McDonnell Center for the Space Sciences

Washington University in St. Louis

DM Searches with VERITAS

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VERITAS Collaboration

86 Scientists

22 Institutions in 4 countries

<u>Support from:</u>

U.S. DOE
U.S. NSF
Smithsonian
STFC (U.K.)
NSERC (Canada)
SFI (Ireland)

U.S.

Adler Planetarium
Argonne Natl. Lab.
Barnard College
DePauw Univ.
Grinnell College
Iowa State Univ.
Purdue Univ.
SAO
UCLA
UCSC
Univ. of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Minnesota
Univ. of Utah
Washington Univ.

Canada

McGill Univ.

U.K.

Leeds Univ.

Ireland

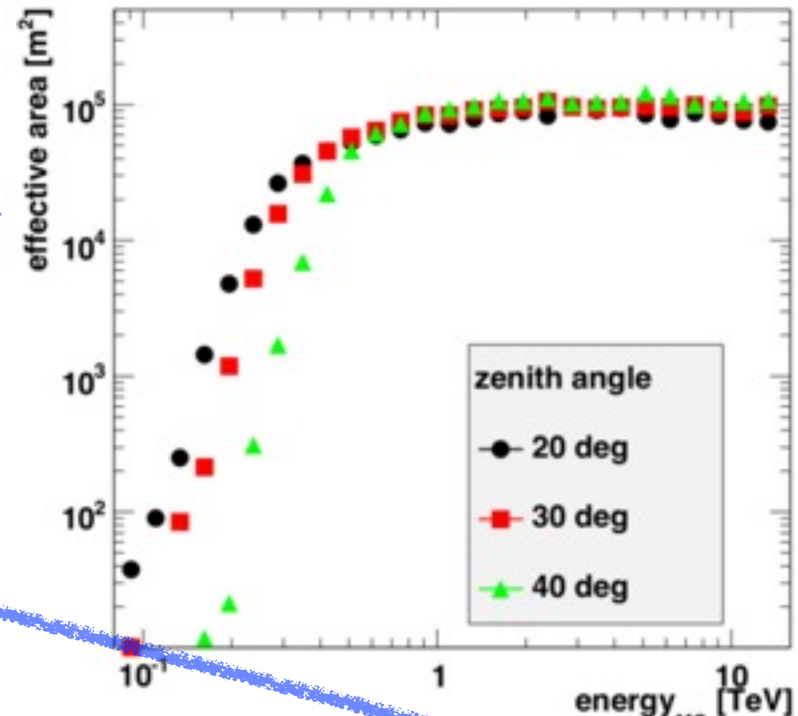
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

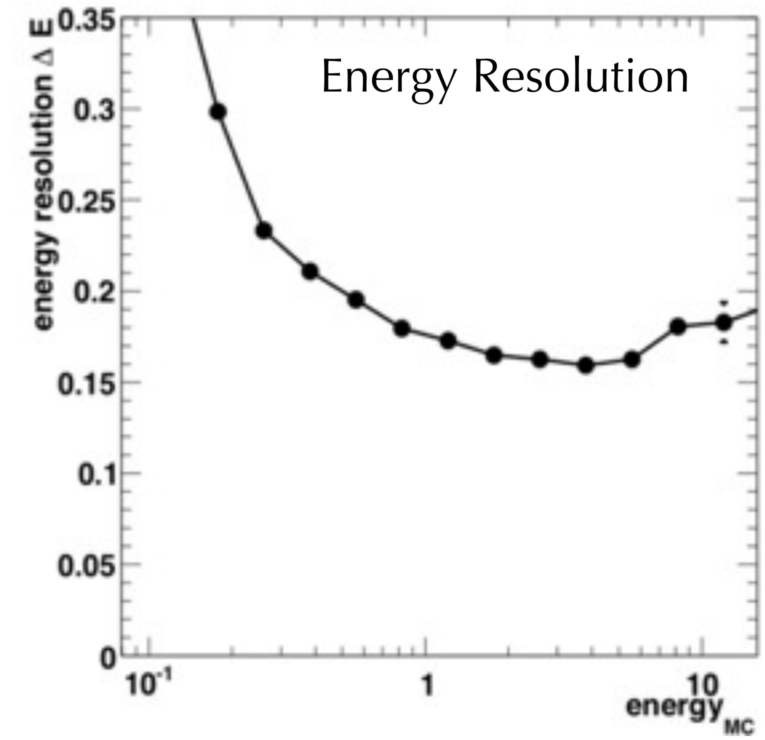
+35 Associate Members
including theorists, MWL partners, IceCube, Fermi, Swift, etc.

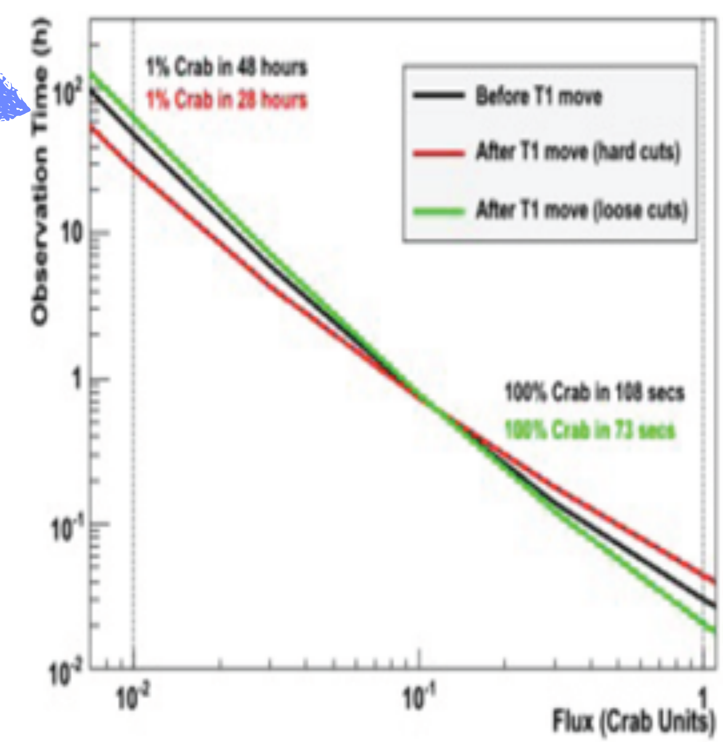
Instrument Characteristics

Canonical Performance Values:

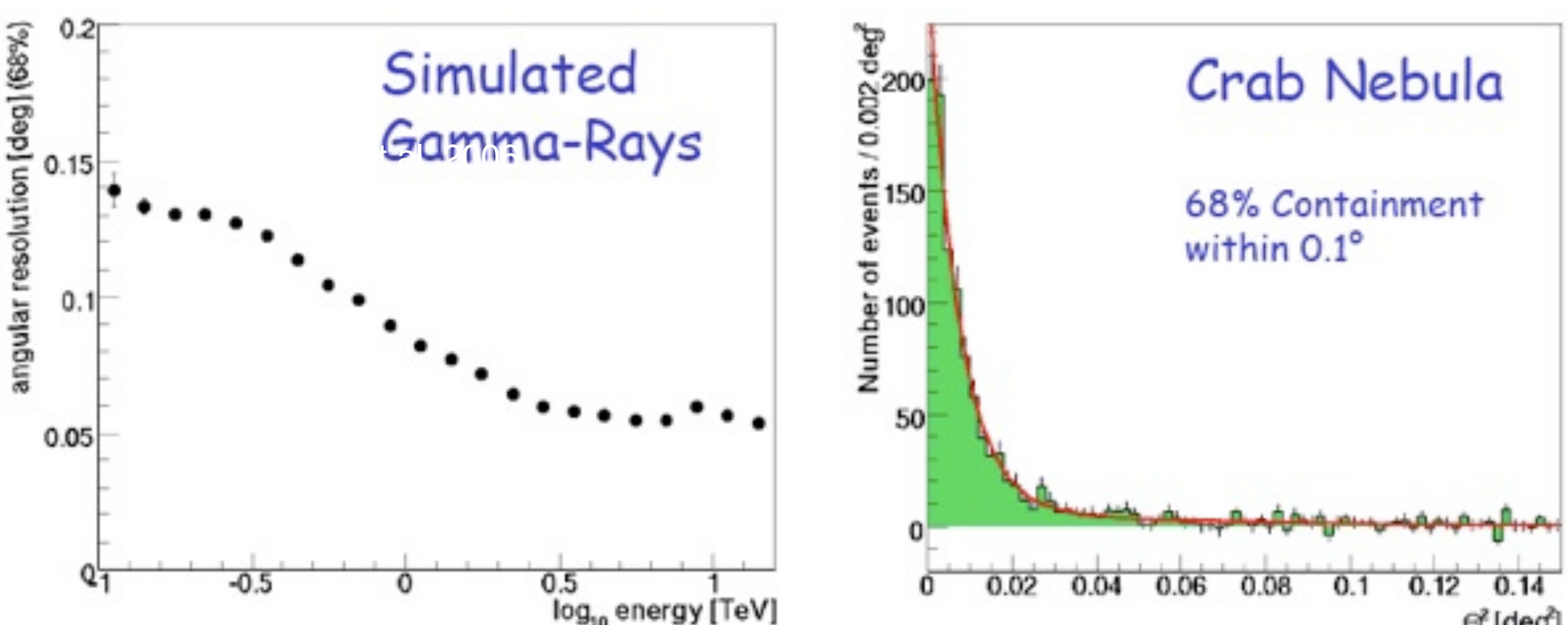
- Energy Range: 100 GeV - 30 TeV (spectra>150 GeV)
- Effective area ~ 10^5 m^2
- Energy Resolution: 15%-20%
- Crab Rate: 50/minute (trigger)
- Sensitivity: 1% Crab in < 30hr
- Angular resolution: r_{68}<0.1°
- Pointing Accuracy: <50″







