REVIEW OF DARK MATTER SEARCHES WITH CHERENKOV TELESCOPES

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Outline

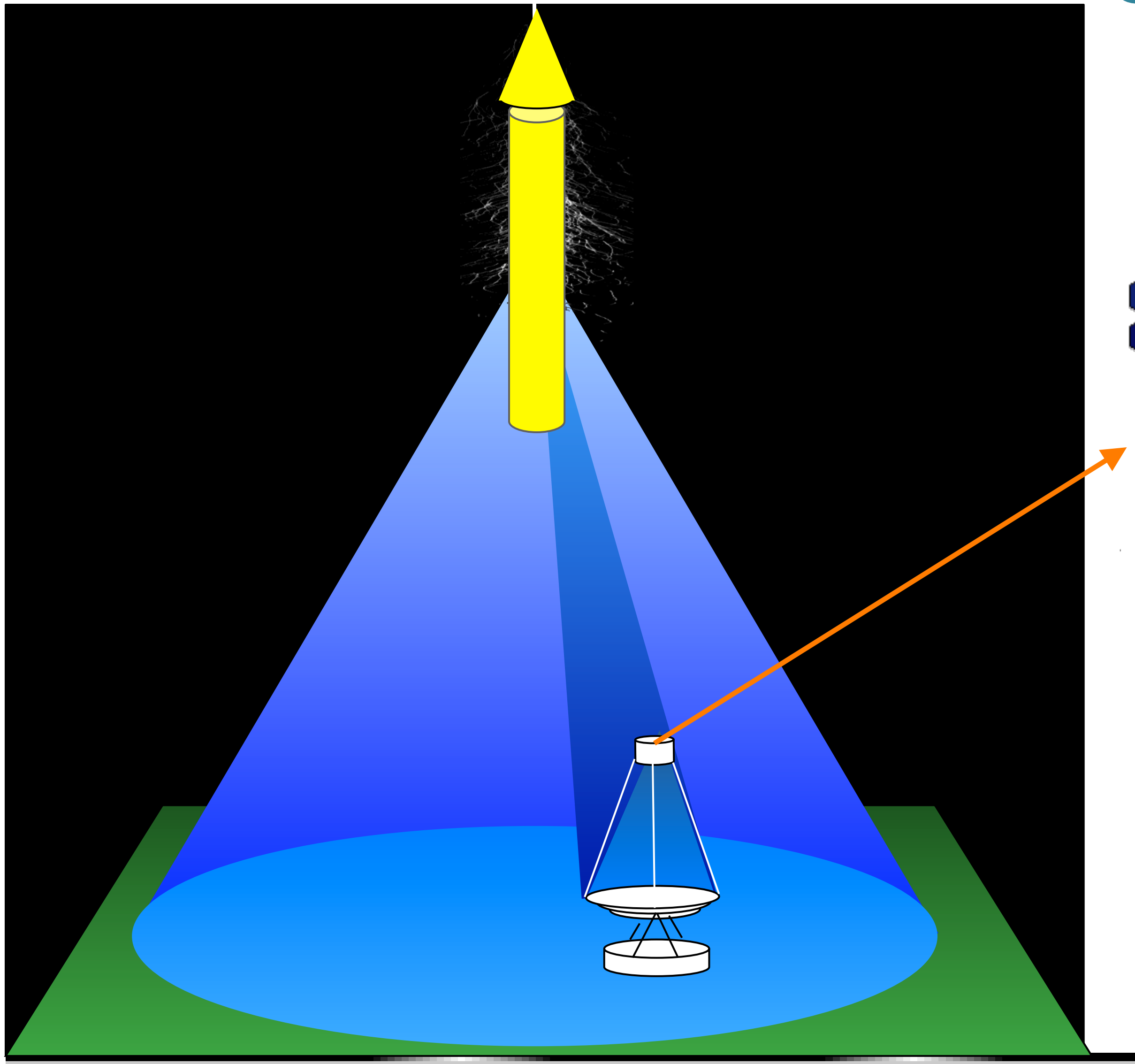
- VHE astronomy with Cherenkov Gamma-ray Telescopes
- Dark matter searches with Cherenkov telescopes
  - Indirect dark matter searches with gamma rays
  - Searches in the Galactic center and halo
  - Searches in galaxy clusters
  - Searches in dwarf spheroidal galaxies
  - Spectral features in the electron (positron) spectrum
- Discussion: how to go further
- Conclusions

CHERENKOV GAMMA RAY TELESCOPES

VHE Gamma-Ray Astronomy

- One of the pillars of Astroparticle Physics
- VHE gamma rays (100 GeV – 100 TeV) produced in non-thermal processes → insight into the mechanisms of the Universe at its extreme
- VHE Gamma-ray astronomy addresses three broad science themes:
  - Cosmic particle acceleration, propagation and interaction
  - Probing extreme environments (pulsars, black holes, …)
  - Physics frontiers (DM, LIV,…)
- Young field, in rapid evolution led by Cherenkov telescopes
  - 1st generation (80 – 90's): Whipple, HEGRA, …
  - 2nd generation (2000's – present): MAGIC, HESS, VERITAS
  - 3rd generation (2020 – 2050?): CTA

Imaging technique



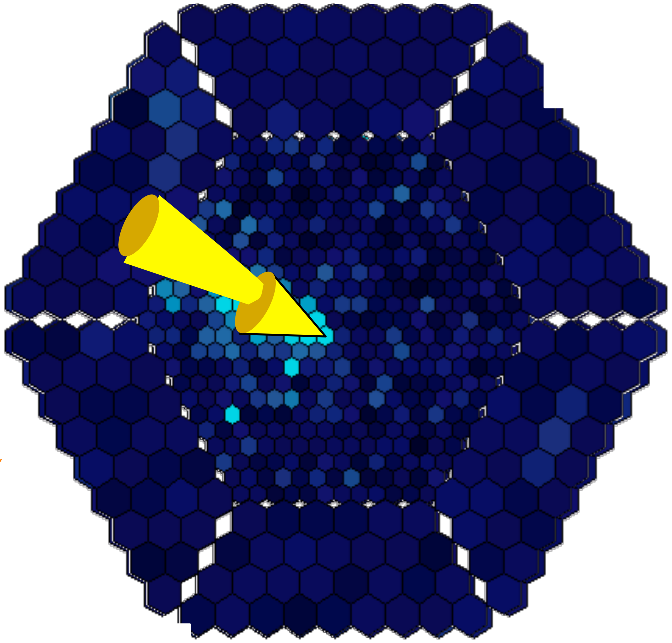
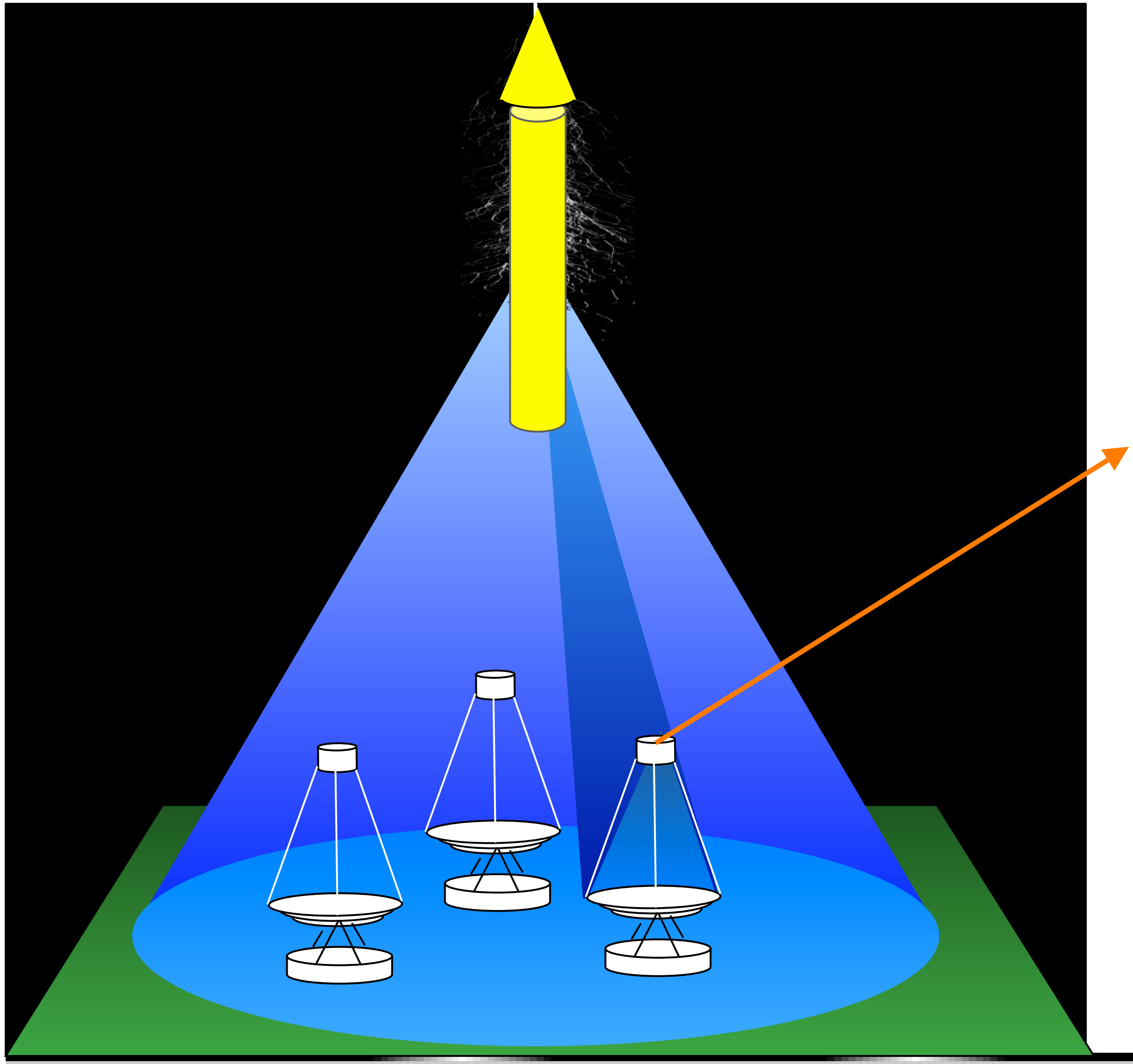


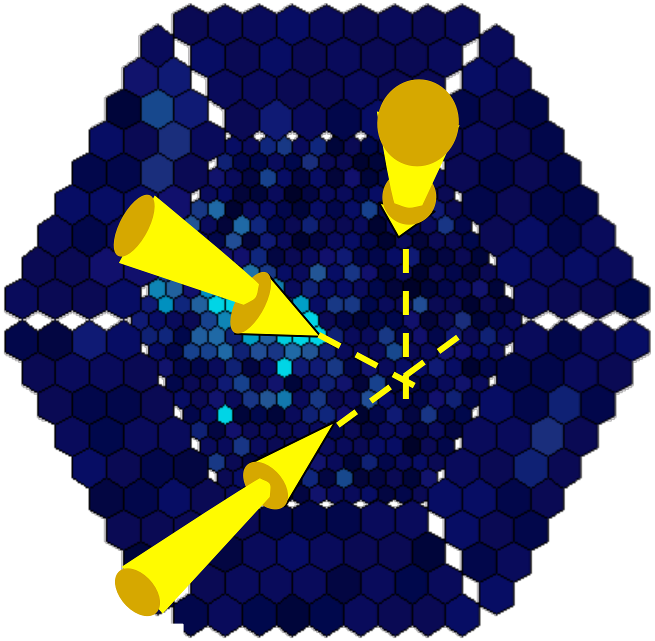
Image intensity
→ Energy of primary

Image orientation
→ Direction of primary

Image shape
→ Kind of primary

Stereoscopy





Better determine:

