Indirect Dark Matter Searches with HAWC

Joe Lundeen for the HAWC Collaboration

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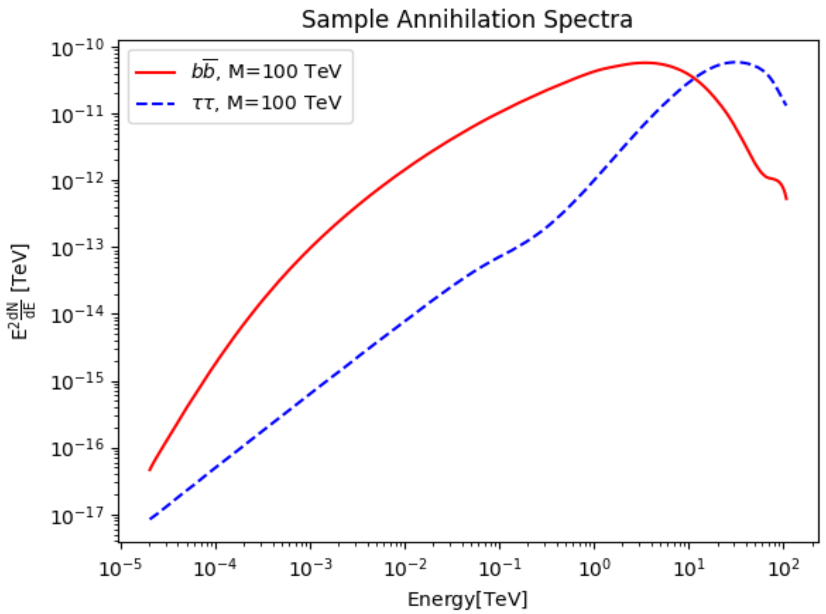
Dark Matter Gamma-ray Spectra

- WIMP dark matter can annihilate or decay to standard model particles → produce photons
- Energy spectrum characterized by hard cutoff at DM mass
- Search for gamma-ray excesses with characteristic shape originating from known DM halos
- Can constrain velocity-weighted cross section or decay lifetime

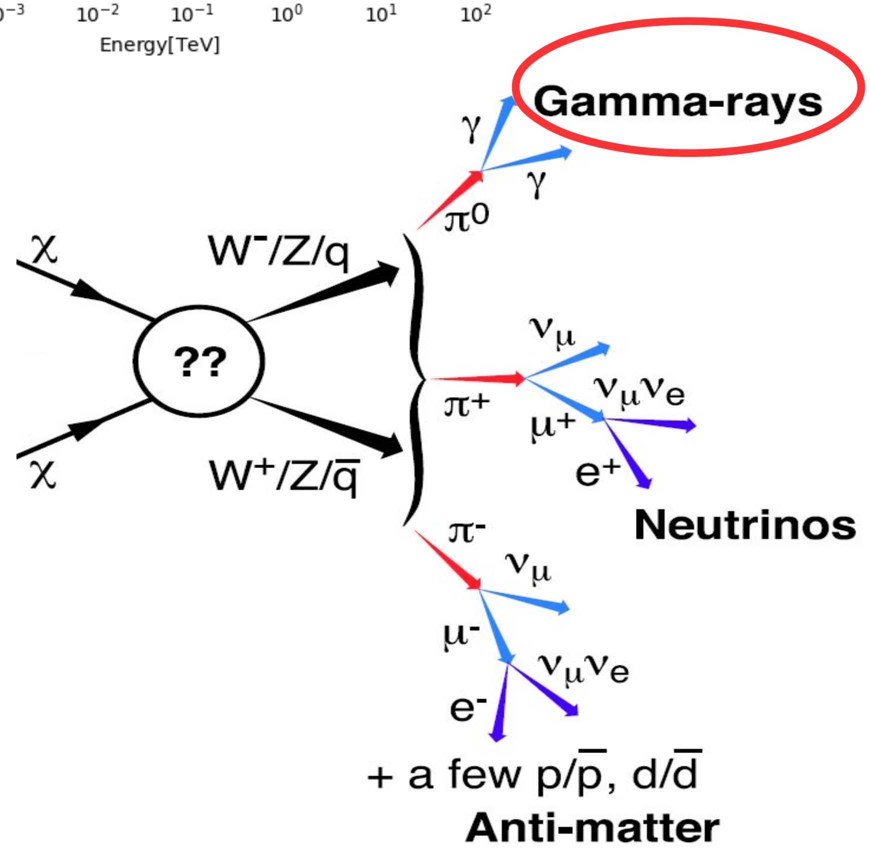


Particle Physics

$$\frac{d\Phi}{dE}_{annihilation} = \frac{J}{8\pi}\frac{\langle\sigma v\rangle}{M^2}\frac{dN(M,channel)}{dE} \qquad \frac{d\Phi}{dE}_{decay} = \frac{D}{4\pi}\frac{1}{\tau M}\frac{dN(M,channel)}{dE}$$

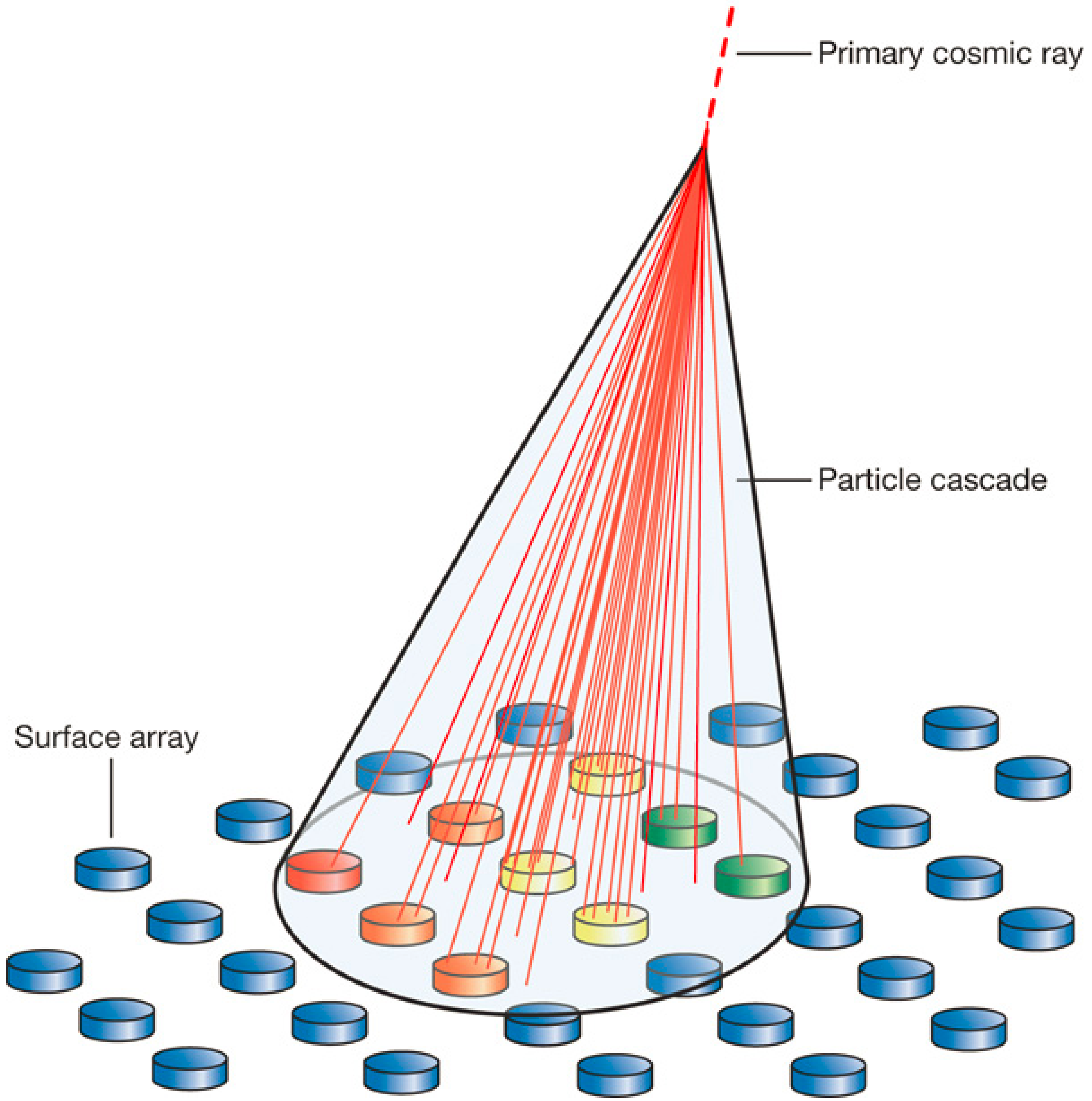
$$J = \int\int \rho_{dm}^2(l,\Omega)\,dl\,d\Omega \qquad D = \int\int \rho_{dm}(l,\Omega)\,dl\,d\Omega$$

Astrophysics



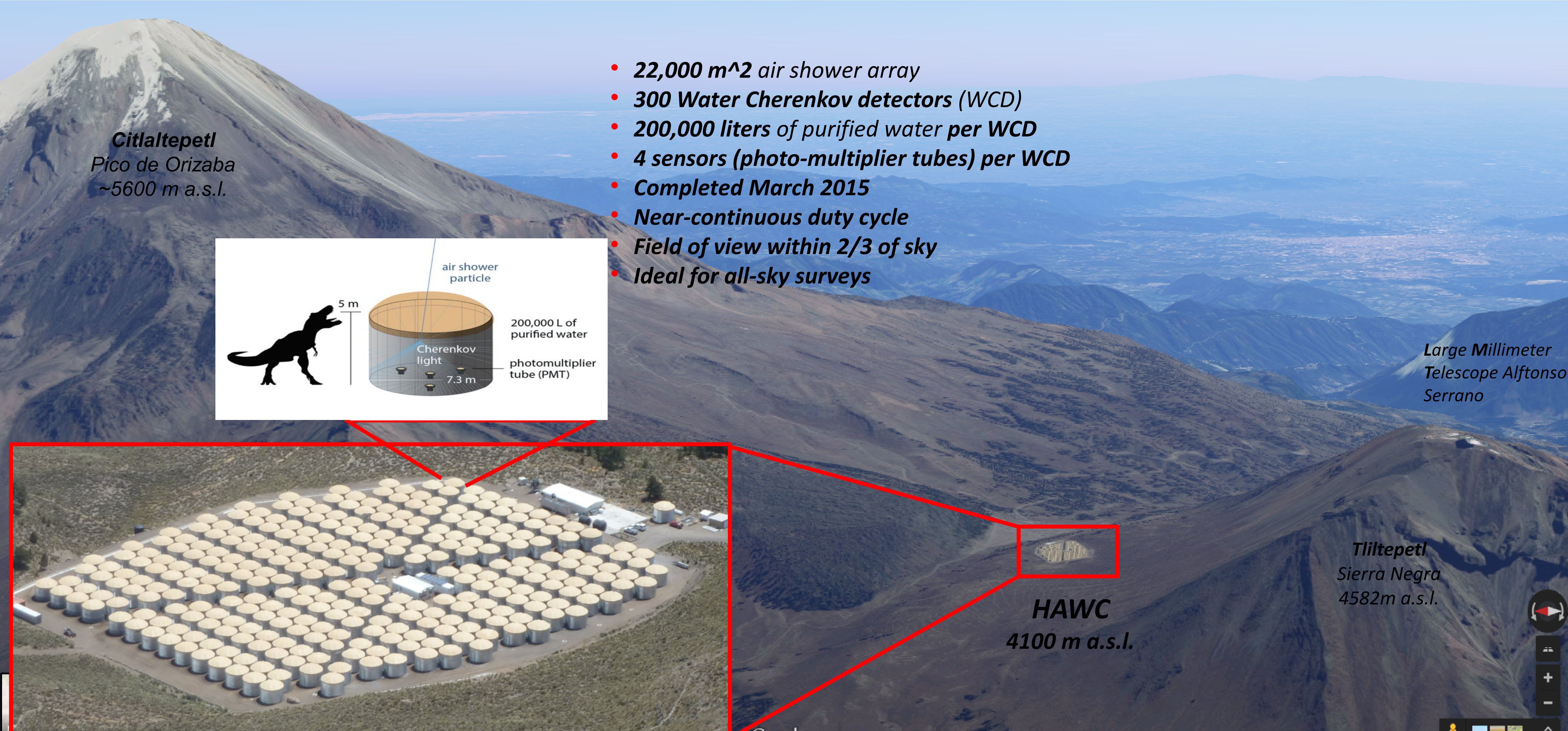
Atmospheric Air Showers

- Cosmic gamma rays interact with the atmosphere
- Disperse energy into more particles (secondaries)
- Secondaries interact with atmosphere again
- Process continues until ionization and Compton-scattering thresholds
- Gamma-ray events can be detected on the ground via these showers



