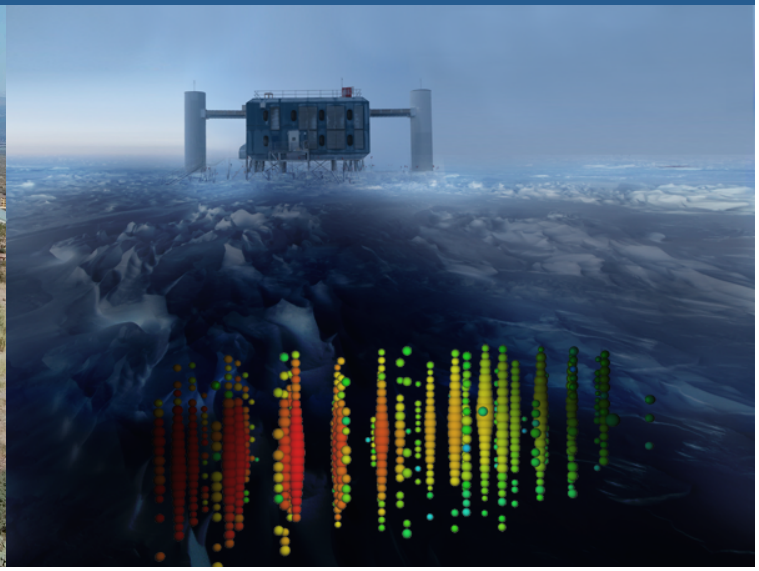
The search for VHE gamma-rays associated with IceCube's high-energy neutrinos using VERITAS





Jon Dumm

for the VERITAS Collaboration

VLVNT, Rome

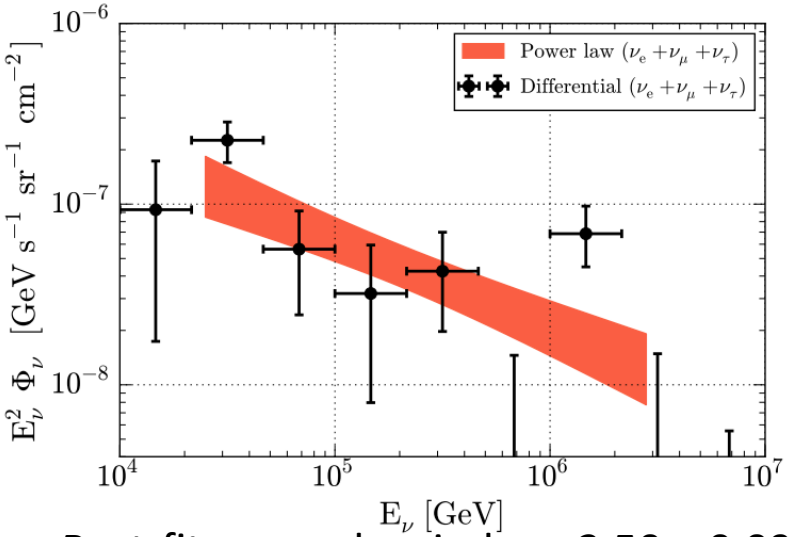
Sep 15, 2015

Outline

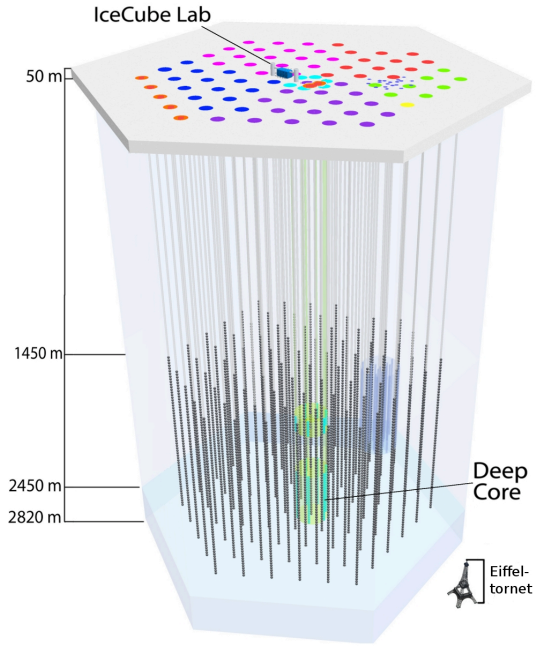
- IceCube's neutrino flux
  - Best astrophysical candidates for follow-up observations
- Multi-messenger picture
  - Associated gamma-ray emission
- Results of VERITAS observations of candidates
- Future plans – real-time alerts

The Astrophysical Nu Flux

- First discovery (5.7 σ) of HE astrophysical neutrinos used events with **contained (C)** interaction vertices arXiv:1405.5303
- More recently, evidence (3.7 σ) was also established using up-going muon tracks, mostly with **uncontained (UC)** vertices arXiv:1507.04005
- Latest characterization of the flux from a 'global fit' to IceCube data arxiv:1507.03991

