Very-high-energy gamma rays in the multimessenger era

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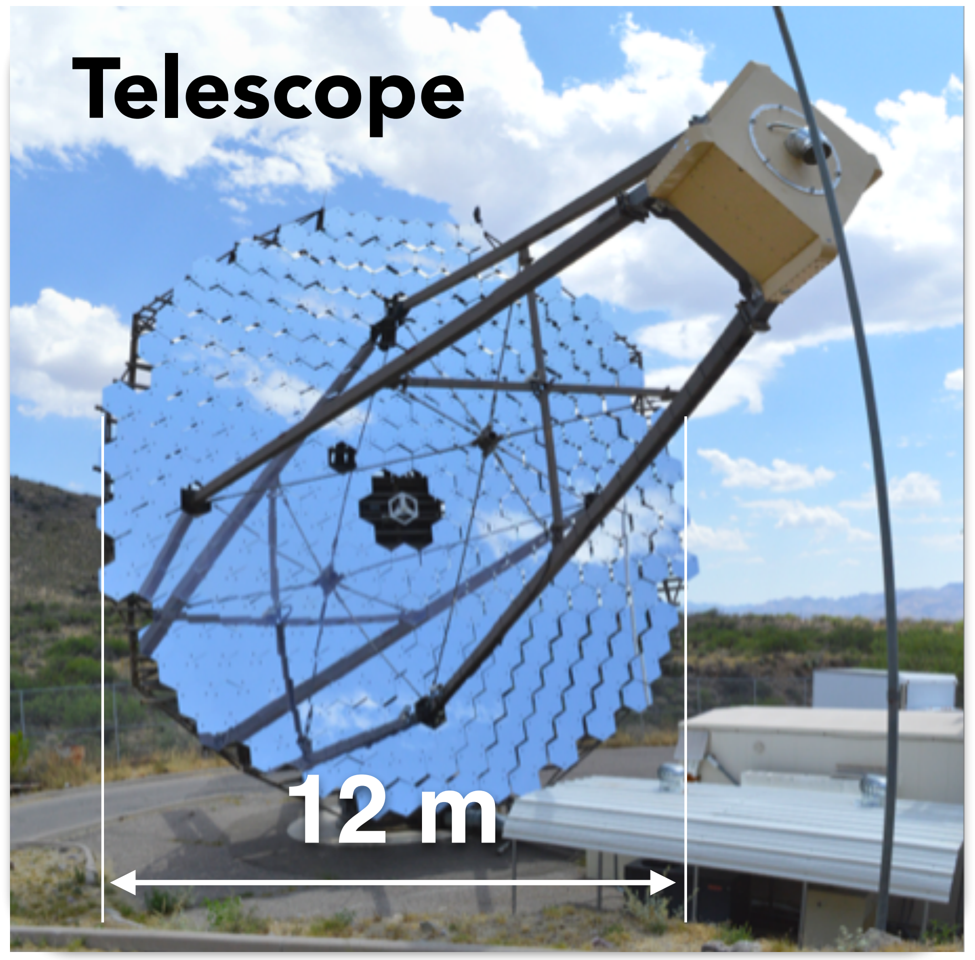
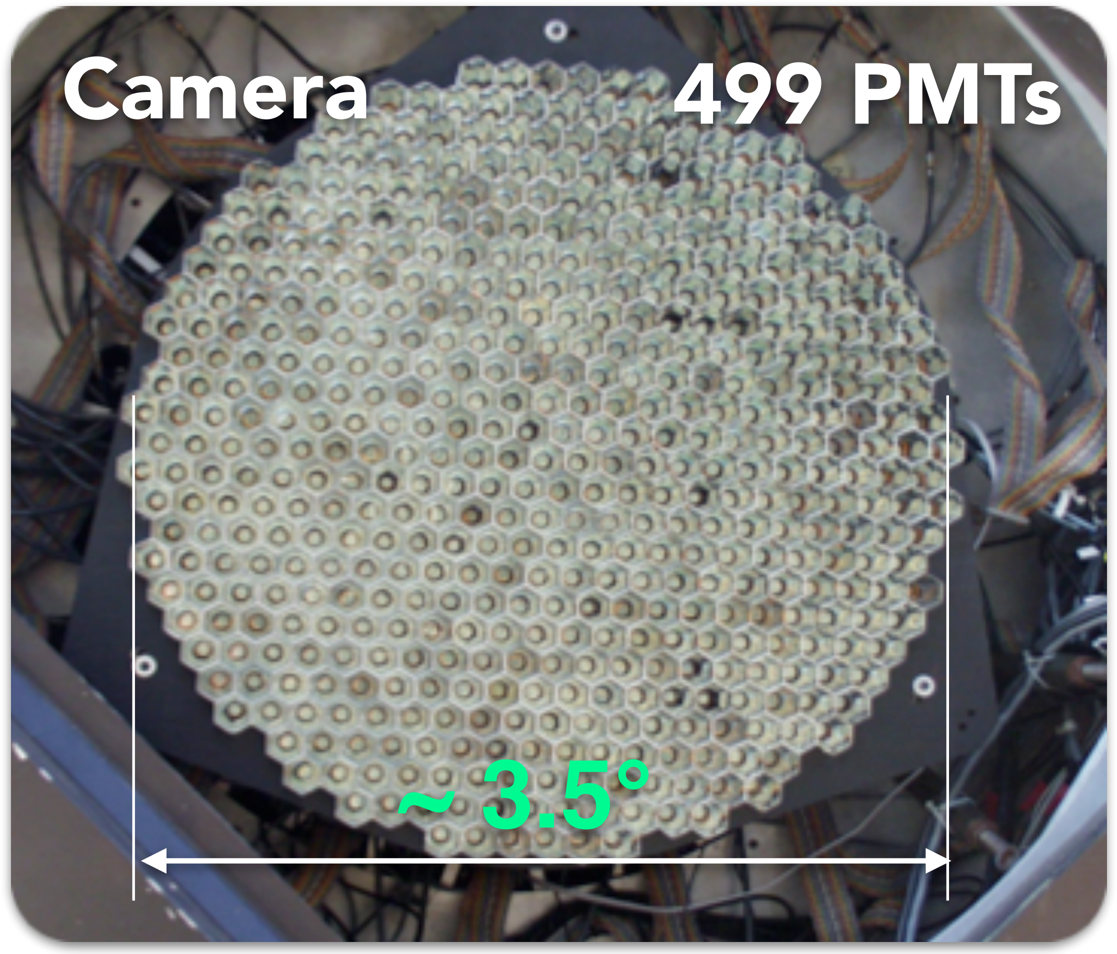
LHAASO Scientific Observation and Multi-messenger Astronomy Workshop - Apr 24-28, 2019

VERITAS telescopes

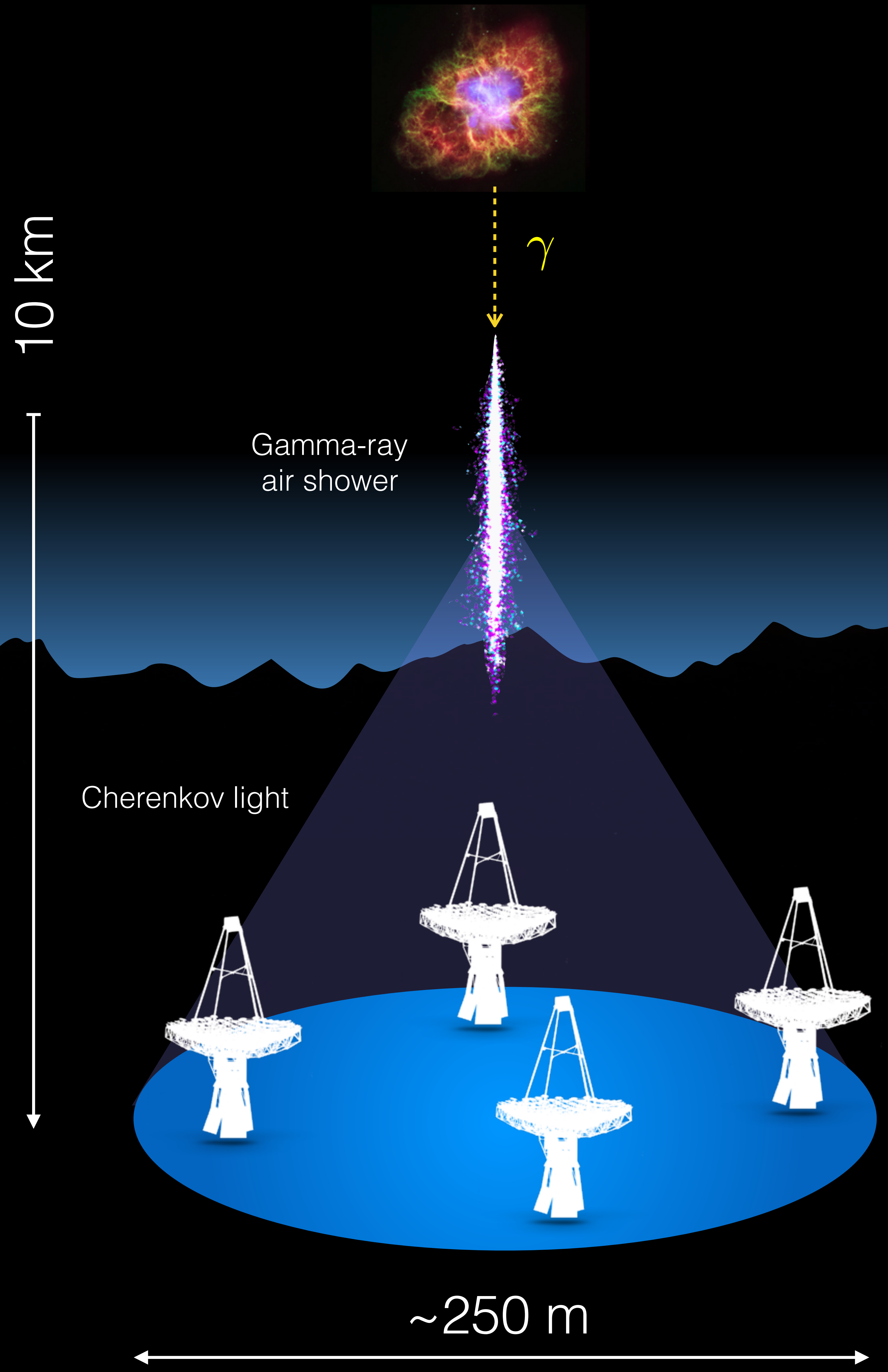
Location: Whipple Observatory, Arizona
Status & highlights: arxiv/1510.01269

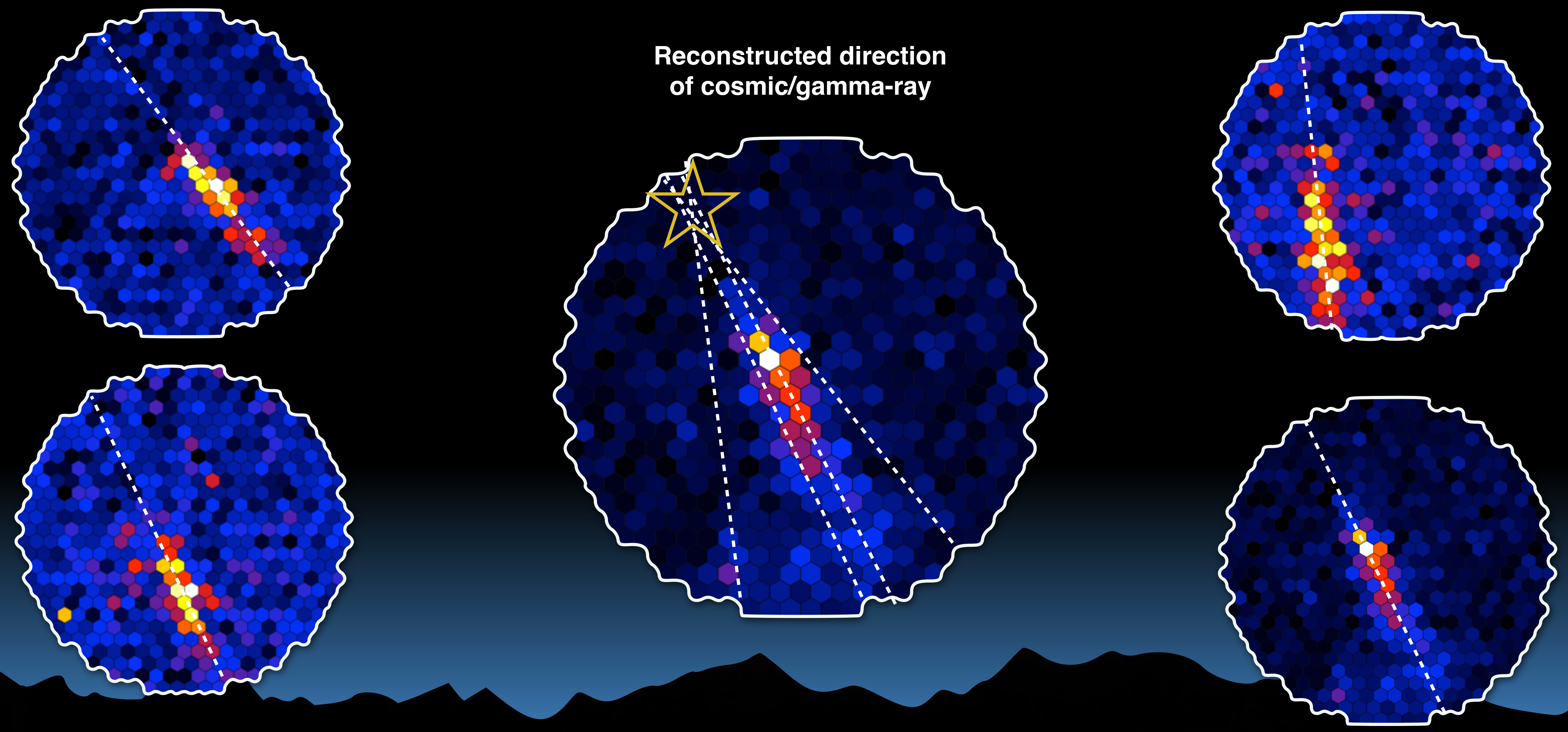




- First light in 2007
- Array of 4 Davies-Cotton Imaging Air Cherenkov Telescopes.
- Energy range: ~ 80 GeV - 30 TeV
- Observing time: **~1300 hrs / year**
- 0.1° angular resolution > 1 TeV
- Detects the Crab Nebula in < 2 minutes.

