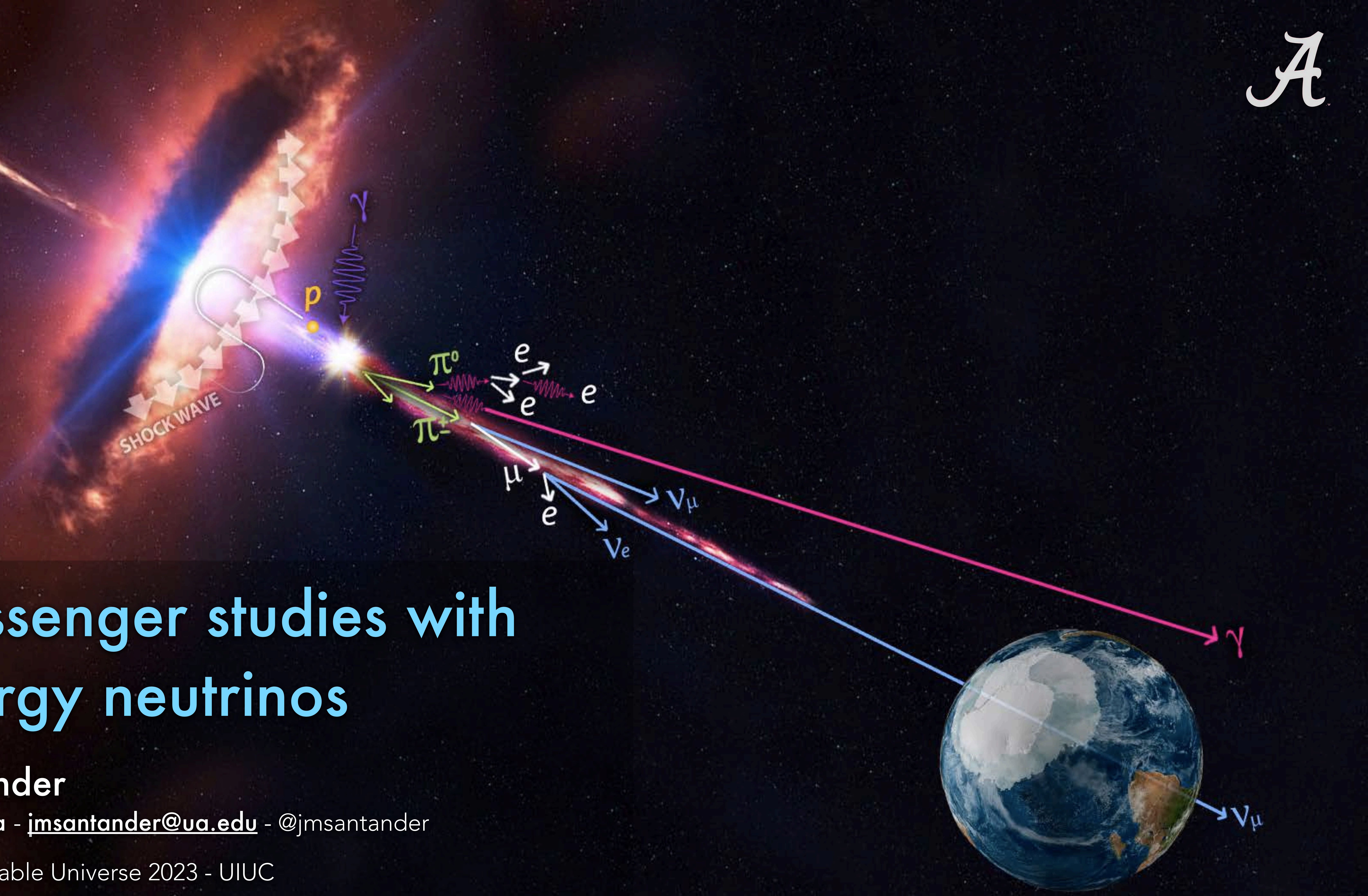
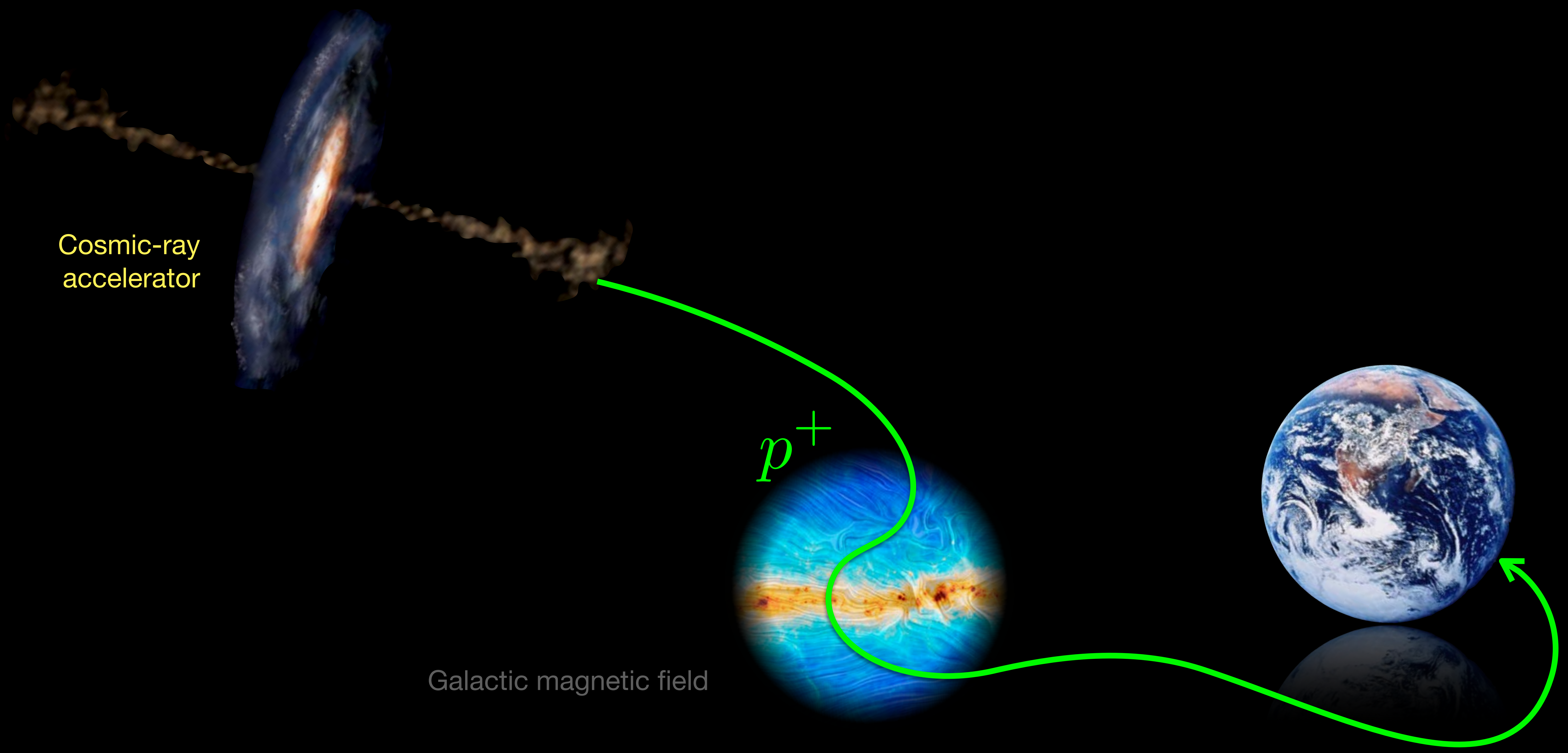


Multimessenger studies with high-energy neutrinos

Marcos Santander
University of Alabama - jmsantander@ua.edu - @jmsantander

The Transient and Variable Universe 2023 - UIUC

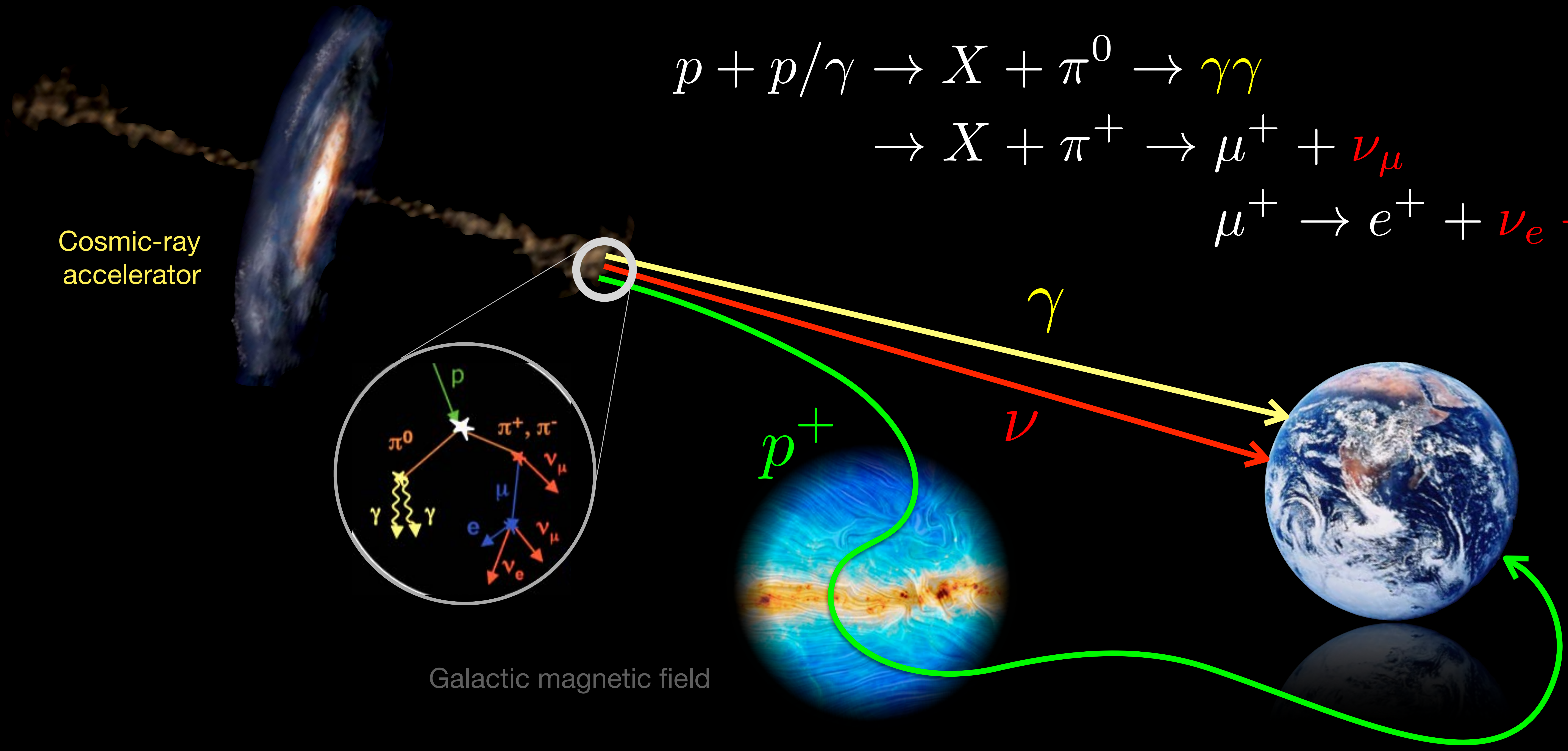
SEARCHING FOR HADRONIC SOURCES



- **Multiple timescales**, from seconds to steady emission.
- 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.

SEARCHING FOR HADRONIC SOURCES

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



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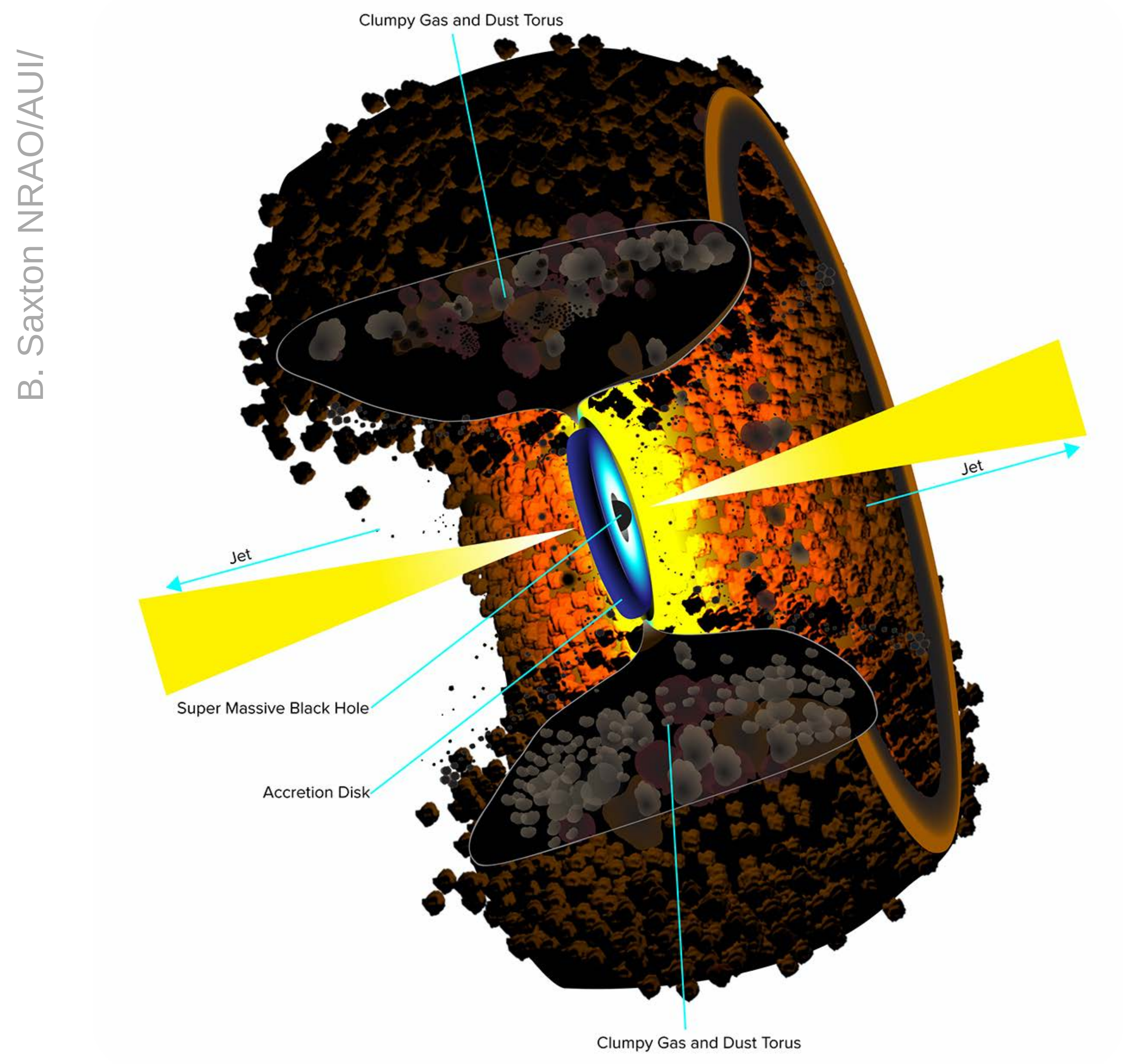
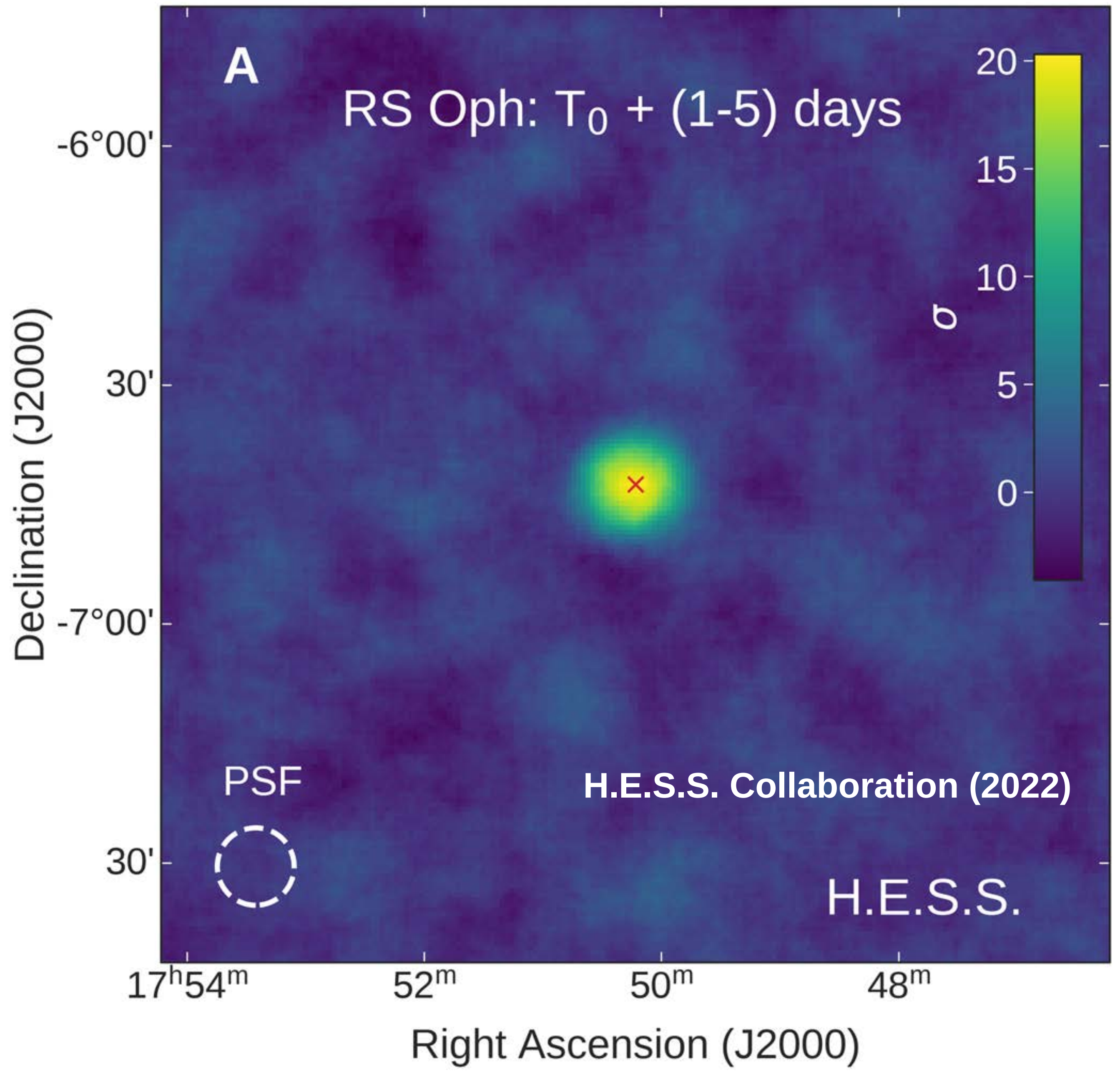
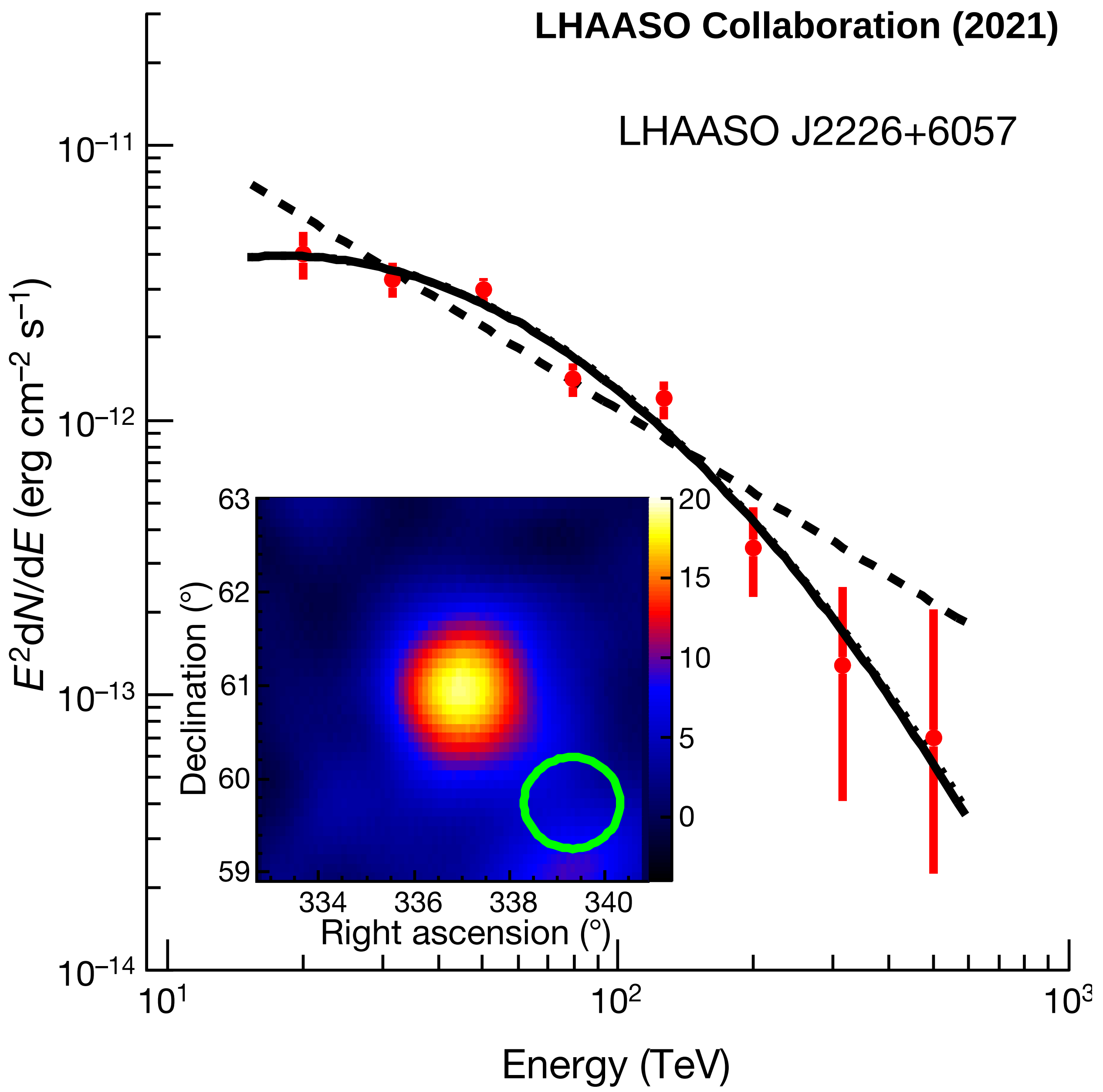
PROBING PARTICLE ACCELERATION WITH NEUTRINOS







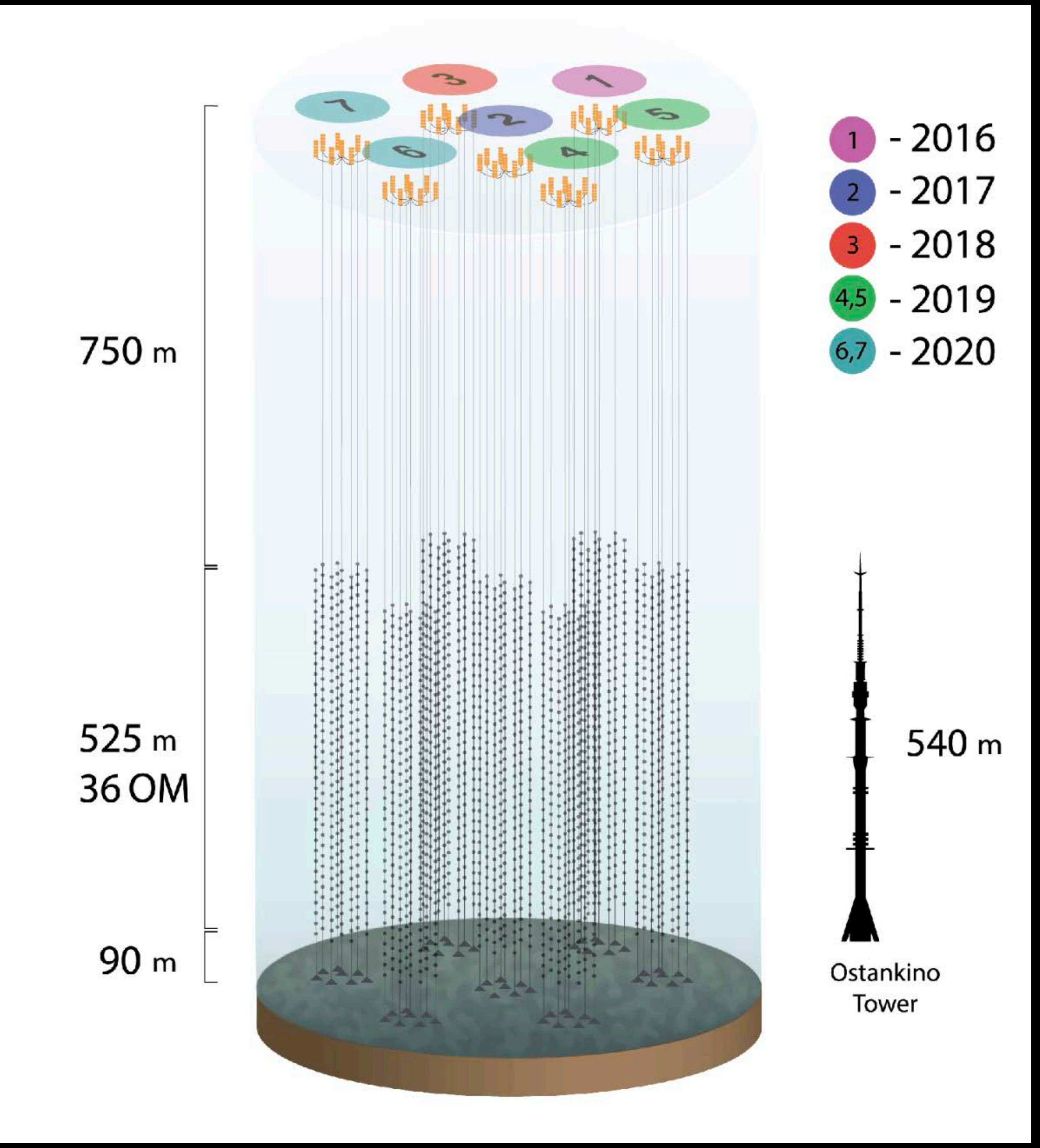
- **Active Galactic Nuclei**
  - Observed across the EM spectrum up to multi-TeV energies.
  - Origin of highest-energy emission uncertain: can be explained by leptonic and hadronic processes.
  - Origin of Ultra-High-Energy Cosmic Rays?

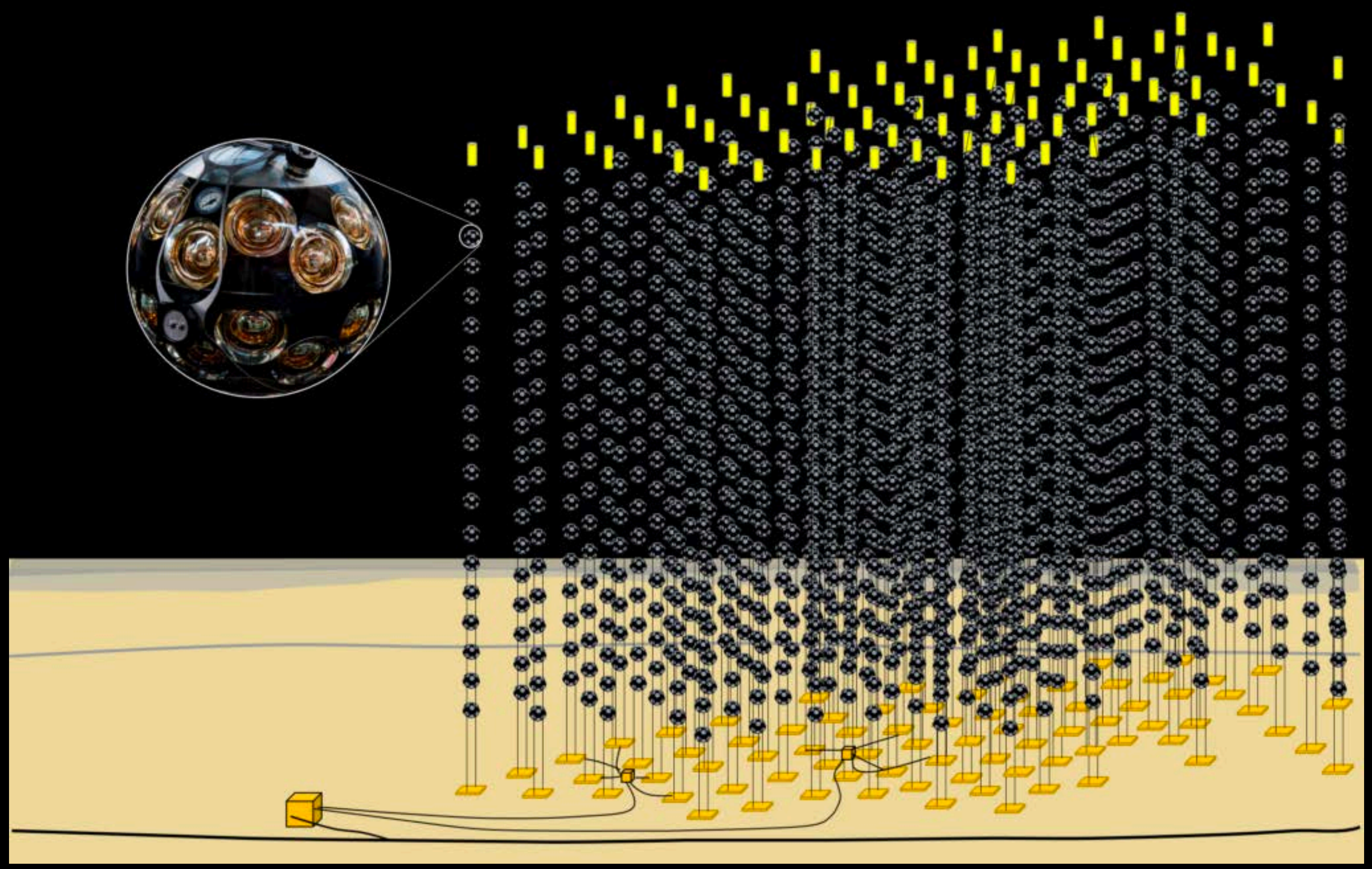
- **Galactic hadronic accelerators**
  - Signatures of hadronic emission have also been observed in transient sources such as novae.
  - Extreme energies reached by Galactic sources, up to PeV, challenging to explain in a leptonic scenario.
  - Galactic cosmic-ray origin

Neutrinos are the telltale sign of hadronic particle acceleration

CURRENT GENERATION OF NEUTRINO TELESCOPES

Future: P-ONE, South China Sea Telescope





Baikal-GVD

- Lake Baikal (Russia)
- Under construction, targeting 1 km^3
- As of 2021 ~0.5 km^3 (8 clusters of 288 sensors each)

KM3NeT

- Mediterranean Sea (Italy/France). Successor of ANTARES.
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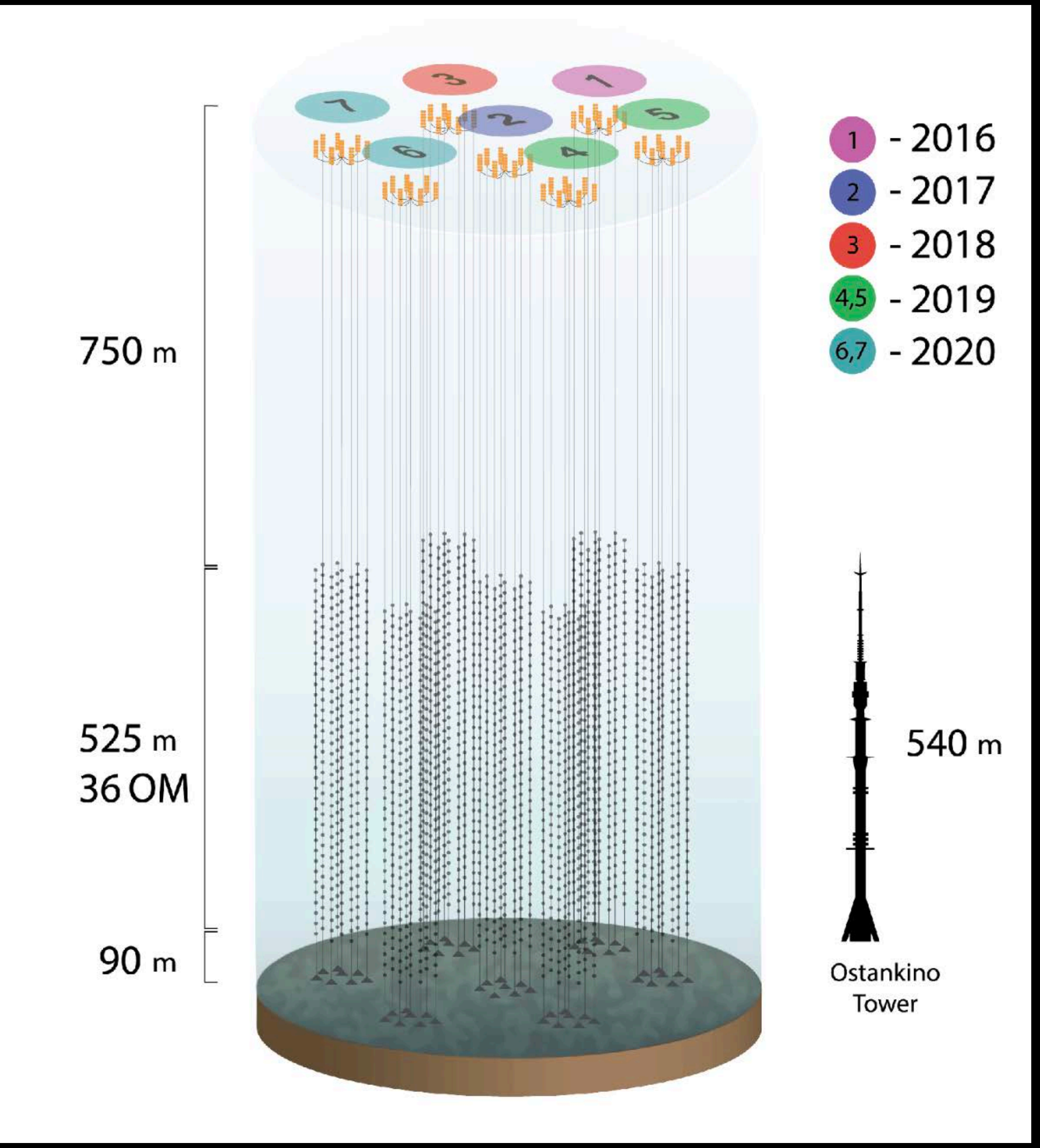

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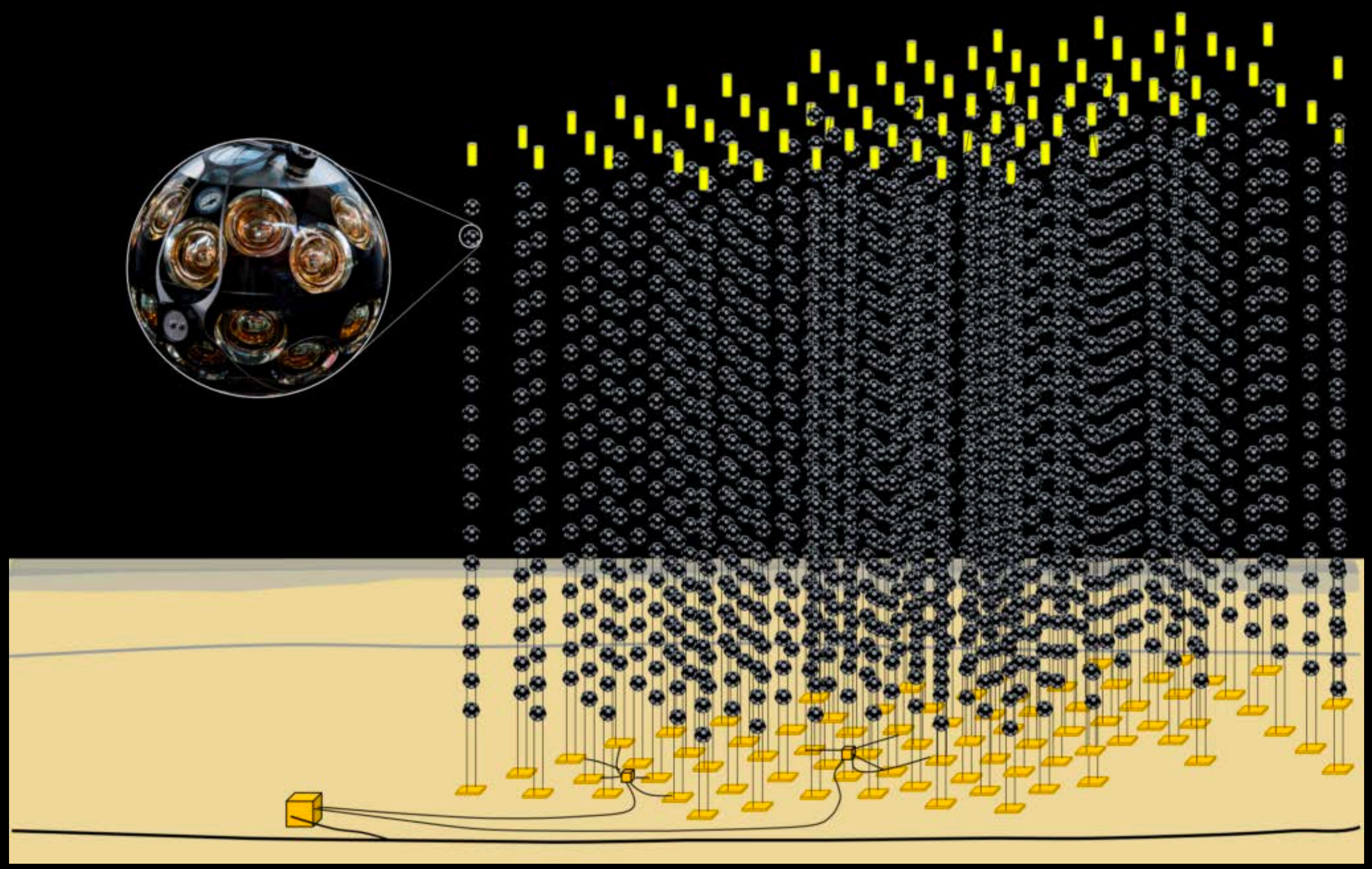

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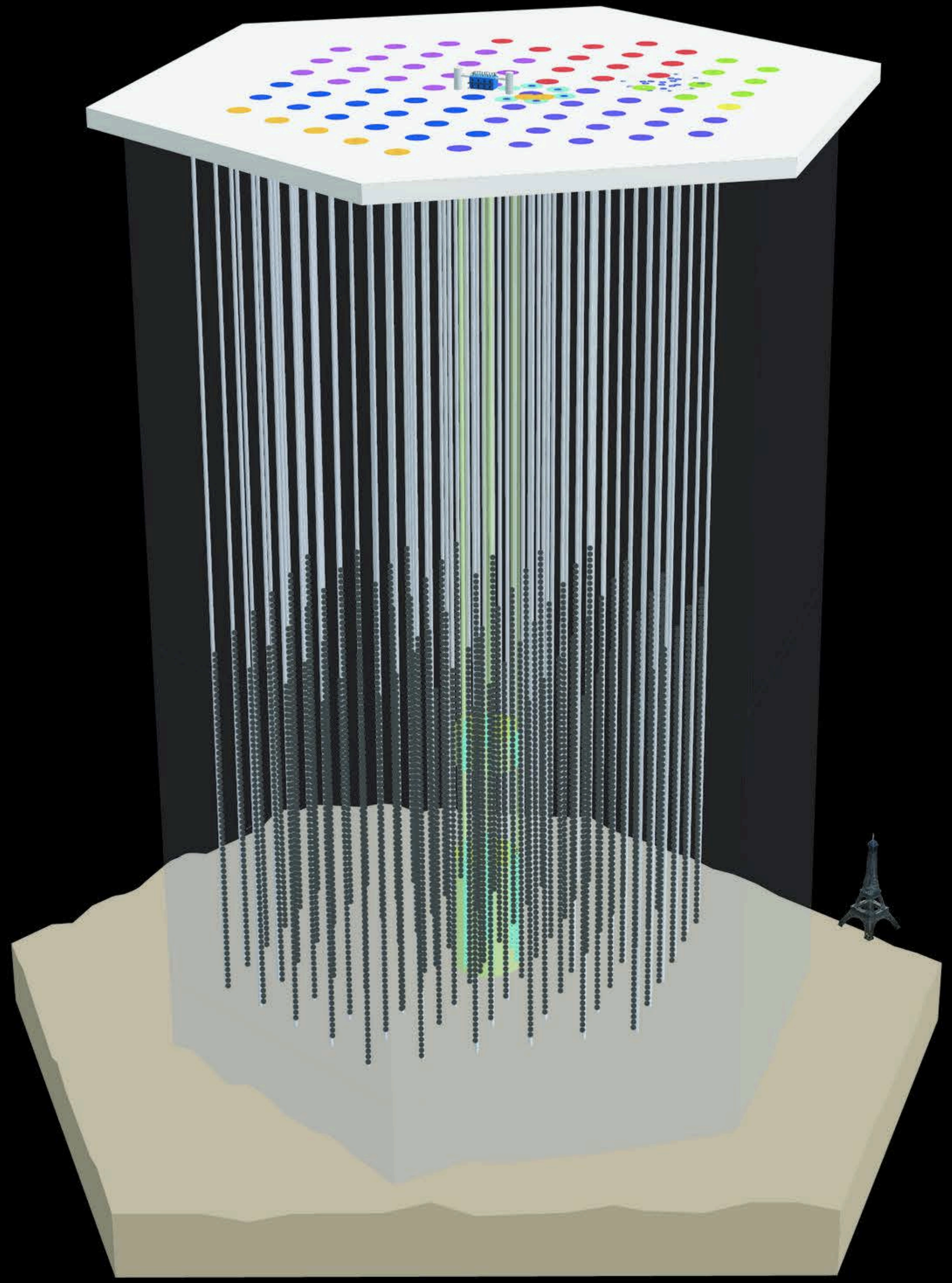
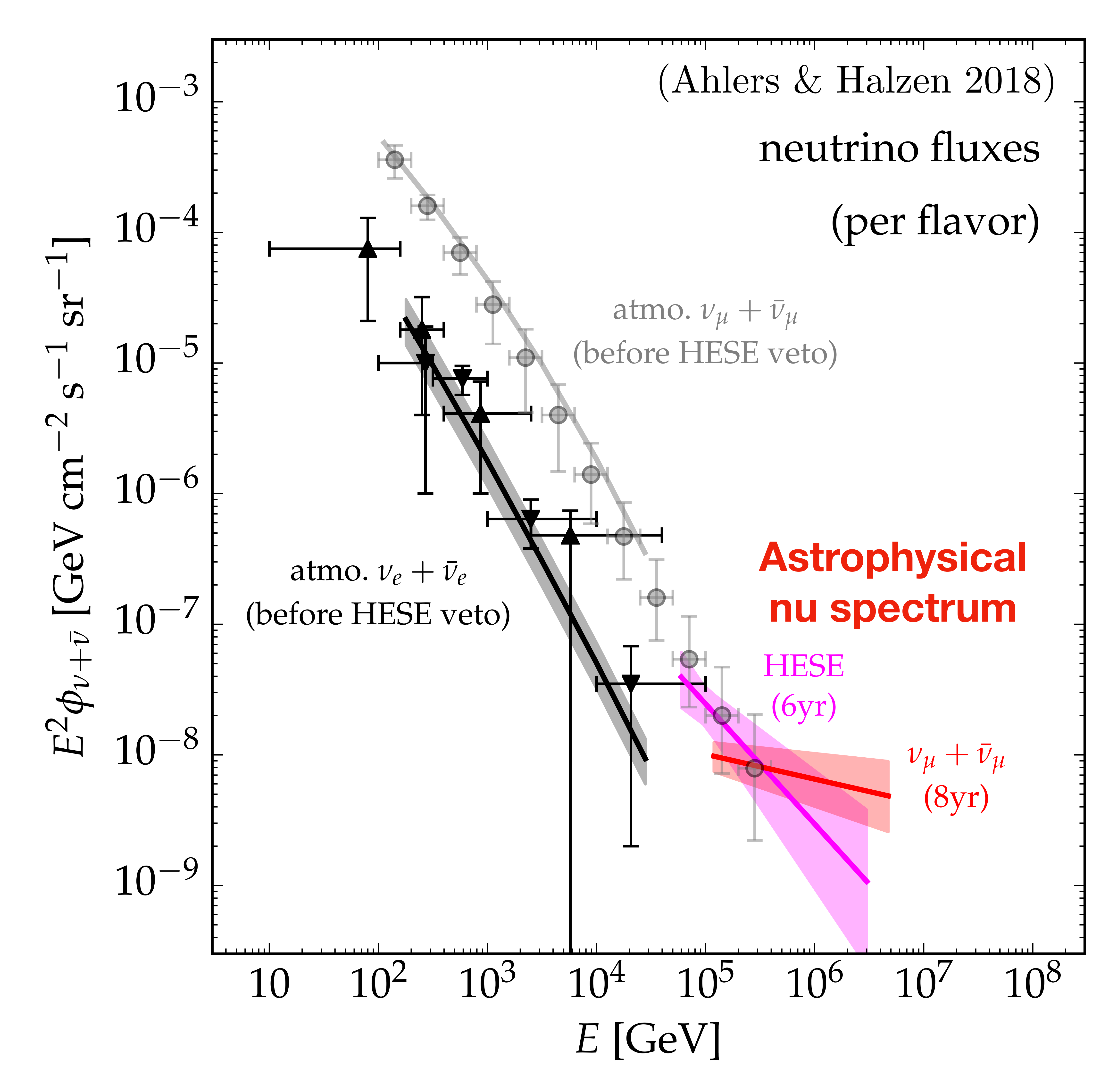


IceCube

- South Pole glacier. 2010.
- **1 km^3**
- 5160 PMTs

HIGH-ENERGY ASTROPHYSICAL NEUTRINOS

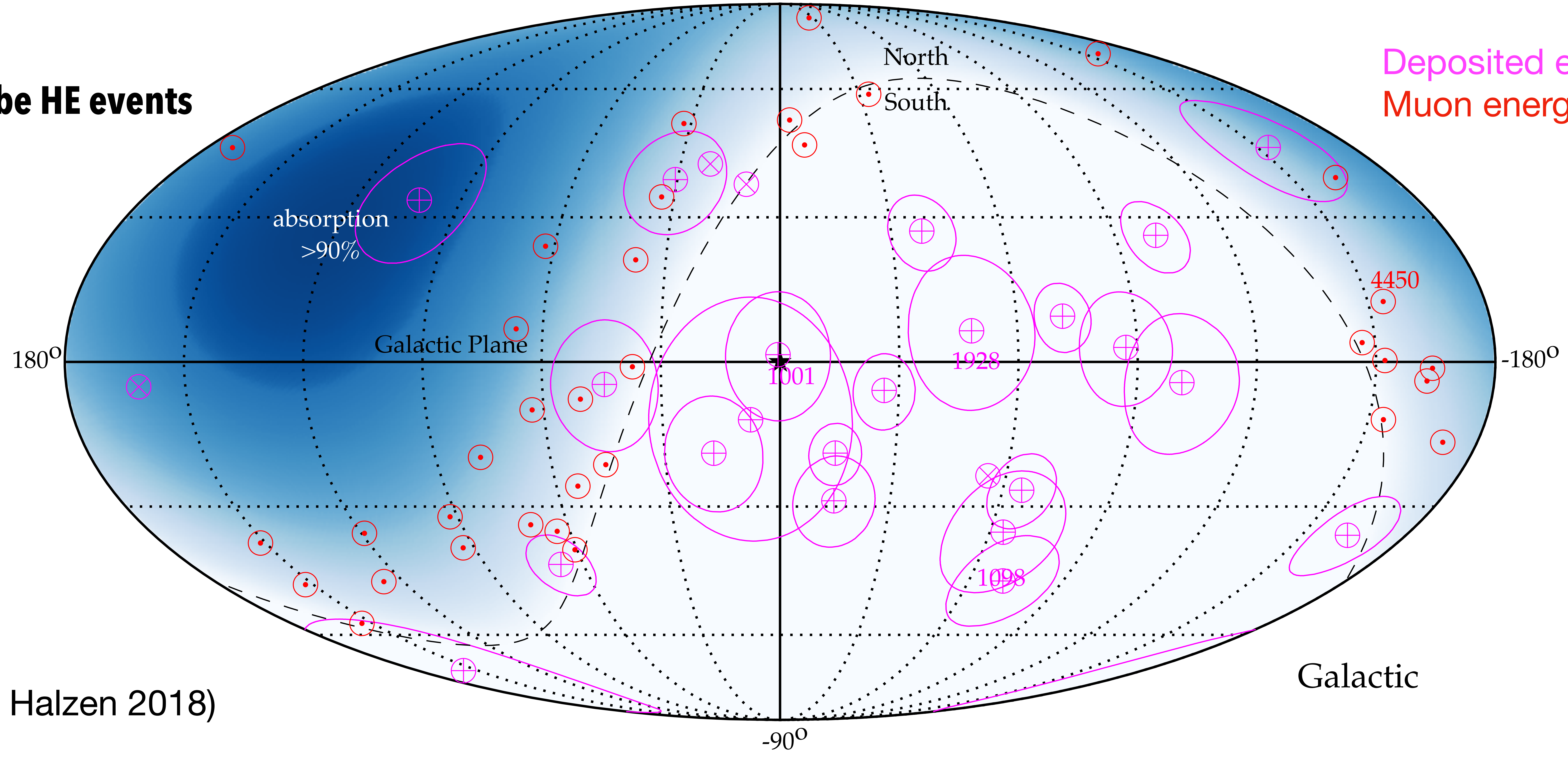


- **Astrophysical neutrino flux detected by the IceCube neutrino observatory in the 10 TeV - 10 PeV energy range.**
- Atmospheric origin excluded at >8σ.
- Flux > 200 TeV consistent with a power-law spectrum with index ~ 2.2-2.8.
- Astrophysical flux dominates above ~200 TeV.
- Baikal-GVD now sees a 3σ excess compatible with IceCube results (arXiv/2211.09447)

ASTROPHYSICAL NEUTRINOS - SKY DISTRIBUTION

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

- **IceCube HE events**



Deposited energy > 100 TeV
Muon energy > 200 TeV

(Ahlers & Halzen 2018)

- Consistent with isotropic distribution, favors **extragalactic origin**.
- No apparent correlation with Galactic plane.

