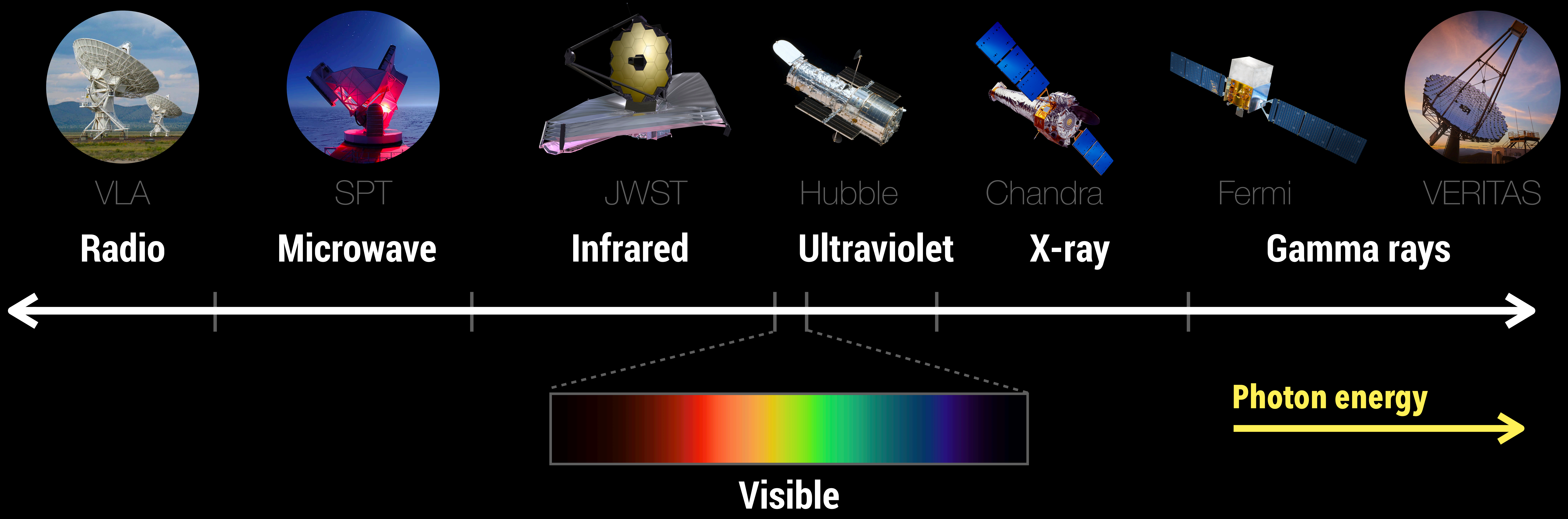
MULTIMESSENGER ASTROPARTICLE PHYSICS
AN OBSERVATIONAL PERSPECTIVE

Marcos Santander
University of Alabama

ISAPP 2022 School - University of Paris - Saclay

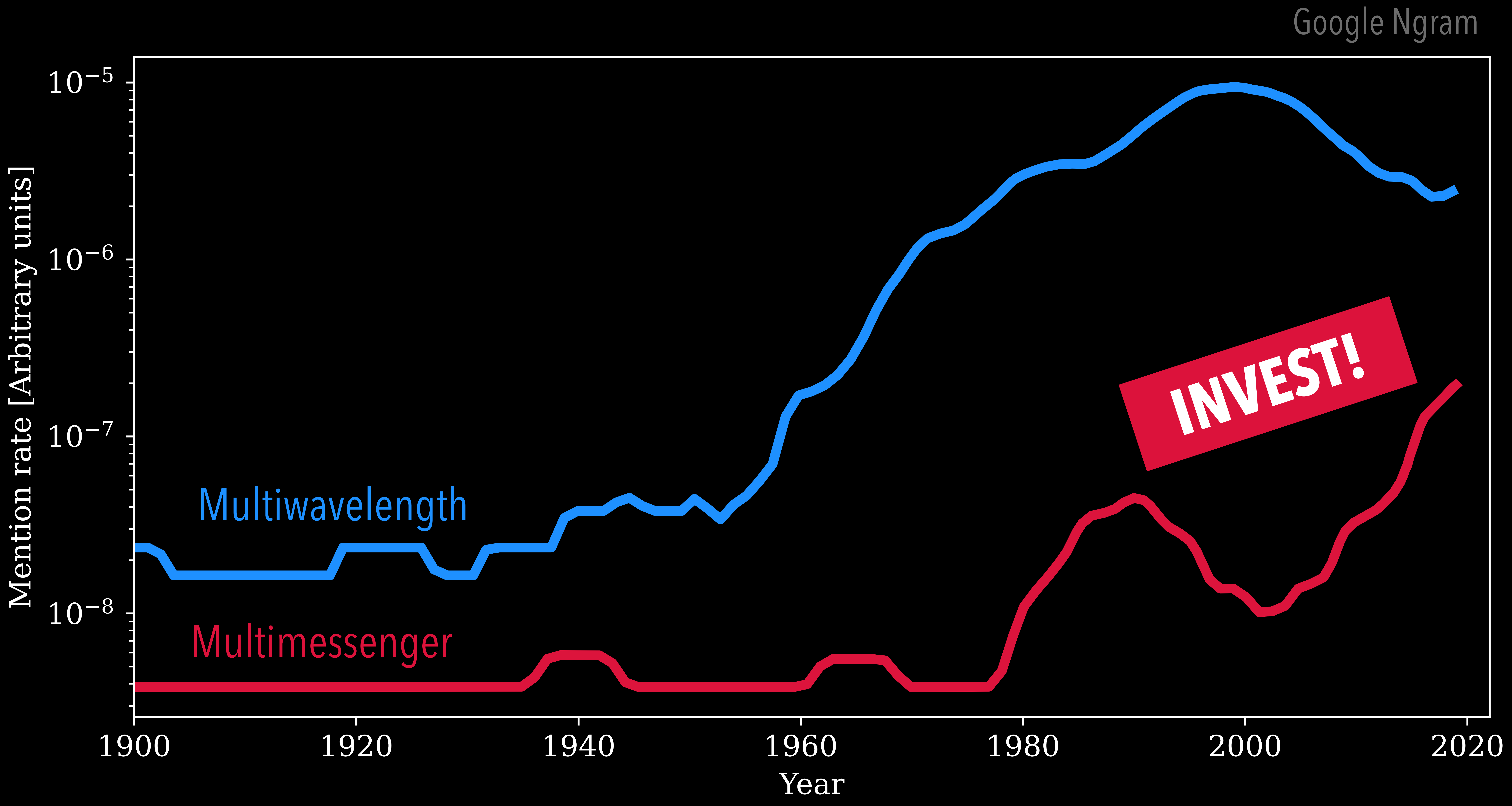
ELECTROMAGNETIC SPECTRUM



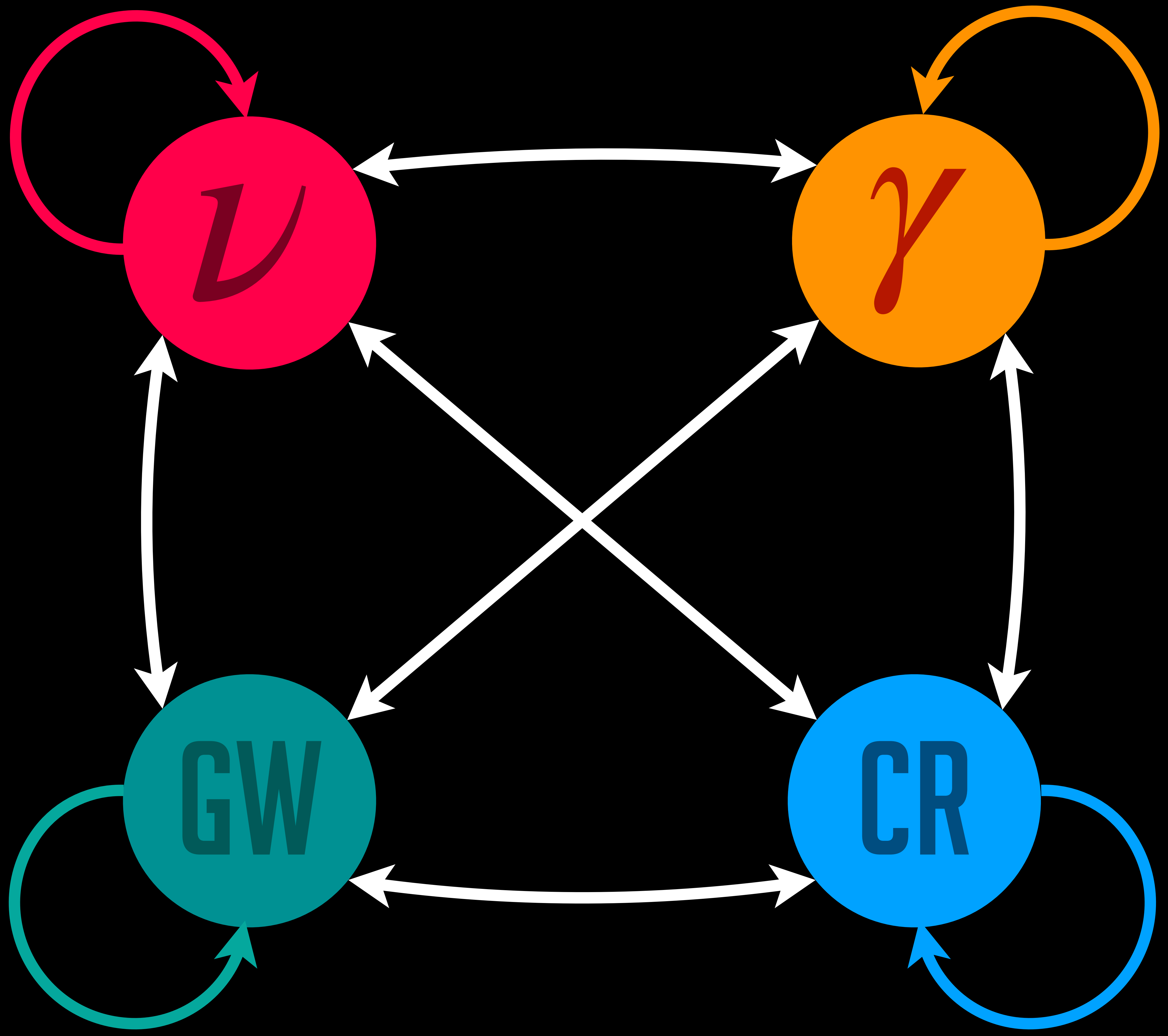
VISIBLE SKY


GAMMA-RAY SKY
Active Galactic Nucleus powered by a supermassive black hole 8.2 billion light years away
Fermi-LAT telescope
(Energy 0.1 - 300 GeV)

MULTIWAVELENGTH VS MULTIMESSENGER



MULTIMESSENGER ASTROPHYSICS STUDIES



We will concentrate on the multimessenger interfaces

PHASE 1 - MM PREDICTIONS - NULL RESULTS

↓

PHASE 2 - FIRST EVIDENCE FOR SOURCE(S)

↓

PHASE 3 - FIRST STRONG DETECTION OF A MM SOURCE

↓

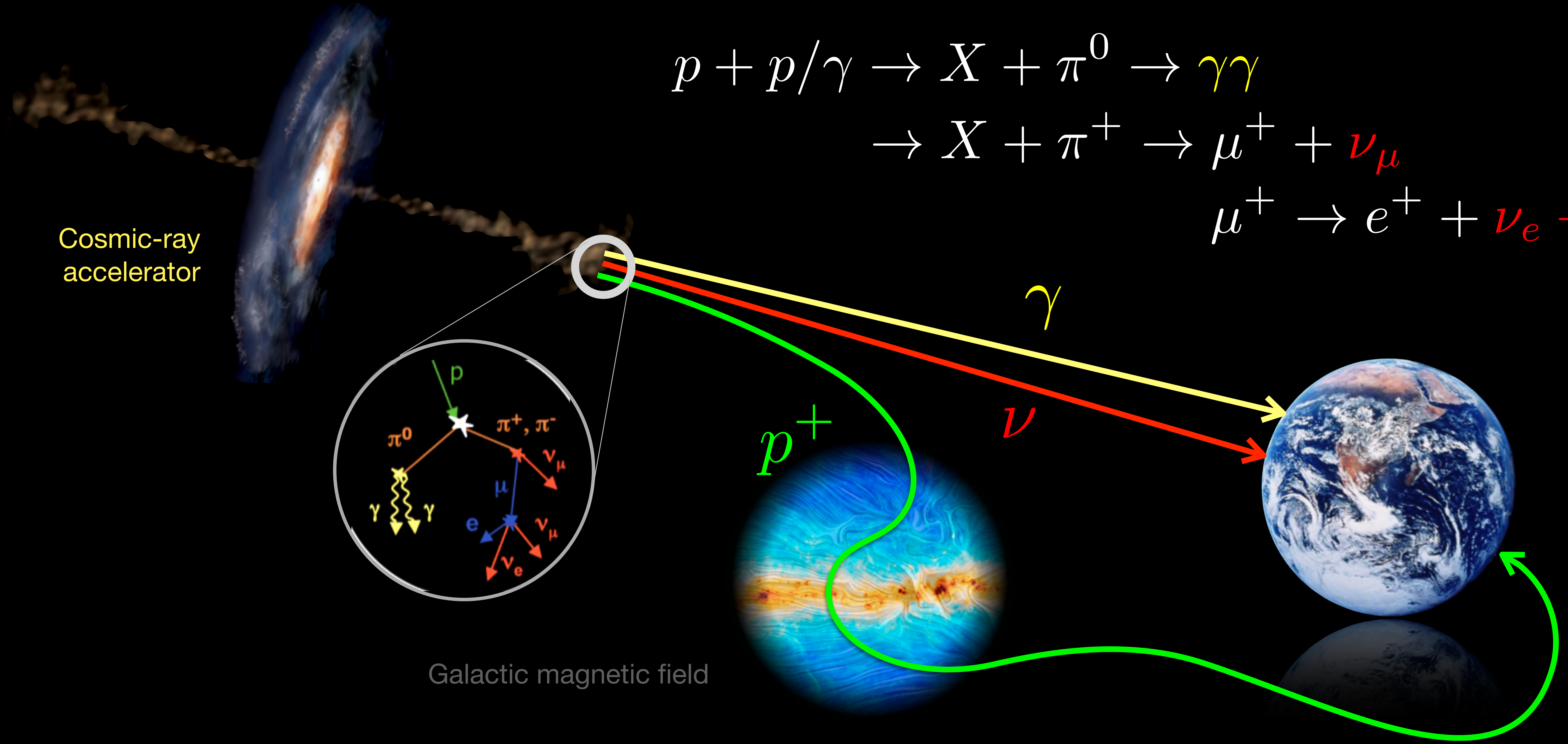
PHASE 4 - MULTIPLE MM SOURCES DETECTED AT HIGH SIGNIFICANCE, CATALOGS, SYSTEMATIC STUDIES

MOST PRESSING QUESTIONS FOR OBSERVATIONAL MMA

- **Counterpart identification.**
  - Challenge: Non-photon observations tend to suffer from poor angular localizations.
- **Follow-up observation and study**
  - Timescale of the emission is not always known.
- **Finding commonalities among the counterparts identified**
  - Physical interpretation, predictions for next observations.

HADRONIC SIGNATURES

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

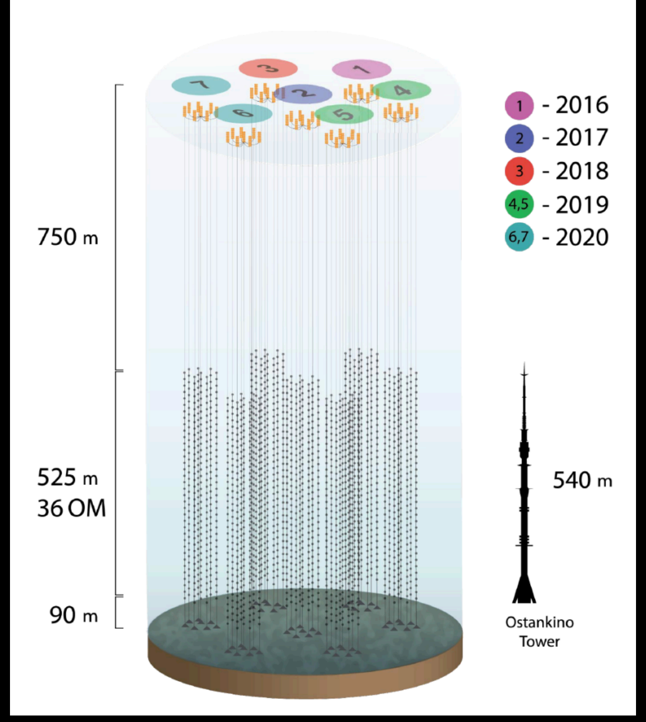


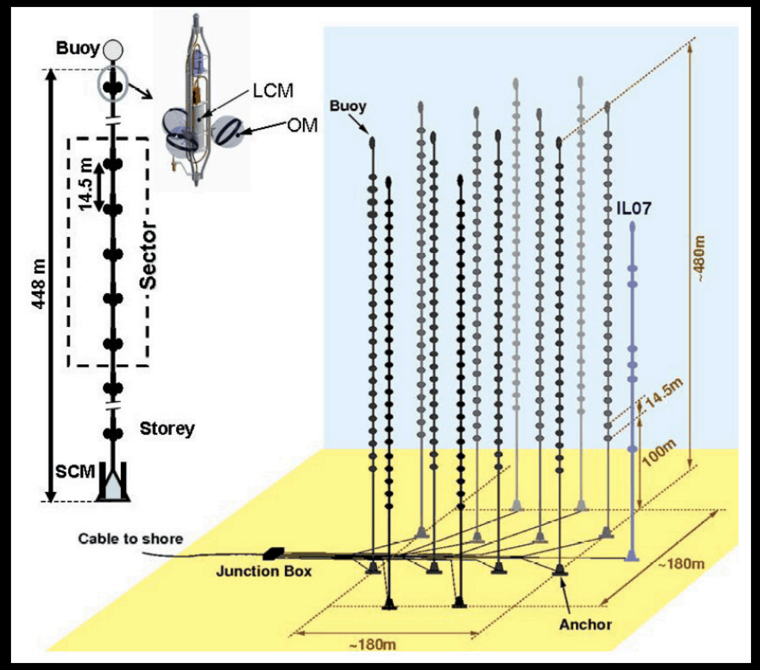
- Low-energy signatures (radio to X-rays) that indicate particle acceleration and interaction.
- For other messengers **(GW)** we'll look for evidence for HE particle acceleration in hadronic channels.

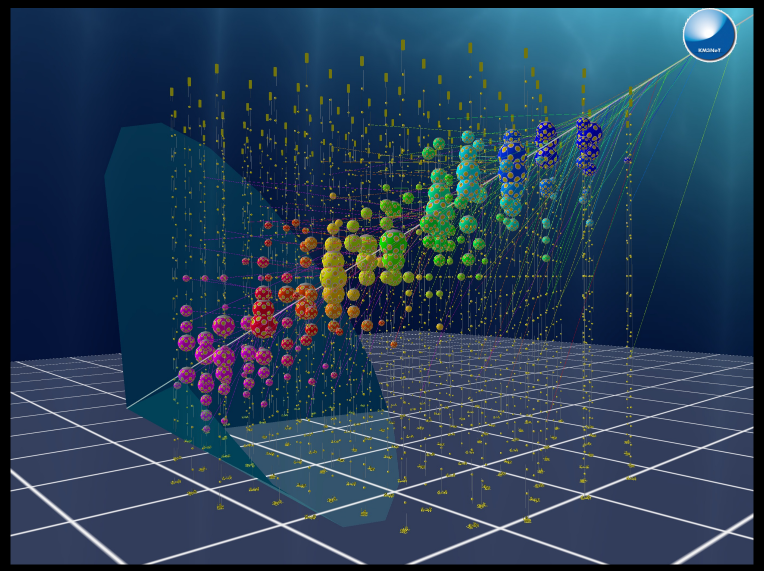
DRIVING FACTORS IN MULTIMESSENGER DETECTIONS

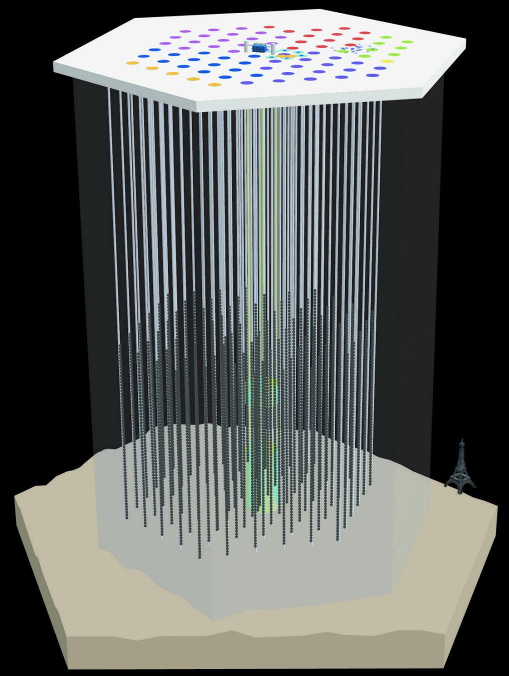
- Angular resolution
- Background rejection (astrophysical probability)
- Response time, broadcast delays.
- Sensitivity of follow-ups. Time and energy coverage.

MULTIMESSENGER INSTRUMENTATION







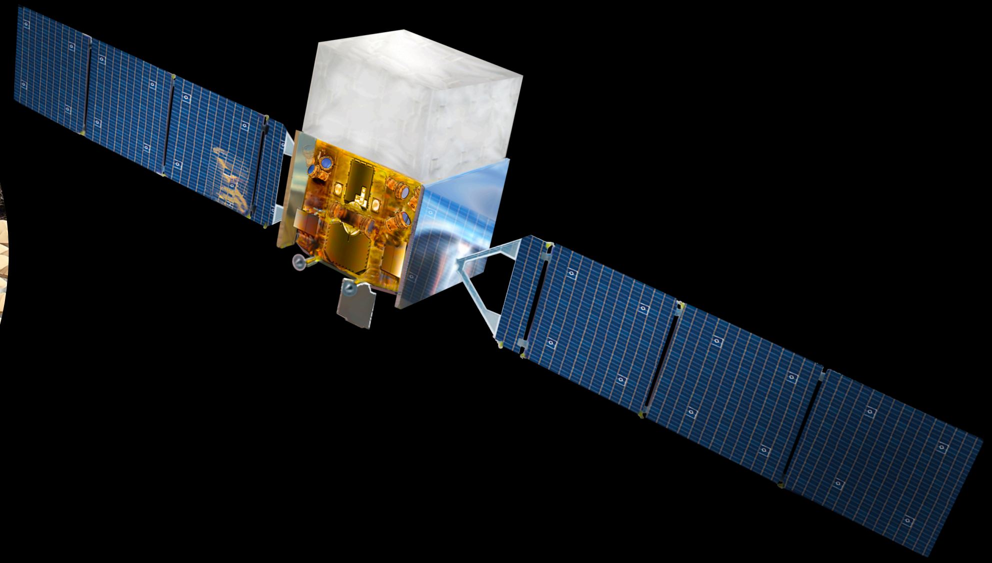


Neutrino telescopes

- 100% uptime
- ~4π sky coverage
- Angular resolution: 0.1°-15°

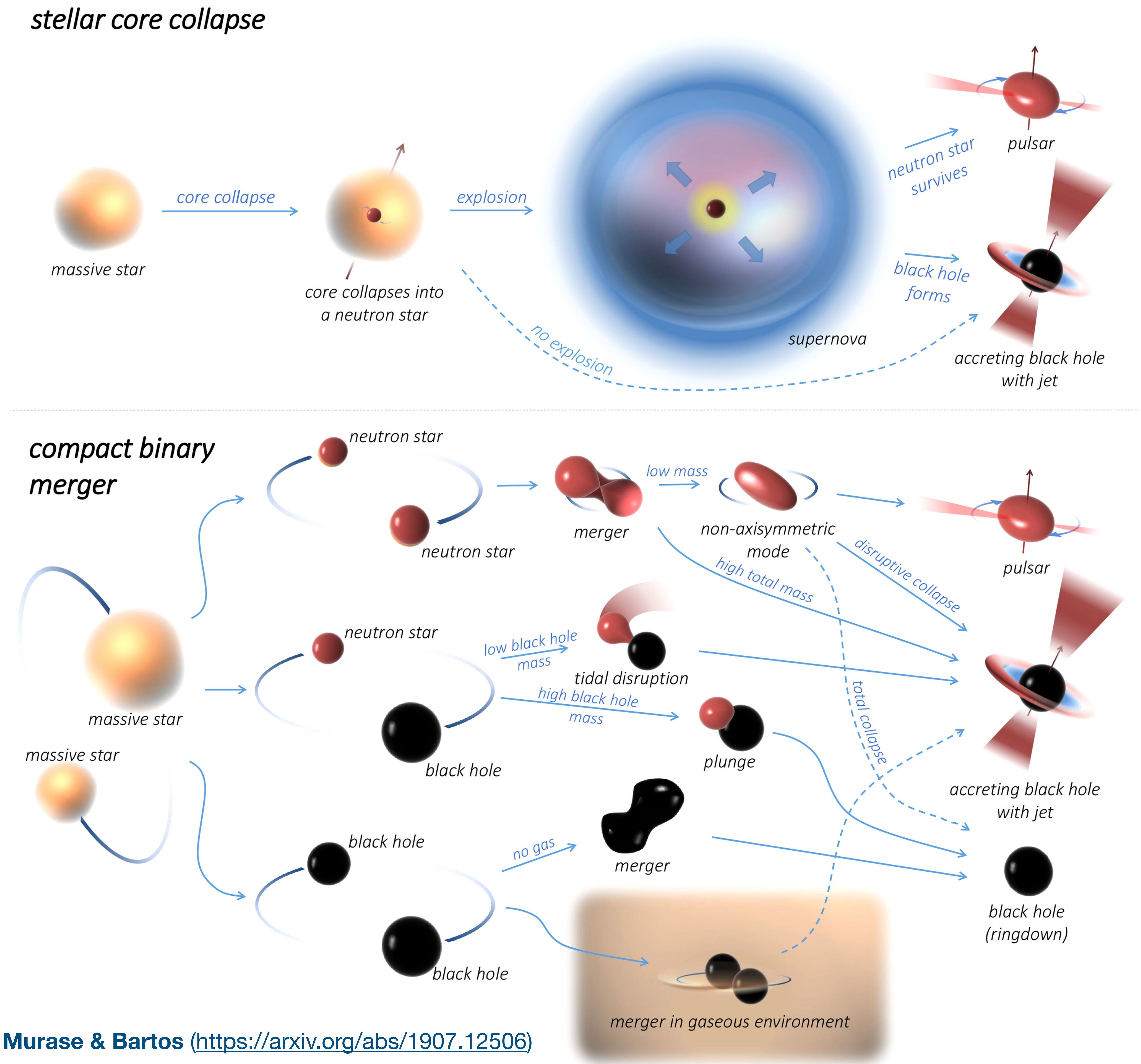
GW interferometers

- 100% uptime
- ~4π sky coverage
- Angular resolution: 10-1000 deg^2



EM telescopes

- Uptime: 100% (wide field) - 20% (pointed)
- Wide field (π sr) and pointed (~deg^2)
- Angular resolution: arcsec-0.1°



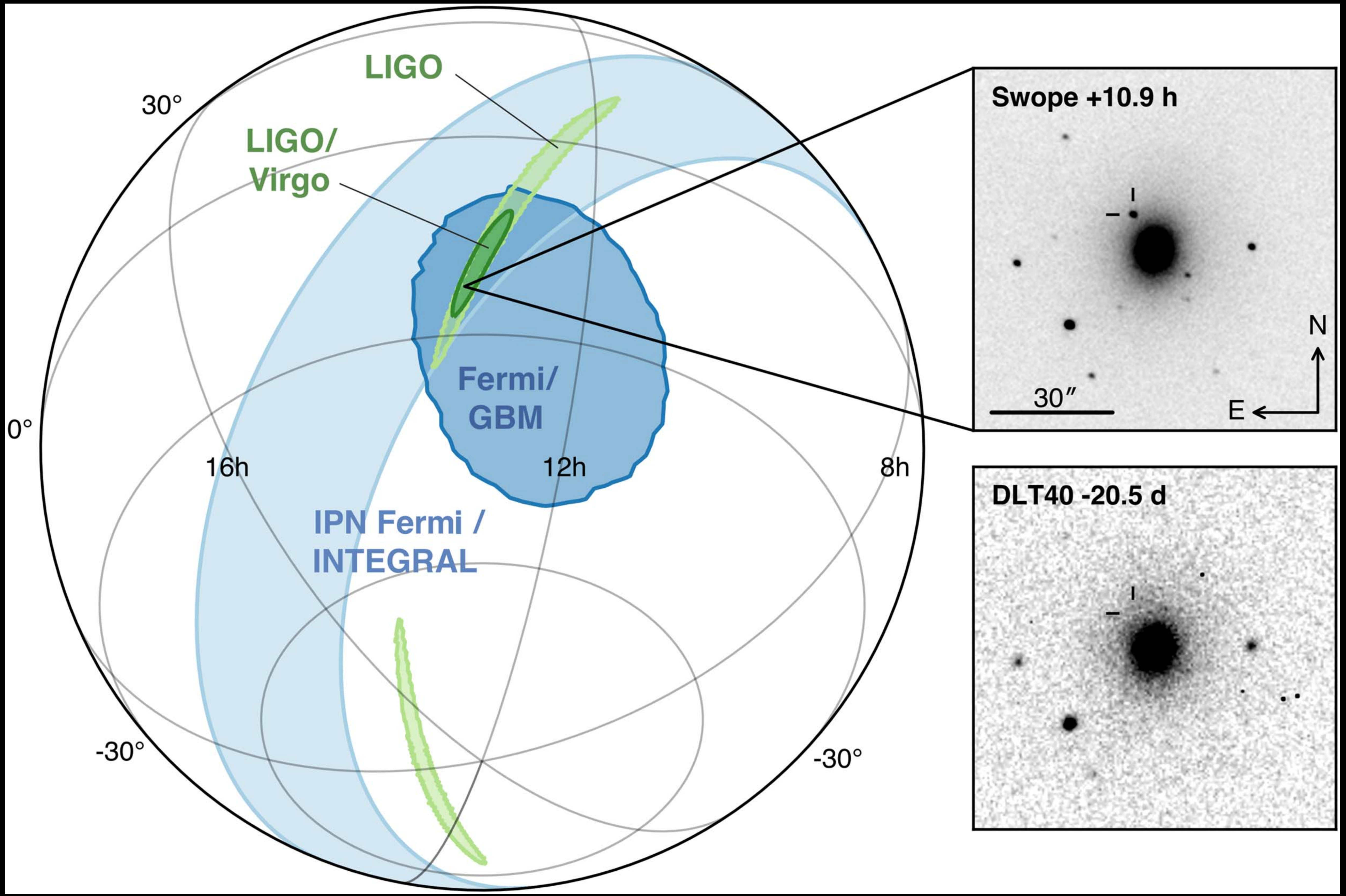
Murase & Bartos (https://arxiv.org/abs/1907.12506)

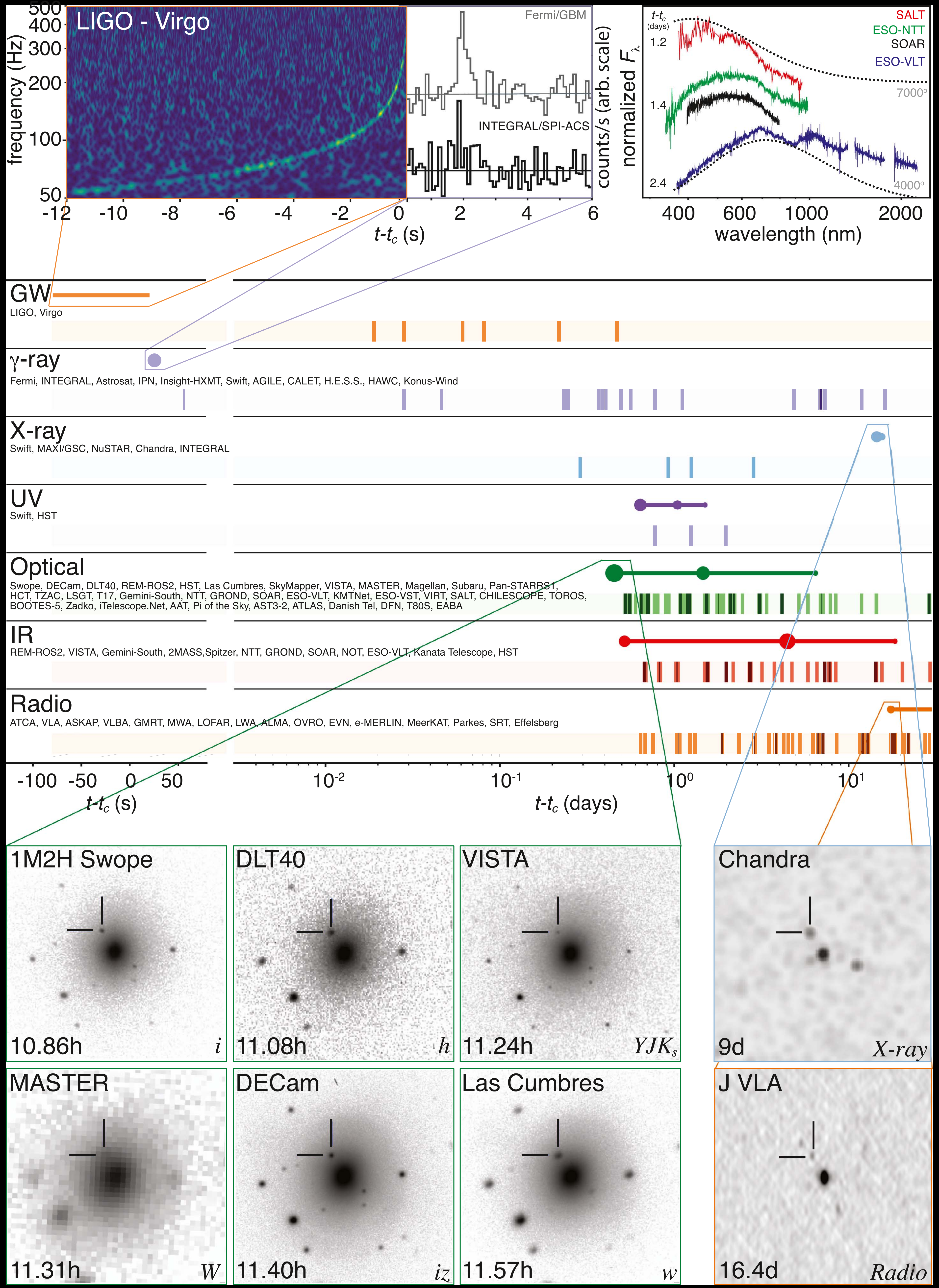
GRAVITATIONAL WAVES EMISSION AND MM SIGNATURES

- Compact object mergers can lead to the creation of relativistic jets and therefore particle acceleration.
- **Hadronic emission possible (gammas and neutrinos)**

GW170817

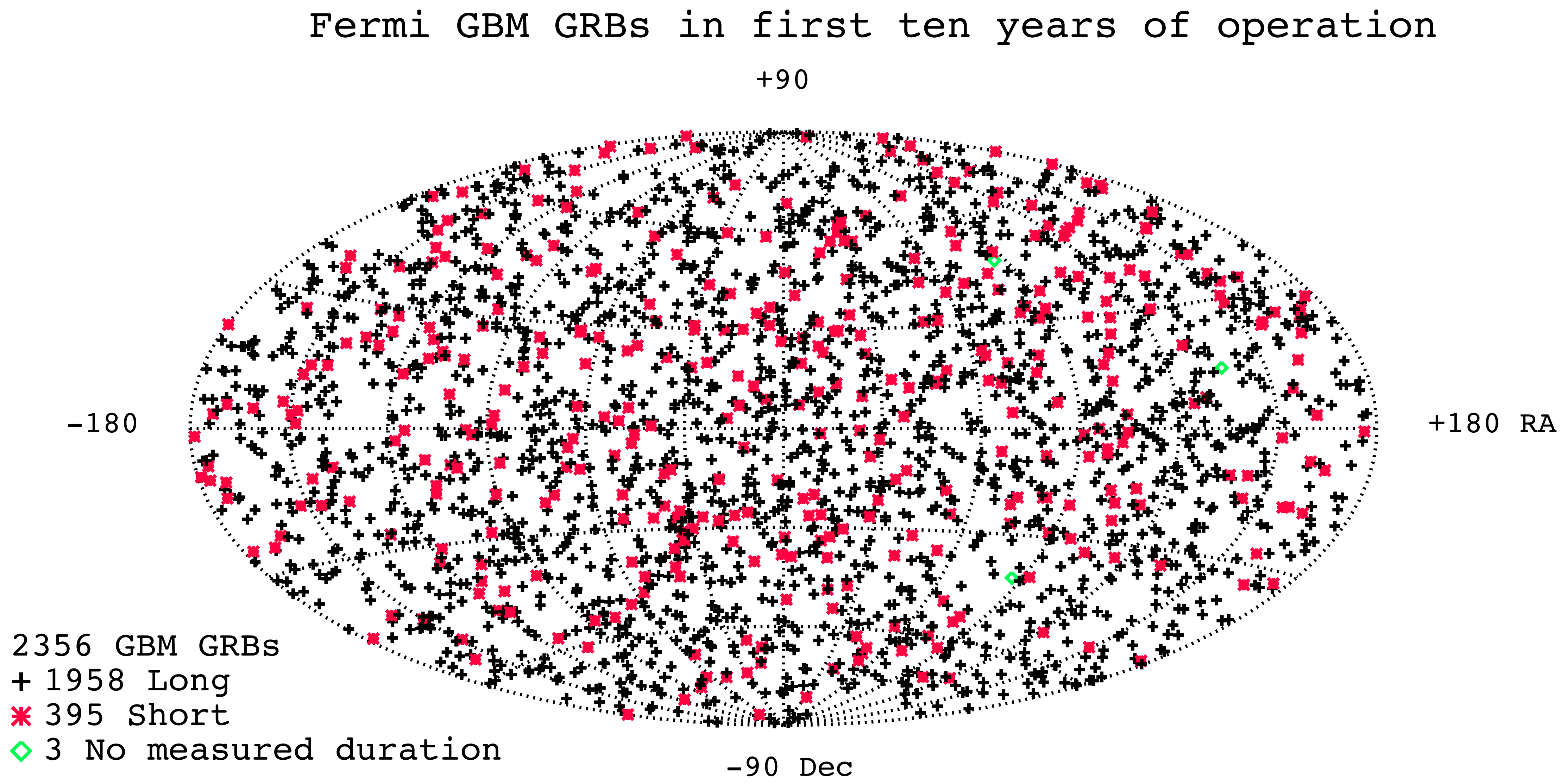
LIGO/Virgo + MMA partners
https://arxiv.org/abs/1710.05833



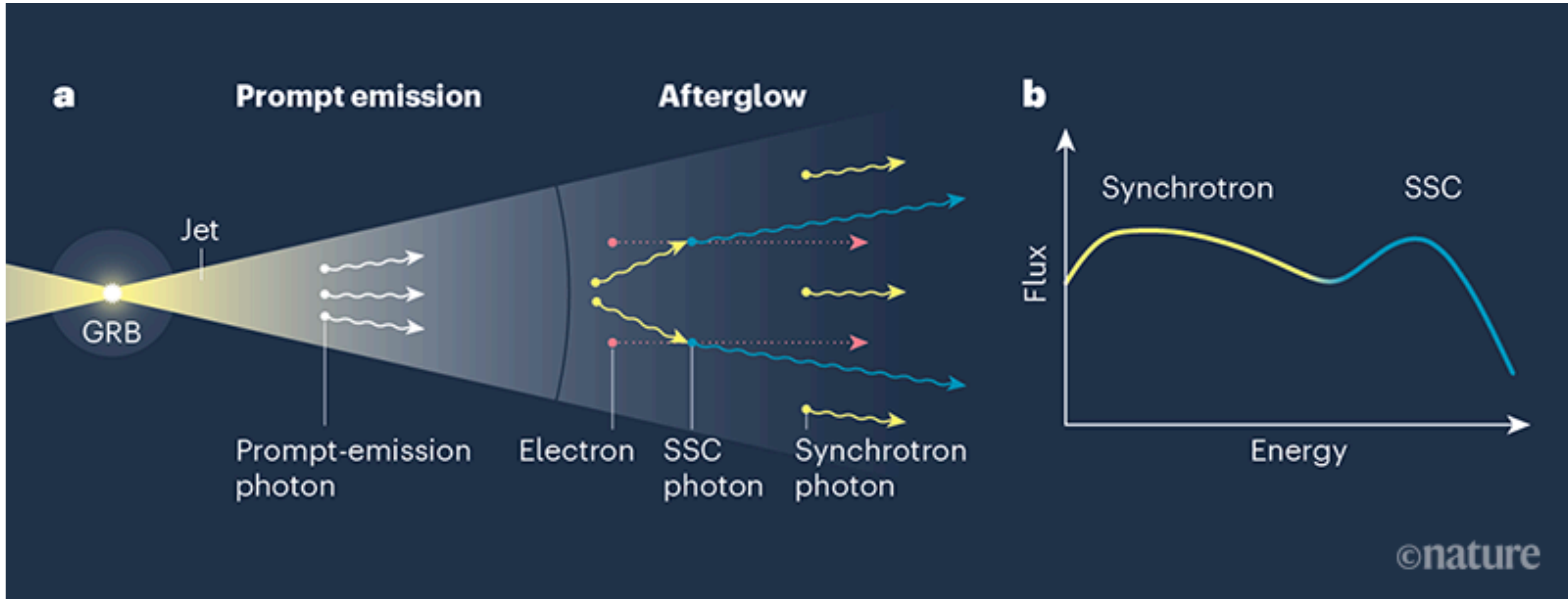


- **First (and only so far) multimessenger detection with GWs.**
- **VHE emission from GW sources?**

GAMMA-RAY BURSTS AS VHE EMITTERS

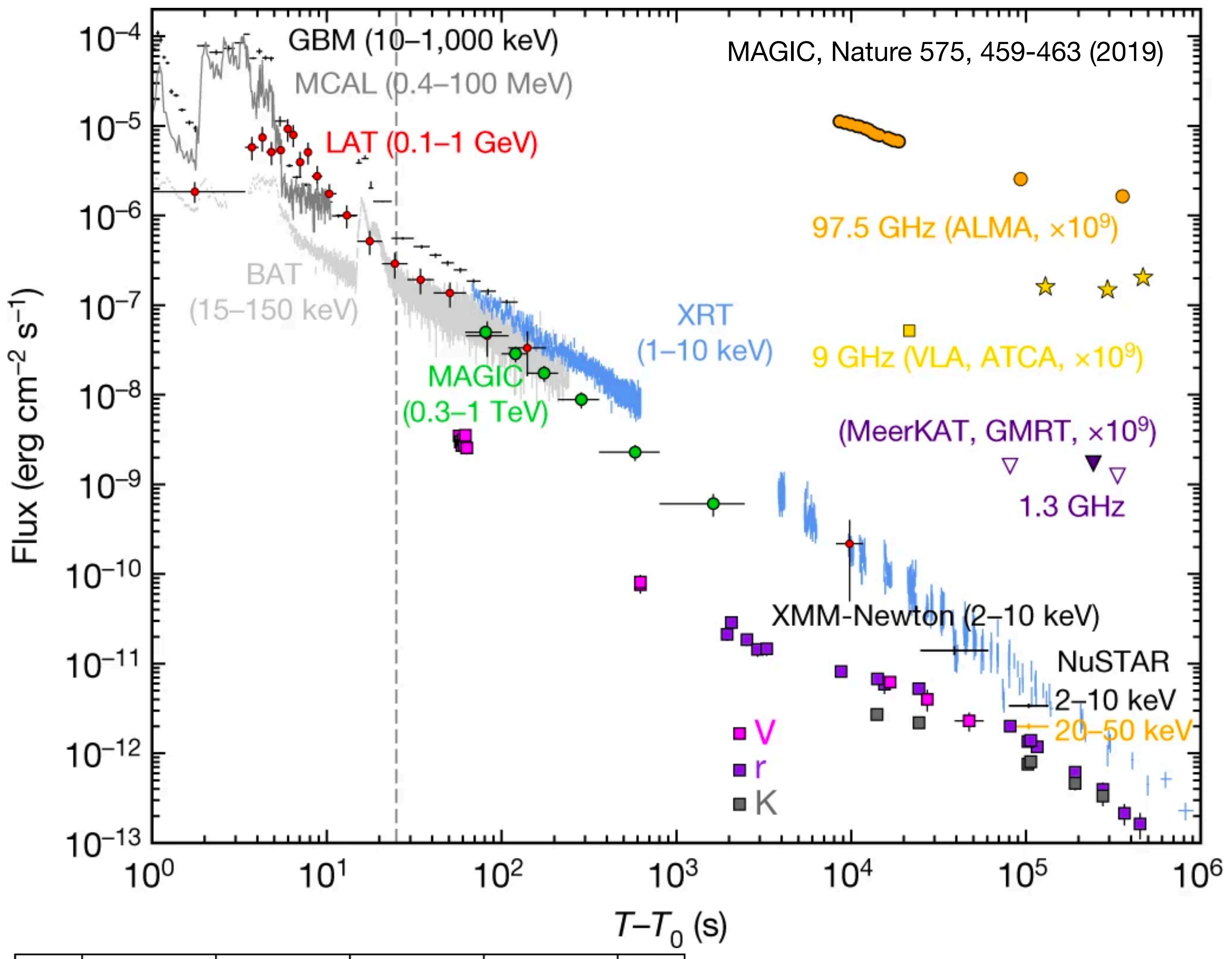


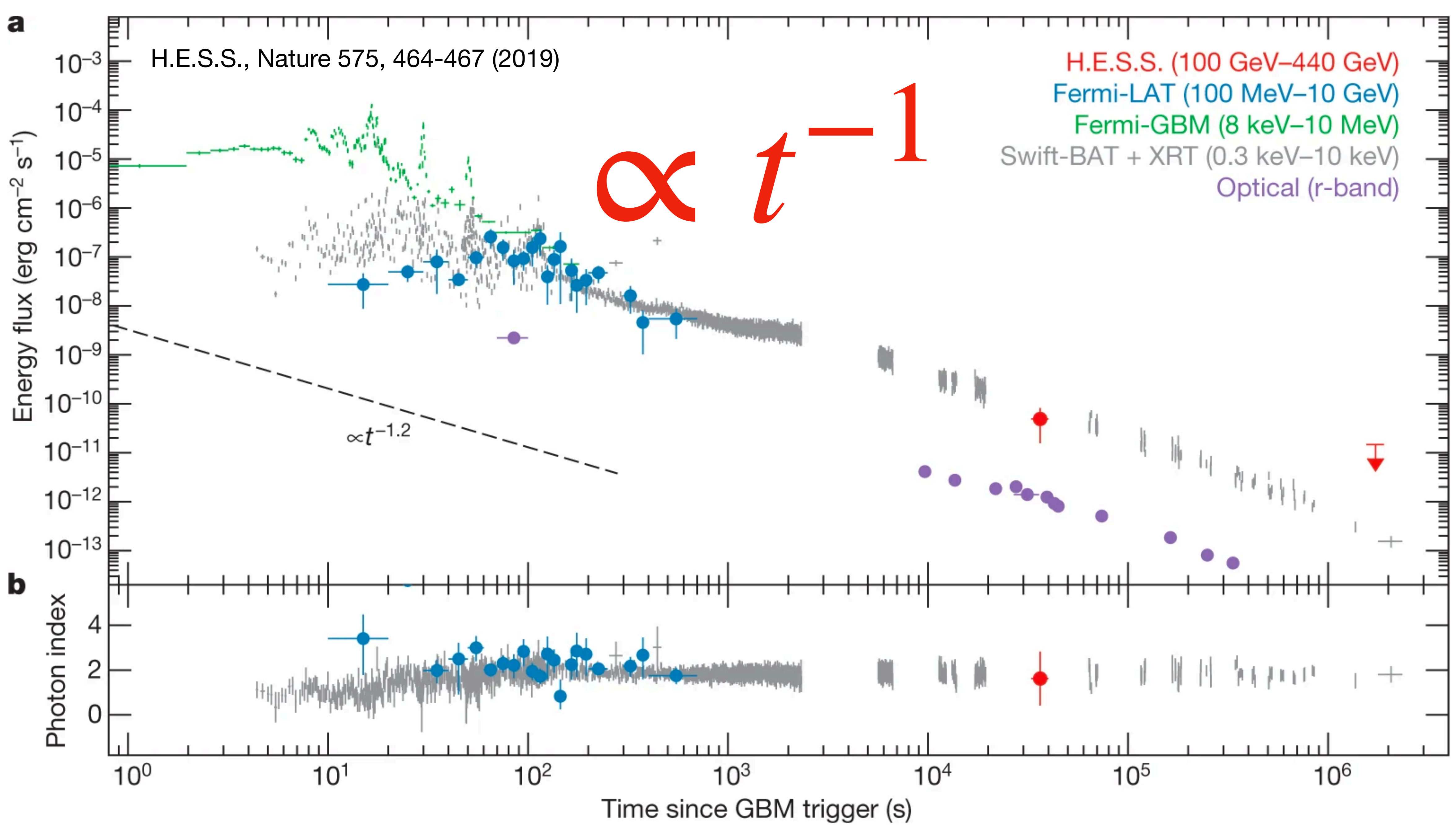
https://arxiv.org/abs/2002.11460

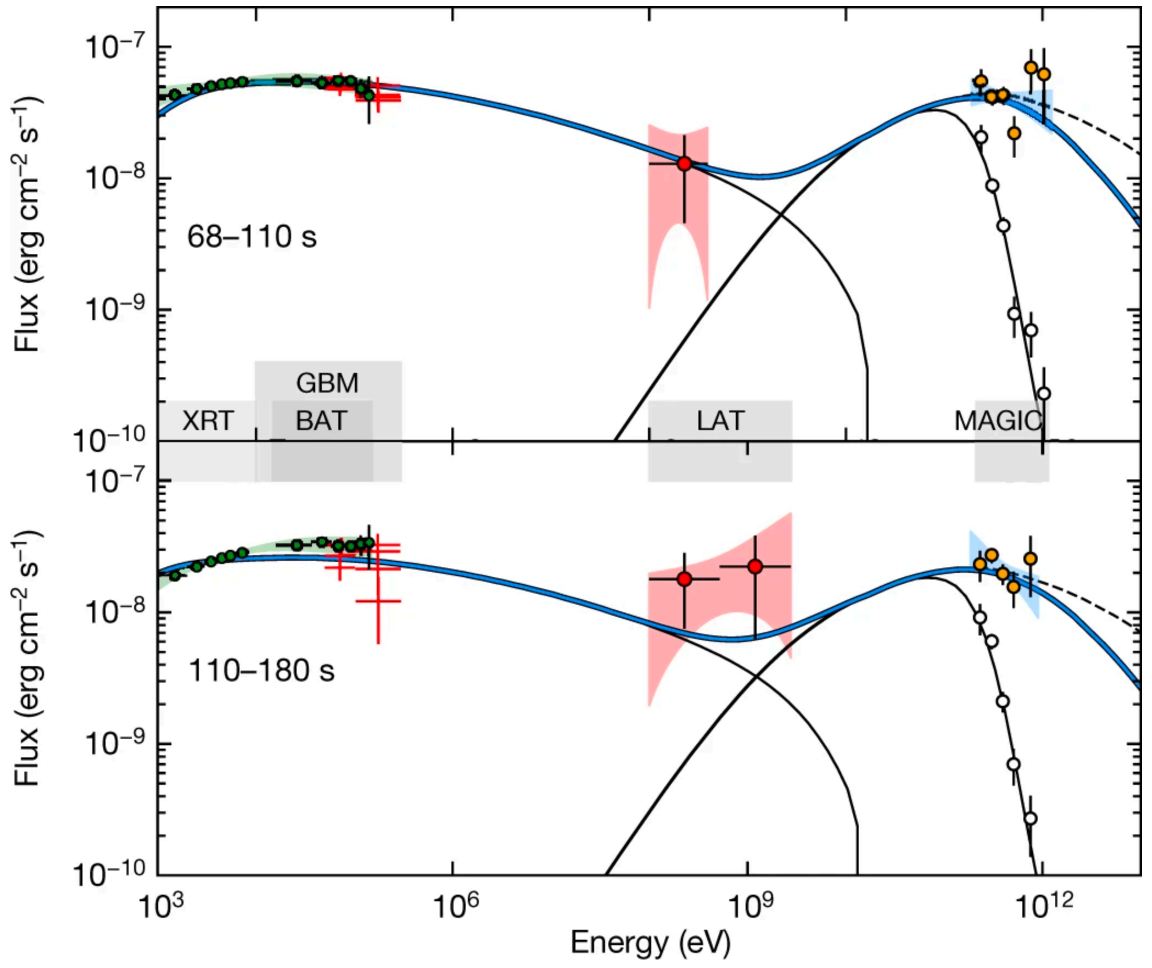


- Brightest gamma-ray transients.
- Cosmological distances, besides GRB/jet physics they can provide EBL constraints.
- Isotropic distribution and short duration requires a wide network of VHE observatories to follow-up these events.

