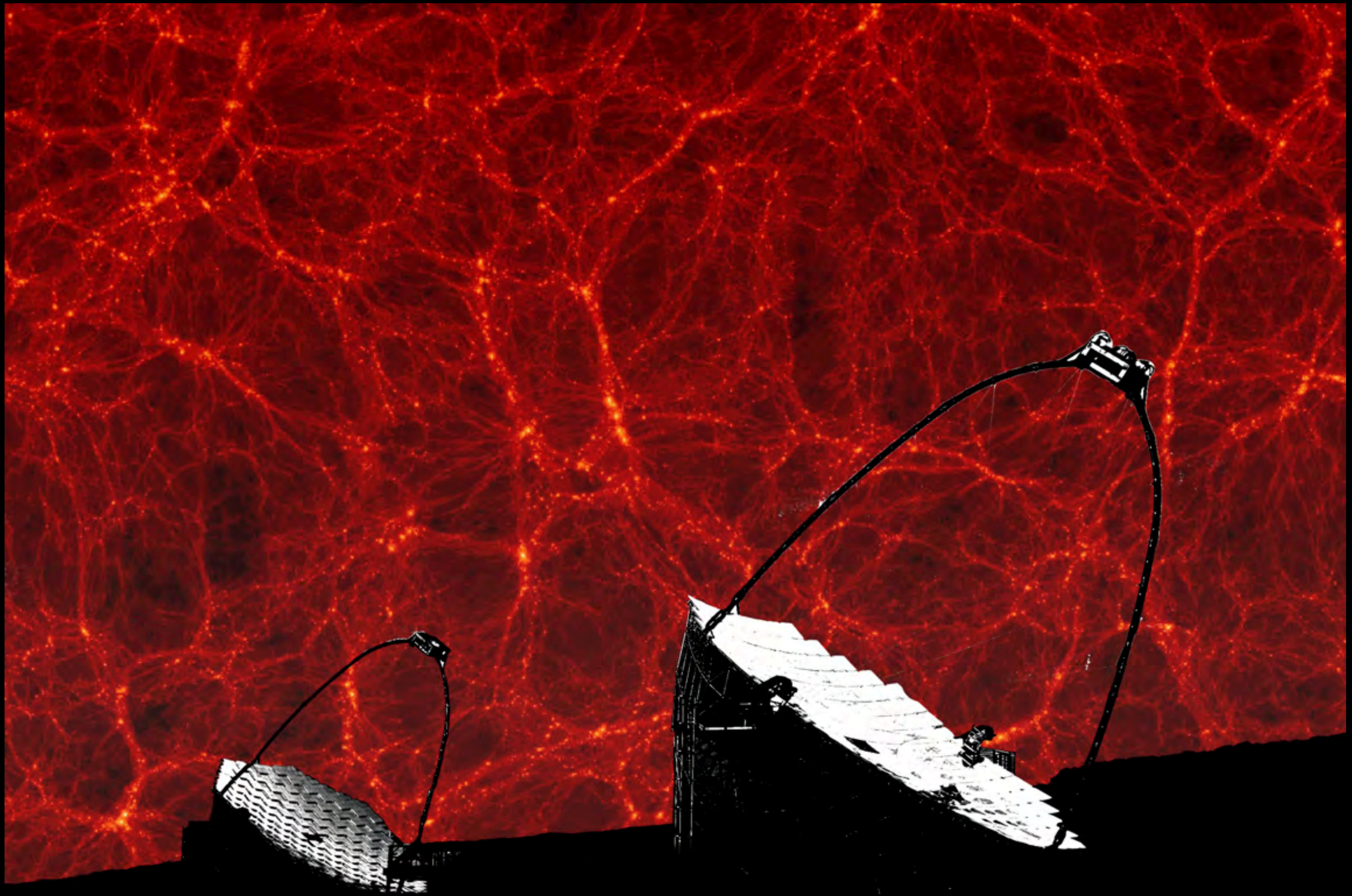


Javier Rico, IFAE

on behalf of the MAGIC Collaboration

Workshop “What are we learning from the gamma-ray sky?

Dark Matter Searches with the MAGIC Telescopes

Minneapolis October 10th 2013

Outline

- ★ MAGIC
- ★ Observations of Segue 1
- ★ Full likelihood analysis
- ★ Results
- ★ Discussion & Conclusions

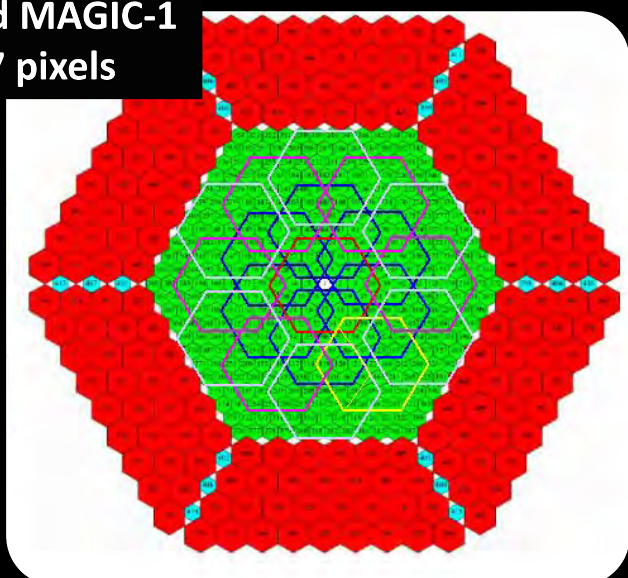
The MAGIC Telescopes

- The MAGIC telescopes at La Palma:
  - 2 telescopes
  - 17 m diameter mirrors
  - 3.5 deg field of view
  - Fast slewing (<40 s to any position)

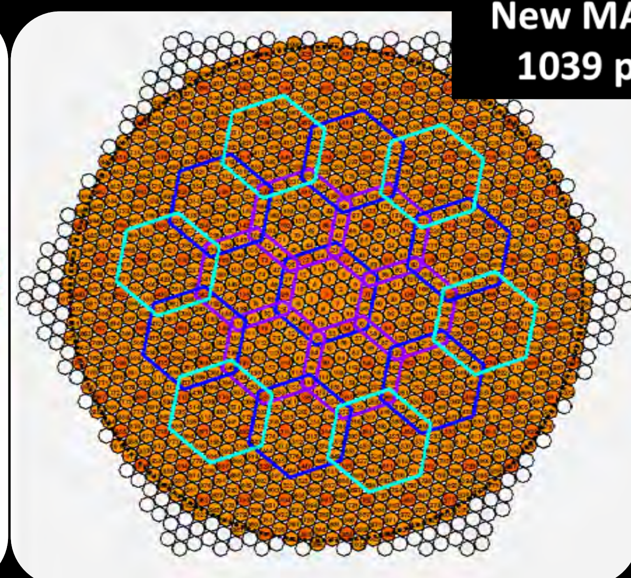
  - Energy threshold ~50 GeV
  - Energy resolution 15 – 25%
  - Angular resolution ~0.1°
  - Sensitivity ~ 0.7% C.U. in 50 h above 250 GeV

MAGIC UPGRADES

- ★ MAGIC has completed the last major upgrade:
  - Replace electronics for Data Acquisition (from heterogeneous MUX+Domino-2 system to homogeneous (Domino-4) system (remove dead-time)
  - New camera for MAGIC-I (more pixels, uniform, larger trigger area)
  - Integrate "sum-trigger" system for low energies



Old MAGIC-1
577 pixels



New MAGIC-1
1039 pixels

Dark Matter Searches with MAGIC

★ Active efforts in indirect dark matter searches

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


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Searches for dark matter annihilation signatures in the Segue 1 satellite galaxy with the MAGIC-I telescope

MAGIC collaboration
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JCAP06(2011)

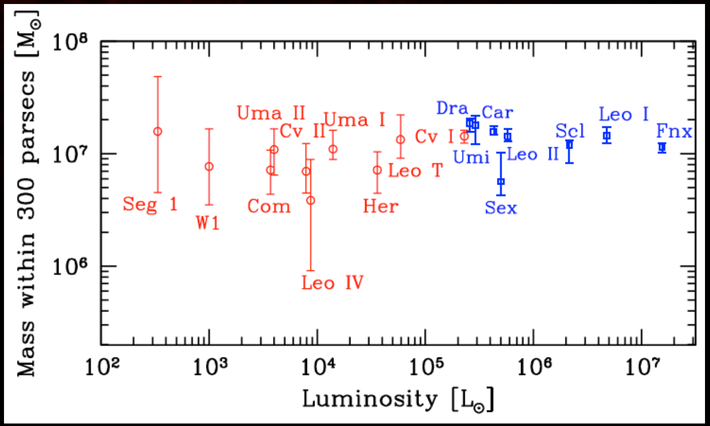
Dark Matter Searches with MAGIC

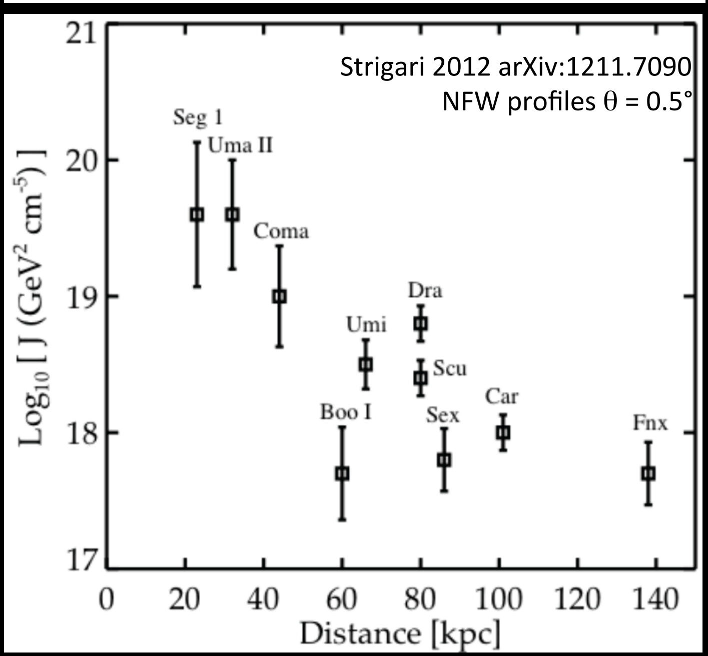
- ★ All existing publications on dark matter searches with one telescope only
- ★ Goal: Improve our best (published) limits by a factor 10

