Investigating the unusually hard gamma-ray spectrum of the extreme blazar 1ES 0229+200 with HAWC

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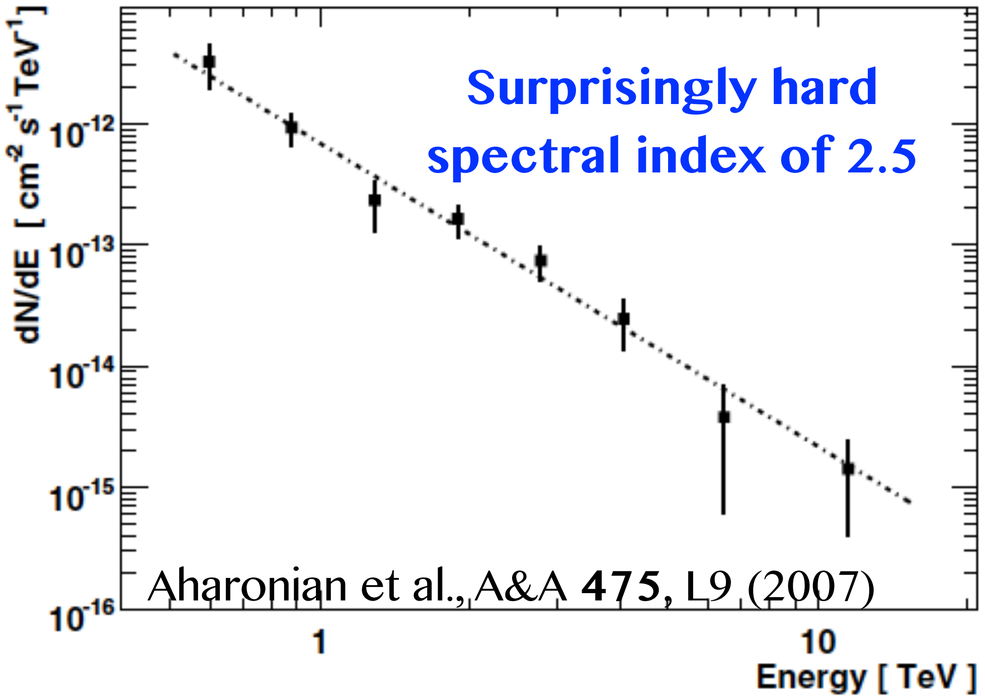
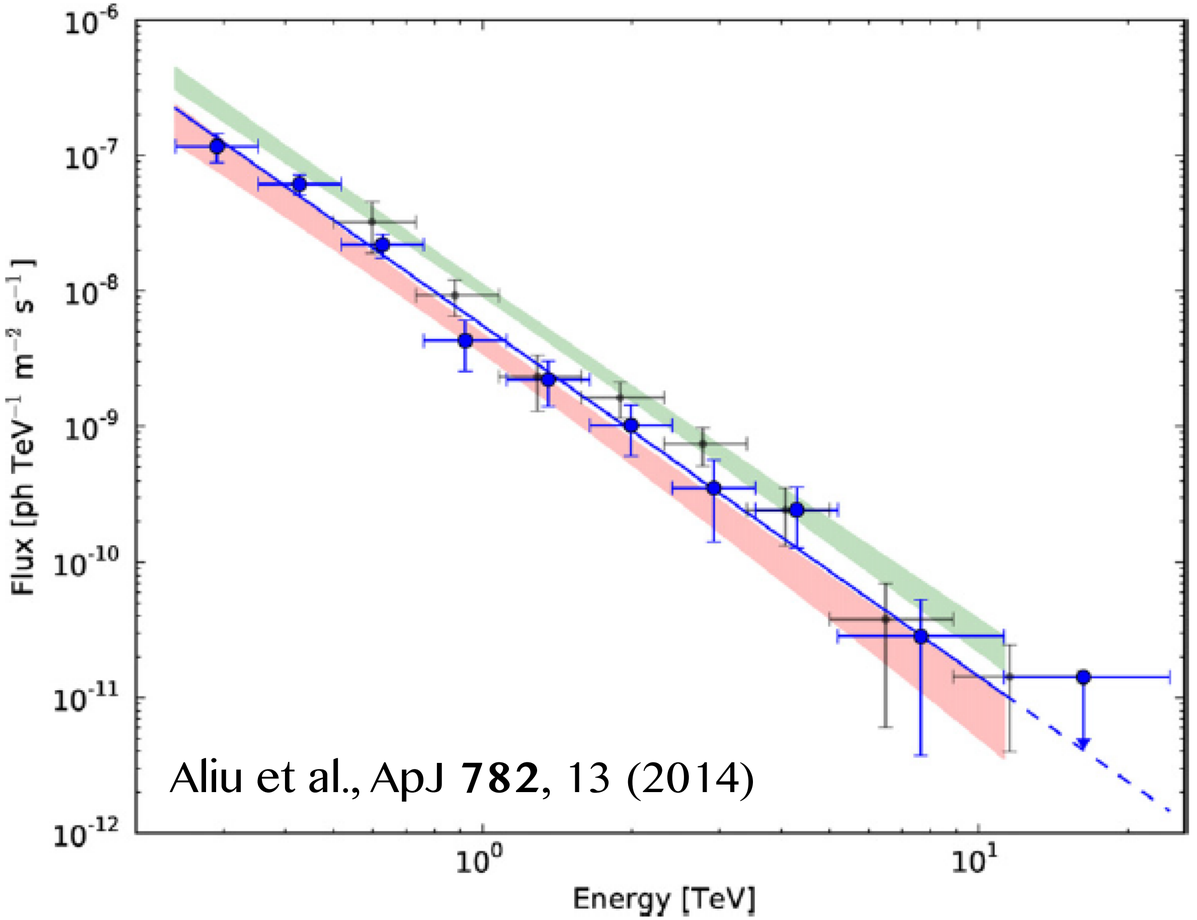
VHE observations of 1ES 0229+200

- Blazar at z = 0.1396
- VHE discovery reported by HESS in 2007
- Evidence for weak variability presented by VERITAS and later confirmed by HESS