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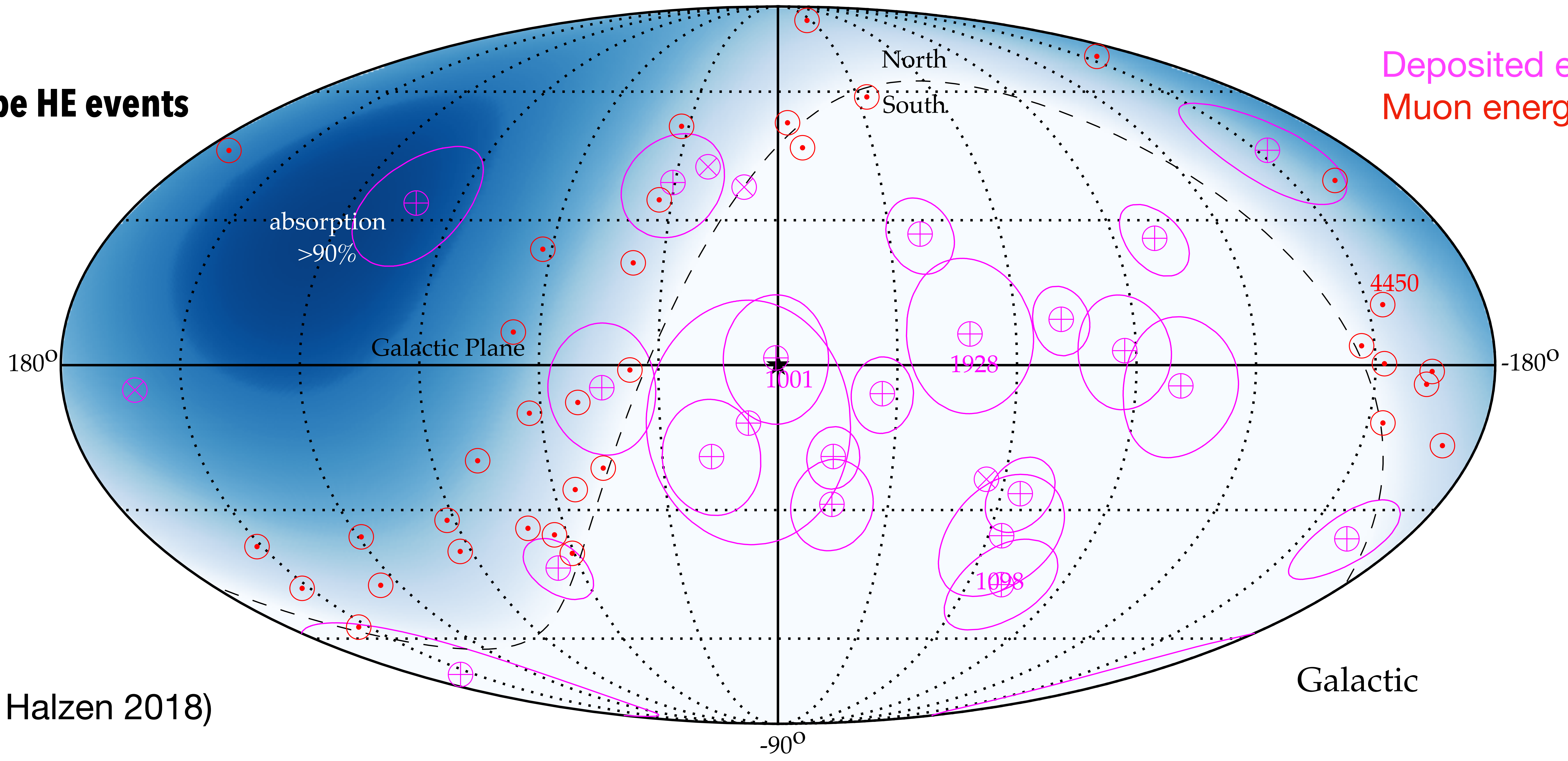

Deposited energy > 100 TeV

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(Ahlers & Halzen 2018)

- Consistent with isotropic distribution, favors **extragalactic origin**.
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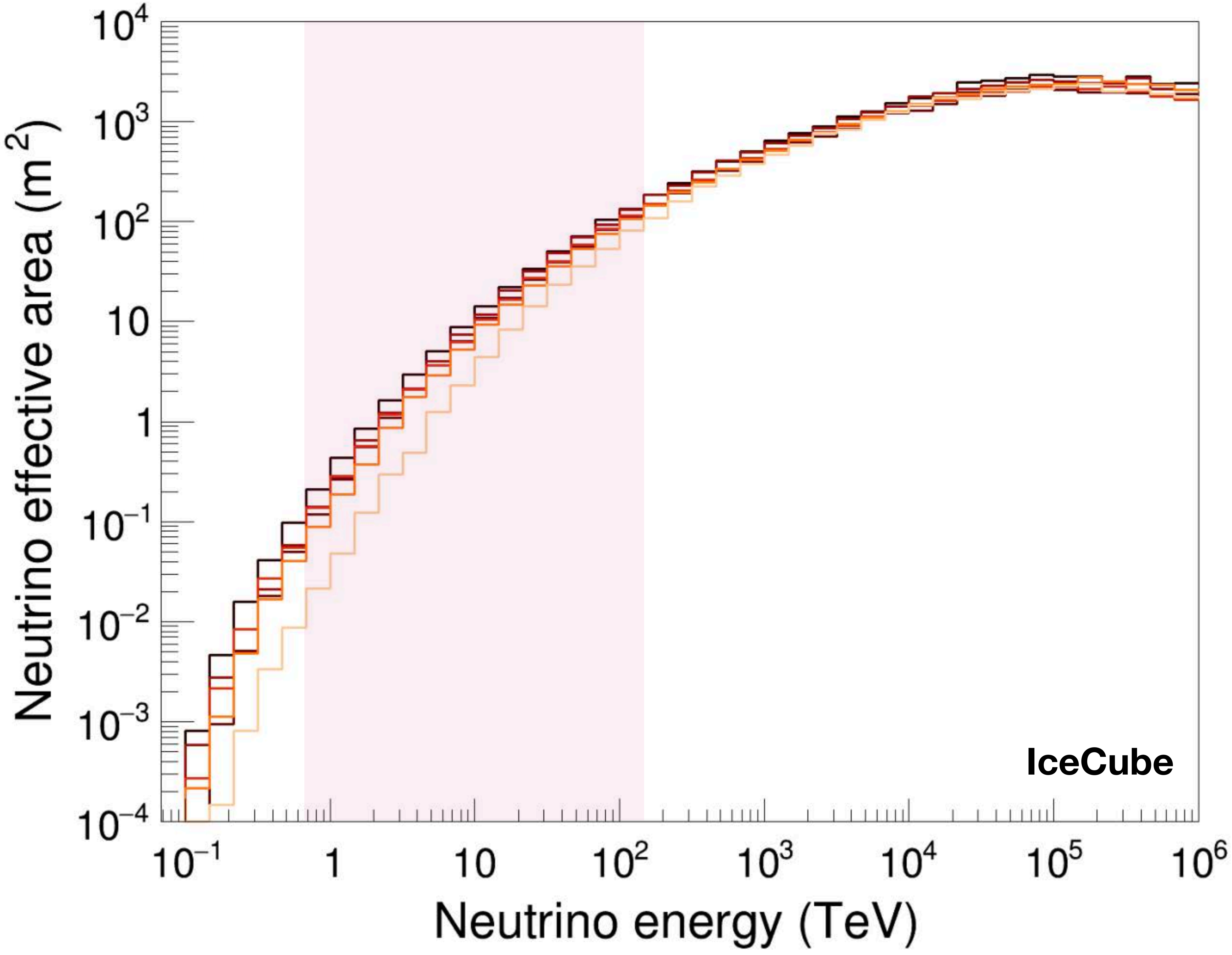
- **HE event rate is low. ~O(10) events / year.**

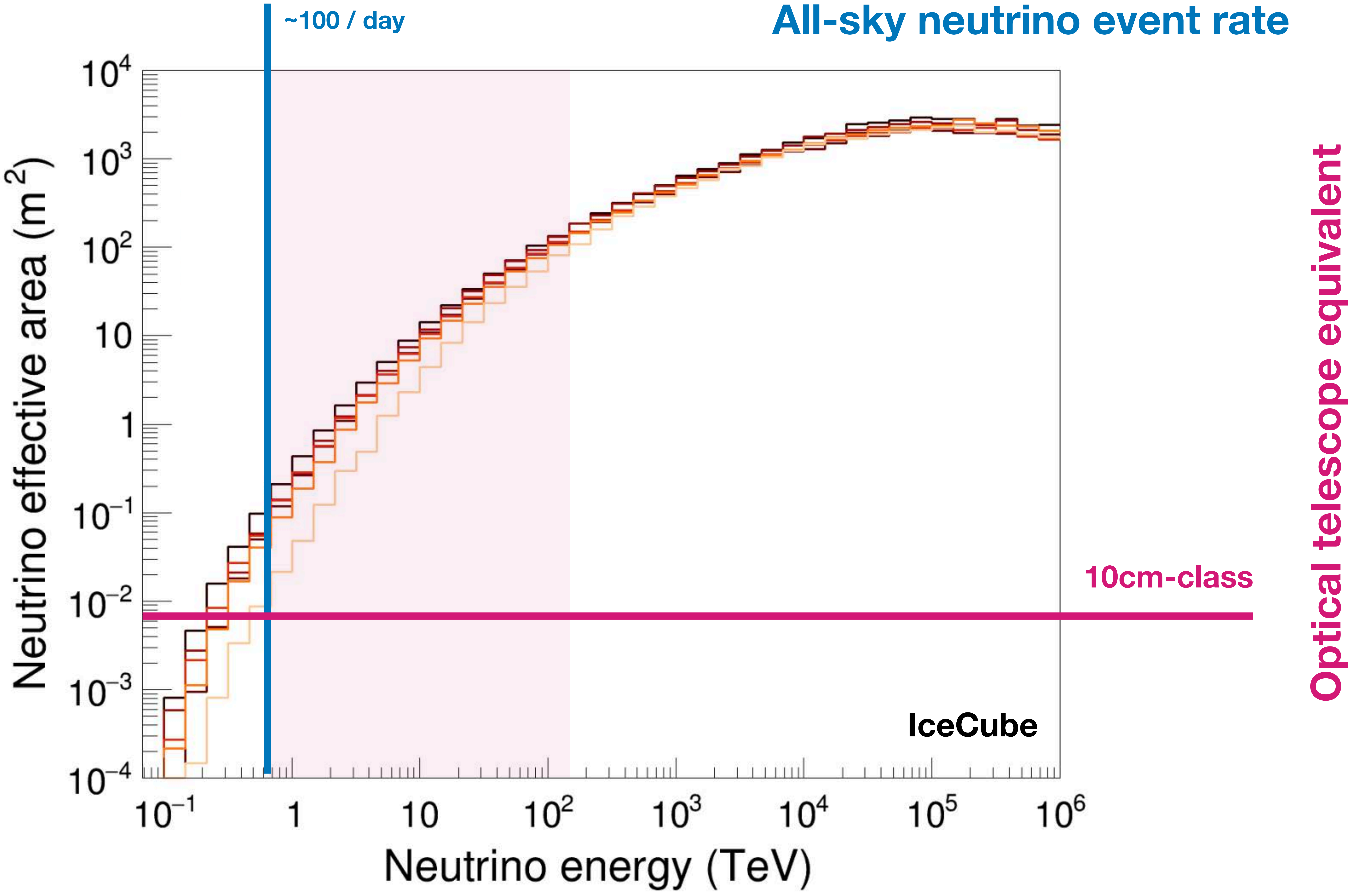
CHALLENGES OF NEUTRINO ASTRONOMY

All-sky neutrino event rate



Optical telescope equivalent

CHALLENGES OF NEUTRINO ASTRONOMY



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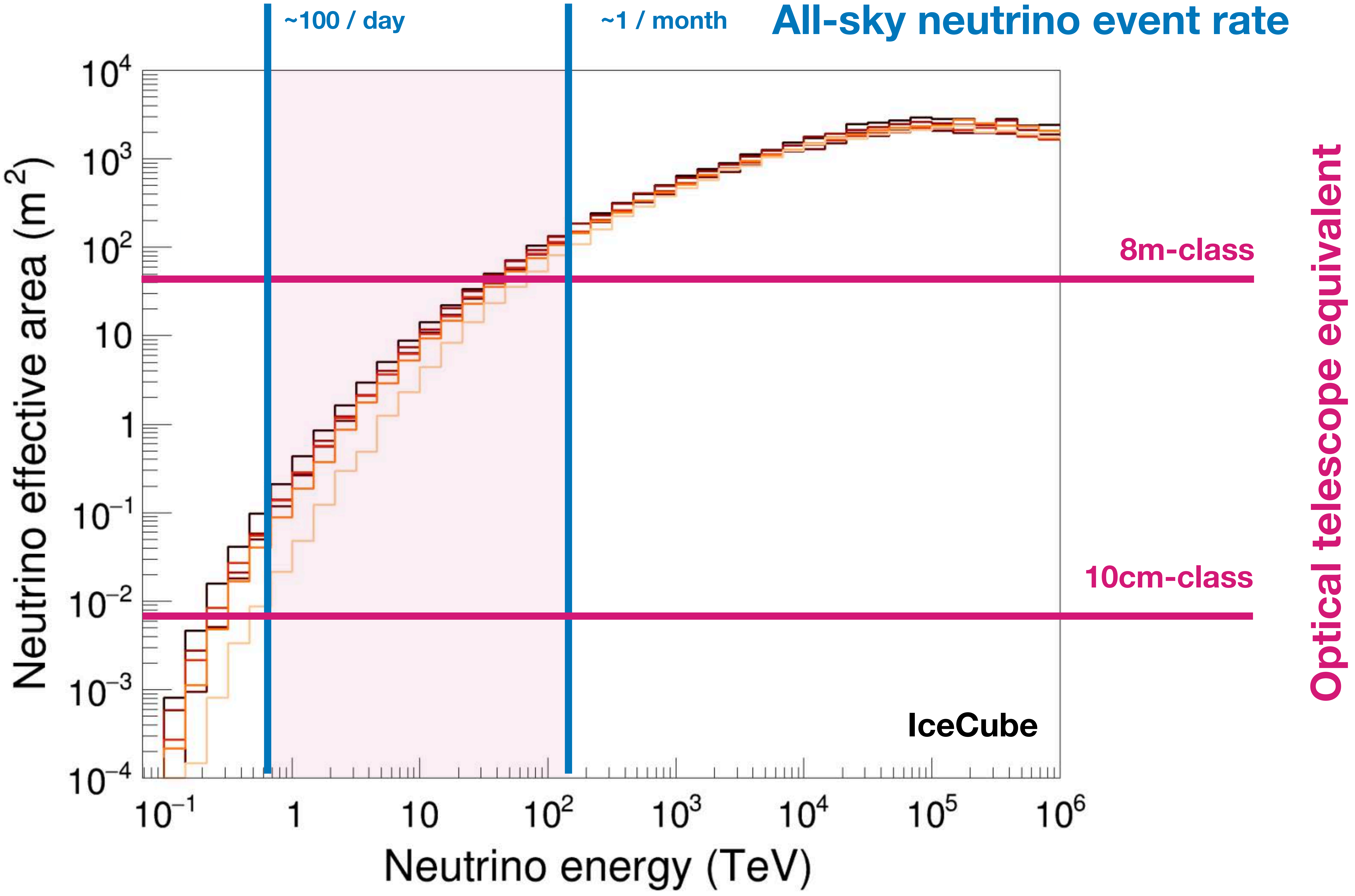
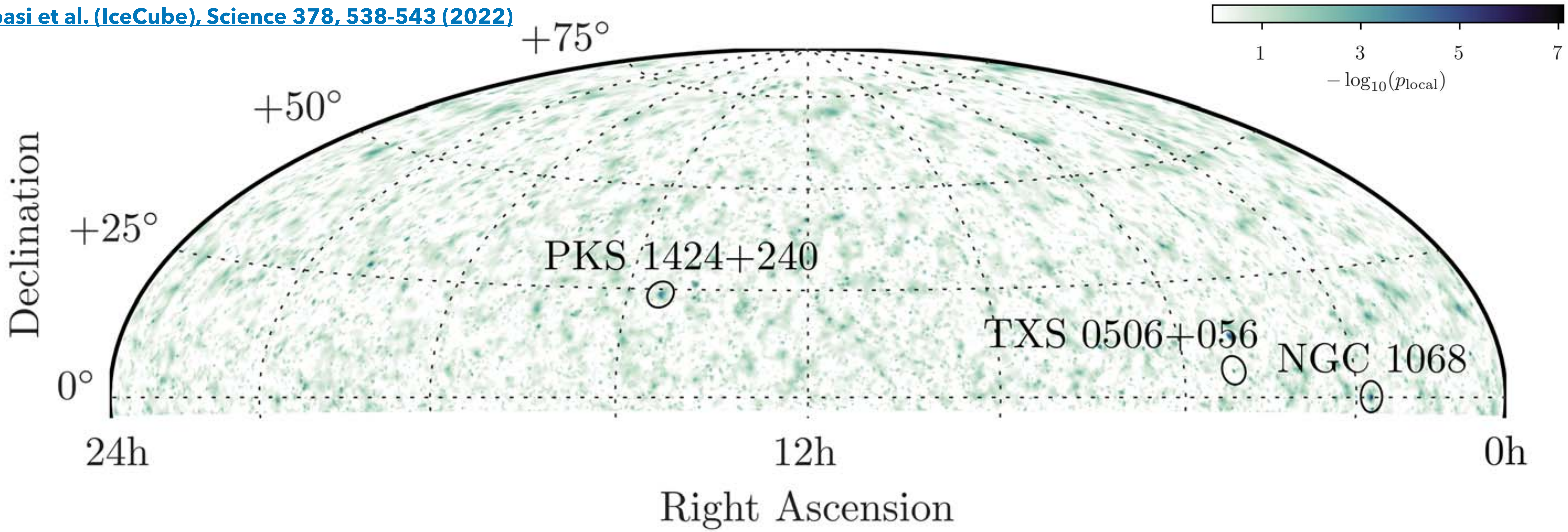


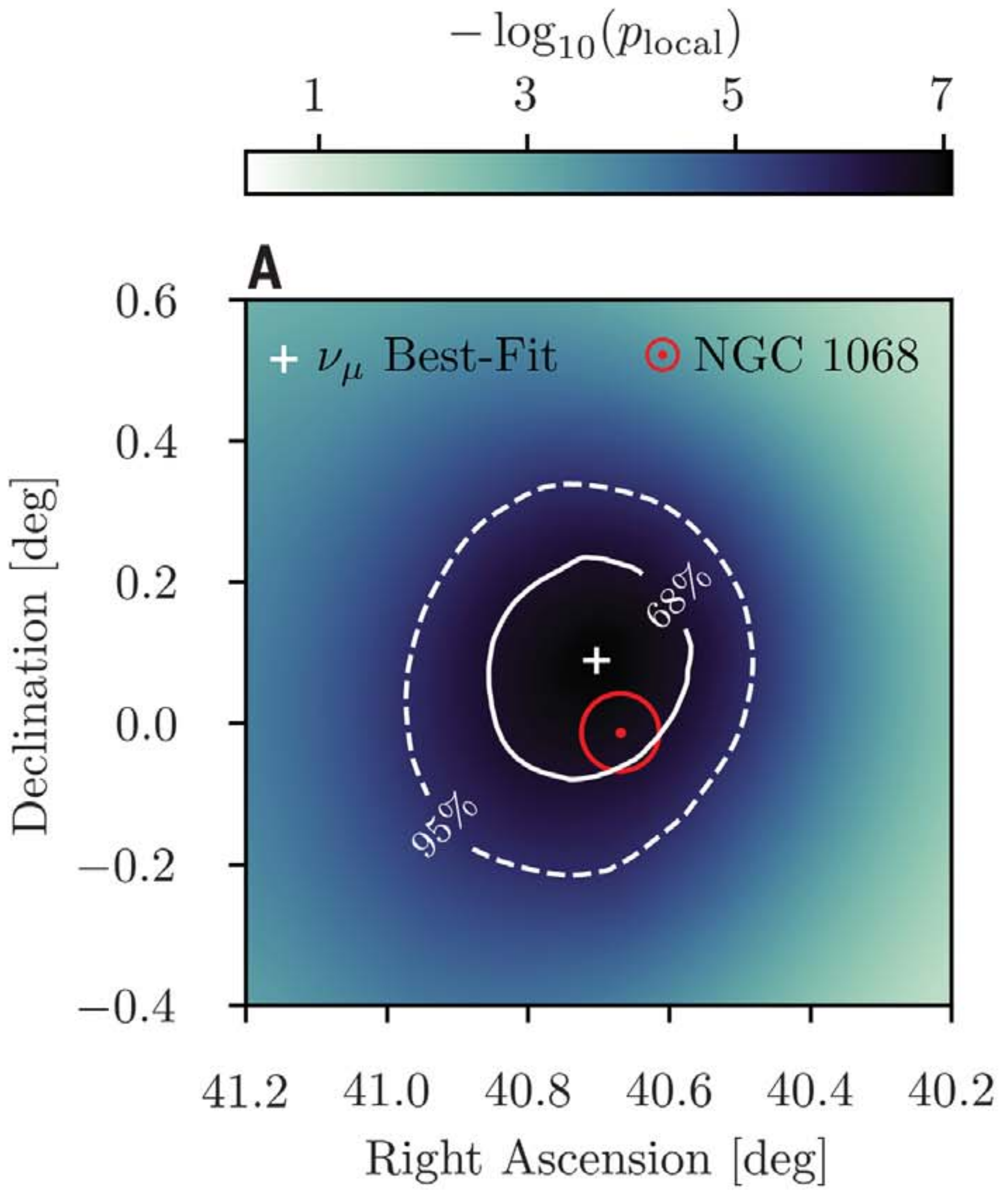
TIME-INTEGRATED NEUTRINO SOURCE SEARCHES

Abbasi et al. (IceCube), Science 378, 538-543 (2022)

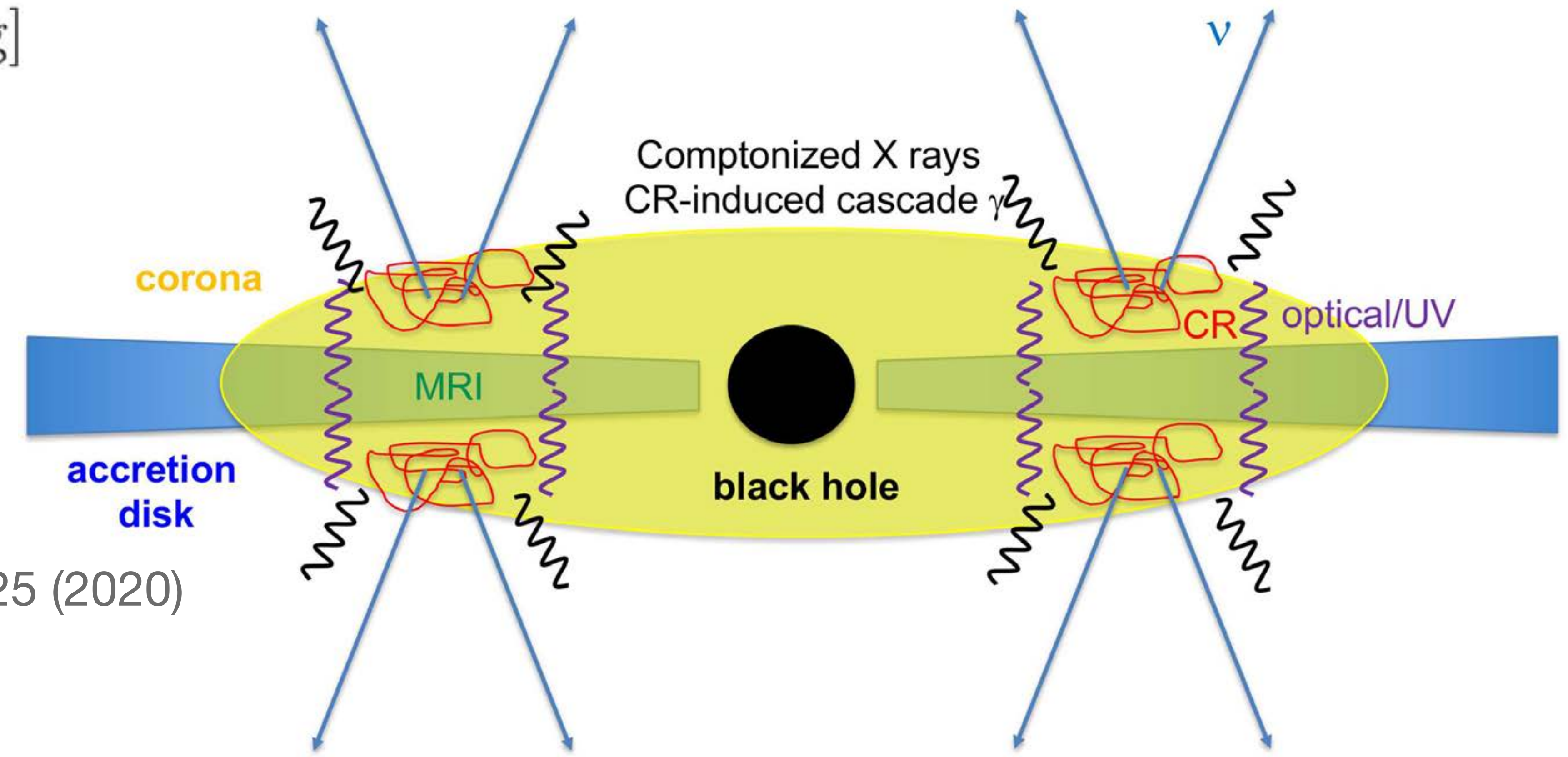


- At lower energies (< 100 TeV), sources can be identified through event **self-clustering in time and/or space.**
- Most sensitive time-integrated search for neutrino sources recently published by IceCube including 10 years of events from the Northern Sky.

RESULTS FROM ICECUBE NORTHERN SKY ANALYSIS



- Hottest source in the catalog is the Seyfert galaxy NGC 1068 (79^{+22}_{-20} event excess, **4.2σ after trials).** Flux of (5.0 ± 1.5) x 10^{-11} TeV^{-1} cm^{-2} s^{-1} at 1 TeV with Γ = 3.2 ± 0.2.
- Cosmic rays may be accelerated near the SMBH (corona region).
- Gammas cascade to lower energy (X-rays) in the dense photon field around the accretion disk.



K. Murase, S. Kimura, P. Meszaros, PRL 125 (2020) 011101
arXiv/1904.04226

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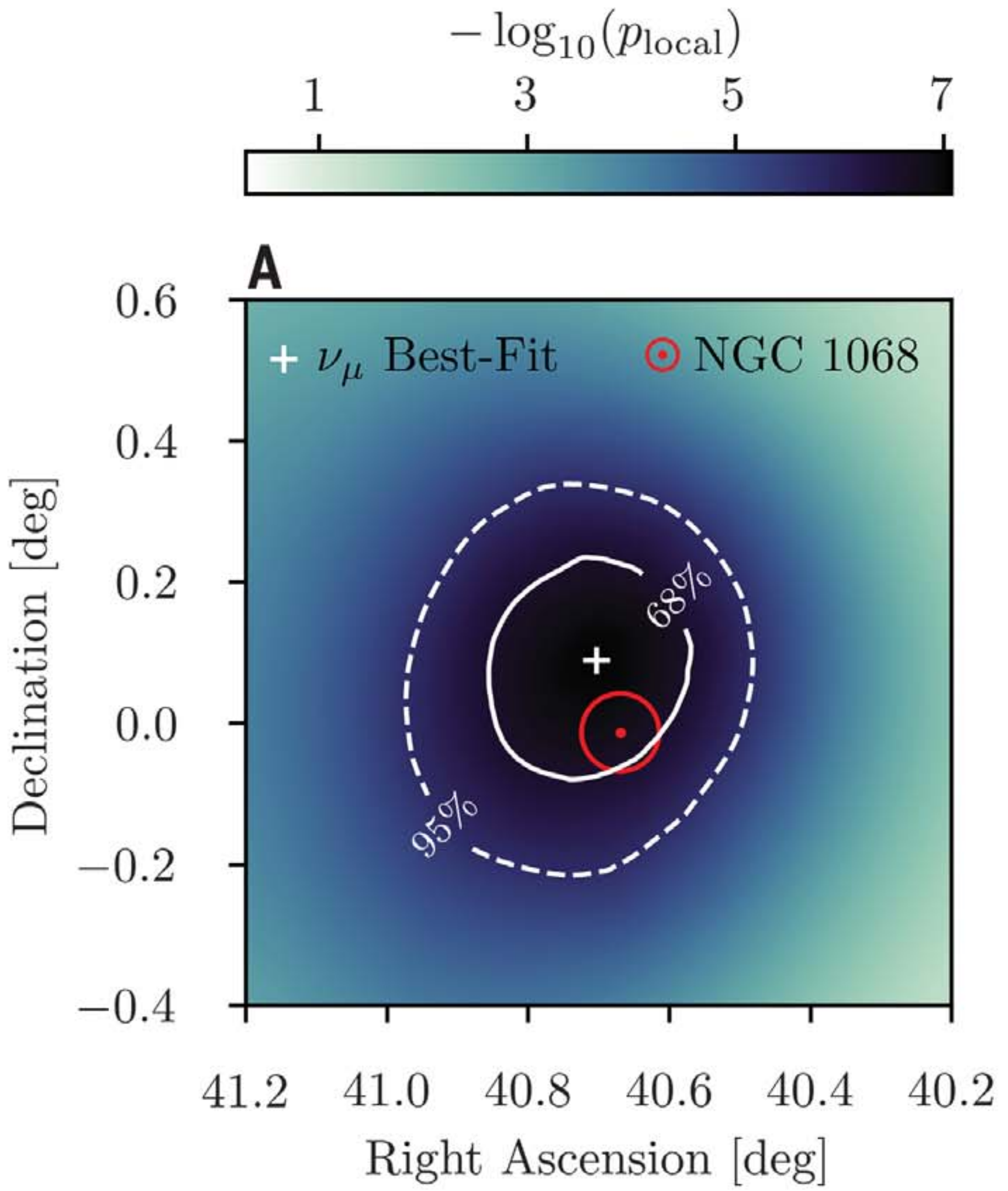

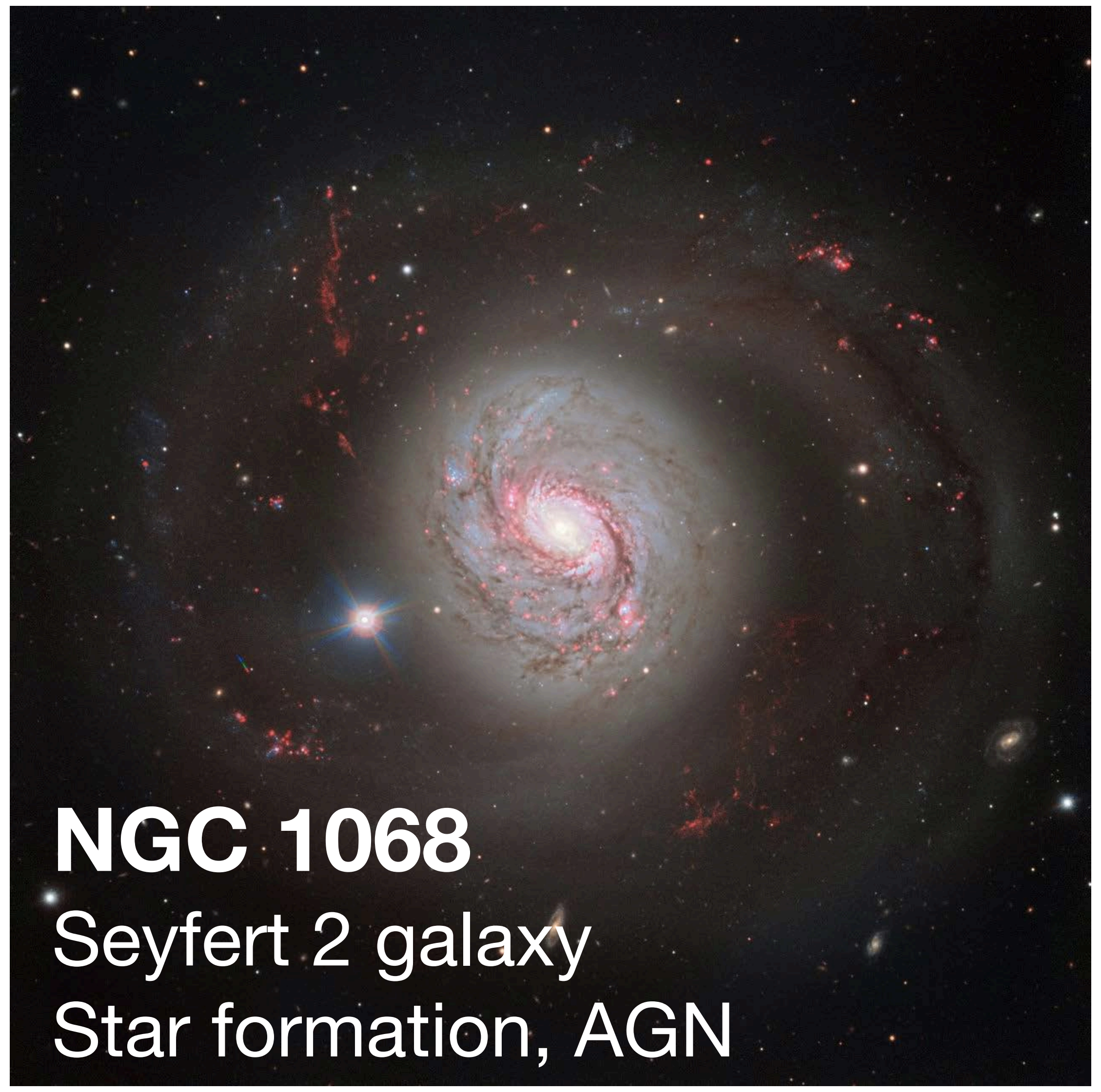

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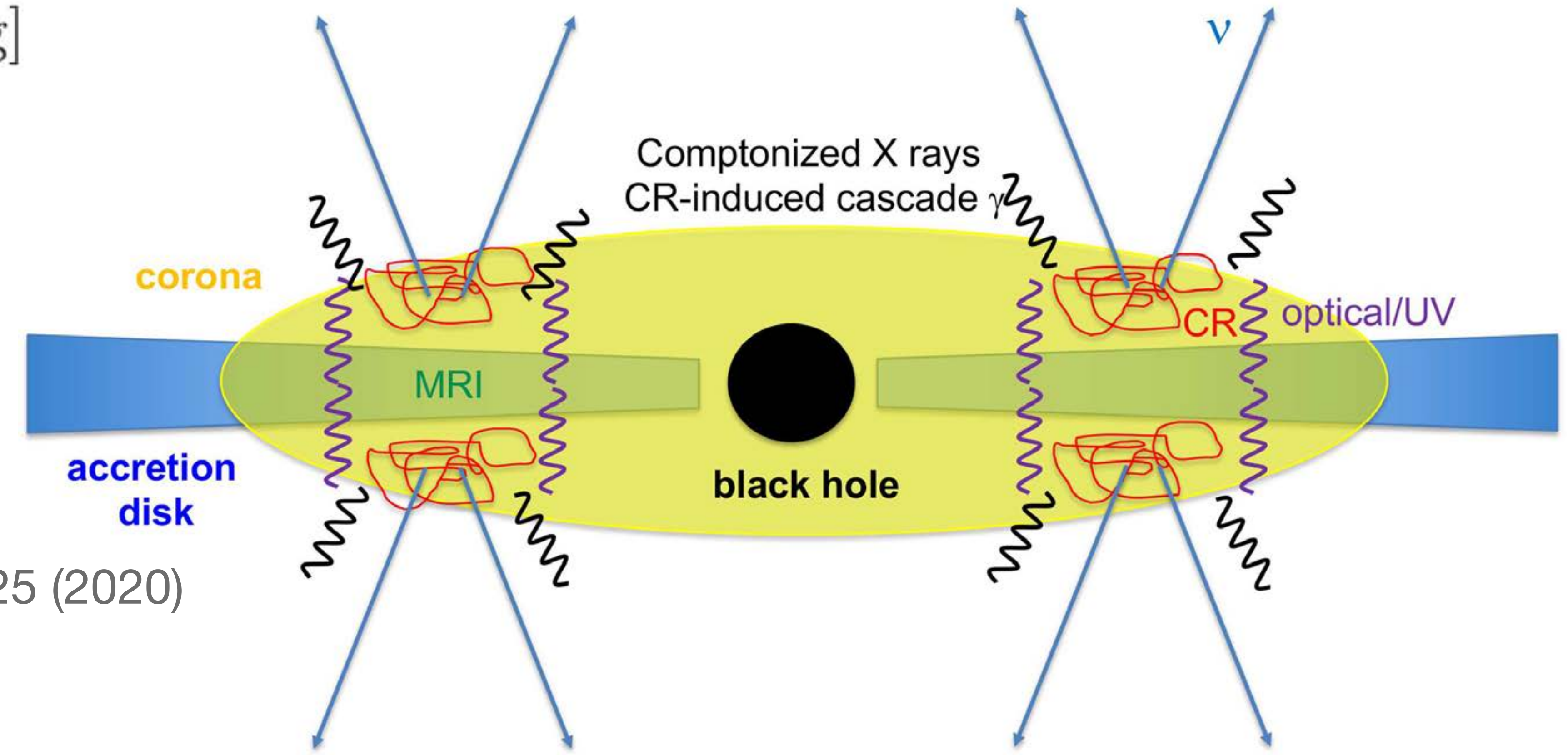

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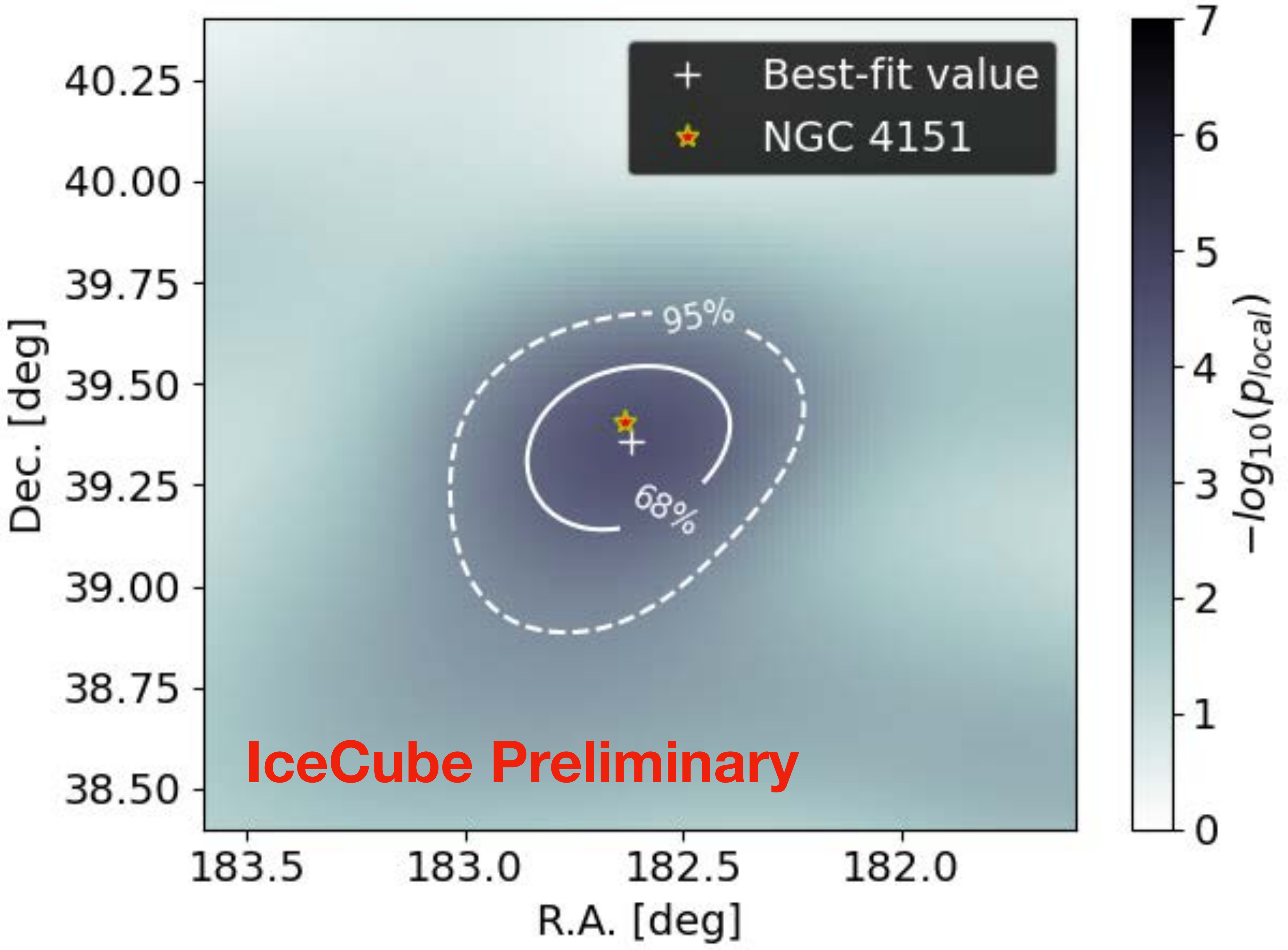
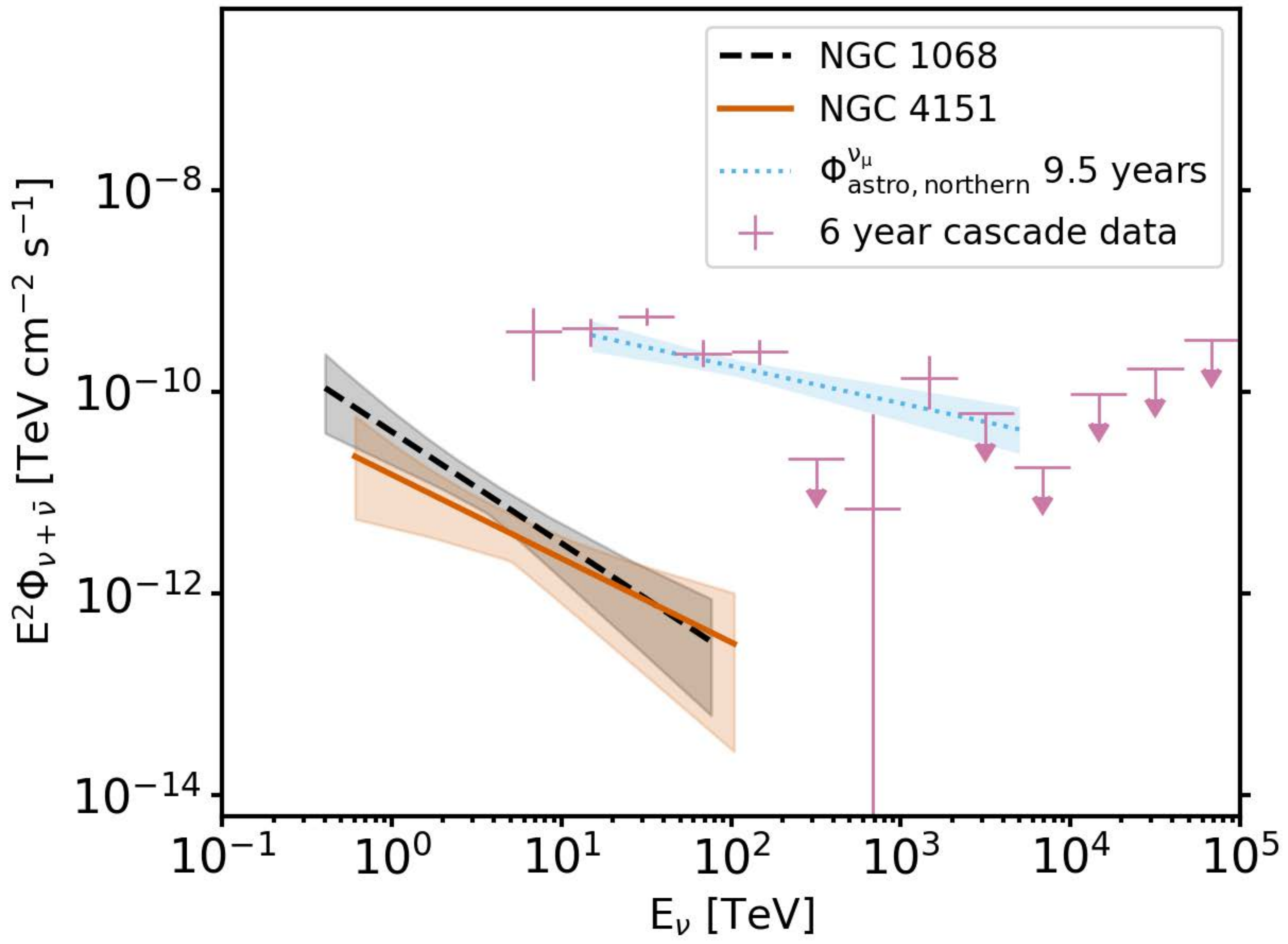
MORE NEUTRINO AGN FROM ICECUBE?

