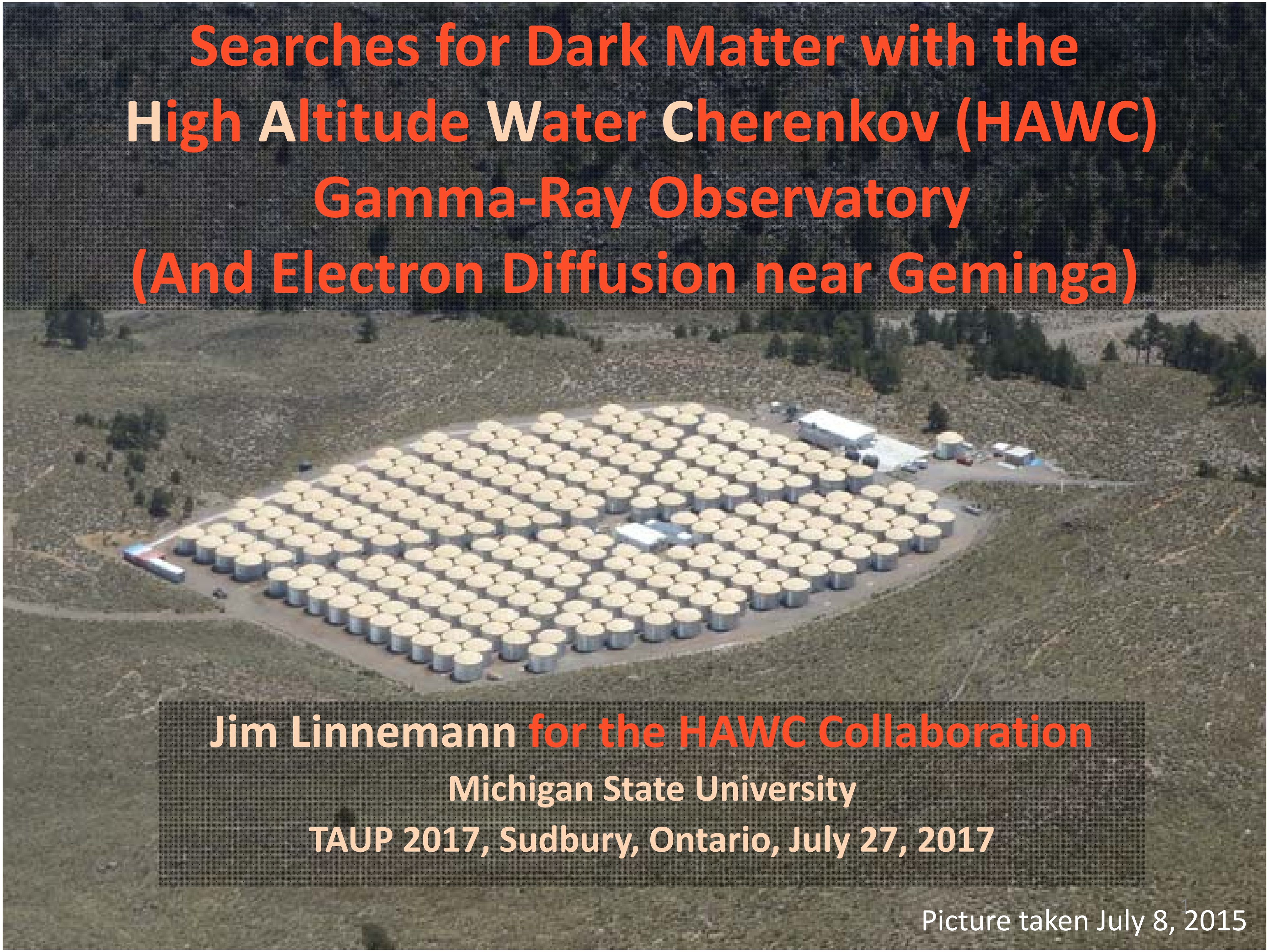
Searches for Dark Matter with the High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory (And Electron Diffusion near Geminga)

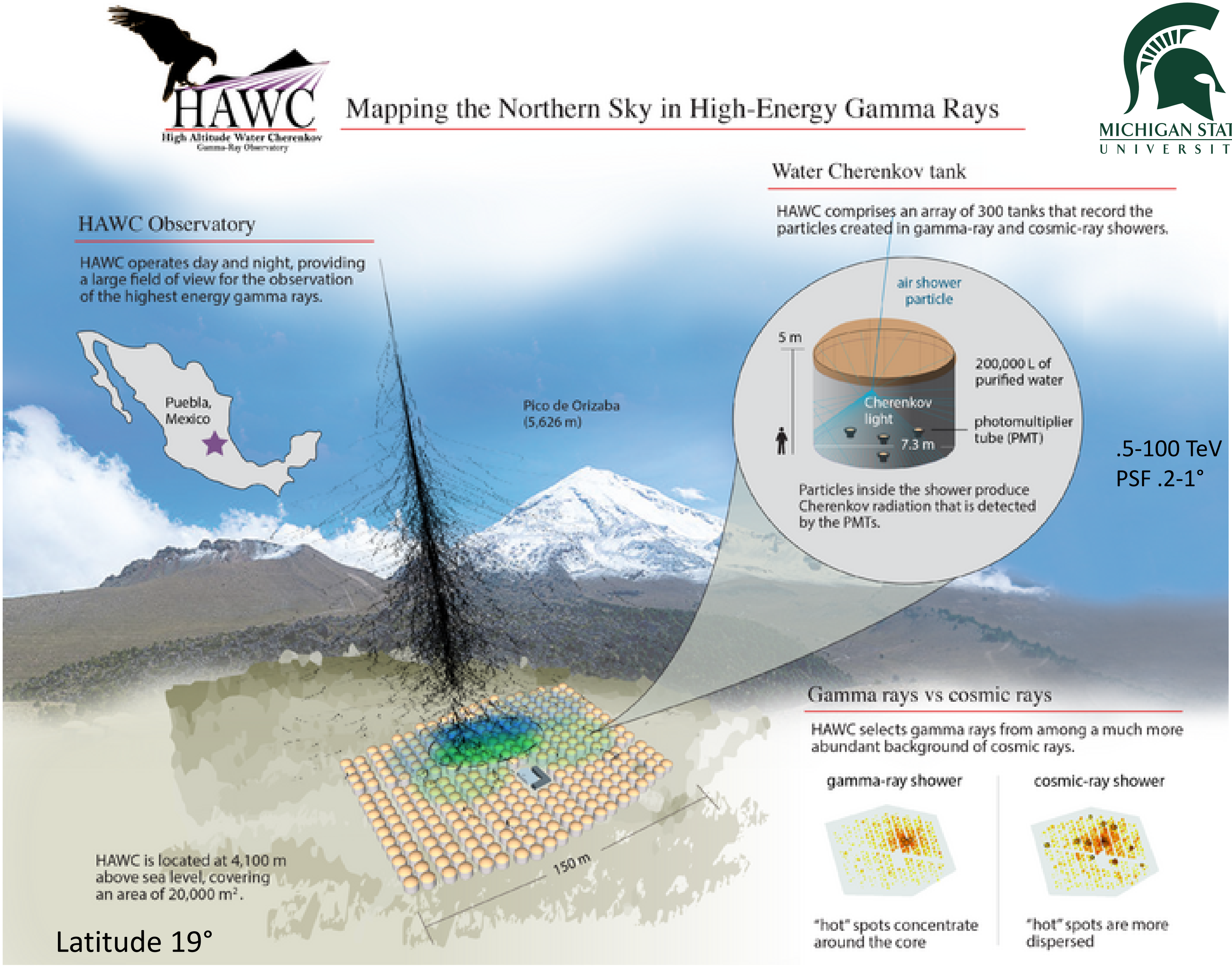


Jim Linnemann for the HAWC Collaboration

Michigan State University

TAUP 2017, Sudbury, Ontario, July 27, 2017

Picture taken July 8, 2015



HAWC

High Altitude Water Cherenkov Gamma-Ray Observatory

Mapping the Northern Sky in High-Energy Gamma Rays

MICHIGAN STATE
UNIVERSITY

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

Latitude 19°

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.

Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

.5-100 TeV
PSF .2-1°

Gamma rays vs cosmic rays

HAWC selects gamma rays from among a much more abundant background of cosmic rays.

