First Limits on the Dark Matter Cross-Section with the High Altitude Water Cherenkov (HAWC) Observatory

TAUP 2015

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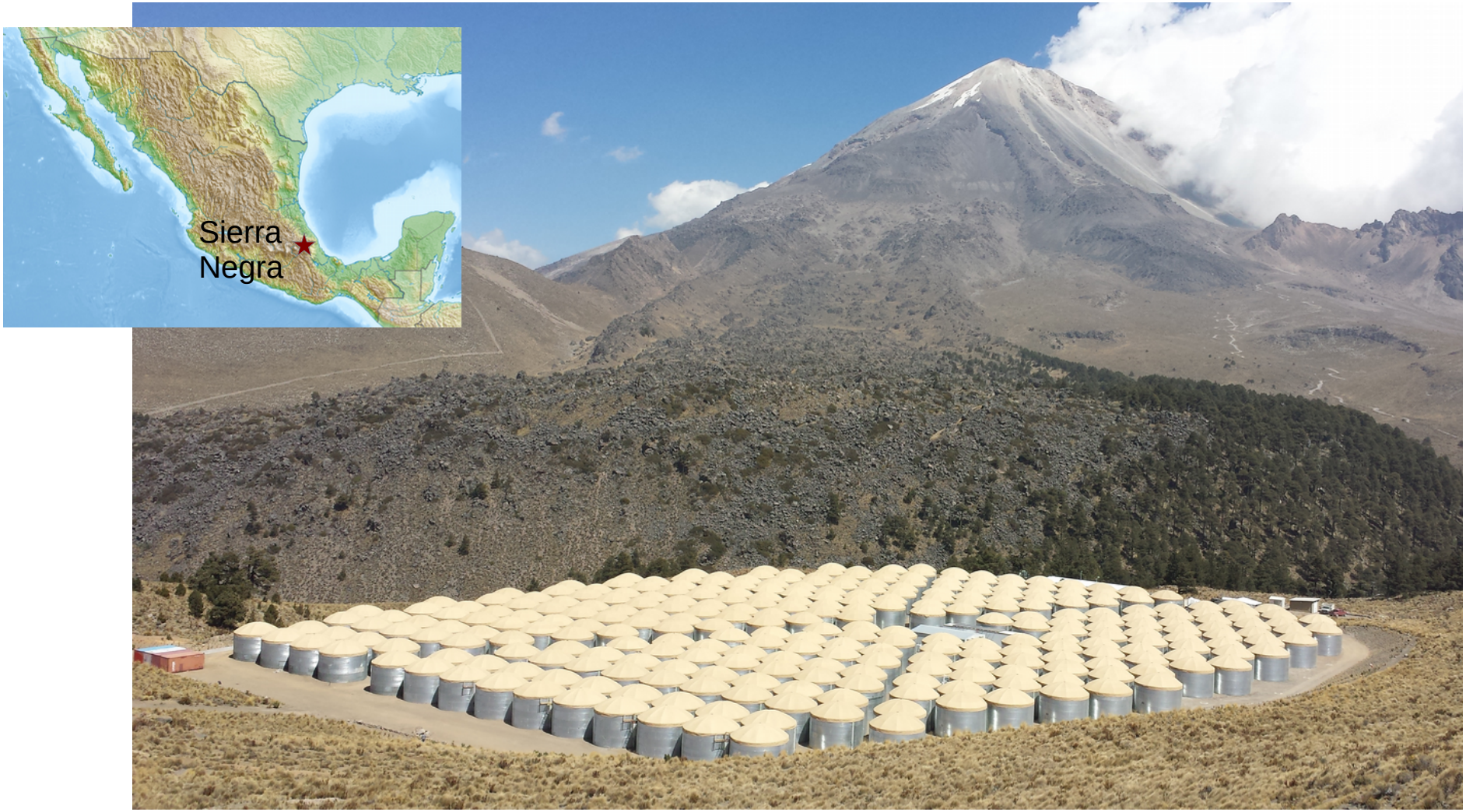
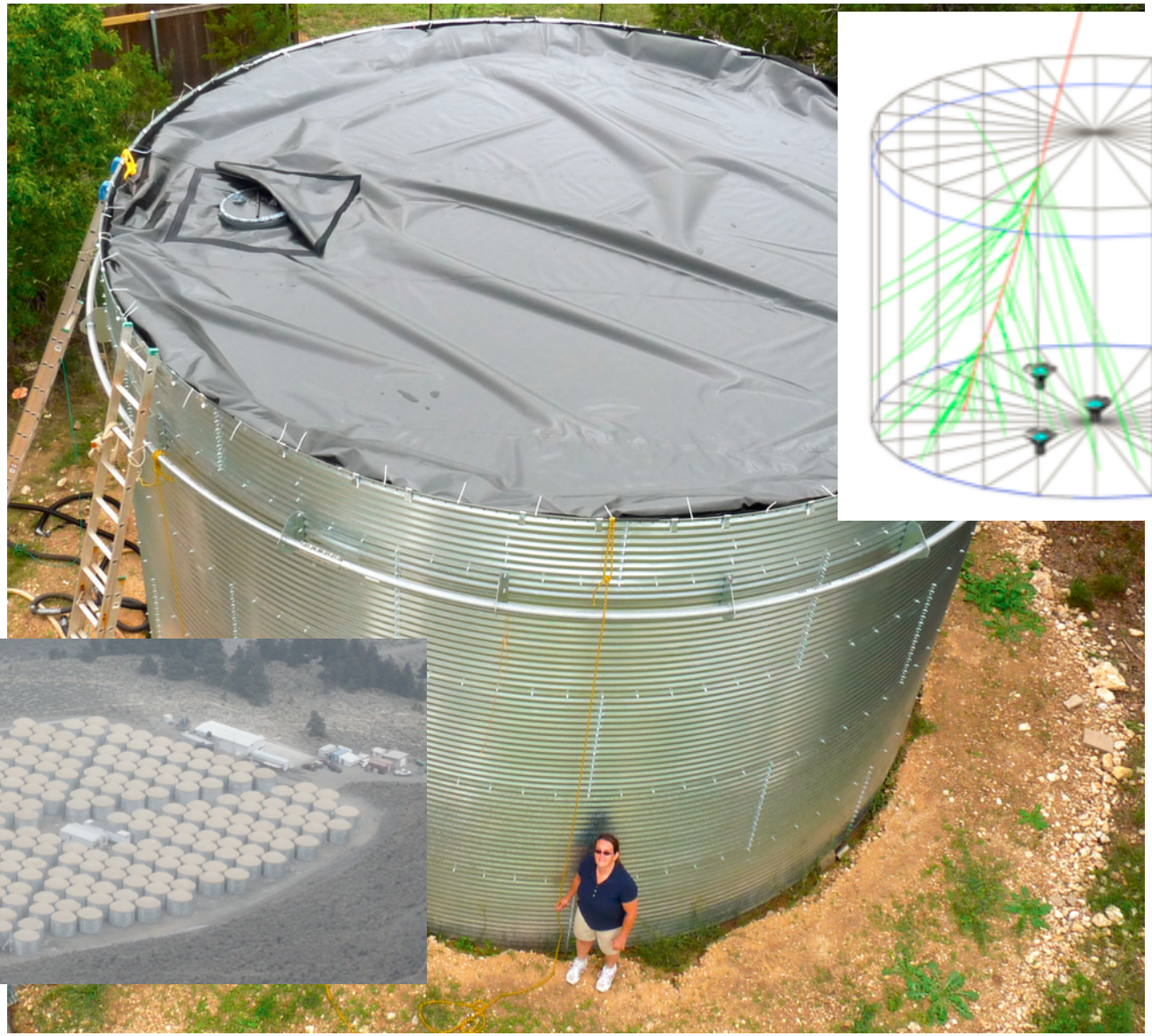
The High Altitude Water Cherenkov Observatory