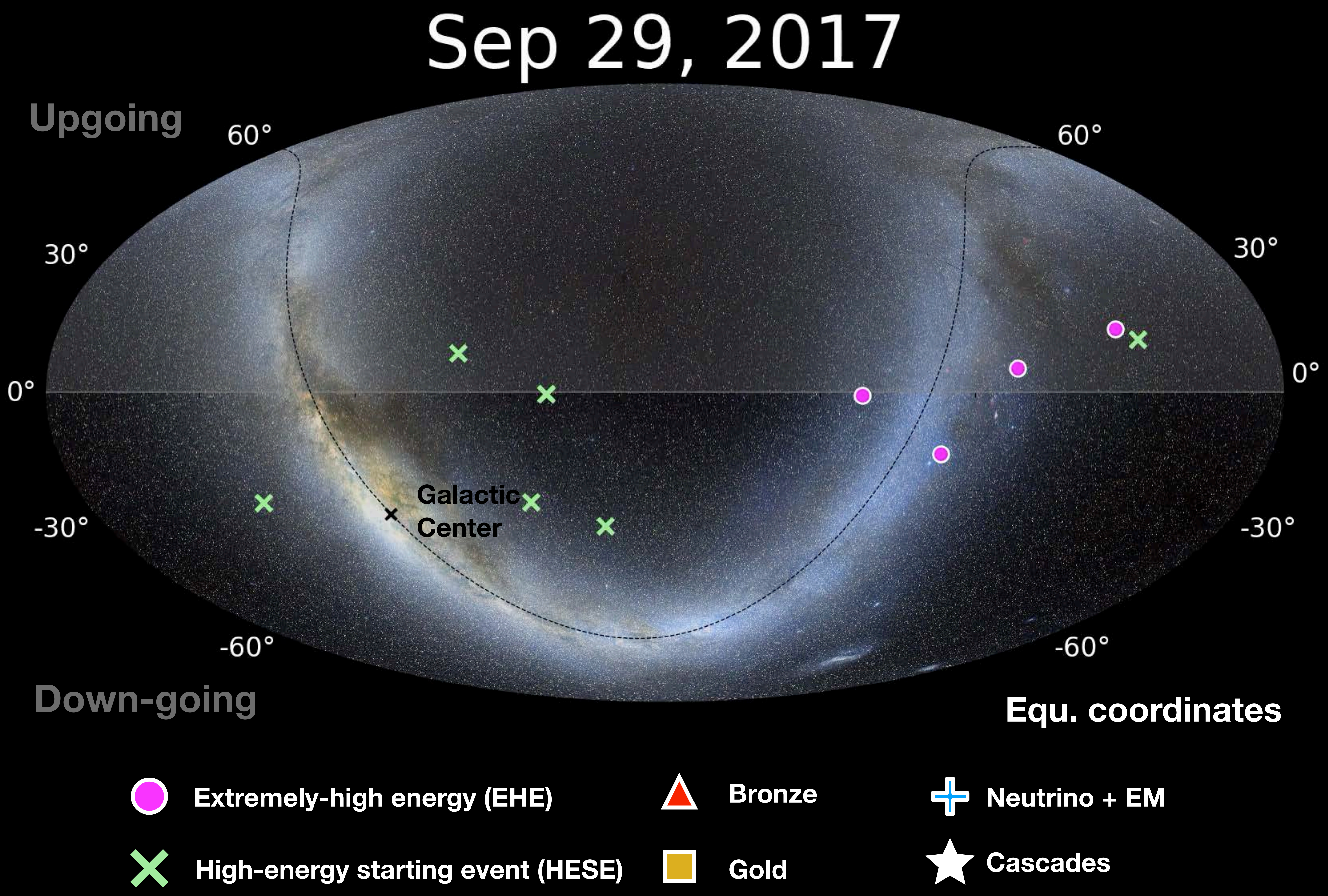
From Sreetama Goswami's thesis





- Neutrino excess at the location of NGC 4151, another Seyfert galaxy (2.93 sigma)
- Spectrum is soft. If Seyferts are a class of neutrino sources, there has to be another class that provides the higher energy neutrinos.

REALTIME NEUTRINO ALERTS



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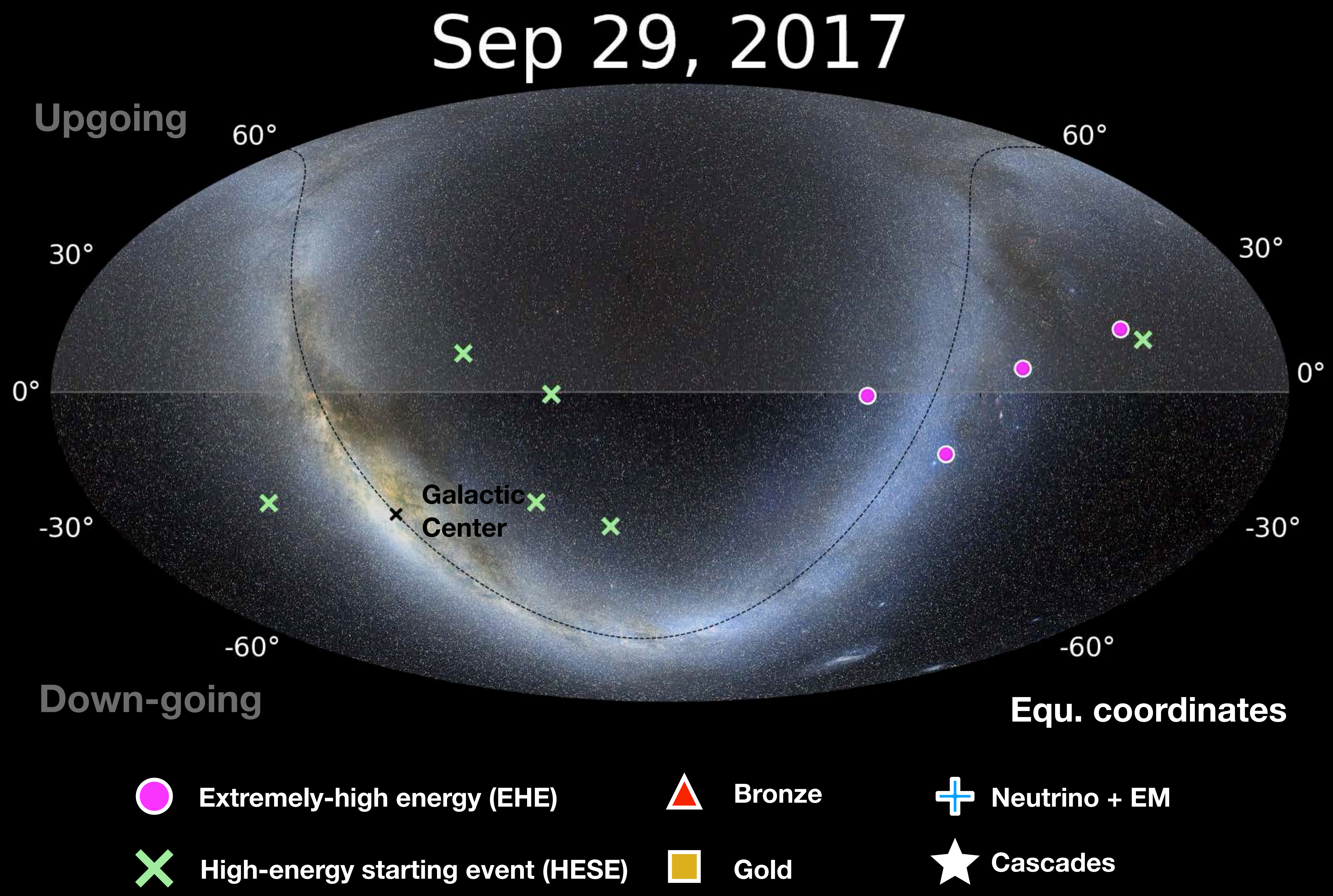

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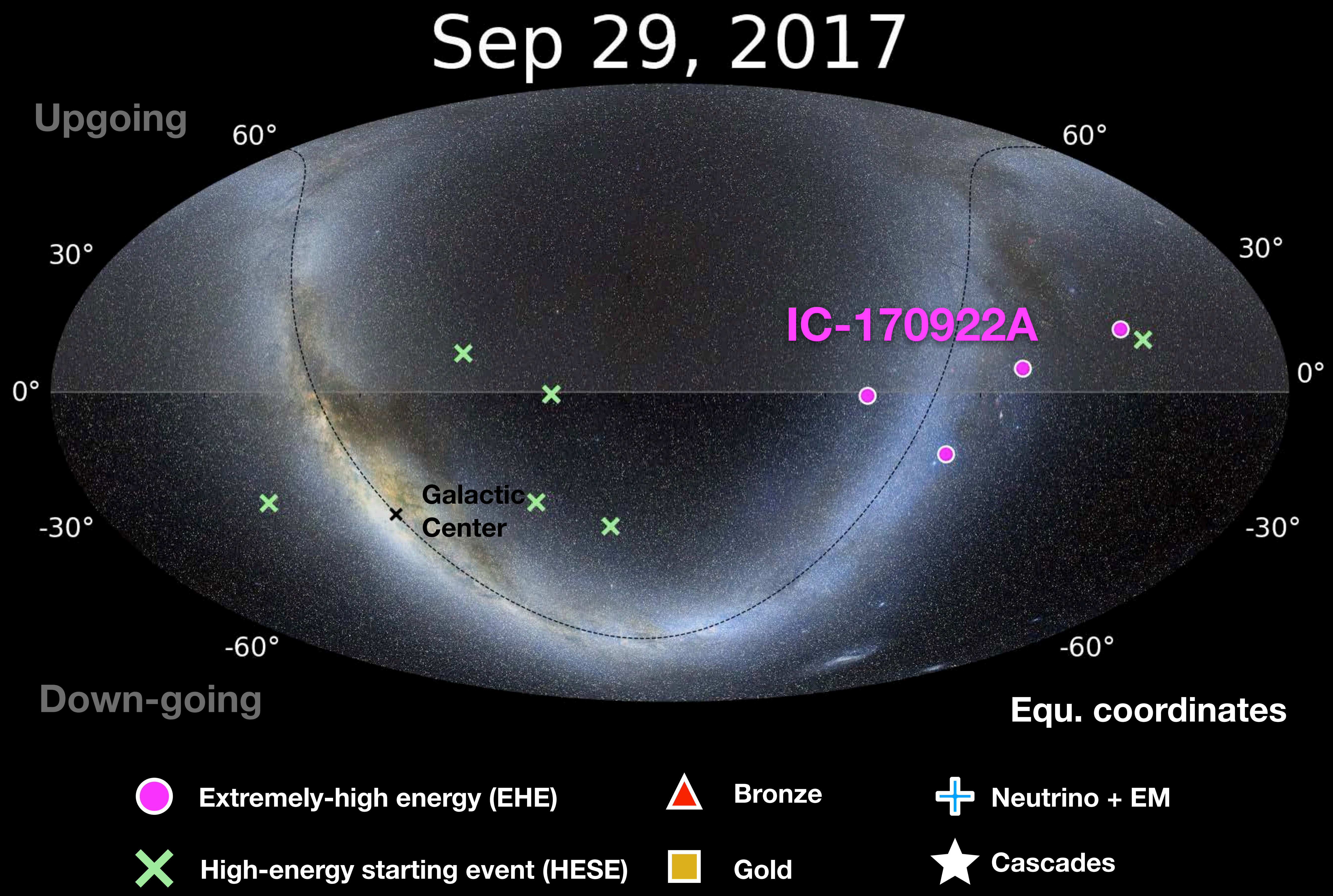

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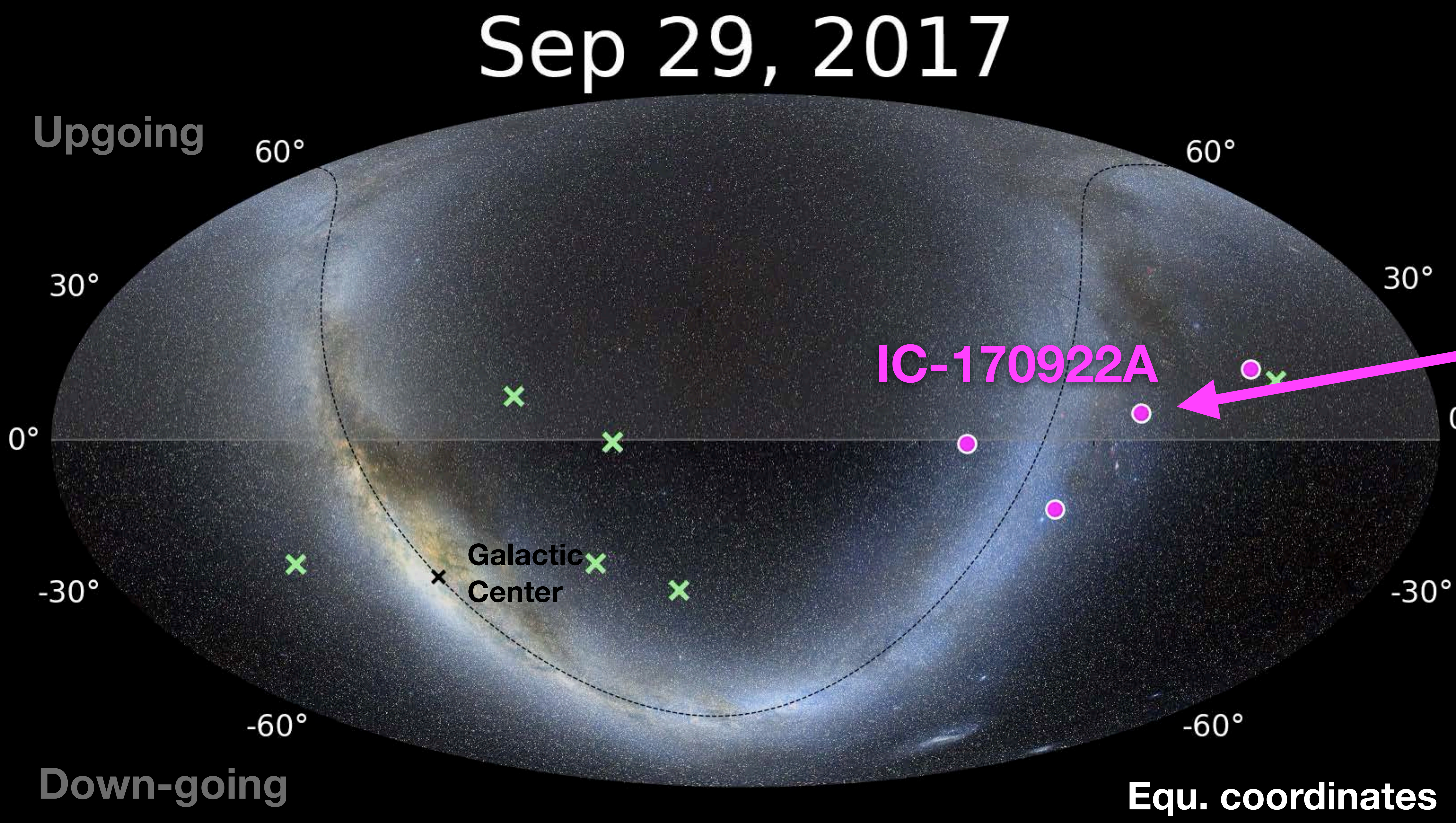
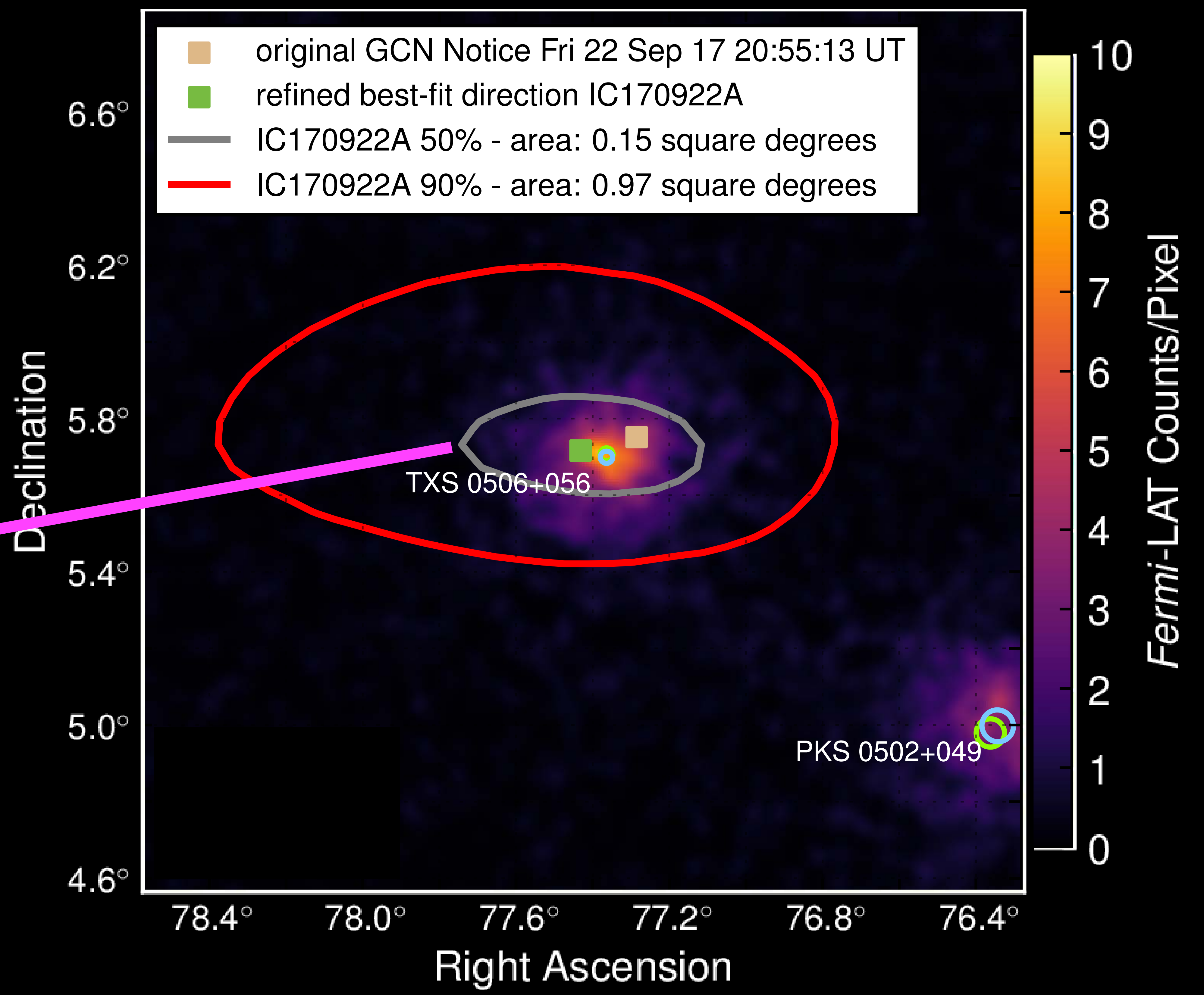
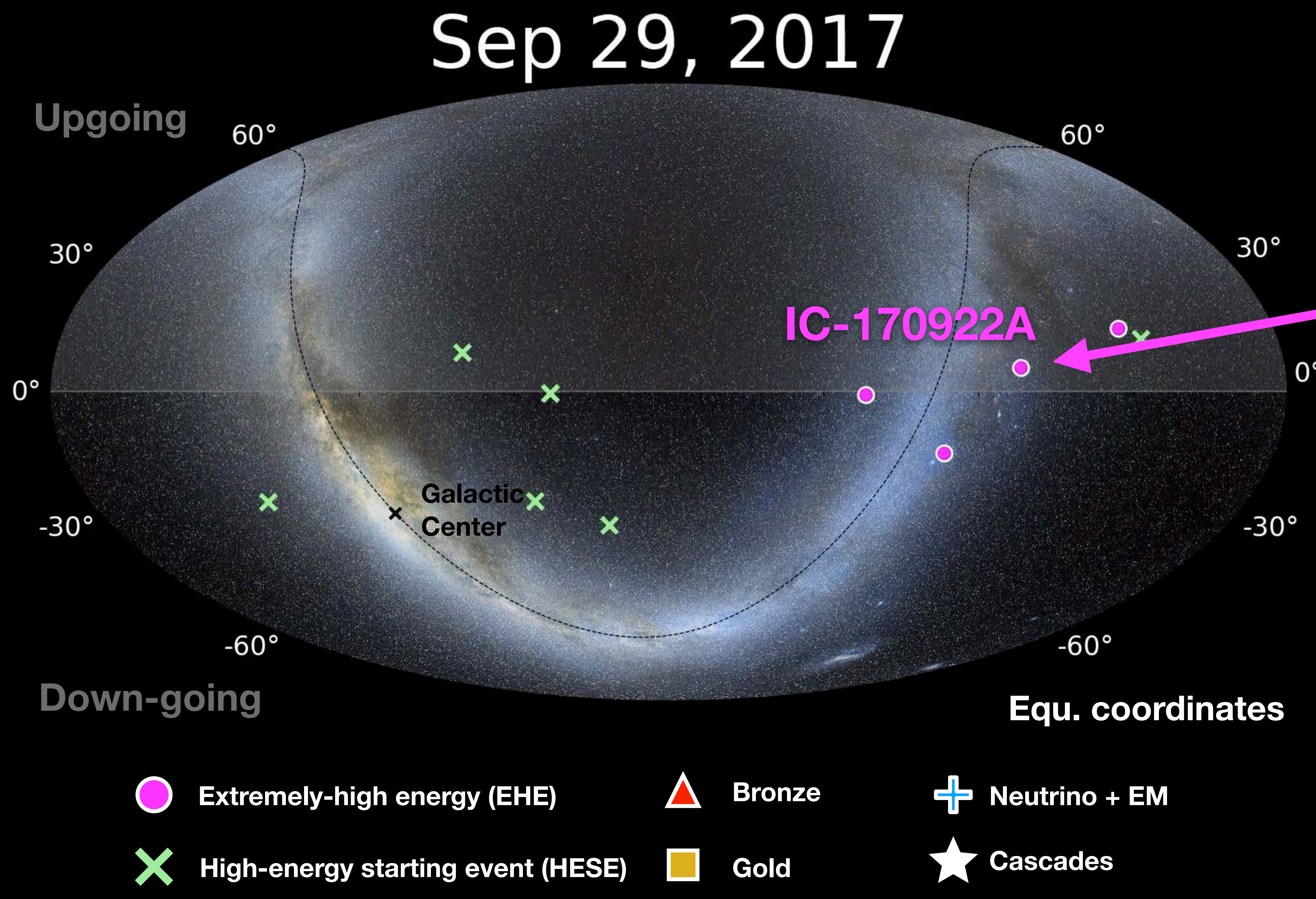


Fermi-LAT
0.1 - 300 GeV



Extremely-high energy (EHE)
High-energy starting event (HESE)
Bronze
Gold
Neutrino + EM
Cascades

REALTIME NEUTRINO ALERTS



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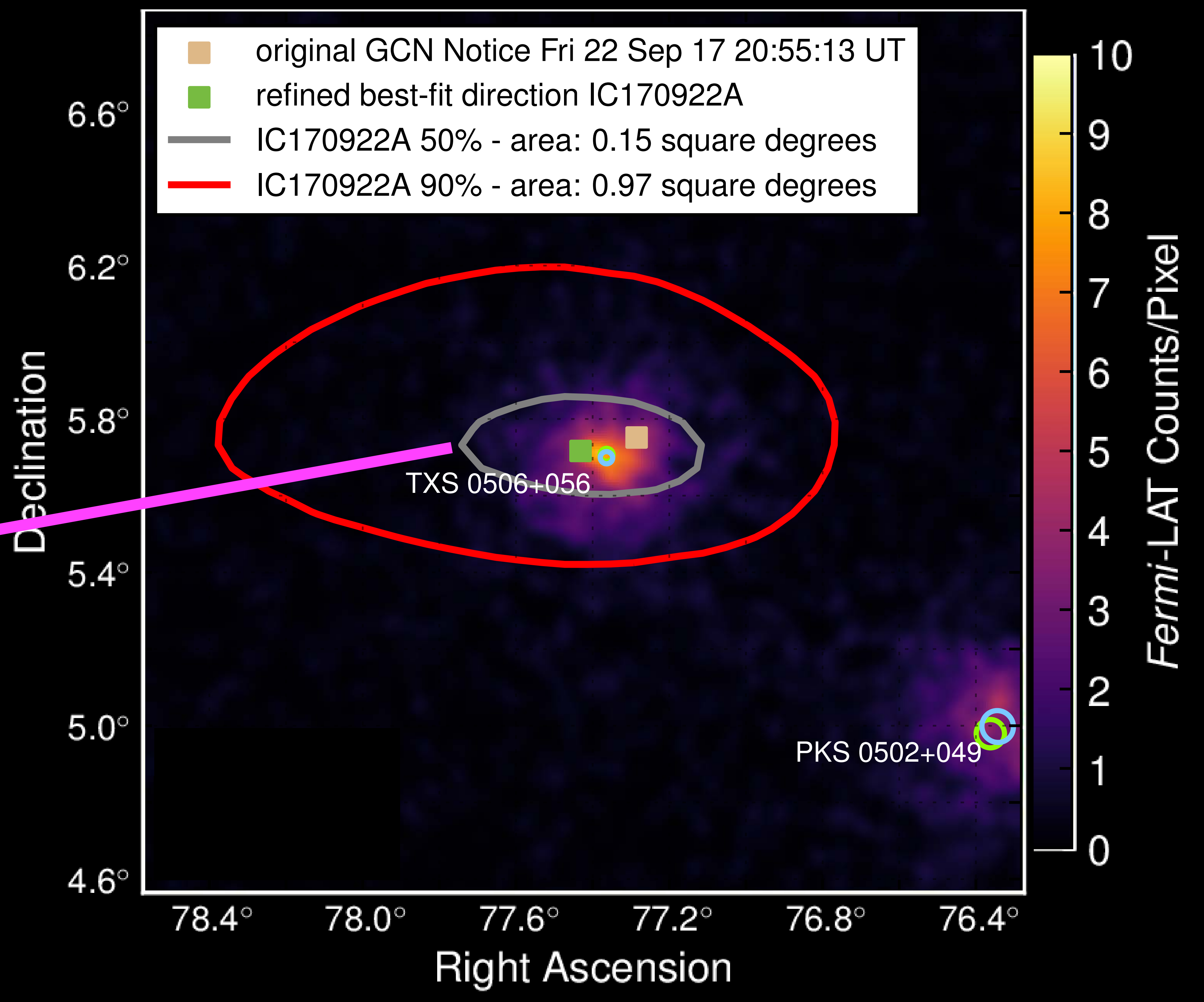

- IceCube-170922A: 290 TeV neutrino energy

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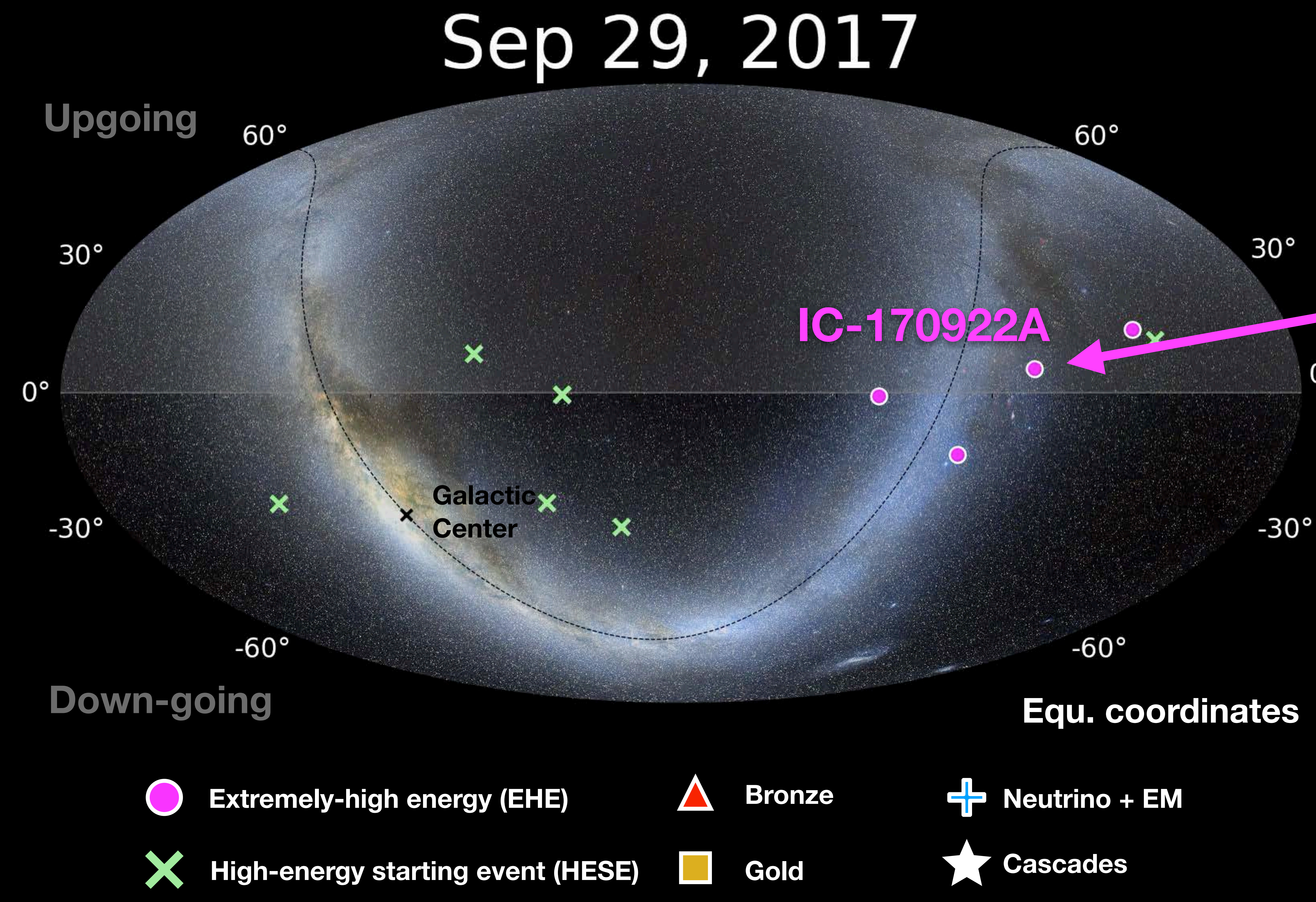

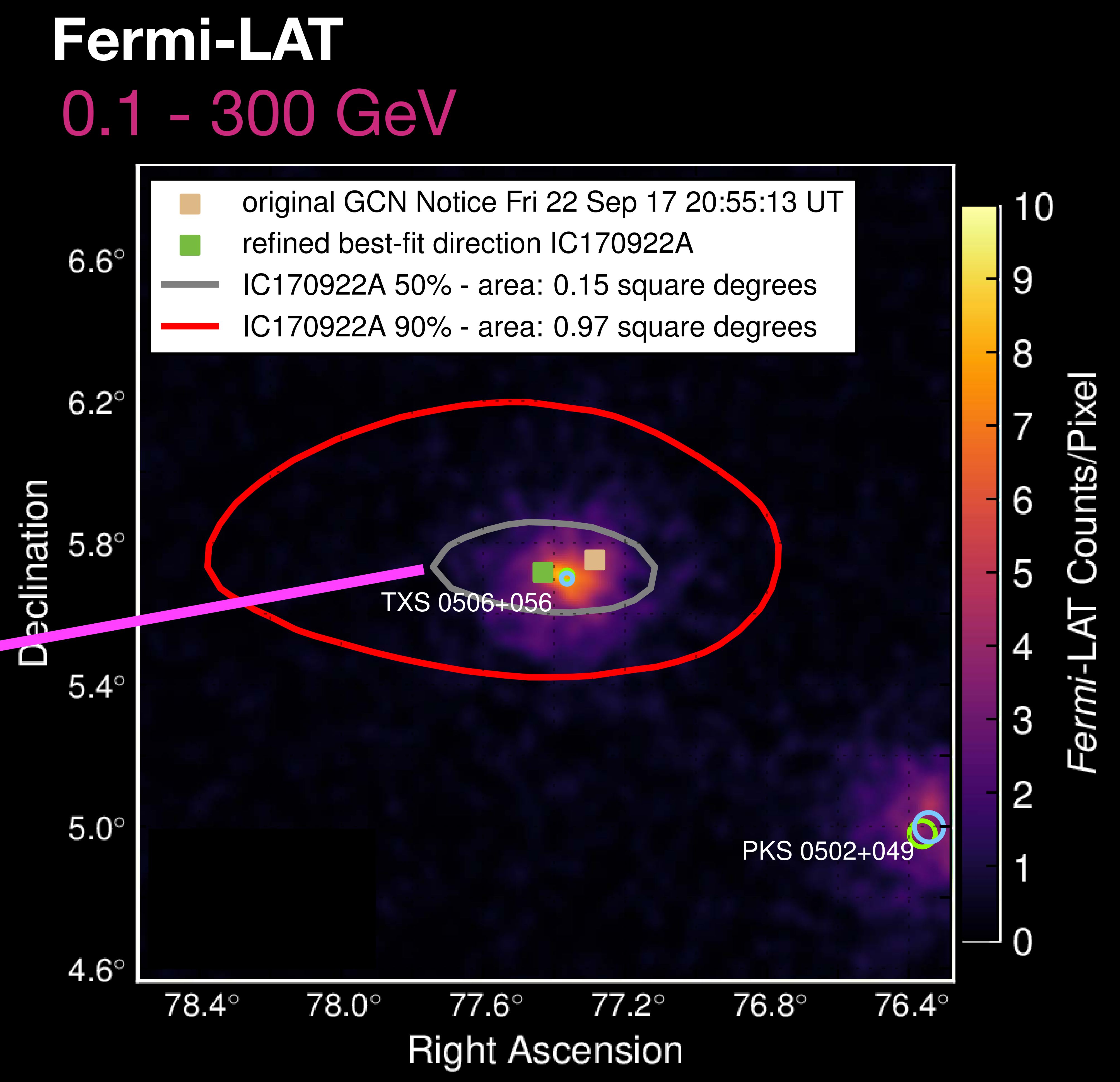

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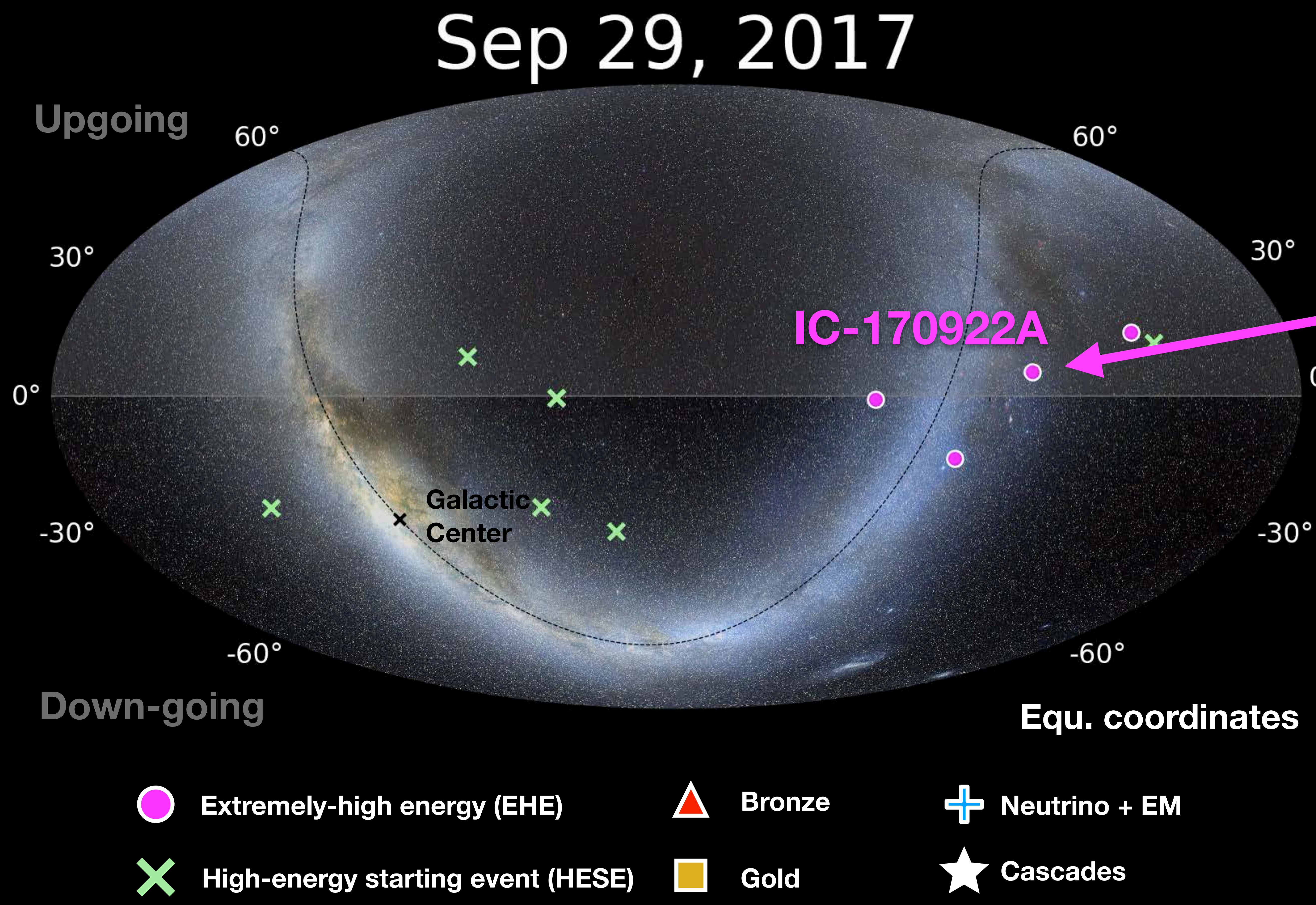

