Neutrino and gamma-ray synergies

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

CRIS-MAC 2024 (Trapani, Italy) June 2024

Neutrino and ~~gamma-ray~~ EM synergies

Marcos Santander

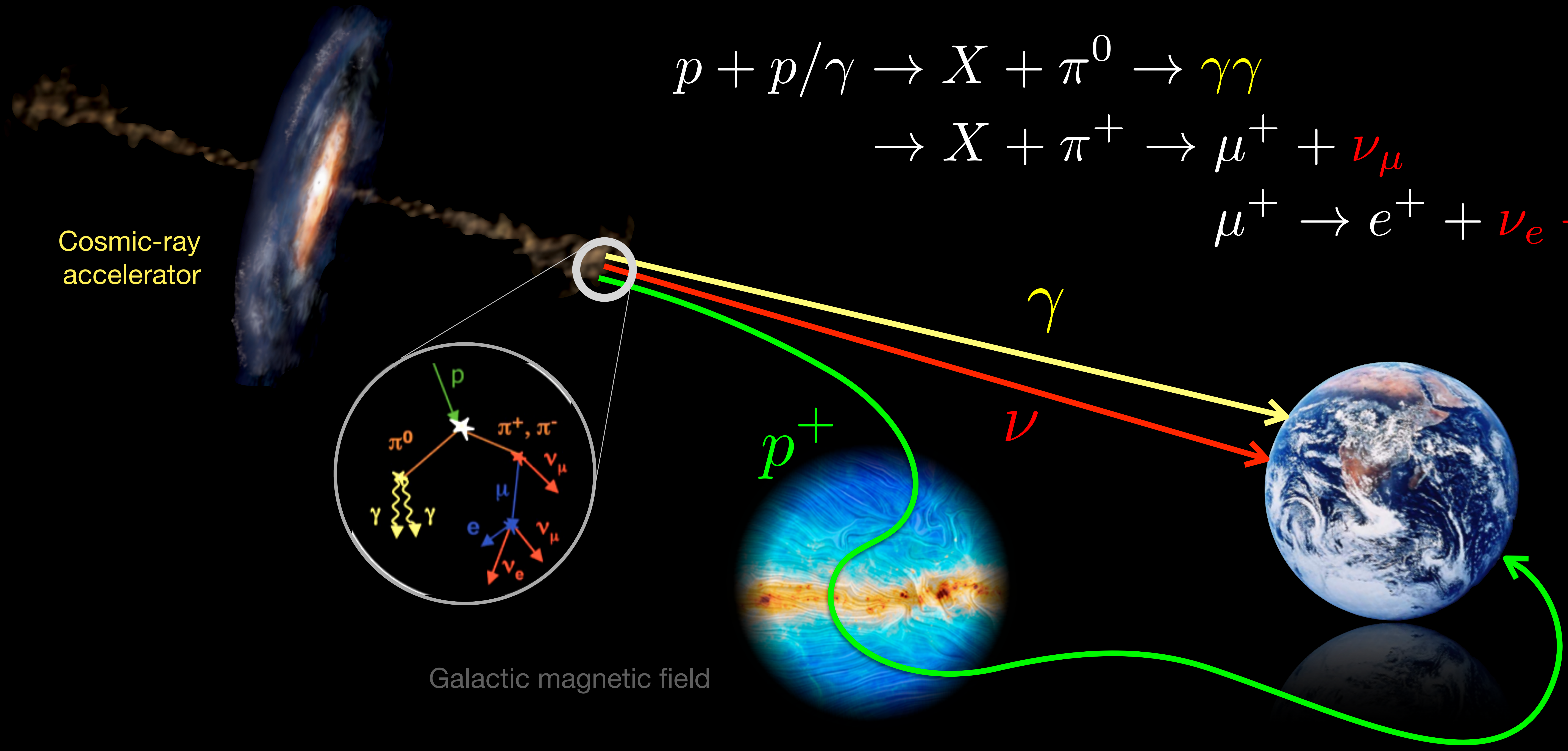
University of Alabama - jmsantander@ua.edu - @jmsantander

CRIS-MAC 2024 (Trapani, Italy) June 2024

SEARCHING FOR EM COUNTERPARTS TO NEUTRINOS

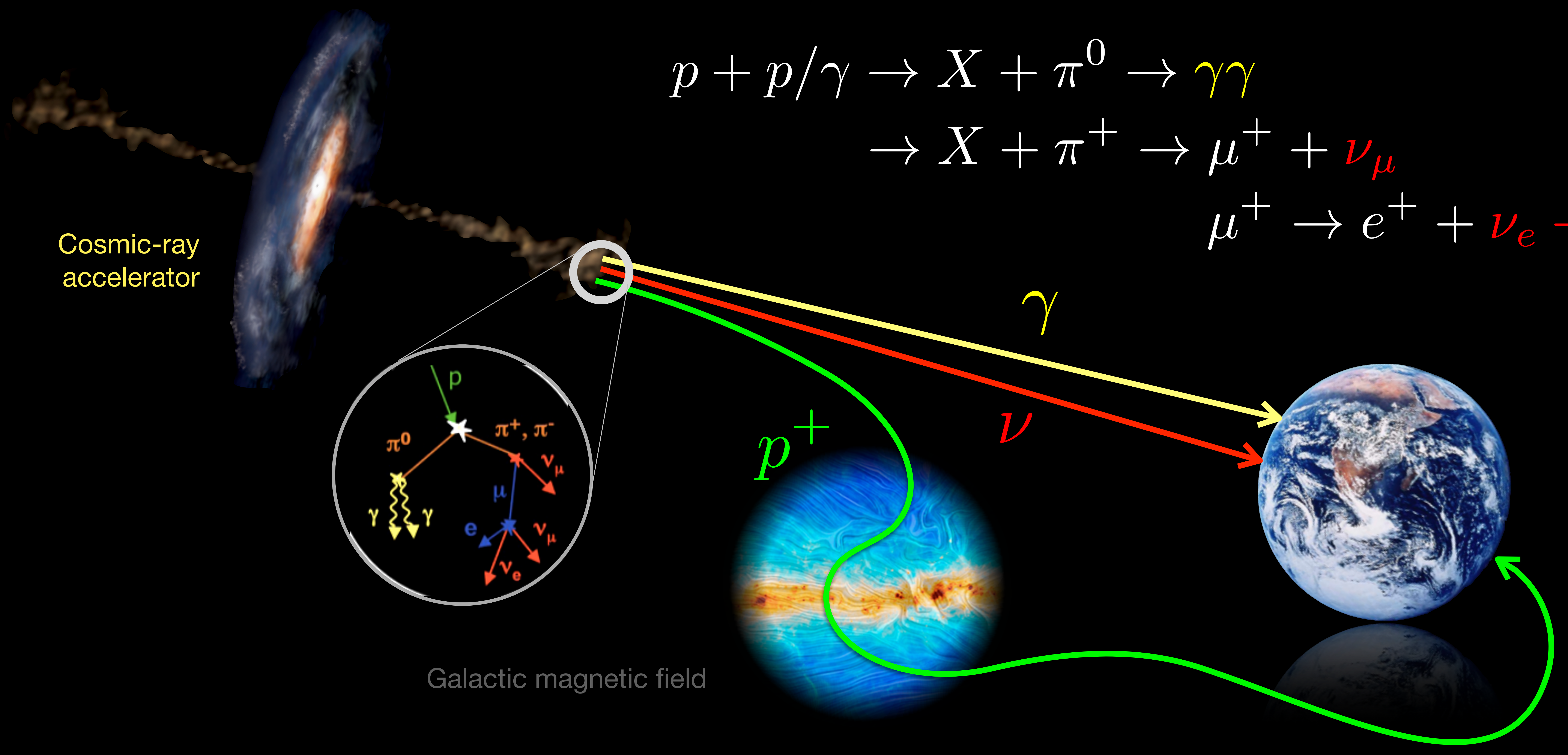
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(oscillates to ~1:1:1)



SEARCHING FOR EM COUNTERPARTS TO NEUTRINOS

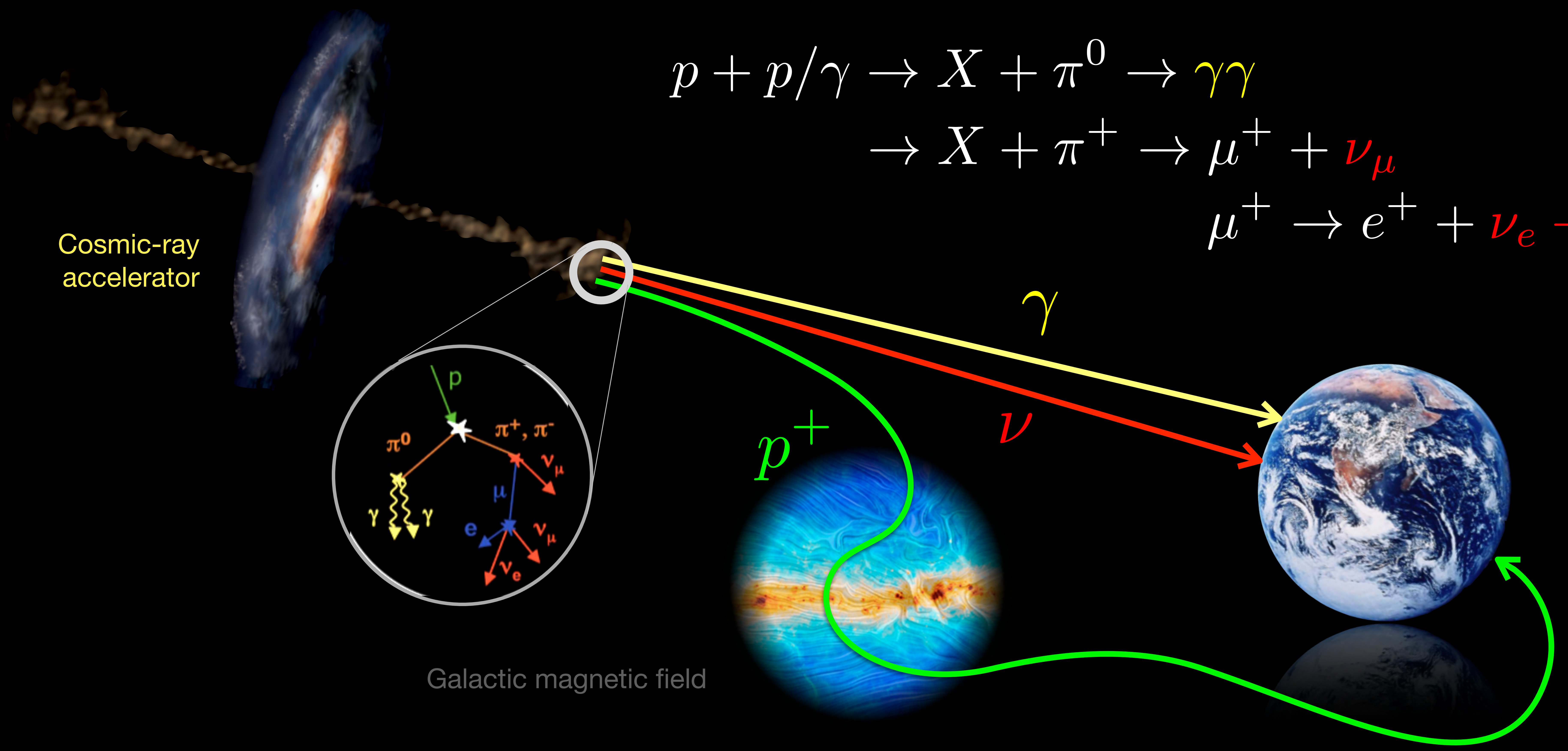
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**



Main source type unclear

SEARCHING FOR EM COUNTERPARTS TO NEUTRINOS

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

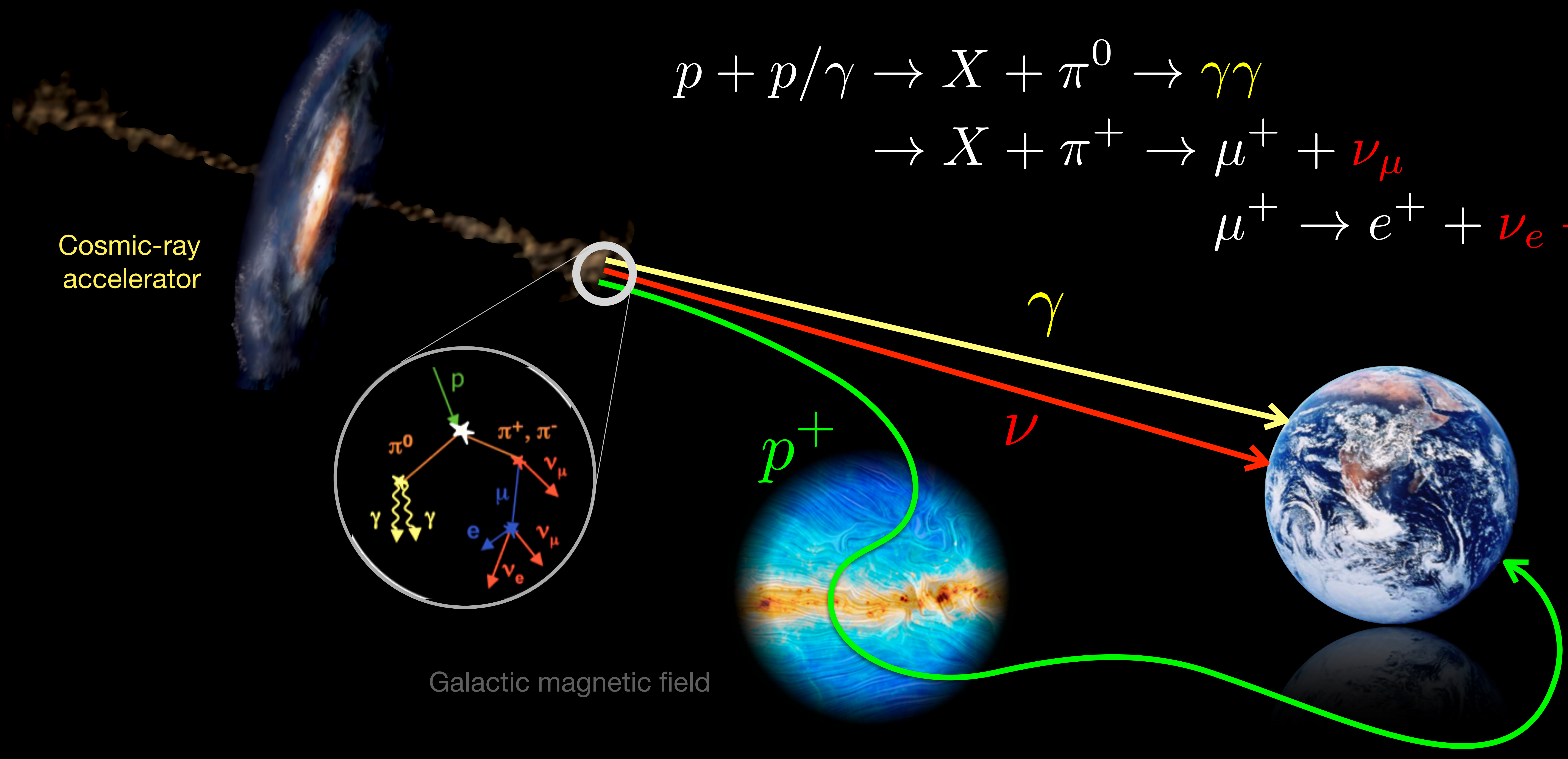


Main source type unclear

Timescale unclear
(Seconds to steady emission)

SEARCHING FOR EM COUNTERPARTS TO NEUTRINOS

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



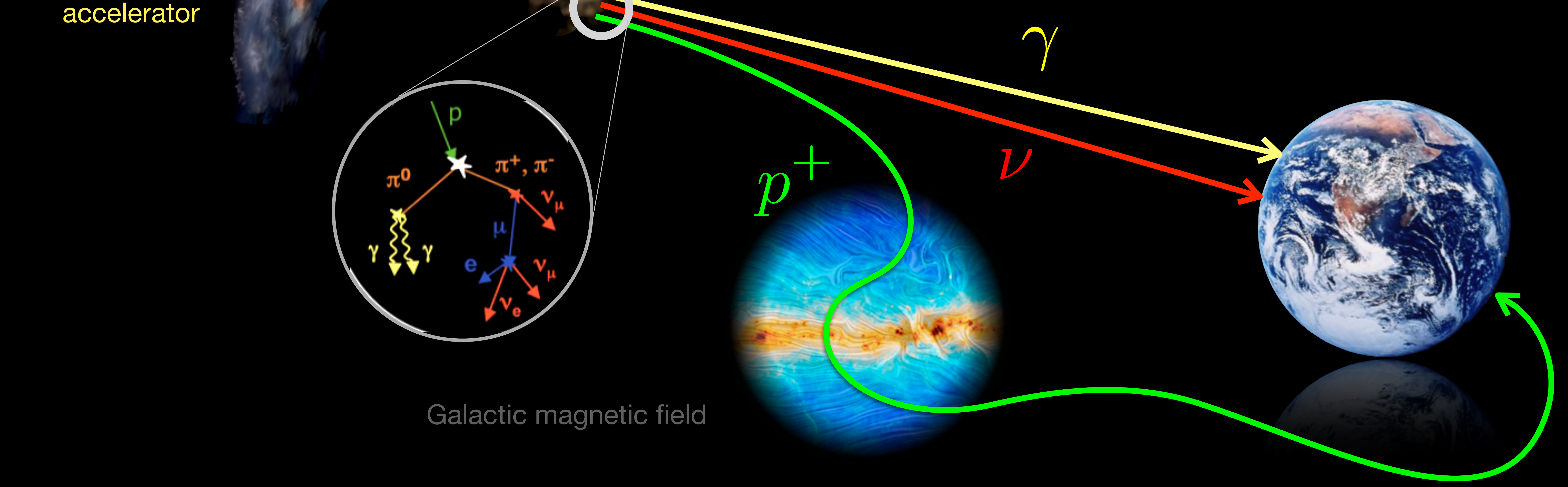
Main source type unclear

Timescale unclear
(Seconds to steady emission)

All-sky distribution!

SEARCHING FOR EM COUNTERPARTS TO NEUTRINOS

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



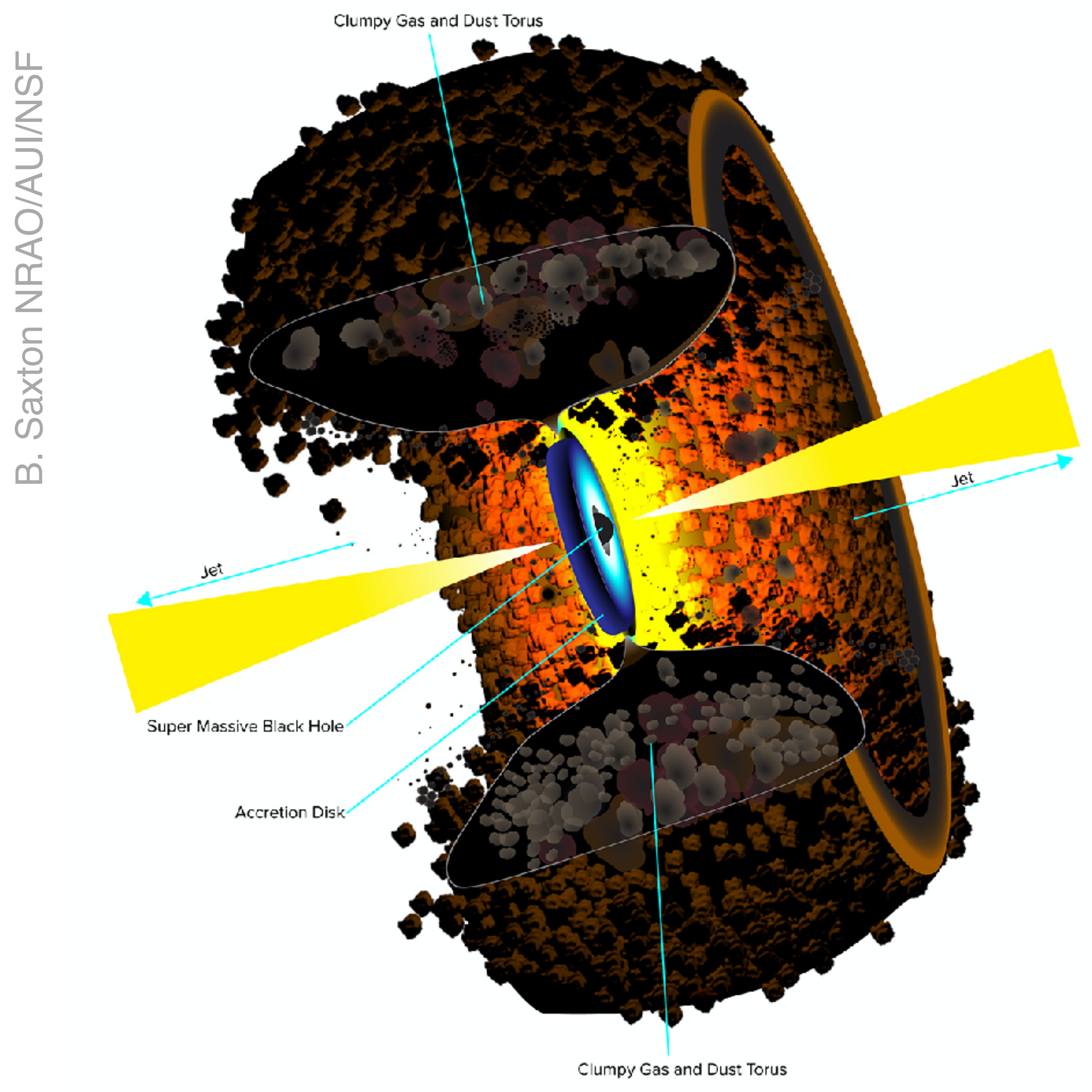
Main source type unclear

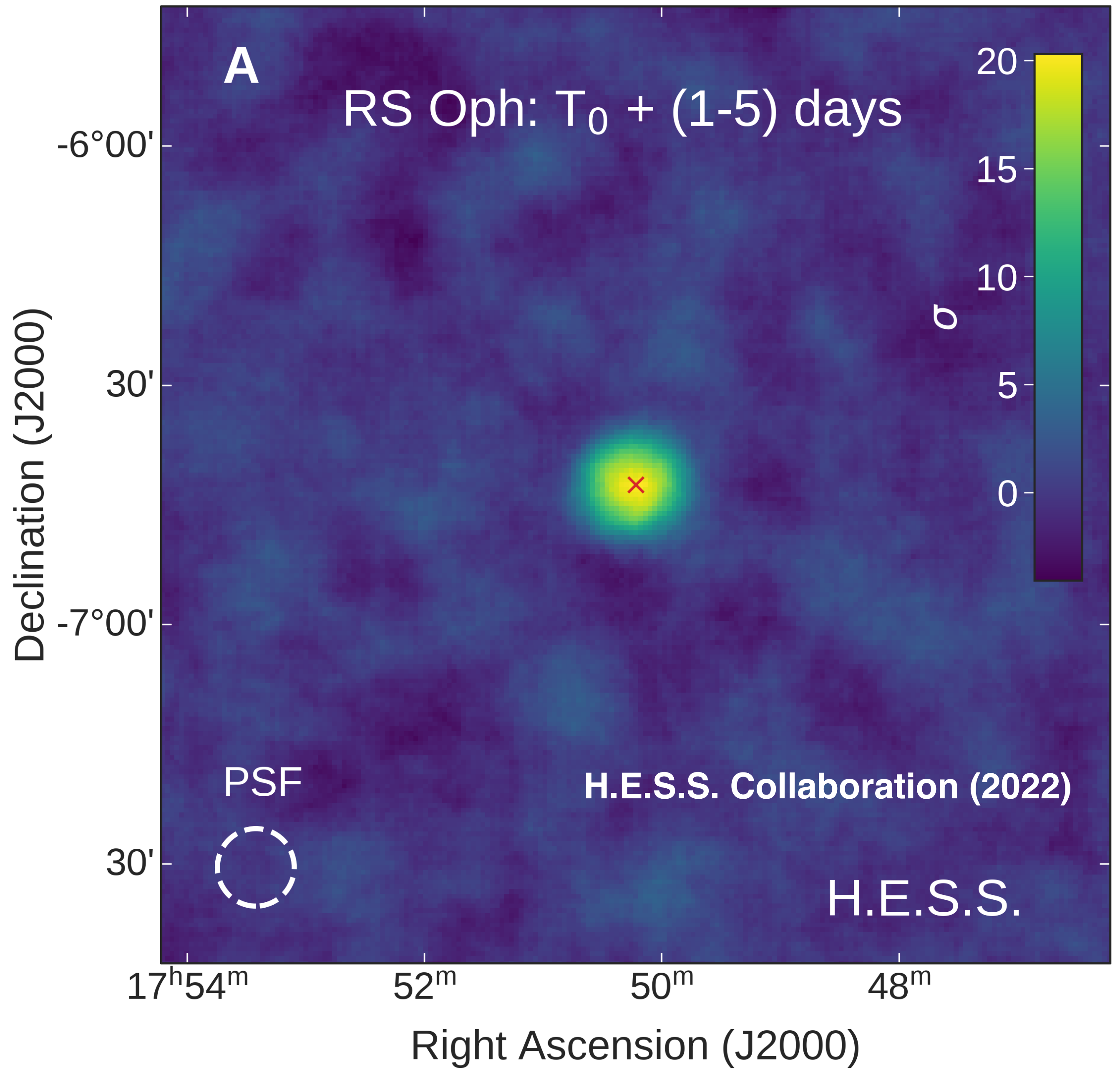
Timescale unclear (Seconds to steady emission)

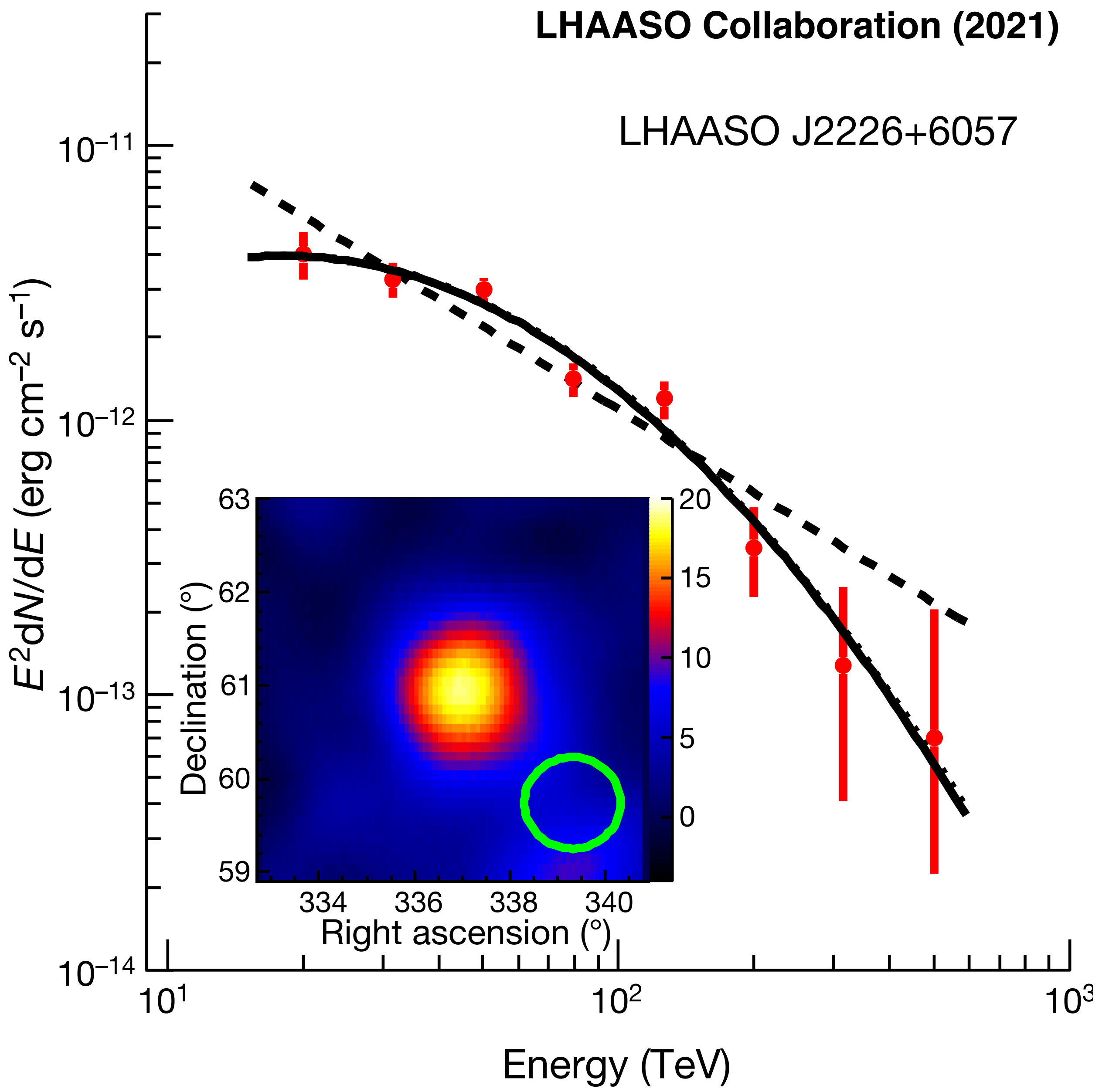
Energy range unclear (Radio? X-rays? Gammas?)

All-sky distribution!

PROBING PARTICLE ACCELERATION WITH NEUTRINOS





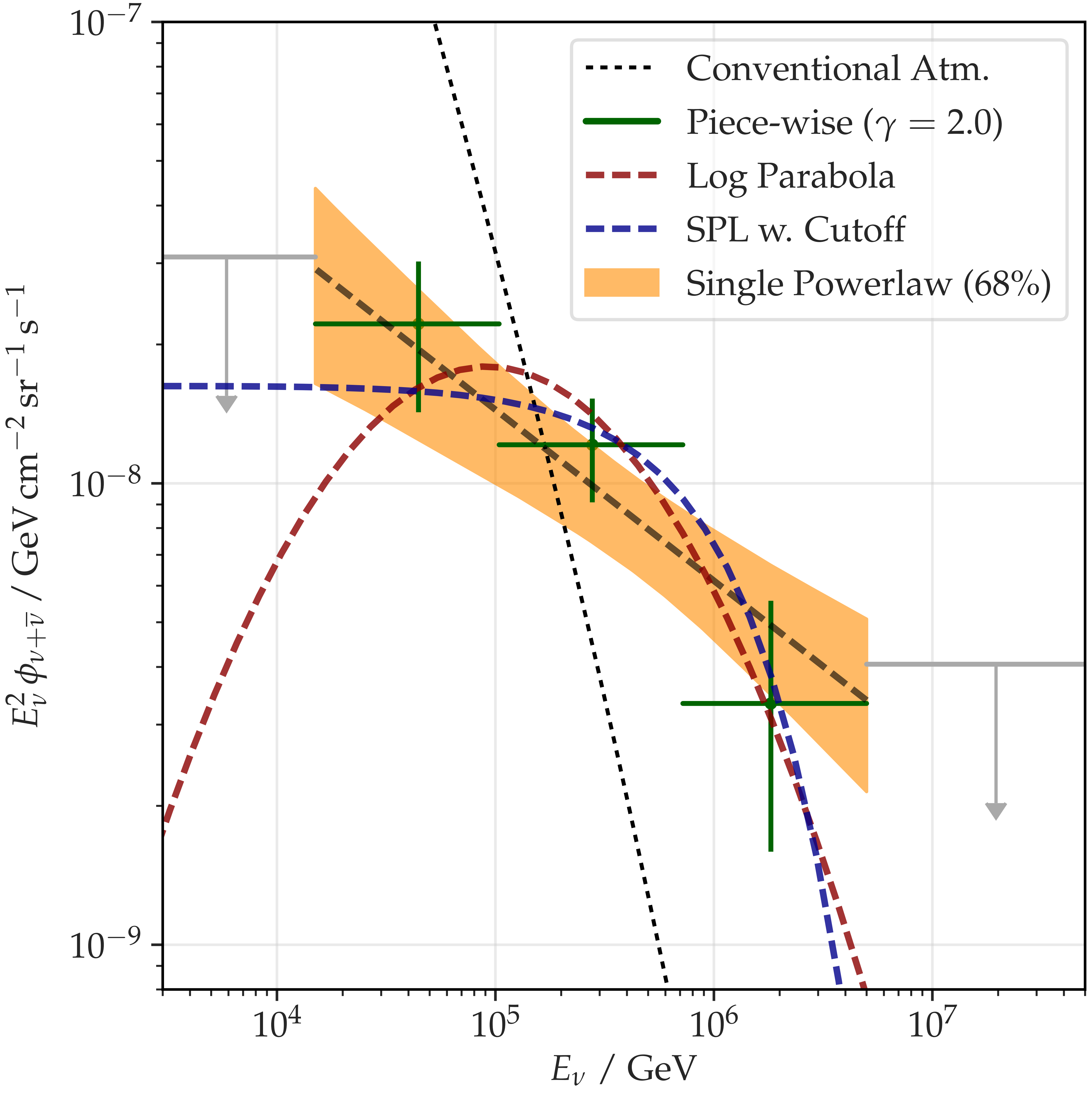


- **Active Galactic Nuclei**
  - Observed across the EM spectrum up to multi-TeV energies.
  - Origin of highest-energy emission uncertain: can be explained by leptonic and hadronic processes.
  - Origin of Ultra-High-Energy Cosmic Rays

- **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

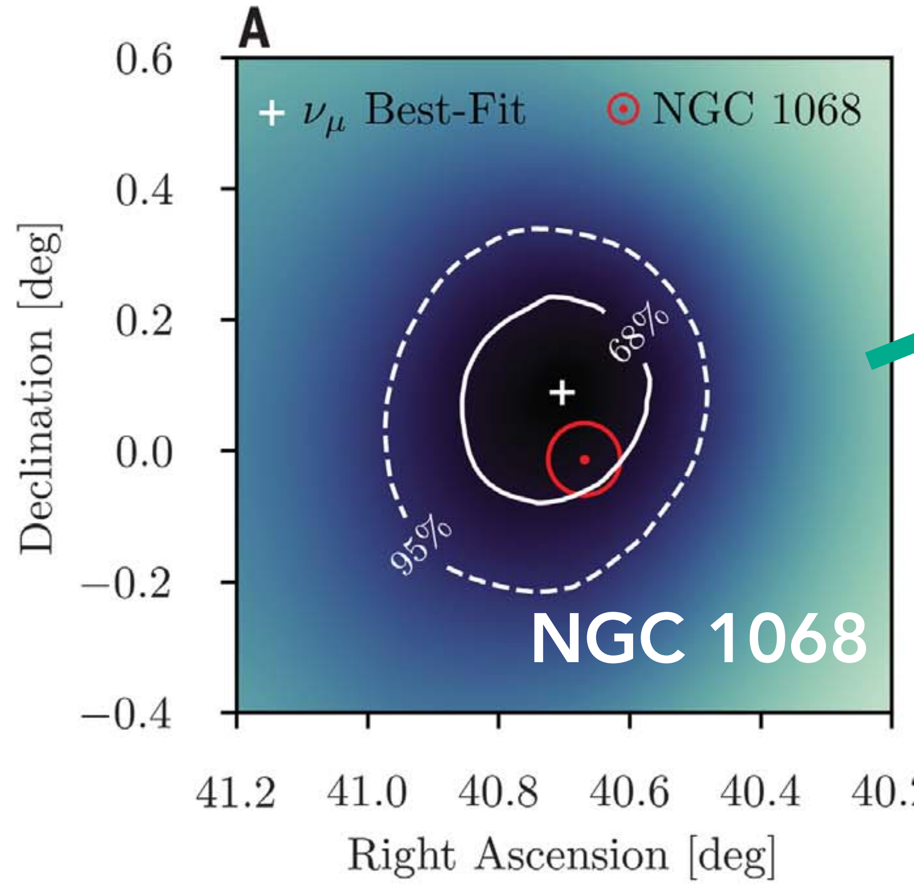


IceCube 2021 (arXiv/2111.10299)

