A multi-messenger search for the origin of high-energy astrophysical neutrinos with VERITAS and Fermi

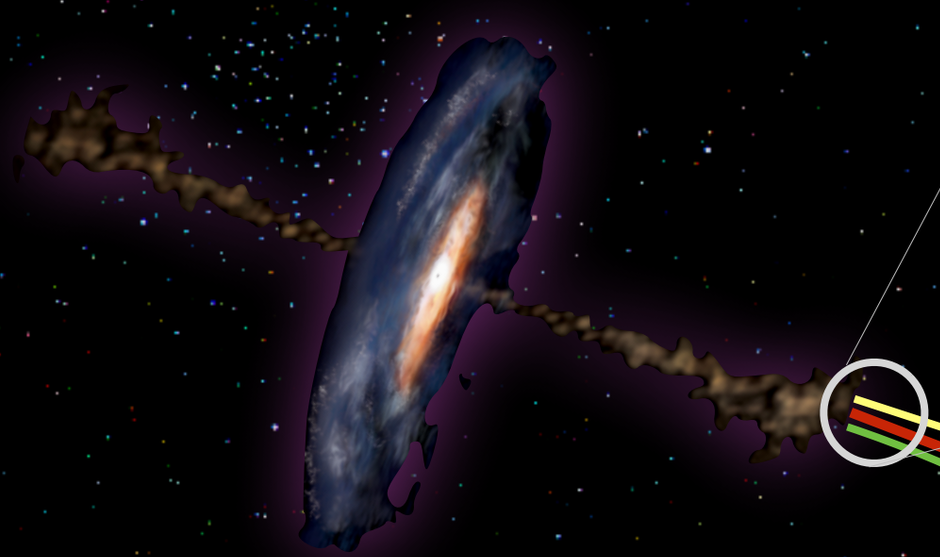
M. Santander for the VERITAS and IceCube Collaborations

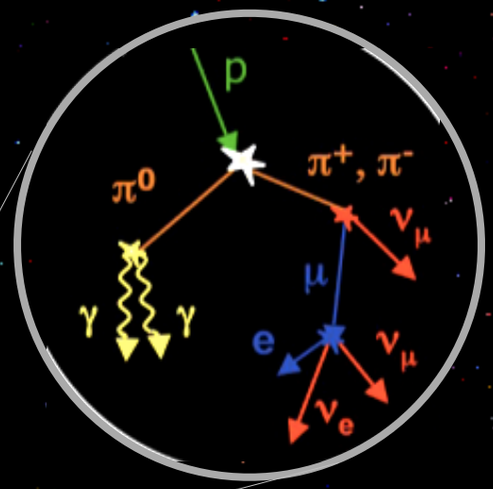
Barnard College, Columbia University

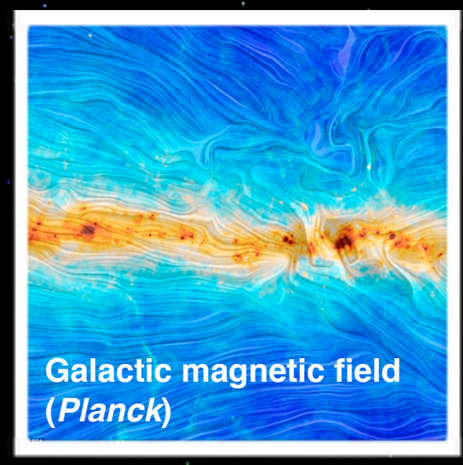
Outline

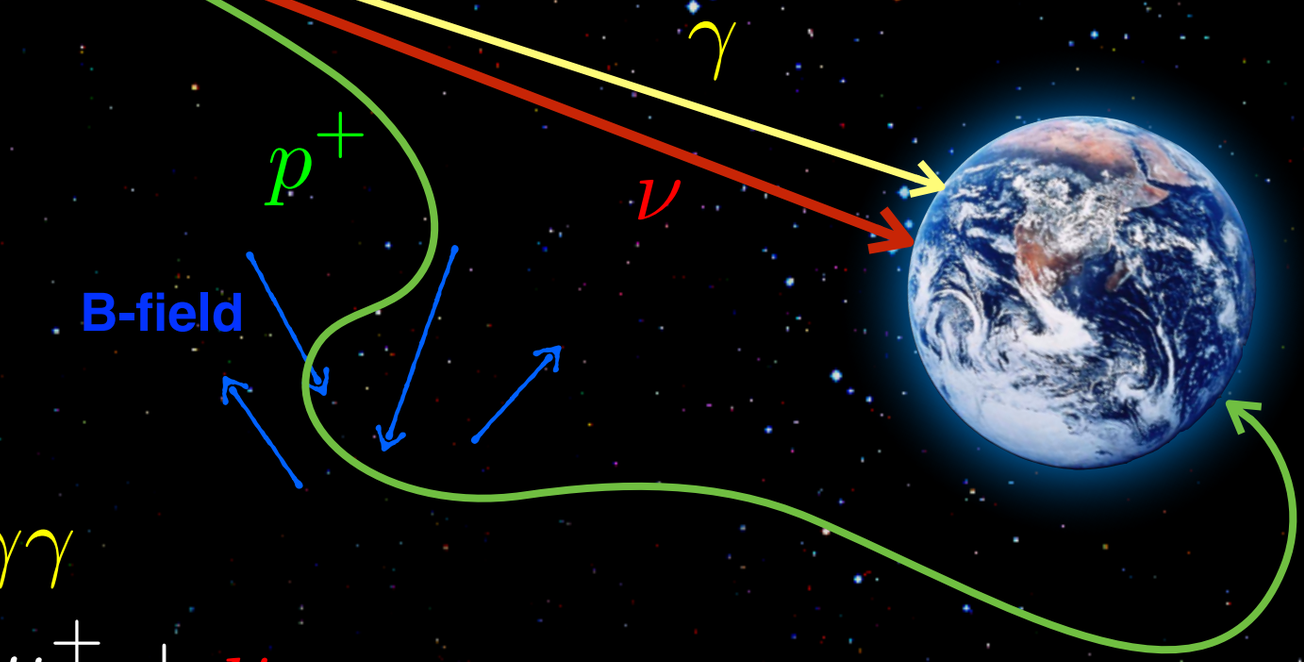
- Multi-messenger search for cosmic-ray sources
- IceCube astrophysical neutrinos
- VERITAS & Fermi observations of neutrino positions
- Future plans

