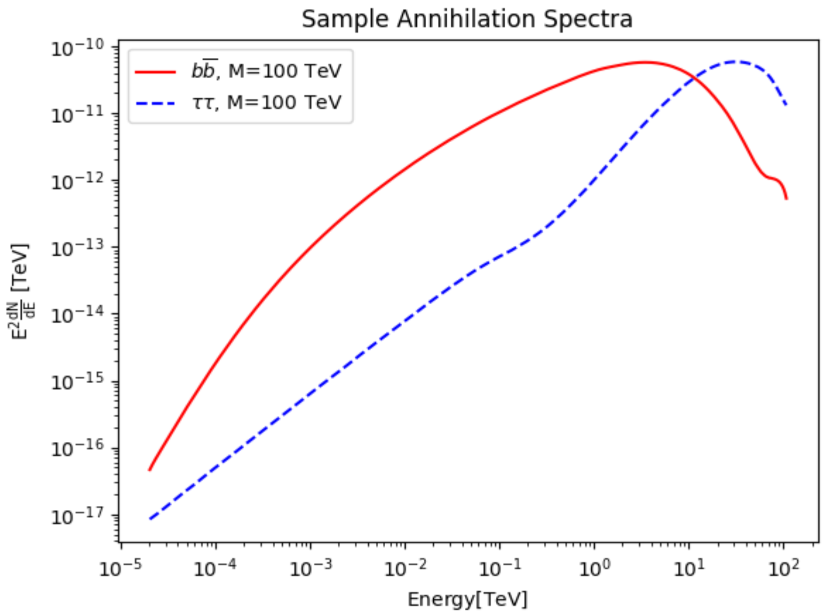
An Optimized Search for Dark Matter in the Galactic Halo with HAWC

Pat Harding and Joe Lundeen for the HAWC Collaboration

ICRC 2021

WIMP Dark Matter

- Weakly Interacting Massive Particle (WIMP) dark matter can annihilate or decay to standard model particles → produces 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

