
# Searching for neutrinos across the globe

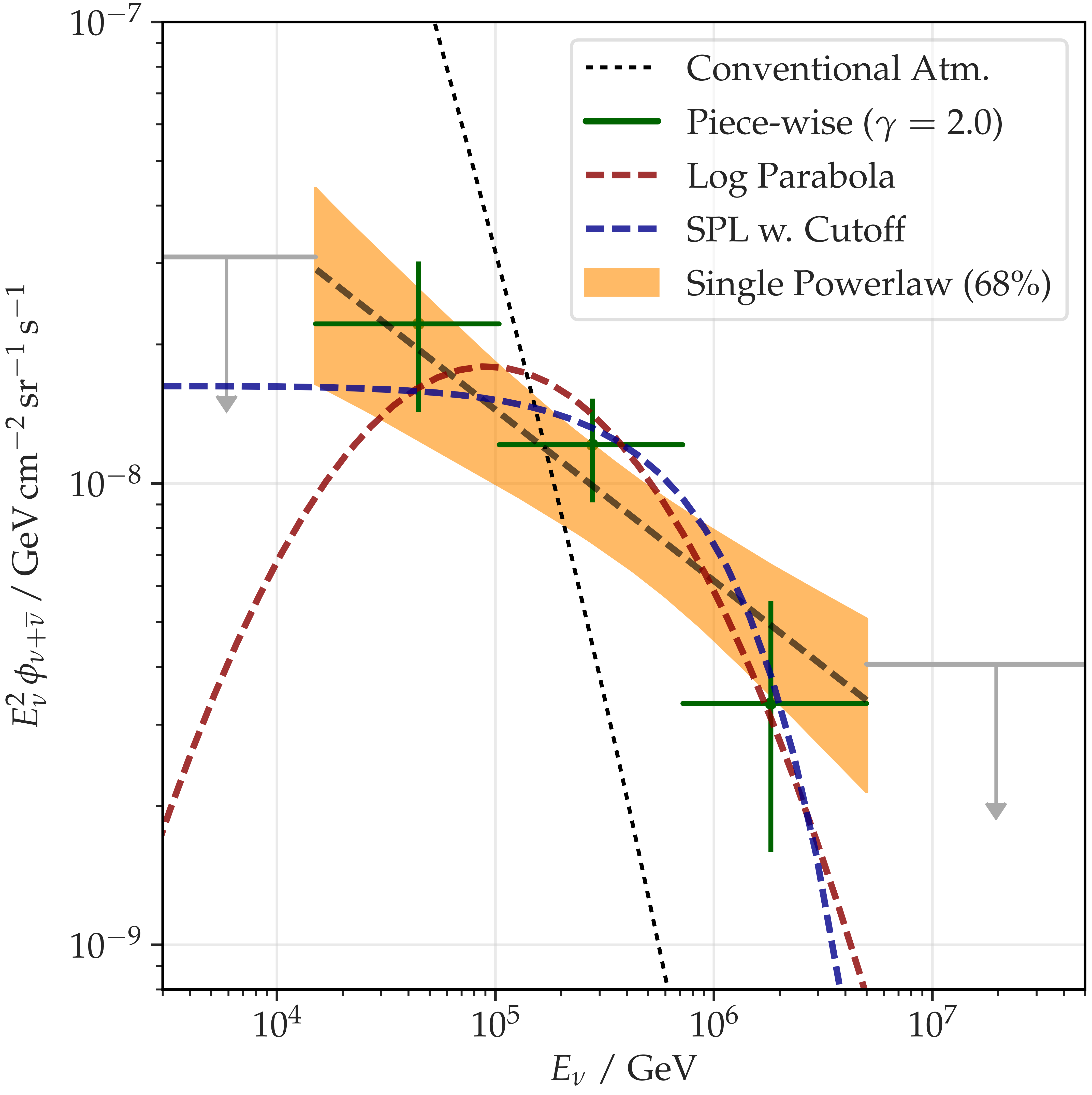

Marcos Santander

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



20 MAGIC Years Symposium - La Palma, Spain, October 2023

# CURRENT OBSERVATIONAL STATUS

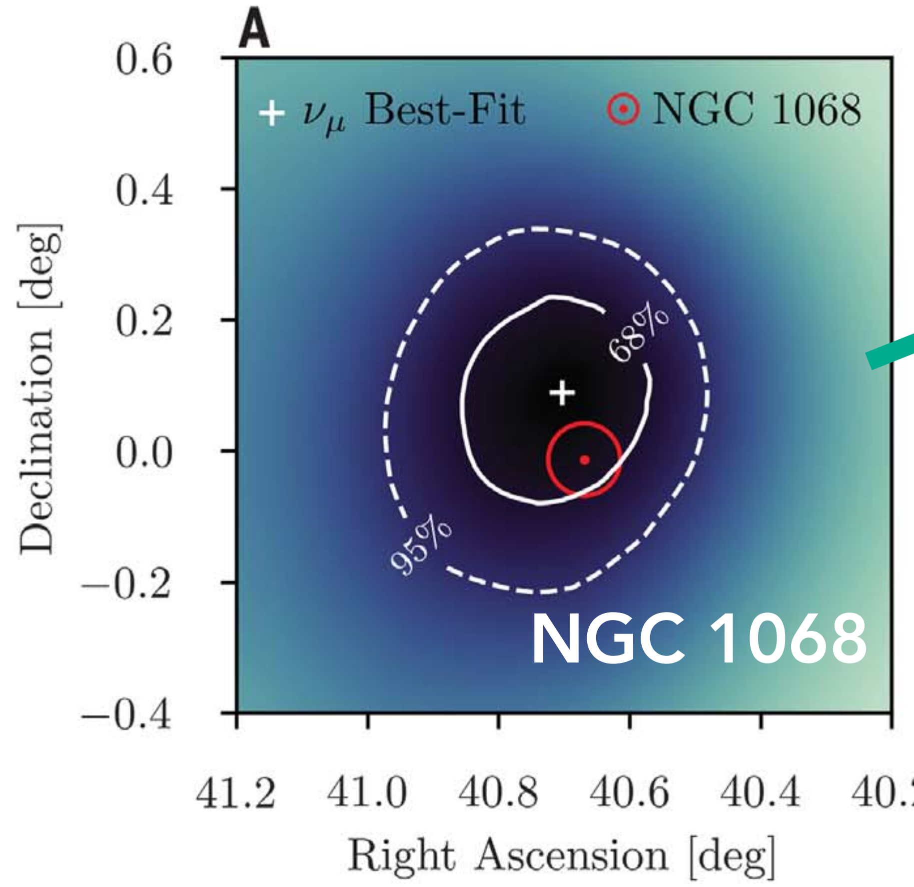



IceCube 2021 (arXiv/2111.10299)

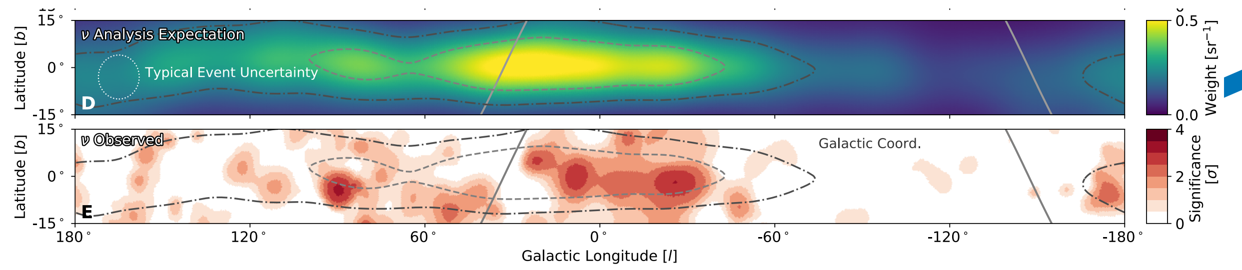
IceCube, MAGIC, ++ 2018 (arXiv/1807.08816)

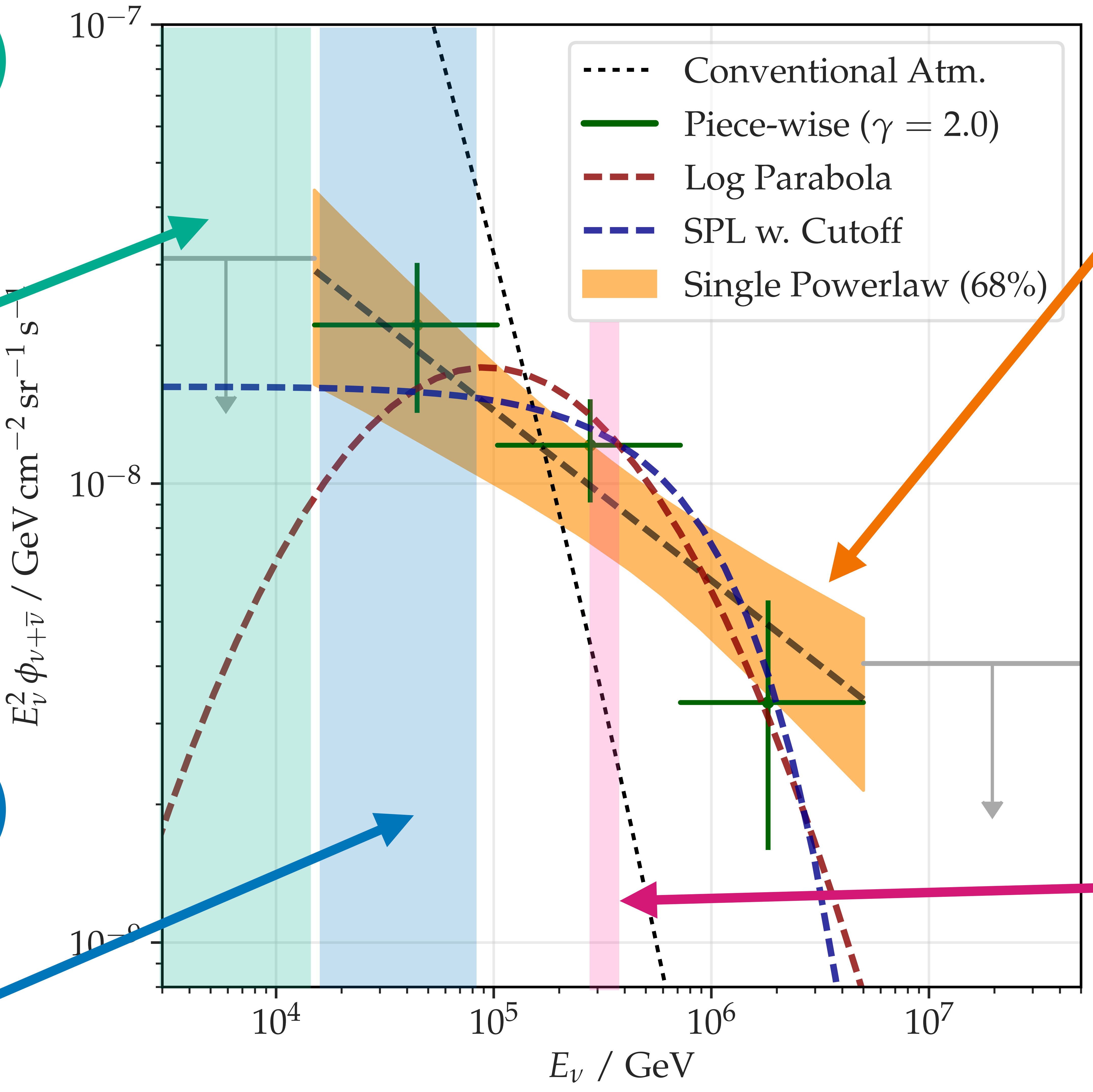
# CURRENT OBSERVATIONAL STATUS

**Neutrino emission from an AGN (2022)** 3




**Neutrinos from the Milky Way (2023)** 4

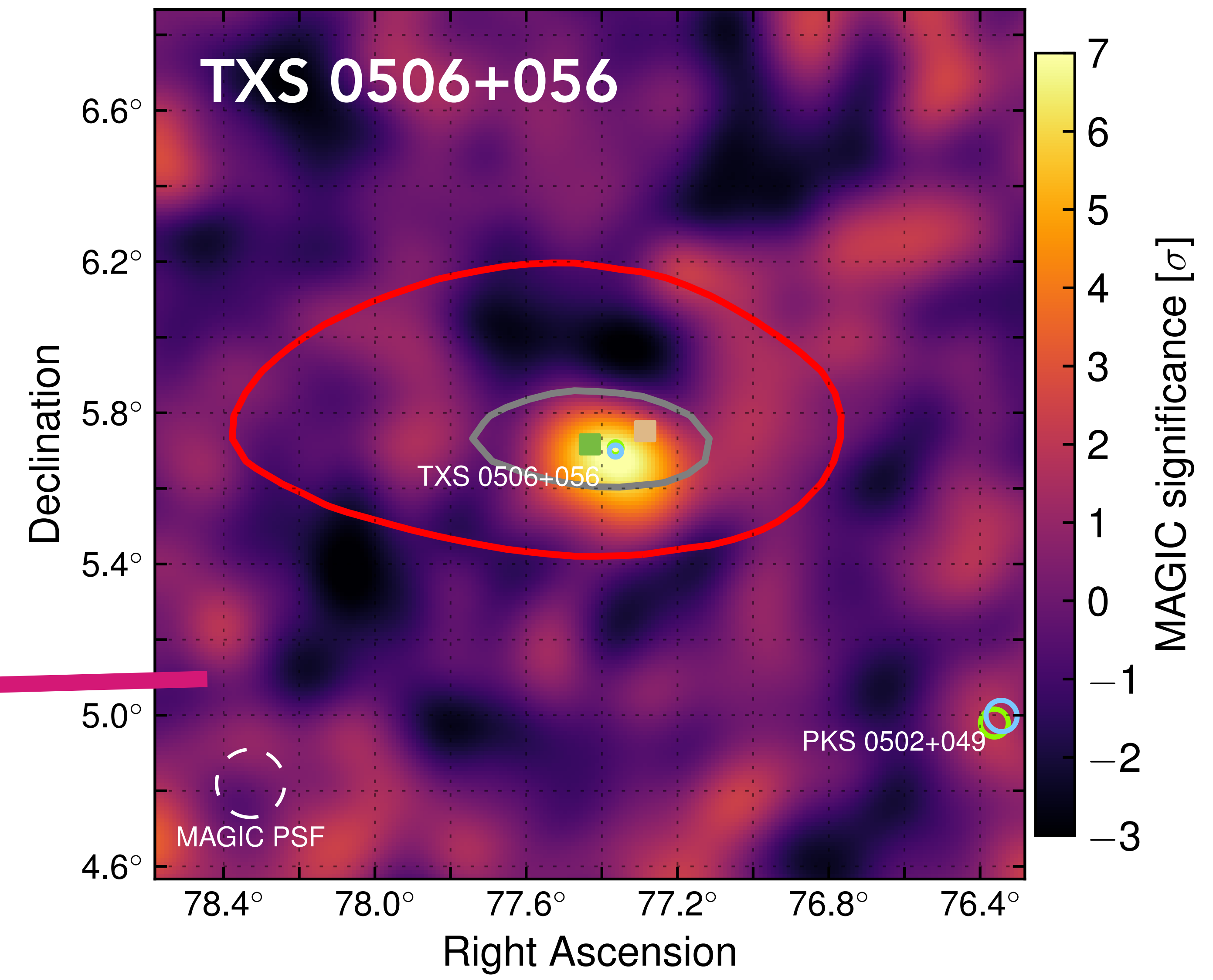



IceCube 2021 (arXiv/2111.10299)

1 **Astrophysical neutrino flux (2013)**

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




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

# CURRENT OBSERVATIONAL STATUS

# Current observational status

## Low-energy regime

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

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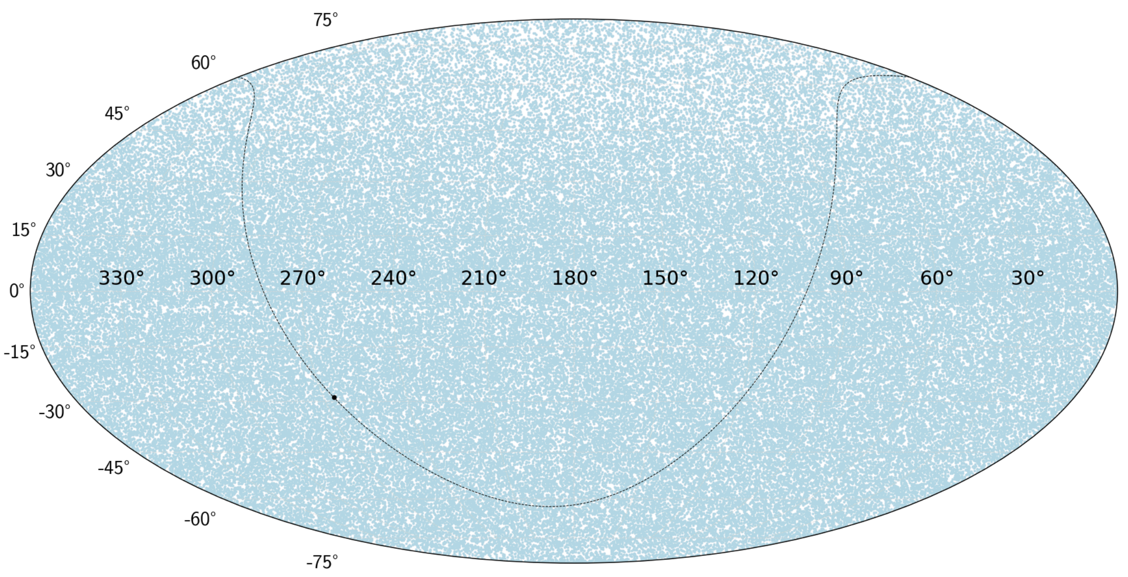
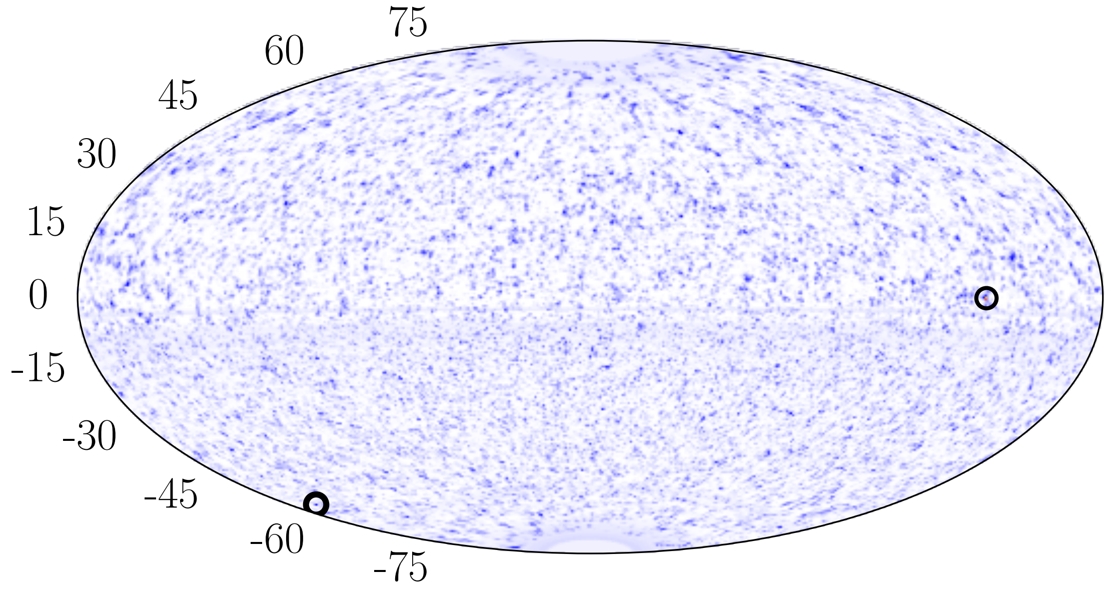
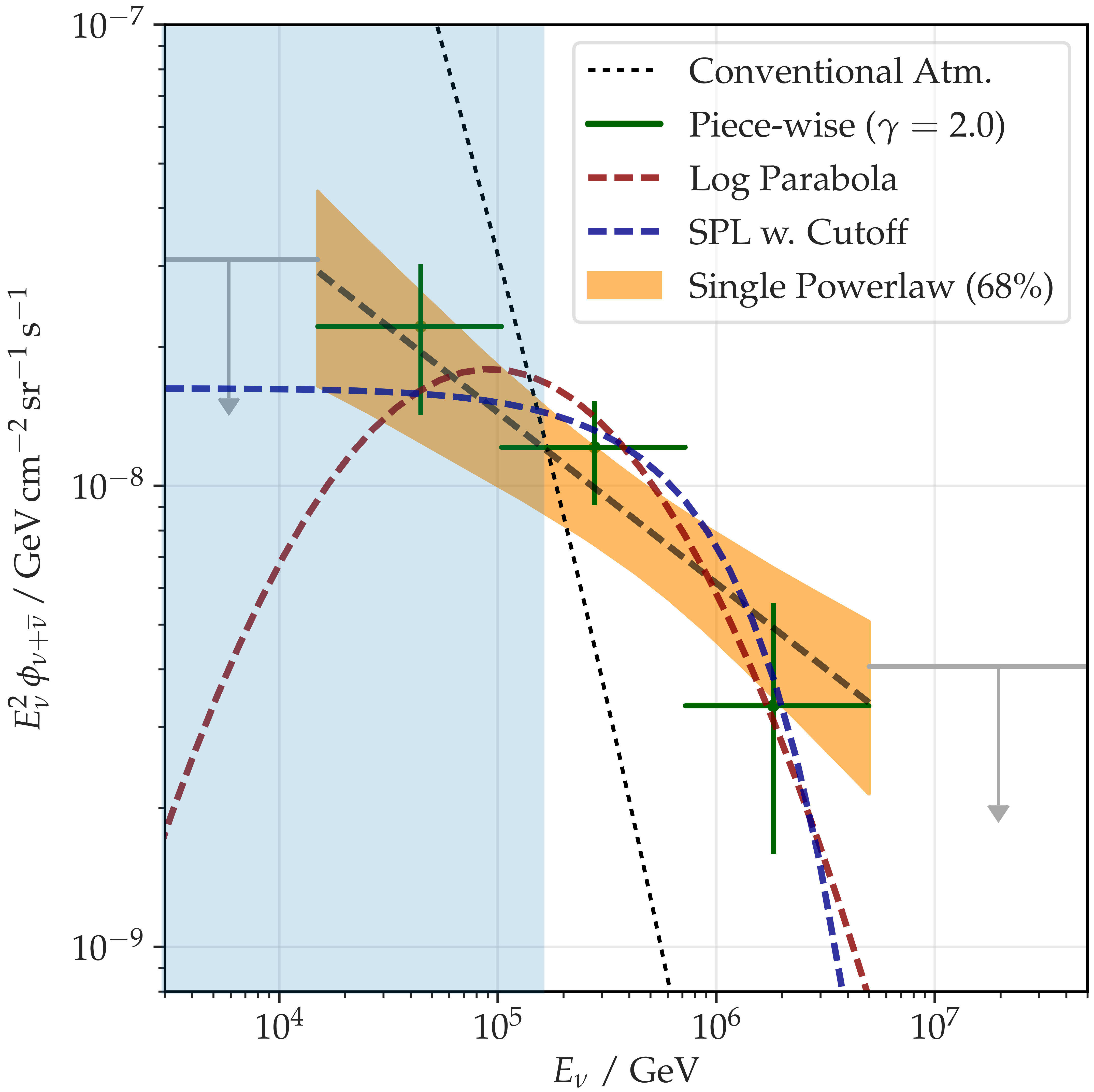