Imaging Atmospheric Cherenkov Telescopes





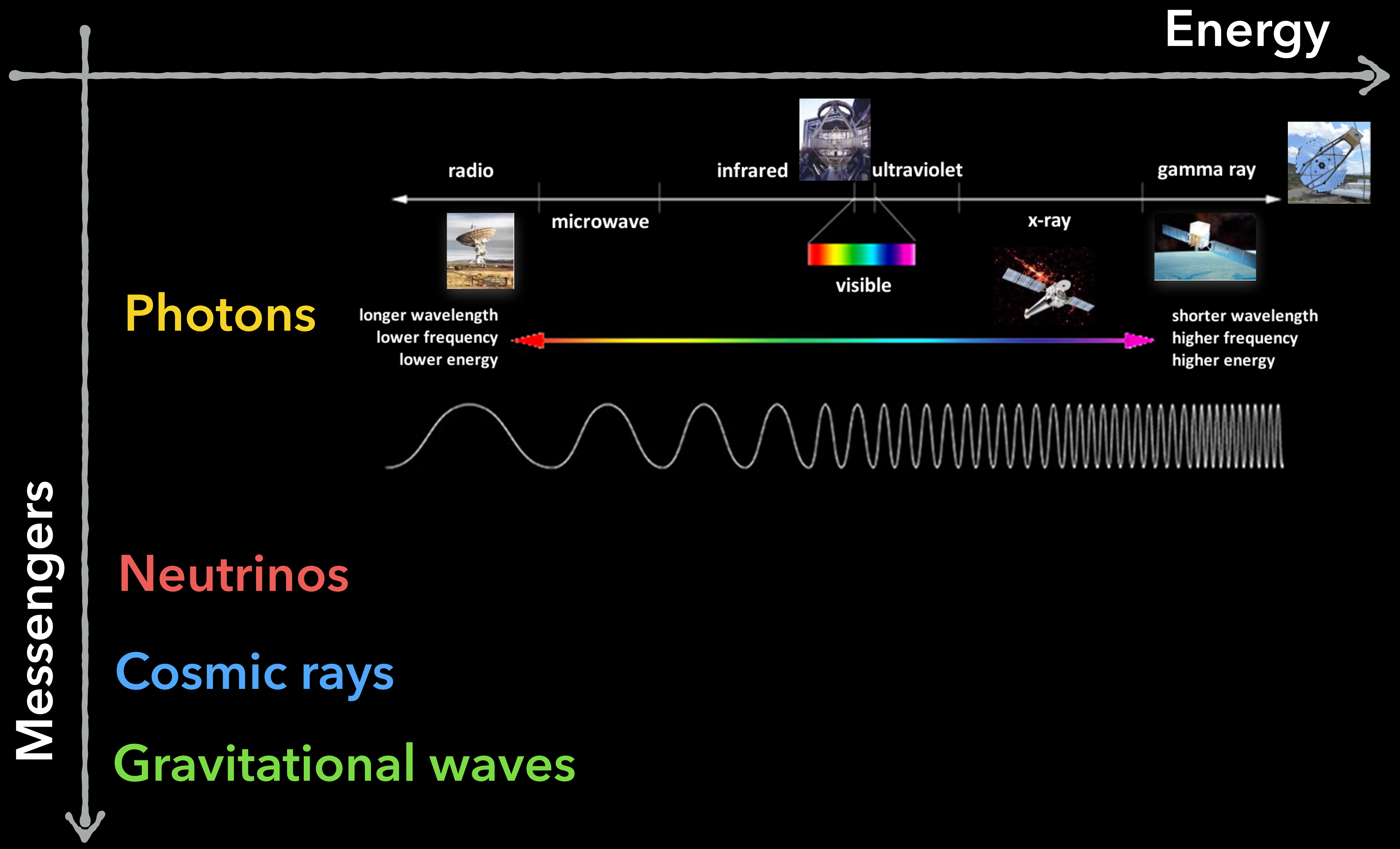
Large γ–ray collection area ***O(10⁵ m²)***

High cosmic-ray background

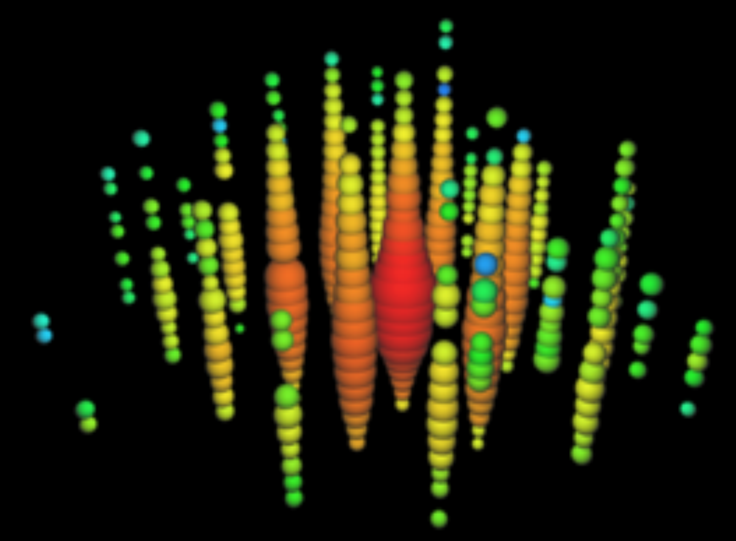
Event reconstruction from EAS image:

- Type of primary event (gamma/hadron)
- Primary energy estimation
- Primary arrival direction

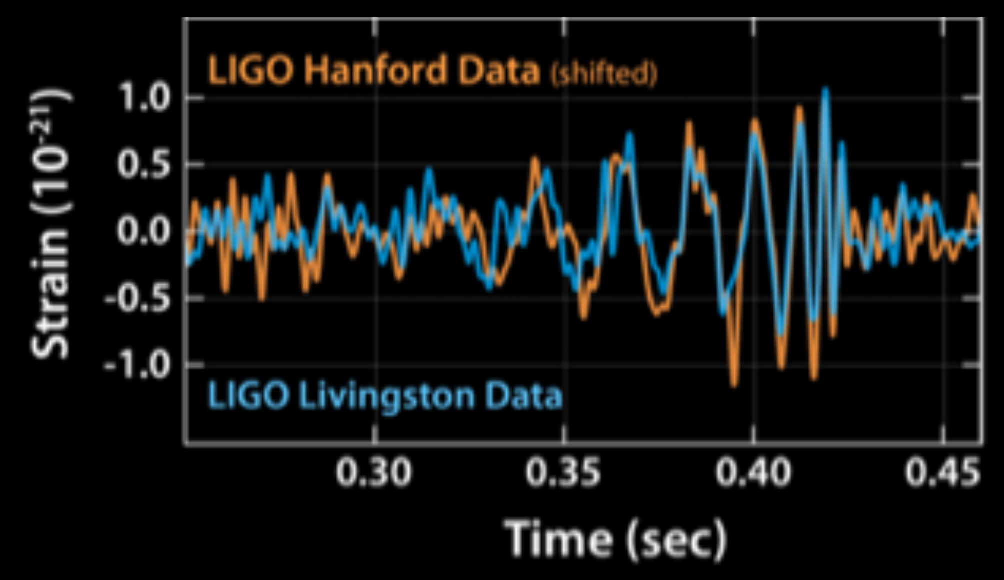
Multi-messenger astronomy



New astrophysical messengers



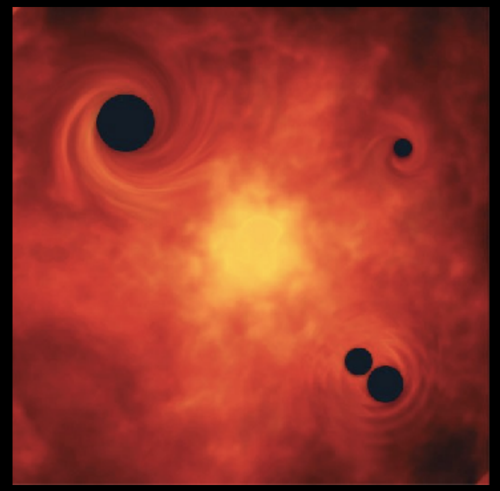
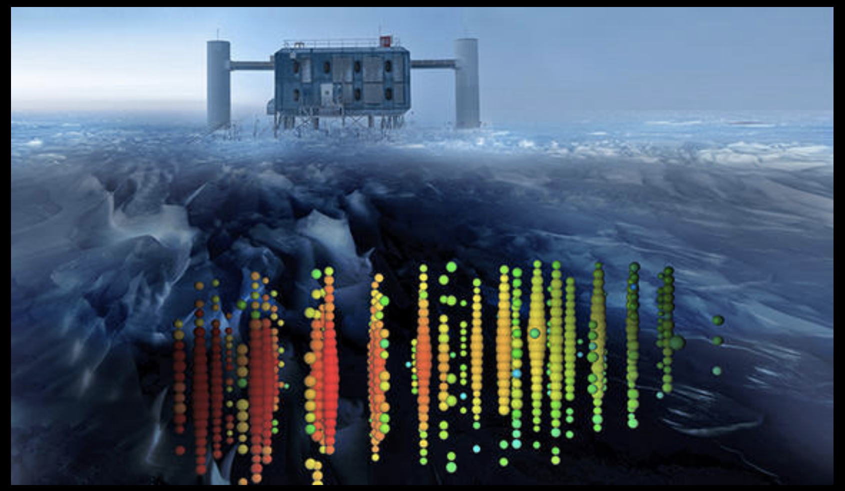
TeV-PeV Neutrinos
IceCube (2013)

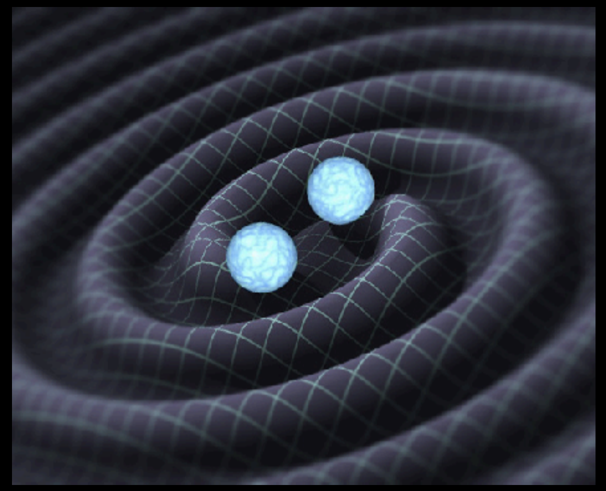


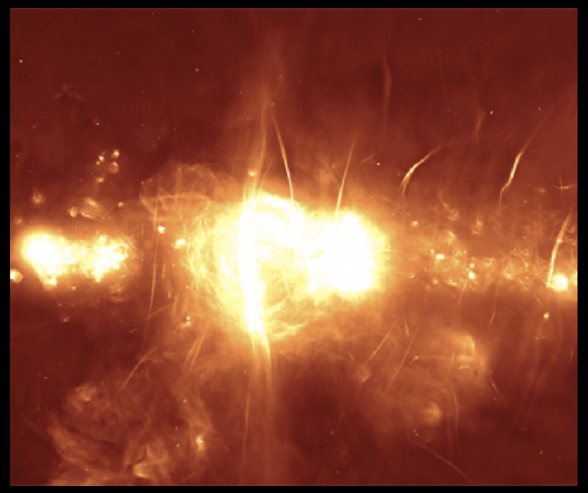
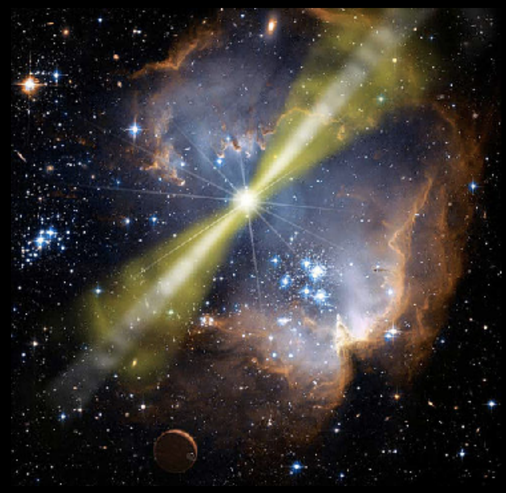
Gravitational waves
LIGO (2016)

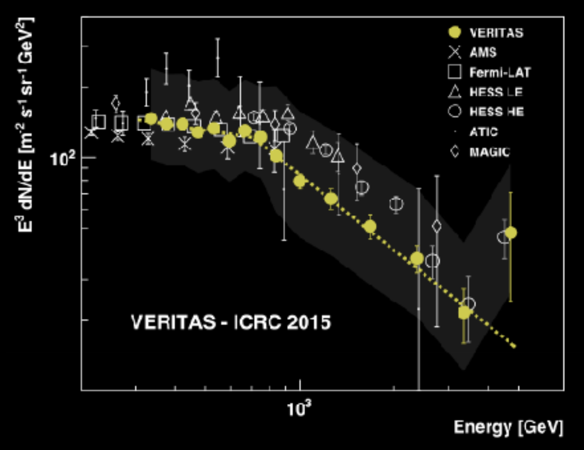
- Search for sources that emit in two or more "cosmic messenger" channels (photons, neutrinos, cosmic rays, and gravitational waves).
- Probe into extremely-energetic astrophysical processes. Improved sensitivity to sources with weak (or attenuated) EM emission and transient events.
- **Localization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