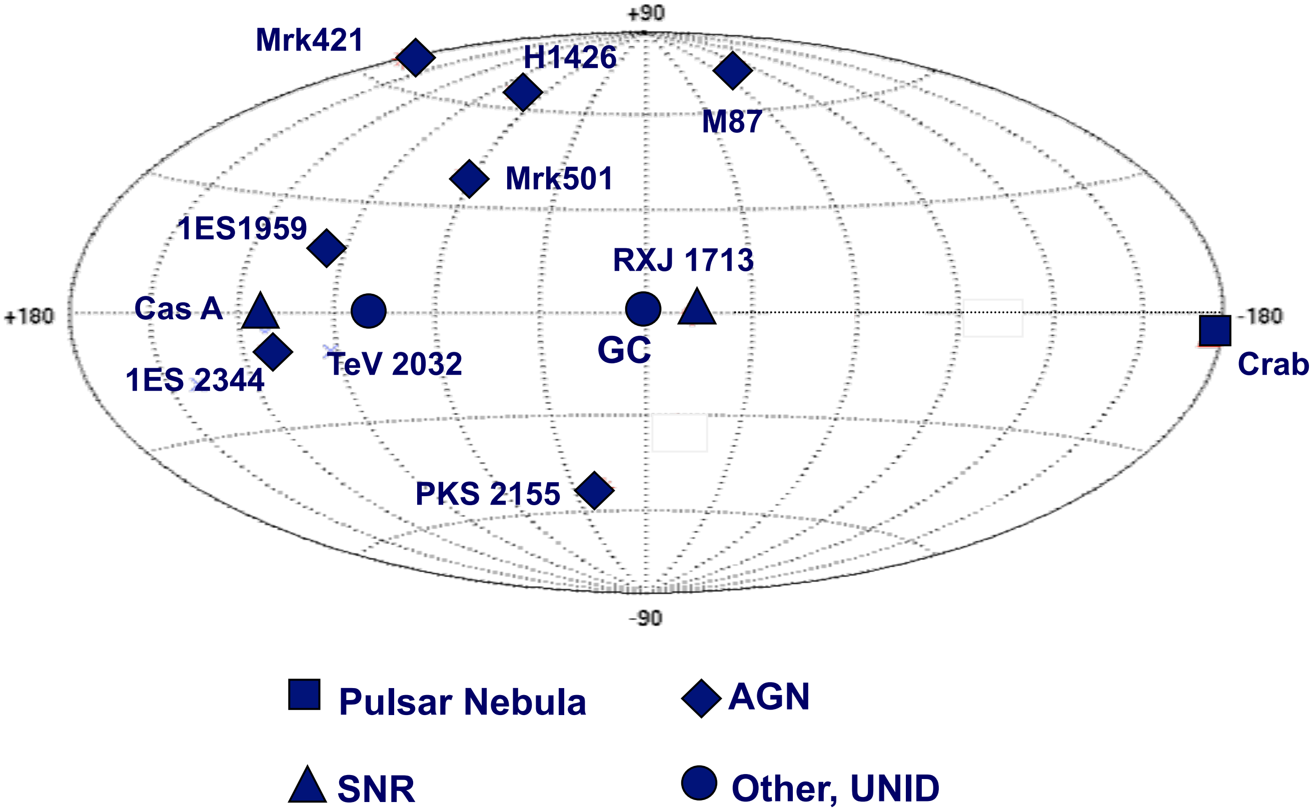
- Energy
- Direction

→ Better discrimination between gammas and CRs

Ground-based Gamma-ray Astronomy

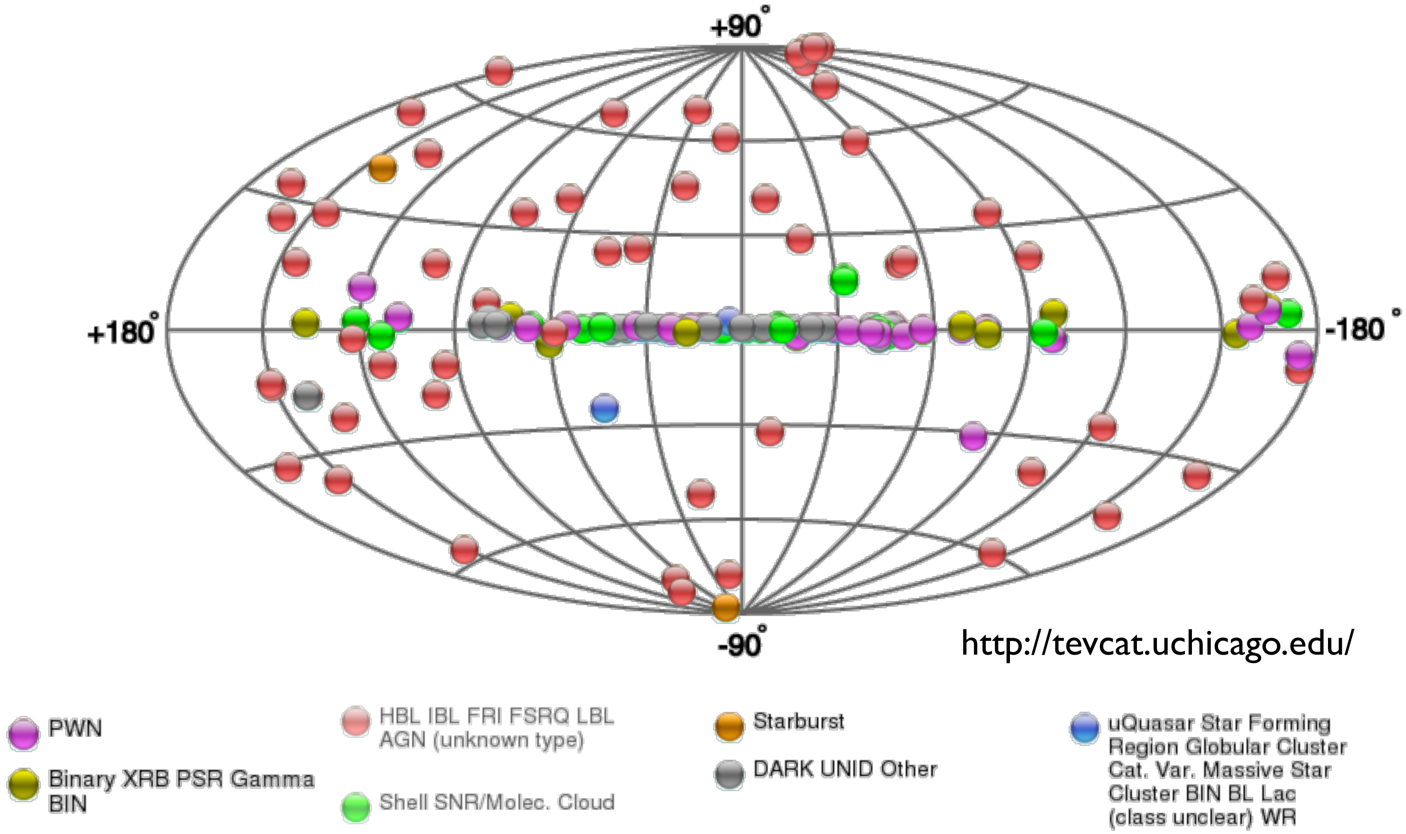
- Gamma-ray fluxes drop exponentially with energy → for E > ~100 GeV we need large collection areas → Cherenkov telescopes
- Huge CR background → Imaging technique
- Energy range ~100 GeV – 100 TeV
- Energy resolution 10 – 15%
- Angular resolution ~0.1° at 1 TeV
- Field of view 3 – 5 deg (~0.005 sr)
- Pointed observations, systematic scans of limited regions
- Several telescopes for better performance

The VHE sky in 2003



Total: 12 sources

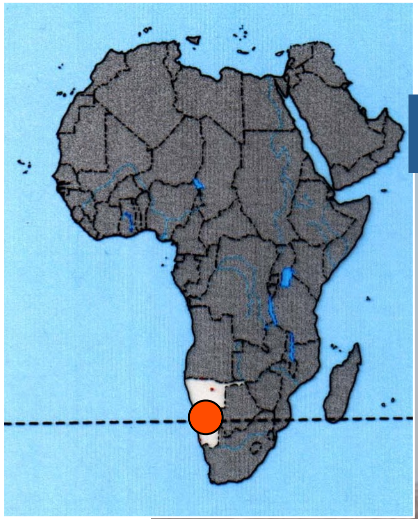
The VHE sky in 2014



http://tevcat.uchicago.edu/

Total: ~150 sources

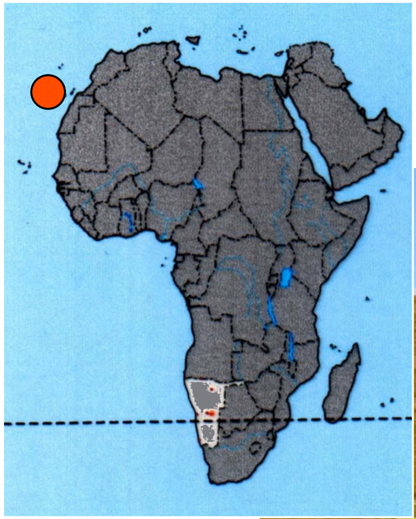
H.E.S.S



- 4 × 12m since 2003
- + 1 × 28m since 2012 (expecting results any moment)
- 5 deg FoV
- Optimal view on the Galactic central region → high impact

- Collaboration: Germany + France + UK + Namibia + South Africa + Czech Republic + Ireland + Armenia + Poland + Australia + Austria + Sweden + USA

MAGIC

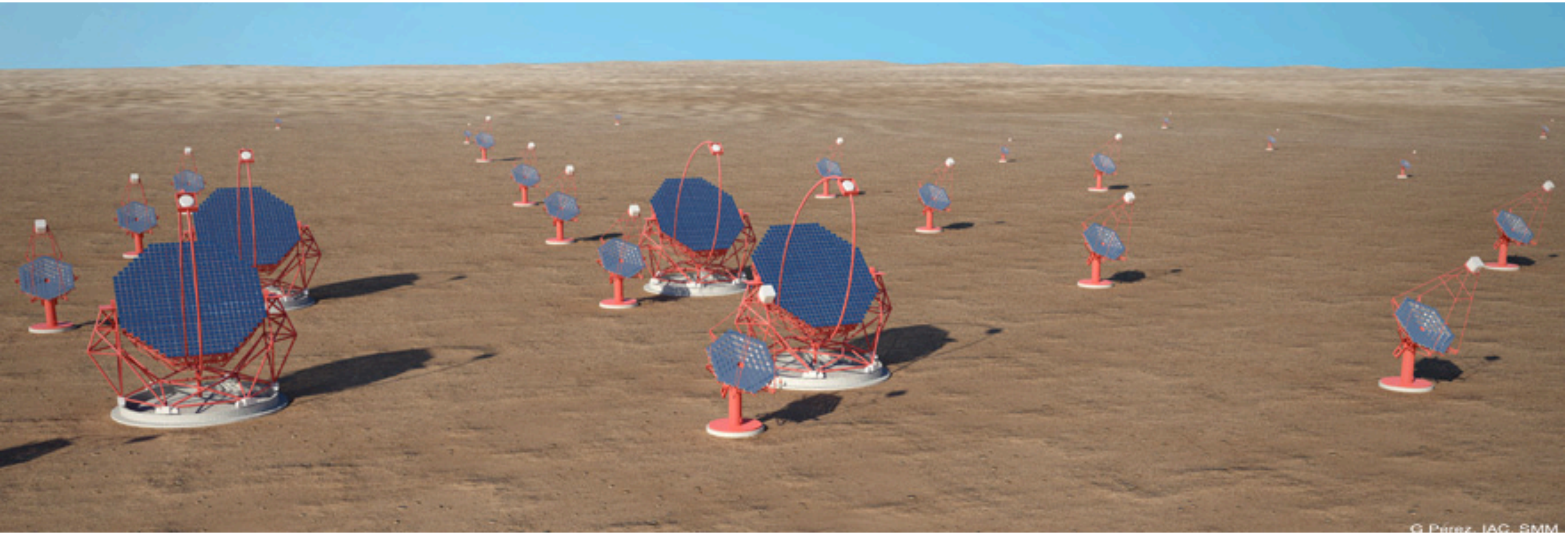


- 2 telescopes (2004, 2009)
- 17 m diameter → 50 GeV energy threshold
- Fast movement to catch fast transients (GRBs)
- Full electronics upgrade (2011) and camera of MAGIC 1 replaced (2012)
- Collaboration: Germany + Spain + Italy + Switzerland + Poland + Croatia + Japan + Bulgaria + Finland

VERITAS

- 4 telescopes (2007)
- 12 m diameter
- Full camera PMTs upgraded (2012)
- 500 pixel/camera
- 3.5 diameter FoV
- Collaboration: USA + Canada + Ireland + UK