- ☆ Stereo system since 2009
  - ✦ Major upgrade finished in 2012
- ☆ Long-term observational campaign on best dark matter candidate
- ☆ Dedicated analysis approach

Segue 1

SEGUE = Sloan Extension for Galaxy Understanding and Exploration





- ★ The most dark matter dominated object known so far
- ★ The least luminous galaxy
- ★ Close, no background, Northern hemisphere, culminates at 13° for MAGIC
- ★ Largest J factor after GC
- ★ $J_{ann}(\theta=0.15°)$:
  - ✦ 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: 157.9 h

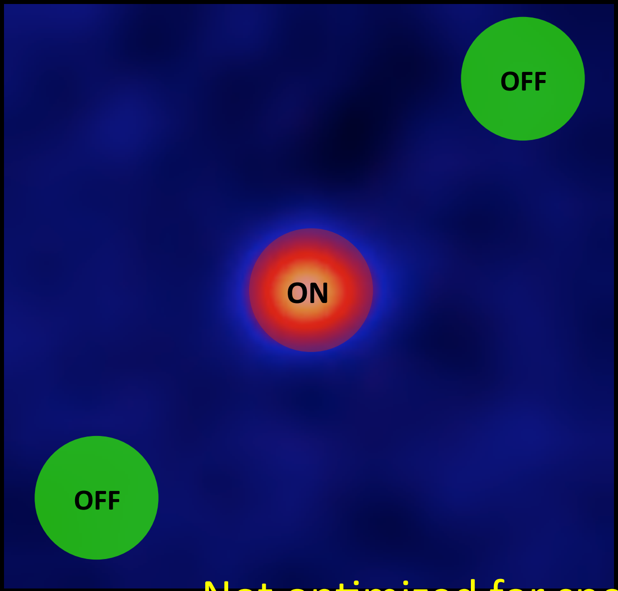
The deepest survey of any dSph by any IACT!

Conventional analysis

ON = signal [?] + bkg

OFF = $\tau \times$ bkg

τ – bkg normalization (e.g ~# wobble positions)



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)

Not optimized for spectra with features!

g & b – estimated by maximizing:

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

ON OFF

Full Likelihood Method

NUM OF EVTS | Spectral shape

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

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:

$$\mathcal{P}(E; M(\theta)) = \frac{dN/dE}{\int_{E_{min}}^{E_{max}} dE \cdot dN/dE}$$

i.e. normalized differential rate
(for background + signal)

Differential rate:

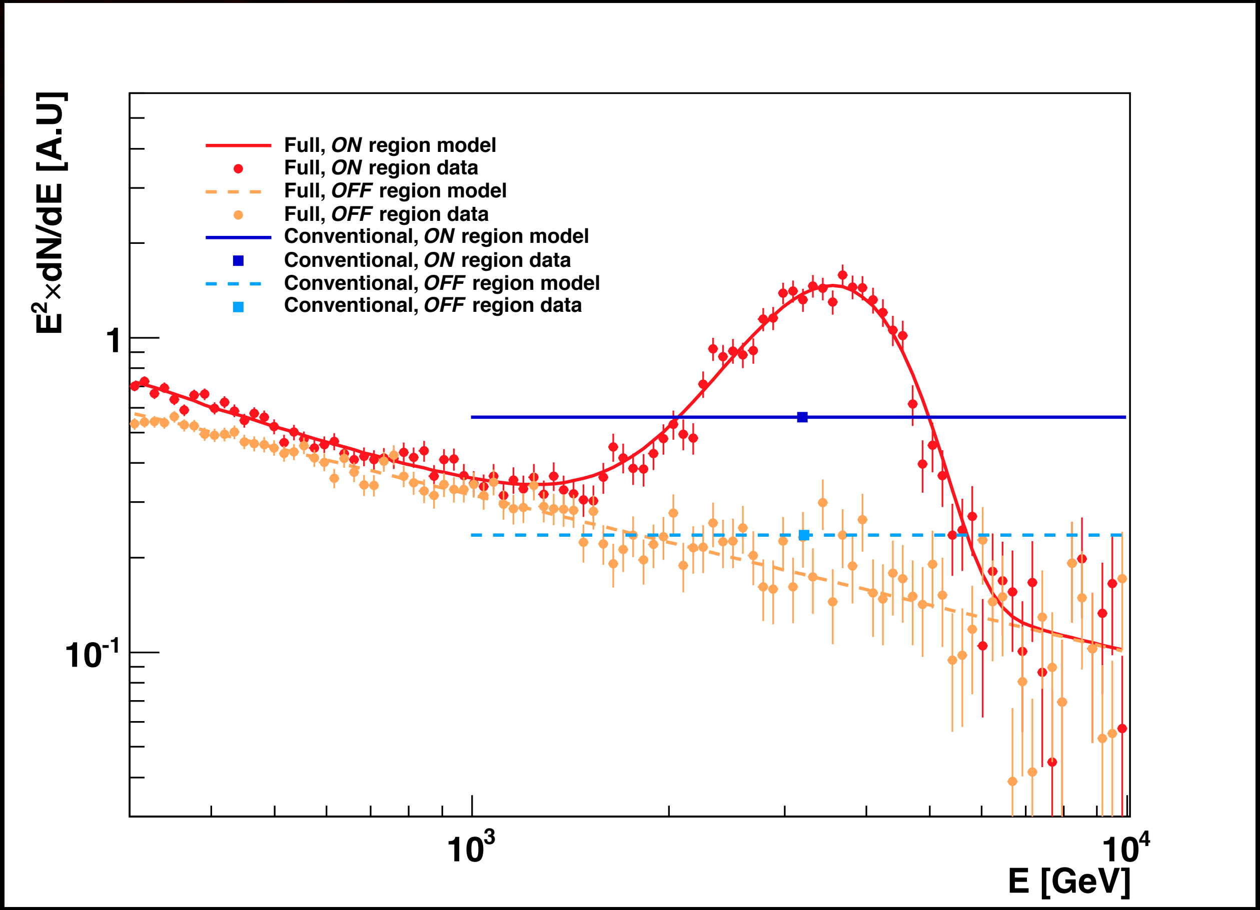
$$\frac{dN}{dE} = T_{obs} \int_0^{\infty} \frac{d\phi}{dE'} R(E; E') dE'$$

i.e. real flux convoluted with response func:

$$R(E; E') = A_{eff}(E') \times G(E; E')$$

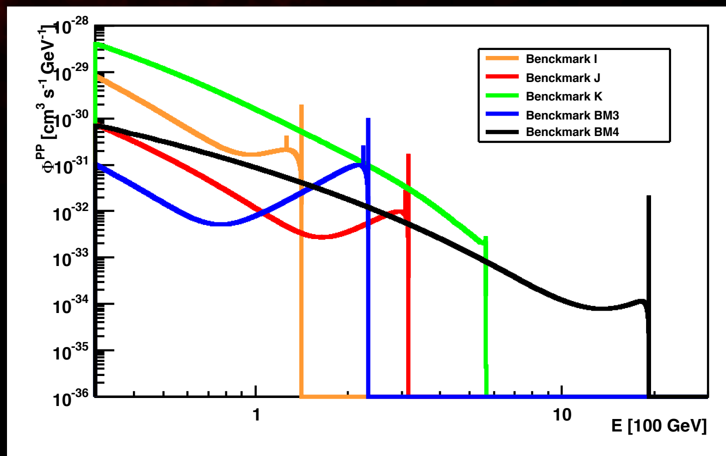
Conventional vs Full Likelihood

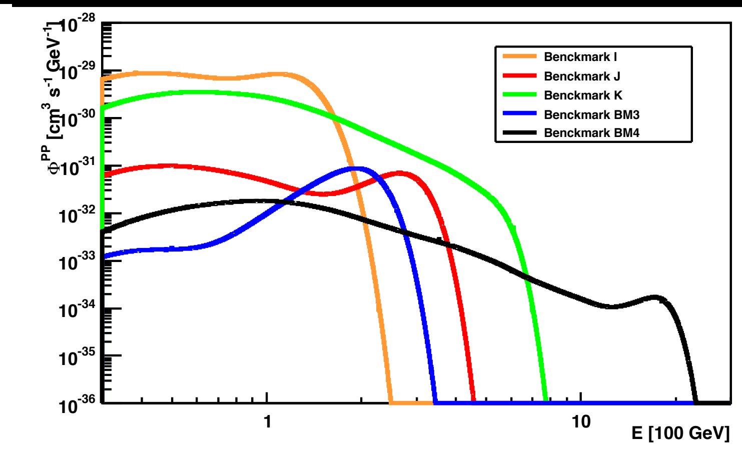
Aleksić, Rico & Martinez JCAP 10 (2012) 032



Full likelihood takes maximal profit of spectral information expected in the DM-induced spectra

