Realtime neutrino astronomy

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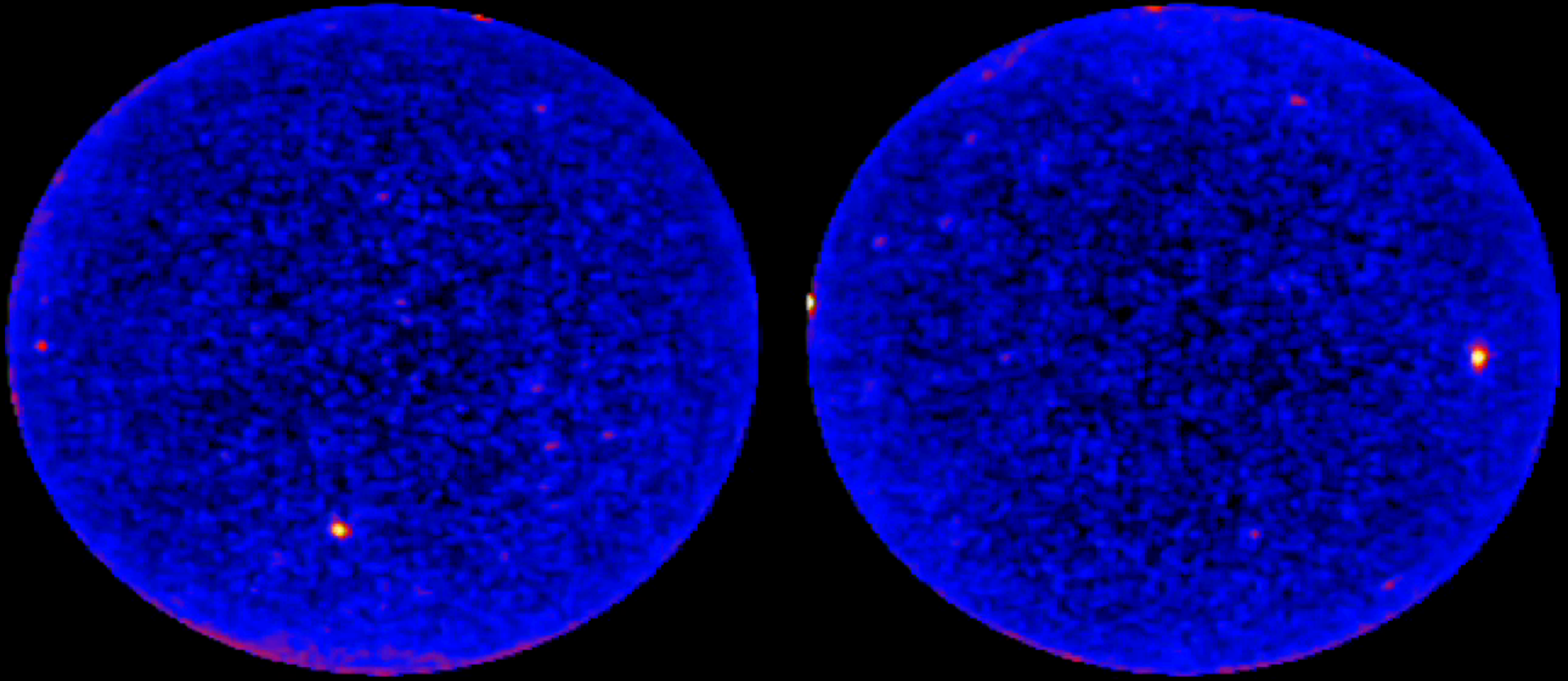
Cosmic Rays and Neutrinos in the Multi-Messenger Era 2024 (Paris, France) Dec 2024

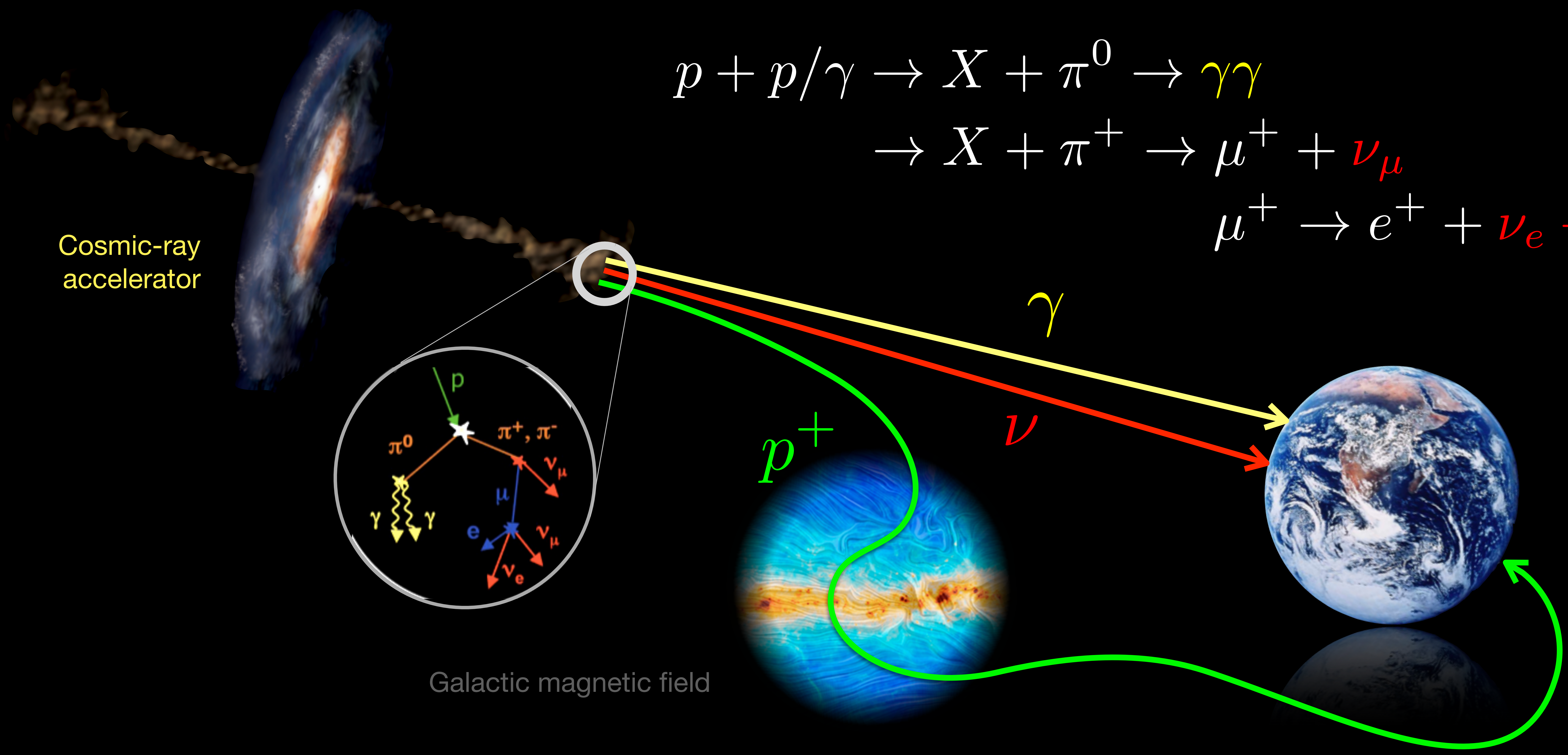
THE HIGH-ENERGY SKY IS DYNAMIC!

Fermi-LAT all-sky (north/south) timelapse



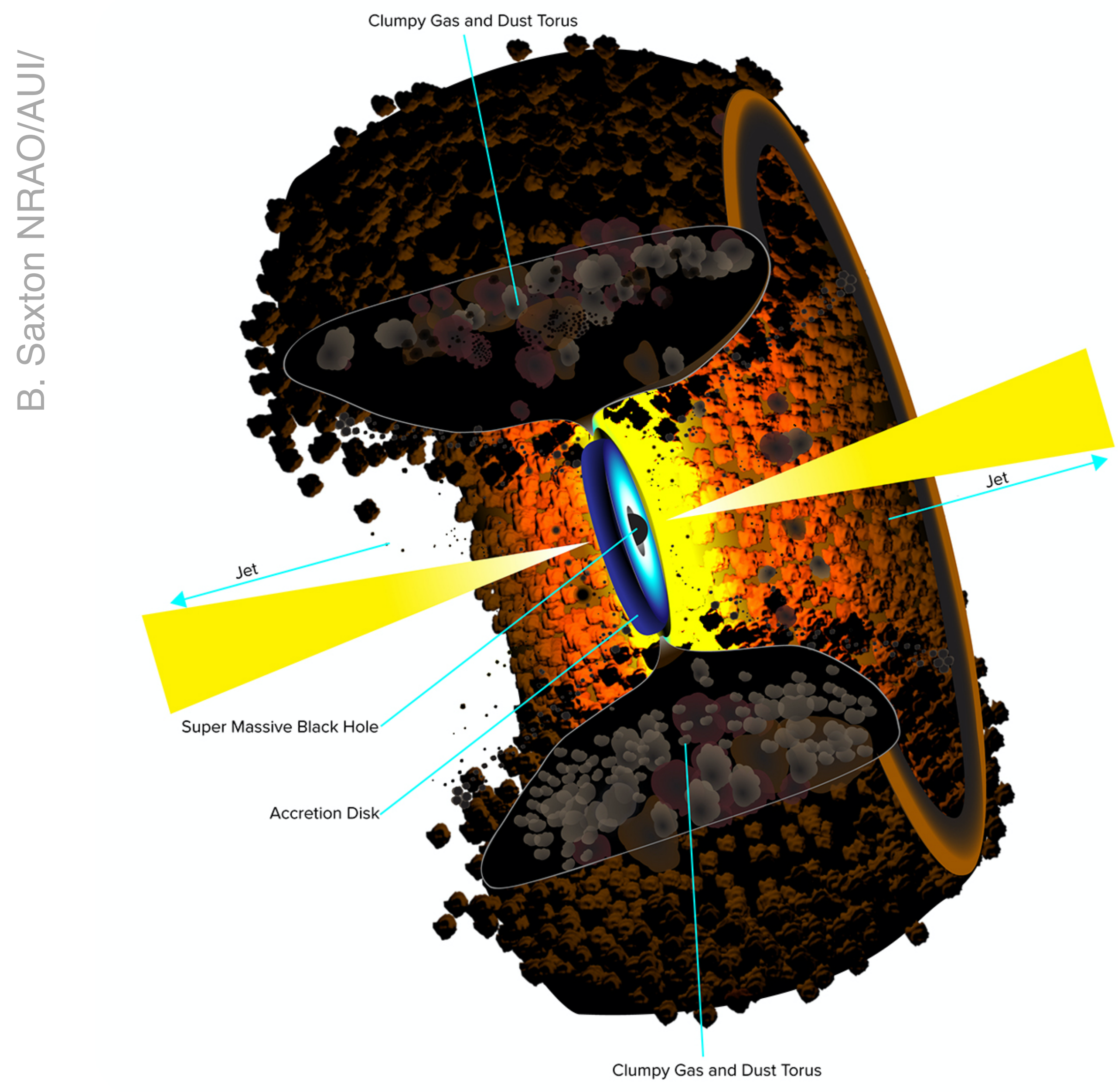
REALTIME SEARCHES FOR NEUTRINO EMITTERS

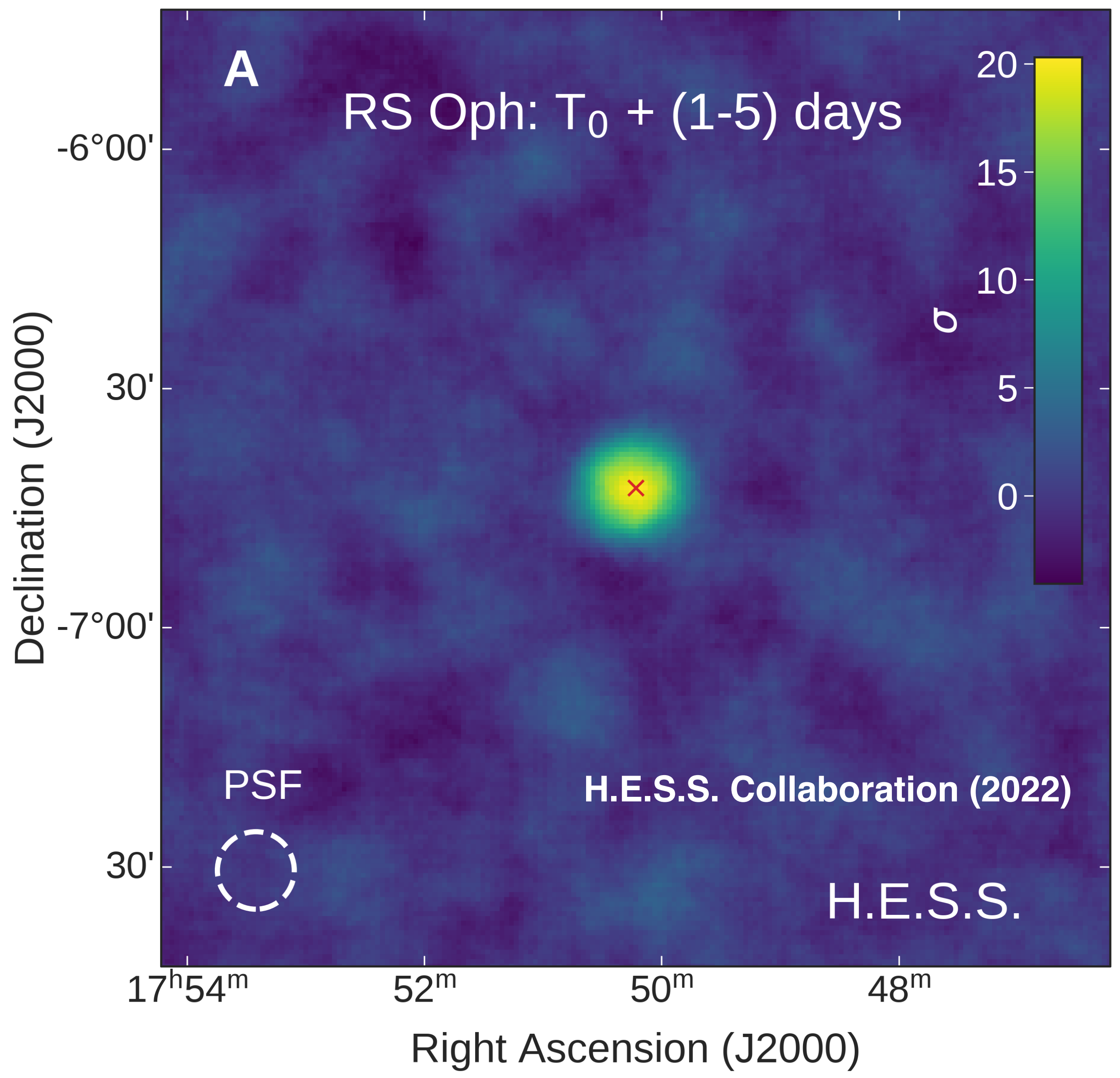
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

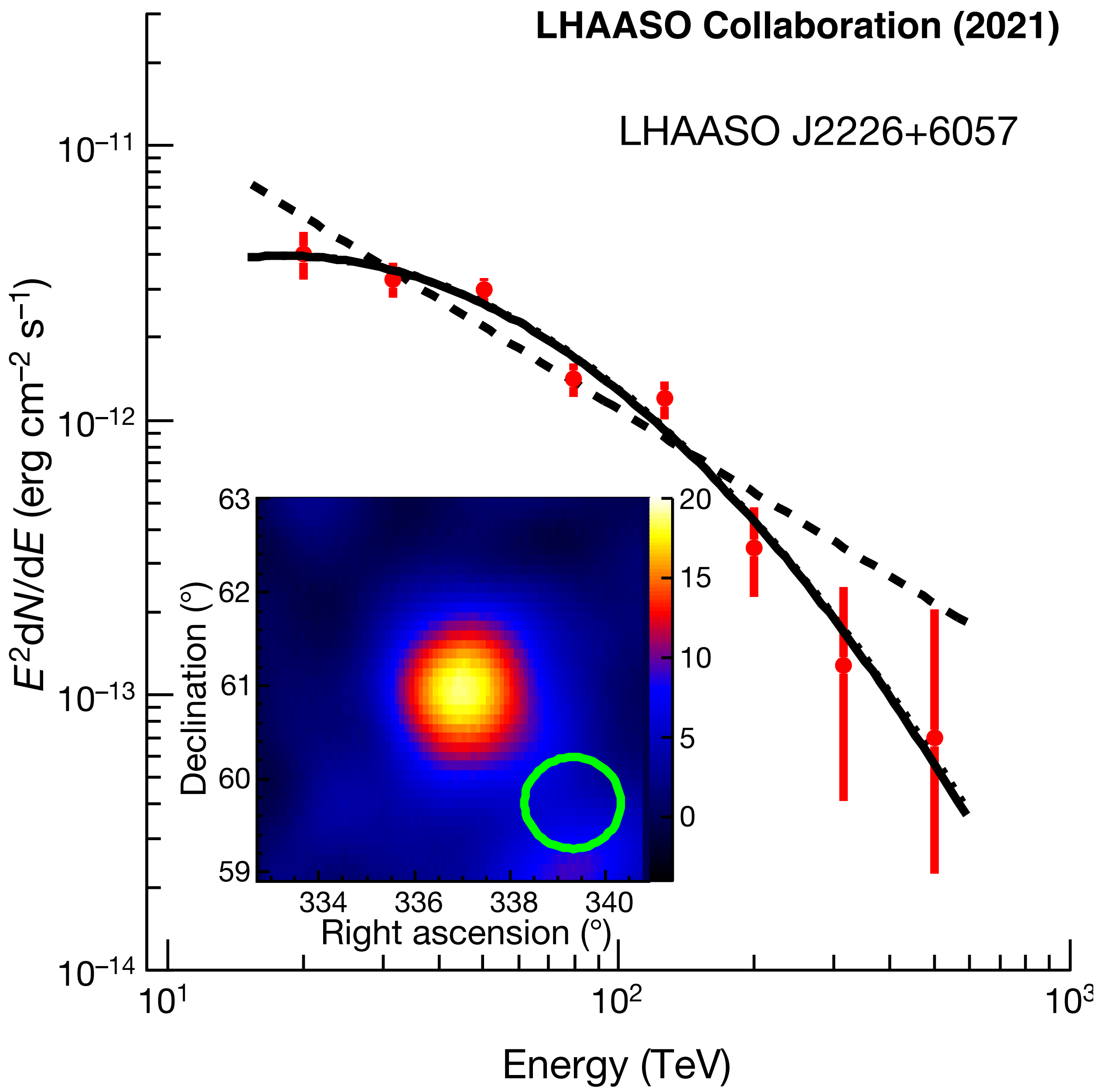


Main source type unclear	Timescale unclear (Seconds to steady emission)	Energy range unclear (Radio? X-rays? Gammas?)	All-sky distribution!

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

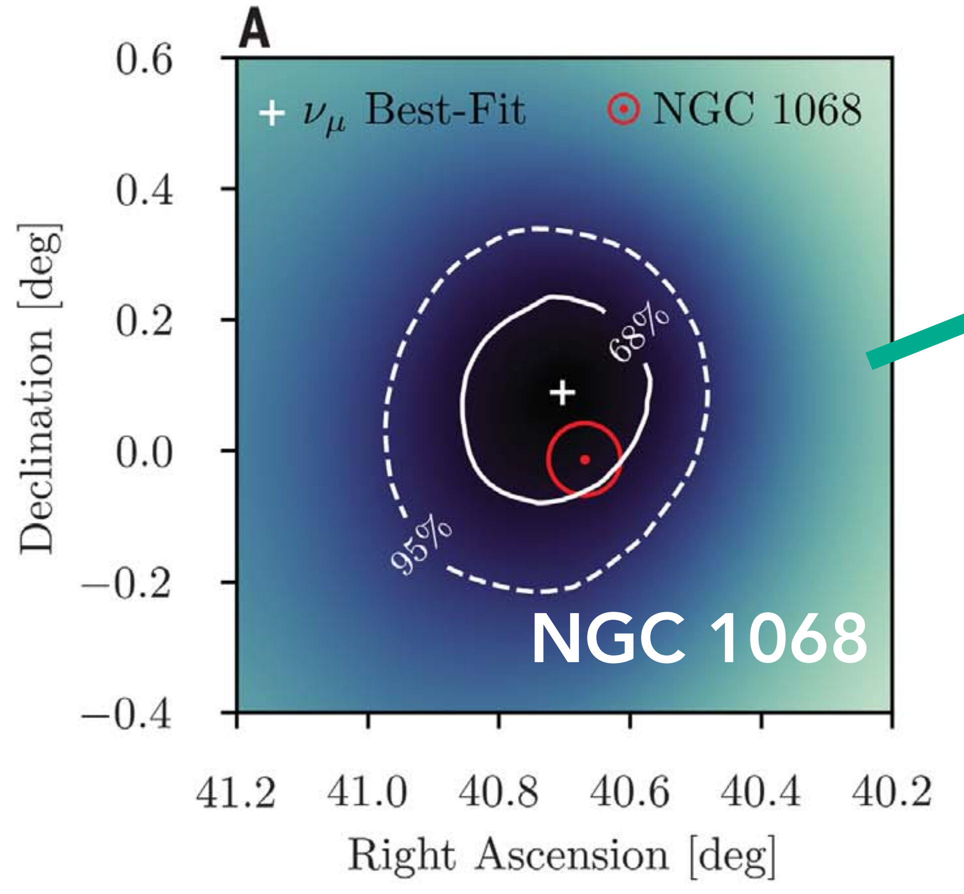
Neutrinos are the telltale sign of hadronic particle acceleration

CURRENT OBSERVATIONAL STATUS FOR NEUTRINOS

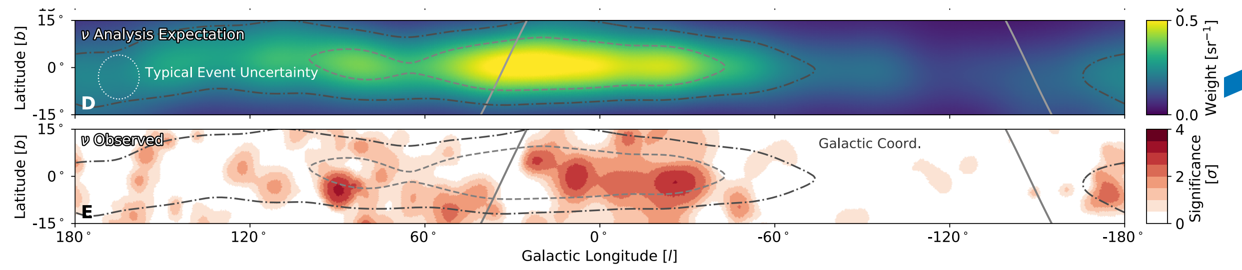
1 Astrophysical neutrino flux (2013)

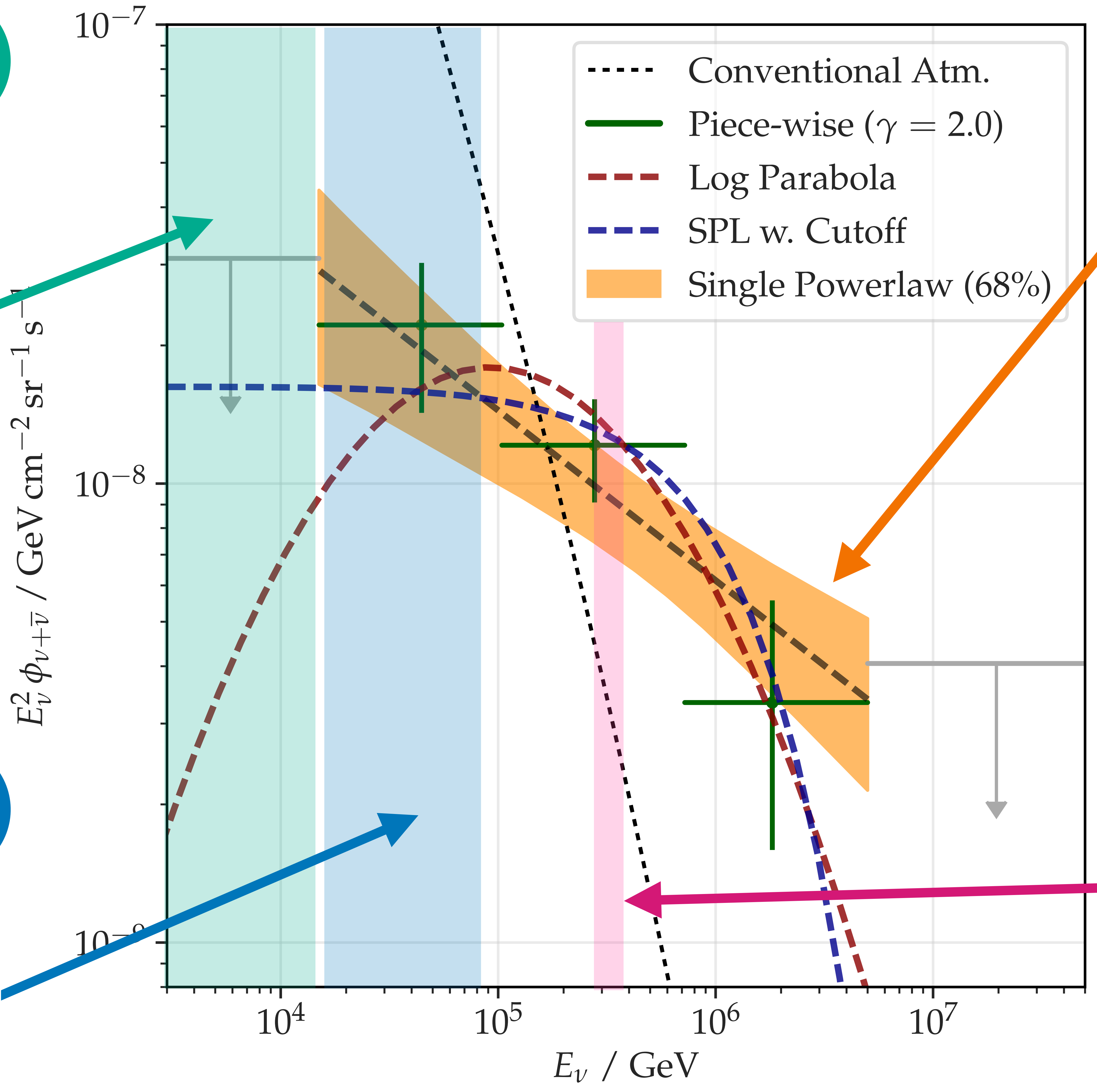
2 Evidence for $\nu + \gamma$ emission from a blazar (2017)

3 Neutrino emission from an AGN (2022)

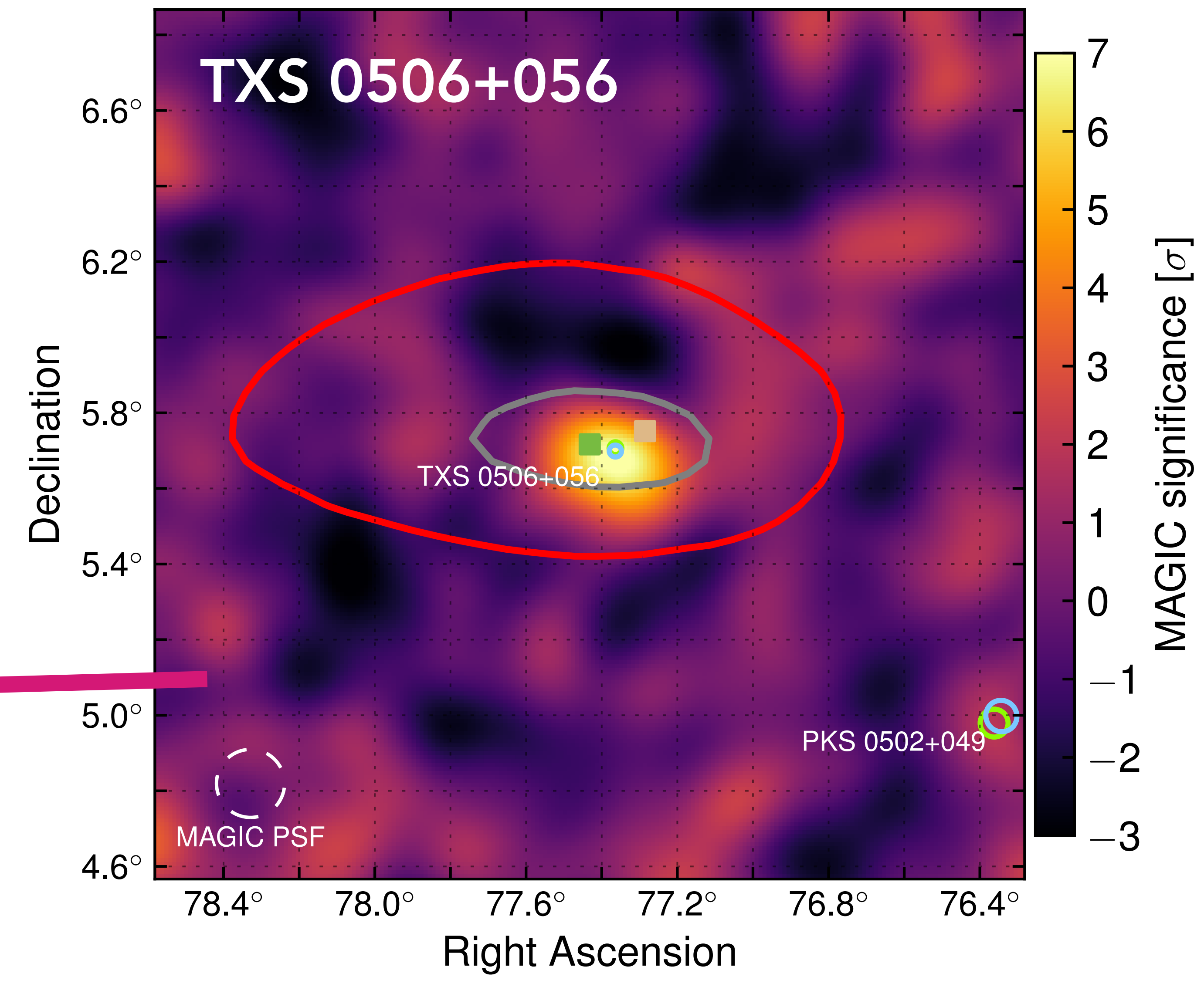


4 Neutrinos from the Milky Way (2023)





IceCube 2021 (arXiv/2111.10299)

