γ-ray searches of neutralino annihilations in the Milky Way

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Gamma-ray Dark Matter searches

- THIS TALK: gamma-ray searches with IACTs and neutralino as the DM particle.
- Gamma-ray DM searches: detection of gamma-rays coming from neutralino annihilations.
- Why gammas?
  - The energy scale of the annihilation products is determined by the mass of the DM particle.
  - Gamma-rays will travel following straight lines
  - Gamma-rays do not suffer from attenuation, therefore retaining the spectral information.
- In gamma-rays, IACTs and satellites: MAGIC, HESS, VERITAS, CANGAROO, Fermi, AGILE…

E. range: 10 MeV - 300 GeV

E. resolution: <10% @ 10 GeV

FoV: ≈2.4 sr

Angular resolution: 0.1º@10 GeV

Fermi/LAT

Morselli's talk!

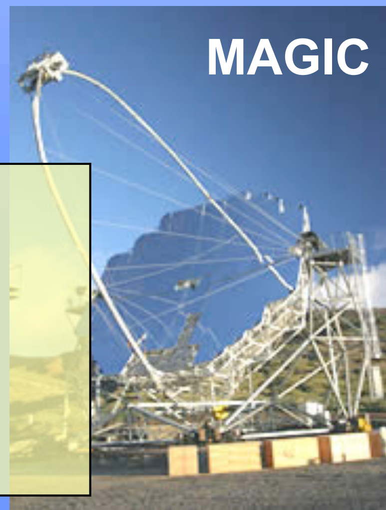
Typical IACT

E. range: 100 GeV - 30 TeV

E. resolution: >20%

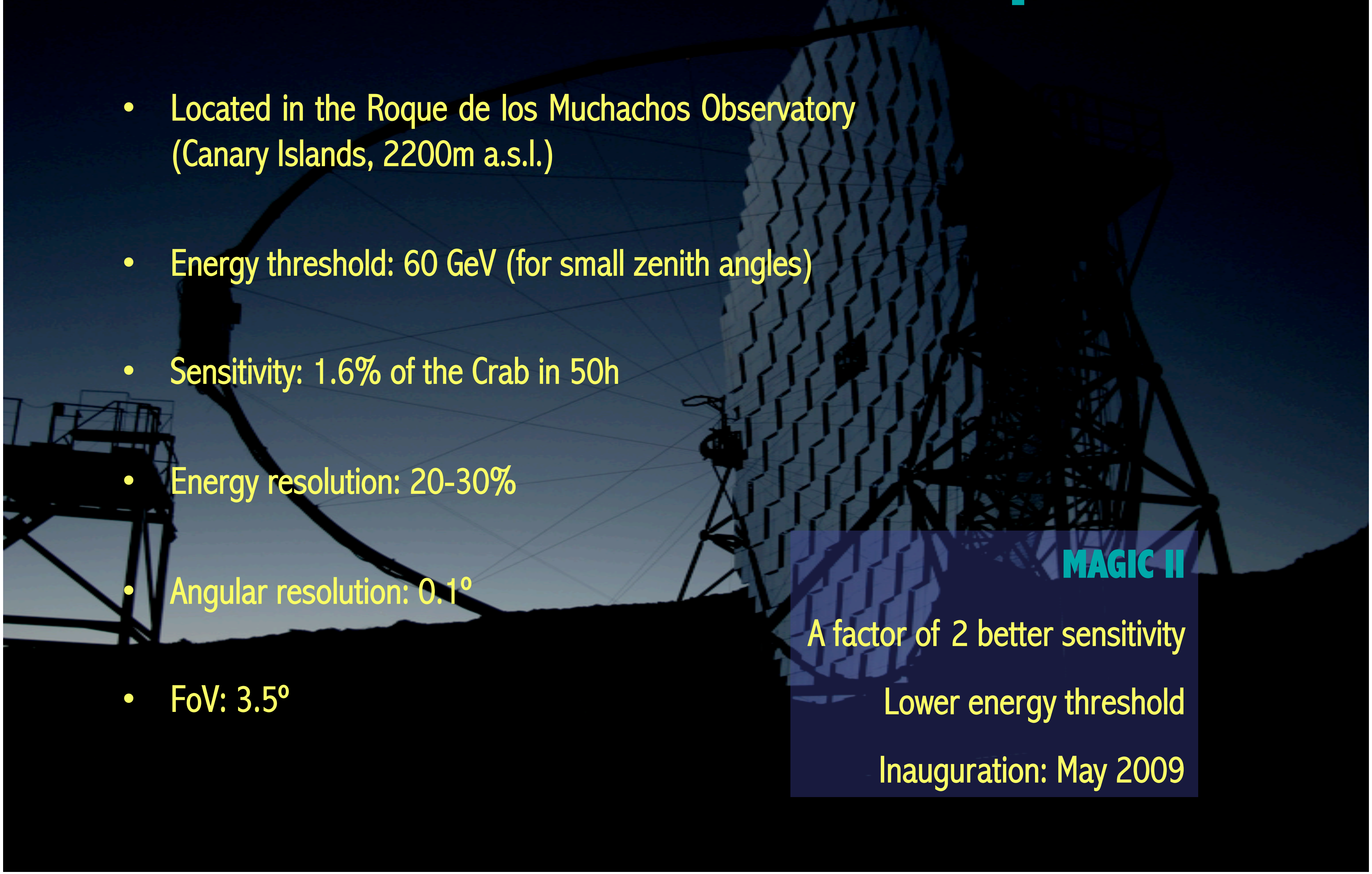
FOV: ≈ 4 deg.

Angular resolution: ≈ 0.1º



Leading IACTs at present

The 17m MAGIC telescope



- Located in the Roque de los Muchachos Observatory (Canary Islands, 2200m a.s.l.)
- Energy threshold: 60 GeV (for small zenith angles)
- Sensitivity: 1.6% of the Crab in 50h
- Energy resolution: 20-30%
- Angular resolution: 0.1º
- FoV: 3.5º

MAGIC II

A factor of 2 better sensitivity

Lower energy threshold

Inauguration: May 2009

The DM gamma signal

$$F_\gamma(E > E_{th}) = \frac{1}{4\pi} f_{susy} \cdot U(\Psi_o)$$ photons cm^{-2} s^{-1}

Particle physics

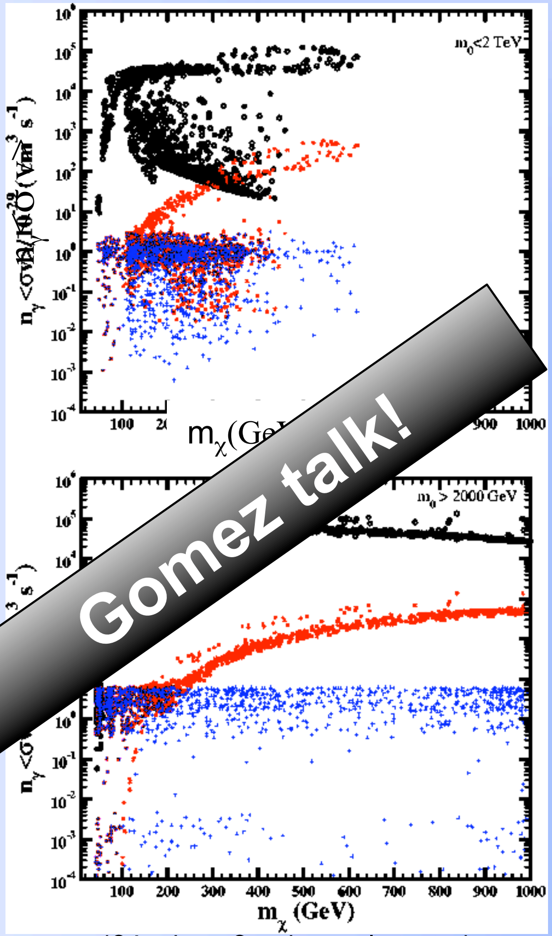
Astrophysics

SUSY Model:

$$f_{susy} = \frac{n_\gamma \langle \sigma \cdot v \rangle}{2 m_\chi^2}$$

- n_γ: Number of photons
- $<\sigma$ v$>$: cross section
- m_χ: neutralino mass

Large uncertainties!



(Sánchez-Conde et al. 2007)

$$U(\Psi_o) = \int J(\Psi) B(\Omega) d\Omega$$

Integral along the l.o.s.: $$J(\Psi) = \int_{l.o.s} \rho_{dm}^2(r) dl$$

Telescope PSF: $$B(\Omega)d\Omega = \exp\left(\frac{-\theta^2}{2\sigma_t^2}\right) \sin\theta d\theta d\phi$$

Where to search?

- Galactic Center
- Dwarf spheroidal galaxies (e.g. Draco, Willman-1…)
- Andromeda
- Galaxy clusters (e.g. Virgo, Coma)
- Etc, etc.

The Galactic Center

In principle the best option…

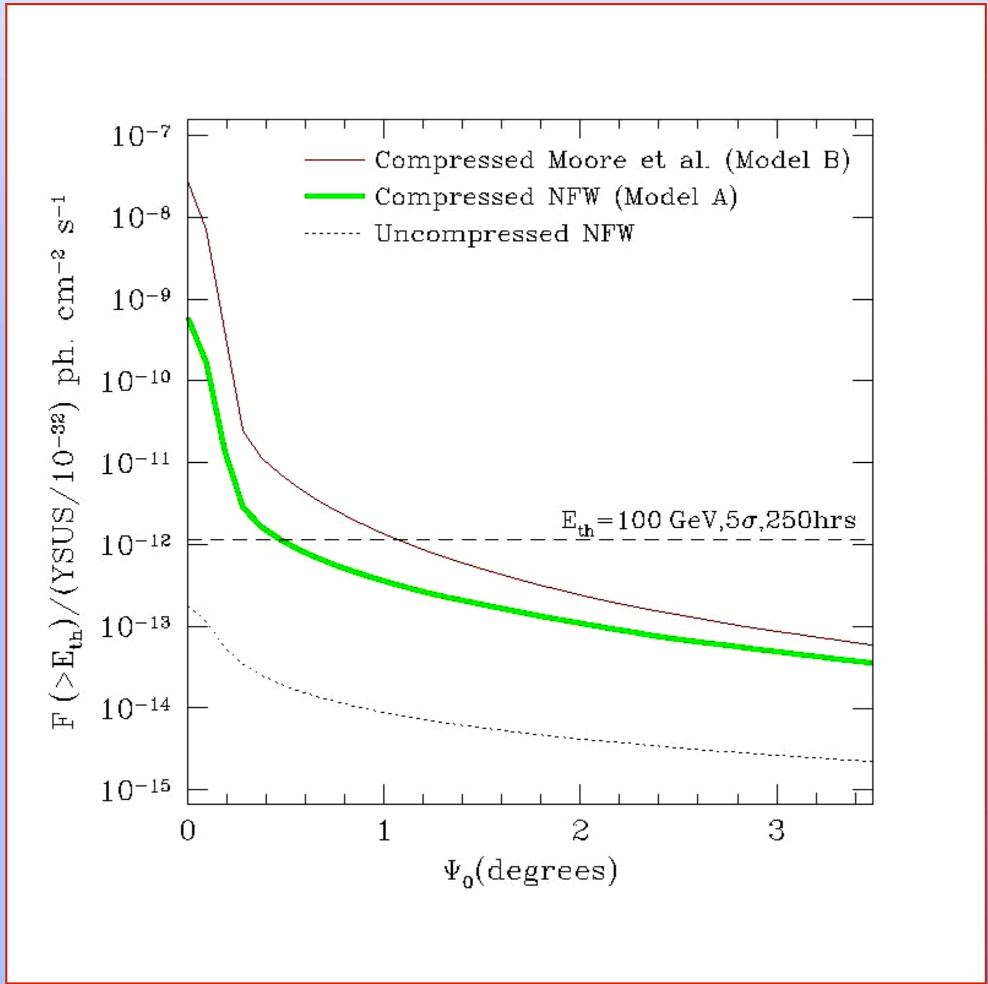
- Very near, so flux should be high. Adiabatic contraction expected to be really important.
- HESS and MAGIC reported a point-like source: a very massive neutralino, no compatible with WMAP cosmology.

  (Aharonian et al. 2004; Albert et al. 2005)
- Later an extended emission was discovered, but associated to the galactic plane and molecular clouds.