"hot" spots concentrate around the core

"hot" spots are more dispersed

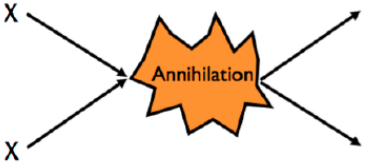
Dark Matter - Indirect Detection

Particle Physics

Astrophysics

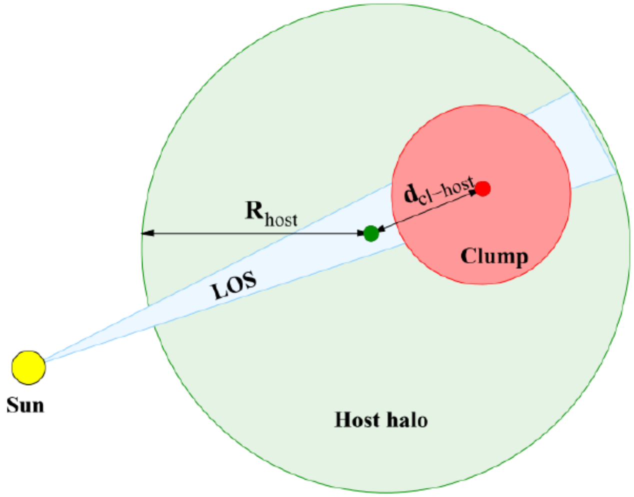
$$\frac{d\phi}{dE}_{annihilation} \propto \frac{<\sigma v>}{M_\chi^2} \frac{dN}{dE} \int d\Omega \int_{l.o.s.} \rho^2 dx$$

$$\frac{d\phi}{dE}_{decay} \propto \frac{1}{\tau M_\chi} \frac{dN}{dE} \int d\Omega \int_{l.o.s.} \rho dx$$



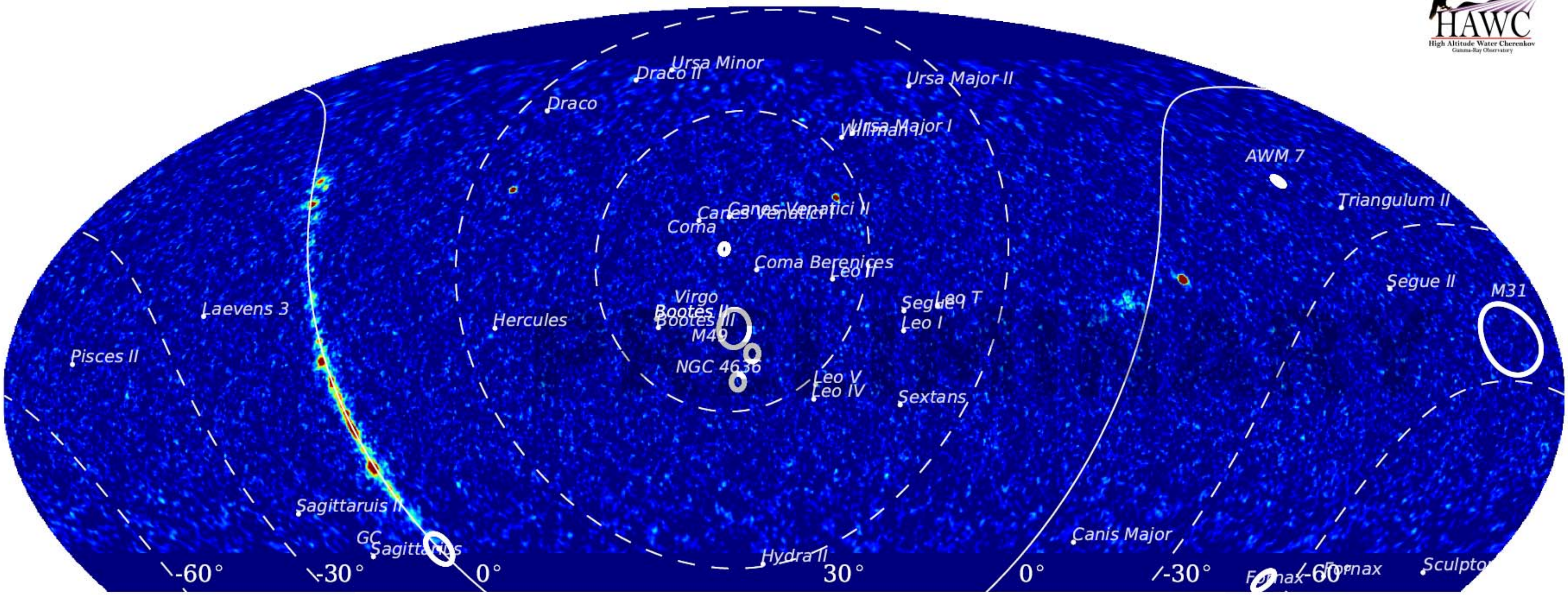
$b, t, W^+, \tau^+, \mu^+, \ldots \rightarrow e^+, e^-, p, \nu, \gamma$

$\bar{b}, \bar{t}, W^-, \tau^-, \mu^-, \ldots \rightarrow e^+, e^-, p, \nu, \gamma$



- Particle Physics part by PYTHIA8
- Astrophysics Part (J- and D- factors) by CLUMPY and references

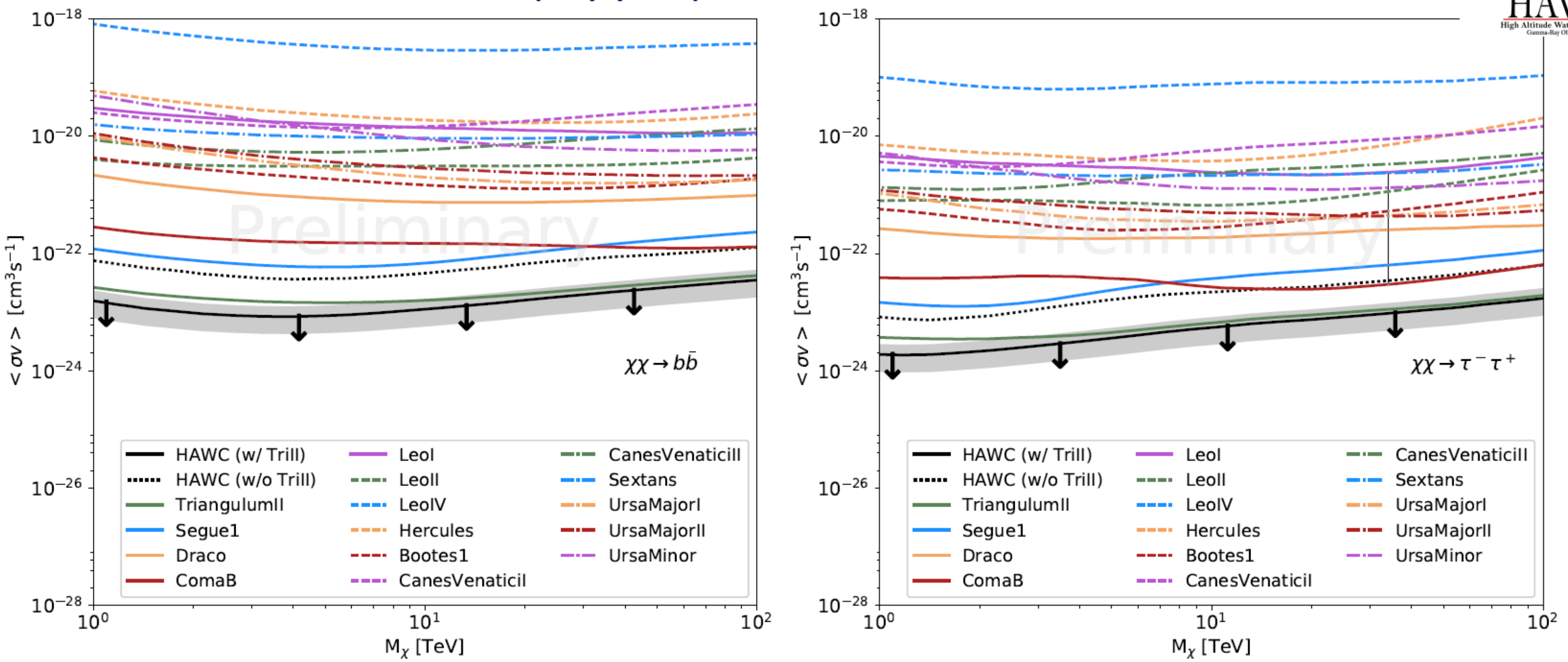
Favorable sources combine
    declination near HAWC latitude: transit near zenith
    large astrophysical J or D factors



