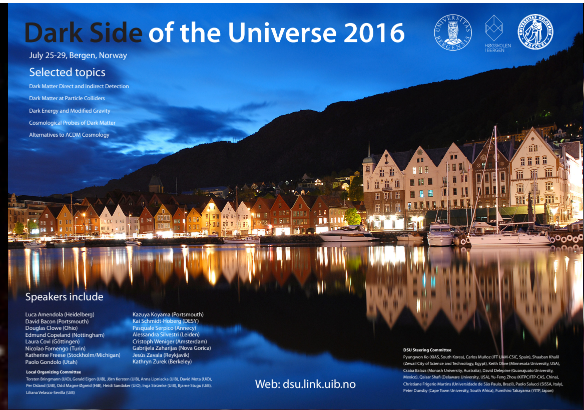


Dark Side of the Universe 2016, Bergen, 25 – 29 July 2016

Indirect Dark Matter searches with the MAGIC Telescopes

S. Lombardi, INAF-OAR & ASDC, Rome
(on behalf of the MAGIC Collaboration)

Co-authors: L.A. Antonelli, M. Doro, P. Giammaria, J. Palacio, J. Rico, M. Vázquez

Outline

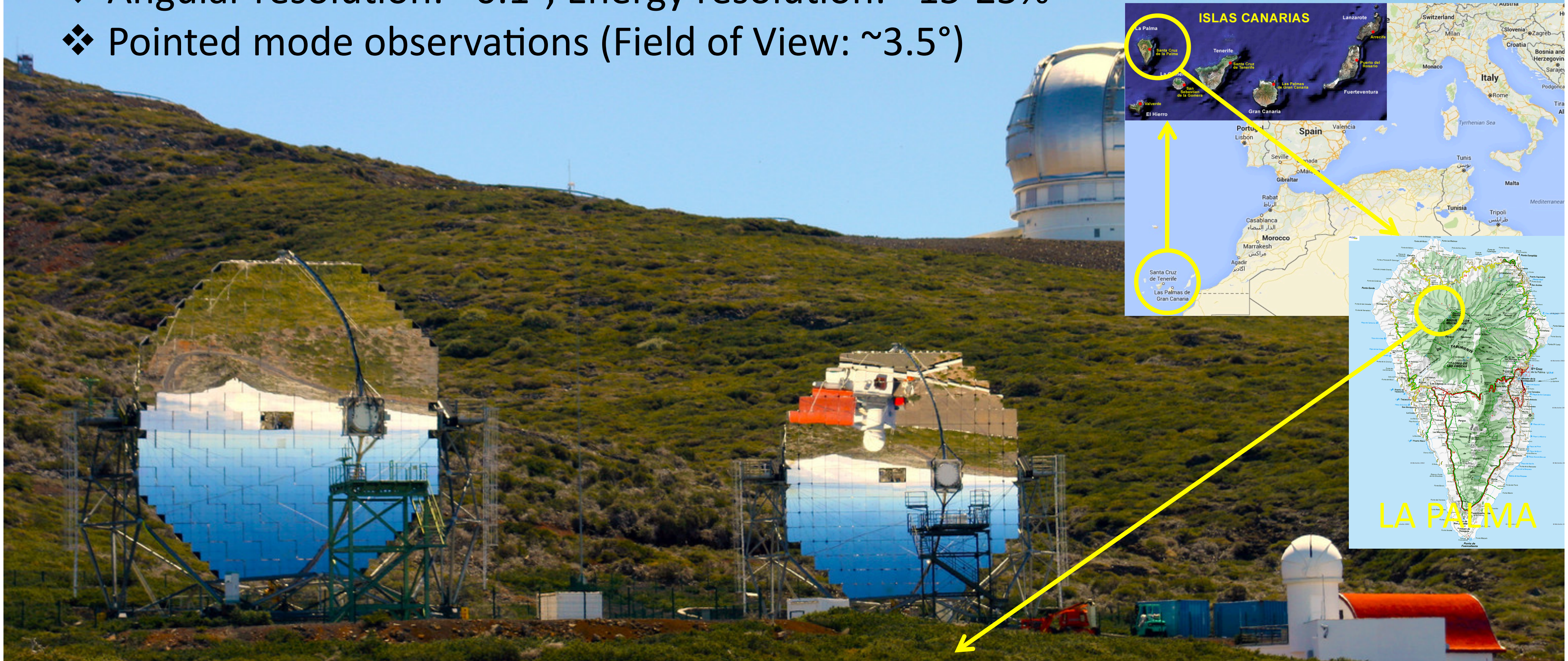
- The MAGIC Telescopes
- Indirect Dark Matter searches with MAGIC
  - MAGIC historical results
  - Recent MAGIC/Fermi-LAT combined results with dwarfs
  - Recent (preliminary) results with the Perseus Cluster
- Summary

The MAGIC Telescopes

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

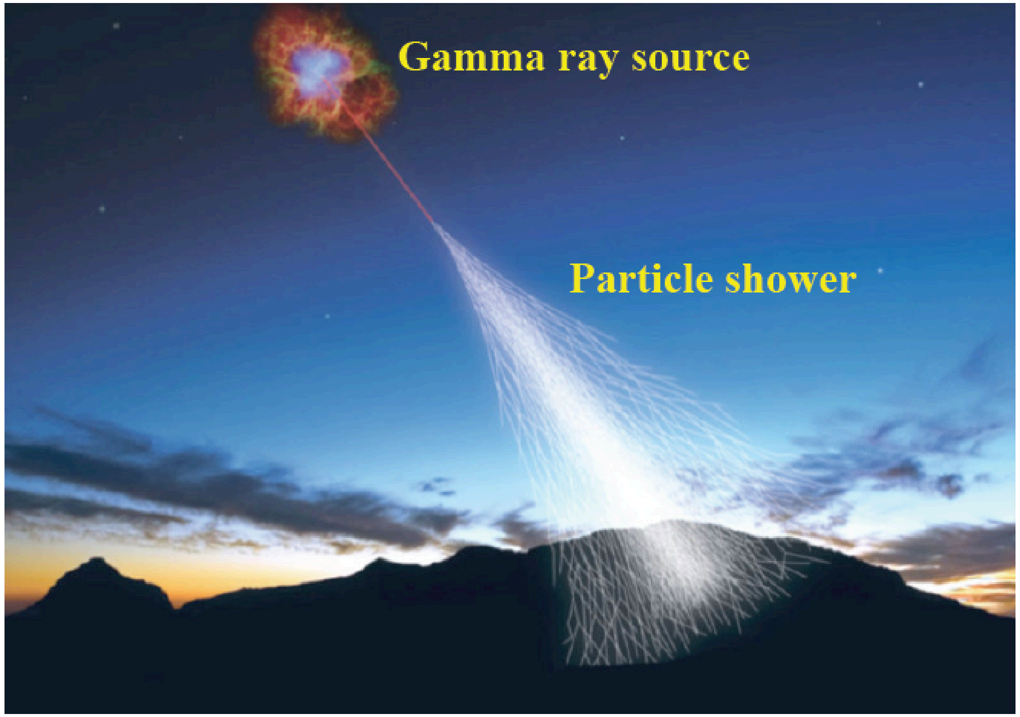
MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescope

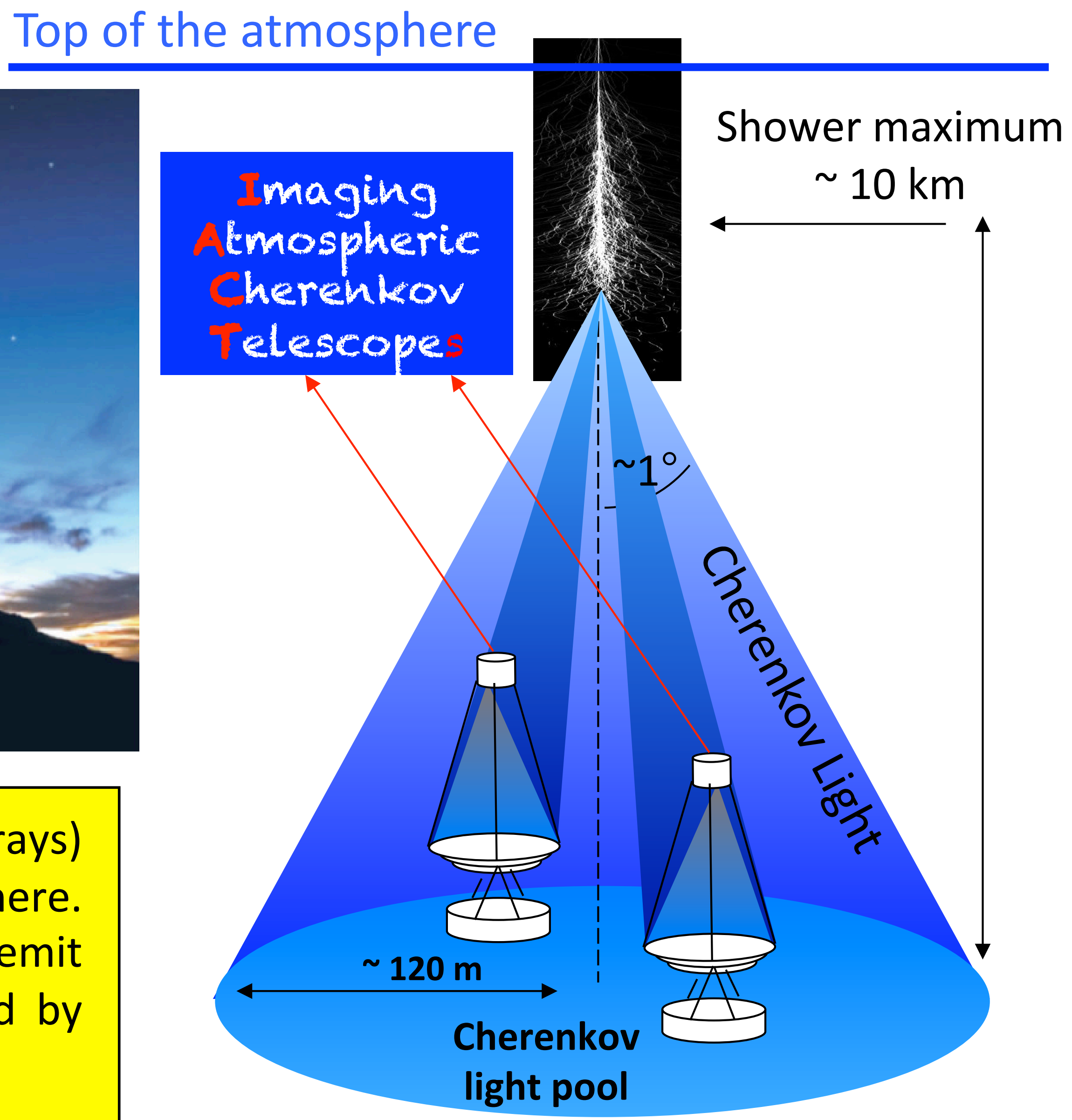
- Collaboration of ~160 scientists from Germany, Spain, Italy, Switzerland, Finland, Croatia, Bulgaria, Poland, India, and Japan
- 2 IACTs of 17m diameter each (MAGIC-I 2004, MAGIC-II 2009)
- Energy range: 50 GeV (with standard trigger) up to ~50 TeV
- Angular resolution: ~0.1°; Energy resolution: ~15-25%
- Pointed mode observations (Field of View: ~3.5°)



Astronomic Observatory of Roque de Los Muchachos (~2200 m a.s.l.), La Palma (Spain)