Multi-messenger astronomy







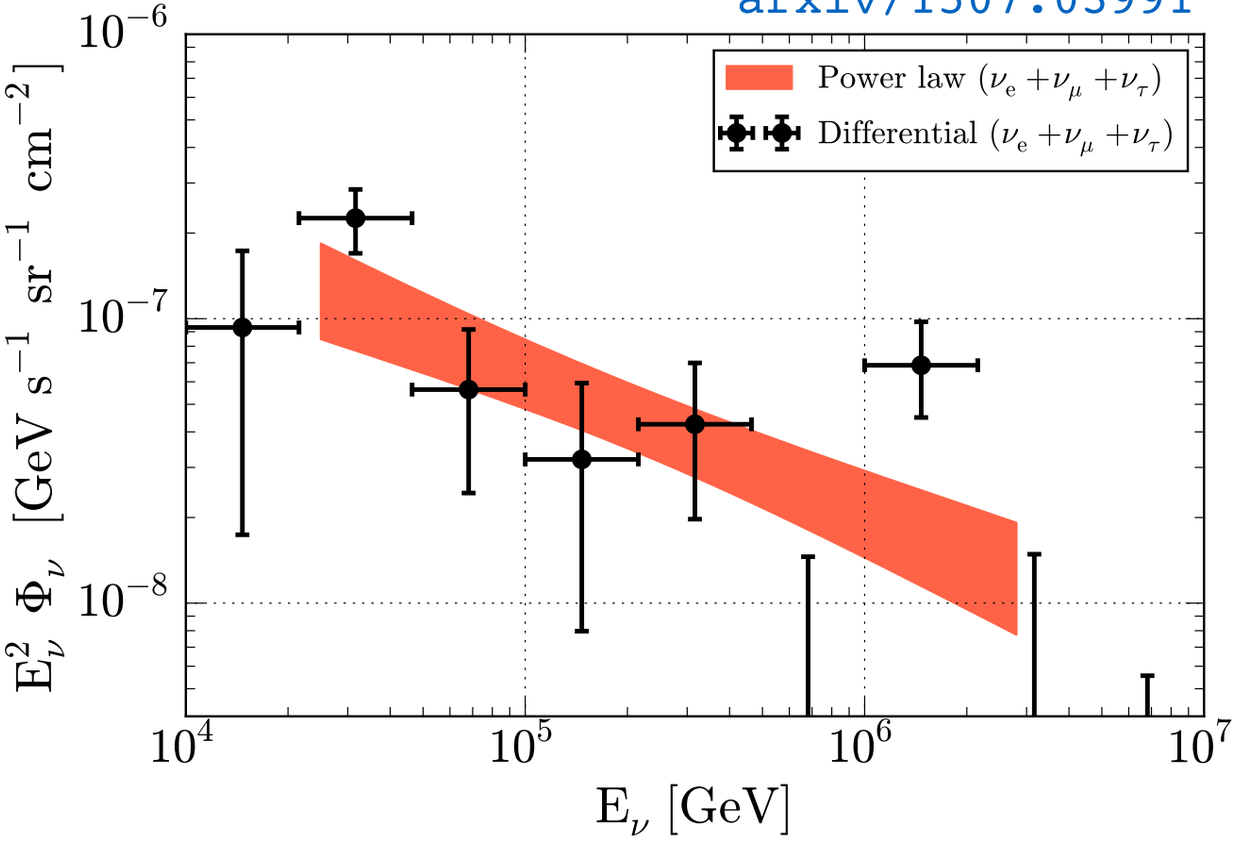


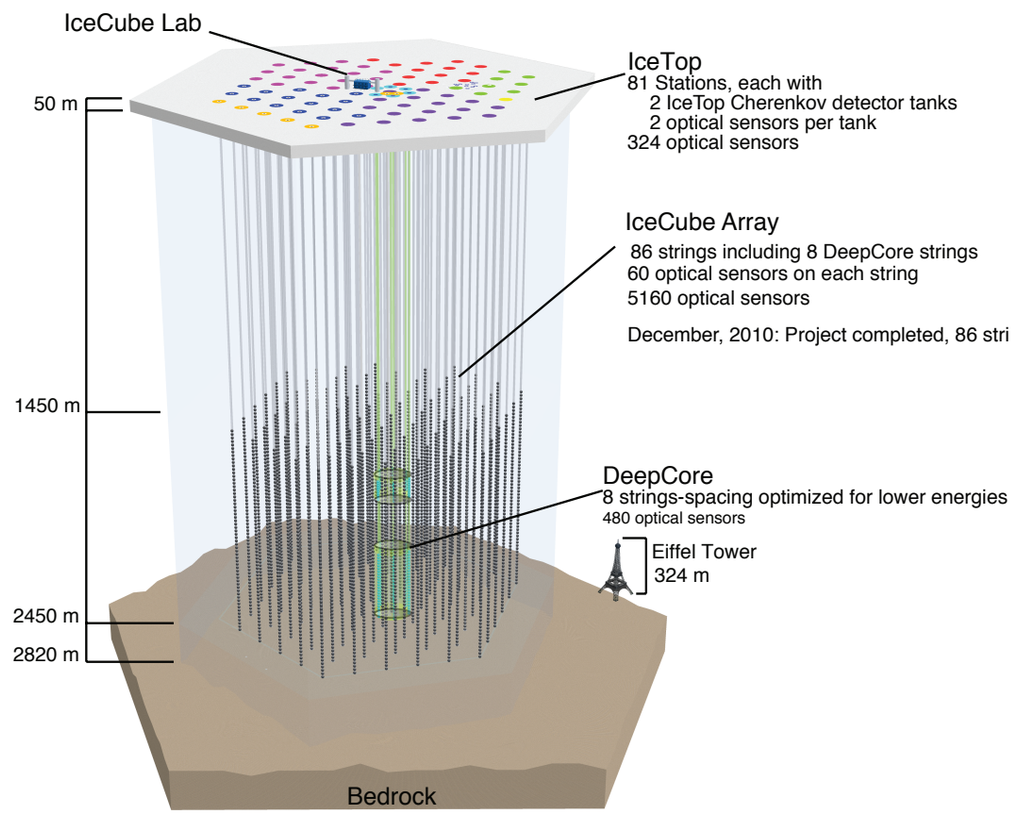
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

IceCube astrophysical neutrinos

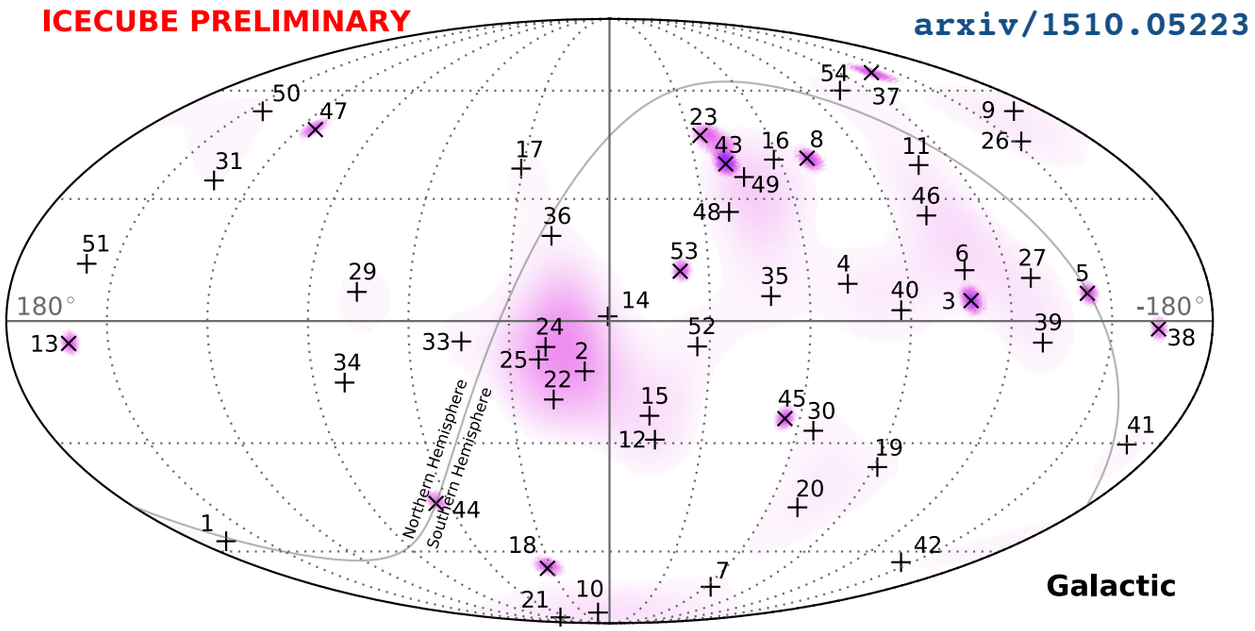
- Evidence for astrophysical neutrinos first observed by IceCube using high-energy neutrino events with contained (**C**) interaction vertices (arxiv/1405.5303).
- New analysis using up-going muon tracks with uncontained vertices (**UC**) shows a similar flux with a 3.7σ significance (arxiv/1507.04005).
- Neutrino energies between tens of TeV to few PeV. Compatible with flavor equipartition.
- Power-law fit to the neutrino spectrum gives an index of **2.50 ± 0.09**

