Indirect Dark Matter Searches with VERITAS

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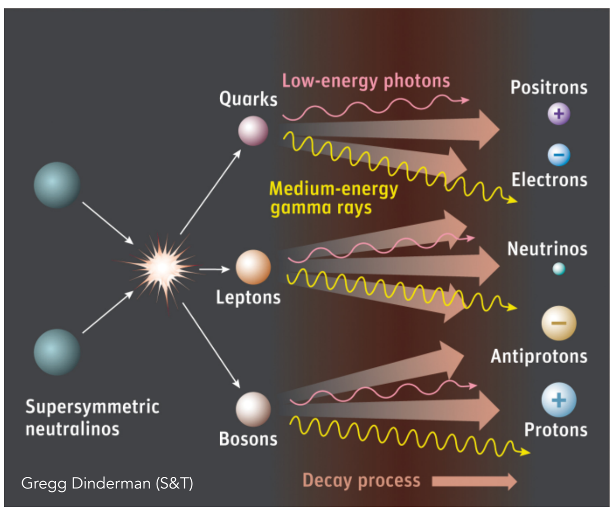
Columbia University
On behalf of the VERITAS Collaboration

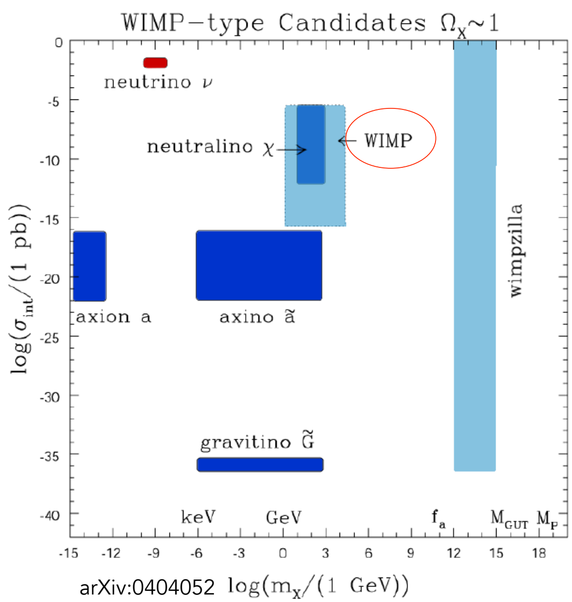
Outline

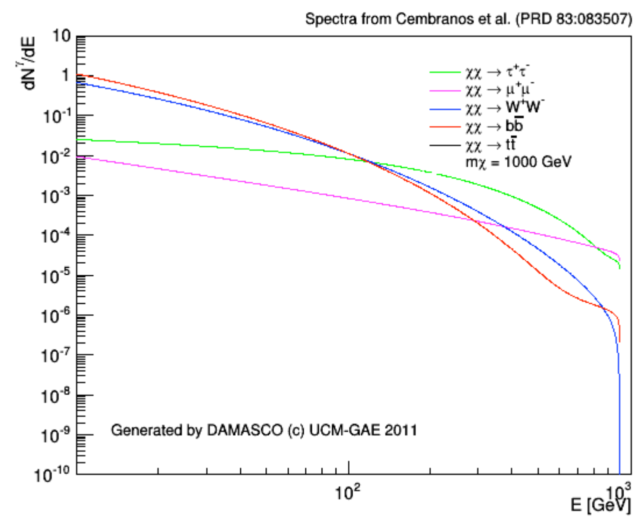
- Indirect Dark Matter Searches in the γ-Ray Band
- VERITAS
- Galactic Center and Halo
- Galaxy Clusters
- Dwarf Spheroidal Galaxies
- Dark Matter Subhalo Candidates

Indirect Dark Matter Searches in the γ-Ray Band

- Basis: Detection of DM annihilation or decay products (SM particles)
- In most cases, entangled with CR and subdominant
- WIMPs with masses in the ~100 GeV range are good DM particle candidates
- Photons are privileged messengers
  - No deflection by B-fields, trace back to source
  - Observation of astrophysical targets
  - Characteristic spectral shape: identification





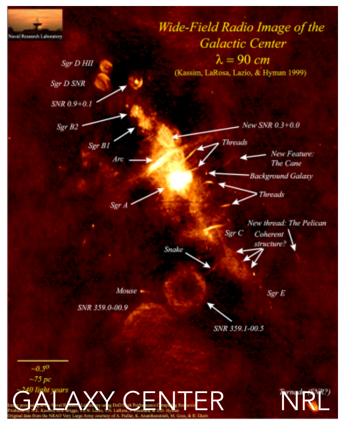


Expected spectrum from from annihilating DM

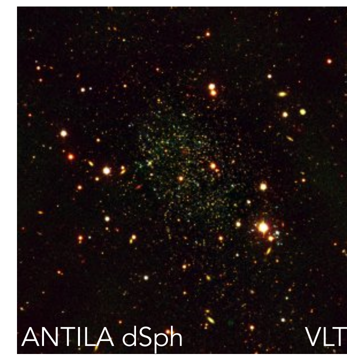
$$\frac{d\Phi}{dE} = \boxed{J(\Delta\Omega)} \times \boxed{\frac{d\Phi^{PP}}{dE}} = \boxed{\int_{l.o.s,V} \rho^2_{DM}(l)\, d\Omega\, dl} \times \boxed{\frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m^2_{DM}}\sum_i B_i \frac{dN_i^\gamma}{dE}}$$

Key concepts: ρ_{DM}, distance, background

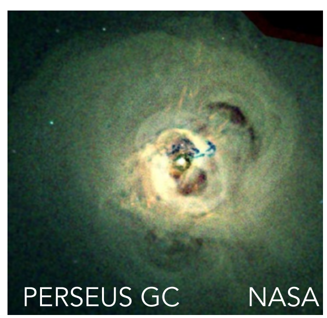
Galactic Center & Halo
- 🟢 High flux
- 🔴 Background Issues



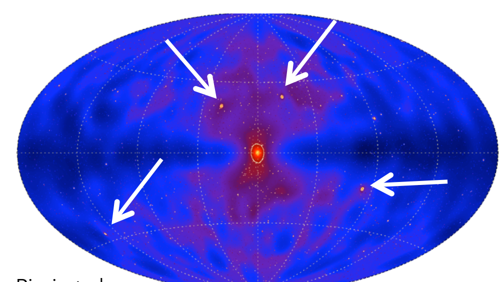
Dwarf Galaxies
- 🟢 Large M/L
- 🟢 No background
- 🔴 Low flux



Galaxy Clusters
- 🟢 Huge DM content
- 🔴 Large distance
- 🔴 High background



Unassociated HE Sources:
- 🟠 DM Subhalos?

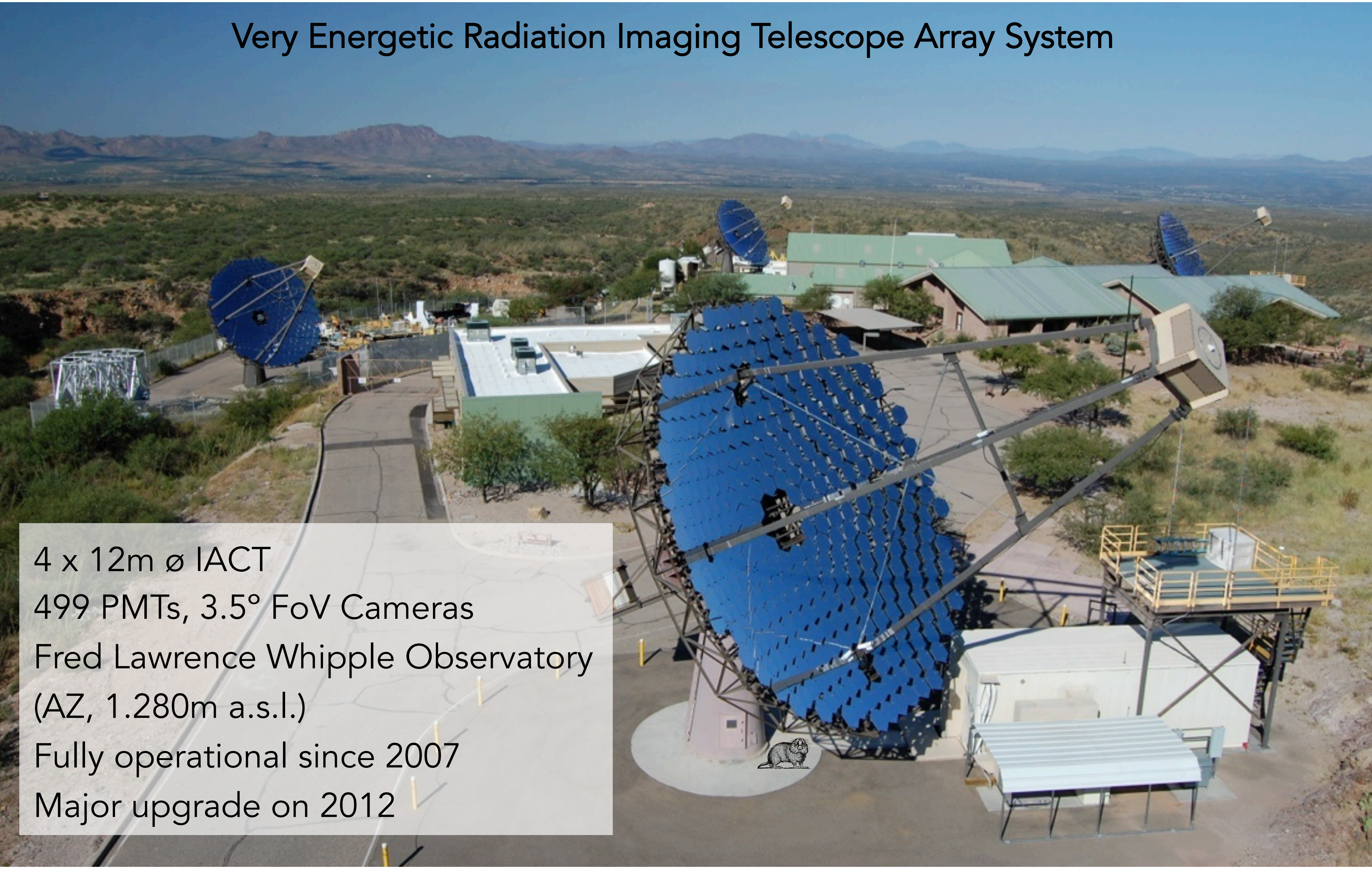


Pieri et al.
PRD 83:0235, 2008

$\chi\chi \rightarrow b\bar{b},\ m_\chi = 40$ GeV

VERITAS

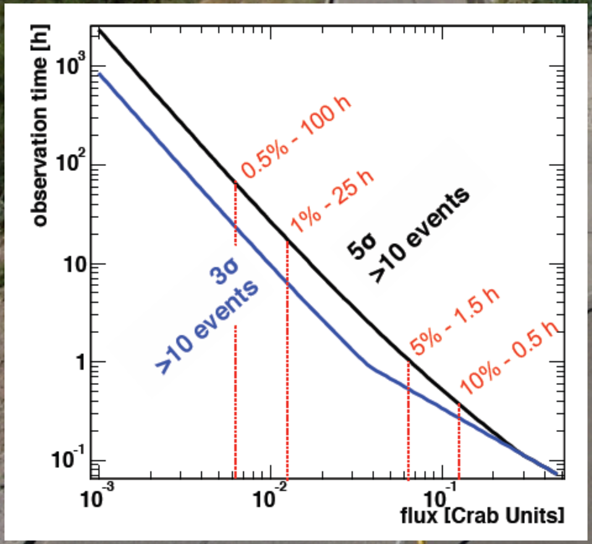
Very Energetic Radiation Imaging Telescope Array System