Pt. Source Sensitivity



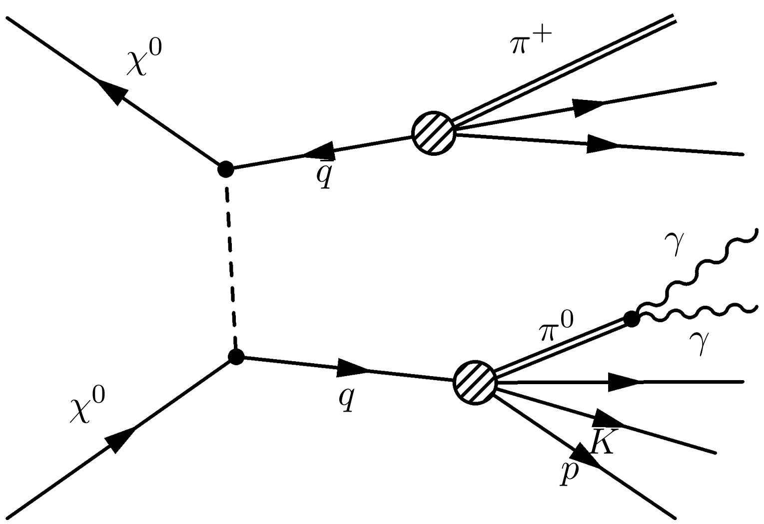
Angular Resolution

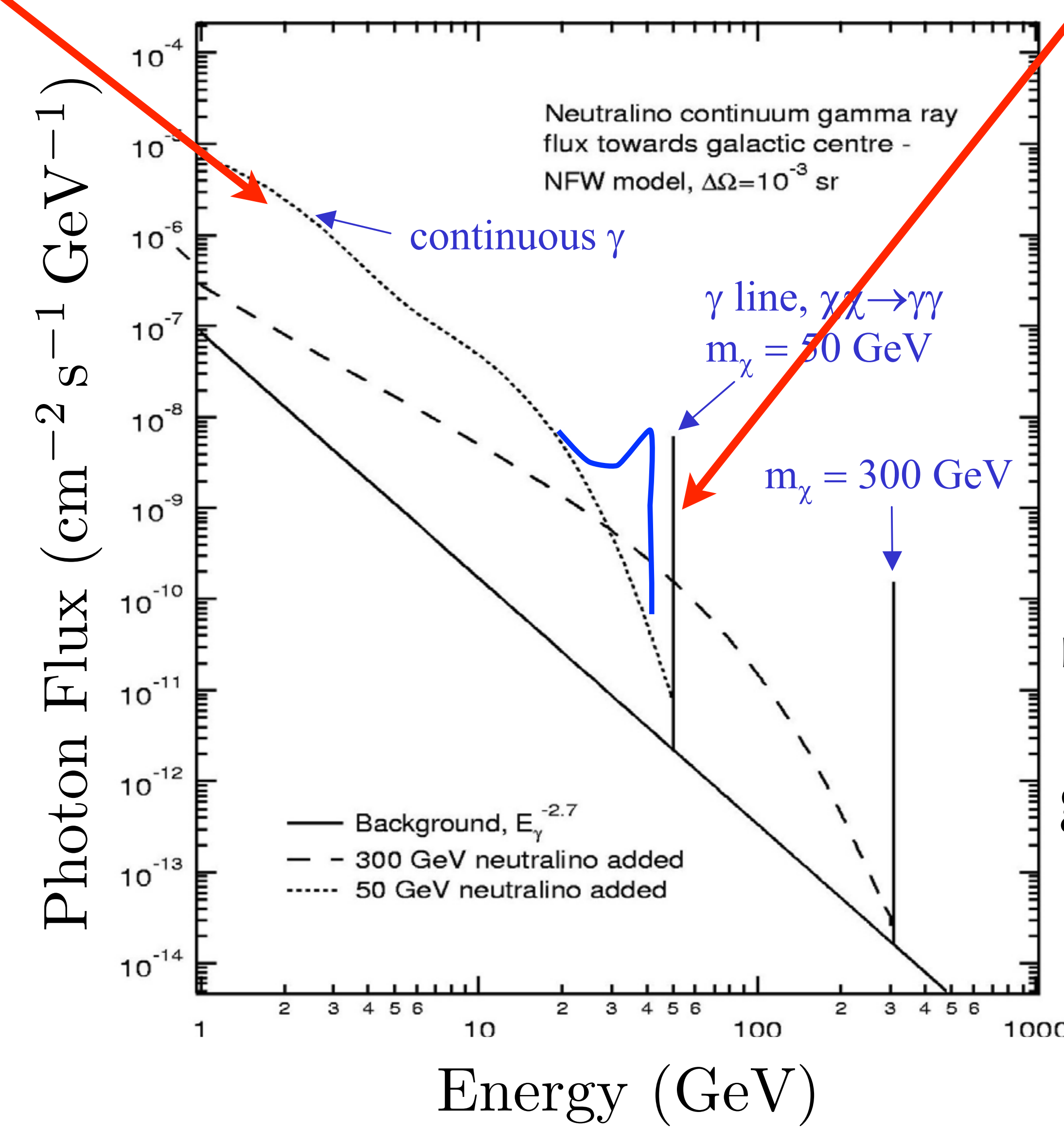
γ-Rays from Dark Matter

Spectral features include continuum emission with a hard spectrum, and for some cases a monochromatic line(s) or a peak near the kinematic limit from internal bremsstrahlung.

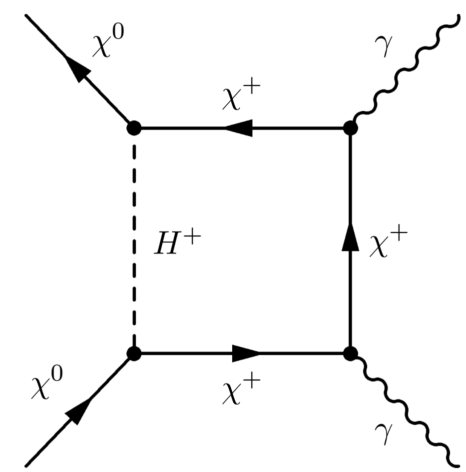
Continuum Emission

Direct Annihilation to Lines





(Bergstrom, Ullio and JB 1998)



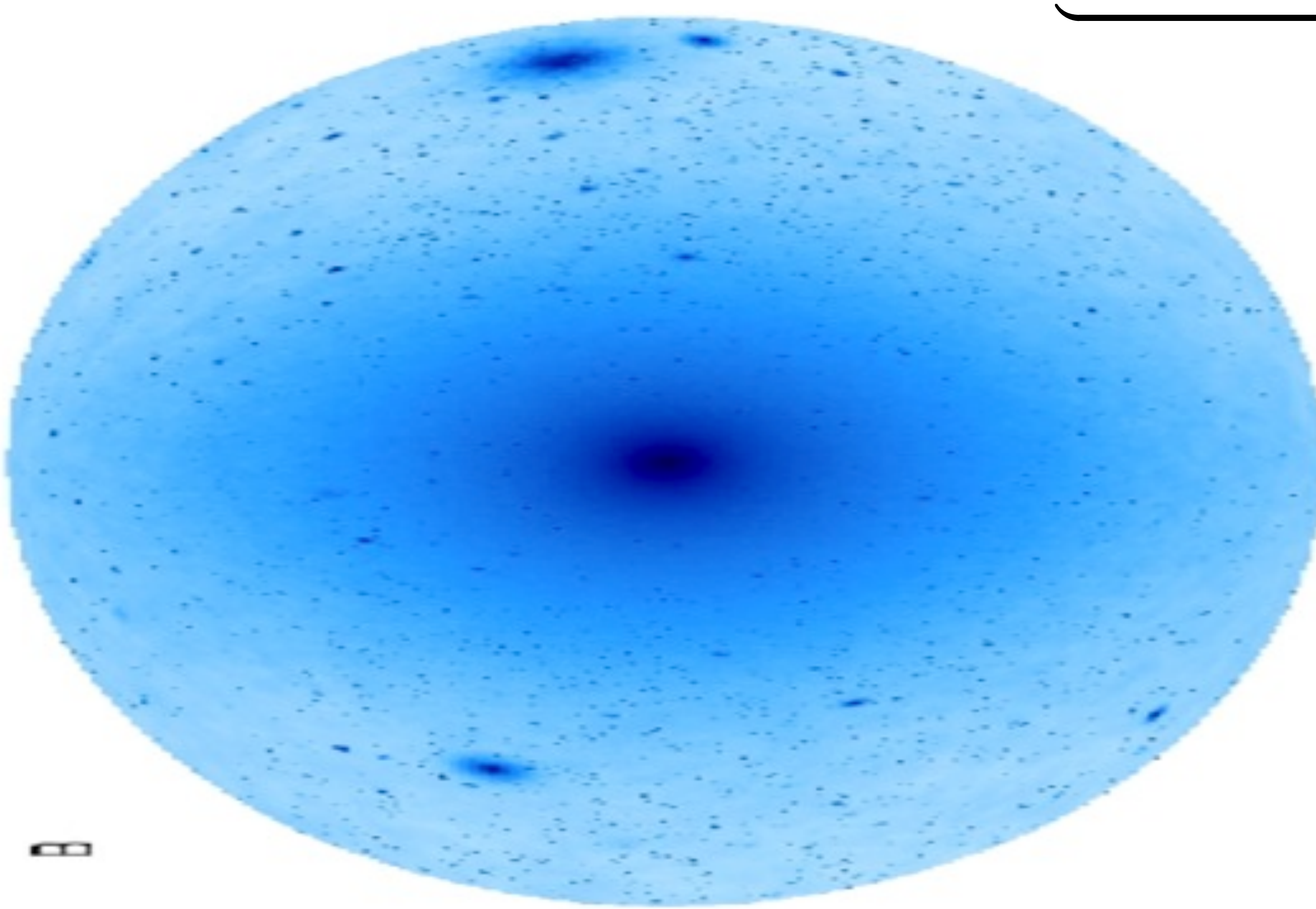
WIMPs can annihilate into quarks that hadronize, form pions and then emit gamma-rays with a continuum spectrum

