Global Dark Matter limits from a combined analysis of MAGIC and Fermi-LAT data

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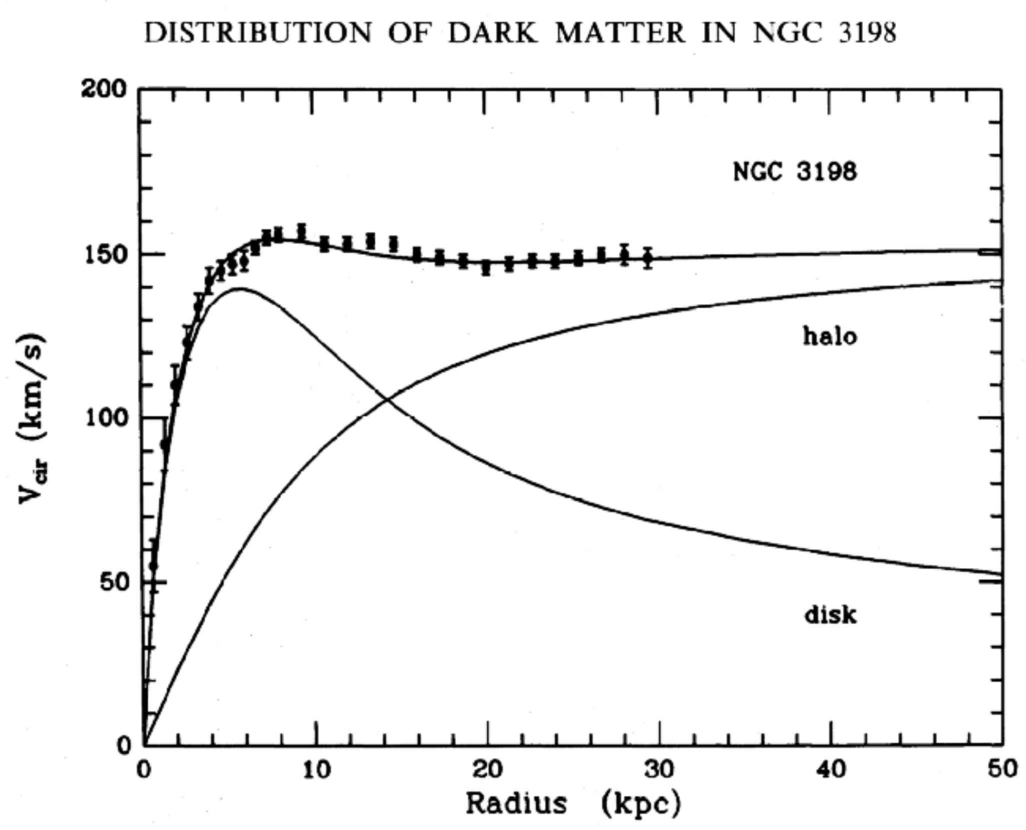
Outline

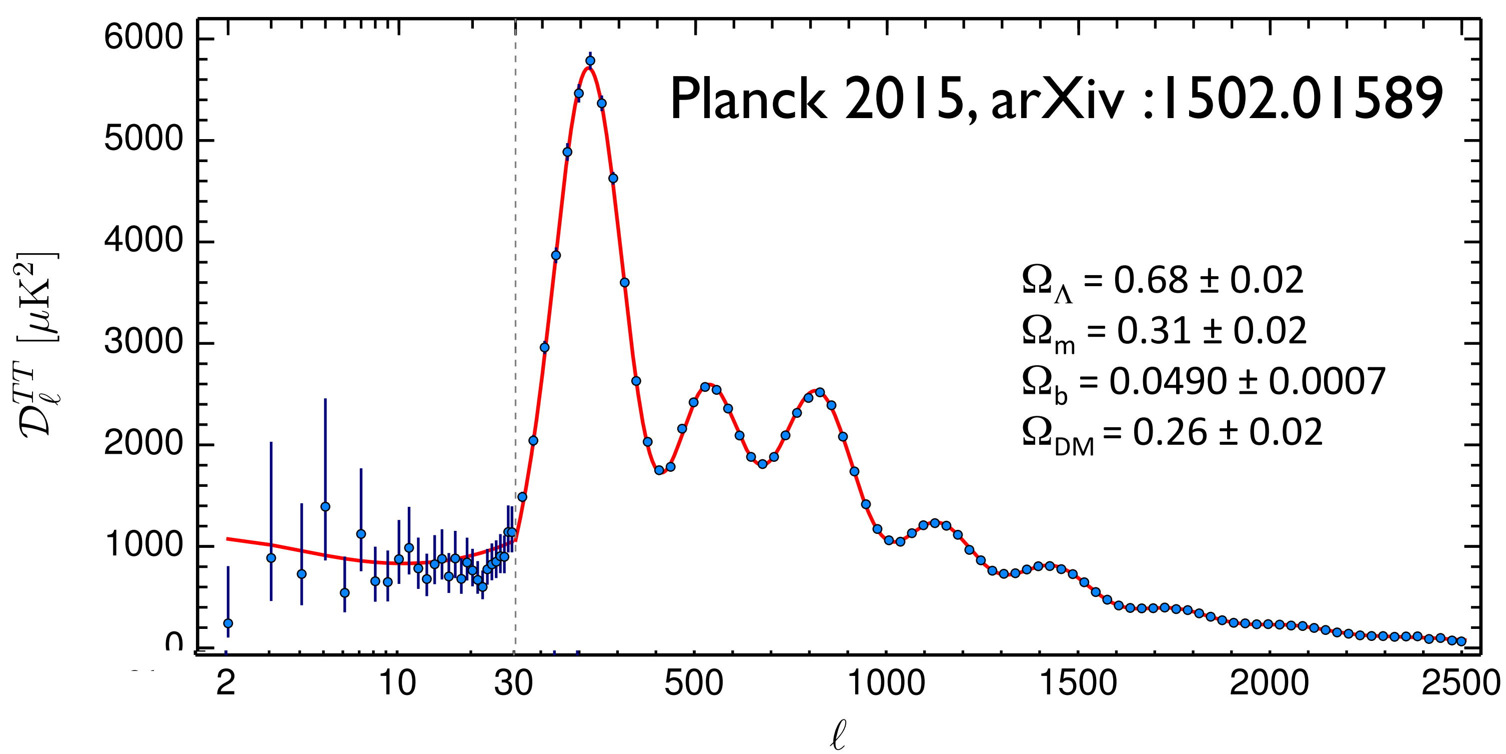
- Dark matter
- Instruments and data samples
  - MAGIC
  - Fermi-LAT
- Analysis
- Results
- Discussion/Conclusions