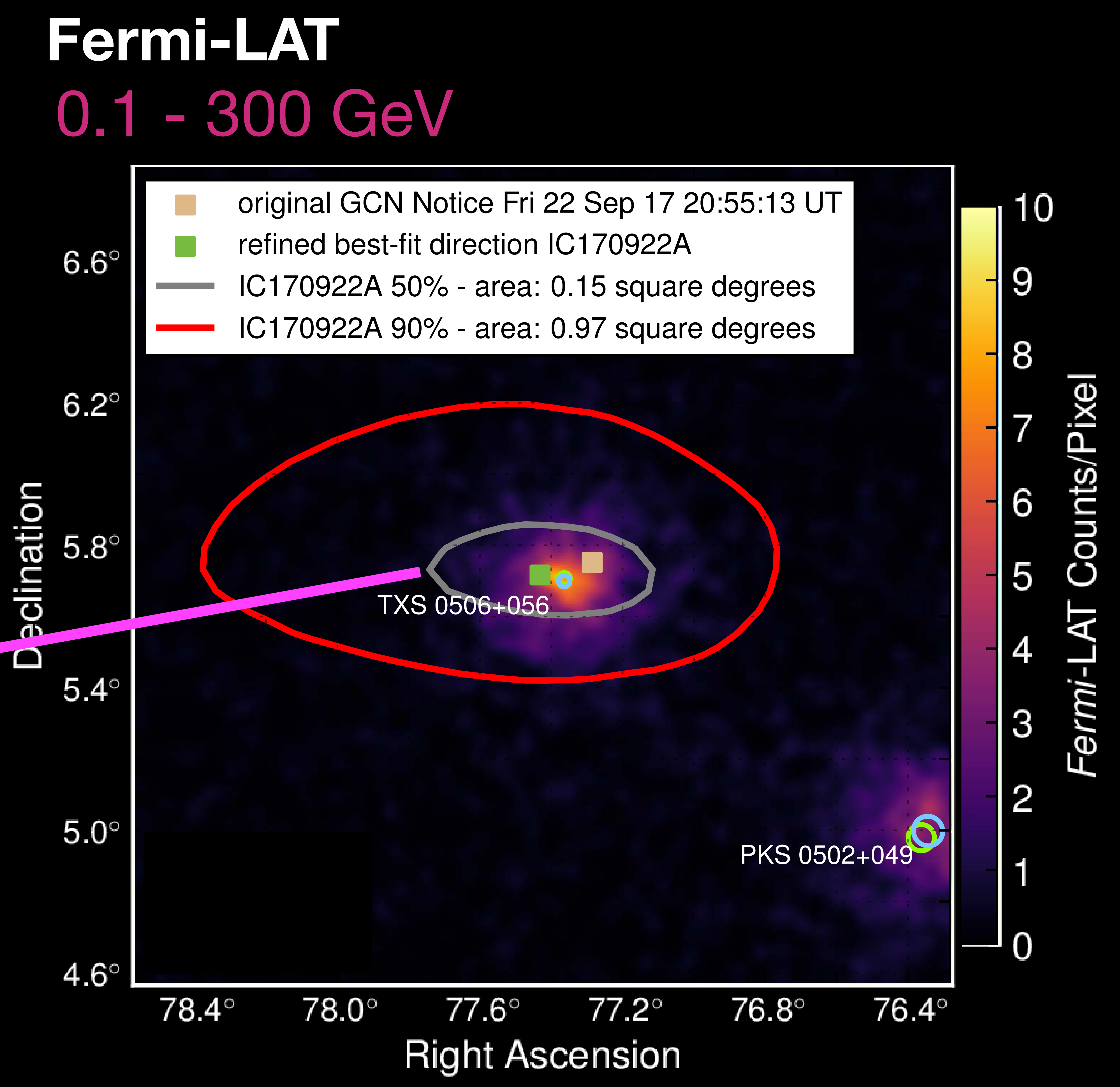

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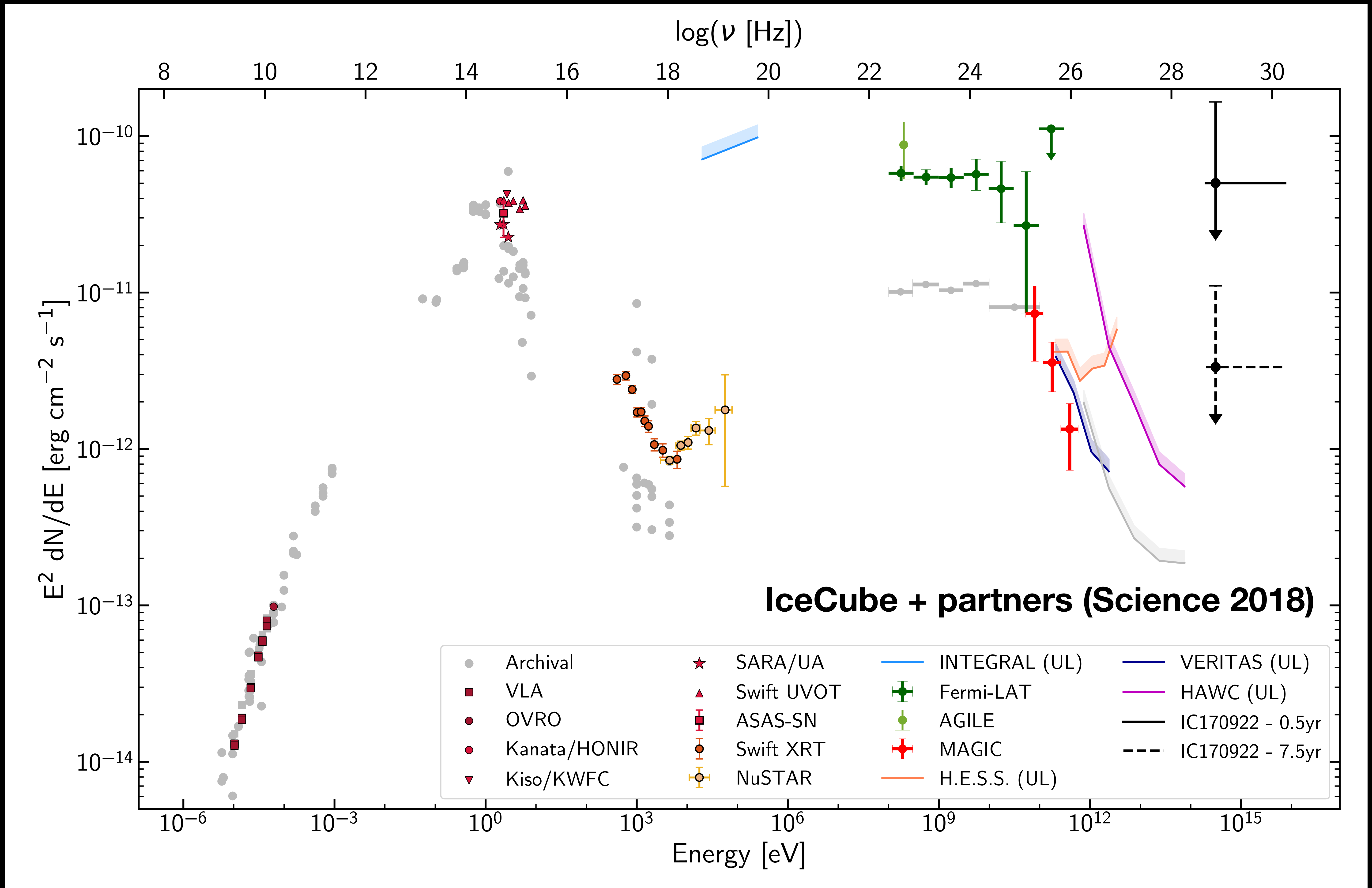
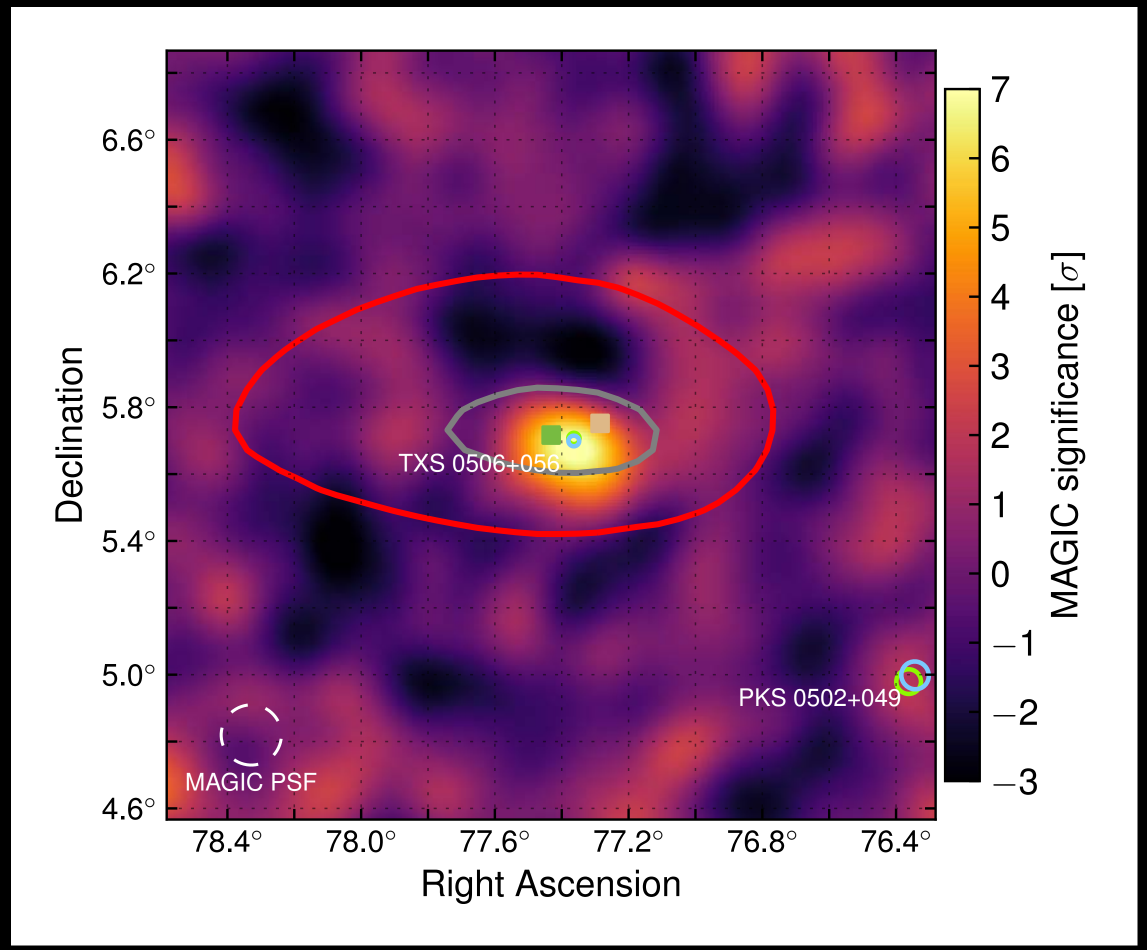
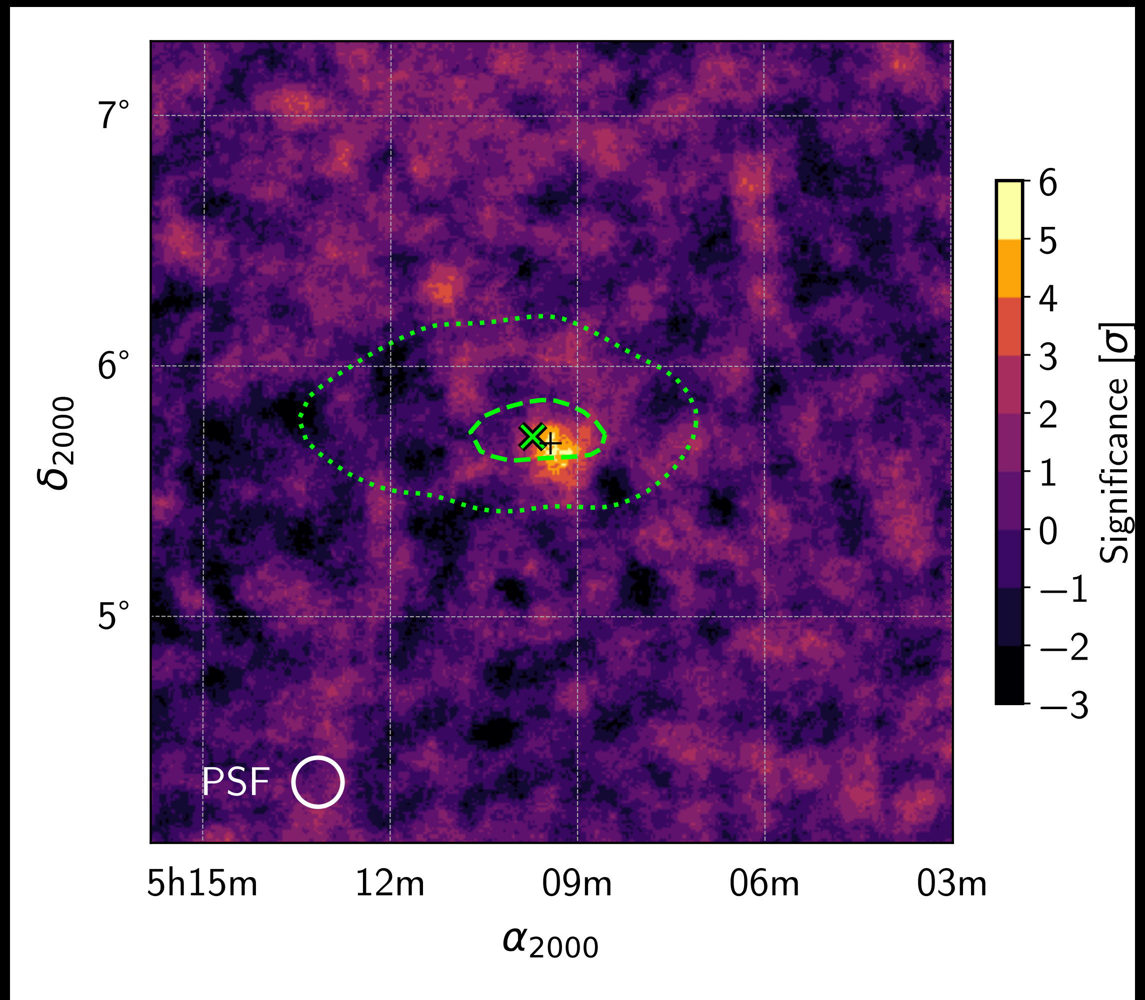
- Similar efforts underway for KM3NeT, Baikal-GVD

PHOTONS FROM TXS 0506+056





MAGIC (ApJL 2018)



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- 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.**

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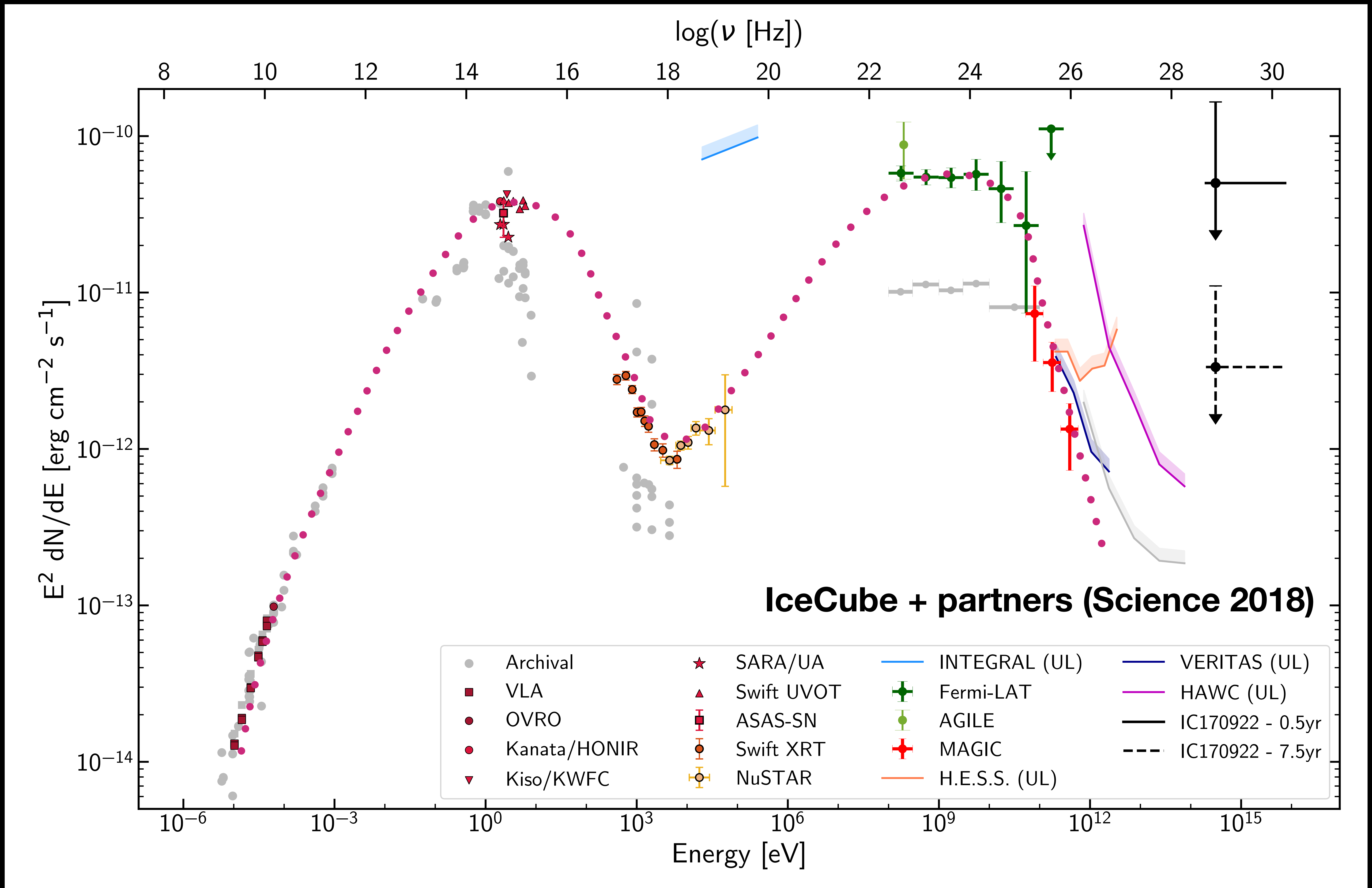

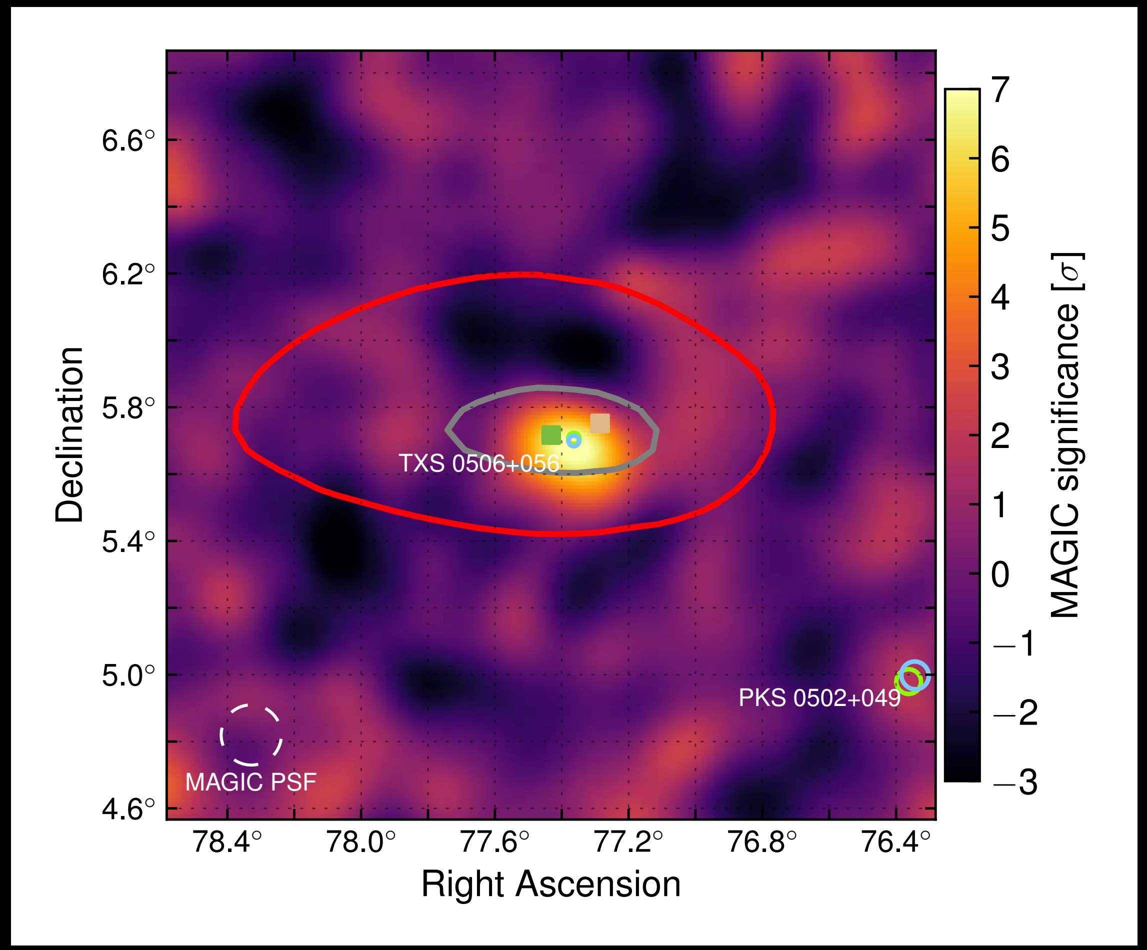

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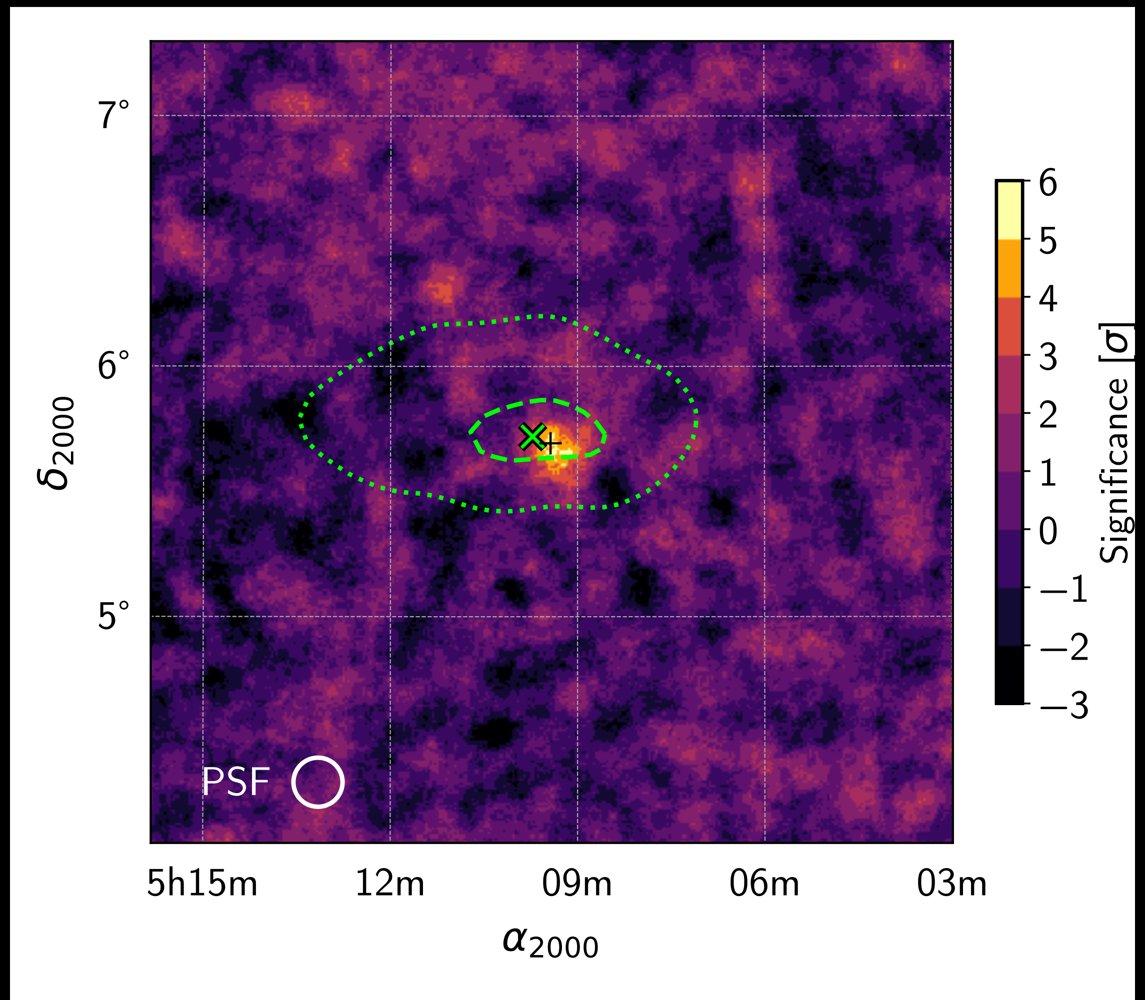

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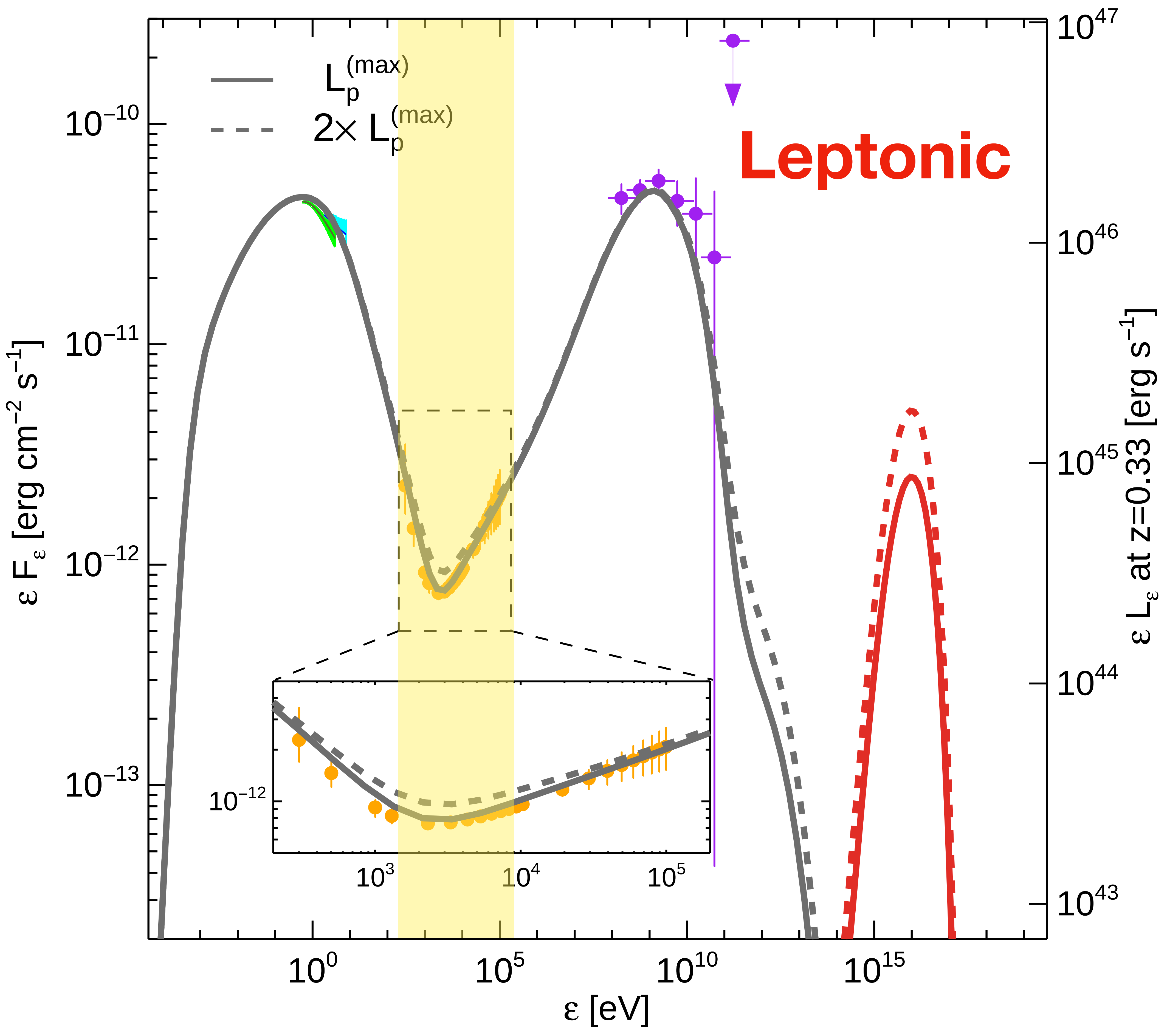
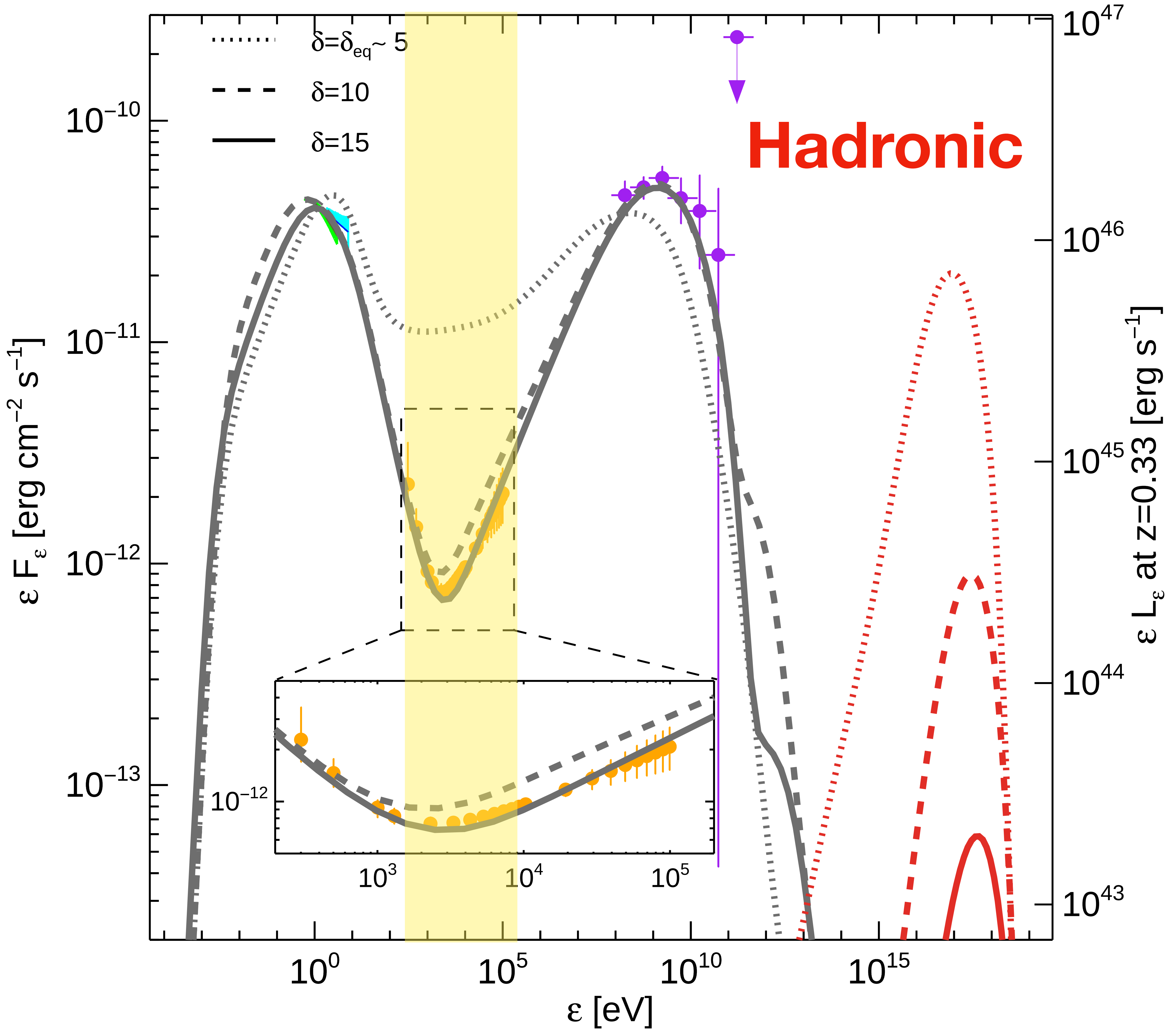
MODELING THE 2017 NEUTRINO EMISSION

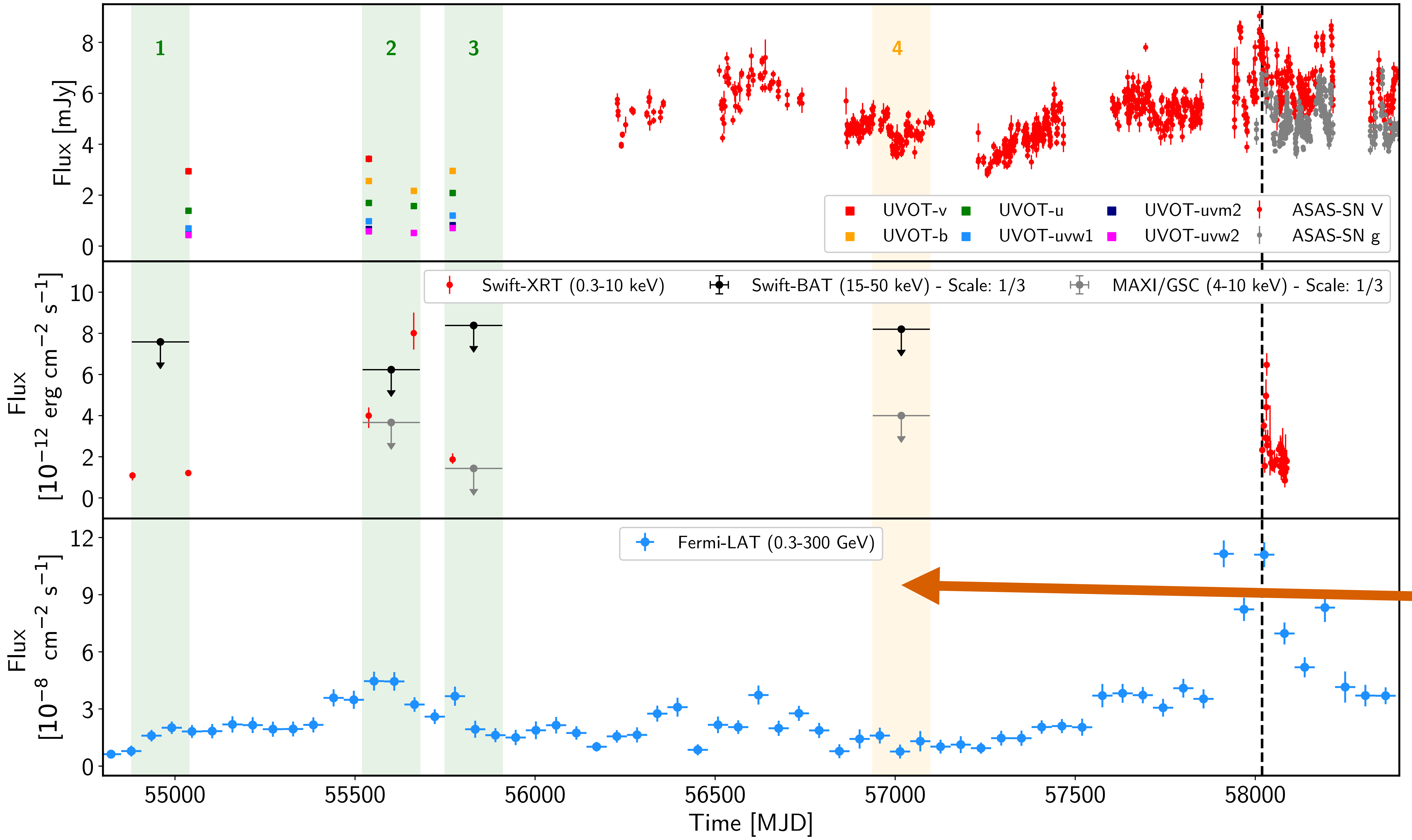
Keivani et al. (arXiv/1807.04537)
among many others

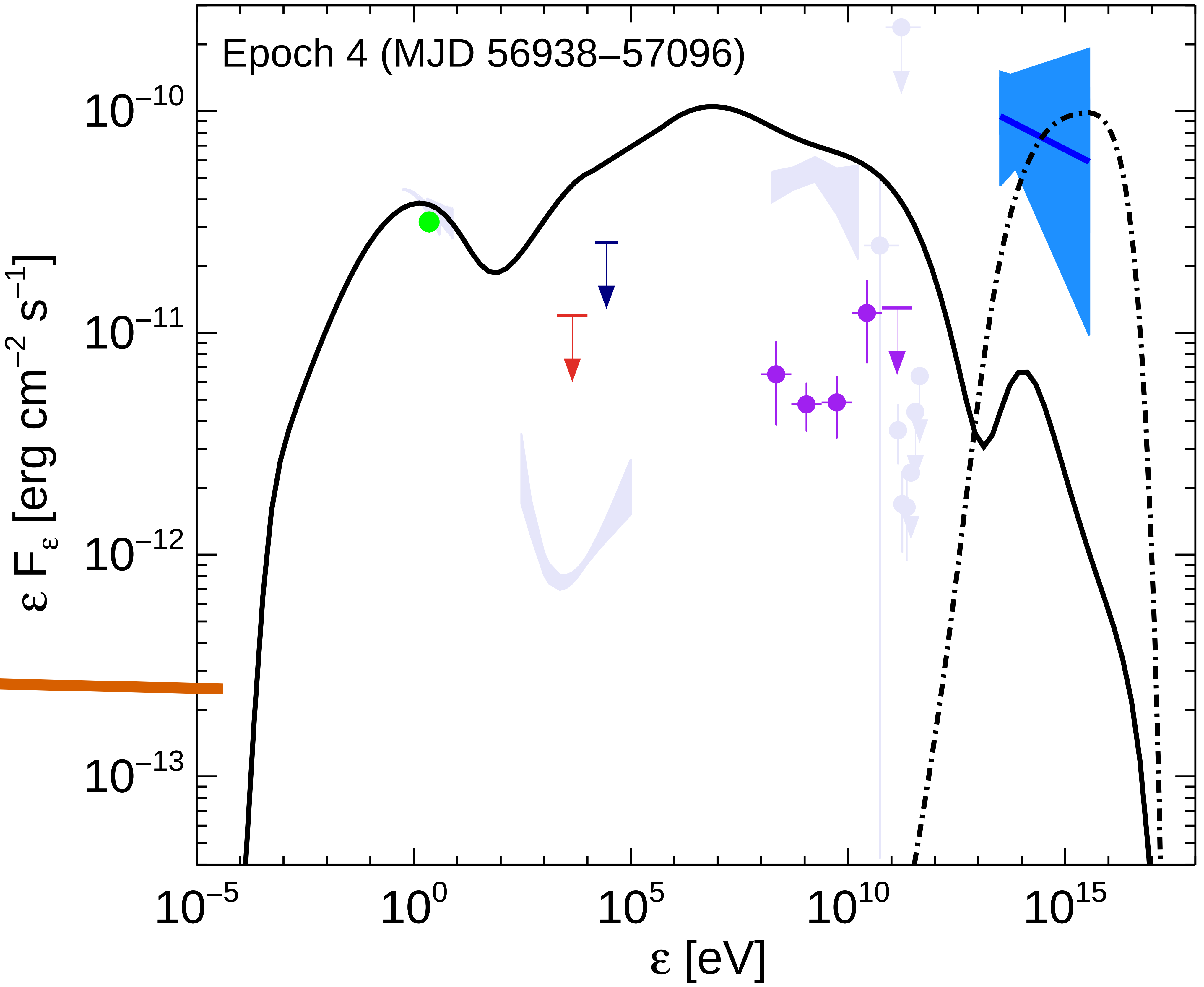




- **Strong constraints on hadronic emission from X-ray observations.**

TIME-DEPENDENT EMISSION FROM TXS 0506+056





Petropoulou, Murase, MS, ++ (2019)

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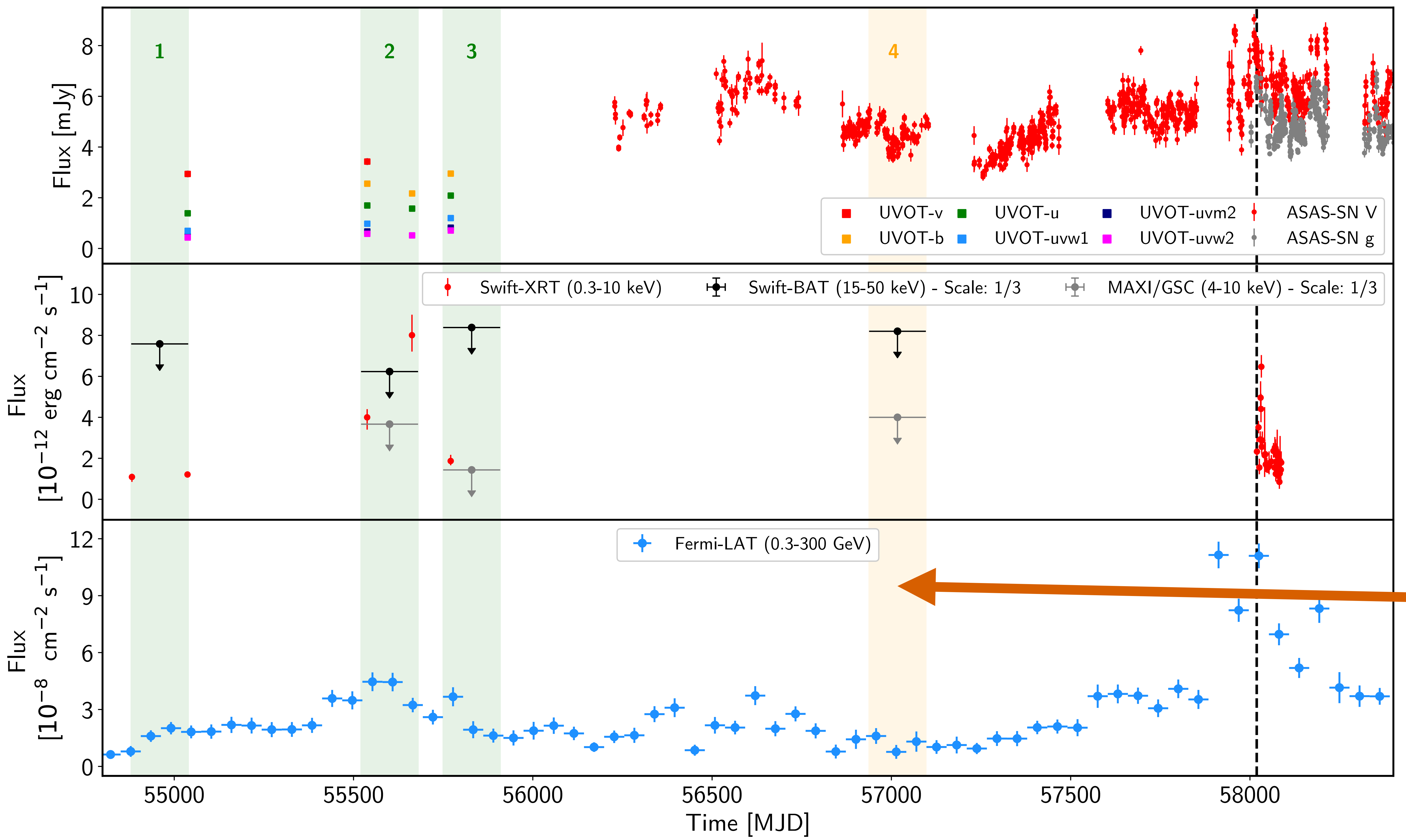

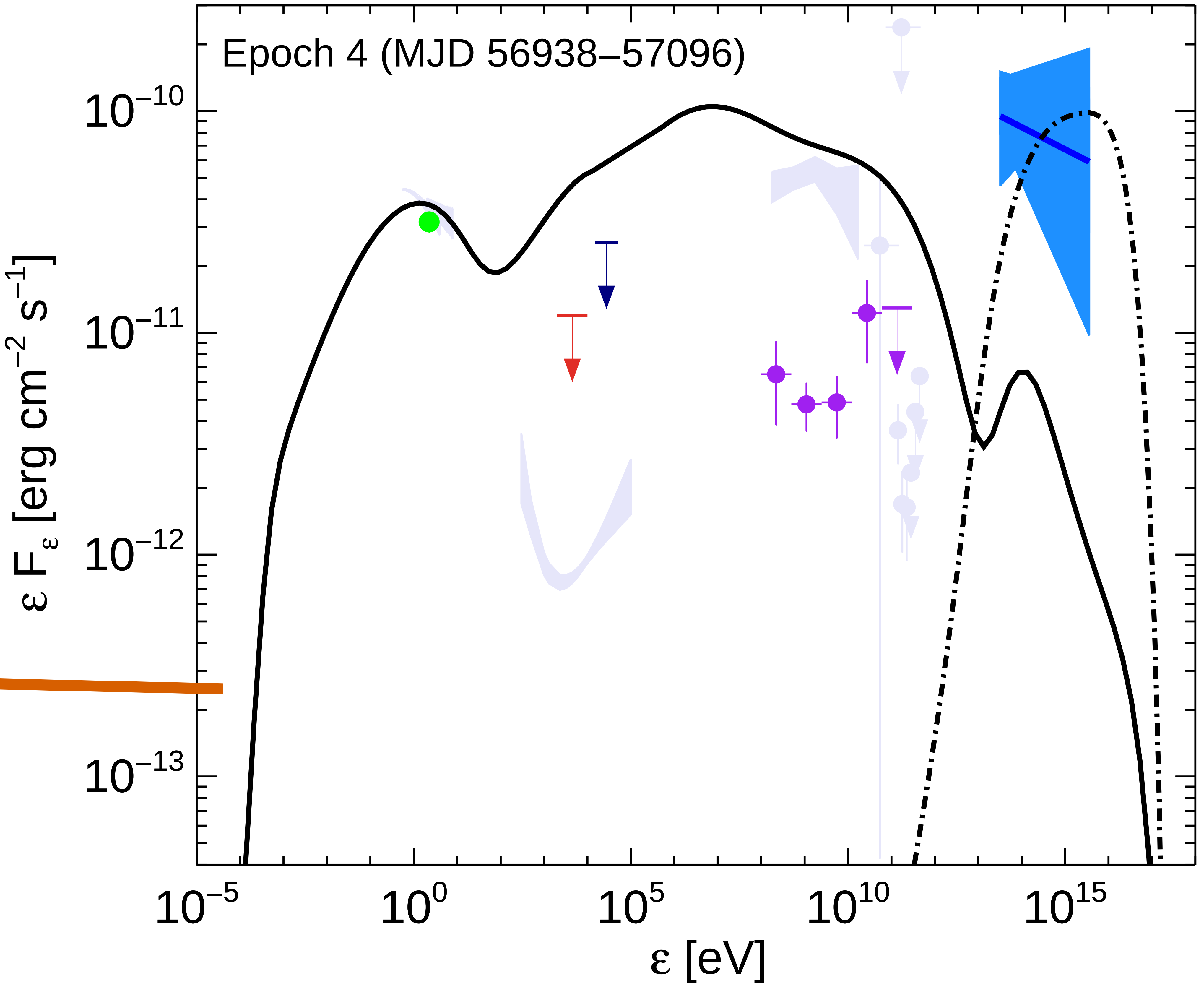

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- Multi-messenger follow ups with be crucial in the coming decade.