Source	RA (deg)	Dec (deg)	log10[J(θ)] (GeV^{2}cm^{-5}sr)	log10[D(θ)] (GeV^{2}cm^{-2}sr)	θ_{max} (deg)
Bootes 1	210.05	14.49	18.47	18.45	0.47
CanesVenatici I	202.04	33.57	17.62	17.55	0.53
CanesVenatici II	194.29	34.32	17.95	17.69	0.13
Coma Berenices	186.74	23.90	19.32	18.71	0.31
Draco	260.05	57.07	19.37	19.15	1.30
Hercules	247.72	12.75	16.93	16.89	0.28
Leo I	152.11	12.29	17.57	18.05	0.45
Leo II	168.34	22.13	18.11	17.36	0.23
Leo IV	173.21	-0.53	16.37	16.48	0.16
Segue 1	151.75	16.06	19.66	18.64	0.35
Sextans	153.28	-1.59	17.96	18.48	1.70
Triangulum II[10]	33.33	36.18	20.44	18.42	0.12
Ursa Major I	158.72	51.94	19.67	19.04	0.53
Ursa Major II	132.77	63.11	18.66	17.78	0.43
Ursa Minor	227.24	67.24	19.24	18.13	1.37
M31	10.68	41.27	20.86	19.10	-
Virgo Cluster	186.75	12.38	19.50	19.44	-

Dark Matter Annihilation (Upper) Limits

95% CL; NFW profile



Ran the analysis for 507 days of HAWC data for five annihilation channels ($b\bar{b}$, $t\bar{t}$, WW, $\tau\tau$, $\mu\mu$)

Combined results were computed for 14 dSph and 14 dSph+TriangulumII

Limits are driven by TriangulumII, Segue1 and Coma B

$\tau\tau$ is the strongest limit for HAWC [see arXiv:1706.01277]

Because γ peaks at highest E

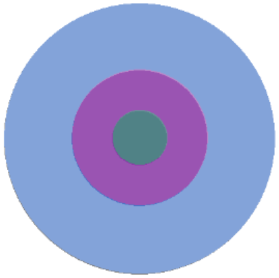
Systematics on the Limits

HAWC Systematics

- Signal passing rate
- Measured number of photo-electrons (PEs) based on simulations
- Simulated PMT charge and the charge from actual data
- Uncertainty associated with the angular resolution

~50% uncertainty [arxiv:1701.01778]
(on flux)

Astrophysical systematics



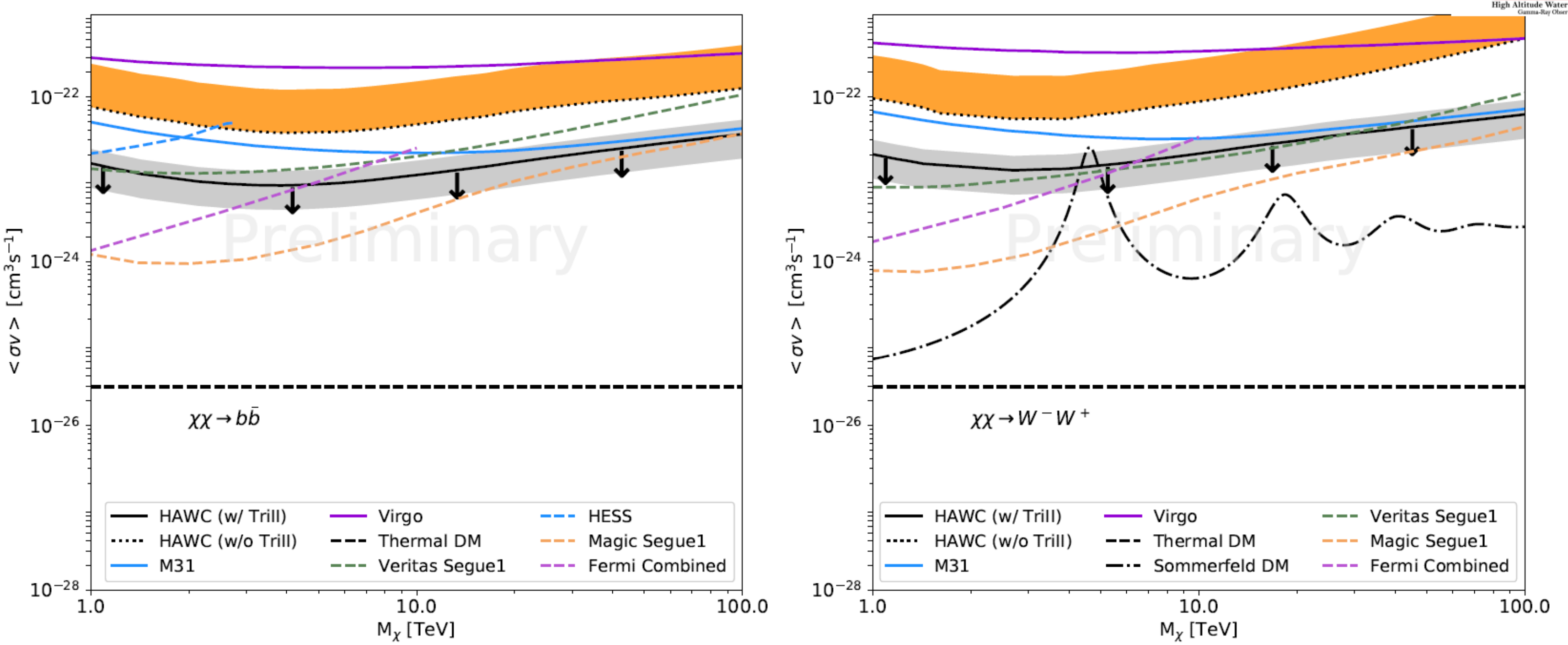
outer blue: 1.0° HAWC PSF
inner green: 0.2° HAWC PSF
J(D) factor integration angle: ~0.5° [purple]

J and D factor Integration angles kept constant, but HAWC PSF changes with energy.

Physical constraint by DM profile yields **one sided uncertainty**

42% uncertainty for annihilation cross-section limits
38% uncertainty for decay lifetime limits

Dark Matter Annihilation (Upper) Limits



Gray band: HAWC systematics, Orange band: Astrophysical systematics

HAWC dSph limits are better than VERITAS and HESS, than Fermi after ~3 TeV.

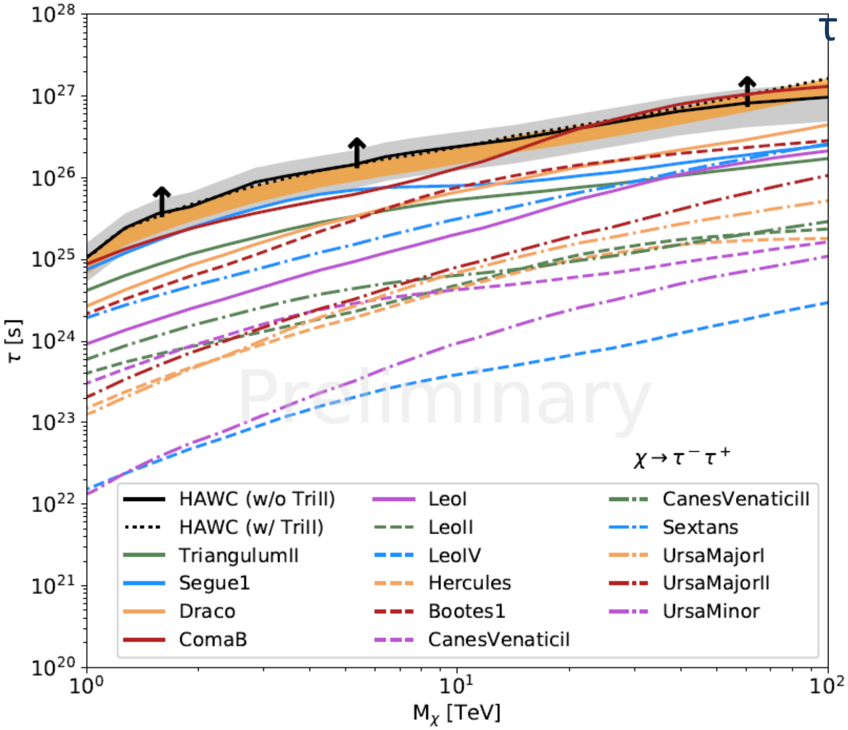
Magic Segue1 limits are driven by negative fluctuation