Dark Matter

- **Dark Matter**:
  - ~85% of matter content in the Universe
  - Interacts gravitationally at all scales
  - Left its imprint in the CMB

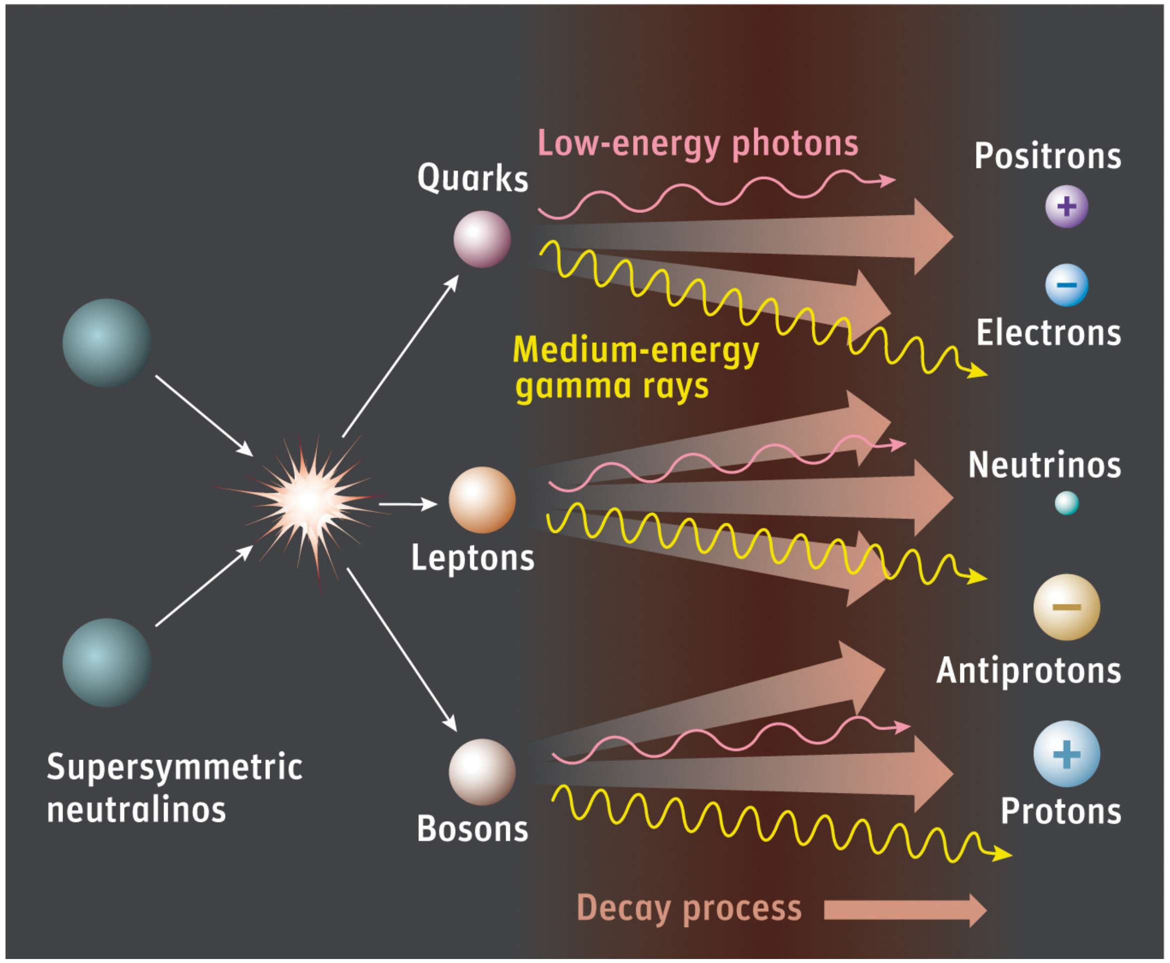


- **Possible candidates: WIMPS**
  - Mass range between ~10 GeV and ~10 TeV
  - Can produce correct relic density for interaction cross section typical of weak scale
  - Predicted by many SM extensions (e.g. SUSY)



Indirect dark matter searches

- Search for SM products of annihilation or decay of DM particles
- Allow exploration of the unique spectral features of DM-processes (e.g. lines, IB peaks, kinematical cut-offs…)
- For neutral particles (neutrino, gamma), messengers points back to DM sites