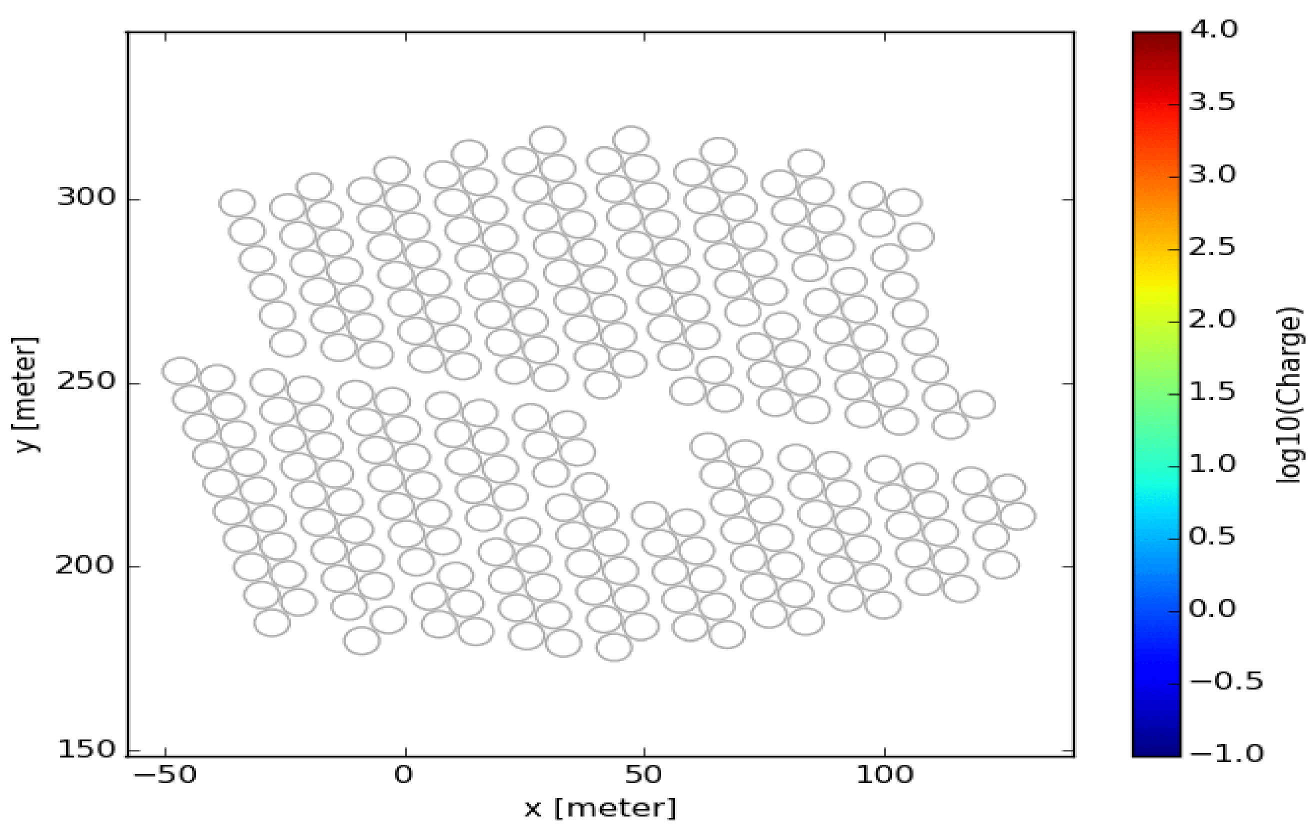
HAWC Detector

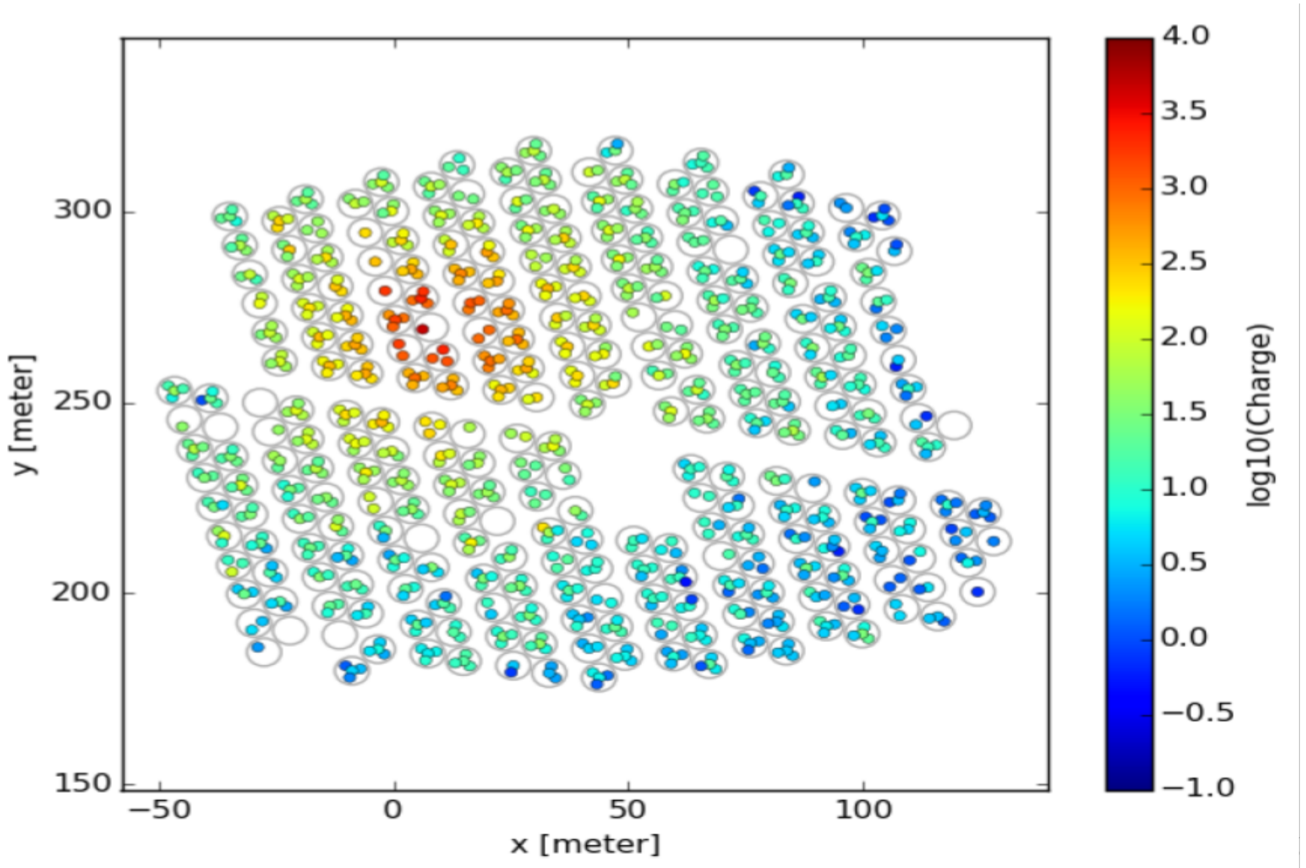
- ***22,000 m^2*** *air shower array*
- ***300 Water Cherenkov detectors*** *(WCD)*
- ***200,000 liters*** *of purified water* ***per WCD***
- ***4 sensors (photo-multiplier tubes) per WCD***
- ***Completed March 2015***
- ***Near-continuous duty cycle***
- ***Field of view within 2/3 of sky***
- ***Ideal for all-sky surveys***



HAWC Data

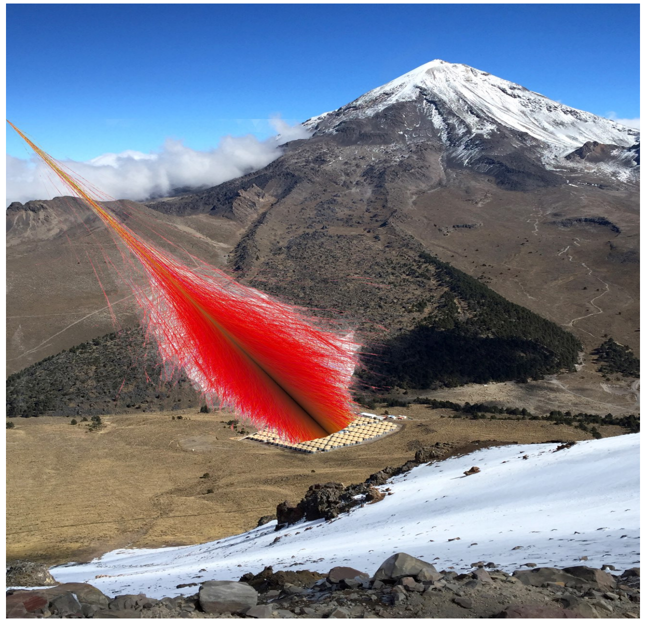
- Raw data consists of time a tank triggers and intensity recorded by PMTs
- Energy deposited on array corresponds to primary gamma-ray energy
- Direction and event classification are derived using lateral distribution of charge

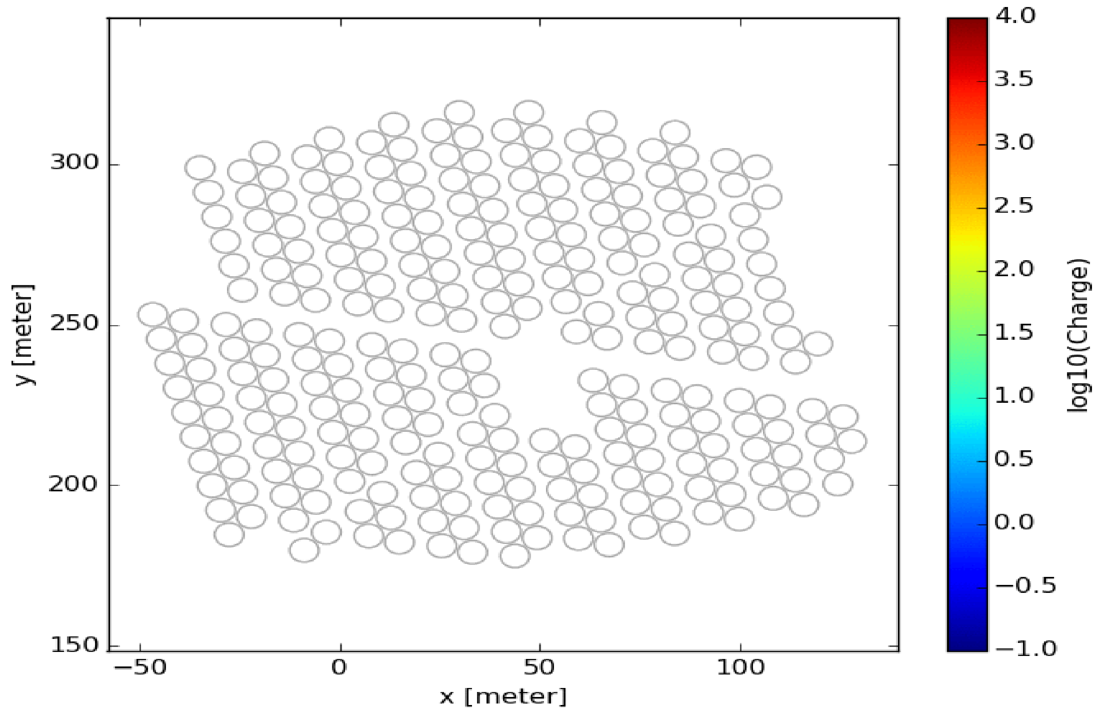


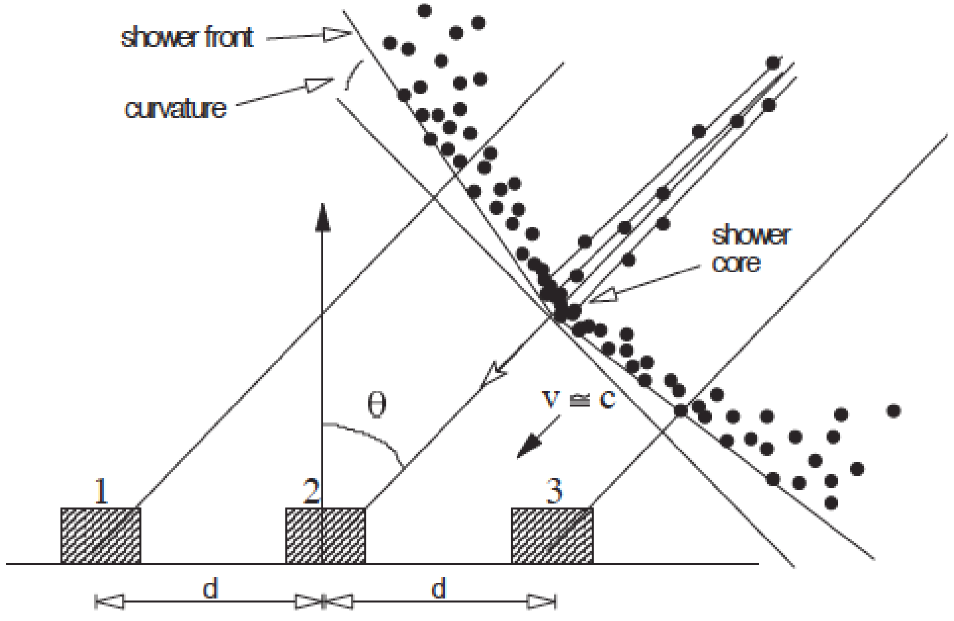


Timing and Angle Fitting

- Use relative timing of PMT hits to reconstruct shower plane → gamma-ray arrival direction

