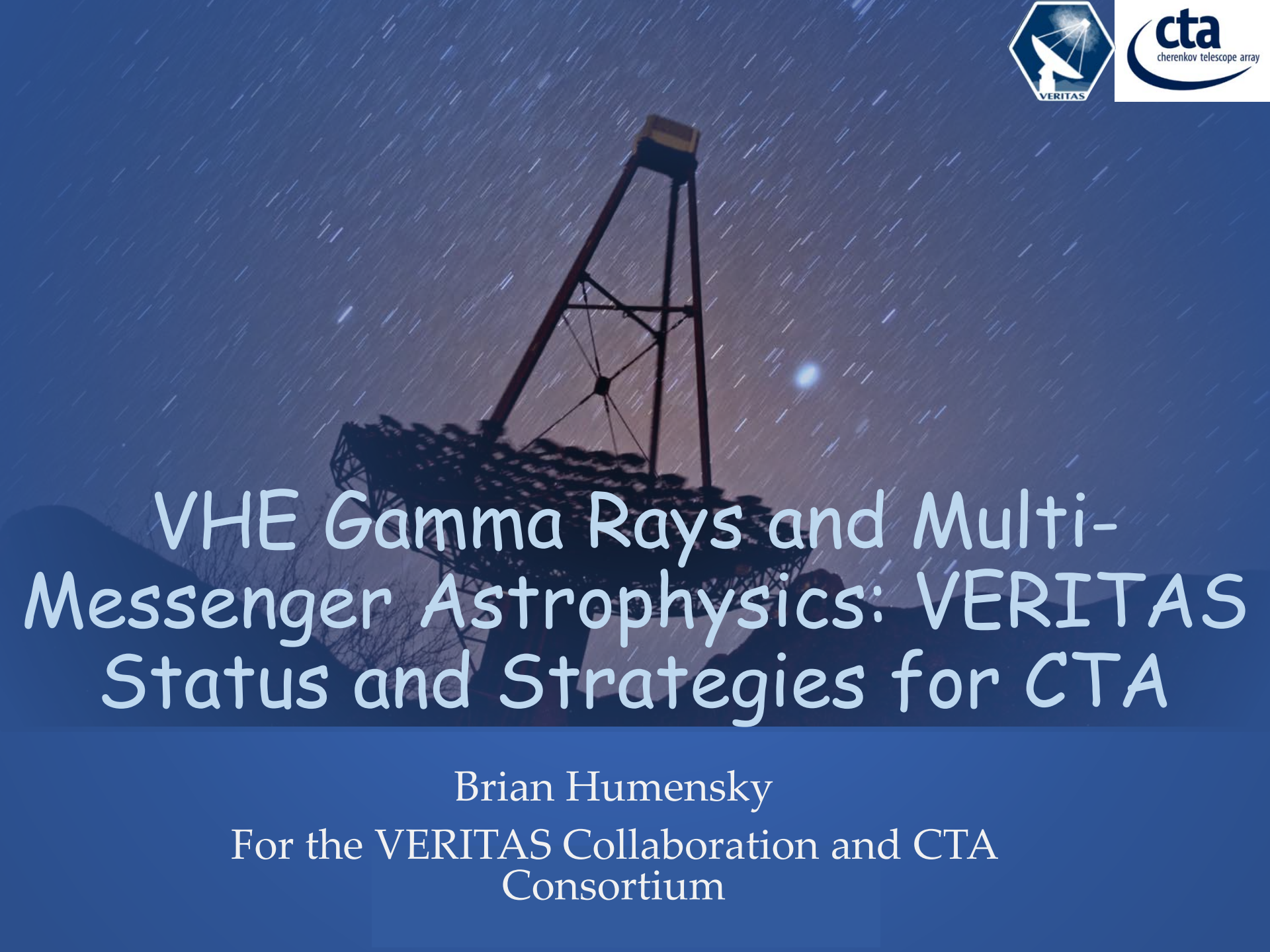


VHE Gamma Rays and Multi-Messenger Astrophysics: VERITAS Status and Strategies for CTA

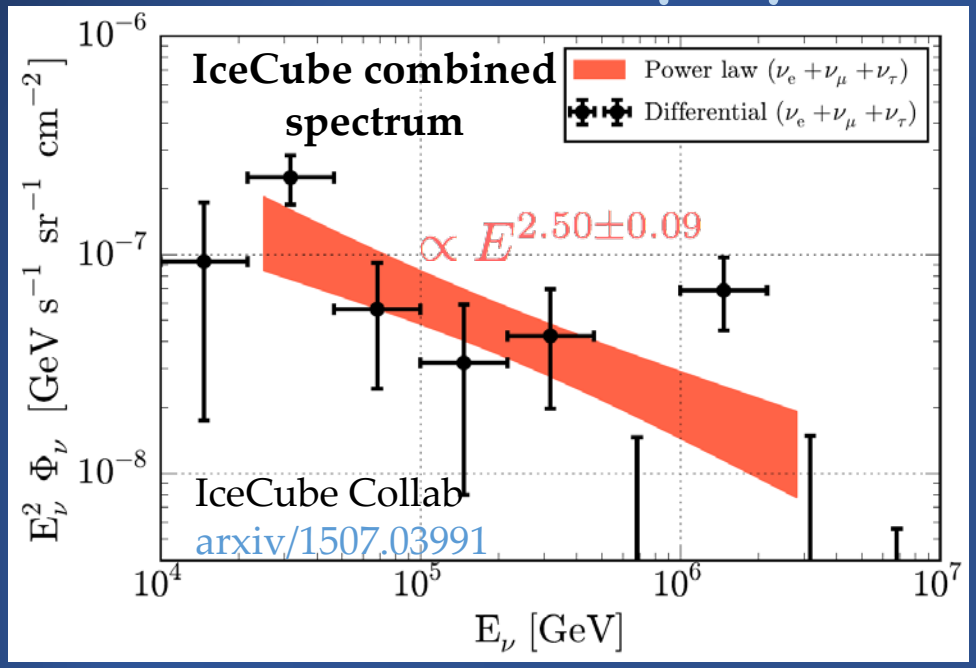
Brian Humensky

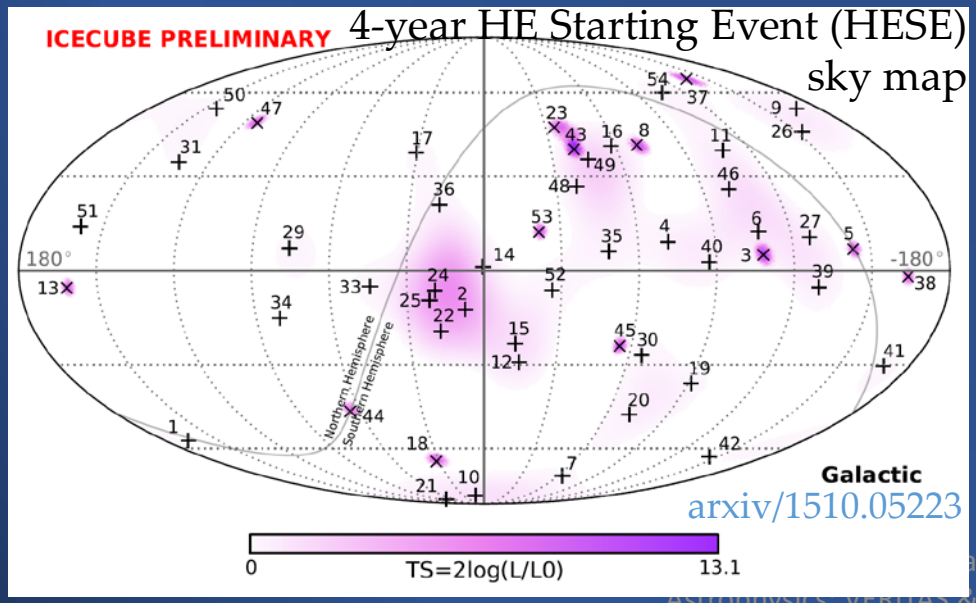
For the VERITAS Collaboration and CTA Consortium