Direct annihilation into a monoenergetic gamma-ray line with gamma-ray energy given by

Gamma-rays from DM

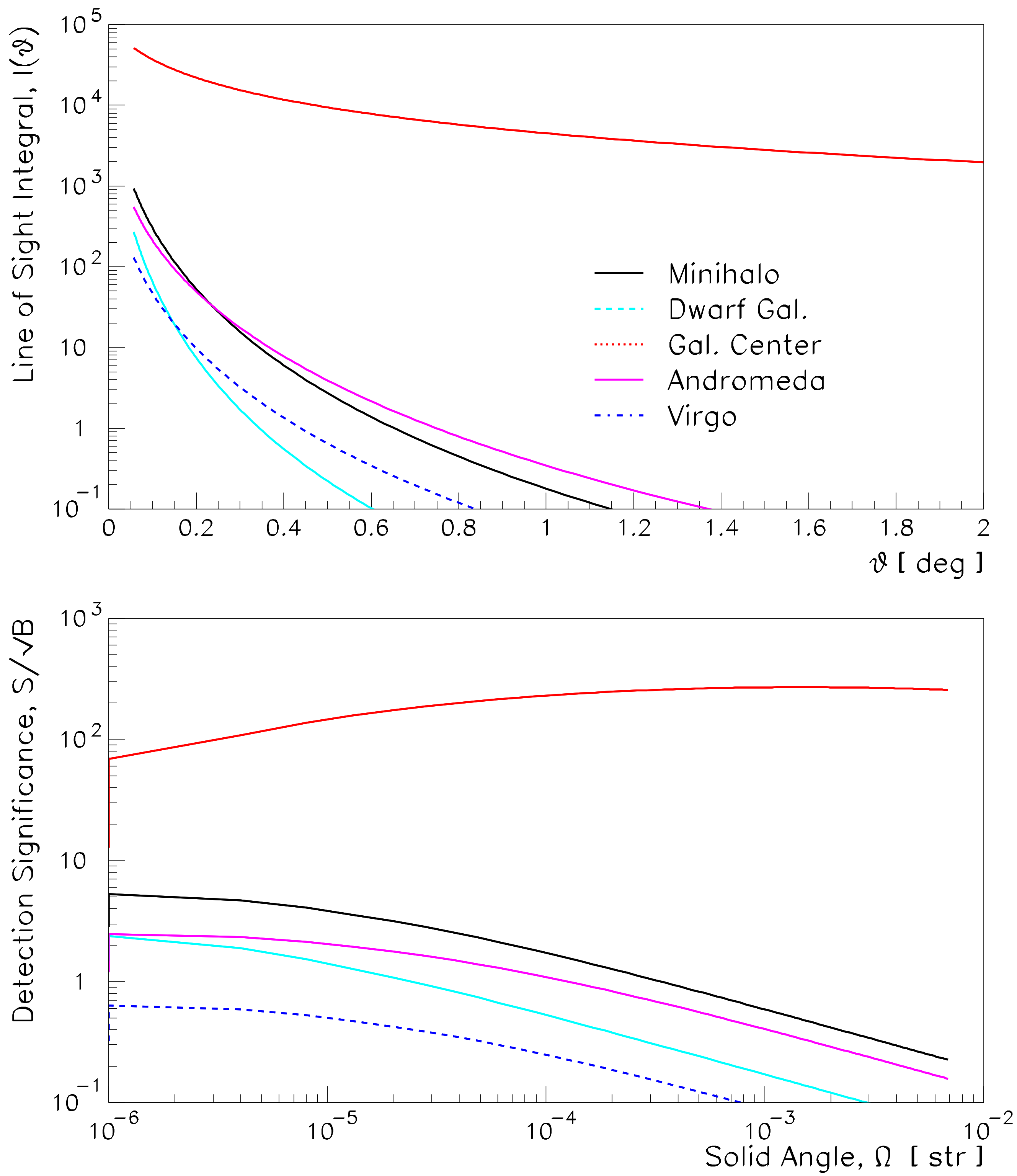
$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right)\left(\frac{\langle\sigma v\rangle}{10^{-26}\mathrm{cm}^{-3}\mathrm{s}^{-1}}\right)\left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{particle physics}} \underbrace{J(\theta)} \;\mathrm{erg\,cm^{-2}s^{-1}sr^{-1}}$$

$$J(\theta) = \underbrace{\frac{1}{8.5\,\mathrm{kpc}}\left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)dl(\theta)}_{\text{astrophysics}}$$

