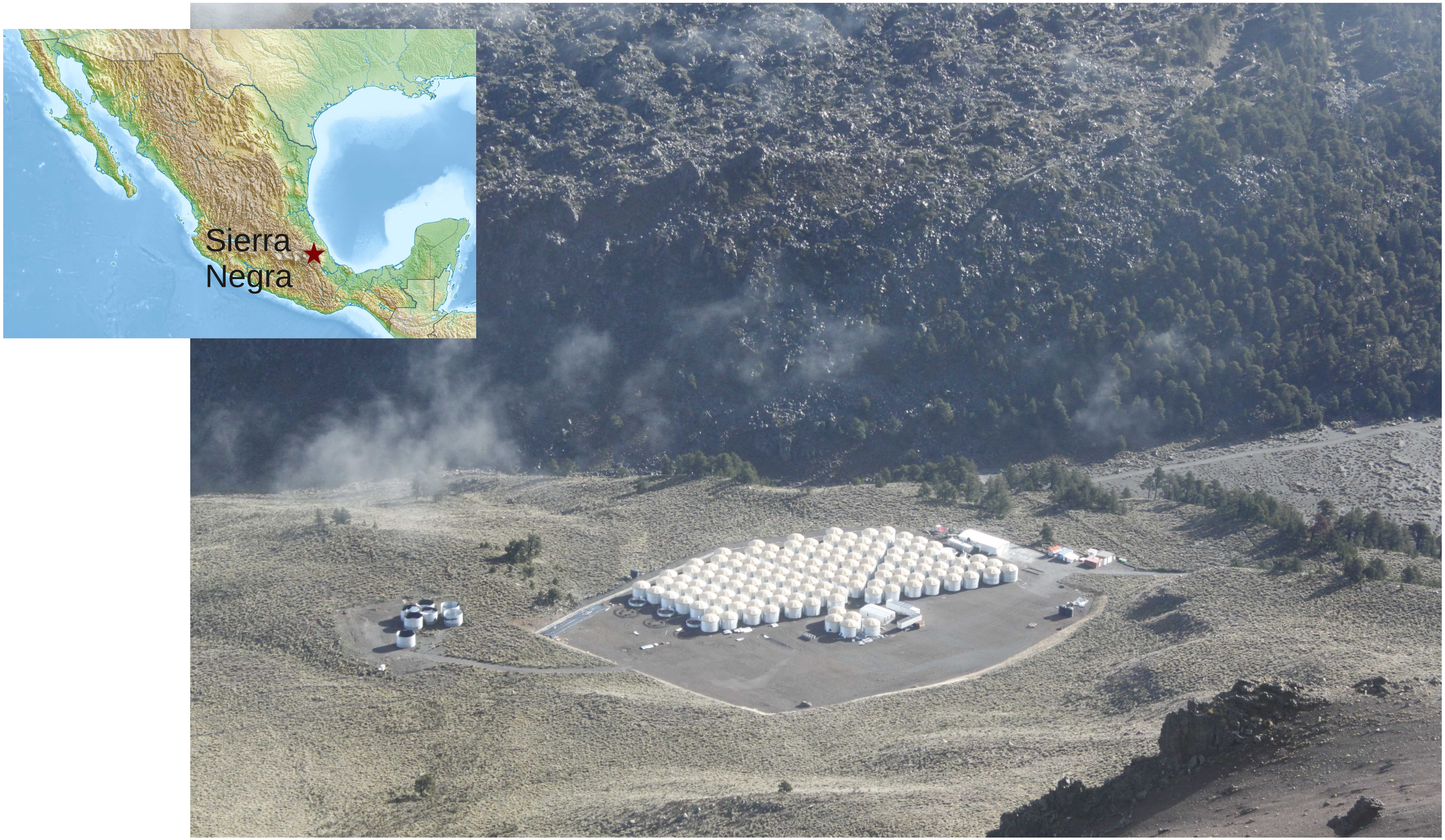
The Search for Dark Matter with The High Altitude Water Cherenkov (HAWC) Observatory

LANL P-25 Physics Seminar

J. Patrick Harding
LANL, P-23
10 December 2013

LA-UR-13-29312

HAWC Observatory



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

HAWC Collaboration

USA:

Los Alamos National Laboratory
University of Maryland
University of Utah
University of New Mexico
Michigan State University
Pennsylvania State University
NASA/Goddard Space Flight Center
University of New Hampshire
Georgia Tech
George Mason University
University of California, Irvine
Colorado State University
Michigan Technological University
University of Alabama
University of Wisconsin, Madison

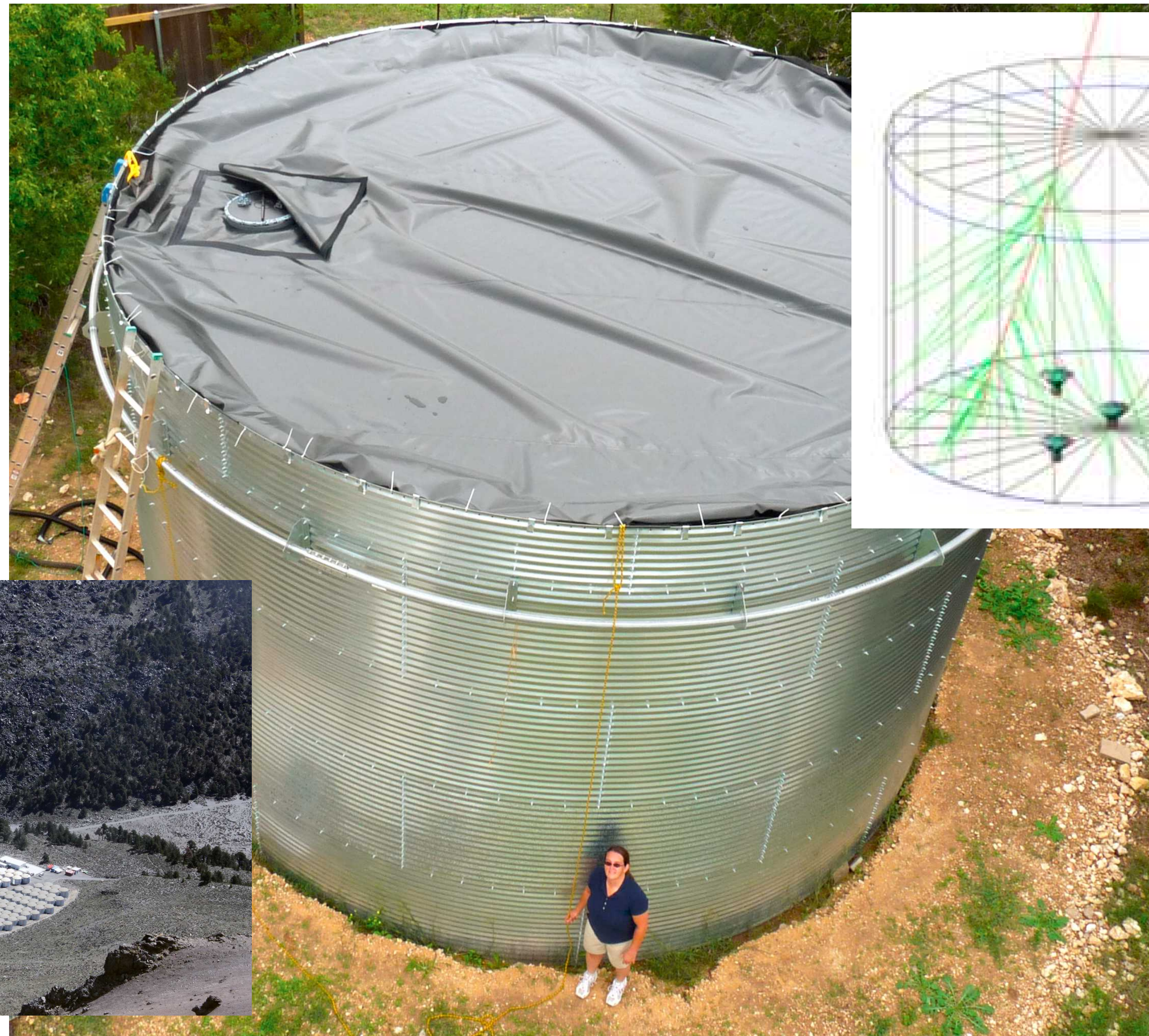
Mexico:

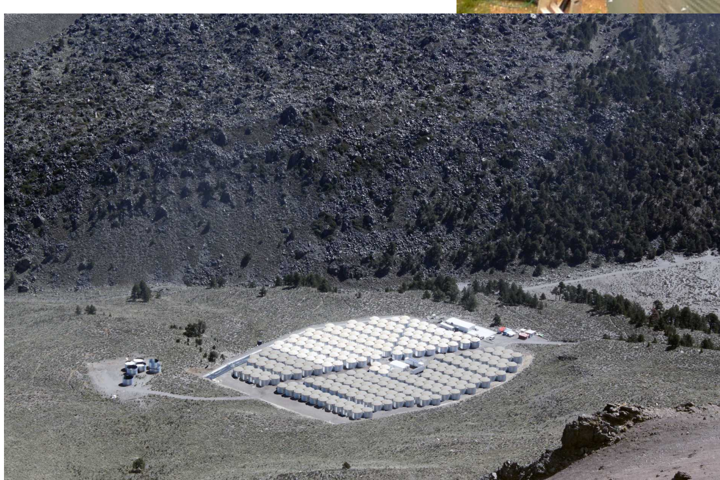
Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Astronomía
- Instituto de Física
- Instituto de Ciencias Nucleares
- Instituto de Geofísica

Universidad Autónoma de Chiapas
Universidad de Guadalajara
Benemérita Universidad Autónoma de Puebla
Universidad Michoacana de San Nicolás de Hidalgo
CINVESTAV
Universidad de Guanajuato
UGTO-IF
Universidad Autonoma del Estado de Hidalgo
Instituto Politecnico Nacional

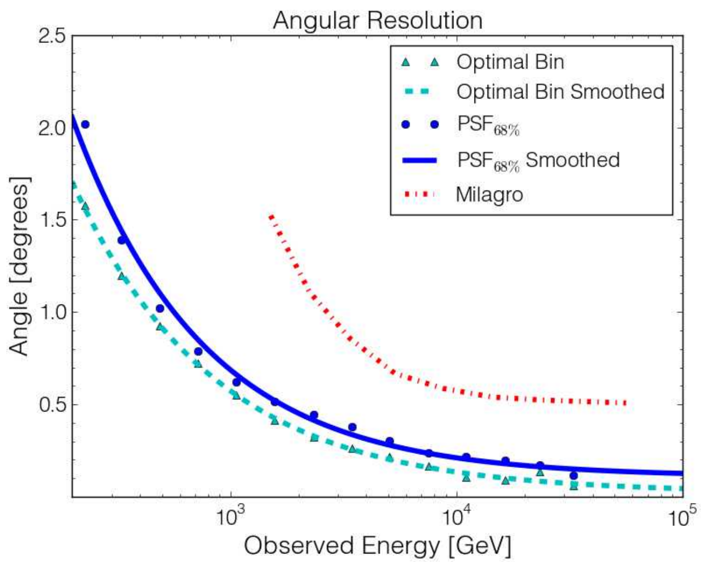
Water Cherenkov Detectors

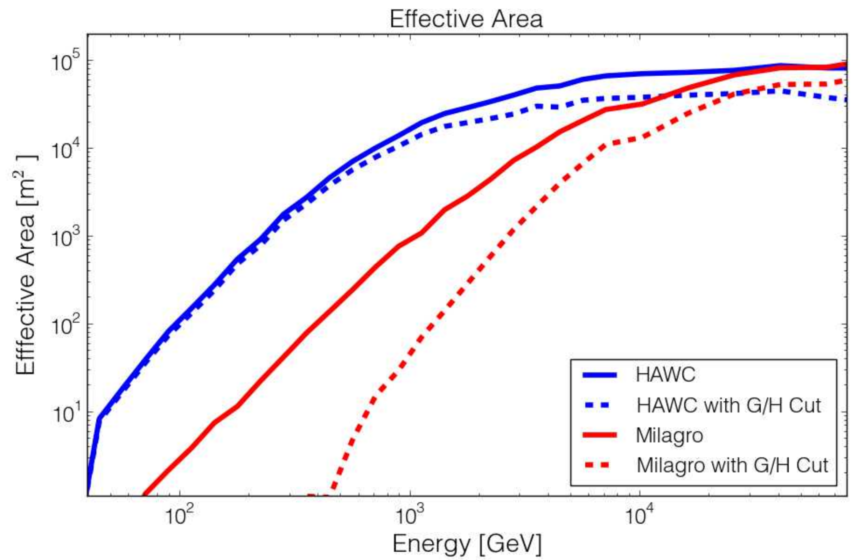
- 150 tanks filled
- 300 tanks by next year
- 5 m x 7.3 m tanks
- 200,000 L of water
- 4 PMTs
  - 3 8” R5912
  - 1 10” R7081 HQE

