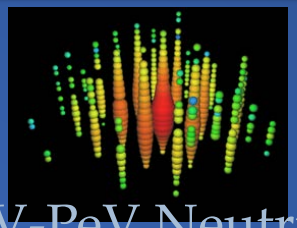
VHE Gamma-ray Searches for Astrophysical Neutrino Sources: VERITAS Status and Prospects for CTA

Brian Humensky

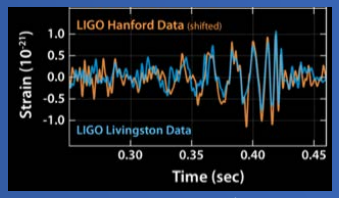
For the VERITAS Collaboration and CTA Consortium

Multi-Messenger Astronomy

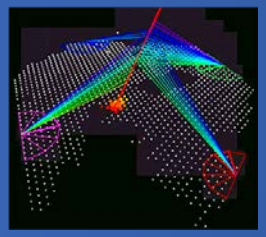
Photons



TeV-PeV Neutrinos
IceCube (2013)



Gravitational waves
LIGO (2016)

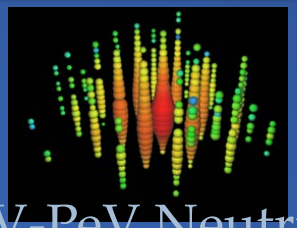


Cosmic rays

- Search for sources that emit in two or more "cosmic messenger" channels (photons, neutrinos, cosmic rays, and gravitational waves).
- Probe into extremely energetic astrophysical processes. Improved sensitivity to sources with weak (or attenuated) EM emission and transient events.

VERITAS Multi-Messenger Program

Photons



TeV-PeV Neutrinos
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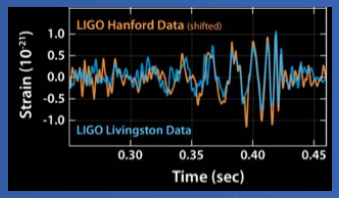
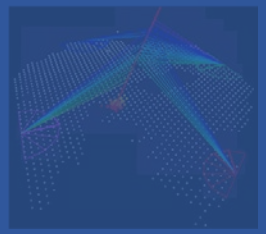


Gravitational waves
LIGO (2016)



Cosmic rays

- **Astrophysical neutrinos:** Observations of IceCube neutrino positions. Prompt follow-up of neutrino alerts.
- **Gravitational waves:** follow-up observations of LIGO/Virgo alerts: 6 alerts so far in O2; 1 followed up.

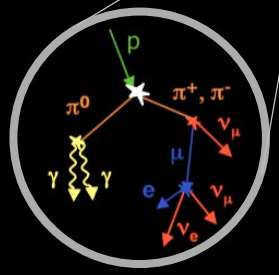
Neutrinos and Gamma Rays

Gamma-ray flux Neutrino flux

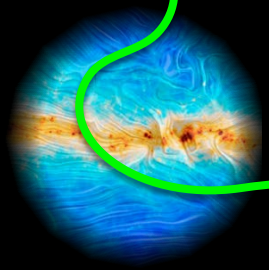
$$\frac{K_\pi}{4} E_\gamma^2 F_\gamma(E_\gamma) \approx \frac{1}{3} \sum E_\nu^2 F_\nu(E_\nu)$$

$K_\pi \begin{cases} 1(p\gamma) \\ 2(pp) \end{cases}$ Hadronic γ's can lose energy via EM cascades or be buried by leptonic backgrounds.

Astrophysical beam dump



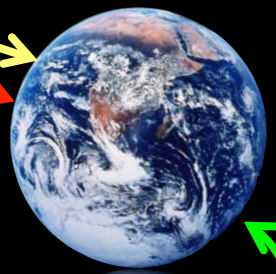
Galactic B-field (Planck)



γ

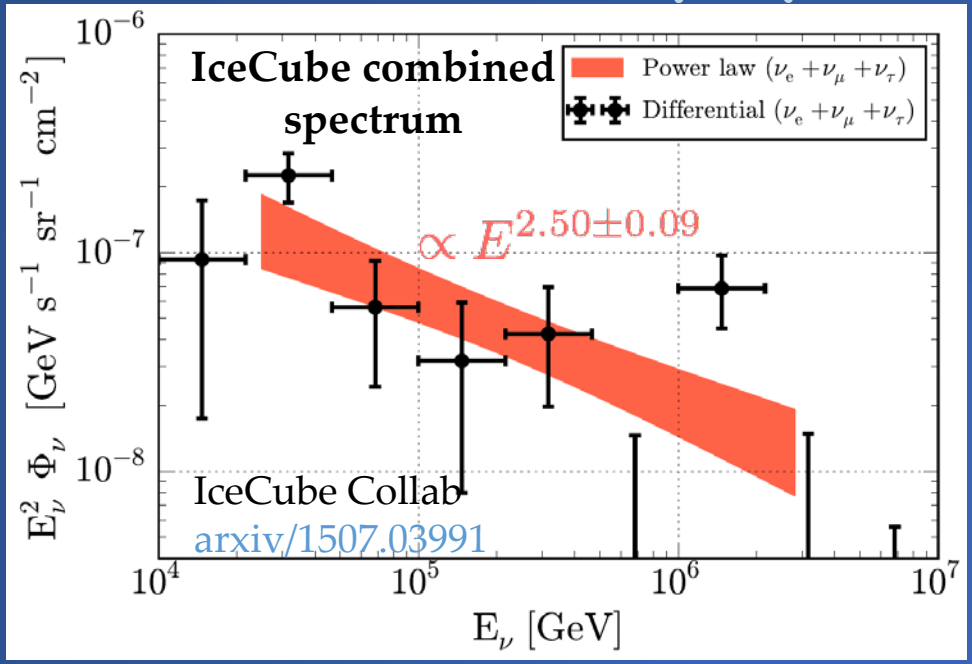
ν

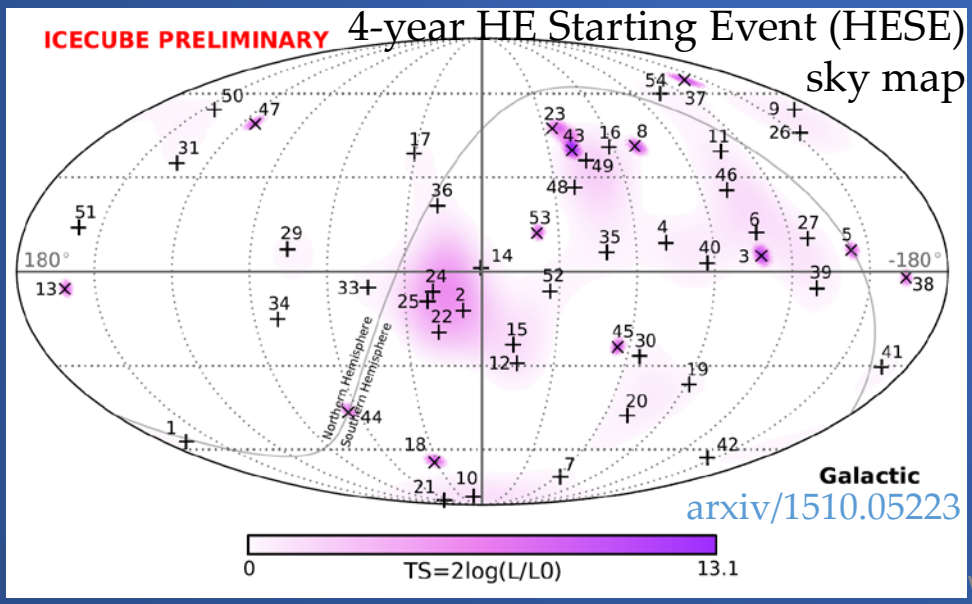
p^+



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

IceCube Astrophysical Neutrinos

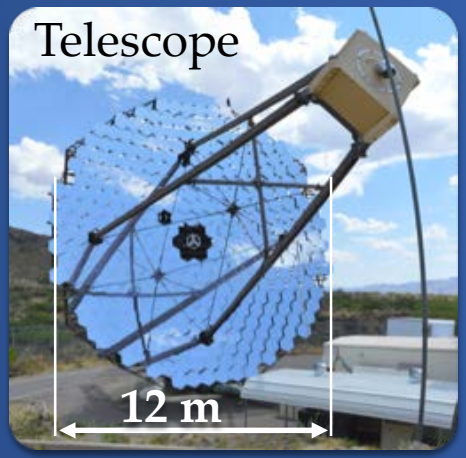


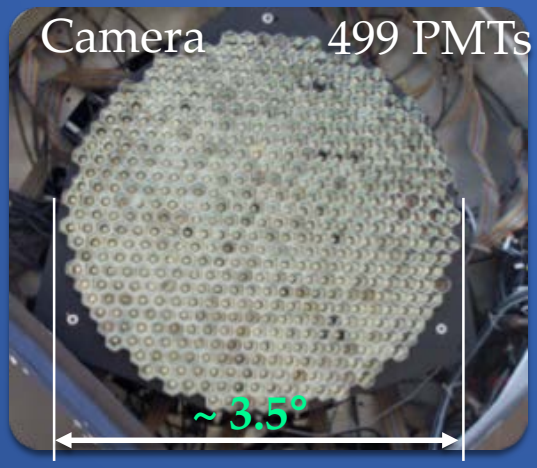


- Astrophysical neutrino flux detected in the **20 TeV - 8 PeV** energy range (various channels and analysis methods).
- Flux consistent with a power-law spectrum with **spectral index in the 2.1 - 2.7** range.
- **Event rate is low:** ~O(10) events/yr.
- Data compatible with flavor equipartition.
- No point-source detection. No correlation with the Galactic plane.
- Point-source upper limits at the level of 1%-10% of the all-sky flux hint at **large number of sources (N > 10-100)**.