Cluster search

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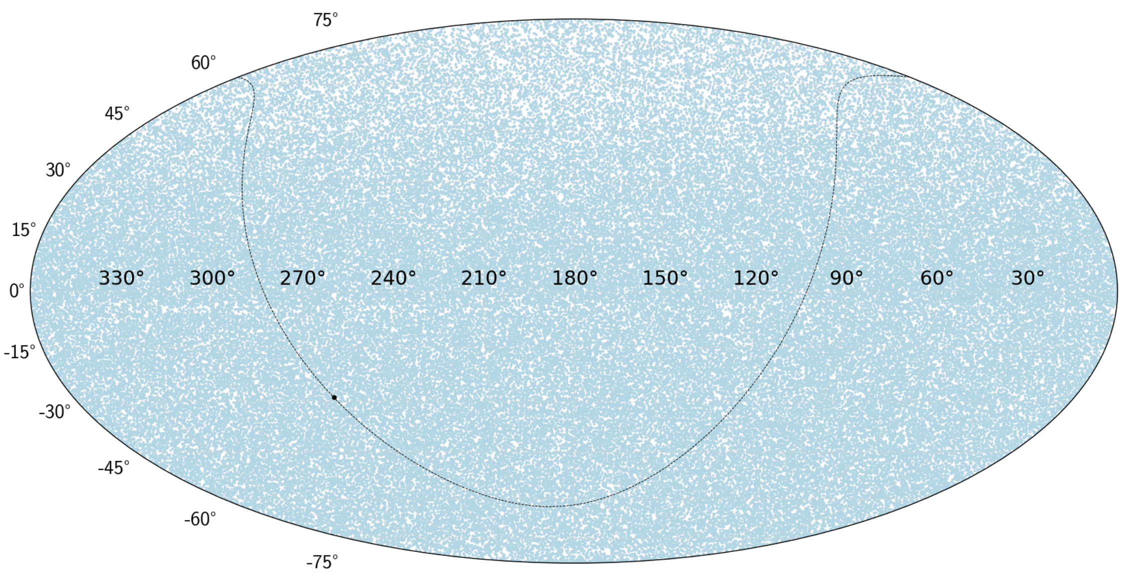


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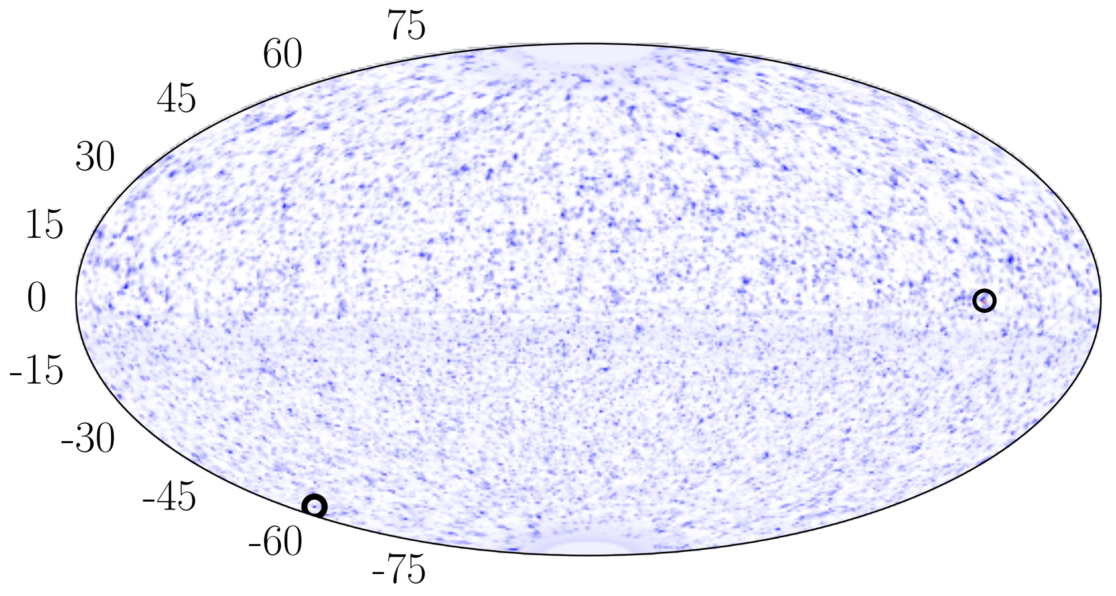
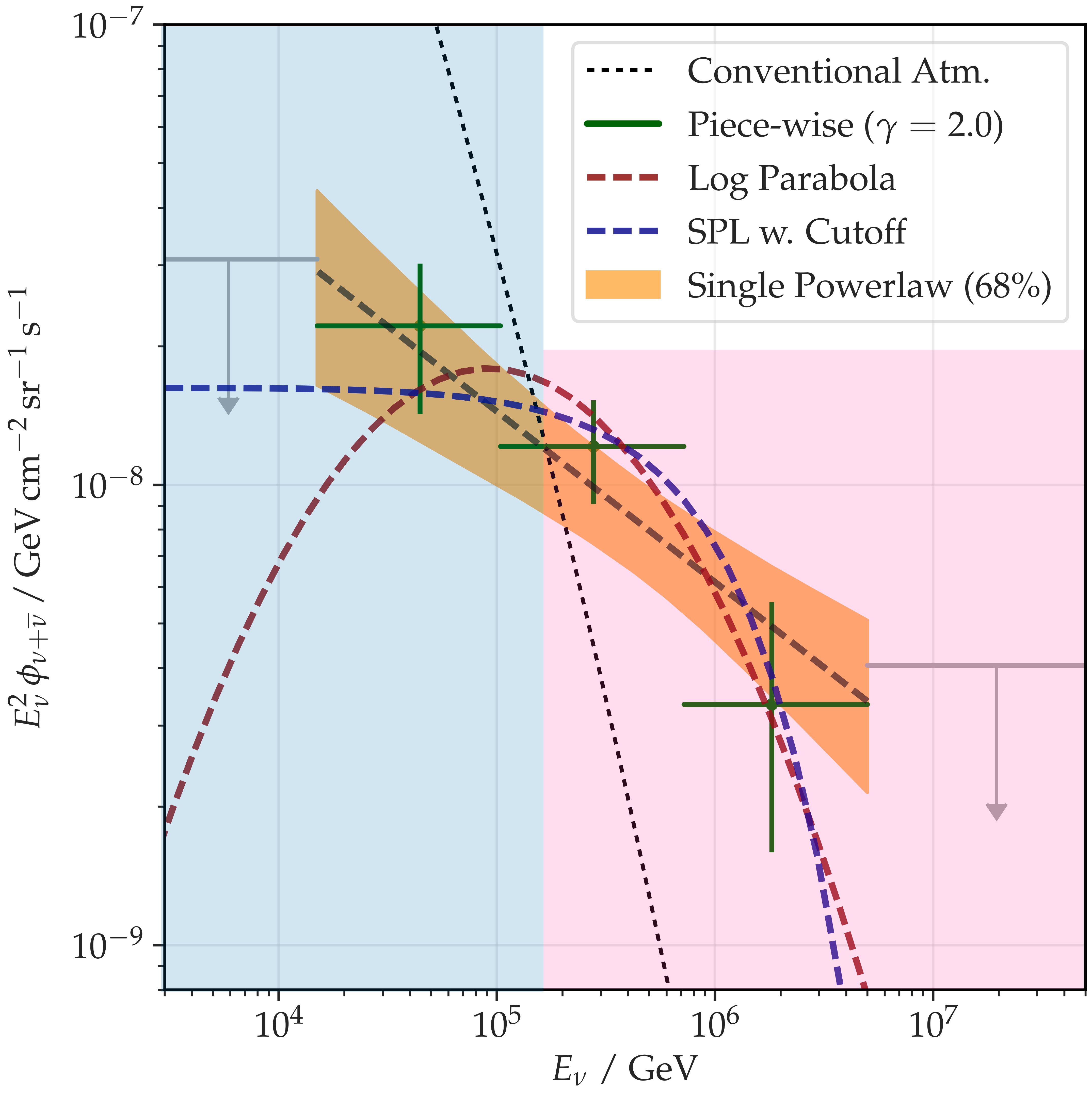
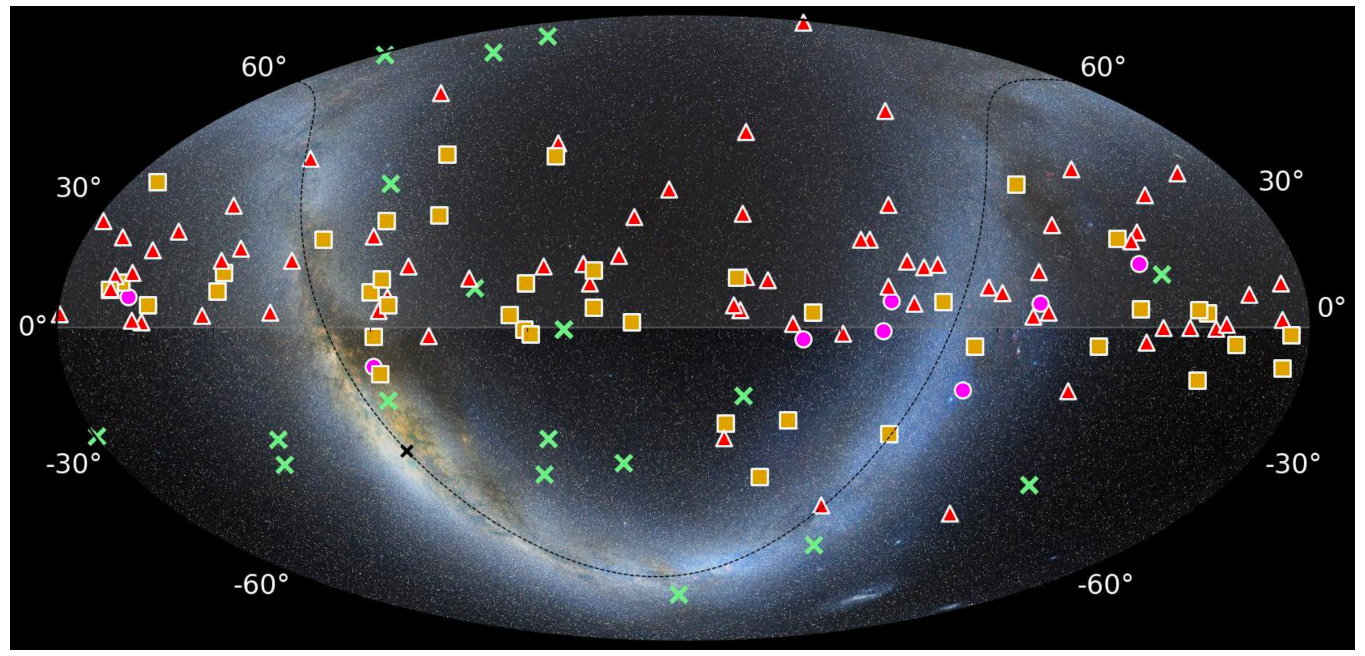



IceCube 2021 (arXiv/2111.10299)

## High-energy regime

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

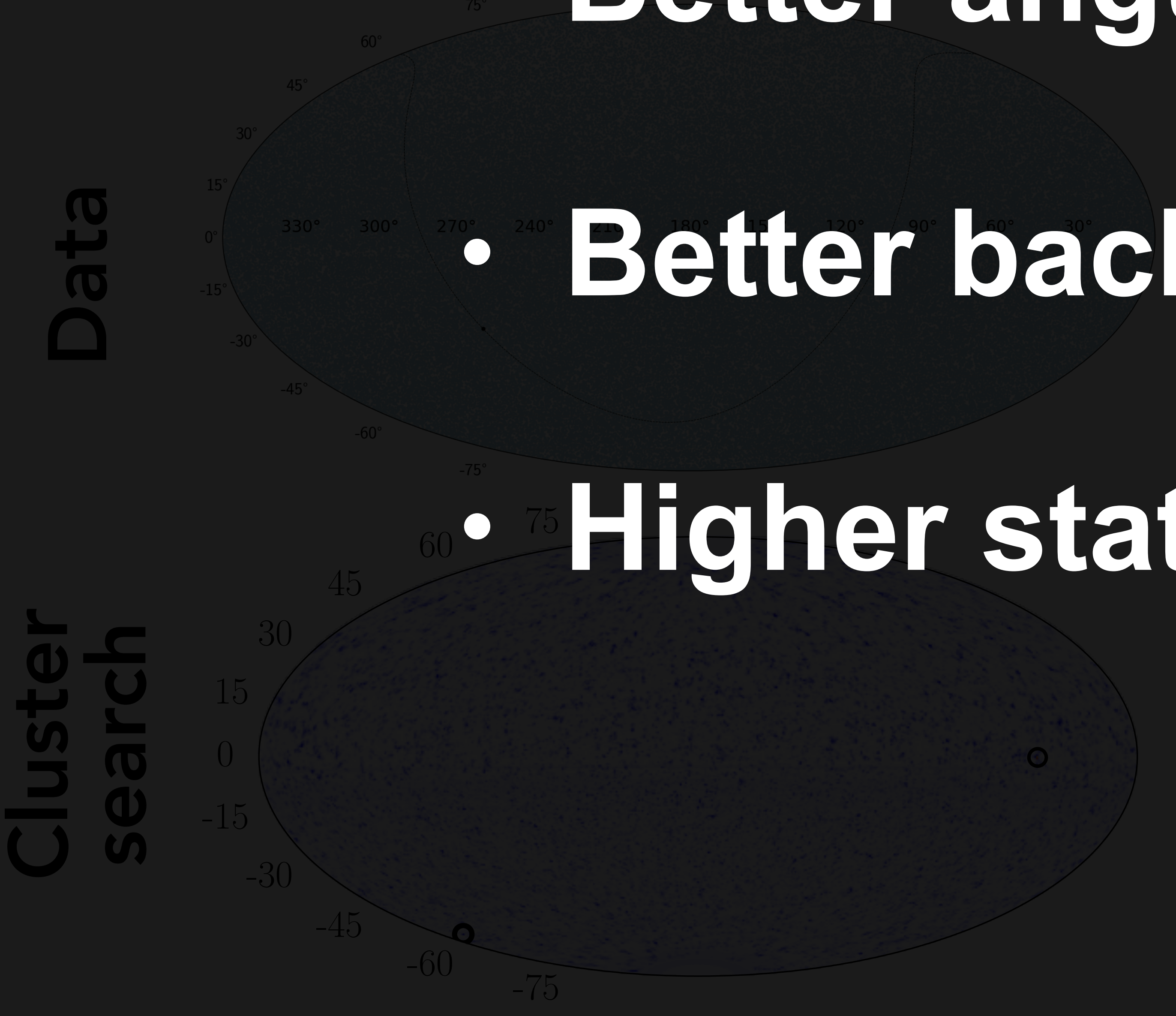


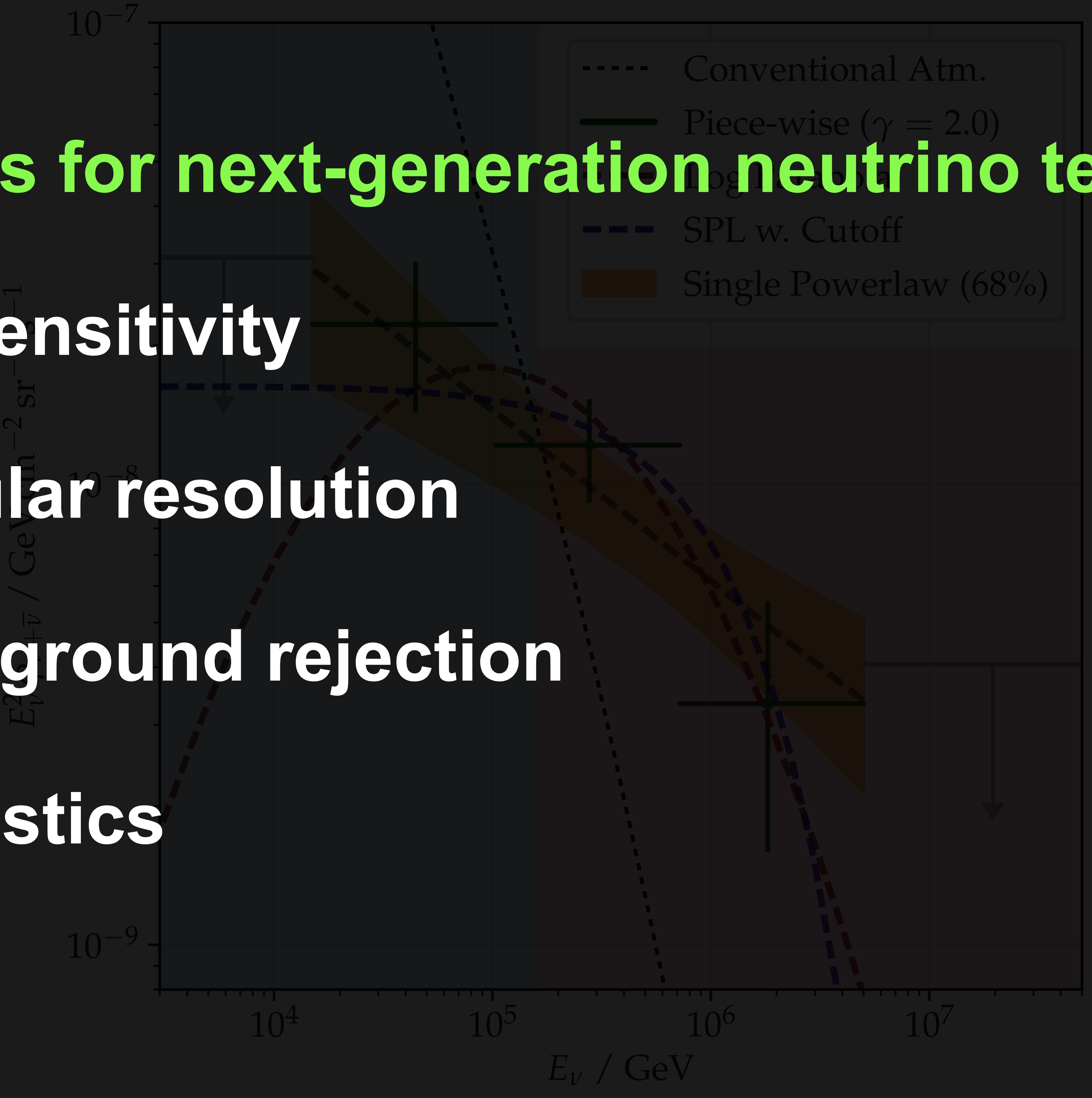

**IceCube realtime alerts**

# Current observational status

## Low-energy regime

- Background dominated
- Sensitivity roughly ∝ PSF²
- Self-cluster… correlation searches