Outline

- **VERITAS Follow-up Programs & Results**
  - **Astrophysical neutrinos**
  - **Gravitational waves**
- Cherenkov Telescope Array: Status & Transients Strategies
  - GW follow-up
- Summary

IceCube Astrophysical Neutrinos



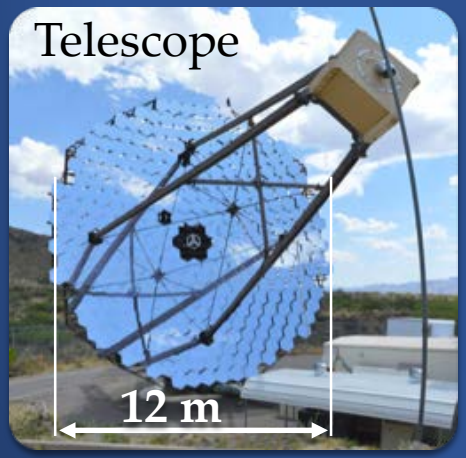


- Astrophysical neutrino flux detected in the **20 TeV - 8 PeV** energy range.
- Consistent with a spectral index in the 2.1 - 2.7 range.
- O(10) events/yr.
- Data compatible with flavor equipartition.
- **No point-source detection. No correlation with the Galactic plane.**
- Point-source upper limits ~ 1%-10% of all-sky flux.

  → Large number of sources (N > 10-100).

VERITAS Overview

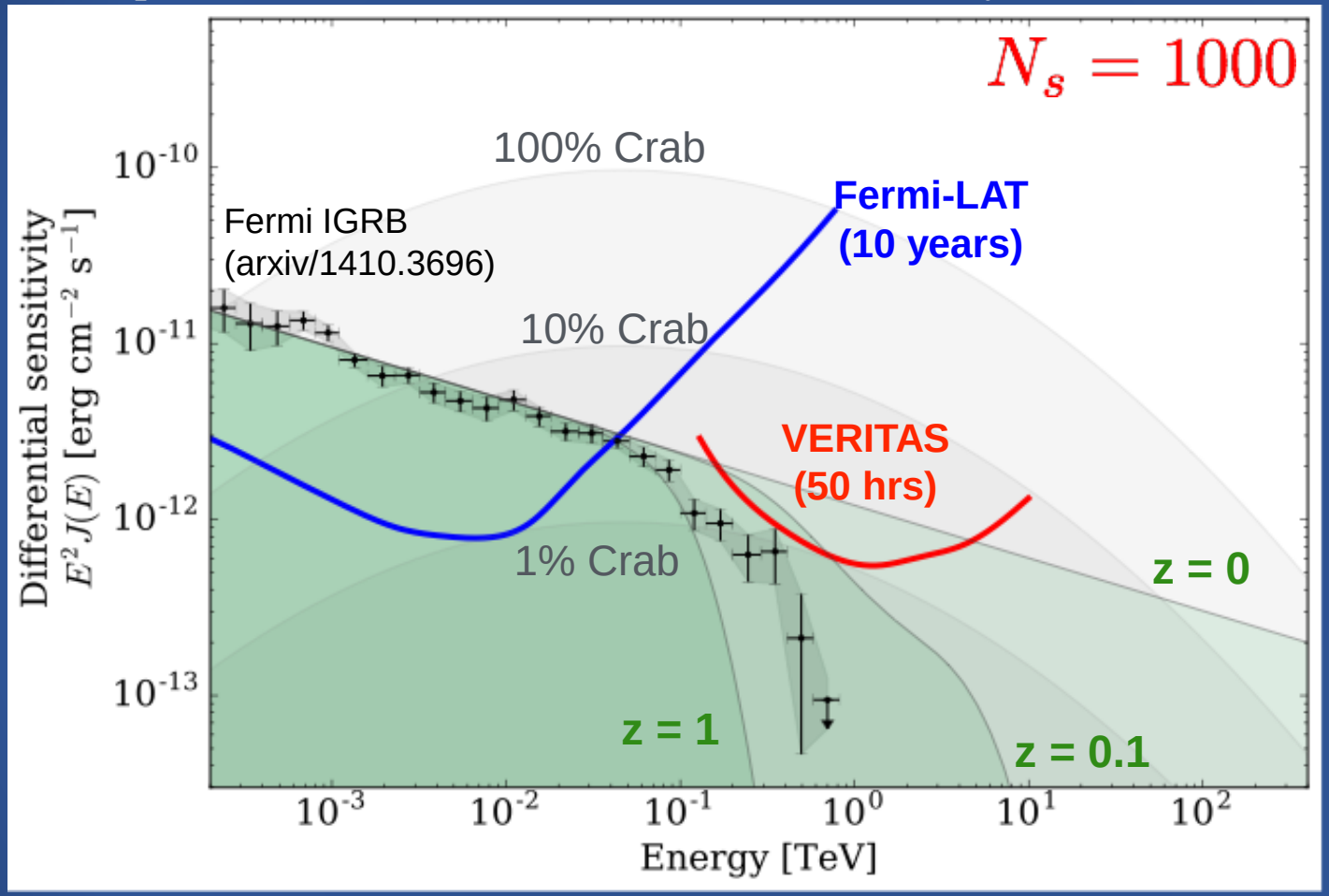
Location: Whipple Observatory, Arizona
Status & highlights: arxiv/1609.02881



- Array of 4 Davies-Cotton Imaging Air Cherenkov Telescopes.
  - First light in 2007.
- Energy range: ~ 80 GeV - 30 TeV.
- Effective area: ~ 10^5 m^2.
- Observing time: ~ 900 hr (dark) + 300 hr (moonlight).
- Angular resolution: 0.1° > 1 TeV.
- Detects the Crab Nebula in ~1 minute.