Sensitivity Improvement





			MAGIC		CTA	
BM	m_x [GeV]	σv [cm^3 s^{-1}]	IF	$\langle\sigma v\rangle_{EDL}$ [cm^3 s^{-1}]	IF	$\langle\sigma v\rangle_{EDL}$ [cm^3 s^{-1}]
I’	141	3.6×10^{-27}	**1.57**	5.65×10^{-23}	**1.48**	1.39×10^{-23}
J’	315	3.2×10^{-28}	**1.80**	1.01×10^{-23}	**1.65**	1.91×10^{-24}
K’	565	2.6×10^{-26}	**1.23**	3.91×10^{-23}	**1.58**	8.39×10^{-24}
BM3	233	9.2×10^{-29}	**1.89**	7.21×10^{-25}	**1.61**	1.35×10^{-25}
BM4	1957	2.6×10^{-27}	**2.10**	2.87×10^{-23}	**3.81**	4.82×10^{-24}

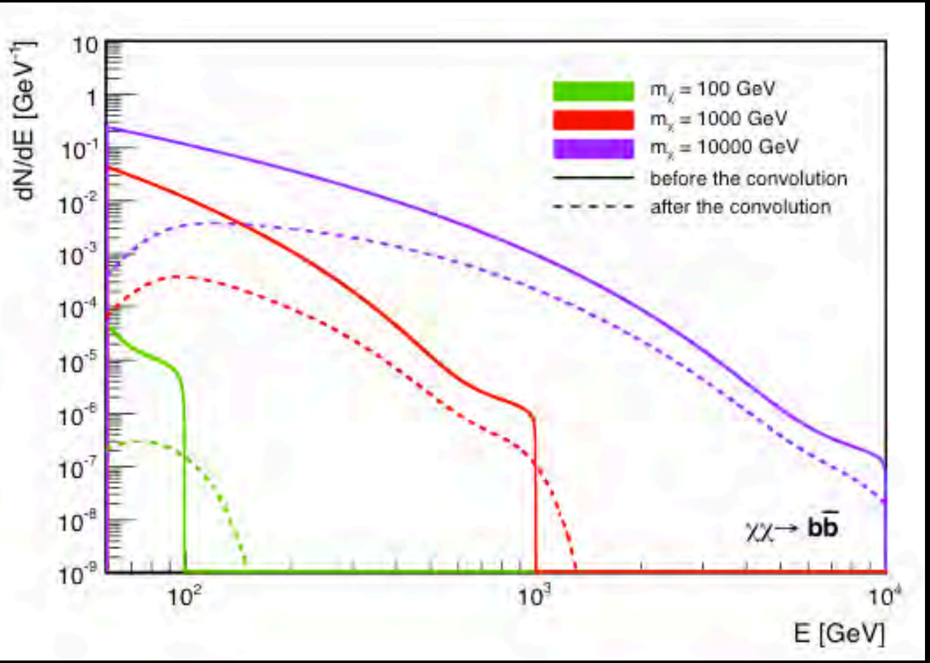
Full Likelihood Method

- *A priori* assumption on the expected spectral shape → maximum advantage of potential features
- Unbiased, stable, robust
- Significant improvement with respect to the conventional analysis ~1.5-2 for simple shapes
- Straightforward combination of results from different instruments / sources

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

Full Likelihood Analysis

- ★ Response function: calculated for each observation period separately
- ★ Background spectral shape: modeled from the Segue 1 observations
- ★ Signal spectral shape: few models of dark matter annihilation and decay:
  - ✦ Secondary photons
  - ✦ Monochromatic line
  - ✦ Virtual Internal Bremsstrahlung
  - ✦ Gamma-ray boxes



- ★ m_χ in the 100 GeV – 10 TeV (200 GeV – 20 TeV) range
- ★ Br = 100%
- ★ Einasto density profile

Full Likelihood Analysis

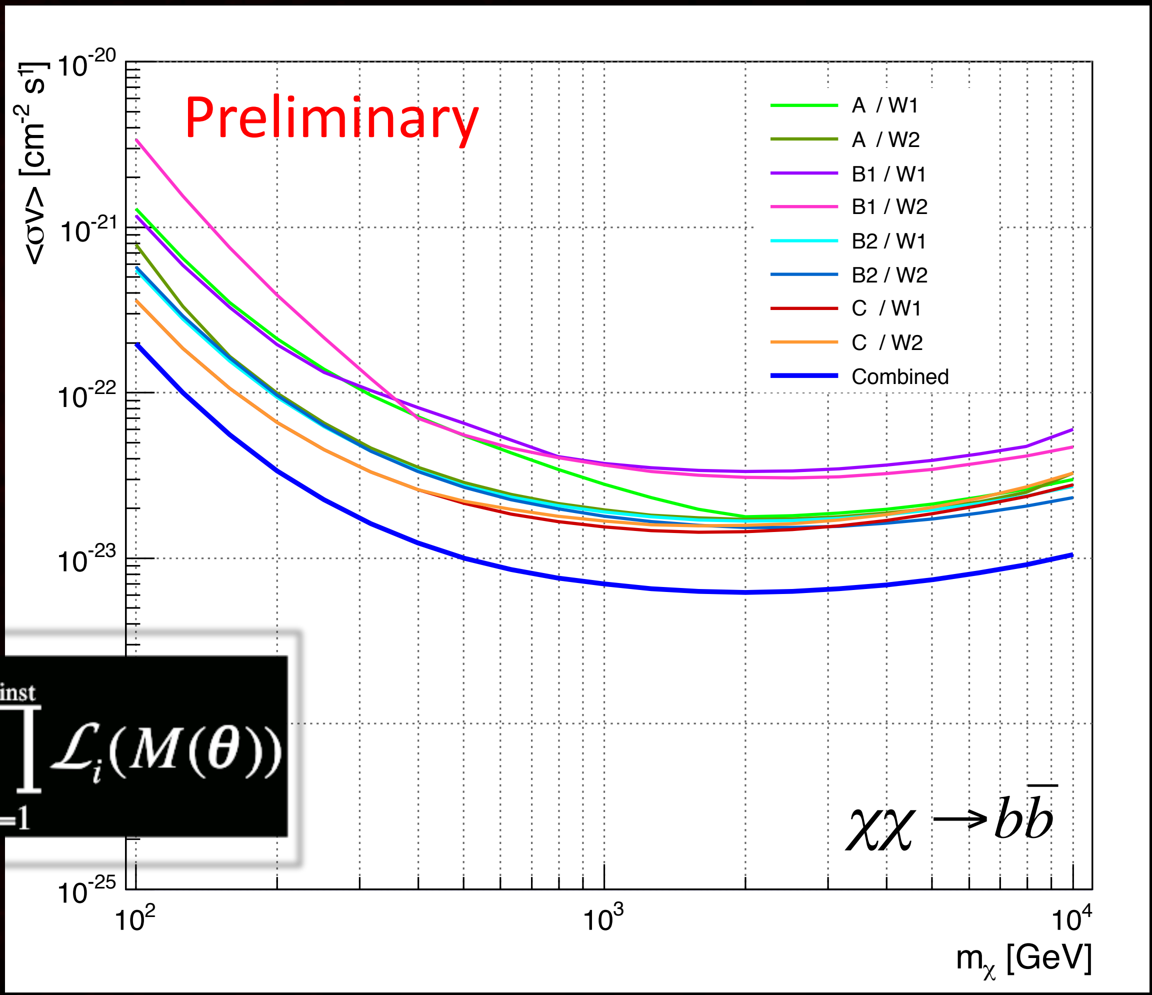
- One-sided confidence intervals, 95% c.l.

- Free parameter: $<\sigma_{\rm ann} v>$ / τ_χ
- Signal intensity bounded positive during fit
- Nuisance parameters: τ and b

- m_χ in the 100 GeV – 10 TeV (200 GeV – 20 TeV) range
- Branching ratio into each final state 100%

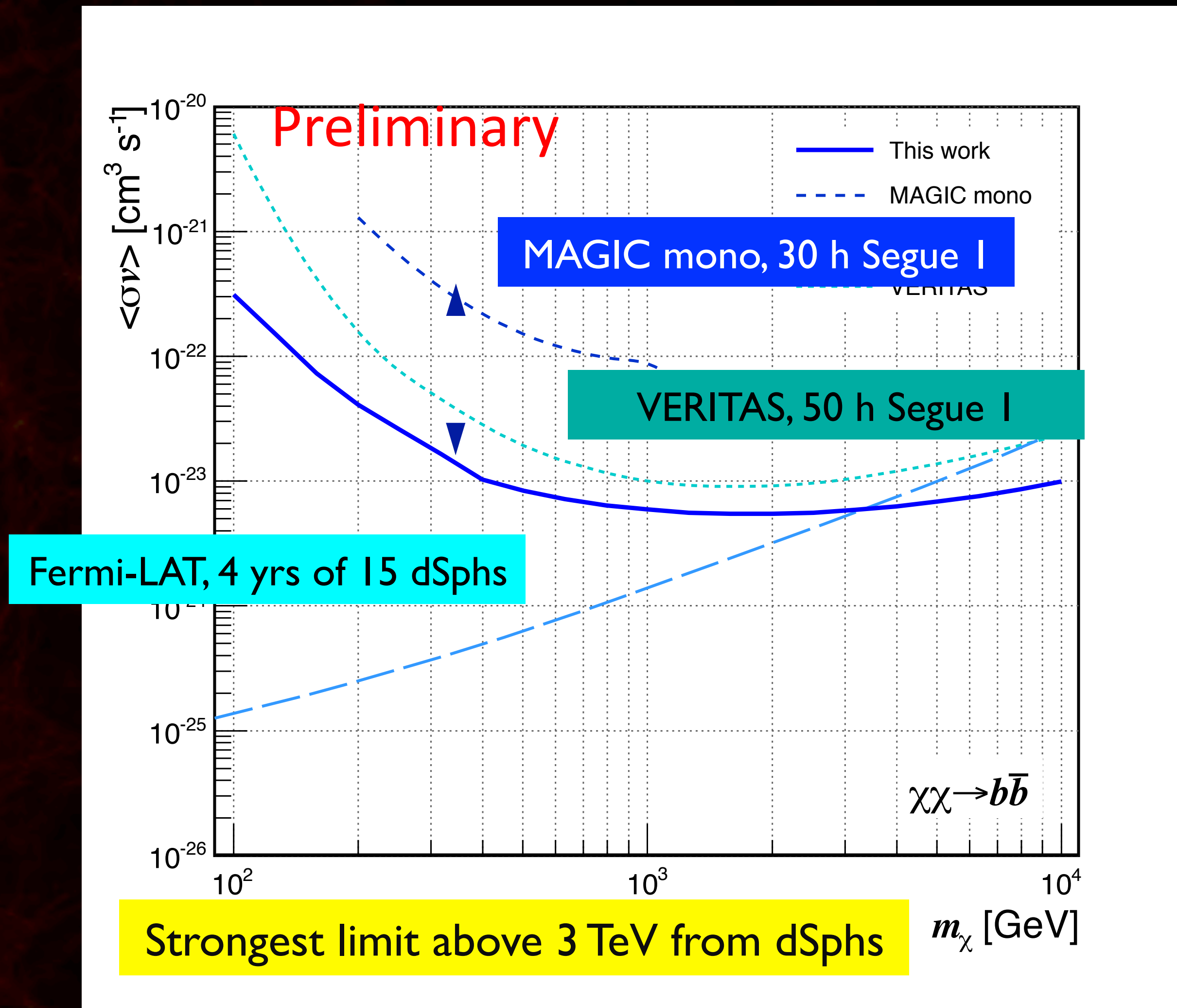
- Einasto dark matter density profile
  - $J_{\rm ann} = 1.1 \times 10^{19}$ GeV^2 cm^{-5} sr
  - $J_{\rm dec} = 2.6 \times 10^{17}$ GeV cm^{-2} sr