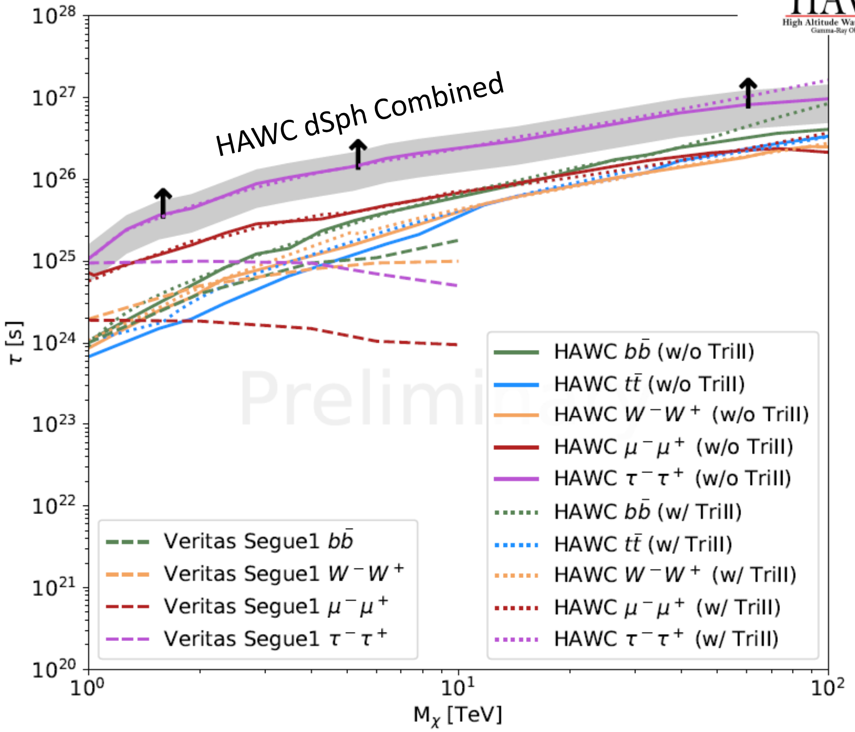
M31 comparable to HAWC dSPh combined (has negative fluctuation)

Virgo is less favorable

Dark Matter Decay (Lower) Limits 95% CL on Lifetime

τ





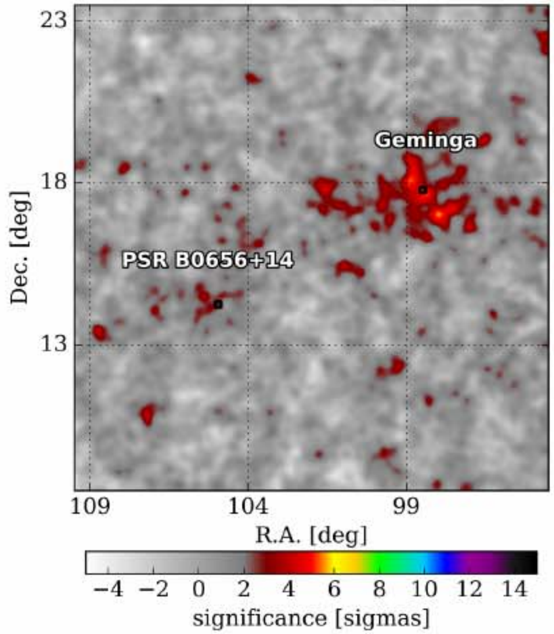
Gray band: HAWC systematics, Orange band: Astrophysical systematics
Limits are driven by TriangulumII, Segue1 and Coma B
(TriangulumII is not so strong, smaller D factor)
HAWC $\tau\tau$ limit is the strongest limit

Virgo gives limits comparable to HAWC dSph combined

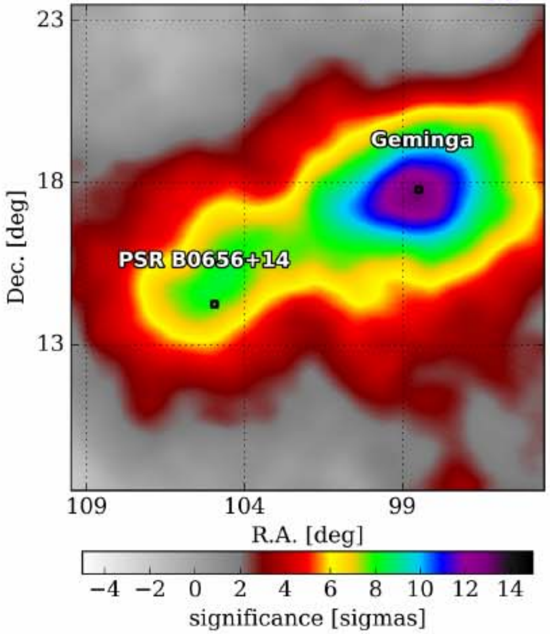
HAWC observations of TeV γ emission near Geminga and Monogem Pulsars

- Gamma-rays sources coincident with **Geminga** and **B0656+14** pulsars were reported in the 2nd HAWC catalog as 2HWC J0635+180 and 2HWC J0700+143 [**HAWC coll. ApJ 843:40 (2017)**].
- Extended TeV gamma-ray emission from PSR B0656+14 is a new discovery by HAWC.
- Both sources show a clear increase in significance for an extended morphology assumption.
- The gamma-ray measurement of both sources can constrain the expected positron flux from them.

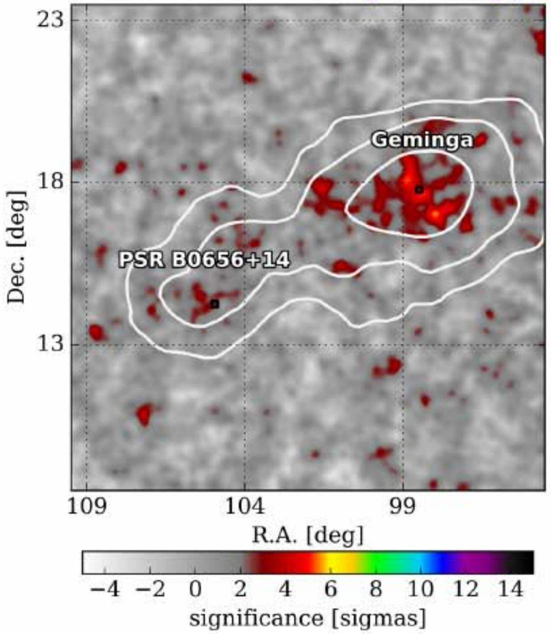
convolved with the PSF



convolved with the diffusion morphology



5, 7, 10 σ contours from diffusion morphology



Electron Diffusion Model

- We assume a model where e^+e^- pairs diffuse into the ISM around the pulsar.
- The **radial distribution of e^+e^-**, at a given time **t**, distance **r** from the source is: [**Atoyan et al. Phys. Rev. D52, 3265 (1995)**]

Continuous injection of e^+e^-

$$f(t,r,E_e) = \frac{Q_0 E_e^{-\Gamma}}{4\pi D(E_e) r}\,\mathrm{erfc}(r/r_d)$$

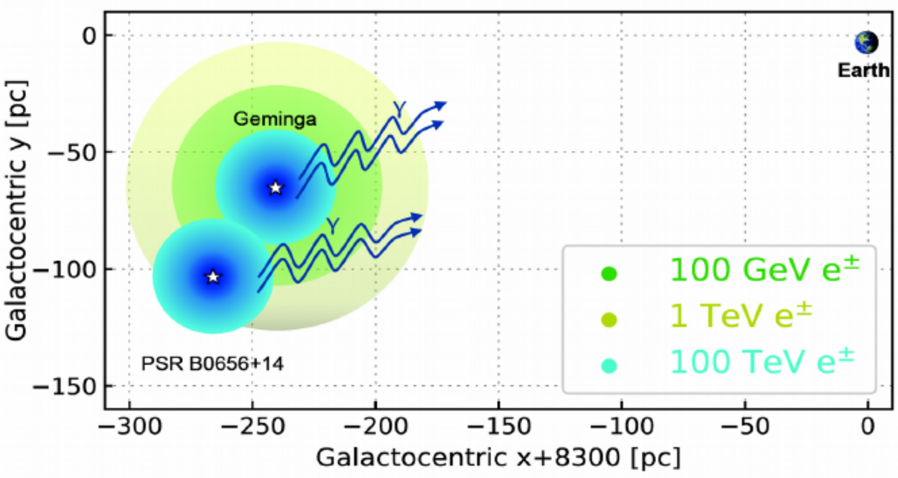
$$D(E_e) = D_0(E_e/10\ \mathrm{GeV})^{\delta}$$ Diffusion coefficient

