EXCELENCIA SEVERO OCHOA

MAGIC

Optimized dark matter searches in deep observations of Segue 1 with MAGIC

Javier Rico
IFAE

+ Jelena Aleksić, Manel Martínez, Saverio Lombardi & Michele Doro

for the MAGIC Collaboration

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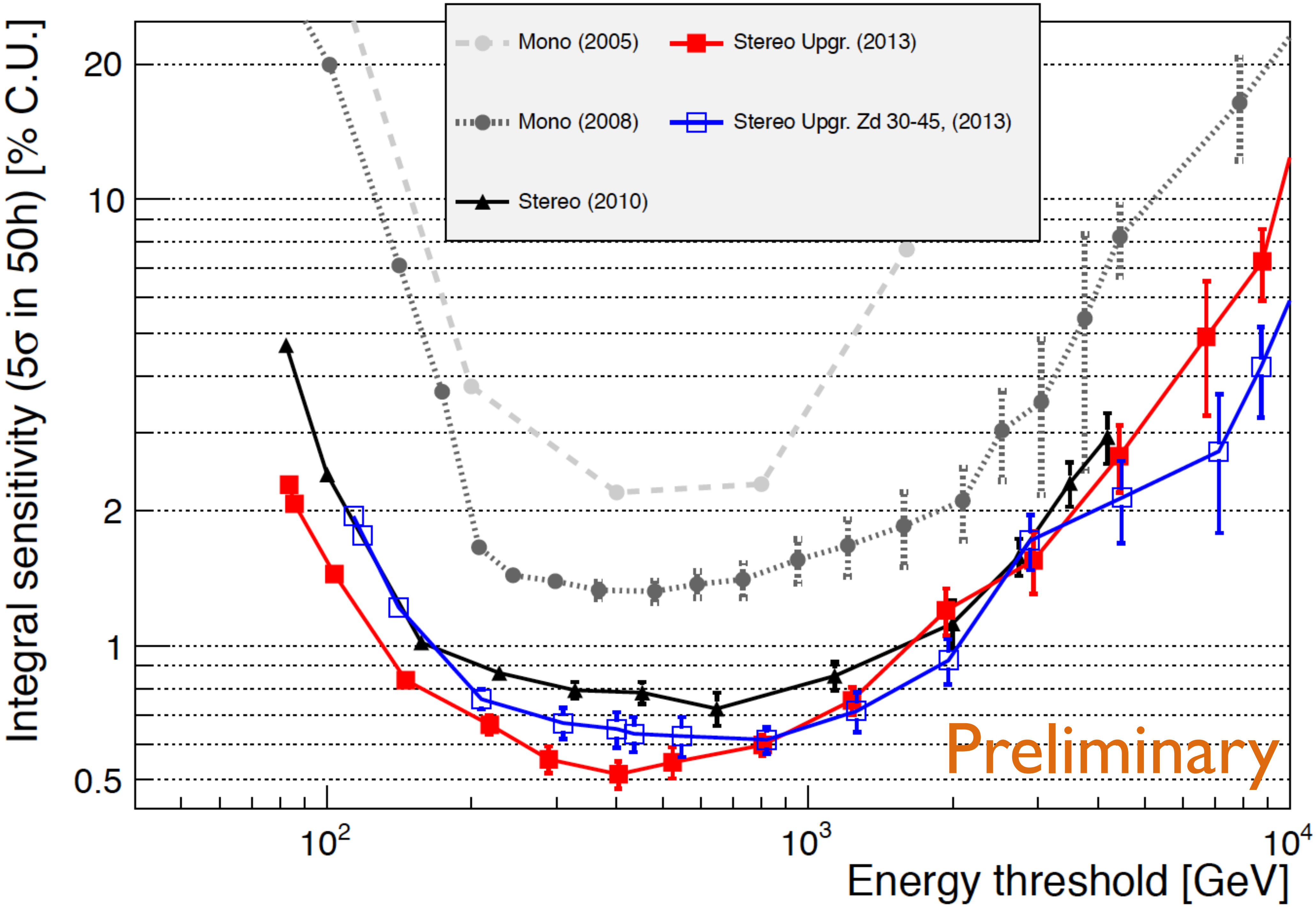
Outline

- ★ MAGIC
- ★ Observations of Segue 1
- ★ Full Likelihood Analysis
- ★ Results of Dark Matter Searches
- ★ Discussion & Summary

The MAGIC Telescopes

- ★ Stereo system (2004, 2009)
- ★ 17 m diameter → energy threshold of 50 GeV
- ★ Fast movement to catch GRB prompt emission
- ★ Energy resolution: ~15 - 25%
- ★ Angular resolution: ~ 0.1°
- ★ Major upgrade: full electronics (2011) and MAGIC-I camera (2012)

MAGIC Performance



DM searches with MAGIC

- ★ Active efforts in indirect dark matter searches

- ★ Galactic Center
  (17 h) ApJ Lett. 638 (2006) L101
- ★ Perseus Galaxy Cluster
  (25 h) ApJ 710 (2010) 634
- ★ Dwarf Spheroidals:
  Segue 1 (30 h): JCAP 06 (2011) 035
  Willman 1 (16 h): ApJ 697 (2009) 1299
  Draco (8 h): ApJ 679 (2008) 428
- ★ Subhalos

- ★ All publications on dark matter searches up to 2013 with single telescope!

DM searches with MAGIC

- GOAL: Improve our best (published) limits by a factor of 10
- Better system:
  - Stereo since 2009
  - Major upgrade in 2012
- Deep exposure of the best candidate
- Dedicated analysis

Segue 1

Sloan Extension for Galaxy Understanding and Exploration

Segue 1	
Coordinates	$10^{h}\,07^{m}\,04^{s}$, $+16^\circ\,04'\,55''$
Distance	23±2 kpc
Number of resolved stars	71
Magnitude	$-1.5^{+0.6}_{-0.8}$
Apparent magnitude	13.8±0.5
Luminosity	$340\ L_\odot$
Mass	$5.8^{+8.2}_{-3.1} \times 10^5\ M_\odot$
M/L	$\sim 3400\ M_\odot/L_\odot$
Half-light radius	29^{+8}_{-5} pc
System velocity	208.5±0.9 km/s
Velocity dispersion	$3.7^{+1.4}_{-1.1}$ km/s
Mean [Fe/H]	−2.5

- The most dark matter dominante object known so far
- The least luminous galaxy
- Close, no background, Northern Hemisphere
- $J_{\mathrm{ann}}(\theta = 0.15^\circ)$:
  - Segue 1: 1×10^{19} GeV^2 cm^{-5}
  - Perseus: 3×10^{17} GeV^2 cm^{-5}
  - GC: 5×10^{20} GeV^2 cm^{-5}

Observations

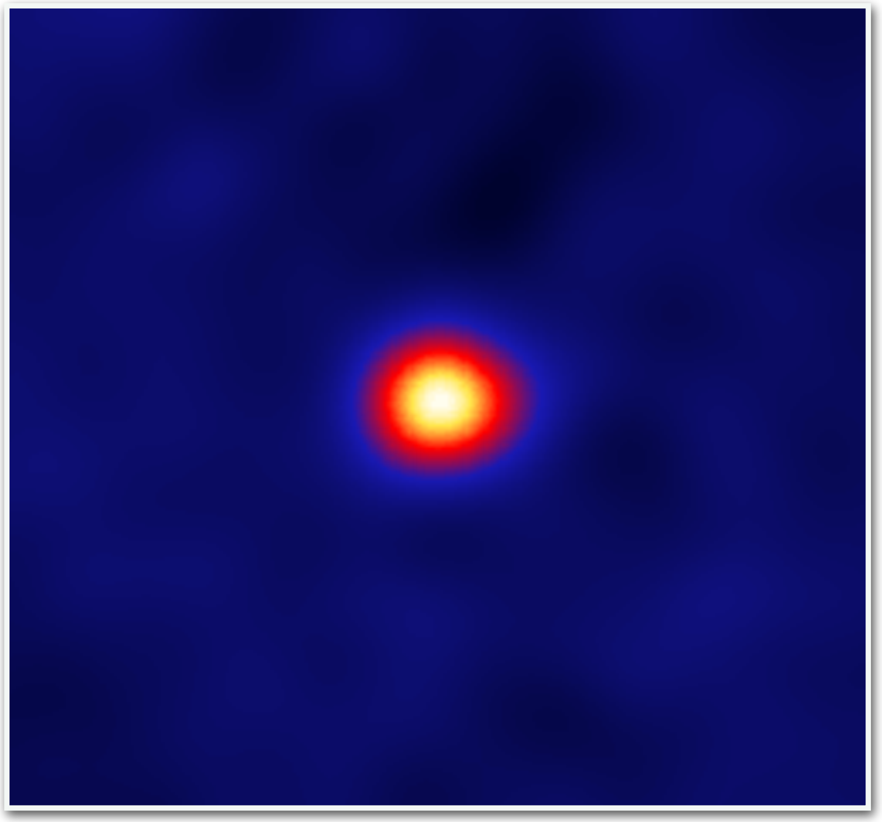
- January 2011 - February 2013
- Low zenith angle (13 - 35 deg)

- Different telescope configurations (!):
  - Jan 2011 - May 2011: 47.0 h
  - Jan 2012 - Feb 2012: 12.3 h
  - Mar 2012 - May 2012: 51.3 h
  - Nov 2012 - Feb 2013: 47.5 h

Total effective observation time: 158 h

The deepest survey of any dSph by any IACT so far!