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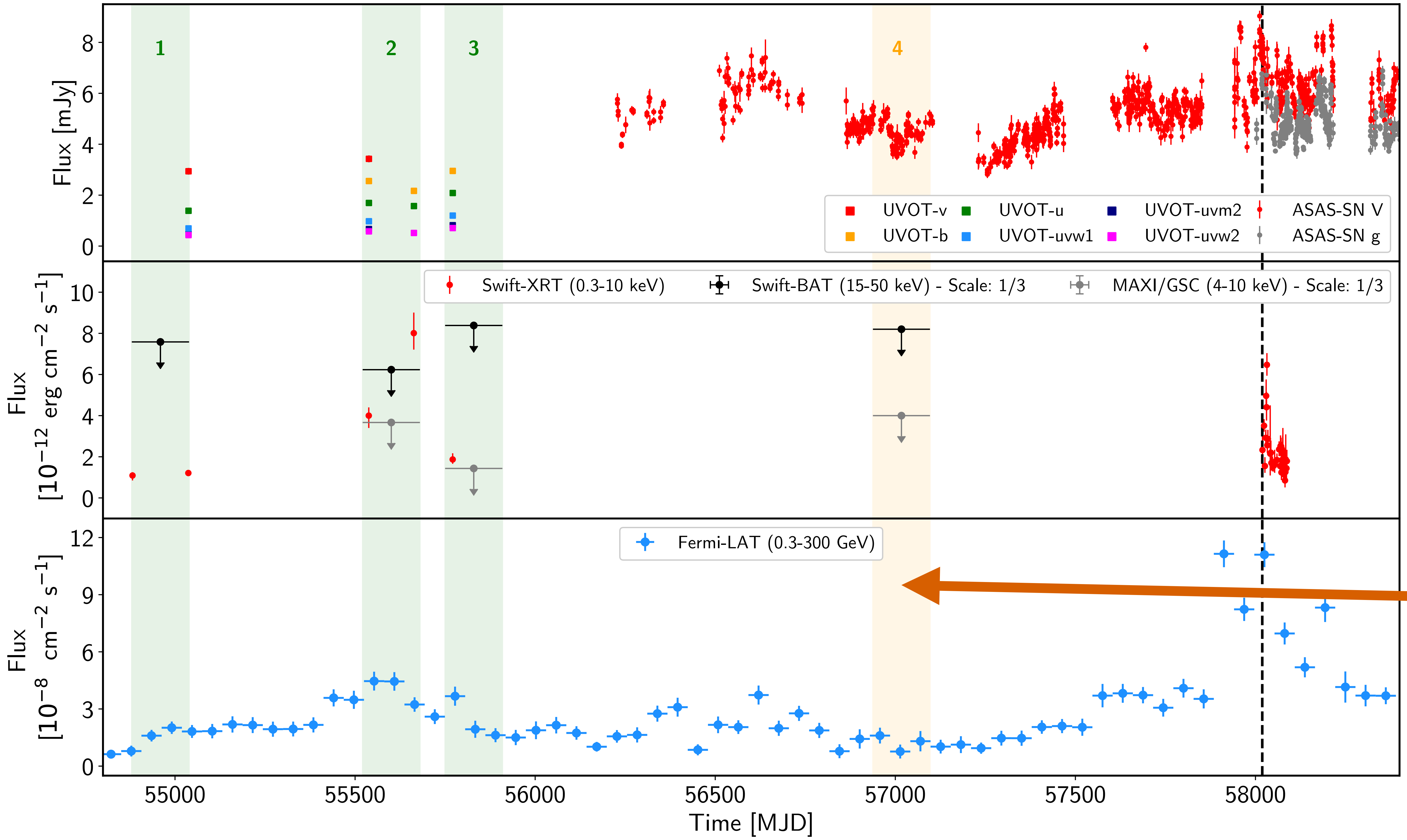

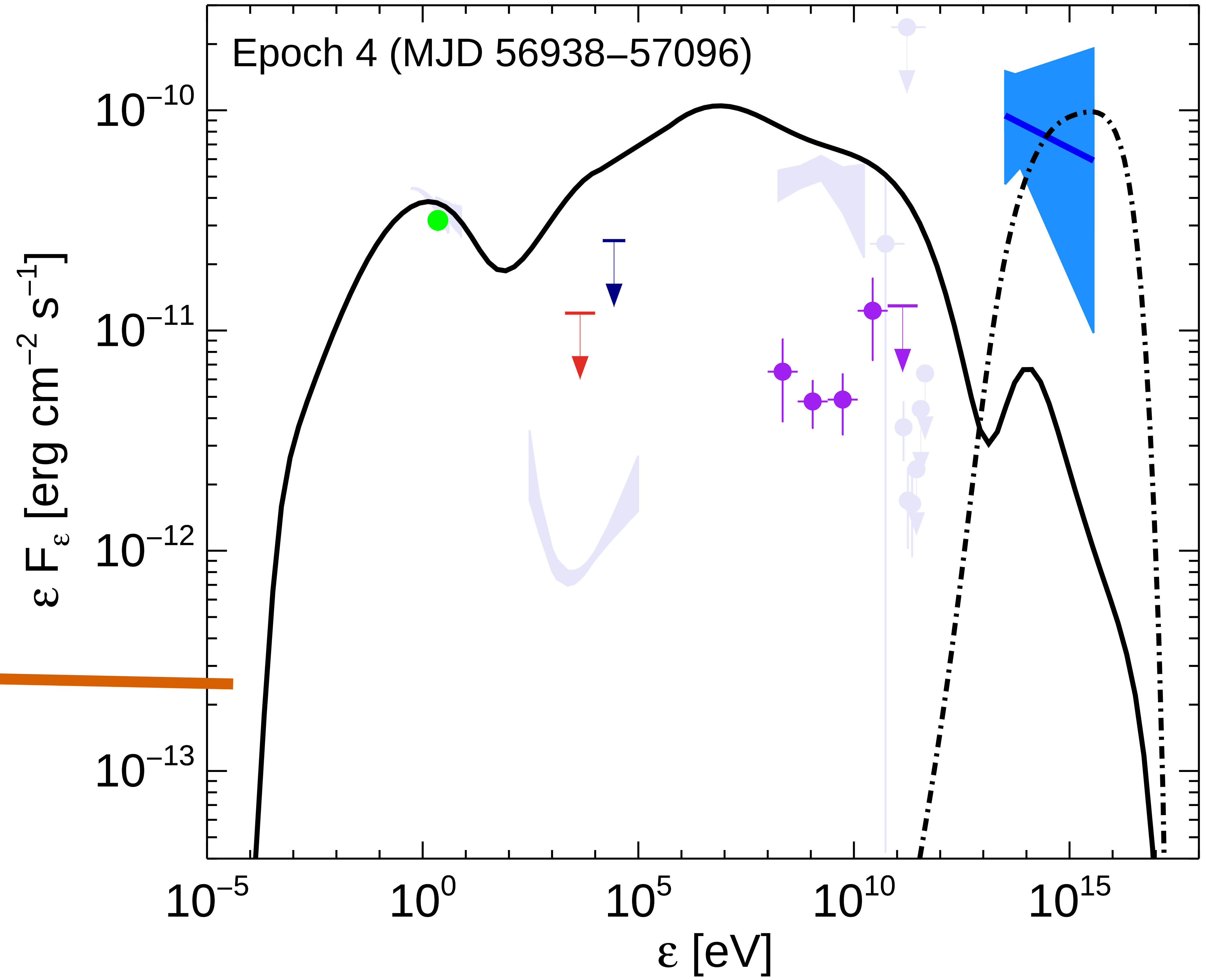

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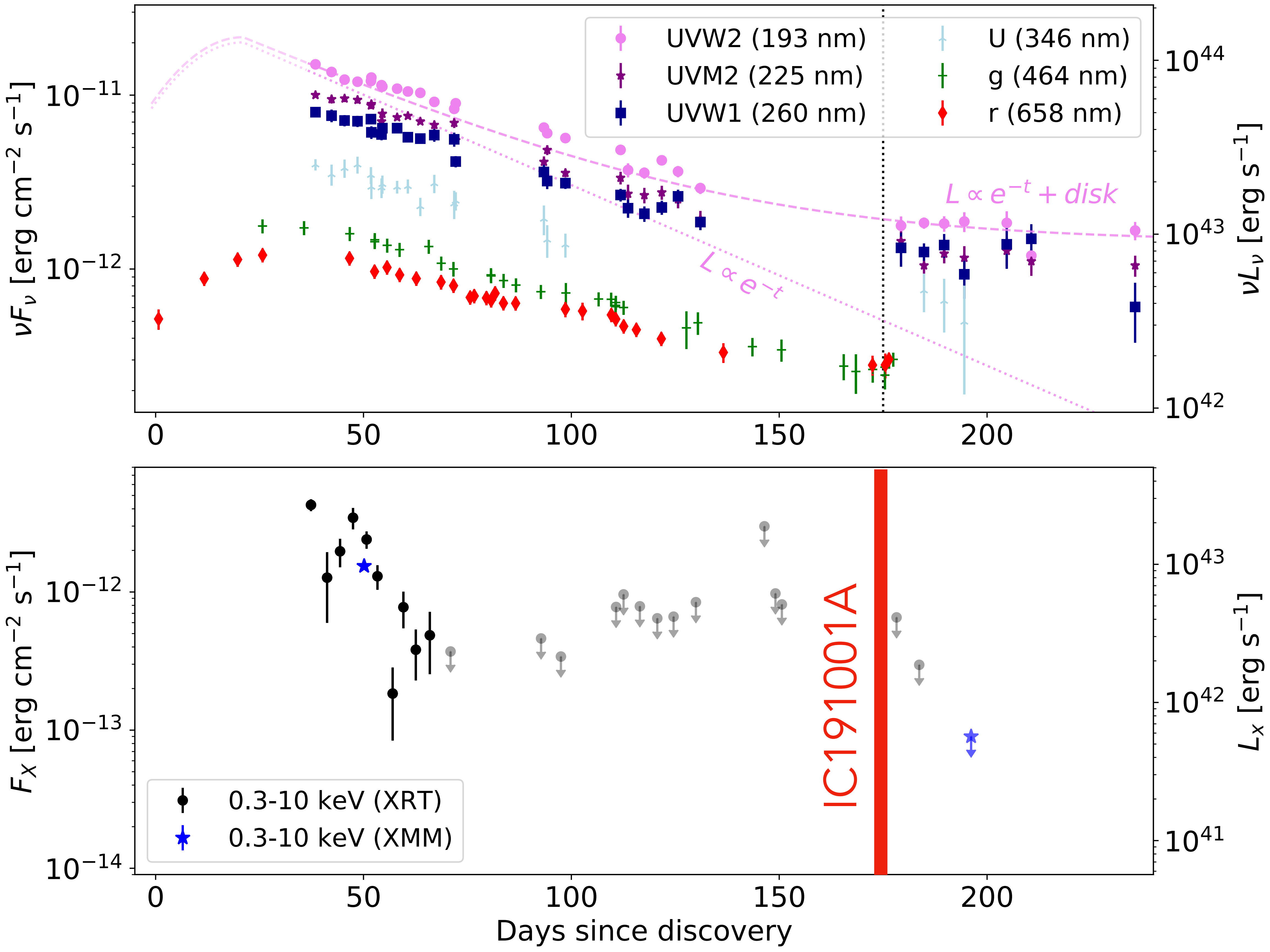
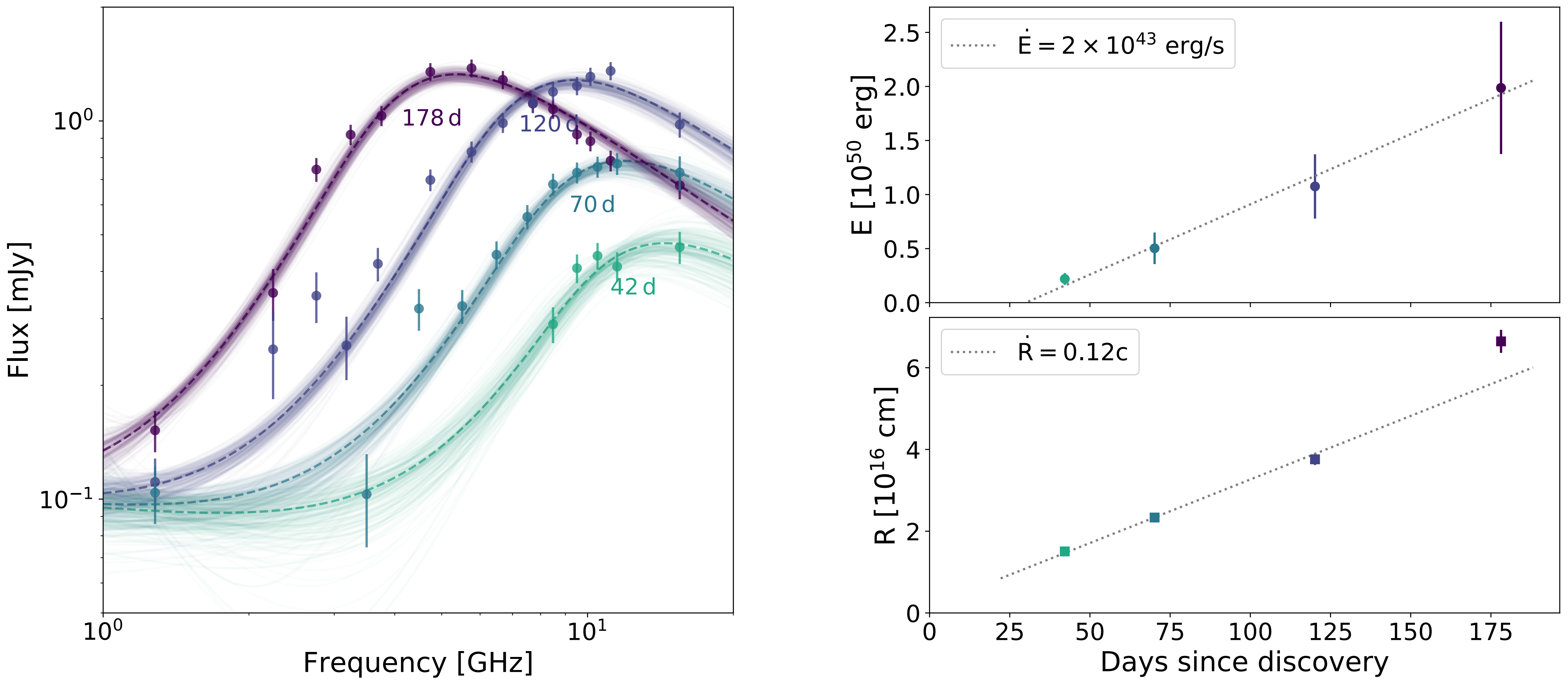
Many modeling efforts for 2014-15/17: Reimer+ 2019, Cerruti+ 2018, Zhang+ 2018, Keivani 2018+, Petropoulou+ 2019

NEUTRINOS FROM TDEs?

R. Stein et al. (ZTF) arXiv/2005.05340



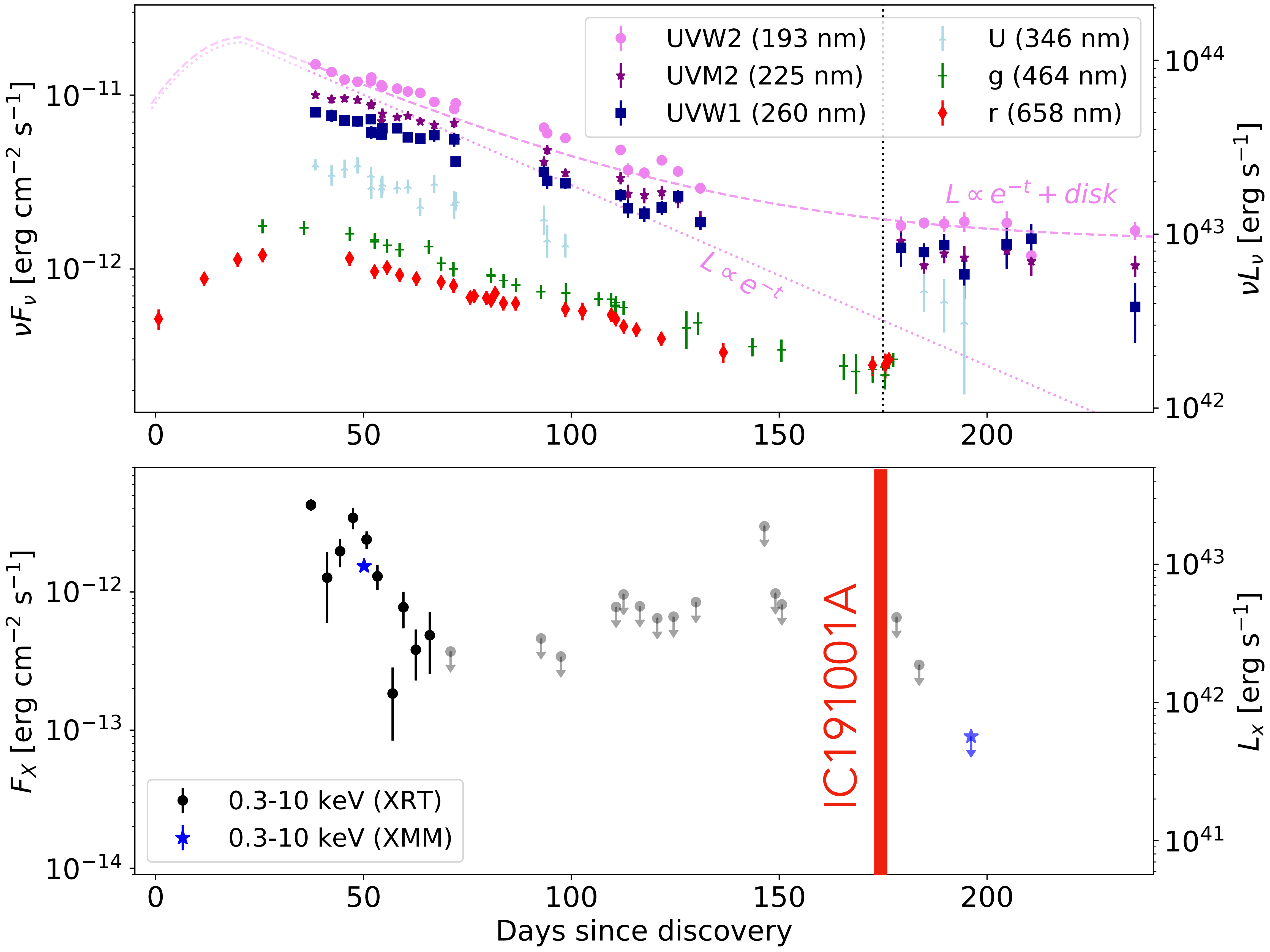


Radio TDE coincident with IC1901001A
0.5% chance probability

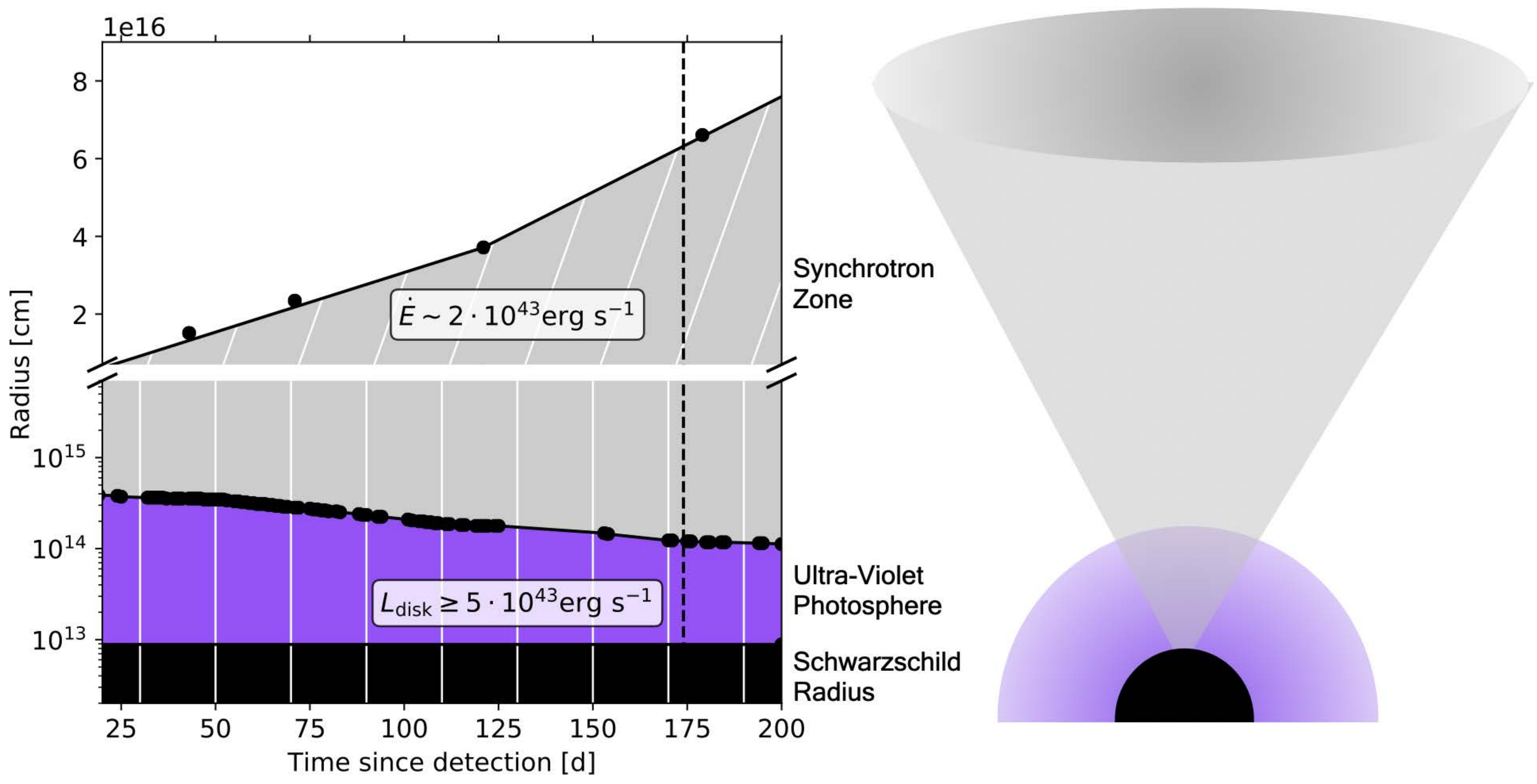
- Radio emission follows the synchrotron from the expansion of the flow.
- Time scales are long, well suited for a constant cadence, large area survey.

NEUTRINOS FROM TDEs?

R. Stein et al. (ZTF) arXiv/2005.05340

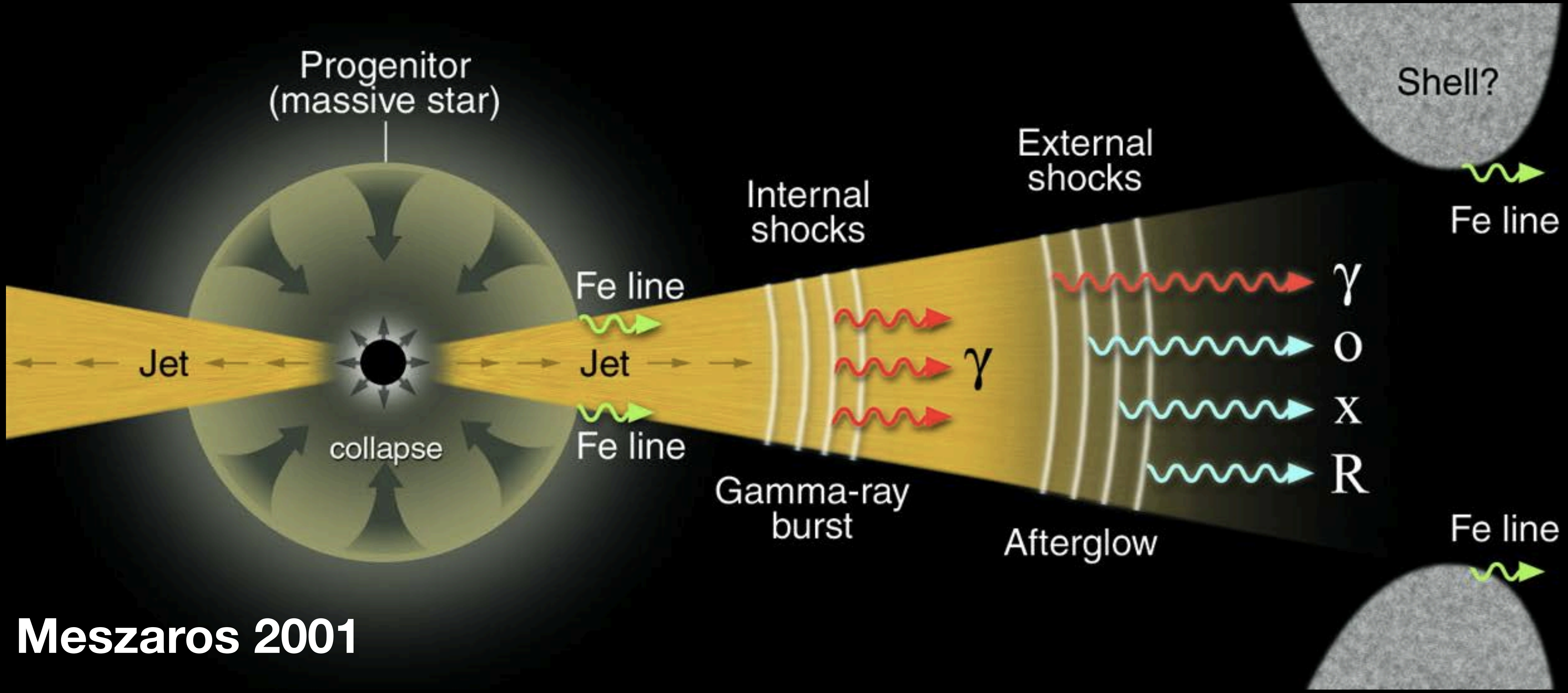


Radio TDE coincident with IC1901001A
0.5% chance probability



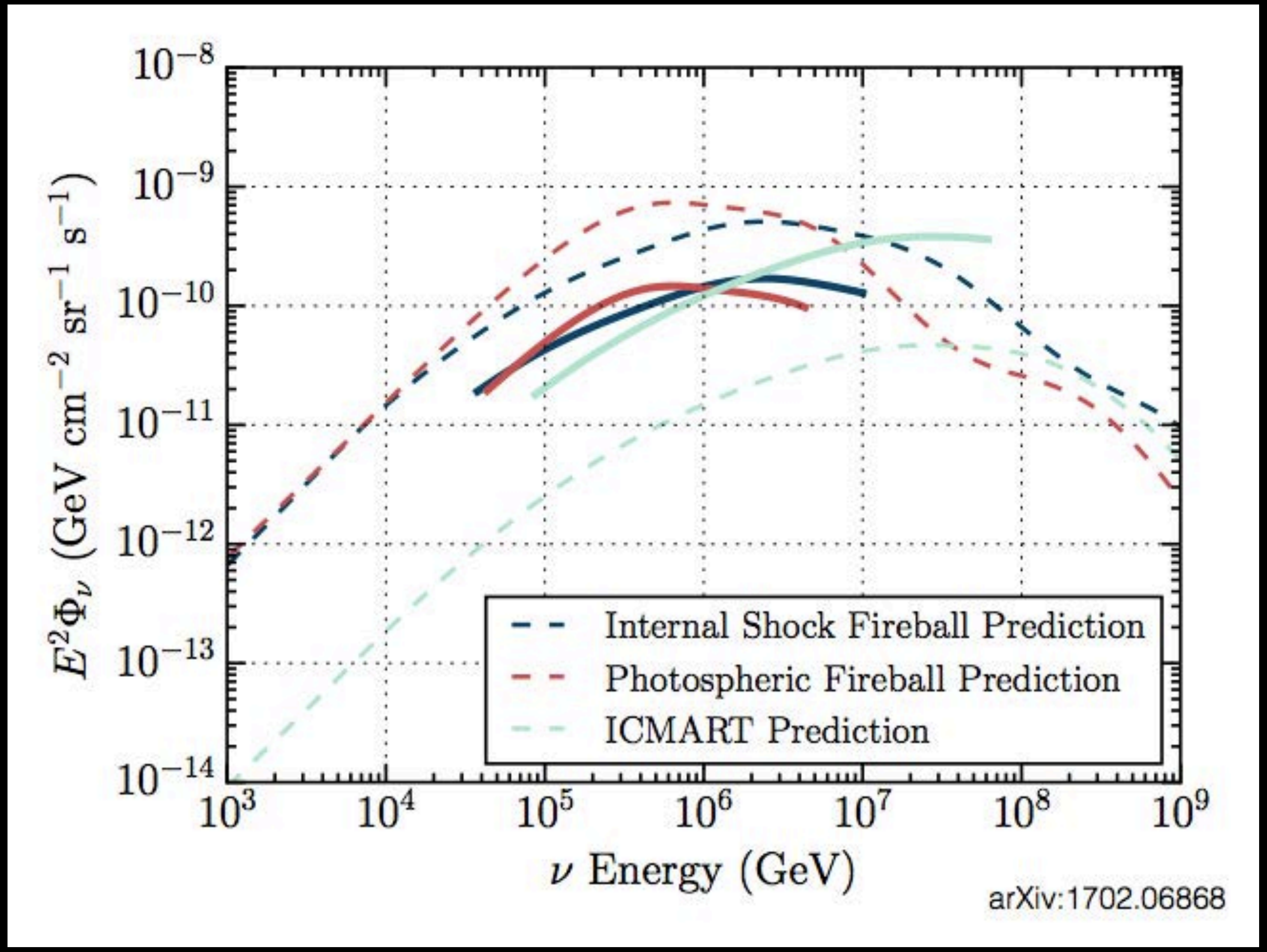
- Radio emission follows the synchrotron from the expansion of the flow.
- Time scales are long, well suited for a constant cadence, large area survey.

NEUTRINOS FROM GAMMA-RAY BURSTS?

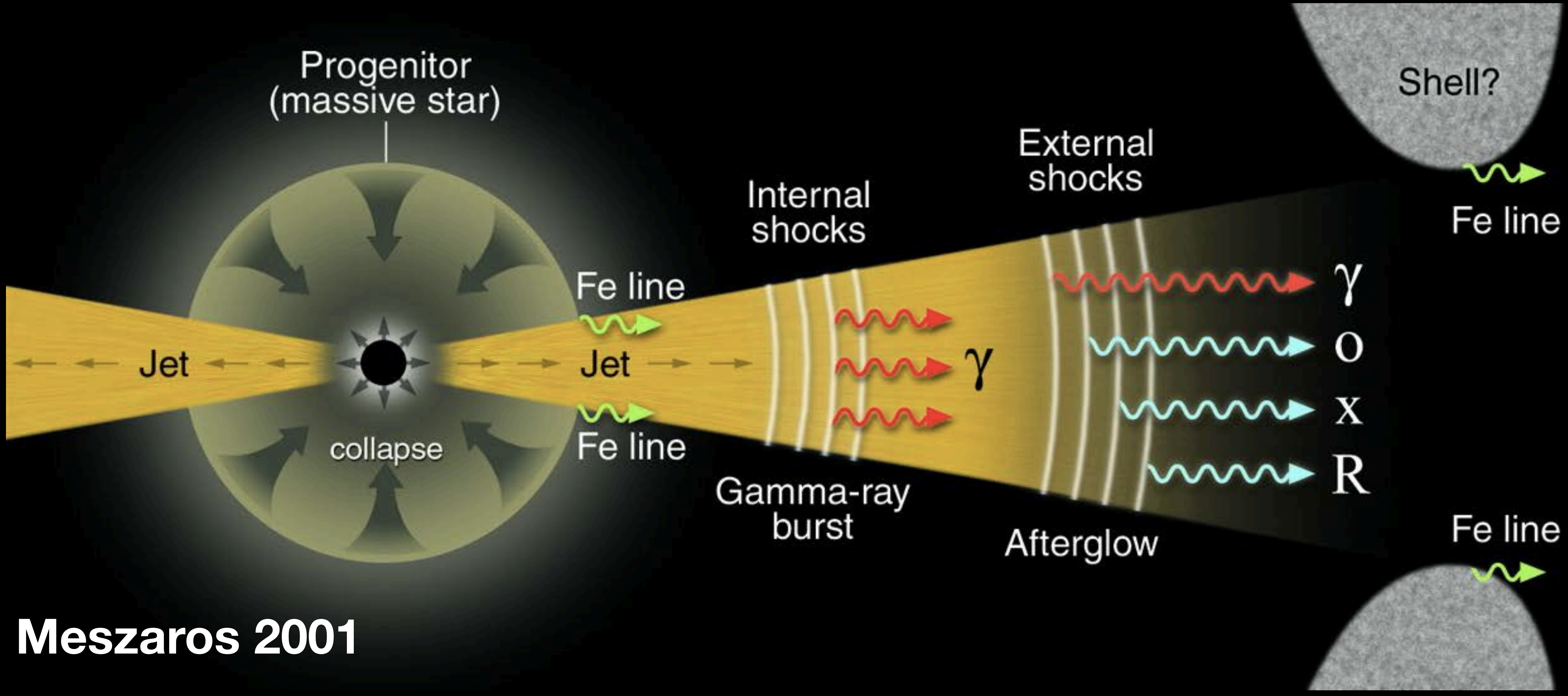


Meszaros 2001

IceCube ApJ 2016



NEUTRINOS FROM GAMMA-RAY BURSTS?



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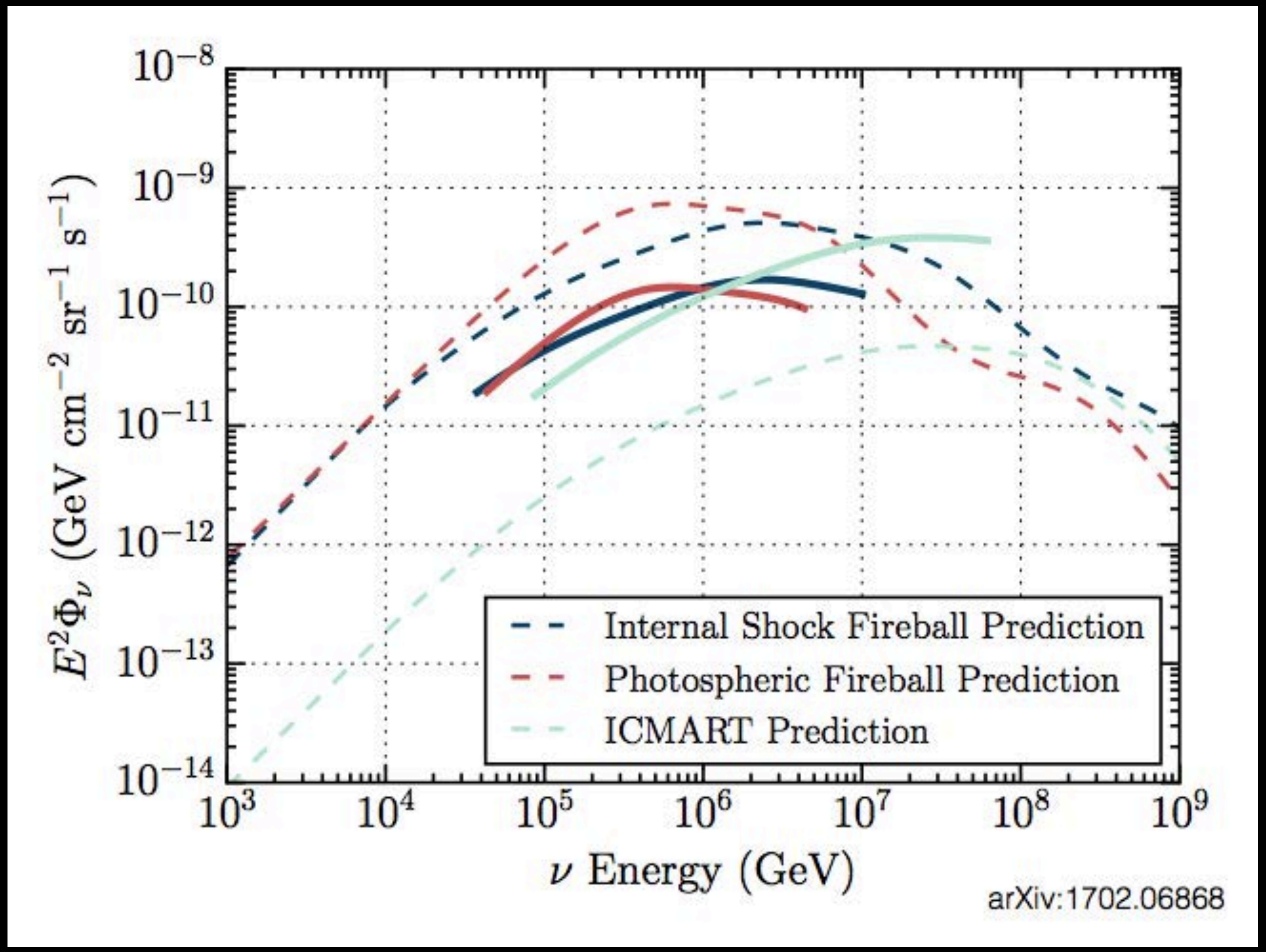
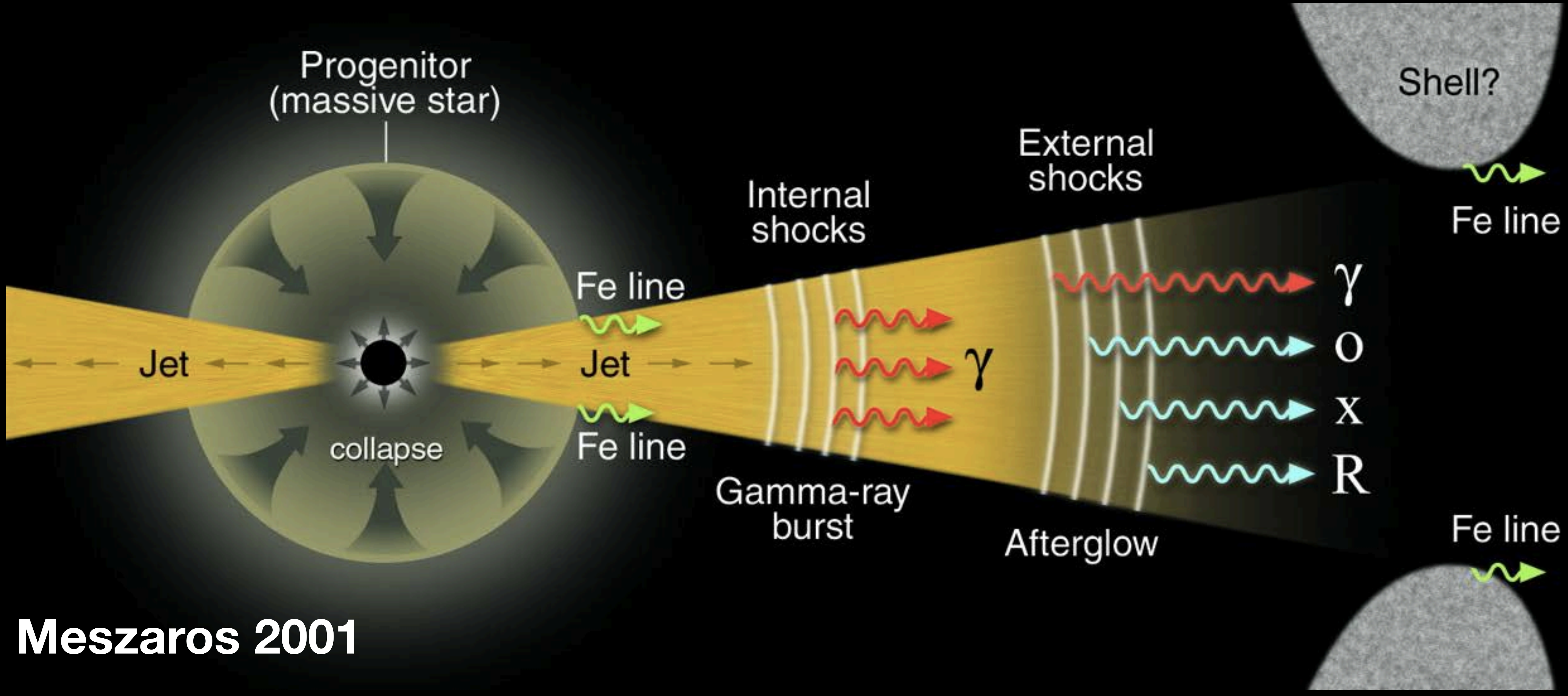


- GRBs are potential cosmic-ray accelerators (Waxman+ ’97, Razzaque+ ’03, Murase+ ’06).

NEUTRINOS FROM GAMMA-RAY BURSTS?