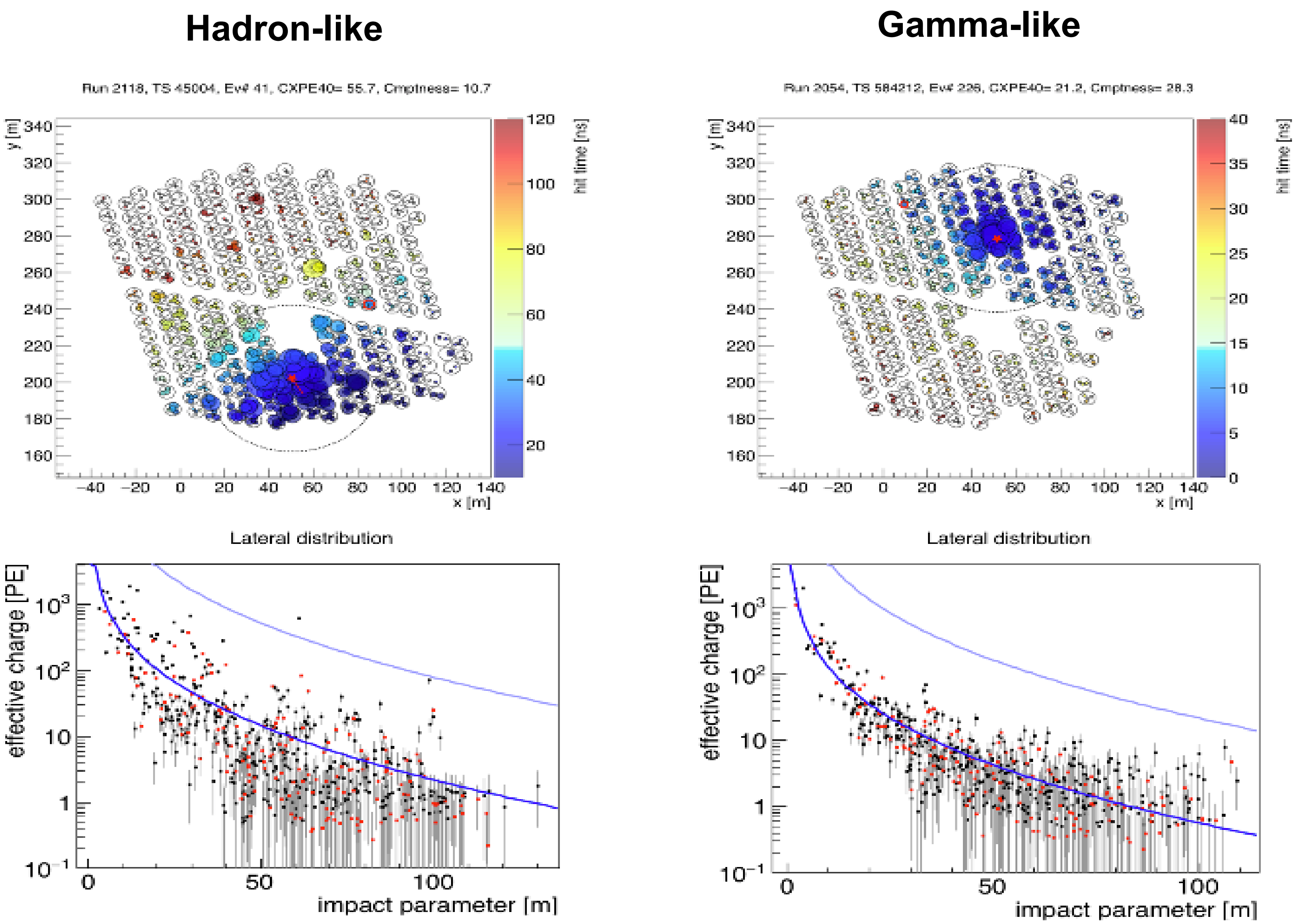






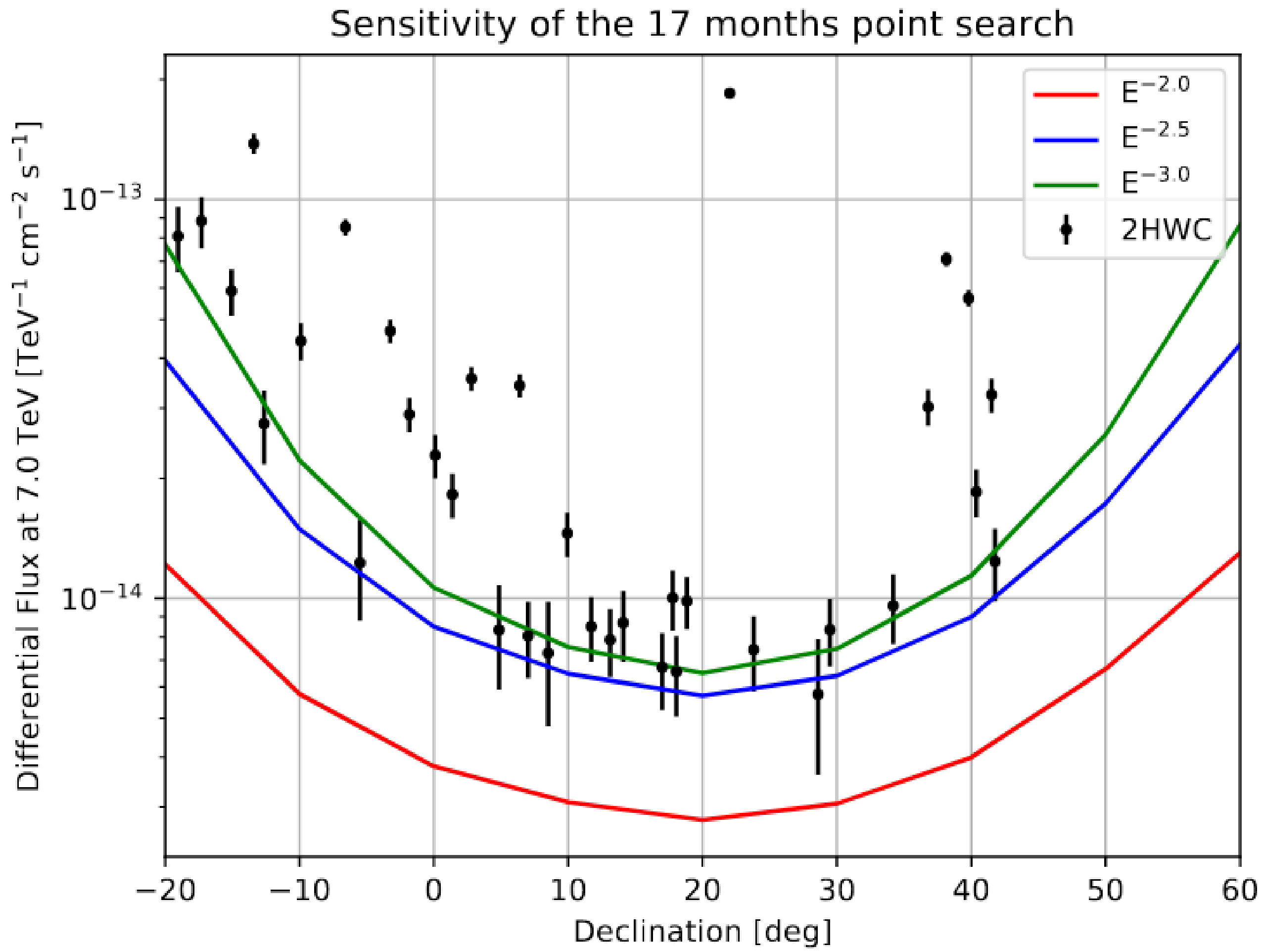
Gamma/Hadron Separation

- Need to separate gamma rays from massive cosmic rays (protons, nuclei etc.)
- Gamma rays travel in the direction they originate from
- Use cuts based on lateral distribution of charge
- Cosmic rays trigger larger signals further from shower core
- Gamma-ray showers are more uniform



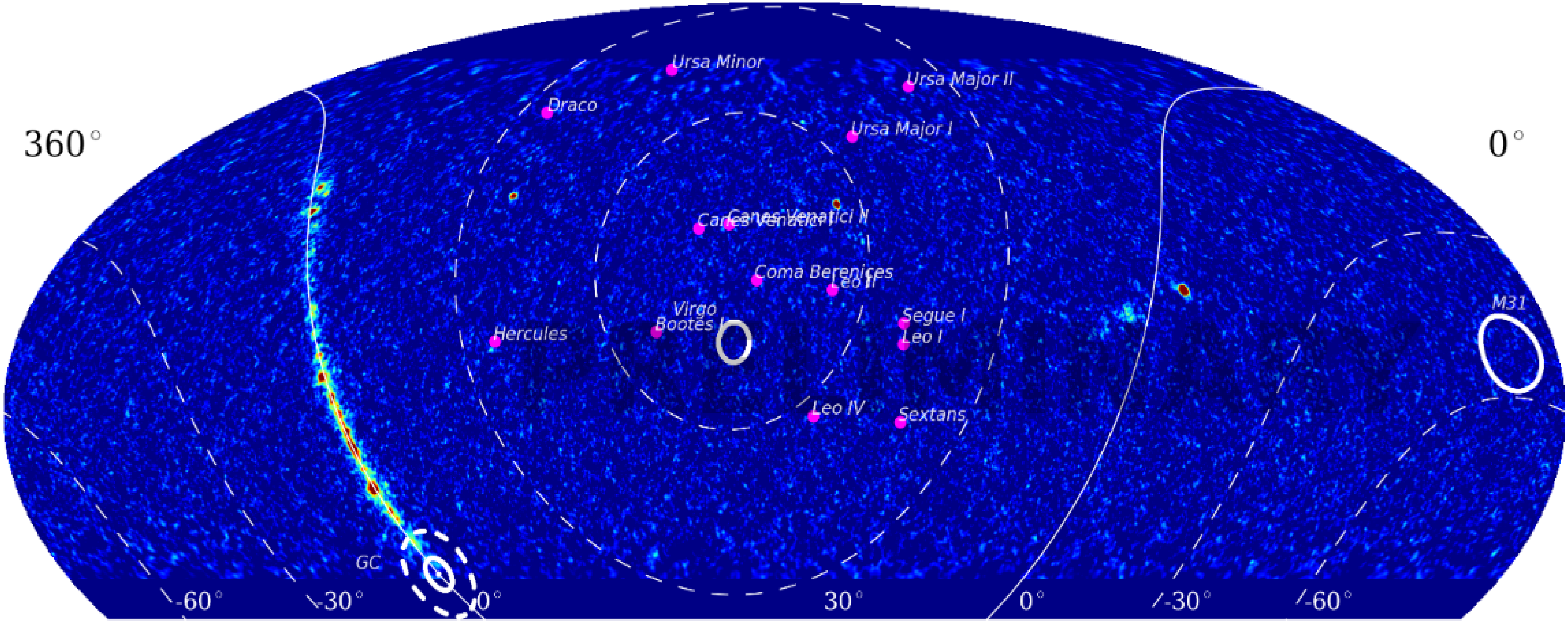
Using HAWC for Dark Matter

- Wide simultaneous field of view (~2 sr)
  - Sensitive to highly-extended sources
  - Direct integration for background estimation
- Observation of ~2/3 of sky every day
  - Ability to survey for new sources
  - Can search for DM in multiple regions simultaneously → combined searches
- Archival data
- Sensitivity is declination-dependent
  - Due to atmospheric attenuation of showers
  - Better sensitivity to sources that transit overhead



Abeysekara et. al. *Astrophys.J. 843 (2017) no.1, 40*

Dark Matter Search Targets



Dwarf Galaxies

- Excellent candidates for DM searches
- Relatively sparse star population
  - No known normal-matter production mechanism for high-energy gamma-rays
  - Very little astrophysical background
- Continuous HAWC duty cycle:
  - Can easily perform combined limits
  - Can add additional limits as more are discovered

- Two Classes:

  Dwarf Spheroidal

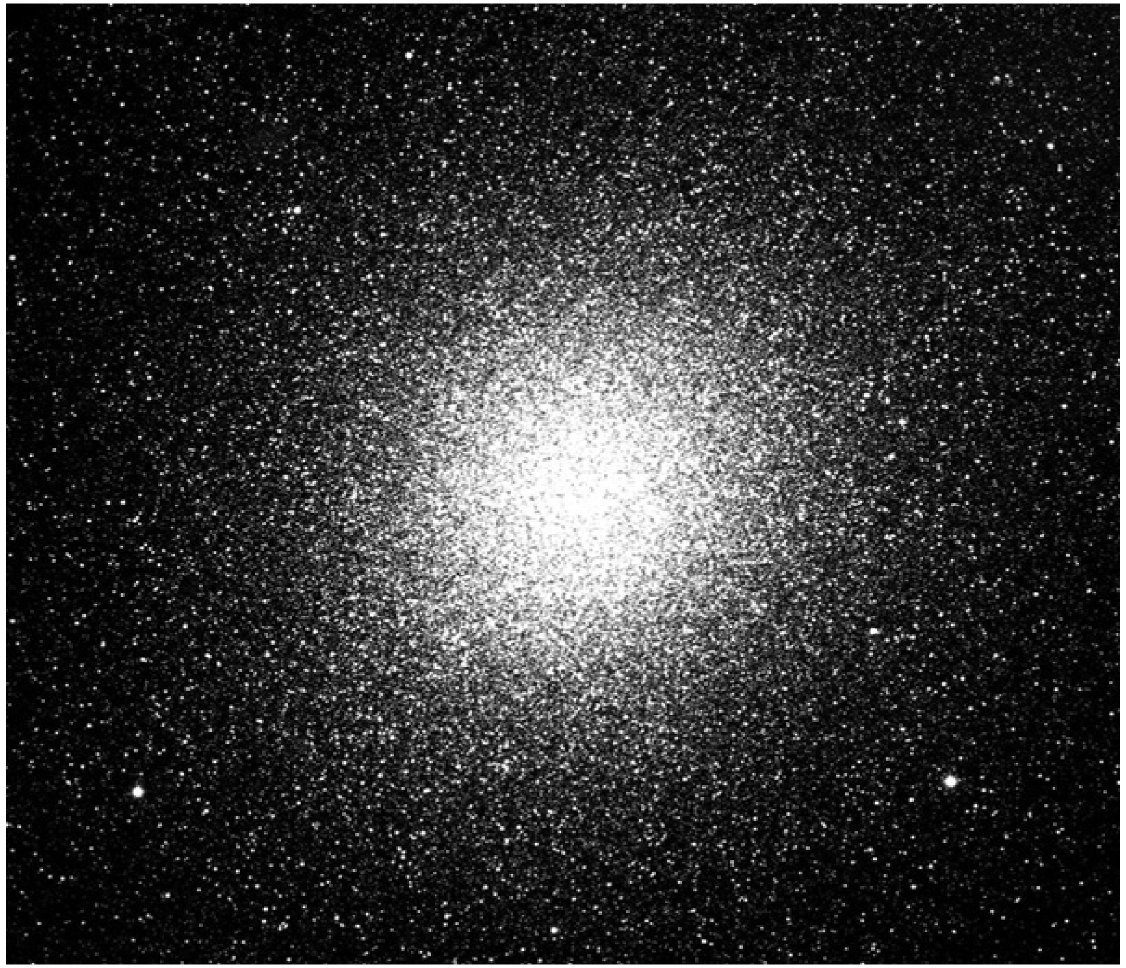
  - 15 candidates

  Dwarf Irregular

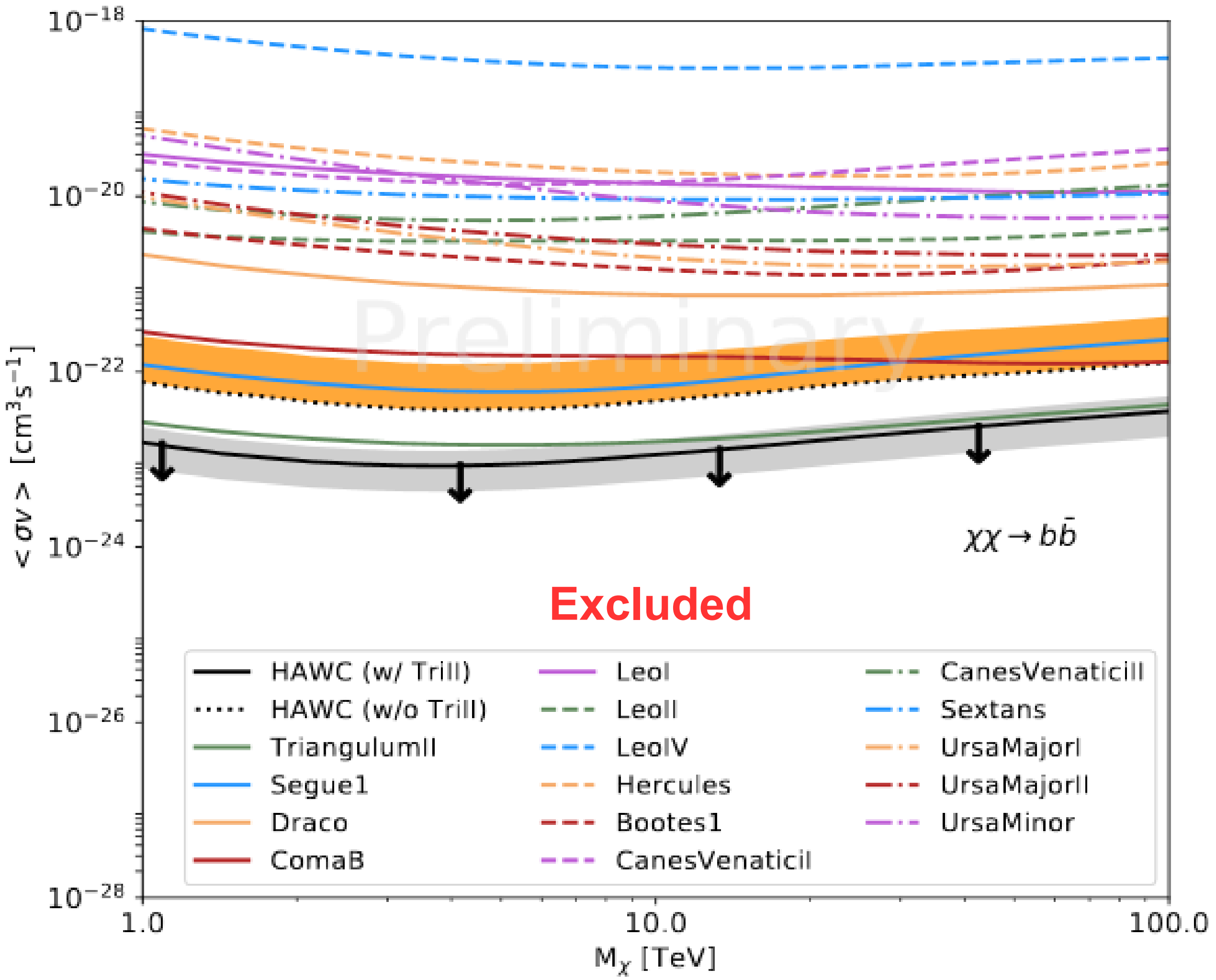
  - 31 candidates

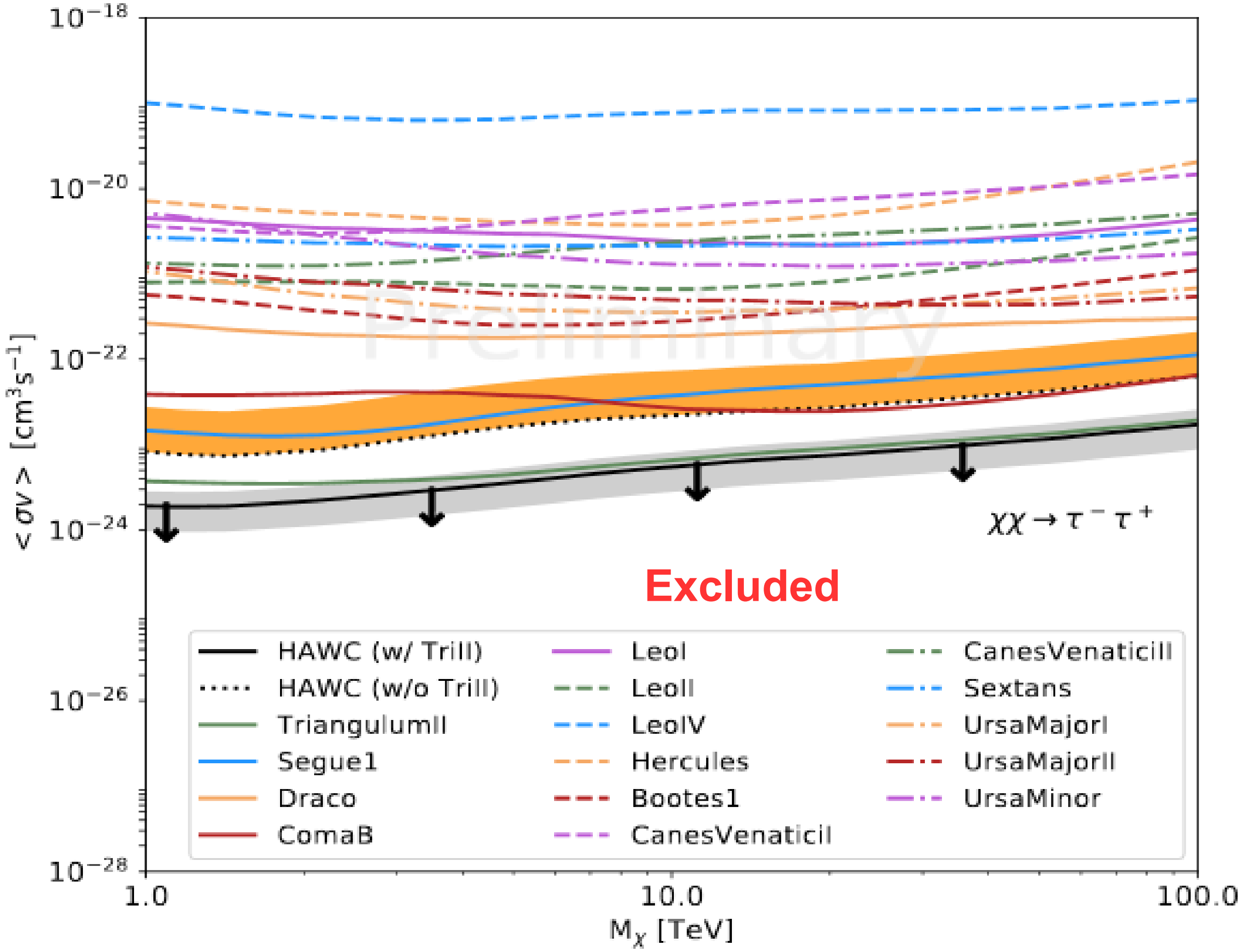
Dwarf Spheroidal Galaxies

- Characterized by regular, spherical shape
- Easy to compute J-factors
- 15 targets considered
- Treated as point-like in current analysis
  - One J for D-factor
  - Future analysis will consider extended templates
- Results published in 2017



Limits from Dwarf Spheroidals

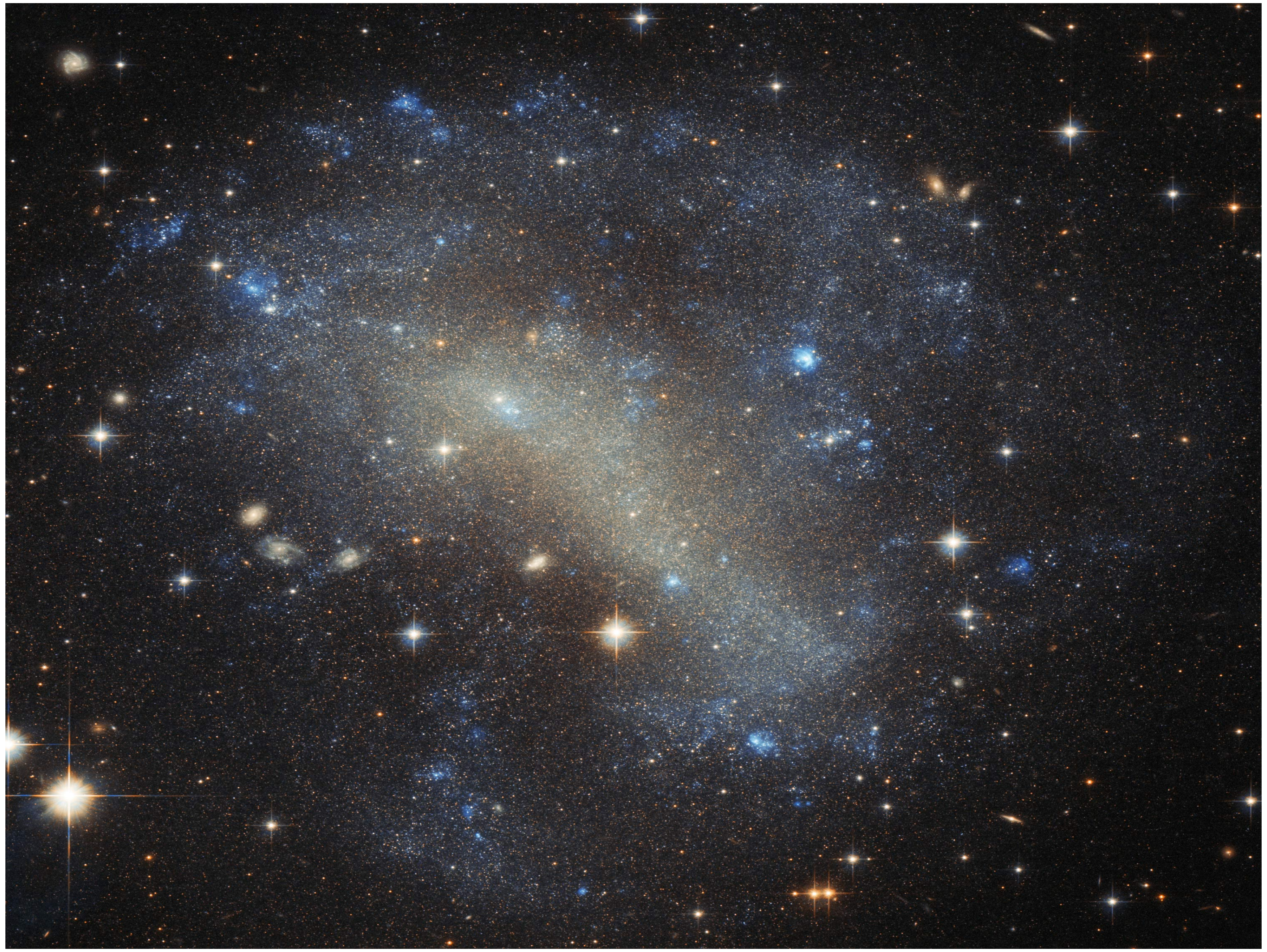




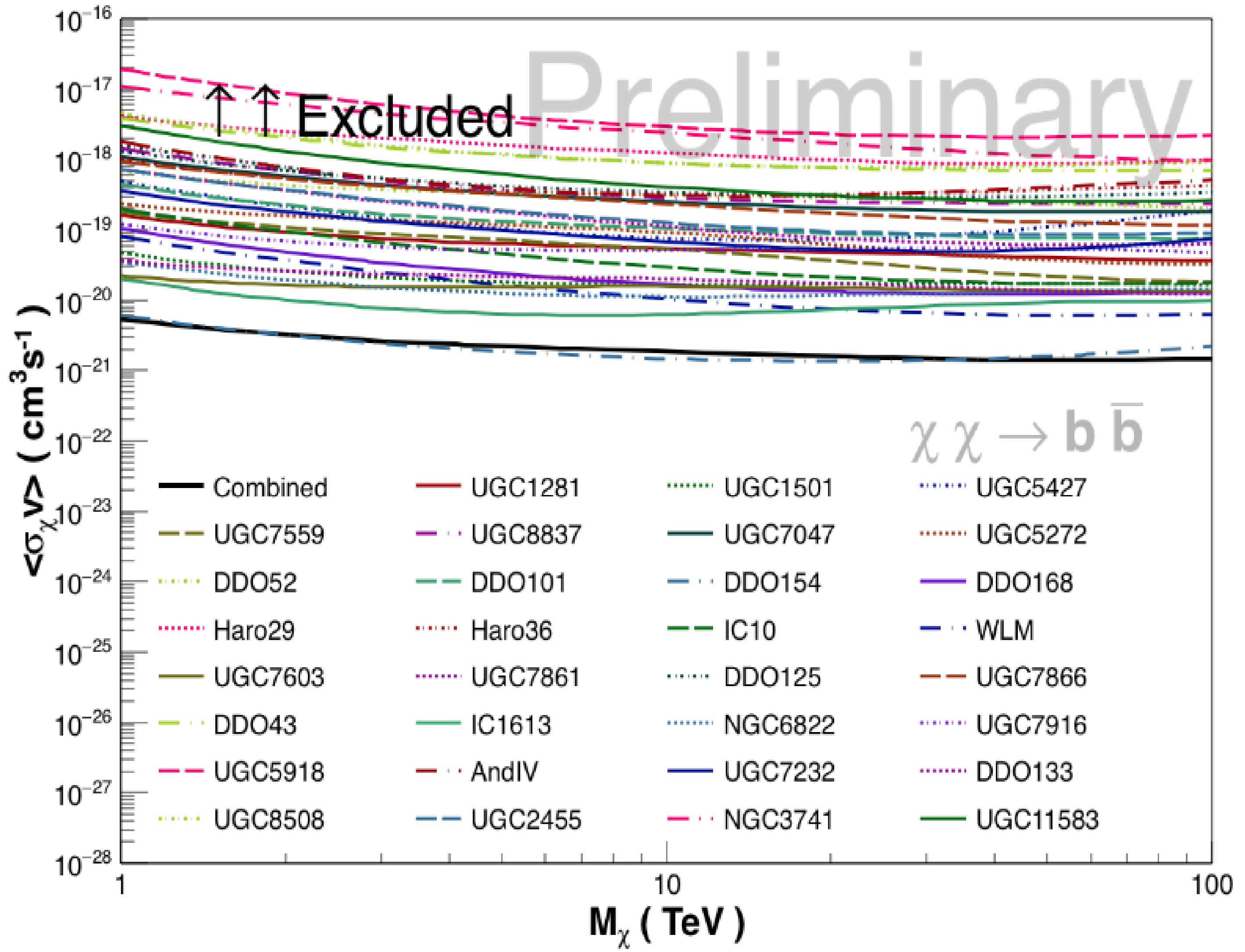
Note: The J-factor of Triangulum II is not well known. Limits are reported with and without Tri II.
See: A. Albert et al., Astrophys. J. 853 (2018) 154.

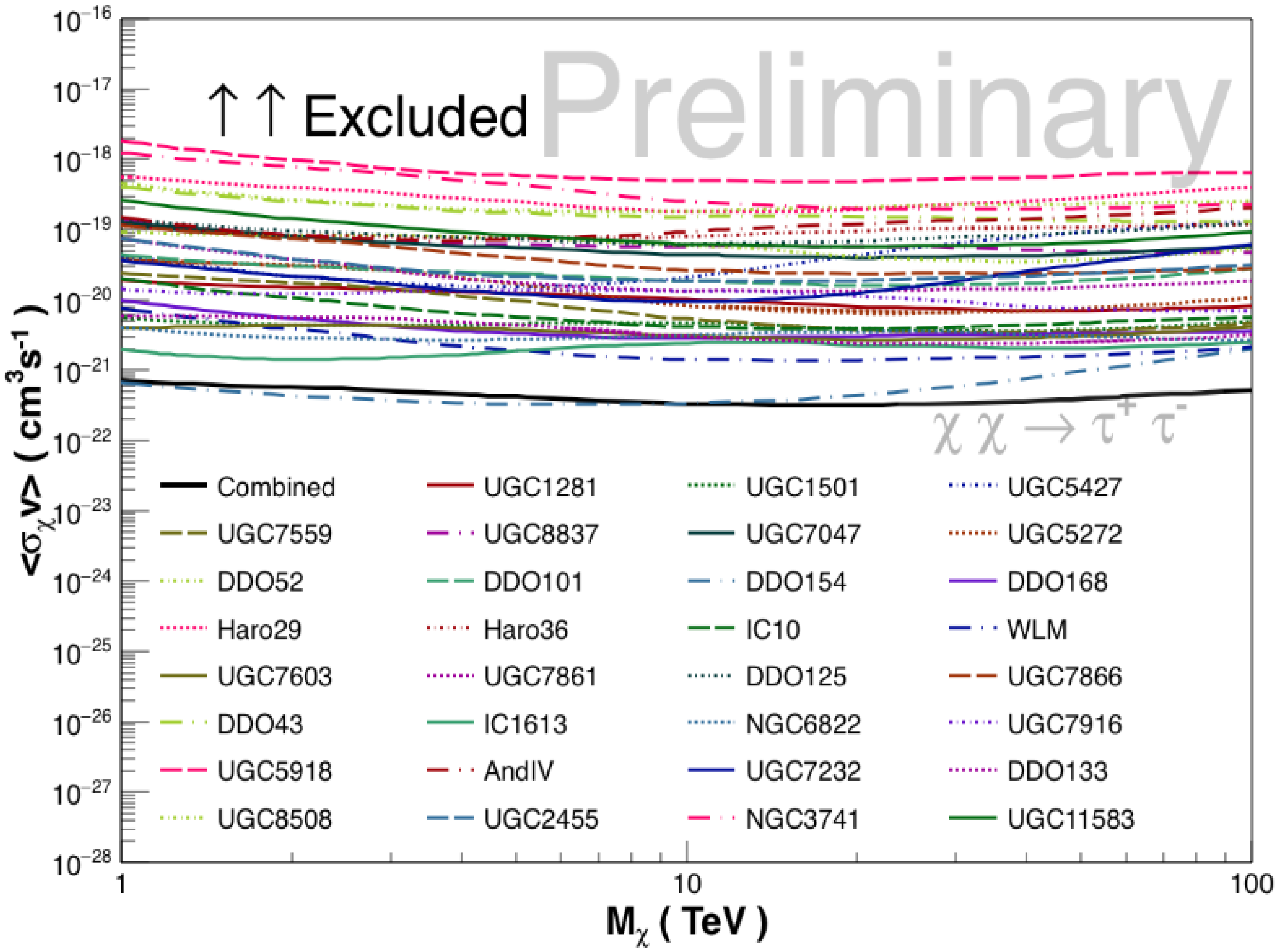
Dwarf Irregular Galaxies

- As indicated by name, non-uniform shape
- More difficult to estimate density profile
- Require careful computation of J and D-factors
- Used 31 targets
- Shown at ICRC 2019
- Full-publication still-pending