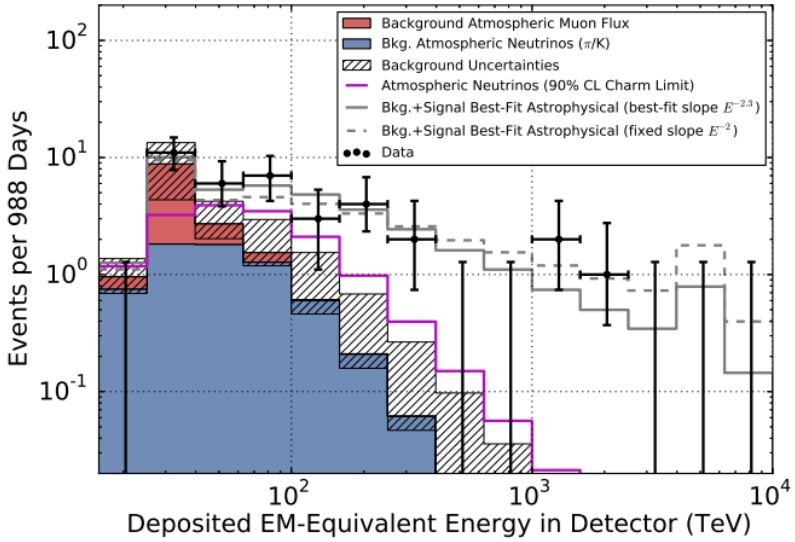


Best-fit power-law index: -2.50 ± 0.09
From 25 TeV to 2.8 PeV

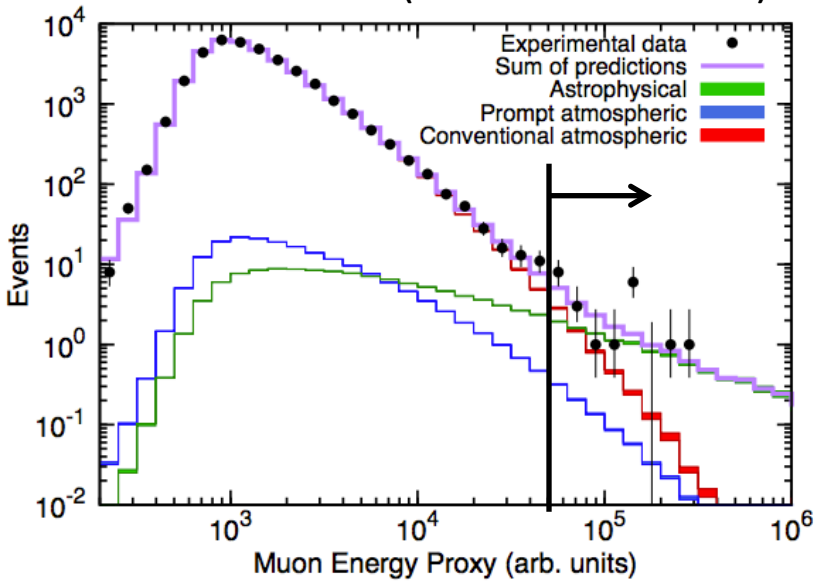


Searching for Nu Sources

Contained (arXiv:1405.5303)

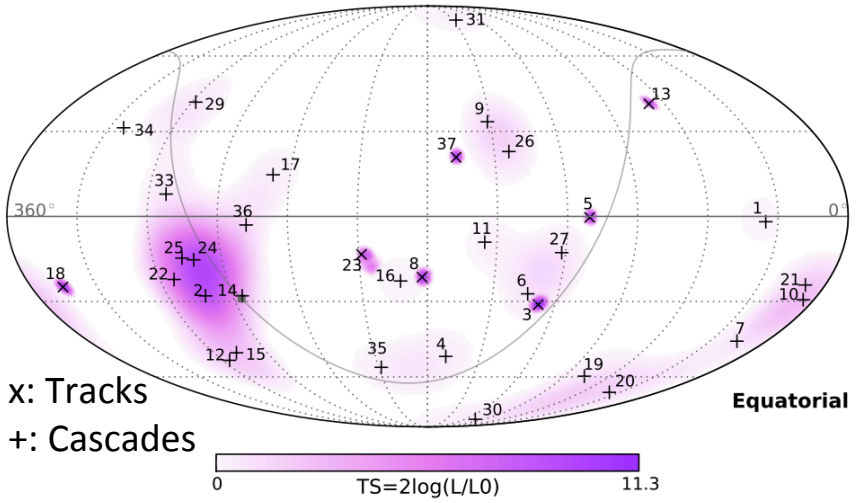


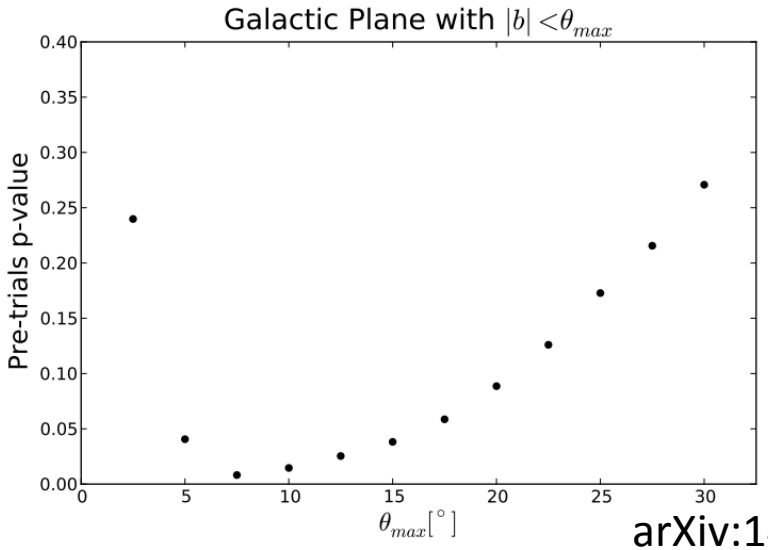
Uncontained (arXiv:1507.04005)



- Both the **contained (C)** and **uncontained (UC)** event samples provide:
  - Possibility to isolate point-like sources based solely on neutrino data
  - Interesting candidates for follow-up observations with other messengers, especially at the highest energies where astrophysical probability very high