Straightforward combinations of samples

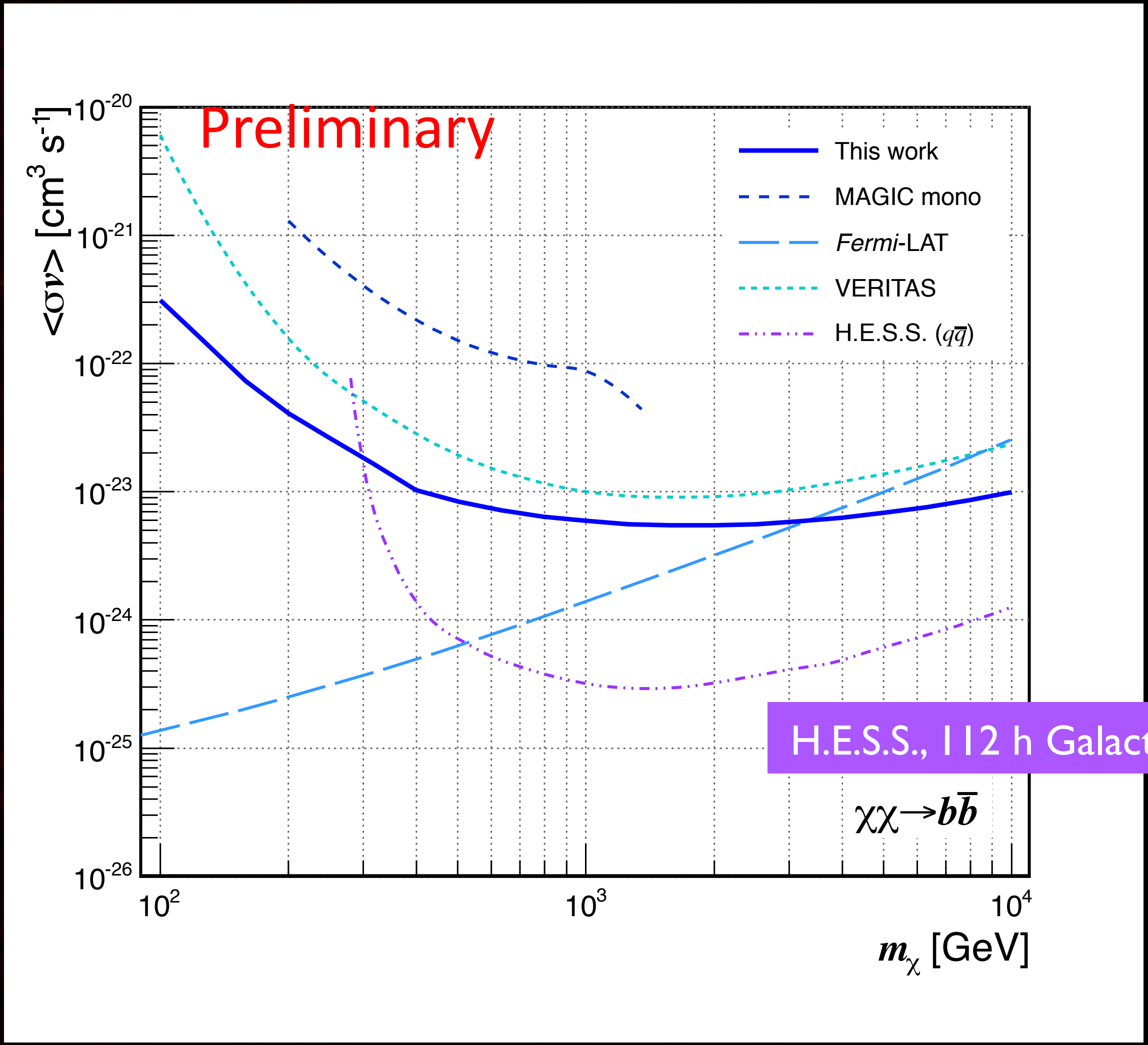


$$\mathcal{L}_T(M(\theta)) = \prod_{i=1}^{N_{\text{inst}}} \mathcal{L}_i(M(\theta))$$

Annihilation: $\chi\chi \rightarrow$ b b-bar

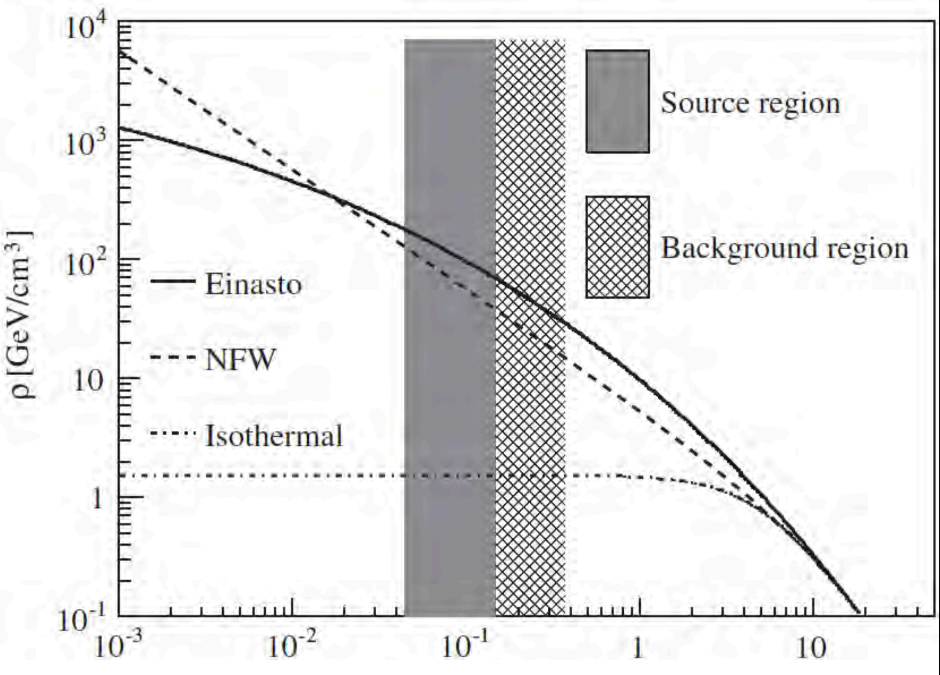


Annihilation: $\chi\chi \rightarrow$ b b-bar



H.E.S.S., 112 h Galactic Halo

But…



Abramowski et al. Phys. Rev. Lett. 106 (2011) 161301

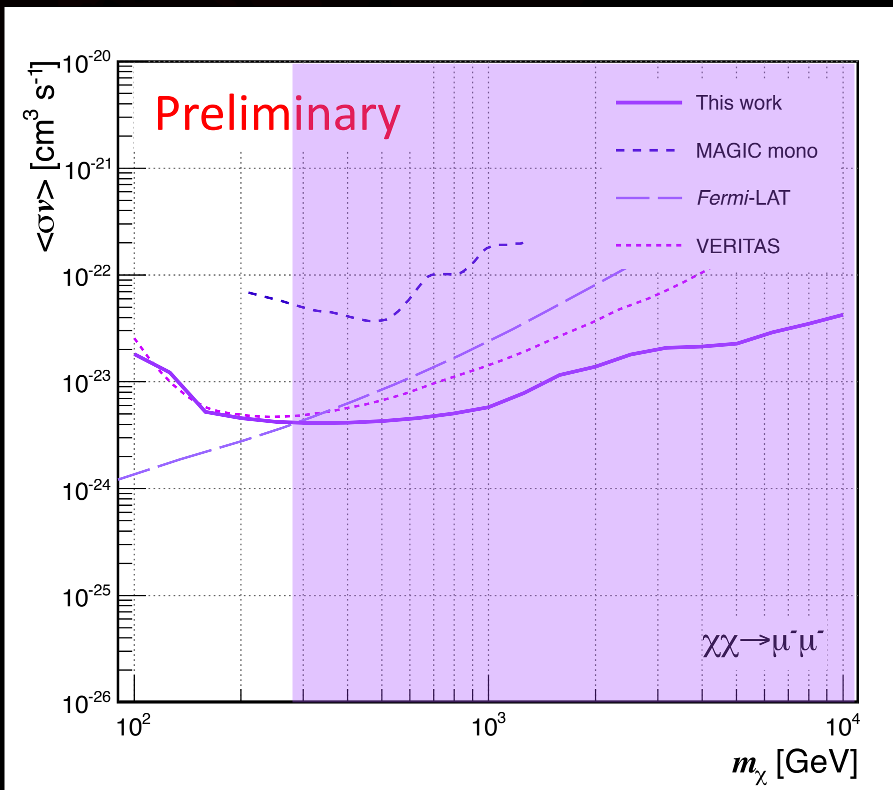
Results from GC halo are based on difference of ρ between Source and Background regions:

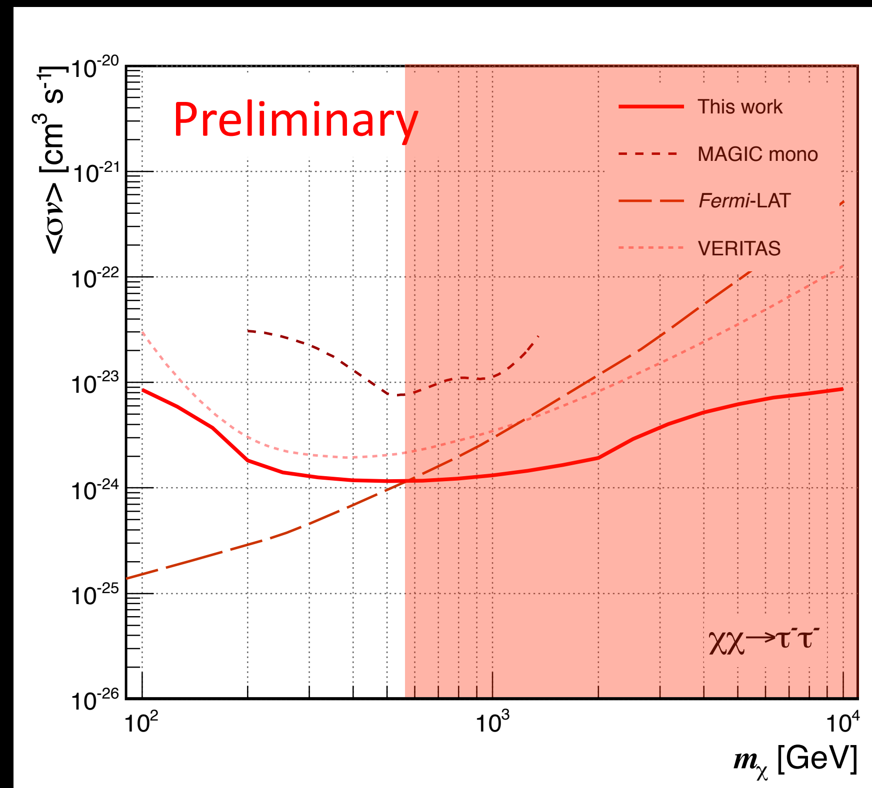
- For NFW, limits are a factor 2 less constraining
- For Isothermal, the method becomes insensitive

N-body simulations don't seem to provide the final answer → we need to understand the role of baryons

Diversification of targets optimal observational strategy

Annihilation: $\chi\chi \rightarrow \mu^+\mu^-$ & $\chi\chi \rightarrow \tau^+\tau^-$

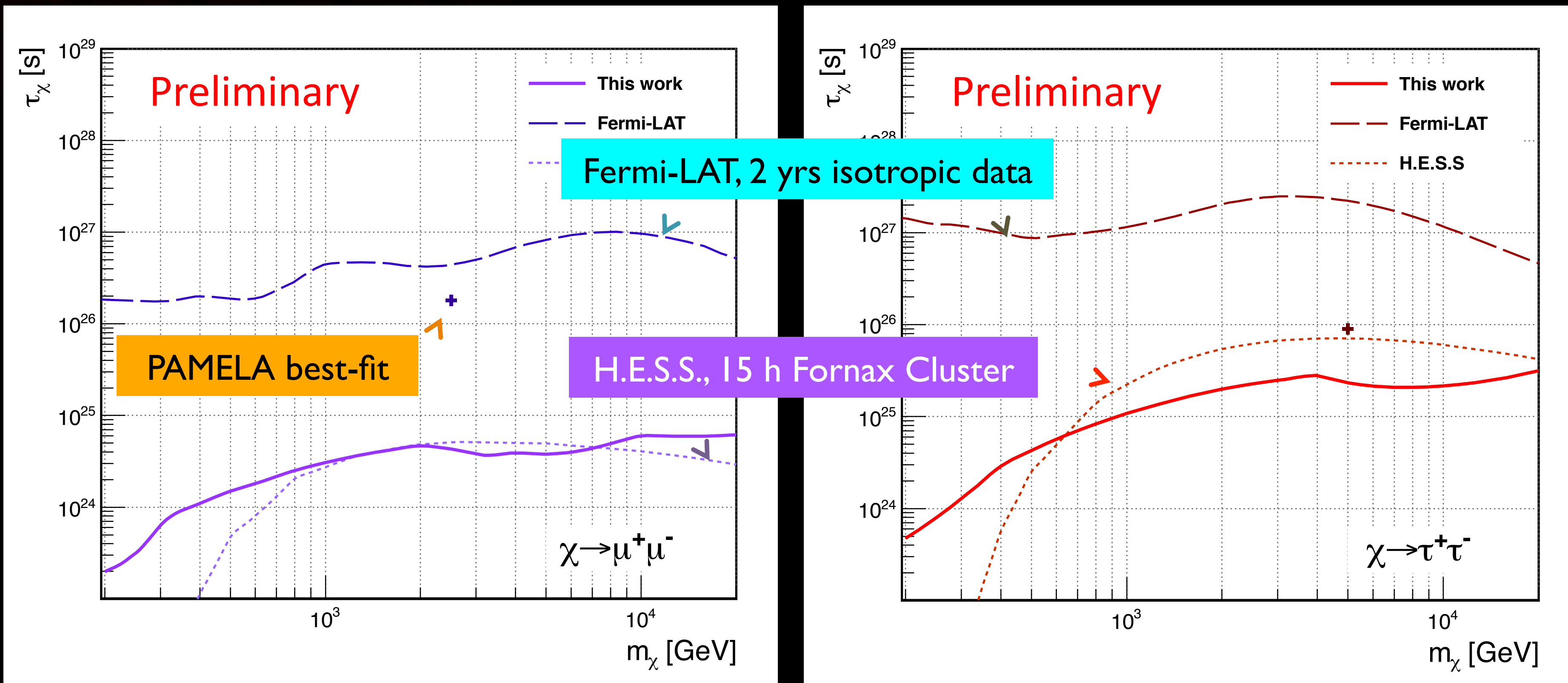




Strongest limit above 300 GeV from dSphs

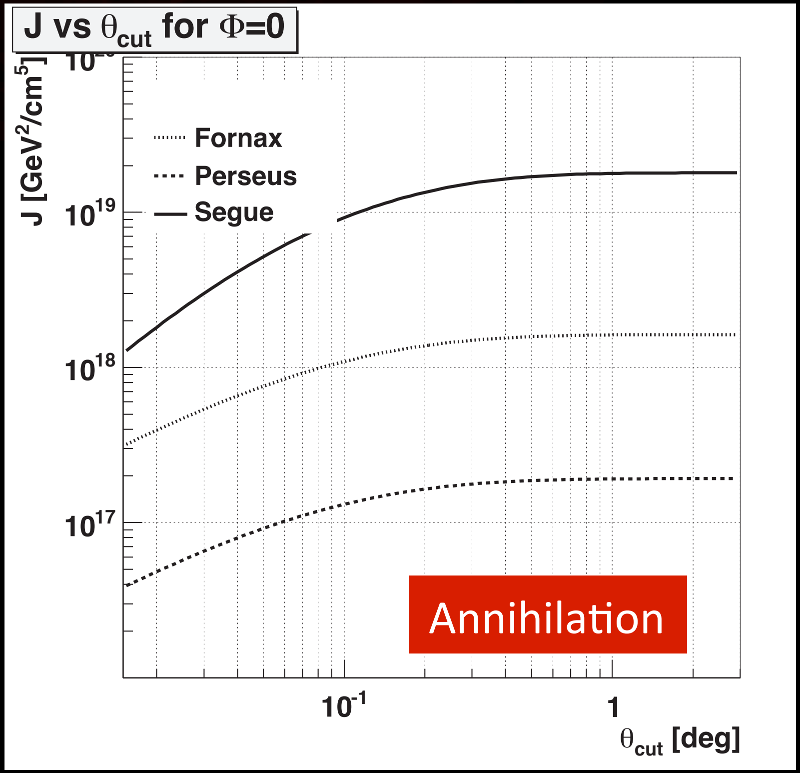
Strongest limit above 550 GeV from dSphs

