High Altitude Water Cherenkov
Gamma-Ray Observatory

Observation of the Moon and Sun with the HAWC Observatory

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08/07/2017

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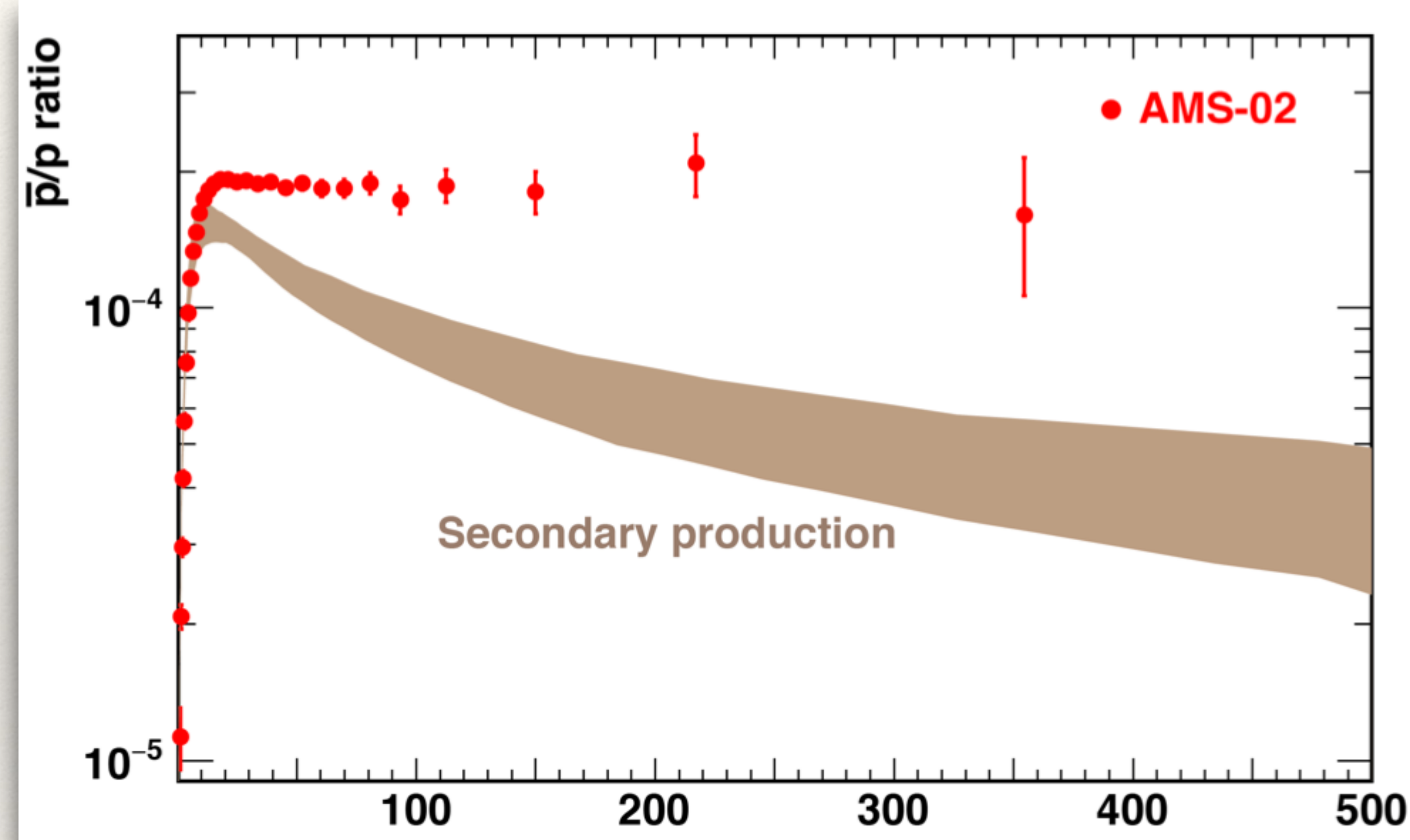
Outline

1. Using the MoonShadow to look for anti-protons in the cosmic ray spectrum.

2. Searching for TeV gamma rays from the Sun.

Direct measurements of p-bar/p

- AMS measurements up to 350 GeV
- Unexpected, constant ratio of p-bar/p
- Constant ratio of positrons to anti-protons
- Ongoing search for explanations and potential for HAWC to contribute.
- TeV limits



Adam Falkowski (CERN)

High Altitude Water Cherenkov Observatory

High Altitude Water Cherenkov Observatory

- 4100 m above sea level
- Sierra Negra and Pico de Orizaba in Mexico
- 300 water tanks with 4 PMT's each