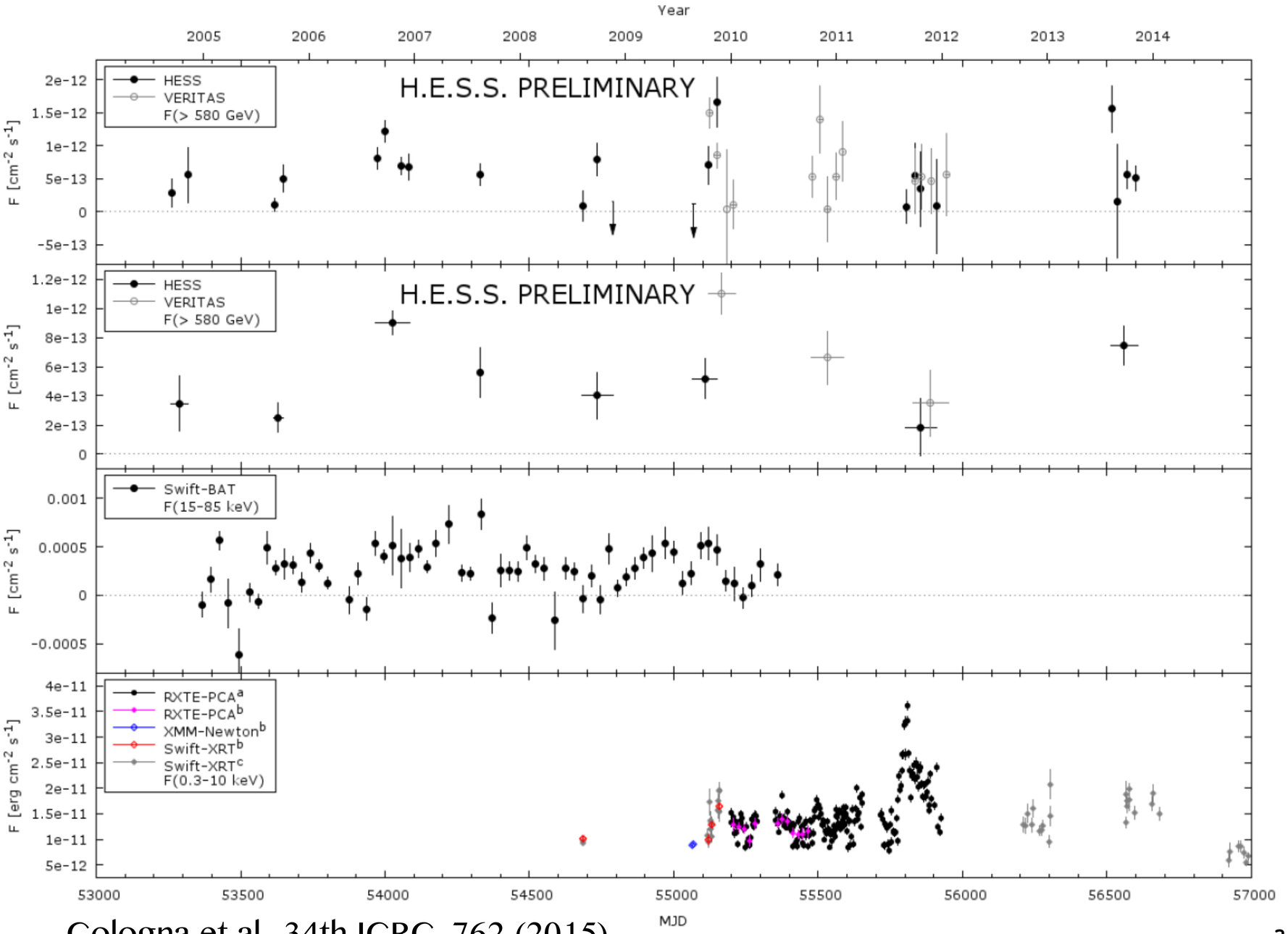
HESS observations extend to >10 TeV



VERITAS identifies a distinct high state

VHE observations of 1ES 0229+200

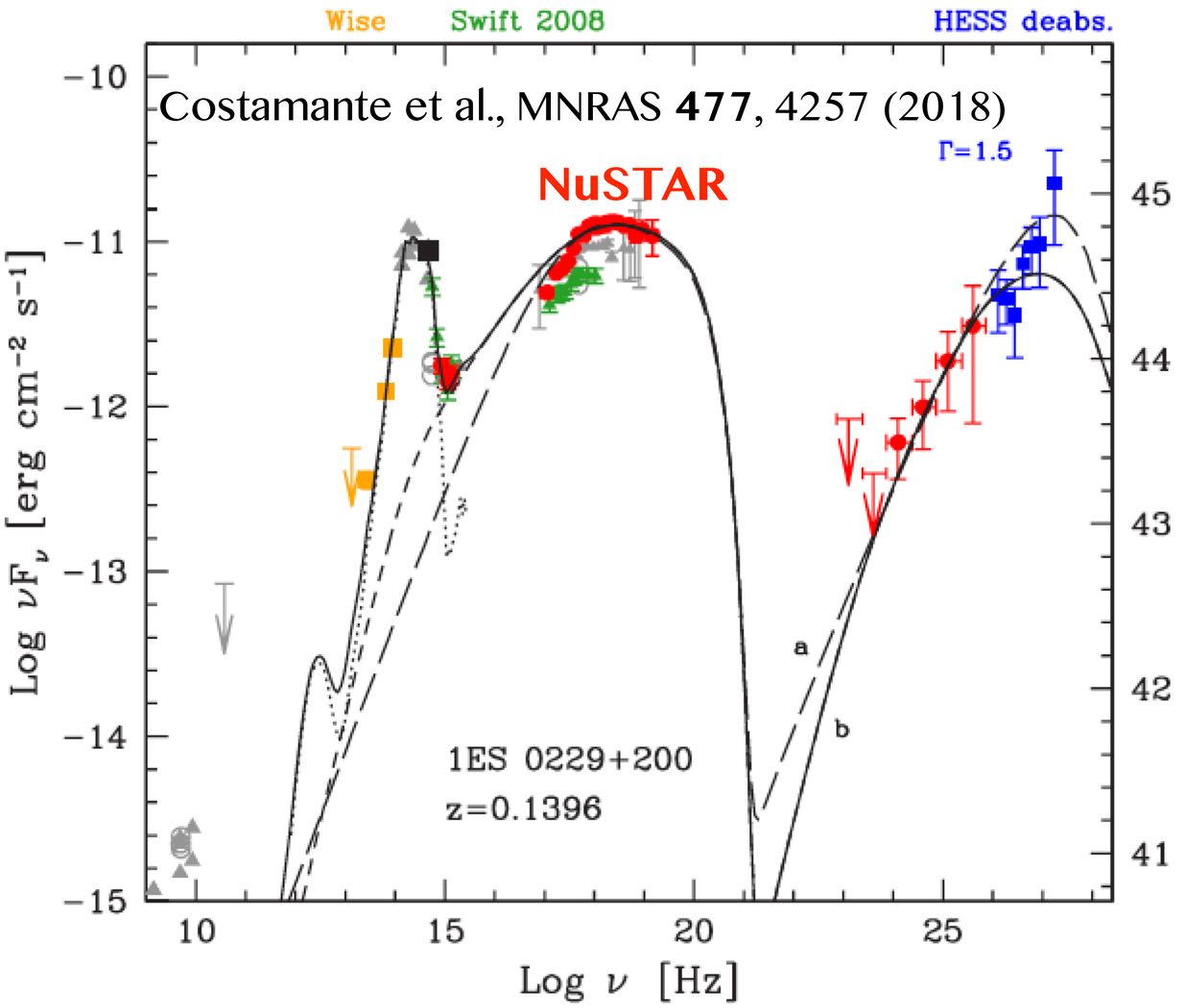
- HESS observations from 2004—2014 reveal variability on month to year time scales
- Surprising steadiness of the source compared to typical blazars
- No evidence for variability in the hard spectral index