RECENT VHE DETECTIONS OF GRBS

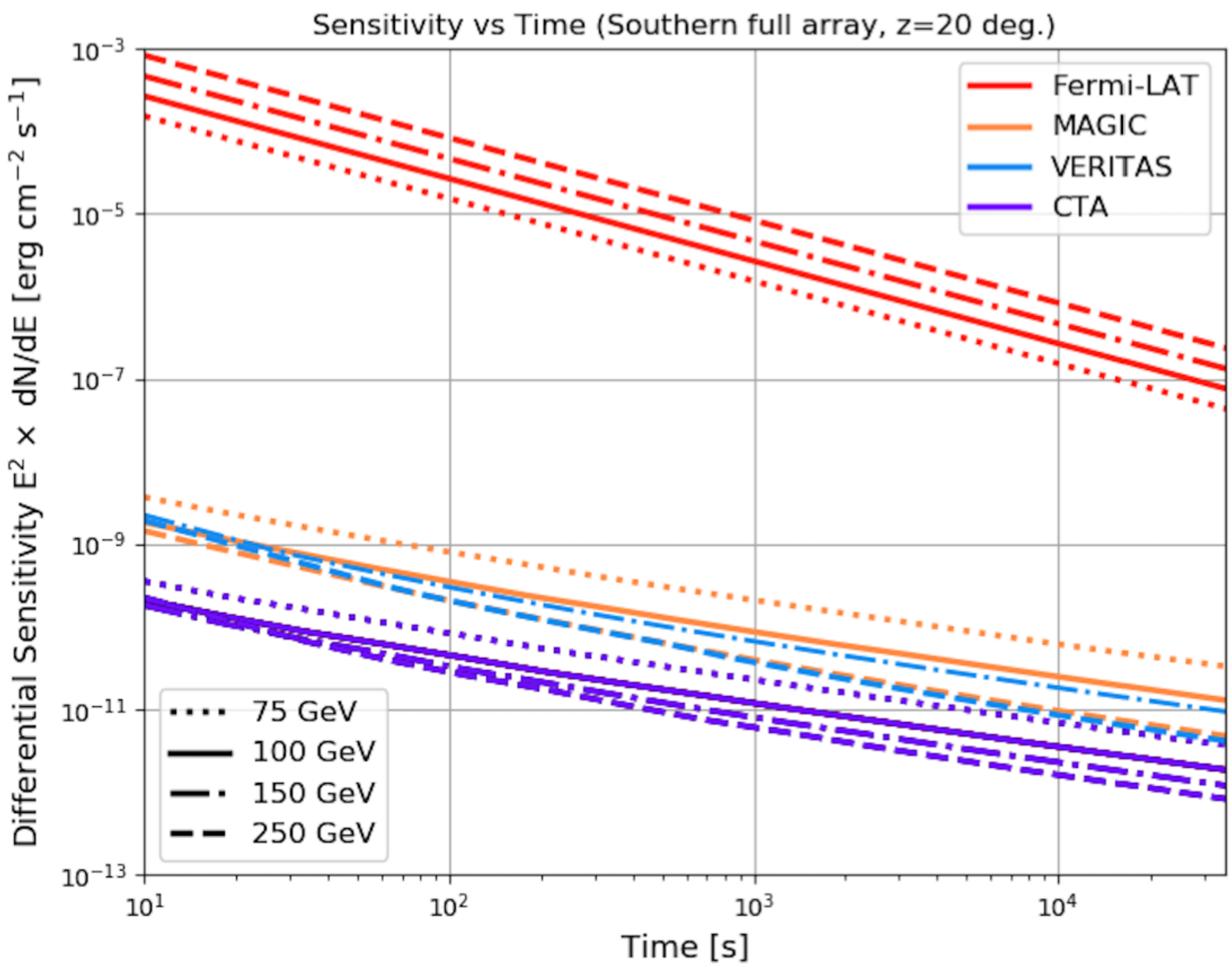






- All IACTs (going back to Whipple) operate a GRB program in search for VHE emission.
- Long-sought evidence first identified by MAGIC and H.E.S.S. in 2018-2019.
- Similar energy in X-ray and VHE favors SSC models.
- Four strong detections so far: GRB 190114C and 201216C by MAGIC, 180720B and 190829A by H.E.S.S.. Evidence of emission from a **short GRB 160821B by MAGIC**.

Transient sensitivity for IACTs

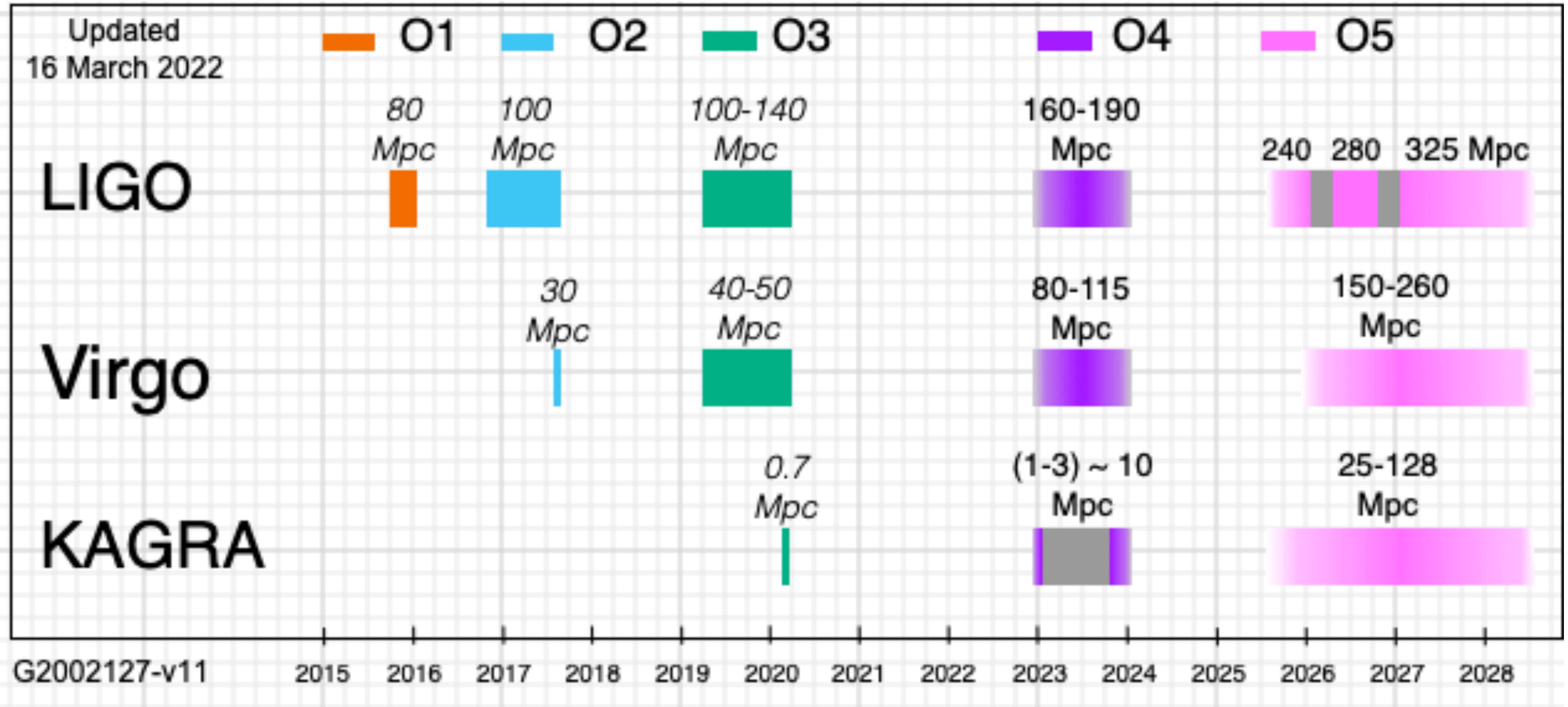


V. Fioretti et al. (CTA Consortium), PoS (ICRC 2019) 673

- Most sensitive instruments in the >100 GeV energy range.

FOLLOW-UP OF GW EVENTS WITH IACTS

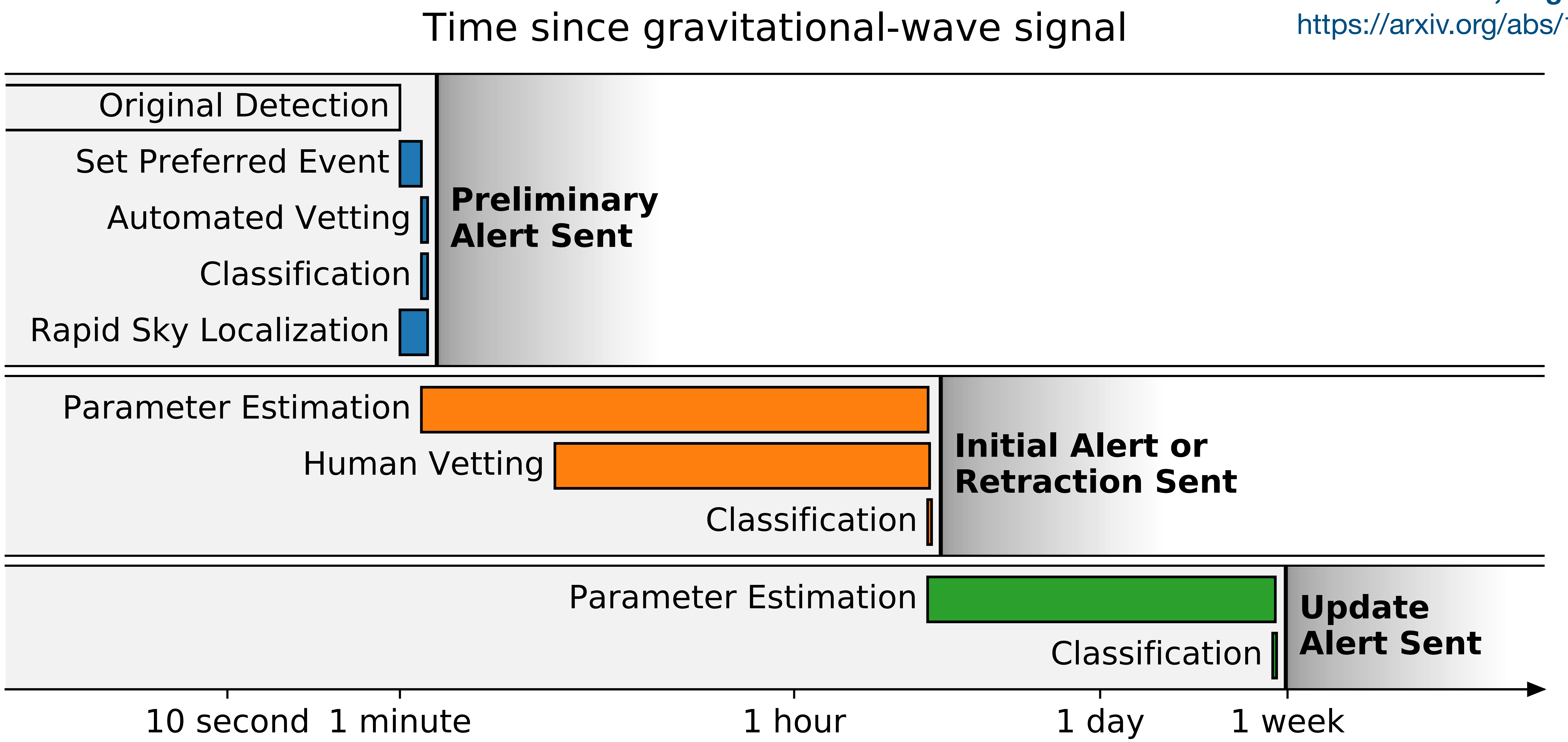
https://www.ligo.org/scientists/GWEMalerts.php



- Given the horizon for GW BNS detections, extragalactic background light absorption not a major issue.

TIMESCALES FOR GW EVENT ALERTS

LIGO, Virgo, KAGRA
https://arxiv.org/abs/1304.0670

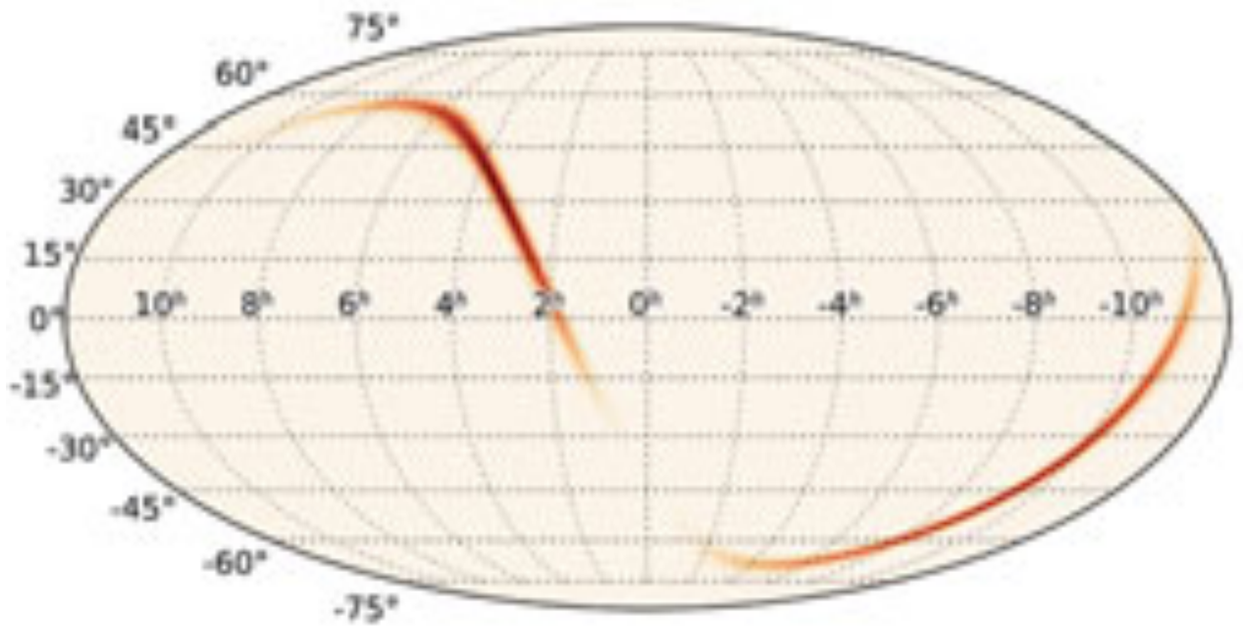


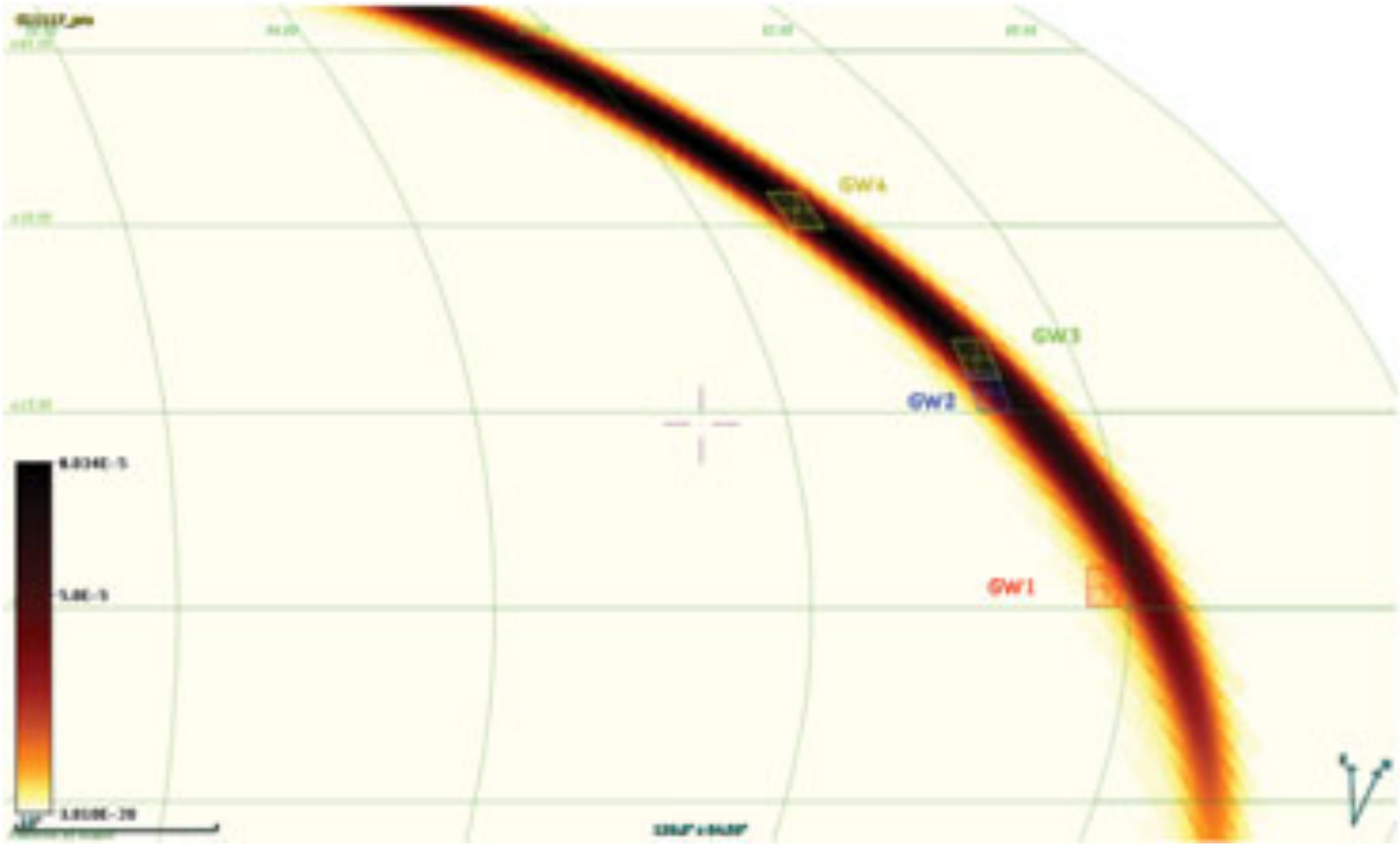
- Critical for VHE follow-ups to reduce any latency.
- As GW detectors improve it will be possible to even get early warnings!

EARLY EFFORTS AND CURRENT STATUS EFFORTS

GW151226 (MAGIC)

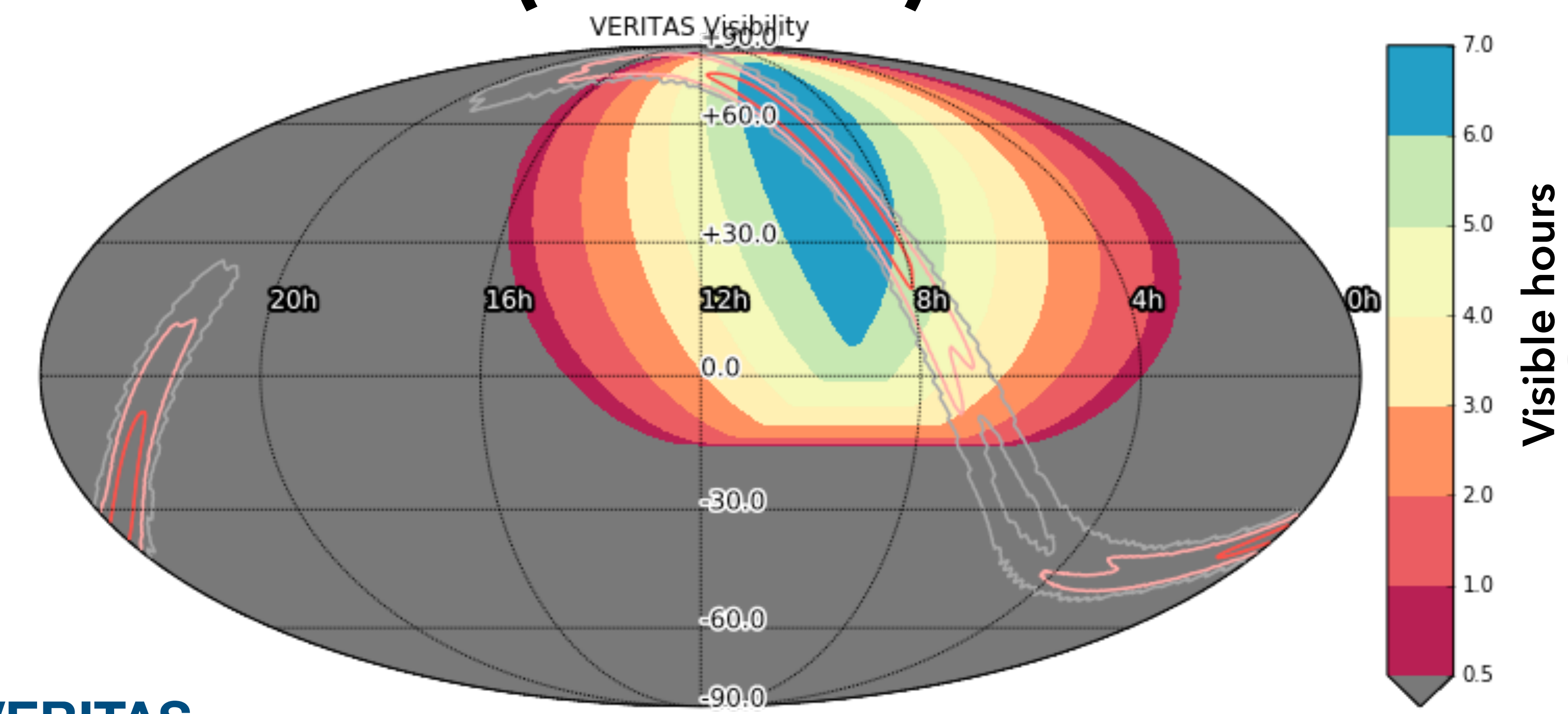
MAGIC [Reference]

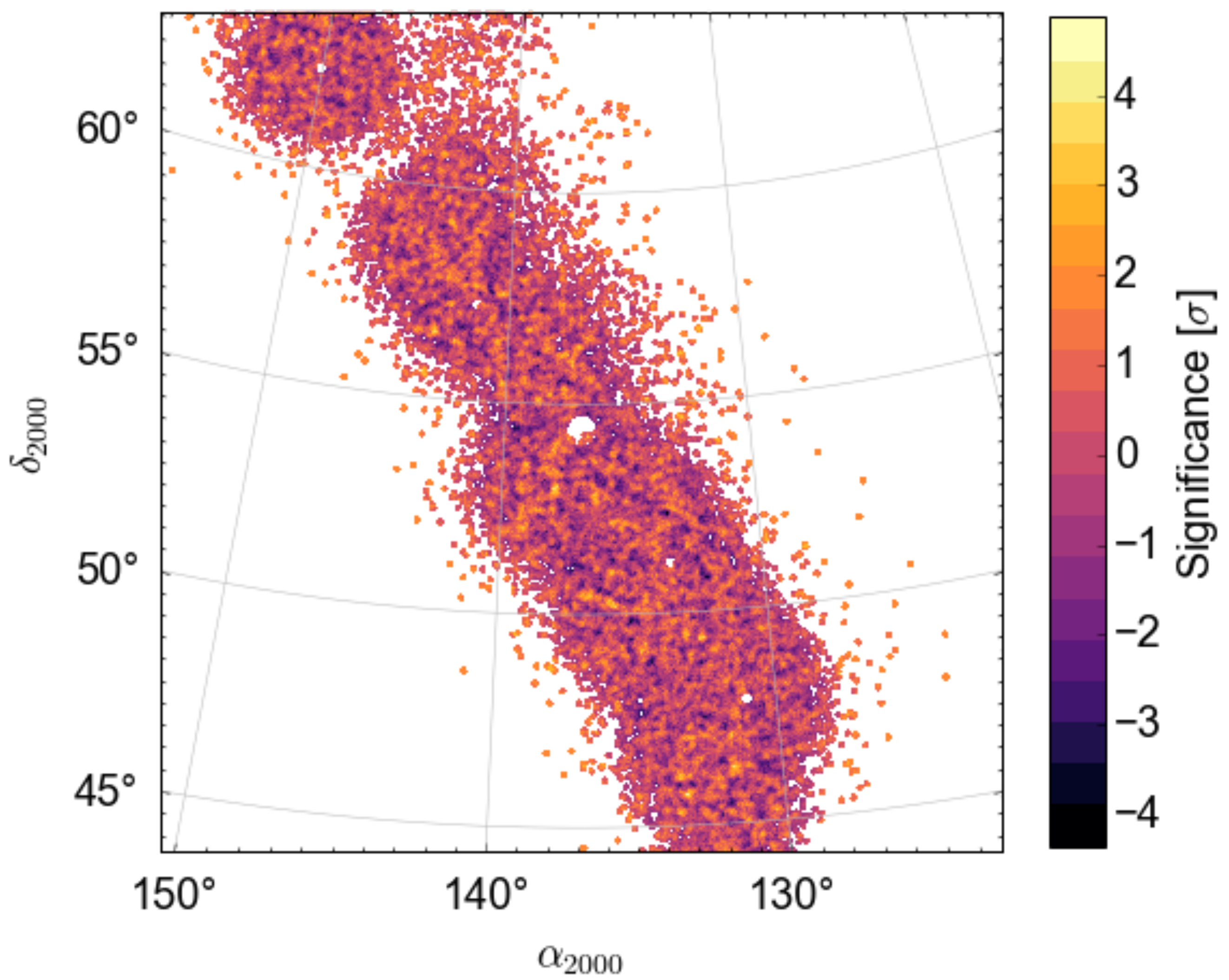


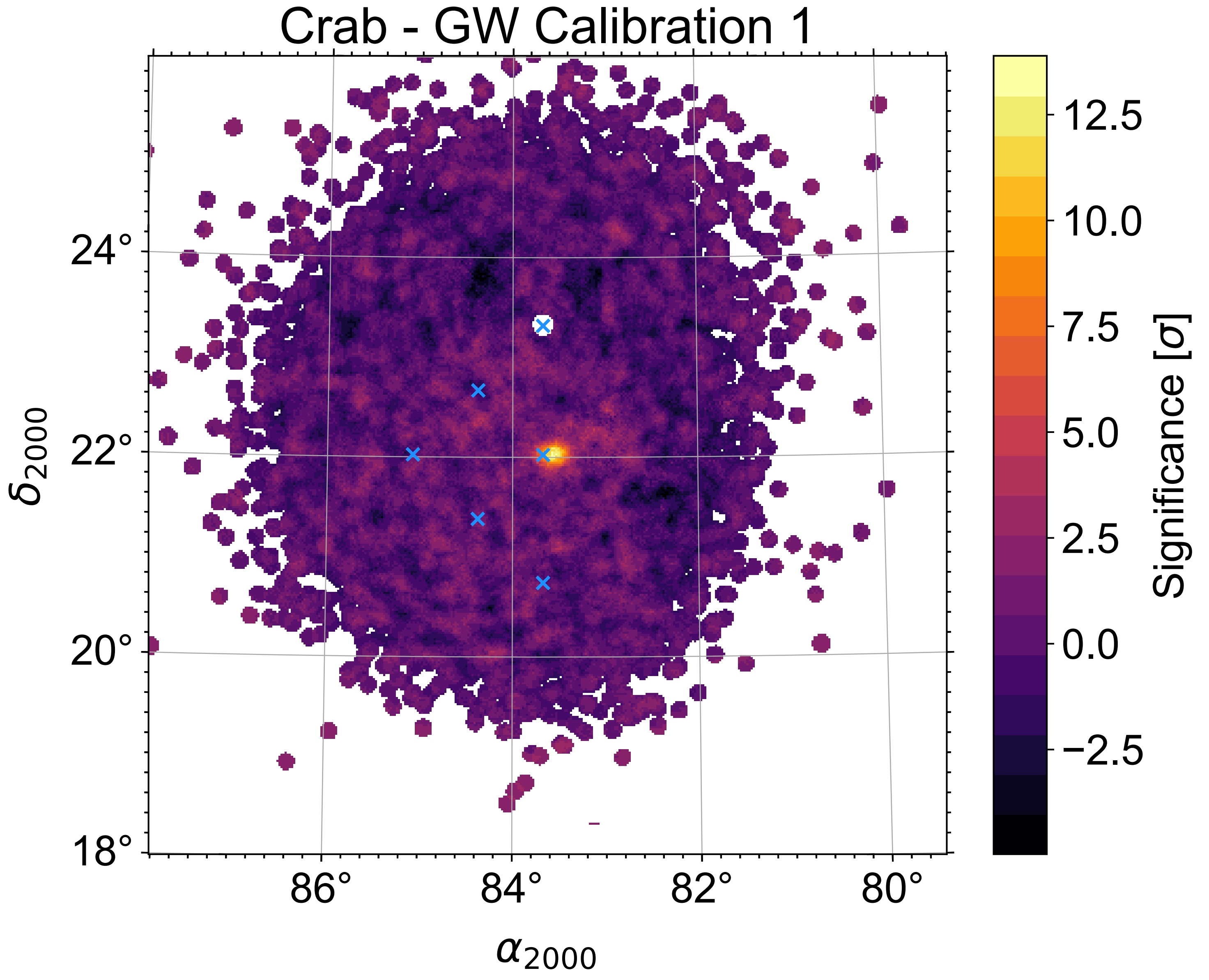


- MAGIC performed its first follow-up (manual tiling) during O1.
- VERITAS performed its first automatic tiling of the uncertainty region in O2 (GW170104).
- Observational capabilities validated using known sources.

GW170104 (VERITAS)





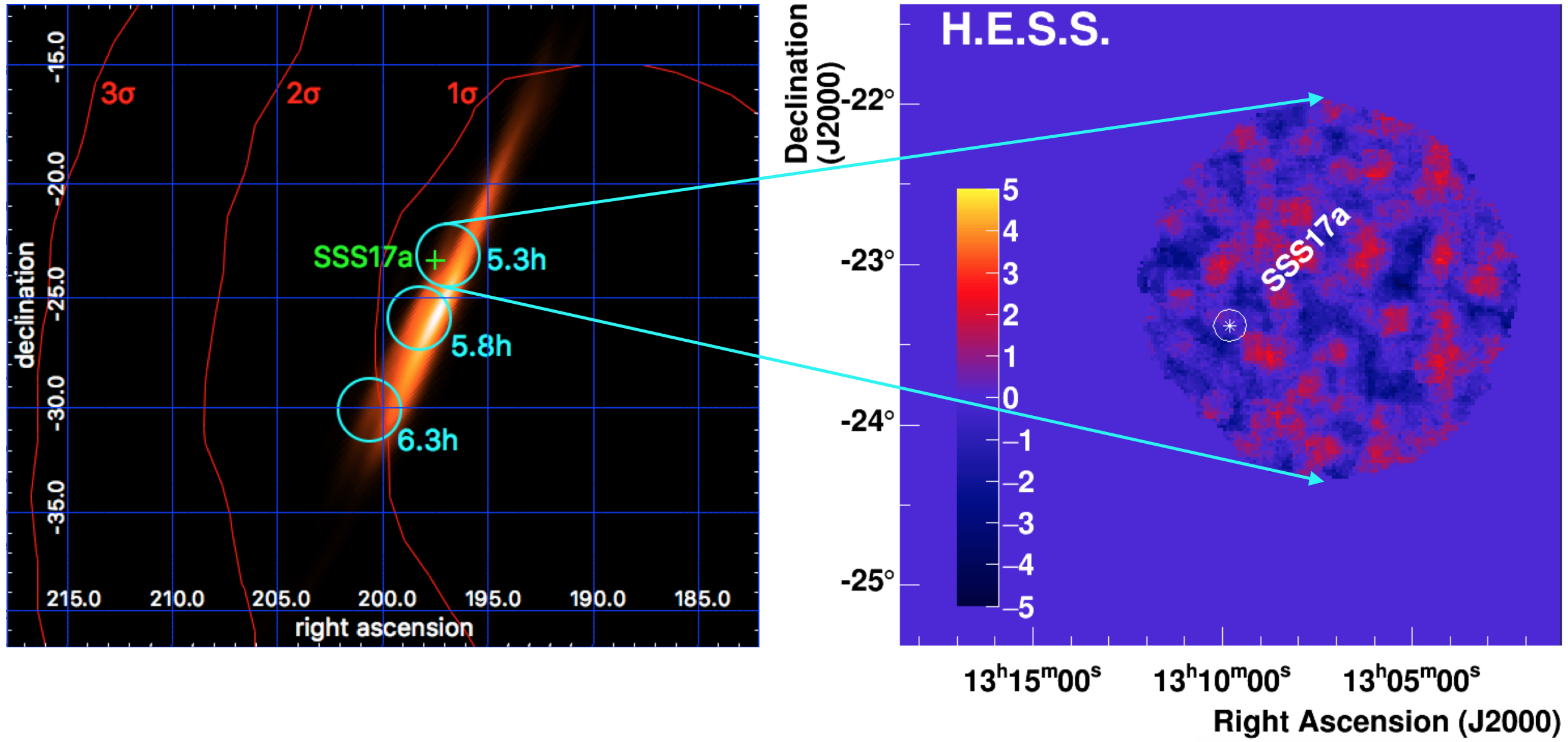


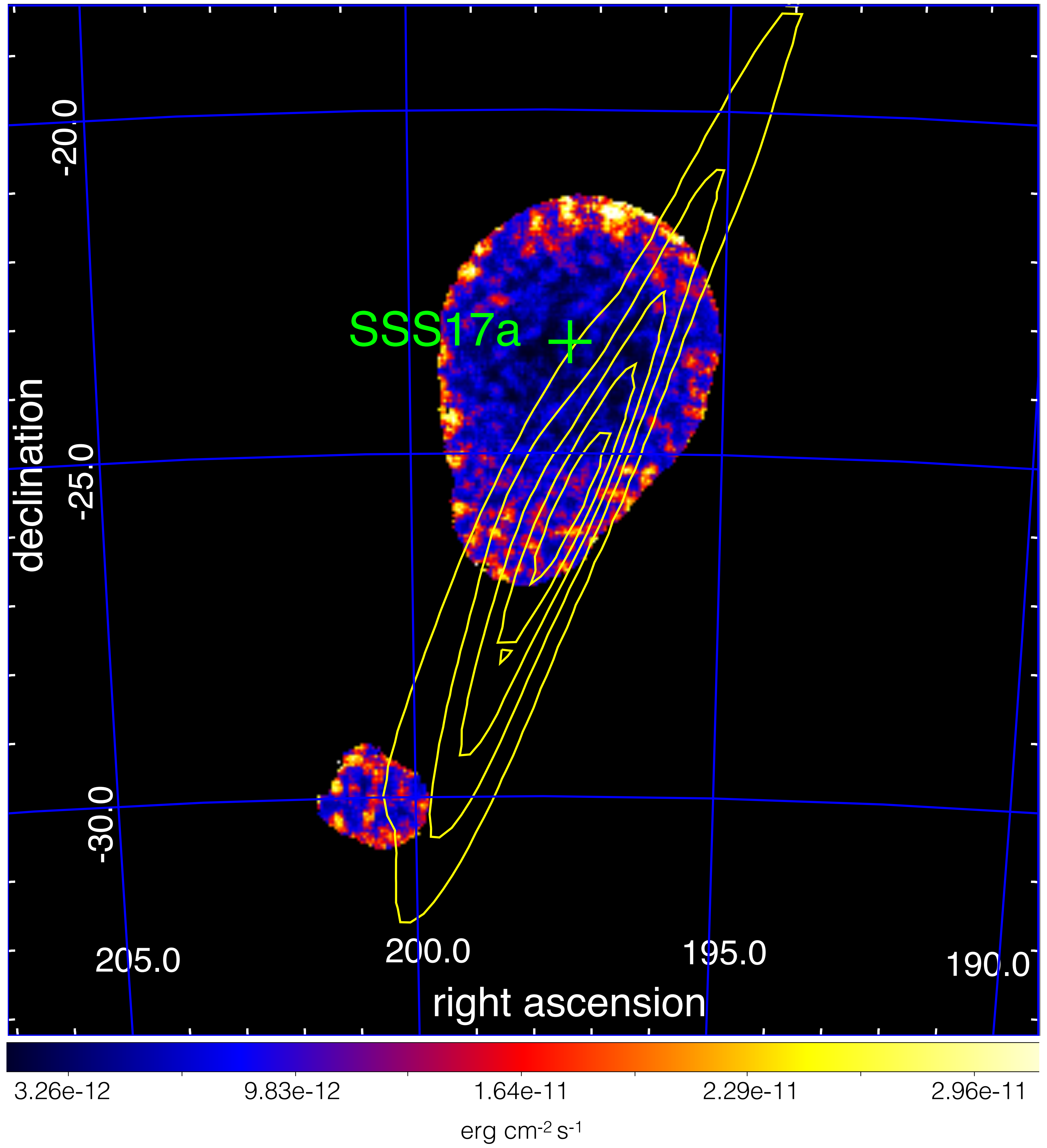
VERITAS
https://arxiv.org/abs/1909.05228

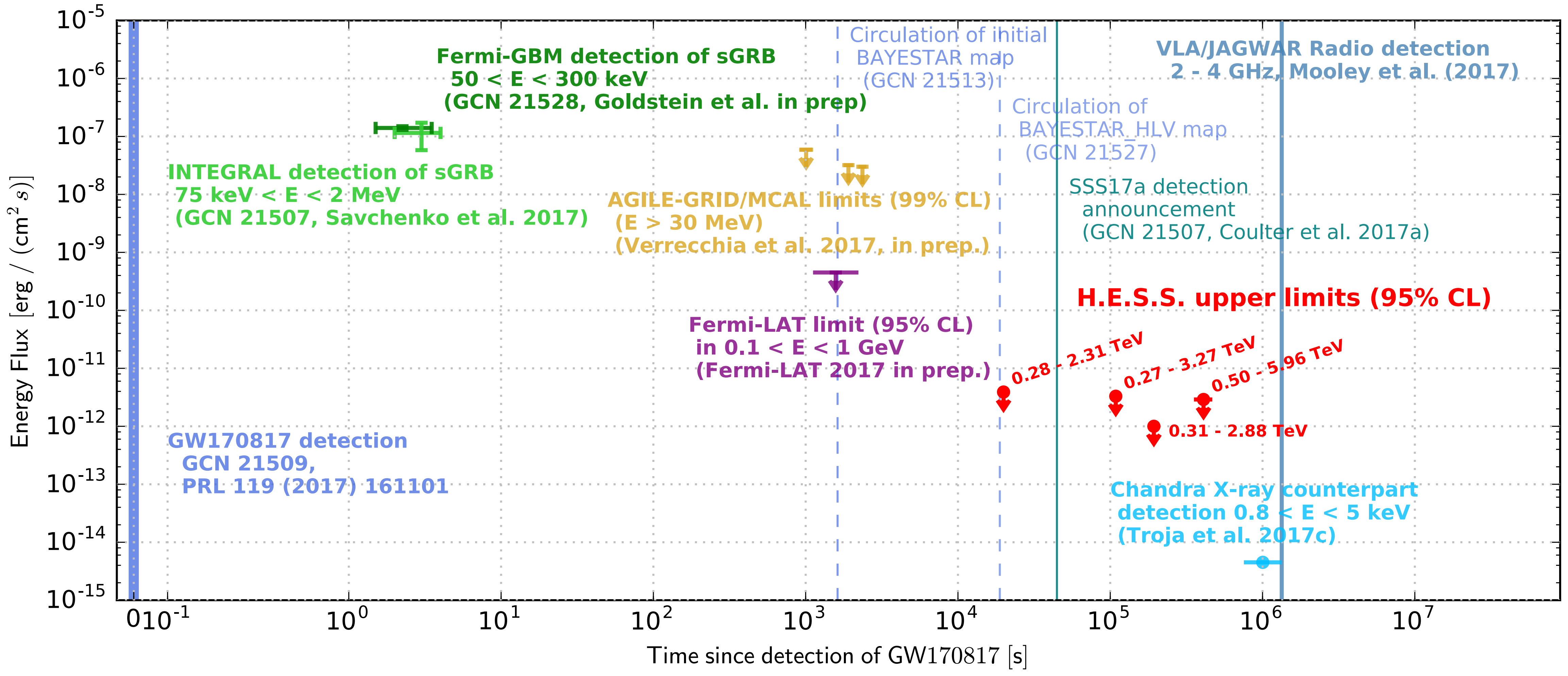
H.E.S.S. FOLLOW-UP OF GW170817

(H.E.S.S.) https://arxiv.org/abs/1710.05862

First follow-up before SSS17a discovery



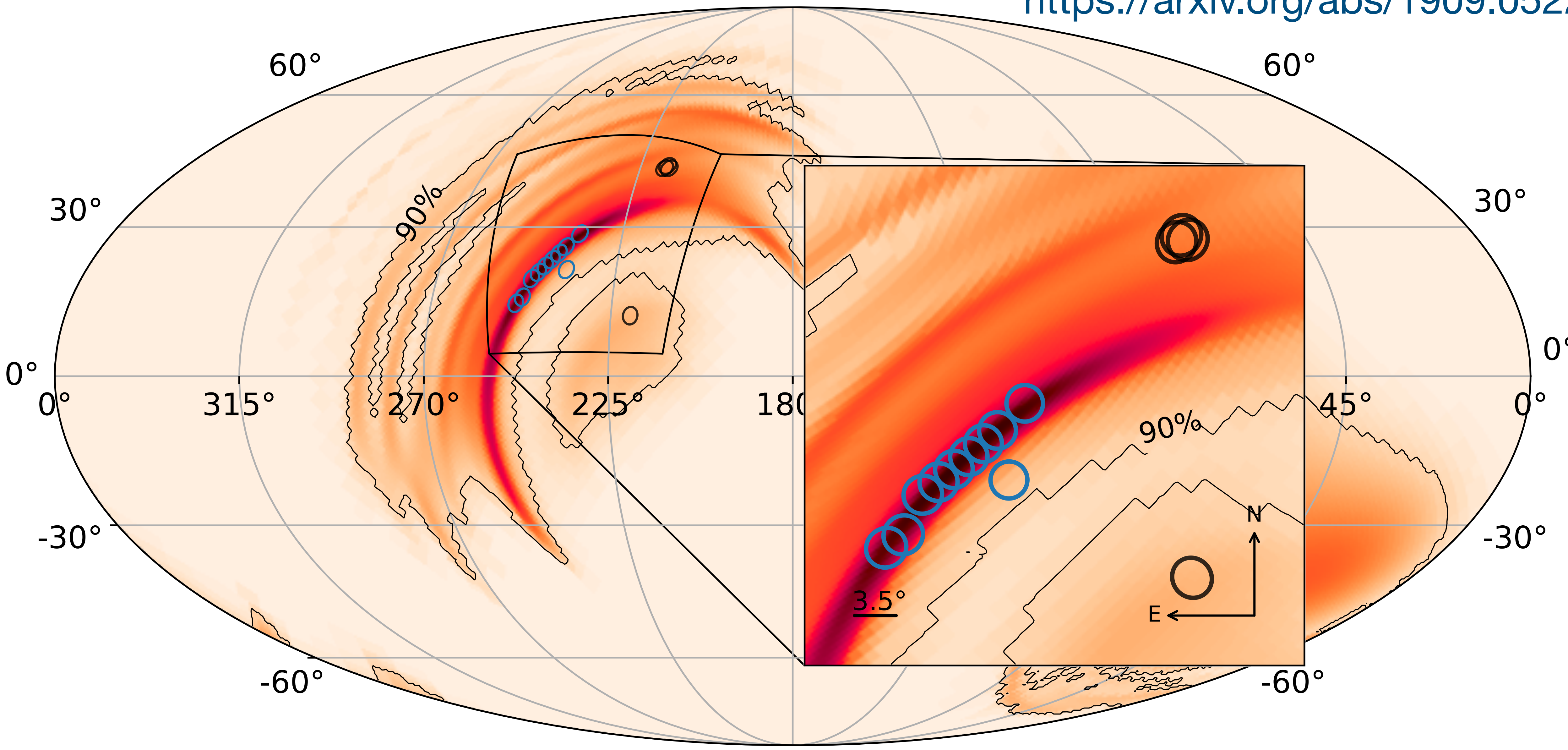




- First BNS merger, fast reaction to GW event and tiling of the uncertainty region.
- No detection, constraints on potential VHE counterpart luminosity.