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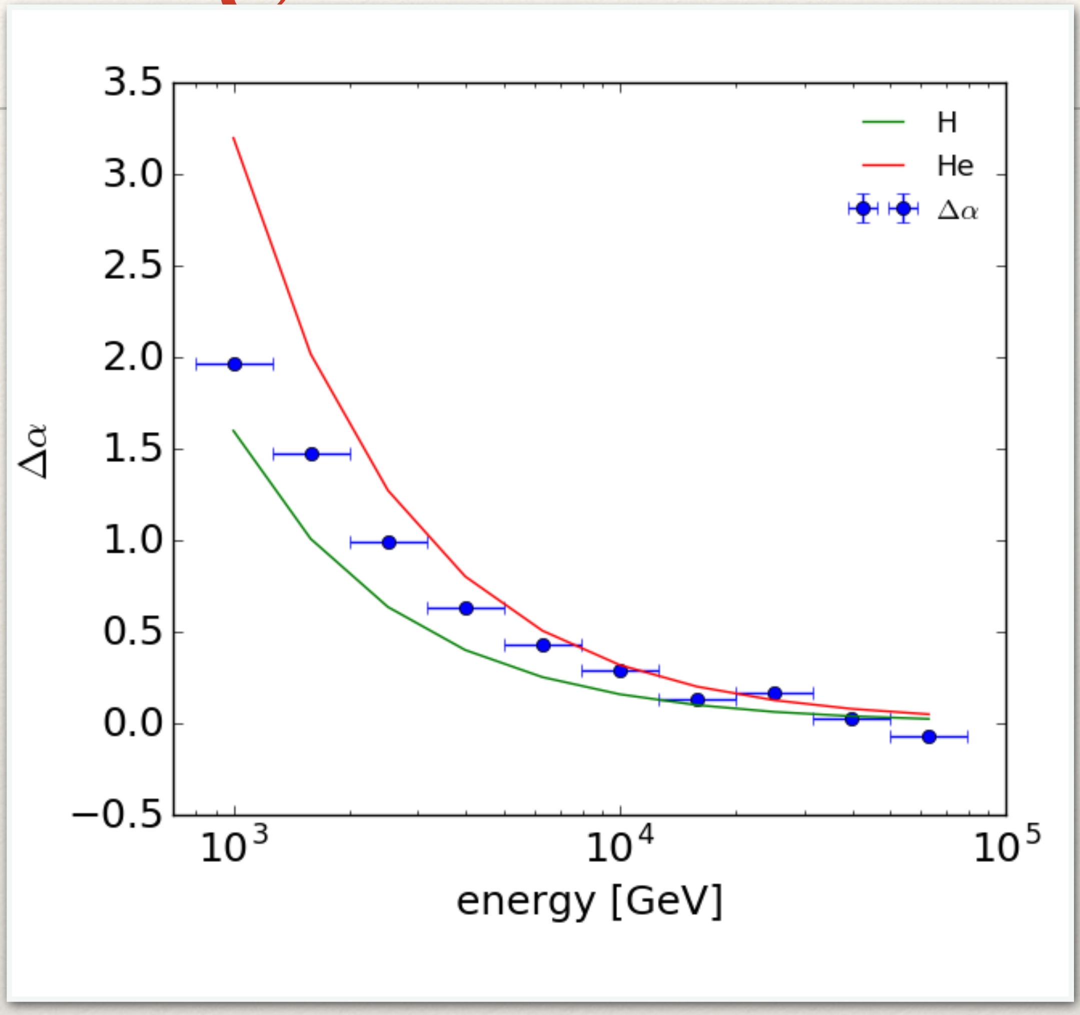
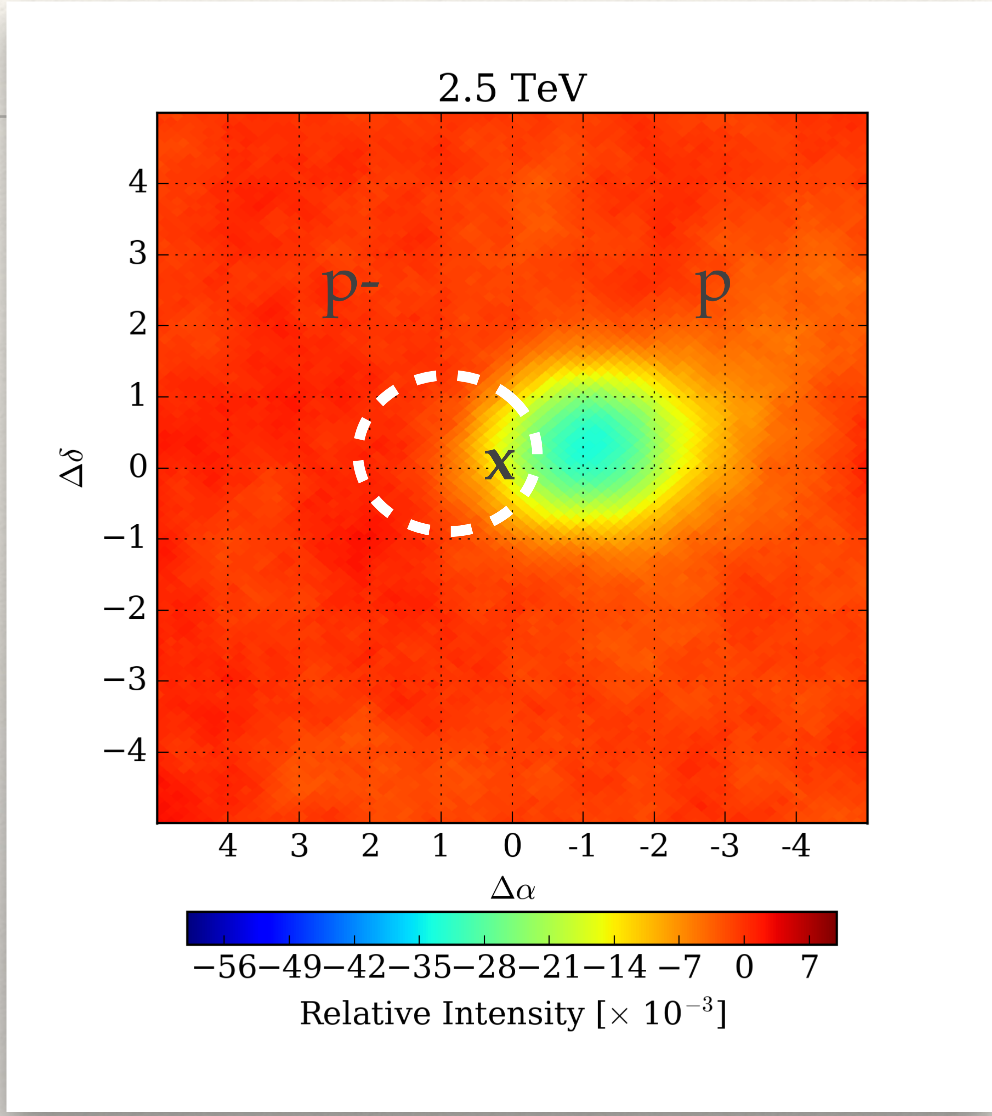
- 2 sr instantaneous field of view
- Area 22,000 m^2
- Trigger rate of 25 kHz
- Energy range 300 GeV to > 100 TeV

Charge discrimination with Moon Shadow



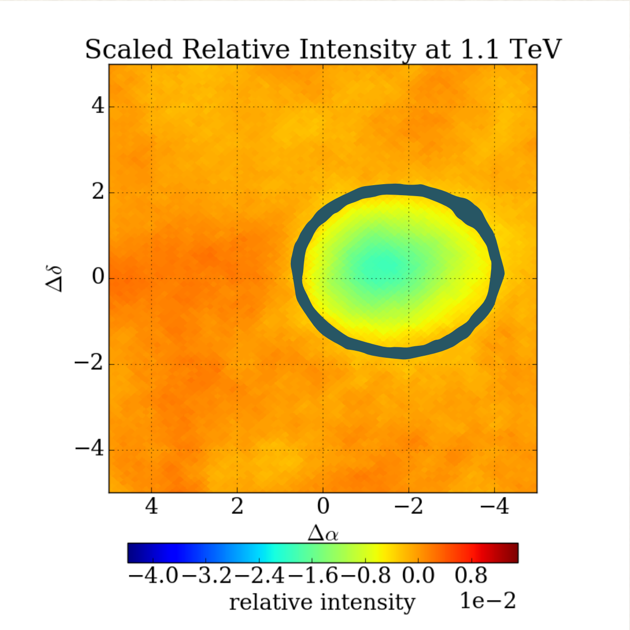


- Observed with high significance.
- Offset in RA described by, $\delta\theta = 1.6^{\circ} Z(\mathrm{TeV}/E)$
- The deflection in $\Delta\alpha$ shows that most of the CR flux consists of protons (Z =1)
- In principle, negatively charged particles should cast a shadow in the opposite direction.

Searching for Antiprotons

- We fit the moon shadow with a 2d gaussian and take its centroid position to be the deflection, ΔR.A.
- Assume the map is a superposition of <u>deficits</u> due to protons and anti-protons.

$$\delta I = \frac{N(\alpha_i, \delta_i) - \langle N(\alpha_i, \delta_i)\rangle}{\langle N(\alpha_i, \delta_i)\rangle}$$