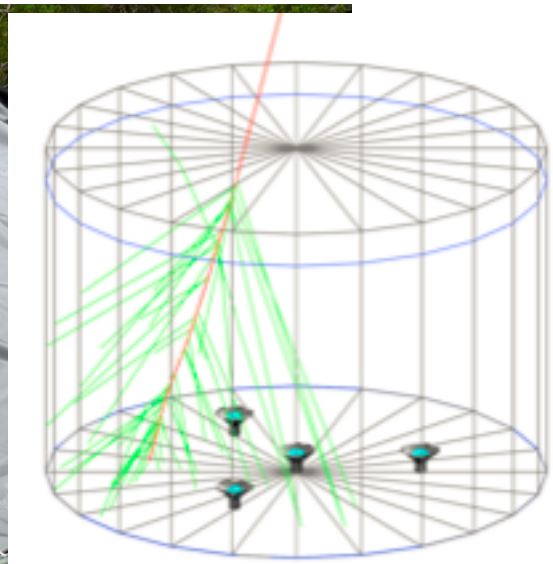


Altitude: 4100 m (13000 ft) Latitude: 19° N

Water Cherenkov Detectors

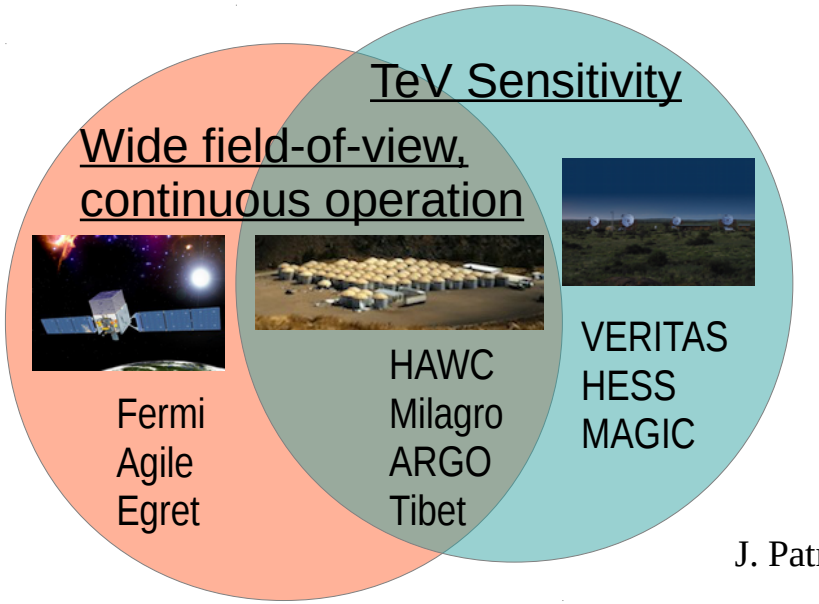
- 300 WCD tanks
- 5 m x 7.3 m tanks
- 200,000L of water each
- 4 PMTs
  - 3 8” R5912
  - 1 10” R7081 HQE
- Inauguration of the completed array in March 2015

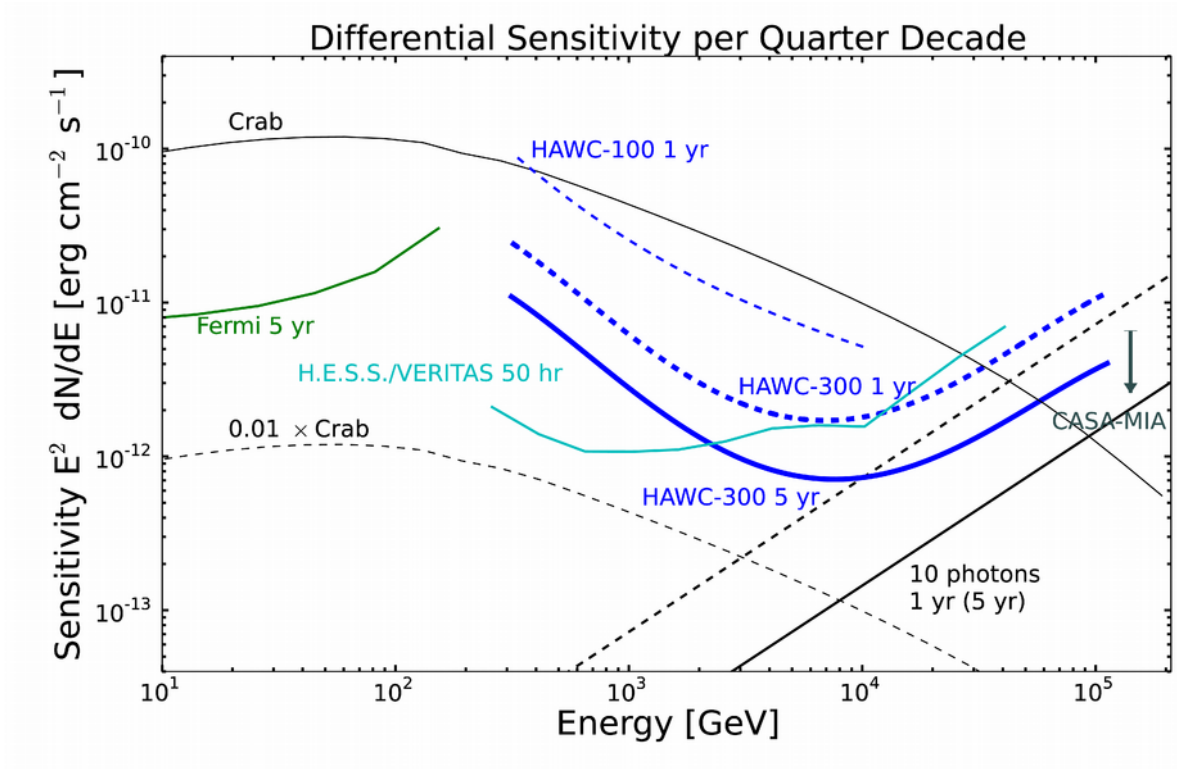




HAWC Sensitivity

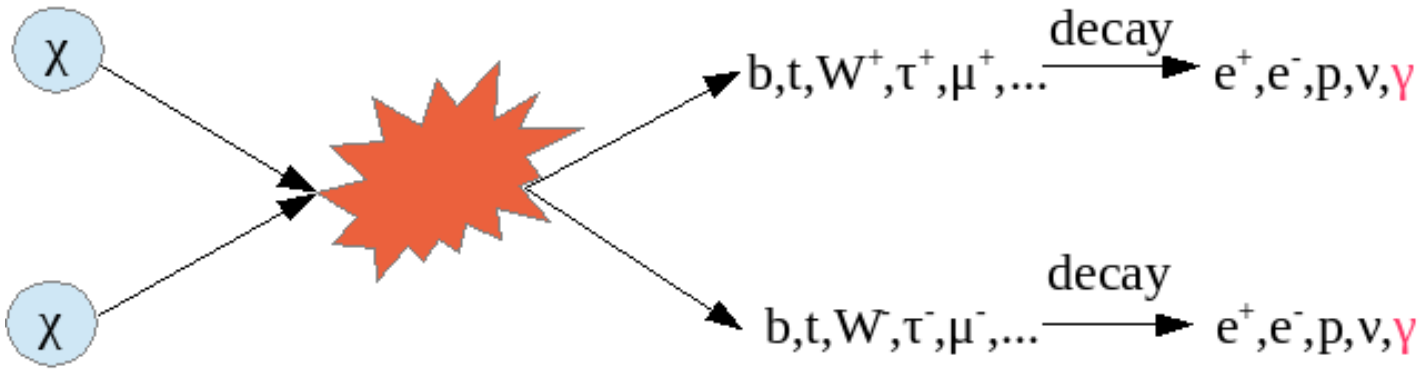
- Average Angular Resolution:
  0.5º (68% containment)
- Field-of-view:
  2 sr (2/3 sky each day)
- Effective Area:
  22500 m^2
- Sensitivity:
  Observe Crab nebula each day





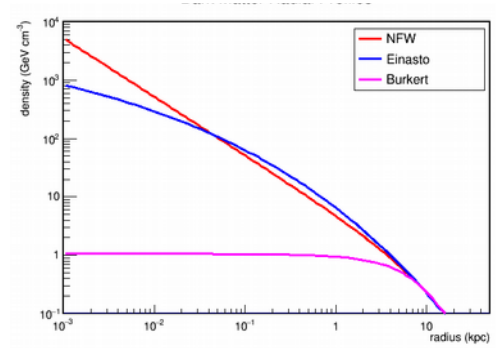
Abeysekara et al., Astropart. Phys. 50-52, 26 (2013)