Cherenkov Telescope Array

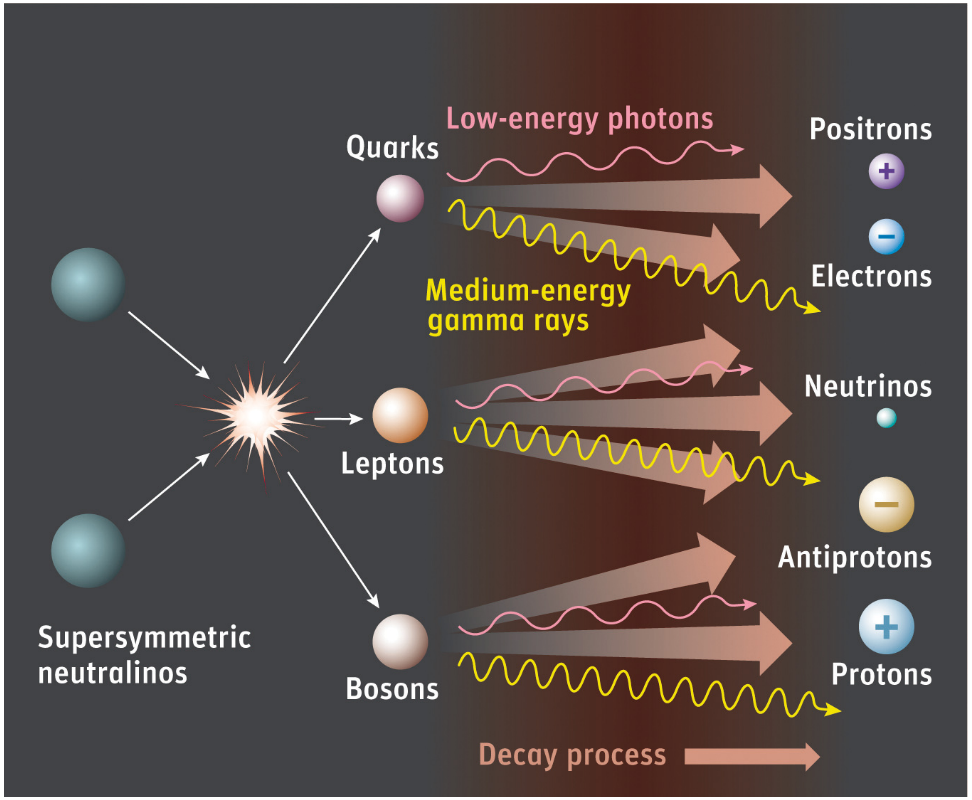


- Northern and Southern sites
- Up to 150 telescopes of 3 different dish sizes
- 10 times better sensitivity
- Energy range 10 GeV – 300 TeV
- Improved angular and energy resolutions
- Operated as an open observatory

DARK MATTER SEARCHES WITH CHERENKOV TELESCOPES

Indirect dark matter searches

$$\text{DM DM} \longrightarrow e^{\pm}, \bar{p}, \gamma, \nu$$



- Charged cosmic rays
  - diffuse through magnetic field
  - anomaly in isotropic CR spectrum
  - positron fraction excess
- Neutrinos
  - point back to the source
  - can escape compact objects
- Photons
  - point back to the source
  - spectral and spatial features
  - gamma-ray domain

Gamma-ray fluxes

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

Annihilation

Particle Physics term

$$\frac{d\Phi^{PP}_{ann}}{dE} = \frac{\langle \sigma_{ann} v \rangle}{8\pi m_\chi^2} \frac{dN}{dE}$$

m_χ – dark matter particle mass

$<\sigma_{ann} v>$ – thermally thermally averaged annihilation cross section times velocity

dN/dE – differential gamma-ray yieldper annihilation

Fixed by the model, source-independent

Astrophysical term

$$J_{ann}(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{los} \rho^2(l,\Omega) dl$$

ρ – dark matter density

$\Delta\Omega$ – solid angle

l – line of sight

Depends on the given source, on the dark matter distribution and on the instrument

Gamma-ray fluxes

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

Decay

Particle Physics term

$$\frac{d\Phi^{PP}_{ann}}{dE} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN}{dE}$$

τ_χ – dark matter particle lifetime

$$<\sigma_{ann} v> / \ 2m_\chi^{\ 2} \longrightarrow 1 / m_\chi \tau_\chi$$

Fixed by the model, source-independent

Astrophysical term

$$J_{ann}(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{los} \rho(l,\Omega) dl$$

$$\rho^2 \longrightarrow \rho$$

Depends on the given source, on the dark matter distribution and on the instrument

Observed targets

Target	Year	Time	Experiment
Globular Clusters			
M15	2002	0.2	Whipple
	2006–2007	15.2	H.E.S.S.
M33	2002–2004	7.9	Whipple
M32	2004	6.9	Whipple
NGC 6388	2008–2009	27.2	H.E.S.S.
Dwarf Satellite Galaxies			
Draco	2003	7.4	Whipple
	2007	7.8	MAGIC
	2007	18.4	VERITAS
Ursa Minor	2003	7.9	Vhipple
	2007	18.9	VERITAS
Sagittarius	2006	11	H.E.S.S.
Canis Major	2006	9.6	H.E.S.S.
Willman 1	2007–2008	13.7	VERITAS
	2008	15.5	MAGIC
Sculptor	2008	11.8	H.E.S.S.
Carina	2008–2009	14.8	H.E.S.S.
Segue 1	2008–2009	29.4	MAGIC
	2010–2011	48	VERITAS
	2010–2013	158	MAGIC
Boötes	2009	14.3	VERITAS

Target	Year	Time	Experiment
Galaxy Clusters			
Abell 2029	2003–2004	6	Whipple
Perseus	2004–2005	13.5	Whipple
	2008	24.4	MAGIC
Fornax	2005	14.5	H.E.S.S.
Coma	2008	18.6	VERITAS
The Milky Way central region			
MW Center	2004	48.7	H.E.S.S.
MW Center Halo	2004–2008	112	H.E.S.S.
Other searches			
IMBH	2004–2007	400	H.E.S.S.
	2006–2007	25	MAGIC
Lines	2004–2008	112	H.E.S.S.
	2010–2013	158	MAGIC
UFOs	–	–	MAGIC
	–	–	VERITAS
All-electron	2004–2007	239	H.E.S.S.
	2009–2010	14	MAGIC
Moon-shadow	–	–	MAGIC

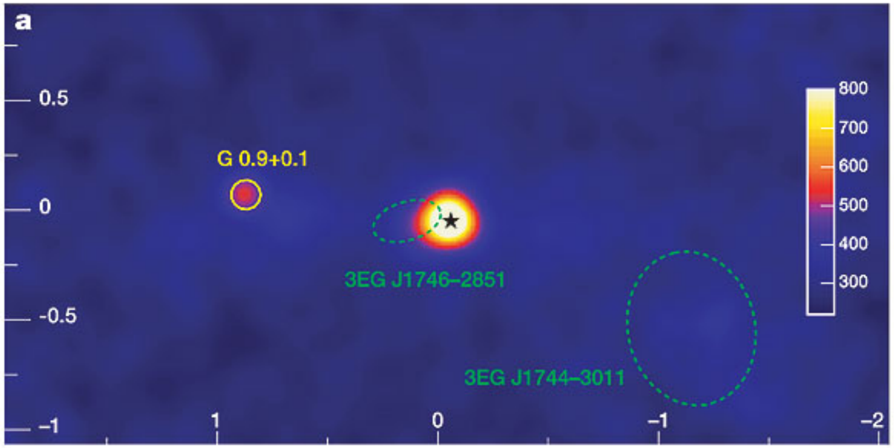
Doro, NIM A742 (2014) 99

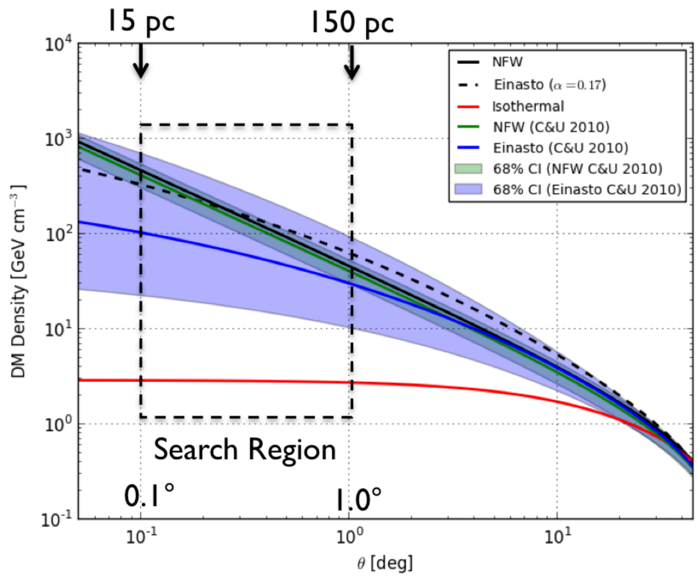
EXPERIMENTAL RESULTS

Galactic center and halo

- Highest J-factor from Earth, thanks to proximity
- Obvious target for dark matter searches
- Two main drawbacks:
  - Astrophysical background:
    - Central source HESS J2745-290
    - Diffuse from CR interactions with molecular clouds
  - Uncertain central DM distribution:
    - SMBH can create DM spike or soften cusp
    - Adiabatic contraction from baryon in-fall would increase DM concentration
    - Feedback would flatten DM distribution

Aharonian et al. 2006, Nature 439, 695



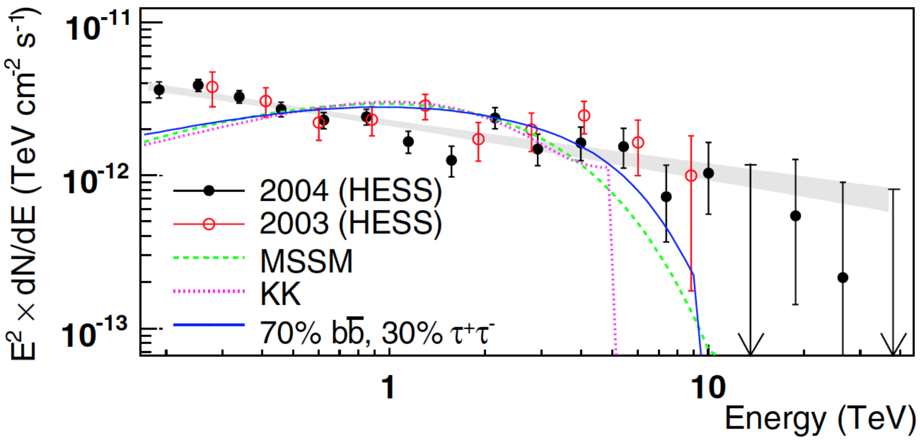


Galactic center observations

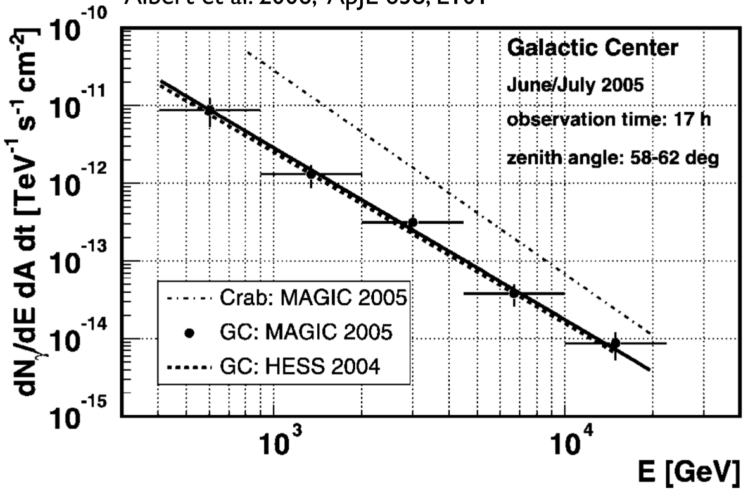
Instrument	Year	T [h]	E [TeV]
HESS	2003	17	0.2-10
HESS	2004	49	0.2-30
MAGIC	2005	17	0.4-20

- Intense central source ~10% Crab at 1 TeV plus extended diffuse emission
- Steady flux
- Pure power law spectrum, no DM features seen
- Limits relatively weak (~10^{-23} $cm^3 s^{-1}$) due to high astrophysical background