- We describe it by a sum of two gaussians,

$$S(x,y) = f_p(x,y) + f_{\bar{p}}(x,y)$$

- The ratio of the amplitudes of the two functions $\sim \bar{p}/p$

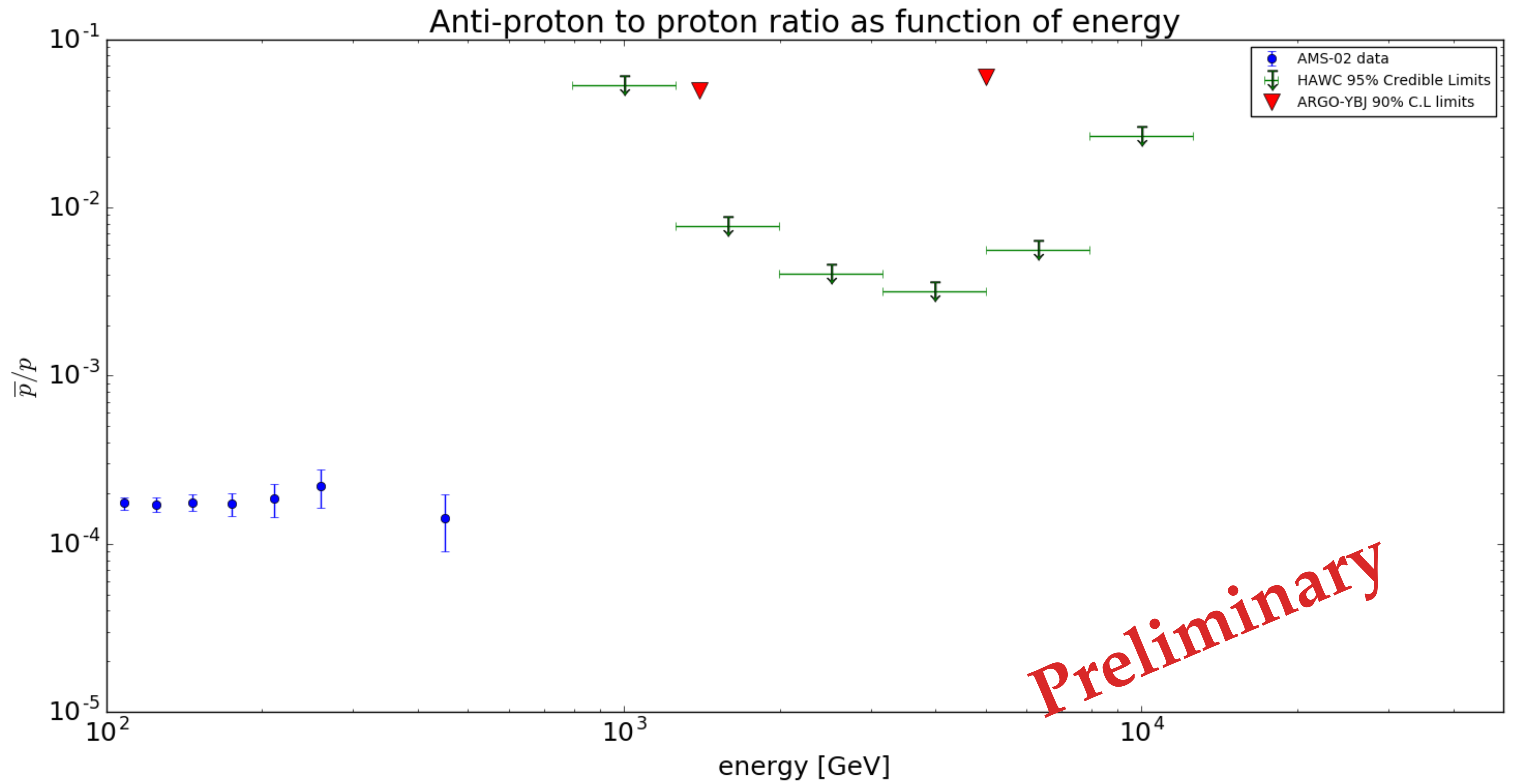
$$f_i(x,y) = A_i \exp\left(-\frac{(x-x_0)^2}{2\sigma_x^2} - \frac{(y-y_0)^2}{2\sigma_y^2}\right)$$

- Quantity of interest $\frac{A_{\bar{p}}}{A_p}$

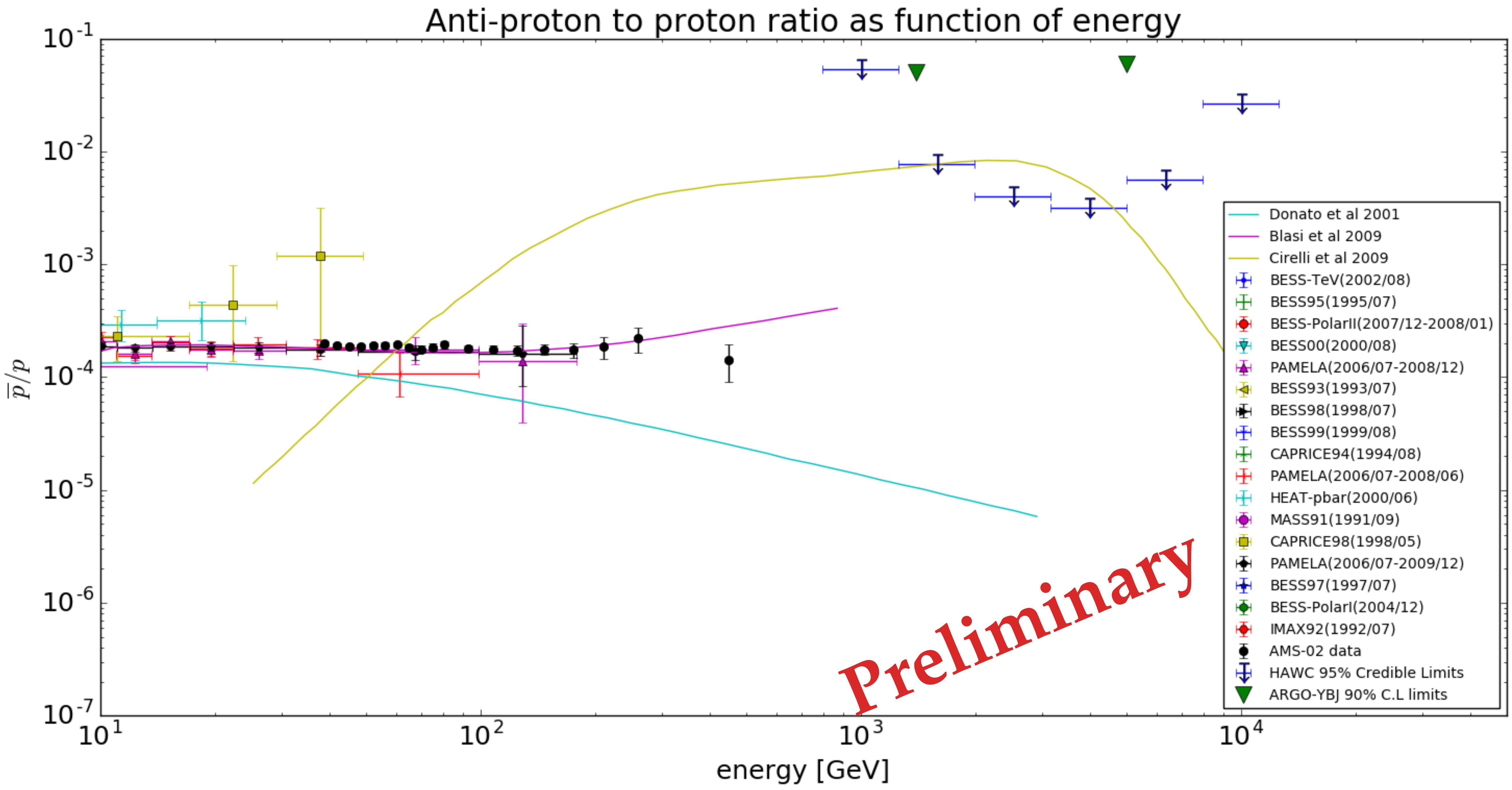
Fitting the moon shadow

- MCMC fit
- Bayesian calculation. Tried different combinations of free and fixed parameters to get the most robust fit.
- Widths of the shadows σ, centroids x_0 and y_0 and the amplitudes A_p and $A_{p\text{-bar}}$.
- Uniform priors constrained within physical boundaries.