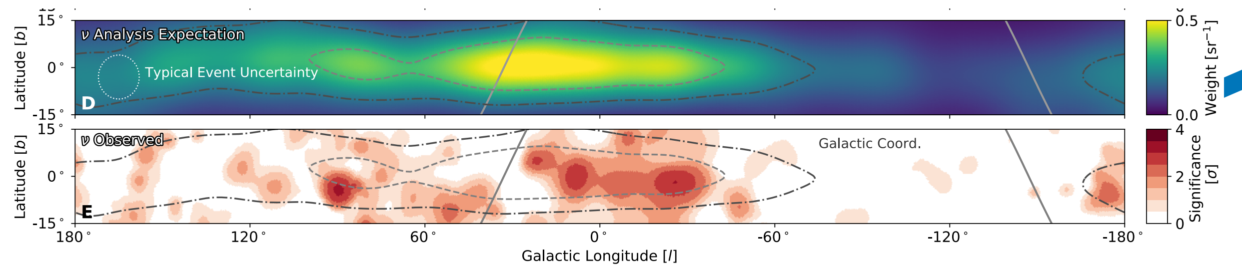
IceCube, MAGIC, ++ 2018 (arXiv/1807.08816)

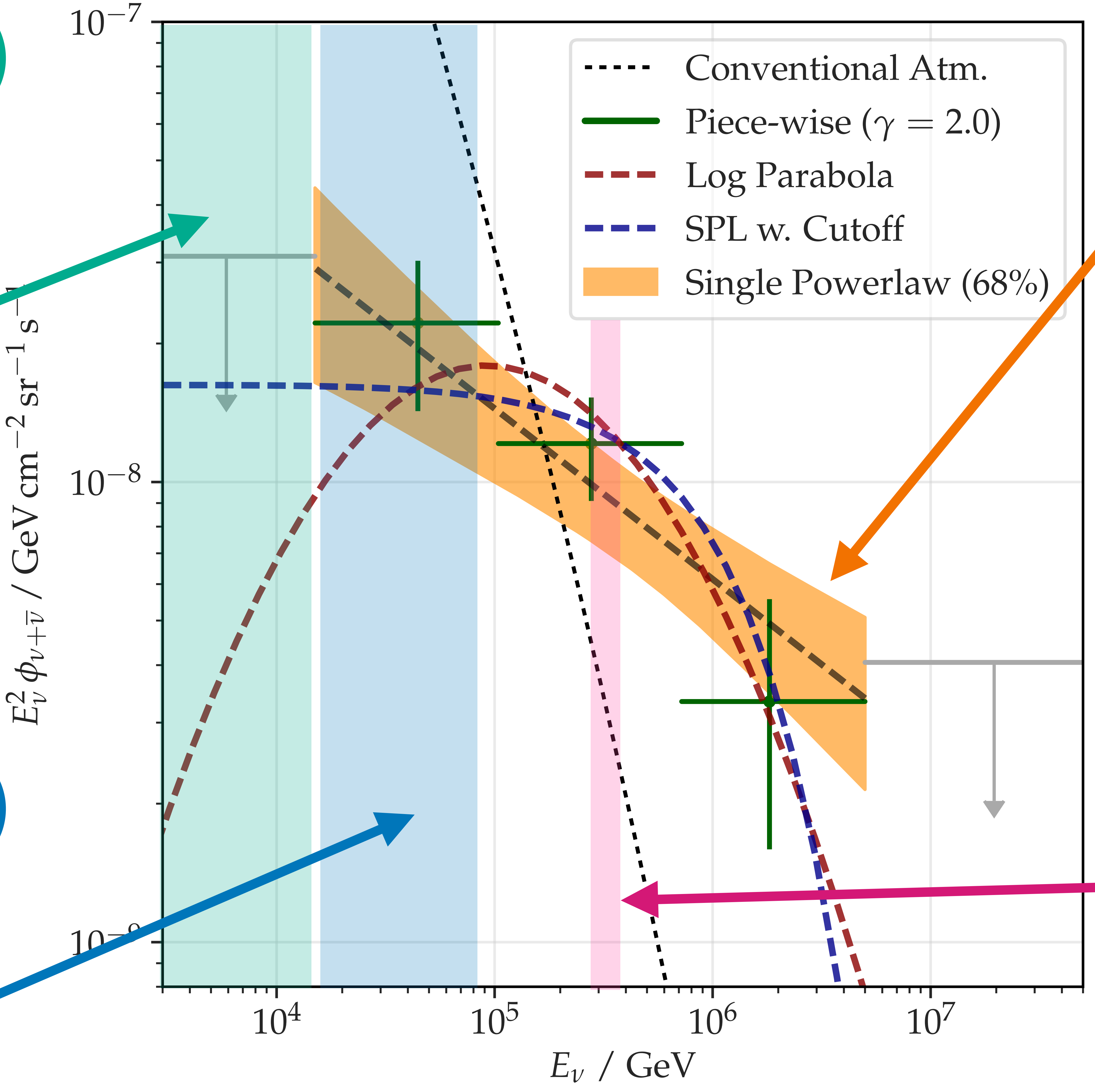
CURRENT OBSERVATIONAL STATUS FOR NEUTRINOS

3 Neutrino emission from an AGN (2022)



4 Neutrinos from the Milky Way (2023)

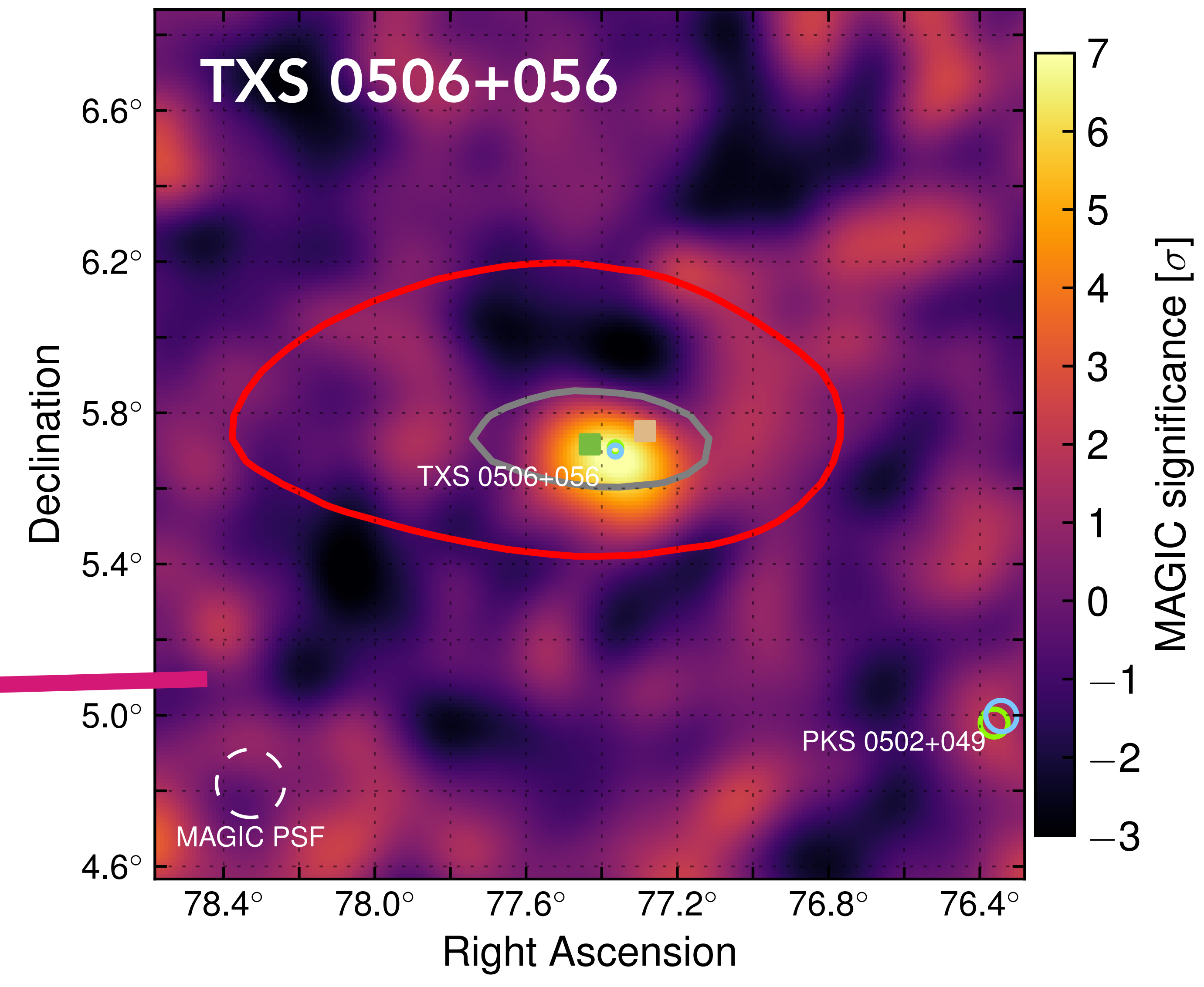




IceCube 2021 (arXiv/2111.10299)

1 Astrophysical neutrino flux (2013)

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



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

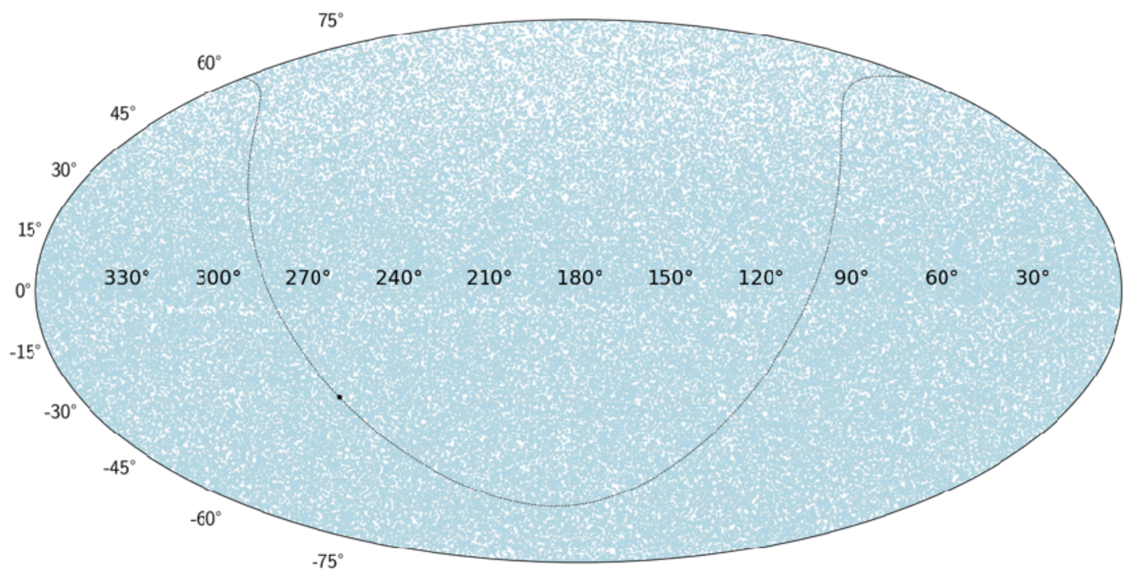
CURRENT OBSERVATIONAL STATUS FOR NEUTRINOS

Current Observational Status for Neutrinos

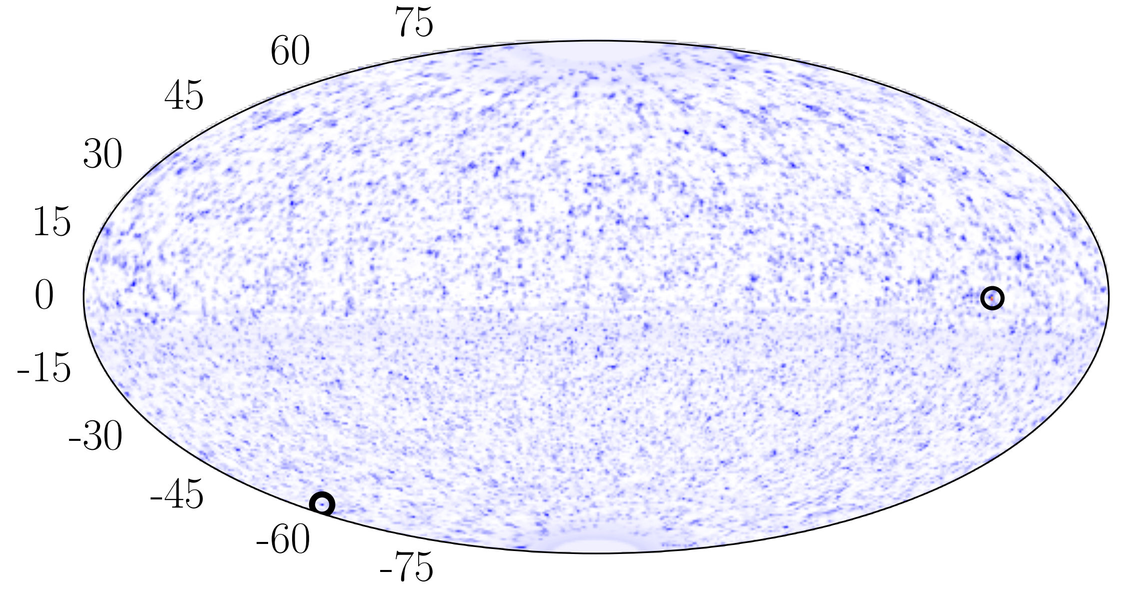
Low-energy regime

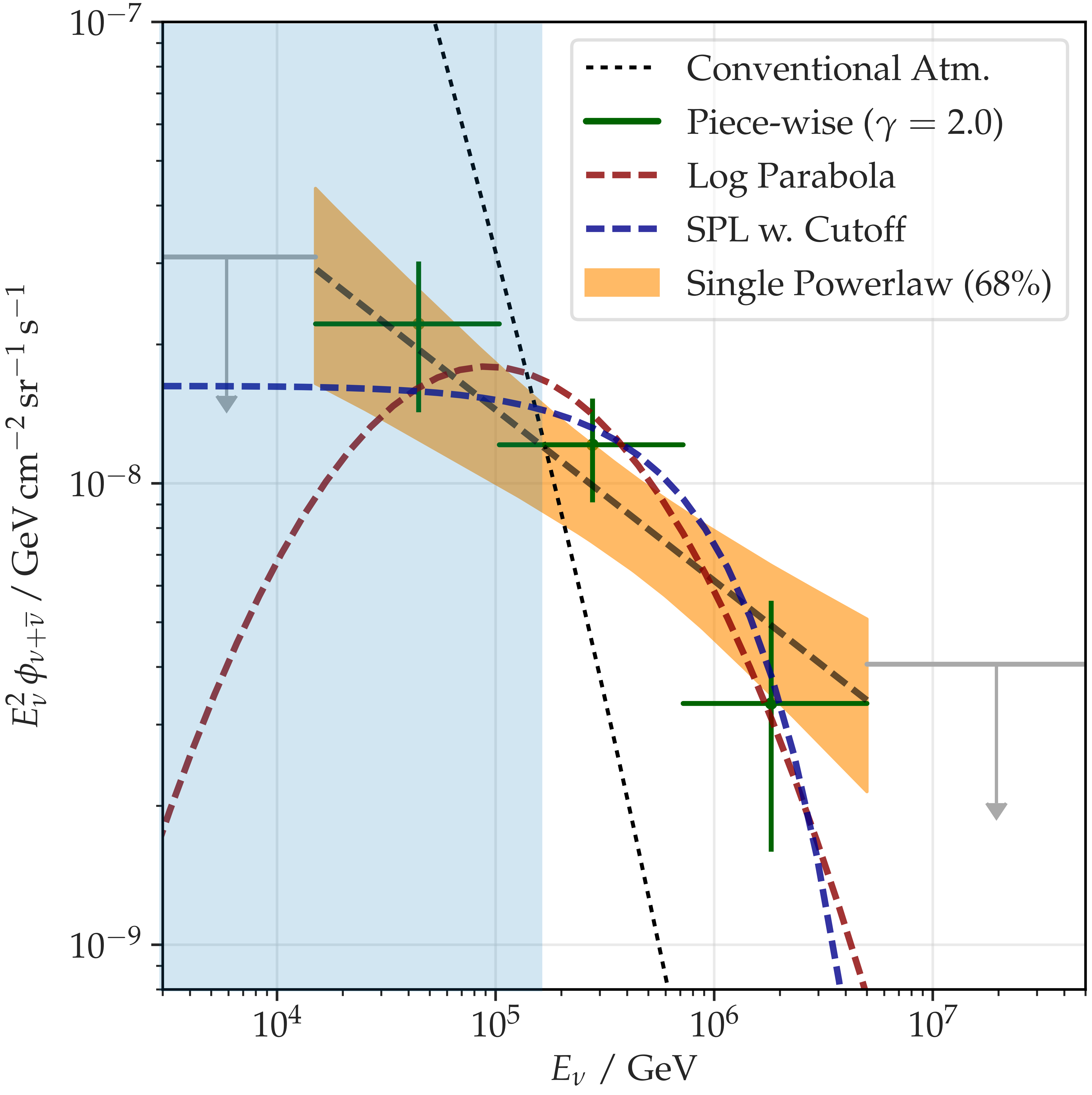
- Background dominated
- Sensitivity roughly ∝ PSF^2
- Self-clustering and correlation searches (temporal too)

Data



Cluster search





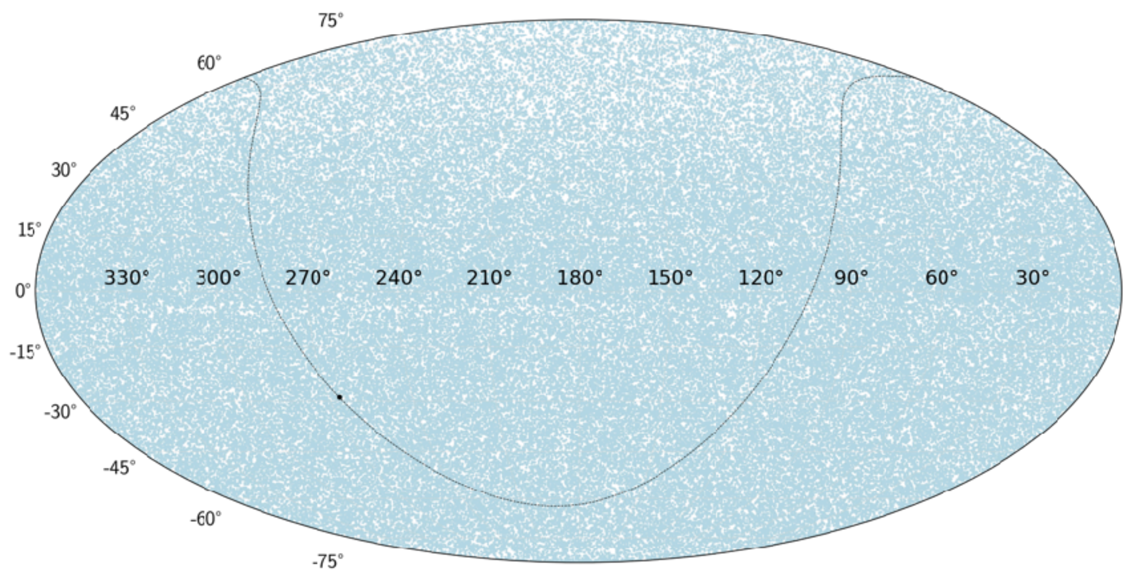
IceCube 2021 (arXiv/2111.10299)

CURRENT OBSERVATIONAL STATUS FOR NEUTRINOS

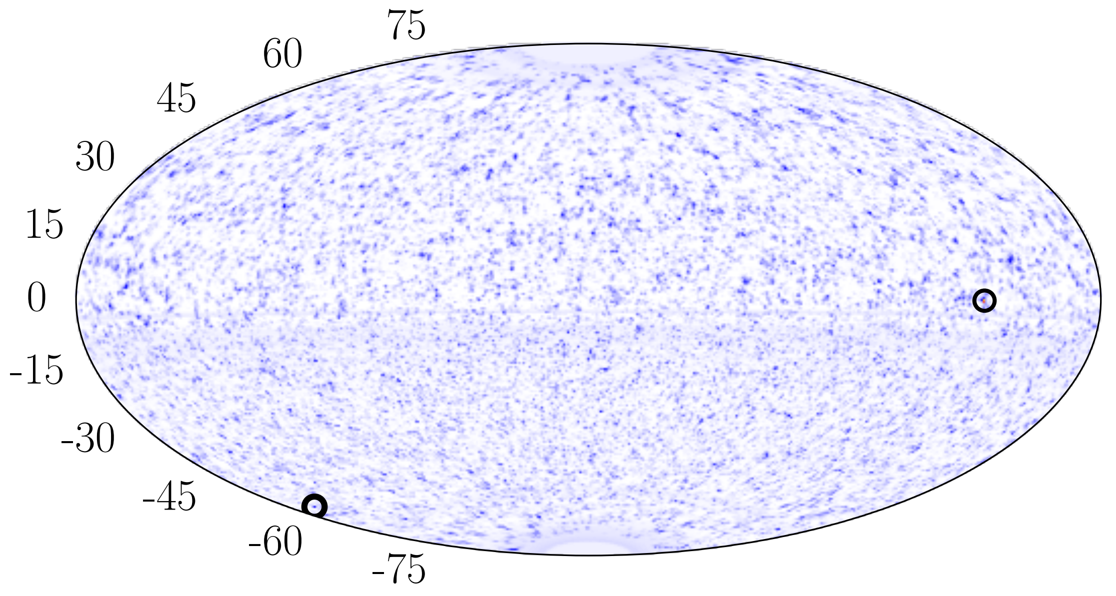
Low-energy regime

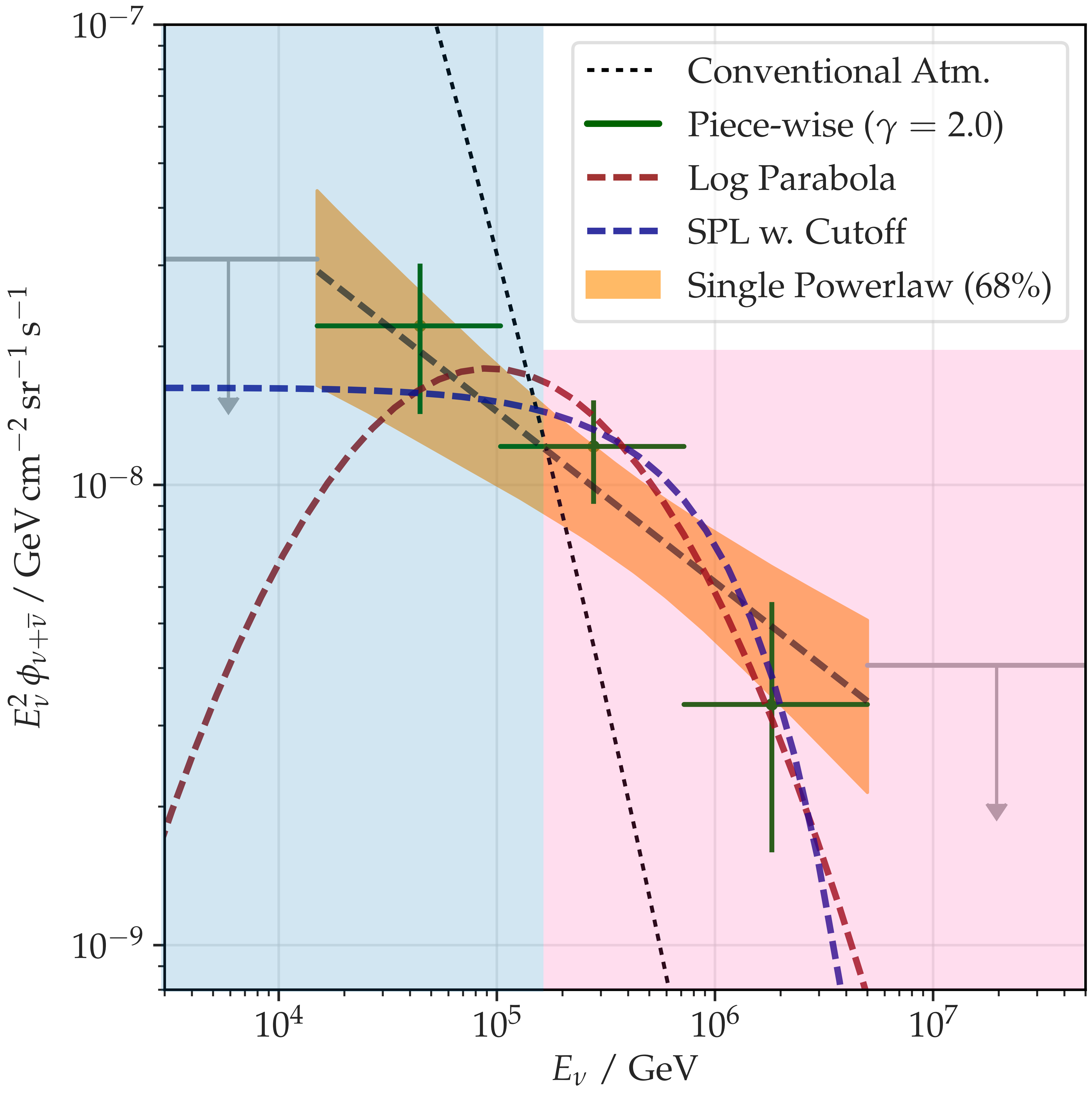
- Background dominated
- Sensitivity roughly ∝ PSF^2
- Self-clustering and correlation searches (temporal too)

Data



Cluster search

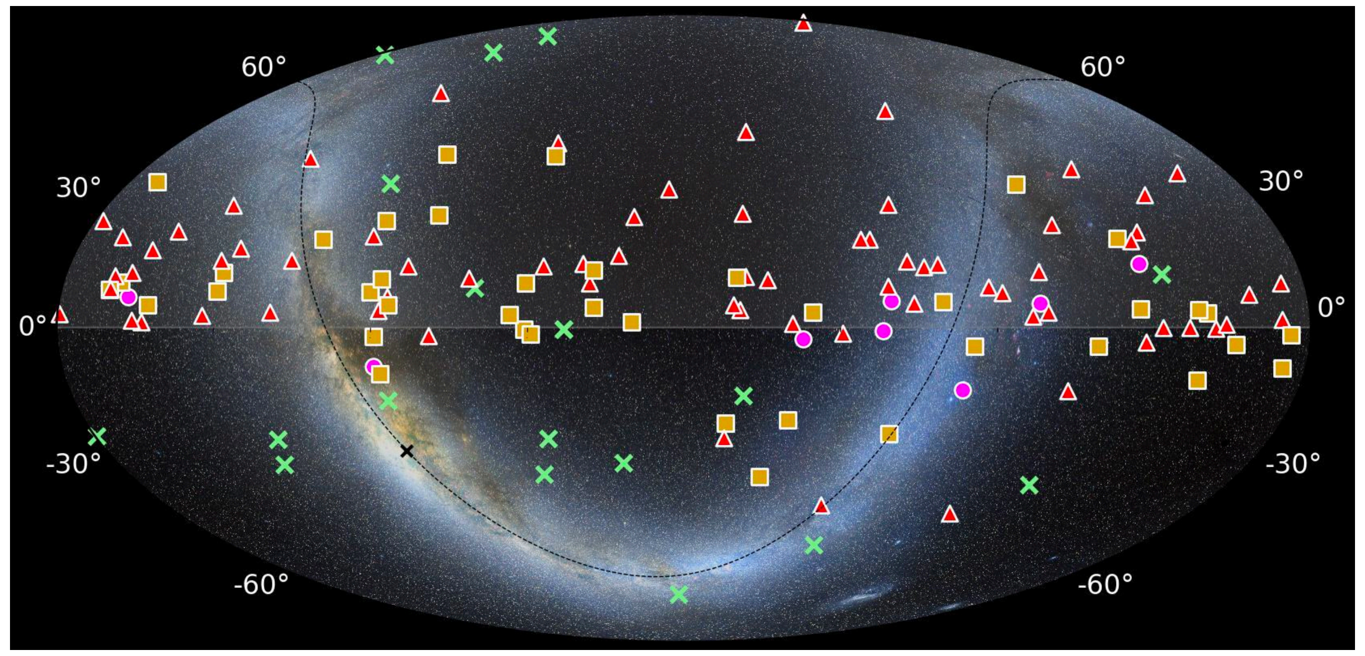




IceCube 2021 (arXiv/2111.10299)

High-energy regime

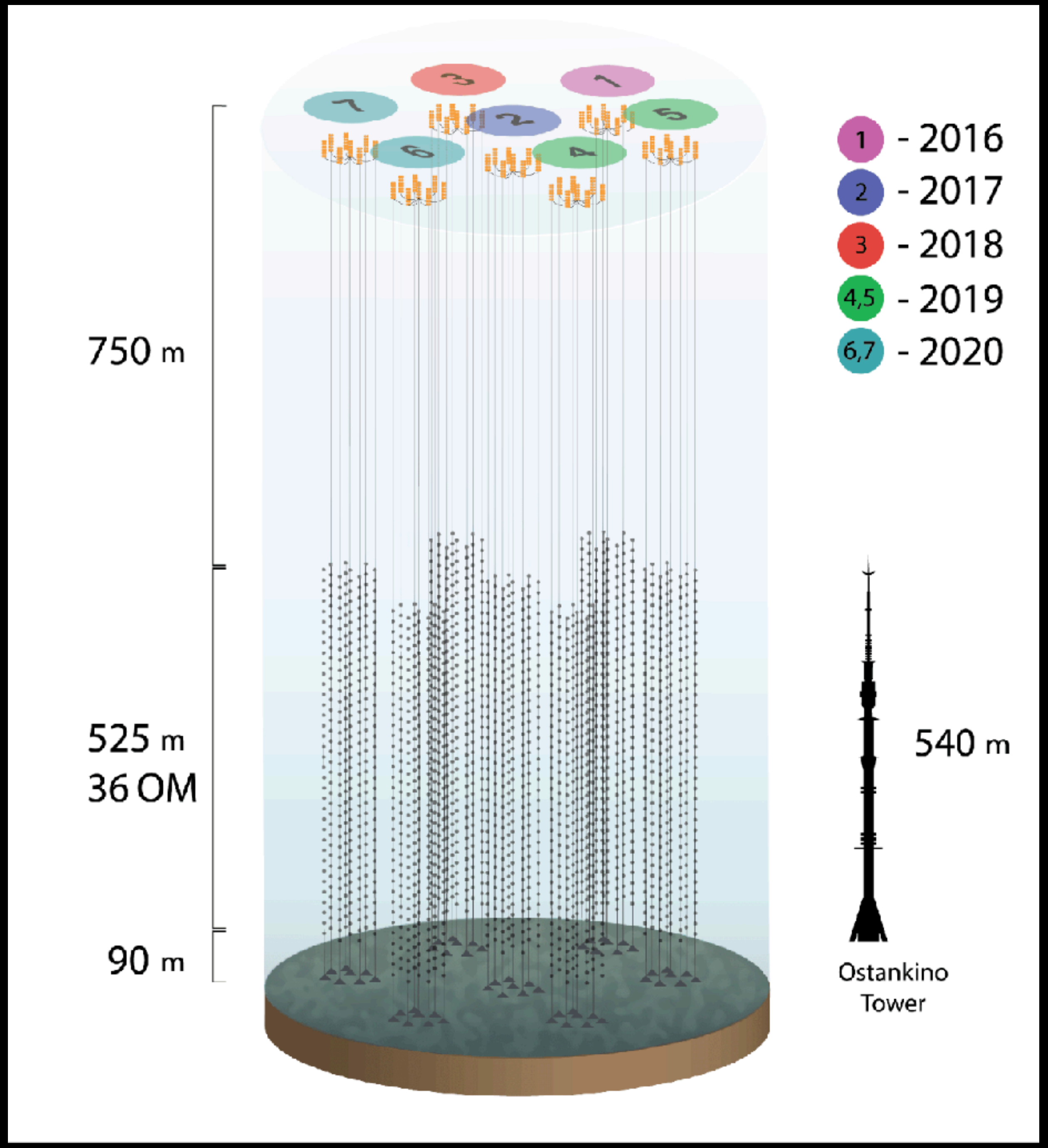
- Signal dominated
- Very low event rate (~10 events per year across the full sky for km^3 detector)
- Correlation studies
- Realtime follow-ups



IceCube realtime alerts

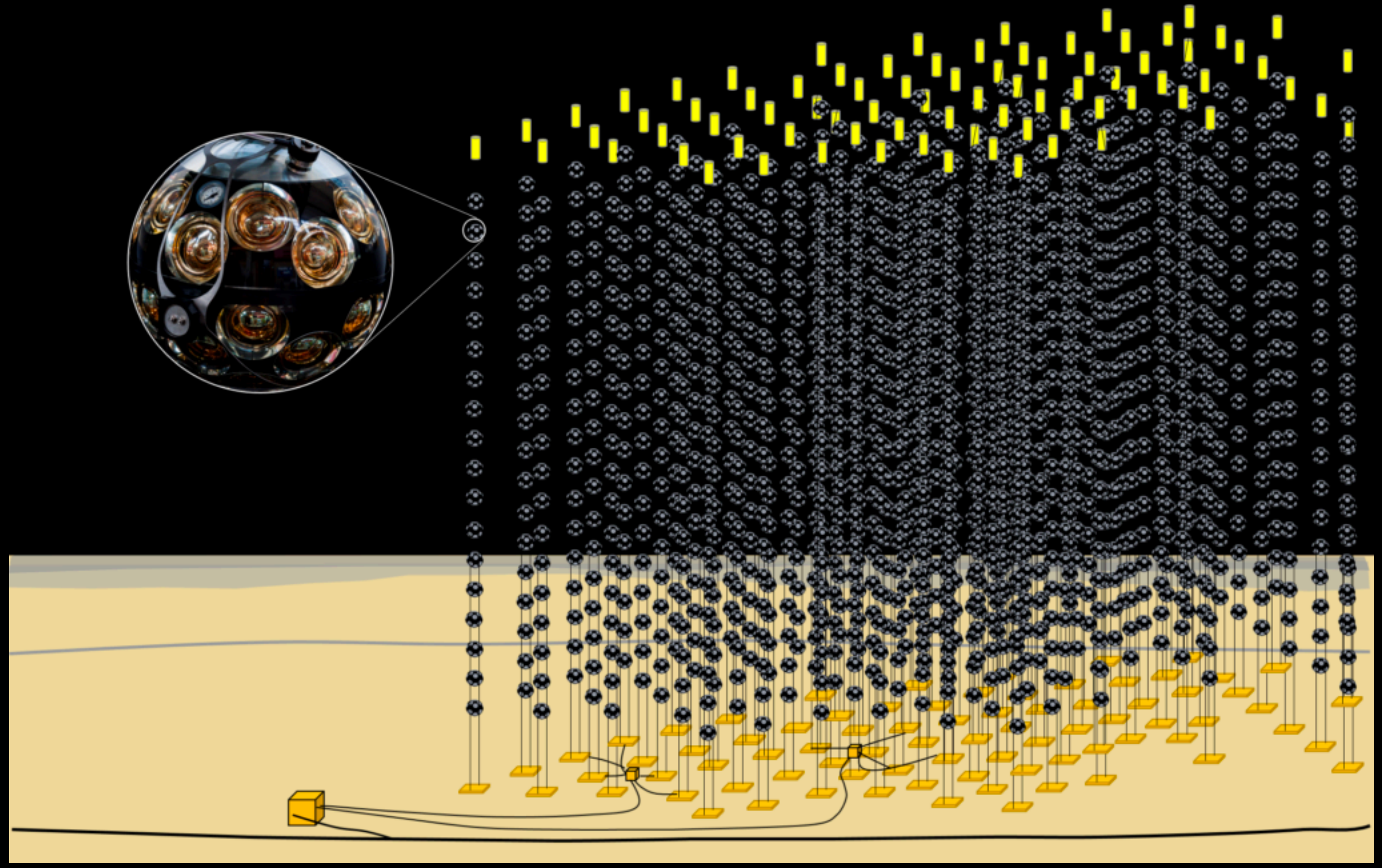
CURRENT GENERATION OF NEUTRINO TELESCOPES

Future: P-ONE, TRIDENT, HUNT, NEON



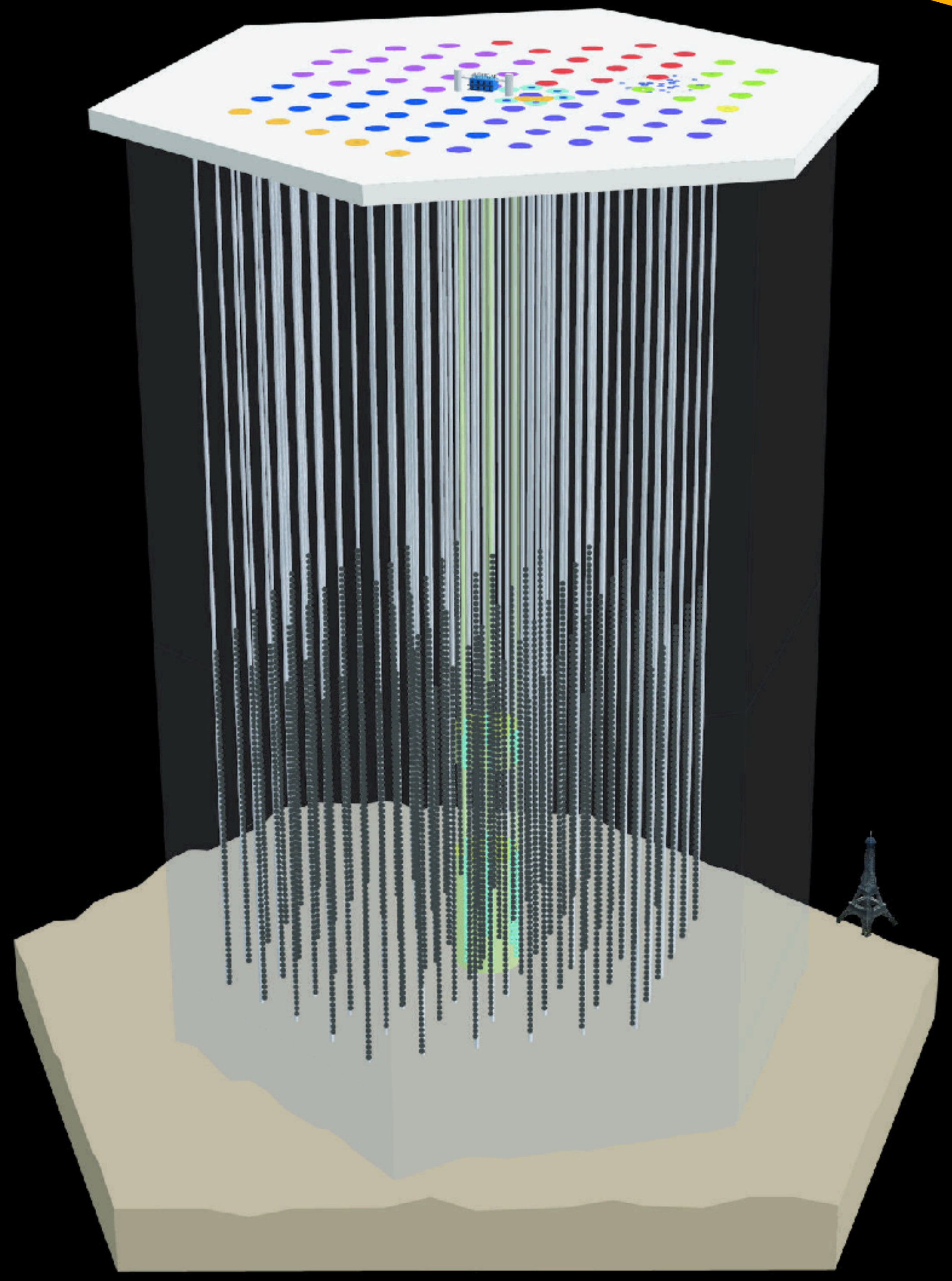
Baikal-GVD

- Lake Baikal (Russia)
- Under construction, targeting 1 km^3
- As of 2023 ~0.5 km^3 (13 clusters of 288 sensors each)