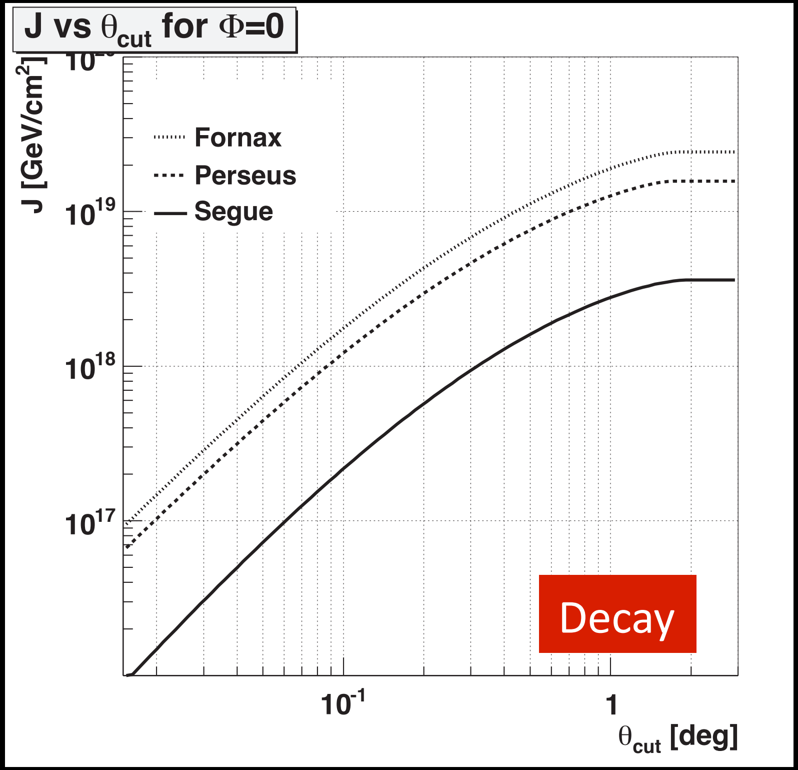
Decay: $\chi \rightarrow \mu^+\mu^-$ & $\chi \rightarrow \tau^+\tau^-$



For decaying DM galaxy clusters are in general better targets: large amounts of DM although less concentrated in average play role since J~ρ

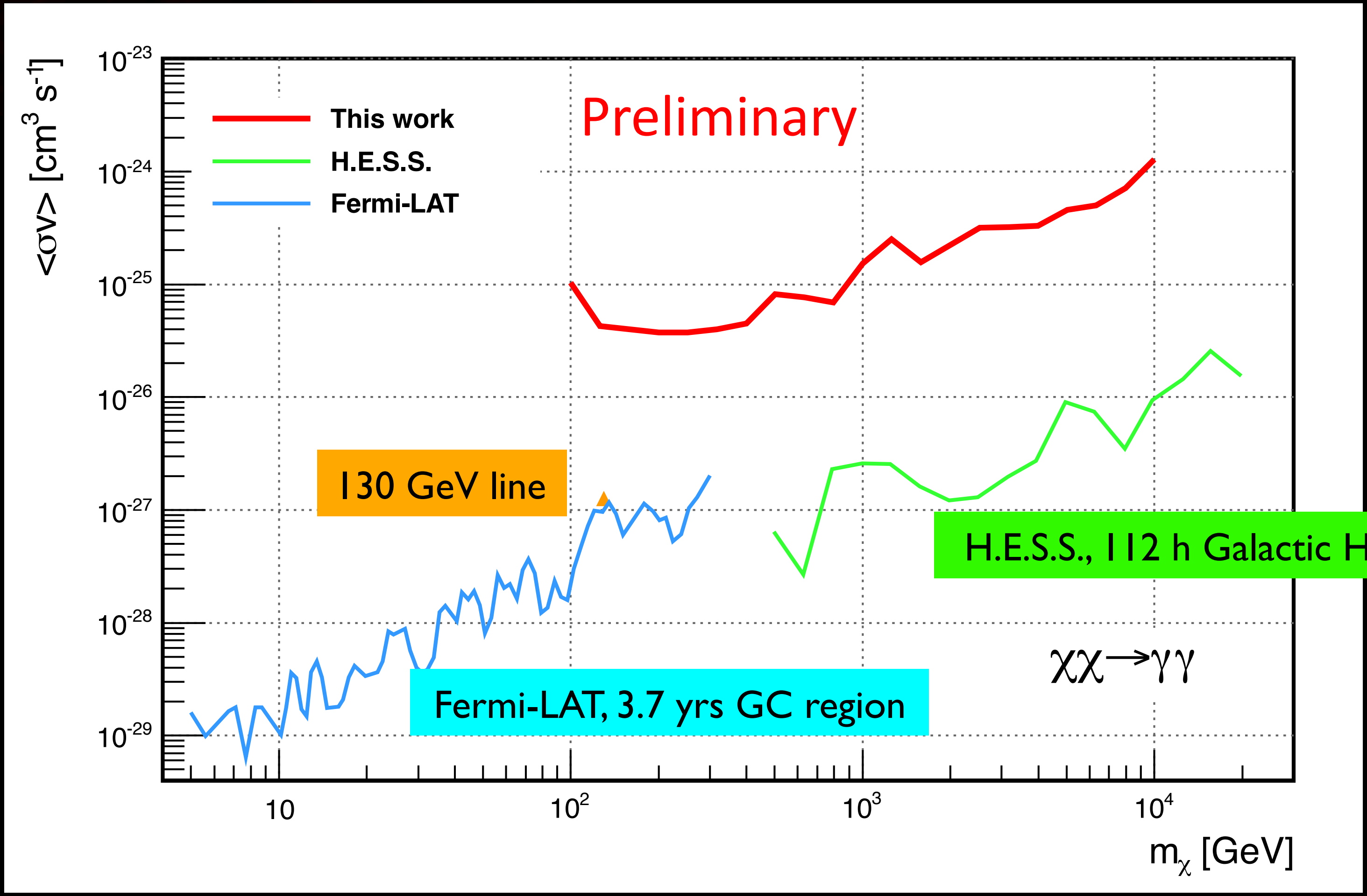
Optimal targets for DM decay searches





While J factors for annihilation are in general higher for dSph than for galaxy clusters (no substructure considered), the situation is inverted for decaying DM, since clusters have much more DM (although less concentrated)

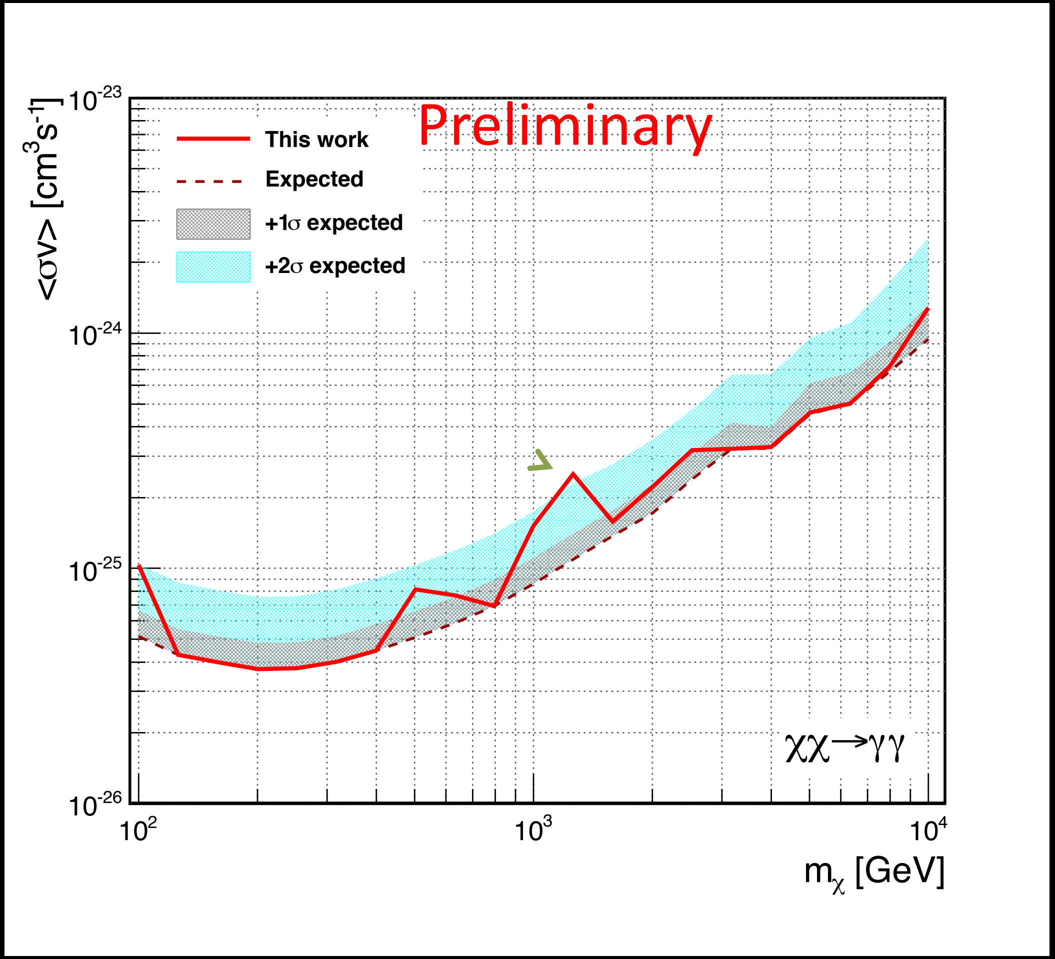
Monochromatic Line (annihilation)



Monochromatic Line (annihilation)