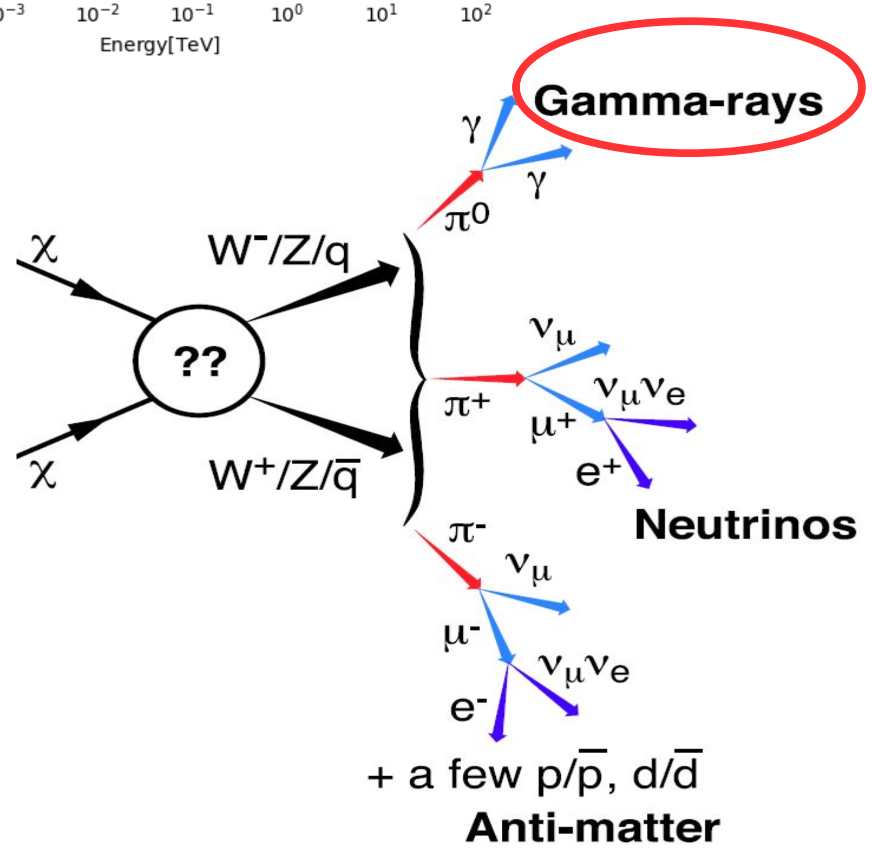


Particle Physics

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

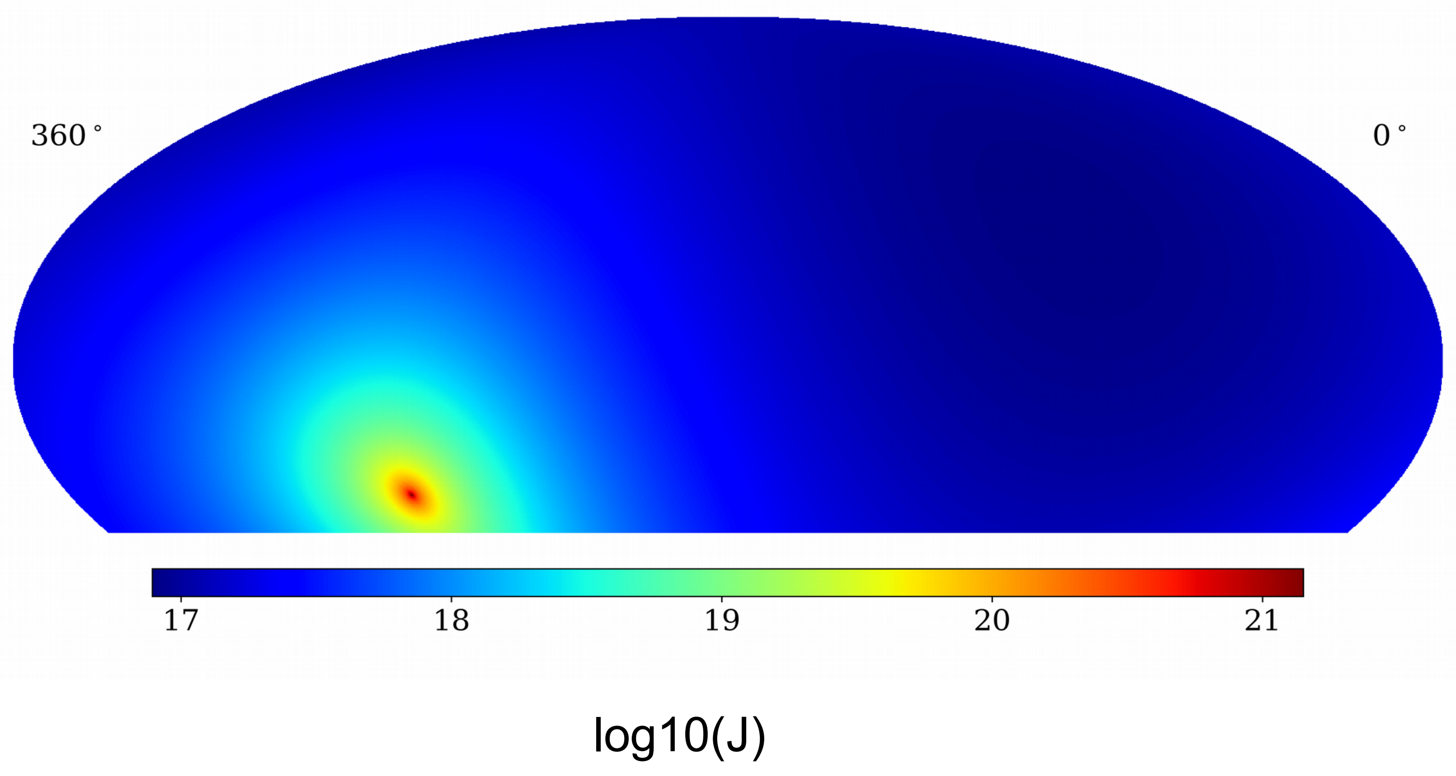
$$J = \int\int \rho_{dm}^2(l,\Omega)\,dl\,d\Omega \qquad D = \int\int \rho_{dm}(l,\Omega)\,dl\,d\Omega$$

Astrophysics



Motivation for Galactic Halo Search

- Galactic Halo
  - Largest close dark matter halo
  - Large expected flux
  - Can set strong constrains on dark matter interaction
- Uncertainty arises from modeling the density profile



Simulated map of J-factor in 0.5x0.5 degree pixels
Celestial RA and Dec coordinates
Generated using CLUMPY package
https://clumpy.gitlab.io/CLUMPY/

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Uncertainty in Density Profile

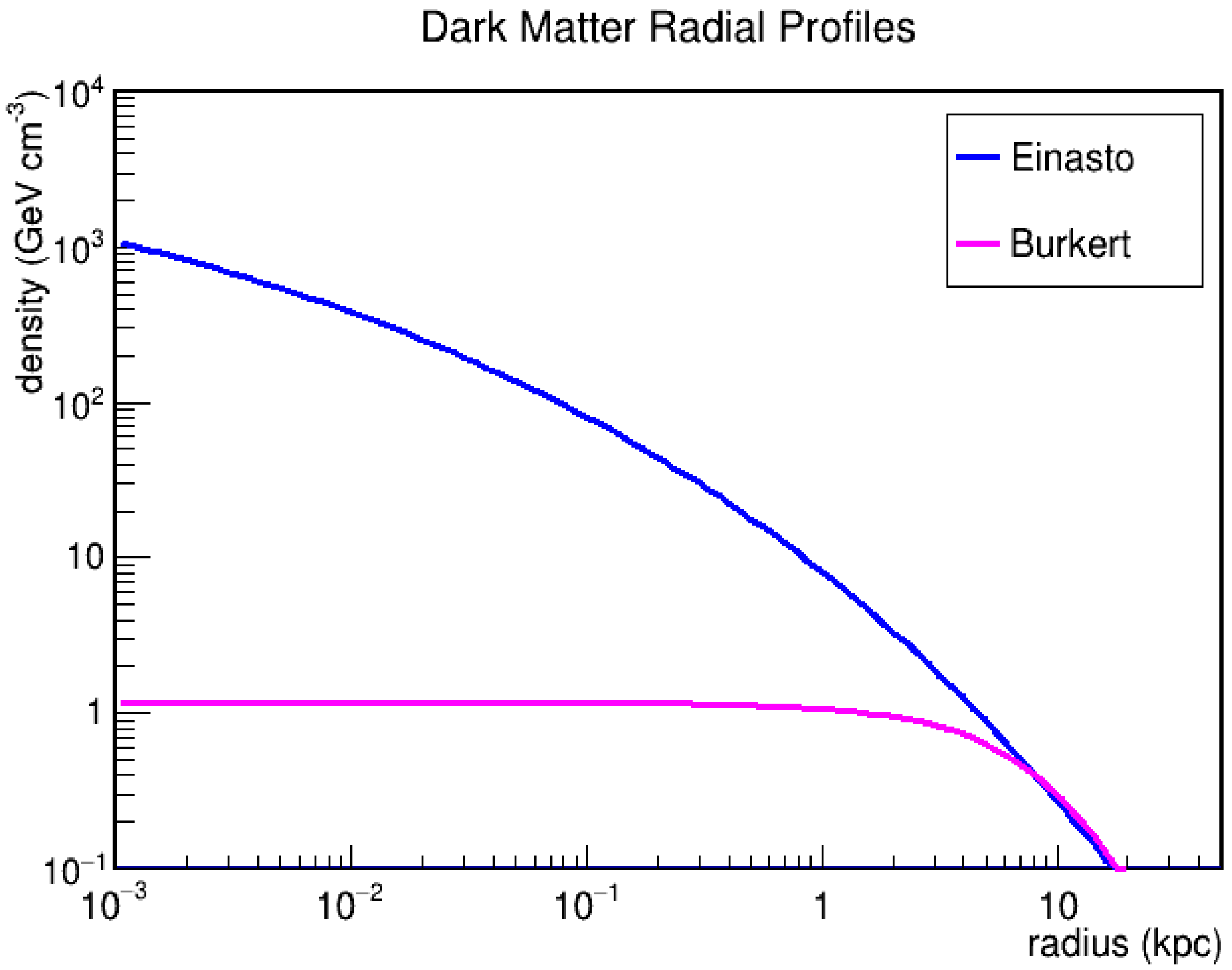
Einasto Profile (Cuspy)