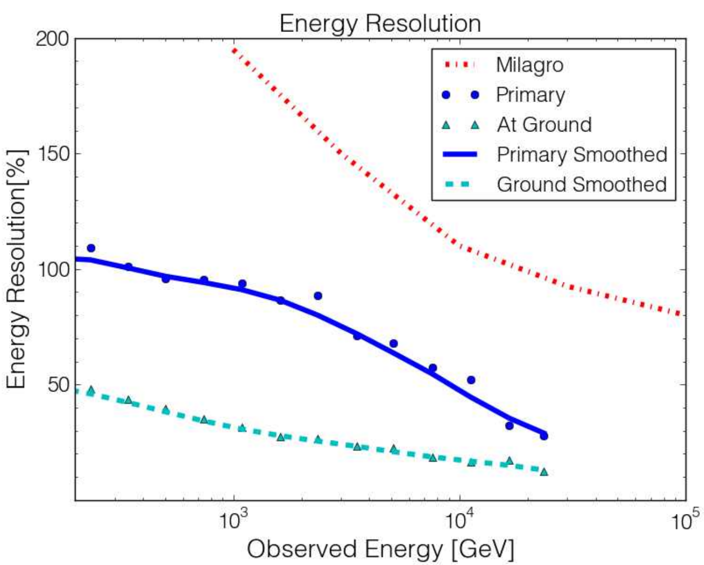


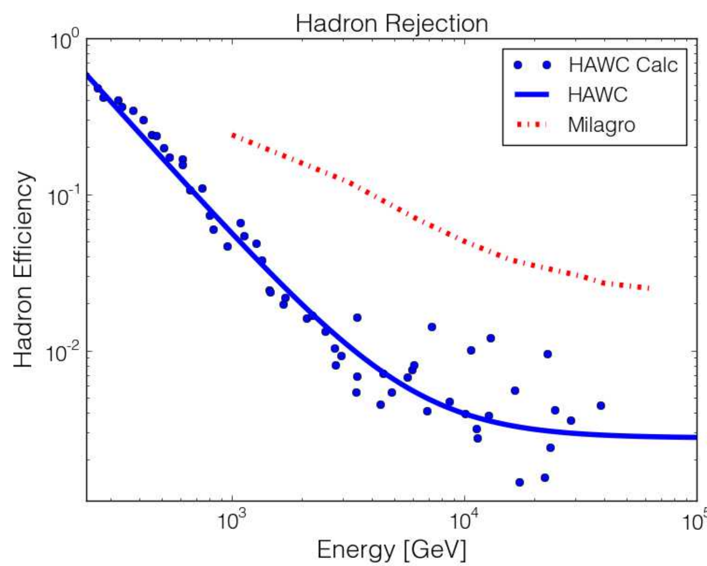


HAWC Performance

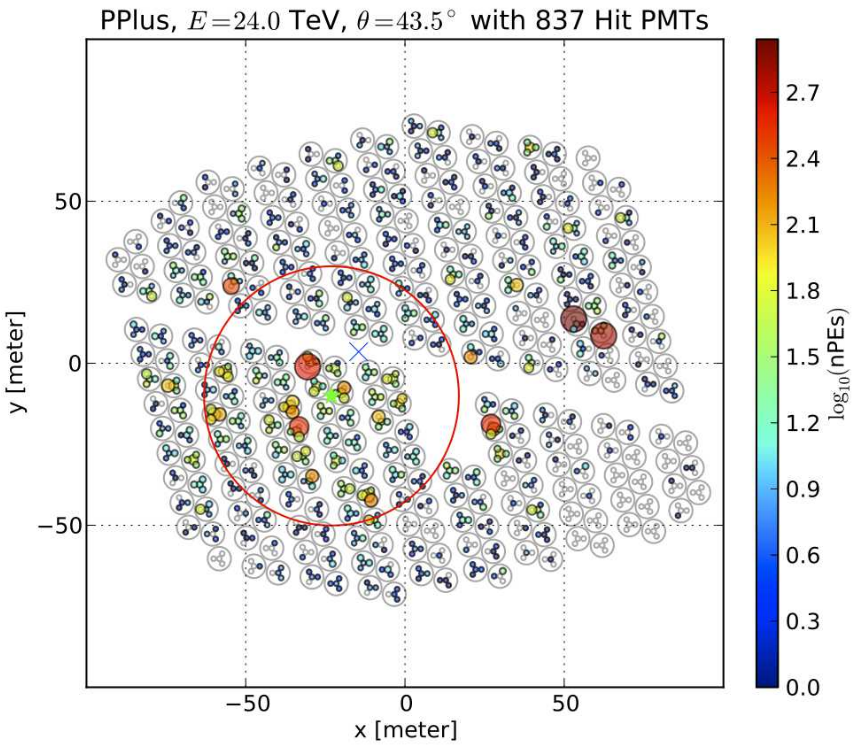


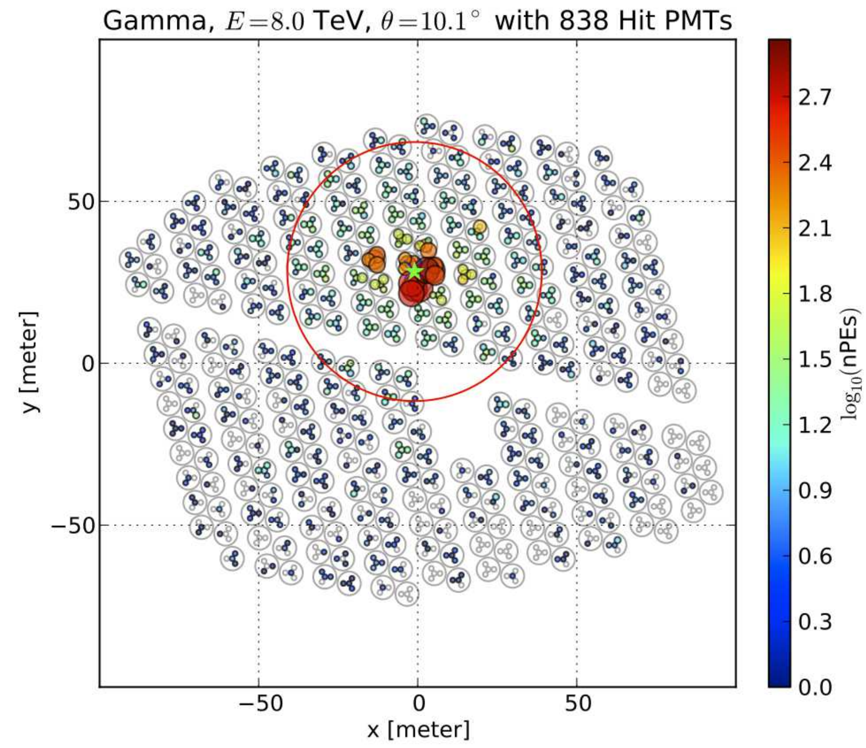






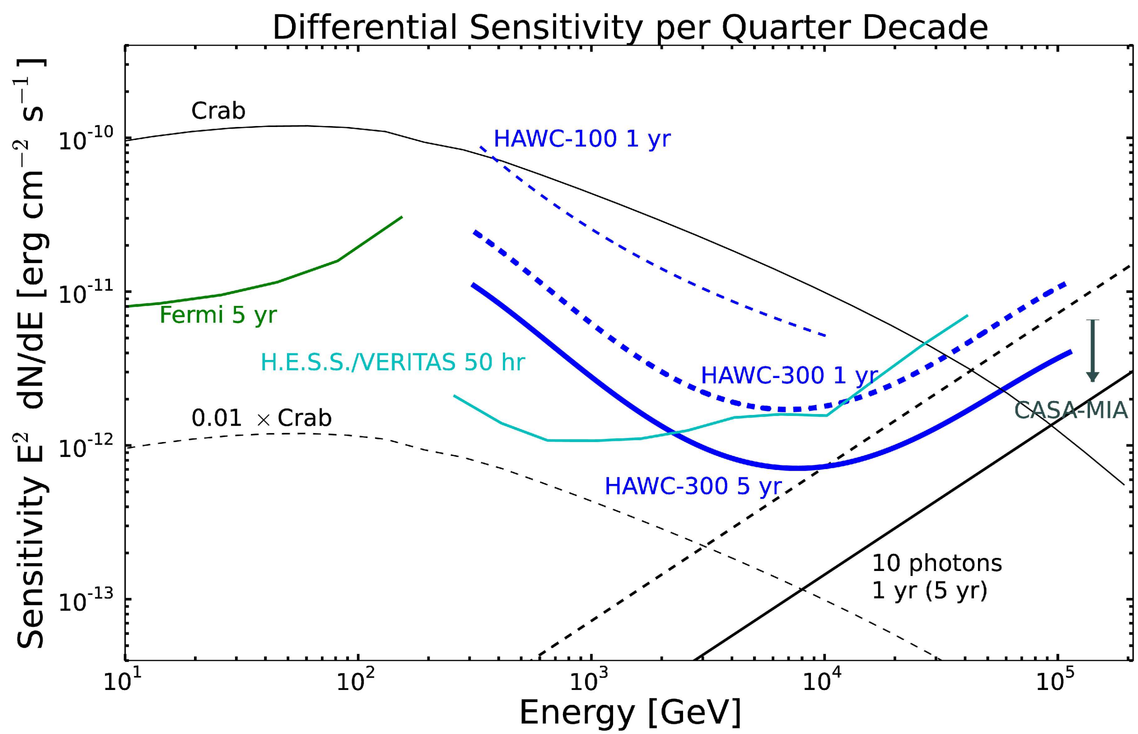
Gamma/Hadron Separation



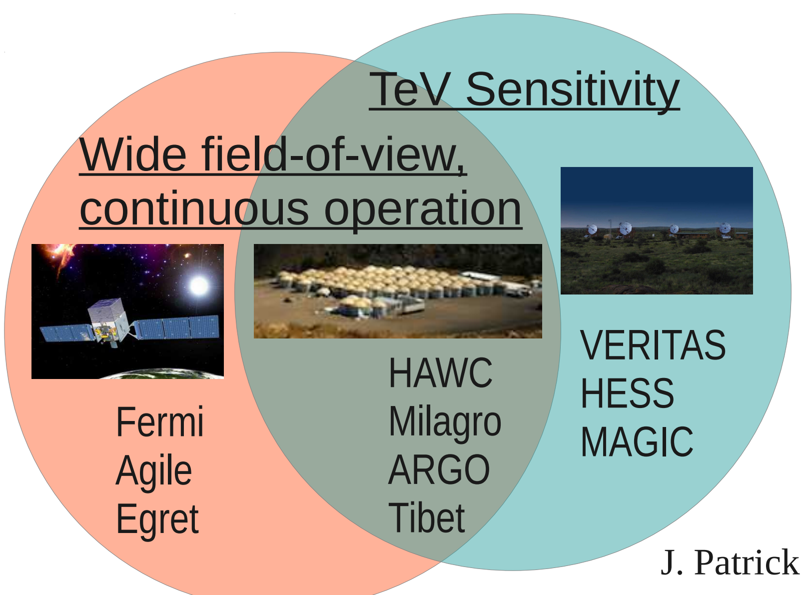


HAWC Sensitivity

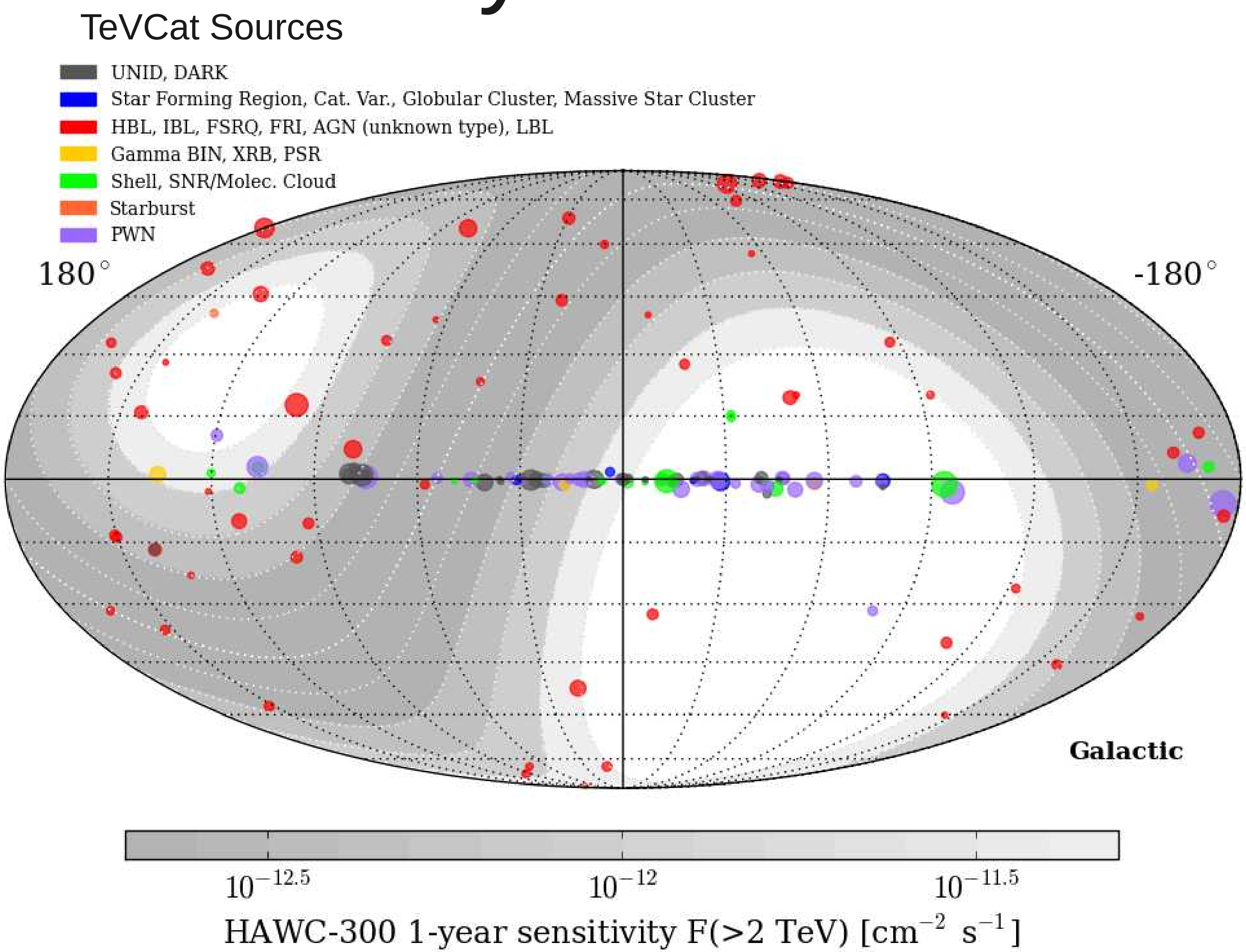
- Angular Resolution:
  ~0.1° – 1.0°
- Field-of-view:
  2 sr (2/3 sky each day)
- Effective Area:
  22500 m^2
- Sensitivity:
  ~ Crab @ 5σ each day



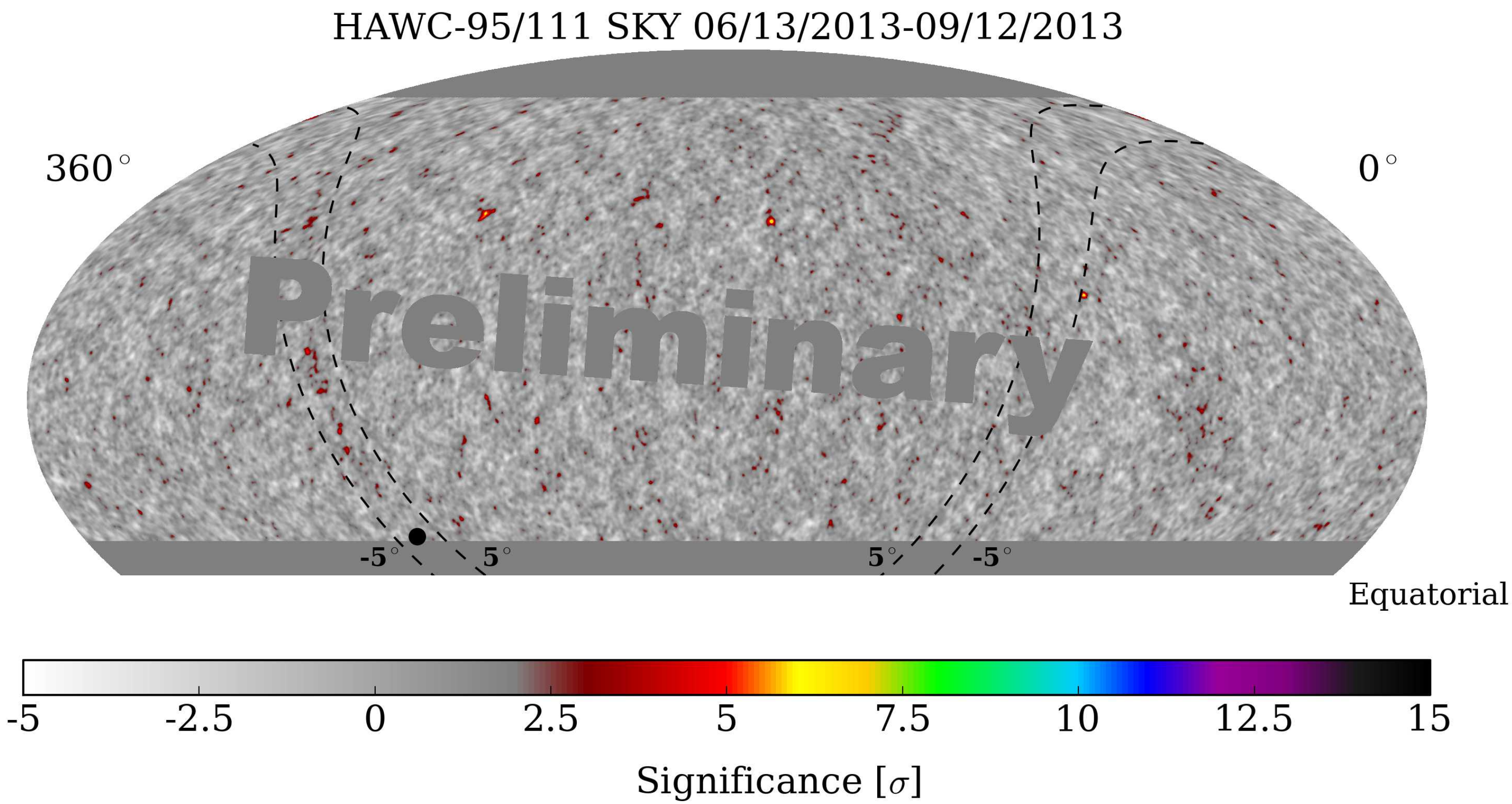
arXiv:1306.5800, Astroparticle Physics in press