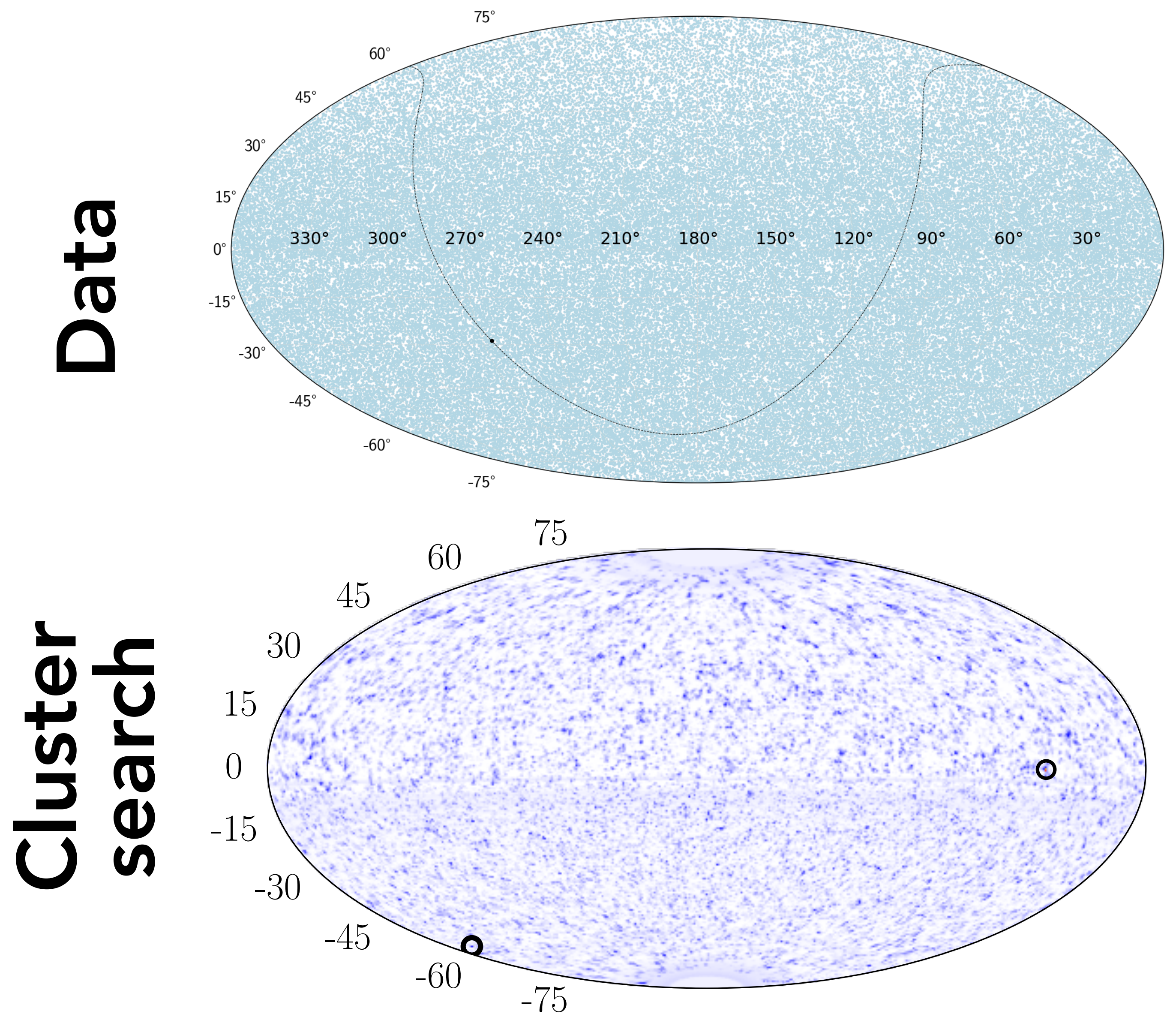


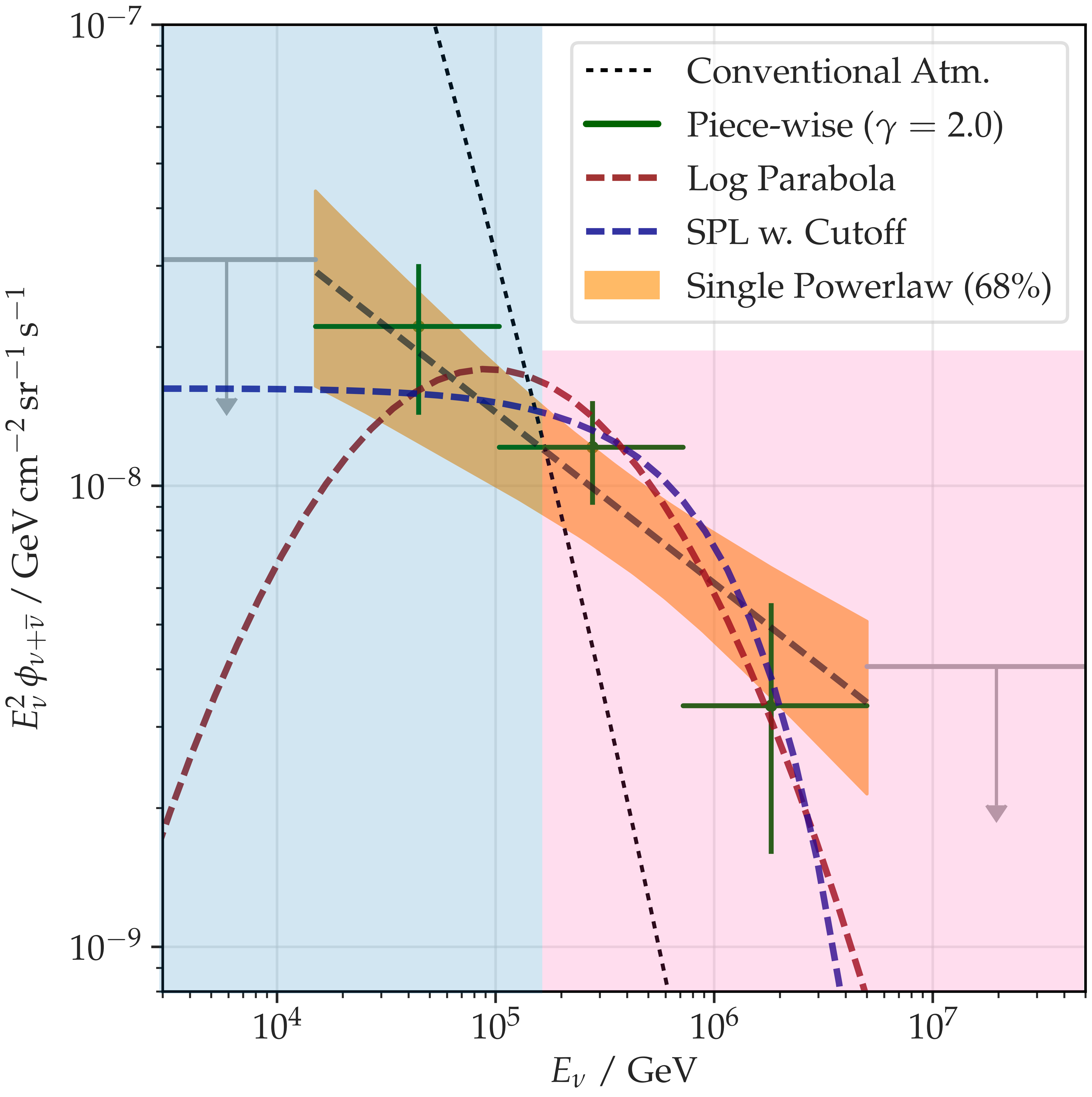
IceCube, MAGIC, ++ 2018 (arXiv/1807.08816)

CURRENT OBSERVATIONAL STATUS FOR NEUTRINOS

Low-energy regime

- Background dominated
- Sensitivity roughly ∝ PSF^2
- Self-clustering and correlation searches (temporal too)

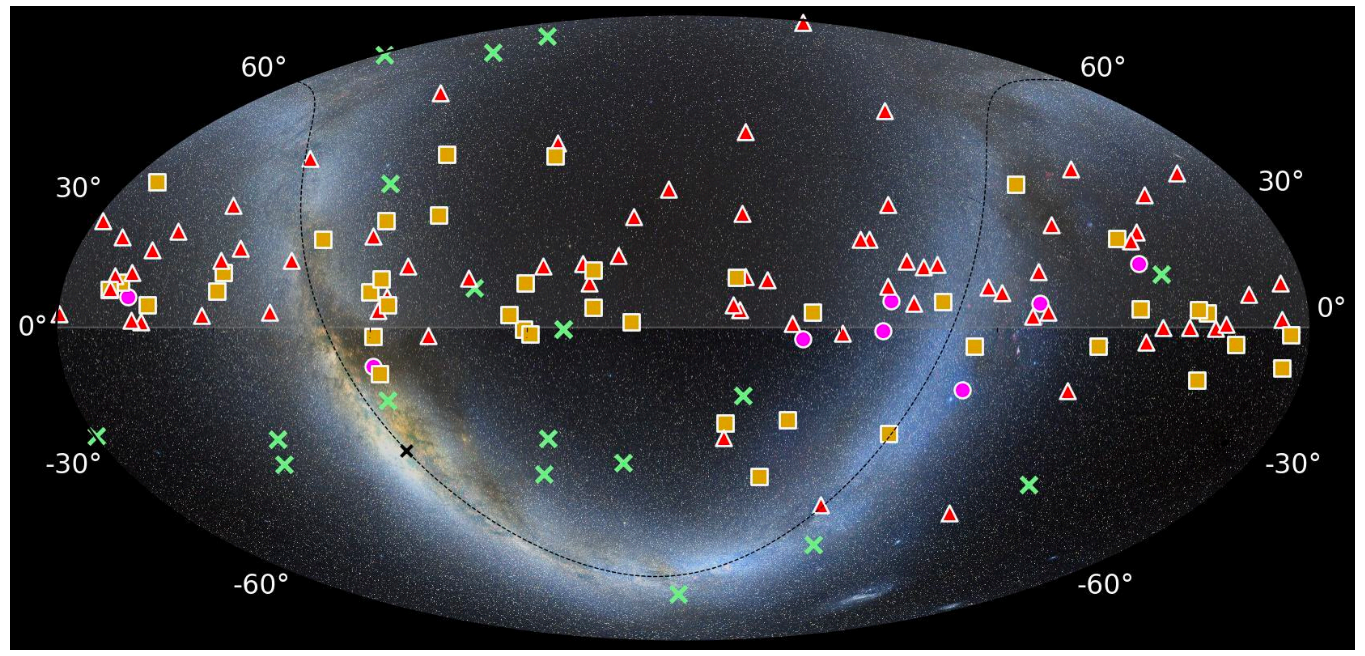




IceCube 2021 (arXiv/2111.10299)

High-energy regime

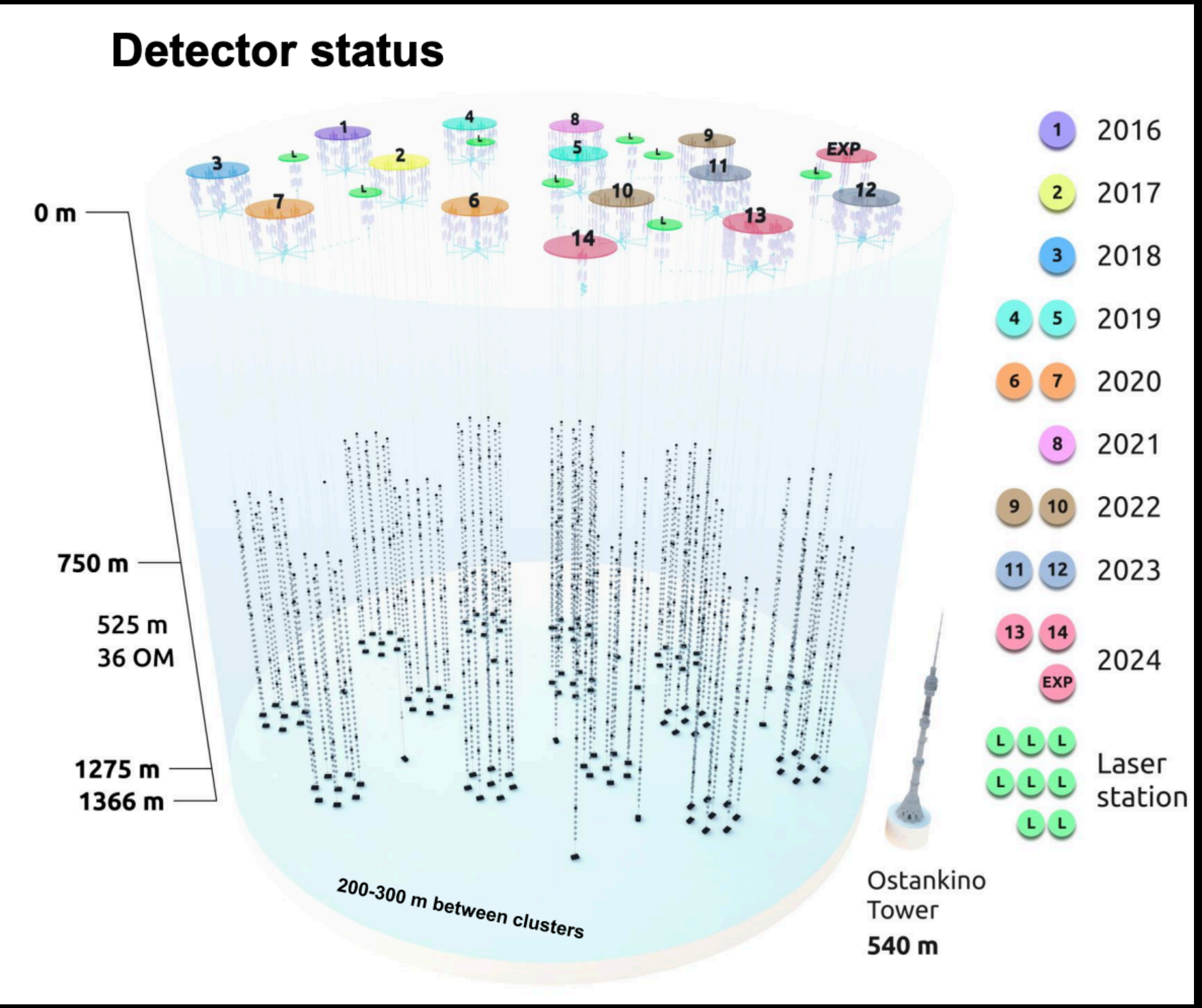
- Signal dominated
- Very low event rate (~10 events per year across the full sky for km³ detector)
- Correlation studies
- Realtime follow-ups



IceCube realtime alerts

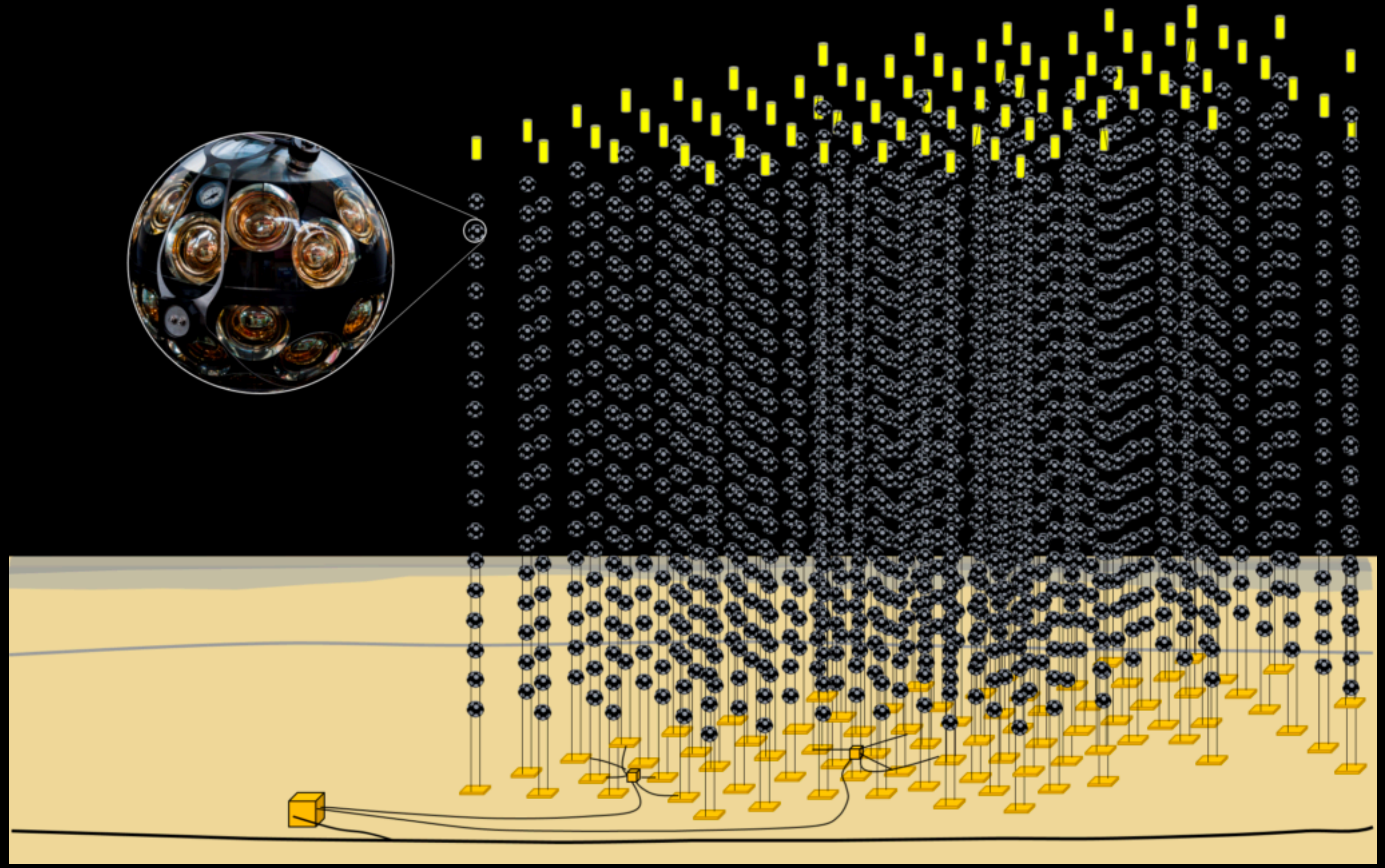
CURRENT GENERATION OF NEUTRINO TELESCOPES

Future: P-ONE, TRIDENT, HUNT, NEON



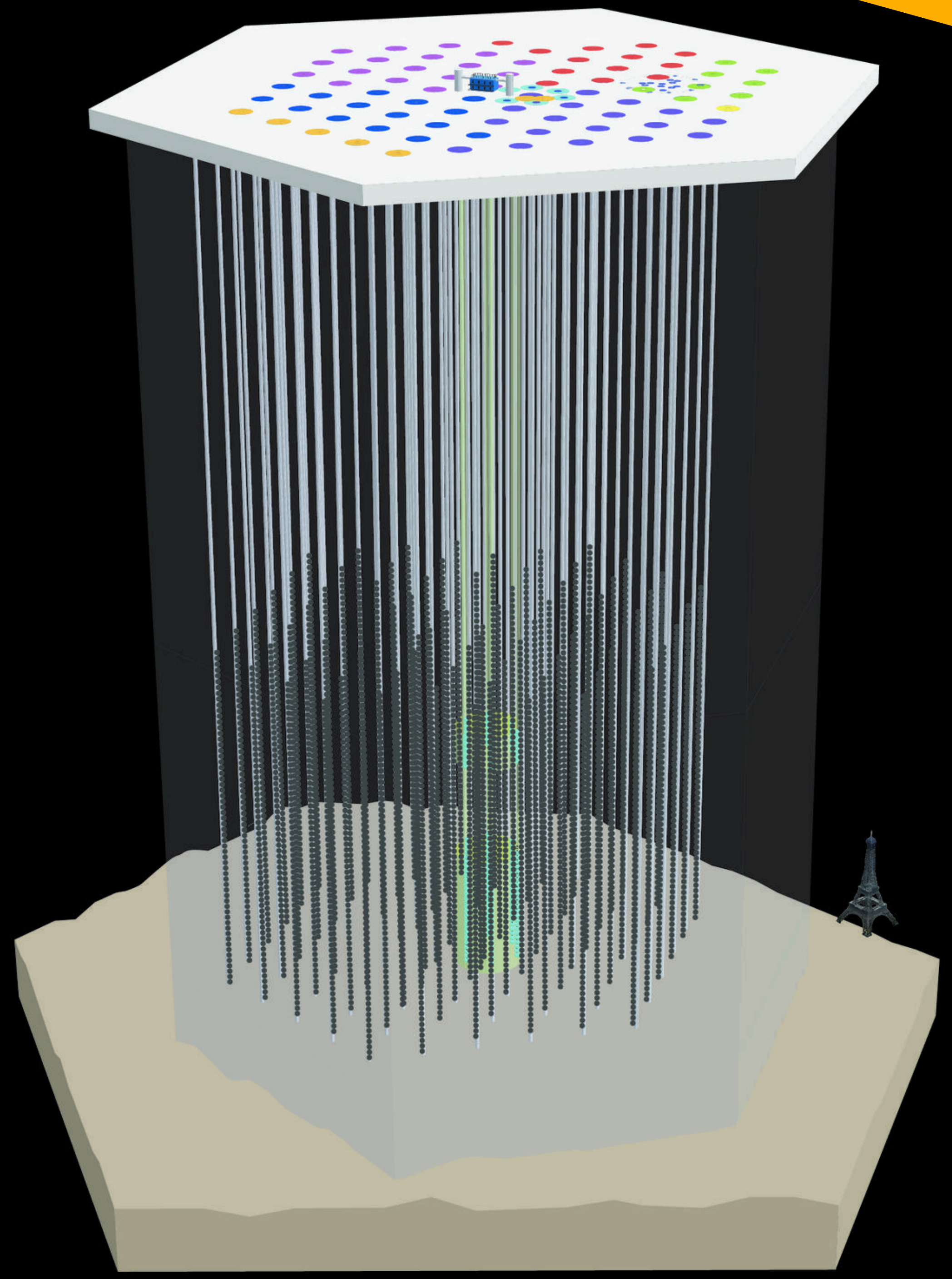
Baikal-GVD

- Lake Baikal (Russia)
- Under construction, targeting 1 km^3
- As of 2024: 14 clusters with 110 strings total. Talk by Rastislav Dvornicky



KM3NeT

- Mediterranean Sea (Italy/France). Successor of ANTARES.
- Under construction (ORCA/ARCA), targeting 1 km^3
- 24+33 detector unit lines operating (see talk by Aart Heijboer)



IceCube

- South Pole glacier. 2010.
- 1 km^3
- 5160 PMTs
- Talk by Erin O'Sullivan

THE CHALLENGE OF IDENTIFYING SOURCES

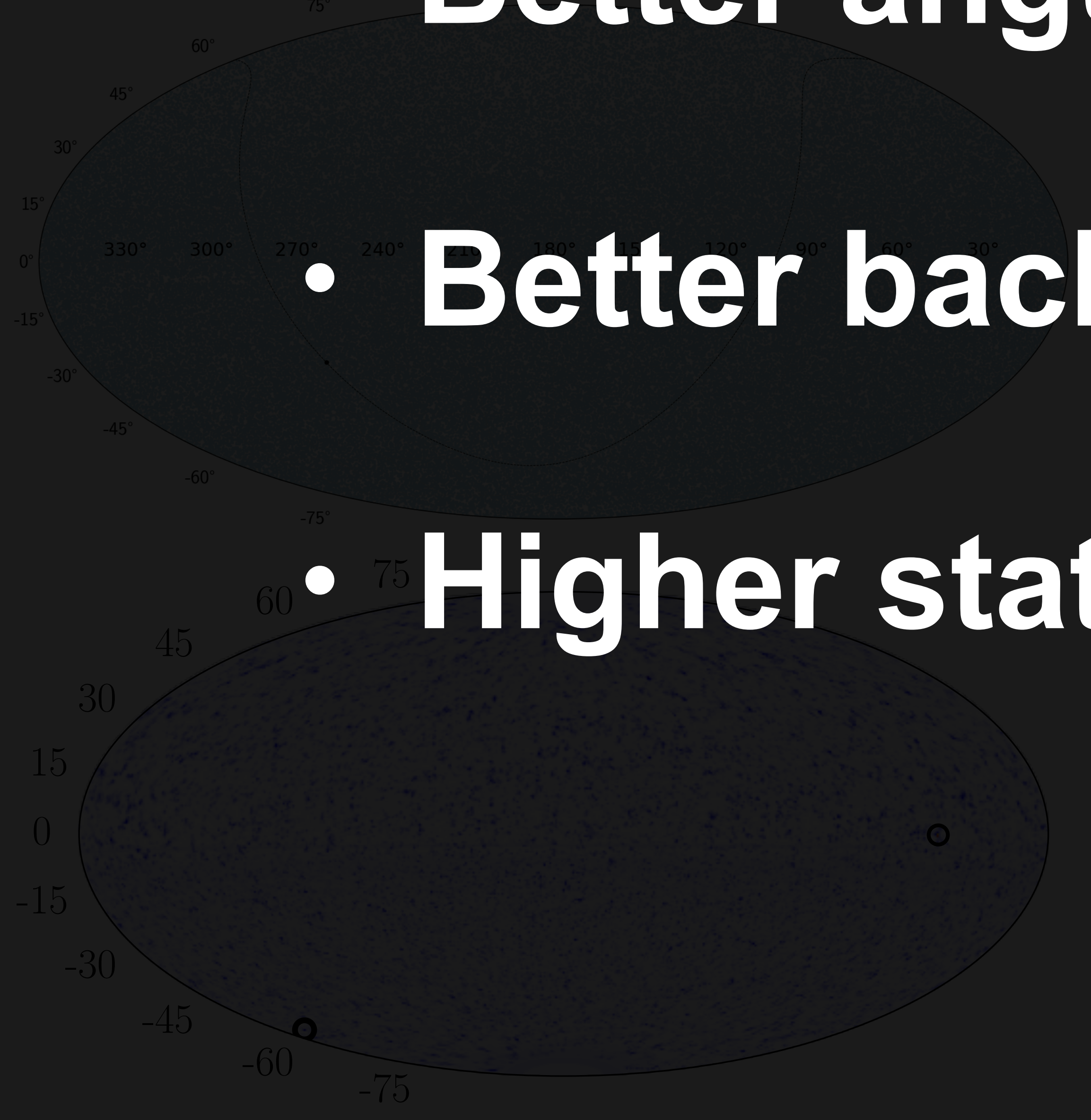
- Requirements for next-generation neutrino telescopes
  - Improved sensitivity
  - Better angular resolution
  - Better background rejection
  - Higher statistics