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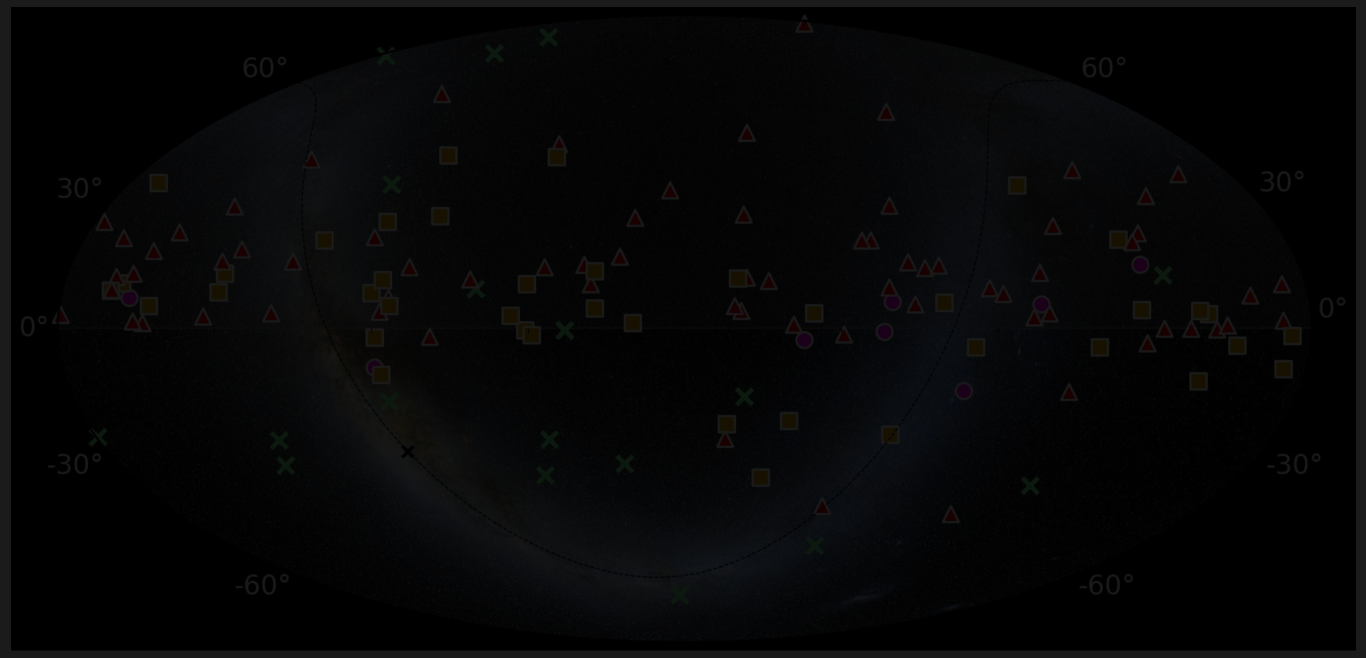

IceCube realtime alerts

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

# CURRENT (AND RECENT) TELESCOPES

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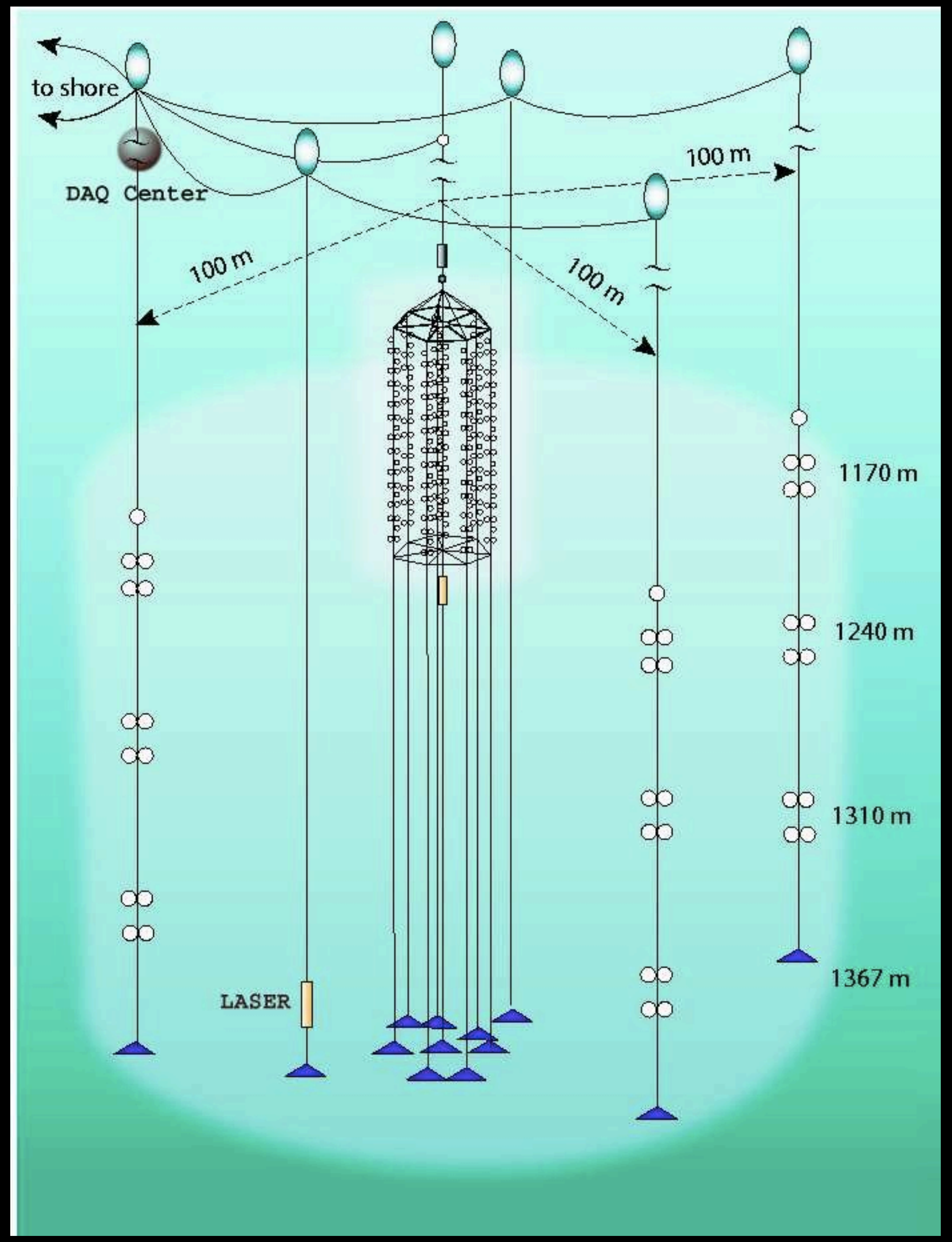


## Baikal NT-200+

- Lake Baikal, Russia. 2004/5
- **1/2000 km$^3$**
- 228 PMTs

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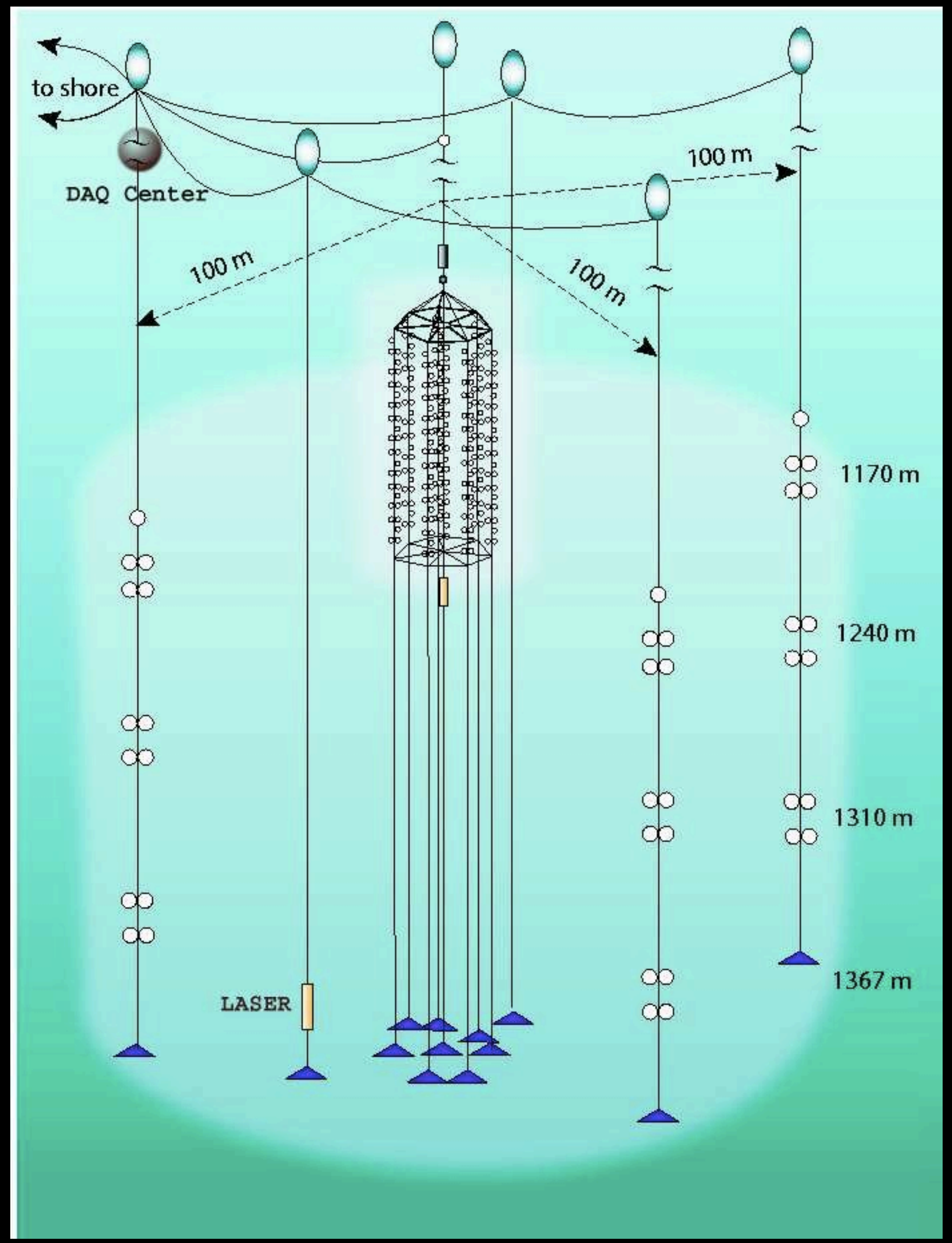


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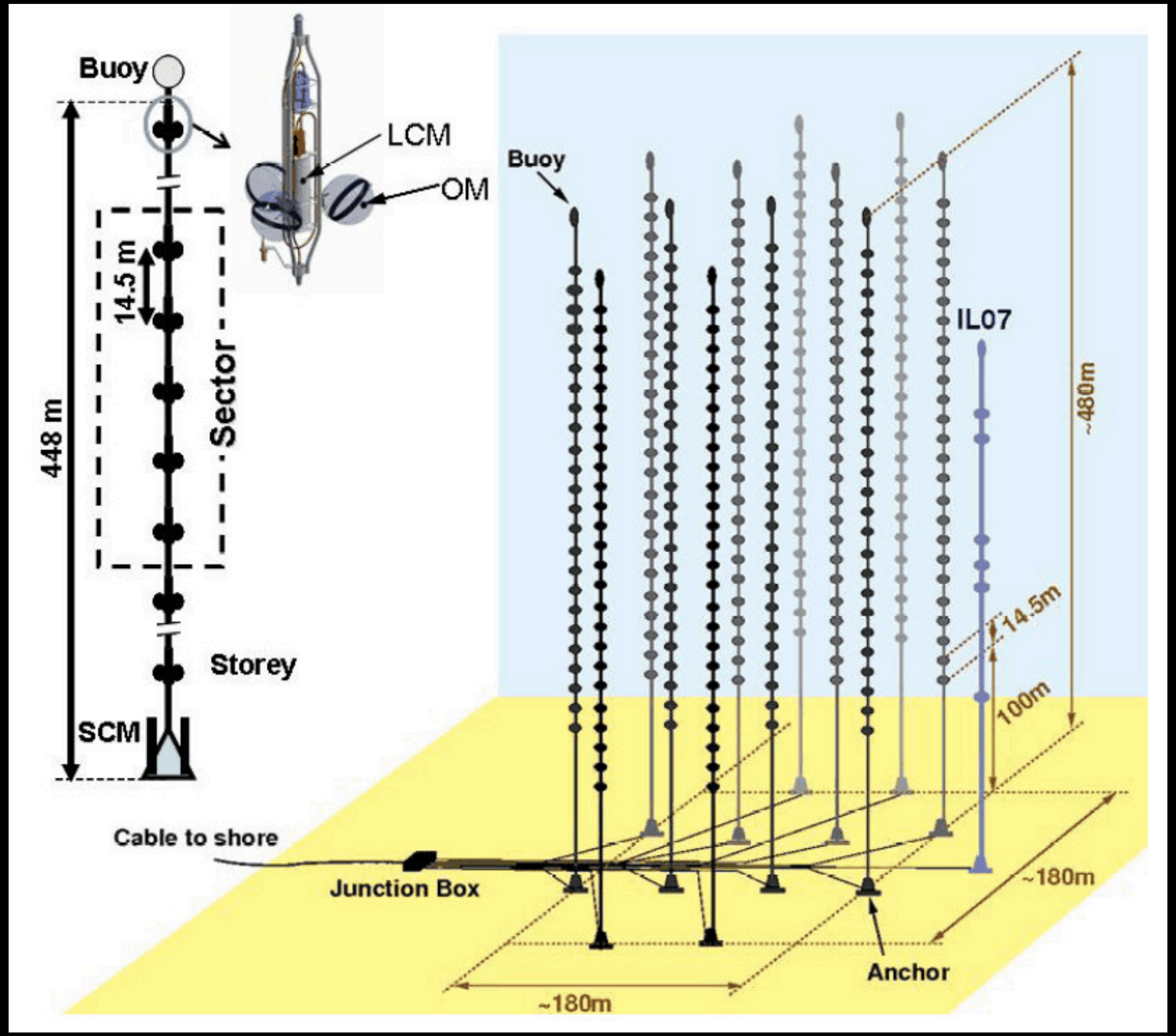


## ANTARES

- Mediterranean Sea (near Toulon, France). 2008-2022.
- **1/100 km$^3$**
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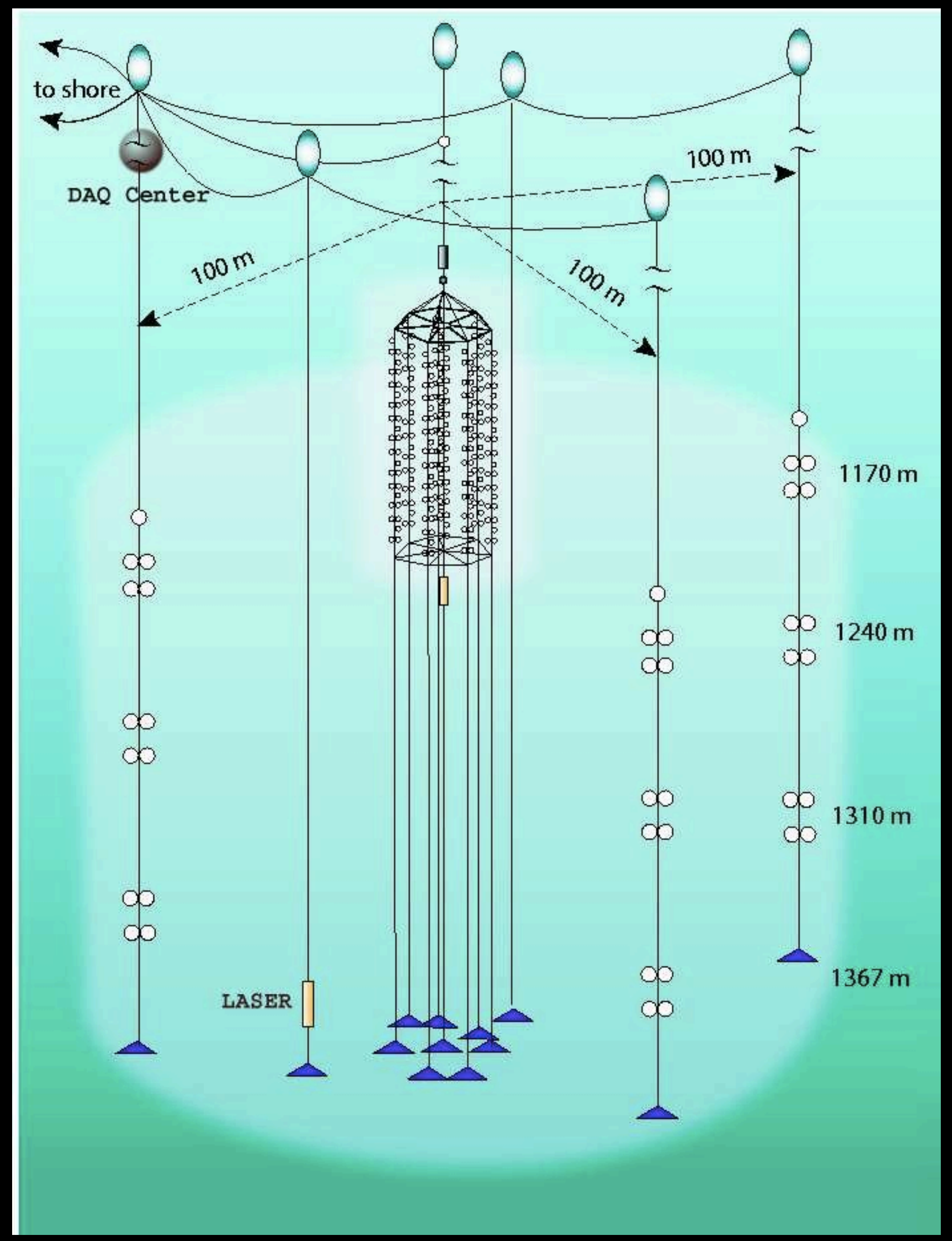


## Baikal NT-200+

- Lake Baikal, Russia. 2004/5
- **1/2000 km³**
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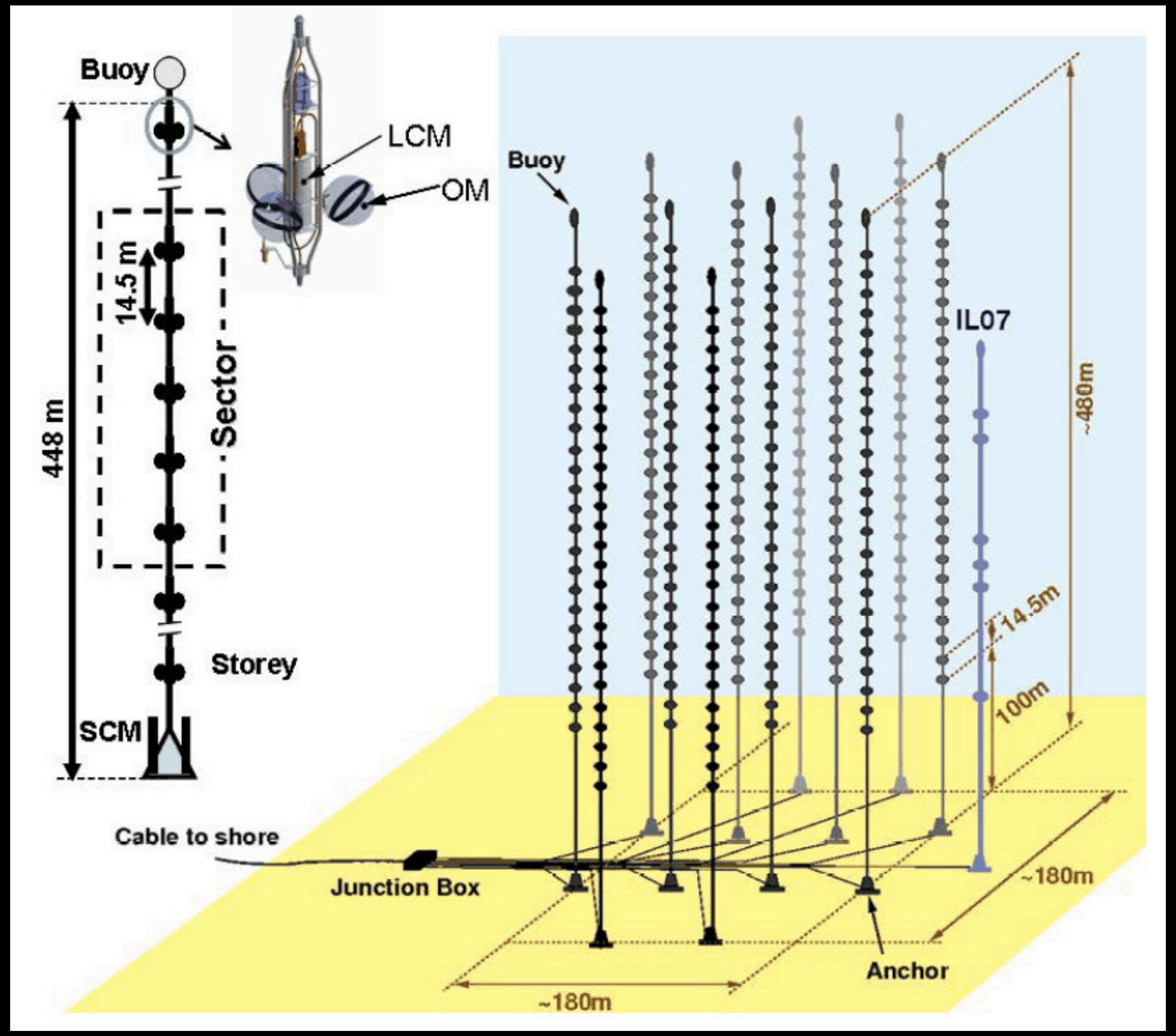