Conventional Analysis



ON = signal [?] + bkg

OFF = τ x bkg

τ — bkg normalization (~number of bkg regions)

n — measured number of ON events

m — measured number of OFF events

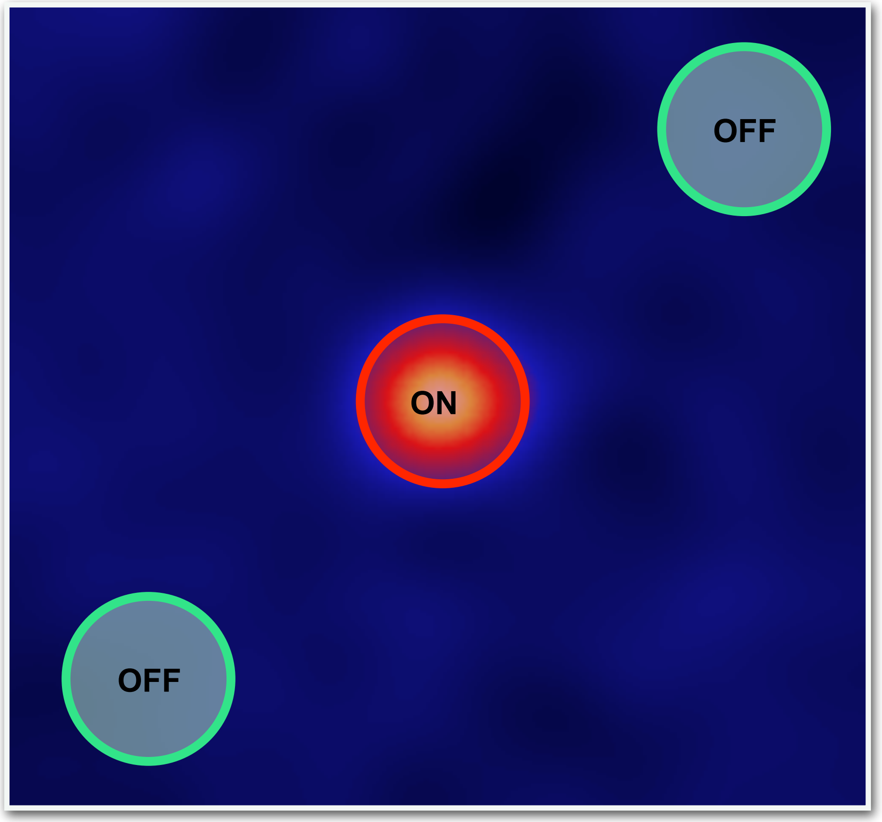
g — estimated number of signal events

b — estimated number of bkg events (in ON region)

g, b — estimated by maximising:

$$\mathcal{L}(g,b\,|\,n,m) = \frac{(g+b)^n}{n!}e^{-(g+b)} \times \frac{(\tau b)^m}{m!}e^{-(\tau b)}$$

Conventional Analysis



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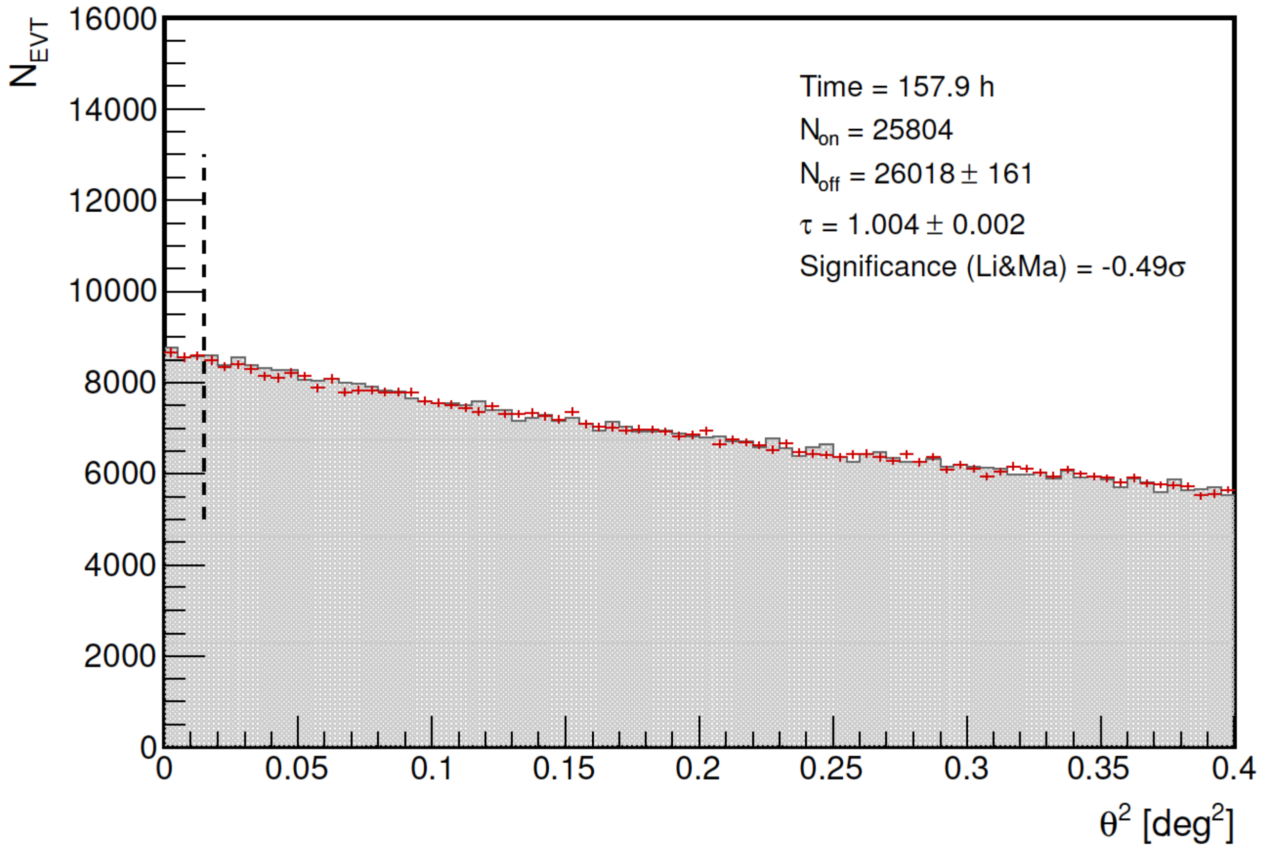
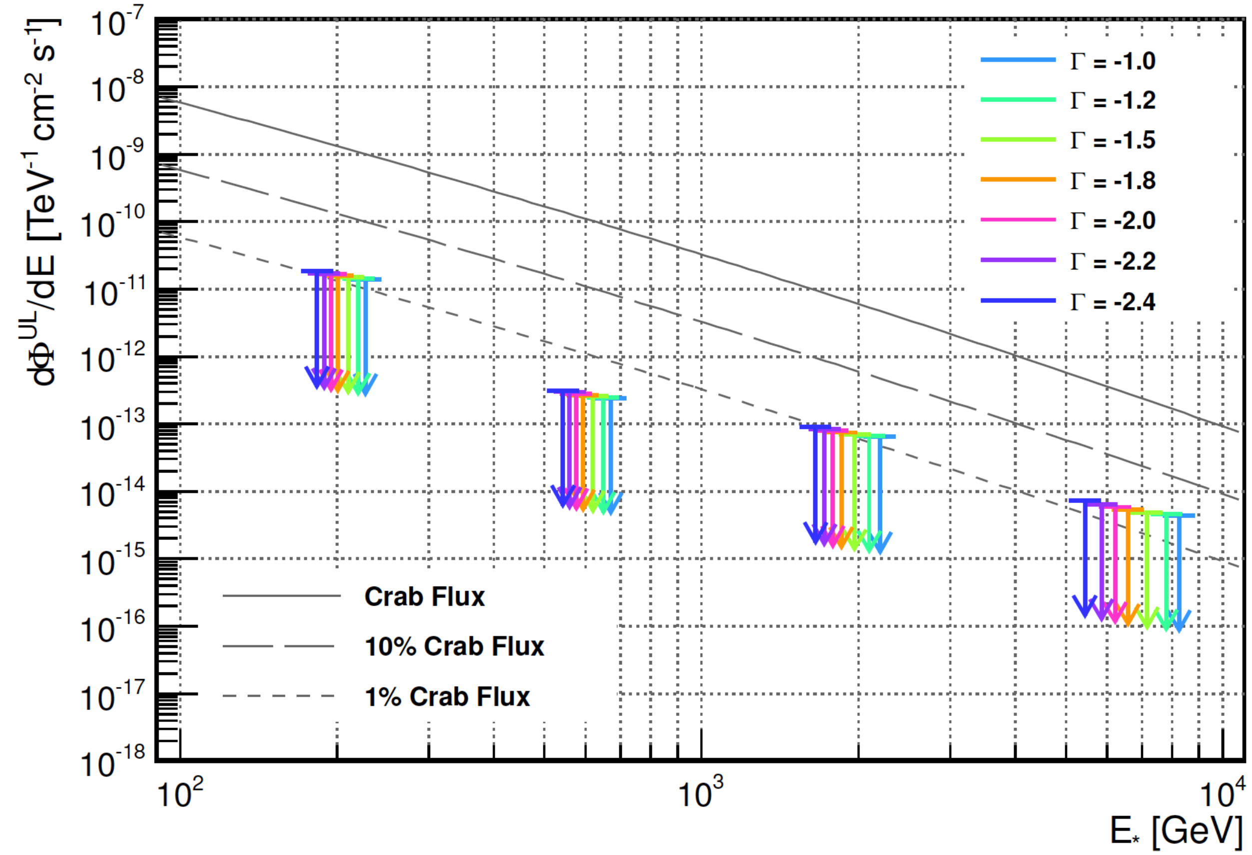
ON OFF