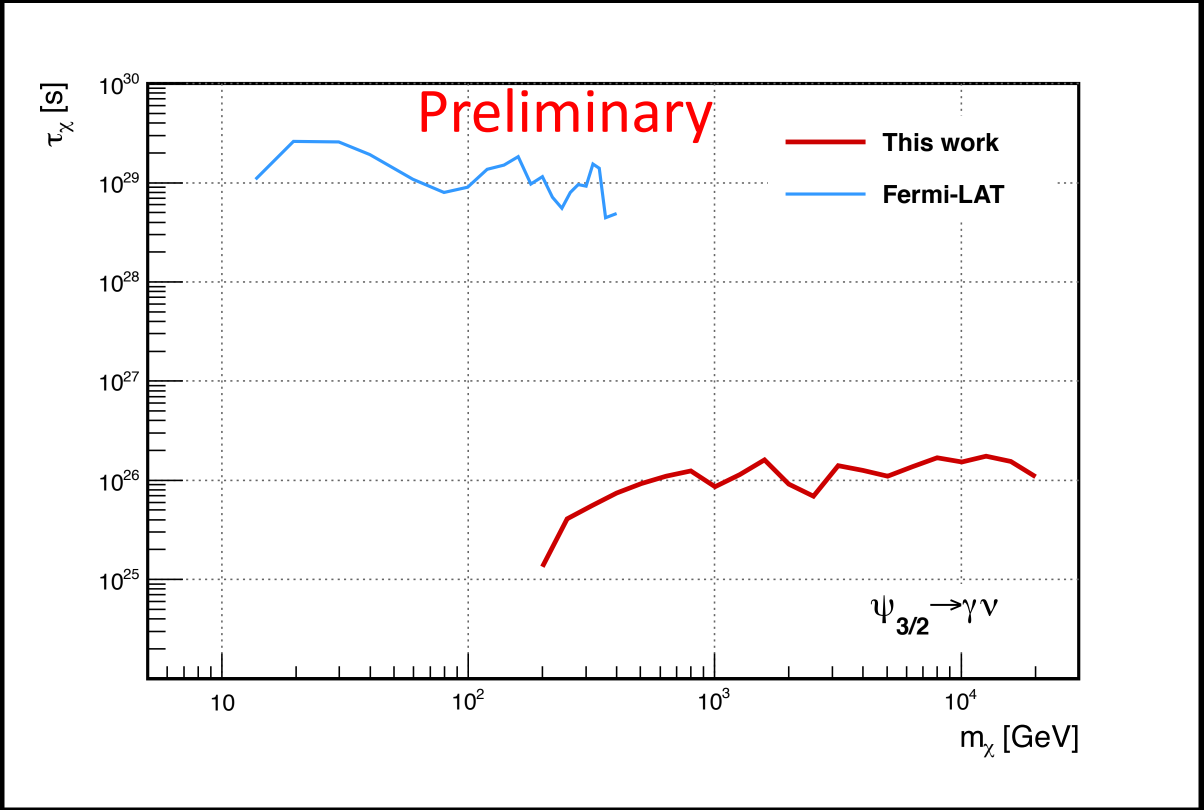
- Maximum deviation from null-hypothesis expectation:

  ~2σ (no trial correction) for m_χ ~1.3 TeV

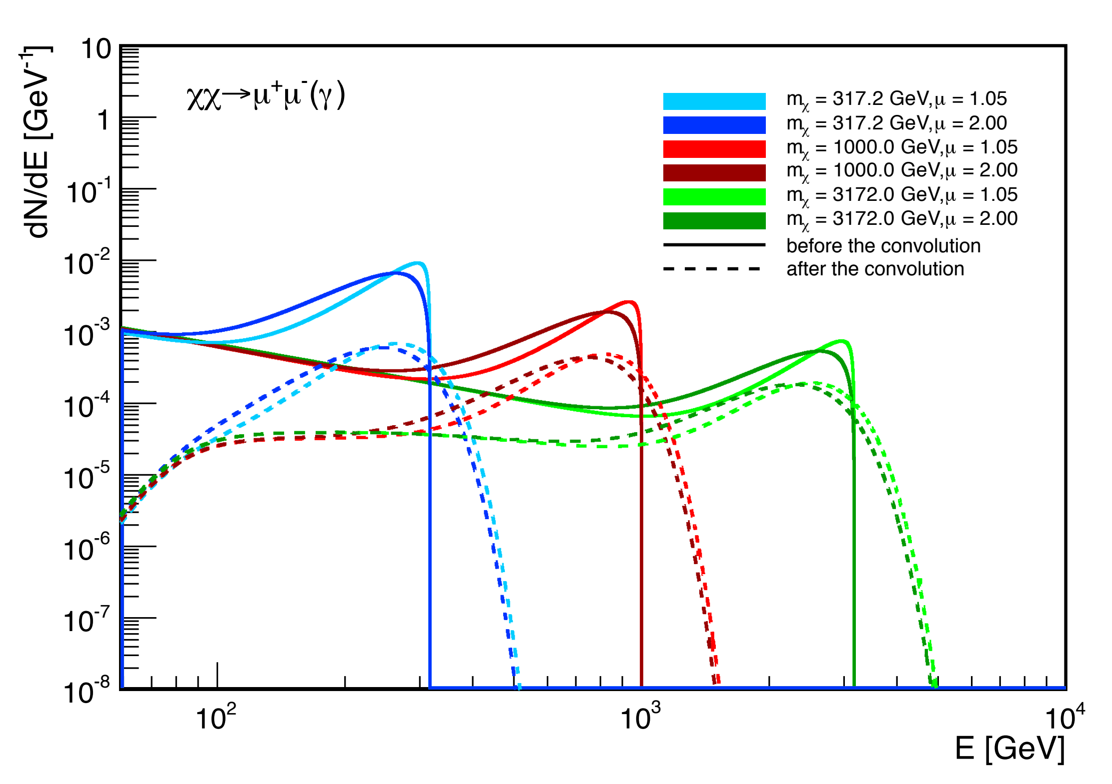


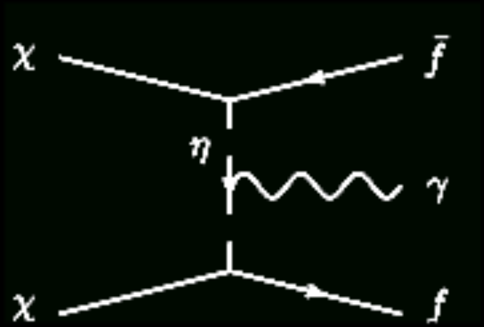
Monochromatic Line (decay)

- ★ Only existing limits (to our knowledge) above m_χ ~500 GeV
- ★ Results from GC halo not very constraining due to the signal & background regions contain almost as much DM-induced γ-ray flux
- ★ Factor ~10 could be gained by going for clusters (also extended but not that much)



Virtual Internal Bremsstrahlung



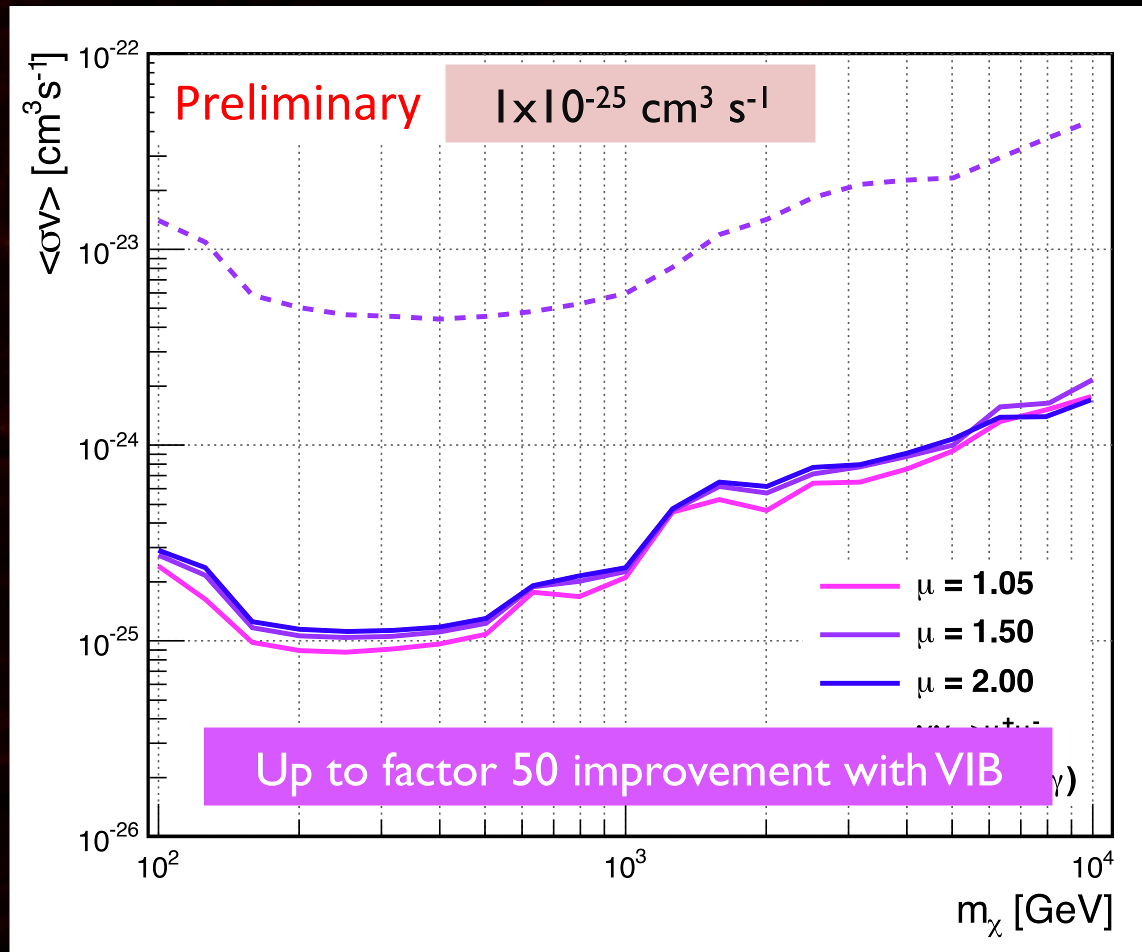


- ★ Mass splitting parameter μ :

