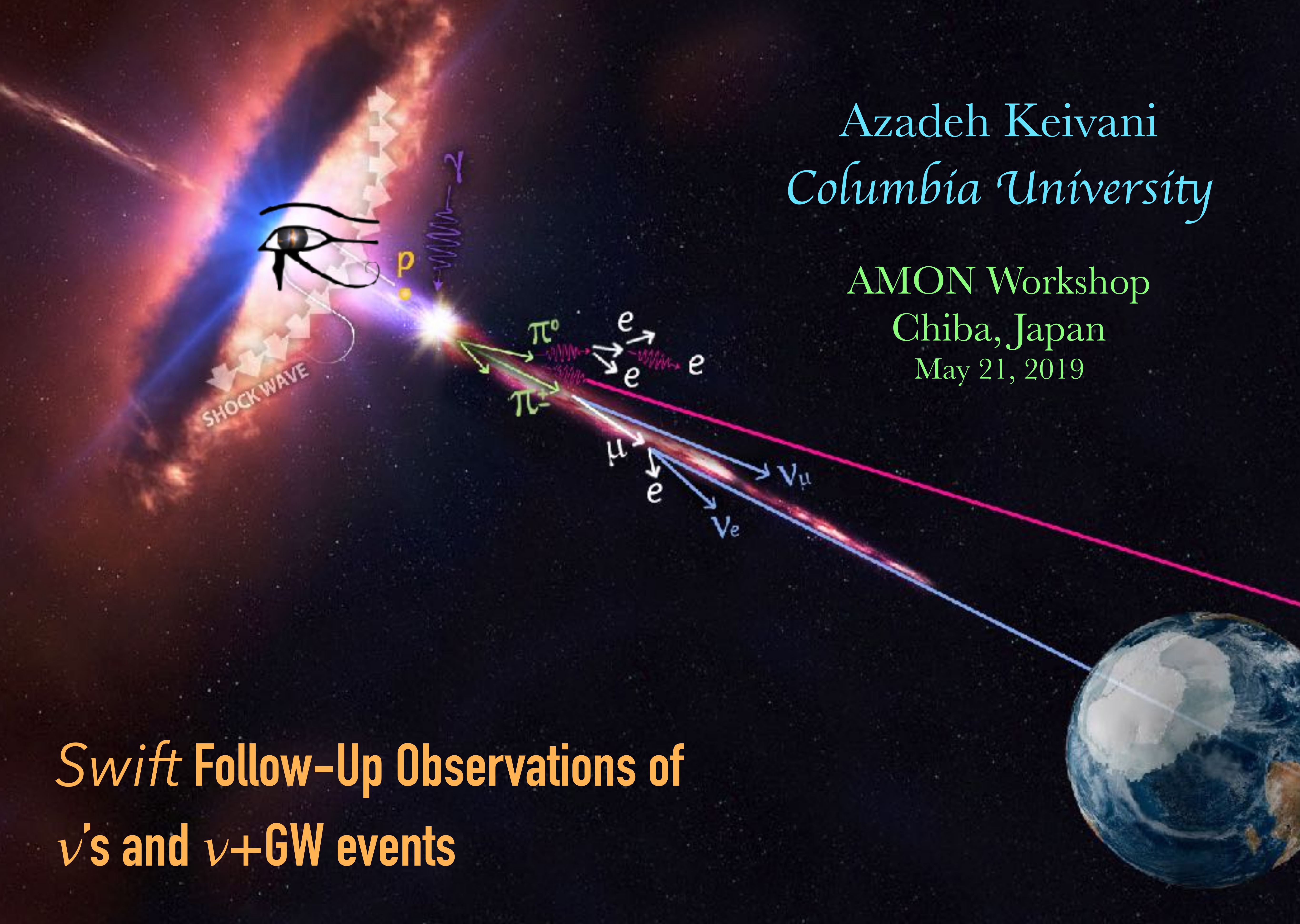
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



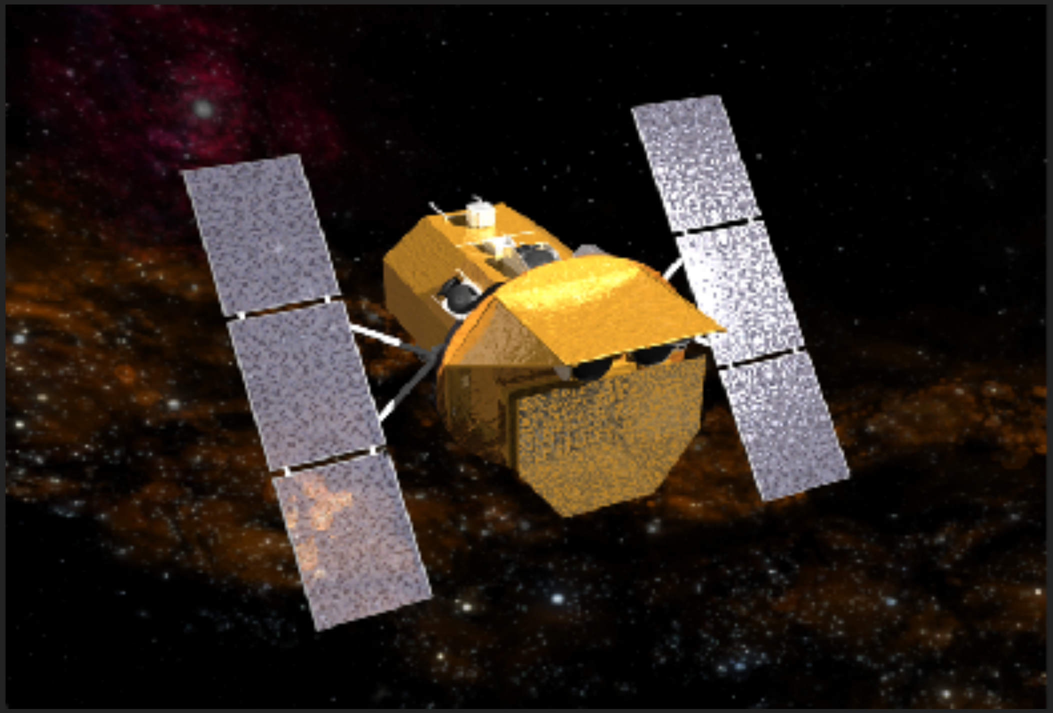
Azadeh Keivani
Columbia University

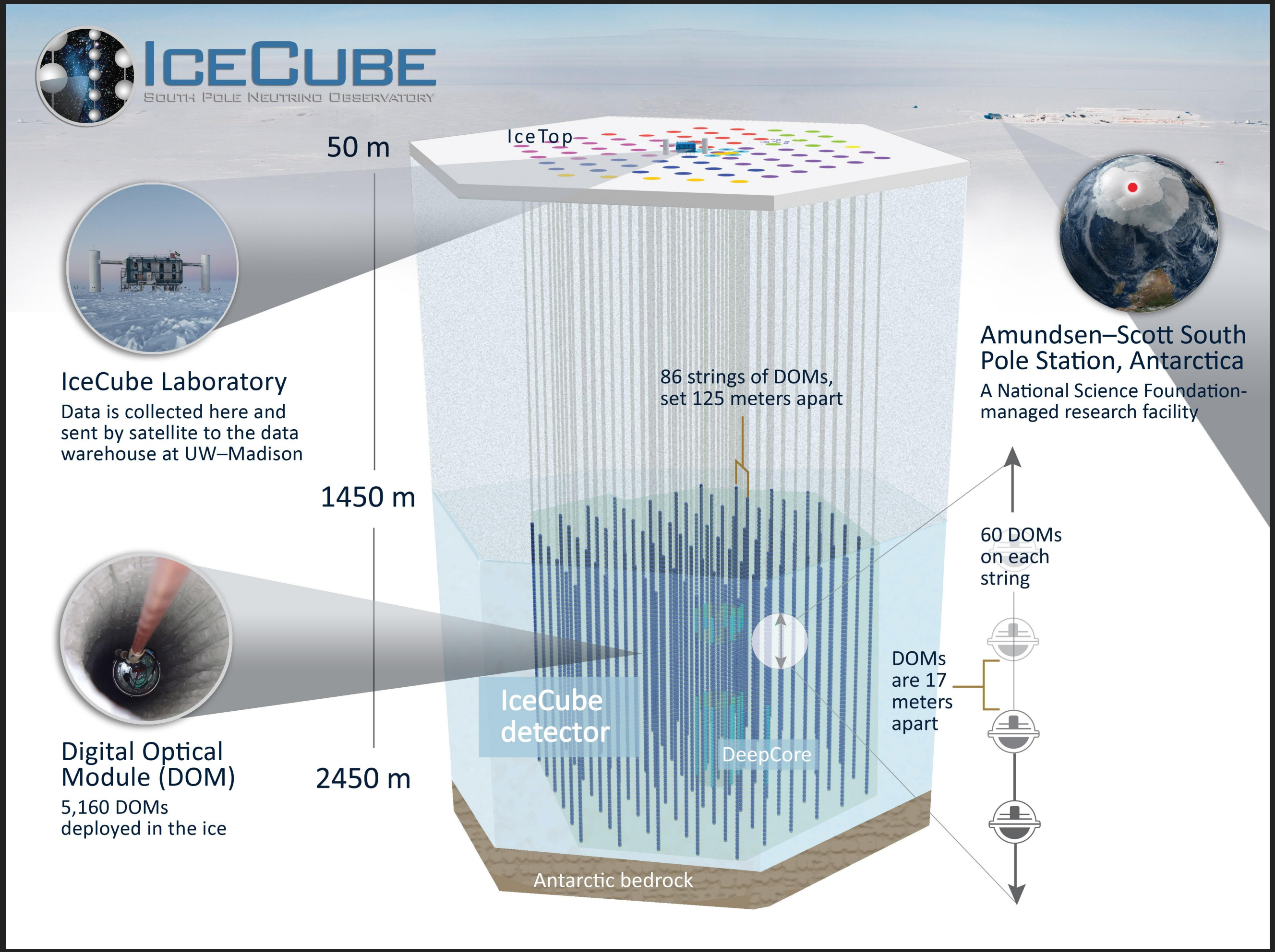
AMON Workshop
Chiba, Japan
May 21, 2019

Swift Follow-Up Observations of ν's and ν+GW events

Swift follow-up of IceCube neutrinos

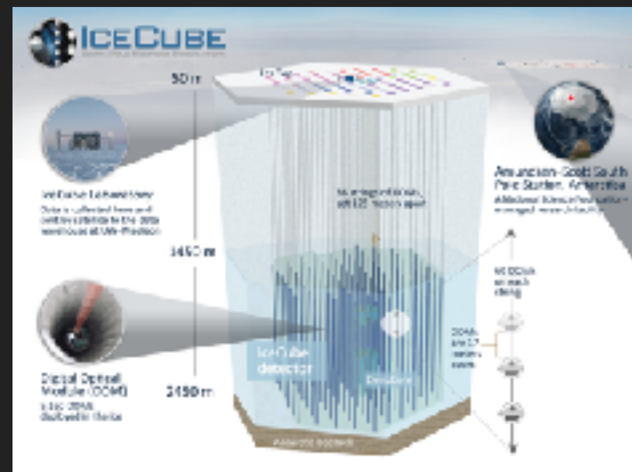
- ★ *Swift* is a powerful tool to search for transients
- ★ *Swift* searches for EM counterpart to IceCube neutrinos
- ★ Set useful constraints on associated transients
- ★ Started in 2016: *Swift* Guest Investigator Program, Cycles 12 and 14 awarded
- ★ Priority I ToO
- ★ Automated system in place