Aharonian et al. 2006, PRL 97, 221102



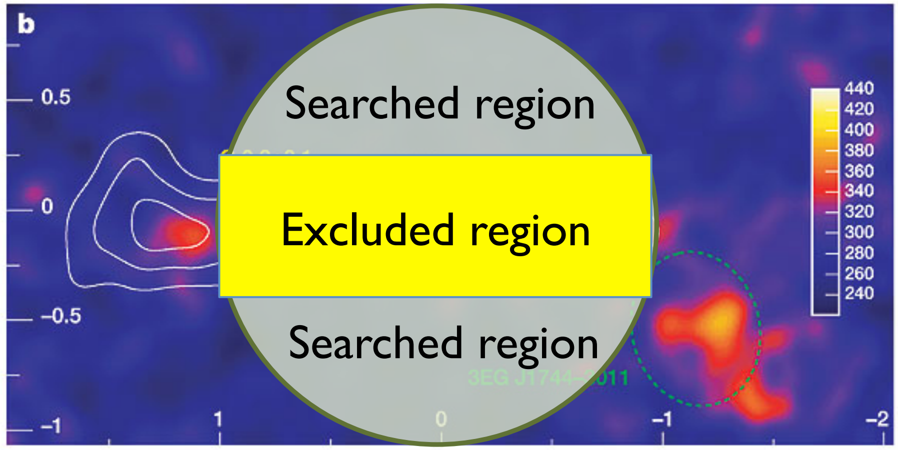
Albert et al. 2006, ApJL 638, L101



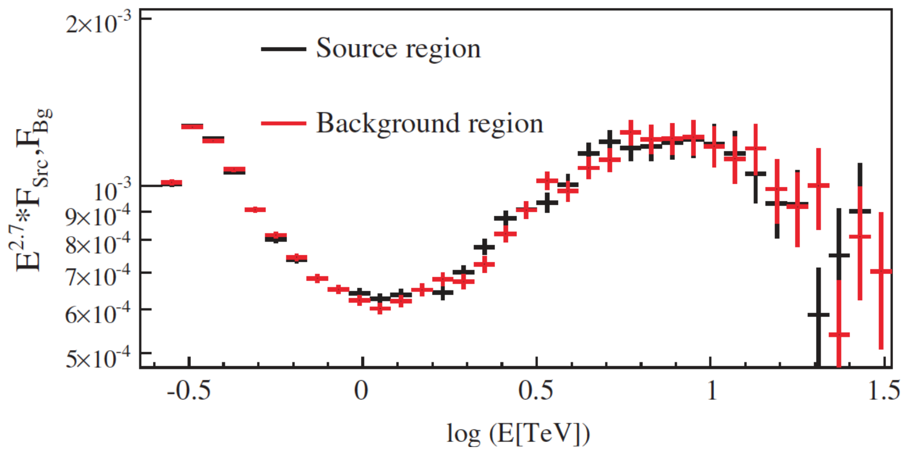
HESS observations of Galactic halo

- 112 h of observations between 2004-2008
- Effective J-factor ~10^{21} $GeV^2 cm^{-5}$ (factor 2 difference between NFW and Einasto)
- Factor ~100 higher than for optimal satellite galaxies
- Method insensitive in case of isothermal profile (DM subtracted as background)
- No sensitivity for decaying scenarios
- No signal seen → upper limits to <σv>

Aharonian et al. 2006, Nature 439, 695

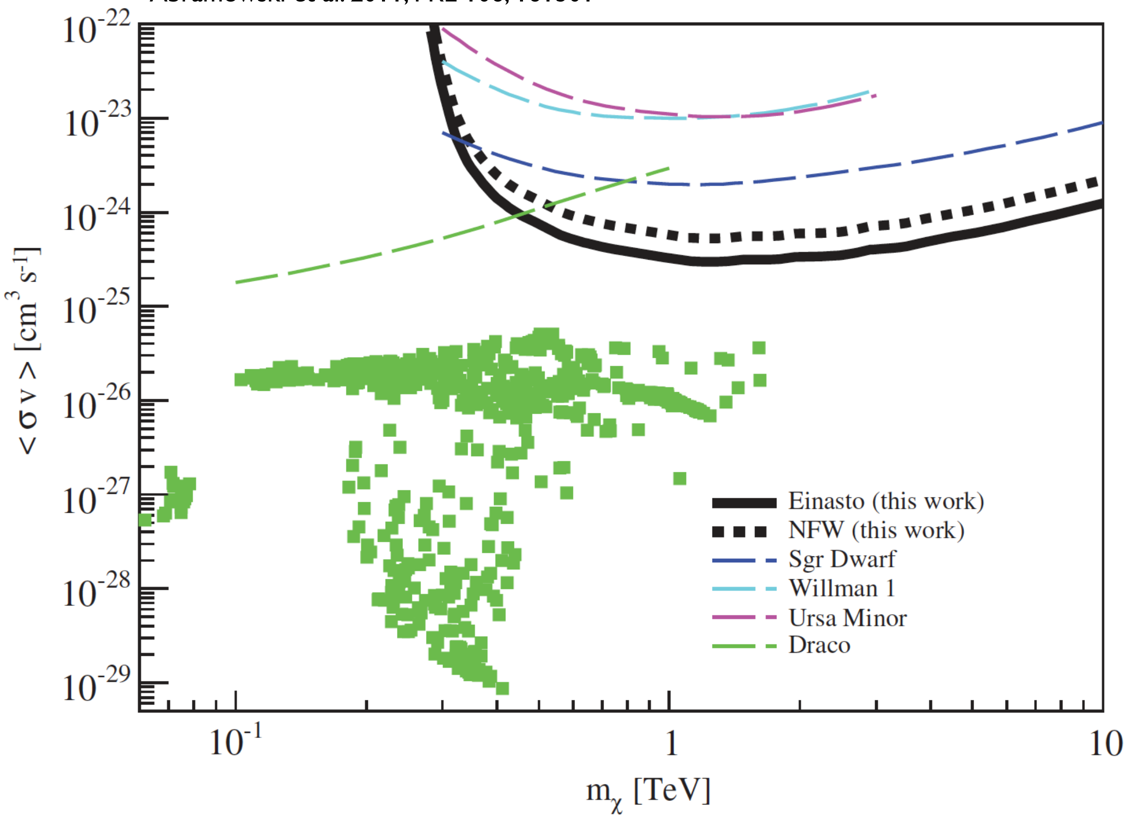


Abramowski et al. 2011, PRL 106, 161301



HESS observations of Galactic halo

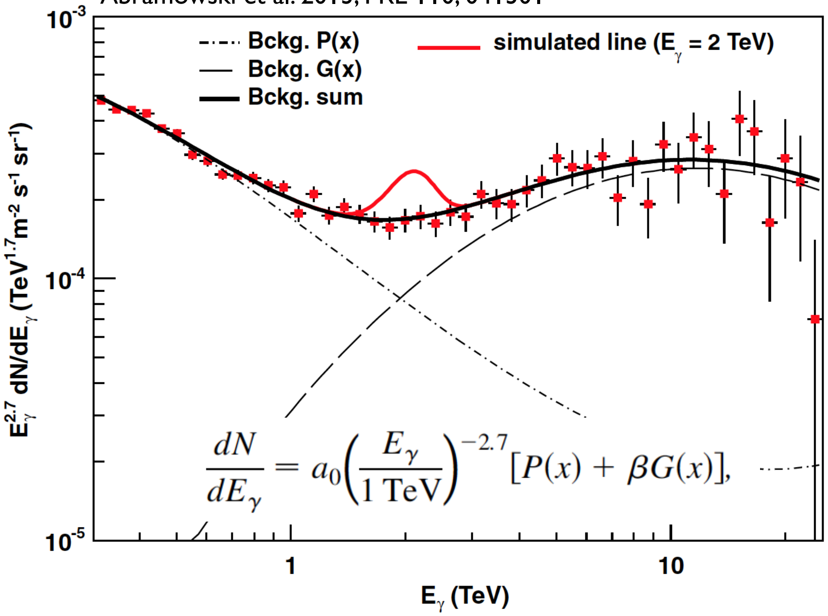
Abramowski et al. 2011, PRL 106, 161301

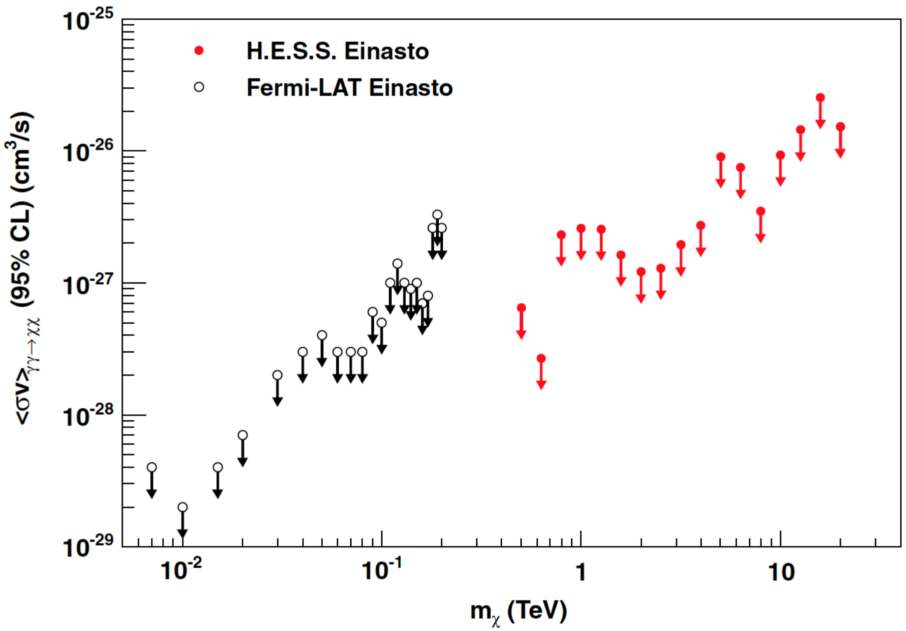


- Best limits attained by Cherenkov telescopes ($<\sigma v> < 3\times10^{25}$ $cm^3 s^{-1}$ at m~1TeV)
- Factor 10 above region of viable super-symmetric models

HESS observations of Galactic halo

Abramowski et al. 2013, PRL 110, 041301





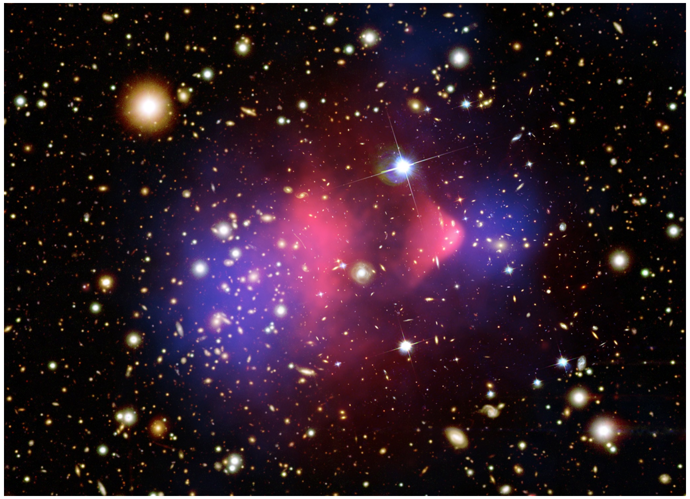
- Lines are searched as spectral features on top of smooth background
- No significant indication → limits in the range 10^{-27}-10^{-26} cm^3/s for masses between 500 GeV and 20 TeV

Galaxy clusters

- Largest structures in Universe:
  - Mass: 10^{14}-10^{15} $M_{\odot}$
  - Size: few Mpc
- Actively evolving
- Contain substantial CR and DM populations
- DM makes ~80% of their mass
- Laboratories to test theories of origin and evolution of the Universe

Perseus cluster (Ritchey-Chretien 32" Telescope)

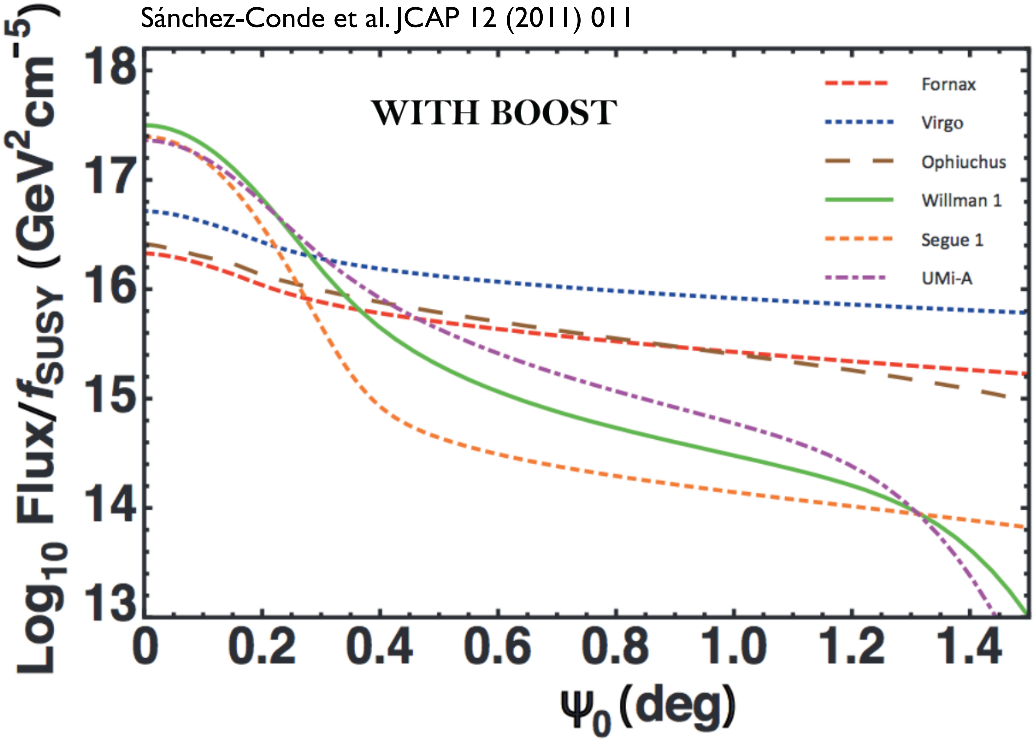
Bullet cluster (NASA)