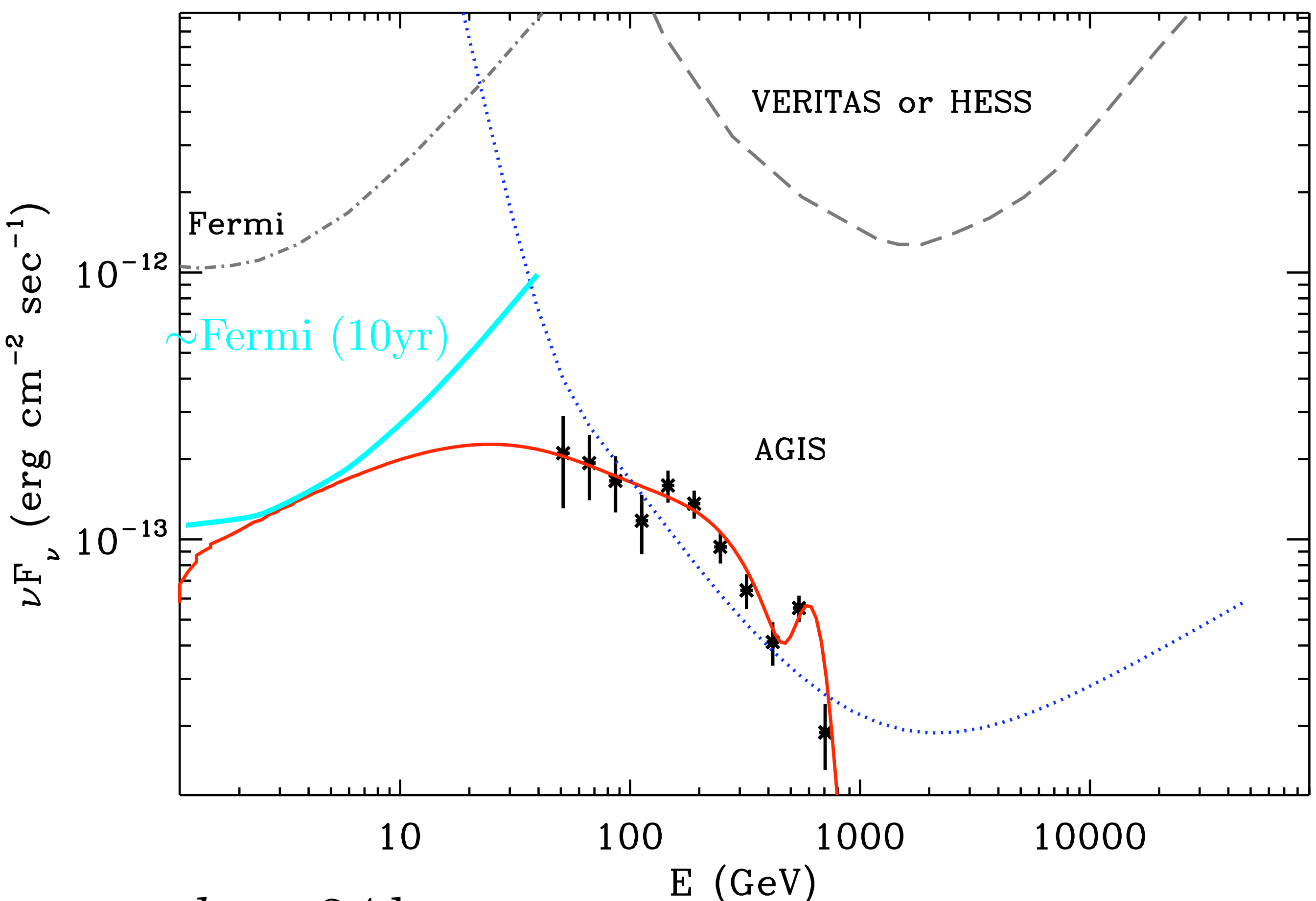


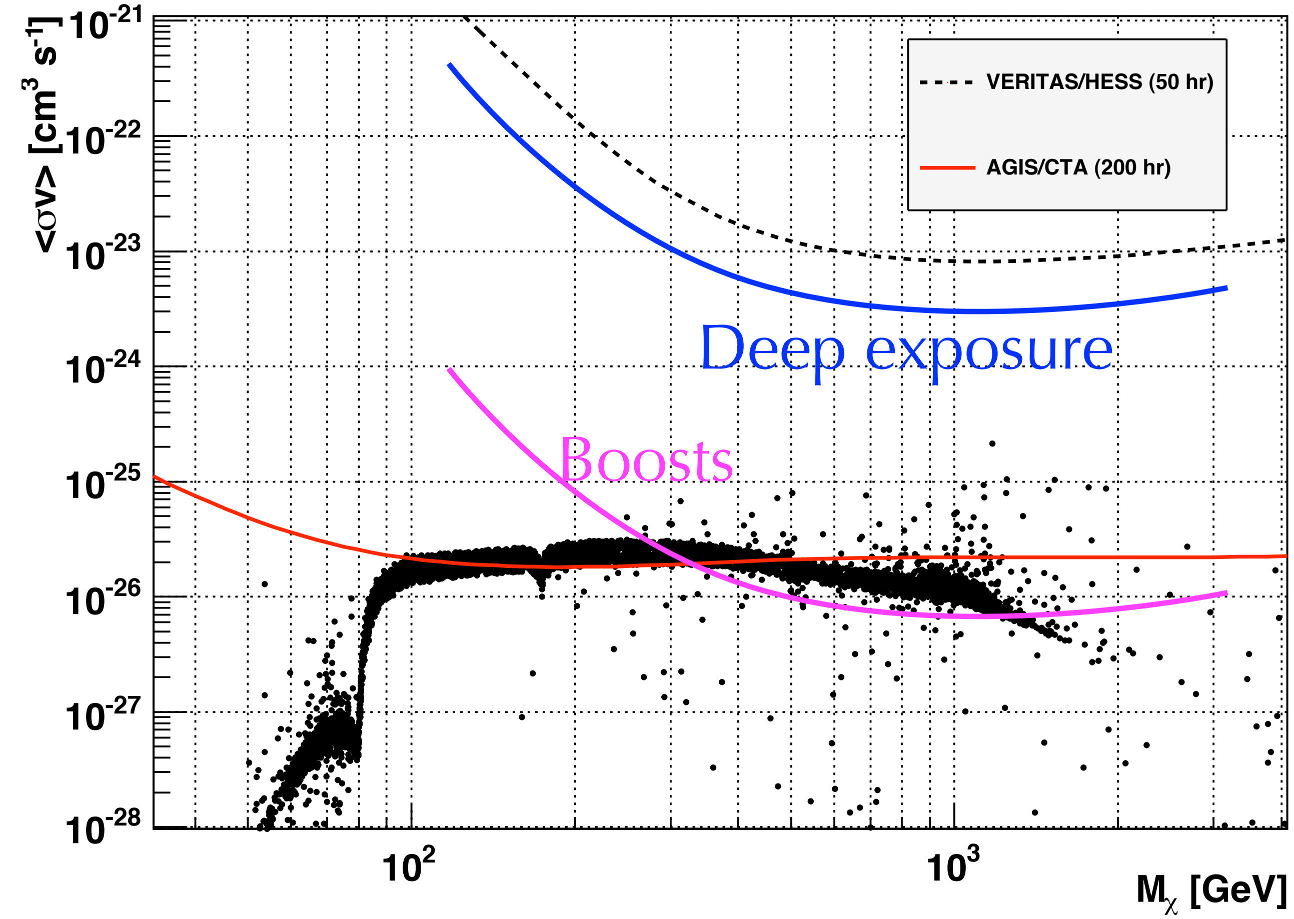
- Line-of-sight integral for MW-like halo in VL Lactea II simulation (M. Kuhlen, et al.)
- Sommerfeld enhancement larger for colder (lower velociy dispersion) dwarf halos $\sigma \propto 1/v^2$

GC & Everything else



Dwarf Galaxy Estimates





$d_s = 24\,\mathrm{kpc}$

$r_s = 300\,\mathrm{pc}$

$r_c = 0.1\,\mathrm{pc}$

$r_{\mathrm{cutoff}} = 6.5\,\mathrm{kpc}$

$\rho_s = 3.0 \times 10^8\, M_\odot\,\mathrm{kpc}^{-3}$

$M_{\mathrm{halo}} = 7.9 \times 10^8\ M_\odot$

$\langle J \rangle = 3.0 \times 10^{17}\, M_\odot^2\,\mathrm{kpc}^{-5}$

$\theta_{\max} = 0.2^\circ$

$m_\chi = 600\,\mathrm{GeV}$

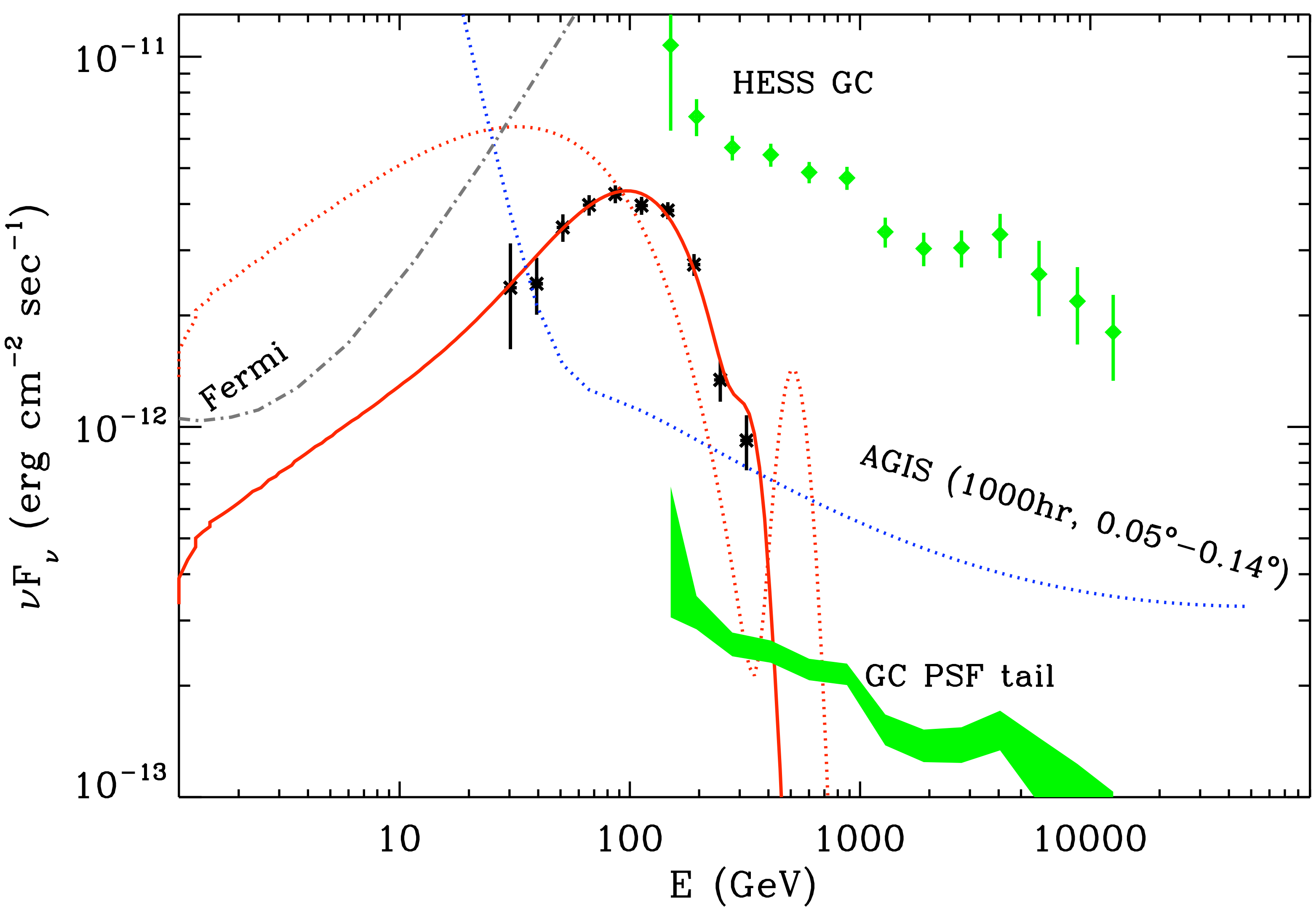
$\langle \sigma v \rangle = 2.0 \times 10^{-26}\,\mathrm{cm}^{-3}\mathrm{s}^{-1}$

branching ratios $\chi\chi \rightarrow b\bar{b}:\ 0.7,\ \chi\chi \rightarrow \tau^+\tau^-\ :\ 0.3$

boost $b = 10$

$\frac{\sigma_E}{E} = 15\%$

Galactic Center Region



NFW profile

No boost $(b = 1)$

Normalized to $\rho_{\rm local} = 0.3\,{\rm GeV\,cm^{-3}}$

$\langle \sigma v \rangle = 2 \times 10^{-26}\,{\rm GeV\,cm^{-3}}$

$d_s = 8.5\,{\rm kpc}$

$r_s = 21.7\,{\rm kpc}$

$r_c = 1\,{\rm pc}$

$\rho_s = 6 \times 10^6\,M_\odot\,{\rm kpc^{-3}}$

$\langle J \rangle_{\rm solid\ angle} = 4.6 \times 10^{17}\,M_\odot^2\,{\rm kpc^{-5}}$