95% Credible Limits on p-bar/p



Upper Limits and Previous Measurements



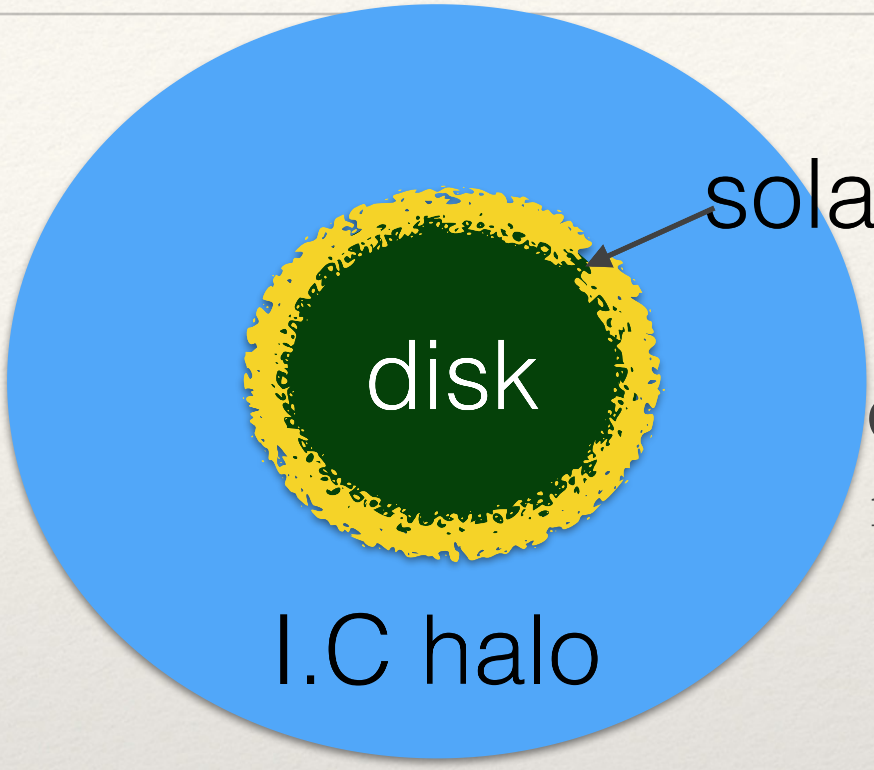
Outlook

- Light component (p/He) separation from heavier elements not yet accomplished.
- Limits likely to improve with more data and can be extended beyond 10 TeV.
- Strongest yet available limits in the > 1 TeV range.
- In the absence of direct measurements, these can be used to constrain propagation scenarios, energy losses for galactic CR, local sources and dark matter annihilation/decay.

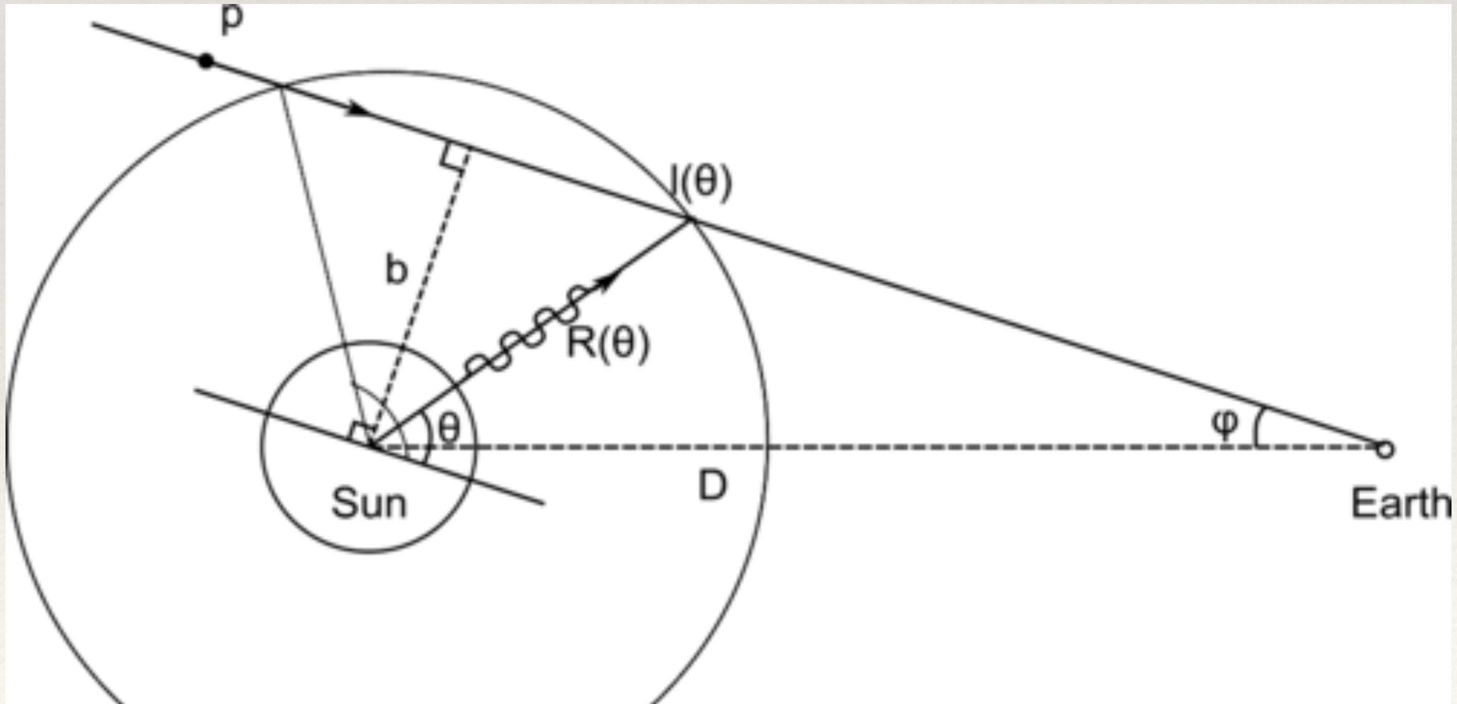
Part 2
TeV Gamma Rays from the Sun

Production Mechanisms

- Hadronic interactions
- Cosmic rays scattering in the sun's atmosphere.
- Solar disk component 0.5°
- Inverse Compton scattering of cosmic ray electrons
- Leptonic component halo up to 10° in diameter.
- Hadronic cosmic rays will also be accompanied by neutrinos

