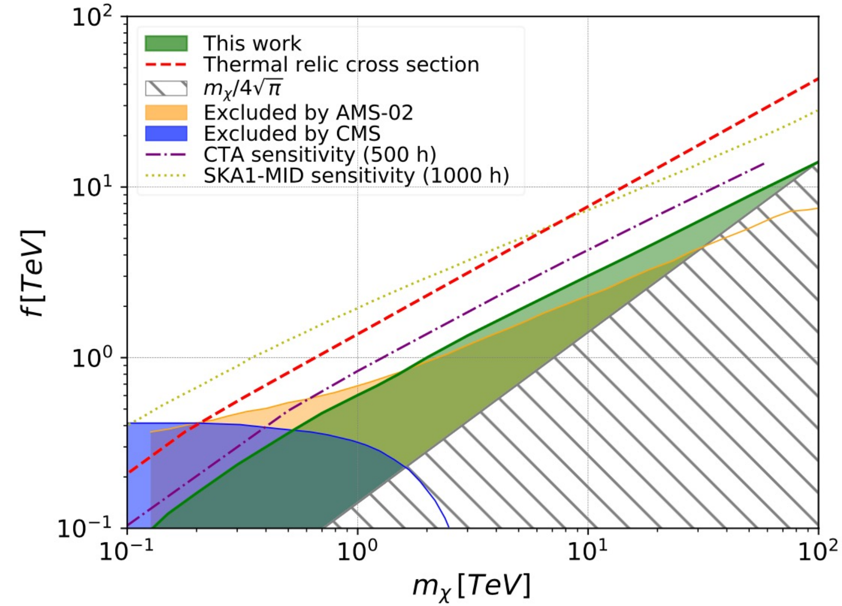


T. Miener et al JCAP05(2022)005

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

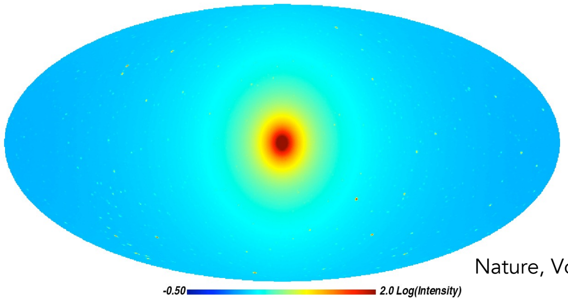
Reanalysis of ~160h from Segue-1 observations by MAGIC
Branon DM model constrained



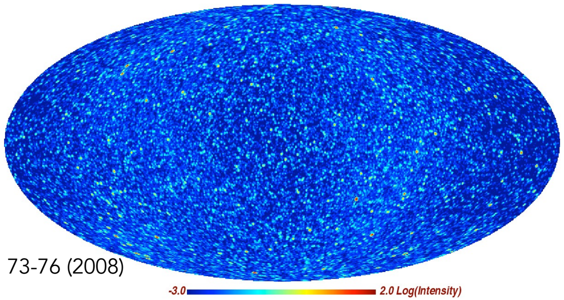


T. Miener *et al* JCAP05(2022)005

Main Halo + Diffuse SubH + Resolved SubH



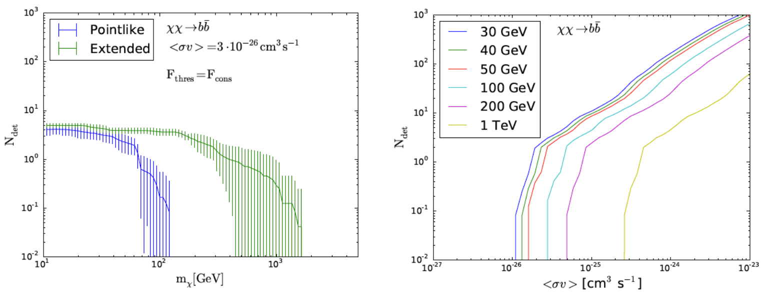
Resolved Subhalos



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

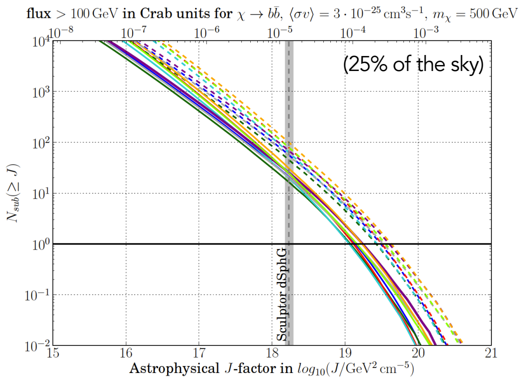
Estimates on the number of detectable subhalos:

Fermi-LAT



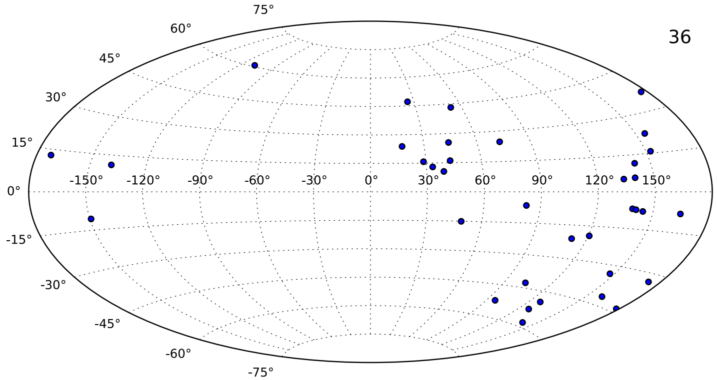
Schoonenberg et al. arXiv:1601.06781

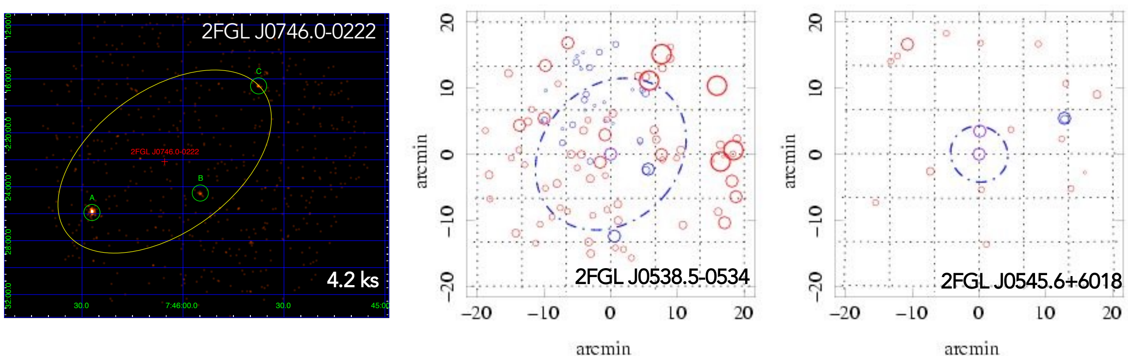
IACT band



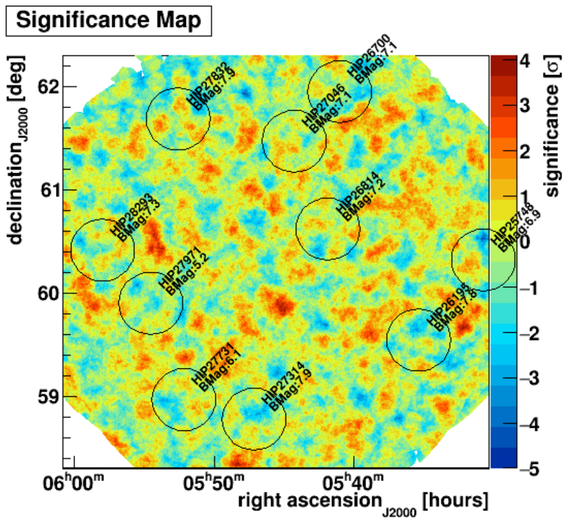
Hütten et al. arXiv:1508.03464

Selection criteria:
- Fermi-LAT catalogs
- Unassociated
- Galactic latitude > 5°
- No variability
- Observable with MAGIC/VERITAS
- Affordable detectability
- $>3\sigma$ in LAT >3 GeV
- No counterparts in catalogs
- No counterparts in Swift-XRT