VERITAS Overview

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

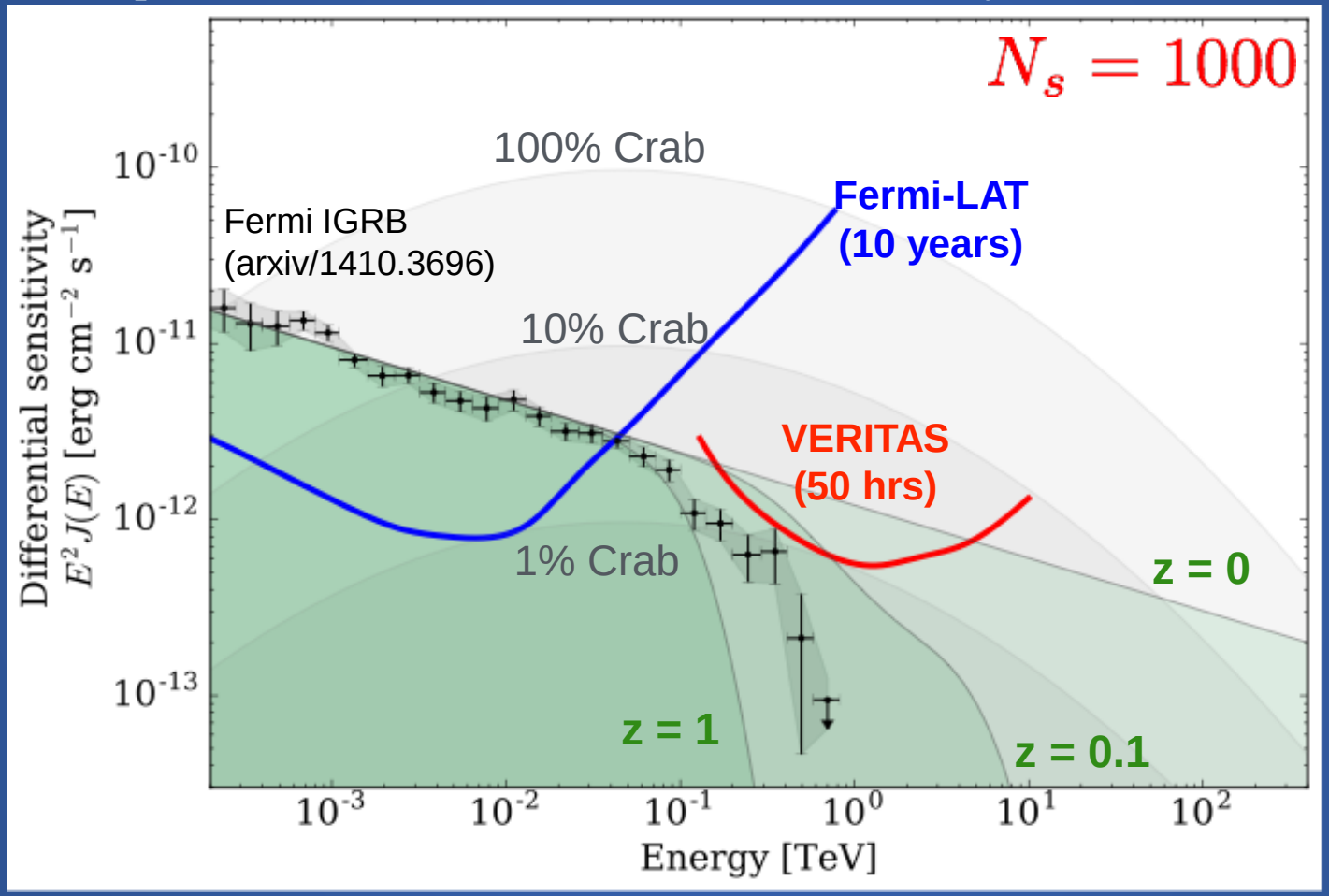




- First light in 2007.
- Array of 4 Davies-Cotton Imaging Air Cherenkov Telescopes.
- Energy range: ~ 80 GeV - 30 TeV.
- Effective area: ~ 10^5 m^2.
- Observing time: ~ 750 hr (dark) + 200 hr (moonlight).
- 0.1° angular resolution > 1 TeV.
- Detects the Crab Nebula in < 2 minutes.

γ-ray flux from IceCube sources

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



Franceschini '08 EBL model

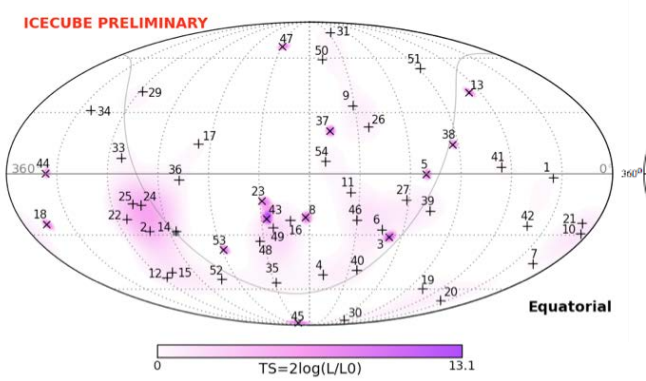
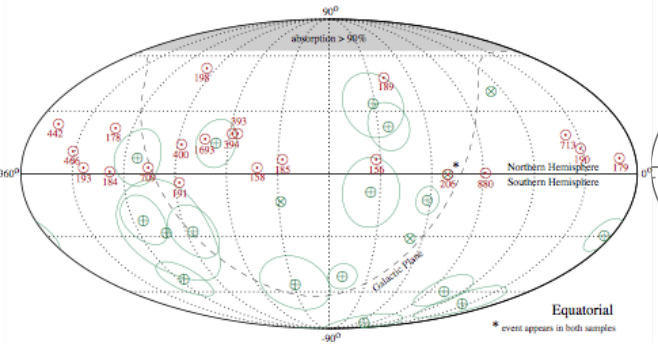
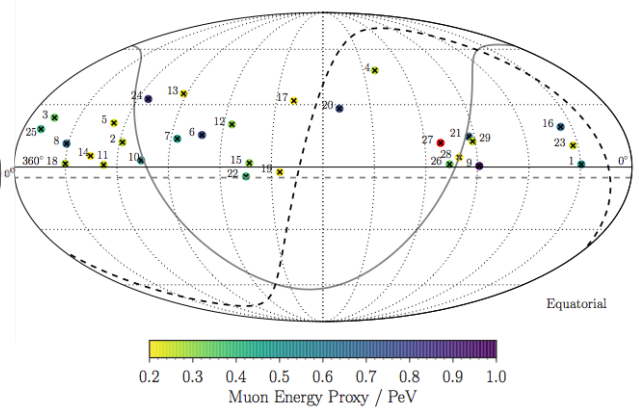
(no EM cascades)

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

γ-ray flux

IceCube flux (arxiv/1405.5303)