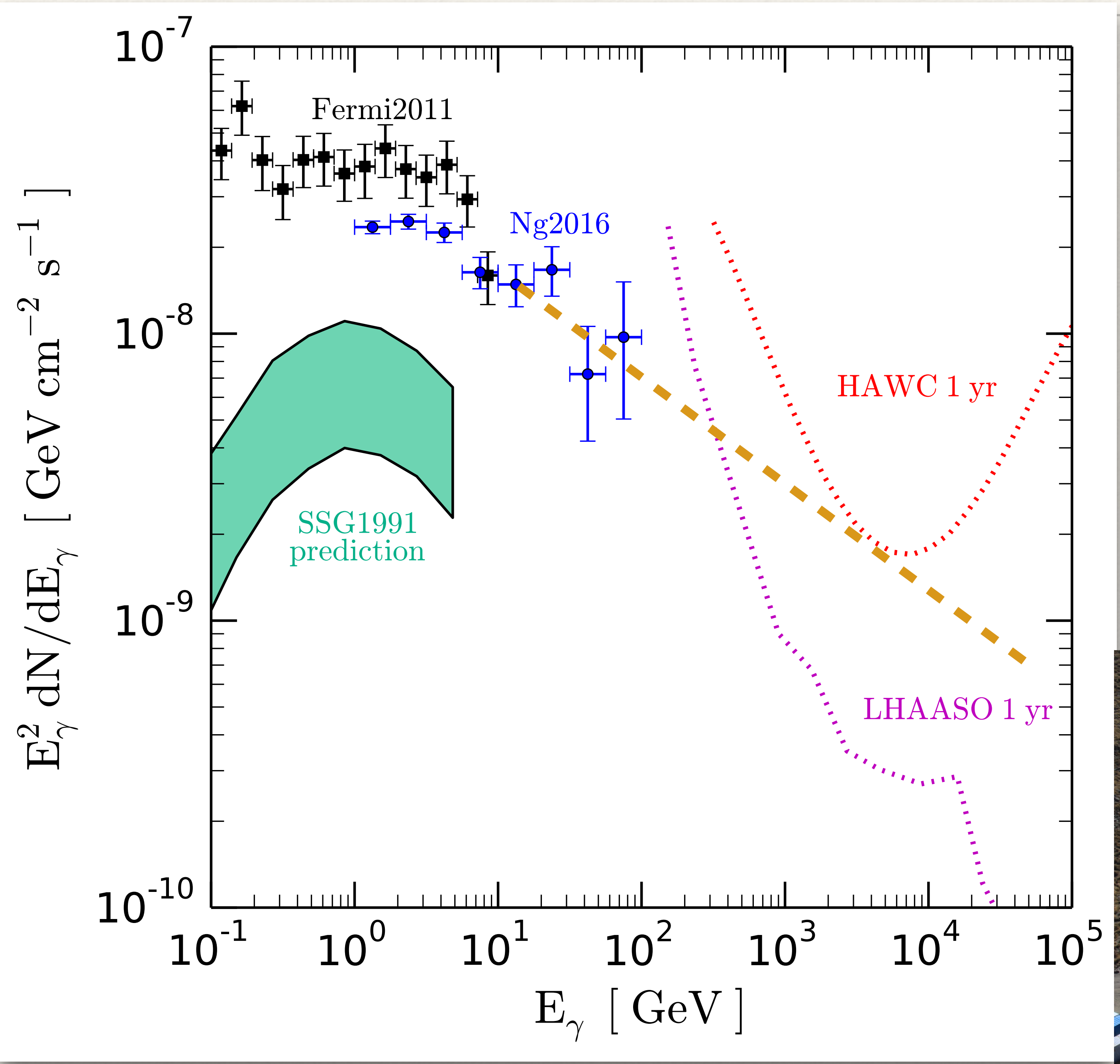


Observed in GeV in FERMI data.