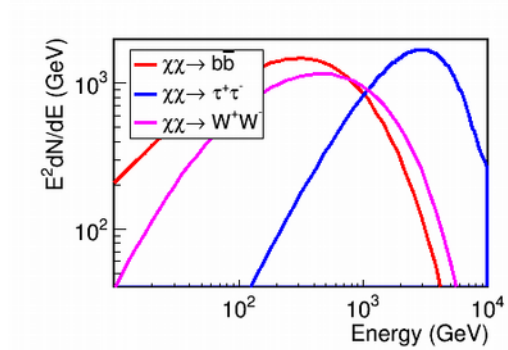
Dark Matter Annihilation and Decay



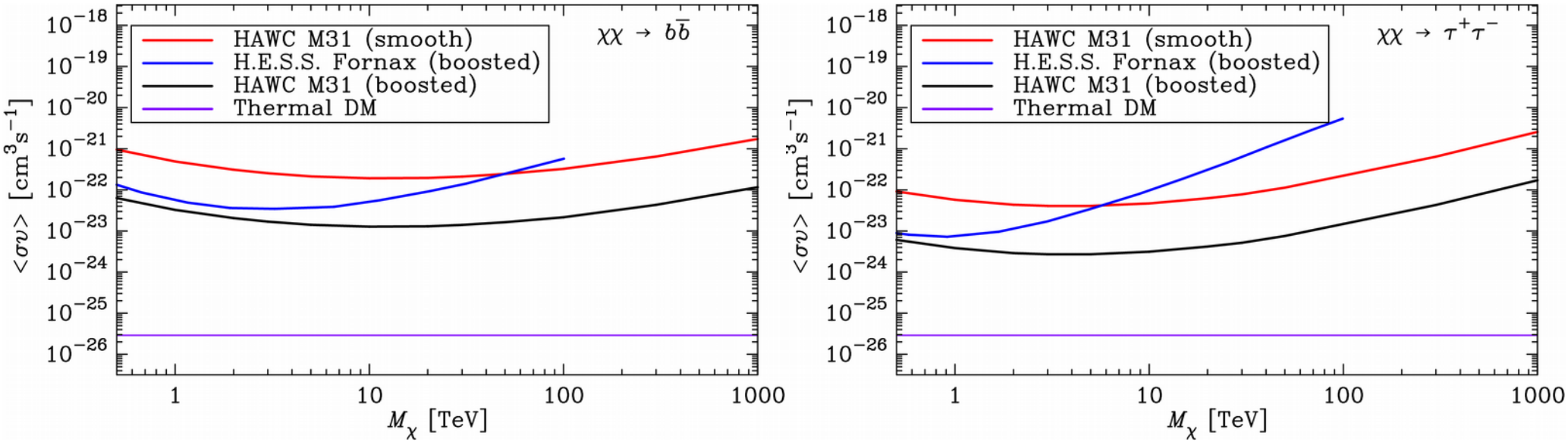
$$Flux_{ann} \propto \frac{\langle \sigma v \rangle}{M_\chi^2} \frac{dN_\gamma}{dE} \int_{l.o.s.} dx\, \rho^2(r)$$

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



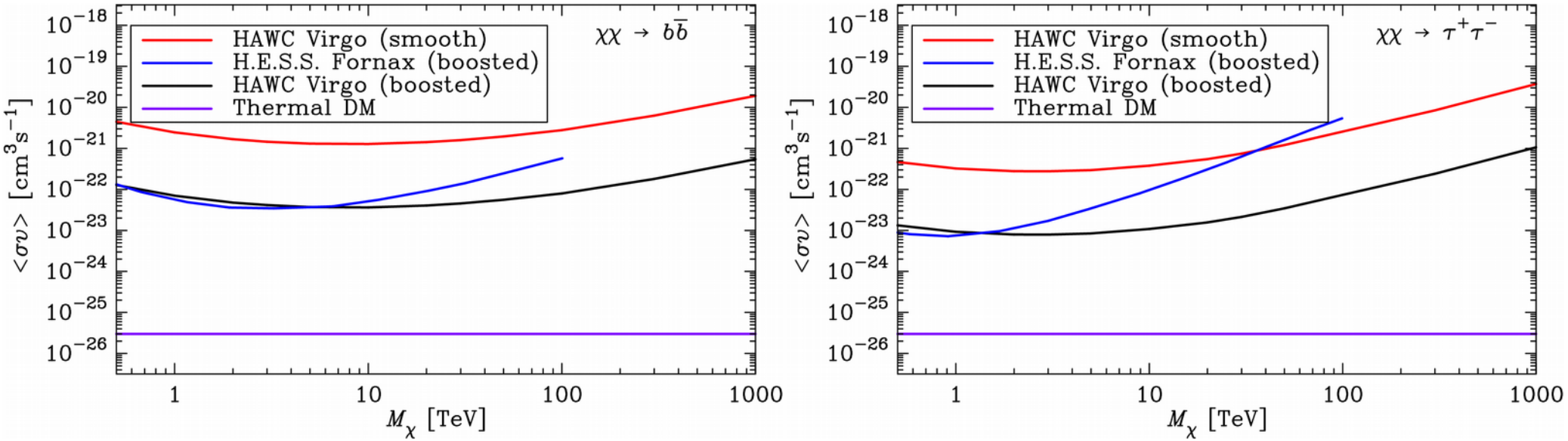


HAWC Sensitivity to Annihilating DM in the M31 Galaxy



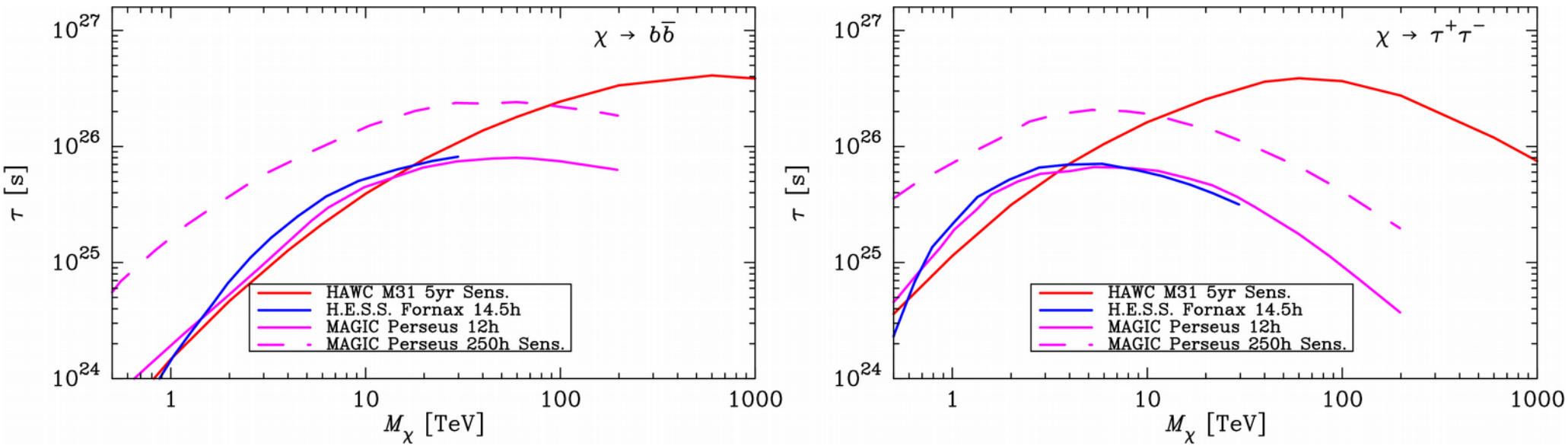
- HAWC 5-year sensitivity to the dark matter annihilation cross-section (95% C.L. upper limits) for the M31 (Andromeda) galaxy
- HAWC limits assuming a conservative model of DM substructure (boosted) and without (smooth) are considered
- Limits from the H.E.S.S. observations of the Fornax galaxy cluster (14.5h) shown for comparison
- HAWC is sensitive to extended objects, like galaxies and galaxy clusters

HAWC Sensitivity to Annihilating DM in the Virgo Cluster



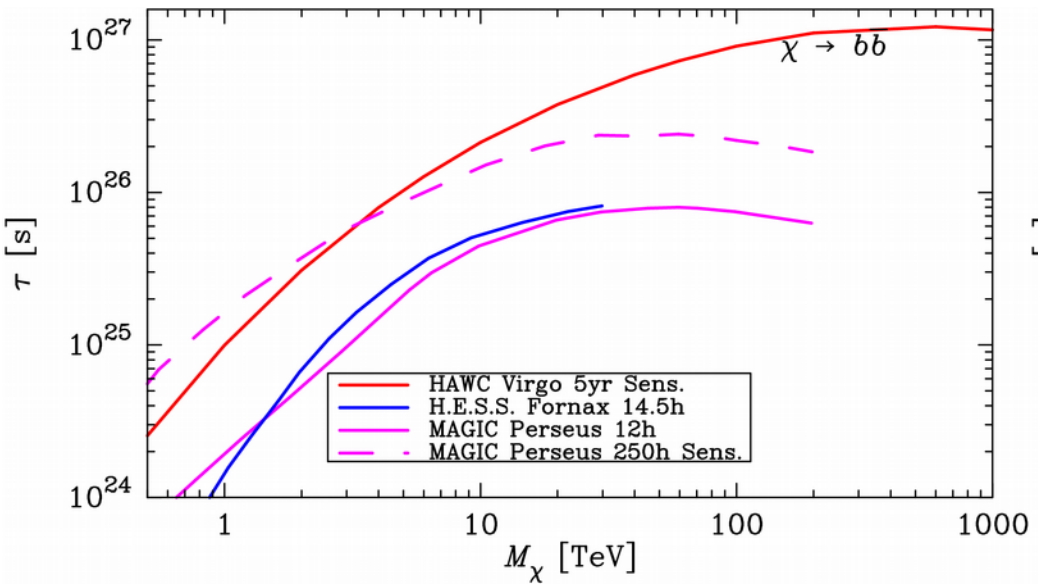
- HAWC 5-year sensitivity to the dark matter annihilation cross-section (95% C.L. upper limits) for the Virgo cluster
- HAWC limits assuming a conservative model of DM substructure (boosted) and without (smooth) are considered
- Limits from the H.E.S.S. observations of the Fornax galaxy cluster (14.5h) shown for comparison
- HAWC is most sensitive to high masses, which produce multi-TeV photons