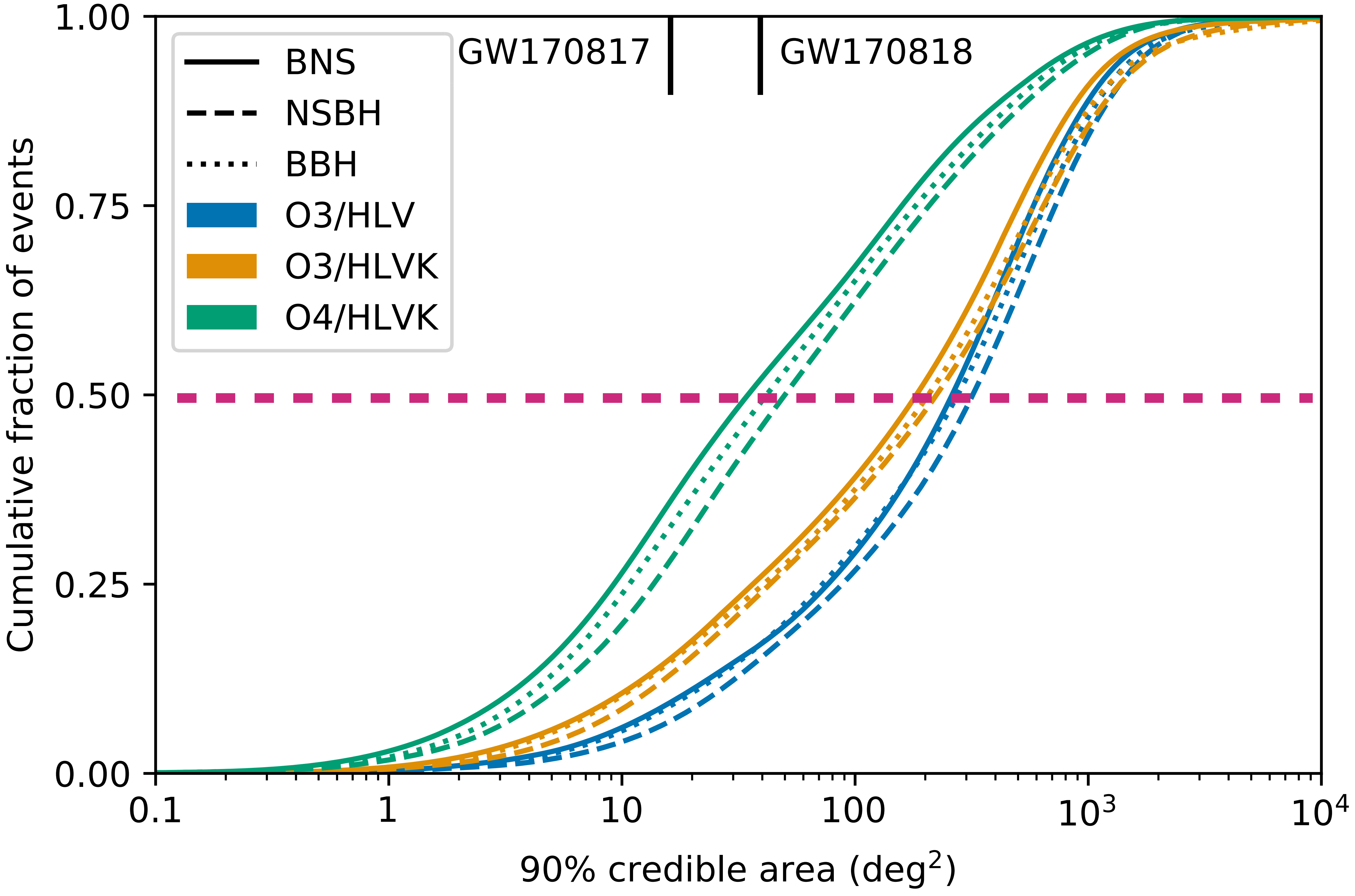
GW EVENT LOCALIZATIONS

VERITAS follow-up
https://arxiv.org/abs/1909.05228



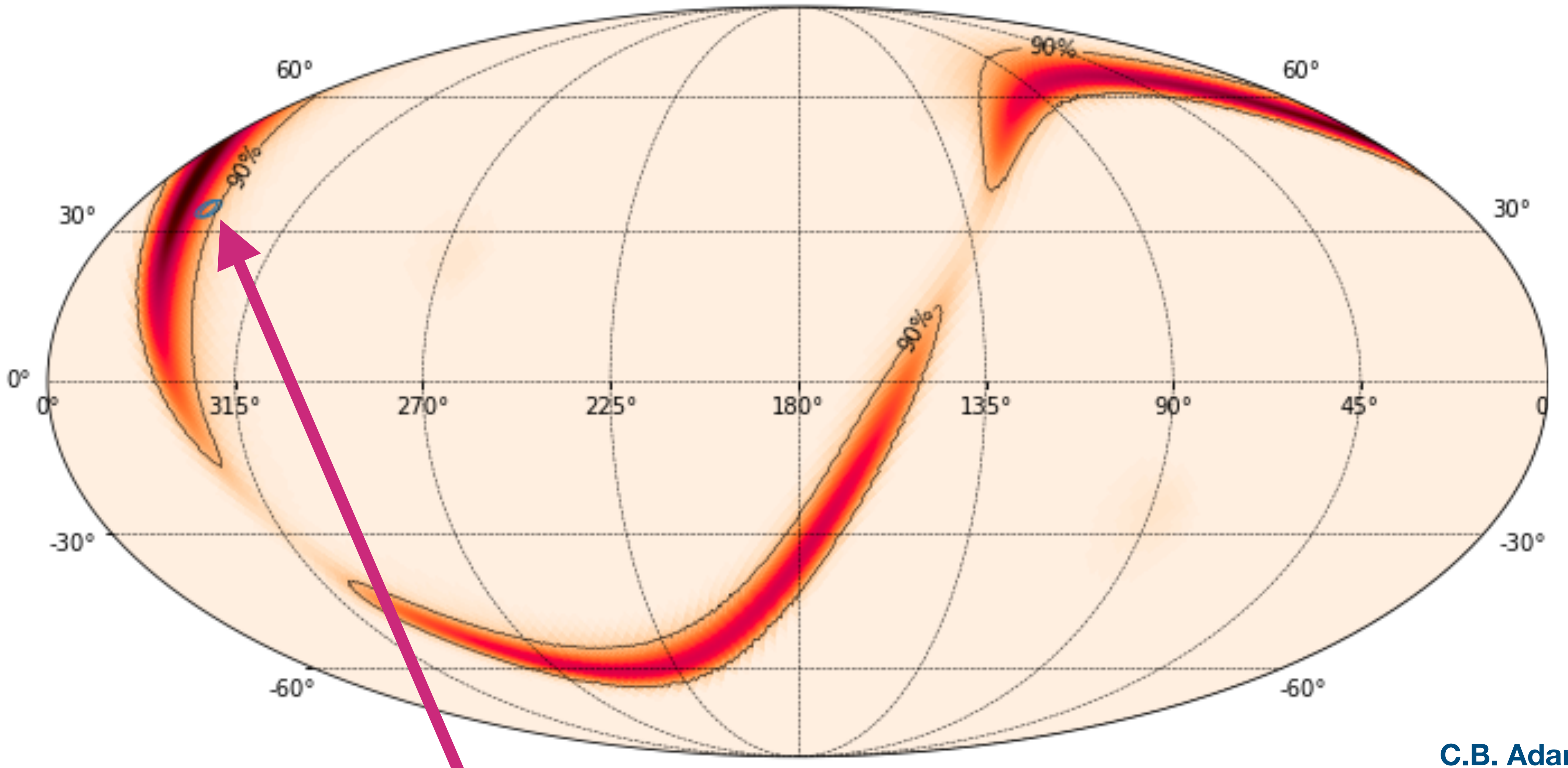
GW190425 - Second BNS merger detection
https://arxiv.org/pdf/2001.01761.pdf

LIGO, Virgo, KAGRA
https://arxiv.org/abs/1304.0670



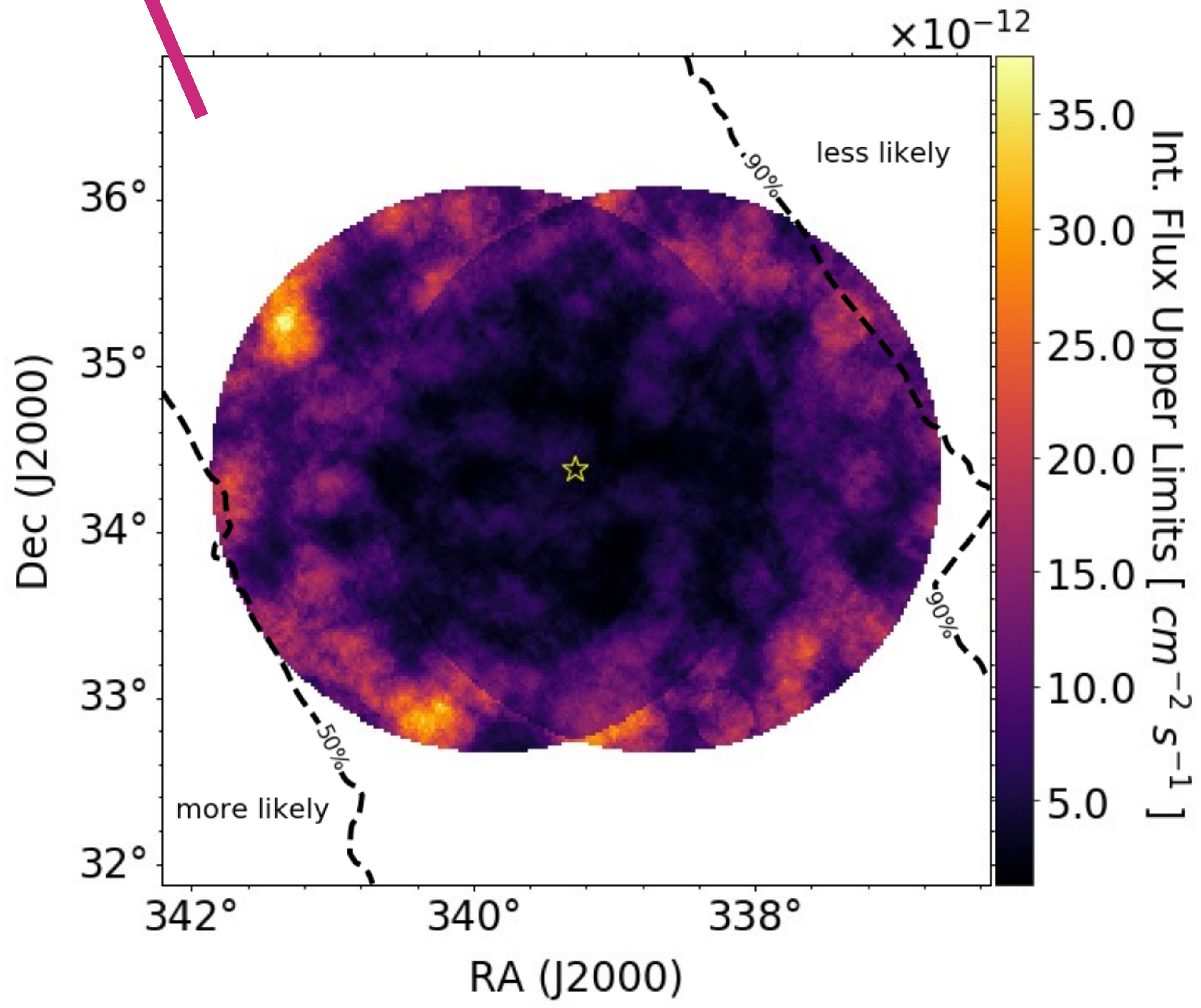
- The field of view of IACTs is currently in the 3°-5° diameter **(~10 deg²)**
- Searching for VHE emission requires tiling a large area very quickly. Trade-offs between exposure and coverage.
- Localizations of counterparts will remain challenging for upcoming runs! Start of O4 set for the end of this year.

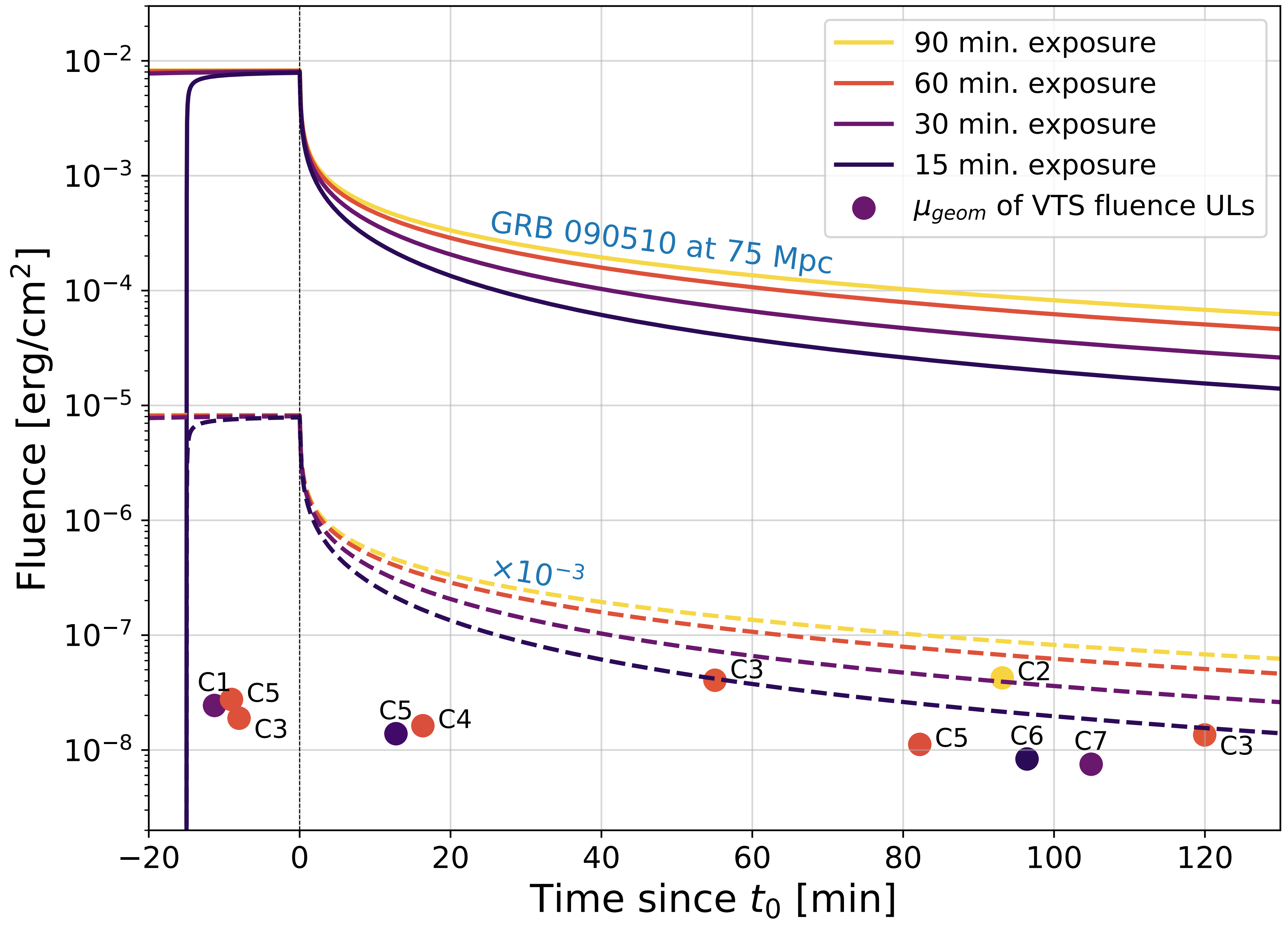
SERENDIPITOUS SEARCHES INVOLVING GW EVENTS



- Serendipitous search for VHE emission coincident with sub-threshold GW events with VERITAS.
- Pathfinder study for CTA and future GW detectors.
- No VHE detection. ULs compared to GRB emission model.
- Accepted for publication in ApJ (2021)

C.B. Adams et al (VERITAS),
arXiv/2106.01386





FUTURE GW ALERTS

https://gracedb.ligo.org/latest/

GraceDB **Public Alerts** Latest Search Documentation Login

Please log in to view full database contents.

Latest as of 7 April 2022 10:11:13 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

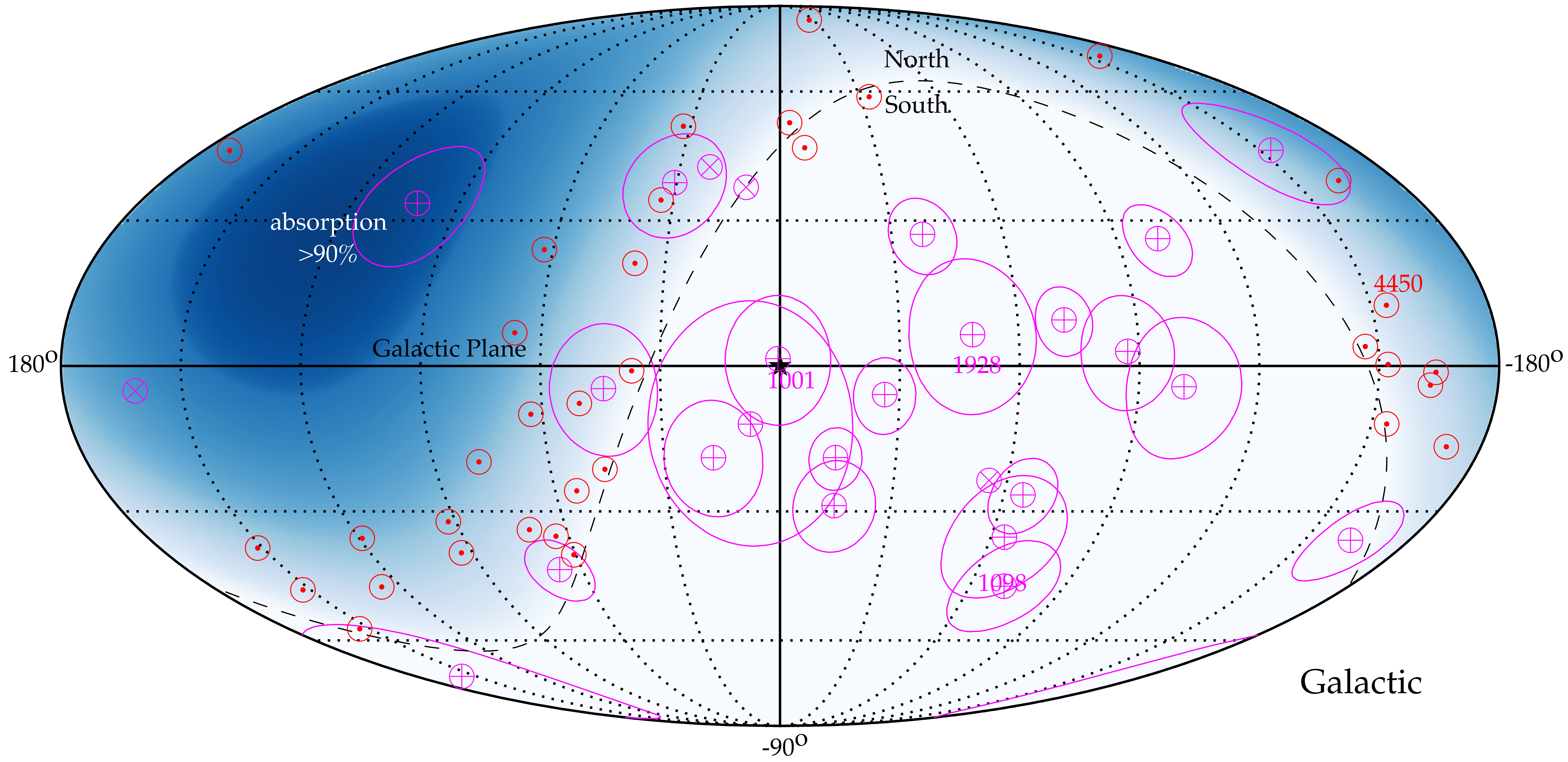
Search

Tap on entry for detailed information

UID	Labels	FAR (Hz)	Created
S200316bj	DQOK ADVOK EM_READY EM_Selected EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT PE_READY	7.098e-11	2020-03-16 21:58:12 UTC
S200311bg	DQOK EM_READY ADVOK EM_Selected EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT PE_READY	8.939e-26	2020-03-11 11:59:09 UTC
S200308e	DQOK ADVNO EM_READY EM_Selected PASTRO_READY EMBRIGHT_READY SKYMAP_READY GCN_PRELIM_SENT	3.619e-09	2020-03-08 01:20:11 UTC
S200303ba	DQOK ADVNO EM_READY EM_Selected EMBRIGHT_READY PASTRO_READY SKYMAP_READY PE_READY	1.316e-08	2020-03-03 12:16:14 UTC
S200302c	DQOK ADVOK EM_READY EM_Selected PASTRO_READY EMBRIGHT_READY SKYMAP_READY GCN_PRELIM_SENT PE_READY	9.349e-09	2020-03-02 01:58:34 UTC
S200225q	DQOK EM_READY ADVOK EM_Selected PASTRO_READY EMBRIGHT_READY SKYMAP_READY GCN_PRELIM_SENT PE_READY	9.186e-09	2020-02-25 06:04:44 UTC

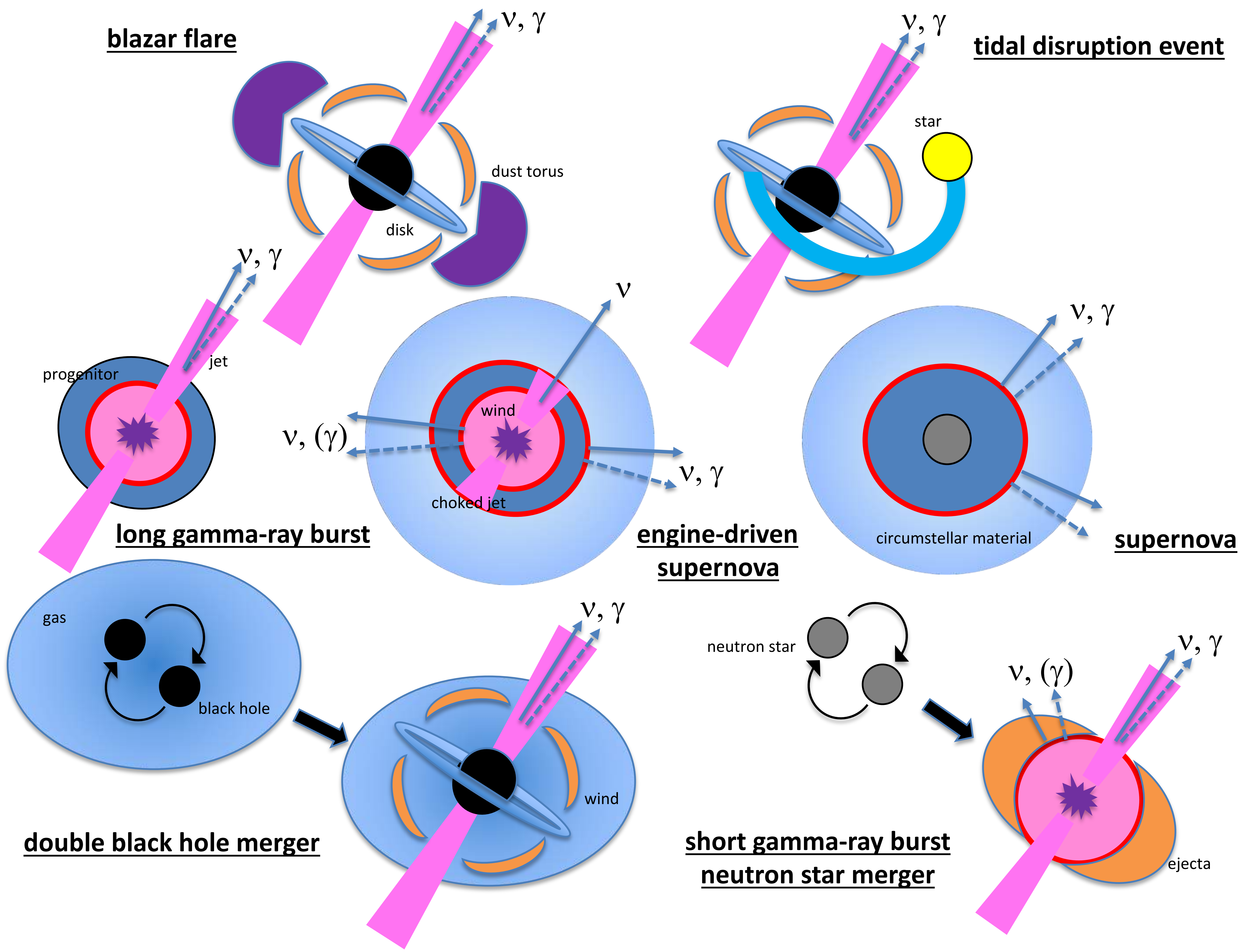
ASTROPHYSICAL NEUTRINOS

Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



- Consistent with isotropic distribution, favors extragalactic origin.
- No apparent correlation with Galactic plane.
- **HE event rate is low. ~O(10) events / year.**

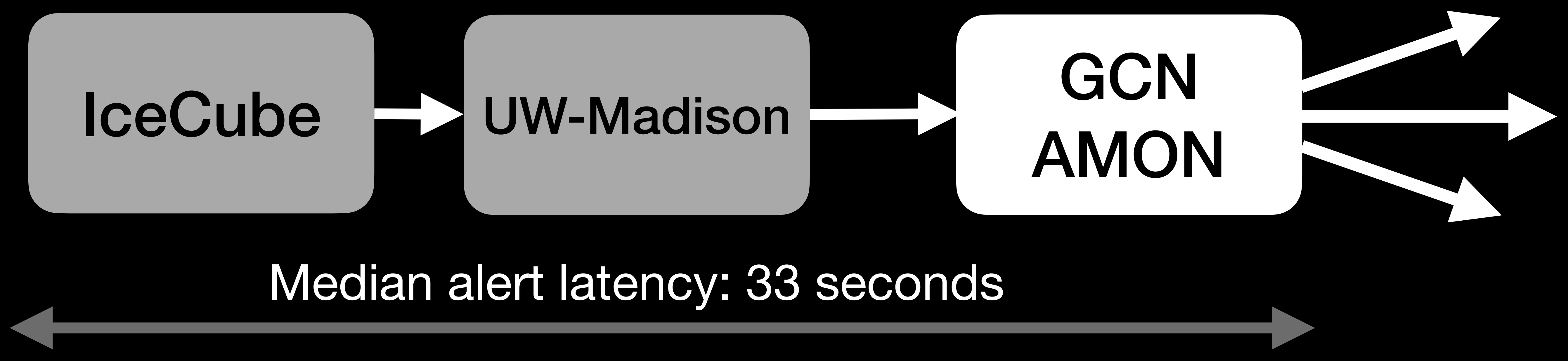
THE NEUTRINO ZOO



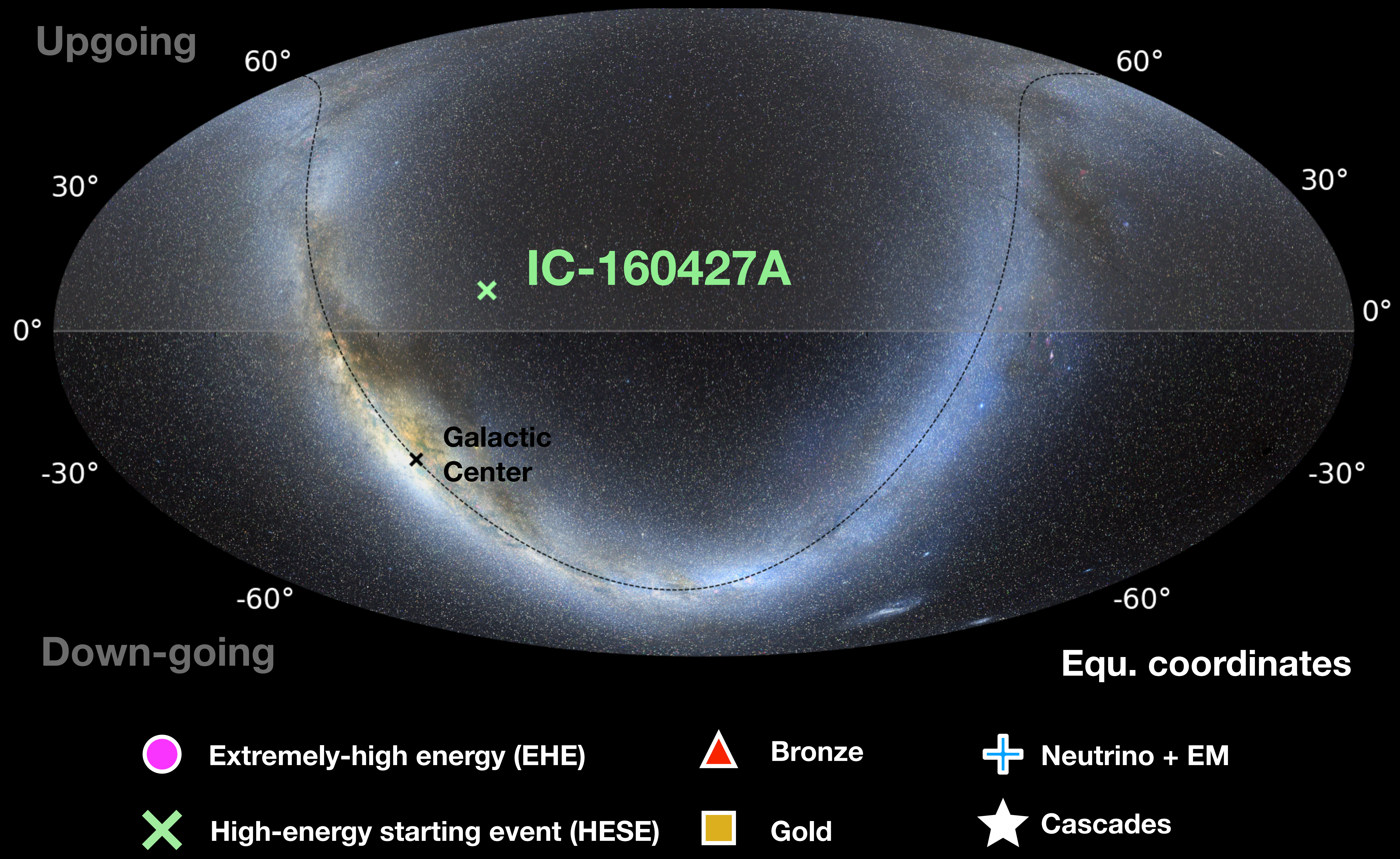
- Non-thermal emission can be observed across the EM spectrum for most of these sources.
- Wide variety of timescales and EM spectral features for these sources!
- **Broadcast neutrinos of potential astrophysical origin.**

Murase & Bartos (https://arxiv.org/abs/1907.12506)

REALTIME ALERTS

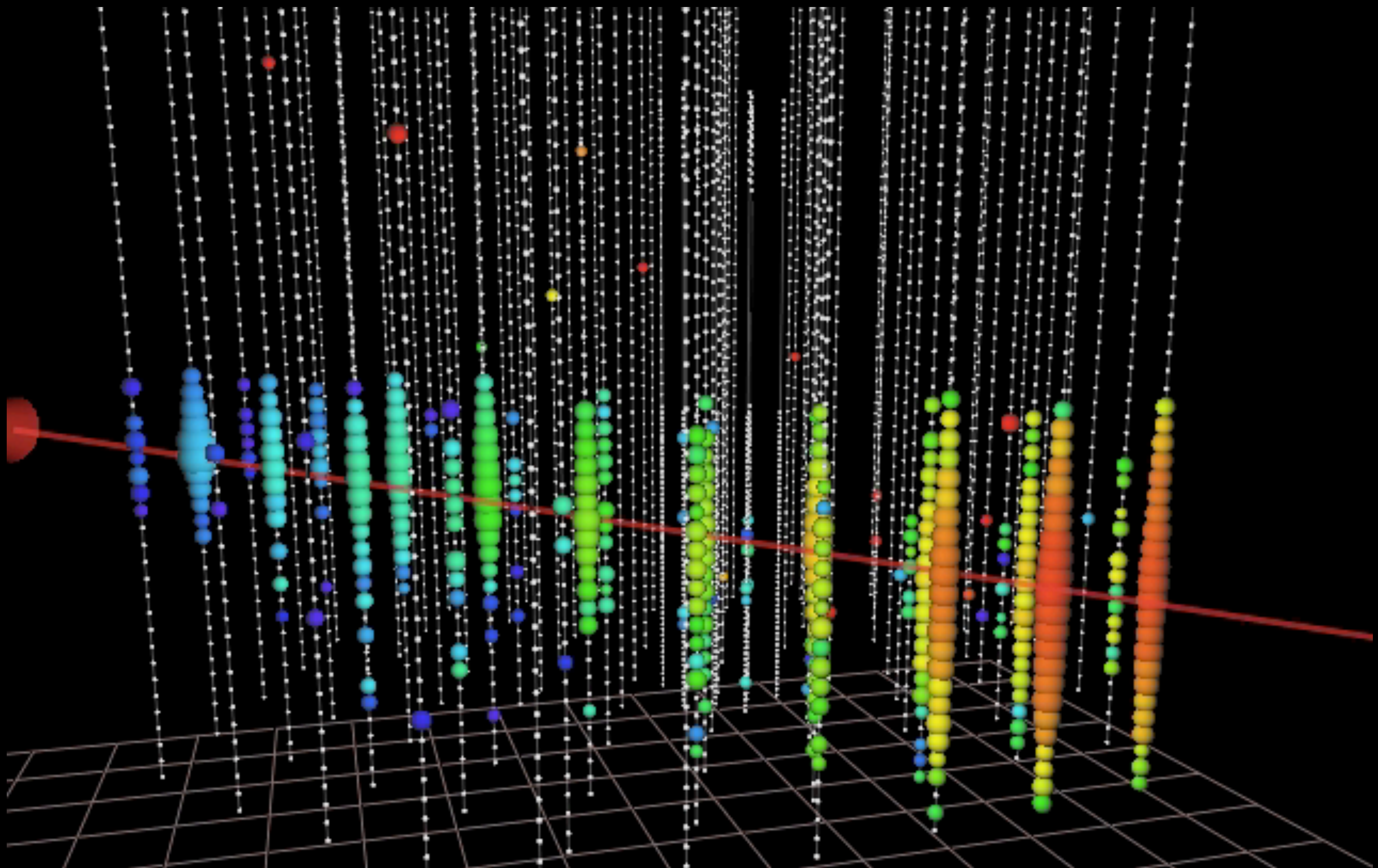


https://gcn.gsfc.nasa.gov/amon.html



- **Original alert streams (2016-2019)**
  - **HESE**: HE starting muon events. Median ang. resolution ~1.5°. 3-4 / year. ~25% astrophysical fraction.
  - **EHE**: HE through-going muons. Median angular resolution < 0.5°. 4-6 / year. ~50% astrophysical fraction.
- First alert on April 2016.
- Alerts issued via GCN: 18 HESE, 9 EHE.

ICECUBE REALTIME ALERTS

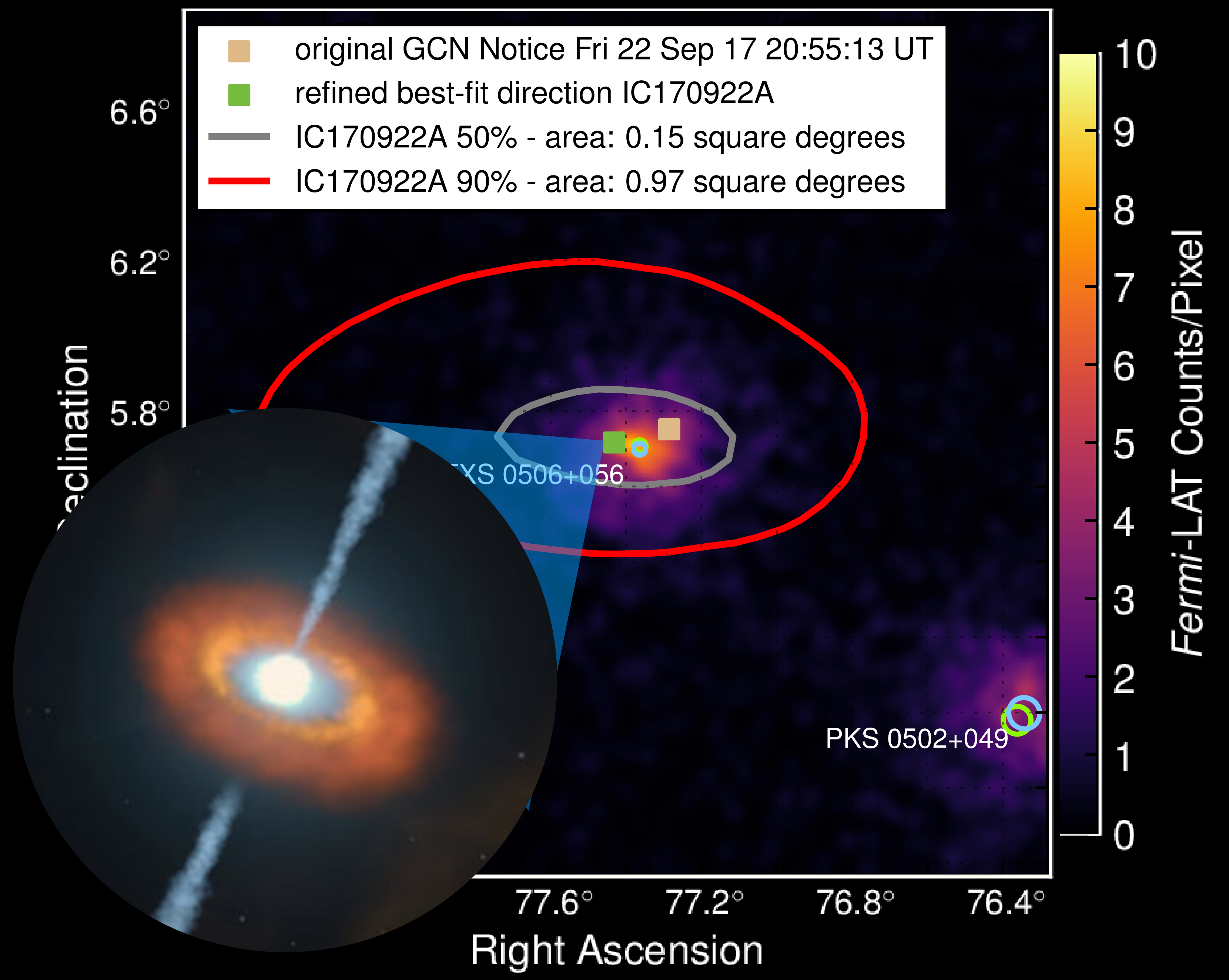


IC170922A

290 TeV neutrino energy (> 183 TeV, 90% CL)

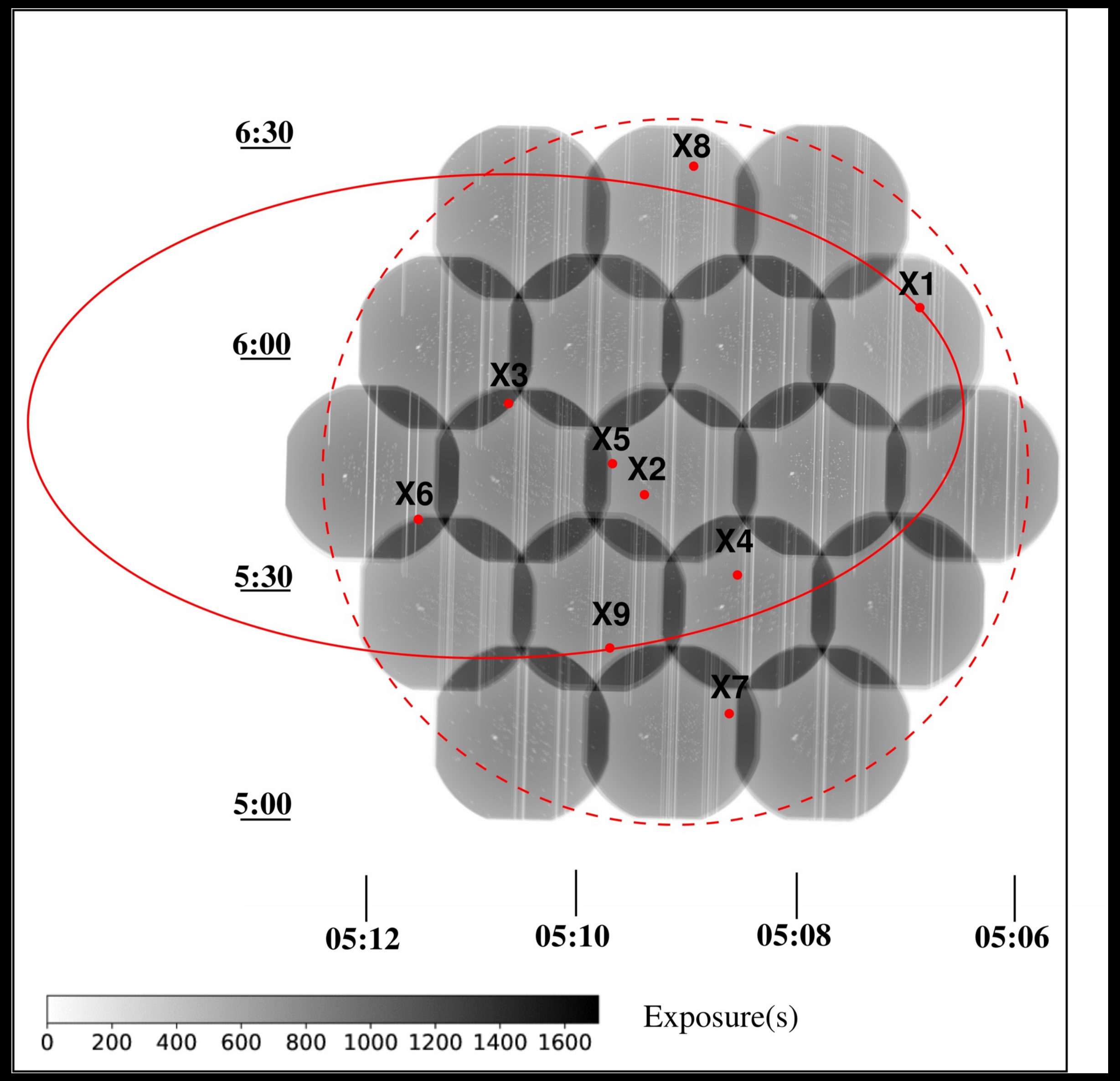
- Alert system implemented in **2016**
- Automatically circulated to the astronomical community a few minutes after detection at the South Pole.

0.1 - 300 GeV



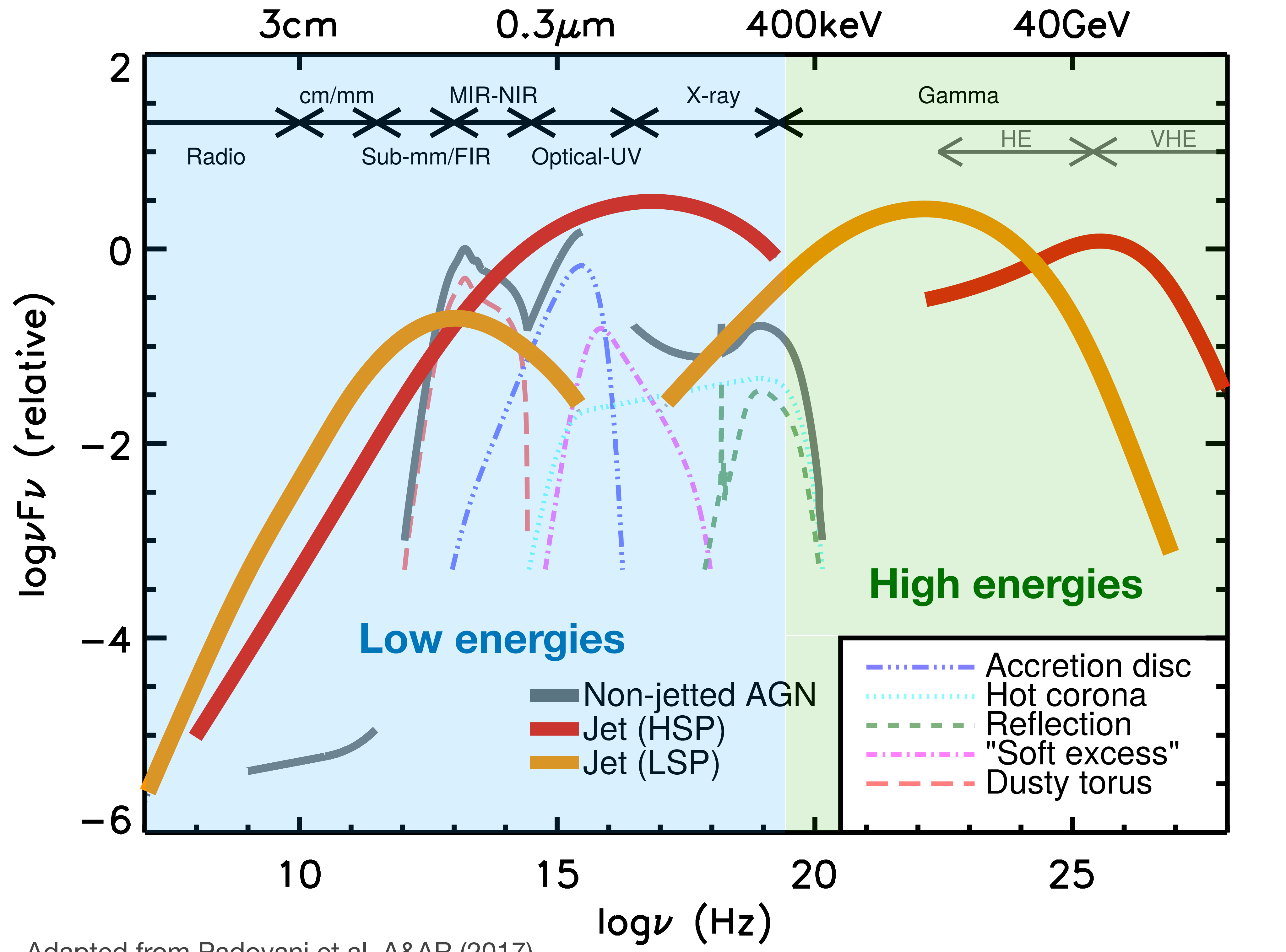
Fermi-LAT

0.3 - 10 keV



Swift-XRT

SPECTRAL ENERGY DISTRIBUTIONS OF BLAZARS

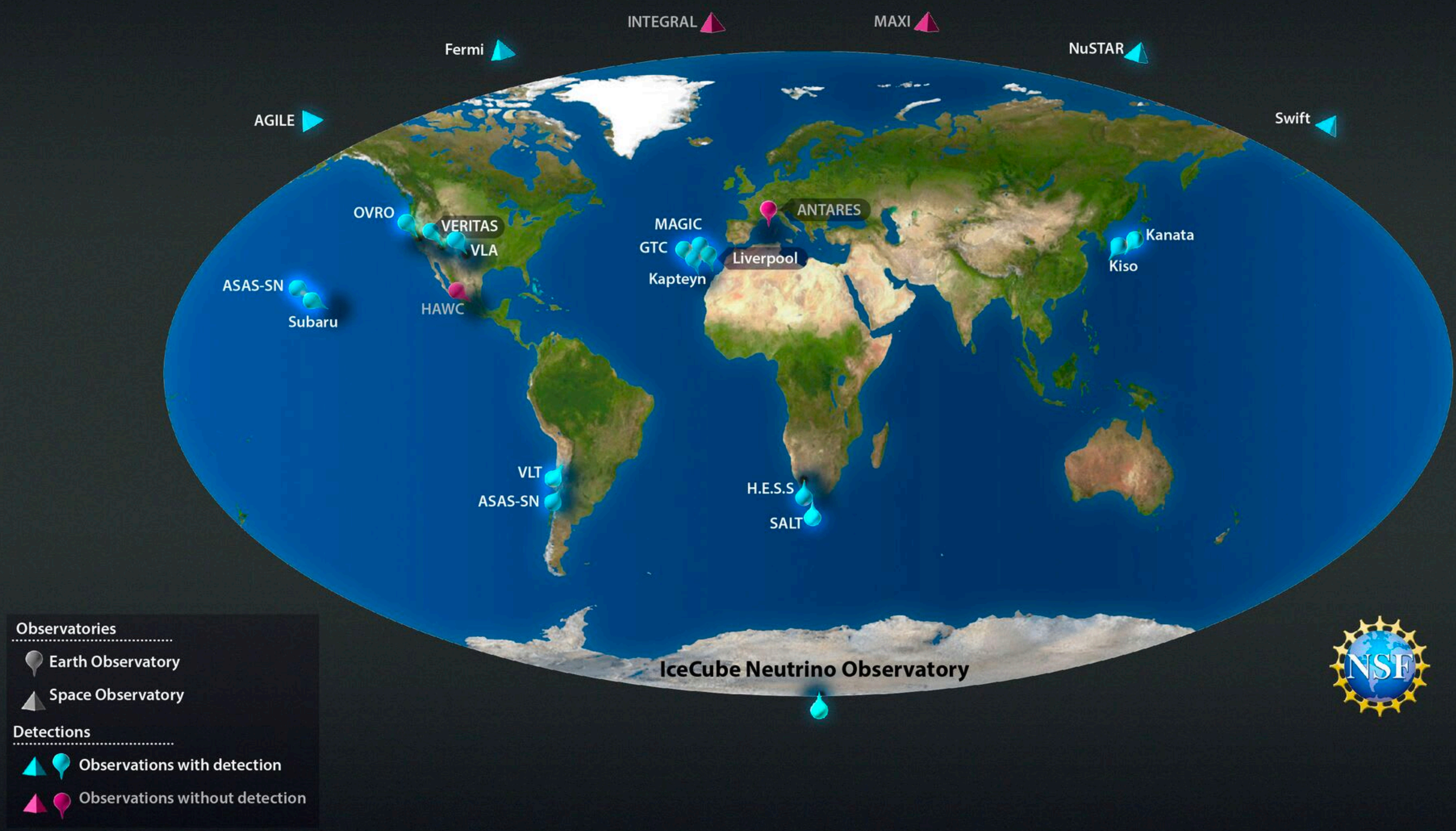


Adapted from Padovani et al. A&AR (2017)

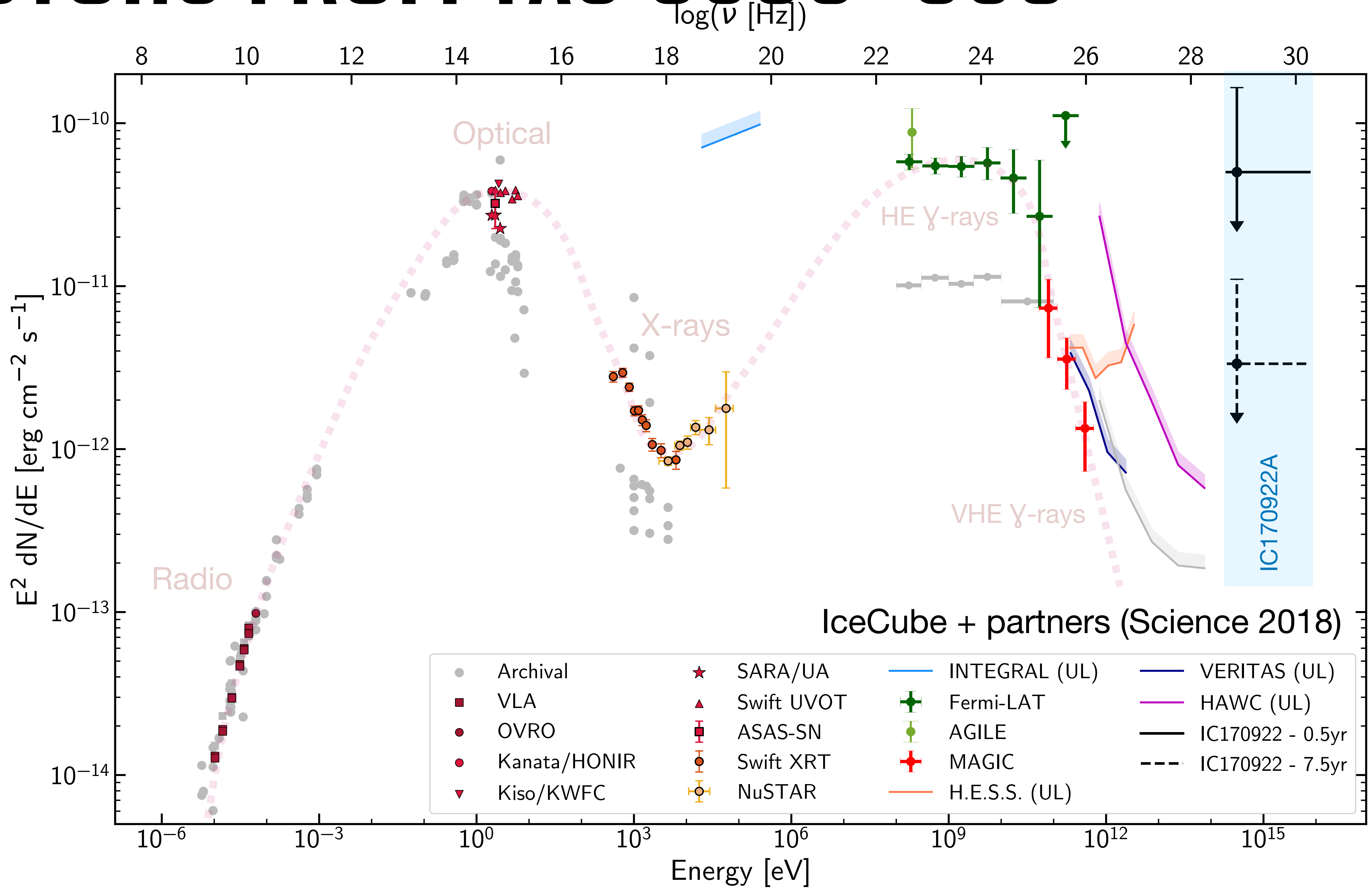
- Broadband SED characterized by two broad emission "bumps"
  - **Low energies (radio to X-ray)**: typically described by synchrotron emission from relativistic e^-/e^+ in the jet.
  - **High energies (X-ray to gammas)**: less understood. Two main models:
    - *Leptonic:* inverse Compton scattering of lower energy photons from e^-/e^+ in the jet.
    - *Hadronic:* Decay of neutral pions from interactions of high-energy hadrons (i.e. cosmic rays) accelerated in the jet. Cosmic rays interact with low energy photons in the jet (p-γ) or with gas/dust (p-p)

- **The identification of hadronic signatures would reveal AGN as cosmic ray accelerators, solving a long-standing question of UHECR origin.**
- It would also provide insights into the particle acceleration in extreme EM and gravitational environments.