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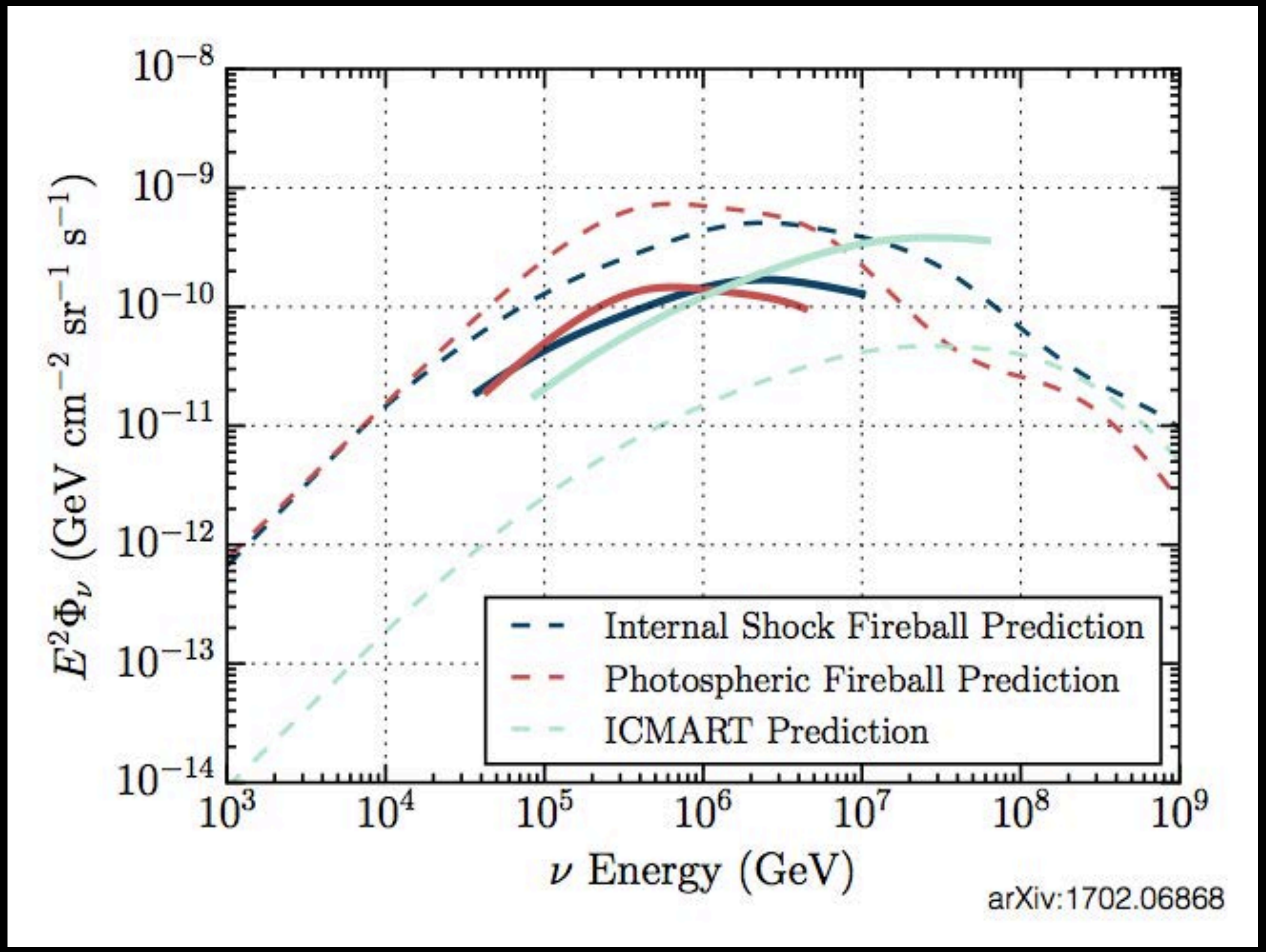

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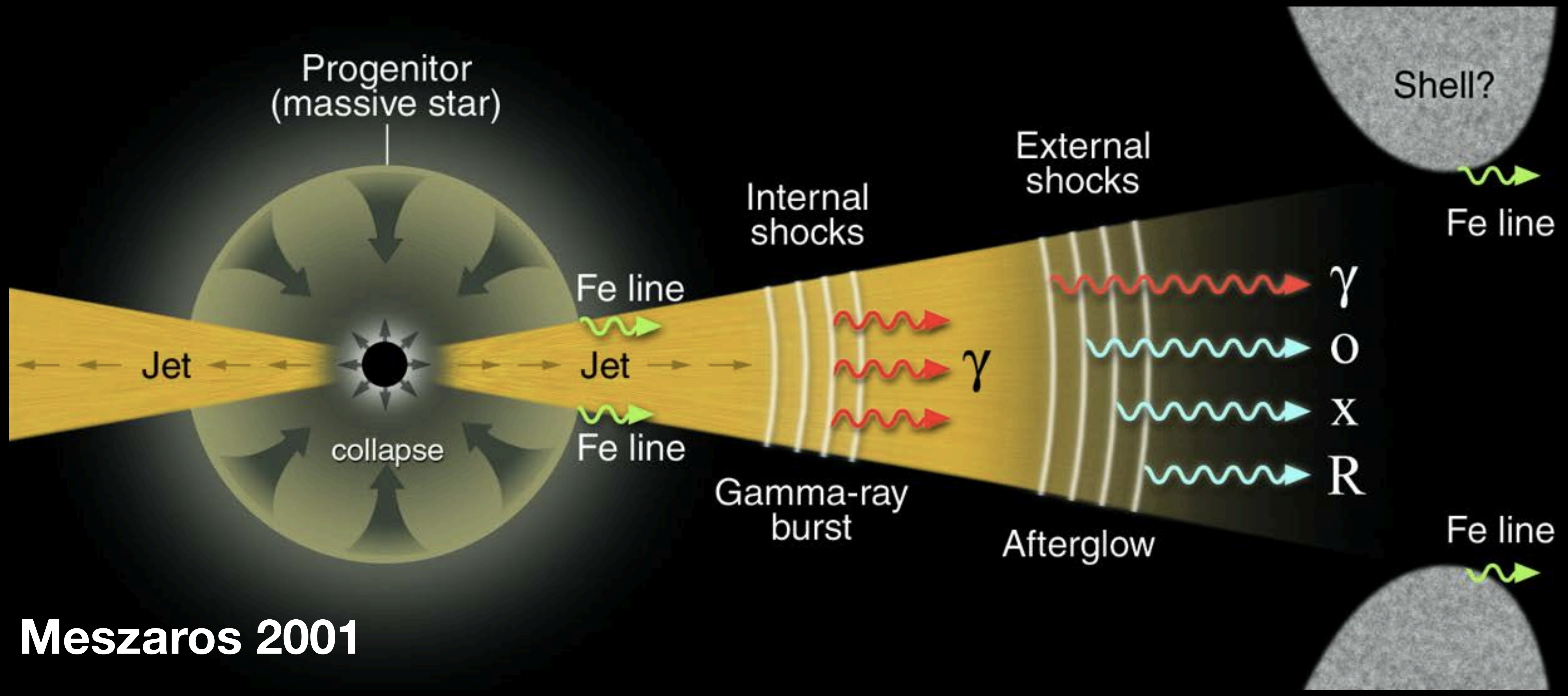
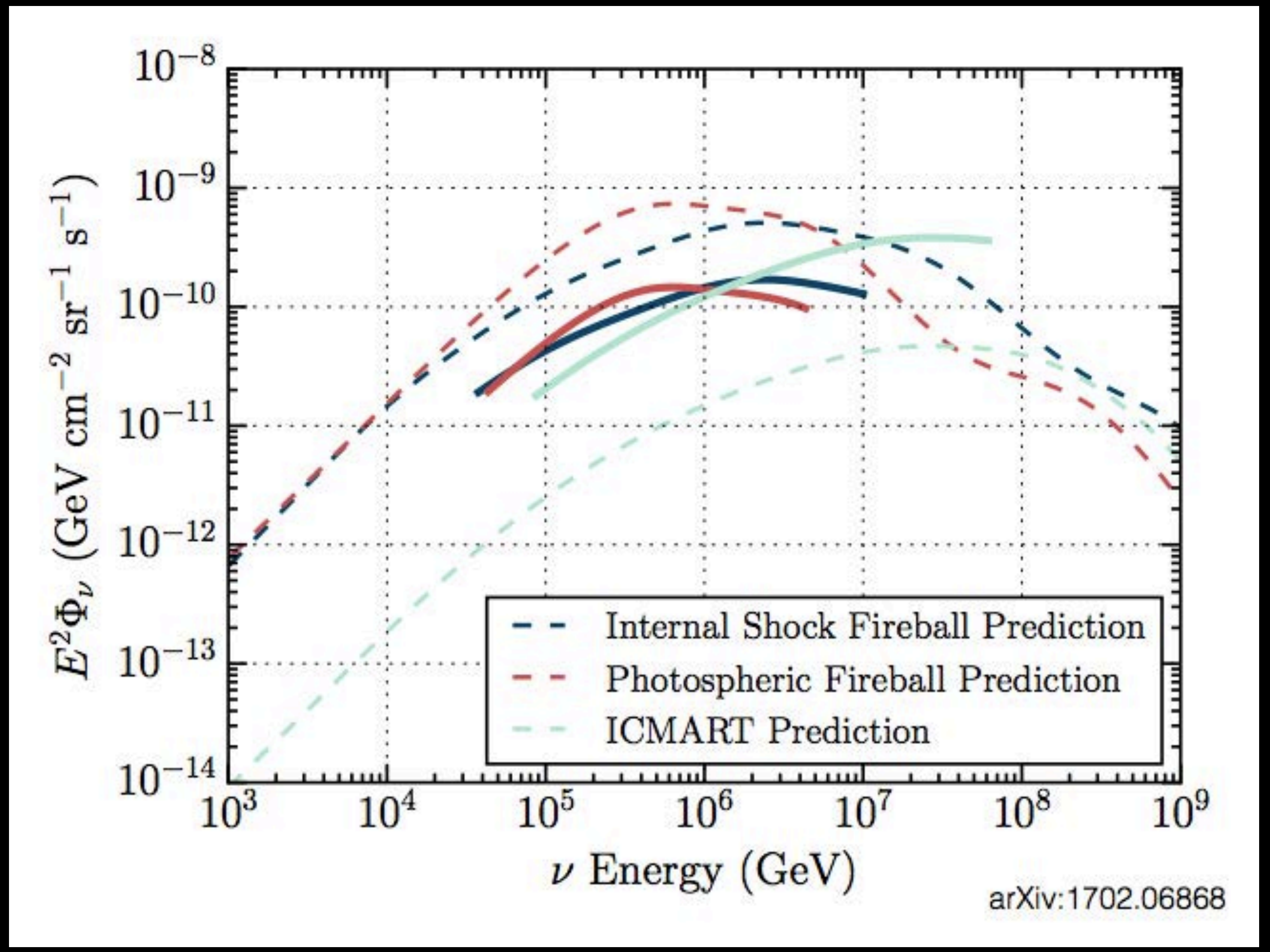
IceCube ApJ 2016

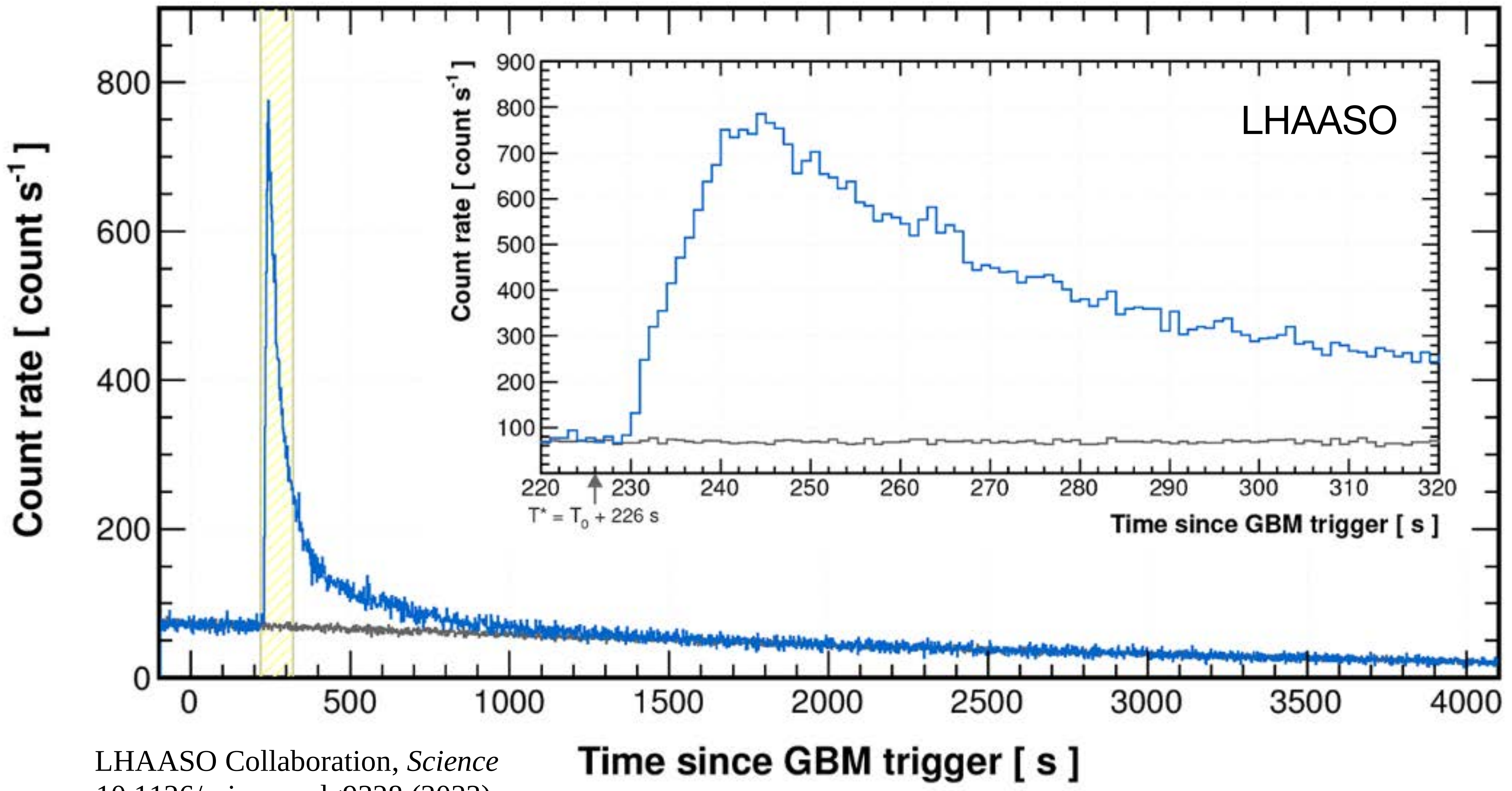


Meszaros 2001



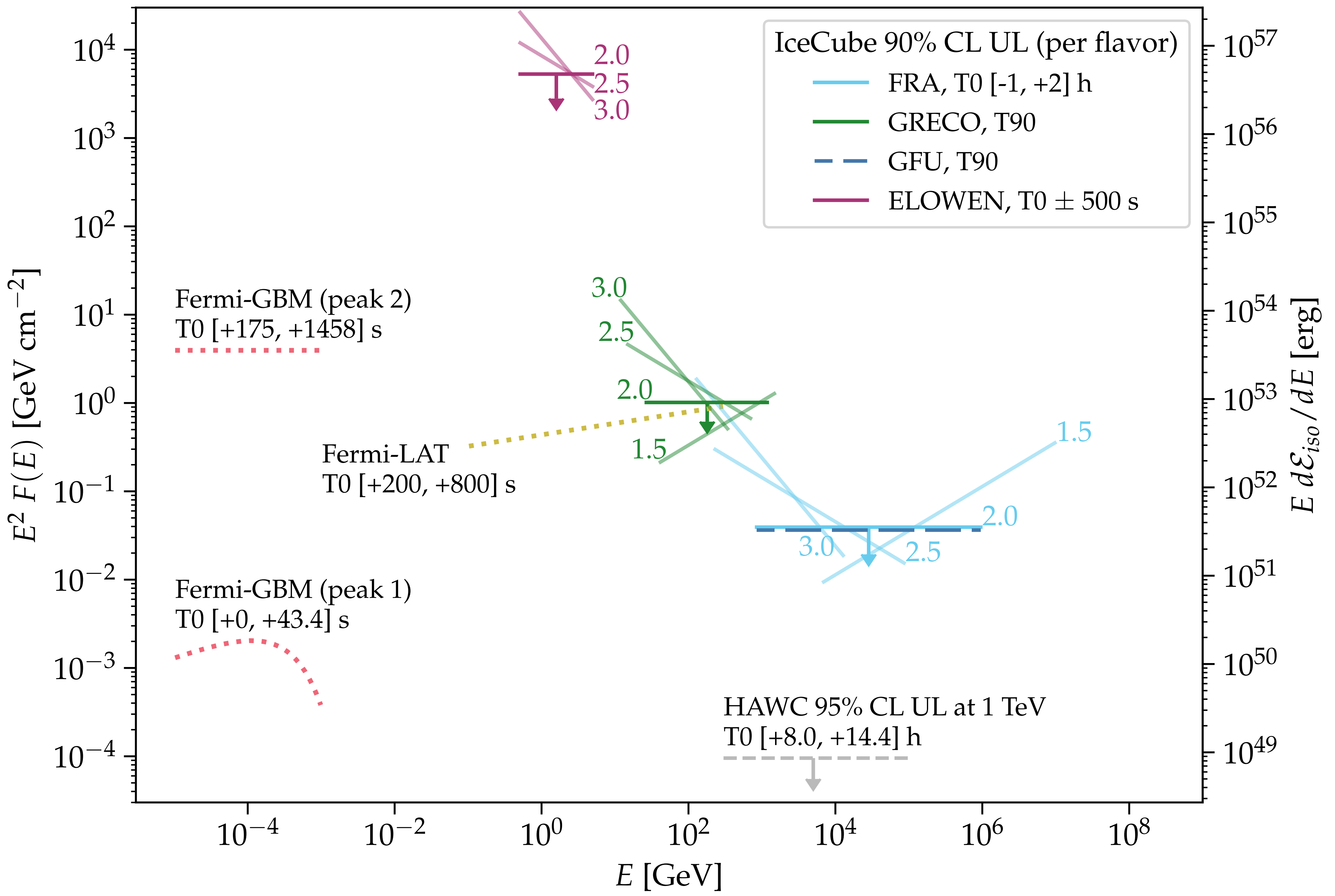
- GRBs are potential cosmic-ray accelerators (Waxman+ '97, Razzaque+ '03, Murase+ '06).
- Short duration limits the impact of backgrounds. > 1000 bursts considered in coincident studies.
- Strong limits on neutrino emission from GRBs. **Contribution to all-sky flux < 1%.**

VHE gammas from the "Boat" GRB?

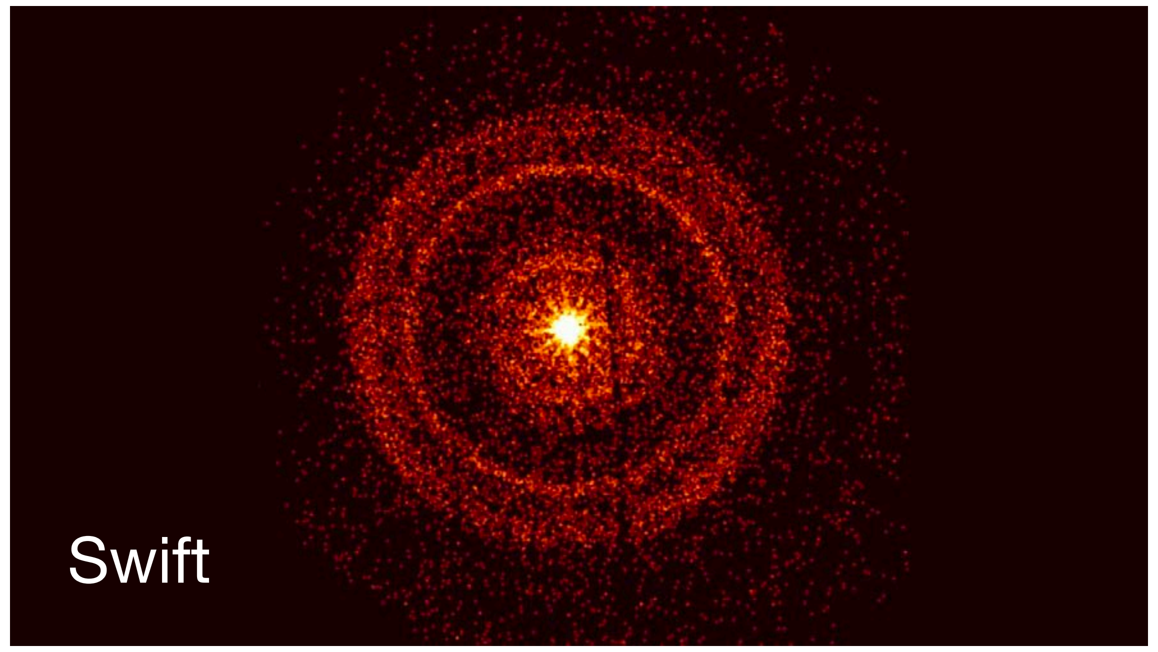


LHAASO Collaboration, *Science* 10.1126/science.adg9328 (2023).

IceCube arXiv/2302.05459



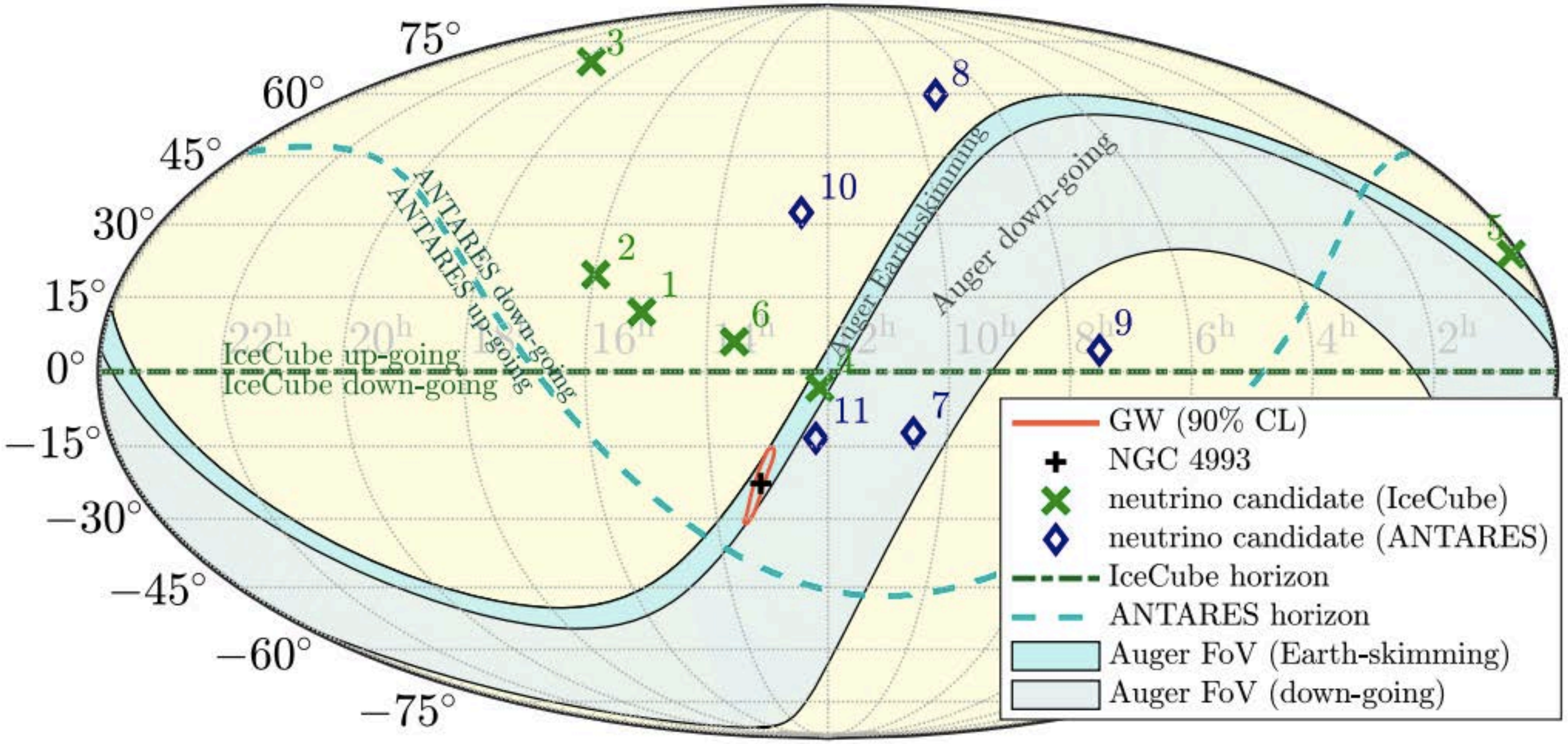
- Brightest GRB of all time (Burns et al. arXiv/2302.14037)
- More than 64k photons detected within the first 2000 s (> 0.2 TeV) by LHAASO

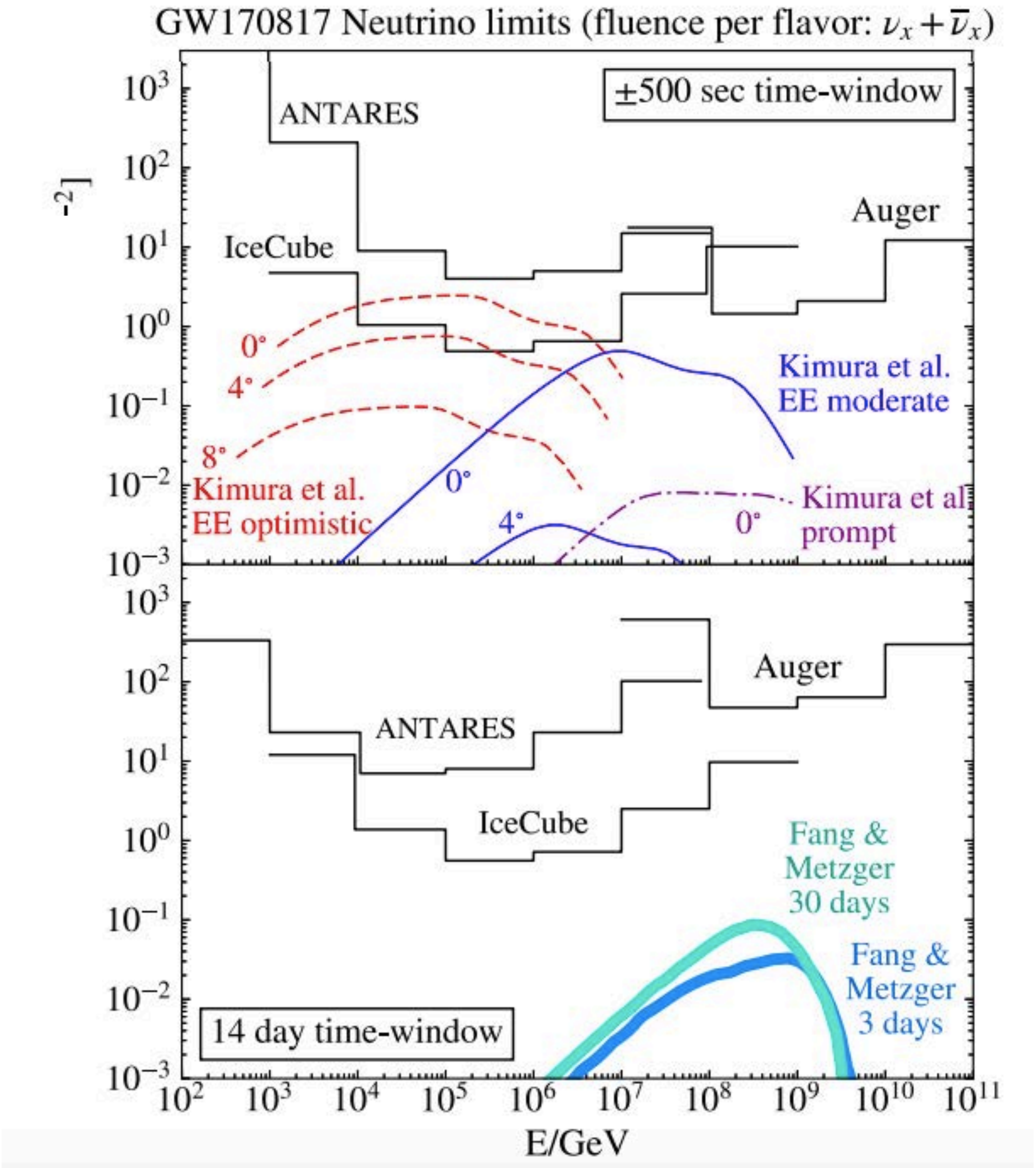


- No neutrinos in IceCube from MeV to >PeV range.
- Constraint a broad range of neutrino emission models.

NEUTRINOS FROM GW SOURCES?

GW170817



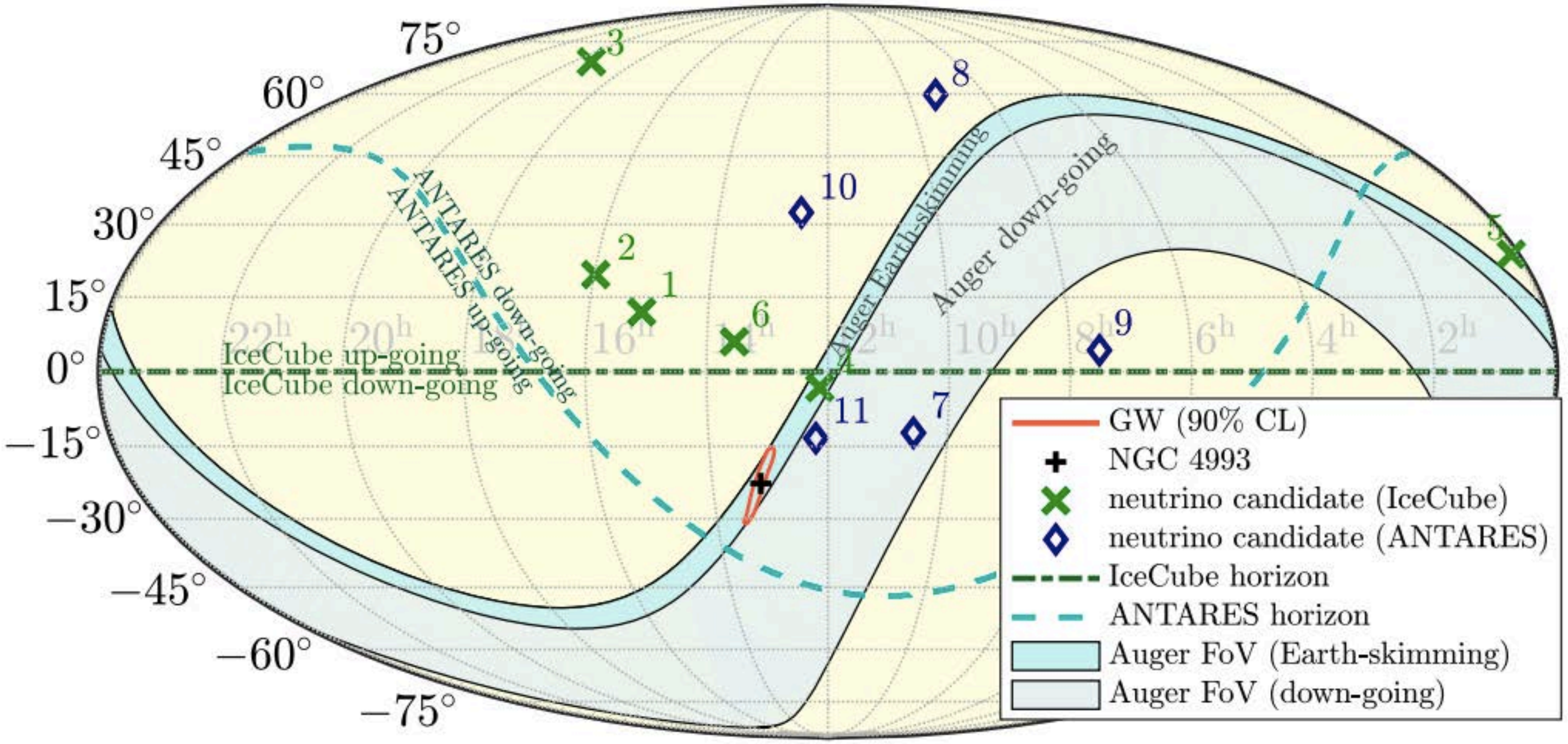


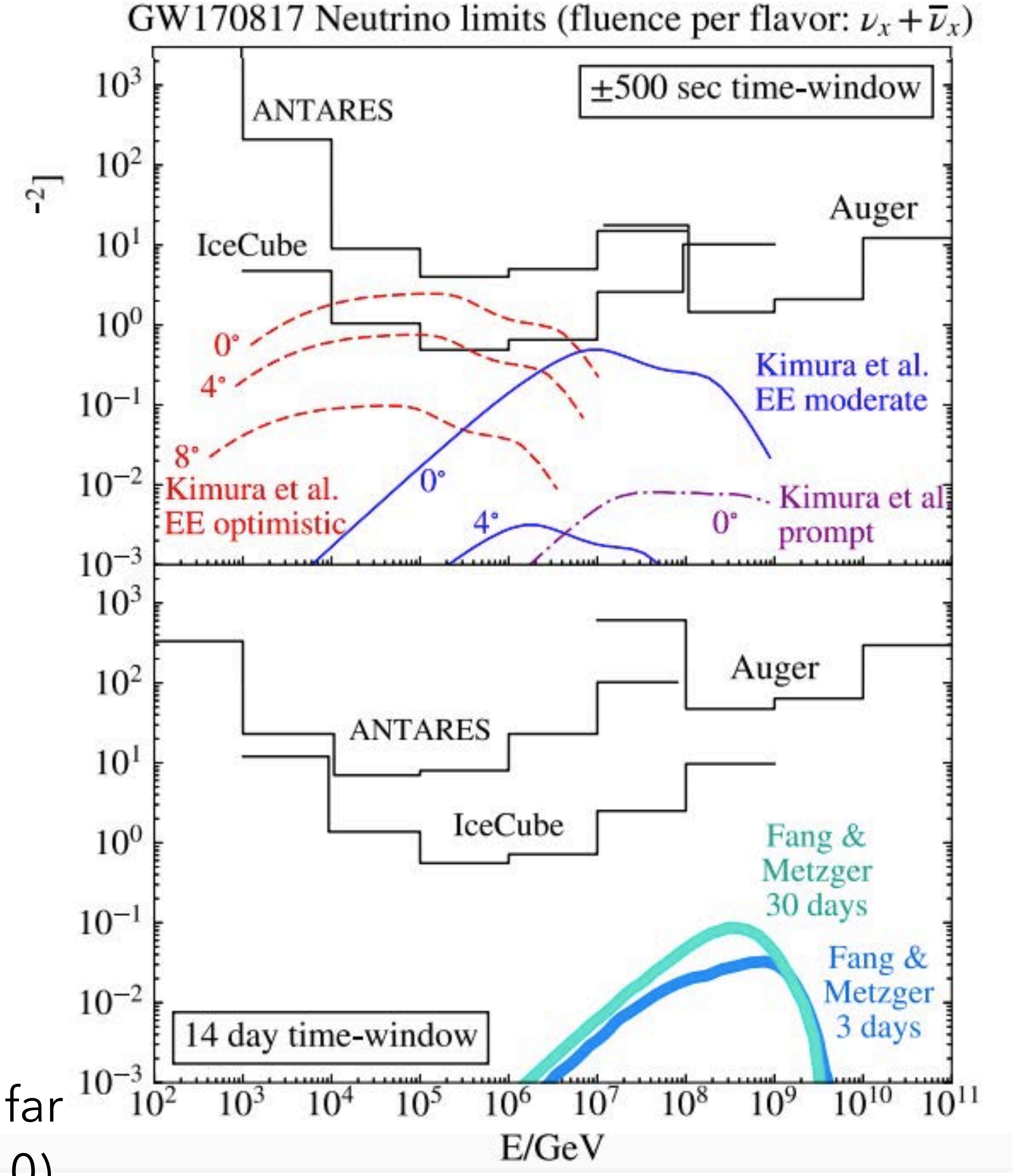
ANTARES / Auger / IceCube

arXiv/1710.05839

NEUTRINOS FROM GW SOURCES?

GW170817



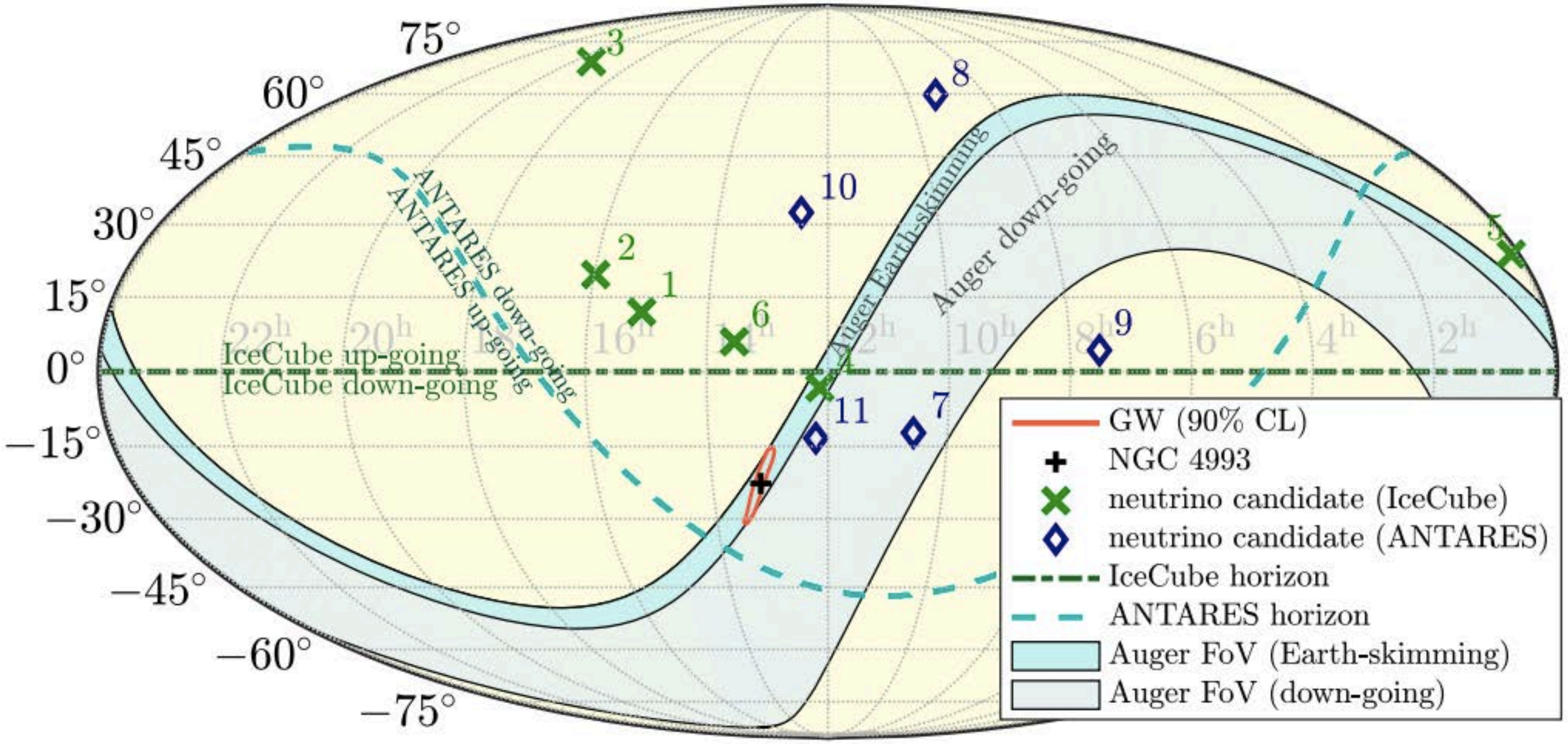


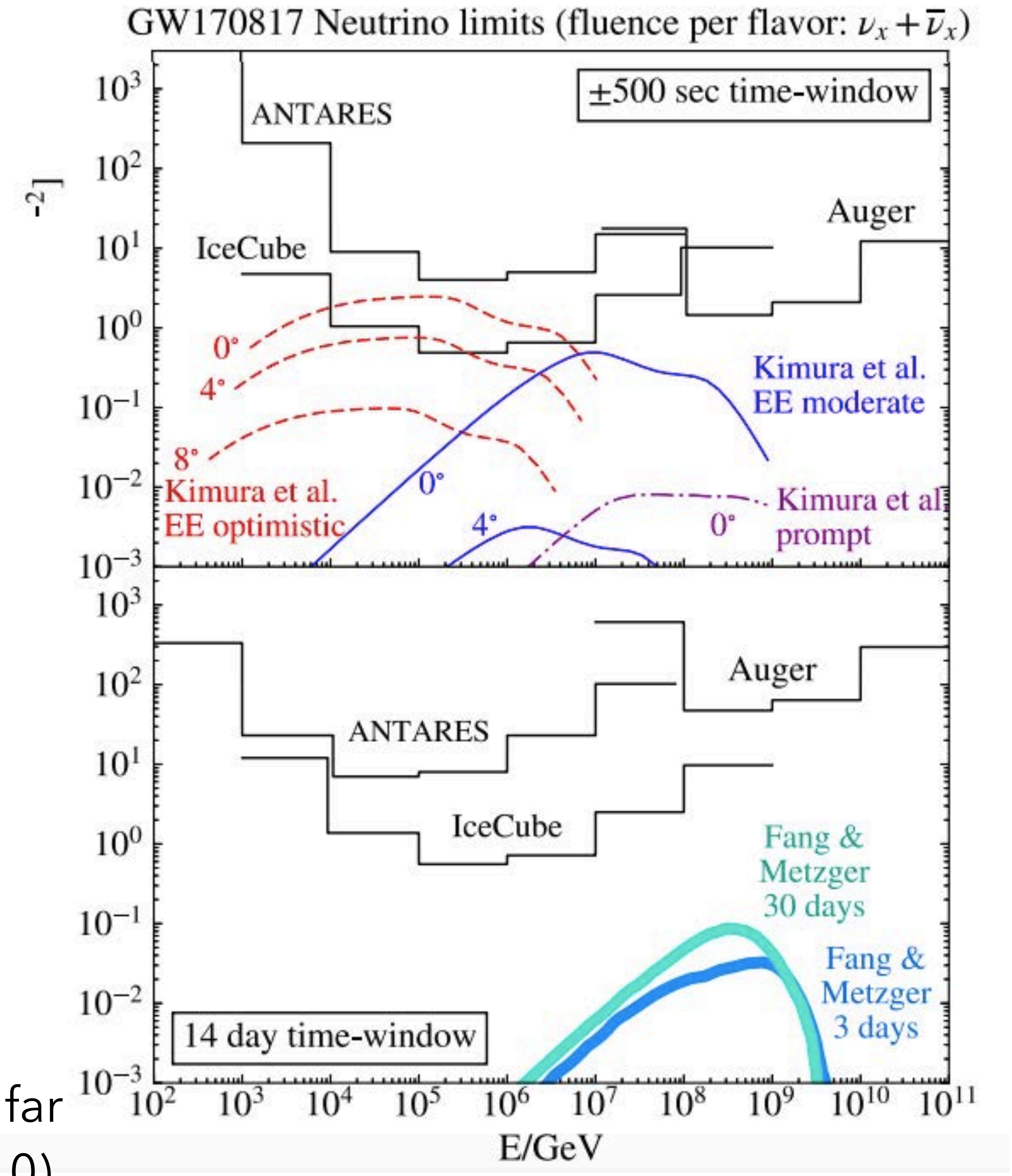
ANTARES / Auger / IceCube
arXiv/1710.05839

- No neutrinos associated with BNS and BBHs detected by LIGO/Virgo so far in ANTARES (arXiv/2003.04022) and IceCube searches (arXiv/2004.02910)

NEUTRINOS FROM GW SOURCES?

GW170817



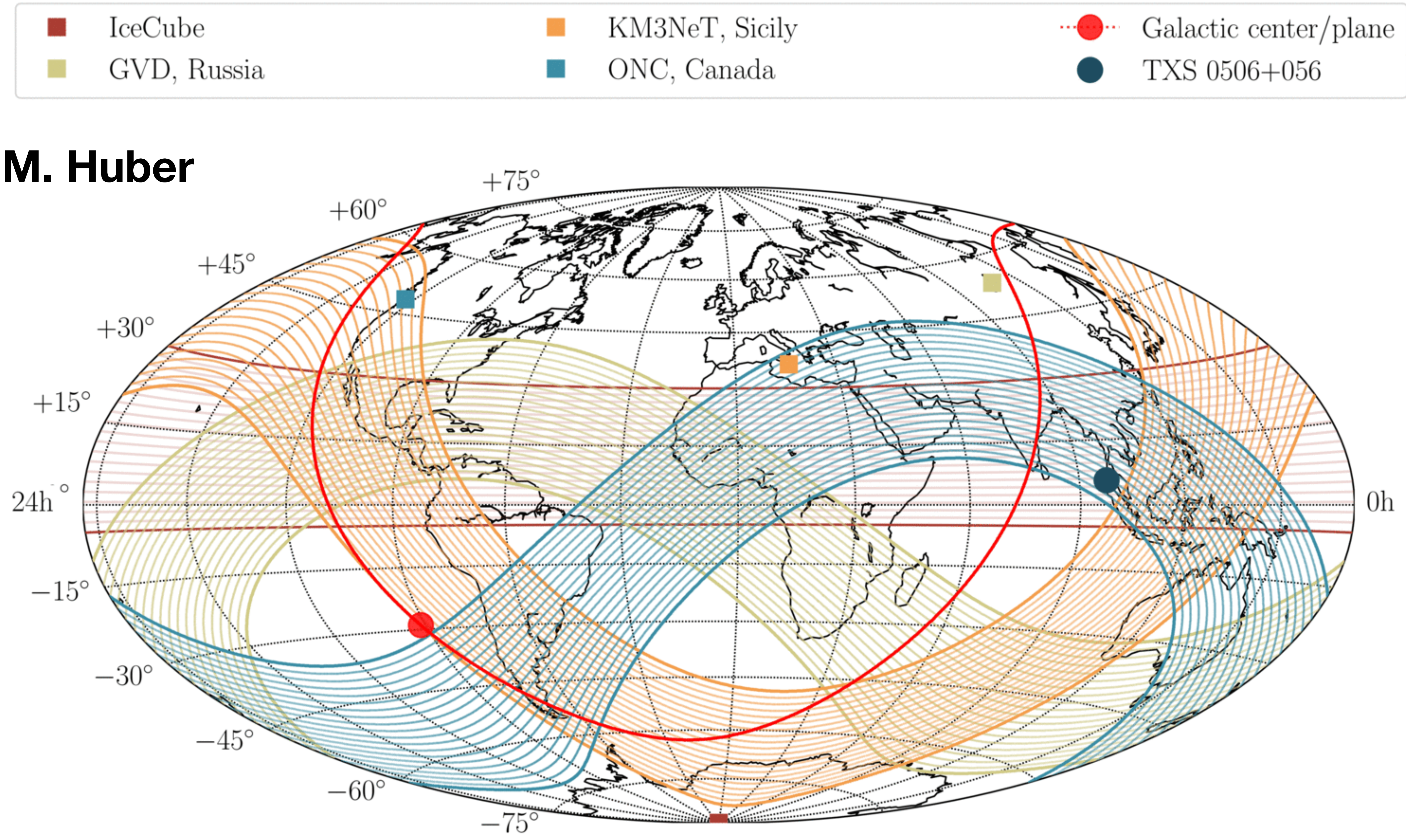


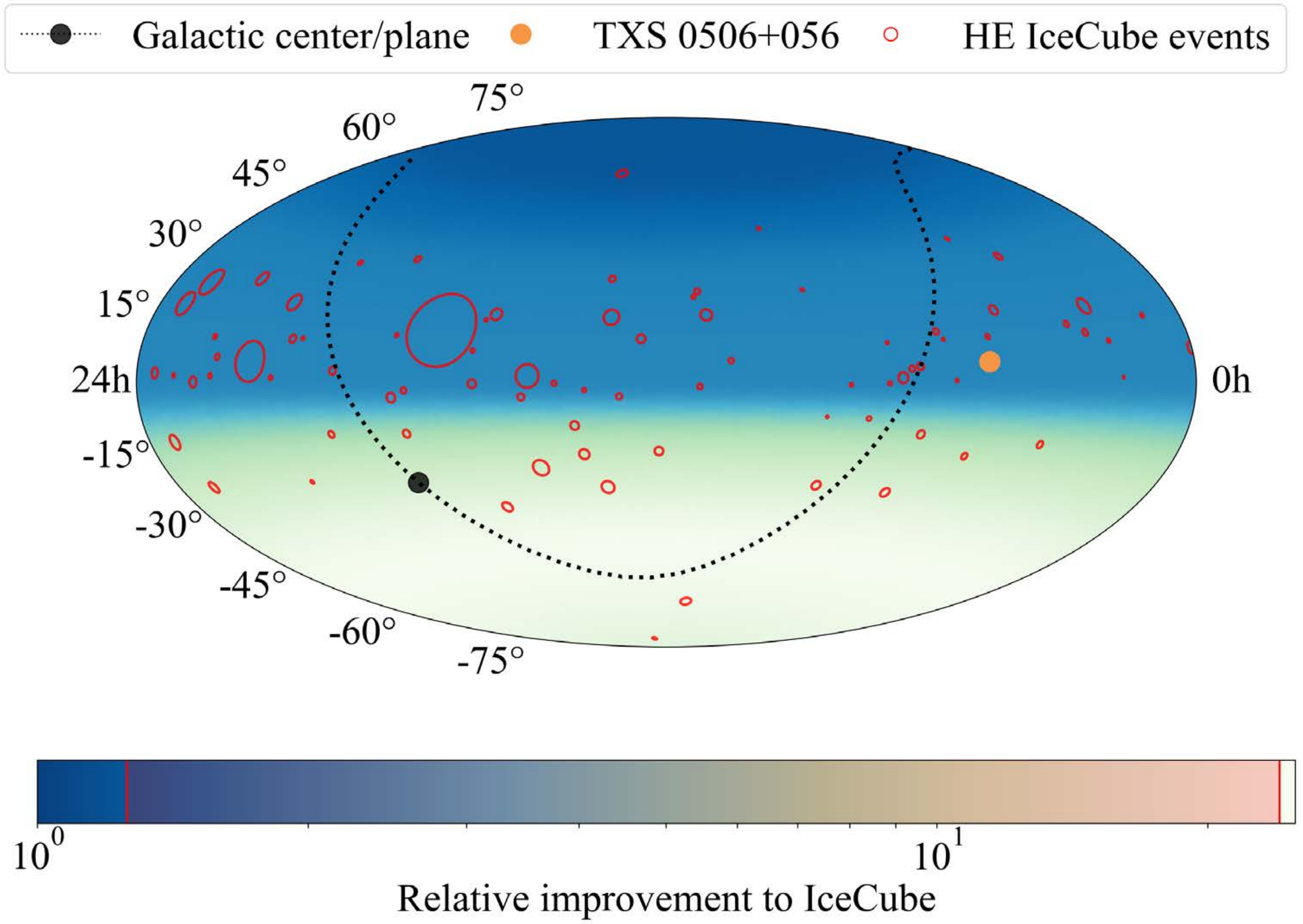
- No neutrinos associated with BNS and BBHs detected by LIGO/Virgo so far in ANTARES (arXiv/2003.04022) and IceCube searches (arXiv/2004.02910)
- IceCube realtime search for coincidences for the current LIGO run.