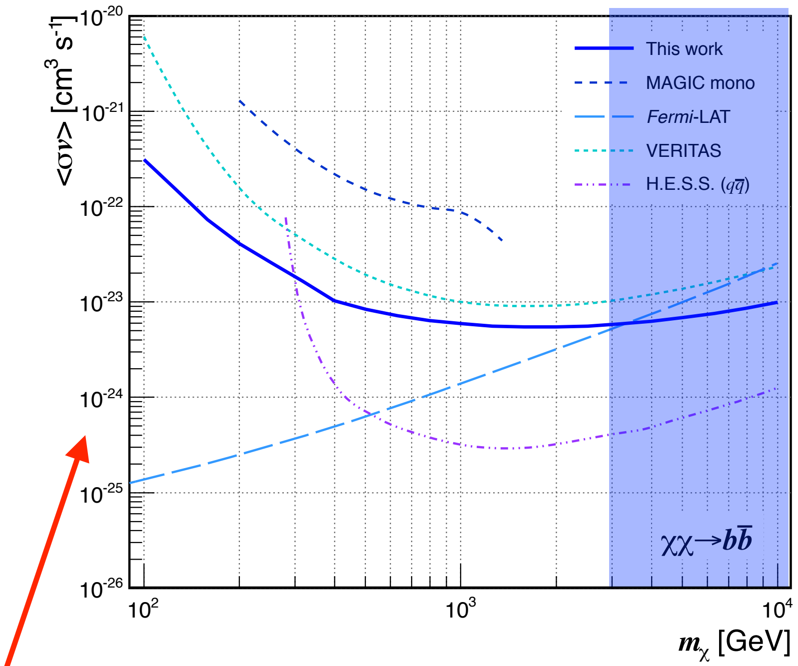
Indirect searches needed to confirm signals in direct or accelerator searches are THE dark matter

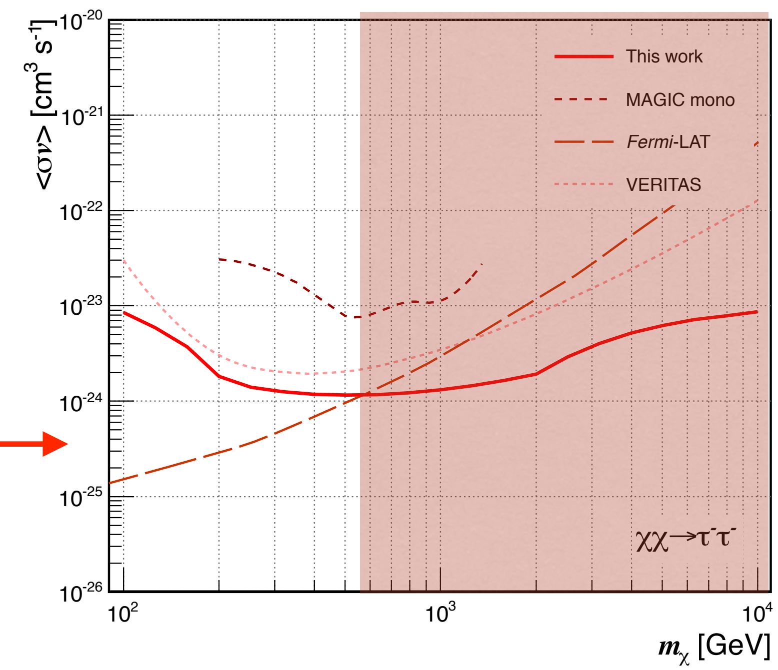
The MAGIC Telescopes

- Collaboration of ~160 scientists from Germany, Spain, Italy, Switzerland, Finland, Croatia, Bulgaria, Poland, India & Japan
- 2-telescope system (MAGIC-1 2004, MAGIC-2 2009)
- 17m diameter reflectors ➜ 50 GeV energy threshold, up to ~10 TeV
- Angular resolution 0.1°; Energy resolution ~15-25%
- Pointed observations: ~0.1-0.2° aperture

DM searches with MAGIC

- ★ MAGIC indirect dark matter searches:
  - Galactic Center:
    - (17 h) ApJ Lett. 638 (2006) L101
  - Perseus Galaxy Cluster
    - (25 h) ApJ 710 (2010) 634
    - (~300 h) In preparation (decay)
  - Dwarf Galaxies:
    - Draco (8 h): ApJ 679 (2008) 428
    - Willman 1 (16 h): ApJ 697 (2009) 1299
    - Segue 1 (30 h): JCAP 06 (2011) 035
    - **Segue 1 (160 h): JCAP 002 (2014) 008**
  - Subhalos
    - (~15 h): In preparation

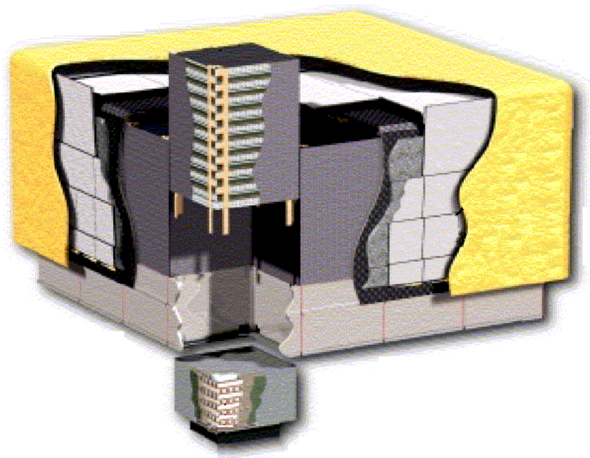




Best limits from dwarfs in high mass range!