The MAGIC Telescopes

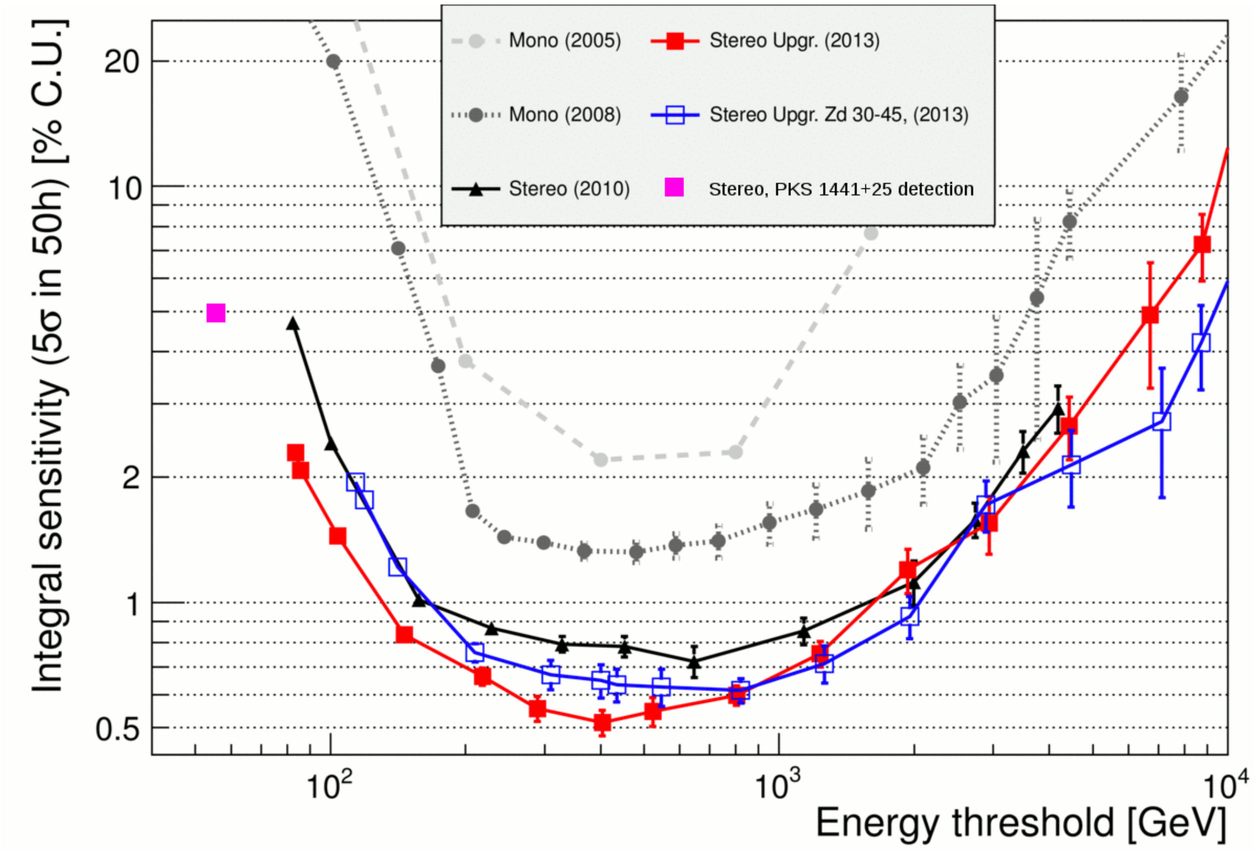


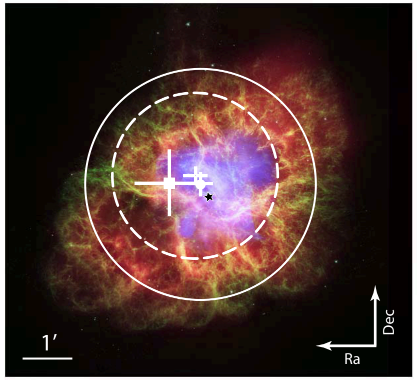


Gamma-rays (and charged cosmic rays) produce showers in the atmosphere. The charged particles in the shower emit Cherenkov light that can be detected by ground-based Cherenkov Telescopes.

The MAGIC Telescopes

Astroparticle Physics, 72 (2016) 76





Crab Nebula used as a standard candle to calibrate and study the performance of Cherenkov Telescopes

- MONO: MAGIC-I Telescope (2004 – 2009)
- STEREO: MAGIC-I & MAGIC-II Telescopes (post readout+camera upgrade)

Energy threshold and sensitivity well suited for Dark Matter searches!

Indirect Dark Matter searches

❖ Overwhelming evidence for a Dark Matter component in the Universe

❖ Particle candidates in-line with observations: Weakly Interacting Massive Particles (WIMPs). Several BSM theories predict WIMPs (SUSY, Extradimensions, ...)

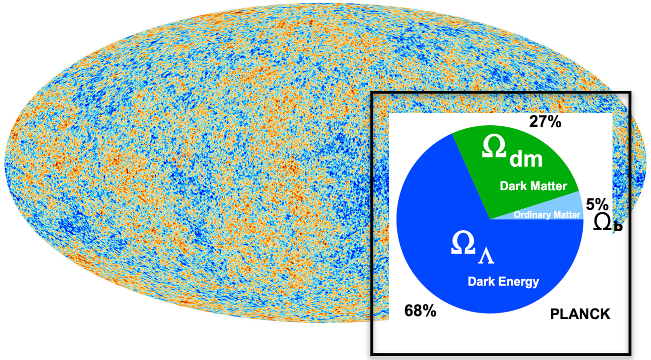
❖ WIMPs mass range: O(10) GeV – O(100) TeV

❖ Indirect DM searches aimed at detecting secondary SM products (**including gamma-rays**) from annihilation or decay of Dark Matter particles

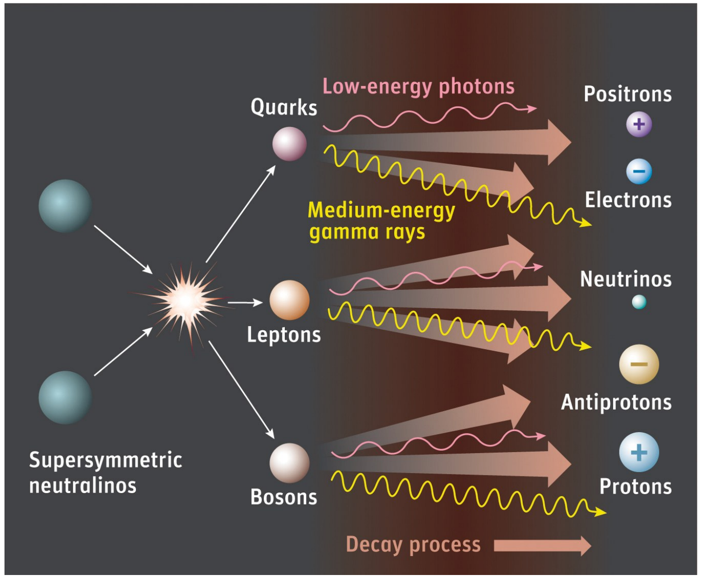
❖ Gamma-rays as final states are of major interest because:
- ○ do not suffer from propagation effects
- ○ trace back to abundance / distribution of DM
- ○ show peculiar spectral features (*smocking guns*)