Astroparticle, Transient, Optical and Multi-Messenger

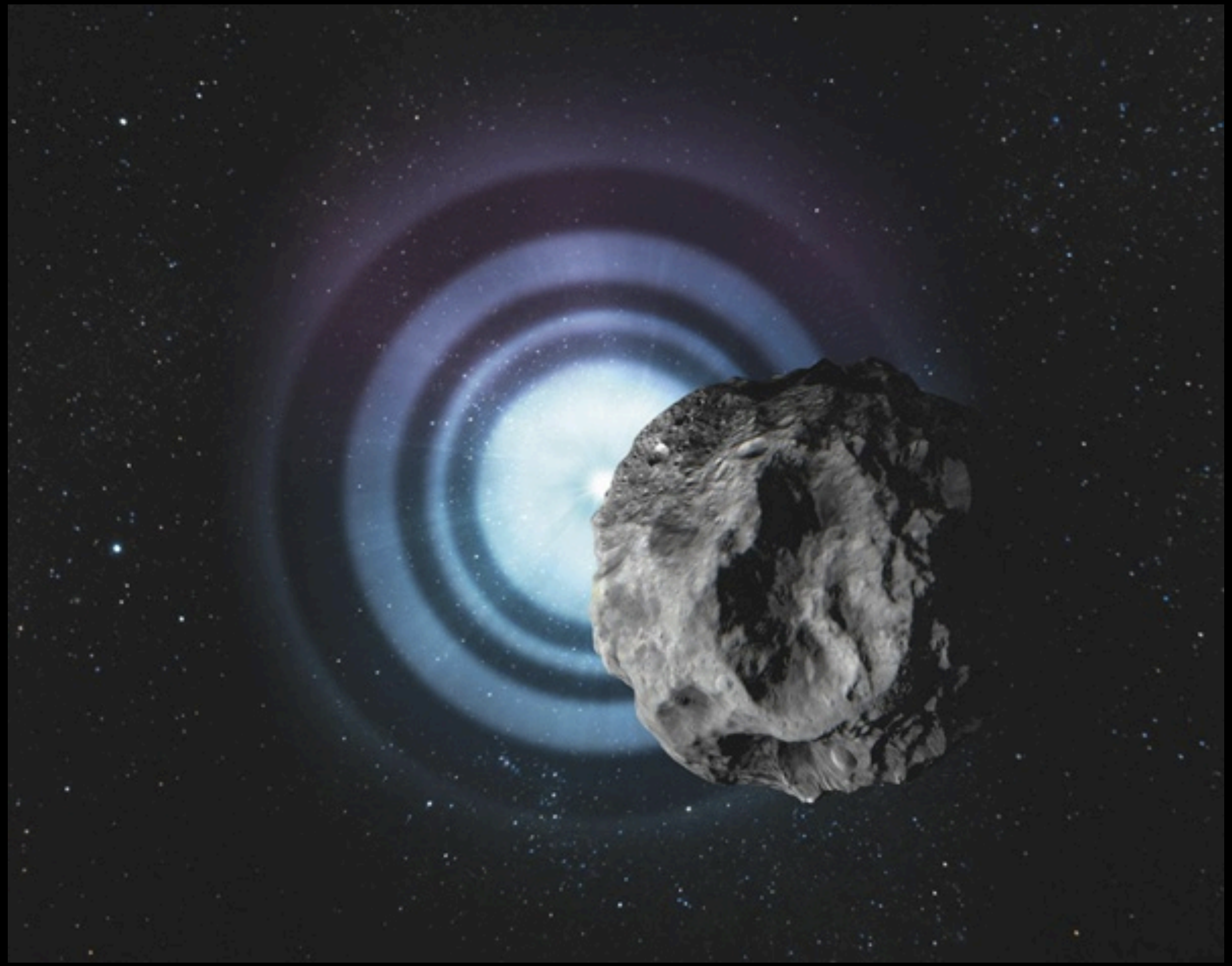


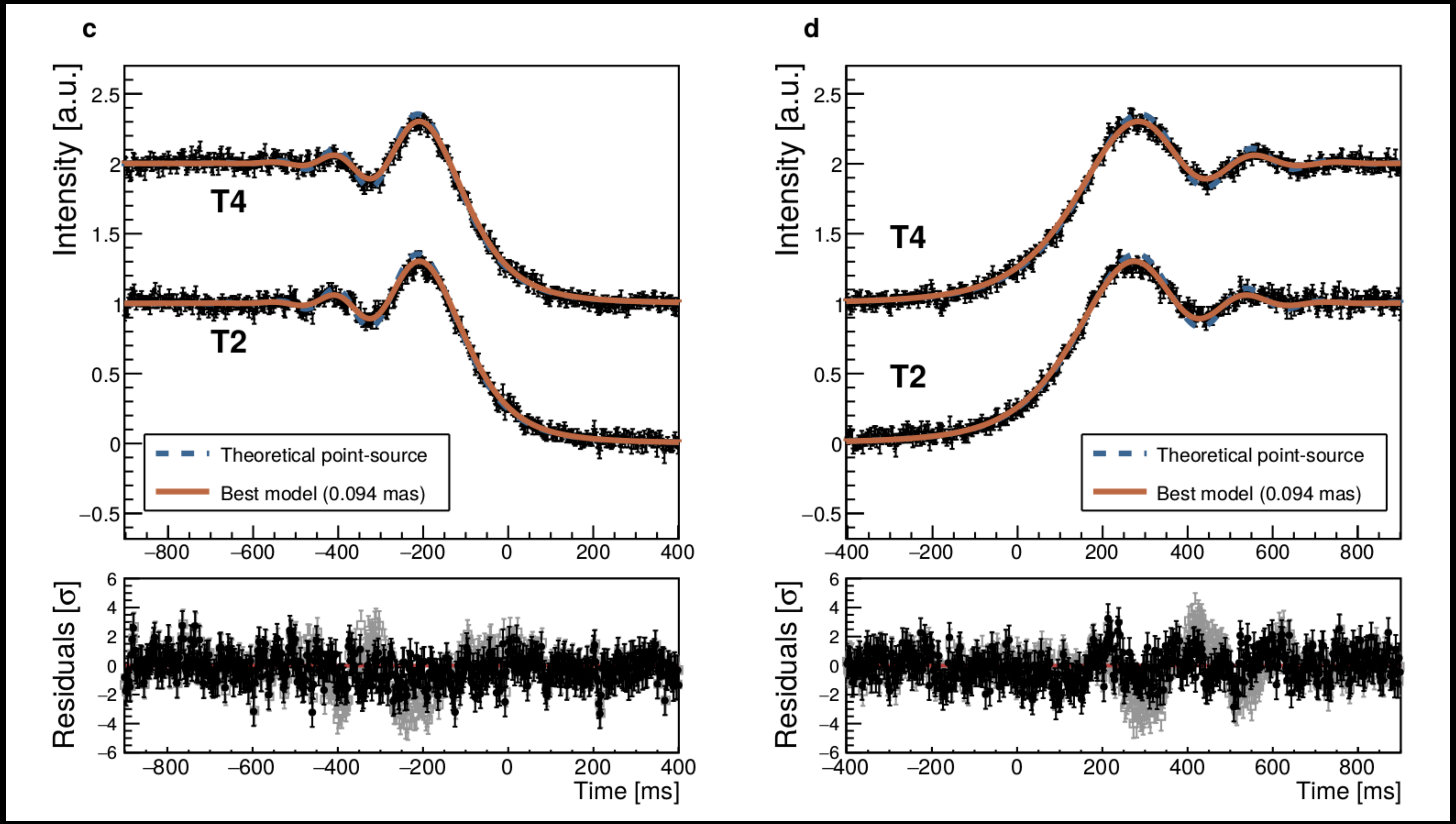




- **Multi-messenger is only a part of the VERITAS science program!**
- **BSM physics**: dark matter, primordial black holes, Lorentz invariance violation.
- **Transients**: gamma-ray bursts, fast radio bursts
- **Astroparticle**: measurement of primary CR spectra (e^-, Fe)
- **Optical:** Stellar occultations, fast optical transients.

A sample of other topics: stellar diameter measurements

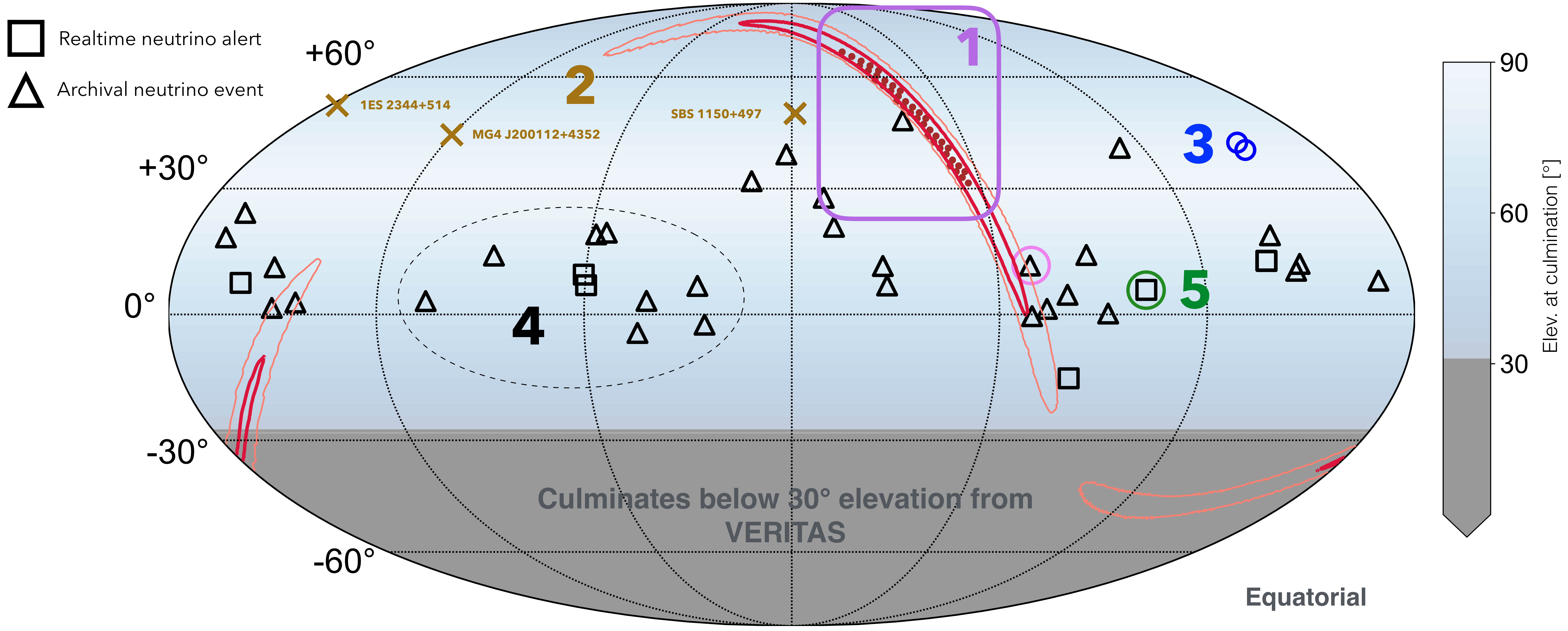




Nature Astronomy (2019)

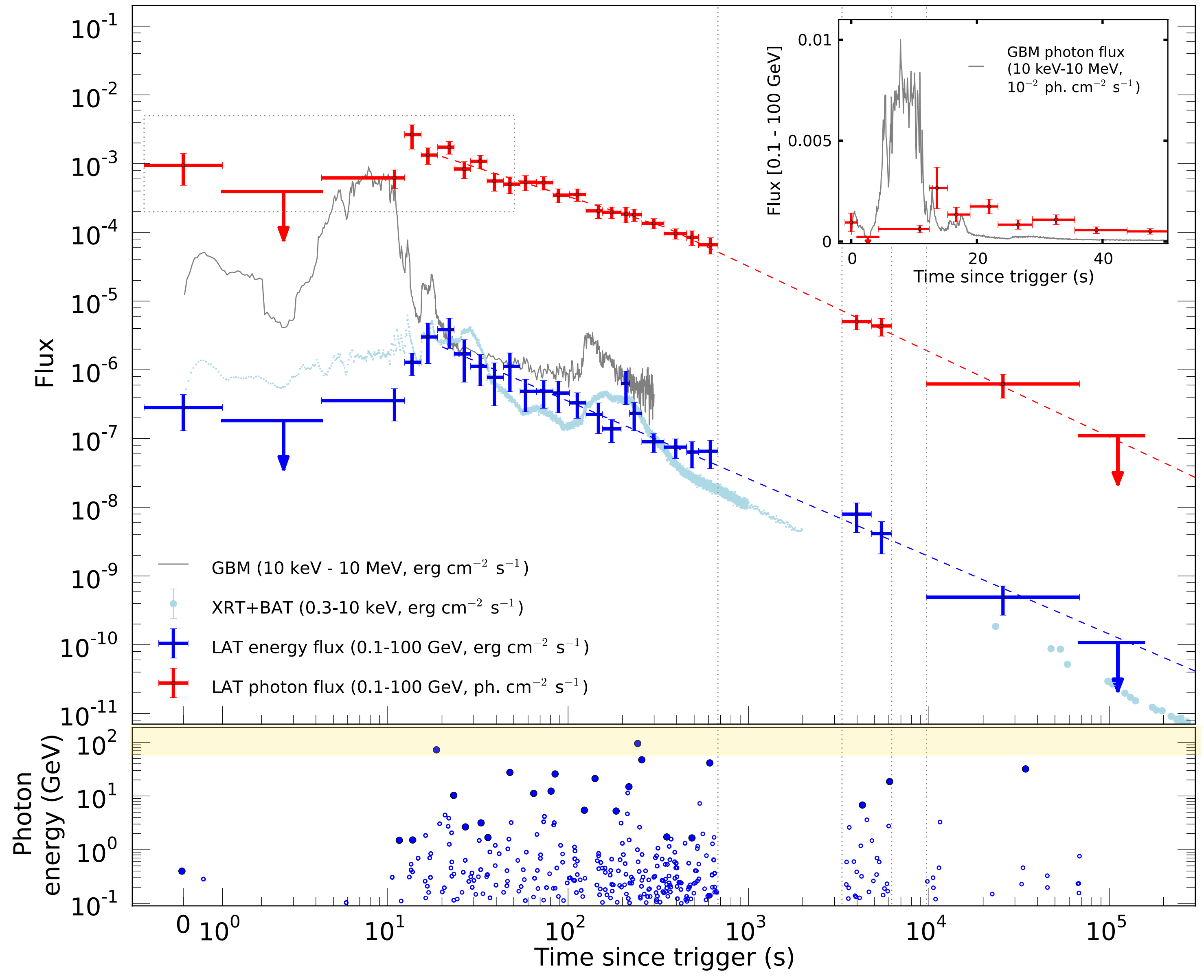
- Observation of a stellar occultation by an asteroid. The diffraction pattern encodes the angular size of the star. Two stars observed: **94 μas and 125 μas diameters**.
- **Illustrates capabilities for optical transient observations by IACTs.**