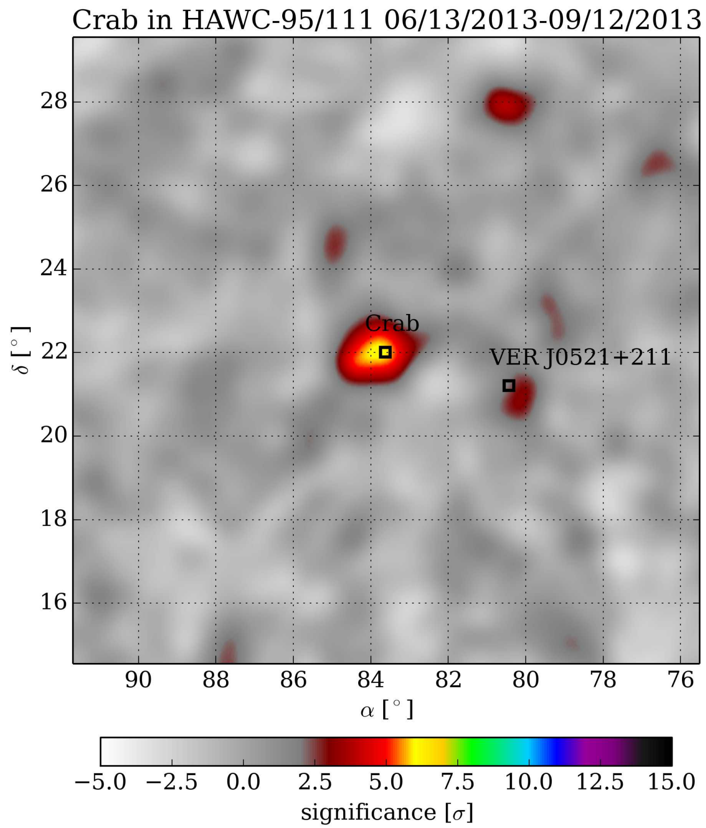
TeV Sky Observable by HAWC



HAWC-95/111 Skymap

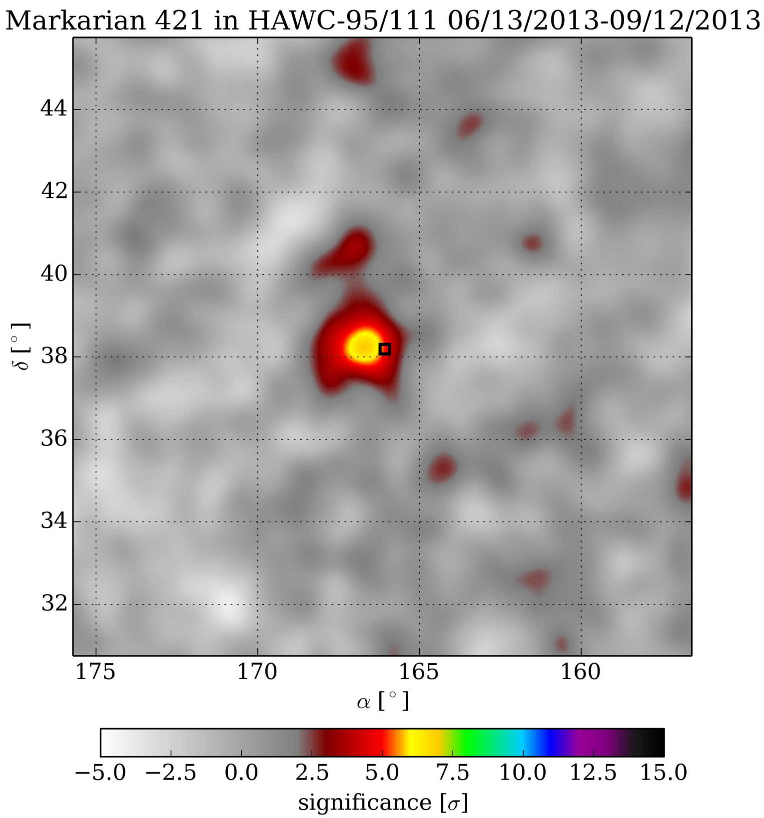


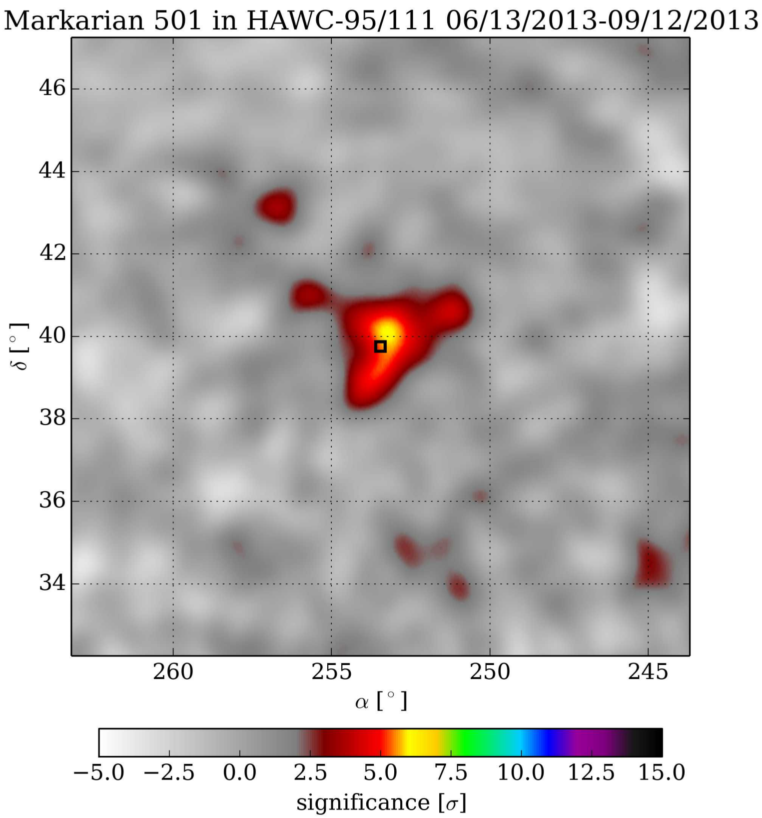
Observations - Crab Nebula



Bright, stable Galactic point source. Ideal for detector calibration.

Observations - Mrk451 and Mrk501



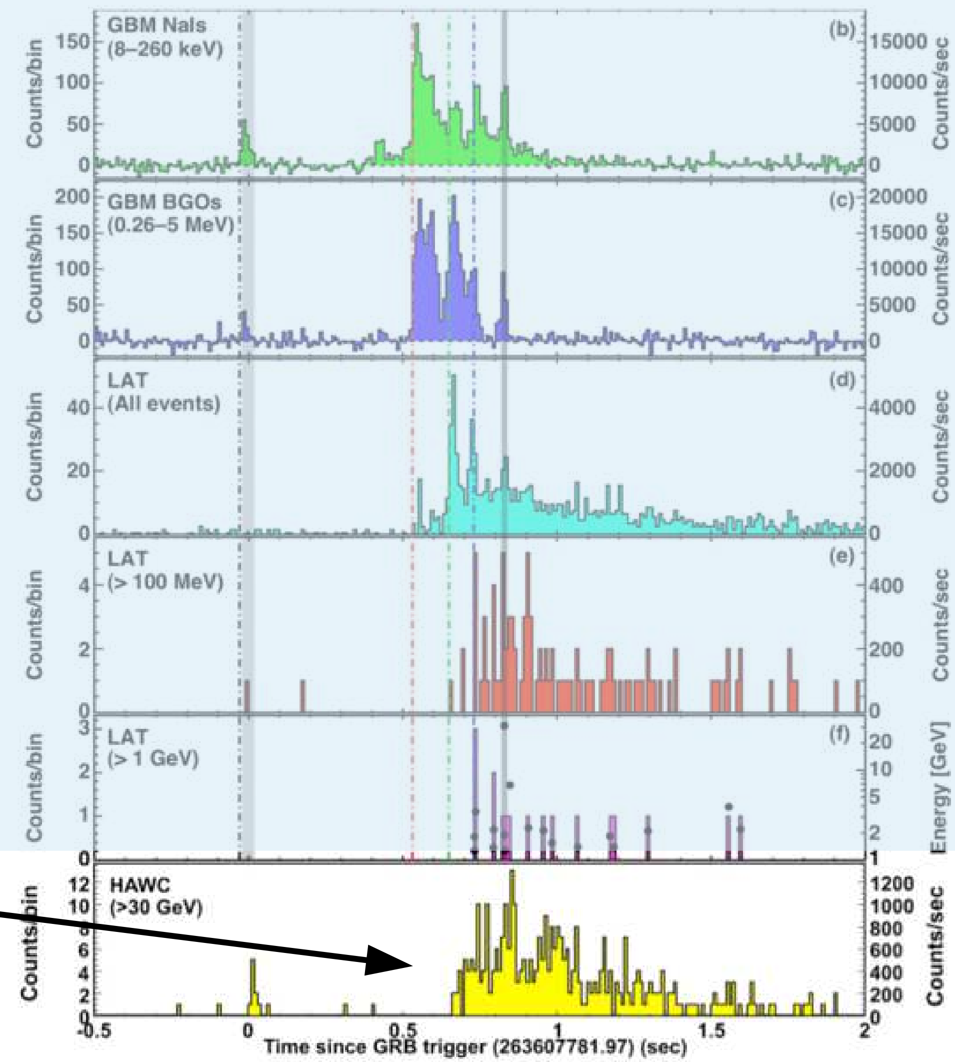


AGN, first extragalactic objects observed by HAWC.

Observations - GRBs

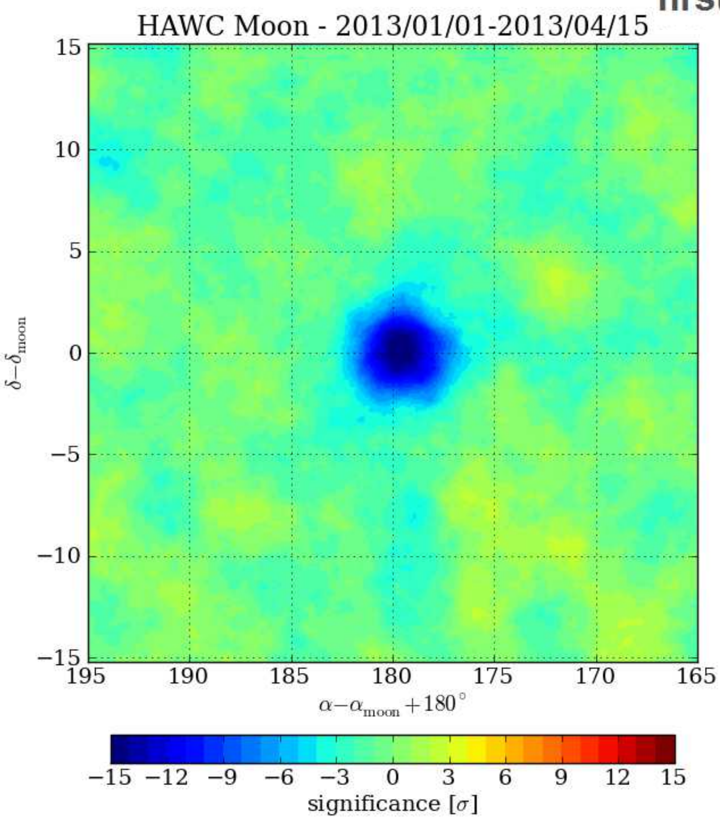
Fermi observation of GRB090510, z=0.9

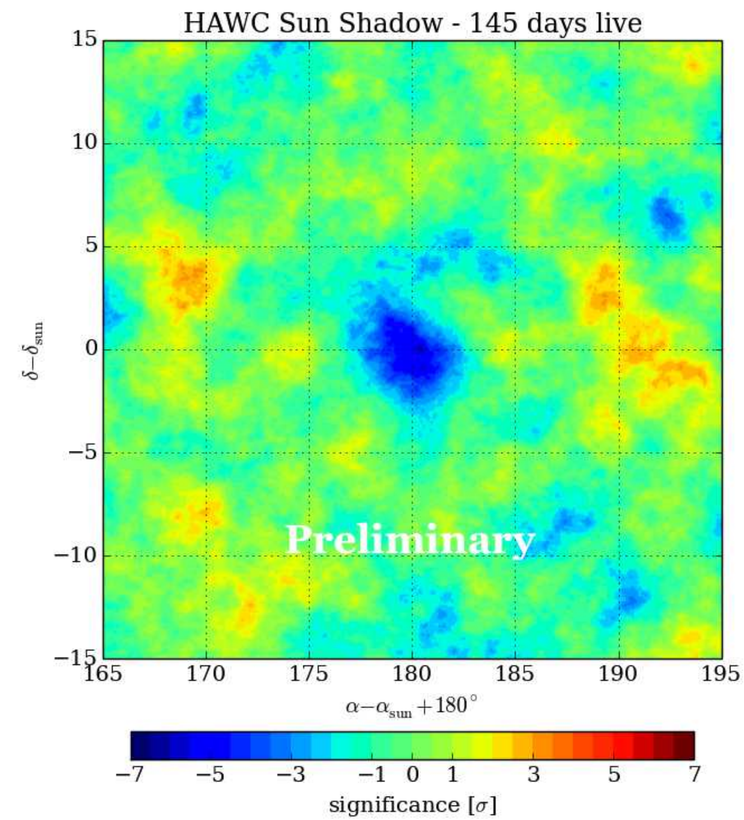
- Highest observed energy was 33 GeV with 16 γ-rays above 1 GeV
- Constrained Lorentz Invariance at the Planck Mass scale



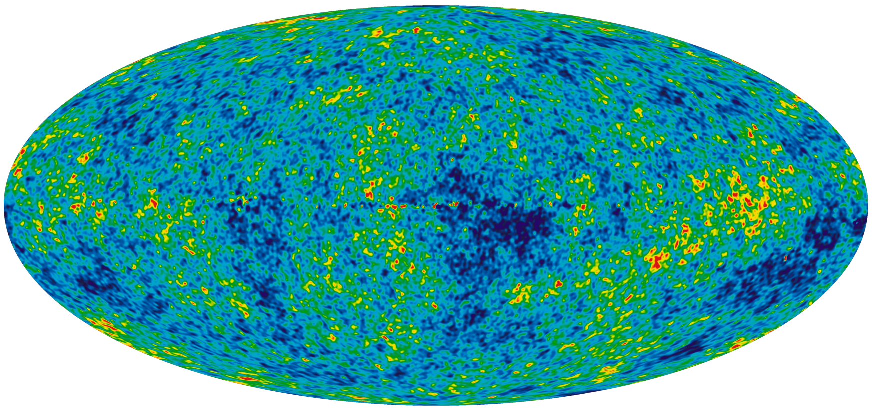
HAWC would detect this GRB if it had occurred in FOV

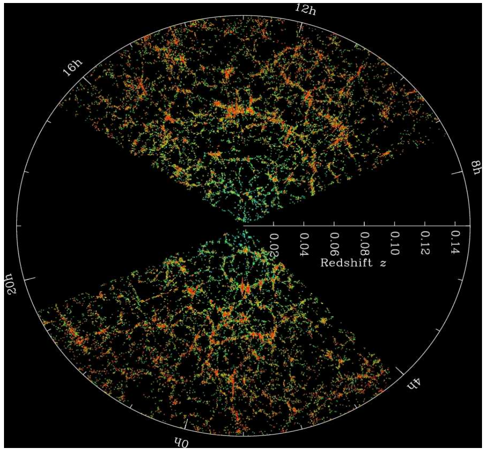
Observations - Moon and Sun Shadows

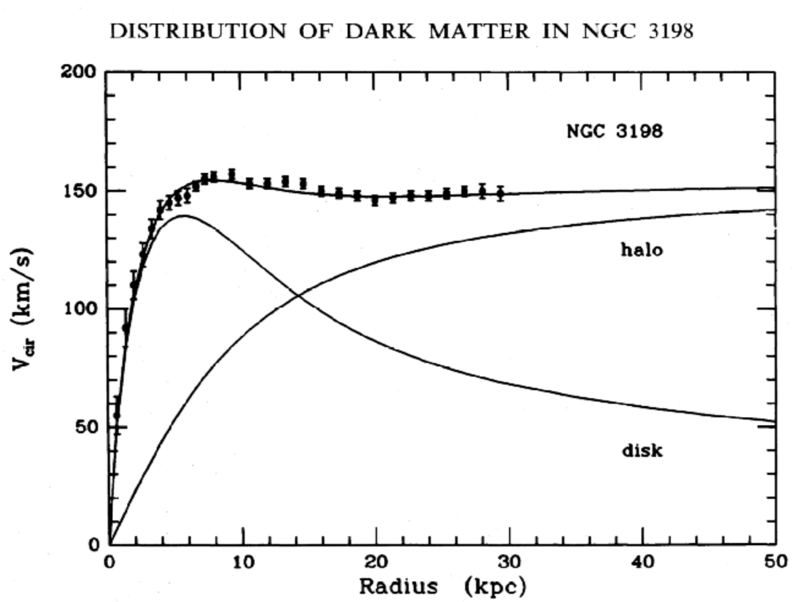


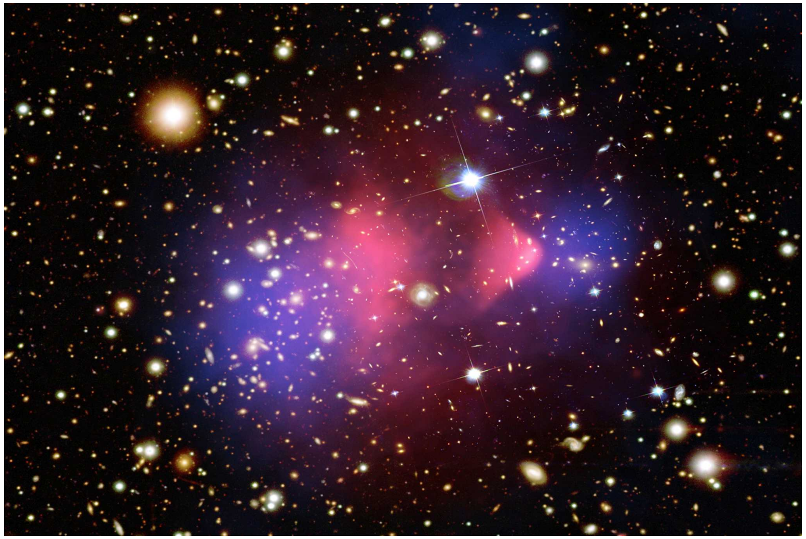


The Search for High-Mass WIMP Dark Matter with HAWC









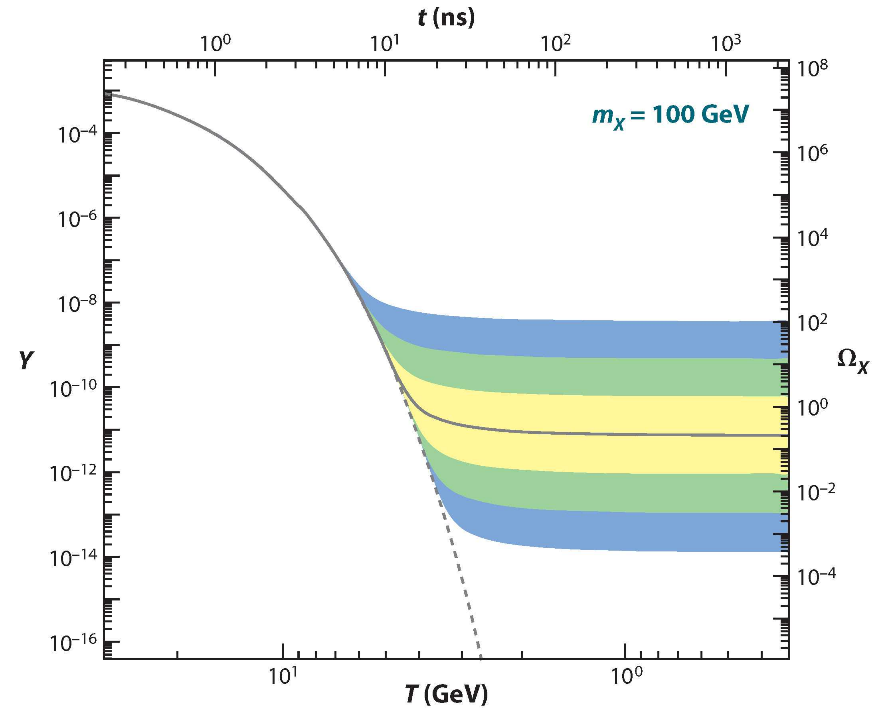
Annihilating WIMP Dark Matter

For s - wave thermal relic cold dark matter :