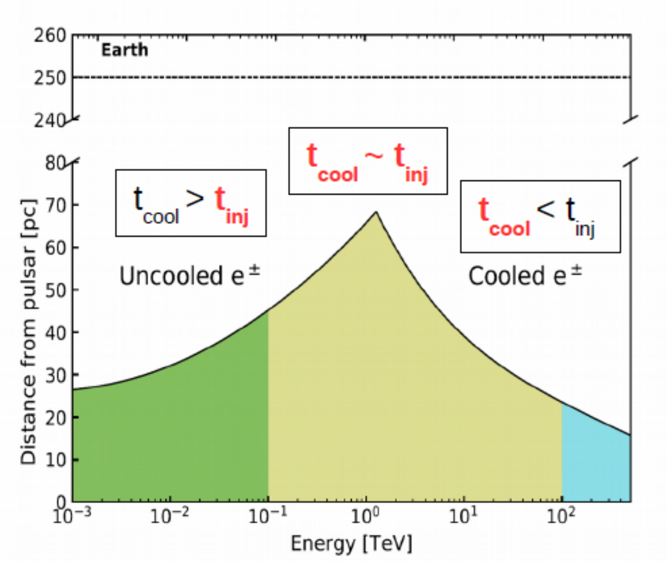
$$r_d = 2\sqrt{D(E_e) t_{\mathrm{E}}}$$ Diffusion radius

t_E = min (t_{cool}, t_{inj}), where t_{inf} = t_{age} ~3.4 x 10^5 yr

t_{cool} = f(E), for E=100TeV, t_{cool} ~ 10^4 yr

- We assume diffusion coefficient index (δ) fixed to 0.33





TeV Gamma-Ray Profile

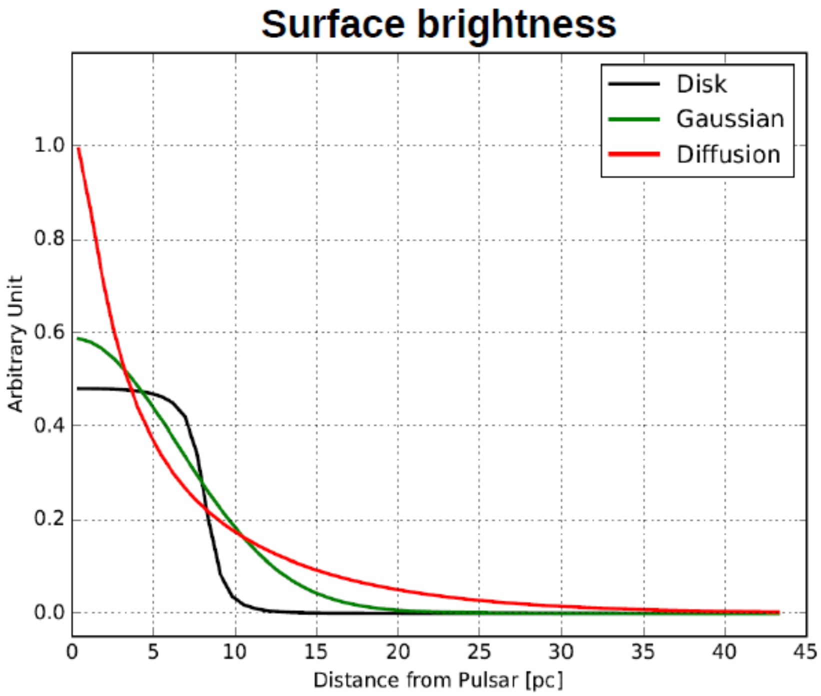
Integrating the **radial distribution** along the observer line-of-sight:

$$f_\theta = \frac{1.2154}{\pi^{3/2}\theta_\mathrm{d}(\theta + 0.06 \cdot \theta_\mathrm{d})} \exp(-\theta^2/\theta_\mathrm{d}^2)$$

$$\theta_\mathrm{d} \equiv \frac{180^\circ}{\pi} \cdot \frac{r_\mathrm{d}}{d_\mathrm{src}}$$ Diffusion angle

- The gamma-rays are produced through **inverse Compton scattering** of CMB, IR, and Optical photons.
- The relation between the electron and gamma-ray energy:

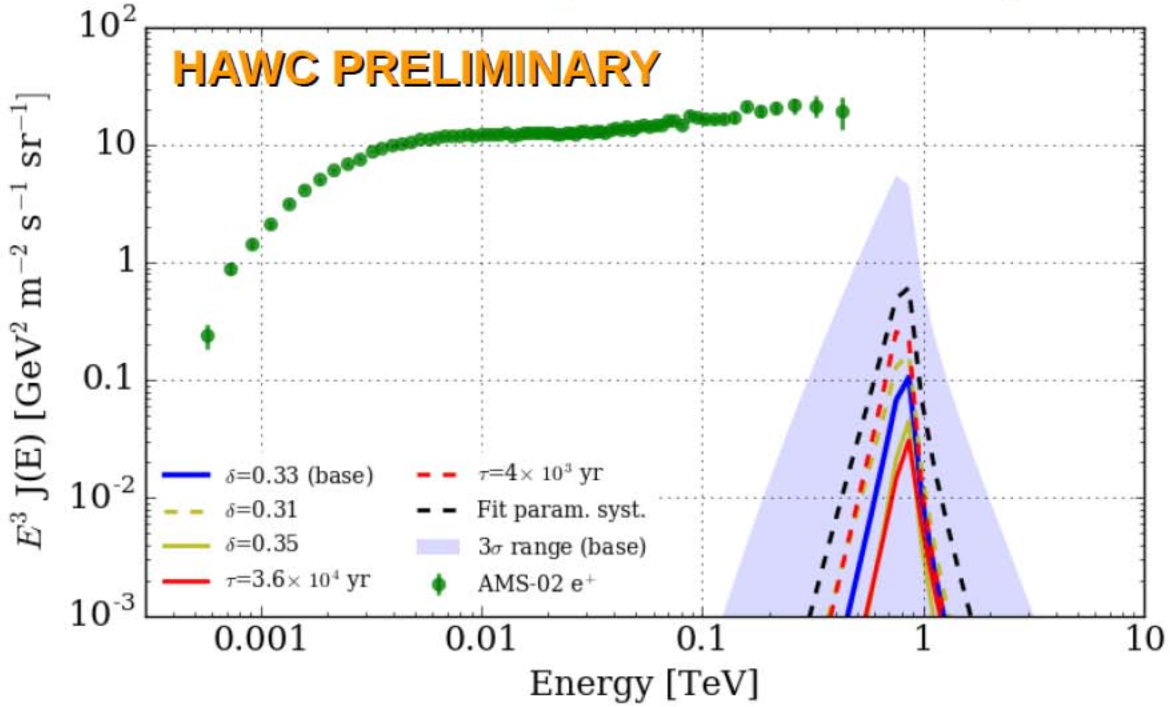
$$\boxed{< E_e > \approx 17 < E_\gamma >^{0.54+0.046\log_{10}(<E_\gamma>/\ \mathrm{TeV})}}$$



- The morphology based on "diffusion propagation model" fits better the HAWC data (using a likelihood analysis) compared to other morphologies tested (Disk and Gaussian).
- We fitted a **power law (N, index)** and a **diffusion morphology (diffusion angle)** to HAWC data.
- Paper under review, the **results of the fit are not public yet**.

Derived Positron Flux at Earth

- The fitted parameters using HAWC data are used as input to the **EDGE** code allowing the **estimation of the positron flux** from both sources.
- The 3σ range is based on statistical uncertainties from simulations.
- Systematics uncertainties include: systematics in the fit parameters, pulsar characteristic initial spin-down timescale (τ), and spectral index of the diffusion coefficient (δ).
- PSR B0656+14 is several orders of magnitude lower than Geminga and out of scale in the plot.