The VERITAS multi-messenger sky



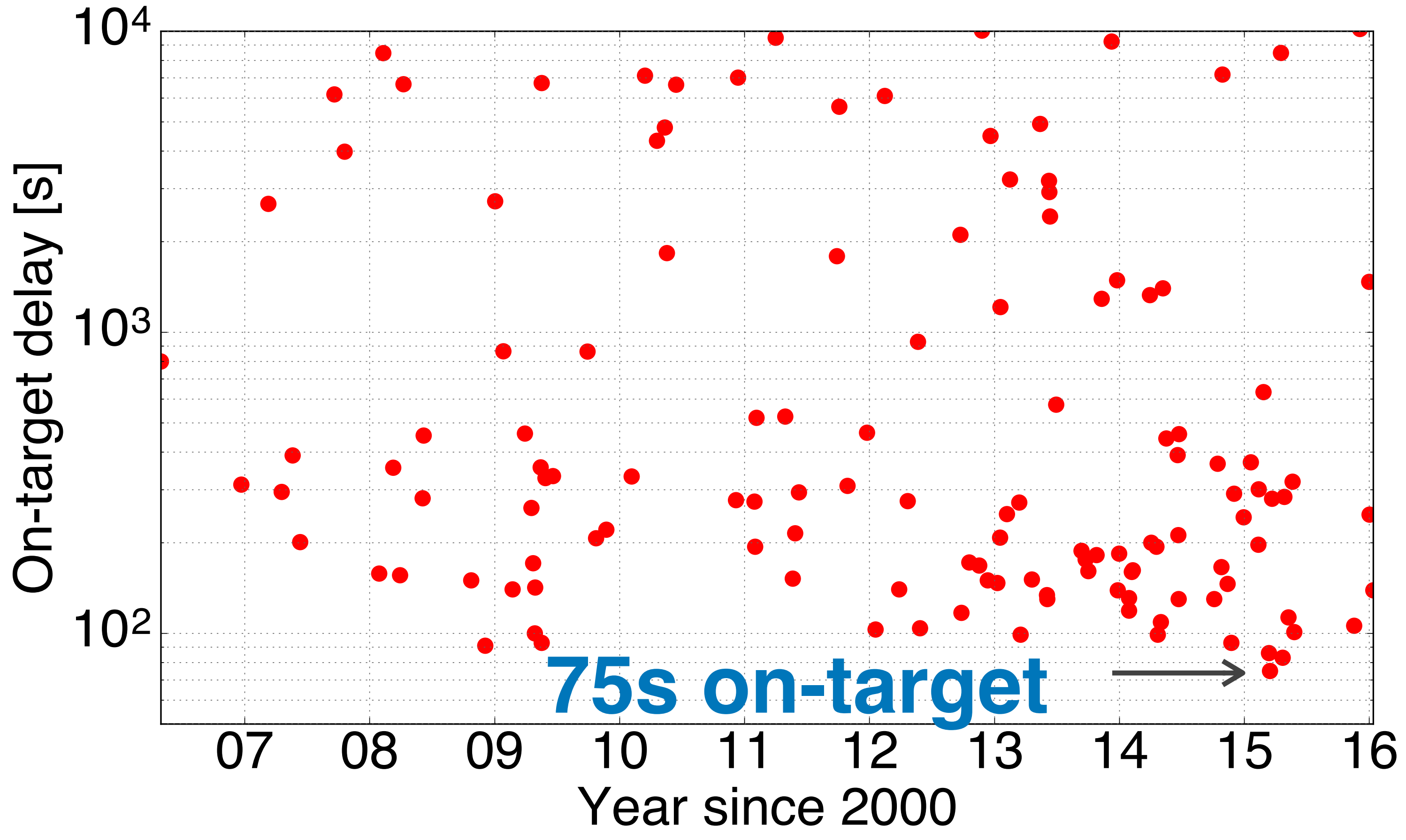
- VERITAS performs follow-up observations of **HE neutrinos** from IceCube and **gravitational waves** from LIGO/Virgo.

VERITAS GRB observations

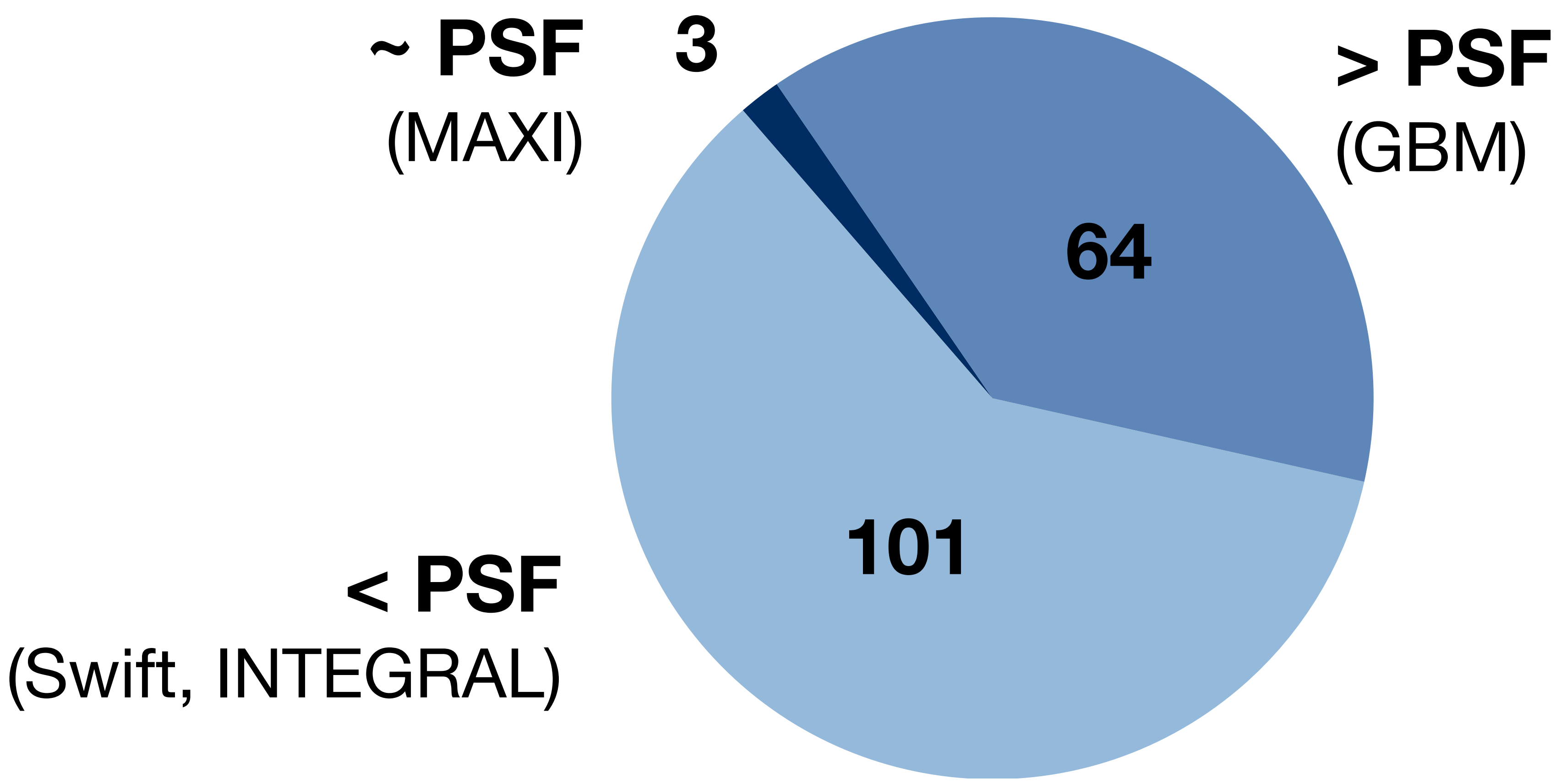


- GRBs were long-suspected as VHE emitters and IACTs follow-up on them. The first VHE GRB was **detected by MAGIC** (190114C).
- VERITAS performs regular follow-ups of GRBs reported by Swift, Fermi or MAXI.
- GRB alerts processed by the telescope control software in realtime. Telescopes are repointed once observers acknowledge the alert. 3 hours of observation above 20° elevation (1 hr for GBM bursts.)
- Non-detections so far, **set constraints on emission medium**.

Response time

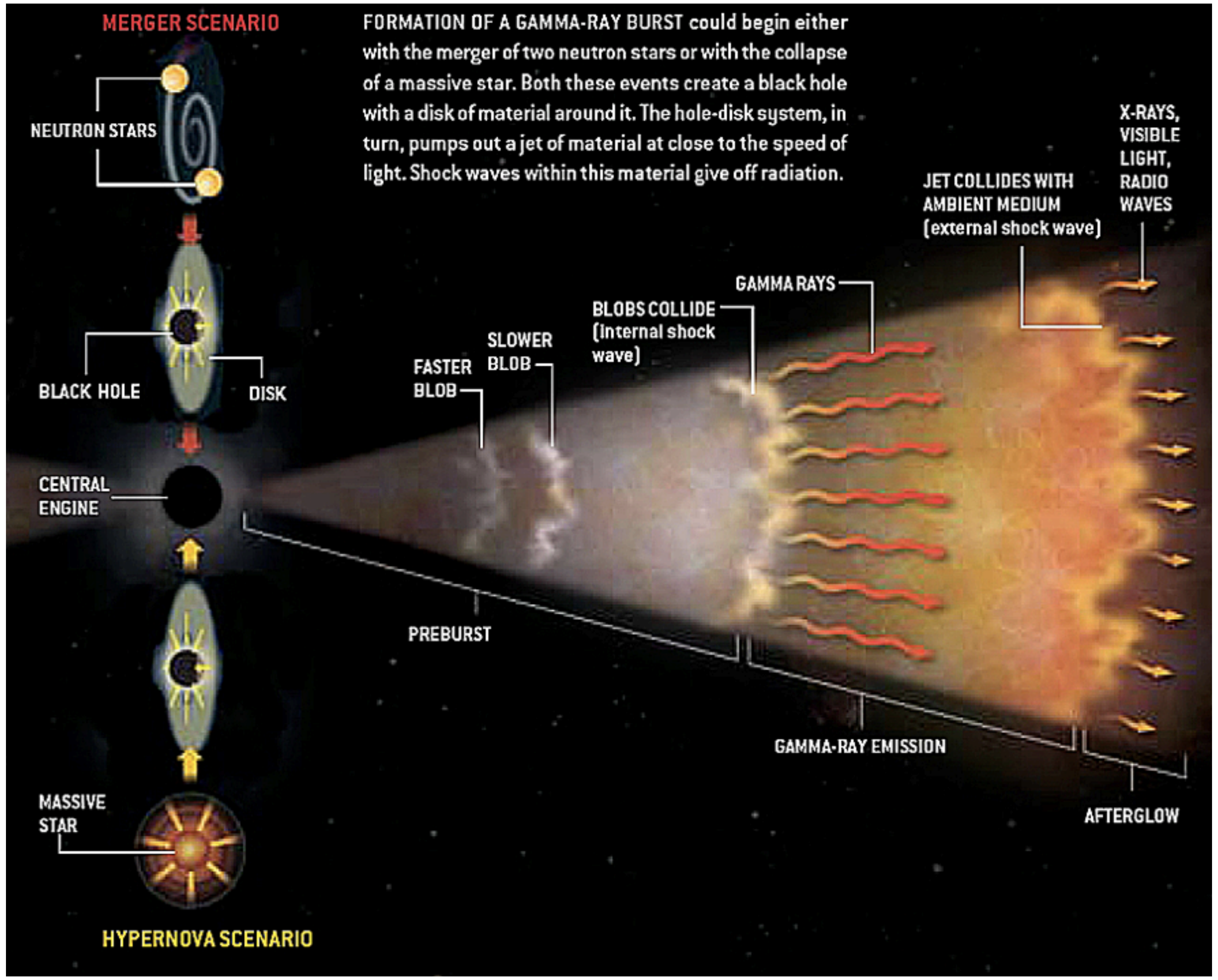


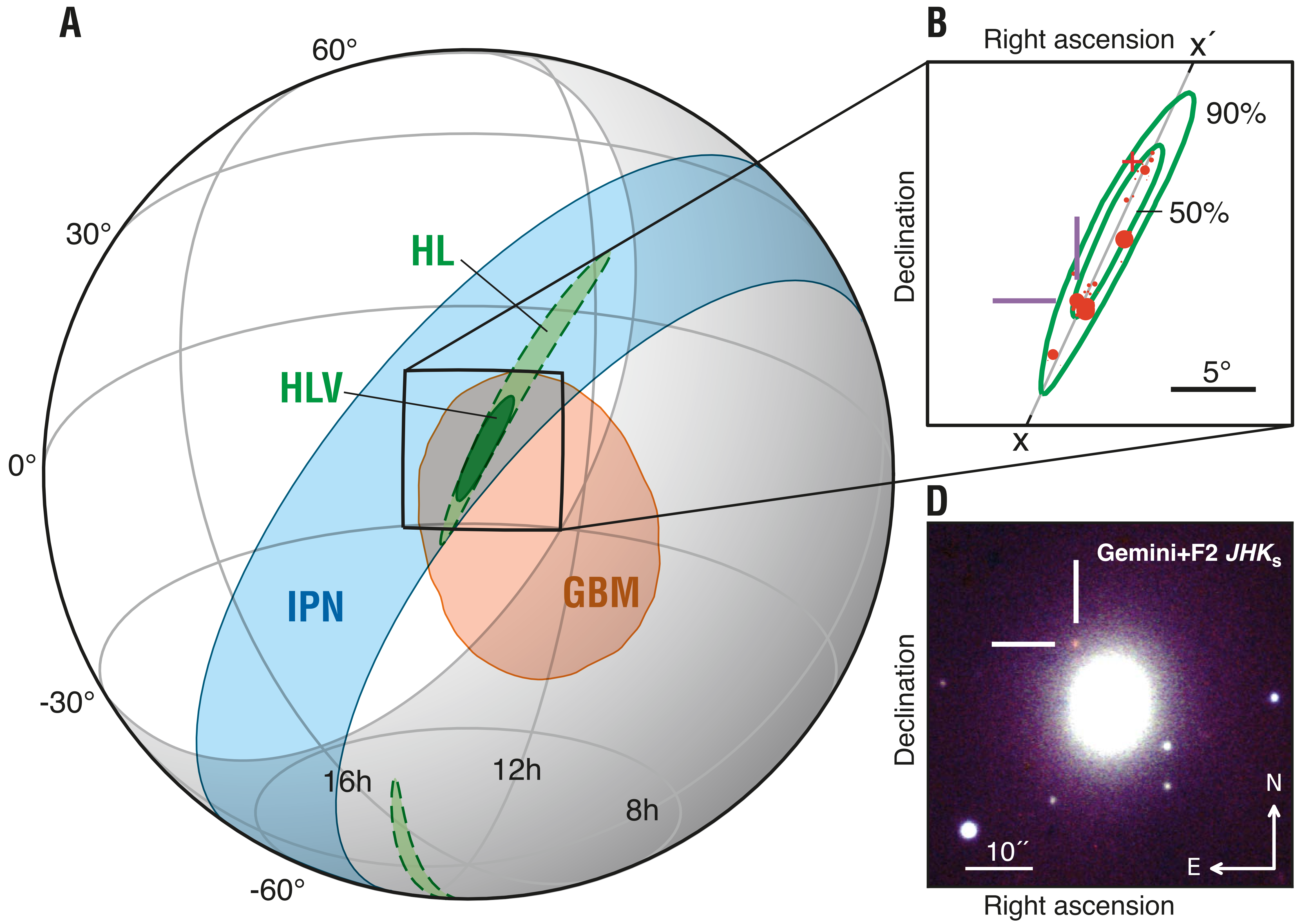
Localization uncertainty



- **Publications**
  - ApJ 743, 62 (2011) - 16 bursts
  - ApJL 795, L3 (2014) - GRB 130427A
  - ApJ 857, 33 (2018) - GRB 150323A