❖ Indirect Dark Matter searches are needed to confirm signals in direct and/or acceleration searches are **THE** Dark Matter

Planck Coll. 2015, A&A 2016



See P. Gondolo and P. Serpico talks



Main targets

❖ *Galactic center?*

+ Highest *J-factor*
– High astroph. bkg
– Uncertainties on inner DM distribution
(Southern Hemisphere)

❖ *Galactic halo?*

+ High *J-factor*
– Not fully-free from astroph. bkg
– Extended
(Southern Hemisphere)

❖ *Galaxy Clusters?*

+ Huge amount of DM
– High astroph. bkg
– Distant
– Extended
– Uncertainties on *J-factors*

Ideal for MAGIC DM ***annihilation*** search

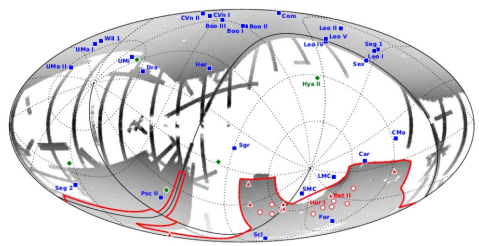
Ideal for MAGIC DM ***decay*** search

❖ *DM Clumps?*

+ Free from astroph. bkg
+ Nearby and numerous
– To be found!
– Bright enough?

❖ *Dwarf Galaxies?*

+ DM dominated (high M/L ratios)
+ Free from astroph. bkg
+ Close (<~100 kpc)
+ Slightly extended at most
+ **~20 new optimal dSphs discovered**
+ Less uncertainties on *J-factors*
– *J-factors* ~100 lower than for GC

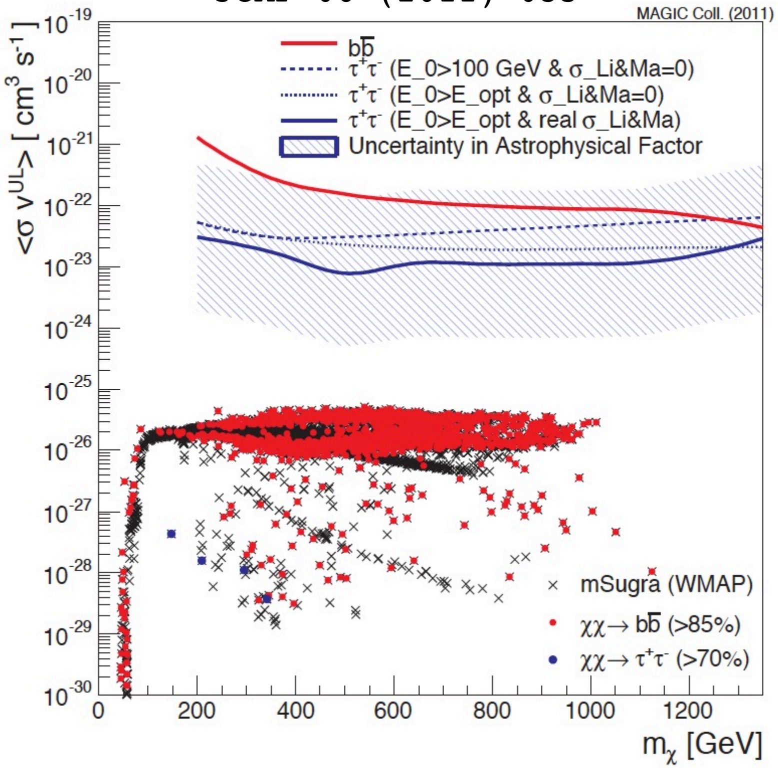


DES Coll., ApJ 813 109 (2015)

Mono mode (MAGIC-I alone) results

- **Galactic Center**
  - (17 h) ApJ Lett. 638 (2006) L101
- **Galaxy clusters**
  - Perseus (25 h) ApJ 710 (2010) 634
- **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**

JCAP 06 (2011) 035



Best mono constraints from Segue 1:

- $<\sigma_{ann}v>^{ul} \sim 10^{-22}$ cm^3 s^{-1} (for $m_{DM} \approx$ 1 TeV to bb-bar)
- Required boost factors ~ 10^3 - 10^5

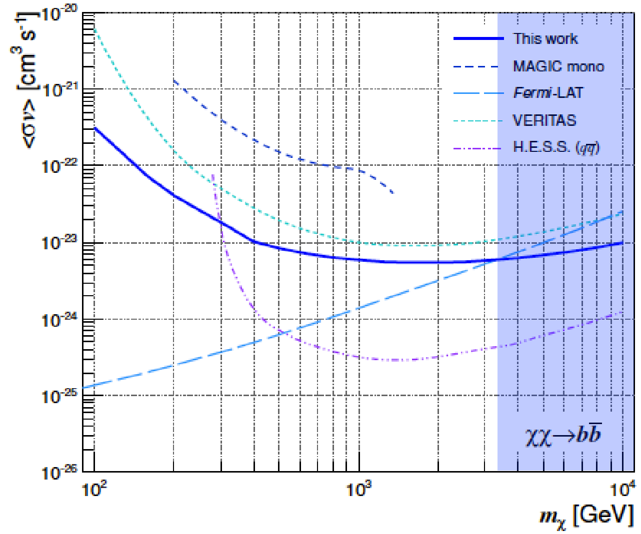
Segue 1 dSPh:

- Ultra-faint dSph Galaxy, 23 kpc from Earth
- $M \approx 6 \times 10^5 M_\odot$, $M/L \approx 3400 M_\odot/L_\odot$
- Einasto DM profile

Stereoscopic mode (MAGIC-I & MAGIC-II) results

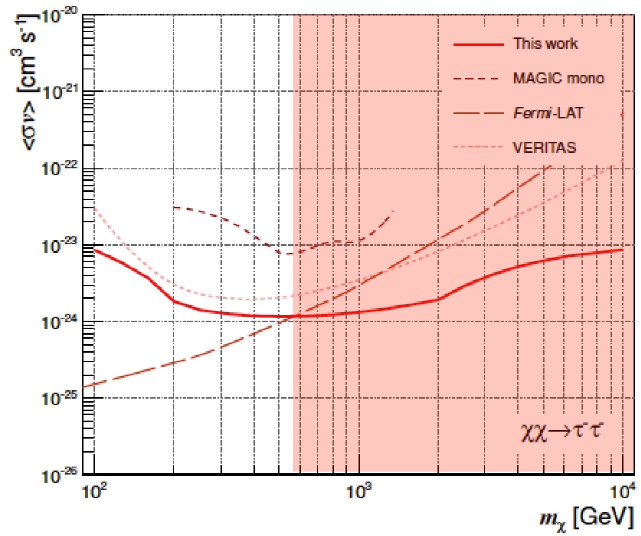
- Galaxy clusters
  - Perseus (~250 h), in preparation (see next)
- Dwarf Galaxies:
  - **Segue 1 (158 h): JCAP 002 (2014) 008**
  - observations of new optimal targets on-going

JCAP 002 (2014) 008



Best constraints (so-far) from Segue 1:

- deepest observation of any dSph by any IACTs
- dedicated analysis optimized for spectra with features (*full-likelihood* analysis, JCAP 10 (2012) 032)
- a factor ~10 better sensitivity w.r.t. mono results
- $<\sigma_{ann}v>^{ul}$ ~ 10^{-23} cm^3 s^{-1} (for $m_{DM} \approx$ 1 TeV to bb-bar) strongest limits from dSphs in >O(1) TeV mass range
- results included in the Particle Data Group (K. A. Olive et al., Review of Particle Physics, Chin. Phys. C, 38, (2014) 090001)



Dark Matter searches with MAGIC

MAGIC and Fermi-LAT combined analysis

Due to expected universality of DM properties, a joint likelihood function $\mathcal{L}$ can be written as a product of the particular likelihood functions for each of the data samples and instruments

$$\mathcal{L}_{iM}(\langle\sigma v\rangle; J_i, \mu_{iM} | \mathcal{D}_{iM}) = \prod_{k=1}^{N} \mathcal{L}_{iMk}(\langle\sigma v\rangle; J_i, \mu_{iMk} | \mathcal{D}_{iMk})$$

MAGIC

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

Fermi Gamma-ray Space Telescope

Generic Instrument j and particular target i

$$\mathcal{L}_i(\langle\sigma v\rangle; J_i, \mu_i | \mathcal{D}_i) = \prod_{j=1}^{N\,instrument} \mathcal{L}_{ij}(\langle\sigma v\rangle; J_i, \mu_{ij} | \mathcal{D}_{ij})$$

nuisance parameters

input data set

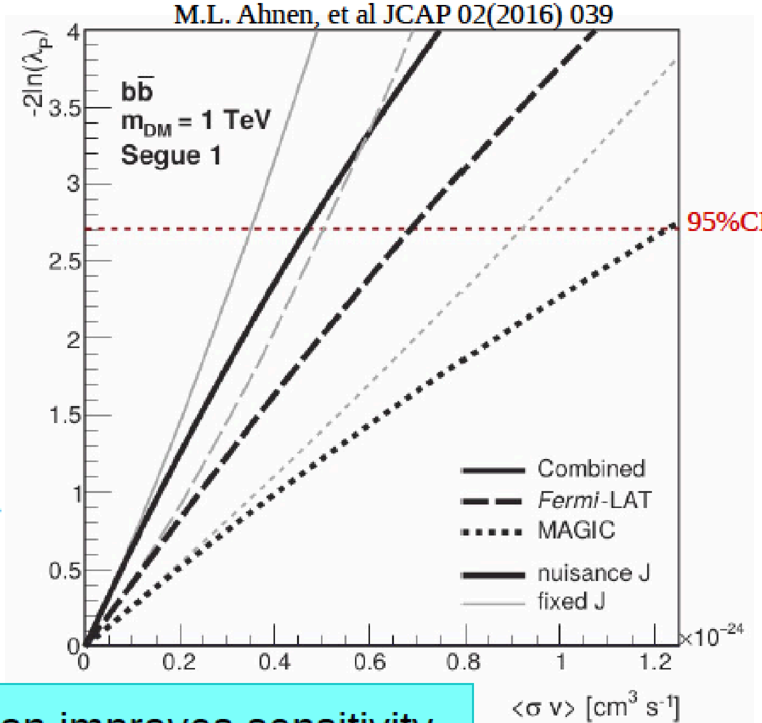
Likelihood ratio as a function of $\langle\sigma v\rangle$ for significance test of DM hyp.

$$\lambda p = \mathcal{L}(\langle\sigma v\rangle; \hat{\hat{\nu}} | \mathcal{D}) / \mathcal{L}(\widehat{\langle\sigma v\rangle}; \hat{\nu} | \mathcal{D})$$

Computation one-side 95% confidence level upper limits by

$$-2 \ln \lambda p(\langle\sigma v\rangle | \mathcal{D}) = 2.71$$

M.L. Ahnen, et al JCAP 02(2016) 039



Combination improves sensitivity

Great advantage of this method:

the details of each experiment, IRFs and event list do not need to be combined or averaged

See also: J. Aleksić, J. Rico, M. Martinez JCAP 10 (2012) 032 and M.L. Ahnen et al. JCAP 02 (2016) 039