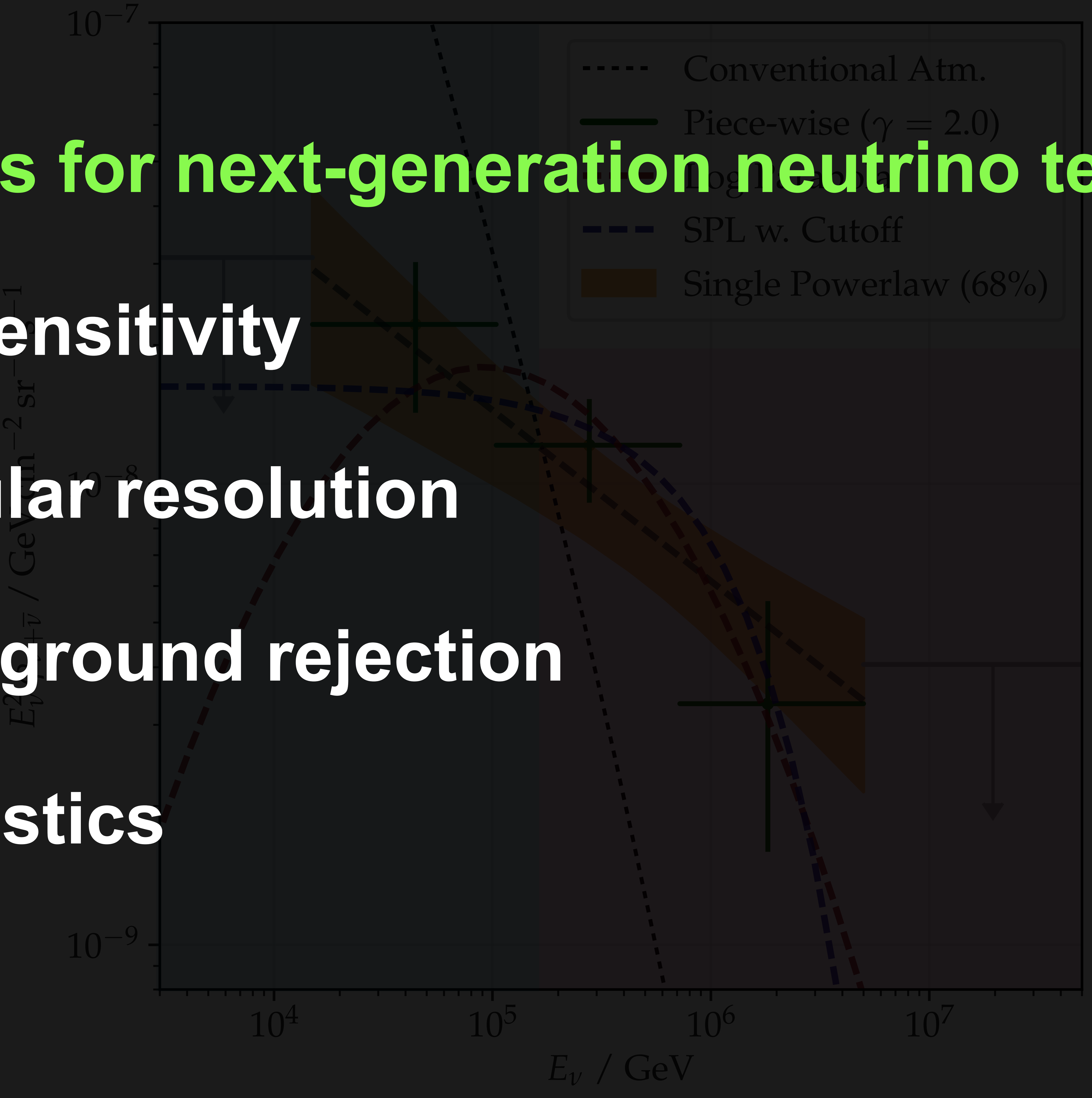
Low-energy regime

- Background dominated
- Sensitivity roughly ∝ PSF^2
- Self-clustering and correlation searches

Data

Cluster search

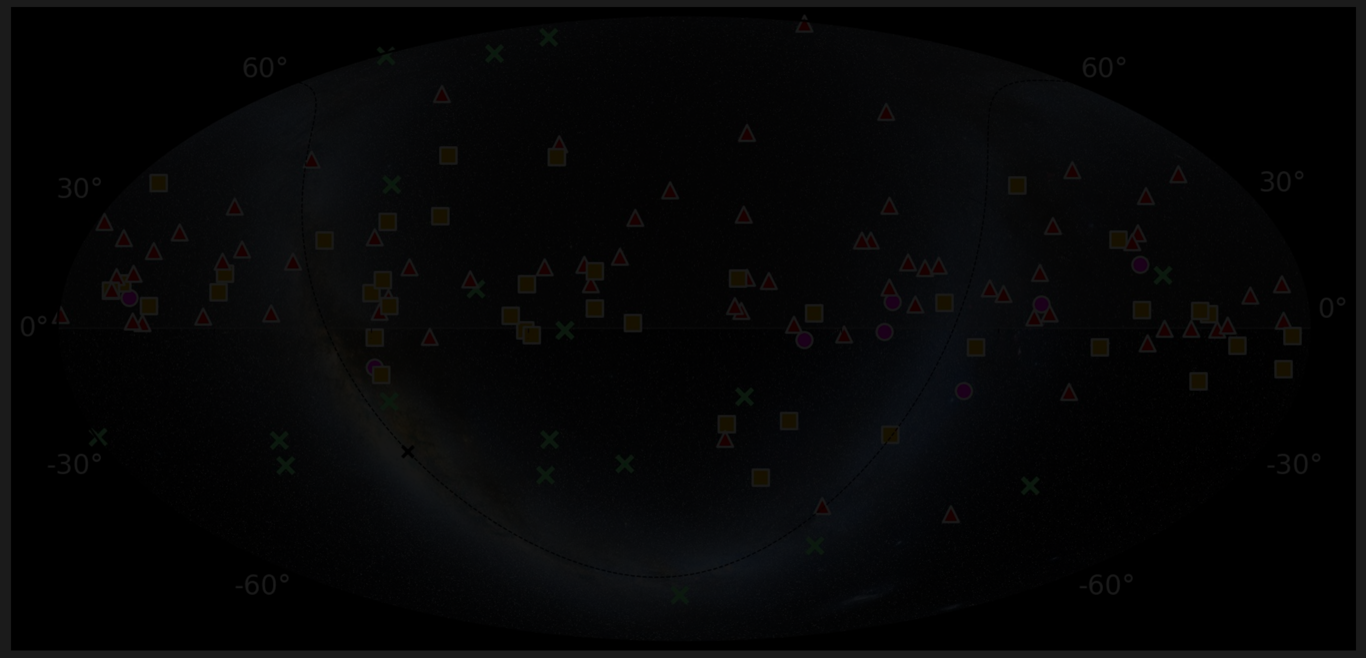




IceCube 2021 (arXiv/2111.10299)

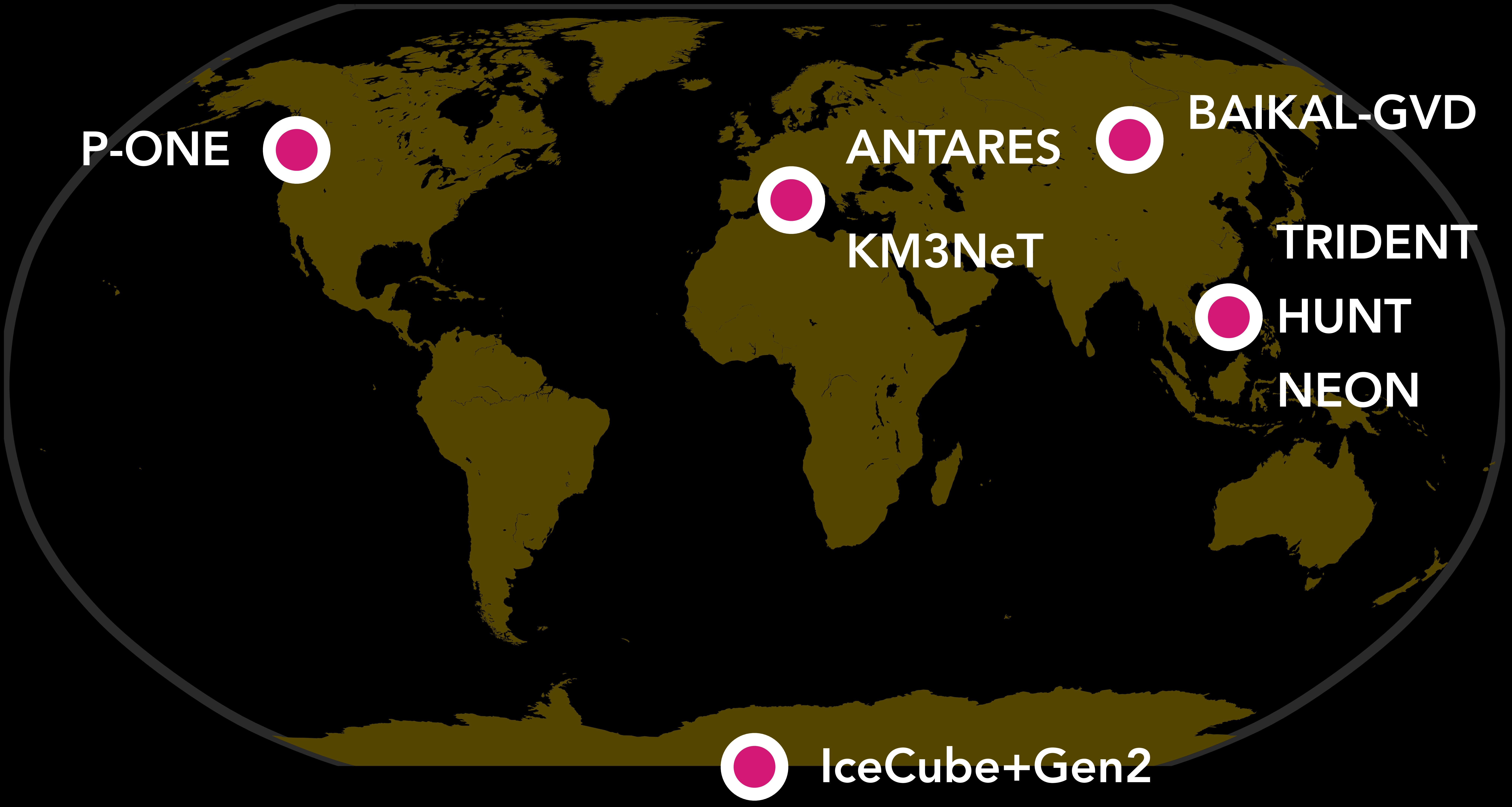
High-energy regime

- Signal dominated
- Very low event rate (~10 events per year across the full sky)
- Correlation studies
- Realtime follow-ups



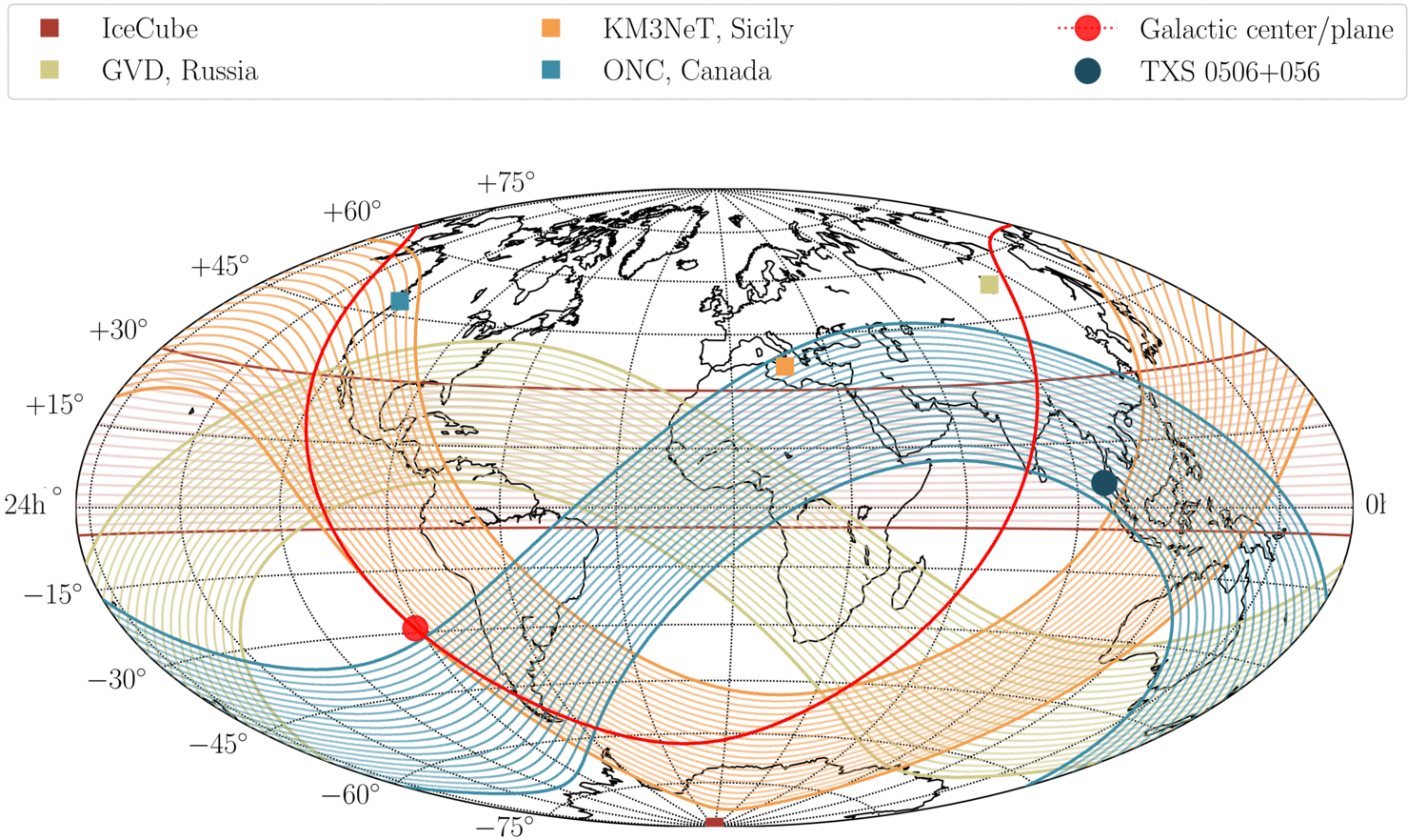
IceCube realtime alerts

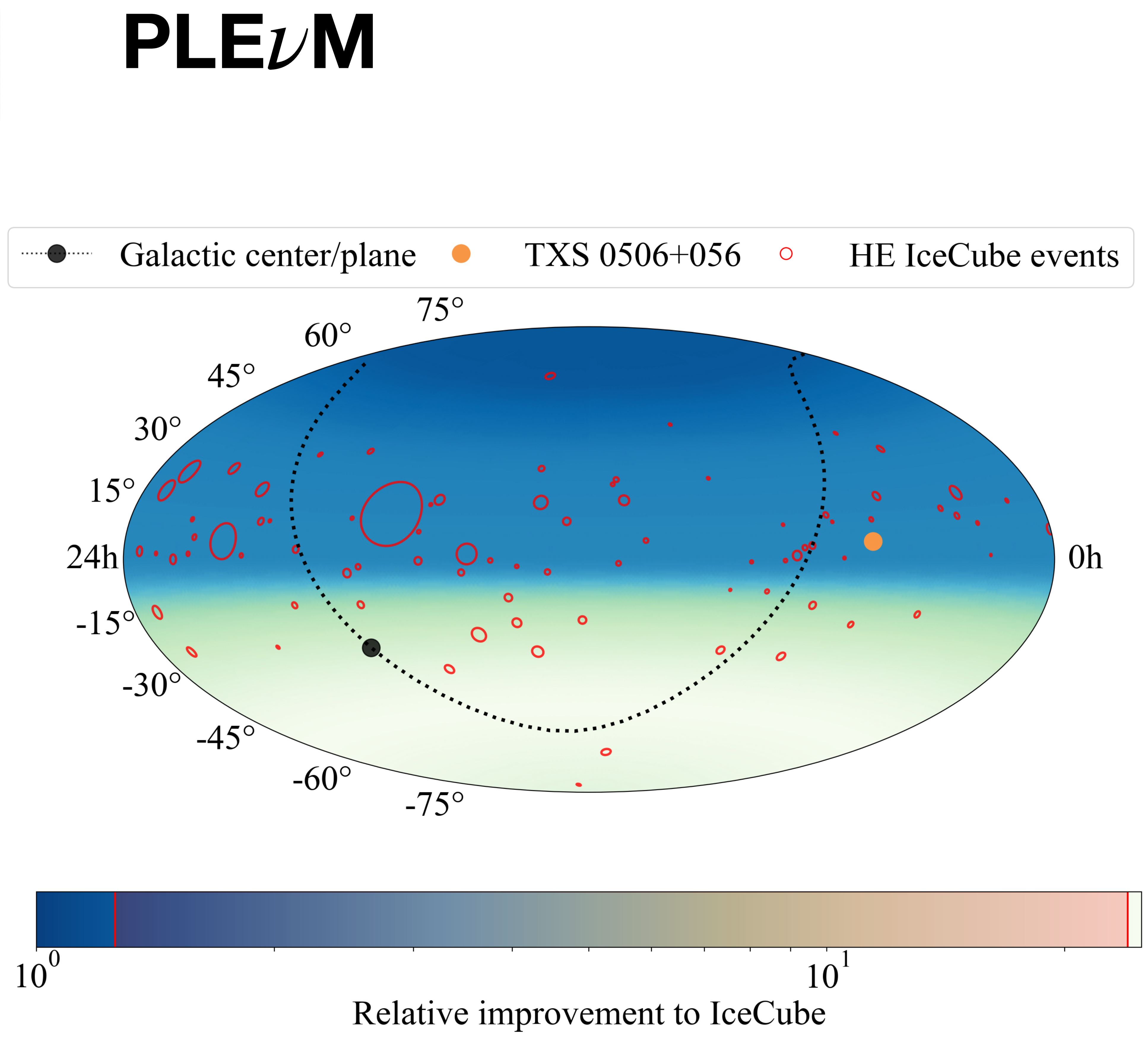
NEUTRINO CHERENKOV TELESCOPES



COMBINING NEUTRINO OBSERVATIONS

https://github.com/PLEnuM-group/Plenum



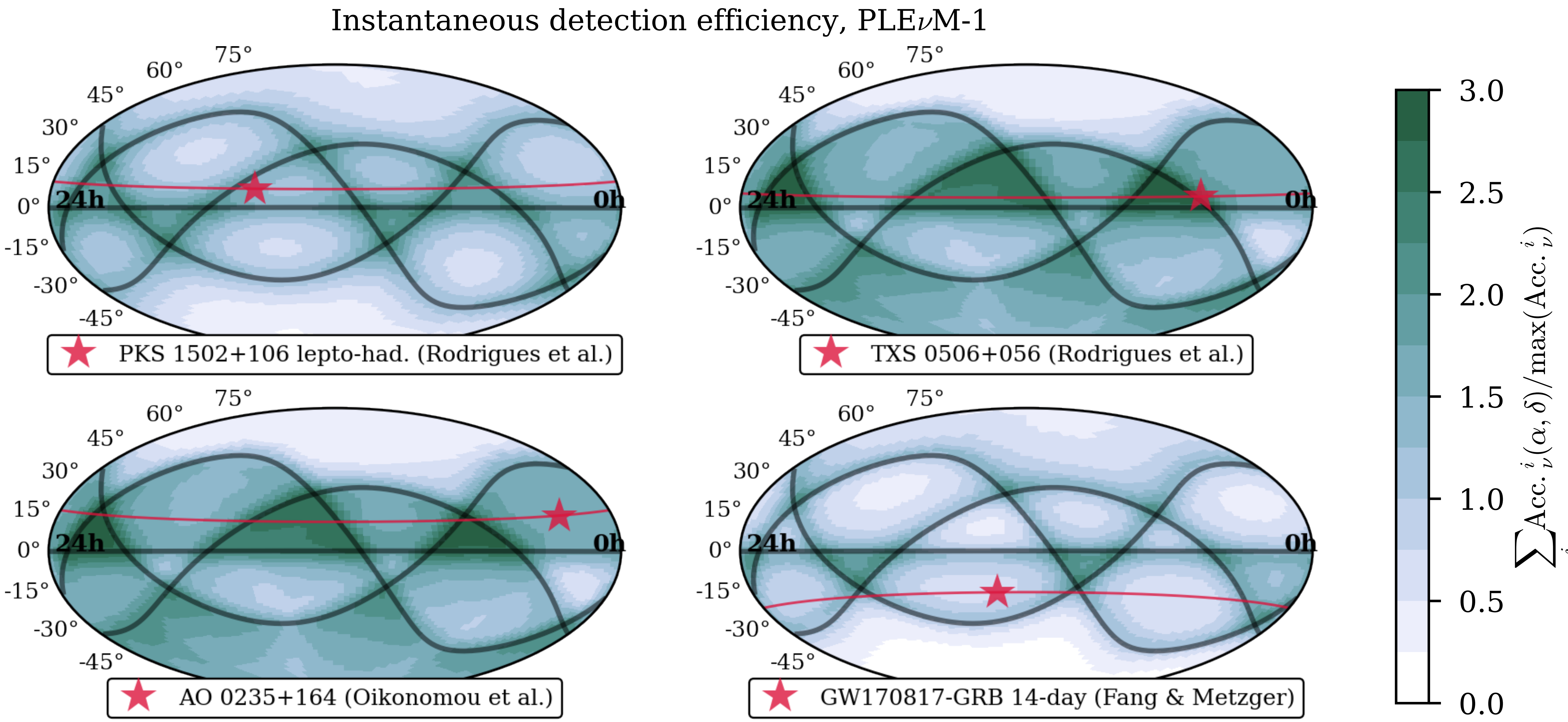


L. Schumacher et al. (arXiv/2107.13534)

- 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**.

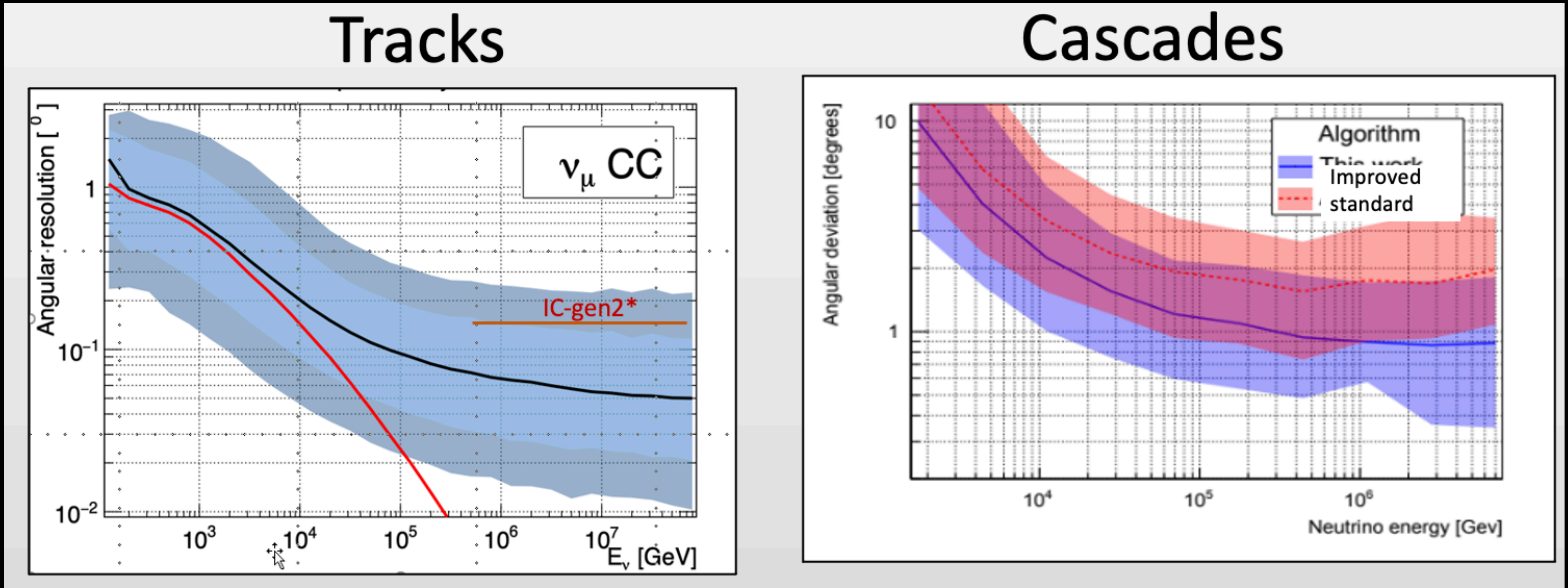
COMBINING NEUTRINO OBSERVATIONS

L. Schumacher et al. ICRC 2023 (Vol 444 991)



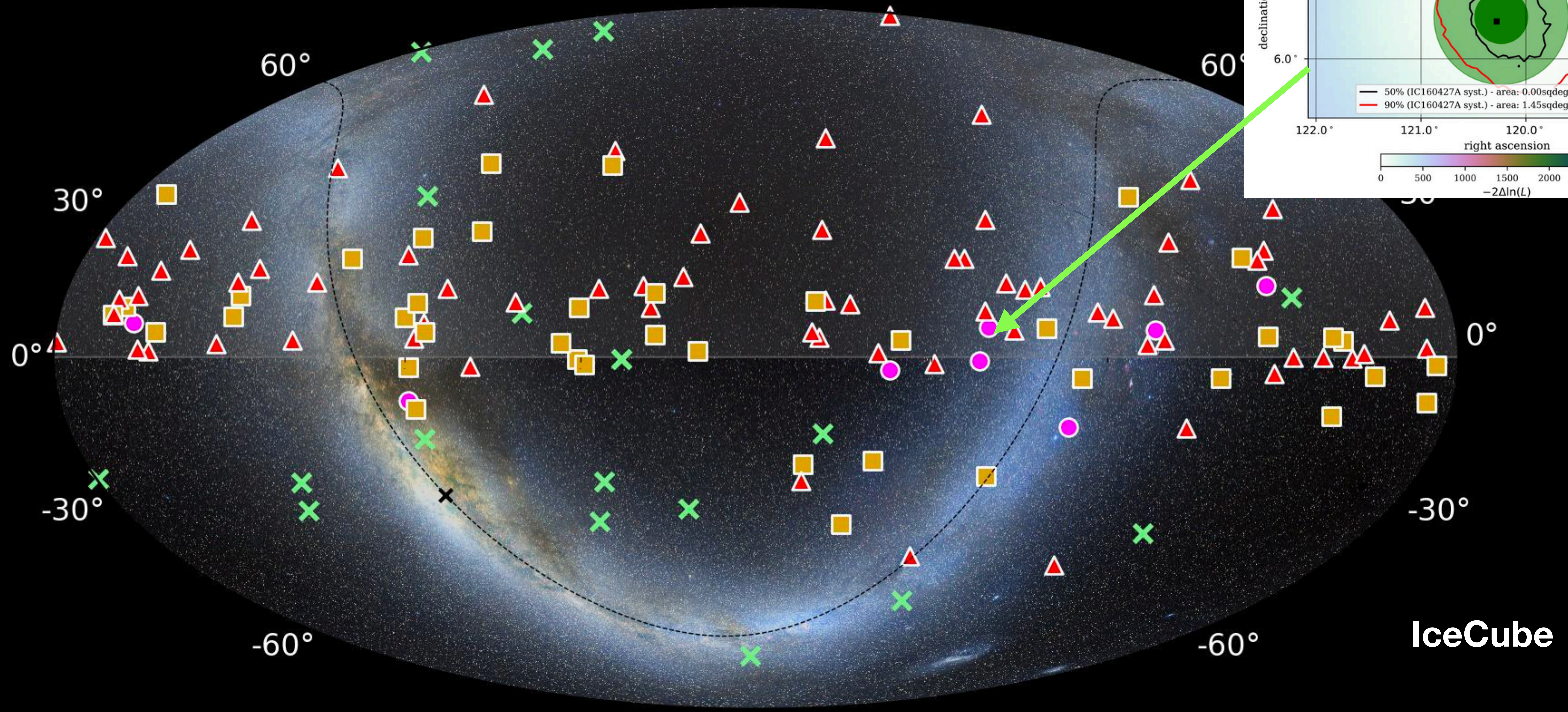
- Significant improvements by combining detectors at different latitudes and longitudes (background suppression).
- Acceptance and sky coverage for alerts increased by a factor of ~5.
- Additional telescopes looking to expand statistics at the highest energies (e.g RNO-G, TRINITY, BEACON, GRAND, TAMBO).
- **There's significant gain in combining neutrino observations from multiple observatories (possibly in realtime)**

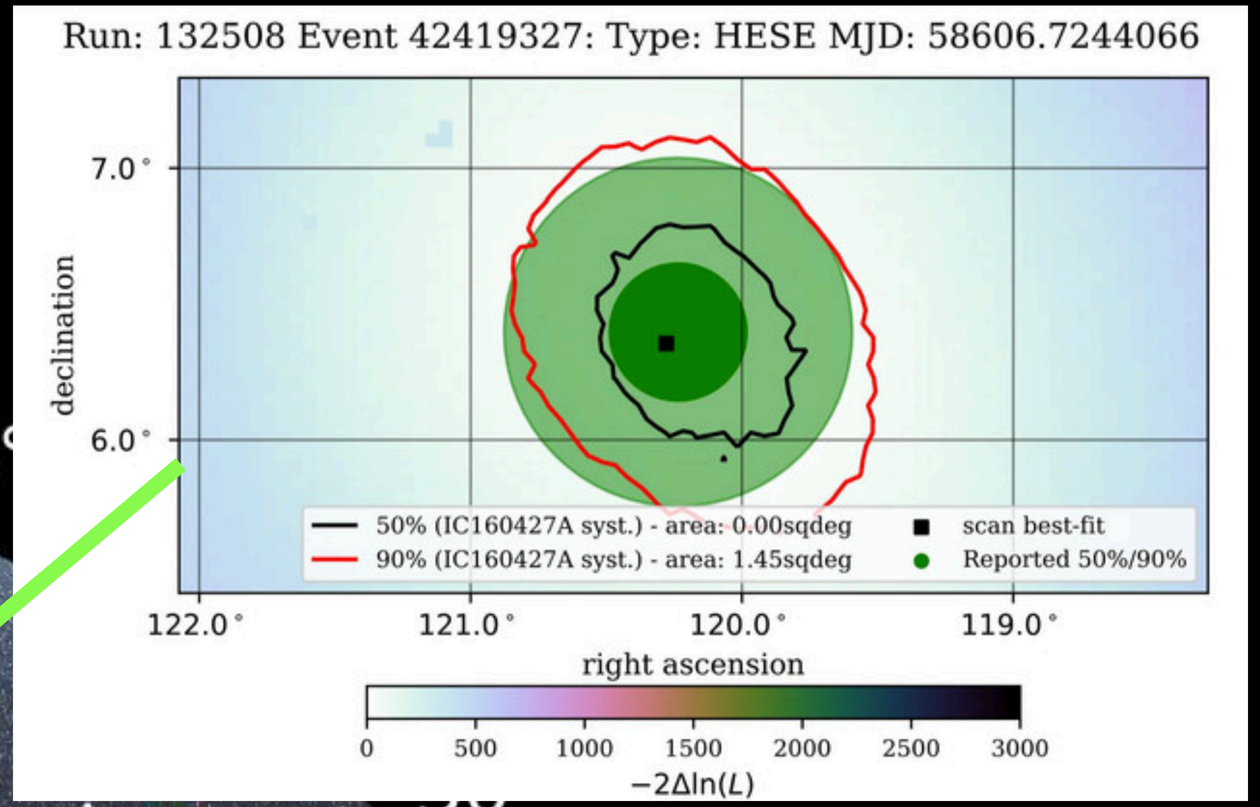
ANGULAR RESOLUTION IMPROVEMENTS



- Chance probability of correlation goes with PSF²
- **Current generation instruments are expected to reach O(0.1°) angular resolution for tracks, 2° for cascades.**
- Enable sensitive searches of neutrino counterparts with EM instruments.