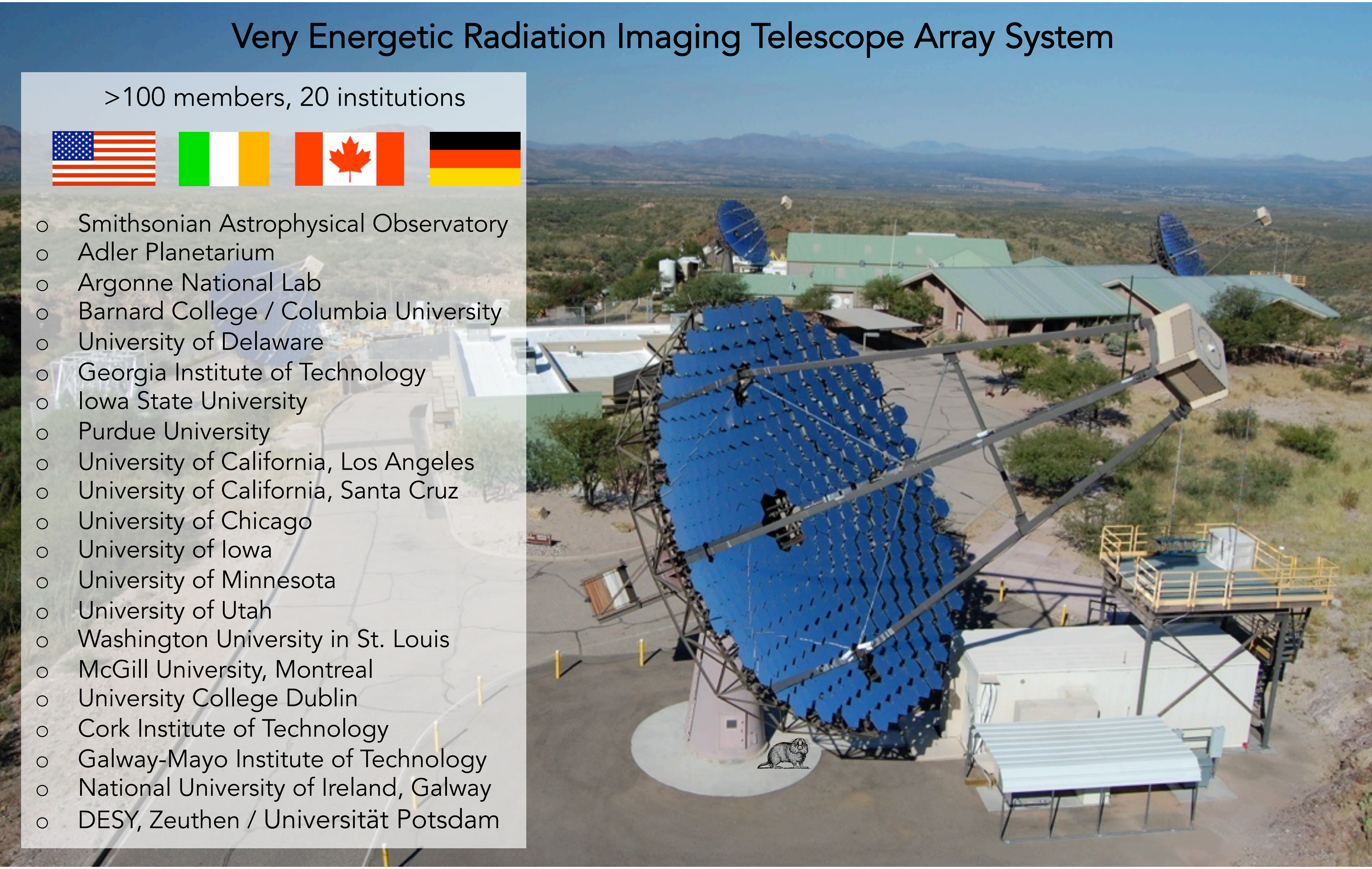
4 x 12m ø IACT
499 PMTs, 3.5° FoV Cameras
Fred Lawrence Whipple Observatory
(AZ, 1.280m a.s.l.)
Fully operational since 2007
Major upgrade on 2012

Very Energetic Radiation Imaging Telescope Array System

- Sensitivity: 1% Crab in ~25h
- Energy range: 60 GeV – 30 TeV
- Angular resolution: 0.1° ($r_{68\%}$)
- Energy resolution: 15% (>300 GeV)
- Sys. errors: Γ ~0.1, flux ~20%
- ~1000h dark time / year
- +300h Moon time / year

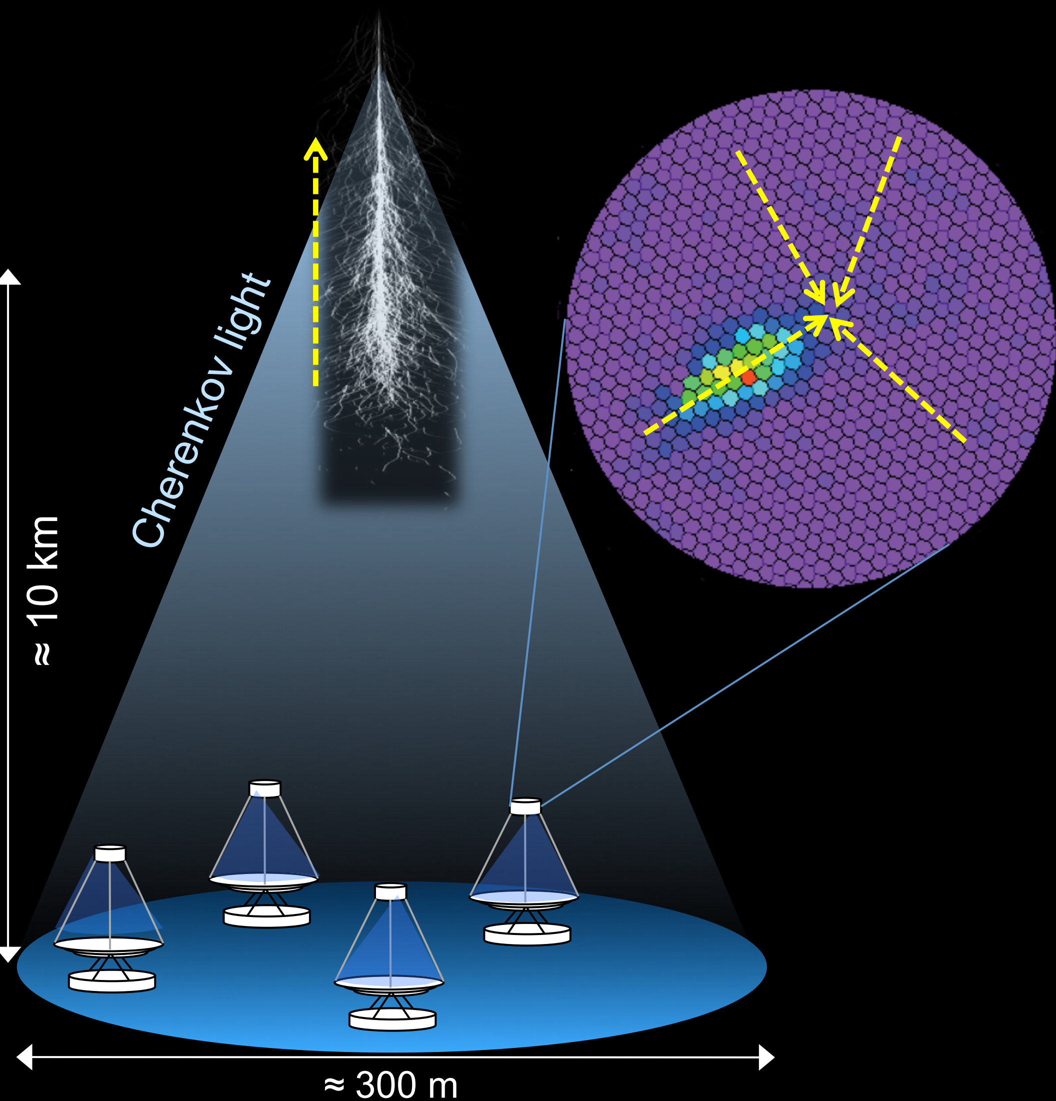


Very Energetic Radiation Imaging Telescope Array System



>100 members, 20 institutions

- Smithsonian Astrophysical Observatory
- Adler Planetarium
- Argonne National Lab
- Barnard College / Columbia University
- University of Delaware
- Georgia Institute of Technology
- Iowa State University
- Purdue University
- University of California, Los Angeles
- University of California, Santa Cruz
- University of Chicago
- University of Iowa
- University of Minnesota
- University of Utah
- Washington University in St. Louis
- McGill University, Montreal
- University College Dublin
- Cork Institute of Technology
- Galway-Mayo Institute of Technology
- National University of Ireland, Galway
- DESY, Zeuthen / Universität Potsdam



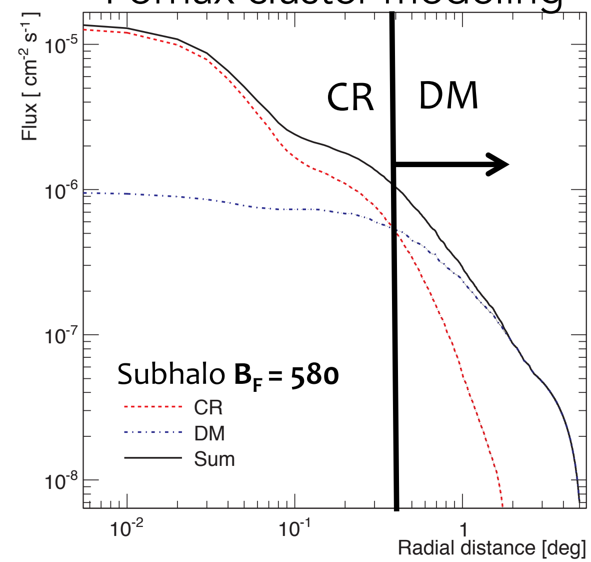
IMAGING ATMOSPHERIC CHERENKOV TECHNIQUE

- Detection of extended air showers (EAS) using the atmosphere as a calorimeter
- Huge γ–ray collection area ($\sim 10^5$ m^2)
- Large background from charged CR
- Energy window: tens GeV - tens TeV
- Event reconstruction from EAS image:
  - Type of primary event
  - Primary energy estimation
  - Primary arrival direction

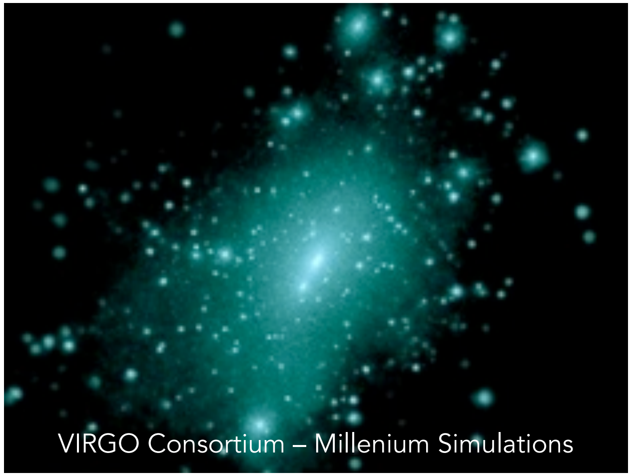
Galaxy Clusters

- Largest virialized objects in the Universe
- Huge DM content:
  - ~80% total mass (ICM 15%, galaxies 5%)
- Cluster members may contain AGN
- CR-induced g-ray signal outshines DM signal
- VHE observations of galaxy clusters can:
  - Test models on intracluster CR population
  - Place limits on fluxes from DM annihilation/decay