Conventional Analysis

Aleksić et al, JCAP 02 (2014) 008



Distribution of events vs distance to signal/background region center



Upper limits to differential gamma-ray flux

No hint of a signal in 158h or observations

Full Likelihood Analysis

NUM OF EVENTS — SPECTRAL SHAPE

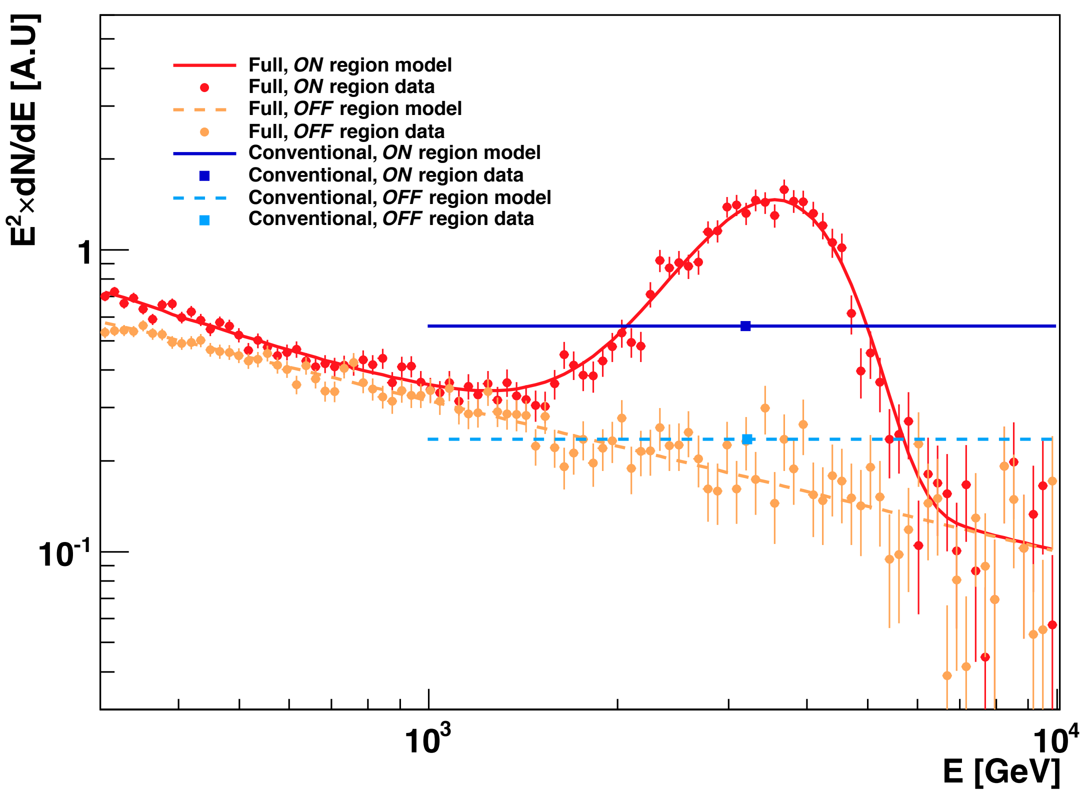
$$\mathcal{L}(N_{EST}, M(\boldsymbol{\theta}) \mid N_{OBS}, E_1, .., E_{N_{OBS}}) = \frac{N_{EST}^{N_{OBS}}}{N_{OBS}!} e^{-N_{EST}} \times \prod_{i=1}^{N_{OBS}} \mathcal{P}(E_i; M(\boldsymbol{\theta}))$$

N_{OBS}, N_{EST} – measured and estimated total number of events

E, E' – measured and true energy

M(θ) – DM model with parameters θ

Aleksić, Rico & Martinez, JCAP 10 (2012) 032



Spectral shape:

$$\mathcal{P}(E; M(\boldsymbol{\theta})) \propto dN/dE$$

$$\frac{dN}{dE} = T_{obs} \int_0^\infty \frac{d\phi}{dE'} R(E;E') dE'$$

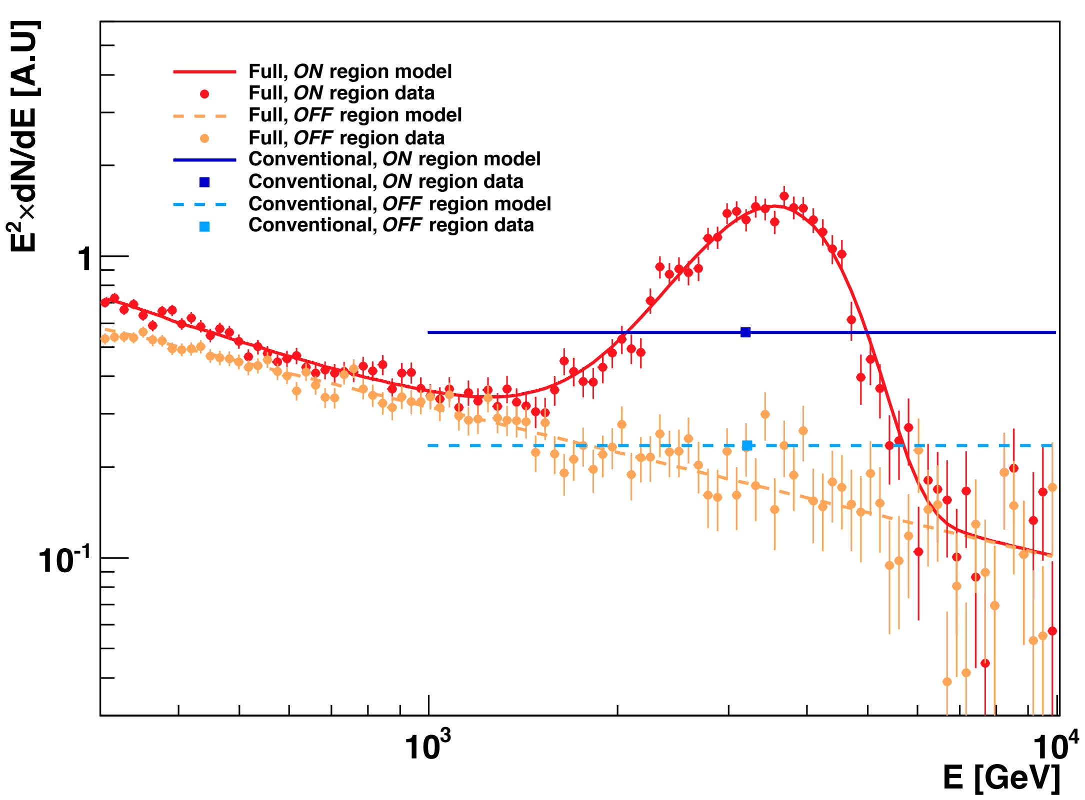
Sensitivity improvement of a factor ~2!