γ-ray flux from IceCube sources

Quasi-isotropic IceCube neutrino flux converted to γ-ray flux from N_s sources



Franceschini '08 EBL model

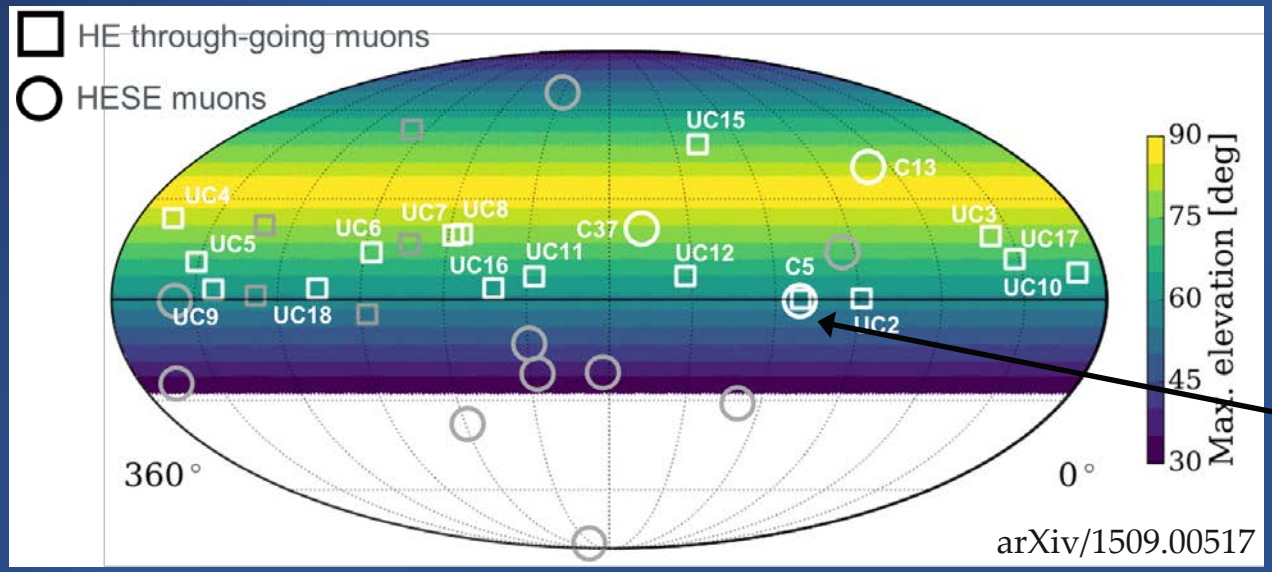
(no EM cascades)

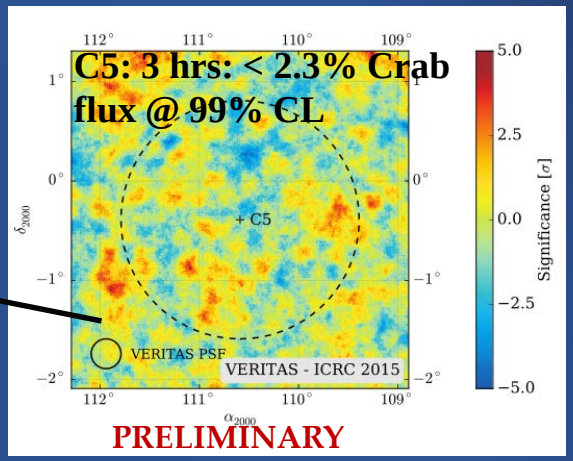
$$E^2\phi_\gamma^s(E) = \frac{4\pi}{N_s} 1.5 \times 10^{-11} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.3} [\mathrm{TeV\ s^{-1}\ cm^{-2}}]$$

γ-ray flux

IceCube flux (arxiv/1405.5303)

Neutrino Event Selection

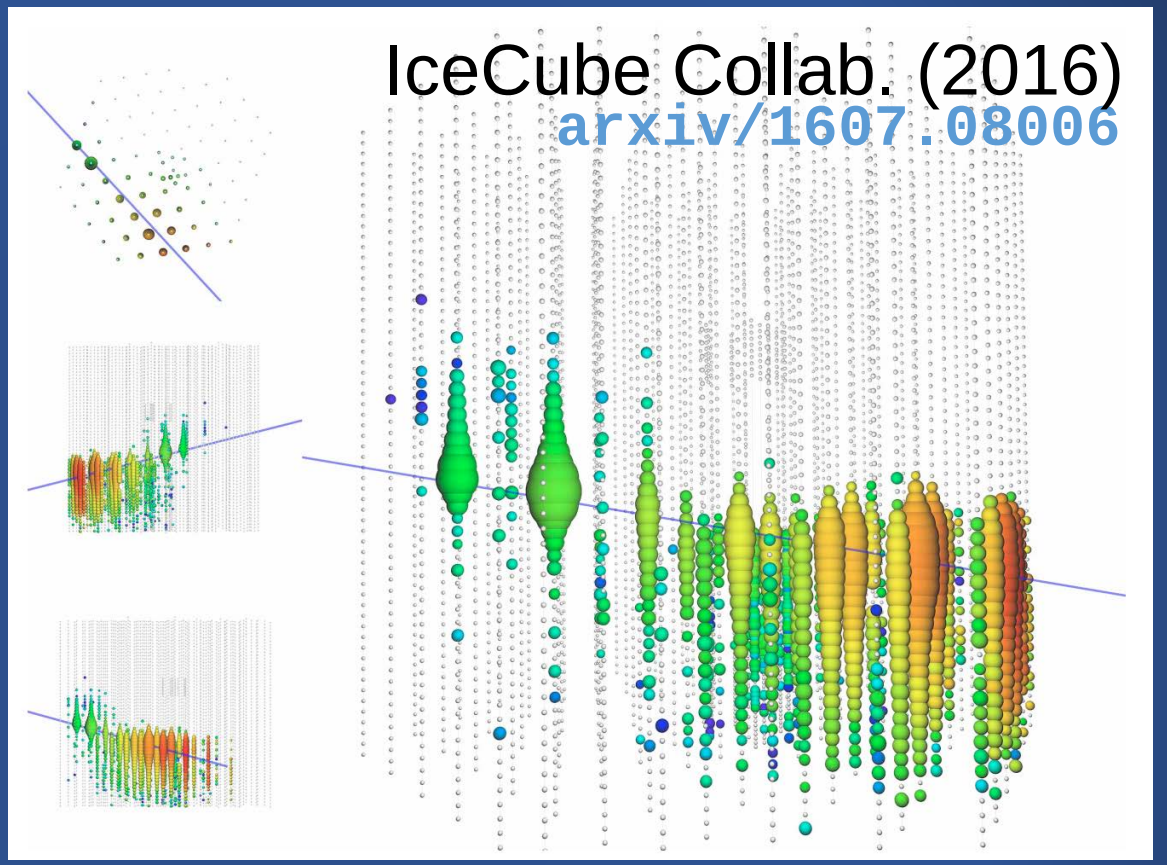




- Muon tracks from CC ν_μ have O(1°) angular resolution.
- Selected events from three IceCube samples:
  - HE starting events (HESE, 13 tracks, arxiv/1510.05223).
  - HE thru-going μ tracks, 2 years (HEMU2, 21 highest-energy events, arxiv/1507.04005).
  - HE thru-going μ tracks, 6 years (HEMU6, 29 highest-energy events, arxiv/1607.08006).
- Astrophysical probability for the events > 50%.
- 57 hours taken on 18 neutrino positions; **no significant excesses detected**.
- **Most 99% CL limits are at 1-5% Crab Nebula flux above 100 GeV.**

PeV muon neutrino event

- E_{dep} ~2.6 +/- 0.3 PeV
- **E_ν ~ 8.7 PeV**
- **p_{atm} < 0.01%**
- Detection: 6/11/2014
- Reported: 7/29/2015
- RA: 110.34°
- Dec: 11.48°
- $r_{50\%}$ < 0.23°
- 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)