  (Aharonian et al. 2006)
- More recently, new HESS data and analysis: DM not excluded (α>1.2)

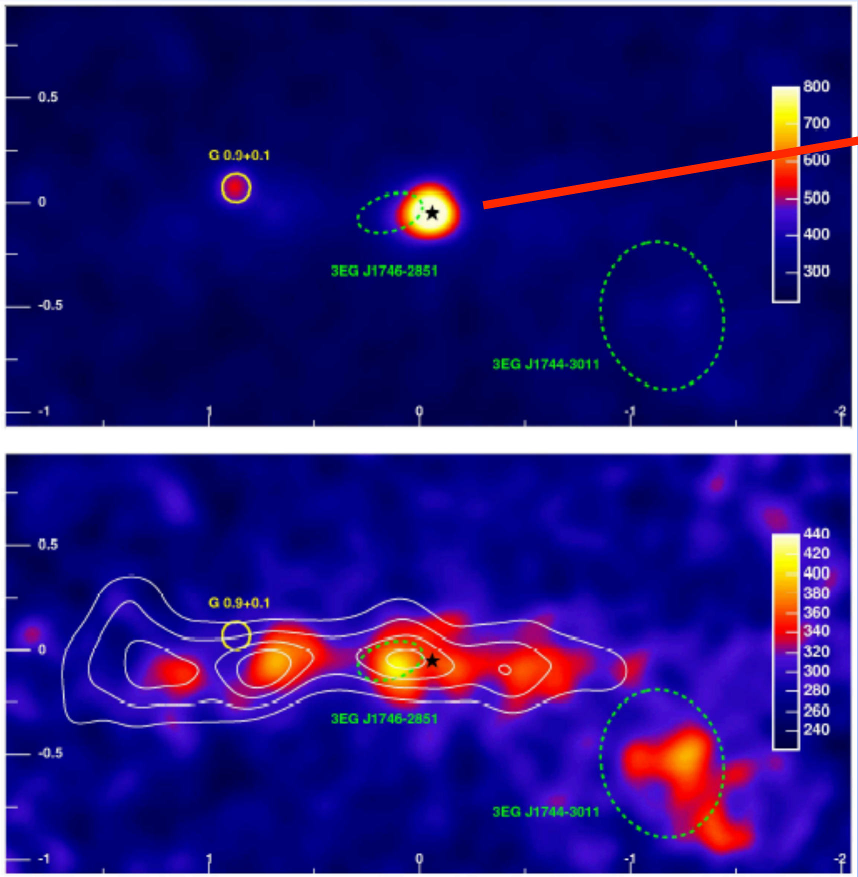
  (Aharonian et al. 2006)

Gamma ray flux predictions

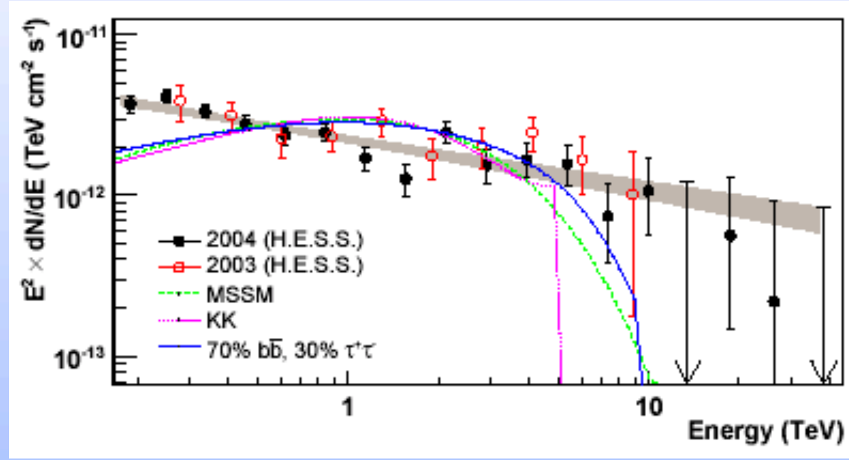


(Prada et al. 2004)

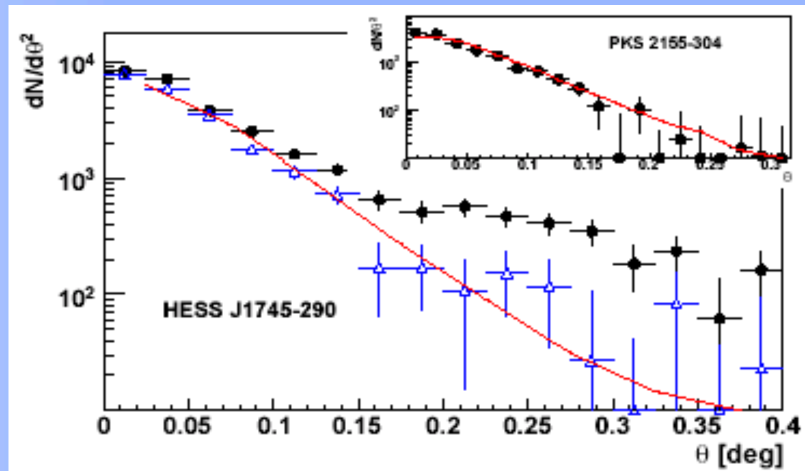
HESS observations of the central 200 pc



Gamma sources at the GC
(Hinton for the HESS collaboration 2006)

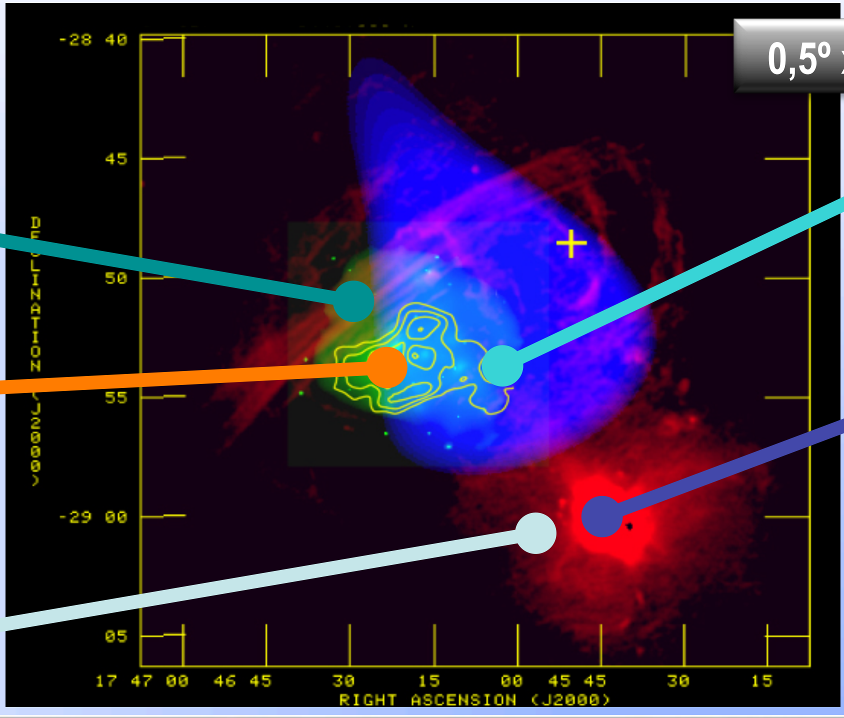


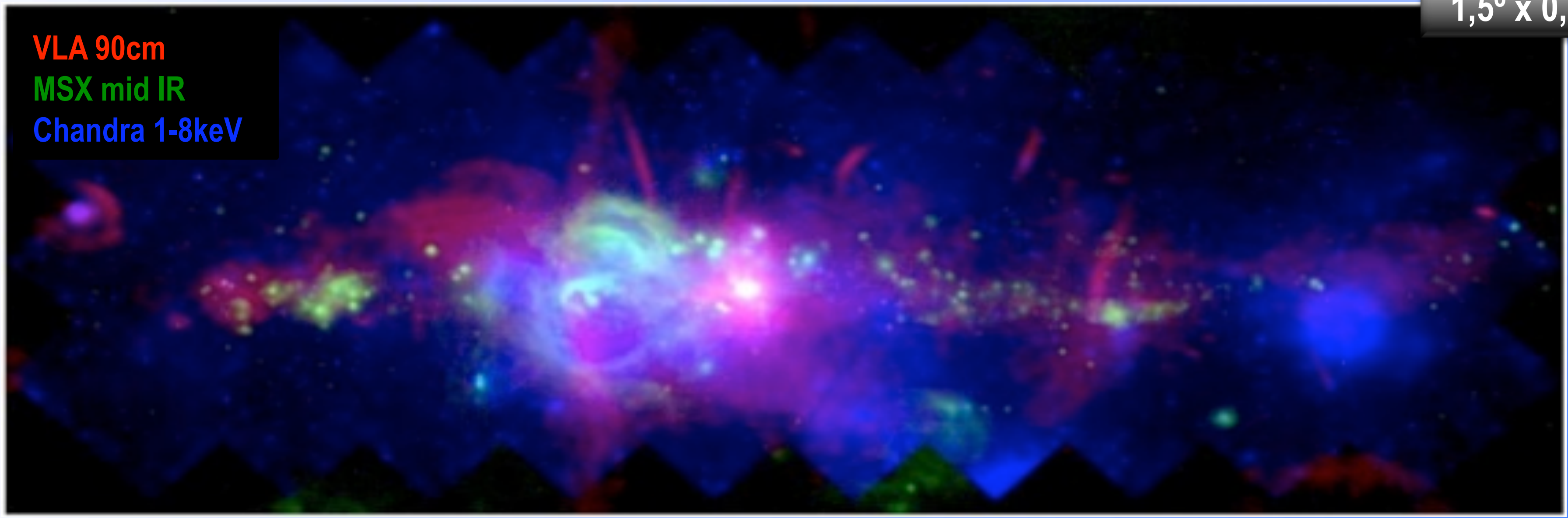
SED including best-fit curves of different predictions of DM annihilation models.



(Aharonian et al. 2006)

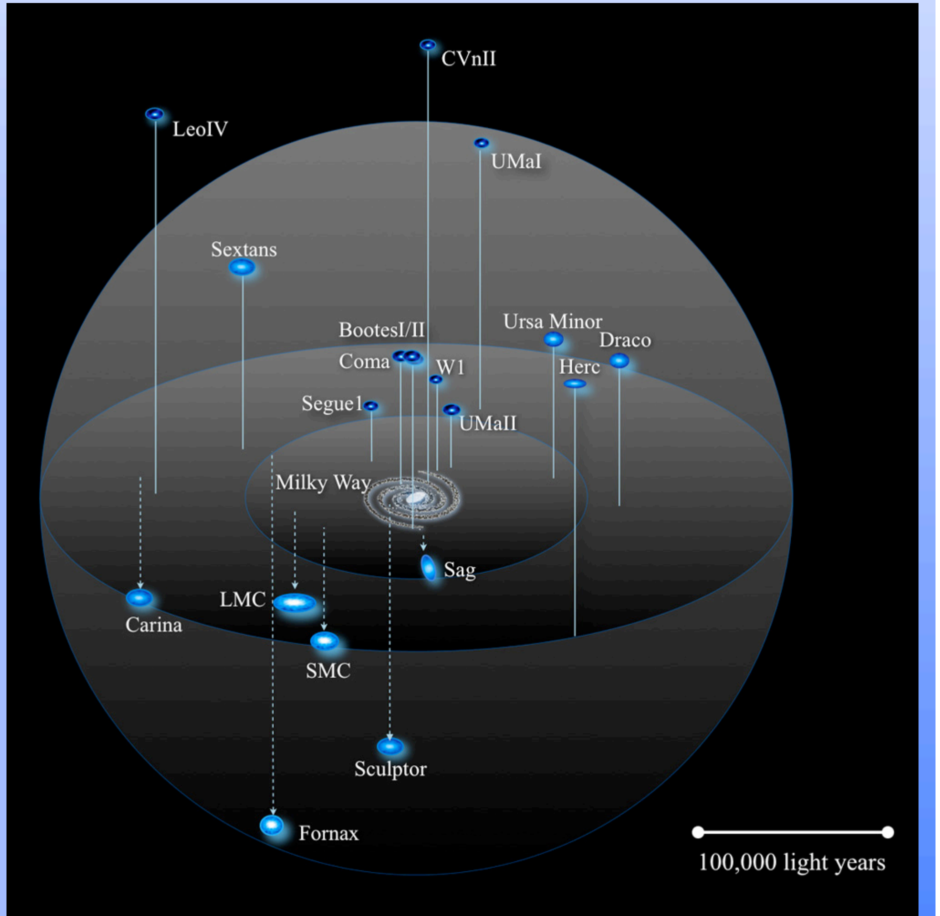
GC is a very crowded region !





Why not dSph galaxies?

- DSphs are the most DM dominated systems known in the Universe: very high M/L ratios.
- Many of them nearer than 100 kpc from the GC (e.g. Draco, UMi and new SDSS dwarfs).
- Most of them are expected to be free from any bright astrophysical gamma source.
  - Low content in gas and dust.
  - In contrast with that expected in the GC, nearby galaxies and galaxy clusters.



Bullock et al. (2009)

New promising dwarfs

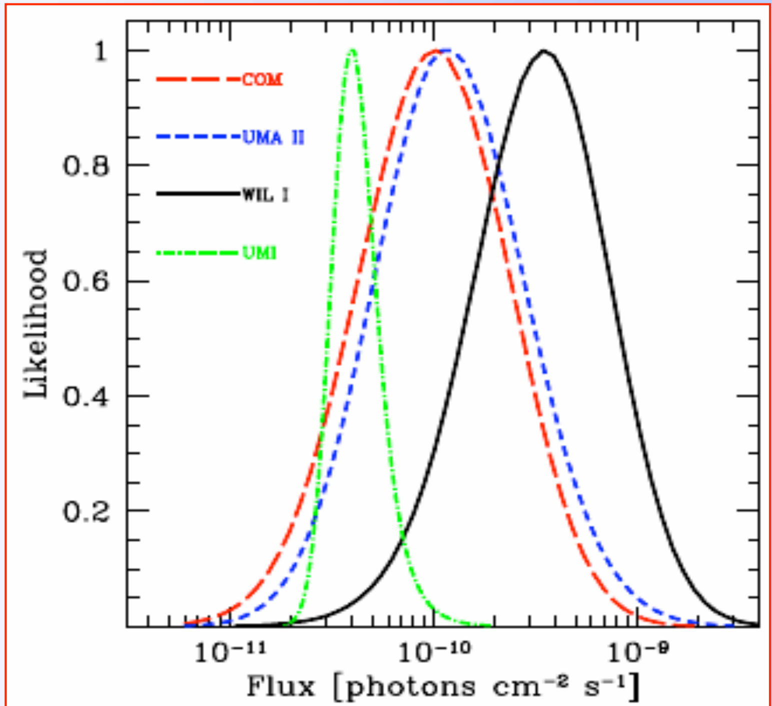
Recently discovered dSph (SDSS): Coma, Willman 1, Segue 1…

- Same M/L than classical dwarfs or higher
- Some of them more than a factor 2 nearer.