Fornax cluster modeling

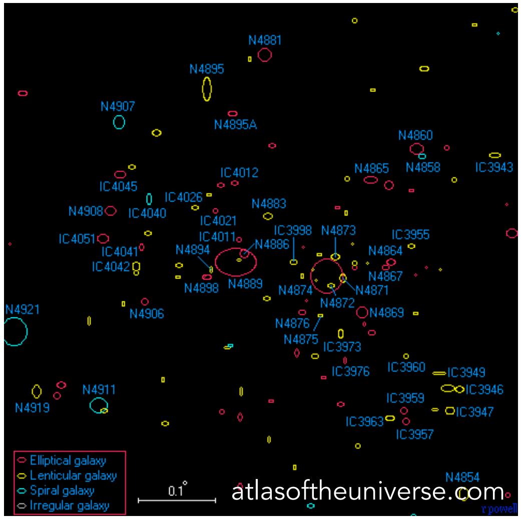


ΛCDM N-body simulations

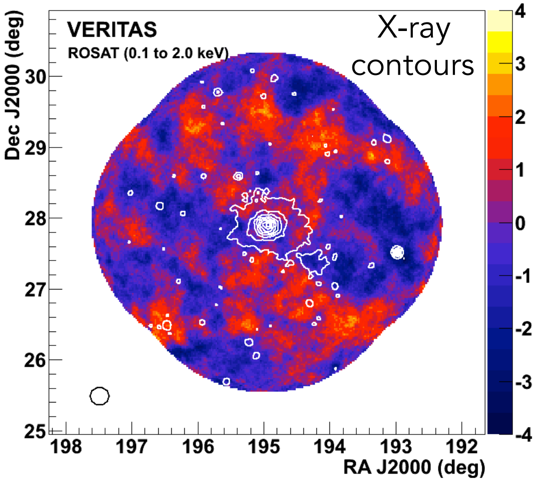


Coma Cluster

Coma Cluster Members

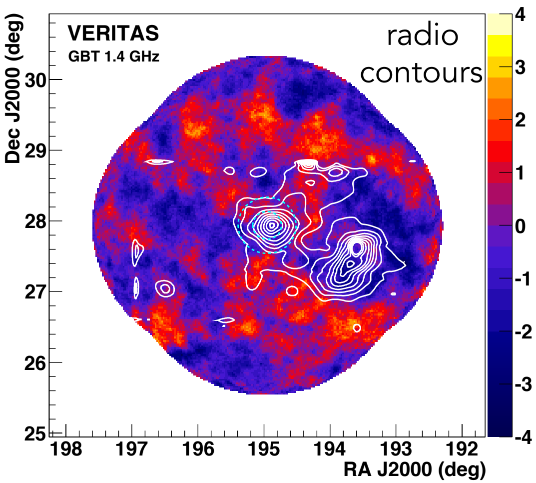


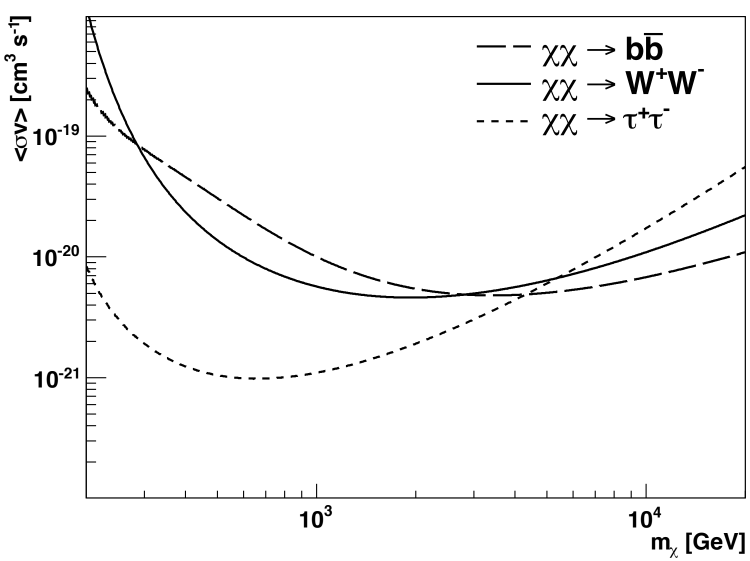
Galaxy Clusters



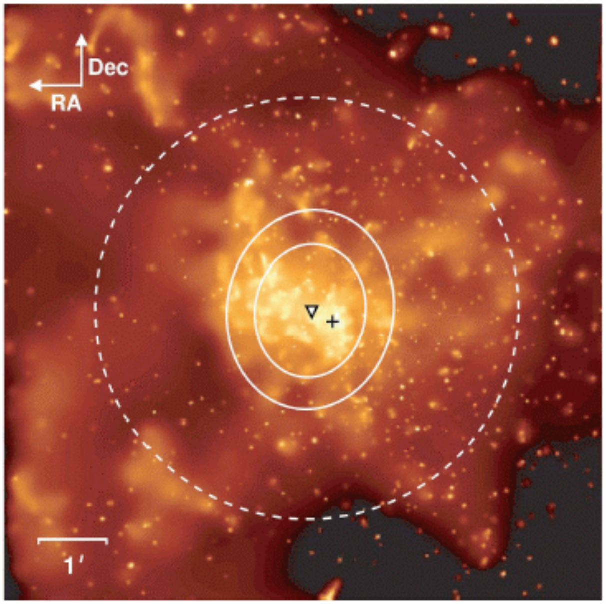
- Observed during 2008 for 19h
- Low Zd observations: 21 deg
- No detection of VHE γ-ray signal…
  … nor HE γ-ray signal with Fermi-LAT

- Cluster DM content modeling: NFW
- Limits to $b\bar{b}$, W^+W^-, and $\tau^+\tau^-$ annihilation channels
  - $\langle\sigma v\rangle^{UL} \sim O(10^{-21})\ cm^3s^{-1}$

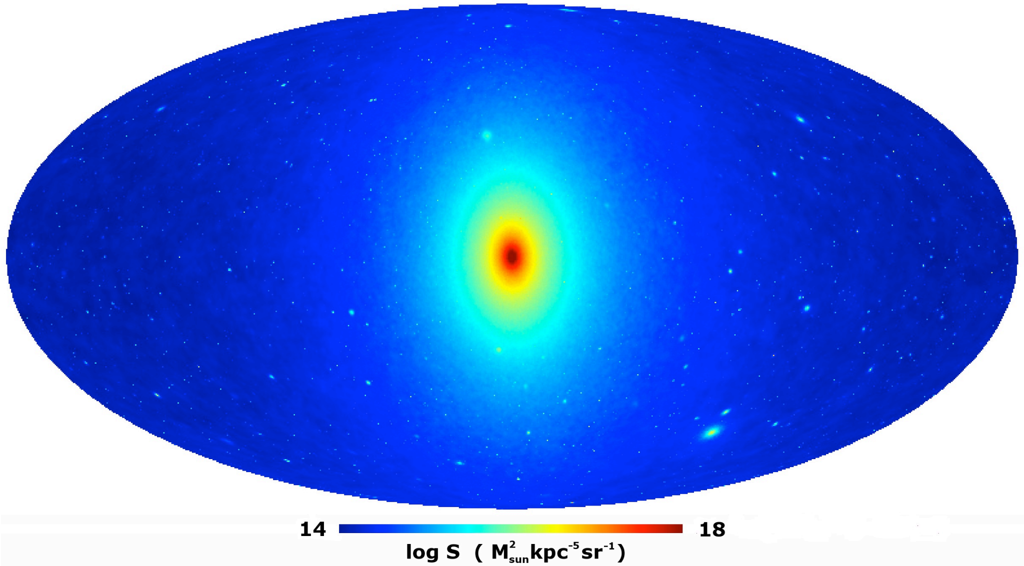




ApJ 757 123 (2012) [arXiv:1208.0676]



A&A 425 (2004) L13-L17 [arXiv:0408145]



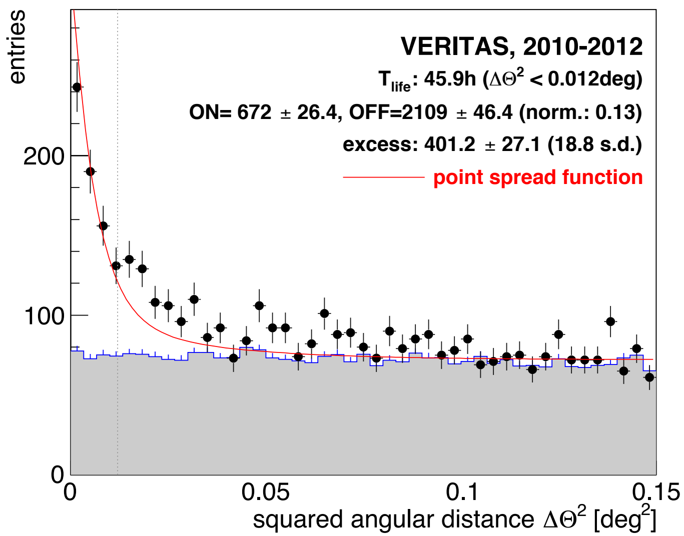
Virgo Consortium - Aquarius simulations

Galactic Center

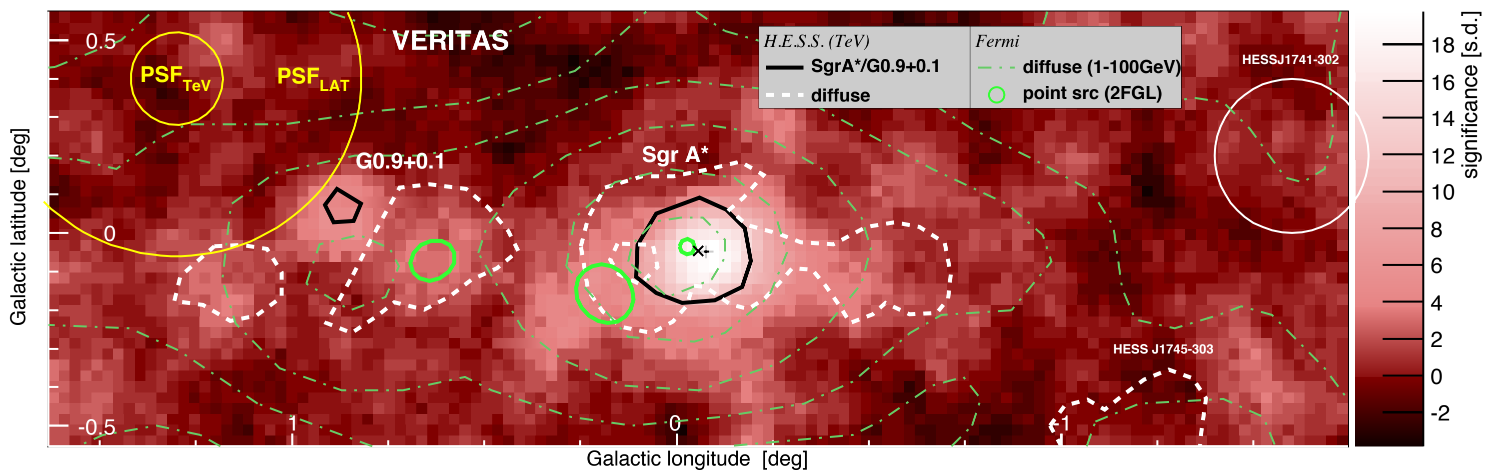
- Brightest DM annihilation signal
- Crowded region, signal confusion
- Conventional emitters outshine DM signal

Galactic Halo

- Large astrophysical factor (model dependent)
- Complicated analysis

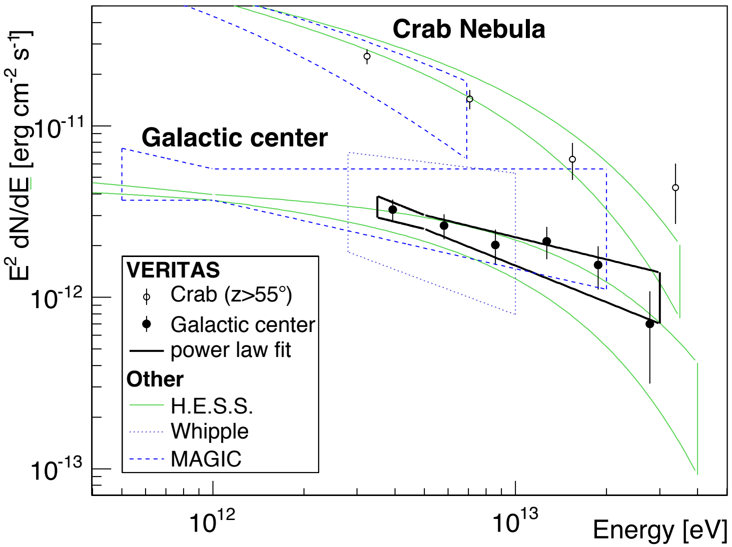


- Observed during 2010-2012 for 46h
- Large Zd observations: 60 deg – 64 deg
- High energy thr. but better A_{eff} at high energies
- Detected at ~18σ