Searching for Nu Sources

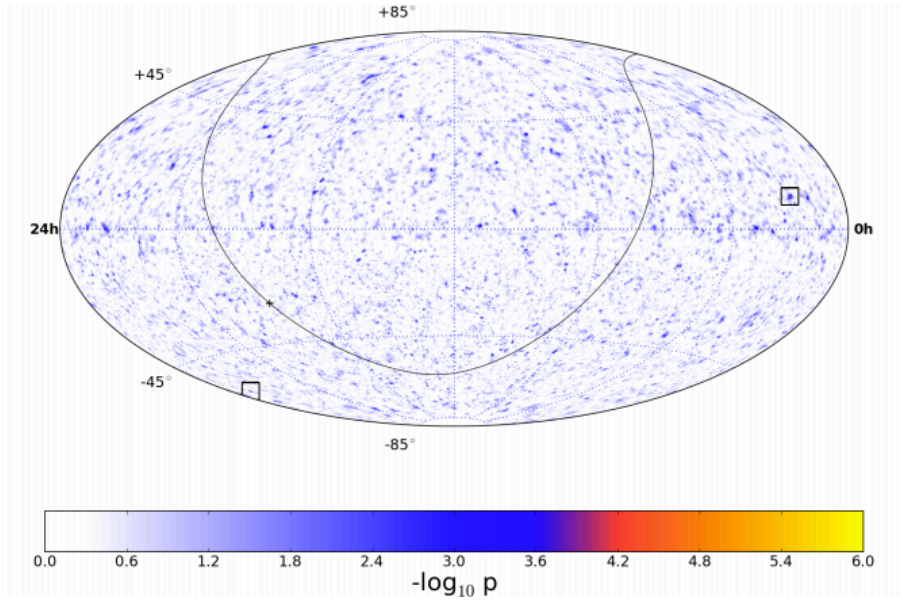


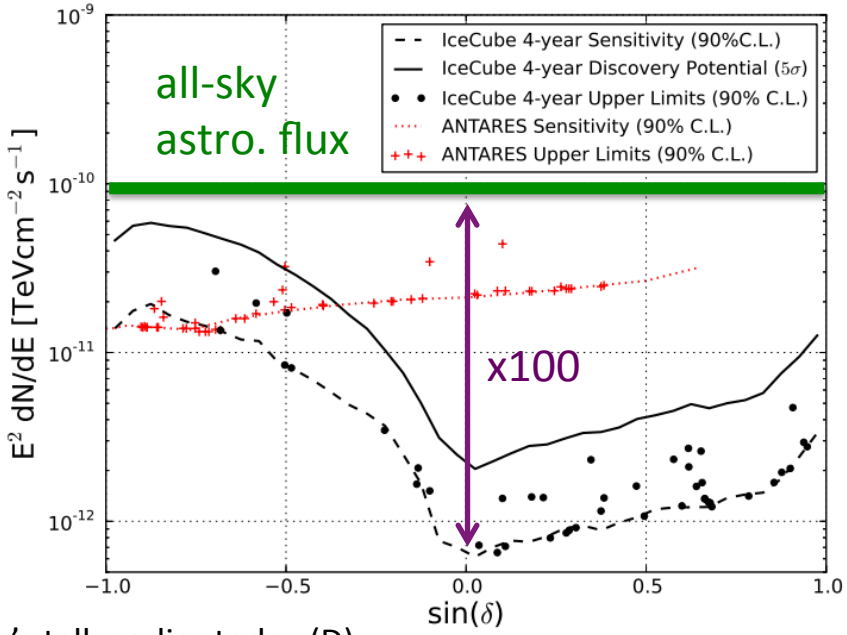


arXiv:1405.5303

- **Contained (C)** event sample consists of 37 neutrino candidate events
  - 28 cascades, ~15° median ang. resolution (CC $\nu_{e,\tau}$ + NC $\nu_{e,\mu,\tau}$)
  - 7 tracks, ~1° median ang. resolution (CC ν_{μ})
- No evidence for neutrino point sources
  - Hottest spot (p=7%) somewhat near the galactic center
- Scan for association with the galactic plane likewise shows no significant evidence for an association

Searching for Nu Sources

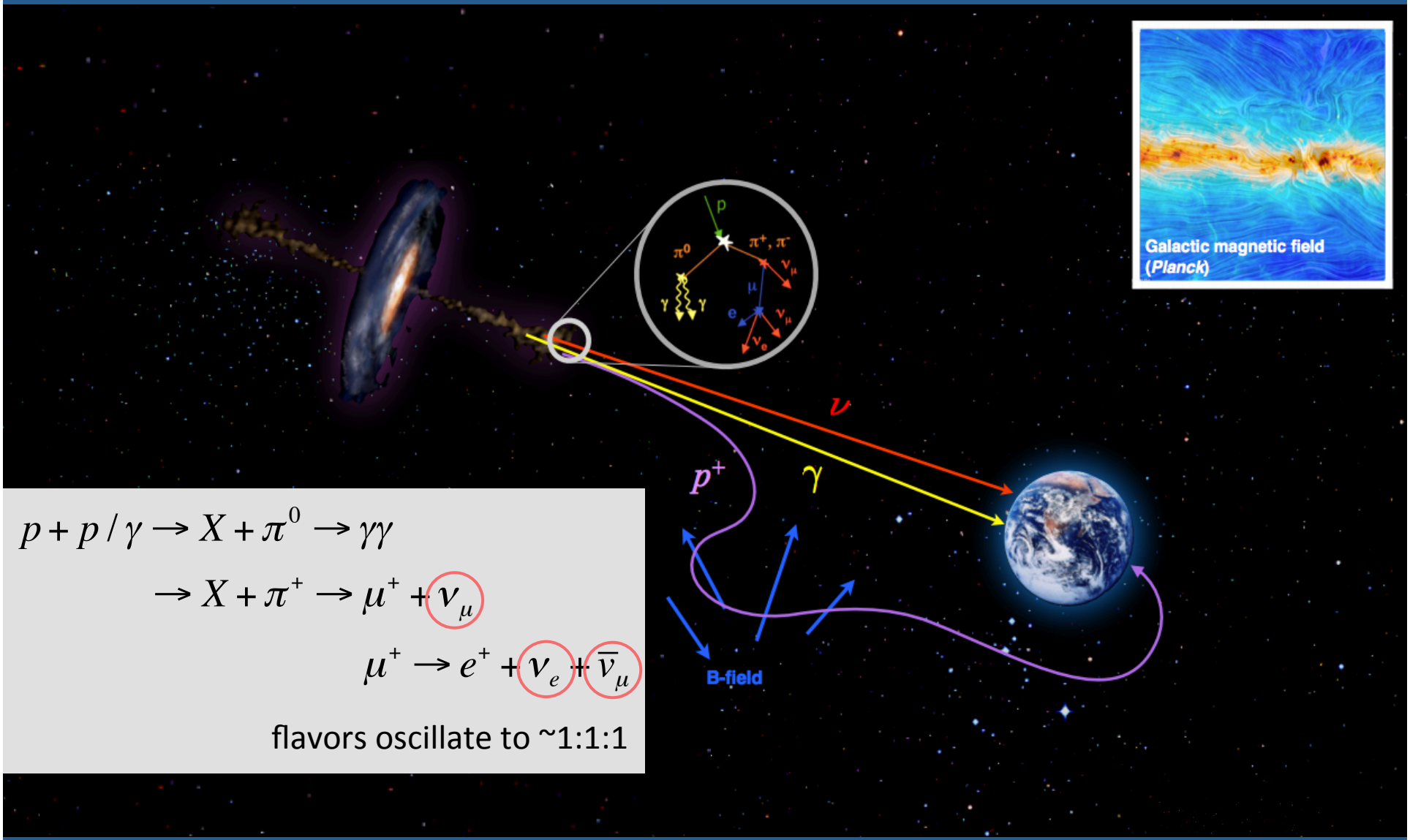




Newer results in S. Coender's talk earlier today (D)