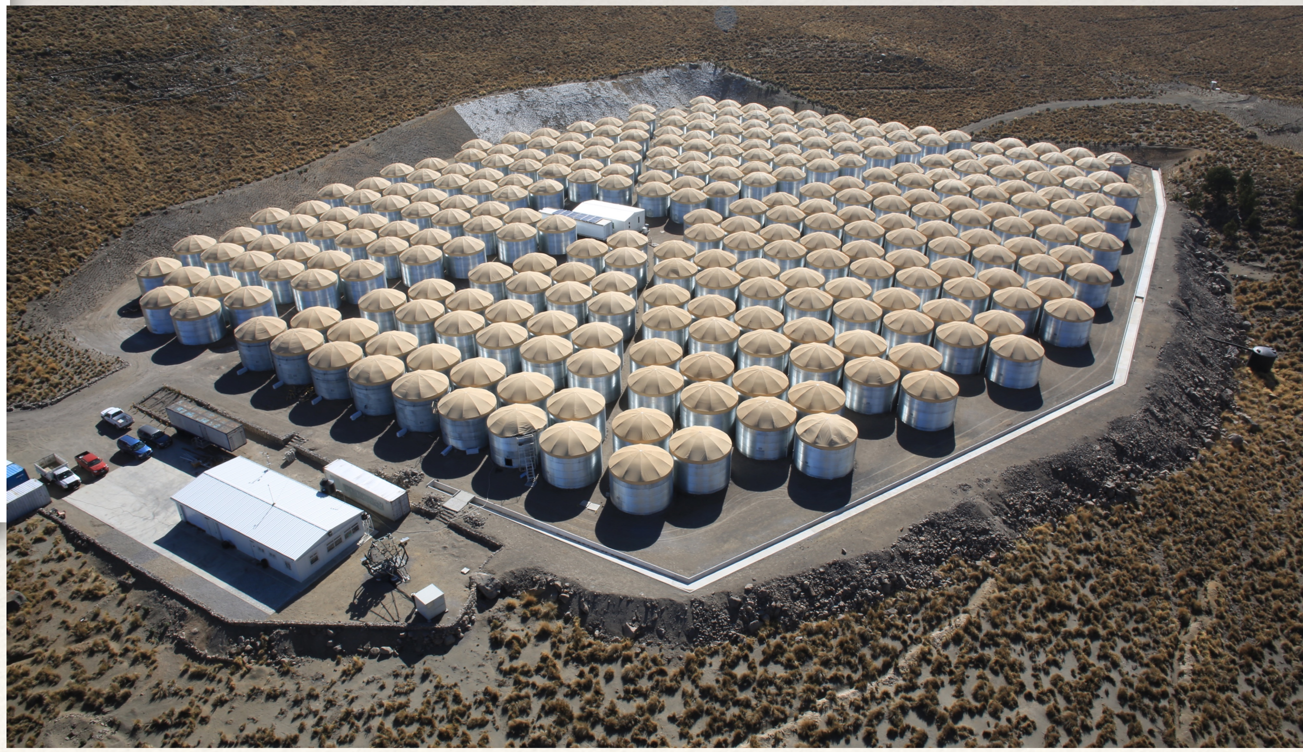


PhysRevD.95.063014

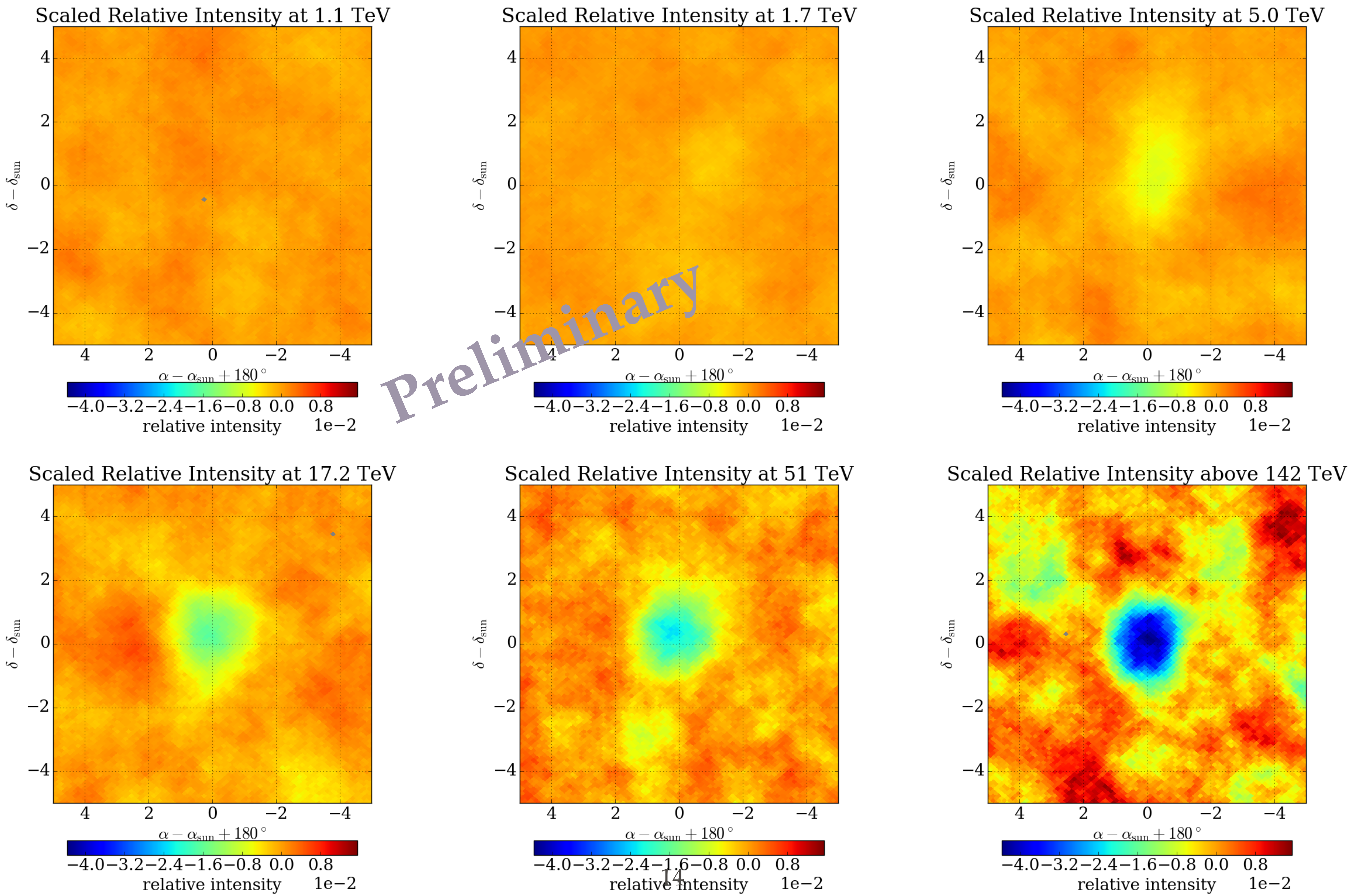
Detection Prospects



Reference: Ng et al. arXiv:1612.02420



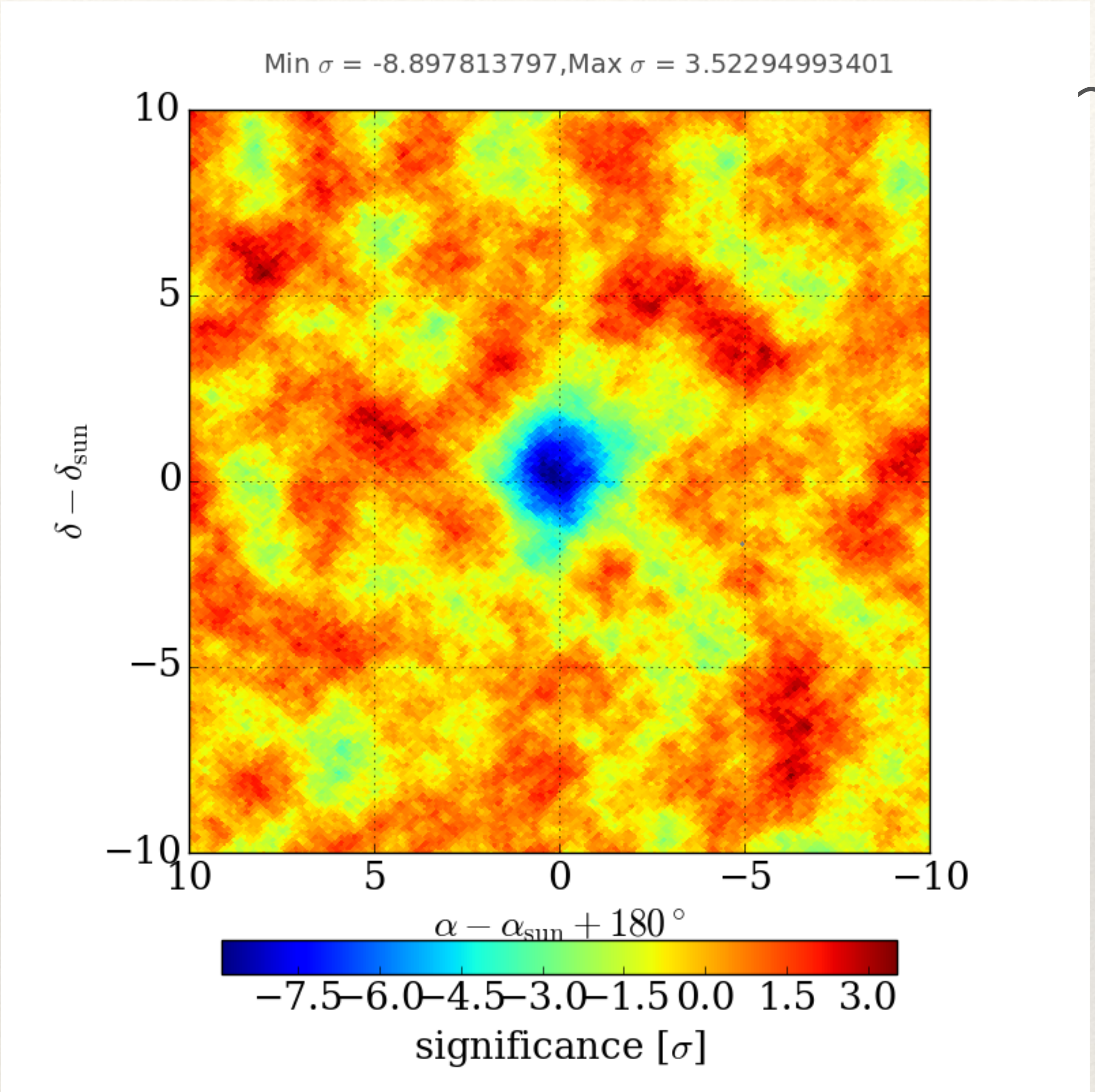
Energy Evolution of the Sun Shadow



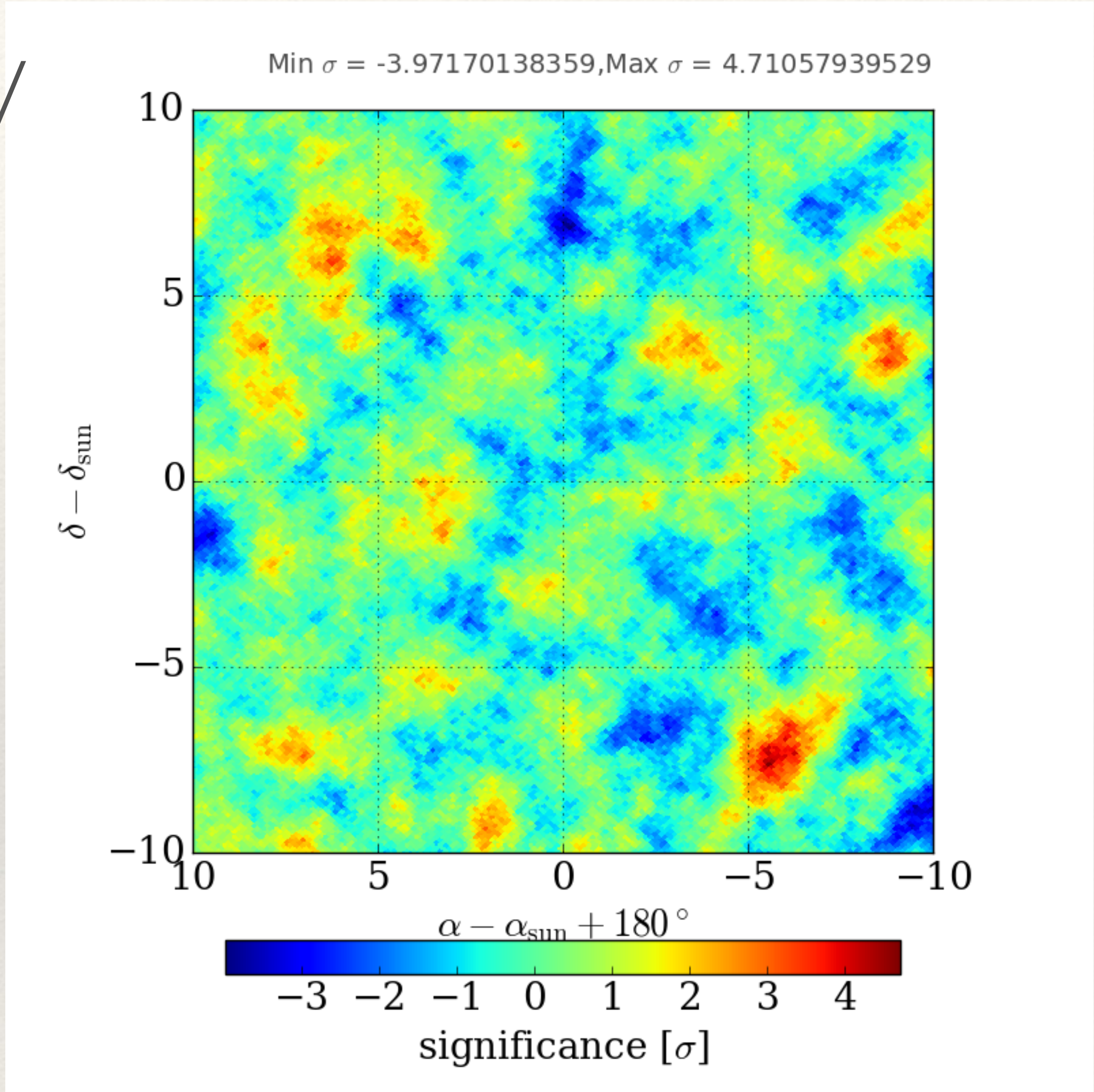
Preliminary search for gamma excess

Cosmic ray Map

Gamma ray Map



~30 TeV



No significant gamma excess near the sun

For details of gamma-hadron separation please see arXiv:1701.01778

Computing upper limits

$$F(E) = A(E/E_p)^{-i}$$

Get γ counts in each bin in a 5° region around the sun

Get *expected* number of counts from a sun-like source accounting for HAWC detector response and g/h separation.