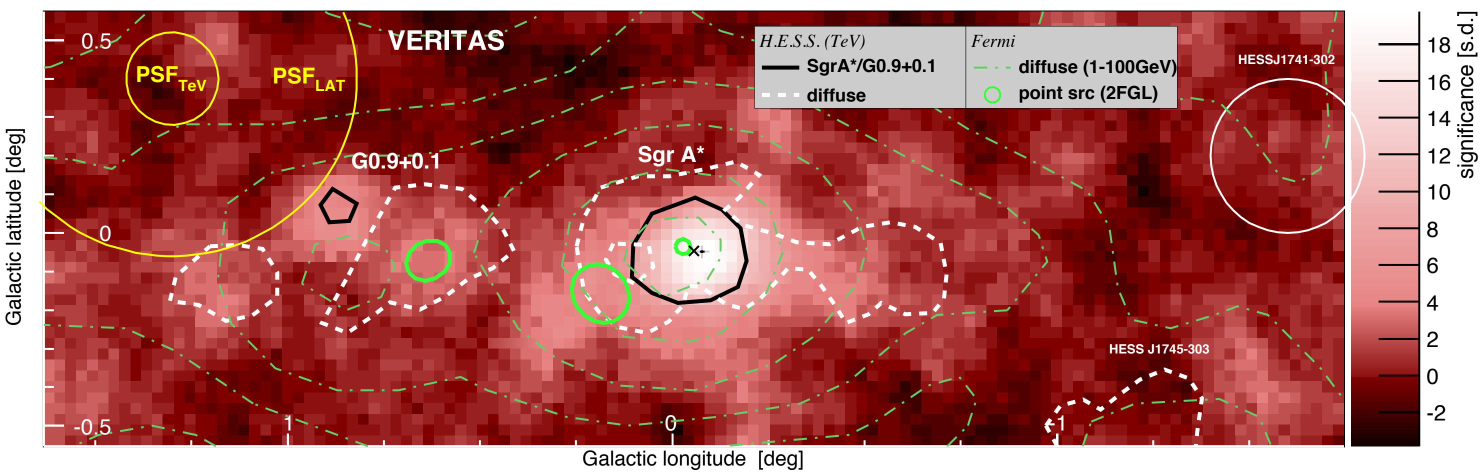


ApJ (accepted) 2014 [arXiv:1406.6383]

Galactic Center and Halo



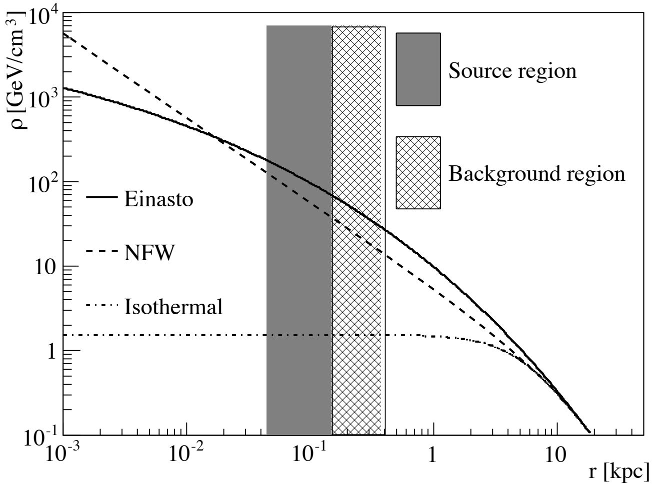
- Position coincident with:
  - Sag A*
  - Sgr A East
  - PWN G359.95-0.04
  - AXJ1745.6-2901
  - 9 maser objects
  - 150 X-ray sources…
- Spectrum compatible with earlier results
- 2.5 TeV – tens of TeV



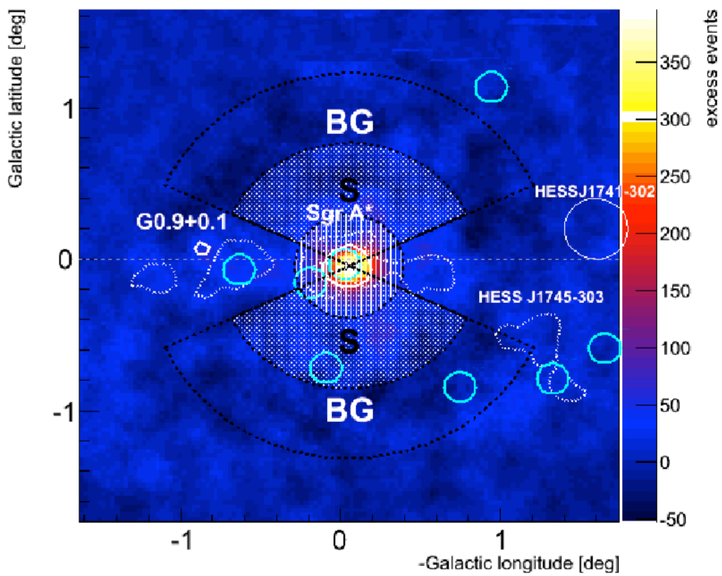
ApJ (accepted) 2014 [arXiv:1406.6383]

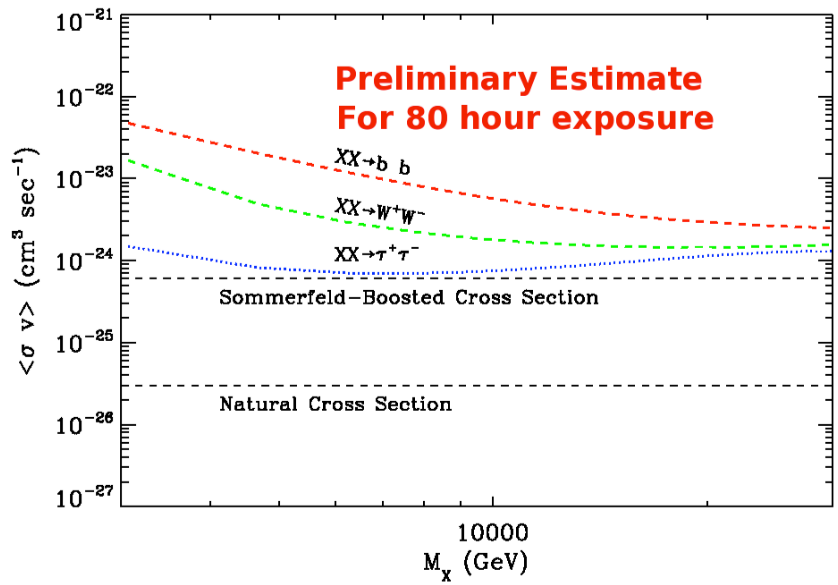
Galactic Center and Halo

PRL 106:1301, 2011 [arXiv:1103.3266]



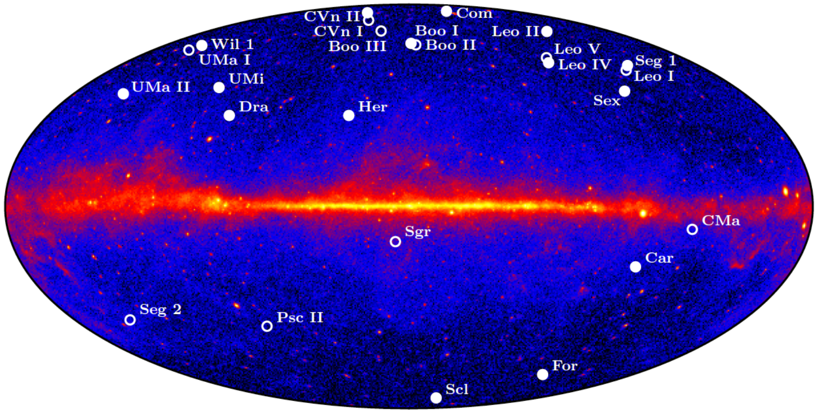
- Large zenith angle observations:
  - Increased energy threshold
  - Increased sensitivity in the TeV range
- Calculation of limits: work in progress
- Estimate: $<\sigma v>^{UL} \sim O(10^{-23})$ - $O(10^{-24})$ $cm^3 s^{-1}$



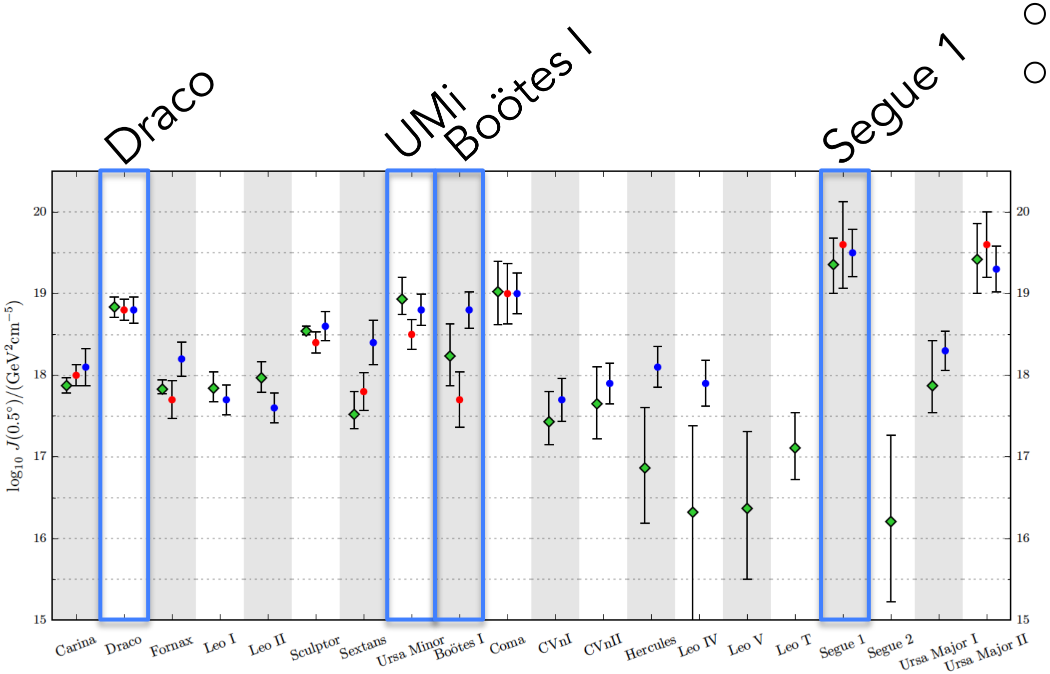


Snowmass CF2-WP, 2013 [arXiv:1304.6367]

Dwarf Spheroidal Galaxies

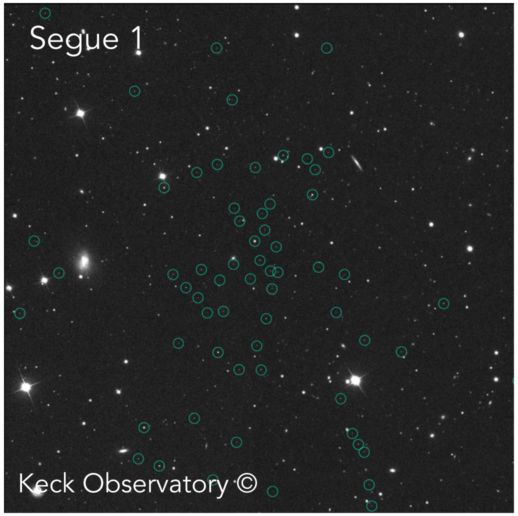


Phys. Rev. D 89, 042001 (2014) [arXiv:1310.0828]



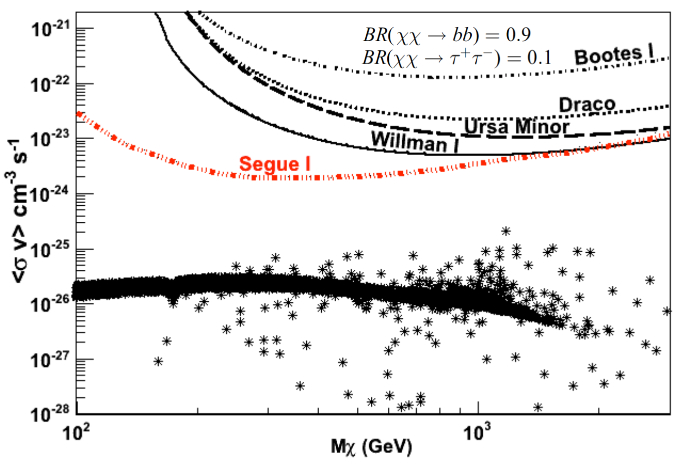
Geringer-Sameth et al. (2014) [arXiv:1408.0002]

- DM content & structure modelling
  - Star members kinematics
  - Most DM dominated systems
- Large M/L
  - Small role of baryons
  - DM distribution not disturbed
- Low intrinsic background at HE
- Known locations, not very extended
- Relatively close (d < 100 kpc)
- High Galactic latitude