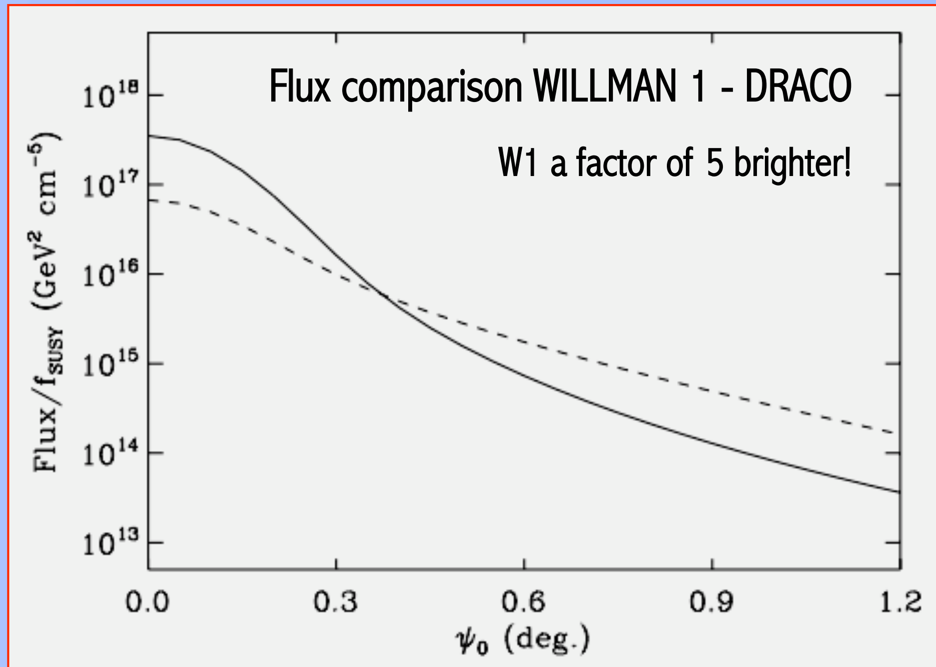
Parameters for WILLMAN 1

Distance (kpc)	38
M (<100 pc) (M_{sun})	1.3×10^6
M/L	~700
r_s (kpc)	0.173
ρ_s (M_{sun}/kpc^3)	4×10^8

(Derived from Strigari et al. (2007) using a NFW profile)



(Strigari et al. 2007)



A tentative list of good candidates

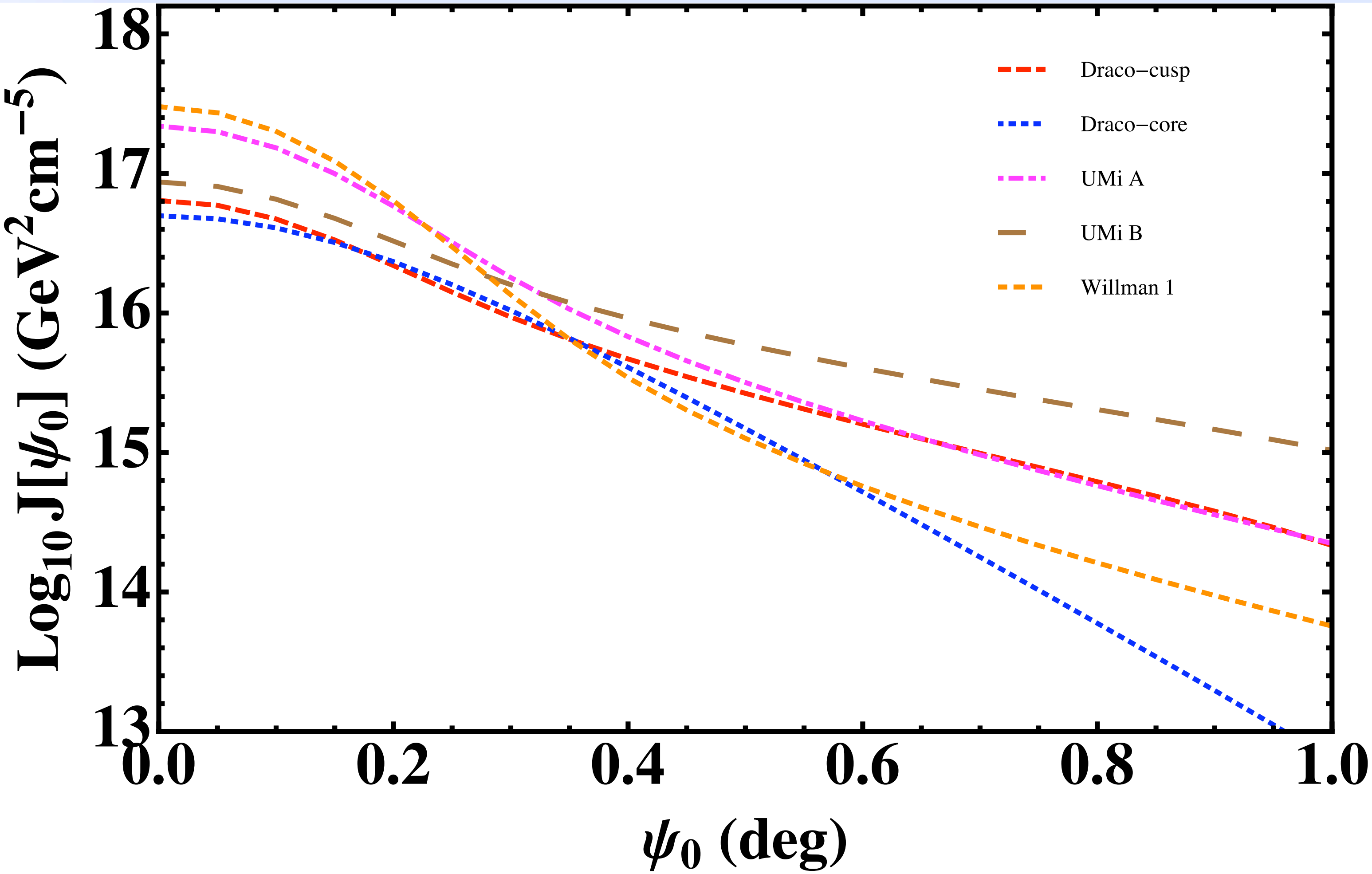
More than 20 satellite galaxies known at present, many of them discovered from SDSS data in the recent years

dSph	D (kpc)	L (10^3 L_{sun})	M/L ratio	Reference	Best positioned IACTs
Carina	101	430	40	(1)	HESS, CANGAROO
Draco	80	260	320	(1)	**MAGIC**, VERITAS
Fornax	138	15500	10	(1)	HESS, CANGAROO
Sculptor	79	2200	7	(1)	HESS, CANGAROO
Sextans	86	500	90	(1)	HESS, CANGAROO
UMi	66	290	580	(1)	**MAGIC**, VERITAS
Coma Berenices	44	2.6	450	(2)	**MAGIC**, VERITAS
UMa II	32	2.8	1100?	(2)	**MAGIC**, VERITAS
Willman 1	38	0.9	700	(2)	**MAGIC**, VERITAS
Segue 1	23	0.3	1300?	(3)	**MAGIC**, VERITAS
Sagittarius**	24	58000	25	(4)	HESS, CANGAROO

(1) Mateo et al. (1998)   (2) Simon & Geha (2007)   (3) Geha et al. (2008)   (4) Helmi & White (2001)

** Not a dSph, but listed here because of its interest

Annihilation flux predictions



- Segue 1 and Willman 1 the best candidates.
- No substructure included!

Sánchez-Conde et al. (2009, in prep.)

___________γ-ray IACTs observations of dSphs

[Present status]

Observations of Draco with MAGIC

Why Draco?

- Draco is probably the dSph with more observational constraints.
- Near (80 kpc from the GC).
- M/L ~ 300
- High in the Northern Sky --> suitable for MAGIC

MAGIC observations and analysis

- Total Observation Time of **7.8 HOURS** (may 2007)
- Zenith Angle ranges between 29º and 42º
- Calibration of the data and Hillas parameterization of the shower images
- Hadronic background supression and energy estimation by Random Forest method

A Dark Matter model for Draco

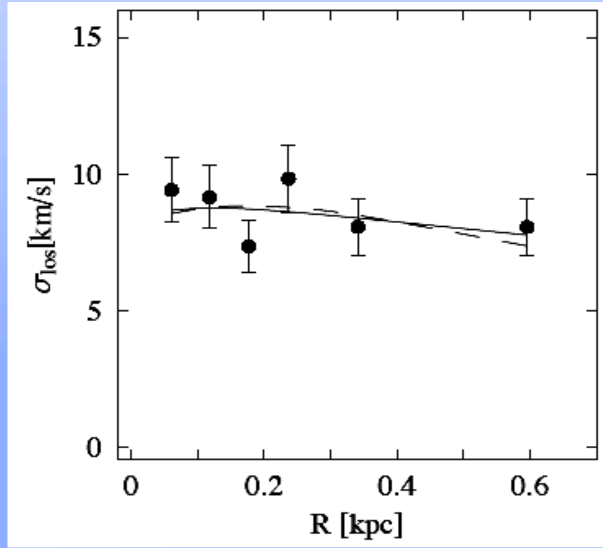
Density profile

$$\rho(r) = C\frac{1}{r^{\alpha}}\exp\left(\frac{-r}{r_b}\right)$$

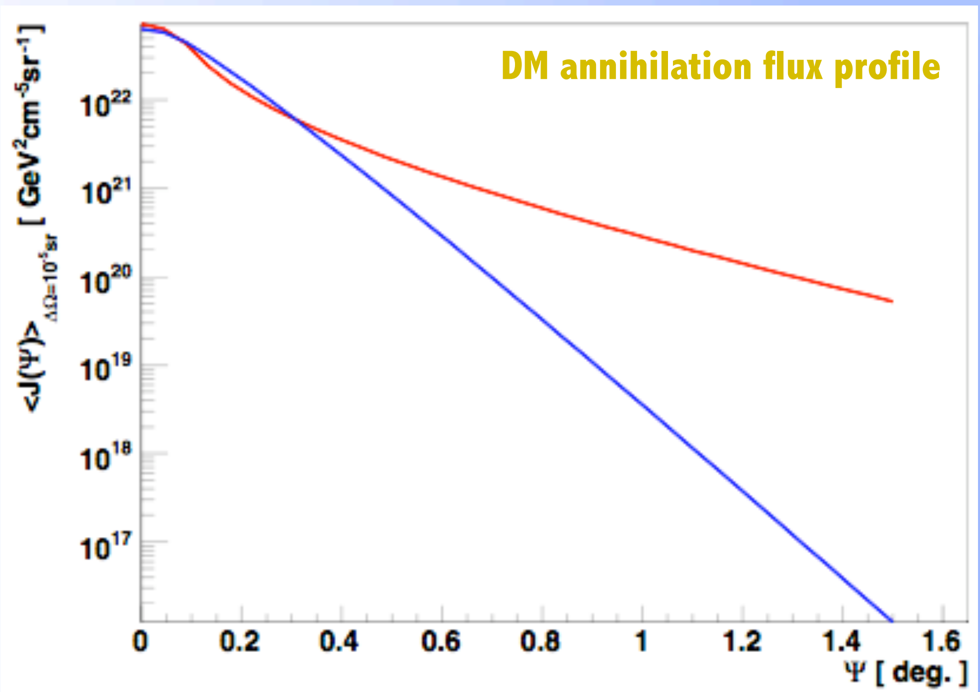
proposed by Kazantzidis et al. (2004)

For a=1, essentially NFW + cut-off

l.o.s. velocity dispersion profile



Estimations for r_b and C according to the latest data analysis

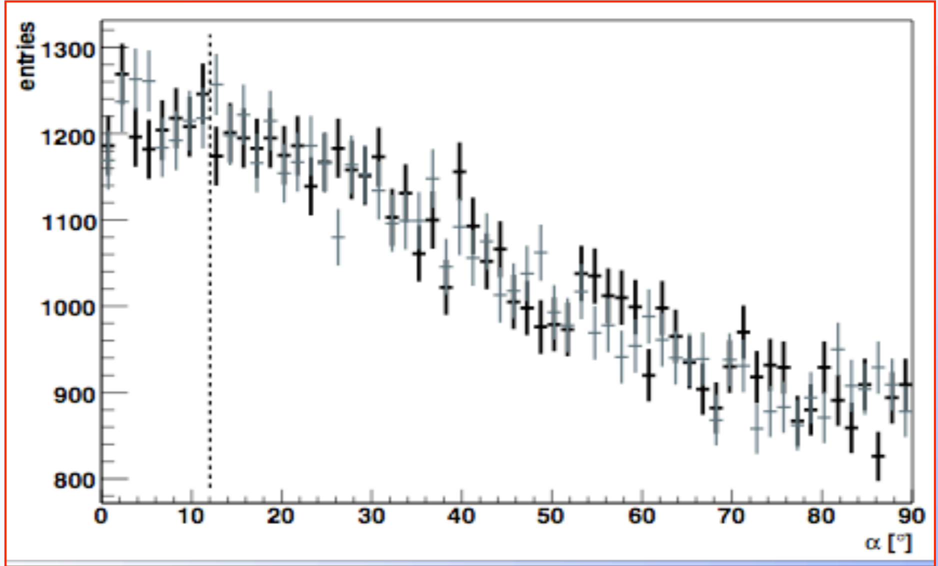


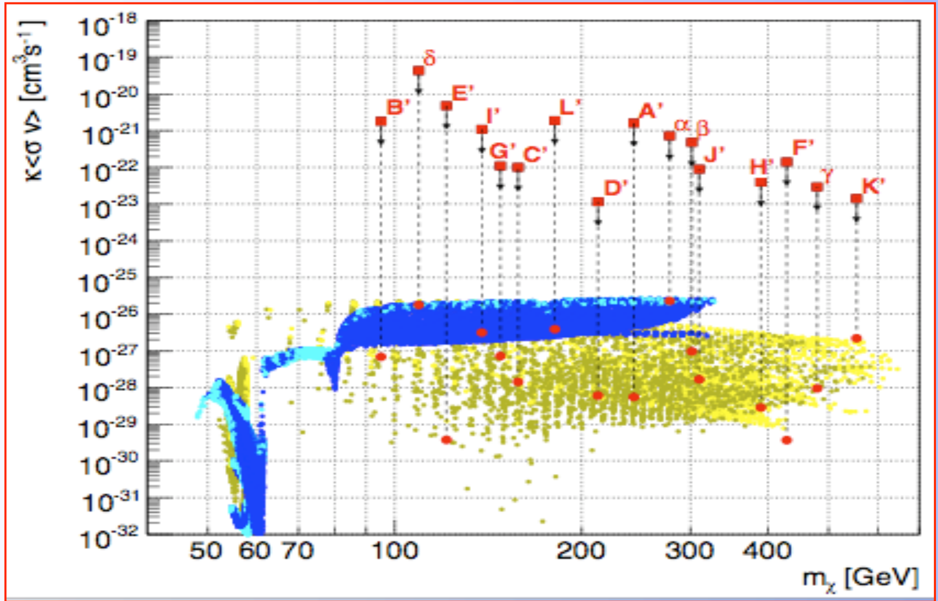
(Sánchez-Conde, Prada, Lokas, Gómez et al. 2007)

Profile	α	C	r_b (kpc)
Cusp	1	3.1×10^7 M_{sun} kpc^{-2}	1.189
Core	0	3.6×10^8 M_{sun} kpc^{-3}	0.238

MAGIC results for Draco

[Albert et al. 2007]





Alpha plot

- E_{th} = 140 GeV
- Signal region $\alpha < 12^{o}$
- No excess signal was found

Flux (2σ, E>140 GeV) = 1.1 x 10^{-11} ph cm^{-2} s^{-1}

(assuming a power-law with spectral index -1.5
and a point-like source)

κ<σ·v> vs mχ for mSUGRA models

- Battaglia et al. (2004) benchmark models
- Our upper limits are O(10^{3}-10^{9}) above the predicted values.
- Very high flux enhancement can be excluded.
- Internal Bremsstrahlung effect -which may boost the signal-, not yet included (Bringmann et al 2007)

Observations of Willman 1 with MAGIC

Why Willman 1?