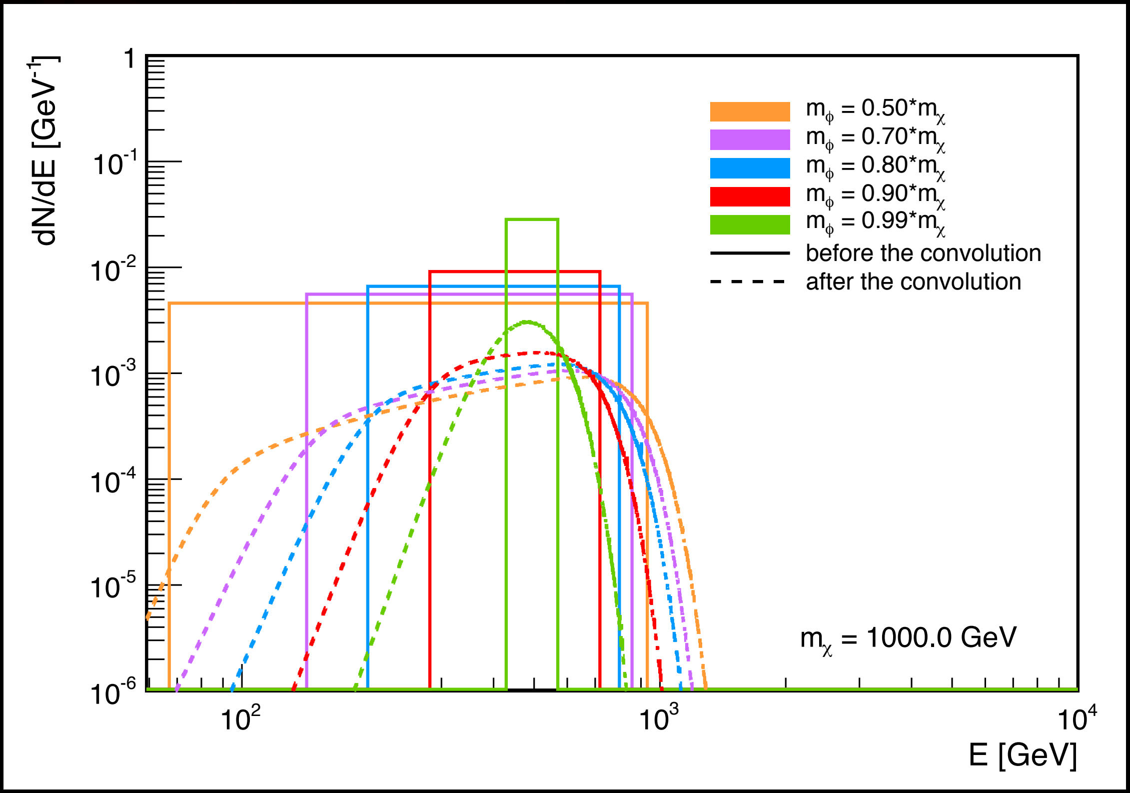
$$\mu = (m_\eta / m_\chi)^2$$

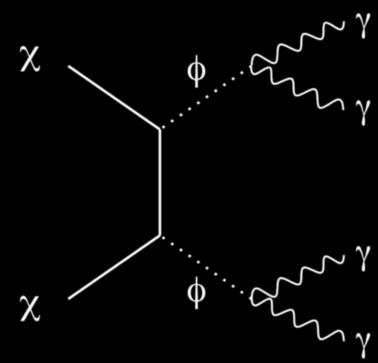
- ★ Degenerate μ values
- ★ Extended spectrum; softened peak

Virtual Internal Bremsstrahlung



Gamma-ray Boxes



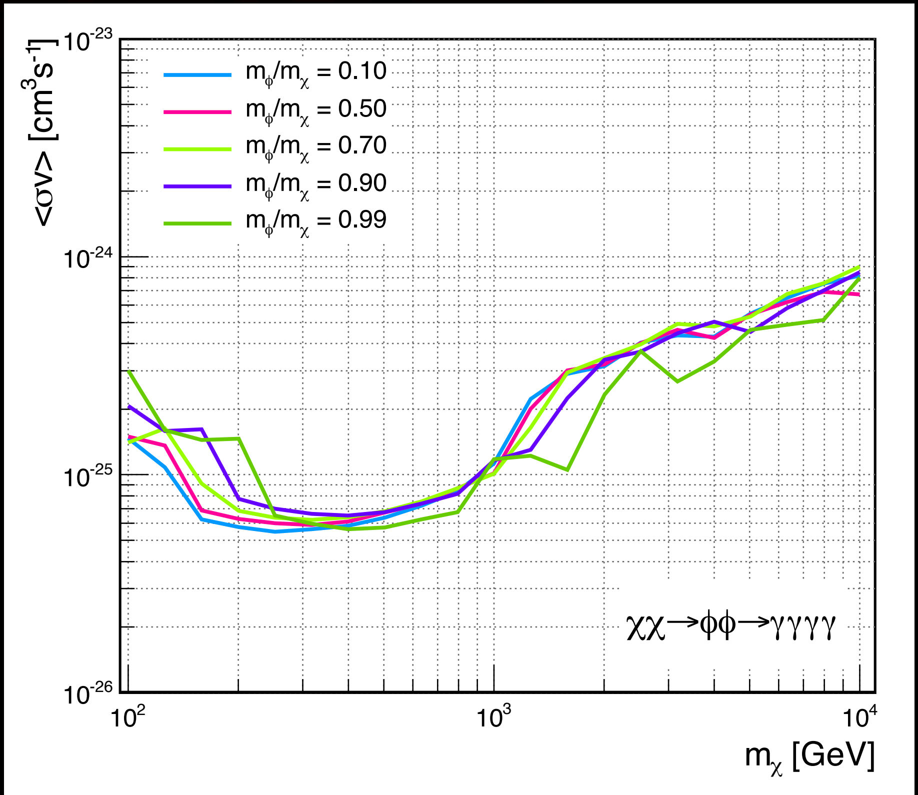


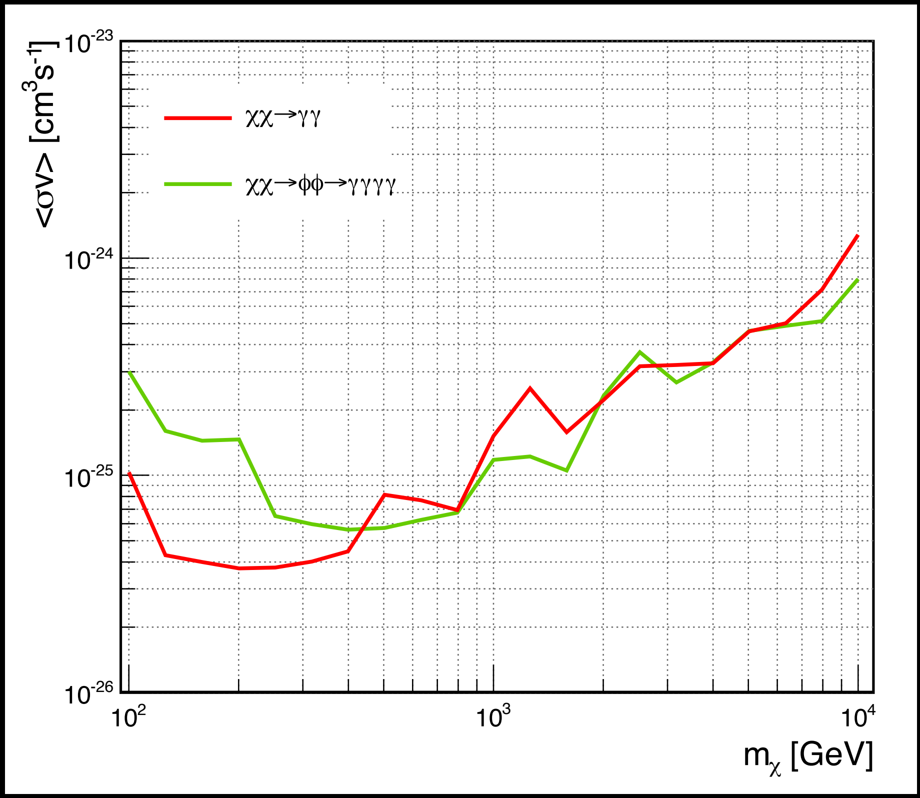
center $E_c = m_\chi / 2$

width $\sqrt{m_\chi^2 - m_\phi^2}$

- ★ Spectra extended, dimmer, edges smoothed after the convolution

Gamma-ray Boxes





6×10^{-26} cm^3 s^{-1}

Significance comparable to the line

How to go beyond?

✧ With MAGIC 1 order of magnitude improvement wrt mono was possible thanks to:

2 better sensitivity of stereo (1)
× $\sqrt{5}$ times from observation time (2)
× ~2 from full likelihood (3)

✧ In the future:

(1) Will be improved factor ~5-10 by CTA (earlier contributions expected from HESS2)

(2) Not much can be done at least by MAGIC standalone (or other single installation)

(3) Not obvious how to go much further

How to go beyond? A proposal

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

$$\mathcal{L}_T(M(\theta)) = \prod_{i=1}^{N_{\rm inst}} \mathcal{L}_i(M(\theta))$$

✧ 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

Conclusions

- ★ 157.9 h of Segue 1 observations with MAGIC: deepest ever survey of any dSph with any IACT
- ★ Complex combined analysis (different configurations)
- ★ Dedicated analysis, optimized for spectra with features
- ★ Strongest limits on various models of dark matter annihilation/decay from dSph with IACT
- ★ Above certain m_χ, strongest limits from dSphs
- ★ We are willing to collaborate in a global DM search with other gamma-ray telescopes to maximize chances of discovering or of setting the most stringent limits attainable by this kind of observations, placing a new landmark in the field.