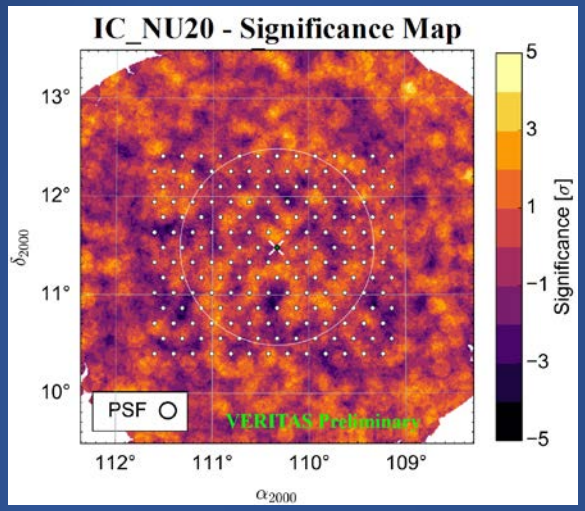
Subjects: Neutrinos, Request for Observations

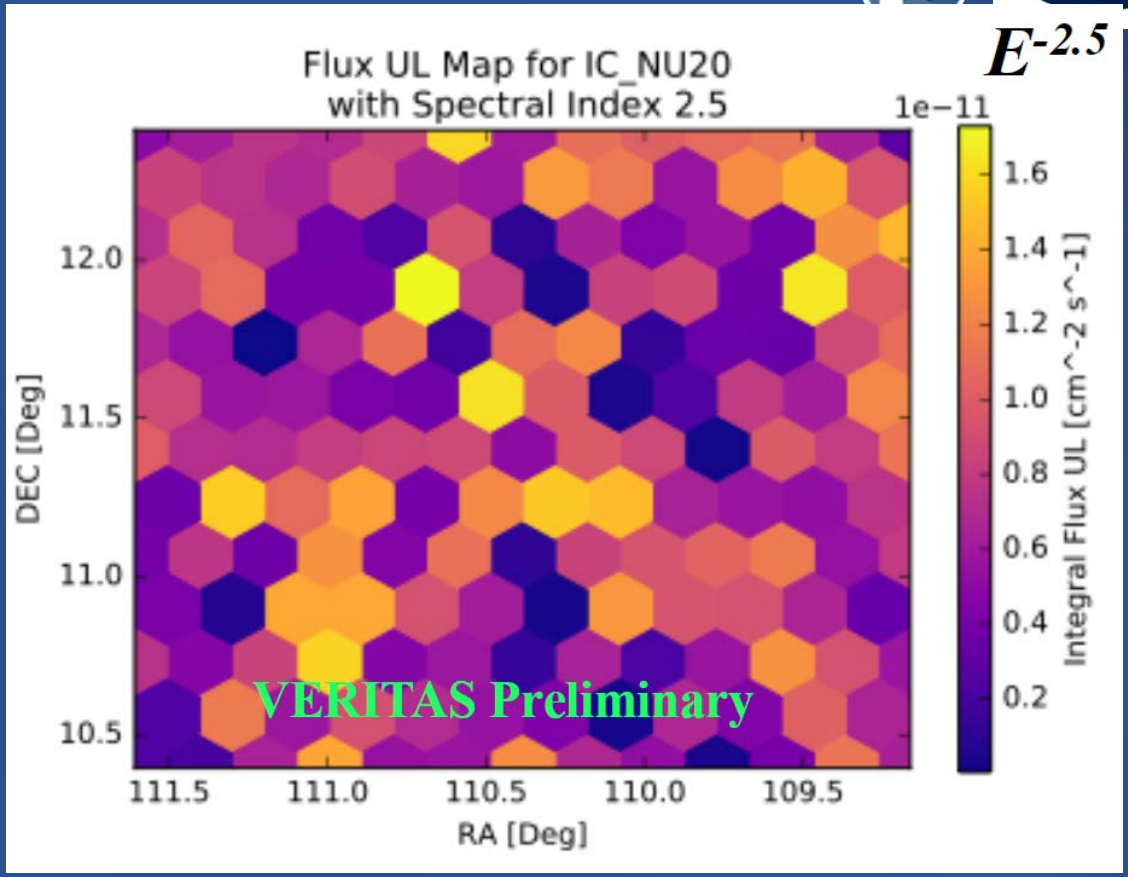
Referred to by ATel #: 7868

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)

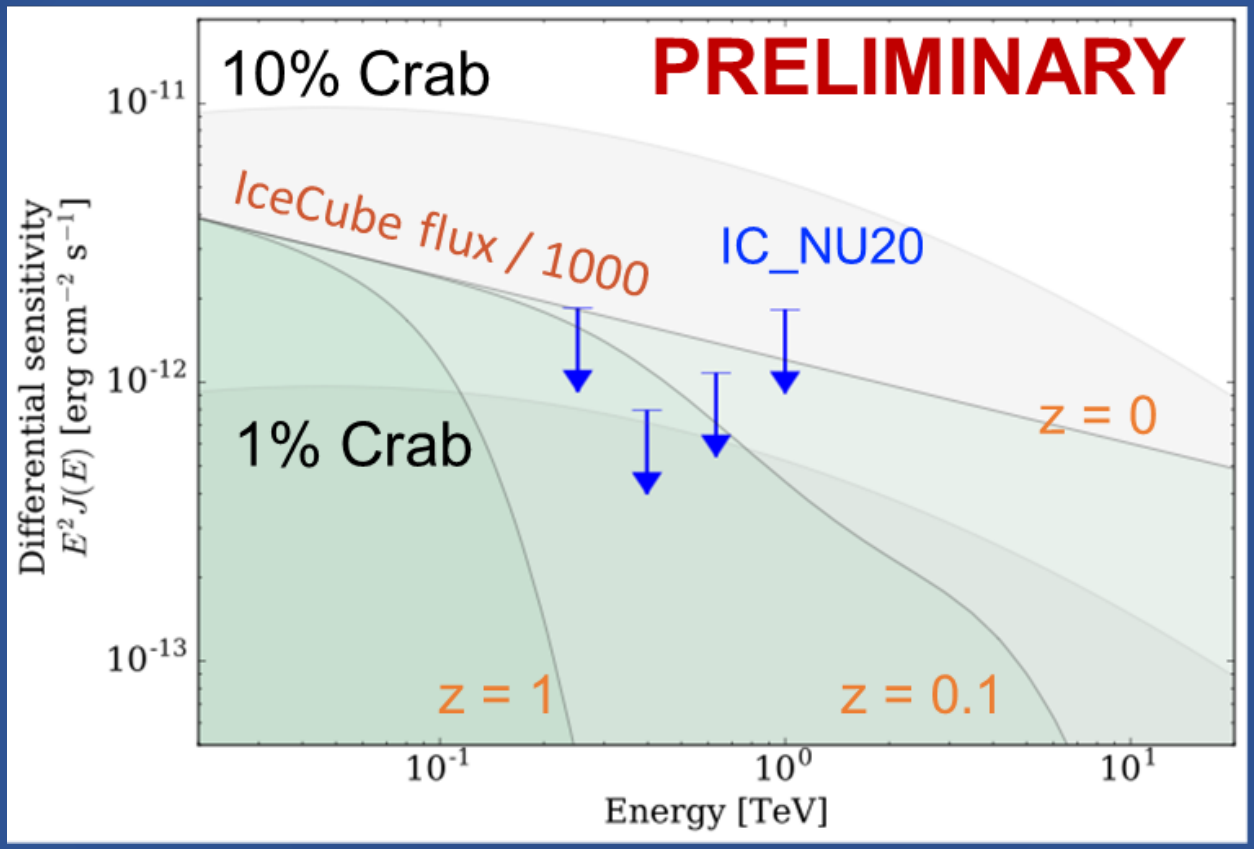
Obs of PeV muon location





- 1.83 hr of live time taken on 03/27/2016 under dark conditions.
- **No gamma emission detected** within the neutrino error circle. UL maps for E > 150 GeV ~ few % of Crab Nebula flux.
- Upper limits ~0.1% of the all-sky astrophysical neutrino flux.