KM3NeT

- Mediterranean Sea (Italy/France). Successor of ANTARES.
- Under construction, targeting 1 km^3
- Current status: 47 detector units deployed by end of 2024 (see R. Castiglione's talk)



IceCube

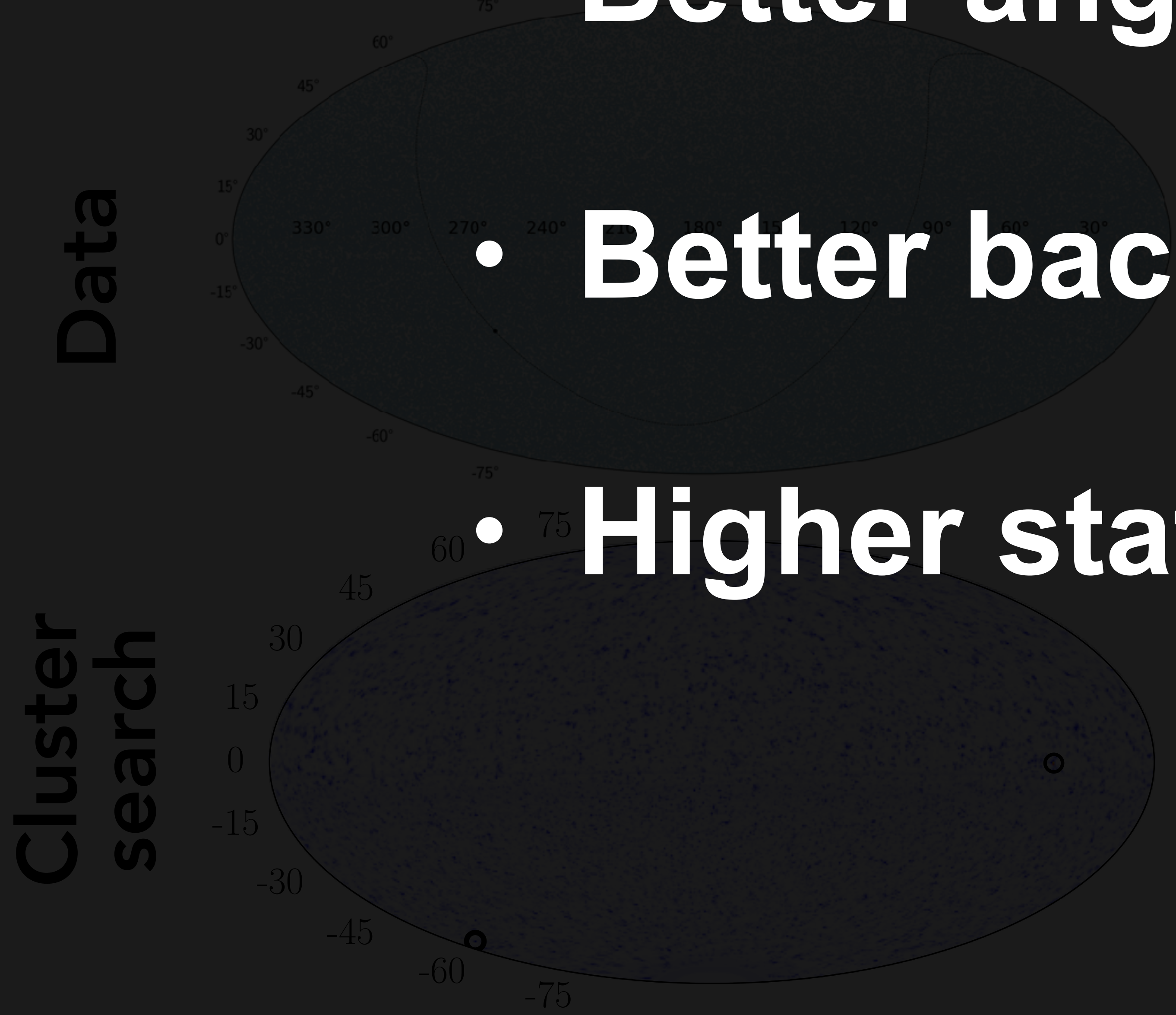
- South Pole glacier. 2010.
- 1 km^3
- 5160 PMTs

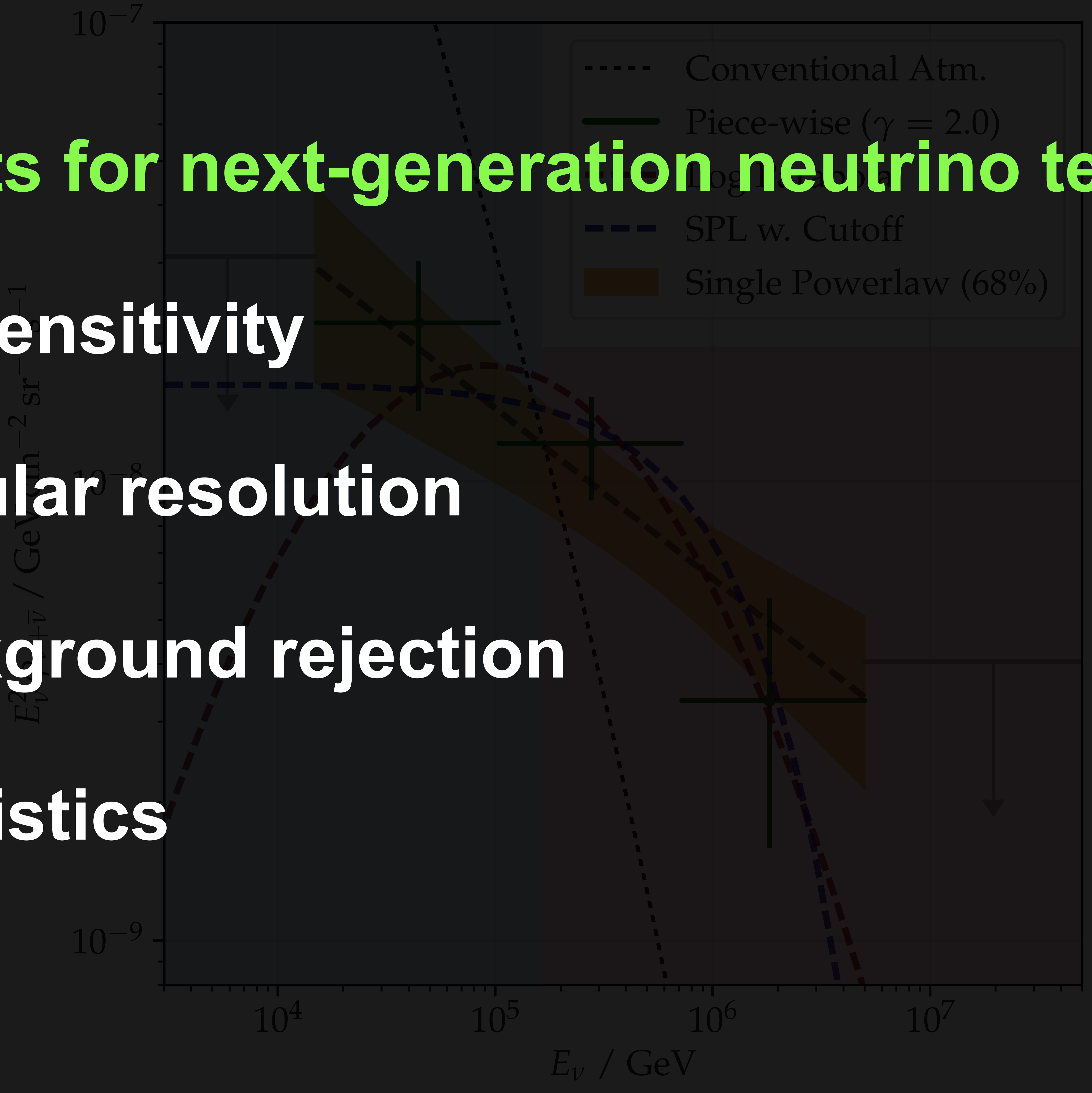
THE CHALLENGE OF IDENTIFYING SOURCES

- **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-cluster
  correlation searches

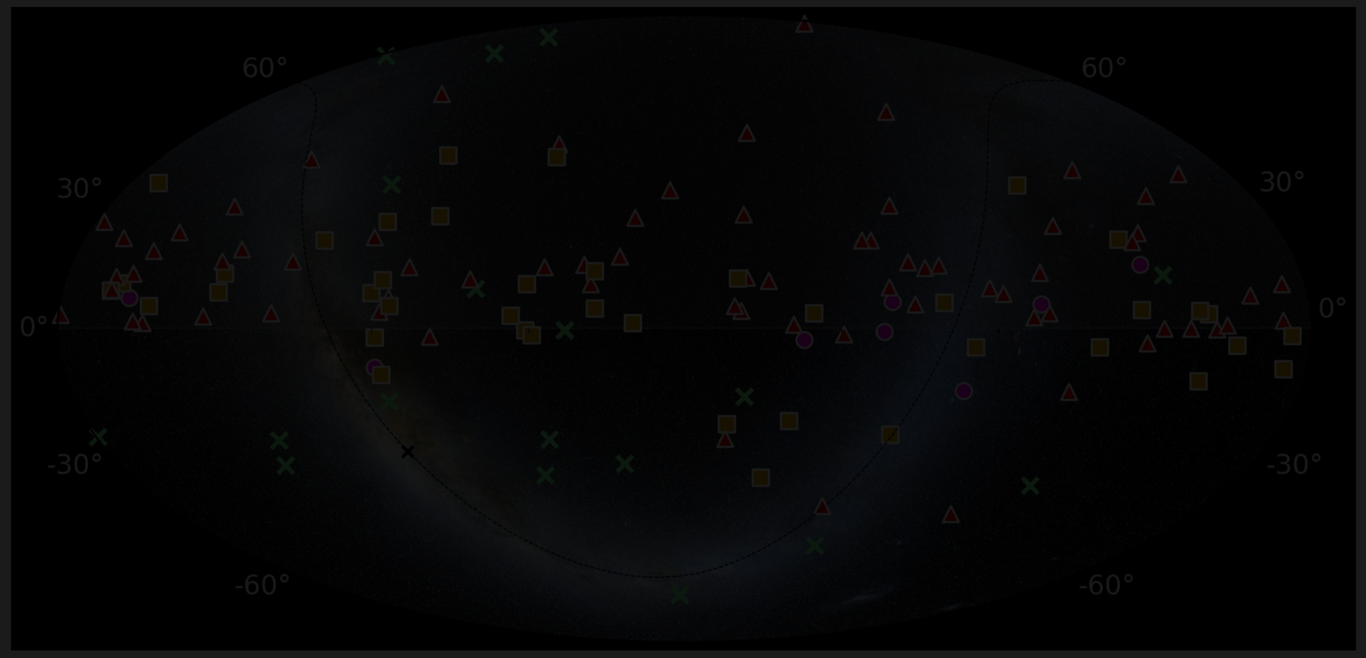




IceCube 2021 (arXiv/2111.10299)

High-energy regime

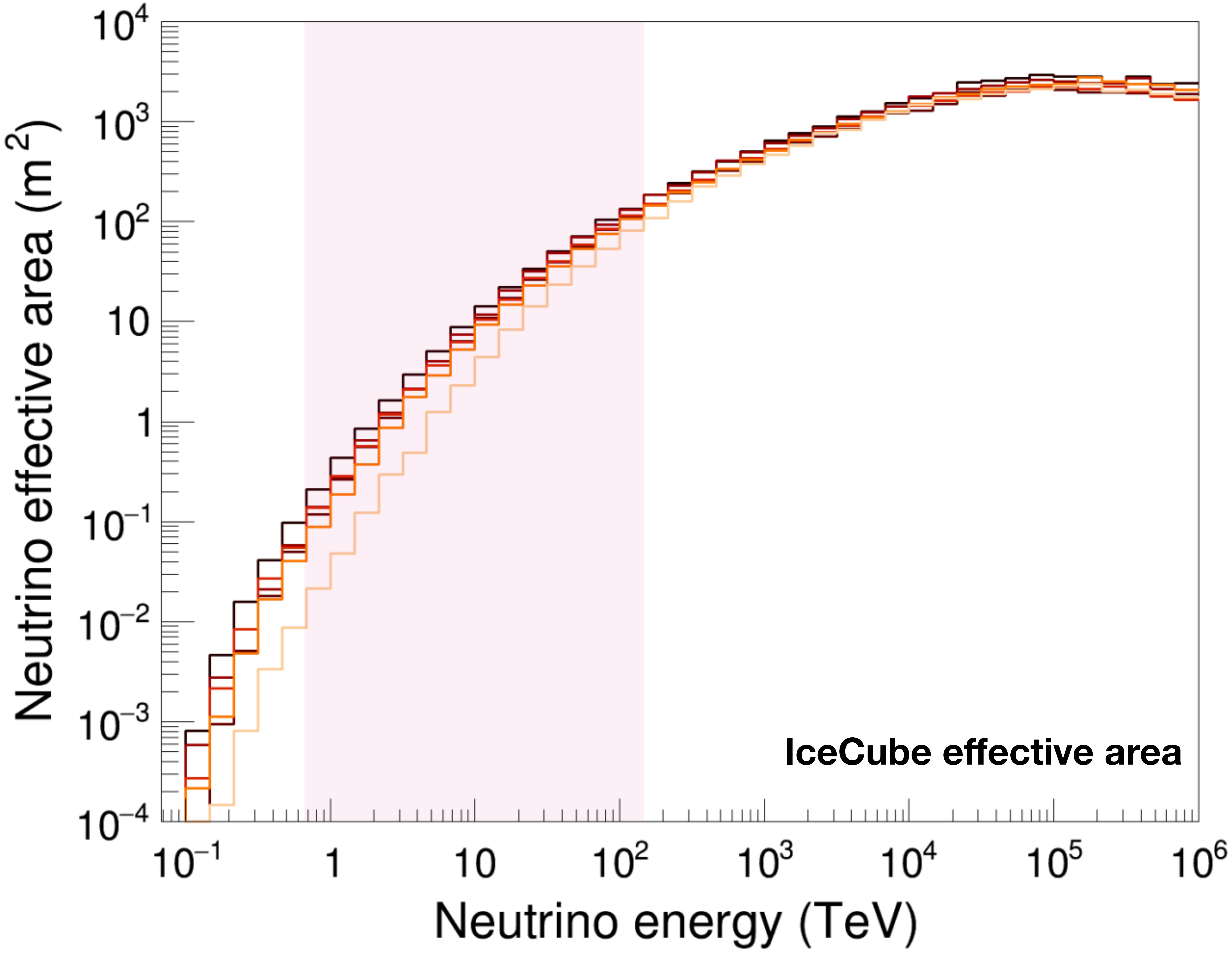
- Signal dominated
- Very low event rate (~10 events per year across the full sky)
- Correlation studies
- Realtime follow-ups



IceCube realtime alerts

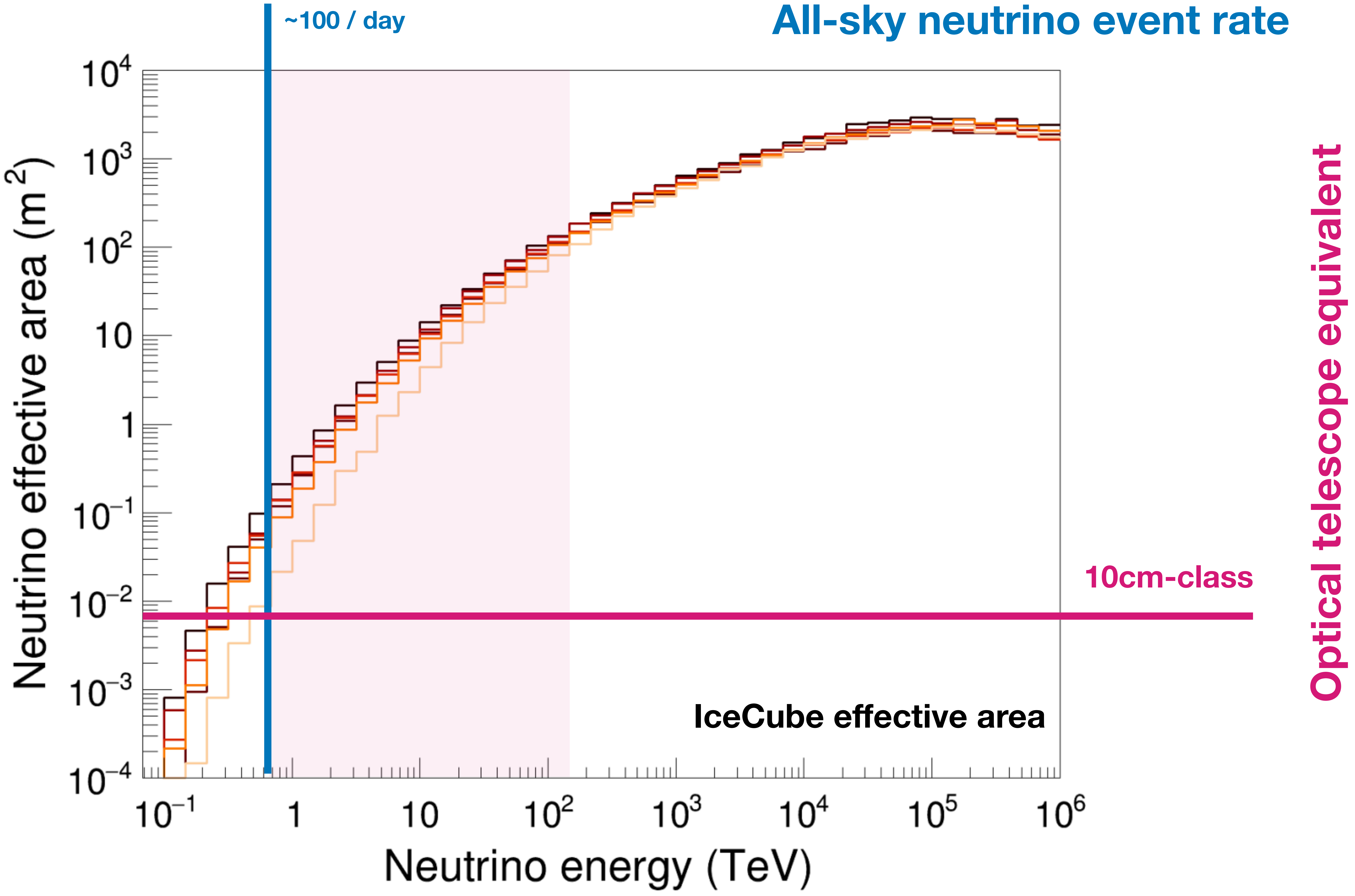
THE CHALLENGE OF IDENTIFYING SOURCES

All-sky neutrino event rate

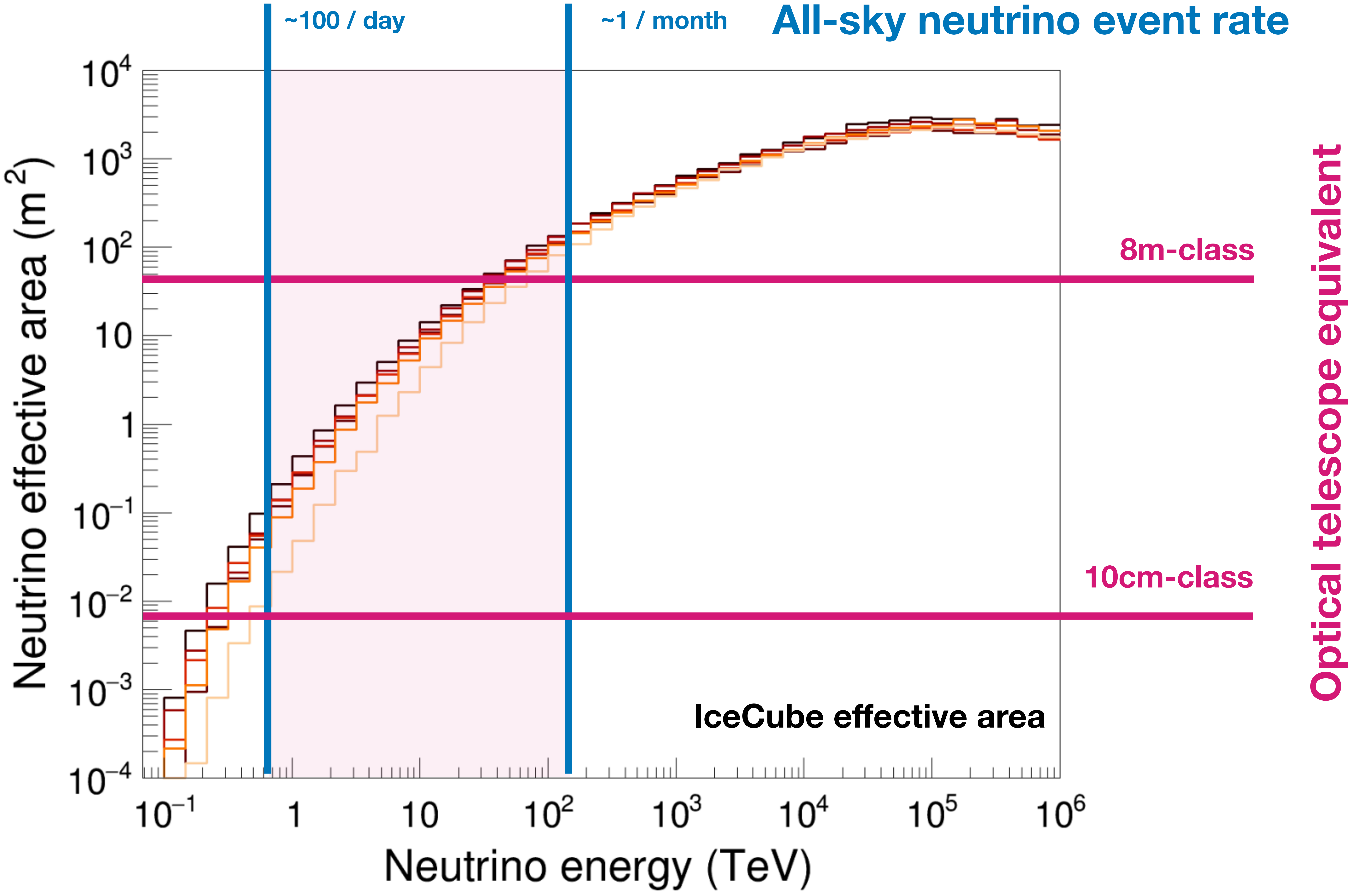


Optical telescope equivalent

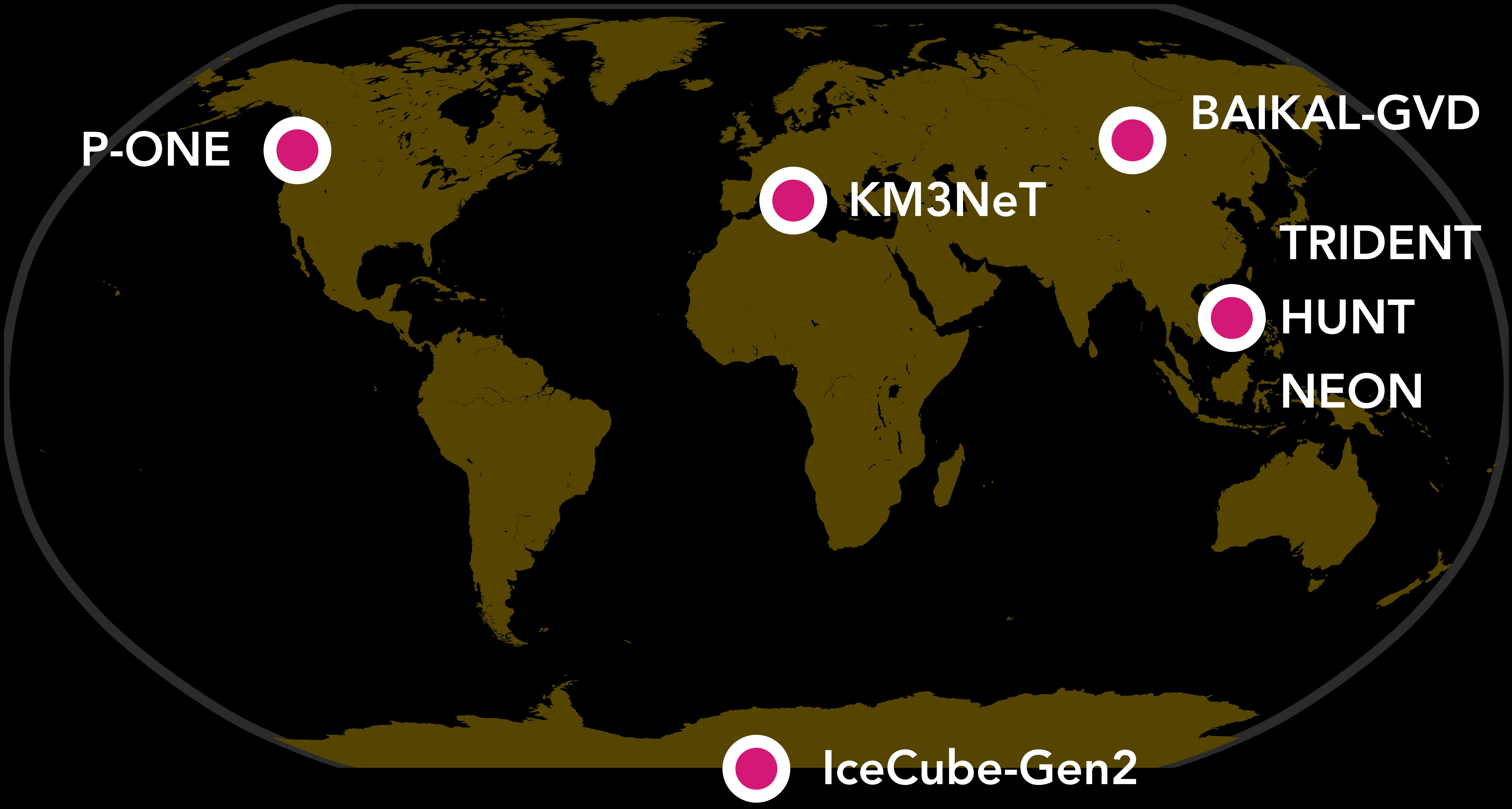
THE CHALLENGE OF IDENTIFYING SOURCES



THE CHALLENGE OF IDENTIFYING SOURCES



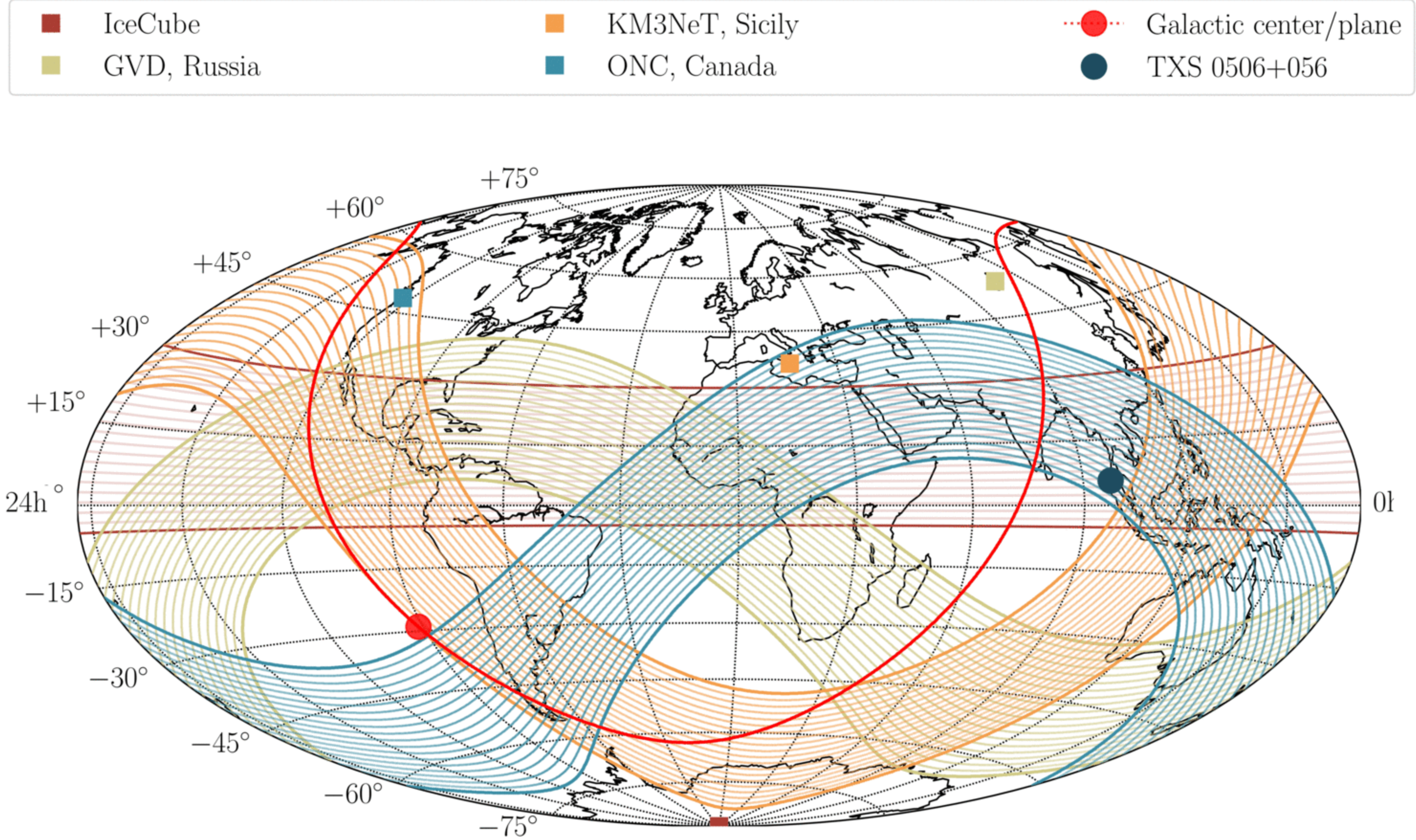
NEUTRINO CHERENKOV TELESCOPES

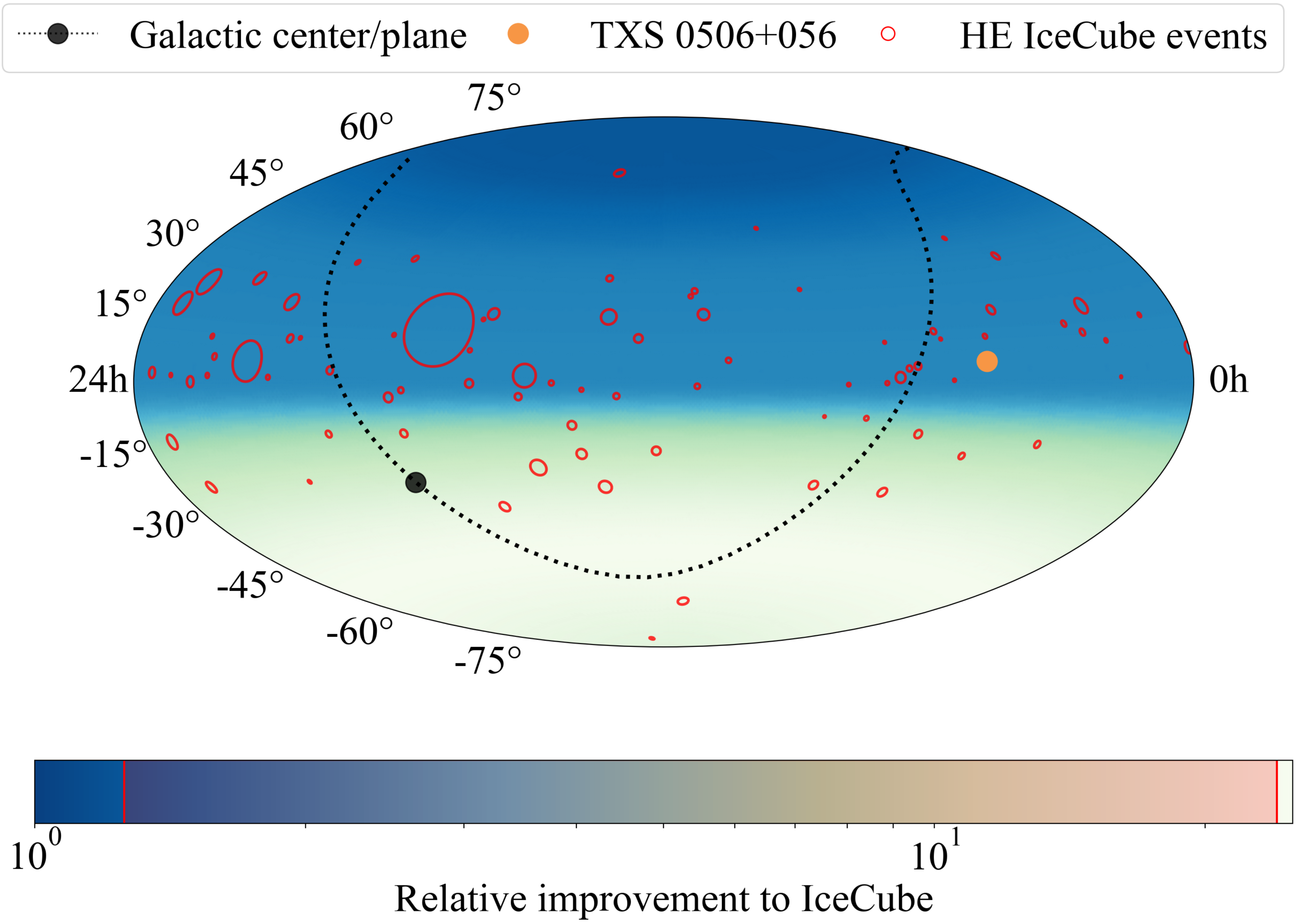


COMBINING NEUTRINO OBSERVATIONS

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

PLEνM



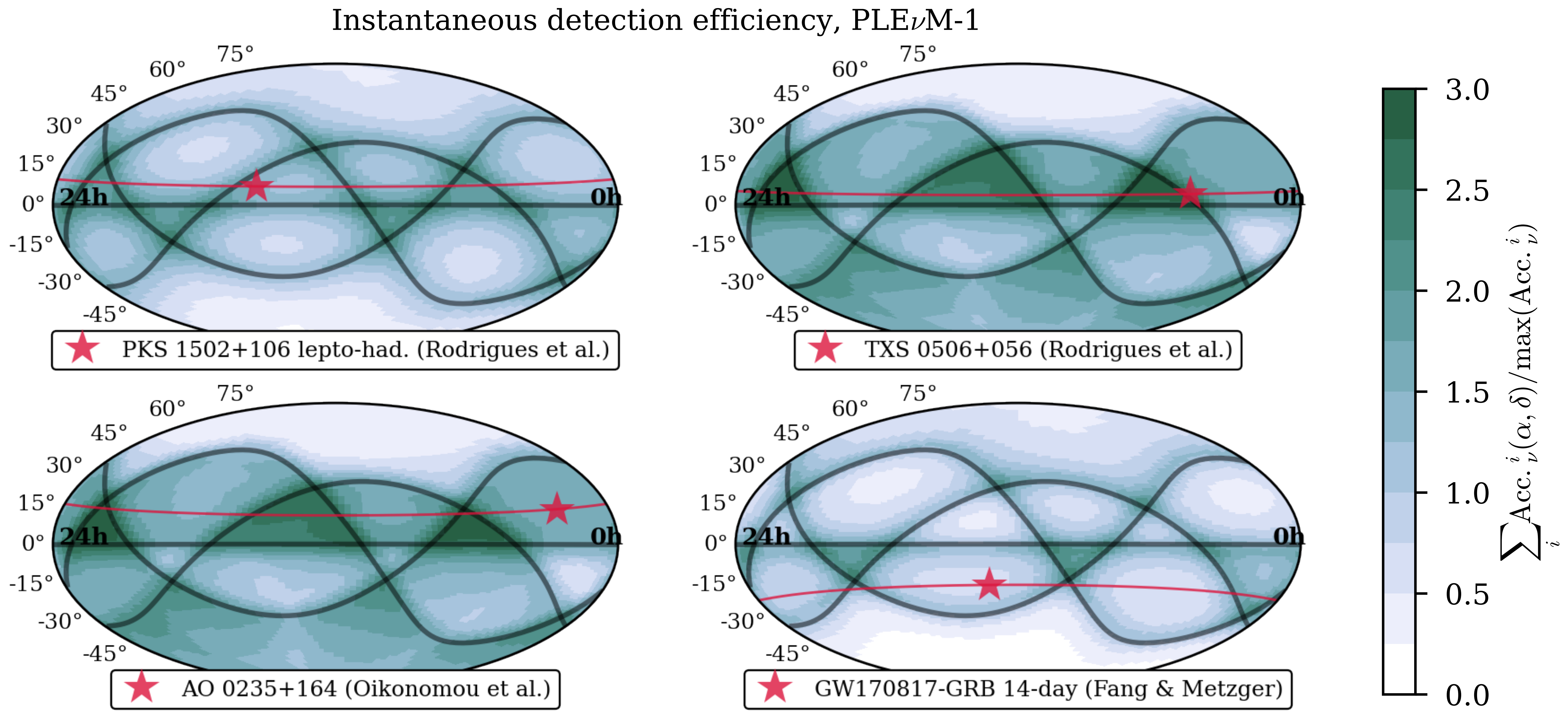


L. Schumacher et al. (arXiv/2107.13534)

- 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**.