- Near (38 kpc from the GC).
- M/L ~ 700
- High in the Northern Sky --> suitable for MAGIC
- Recently discovered by SDSS team -> more atractive!

MAGIC observations and analysis

- Total Observation Time of 15.5 HOURS (march-may 2008)
- Zenith Angle ranges between 29º and 42º
- Calibration of the data and Hillas parameterization of the shower images
- Hadronic background supression and energy estimation by Random Forest method

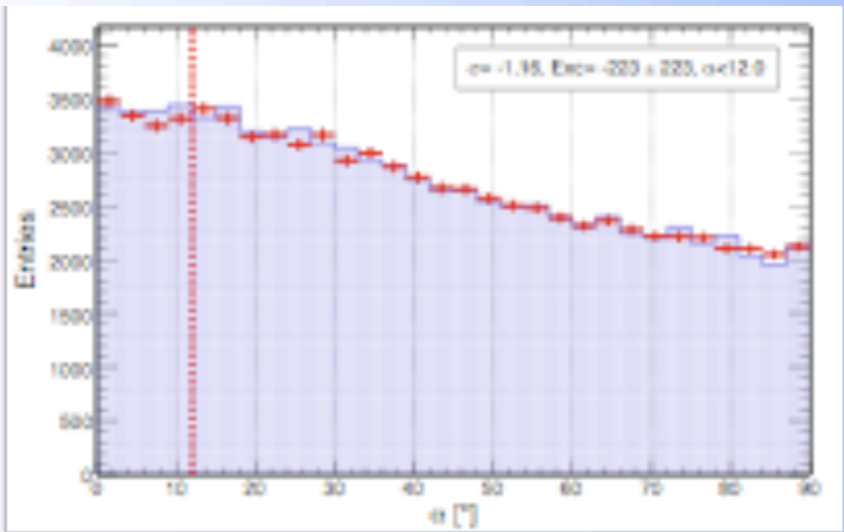
DM halo modeling for Willman 1

- Exact modeling difficult to carry out, since observational data are very scarce.
- Only 47 stars were used in Strigari et al. (2007) to derive (ρ_0, r_s) (by means of a likelihood analysis).
  - Removal of interlopers.
  - Only the inner half of the galaxy.
  - Null tidal stripping.
  - They adopt a NFW DM density profile.

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

Parameter	Value
distance (kpc)	38
Mass (<100 pc) ($M_\odot$)	1.3×10^6
M/L	~700
r_s (kpc)	0.18
ρ_s ($M_\odot$)	4×10^8

Results for Willman 1



[Albert et al. 2008]

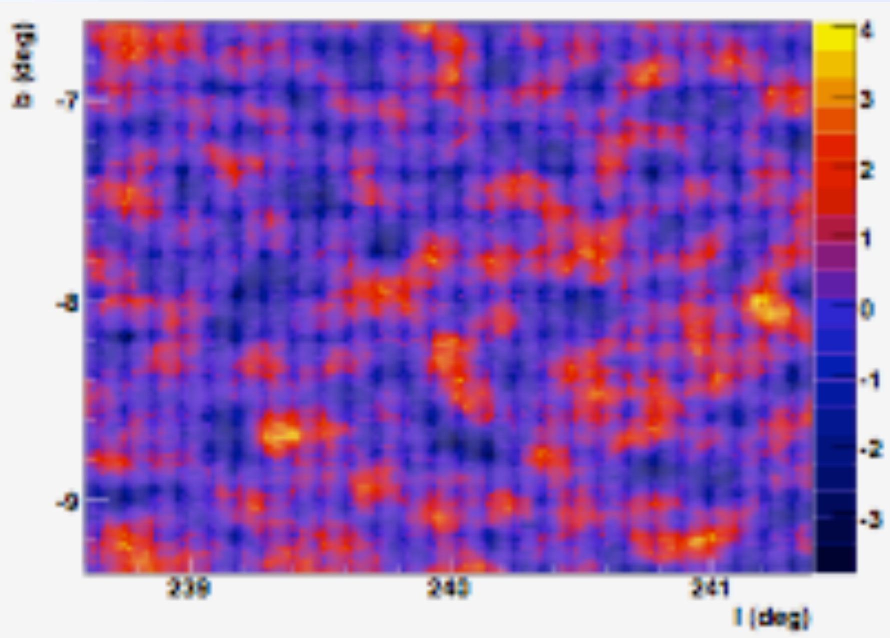
- E_{th} = 100 GeV
- Signal region $\alpha < 12°$
- No excess signal was found:

Flux (2σ, E>100 GeV) = 6 x 10^{-12} ph cm^{-2} s^{-1}

(power-law with spectral index -1.5 and a point-like source)

- Our upper limits are O(10^3-10^5) above the predicted values.
- Very high flux enhancement can be excluded.
- IB effect ALREADY included

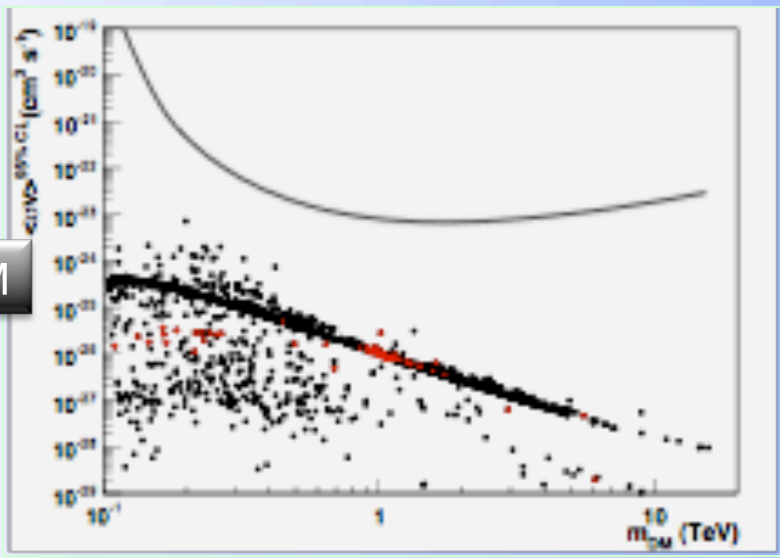
Results from other experiments

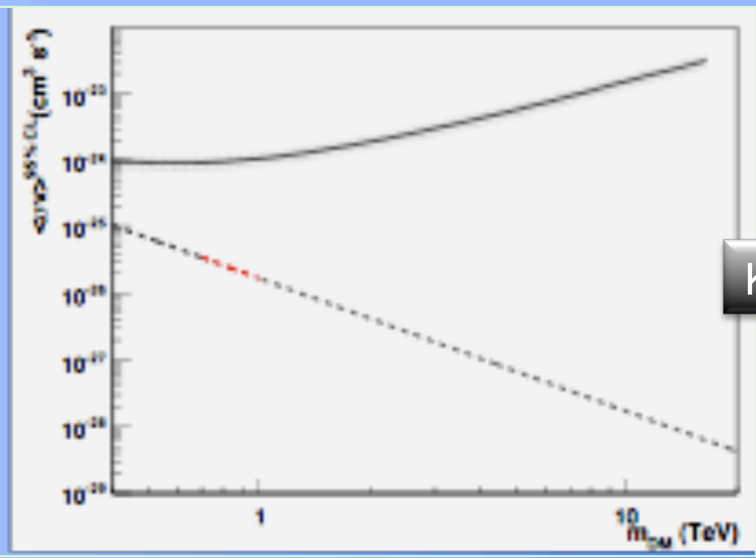


HESS observations of Canis Major

- 9.6 hours of exposure time in November 2006.
- ZA below 20º; E_{th} = 100 GeV ?
- No significant excess was found.
- They do not exclude any pMSSM or KK models compatible with WMAP+SDSS constraints.
- u.l. to CMa mass: 10^9 solar masses

pMSSM

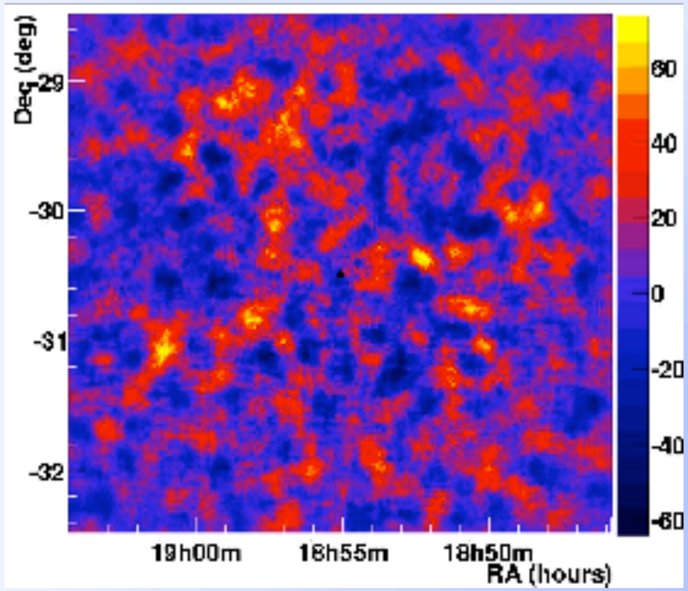




KK

Aharonian et al. (2009)

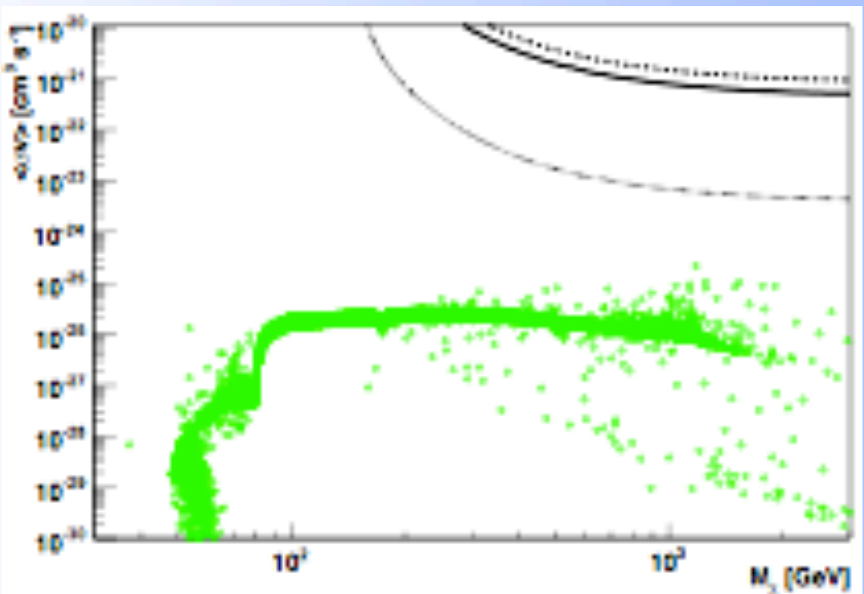
Results from other experiments



HESS observations of Saggitarius

- 11 hours of exposure time in June 2006.
- Average ZA of 19º; E_{th} = 250 GeV.
- No significant excess was found.
- They exclude some pMSSM models with a core DM density profile for Sgr.

Aharonian et al. (2007)



Whipple observations of Draco and UMi

- 14.3h (Draco) and 17.2h (UMi) of observation time in 2003.
- E_{th} = 400 GeV.
- No significant excess was found.
- Not possible to exclude any MSSM models.

Wood et al. (2008)

Latest results

[Results presented at the ICRC high-energy meeting in July]

- **VERITAS (100h):**
  - E_{th}=150 GeV.
  - They observed Draco, Ursa Minor, Willman 1, M5, M33, M32.
  - No signal was found.
  - For mSUGRA models, minimum required boost factors of the order of 1000.

