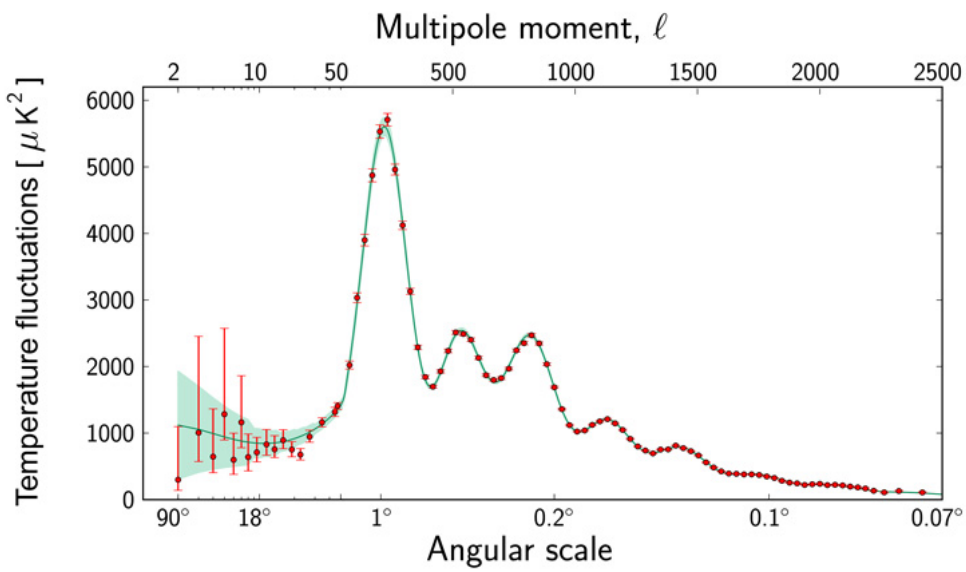
TeV Dark Matter

James Buckley
for the VERITAS collaboration
Washington University, St. Louis

VERITAS 10 Year Celebration   Tucson   June 27, 2017

The Dark Matter Creed



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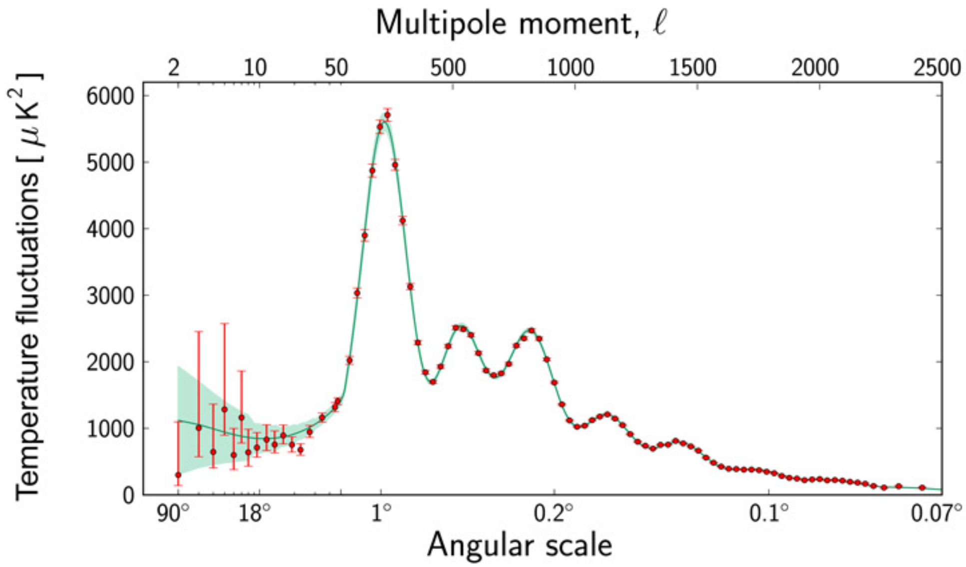

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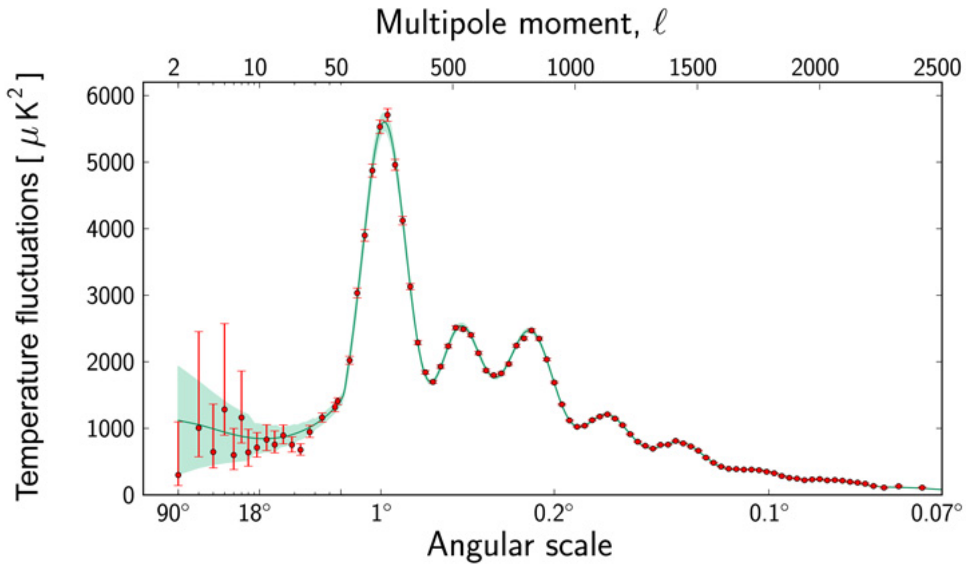

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2. Cold DM is an essential element needed to explain structure formation.

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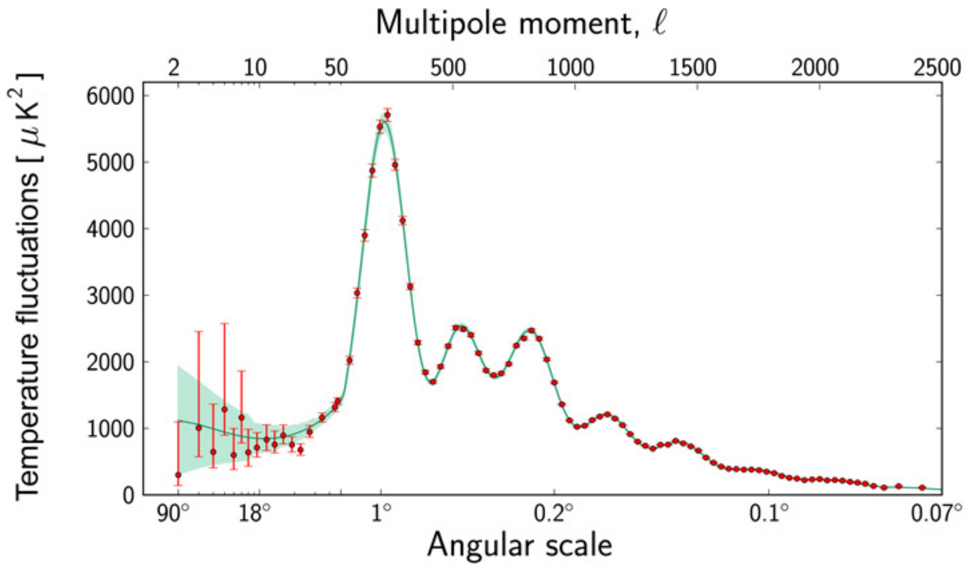

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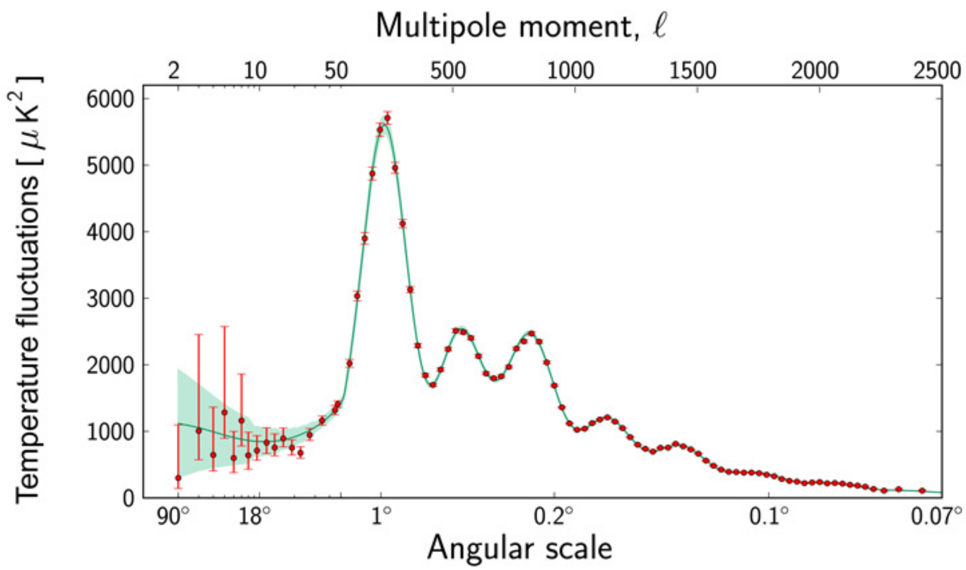

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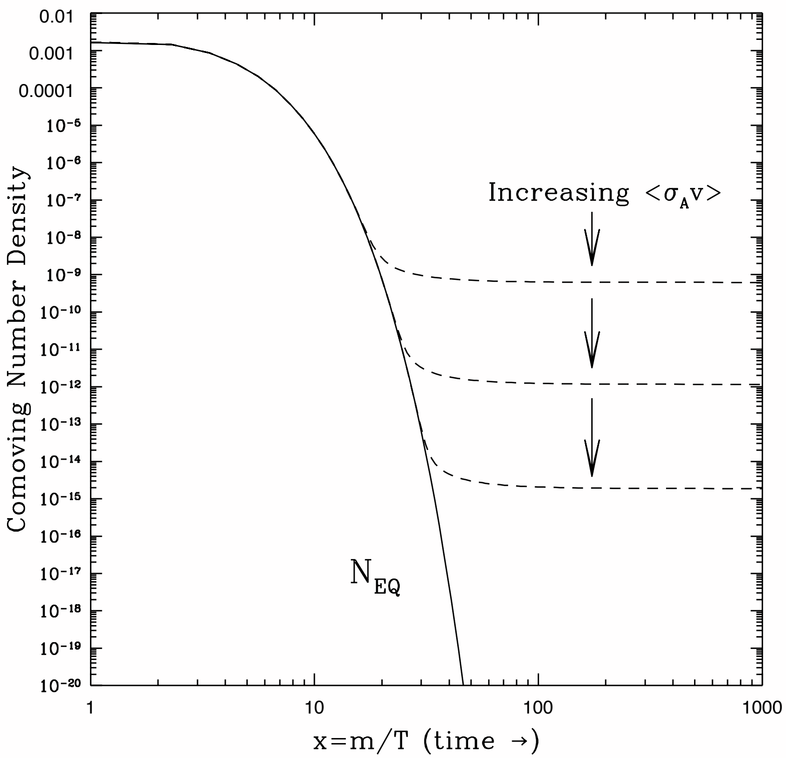
4. Bullet cluster image shows gravitational mass inferred from lensing (blue) and X-ray emission from baryonic matter (red). Together with large variation in mass to light ratio for galaxies, DM is not modified gravity, not ordinary baryonic gas.

The WIMP Miracle



- In the beginning the universe was very hot, DM particles and SM particles were in thermal equilibrium.
- Particles in equilibrium were Boltzmann suppressed $\sim e^{-mc^2/kT}$
- annihilation and recombination rates $\Gamma \sim n^2 \langle \sigma v \rangle$
- As the number density n dropped due to expansion, particles with the smallest $\langle \sigma v \rangle$ fell out of equilibrium first
- *the weak survive* with a relic density

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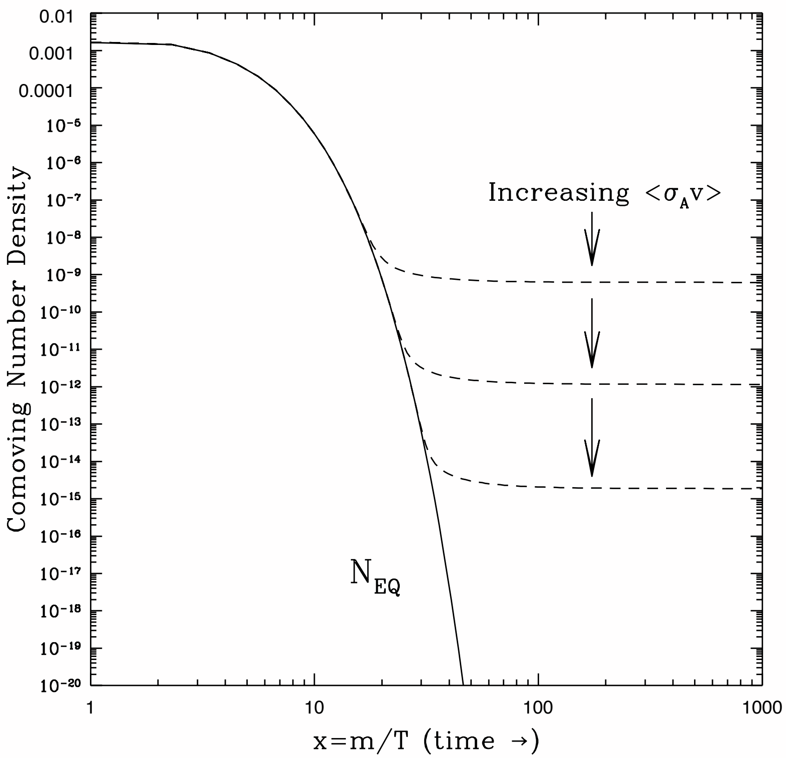

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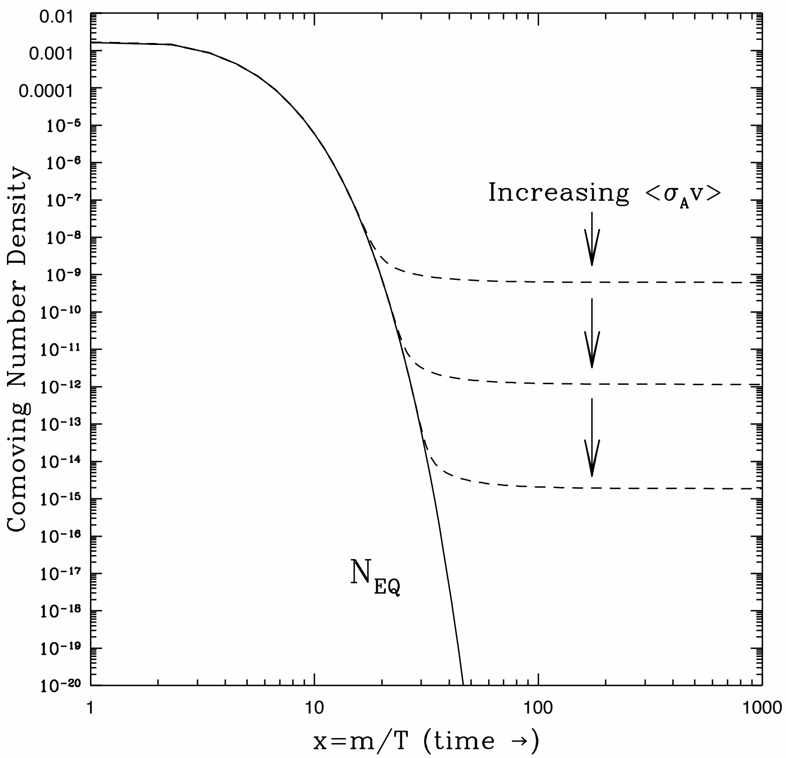

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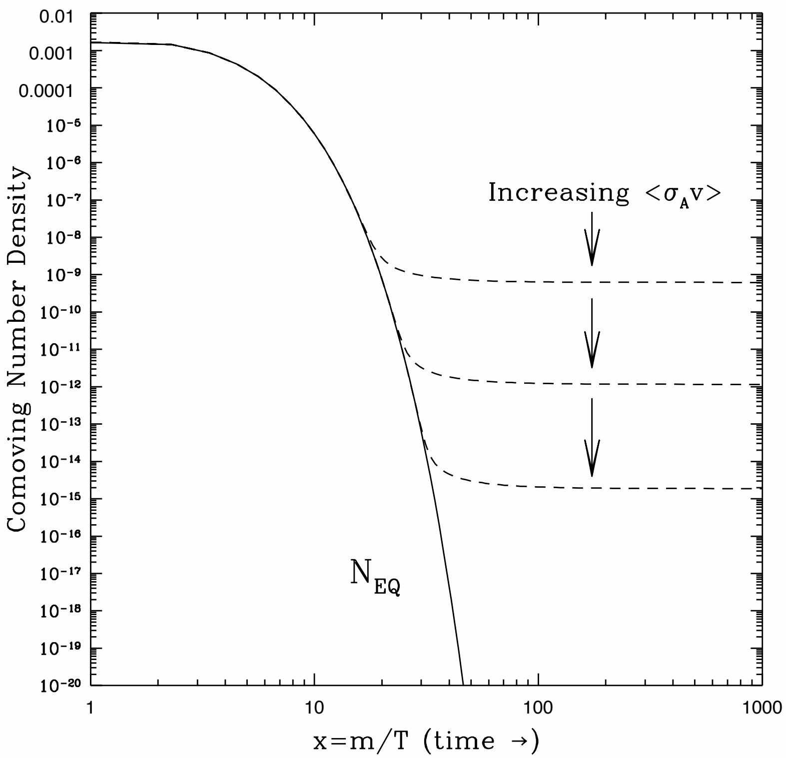

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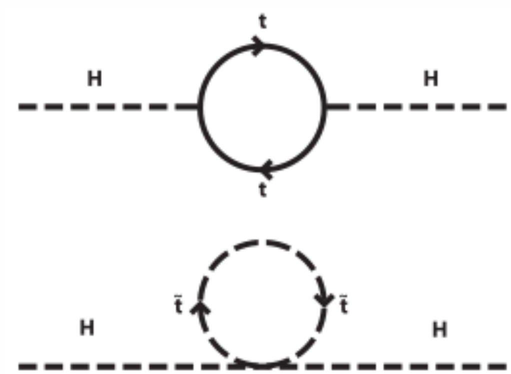
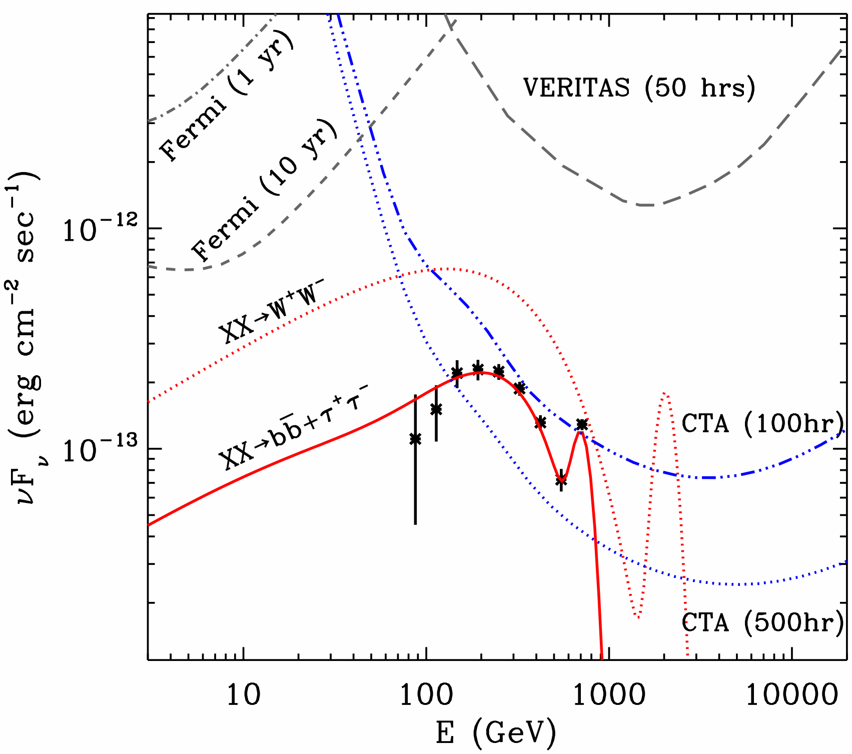


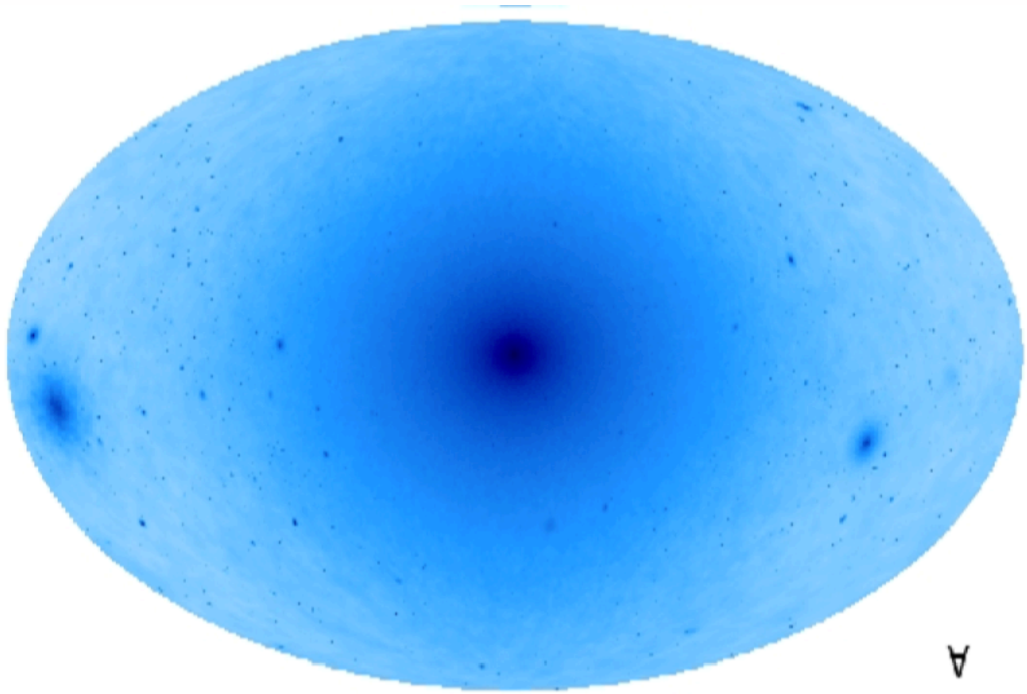
Gamma-rays from DM

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

(from Bergström, Ullio, Buckley, 1998)

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





Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

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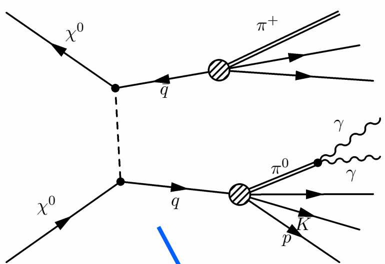

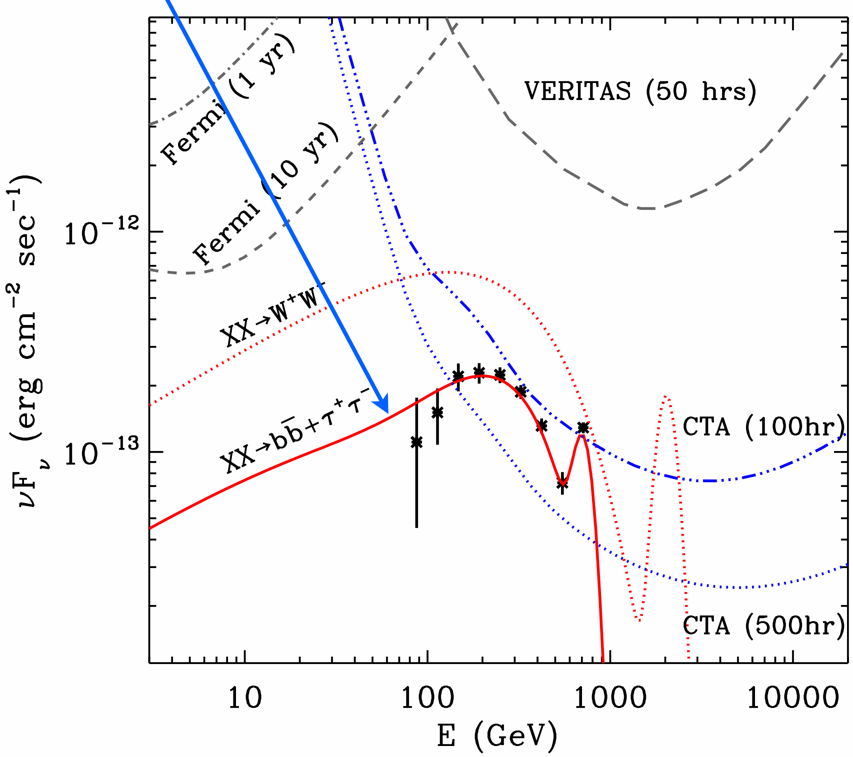

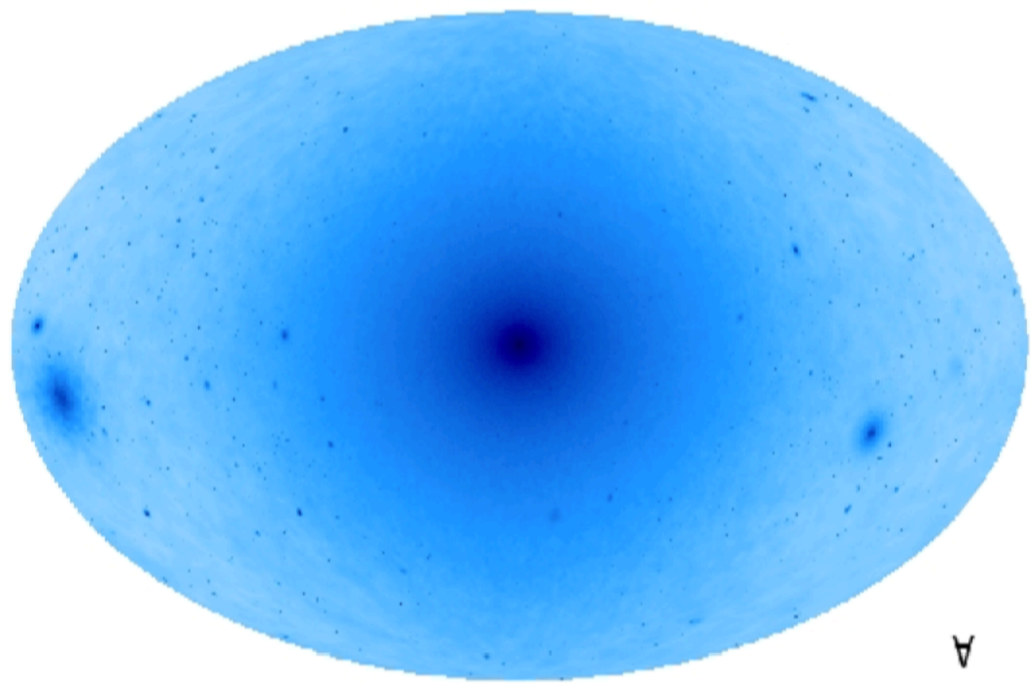

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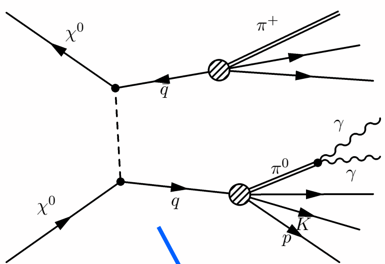