Estimate the observed flux in each bin and compute 95 CL limits

Spectrum ⟷ fractionalHit bin counts

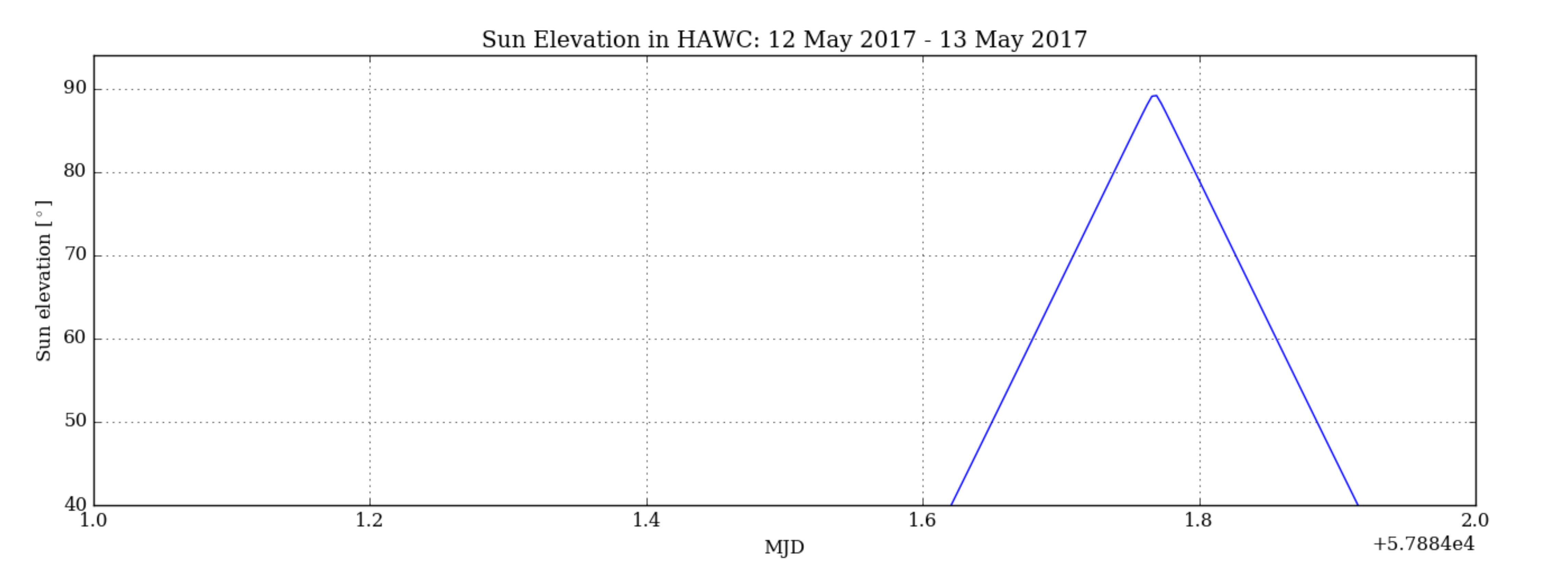
$$\frac{F_{obs}}{F_{exp}} \propto \frac{\gamma_{obs}}{\gamma_{exp}}$$

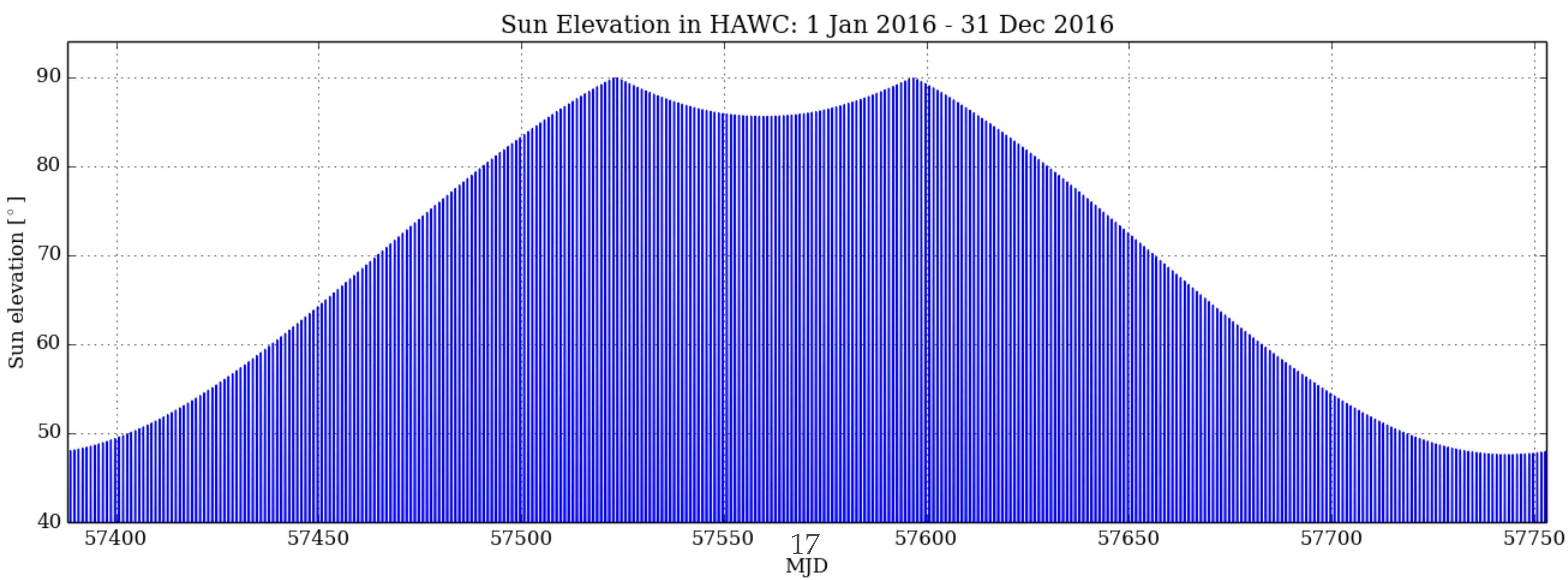
Problem

Assumptions:

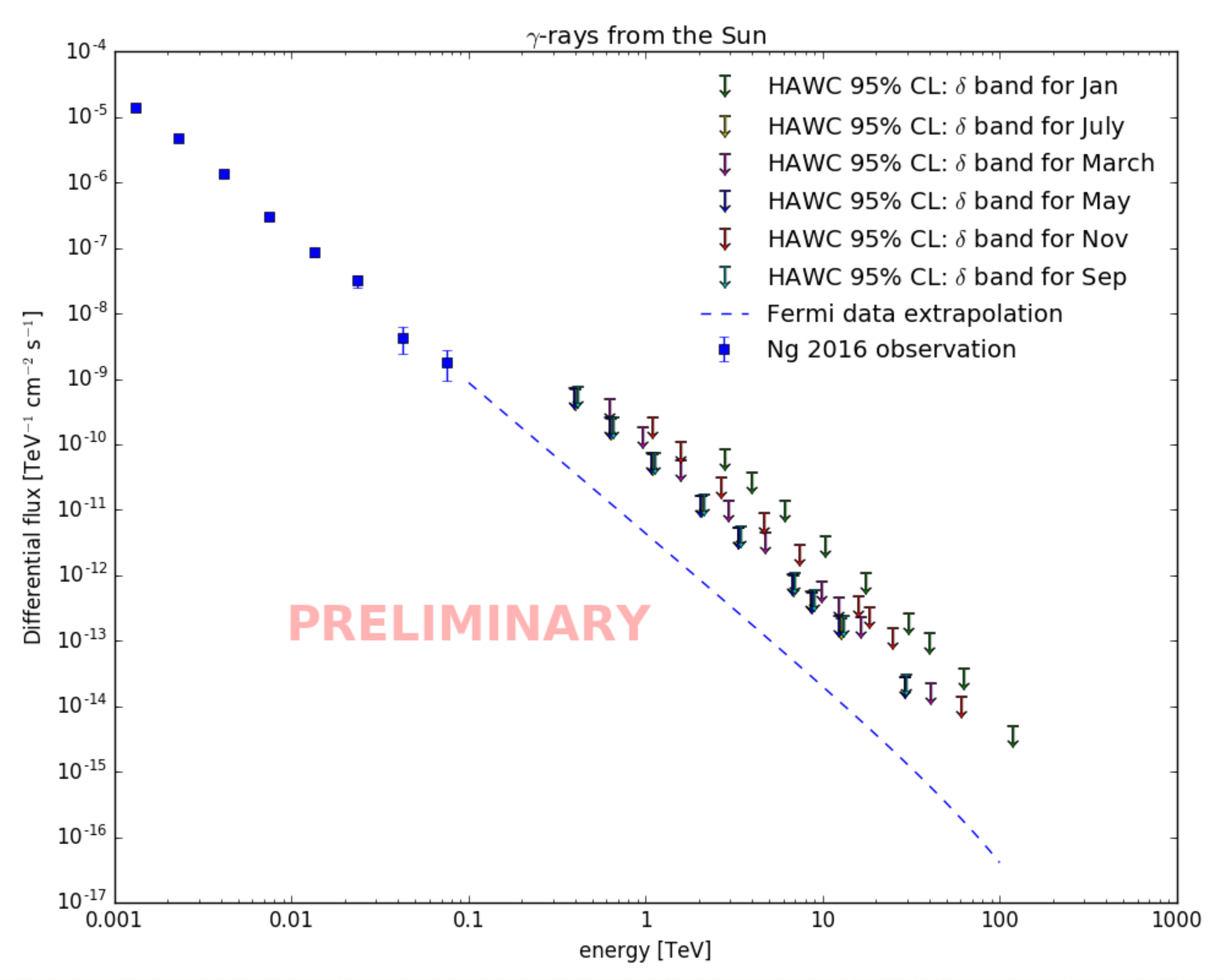
1. Point Source
2. No time-dependence
3. Constant dec

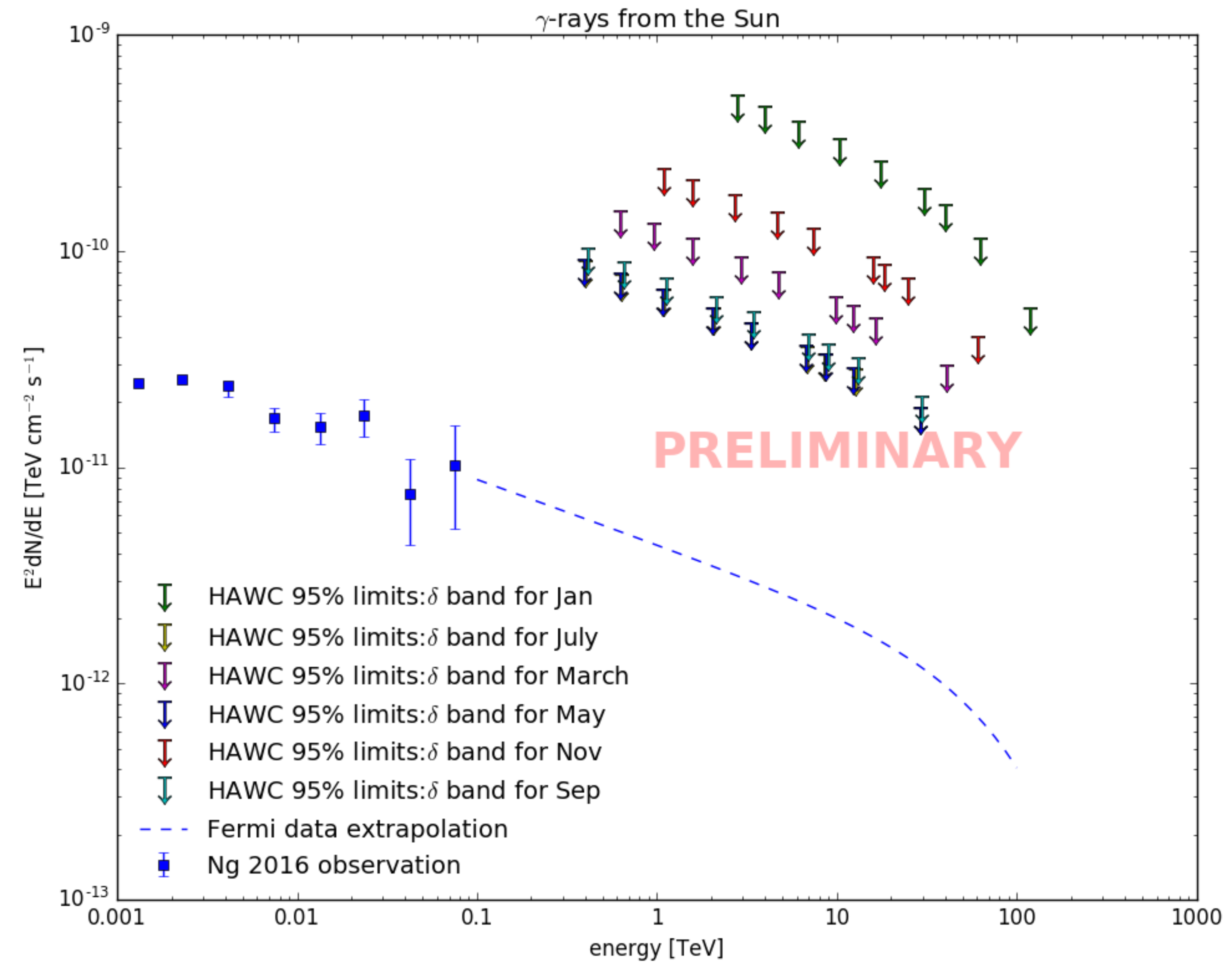
Changing Position of the Sun above HAWC





Upper Limits on Sun Gamma Flux at different declinations





γ-rays from the Sun
E²dN/dE [TeV cm⁻² s⁻¹]
energy [TeV]
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
0.001
0.01
0.1
1
10
100
1000
PRELIMINARY
HAWC 95% limits:δ band for Jan
HAWC 95% limits:δ band for July
HAWC 95% limits:δ band for March
HAWC 95% limits:δ band for May
HAWC 95% limits:δ band for Nov
HAWC 95% limits:δ band for Sep
Fermi data extrapolation
Ng 2016 observation

Summary and Future Goals

- First upper limits from HAWC on TeV gamma rays from the Sun
- Very simplified analysis. The limits can be made stronger.
- Further analysis in progress: Developing tools to take into account a moving source of gamma rays.
- Back-tracing cosmic rays in the IMF and geomagnetic fields on a GPU cluster.
- Implications for constraining important physical processes including B-field induced flux enhancements, cosmic ray mass composition near the knee and dark matter annihilation in the Sun.
- Prospects for multi-messenger astronomy with neutrino counterparts.