VHE emission from gravitational wave sources

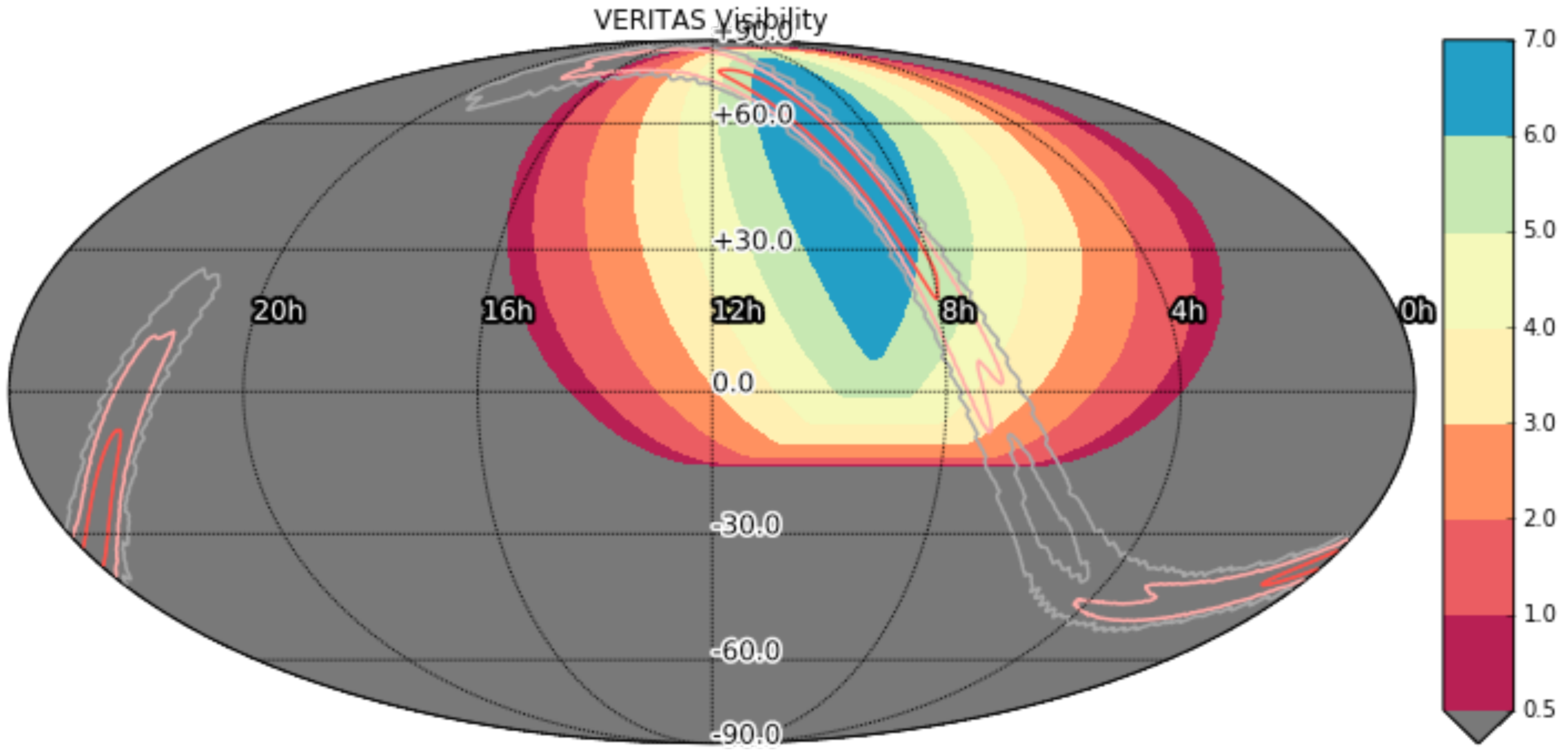


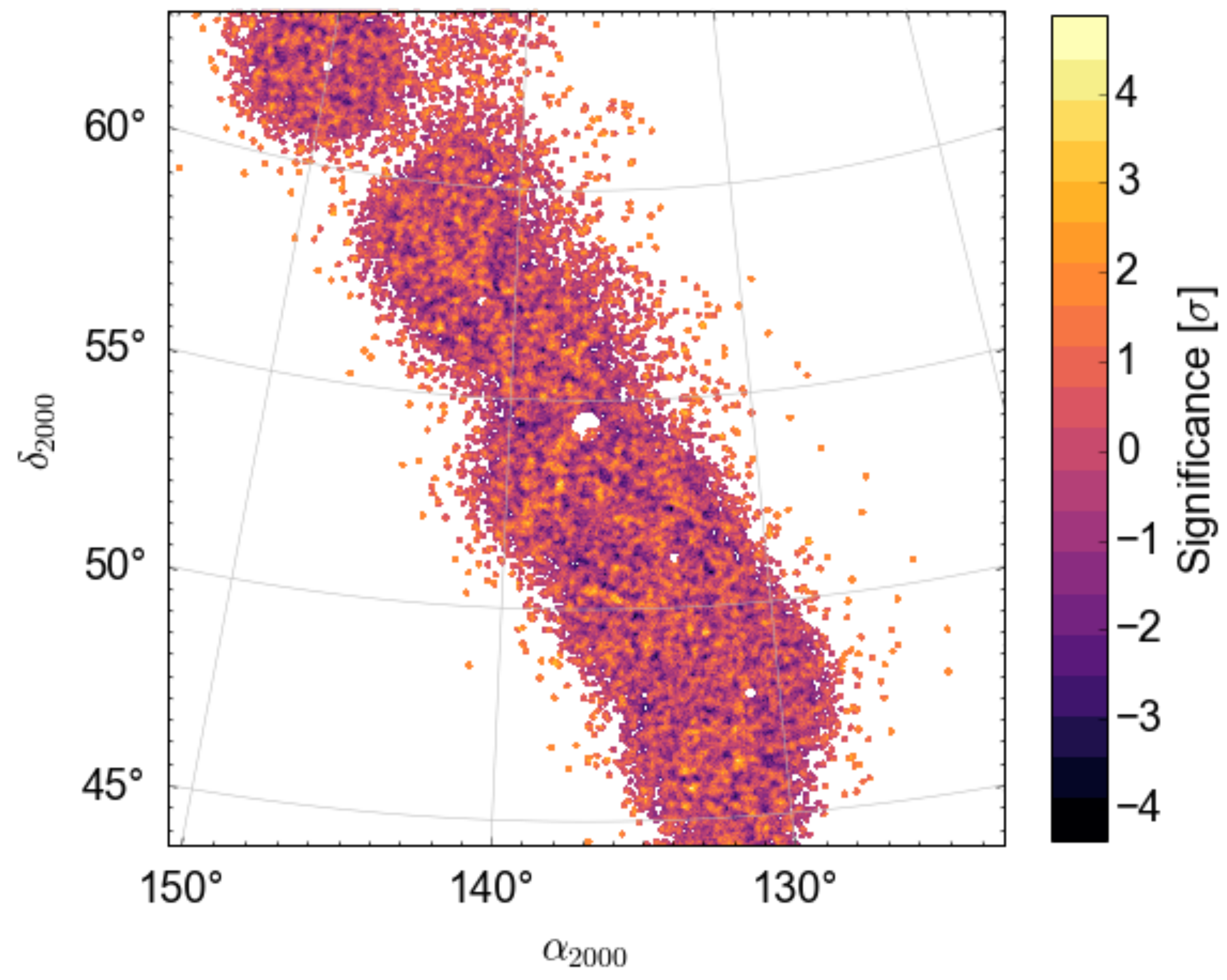


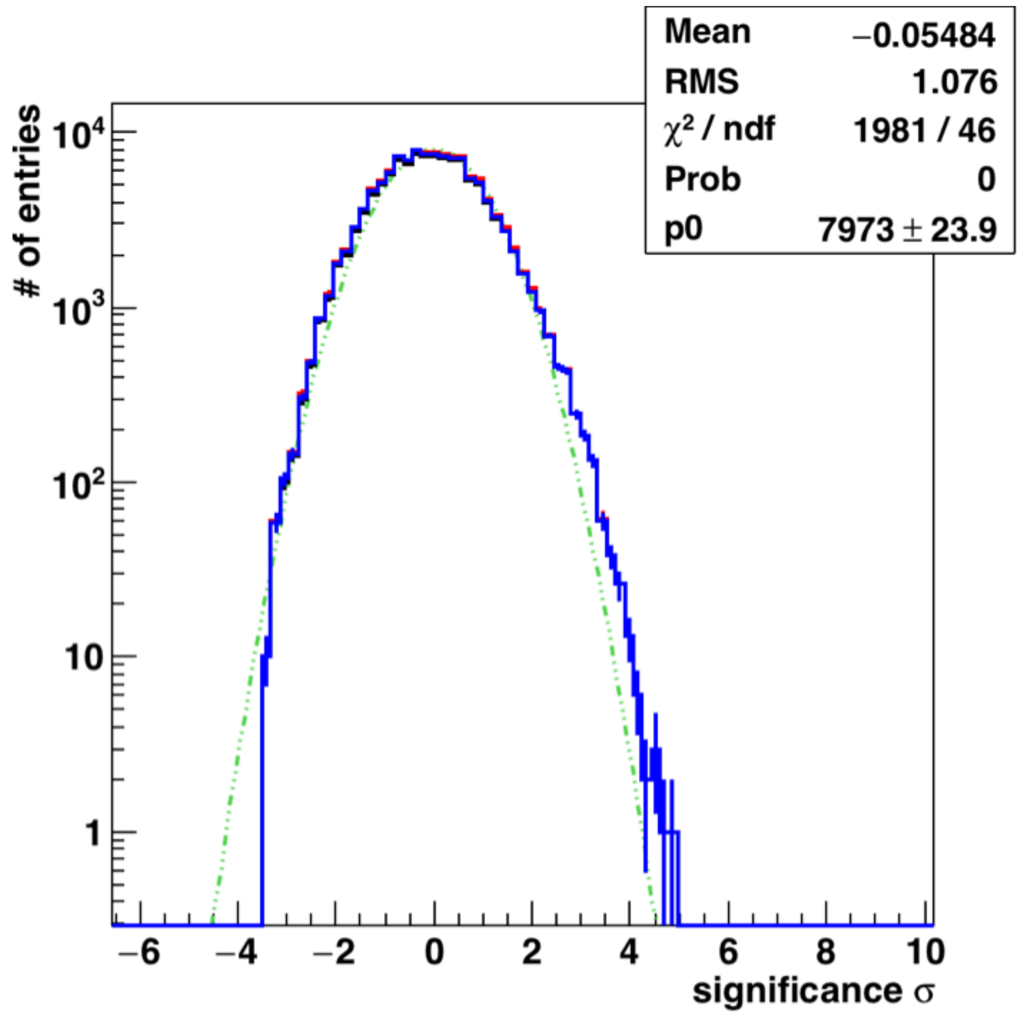
- **GW170817**: First detection of GWs from a neutron star merger which triggered a GRB and a kilonova.
- LIGO provides a horizon for nearby GRB detections, unaffected by EBL absorption.

1) First systematic IACT follow-up of a GW alert

- **GW170104**: 50-M_{sun} BBH merger at z = 0.2 detected by LIGO.
- No EM emission expected. Alert was 6.5 hours old when received. Good visibility of the core region of the event.



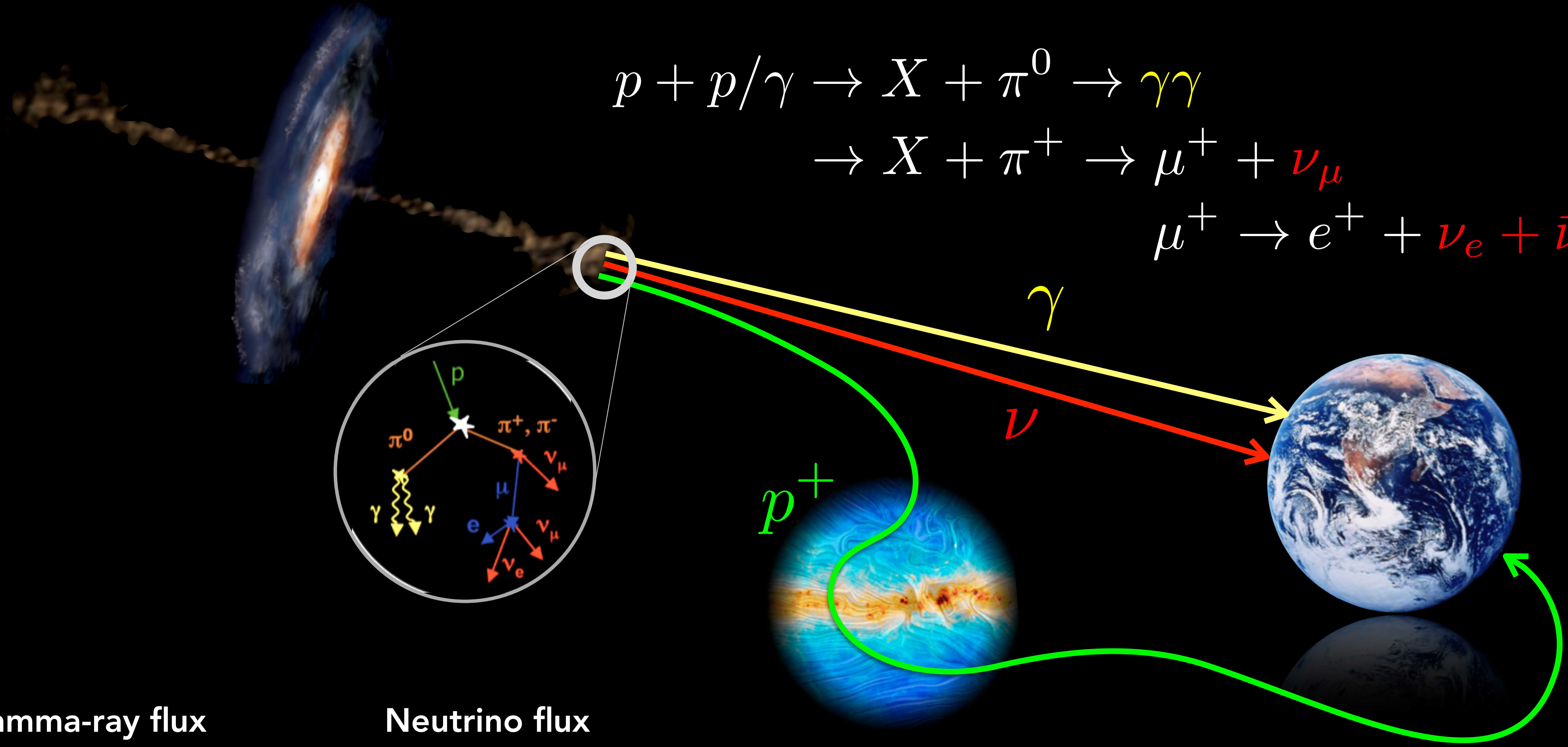




- Preliminary results circulated as GCN #21153
- Currently following up alerts in O3. **First follow-up on 04/12/19**

Neutrinos and gamma rays

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



Gamma-ray flux **Neutrino flux**

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

$E_\gamma = 2E_\nu$

IceCube follow-up programs

Goal: Searching for hadronic VHE emission at the location of single (or clusters of) high-energy muon neutrinos (~1° ang. resolution).