ANTARES / Auger / IceCube
arXiv/1710.05839

A GLOBAL NEUTRINO TELESCOPE NETWORK

M. Huber

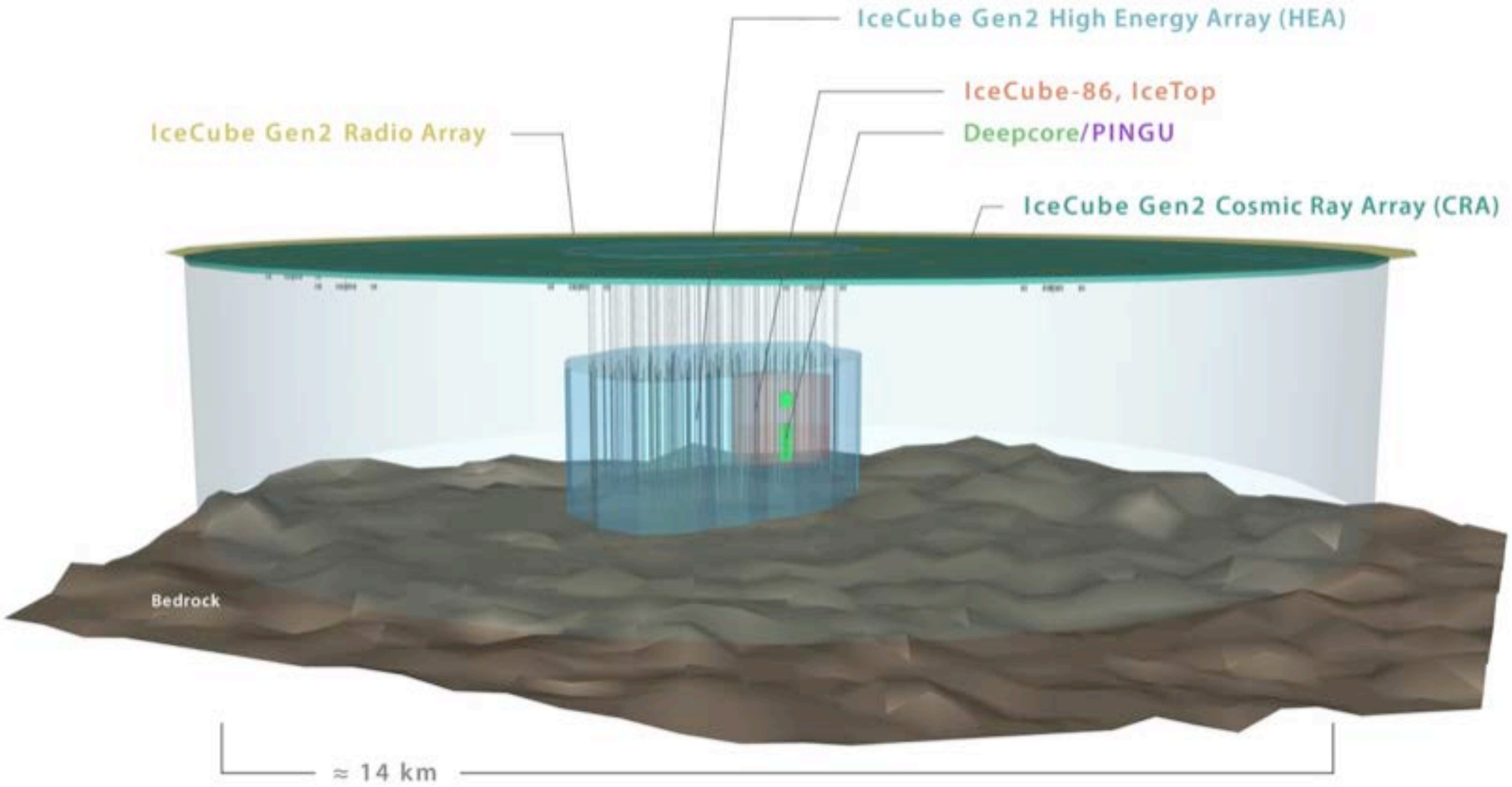




Sensitive to spectral index

- 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**.

ICECUBE-GEN2

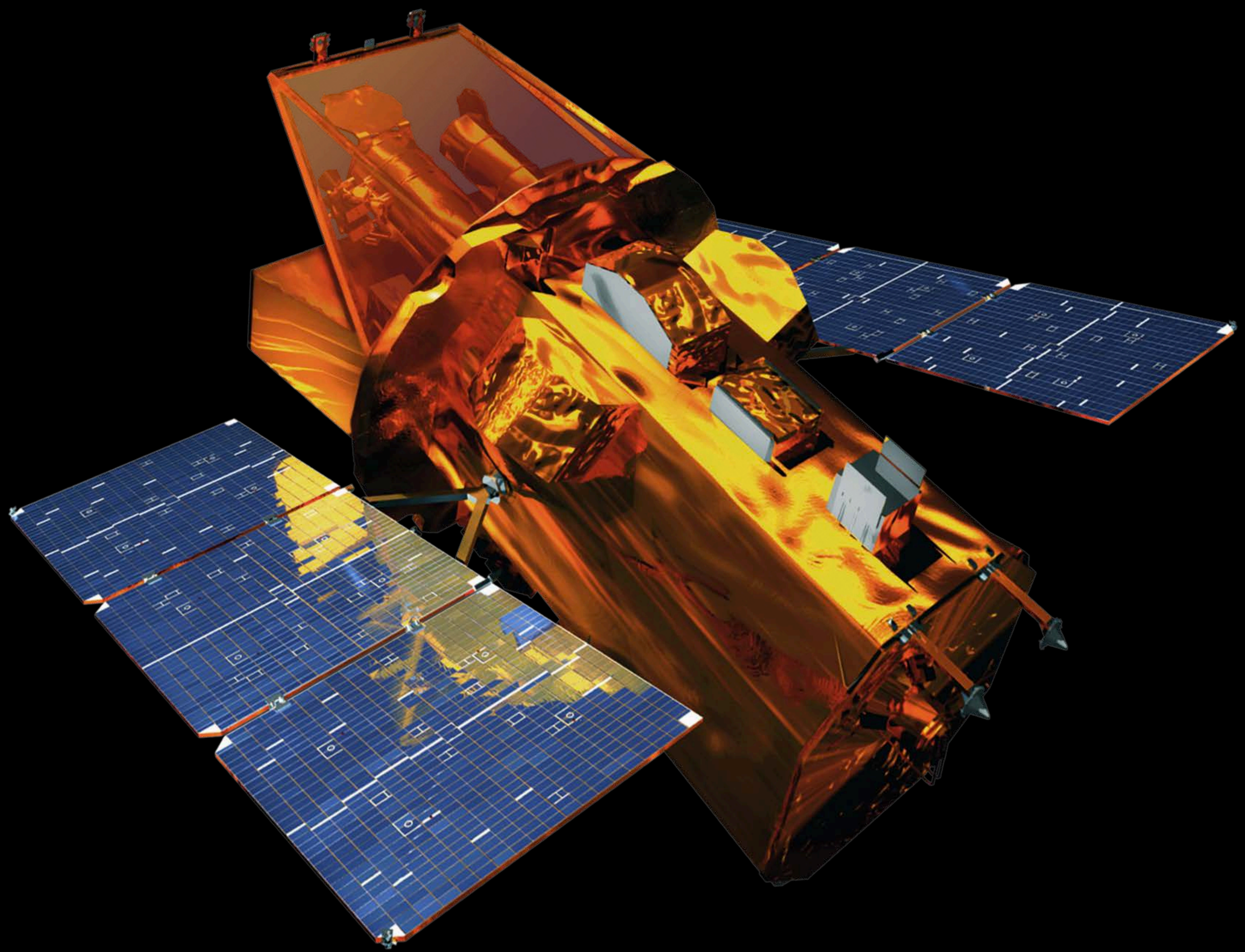


Astronomy with Gen2
arXiv/1911.02561

- 6.2-9.5 km^3 volume.
- >5x improvement in point-source sensitivity over IceCube.
- ~0.2° angular resolution.
- Proposed array for radio neutrino detection to extend the high-energy reach of the instrument.

X-RAY COVERAGE

Neil Gehrels *Swift* Observatory



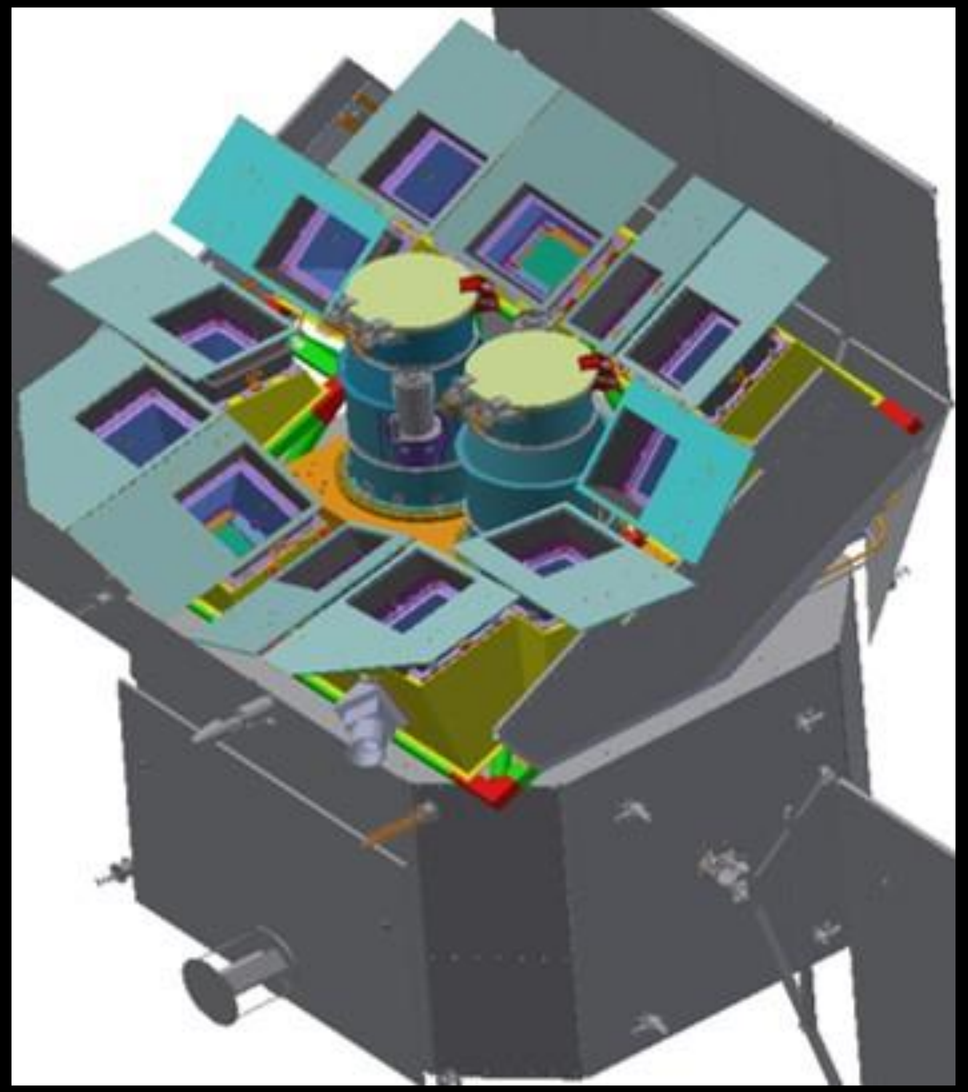
XRT sensitivity in the 0.3-10 keV
Fast response, low overhead.
110 cm^2
~10^{-13} erg/cm2/s in ~2 ks
~0.4 deg FoV
Launched in 2004.

SVOM (China-France)

Rapid follow-ups of GRBs
Launch date of Spring 2024
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)

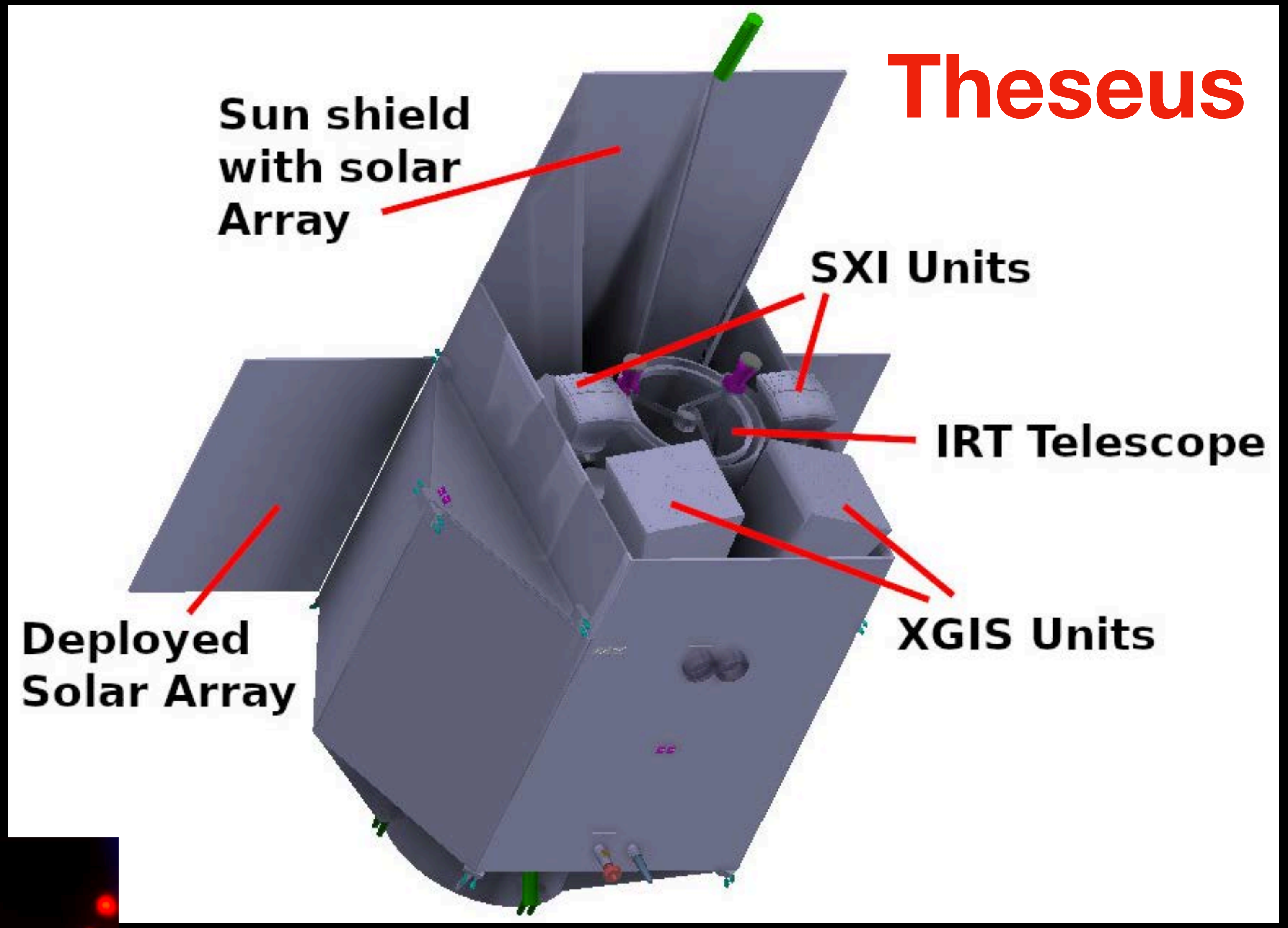


Late 2023 launch?

lobster-eye MPO + CMOS
FoV: 3600 sq deg (1.1 sr)
band: 0.5 – 5 keV soft X-ray
eff. area: ~3 cm^2 @1keV
FWHM: ~ 5’, positioning <1’
Sensitivity: 10-100 x increase

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

X-RAY COVERAGE



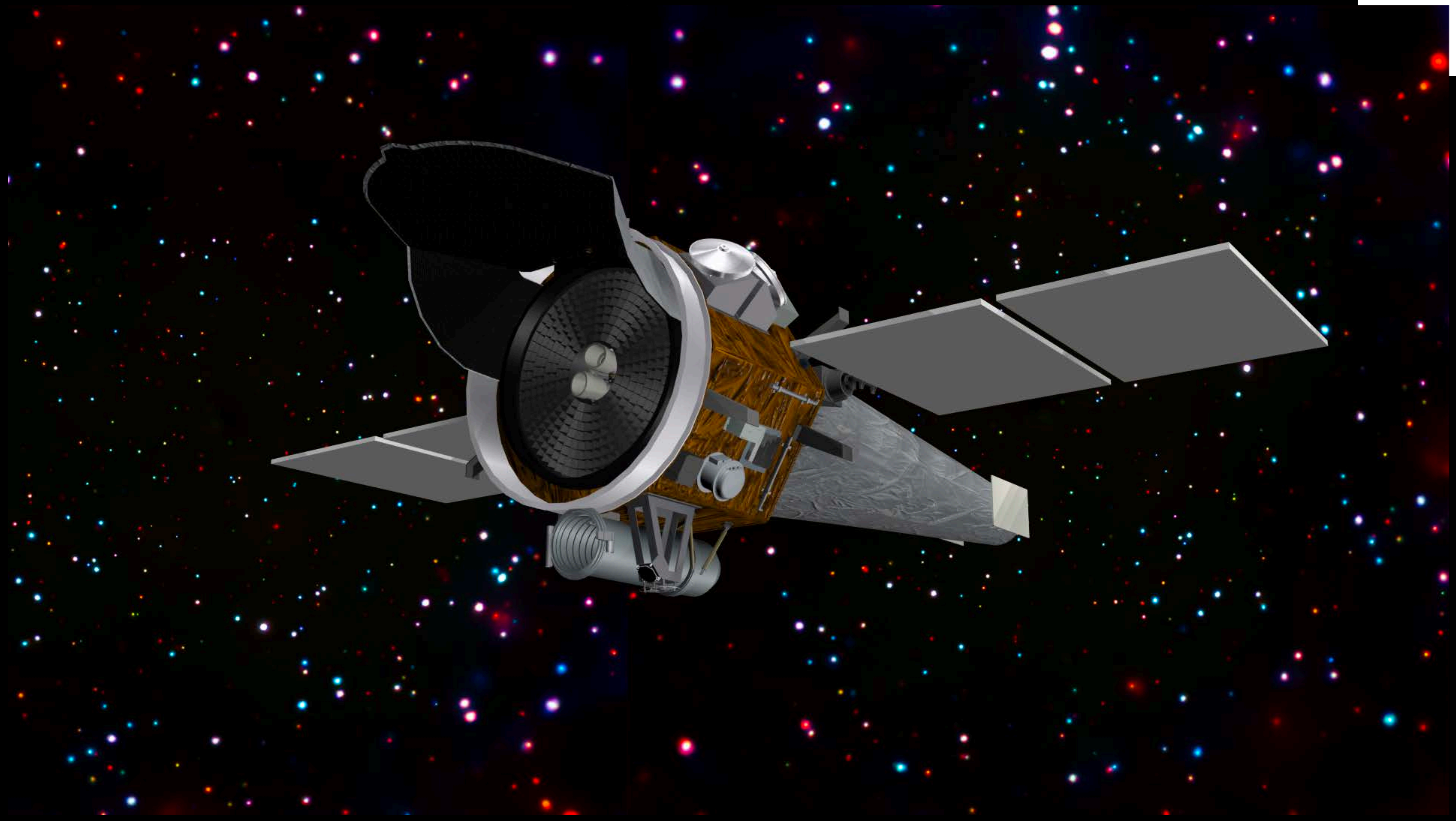
Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2'

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

Not selected as of 2023.

STAR-X (NASA)

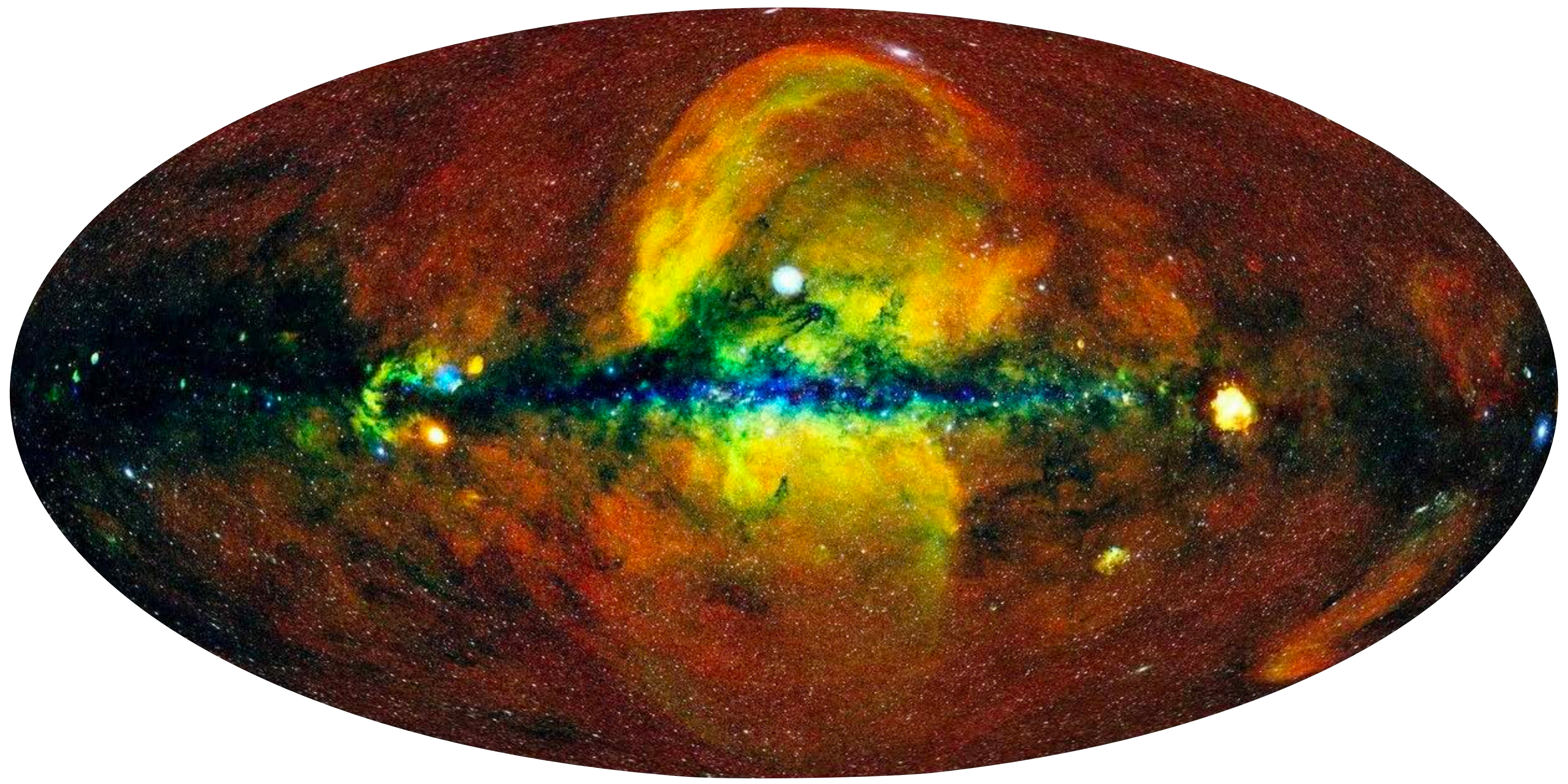
PI W. Zhang (NASA)



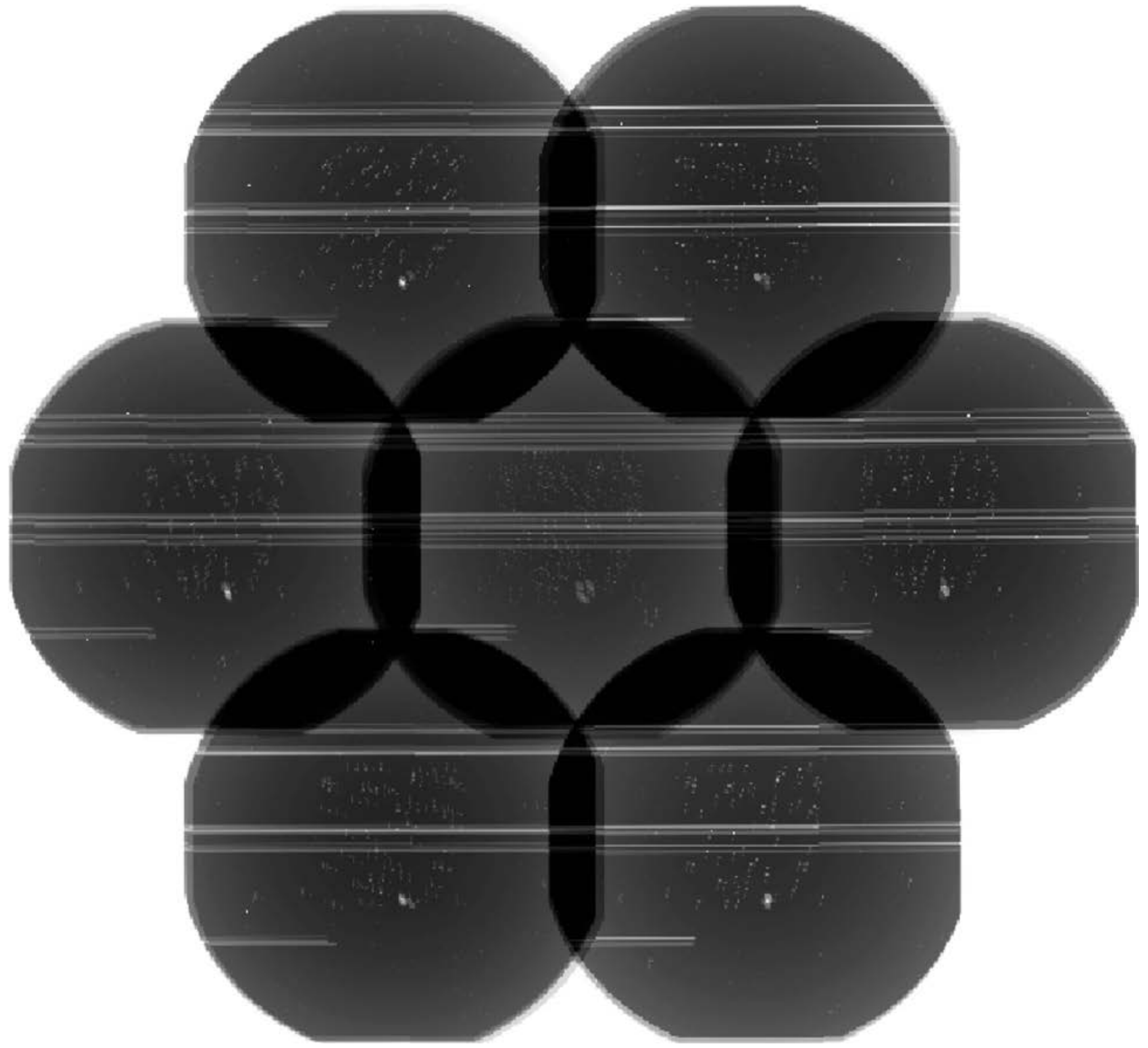
Selected (with UVEX) for a MIDEX Concept Study
x7 FoV of Swift XRT
x16 effective area

	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	

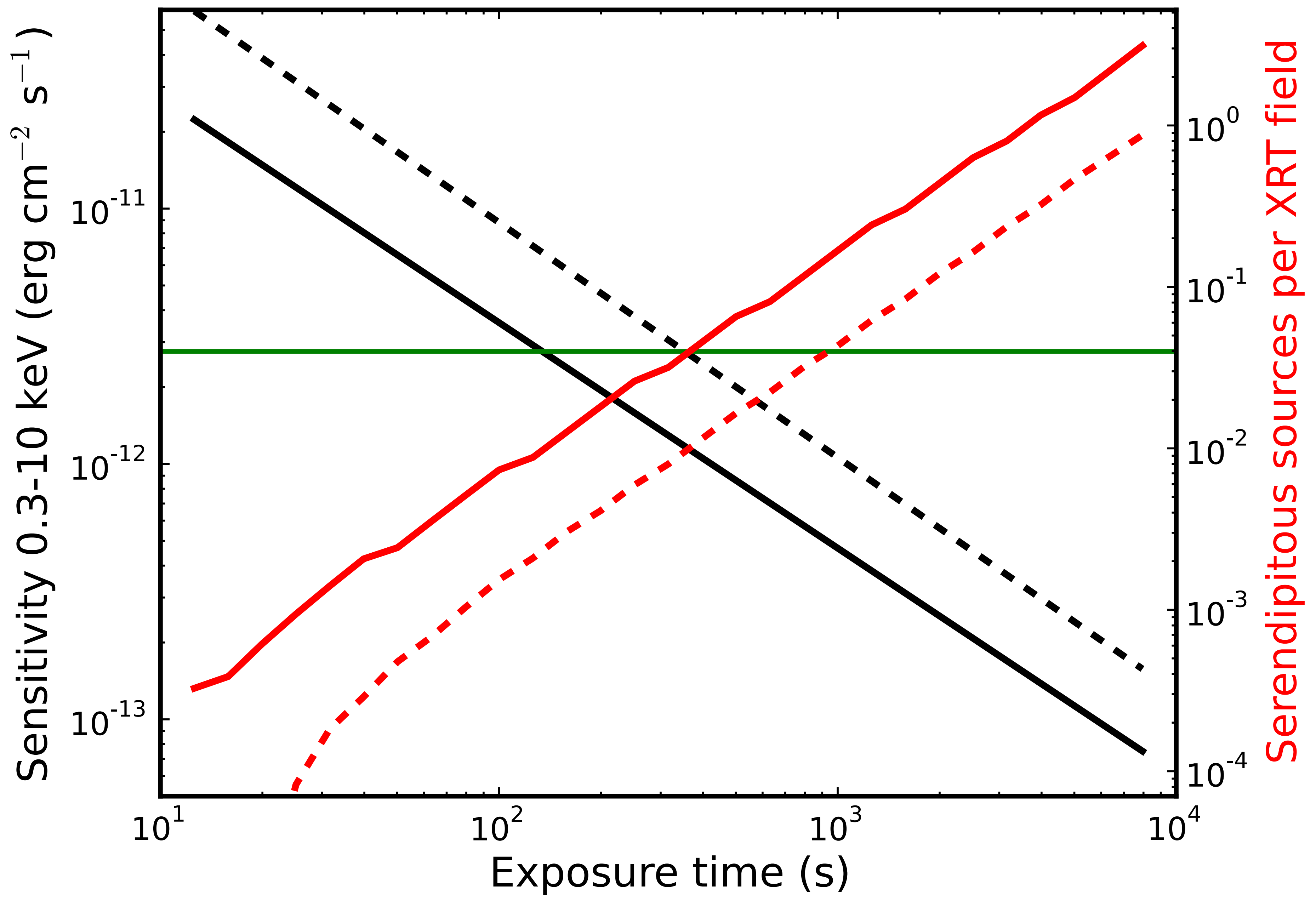
NEUTRINO-EM SOURCE ASSOCIATIONS IN THE NEXT DECADE



- Pointed follow-ups require a good reference catalog to compare against **(e.g eROSITA)**. 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 association probabilities is a critical factor in correlation claims.**



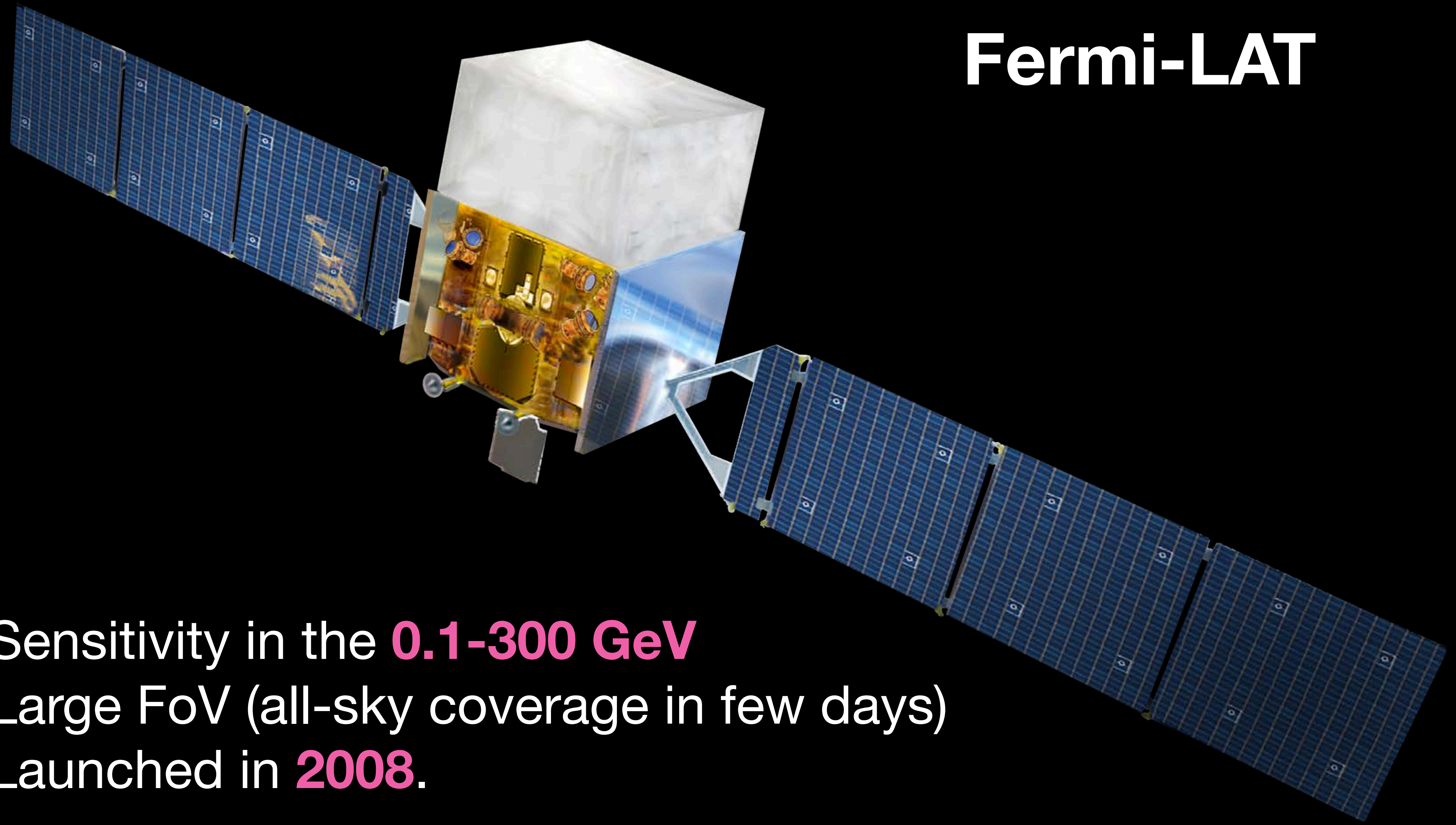
Swift tiling of neutrino position



Swift follow-up of neutrino events

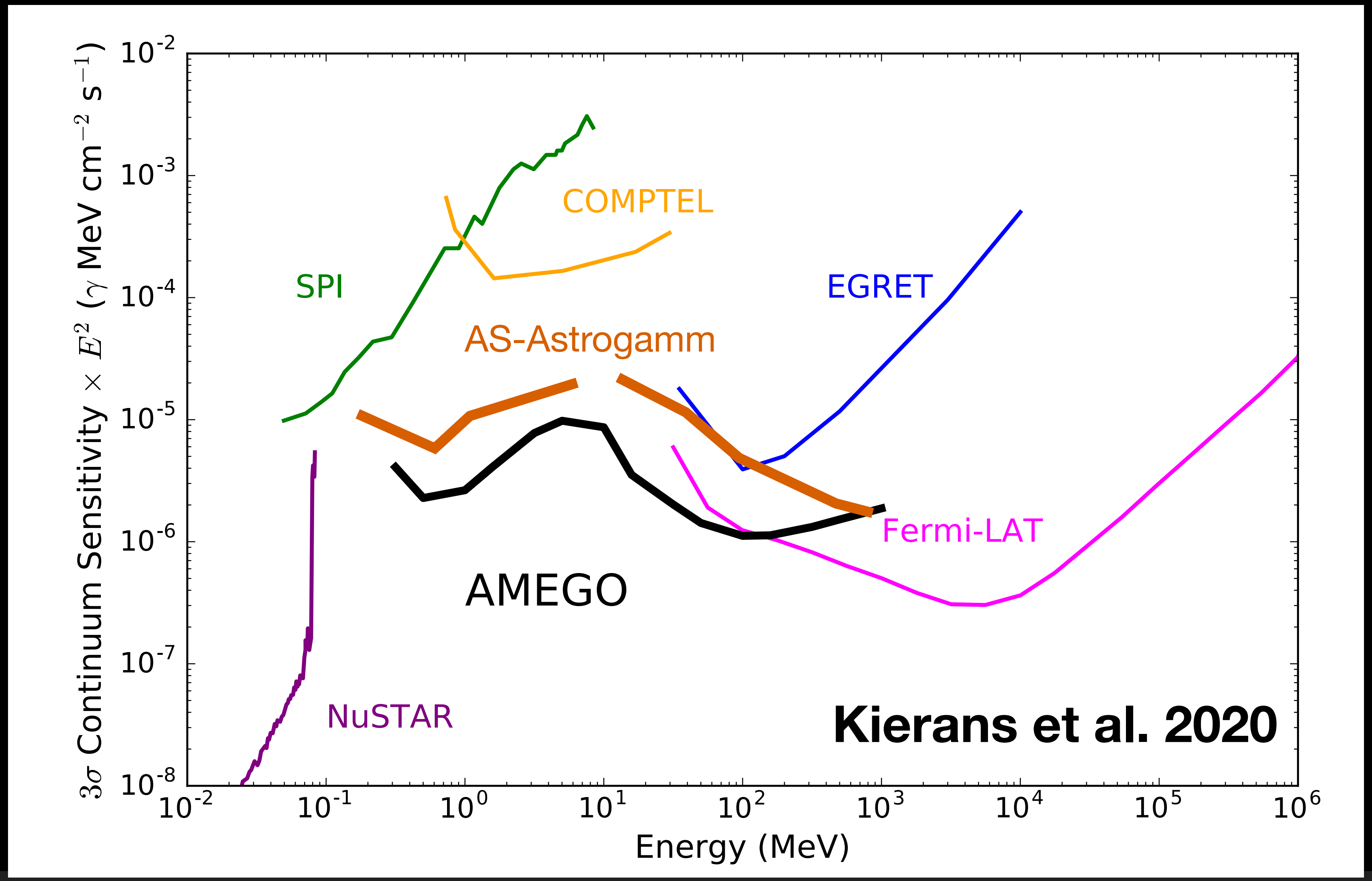
Evans et al.
https://arxiv.org/abs/1501.04435

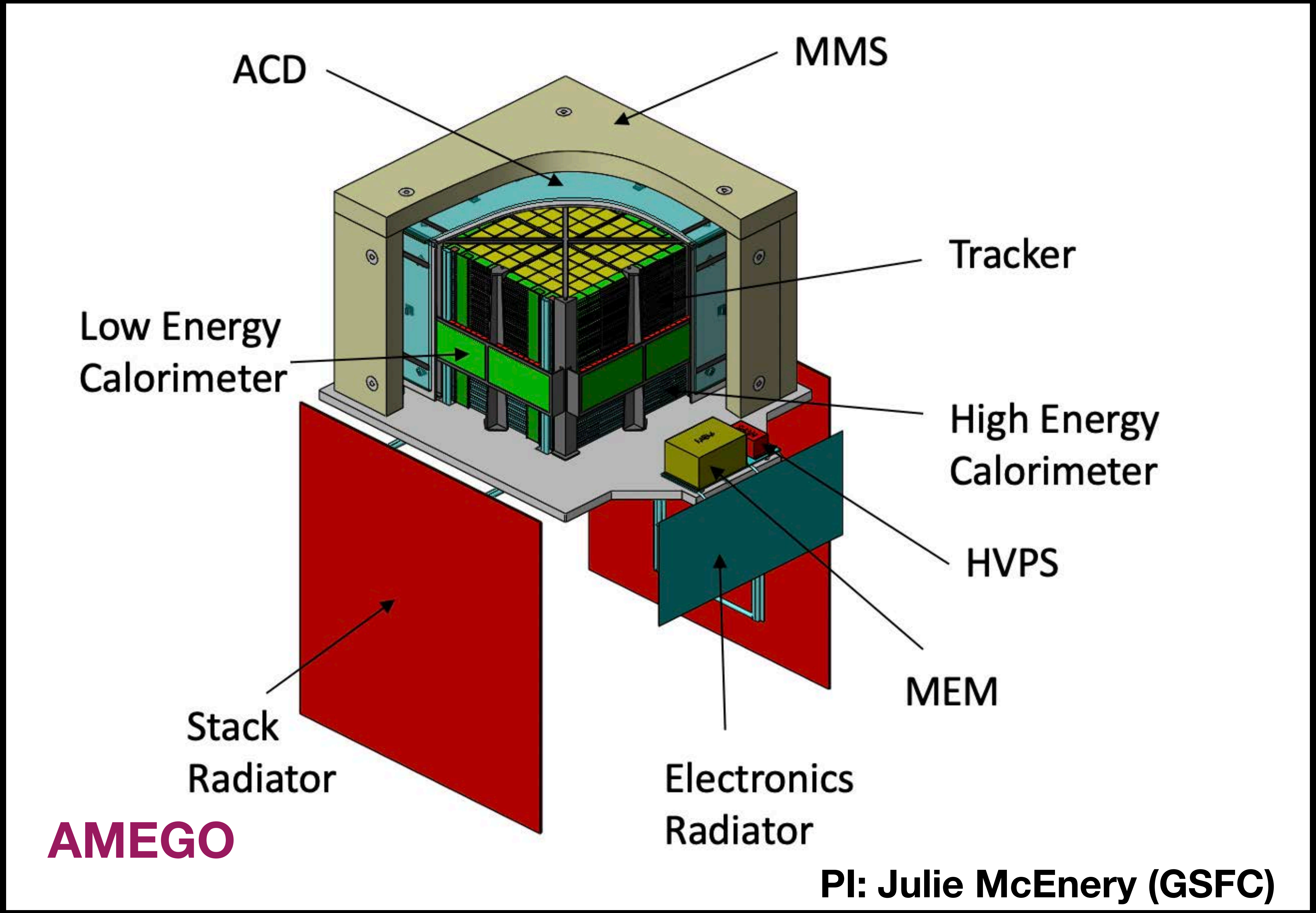
MEV-GEV COVERAGE



Fermi-LAT

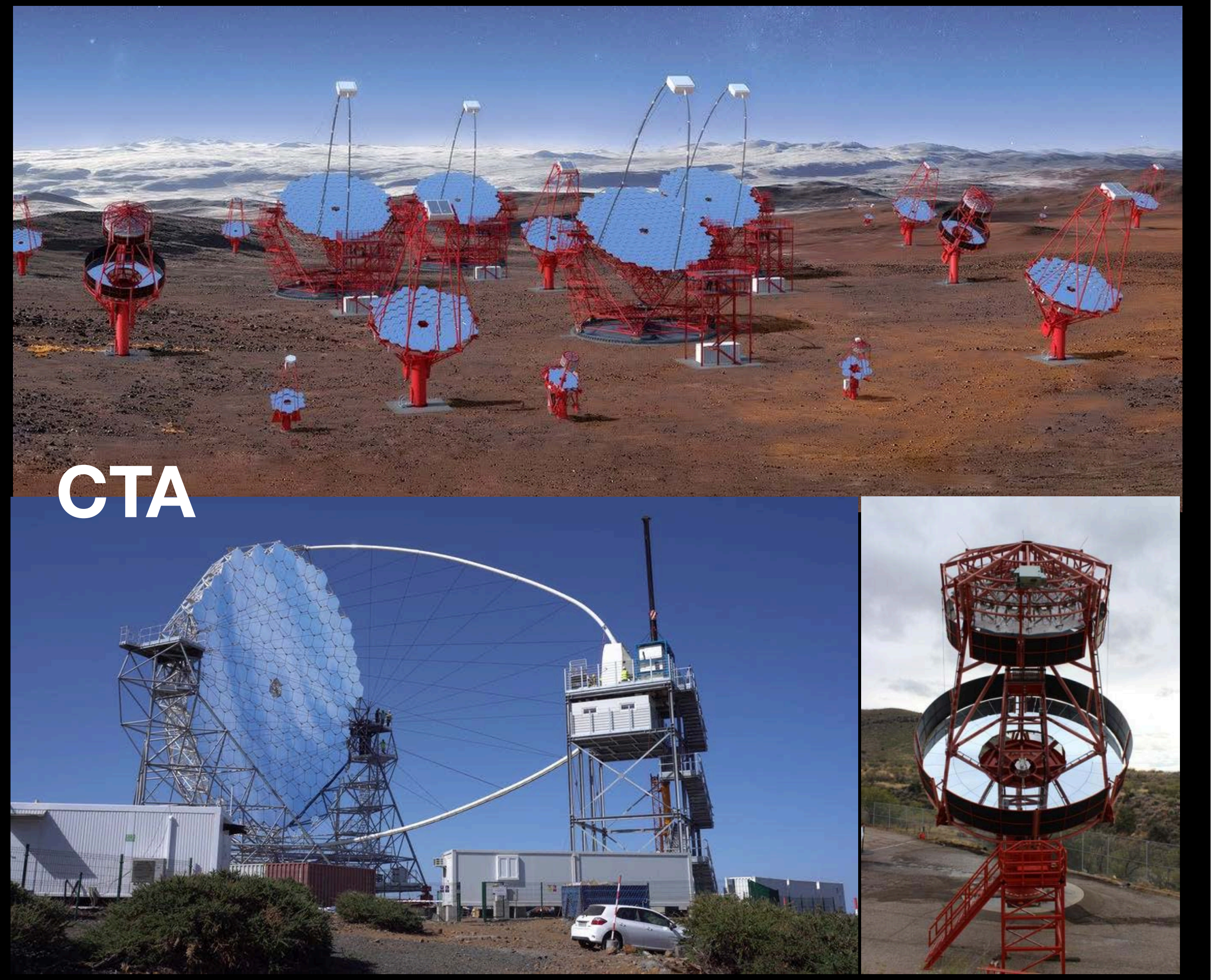
Sensitivity in the **0.1-300 GeV**
Large FoV (all-sky coverage in few days)
Launched in **2008**.