AMS-02 points from **PRL 113, 121102 (2014)**

Summary

Indirect DM Search:

Results for 15 dSph, Virgo Cluster and M31 were shown (analysis as point sources)

Annihilation:
Better limits in $\tau\tau$ and $\mu\mu$ channels for $M_\chi >$ ~3 TeV than other experiments

Decay:
Better limits in all channels compared to other experiments

M31 results compliment dSph results for annihilation (expected due to peaked profile)

Virgo Cluster results compliment dSph results for decay (expected due to total DM)

Limits will improve with:

- including more dSph galaxies
- more observation time
- HAWC's capability to make full extended source analysis
- including more extended sources and run stacked analysis

Electron Diffusion near Geminga and Monogem:

HAWC has reported an extended TeV gamma-ray emission from Geminga (confirmation of Milagro observations) and B0656+14 (discovery) pulsars.

Under the assumption of isotropic and homogeneous diffusion these two pulsars are **unlikely to be the dominant source of the positron flux excess** above 10 GeV reported by satellites.

Full analysis details will be public soon.

Thanks for slides to: T. Yapici, F. Salesa Greus

Backup Slides

References for DM Limits

[1] ”Stellar mass map and dark matter distribution in M31”, Tamm et al., Astronomy Astrophysics, 546, 2012 (arXiv: 1208.5712)

[2] ”Investigating the Andromeda Stream: I. Simple Analytic Bulge-Disk-Halo Model for M31”, Geehan et al., Monthly Notices of the Royal Astronomical Society, 366-3, 2006 (arXiv: astro-ph/0501240)

[3] ”Constraining Extended Gamma-ray Emission from Galaxy Clusters”, Han et al., Monthly Notices of the Royal Astronomical Society, 427-2, 2012 (arXiv: 1207.6749)

[4] ”The flattening of the concentration-mass relation towards low halo masses and its implications for the annihilation signal boost”, Sanchez-Conde et al., Monthly Notices of the Royal Astronomical Society, 442-3, 2014 (arXiv: 1312.1729)

[5] ”Profiles of dark haloes: evolution, scatter, and environment”, Bullock et al., Monthly Notices of the Royal Astronomical Society, 321-3, 2001 (arXiv: astro-ph/9908159)

[6] ”Dark matter halo concentrations in the Wilkinson Microwave Anisotropy Probe year 5 cosmology”, Duffy et al., Monthly Notices of the Royal Astronomical Society: Letters, 390-1, 2008 (arXiv: 0804.2486)

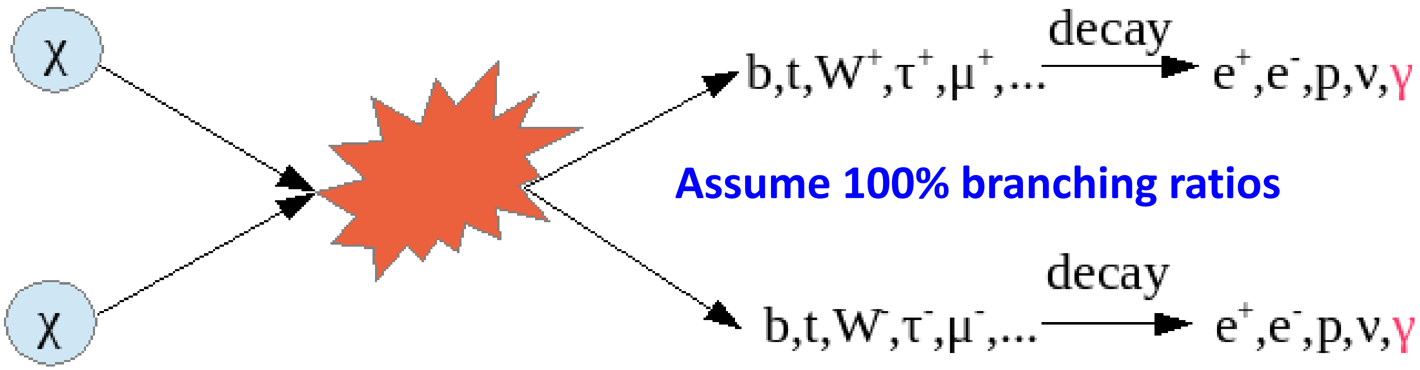
[7] ”The subhalo populations of CDM dark haloes”, Gao et al., Monthly Notices of the Royal Astronomical Society, 355-3, 2004

[8] ”A brief introduction to PYTHIA 8”, Sjostrand et al., Computer Physics Communications, 178-11, 2008

[9] ”CLUMPY: Jeans analysis, γ-ray and ν fluxes from dark matter (sub-)structures”, Bonnuvard et al., Computer Physics Communications, 200, 2016

[10] ”Dark MAtter Annihilation and Decay from Non-spherical Dark Halos in the Galactic Dwarf Satellites”, Mon. Not. R. Astron. Soc., 2016 (arxiv:1603.08046v2)

Dark Matter
Annihilation and Decay



$b,t,W^+,\tau^+,\mu^+,\ldots \xrightarrow{\text{decay}} e^+,e^-,p,\nu,\gamma$

Assume 100% branching ratios

$b,t,W^-,\tau^-,\mu^-,\ldots \xrightarrow{\text{decay}} e^+,e^-,p,\nu,\gamma$

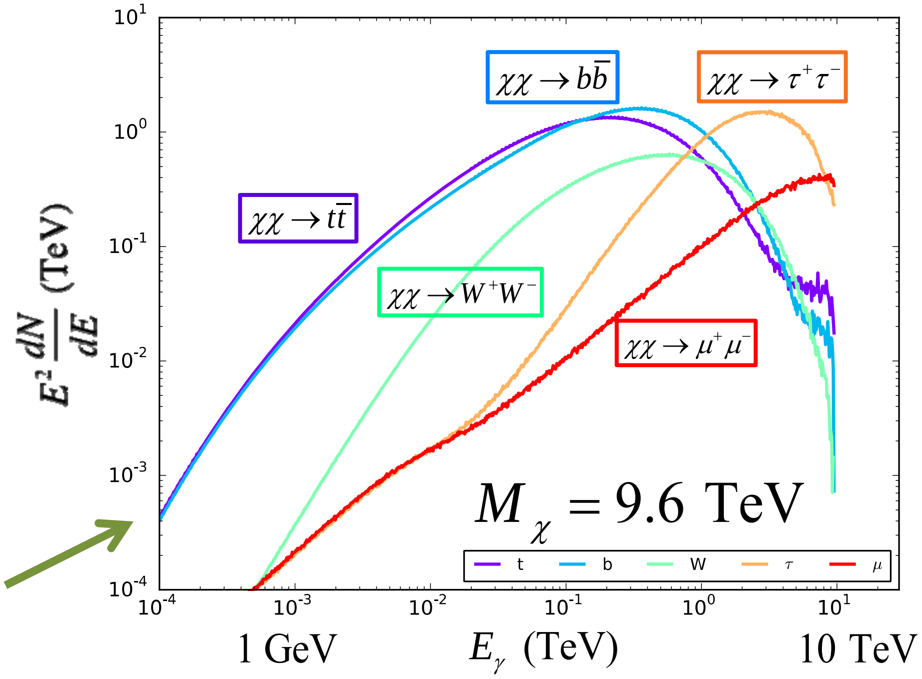
Annihilation

$$Flux_{ann} \propto \frac{\langle \sigma v \rangle}{M_\chi^2} \frac{dN_\gamma}{dE} \int d\Omega \int_{l.o.s.} dx \rho^2(r)$$

Decay

$$Flux_{decay} \propto \frac{1}{\tau} \frac{1}{M_\chi} \frac{dN_\gamma}{dE} \int d\Omega \int_{l.o.s.} dx \rho(r)$$