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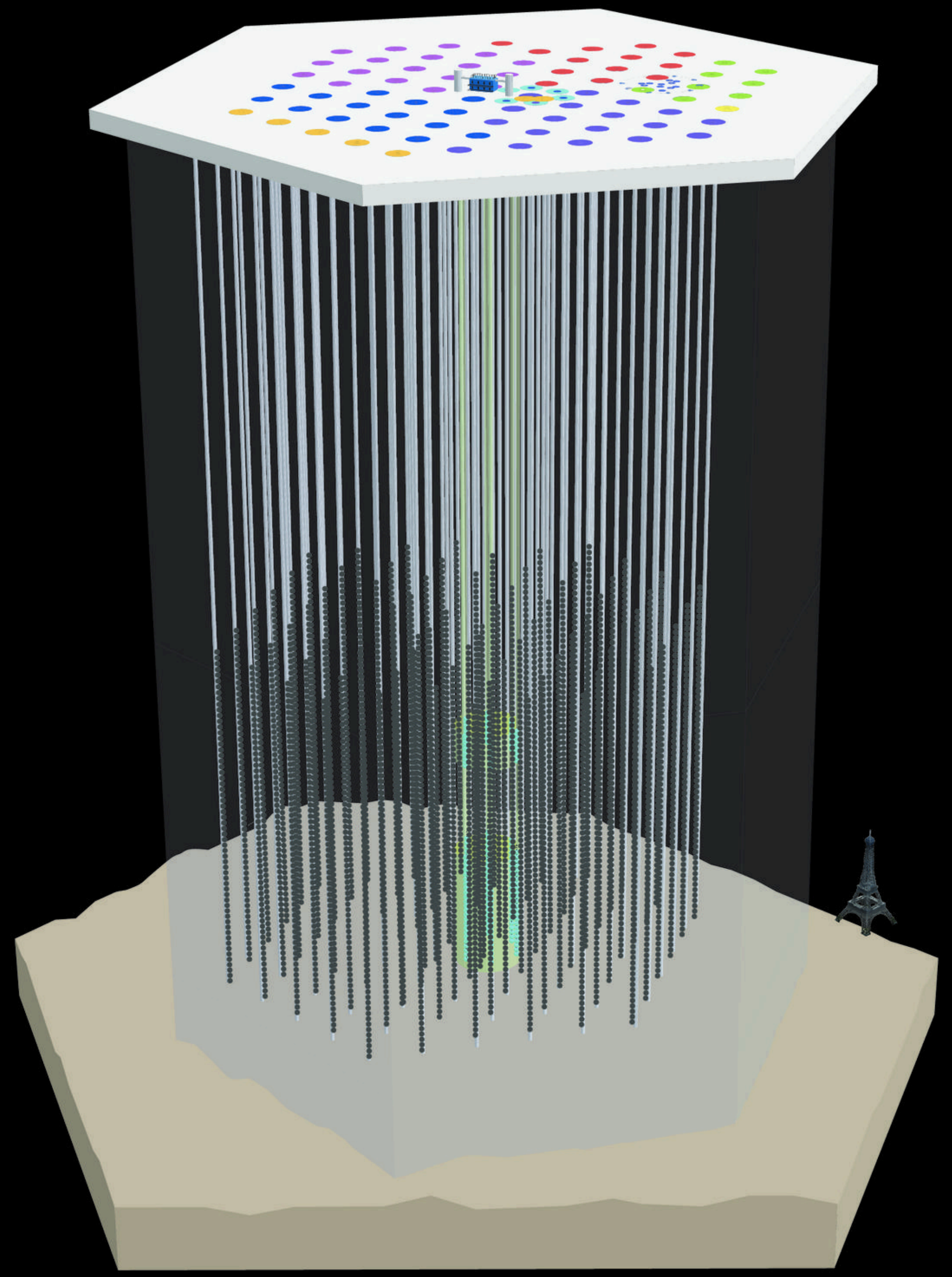
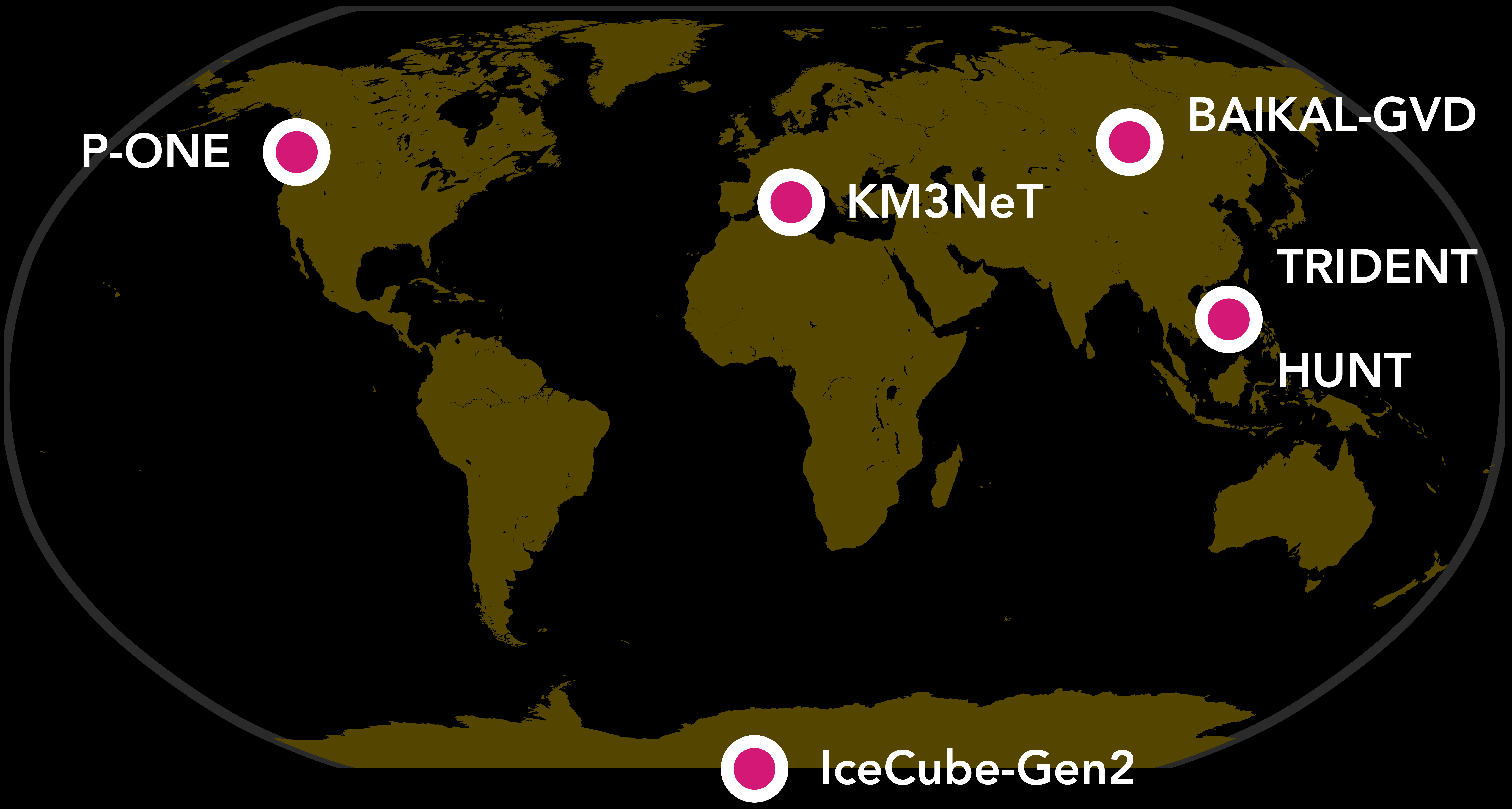


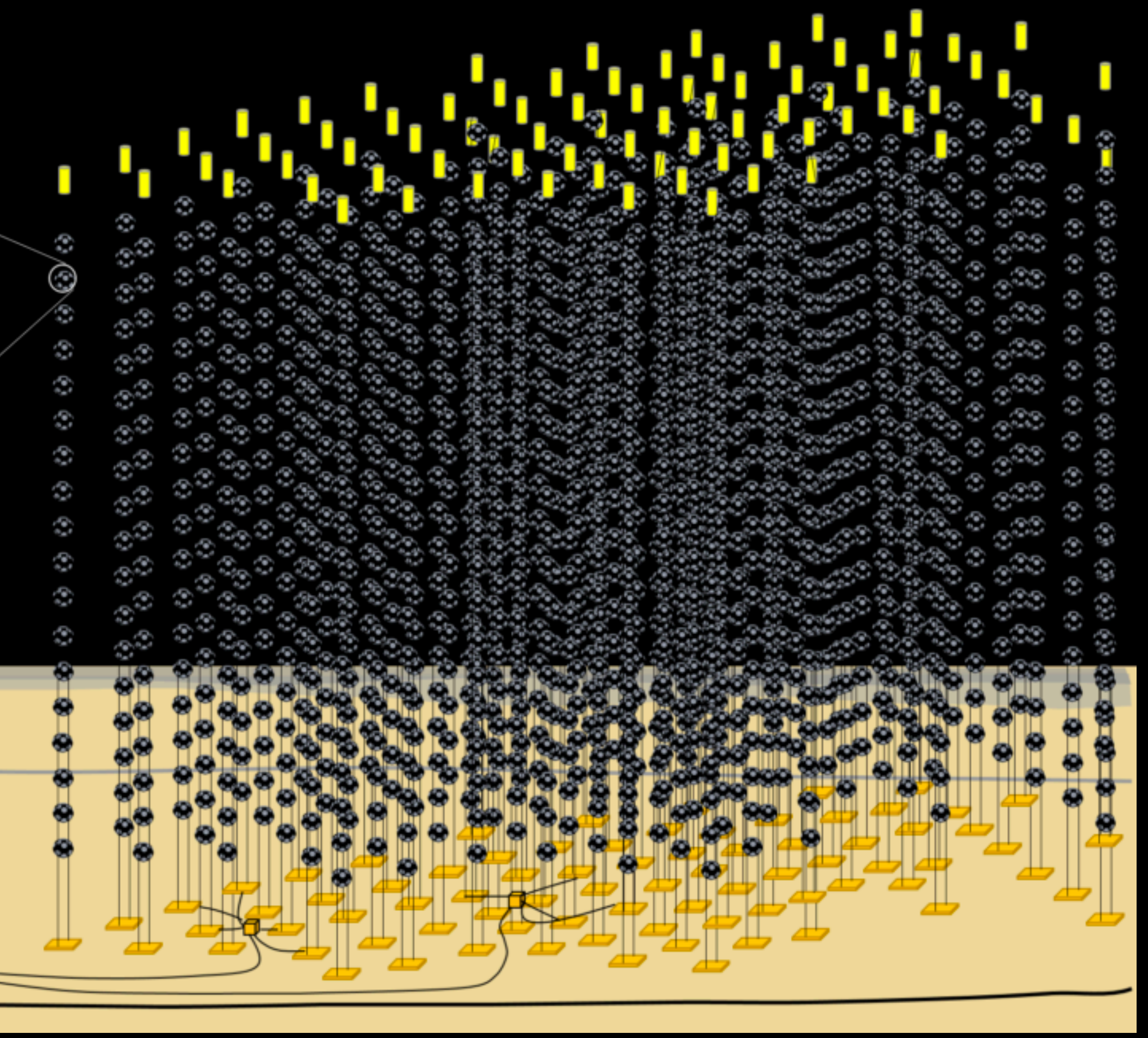
## IceCube

- South Pole glacier. 2010.
- **1 km³**
- 5160 PMTs

# UPCOMING ICE/WATER CHERENKOV TELESCOPES

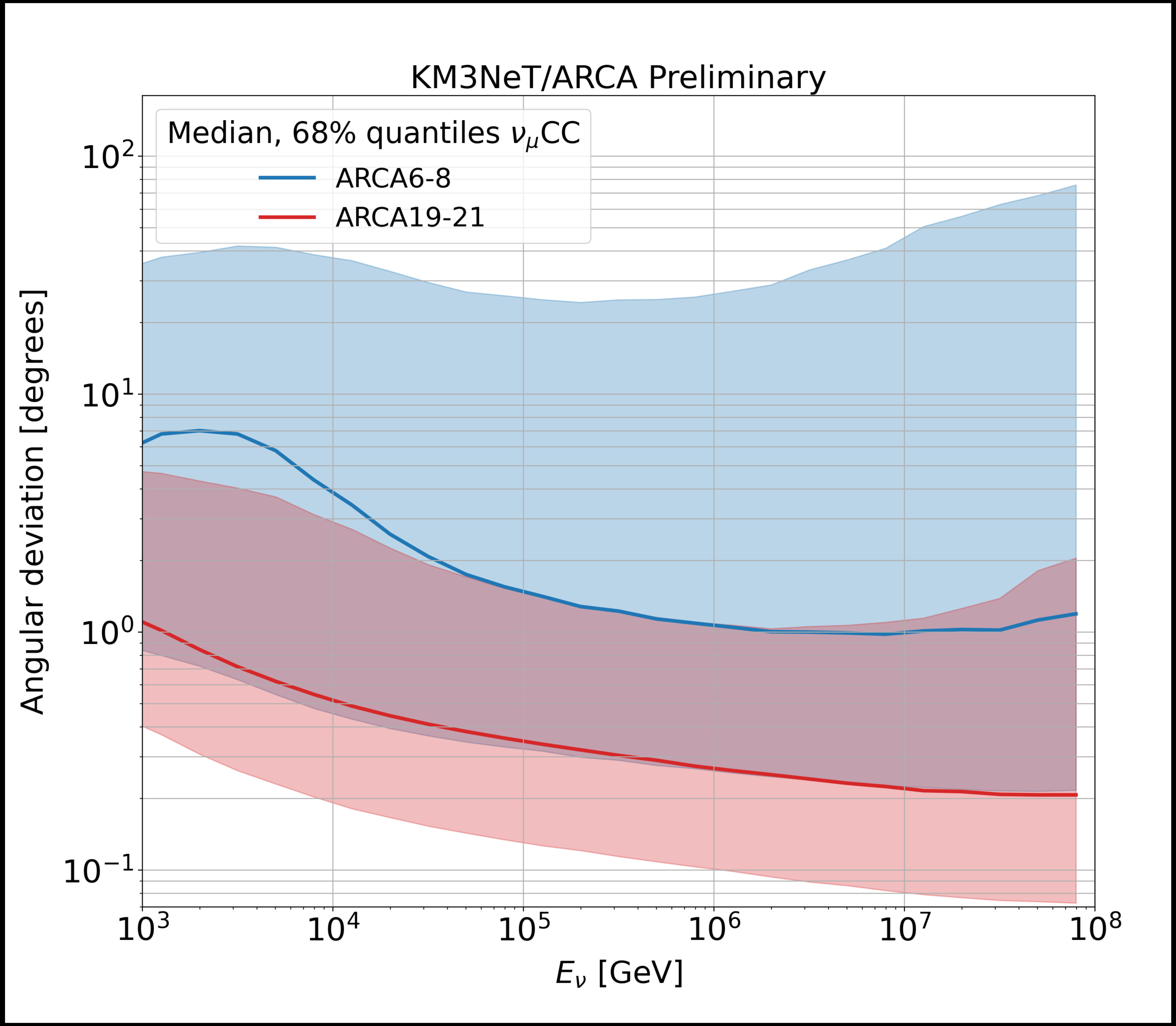


# KM3NET



- Mediterranean Sea, near Portopalo di Capo Pessaro, Sicily, Italy.
- **Targeting 1 km$^3$.** Will consist of two detector blocks with 115 lines each, 18 detectors per line. 28 are installed and operational at the moment.
- **Angular resolution of 0.1° expected for muon tracks. 2° for cascades.**
- First results from the 6-22 line detector (up to Dec 2022) presented at the ICRC.

# KM3NET




KM3NeT ICRC 2023 (Vol 444 1018)

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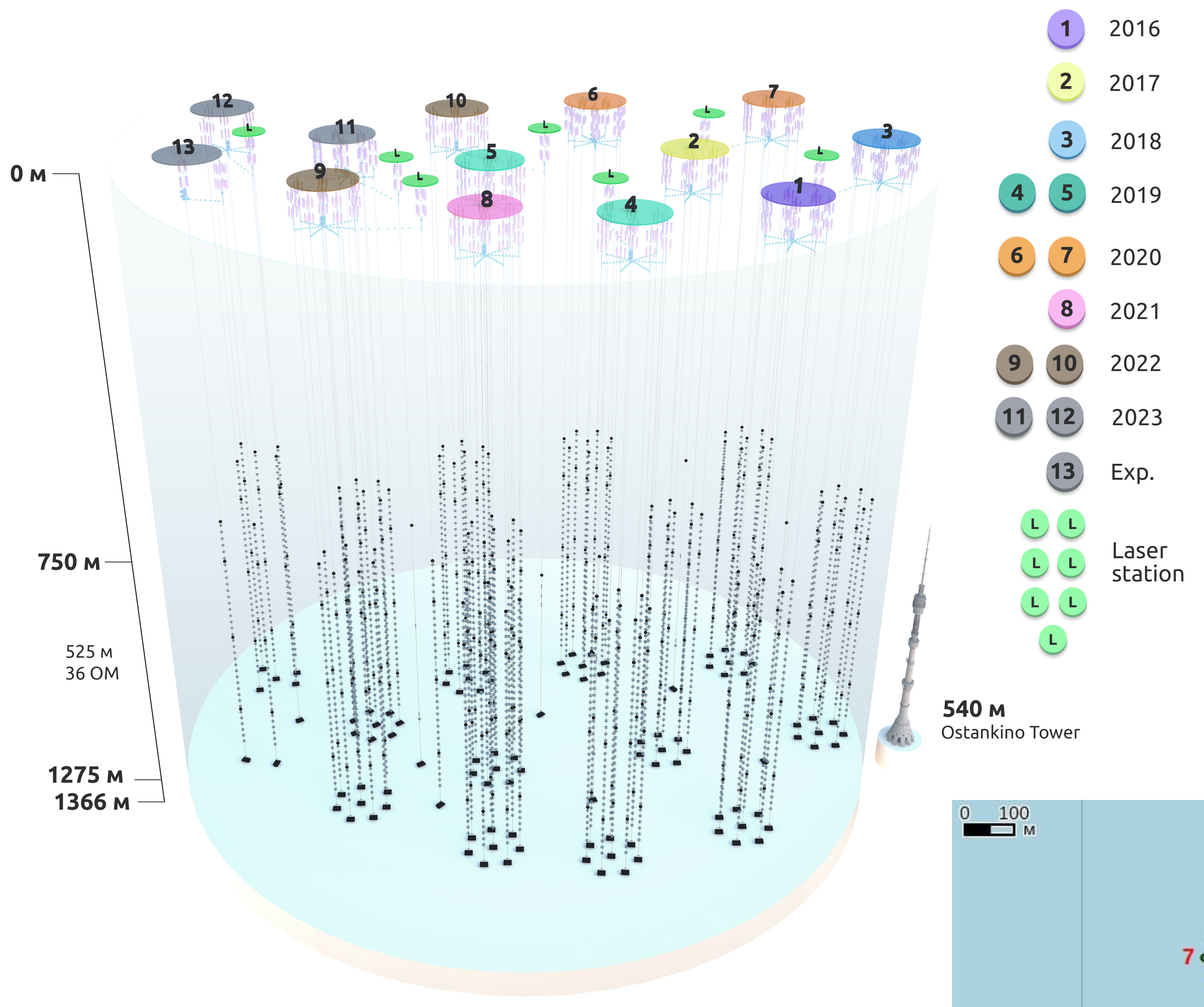
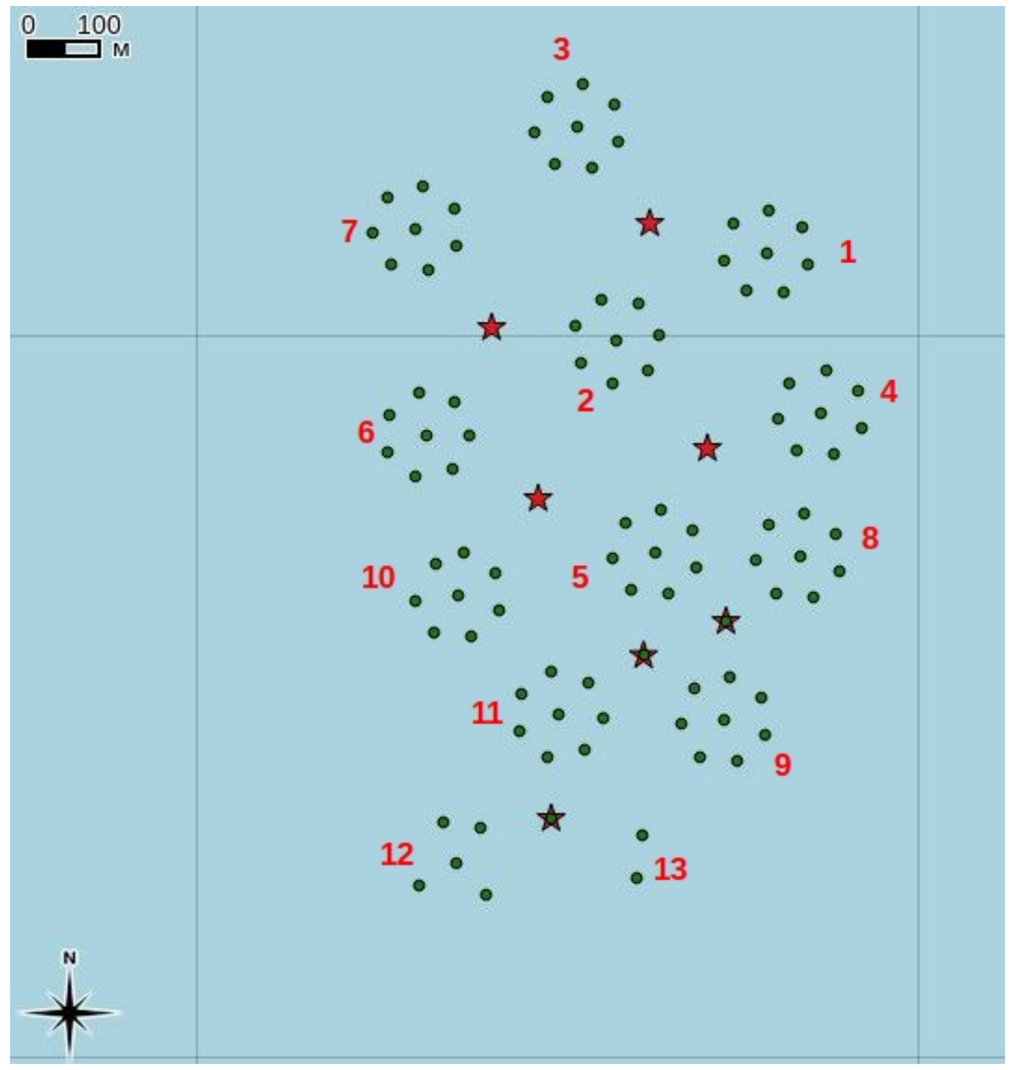
- First results from the 6-22 line detector (up to Dec 2022) presented at the ICRC.