arxiv/1507.03991

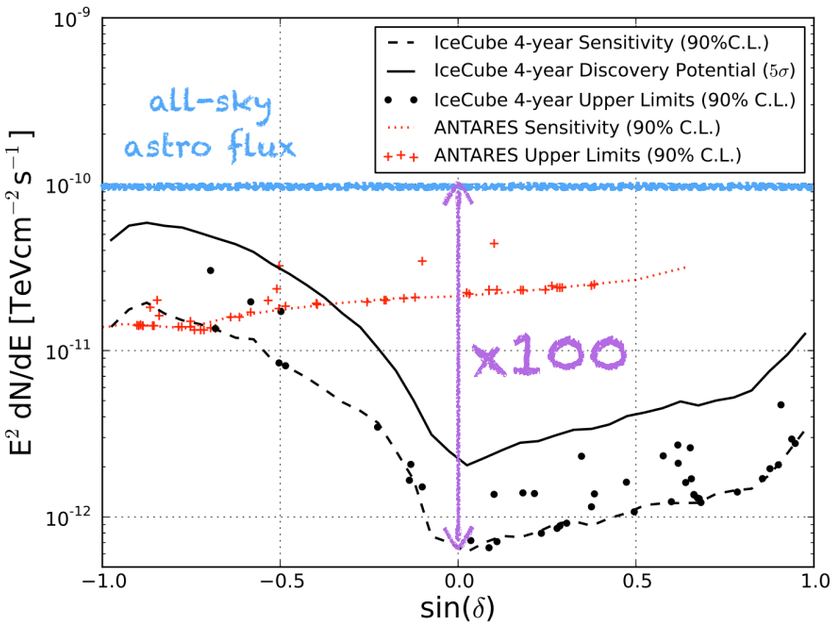




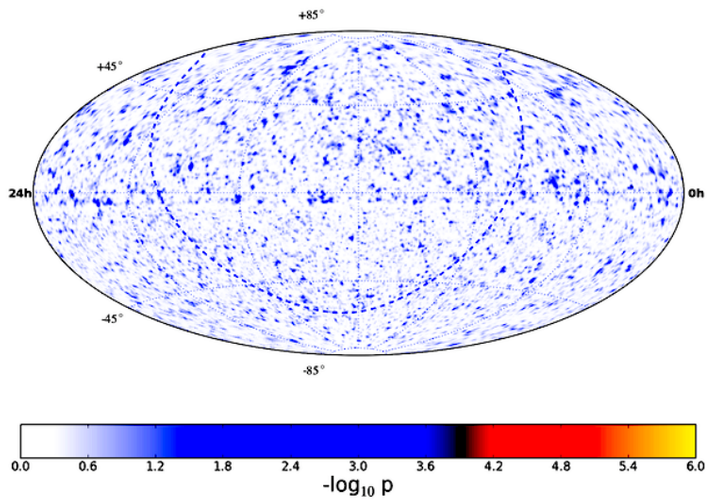
IceCube neutrino point-source searches



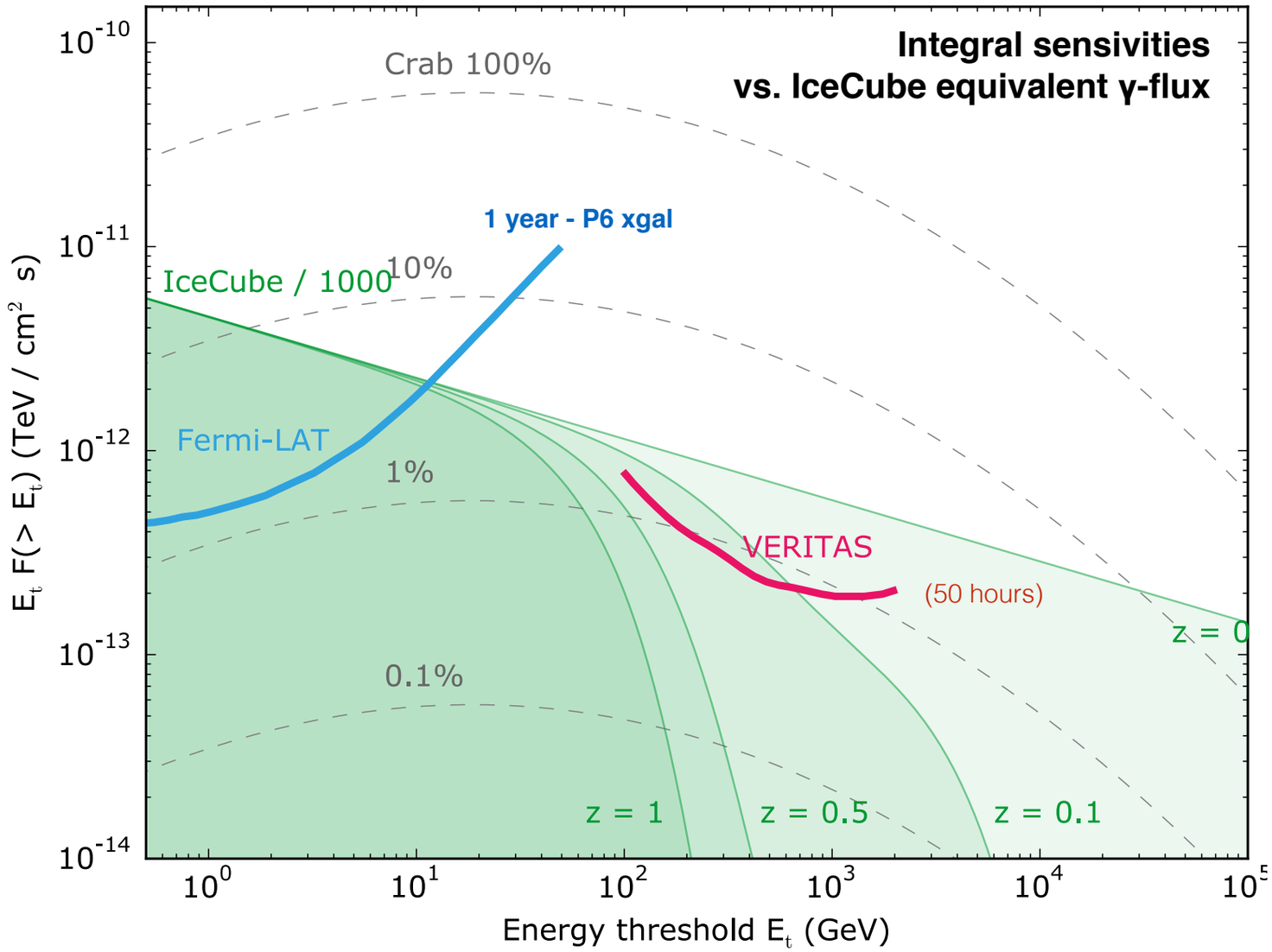
- Contained (**C**) sample: **54** neutrino candidate events in **4 years**.
  - 39 cascades, ~15° ang. resolution (CC $\nu_{e,\tau}$ + NC $\nu_{e,\mu,\tau}$)
  - 13 tracks, ~1° ang. resolution (CC ν_{μ})
  - 2 events are likely background events.
- No evidence for neutrino point sources.



- Previous point-source searches (using muon tracks) have set ULs at a flux level that is **x10-100** lower than the all-sky astrophysical flux.
- Large number of weak sources? transients?

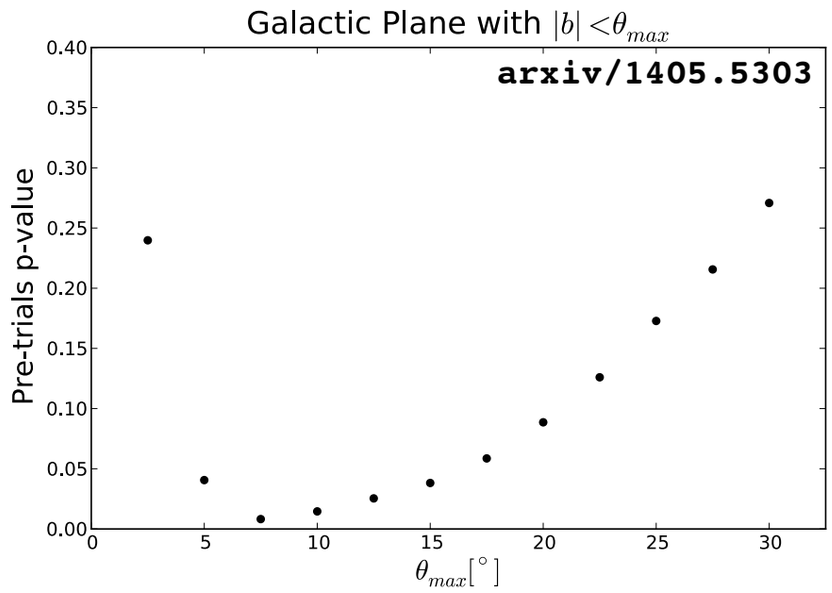


Gamma-ray searches for neutrino sources



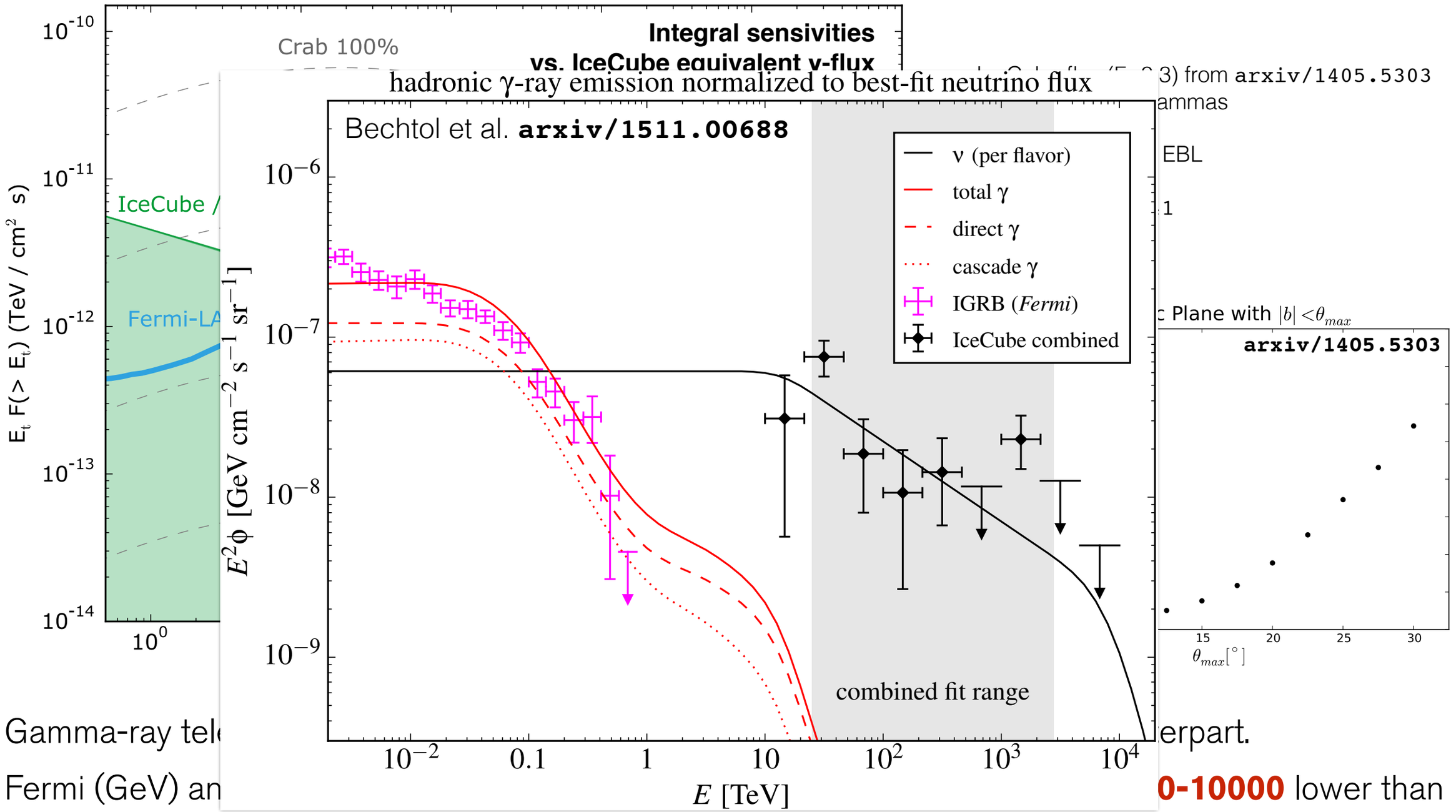
IceCube flux (Γ~2.3) from `arxiv/1405.5303` converted 1:1 to gammas

Franceschini et al. EBL model
`arxiv/0805.1841`



- Gamma-ray telescopes can be used to search for the hadronic gamma-ray counterpart.
- Fermi (GeV) and IACTs like VERITAS (TeV) can set limits on fluxes that are **x1000-10000** lower than the all-sky IceCube flux.
- Sensitivity is a function of redshift for VHE searches.
- No significant correlation between contained tracks and Fermi sources (`arxiv/1505.00935`)