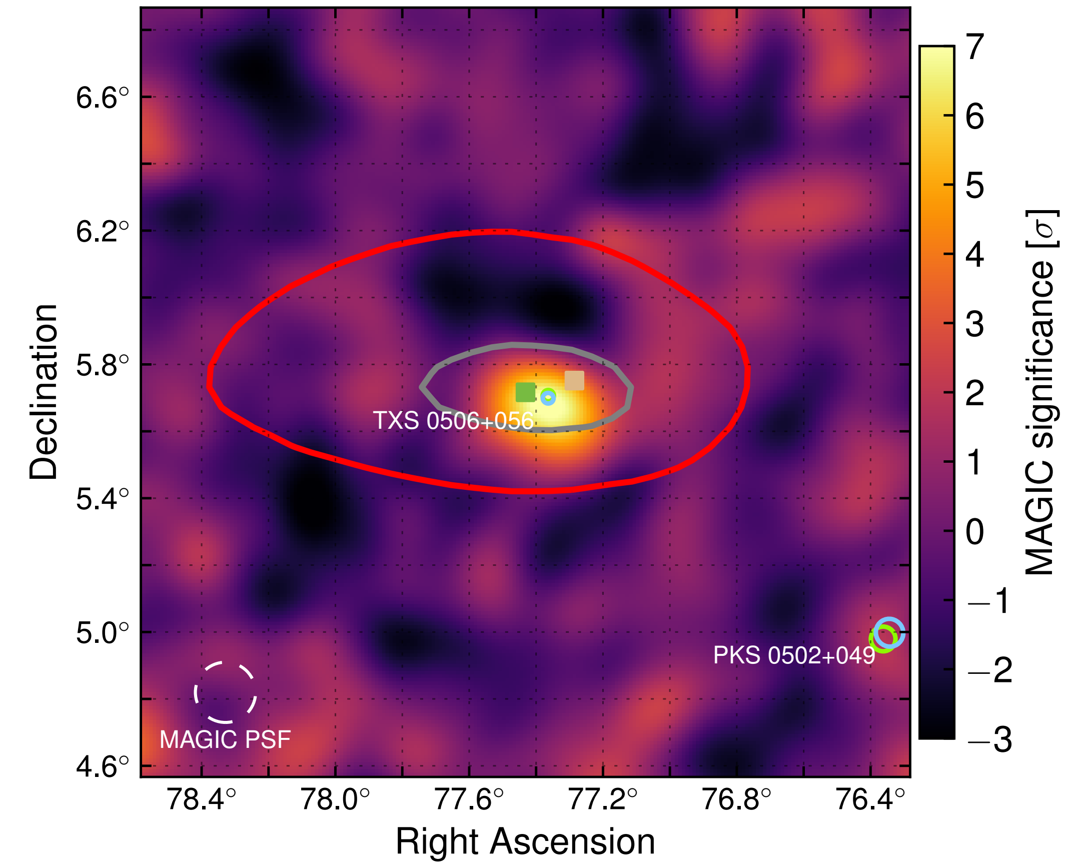
Follow-up Observations of IceCube Alert IC170922



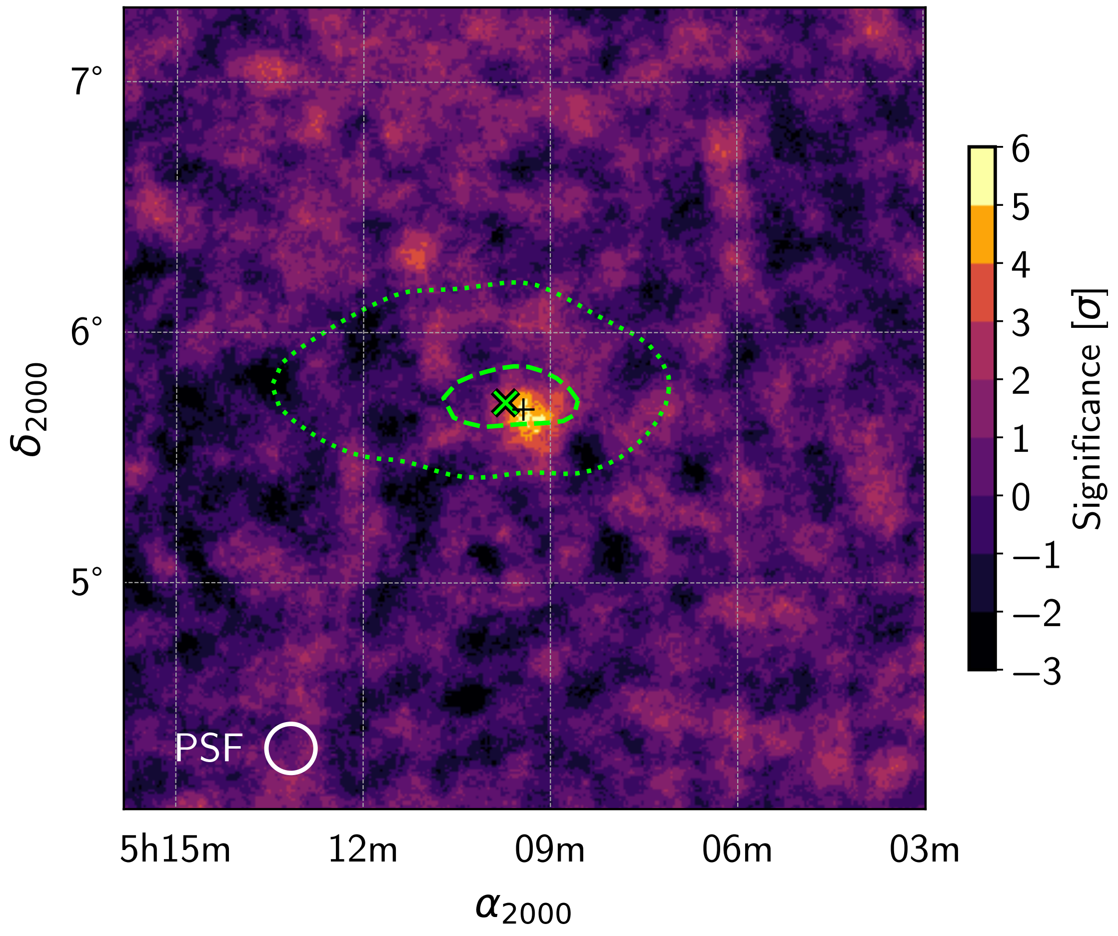
PHOTONS FROM TXS 0506+056



VHE gamma rays



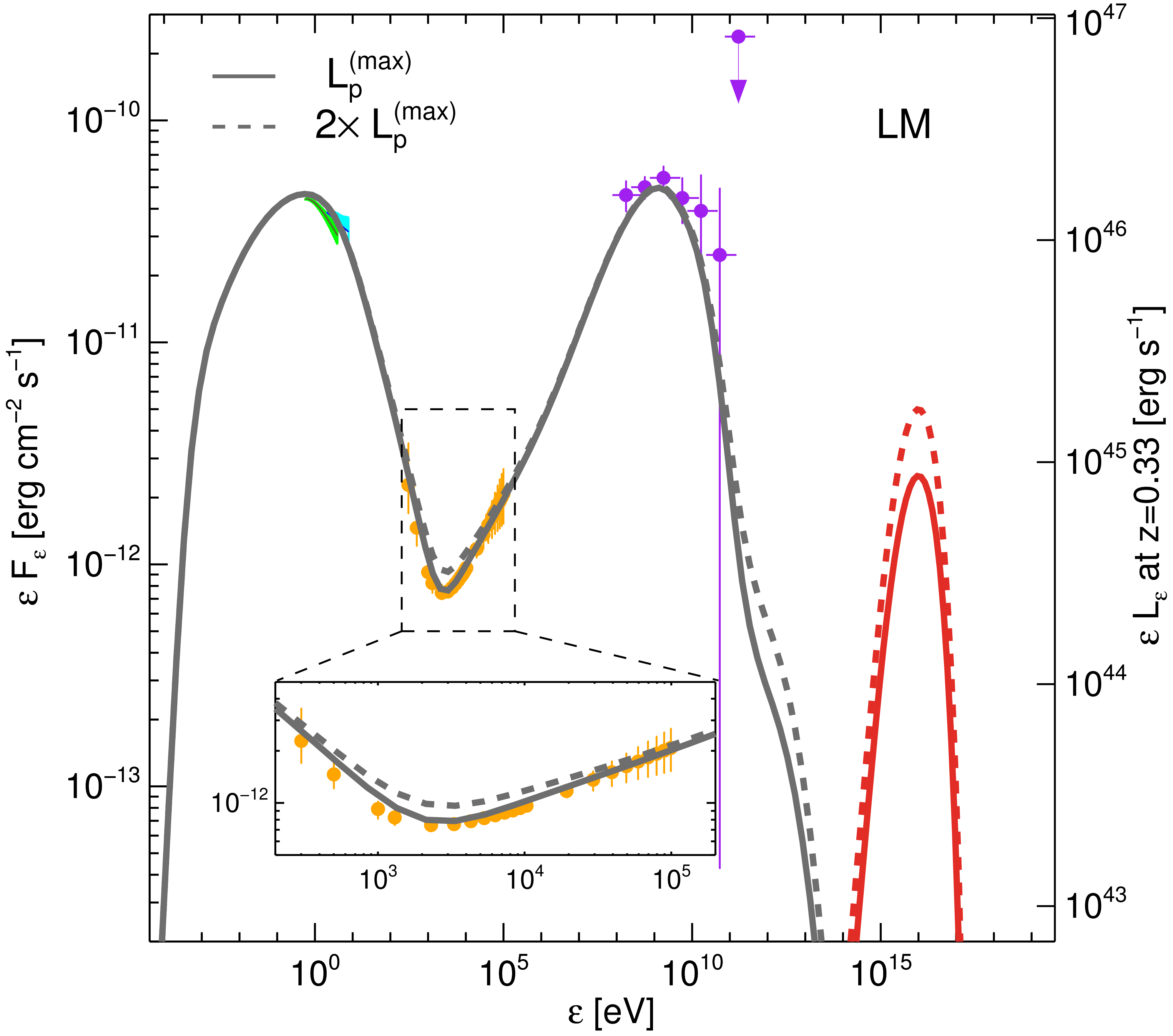
MAGIC
(ApJL 2018)

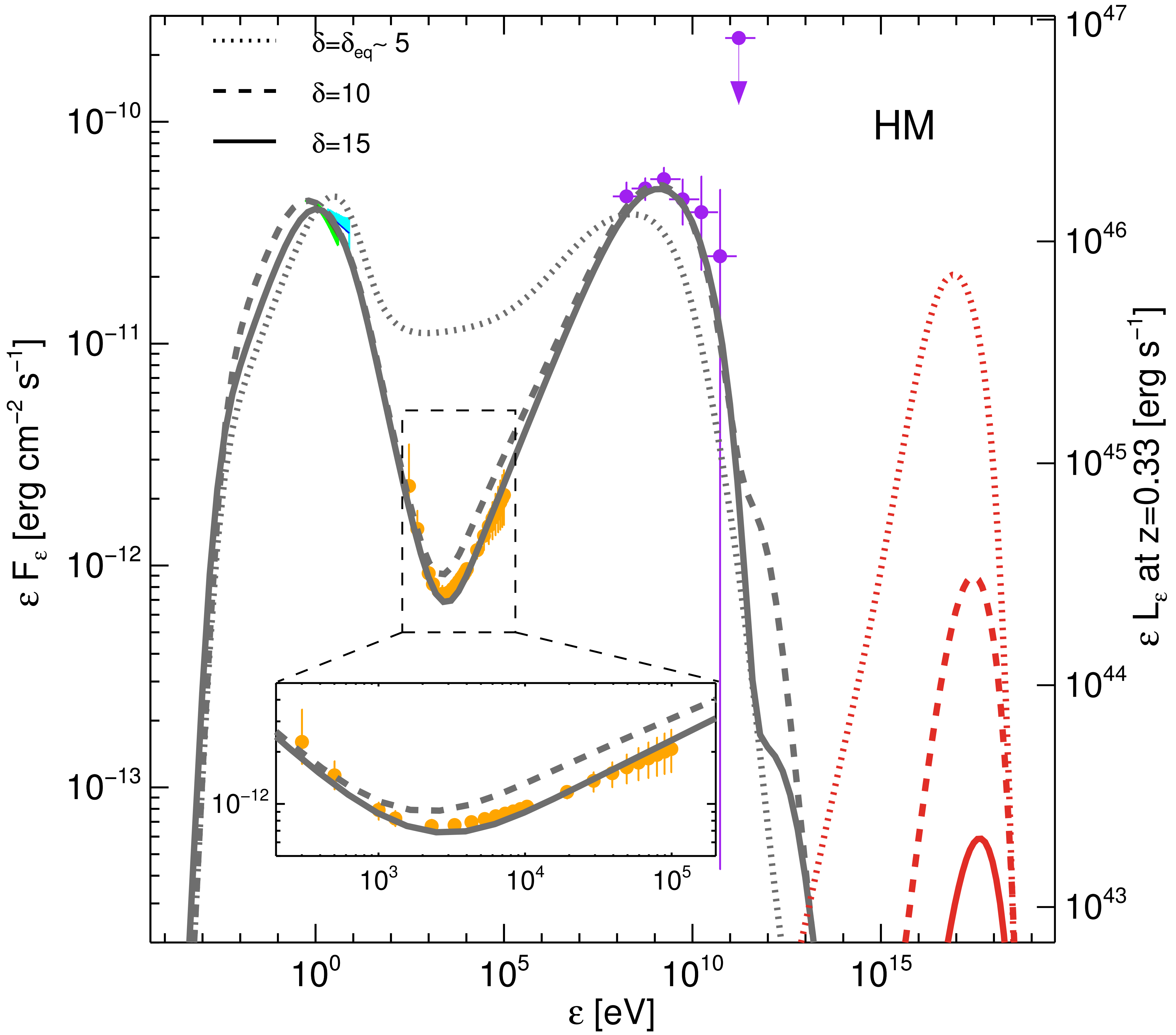


VERITAS
(ApJL 2018)

- TXS 0506+056: *Fermi* blazar at z=0.34. Broad multi-wavelength follow-up campaign, led to the **detection of the source >100 GeV** by ground-based gamma-ray instruments.
- **3σ chance coincidence correlation. Evidence for a connection between TXS 0506+056 and IC170922A.**

MODELING THE 2017 NEUTRINO EMISSION



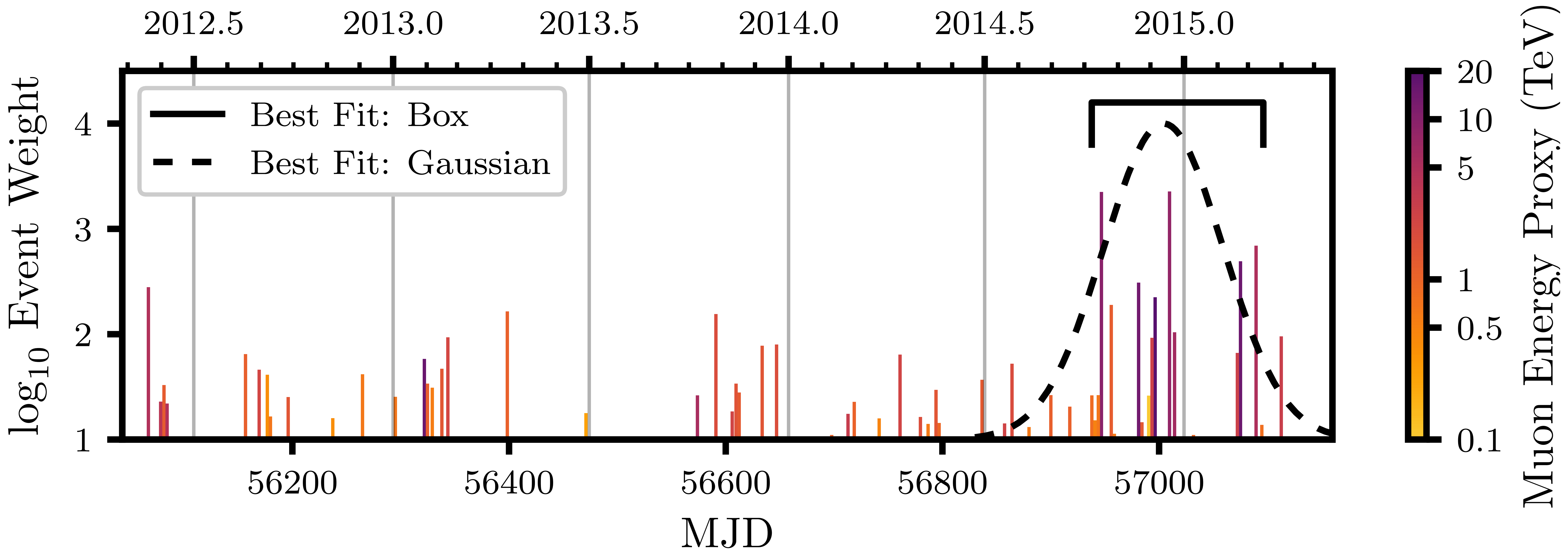


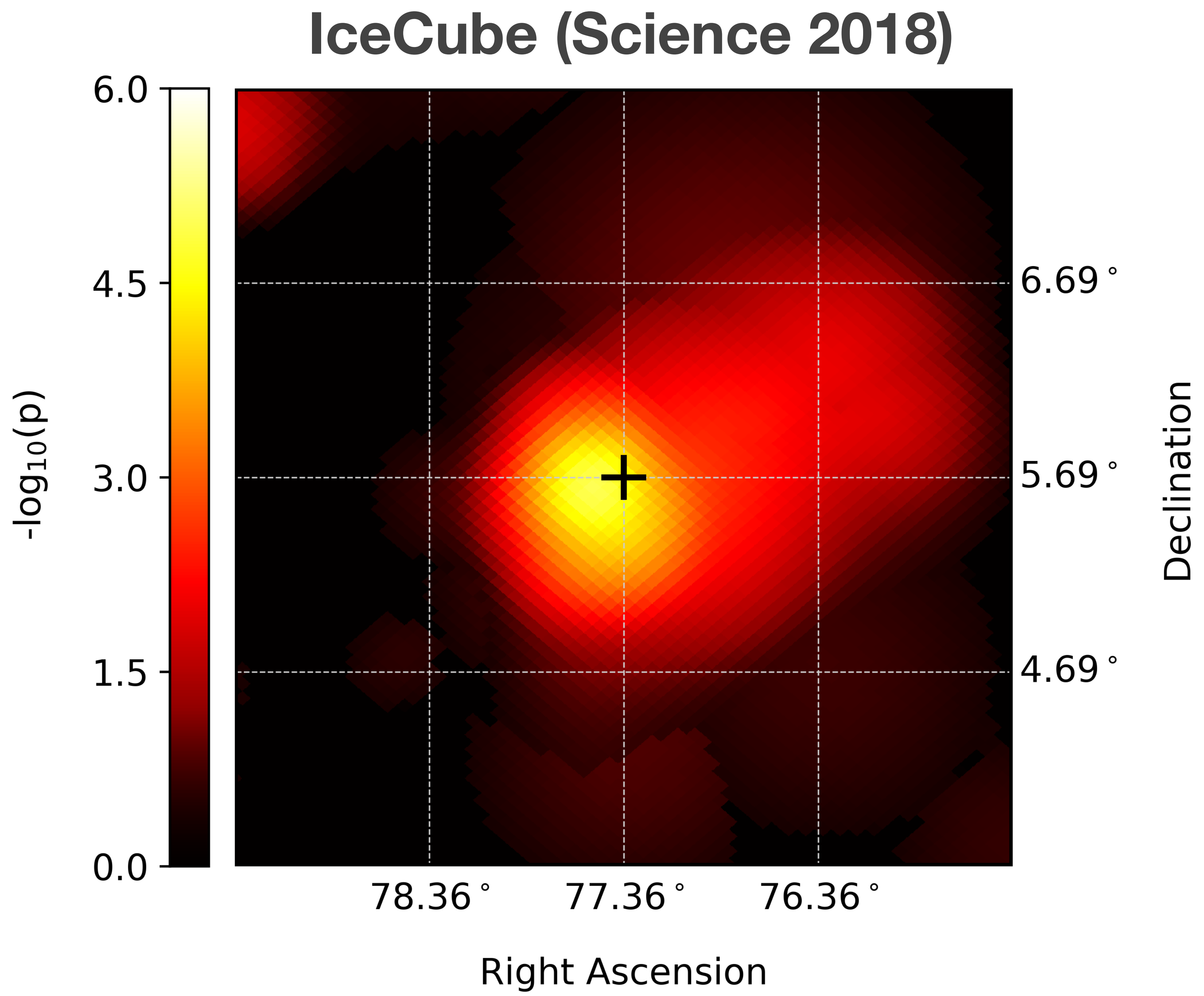
- Strong constraints on hadronic emission from X-ray observations

Keivani et al. (arXiv/1807.04537) among many others

- ~1% probability that the neutrino is associated with the source based on SED modeling.

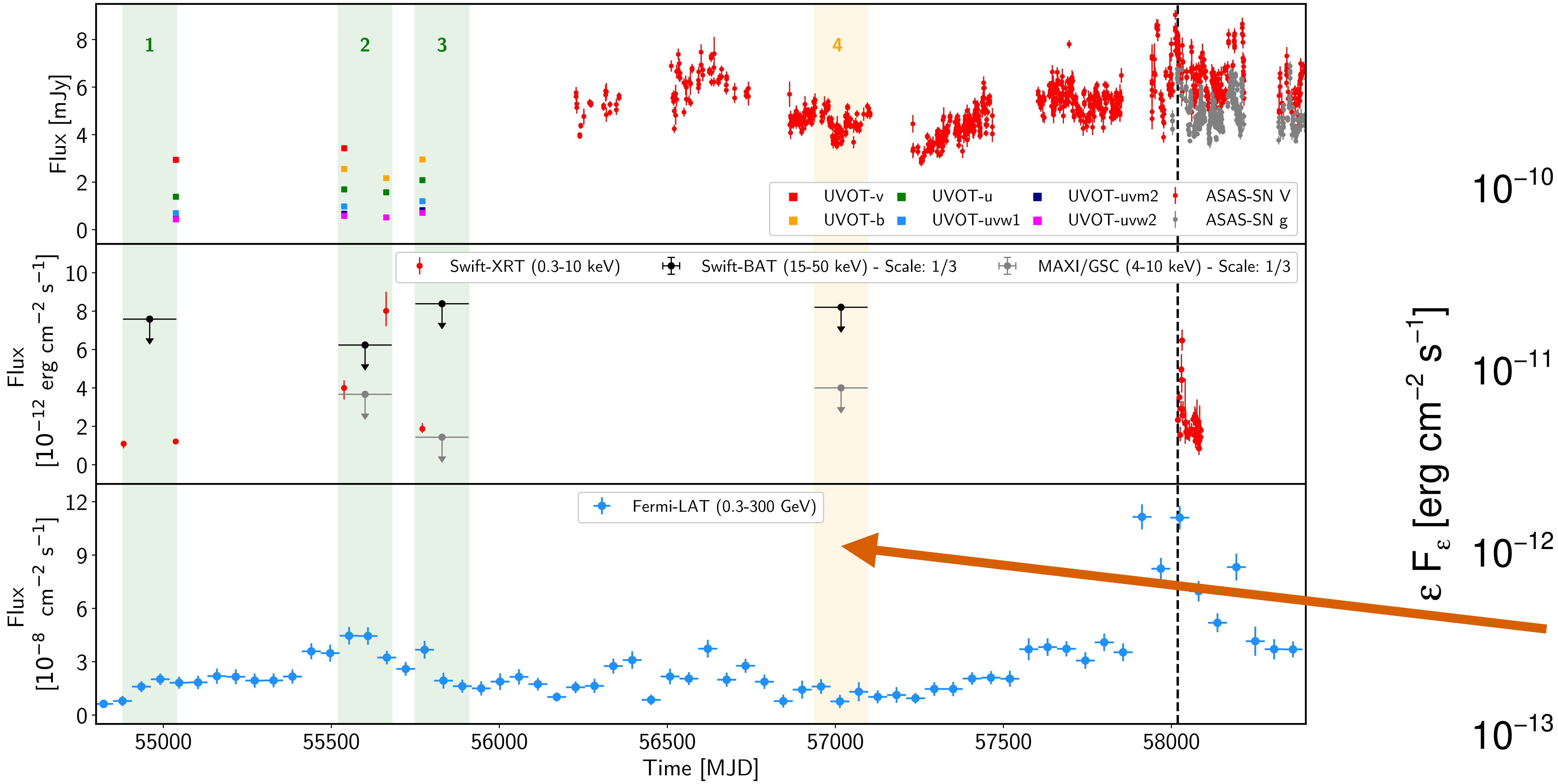
ARCHIVAL NEUTRINO EVENTS FROM ICECUBE



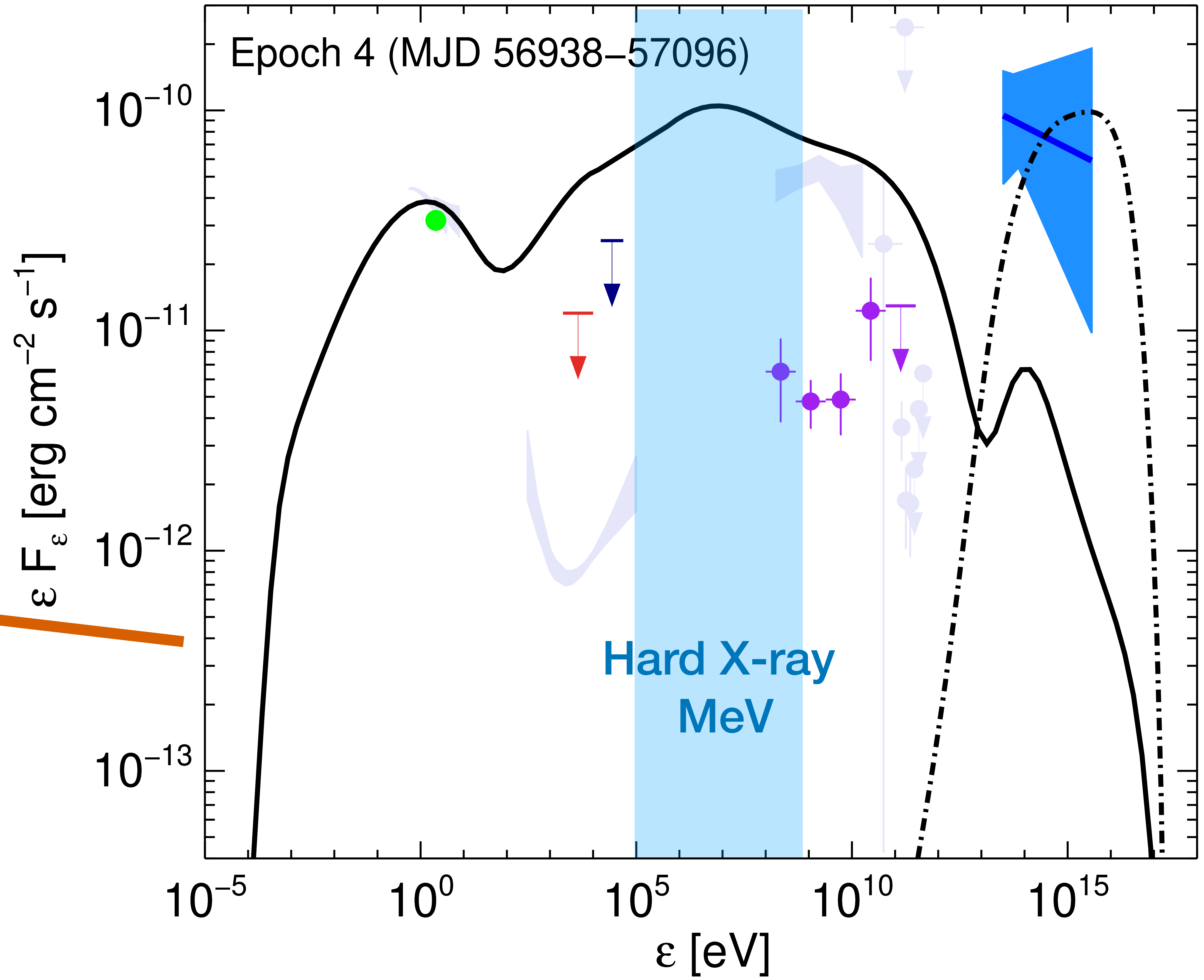


- Archival analysis revealed a **13±5 neutrino excess (3.5σ)** in 2014-2015 over 110 days.
- No follow-up campaign. **What's happening on the EM side?**

EM EMISSION FROM TXS 0506+056 AROUND THE FLARE



Petropoulou, Murase, MS, ++ (2019)

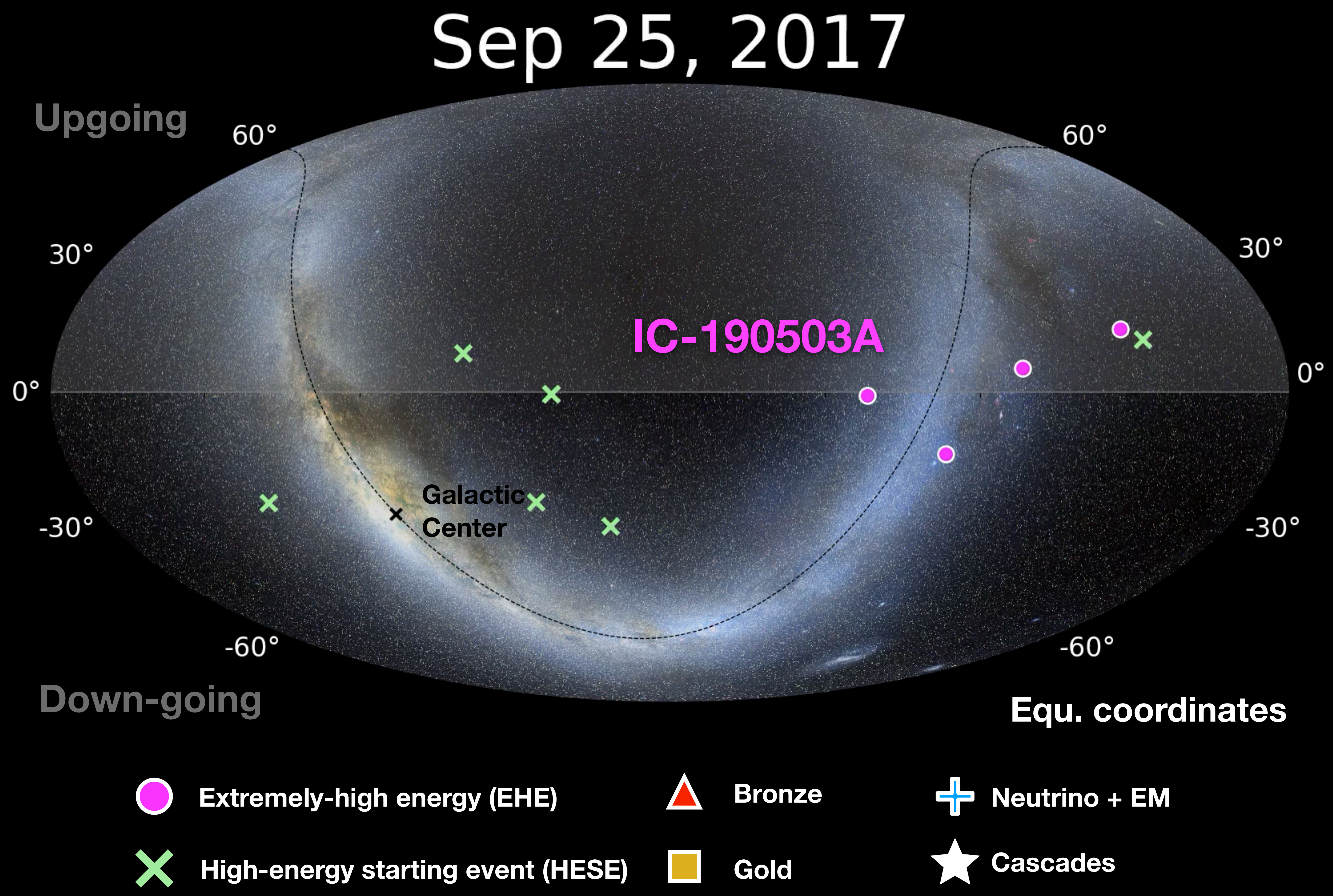


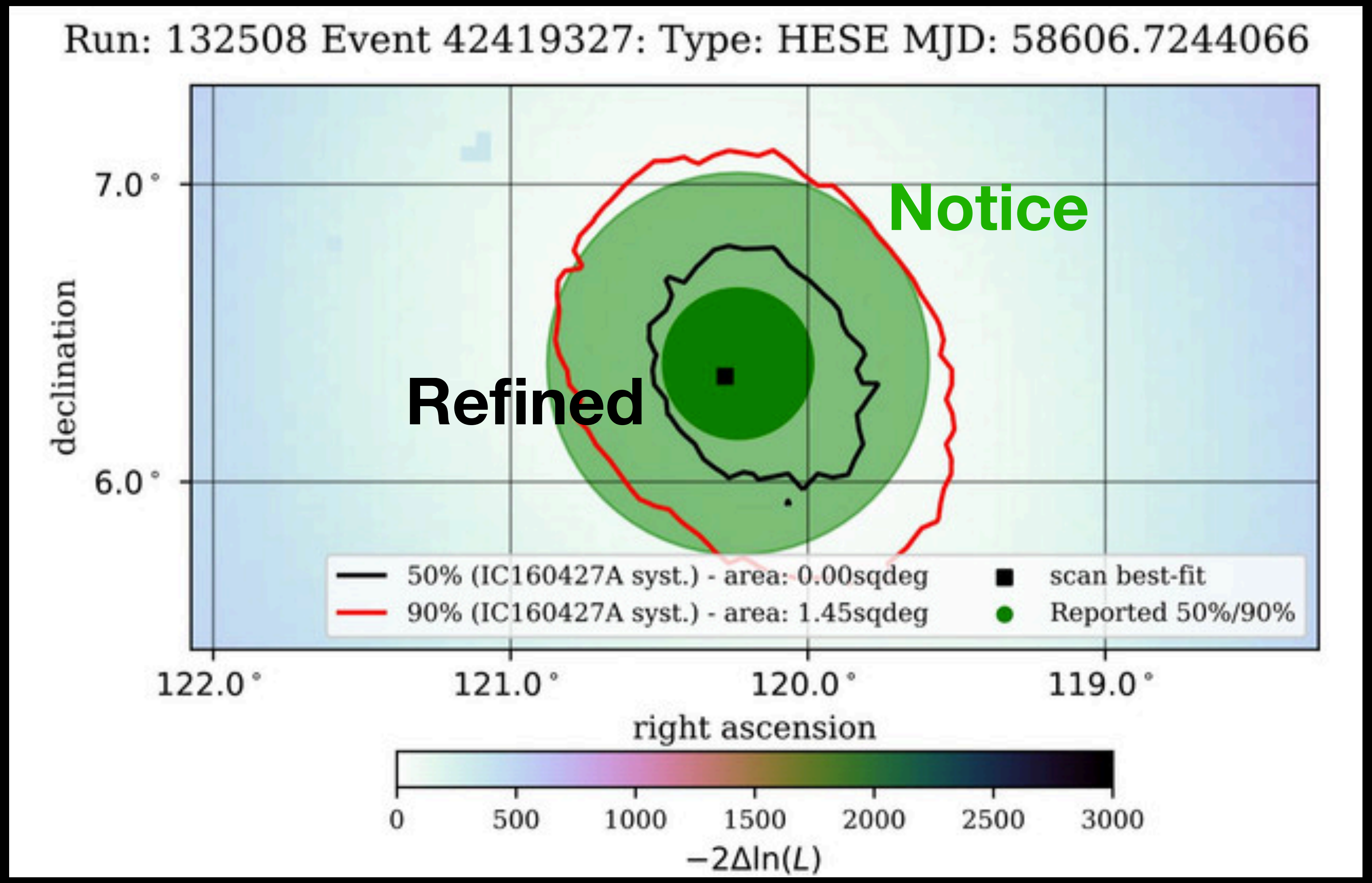
- No evidence for EM flaring activity from the source in 2014-2015.
- Most models over-predict the X-ray to gamma fluxes.
- **Multi-messenger follow ups with be crucial in the coming decade.**

Many modeling efforts for 2014-15/17: Reimer+ 2019, Cerruti+ 2018, Zhang+ 2018, Keivani 2018+, Petropoulou+ 2019

REALTIME ALERTS

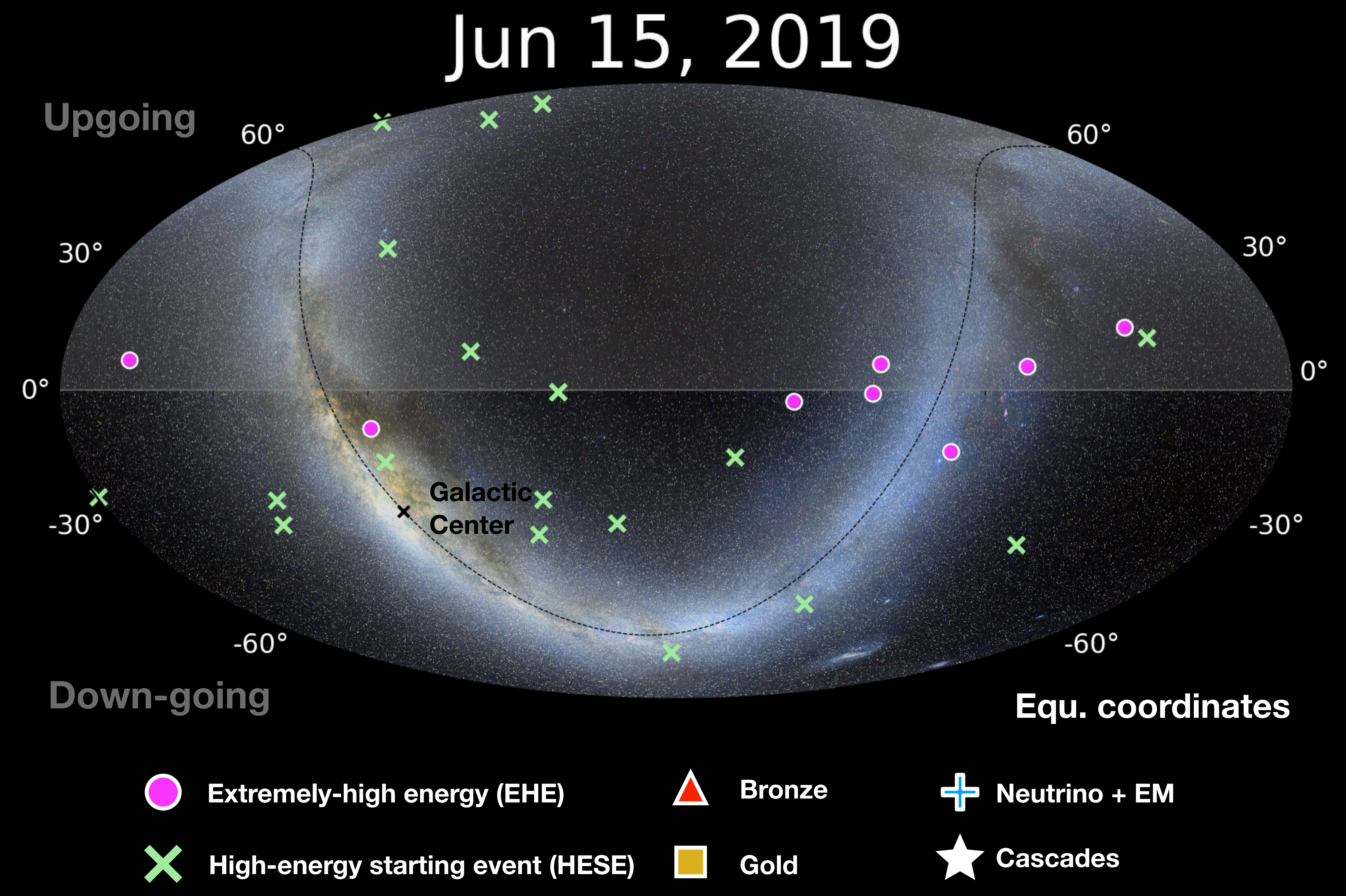
- Initial GCN Notice followed by GCN circular with refined position and error estimates (within couple of hours)





- Typically followed up by multiple multimessenger/ multiwavelength facilities.
- **Example: IC-190503A event**
  - ~145 TeV EHE event
  - Follows up by ZTF, ASAS-SN, Kanata, INTEGRAL, IceCube, Fermi-GBM, ANTARES, Fermi-LAT, Lick/ KAIT, Swift-XRT, Insight-HXMT (9 GCNs, 3 ATels)

REALTIME ALERTS



Unified track alert streams

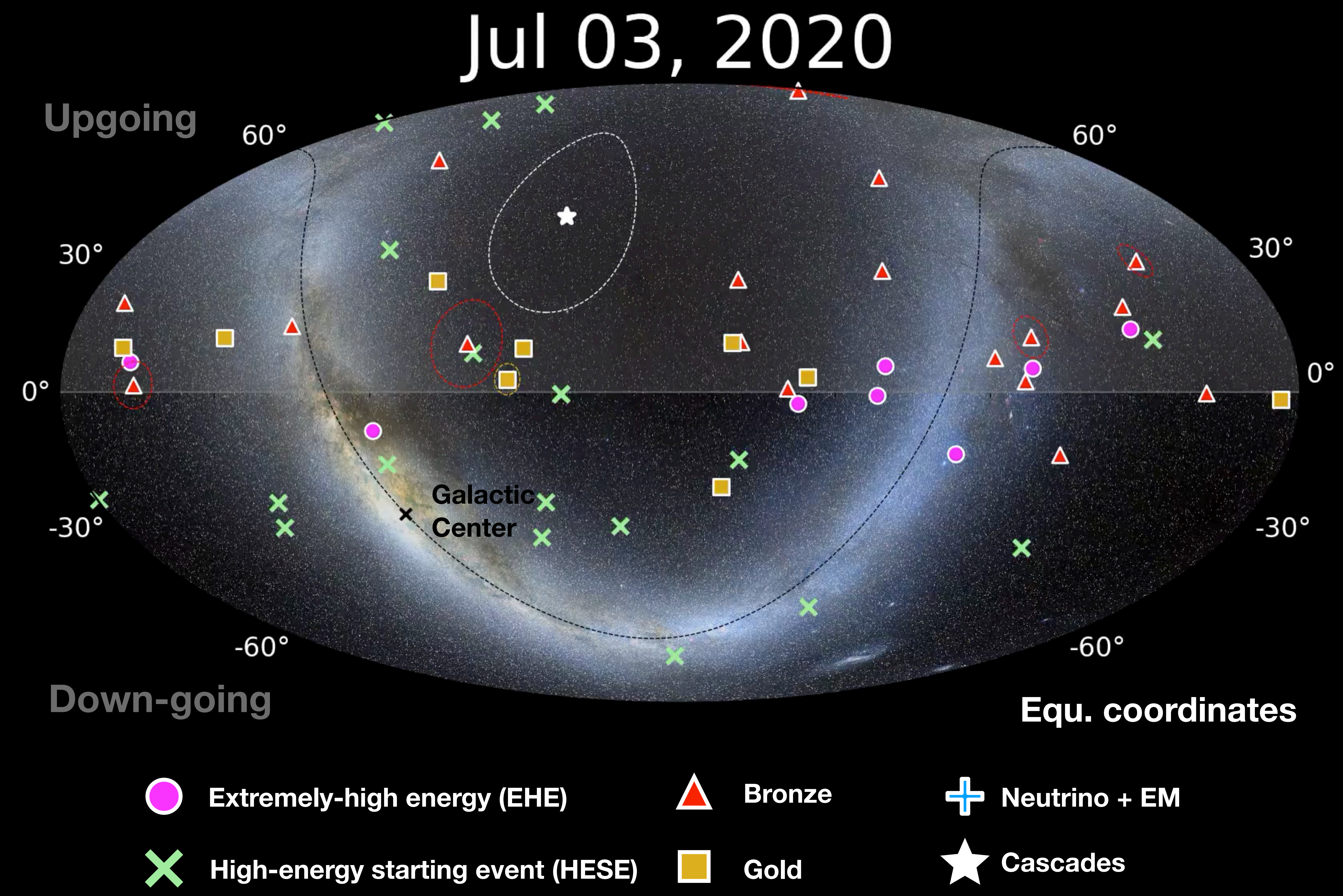
- Signalness = $N_{signal} / (N_{signal} + N_{background})$
- Improved selection based on signalness combines through-going and starting tracks.
- Doubled effective area at 0.1 - 1 PeV
- **Gold** stream: ~50% signalness (16 issued)
- **Bronze** stream: ~30% signalness (26 issued)

[PoS-ICRC2019-1021]

- As of Dec 2nd, 2020: 16 gold and 26 bronze alerts issued

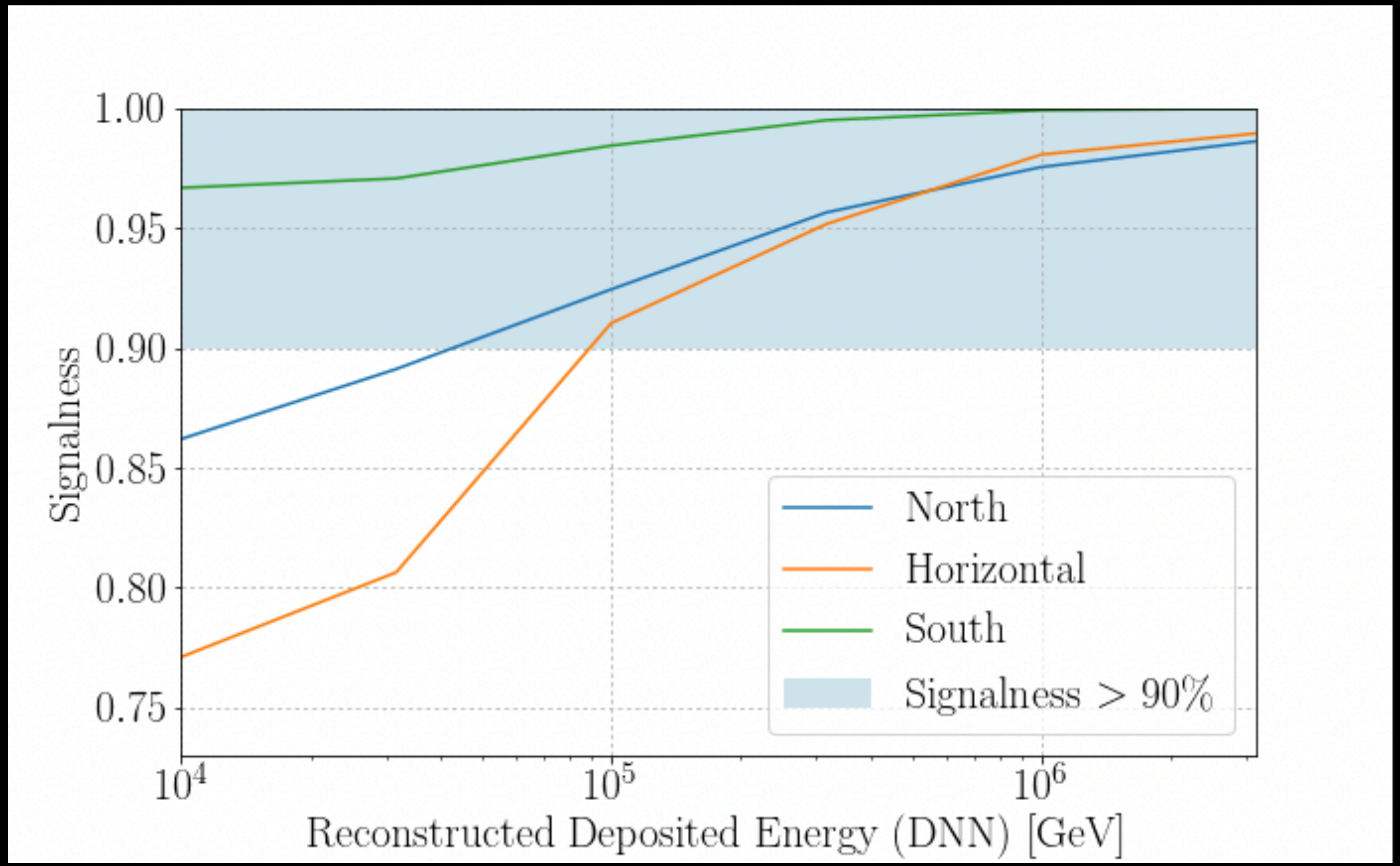
https://gcn.gsfc.nasa.gov/amon_icecube_gold_bronze_events.html