- **Uncontained (UC)** event samples provide O(100k) events/yr
  - Typical median ang. resolution < ~1°
- IceCube point-source searches of **UC** samples set ULs ~**10 to 100 times** lower than the all-sky measured flux
  - Implies large number of weak sources

Multi-messenger Astronomy



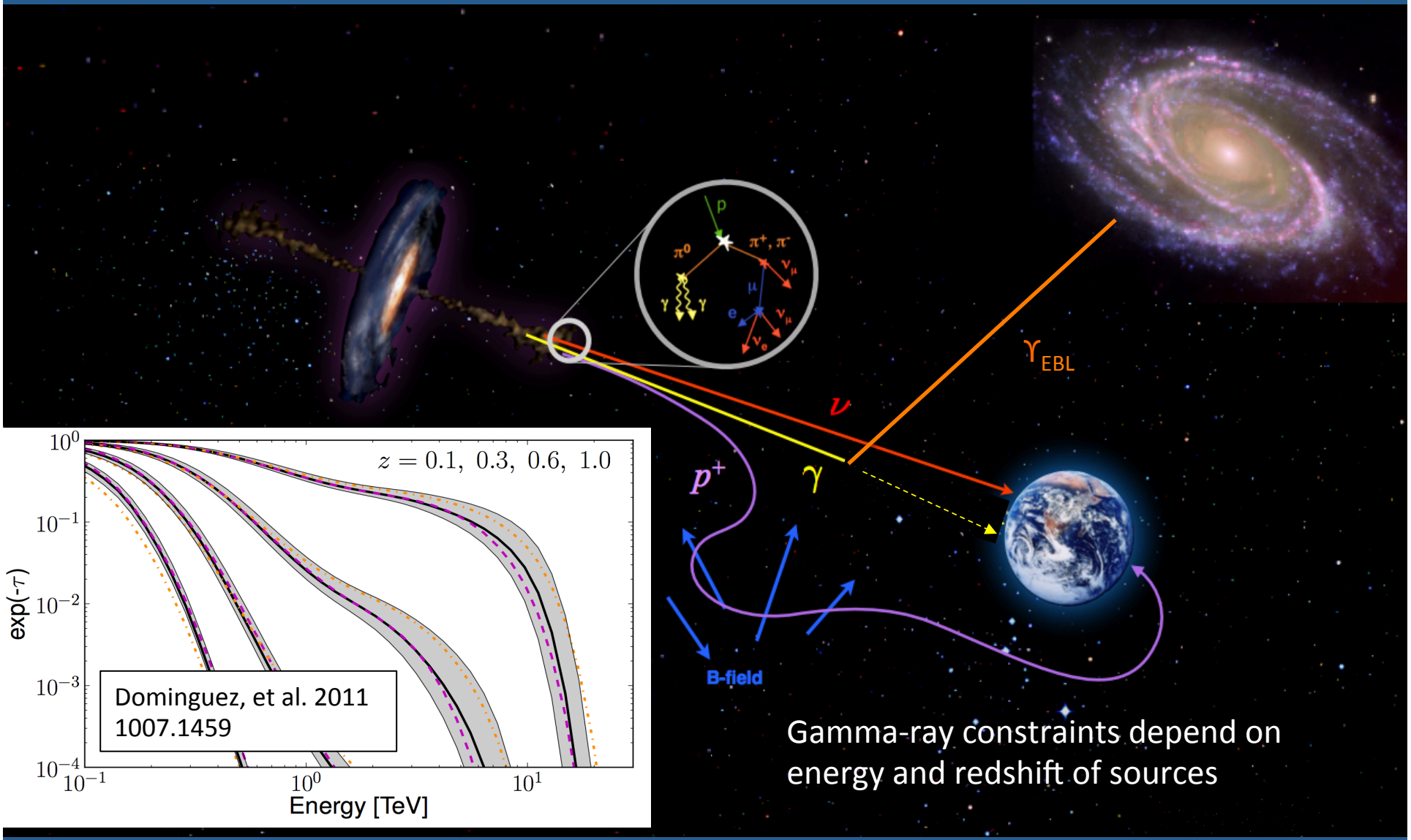
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$

$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$

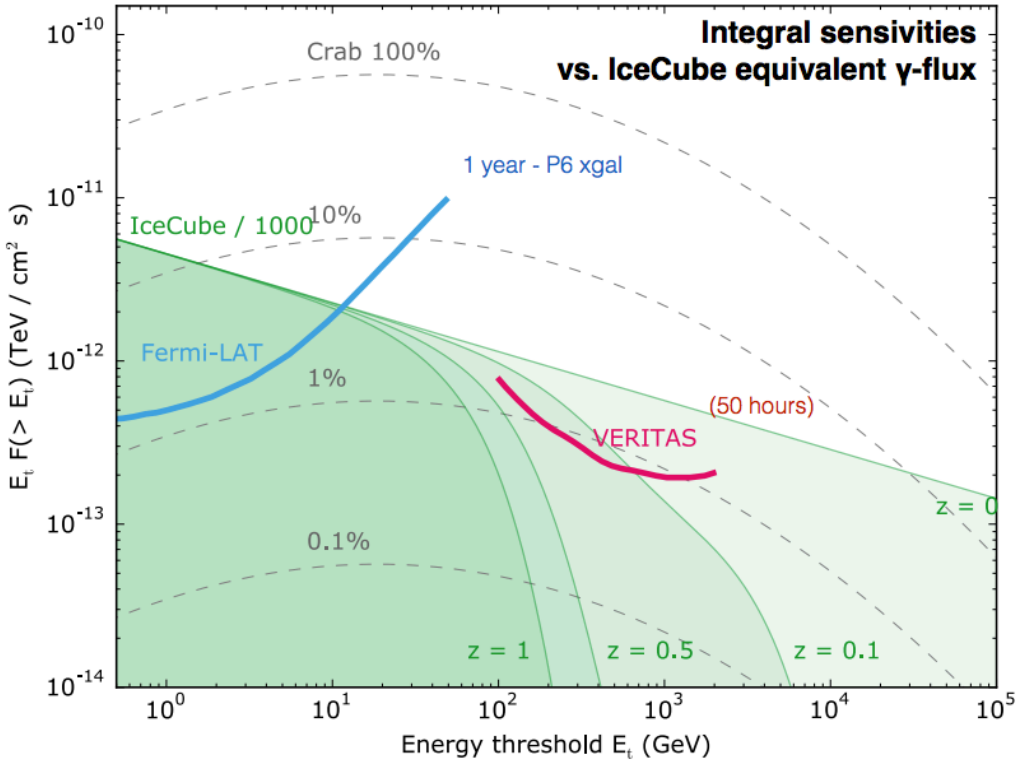
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