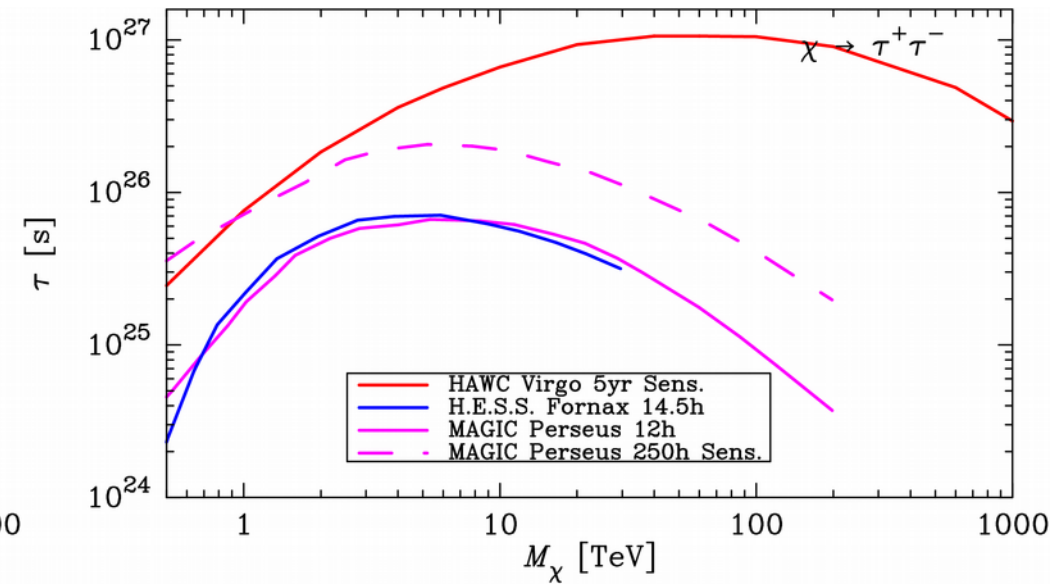
HAWC Sensitivity to Decaying DM in the M31 Galaxy



- HAWC 5-year sensitivity to the dark matter decay lifetime (95% C.L. lower limits) for the M31 (Andromeda) galaxy
- Limits from the H.E.S.S. observations of the Fornax cluster (14.5h), MAGIC observations of the Perseus cluster (12h), and MAGIC sensitivity to the Perseus cluster (250h) shown for comparison
- HAWC is particularly sensitive to DM decay, which produces very extended emission (1.5° for M31, 3.3° for Virgo cluster)

HAWC Sensitivity to Decaying DM in the Virgo Cluster





- HAWC 5-year sensitivity to the dark matter decay lifetime (95% C.L. lower limits) for the Virgo cluster
- Limits from the H.E.S.S. observations of the Fornax cluster (14.5h), MAGIC observations of the Perseus cluster (12h), and MAGIC sensitivity to the Perseus cluster (250h) shown for comparison
- As the most massive object HAWC can observe, the Virgo cluster should give the best decay limits

HAWC DM Limits

- Data used in this analysis collected from August 2013 - March 2014
  - detector grew from 362 PMTs in 108 WCDs to 491 PMTs in 134 WCDs
- Limits calculated for WIMP masses annihilating with 100% branching ratios into:

$$b\bar{b},\ \tau^+\tau^-,\ \mu^+\mu^-,\ t\bar{t},\ W^+W^-$$

- M_χ ranging from 0.5 TeV - 1000 TeV
- Individual limits done for 14 dwarf spheroidal galaxies, and were treated as point sources

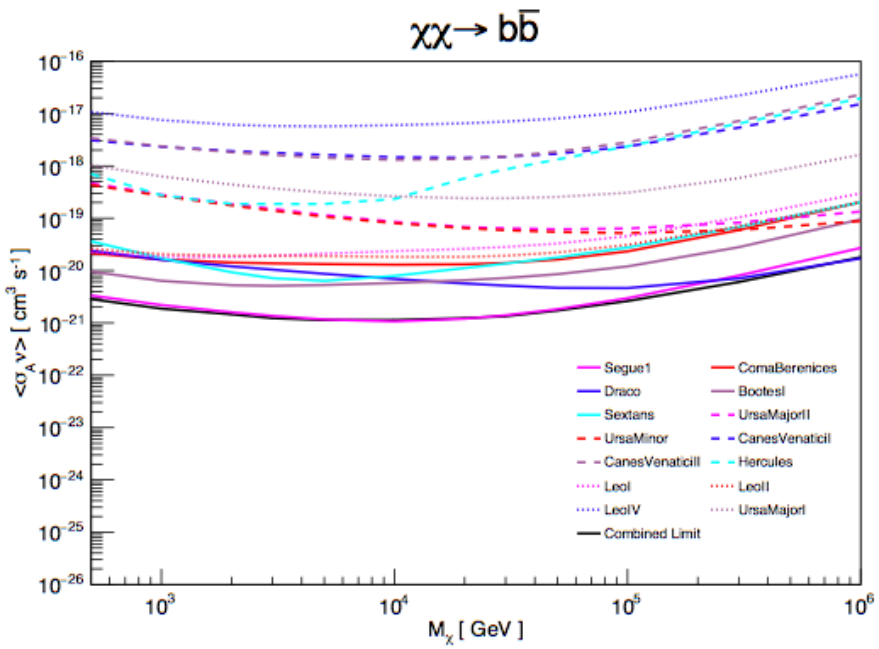
Stacked analysis done with all 14 dwarf spheroidal galaxies to produce a combined limit for each DM annihilation channel

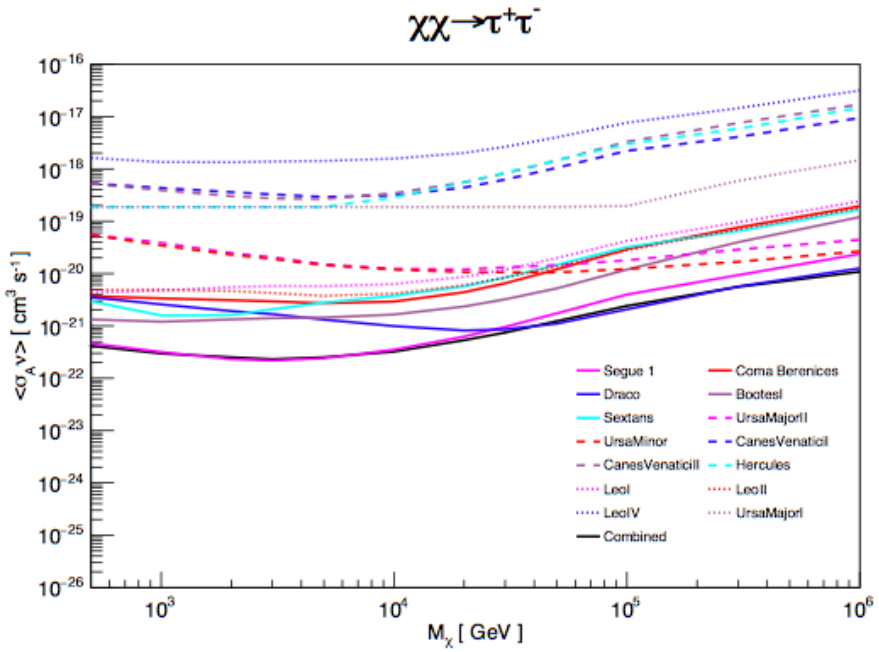
Two dark matter density profiles were used in this analysis: 1) Einasto (Segue 1 with $\alpha = 0.303$) and 2) NFW (all other sources)