Cologna et al., 34th ICRC, 762 (2015)

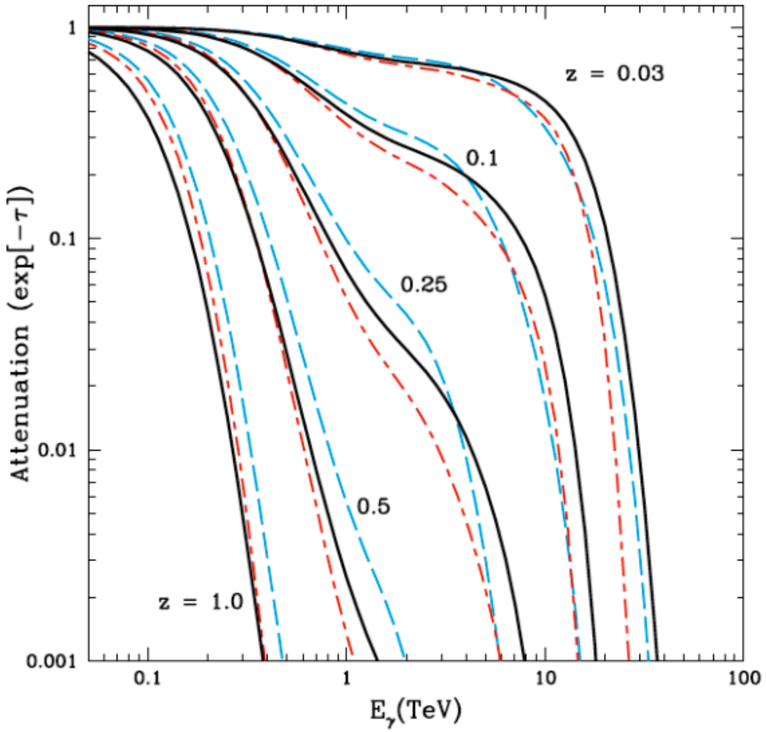
1ES 0229+200 as an EHBL

- The VHE spectrum of 1ES 0229+200 is remarkably hard, especially after de-absorption on the EBL
- NuSTAR observations show peak synchrotron power output at 9 keV
- Suggested new class of extreme blazars: EHBLs
  - Unique properties of these blazars may arise from processes other than those that are typically considered



Line-of-sight cosmic-ray interactions

- Cosmic-ray interactions along the line of sight originally proposed to explain the apparent steadiness of emission from 1ES 0229+200
- As blazars are favored candidates for the acceleration sites of extragalactic cosmic rays, it is worth investigating the fraction of the VHE emission that could arise from these effects