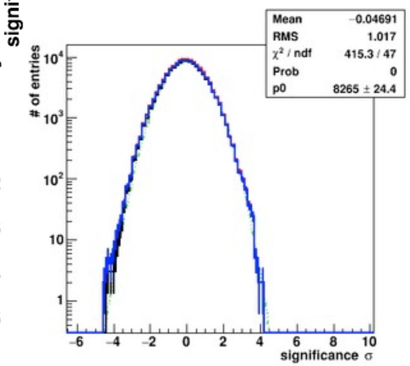


2FGL J0545.6+6018 Observations – VERITAS



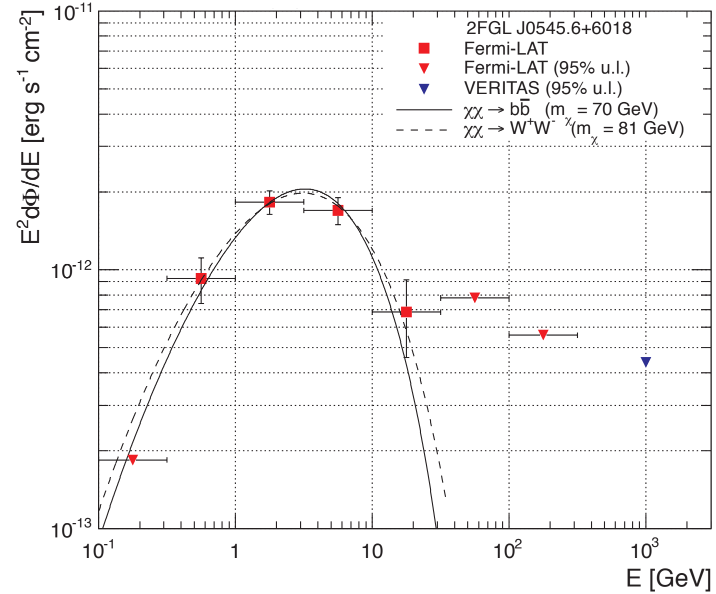
Exposure = **511 min**

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}



Channel	m_{WIMP} [GeV]	$\log_{10}(J)$ $[\log_{10}(\mathrm{GeV}^2\ \mathrm{cm}^{-5})]$	$\chi^2/d.o.f.$	$p-value$
$b\bar{b}$	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

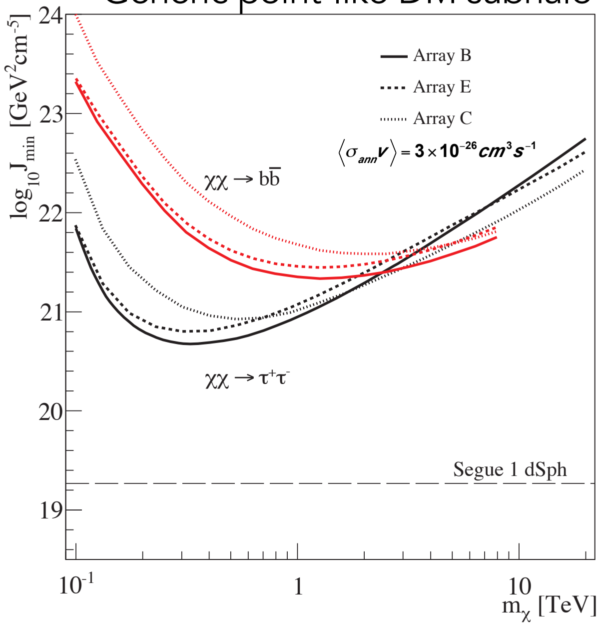
DN et al. PoS(ICRC2016)

Boost factors required for detection

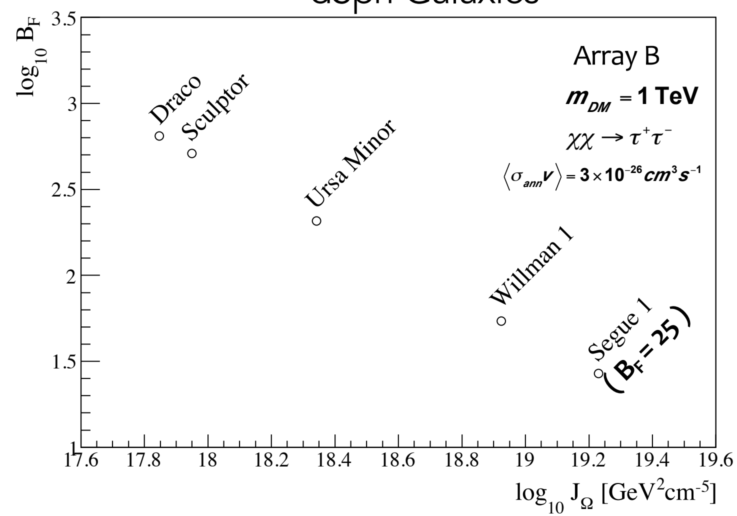
$$\frac{d\Phi}{dE} = B_F \times J(\Delta\Omega) \times \frac{d\Phi^{PP}}{dE}$$

5σ detection in 100h obs.