Gamma-ray searches for neutrino sources



- Gamma-ray tel… …erpart.
- Fermi (GeV) an… …**0-10000** lower than the all-sky IceCube flux.
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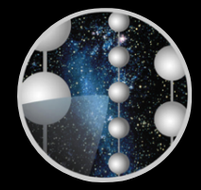
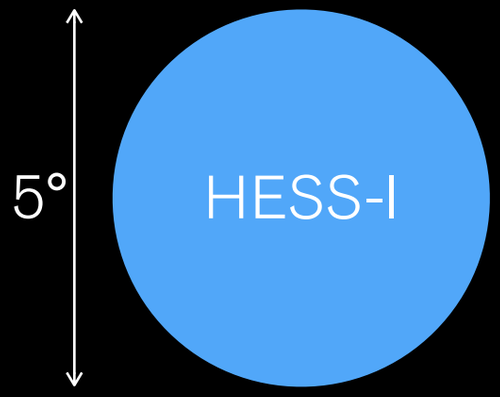
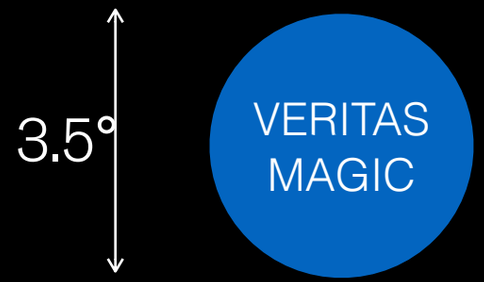
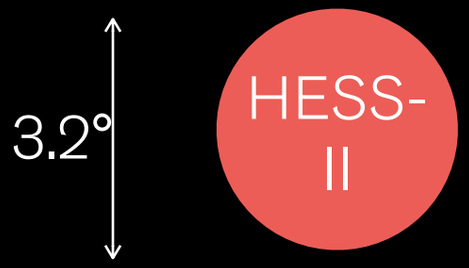
Gamma-ray FoVs and IceCube events