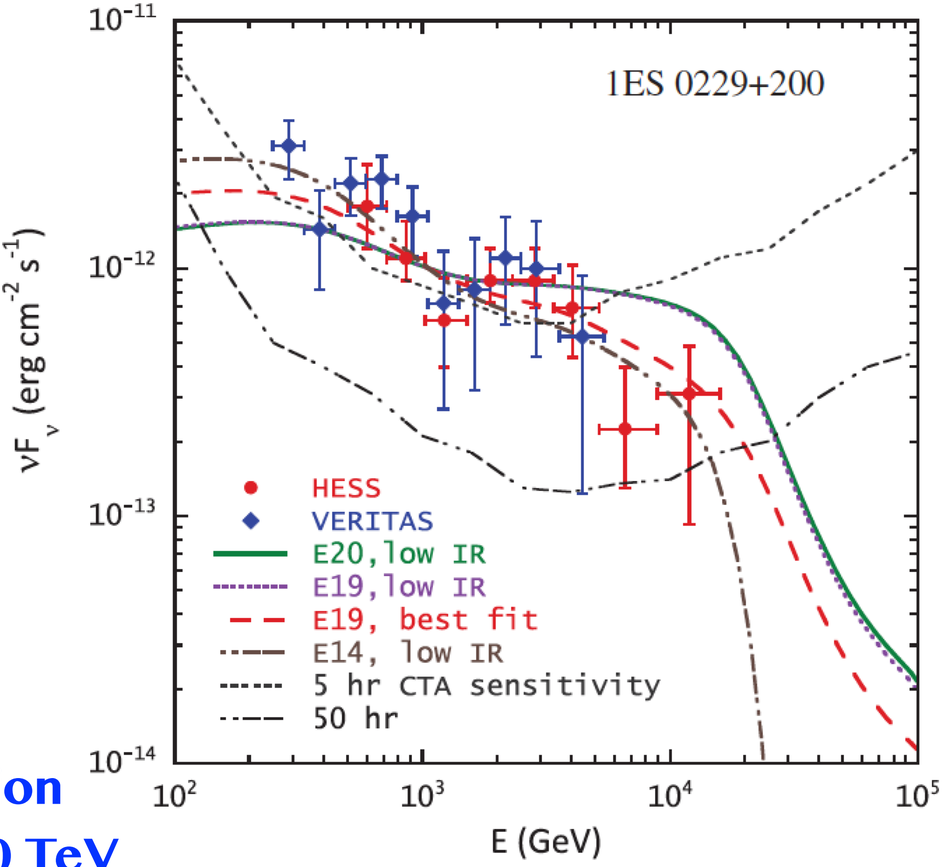


Primack et al., AIPC **1381**, 72 (2011)

EBL attenuates gamma rays on cosmic scales

UHECR interactions with EBL along the line of sight could produce secondary gamma rays

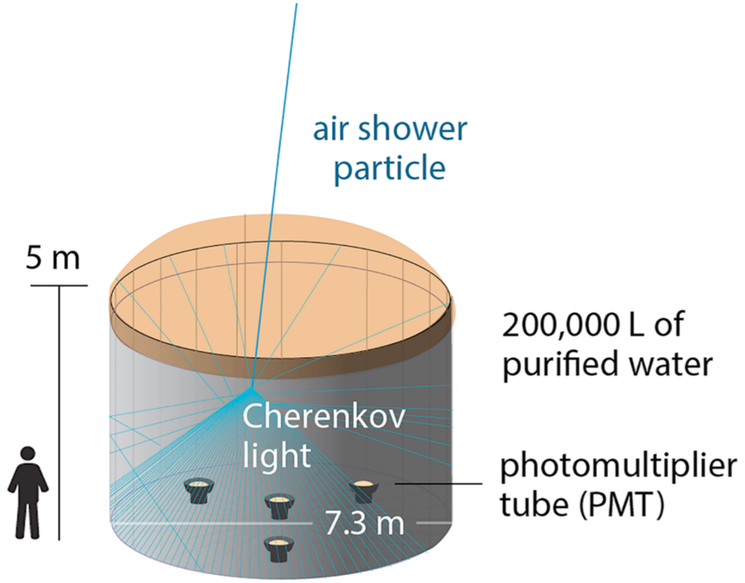
Gamma-ray emission predicted up to >100 TeV

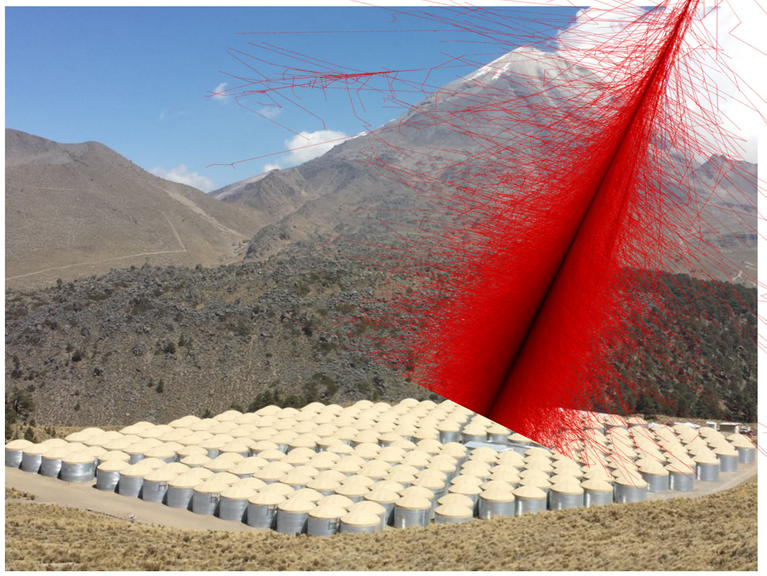


Murase et al., ApJ **749**, 63 (2012)

The HAWC observatory

- High Altitude Water Cherenkov
- 4100 m above sea level at 19º N latitude
- 300 close-packed optically isolated water Cherenkov detectors
- Wide field of view (~2 sr) with near 100% duty cycle
- Sensitive to air showers from gamma rays and cosmic rays above 100 GeV
- Continuous and unbiased monitoring