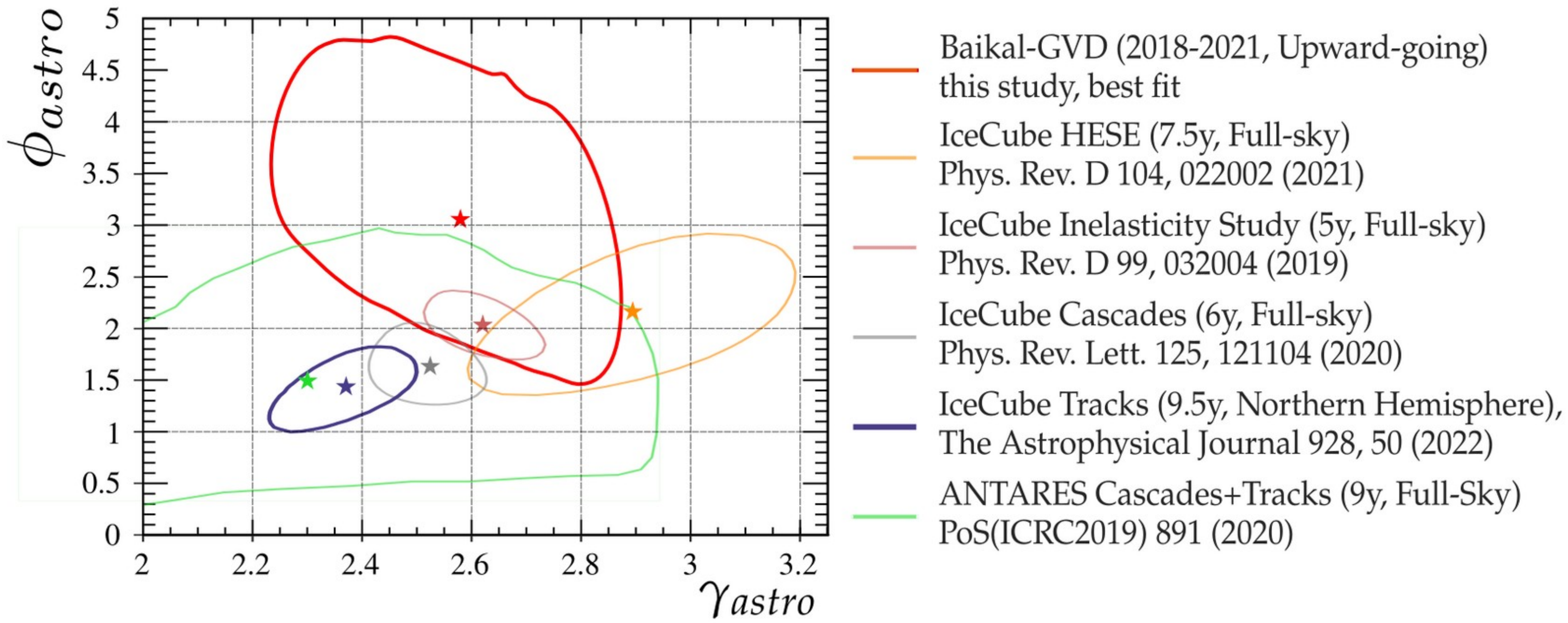
# BAIKAL-GVD

- Under construction in Lake Baikal, Russia. Also targeting 1 km3.
- Clusters of 8 strings each, as of the Winter of 2022-23, 13 clusters had been installed.
- First hints of a diffuse astrophysical flux presented at 2023 ICRC.



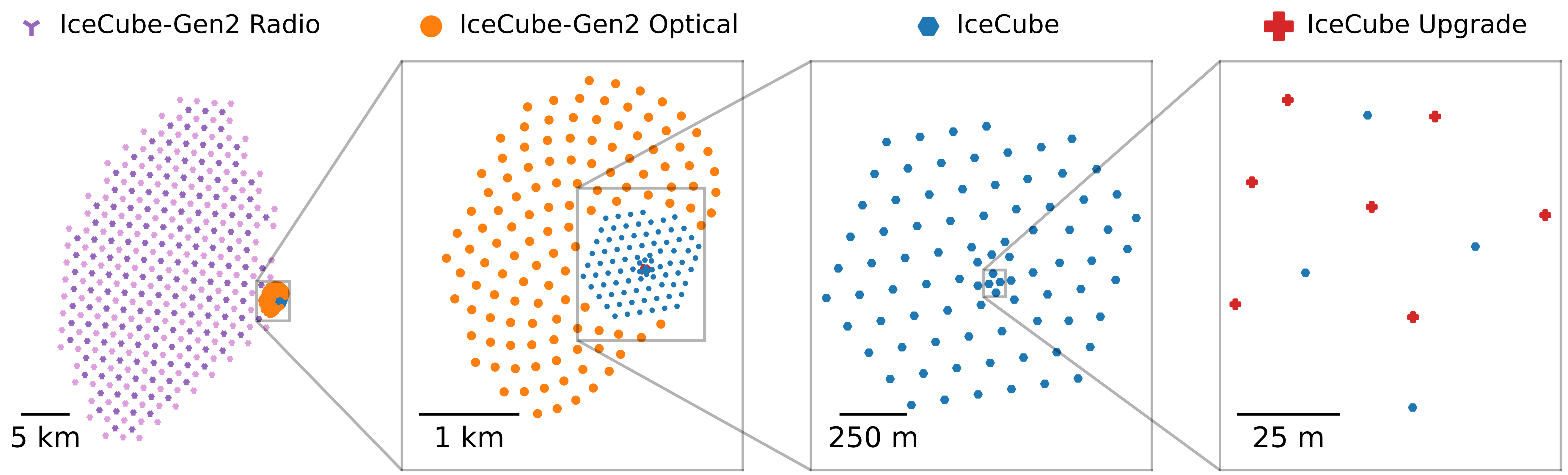



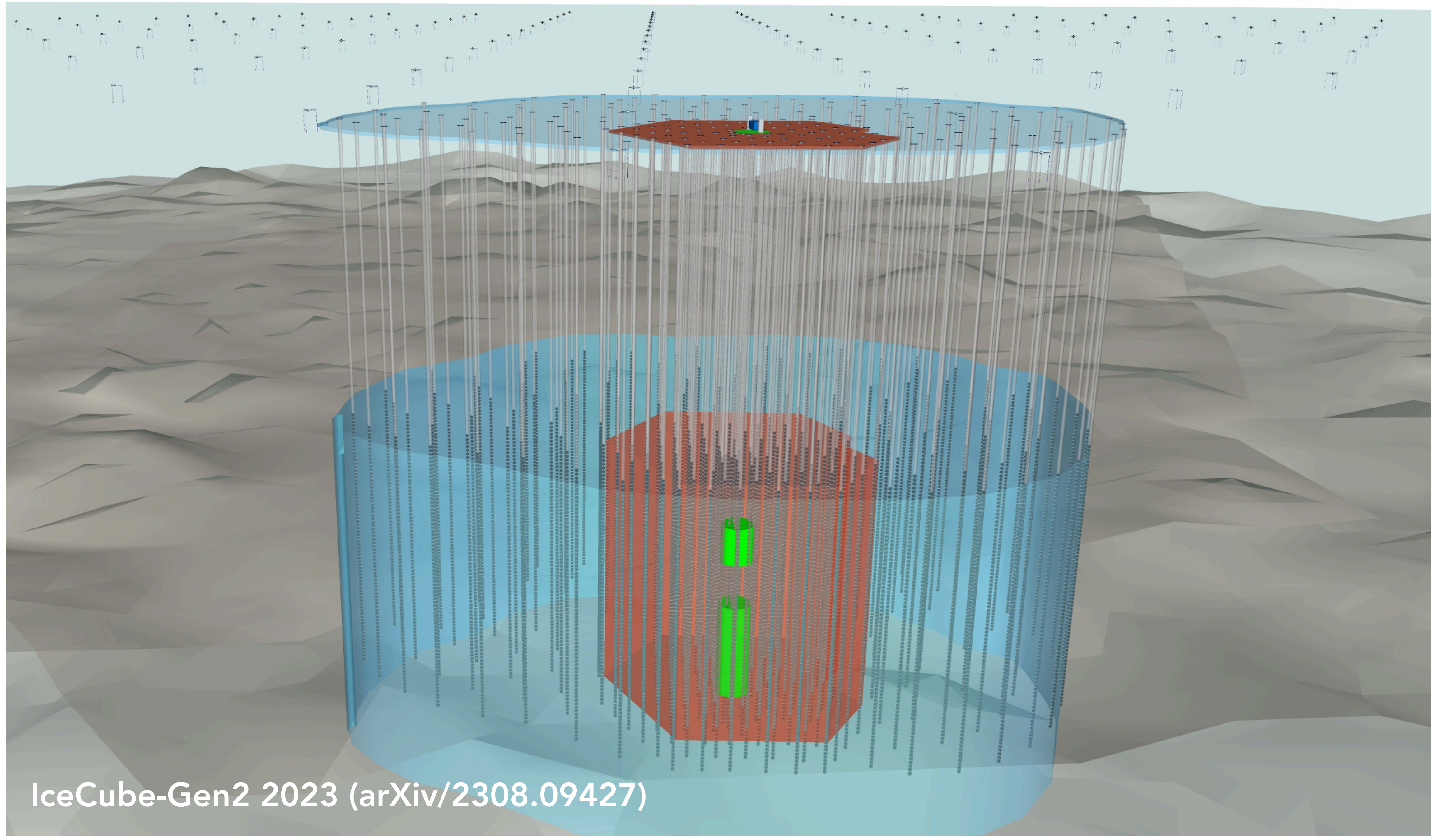

Baikal-GVD Collaboration ICRC 2023 (Vol 444 976)



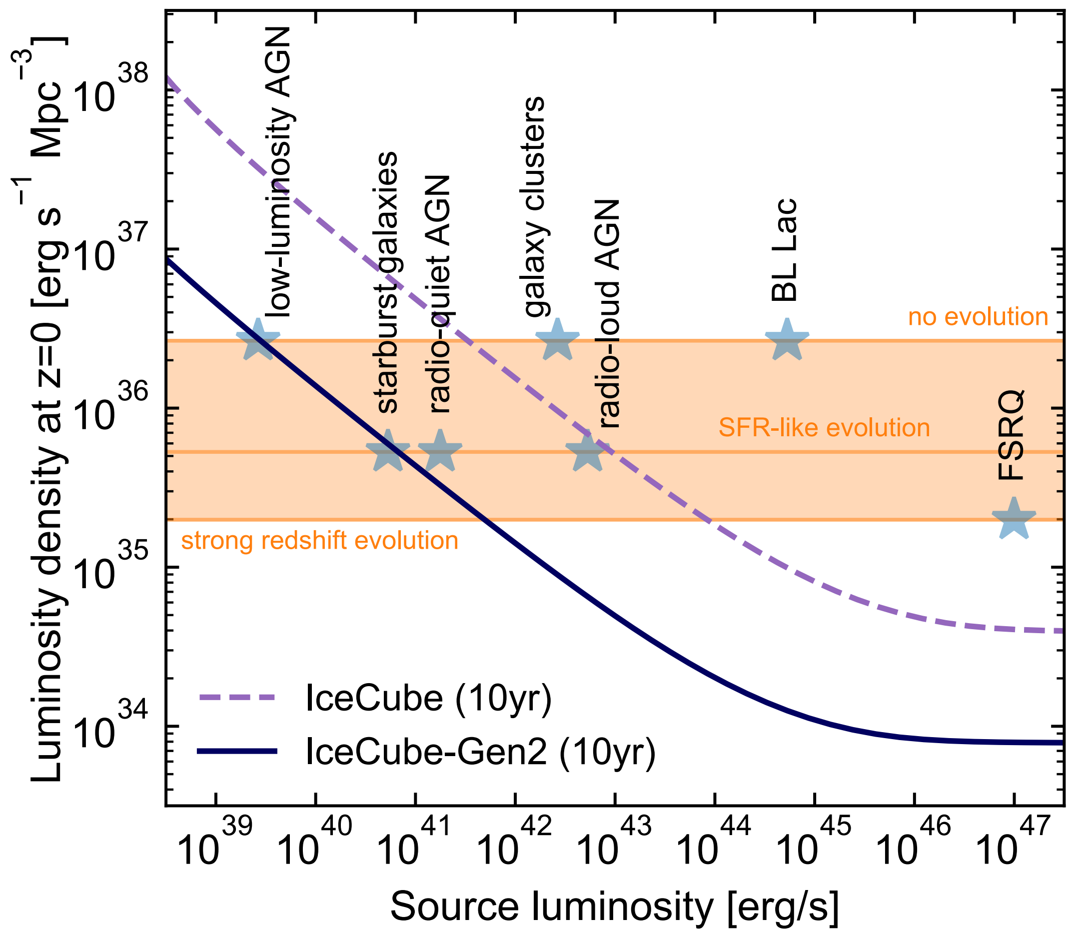

Baikal-GVD Collaboration ICRC 2023 (Vol 444 1015)