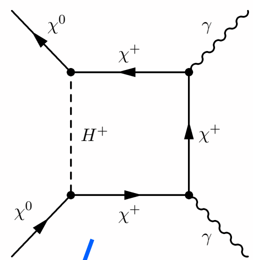

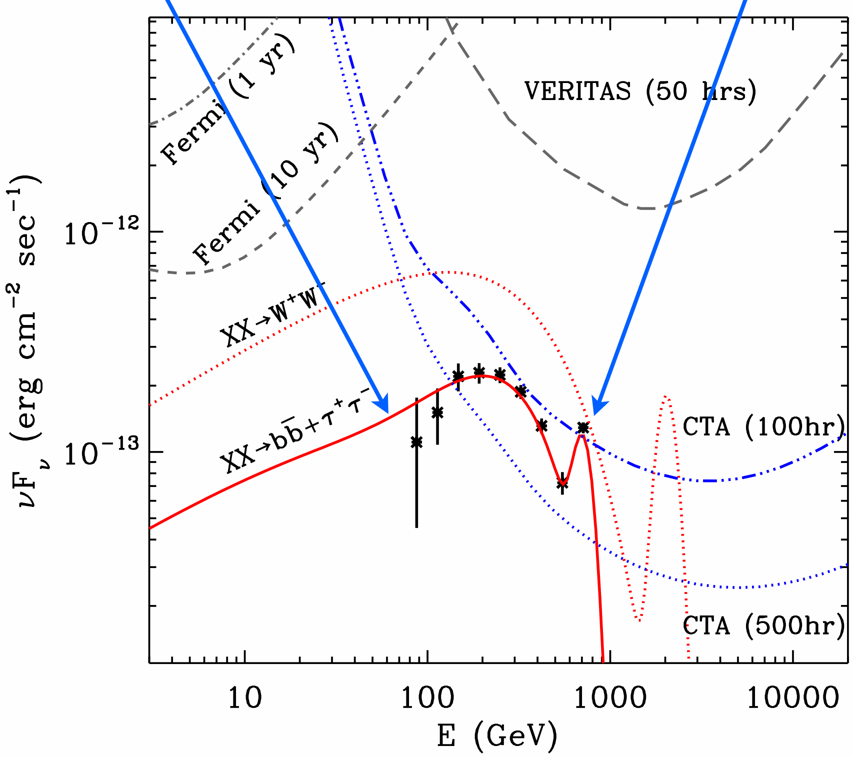

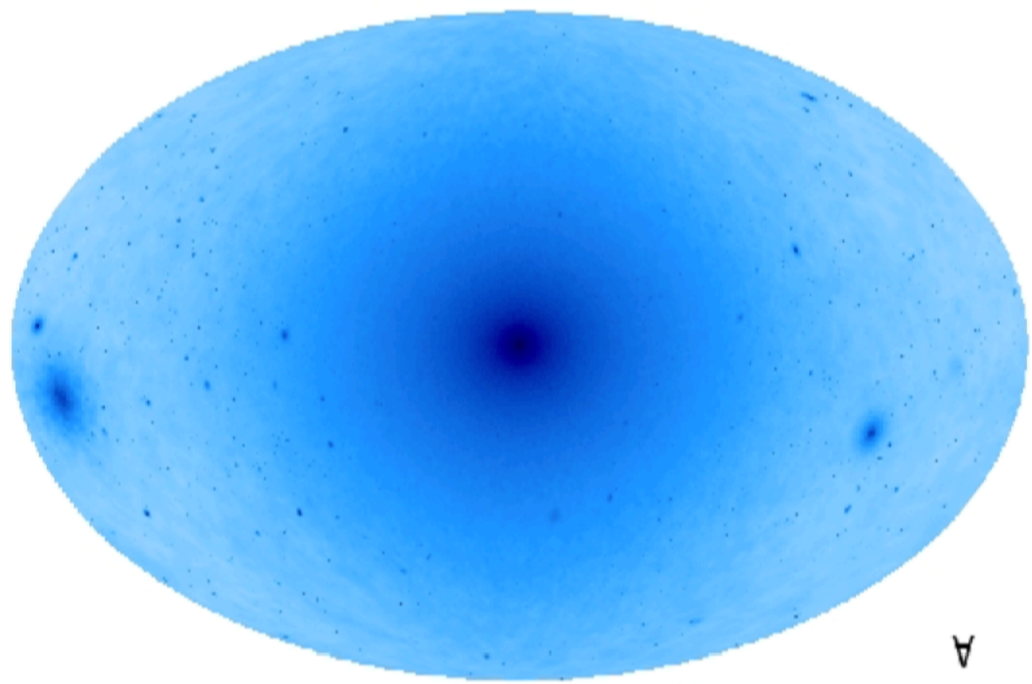

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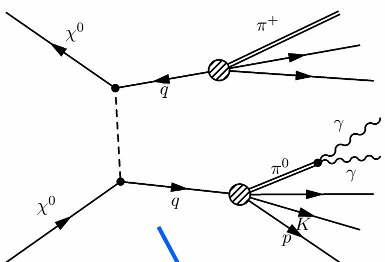

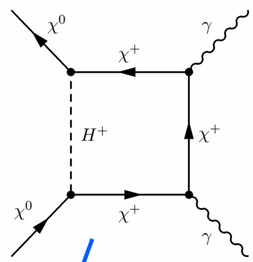

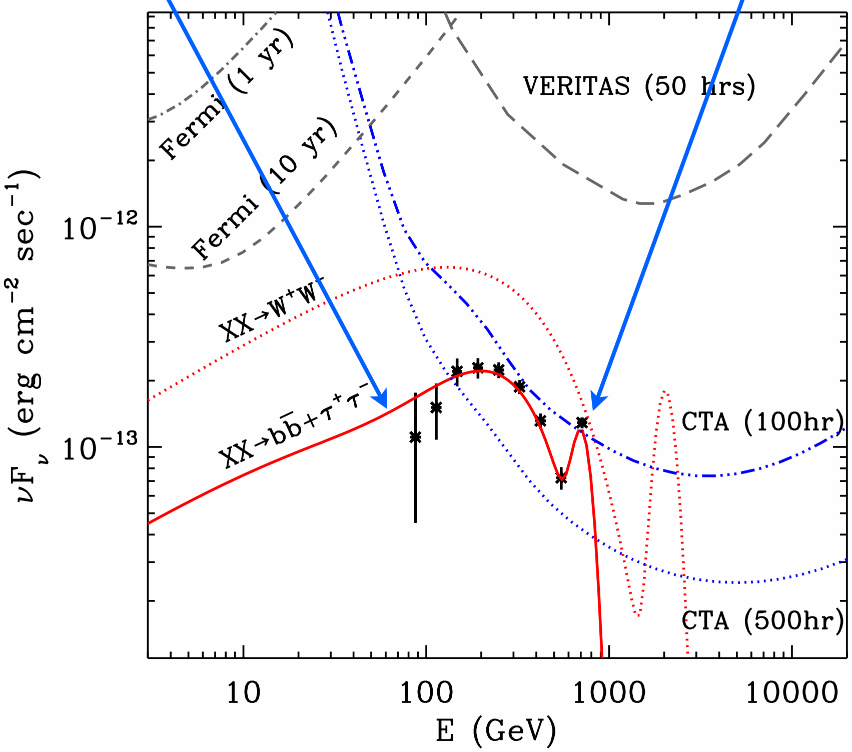

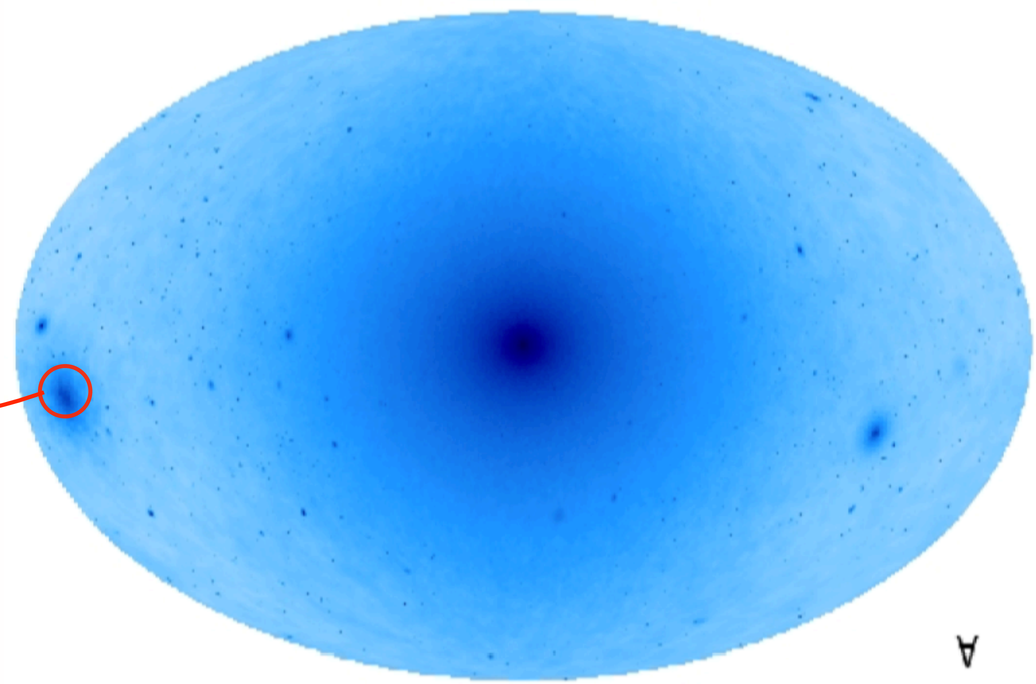

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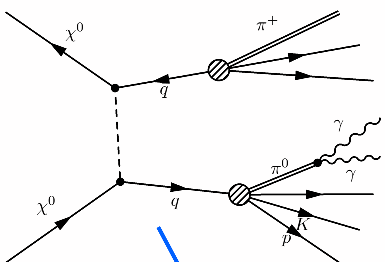

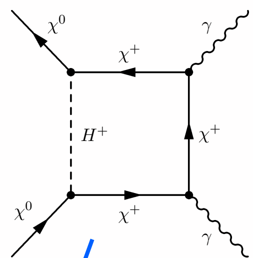

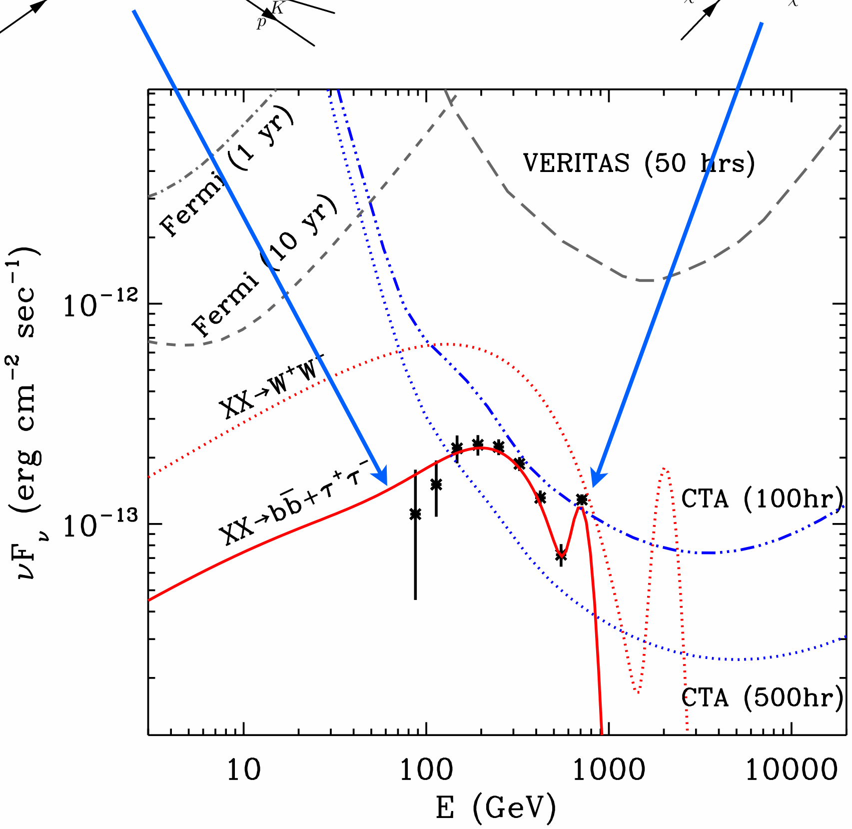

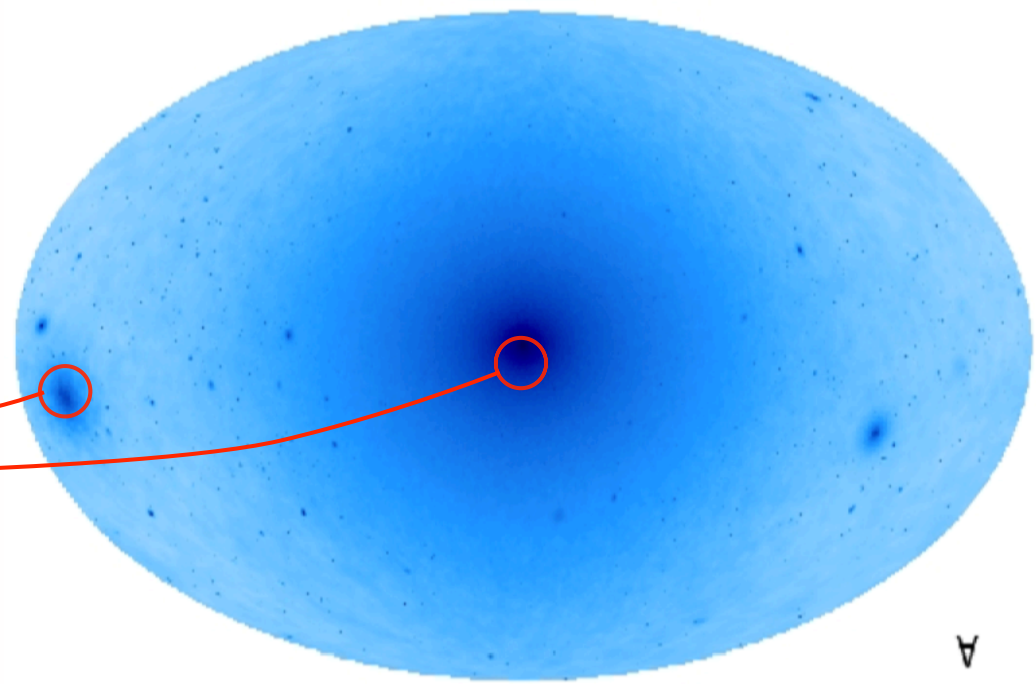

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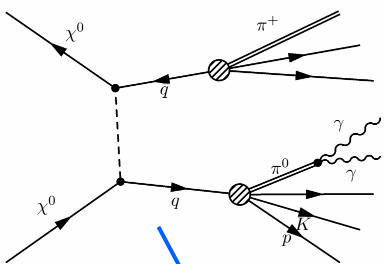

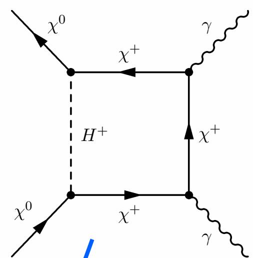

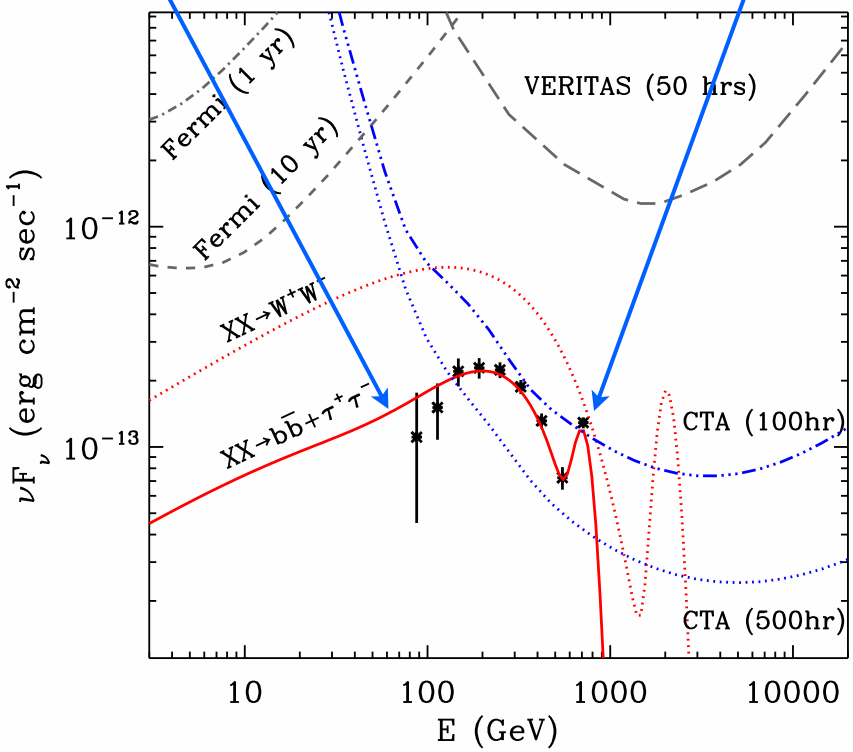

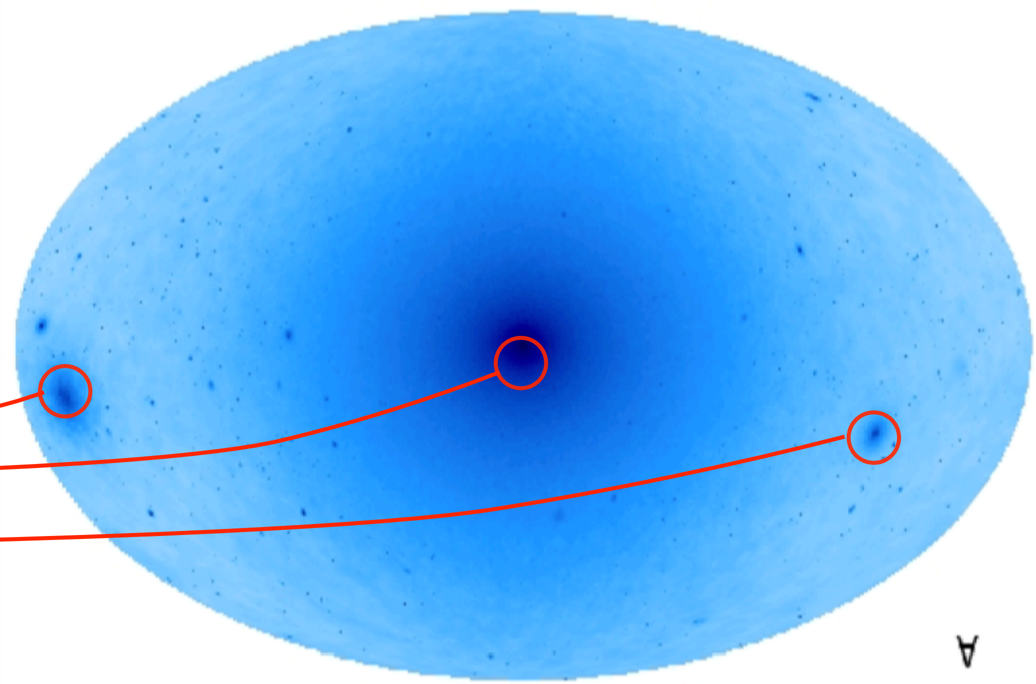

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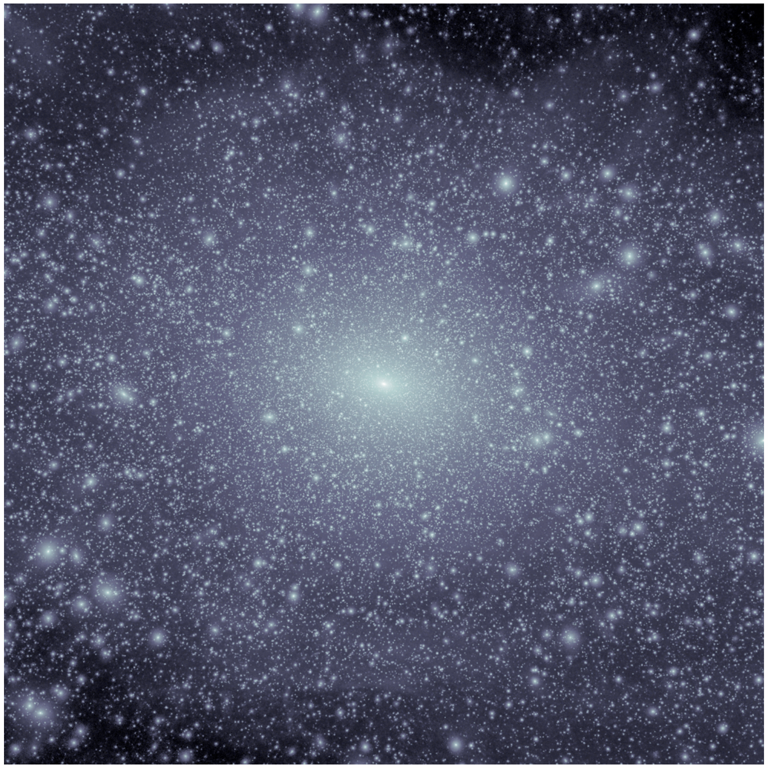

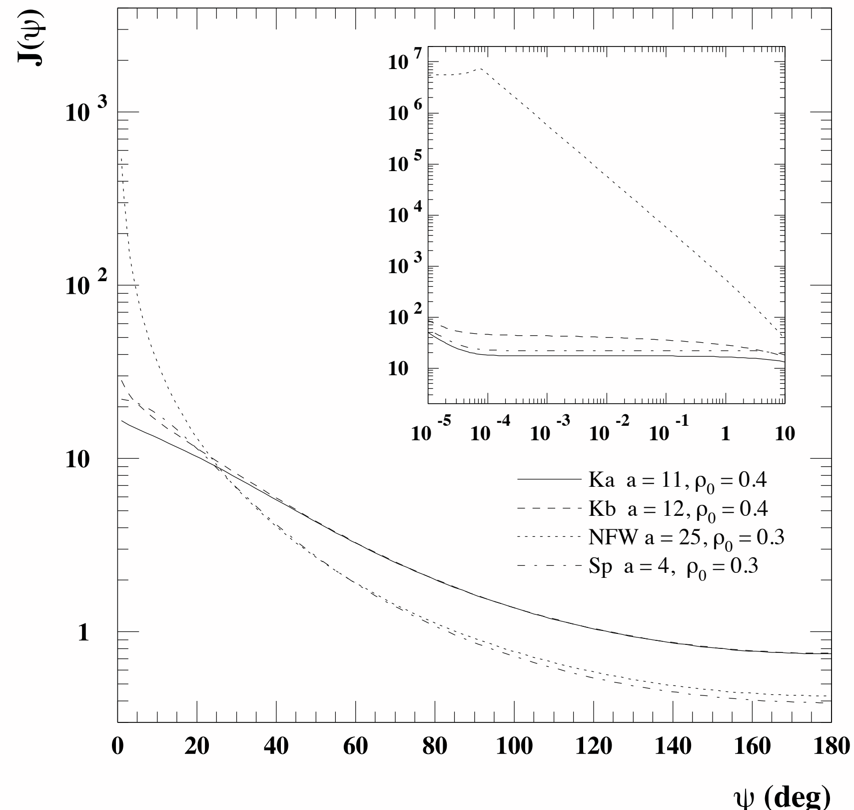

(Annihilation rate versus angular distance from halo center BUB98)

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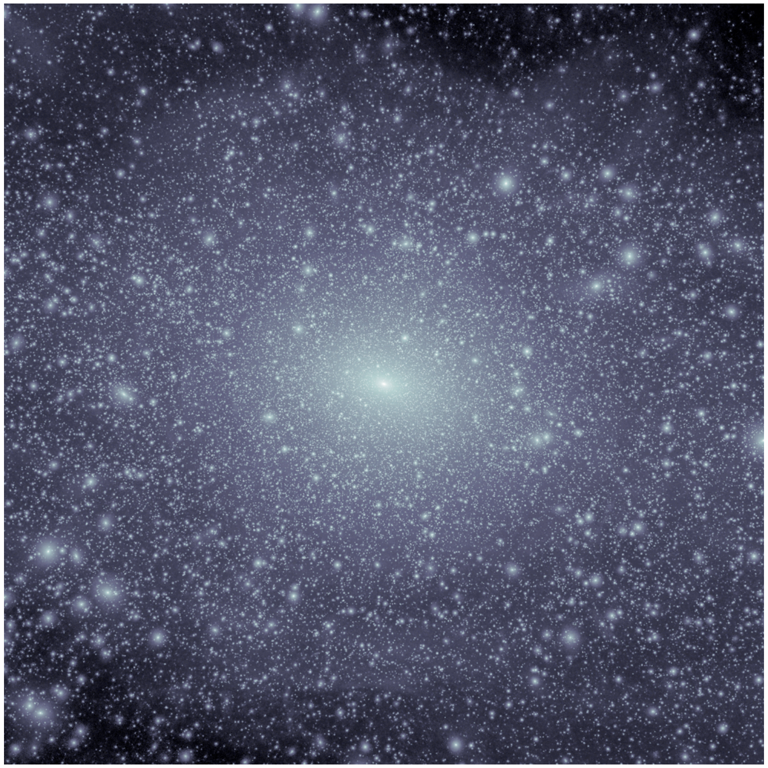

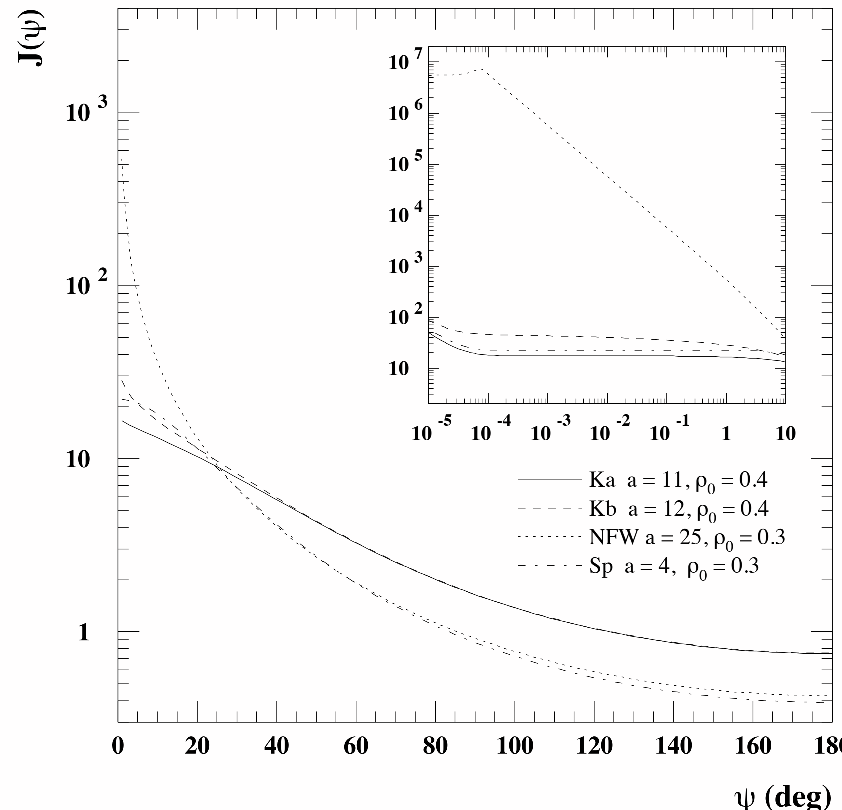

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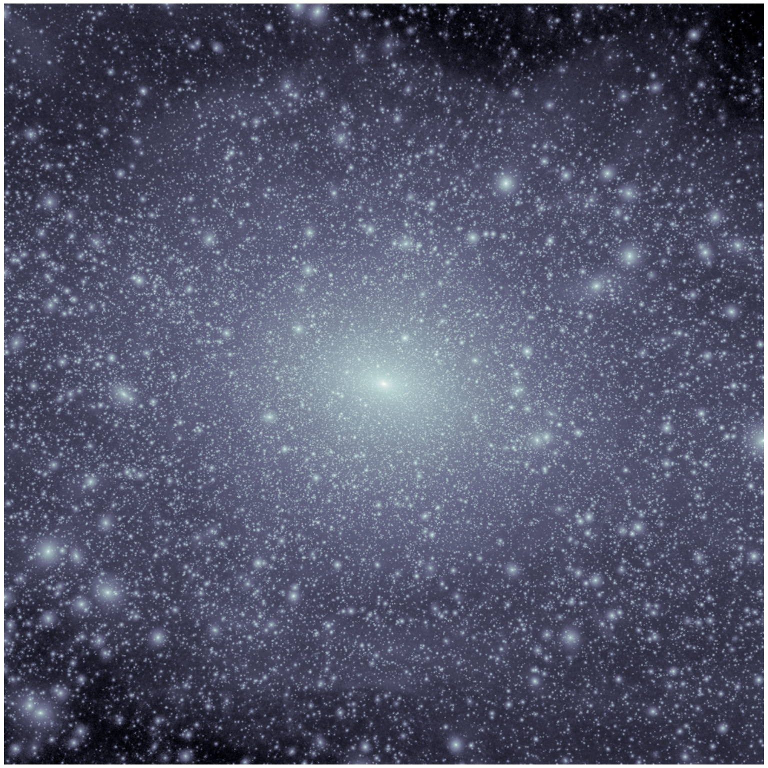