MAGIC and Fermi-LAT combined analysis

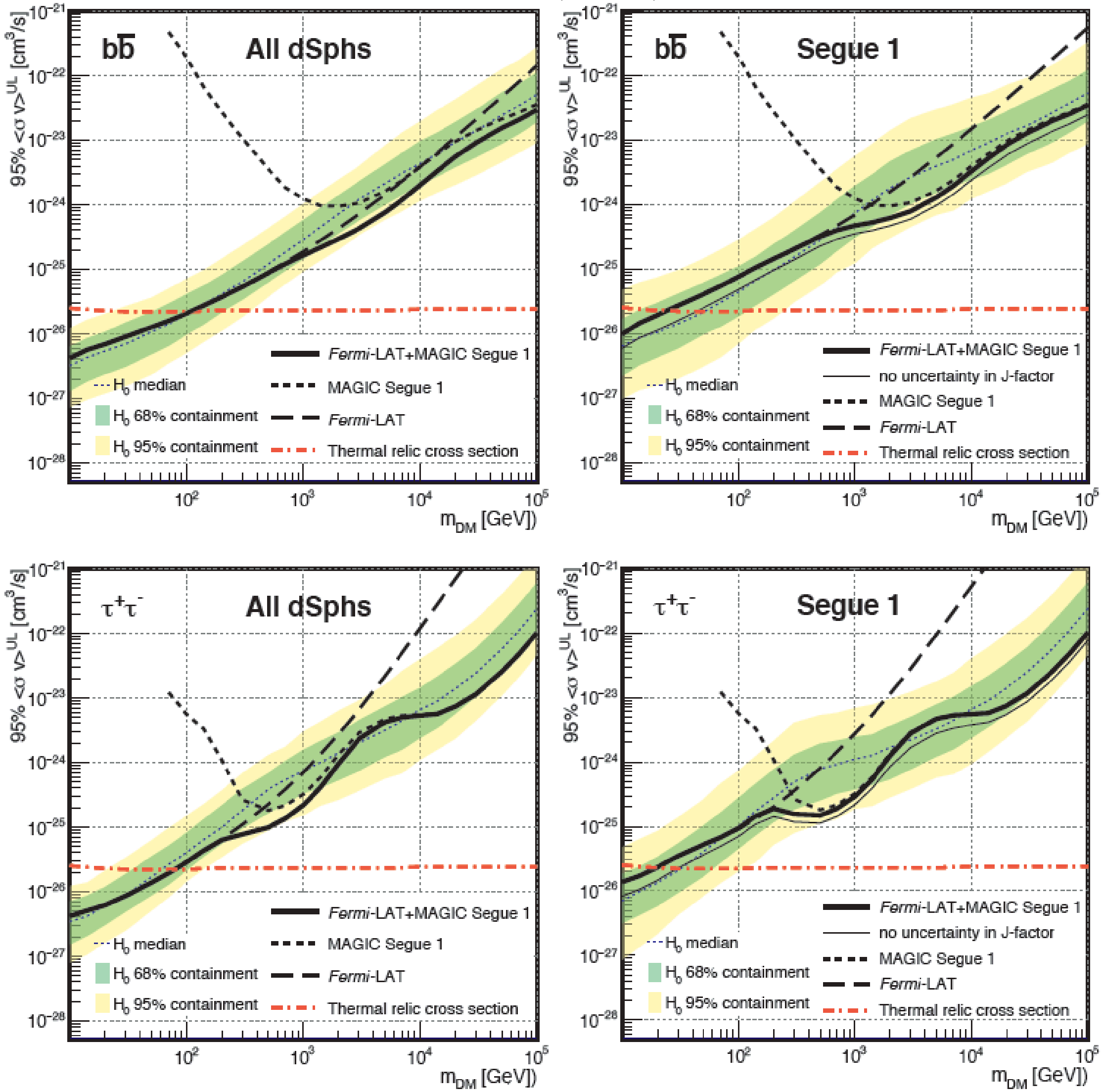
- ❖ Combination of observations by
  - ○MAGIC: Segue 1 (158 h)
  - ○Fermi-LAT: 15 dwarfs (6 years, Pass8)

- ❖ Coherent limits on the annihilation cross-section for dark matter particle masses between 10 GeV and 100 TeV (widest range so far explored)

- ❖ In the intermediate mass range (few hundred GeV to few tens TeV) improvement of the combined limits with respect to the individual ones by a factor ~2

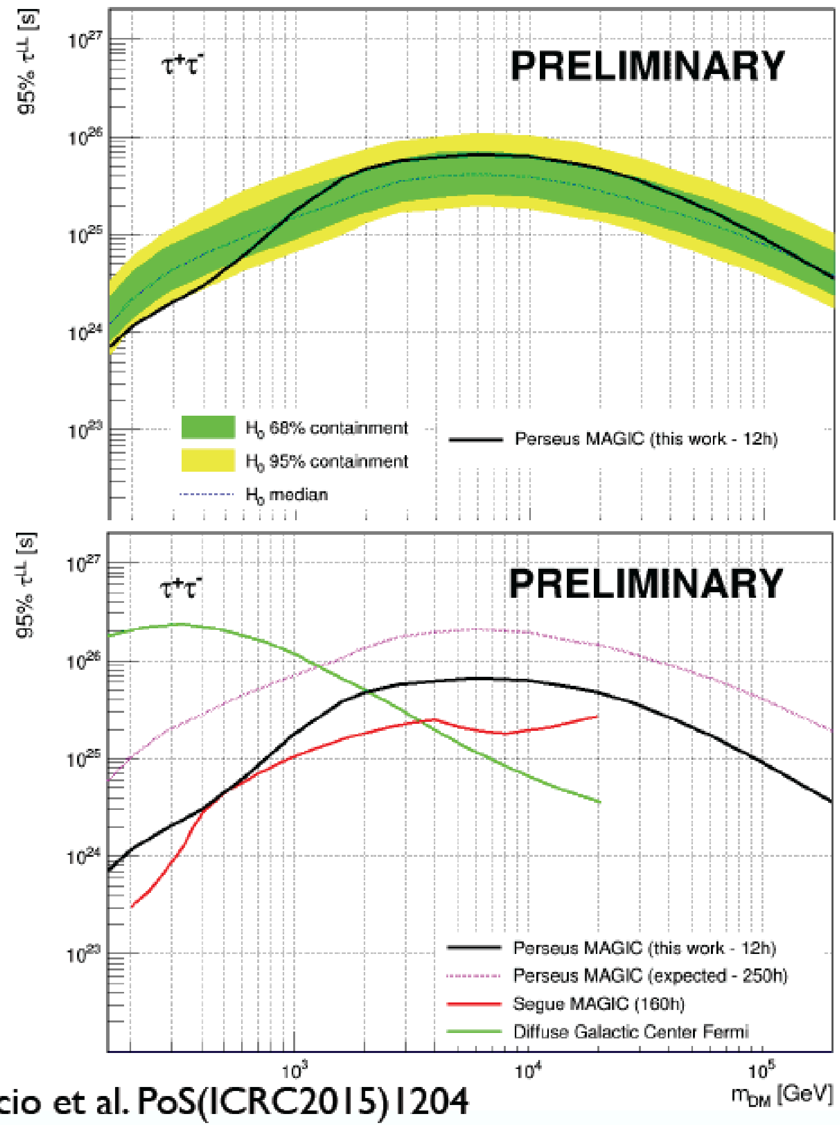
- ❖ Annihilation limits for DM particle masses below O(1) TeV dominated by Fermi-LAT, above O(1) TeV by MAGIC (and IACTs, in general)