Limits from Dwarf Irregular Galaxies

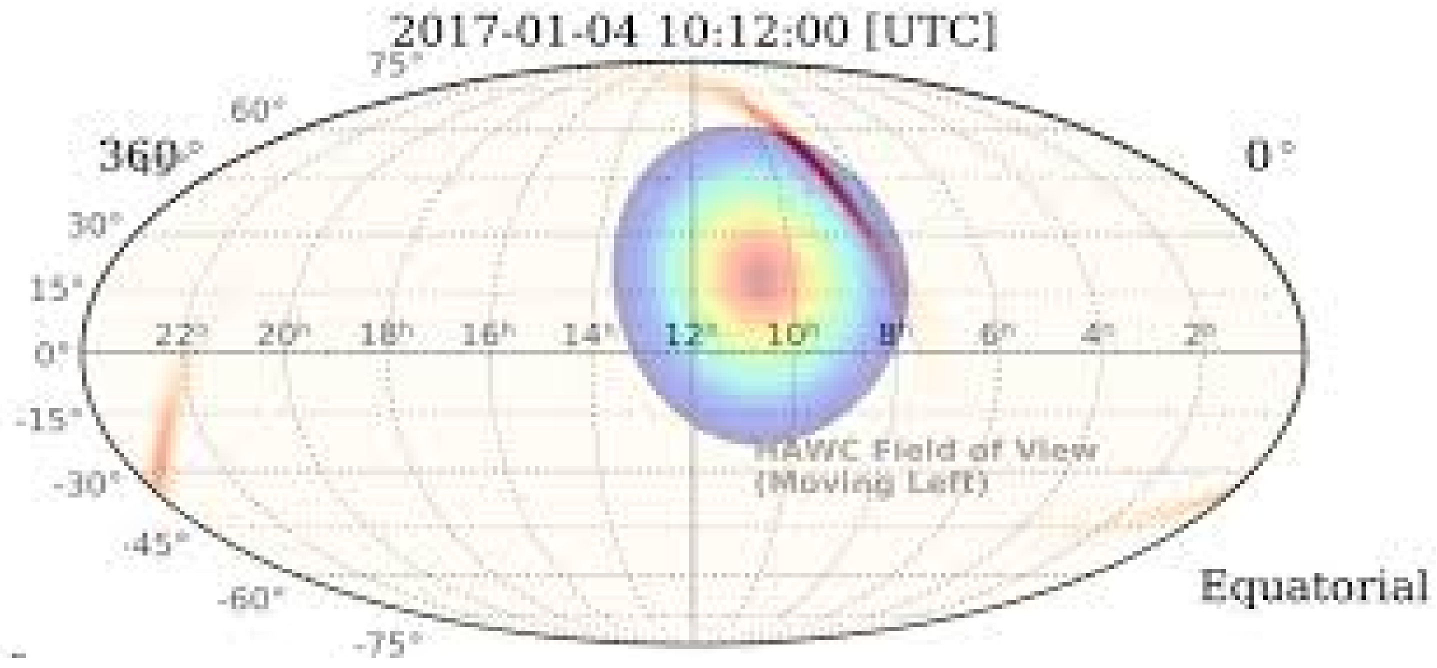




Cadena, Sergio Hernández, et al. "Constraints on cross-section and lifetime of dark matter with HAWC Observations of dwarf Irregular galaxies." arXiv preprint arXiv:1908.08884 (2019).

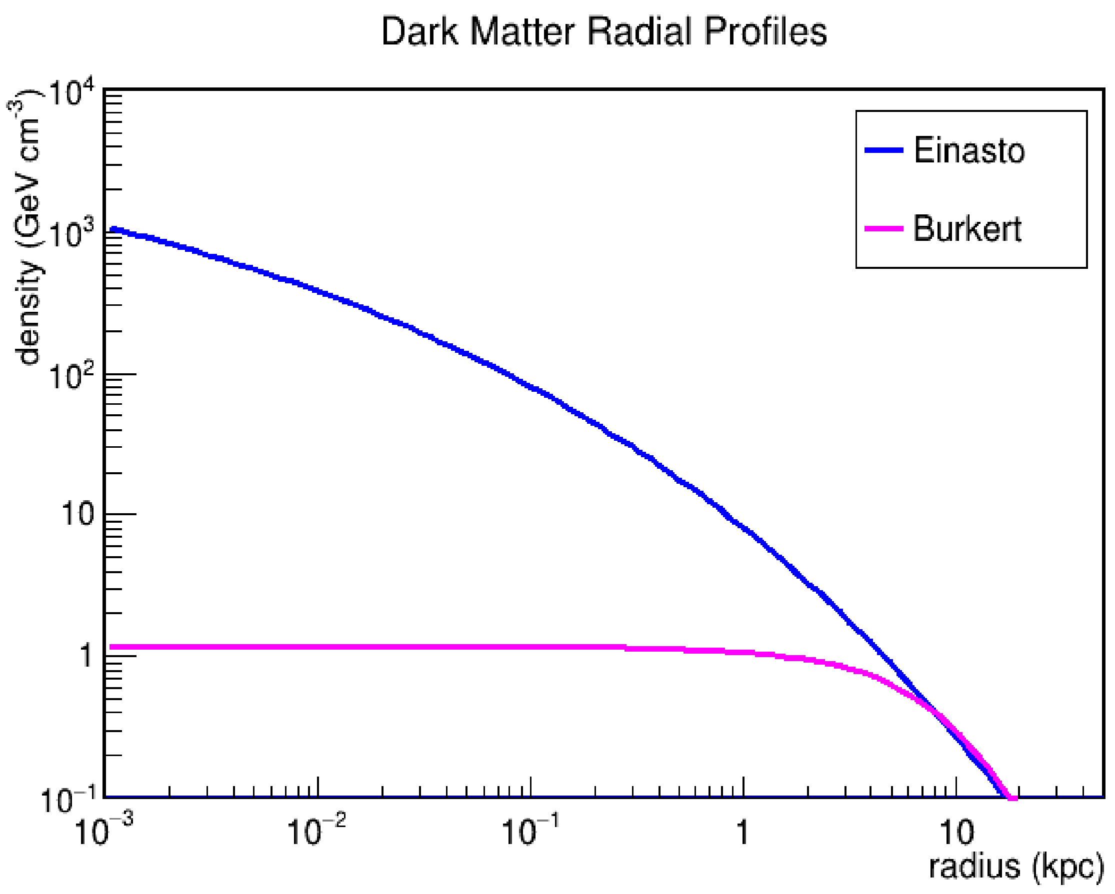
Extended Targets

- M31 galaxy, Virgo Cluster, and Galactic halo
- Wide field allows for simultaneous observation of entire source
- Allows for full treatment of morphology
- Background estimation
  - Need “off” regions sufficiently far from source avoid signal contamination
  - Wide field of view and continuous duty-cycle allows for simultaneous observation of “on” ar “off” regions
- Need to consider systematics from spatial profile
- Particularly well-suited for setting decay lower-limits



Density Profile Uncertainty

- Behavior of dark matter density not well constrained towards center of large halos
- J-factors and D-factors typically have large systematic from density profile
- Signal boosts from theorized substructure contribution



Einasto Profile (Cuspy)

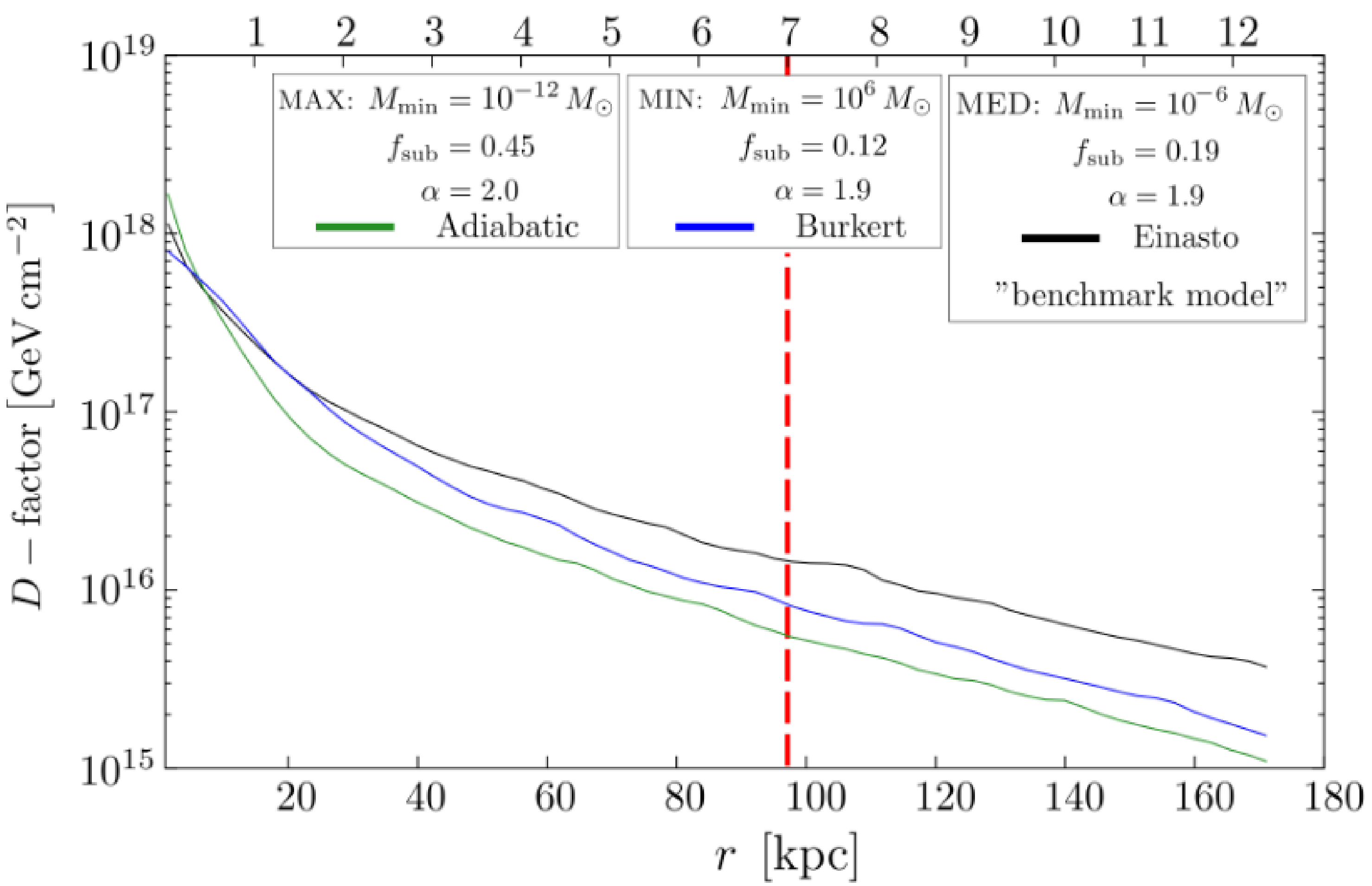
$$\rho(r) = \rho_s e^{\frac{-2}{\alpha}[(r/r_s)^{\alpha}-1]}$$