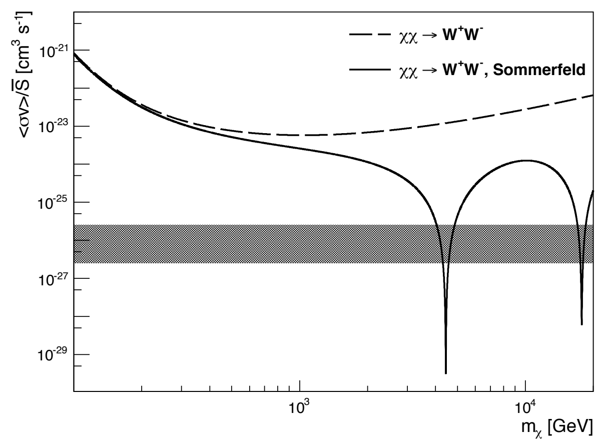


Dwarf Spheroidal Galaxies

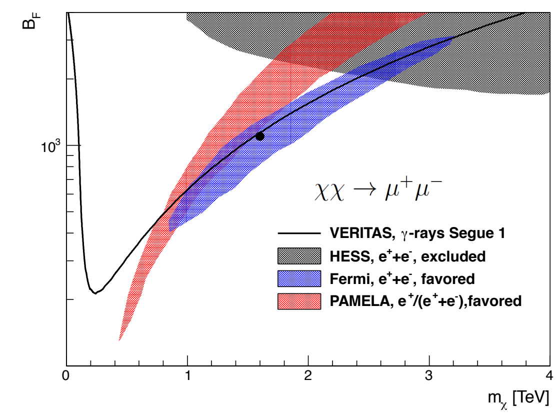
Source	Dist. (kpc)	$\log_{10} J(\Omega)$ ($GeV^2 cm^{-5}$)	Exp. (h)	Sig. (σ)	E_{th} (GeV)	Int. Flux UL 95% CL (cm-1s-1 >300 GeV)
Segue I	23	19.0	47.8	1.4	300	0.8×10^{-12}
Draco	80	18.4	18.4	-1.5	340	0.5×10^{-12}
Ursa Minor	66	18.9	18.9	-1.8	380	0.4×10^{-12}
Boötes I	62	17.9	14.3	1.4	300	2.2×10^{-12}
Willman I	38	18.9	13.7	-0.1	320	1.2×10^{-12}



$<\sigma v>^{UL} \sim O(10^{-24})$ $cm^{-3}s^{-1}$



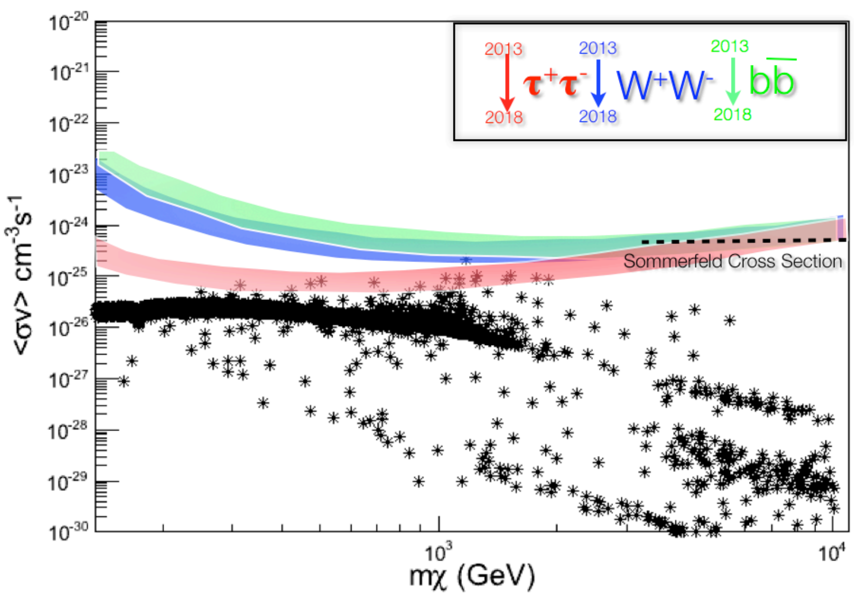
Excludes particular masses on Sommerfeld-enhanced models



Constraints boost factors on DM models that may explain CR lepton anomalies

ApJ 720:1174 (2010) [arXiv:1006.5955]
Phys. Rev. D 85, 062001 (2012) [arXiv:1202.2144]

Source	Dist. (kpc)	$\log_{10}J(\Omega)$ (GeV^2cm^{-5})	Exp. (h)	Sig. (σ)	E_{th} (GeV)	Int. Flux UL 95% CL (cm-1s-1 >300 GeV)
Segue I	23	19.0	91.9	0.7	150	0.4×10^{-12}
Draco	80	18.4	49.9	-1.0	220	0.3×10^{-12}
Ursa Minor	66	18.9	59.7	0.0	290	0.3×10^{-12}
Boötes I	62	17.9	14.3	-1.0	170	0.5×10^{-12}
Willman I	38	18.9	13.7	-0.6	180	1.2×10^{-12}

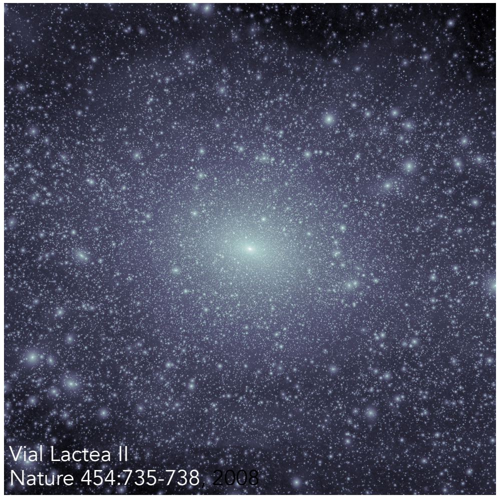


Snowmass 2013, CF2-WP [arXiv:1304.6367]

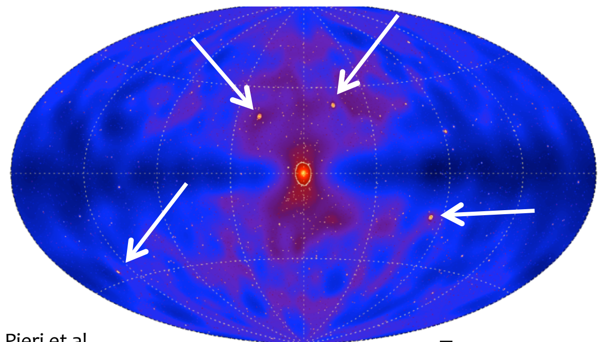
- Stacking analysis efforts ongoing
- Extrapolation of DM program to 2018:
  - Proving $O(10^{-25})$ $cm^{-3}s^{-1}$ region
- Conservative scenario:
  - No boost to DM signal
  - No analysis improvements

Dark Matter Subhalo Candidates

N-body CDM simulations



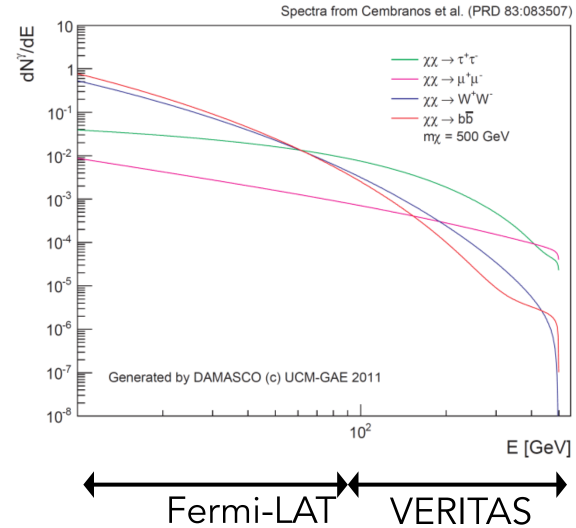
Fermi sensitivity to galactic DM annihilation



Pieri et al.
PRD 83:0235,

$\chi\chi \rightarrow b\bar{b},\ m_{\chi} = 40$ GeV

DM annihilation spectral shape



Main hypotheses

N-body simulations predict the existence of DM galactic subhalos

DM subhalo close enough may provide a sufficiently high J factor to shine at HE & VHE

Dark Matter subhalos are detected by Fermi and characterised by VERITAS

Too small to have attracted enough baryonic matter to start star formation: invisible at other wavelengths

Number of detectable DM subhalos

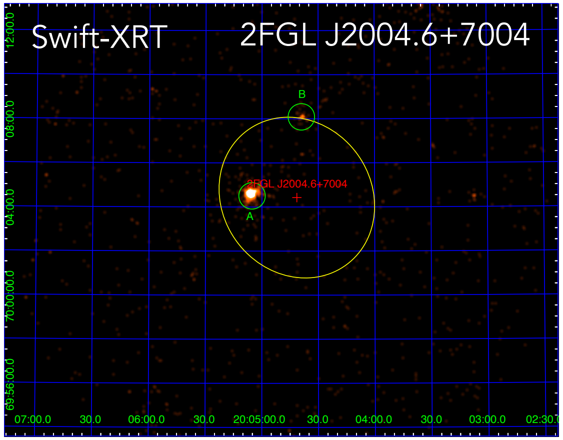
Depends on N-body simulations, WIMP mass, annihilation channels, DM profiles…

From 2 up to > 40 detectable DM subhalos in Fermi data

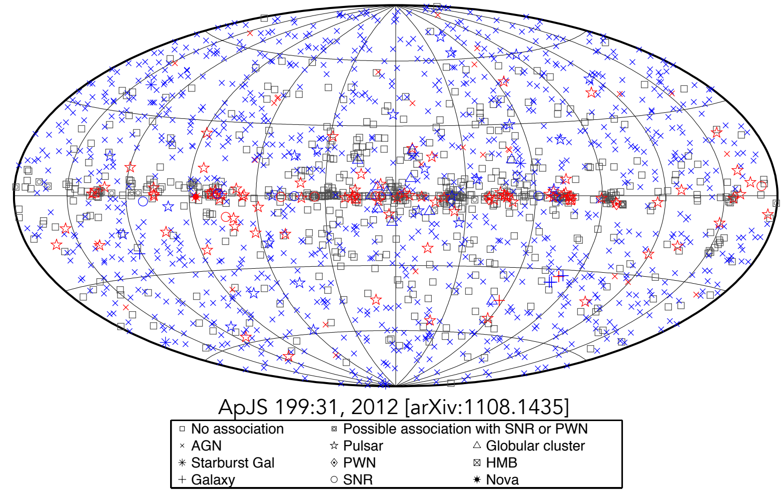
Dark Matter Subhalo Candidates

Selection criteria:

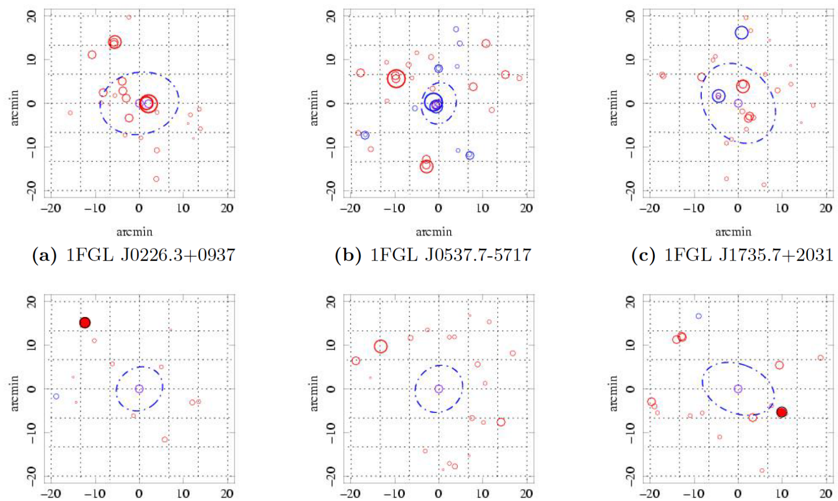
- 2FGL filtering
  - Exclude the galactic plane
  - No variability
  - No evidence for spectral curvature
  - Observable with VERITAS
- Feasible detection with VERITAS
- Search for counterparts in HEASARCH
- Search for counterparts in Swift data