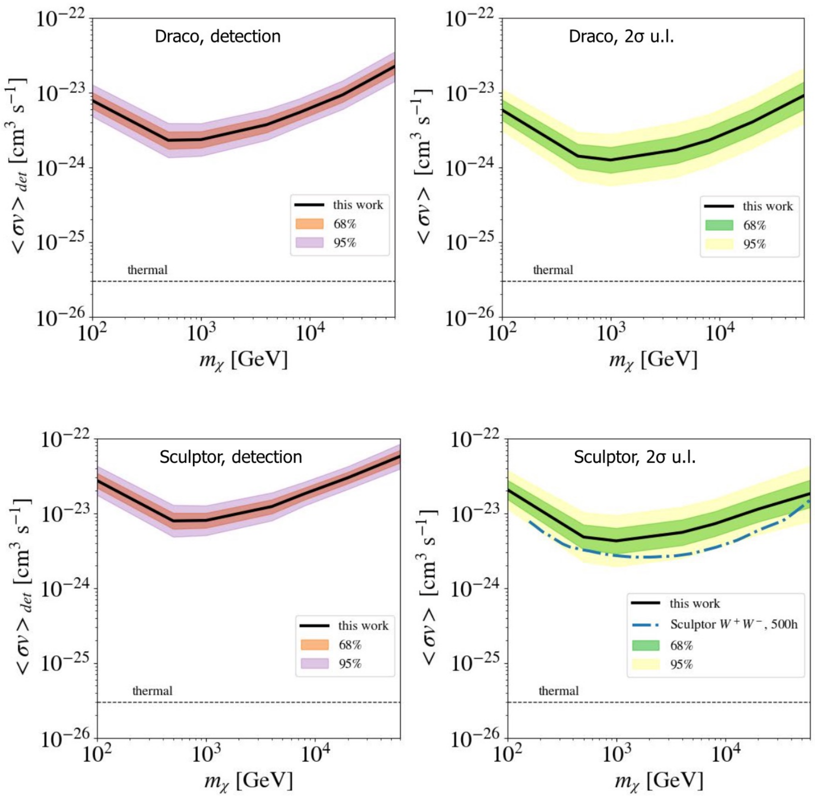
Generic point-like DM subhalo

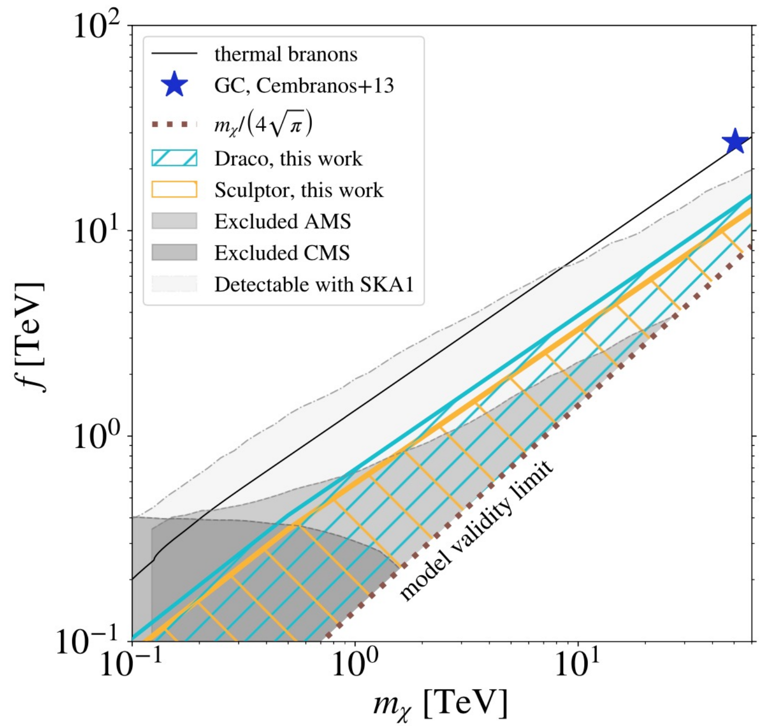


dSph Galaxies



Doro et al. APP 43 (2013)





A. Aguirre-Santaella *et al* JCAP10(2020)041

- Machine-learning-powered DM searches
- Exploring more TeV models and produce further model-dependent limits
- Multi-messenger, combined searches (adding neutrino telescopes)
- Proposing new targets for observations
- Enhancing next-gen γ-ray telescopes sensitivity to DM signals