JCAP 02 (2016) 039



MAGIC (preliminary) results on DM particle decay lifetime

- Deep survey of Perseus cluster by MAGIC
  - ~250 h (2009 – 2016, stereoscopic mode) (Astron. Astrophys 589 (2016) A33)
  - Extended DM halo, signal region to be optimized
  - Two gamma-ray sources to be subtracted (NGC 1275, IC 310)
- Analysis optimization checked on 12 h
- Sensitivity ~8 × 10^{25} s
- Better results than 158 h of Segue 1
- No signal found ➔ most constraining limits for high mass (TeV) range
- With whole data sample (~250 h) sensitivity will improve by a factor ~4



Palacio et al. PoS(ICRC2015)1204

Summary

- The MAGIC Collaboration has a rich program for indirect Dark Matter searches (and of Fundamental Physics, in general):
  - **Dwarf Galaxies**:
    - deepest survey (Segue 1, 158 h) so far of any dSph with IACTs
    - strongest limits E>O(1) TeV from dSph on various DM models
  - **Fermi-LAT/MAGIC dSphs combined results**:
    - coherent limits in the wide energy window of 10 GeV – 100 TeV
    - improvement of limits by a factor ~2 in the intermediate mass range
    - development of efficient tools for optimized global DM search with current- and next-generation gamma-ray and neutrino instruments
  - **Perseus cluster**:
    - deep survey (~250 h), expected very competitive DM decay-life limits
- MAGIC DM observation strategy: **diversification of targets**
  - reducing targets selection biases (due to *J-factor* uncertainties)
  - increasing of chances for DM discovery
  - straightforward stacking of results (*full-likelihood* analysis)
- Observations of new optimal DM targets are on-going: **new results are coming!**

Backup

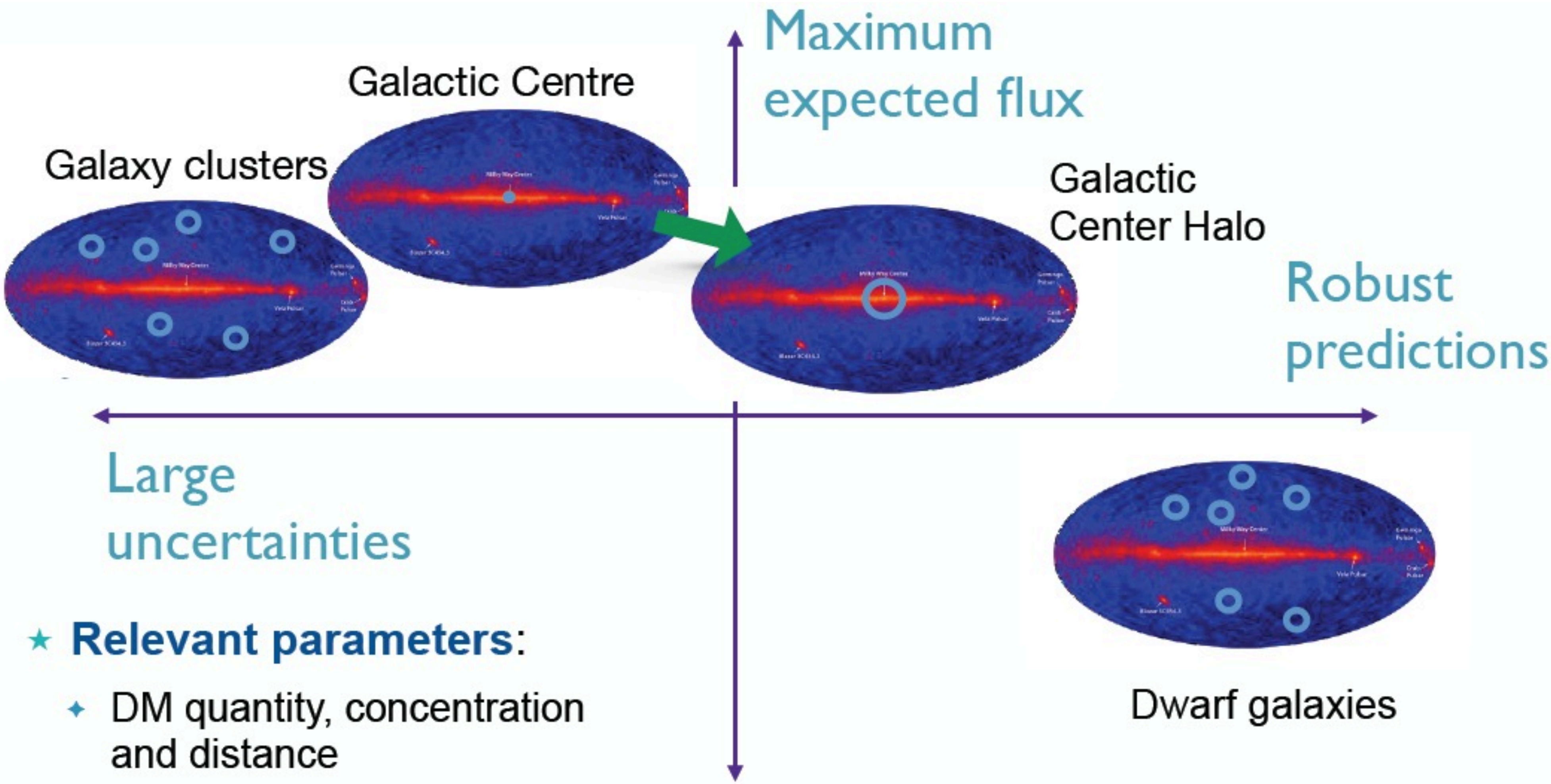
Indirect Dark Matter searches

- Expected **differential gamma-ray fluxes**:

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

	Particle Physics factor:	Astrophysical factor:
Annihilation:	$\frac{d\Phi^{PP}}{dE'} = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann} v\rangle}{2m_\chi^2}\frac{dN}{dE'}$	$J_{\rm ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho^2(l,\Omega)\,dl\,d\Omega.$
Decay:	$\frac{d\Phi^{PP}}{dE'} = \frac{1}{4\pi\,\tau_\chi m_\chi}\frac{dN}{dE'}$	$J_{\rm dec}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho\,(l,\Omega)\,dl\,d\Omega.$
	Large uncertainties from Fund. Phys. No target dependences (straightforward stacking analysis)	Large uncertainties from DM profiles (robust limits from less uncertain targets)

Main targets



- **Relevant parameters**:
  - DM quantity, concentration and distance
  - Uncertainties
  - Astrophysical background

Annihilation vs decay

$$\frac{d\Phi_\gamma}{dE} = \frac{d\Phi_\gamma^{PP}}{dE} \times J(\Omega)$$

$$J(\Omega) = \int_\Omega \int_{los} \rho^2(r) dr d\Omega$$ Annihilation

$$J(\Omega) = \int_\Omega \int_{los} \rho(r) dr d\Omega$$ Decay

- dSph vs galaxy clusters as DM targets
  - dSph are closer and more concentrated, less uncertainty and foreground
  - galaxy cluster total mass is huge, compensate their larger distance

	Jann [GeV^2·cm^-5]	**Jdec** [GeV·cm^-2]
Segue 1	1e19	2e17
Perseus	1e17	2e18
Fornax	1e18	1e19

- In general dSph are better candidates for annihilation and galaxy clusters for decay

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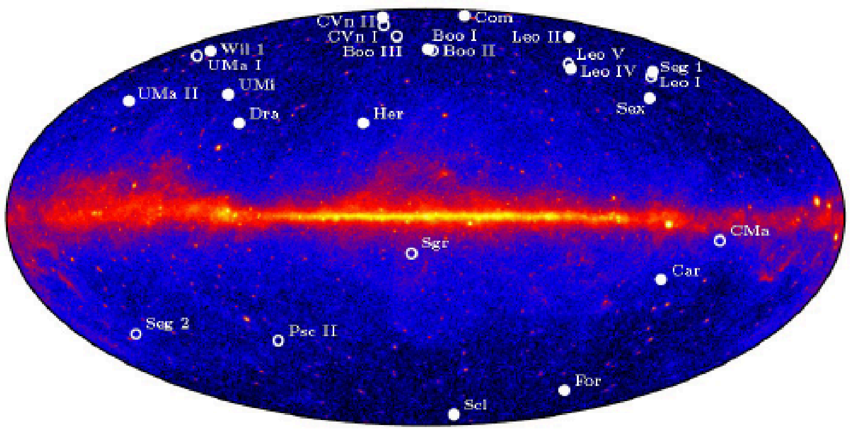
MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescope

- Believed to be the smallest, faintest DM dominated system: high mass-to-light ratio estimated to be up to 4000 M⊙/L⊙ (*Wolf 2010*)
- Free from γ-ray background (ancient stellar population, devoid of gas) (*Fermi*-LAT sky scan)
- DM extragalactic target closest to us (few kpc up to 130 kpc)

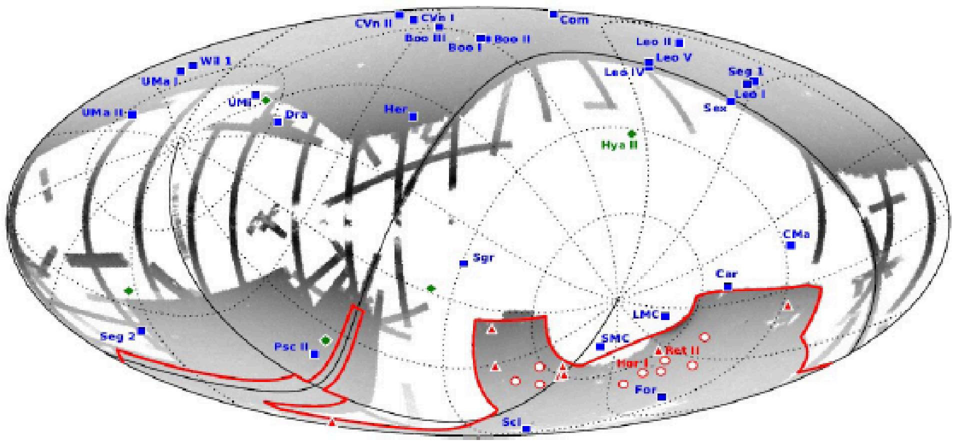
- DES, Pan-STARRS, recent deep sky surveys increase known dwarf population → catching up Λ Cold Dark Matter cosmological model prediction
- Dedicated astrometric method to disentangle member stars in order to reduce uncertainties of M/L ratios evaluation for better estimating DM content (Dana I. et al., arXiv:1606.00977; Fabrizio M. et al. A&A 570, A61 2014)

Up to 2014: 25 known dwarfs



Ackerman et al., *Fermi*-LAT Coll., arXiv:1310.0828

Today: +20....and updating



A. Dirlica-Wagner et al. DES Coll., arXiv:1508.03622

DM search in the Perseus cluster

Aleksić et al. A&A 541 (2012) A99