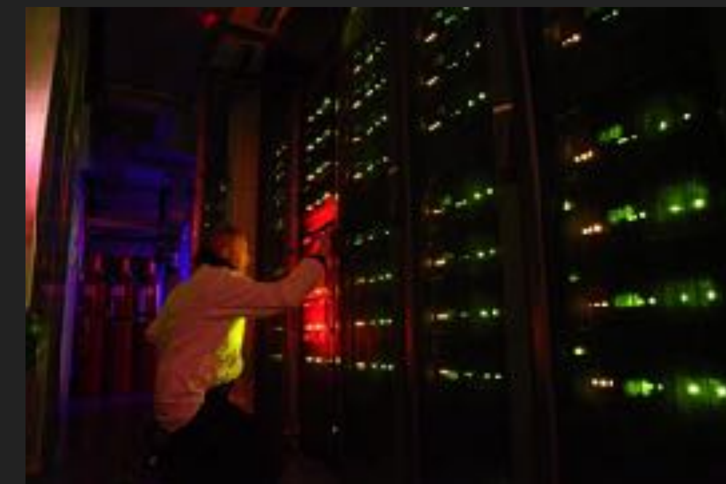


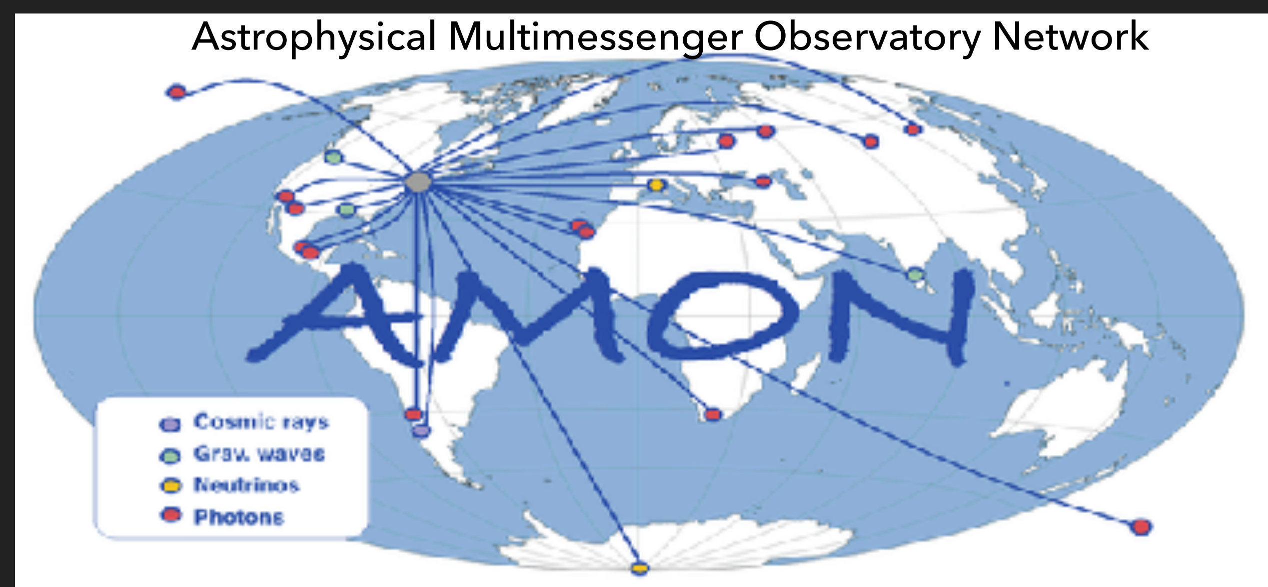
IceCube Realtime Alert System and AMON

High-energy ν's detected at the South Pole



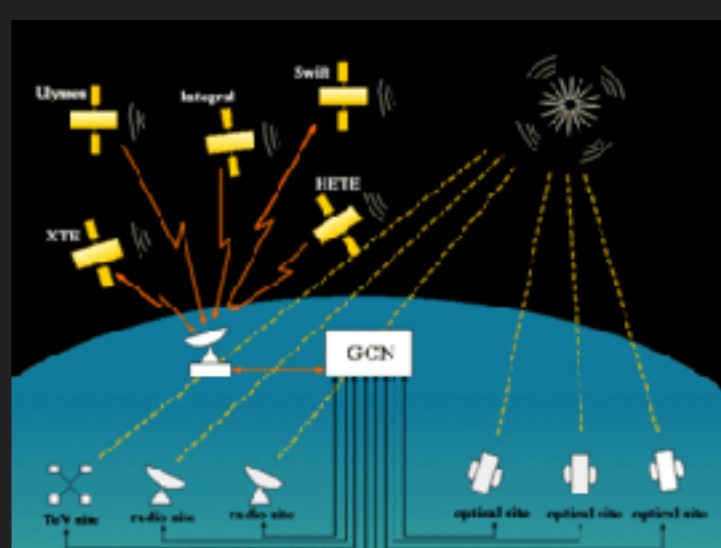
Transferred to UW-Madison





Sent to AMON at Penn State

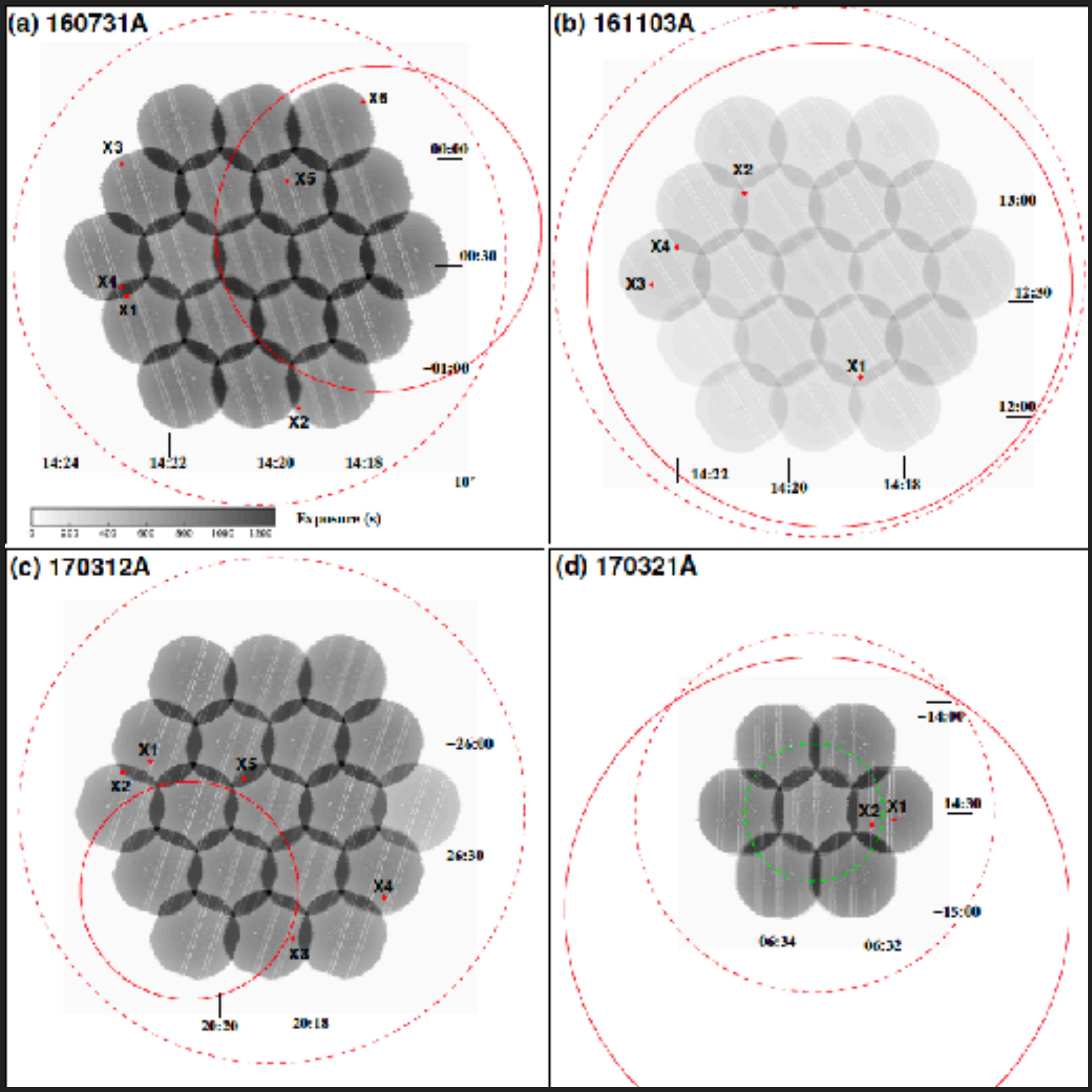
Sent to GCN



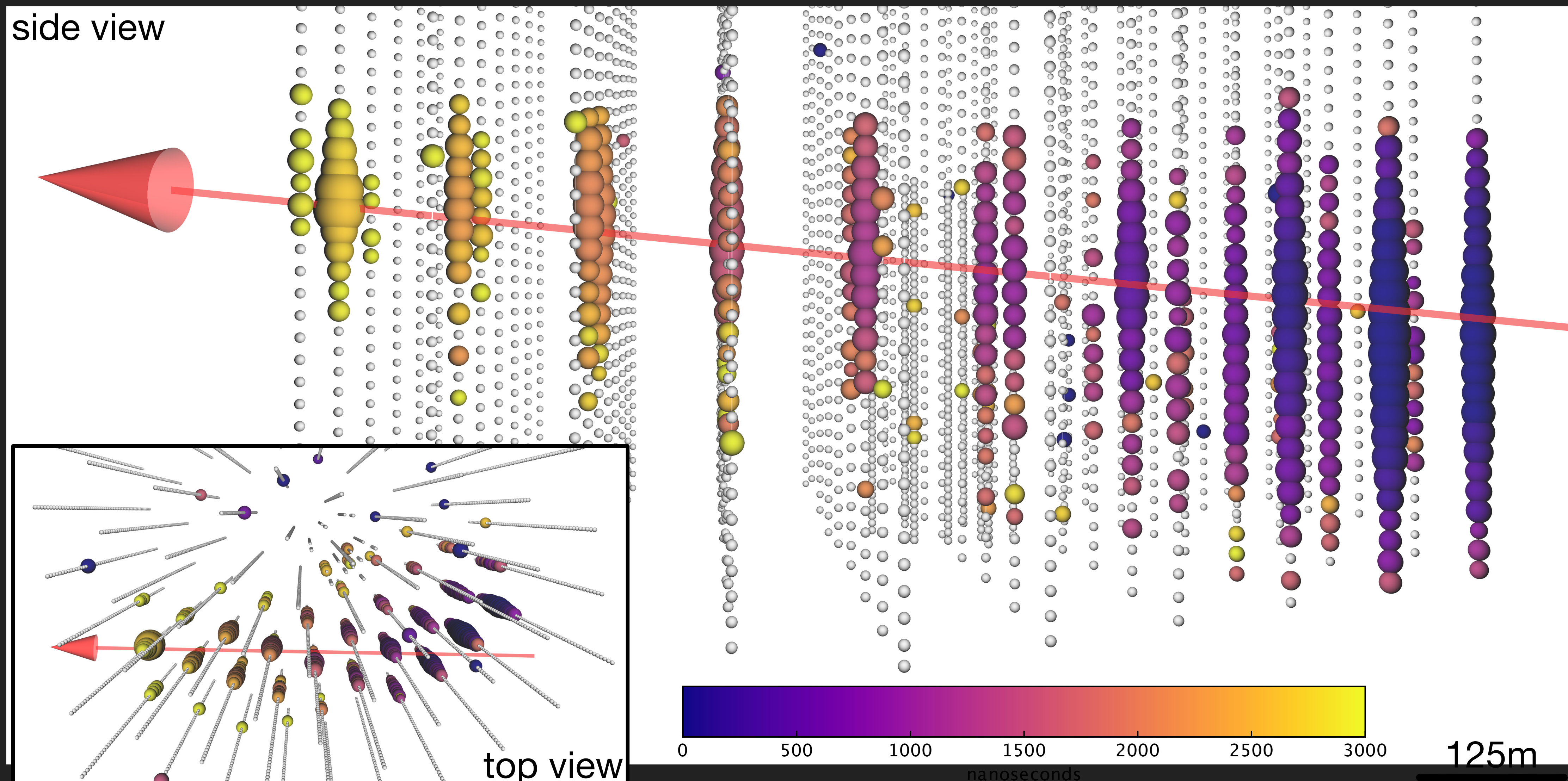
(Automatically) trigger observatories

Swift Observations

- IceCube high energy neutrinos trigger *Swift* via AMON
- Rapid-response mosaic-type follow-up observations
- 7 or 19-point tiling depending on the size of neutrino error region
- ~1 ks of photon counting per tile
- X-ray sources found using automated scripts in place (Evans et al. ApJS 210, 8, 2014)
- Energy range: 0.3-10 keV
- In case of interesting sources monitoring of certain sources requested



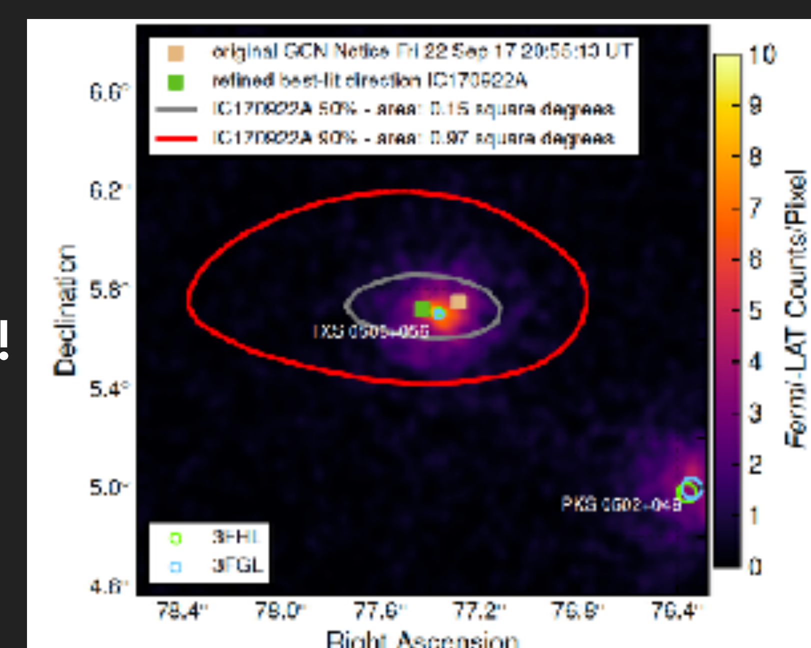
IceCube-170922A: A High-Energy Neutrino



On Sept 22, 2017, IceCube detected a high-energy ν ≅ 290 TeV energy!
Selected by Extremely High-Energy (EHE) stream

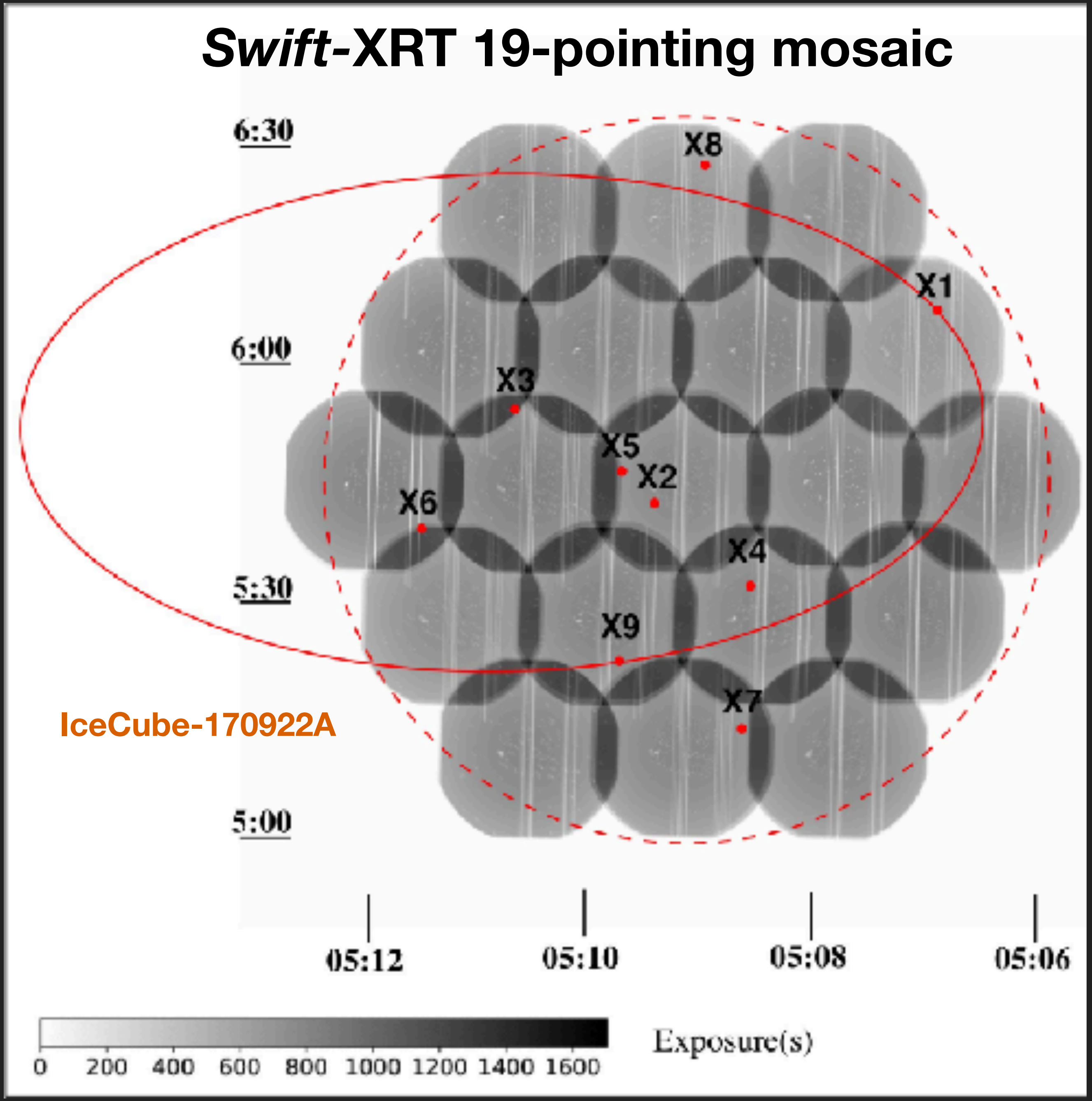
IceCube Collaboration, et al., Science 361, eaat1378 (2018)

Swift XRT was the first to observe and report TXS 0506+056 in the FoV!
Fermi LAT was the first telescope to report that TXS 0506+056 was in a flaring state!
An extensive multi-wavelength campaign happened!