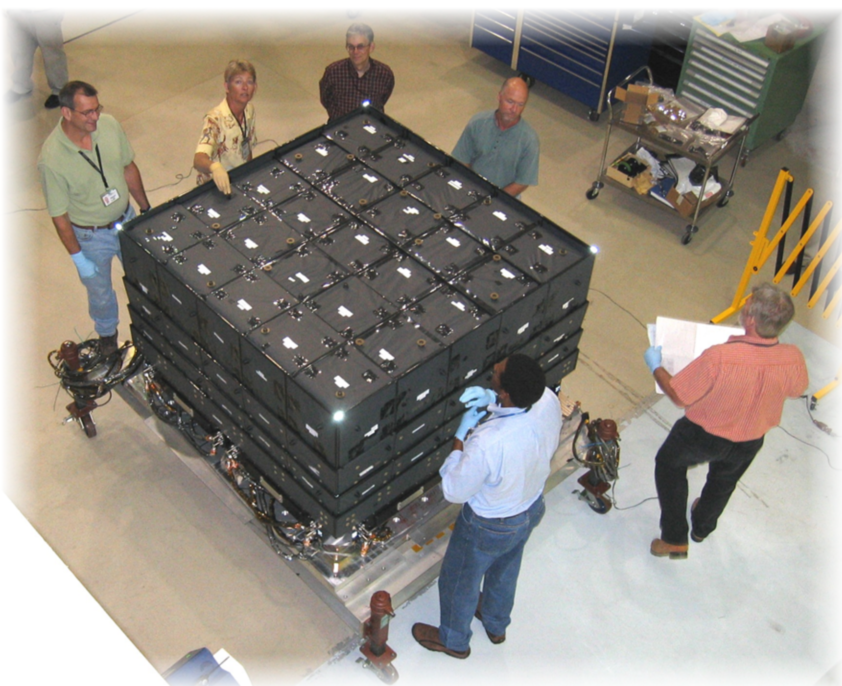
Fermi Large Area Telescope

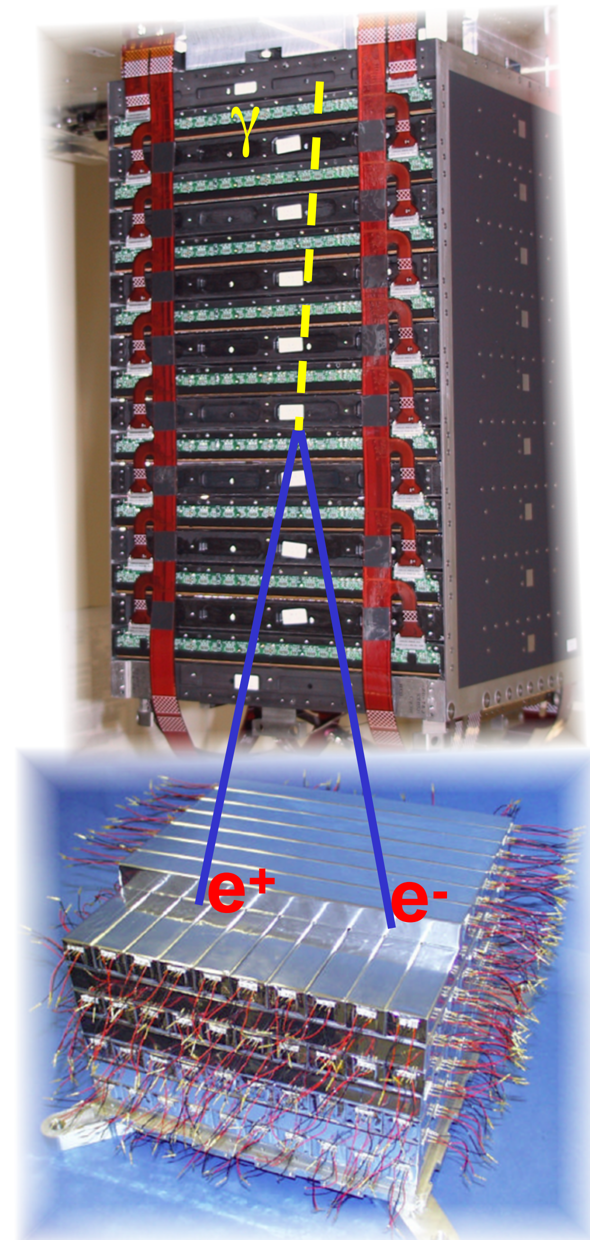
Atwood, W. B. et al. 2009, ApJ, 697, 1071



Large Area Telescope (LAT)
- Launched June 2008 with Fermi Observatory
- Modular - 4x4 array
- 3ton – 650watts

Anti-Coincidence Detector (ACD)
- Charged particle rejection
- Segmented (89 tiles + 8 ribbons)





Tracker (TKR)
- Convert gamma rays to e^+/e^- pairs
- Use particle tracks to reconstruct gamma-ray direction
- Si-strip detectors with Tungsten conversion foils ($1.5\ X_0$ on-axis)

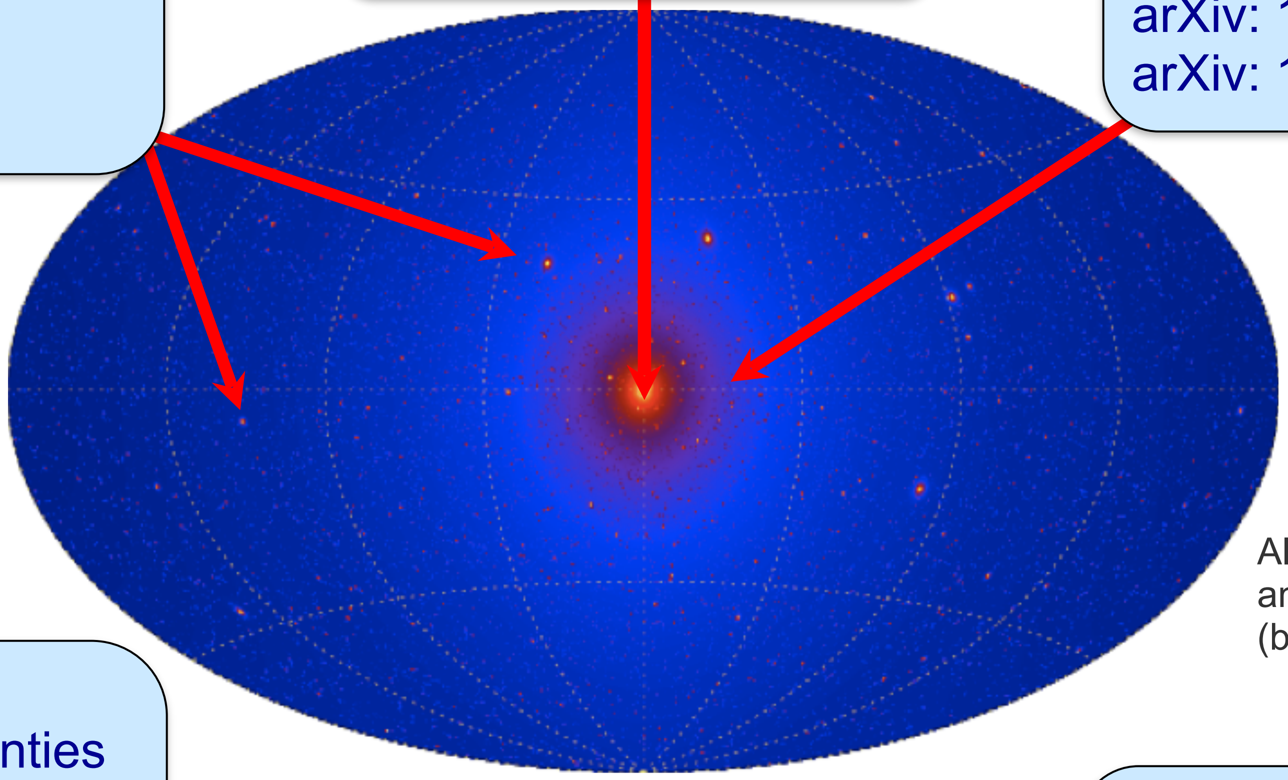
Calorimeter (CAL)
- Measure gamma-ray energy
- 1536 CsI(Tl) crystals ($8.6\ X_0$ on-axis)
- Use shower shape for EM vs HAD separation