Fermi LAT Second Source Catalog



ApJS 199:31, 2012 [arXiv:1108.1435]



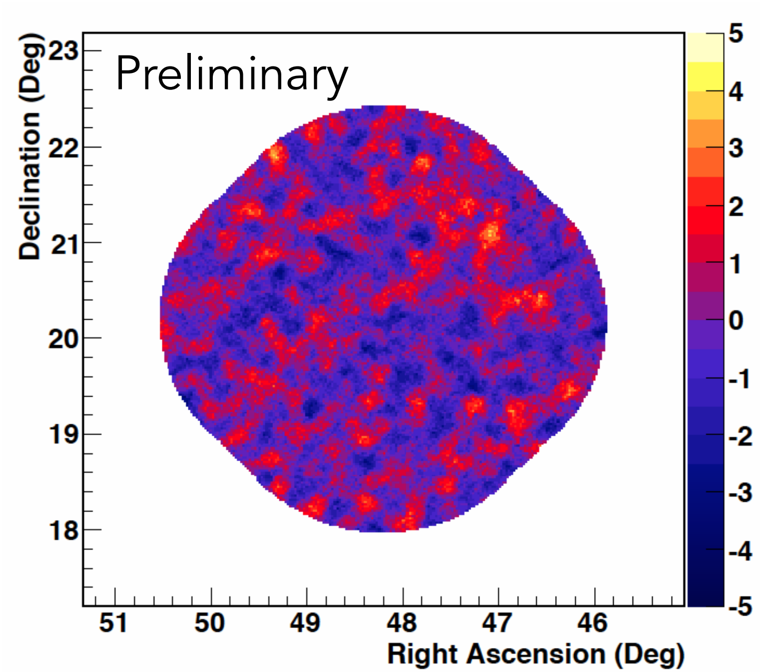
(a) 1FGL J0226.3+0937 (b) 1FGL J0537.7-5717 (c) 1FGL J1735.7+2031

(d) 1FGL J0338.8+1313 (e) 1FGL J1351.8-1353 (f) 1FGL J2347.3+0710

ASDC Data Explorer

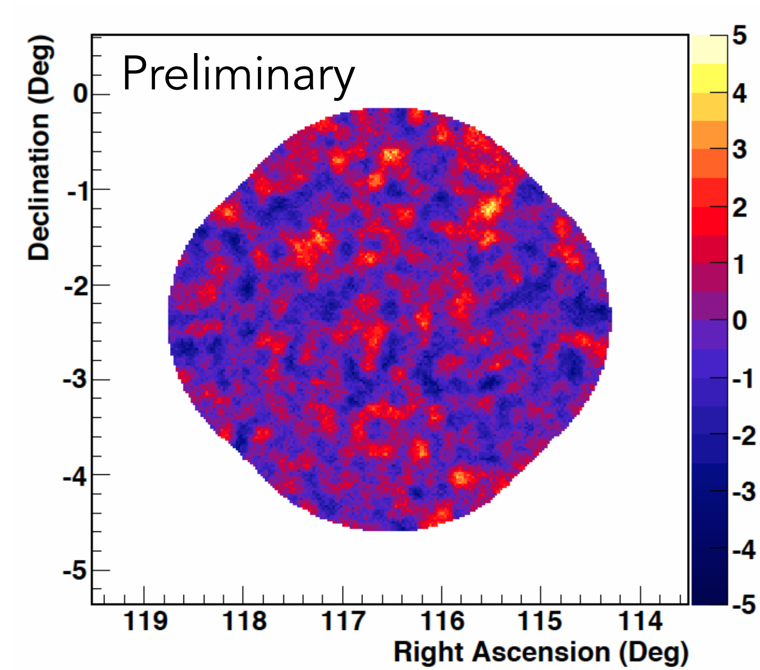
Dark Matter Subhalo Candidates

2FGL J0312.8+2013



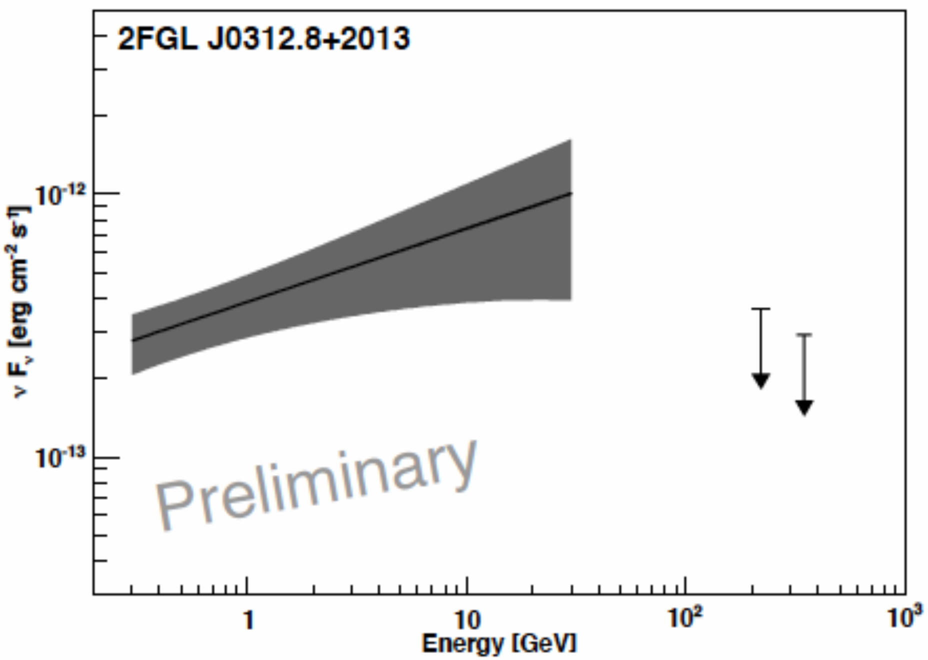
Exposure	9.7h
Excess events	-25.7 ± 16.9 (-1.5σ)
$F_{E>219GeV}$ (99% c.l.)	< 1.78×10^{-12} cm^{-2} s^{-1} < 0.9% Crab Nebula

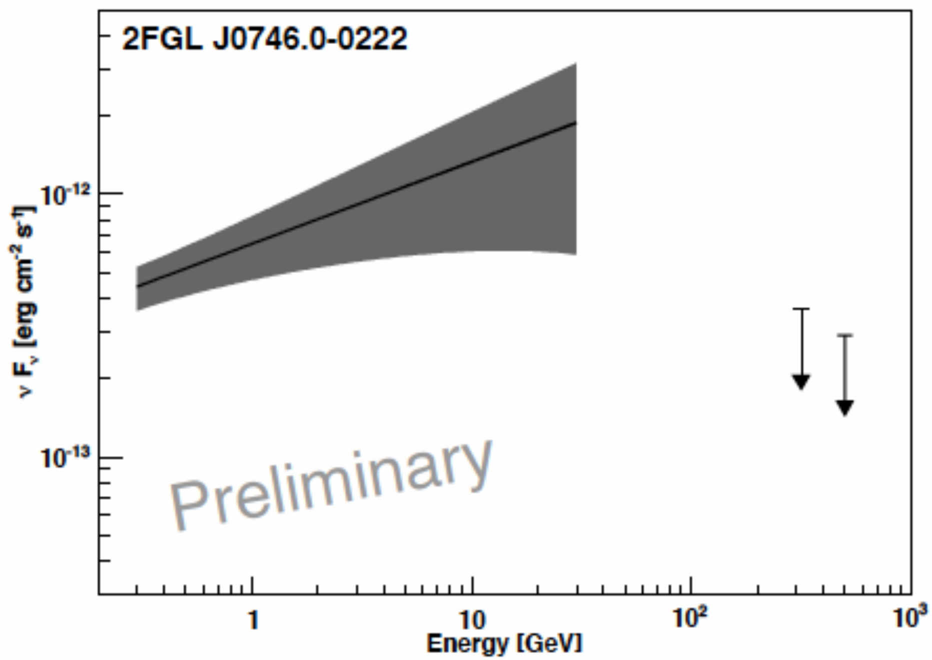
2FGL J0746.0-0222



Exposure	9.1h
Excess events	-14.5 ± 15.8 (-0.9σ)
$F_{E>316GeV}$ (99% c.l.)	< 1.23×10^{-12} cm^{-2} s^{-1} < 1.1% Crab Nebula

Dark Matter Subhalo Candidates





TS	26.3
Γ	1.72 ± 0.24
$F_{0.1\text{-}100\ \mathrm{GeV}}$	$(1.76 \pm 1.29) \times 10^{-9}\ \mathrm{cm^{-2}\ s^{-1}}$

TS	70.9
Γ	1.67 ± 0.14
$F_{0.1\text{-}100\ \mathrm{GeV}}$	$(2.84 \pm 1.09) \times 10^{-9}\ \mathrm{cm^{-2}\ s^{-1}}$

Direct extrapolation of Fermi spectra to VHE band is in tension with VERITAS results

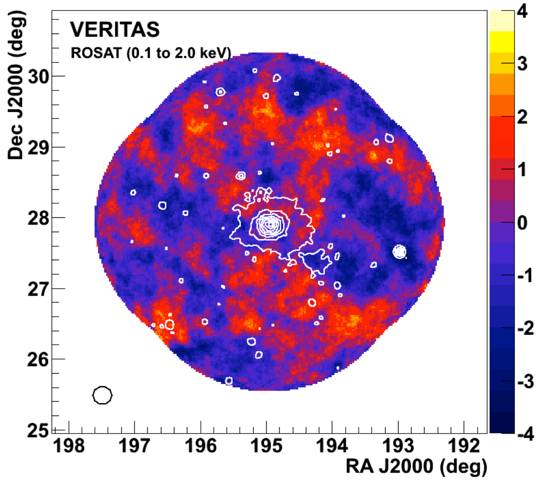
Conclusions

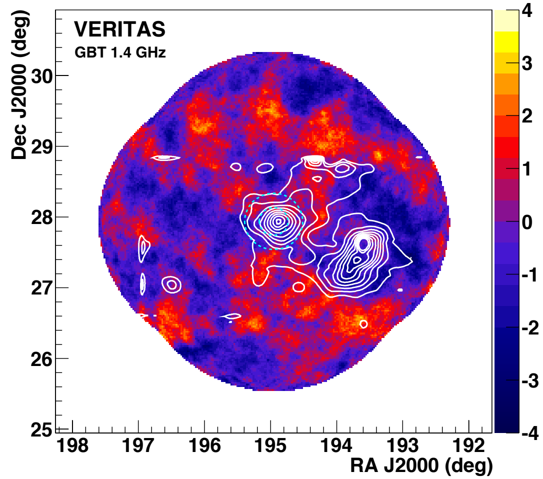
- VERITAS has an ambitious ongoing program on DM searches
  - More that 1000 h on DM targets upon completion
- Limits to DM originated signals have been already placed
  - Coma Cluster: $\langle\sigma v\rangle^{UL} \sim O(10^{-20})$ - $O(10^{-21})$ $cm^3 s^{-1}$
  - Segue 1: $\langle\sigma v\rangle^{UL} \sim O(10^{-23})$ - $O(10^{-24})$ $cm^3 s^{-1}$
  - Galactic Halo: work ongoing
- The continuation of the program may allow to place very competitive limits
  - Dwarf spheroidal stacking analysis
  - Galactic Halo analysis
  - $\langle\sigma v\rangle^{UL} \sim O(10^{-24})$ - $O(10^{-25})$ $cm^3 s^{-1}$
- High-risk high-reward approaches also being conducted
  - Potential DM subhalo searches

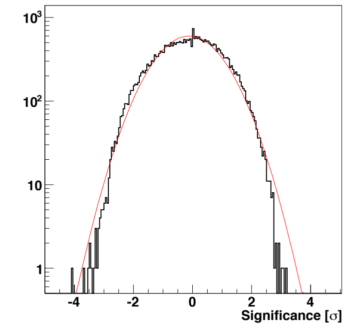
Stay tuned!