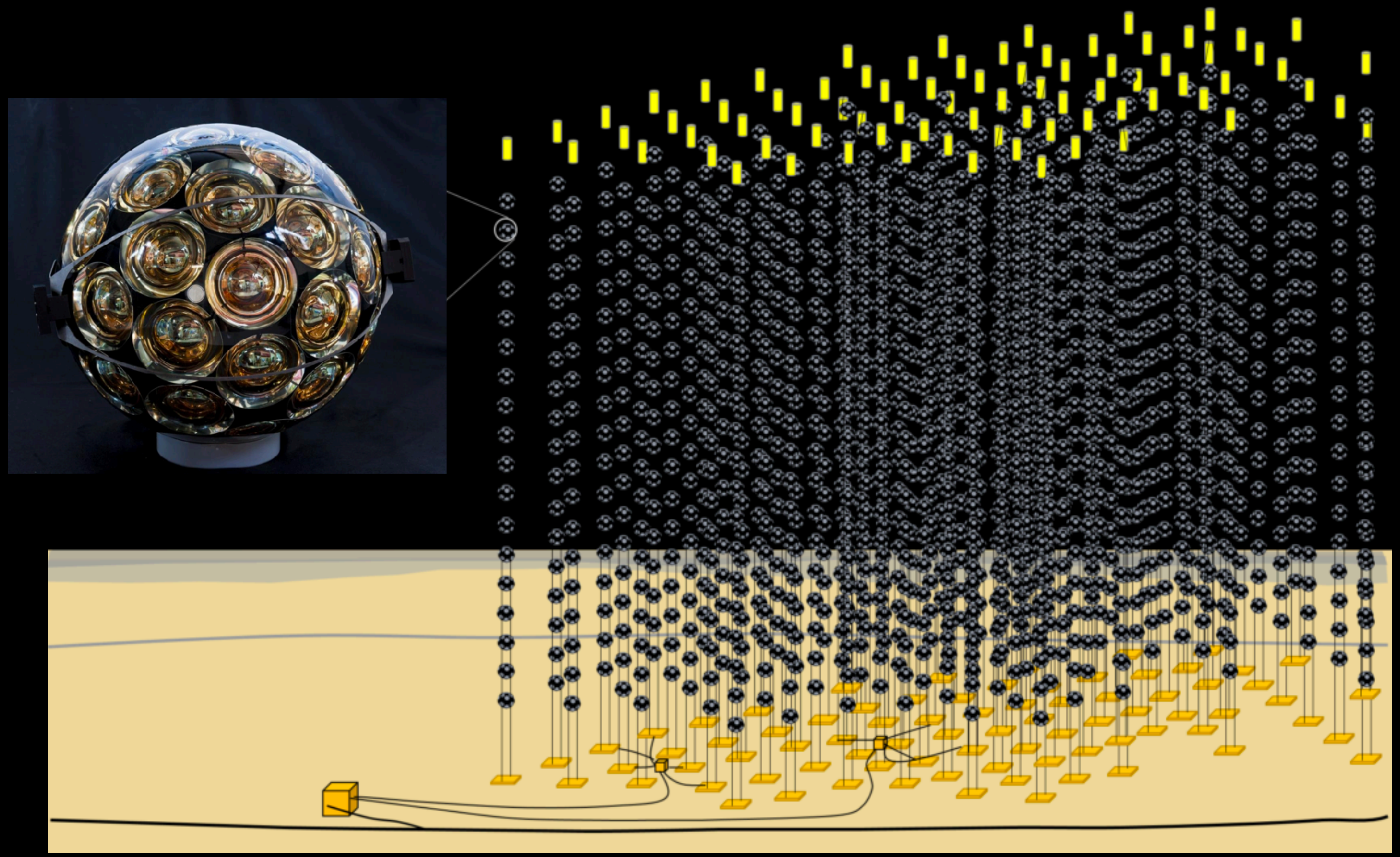
COMBINING NEUTRINO OBSERVATIONS

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



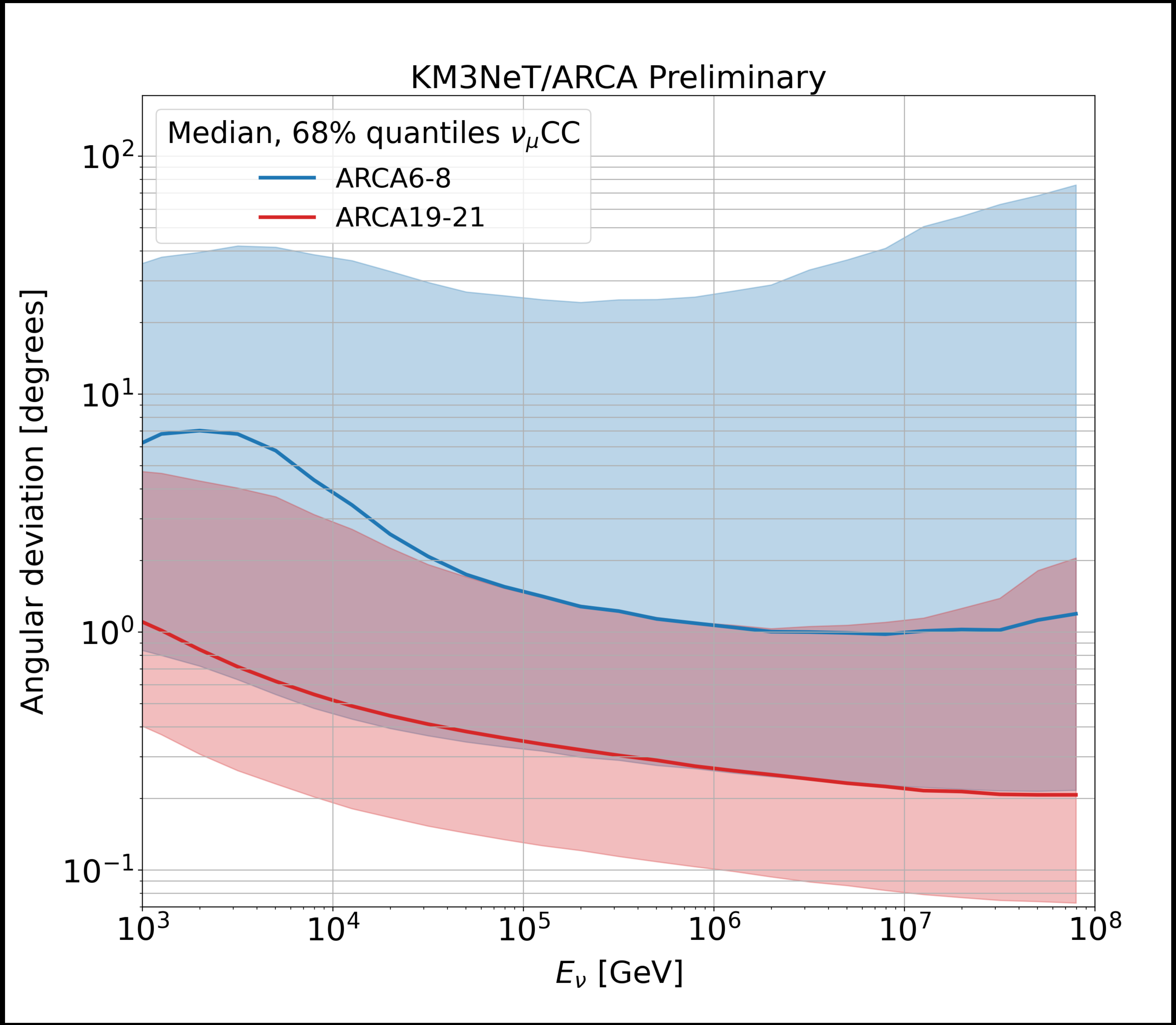
- Significant improvements by combining detectors at different latitudes and longitudes (background suppression).
- Acceptance and sky coverage for alerts increased by a factor of ~5.
- Additional telescopes looking to expand statistics at the highest energies (e.g RNO-G, TRINITY, BEACON, GRAND, TAMBO).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

ANGULAR RESOLUTION IMPROVEMENTS



- Chance probability of correlation goes with PSF^2
- **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.
- E.g.: See the VHE event in R. Coniglione's talk

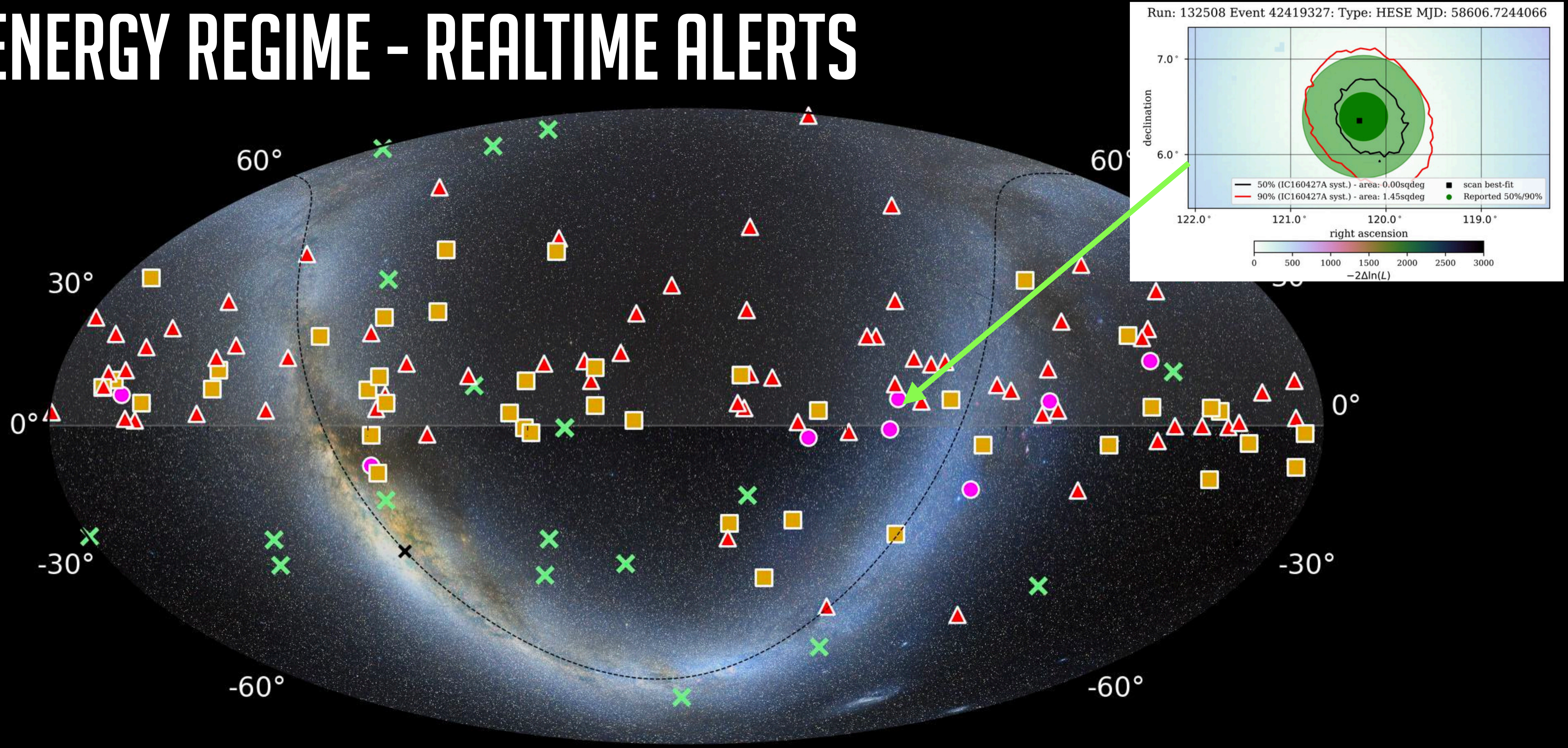
ANGULAR RESOLUTION IMPROVEMENTS



KM3NeT ICRC 2023 (Vol 444 1018)

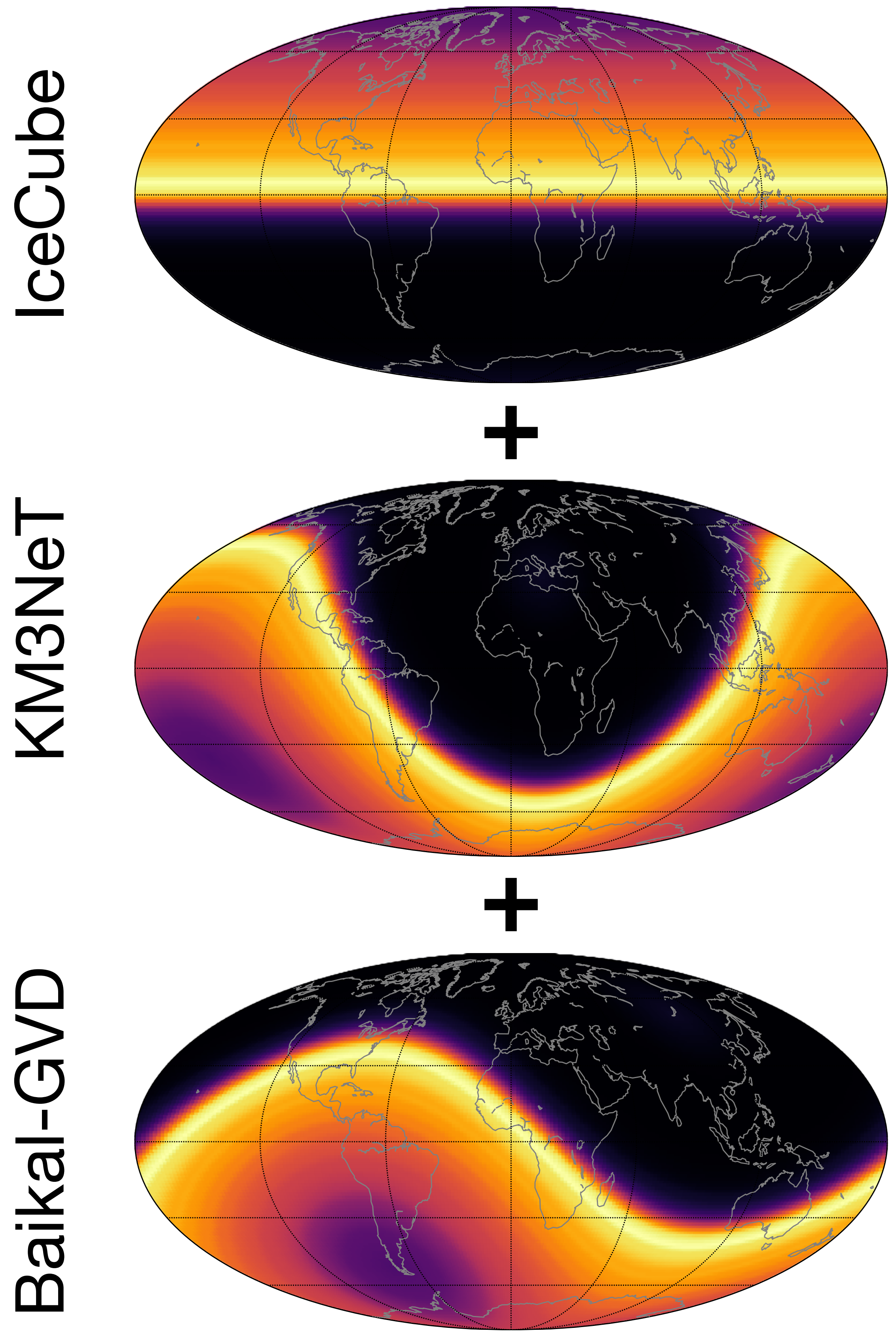
- Chance probability of correlation goes with PSF^2
- **Current generation instruments are expected to reach O(0.1°) angular resolution for tracks, 2° for cascades.**
- Enable sensitive searches of neutrino counterparts with EM instruments.
- E.g.: See the VHE event in R. Coniglione's talk

HIGH-ENERGY REGIME - REALTIME ALERTS



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

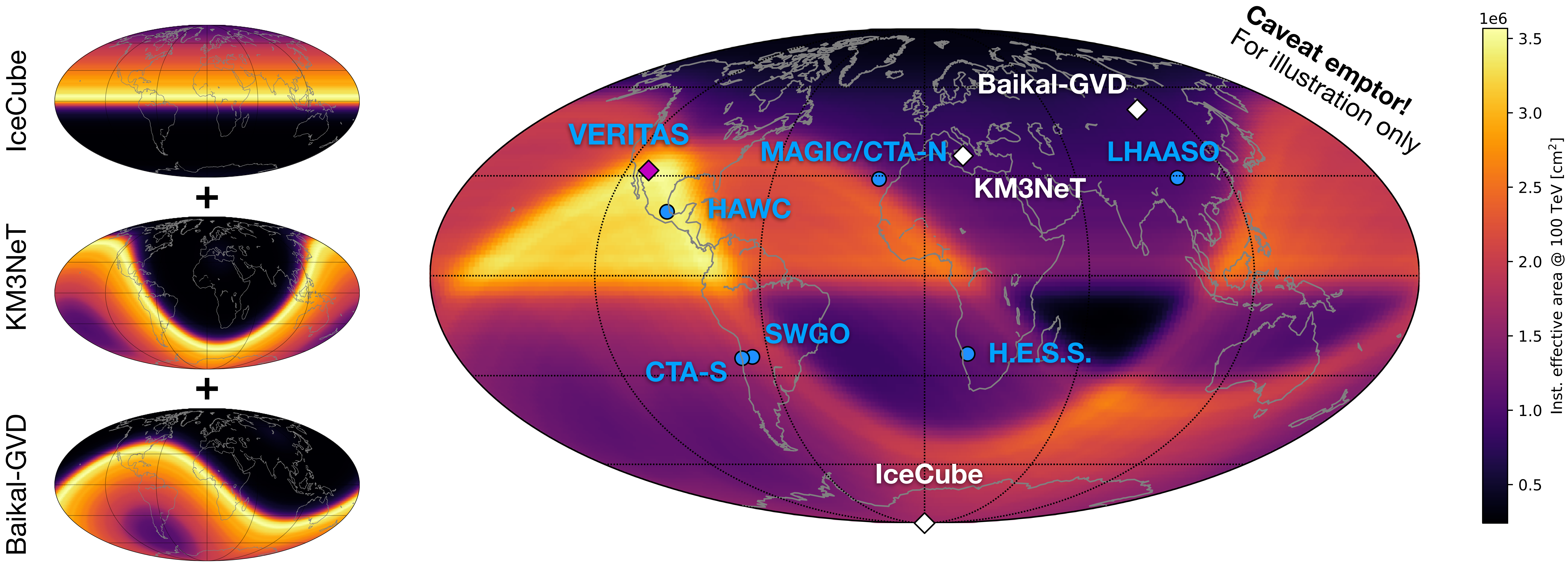
INSTANTANEOUS SENSITIVITIES FOR GROUND-BASED INSTRUMENTS



Caveat emptor!
For illustration only

- 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).
- For fast transients, some locations are better than others in terms of visibility!

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).
- For fast transients, some locations are better than others in terms of visibility!

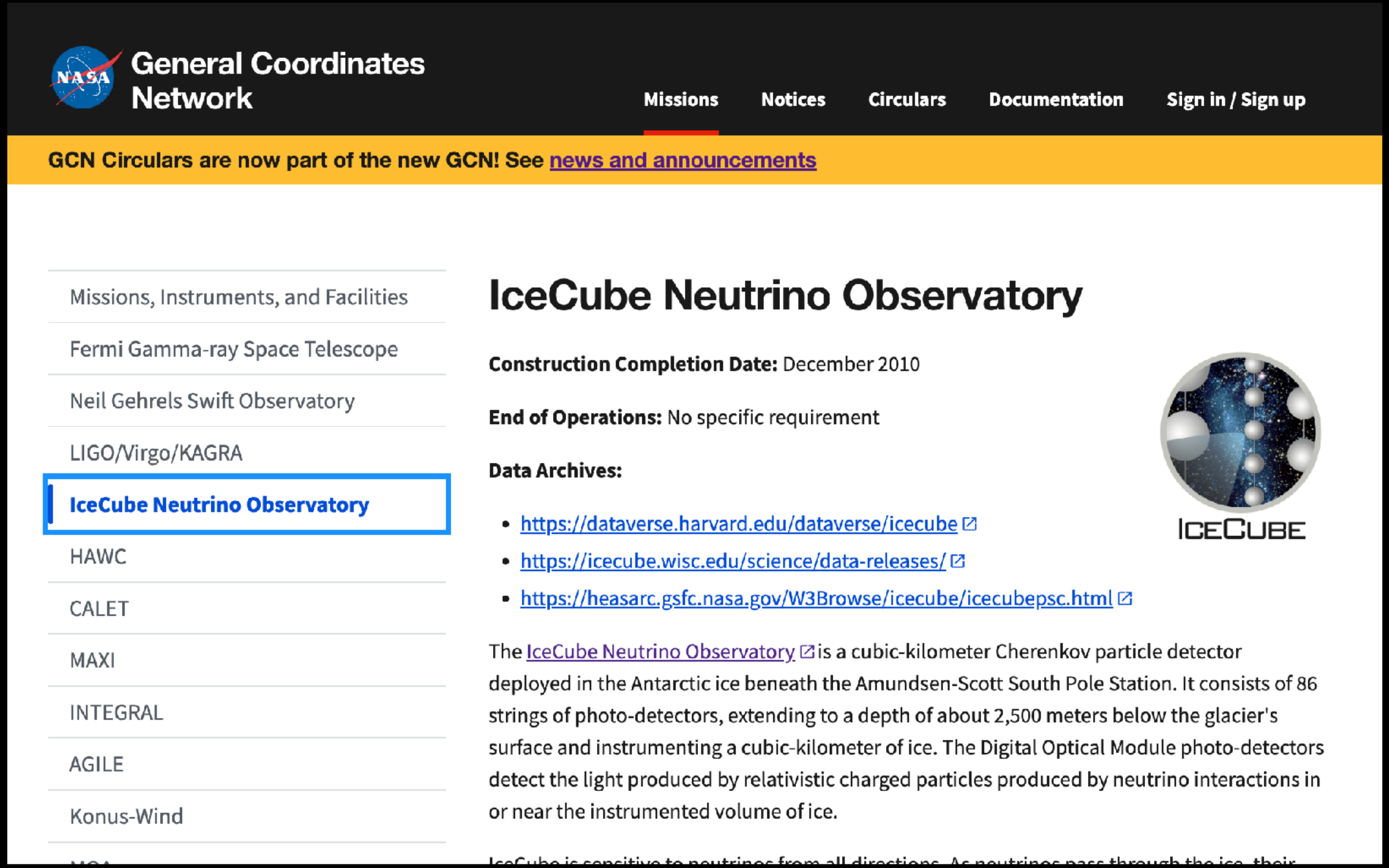
FULLY INTEGRATING NEUTRINO TELESCOPES INTO TDAMM

- 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.

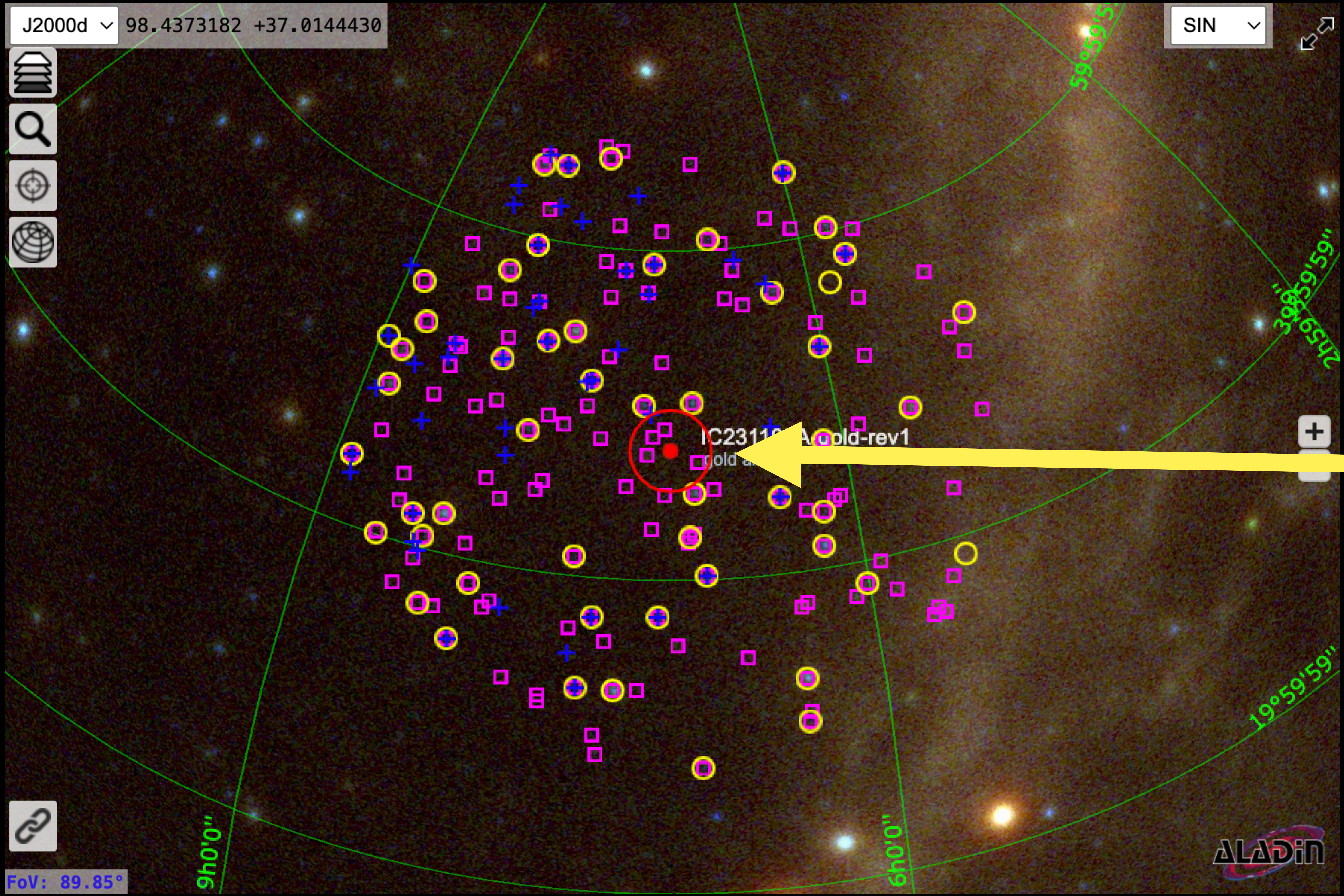
  - Most searches for transient/variable sources should be done in realtime if possible. Neutrino telescopes already working in that direction.

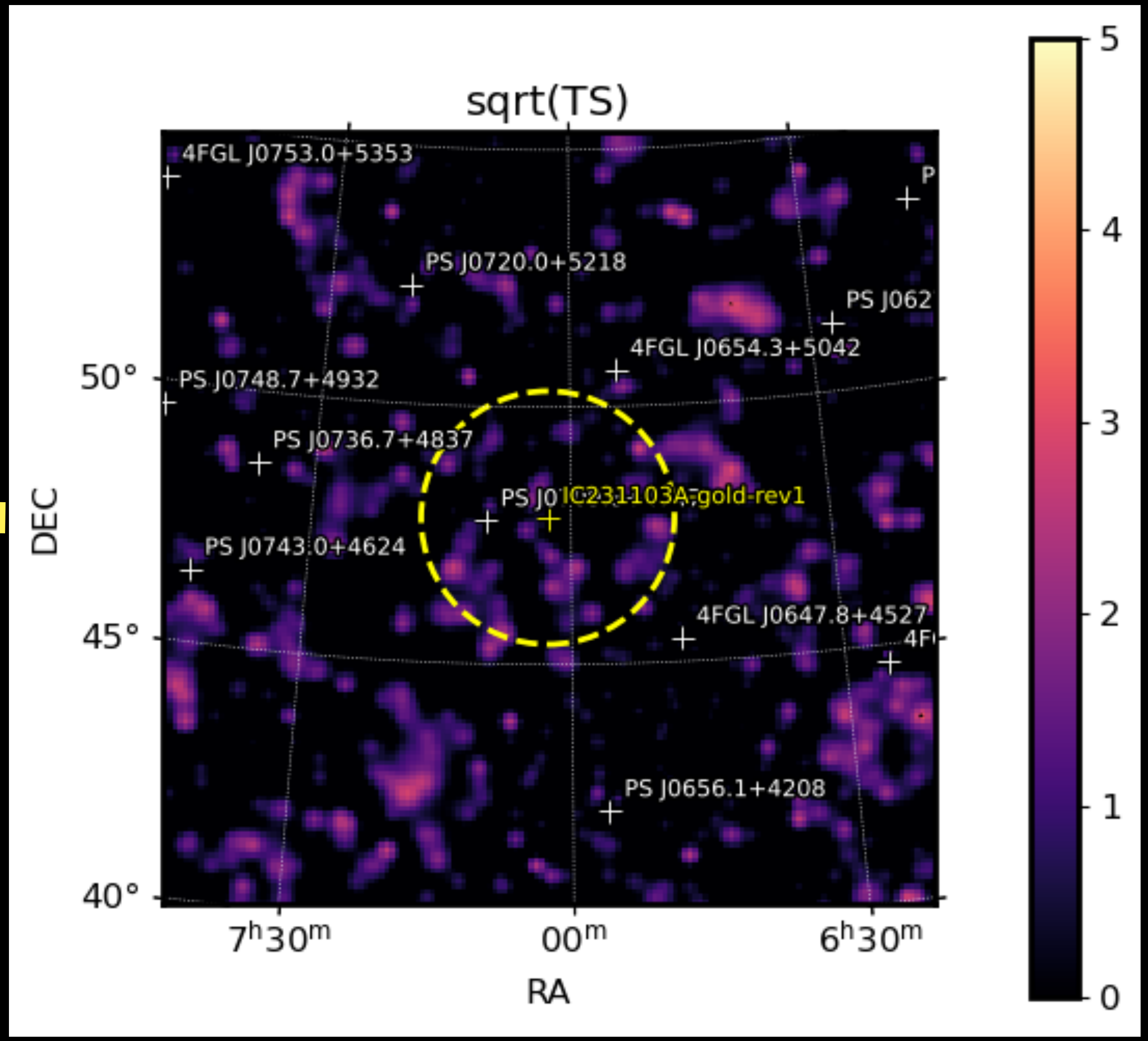
  - EM searches for counterparts should algo go in this direction