DM searches with Fermi-LAT

Satellites
Low astrophysical background but low statistics
arXiv: 1310.0828
arXiv: 1405.1030
arXiv: 1503.02641
arXiv: 1503.02632

Galactic Center
Good statistics but source confusion/diffuse background

Milky Way Halo
Large statistics but diffuse background
arXiv: 1205.6474
arXiv: 1503.07169



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

Spectral Lines
No astrophysical uncertainties but low sensitivity due to small expected BR
arXiv: 1305.5597
arXiv: 1406.3430
arXiv: 1506.00013

Galaxy Clusters
Low background but low statistics
arXiv: 1002.2239

Extragalactic
Large statistics but astrophysics, galactic diffuse background
arXiv:1501.05464

Analysis

- In *all* DM searches, we try to measure the same *universal parameter*, e.g. $\langle\sigma v\rangle$ through gamma-ray flux:

$$\frac{d\Phi}{dE}(\Delta\Omega) = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle\, J(\Delta\Omega)}{2m_{\mathrm{DM}}^2}\,\frac{dN}{dE}$$

- Different observations of different targets differ in the astrophysical or J-factor

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} dl\, \rho^2(l,\Omega)$$

- Aim: combine measurements of $\langle\sigma v\rangle$ from different targets and instruments

Some technical details

- As a first step we have combined MAGIC with Fermi-LAT results, using published data:
  - MAGIC: Segue 1 stereo, 158 hours [Aleksić et al. JCAP 02 (2014) 008]
  - Fermi-LAT: 15 dwarfs, 6 years, pass 8 [Ackerman et al. arXiv:1503.02641]
- Mass range from 10 GeV to 100 TeV
- Annihilation channels: $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, W^+W^-
- J-factors following Martinez [arXiv:1309.2641] (Fermi-LAT approach)
- Annihilation spectra from 10^7 simulations of a 2-body decay of generic resonance with $m=2m_{DM}$ using PYTHIA 8.205
- Ultimate goal: merge ALL results from observations from dwarf satellite galaxies

Likelihood Analysis

- For each channel and mass, compute the profile likelihood ratio:

$$\lambda_P(\langle\sigma v\rangle\,|\,\boldsymbol{\mathcal{D}}) \equiv \frac{\mathcal{L}(\langle\sigma v\rangle;\hat{\hat{\boldsymbol{\nu}}}\,|\,\boldsymbol{\mathcal{D}})}{\mathcal{L}(\widehat{\langle\sigma v\rangle};\hat{\boldsymbol{\nu}}\,|\,\boldsymbol{\mathcal{D}})}$$

where the likelihood is:

$$\mathcal{L}(\langle\sigma v\rangle;\boldsymbol{\nu}\,|\,\boldsymbol{\mathcal{D}}) = \prod_{i=1}^{N_{\rm target}} \mathcal{L}_i(\langle\sigma v\rangle;J_i,\boldsymbol{\mu}_i\,|\,\boldsymbol{\mathcal{D}}_i)\cdot\mathcal{J}(J_i\,|\,J_{{\rm obs},i},\sigma_i)$$

The J-factor is treated as nuisance parameter with

$$\mathcal{J}(J\,|\,J_{\rm obs},\sigma) = \frac{1}{\ln(10)J_{\rm obs}\sqrt{2\pi}\sigma}\times e^{-\left(\log_{10}(J)-\log_{10}(J_{\rm obs})\right)^2/2\sigma^2}$$

(Gaussian in $\log_{10}$J normalized wrt J)

And, for each target:

$$\mathcal{L}_i(\langle\sigma v\rangle;J_i,\boldsymbol{\mu}_i\,|\,\boldsymbol{\mathcal{D}}_i) = \prod_{j=1}^{N_{\rm instrument}} \mathcal{L}_{ij}(\langle\sigma v\rangle;J_i,\boldsymbol{\mu}_{ij}\,|\,\boldsymbol{\mathcal{D}}_{ij})$$

Fermi-LAT likelihood

- For each dwarf, the contribution of Fermi-LAT measurements to the total likelihood is given by:

$$\mathcal{L}_{iF}(\langle \sigma v \rangle; J_i, \hat{\boldsymbol{\mu}}_{iF} \,|\, \boldsymbol{\mathcal{D}}_{iF}) = \prod_{k=1}^{N_{\mathrm{E-bins}}} \mathcal{L}_{iFk}\left(\overline{E\Phi}_k(\langle \sigma v \rangle, J_i)\right)$$

with

$$\overline{E\Phi}_k(\langle \sigma v \rangle, J_i) = \int_{E_{\min,k}}^{E_{\max,k}} dE\, E\, \frac{d\Phi}{dE}(\langle \sigma v \rangle, J_i)$$