Full Likelihood Analysis

- ★ A priori assumption on the expected spectral shape
  → maximum advantage of potential features
- ★ Unbiased, stable and robust
- ★ Significant improvement wrt the Conventional analysis
- ★ Straightforward combination of results from different instruments / sources

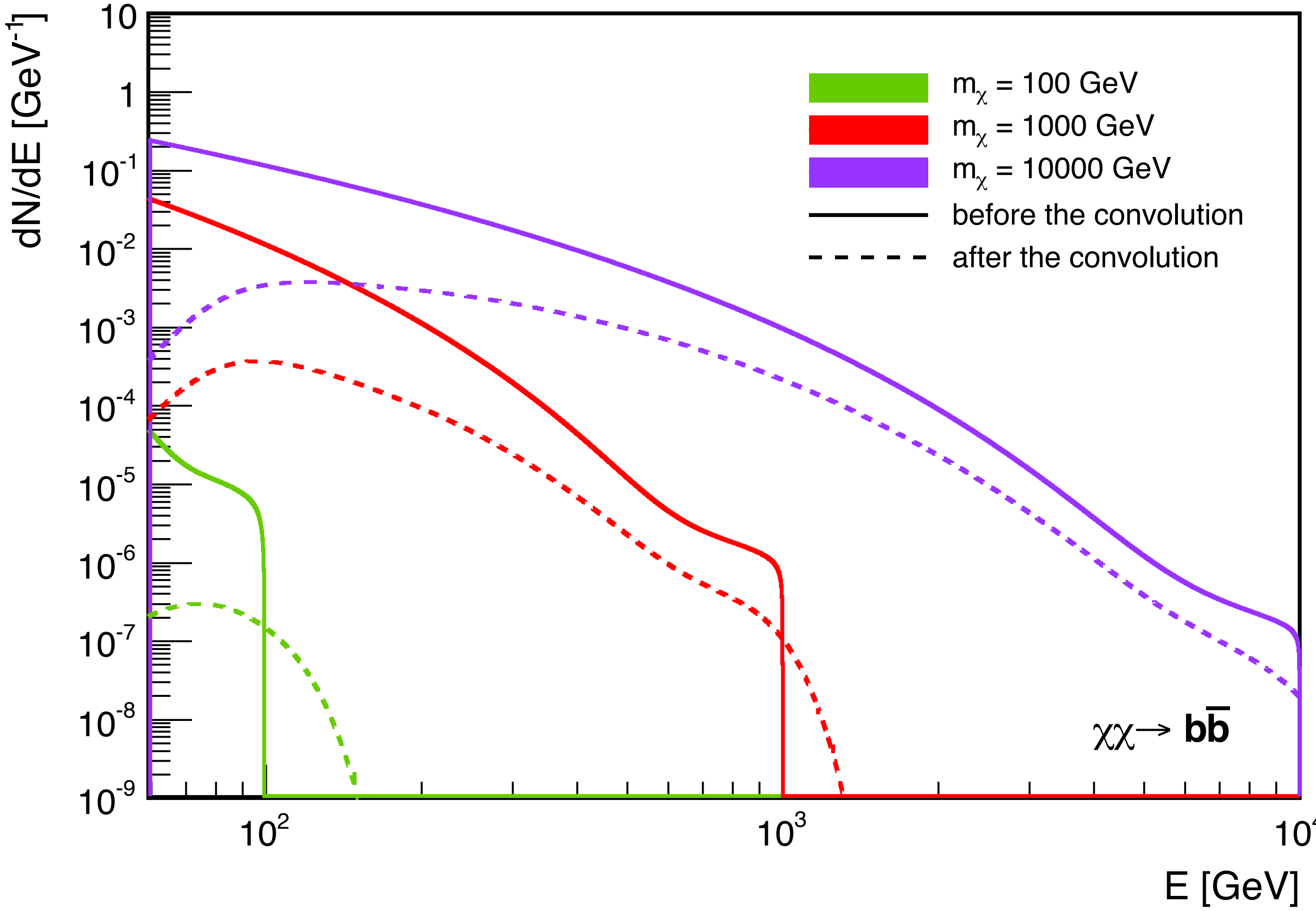
$$\mathcal{L}_{\text{Global}}(M(\theta)) = \prod_{i=1}^{N_{\text{inst}}} \mathcal{L}_i(M(\theta))$$

Aleksić, Rico & Martinez, JCAP 10 (2012) 032



Full Likelihood Analysis

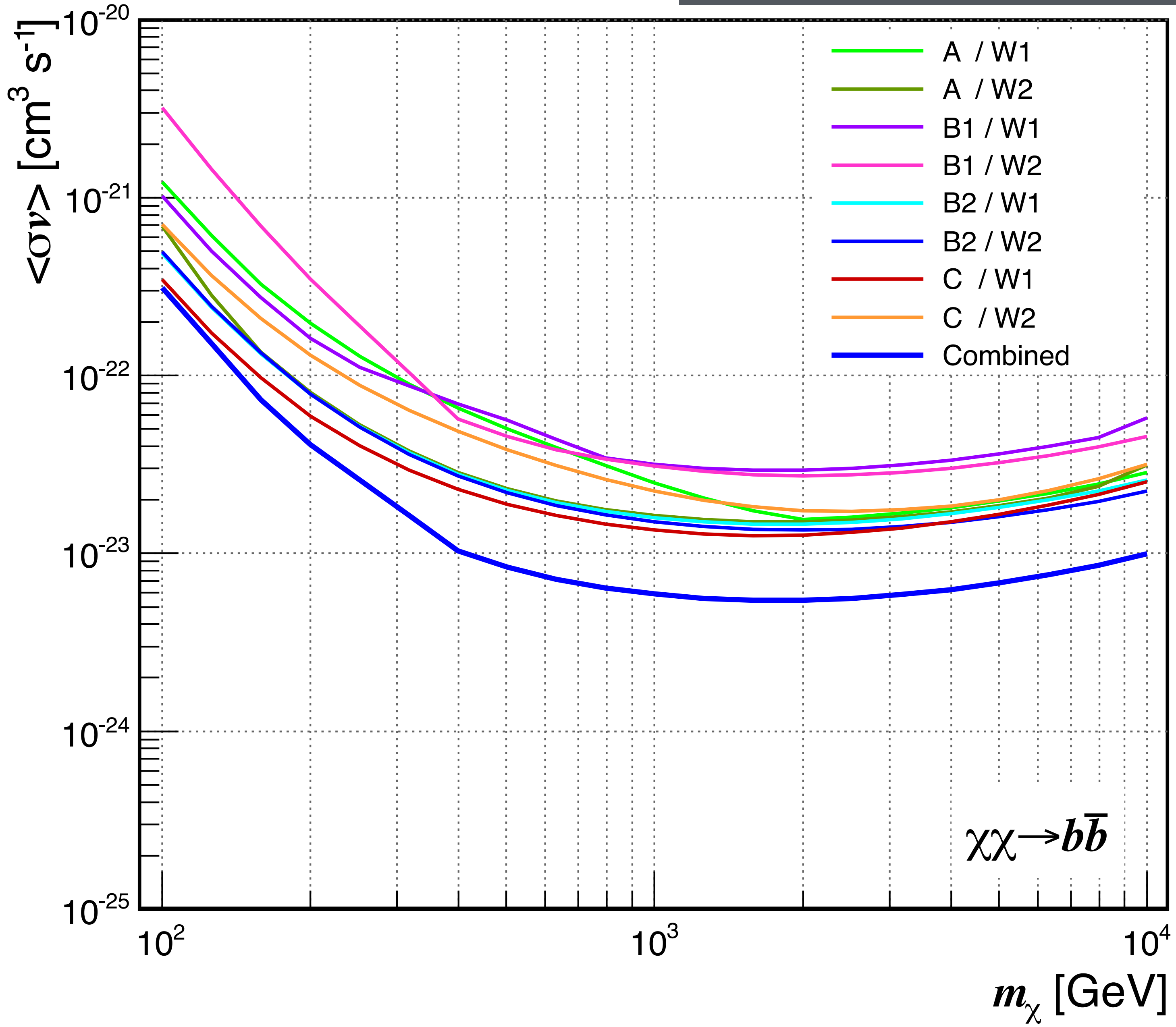
- Response function: calculated for each observation period separately
- Background spectral shape: modeled from the Segue I observations
- Signal spectral shape: few models of dark matter annihilation and decay:
  - Secondary photons
  - Monochromatic lines
  - Virtual Internal Bremsstrahlung
  - Gamma-ray boxes



- m_χ in the 100 GeV —10 TeV (200 GeV — 20 TeV) range
- Br = 100 %
- Einasto density profile
- No enhancements