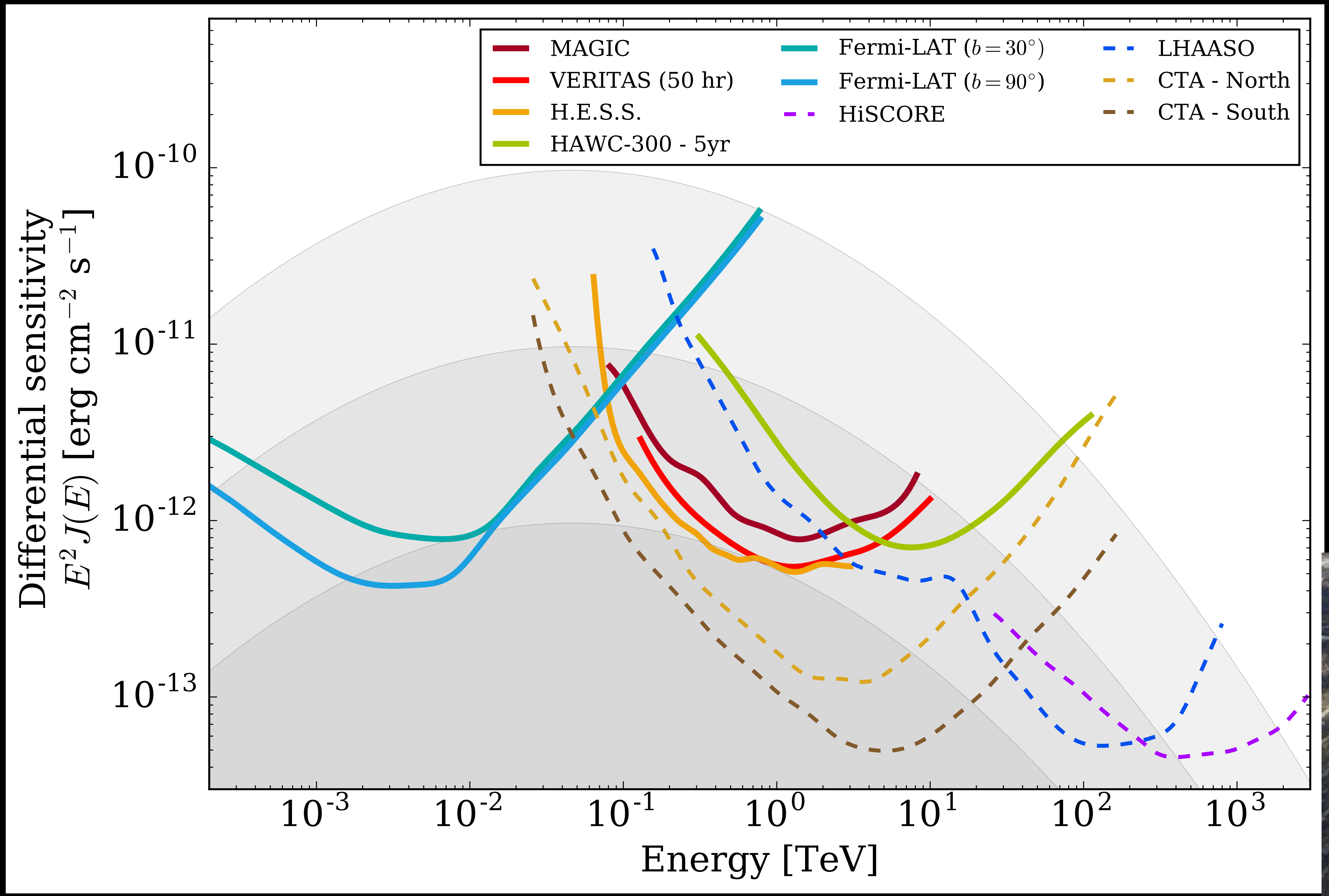


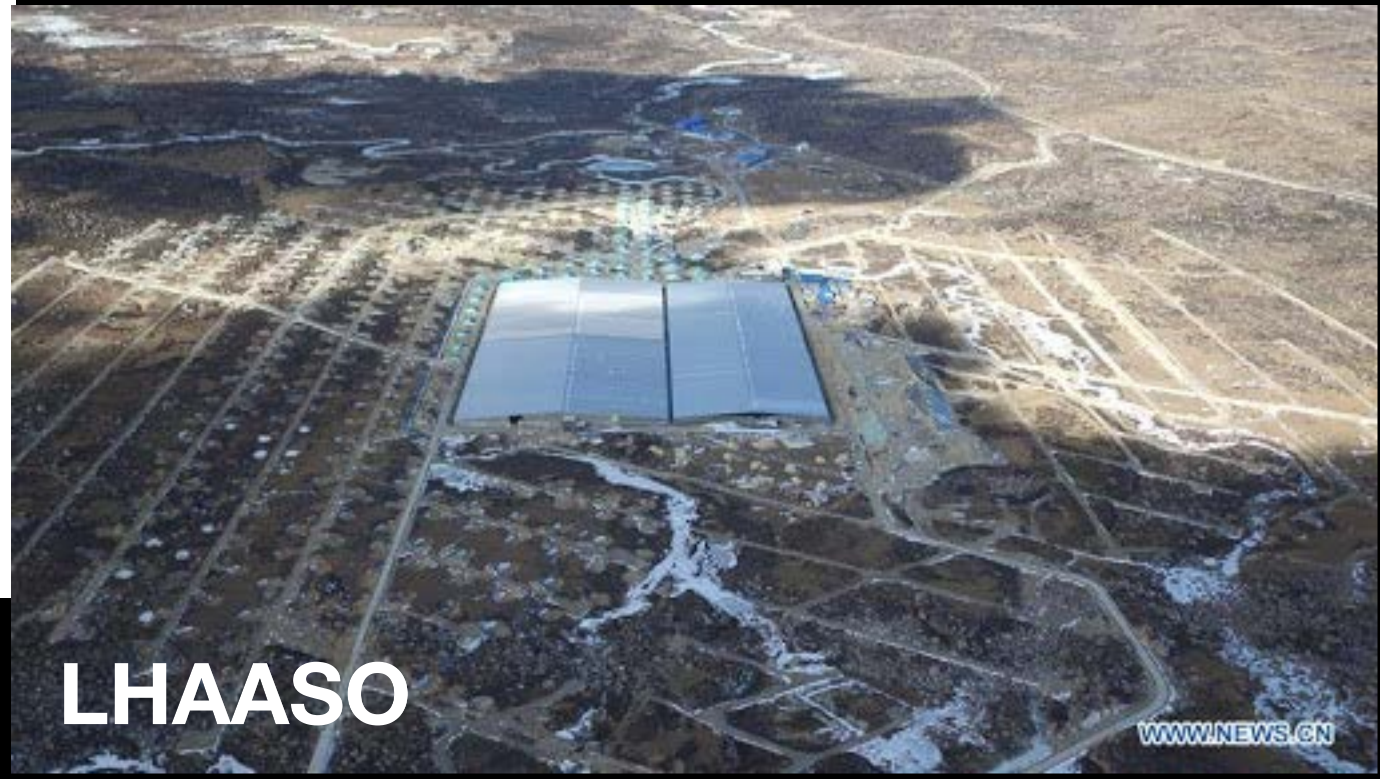


- AMEGO angular resolution: 3° (1 MeV), 10° (10 MeV)
- AMEGO prototype (**ComPair**) for balloon flight.
- European MeV effort concentrated on **All-Sky-Astrogamm** mission study.
- Continued support for **Fermi**.

VHE EM 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.

WISHLIST FOR MMA STUDIES WITH NEUTRINOS

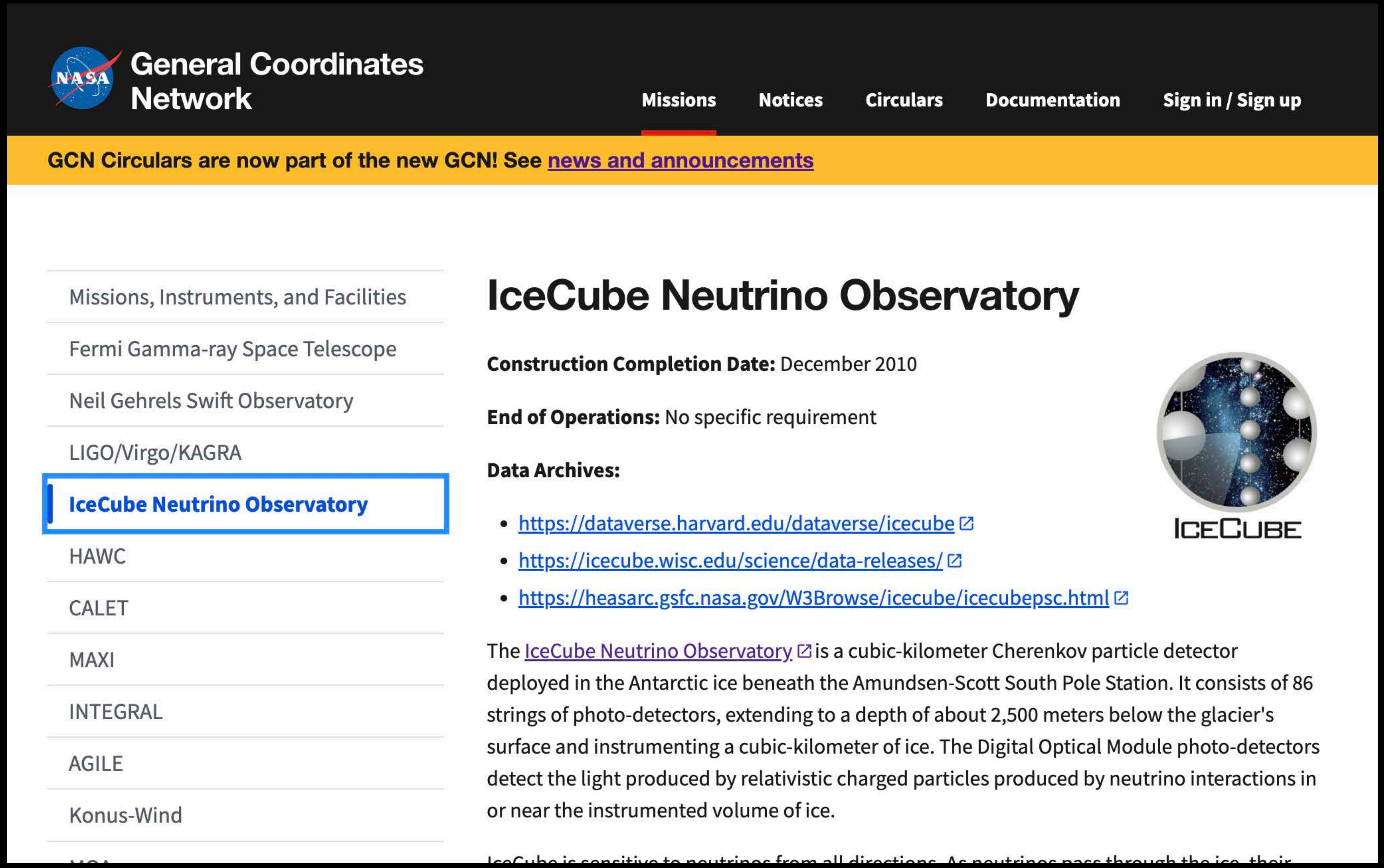
- **On the threshold of neutrino astronomy.**
- Increase the number of neutrino events >100 TeV (high astrophysical purity)
- Improve the angular resolution (correlation probability goes with PSF^2)
- As neutrino telescopes are 4π instruments, you need **wide-field, continuous, broad-band, sensitive coverage across the EM spectrum**.
  - **New instruments** where sensitivity is currently lacking (soft X-rays to MeV range, improved sensitivity in the VHE range).
  - **Continued operation** of instruments with no obvious substitute (e.g. Fermi)

INTEGRATING NEUTRINO TELESCOPES INTO TDAMM

- Working together to agree on data formats for neutrino results (both within the neutrino groups and with the broader astrophysics community).

- Current infrastructure relies largely on the NASA general coordinates network (GCN). IceCube collaboration with SciMMA.

- Most searches for transient/variable sources should be done in realtime if possible. IceCube already working in that direction.



https://gcn.nasa.gov/missions/icecube

A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

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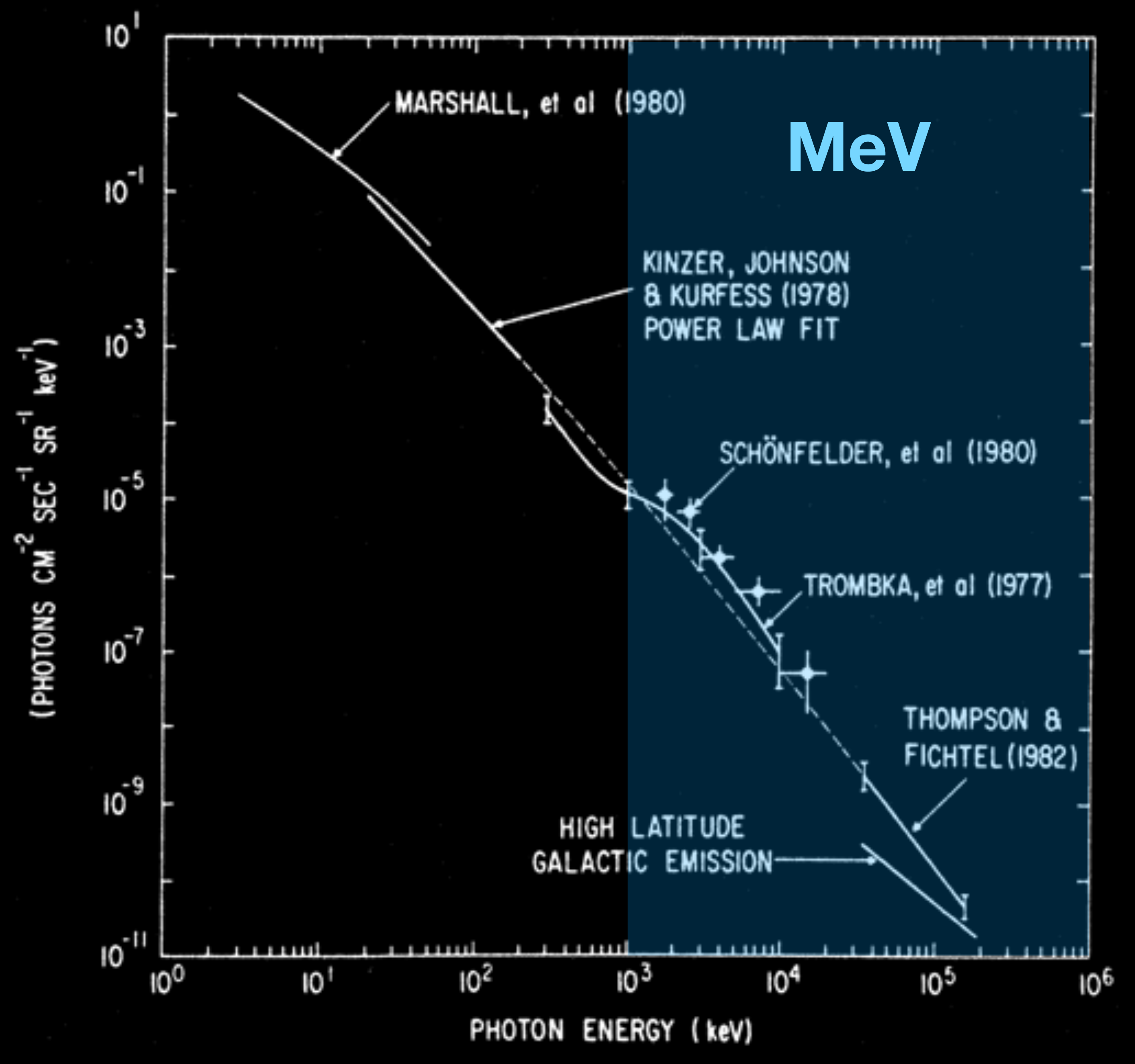

Diffuse background measurements
(1968-1972)

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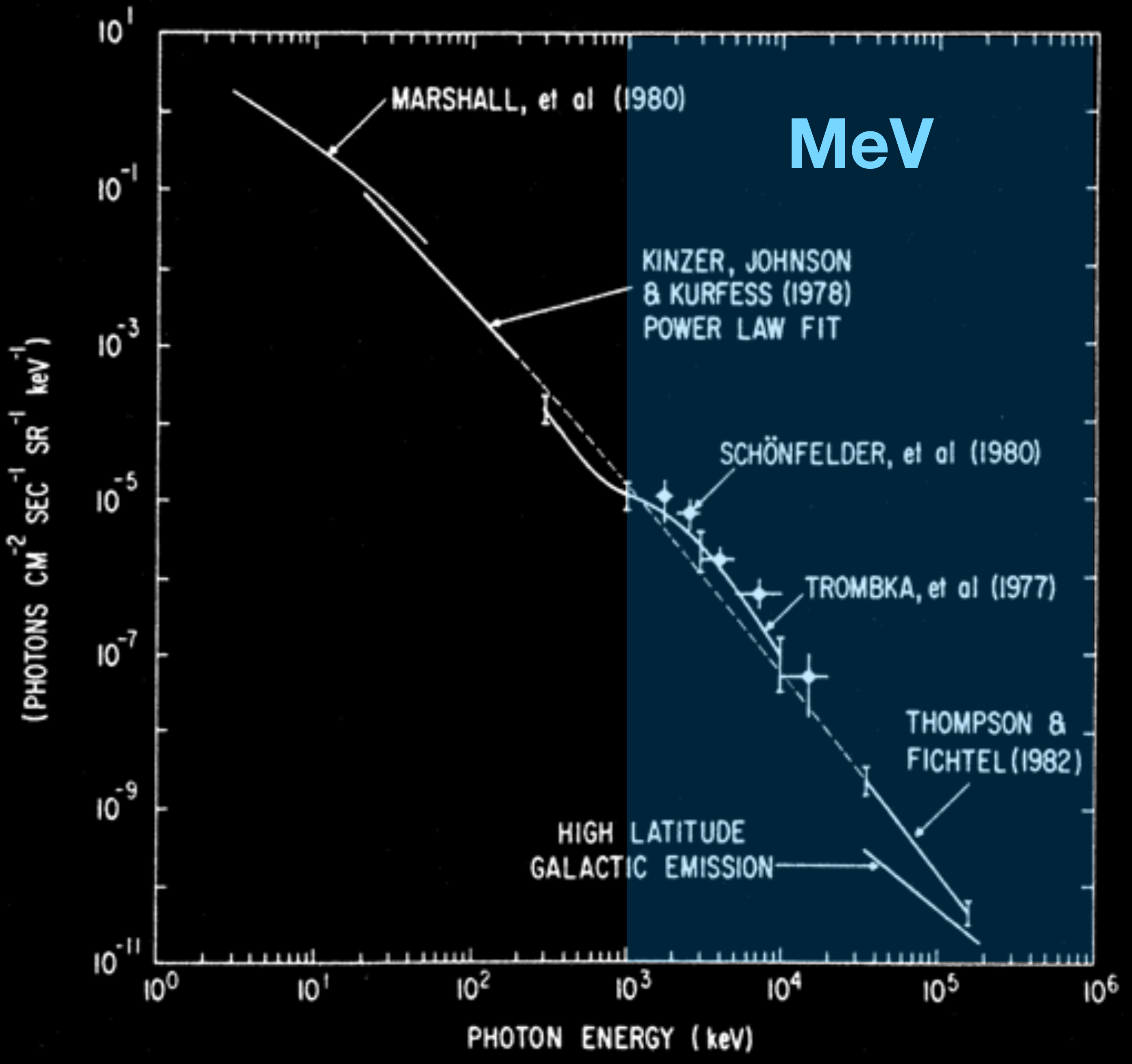

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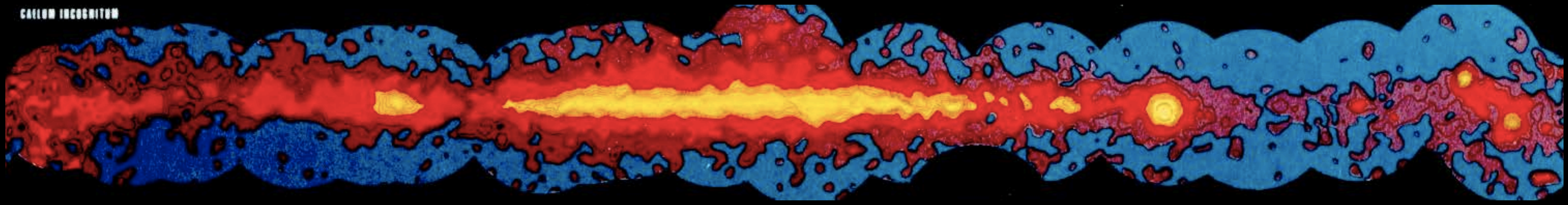

Galactic emission and few point sources (COS-B 1975-1982)

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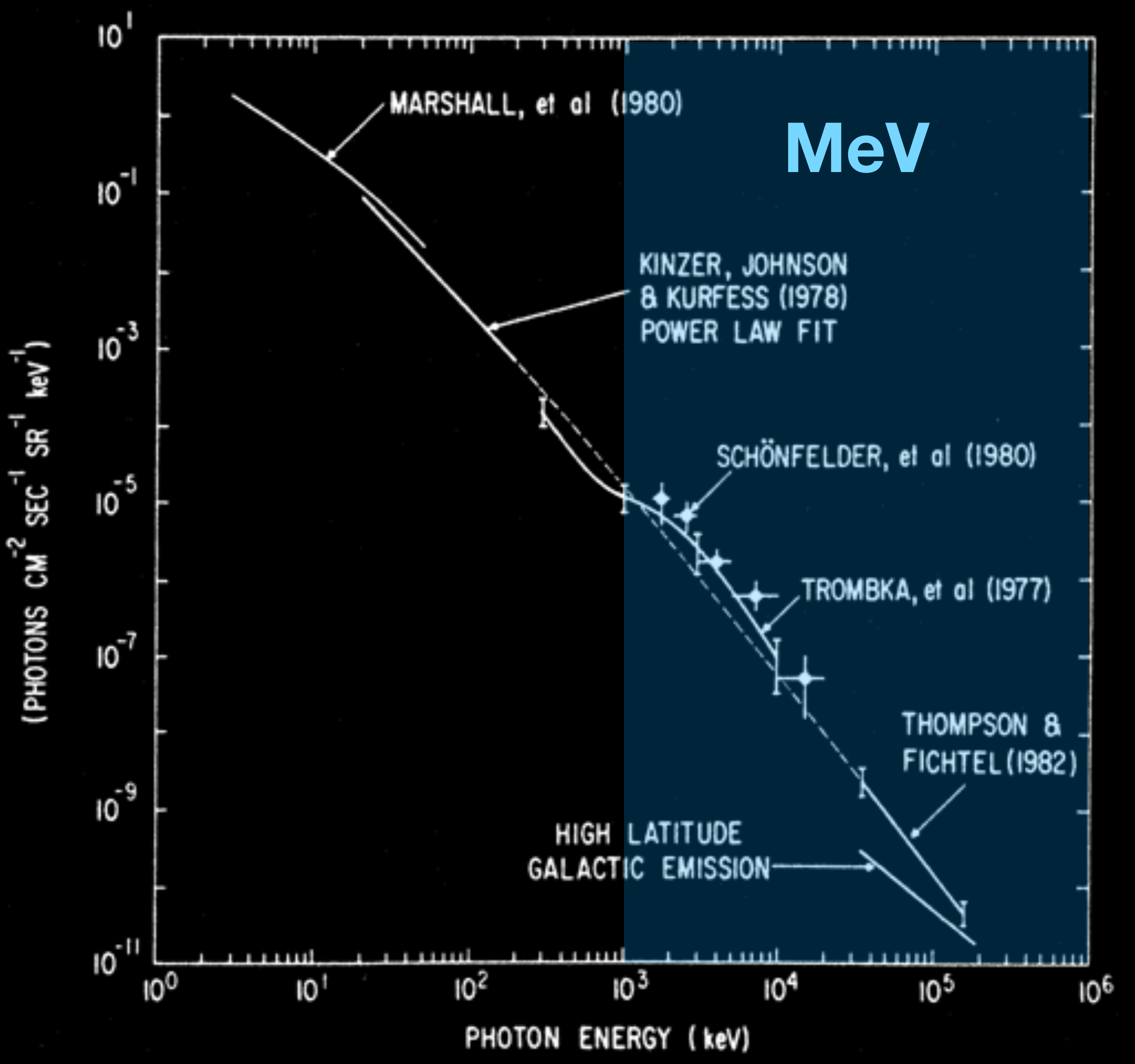

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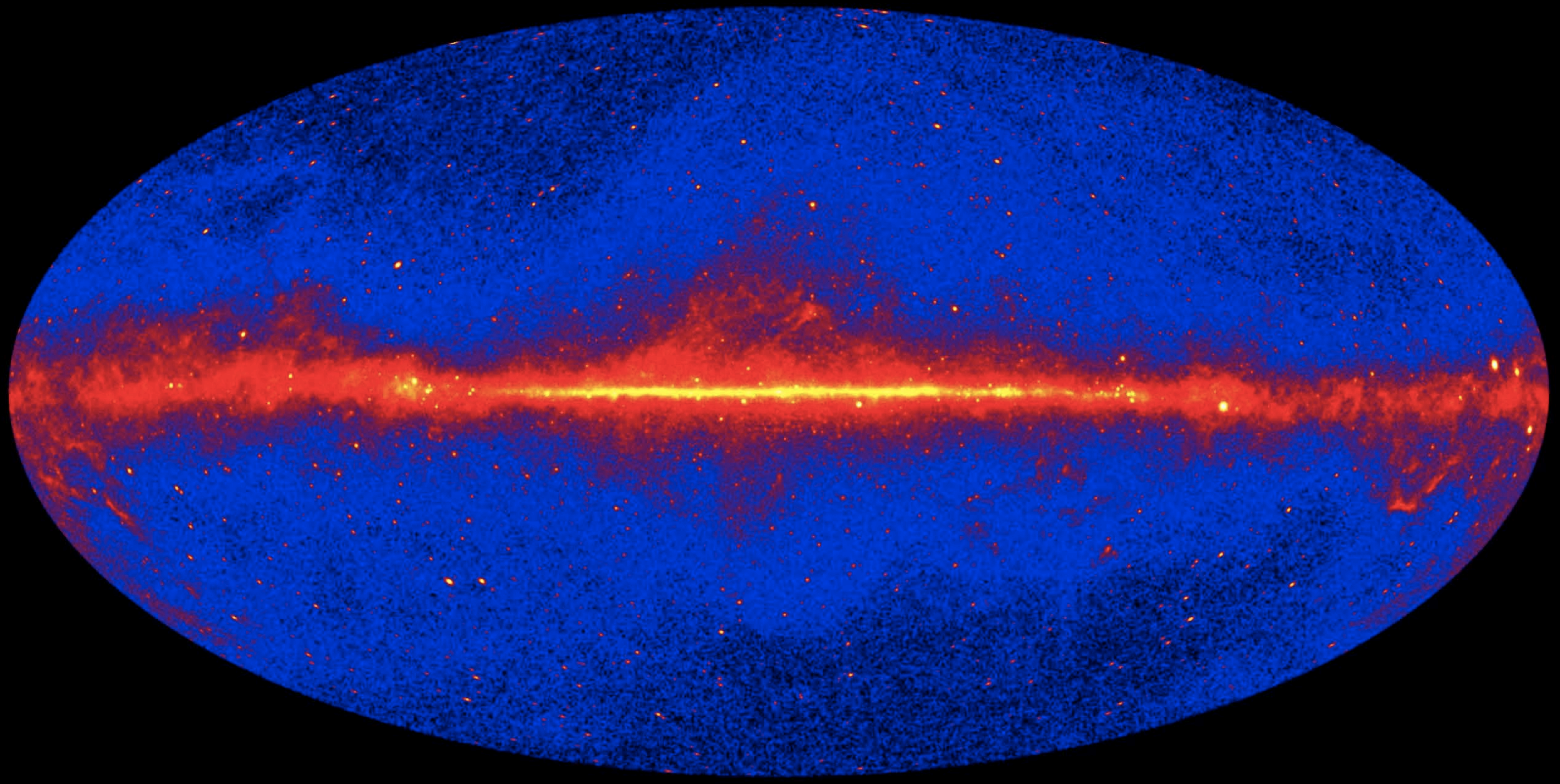
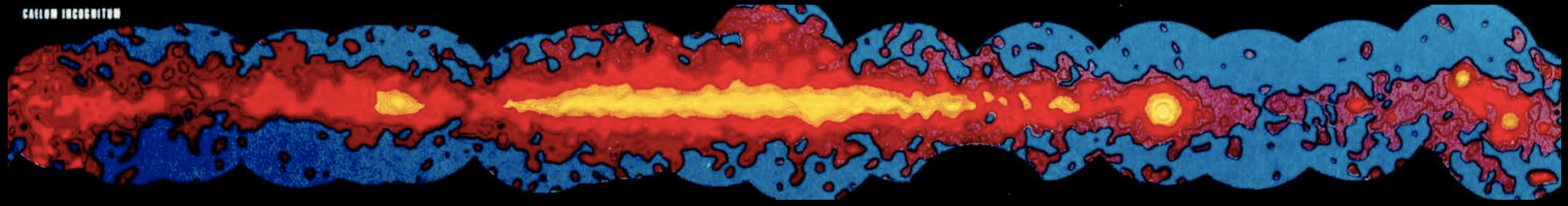


O(10³) points source, spectra, light curves
(Fermi-LAT, 2008-now)



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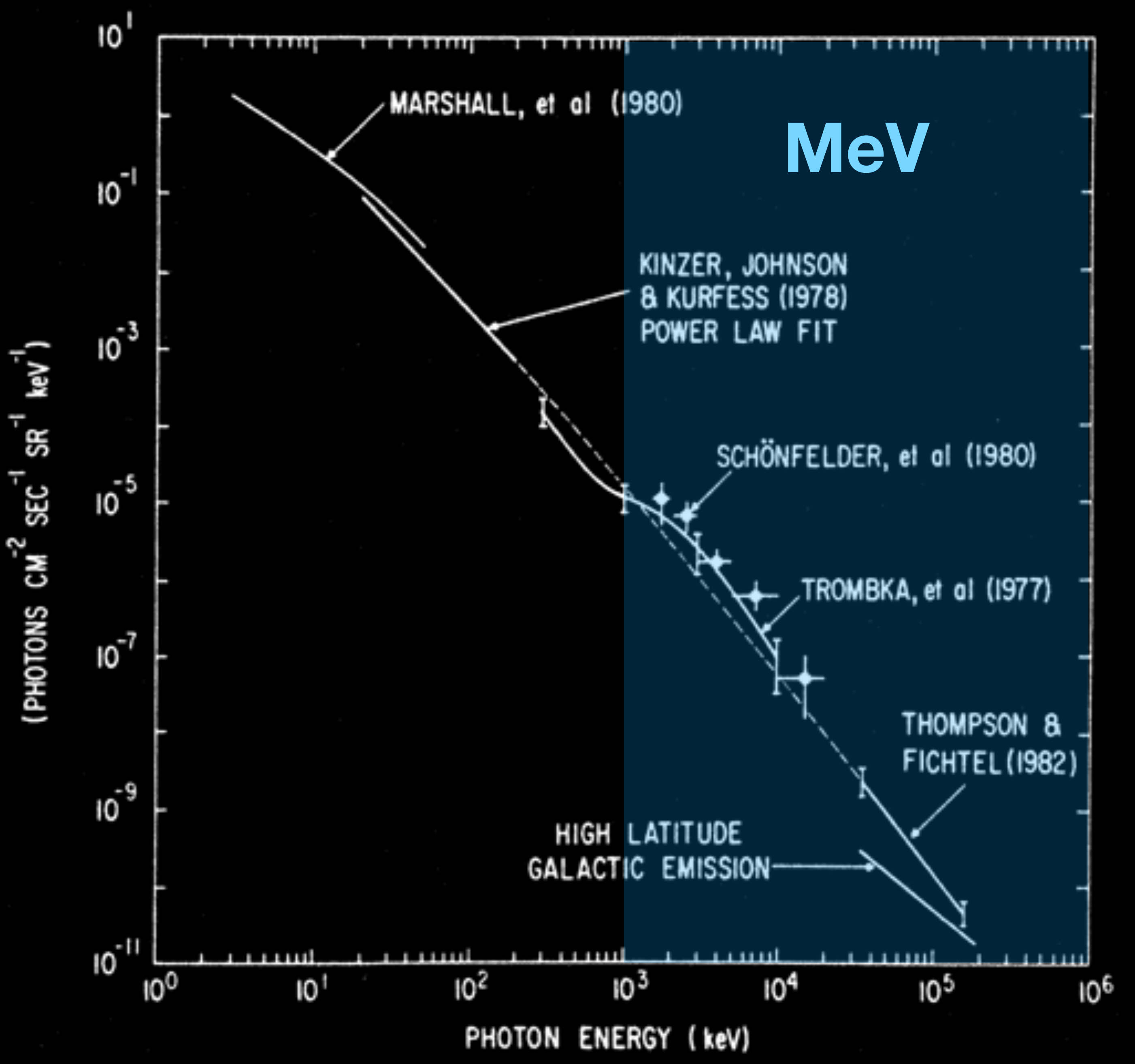

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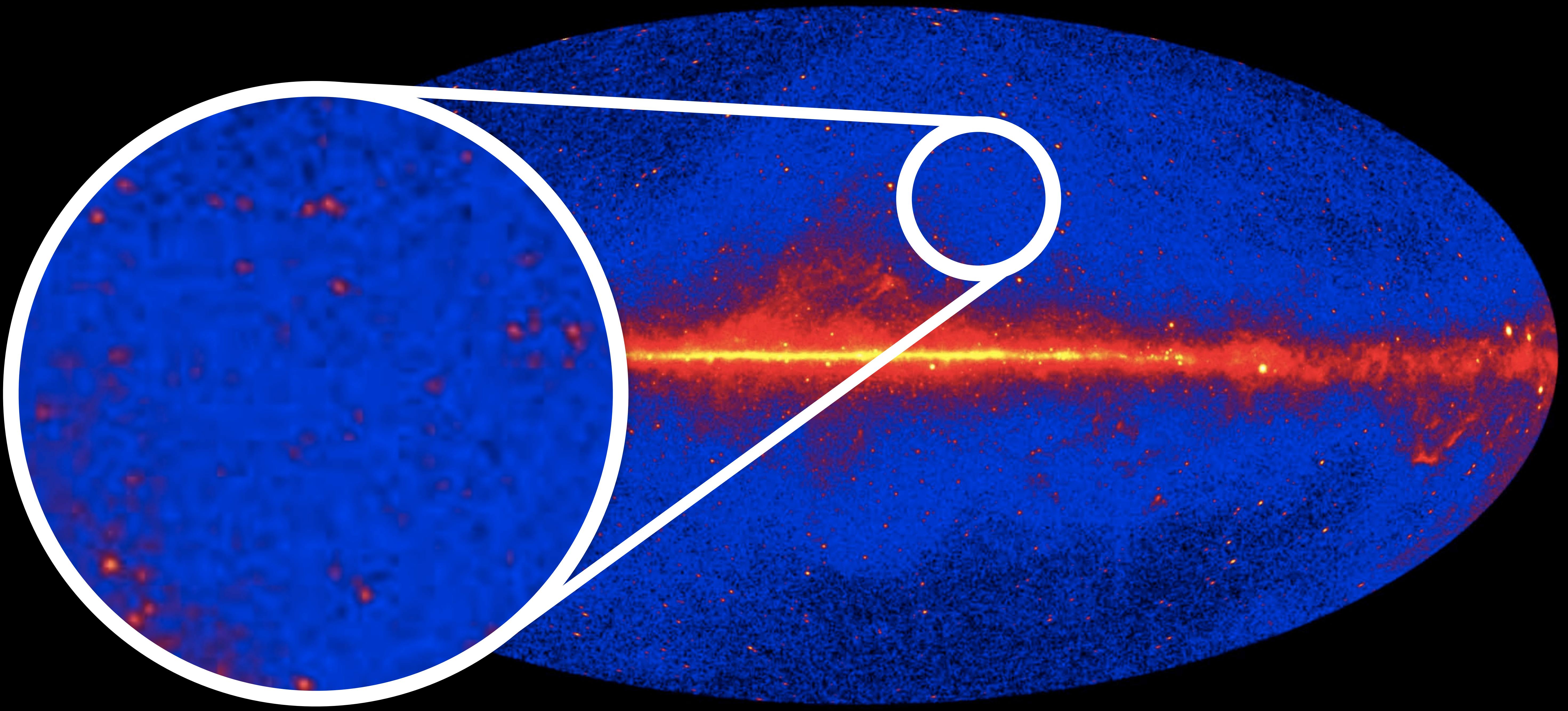
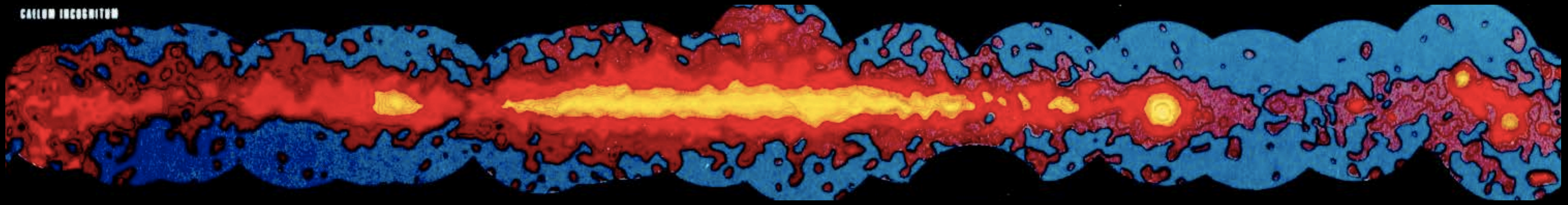


O(10^3) points source, spectra, light curves
(Fermi-LAT, 2008-now)



Galactic emission and few point sources (COS-B 1975-1982)

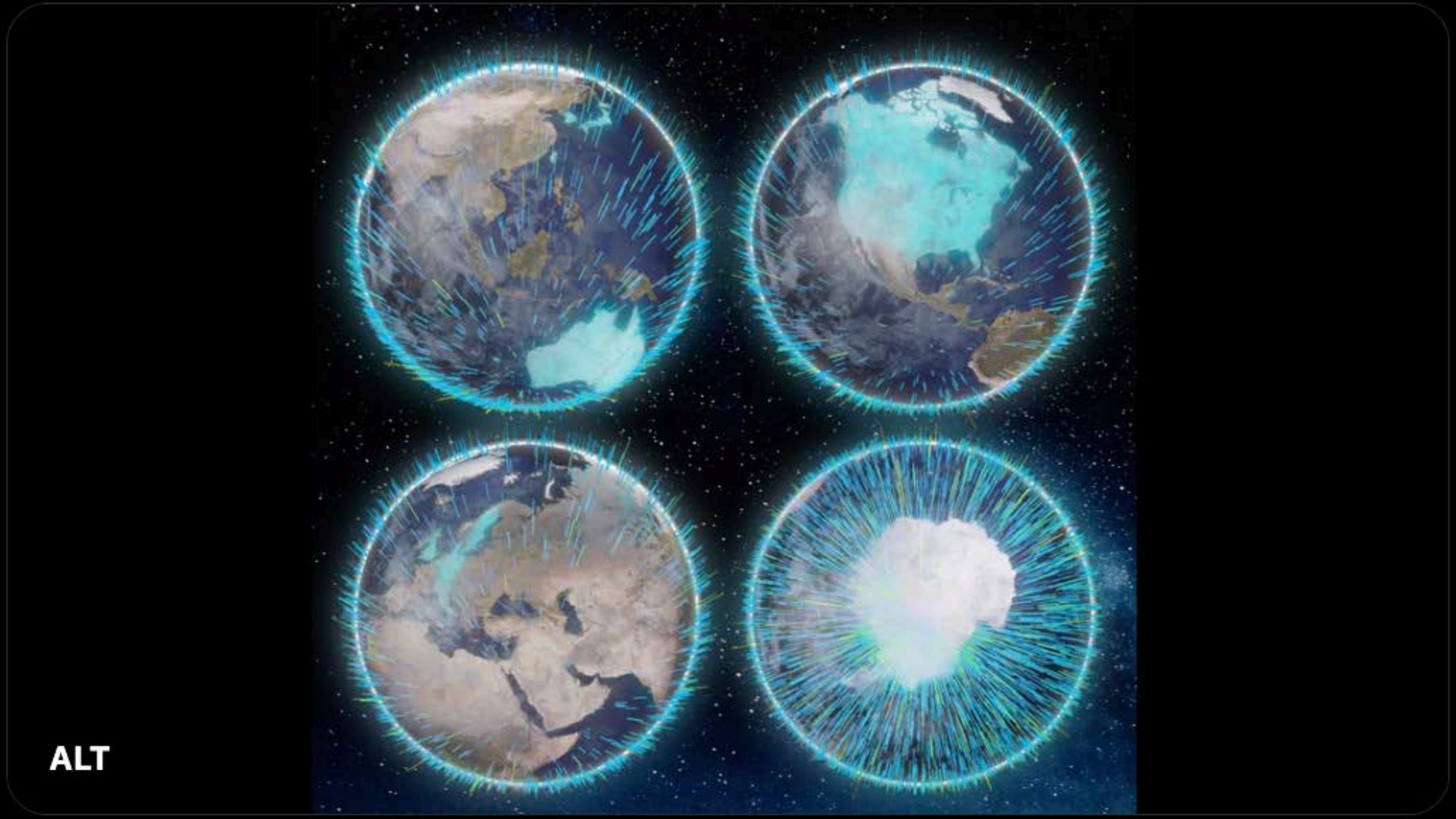
NEW ICECUBE RESULTS COMING UP!

IceCube Neutrino Observatory
@uw_icecube

📢 Major announcement coming soon!

Join us Thursday, June 29 @ 2:00 PM EDT to hear some exciting IceCube results!

Details ➡️ icecube.wisc.edu/news/collabora...



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