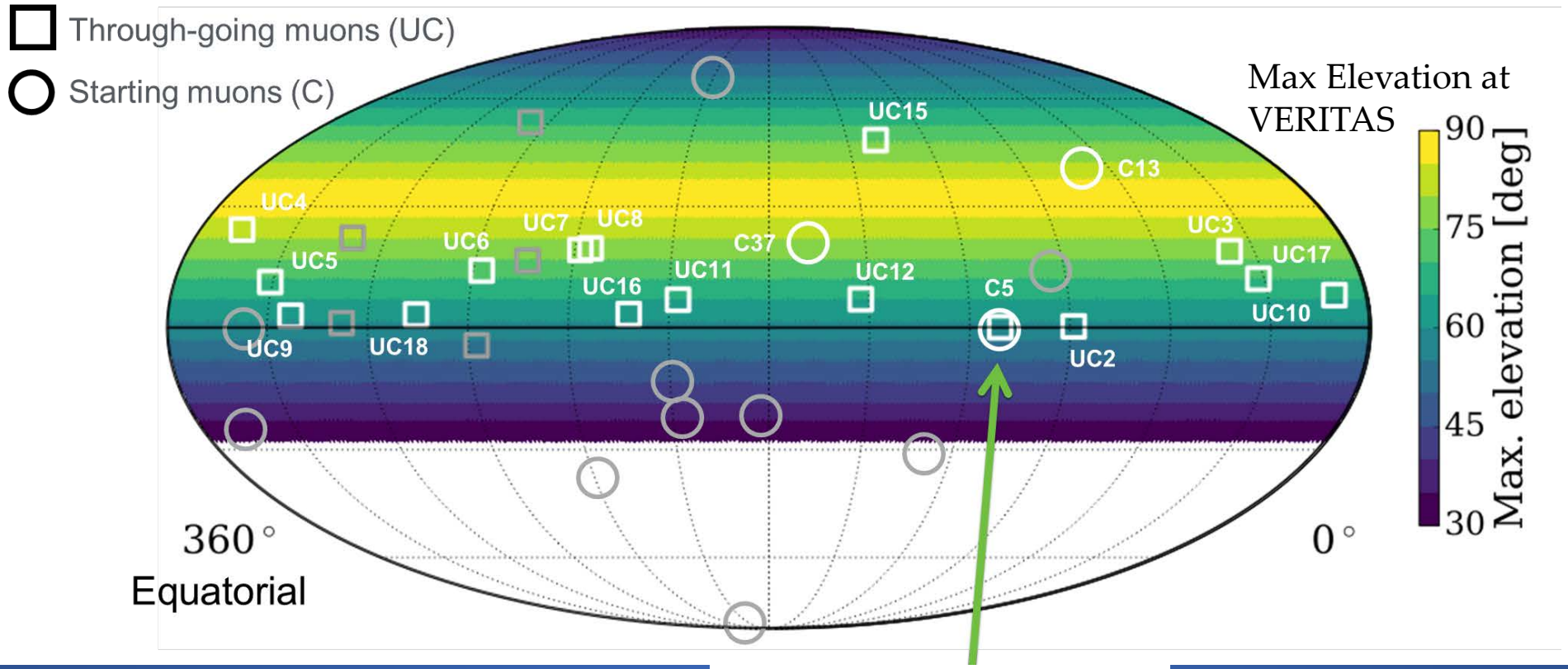
Neutrino Event Selection

4-year HE Starting Events (HESE)	2-year Northern HE Muons	6-year Northern HE Muons
		
IceCube Collab (ICRC 2015) arxiv/1510.05223	IceCube Collab (PRL 2015) arxiv/1507.04005	IceCube Collab (2016) arxiv/1607.08006
13 muon track positions	21 highest-energy muon track positions	29 muon track positions (E_{proxy} > 200 TeV)

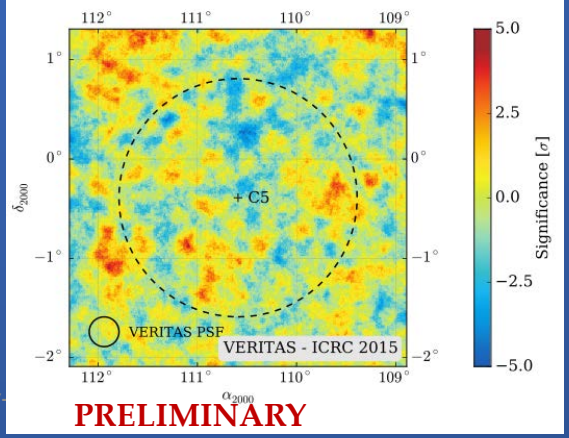
Requirements for observations with VERITAS

- Good angular angular resolution: Muon tracks from CC ν_μ have O(1°) resolution. Cascades from CC $\nu_{e,\tau}$ + NC $\nu_{e,\mu,\tau}$ have ~15° angular resolution.
- Observable from VERITAS: Northern events or at low Southern declinations.
- High astrophysical probability: high-energy events have a low atmospheric probability.

Obs of Muon Neutrino Positions



- A total of 57 hours have been taken on 18 neutrino positions.
- No significant excesses detected.
- Most 99% CL upper limits for through-going muons are at the 1-5% Crab Nebula flux above 100 GeV.

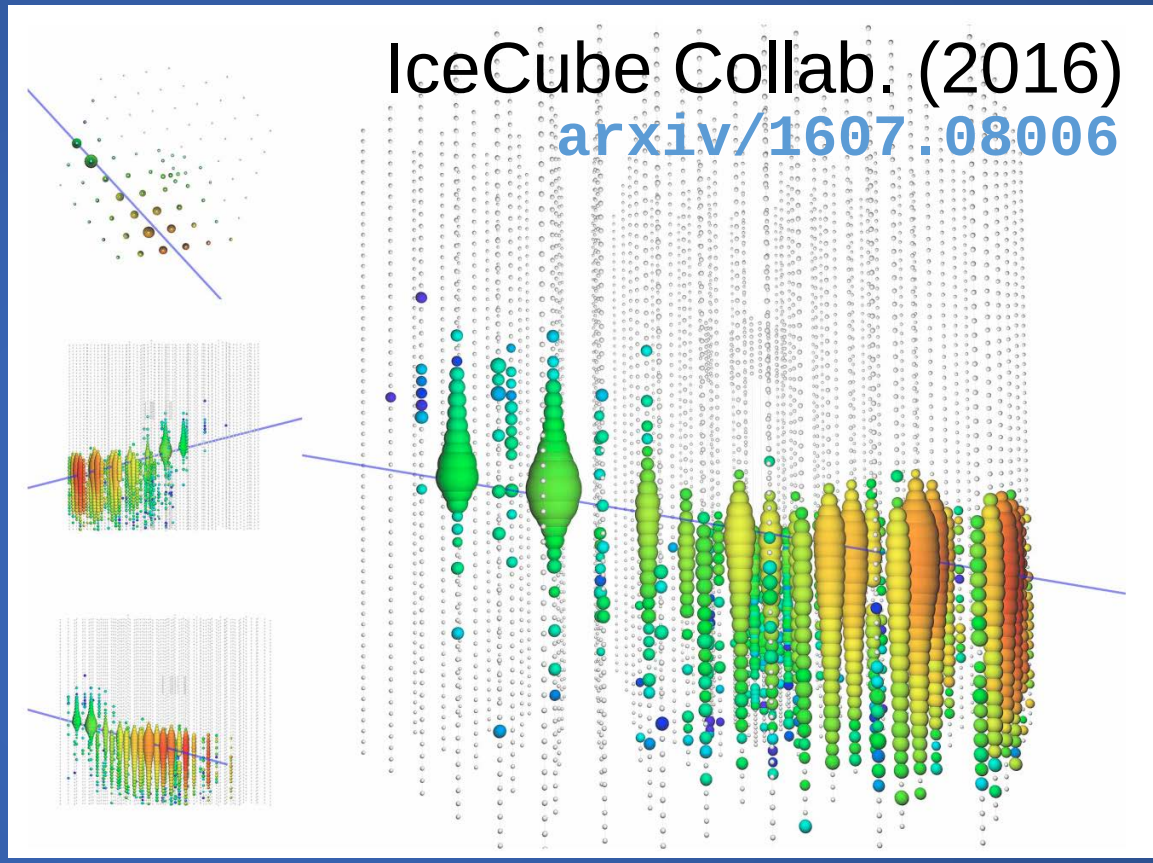


ICRC Proc 2015
arXiv/1509.00517

C5: 3 hrs exposure
Soft-spectrum cuts
99% UL: 2.3% Crab flux
Wobble 0.5° - 0.7°

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)

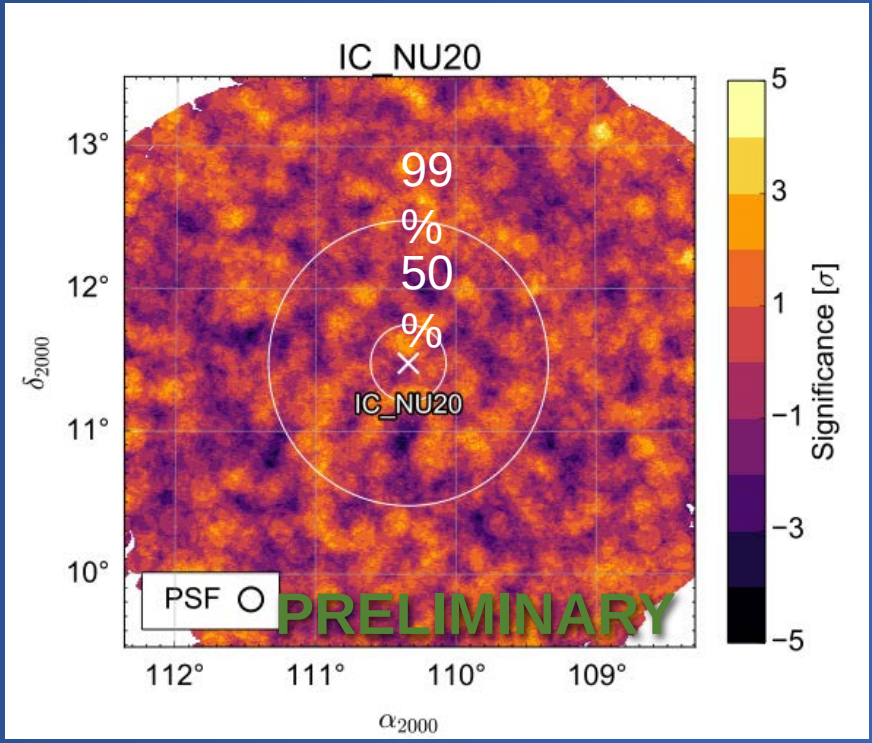
Subjects: Neutrinos, Request for Observations