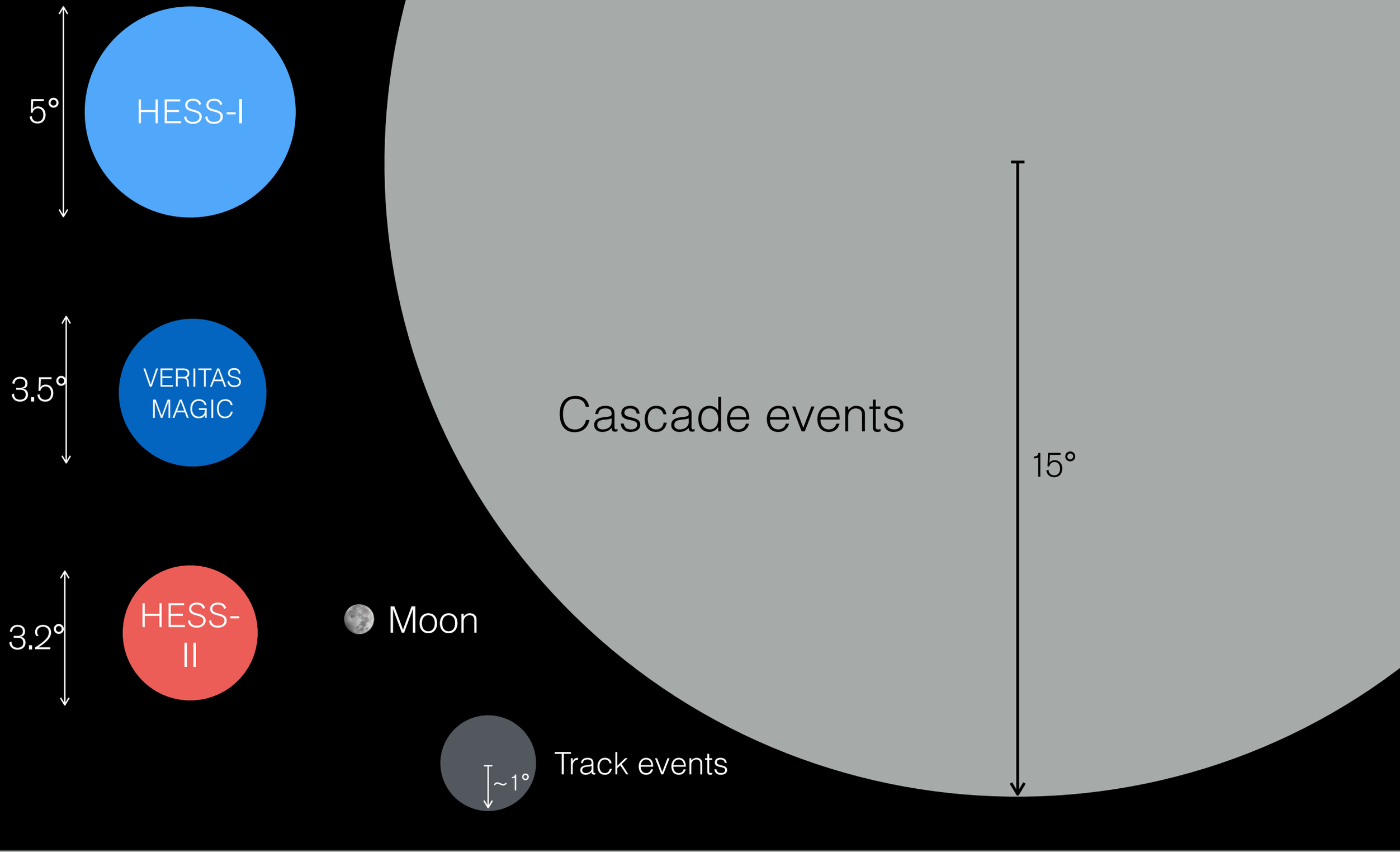




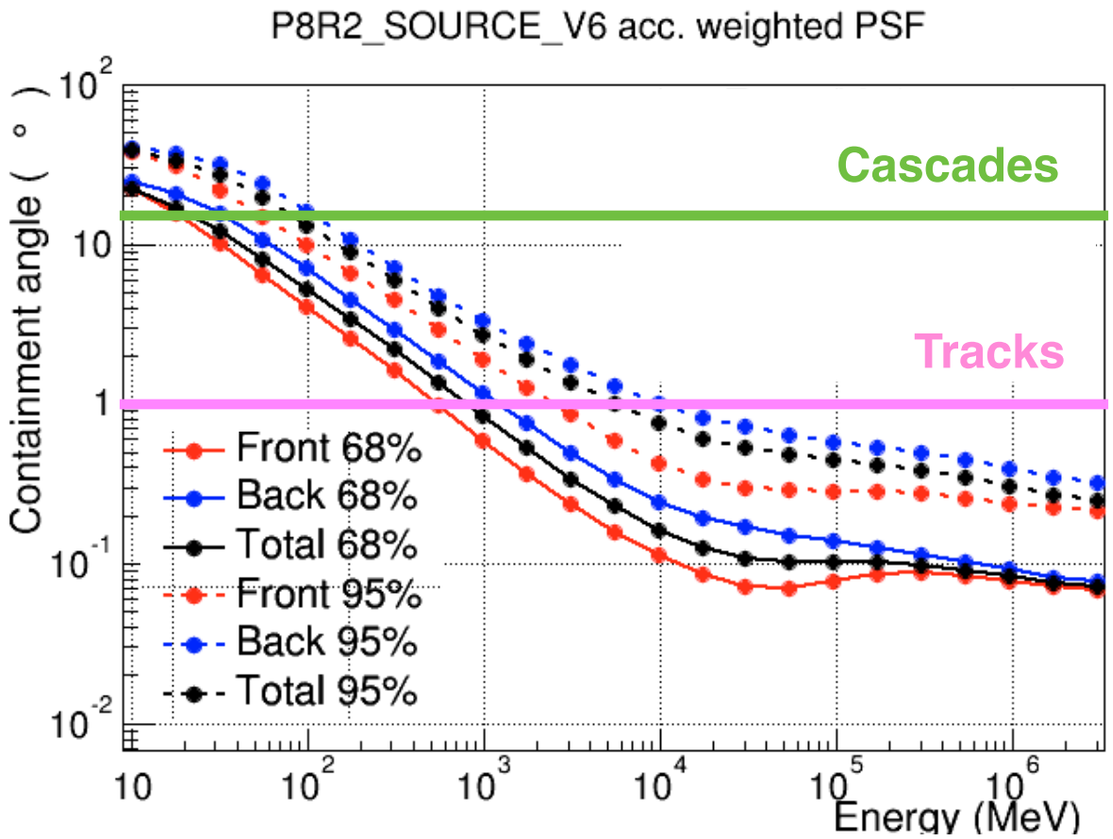
Moon

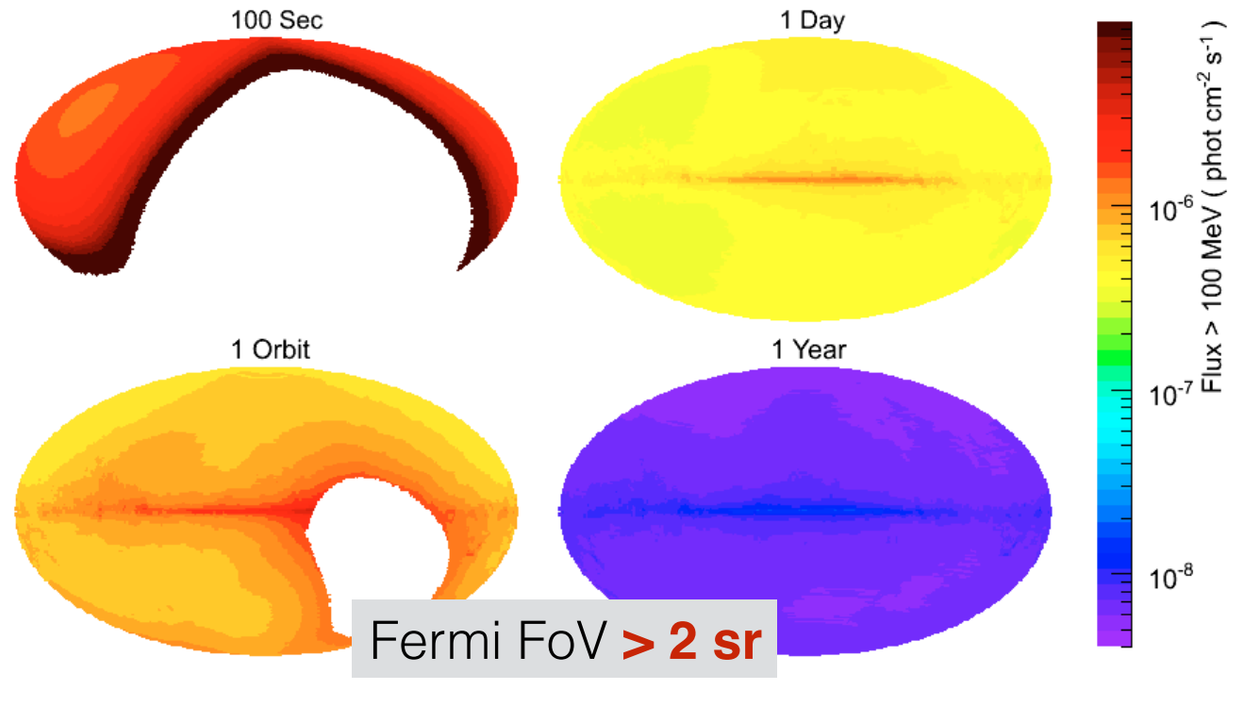
Track events

Gamma-ray FoVs and IceCube events

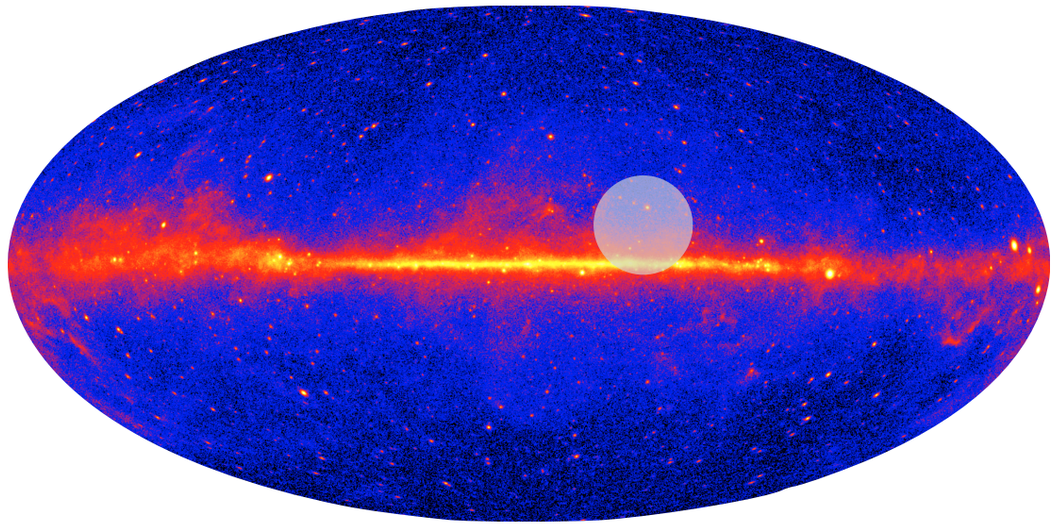


Gamma-ray FoVs and IceCube events





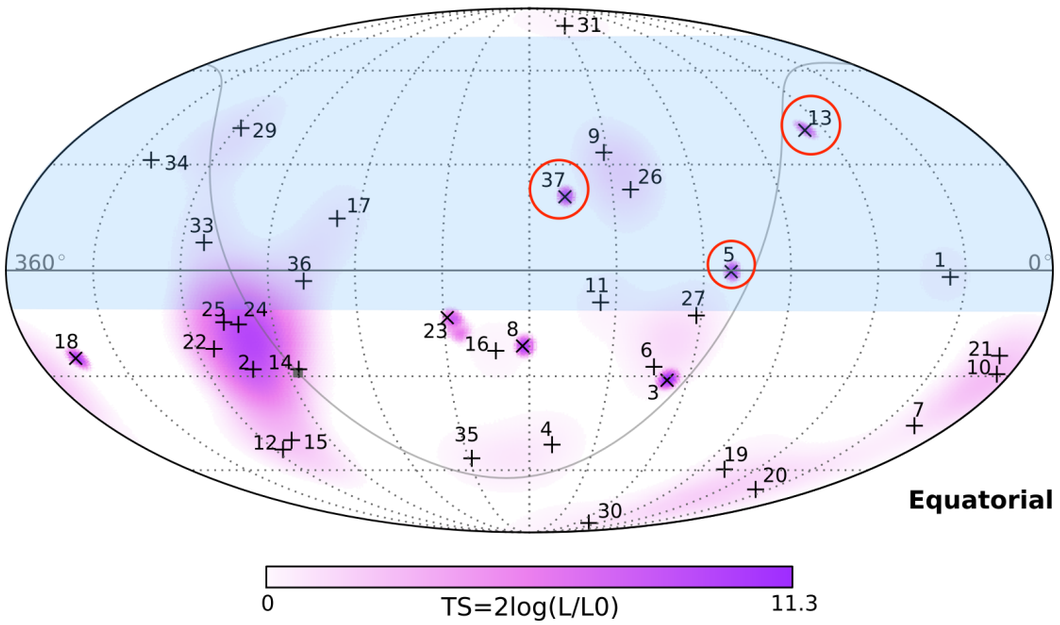
- Fermi-LAT has large field of view and high duty cycle.
- >2 sr instantaneous FoV. Entire sky covered in 3 hours.
- Angular resolution comparable to cascades > 100 MeV and muon tracks > 1 GeV.
- Large number of sources. Chance correlations ~ 37% for tracks. Worse for cascades.



Muon positions to observe with VERITAS

Contained events (C)

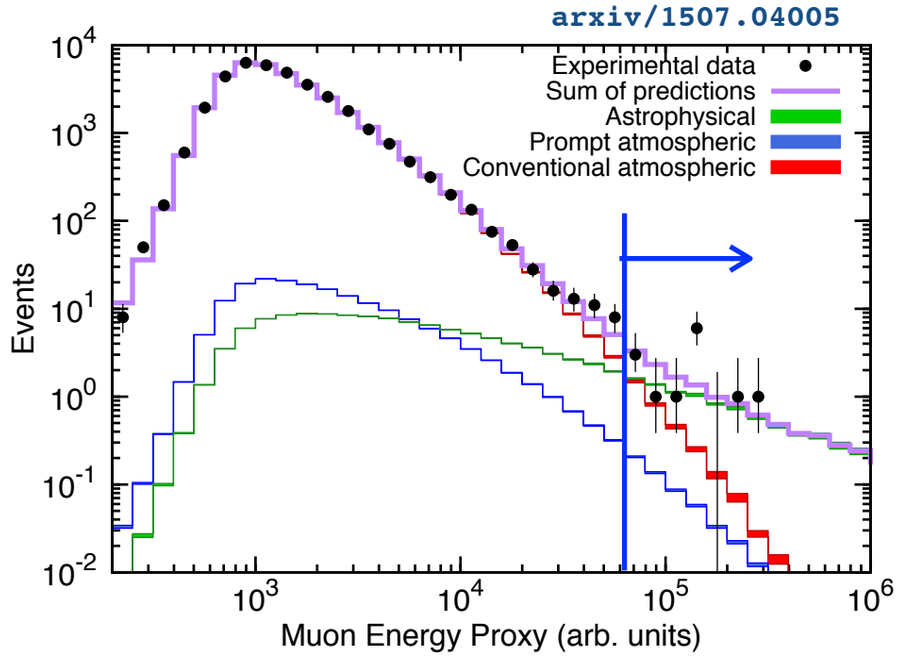
arxiv/1405.5303



- Three HE contained-vertex muons in the northern sky observable from VERITAS.
- Positions are publicly available.
- Angular uncertainty < 1.2° for muons.

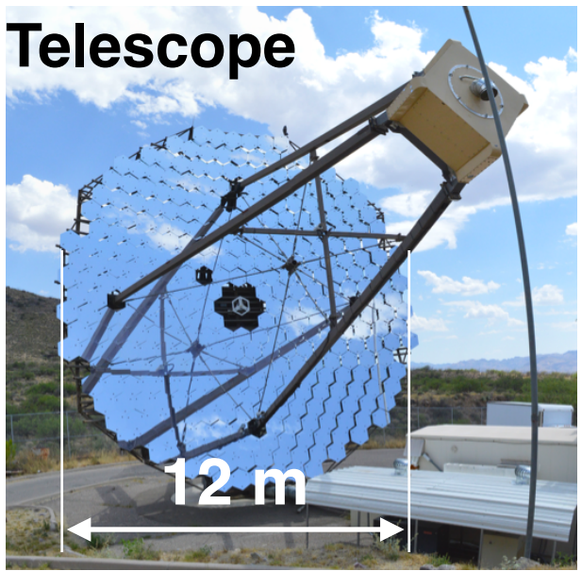
Uncontained events (UC)

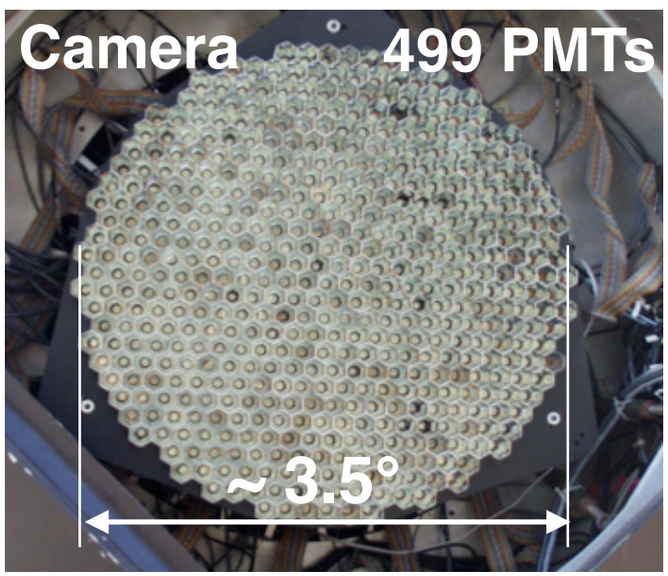
arxiv/1507.04005



- Uncontained muon events.
- Event positions from a 2-year sample of HE northern-sky muon neutrino candidates.
- 20 highest energy events in the sample.
- Relatively high astrophysical purity (ignoring atmospheric & astrophysical flux uncertainties)
- Event positions not yet published. Shared through IceCube-VERITAS MoU.
- Typical angular uncertainty < 1°.