Variety of follow-up approaches:

months-years

- Searches for VHE emission at "archival" muon neutrino positions that are likely astrophysical ($E_\nu \gtrsim 100$ TeV)
- Correlation studies of neutrino and gamma-ray emission from VHE sources.

days weeks

- Observation of neutrino "flares" from known VHE sources.
- Observation of neutrino multiplets.

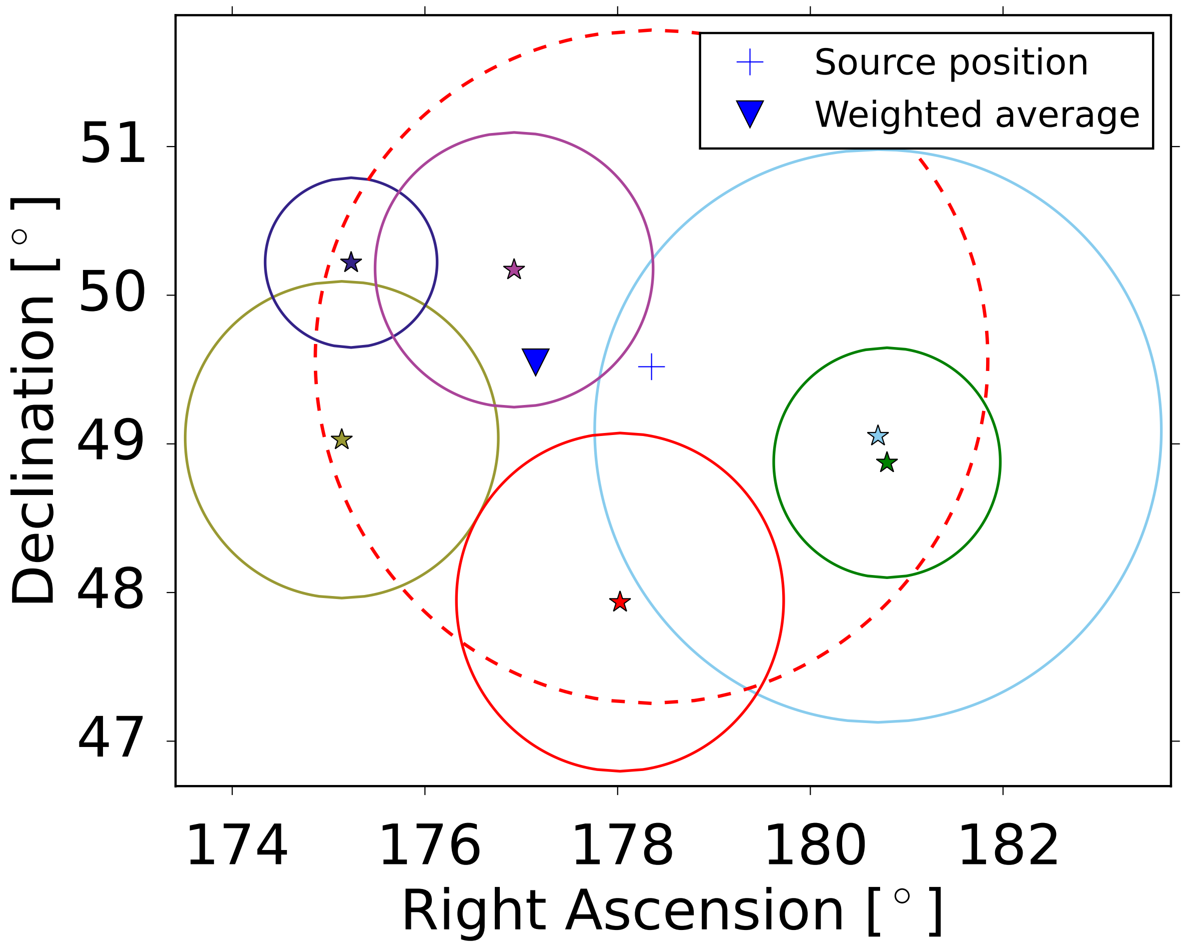
second minutes

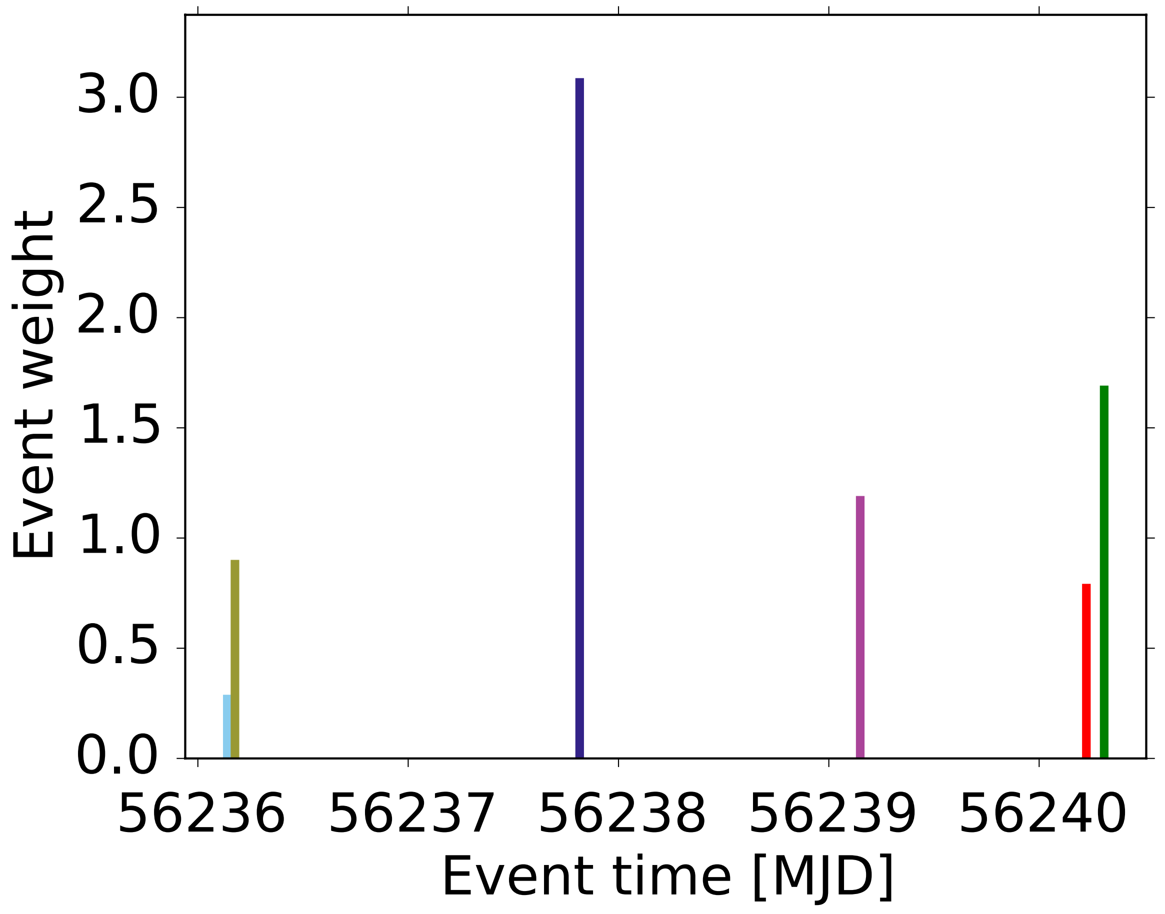
- Observation of prompt online HESE alerts.
- Observation of prompt EHE alerts.

Follow-up time scale

Search for neutrino “flares”and “multiplets”

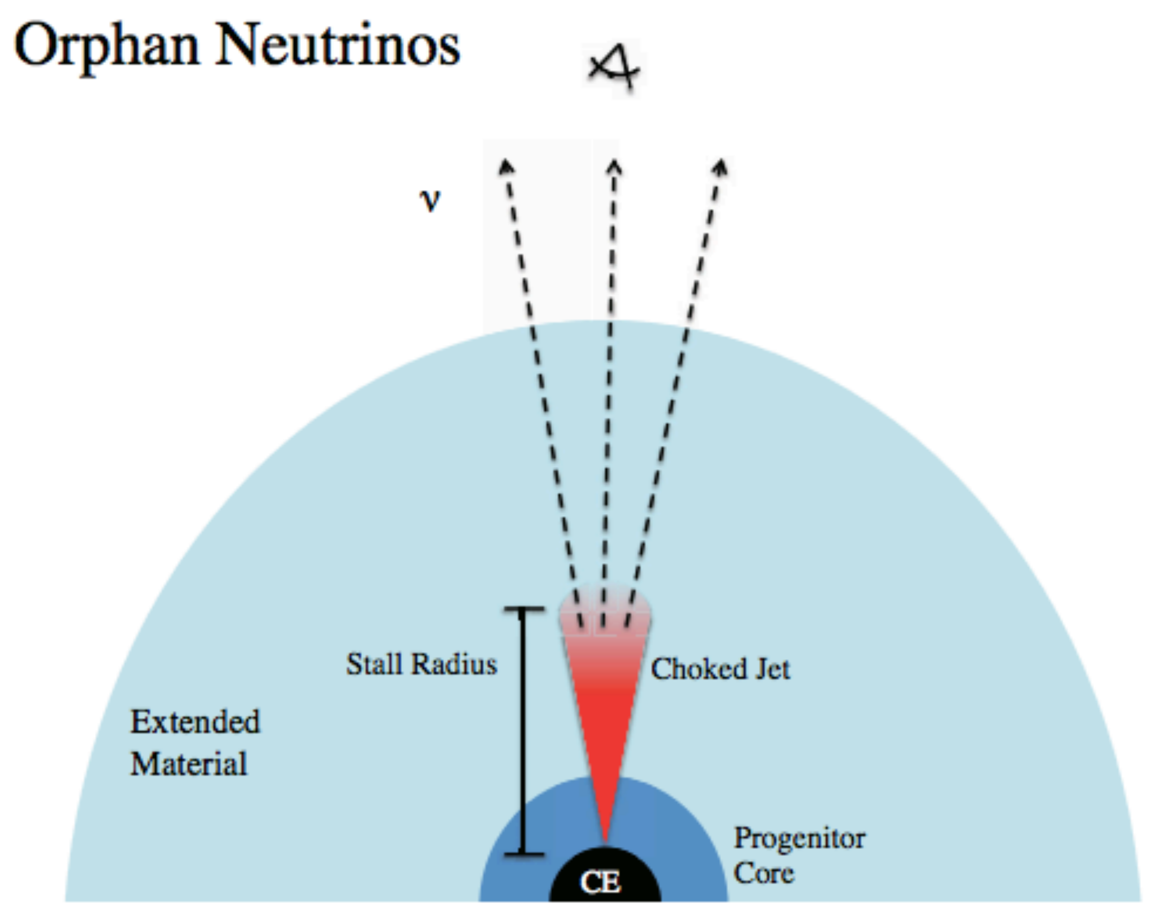
2) Search for a time-dependent neutrino emission from known VHE sources (days)