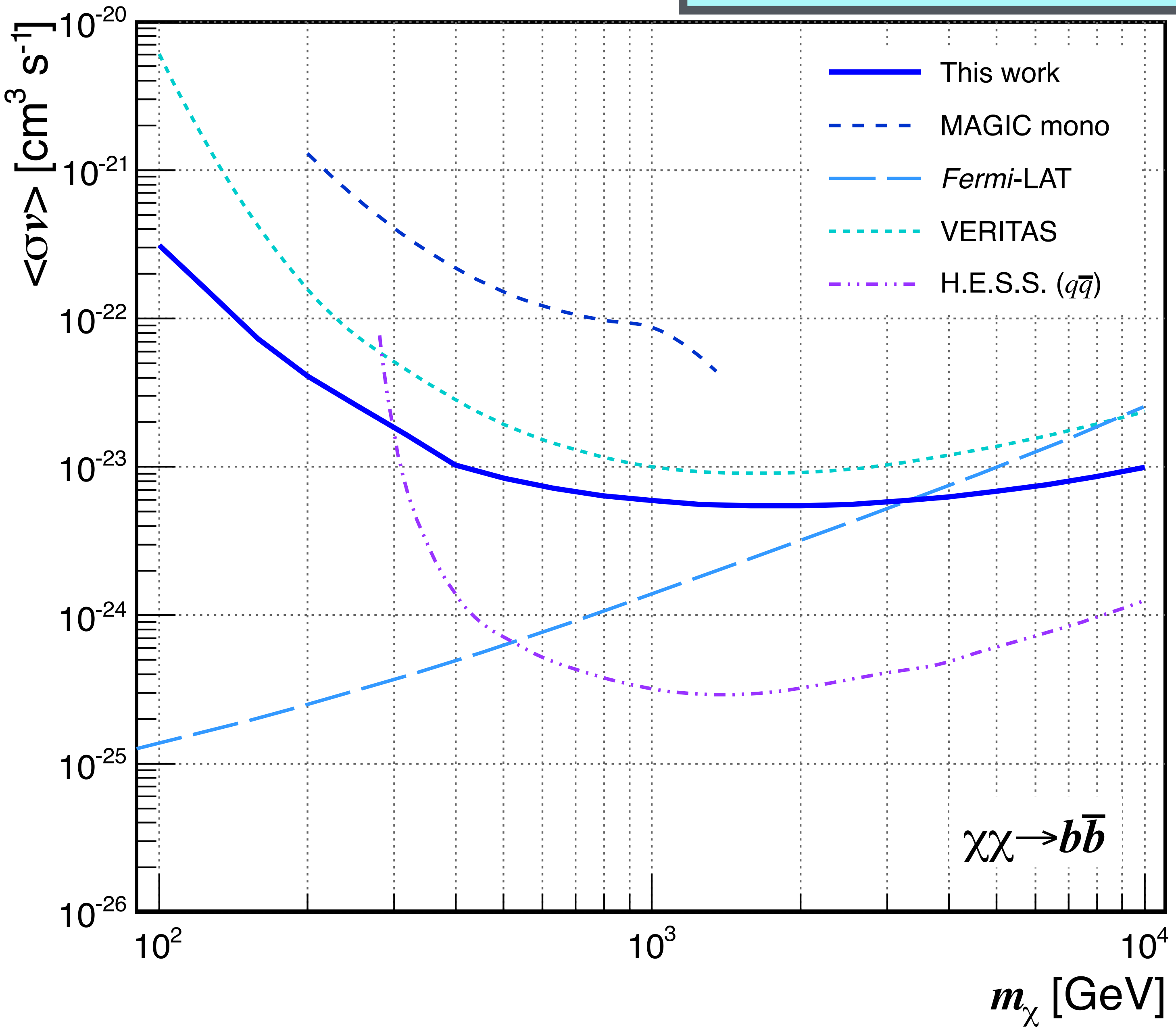
Straightforward combination

Aleksić et al, JCAP 02 (2014) 008



Annihilation into *b* quarks

Aleksić et al, JCAP 02 (2014) 008



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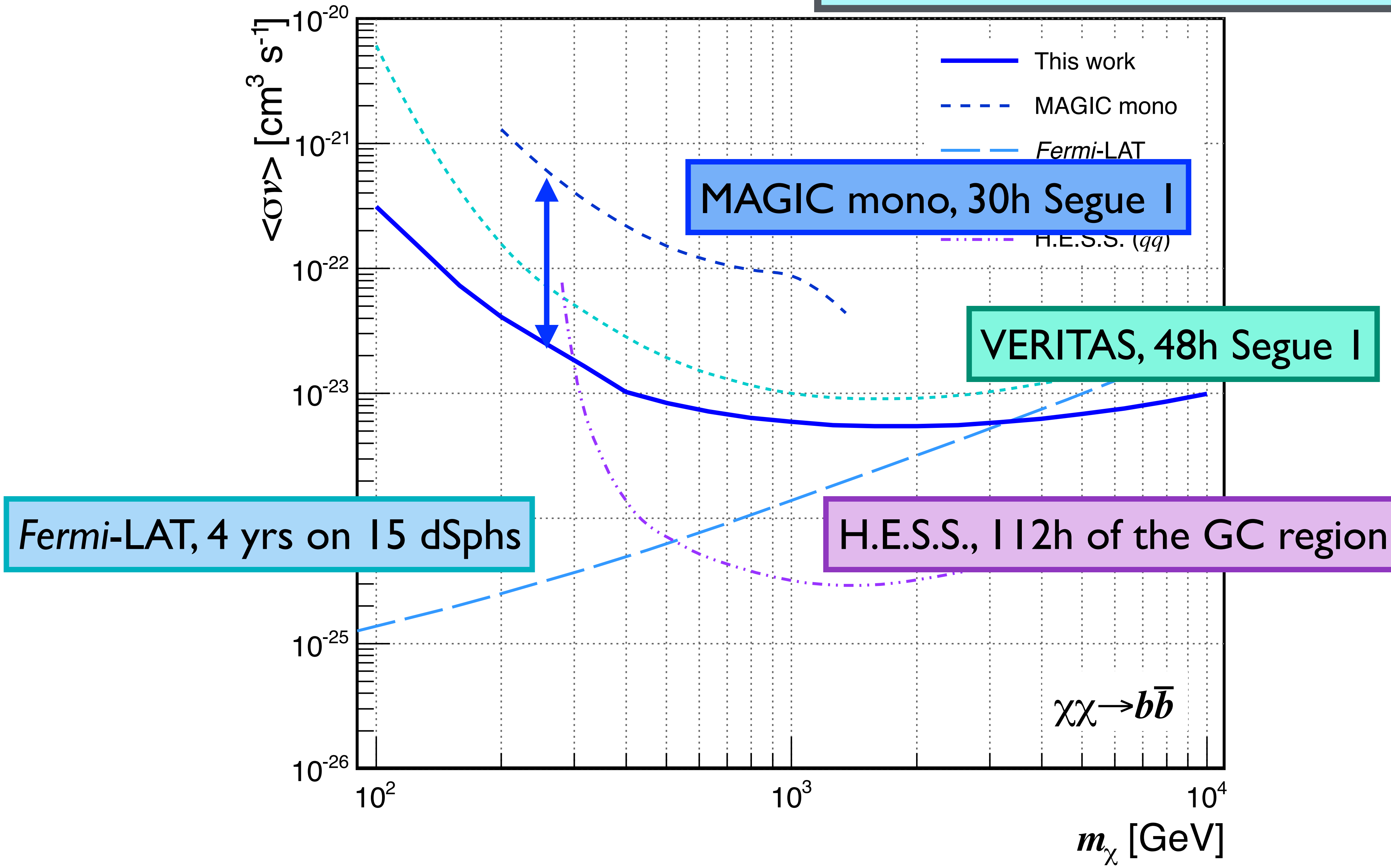
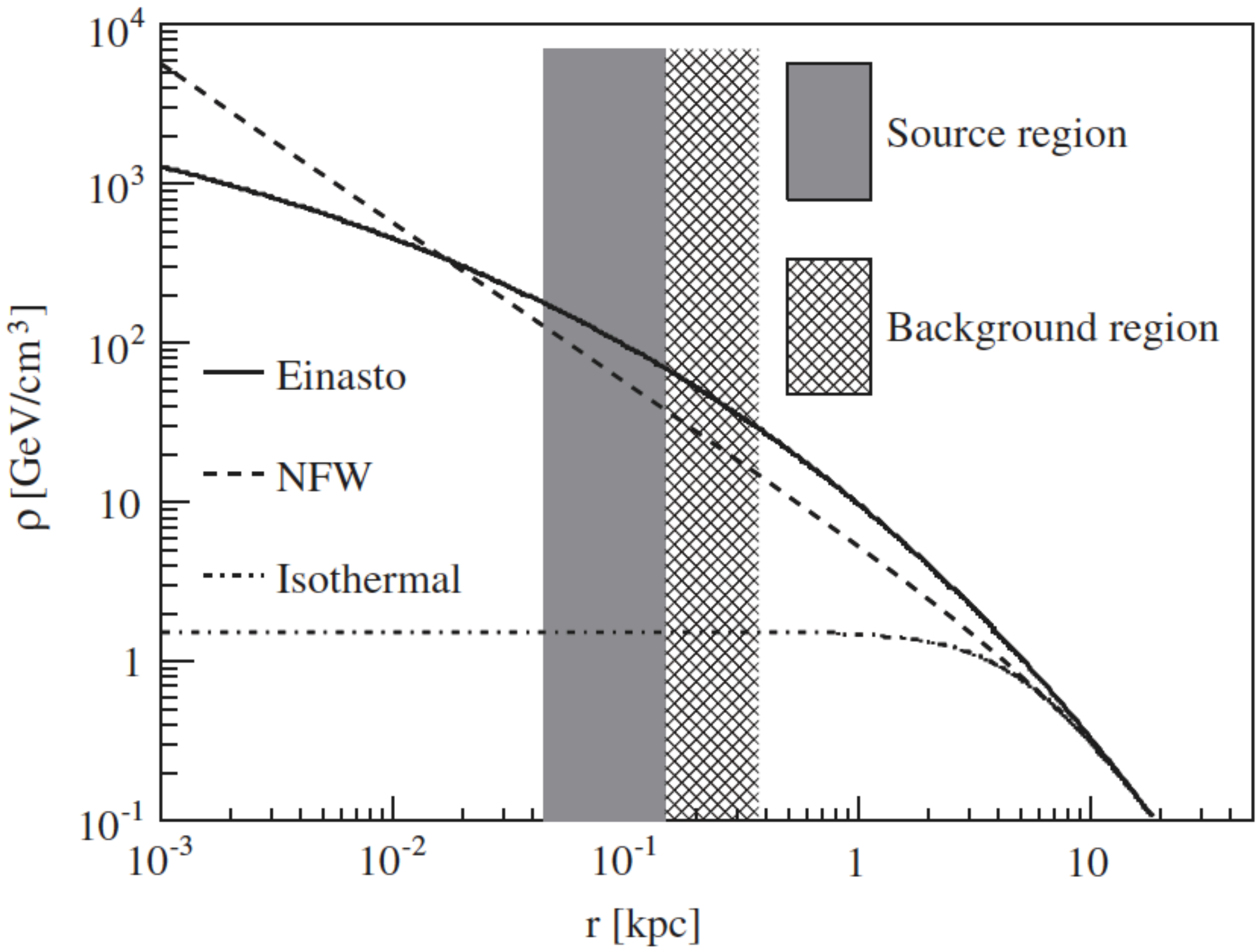
Aleksić et al, JCAP 02 (2014) 008