flavors oscillate to ~1:1:1

Extragal Background Light



Gamma-ray Searches



IceCube flux from arxiv:1405.5303 converted 1:1 to gamma rays and spread over 1000 uniform sources

Franceschini et al. EBL absorption model arxiv:0805.1841

- Fermi (GeV) and IACTs like VERITAS (>100 GeV) can set point-source limits on the flux that are **1000 to 10000 times** lower than the all-sky IceCube flux

- Sensitivity is a function of redshift > 100 GeV due to EBL absorption

Fermi-LAT Analysis

arXiv:1505.00935

- Fermi-LAT analysis of the **contained (C)** events by Brown, Adams, & Chadwick (2015) found one known gamma-ray source in coincidence

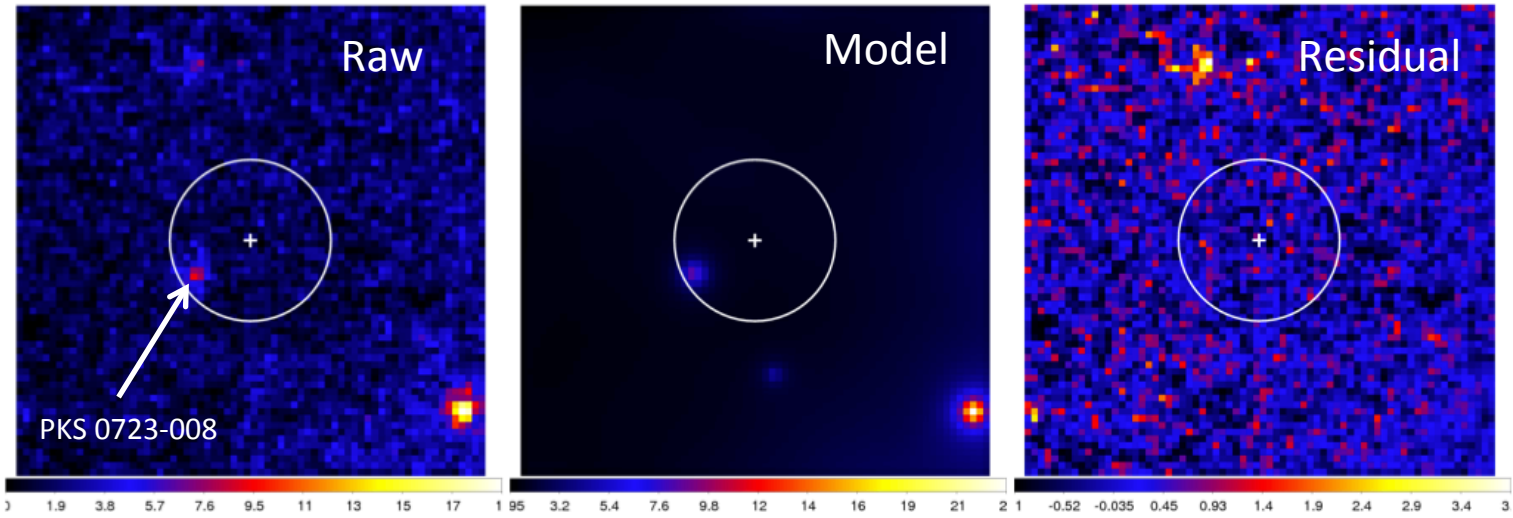
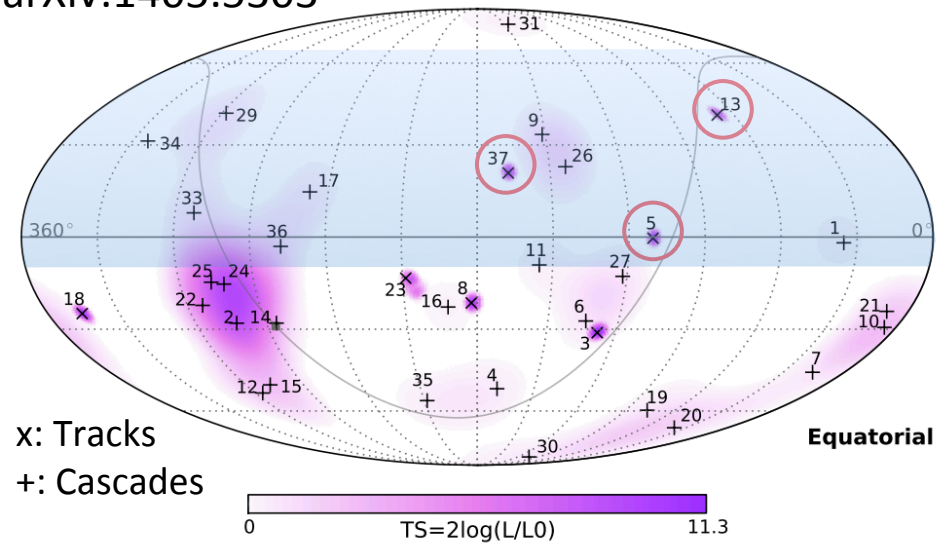


Figure 2. $7° \times 7°$ sky, model and residuals maps for Event 5. There is an excess in the residuals map consistent with a point source at $(\alpha_{J2000}, \delta_{J2000}) = (111.419, 2.221)$.