$$\Omega_{\mathrm{CDM}} h^2 \approx \frac{3\times10^{-25}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$$

$$\Omega_{\mathrm{CDM}} h^2 = 0.1196 \pm 0.0031\ \text{(Ade et al. 2013)}$$

$$\langle \sigma v \rangle \approx 3\times10^{-26}\ \mathrm{cm^3 s^{-1}}$$

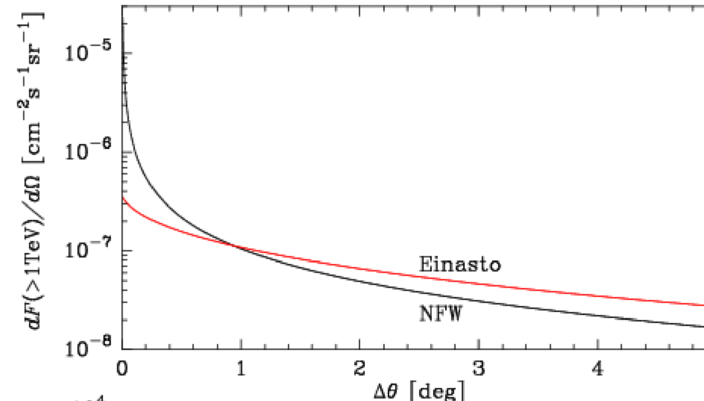


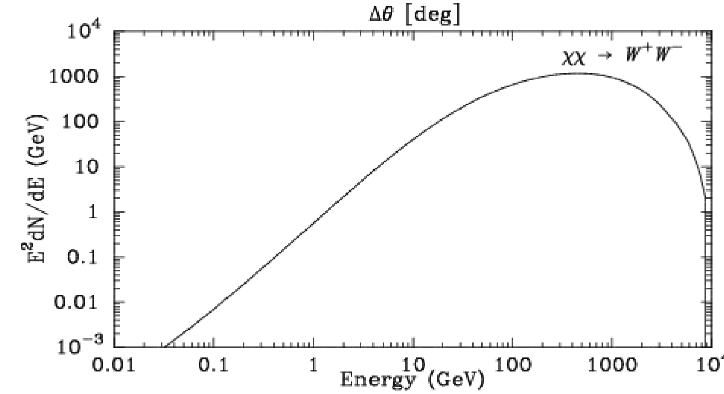
- Expected thermal cross-section is nearly independent of dark matter mass
- Is the weak-scale cross-section σ ~ 1 pb
- Weak-scale cross-section + weak-scale mass = <u>W</u>eakly <u>I</u>nteracting <u>M</u>assive <u>P</u>article dark matter

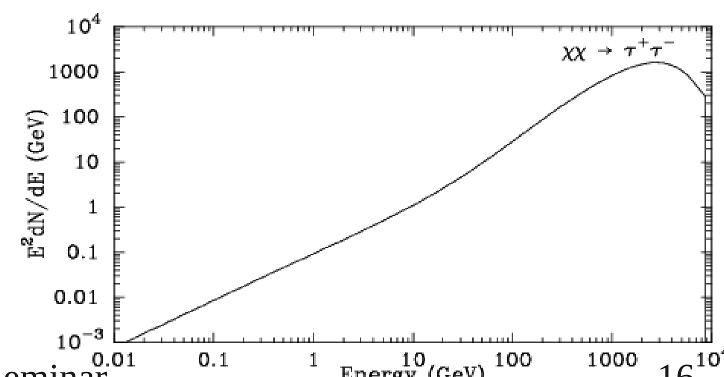
Dark Matter Annihilation Flux

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

- For GC, optimal bin depends strongly on DM profile
- For dwarf galaxies, flux is not very sensitive to DM profile
- Flux peaks sharply, dependent on DM channel

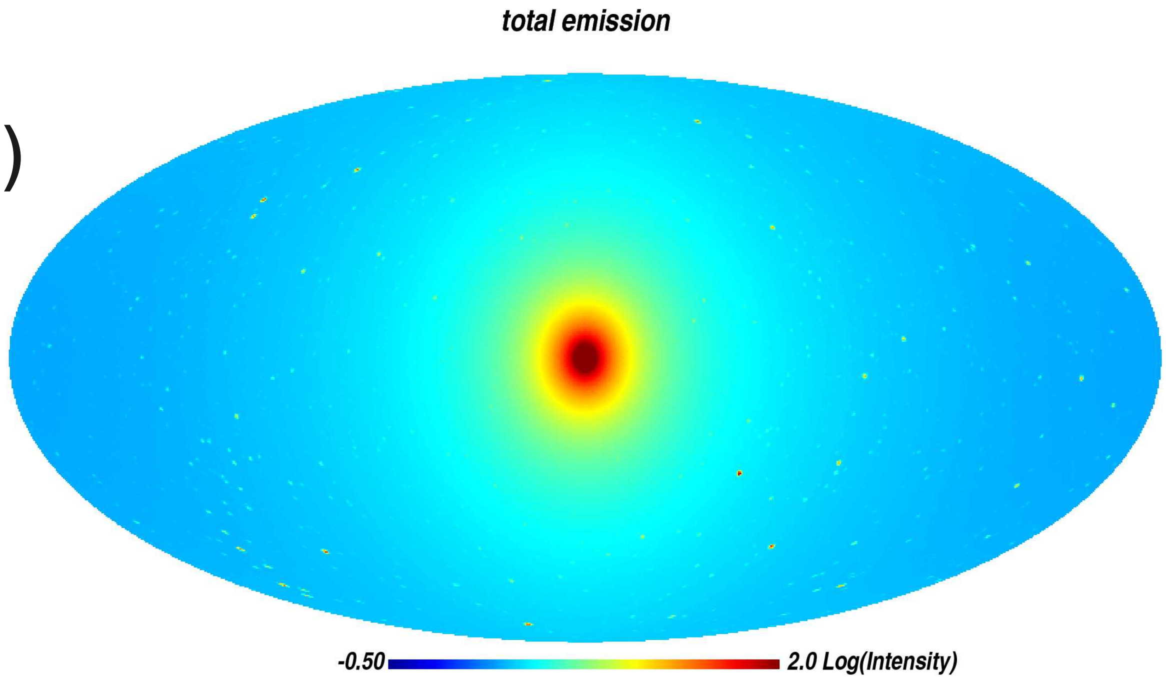






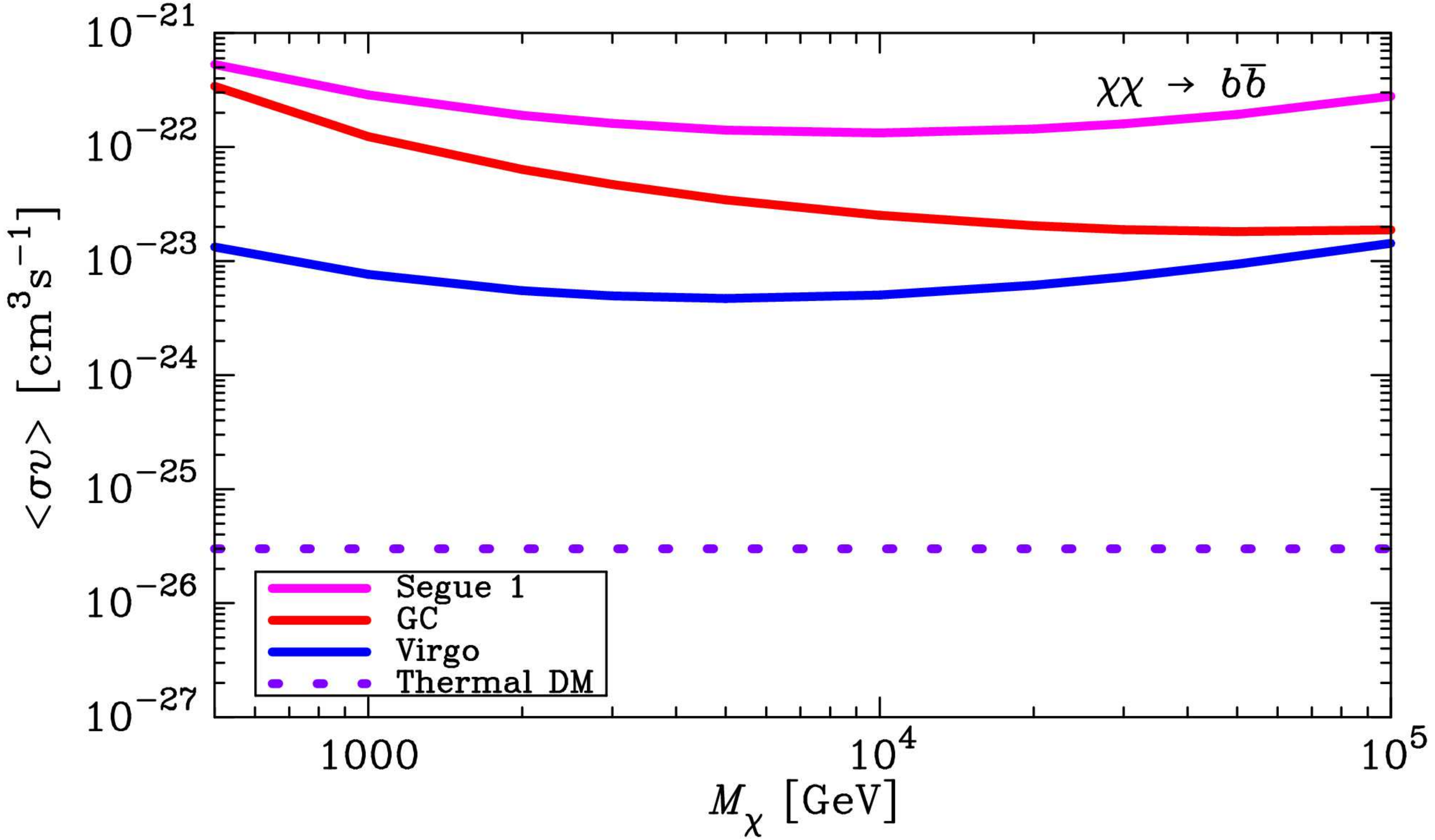
HAWC WIMP DM Sources

- Dwarf Galaxies
  - Draco, Coma Berenices, Segue 1, ...
- Galaxies
  - M31 (Andromeda)
- Galaxy Clusters
  - Virgo Cluster, ...
- Galactic Center
  - NFW profile
  - Einasto profile



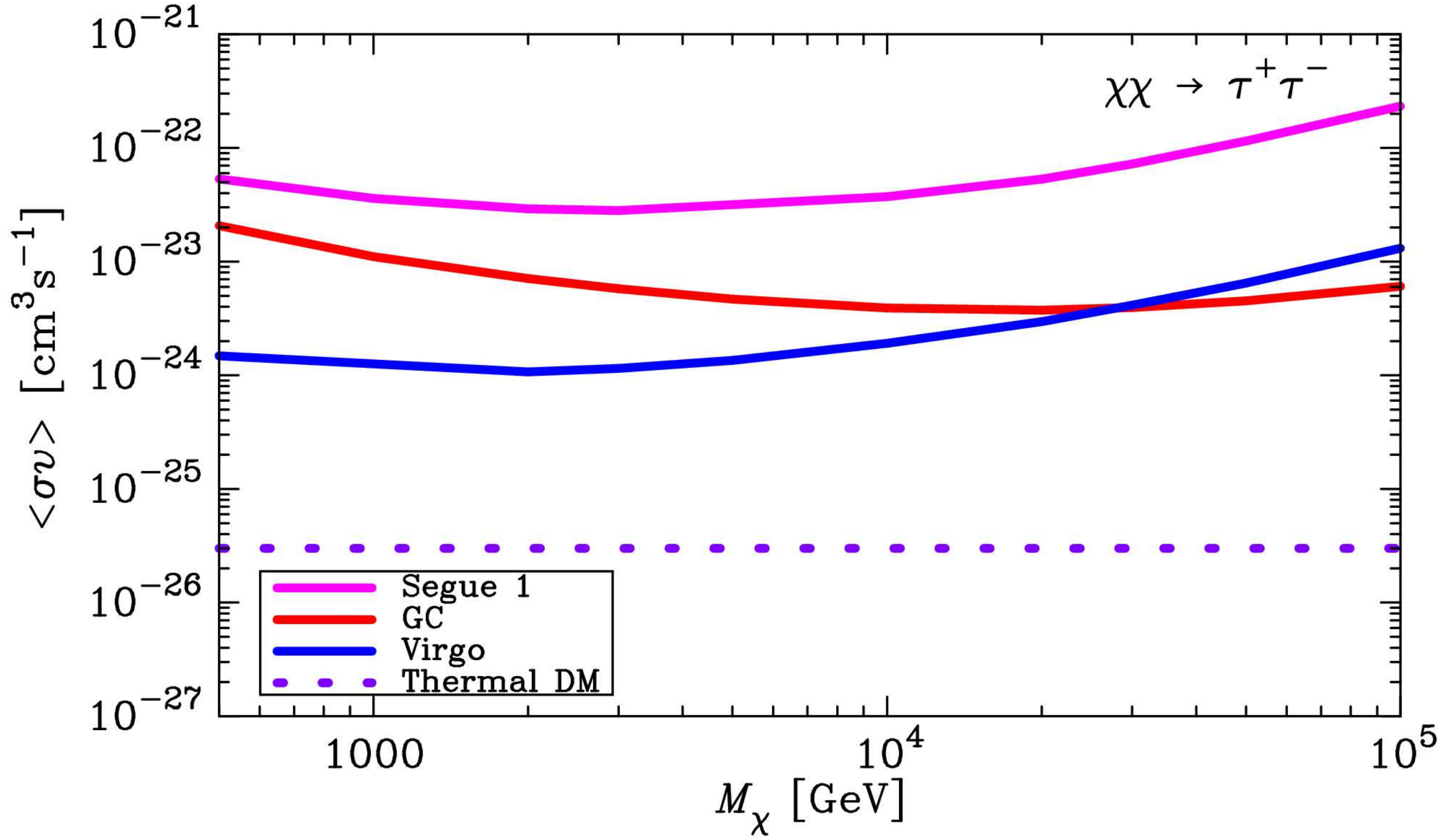
Springel et al. 2008

HAWC $b\bar{b}$



The expected HAWC 5-year limits for the $b\bar{b}$ channel for the Segue 1 dwarf galaxy, Galactic center with an Einasto profile, and Virgo cluster.