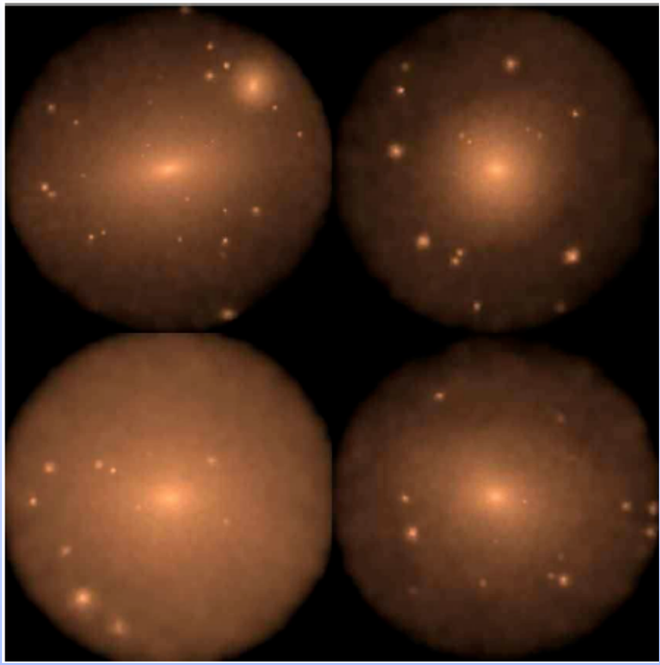
- **Fermi satellite (9 months of data)**:
  - E_{th}=200 MeV.
  - They observed 10 dSphs: Segue 1, Ursa Major II, Segue 2, Willman 1, Coma Berenices, Ursa Minor, Sculptor, Draco, Sextans, Fornax.
  - No signal found.
  - They also looked for possible DM spectral line signatures all over the sky: no hint of lines up to 300 GeV.

Boost factors

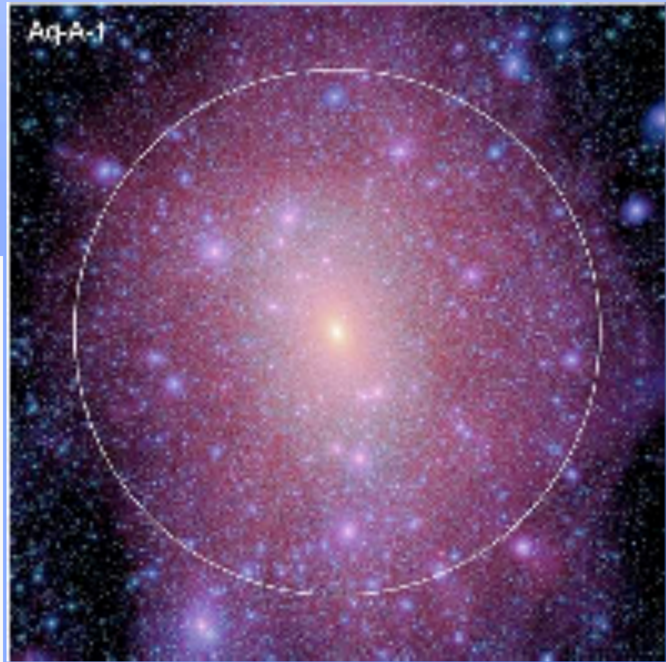
[Or how to increase the chances of detection]

Substructure

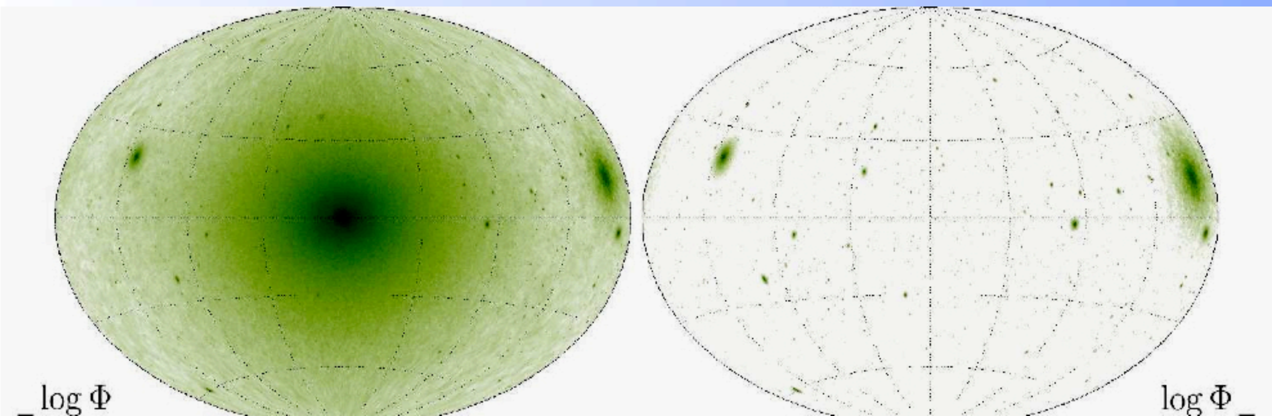
- Enhancement of the DM annihilation signal
  - A factor 2-3 for dwarfs according to VL-II
  - A factor >10 for MW size halos and galaxy clusters.
- Nearby subhalos good candidates for DM searches (microhalos?)
- Recent Aquarius simulation (Springel et al. 2008):
  - More subestructure than VL I-II simulations.
  - Less (sub-)subestructure than VL I-II simulations.
  - Different boost factors! More than 200 for clusters.
- VL-II vs Aquarius: substructure dominates the annihilation signal or not?



(Diemand et al. 2006)



(Springel et al. 2009)

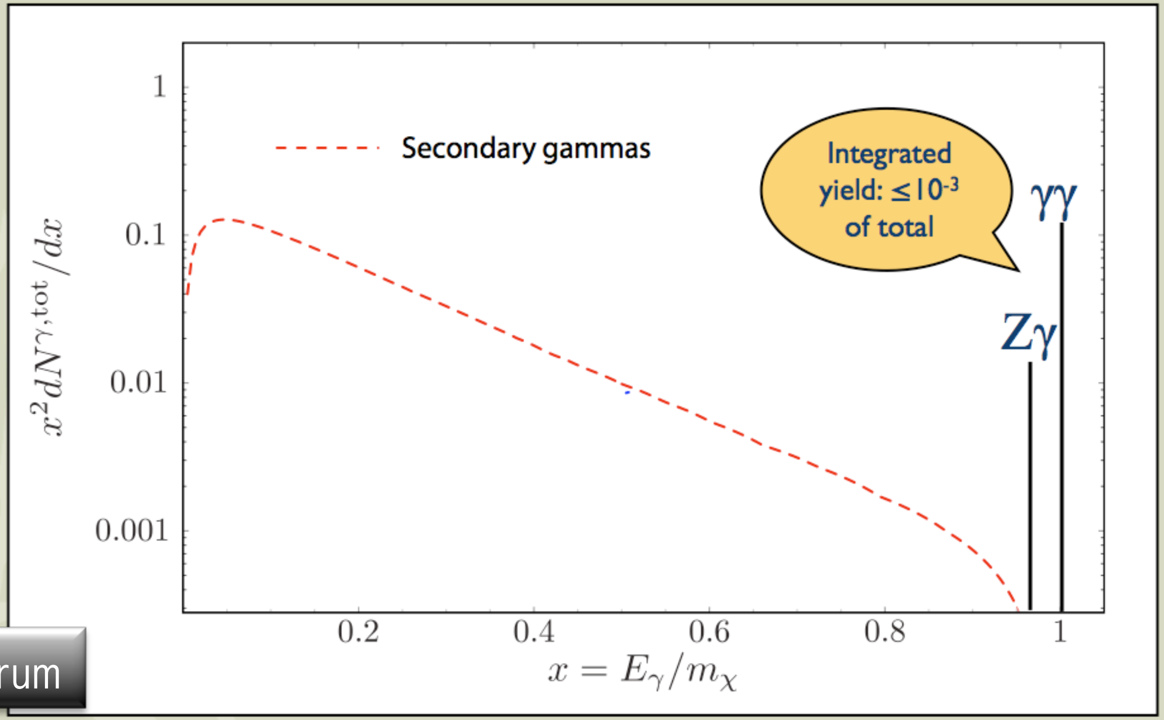


(Kuhlen et al. 2008)

Internal Bremsstrahlung

Commonly neglected first-order radiative corrections (IB) may be very important, specially for IACTs.

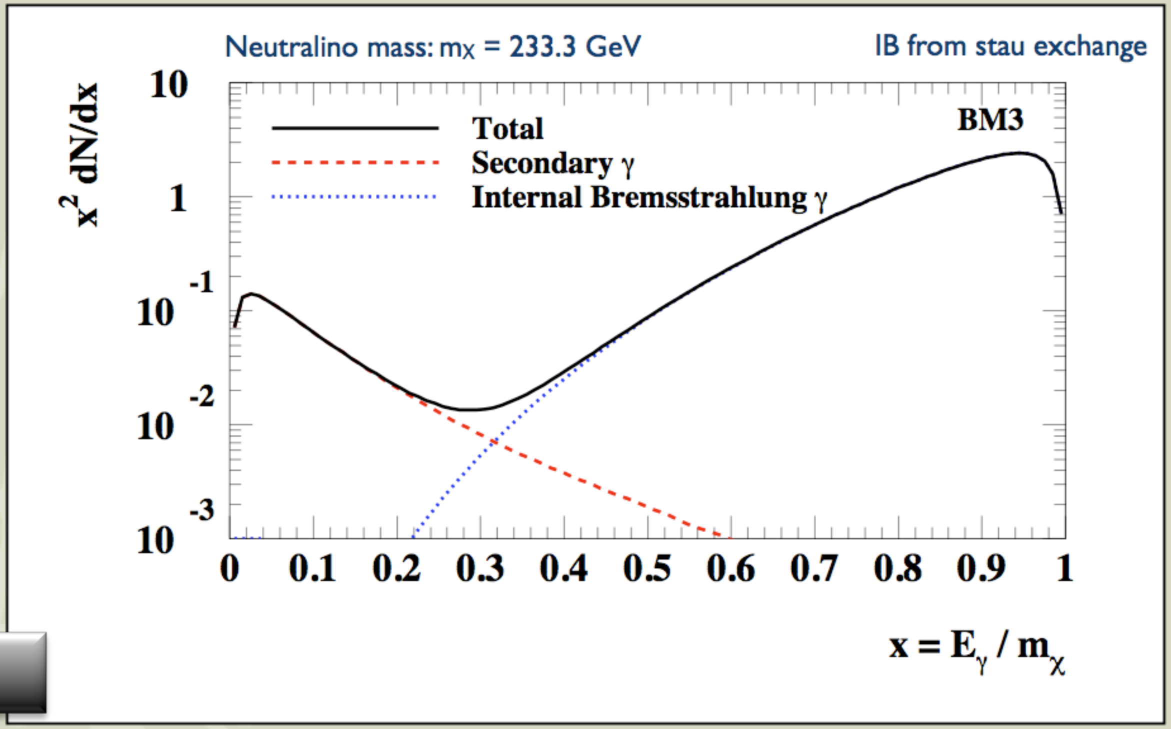
Typical gamma-ray annihilation spectrum



Boosts up to 3-4 orders of magnitude for some models.

Gomez talk!

IB at work!



T. Bringmann, L. Bergström and J. Edsjö, arXiv: 0710.3169, JHEP 01 (2008) 049

Sommerfeld effect

$\langle \sigma v \rangle_{\text{today}} = S \cdot \langle \sigma v \rangle_{\text{freeze-out}}$ **where** $S \sim 1/v$ **or** $S = 1/v^2$

- Typical velocities in the halo are $v/c \approx 10^{-3}$, compared to $v/c \approx 0.1$-1 in the early Universe, so S could be as high as 10^3 (10^6).
- Specially important for colder substructures (e.g. dSph galaxies).
- Neutralino masses of some TeV.

Kuhlen et al. (2009)

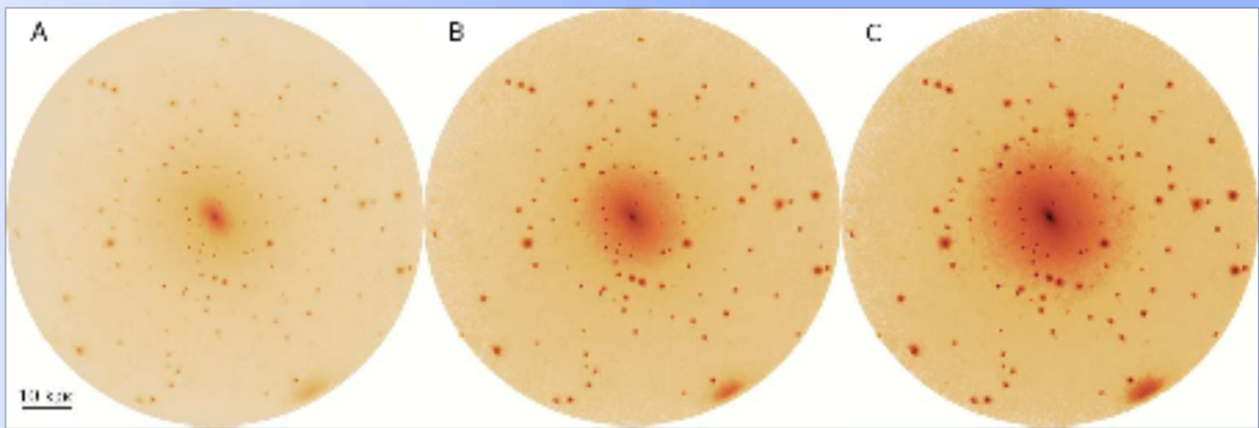
VL-II

$M = 2 \times 10^9\ M_{\odot}$

A: $S = 1$

B: $S \sim 1/v$

C: $S \sim 1/v^2$



L=1 L=2200 L=160000

But… how to be sure?