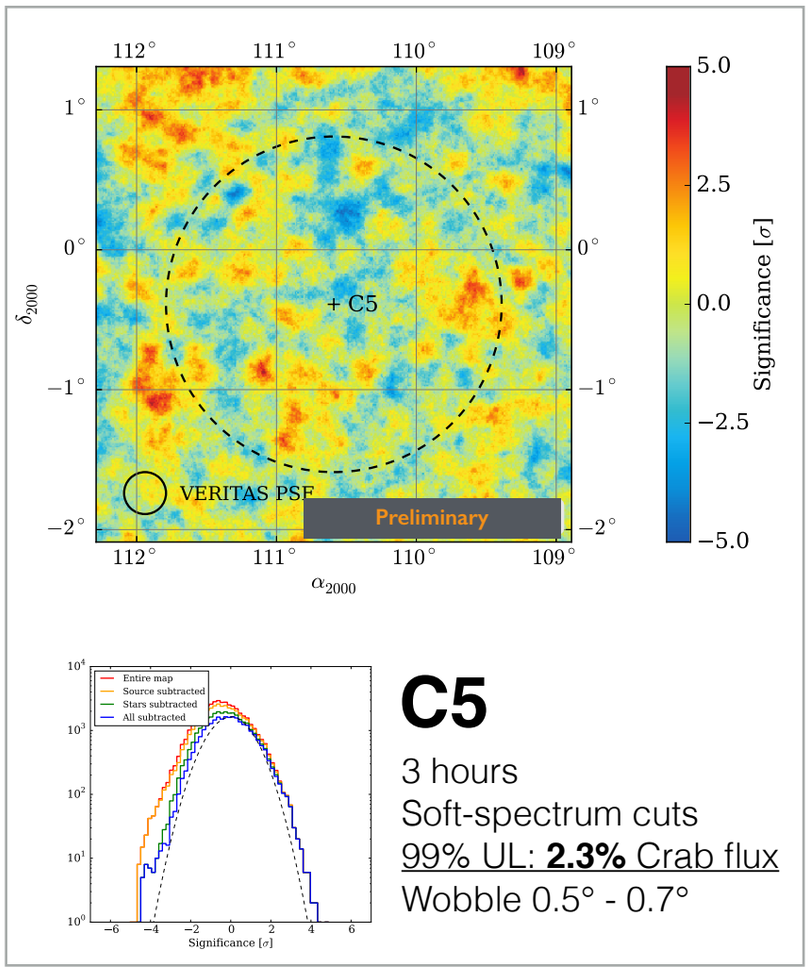
VERITAS Overview





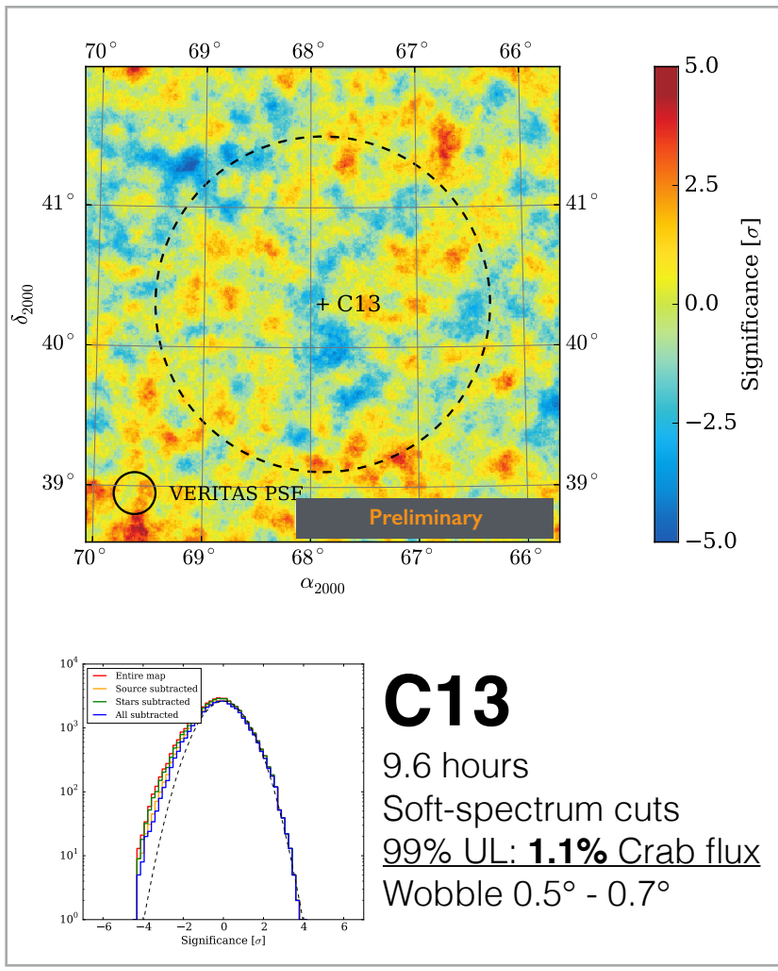
- First light in 2004
- Array of 4 Davis-Cotton Imaging Air Cherenkov Telescopes.
- Energy range: ~ 80 GeV - 30 TeV
- Effective area: ~ 10^5 m^2
- Observing time: ~ 750 hr (dark) + 200 hr (moonlight)
- **0.1°** angular resolution > 1 TeV