REALTIME ALERTS



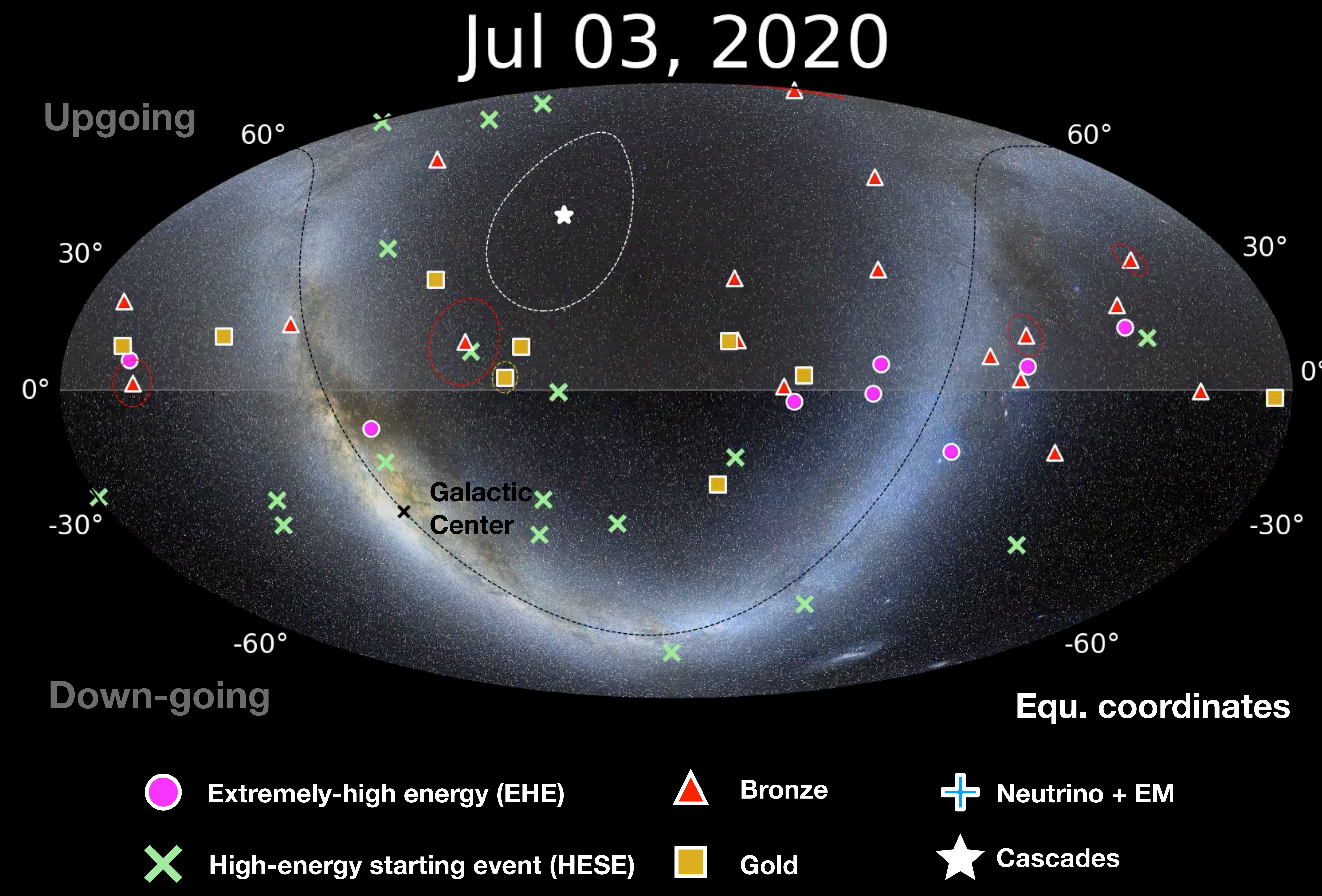
Cascade alerts

- HESE events are selected using a deep neural network (DNN) classifier.
- 50% have an uncertainty < 7°, 68% is < 9°.
- Signalness > 0.9 at energies above 100 TeV
- Online July 2020, two alerts as of Dec 2020.