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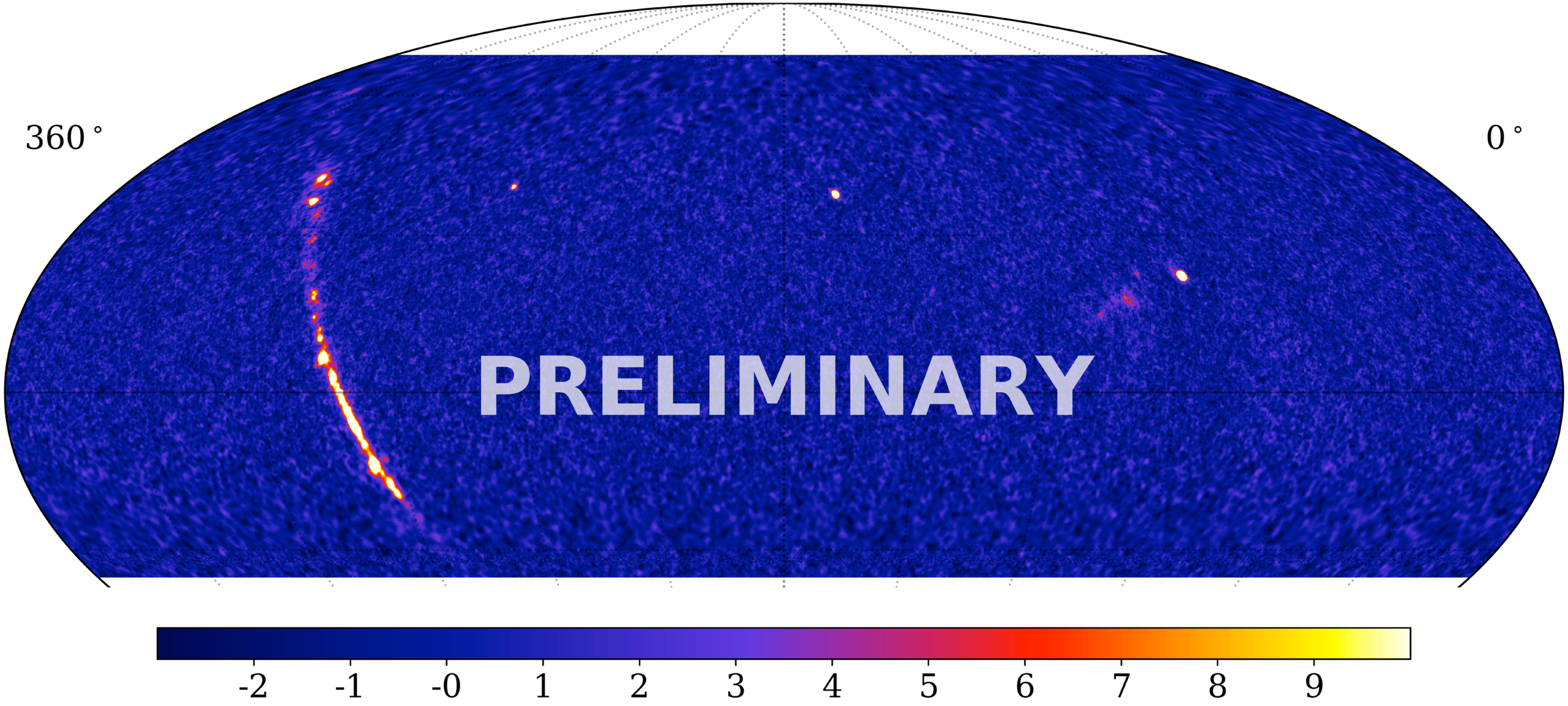
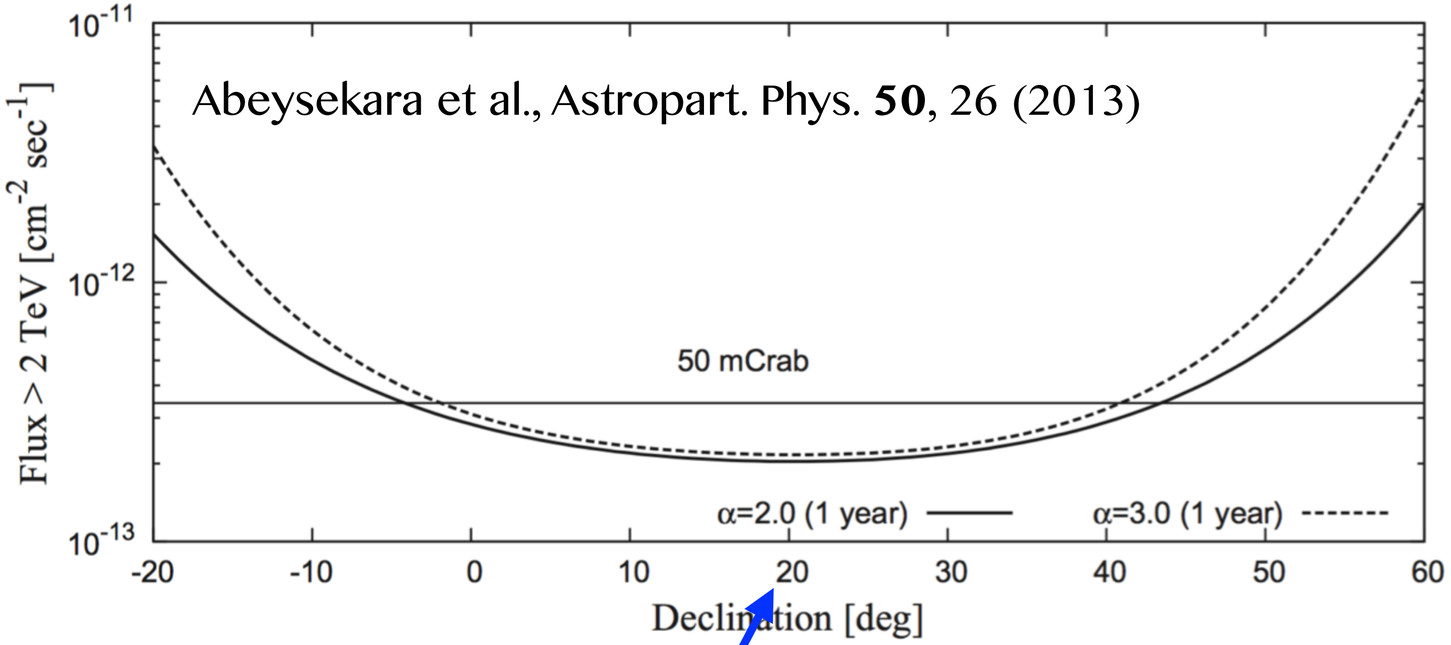
The HAWC observatory