Use M_χ from 0.5 – 100 TeV
Photon spectrum from PYTHIA 8
for M_χ = 9.6 TeV



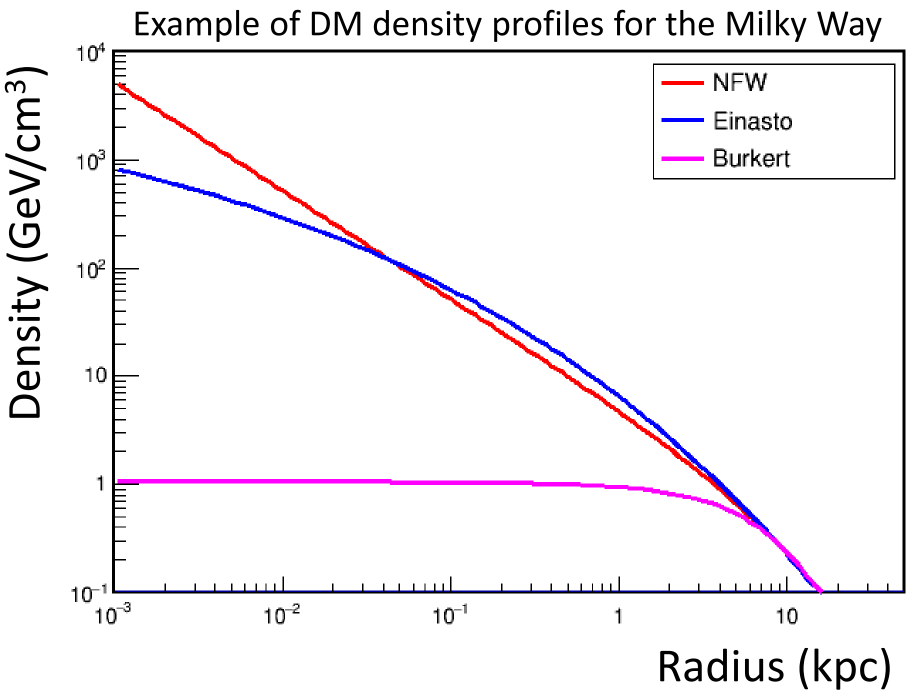
Dark Matter Annihilation and Decay

Annihilation

$$Flux_{ann} \propto \frac{\langle \sigma v \rangle}{M_\chi^2} \frac{dN_\gamma}{dE} \underbrace{\int d\Omega \int_{l.o.s.} dx \rho^2(r)}_{\text{J - factor}}$$

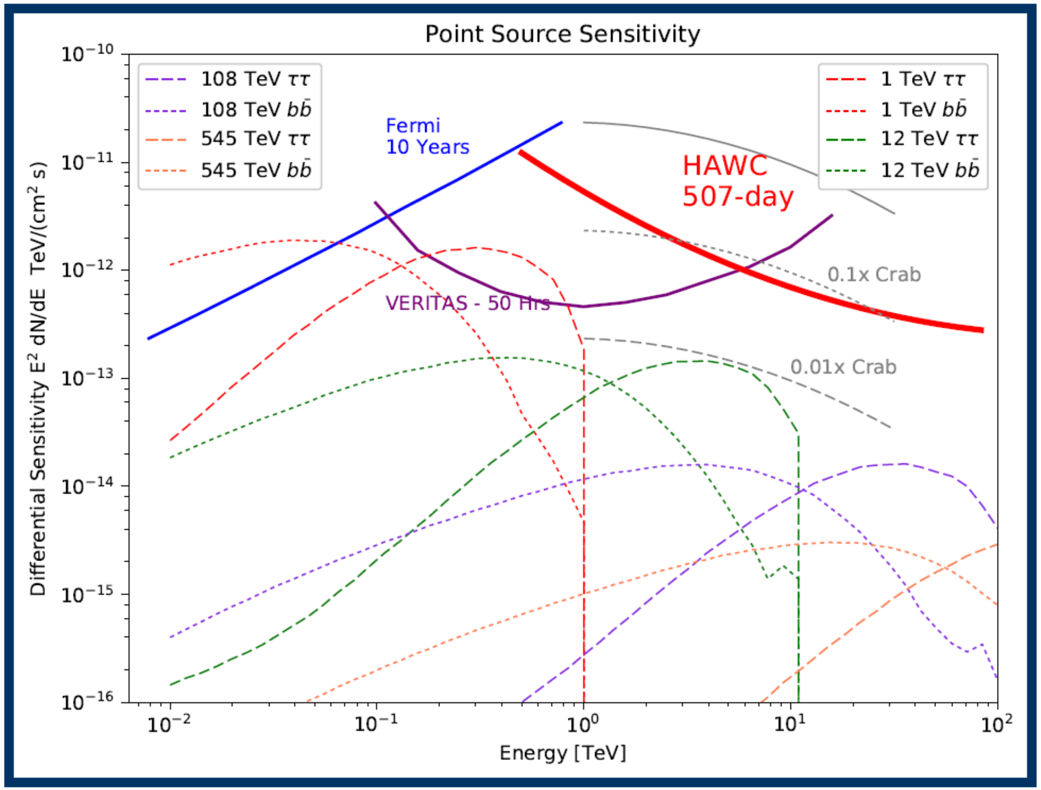
Decay

$$Flux_{decay} \propto \frac{1}{\tau} \frac{1}{M_\chi} \frac{dN_\gamma}{dE} \underbrace{\int d\Omega \int_{l.o.s.} dx \rho(r)}_{\text{D - factor}}$$



- All sources treated as point-like
- Used a smooth NFW dark matter density profile taken from Geringer-Sameth et al., Astrophys. J. 801 no.2, 74 (2015)
- J and D factors were calculated using CLUMPY