Swift Observations of IceCube-170922A

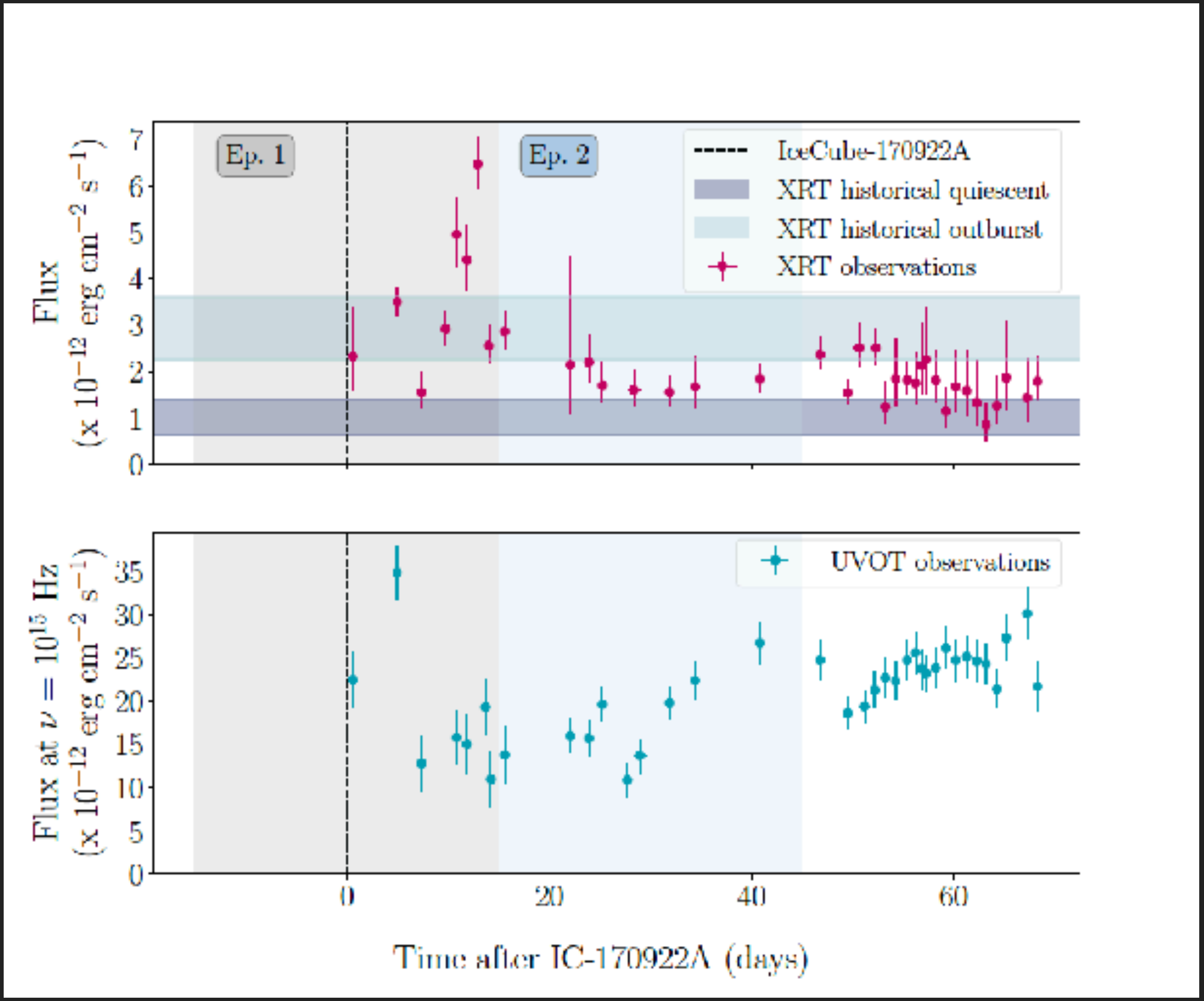
- IceCube-170922A triggered *Swift* in automated fashion via AMON
- 19-point tiling
- 3.25 hr after the neutrino detection
- Spanned 22.5 hr
- 9 X-ray sources
- X2: TXS 0506+056 (4.6′ away)
- Peak Flux:
  3.8e-12 ± 8.6e-13 erg cm^{-2} s^{-1}
  (0.3-10 keV)
- Following the Fermi report of TXS 0506+056 in a GeV-flaring state: Swift monitoring campaign started



AK, P.A.Evans, et al., GCN Circular 21930 (2017)

Swift Flux of TXS 0506+056

- 36 more epochs until the end of Nov 2017 (~54 ks)
- Mean flux = 2.27e-12 erg cm^{-2} s^{-1} (0.3-10 keV)
- N_H = 1.11 x 10^{21} cm^{-2}
- Horizontal bands: XRT historical data
- Two epochs: [-15d, +15d] & [+15d, +45d]

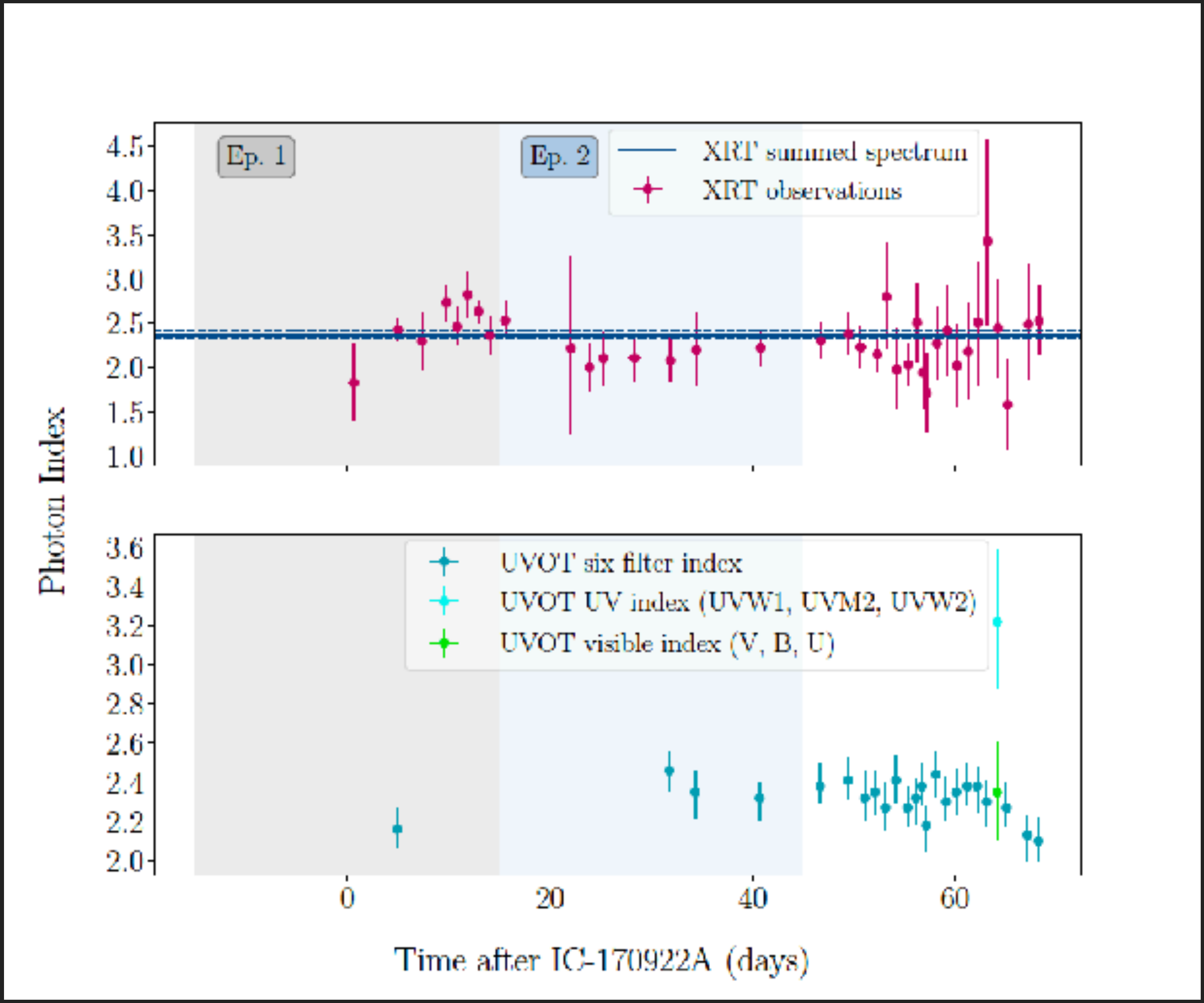


P.A.Evans, AK, et al., ATel 10792 (2017)

AK, Murase, Petropoulou, Fox, et al. ApJ 864 (2018)

Swift Spectral Variability of TXS 0506+056

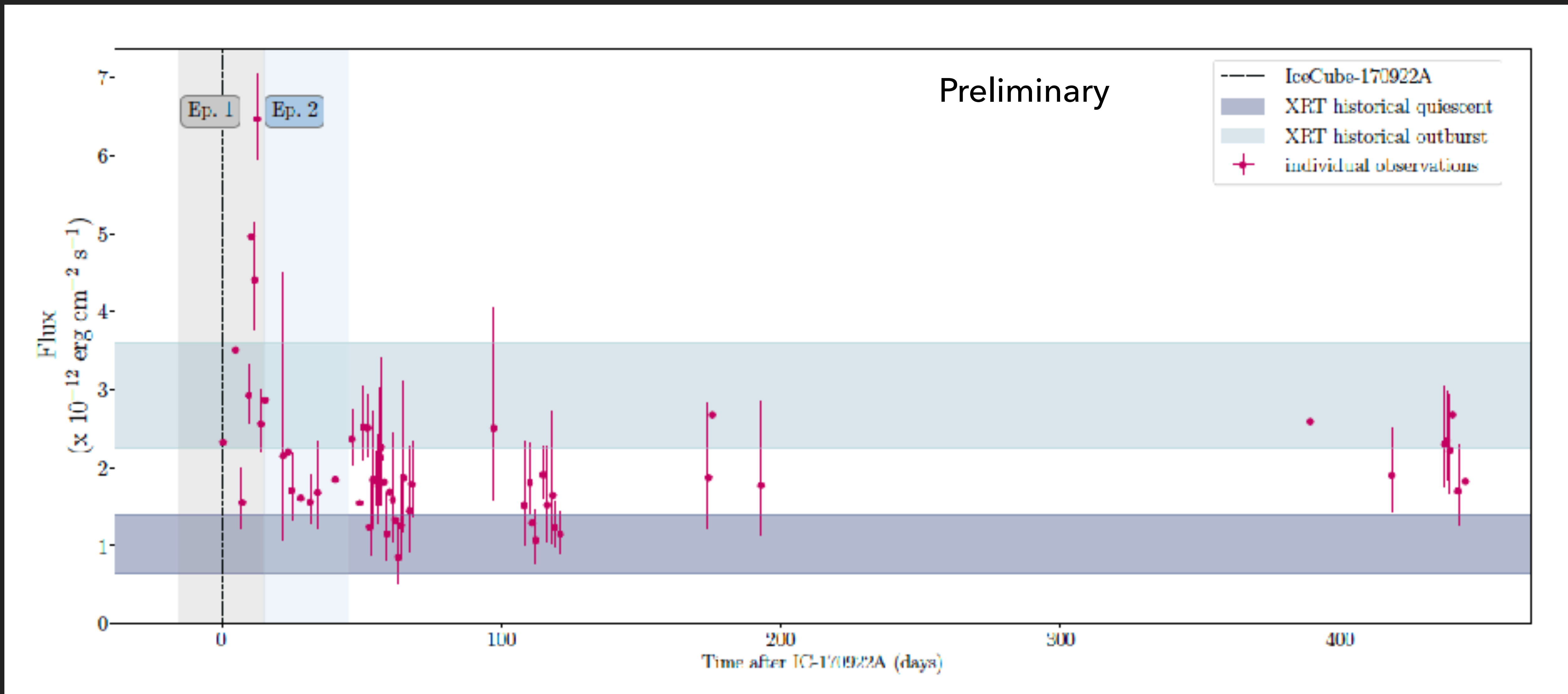
- Solid horizontal: photon index of the stacked X-ray spectrum over the 2 epochs
- Dashed lines: uncertainties
- $\alpha_{XRT} = 2.37 \pm 0.05$
- UVOT photon index obtained from a power-law fit to the energy flux spectrum