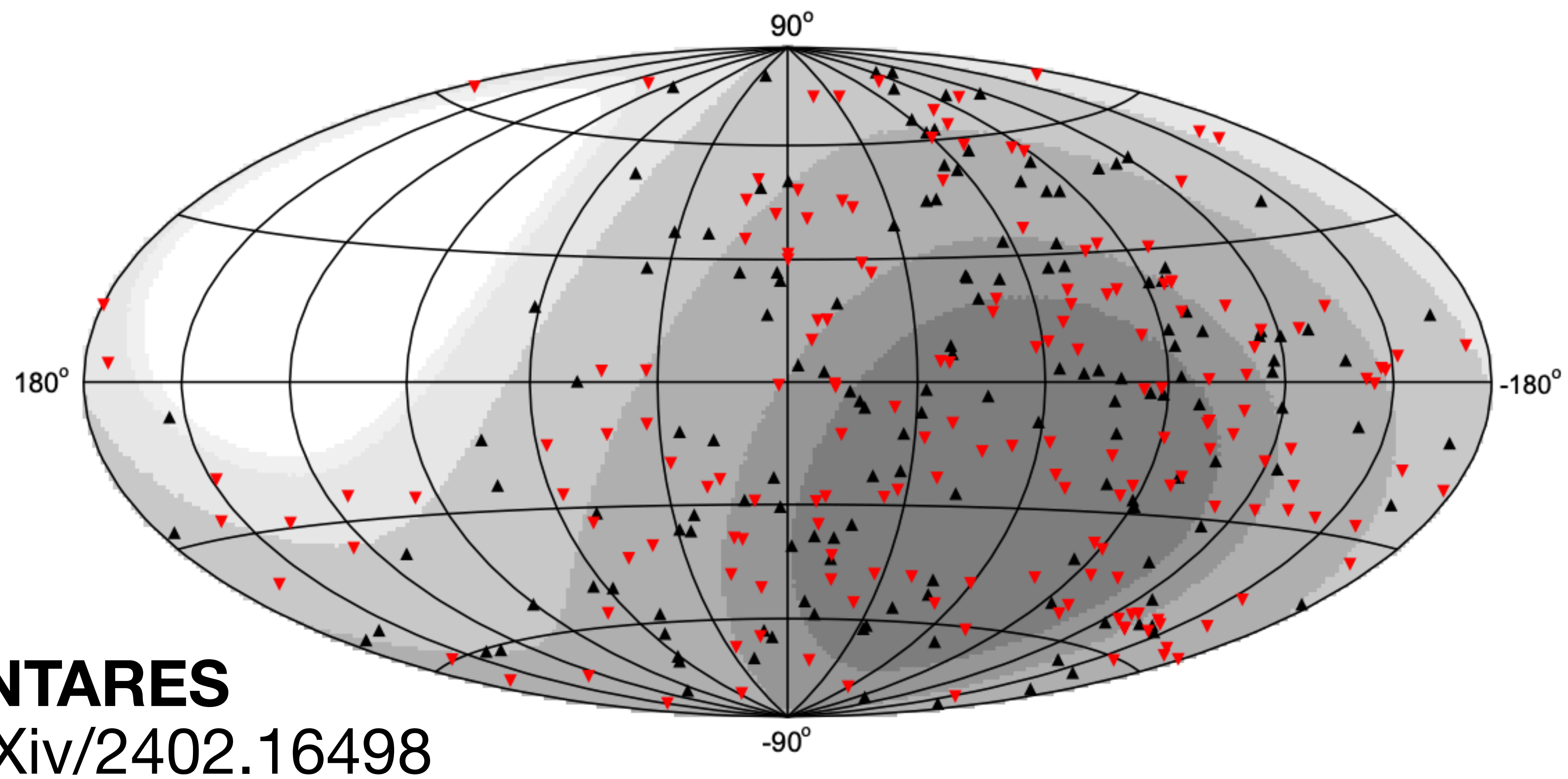
REALTIME ALERTS



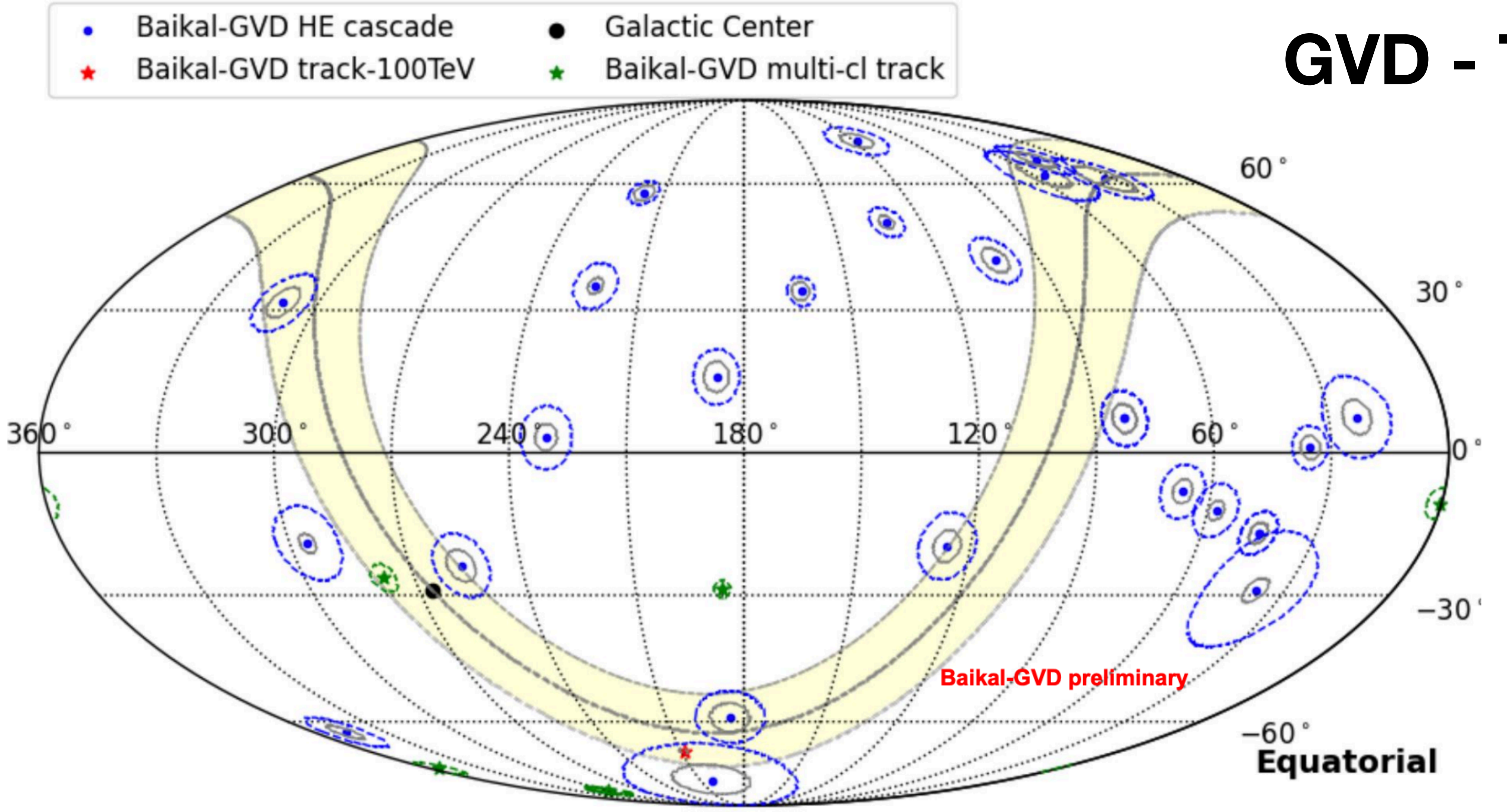


- **Characterizing potential counterparts requires broadband EM observations.**
- Understanding the PSF of neutrino telescopes is challenging! Limited by systematic uncertainties.

REALTIME ALERTS

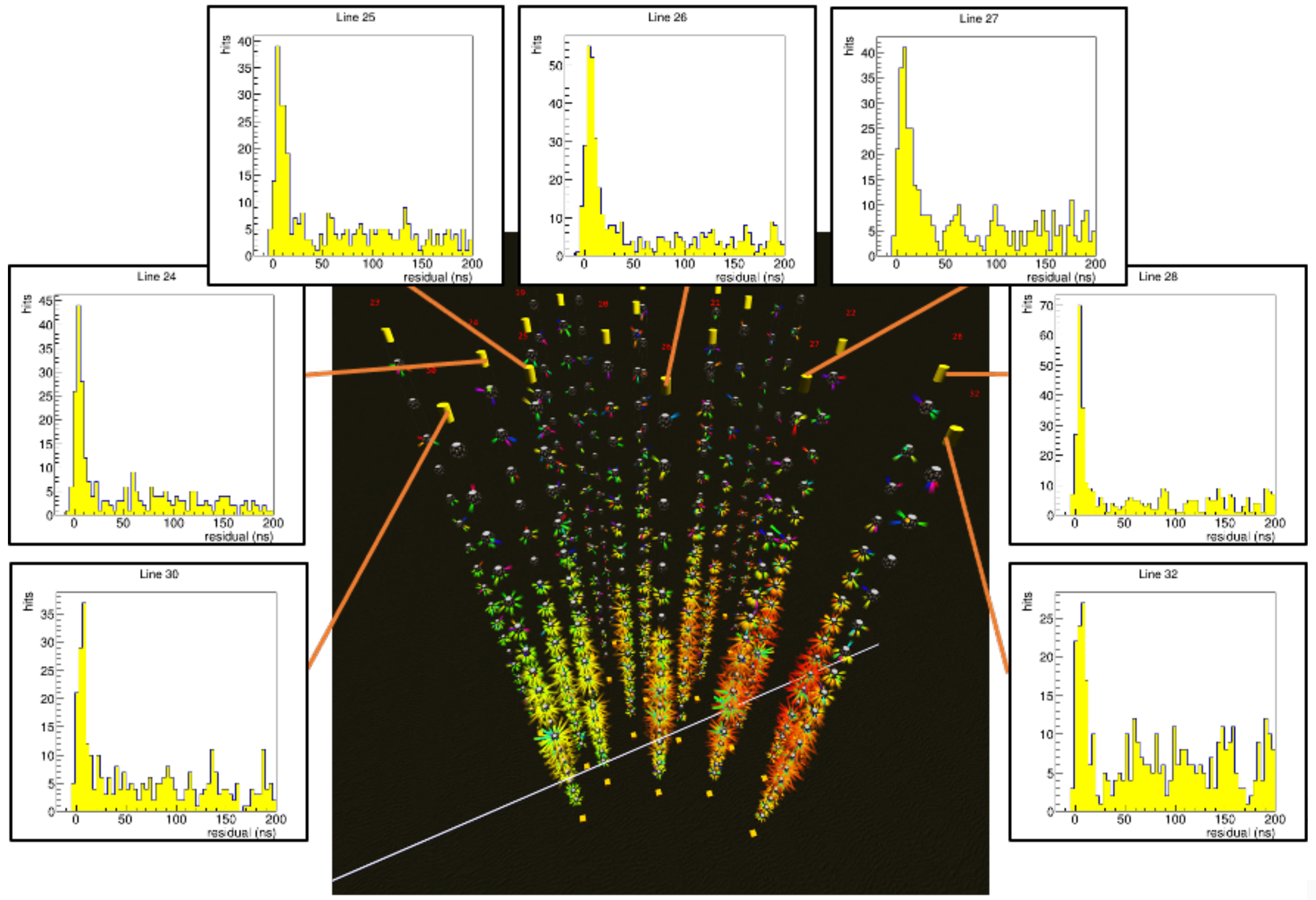


ANTARES
arXiv/2402.16498



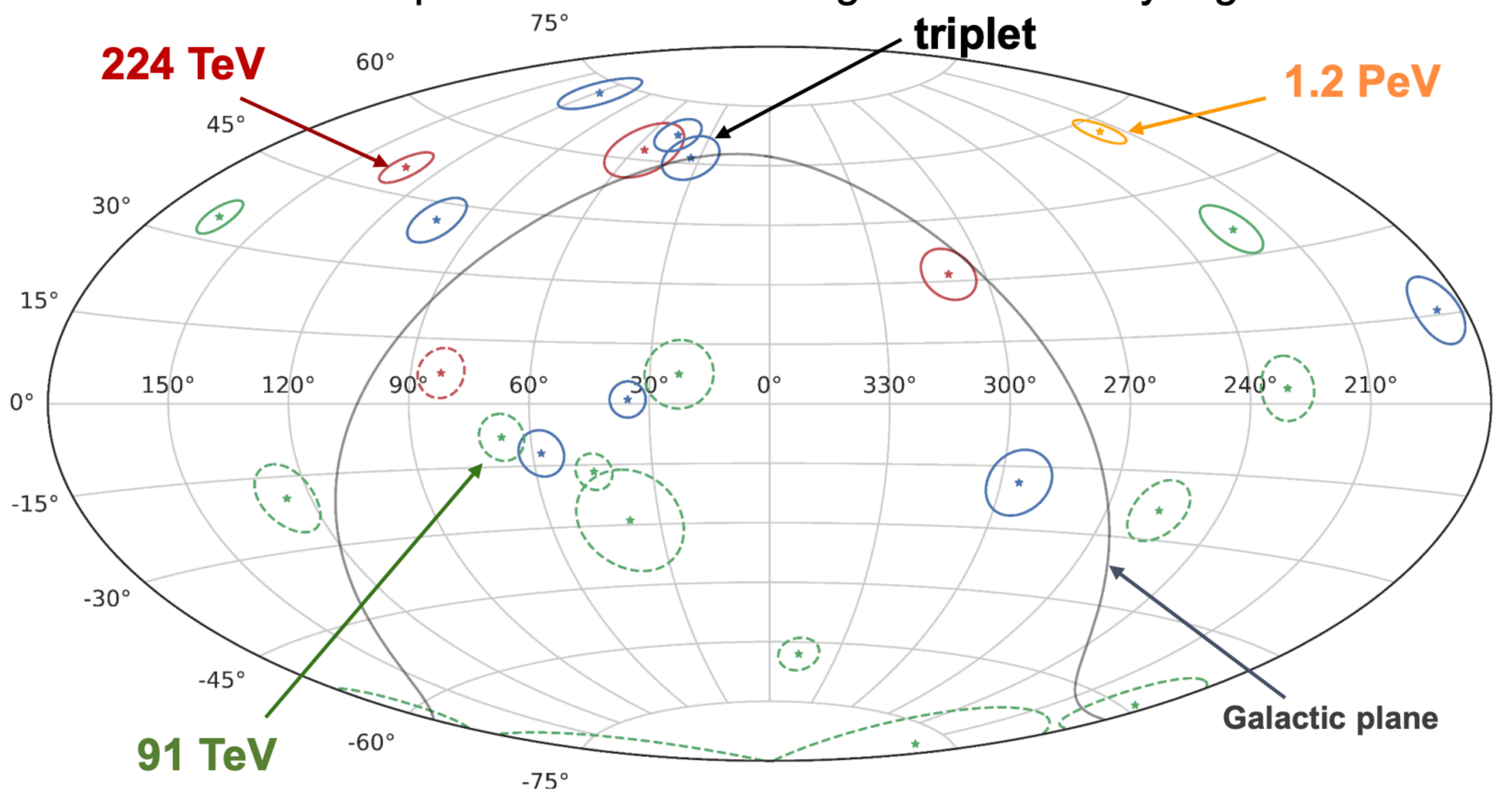
GVD - Tracks

KM3NeT



GVD - Cascades

Best fit positions and 90% angular uncertainty regions



color represents energy:
E_{rec} < 100 TeV
100 TeV < E_{rec} < 200 TeV
200 < E_{reco} < 1000 TeV
E_{rec} > 1 PeV

- Global neutrino observatory network becoming a reality.

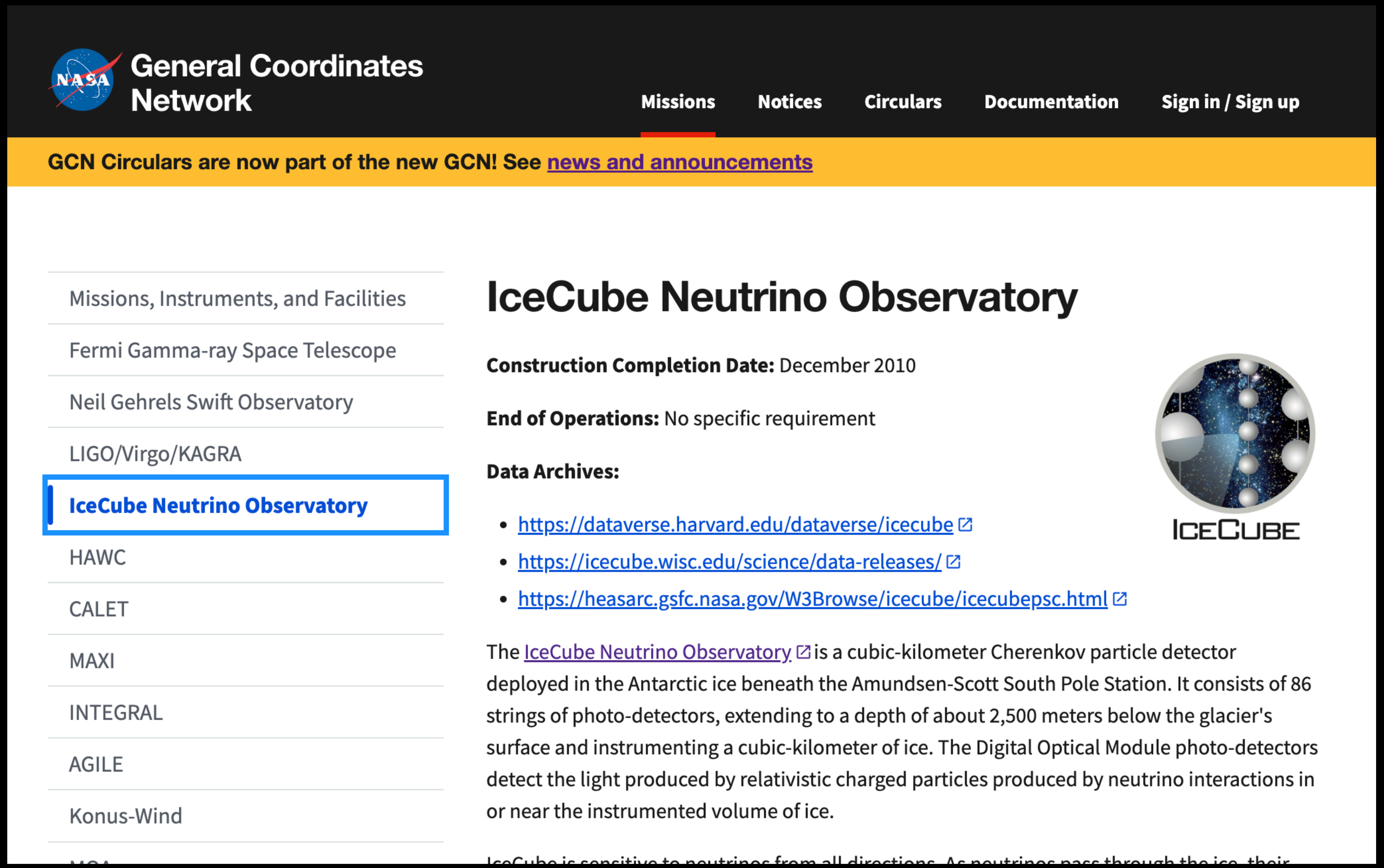
FULLY INTEGRATING NEUTRINO TELESCOPES INTO TDAMM

- 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.

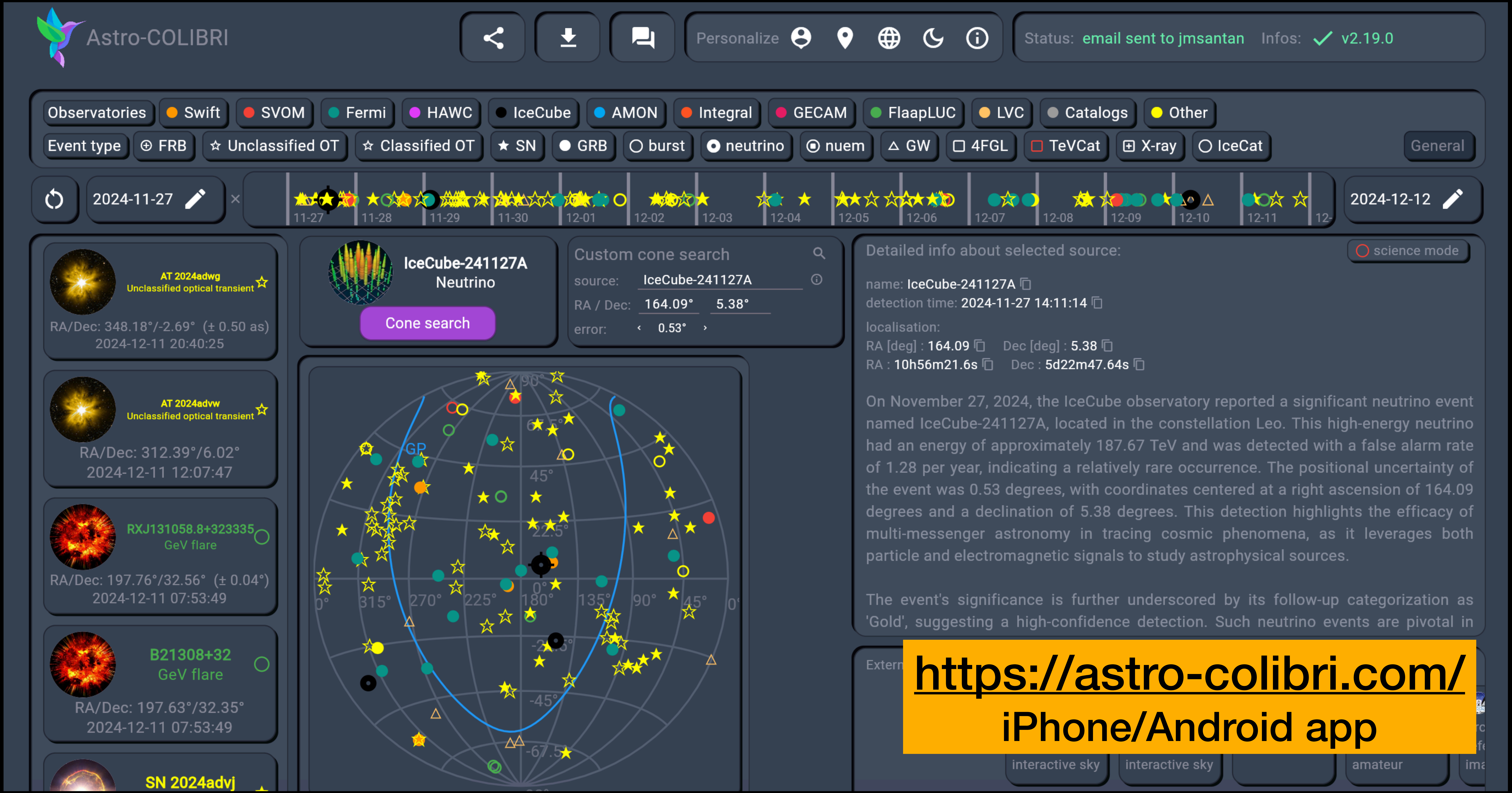
  - Most searches for transient/variable sources should be done in realtime if possible. Neutrino telescopes already working in that direction.

  - EM searches for counterparts should algo go in this direction



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

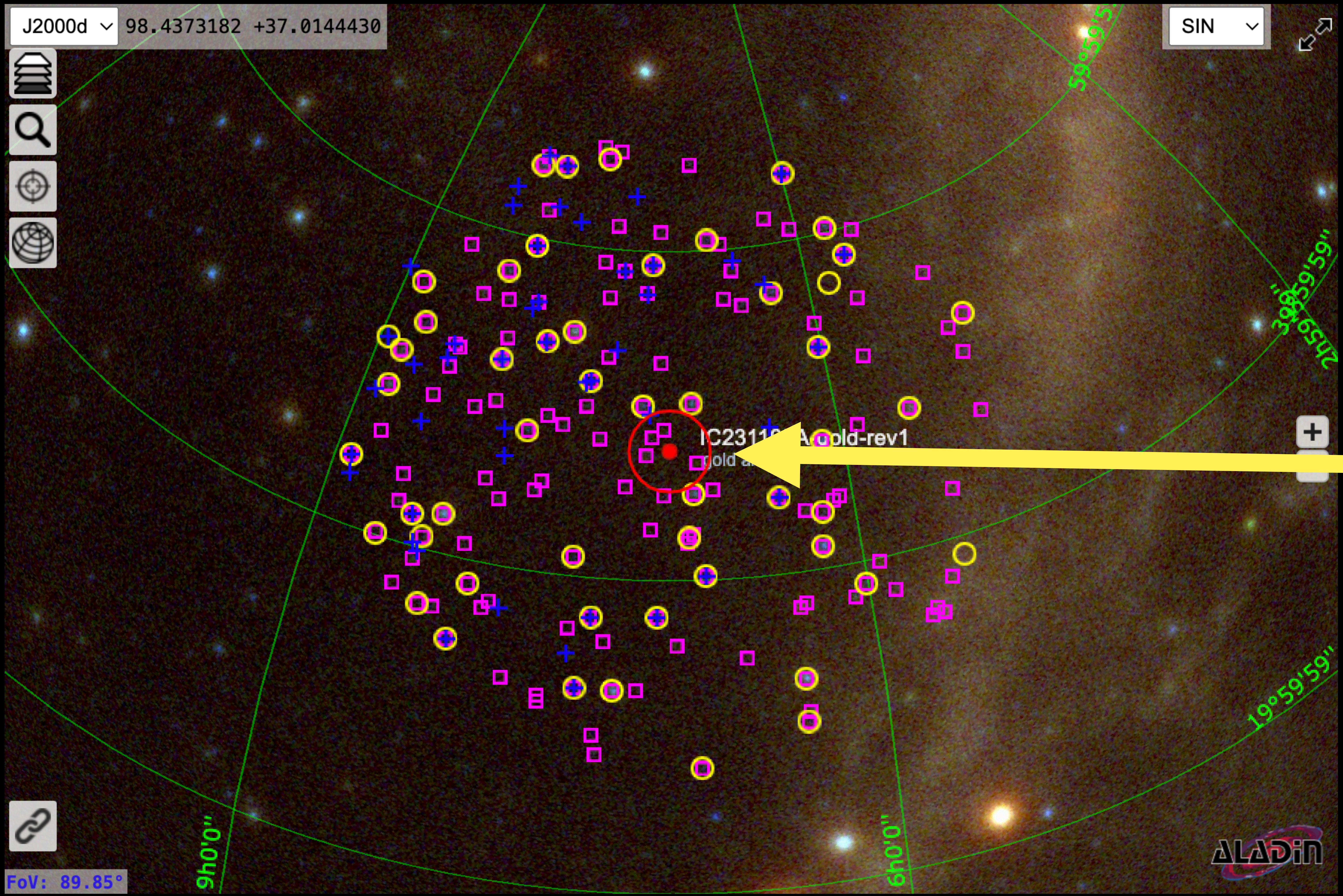
TOOLS FOR DISSEMINATING REALTIME DETECTIONS EXIST!