Sources Considered: 14 Dwarf Galaxies

Source	*RA*	*Dec*	ρ_s GeV/cm^3	r_s kpc	*R* kpc	*J* GeV^{2}cm^{-5}sr
Bootes 1	210.05	14.49	8.12	0.27	66	3.8×10^{18}
Canes Venatici I	202.04	33.57	0.79	0.55	218	2.9×10^{16}
Canes Venatici II	194.29	34.32	4.77	0.13	160	2.5×10^{16}
Coma Berenices	186.74	23.90	9.76	0.16	44	2.6×10^{18}
Draco	260.05	57.07	0.98	2.1	76	2.0×10^{19}
Hercules	247.72	12.75	0.80	0.32	132	1.6×10^{16}
Leo I	152.11	12.29	16.20	0.28	254	1.2×10^{18}
Leo II	168.34	22.13	162.01	0.06	233	1.2×10^{18}
Leo IV	173.21	-0.53	1.99	0.15	154	7.3×10^{15}
Segue 1	151.75	16.06	4.18	0.15	23	1.8×10^{19}
Sextans	153.28	-1.59	3.38	0.37	86	1.0×10^{18}
Ursa Major I	158.72	51.94	2.39	0.31	97	2.3×10^{17}
Ursa Major II	132.77	63.11	13.79	0.17	32	1.1×10^{19}
Ursa Minor	227.24	67.24	3.89	0.65	76	9.6×10^{18}

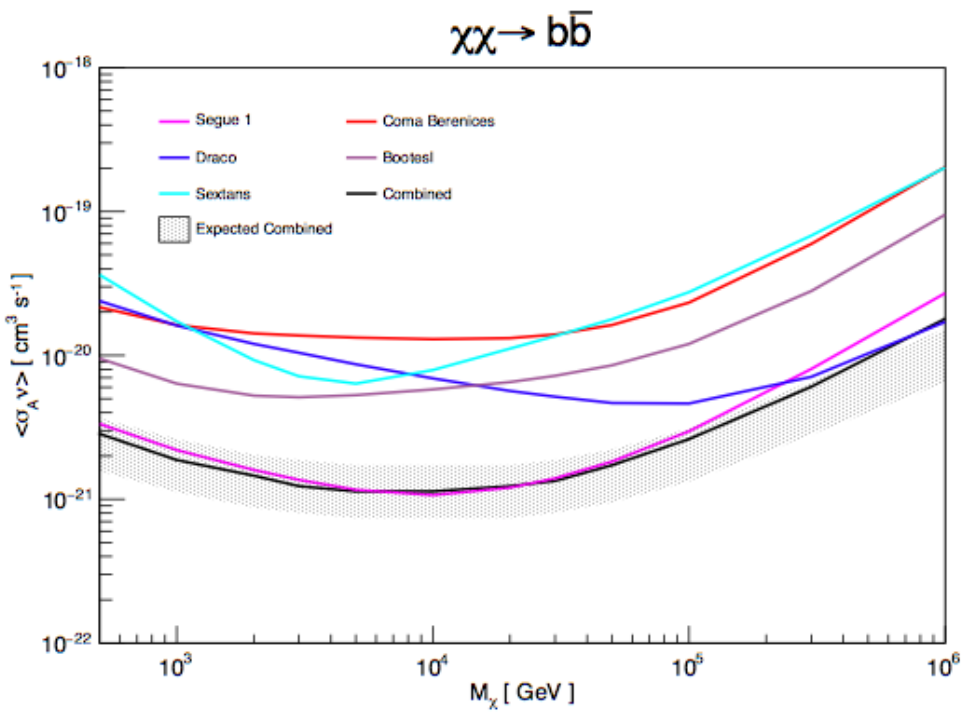
First Limits with HAWC Data





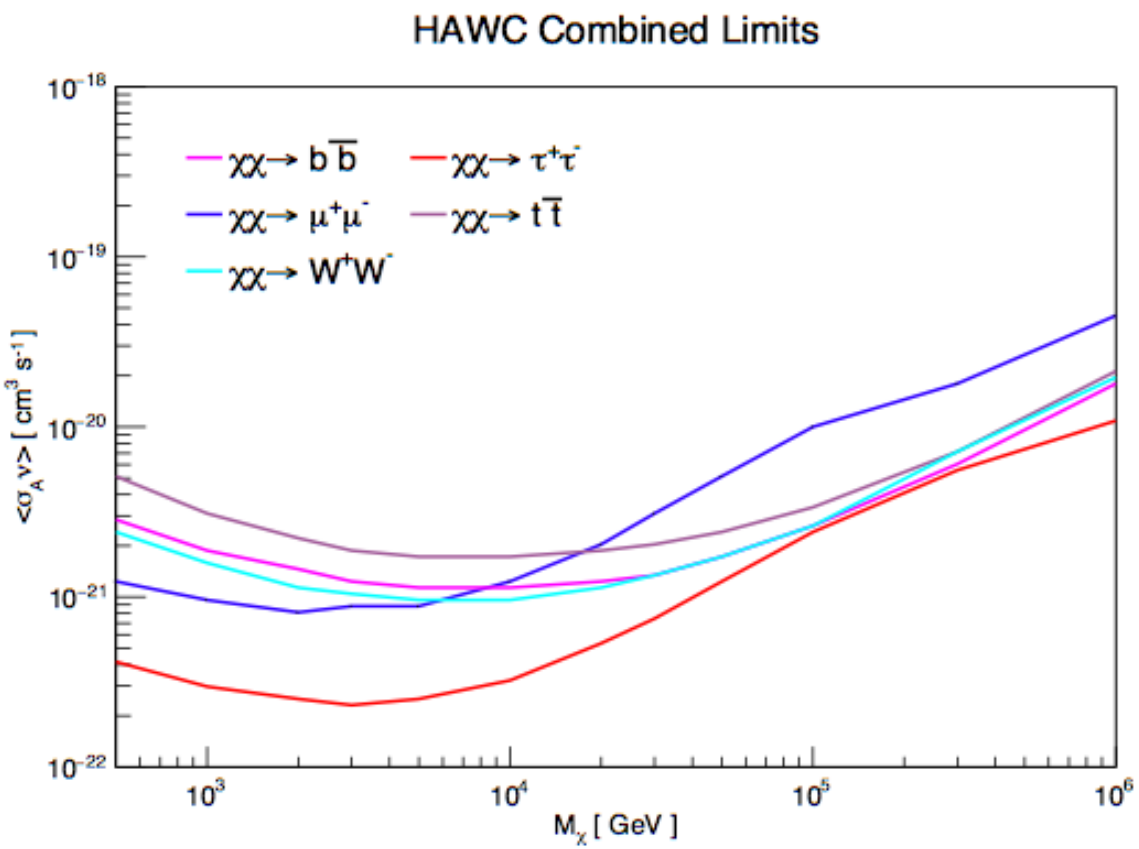
- Individual limits for 14 dwarf spheroidal galaxies within the HAWC field-of-view
- Combined limit for each annihilation channel from stacked analysis with all 14 sources (solid black line)

HAWC Combined Limits from the Dwarf Galaxies



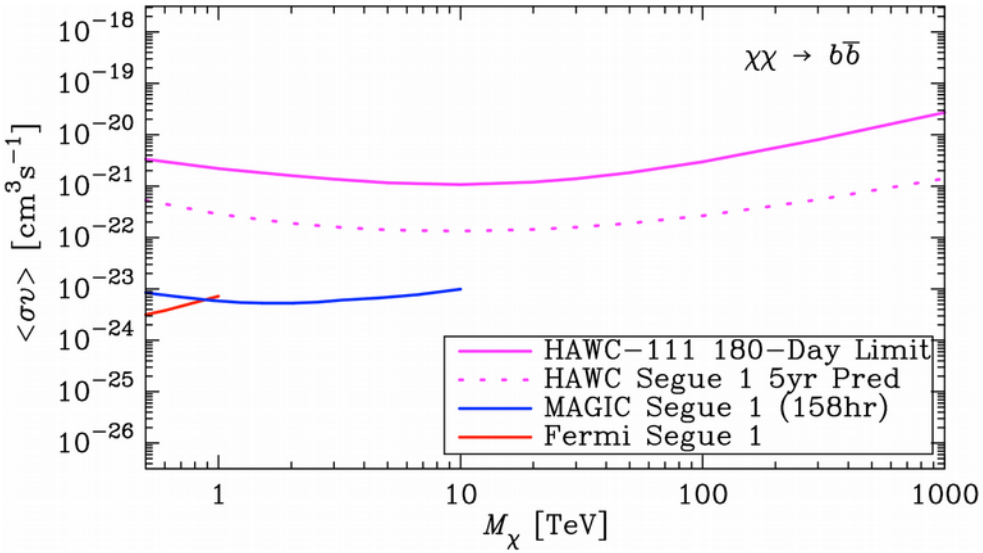
- Individual limits for the 5 dwarf spheroidal galaxies HAWC is most sensitive to are shown to the left
- Segue 1, Draco, BootesI, Sextans and Coma Berenices
- 14 source combined limit is shown (solid black line)
- HAWC expected 14 source combined limit is also shown with the associated systematic error on the expected number of counts from simulation (hatched gray area)