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

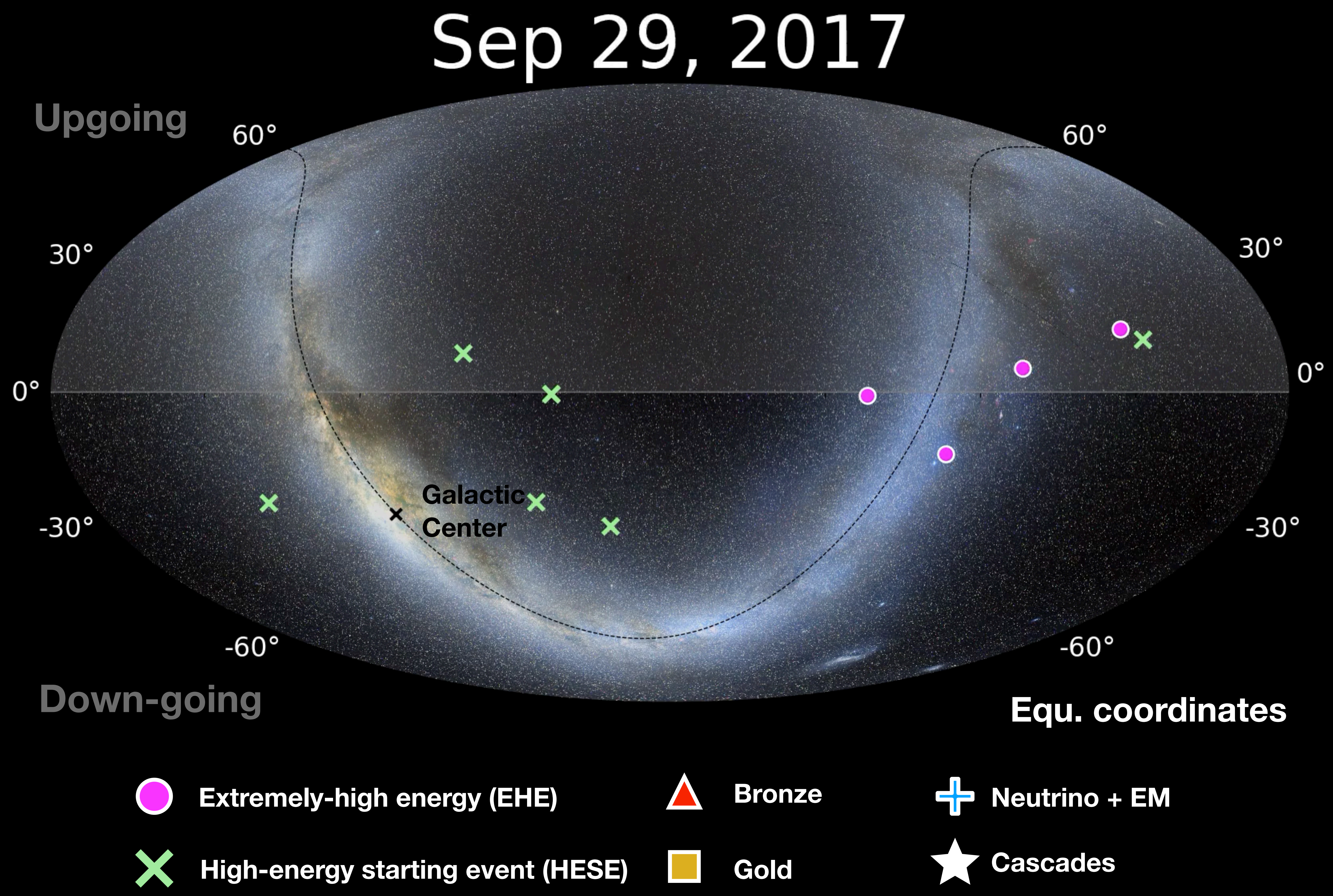
AN EXAMPLE WITH FERMI-LAT



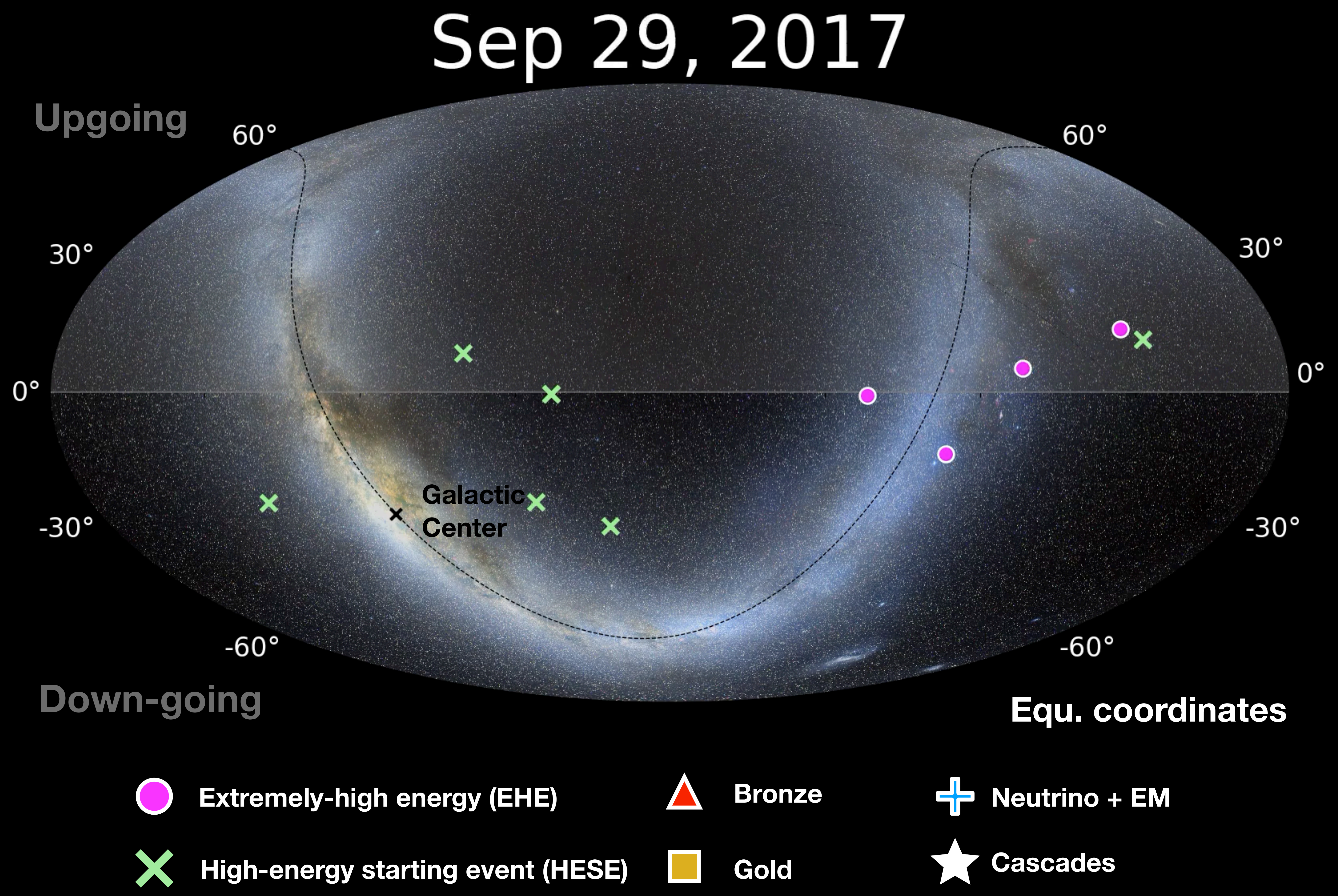


- https://multimessenger.ua.edu/fermi/ (Under development)

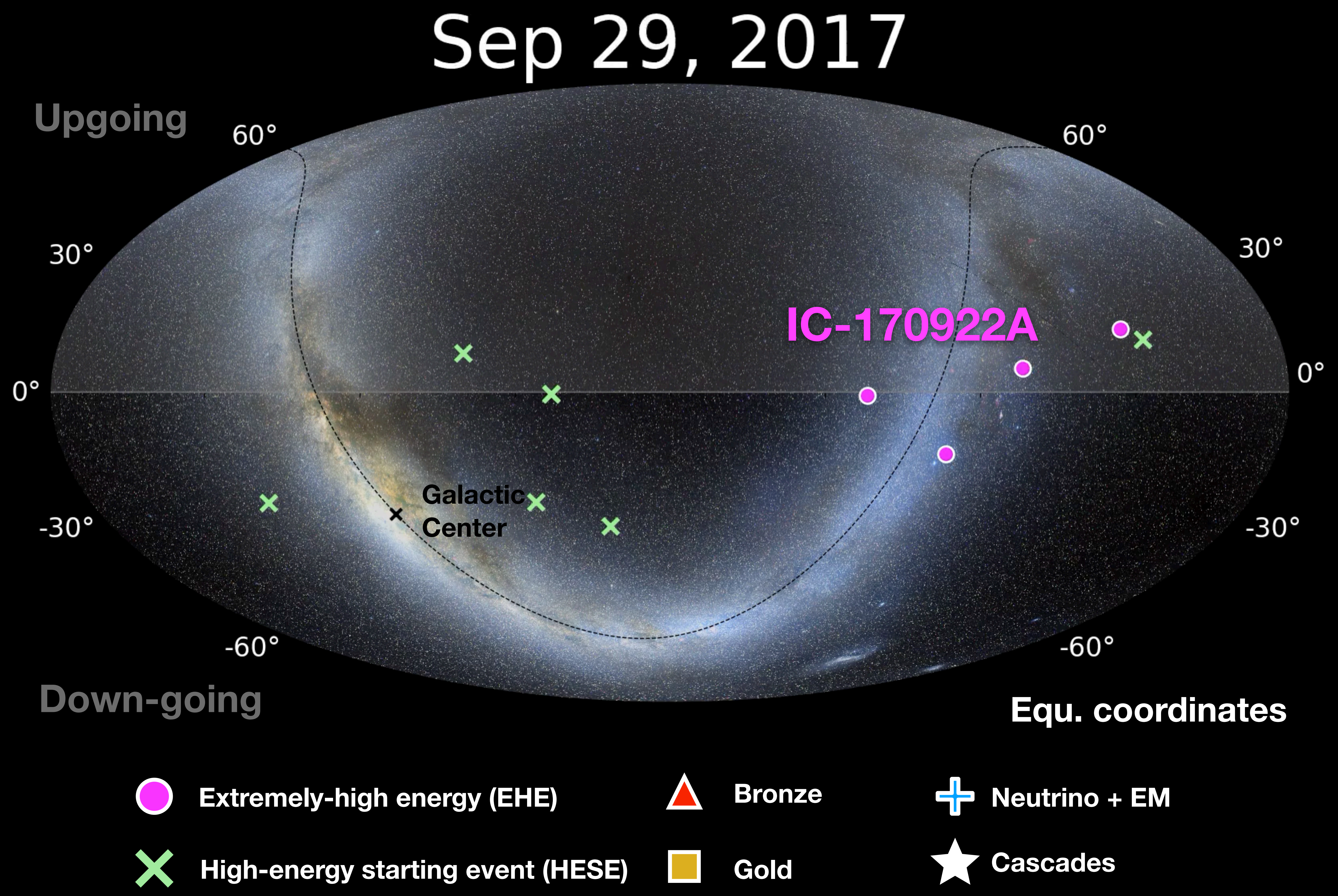
REALTIME NEUTRINO ALERTS



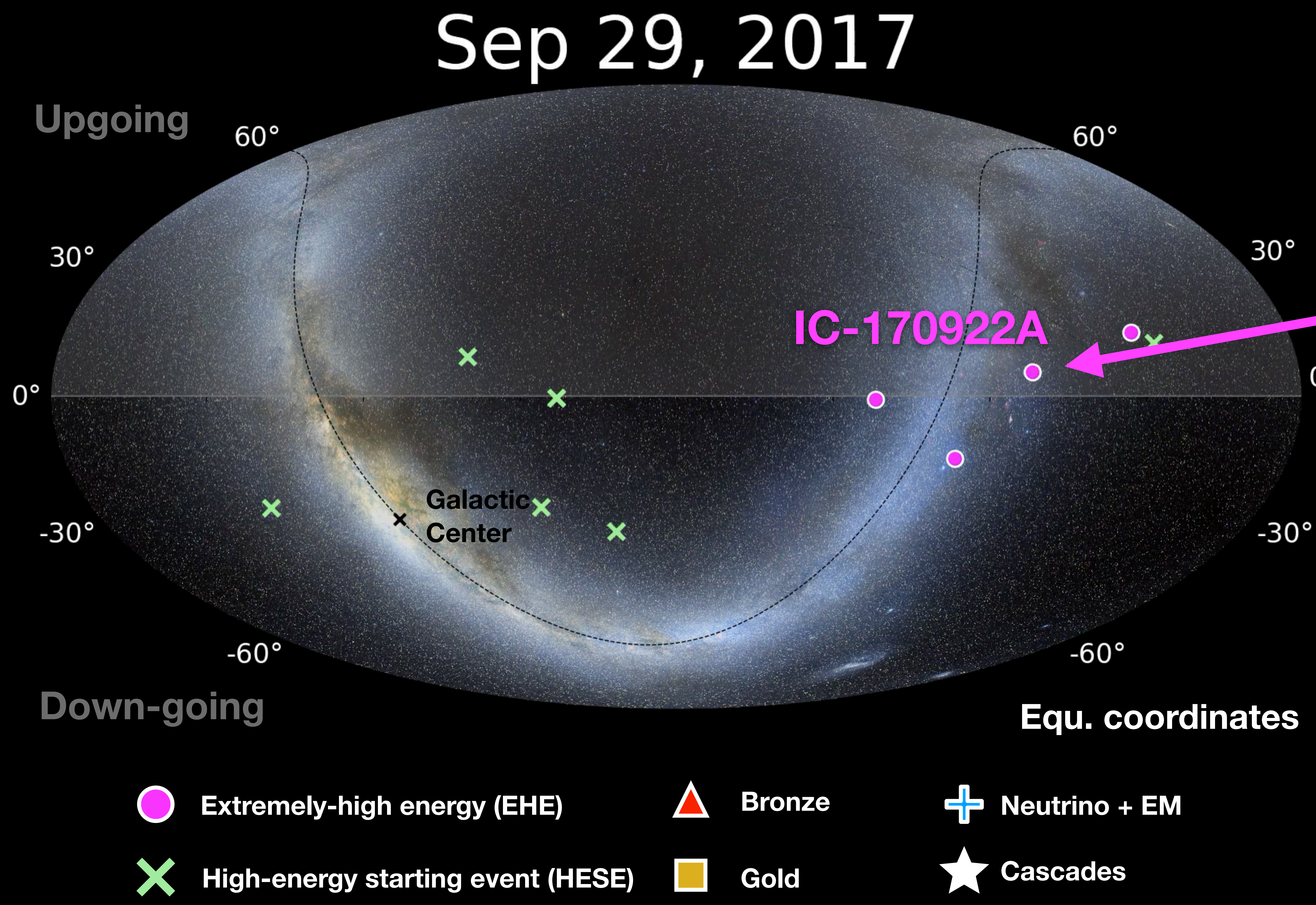
REALTIME NEUTRINO ALERTS

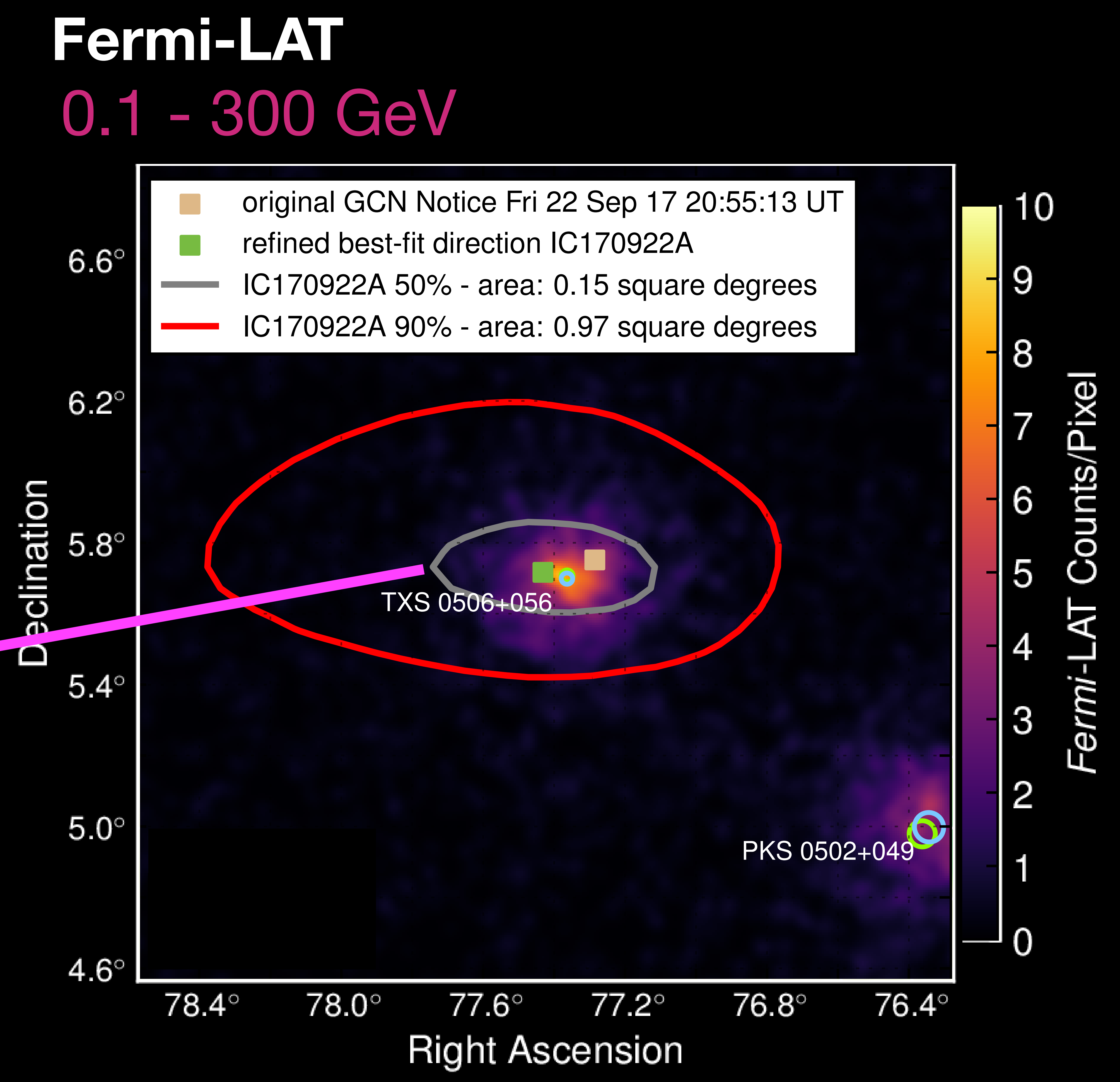


REALTIME NEUTRINO ALERTS

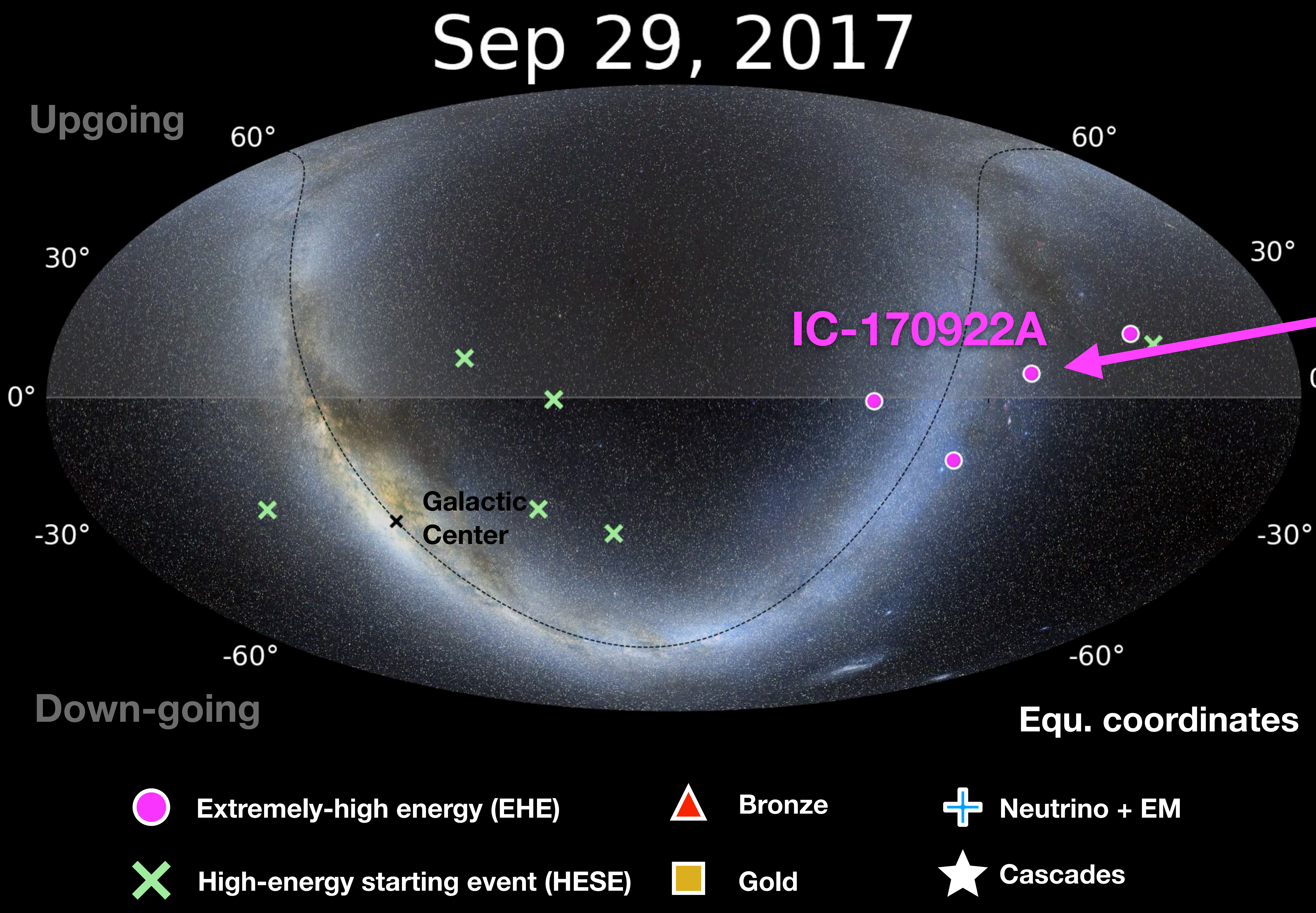


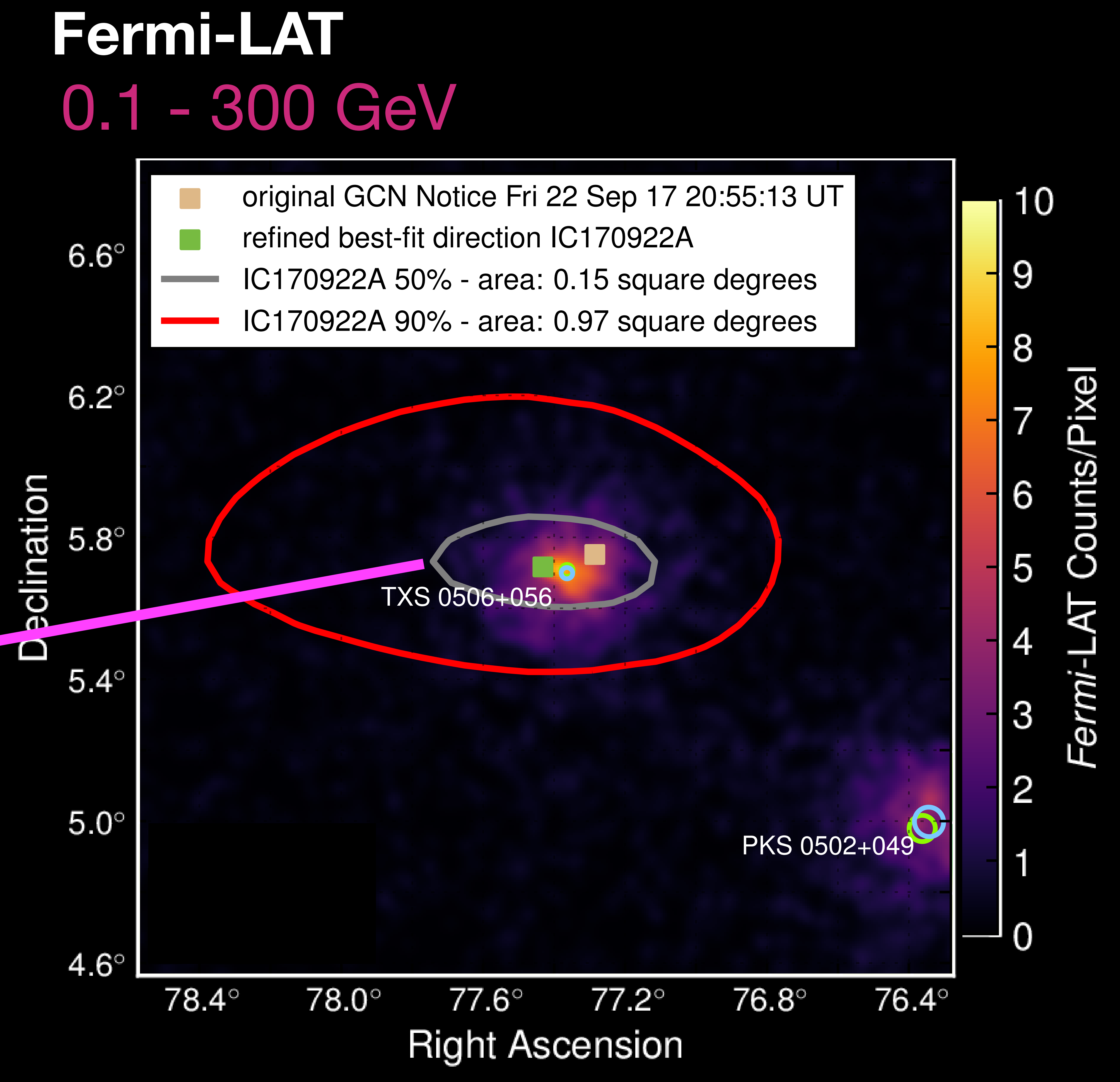
REALTIME NEUTRINO ALERTS





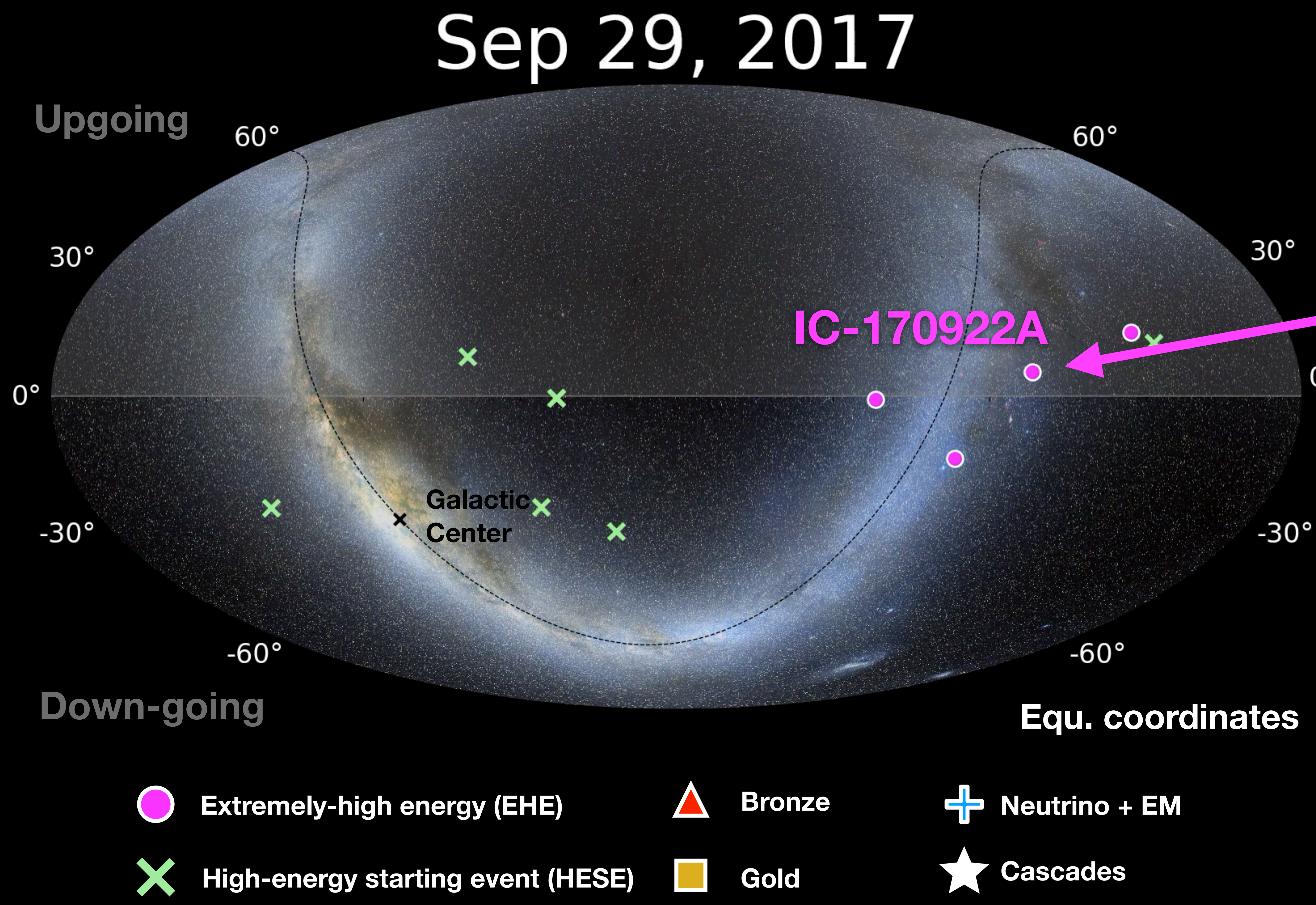
REALTIME NEUTRINO ALERTS

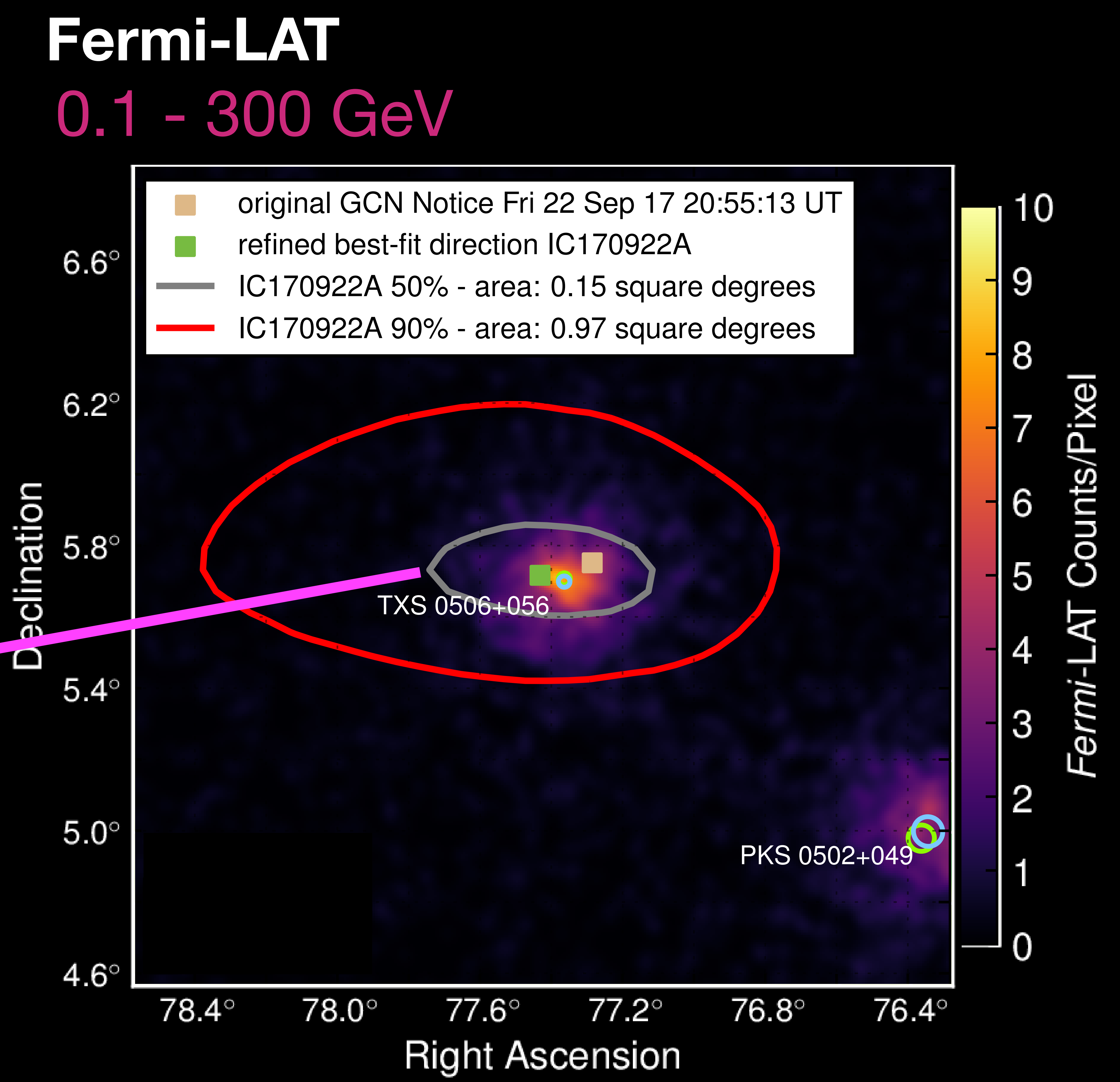




- IceCube-170922A: 290 TeV neutrino energy

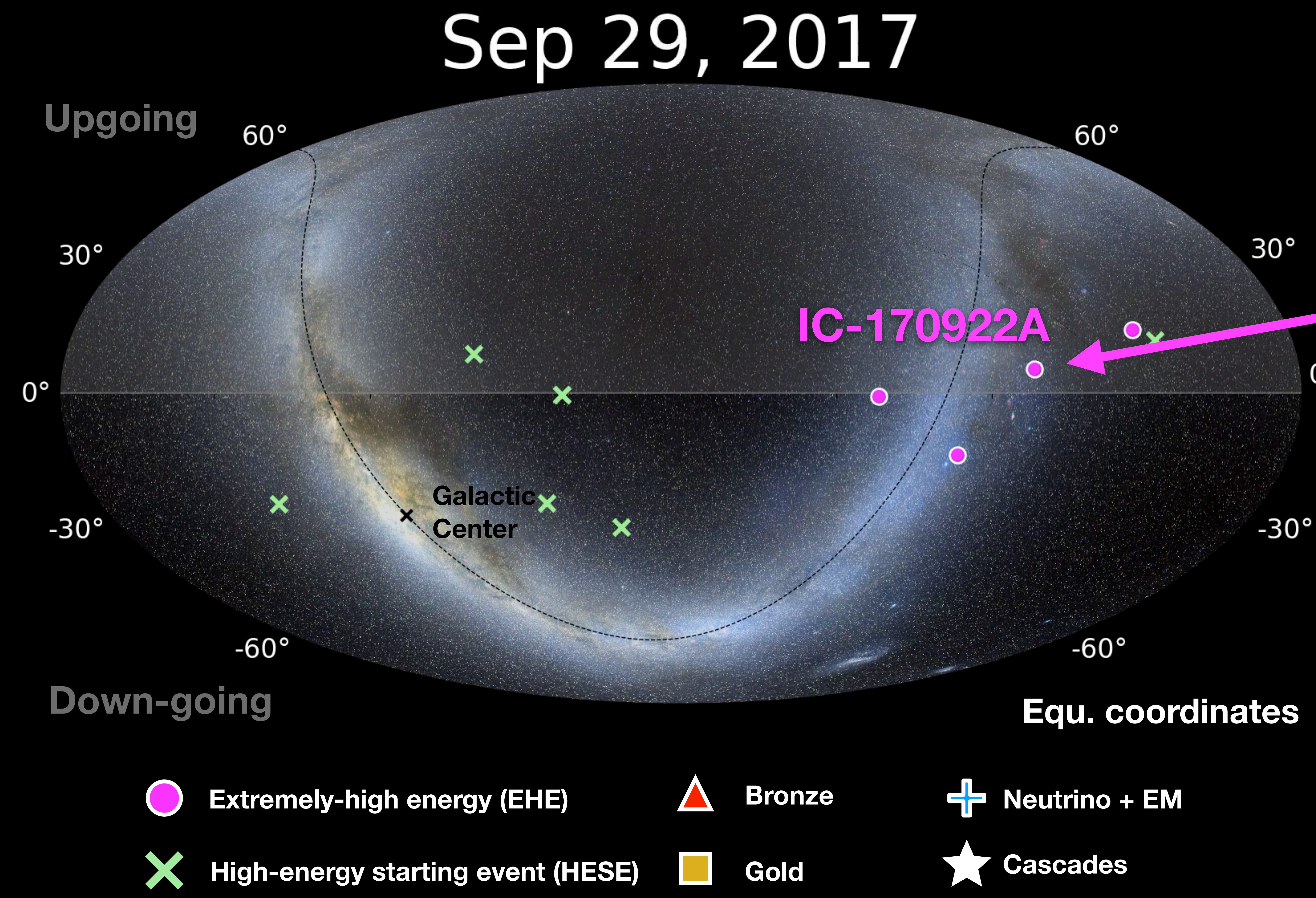
REALTIME NEUTRINO ALERTS



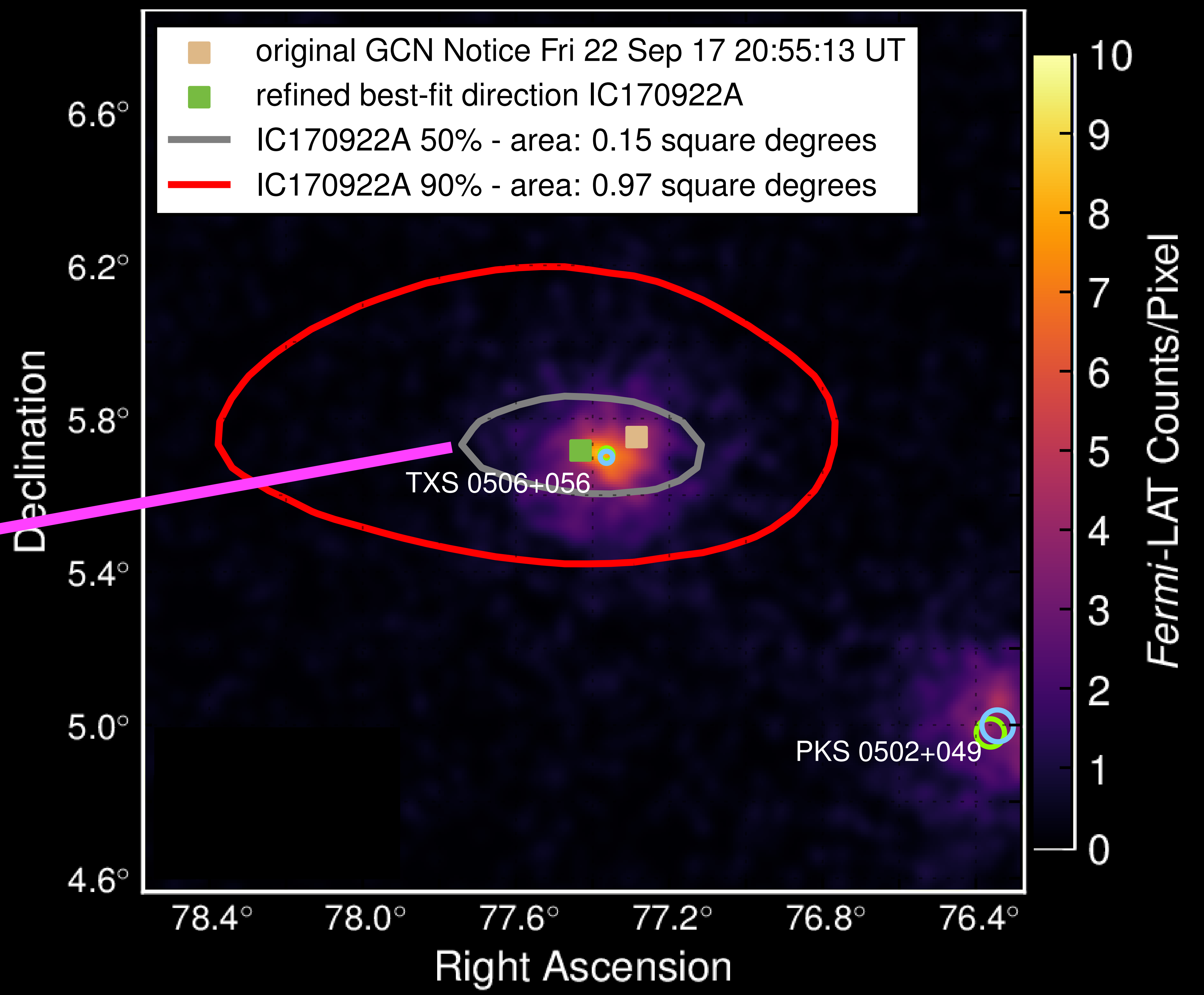


- IceCube-170922A: 290 TeV neutrino energy
- Correlated with flaring, hard-spectrum gamma-ray blazar **TXS 0506+056** (3σ). Additional neutrino emission in 2014-2015.