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

Burkert Profile (Cored)

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

- Systematic is largest at center of halo
- Large ROI mitigates effect of profile choice



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HAWC High Altitude Water Cherenkov Gamma-Ray Observatory

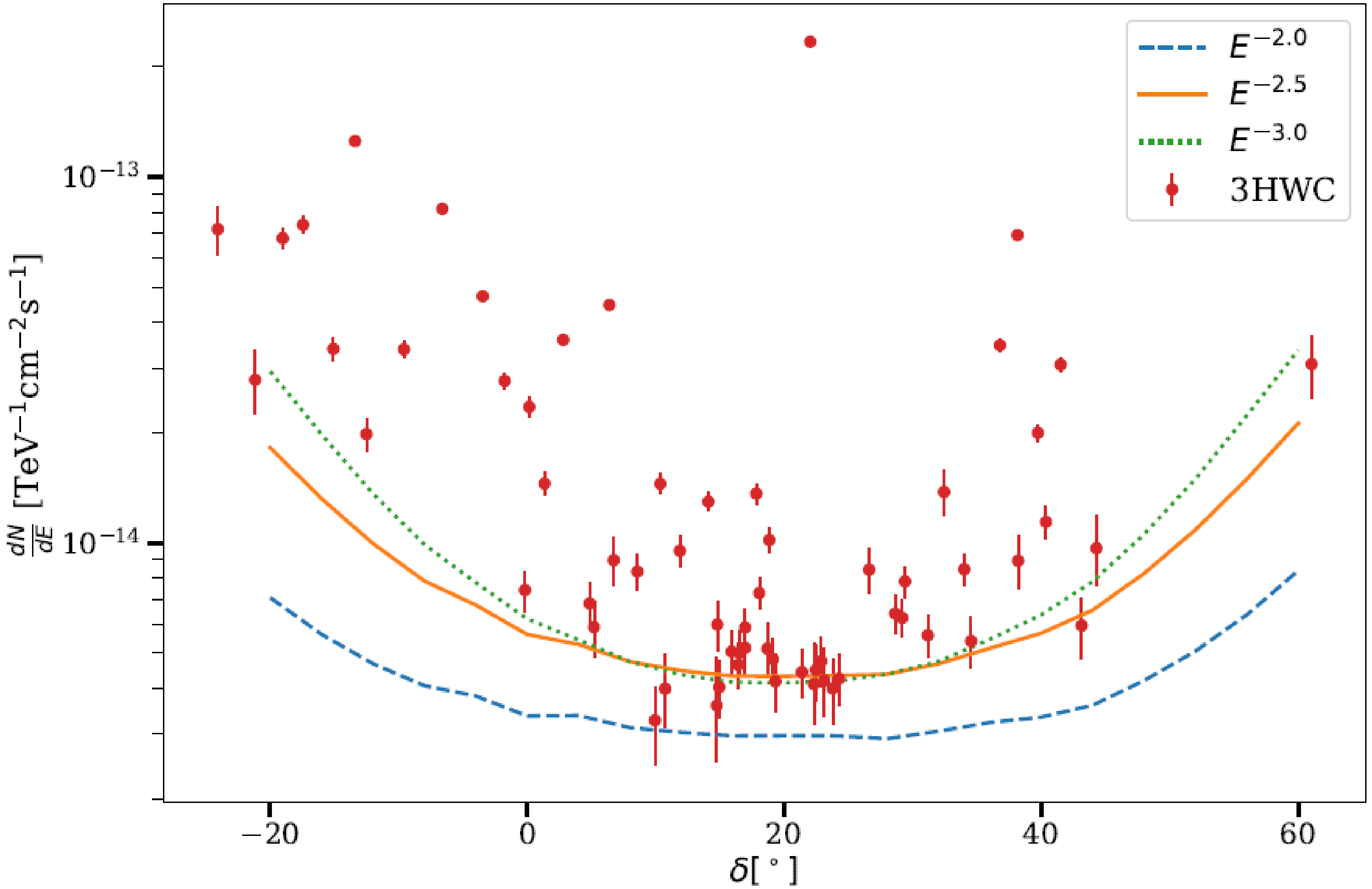
HAWC Detector

Los Alamos NATIONAL LABORATORY EST. 1943

- **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***
- ***~ 2 sr instantaneous field of view***
- ***Coverage of 2/3 of sky***
- ***Ideal for all-sky surveys***
- ***Sensitive to gamma-rays up to hundreds of TeV***

HAWC Properties and Advantages

- Wide simultaneous field of view
  - 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
- Sensitivity is declination-dependent
  - Due to atmospheric attenuation of showers
  - Better sensitivity to regions that transit overhead