Obs of PeV muon location



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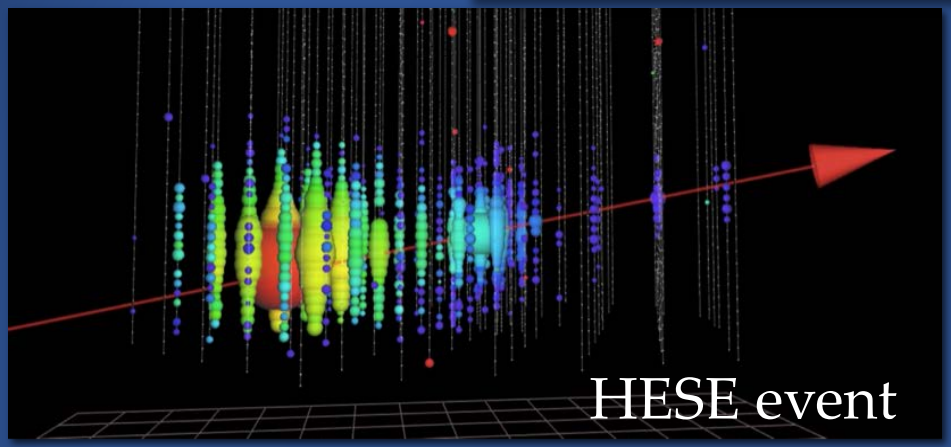
Rapid ν follow-up observations

AMON GCN Circular
04/27/2016

TITLE: GCN CIRCULAR
NUMBER: 19363
SUBJECT: ICECUBE-160427A neutrino candidate event: updated direction information
DATE: 16/04/29 16:29:47 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

IceCube detected a candidate cosmic neutrino IceCube-160427A, "AMON ICECUBE HESE 127853 67093193" at 05:52:32.00 UT on 16/04/27 (http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon) The event was a high energy starting event (HESE) with track-like characteristics and it arrived when the IceCube detector was in a normal operating state.
â€‹
More sophisticated reconstruction algorithms have been applied offline, with the direction refined to RA=240.57d and DEC=+9.34 and the position uncertainty reduced to an estimated 0.6 degrees or 36 arcminuntes radius (stat+sys, 90% containment). We enc by ground and space-based instruments to help identify a possible astrophysical source for the neutrino.



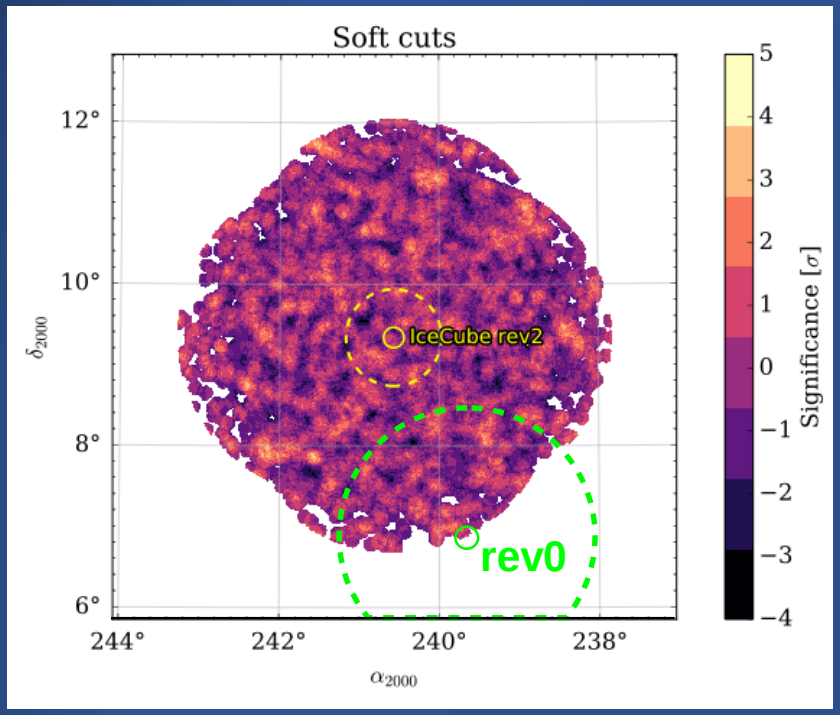
VERITAS follow up
http://gcn.gsfc.nasa.gov/gcn3/19377.gcn3

Detection: 05:52:32 UT
Alert sent: 05:53:53 UT
Follow-up start: 05:55:45 UT

112 seconds (alert to follow up)

- Receive real-time GCN alerts for IceCube muon neutrino events through the AMON network (http://amon.gravity.psu.edu).
  - About 4/yr, ~1 astrophysical for contained events.
- Alerts are received and processed by the VERITAS software and require simple confirmation by observer.

Rapid ν follow-up observations



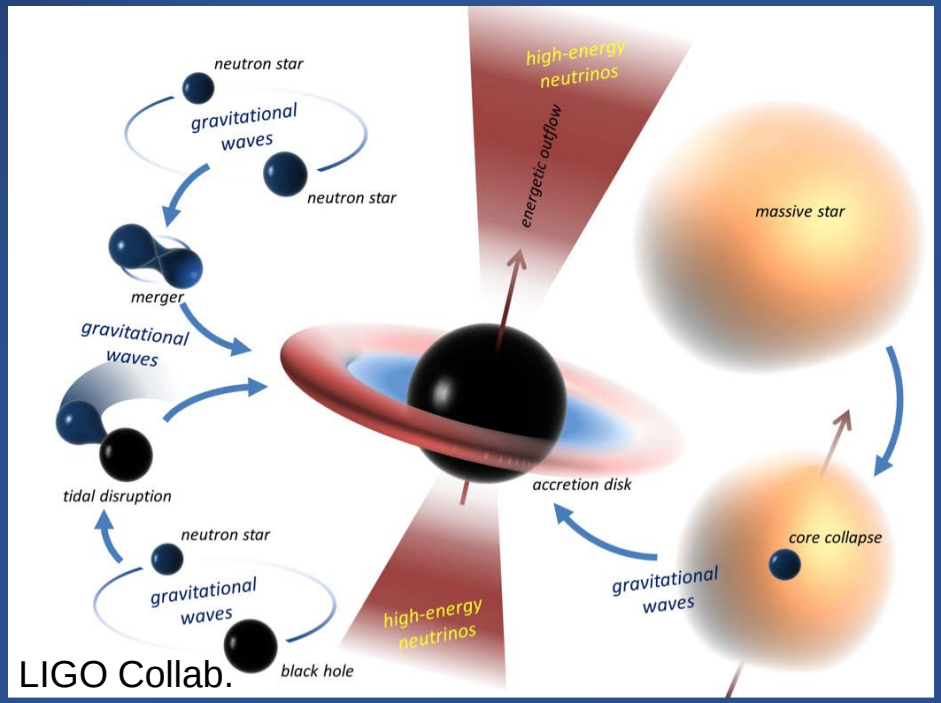
	Time	RA	Dec	Err (50%)	Err (90%)
rev0	Apr 27, 05:54	239.66°	6.85°	1.6°	8.9°
rev2	Apr 27, 23:24	240.56°	9.34°	—	0.6°