(Energy flux within a given energy bin)

the values the likelihood vs. $\overline{E\Phi}_k$ are tabulated and released publicly by Fermi-LAT (e.g. http://www-glast.stanford.edu/pub_data/713/)

MAGIC likelihood

- For MAGIC we have different Segue 1 samples:

$$\mathcal{L}_{iM}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{iM} \,|\, \boldsymbol{\mathcal{D}}_{iM}) = \prod_{k=1}^{N_{\rm samples}} \mathcal{L}_{iMk}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{iMk} \,|\, \boldsymbol{\mathcal{D}}_{iMk})$$

each sample contribution to the likelihood is given by

$$\mathcal{L}(\langle\sigma v\rangle; J, \boldsymbol{\mu} \,|\, \boldsymbol{\mathcal{D}}) = \mathcal{L}\big(g(\langle\sigma v\rangle, J,); b, \tau \,|\, \{E'_l\}_{l=1,\ldots,N_{\rm ON}}, \{E'_m\}_{m=1,\ldots,N_{\rm OFF}}\big)$$

$$= \frac{(g+b/\tau)^{N_{\rm ON}}}{N_{\rm ON}!} e^{-(g+b/\tau)} \frac{b^{N_{\rm OFF}}}{N_{\rm OFF}!} e^{-b} \prod_{l=1}^{N_{\rm ON}} f(E'_l \,|\, g; b, \tau) \prod_{m=1}^{N_{\rm OFF}} h(E'_m \,|\, b)$$

Poisson ON | Poisson OFF | ON E' PDF | OFF E' PDF

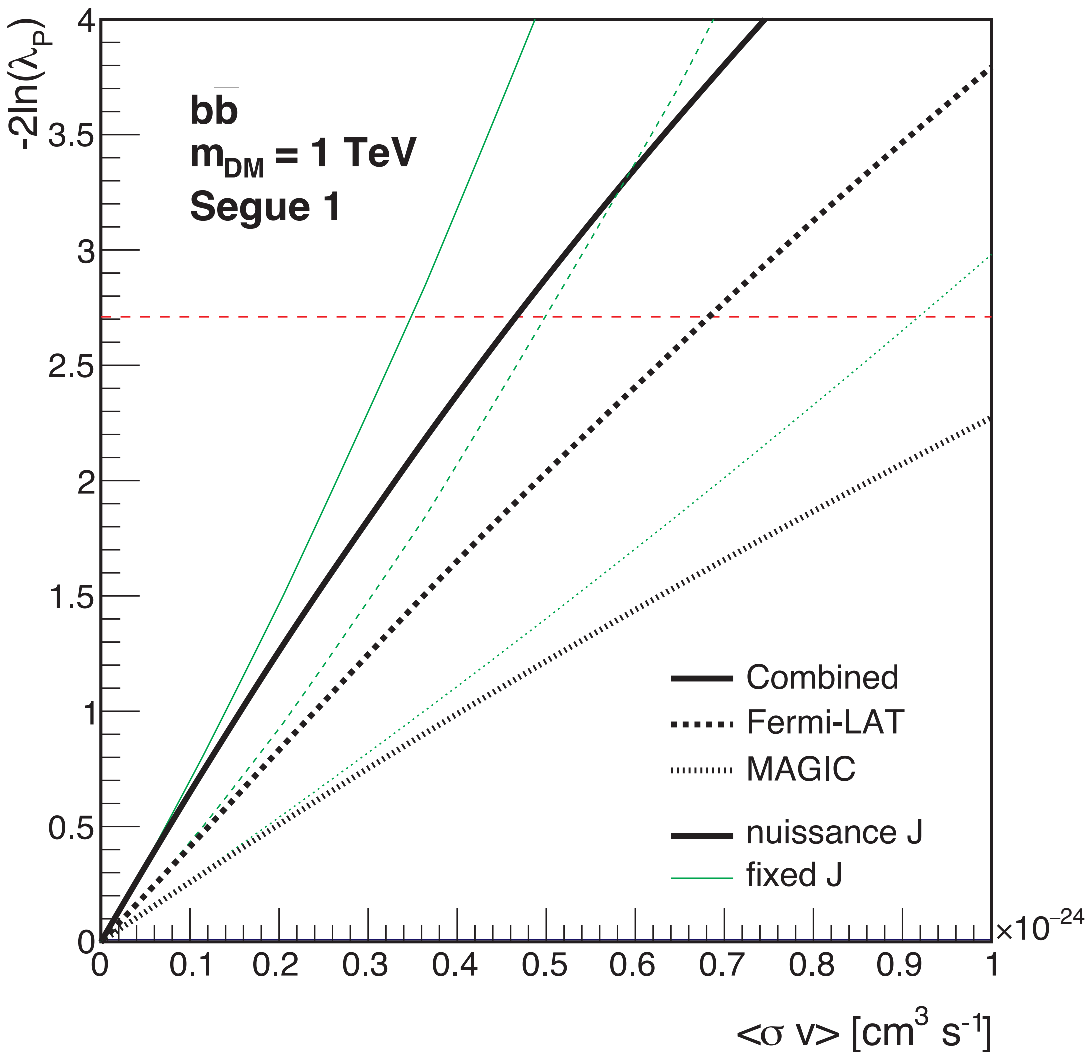
(a.k.a. Full Likelihood: Aleksić, Rico & Martinez JCAP 10 (2012) 032)

Results

- 1-sided 95% CL upper limits to <σv> computed by solving:

$$-2\ln\lambda_P(\langle\sigma v\rangle \,|\, \boldsymbol{\mathcal{D}}) = 2.71,$$

- Only positive <σv> are considered (Fermi-LAT prescription)



- 1- and 2-σ bands are computed from 300 fast-simulated MAGIC samples + 300 Fermi empty FoVs J-factors also randomized