Abeysekara et. al. *Astrophys.J. 905 (2020) no.1, 76*

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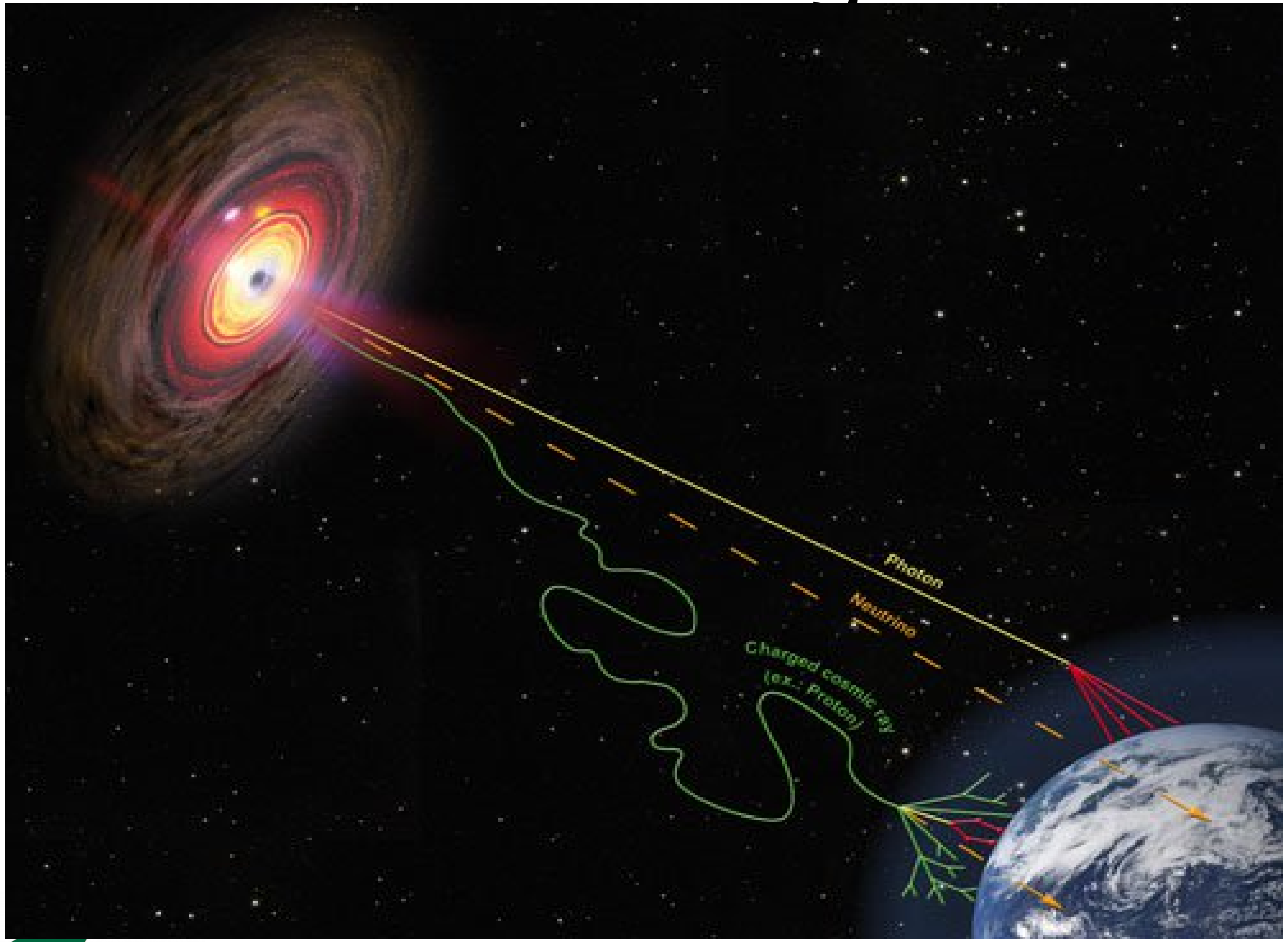
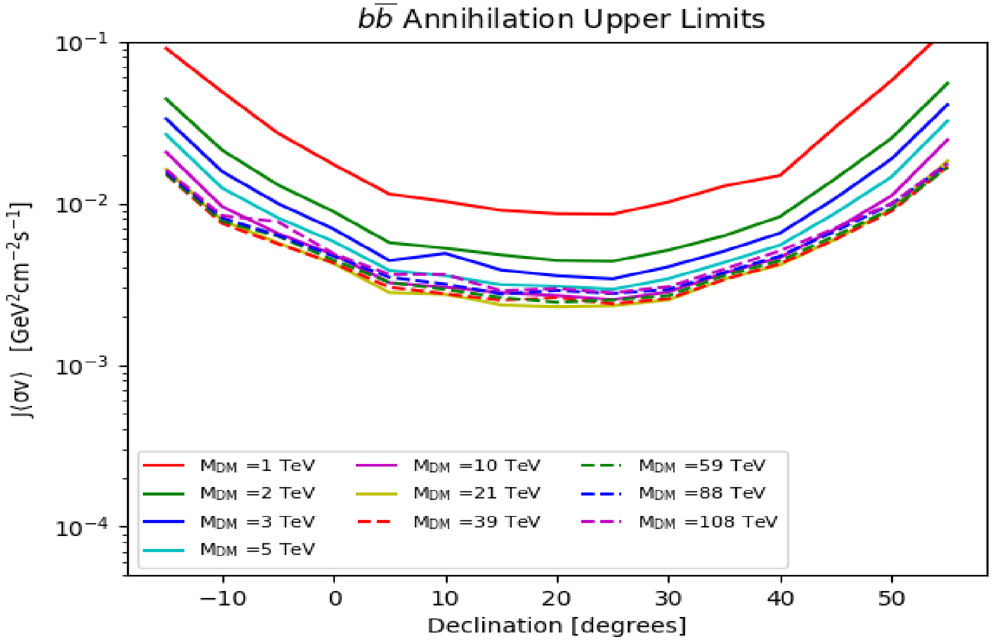
Charged Cosmic Rays