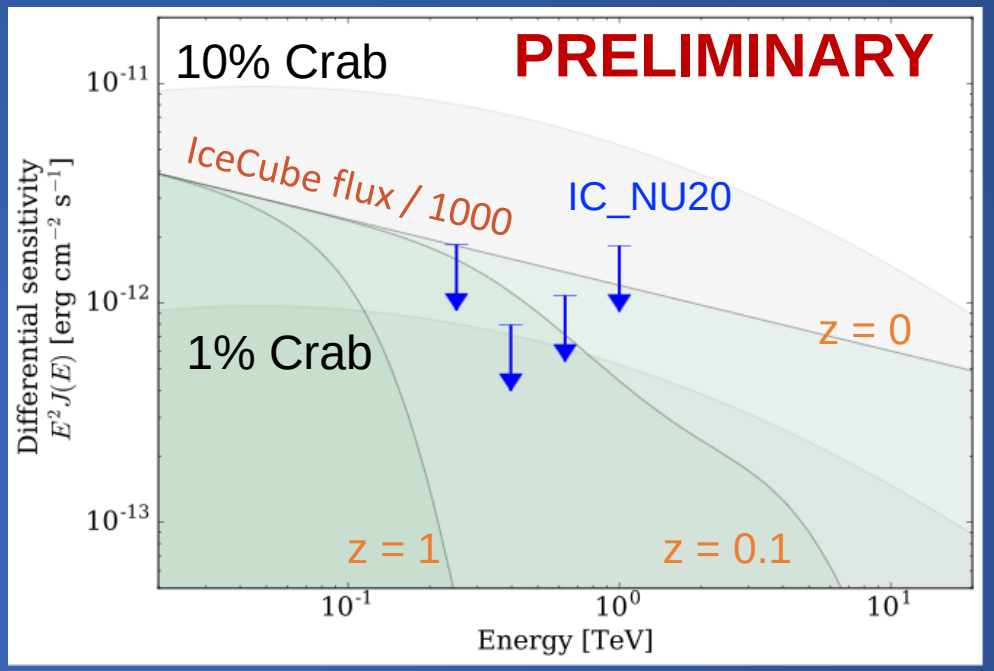
Referred to by ATel #: 7868

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

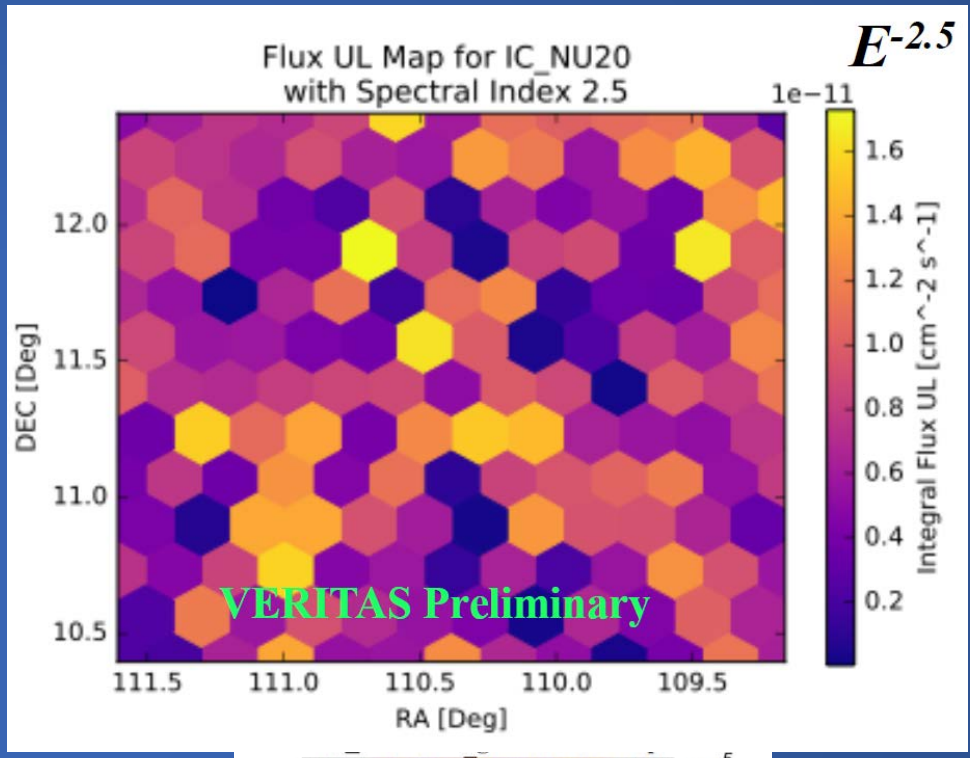


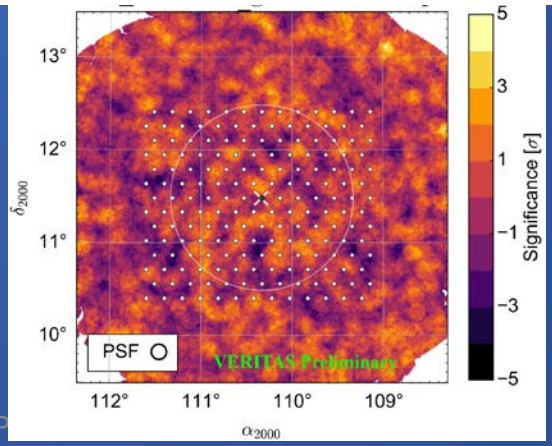


- 4 runs (1.83 hr of live-time) taken on 03/27/2016 under dark conditions. Analysis optimized for soft-spectrum sources.
- **No gamma emission detected** within the neutrino error circle. ULs at the level of a few percent of the Crab.
- Upper limits at the level of 0.1% of the all-sky astrophysical neutrino flux (depends on spectral extrapolation and source redshift).

PeV Neutrino: Upper Limit Map

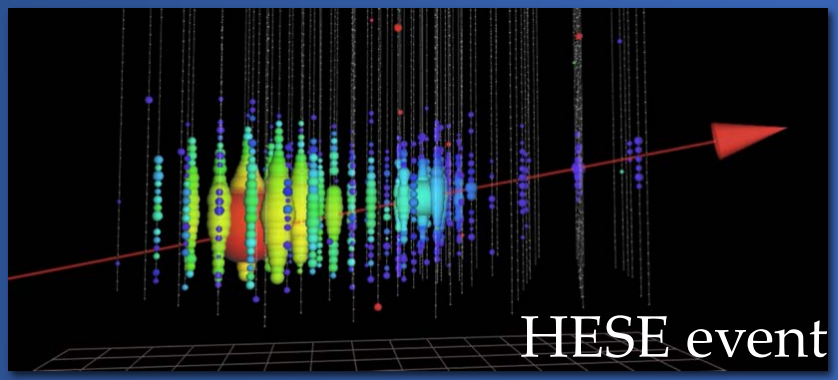
- Producing γ-ray flux upper limit maps (95% confidence level) for spectral indices of 2, 2.5, and 3.
- Triangular grid in ~1° containment region around the position of neutrino as reported by IceCube.
- Grid spacing (~0.16°) roughly matches VERITAS PSF at low energy.
- The map shows the integral γ-ray flux UL above 150 GeV for each point on the grid.
- UL maps ***set constraints on any nearby source*** within the neutrino position's uncertainty region.





Rapid ν follow-up observations

- IceCube distributes real-time GCN alerts for 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 observations are started automatically.



04/27/2016

AMON GCN Circular

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

TITLE: GCN CIRCULAR
NUMBER: 19377
SUBJECT: VERITAS rapid follow-up observations of IceCube event 160427A
DATE: 16/05/03 00:39:16 GMT
FROM: Reshmi Mukherjee at Columbia U/VERITAS <muk@astro.columbia.edu>

Title: GCN CIRCULAR
Subject: VERITAS rapid follow-up observations of IceCube event 160427A
From: VERITAS Collaboration

On April 27th, 2016, the IceCube collaboration reported the detection of a high-energy neutrino of potential astrophysical origin (GCN #19363). The neutrino event (run ID: 127853, event ID: 67093193) was detected at 05:52:32 UTC and follow-up observatories, VERITAS among them, were notified at 05:53:53 through a GCN/AMON notice.
See http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon for details.