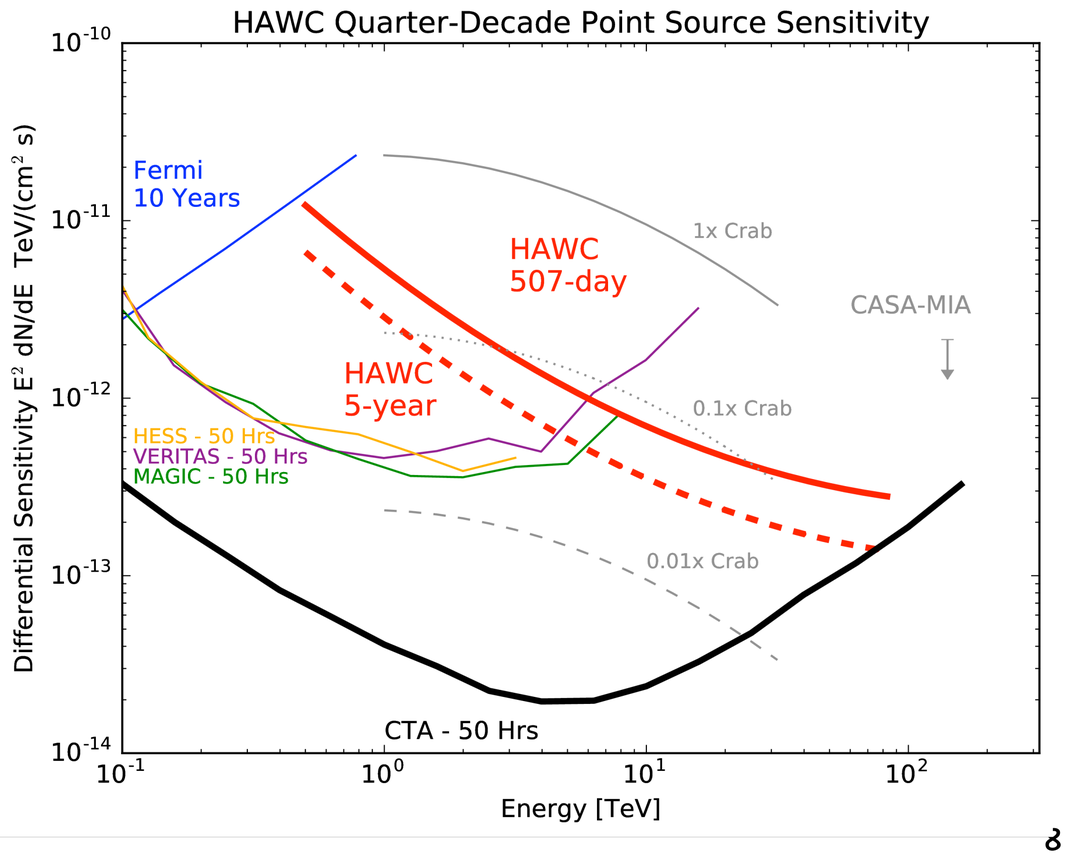
HAWC significance map in equatorial coordinates,
data range from 26 November 2014 to 24 April 2018

HAWC view of 1ES 0229+200



Declination of 1ES 0229+200 optimal for HAWC latitude

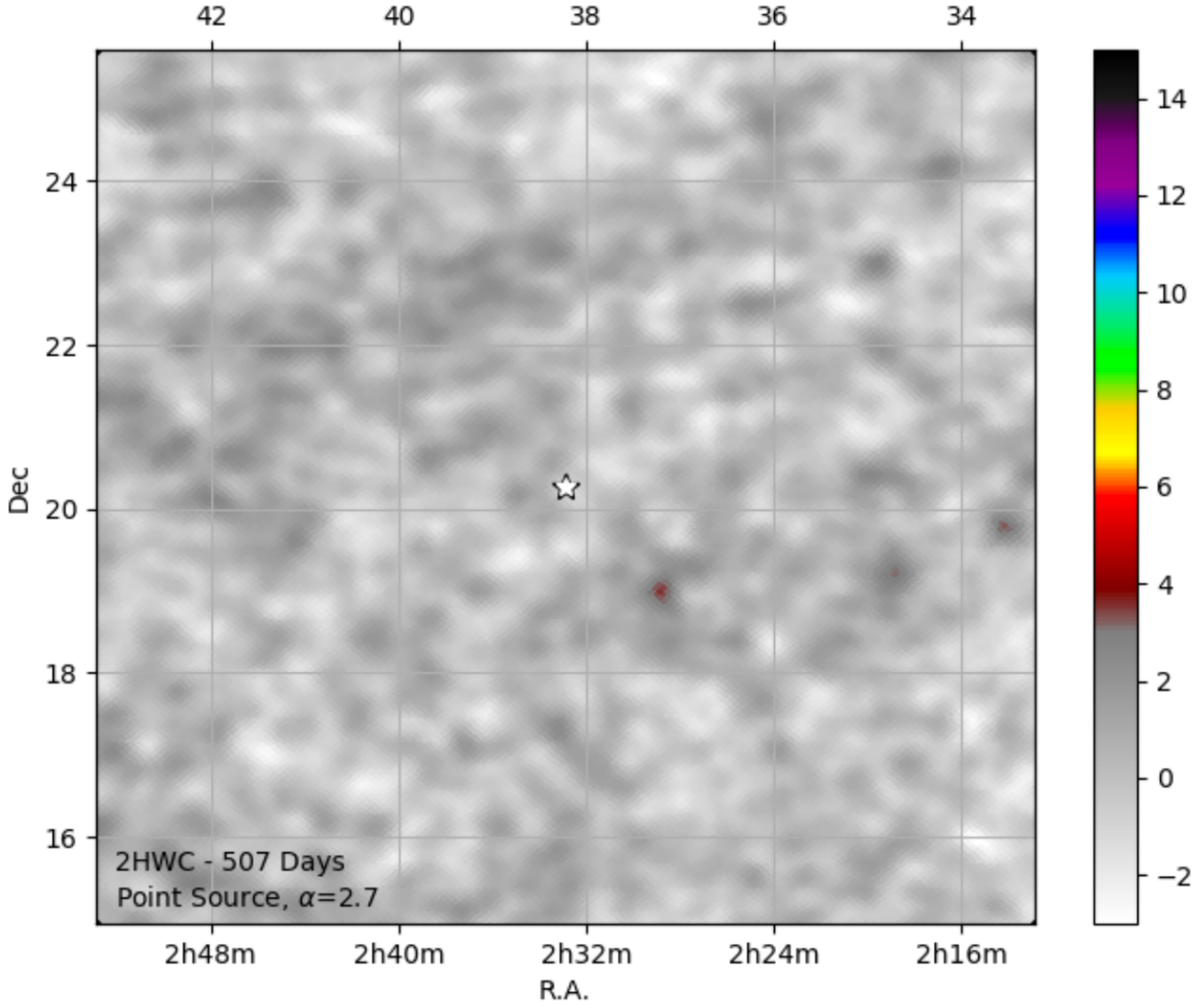
Hard spectrum ideal for HAWC sensitivity in multi-TeV regime