However…

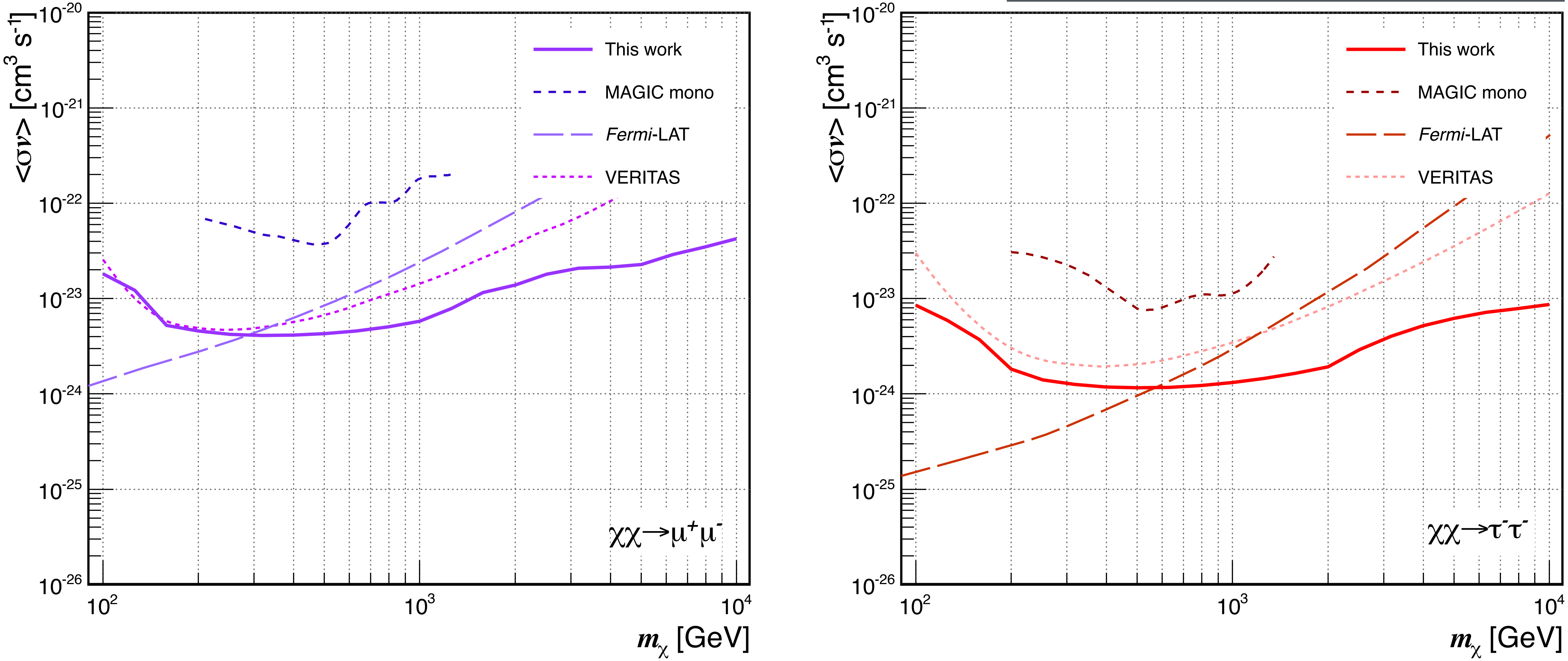
Abramowski et al., Phys. Rev. Lett. 106 (2011)



- Results from the GC halo are based on DM density differences between Source and Bkg region:
  - NFW: factor 2 less constraining
  - Isothermal: insensitive
- N-body simulations do not seem to provide the final answer → role of baryons must be understood
- Diversification of targets is the optimal observational strategy