for $\theta_{\rm min} = 0^\circ$, optimum $\theta_{\rm max} = 1.0^\circ$

for $\theta_{\rm min} = 0.05^\circ$, optimum $\theta_{\rm max} = 1.4^\circ$

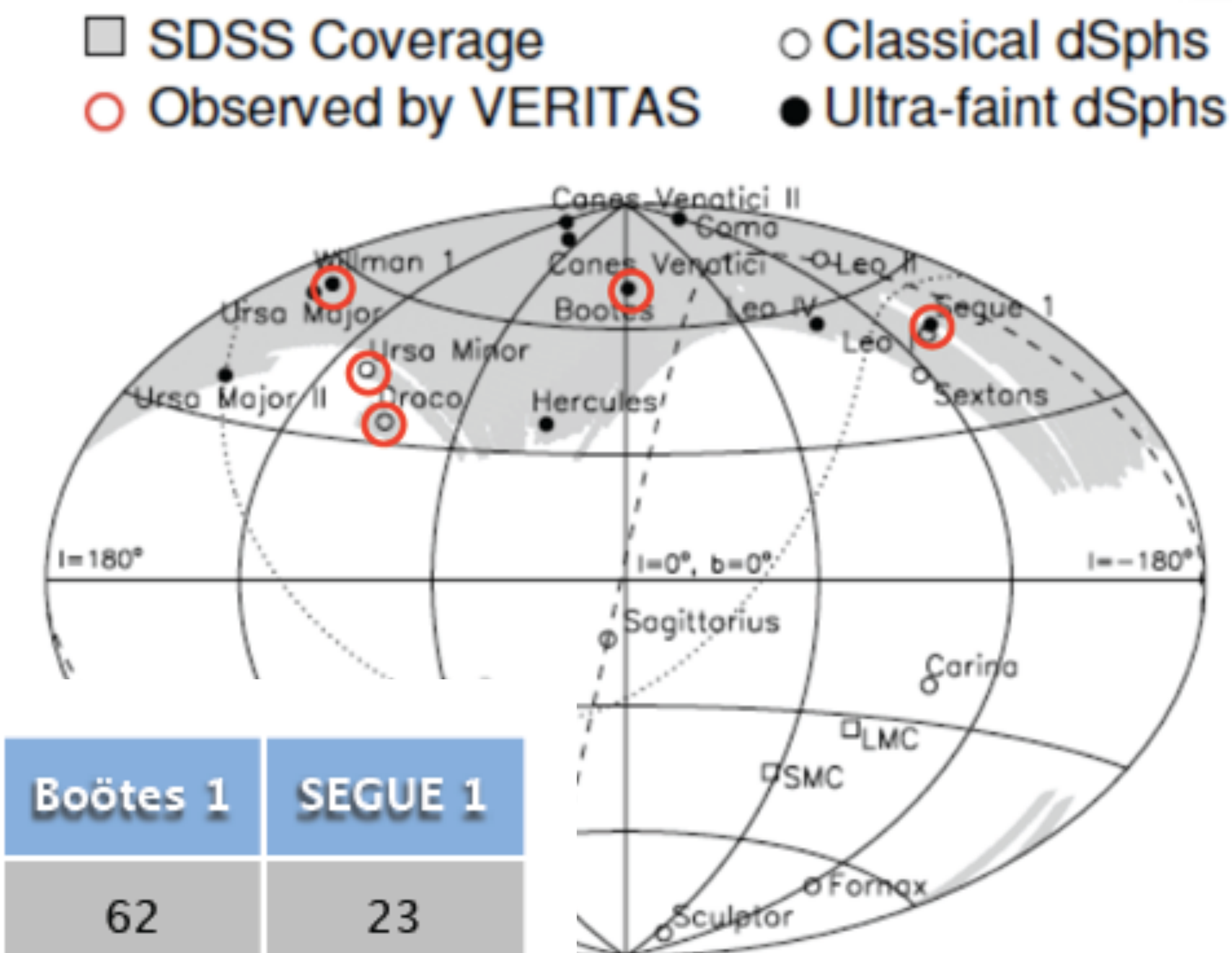
$\frac{\sigma_E}{E} = 15\%$

branching ratio for $\chi\chi \to \gamma\gamma + \chi\chi \to Z\gamma : 2 \times 10^{-3}$

Solid red curve for $m_\chi = 330\,{\rm GeV}$, $\chi\chi \to \tau^+\tau^-$ 80%

Dotted red curve for $m_\chi = 500\,{\rm GeV}$, $\chi\chi \to W^+W^-$, $b = 3$

VERITAS Target Selection



Belokurov et al. (2007)

Quantity/dSph	Ursa Minor	Draco	Willman 1	Boötes 1	SEGUE 1
Distance (kpc)	66	80	38	62	23
ρ_s ($M_\odot$/kpc^3)	4.5x10^7	4.5x10^7	4x10^8	---	1x10^8
r_s (kpc)	0.79	0.79	0.18	---	0.07
J ($\rho_c^2 R_H$)	7	4	22	3	3
J (GeV^2 cm^{-5})	2.68×10^{18}	1.53×10^{18}	8.43×10^{18}	1.15×10^{18}	1.15×10^{18}

nb: J in units of $\rho_c^2 \times R_H = 3.83 \times 10^{17}$ GeV^2 cm^{-5}

VERITAS Dwarf Observations

dSph	Period	Exposure (hrs)	Zenith Angle(°)
Ursa Minor	2007 Feb–May	18.9	35–46
Draco	2007 Apr–May	18.4	26–51
Willman 1	2007 Dec–2008 Feb	13.7	19–28
Boötes 1	2009 Apr–May	14.3	17–29
SEGUE 1	2009 Dec–2010 Mar	27.6	16–32

Disclaimer

- To date, only relatively short exposures have been obtained on Dwarf observations (note there are roughly 1000 hours of observing time each year)
- A dedicated experiment, looking at several carefully selected sources (in different RA bands) might obtain as much as 100 times the exposure of any one of these observations.

Dwarf Galaxies

SEGUE 1 Results
PRELIMINARY

No Significant Excess from any dSph

Quantity/dSph	Ursa Minor	Draco	Willman 1	Boötes 1	SEGUE 1
Excess (counts)	−30.4	−28.4	−1.45	28.5	−17.5
Significance (σ)	−1.77	−1.51	−0.08	1.35	−1.1
95% CL upper limit (counts)	15.6	18.8	36.7	72.0	13.4
Energy threshold (GeV)	380	340	320	300	300
95% CL flux upper limit ($cm^{-2}s^{-1}$)	0.40×10^{-12}	0.49×10^{-12}	1.17×10^{-12}	2.19×10^{-12}	0.28×10^{-12}

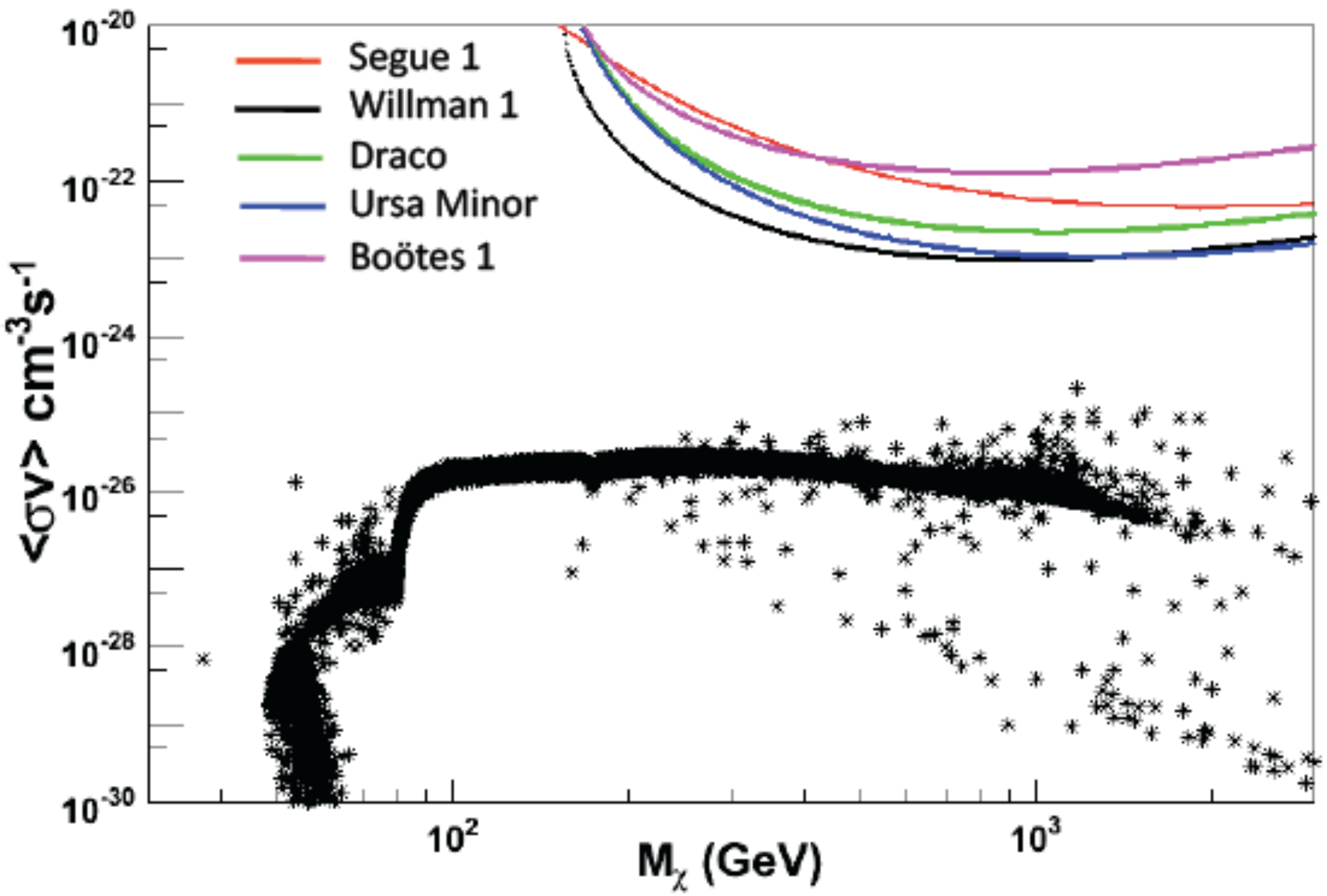
Similar limits for MAGIC on Draco & Willman 1
Improvement of ×40 for Whipple 10m on Ursa Minor & Draco