VERITAS performed follow-up observations of the alert position (RA: 239.6639Â°, Dec: 6.8528Â°, in J2000 coordinates) between 05:55:45 UTC, 193 s after the neutrino detection, and 07:39:36 UTC in normal â€˜wobbleâ€™ mode, where the pointing direction of the telescope is offset from the source

http://gcn.gsfc.nasa.gov/gcn3/19377.gcn3

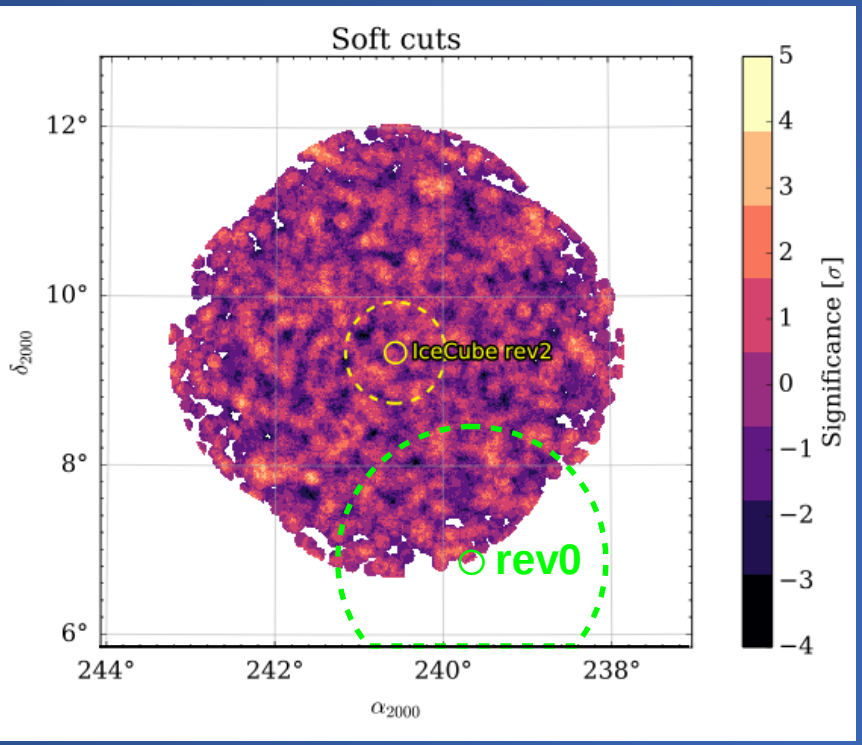
Detection: 05:52:32 UT

Alert sent: 05:53:53 UT

Follow-up start: 05:55:45 UT

112 seconds (alert to follow up)

Rapid ν follow-up observations



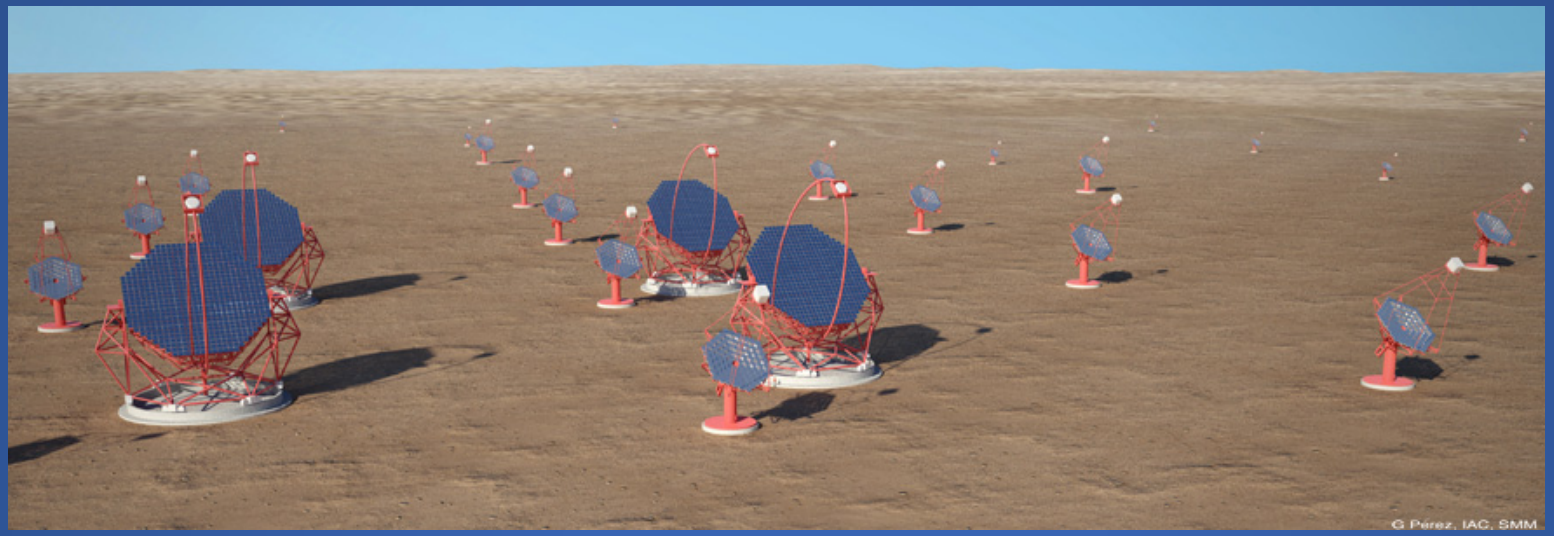
	Time	RA	Dec	Err (50%)	Err (90%)
rev0	Apr 27, 05:54	239.66°	6.85°	1.6°	8.9°
rev2	Apr 27, 23:24	240.56°	9.34°	—	0.6°

- Rev0: 71 min live-time (reduced high voltage)
- Rev2: 118 min live-time (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).
  - Rate ~ 4-6/year (~2 astro/~4 bkg). Latency ~ 0.5 - 3 min. Ang res: 0.1°-0.4°.

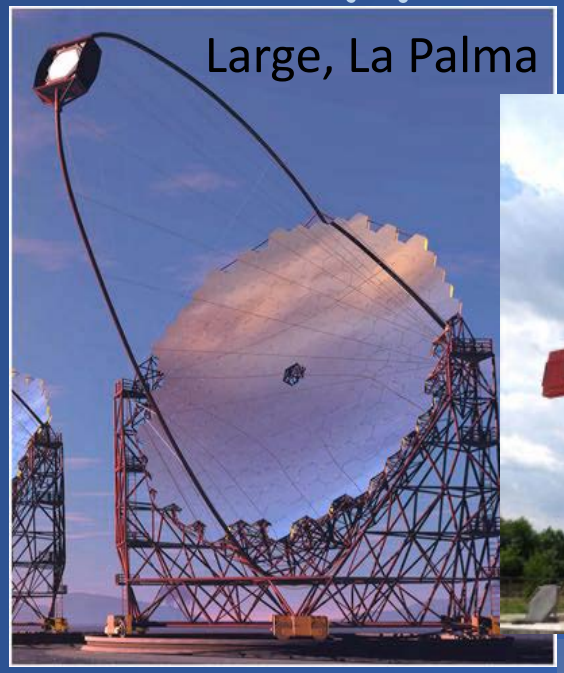
(http://gcn.gsfc.nasa.gov/notices_amon/6888376_128290.amon)

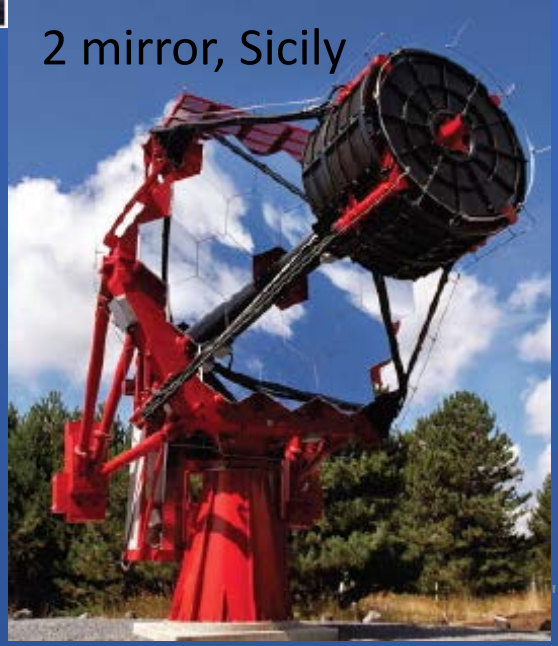
Cherenkov Telescope Array



- Arrays in northern and southern hemispheres for 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 – expand collection area >10 TeV (up to 300 TeV).
- Northern array adds 15 MSTs (no SSTs).