Despite the uncertainties in the flux, critical features in the spectrum will be universal:

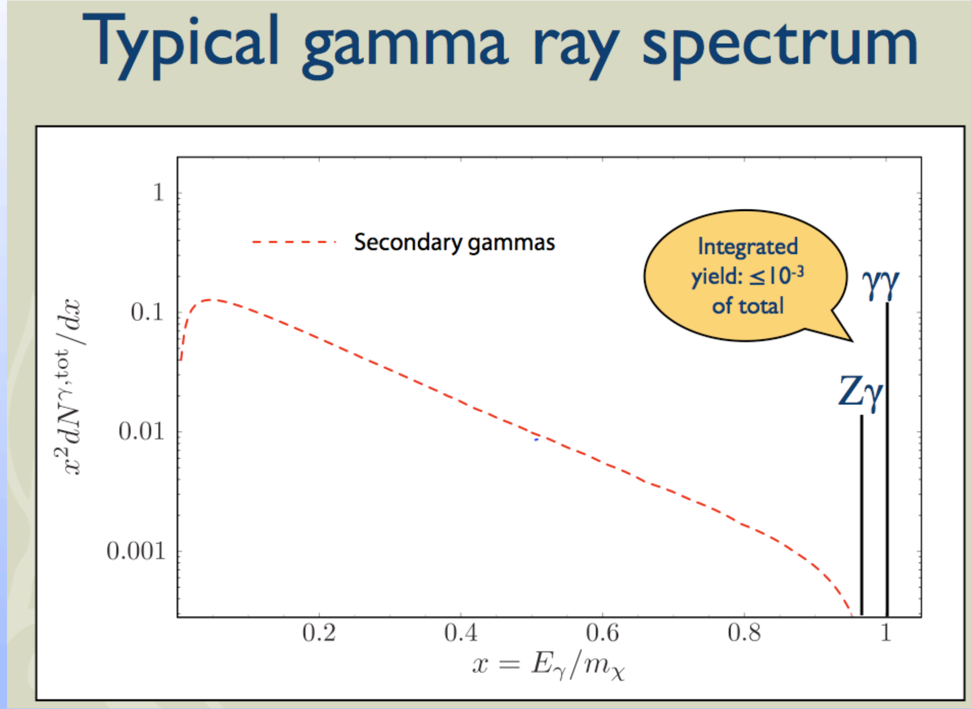
1) Monoenergetic lines -> smoking gun!

2) Continuum gamma-ray spectrum

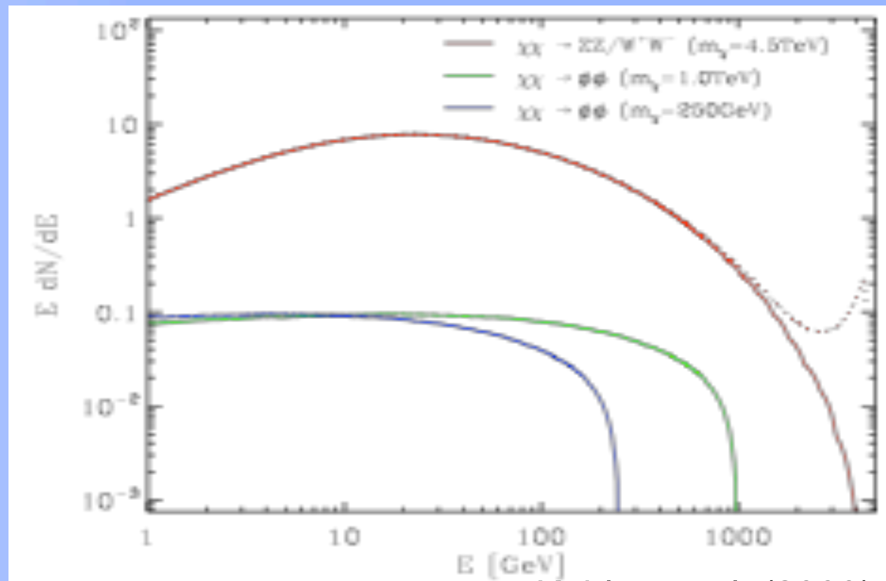
3) Cut-off at the energy of the mass particle

Independent of the source!

Direct detection should confirm it



Bringmann et al. (2008)



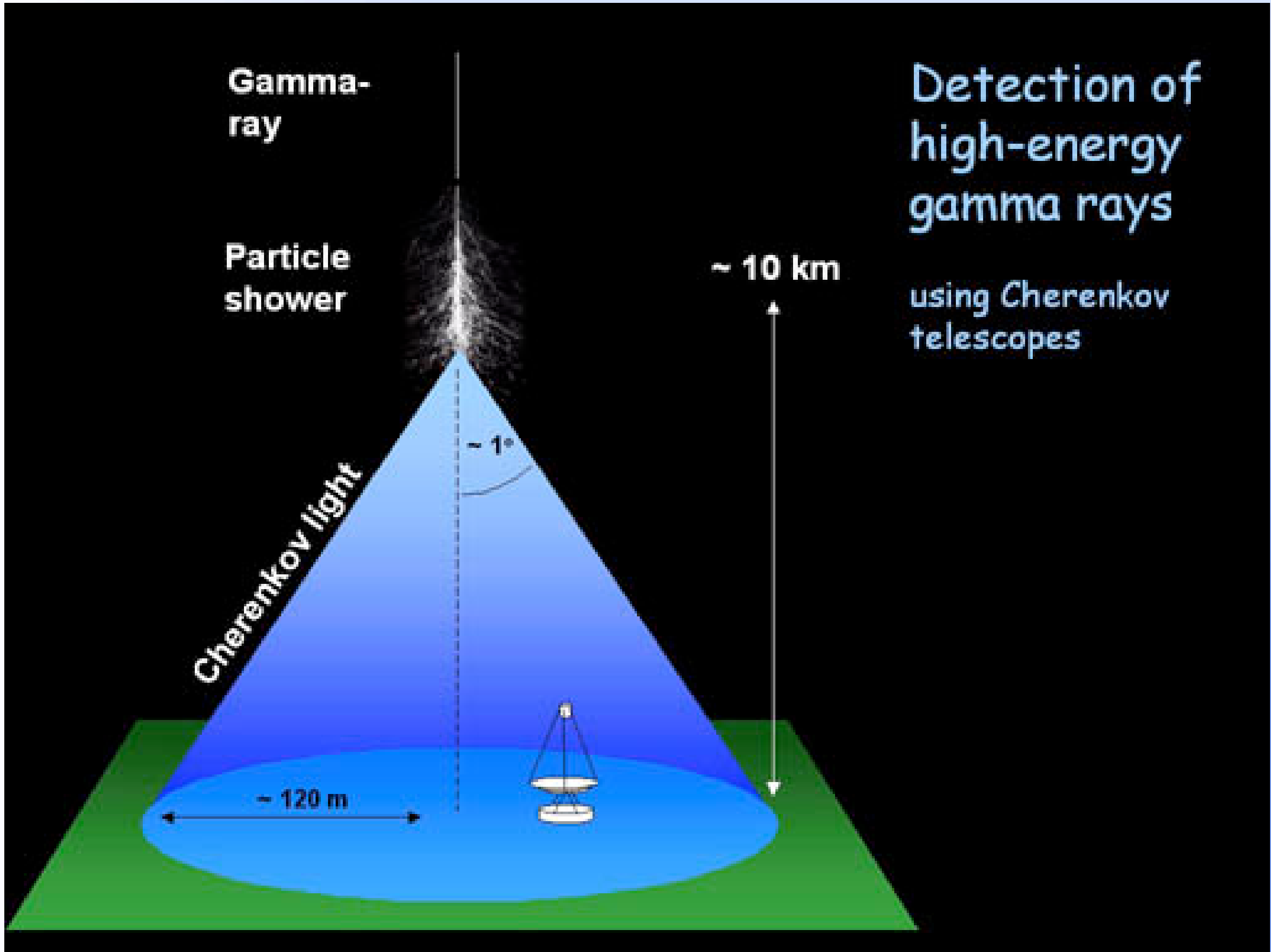
Kuhlen et al. (2009)

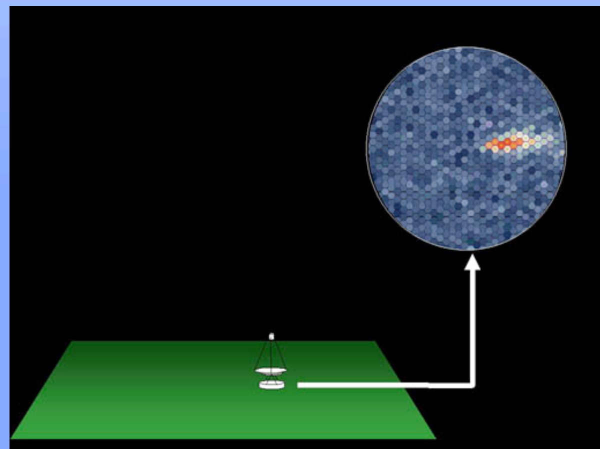
Future of γ-ray DM searches

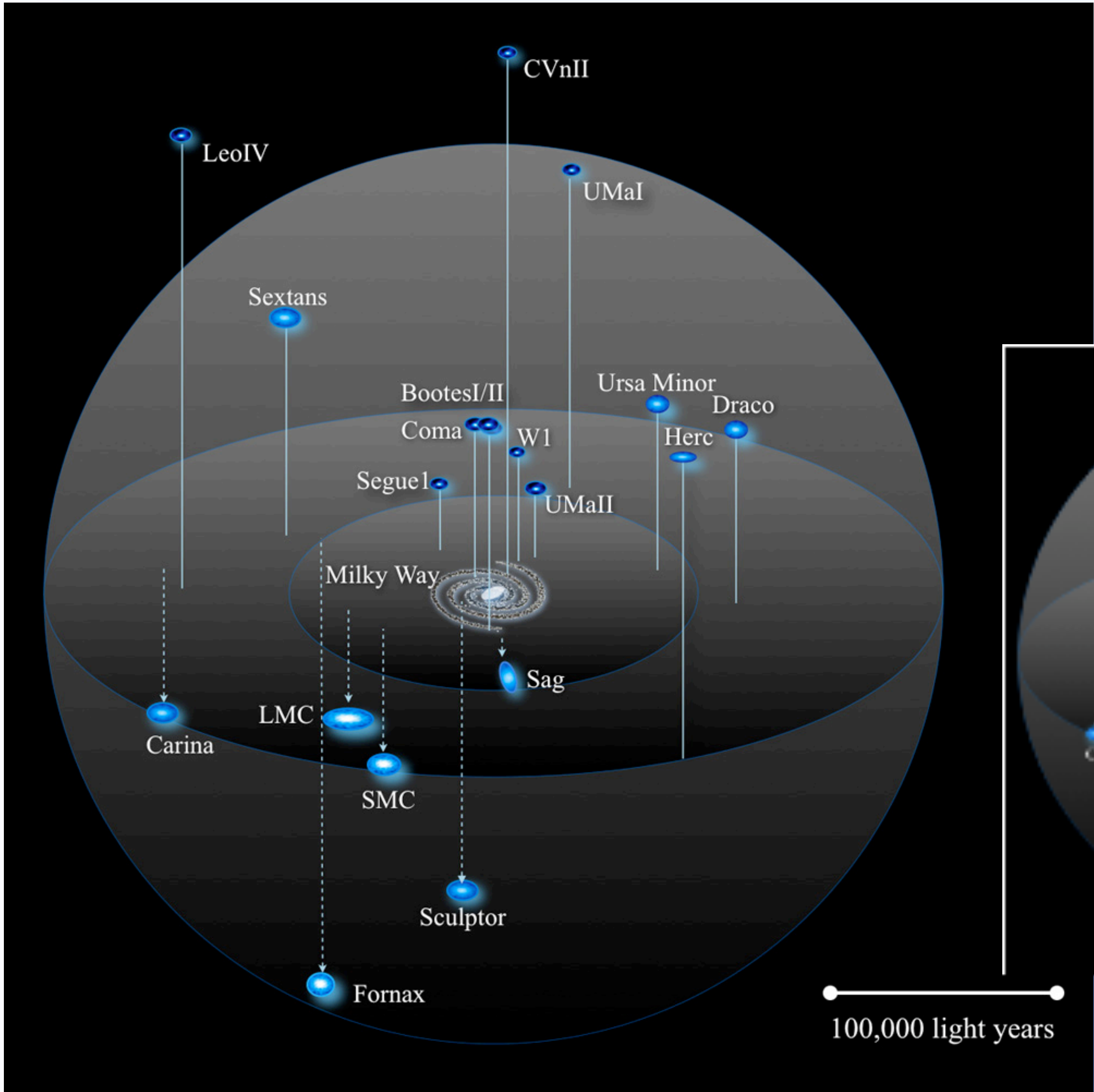
- No gamma-ray signal from DM annihilation has been detected up to now.
- DSph galaxies satellites of the MW probably the best candidates at present. However, galaxy clusters could be at the same flux level.
- Fermi especially important in DM searches:
  - All-sky survey -> great to seach for subestructure and new candidates!
  - IACT follow-up of the new DM candidates discovered by Fermi (complementary spectral ranges!).
- Instruments that join an improved sensitivity with a Large FoV: MAGIC II, CTA…
- Spectral information is crucial!
- From the theoretical side:
  - Explore and make predictions for other possible DM scenarios: IMBHs, microhalos, other particle physics models…
  - LHC will reduce the uncertainties coming from particle physics.
  - IB may be important, specially for IACTs.
  - Sommerfeld effect could be specially important for dwarfs.