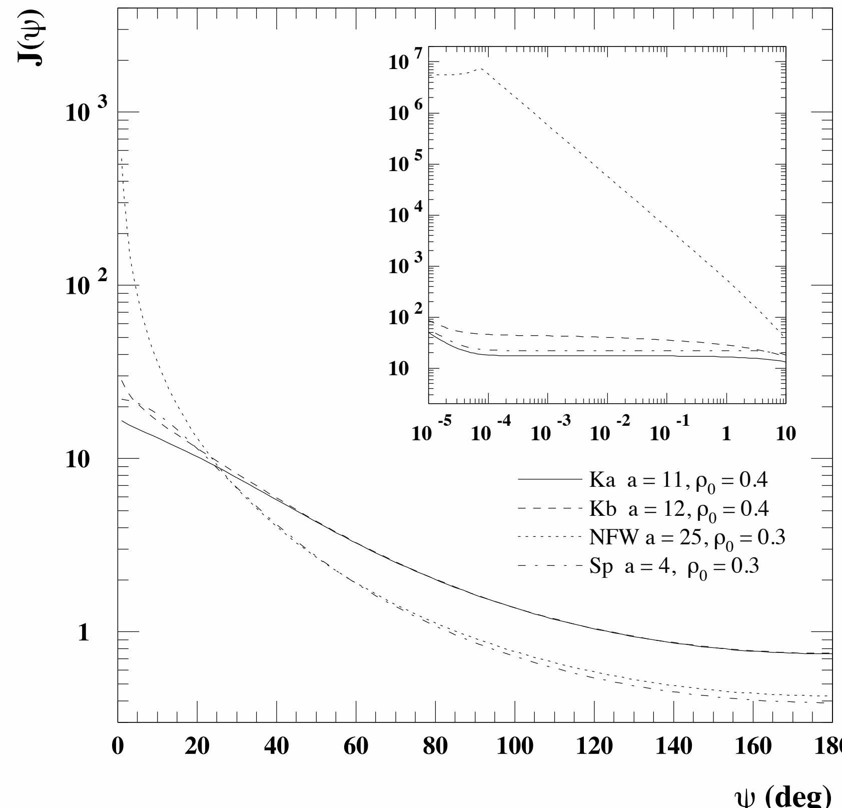

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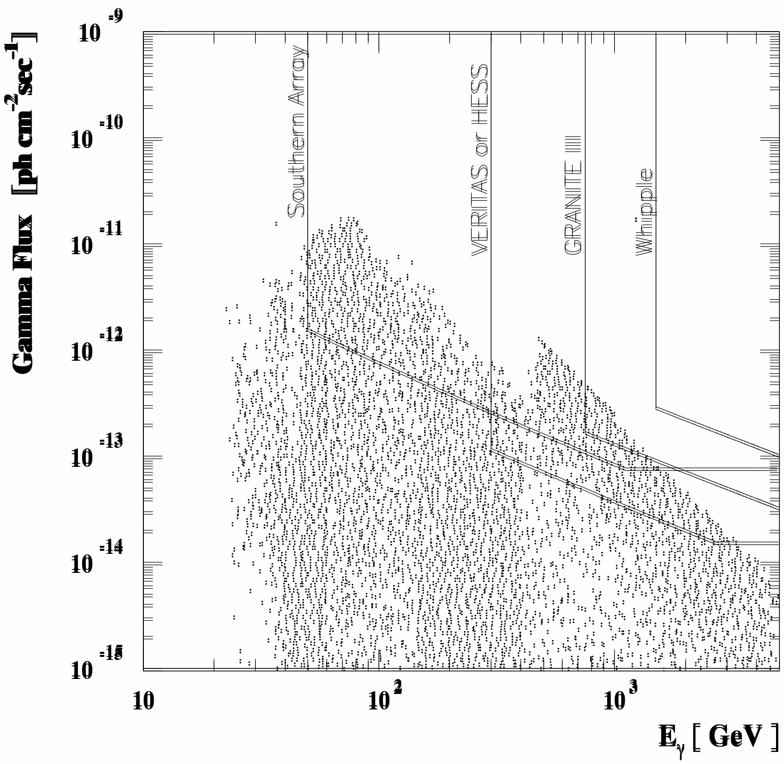
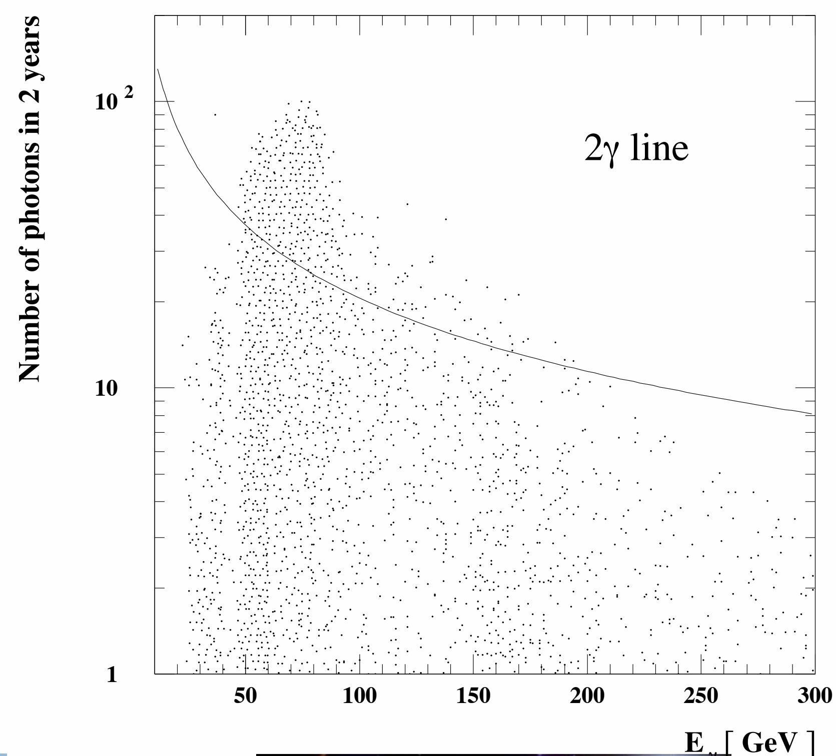
- The possibility annihilation to a gamma-ray line showed the possibility of obtaining a smoking gun signature of dark matter detection.

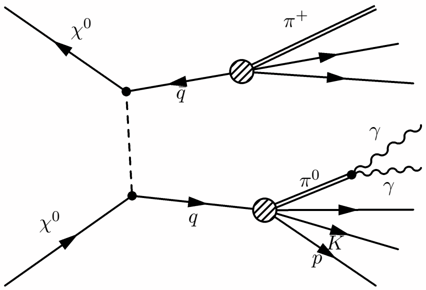
Gamma-Rays from DM (circa '90s)

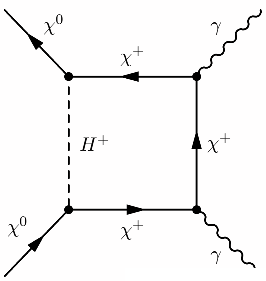
- Projected sensitivity to DM annihilation lie in the Galactic Center (BUB98) provided a motivation for DOE support of VERITAS and Fermi.

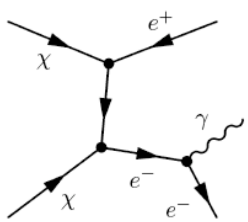


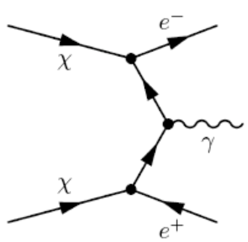


DM and Gamma-Rays









Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^\pm, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^\pm \to l^\pm \nu_l,\ W^\pm \to u\bar{d} \to \pi^\pm,\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0 Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^\pm$	$\tau^\pm \to \nu_\tau e^\pm \nu_e,\ \tau \to \nu_\tau W^\pm \to p, \bar{p}$, pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	 Z^0 decay	γ γ	Loop suppressed Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$	$e^\pm$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

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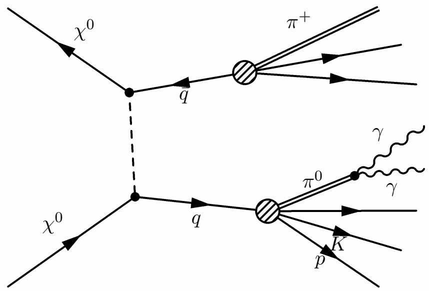
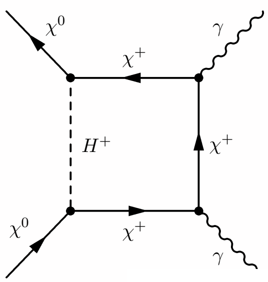
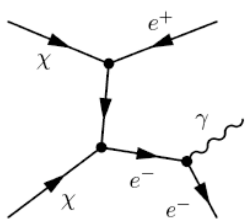
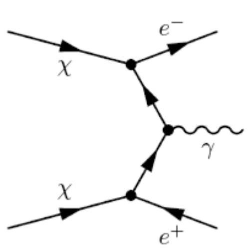




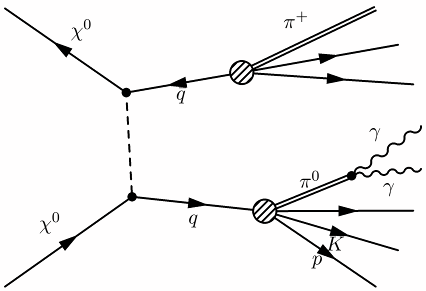


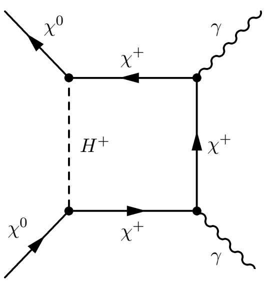


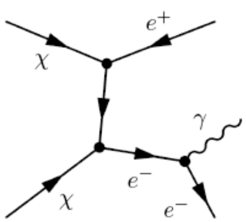
Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_\tau e^{\pm}\nu_e,\ \tau \to \nu_\tau W^{\pm} \to p, \bar{p}$, pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	 Z^0 decay	γ γ	Loop suppressed Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

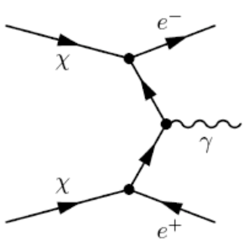
internal/final state bremms
inverse Compton γ's

DM and Gamma-Rays









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$\chi\chi \to \phi\phi$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

internal/final state bremms
inverse Compton γ's

All channels lead to γ-rays. Cross section for γ-ray production is closely tied to total annihilation cross section in the early universe.

Dark Matter Detection

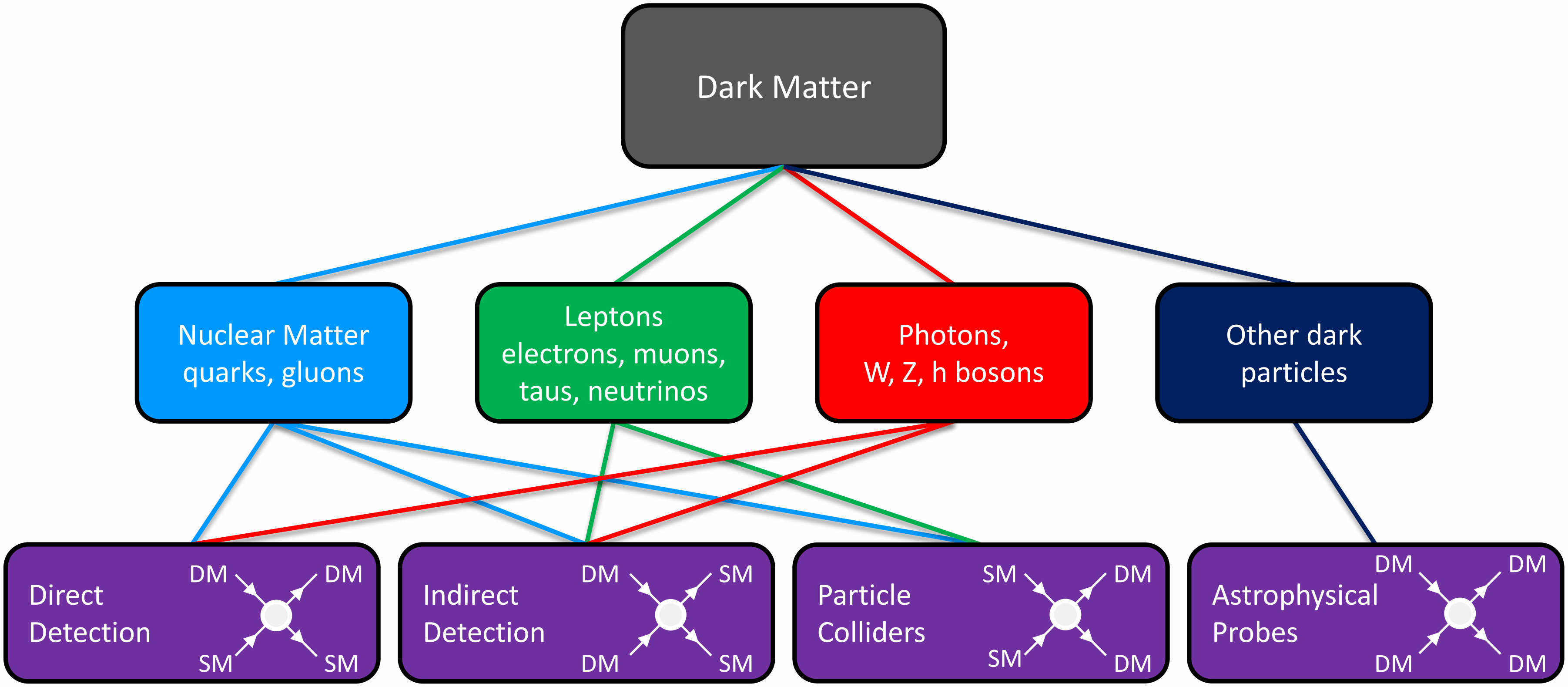


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*

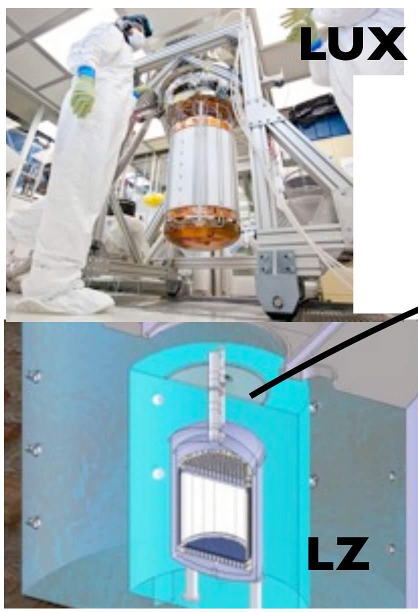
- From Snowmass CF4 report and "*Dark Matter in the Coming Decade: Complementarity Paths to Discovery and Beyond*", Buaer, Buckley, Cahill-Rowley, Cotta, Drlica-Wagner, Feng, Funk, Hewett, Hooper, Ismail, Kaplinghat, Kusenko, Matchev, McKinsey, Rizzo, Shepherd, Wijangco, Tait, and Wood, 2013 (arXiv:1305.1605v1 [hp-ph])

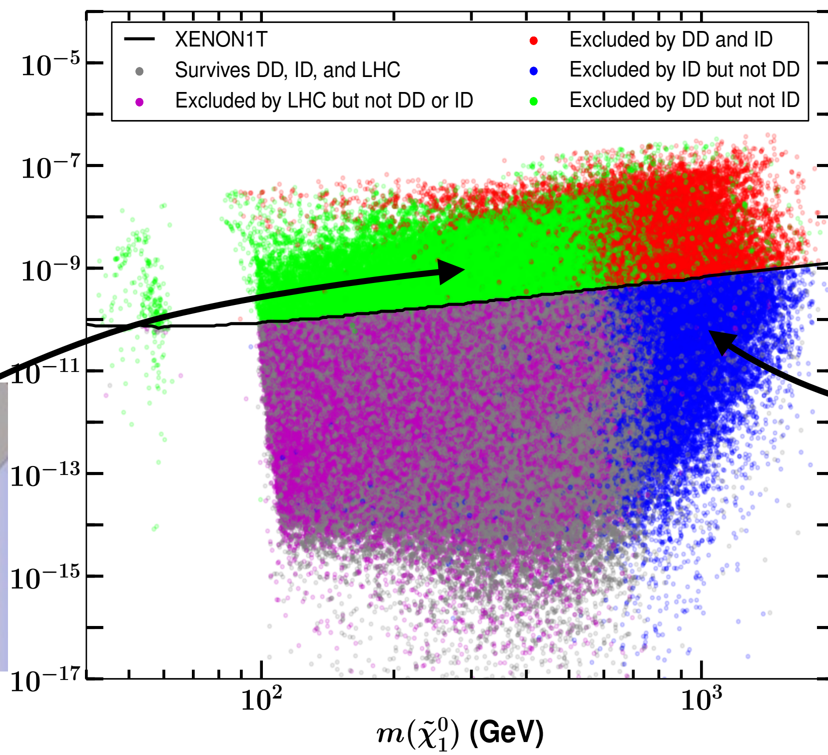
Dark Matter Complementarity

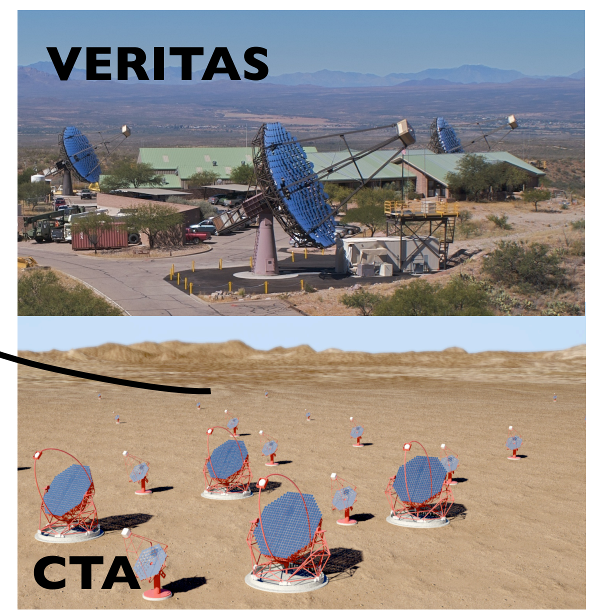
Coupling to matter in early universe implies coupling of DM to matter in the present universe:

$$\text{Direct Detection}: \ \text{WIMP scattering rate} \ \sim n_{\rm nuclei} \frac{\rho_\chi}{m_\chi} \langle \sigma_{\rm SI} \, v_{\chi,n} \rangle$$

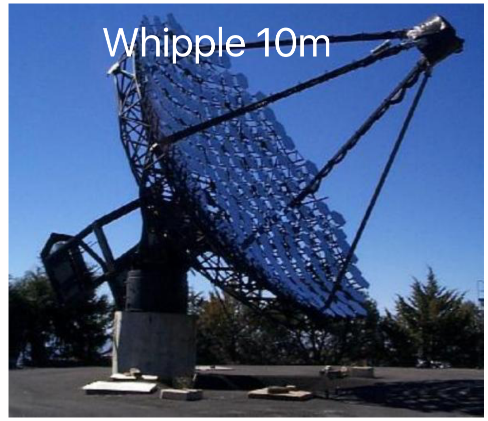
$$\text{Indirect Detection}: \ \text{WIMP annihilation rate} \ \sim \left(\frac{\rho_\chi}{m_\chi}\right)^2 \langle \sigma_{\chi\chi} v_{\rm rel} \rangle$$

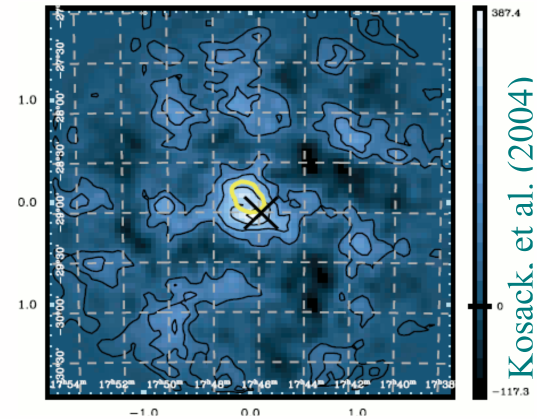






Brief History…





- EGRET detected GC source 3EG J1746-2851 (Hartman et al. 1999). With support of DOE (PK) Whipple 10m observed GC for almost ten years (1995-2003) resulting in ~4 sigma indication of emission from GC. HESS definitively detected the GC, followed by MAGIC and VERITAS - rich astrophysics, but DM sensitivity is diluted by the point source.

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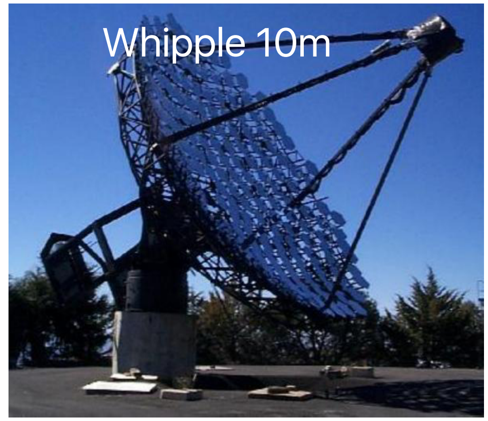

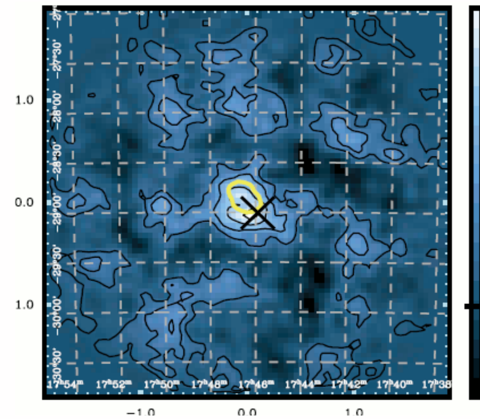

Kosack. et al. (2004)

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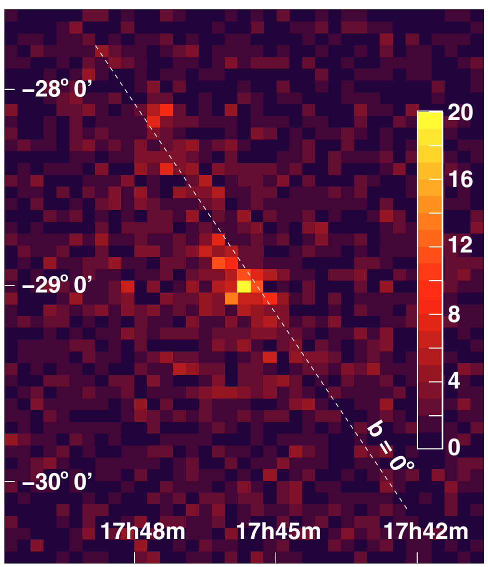
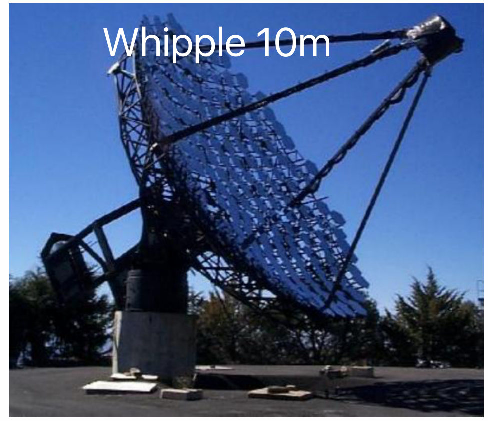
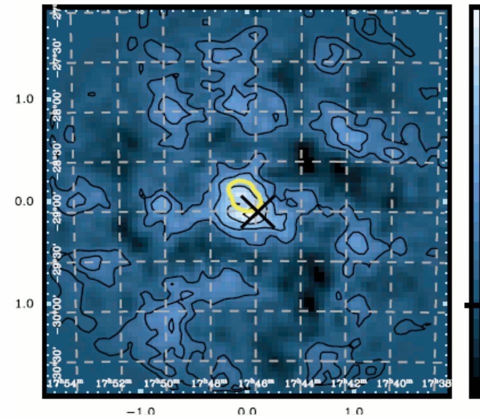


Aharonian et al., A&A 425, L13 (2004)

Brief History...