REALTIME NEUTRINO ALERTS

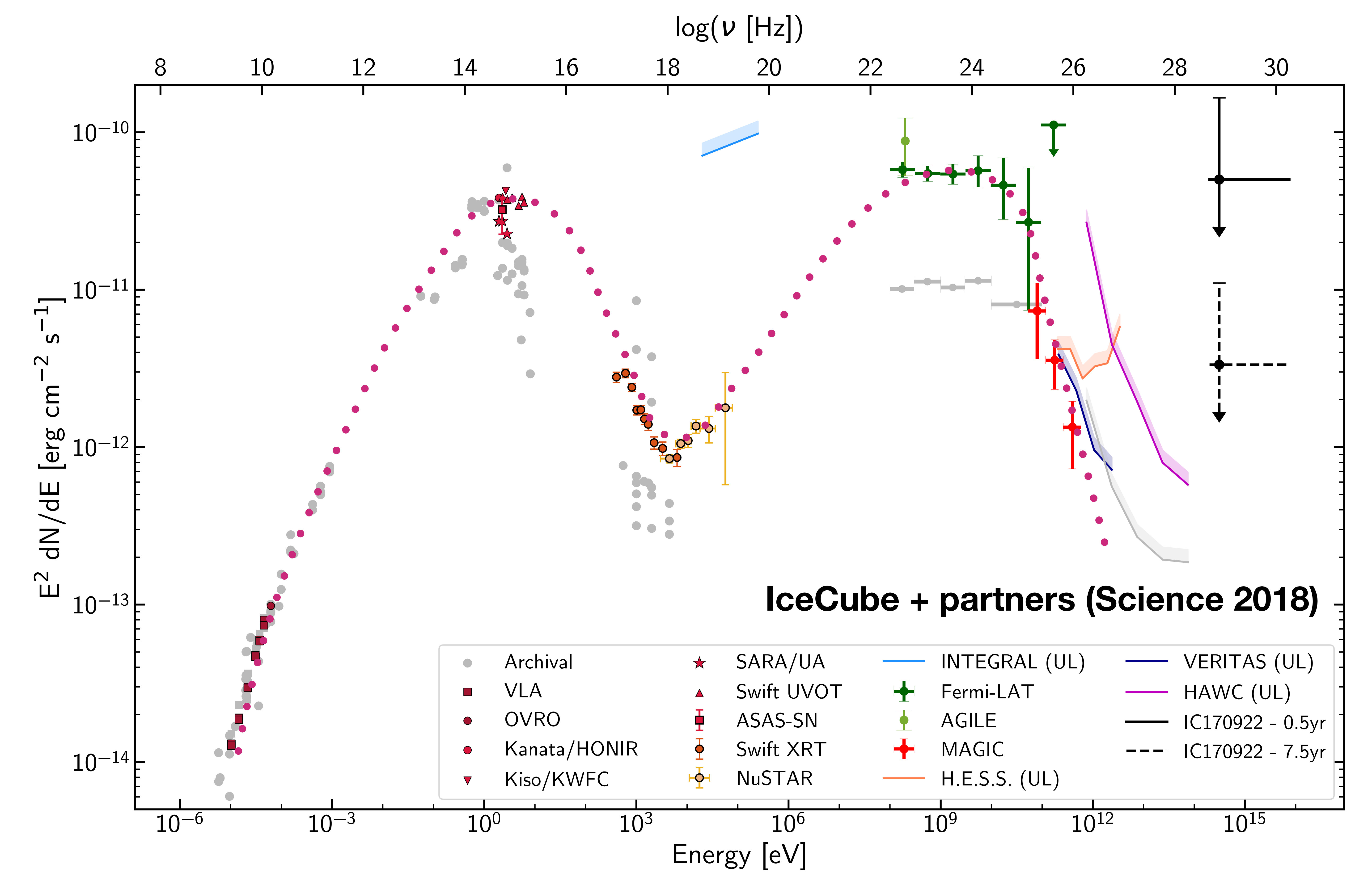


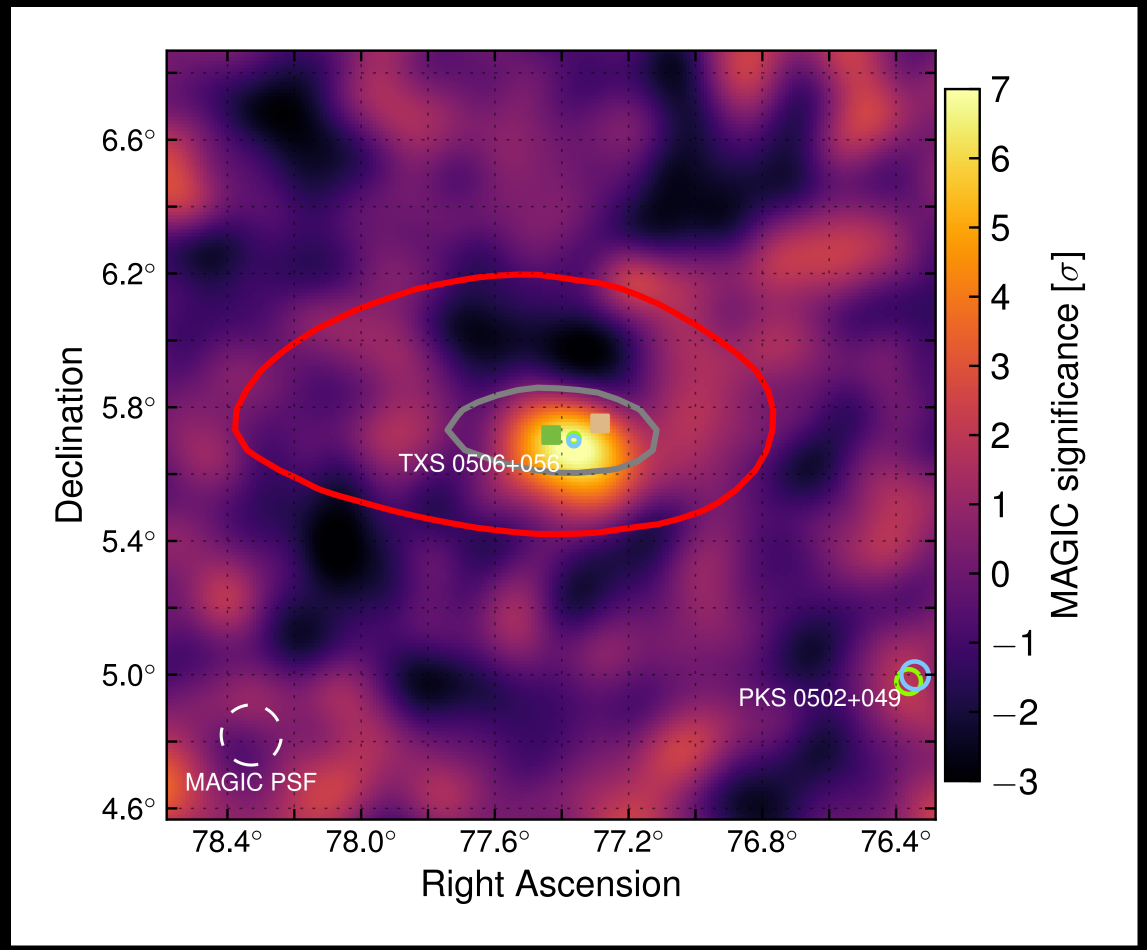
Fermi-LAT
0.1 - 300 GeV



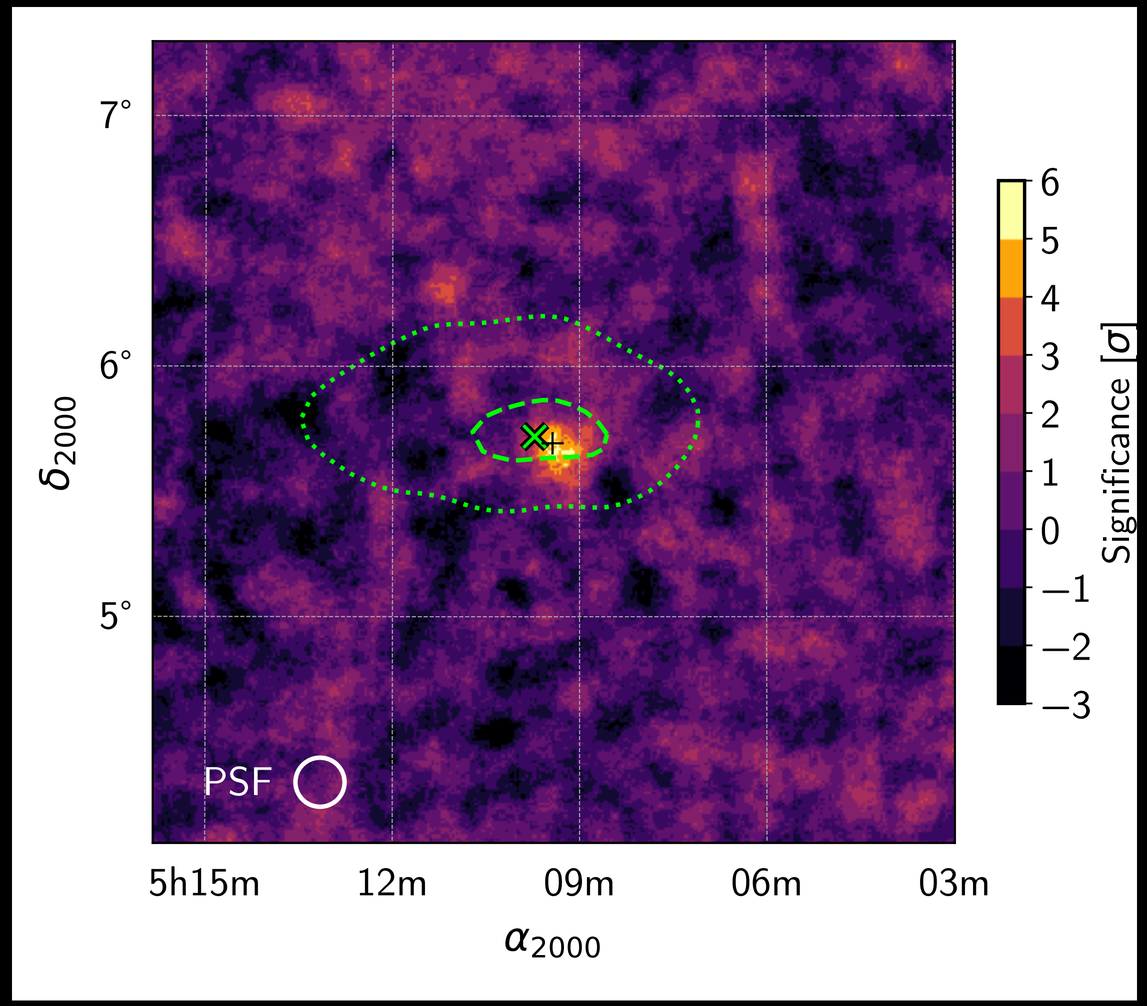
- IceCube-170922A: 290 TeV neutrino energy
- Correlated with flaring, hard-spectrum gamma-ray blazar **TXS 0506+056** (3σ). Additional neutrino emission in 2014-2015.
- **Efforts to start realtime programs in KM3NeT, Baikal-GVD are underway.**

PHOTONS FROM TXS 0506+056





MAGIC (ApJL 2018)

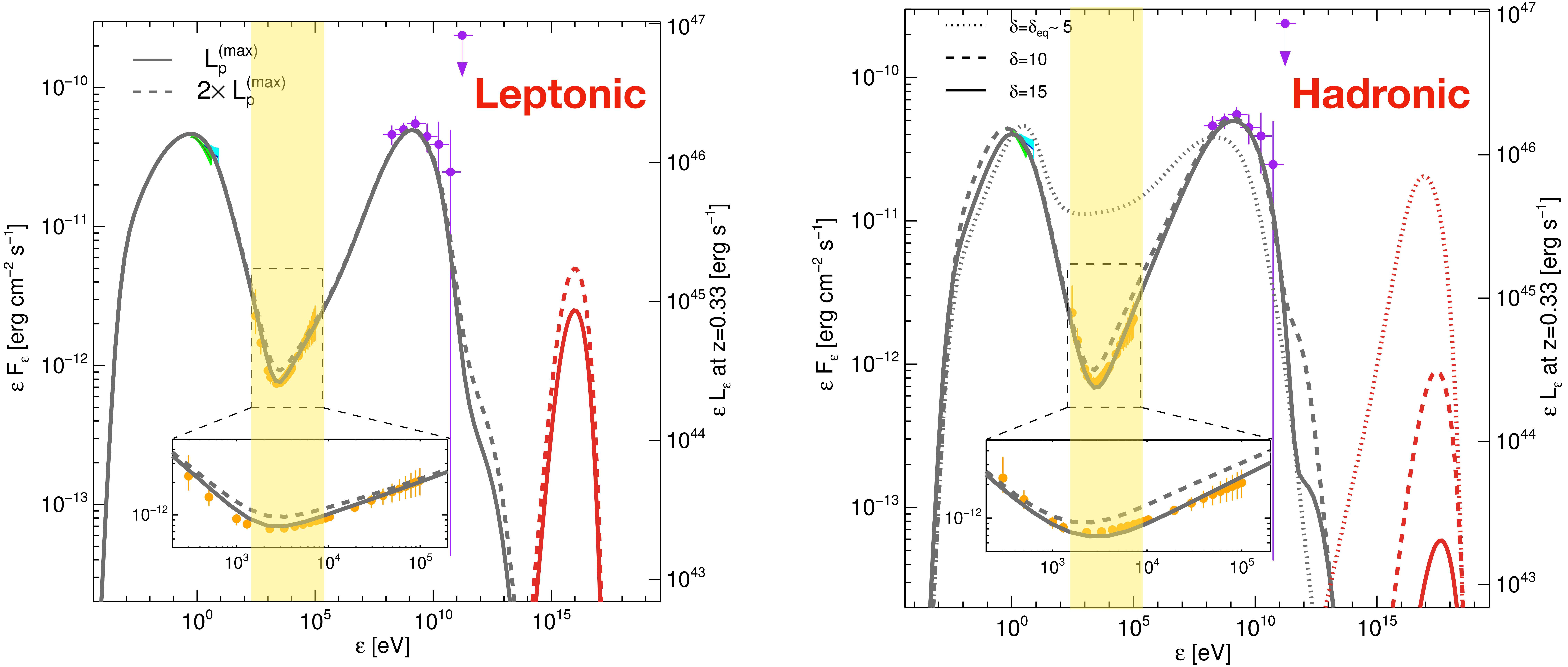


VERITAS (ApJL 2018)

- 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.**

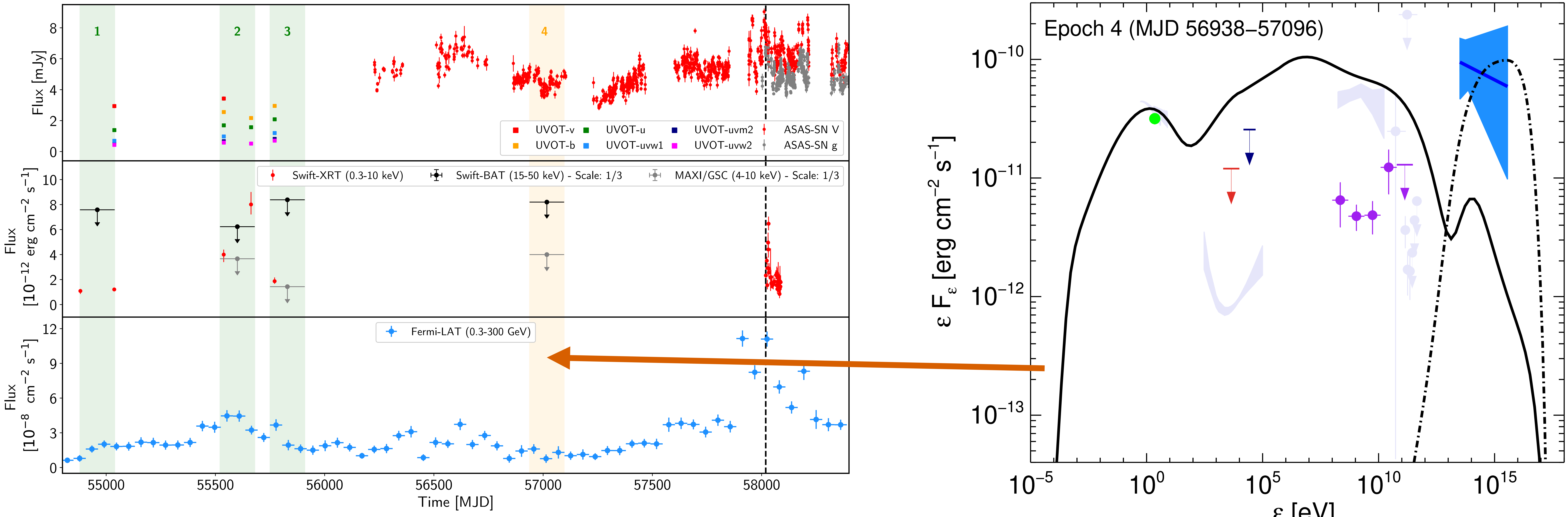
MODELING THE 2017 NEUTRINO EMISSION

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*

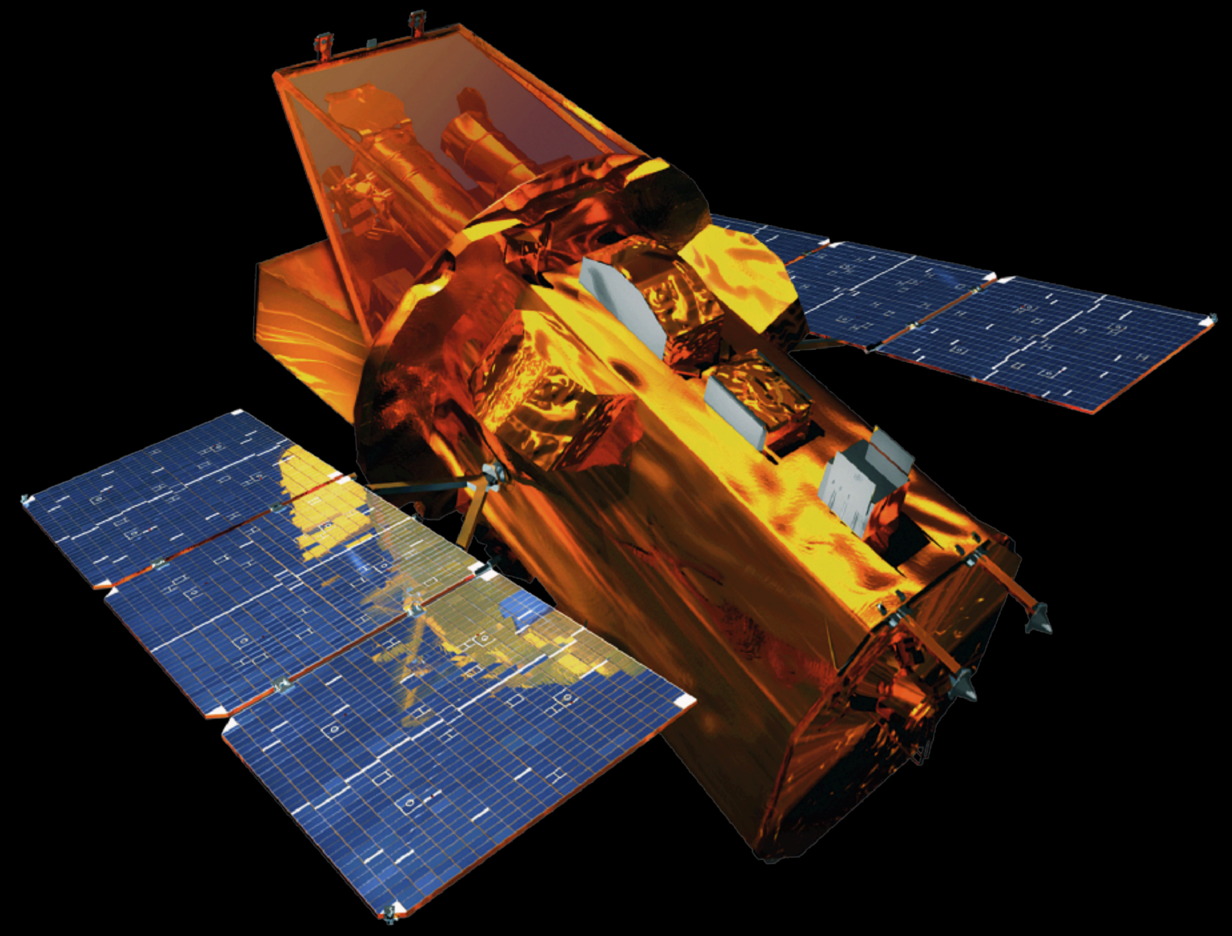
THE NEXT DECADES FOR FOLLOW-UP INSTRUMENTS

- 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: 15% ToO then: 40% ToO
MXT	0.2−10 keV	2×10^{-12} erg cm^{-2} s^{-1} in 3000 s	1 deg^2	13"			
VT	0.4−1 μm	22.5 mag in 300 s	0.2 deg^2	< 1"			
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	?

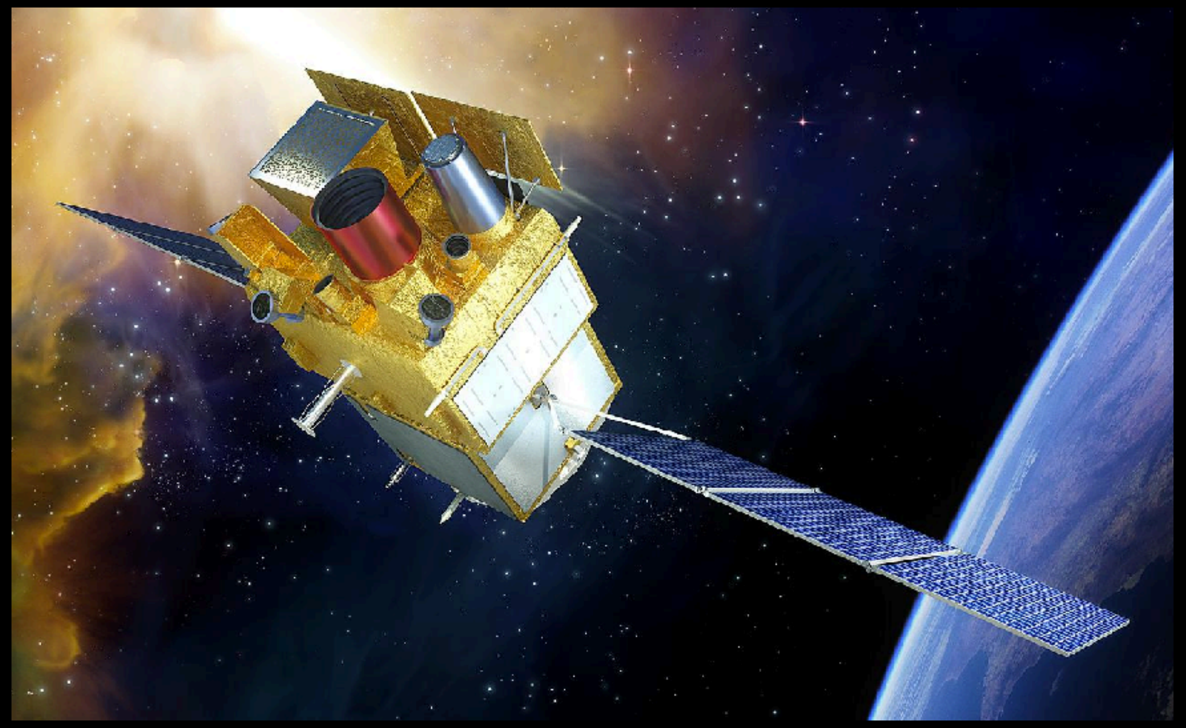
X-RAY COVERAGE

Neil Gehrels *Swift* Observatory



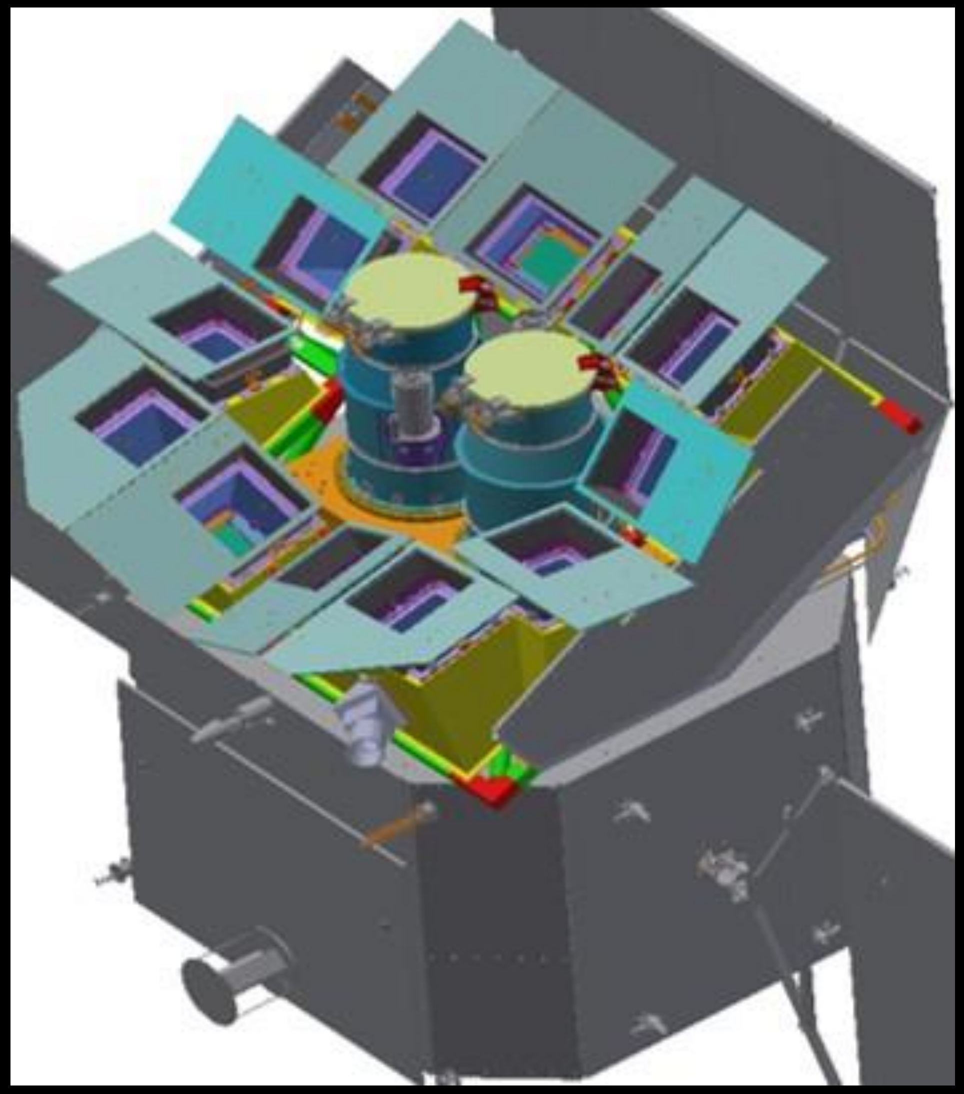
XRT sensitivity in the 0.3-10 keV
Fast response, low overhead.
110 cm^2
~0.4 deg FoV. Launched in 2004.

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)

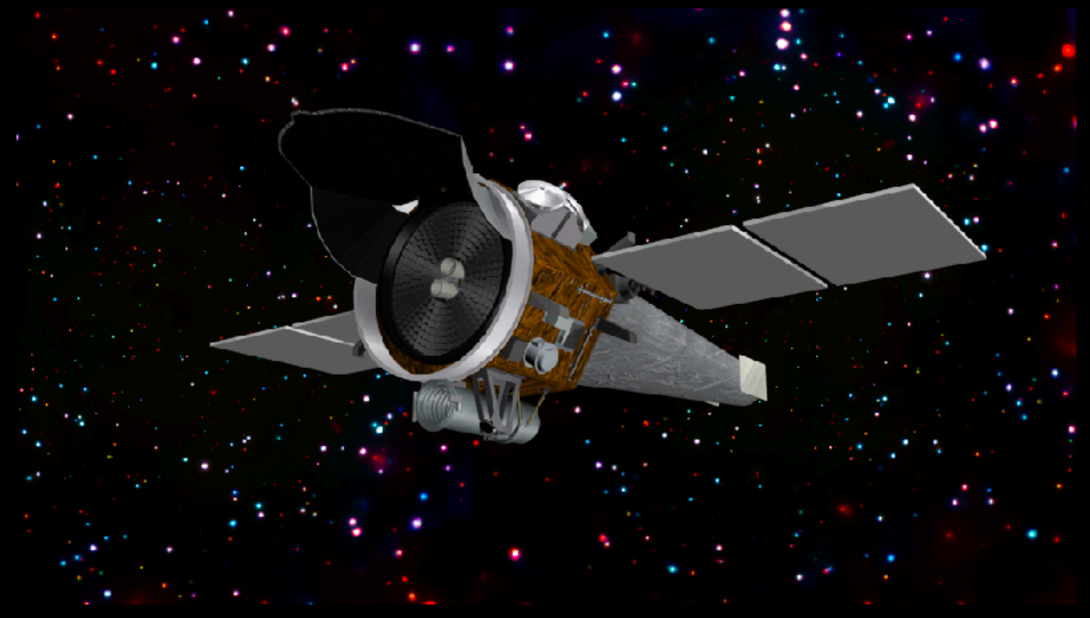


Launched January 2024

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’

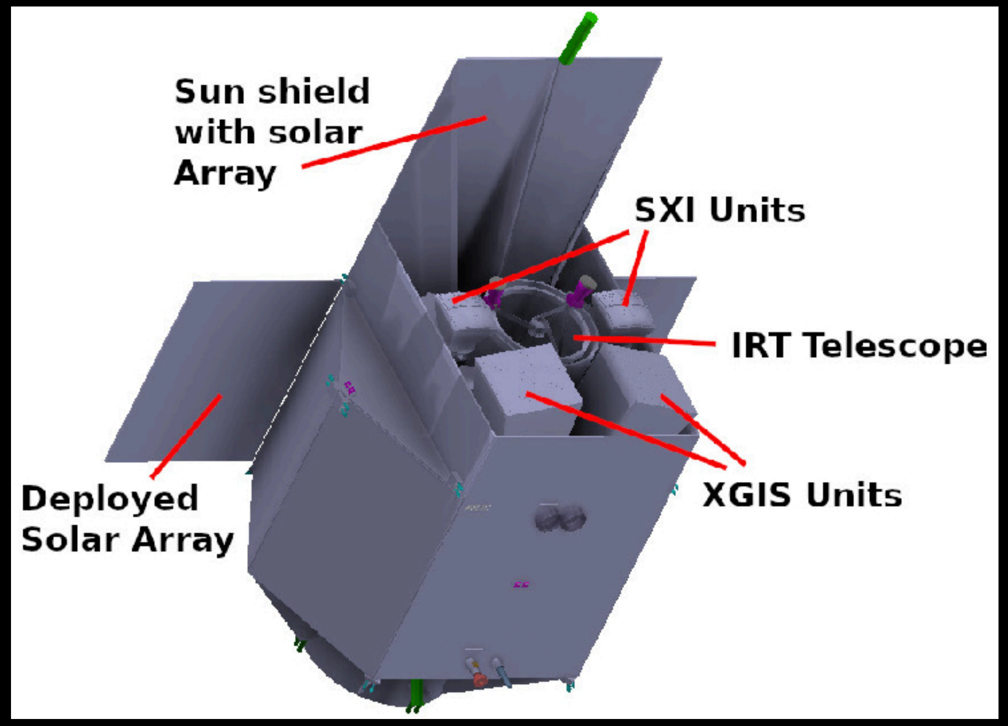
Wolter-1 type + CCD
FoV: 38’
band: 0.3-10keV
eff. area: 2x 300cm^2 @1keV
angular FWHM: 30”

STAR-X (NASA)



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

THESEUS (ESA)

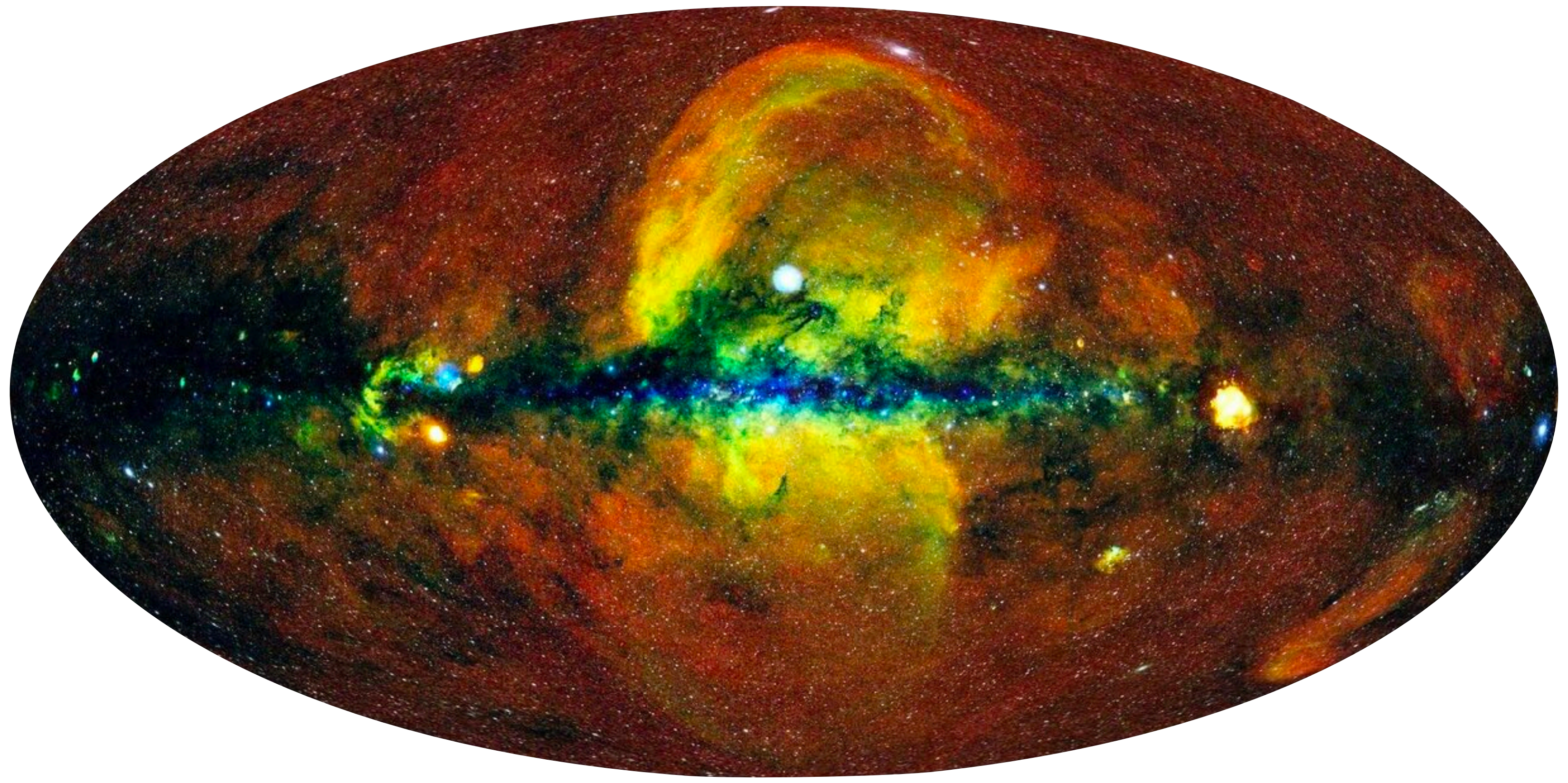


Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2’