Galaxy clusters

- Substructures can increase annihilation flux by factors O(100) wrt prediction for smooth halo
- Sources appear extended for Cherenkov telescopes
- Big uncertainties due to extrapolation of simulations by several orders of magnitude
  - Enhance chances of discovery
  - Difficult to translate negative result into limits

Sánchez-Conde et al. JCAP 12 (2011) 011



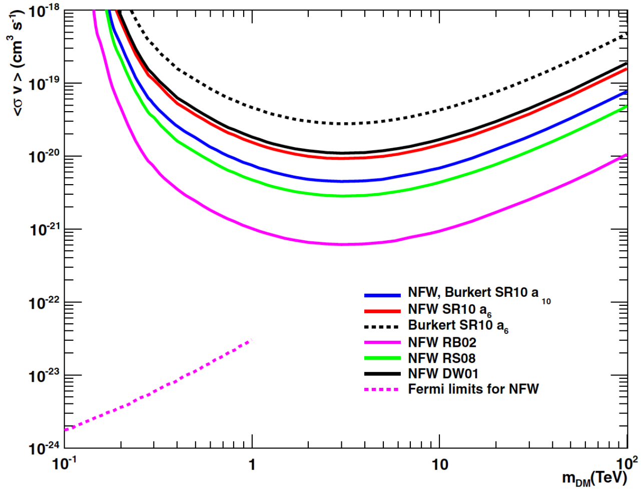
HESS observations of galaxy clusters

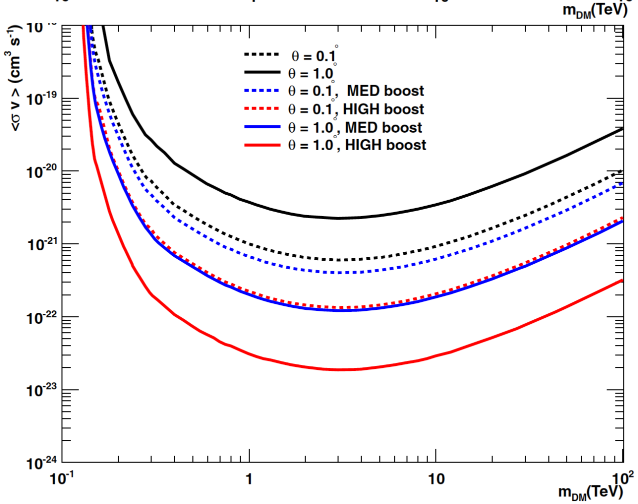
- Observed cluster with one of best DM emission prospects

Target	Year	T [h]	J [GeV^{2}cm^{-5}]
Fornax	2005	15	(0.06-1)x10^{18}

- Quite some uncertainty in the DM profile (O(1-2) between different parameterizations)
- Quite some uncertainty from substructures (O(2))
- Integration region up to 1deg radius for substructures
- Limits are O(3-4) worse than for Galactic center halo

Abramowski et al. 2012 ApJ 750, 123
Erratum: Abramowski et al. 2014 ApJ 783, 63





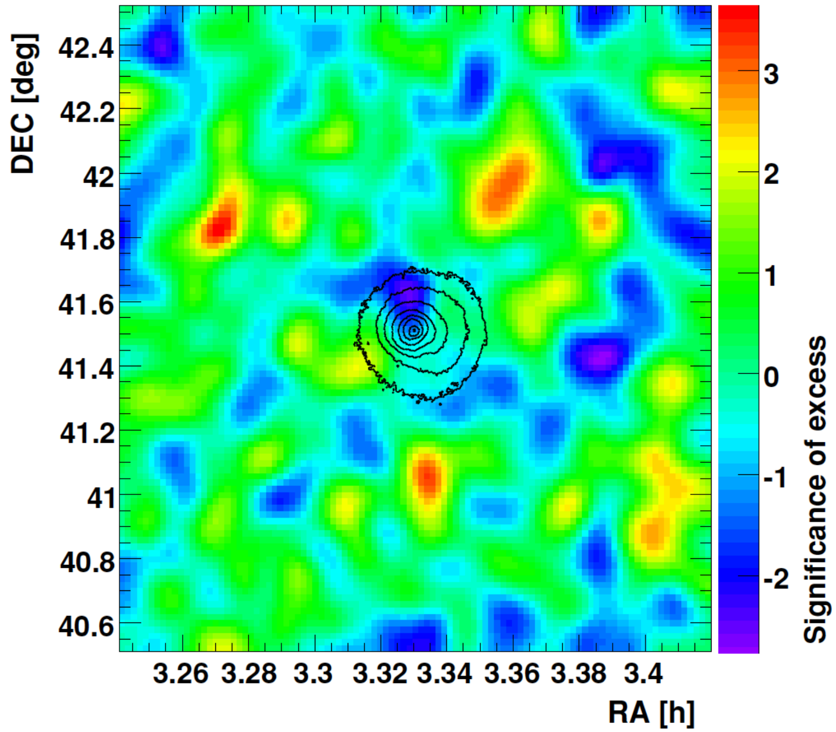
MAGIC observations of galaxy clusters

- Main aim is to look for gamma rays from CR interactions with IC medium

Target	Year	T [h]	J [GeV^{2}cm^{-5}]
Perseus	2008	24	1×10^{17}

- Limits O(4-5) worse than for Galactic center halo

Aleksić et al. 2010 ApJ 710, 634



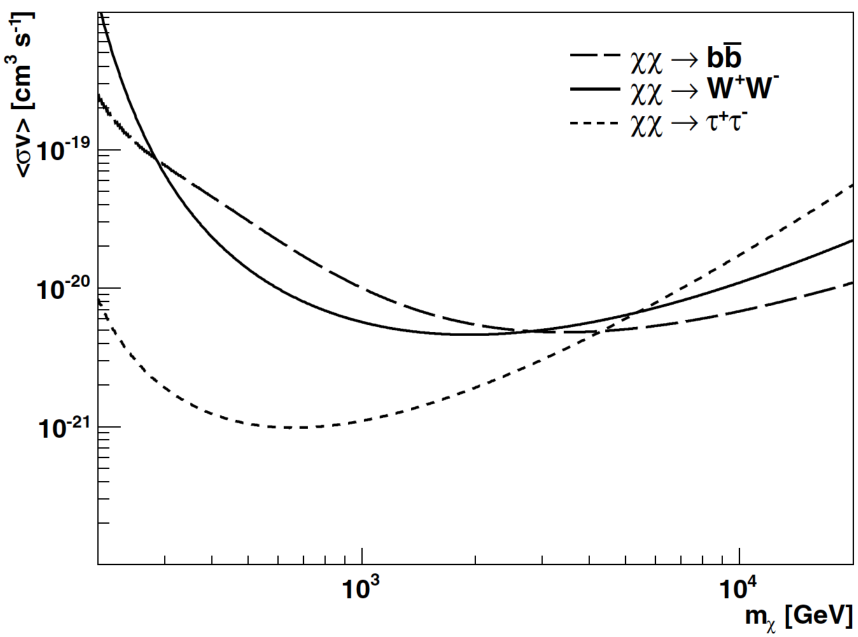
VERITAS observations of galaxy clusters

- Main aim is to look for gamma rays from CR interactions with IC medium

Target	Year	T [h]	J [GeV^2cm^{-5}]
Coma	2008	19	0.8×10^{17}

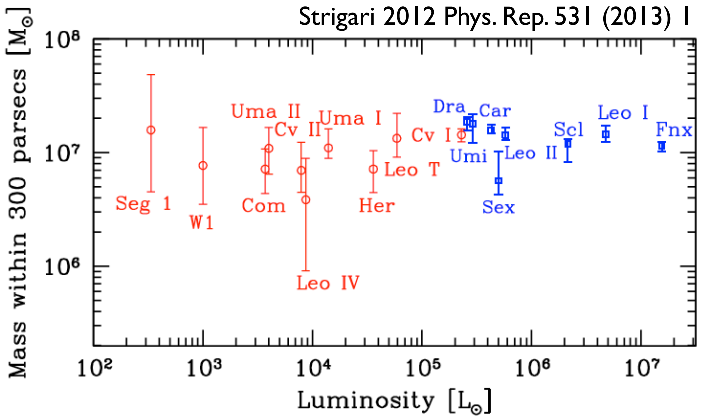
- Limits O(4-5) worse than for the Galactic center halo

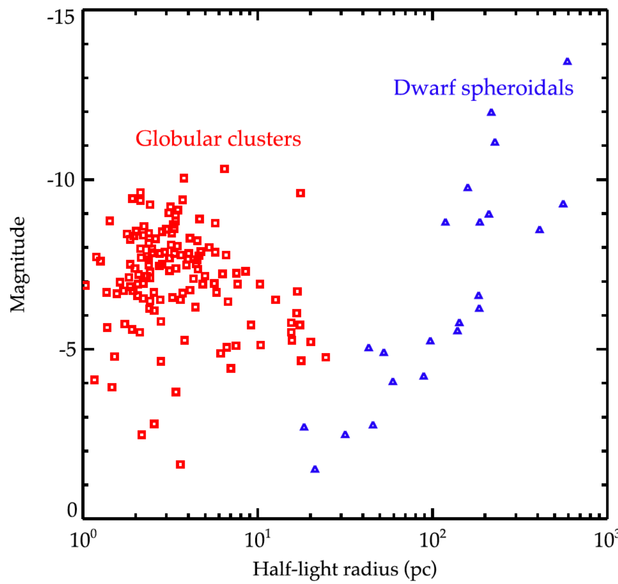
Arlen et al. 2012 ApJ 757, 123



Satellite galaxies

- Dark matter clumps in the Galaxy with stellar activity (25 known so far)
- Distance up to 250 kpc
- Ultra-faint population discovered by Sloan Digital Sky Survey (North)
- Dark matter distribution fitted using stellar kinematics
  - Unless tidally disrupted
  - All have similar masses
  - Large mass-to-light ratios → most dark matter dominated objects → luminous matter marginal role
- Most robust astrophysical probe into the nature of dark matter





Satellite galaxies

Ackermann et al. 2014, PRD 89, 042001

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\log_{10}(\mathrm{J}^{\mathrm{NFW}})^{a}$ ($\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr}]$)	
Bootes I	358.1	69.6	66	18.8 ± 0.22	VERITAS
Bootes II	353.7	68.9	42	...	
Bootes III	35.4	75.4	47	...	
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26	
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25	
Canis Major	240.0	−8.0	7	...	HESS
Carina	260.1	−22.2	105	18.1 ± 0.23	HESS
Coma Berenices	241.9	83.6	44	19.0 ± 0.25	
Draco	86.4	34.7	76	18.8 ± 0.16	MAGIC, VERITAS
Fornax	237.1	−65.7	147	18.2 ± 0.21	
Hercules	28.7	36.9	132	18.1 ± 0.25	
Leo I	226.0	49.1	254	17.7 ± 0.18	
Leo II	220.2	67.2	233	17.6 ± 0.18	
Leo IV	265.4	56.5	154	17.9 ± 0.28	
Leo V	261.9	58.5	178	...	
Pisces II	79.2	−47.1	182	...	
Sagittarius	5.6	−14.2	26	...	HESS
Sculptor	287.5	−83.2	86	18.6 ± 0.18	HESS
Segue 1	220.5	50.4	23	19.5 ± 0.29	MAGIC, VERITAS
Segue 2	149.4	−38.1	35	...	
Sextans	243.5	42.3	86	18.4 ± 0.27	
Ursa Major I	159.4	54.4	97	18.3 ± 0.24	
Ursa Major II	152.5	37.4	32	19.3 ± 0.28	
Ursa Minor	105.0	44.8	76	18.8 ± 0.19	VERITAS
Willman 1	158.6	56.8	38	19.1 ± 0.31	MAGIC, VERITAS