- Rev0: 71 min livetime (moon → reduced HV)
- Rev2: 118 min livetime (reduced high voltage) taken on Apr 28th.
- **No γ-ray signal in the ROI.**

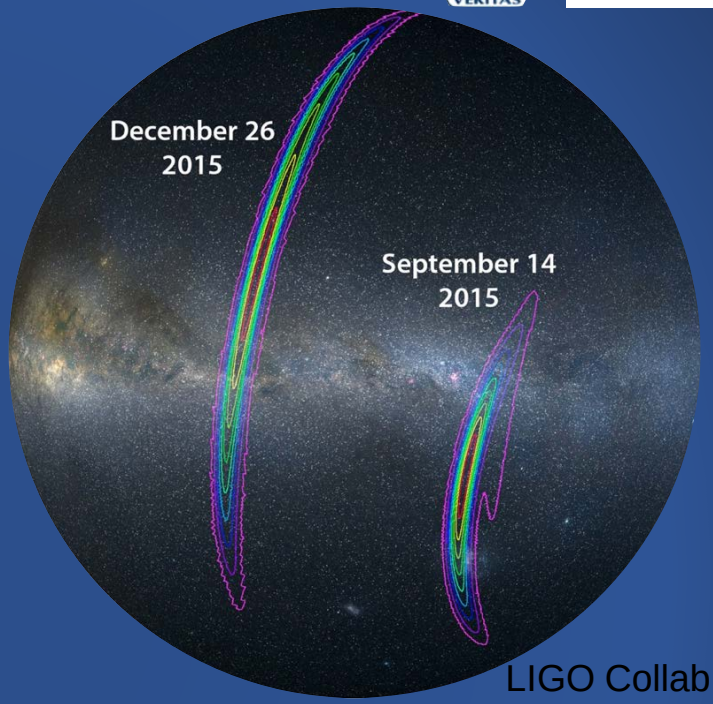
- **More neutrino alerts now coming from IceCube!**
  - Selection of IceCube extreme high-energy (EHE) muon neutrinos.
  - GCN alerts went public on July 15th, 2016.
  - First alert on Jul 31st, 2016. VERITAS was not operating (monsoon season).

(http://gcn.gsfc.nasa.gov/notices_amon/6888376_128290.amon)

Gravitational wave follow-up



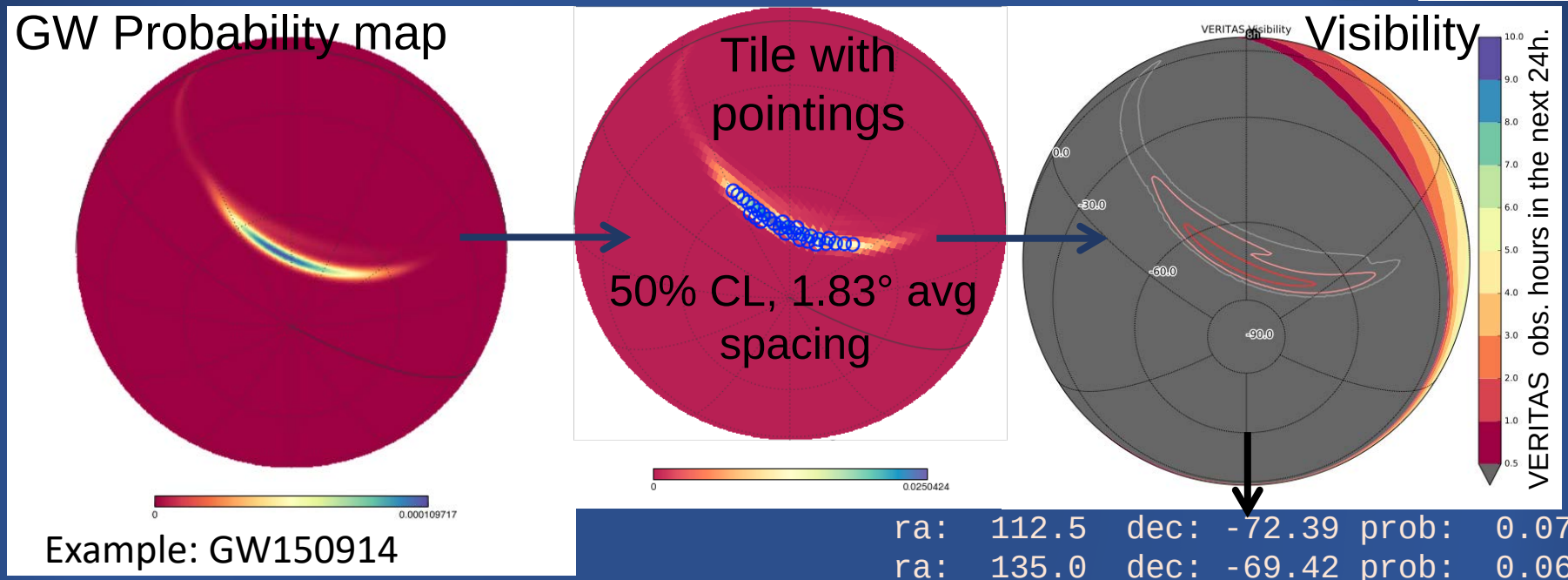
LIGO Collab.



LIGO Collab.

- LIGO detections: 3 high-confidence events associated with BH-BH mergers (not expected to be EM bright).
- NS-NS merger within the LIGO horizon (~100 Mpc) may be detected by TeV instruments (Bartos *et al.* arXiv/1403.6119).
- VERITAS 10 deg^2 FoV to scan the O(100 deg^2) GW localization region.