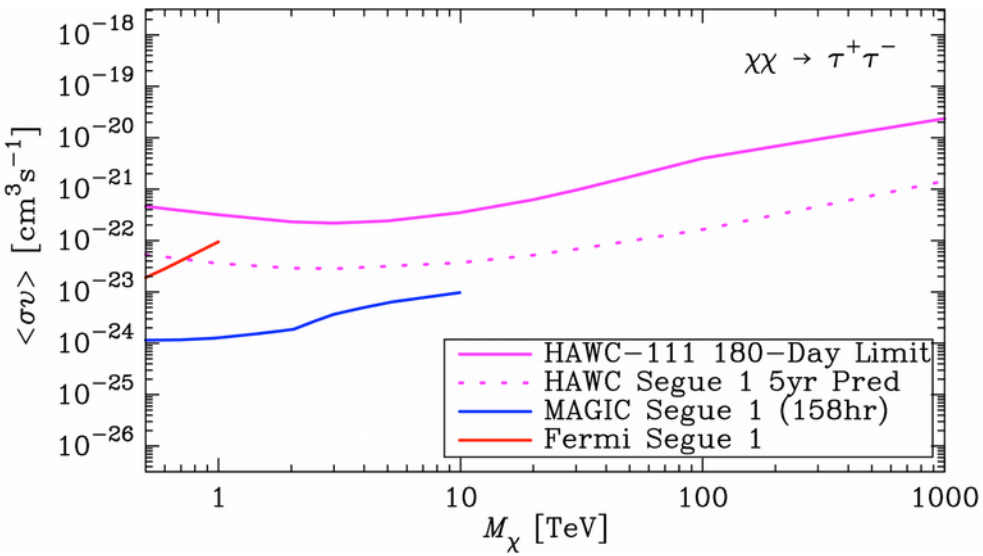
Combined Limits



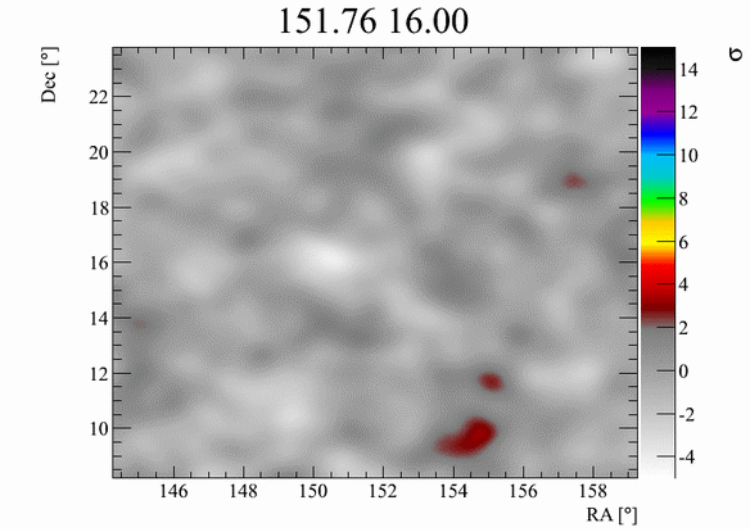
- HAWC 14 source combined limits for five annihilation channels in this analysis
- Limits are spectrally dependent

Comparison to Other Experiments





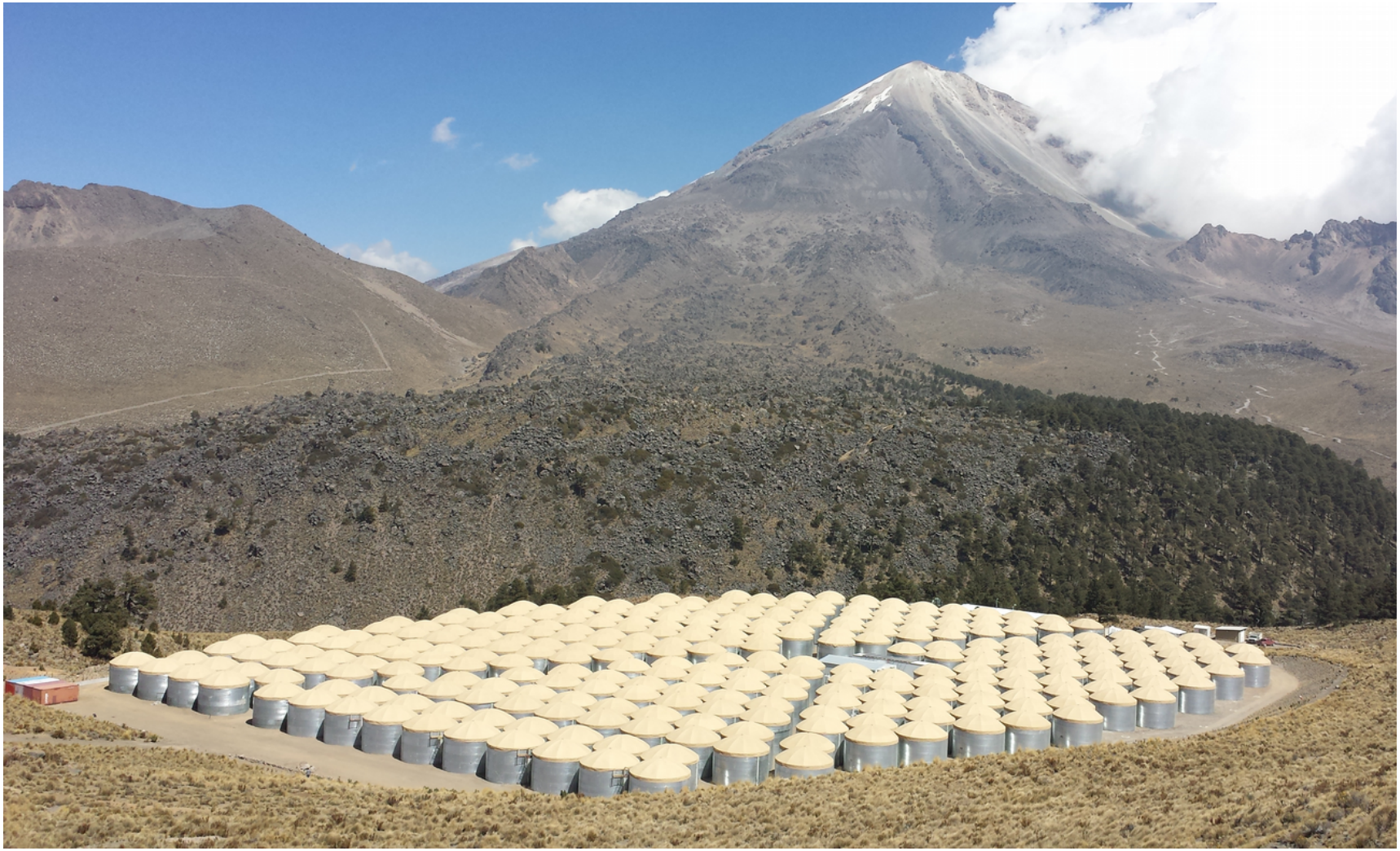
- Individual Segue1 limit for HAWC-111 180-day
- HAWC Segue 1 5-year predicted limit (dashed magenta line)
- Compared to Segue 1 limits from MAGIC and Fermi-LAT



HAWC is Now!