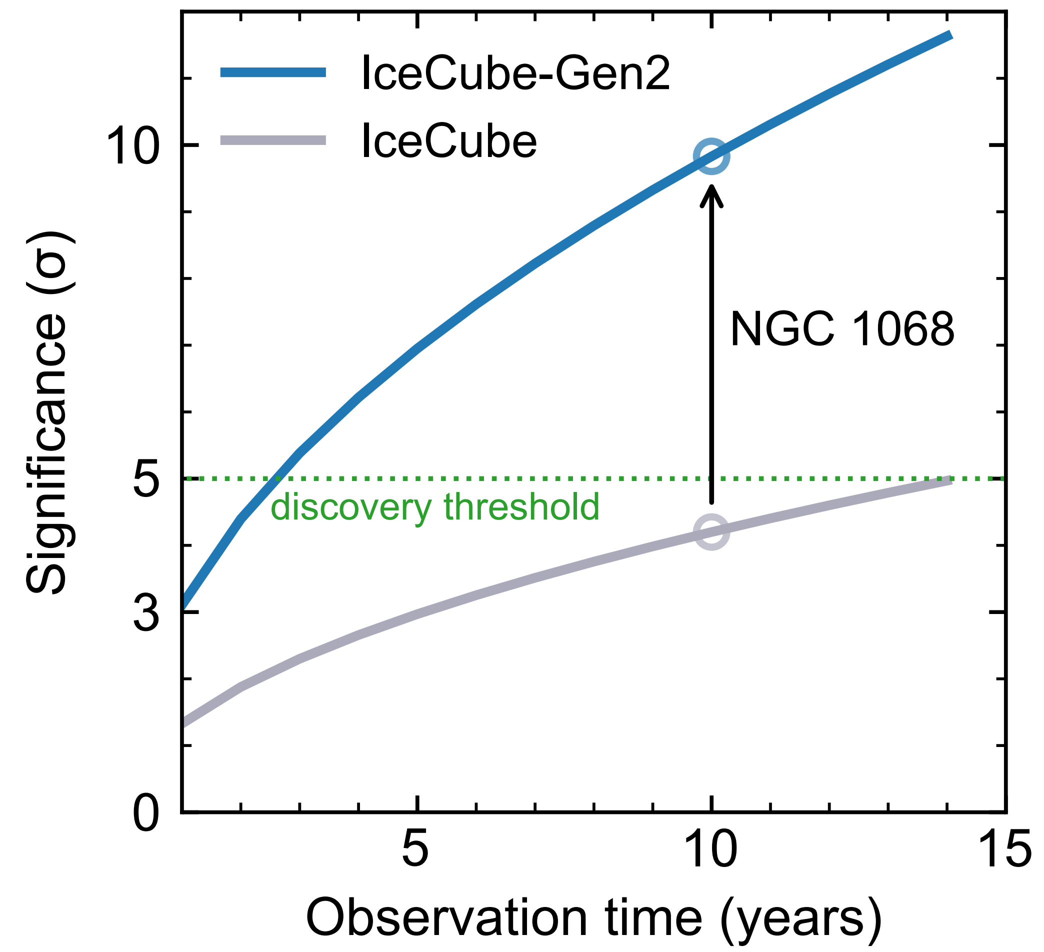
# ICECUBE-GEN2



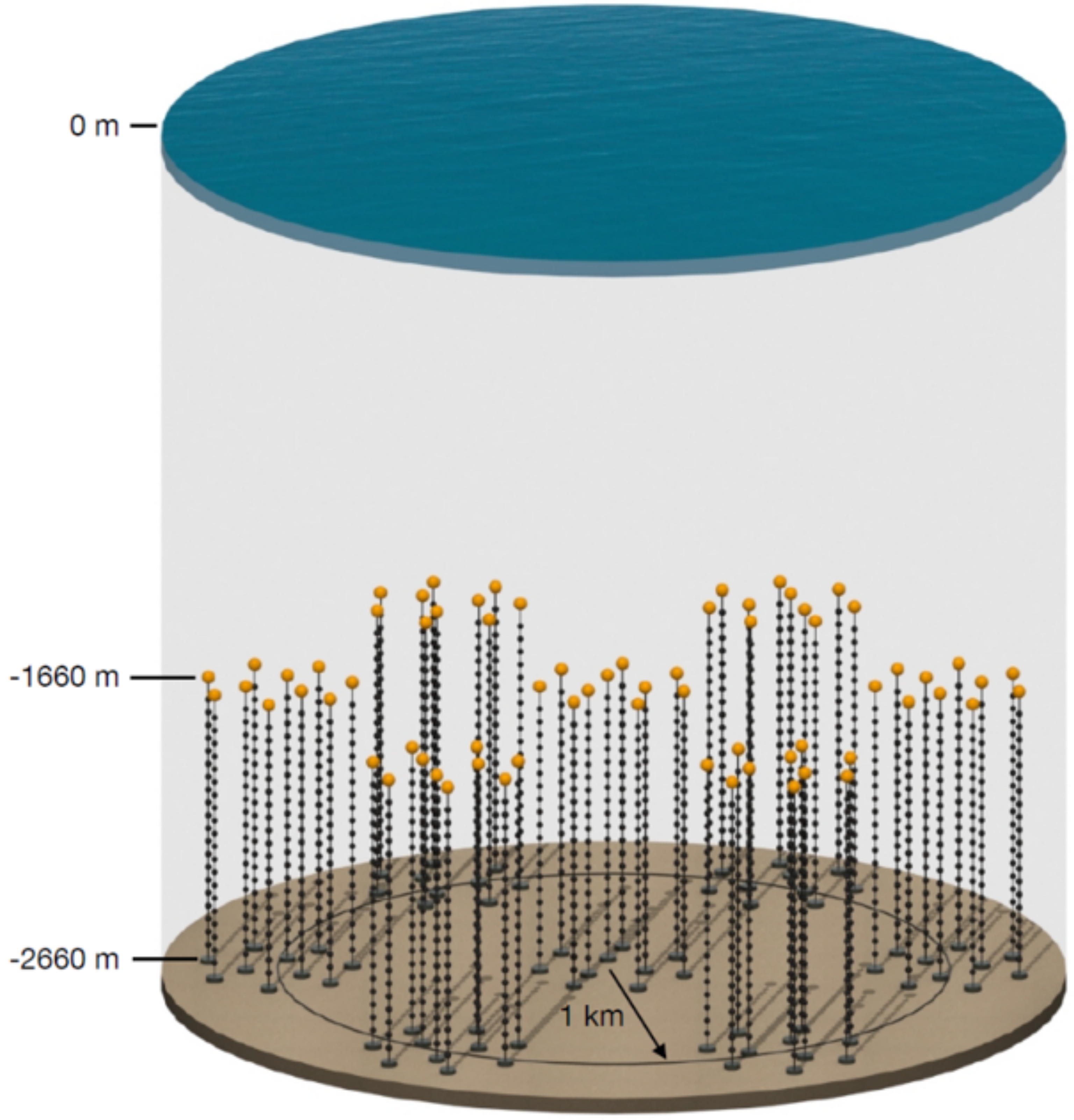



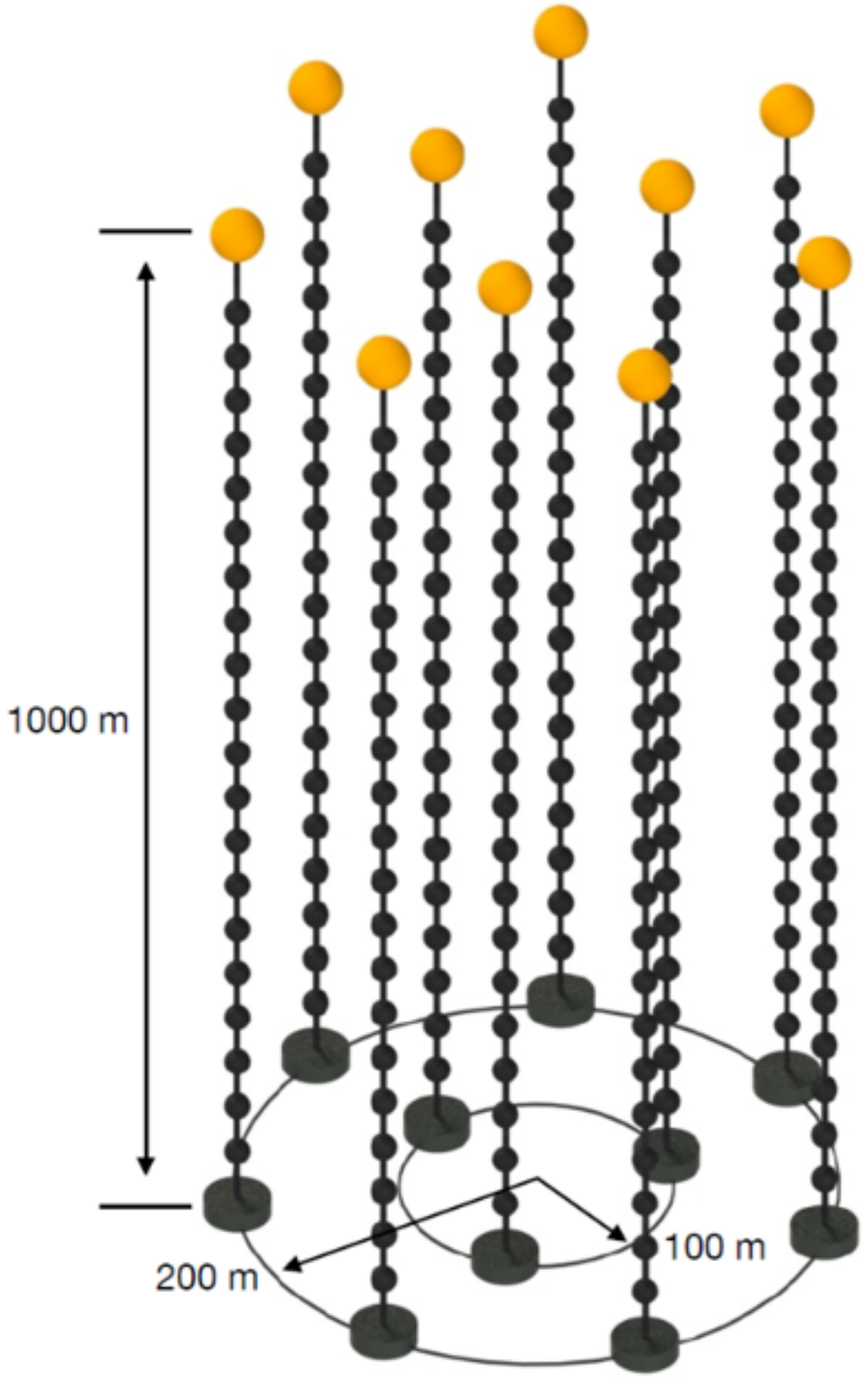

- Detector volume of ~8 km$^3$. Strings farther apart than in current IceCube, optimized for high energies.
- Angular resolution improved by x3 wrt current IceCube.
- Strong source detections within reach of the first 10 years of operation.
- Endorsed by the Astro2020 Decadal Survey in the U.S.
- IceCube Upgrade to be installed in the 2025-26 Austral summer (pending updates).



# P-ONE

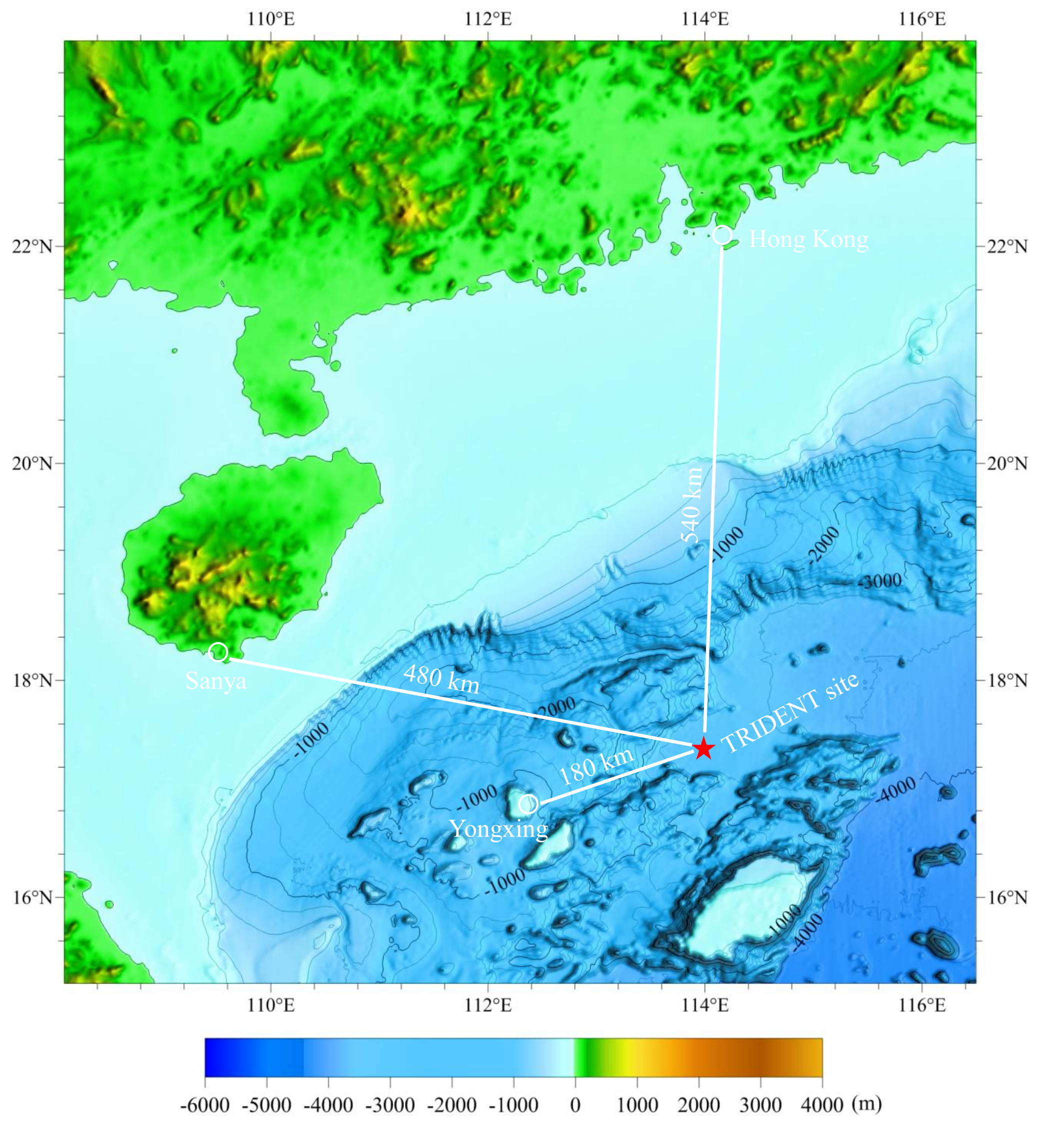


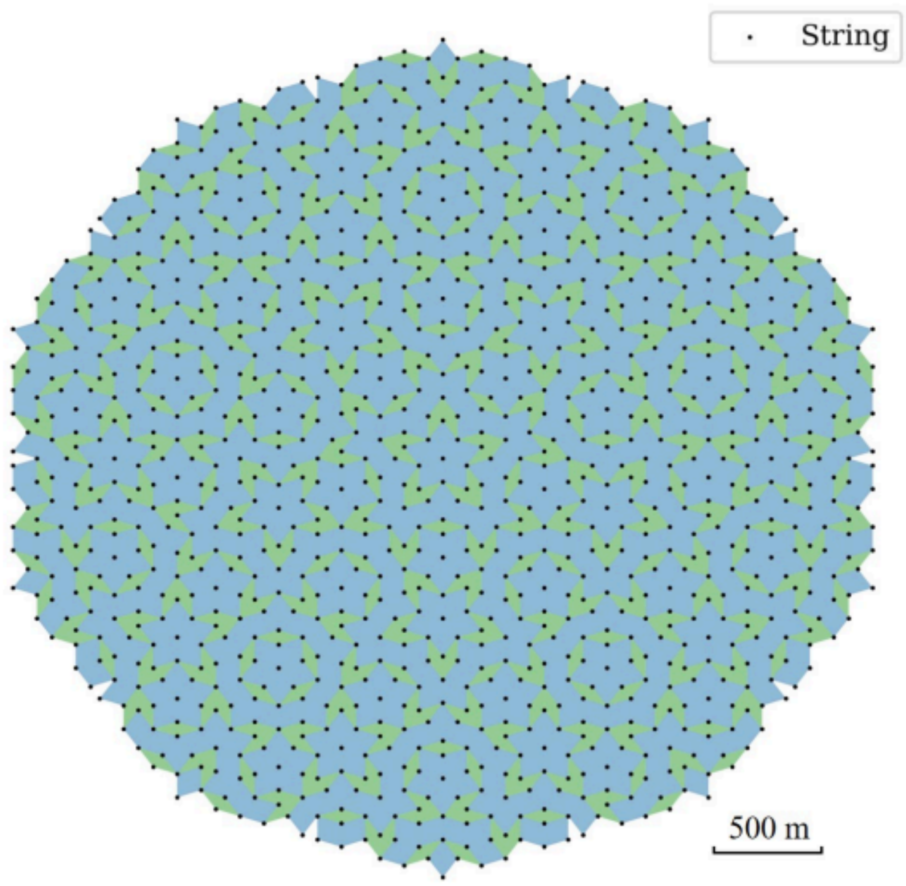




- Cascadia basin off the coast of British Columbia, Canada.
- Deployed two pathfinder lines (STRAW-a/b in 2018 and 2020), currently working on the development of a prototype line.
- **Targeting 1 km³**. 7 clusters of 10 lines each, 20 detectors per line.

P-ONE Collaboration ICRC 2023 (Vol 444 1197)

# TRIDENT



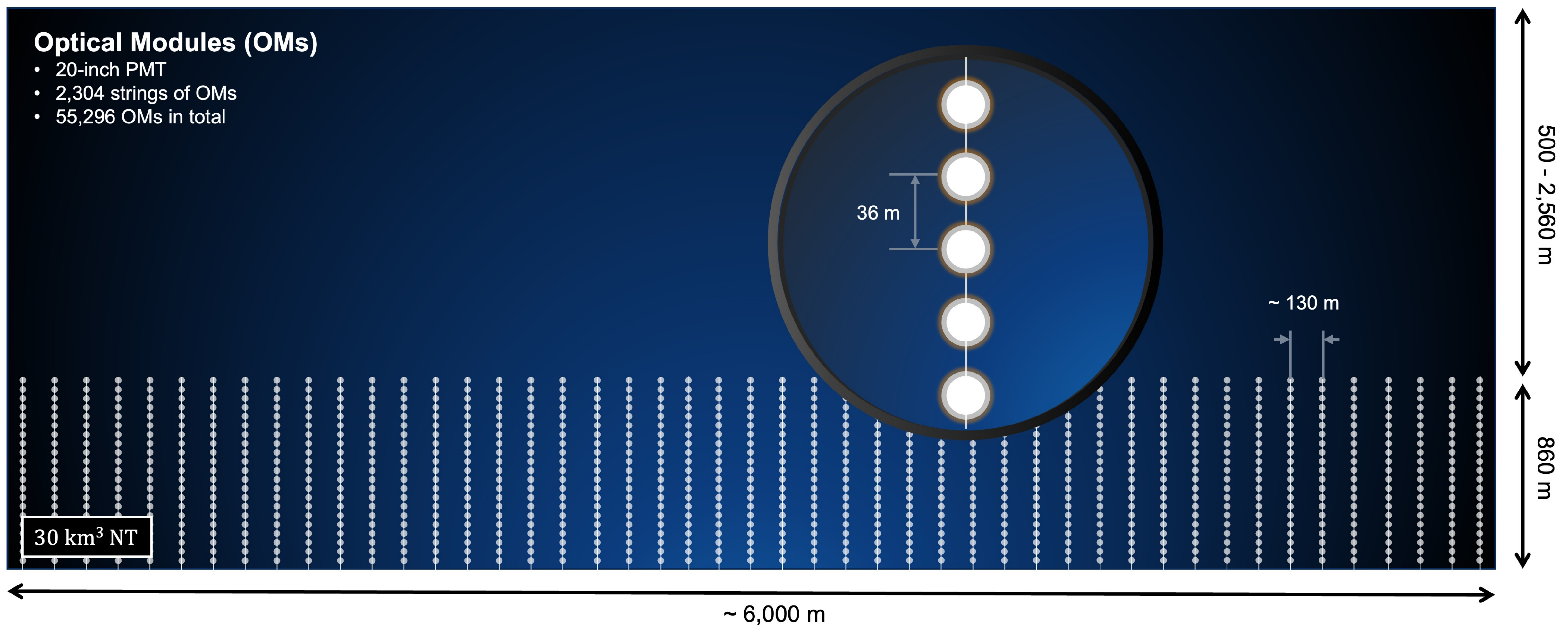




TRIDENT Collaboration (2022, arXiv/2207.04159)

- Projected volume of 7.5 km$^3$ with ~1200 strings.
- Testing for a site for a neutrino telescope in the South China Sea.
- Optimization of detector layout and optical modules.

# HUNT

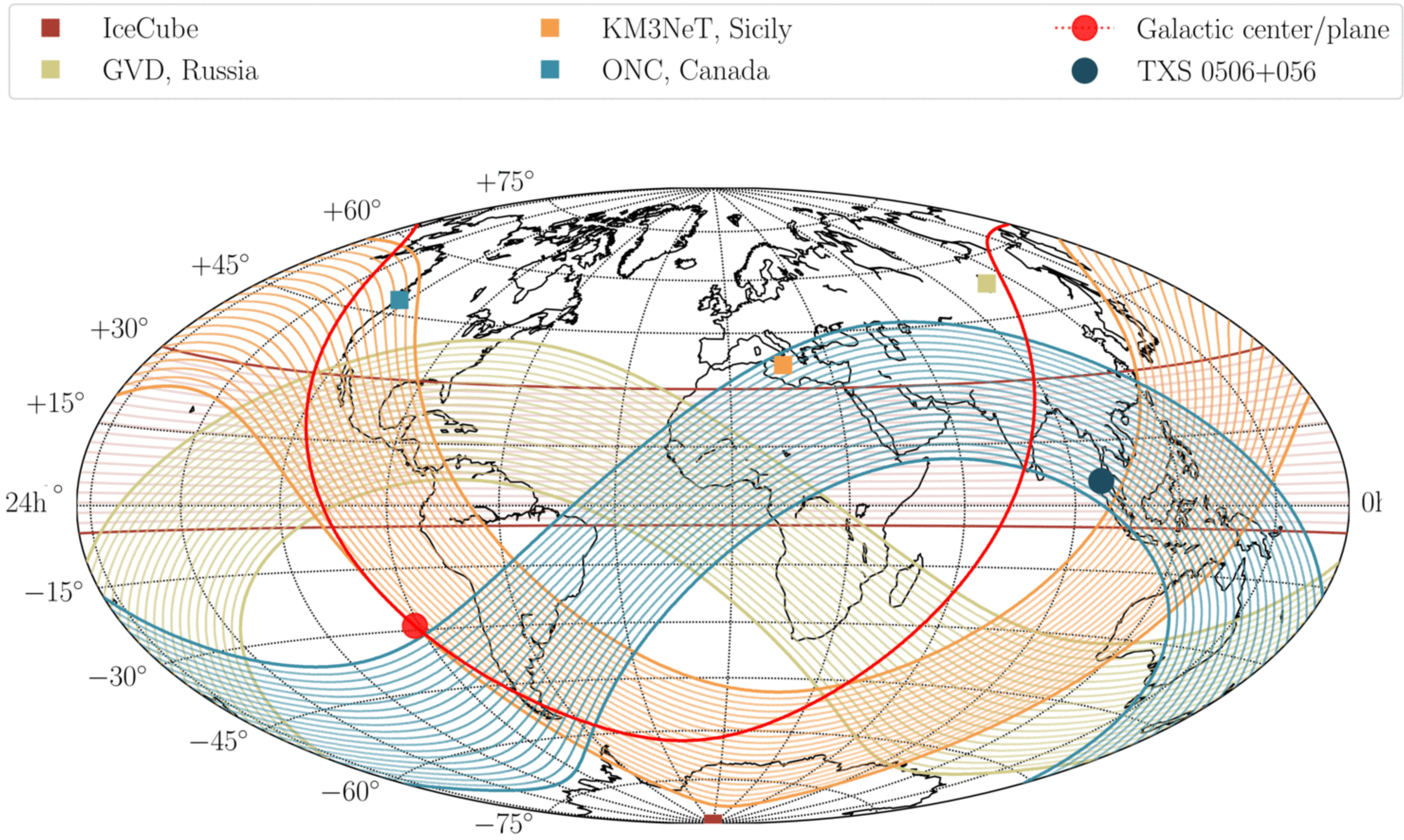
HUNT Collaboration ICRC 2023 (Vol 444 1080)



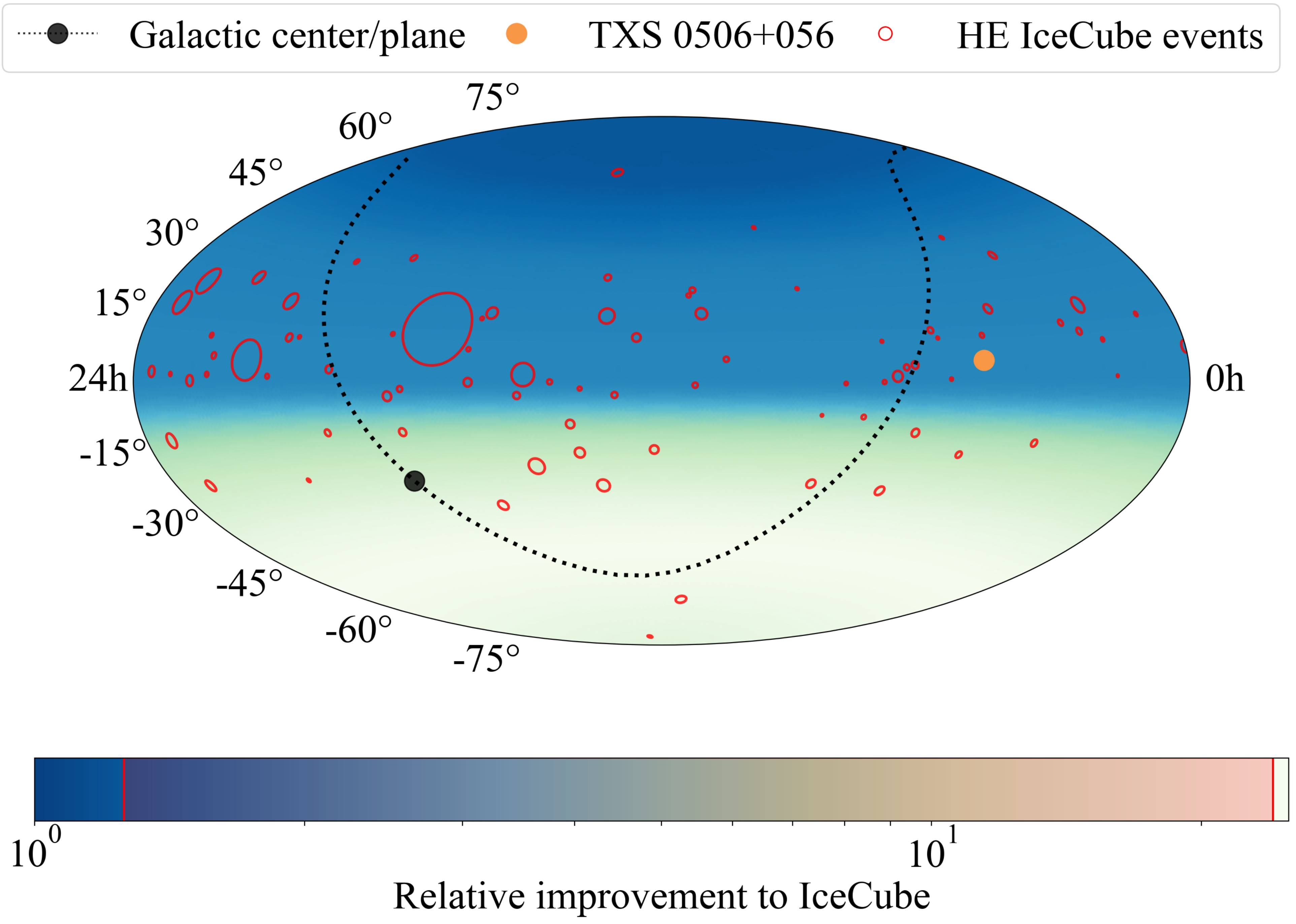

- Proposed to be built in the South China Sea.
- 2304 strings. Each with 24 optical modules to cover a volume of **30 km$^3$**.
- Main goal is to target PeV neutrino astronomy.
- First pathfinder (2 modules) tested in the sea in Feb 2023.