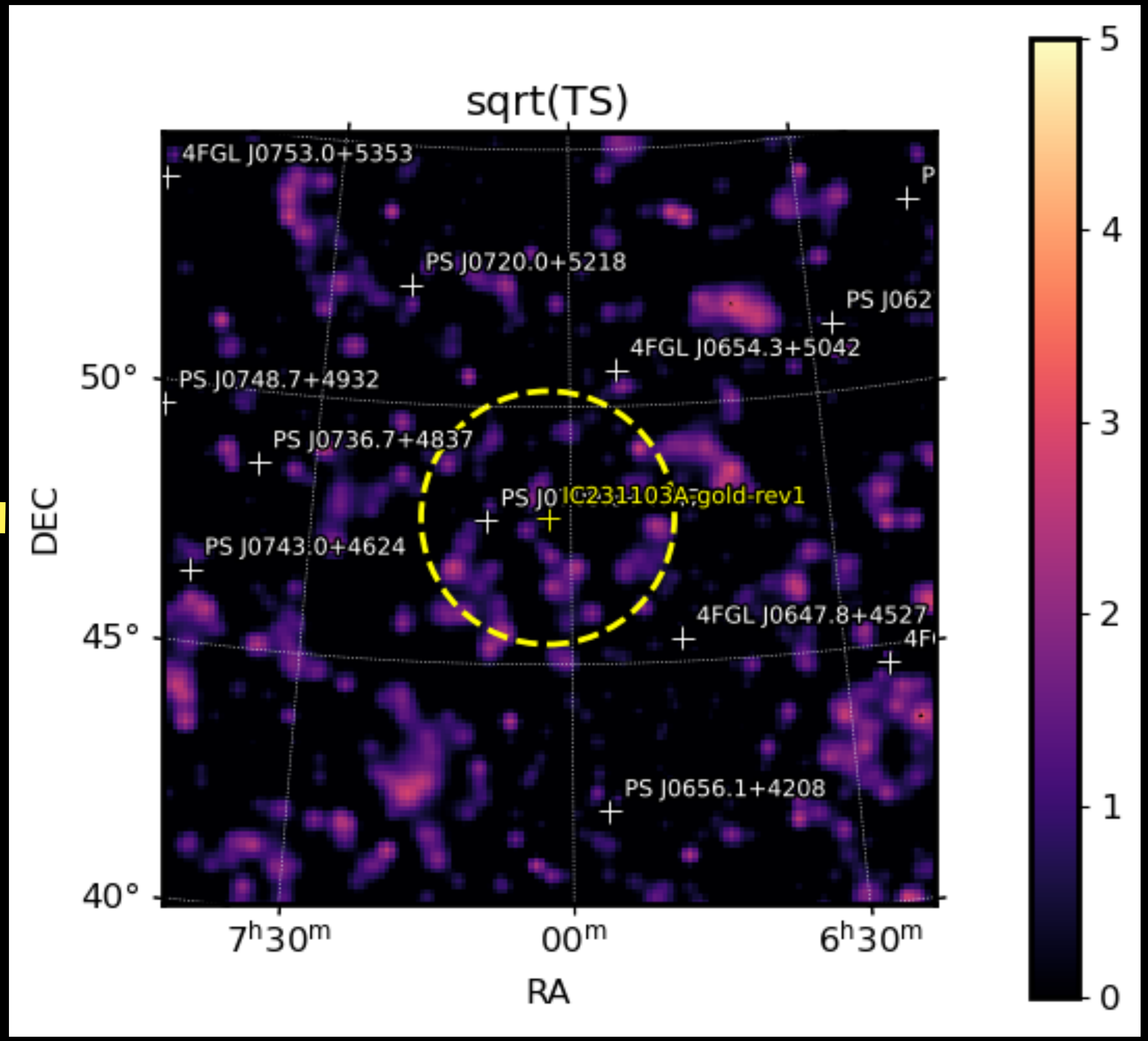


https://astro-colibri.com/

iPhone/Android app

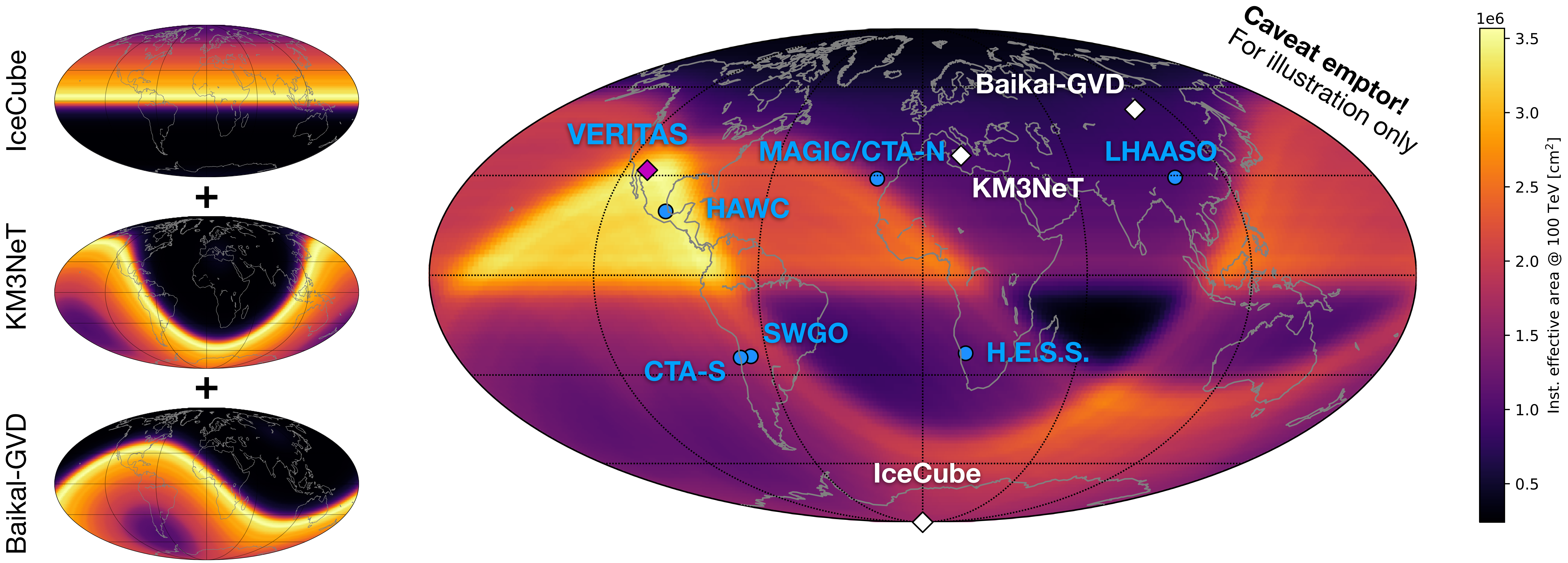
AN EXAMPLE WITH FERMI-LAT





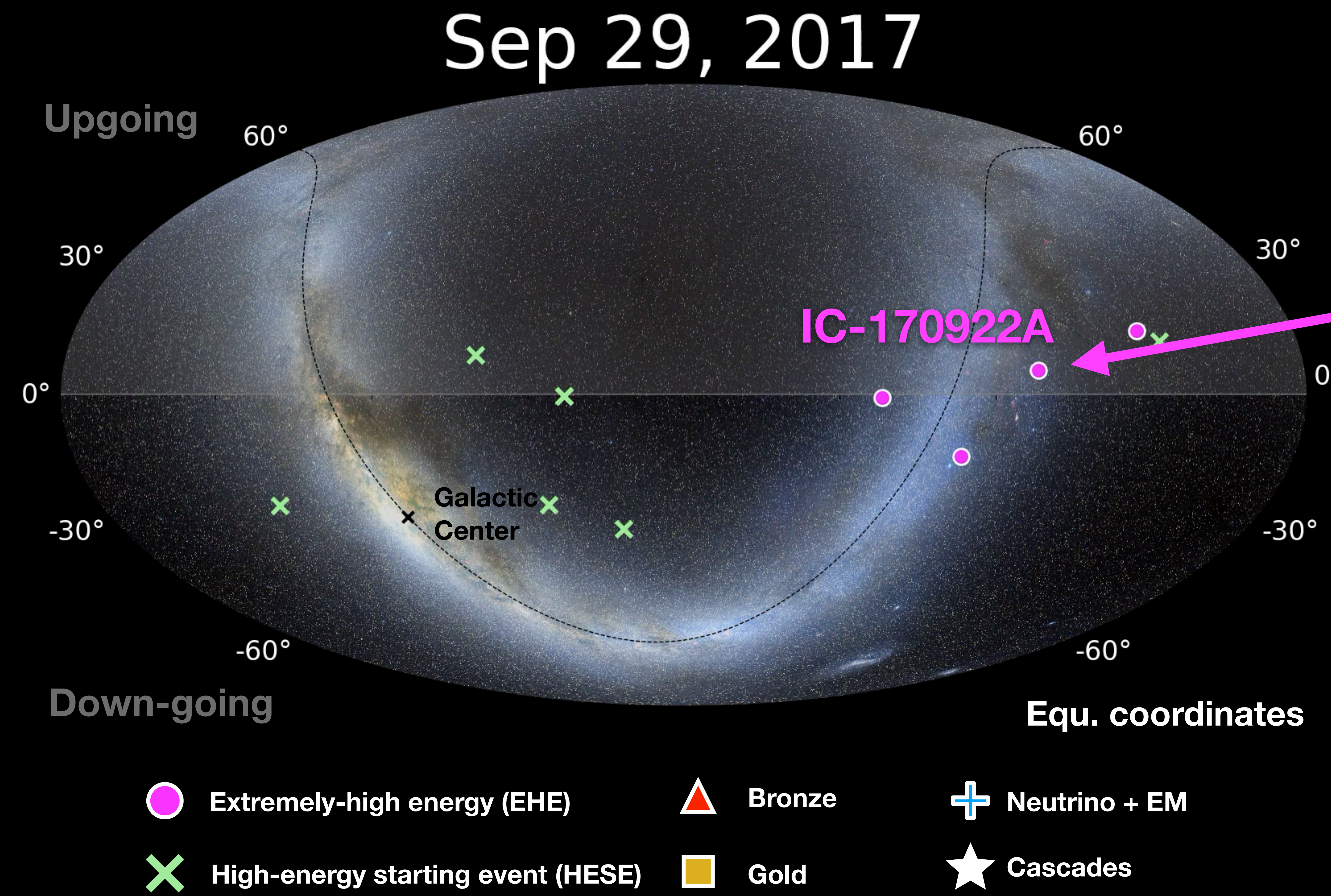
- https://multimessenger.ua.edu/fermi/ (Under development)

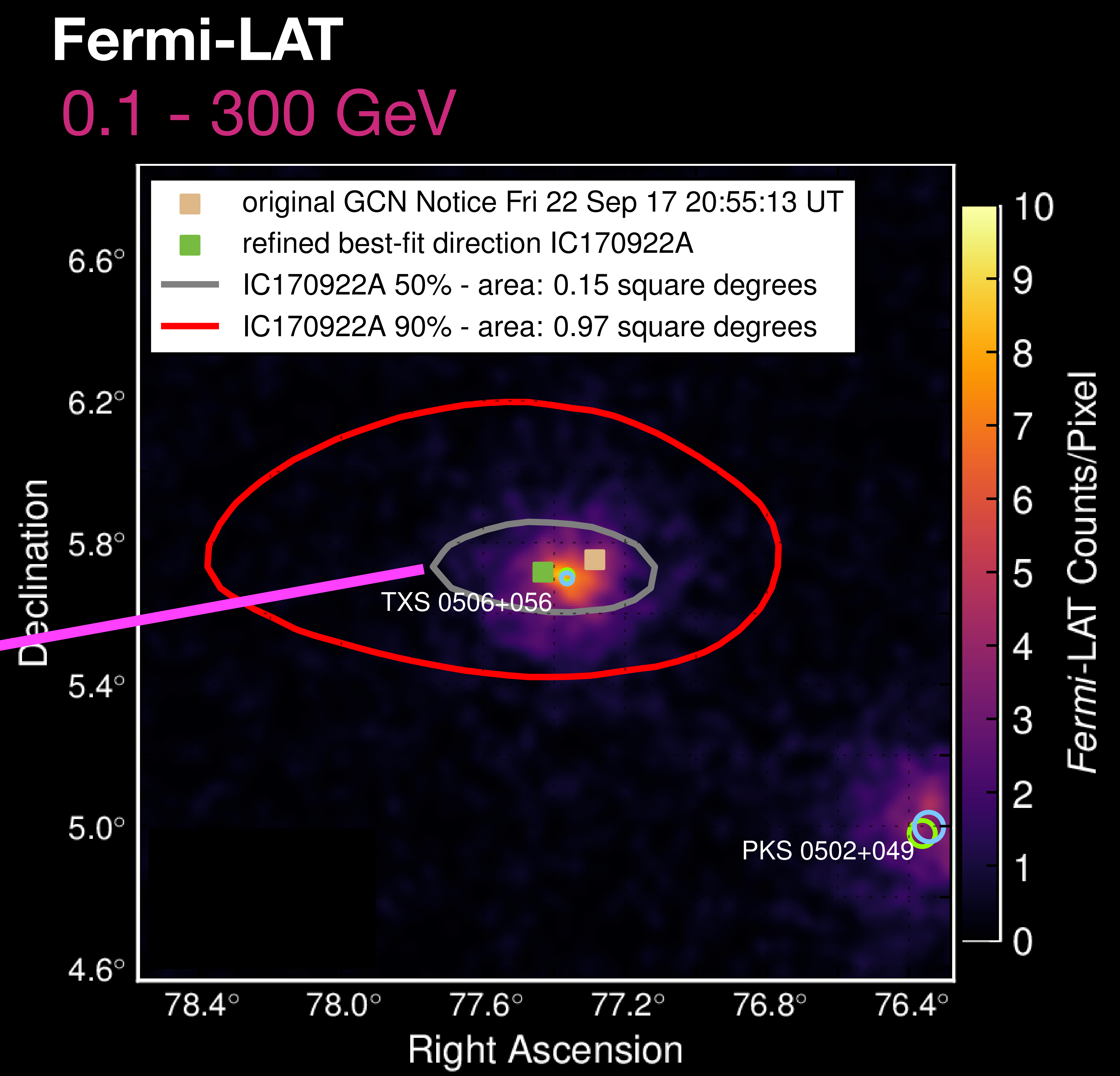
INSTANTANEOUS SENSITIVITIES FOR GROUND-BASED INSTRUMENTS



- 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).
- Some locations are favored for fast transients.

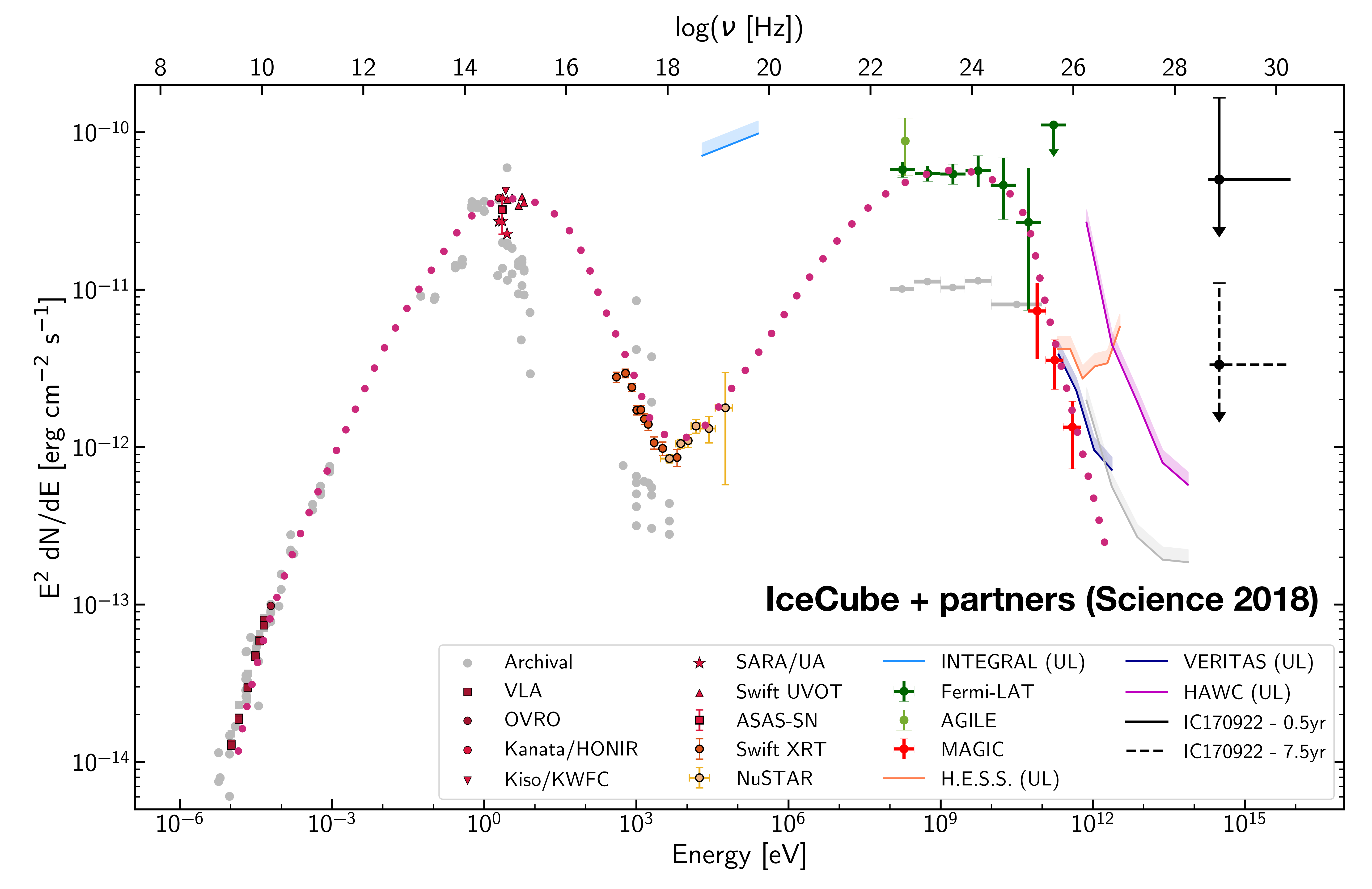
REALTIME NEUTRINO ALERTS

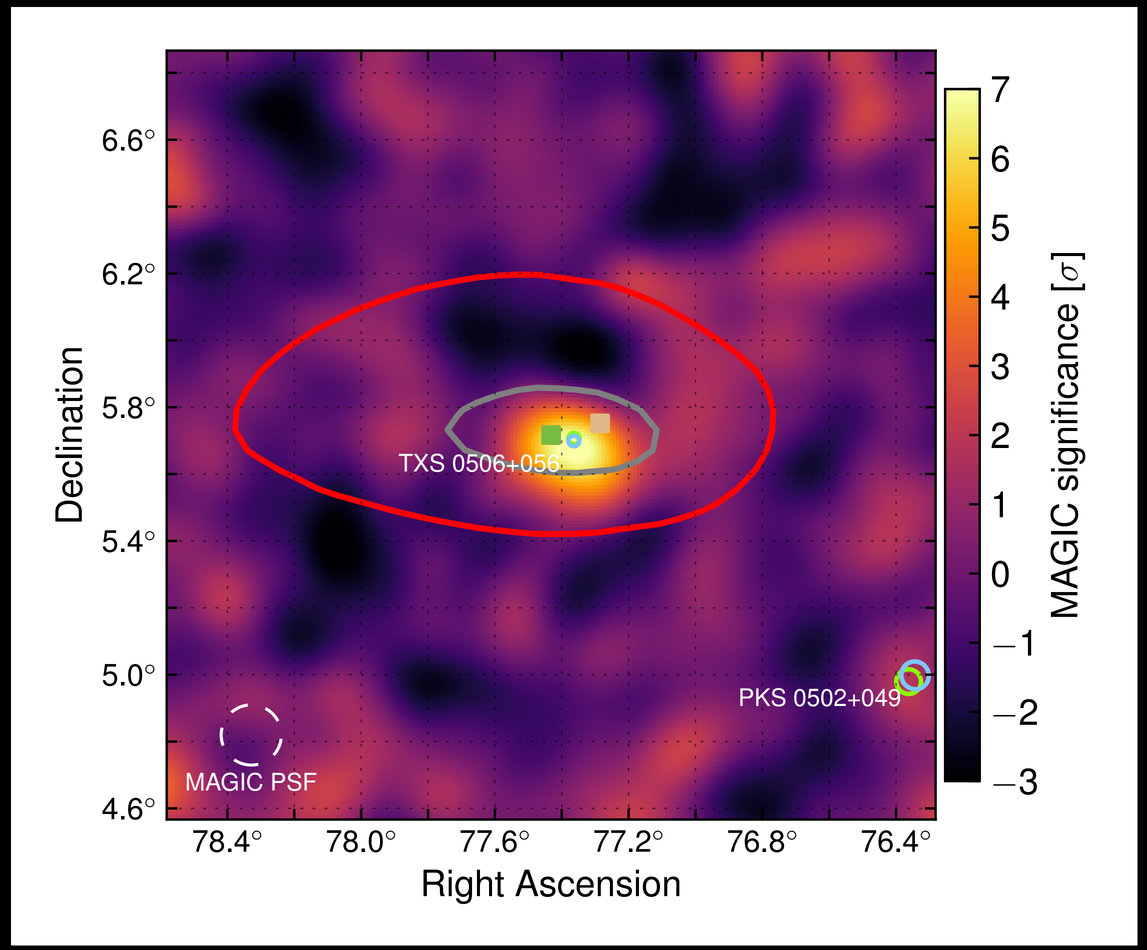




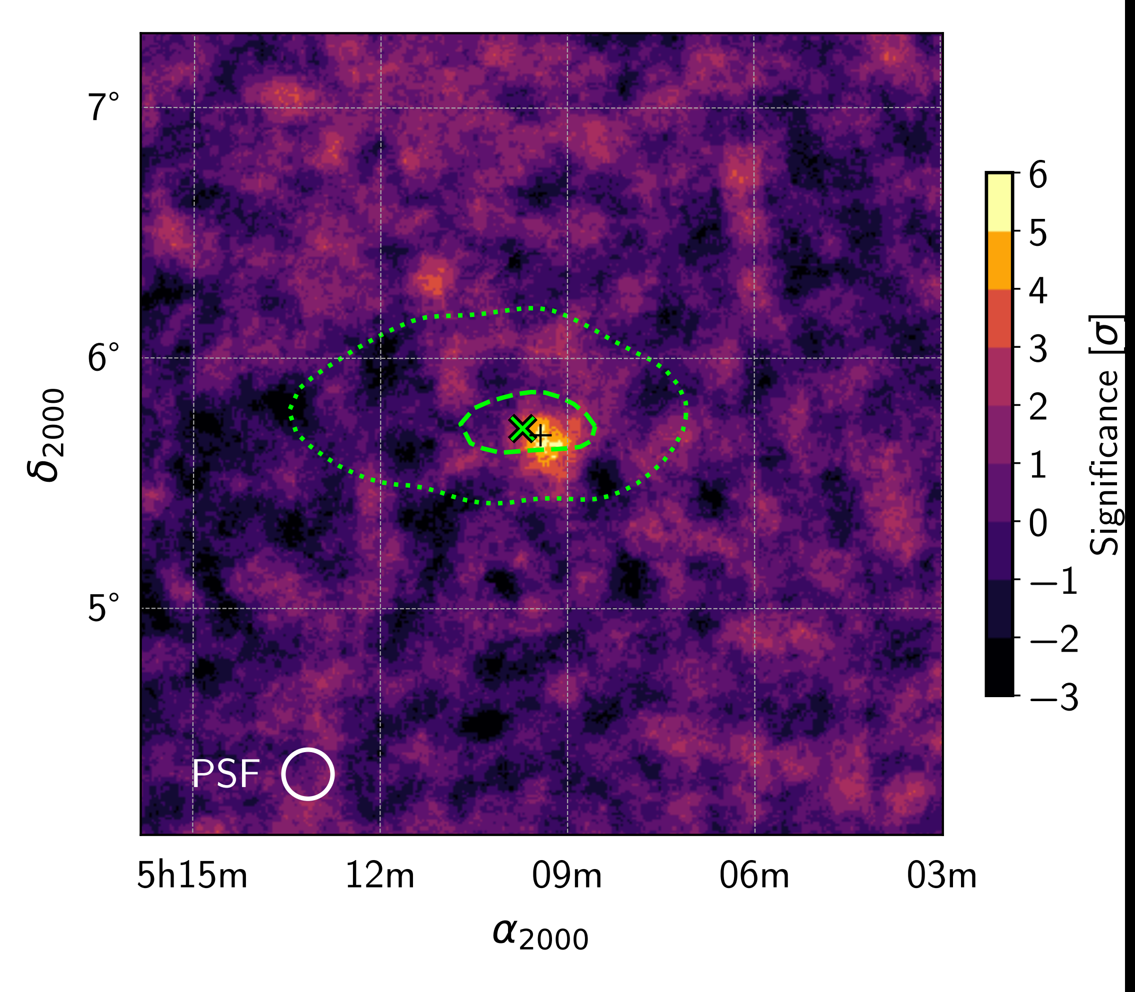
- IceCube-170922A: 290 TeV neutrino energy
- Correlated with flaring, hard-spectrum gamma-ray blazar **TXS 0506+056** (3σ). Additional neutrino emission in 2014-2015.
- **Efforts to start realtime programs in KM3NeT, Baikal-GVD are underway.**

PHOTONS FROM TXS 0506+056





MAGIC (ApJL 2018)