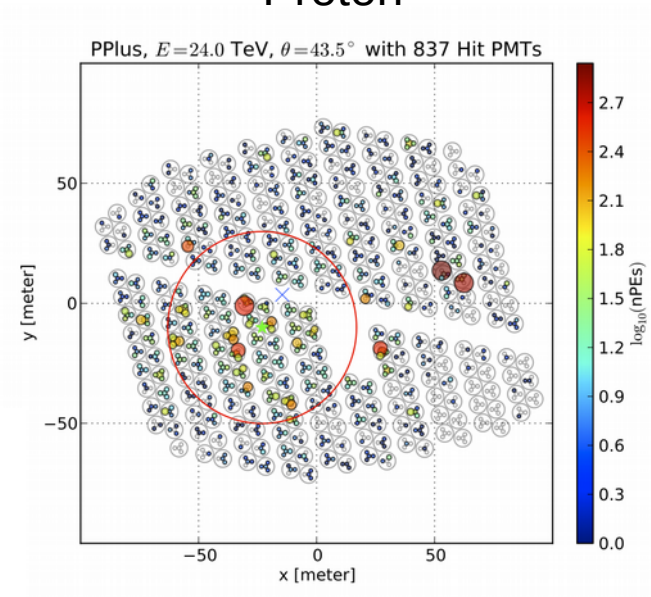
- HAWC is sensitive to gamma rays from DM annihilation and decay
- Dark matter limits with ~1/3 of the detector have been made
  - Final observations should be an order of magnitude more sensitive
- HAWC is complete and taking data with the full detector
  - Further analysis coming soon

Extras

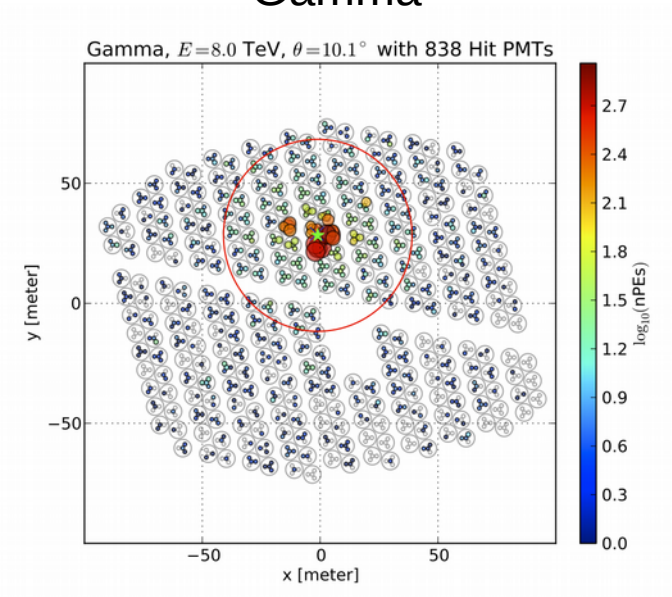


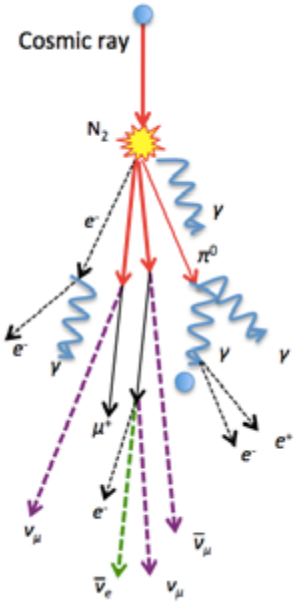
Gamma/Hadron Separation

Proton

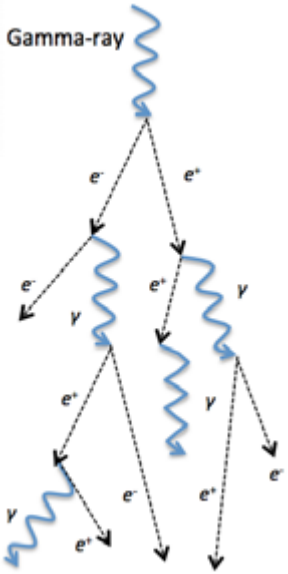


Gamma





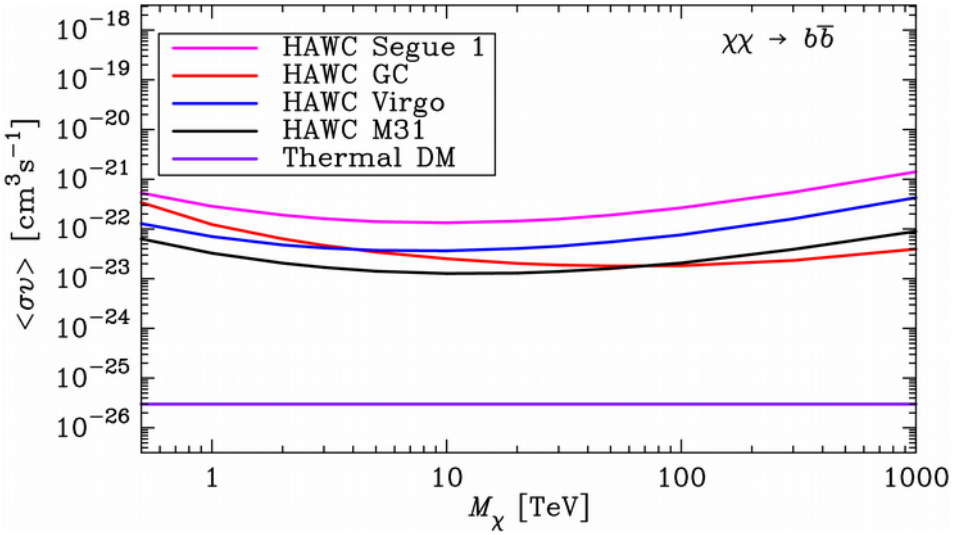
- Hadron-induced showers produce subshowers with a lot of transverse momentum and muons, so their distributions tend to clump in several regions on the array
- Gamma-ray showers produce a smoother, more peaked distribution on the array
- Looking for the sub-showers on the array and the larger spread of the hadronic showers, we can distinguish gammas from hadrons

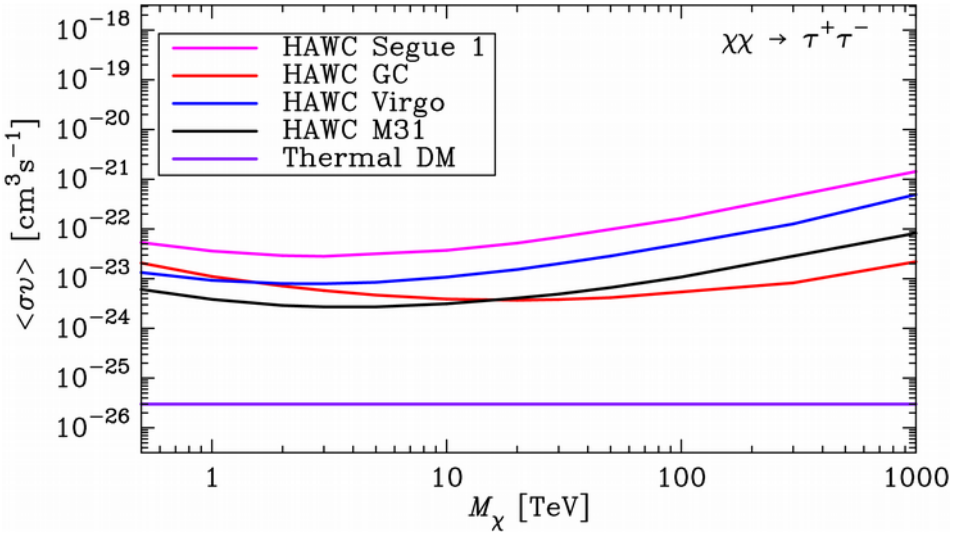


TeV-Mass Dark Matter

- High-mass high-flux DM proposed to explain several astrophysical observations
  - PAMELA/Fermi/AMS positron excess
  - H.E.S.S. Galactic center gamma-ray excess
  - IceCube PeV neutrinos
- Lack of observed DM at LHC implies DM mass >TeV
- Can be consistent with production of DM
  - DM production by decay of heavy particles
  - Sommerfeld enhancement give larger cross-section today than in the early universe