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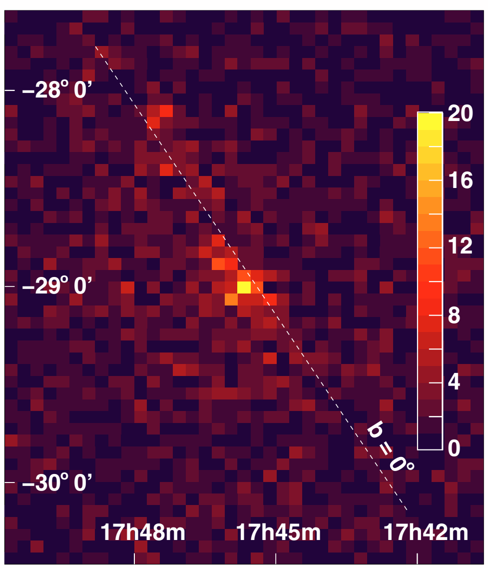

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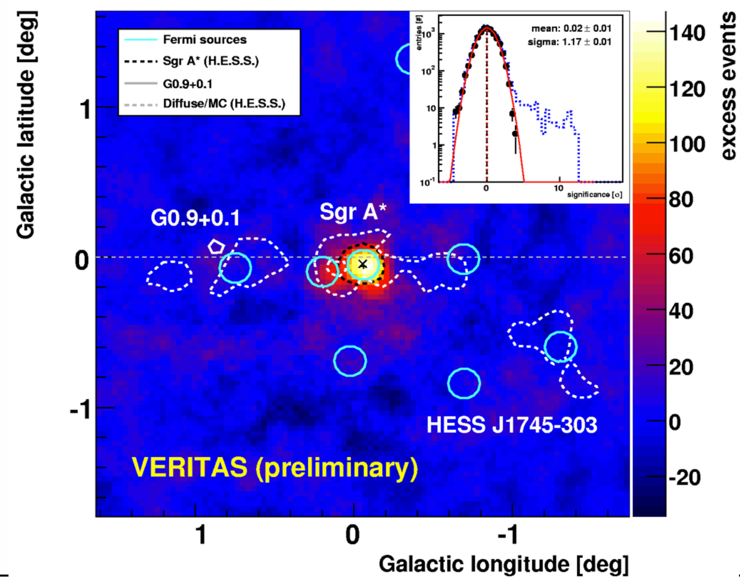
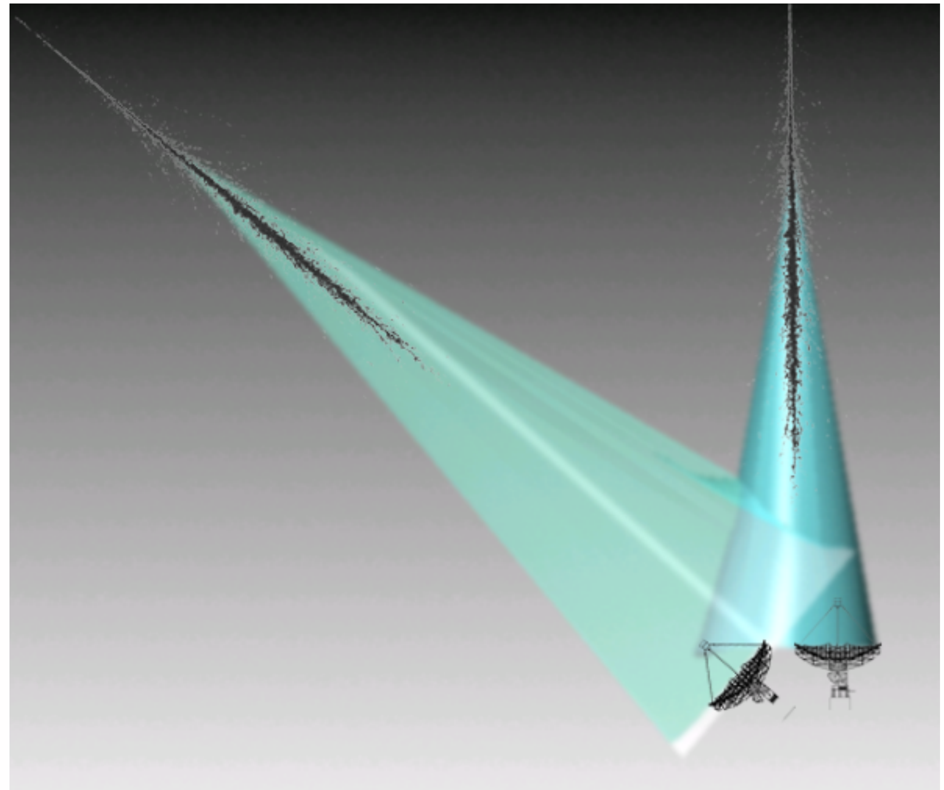


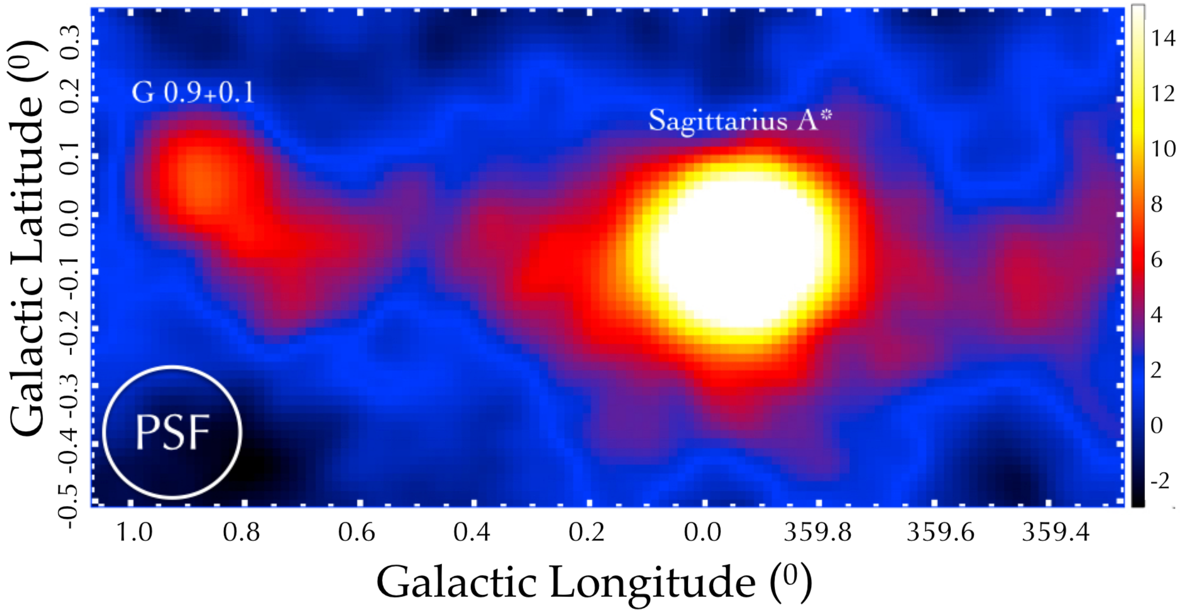
Large Zenith Angle

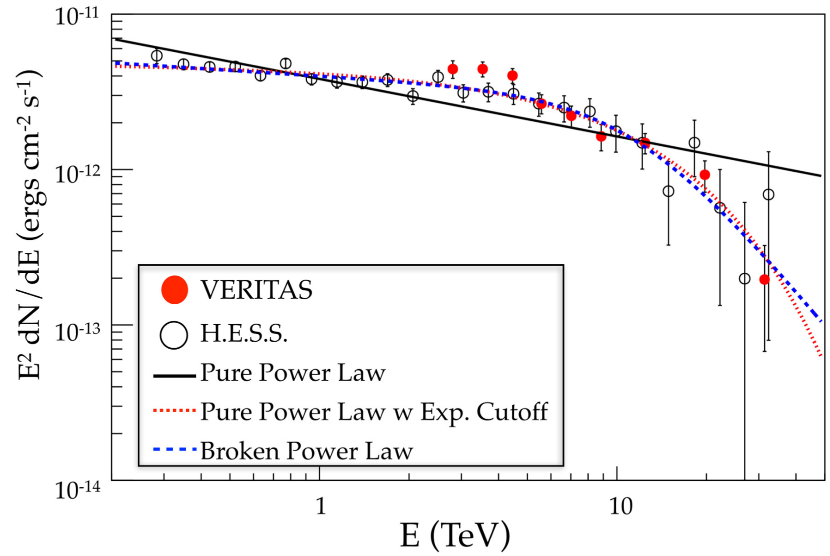
GC transits at ~30 deg Elevation



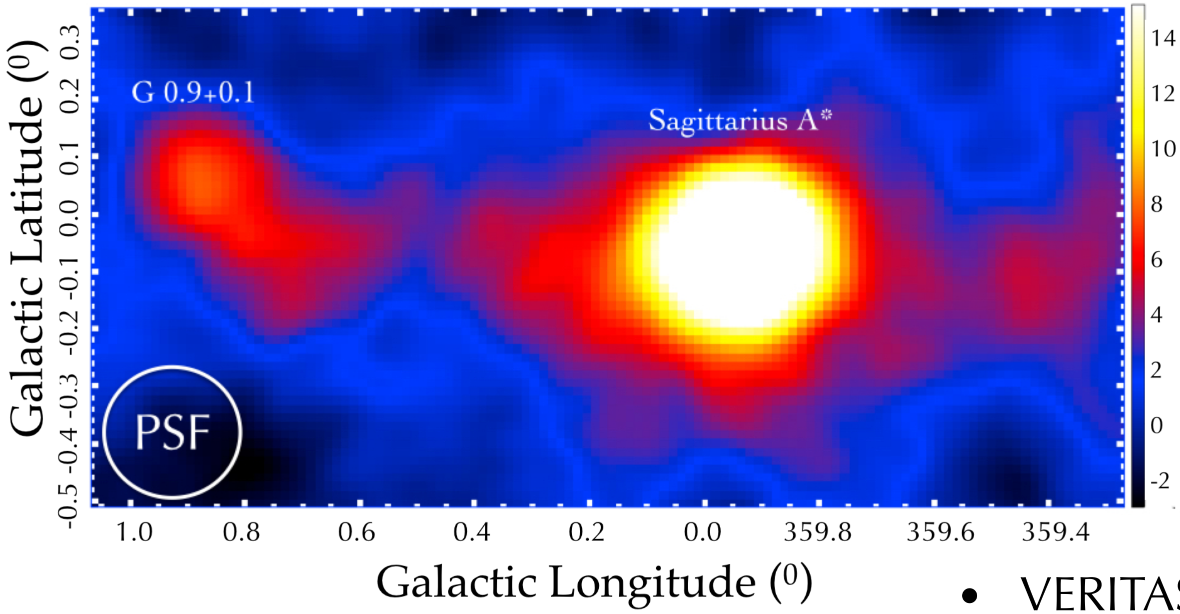
- While it is more sensible to build a telescope in the southern hemisphere to look for DM from the Galactic Center, LZA observations provide an enormous effective area at high energies - especially important for annihilation channels that result in gamma-ray emission near the kinematic maximum.

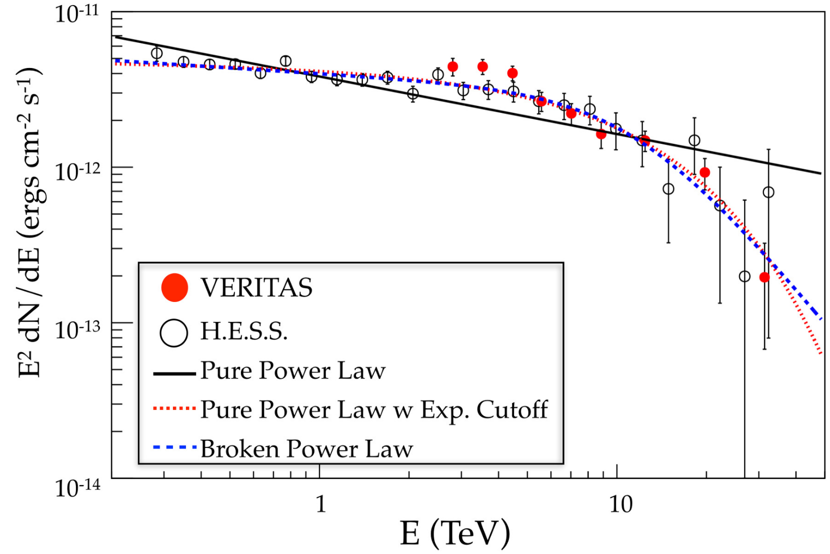
VERITAS GC Data





VERITAS GC Data





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- 85 hours of Large Zenith Angle (~30deg elevation at transit) from 2010-2014.

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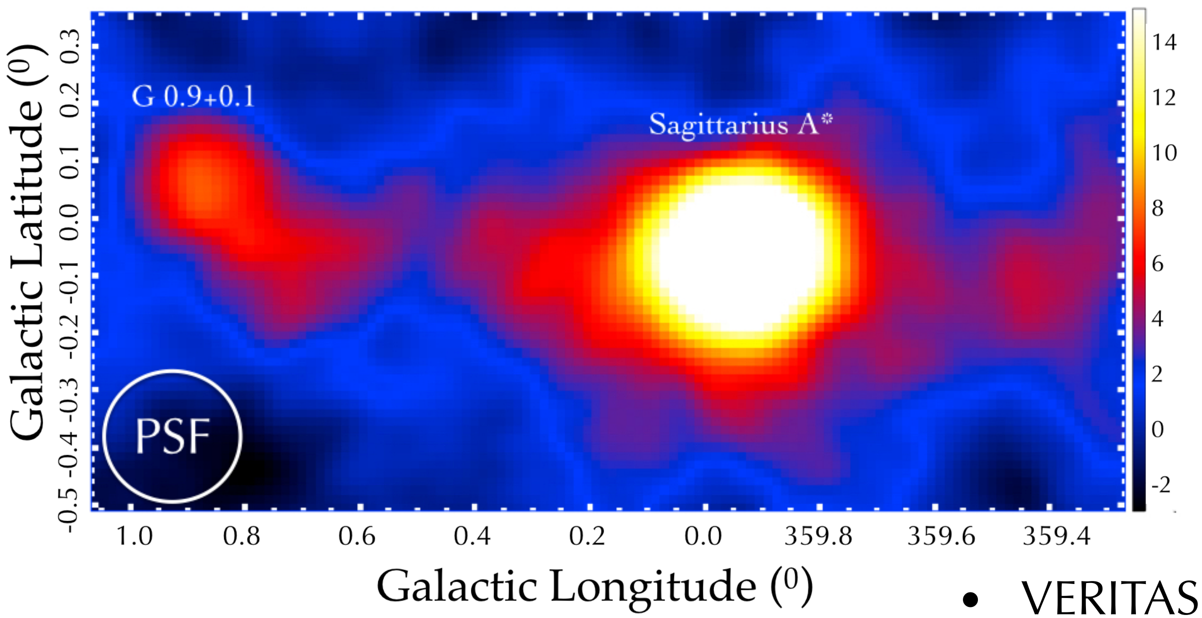

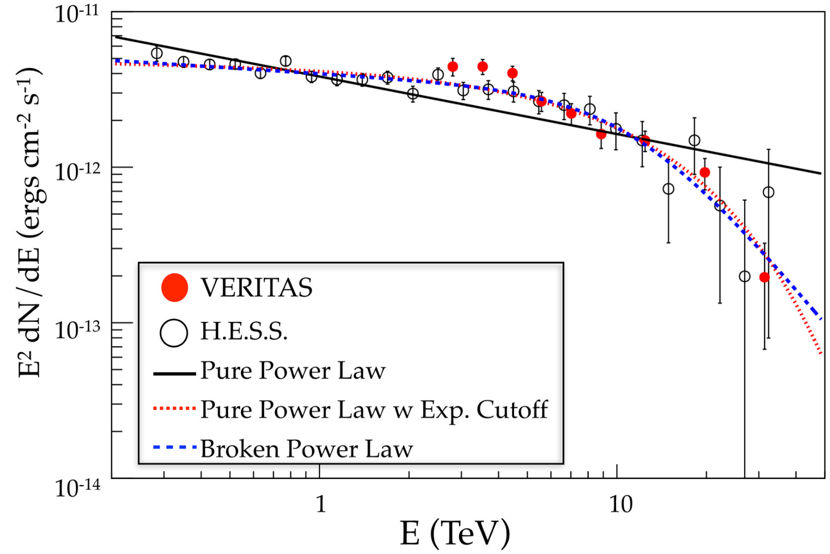

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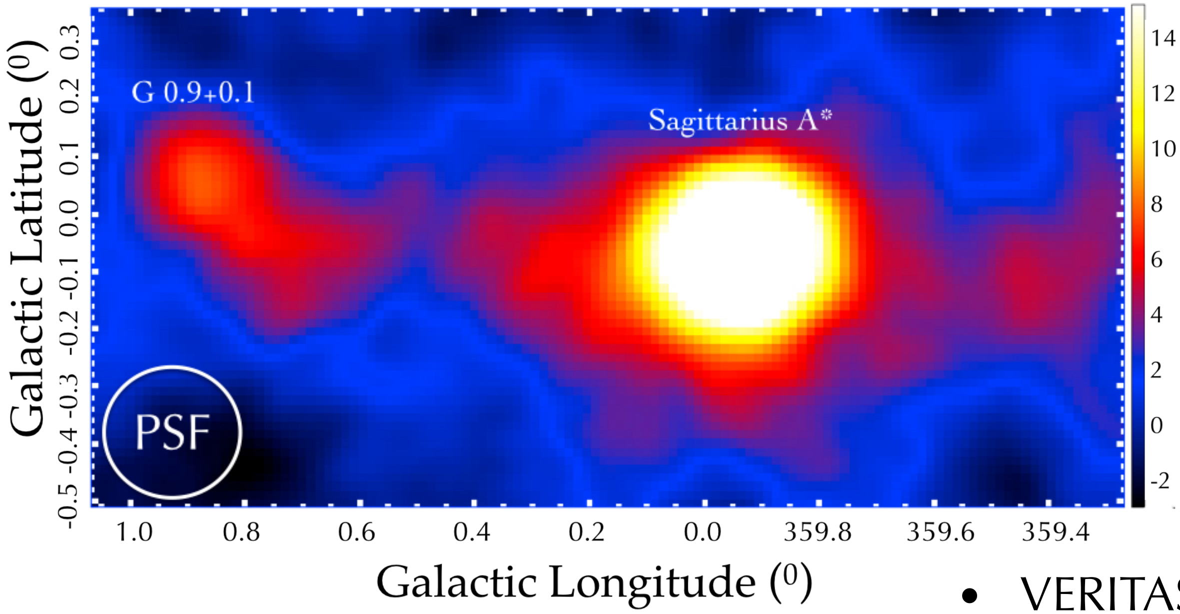

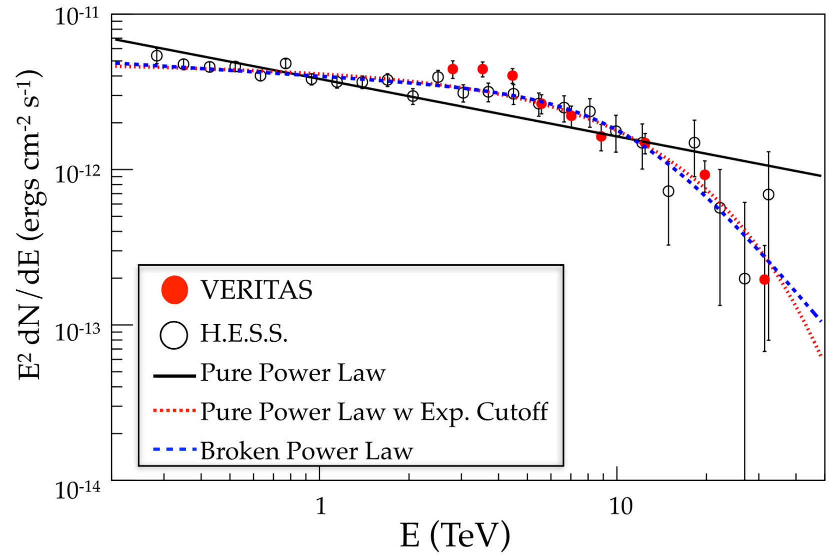

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- Lots of other sources in GC region!

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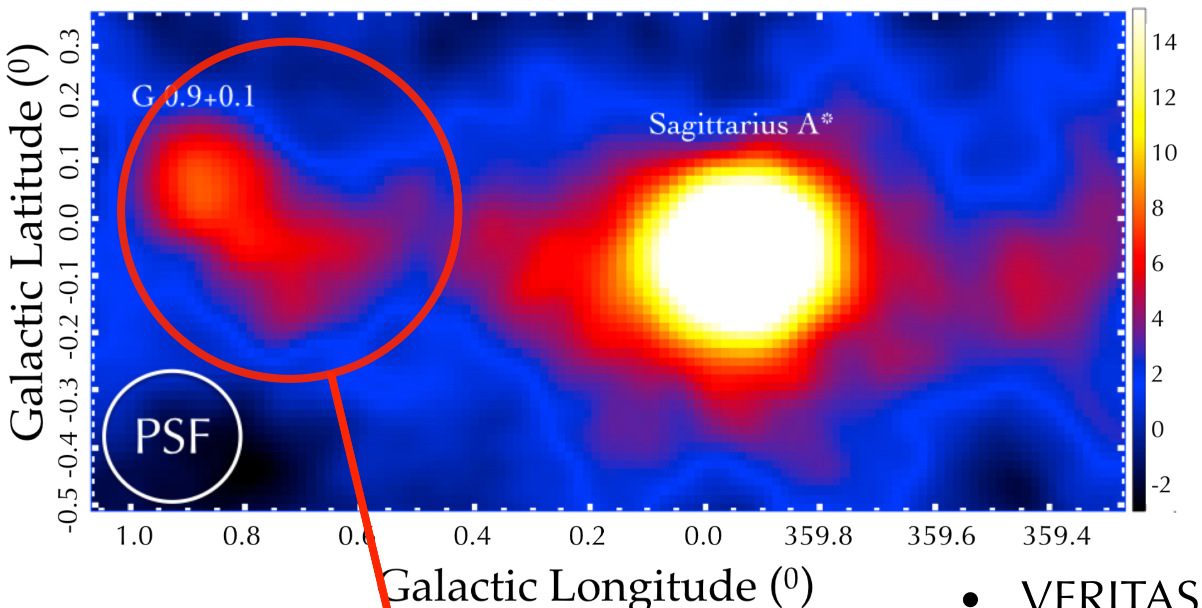

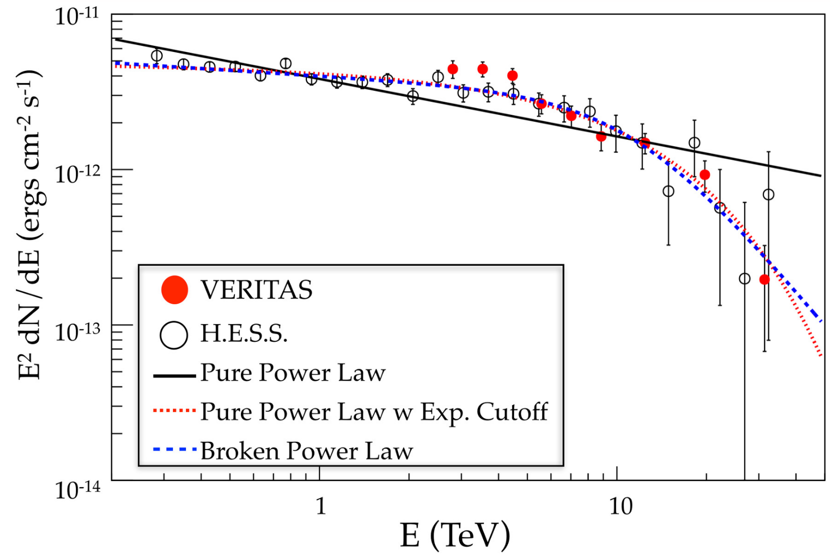

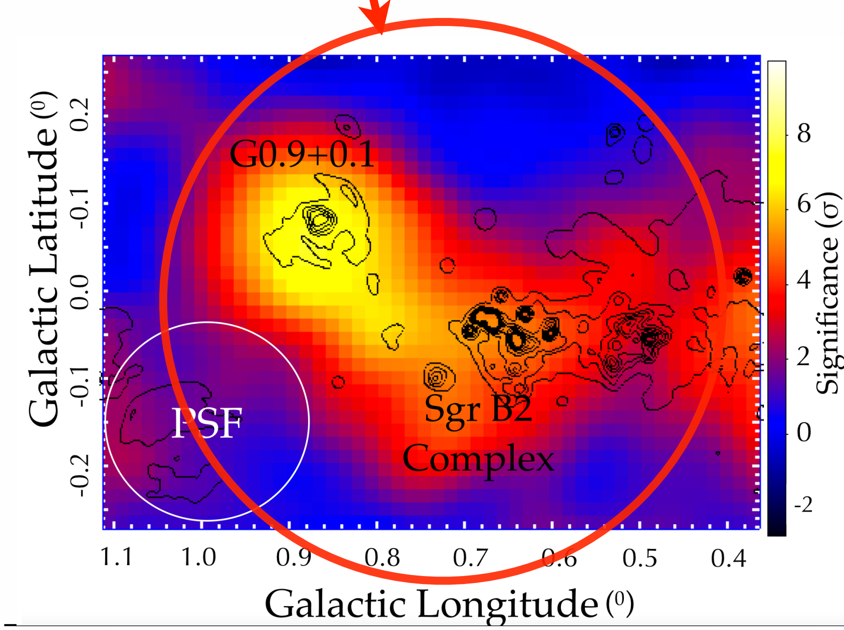

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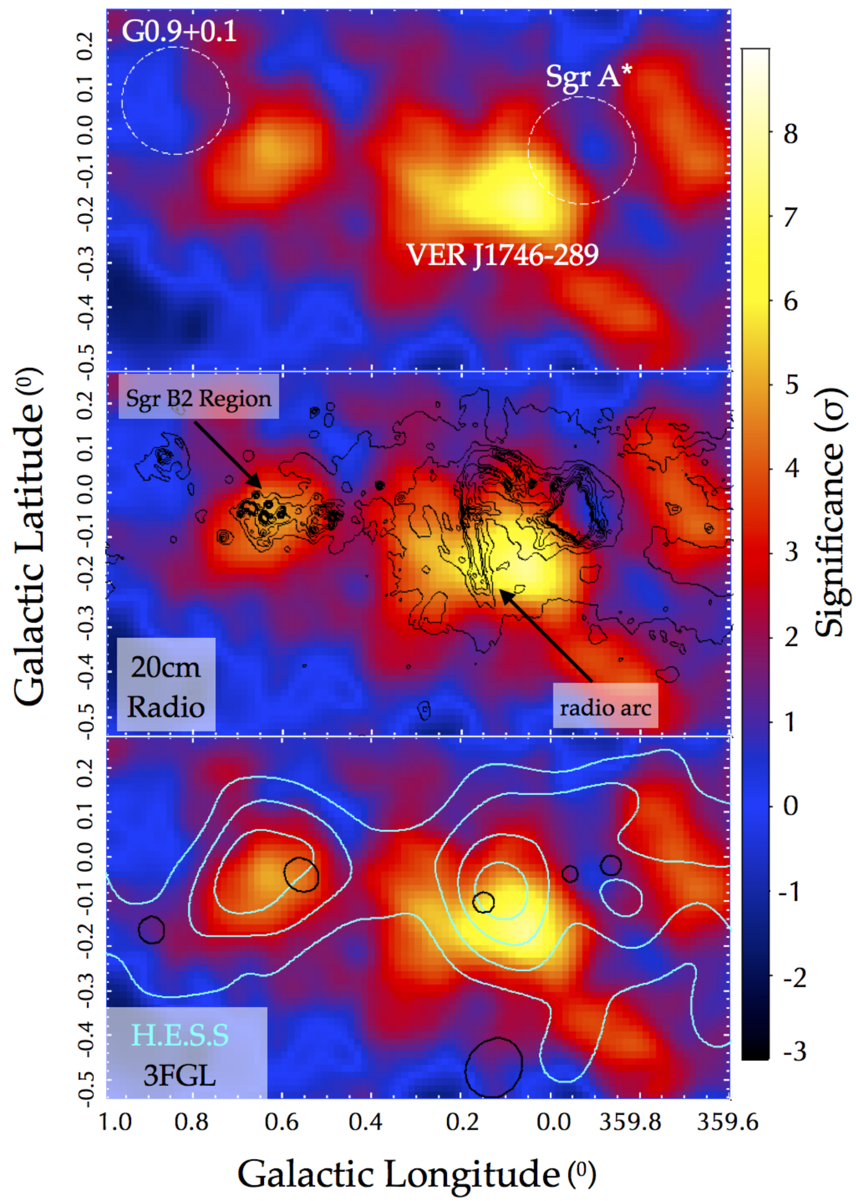
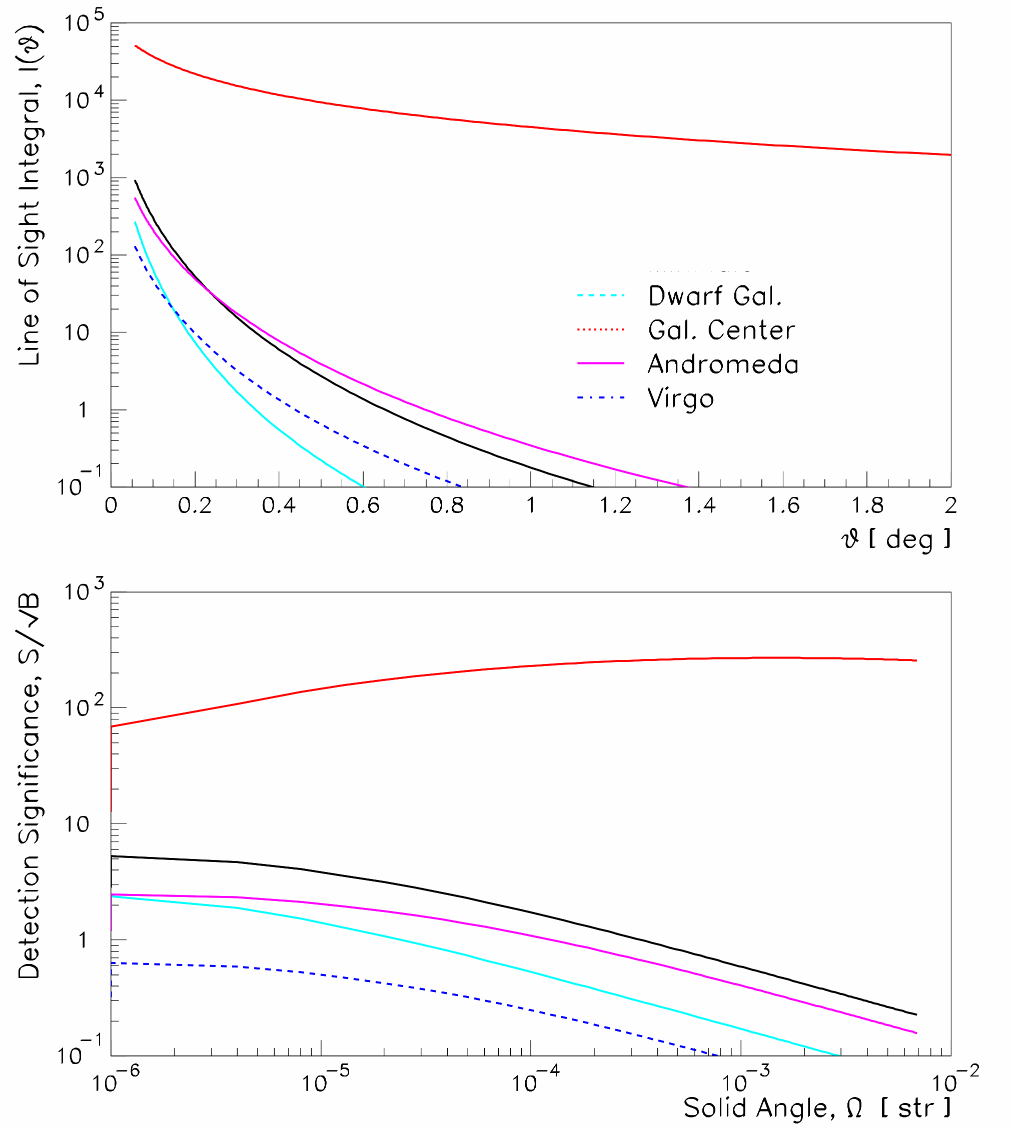
GC Region



- Residual emission after subtraction of point sources Sgr A* and G0.9+0.1.
- Good agreement with HESS, and overlap with VLA radio morphology.
- Tough to do DM upper limits due to astrophysical gamma-ray backgrounds AND subtle systematic effects of sky brightness differences along the Galactic plane.