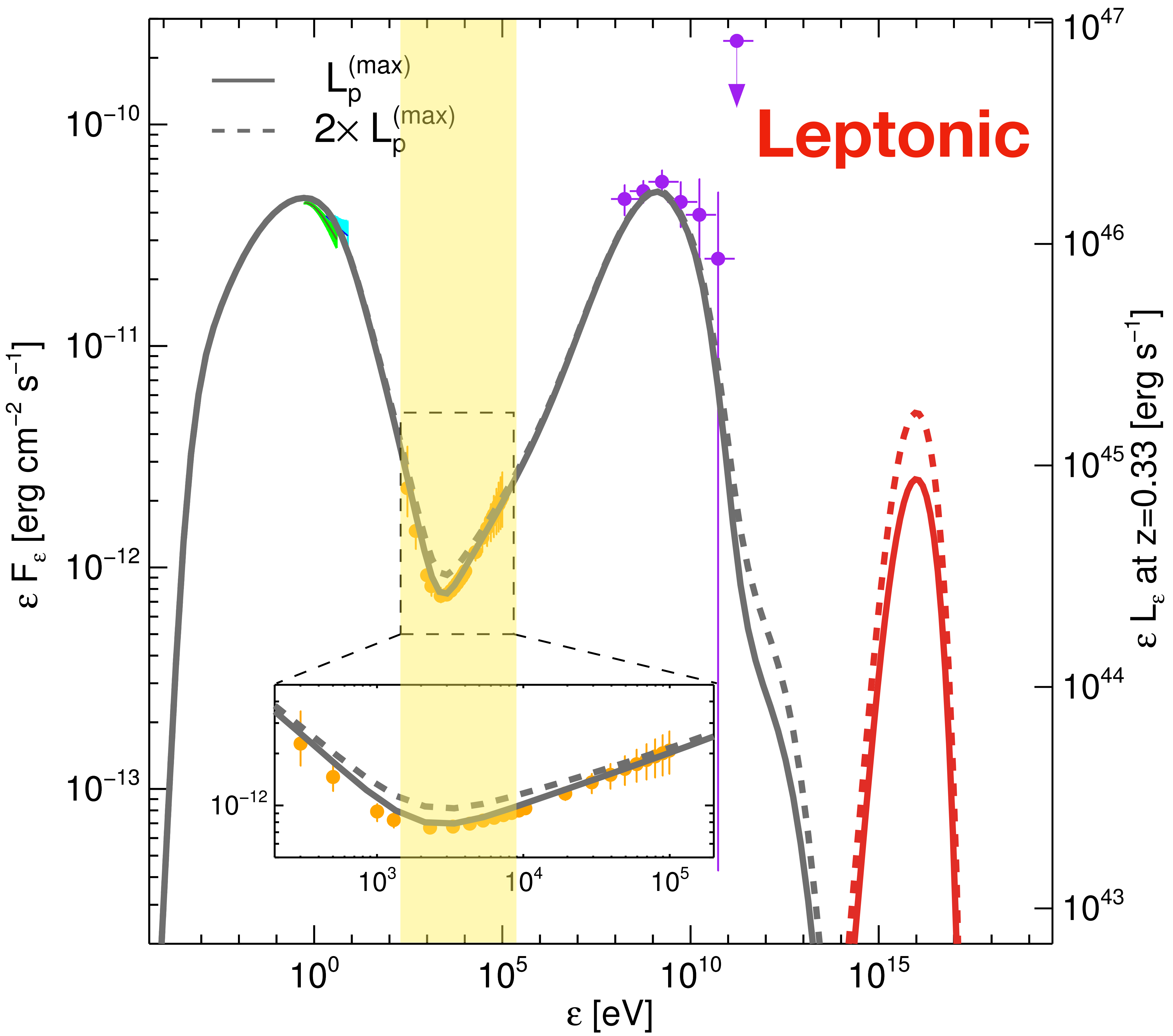


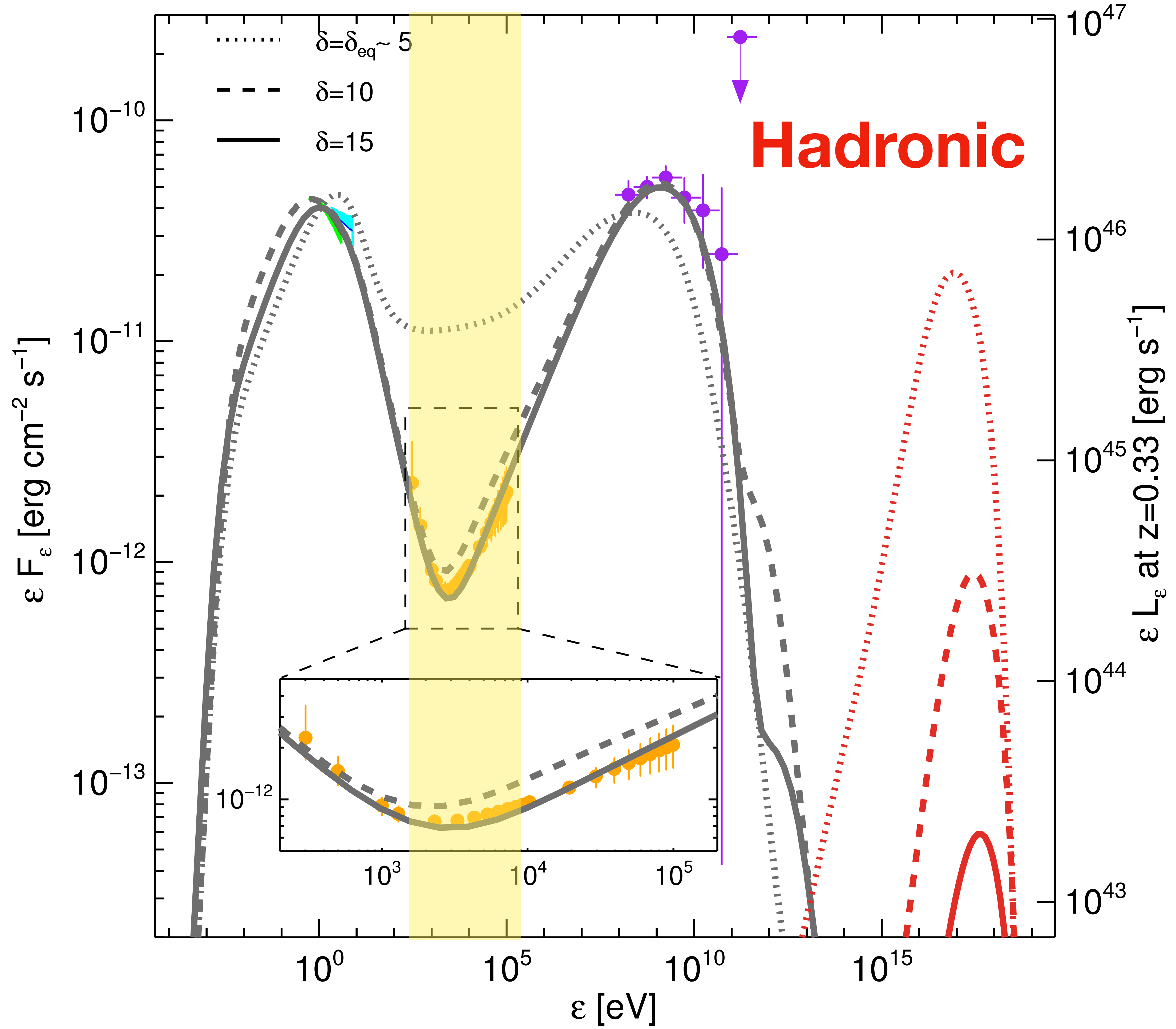
VERITAS (ApJL 2018)

- 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

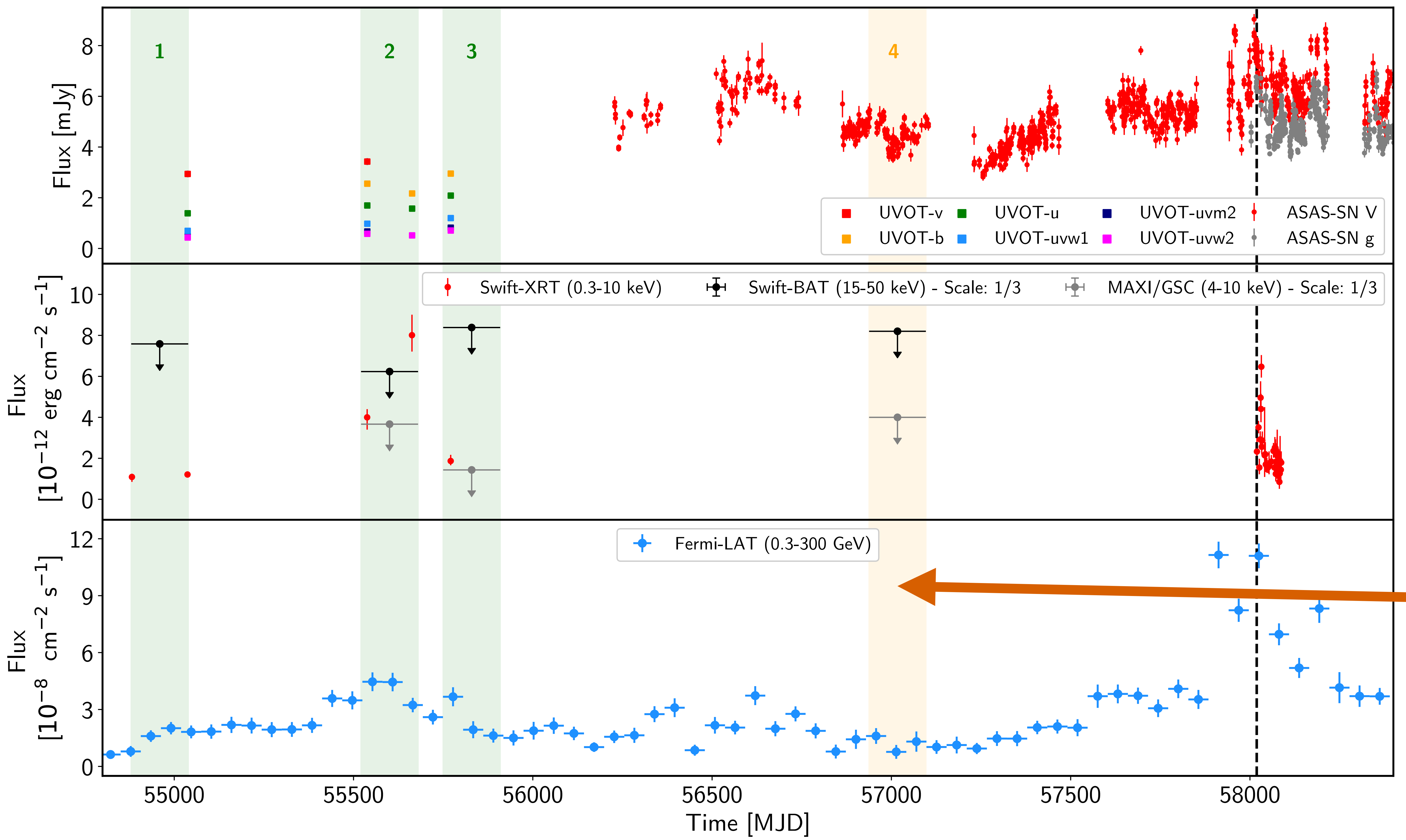
Keivani et al. (arXiv/1807.04537)
among many others

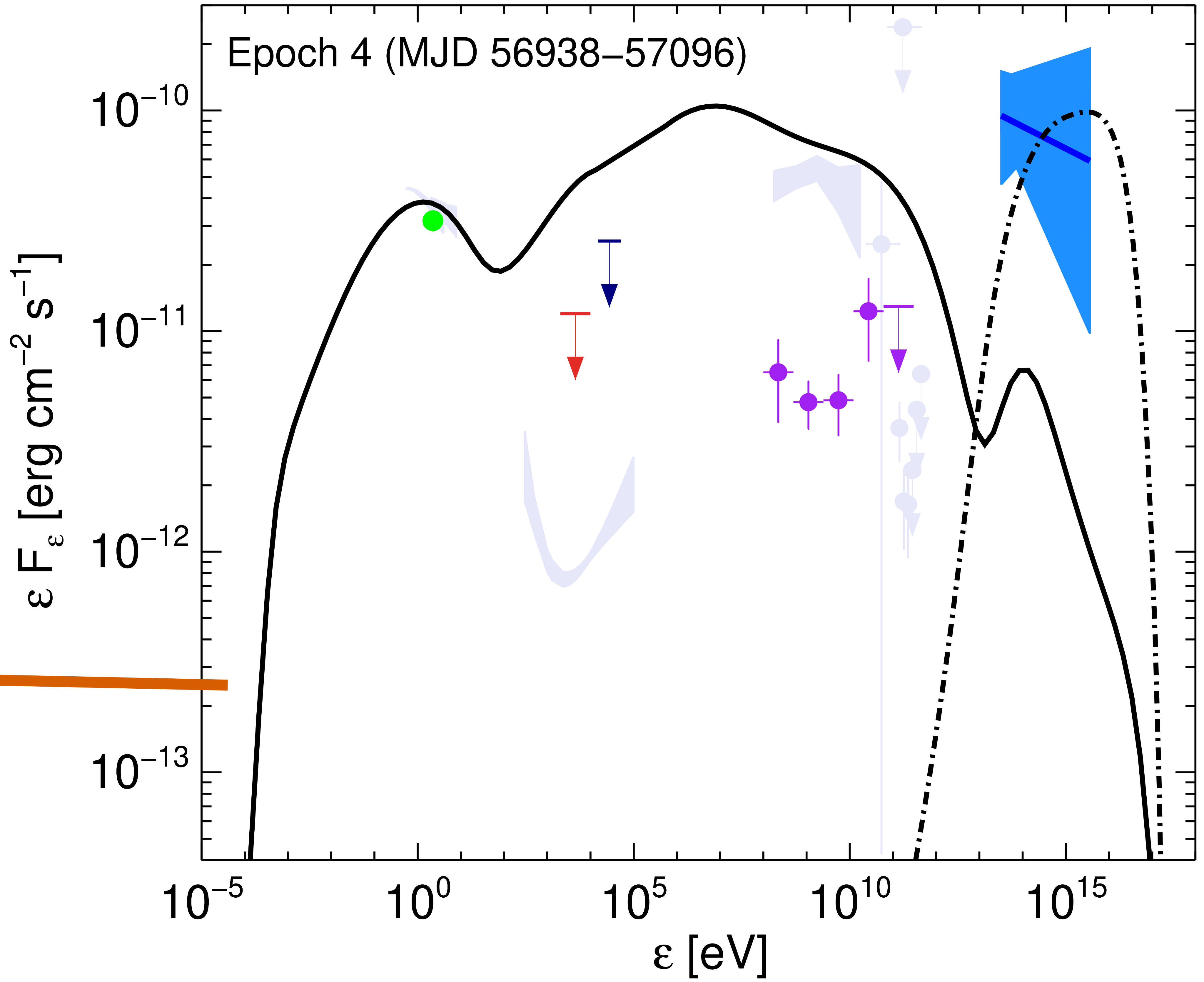




- **Strong constraints on hadronic emission from X-ray observations.**

TIME-DEPENDENT EMISSION FROM TXS 0506+056





Petropoulou, Murase, MS, ++ (2019)

- IceCube archival analysis revealed a **13±5 neutrino excess (3.5σ)** in 2014-2015 over 110 days.
- 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

THE NEXT DECADES FOR NEUTRINOS

- **Guepin, Kotera, Oikonomou (arXiv/2207.12205)**

2021 / 2025 / >2030	Minimum energy	Peak energy	Differential sensitivity limit [u.l.]	iFoV	dFoV	ang. res.	ν alert types, *examples*
ANITA	0.1 EeV	100 EeV	[2.4×10^{-7} GeV cm^{-2} s^{-1} sr^{-1} in 24 d]	6% [7°×360°]	19% [26°×360°]	2.8°	-
PUEO	0.1 EeV	20 EeV	4.2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 30 d	6 %	20 %	<2.8°	-
ARA	10 PeV	1−3 EeV	3.6×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} by 2030	35 %	35 %	5°	-
RNO-G	50 PeV	1 EeV	5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	30% [45°×360°]	>50%	2°×10°	*planned*
ARIANNA-200	30 PeV	1 EeV	4×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	50 %	>50%	2.9−3.8°	*GCN, AMON*
BEACON	30 PeV	1 EeV	6×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	6 %	19.5%	0.3°−1°	*planned*
Auger	50 PeV	0.3−1 EeV	[1.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 2019]	30 %	92.8%	<1°	no alerts, AMON
POEMMA Cerenkov	10 PeV	0.5 EeV	3.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	0.6 %	18−36%	0.4°	*planned*
fluorescence	10 EeV	100 EeV	1.5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	?	?	1°	*planned*
GRAND	50 PeV	0.4 EeV	2×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	45 %	100 %	0.1°	*planned*
IceCube-Gen2 Radio	10 PeV	0.3 EeV	2×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	43% [55°×360°]	43% [55°×360°]	2°×10°	*planned*
Ashra-NTA	1 PeV	0.1 EeV	10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	25% [30°×360°]	>80%	0.1°	*planned*
Trinity	0.1 PeV	0.1 EeV	5×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	6% [7°×360°]	62 %	<1°	*planned*
TAMBO	0.3 PeV	10 PeV	?	27 %	62 %	1°	*planned*
RET-N	10 PeV	0.1 EeV	1.5×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	50 %	>50%	?	*planned*
ANTARES up(cascade)	20 GeV(1 TeV)	50(100) TeV	[2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 11 yr] (up+casc.)	50%(100%)	75%(100%)	0.3-0.4°(3°)	ν_μ only: GCN, AMON
IceCube up(cascade)	300 GeV	100 TeV	[1.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 3 yr] (up+casc.)	54%(100%)	54%(100%)	0.4°(10°)	GCN, AMON, SNEWs
IceCube-Gen2 up(cascade)	5 TeV	300 TeV	2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in < 90 d (up+casc.)	54%(100%)	54%(100%)	0.3°(10°)	*GCN, AMON, SNEWs*
KM3Net ARCA up(cascade)	100 GeV(1 TeV)	100(100) TeV	5.8×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 1.5(1 yr)	50%(100%)	75%(100%)	0.1°(1.5°)	*GCN, AMON*
Baikal-GVD up(cascade)	100 GeV(1 TeV)	100(100) TeV	(5.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr)	50%(100%)	72%(100%)	<1°(4.5°)	*private MoU, GCN*
P-ONE up(cascade)	1 TeV	100 TeV	1.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 2 yr	50%(100%)	73%(100%)	0.1°(1−3°)	*planned*

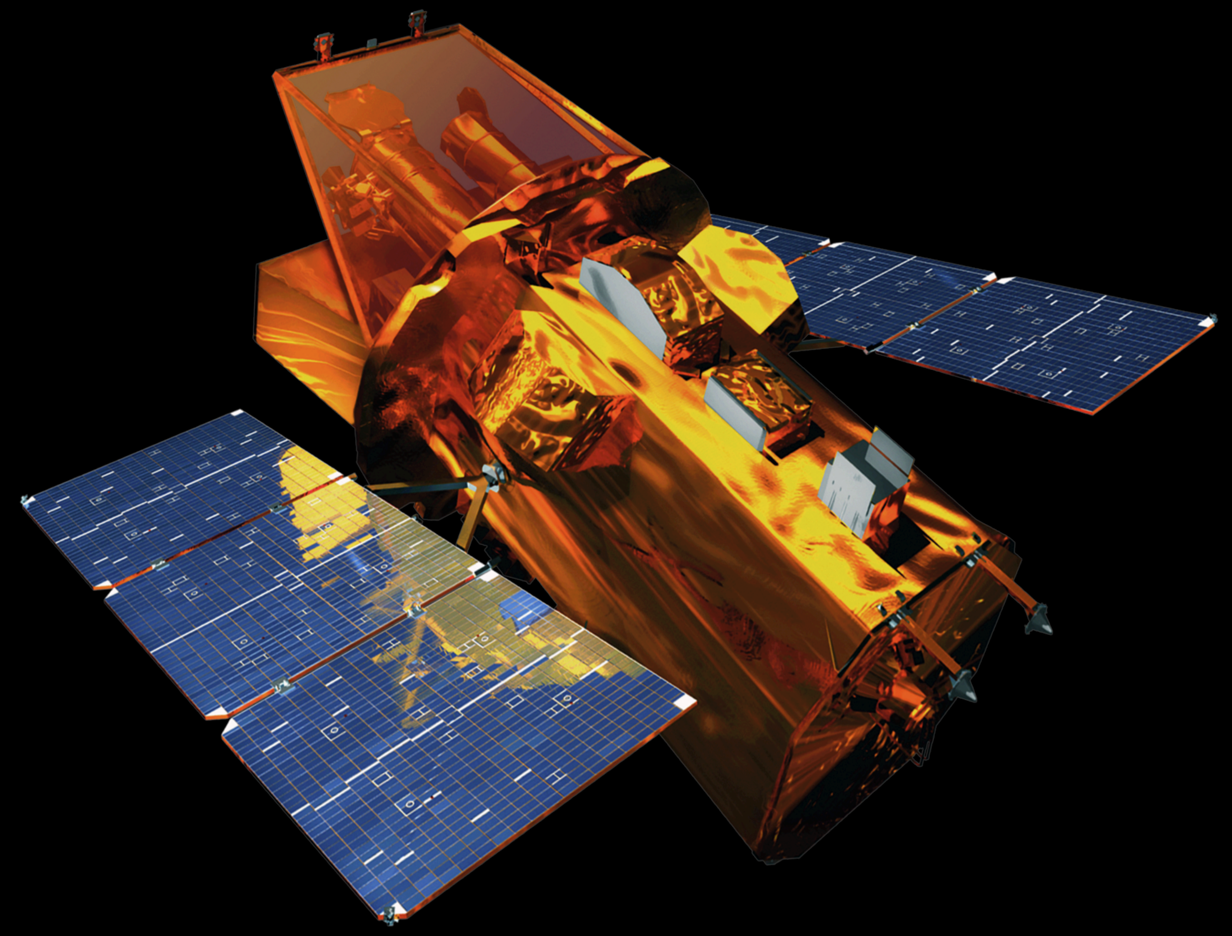
THE NEXT DECADES FOR FOLLOW-UP INSTRUMENTS

- Guepin, Kotera, Oikonomou (arXiv/2207.12205)

2021 2025 >2030	Band Width	Differential sensitivity limit	FoV	ang. res.	slew [survey] speed	resp. delay	ν foll. rate [% alerts] *examples*
LHAASO	100 GeV−1 PeV	5×10^{-14} erg cm^{-2} s^{-1} in 1 yr	2 sr	0.3°	[2/3 sky/day]	-	?
CTA	20 GeV−300 TeV	6×10^{-14} erg cm^{-2} s^{-1} in 50 h	10−20°	< 0.15°	180°/20 s	20 s	20 h/yr (2016)
HAWC	100 GeV−100 TeV	6×10^{-13} erg cm^{-2} s^{-1} in 1 yr	2 sr	0.1°	[2/3 sky/day]	-	[90% IC Gold alerts]
H.E.S.S.	30 GeV−100 TeV	6×10^{-13} erg cm^{-2} s^{-1} in 50 h	5°	0.1°	10°/min	60 s	60−70 h/yr
MAGIC	50 GeV−50 TeV	9×10^{-13} erg cm^{-2} s^{-1} in 50 h	3.5°	0.07°	7°/s	20 s	60 h/yr, 15% ToO
VERITAS	85 GeV−30 TeV	6×10^{-13} erg cm^{-2} s^{-1} in 50 h	3.5°	0.1°	1°/s	90 s	45 h/yr
Fermi LAT	20 MeV−300 GeV	5×10^{-13} erg cm^{-2} s^{-1} in 10 yr	2.4 sr	0.15°	[all-sky/3 h]	4−5 h	[100% IC alerts]
GBM	10 keV−25 MeV	2 ph cm^{-2} s^{-1} in 1 s	9 sr	10°	[all-sky/1 h]	5−6 h	[60% IC alerts]
INTEGRAL IBIS	15 keV−10 MeV	1.2×10^{-12} erg cm^{-2} s^{-1} in 10^3 s	64 deg^2	0.2°	0.2°/s	min	[all ANTARES
SPI-ACS	100 keV−2 MeV	10^{-3} ph cm^{-2} s^{-1} MeV^{-1} in 10^6 s	4π	-	-	min	and GCN IC alerts]
XMM-Newton	0.2−12 keV	10^{-15} erg cm^{-2} s^{-1} in 10^6 s	0.5°	6"	90°/h	few h	*PKS 1502+106, Kloppo*
Athena-WFI	0.1−15 keV	3×10^{-16} erg cm^{-2} s^{-1} in 10^5 s	0.4 deg^2	< 5"	1°/min	4 h	[5 ToO/month]
Swift BAT	15−150 keV	6×10^{-10} erg cm^{-2} s^{-1} in 2000 s	1.4 sr	0.4°	1°/s	min−h	50% ToO
XRT	0.2−10 keV	5×10^{-13} erg cm^{-2} s^{-1} in 10^4 s	0.1 deg^2	18"			
UVOT	0.16−0.62 μm	19 mag in 300 s	0.1 deg^2	2.5"			
SVOM ECLAIRs	4−150 keV	7.2×10^{-10} erg cm^{-2} s^{-1} in 10^3 s	2 sr	< 0.2°	45°/5 min	min−h	first 3 yrs:
MXT	0.2−10 keV	2×10^{-12} erg cm^{-2} s^{-1} in 3000 s	1 deg^2	13"			15% ToO
VT	0.4−1 μm	22.5 mag in 300 s	0.2 deg^2	< 1"			then: 40% ToO
ASAS-SN	380−555 nm	19.5 mag in 30 min	72 deg^2	7.8"	[vis. sky/days]	min−day	[70−80% all IC GCN alerts]
ATLAS	420−975 nm	19.7 mag in 30 s	29 deg^2	2"	[4×vis. sky/day]	45 s	[no ν alert yet]
Pan-STARRS	400−900 nm	23.1 mag in 904 s	14 deg^2	1.0−1.3"	[vis. sky/week]	h−day	[6 follow ups]
ZTF	400−650 nm	21.0 mag in 300 s	47 deg^2	2"	[vis. sky/2 days]	h−day	[74% IC Gold alerts]
Vera Rubin Obs. (LSST)	0.3−1 μm	24.5 mag in 30 s	9.6 deg^2	0.7"	[100 deg^2/5 min]	-	-
MASTER-II(VWF)	400−800 nm	19(12) mag in 1 min(5 s)	8(400) deg^2	1.9"(22")	30°/s(8°/s)	min−h	[99% GCN neutrino alerts]
TAROT	350−980 nm	18.5 mag in 180 s	4 deg^2	3.5"	50°/s	s−day	<3% obs. time [70% GCN alerts]
GEMINI (GMOS)	0.36−1.03 μm, spec	25 mag in 2.5 days	30.23'^{2}	0.07"/pix	obj./2 min	20 min	*SN PTF12csy*
GTC (OSIRIS)	0.365−1.05 μm, spec	27 mag in 1 h	0.02 deg^2	0.127"/pix	obj./min	min	*TXS 0506+056*
Keck (LRIS)	0.32−1 μm, spec	23 mag in 20 s	46.8'^{2}	0.135"/pix	1.5°/s	h	*SN PTF12csy*
VLT (X-shooter)	0.3−2.4 μm, spec	23 mag in 60−120 s	2.2'^{2}	0.173"/pix	obj./5 min	30 s	*TXS 0506+056, IC190331A*
VLA	1−50 GHz	186 μJy in 1 min	0.16 deg^2	0.12"	[20 deg^2/h]	days	*TXS 0506+056, ANTARES events*
MWA	80−300 MHz	4.6 mJy at 1 s	610 deg^2	0.9'	obj./8 s	6−40 s	[30% IC Gold, >30% ANTARES]
SKA1(2)-MID	350 MHz−15.3 GHz	2(0.1) μJy in 1 h	1(10) deg^2	0.04°−0.7°	?	1 s	?

X-RAY COVERAGE

Neil Gehrels *Swift* Observatory



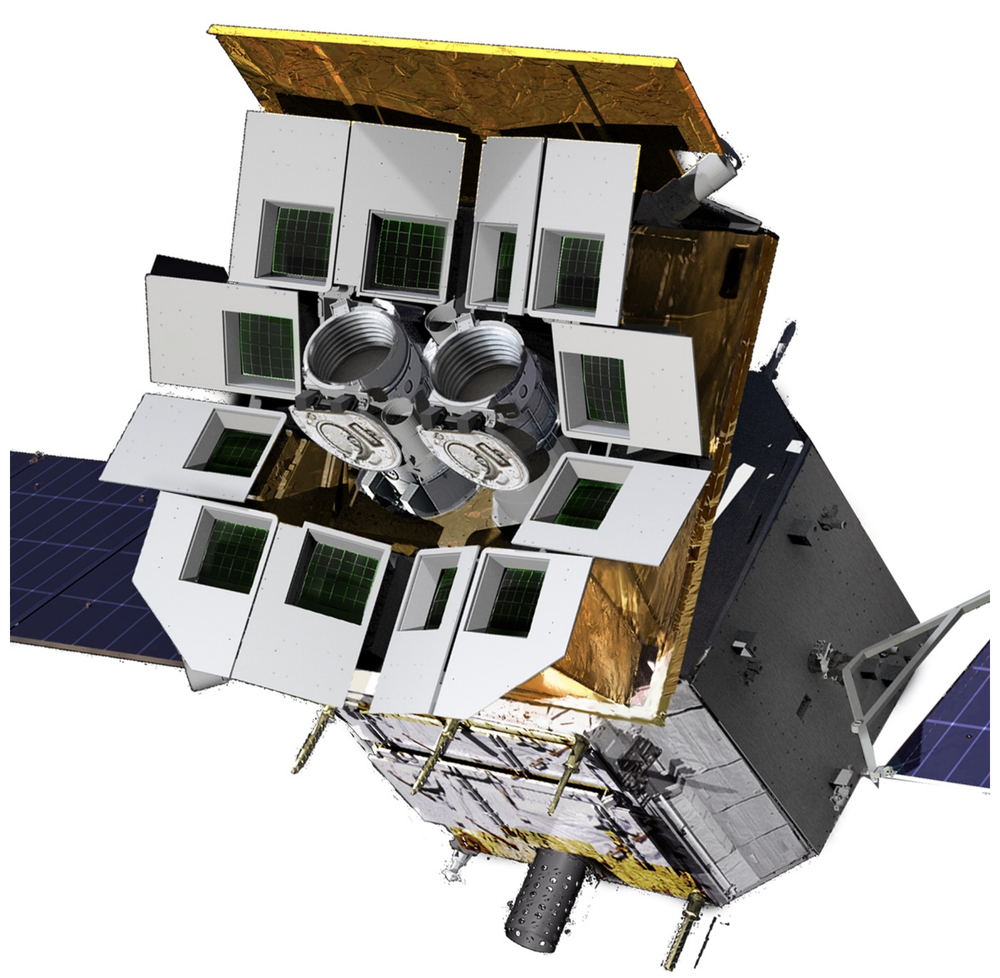
XRT sensitivity in the 0.3-10 keV
Fast response, low overhead.
110 cm^2
~0.4 deg FoV. Launched in 2004.