(Robert Wagner, ANL)

Particle Constraints

$$\frac{R_\gamma(95\%\ \mathrm{C.L.})}{\mathrm{hr}^{-1}} > \frac{J}{1.09\times 10^4}\left(\frac{\langle\sigma v\rangle}{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \int_0^\infty \frac{A(E)}{5\times 10^8\mathrm{cm}^2}\left(\frac{300\ \mathrm{GeV/c}^2}{m_\chi}\right)^2 \frac{EdN/dE(E,m_\chi)}{10^{-2}}\frac{dE}{E}$$

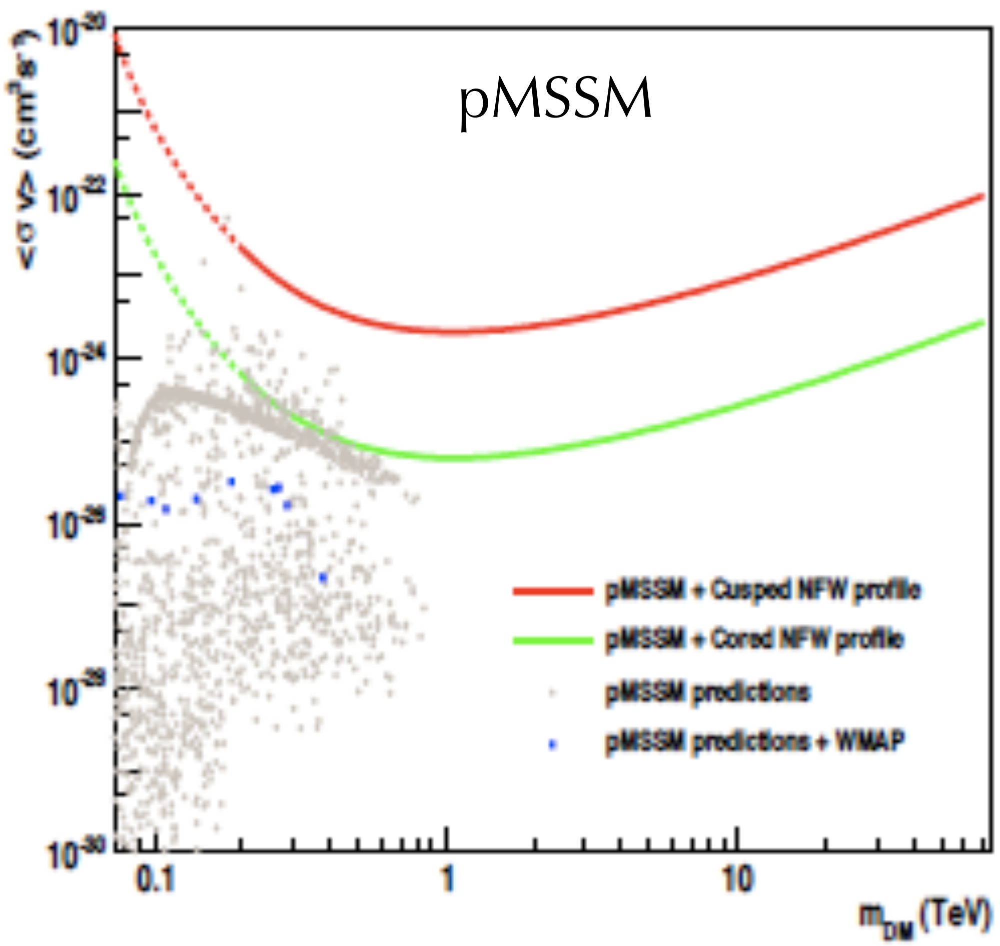
- MSSM model points from DarkSUSY within 3 standard deviations of WMAP relic density.
- 95% CL upper limits

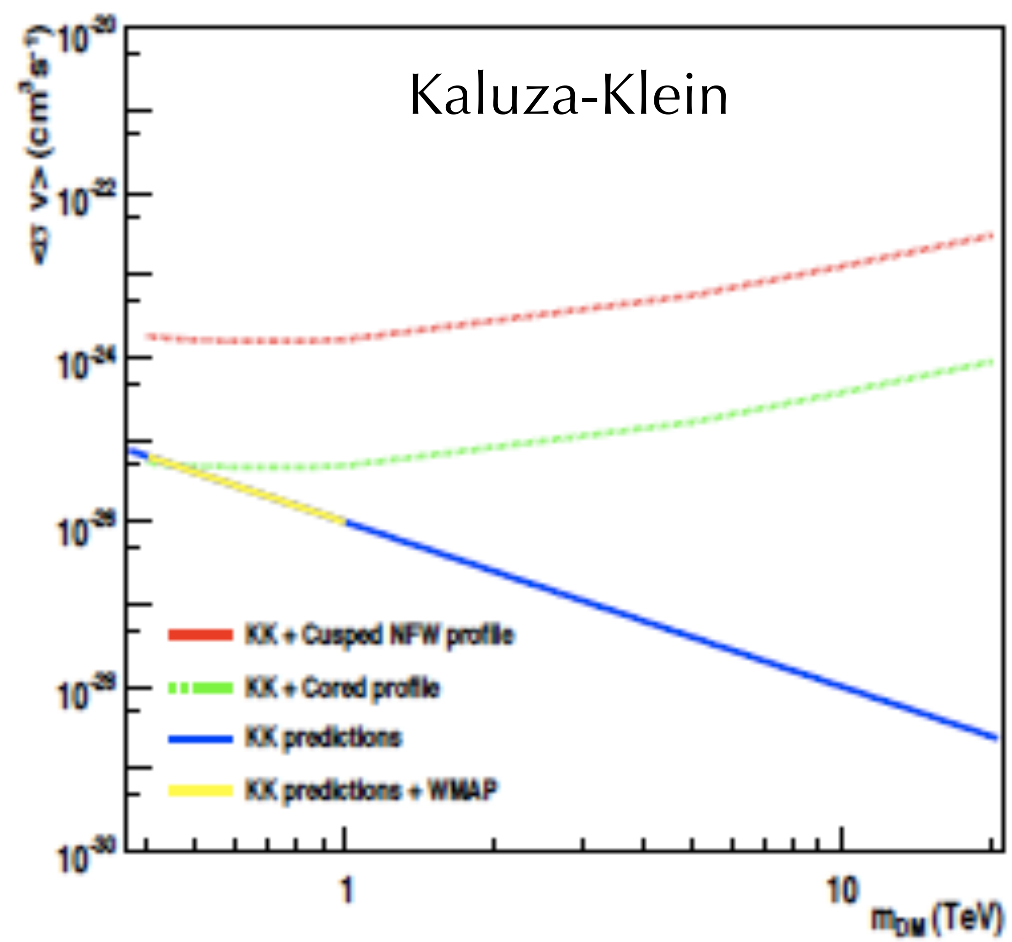


(Robert Wagner, ANL)

HESS Sgr Dwarf Limits

- $\langle\sigma v\rangle_{WIMPs}$ as a function of the DM particle mass:





$\langle\sigma v\rangle_{WIMPs} \approx 10^{-25}cm^3.s^{-1}$ (core)
$\langle\sigma v\rangle_{WIMPs} \approx 10^{-23}cm^3.s^{-1}$ (NFW)

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$\langle\sigma v\rangle_{WIMPs} \approx 10^{-24}cm^3.s^{-1}$ (NFW)

Aharonian F., et al. (H.E.S.S. collaboration), Astropart. Phys., 29, 55 (2008)

- Systematics of the core profile: ± 2 orders of magnitude (Matthieu Vivier)