HAWC $\tau^+\tau^-$

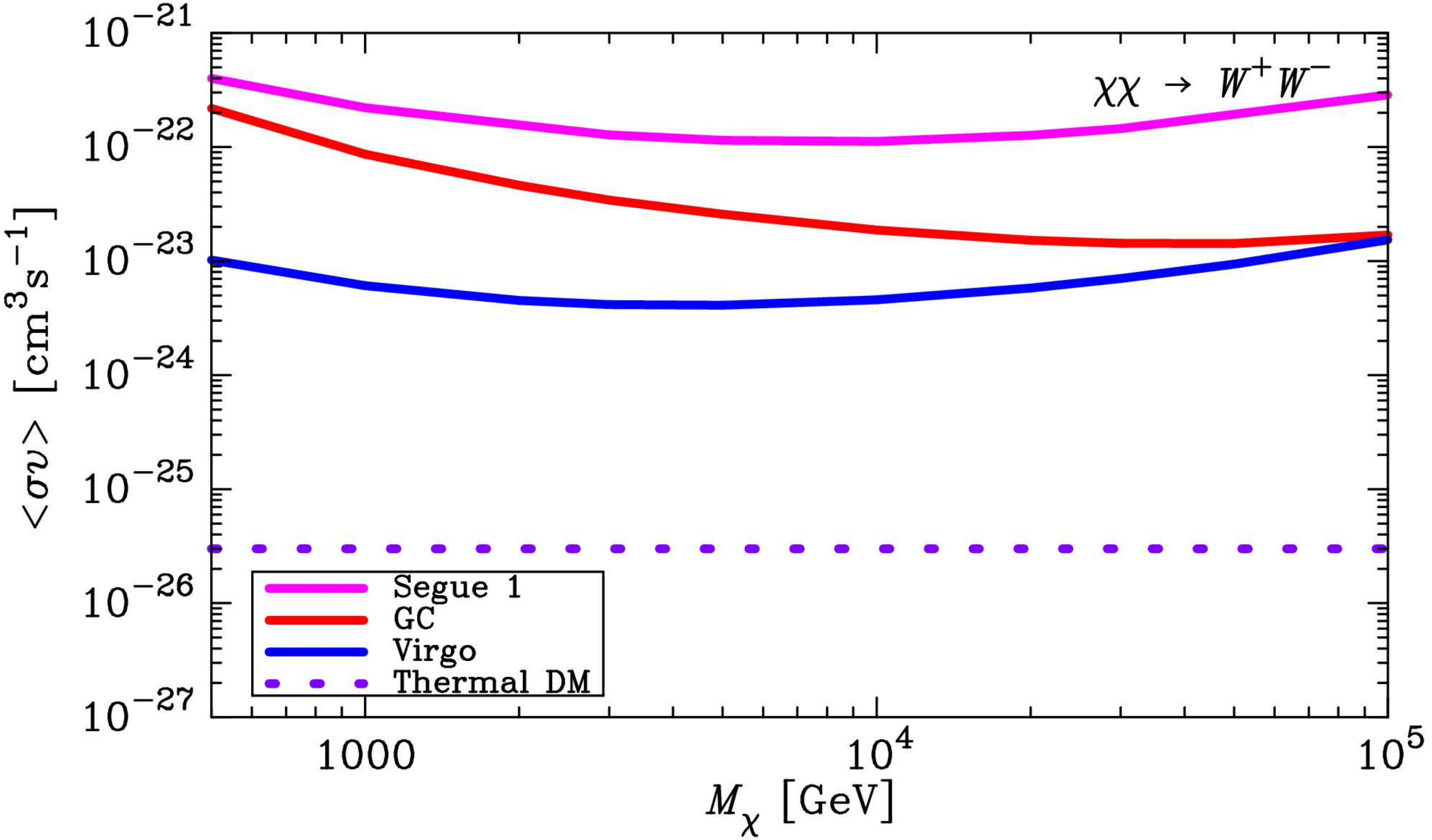


The expected HAWC 5-year limits for the $\tau^+\tau^-$ channel for the Segue 1 dwarf galaxy, Galactic center with an Einasto profile, and Virgo cluster.

High Altitude Water Cherenkov Gamma-Ray Observatory

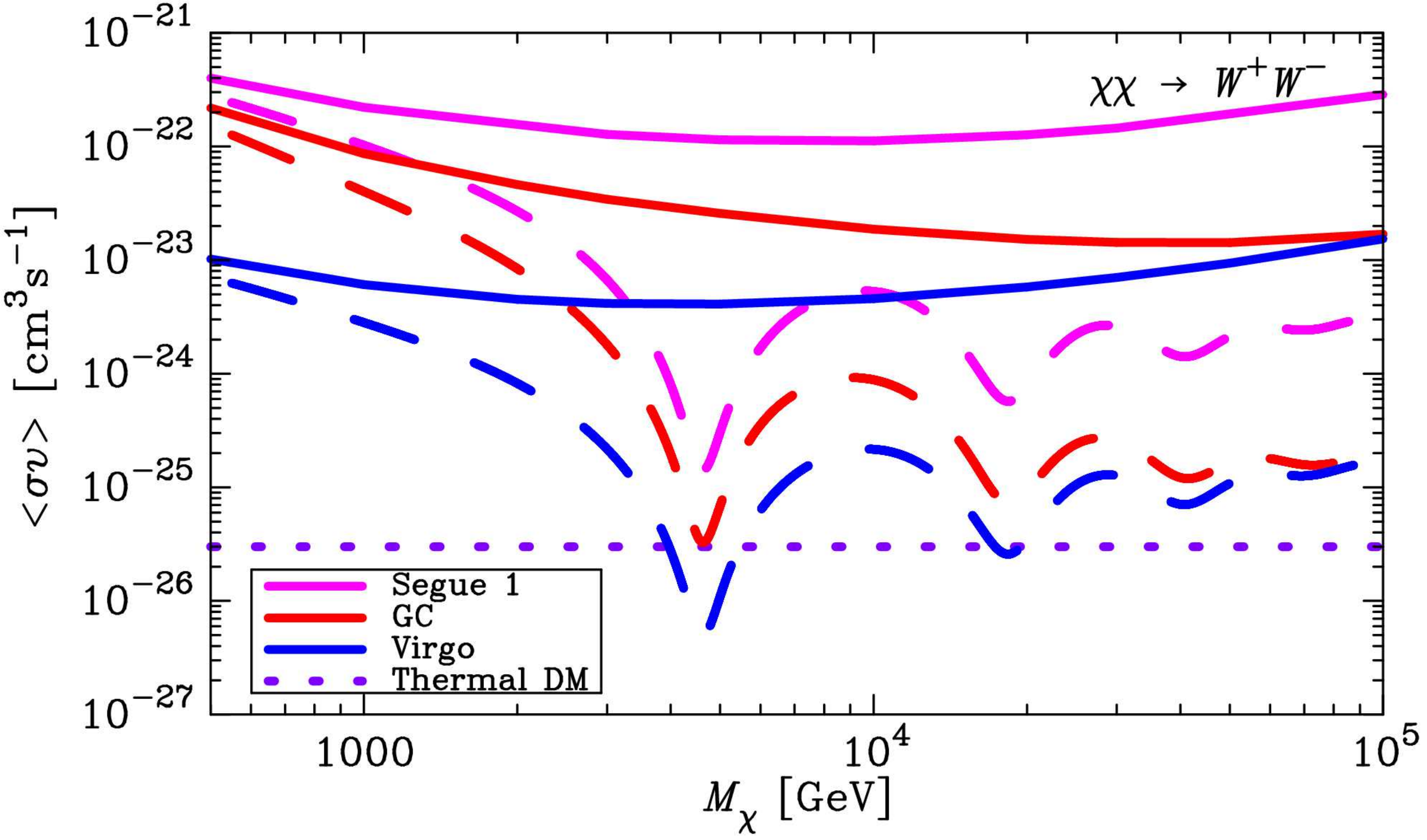
HAWC W^+W^-

Los Alamos NATIONAL LABORATORY EST. 1943



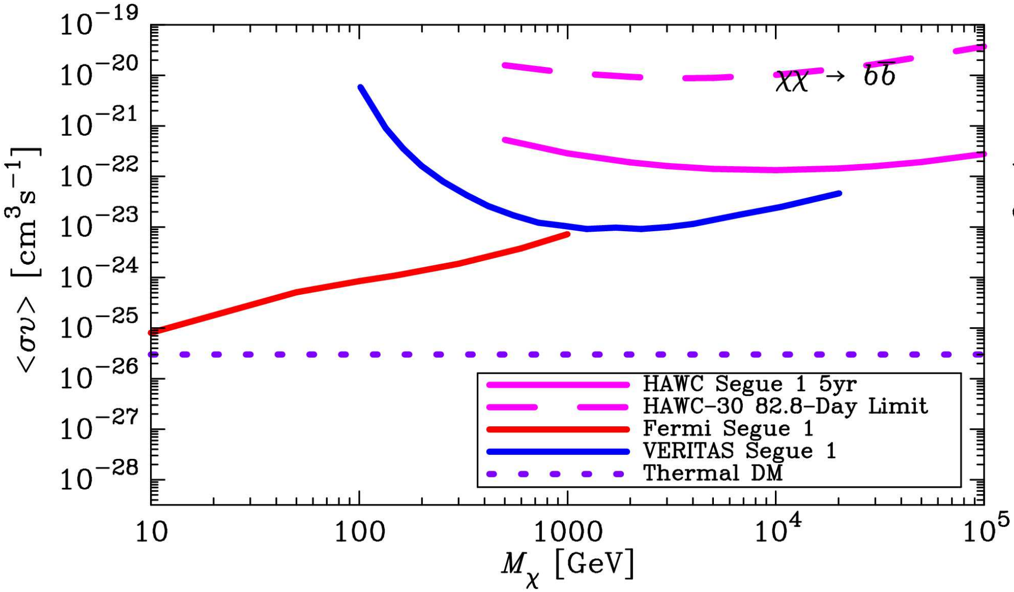
The expected HAWC 5-year limits for the W^+W^- channel for the Segue 1 dwarf galaxy, Galactic center with an Einasto profile, and Virgo cluster.

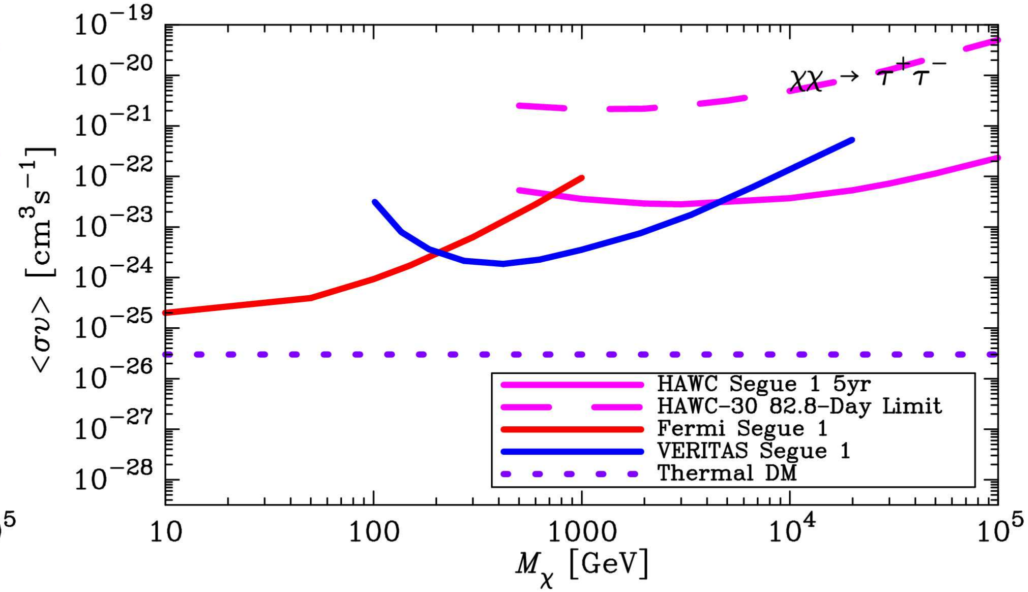
HAWC W^+W^-



The expected HAWC 5-year limits for the W^+W^- channel for the Segue 1 dwarf galaxy, Galactic center with an Einasto profile, and Virgo cluster, including the natural Sommerfeld enhancement from DM exchange of SM gauge bosons (dashed lines).

Limits Comparison



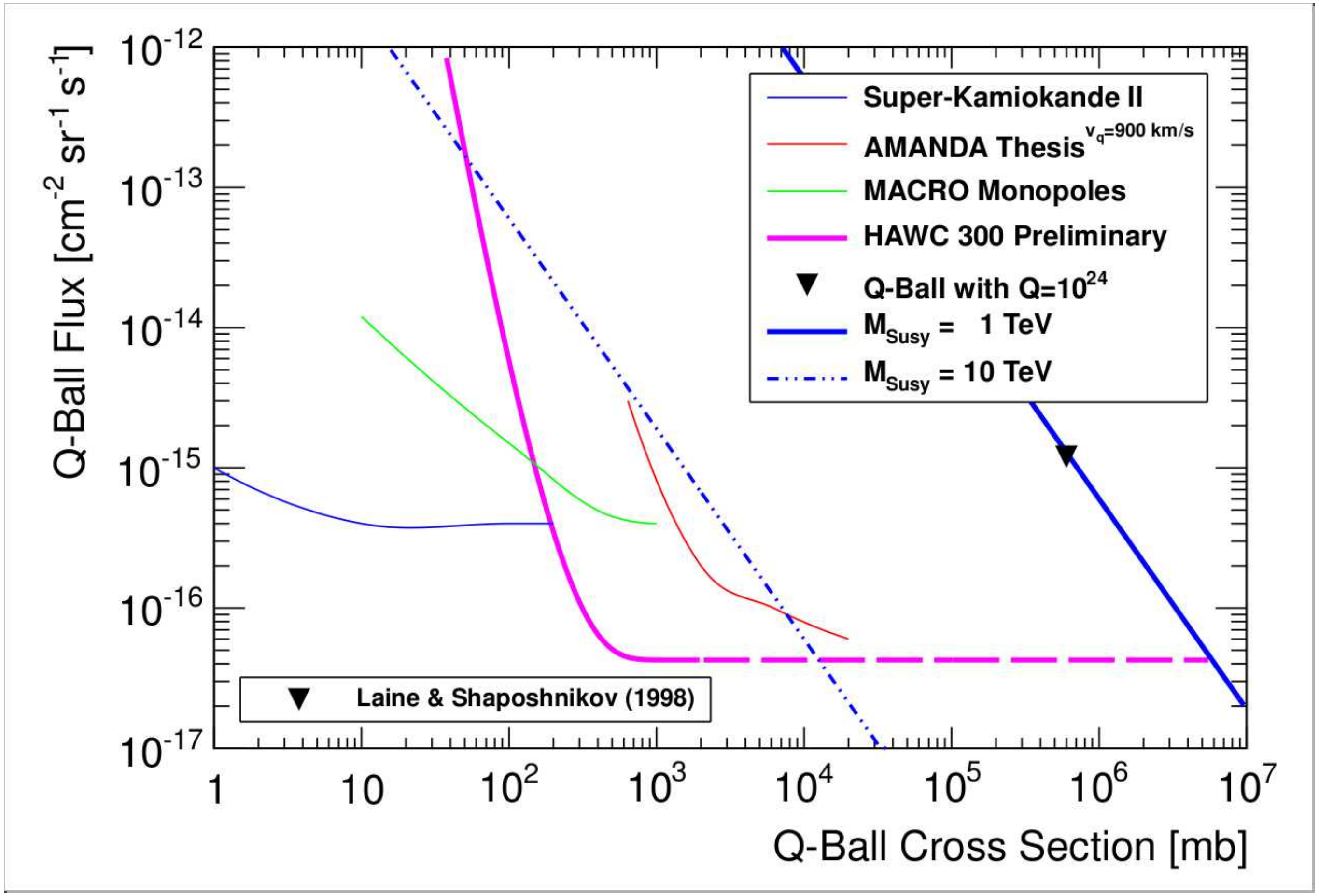


- HAWC $b\bar{b}$ will be strongest above ~50 TeV
- HAWC $\tau^+\tau^-$ will be strongest above ~5 TeV
- HAWC is already searching for the dark matter

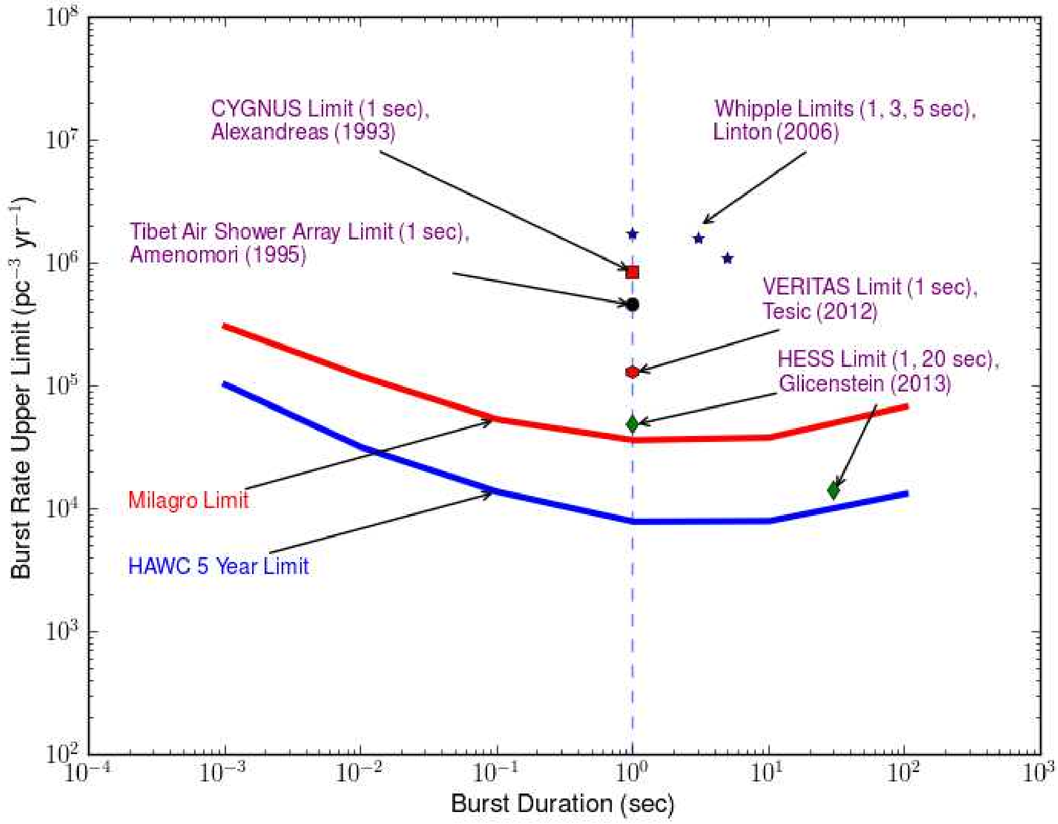
Additional HAWC WIMP DM Searches

- Stacked dwarf spectra
- Stacked cluster spectra
- Diffuse gamma-ray background
- Search for DM source of AMS-02 anomaly (in $\mu^+\mu^-$ channel)
- Search for inverse Compton emission from charged products of DM annihilation
- Dark matter decay
- Undetected dwarf galaxies
- Cosmic-ray channels