# COMBINING NEUTRINO OBSERVATIONS

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




PLEνM

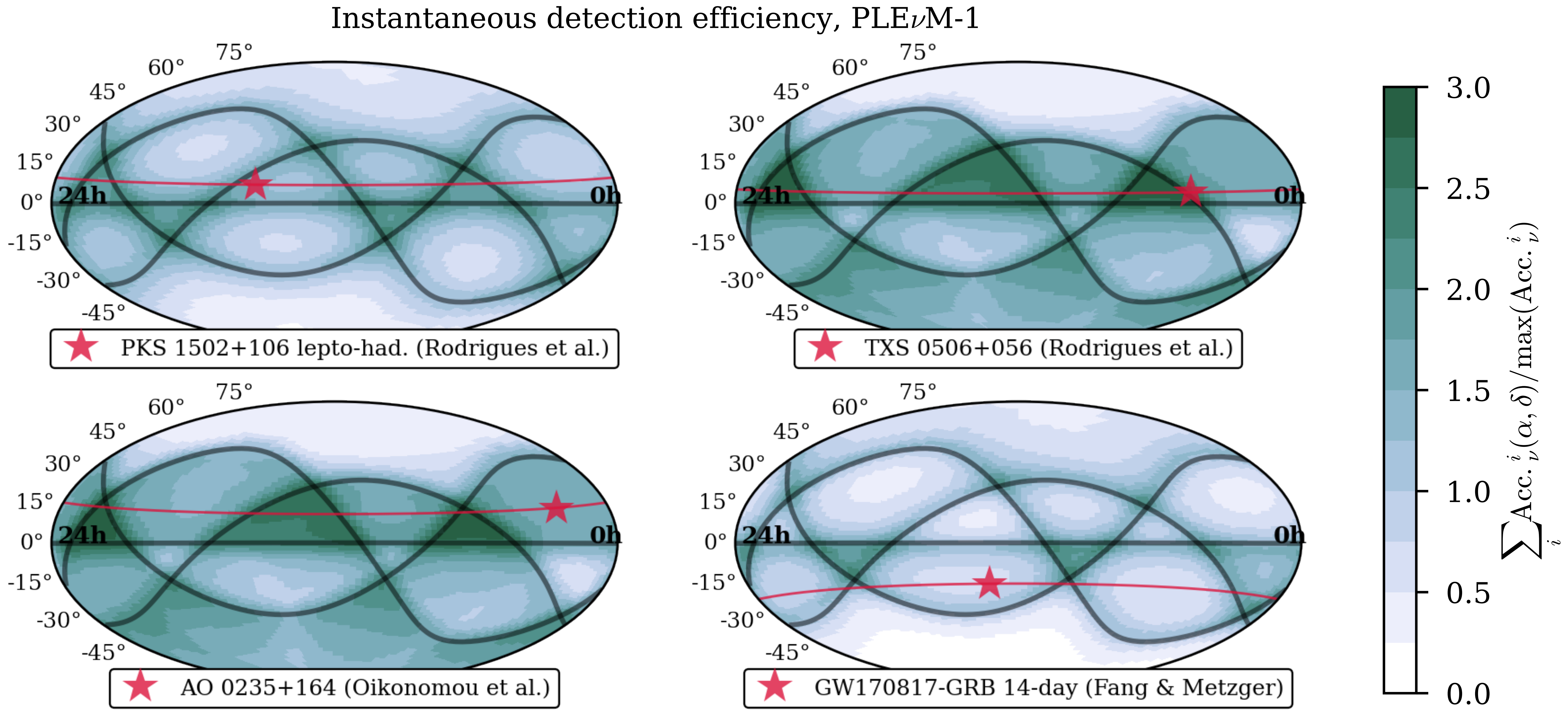



L. Schumacher et al. (arXiv/2107.13534)

- 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**.

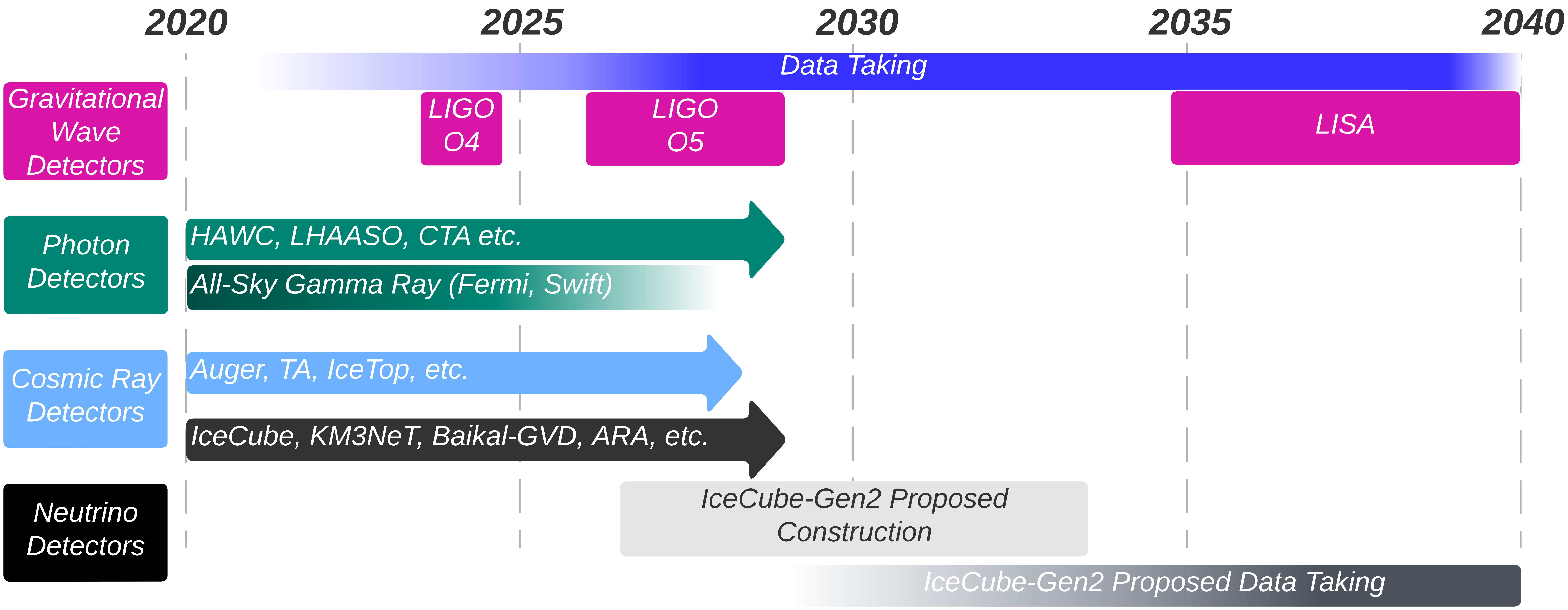
# COMBINING NEUTRINO OBSERVATIONS

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



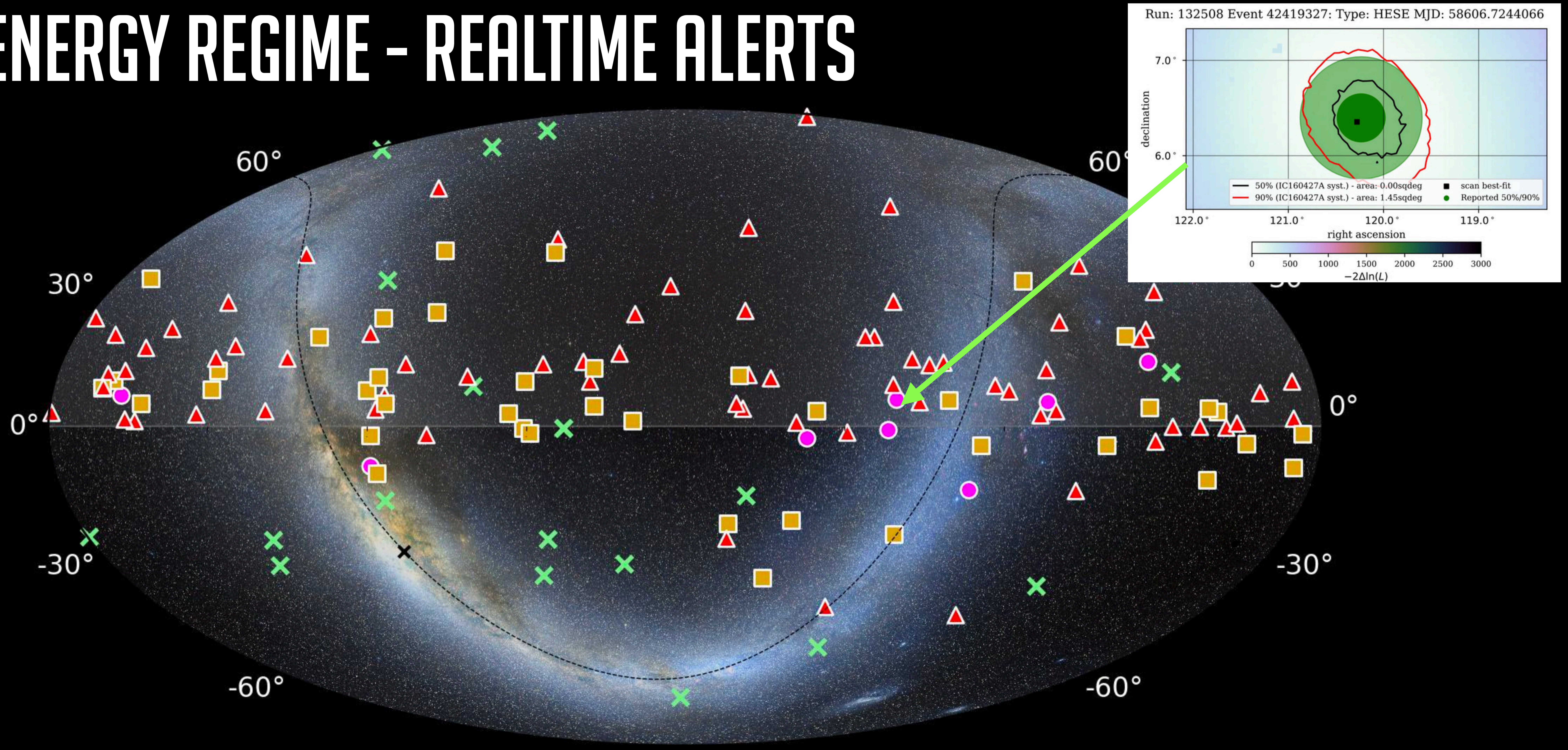

- Significant improvements by combining detectors at different latitudes and longitudes (background suppression).
- Acceptance and sky coverage for alerts increased by a factor of ~5.
- Additional telescopes looking to expand statistics at the highest energies (e.g RNO-G, TRINITY, GRAND, TAMBO).

# THE NEXT DECADE(S)




- **These telescopes will be operating in a rich multimessenger landscape!**

# HIGH-ENERGY REGIME – REALTIME ALERTS




- Characterizing potential counterparts requires broadband EM observations.
- Understanding the PSF of neutrino telescopes is challenging!

# A PAGE FROM HISTORY

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

**Neutrino Triggered Target of Opportunity (NToO) test run with AMANDA-II and MAGIC**

M. ACKERMANN[1,5], E. BERNARDINI[1], N. GALANTE[2], F. GOEBEL[2], M. HAYASHIDA[2], K. SATALECKA[1], M. TLUCZYKONT[1], R. M. WAGNER[2], FOR THE ICECUBE[3] AND MAGIC COLLABORATIONS[4]
[1]*DESY, Platanenallee 6, 15738 Zeuthen*
[2]*MPPMU, Föhringer Ring 6, 80805 München*
[3]*See special section of these proceedings*
[4]http://magic.mppmu.mpg.de/collaboration/members
[5]*Now at SLAC, Stanford University, USA*
*elisa.bernardini@desy.de*

IceCube and MAGIC Collaborations, ICRC 2007 (arXiv/0709.2640)

Bernardini et al. (IceCube) astro-ph/0509396

sen sky bins contain a fraction of the signal Monte Carlo events, passing the same selection, which varies between about 60% up to about 85%, according to the source declination and the assumed spectral index.

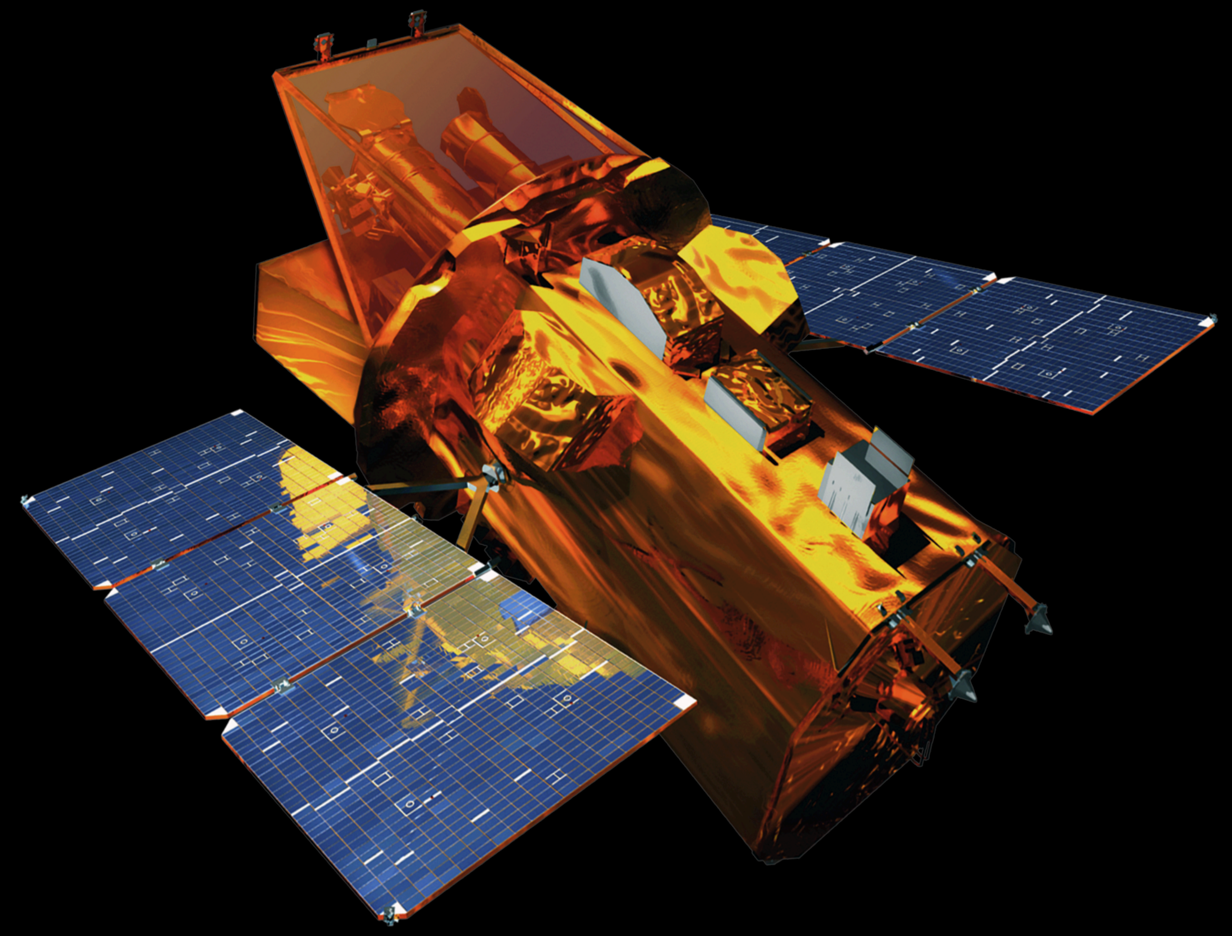
In conclusion, we encourage the long-term and unbiased monitoring at different wavelengths of those neutrino candidate sources which show an evident character of variability in the high energy gamma-ray emission (Blazars in particular). We also encourage the establishment of working groups to further develop the multi-messenger approach, i.e. to involve neutrino observations within the already effective multi-wavelength campaigns, and, in general, multidisciplinary investigations of objects like the Blazar 1ES1959+650 and similar.

## Acknowledgments

- First VHE gamma-ray follow-up of neutrinos performed by MAGIC and AMANDA-II in **2006**!

# X-RAY COVERAGE

**Neil Gehrels *Swift* Observatory**

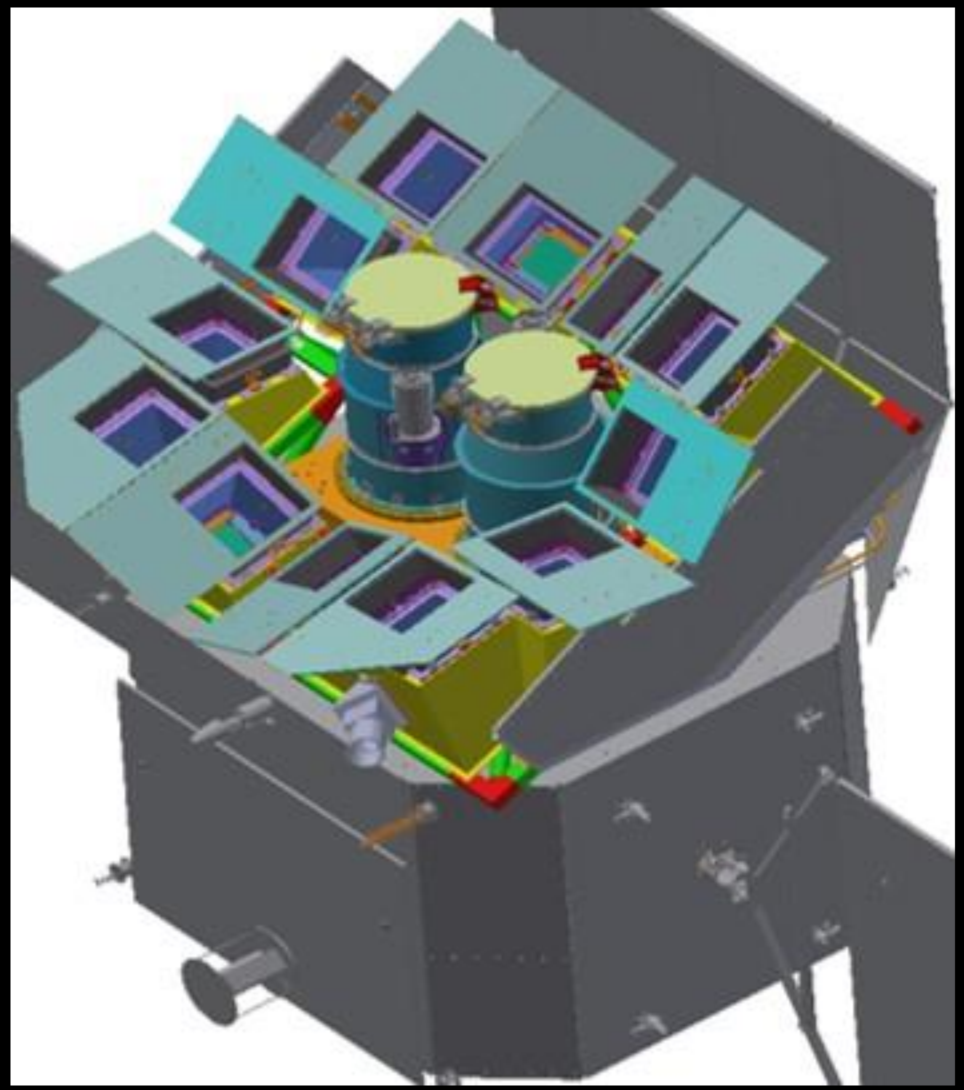


**XRT sensitivity in the 0.3-10 keV**
Fast response, low overhead.
110 $cm^2$
~0.4 deg FoV. Launched in 2004.

**SVOM** (China-France)

Rapid follow-ups of GRBs
Launch date of Spring 2024
0.2-10 keV
"Lobster eye" optics with 1 deg FoV

**Einstein Probe** (China-ESA)

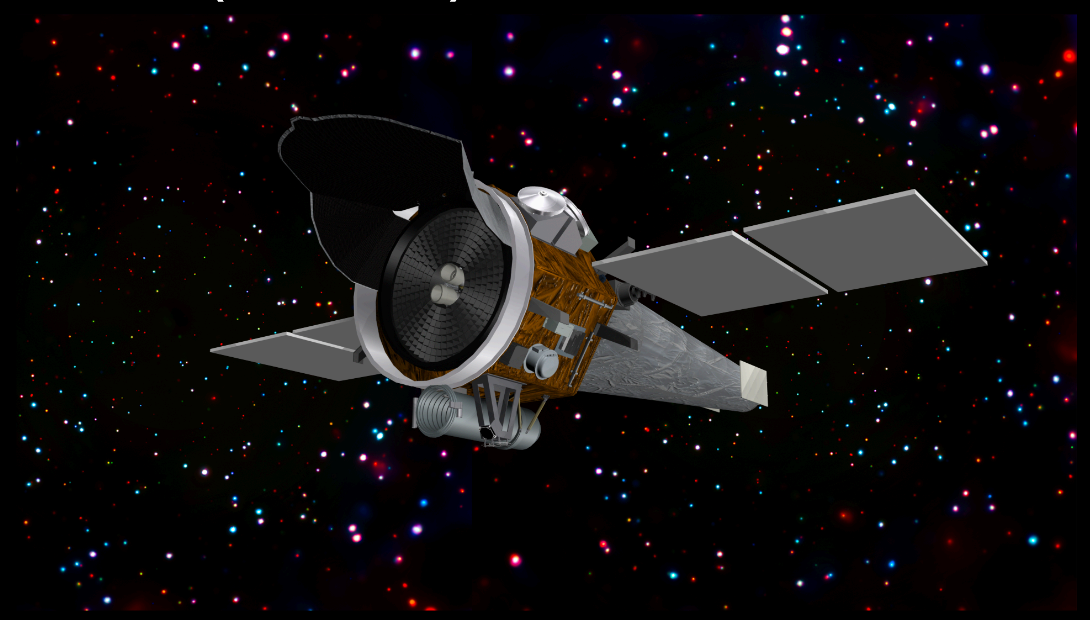


Late 2023 launch?