(Fermi-VERITAS-)HAWC Sensitivity

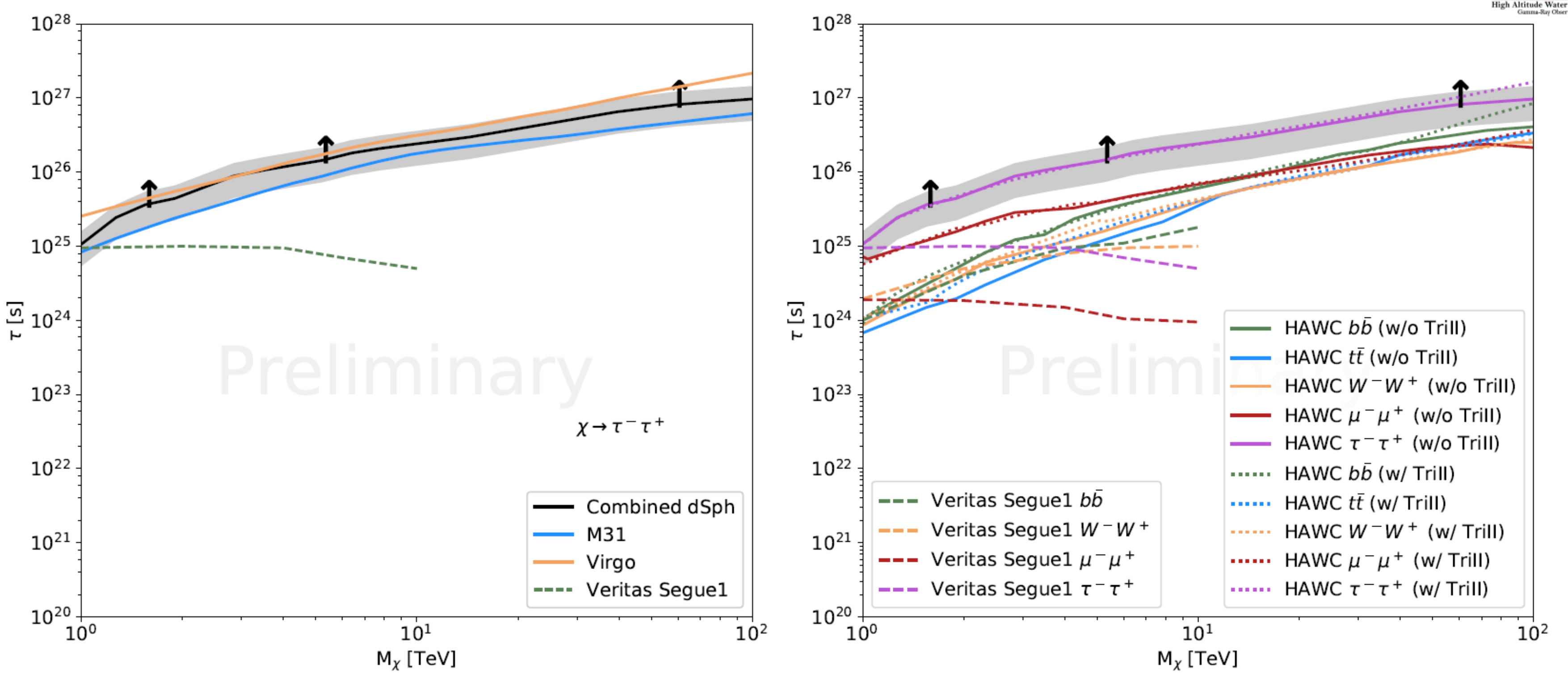


annihilation values are calculated for Segue 1, $< \sigma v > = 10^{-23}$

HAWC scanned for 1-100 TeV M_χ

Tau and muon channels peak at higher energy than b and W channels

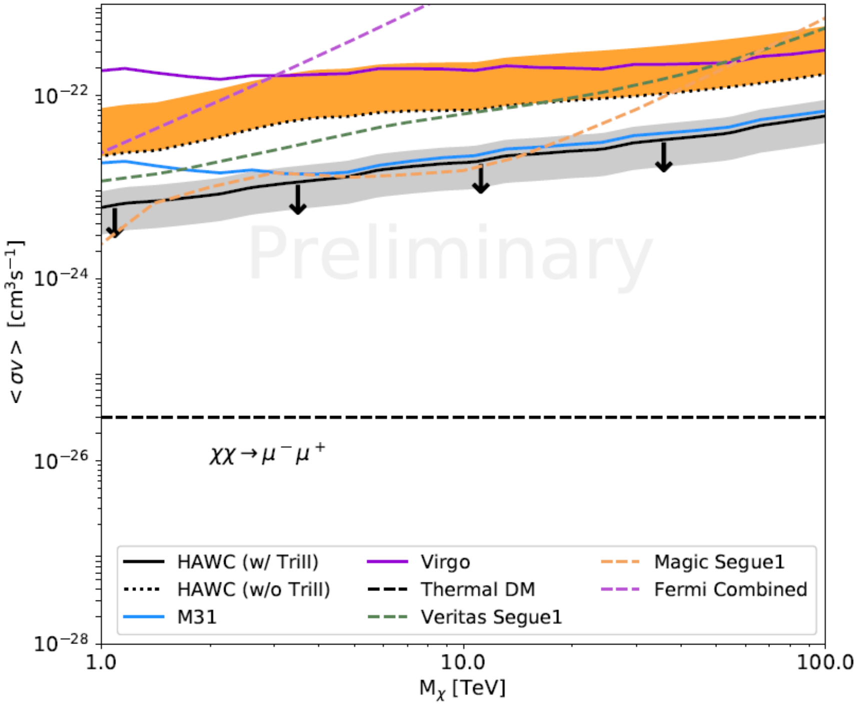
Dark Matter Decay (Lower) Limits

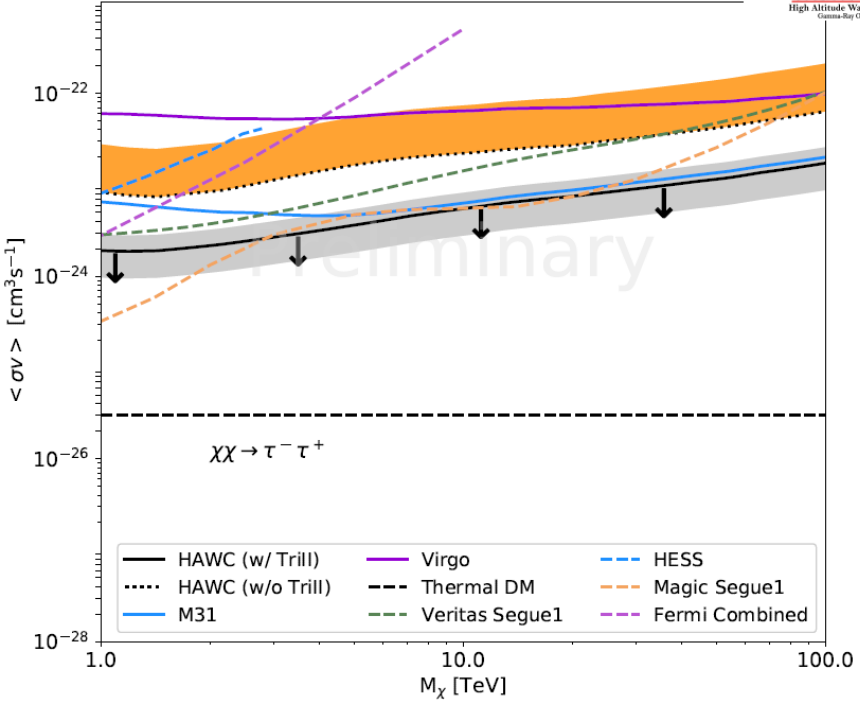


Virgo is a good source for searching DM decay

With the extended source analysis, this will only get better

Dark Matter Annihilation (Upper) Limits

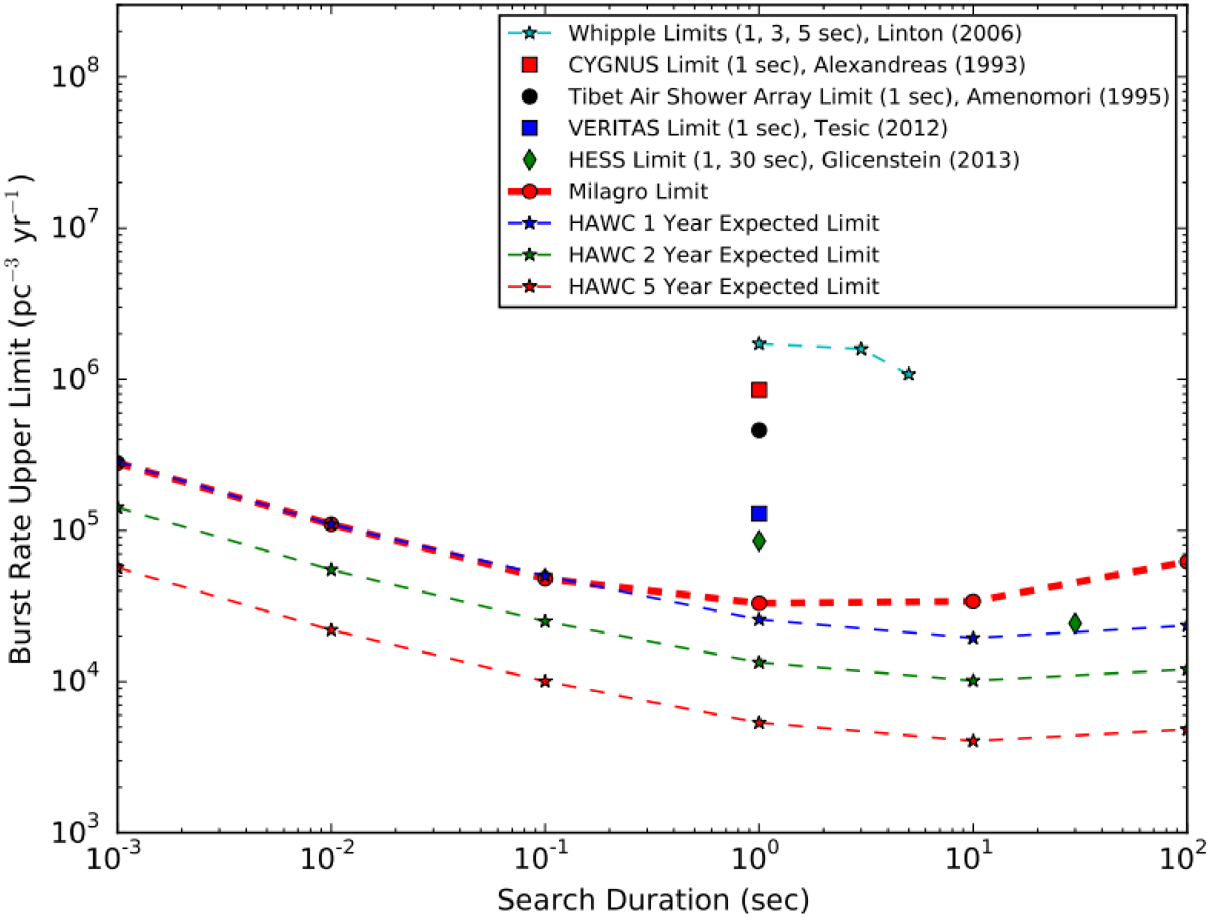




Because of their gamma-ray spectrum, leptonic channel are expected to yield better limits
HAWC dSph limits are better after a few TeV
M31 limits are comparable and Virgo limits are not good (as expected)
M31 is a good source for searching DM annihilation

HAWC M31 limit has negative statistical fluctuation

PBH Limits (HAWC in progress)



Arxiv 1510.04372

Figure 20: Published PBH burst rate density 99% CL upper limits and sensitivities for various experiments [13; 7; 8; 9; 10; 11; 12]. The upper limits and sensitivities shown are derived using the Standard Emission Model description for the PBH emission spectra.