Other DM Limits

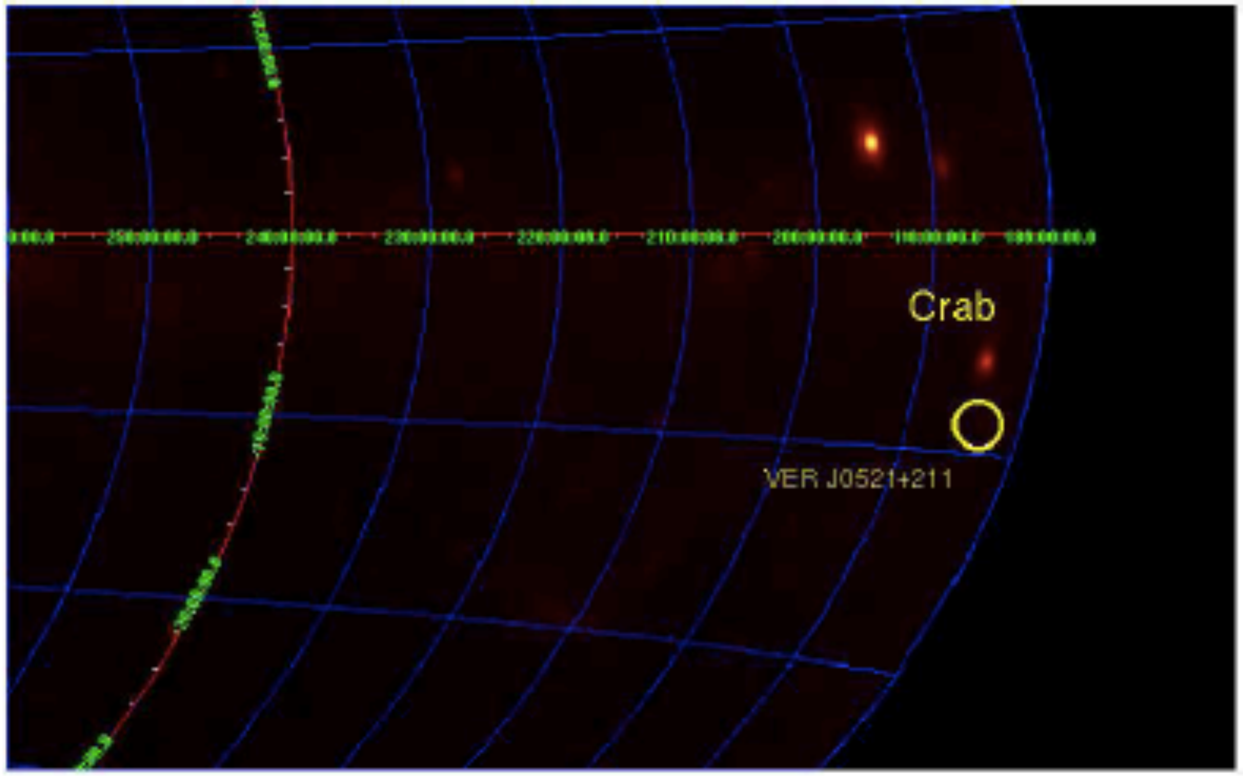
Target	Distance (kpc)	f^{AP} (NFW profile, 10^{24} GeV^2 cm^{-5})	T_{obs} (h)	Instrument	Annihilation spectrum	$<\sigma v>^{95\%}$ (cm^3 s^{-1})
Galactic Center	8	??	48.7	H.E.S.S.	Bergström	$< 10^{-24}$
Canis Major	8	5.9	9.6	H.E.S.S.	Bergström	$< 6 \times 10^{-24}$
Sagittarius	24	2.2	11	H.E.S.S.	Bergström	$< 6 \times 10^{-24}$
Draco	82	1	14.3	WHIPPLE	$\chi\chi \rightarrow \tau^+\tau^-$	$< 10^{-22}$
Ursa Minor	66	0.7	17.2	WHIPPLE	$\chi\chi \rightarrow \tau^+\tau^-$	$< 2 \times 10^{-22}$

(Matthieu Vivier)

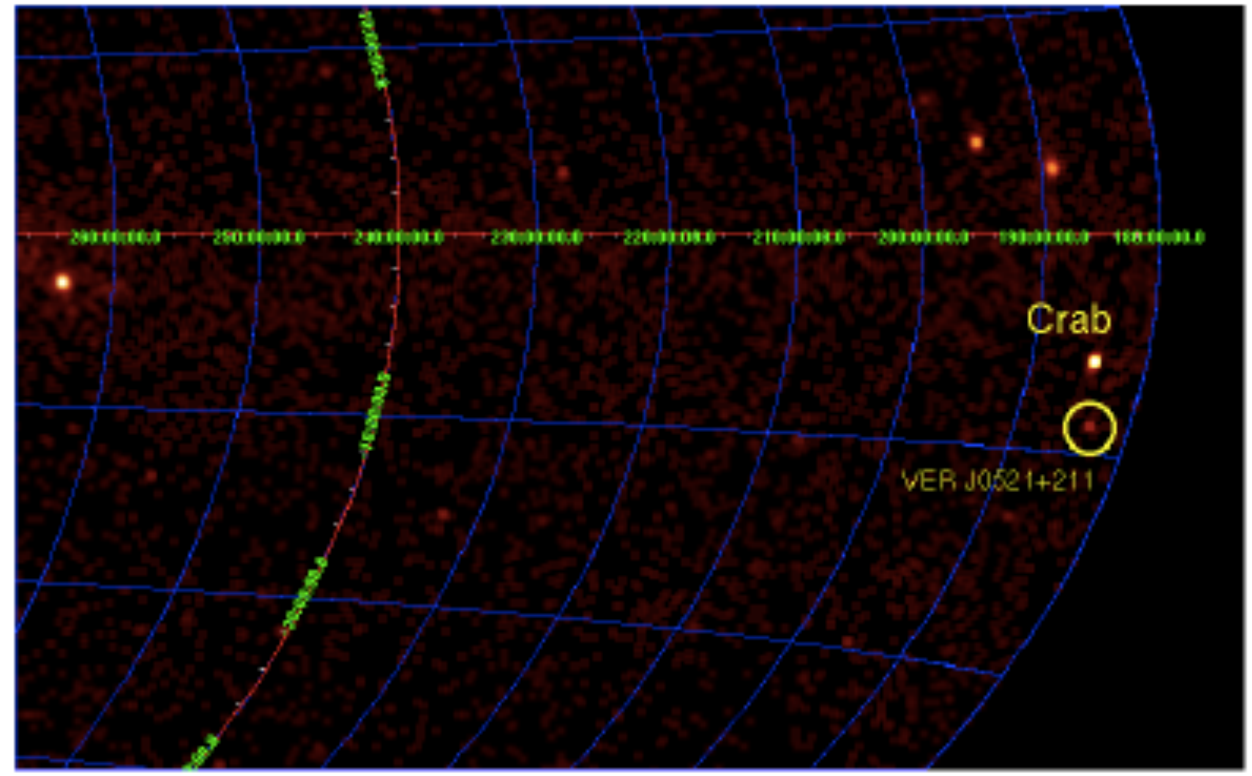
N-body Sims & Subhalos

- N-body simulations have resolutions approaching 10^4 solar masses
- Some quantitative info about galactic subhalos ranging up to 10^7 solar masses, aka Dwarf satellites.
- VL Lactea II and Aquarius simulations find 300,000 and 40,000 resolved subhalos in Milky-Way sized halo (respectively)
- VL-II finds clumps more cuspy with density profile power-law index of 1.2
- Mass function integral number of subhalos with mass $M > M_H$ is $N(M > M_H) \propto M_H^{-1}$
- Minimum subhalo distance with probability~1: $R_H \sim 3(M_H/10^5\, M_\odot)^{1/3}$ kpc.

Fermi DM ToO



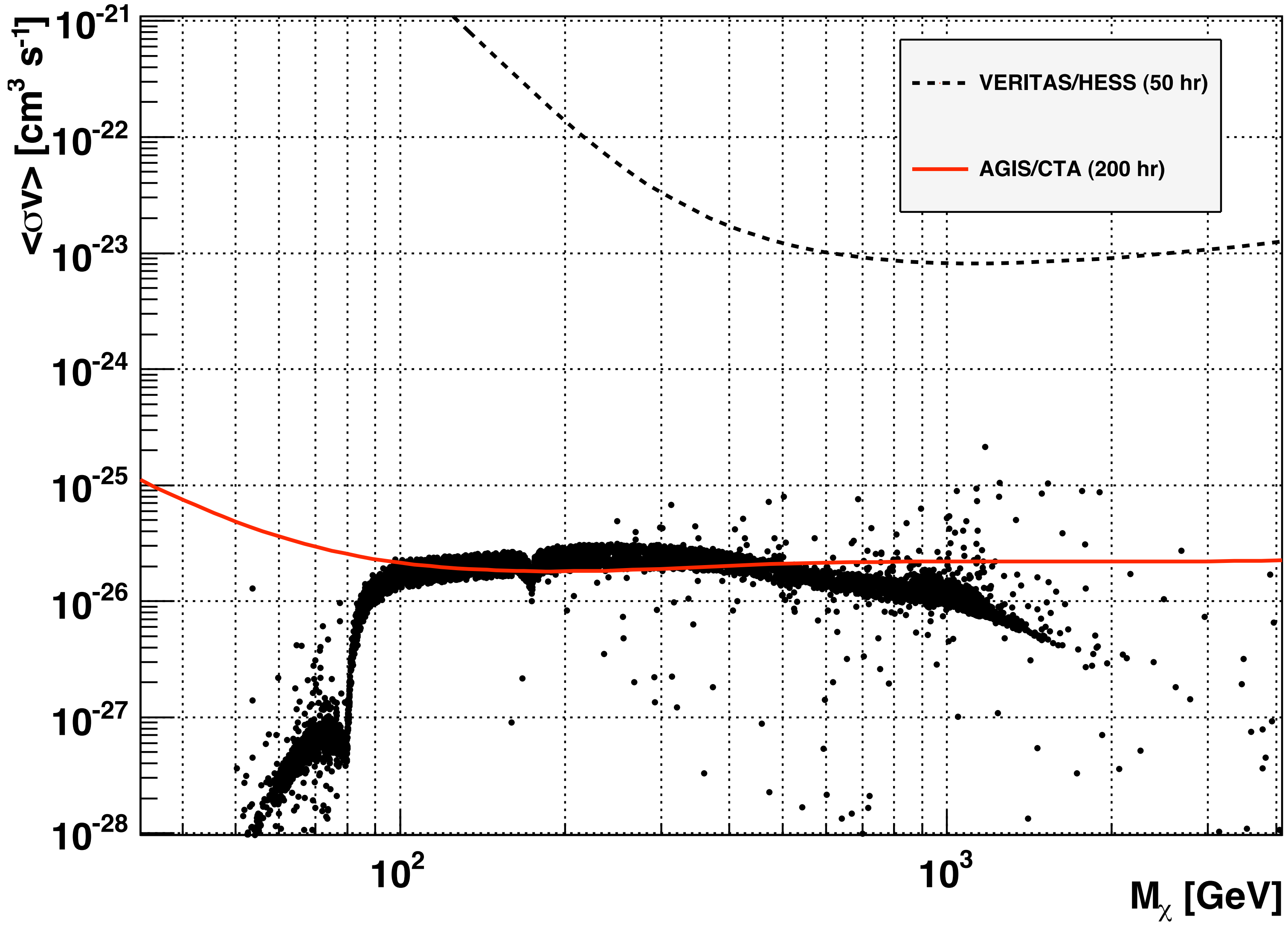
(Fermi Skymap, 1-10 GeV)



(Fermi Skymap, 10-100 GeV - M. Beilicke)

- Approved Fermi GI proposal for ``Dark Matter Targets of Opportunity'' (Buckley, Beilicke, Byrum, Conrad, Ferrer, Humensky, Krawczynski, Murgia and Smith)
- Example: Fermi Skymap Left: 1-10 GeV, Right: 10-100 GeV (Matthias Beilicke)
- Proof of principle: Matthias' and Jamie's analysis of Fermi high-energy sources leasing to ToO VERITAS discovery of J0521 - not a DM source, but the same principal.
- Use TAC-approved 15 hr allocation as in the DM KSP to follow up best DM ToOs

Future ACT Considerations



(Matthew Wood, UCLA)

- Need an order of magnitude from exposure time, an order of magnitude from a new instrument, and maybe a bit of a boost!