https://gcn.gsfc.nasa.gov/amon_icecube_cascade_events.html

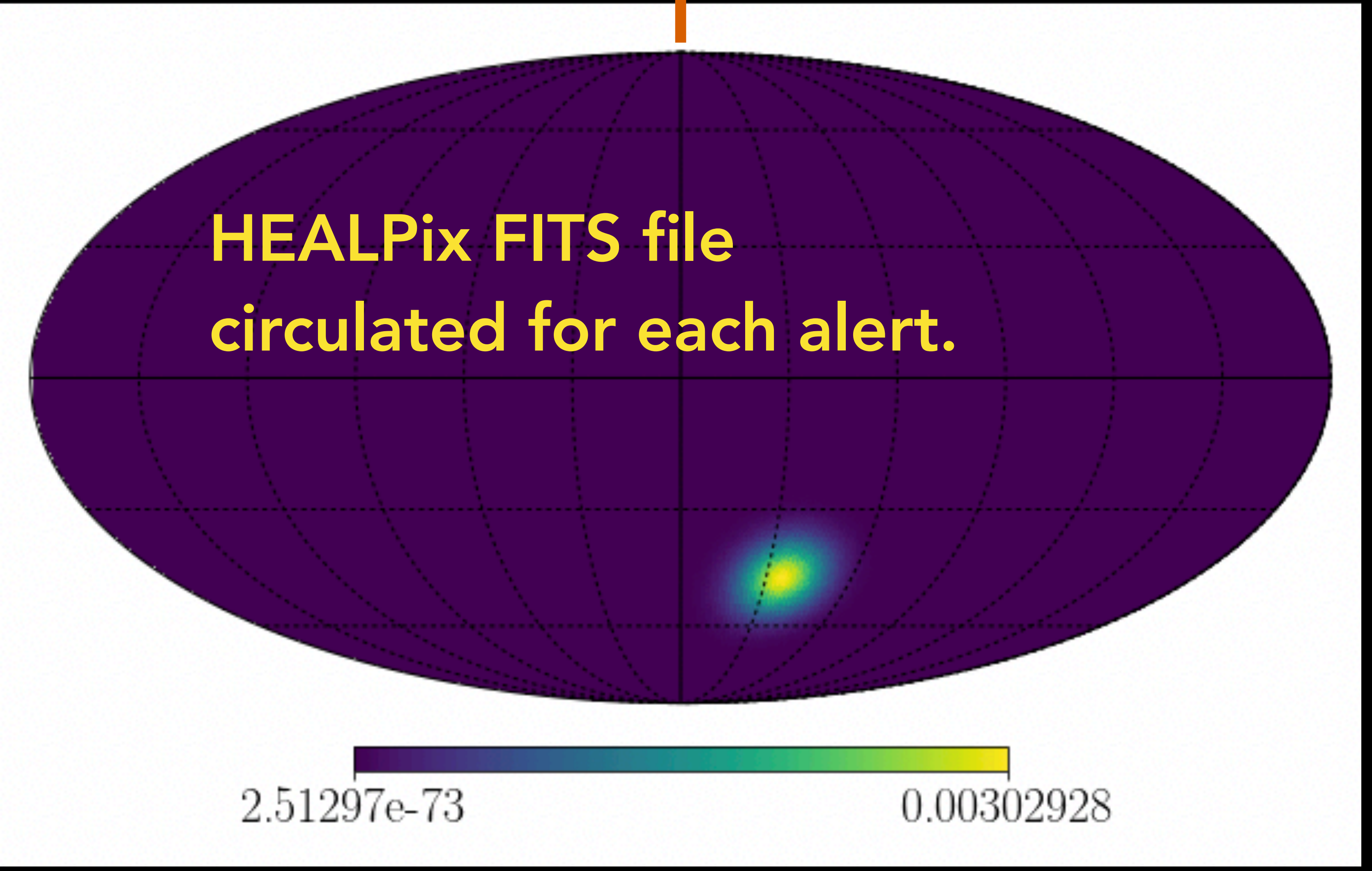
REALTIME ALERTS



Cascade alerts

GCN Notice

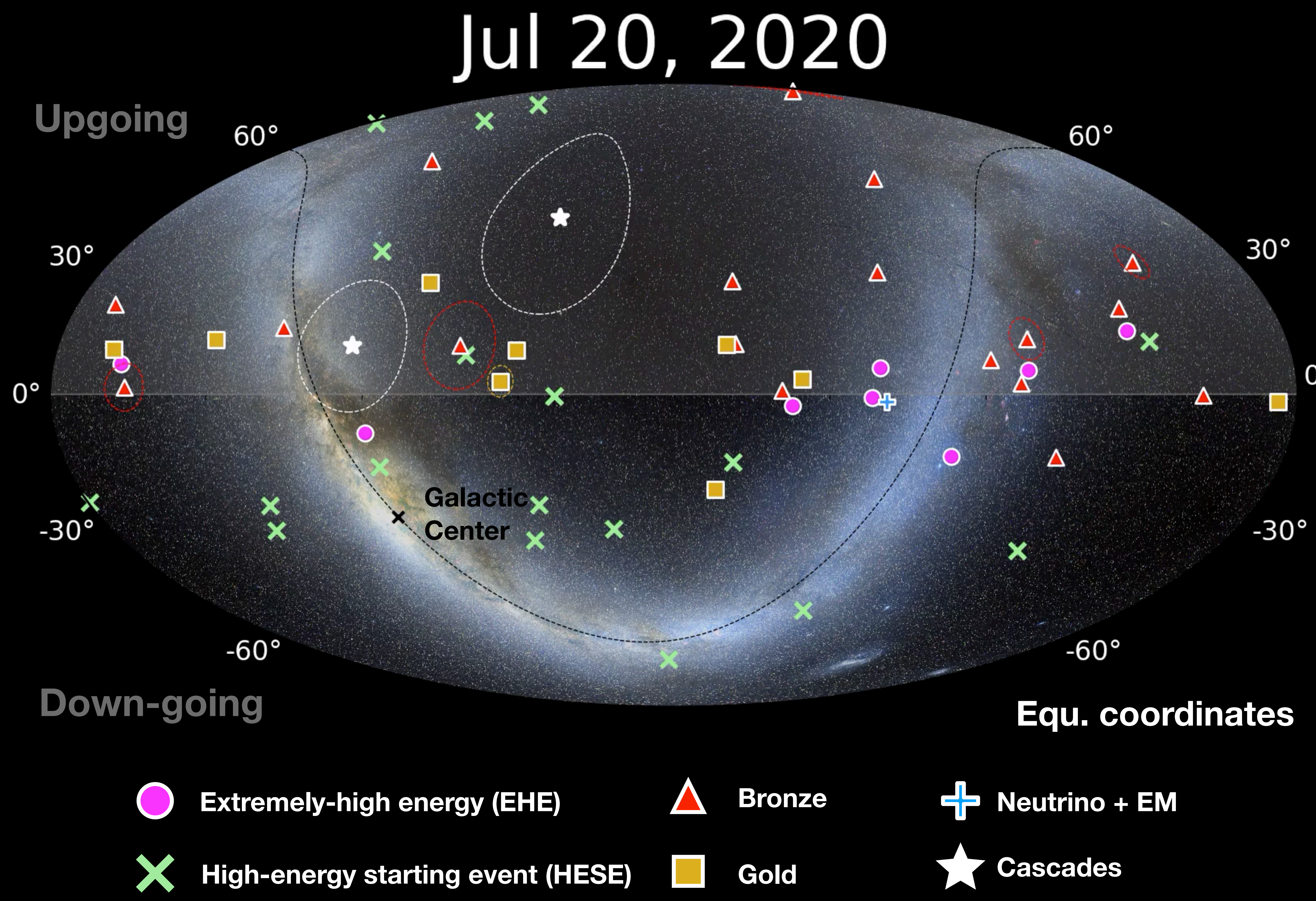
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 29 Jul 20 21:58:55 UT
NOTICE_TYPE:      ICECUBE Cascade
EVENT_NAME:       IceCubeCascade-200707b
STREAM:           26
RUN_NUM:          134262
EVENT_NUM:        14361443
SRC_RA:           273.9880d {+18h 15m 57s} (J2000),
                  274.2275d {+18h 16m 55s} (current),
                  273.4044d {+18h 13m 37s} (1950)
SRC_DEC:          +11.5828d {+11d 34' 58"} (J2000),
                  +11.5910d {+11d 35' 28"} (current),
                  +11.5649d {+11d 33' 53"} (1950)
SRC_ERROR:        28.42 [deg radius, stat+systematic, 90% containment]
SRC_ERROR50:      15.59 [deg radius, stat+systematic, 50% containment]
DISCOVERY_DATE:   19037 TJD;   189 DOY;   20/07/07 (yy/mm/dd)
DISCOVERY_TIME:   33610 SOD {09:20:10.40} UT
REVISION:         0
ENERGY:           11.93 [TeV]
SIGNALNESS:       9.0012e-01 [dn]
FAR:              0.3110 [yr^-1]
SUN_POSTN:        129.63d {+08h 38m 30s}  +18.46d {+18d 27' 48"}
SUN_DIST:         133.93 [deg]   Sun_angle= -9.6 [hr] (East of Sun)
MOON_POSTN:       246.97d {+16h 27m 53s}  -19.95d {-19d 57' 01"}
MOON_DIST:         41.41 [deg]
GAL_COORDS:        39.40, 13.06 [deg] galactic lon,lat of the event
ECL_COORDS:       274.77, 34.96 [deg] ecliptic lon,lat of the event
SKYMAP_FITS_URL:
https://roc.icecube.wisc.edu/public/hese_cascades/hese_59037_run00134262.evt000014361443.fits
SKYMAP_PNG_URL:
https://roc.icecube.wisc.edu/public/hese_cascades/hese_59037_run00134262.evt000014361443.png
COMMENTS:         IceCube Cascade event.
COMMENTS:         The position error is the combined statistical and the systematic.
```



https://gcn.gsfc.nasa.gov/amon_icecube_cascade_events.html

REALTIME ALERTS

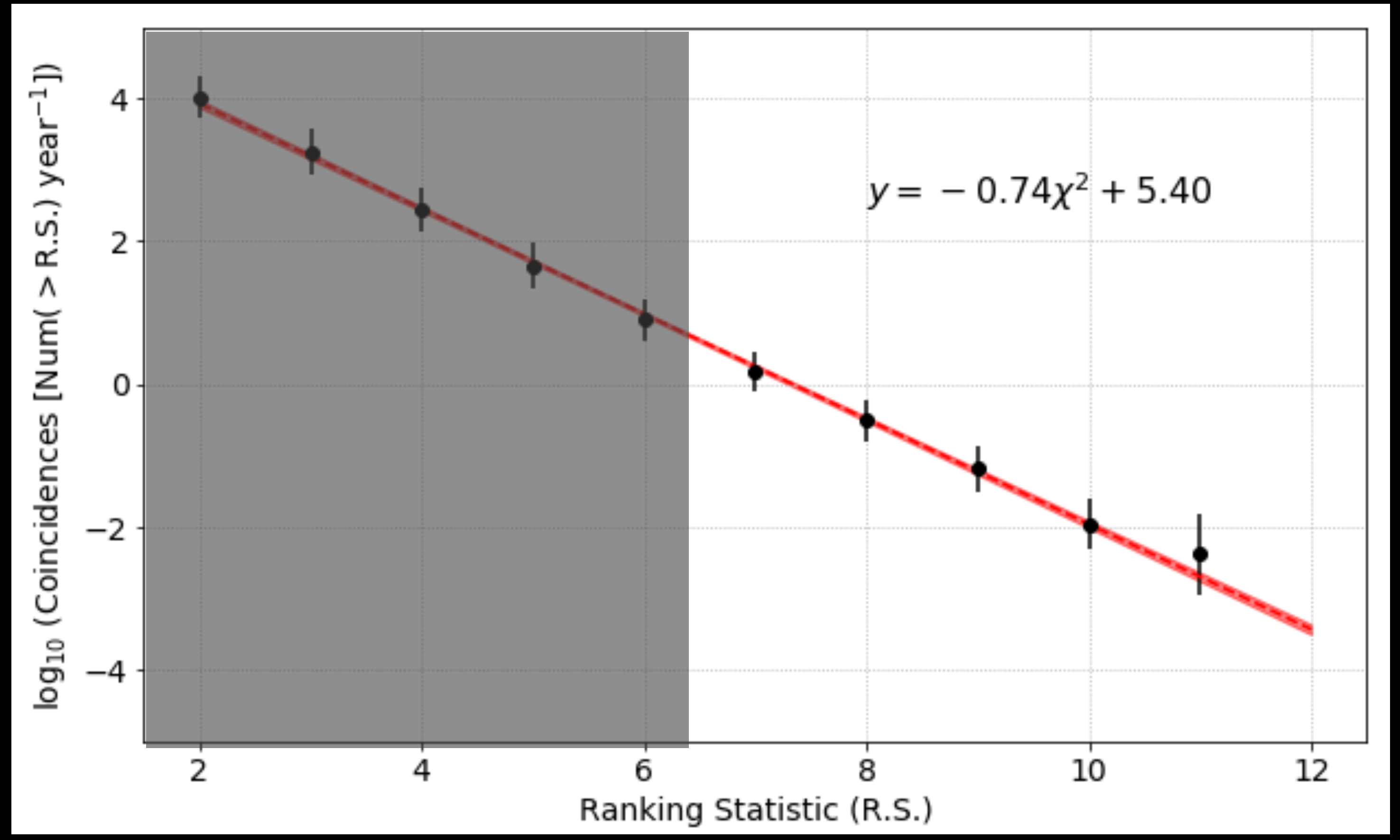
Neutrino-gamma coincidences



[PoS-ICRC2019-841]

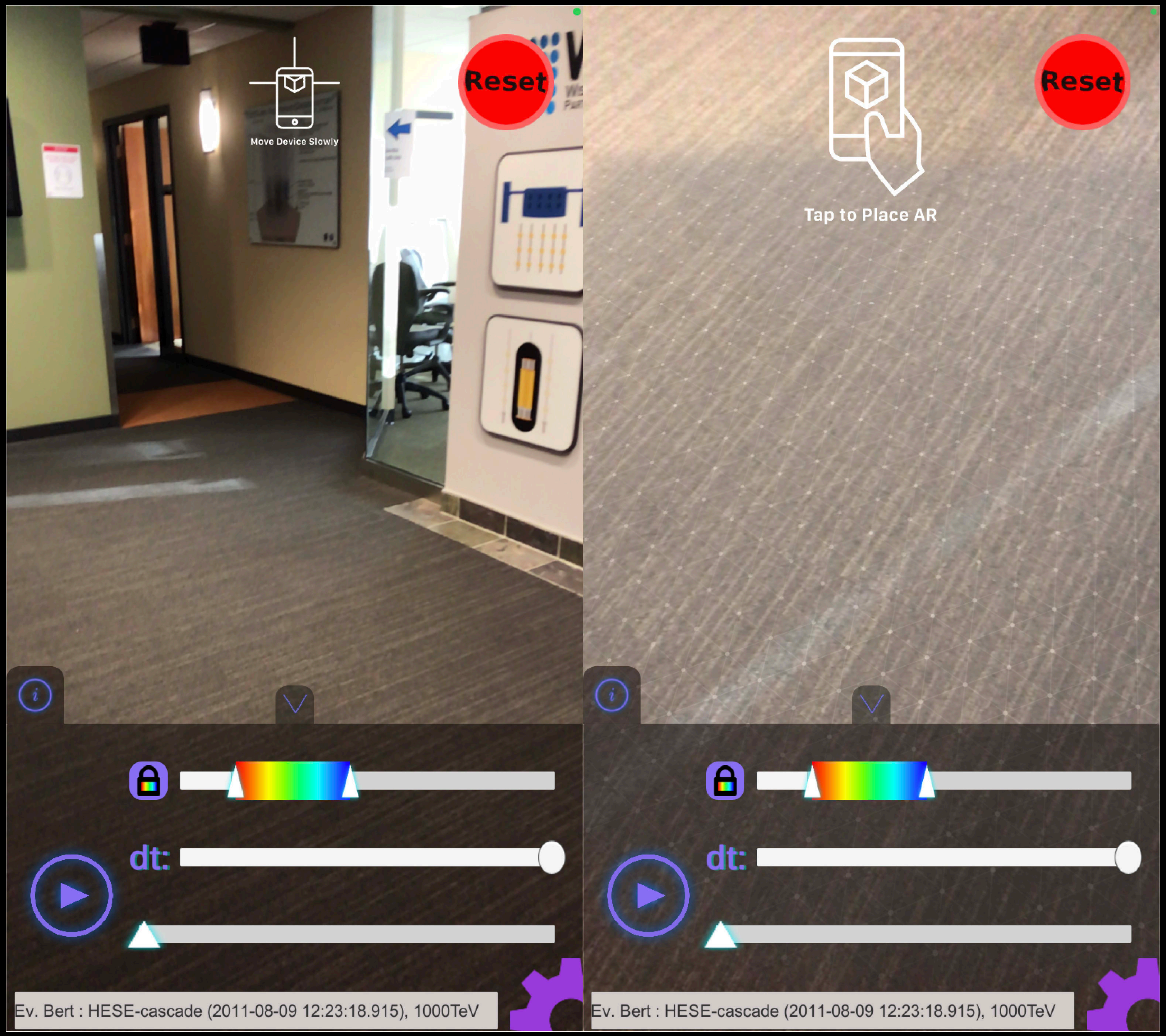
- HAWC + IceCube: HAWC daily transit hotspot correlated by AMON with IceCube neutrinos within 3.5°.
- Ranking statistic (RS) distribution derived from 2 years of scrambled data. Cuts on RS defined to send 4 alerts per year to GCN.
- Started April 2020, **3 alerts sent so far**

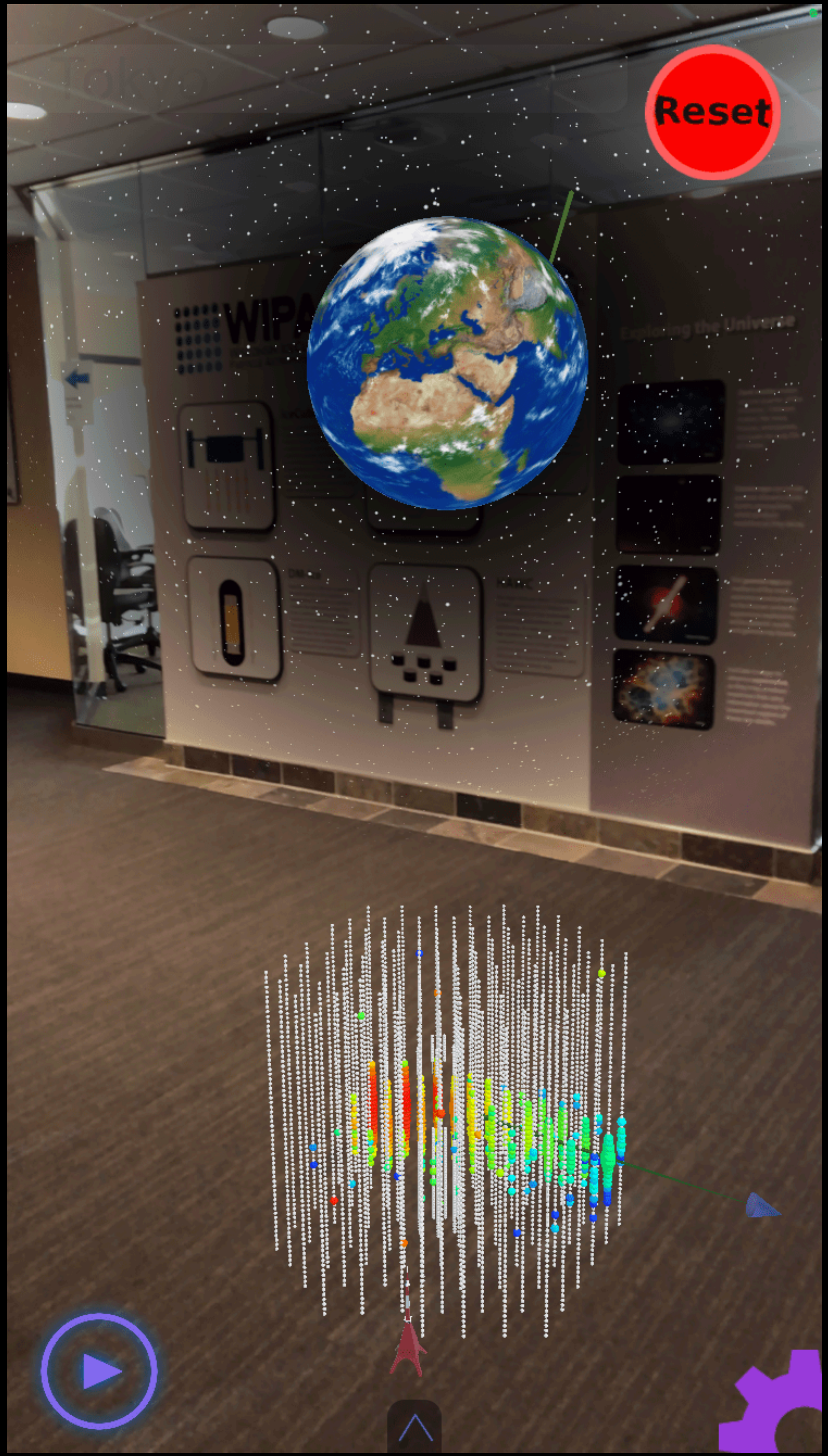
$$\chi^2_{6+2n_\nu} = -2\ln[p_\lambda p_{HAWC} p_{cluster} \prod_i^{\nu} p_{IC,i}],$$



https://gcn.gsfc.nasa.gov/amon_nu_em_coinc_events.html

GET THEM ON YOUR PHONE!



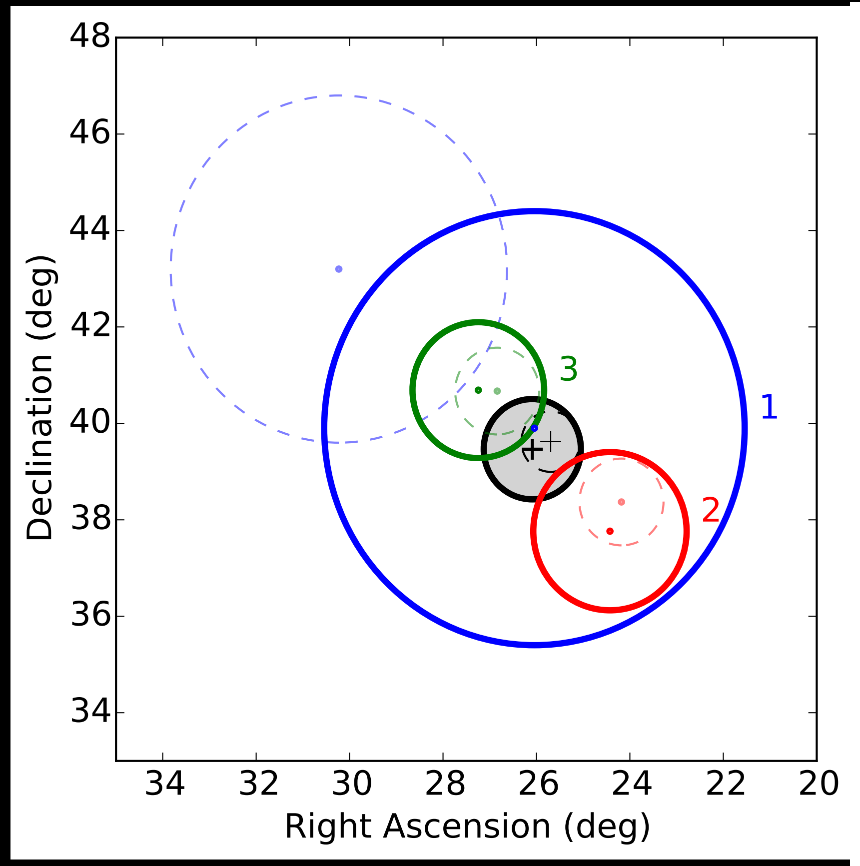


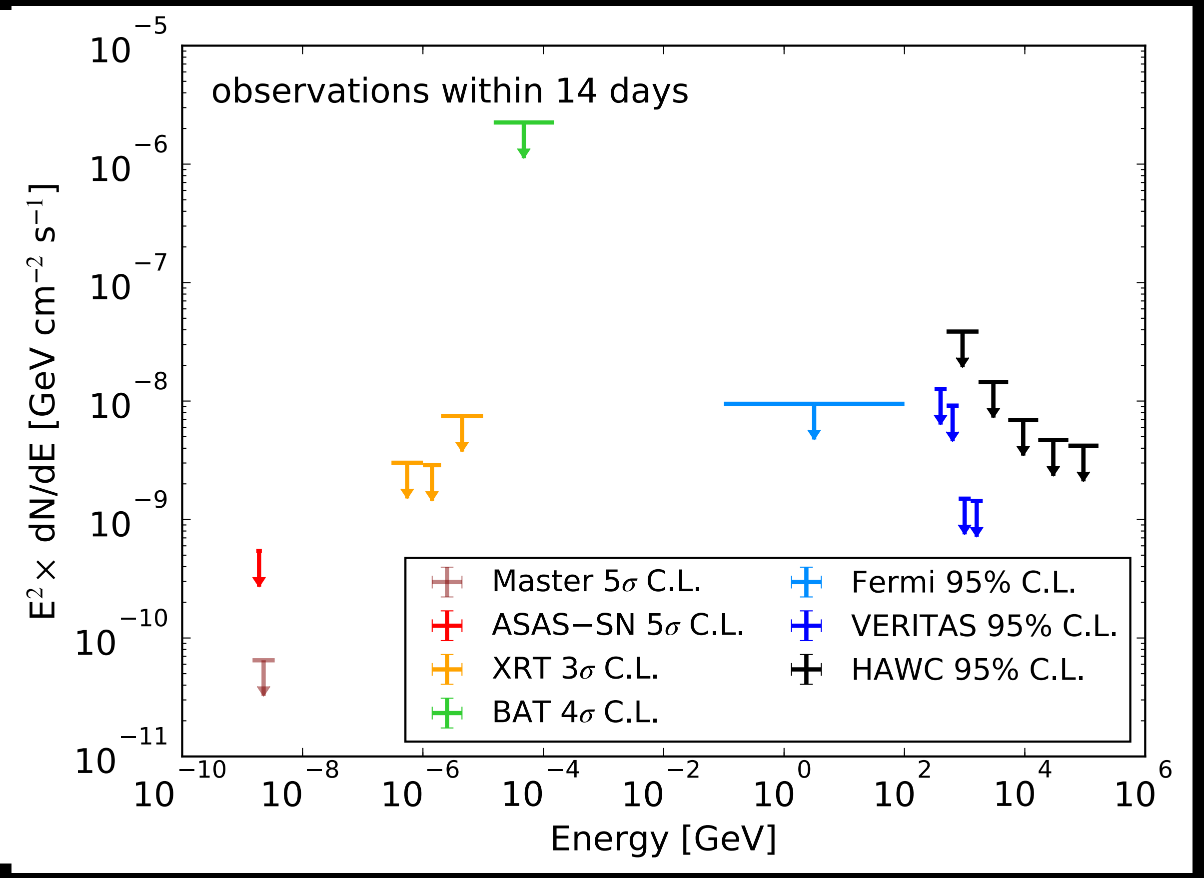
- Search for IceCubeAR in the iOS App Store and in the Google Play Store

CLUSTERING SEARCHES

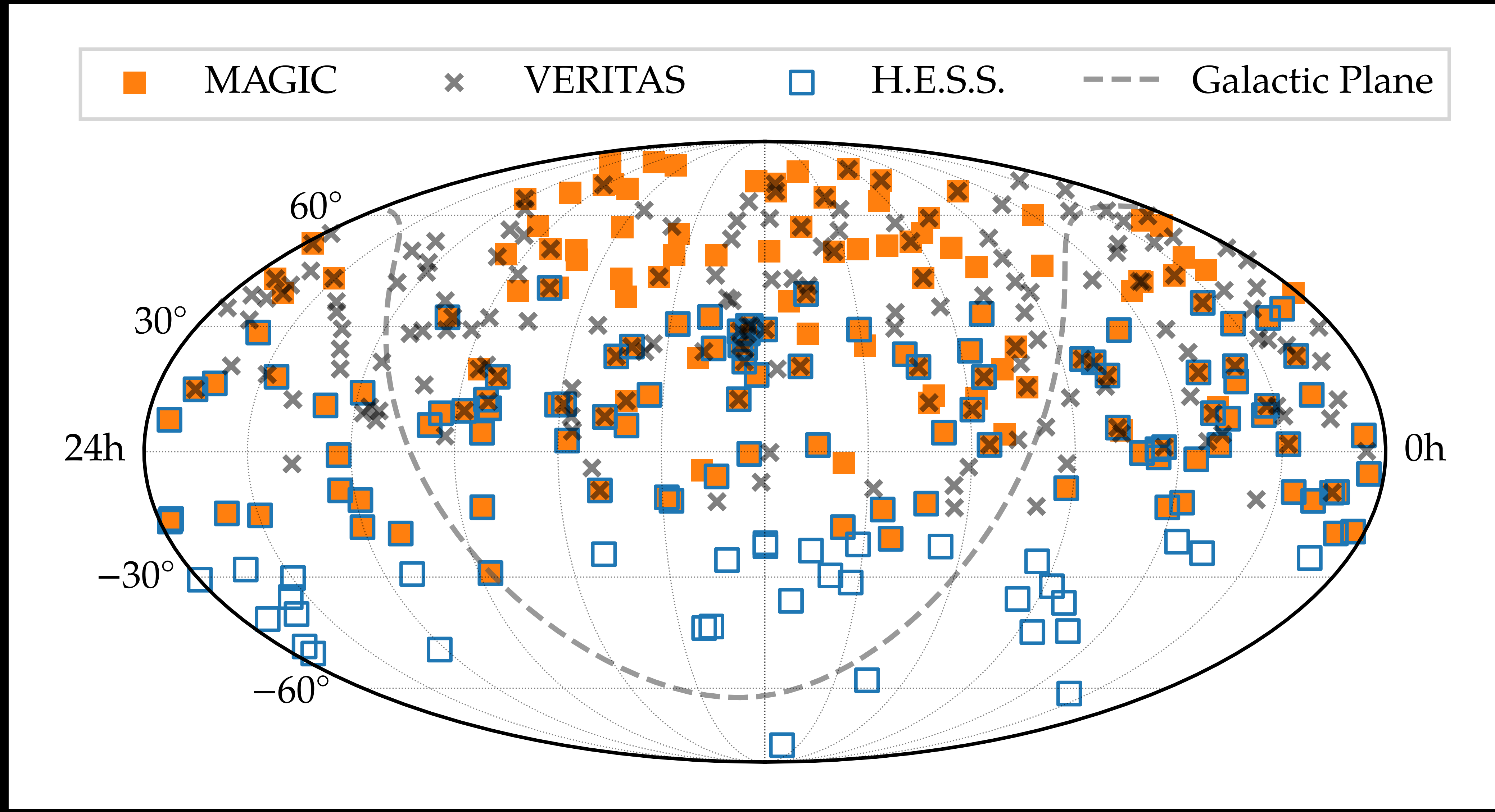
- Spatial correlations can reveal an astrophysical signal buried in the atmospheric neutrino background.
- **Optical follow-up (OFU):** GRB/SN
  - 2+ events in 100 s, within 3.5°
  - Private alerts to ZTF and Swift
- **Gamma-ray follow-up (GFU):**
  - Likelihood analysis on variable time-scales correlated with known or likely VHE gamma emitters.
  - Private alerts to MAGIC, VERITAS, H.E.S.S.
  - Online event selection / reconstruction
  - Similar sensitivity to previous offline searches

Neutrino triplet (2016) [A&A 607, A115 (2017)]





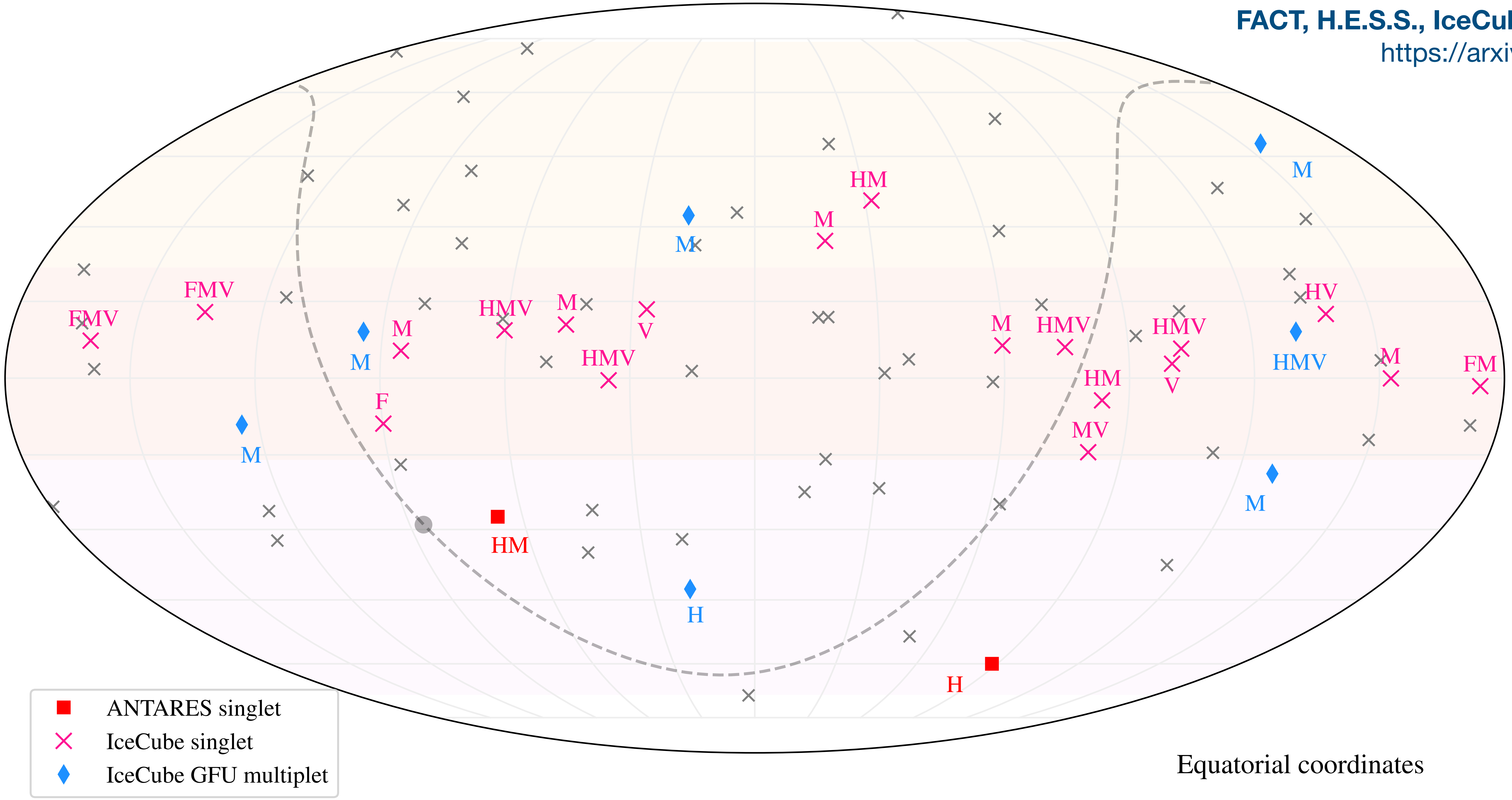
Sources from IACTs [2016 JINST 11 P11009]



GAMMA-RAY FOVS AND ICECUBE EVENTS

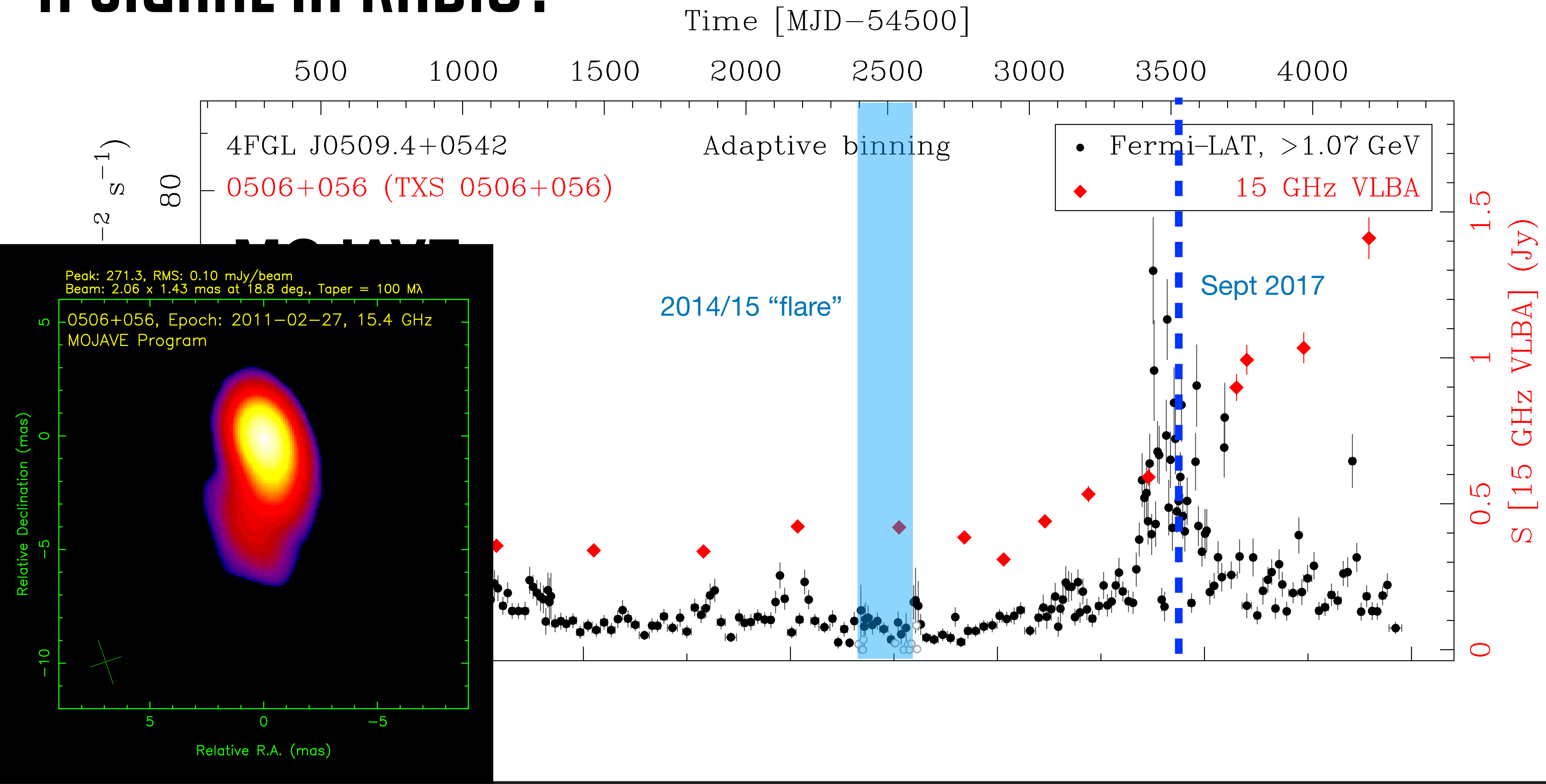
NEUTRINO FOLLOW-UP PROGRAMS WITH IACTS

FACT, H.E.S.S., IceCube, MAGIC, VERITAS
https://arxiv.org/abs/2109.04350

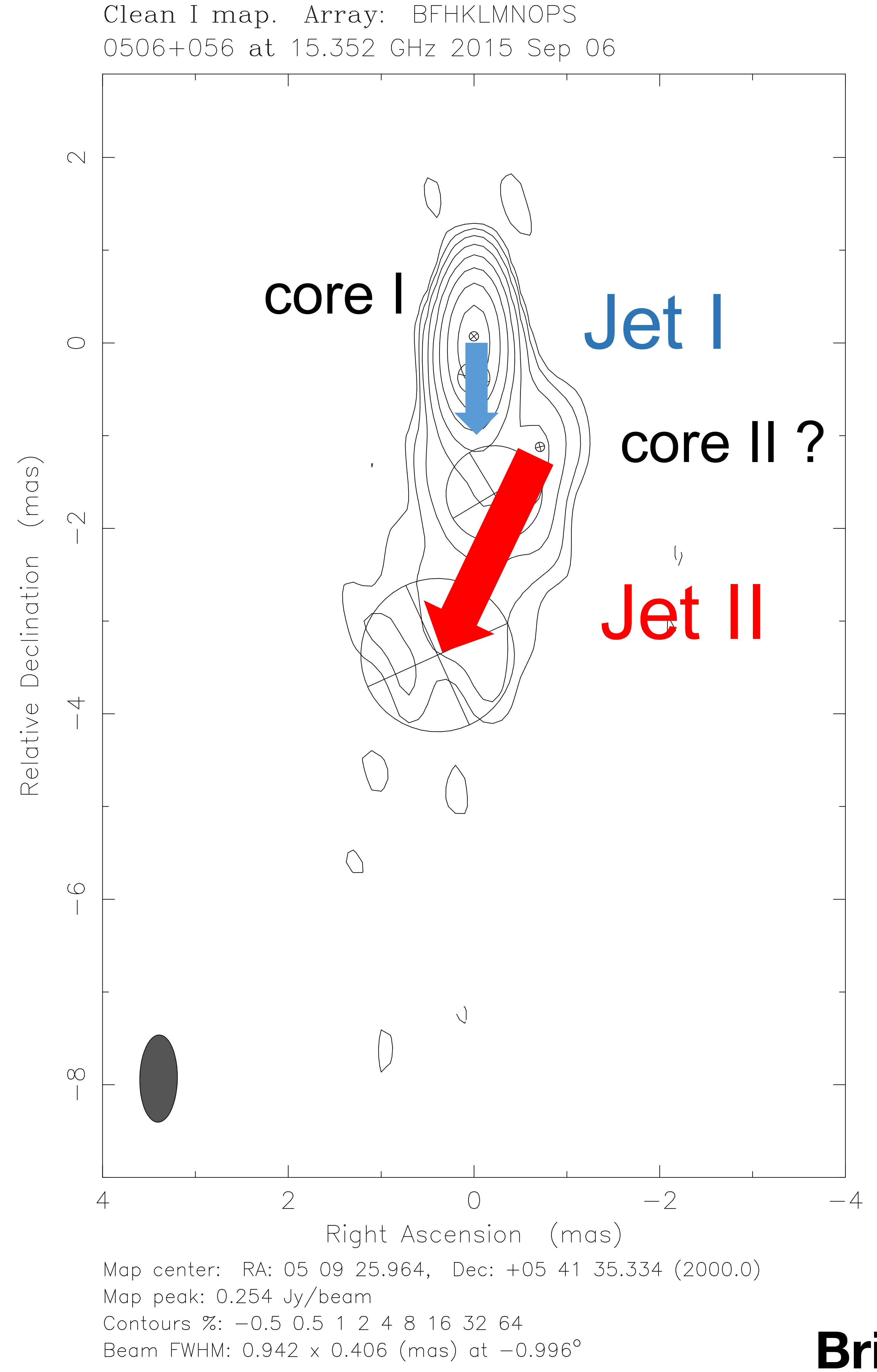


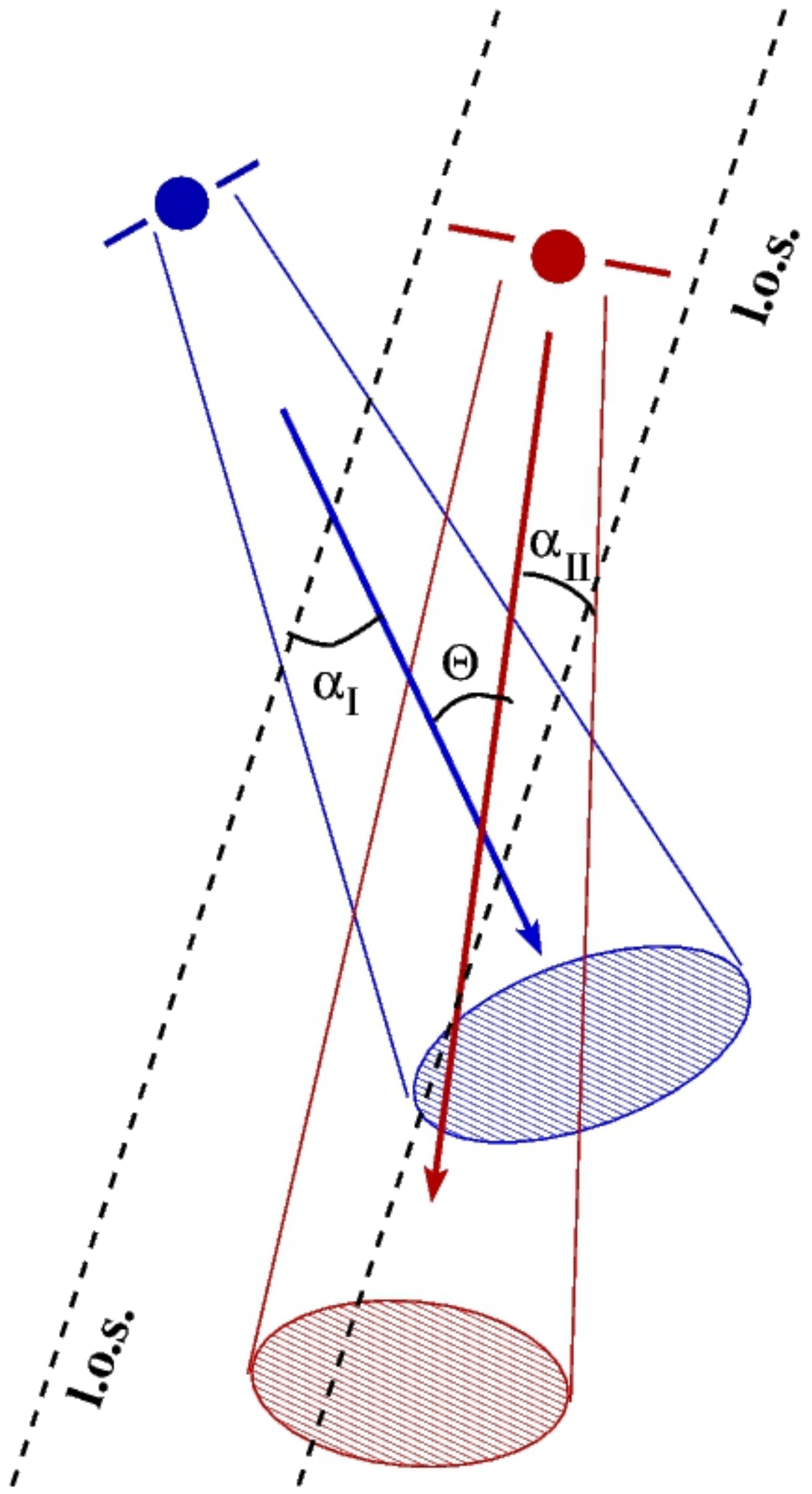
- All IACTs participate in neutrino follow-up programs. No VHE detections beyond TXS 0506+056.

A SIGNAL IN RADIO?



A COSMIC COLLIDER?



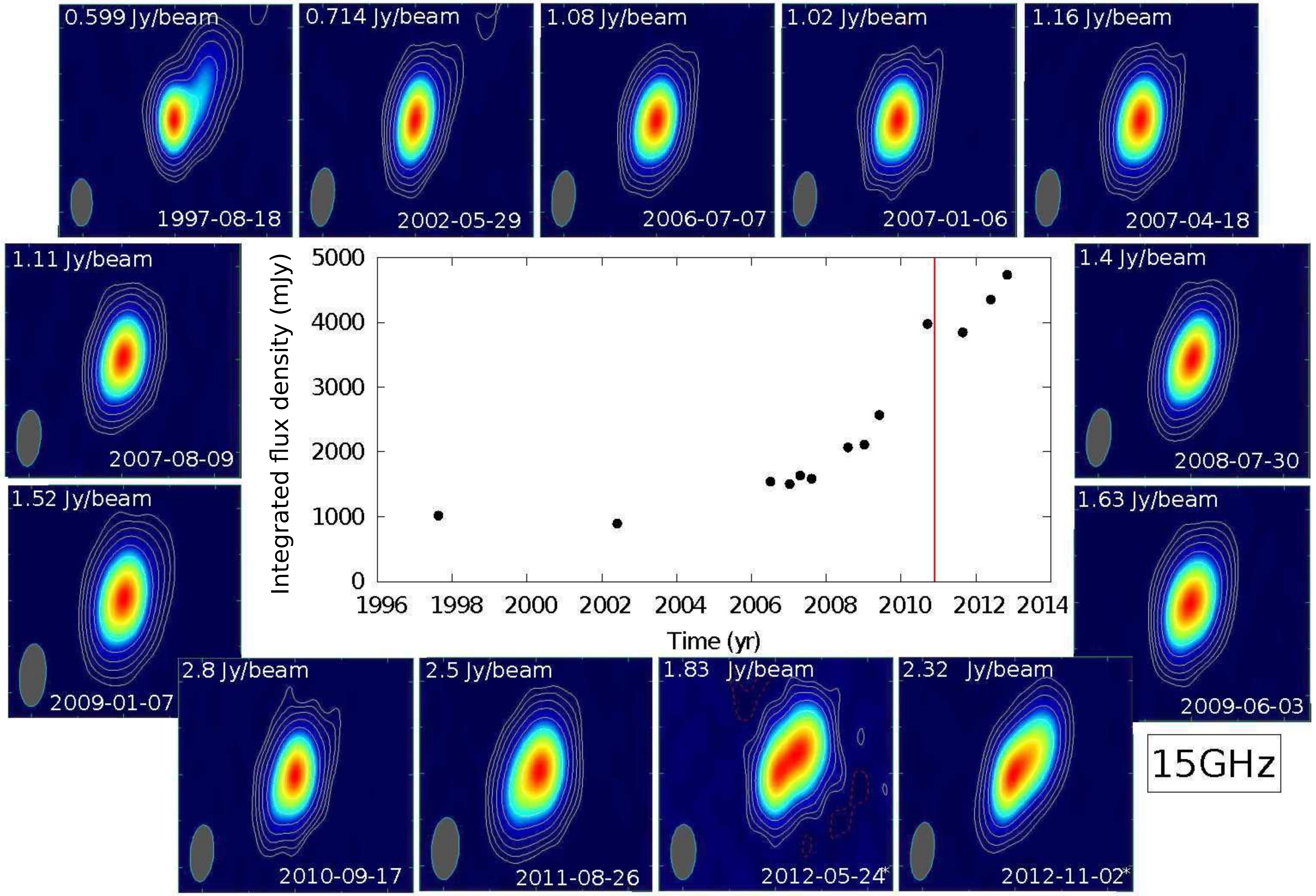


Britzen et al. (A&A 630, A103, 2019)

- Point to unique jet kinematics of TXS 0506+056
- A few models are discussed:
    - Precessing inner jet.
    - Collision of jetted material.
    - Discovery of a binary AGN-jet on parsec scales?

OTHER EXAMPLES

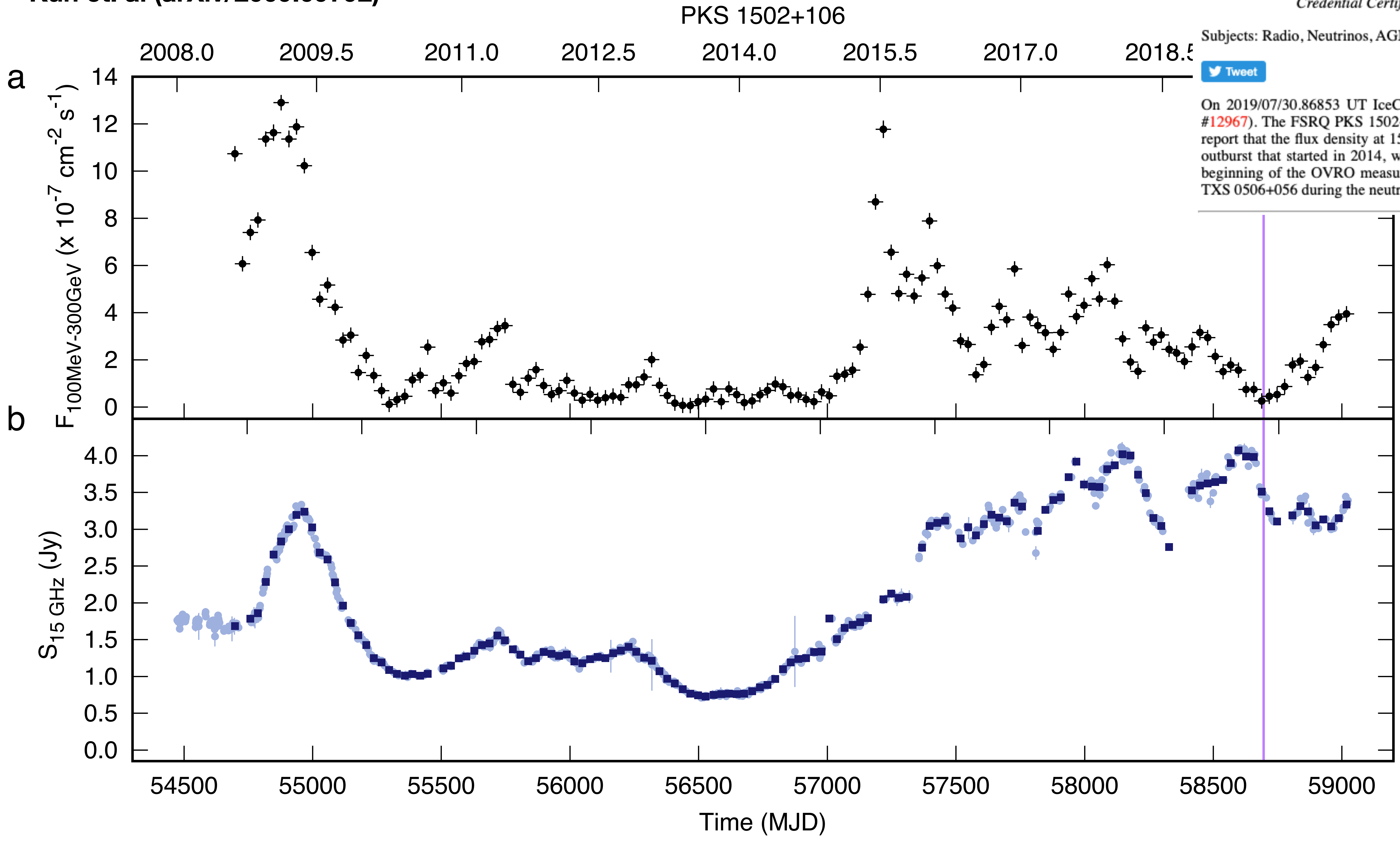
Kun et. al (arXiv/1607.04041)

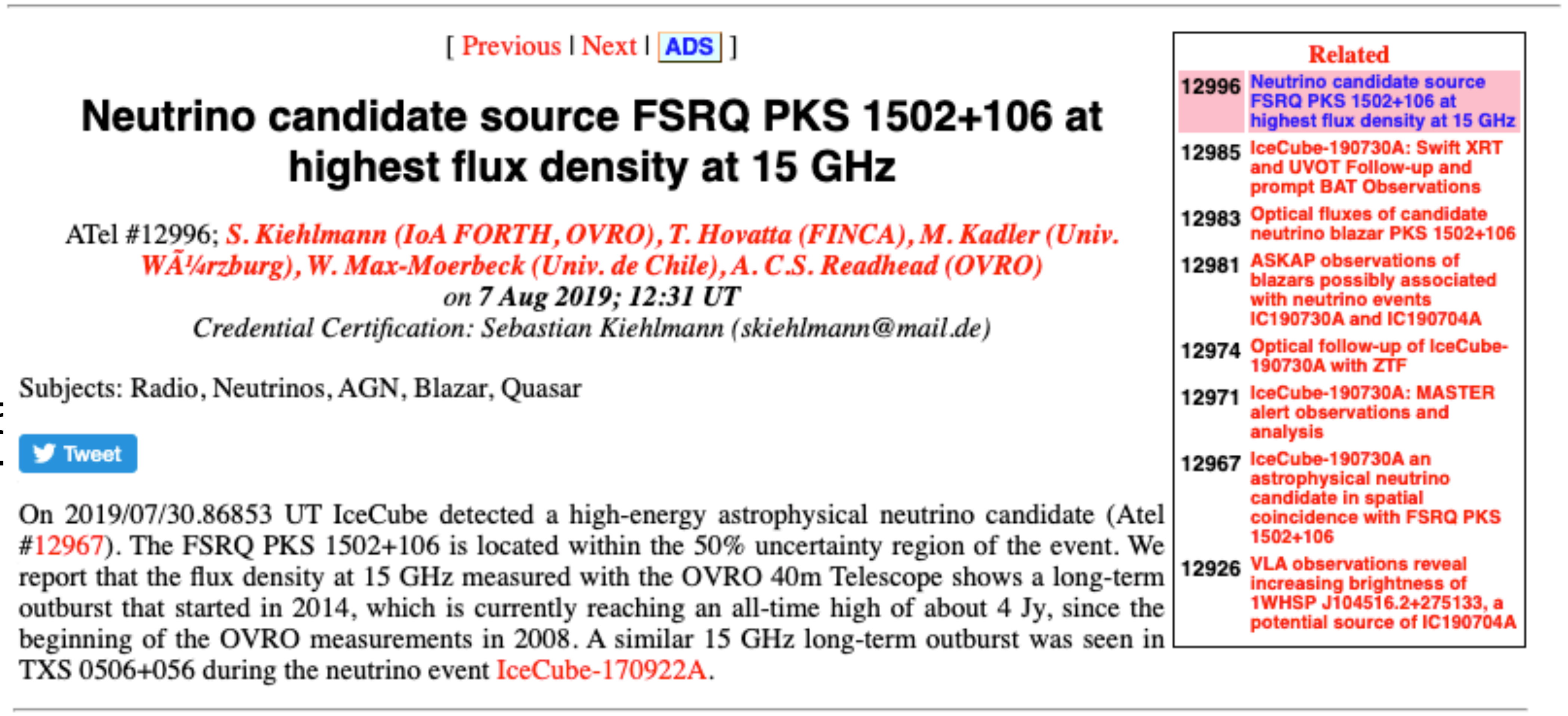


- FSRQ PKS 0723–008 in the region of an high-energy neutrino track.
- MOJAVE light curve shows steady flux increase around the time of the neutrino event.

PKS 1502+106

Kun et. al (arXiv/2009.09792)





[Previous | Next | ADS]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on **7 Aug 2019; 12:31 UT**
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

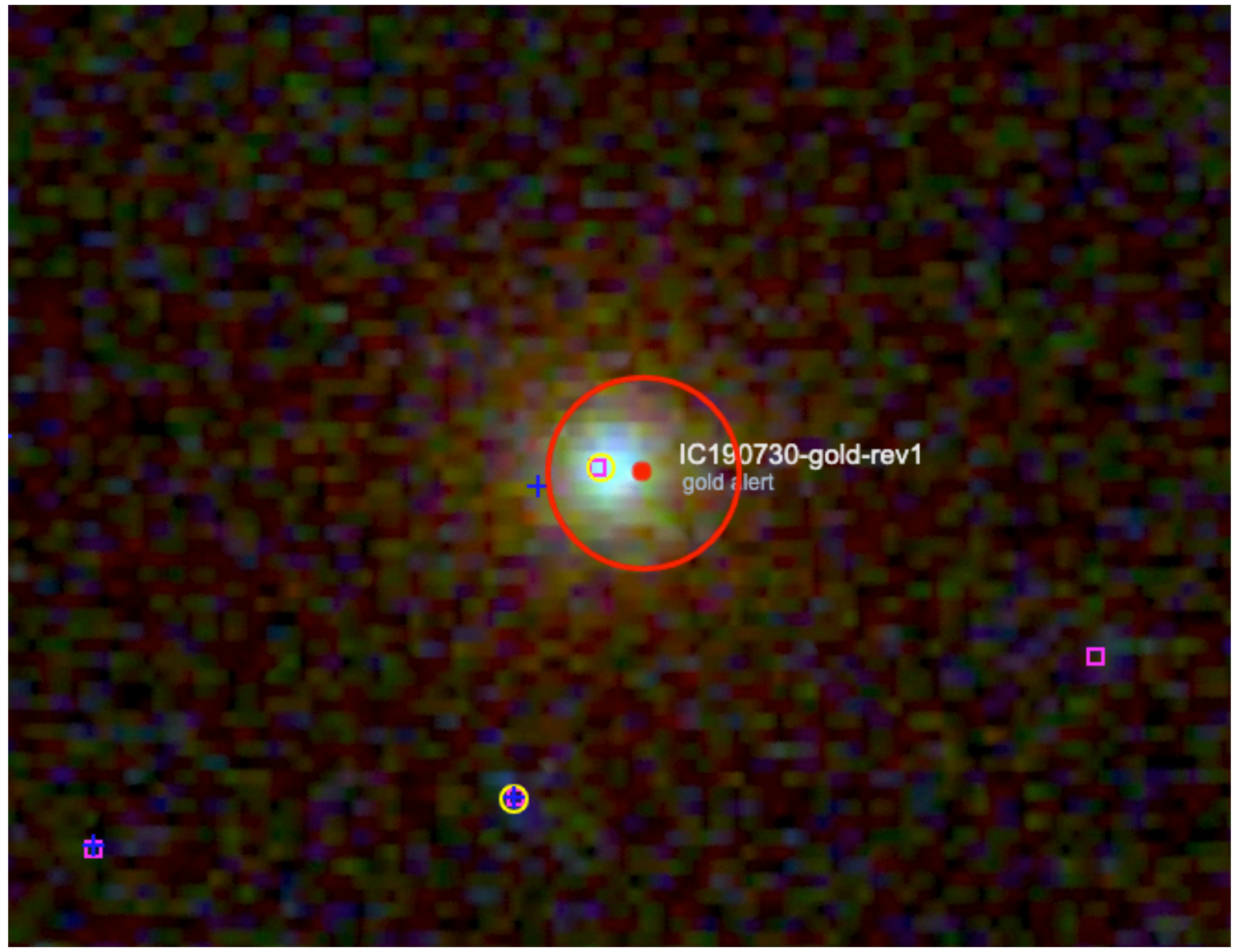
Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

Related

- 12996 Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
- 12985 IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
- 12983 Optical fluxes of candidate neutrino blazar PKS 1502+106
- 12981 ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
- 12974 Optical follow-up of IceCube-190730A with ZTF
- 12971 IceCube-190730A: MASTER alert observations and analysis
- 12967 IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
- 12926 VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A

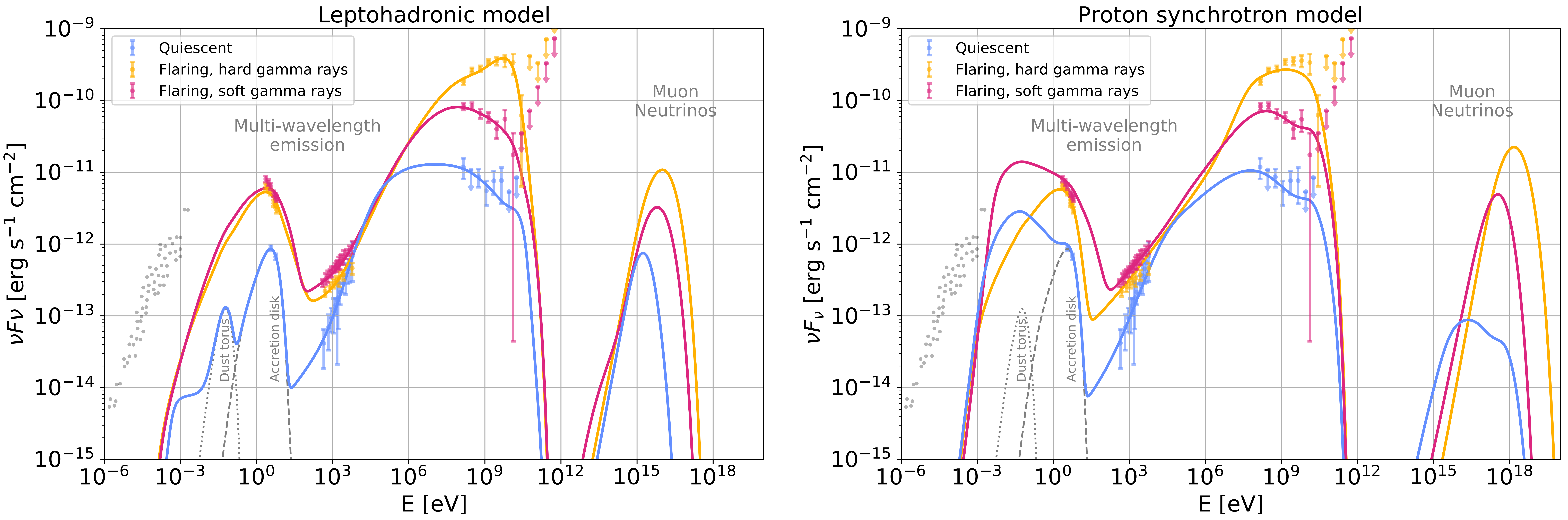
- Neutrino event on July 30th, 2019
- Among the brightest FSRQs.



Neutrino emission during gamma-ray low-state?

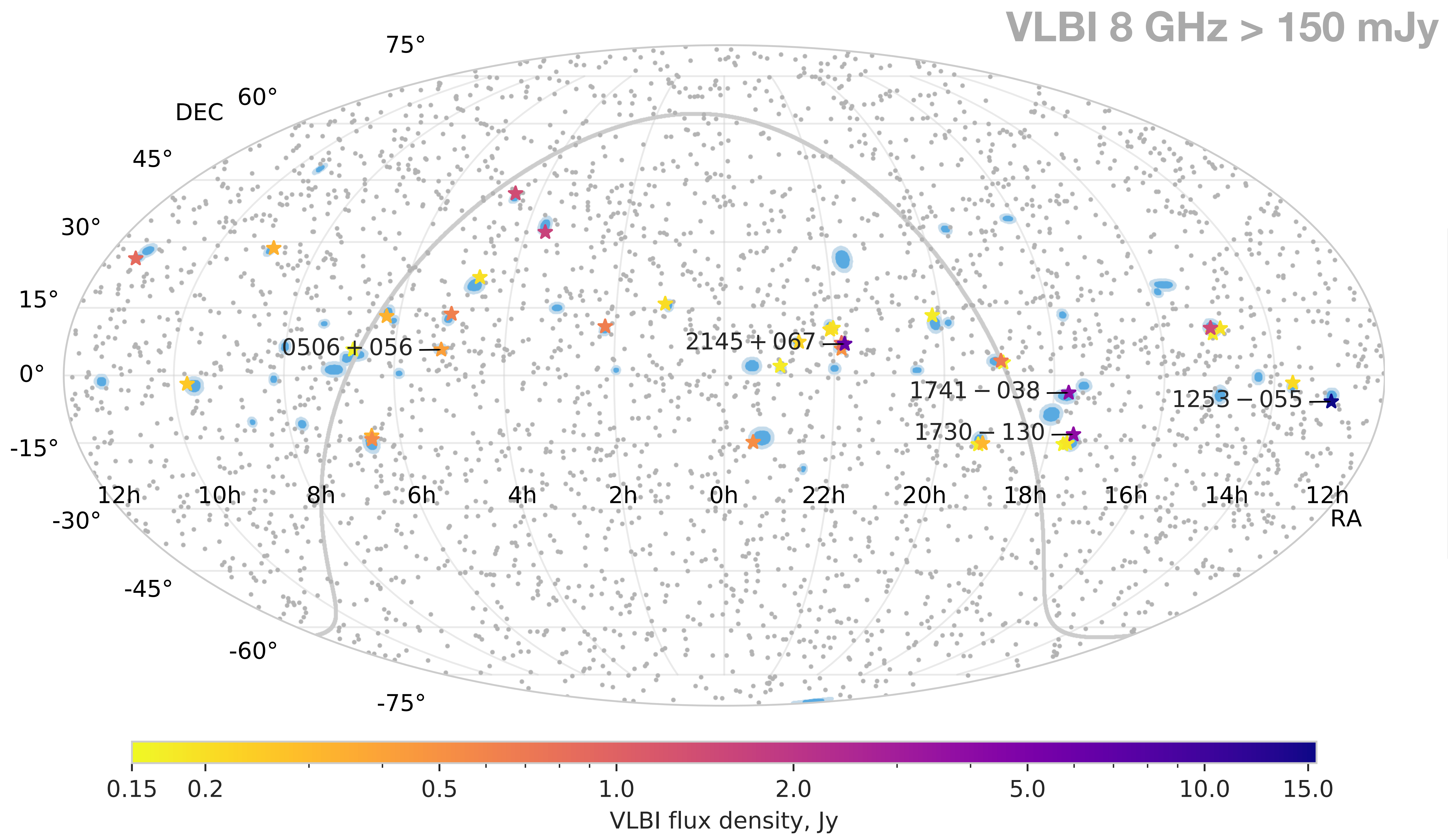
MODELING OF PKS 1502+106

Rodrigues et al. (arXiv/2009.04026)

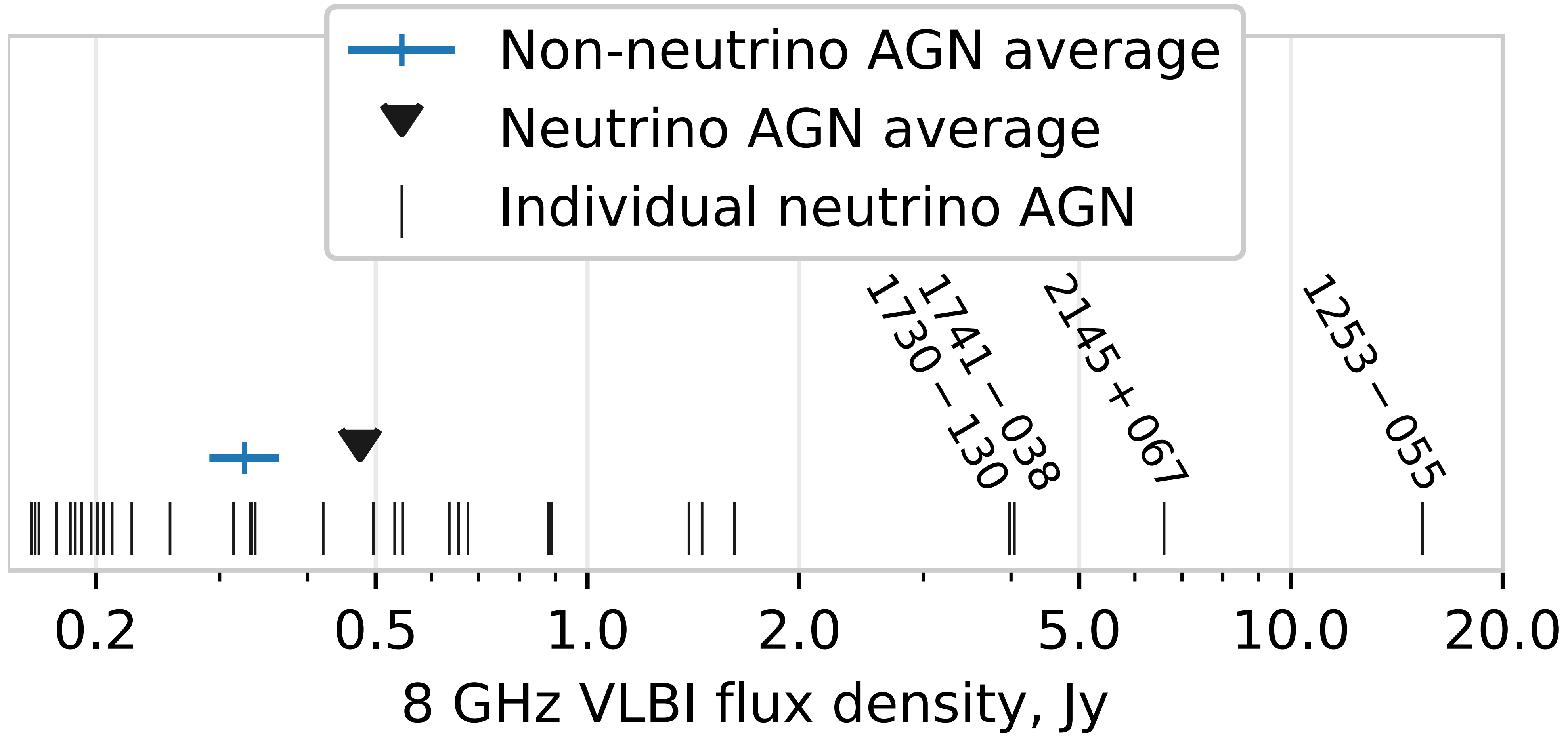


- Rodrigues et al. argue for neutrino emission during the quiescent state of the source.
- Lepto-hadronic and proton synchrotron models describe the broadband SED of the source.
- Soft X-ray spectrum suggest a hadronic contribution.

RADIO-SELECTED AGN

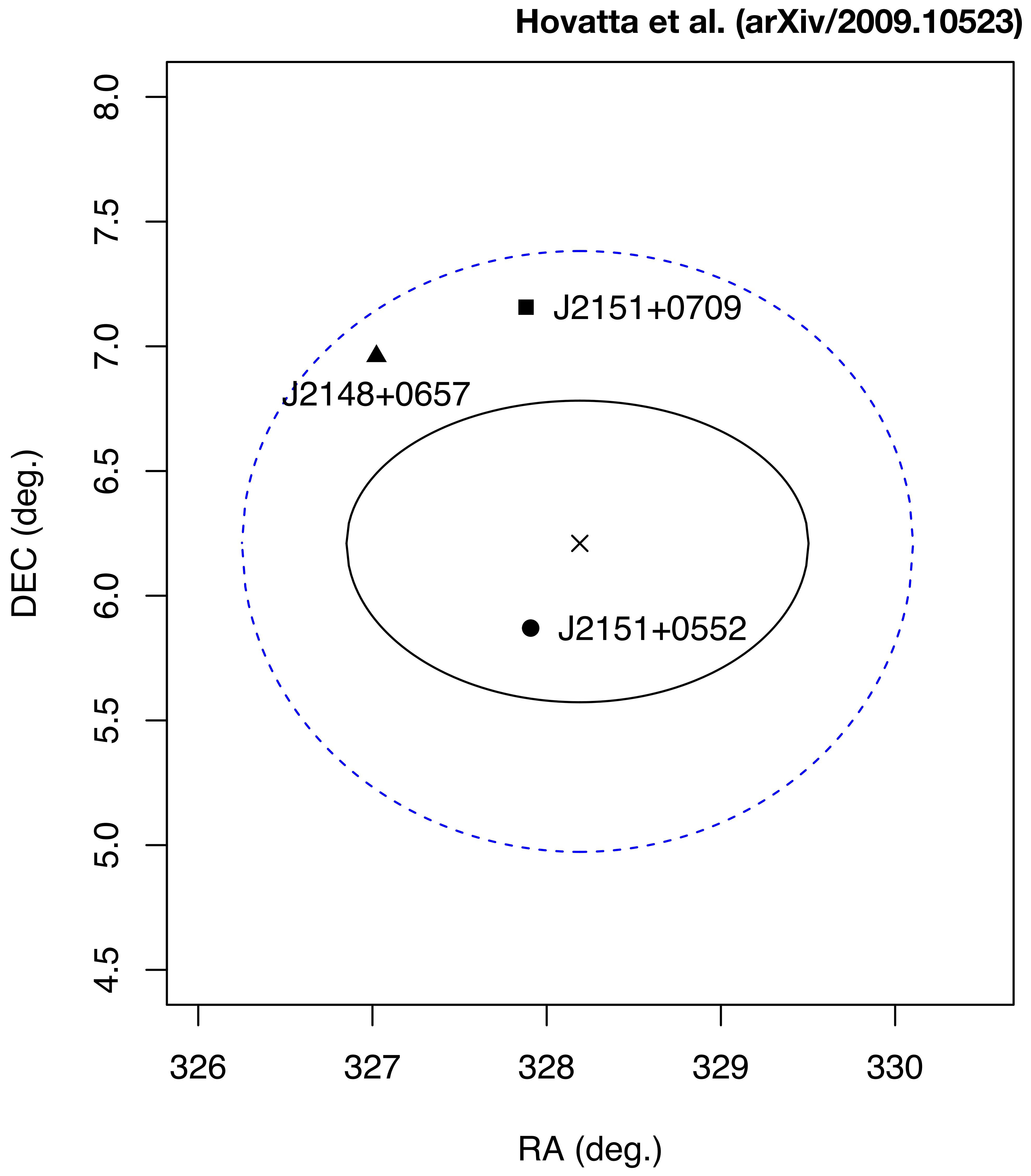


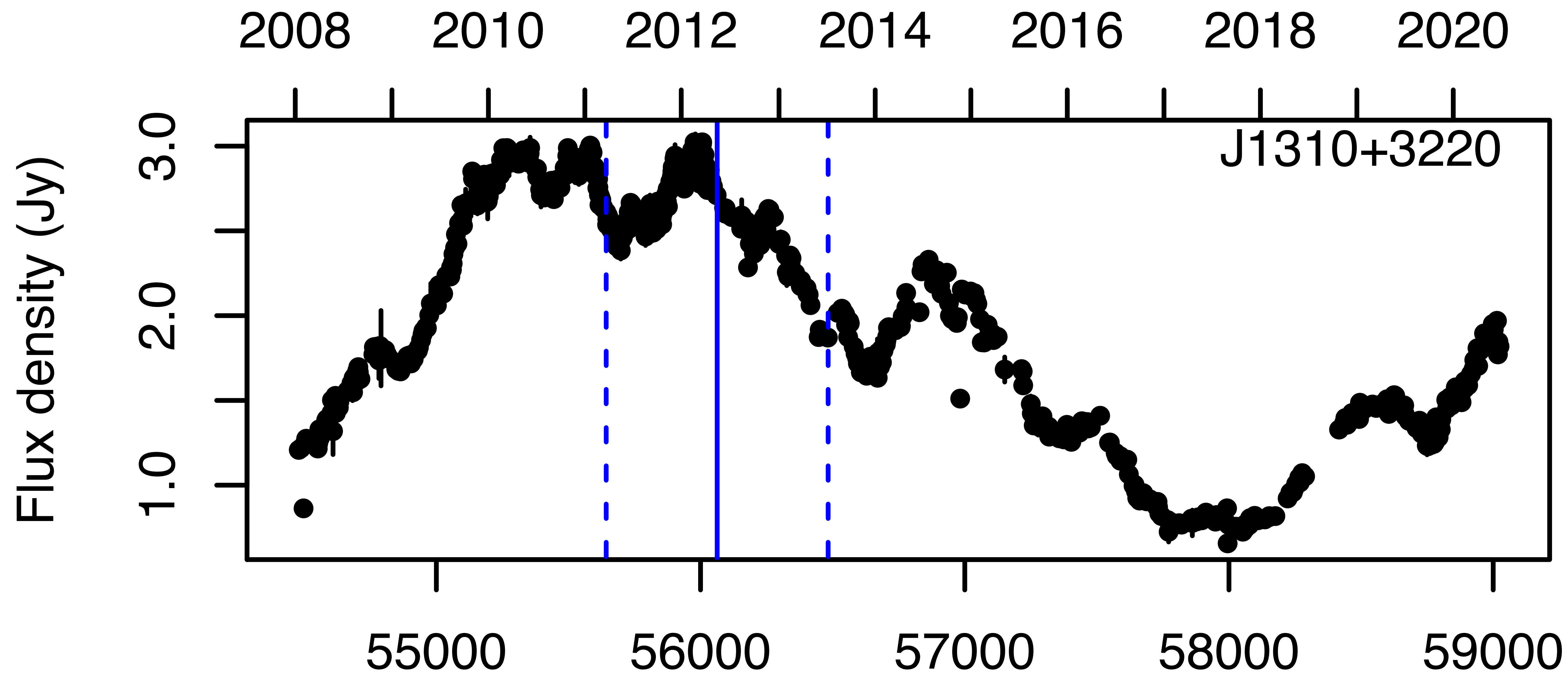
Plavin et al. (arXiv/2001.00930)



- AGN near high-energy neutrino events seem to be louder in radio.
- Correlation significance estimated at 0.2%.

OVRO ASSOCIATIONS

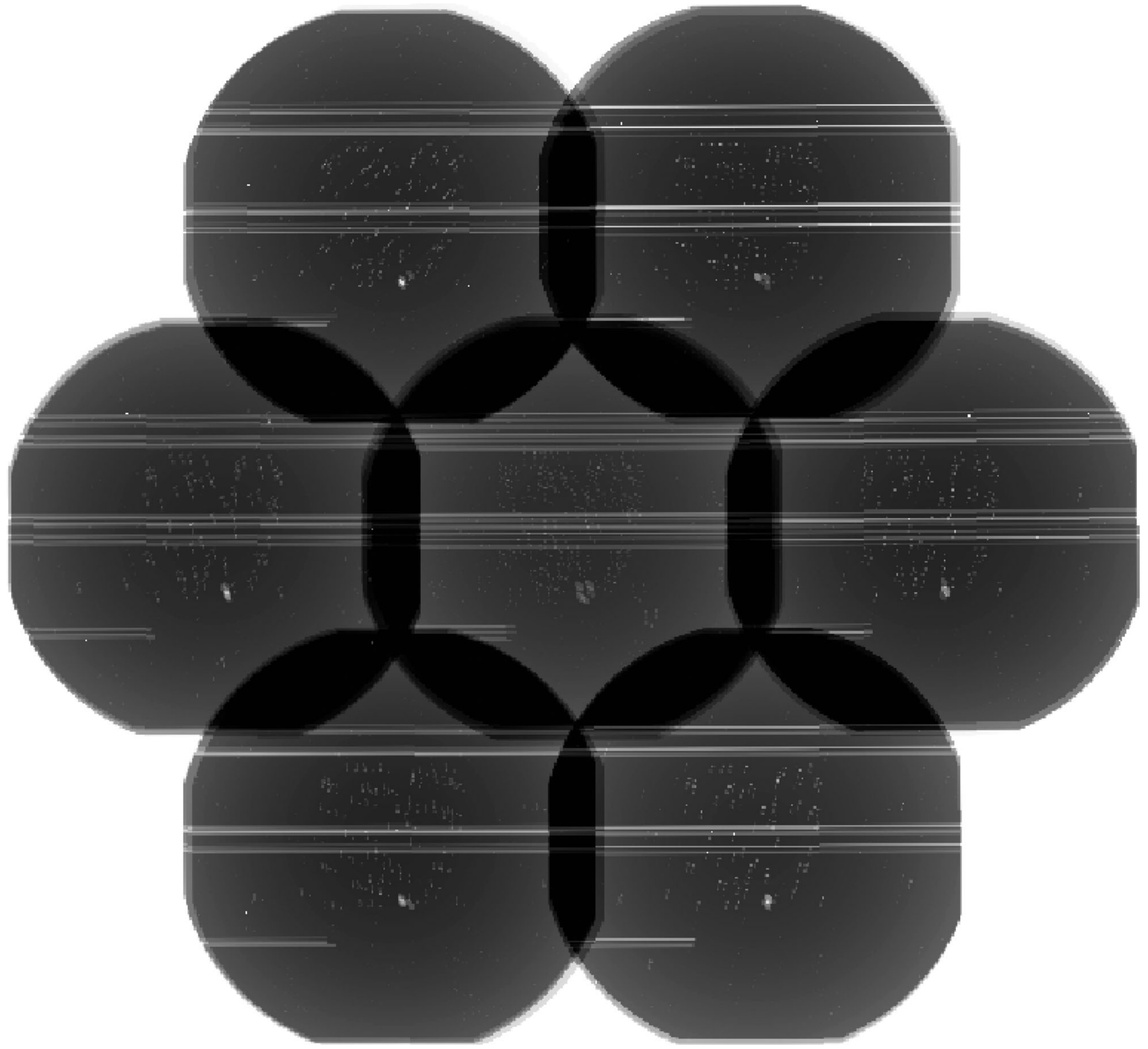


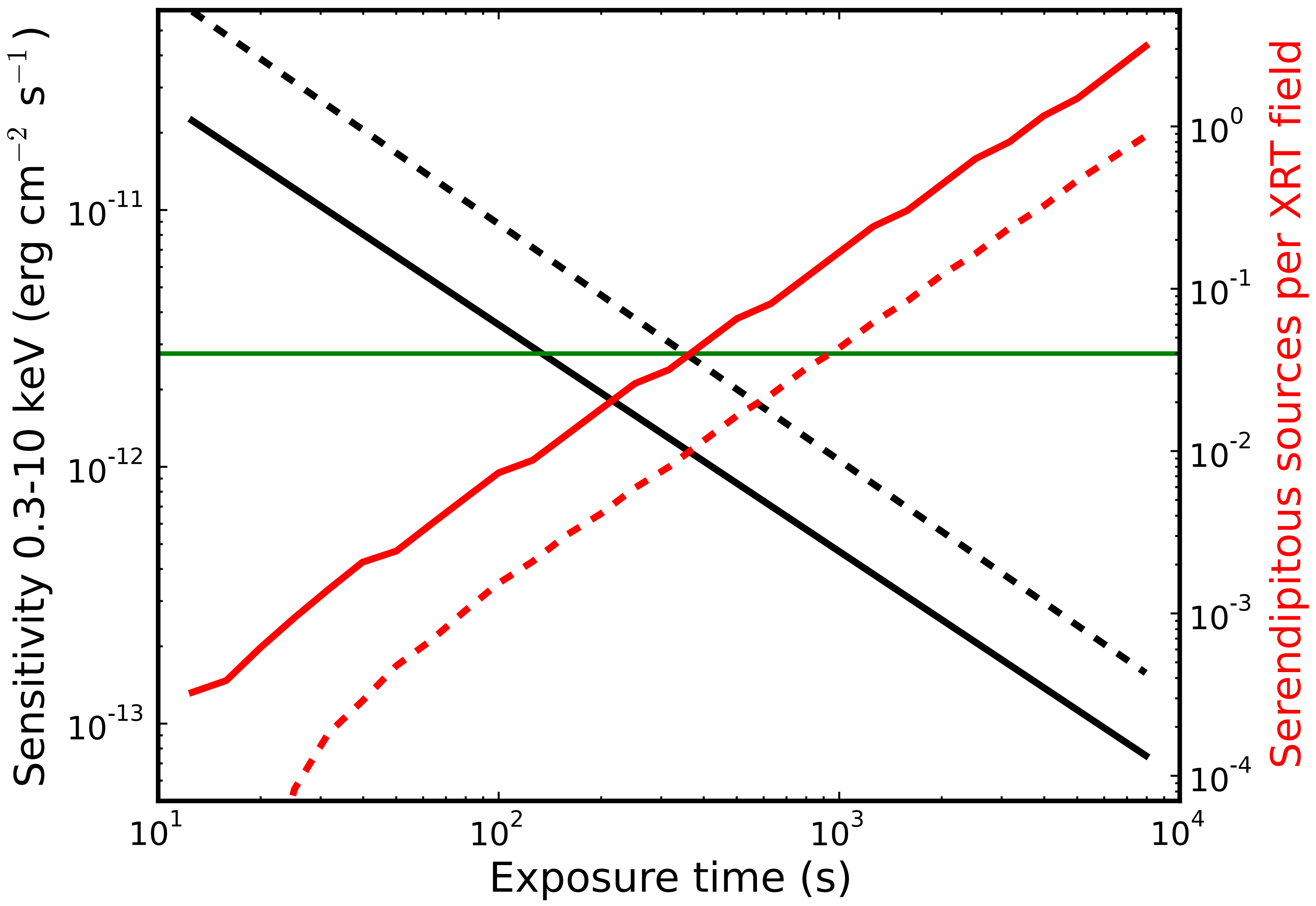


- No evidence for correlation in the OVRO sample (12-28% of the 57 neutrinos evaluated).
- Associations are mostly LSP FSRQs, although the sample is also dominated by that subclass.

ASSOCIATION PROBABILITY A CRITICAL FACTOR

- We don't know (yet!) what exactly we're looking for!
- Sources are transient or highly variable, hampering strong predictions. An emerging pattern is necessary.
- **Calculation of probabilities is a critical factor in correlation claims.**





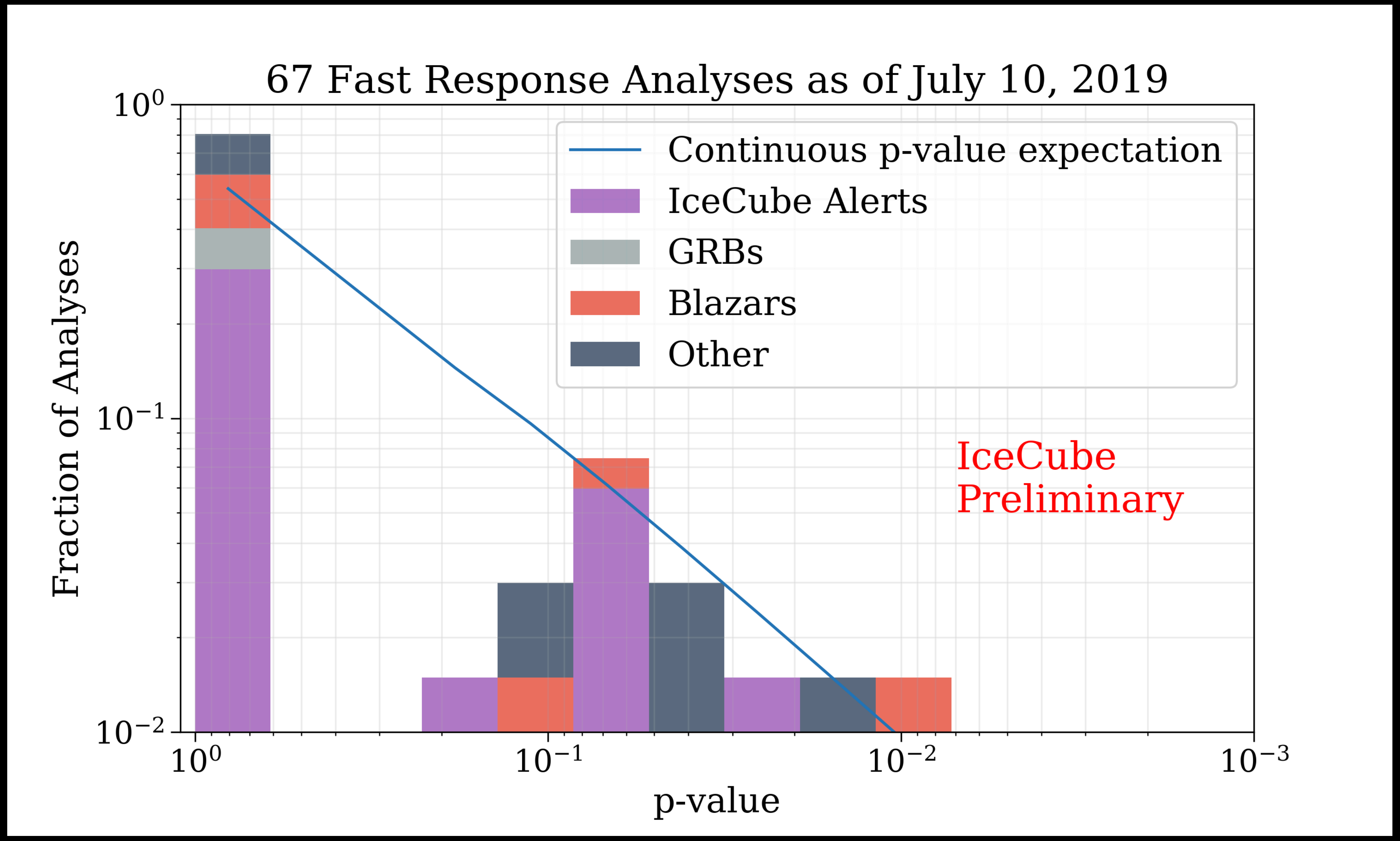
Swift follow-up of neutrino events

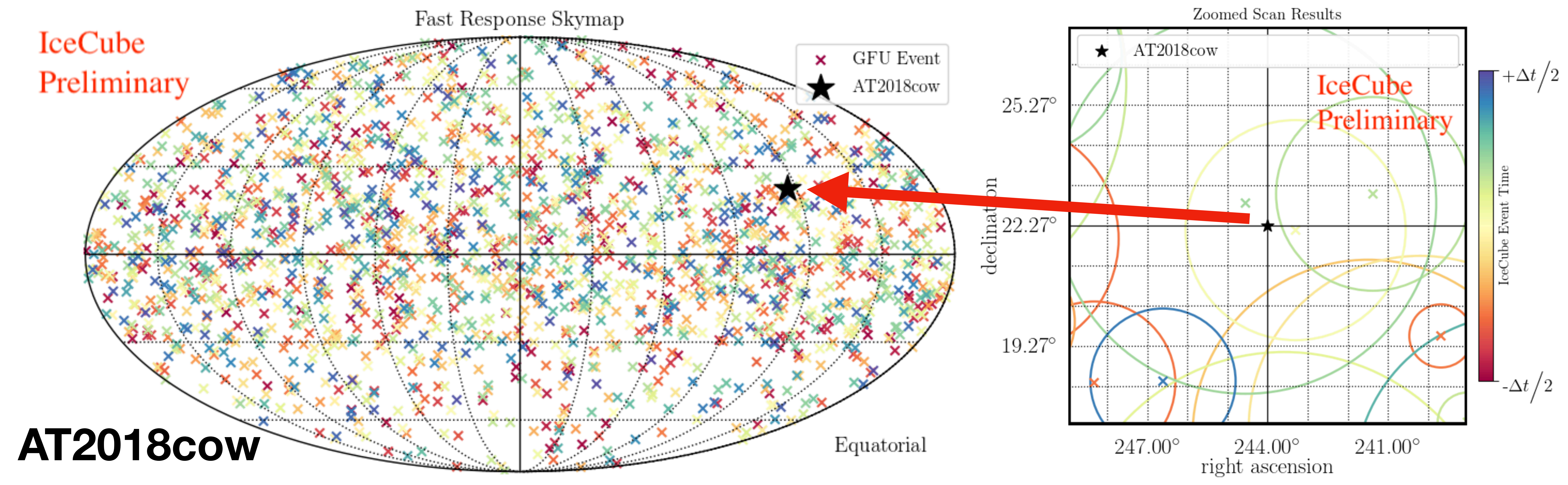
Evans et al.
https://arxiv.org/abs/1501.04435

FAST RESPONSE ANALYSIS

Did IceCube see something?

- Fast response analysis following:
  - IceCube HE alerts (search for additional, LE nus). 102 up to Dec 2020.
  - HE astrophysical events with potential neutrino emission: ATels, GCN, etc. 60 up to Dec 2020.



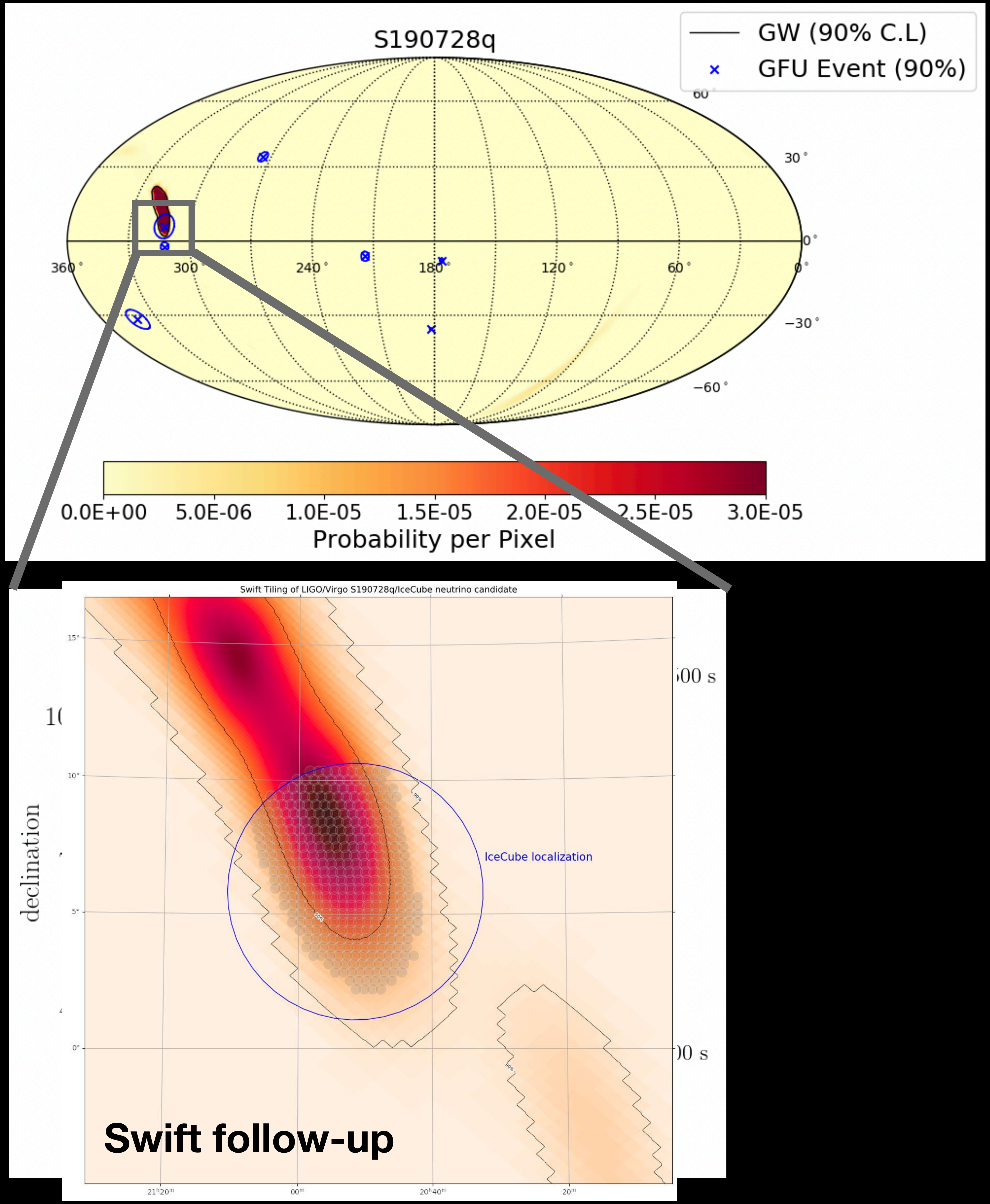


[PoS-ICRC2019-1026]

GRAVITATIONAL WAVES

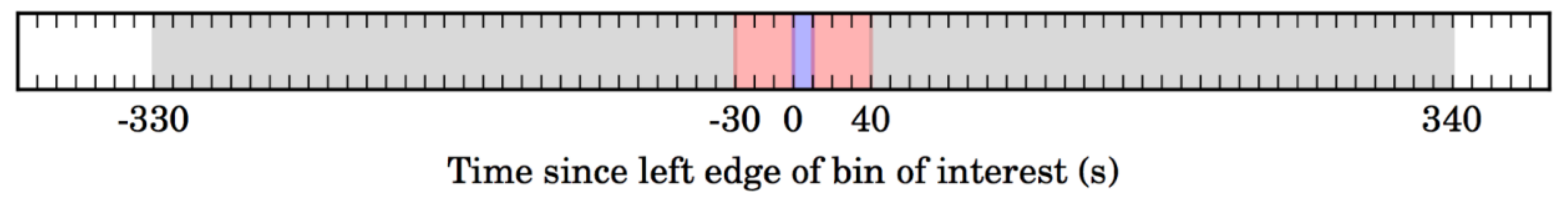
- Two independent analysis of neutrino candidates within 500 s of the GW trigger.
  - Unbinned maximum likelihood search: test for point source consistent with GW localization.
  - Bayesian approach: probability of a joint GW+nu joint signal with astrophysical priors
- Results are reported in GCN circulars. 56 GW follow-ups during O3 run of LIGO/Virgo.
- Example: GW190728, BBH merger
  - p-value ~ 0.01 in both analyses, triggered MWL follow-up
  - https://gcn.gsfc.nasa.gov/gcn3/25210.gcn3

[Astrophys. J. Lett. 898 (2020) L10]



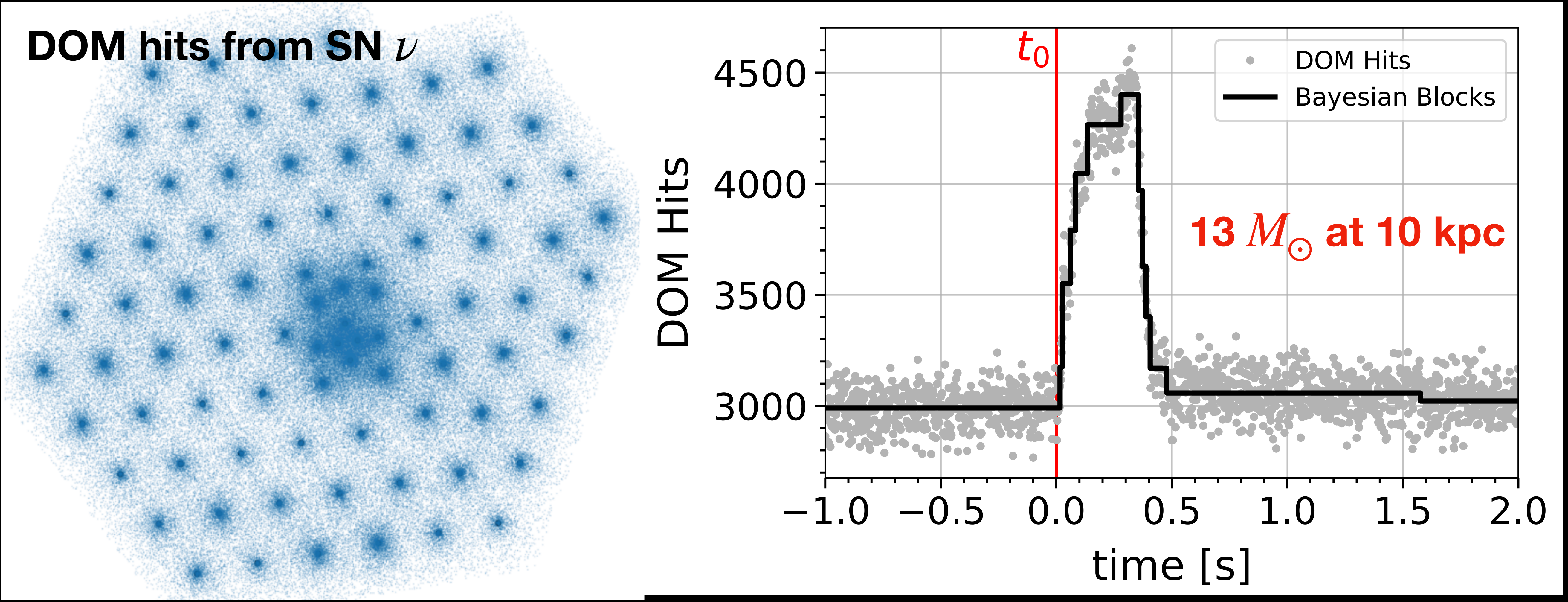
GALACTIC SUPERNOVAE

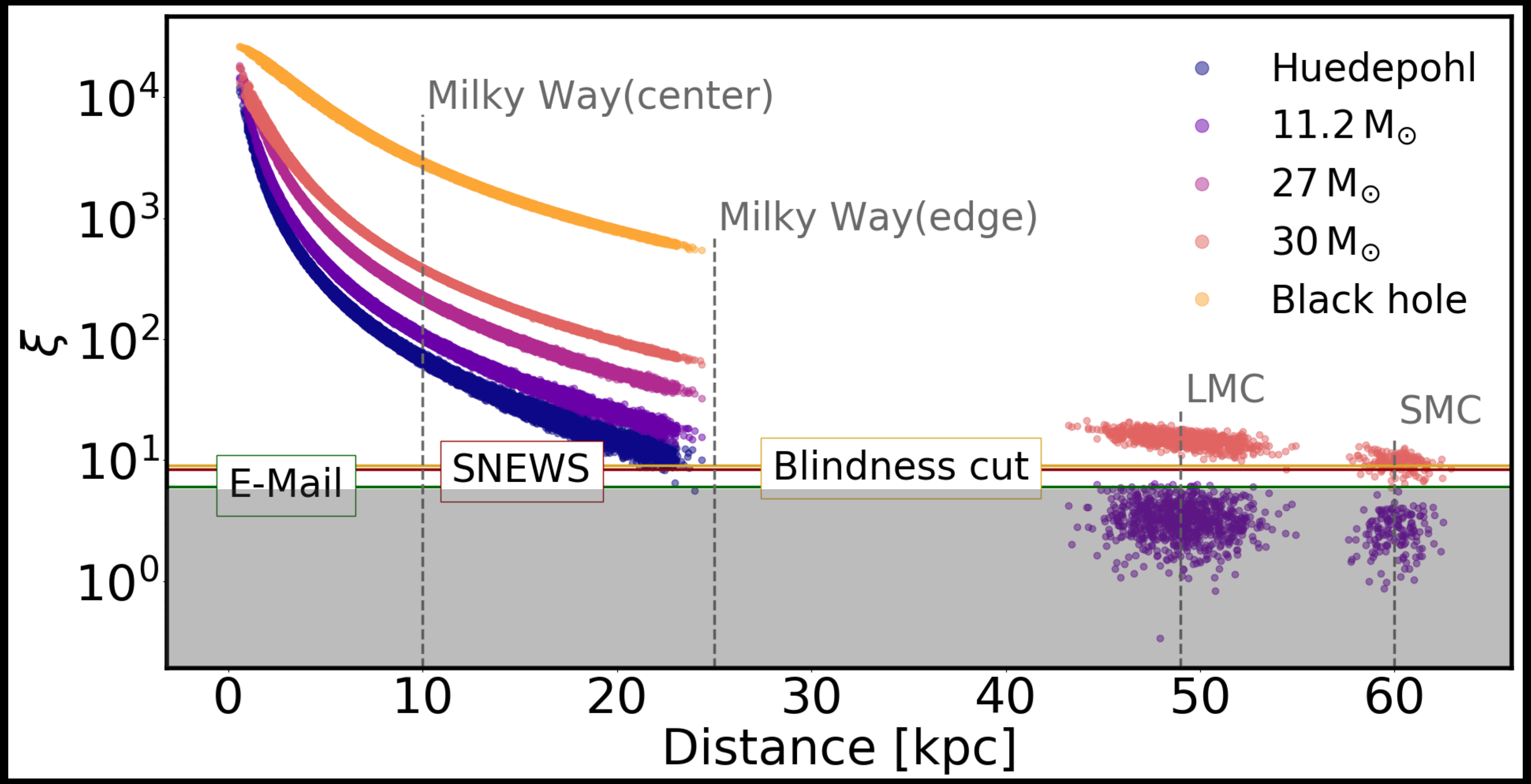
- A Galactic core-collapse supernova would be seen by IceCube as an overall increase in the DOM noise rate produced by Cherenkov photons from 10 MeV neutrino interactions.