VERITAS observations of contained muons



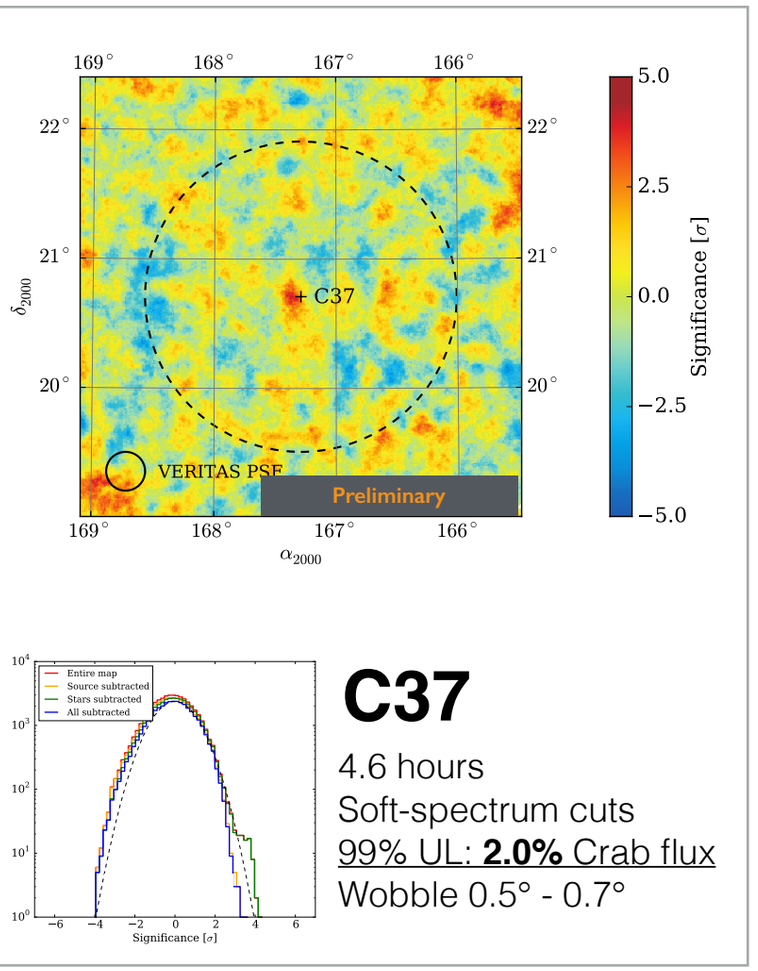
C5

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



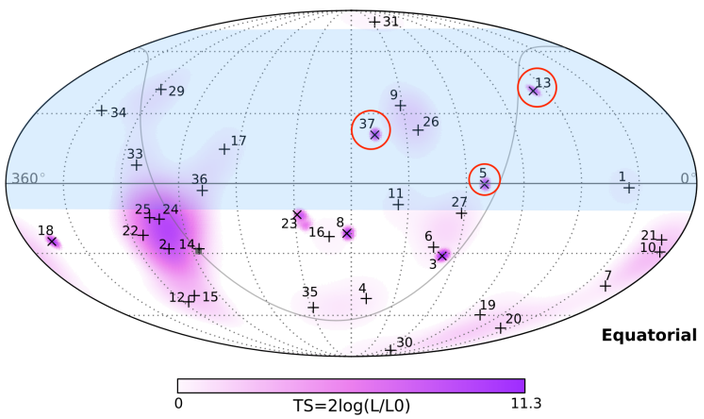
C13

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°



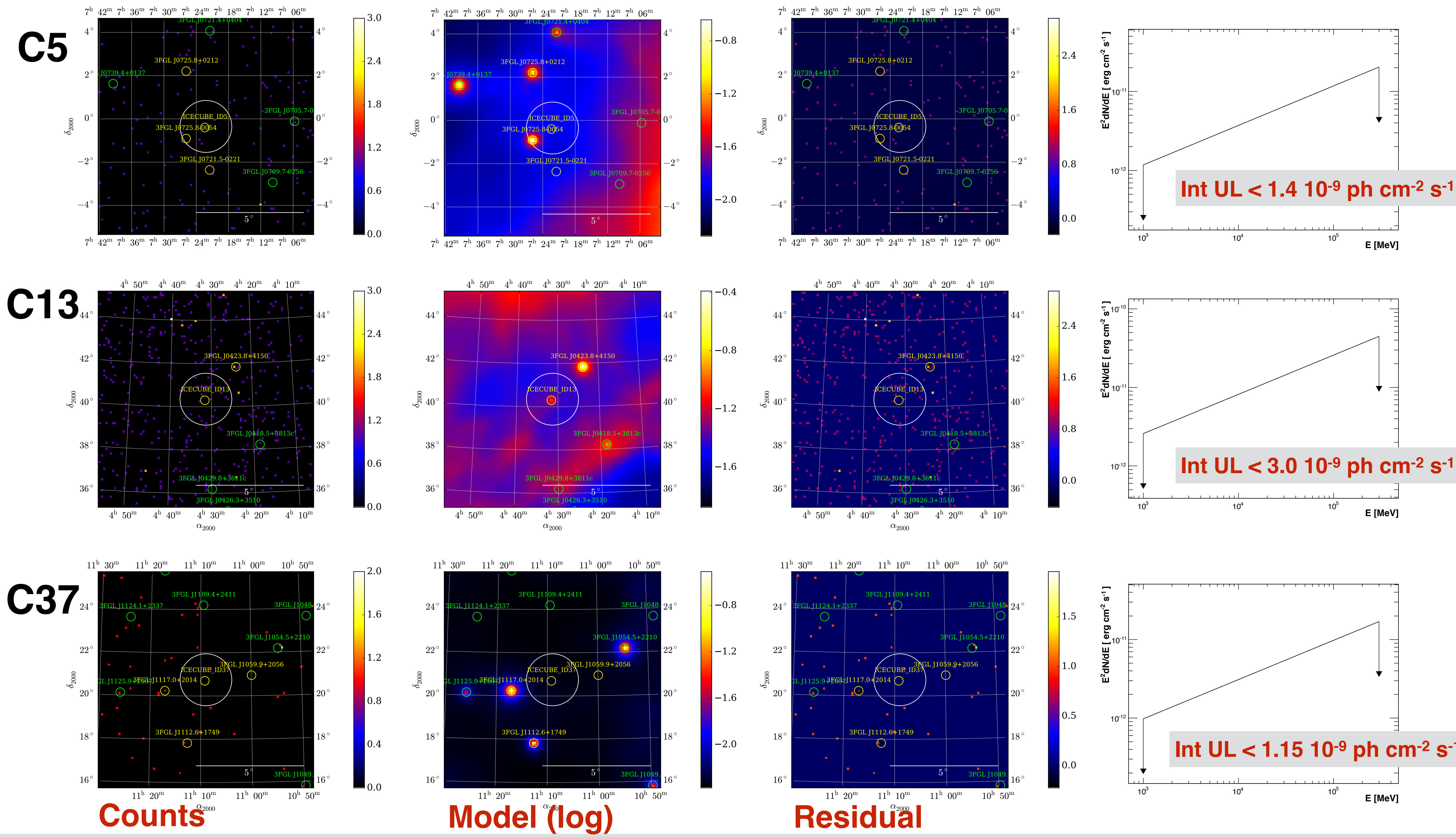
- No significant gamma-ray emission detected above 100 GeV.
- Most significant hotspot is in the C37 field. Significance: 4.3σ pre-trials, **2.0σ** post-trials.

VERITAS

LAT observations of contained muons

- Pass 8 analysis with 1 GeV < E < 300 GeV for Δt = ± 7 days wrt time of the event.
- No significant cluster of photons at the position of the neutrino (sqrt(TS) < 1)

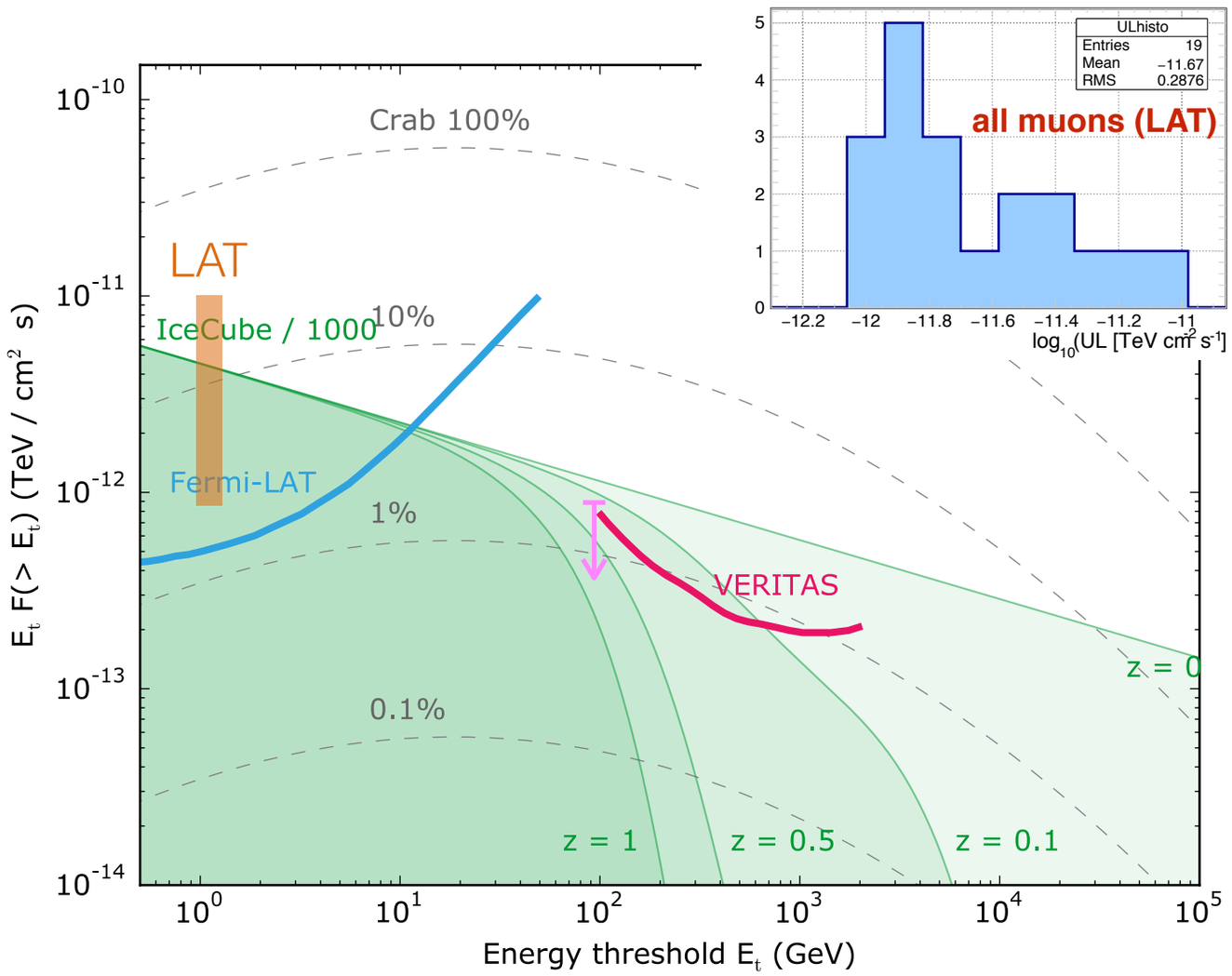
***Fermi*-LAT**



Observations of uncontained muons

***ULs with no trials corrections.**

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%



- Most 99% CL upper limits for uncontained muons are at the 1-5% Crab nebula flux above 100 GeV.
- For the LAT, ULs on uncontained muons are in the ~(10^{-12} - 10^{-11}) TeV cm^{-2} s^{-1} above 1 GeV.
- Given the current limits and an neutrino spectral index of 2.3 this would rule out steady sources with a gamma-ray flux that is 1/1000 of the all-sky neutrino flux if they are at $z < 0.2$.

PeV muon neutrino event

- E_{dep} **~2.6 +/- 0.3 PeV**
- Time: 6/11/2014
- RA: 110.34°
- Dec: 11.48°
- $r_{50\%}$ < 0.27°
- **p_{atm} < 0.01%**
- ATel #7868

Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

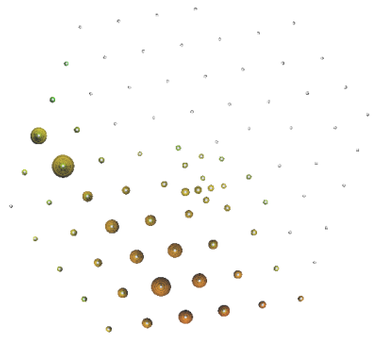
ATel #7856; *Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration*
on ***29 Jul 2015; 20:47 UT***
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

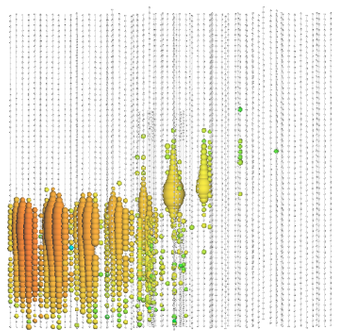
Subjects: Neutrinos, Request for Observations