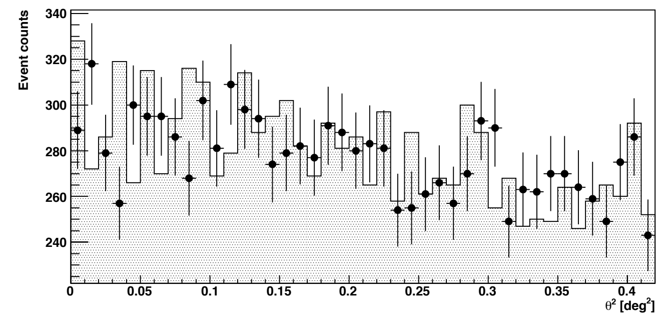
Backup

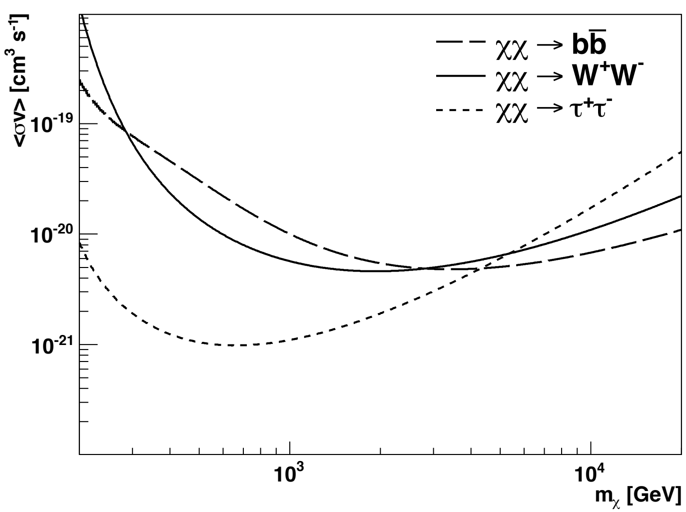
Galaxy Clusters

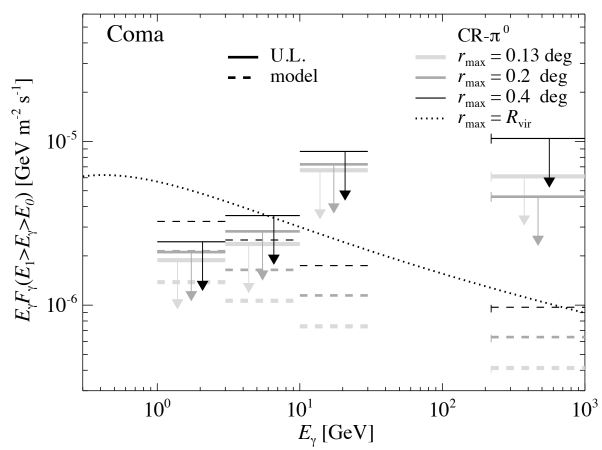


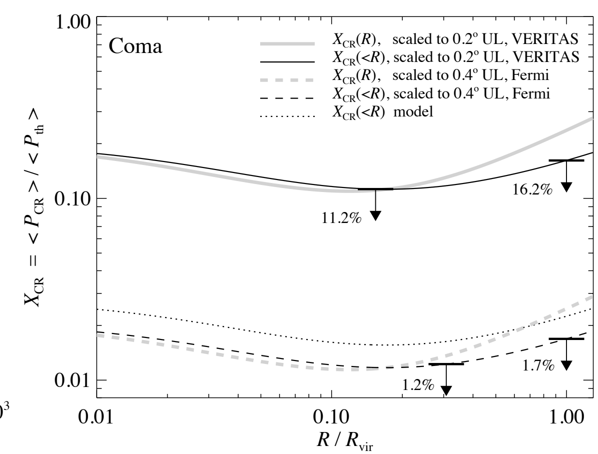








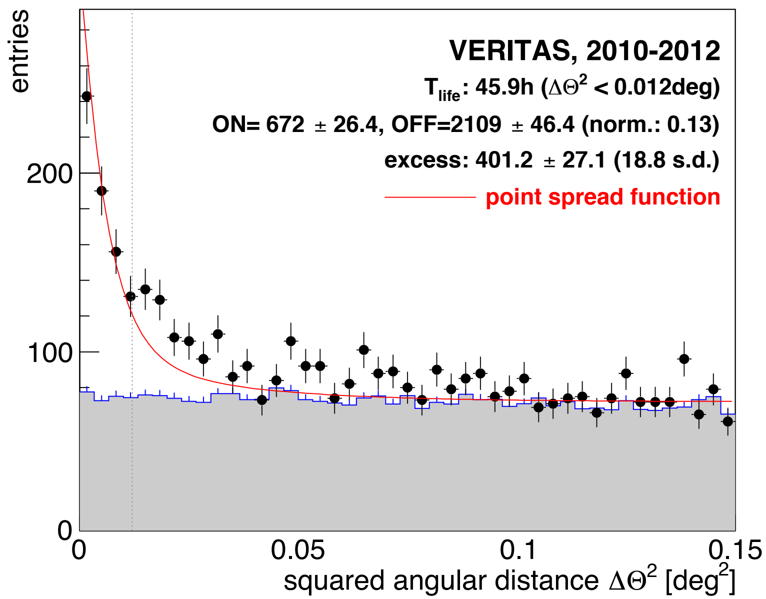


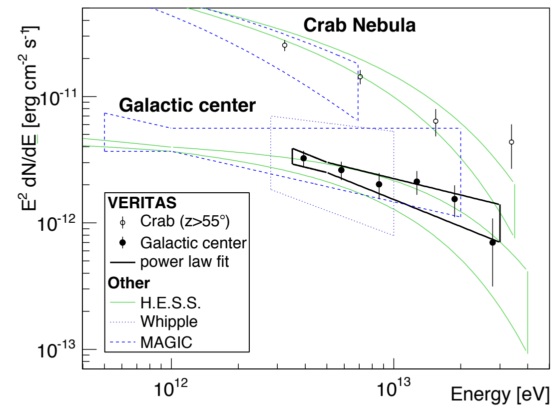


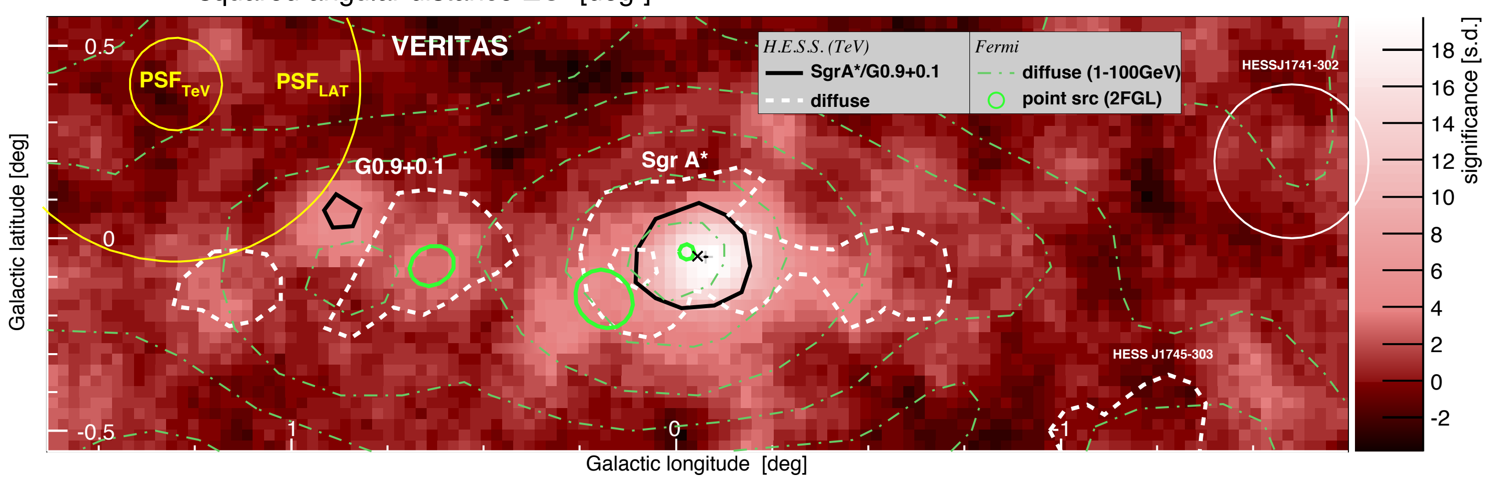
Upper limits on the DM annihilation cross section times velocity $\langle\sigma v\rangle$ from VERITAS observations of the Coma cluster.

Channel	R [deg]	m_χ [GeV]	$\langle\sigma v\rangle$ [cm^3 s^{-1}]
W^+W^-	0	2000	1.1×10^{-20}
	0.2	1900	4.3×10^{-21}
	0.4	1900	8.4×10^{-21}
$b\bar{b}$	0	3500	1.2×10^{-20}
	0.2	3400	4.4×10^{-21}
	0.4	3500	8.7×10^{-21}
$\tau^+\tau^-$	0	670	2.4×10^{-21}
	0.2	650	9.1×10^{-22}
	0.4	660	1.8×10^{-21}

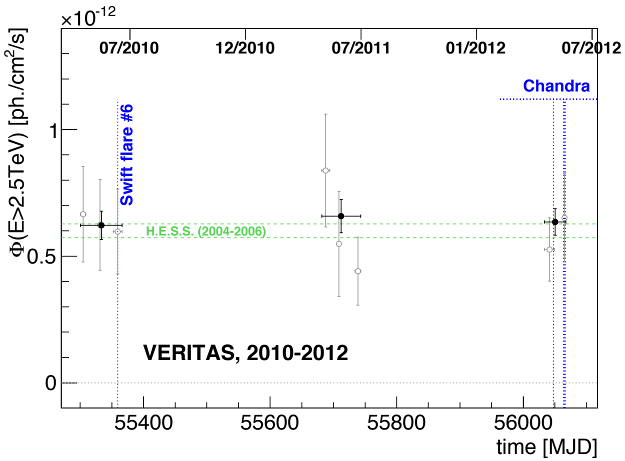
R [deg]	$\langle J\rangle_{\rm signal}$ [GeV^2 cm^{-5} sr]	$\alpha\,\langle J\rangle_{\rm bkg}$ [GeV^2 cm^{-5} sr]
0	5.7×10^{16}	1.3×10^{14} (negligible)
0.2	8.1×10^{16}	4.4×10^{14} ($< 0.01\,\langle J\rangle_{\rm signal}$, negligible)
0.4	9.4×10^{16}	1.3×10^{15} ($\simeq 0.01\,\langle J\rangle_{\rm signal}$, negligible)

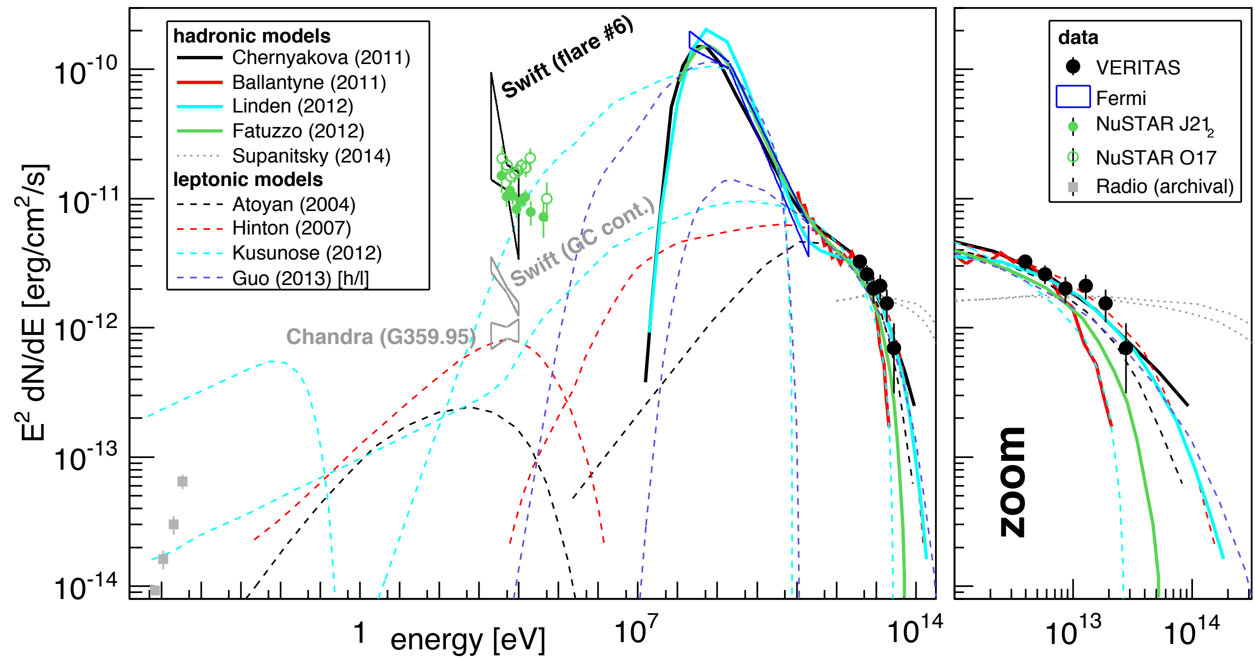






ApJ (accepted) 2014 [arXiv:1406.6383]