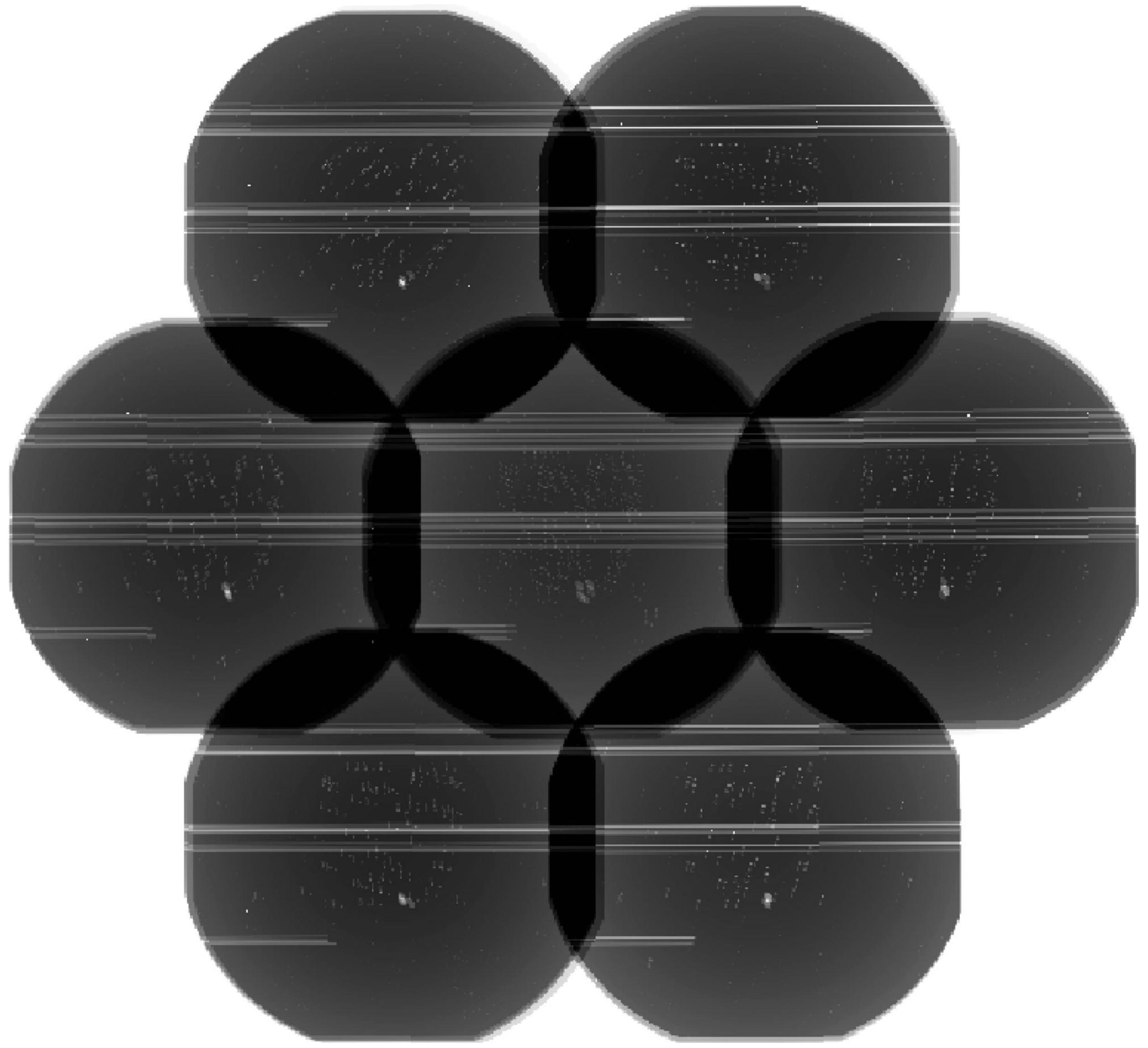
XGIS: 2 keV - 10 MeV with FoV >2 sr with < 15’ GRB localization

Not selected as of 2023. Resubmission planned.

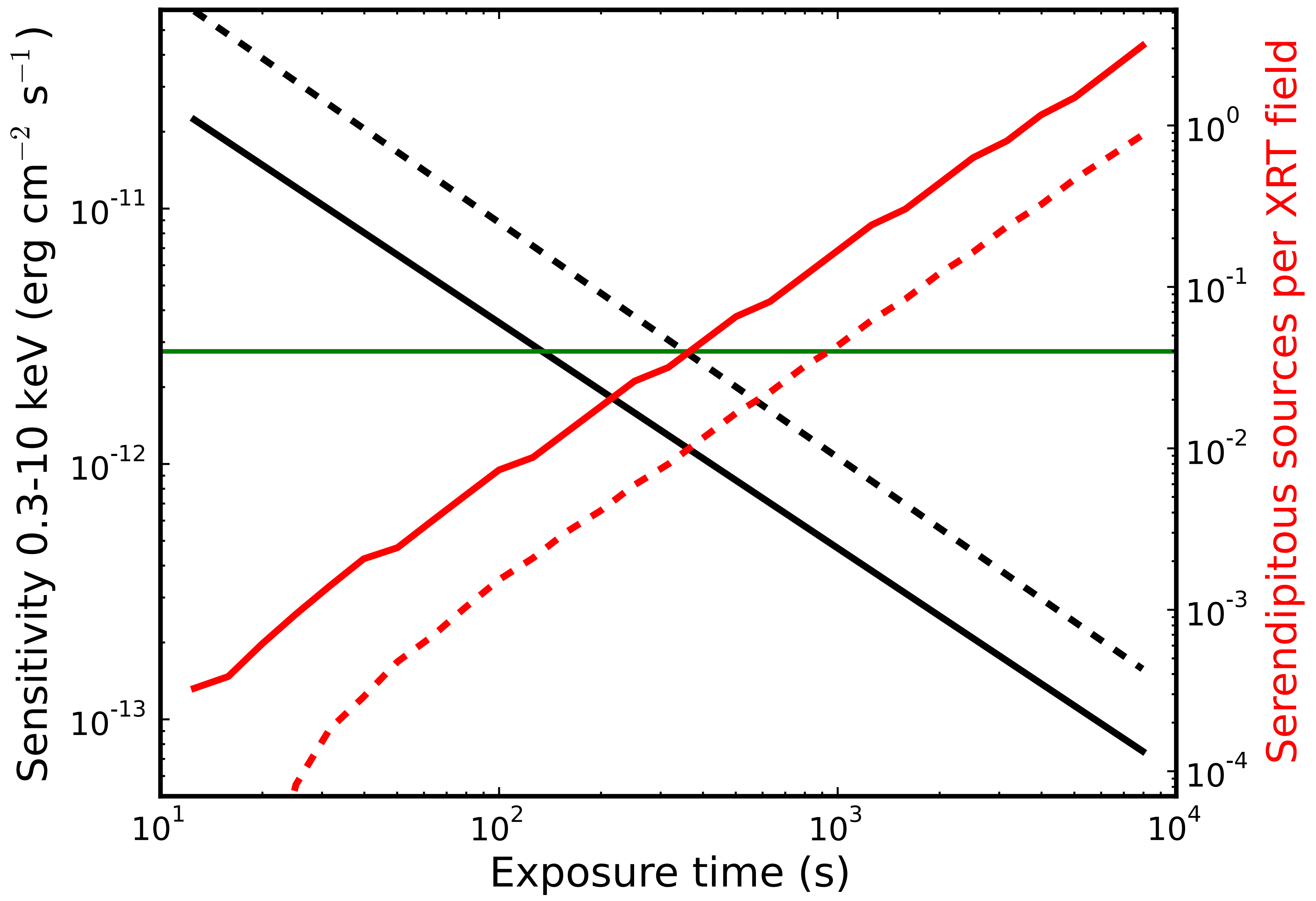
NEUTRINO-EM SOURCE ASSOCIATIONS IN THE NEXT DECADE



- 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.**



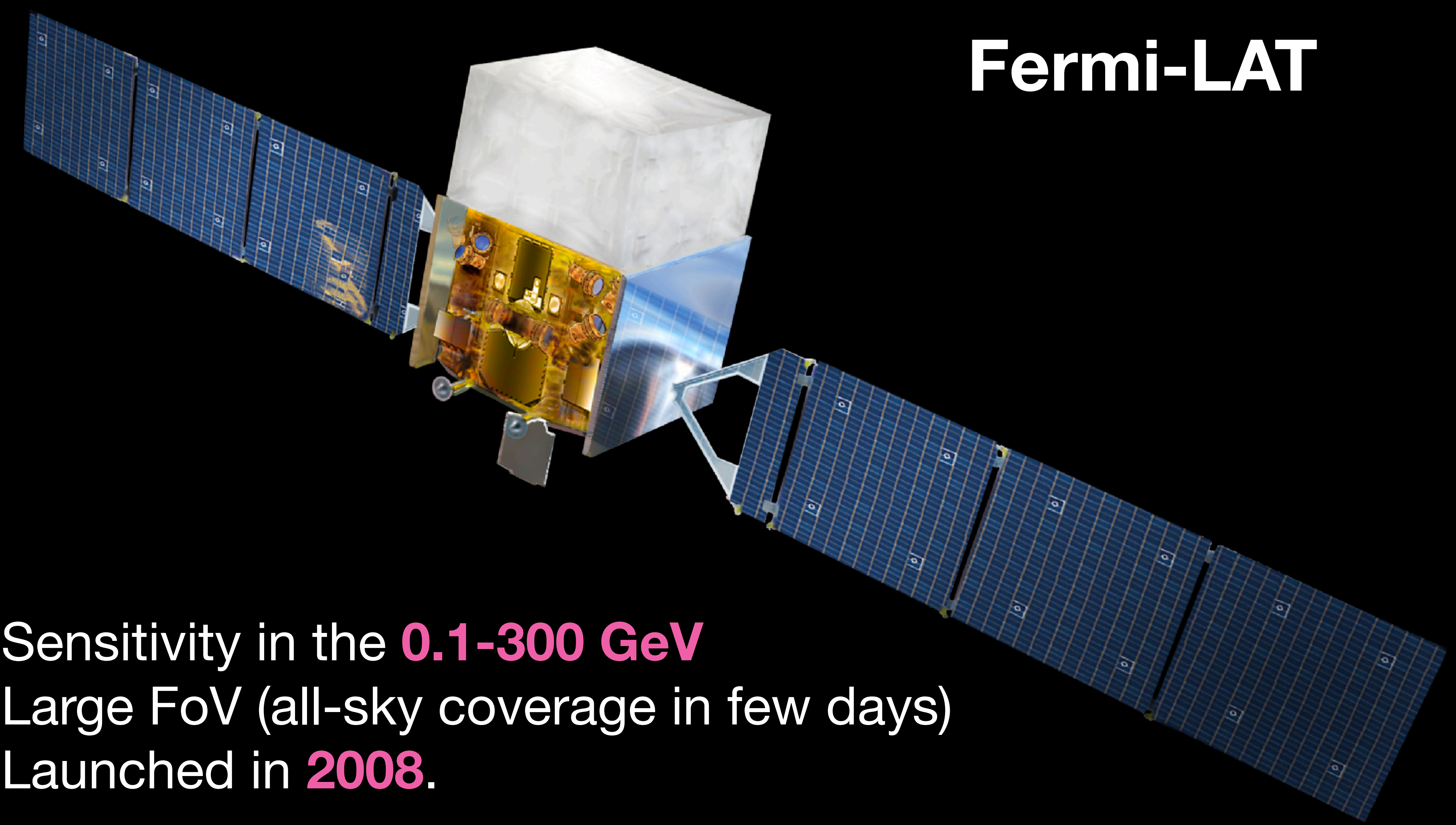
Swift tiling of neutrino position



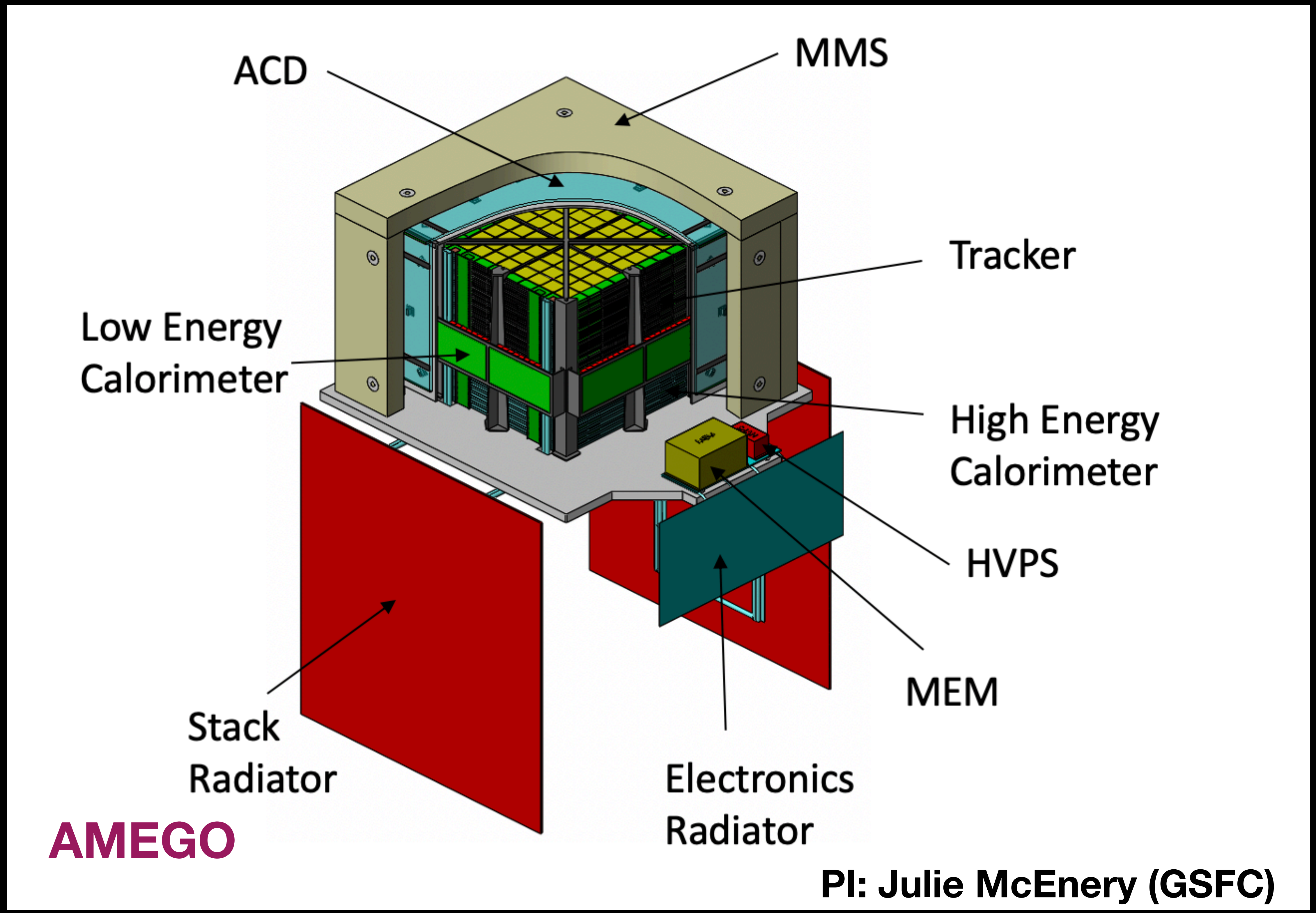
Swift follow-up of neutrino events

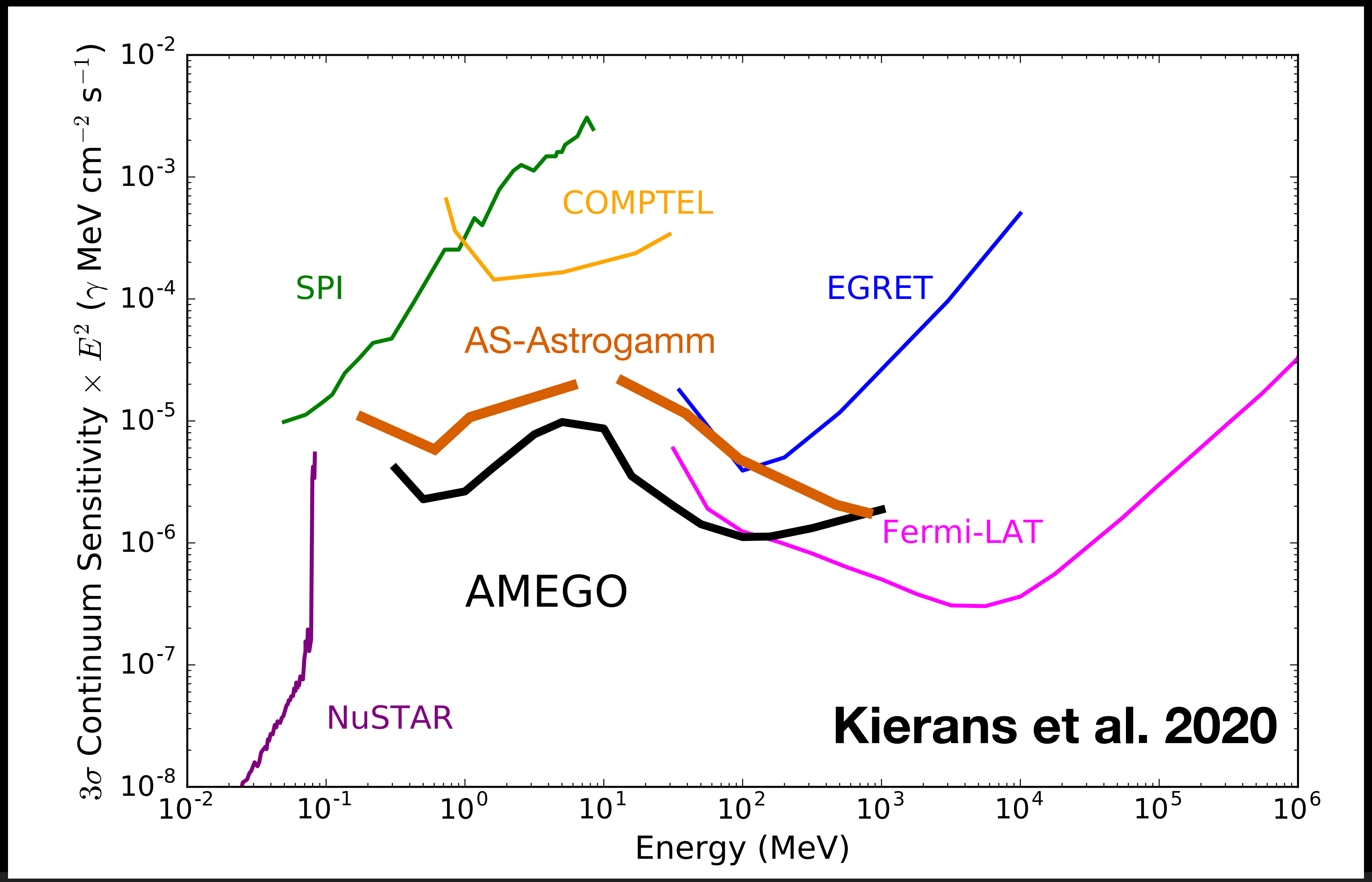
Evans et al.
https://arxiv.org/abs/1501.04435

MEV-GEV COVERAGE



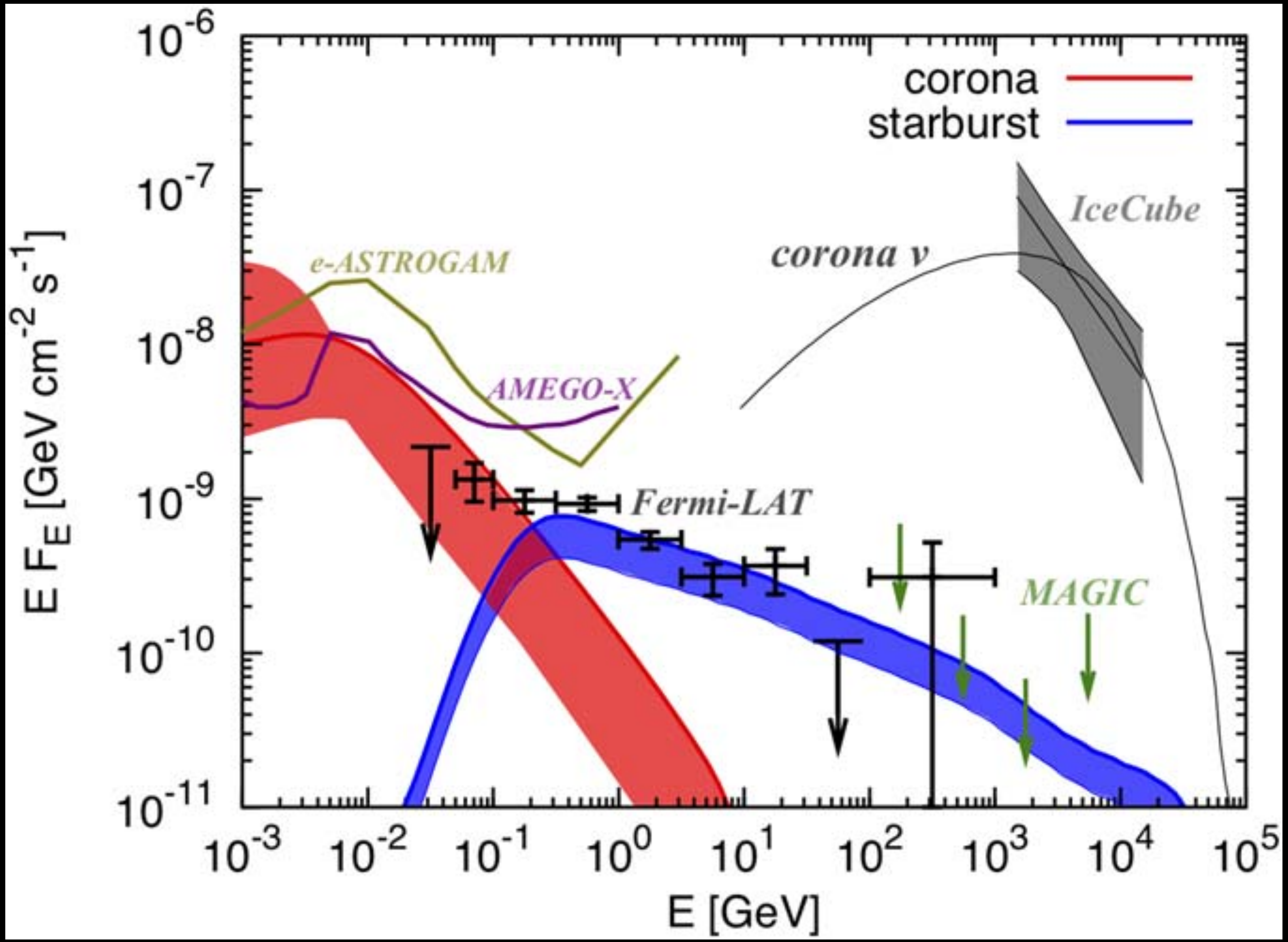
Sensitivity in the **0.1-300 GeV**
Large FoV (all-sky coverage in few days)
Launched in **2008**.





- 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.

NGC 1068 AND THE NEED FOR MEV DETECTORS



Ajello, Murase, McDaniel arXiv/2307.02333

- MeV emission expected from NGC 1068
- Lacking sensitive observations in the near future!
- Hard X-rays are also promising (e.g. up to 80 keV with HEX-P)

NEW MISSIONS ARE NEEDED!

- In particular for gammas, there is no MeV-GeV mission planned for the next decade.

FIG SAG

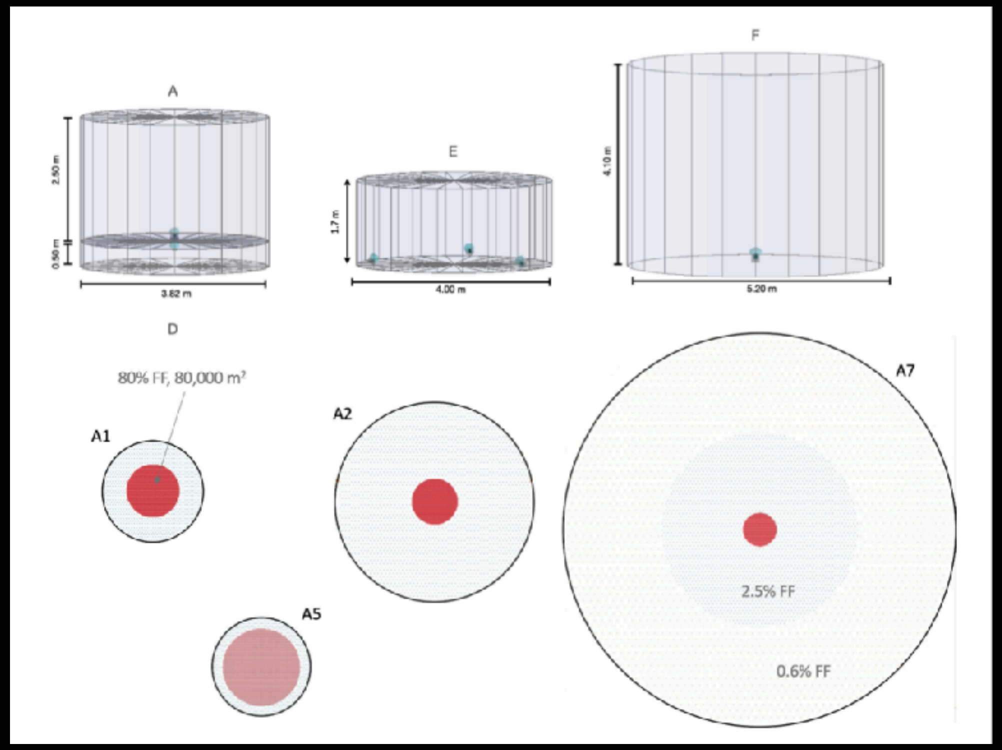
Future Innovations in Gamma rays Science Analysis Group

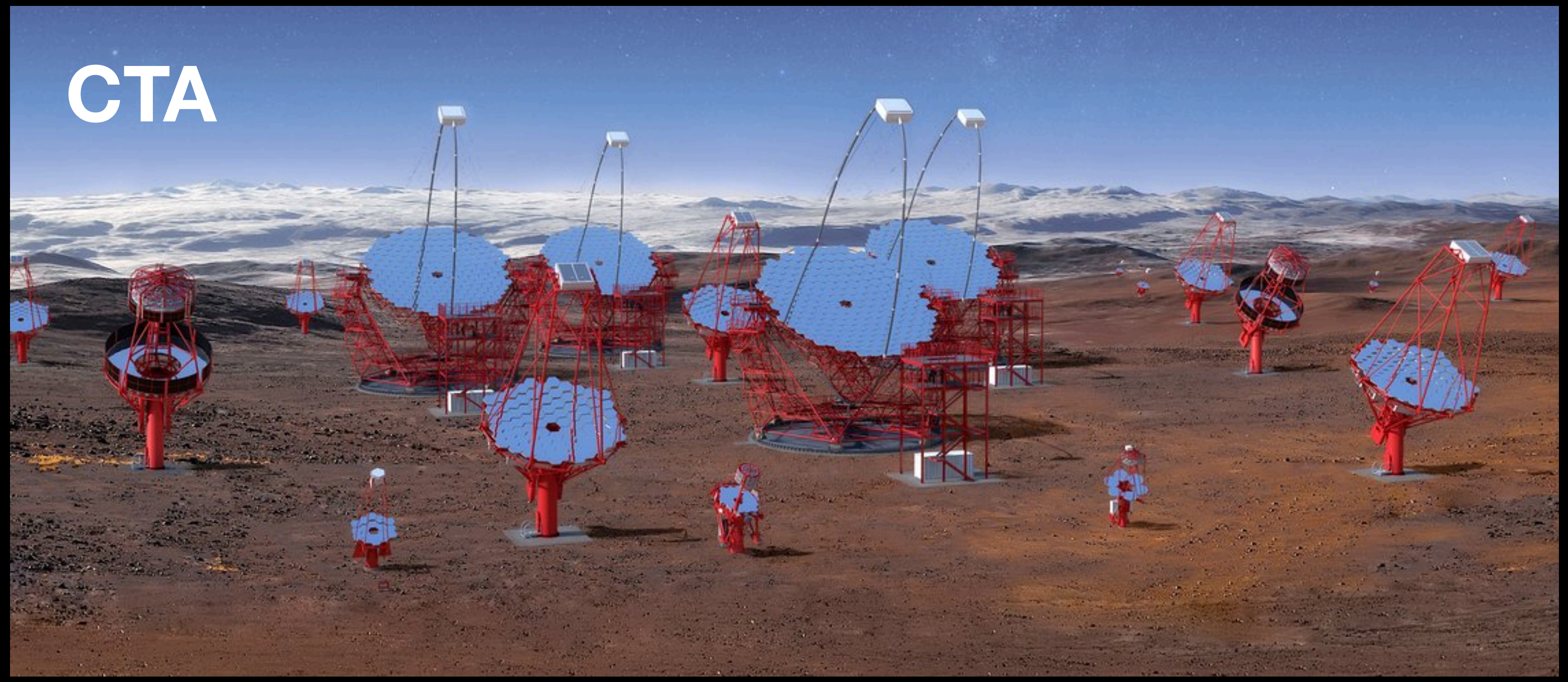
- Astrophysical gamma rays span ten orders of magnitude in energy and capture key physics from a broad range of astrophysical phenomena. This NASA SAG will explore gamma-ray science priorities, necessary capabilities, new technologies, and theory/modeling needs drawing on the 2020 Decadal to inspire work toward 2040.
  To get involved and stay informed, please enter your contact information in this form or join this Slack channel. Also visit the SAG website. In-person meeting next week at Michigan Tech, will produce a report.

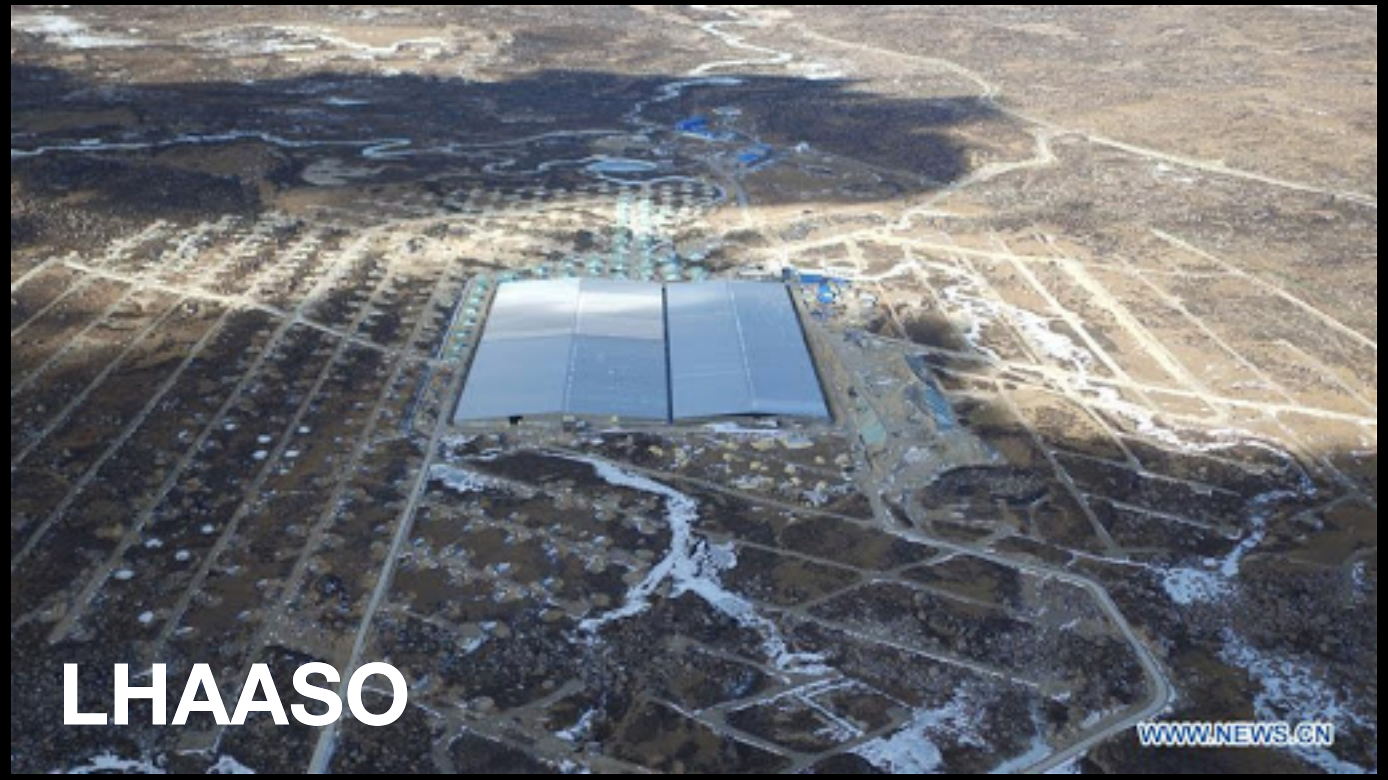
- Chairs: Chris Fryer, Michelle Hui.