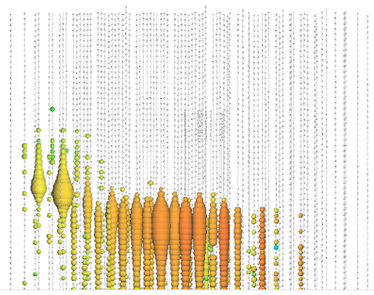
Referred to by ATel #: 7868

Tweet 31 Recommend 133

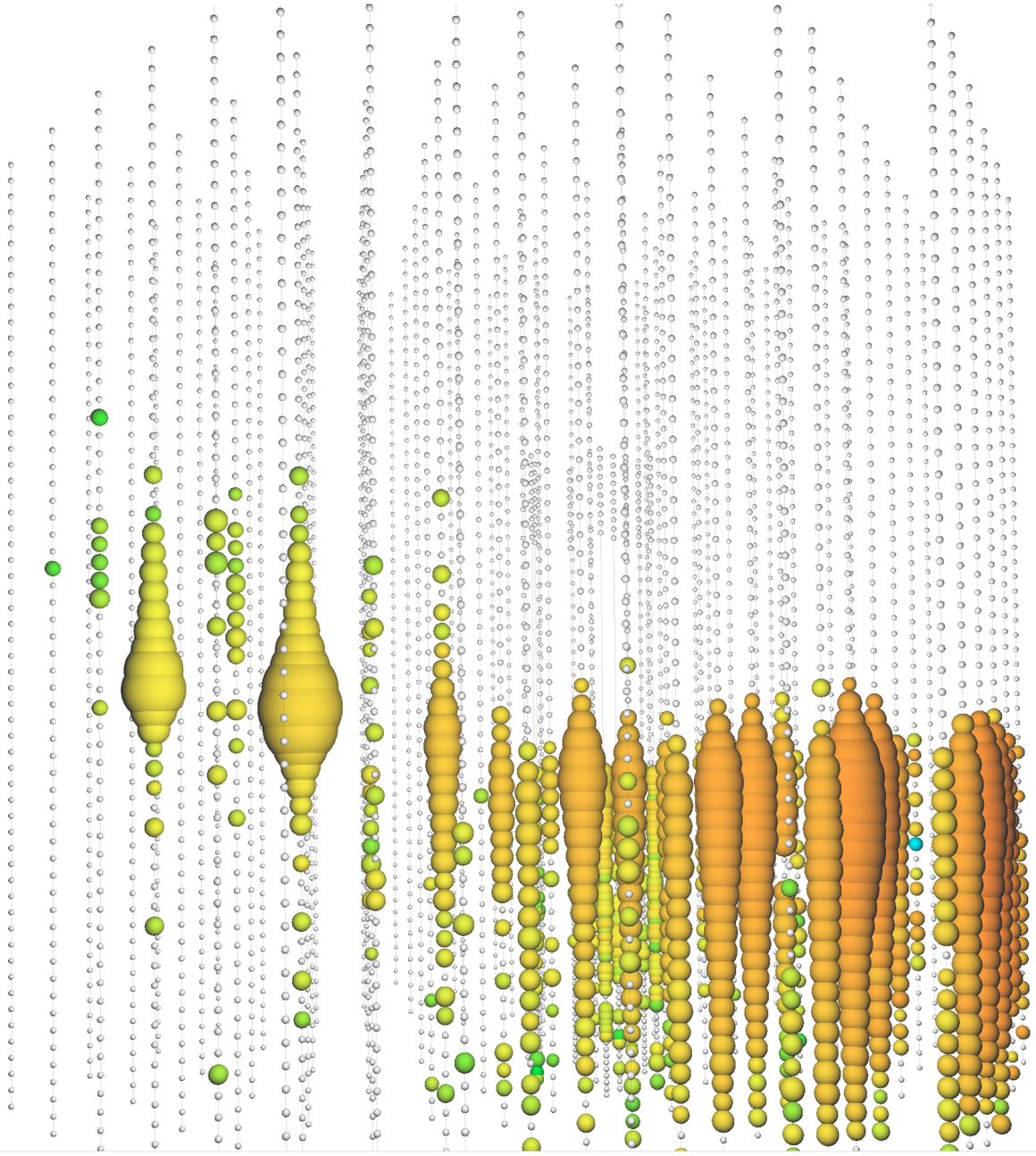
We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the instrumented volume of IceCube, which is also a lower bound on the muon and neutrino energy. The reconstructed direction of the event (J2000.0) is R.A.: 110.34 deg and Decl.: 11.48 deg. For simulated events with the same topology, 99% of them are reconstructed better than 1 deg and 50% better than 0.27 deg. The probability of this event being of atmospheric origin is less than 0.01%. The IceCube contact persons for this event are Leif Raedel (RWTH Aachen University, raedel@physik.rwth-aachen.de) and Sebastian Schoenen (RWTH Aachen University, schoenen@physik.rwth-aachen.de)



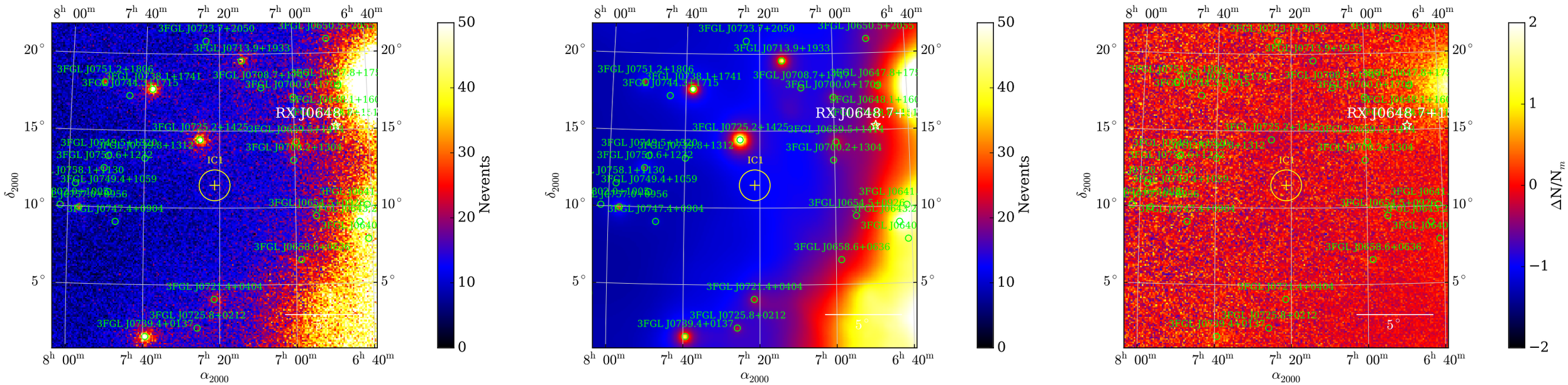


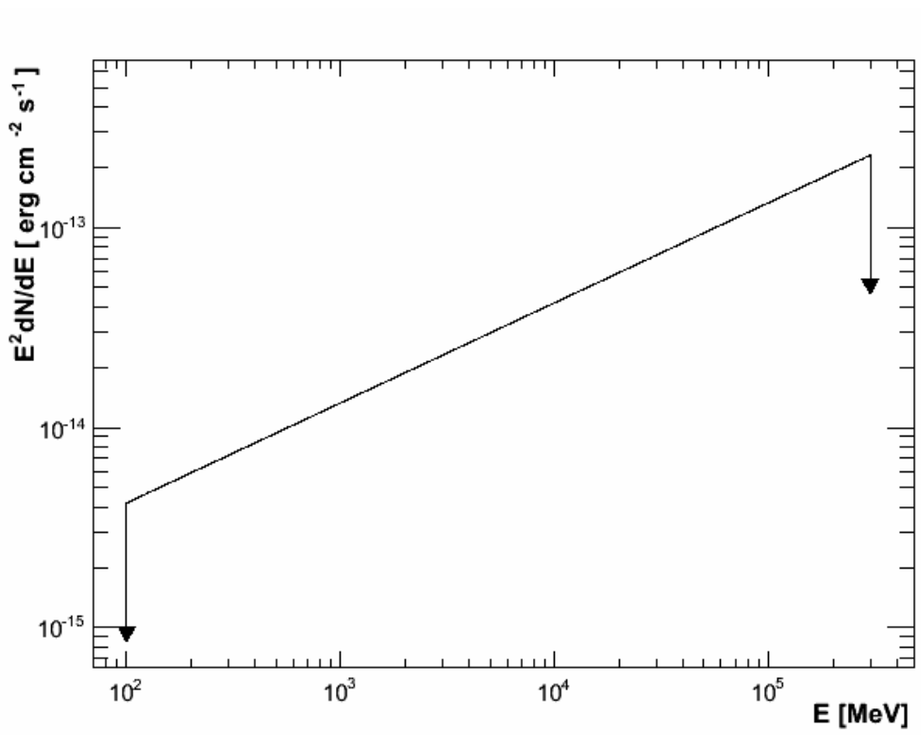


arxiv/1510.05223



PeV muon neutrino event





Fermi-LAT

- Energy range: 100 MeV to 300 GeV
- Time range: 2008-08-04 to 2015-06-17.
- Pass 7 reprocessed, source class events. 15° RoI.
- No sources 3FGL within 3°, all remaining sources assumed to have constant flux at the level of the 3FGL catalog. One TeVCat source ~ 8° away.
- No new source found to be contained in the error circle of the neutrino.

Conclusions and future plans

Summary

- ~40 hours of VERITAS data on IceCube HE neutrino positions.
- No significant detection of VHE gamma-ray emission associated at the neutrino positions. 99% flux ULs above 100 GeV at a few percent of the Crab nebula flux.
- These values start to constrain the number of steady sources and their distances.
- Preliminary Fermi-LAT results on HE uncontained muons.

Next steps

- Continue observations of HE muon events which are likely astrophysical.
- Preparing to receive real-time alerts from IceCube to increase the sensitivity to transient sources.
- CTA coming up with order-of-magnitude increase in sensitivity.