http://www.hap-astroparticle.org/img/

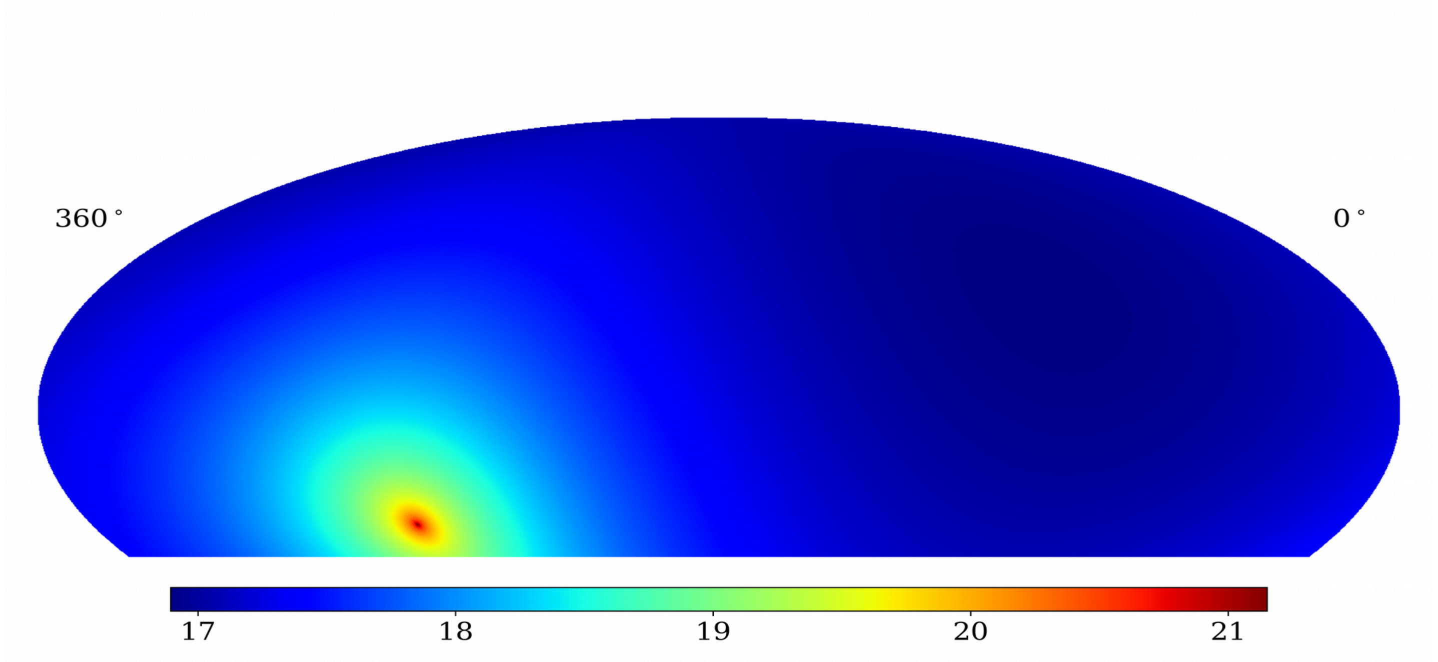
- Deflected by interstellar magnetic fields
- Arrival direction does not point back to source
- Outnumber gamma rays by a substantial amount
- Want to separate from gamma rays

Optimizing an ROI



- Use characteristic sensitivity estimate from: A. U. Abeysekara et al. Searching for Dark Matter Sub-structure with HAWC. JCAP, 1907(07):022, 2019.
- Accounts for HAWC sensitivity to dark matter-like spectra across the sky

- Use CLUMPY simulation of Galactic main halo
- Calculate J-factor for individual pixels
  - Integrate of pixel-width solid angle
  - ~.05 x .05 degrees
- Make a cut on expected sensitivity



log(J)

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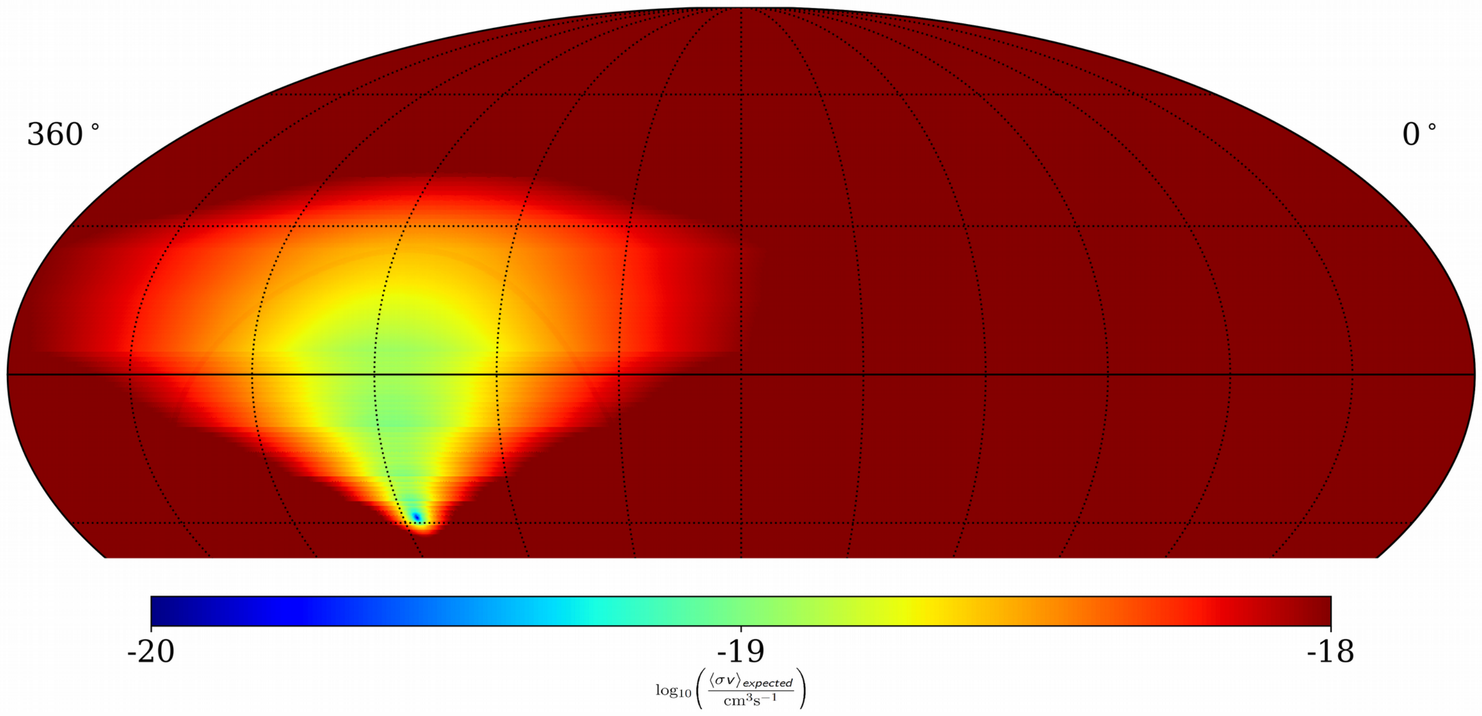
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