- "We find however, that the chance probability for Fermi-LAT detected AGN to be spatially coincident with a single HESE track-like event is high (~37%)"

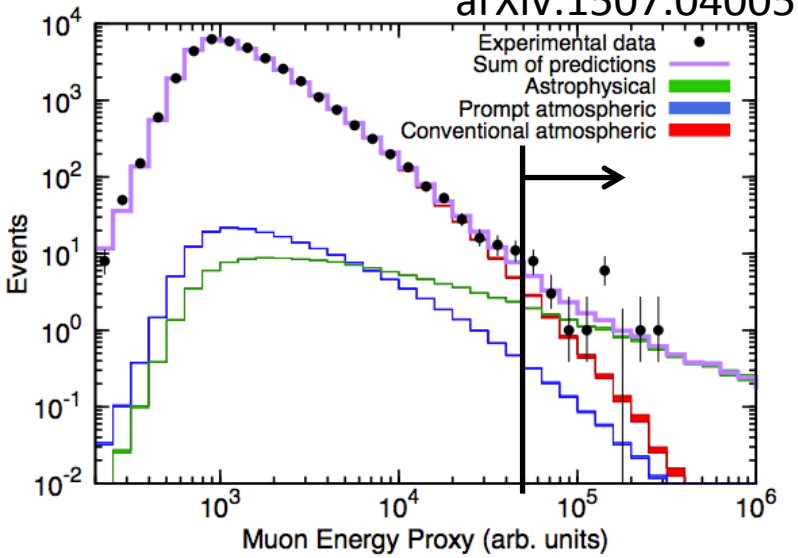
VERITAS Candidate Events

arXiv:1405.5303



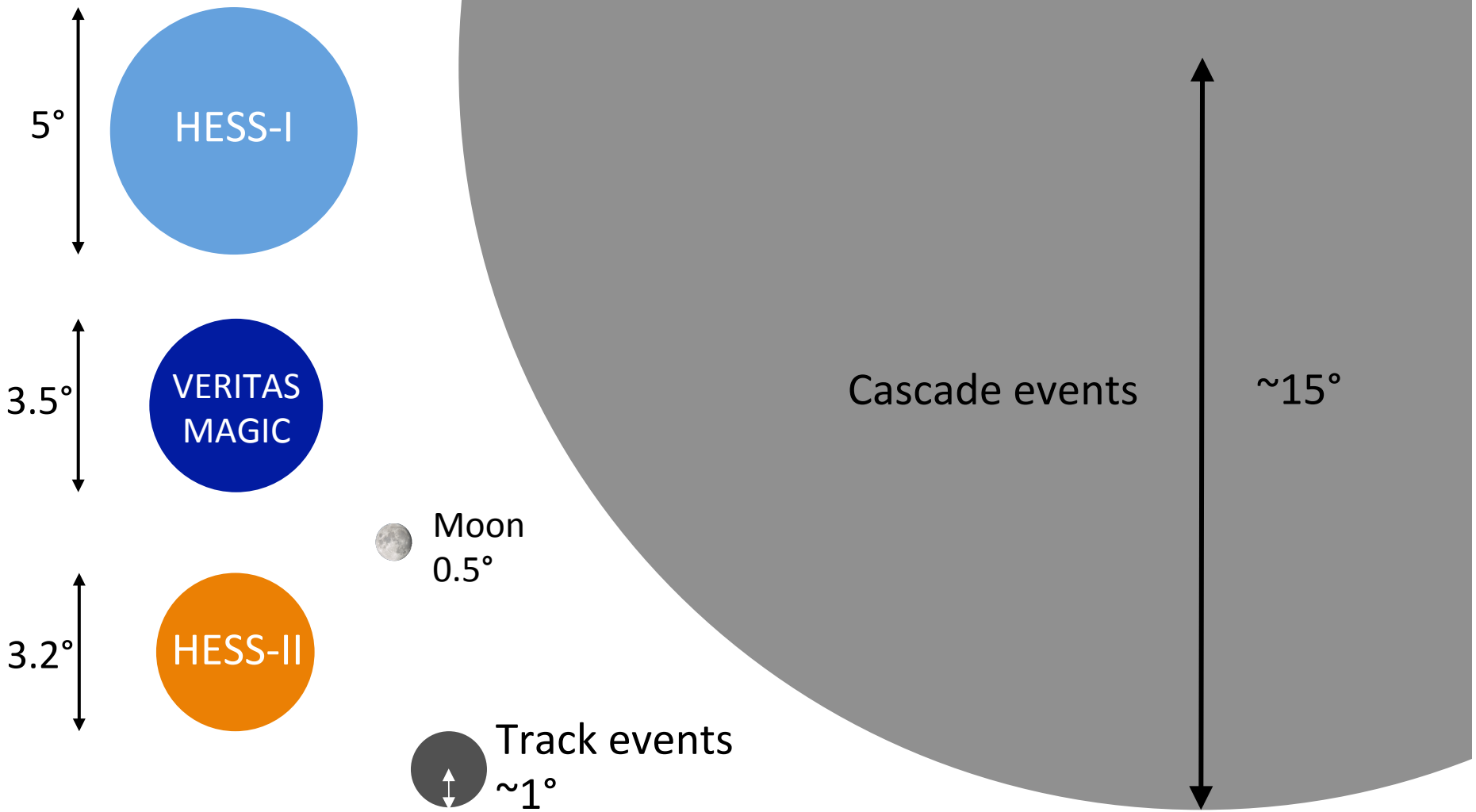
- **Three** HE **contained**-vertex tracks in the northern sky observable by VERITAS
- Positions are publicly available
- Angular uncertainty < 1.2° for the tracks

arXiv:1507.04005



- **20** highest energy **uncontained** tracks
- Events from a 2-year HE northern-sky diffuse muon neutrino search
  - Directions not public, shared through MoU
- Relatively high astrophysical purity
- Angular uncertainty < 1.0°