P.A.Evans, AK, et al., ATel 10792 (2017)

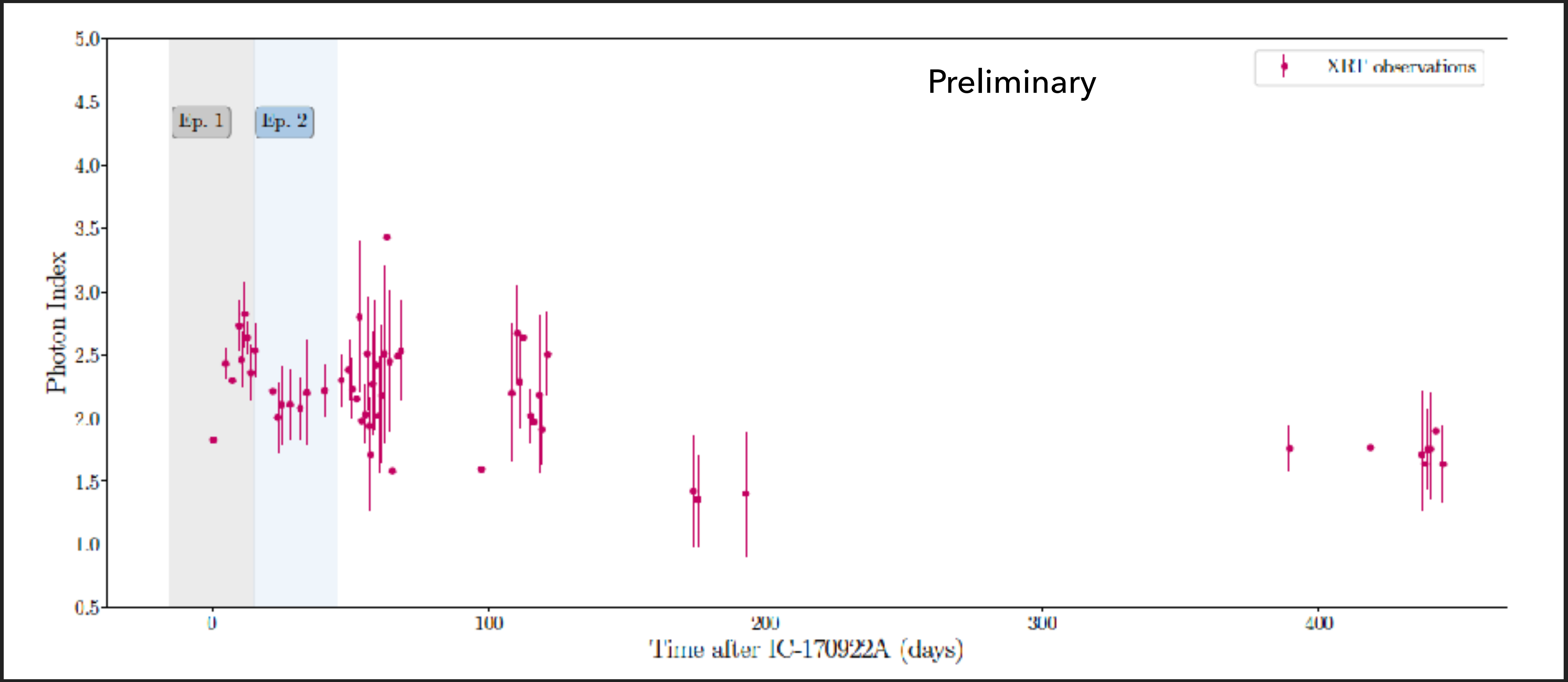
AK, Murase, Petropoulou, Fox, et al. ApJ 864 (2018)

Swift Flux: More Observations of TXS 0506+056



- ⭐22 more epochs after Nov 2017 (Dec 2017 - Dec 2018)
- ⭐Observation in the 0.3-10 keV
- ⭐$N_H = 1.11 \times 10^{21}$ cm^{-2}
- ⭐Horizontal bands: XRT historical data (from before IceCube-170922A)

Swift Spectral Variability: More Observations of TXS 0506+056



- ⭐36 epochs in Ep. 1 and Ep. 2
- ⭐22 more epochs after Nov 2017 (Dec 2017 - Dec 2018)
- ⭐Observation in the 0.3-10 keV

IceCube-190331A: A High-Energy Neutrino

IceCube Collaboration, GCN Circular 24028 (2019)

- ⭐ March 31, 2019:
  IceCube detected a high-energy ν,
  deposited charge ~ 199 kpe!
- ⭐ Selected by high-energy starting event (HESE) stream
- ⭐ Initial direction was incorrect
- ⭐ Direction in Sun avoidance region for *Swift* initially
- ⭐ Observations started 9 days later
- ⭐ *Swift* followed up the updated direction

TITLE: GCN CIRCULAR
NUMBER: 24028
SUBJECT: IceCube-190331A - IceCube observation of a high-energy neutrino candidate event
DATE: 19/03/31 19:12:37 GMT
FROM: Claudio Kopper at IceCube/U of Alberta <ckopper@icecube.wisc.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On March 31, 2019, IceCube detected a track-like, very-high-energy event with a high probability of being produced by a muon neutrino of astrophysical origin. The event was identified by the High Energy Starting Event (HESE) track selection. The IceCube detector was in a normal operating state. HESE tracks have a neutrino interaction vertex inside the detector and produce a muon that only partially traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert was issued, visual inspection of the event revealed that the online directional reconstruction reported in the original GCN (https://gcn.gsfc.nasa.gov/notices_amon/15947448_132379.amon) was very incorrect, biased by the topology of the event. More sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2019/03/31
Time: 06:55:43.44 UT
RA: 337.68deg (+0.23deg -0.34deg 90% PSF containment) J2000
Dec: -20.70deg (+0.30deg -0.48deg 90% PSF containment) J2000

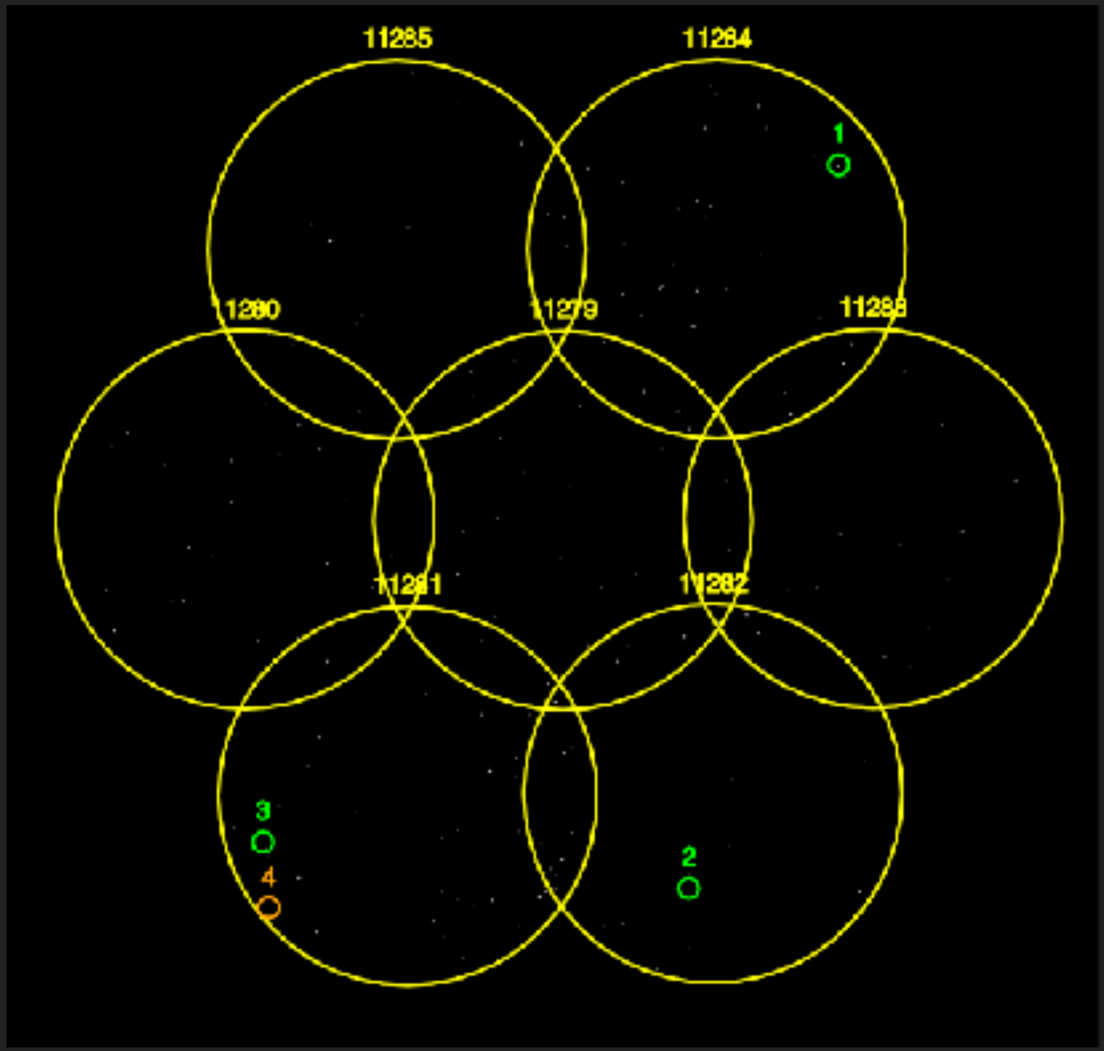
Additionally, given the large deposited energy observed in this event (one of the highest observed so far), it has a very high likelihood of being of astrophysical origin. We strongly encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

There are no Fermi 4FGL catalog sources in the 90% region. The nearest source is 1RXS J223249.5-202232 (4FGL J2232.6-2023) at RA: 338.1725deg, Dec: -20.3909deg.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu .

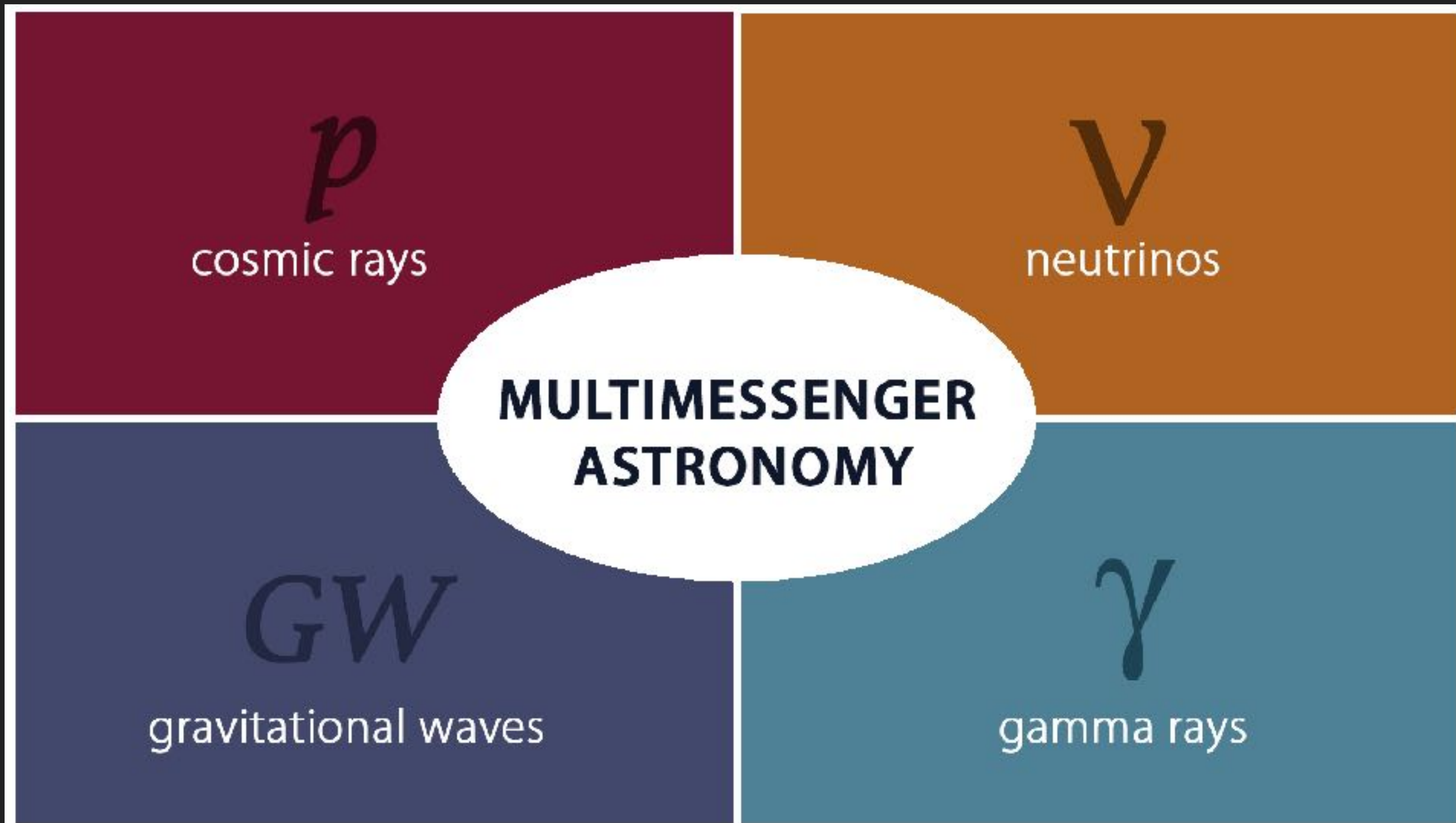
Swift Observations of IceCube-190331A

- 7-point tiling
- Four X-ray sources
- Three consistent with expectations for serendipitous (unrelated) sources
- **Source #1:** 1WGA J2229.4-2018 from ROSAT/WGACAT (15″ away)
- 1.5σ above WGACAT flux
- More observations performed
- No significant variability observed
- Work under progress