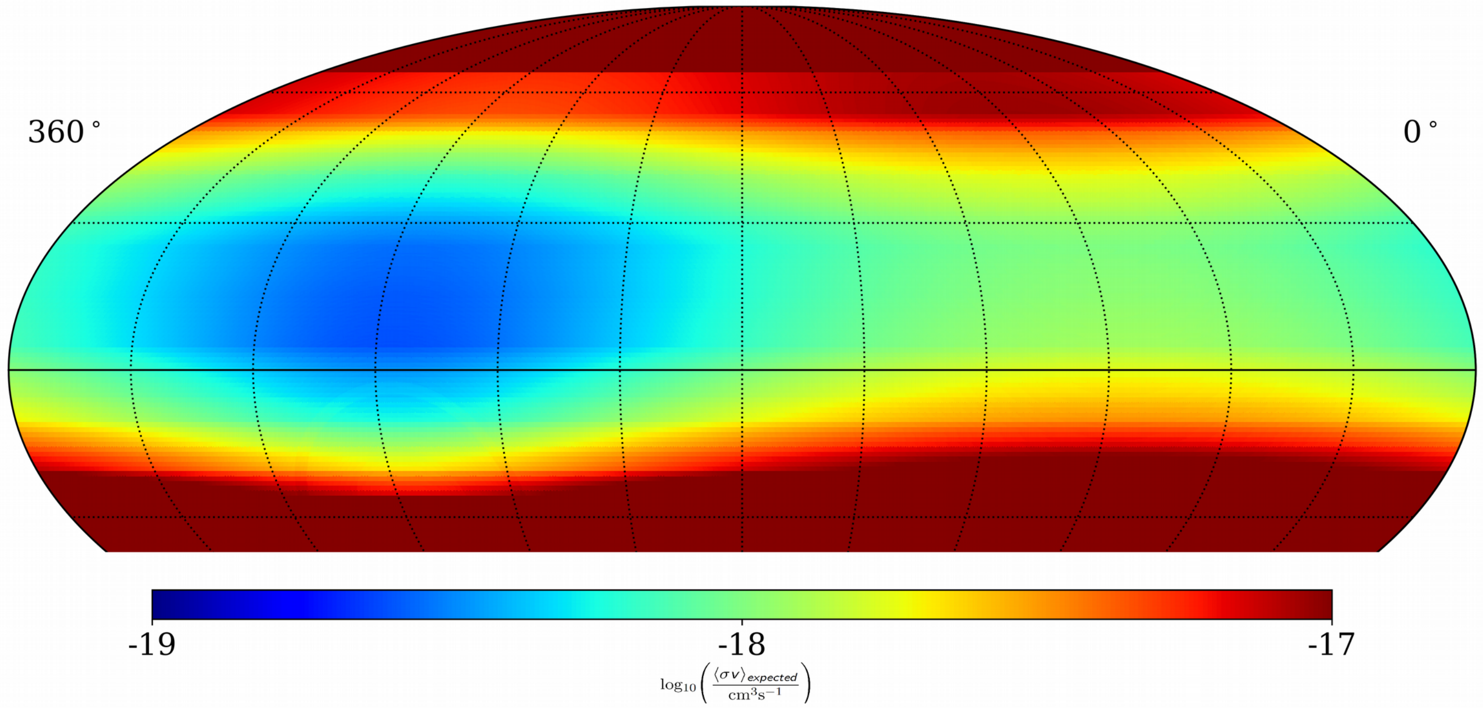
Los Alamos
NATIONAL LABORATORY
EST. 1943

Estimated Sensitivity

Einasto



Burkert



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Model Background Technique

- New background estimator based on two sets of maps
- With standard gamma/hadron cuts (G)
- Other with reversed cuts that pass hadrons (H)
- Hadron map contains pure background
- Can relate behavior of hadrons in H map to background component of G map
- Optimized for highly-extended sources
- See: Pooja Surajbali. *A Novel Approach towards the Search for Gamma-ray Emission from the Northern Fermi Bubbles with HAWC*

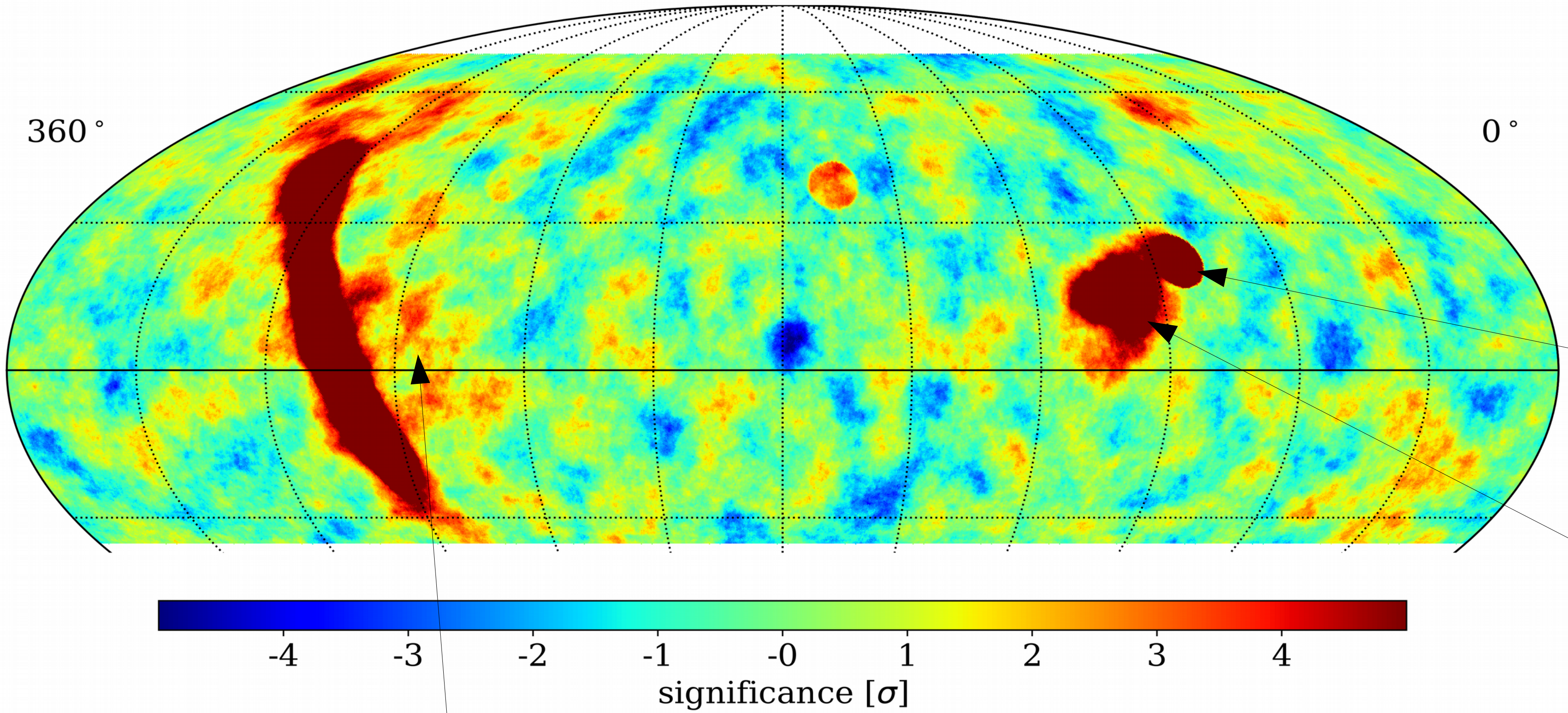
$$\alpha_i(RA, Dec) = a_i(Dec) \times b_i(RA)$$