IACT FOVs & IceCube Events

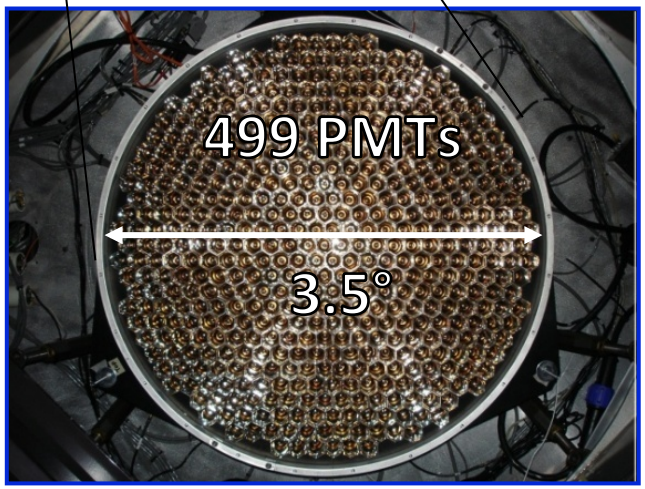


VERITAS

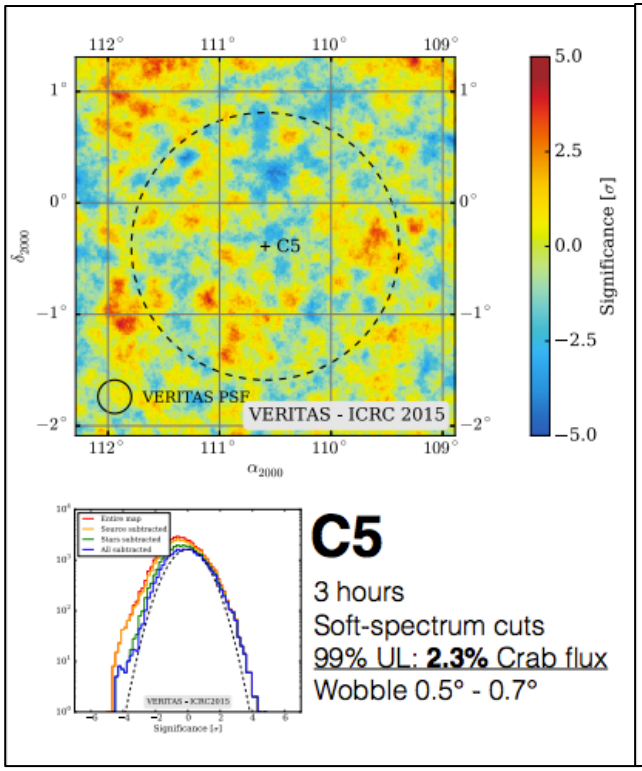


- Array of four 12-m IACTs
- 85 GeV – 30 TeV
- 15 – 25% energy resolution
- 0.1° angular resolution
- 1% Crab detection in < 30 hrs
- ~1000 hrs of observations/yr