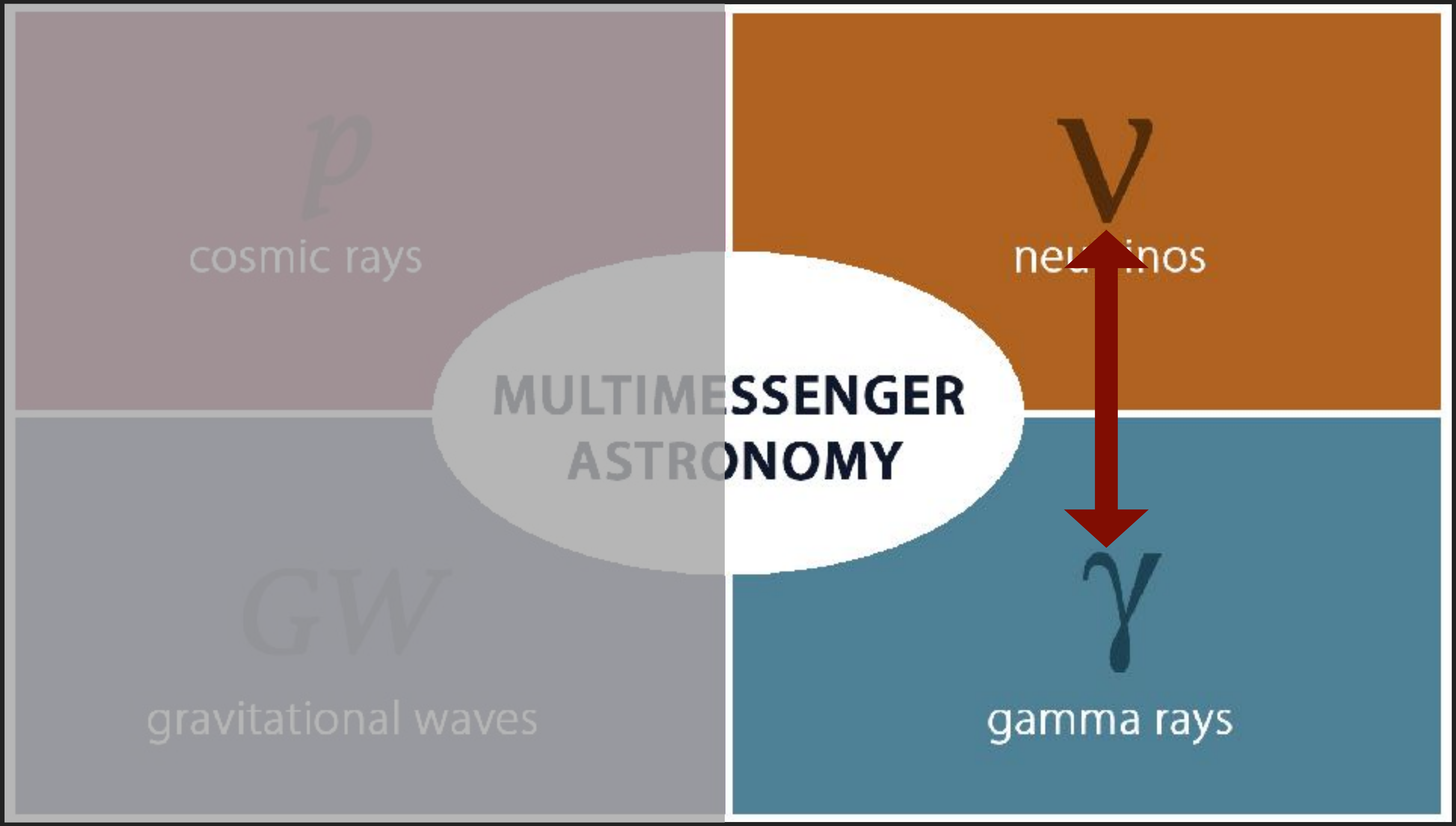


AK, M. Santander, et al., GCN Circular 24094 (2019)