Where to Look for DM



JB 2002

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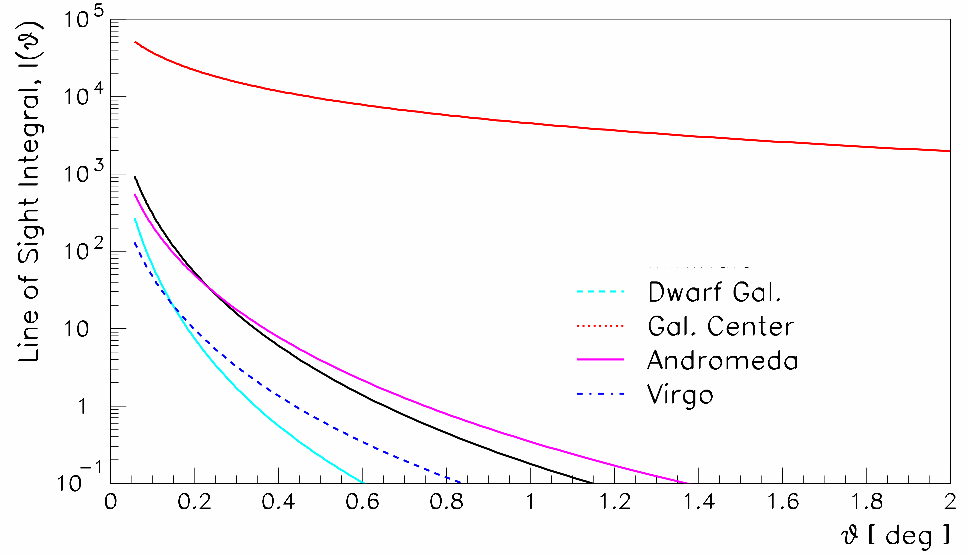

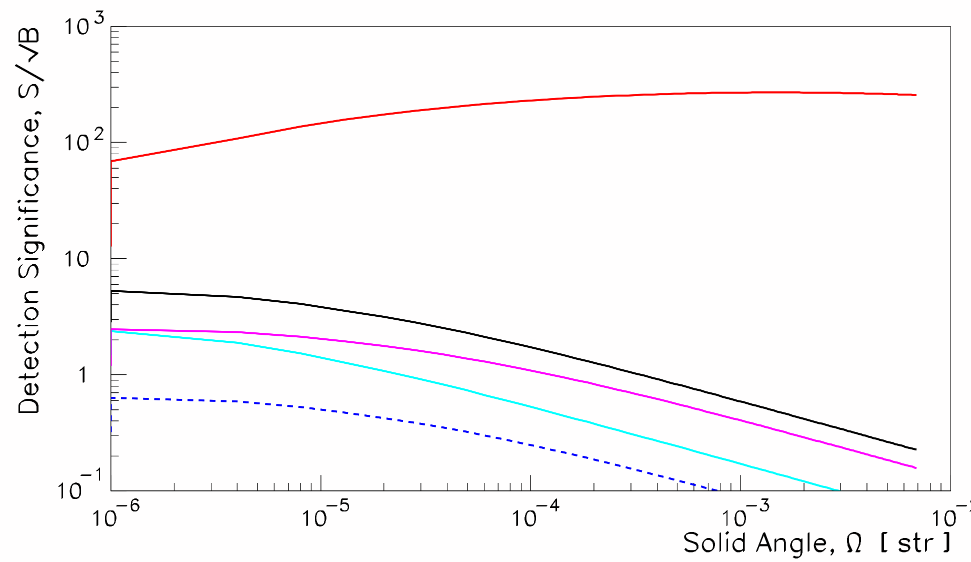

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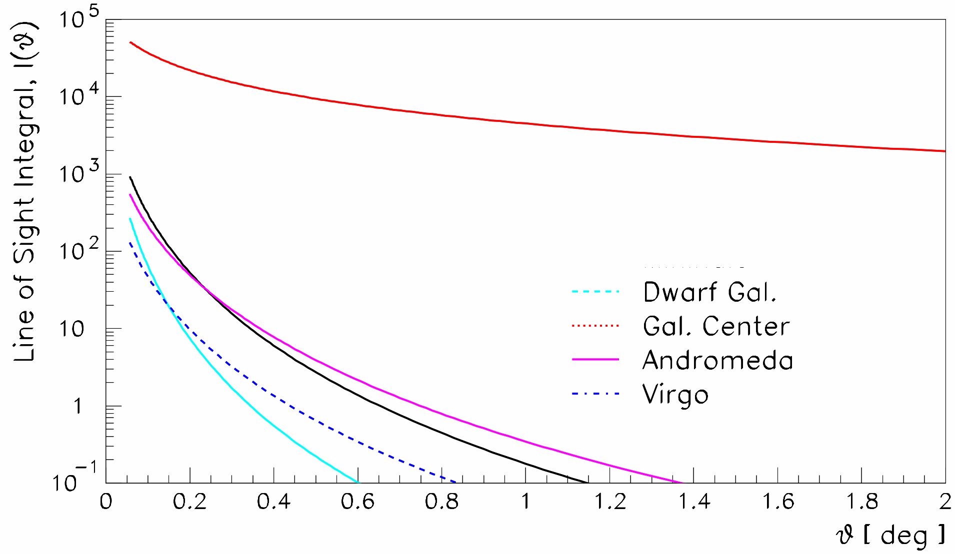

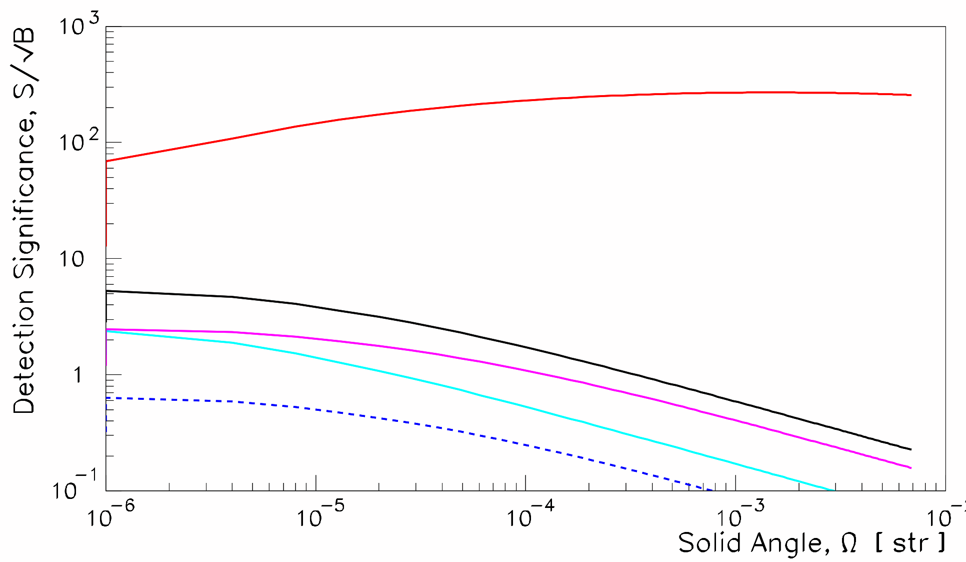

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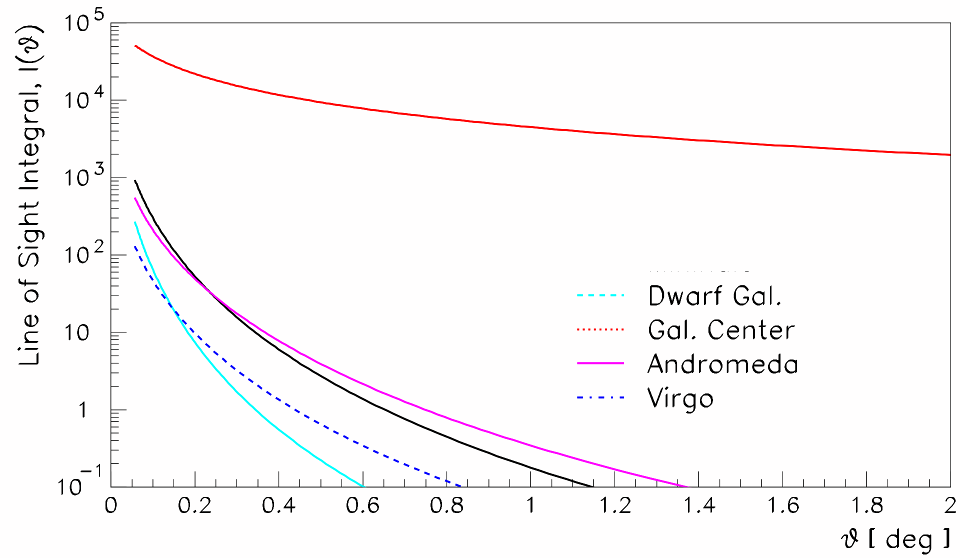
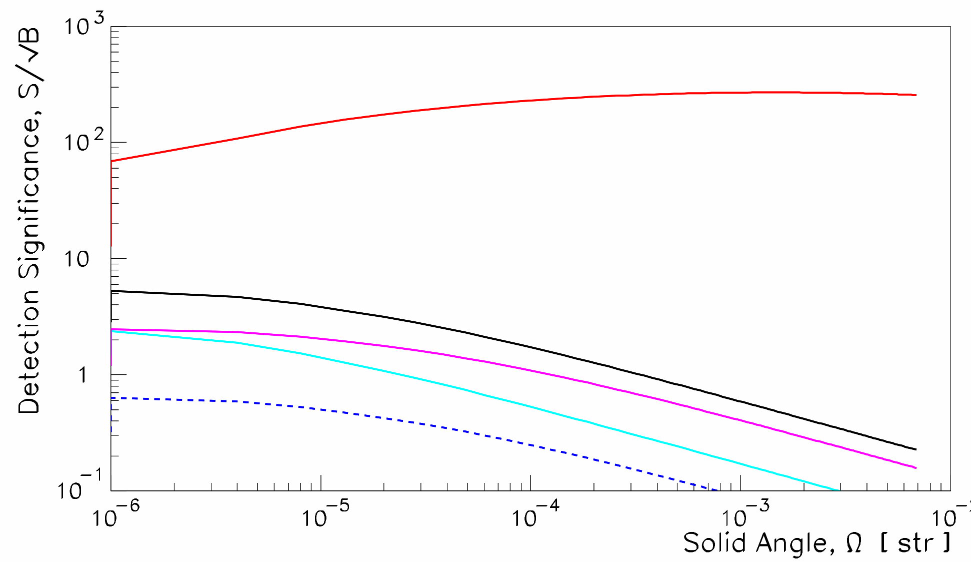
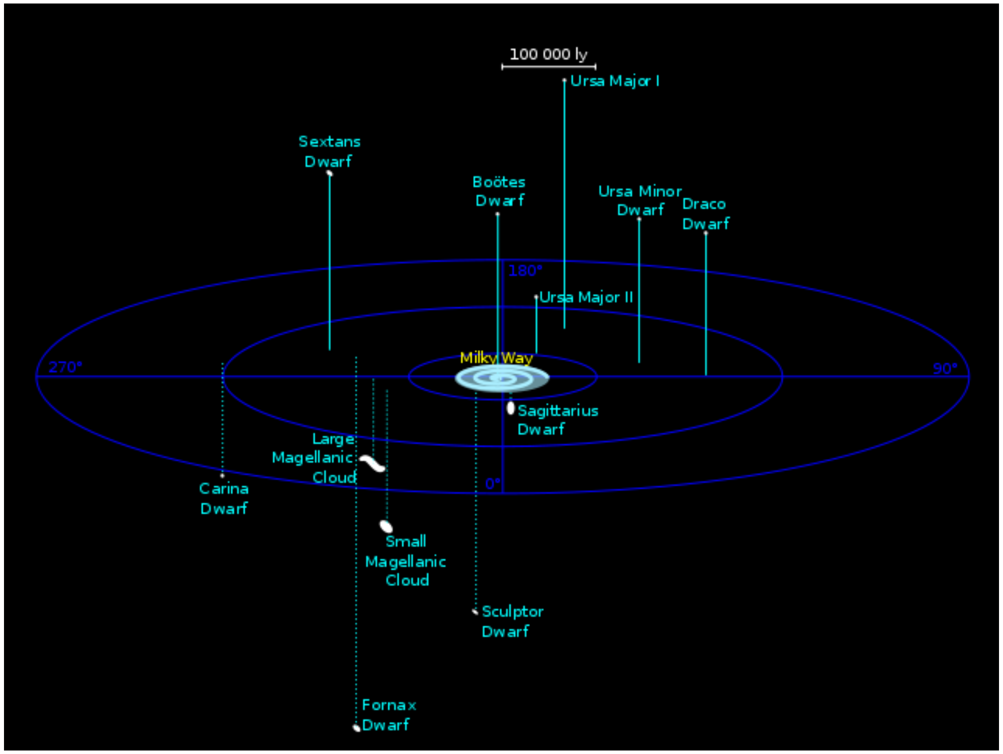




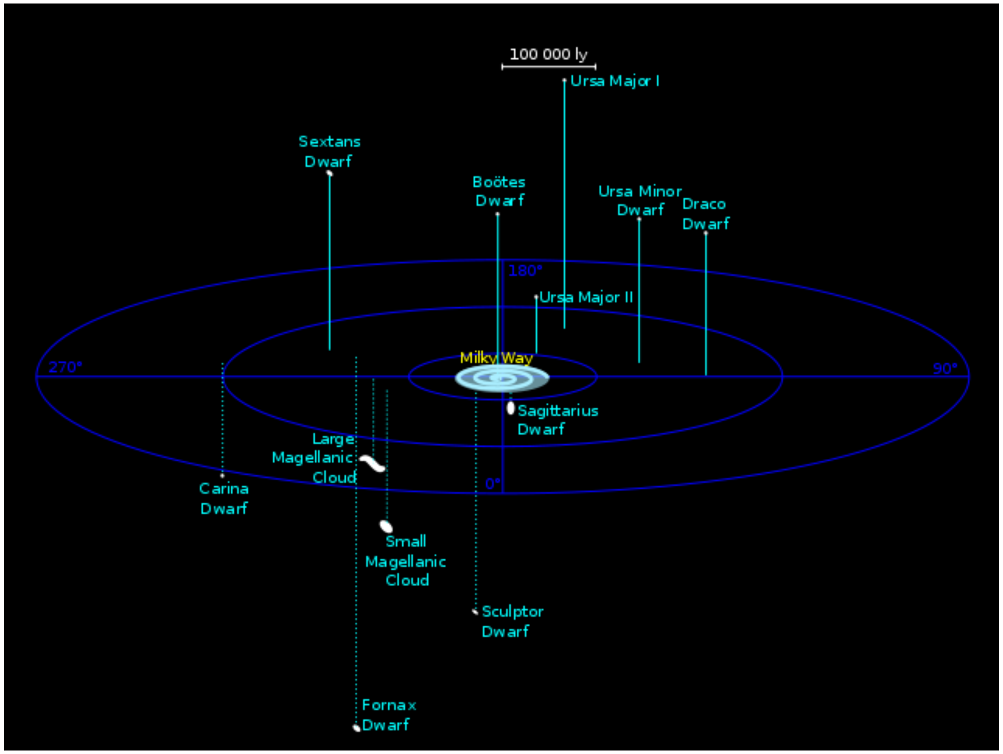
JB 2002

Dwarf Galaxies



- Dwarf galaxies are very dark matter dominated objects with mass to light ratios approaching 1000
- Total masses typically $\sim 10^7 M_\odot$

Dwarf Galaxies



- Dwarf galaxies are very dark matter dominated objects with mass to light ratios approaching 1000
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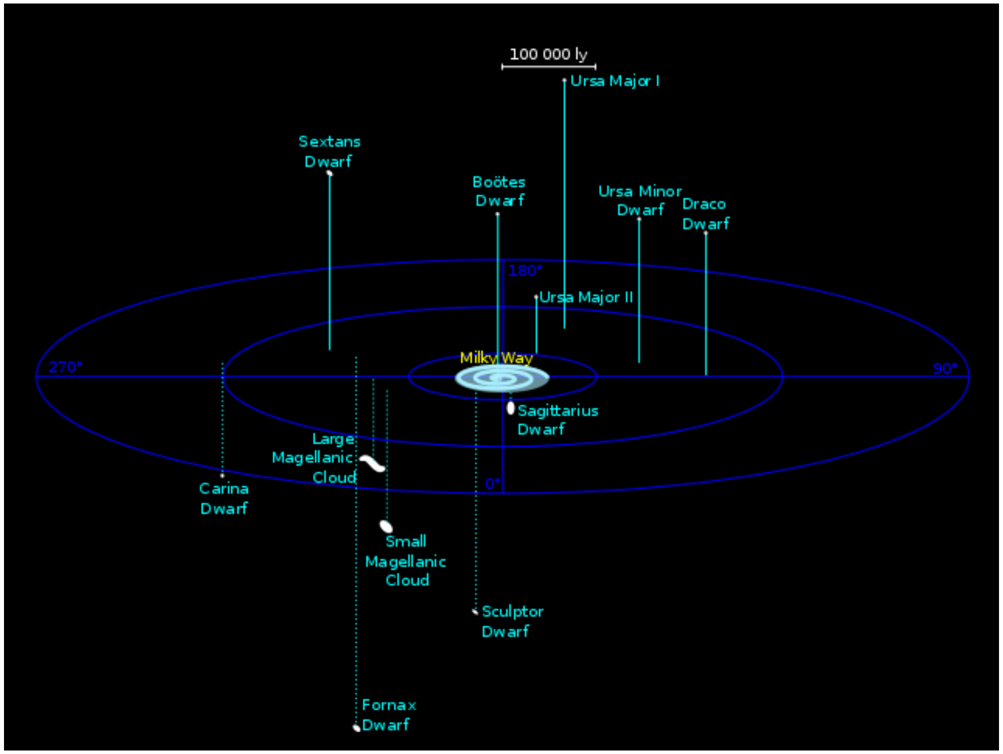
- DES and other instruments are releasing tension by discovering more objects, providing more targets for gamma-ray telescopes.

Dwarf Galaxies



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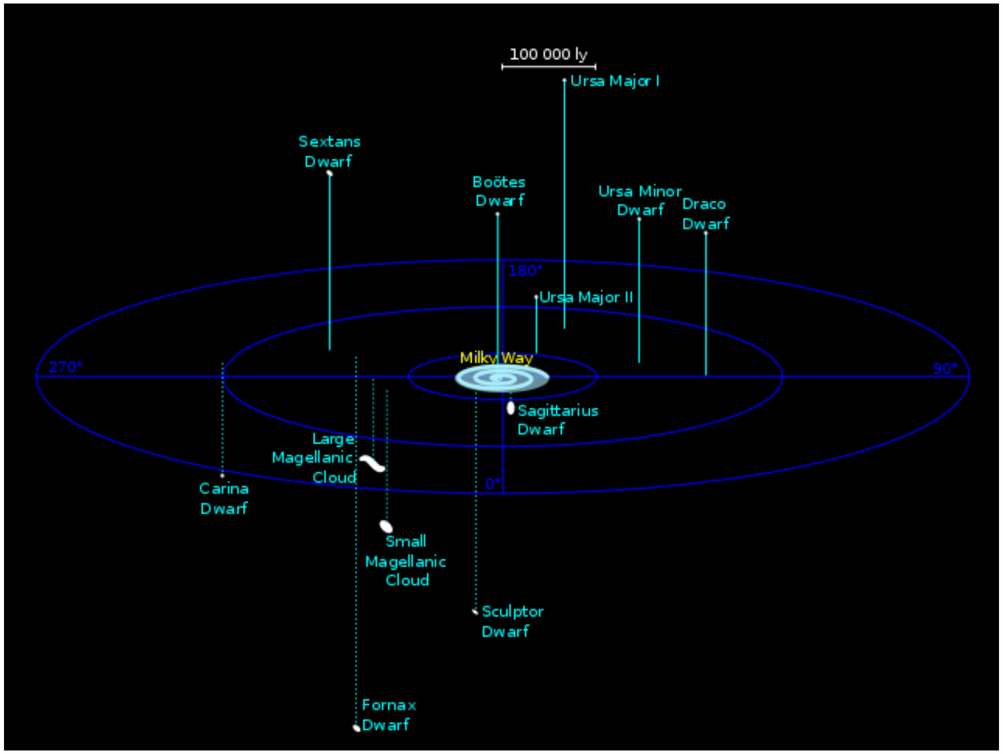

Image showing identification of stars in Dwarf galaxy for DES J0335.6-5403. Only about 300 could be detected with DES data. (Credit: Fermilab/Dark Energy Survey)

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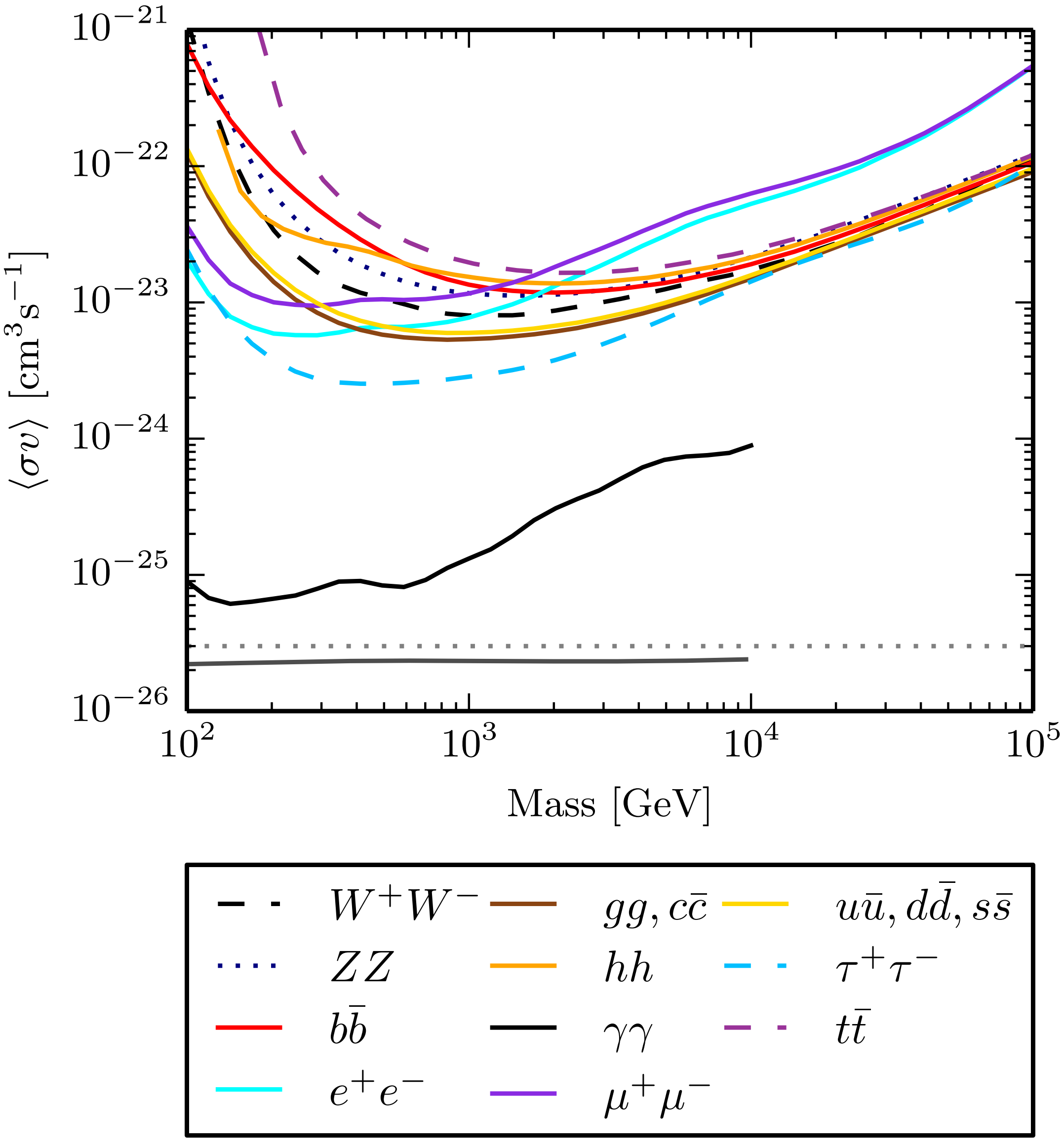
Ten Years of Dwarf Galaxy

Stellar velocity dispersion of stars in Dwarf galaxies giving density profiles, and J-factors (the figure of merit for detectibility). VERITAS conducted a 10 year program of Dwarf observing.