SVOM (China-France)

Rapid follow-ups of GRBs
Launch date on Jun 22, 2024
0.2-10 keV
“Lobster eye” optics with 1 deg FoV

Einstein Probe (China-ESA)

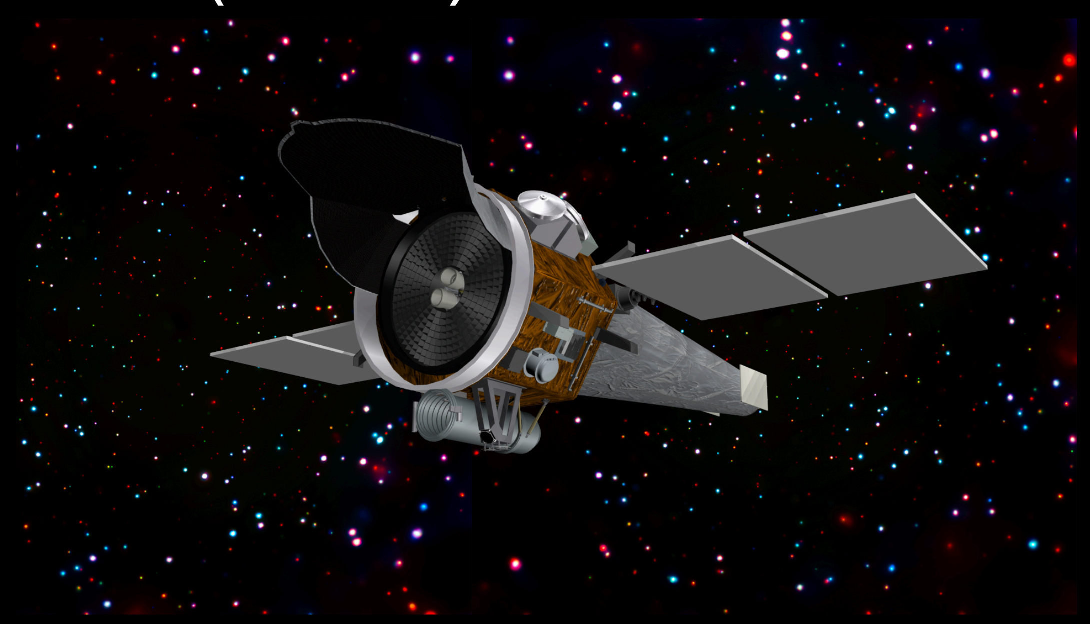
Launched January 2024



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’

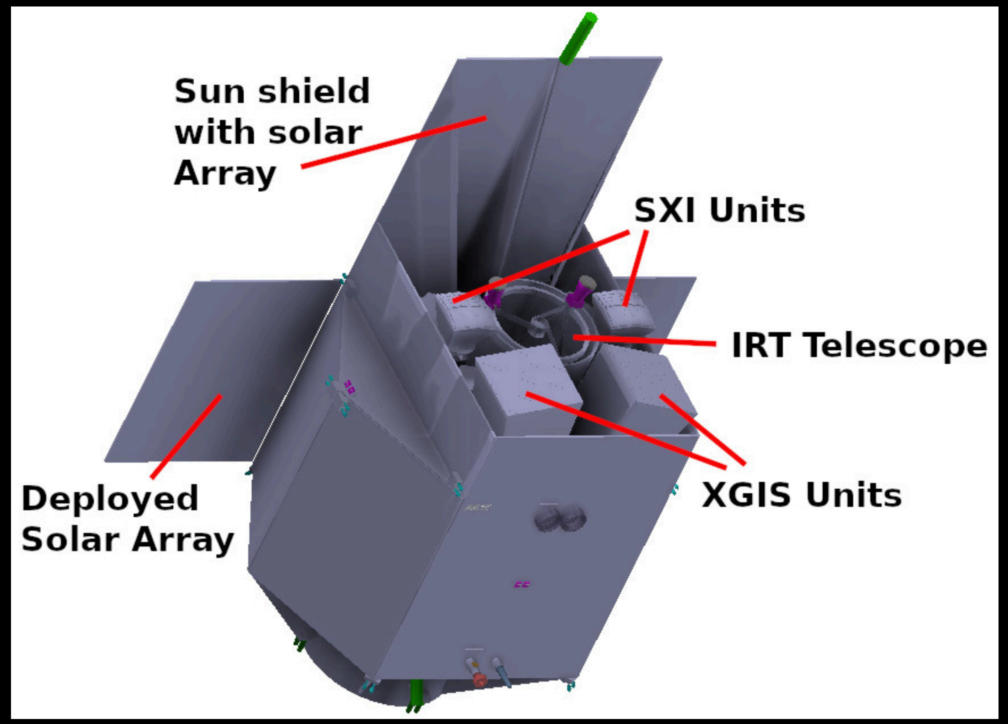
Wolter-1 type + CCD
FoV: 38’
band: 0.3-10keV
eff. area: 2x 300cm^2 @1keV
angular FWHM: 30”

STAR-X (NASA)



Not selected for further study
By NASA
x7 FoV of Swift XRT
x16 effective area

THESEUS (ESA)

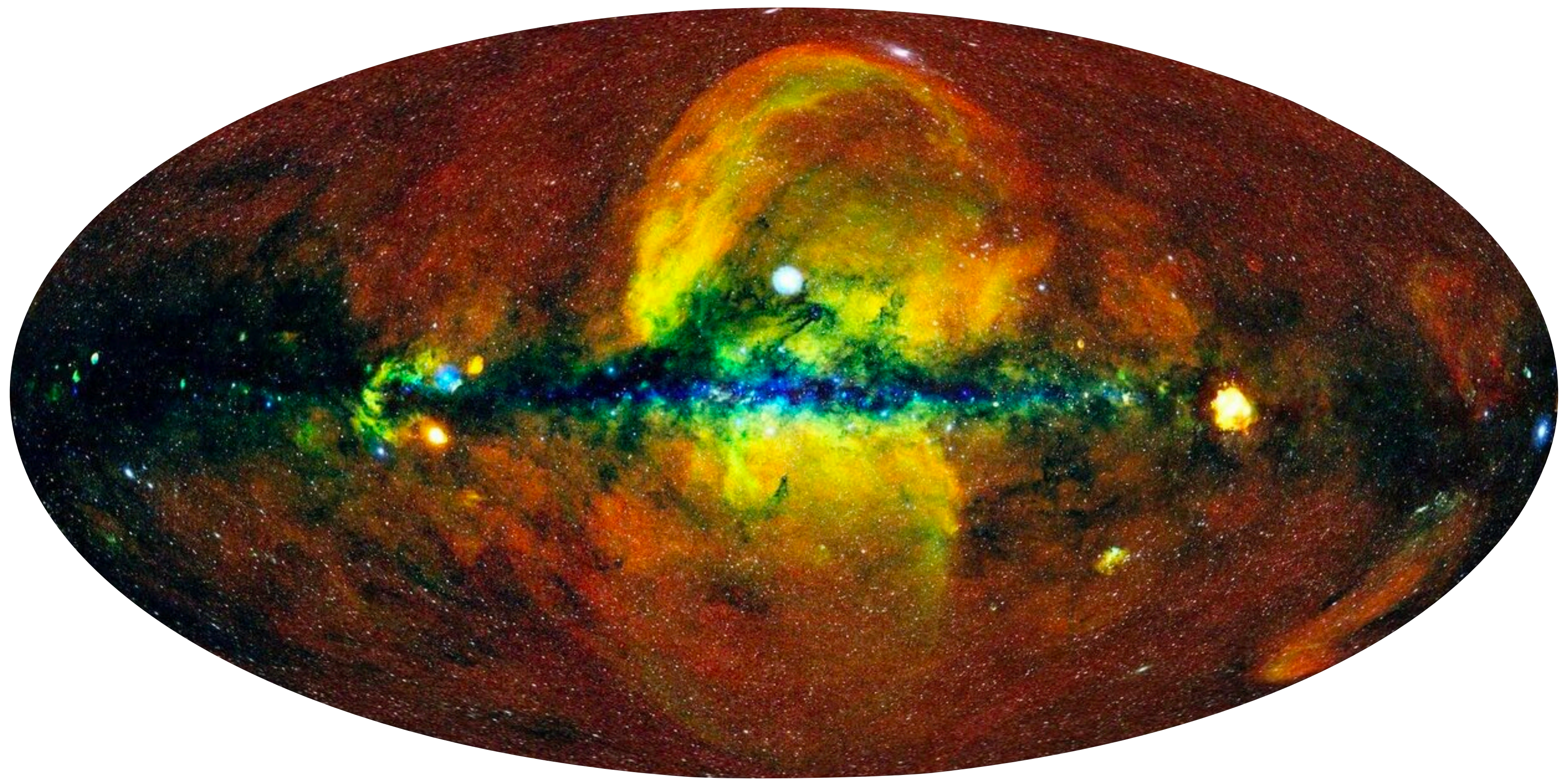


Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2’

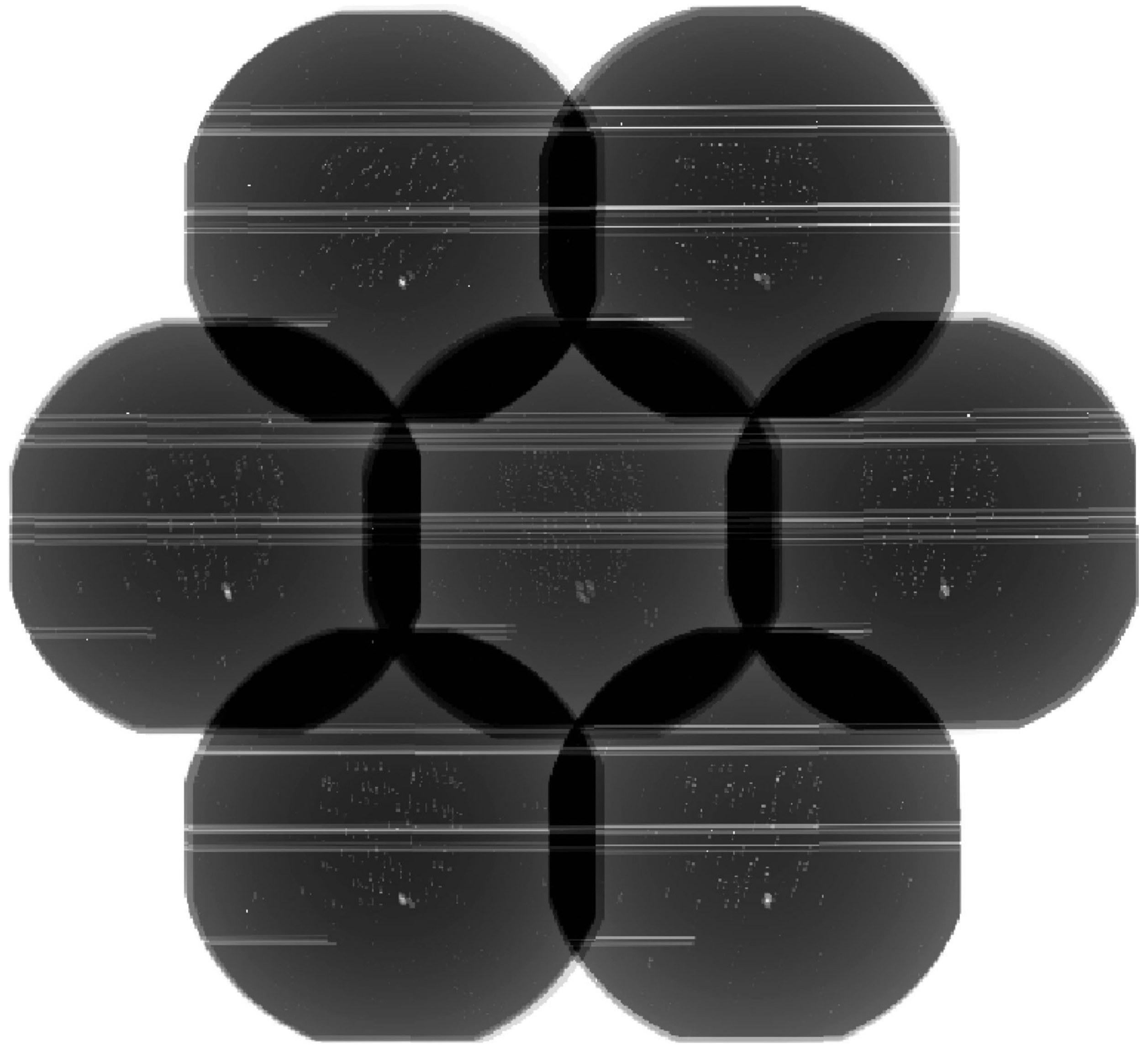
XGIS: 2 keV - 10 MeV with FoV >2 sr with < 15’ GRB localization

Not selected as of 2023. Resubmission planned.

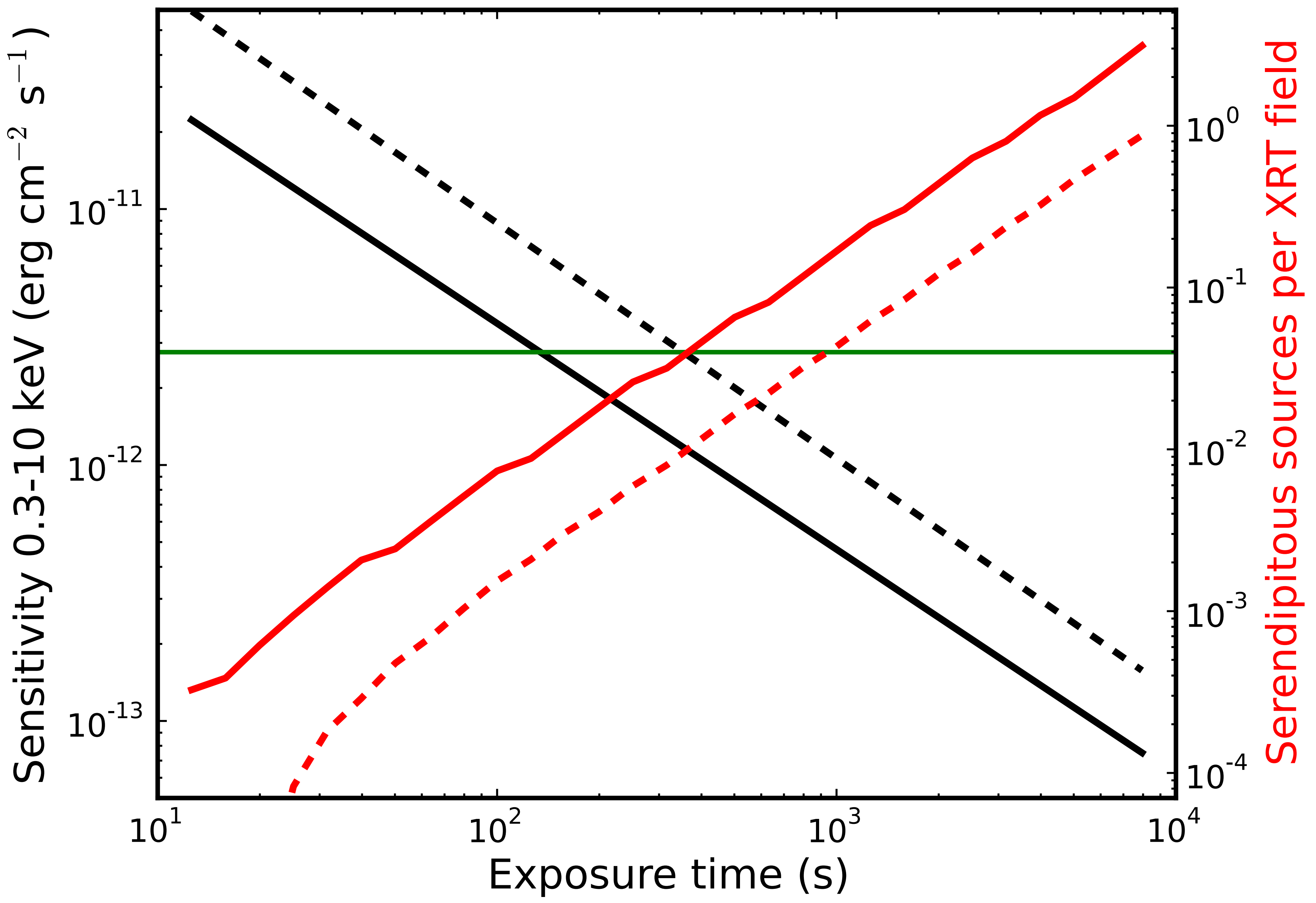
NEUTRINO-EM SOURCE ASSOCIATIONS IN THE NEXT DECADE



- 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.**



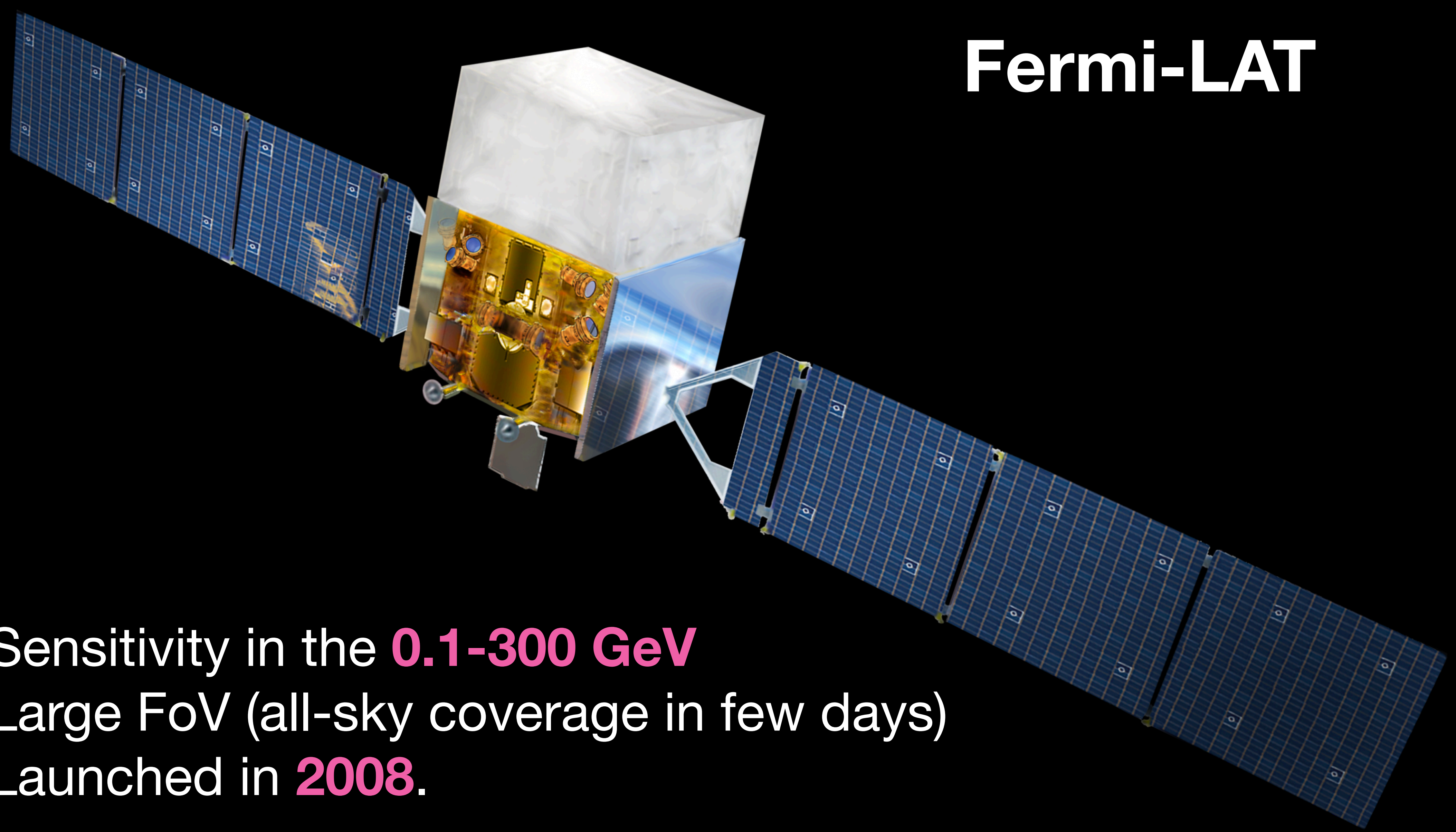
Swift tiling of neutrino position



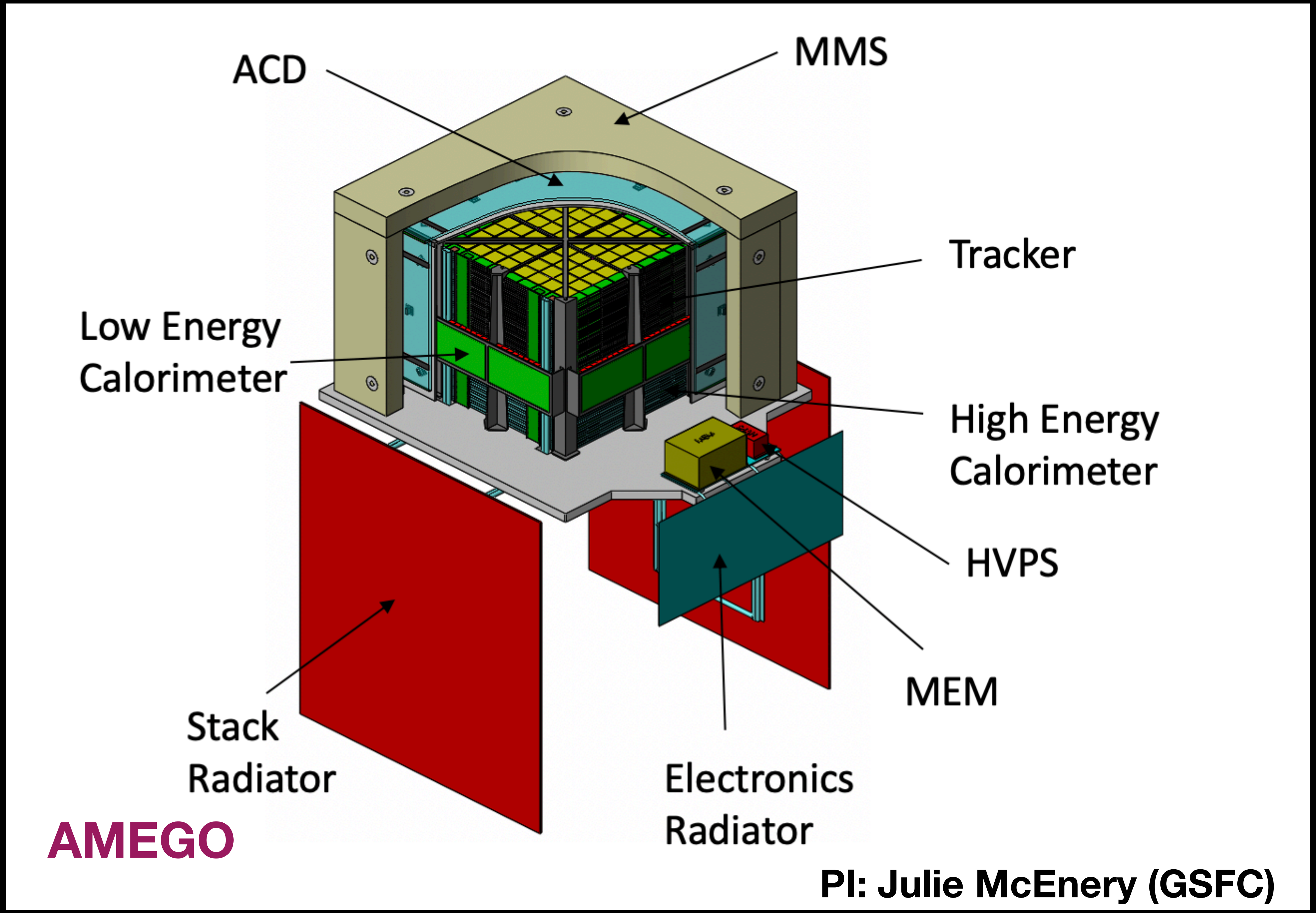
Swift follow-up of neutrino events

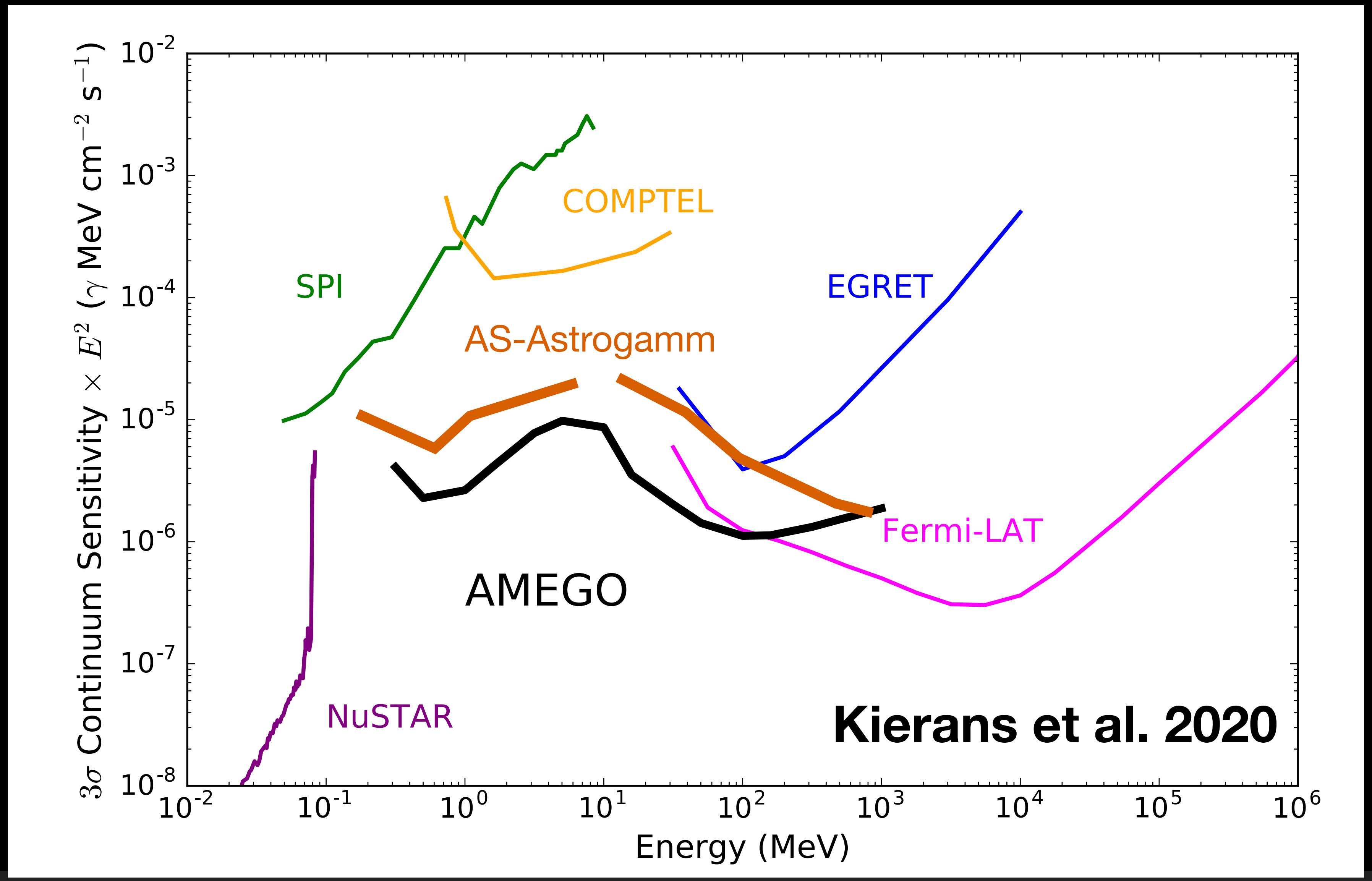
Evans et al.
https://arxiv.org/abs/1501.04435

MEV-GEV COVERAGE



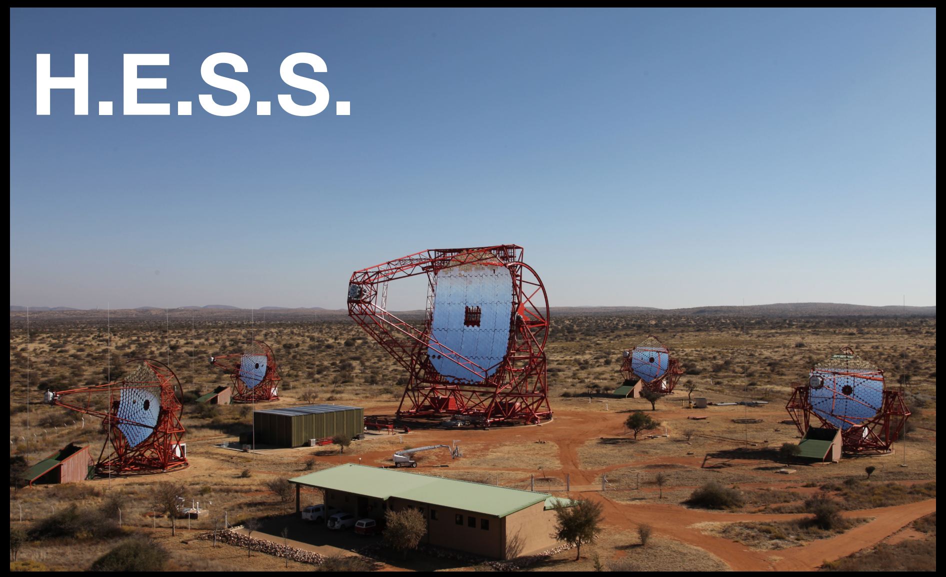
Sensitivity in the **0.1-300 GeV**
Large FoV (all-sky coverage in few days)
Launched in **2008**.