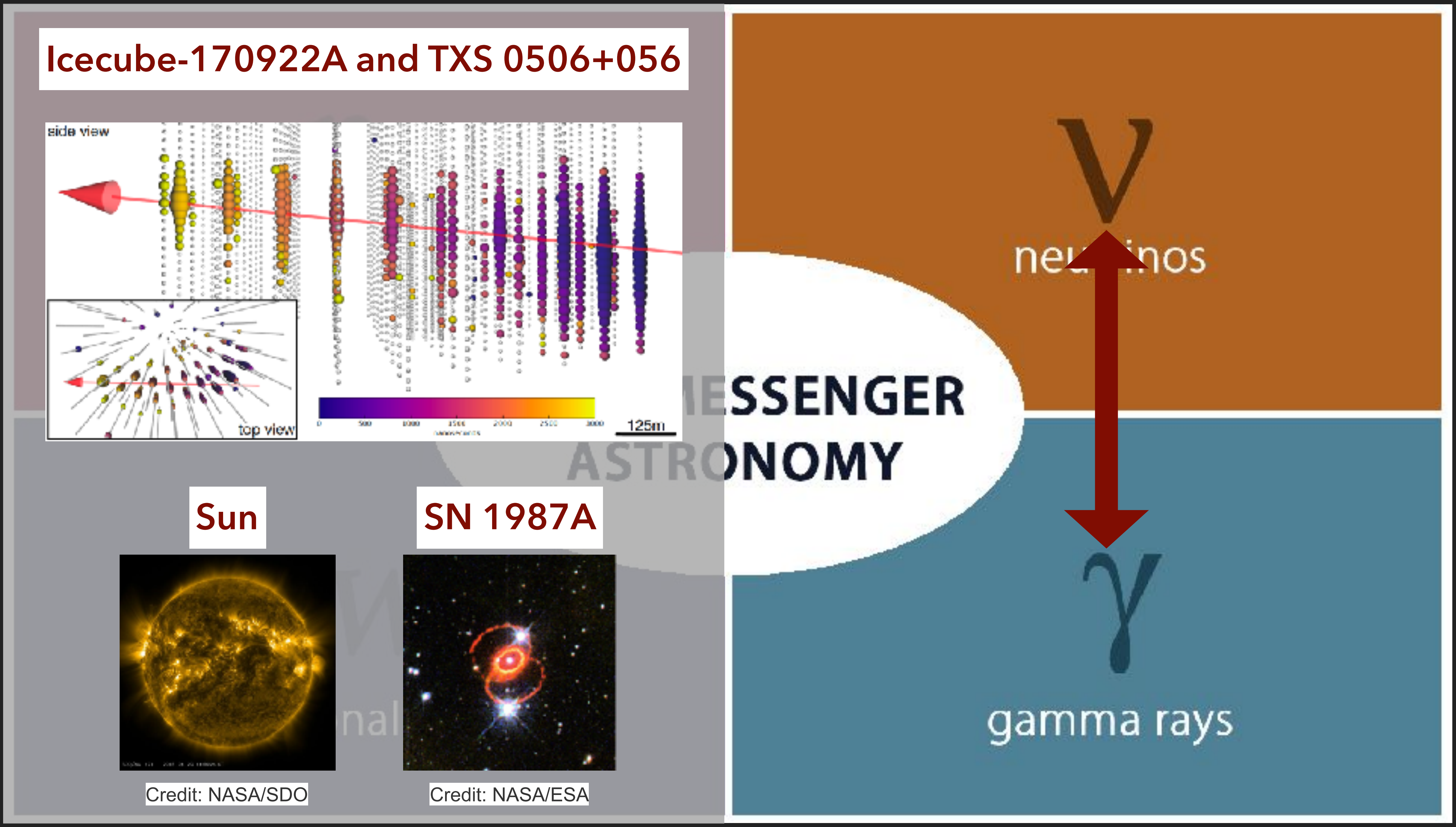
Multi-Messenger Astrophysics



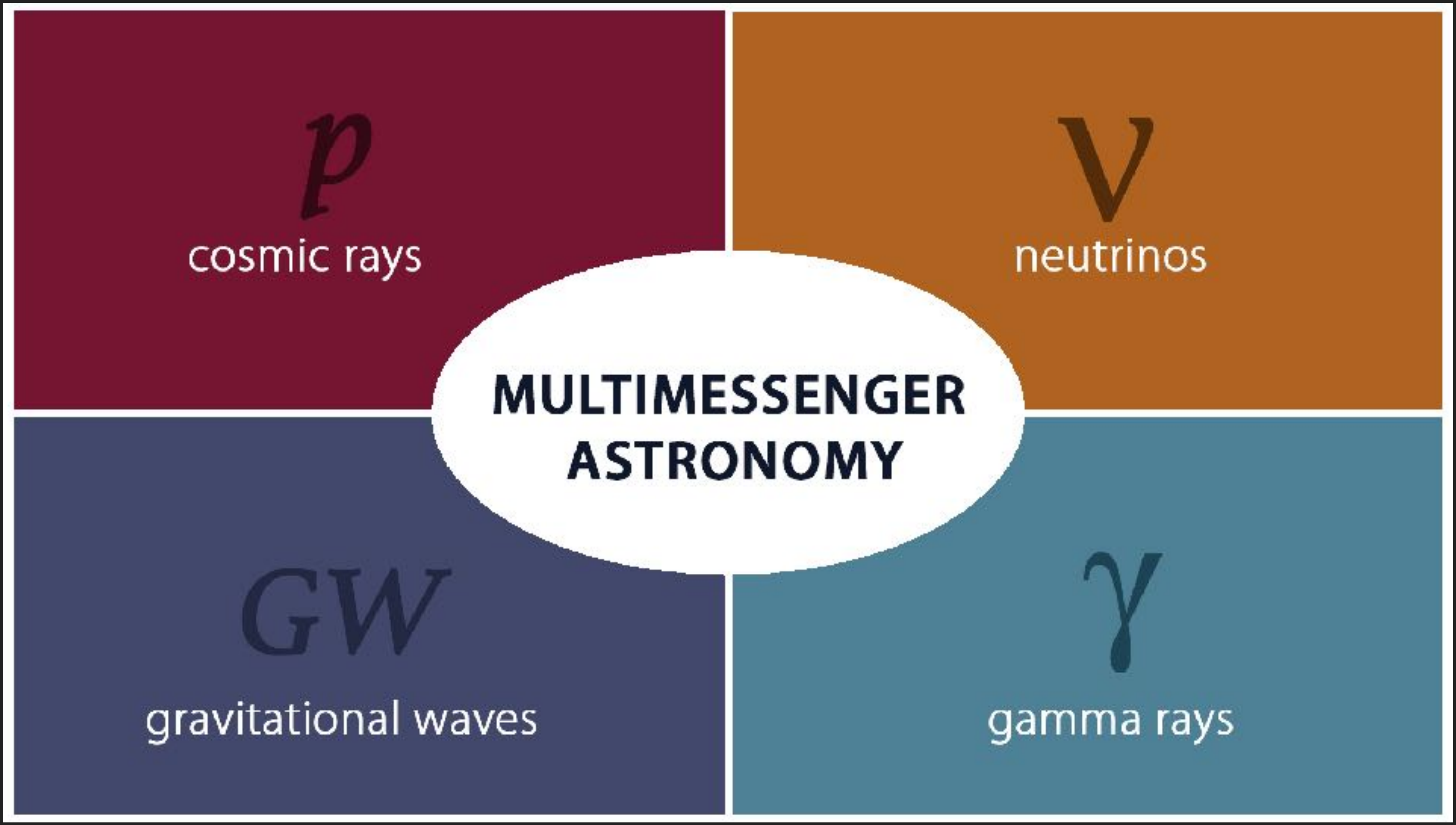
Multi-Messenger Astrophysics



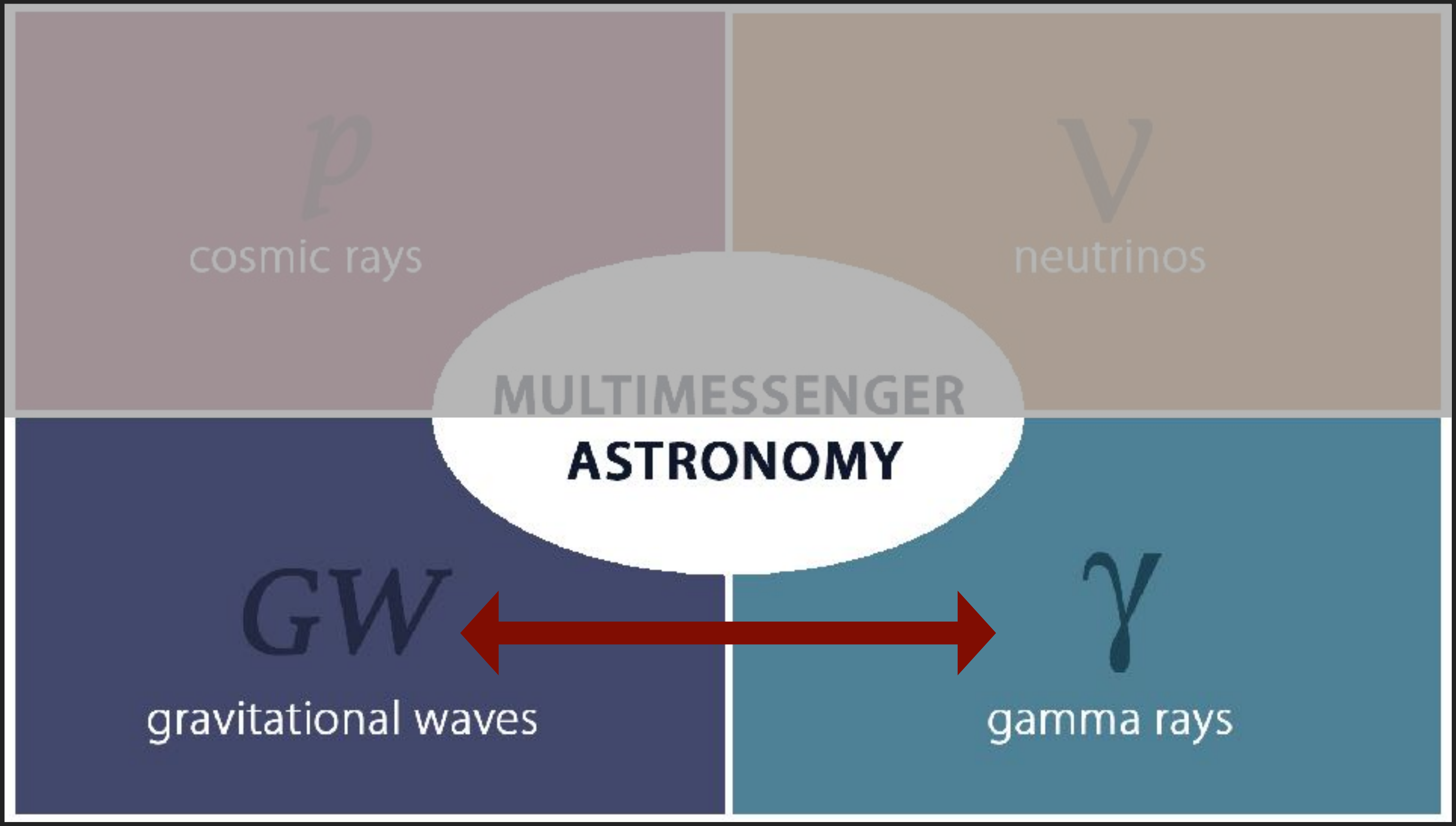
Multi-Messenger Astrophysics



Multi-Messenger Astrophysics



Multi-Messenger Astrophysics



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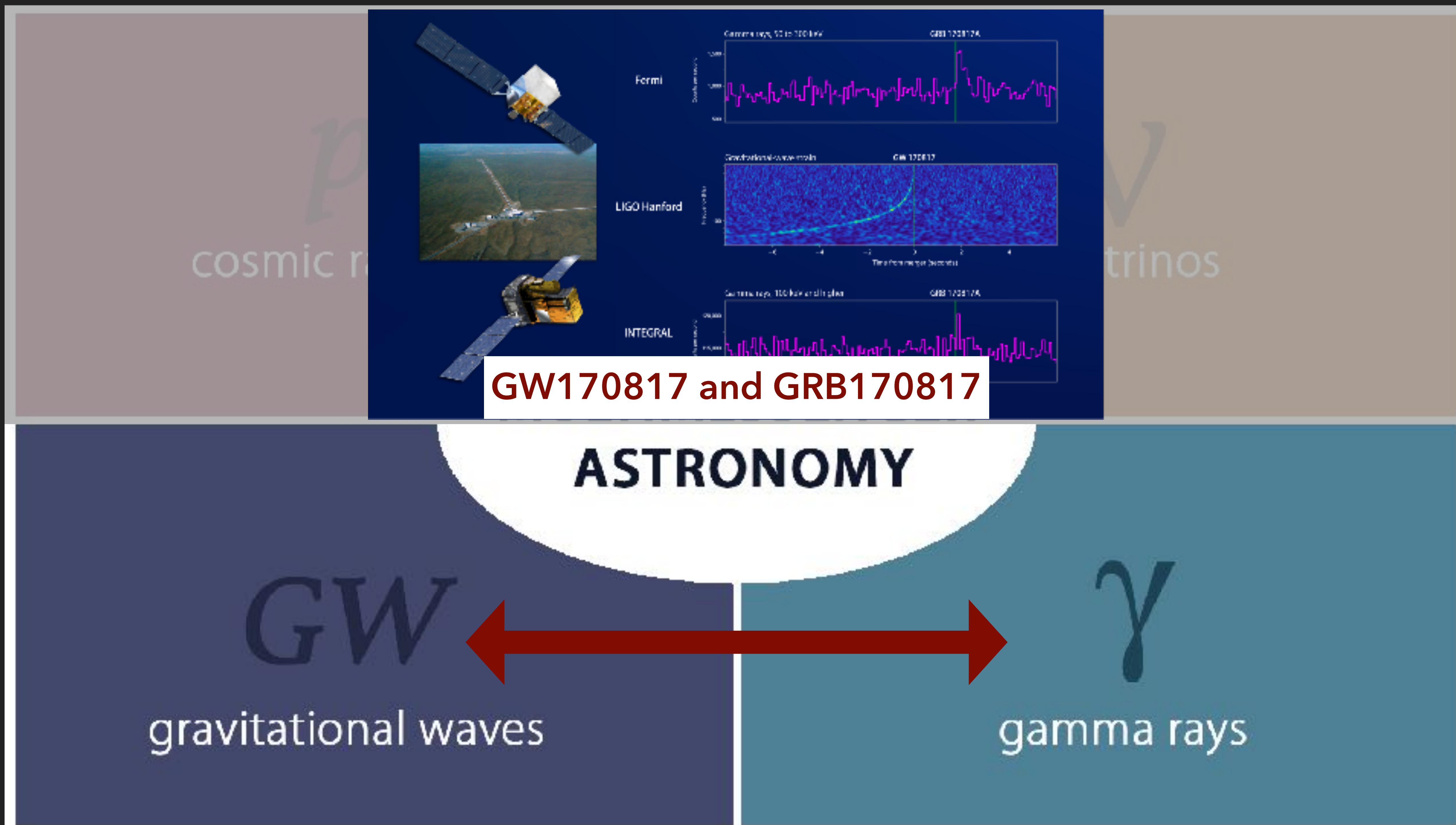
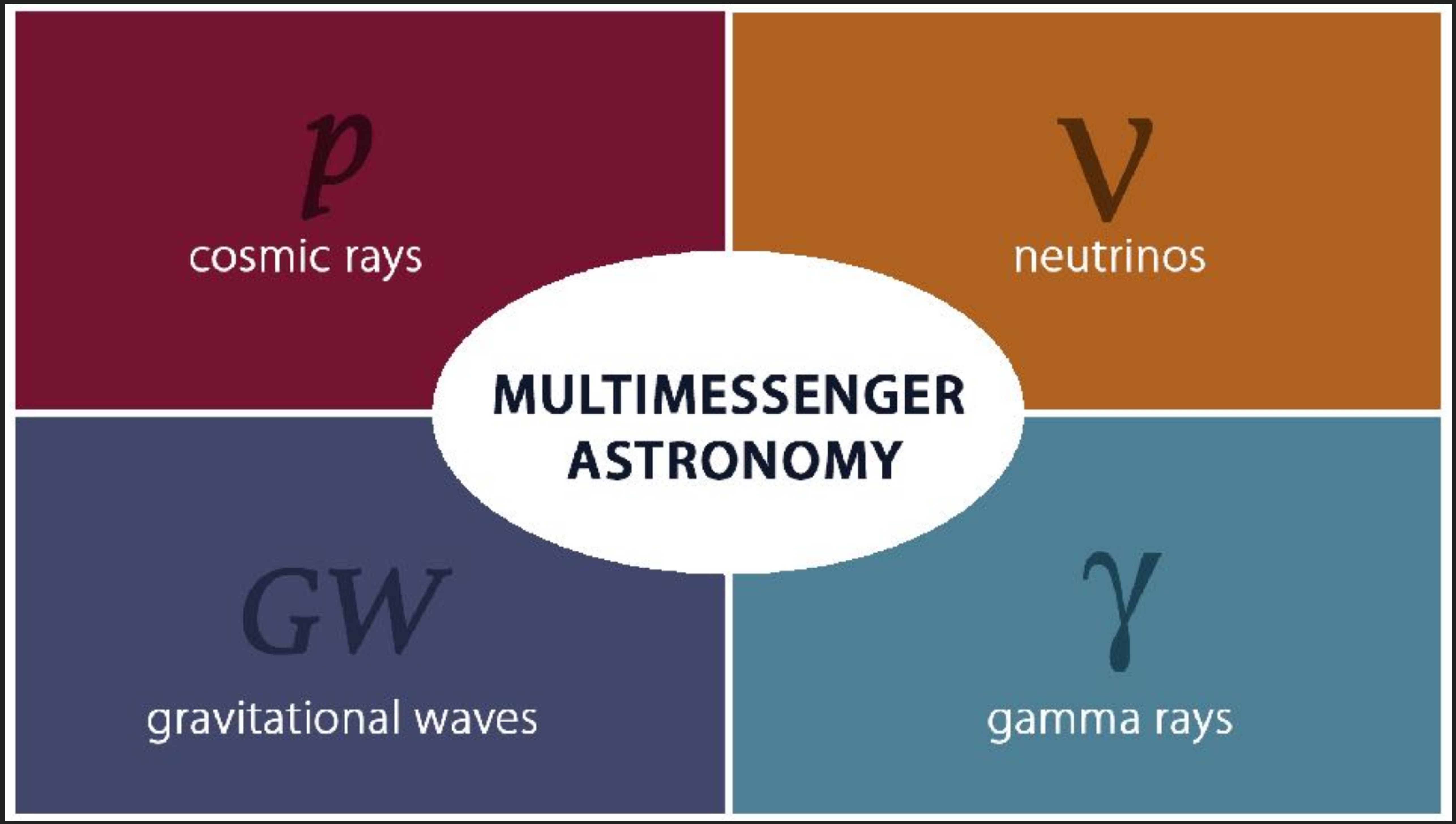
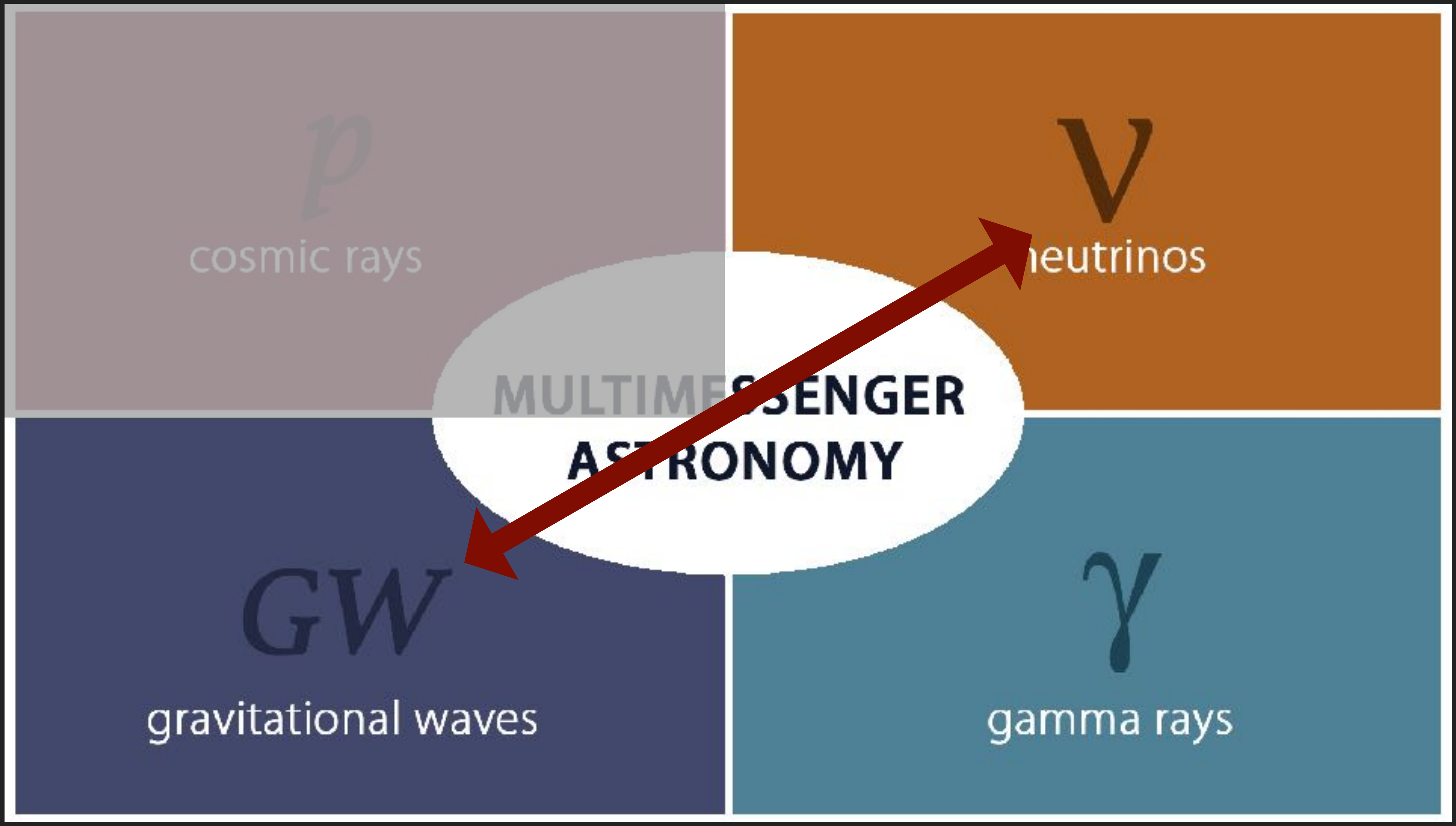