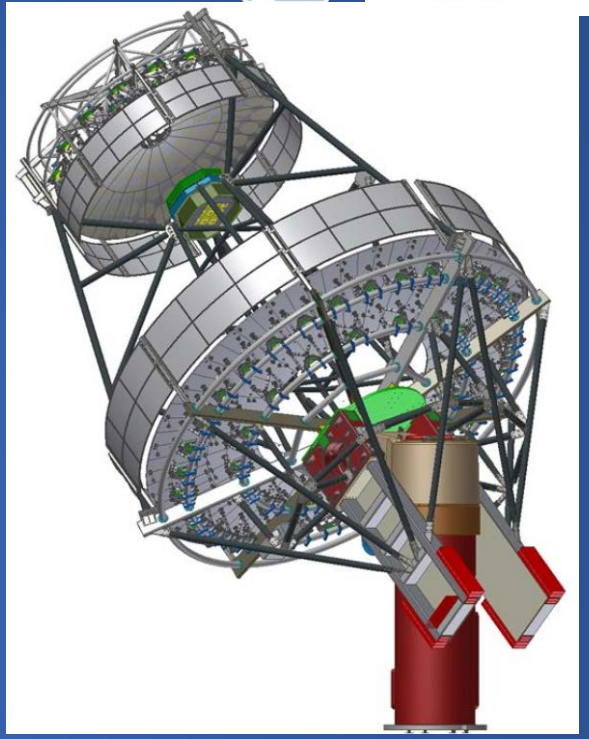
Prototype CTA Telescopes

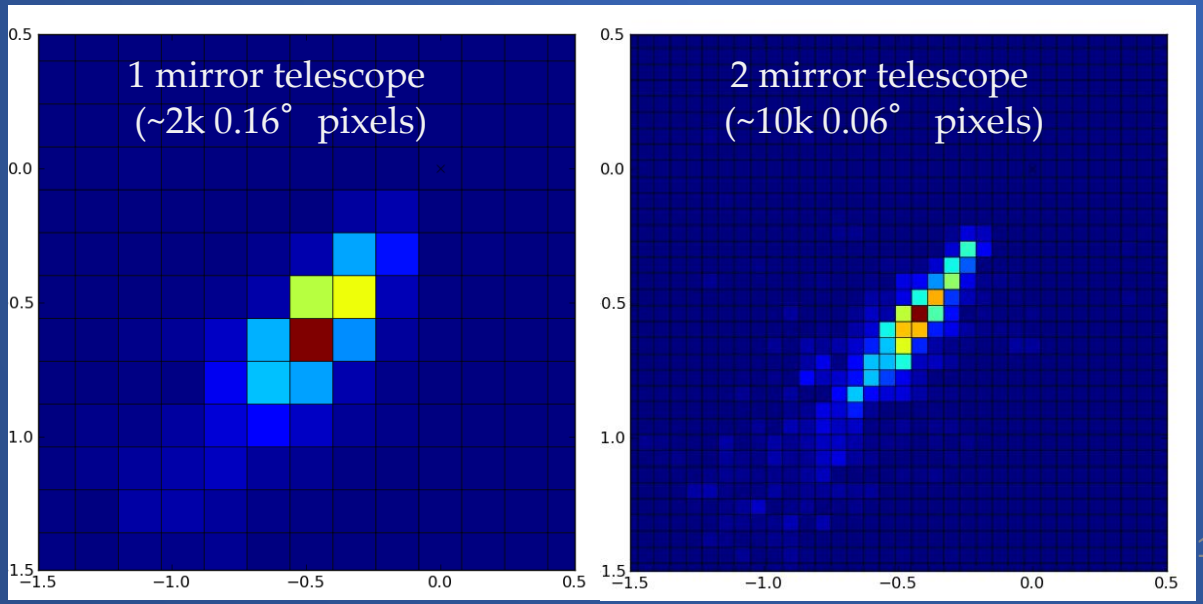




Schwarzschild-Couder Telescope

- New dual-mirror telescope technology for excellent performance.
- Allows better optical angular resolution over wide (8° diameter) field of view, compact camera.
- Small focal plane well suited for modern dense, highly integrated photo-detectors (silicon photomultipliers) and electronics (application-specific integrated circuits).
- Improved γ-ray angular resolution and background rejection allow qualitatively improved sensitivity.

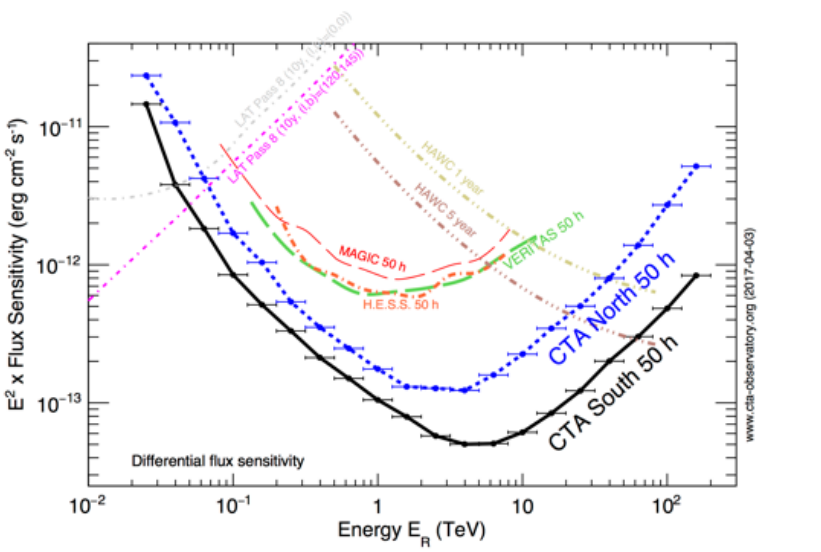


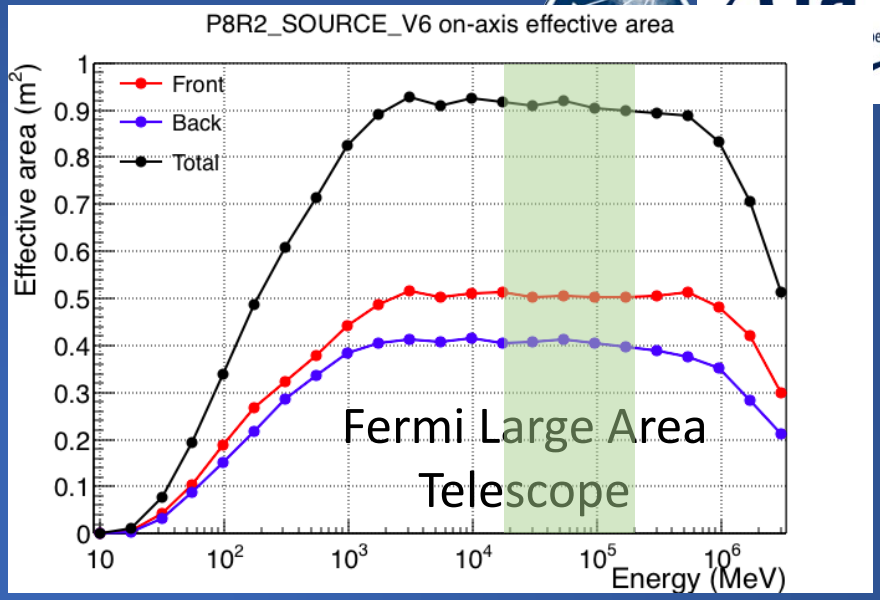


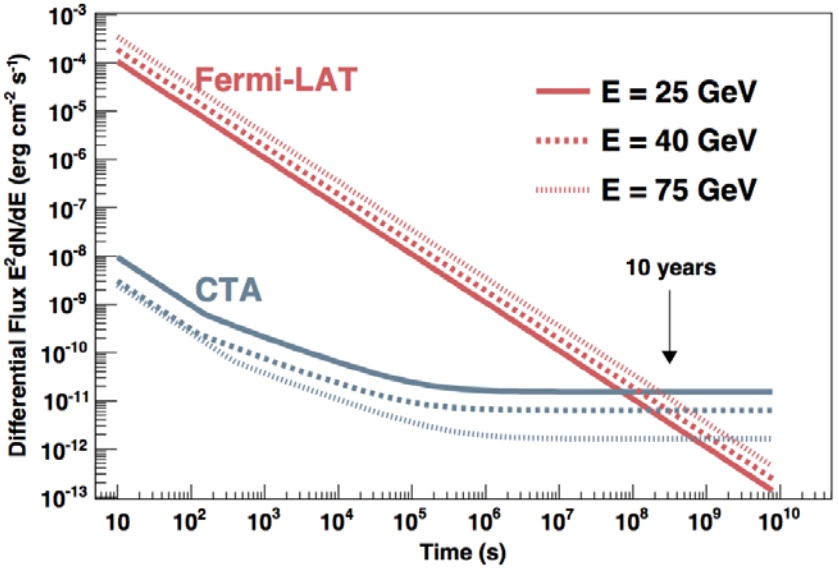
Both images of 1 TeV showers, zoomed in (2° across, compared to 8° field of view)