- SNDAQ searches for correlated noise rate increases in a 0.5 s time bin with respect to a moving average calculated over a ±5 min window. Can be triggered by SNEWS and LIGO GW alerts. SNDAQ retrieves waveforms from HitSpool buffers.



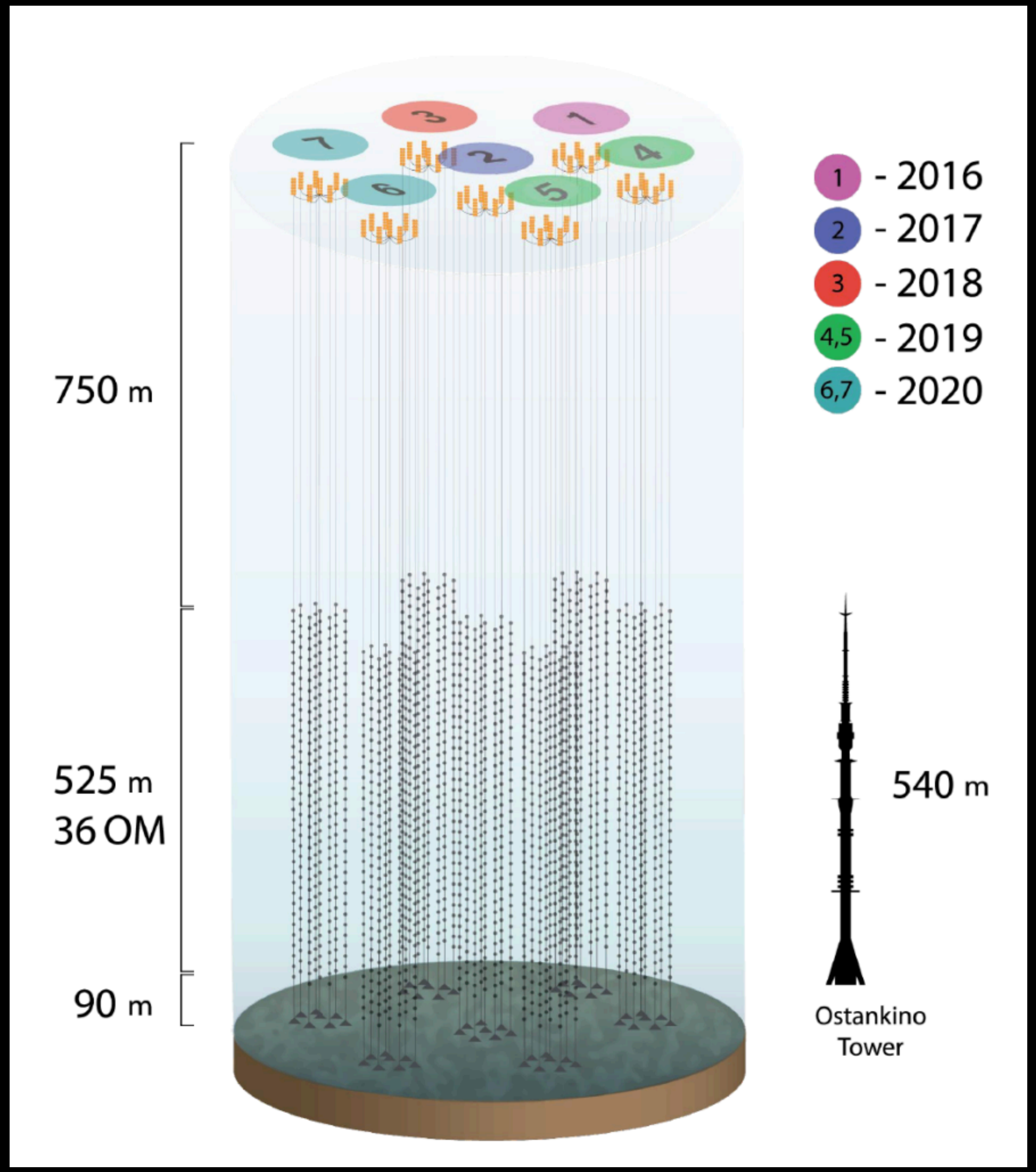
- Alerts over significance threshold sent to SNEWS.

[A&A 535, 2011, A109]
[PoS-ICRC2019-889]



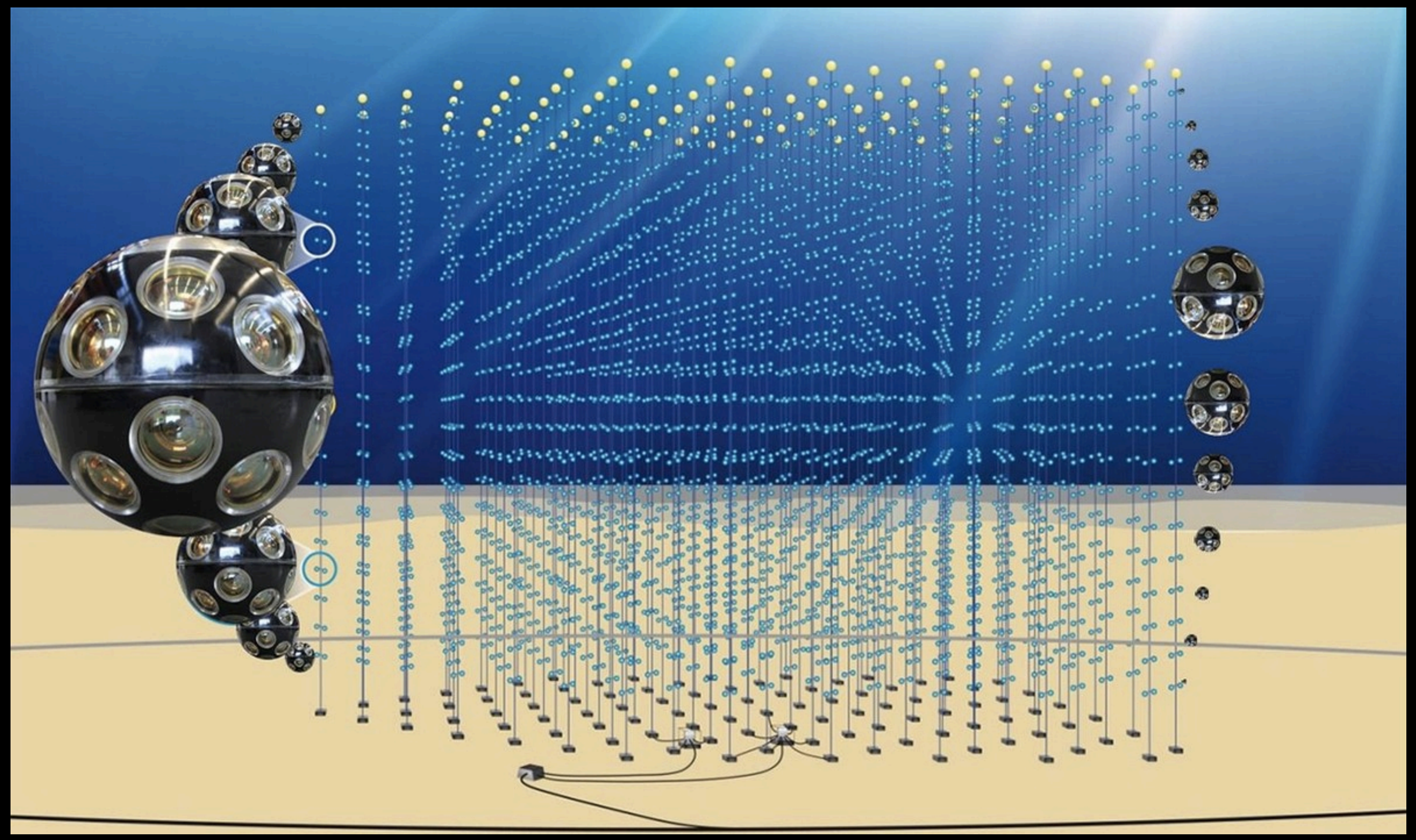


MORE NEUTRINOS WITH BETTER ANGULAR RESOLUTION



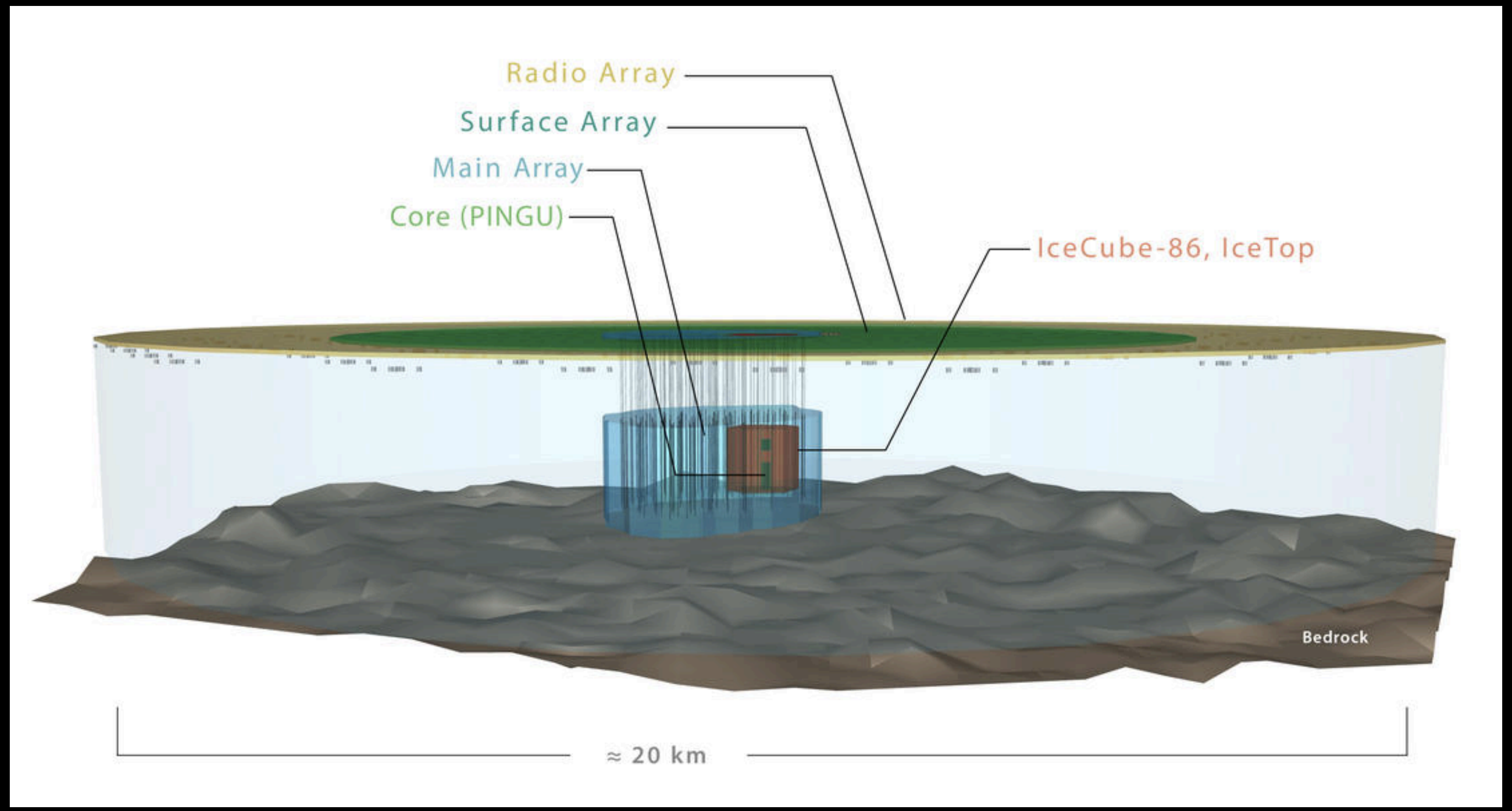
Baikal-GVD

- Target km^3-scale detector (10^4 sensors).



KM3NeT

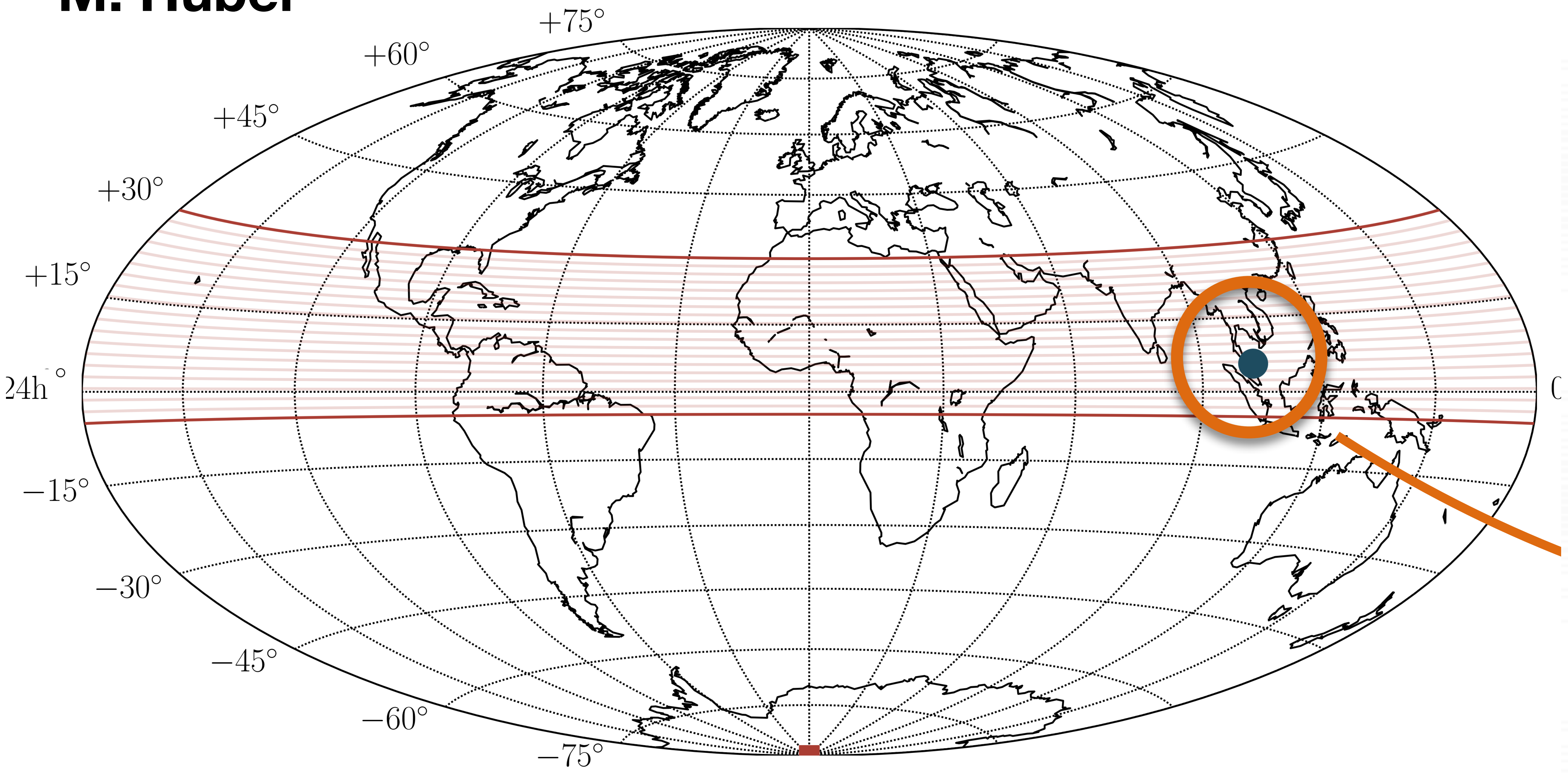
- Target km^3-scale detector (~4k sensors in ARCA)
- 0.1° angular resolution



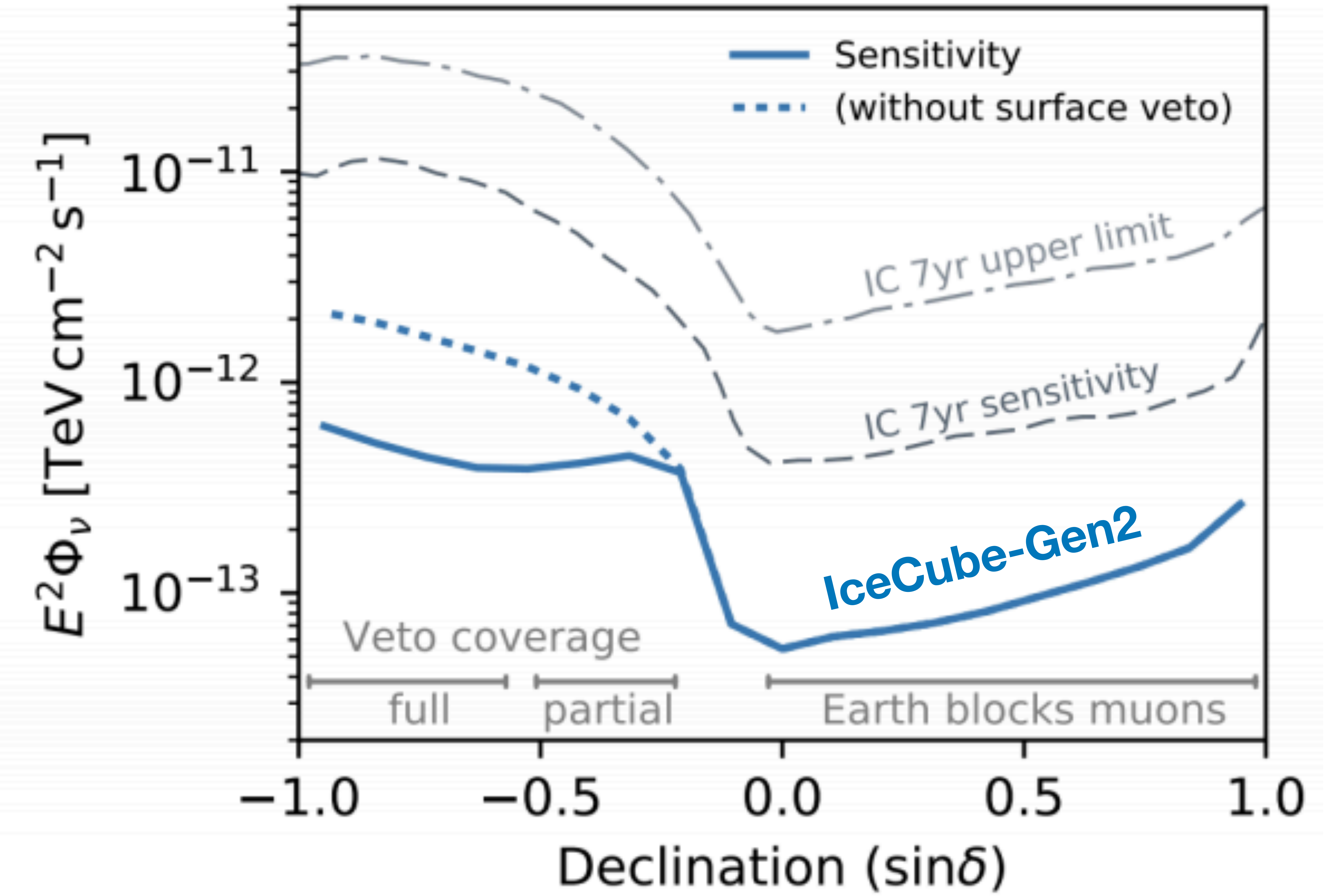
IceCube Gen2

- 6.2-9.5 km^3 volume. >5x improvement in sensitivity over IceCube.
- ~0.2° angular resolution.
- Deployment to start in mid 2020s.

A GLOBAL NEUTRINO TELESCOPE NETWORK



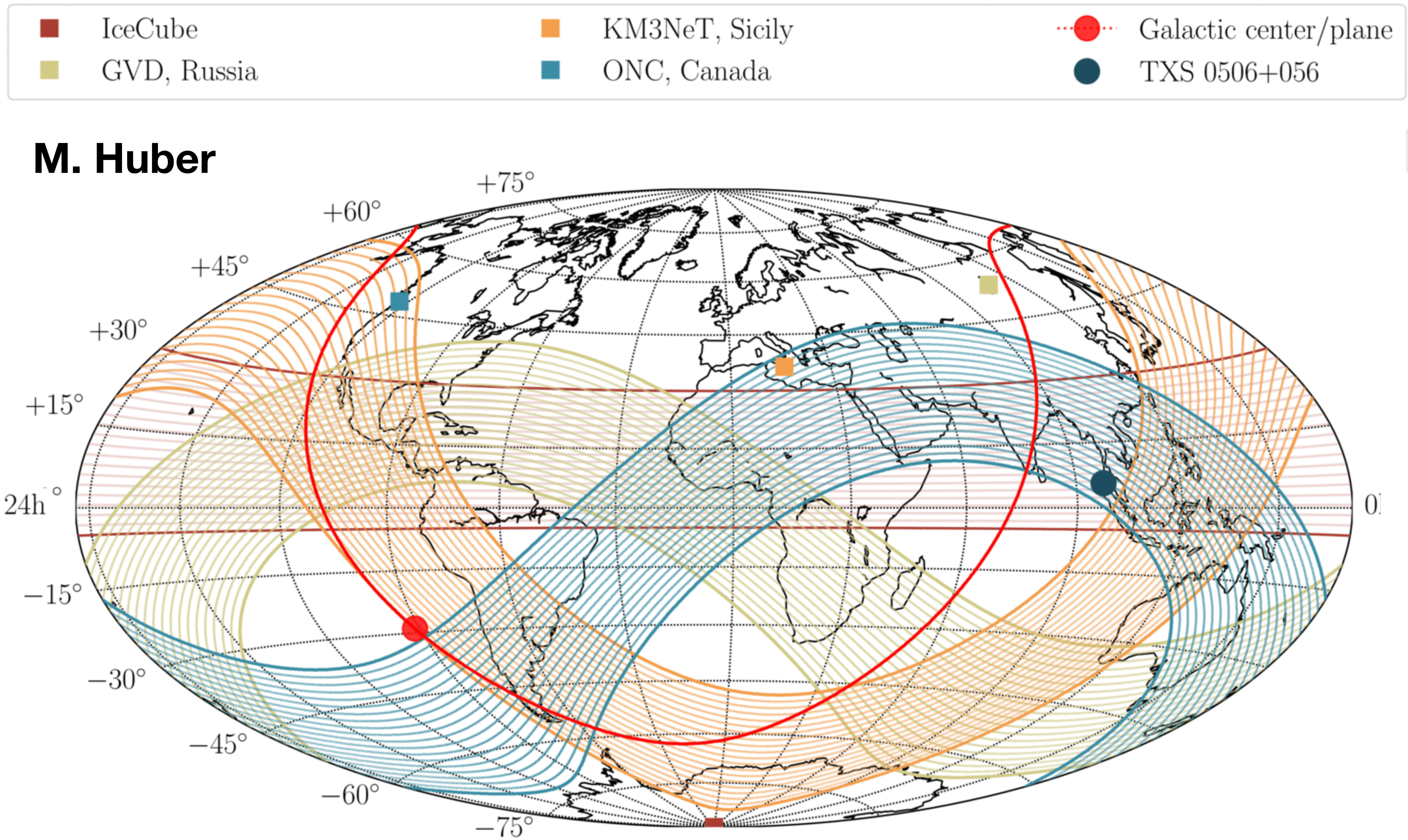
~30% sky coverage from IceCube

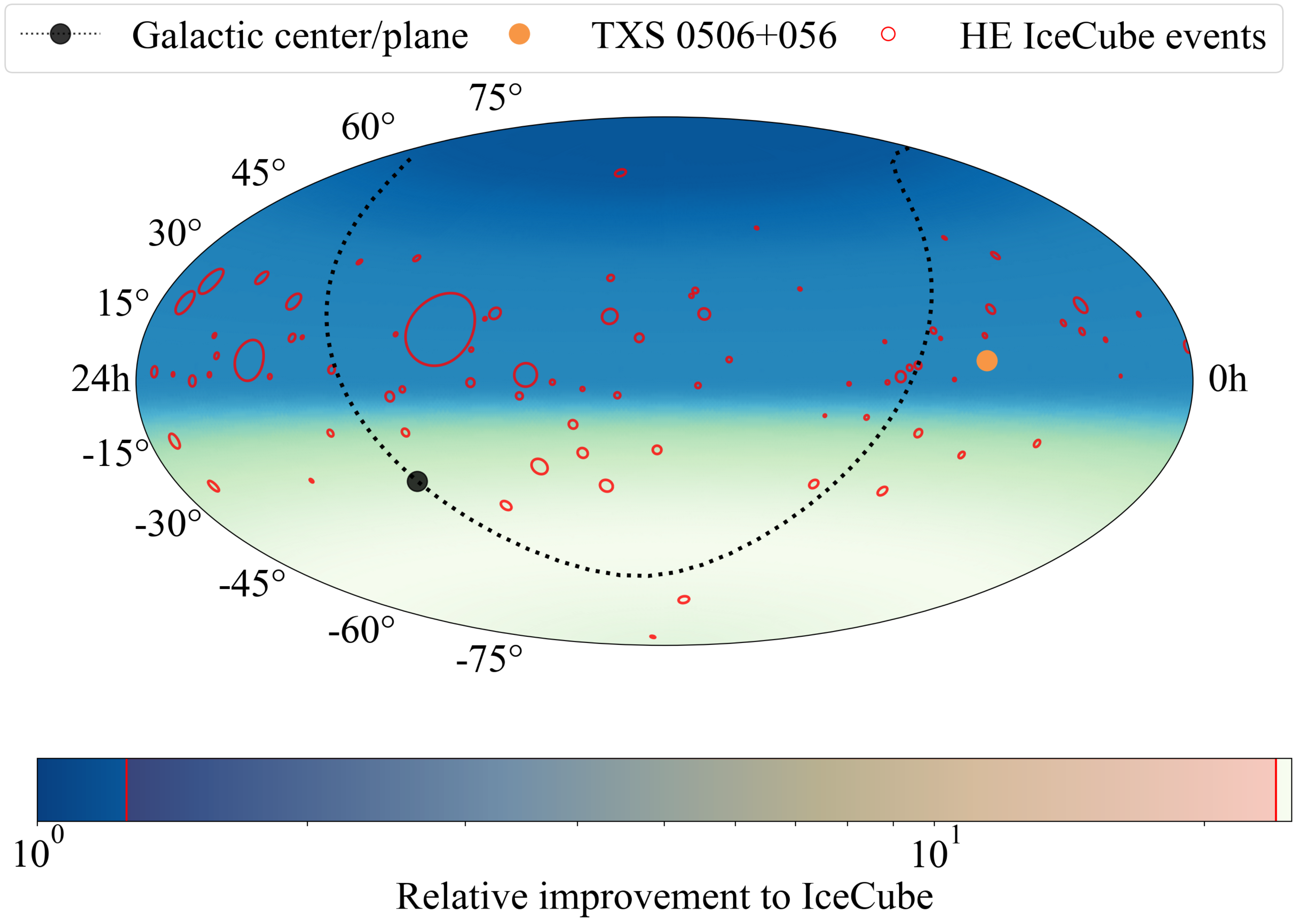


- IceCube is most sensitive near the celestial equator.
- A source similar to TXS 0506+056 may be missed if elsewhere in the sky.
- A network of neutrino telescopes is desirable to cover the entire sky with similar sensitivity.

A GLOBAL NEUTRINO TELESCOPE NETWORK

M. Huber

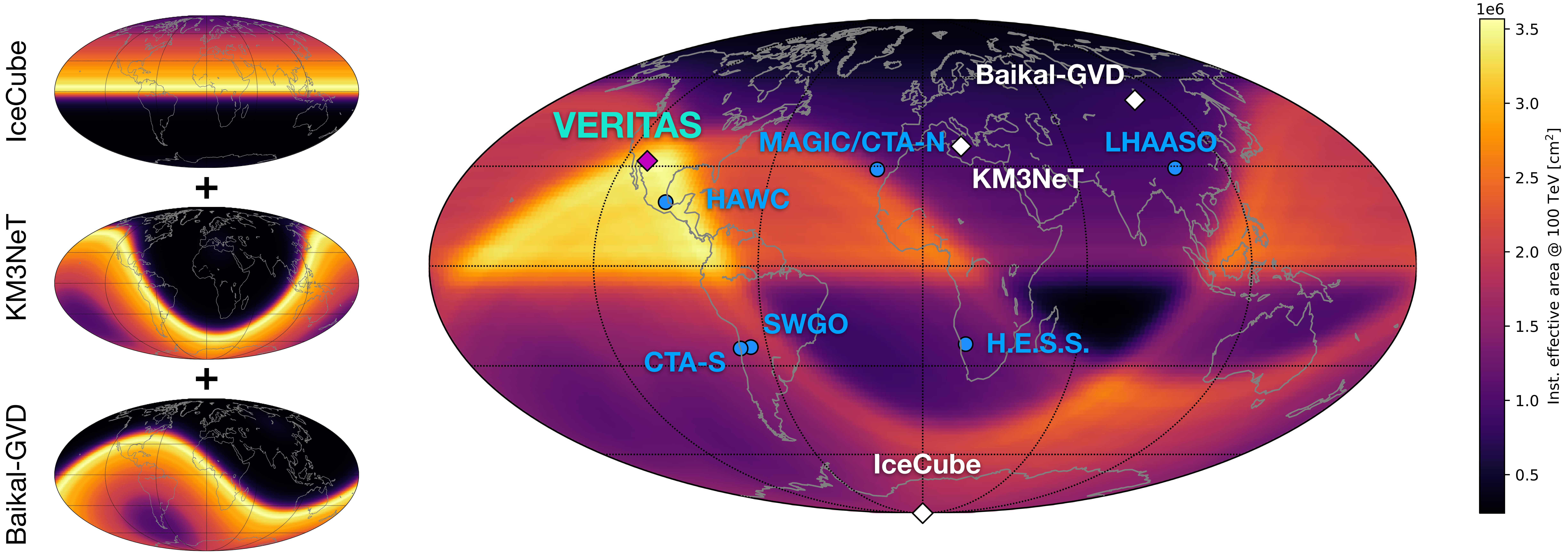




Sensitive to spectral index

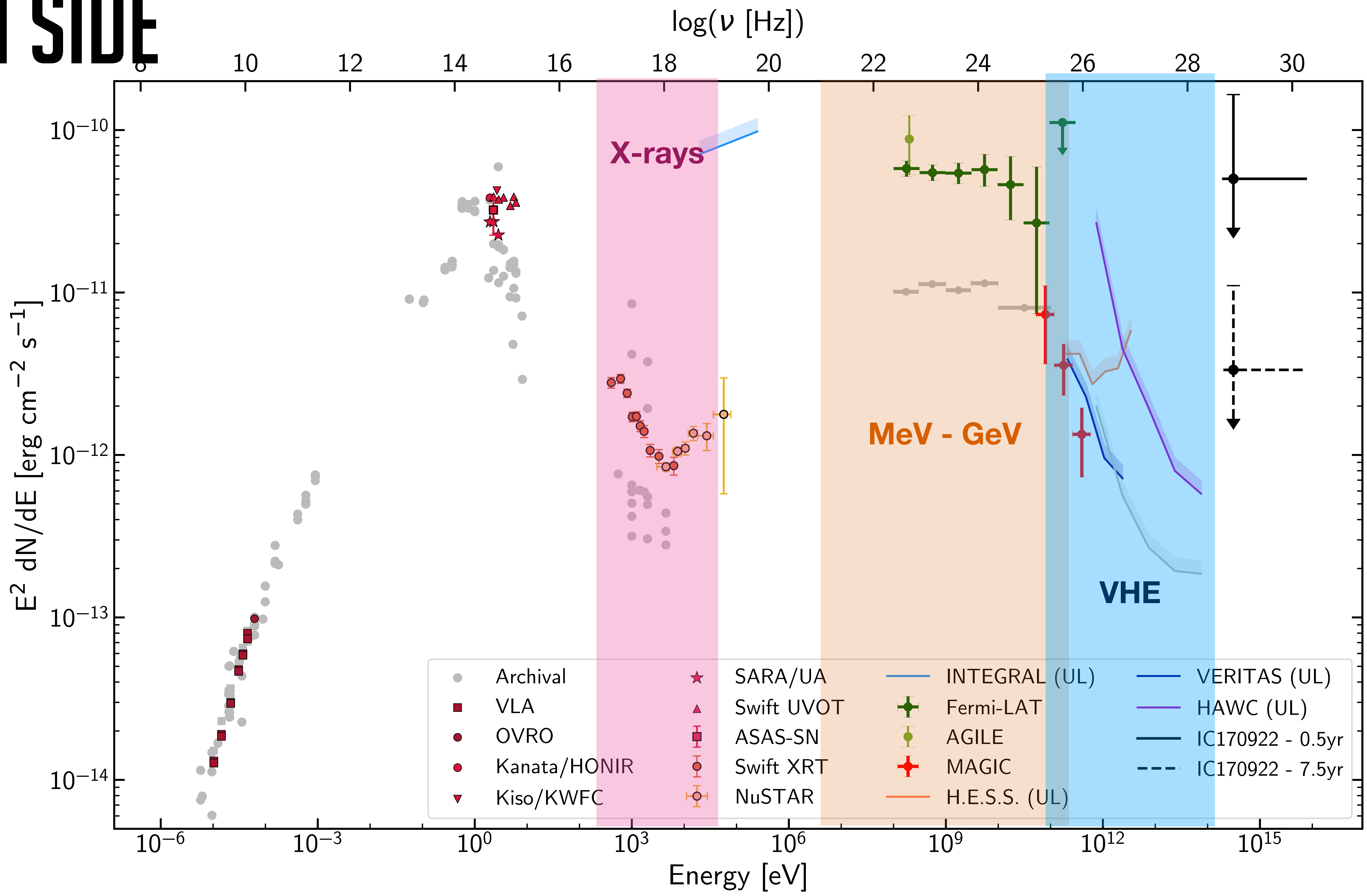
- An improvement of ~25x in sensitivity could be accomplished by this network (wrt current IceCube).
- Prompt, well-reconstructed alerts from this network would enable sensitive **EM follow-ups**.

PROSPECTS FOR FUTURE IACT FOLLOW-UPS



- Instantaneous effective area for a combined IceCube (current generation) + Baikal-GVD + KM3NeT using IceCube-86 ν_μ effective areas for orientation at 100 TeV (where the astrophysical flux starts to dominate).
- Highest sensitivity for a combined global network of neutrino telescopes (e.g. PLE**ν**M concept)

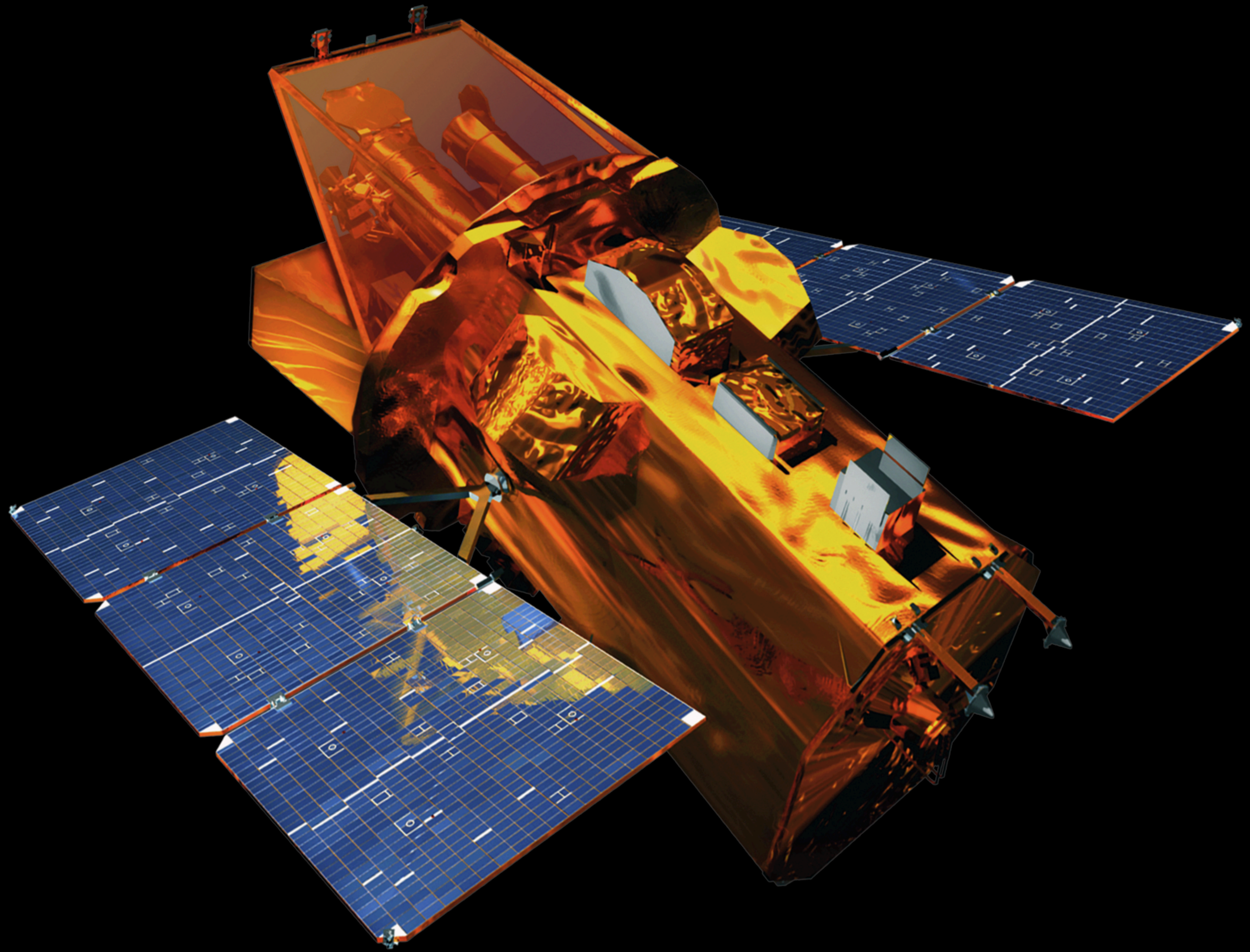
THE EM SIDE



log(ν [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E² dN/dE [erg cm⁻² s⁻¹]
X-rays
MeV - GeV
VHE
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
IC170922 - 0.5yr
IC170922 - 7.5yr

X-RAY COVERAGE

Neil Gehrels *Swift* Observatory



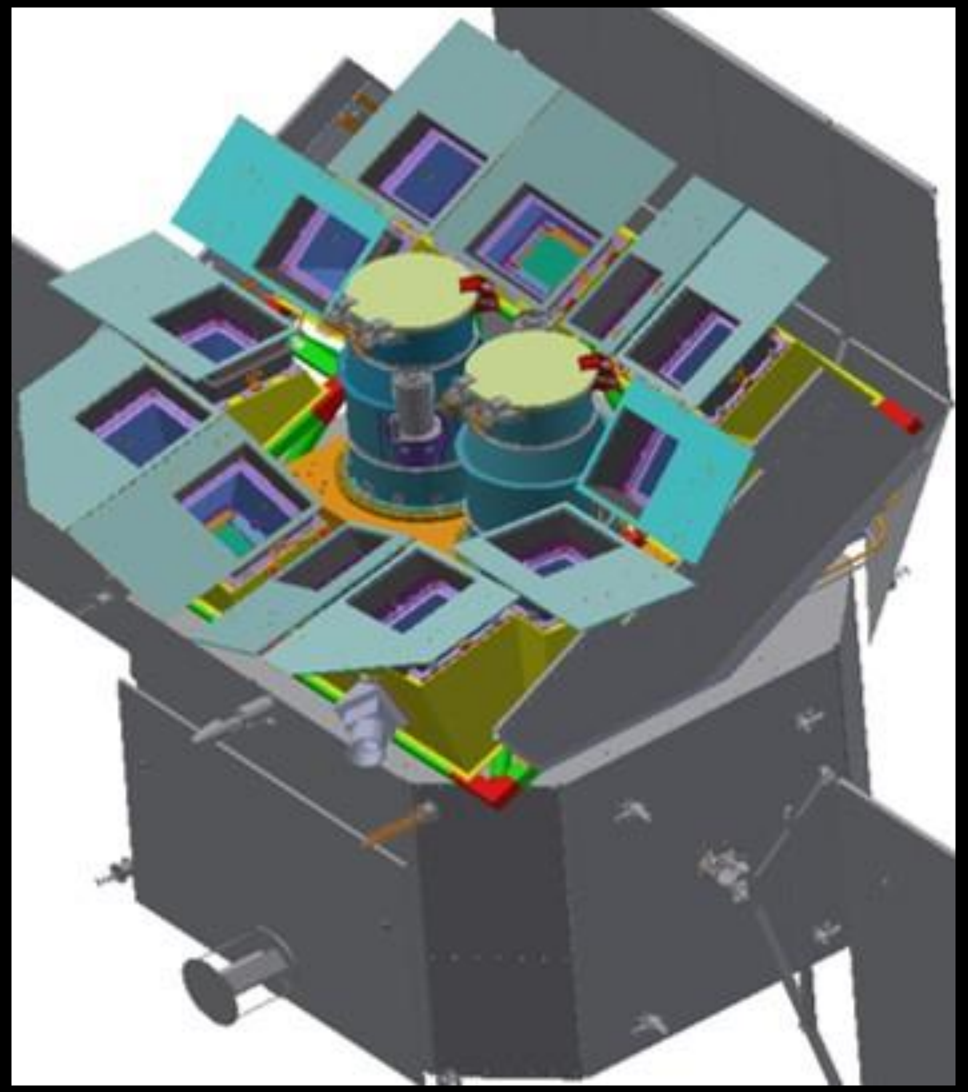
XRT sensitivity in the 0.3-10 keV
Fast response, low overhead.
~10^{-13} erg/cm2/s in ~2 ks
~0.4 deg FoV
Launched in 2004.

SVOM (China-France)

Rapid follow-ups of GRBs
Launch date of Mid 2023
0.2-10 keV
“Lobster eye” optics with 1 deg FoV

Jul 2020: NJU-HKU No.1 lobster-eye demonstrator launched.

Einstein Probe (China-ESA)

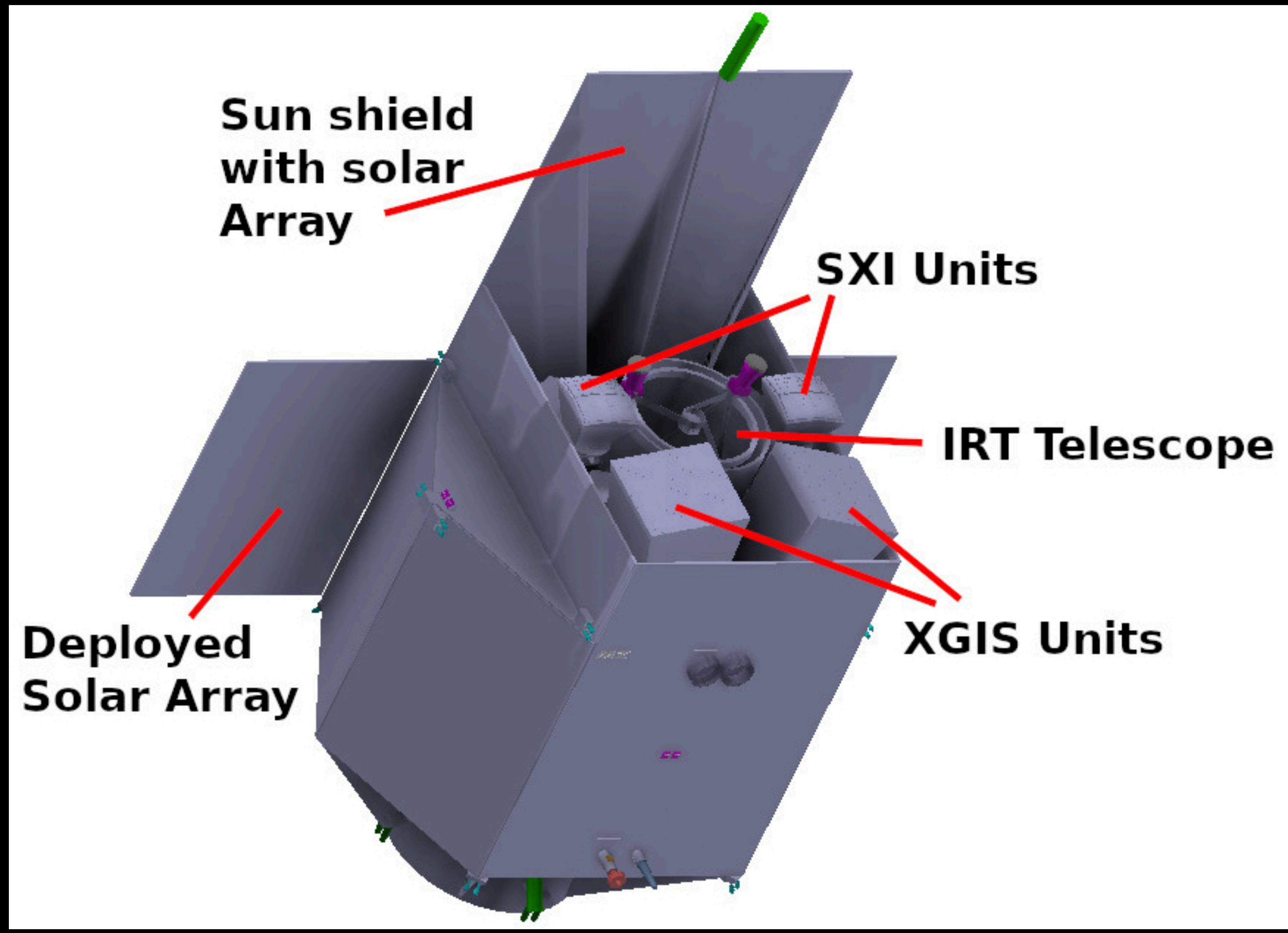


Late 2022 launch

lobster-eye MPO + CMOS
FoV: 3600 sq deg (1.1 sr)
band: 0.5 – 5 keV soft X-ray
eff. area: ~3 cm² @1keV
FWHM: ~ 5’, positioning <1’
Sensitivity: 10-100 x increase

Wolter-1 type + CCD
FoV: 38’
band: 0.3-10keV
eff. area: 2x 300cm² @1keV
angular FWHM: 30”
positioning accuracy: <10”

X-RAY COVERAGE

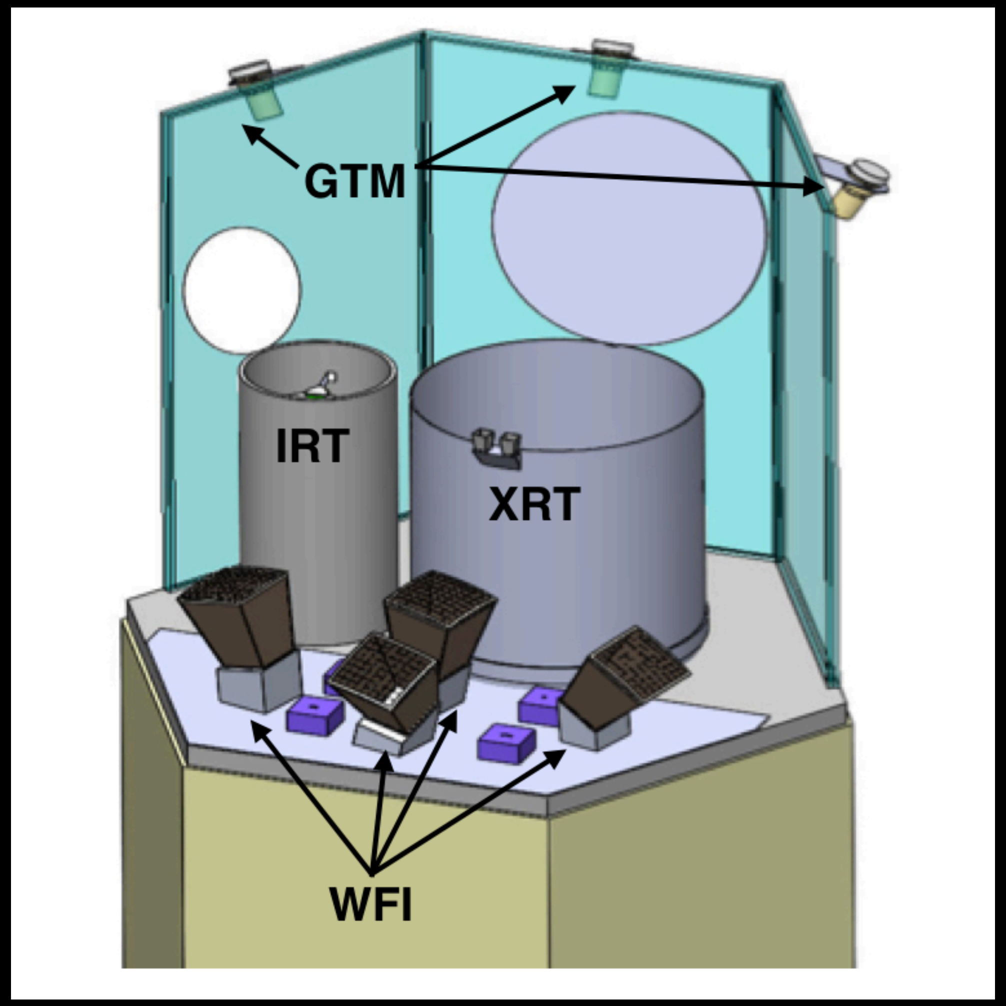


Theseus

Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2’

XGIS: 2 keV - 10 MeV with FoV >2 sr with < 15’ GRB localization

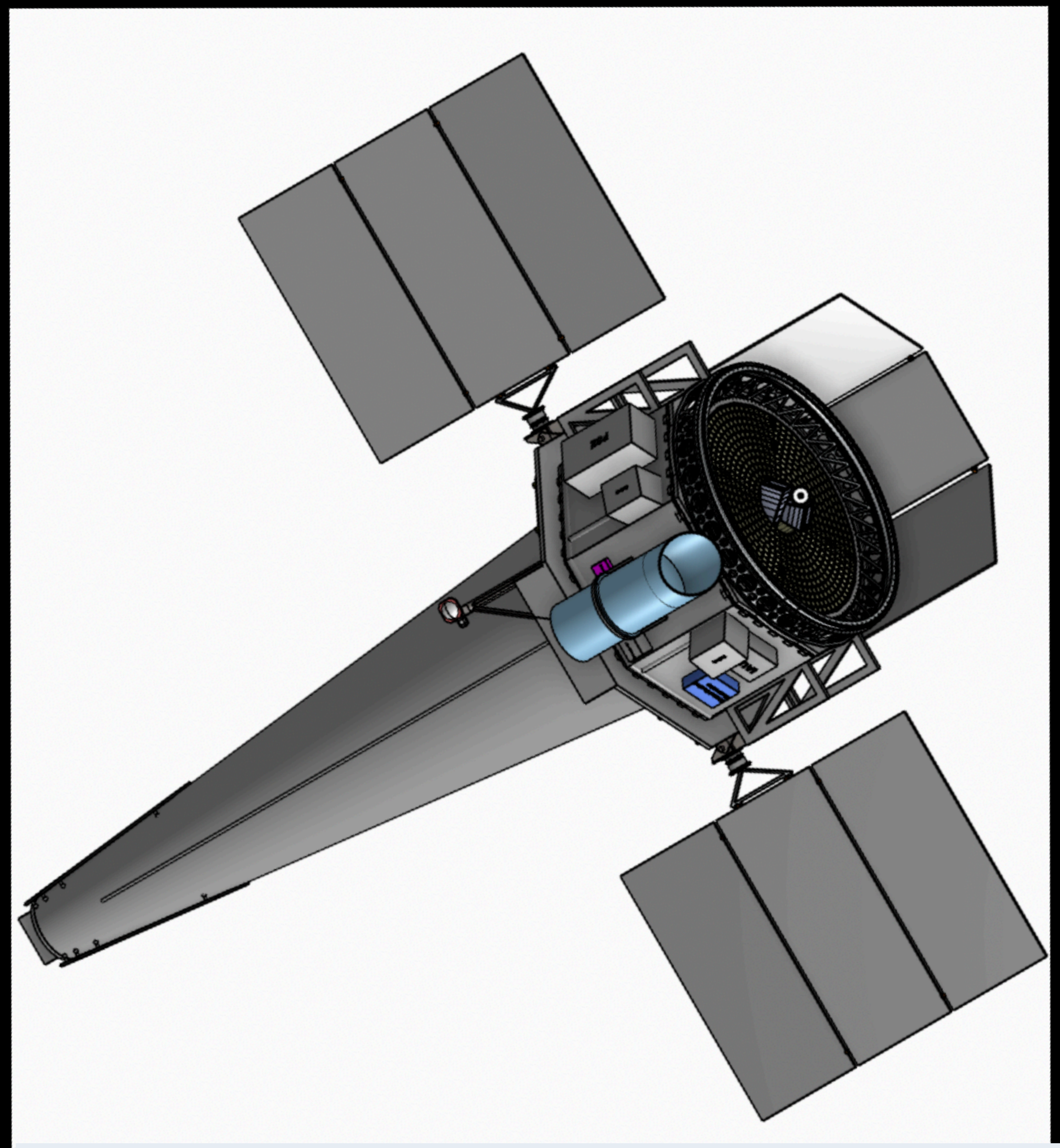
Not selected yet



TAP (NASA)

Instrument Properties

Parameter	WFI	XRT
Quantity	4-6	1
FoV	N x 19°x19° (0.5 sr)	1° diameter
Aperture Diameter	n/a	130 cm; fl=500 cm
PSF/FWHM	8 arcmin	3 arcsec
Energy Range	0.3 - 5 keV	0.5-6 keV
Sensitivity	10^{-11} erg cm^2 s^{-1} (2ks)	2x10^{-15} erg cm^2 s^{-1} (2ks)

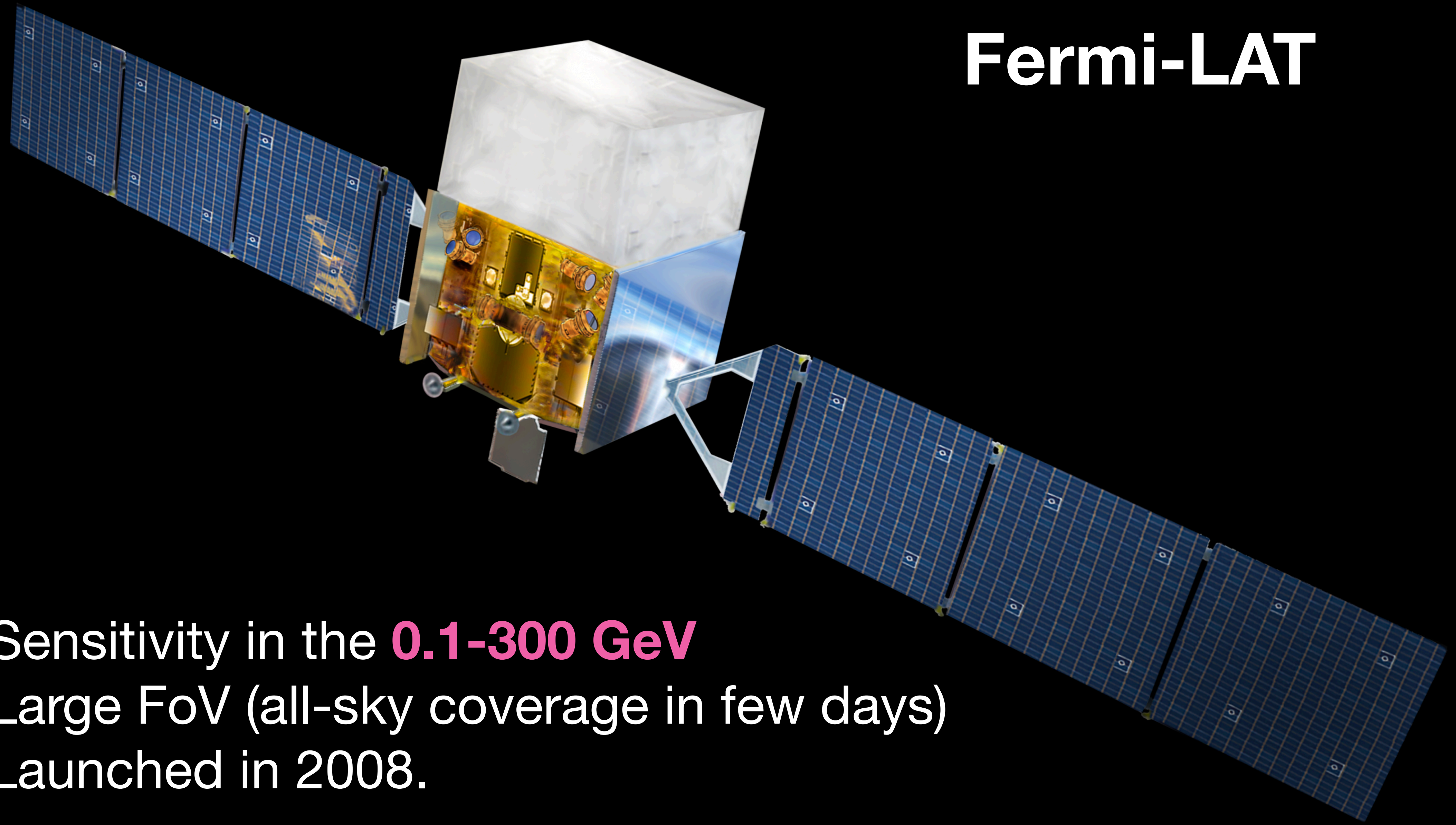


STAR-X (NASA)

W. Zhang (NASA)

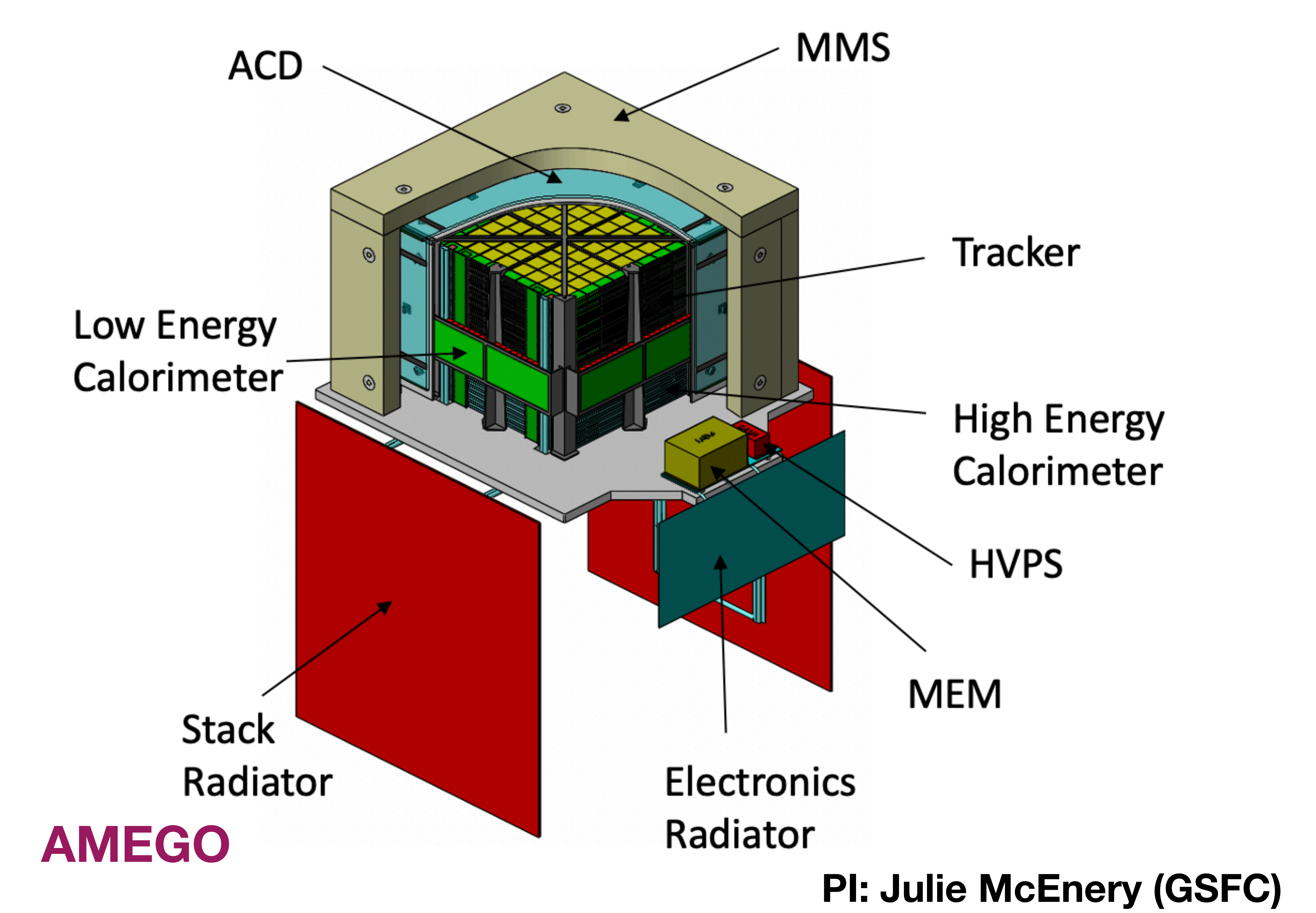
	X-ray Telescope (XRT)	UV Telescope (UVT)
PSF	2.5” on-axis 10” 0.5º off-axis	4.5”
FOV	1 deg^2	1 deg^2
Band width	0.5 – 5 keV	160 – 350 nm
Effective Areas	@1keV: 1,800 cm^2 on-axis 900 cm^2 0.5º off-axis	7 different filters: 25 - 55 cm^2
TOO Response	~60 minutes	
Field of Regard	80% of the sky every 90 minutes	

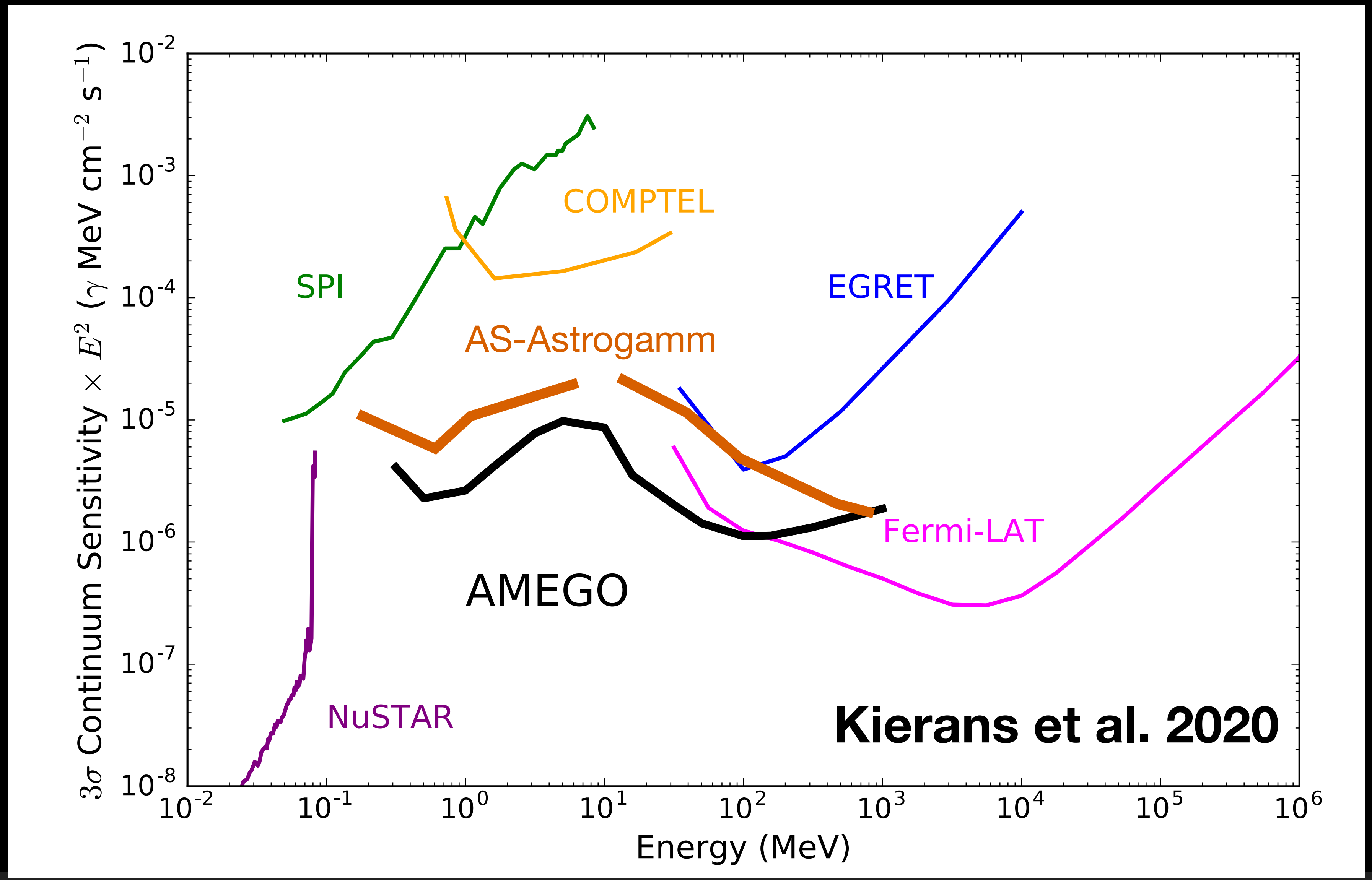
MEV-GEV COVERAGE



Fermi-LAT

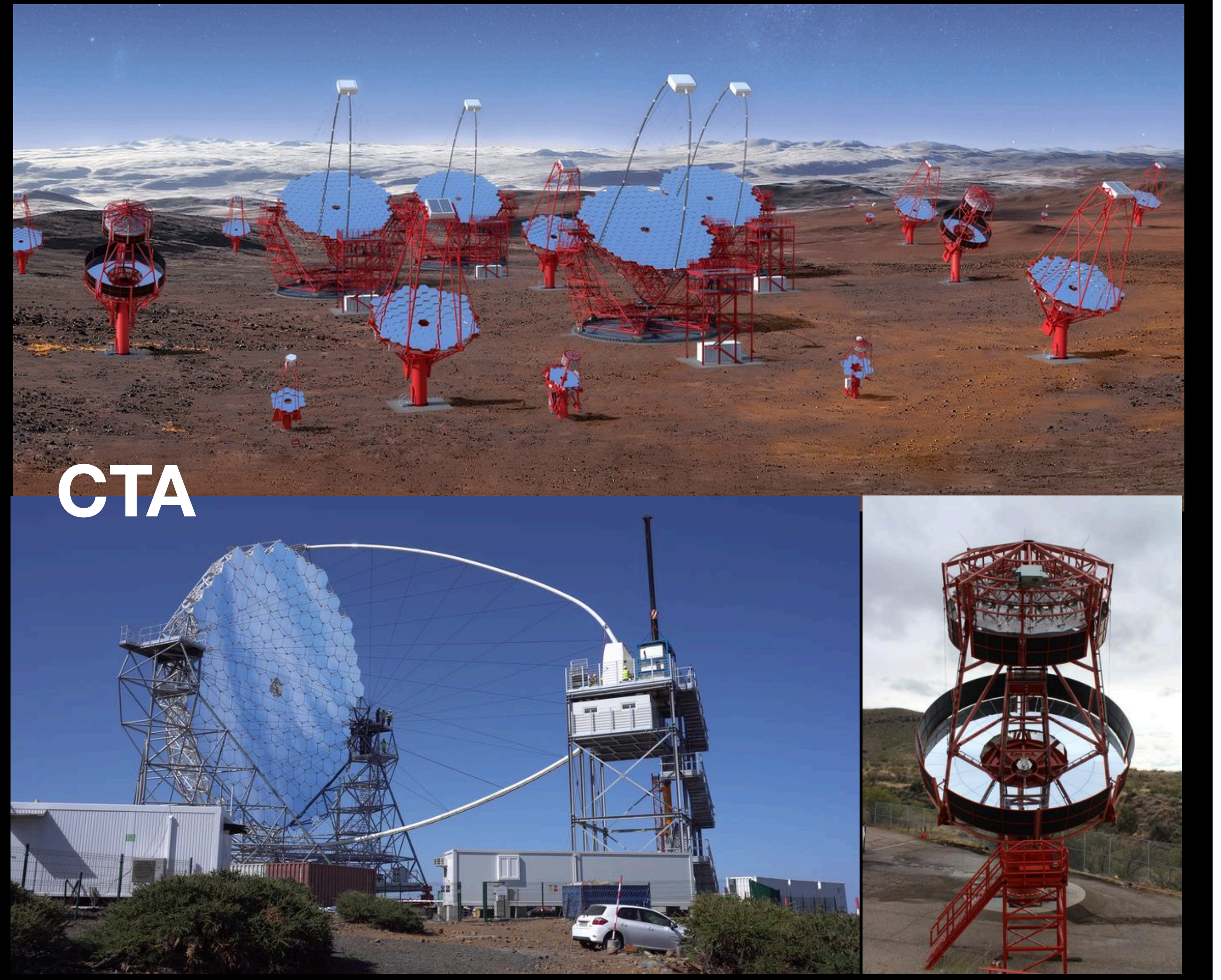
Sensitivity in the 0.1-300 GeV
Large FoV (all-sky coverage in few days)
Launched in 2008.

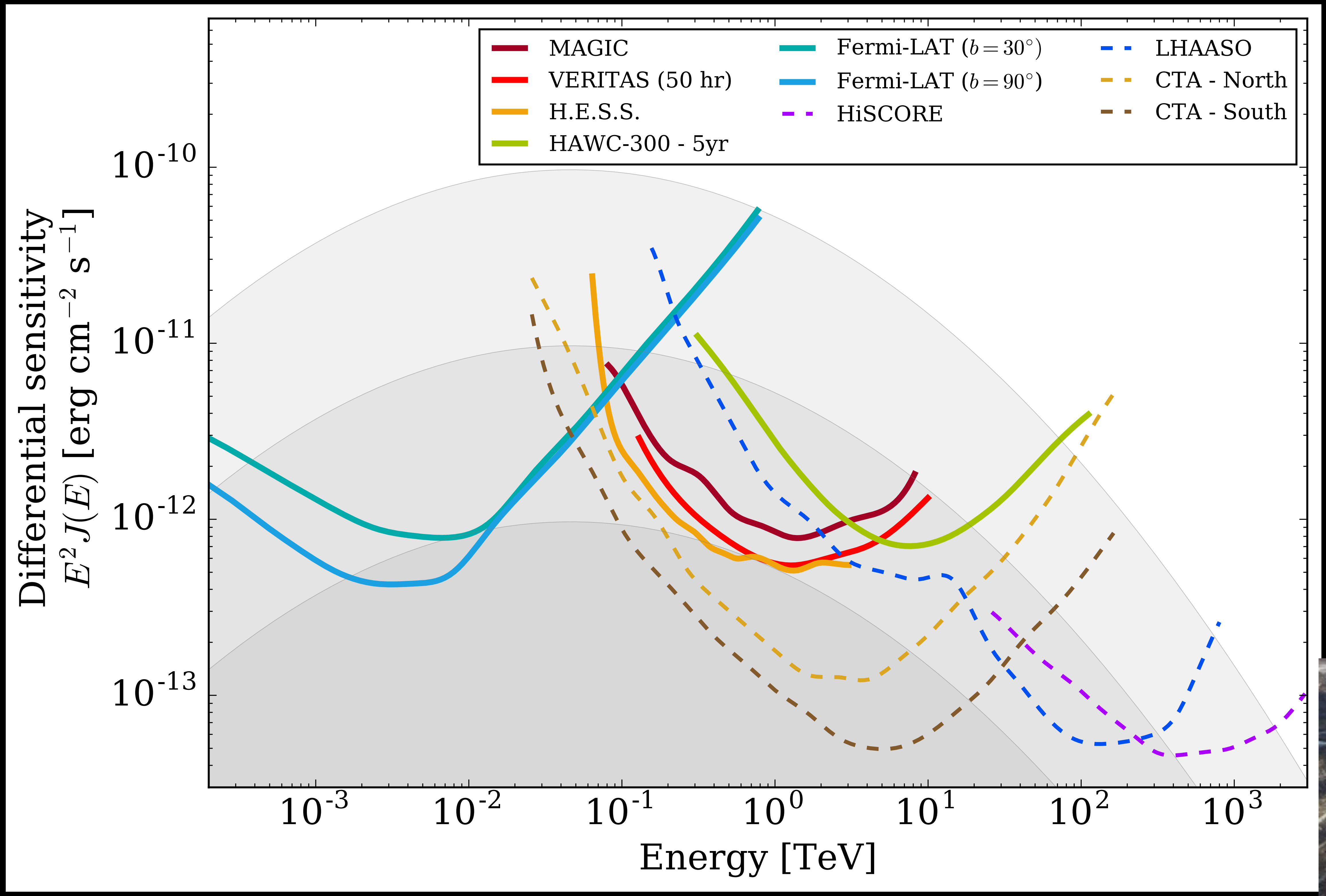


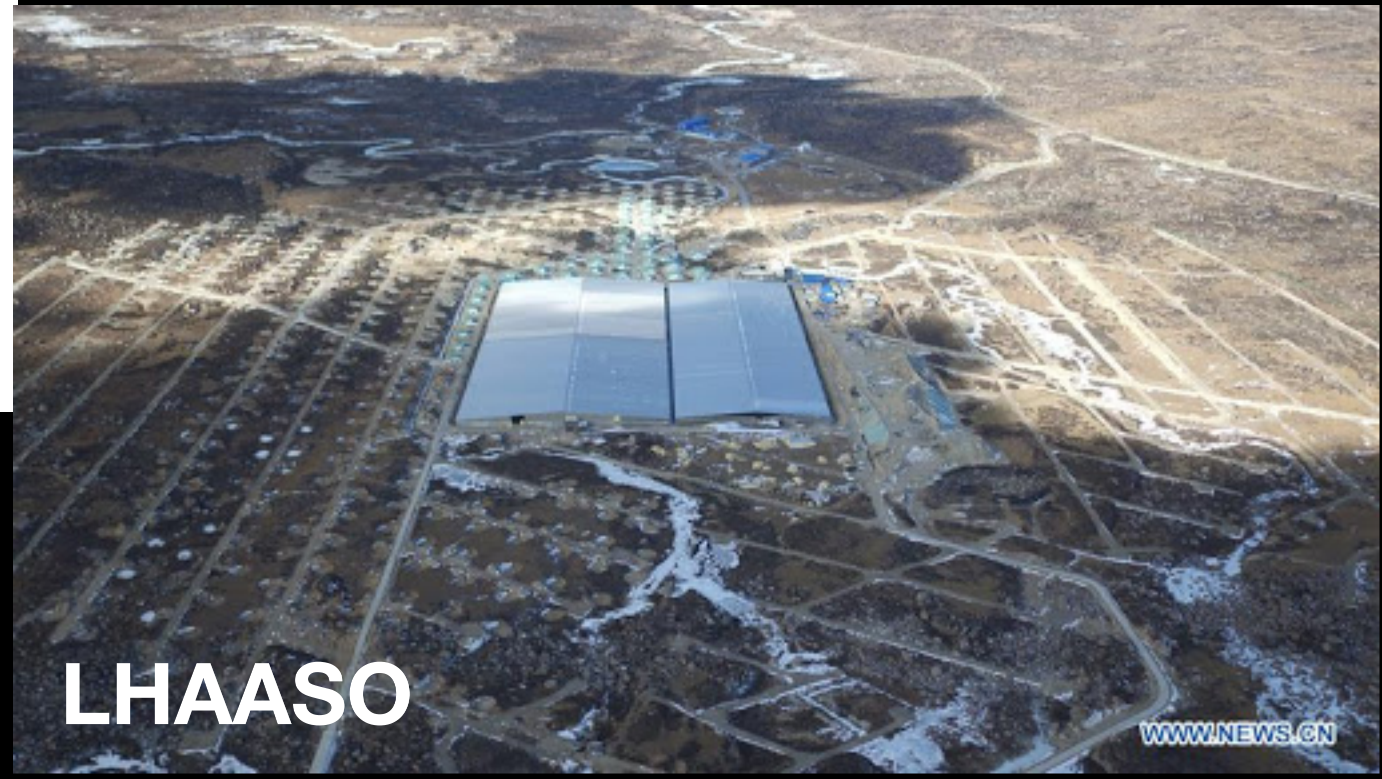


- AMEGO angular resolution: 3° (1 MeV), 10° (10 MeV)
- AMEGO prototype (**ComPair**) to be tested in 2021, balloon flight in 2022.
- Explorer mission (**AMEGO-X**) in development for MidEx AO. 2.5 sr FoV. 0.3-1 GeV.
- European MeV effort concentrated on **All-Sky-Astrogamm** mission study.

VHE COVERAGE







SWGO in the Southern Hemisphere

- CTA to provide a x10 improvement in sensivity in the VHE band (>50 GeV). Prototypes telescopes already detecting sources, observations to start in ~2025.
- Neutrino follow-ups and strong AGN science program for CTA.
- Air shower arrays (HAWC, LHAASO, proposed SWGO) provide large FoV coverage with high duty cycle although with a higher threshold.

COMMUNICATION INFRASTRUCTURE

GODDARD SPACE FLIGHT CENTER

GCN Help/FAQ
GCN What's New
NASA Homepage

SEARCH NASA

GCN HOME | ABOUT GCN | BURST/TRANS INFORMATION | MEMBERSHIP | ARCHIVES | SEARCH GCN FOR BURSTS

GCN: The Gamma-ray Coordinates Network (TAN: Transient Astronomy Network)

14 Feb 2022: There was trouble in printing and processing of Circular #31590.

27 Dec 2021: Earlier today an acciedent in processing caused some old email Notices to be resent. There were 3 intervals of old Notices from short windows of time: Oct 23, Nov 01, and Dec 04, 2021. They were correct Notices of their time and content, but just retransmitted (duration of ~1 hour between 06:40 to 07:40 UT today). This occurred for only those recpients that use the email method. We apologize for the confusion that occurred.

03 Nov 2021: The Time-domain Astronomy Coordination Hub (TACH) project is pleased to announce a new community tool to access the archive of GCN Notices and Circulars. The GCN Viewer ingests new notices and circulars in real time, and associates events detected by multiple facilities, providing useful categorization and searchability. This first public release of the GCN Viewer provides this functionality, and new features will be added with forthcoming releases. The new TACH archive of the GCN Notices & Circulars is accesible through the GCN Viewer at https://heasarc.gsfc.nasa.gov/tachgcn

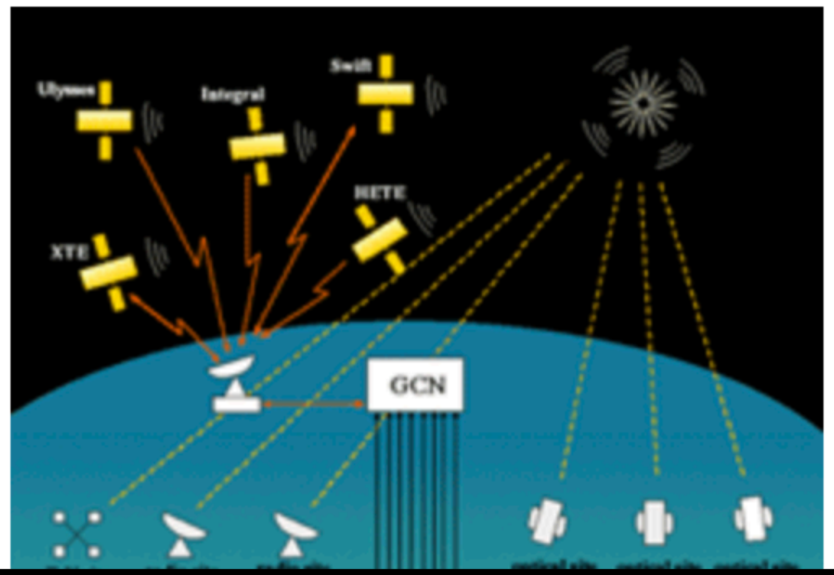
Posted 23 Mar 2020 (last updated 18 Oct 20):
Due to the policies and constraints during the CoronaVirus pandemic,
my response to your requests and questions may not be as fast as normal.
Example: changes to your site_configuration may take up to 7 days (instead of the usual 2-4 days).
Being at home teleworking, requires making the site_config file change a remote operation instead of the normal on-site operation.
Which is doable, but I try to keep that method to a minimum. I will wait longer to do the file change
or I will use a weekly 4-hr pass to do work on-site.

The GCN system distributes:

1. **Locations of GRBs and other Transients (the Notices)** detected by spacecraft (most in real-time while the burst is still bursting and others are that delayed due to telemetry down-link delays).
2. **Reports of follow-up observations (the Circulars)** made by ground-based and space-based optical, radio, X-ray, TeV, and other particle observers.

These two functions provide a one-stop shopping network for follow-up sites and GRB and transient researchers.

The GCN system can be explored using the links above and below.

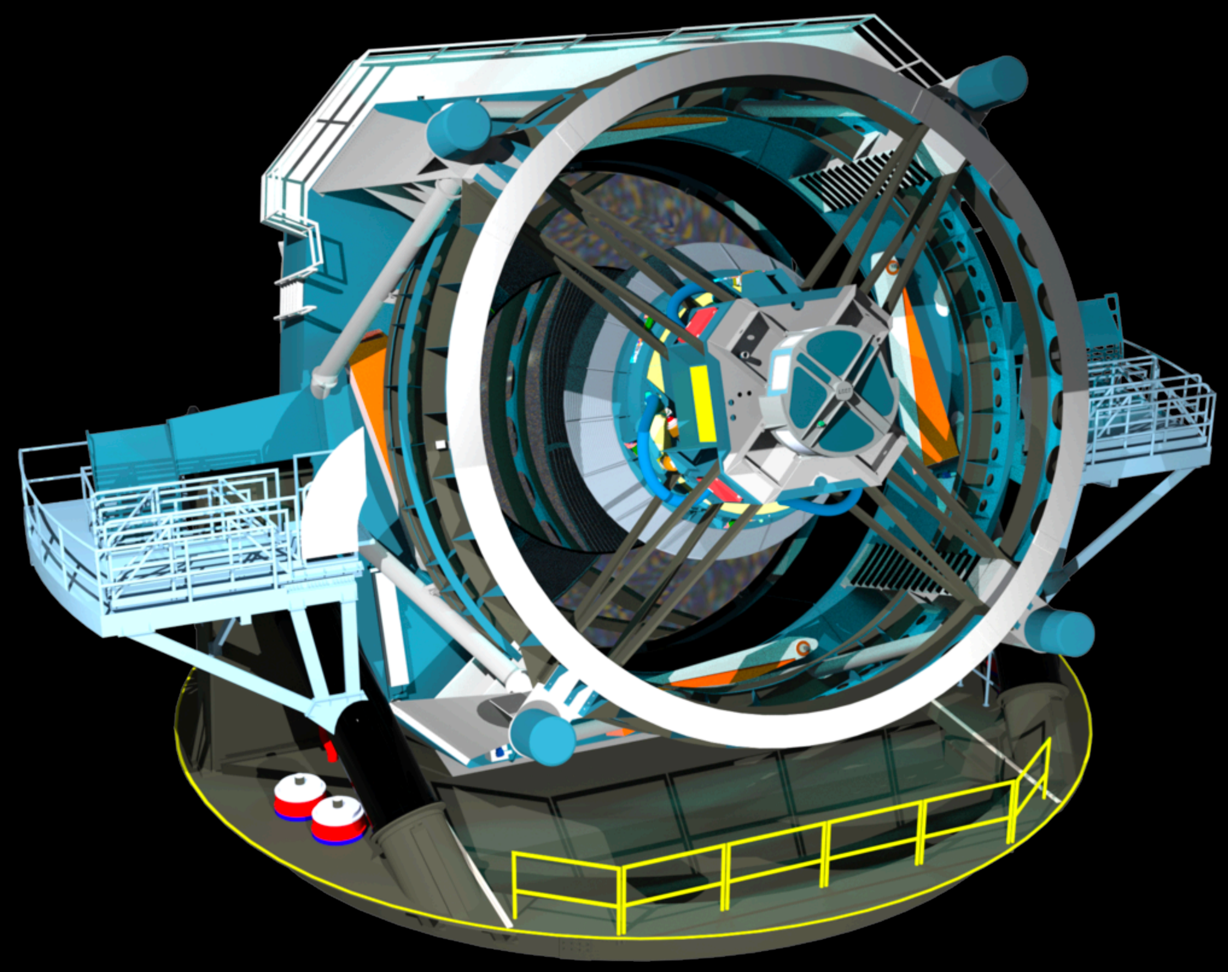


https://gcn.gsfc.nasa.gov/

- Current infrastructure relies largely on the NASA gamma-ray coordinates network.
- GCN notices and free-text circulars.
- Challenging for high alert rates, interpretation.
- Other networks (AMON) target multimessenger triggers.