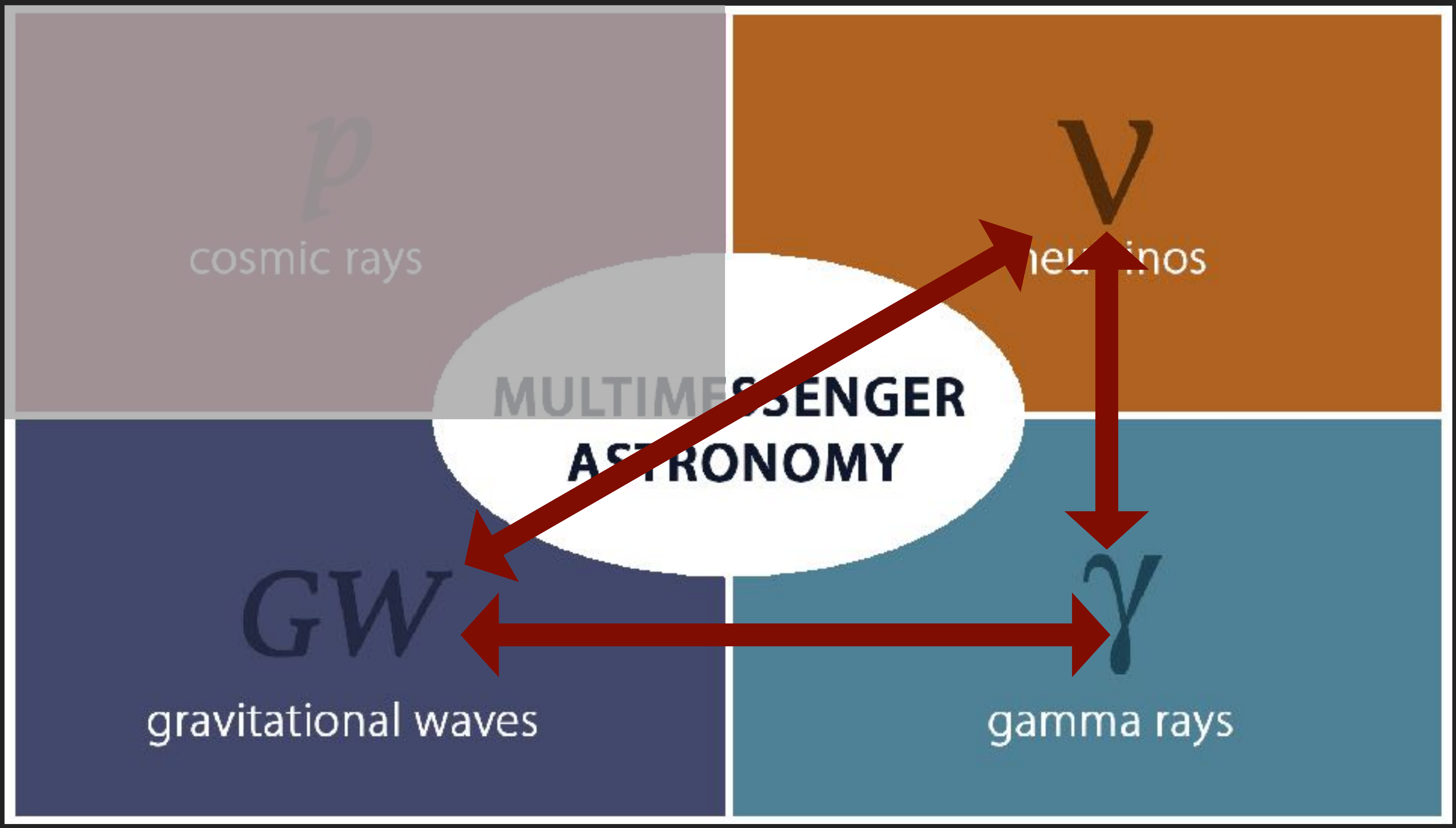
Multi-Messenger Astrophysics



Multi-Messenger Astrophysics

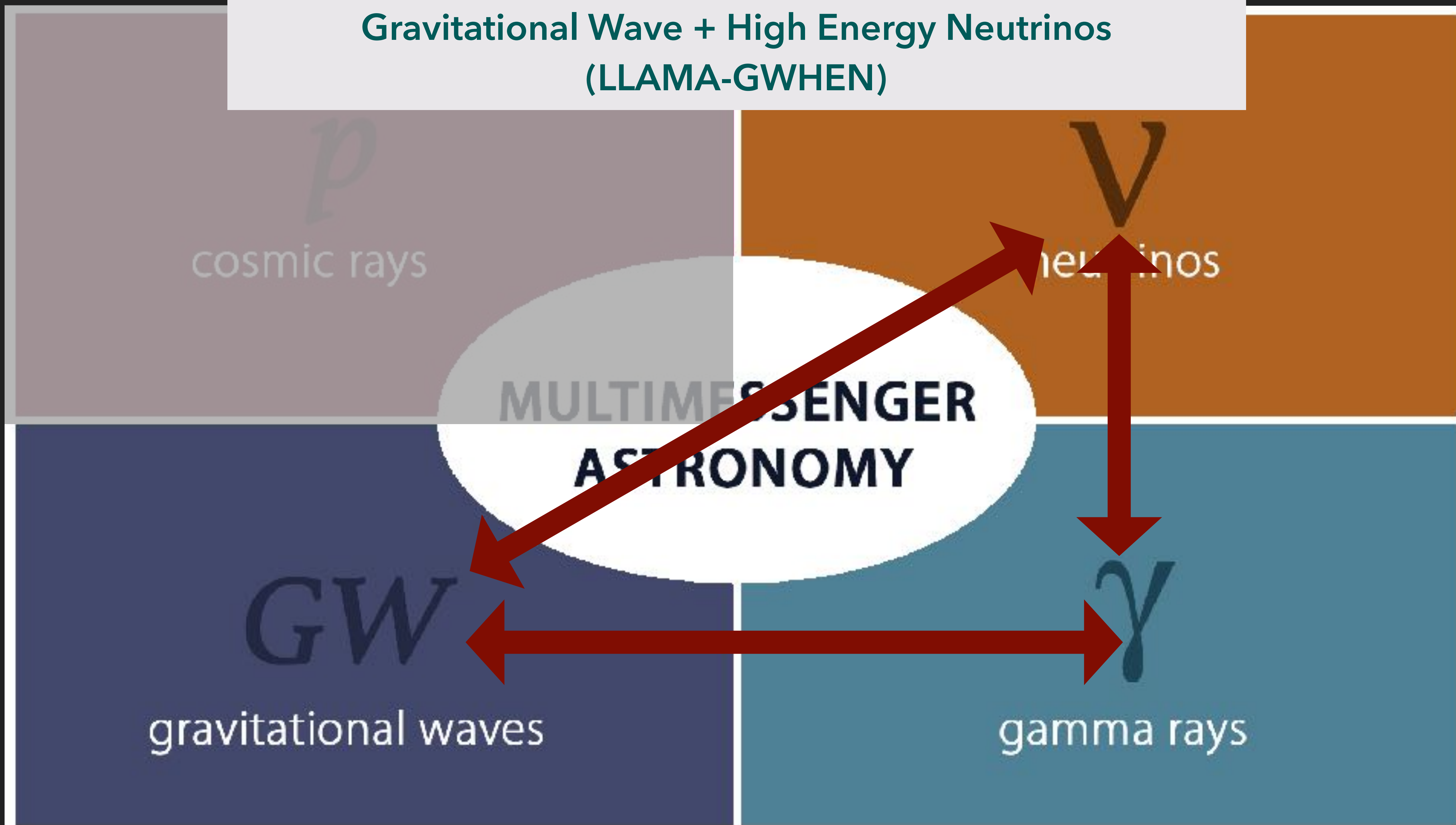


Multi-Messenger Astrophysics



Multi-Messenger Astrophysics

Low-Latency Algorithm for Multi-messenger Astrophysics
Gravitational Wave + High Energy Neutrinos
(LLAMA-GWHEN)



Gravitational Waves and High-Energy Neutrinos

Low-Latency Algorithm for Multi-messenger Astrophysics
Gravitational Wave + High Energy Neutrinos
(LLAMA-GWHEN)

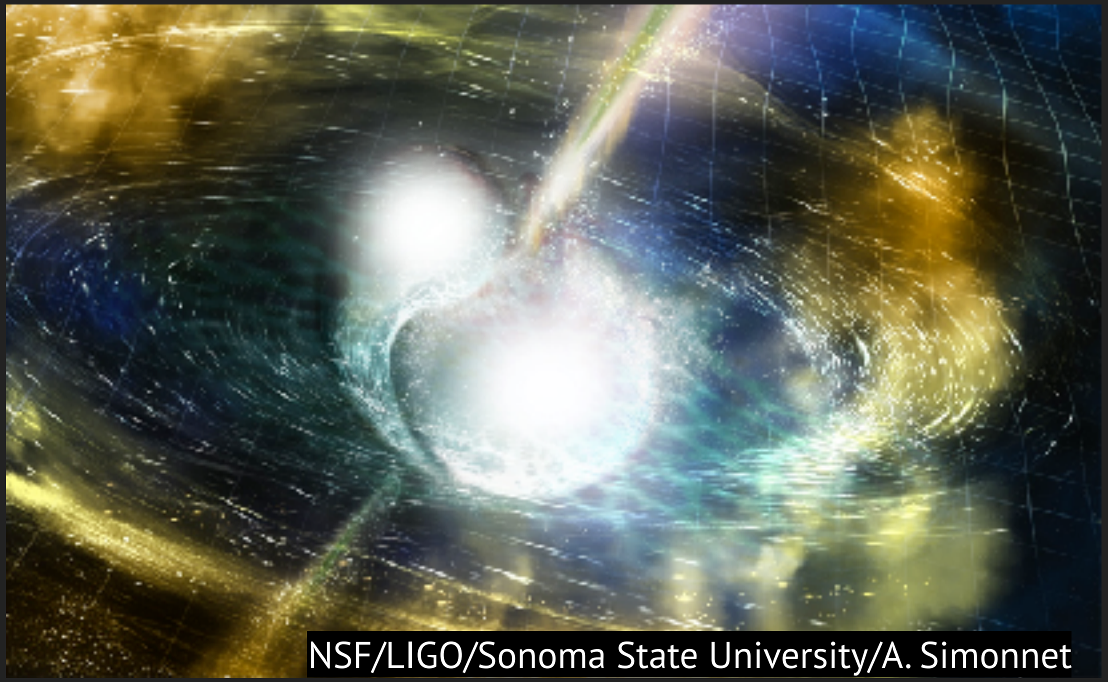
We search for common sources of gravitational waves (GWs) and high-energy neutrinos (HENs) in realtime!

No astrophysical source has yet been observed simultaneously with both messengers!

Work by Columbia University and University of Florida

Candidate Sources

- Several sources proposed:
  - Binary neutron star (BNS) merger
  - Neutron star – black hole merger
  - Core-collapse supernova
  - Gamma-ray burst (GRB)
  - Soft gamma repeater
  - …


NSF/LIGO/Sonoma State University/A. Simonnet

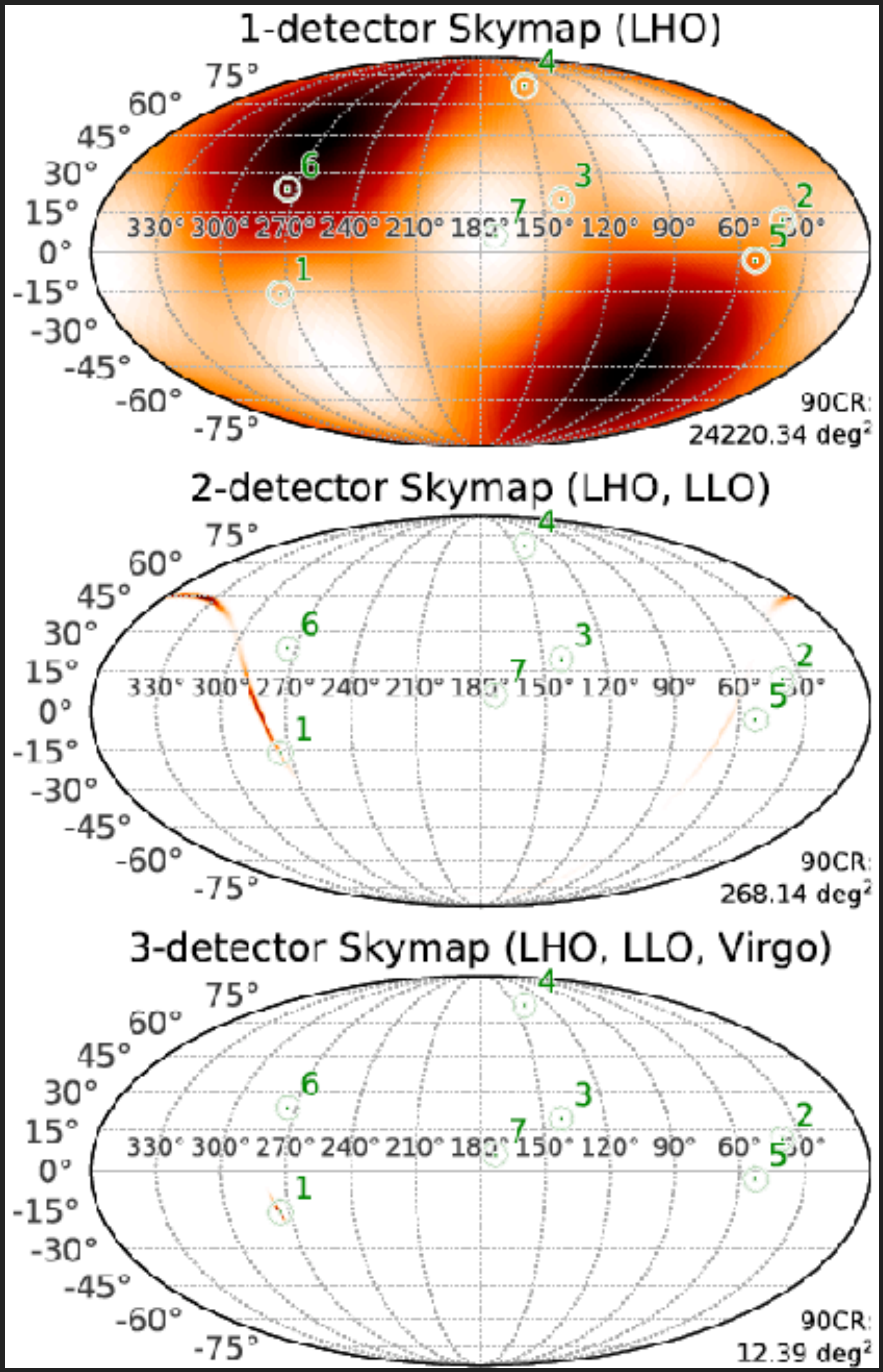
- The most promising:
  Short GRBs associated with BNS mergers
- Create relativistic outflows producing HENs
- Revealing unknown sources

Advantages of GW+HEN realtime search

- **Improved localization:**
  - GW area size is a limiting factor for EM follow-up efforts (10s-1000s deg^2)
  - Neutrinos can provide far superior localization (0.5 deg^2)

- **Sub-threshold search:**
  - Events with low significances standalone
  - Joint GW+HEN event with higher significance
  - Further follow-up observations increase discovery potential