BACKUP

IACT technique



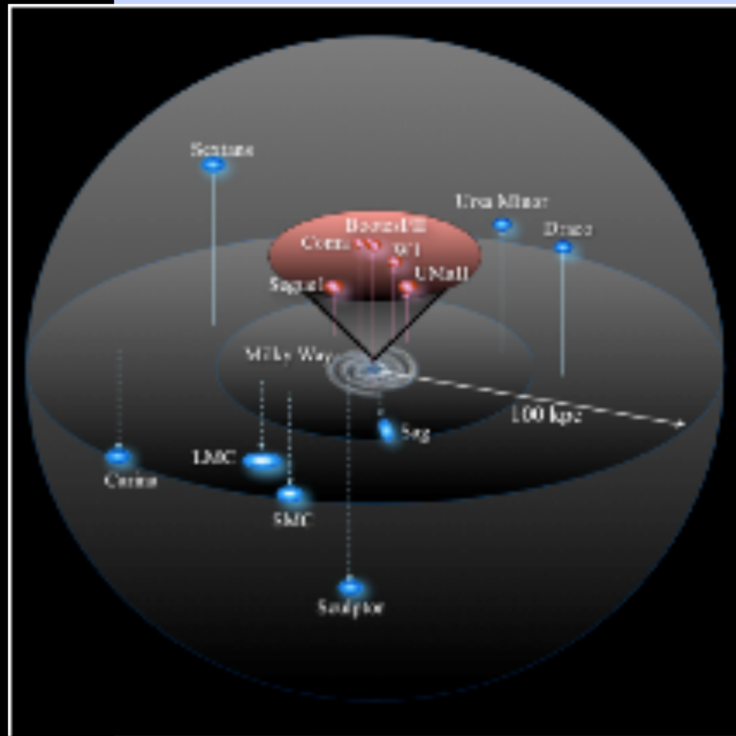




Detection complete up to 50 kpc

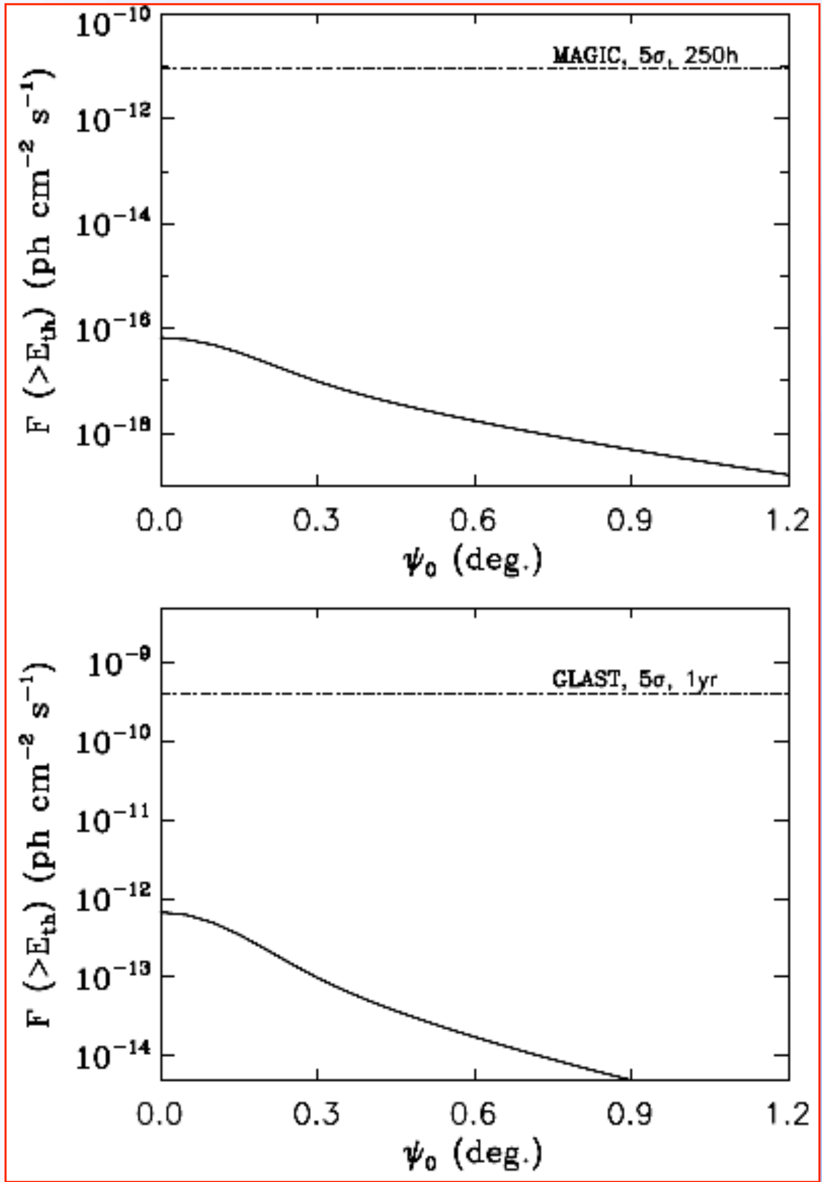
500 dSphs inside R_{vir}?

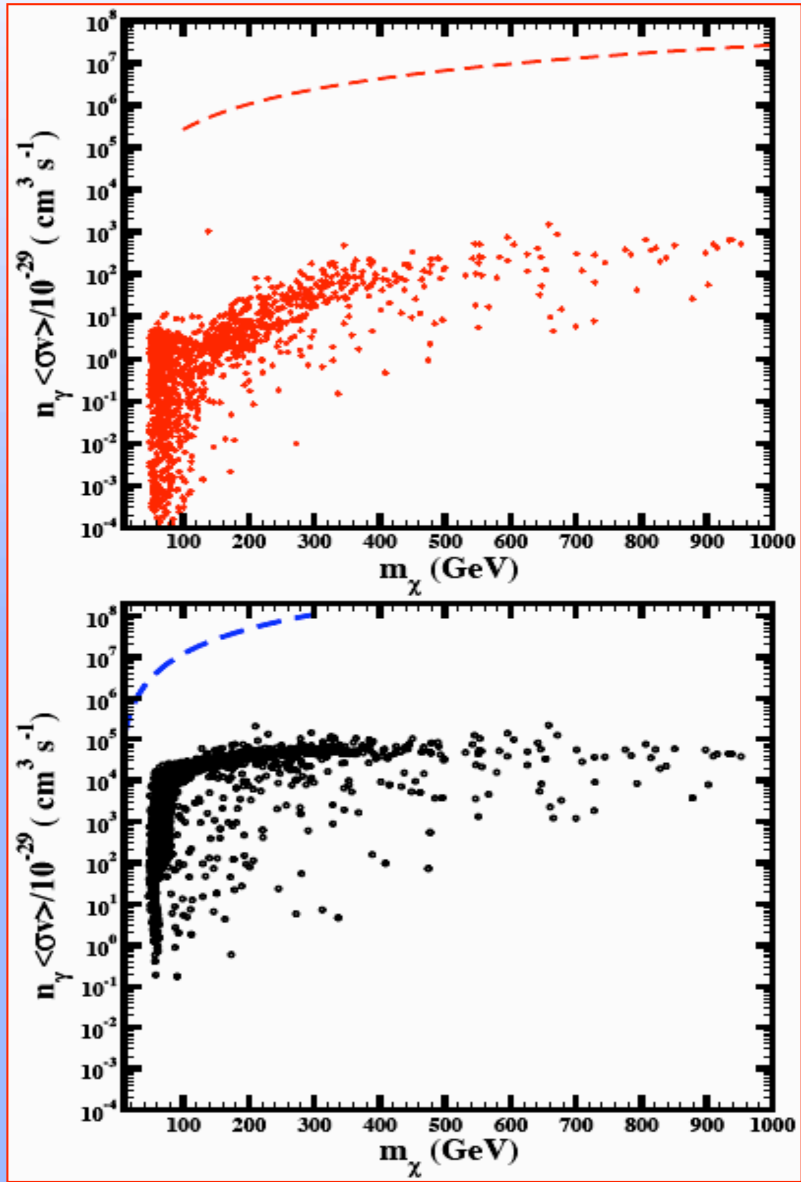
(Walsh et al. 2009; Tollerud et al 2008)



(Bullock et al. 2009)

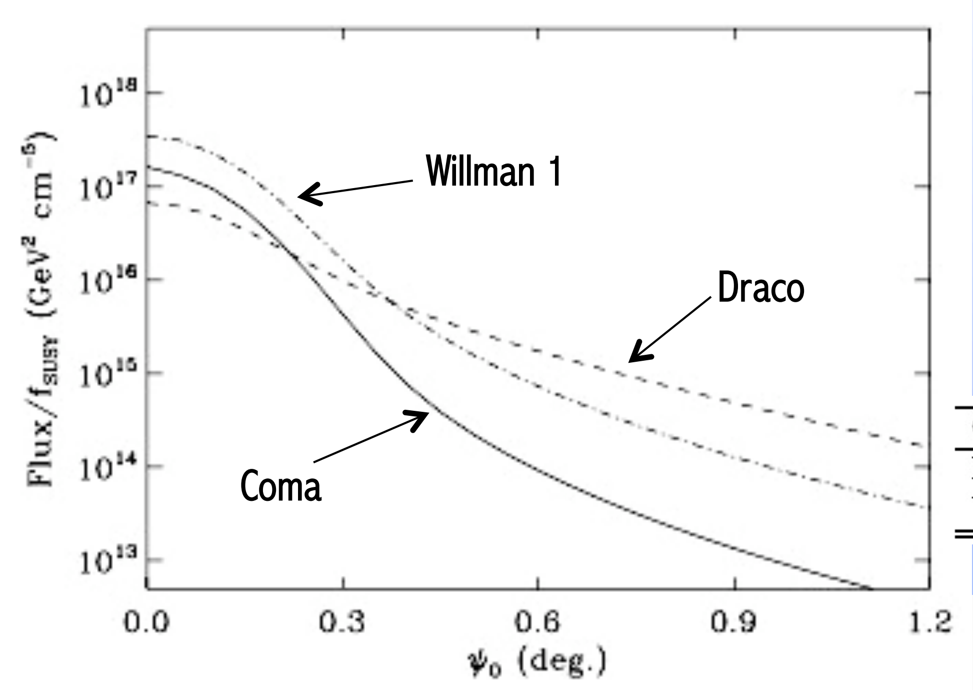
Detection prospects for Draco





(Sánchez-Conde et al. 2007)