17

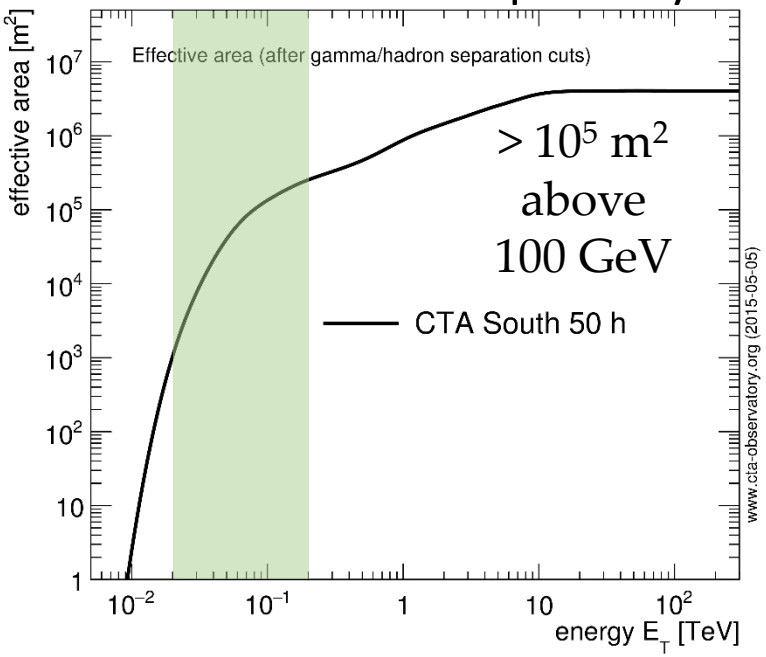
CTA Sensitivity







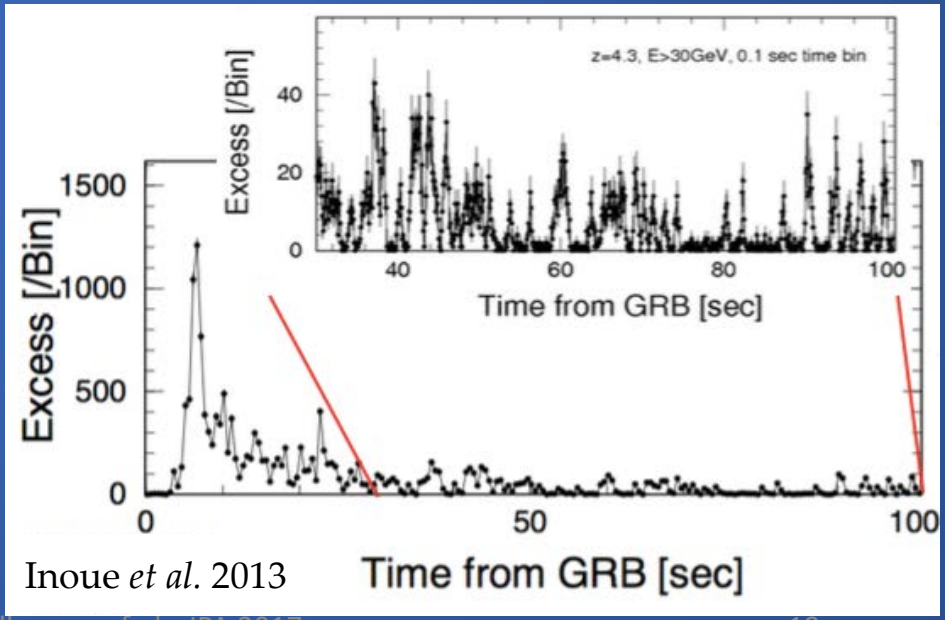
Cherenkov Telescope Array



CTA Transient Follow-up

- Large Size Telescopes (LSTs) can slew in < 20 sec; Medium Size (MSTs) in < 90 sec.
- Real-time analysis (< 30 sec) for serendipitous transient detection and broadcasting of alerts.
- 4.5 ° (LST) / 8° (MST) field of view per telescope; can cover large areas with tiling, divergent pointing.
- **Astrophysical neutrinos:** search for electromagnetic counterpart, to identify neutrino (and cosmic ray) origins.

- GRB light curves and spectra with high statistics (nearby).
- Gravitational waves: black hole or neutron star mergers; core collapse of massive stars.
- Triggers from optical/IR/radio transient factories: TDEs, FRBs, SNe, Galactic transients inc. novae, Crab nebula flares...



Inoue *et al.* 2013

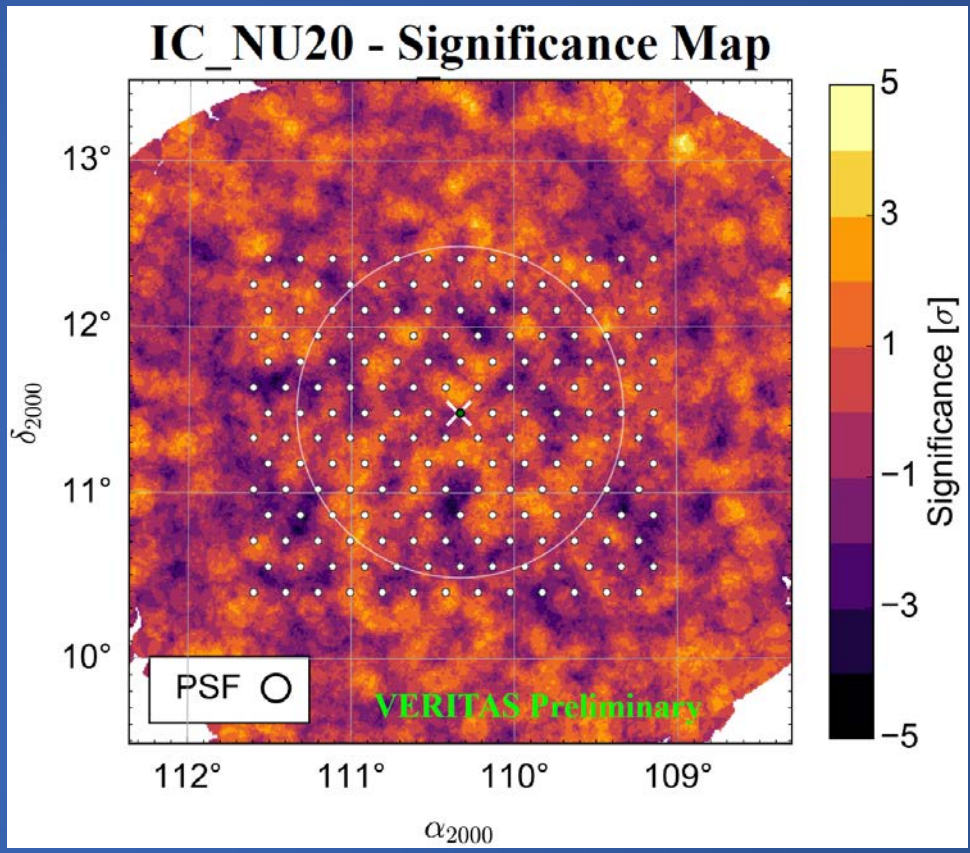
Conclusions and Outlook

- 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 2017.**

Backup Slides

PeV Neutrino: Upper Limit Map

- Producing γ-ray flux upper limit maps for spectral indices of 2, 2.5, and 3.
- Triangular grid in ~1° containment region around the position of neutrino as reported by IceCube.
- Grid spacing (~0.16°) roughly matches VERITAS PSF at low energy.
- The map shows the integral γ-ray flux UL above 150 GeV for each point on the grid.
- UL maps ***set constraints on any nearby source*** within the neutrino position's uncertainty region.