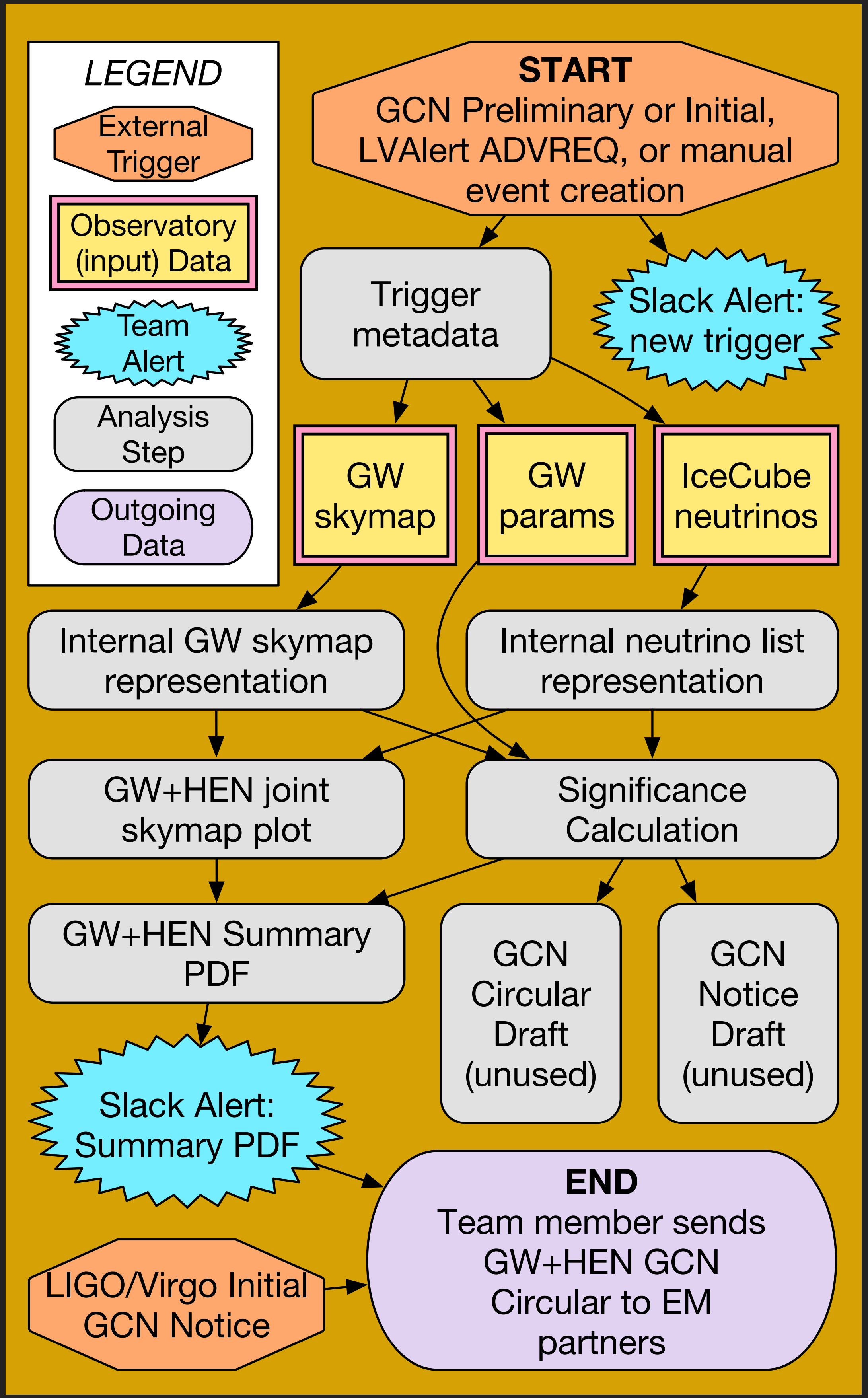
- **Higher event rate:**
  - Automation is needed for higher GW and HEN alert rates to avoid analysis backlogs



S. Countryman, AK, I. Bartos, et al (2019) arXiv:1901.05486

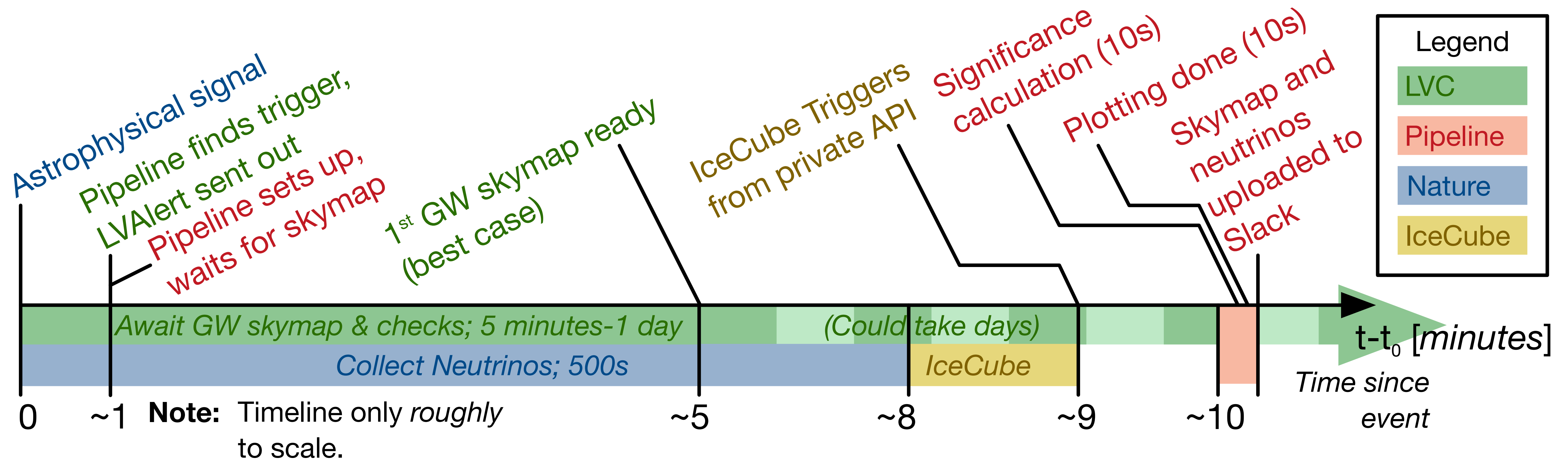
Data Stream

- GW triggers:
  LIGO/Virgo significant candidate events generated by detection pipelines (cWB, GstLAL, and PyCBC) stored on GraceDB including skymaps
- Pull data from GraceDB (currently only public alerts)
- IceCube triggers:
  GFU stream
- Pull data from IceCube's GFU API
- LLAMA-GWHEN runs the analysis
- Produce joint skymap and significance
- Prepare a summary document and a GCN Circular draft



Timeline

- LVAlert sent out, pipeline finds trigger ~1 min
- Collect neutrinos = 500s
- LLAMA-GWHEN analysis ~ 10 s
- Produce plots and upload results ~ 10 s



GW+HEN event significance

- Test Statistic (TS) based on astrophysical priors and detector characteristics (empirical)
- Define whether a GWHEN correlated signal is:
  - Real event (P_{signal})
  - Chance coincidence of background GW and background neutrino (P_{null})
  - Chance coincidence of astrophysical GW and background neutrino or vice versa ($P_{coincidence}$)
- Calculate p-values using Bayesian odds ratio as TS

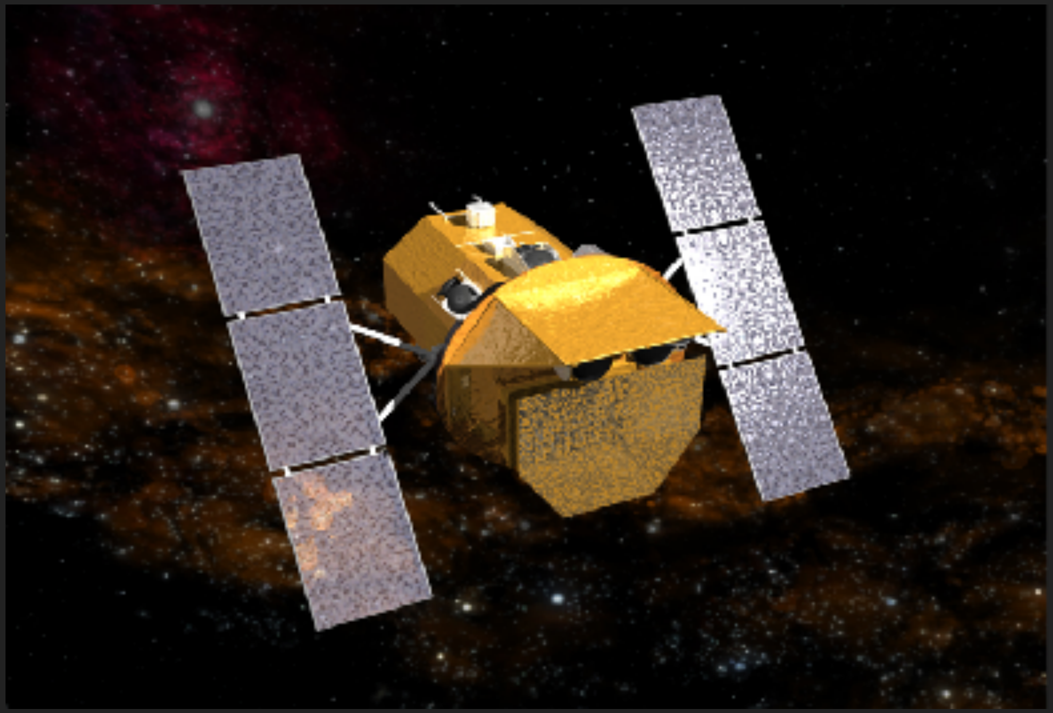
$$\mathrm{TS} = \frac{P_{signal}}{P_{null} + P_{coincidence}}$$

I. Bartos, D. Veske, AK, et al (2019) arXiv:1810.11467

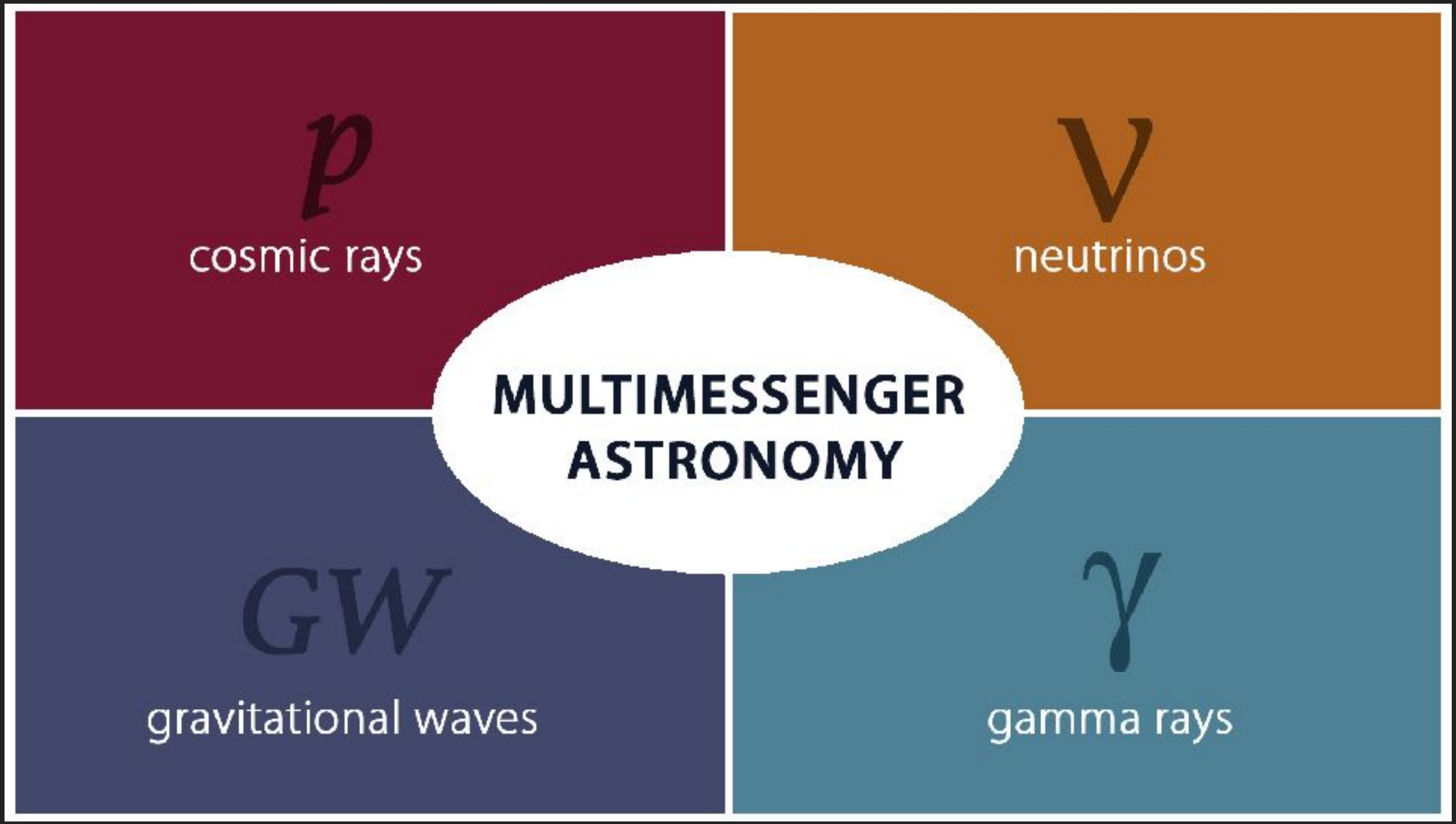
Electromagnetic Follow-Up Observations

- Rapid identification of significant GW+HEN coincidence enabling faster and more efficient EM follow-up observations
- Crucial in understanding underlying mechanisms and physics of the sources

- *Swift*-XRT and UVoT target of opportunity (ToO) follow-up:
  - Approved proposal
  - Cycle 15 guest investigator program (2019-2020)
  - Granted four "Highest Priority" ToO
  - PI: AK
  - Co-I's: I. Bartos, P. Evans, D. Fox, J. Kennea, Z. Marka, S. Marka



Thank you!


p
cosmic rays
ν
neutrinos
MULTIMESSENGER
ASTRONOMY
GW
gravitational waves
γ
gamma rays