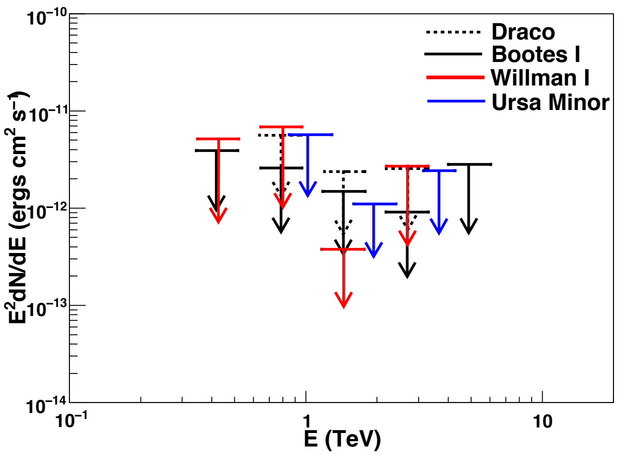


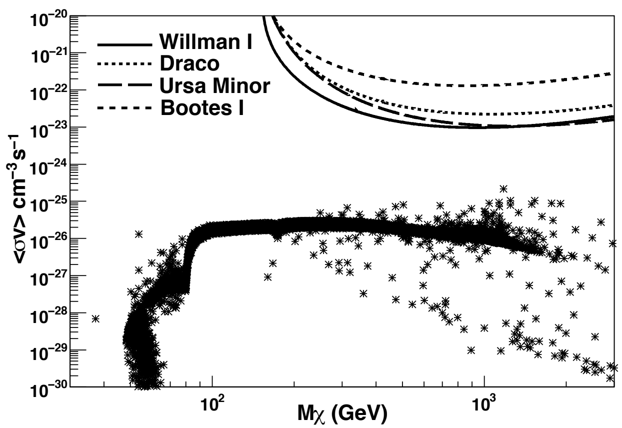


year	begin [MJD]	end [MJD]
2010	55300.4	55308.4
	55328.3	55334.4
	55352.3	55366.3
2011	55681.4	55694.4
	55707.3	55710.4
	55734.2	55743.3
2012	56033.4	56049.5
	56063.3	56067.4

ApJ (accepted) 2014 [arXiv:1406.6383]

Dwarf Spheroidal Galaxies





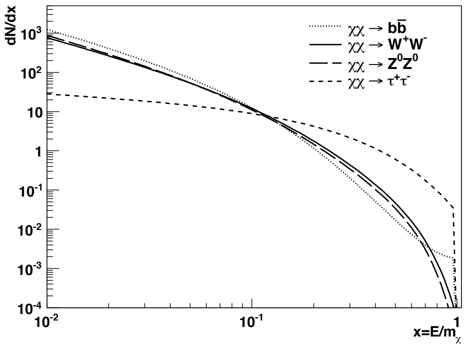
Source	Period	Exposure (hr)	Zenith Angle (°)
Draco	2007 Apr–May	18.38	26–51
Ursa Minor	2007 Feb–May	18.91	35–46
Boötes 1	2009 Apr–May	14.31	17–29
Willman 1	2007 Dec–2008 Feb	13.68	19–28

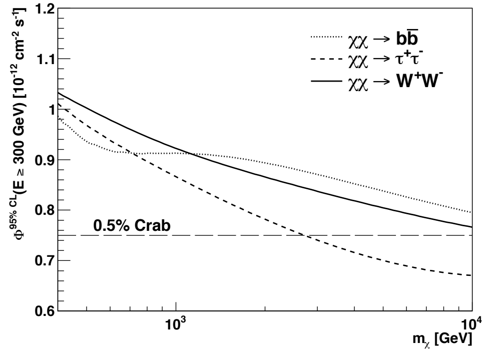
Quantity	Draco	Ursa Minor	Boötes 1	Willman 1
α [J2000.0]	$17^h20^m12\overset{s}{.}4$	$15^h09^m11\overset{s}{.}3$	$14^h00^m06^s$	$10^h49^m22\overset{s}{.}3$
δ [J2000.0]	$57°54'55''$	$67°12'52''$	$14°30'00''$	$51°03'03''$
L_V [$L_\odot$]	$(2.7 \pm 0.4) \times 10^5$	$(2.0 \pm 0.9) \times 10^5$	$(3.0 \pm 0.6) \times 10^4$	$(1.0 \pm 0.7) \times 10^3$
r_h [pc]	221 ± 16	150 ± 18	242 ± 21	25 ± 6
R_d [kpc]	80	66	62	38
ρ_s[$M_\odot$/kpc^3]	4.5×10^7	4.5×10^7	...	4×10^8
r_s [kpc]	0.79	0.79	...	0.18
$J(\rho_s, r_s)$	4	7	3	22

Quantity	Draco	Ursa Minor	Boötes 1	Willman 1
Exposure (s)	66185	68080	51532	49255
On source (counts)	305	250	429	326
Total background (counts)	3667	3084	4405	3602
Number of background regions	11	11	11	11
Significance[a]	−1.51	−1.77	1.35	−0.08
95% CL (counts)[b]	18.8	15.6	72.0	36.7
Average effective area (cm^2)	5.84×10^8	5.71×10^8	6.37×10^8	6.37×10^8
Energy threshold (GeV)[c]	340	380	300	320
Flux limit 95% CL (cm^{-2} s^{-1})	0.49×10^{-12}	0.40×10^{-12}	2.19×10^{-12}	1.17×10^{-12}

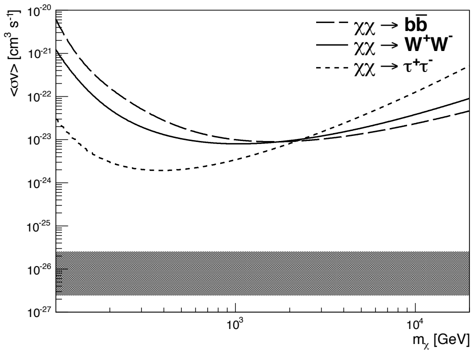
ApJ 720:1174, 2010 [arXiv:1006.5955]

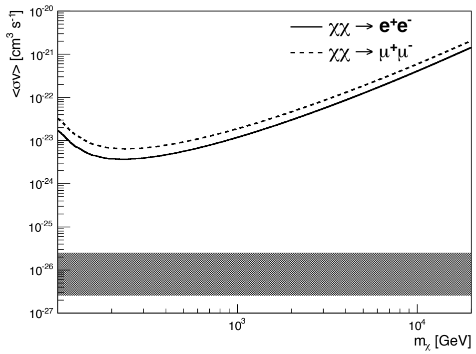
Dwarf Spheroidal Galaxies

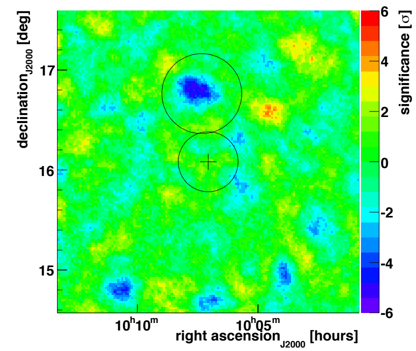


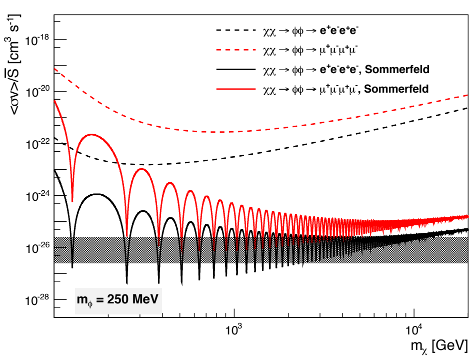


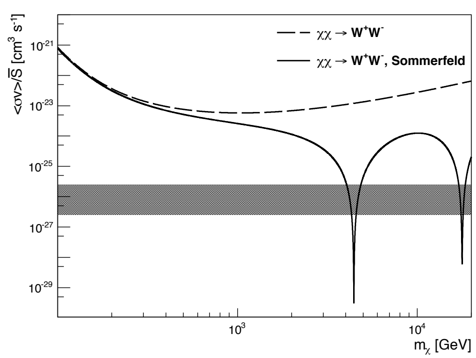
Self-annihilating DM
Limits from VERITAS Segue1 observations

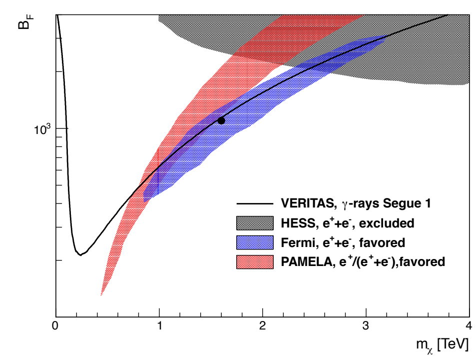






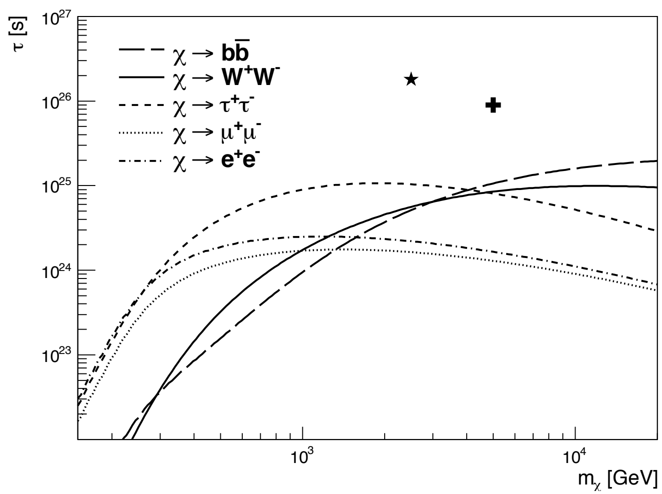


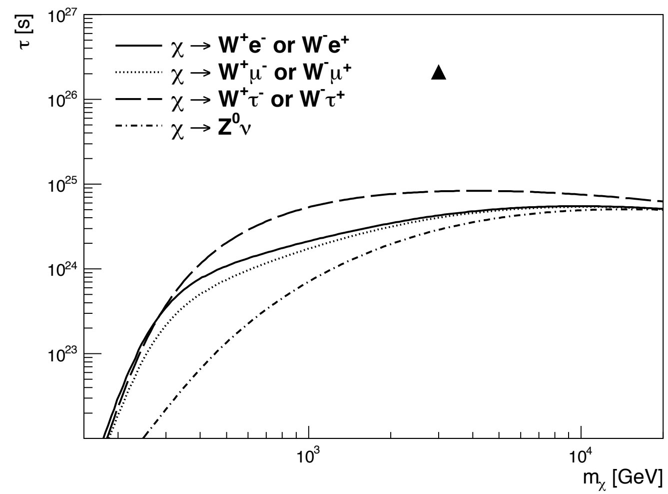




Phys. Rev. D 85, 062001 (2012) [arXiv:1202.2144]

Decaying DM – Limits from VERITAS Segue1 observations





Phys. Rev. D 85, 062001 (2012) [arXiv:1202.2144]

Dark Matter Subhalo Candidates

2FGL extrapol.

$$R_{exc} = \int_{E_{th}}^{\infty} \phi(E) A_{eff}(E)\, dE$$

$$R_{bkg}$$

Vegas 2.4

Obs. Time needed for a 5σ detection

$$\boxed{t = 25 \frac{R_{exc} + 2R_{bkg}}{R_{exc}^2}}$$

From Li&Ma (5), α=1