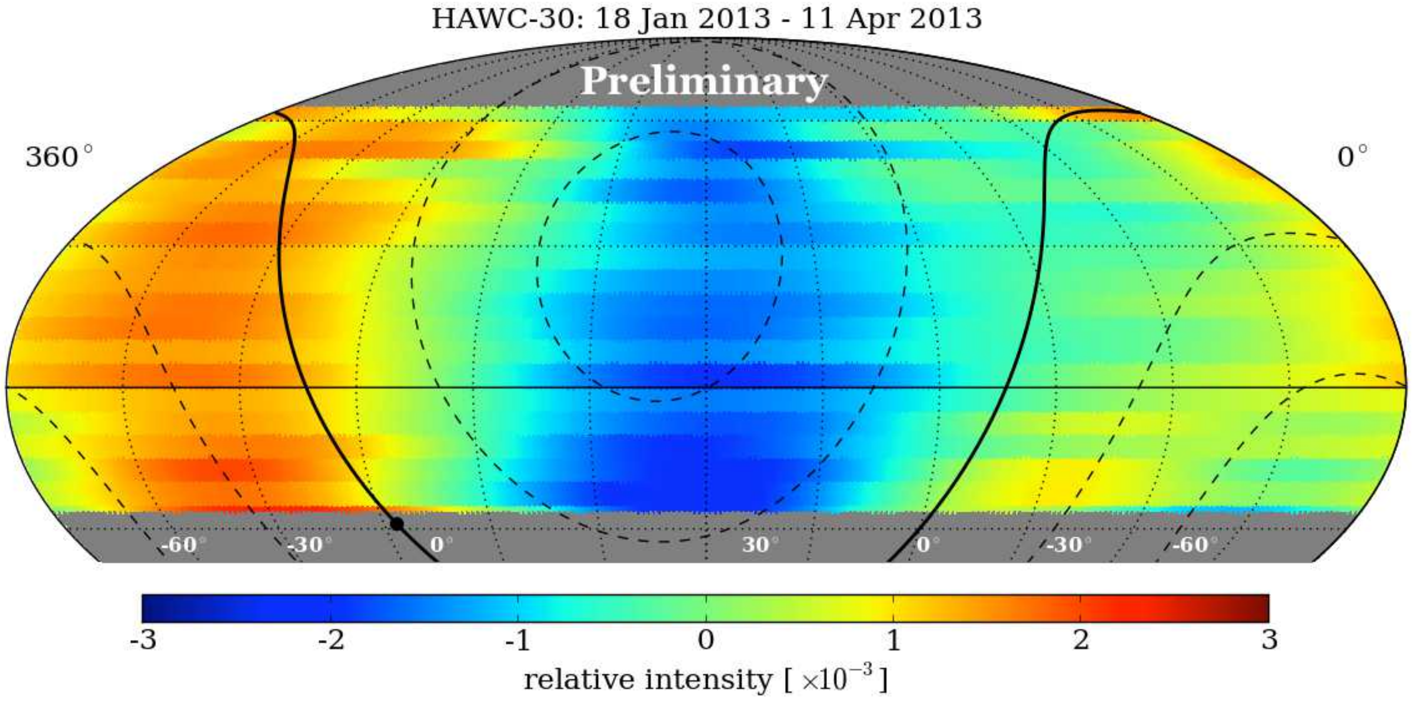
HAWC Non-WIMP DM Searches - QBalls



HAWC Non-WIMP DM Searches – PBHs

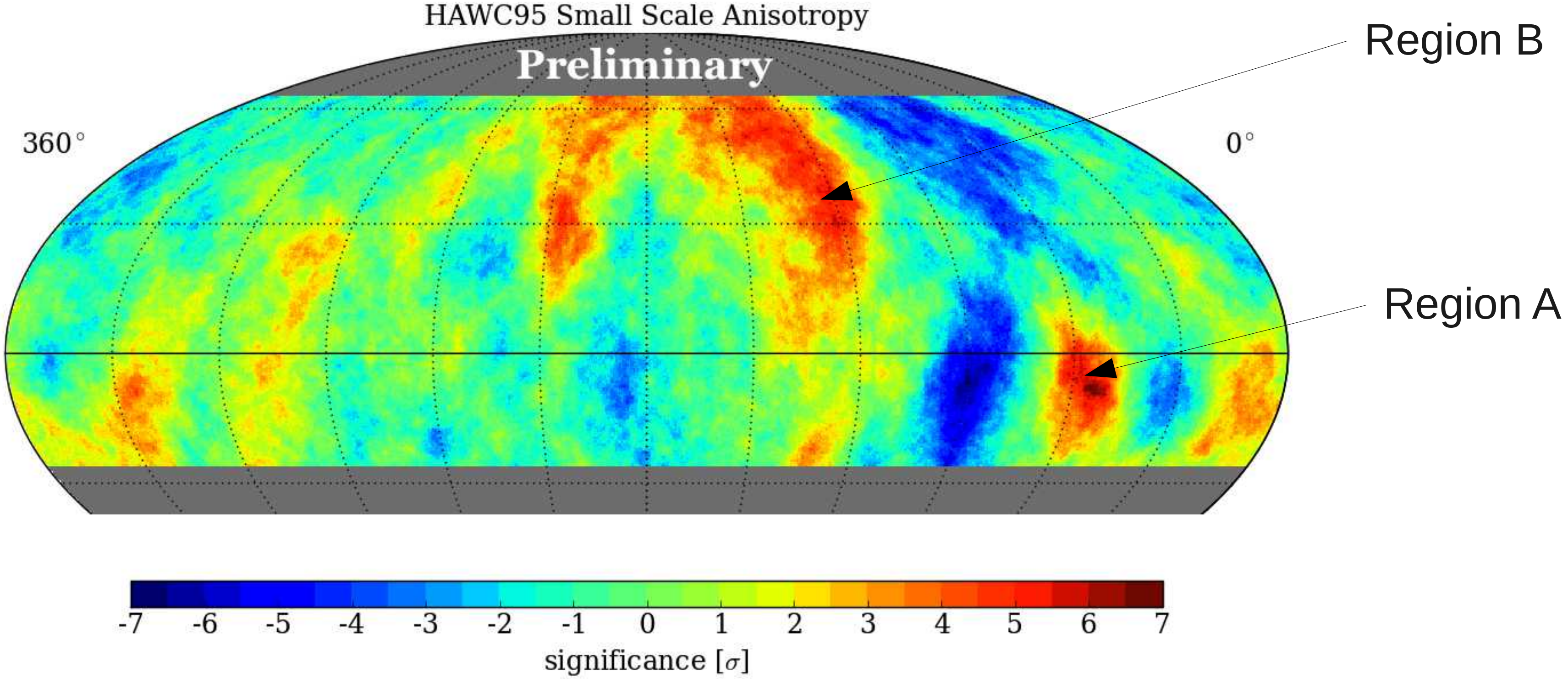


HAWC Large Scale Cosmic Ray Anisotropy



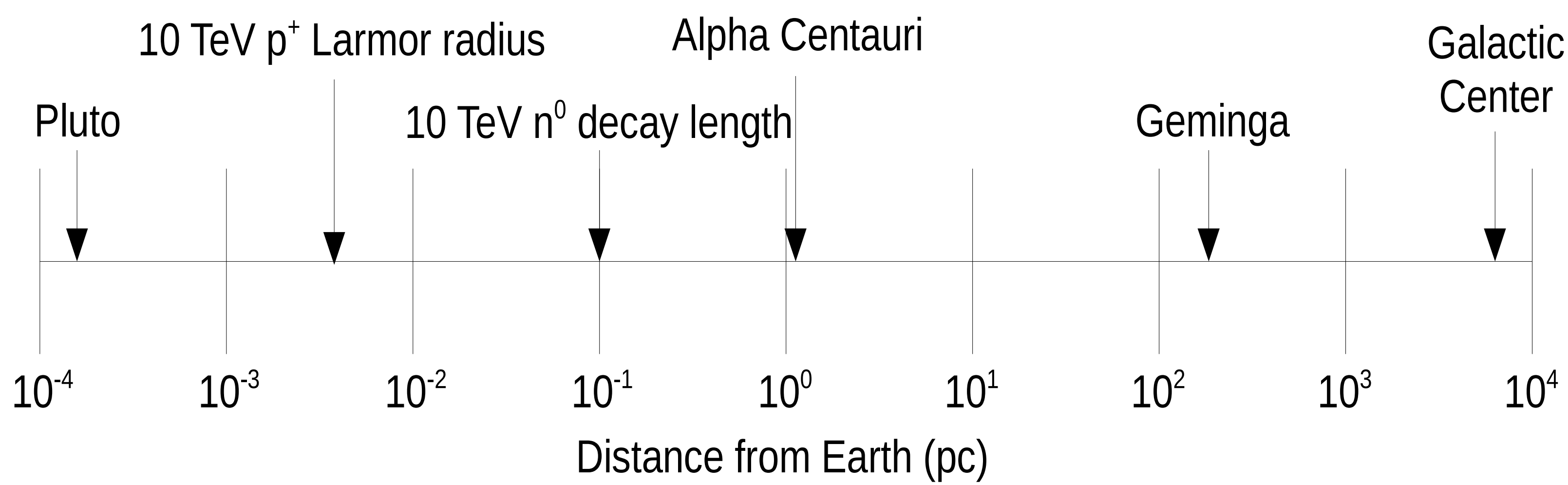
3-term harmonic fits within 18 declination bands

HAWC Small Scale Cosmic Ray Anisotropy

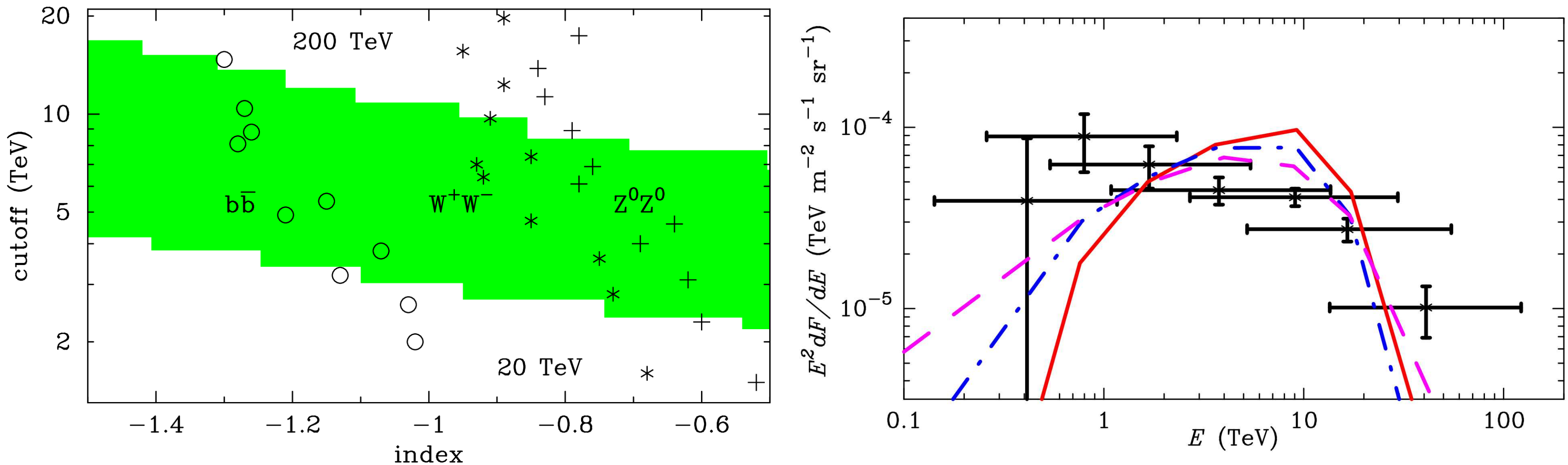


The Impossible Signal

- From propagation over long distances, CRs should be isotropized due to diffusion in the turbulent magnetic field.
- For 10 TeV CRs, the Larmor radius in the local 2 μG magnetic field is only 0.005 pc
- For a source of neutrons, the decay length of a 10 TeV neutron is 0.1 pc
- No source of CRs is so close to Earth
- Coherent magnetic field connecting the source to Earth can do it
  - But must be <100 pc long, with shorter lengths increasingly likely
- Must have *both* non-standard propagation *and* a nearby source



Anisotropy from DM?



JPH, arXiv:1307.6537

- Left: Milagro-consistent spectra (green region) vs DM spectral parameters
  - W^+W^- (stars), Z^0Z^0 (crosses), $b\bar{b}$ (circles) from 20-200 TeV
- Right: 60 TeV W^+W^- (red), 50 TeV Z^0Z^0 (blue), 100 TeV $b\bar{b}$ (magenta) vs Milagro spectrum
  - Need better error bars to distinguish spectra
  - Energy losses during propagation should shift peaks to right and soften cutoffs
- The needed channels/masses/cross-sections are the same as those to explain the HESS extended GC source with dark matter

Constraints on the DM Subhalo Explanation

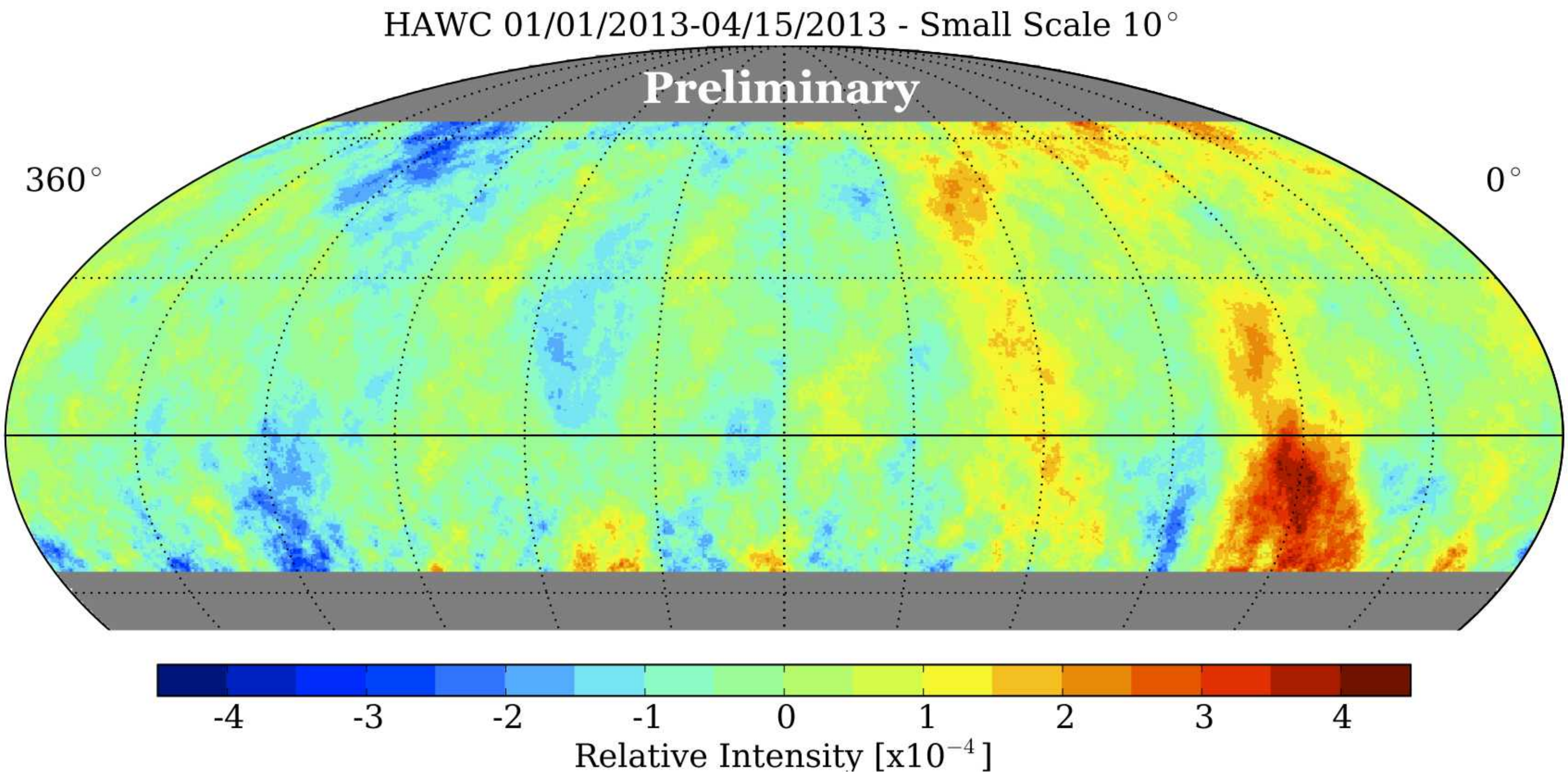
- Meets all constraints:
  - Diffuse anti-protons (PAMELA, ARGO)
  - Diffuse positrons (AMS)
    - But pointed could detect it
  - All-sky gamma-rays (Fermi, Milagro)
    - For expected extended source
  - Pointed gamma-rays (HESS, VERITAS, MAGIC)
    - Would see it if they look at it for ~50 hours
  - HAWC
    - Will detect it, if dec > -30

HAWC is now!