PeV Neutrino: Upper Limit Map

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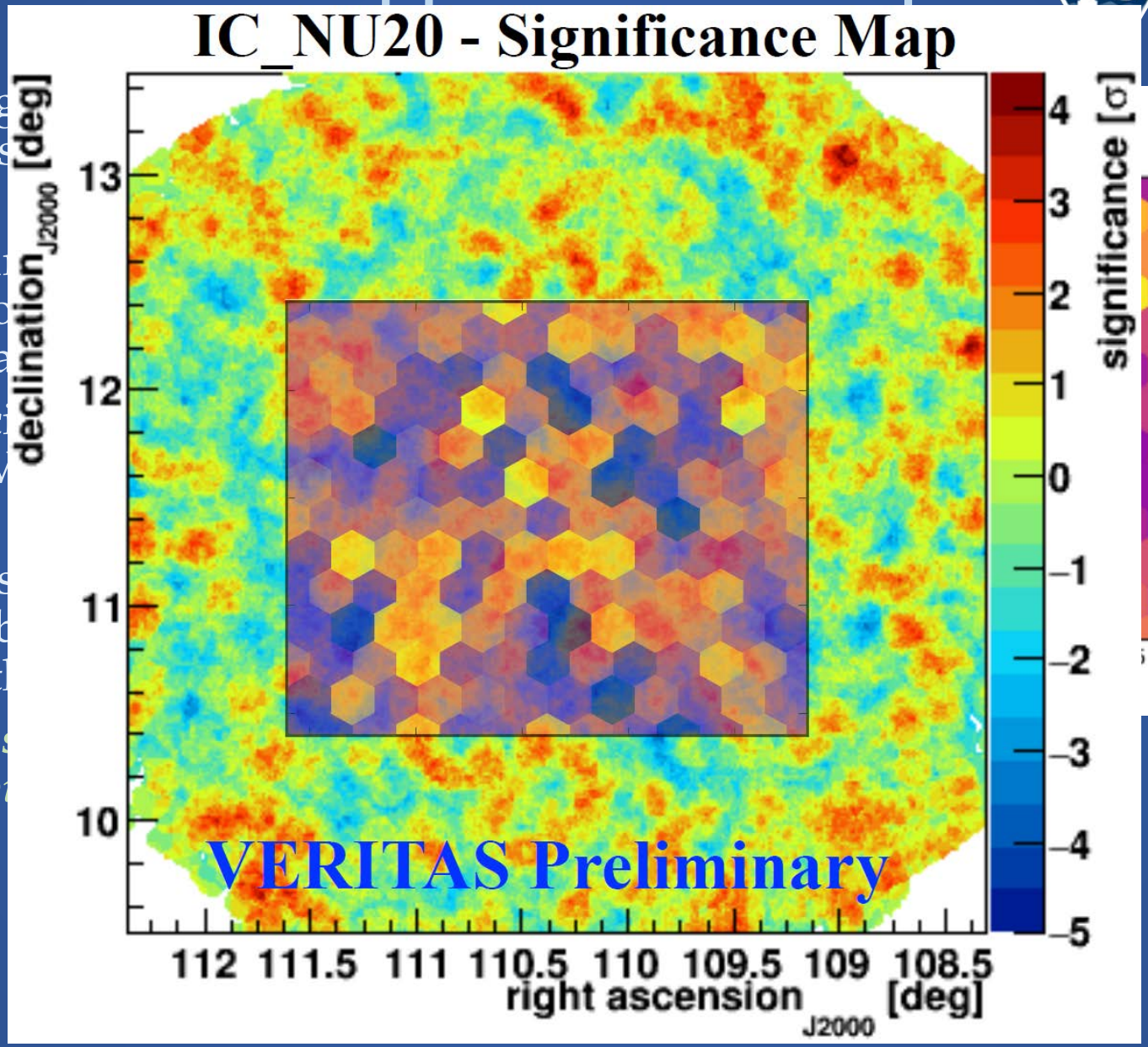
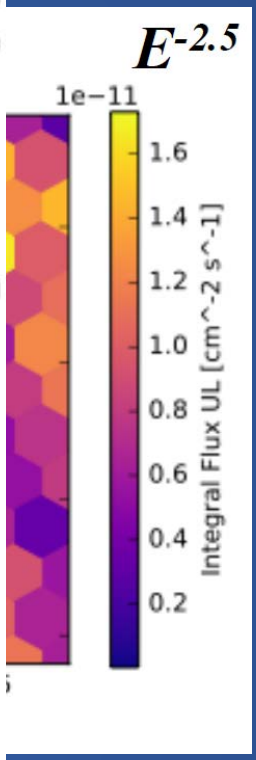
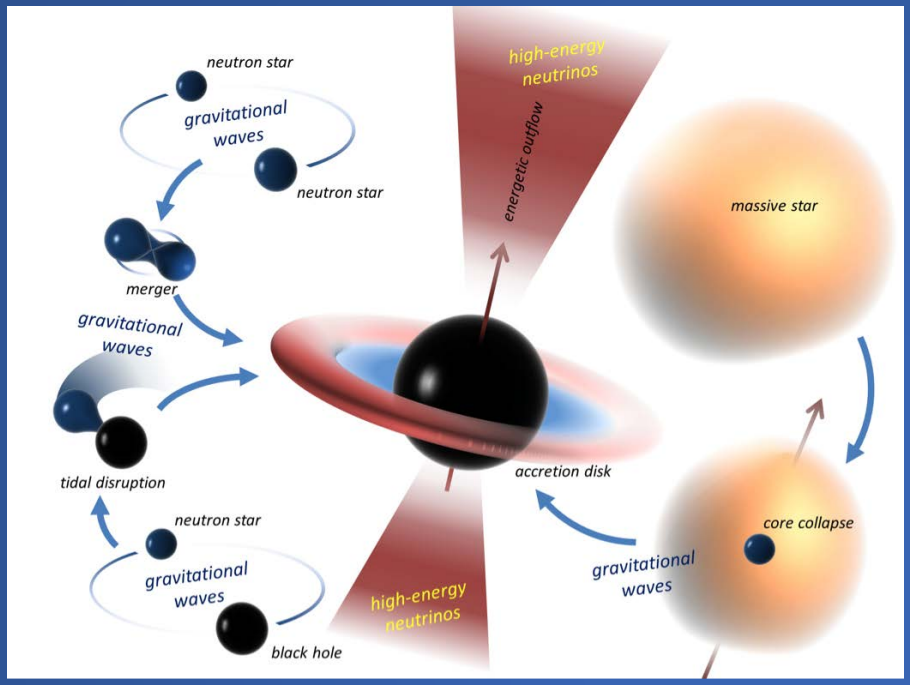
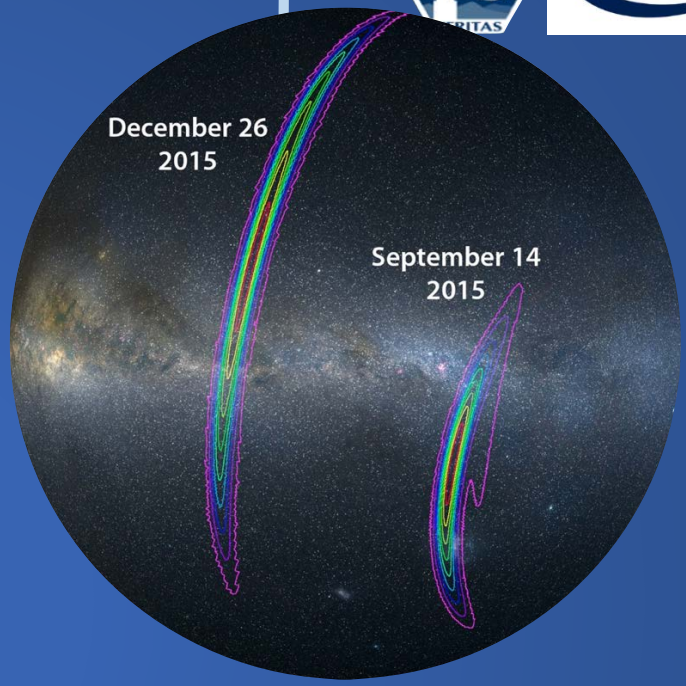




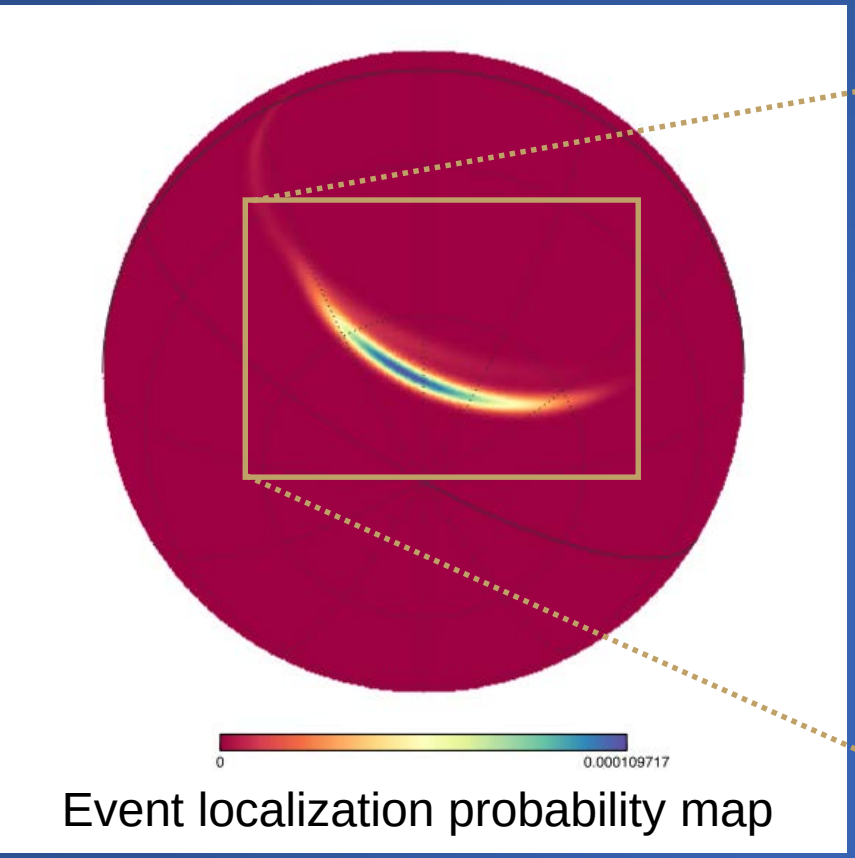
Gravitational Wave Follow-up





- LIGO detections: 2 events associated with BH-BH mergers (not expected to be EM bright). Associated keV emission detected by Fermi-GBM? (GBM Collab. arXiv/1602.03920).
- NS-NS merger may be associated with short GRBs. A NS-NS merger within the LIGO horizon (~100 Mpc) may be detected by TeV instruments (Bartos et al. arXiv/1403.6119)
- VERITAS is part of the LIGO GW follow-up community. It can use its ~10 deg^2 FoV to cover the O(100 deg^2) error region.

Gravitational Wave Follow-up



Event localization probability map

- LIGO O2 run in progress; Virgo joining later in 2017 will improve the event localization to O(10 deg^2).
- VERITAS response system operating: GW alert will be processed and observations will start automatically.
- Localization map for the GW alert is available a few minutes after detection, goes out to follow-up instruments after data-quality checks are performed.