Dwarf	$\log_{10} J_1(0.5°)$ [GeV^2 cm^{-5}]	$\log_{10} J_2(0.5°)$ [GeV^2 cm^{-5}]	$\log_{10} D_1(0.5°)$ [GeV cm^{-2}]	Exposure v4 [min]	Exposure v5 [min]	Exposure v6 [min]	Total Expos [min]
Segue 1	$19.4^{+0.3}_{-0.4}$	$17.0^{+2.1}_{-2.2}$	$18.0^{+0.2}_{-0.3}$	0	6121	4921	11042
Ursa Major II	$19.4^{+0.4}_{-0.4}$	$19.9^{+0.7}_{-0.5}$	$18.4^{+0.3}_{-0.3}$	0	0	10869	10869
Ursa Minor	$18.9^{+0.3}_{-0.2}$	$19.0^{+0.1}_{-0.1}$	$18.0^{+0.2}_{-0.1}$	711	2209	6844	9724
Draco	$18.8^{+0.1}_{-0.1}$	$19.1^{+0.4}_{-0.2}$	$18.5^{+0.1}_{-0.1}$	1169	2170	3435	6813
Coma Berencies	$19.0^{+0.4}_{-0.4}$	$19.6^{+0.8}_{-0.7}$	$18.0^{+0.2}_{-0.3}$	0	0	2204	2204
Segue II	$16.2^{+1.1}_{-1.0}$	$18.9^{+1.1}_{-1.1}$	$15.9^{+0.4}_{-0.4}$	0	0	1128	1128
Boötes 1	$18.2^{+0.4}_{-0.4}$	$18.5^{+0.6}_{-0.4}$	$17.9^{+0.2}_{-0.3}$	960	0	0	960
Leo II	$18.0^{+0.2}_{-0.2}$	$17.8^{+0.2}_{-0.2}$	$17.2^{+0.4}_{-0.5}$	0	0	946	946
Willman 1	N/A	N/A	N/A	931	0	0	931
Triangulum II	N/A	N/A	N/A	0	0	909	909
Canes Ver. II	$17.7^{+0.5}_{-0.4}$	$18.5^{+1.2}_{-0.9}$	$17.0^{+0.2}_{-0.2}$	0	0	864	864
Canes Ver. I	$17.4^{+0.4}_{-0.3}$	$17.5^{+0.4}_{-0.2}$	$17.6^{+0.4}_{-0.7}$	0	0	850	850
Hercules I	$16.9^{+0.7}_{-0.7}$	$17.5^{+0.7}_{-0.7}$	$16.7^{+0.4}_{-0.4}$	0	0	794	794
Sextans I	$18.0^{+0.2}_{-0.2}$	$17.6^{+0.2}_{-0.2}$	$17.9^{+0.1}_{-0.2}$	0	0	783	783
Draco II	N/A	N/A	N/A	0	0	598	598
Ursa Major I	$17.9^{+0.6}_{-0.3}$	$18.7^{+0.6}_{-0.5}$	$17.6^{+0.2}_{-0.4}$	0	0	482	482
Leo I	$17.8^{+0.2}_{-0.2}$	$17.8^{+0.5}_{-0.2}$	$17.9^{+0.2}_{-0.2}$	0	0	409	409
Leo V	$16.4^{+0.9}_{-0.9}$	$16.1^{+1.2}_{-1.0}$	$15.9^{+0.5}_{-0.5}$	0	0	167	167
Leo IV	$16.3^{+1.1}_{-1.7}$	$16.2^{+1.5}_{-1.6}$	$16.1^{+0.7}_{-1.1}$	0	0	151	151

VERITAS Combined



"Dark matter constraints from a joint analysis of dwarf Spheroidal galaxy observations with VERITAS", Archambaldt et al. (for VERITAS), PRD, 95, 082001 (2017)

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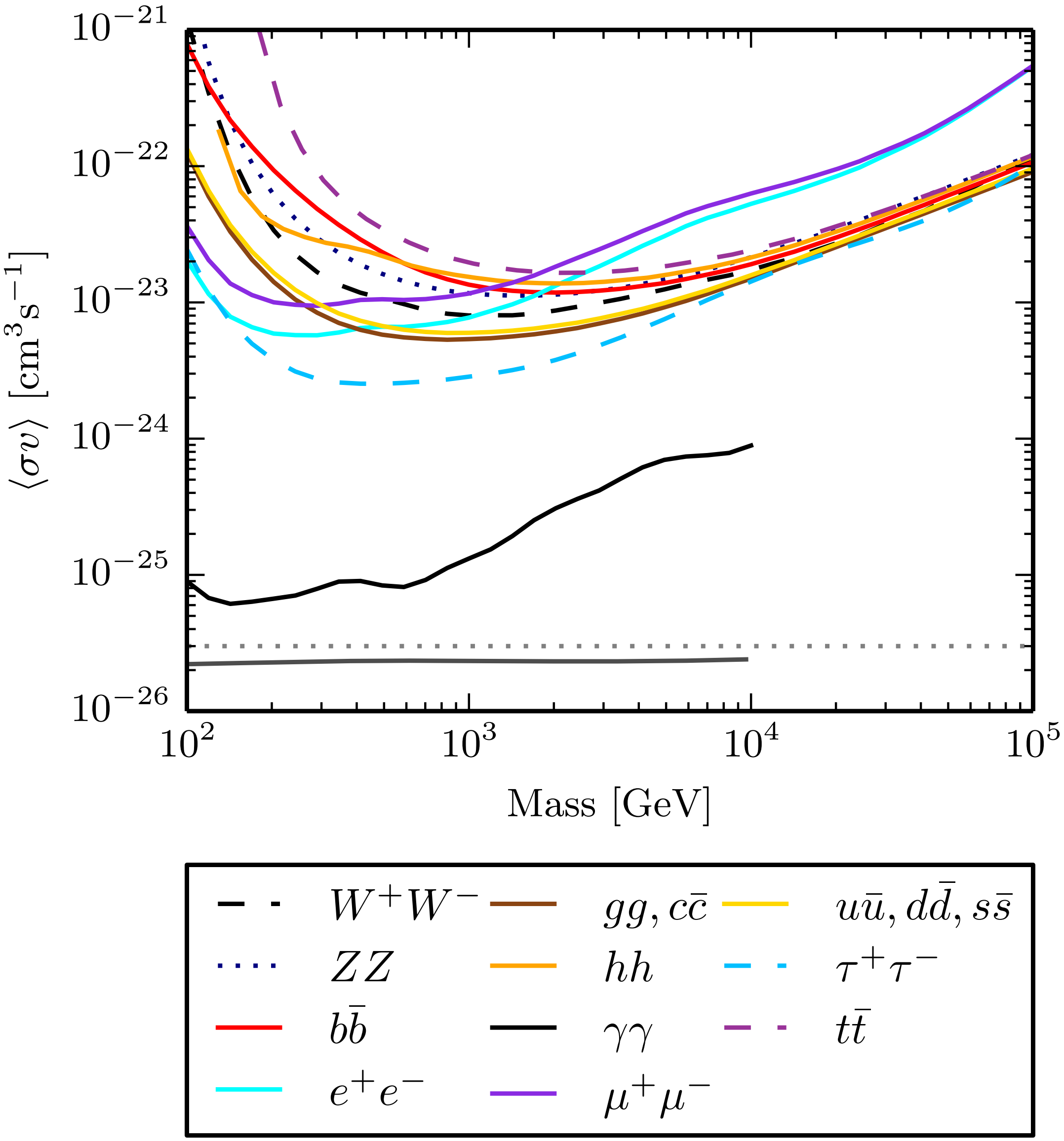

- VERITAS 95% CL velocity-averaged cross section as a function of DM mass for stacked dwarf galaxy observations for different Annihilation channels.

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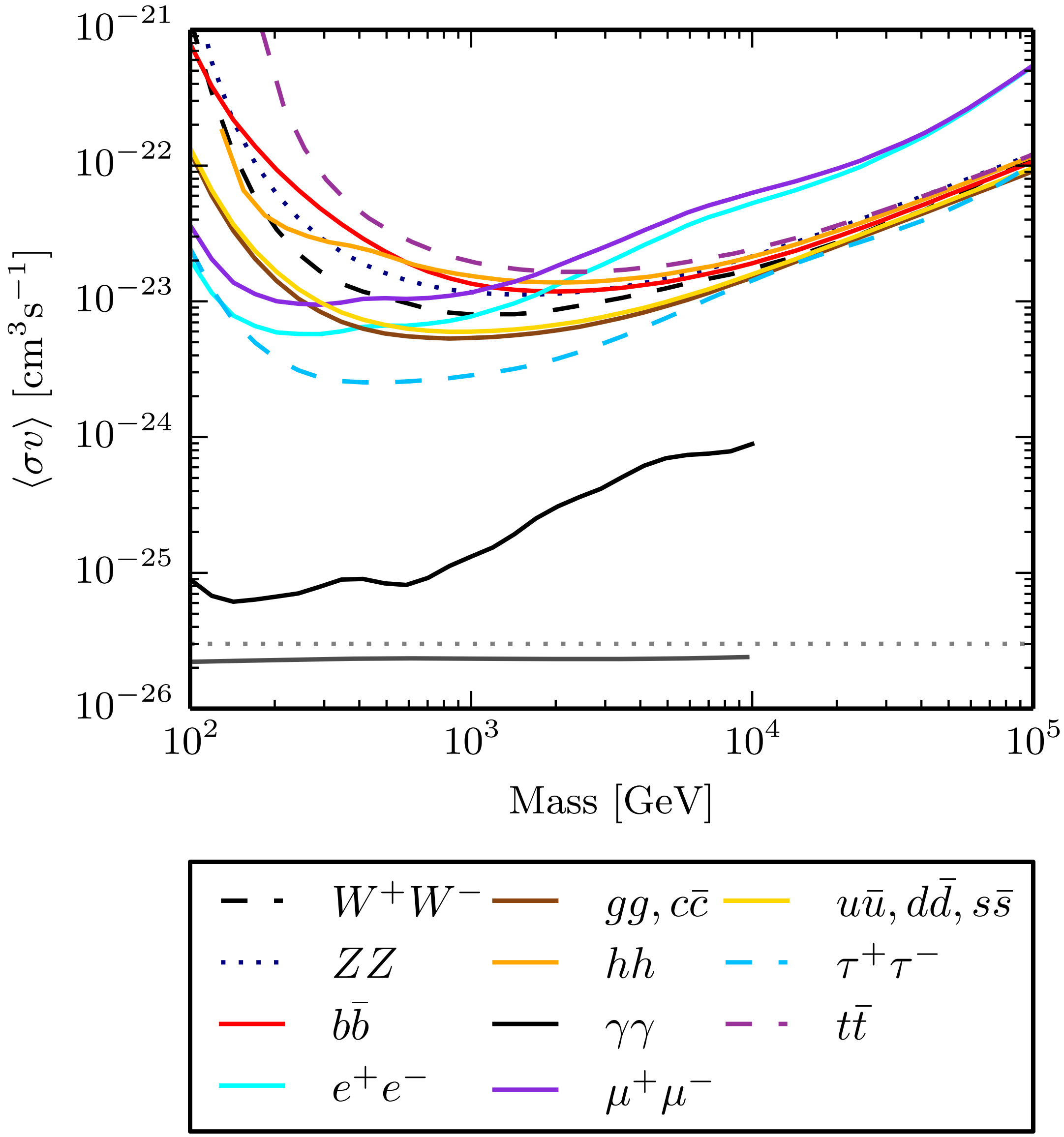
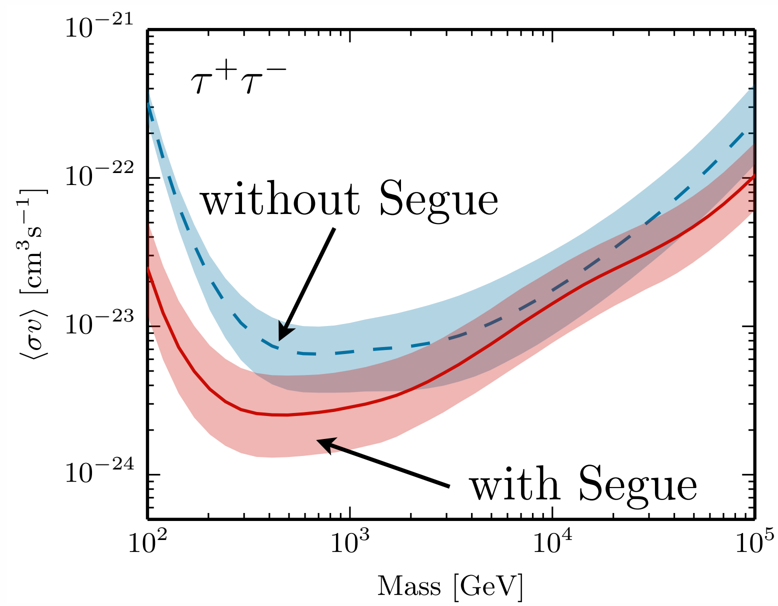


- VERITAS 95% CL velocity-averaged cross section as a function of DM mass for stacked dwarf galaxy observations for different Annihilation channels.
- Results depend on Dwarf galaxies with the highest J-factor. New measurements (e.g., DES) are revealing more, and perhaps better Dwarfs.



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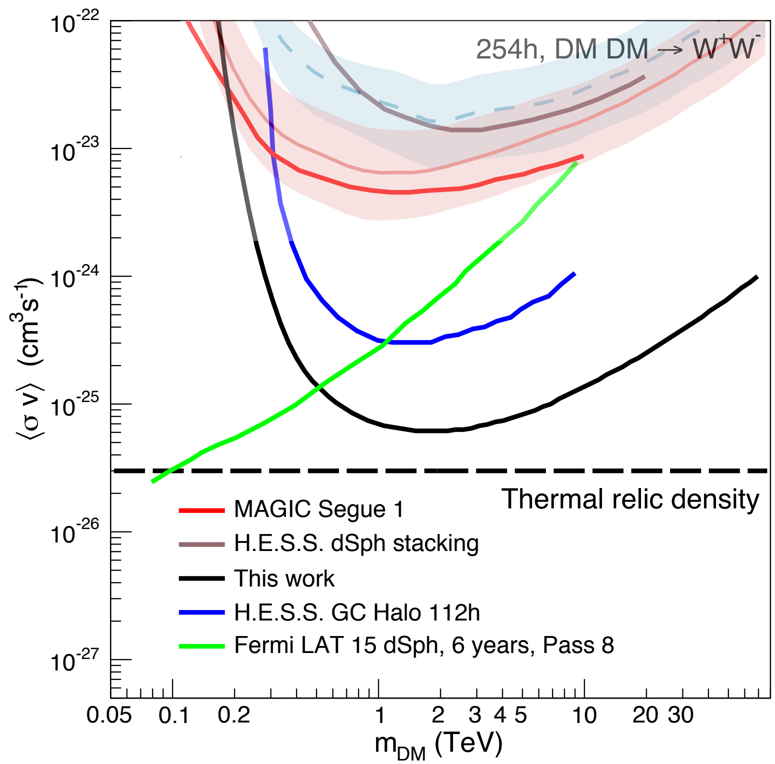
VERITAS DM Limits



(From Abdallah et al. for HESS, 2016, PRL, 117, 1301)

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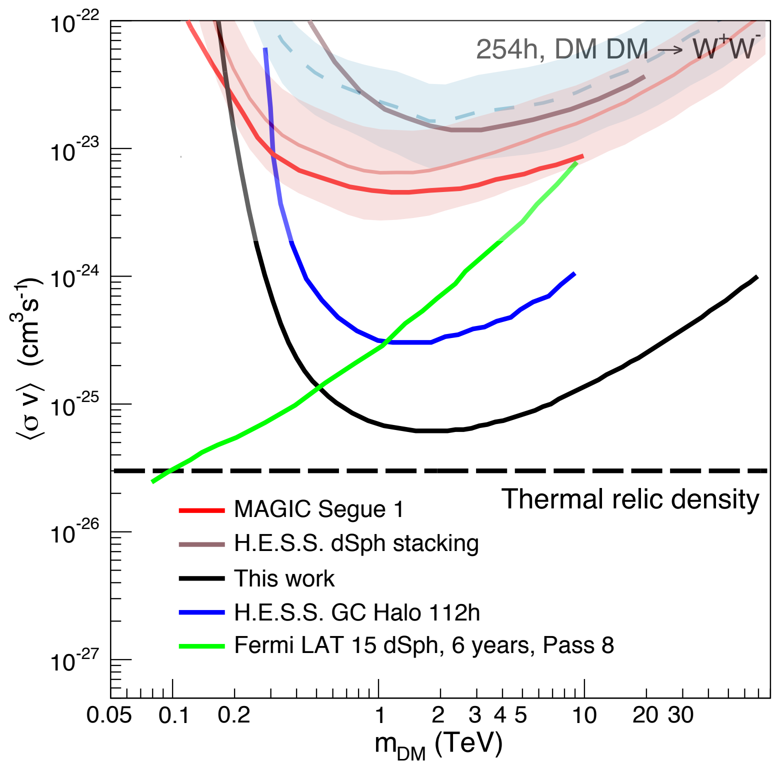

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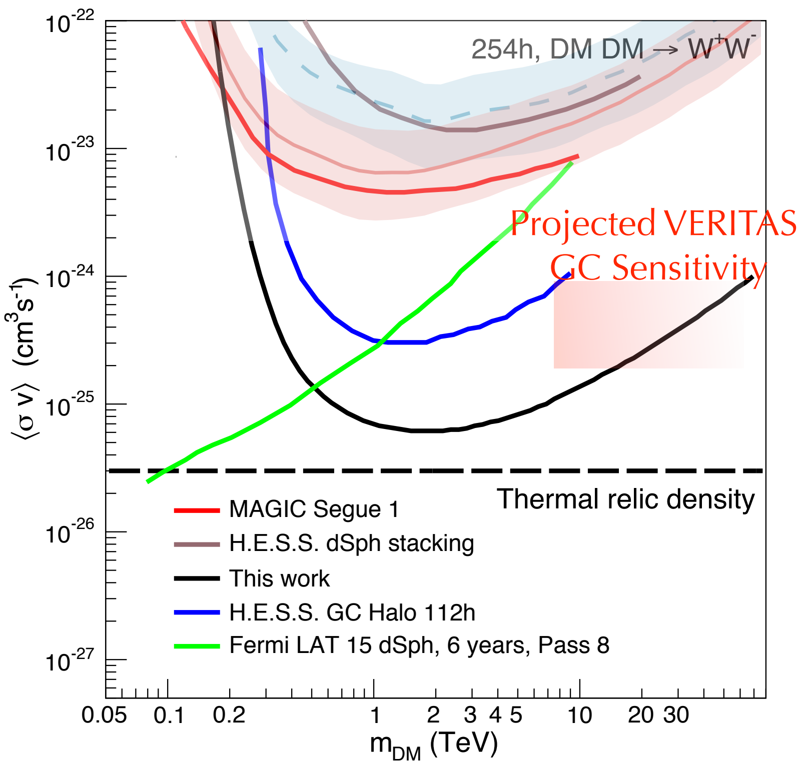

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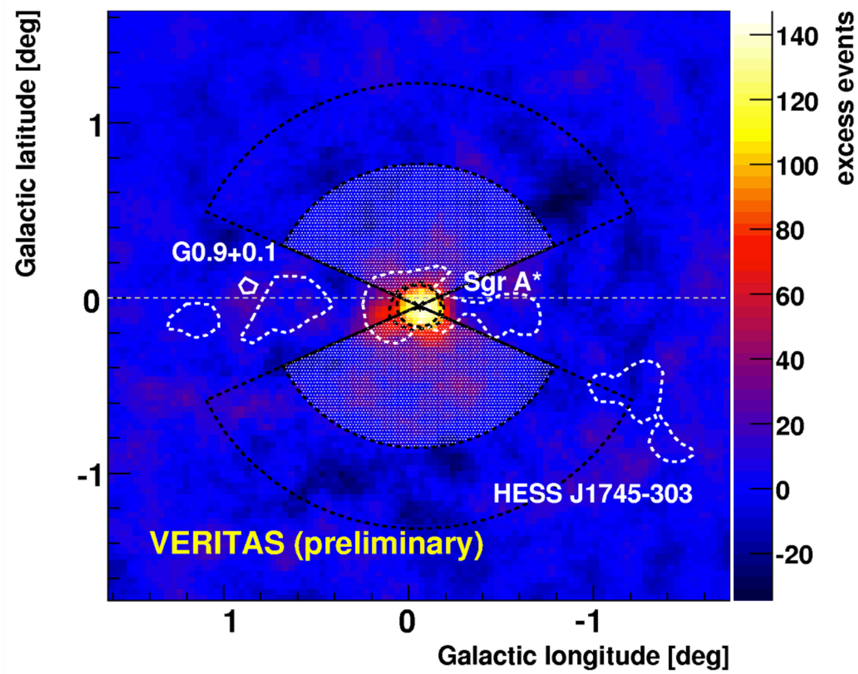
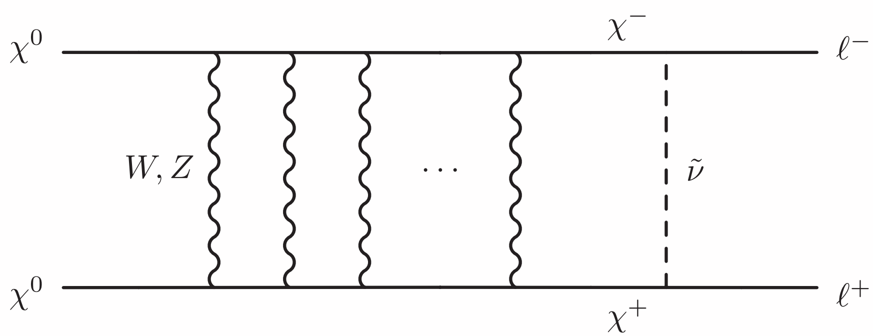


- VERITAS Dwarf limits competitive with other measurements.

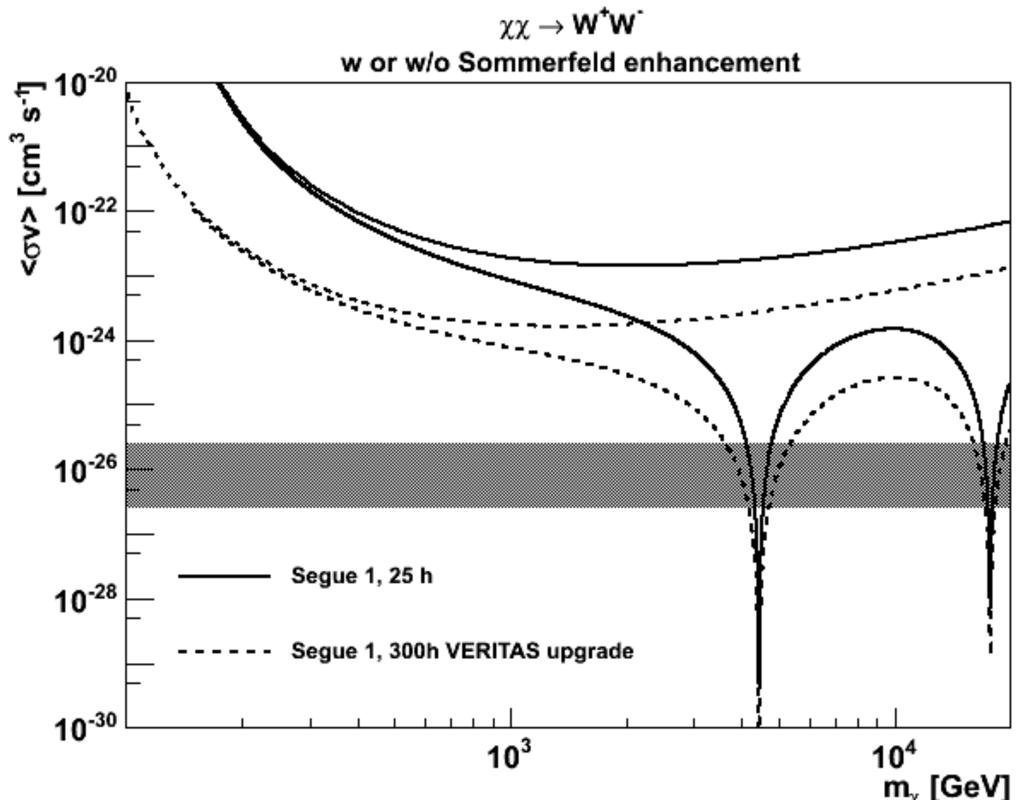
- Emission from GC can be removed by considering an annulus about the source, excising the source position. Stay tuned for upper limits - still working on systematics from numerous sources in the GC region, but upper limits should reach the Sommerfeld-boosted natural cross section at 10s of TeV.

W/Z Sommerfeld Enhancement

At sufficiently high neutralino masses, the W and Z can act as carriers of a long-range (Yukawa-like) force, resulting in a velocity dependent enhancement in cross section (1/v or even $1/v^2$ enhancement near resonance)



Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)



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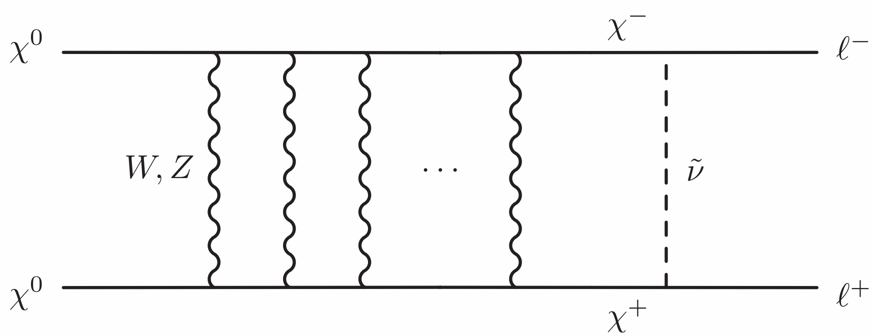

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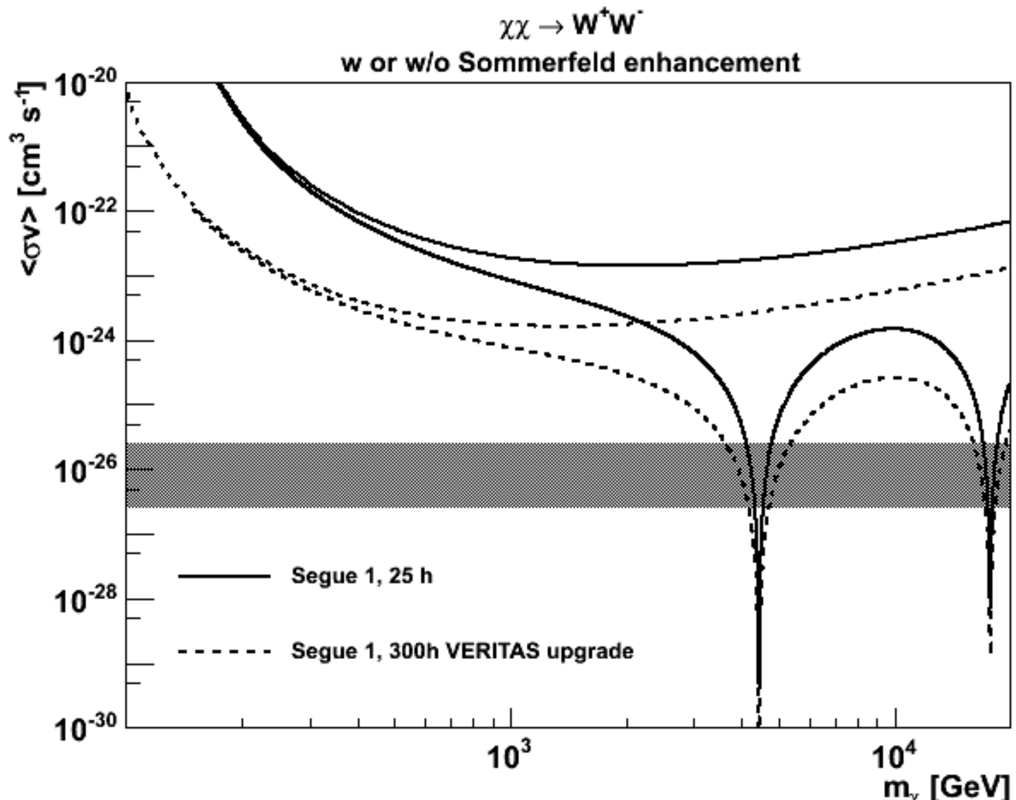

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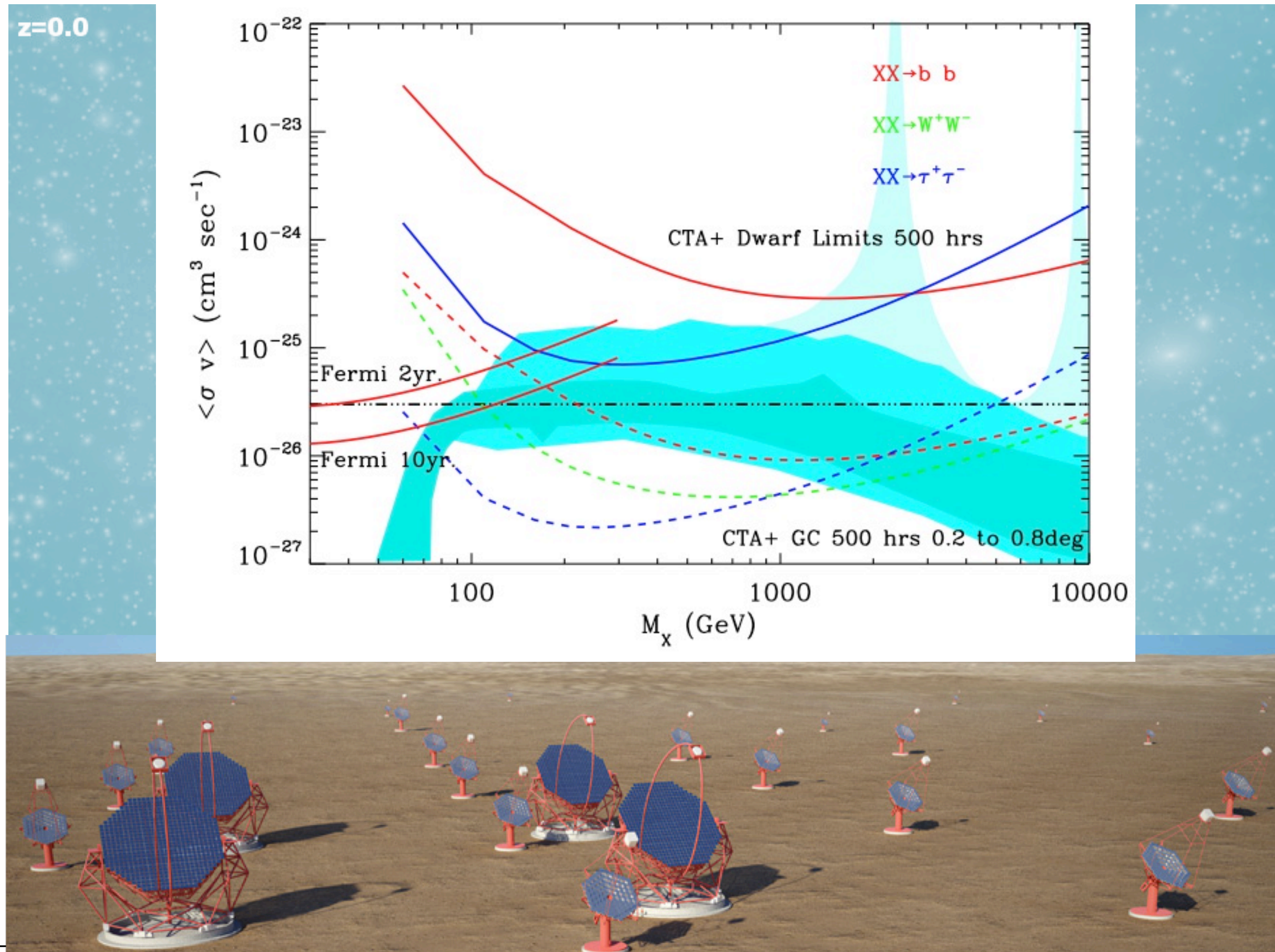
- At high mass, we generically expect Sommerfeld enhancement from W, Z exchange for standard neutralinos can give large enhancement in cross section,

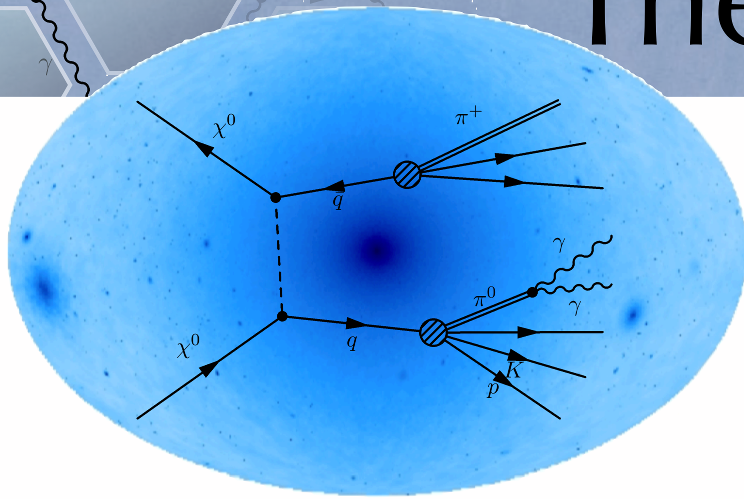
The Future of Gamma-Rays for DM studies

Future?