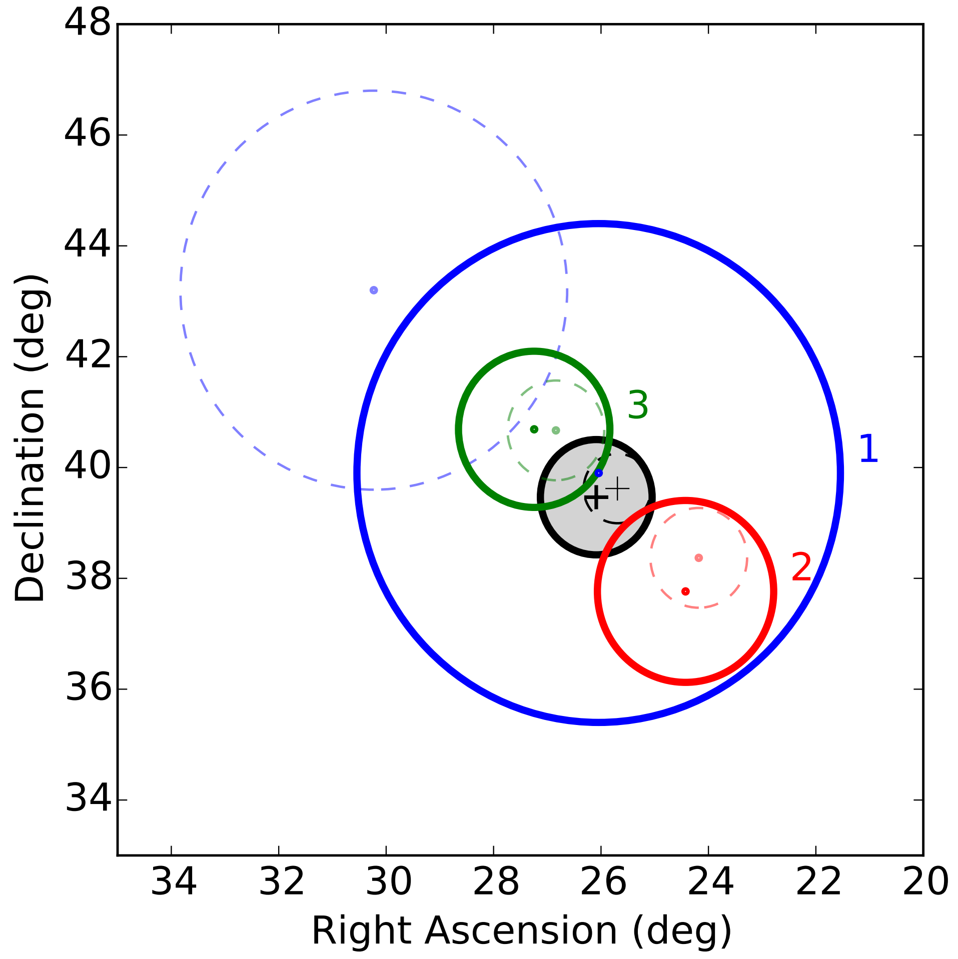


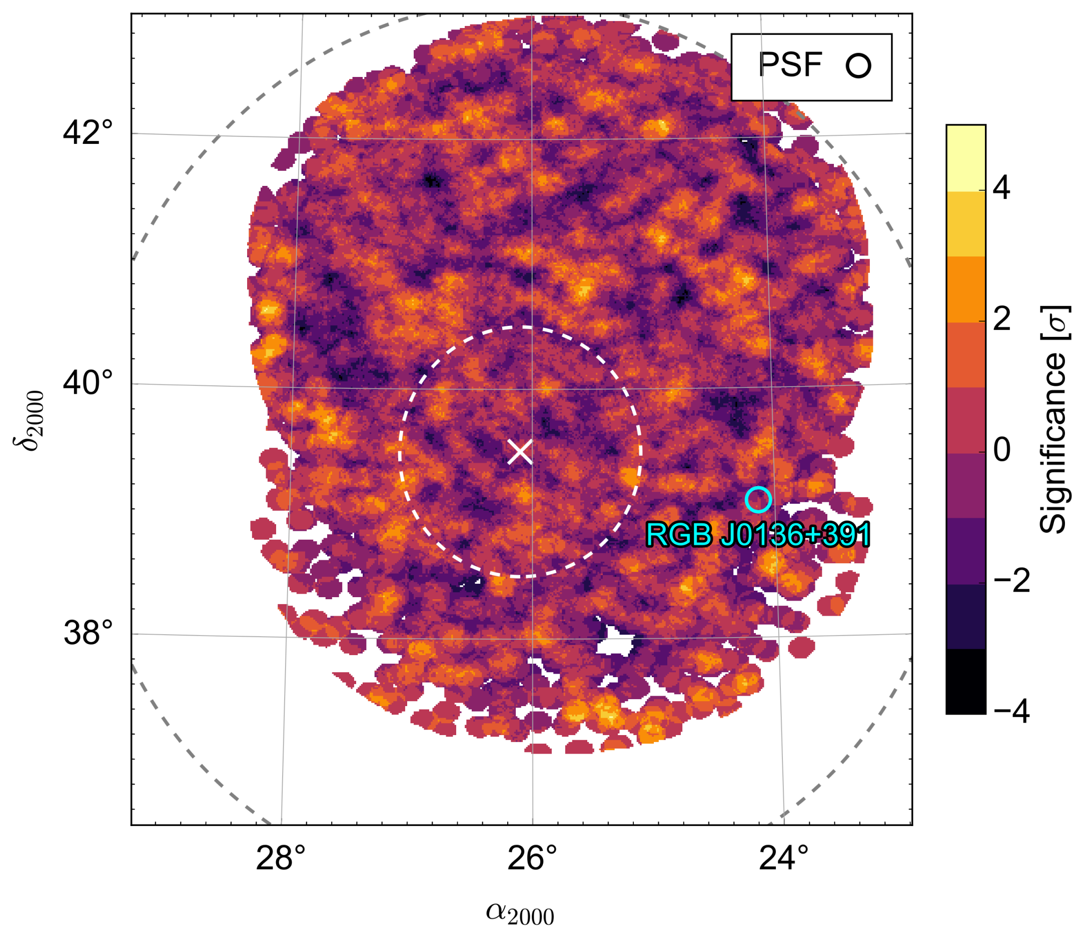


- Three alert follow-ups with VERITAS
- 2016 JINST 11 P11009 (IceCube, MAGIC, VERITAS)
- Neutrino candidates are identified around a list of VHE sources. Number, energy, and position of the events are considered and an alert is sent by IceCube once a trigger condition is satisfied.

3) Search for neutrino “bursts” (multiplicity >= 2) (minutes)



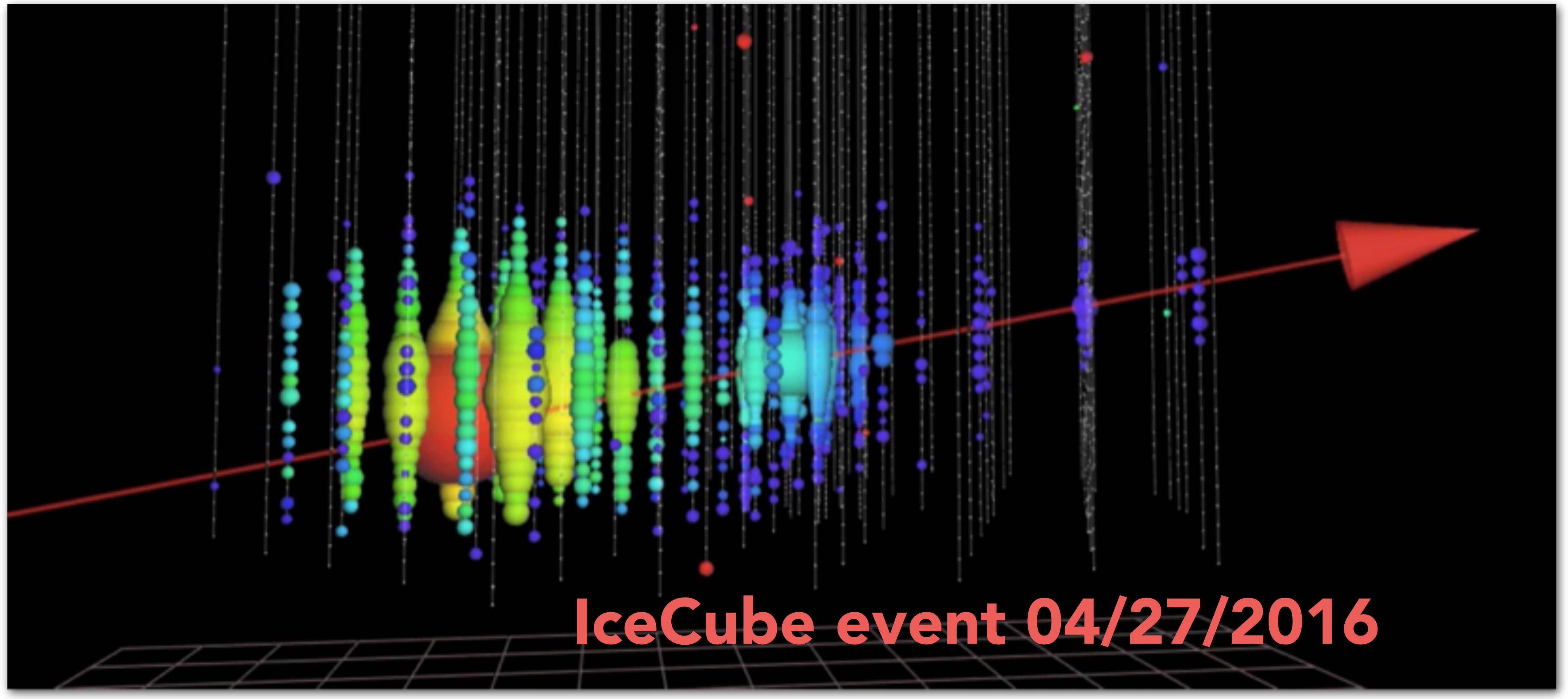




- Two or more neutrinos in spatial coincidence within 100 s.
- Most significant: event triplet detected in Feb 2016. VERITAS observations constrain VHE emission.
- IceCube and MWL partners (including VERITAS) A&A 607, A115 (2017)

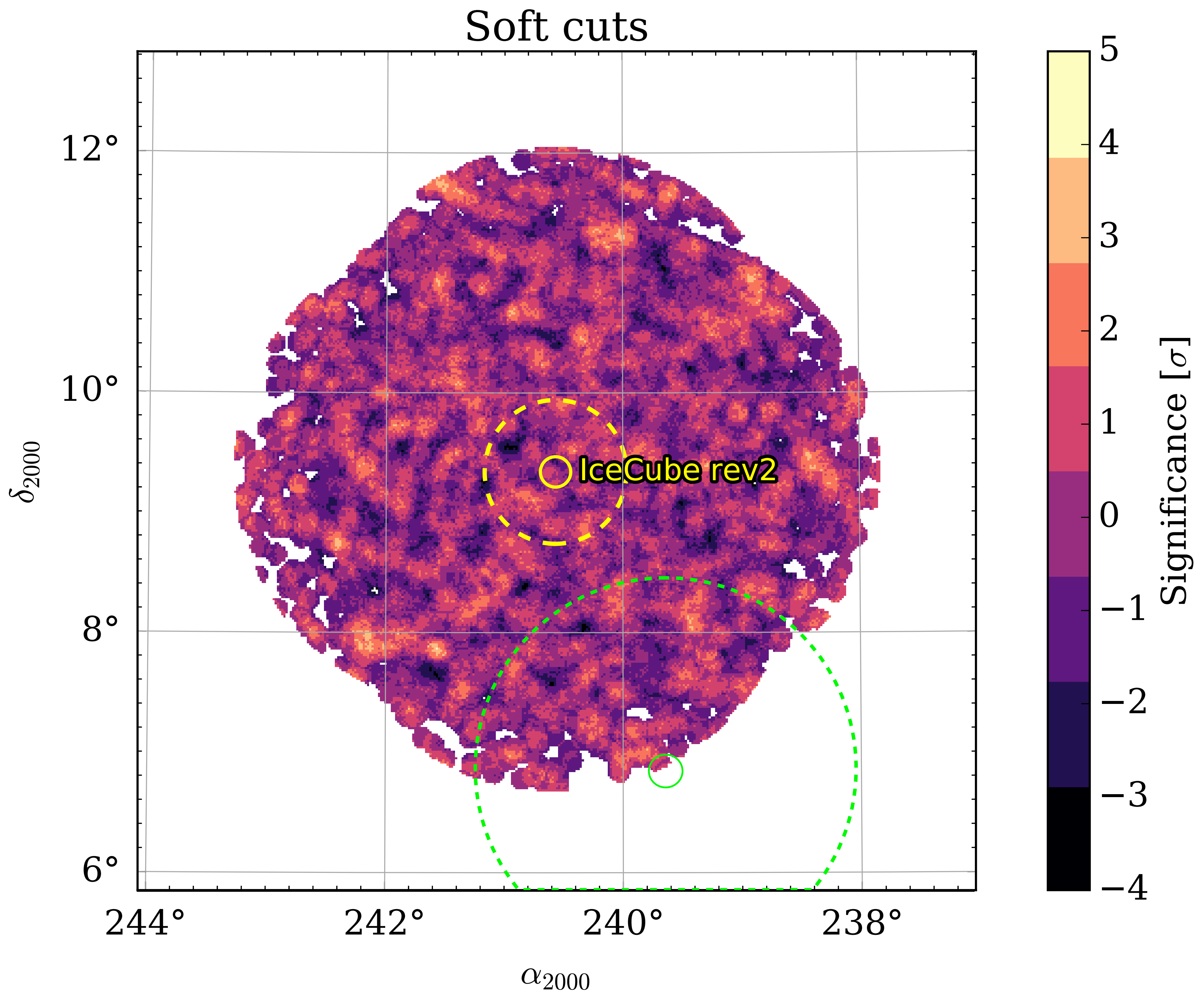
Rapid neutrino follow-up observations

- IceCube distributes realtime GCN alerts for muon neutrino events. Two event streams with ~ 4 event/year each. p_{astro}: 25% and 50%.
- Alerts are received and processed by the VERITAS software as GRBs.
- Alerts started in April 2016, first follow-up by VERITAS on April 27, 2016.
- 4 alerts followed-up to date.