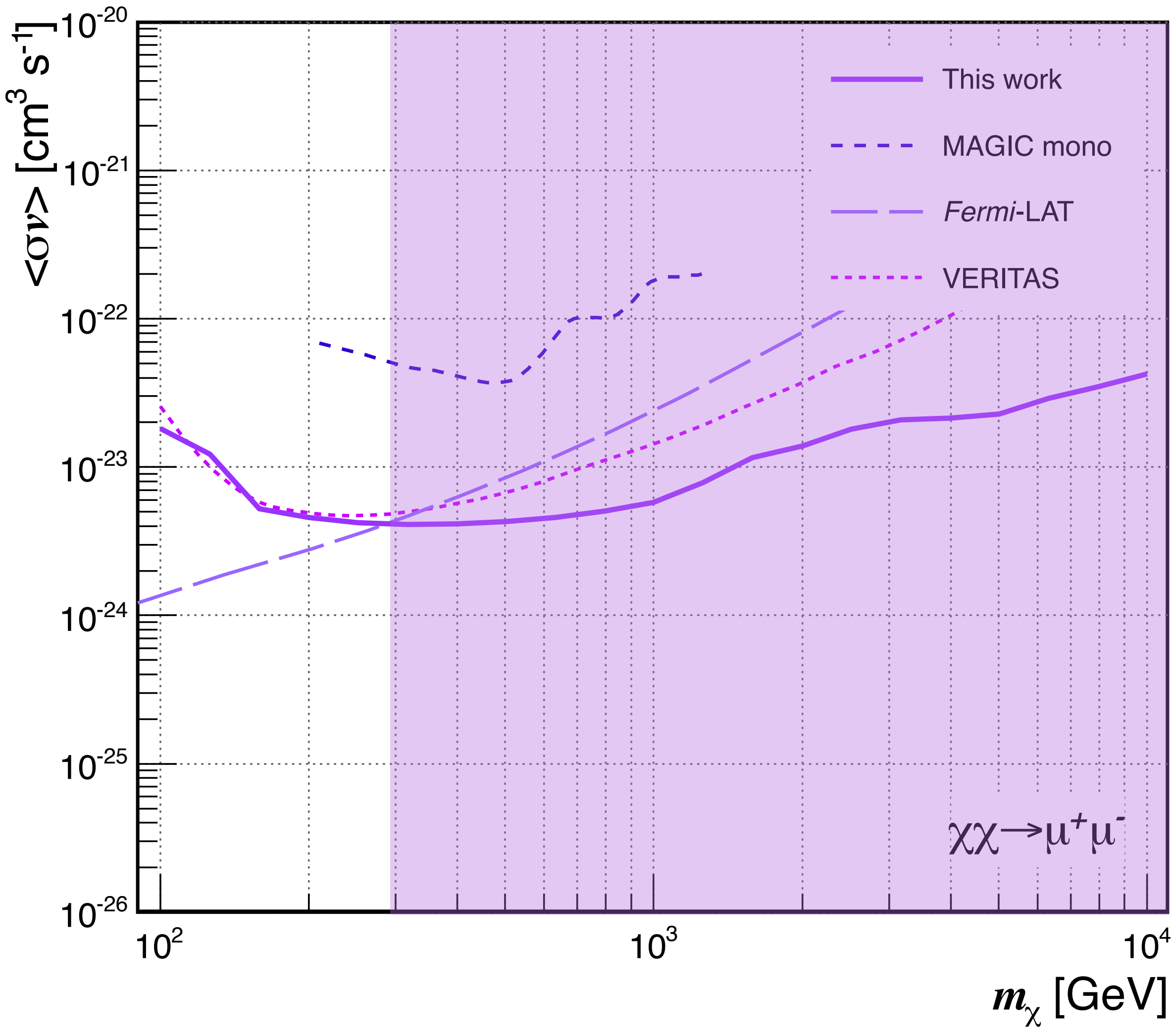
Annihilation into leptons

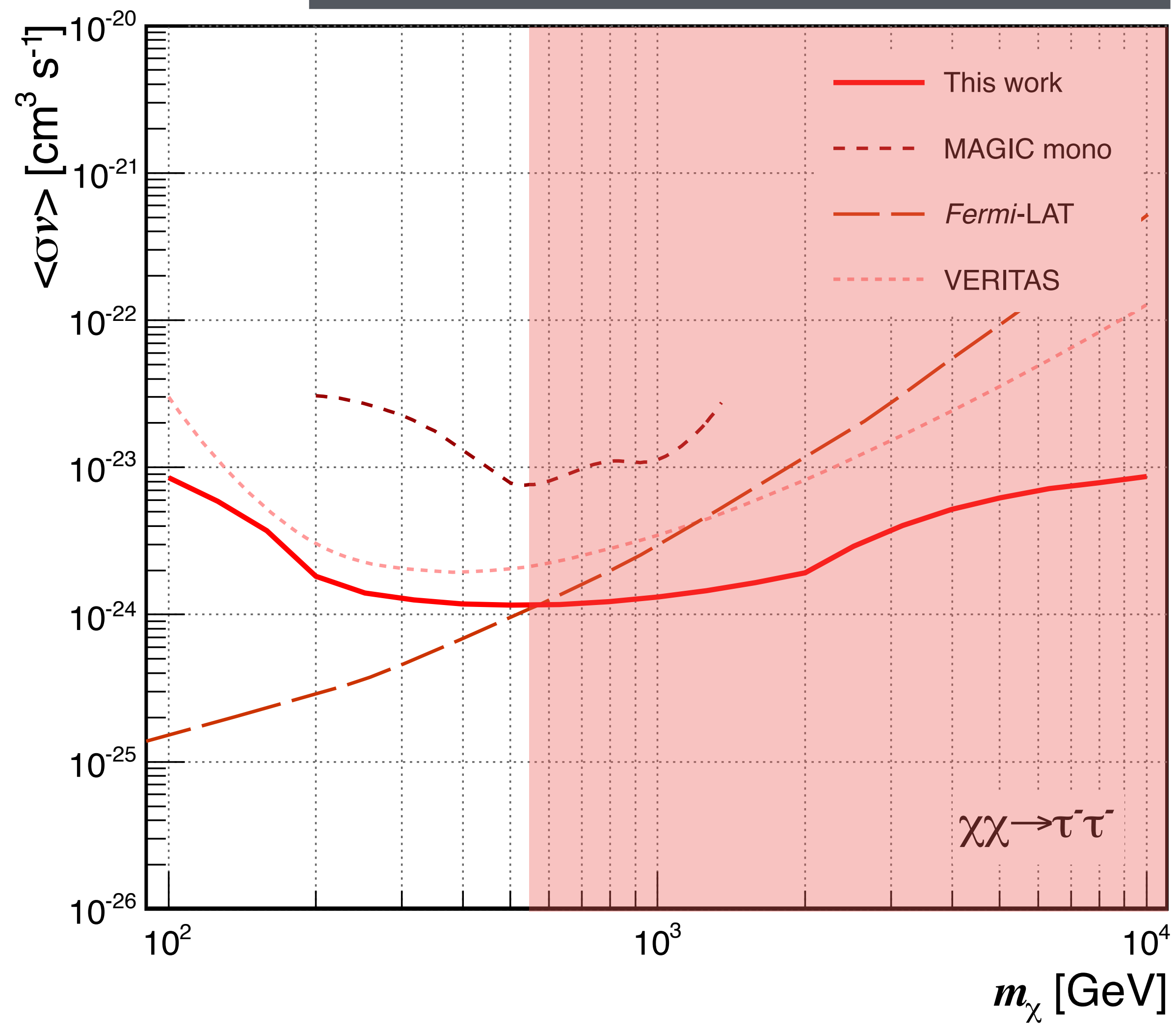
Aleksić et al, JCAP 02 (2014) 008



Annihilation into leptons

Aleksić et al, JCAP 02 (2014) 008



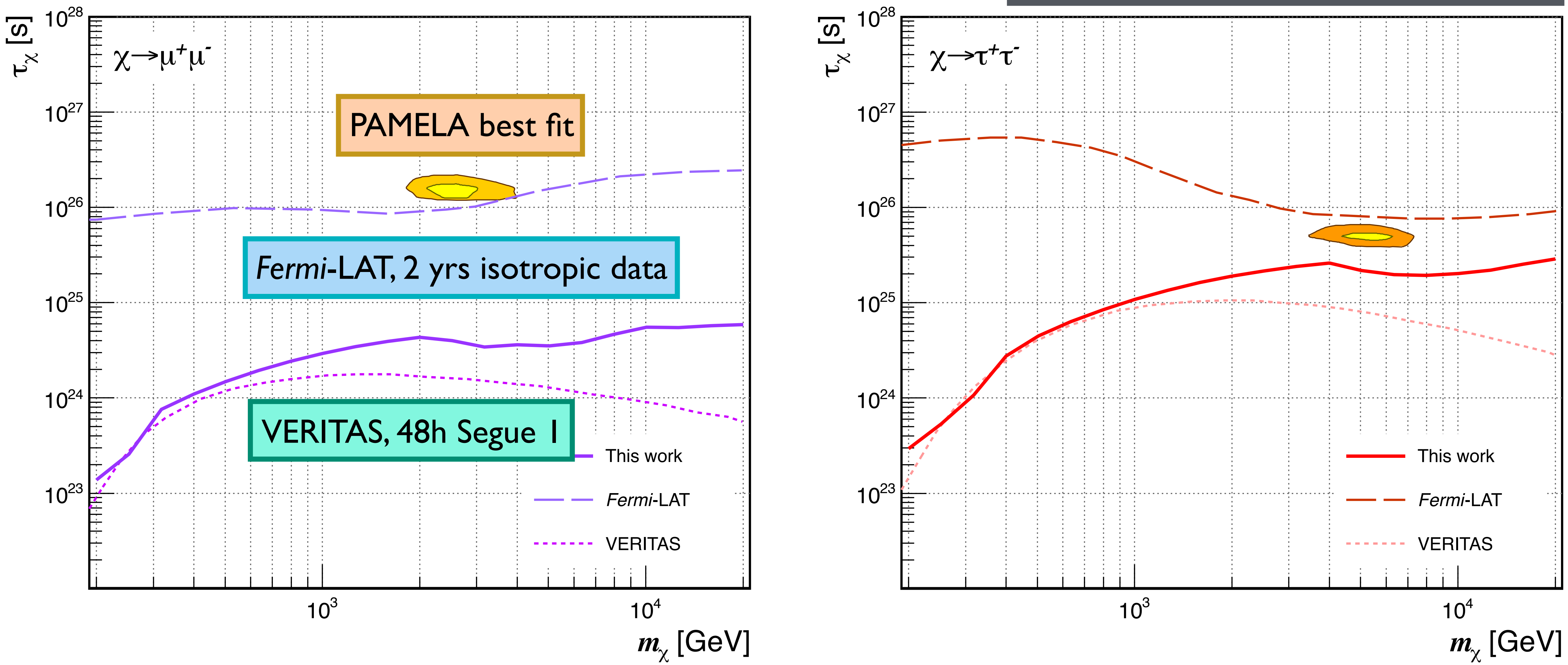


Strongest limit above 300 GeV from dSphs

Strongest limit above 550 GeV from dSphs

Decay into leptons

Aleksić et al, JCAP 02 (2014) 008

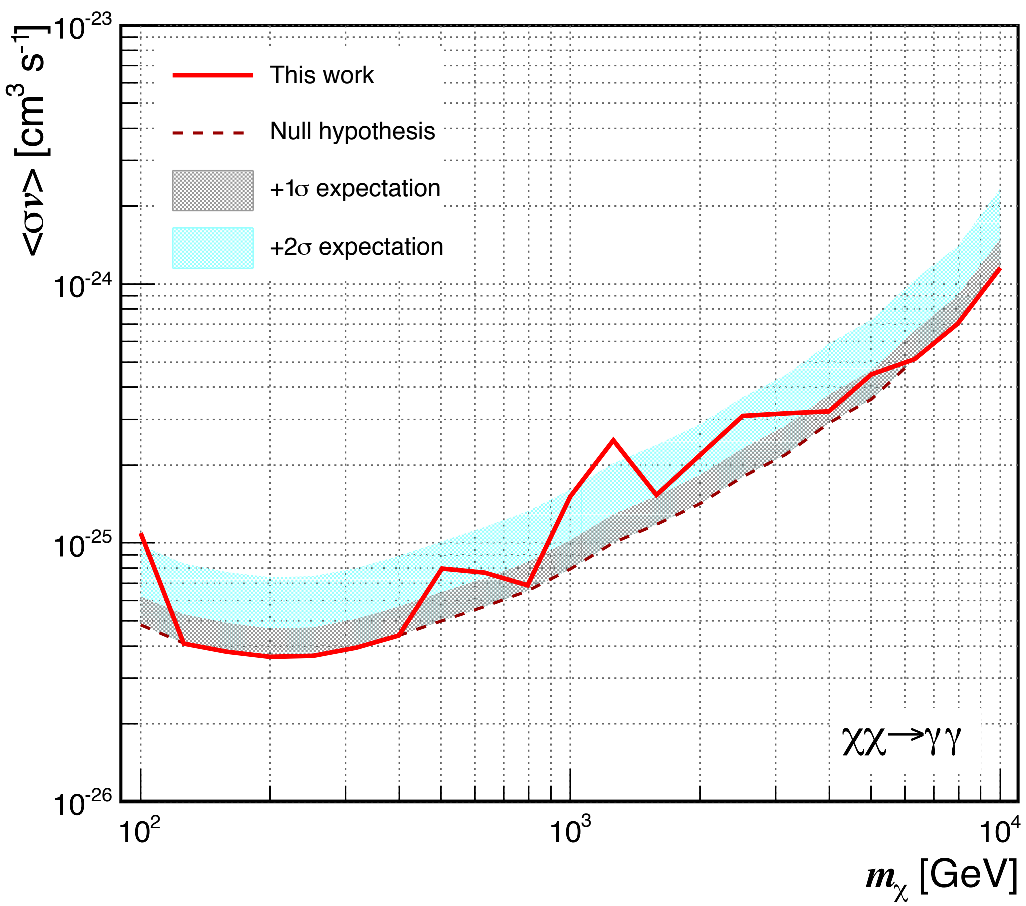


Strongest limits from IACTs

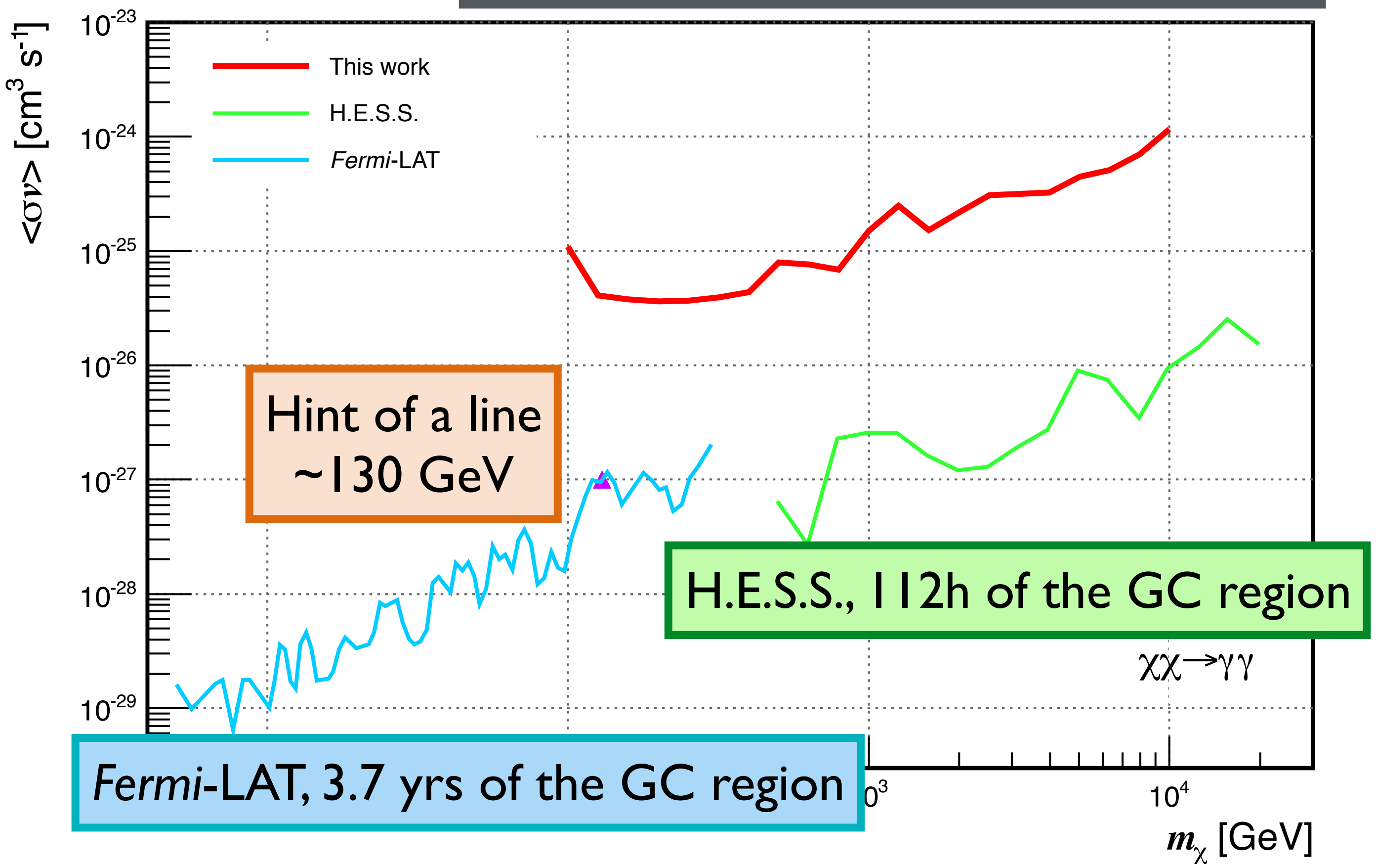
- In general, dSphs are suboptimal targets for decaying dark matter searches

Annihilation into line

- ★ As expected, weaker limits than from *Fermi*-LAT and H.E.S.S. observations of the Galactic Center region



Aleksić et al, JCAP 02 (2014) 008



- ★ Maximum deviation from the null hypothesis expectation is of order of 2σ, for m_χ ~ 1.3 TeV (no trial correction)

How to go further?

- With MAGIC, one order of magnitude improvement (wrt mono) due to:

	~2 analysis optimization	(1)
x	2 better sensitivity of stereo	(2)
x	$\sqrt{5}$ deep observation	(3)
+	target	(4)

- Further improvements?
  1. not obvious how to gain more
  2. exploit the sensitivity improvement of factor ~5-10 by CTA
  3. individual instruments reaching their limit → merge results
  4. explore new targets and signatures (like decay in galaxy clusters)

How to go further? A proposal

- Use a global likelihood to combine results from different telescopes (MAGIC, VERITAS, HESS & Fermi-LAT):

$$\mathcal{L}_{\text{Global}}(M(\theta)) = \prod_{i=1}^{N_{\text{inst}}} \mathcal{L}_i(M(\theta))$$

- This can get us another factor ~2 wrt to present results (thanks to longer global exposure)
- Combination of instruments is rather trivial, no "private" information from Collaborations needs to be shared
- Combination of sources of same type (dSph, clusters…) also simple and desirable:
  - Use all dSph from all instruments to search for annihilating DM
  - Use all clusters from all instruments to search for decaying DM
  - Annihilation from GC dominated by HESS
- In progress!

Summary

- ★ 158 h of Segue 1 with MAGIC: deepest ever survey of any dwarf galaxy by any IACT
- ★ Complex combined analysis (different configurations)
- ★ Dedicated analysis, optimised for spectra with features
- ★ Strongest limits on various models of dark matter annihilation/decay from dwarf galaxies with IACTs
- ★ For m_χ > few hundred GeV: strongest limits from dSphs