Burkert Profile (Cored)

$$\rho(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

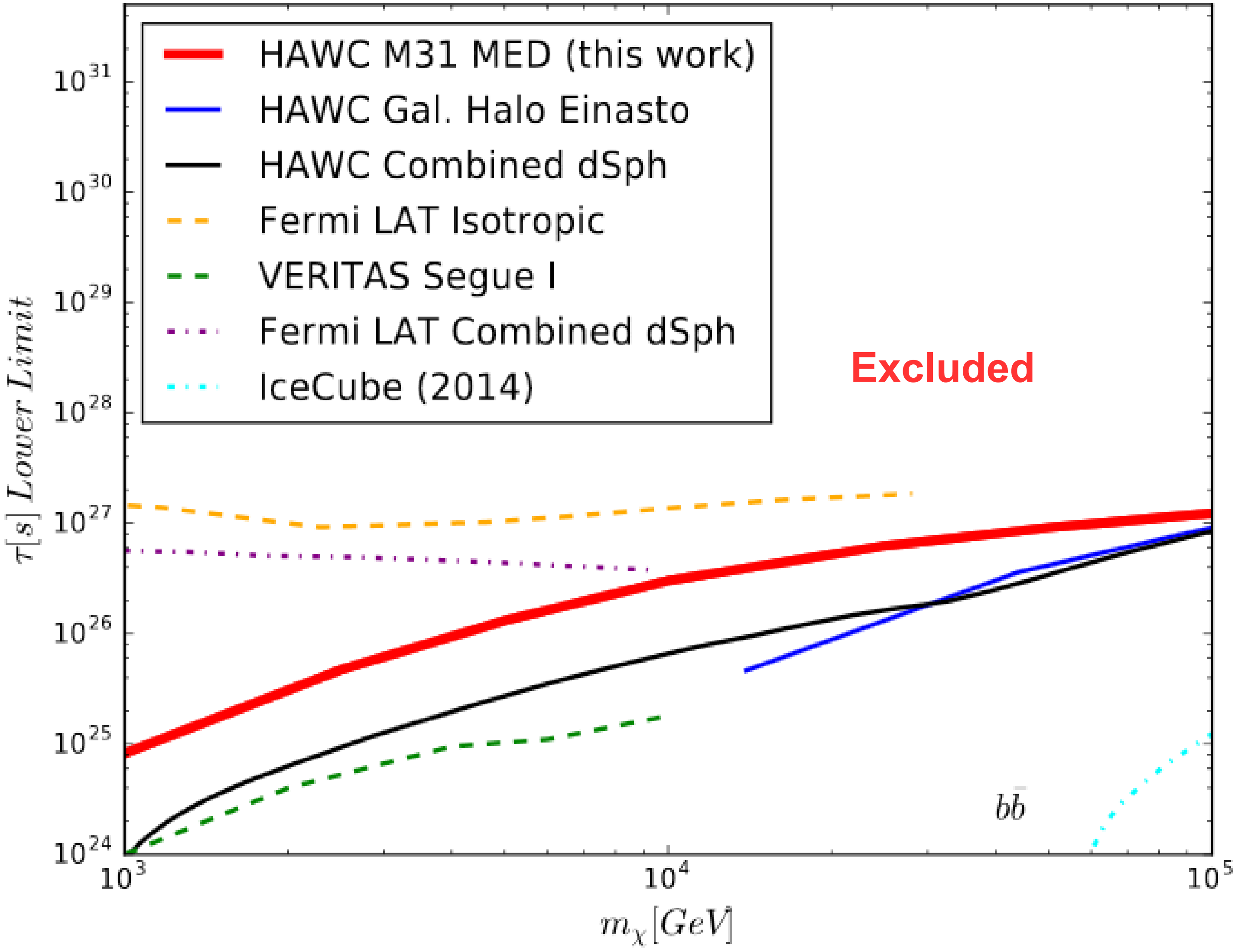
M31

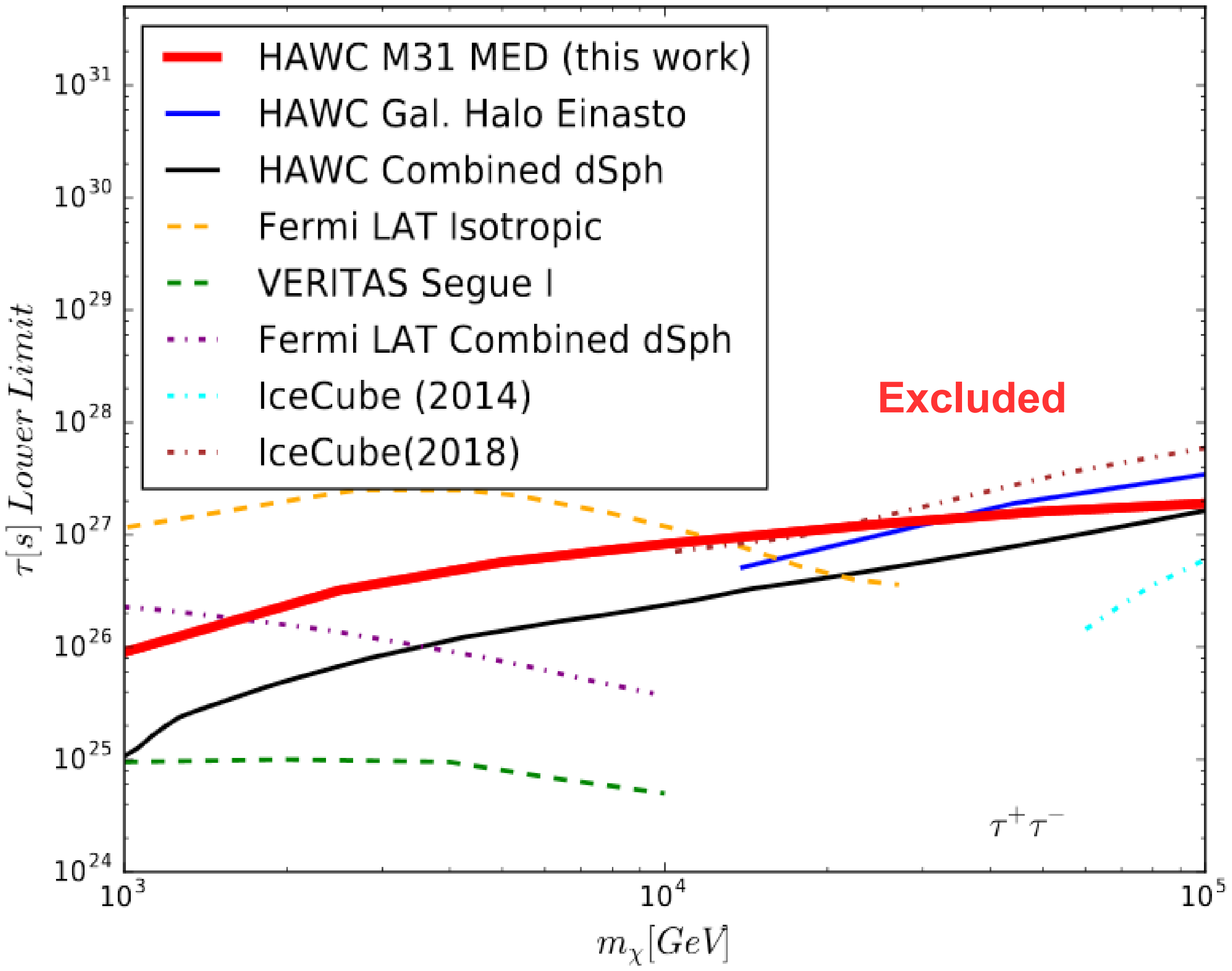
- Closest galaxy (besides the Milky Way)
  - High expected flux
- Also highly extended
  - Requires treatment of morphology
  - Considered different density profiles
- Substructure
  - Different models of substructure content considered
  - Results shown for median model
- Yields strong decay limits



See: Albert et. al. *Search for Dark Matter Gamma-ray Emission from the Andromeda Galaxy with the High-Altitude Water Cherenkov Observatory*