VERITAS Follow-up strategy

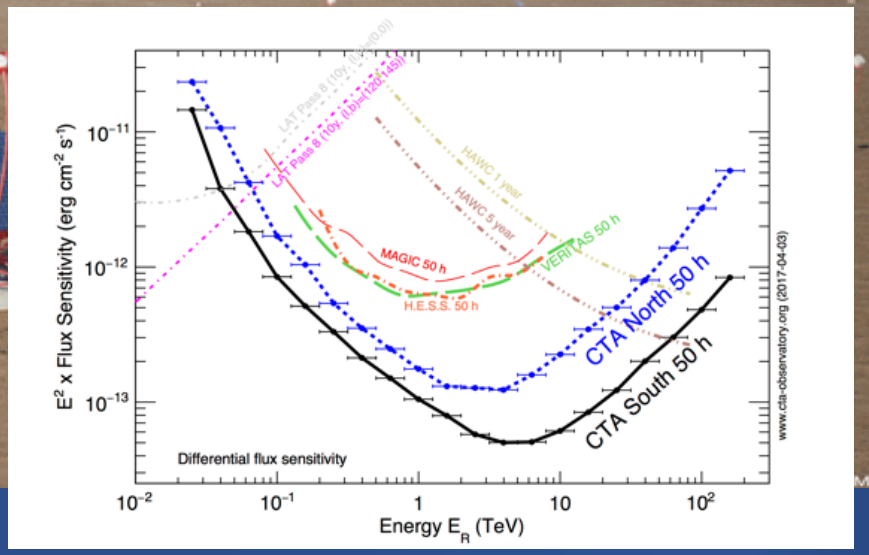


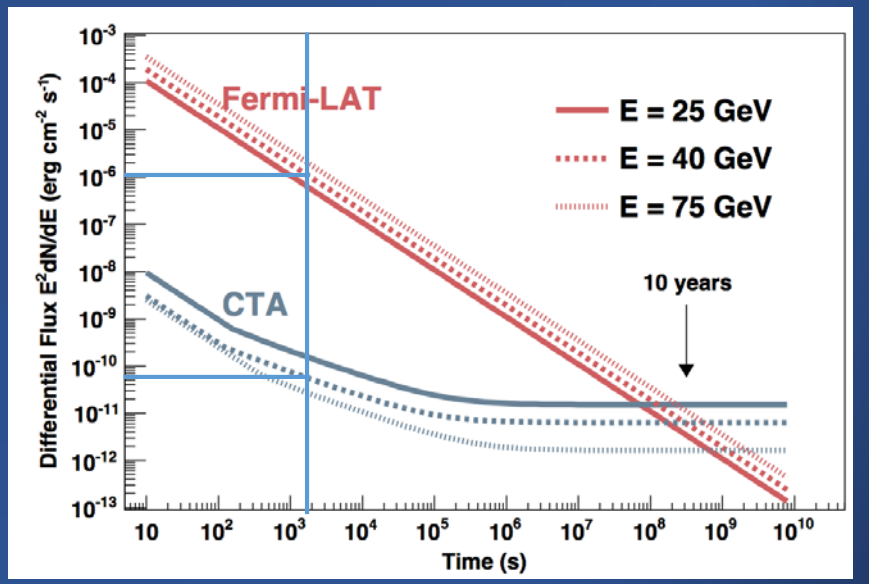

```
ra:   112.5   dec: -72.39 prob:   0.073
ra:   135.0   dec: -69.42 prob:   0.067
…
```

- Define list of pointings to cover some containment level.
- Define ordering (westward pointings first).
- 5 min per pointing → sensitivity ~50% Crab Nebula flux.

- VERITAS follow-up of LIGO GW170104: 39 pointings, no detection (GCN #21153).
  - Elevation > 50°.
  - Covered region includes 27% of containment probability.
  - Poor weather during most pointings.

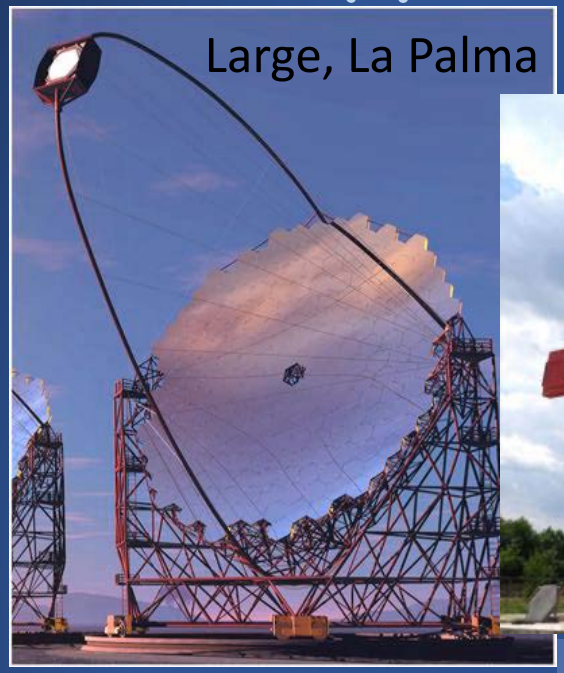
Cherenkov Telescope Array

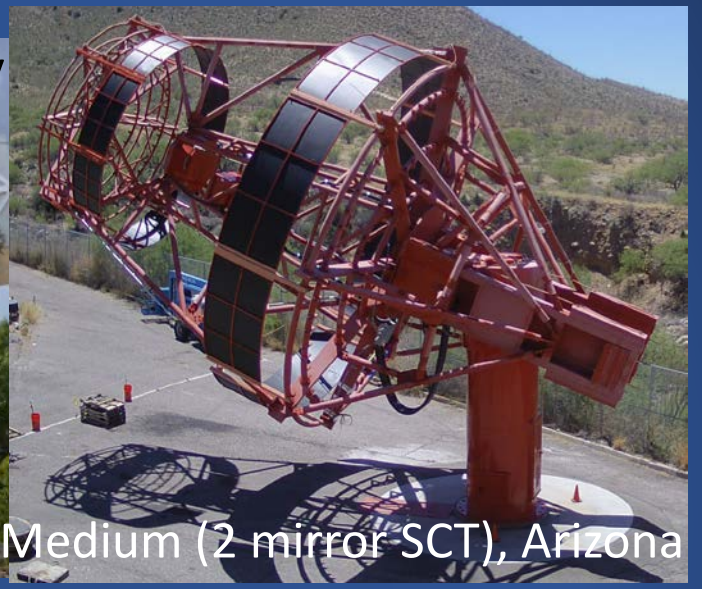


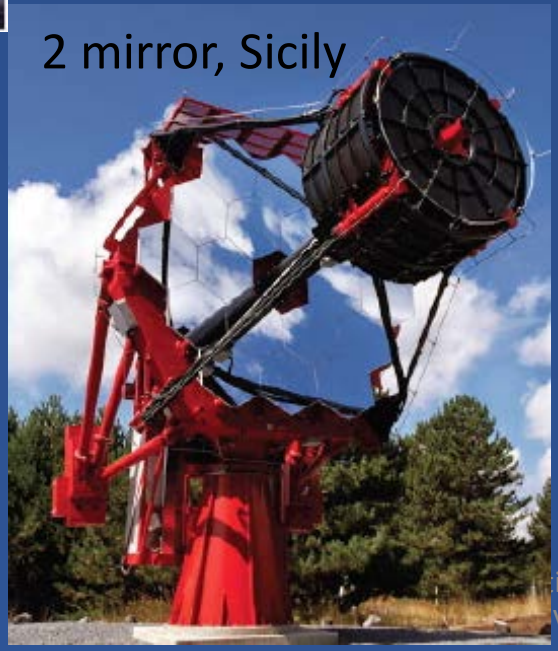


- Arrays in north (La Palma, Spain) and south (Paranal, Chile) → full-sky coverage.
  - 4 large (23 m) telescopes (LSTs) in the center: 20-GeV threshold.
- Southern array adds:
  - 25 medium (9-12 m) telescopes (MSTs): 100 GeV – 10 TeV.
  - 70 small (~4 m) telescopes (SSTs) covering >3 km^2: 1 – 300 TeV.
- Northern array adds 15 MSTs (no SSTs).