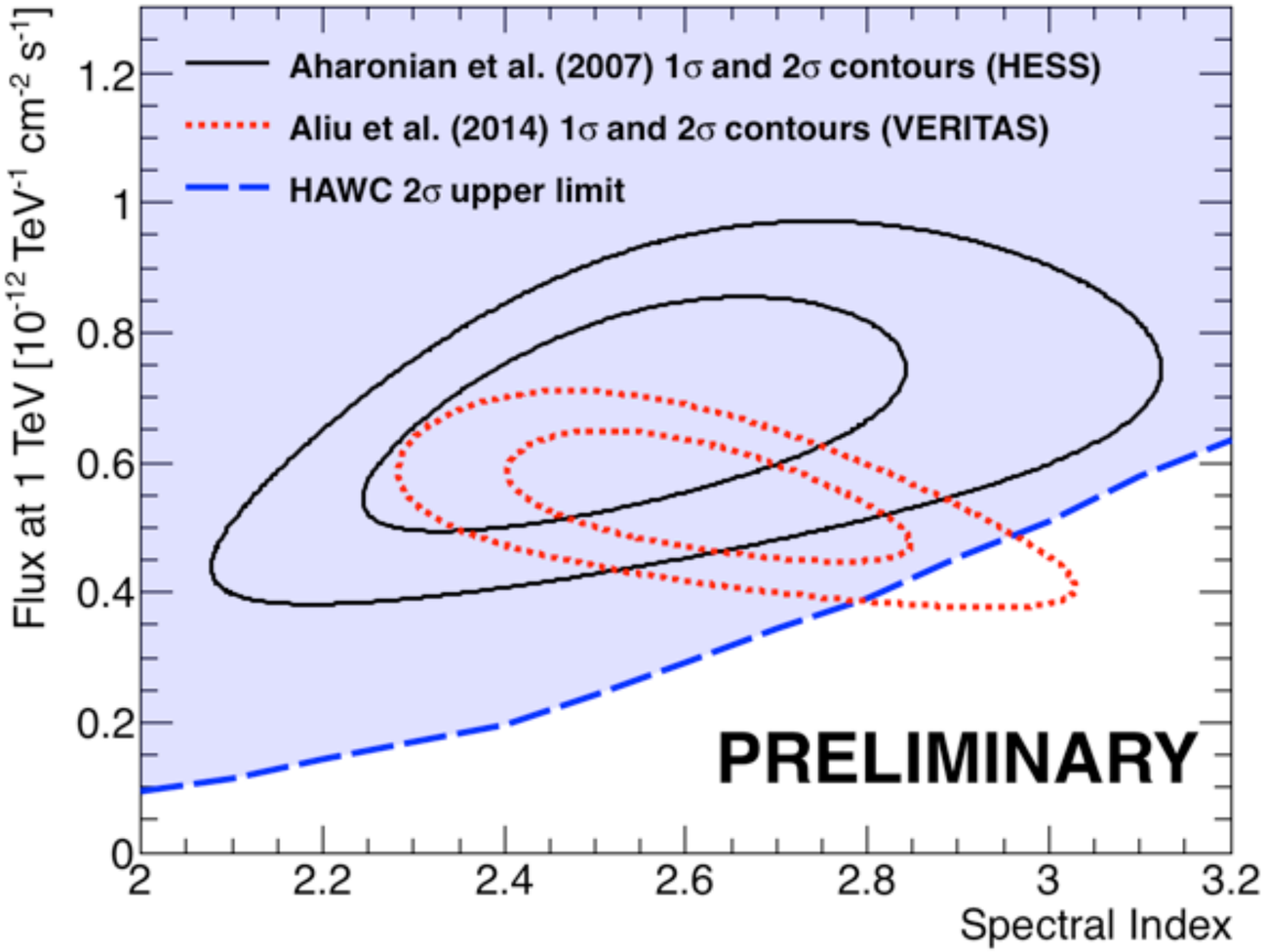
HAWC view of 1ES 0229+200

- Nothing significant in the publicly available 507-day HAWC maps: you can see for yourself at https://data.hawc-observatory.org/

- Source is also absent in more recent HAWC maps using 1034 days of data spanning the time range from 11 June 2015 to 25 July 2018