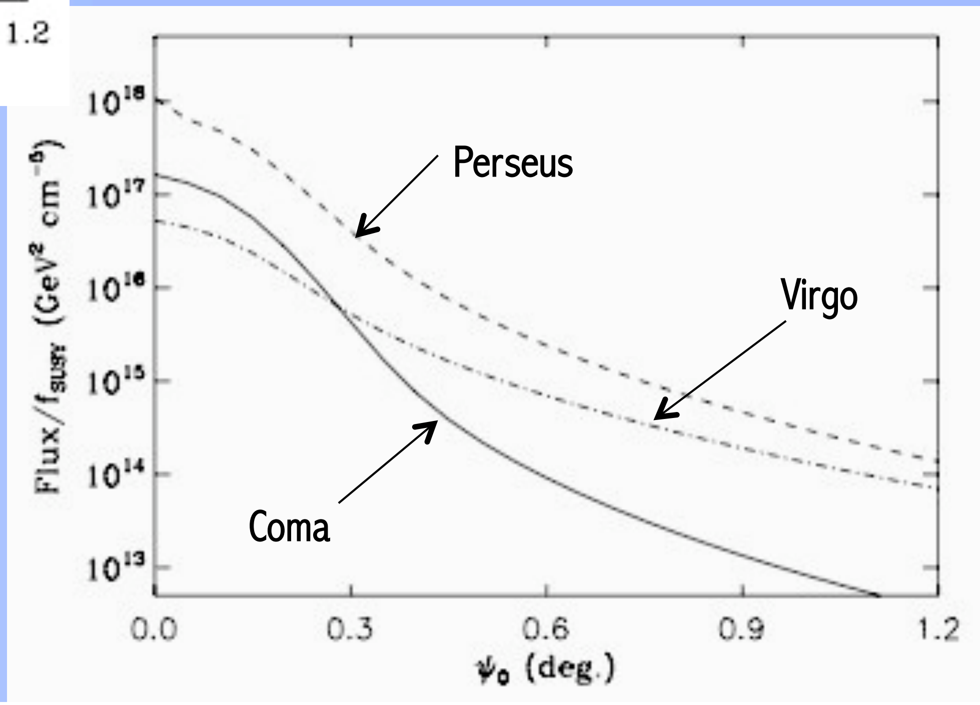
Galaxy Clusters



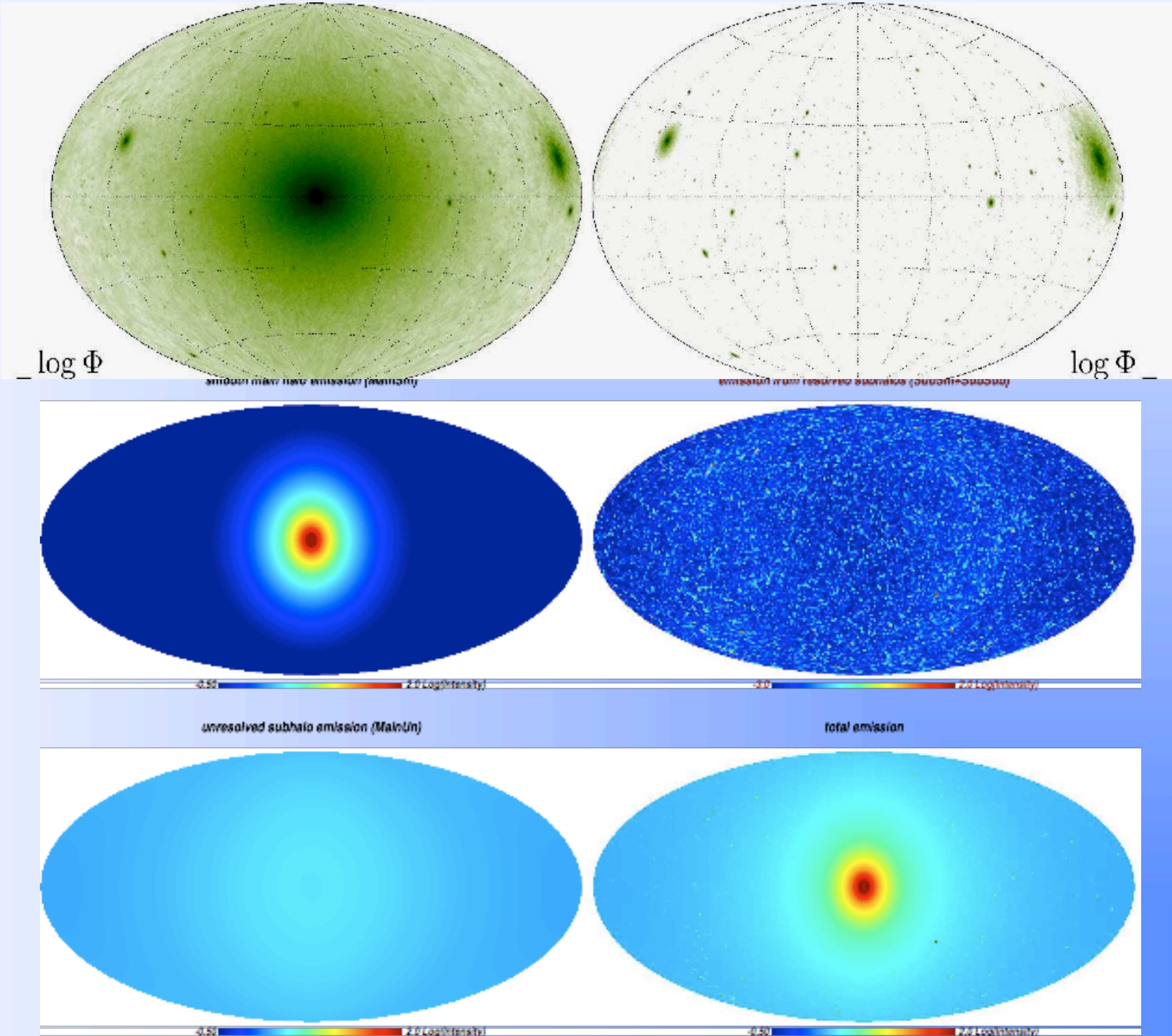
Parameters for COMA	
Distance (Mpc)	101.3
M_{vir} (M_{sun})	0.9×10^{15}
r_s (Mpc)	0.278
ρ_s (M_{sun}/Mpc^3)	1.06×10^{16}

Cluster	D (Mpc)	c	M_{vir} ($10^{15} M_{\odot}$)	r_s (Mpc)	ρ_s ($10^{15} M_{\odot}$ Mpc^{-3})
Perseus	77	6	0.9	0.463	9.26
Virgo	17	6.4	0.7	0.238	1.81

- Similar DM annihilation fluxes than those expected from dwarfs.
- Role of substructure more important in clusters (not included in figures).
- Gamma-ray observations also justified by non exotic physics -> problem: possible “contamination”



VL-II vs Aquarius

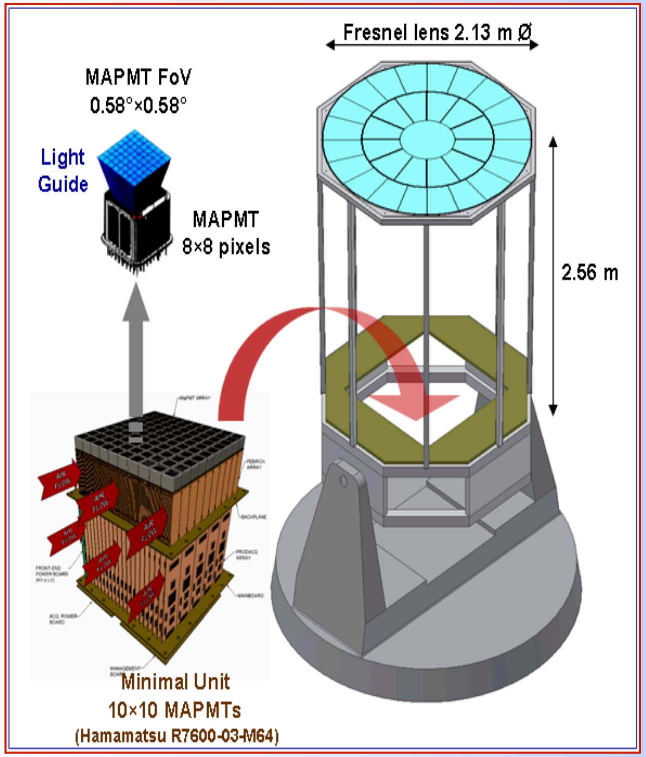


GAW: Gamma Air Watch

astro-ph/0707.4541

GAW is a R&D path-finder experiment for gamma-ray astronomy:

- 3 identical telescopes working in steoroscopic mode (80m side).
- Energy range: above 0.7 TeV.
- PSF around 0.2 deg.
- 24 x 24 deg. FoV (current IACTs 4x4 deg. Typically!).
- Main Goal: To test the feasibility of a new generation of IACT Cherenkov telescopes, which join high sensitivity with large Field of View.



Who

GAW is a collaboration effort of Research Institutes in Spain (IAA, US, UHU), Italy (INFN, U. La Sapienza) and Portugal (LIP).

How

Two phases:
- Phase I: first telescope will be completed, but only with a 6 x 6 deg. FoV (100 MAMPTs).
- Phase II devoted to the completion of the 2nd and 3rd telescopes. Full 24 x 24 deg. FoV.

Present Status

- The structure has just arrived and stored at CAHA.
- Fresnel lens under bidding process.
- Most of the rest of components already acquired.
- Counting house already built at CAHA.

Science with GAW

The GAW main scientific goal is to perform an **all-sky survey** above 0.7 TeV.

Phase I (6 x 6 deg)

- *Ultra-High Energy Photons from Blazars*
- *Ultra-High Energies from SNRs*
- *Ultra-High Energies from GRBs*
- *Microquasars*
- *Follow-up of EGRET, AGILE and GLAST sources*

Phase II (24 x 24 deg; 3 telescopes)
(Topics of Phase I also included!)

- *Dark Matter Searches*
- *GAW all-sky survey*

More info: http://gaw.ifc.inaf.it

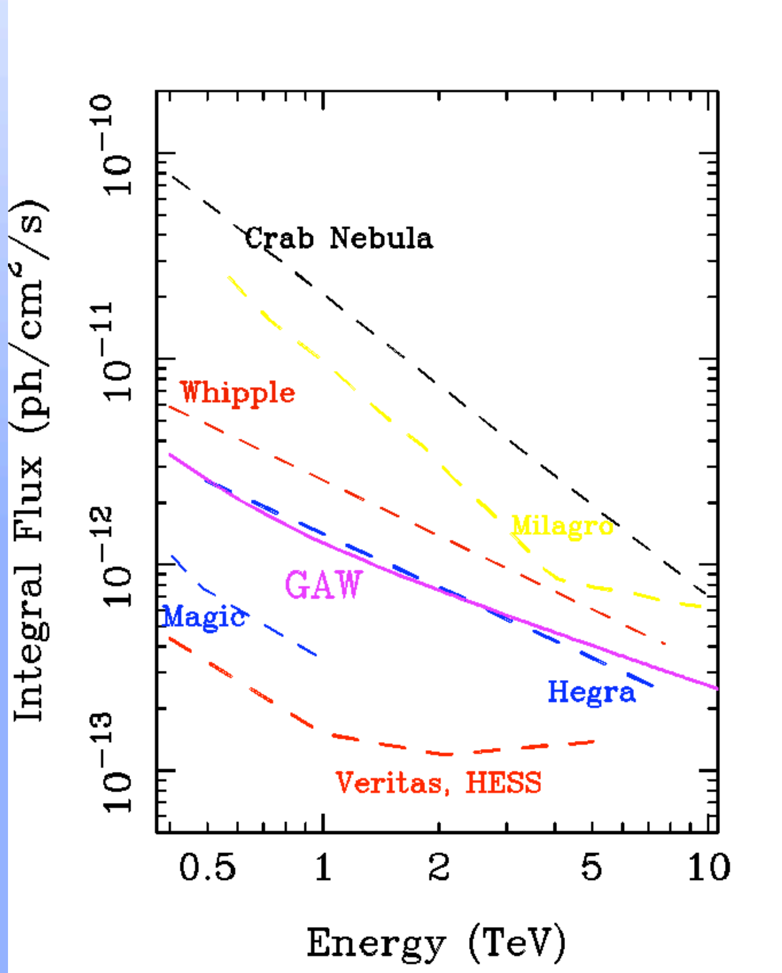
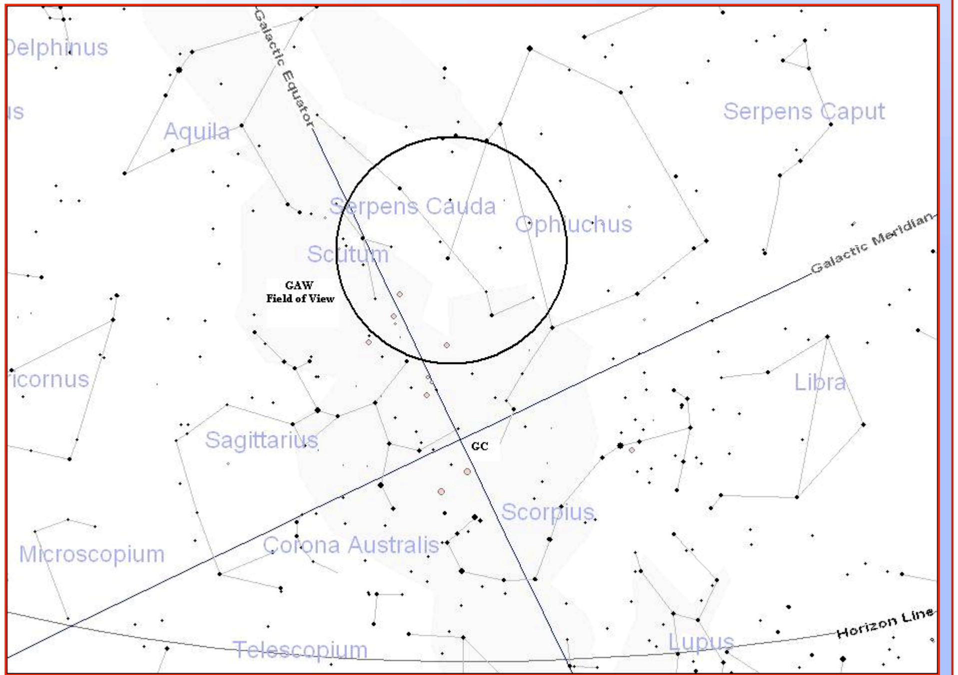
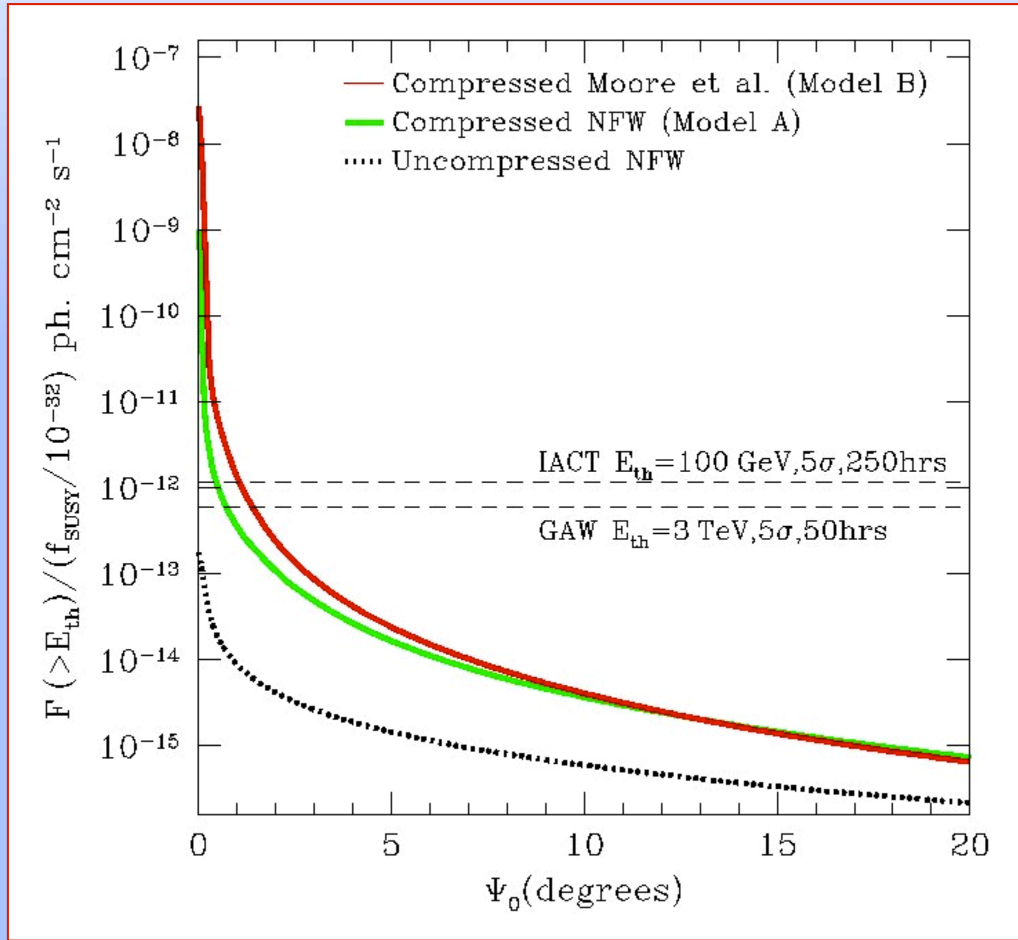


FIGURE: GAW Sensitivity compared to other ACTs

GAW and DM searches: (far from) the GC



450 sq. degrees with a GAW pointing 20° north from the GC



GC flux estimations and GAW prospects