Angular Distribution

• For an NFW halo profile the 90% containment source size is roughly 0.2 deg for a 10^6 solar mass halo at 6.5 kpc or for a 10^5 solar mass halo at 3 kpc

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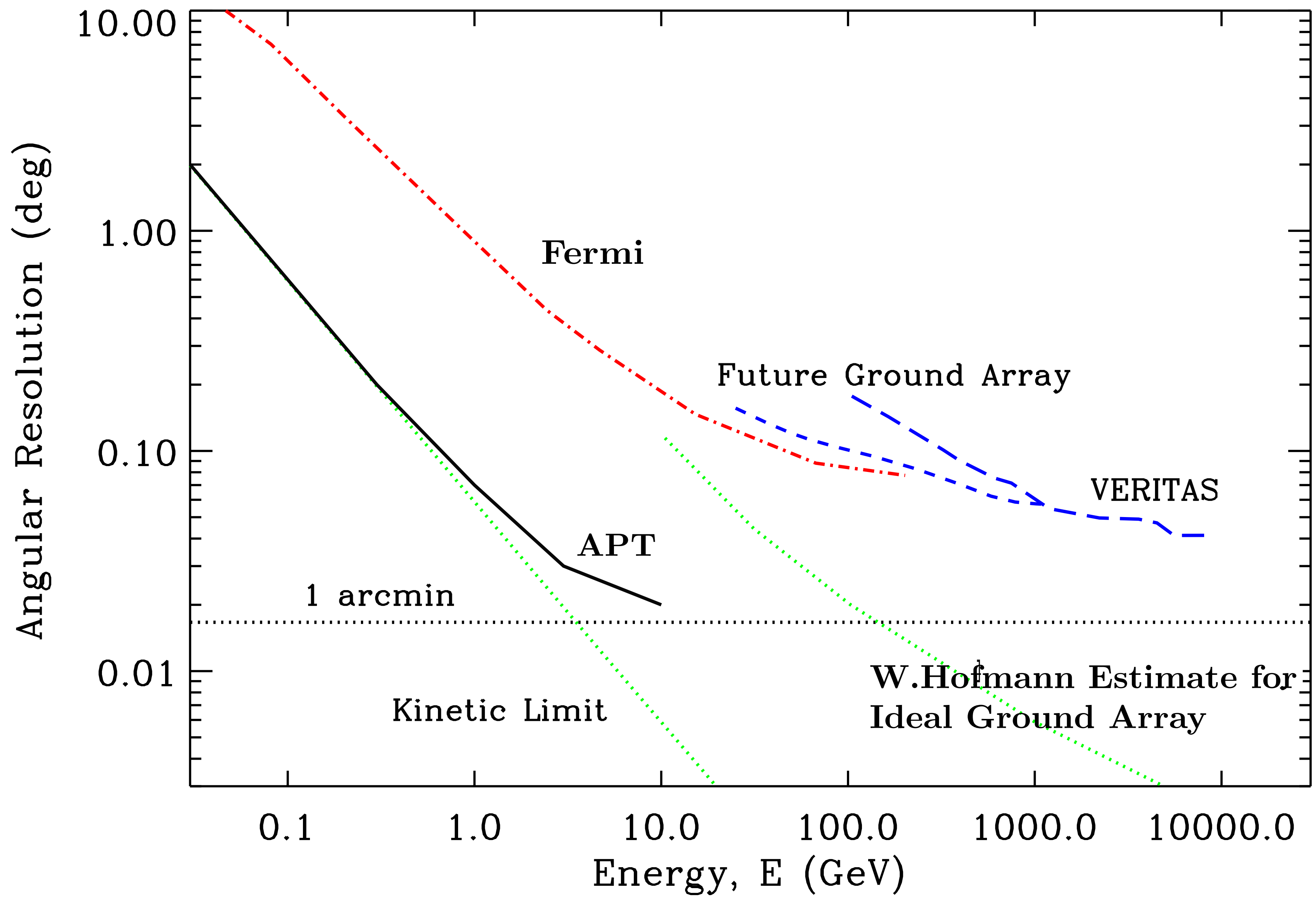
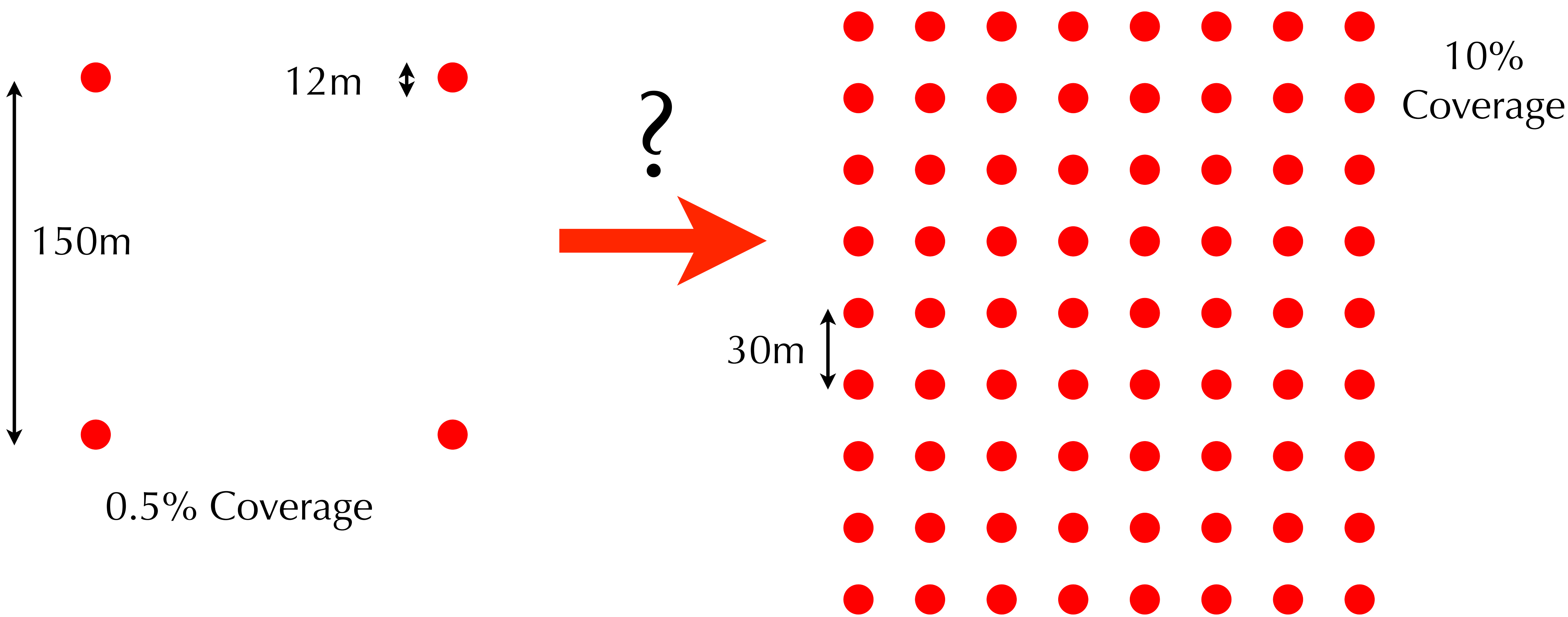


Optimization



- For dark matter searches, it is important to minimize energy, maximize sensitivity while maintaining good angular resolution and energy resolution - is there a way to minimize threshold and still obtain good performance?

- Extreme case: Putting 9 times as many 12m telescopes in a 150m unit cell (4 to 36) could reduce the energy threshold by a factor of 3 (100 GeV to 30 GeV) while maintaining very high angular and energy resolution

Conclusions

- VERITAS is a good (and improving) instrument for continued observations of DM candidates. With reduced energy threshold, and continued observations over the coming decade (before CTA operation) constraints will continue to improve.

- VERITAS will follow-up DM "ToO"s discovered in Fermi sky map.

- However: for GC astrophysical background is difficult, and Dwarf limits are still 2 orders of magnitude away.

- Some models that produce large boosts (astrophysics, particle physics) are already constrained. In general, we expect clarification on astrophysical boosts (and on Leptophilic DM) over coming years.

- To get limits on generic predictions, need order of magnitude from exposure (dedication of a large percentage of observing time), and more than an order of magnitude improvement in sensitivity at ~100 GeV

- We are looking forward to working on CTA!