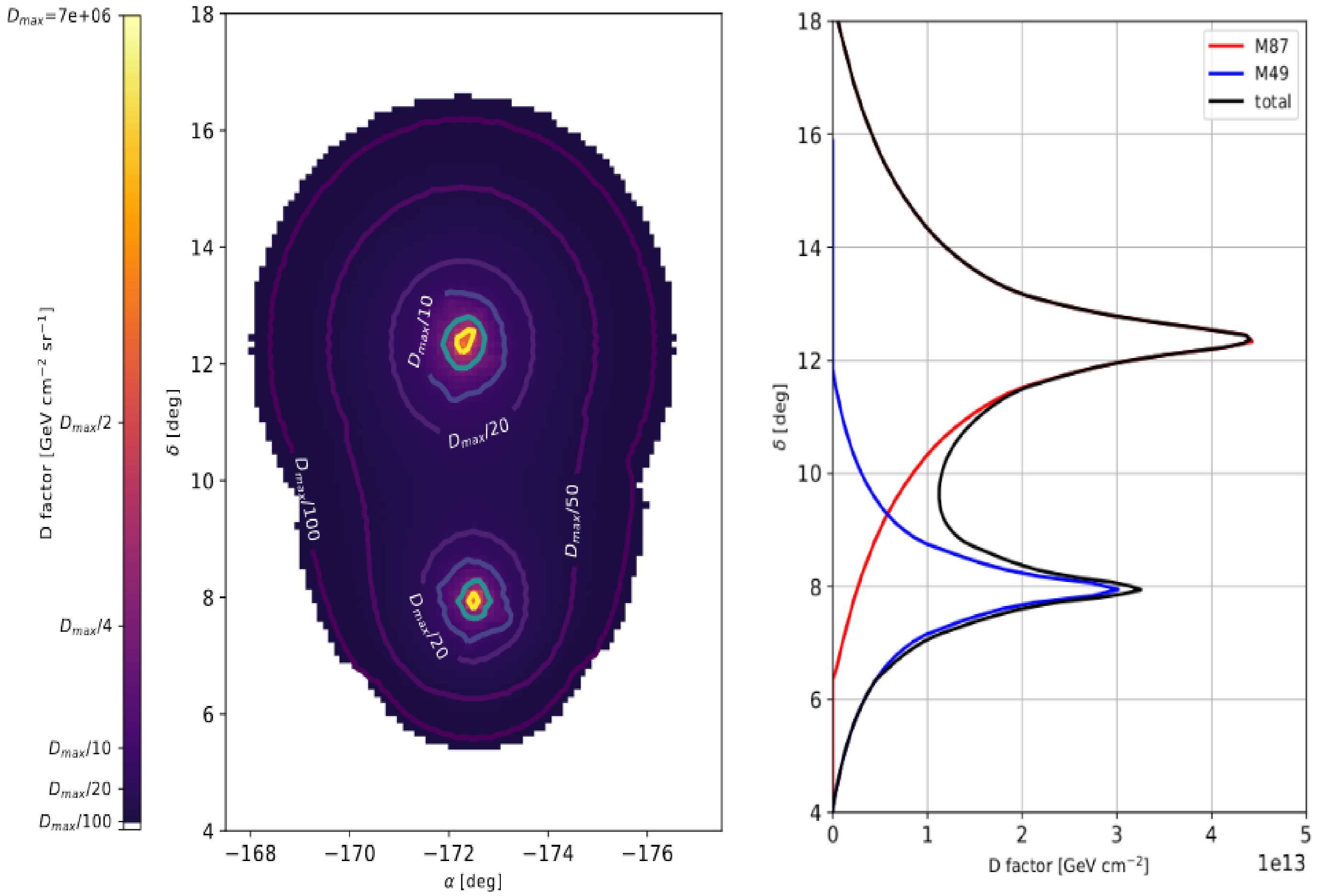
Decay Limits from M31



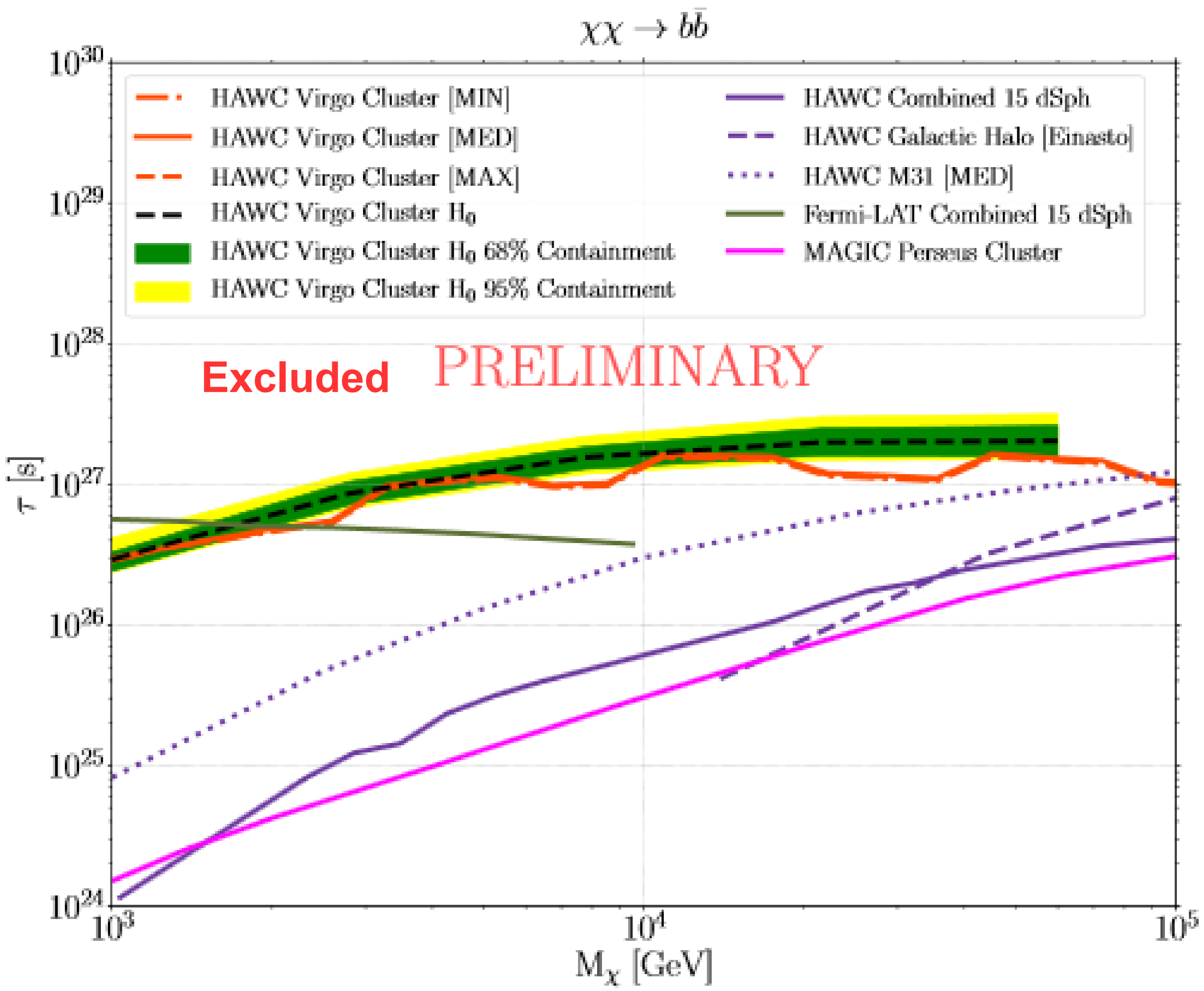


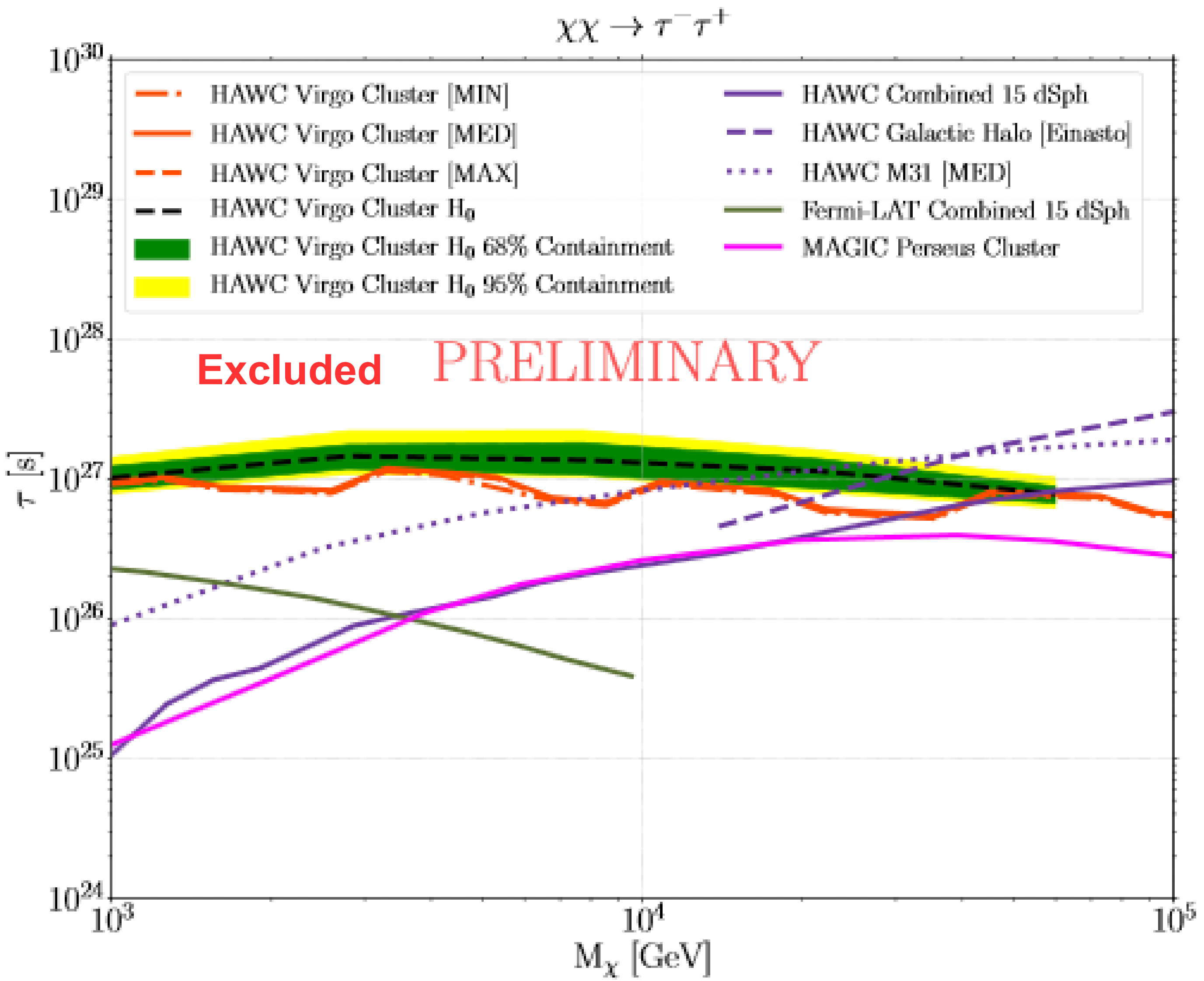
The Virgo Cluster

- Highly extended
  - ~10 x10 degrees
  - Morphology consists of two distinct peaks
- Different models of substructure contribution
  - High, median, and low substructure content models
  - Only results from median case shown here
- High dark matter content
- Nicely compliments constraints from other observations



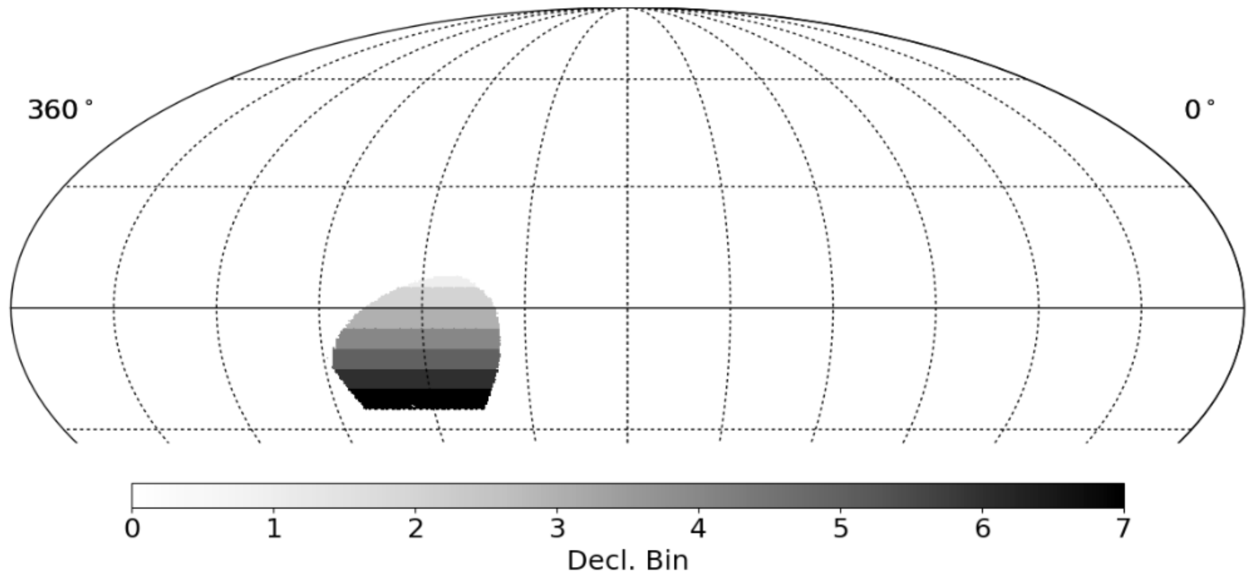
Decay Limits from Virgo

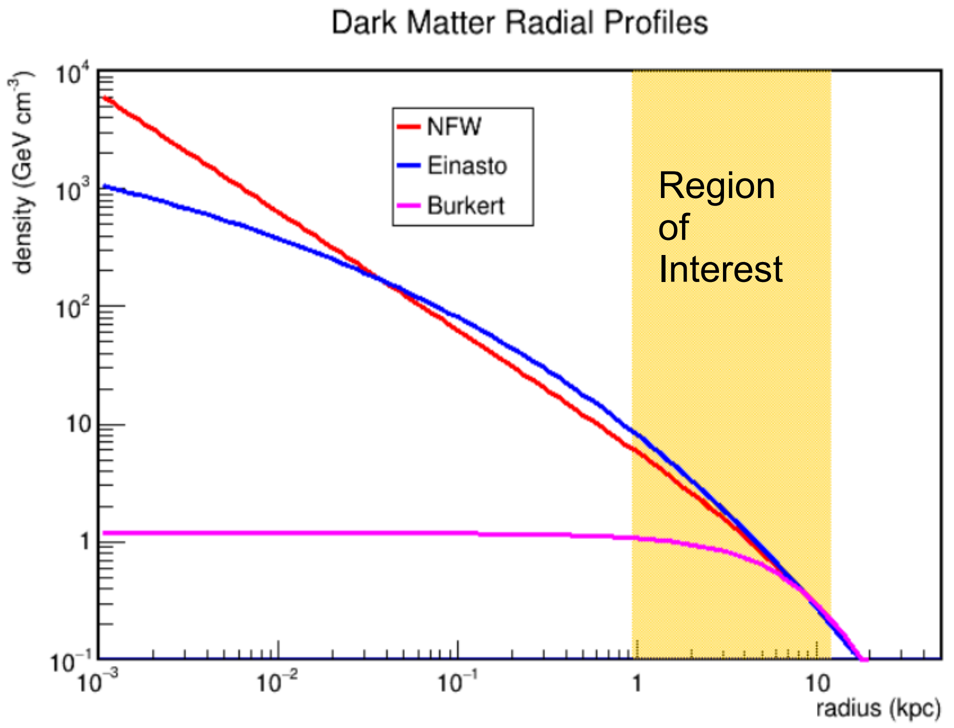




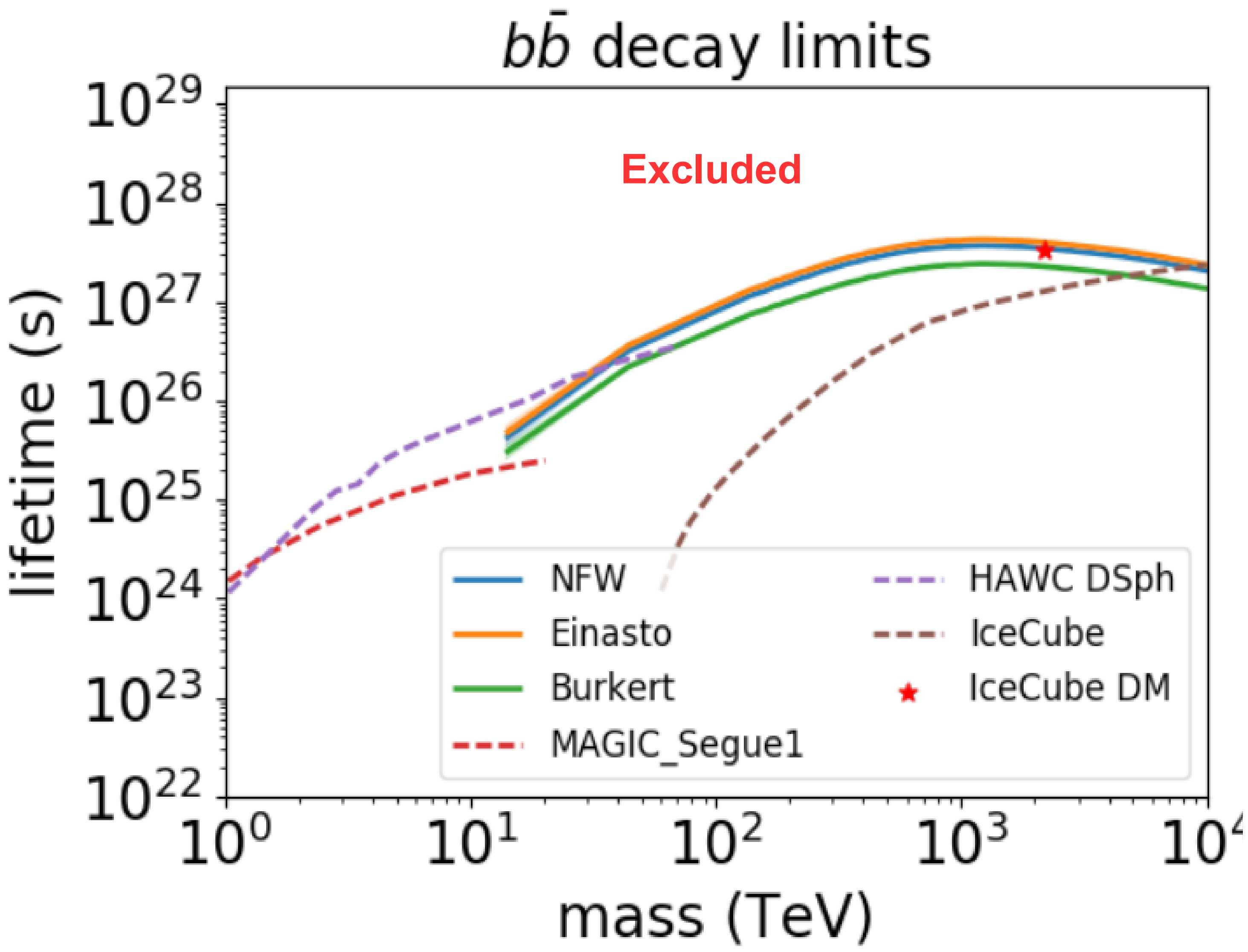
The Galactic Halo

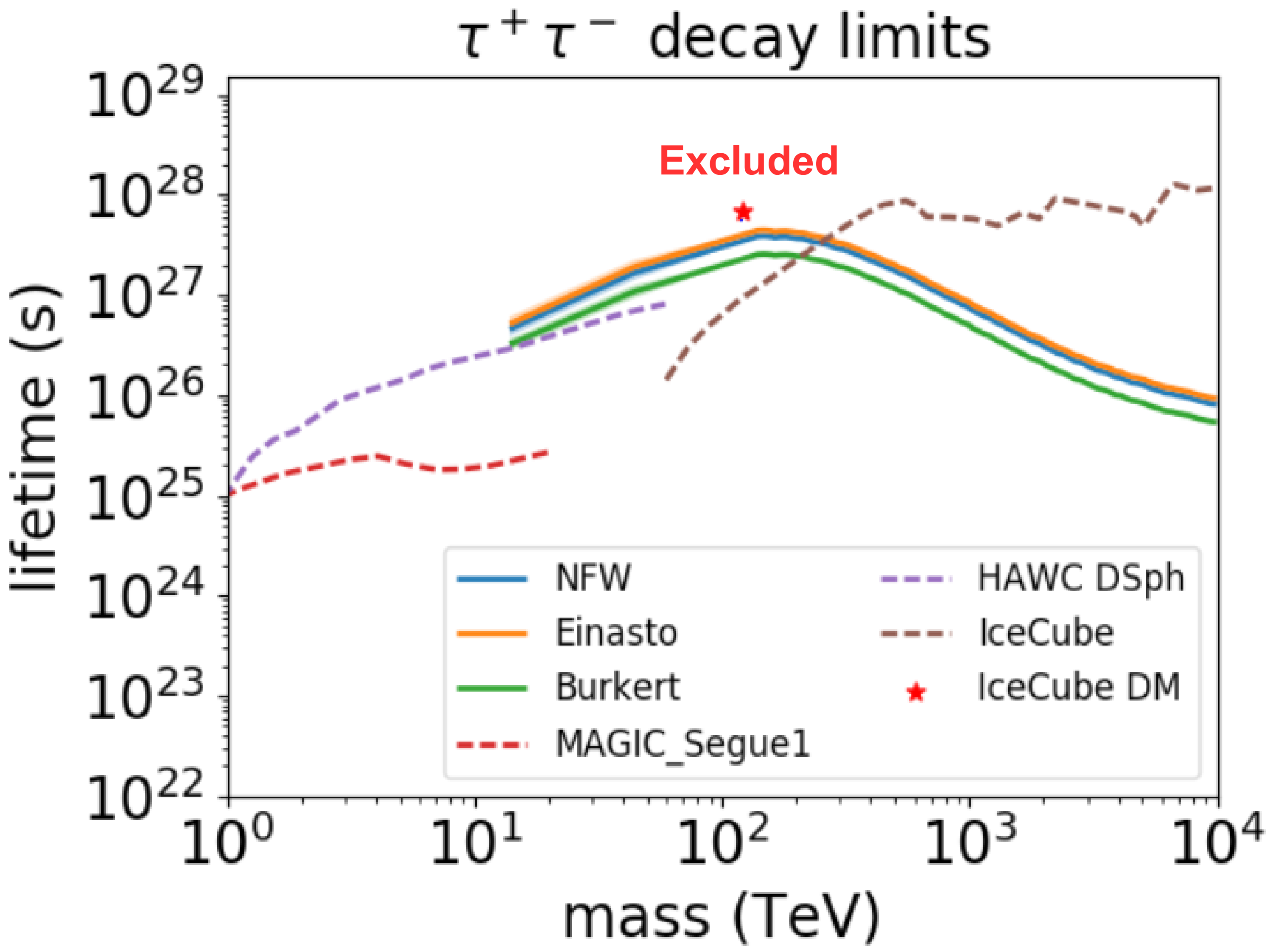
- Closest large halo → large expected flux
- Largest flux expected towards the Galactic center, however:
  - Large systematic from unconstrained density profile
  - Possible contamination from visible-matter sources
- HAWC field of view enables observation of larger regions further from the center
  - Mitigates effect of density profile
  - Avoids contamination from sources in Galactic plane
- Previous analysis in Fermi Bubble region (see: HAWC Collaboration, A. U. Abeysekara et al., JCAP 1802 (2018) 049.)