Dark matter global limits

Left

Fermi-LAT: 15 dwarfs

MAGIC: Segue 1

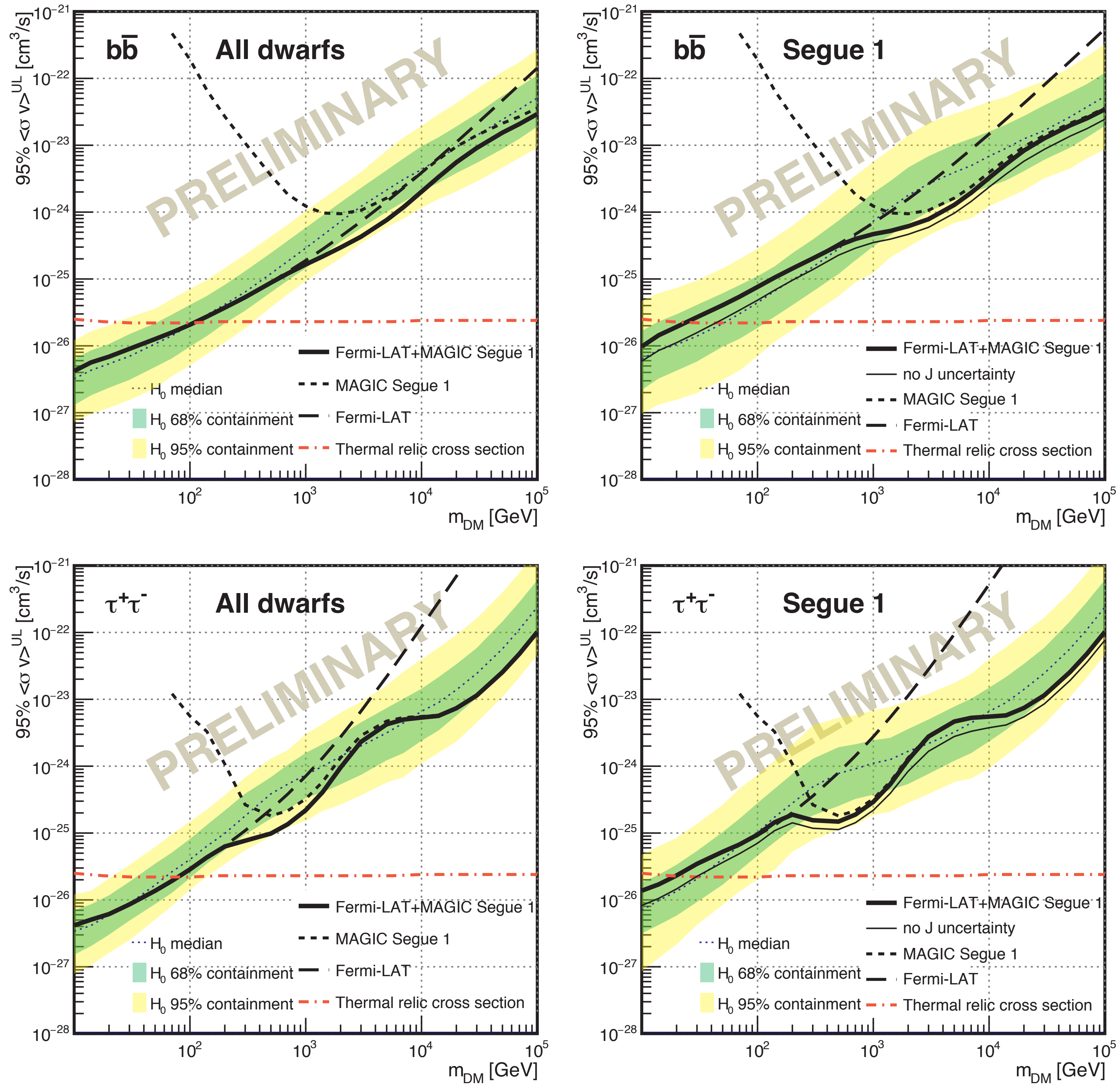
Right

Fermi-LAT: Segue1

MAGIC: Segue1

- Fermi-LAT+MAGIC Segue 1
- no J uncertainty
- MAGIC Segue 1
- Fermi-LAT
- Thermal relic cross section

- H_0 median
- H_0 68% containment
- H_0 95% containment



Discussion/Conclusions

- First time a coherent analysis for DM mass from 10 GeV to 100 TeV
- No DM signal found
- Best limits in the explored region from dwarfs
- Low- (High-)mass range dominated by Fermi (MAGIC)
- In the range of similar sensitivity, improvement of limits by a factor up to ~2 wrt single instrument
- The method is completely generic and can easily incorporate measurements from other instruments sensitive to similar mass range (VERITAS, HESS, HAWC, maybe also neutrino telescopes like IceCube, Antares,…)
- We hereby invite colleagues from these collaborations to this cooperative effort

Astrophysics and particle physics

- ★ J-factors for 15 dwarf galaxies following Martinez [arXiv: 1309.2641] (Fermi-LAT approach)
- ★ Annihilation spectra from 10^7 simulations of a 2-body decay of generic resonance with $m=2m_{DM}$ using PYTHIA 8.205

Name	l [deg]	b [deg]	Distance [kpc]	$\log_{10}(J_{obs})$ [$\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5})$]
Bootes I	358.1	69.6	66	18.8 ± 0.22
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Carina	260.1	22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Sculptor	287.5	83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
				* 19.3 ± 0.29
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31

MAGIC likelihood

★ For MAGIC we have different Segue 1 samples:

$$\mathcal{L}_{iM}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{iM} \,|\, \boldsymbol{\mathcal{D}}_{iM}) = \prod_{k=1}^{N_{\rm samples}} \mathcal{L}_{iMk}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{iMk} \,|\, \boldsymbol{\mathcal{D}}_{iMk})$$