Prototype CTA Telescopes

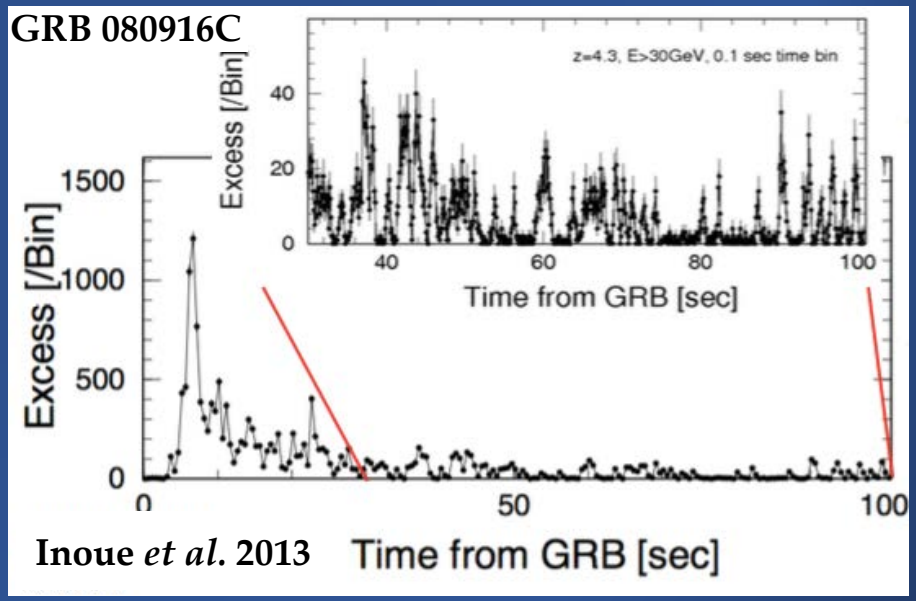






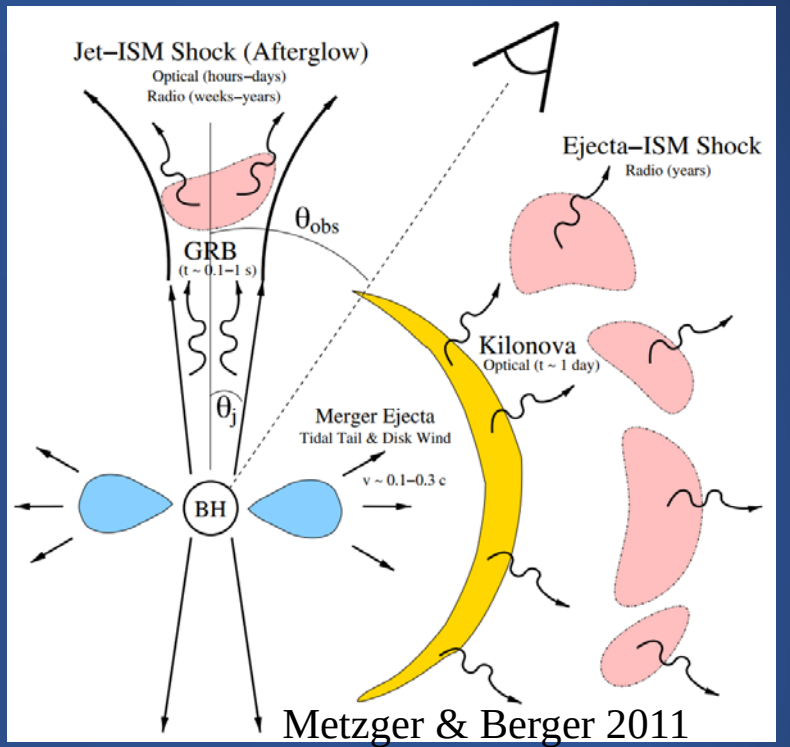
CTA Transient/Multi-Messenger Follow-up

- **Rapid slewing!** Large Size Telescopes (LSTs) < 20 sec; Medium Size (MSTs) < 90 sec to any point on sky.
- **Real-time analysis (< 30 sec)** for serendipitous transient detection and broadcasting of alerts.
- **Wide field of view: 4.5° (LST) / 8° (MST)** per telescope; rapidly cover large areas with tiling, divergent pointing.
- **Astrophysical neutrinos:** search for electromagnetic counterpart, to identify neutrino (and cosmic ray) origins.
- **Gravitational waves:** black hole or neutron star mergers; core collapse of massive stars.
- GRB light curves and spectra with high statistics (nearby).
- Triggers from optical/IR/radio transient factories: TDEs, FRBs, SNe, Galactic transients inc. novae, Crab Nebula flares...

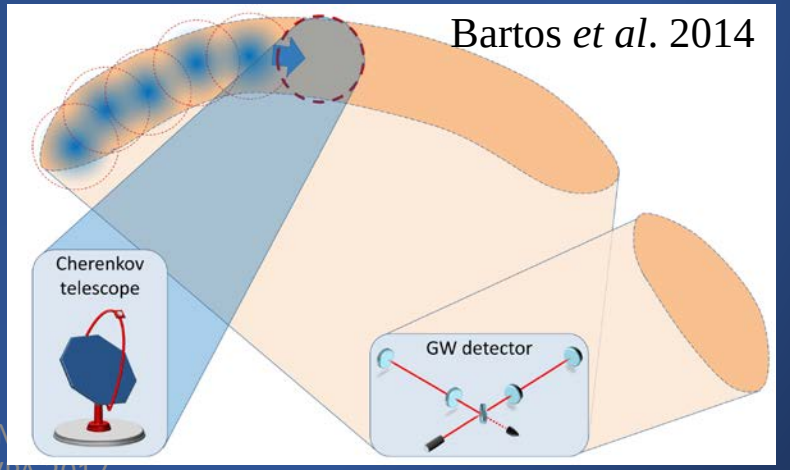


CTA Gravitational Wave Follow-up

- VHE emission prospects:
  - Short GRB on-axis prompt or afterglow emission (e.g., GRB 090510).
  - Short GRB off-axis "orphan" afterglow?
  - Merger ejecta / CBM interaction?
    - ✓ Potential "prompt" component from fastest part of ejecta (Kyutoku *et al*. 2014).
- Efficient scan of large error region via tiling or divergent pointing (Bartos et al. 2014).
- Detections would provide:
  - Any emission: localization of host galaxy.
  - On-axis: test of short GRB origin.
  - Off-axis: insight into merger physics.



Metzger & Berger 2011



Bartos *et al*. 2014

Conclusions and Outlook

- Active multi-messenger program under way for VERITAS and planned for CTA.
- **Searches for γ-ray emission associated with astrophysical neutrinos can constrain the density of neutrino sources.**
- Rapid follow-up observations increase the sensitivity of this search to transient events.
  - **CTA LSTs: < 20 s to reach any point on sky.**
- VERITAS follow-up observations of GW events have begun & planning is underway for CTA.
- CTA will drastically increase the sensitivity of these searches.
  - **On-site construction beginning in 2018.**