- Over 165 tanks constructed, with 4 more per week
- Operations with 111 tanks began 1 August 2013
- Full detector complete in 2014

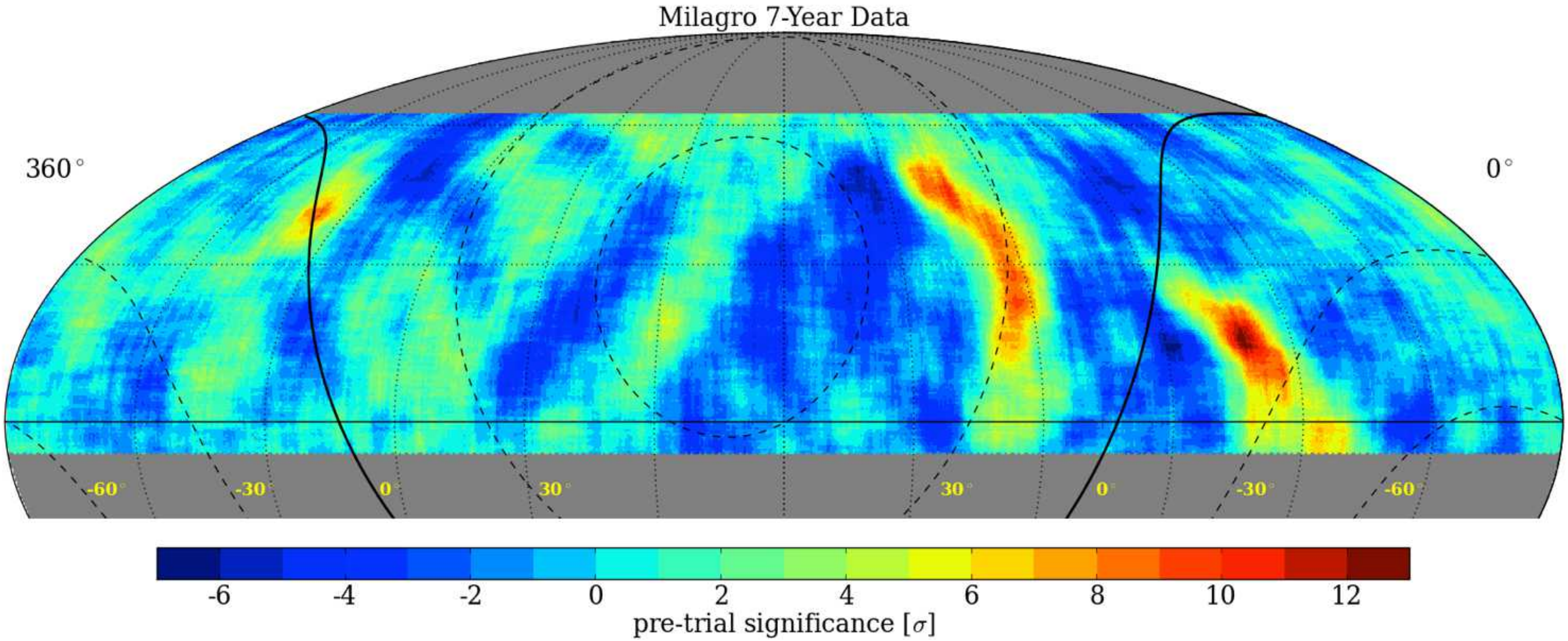
Backup Slides

HAWC Small Scale Anisotropy



Comparison to Milagro Skymap

Milagro Anisotropy: PRL 101:221101, 2008



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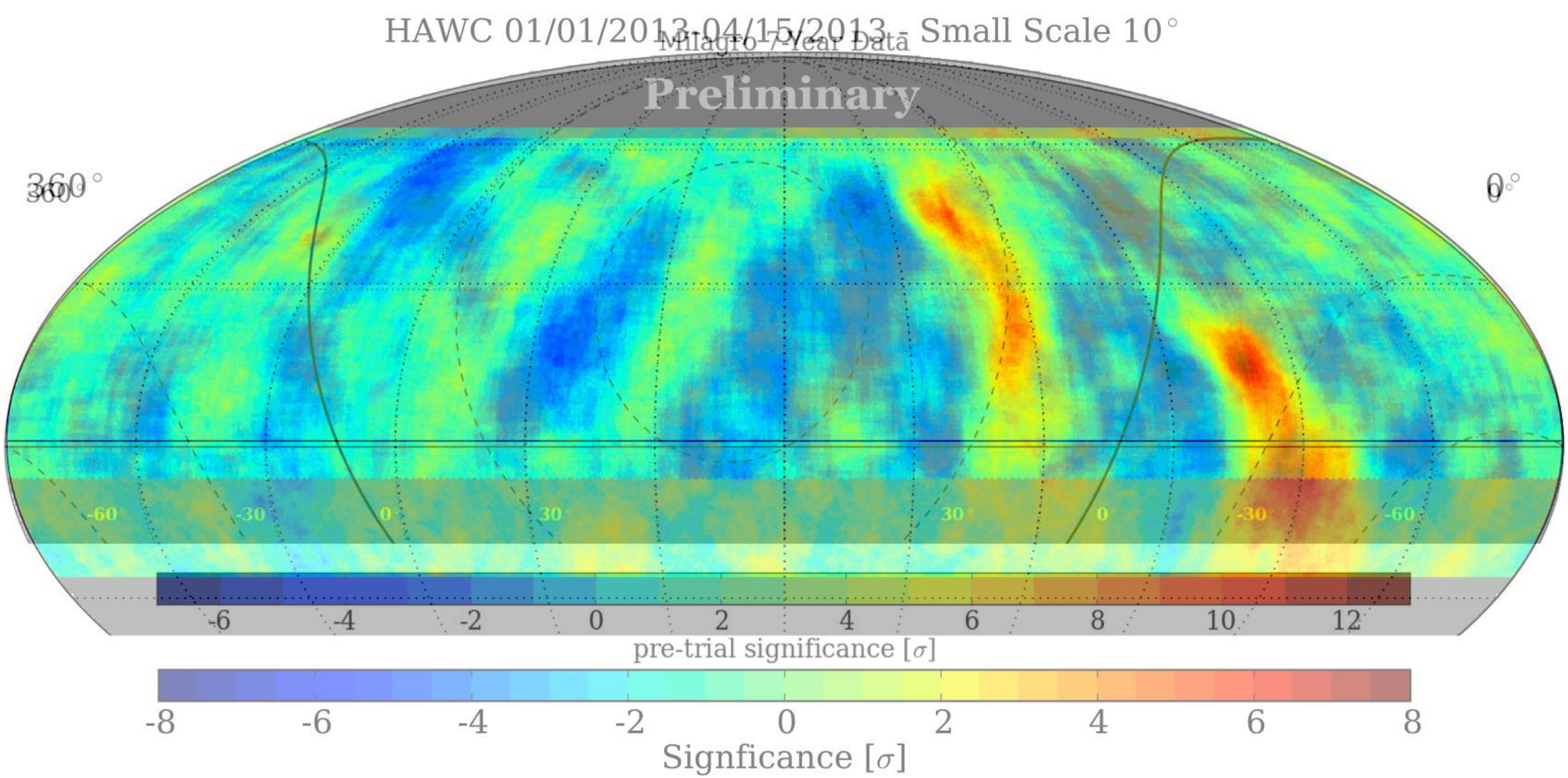

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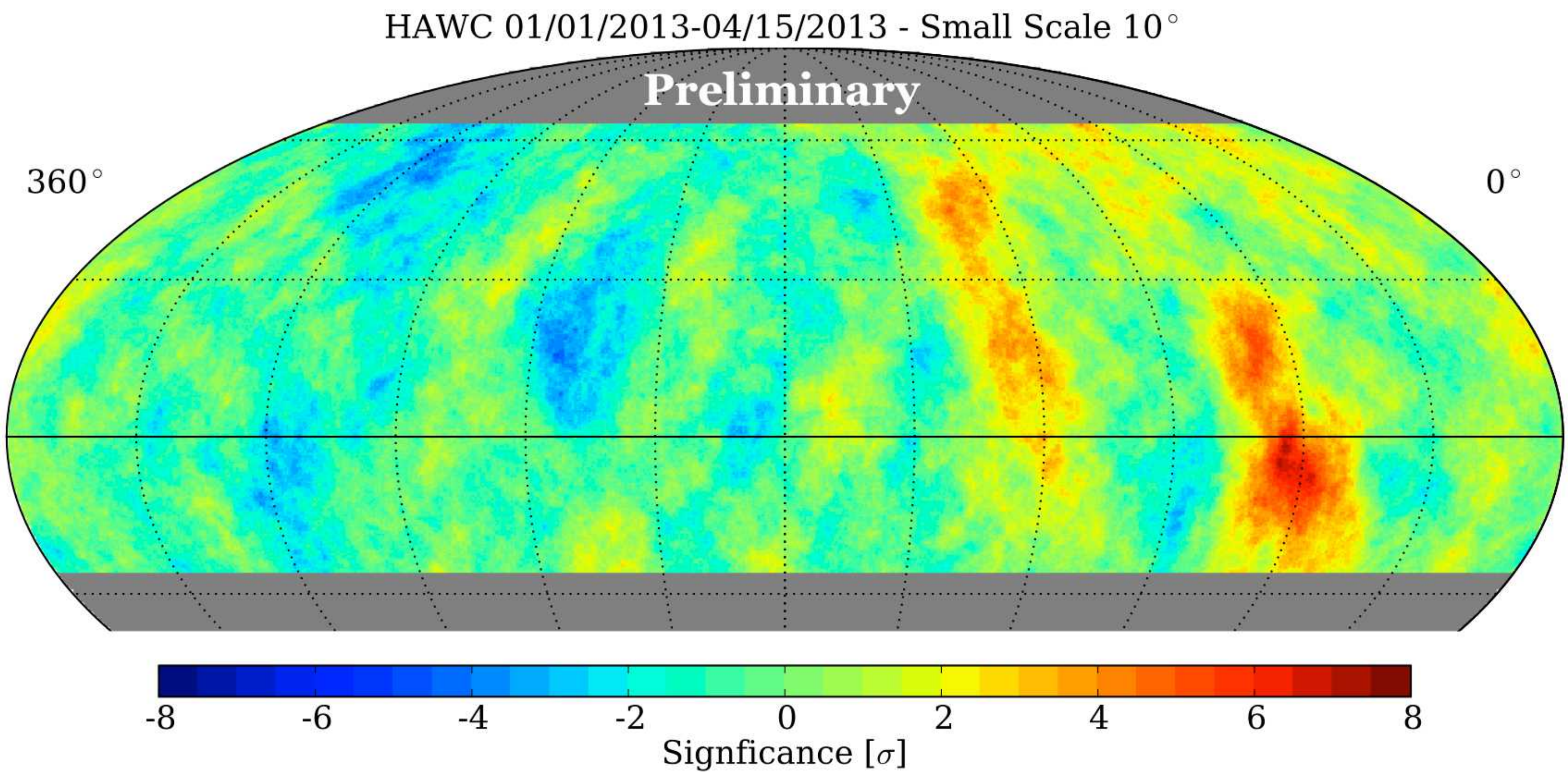
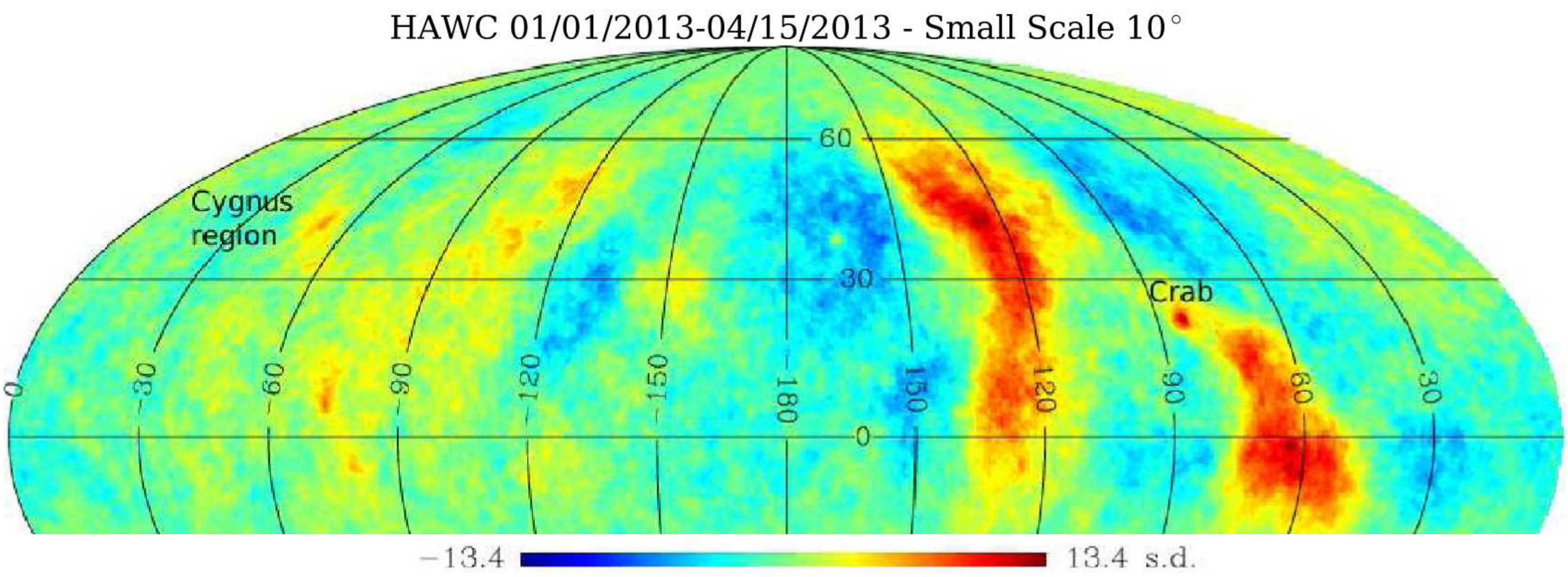