COVERAGE IN THE VERY-HIGH-ENERGY RANGE

SWGO

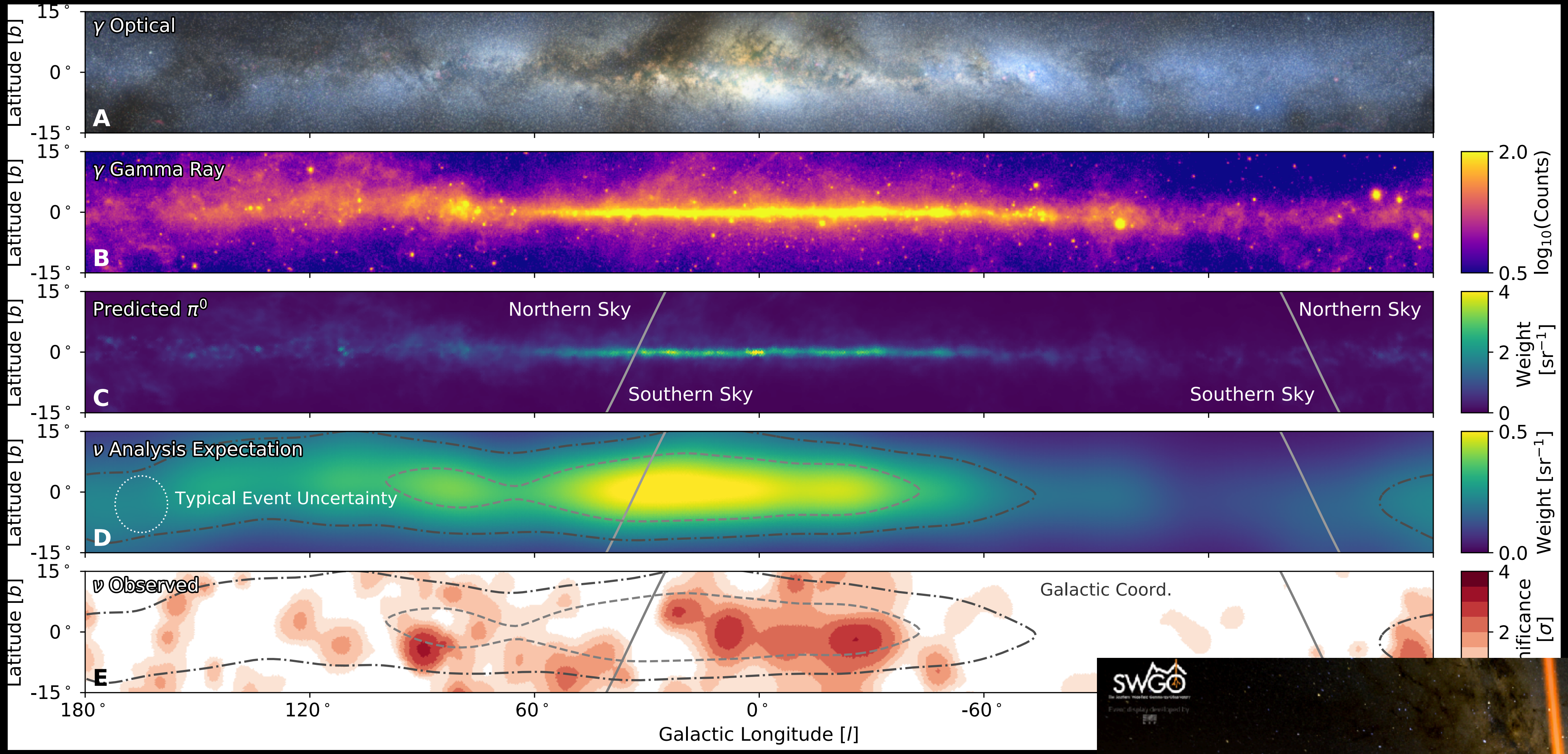




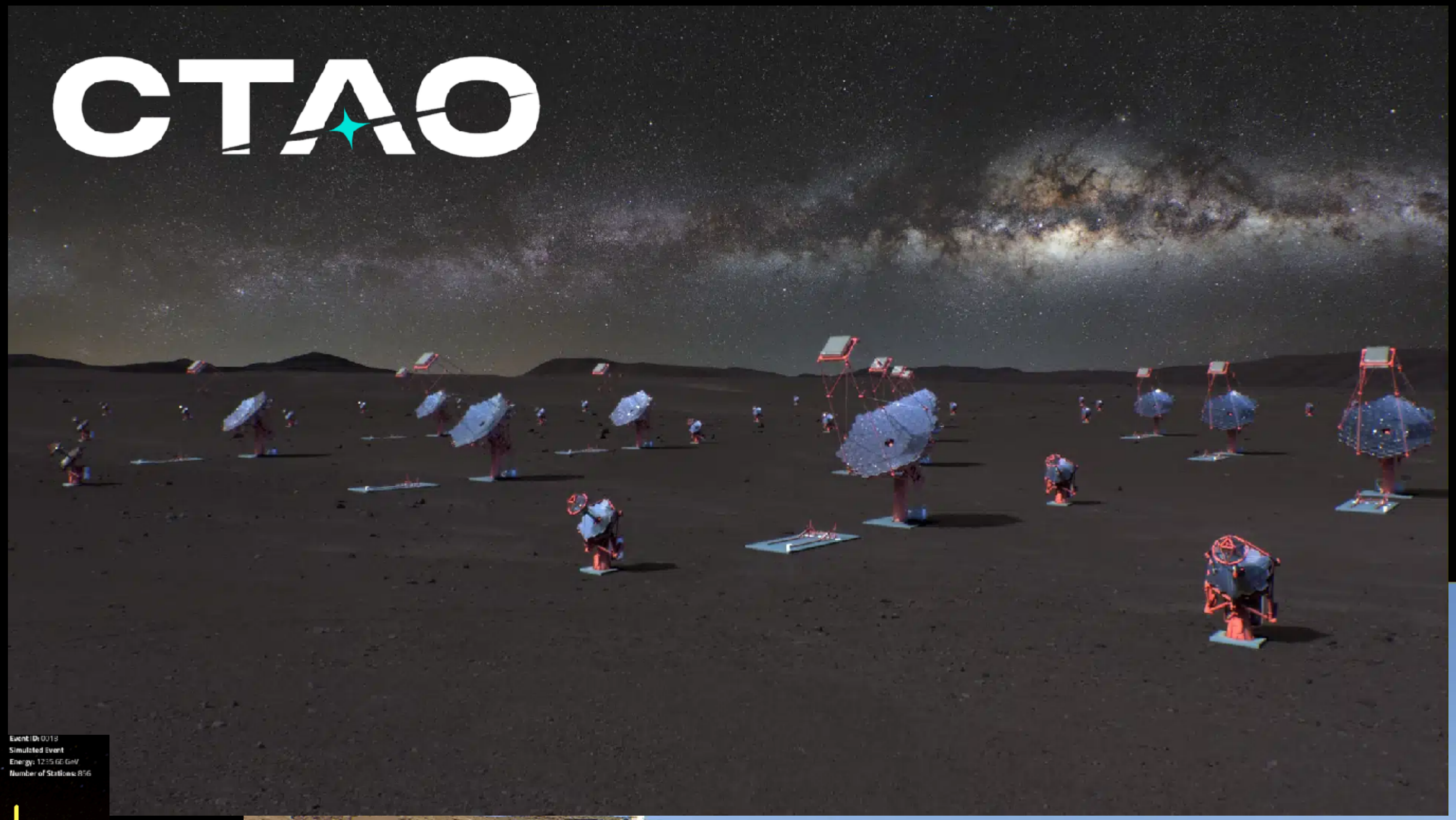


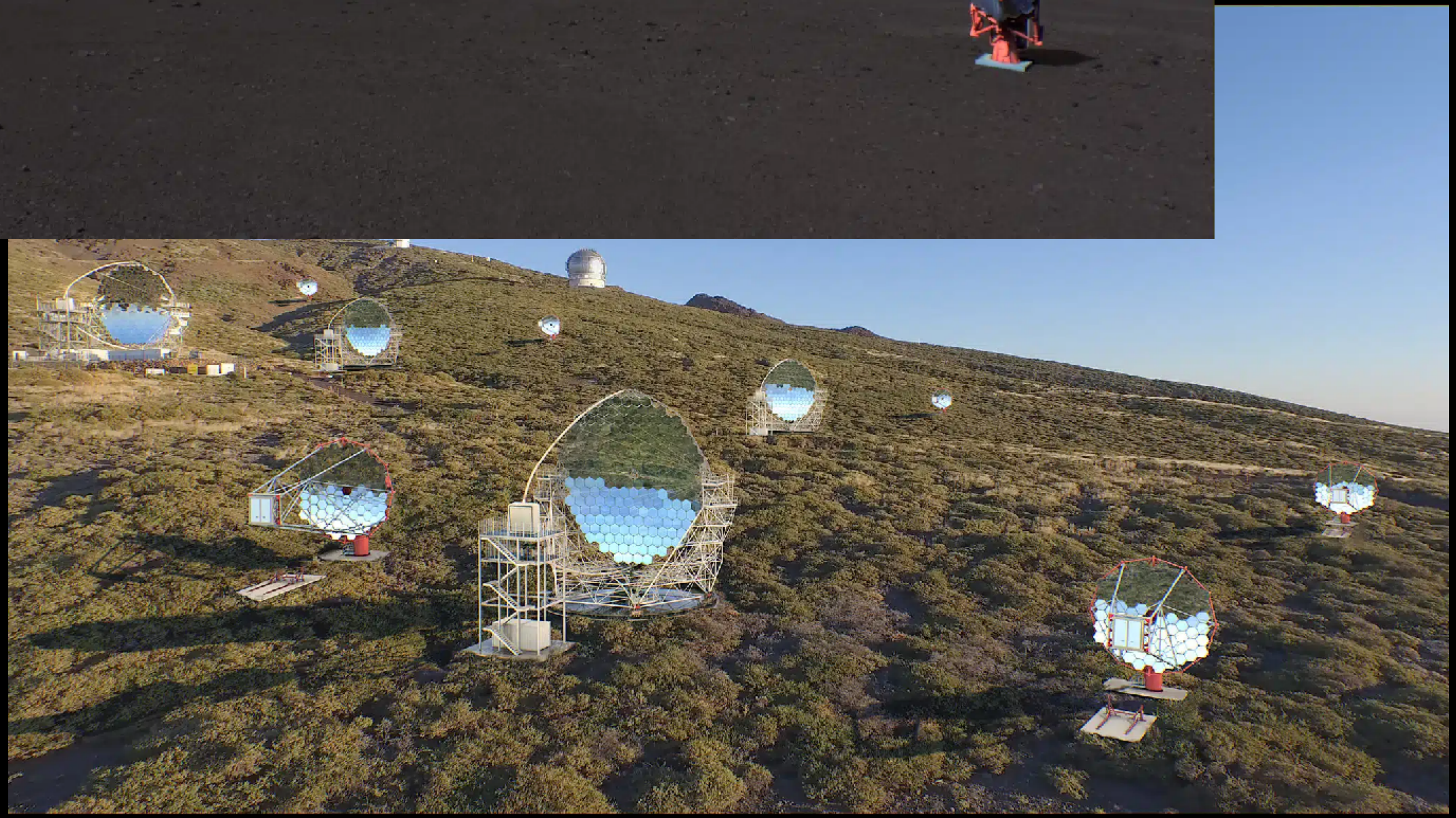
- CTA to provide a x10 improvement in sensivity in the VHE band (>50 GeV). Prototypes telescopes already detecting sources!
- Neutrino follow-ups and strong AGN science program for CTA.
- Air shower arrays (HAWC, LHAASO, proposed SWGO) provide large FoV coverage for diffuse/extended sources.

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.

WISHLIST FOR MMA STUDIES WITH NEUTRINOS

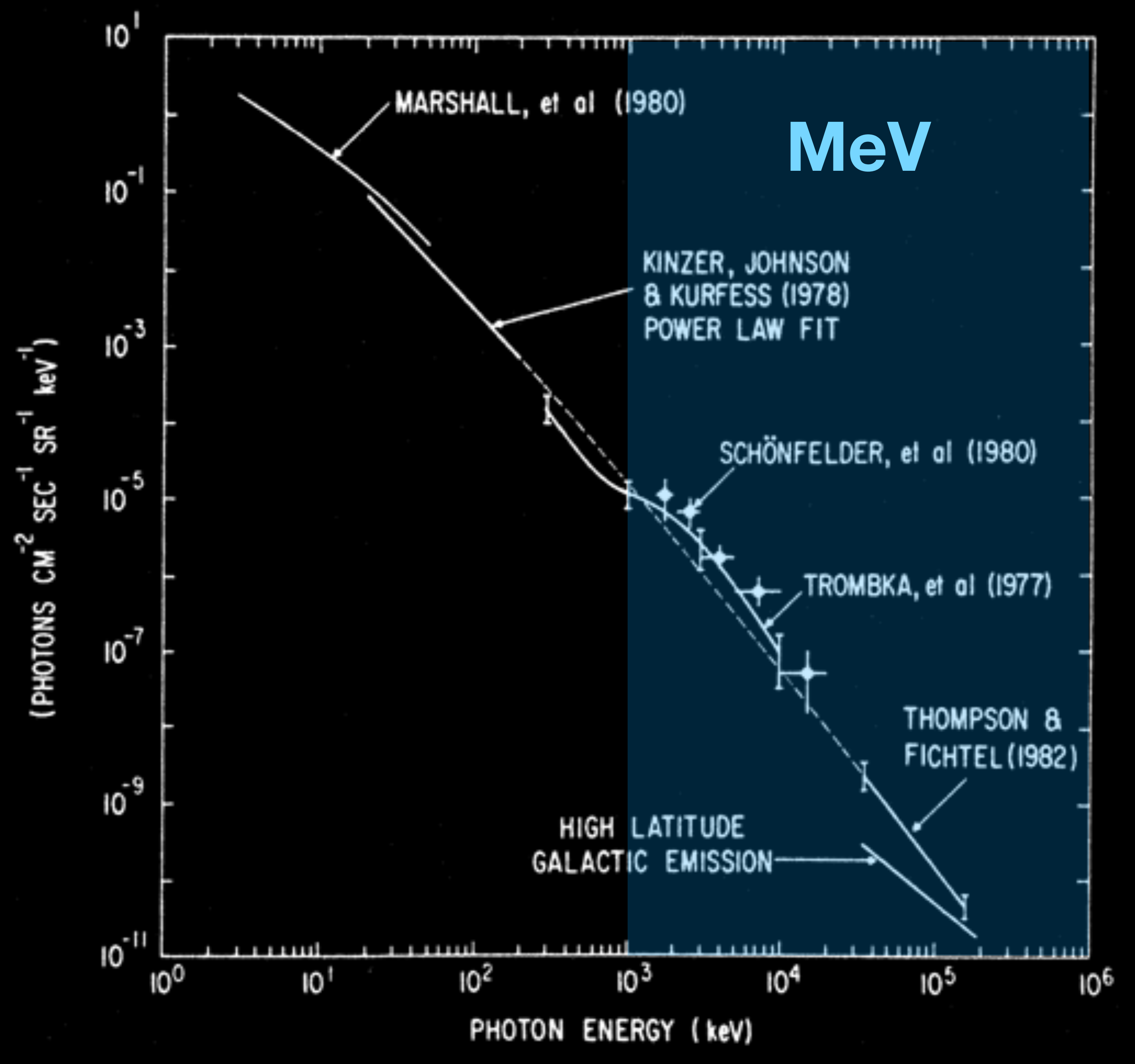
- **On the threshold of real neutrino astronomy, but…**
- Increase the number of neutrino events >100 TeV (high astrophysical purity)
- Improve the angular resolution (correlation probability goes with PSF^2)
- As neutrino telescopes are 4π instruments, you need **wide-field, continuous, broad-band, 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?)

A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

Credit: Naoko Kurahashi Neilson

A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

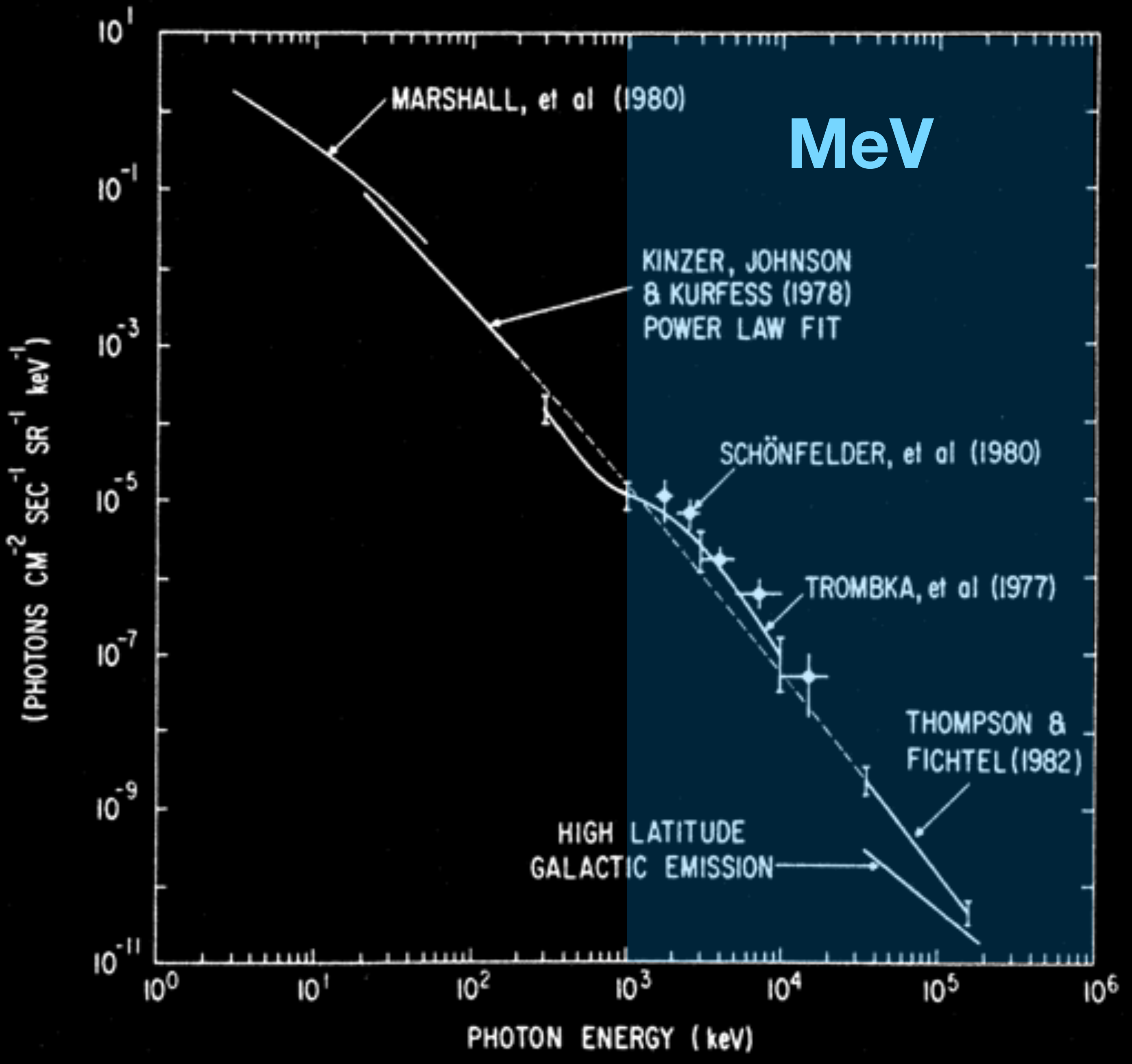
Credit: Naoko Kurahashi Neilson



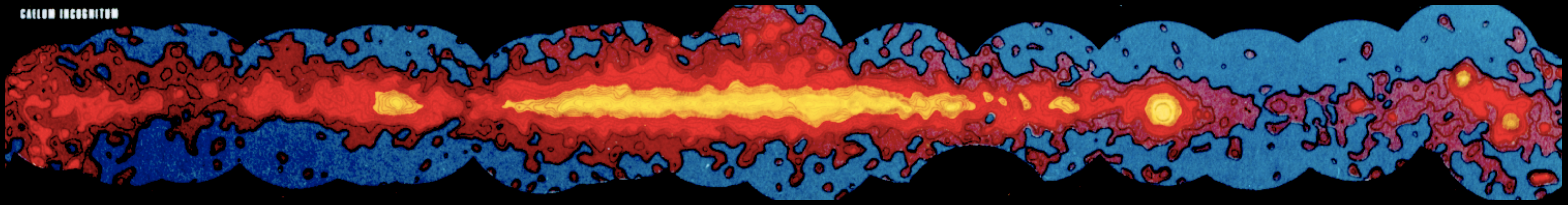
Diffuse background measurements
(1968-1972)

A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

Credit: Naoko Kurahashi Neilson



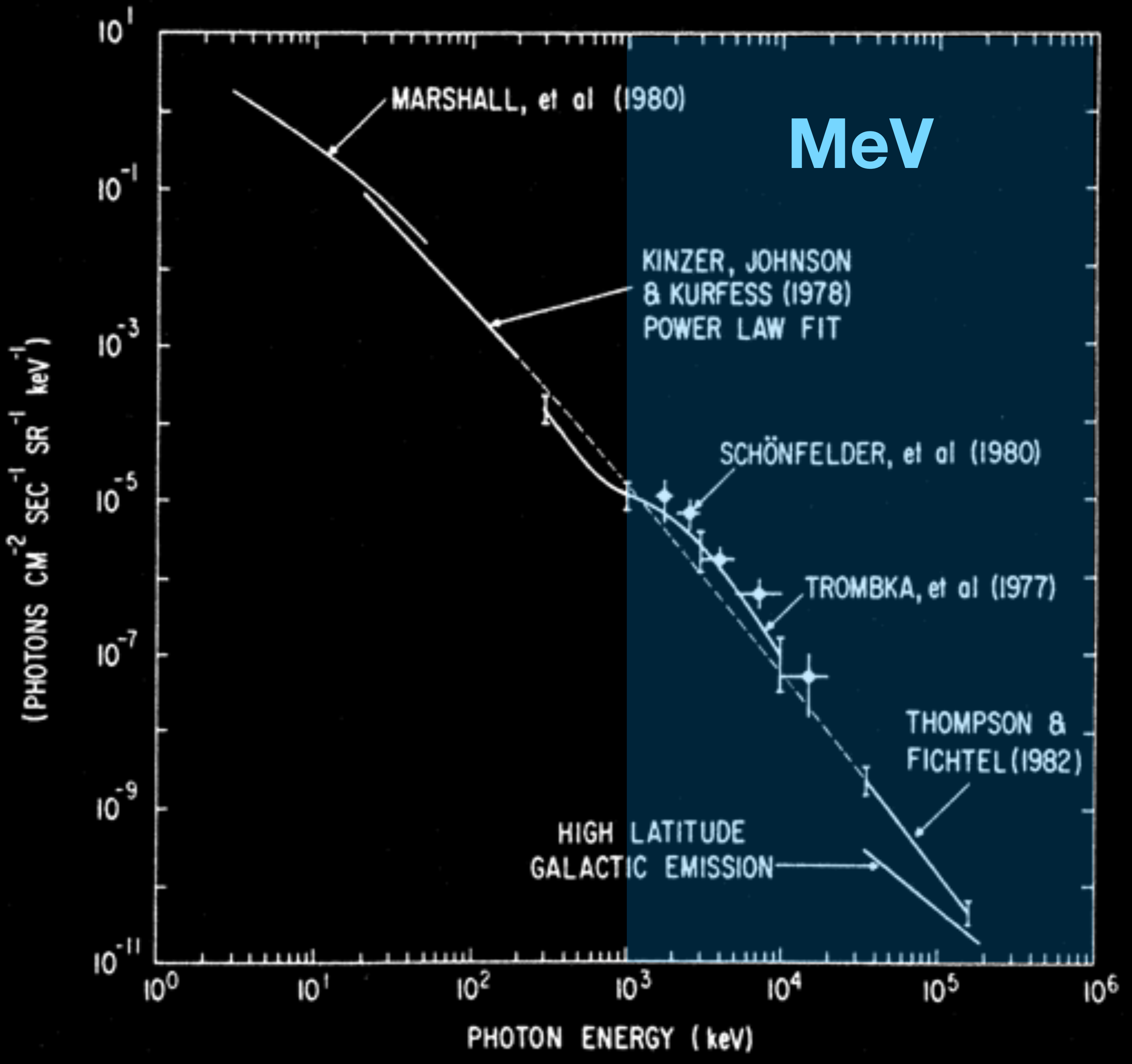
Diffuse background measurements
(1968-1972)



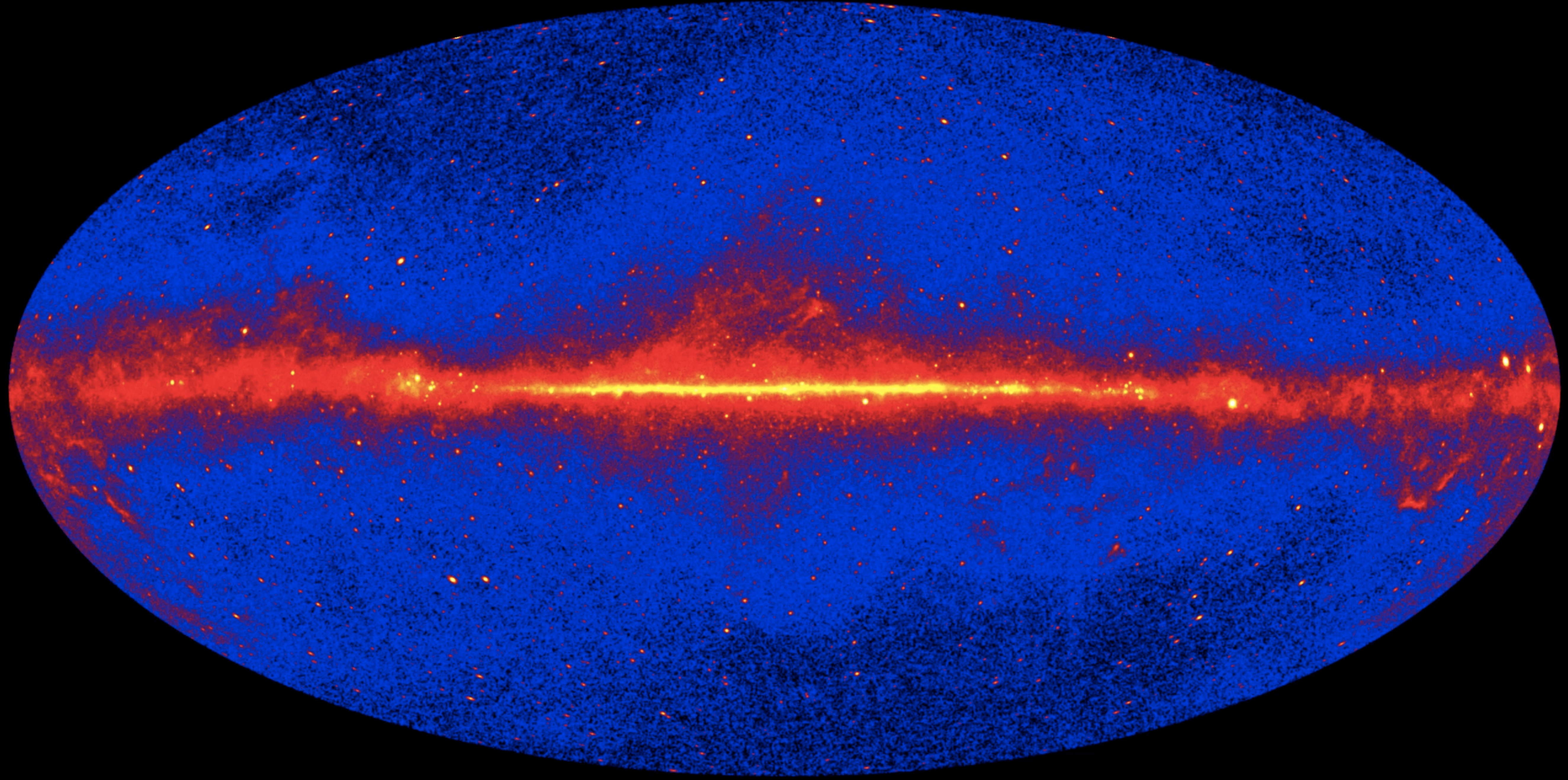
Galactic emission and few point sources (COS-B 1975-1982)

A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

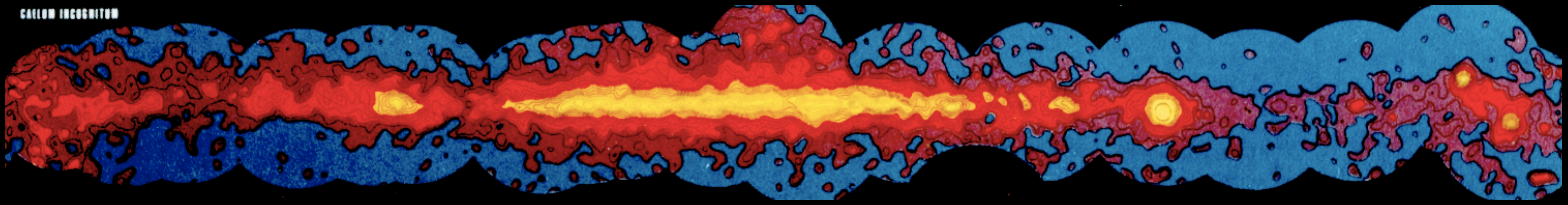
Credit: Naoko Kurahashi Neilson



Diffuse background measurements
(1968-1972)



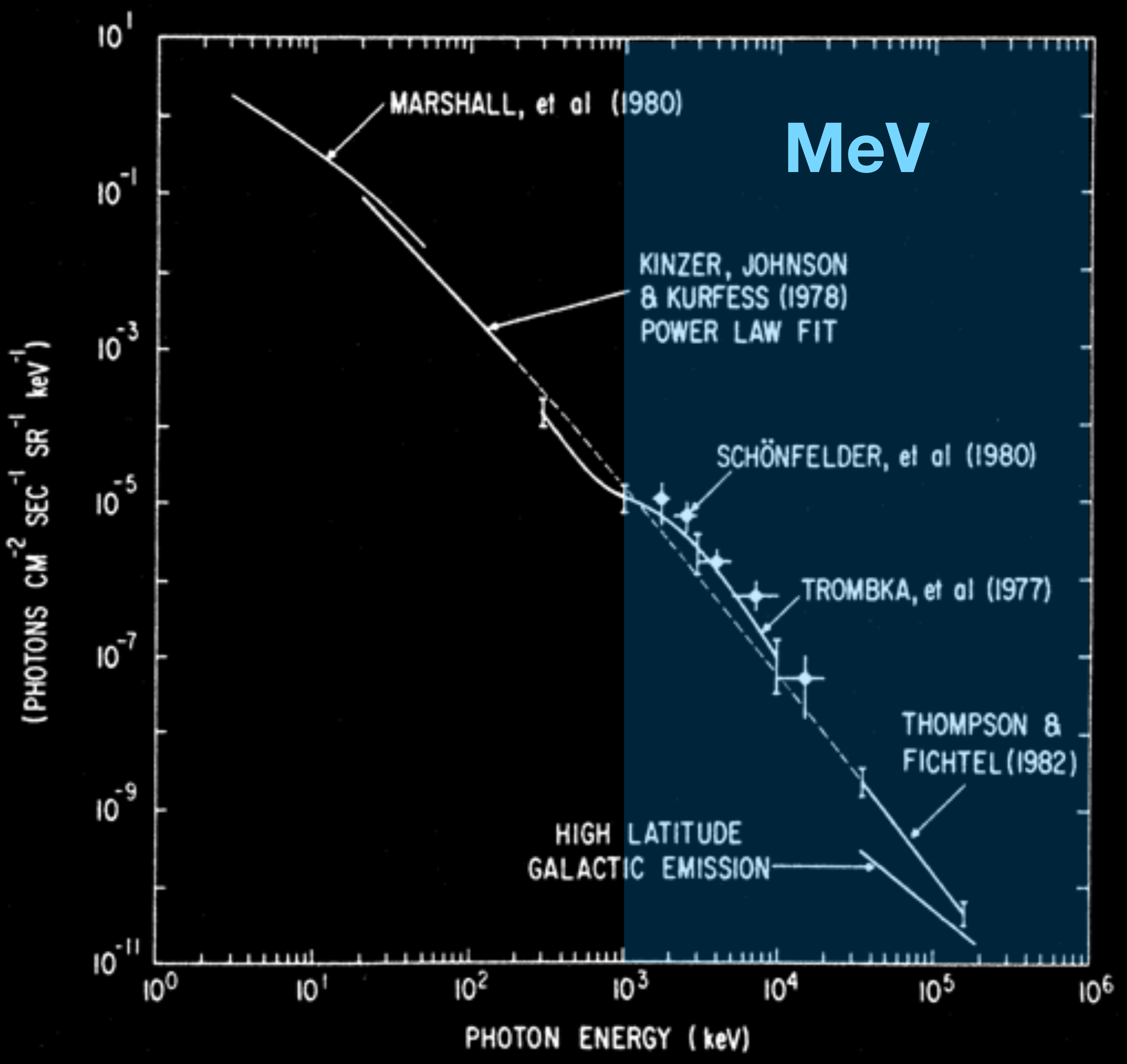
O(10^3) points source, spectra, light curves
(IACTs, Fermi-LAT, 1989-now)



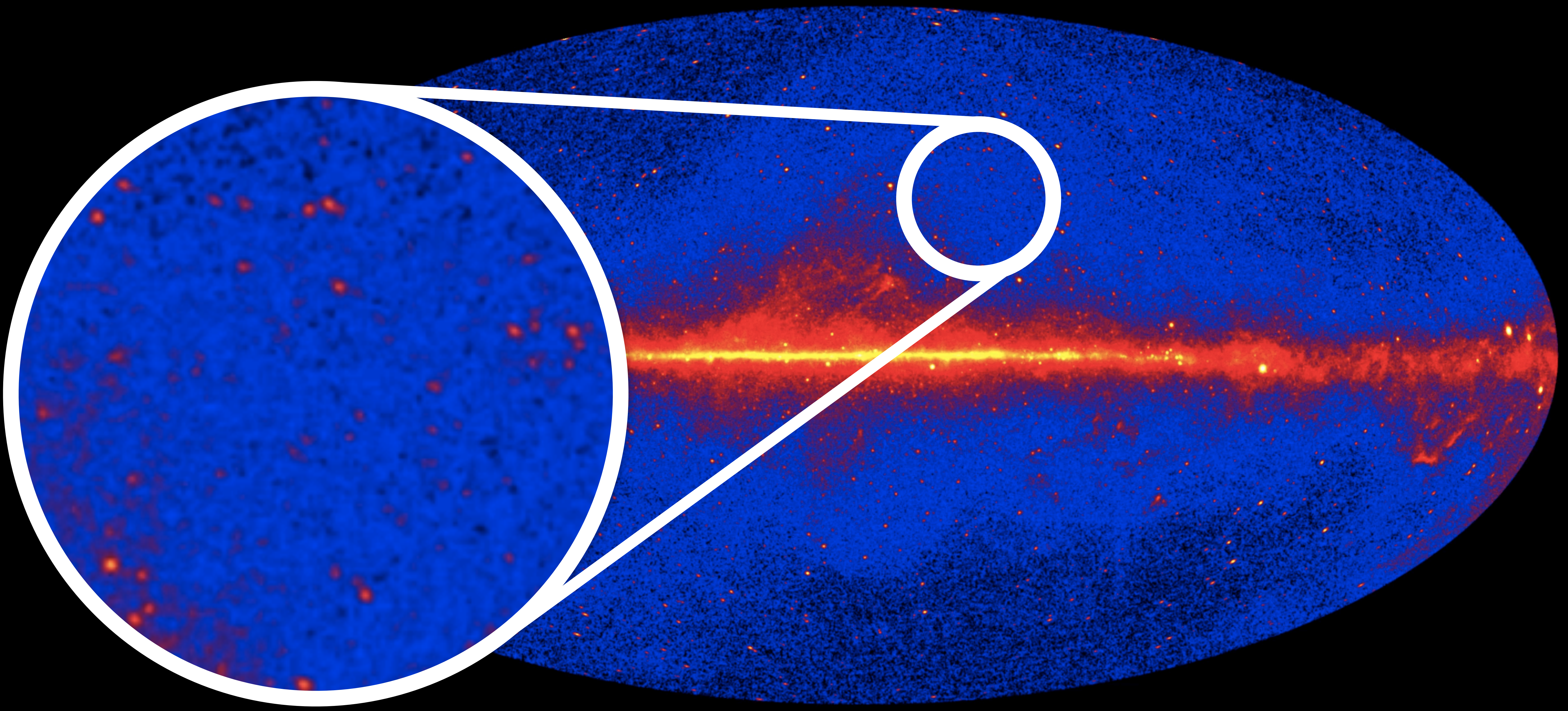
Galactic emission and few point sources (COS-B 1975-1982)

A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

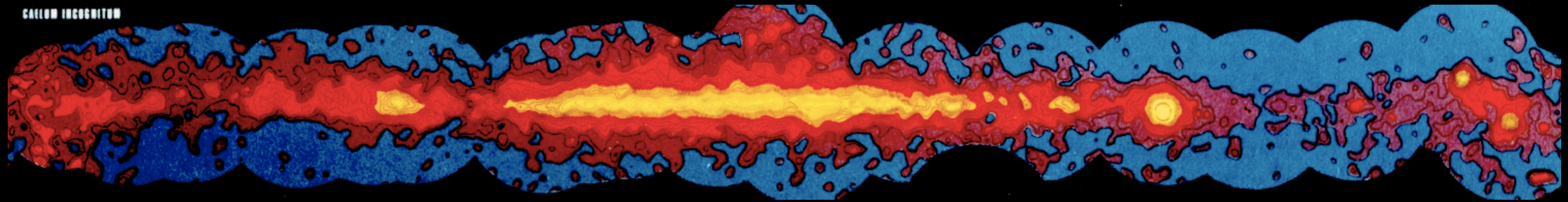
Credit: Naoko Kurahashi Neilson



Diffuse background measurements
(1968-1972)



O(10^3) points source, spectra, light curves
(IACTs, Fermi-LAT, 1989-now)



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

THANK YOU!

THANK YOU!