- If NSF and DOE had the budget to follow through on the advice of the NWNH decadal survey, Snowmass and P5 we could achieve...



The Future



The WIMP miracle is the only reason we are looking, or know where to look. Only way to design an instrument is by starting with a hypothesis.

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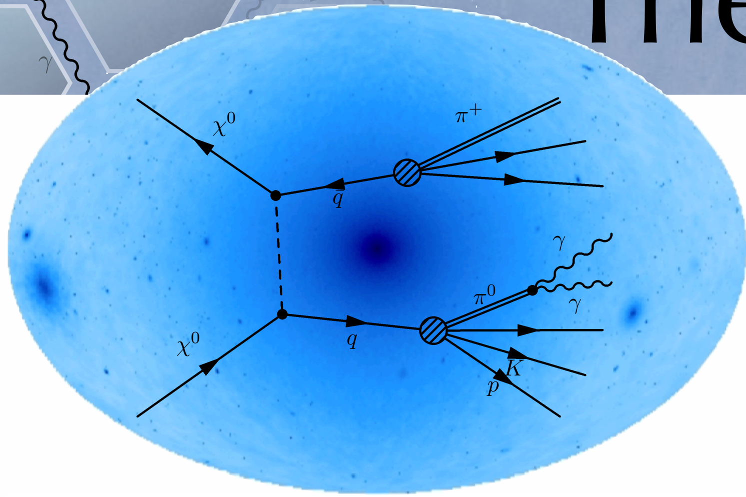

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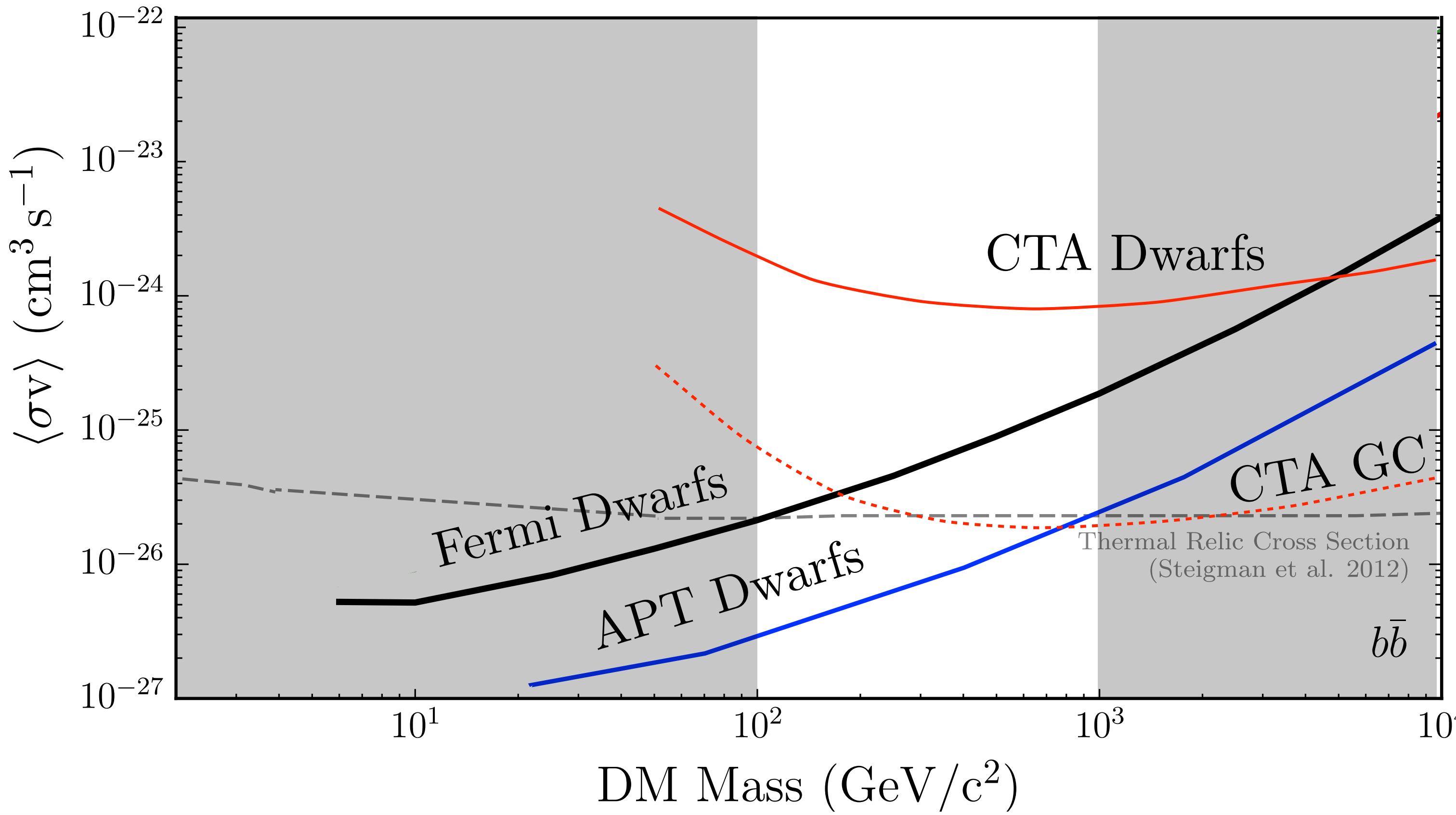

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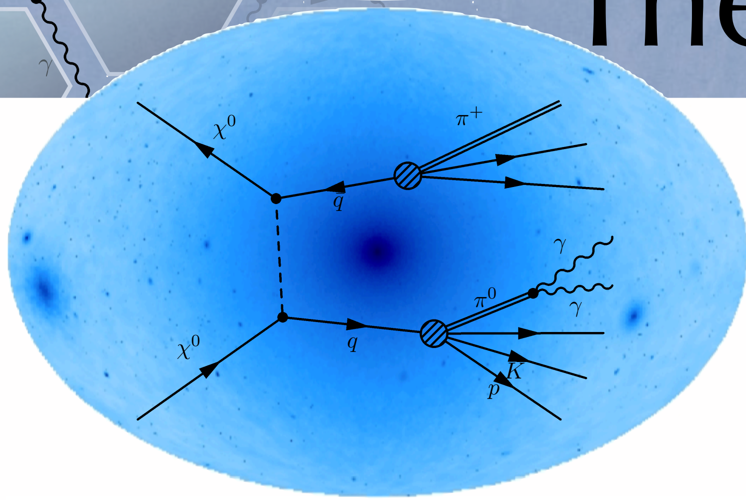

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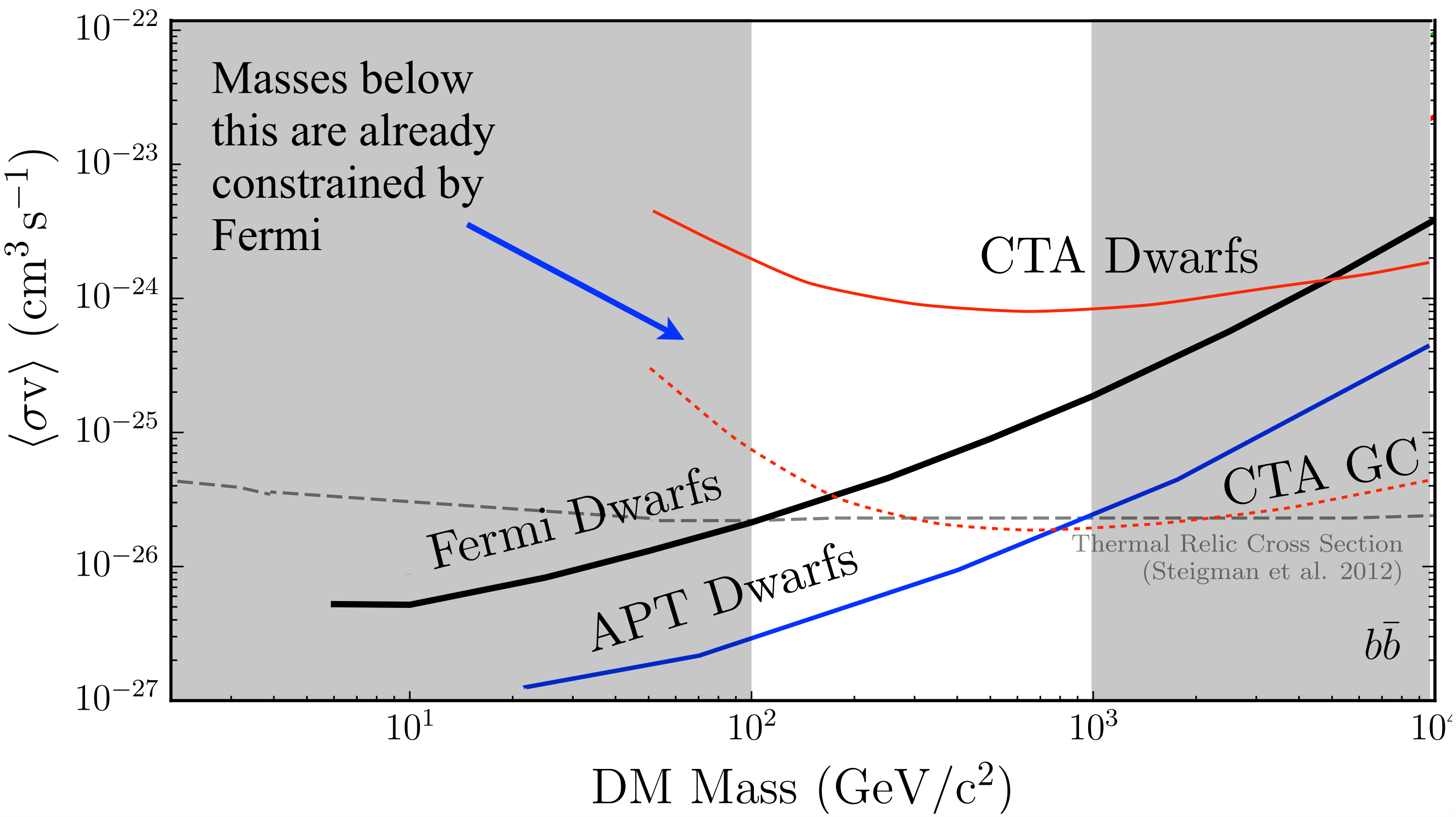

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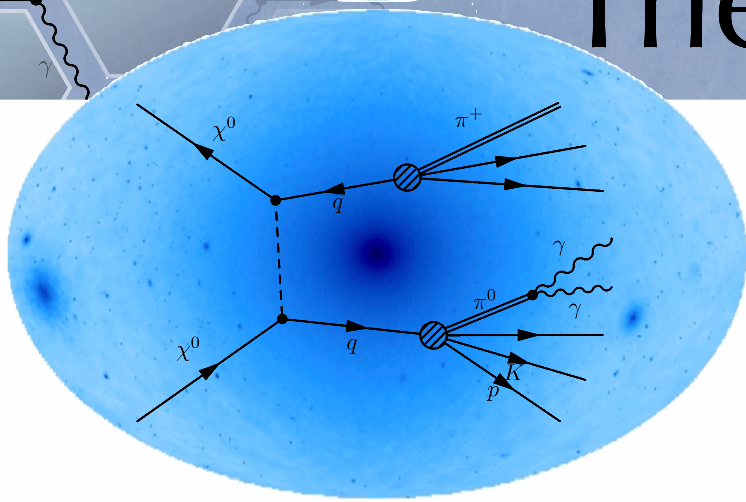

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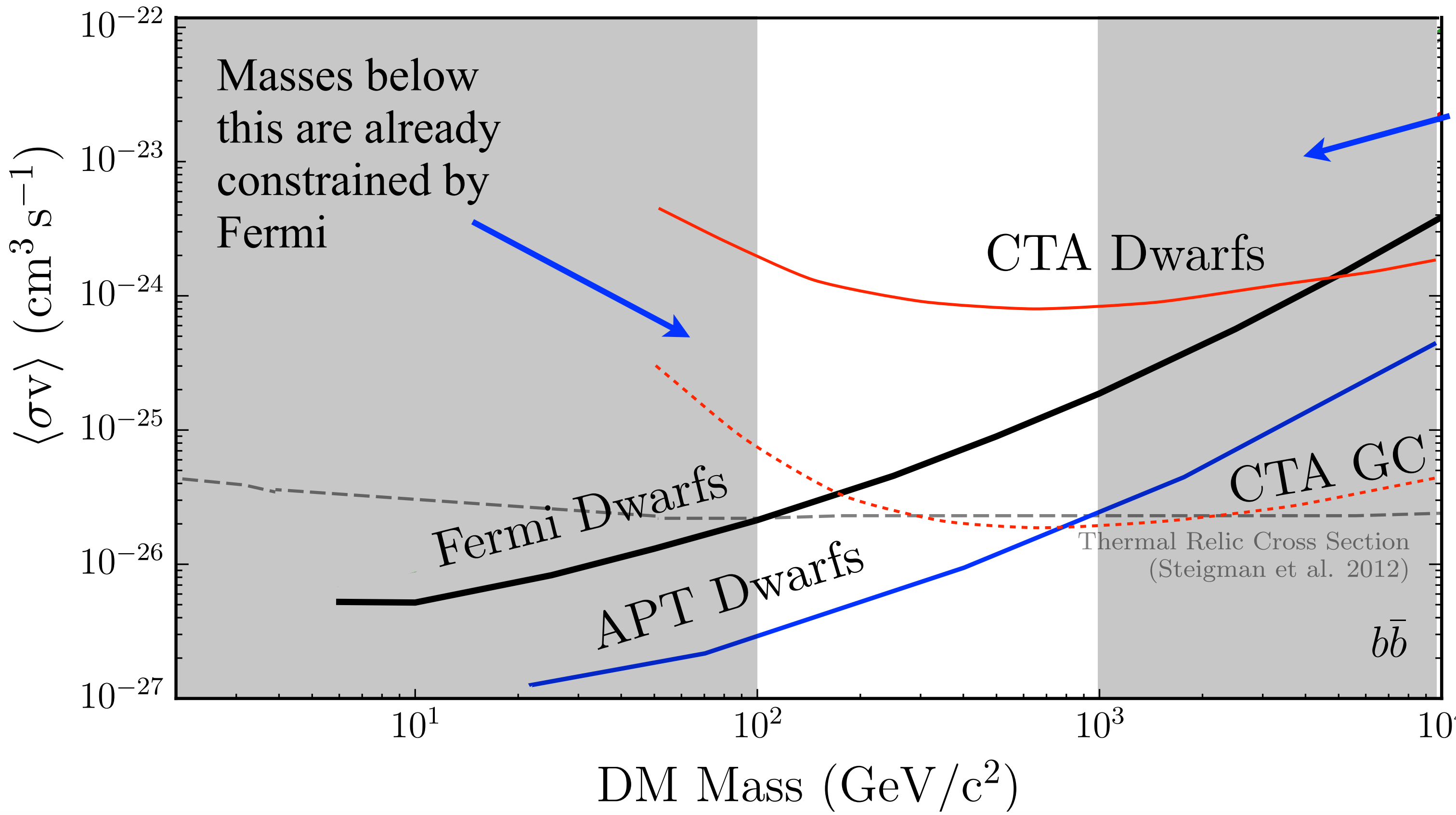
Masses above the natural range motivated by hierarchy problem - reason for SUSY, or exceed unitarity bound



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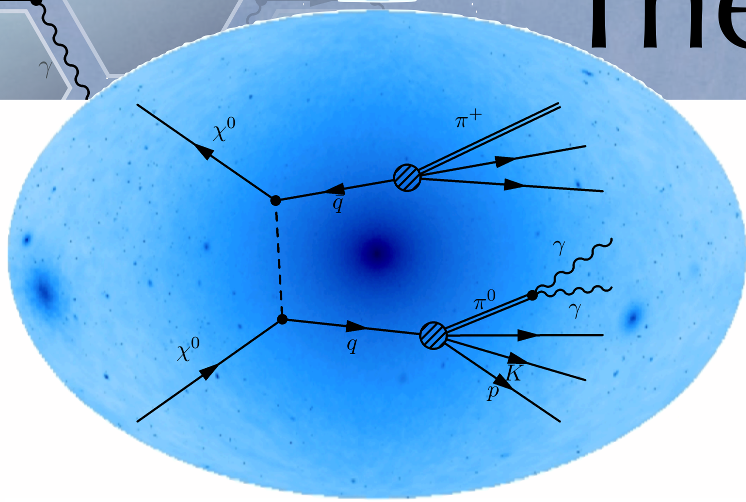

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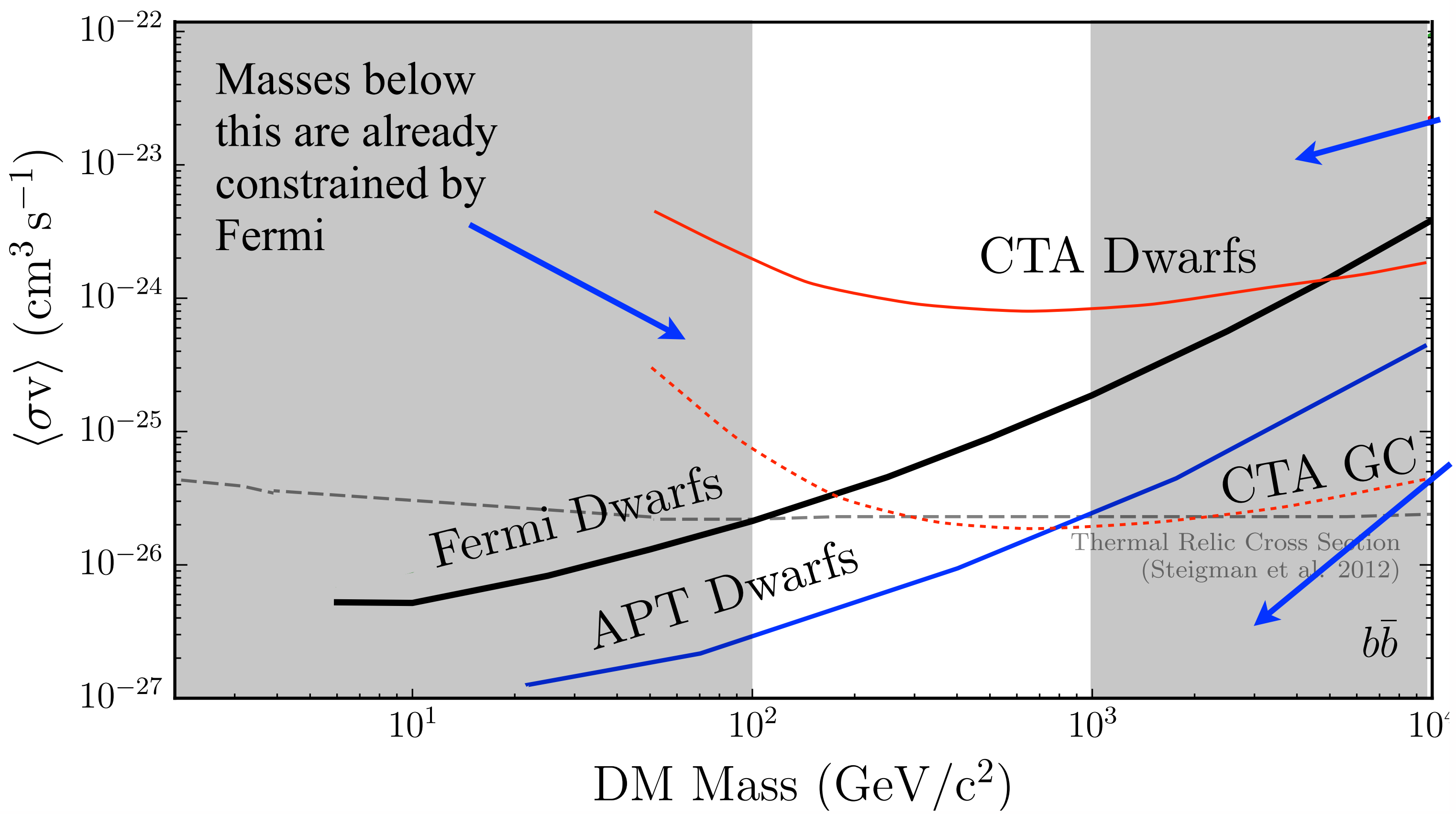
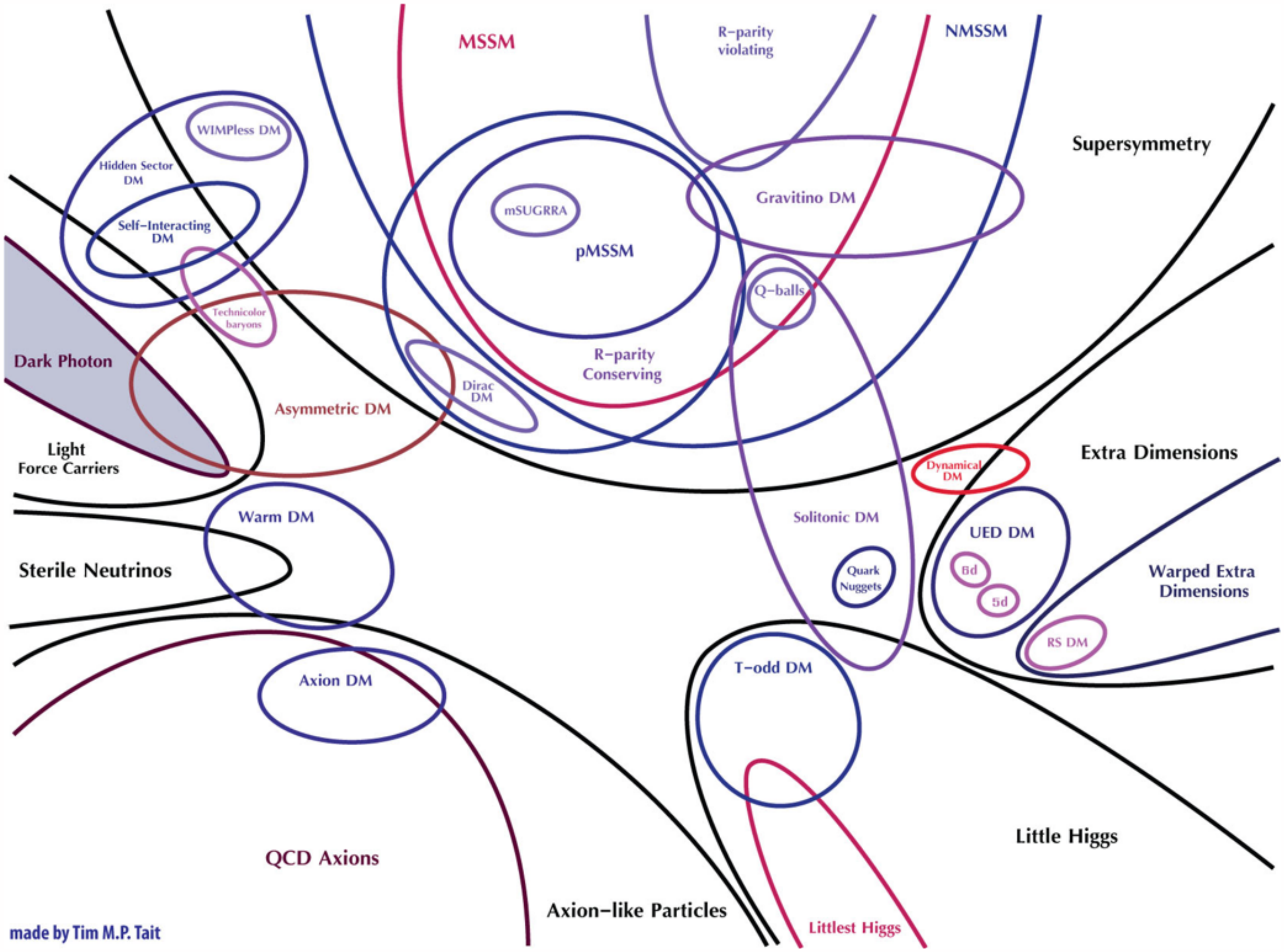
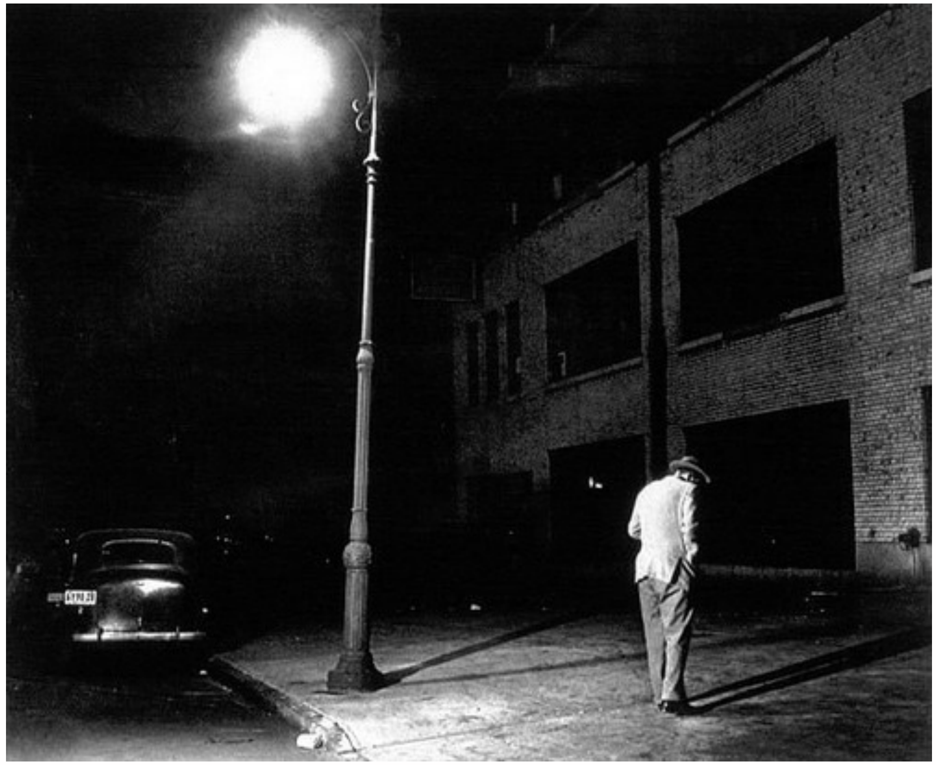