Comparison to ARGO-YBJ Skymap

ARGO Anisotropy: G. Di Sciascio, ISVHECRI 2012



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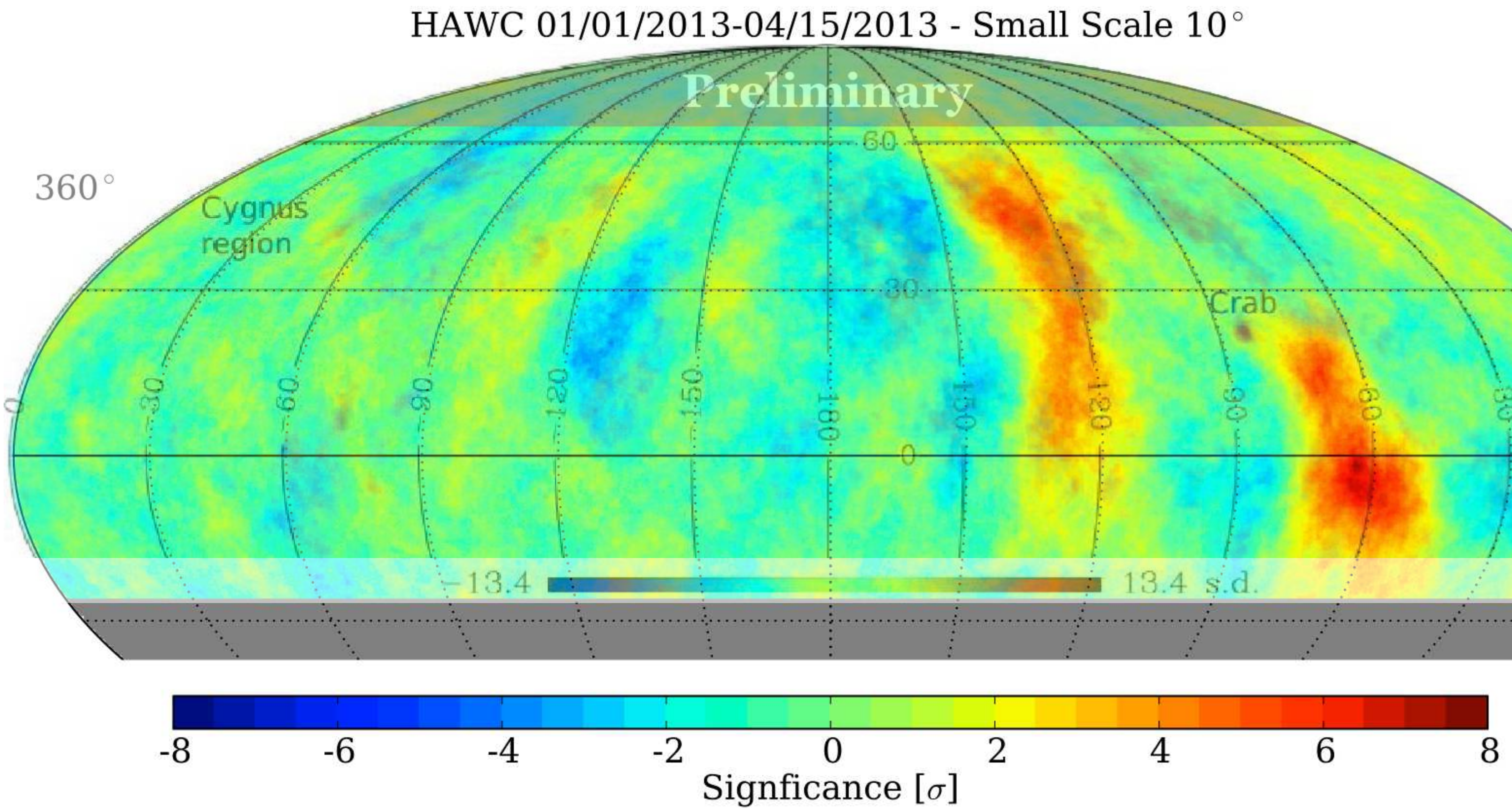

Comparison to ARGO-YBJ Skymap

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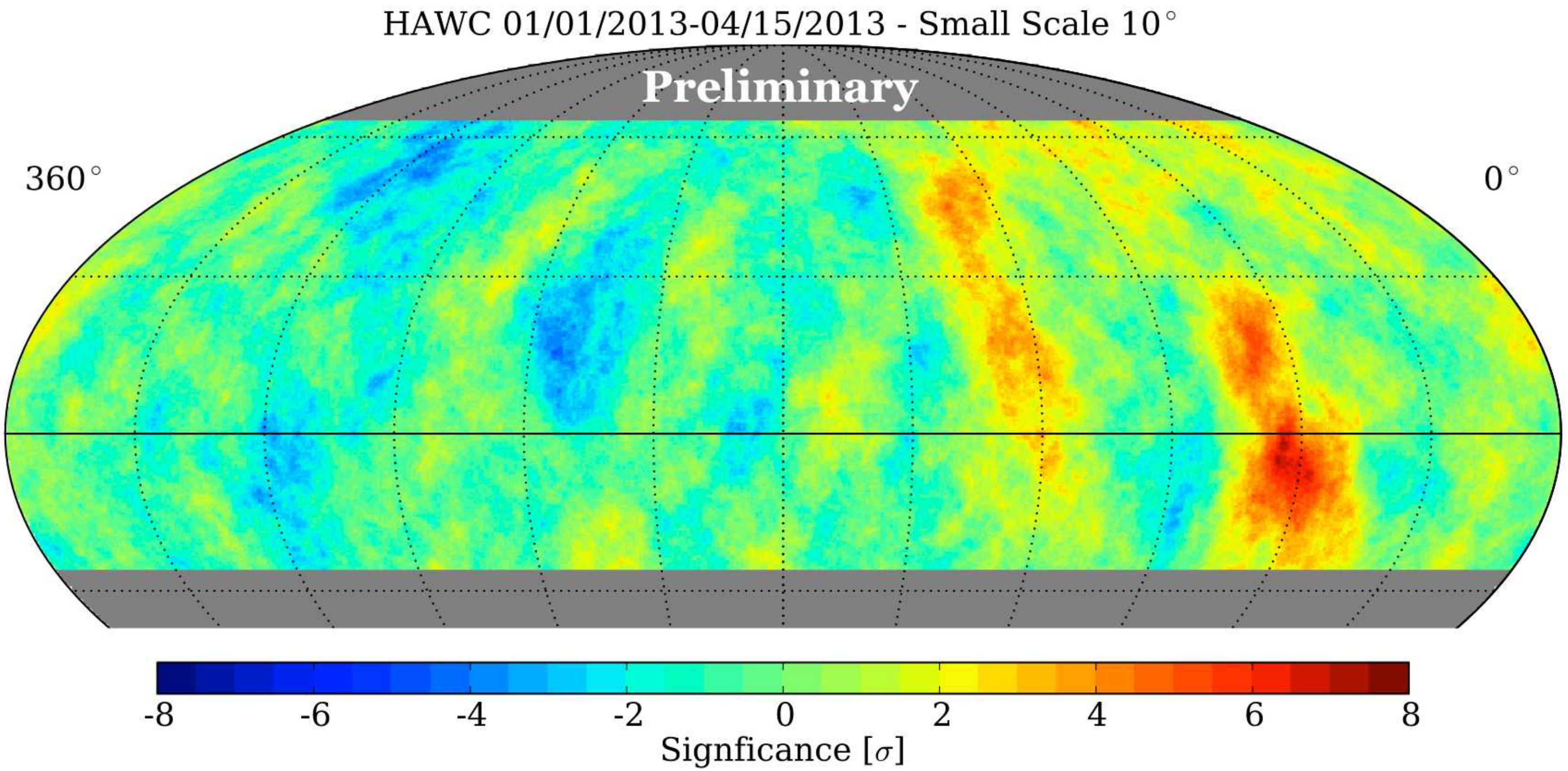
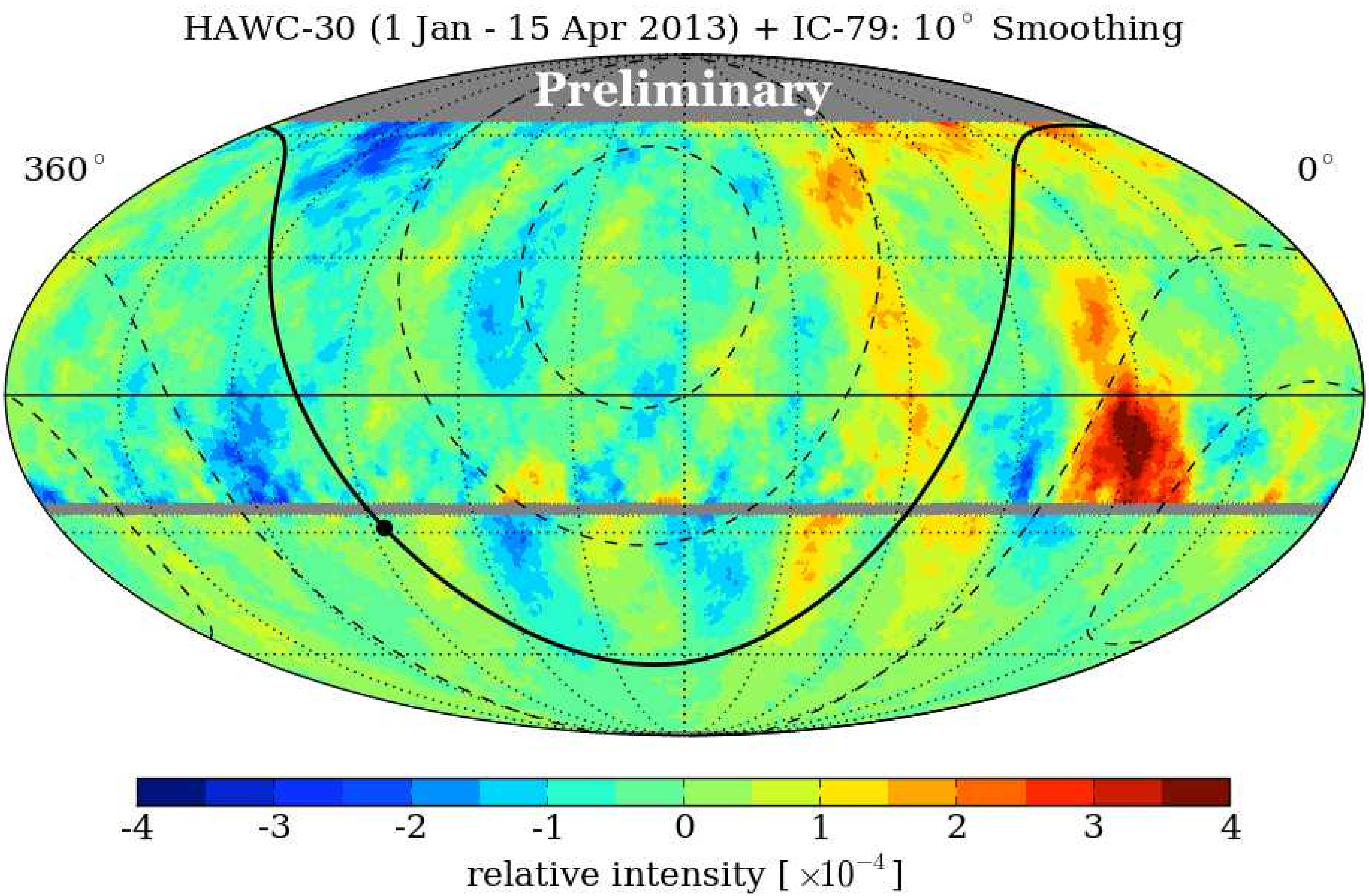


Comparison to IceCube Skymap

IceCube Anisotropy: ApJL 718:194, 2010

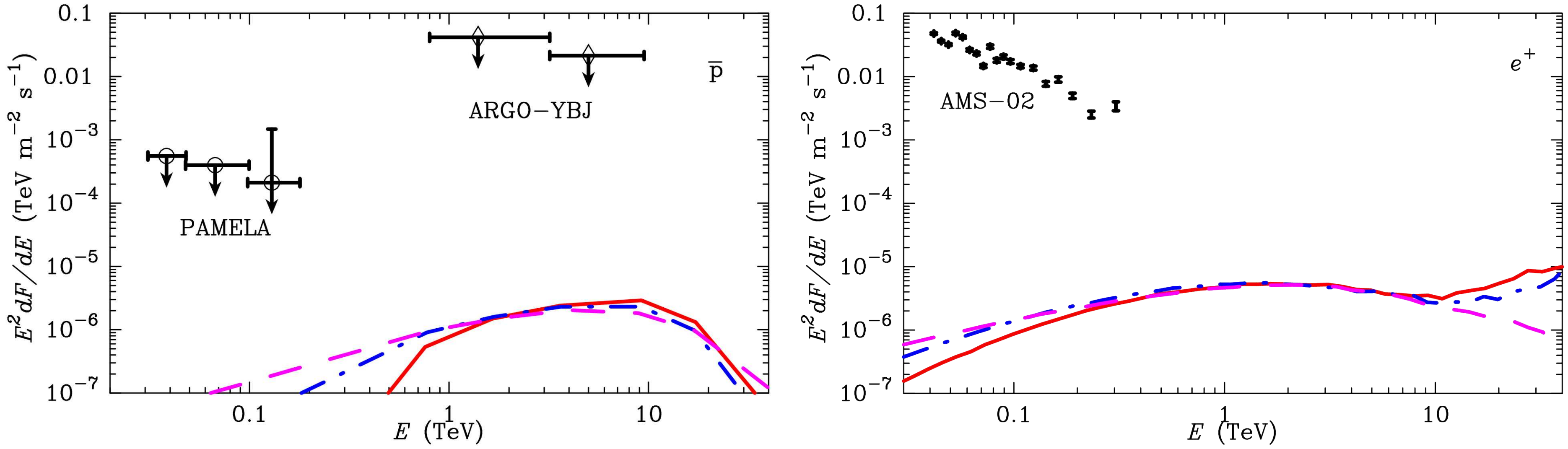


Local Dark Matter Subhalo

M_{vir}	D_{min}	$J_{\Delta\Omega}(D_{min})$	$J_{\Delta\Omega}(D_{min}$-100 pc)
$10^9 M_\odot$	933 pc	119	137
$10^8 M_\odot$	465 pc	114	158
$10^7 M_\odot$	225 pc	112	247
$10^6 M_\odot$	108 pc	112	2840
$10^5 M_\odot$	51.3 pc	111	-
$10^4 M_\odot$	24.1 pc	110	-
$10^3 M_\odot$	11.2 pc	109	-

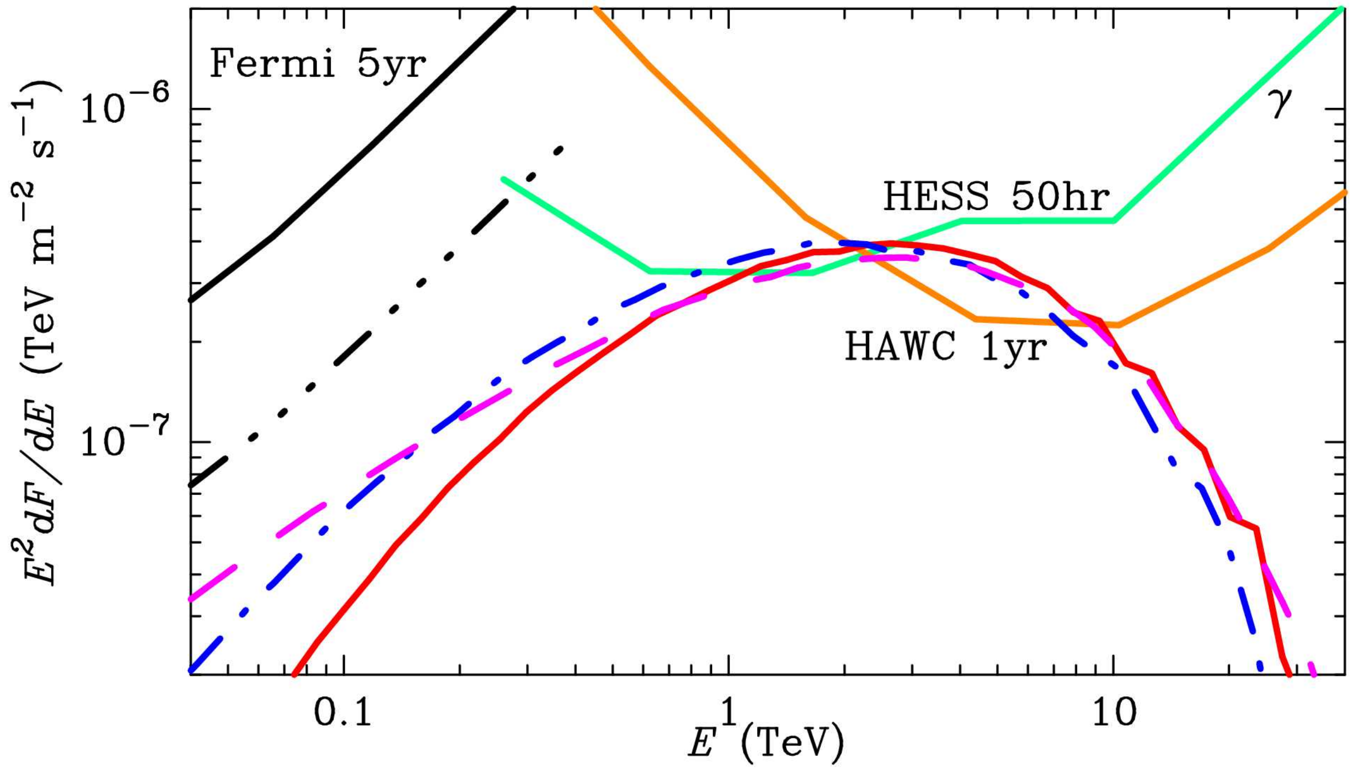
- Expect many subhalos from DM substructure
- Minimum distance D_{min} to a subhalo consistent with the local DM density
- Scaling with subhalo mass from Bolshoi simulation
- DM flux to source is ~ independent of subhalo mass
- DM flux to magnetic stream is highly scenario-dependent

Antiproton and Positron Constraints



- Total flux from DM subhalo compared to total isotropic flux from limits (for 0.03 sr region)
  - Should be seen at ~10^{-4}-10^{-3} small-scale anisotropy in 100s of GeV
- Shown: 60 TeV W^+W^- (red), 50 TeV Z^0Z^0 (blue), 100 TeV $b\bar{b}$ (magenta)

Gamma-Ray Constraints



- Experimental sensitivities to 5°-extended gamma-ray sources
  - Fermi 5-year sensitivity to 1°-extended gamma-ray source shown as well
- Shown: 60 TeV W^+W^- (red), 50 TeV Z^0Z^0 (blue), 100 TeV $b\bar{b}$ (magenta) DM fluxes