$$a_i(Dec) = \frac{G_{Dec}}{H_{Dec}}$$

$$b_i(RA) = S_G\left(\frac{G_i}{H_i} \div a_i(Dec)\right)$$

New Sources

- Significance maps with α-background reveals new emission just off Galactic Plane
- Morphologically inconsistent with dark matter: will remove from ROI



Spectral assumption for maps:
Simple power law, index 2.7
5-degree disk source morphology

Crab

Geminga

New emission

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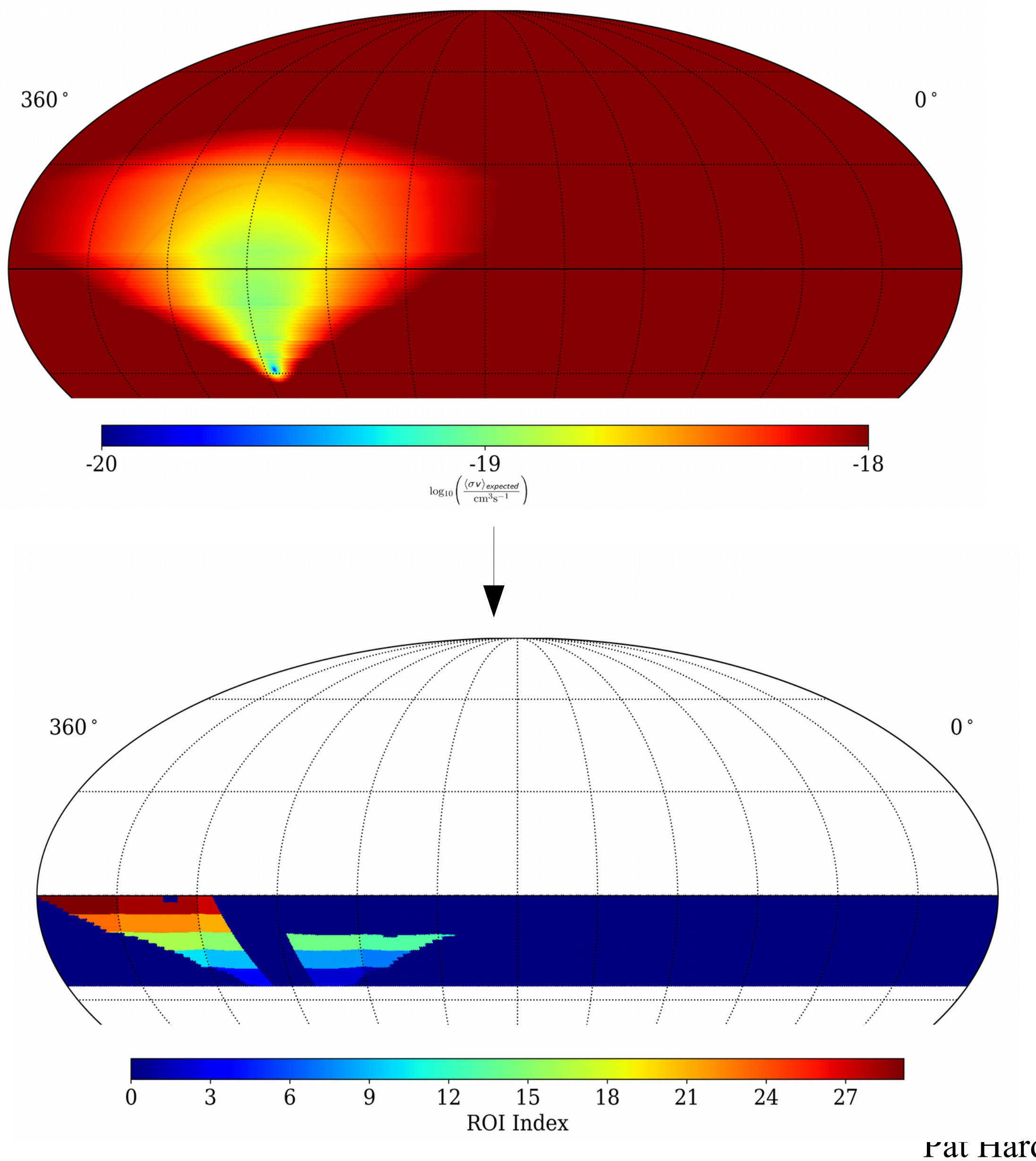
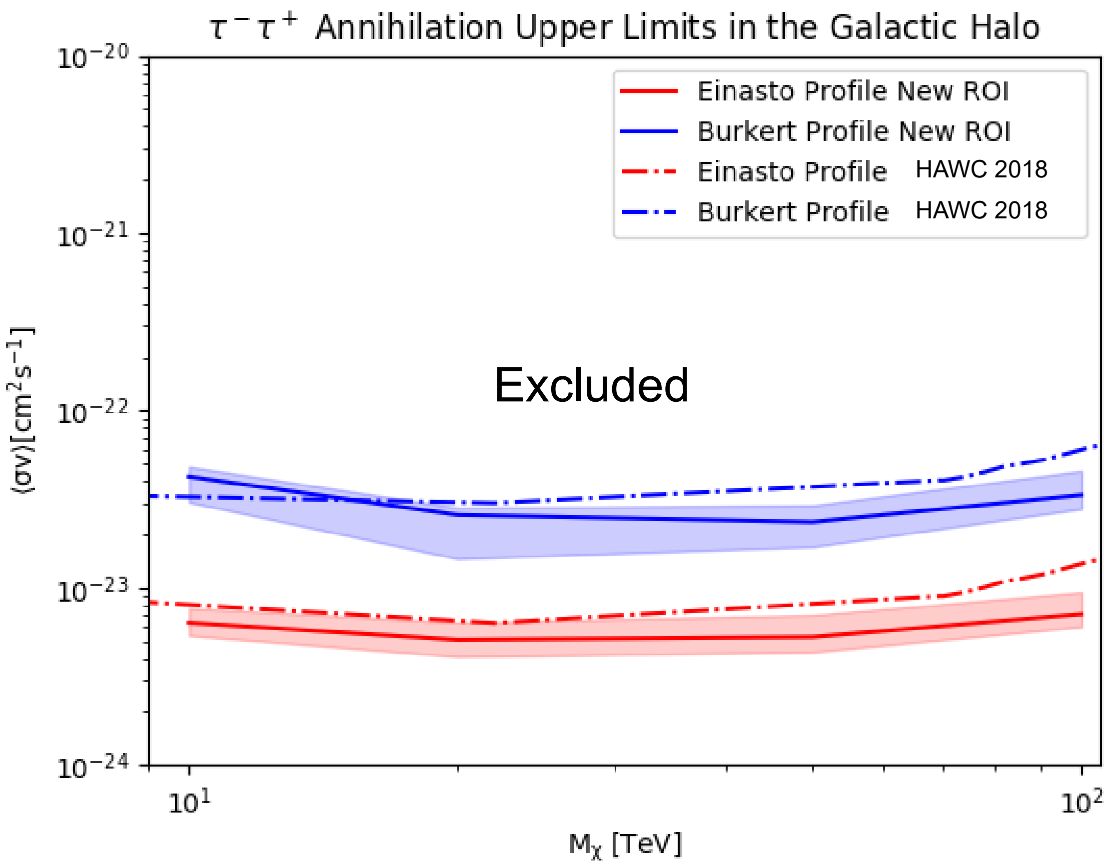
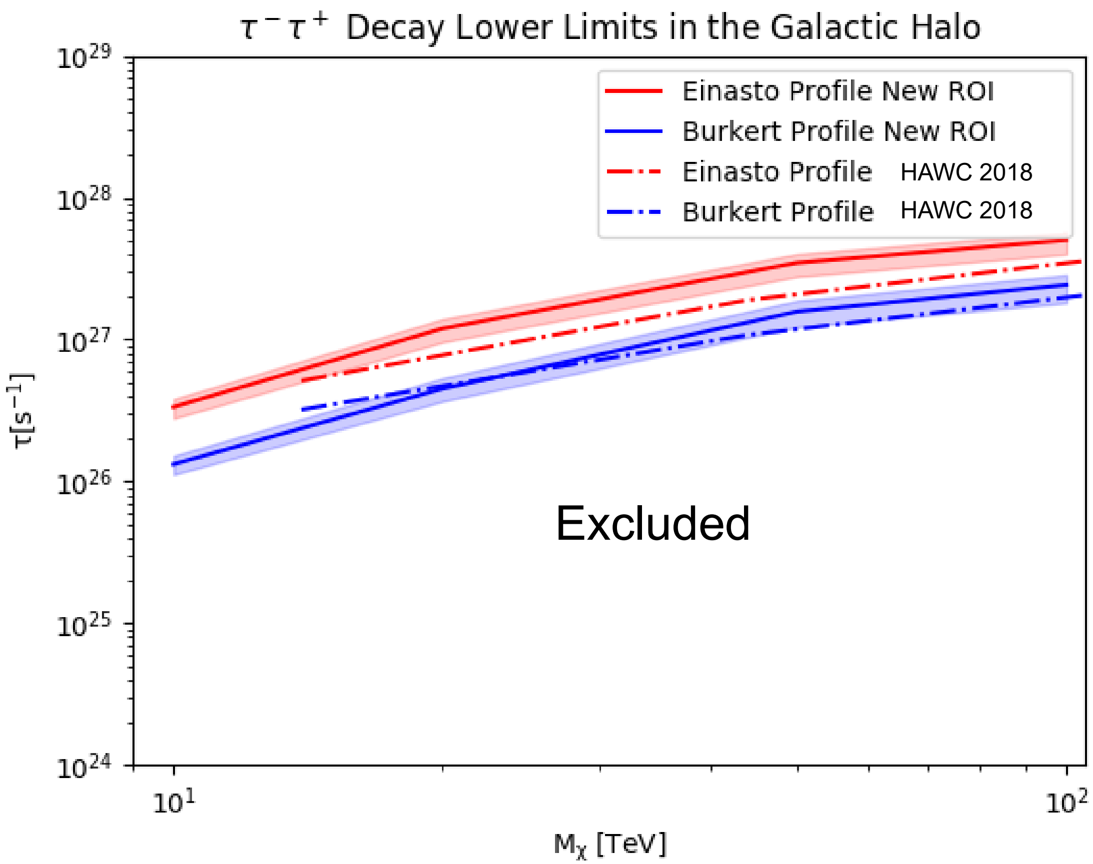
Optimal ROI

- Selected by sensitivity cut + constraint to avoid non-DM sources
- Constraints:
  - ROI cannot span more than 180 degrees at widest
  - Remove above equator
  - Exclude pixels associated with new source
- Under these conditions, same ROI results regardless of assumed density profile



DM Limits





- Able to show results for both cuspy and cored profiles
- Improvement over prior HAWC Galactic halo results from JCAP 02 (2018) 049

Summary

- HAWC's wide field of view and continuous duty cycle make it ideal for surveys and extended source analysis
- Found optimal ROI for Galactic dark matter search
- Set constraints on dark matter annihilation and decay
- Robust to both detector and source model systematics
- For more on dark matter with HAWC see:
  - Mora Durocher: *Limits on Diffuse Dark Matter with HAWC*
  - Celine Armand: *Combined Dark Matter Searches Towards Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS*
  - Mehr Un Nisa: *Search for TeV decaying dark matter from the Virgo cluster of galaxies*