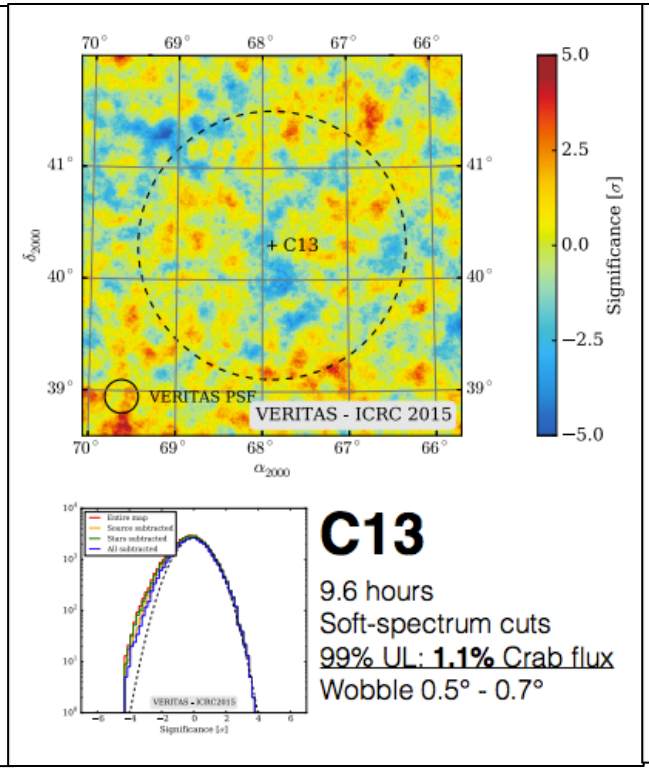


Contained Event Observations by VERITAS



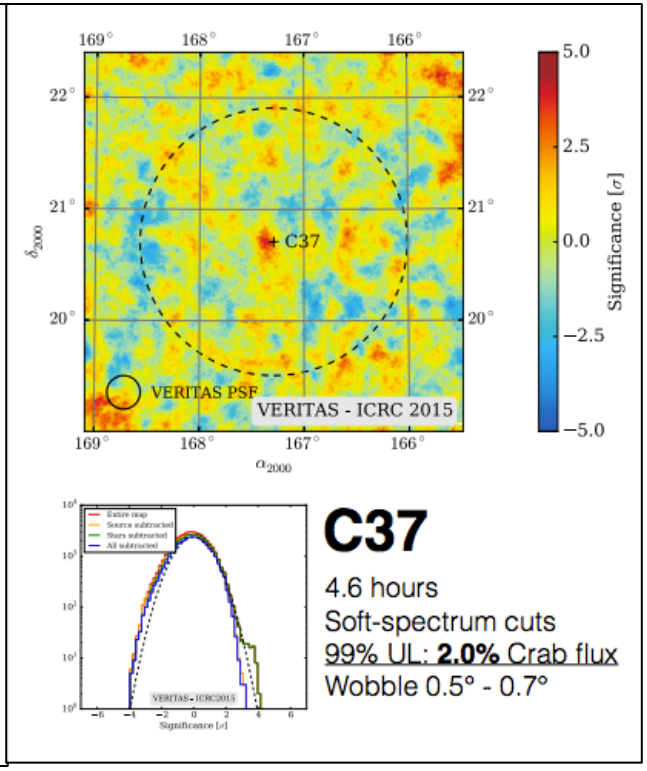
C5

3 hours
Soft-spectrum cuts
99% UL: **2.3%** Crab flux
Wobble 0.5° - 0.7°



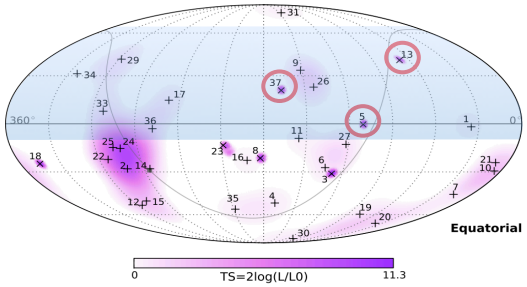
C13

9.6 hours
Soft-spectrum cuts
99% UL: **1.1%** Crab flux
Wobble 0.5° - 0.7°



C37

4.6 hours
Soft-spectrum cuts
99% UL: **2.0%** Crab flux
Wobble 0.5° - 0.7°

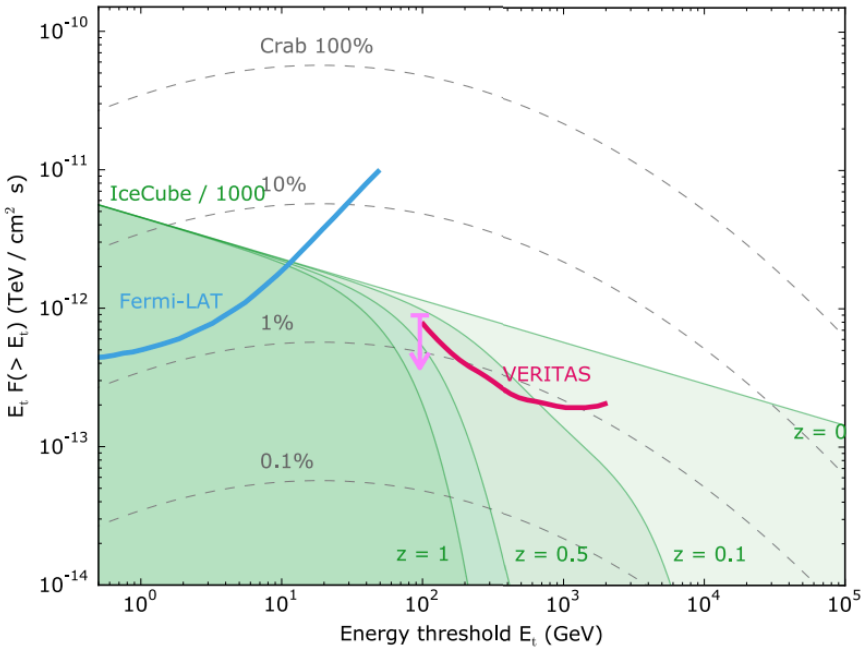


- No significant >100 GeV gamma-ray emission
- Most significant hotspot is in **C37** field: 4.3σ pre-trials, 2.0σ post-trials

Uncontained Event Observations by VERITAS

ID	Obs. time [min]	UL (99%) [$\times 10^{-12}$ cm^{-2} s^{-1}]	UL (99%) [C.U.]
C5	180	8.3	2.3%
C13	574	4.0	1.1%
C37	275	7.3	2.0%
UC2	25	21.2	5.8%
UC3	180	6.3	1.7%
UC4	122	9.9	2.7%
UC5	90	6.7	1.8%
UC6	25	9.5	2.6%
UC7	15	39.6	10.9%
UC8	60	9.3	2.6%
UC9	40	15.2	4.2%
UC10	90	9.4	2.6%
UC11	209	4.4	1.2%
UC12	25	9.5	2.6%
UC15	90	7.4	2.0%
UC16	40	8.6	2.4%
UC17	150	4.4	1.2%
UC19	210	3.9	1.1%

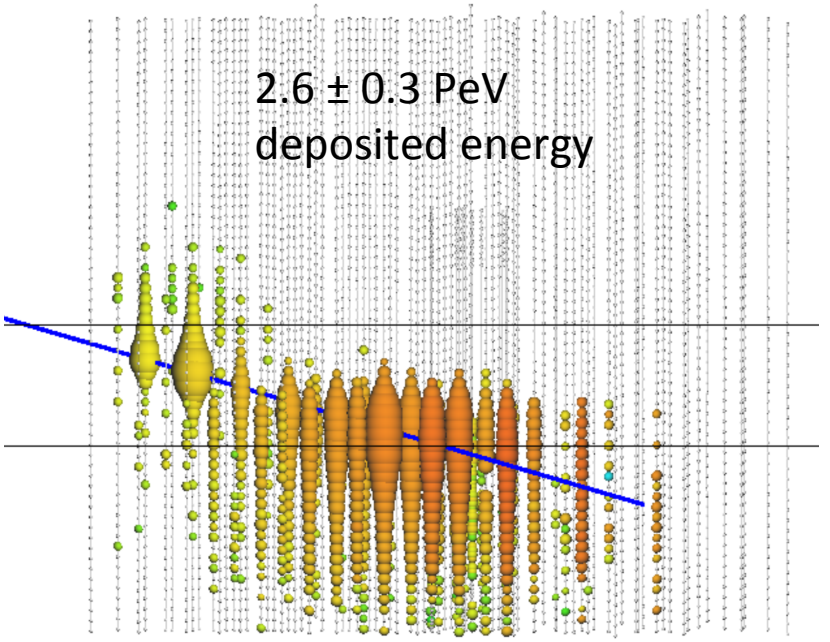
*ULs directly at neutrino reconstructed direction with no trials corrections



- Almost all 99% CL upper limits are 1—5% of the Crab Nebula flux > 100 GeV
- These ULs allow us to exclude gamma-ray flux at the level of 1/1000th the all-sky neutrino flux for sources with $z < 0.2$
  - Assumptions: pure power law with index -2.3, steady flux

Next Steps

- All previous observations took place several months or even years after the initial neutrino detection by IceCube. However, real-time alerts now possible after a number of technical improvements
  - Faster online reconstruction
  - New satellite modem and protocol for reduced latency in sending entire events to the north
  - Improved infrastructure for monitoring health of the detector and sending alerts via AMON
  - A test alert stream is currently active
- Deeper observations of fewer targets but higher-priority targets
- Fermi analysis of uncontained HE tracks underway
  - Prior results only for contained tracks



Summary

- ~40 hours of VERITAS data on IceCube HE neutrino candidate positions
- No significant detection of VHE gamma-rays associated with the neutrinos
  - 99%CL upper limits >100 GeV at the few % of the Crab Nebula flux level
- These ULs allow us to infer constraints on the possible origins of the neutrino flux
  - Likely a large number of sources and/or relatively large redshifts
- Next steps are to perform prompt follow up observations
  - Aim for observations to start within a few minutes of neutrino detection

Thank you.



Photo by Wystan Benbow, Smithsonian Astrophysical Observatory