Ground-based observations (CTA) of GC are better in this regime

The Tait Venn Diagram



Looking Under the Lamp



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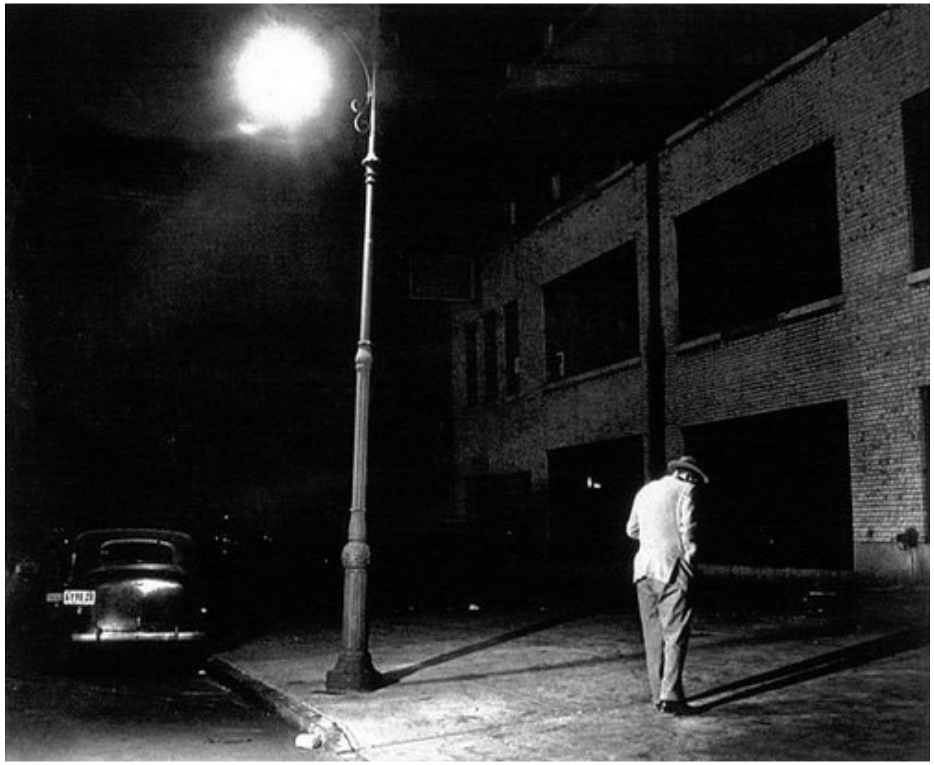

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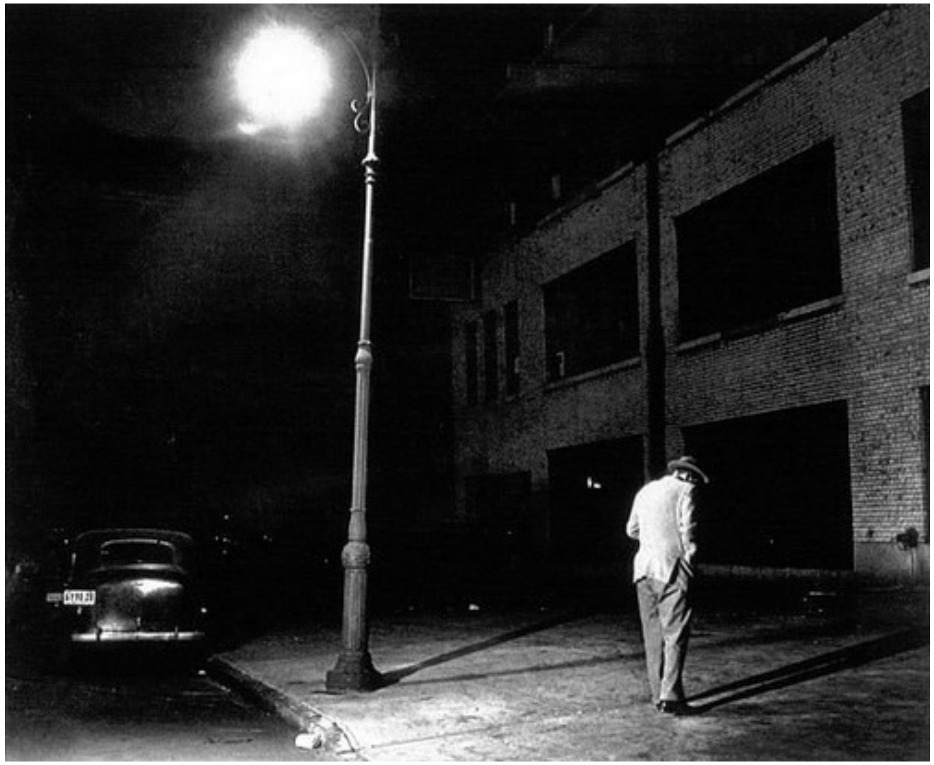

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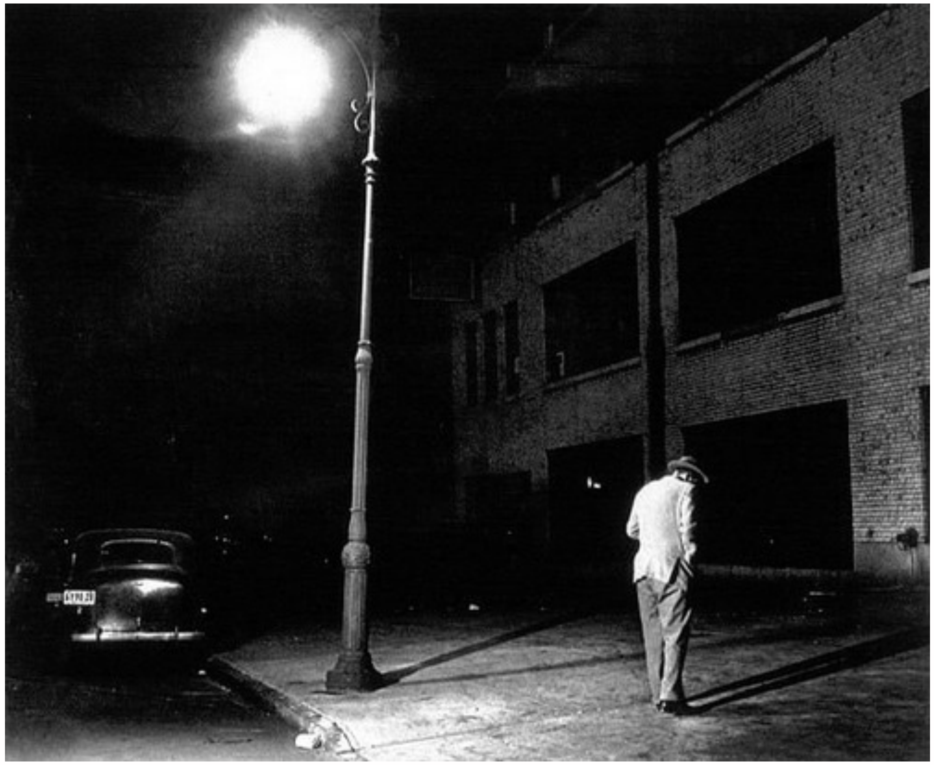

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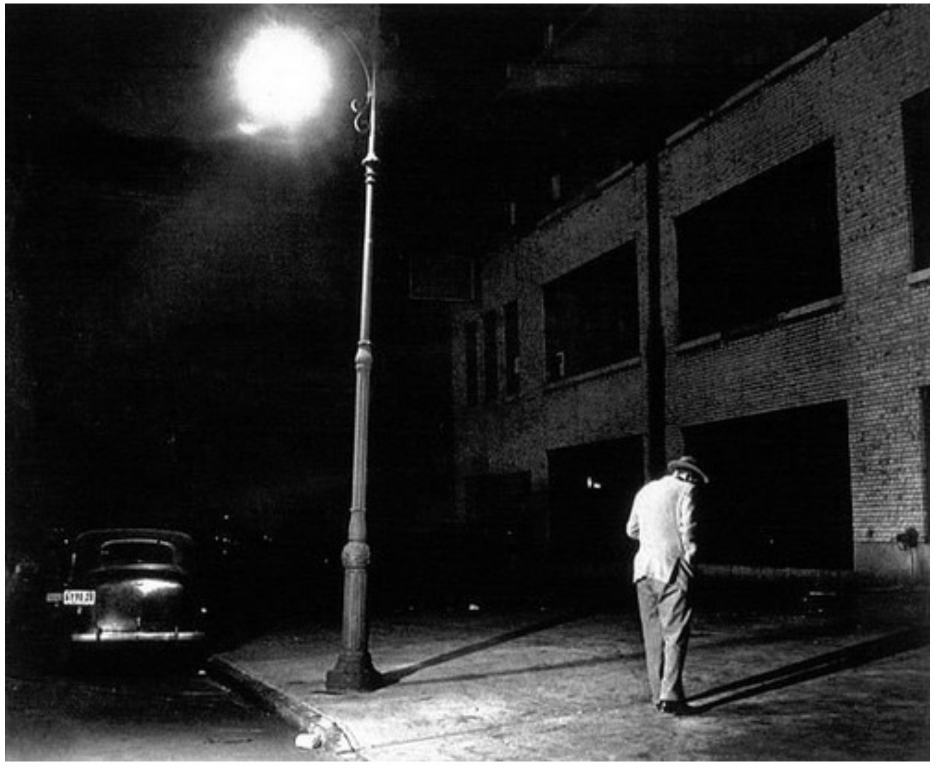

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- Theorem: If you don't look under the lamp post where there is light it is really hard to see anything!
  - Corollary 1: A theory that is not falsifiable is not a theory.
  - Corollary 2: ``Outside of a dog a book is a man's best friend. Inside a dog it is too dark to read'' (G. Marx).

Axions

One expects CP violating term in QCD Lagrangian:

$$\mathcal{L}_{\rm QCD} = \frac{1}{4} G_a^{\mu\nu} G_{a\mu\nu} + g\phi\, G_a^{\mu\nu} \tilde{G}_{a\mu\nu} + \text{interactions.}$$

$$Note: F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{B}\cdot\vec{E} \leftrightarrow G_{\mu\nu}\tilde{G}^{\mu\nu} = \vec{B}_a \cdot \vec{E}_a \text{ which is odd under } T \Rightarrow \text{odd under } CP$$

Peccei-Quinn solution: introduce new Higgs field (with MH potential), axion is the axial mode of the field. At $T < f_a$ symmetry broken, and classical field settles at some value of a. Tilting of hat at

When $T \sim \Lambda_{\rm QCD}$ tilting of hat gives an axion field a VEV $\langle a \rangle$ that cancels ut the CP violating term,and the a field oscillates about its VEV with a mass given by the curvature of the potential.

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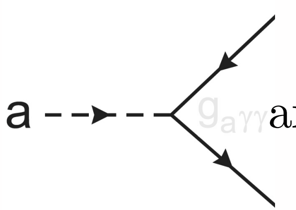
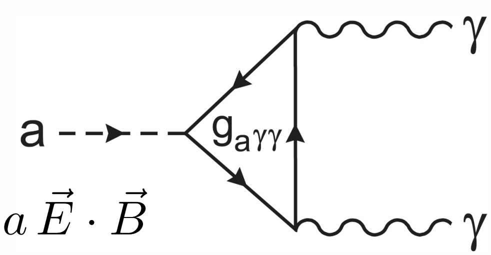


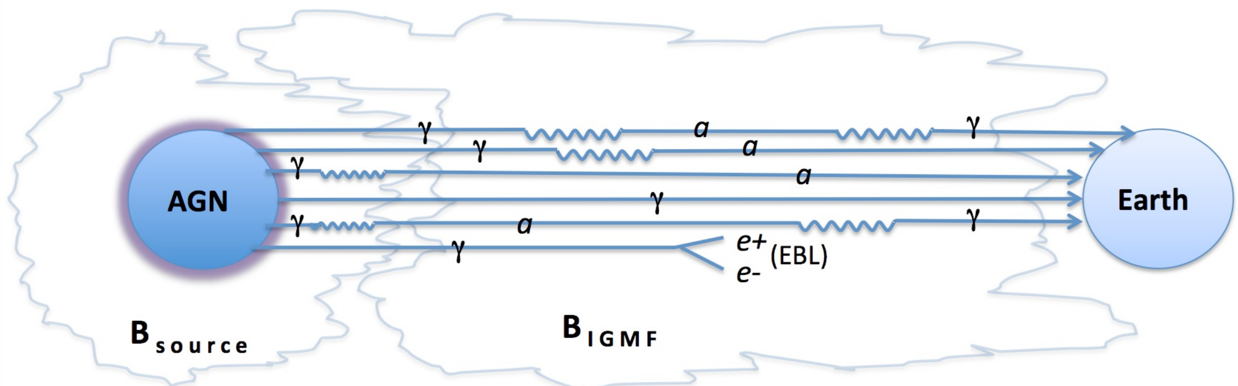
axion coupling to gluons $\Rightarrow$



$$\mathcal{L}_{\rm EM} \mathrel{+}= g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a\, \vec{E}\cdot\vec{B}$$

Axions (and ALPs) can be detected in Haloscopes like ADMX (from the Primakoff process), cooling curves of stars and compact objects, or light-through-wall experiments (terrestrial or astrophysical)

TeV Probes of ALPs



- TeV gamma-ray astronomy can provide a ``light through walls'' experiment where absorption of TeV gamma-rays off of the EBL (or magnetic fields) can be avoided if gamma-rays convert to axions and are regenerated before reaching earth.

- AGN spectra may show VHE emission above expected cutoff by EBL, light-curves and spectra of pulsars might be modified by axion-photon oscillations in pulsar magnetosphere. Complementarity again...

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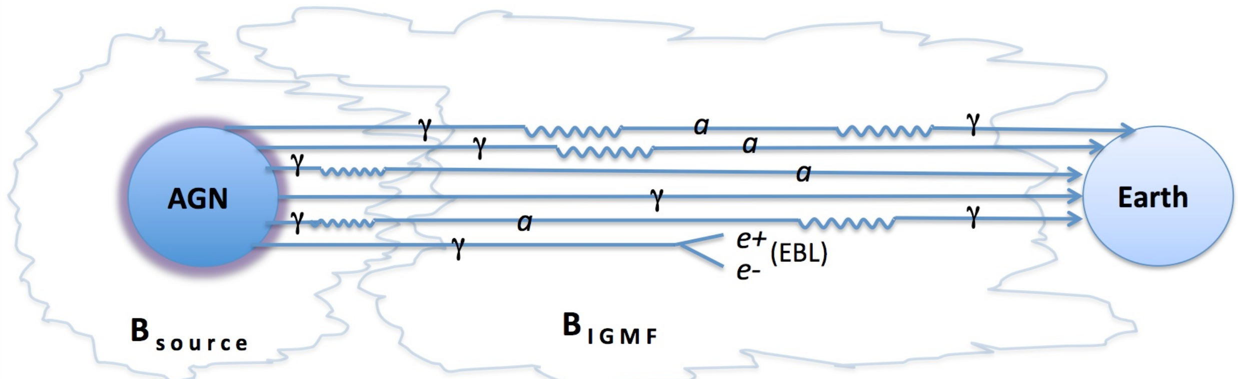

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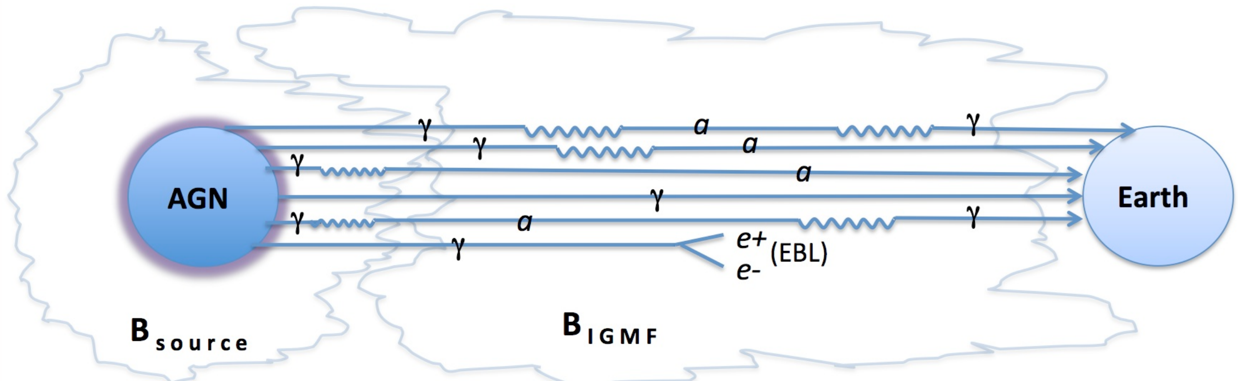

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- Even if VERITAS and CTA fail to detect dark matter, they reveal new information about the most violent processes in the universe including phenomena ranging from relativistic jets from supermassive black holes, exploding stars, the origin of cosmic rays, the nature of pulsar magnetospheres, the history of star formation imprinted on the primordial starlight, constraints on the primordial magnetic field, and multimessenger science through searches for electromagnetic counterparts of gravitational wave and neutrino sources.

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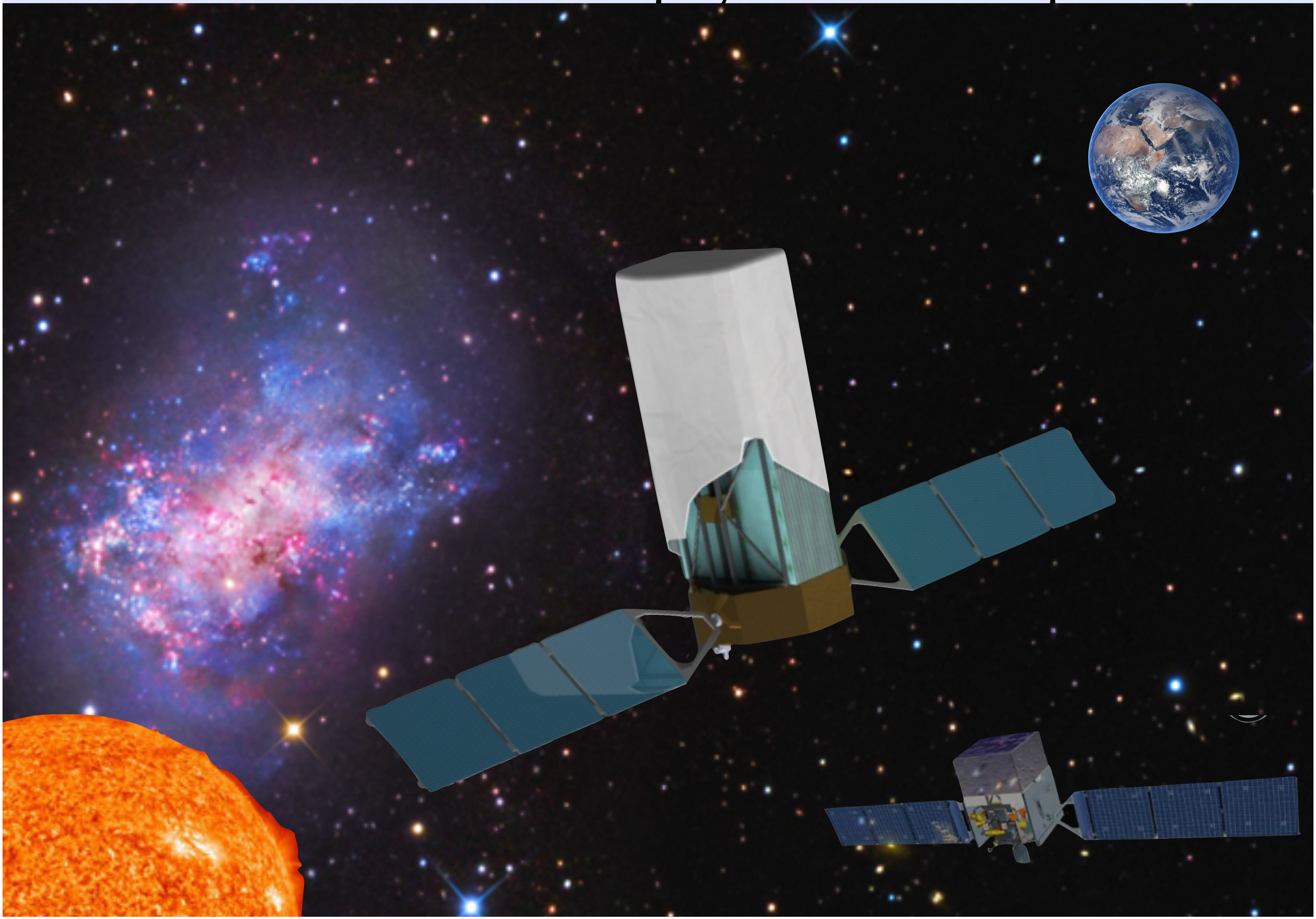
- VERITAS has a bright future behind it!

Advanced Particle-astrophysics Telescope (APT)

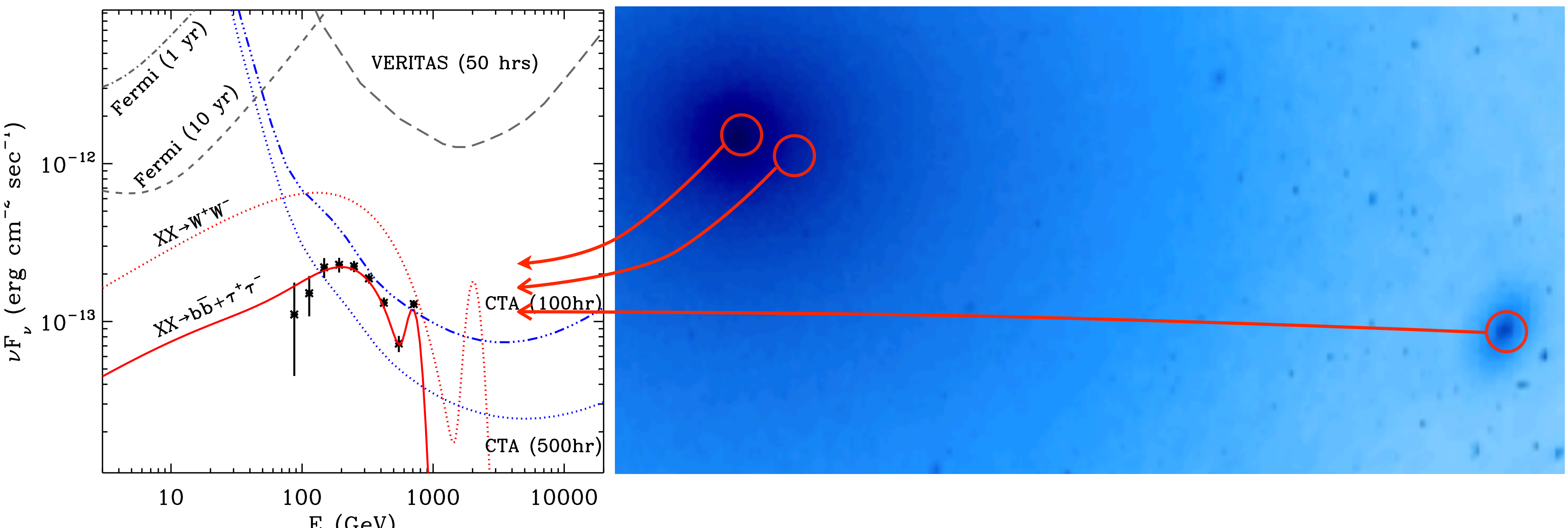


Snowmass Tough Questions

``Given large and unknown astrophysics uncertainties (for example, when observing the galactic center), what is the strategy to make progress in a project such as CTA which is in new territory as far as backgrounds go? How can we believe the limit projections until we have a better indication for backgrounds and how far does Fermi data go in terms of suggesting them? What would it take to convince ourselves we have a discovery of dark matter?''

Backgrounds get lower at higher energies, but even at 1-3 GeV with no background subtraction get a limit within $1^\circ \sim 1 \times 10^{-7}\mathrm{cm}^{-2}\ \mathrm{s}^{-1} \Rightarrow \langle \sigma v \rangle = 1.6 \times 10^{-25}\ \mathrm{cm}^{3}\mathrm{s}^{-1}$

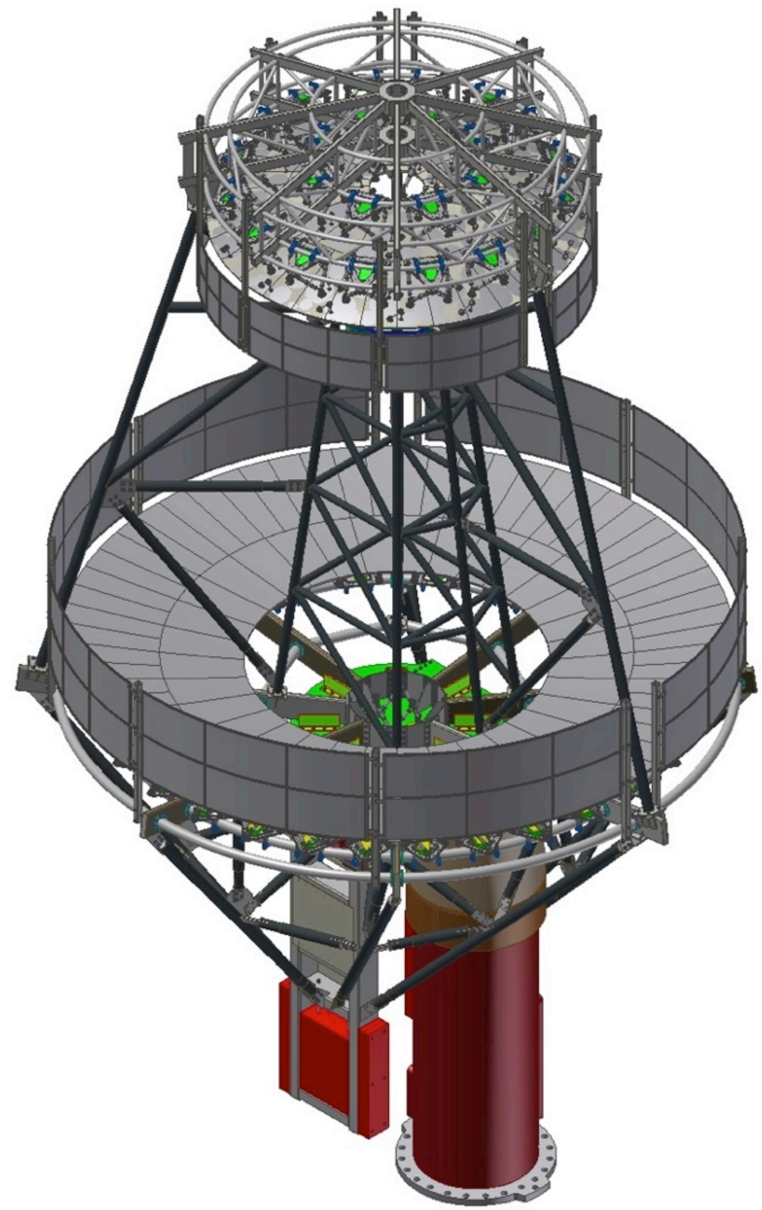
(Tim Linden, SLAC CF meeting)



Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by $\sim E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.

CTA-US SCT Design Concept

Optical properties		
	Focal length	5.5863 m
	f/D	0.5781
	Dish diameter (primary)	9.6638 m
	Mirror area	50.31 m^2
	Mirror effective area	40 m^2
	Largest mirror facet (diagonal)	1.75 m
	On-axis PSF real optical parameters, 2 x max (RMS_x,RMS_y)	3.5'
	PSF 3.5° off-axis real optical parameters, 2 x max (RMS_x,RMS_y)	4.4'
	Time Spread RMS	negligible
Camera Characteristics		
	Camera housing width	1.45 m
	Camera housing depth	1.07 m
	Total pixel number	11,328
	Pixel linear size	6.2 mm
	Pixel angular size	3.8'
	FoV	8.3°
	Photosensors PDE at 500 nm peak	38 %
	Sampling frequency	1 GSa/s
	Readout rate	≤10 kHz
Mechanical Properties: telescope structure		
	Telescope height pointing horizontally	11.51 m
	Telescope height pointing vertically	17.94 m
	Telescope length pointing horizontally	17.22 m
	Telescope width	10.52 m
	Foundation above ground (radius)	3 m
Mechaical Properties: drives		
	Elevation range	-5° – 92°
	Azimuth range	±270°
	Maximum time to acquire target at elevation >30°	90 s
	Tracking precision	<0.1°
Total telescope weight		51 tons



SCT design for MST proposed in 2006 by CTA-US

SCT Prototype