~280 hour of Cherenkov telescopes on satellite galaxies

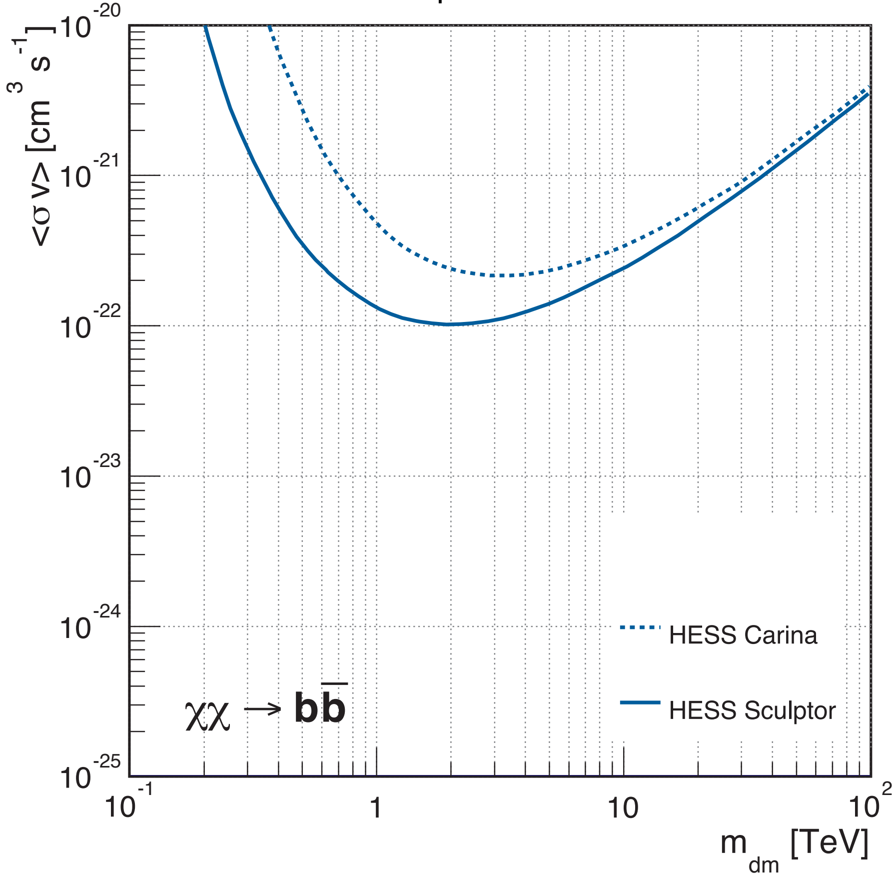
HESS observations of satellite galaxies

- Short observations on classical dwarf spheroidal galaxies (low J)

Target	Year	T [h]	J [GeV^{2}cm^{-5}]
Sagittarius	2006	11	?
Canis Major	2006	10	?
Sculptor	2008	12	3×10^{18}
Carina	2008-2009	15	4×10^{17}

- No limit possible from unknown J-factors

Abramowski et al. 2011 ApP 34, 608
Aharonian et al. 2009 ApJ 691, 175
Aharonian et al. 2008 ApP 29, 55

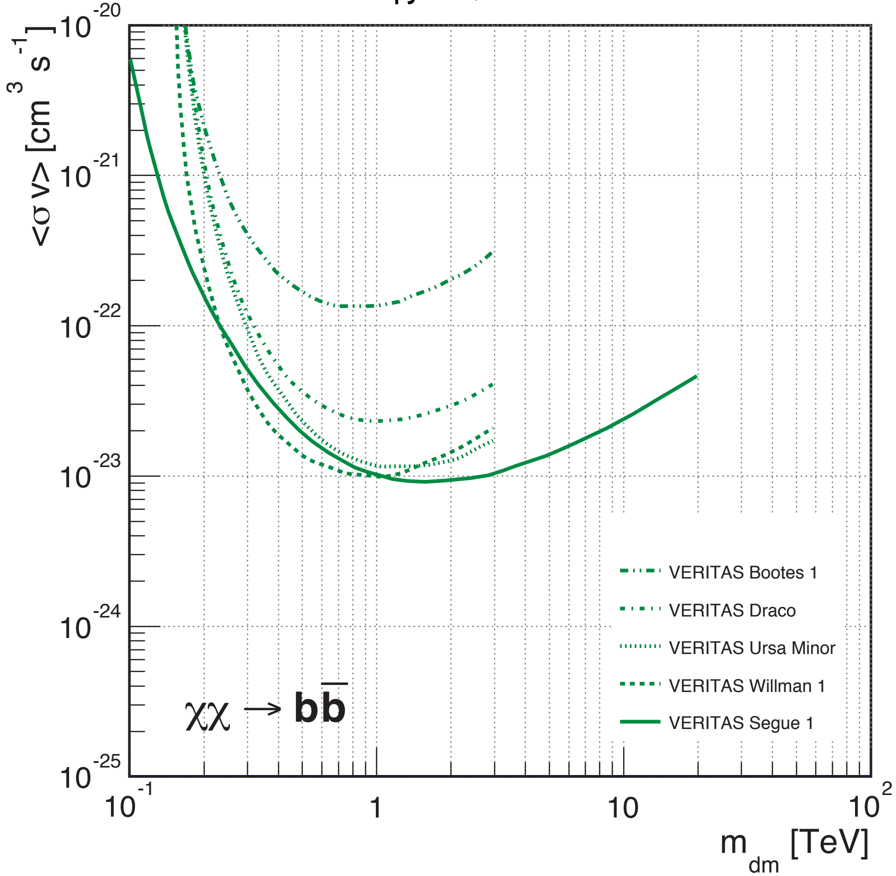


VERITAS observations of satellite galaxies

- Longer observations including ultra-faint galaxies

Target	Year	T [h]	J [GeV^{2}cm^{-5}]
Draco	2007	18	1.5×10^{18}
Ursa Minor	2007	19	2.7×10^{18}
Willman 1	2007-2008	14	8×10^{18}
Bootes 1	2009	14	1.2×10^{18}
Segue 1	2010-2011	48	1.1×10^{19}

Aliu et al. 2012 PRD 85, 062001
Acciari et al. 2010 ApJ 720, 1174



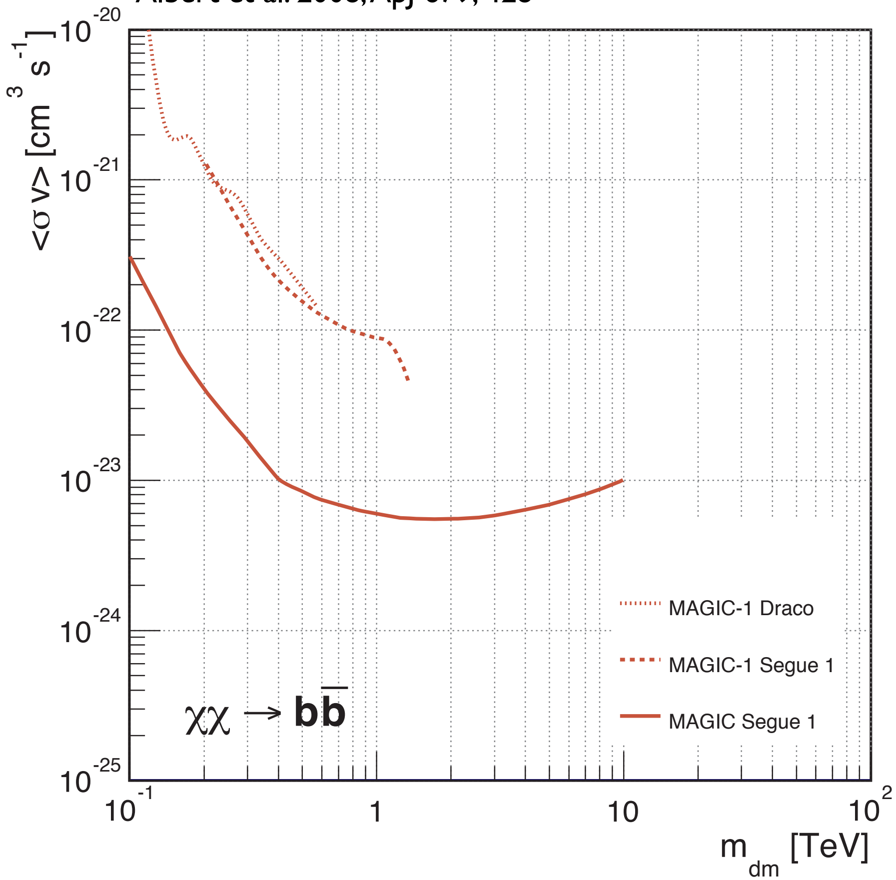
MAGIC observations of satellite galaxies

- Longest exposure on the optimal target

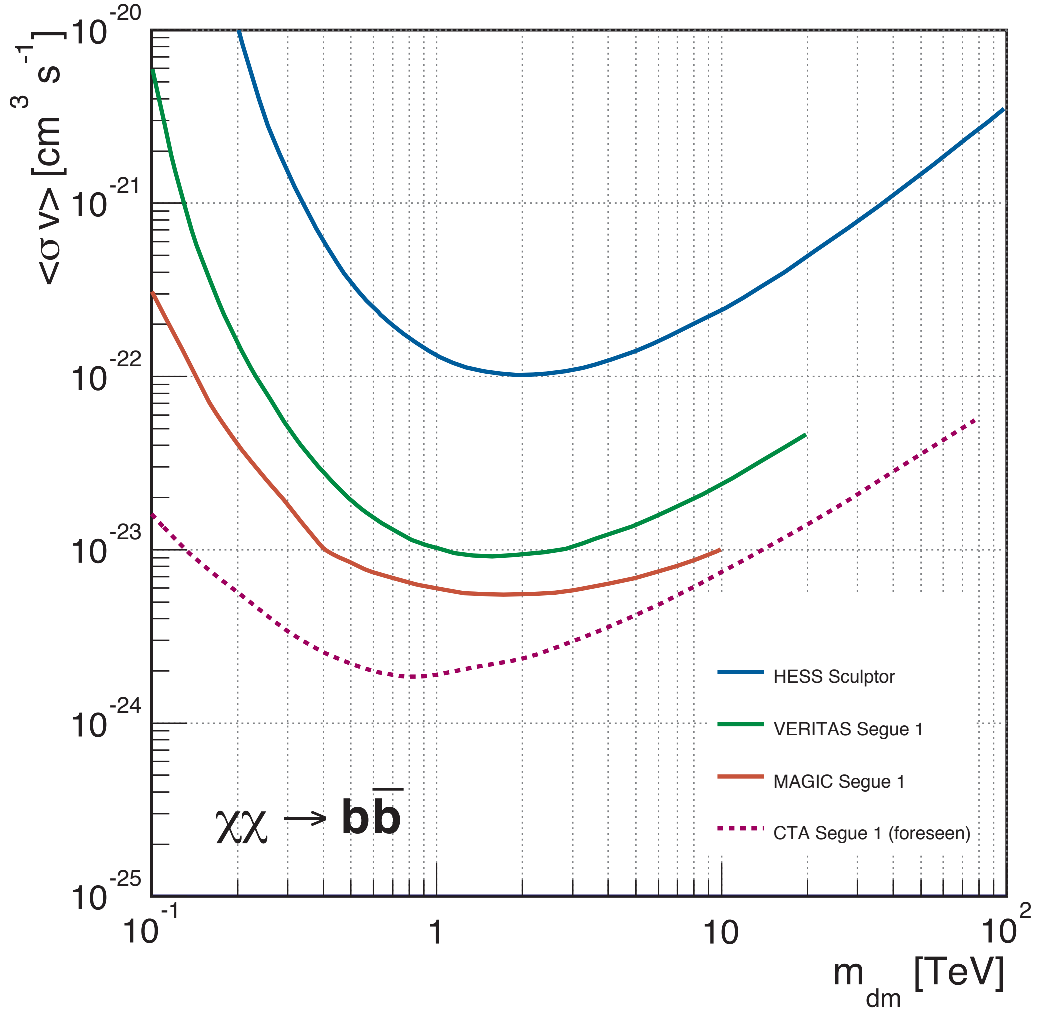
Target	Year	T [h]	J [GeV^2cm^{-5}]
Draco	2007	8	5×10^{17}
Willman 1	2008	16	4×10^{18}
Segue 1 (MAGIC 1)	2008-2009	29	1.1×10^{19}
Segue 1	2010-2013	158	1.1×10^{19}