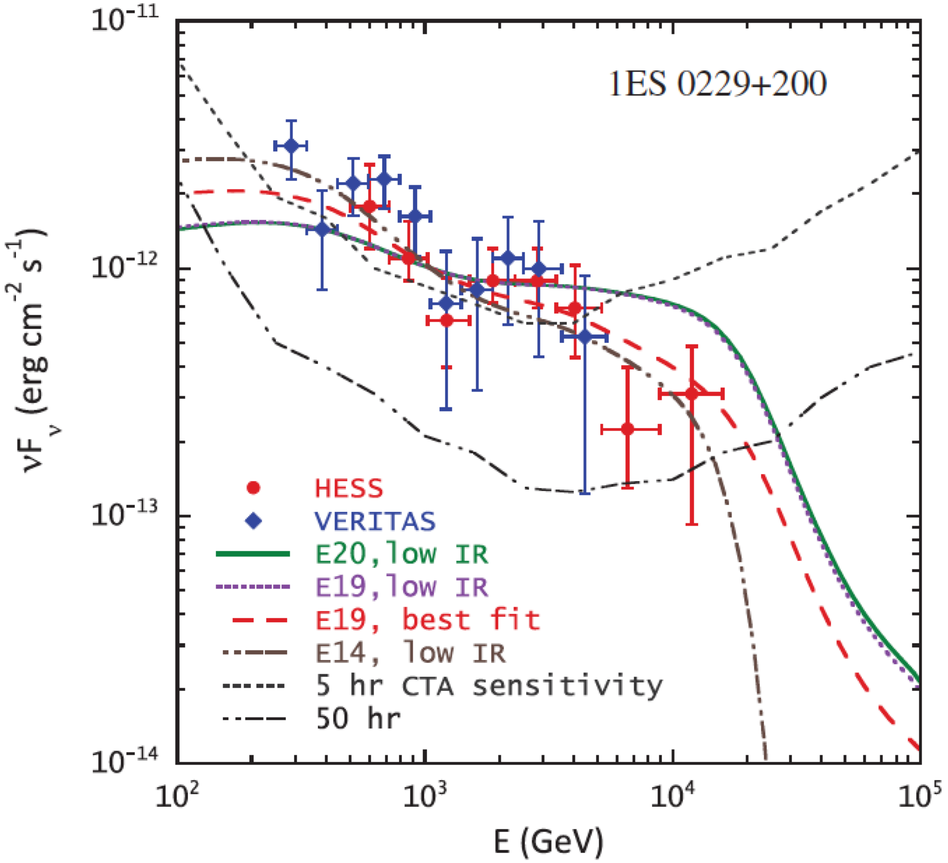


HAWC upper limits on 1ES 0229+200

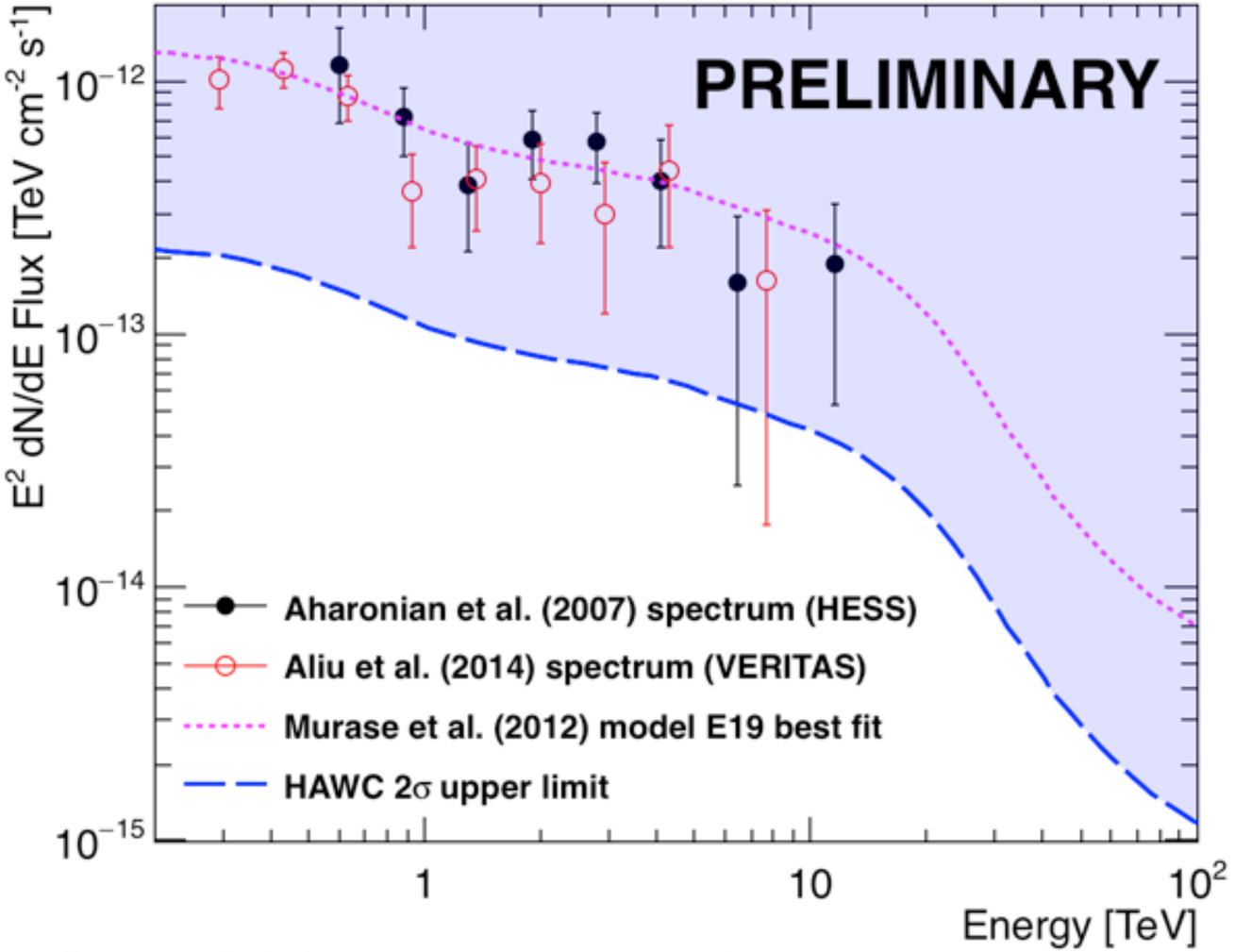


- Model the spectrum as a simple power law with a hard cutoff at 10 TeV
- Fit the HAWC data using the Feldman-Cousins method to produce confidence intervals at the 2σ level; fits result in upper limits
- HAWC results are broadly inconsistent with the HESS and VERITAS confidence bands allowed by the reported spectra

HAWC constraints on the CR LoS model



Murase et al., ApJ **749**, 63 (2012)



- Test viability of E19 best fit model from Murase et al. (2012)
- HAWC constrains the long-term VHE emission from the source to be no more than 11% of the model prediction (2σ confidence level)

Interpretation of HAWC results

- Possible causes for the discrepancy between HAWC and IACTs:
  - Different time range (IACT observations end by 2014, HAWC starts in 2015)
  - Simple power law provides a poor description of the emission
  - IACT observations may not represent the long-term average well

- Cosmic-ray interaction models are constrained by the HAWC observations
  - E19 best fit model from Murase et al. (2012) can contribute at a level of only 11% of the originally modeled flux: this is a tighter constraint on the CR contribution than previously reported variability studies