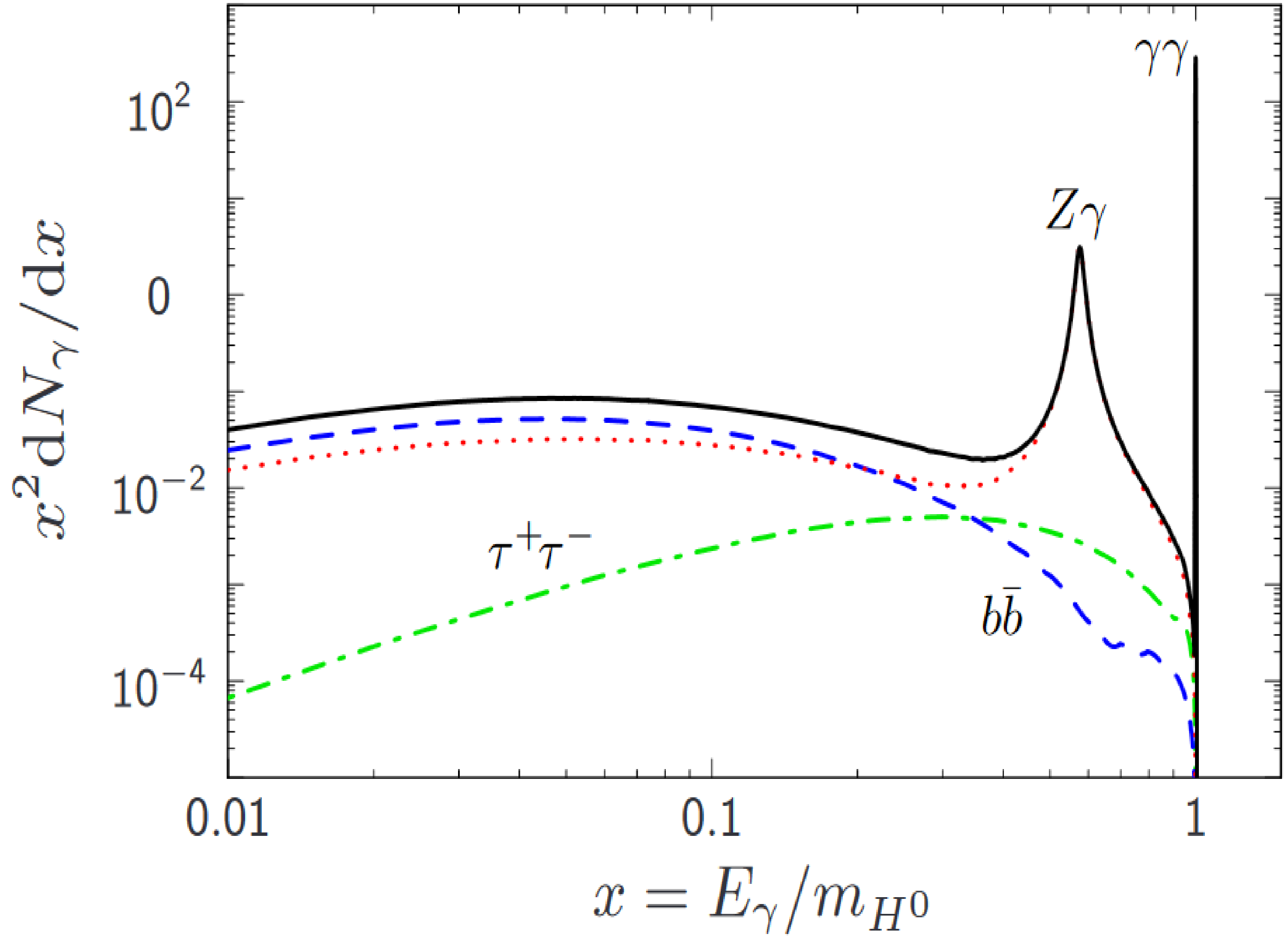
Decay Limits from the Galactic Halo





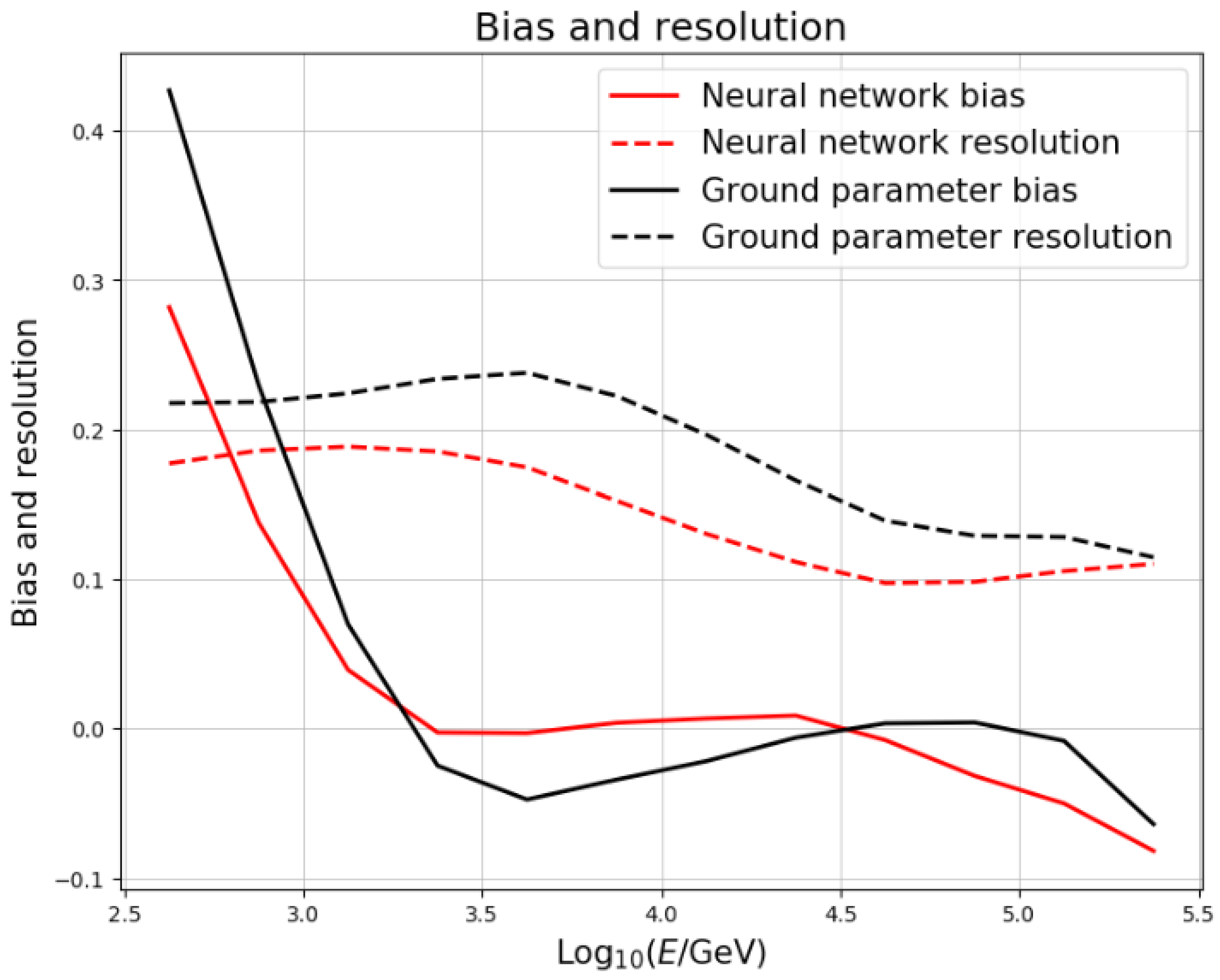
Gamma-ray Lines

- Direct annihilation of dark matter to gamma-rays
- Manifests as a delta function in energy spectrum
- "Smoking gun" for dark matter
  - Only mechanism that can produce this shape at TeV scale
  - Location of line immediately reveals the dark matter mass.
- Recently improved energy resolution allows HAWC to search for this feature



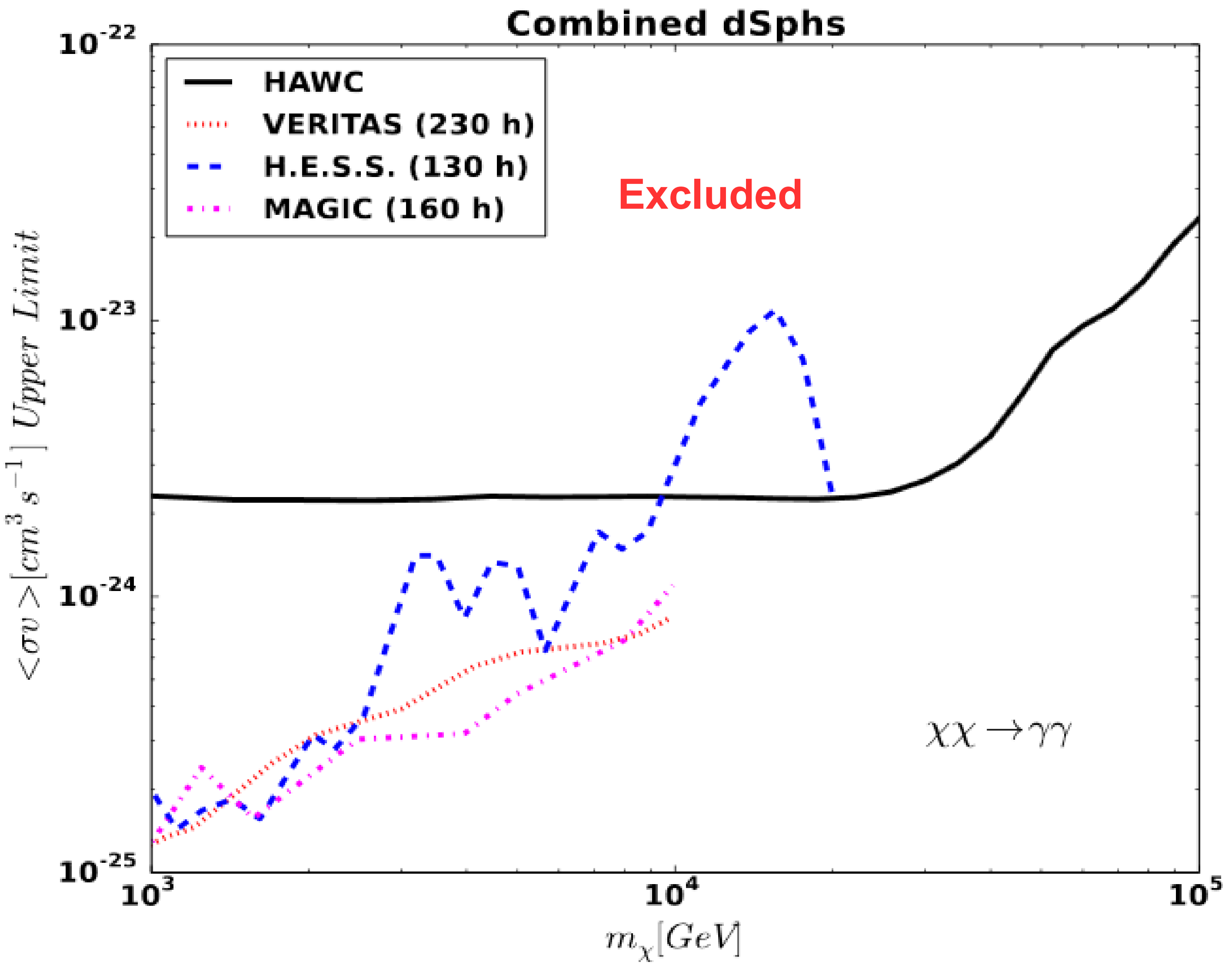
Energy Estimation

- Two direct energy estimation algorithms currently used
  - Ground parameter: based on evaluation of lateral distribution of charge
  - Neural network: trained on a set of variables expected to correlate with primary energy
- Both have resolution on the order of 15% above 1 TeV
  - Enough to distinguish possible line features
- Neural net used in this analysis
  - Better resolution at highest energies
- See: Abeysekara, A. U., et al. "Measurement of the Crab Nebula spectrum past 100 TeV with HAWC." The Astrophysical Journal 881.2 (2019): 134.



Searching for Lines in the Dwarfs

- Performed combined search using 10 dwarf spheroidal galaxies
  - Subset of those considered in continuous search
  - No significant detection of line features
- Most constraining limits above ~20 TeV
- Nicely compliment searches by IACTs



Albert, Andrea. "Searching for Gamma-ray Spectral Lines in Dwarf Galaxies with HAWC." Bulletin of the American Physical Society (2019).

Joint Limits

- Joint search of the dwarf spheroidals with multiple experiments
  - HAWC, HESS, MAGIC, VERITAS, Fermi-LAT
- Complete coverage of all multi-GeV through multi-TeV dark matter masses
- First ever analysis of its kind
- Preliminary results presented at TeVPA 2019

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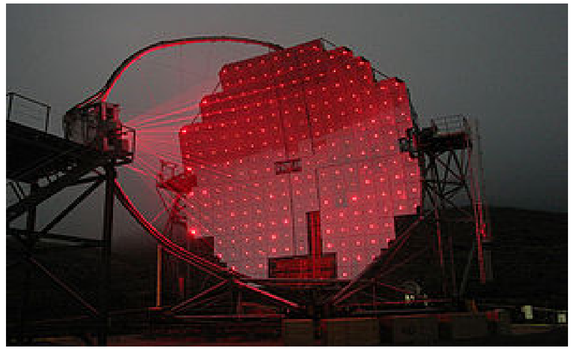

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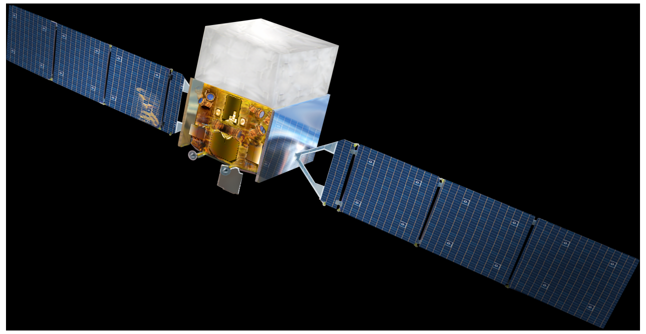

Summary

- HAWC's wide field of view and continuous duty cycle make it ideal for surveys and extended source analysis
- Can easily perform combined searches
  - Improves sensitivity of constraints
  - Currently extending to combinations with other experiments
- Sensitive to extended sources: yield strong decay limits
- Now able to search for gamma-ray lines
  - Energy estimators also allow searches at higher masses
- More results coming from Galactic halo