```
TITLE:   GCN CIRCULAR
NUMBER:  31839
SUBJECT: IceCube-220405A - IceCube observation of a high-energy neutrino candidate track-like event
DATE:    22/04/06 02:12:43 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@umd.edu>

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

On 2022-04-05 at 22:20:03.41 UT IceCube detected a track-like event with a moderate probability of
being of astrophysical origin. The event was selected by the ICECUBE_Astrotrack_Bronze alert stream.
The average astrophysical neutrino purity for Bronze alerts is 30%. This alert has an estimated false
alarm rate of 2.02 events per year due to atmospheric backgrounds. The IceCube detector was in a
normal operating state at the time of detection.

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon_g_b/136506_15341152.amon),
more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2022-04-05
Time:  22:20:03.41 UT
RA: 320.62 (+1.37, -1.13 deg  90% PSF containment) J2000
Dec: 29.06 (+0.94, -0.68 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical
source for the candidate neutrino.

There are no sources in the  4FGL-DR2 Fermi-LAT catalog in the 90% uncertainty region.  The nearest
source is 4FGL J2115.4+2932 (318.87 deg, 29.55 deg J2000, 1.82 deg away from the best-fit neutrino
position).

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
```

ALERT BROKERS



- Current push largely driven by the needs of the Vera Rubin Observatory (millions of transients **per night**)

ANTARES

FINK

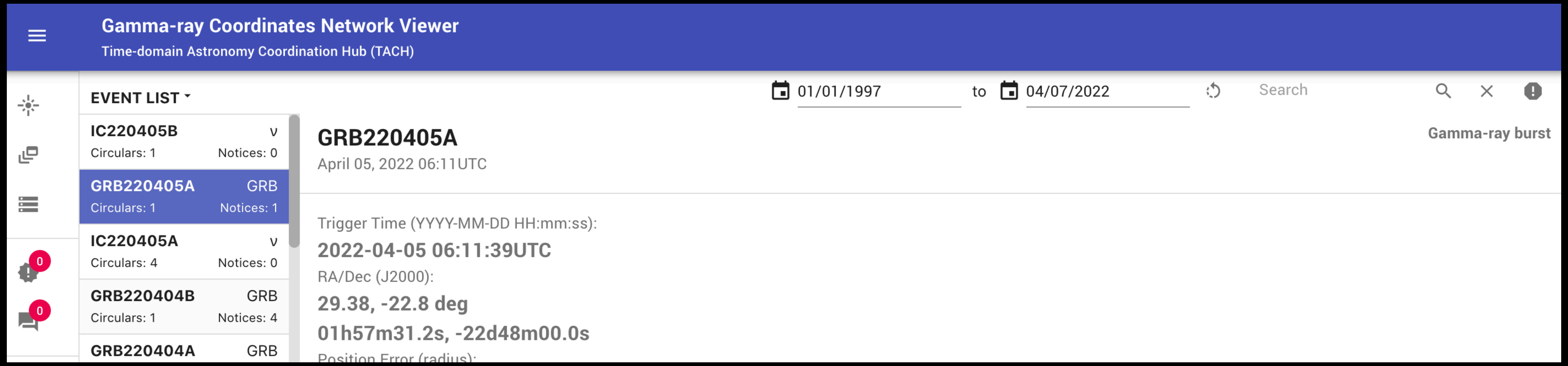
ALeRCE Automatic Learning for the Rapid Classification of Events

AMPEL

LASAIR

- Some efforts are targeted specifically for MMA alerts. Upgrades to GCN (TACH)

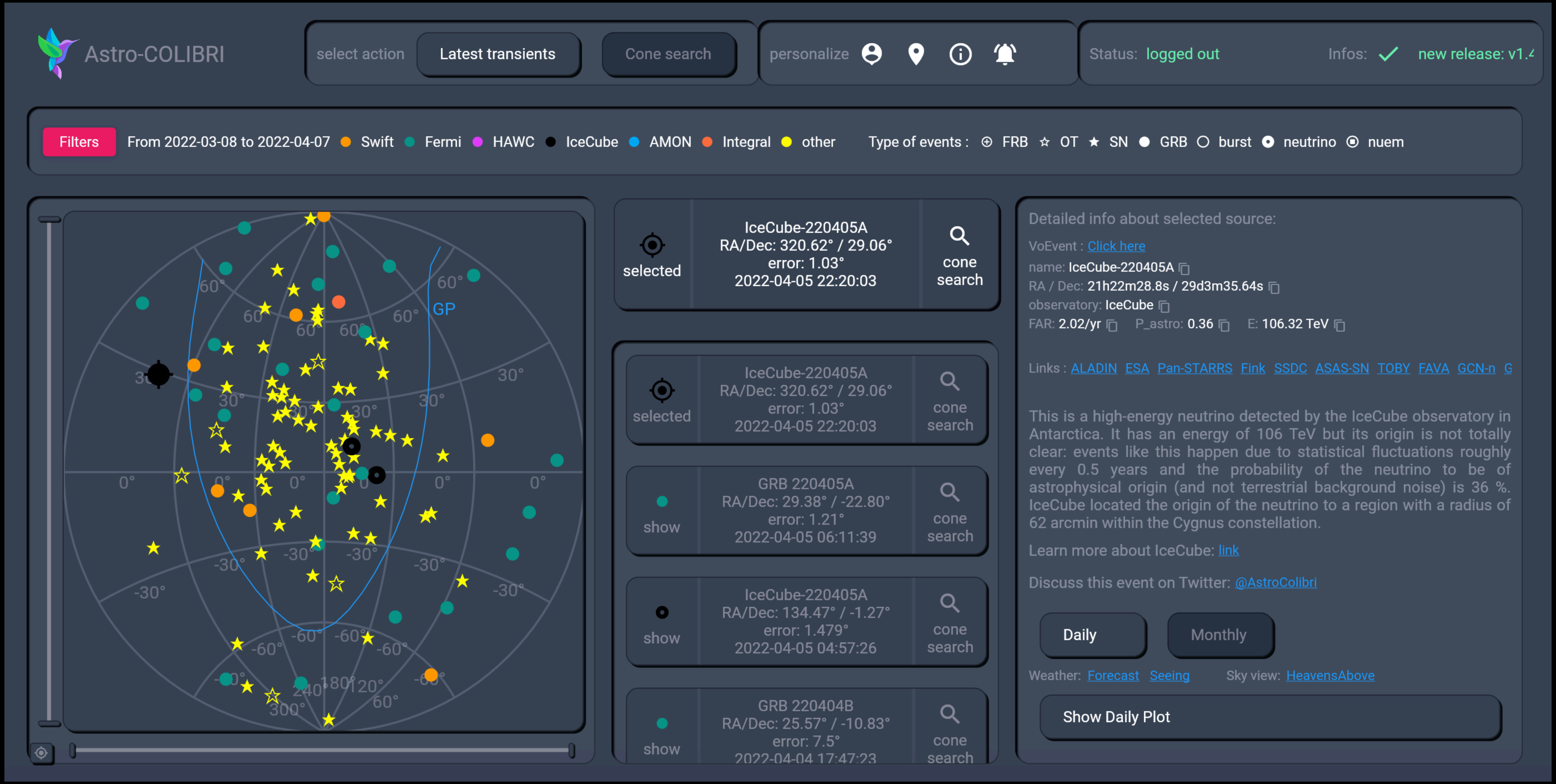
Hopskotch



https://heasarc.gsfc.nasa.gov/wsgi-scripts/tach/gcn_v2/tach.wsgi/

ASTRO-COLIBRI

https://astro-colibri.com/



- **Associated phone app!**

SUMMARY

- Exciting time for observational multimessenger astrophysics:
  - First GW+EM source unambiguously identified
  - Evidence for the first multimessenger sources of EM + TeV neutrinos
- Still in the early discovery phase. Main goal is identifying additional sources!
- Main requirements are improved angular resolution and sensitivities, broad EM spectral coverage.
- Improvements in communication infrastructure are a must given the large expected rate of multimessenger triggers.

HANDS-ON SESSION

- **We'll do three activities:**

  A. Follow-up of a GW event with an IACT.

  B. Follow-up of a neutrino event with an IACT.

  C. Searching for neutrino sources in neutrino telescope data.

- Jupyter notebooks are available here: https://github.com/jmsantander/isapp2022

- Get a copy: `git clone https://github.com/jmsantander/isapp2022.git`