- Willman limits on benchmark models only

Alekšić et al. 2014, JCAP 02, 008
Alekšić et al. 2011, JCAP 06, 035
Aliu et al. 2009, ApJ 697, 1299
Albert et al. 2008, ApJ 679, 428

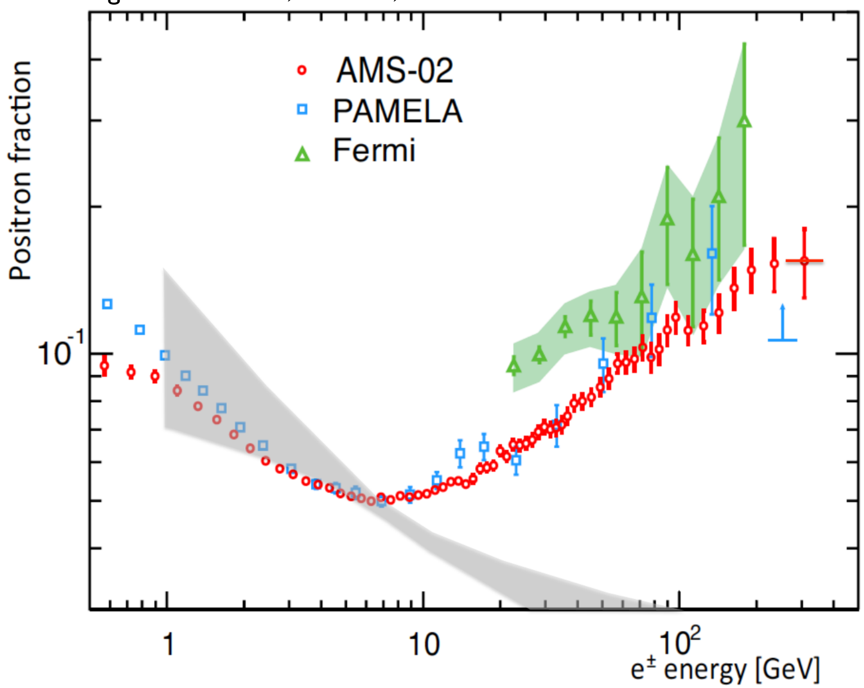


Summary observations of satellite galaxies



Spectral signatures from electrons/positrons

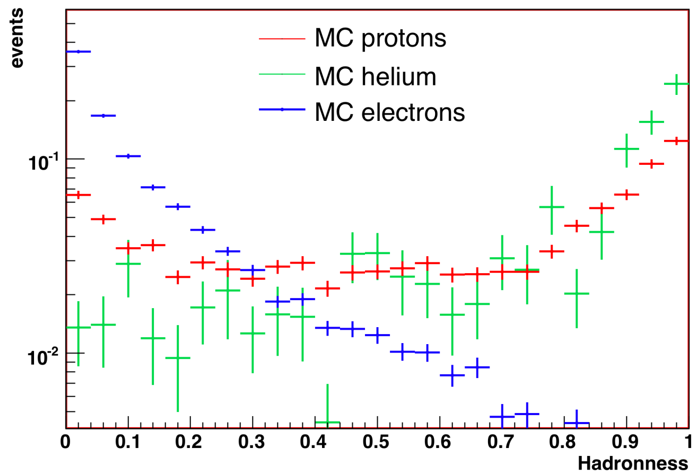
Aguilar et a. 2013, PRL 110, 141102

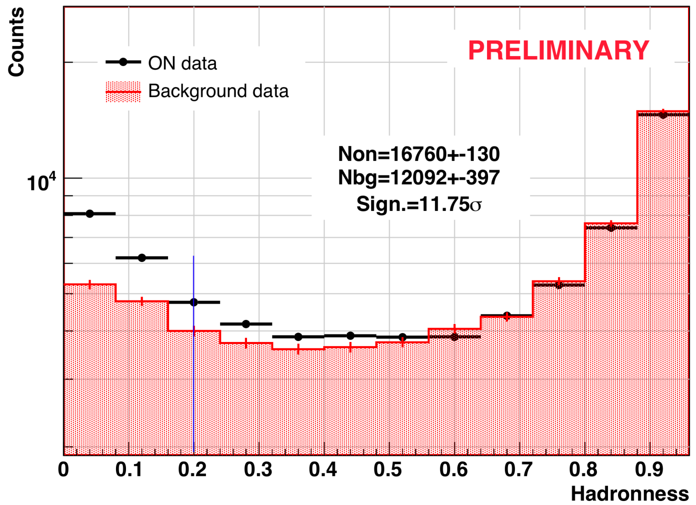


- Primary sources produce equal amounts of particles and antiparticles
- Nearby primary source modifies electron/positron spectra wrt standard CR propagation and interaction
- Primary sources: PWN, μQSR, DM
- Cherenkov telescope can look for those (electrons/positrons produce EM showers just like gammas)
- Spatial information is lost due to magnetic fields → new analysis techniques

All-electron spectrum

- Alternative technique: measure all-electron spectrum from fields free of gamma-ray sources
- Electron shower ≈ gamma shower → separation power through image analysis (hadronness)
- Electrons more abundant than gammas in isotropic flux
- Diffuse flux → spatial information not used
- Instead, use hadronness distributions from data vs Monte Carlo





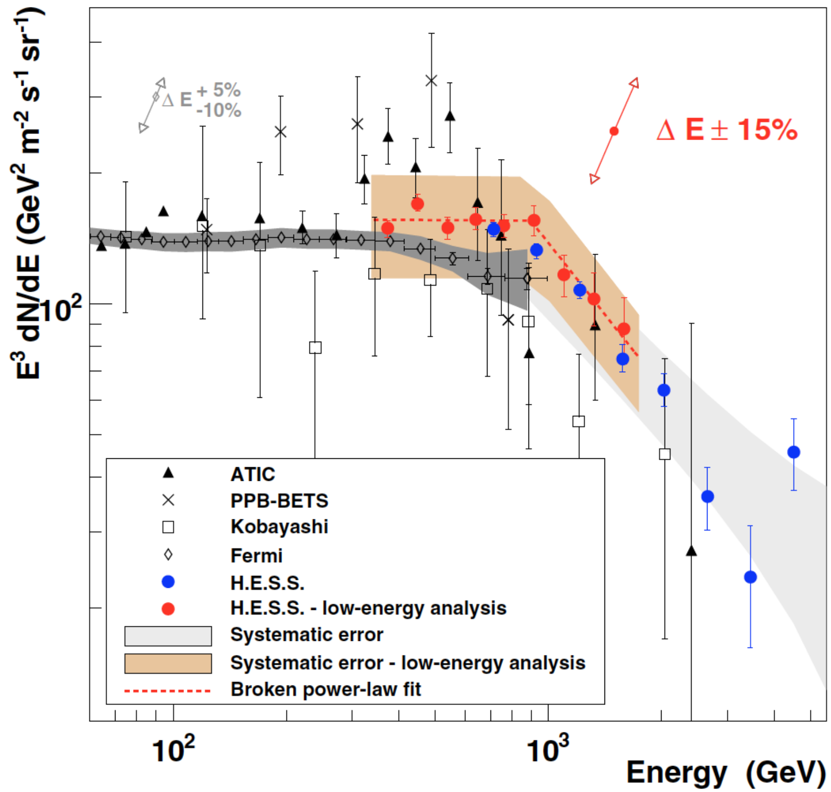
All-electron spectrum measurements

- HESS: analysis at high and low energies

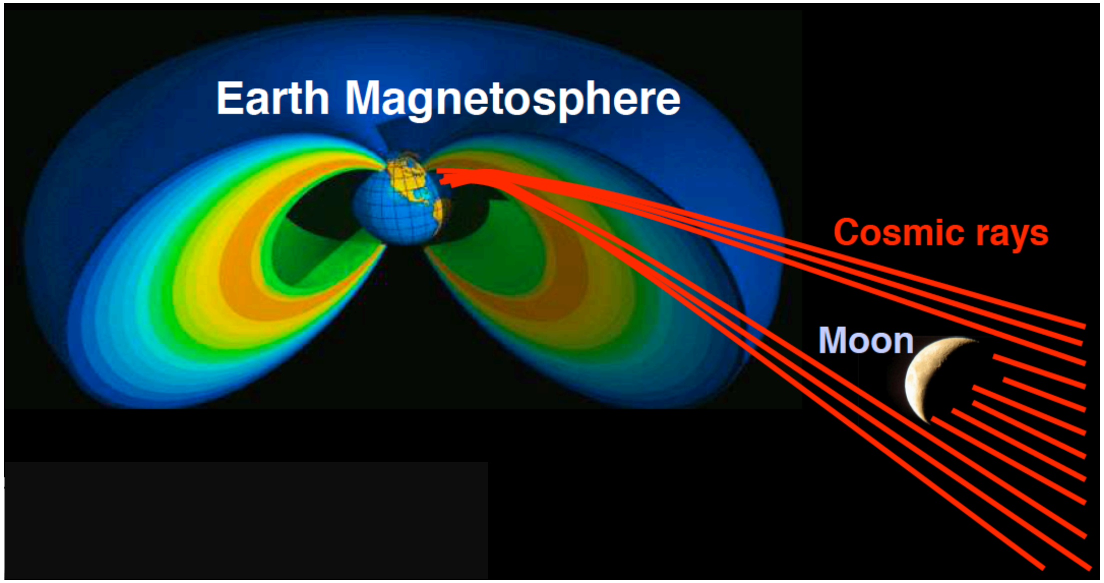
Instrument	Year	T [h]	E [TeV]
HESS	2004-2007	239	0.7-5
HESS	2004-2005	77	0.4-1
MAGIC	2009-2010	14	0.1-3

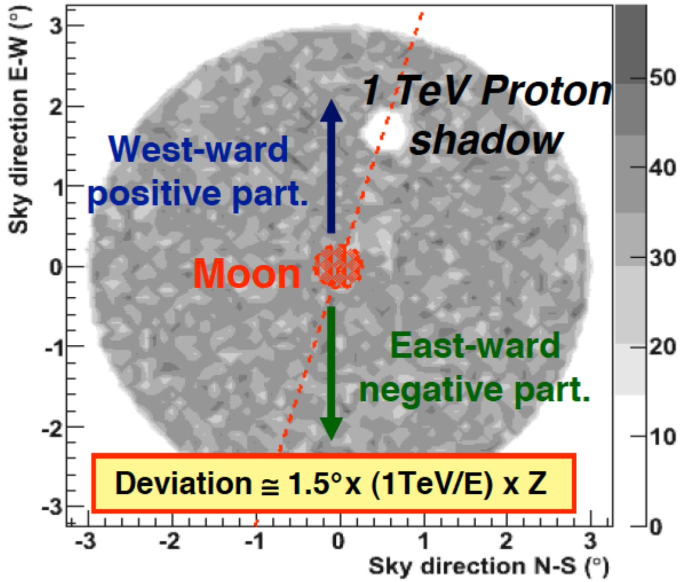
- ATIC feature not confirmed
- Spectral break at 1 TeV (Γ: 3.0→4.1)
- MAGIC: preliminary confirmation (Borla-Tridon 2011)

Aharonian et al. 2009 A&A 508, 561
Aharonian et al. 2008 PRL 101, 261104



Moon shadow

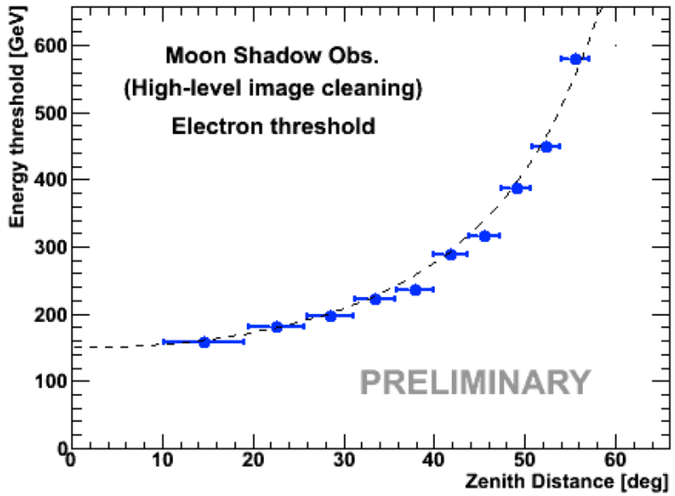




- Moon + Earth magnetosphere → natural CR spectrometer
- The Moon shadow position depends on:
  - CR kinetic energy
  - CR charge
- MAGIC can observe close to the Moon (low gain PMTs) and measure the ratio e+/e- in the flux of cosmic rays in the energy range 300 GeV – 1 TeV