★ each sample contribution to the likelihood is given by

$$\mathcal{L}(\langle\sigma v\rangle; J, \boldsymbol{\mu} \,|\, \boldsymbol{\mathcal{D}}) = \mathcal{L}\big(g(\langle\sigma v\rangle, J,); b, \tau \,|\, \{E'_l\}_{l=1,\dots,N_{\rm ON}}, \{E'_m\}_{m=1,\dots,N_{\rm OFF}}\big) \quad (3.13)$$

$$= \frac{(g+b/\tau)^{N_{\rm ON}}}{N_{\rm ON}!} e^{-(g+b/\tau)} \frac{b^{N_{\rm OFF}}}{N_{\rm OFF}!} e^{-b} \prod_{l=1}^{N_{\rm ON}} f(E'_l \,|\, g; b, \tau) \prod_{m=1}^{N_{\rm OFF}} h(E'_m \,|\, b)$$

(a.k.a. Full Likelihood)

★ with:

$$g(\langle\sigma v\rangle, J) = \int_{E'_{\rm min}}^{E'_{\rm max}} dE' \int_0^\infty dE \frac{d\Phi}{dE}(\langle\sigma v\rangle, J)\, A(E)\, G(E; E')$$

(number of gamma rays)

$$f(E' \,|\, g; b, \tau) = \frac{\frac{1}{\tau} h(E') + \frac{g}{b} p(E')}{\frac{1}{\tau} + \frac{g}{b}}$$

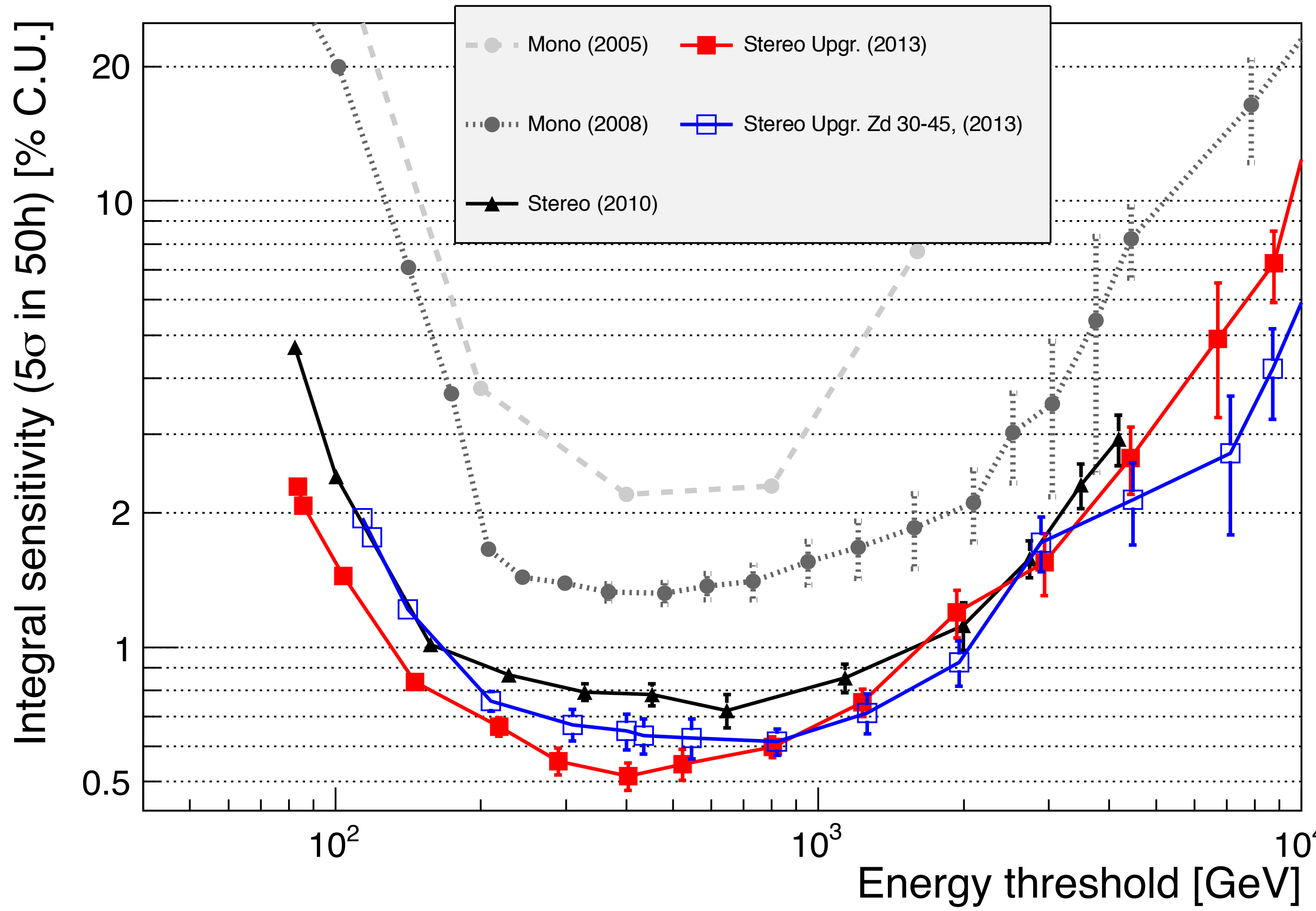
(On PDF)

$$p(E') = \frac{\int_0^\infty dE \frac{d\Phi}{dE}(\langle\sigma v\rangle, J)\, A(E)\, G(E; E')}{g}$$

(signal PDF)

MAGIC Performance

Aleksić et al. ApP (2015) in press



- ⋆ Electronics and MAGIC-1 camera upgrade during 2011 - 2012
- ⋆ Best sensitivity: 0.6% Crab Nebula in 50 hrs at E~400 GeV
- ⋆ Improved angular and energy resolutions
- ⋆ Now in a period of steady observations ruled by Key Observation Program