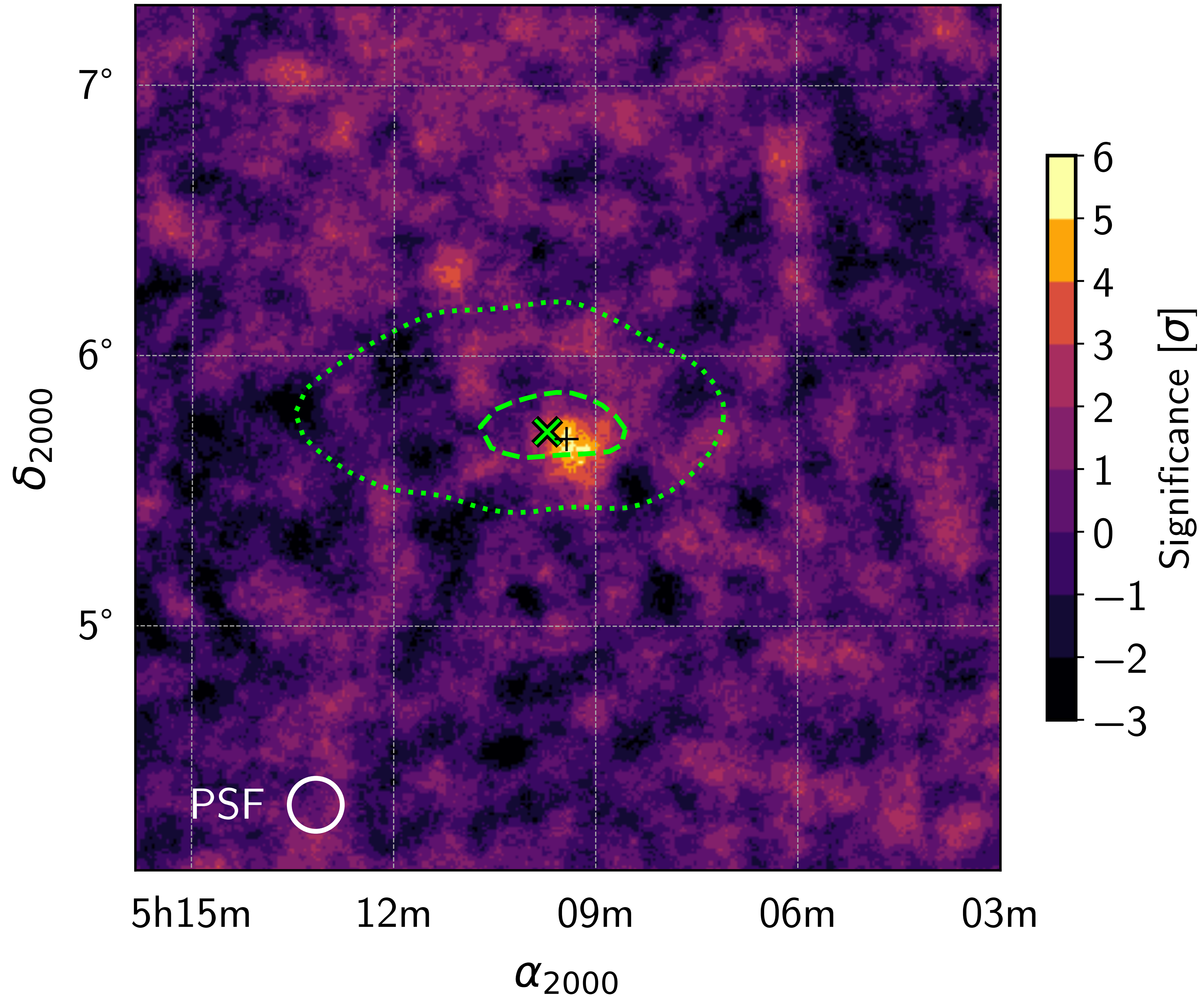


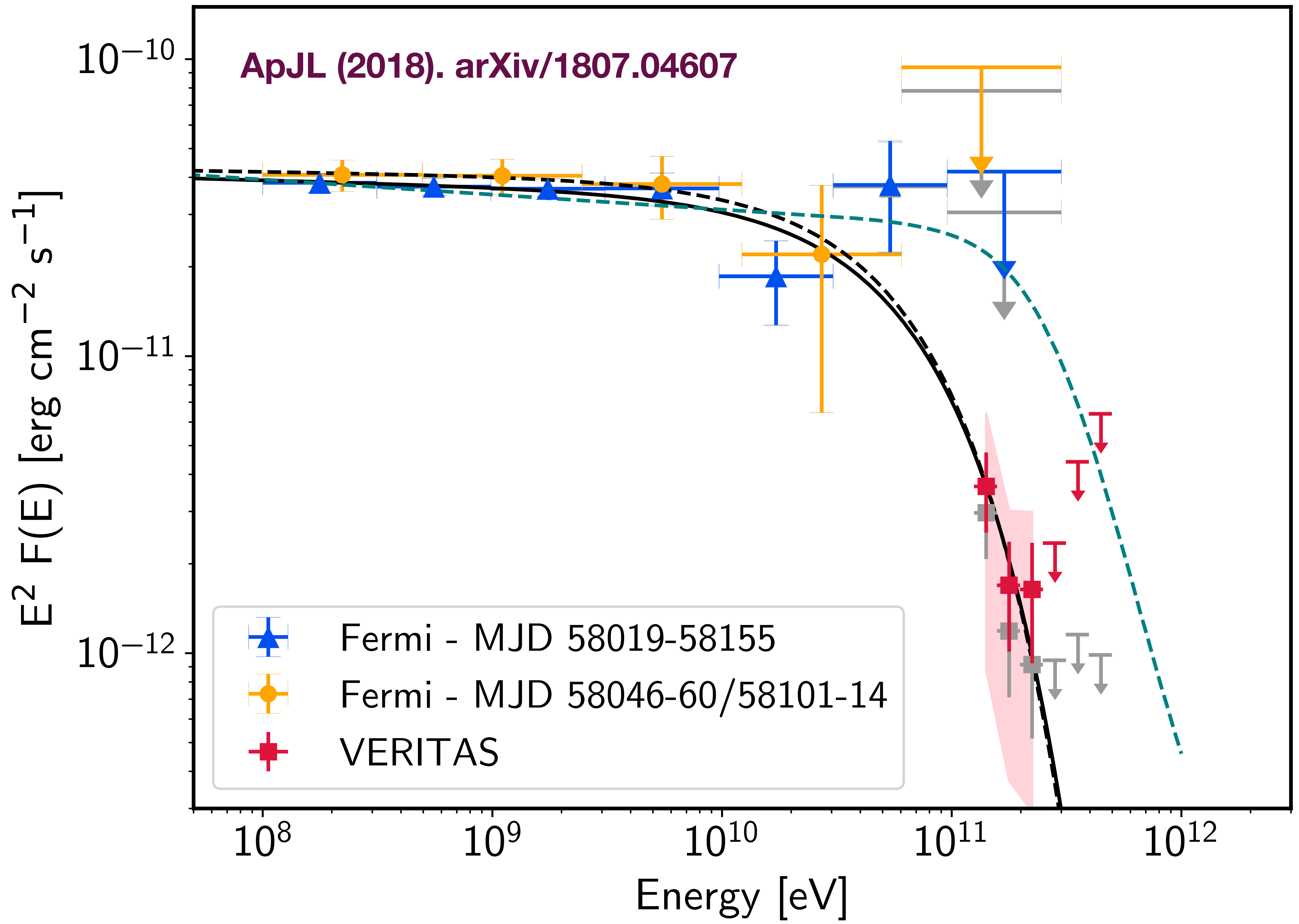
Observation latency: 112 s

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



VERITAS observations of IC170922A

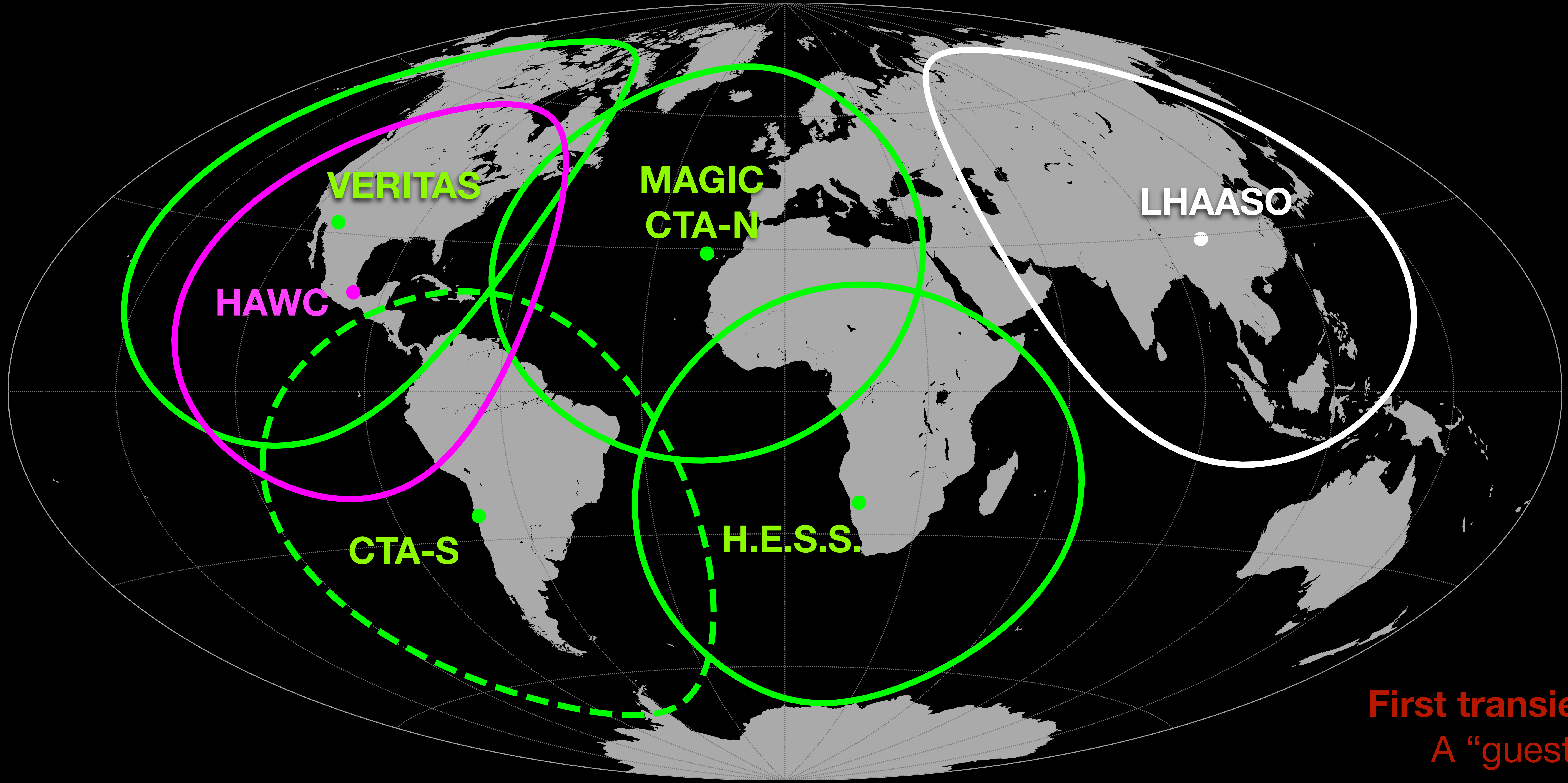


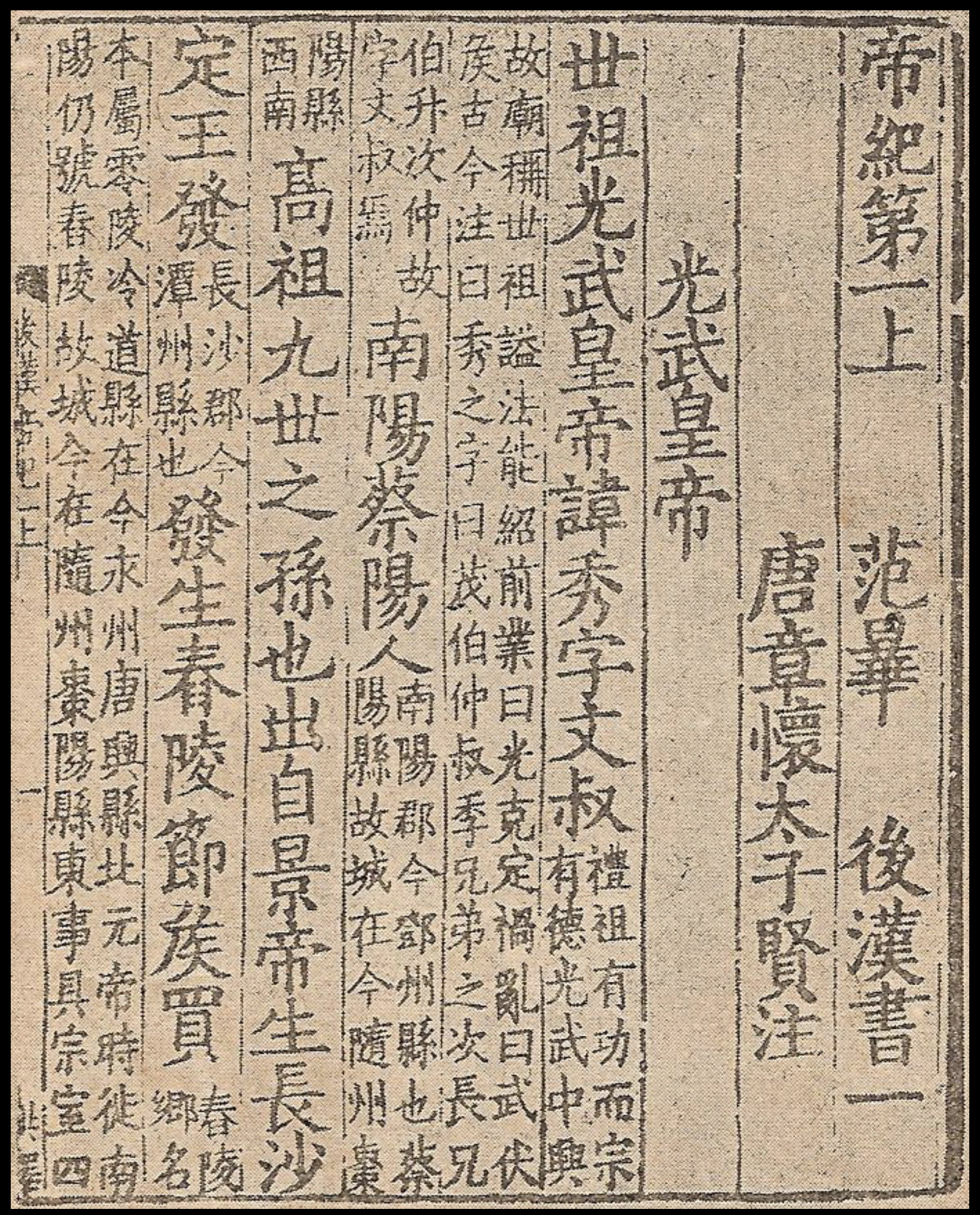


- **IceCube detected a HE neutrino** of potential astrophysical in origin on Sept 22, 2017.
- The event is colocated with the blazar **TXS 0506+056**, observed in a flaring state by *Fermi*. MAGIC detected VHE emission from the blazar within a few days of the neutrino.
- **VERITAS detected the blazar in extended observations through Feb 2018** at a lower flux than MAGIC, also with a soft spectrum (~ E^{-5}).

See papers here: https://icecube.wisc.edu/pubs/neutrino_blazar

VHE gamma-ray landscape





帝紀第一上　范曄　後漢書一
唐章懷太子賢注
光武皇帝
世祖光武皇帝諱秀字文叔禮祖有功而宗有德光武中興故廟稱世祖諡法能紹前業曰光克定禍亂曰武伏侯古今注曰秀之字曰茂伯仲叔季兄弟之次長兄伯升次仲故字文叔焉南陽蔡陽人南陽郡今鄧州縣也蔡陽縣故城在今隨州棗陽縣西南高祖九世之孫也出自景帝生長沙定王發長沙郡今潭州縣也發生舂陵節侯買舂陵鄉名本屬零陵冷道縣在今永州唐興縣北元帝時徙南陽仍號舂陵故城今在隨州棗陽縣東事具宗室四

First transient astrophysical source: SN 185

A “guest star” in the *Book of the Later Han*

- The start of LHAASO operations will not only improve our view of the VHE sky but also increase the global VHE coverage to transient and multi-messenger events.
- **Our best wishes for a successful operation of LHAASO and many discoveries. We look forward to future collaborations!**

Thank you!

The VERITAS Collaboration