Current approach and limitations

- MAGIC observes currently at 4° from the Moon, reducing the PMT gain by factor 2
  - → possible until NSB = 40×NSB_{dark} or Moon phase = 50%
- Performance not much degraded (evaluated with data)
  - Energy threshold ~150-600 GeV
  - Sensitivity above 300 GeV = 1.2% Crab (factor 1.5 worse)



- Measurement possible between 0.3-1 TeV
- Giving this, the needed observation times are:
  - 30-90 h for e^-
  - 100-800 h for e^+
- The problem: keeping two contradicting conditions:
  - Zd < 50° (for low energy threshold)
  - NSB < 40×NSB_{dark} → high Zd

results in narrow observation window per year (~20 for e^- and ~20 for e^+) which need to be perfect weather

- The solution: use UV-pass filters (stay tuned)

DISCUSSION

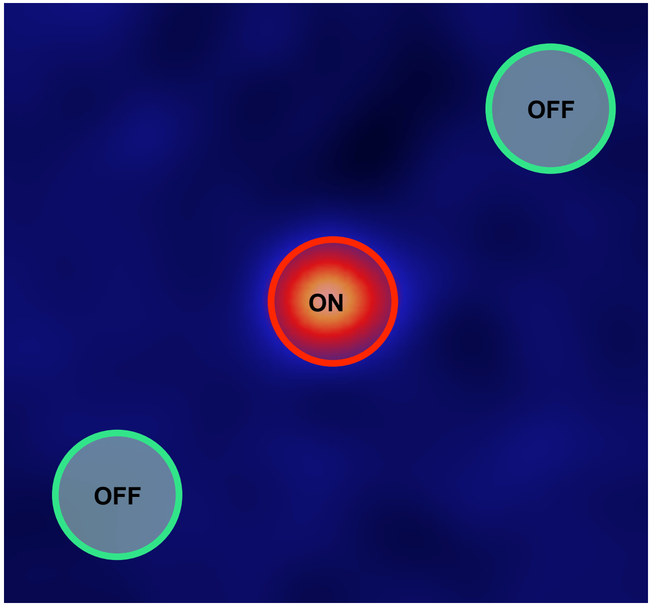
How to go further?

- With MAGIC, one order of magnitude improvement wrt mono was possible thanks to:

	~2	analysis optimization	(1)
×	2	better sensitivity of stereo	(2)
×	$\sqrt{5}$	times from observation time	(3)
+		choice of optimal target	(4)

- Further improvement?
  1) Not obvious how to gain more
  2) Exploit the sensitivity leap of factor ~5-10 by CTA
  3) Not much can be done at least by each instrument on its own → merge results
  4) Explore other targets; new dSph to be discovered by DES

Conventional analysis



ON = signal [?] + bkg

OFF = τ × bkg

τ – bkg normalization (~ # background 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 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 analysis

NUM OF EVTS | 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

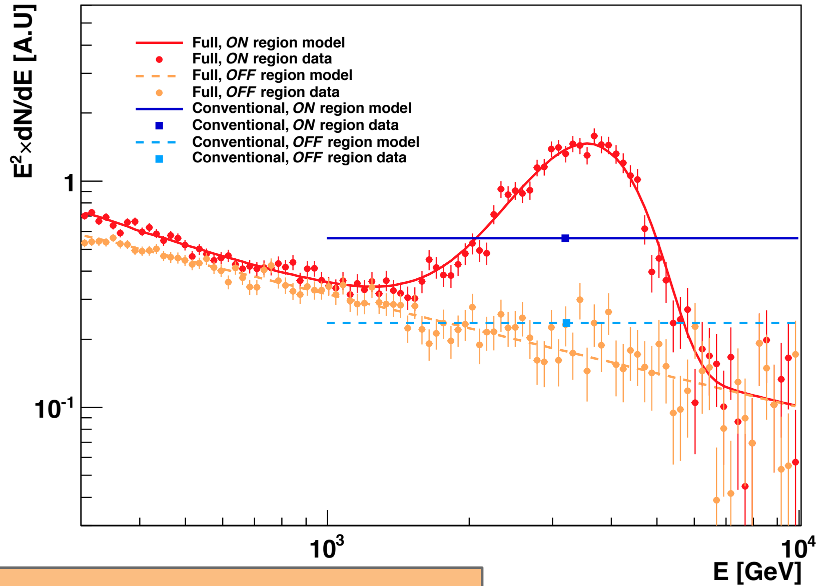
M(θ) – DM model with parameters *θ*

Aleksić, Rico & Martinez JCAP 10 (2012) 032

<u>Spectral shape:</u>

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

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

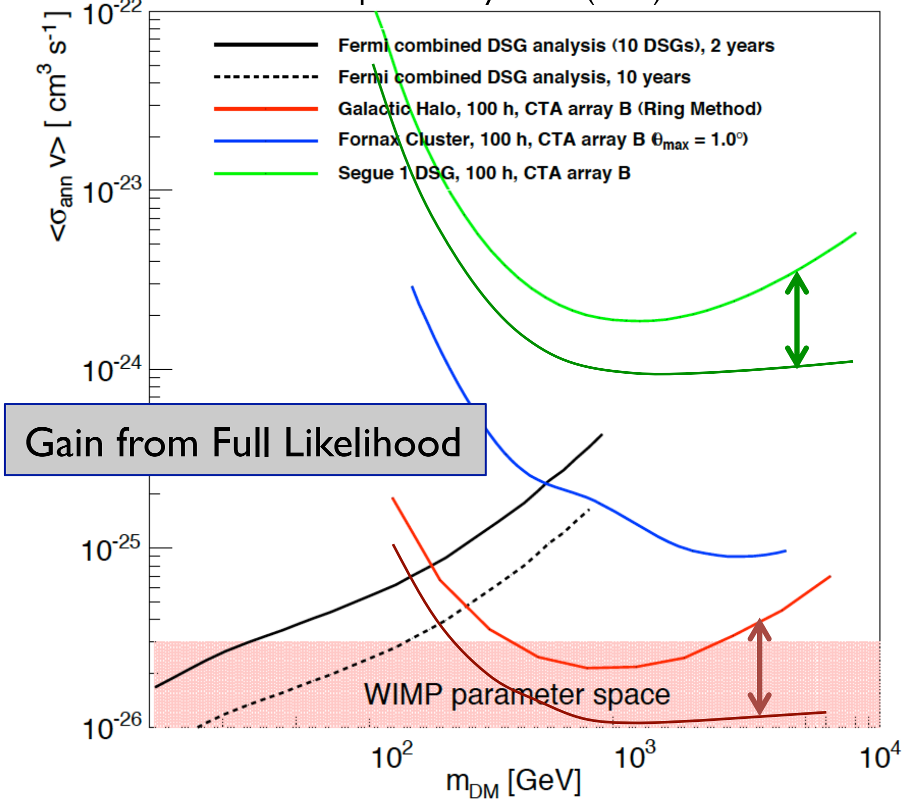


Sensitivity improvement of a factor ~2!

Prospects for CTA

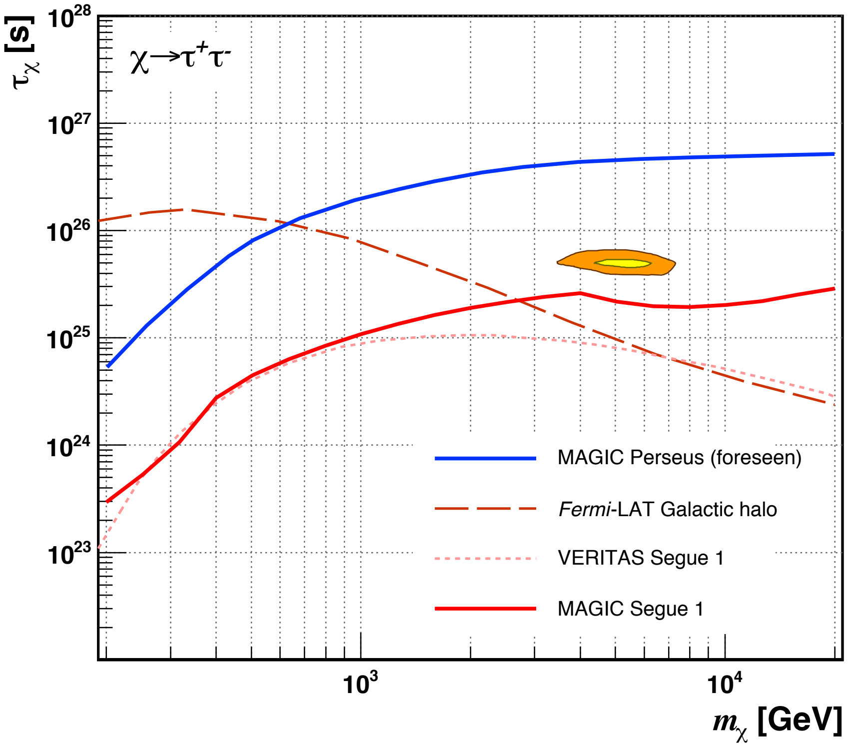
- Dark matter searches are one of the main scientific objectives for CTA
- Factor ~5-10 more sensitive than with current instruments
- For the baseline density profiles it is expected to explore WIMP parameter space
- Full Likelihood still to be considered
- SUSY parameter space to be probed by observations of the Galactic center halo

Astroparticle Physics 43 (2013) 189-214



Satellite galaxies vs galaxy clusters

	$J_{ann}(0.1°)$ [GeV^2/cm^5]	$J_{dec}(0.1°)$ [GeV/cm^2]
Segue 1	10×10^{18}	2×10^{17}
Fornax cluster	1×10^{18}	20×10^{17}
Perseus cluster	0.2×10^{18}	15×10^{17}

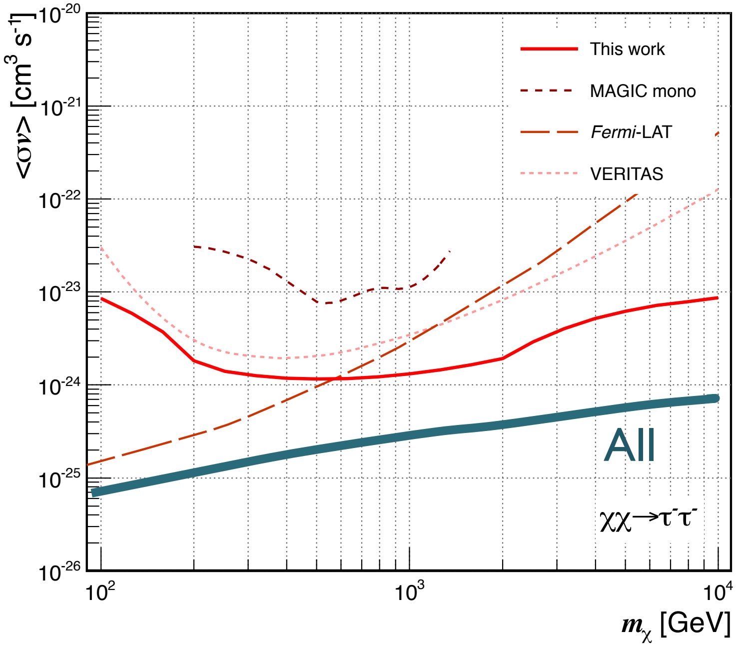


- Annihilation fluxes higher for satellite galaxies than for galaxy clusters (assuming smooth DM distribution)
- Inverse situation for decay scenarios → use clusters for decaying dark matter

Global dark matter search

- Use a global likelihood to combine results from different telescopes (MAGIC, VERITAS, HESS & *Fermi*-LAT)
- Another factor ~2 improvement 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 the same type also simple and desirable:
  - Use all dwarfs from all instruments to search for annihilating dark matter
  - Use all clusters from all instruments to search for decaying dark matter

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



Aleksić et al. JCAP 02 (2014) 008

- Negotiations with *Fermi*-LAT and VERITAS are already under way

Conclusion

- Cherenkov telescopes have searched for DM from several promising targets
- CTA will explore SUSY parameter space
- The present generation has not been fully exploited yet:
  - Exploiting DM unique spectral features is the key for optimal search
  - Decay signals not optimally exploited yet
  - As instruments reach their statistics limit → merge results

THANK YOU!