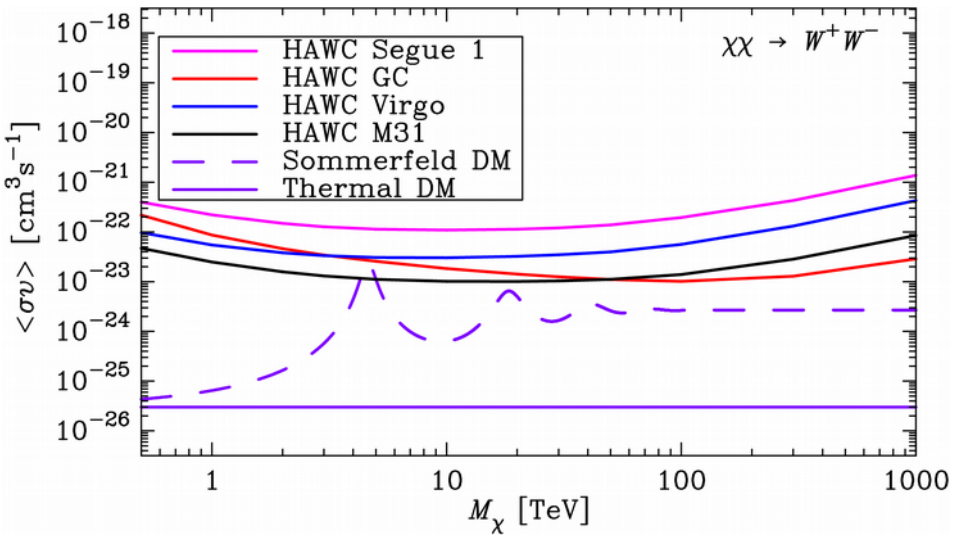
Comparison of HAWC Sources and Channels

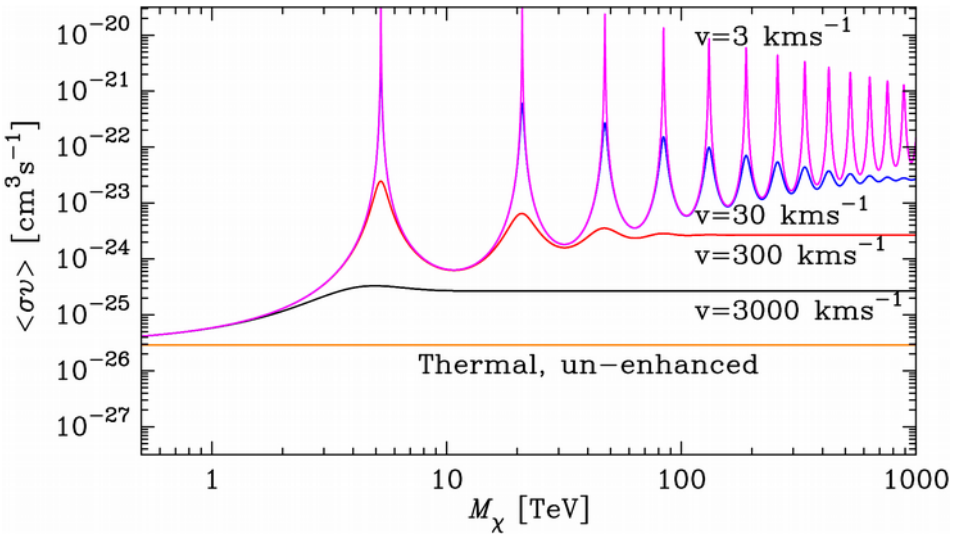




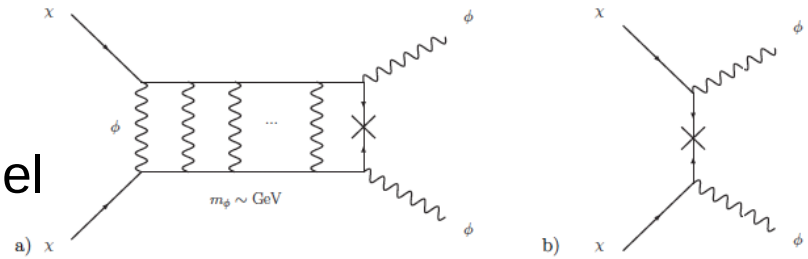
- HAWC 5-year sensitivity to the dark matter annihilation cross-section for the $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels
- At lower masses, the substructure in the M31 galaxy gives the best limits
- At higher masses, the large DM density at the Galactic center gives the best limits
- The harder leptonic channel is better constrained at low masses, though similarly constrained at high masses

Annihilation to Gauge Bosons





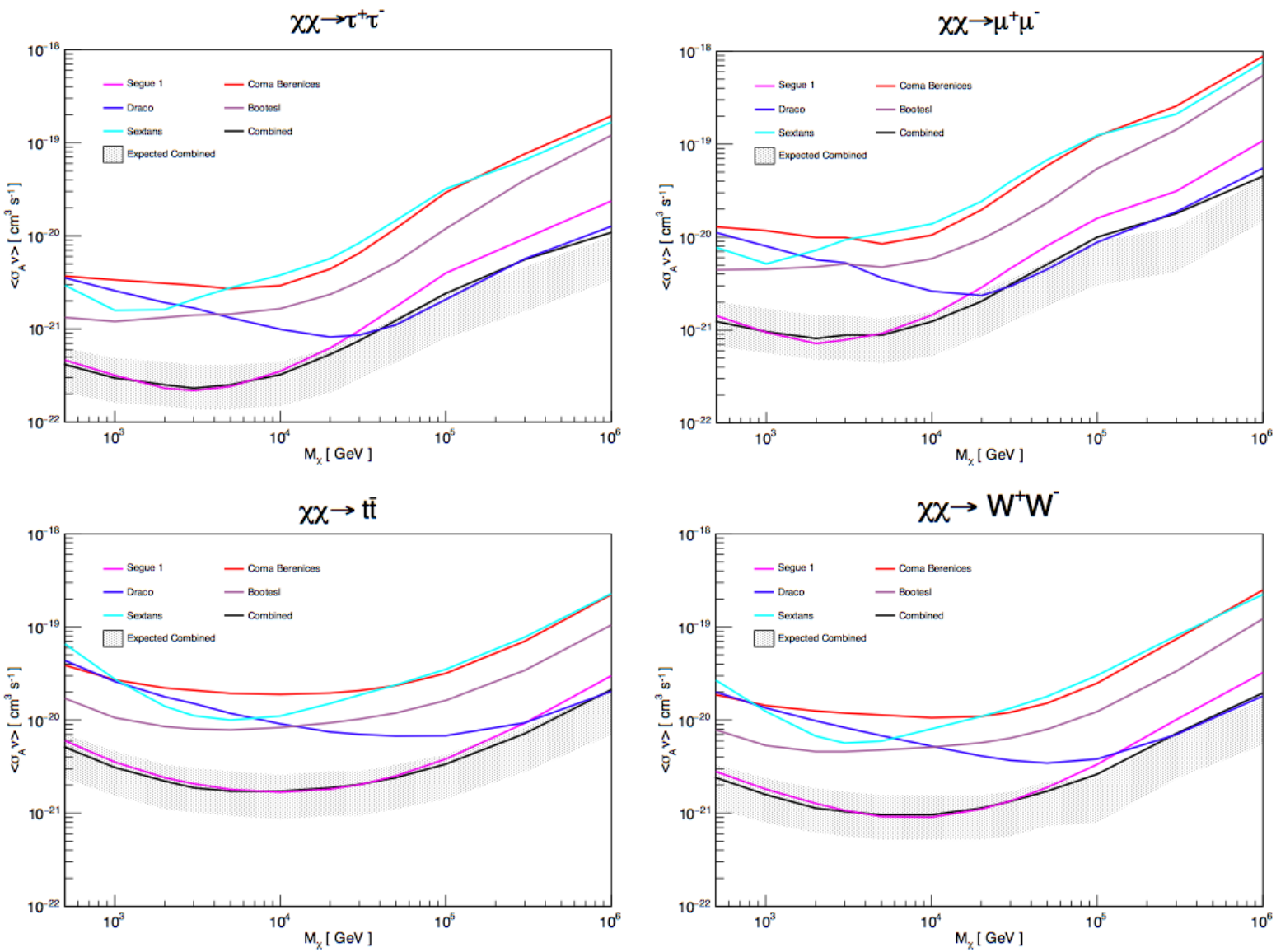
- HAWC 5-year sensitivity to the dark matter annihilation cross-section for the W^+W^- annihilation channel is similar to the $b\bar{b}$ channel
- However, the exchange of the (relatively) light gauge bosons create a velocity-dependent resonance in the cross-section, increasing it by orders of magnitude. This is known as “Sommerfeld Enhancement”.
- For these channels, HAWC can probe thermal cross-sections



Data for One Study

Bin #	Obs. Sig	Bkg	Expected bbbar	Expected tautau	Expected WW
0	1126	3.18E7	239	278	226
1	3056	1.12E7	171	238	168
2	-809	2.47E6	84	145	88
3	-694	4.67E5	35	84	40
4	-31	4.55E5	16	54	20
5	-68	7.01E3	4.7	26	6.7
6	25	1.42E3	0.76	8.3	1.3
7	6	95.99	0.13	2.1	0.23
8	3	11.04	0.01	0.19	0.01
9	4	15.88	0	0.08	0

Data is for Segue 1 with a 10 TeV DM mass and $\langle\sigma v\rangle = 10^{-22}\ cm^3/s$


χχ→τ+τ-
χχ→μ+μ-
χχ→ tt̄
χχ→ W+W-
Segue 1
Coma Berenices
Draco
Bootesl
Sextans
Combined
Expected Combined
<σA v> [cm3 s-1]
MX [GeV]