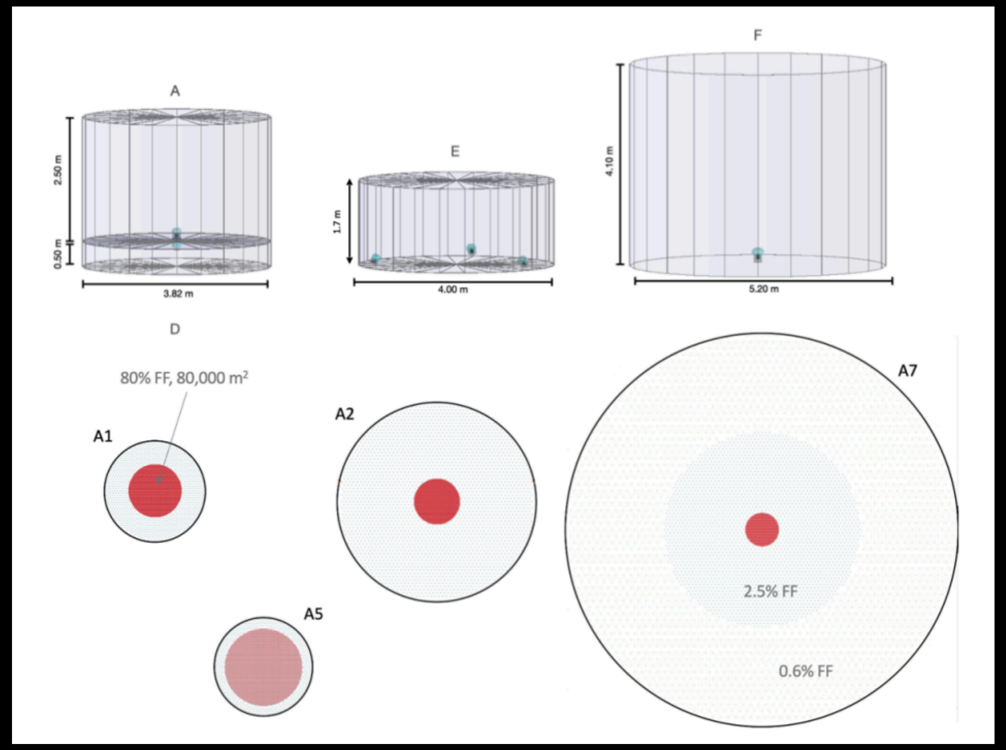


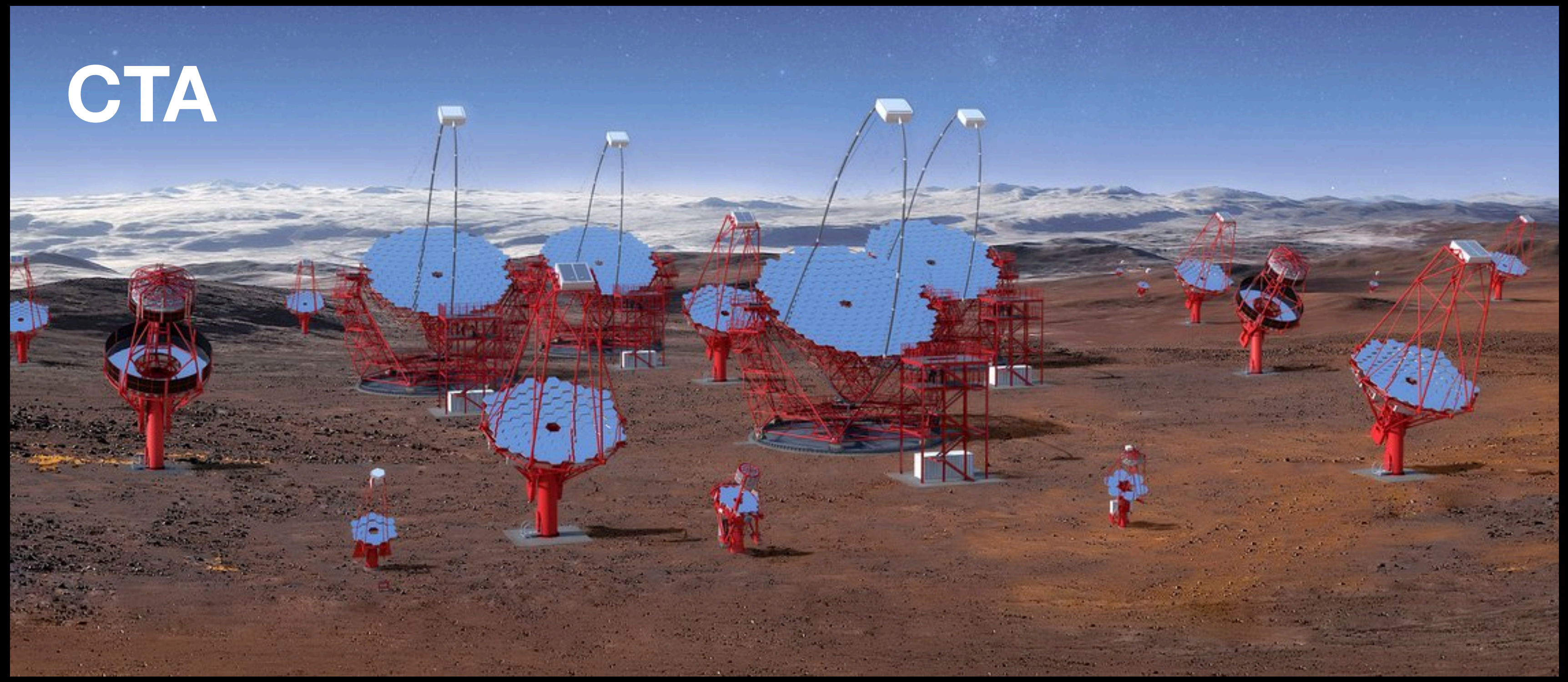
- AMEGO angular resolution: 3° (1 MeV), 10° (10 MeV)
- ComPair prototype for AMEGO.
- AMEGO-X Explorer proposed, no selected.
- e-ASTROGAM not selected at the moment.

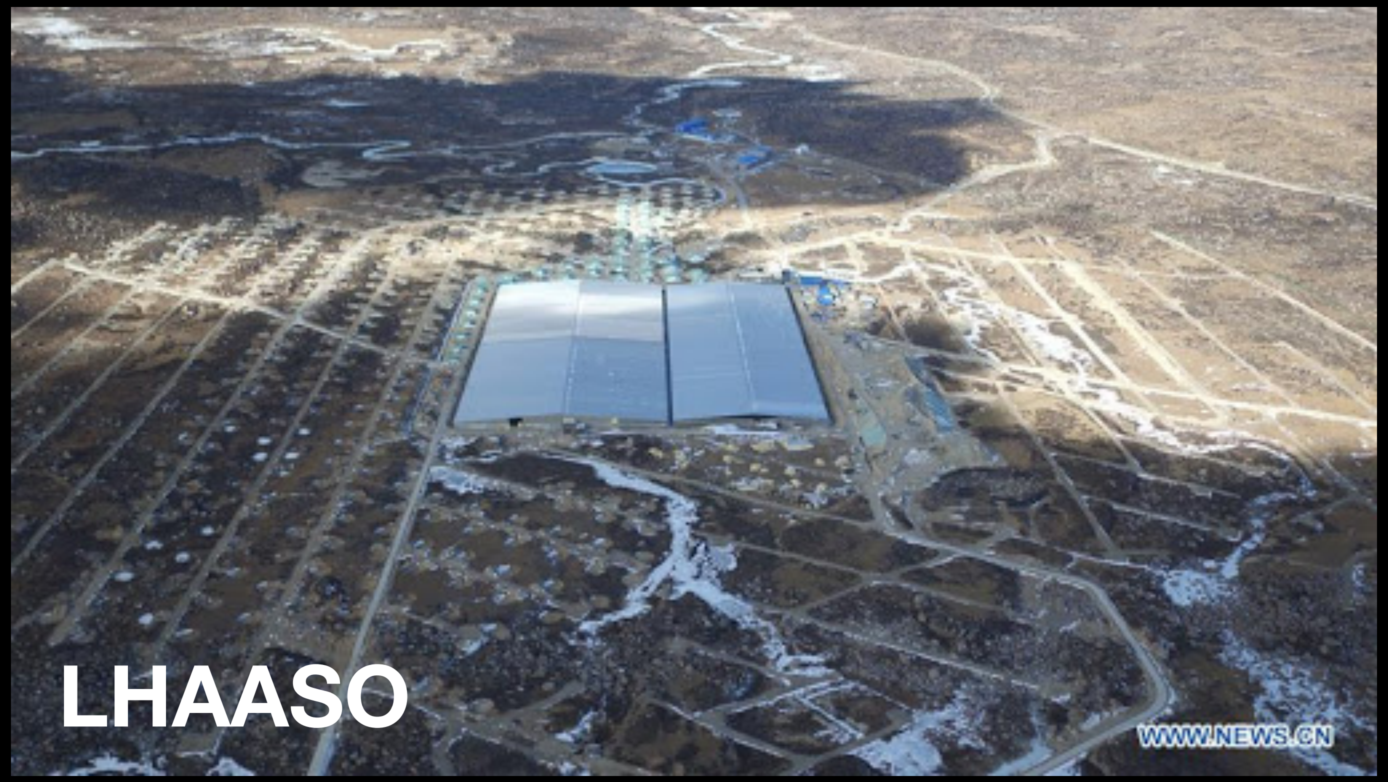
COVERAGE IN THE VERY-HIGH-ENERGY RANGE



SWGO

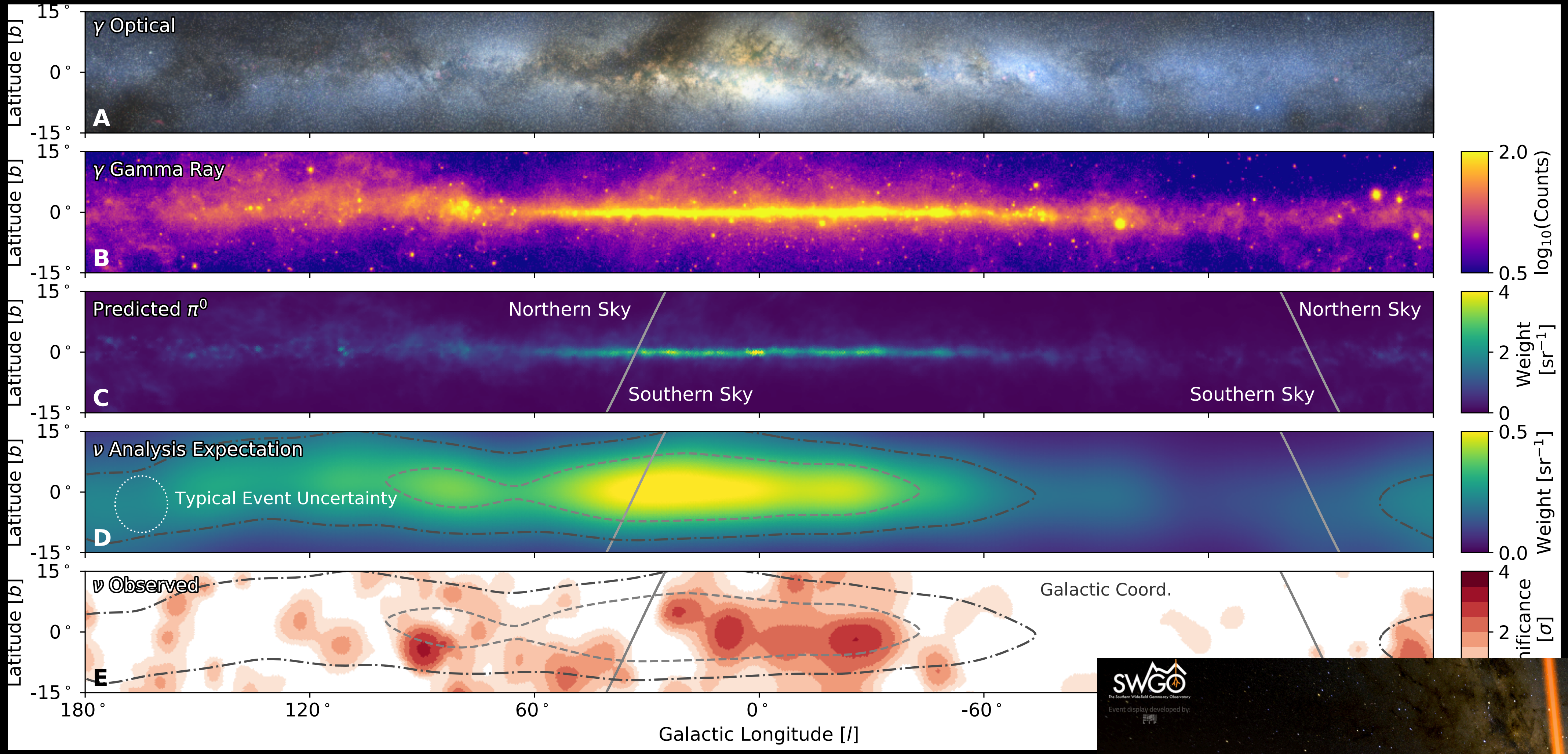




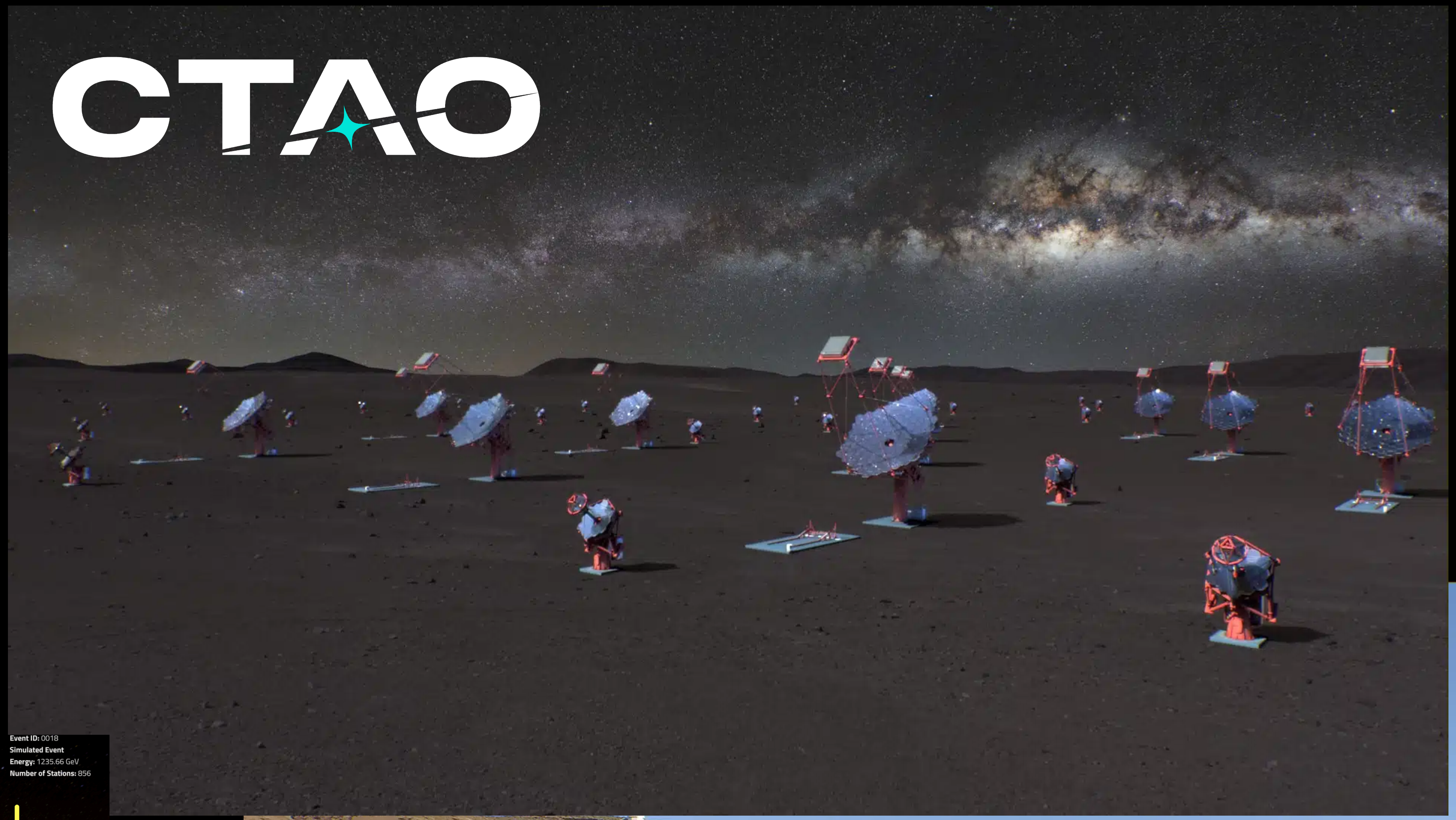


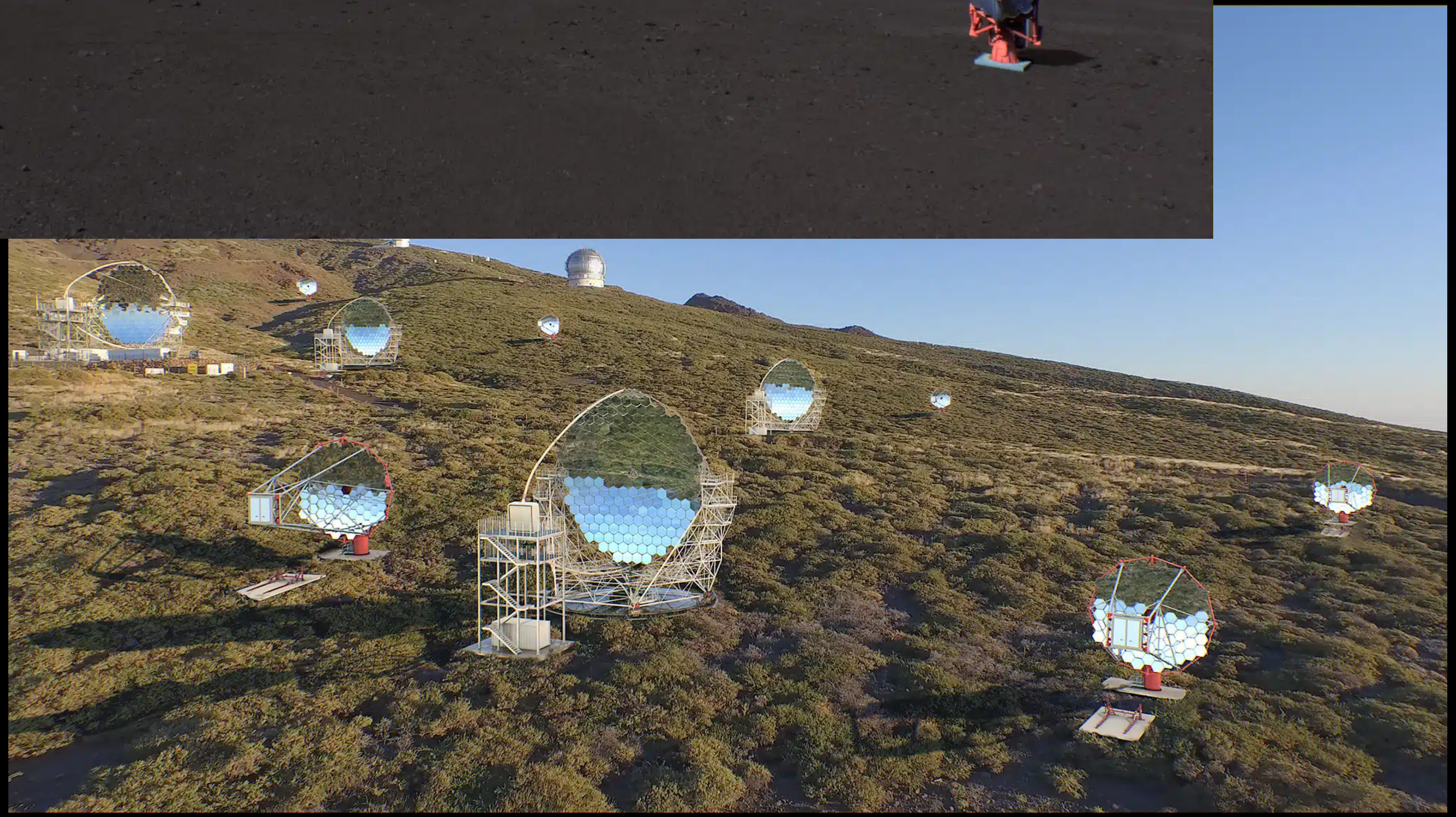
- CTA to provide a x10 improvement in sensivity in the VHE band (>50 GeV). Prototypes telescopes already detecting sources!
- Neutrino follow-ups and strong AGN science program for CTA.
- Air shower arrays (HAWC, LHAASO, proposed SWGO) provide large FoV coverage for diffuse/extended sources.

SYNERGISTIC OPPORTUNITIES FOR SWGO



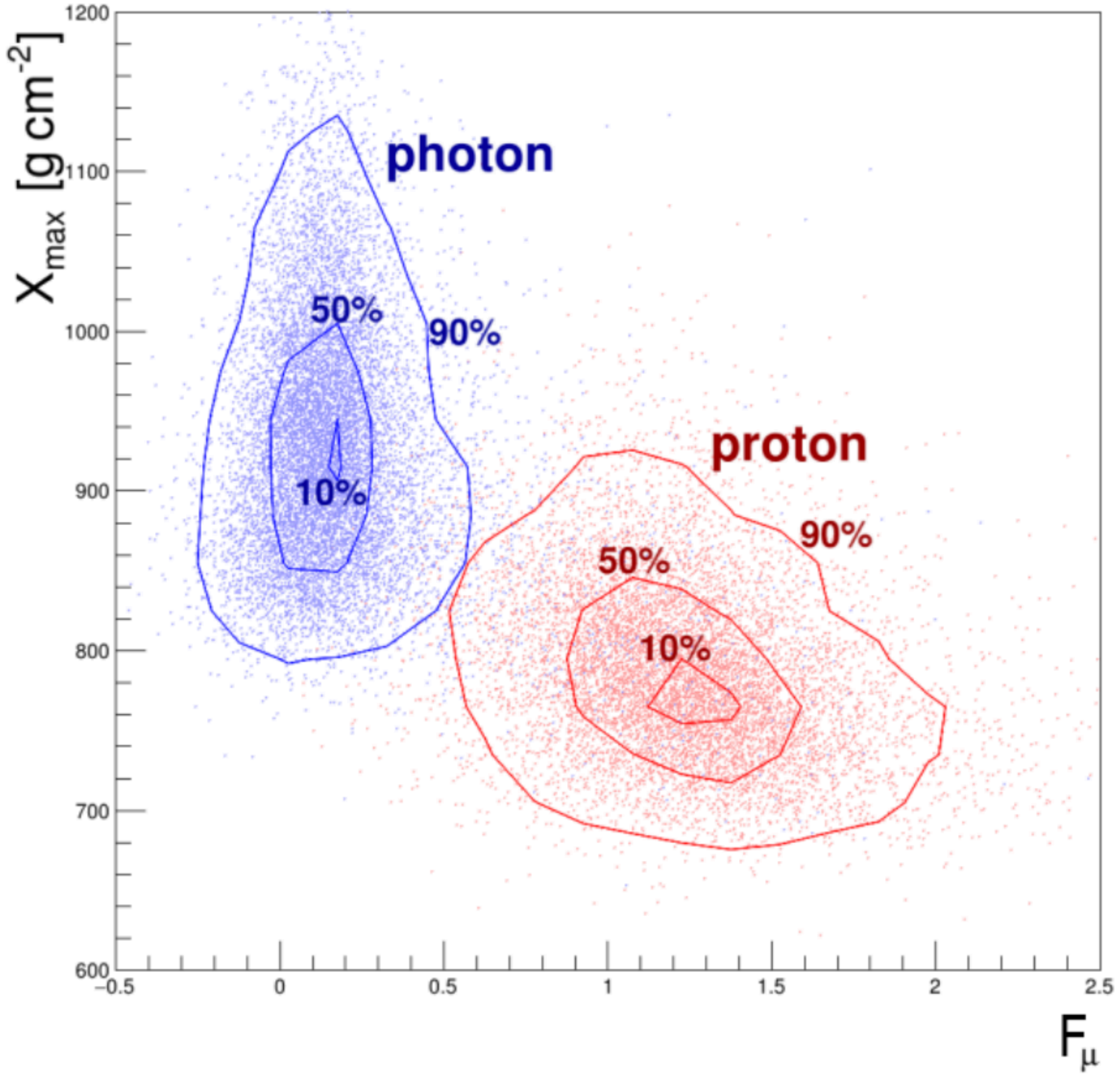
IceCube
arXiv/2307.04427





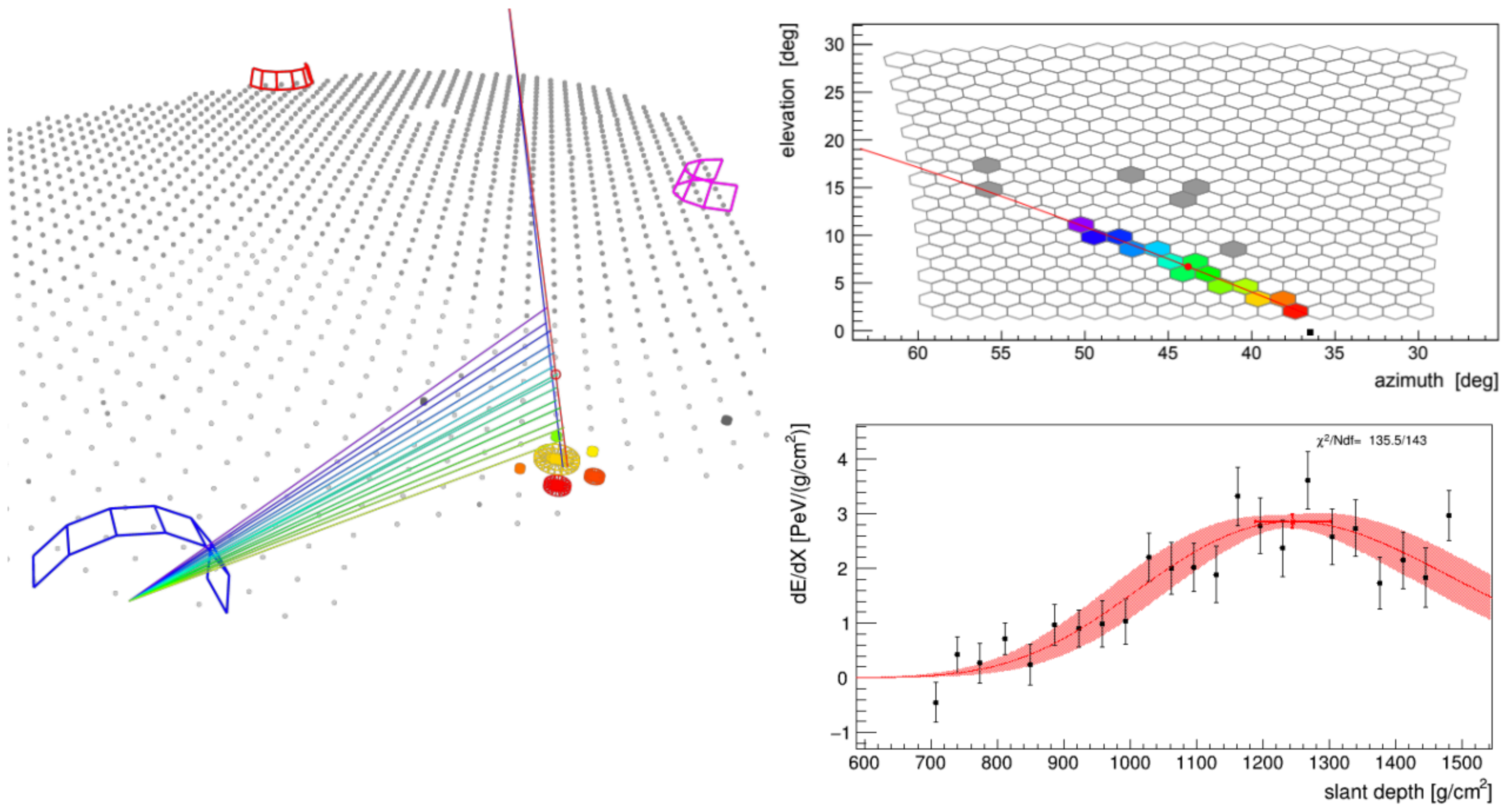
- CTAO + SWGO: Characterize VHE-UHE emission from the Galaxy in the southern hemisphere.
- Prompt VHE follow-ups of neutrino alerts.

MORE SYNERGIES? UHE PHOTONS AND NEUTRONS



Most significant photon candidate event in Auger

arXiv/2406.07439 (Auger Collab.)



- Release photon candidates in realtime? (Even with low signalness!)
- Neutron multiplets? (Talk by D. De Oliveira Franco at this workshop)

WISHLIST FOR MMA STUDIES WITH NEUTRINOS

- **On the threshold of real neutrino astronomy, but…**
- 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). Continue exploring other wavebands with new capabilities (Rubin, ngVLA, SKA, CMB-S4 are coming up!)
  - **Continued operation** of instruments with no obvious substitute (e.g. Fermi)
  - **Stronger integration** among neutrino telescopes and with the EM community.
  - **Better source candidates!** Search for hadronic emission signatures (orphan flares? PeV emission?)


THANK YOU!

THE CHALLENGE OF IDENTIFYING SOURCES