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'

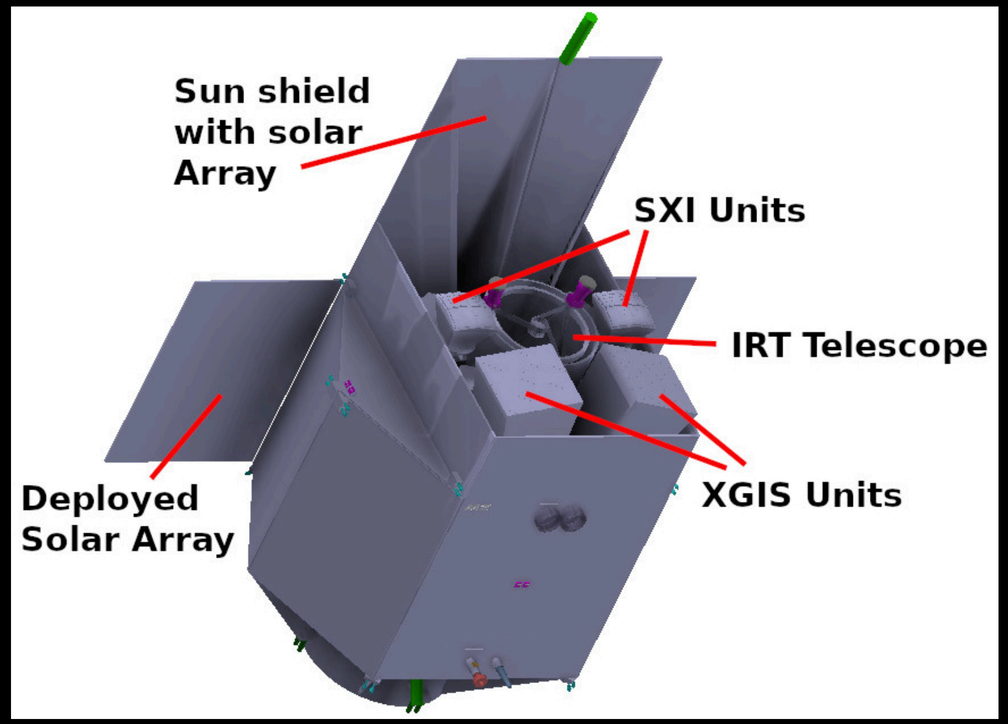
Wolter-1 type + CCD
FoV: 38'
band: 0.3-10keV
eff. area: 2x 300$cm^2$ @1keV
angular FWHM: 30"

**STAR-X** (NASA)



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

**THESEUS** (ESA)

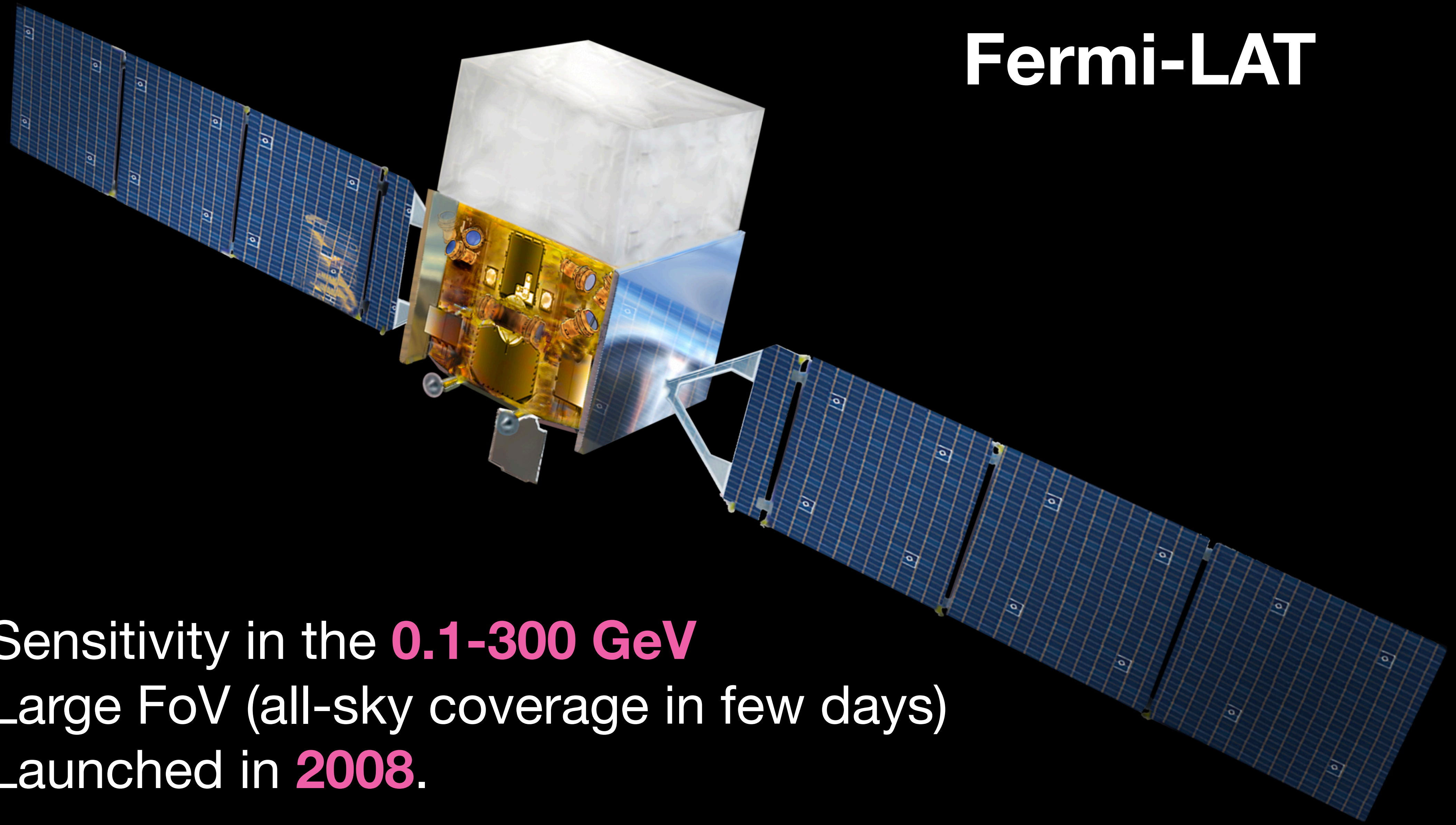



Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2'

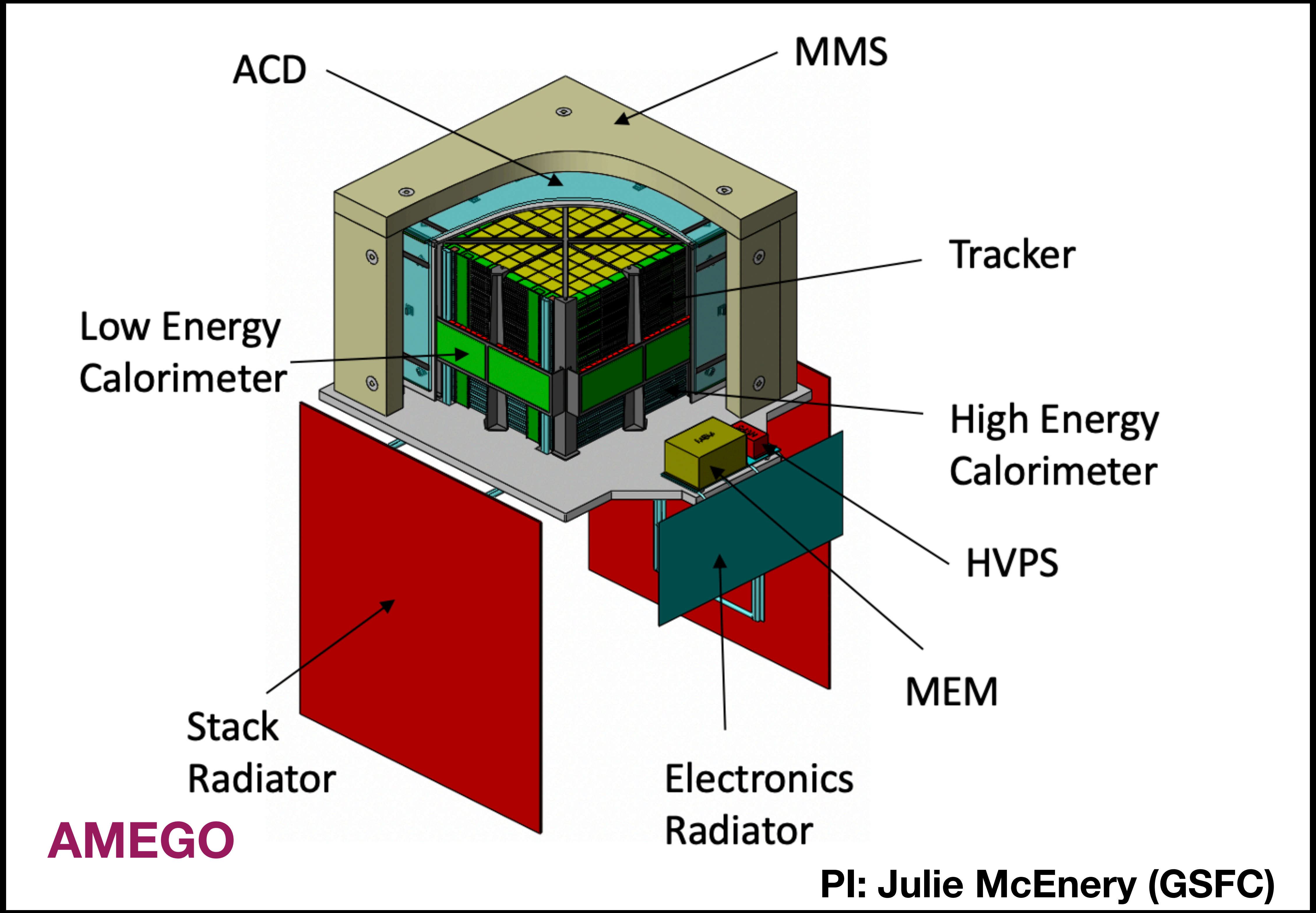
XGIS: 2 keV - 10 MeV with FoV >2 sr with < 15' GRB localization

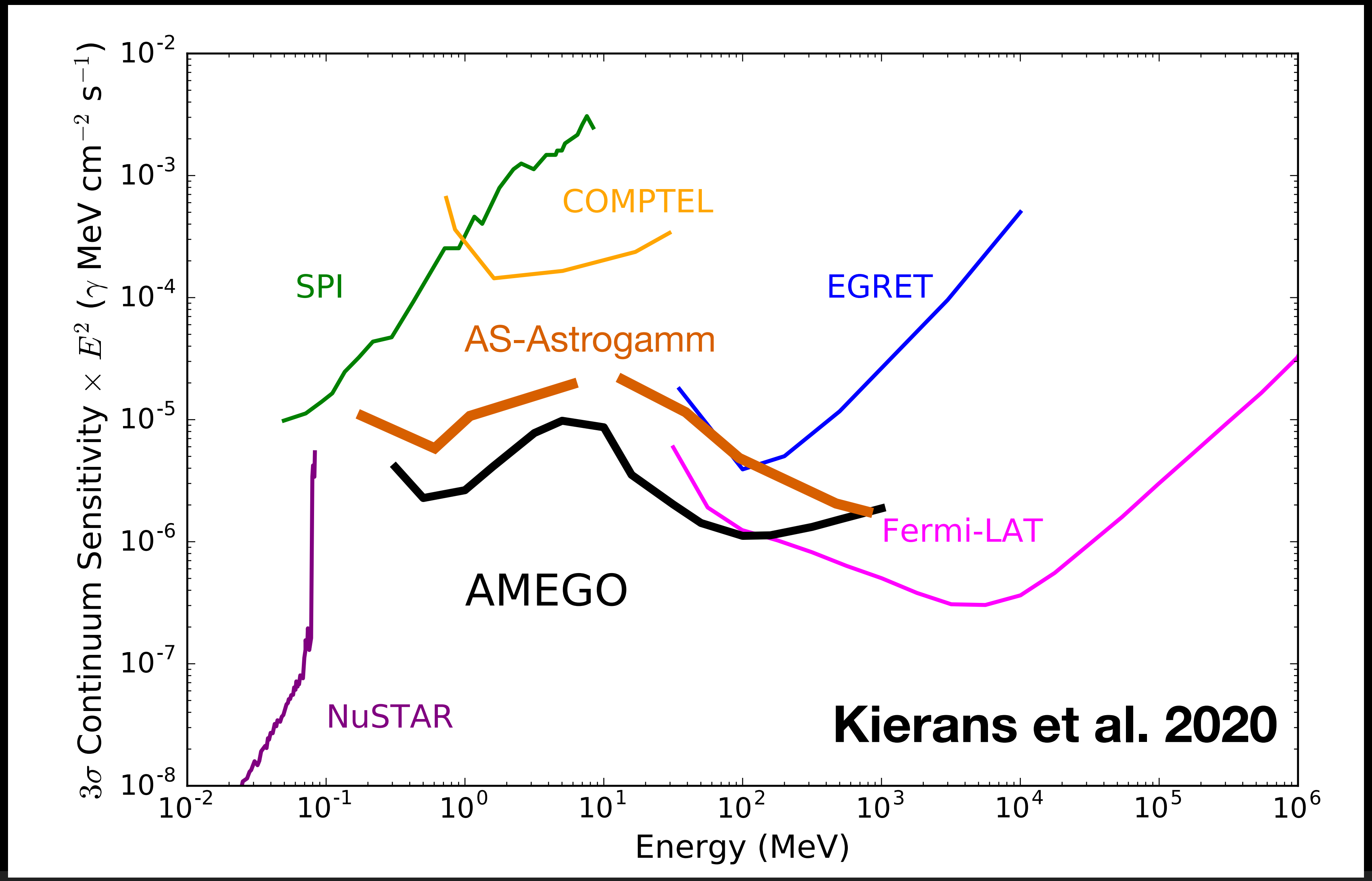
Not selected as of 2023.

# MEV-GEV COVERAGE




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



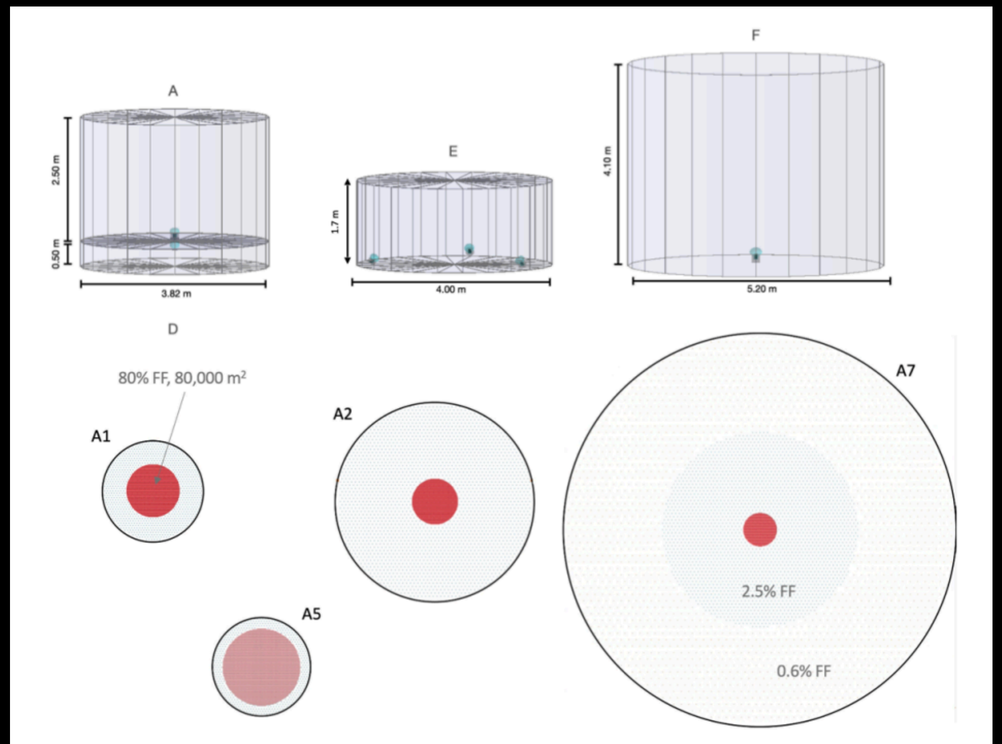



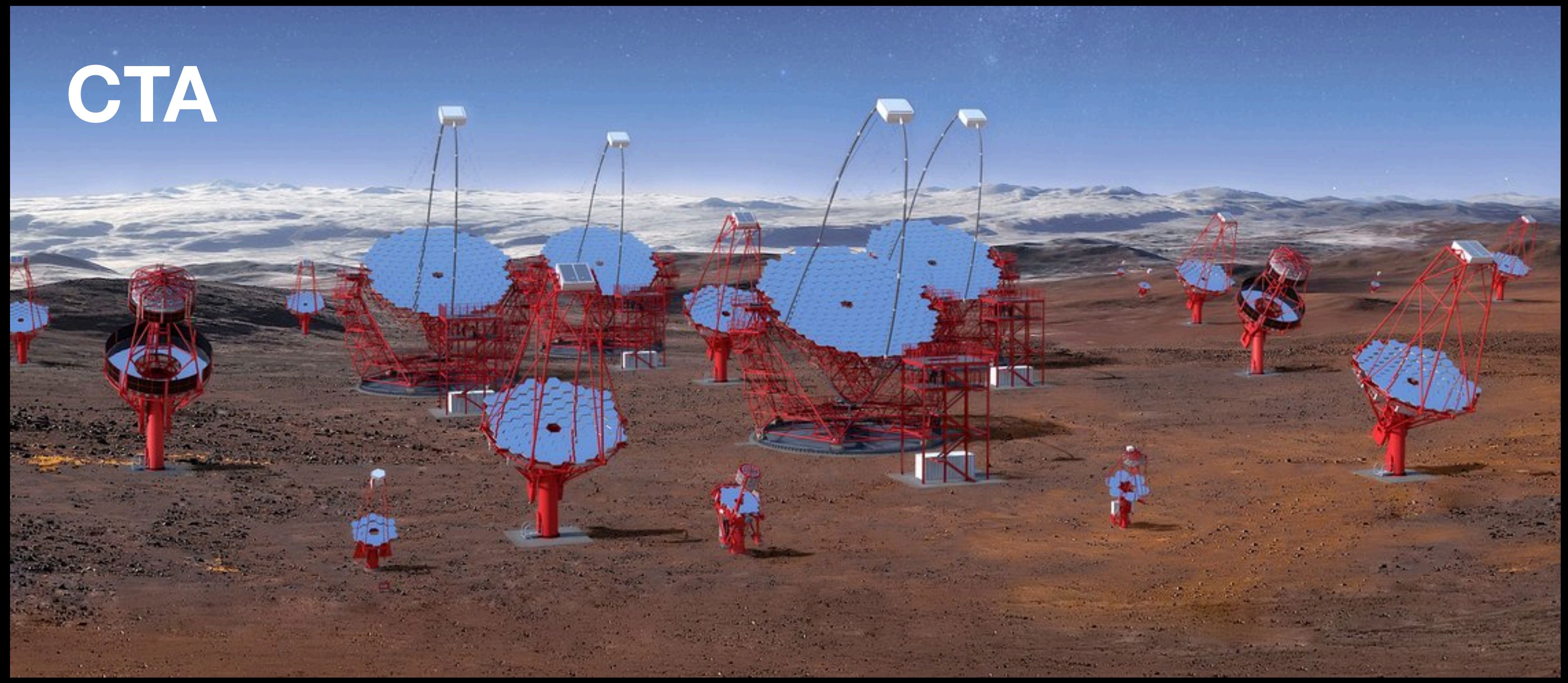

- AMEGO angular resolution: 3° (1 MeV), 10° (10 MeV)
- ComPair prototype for AMEGO.
- AMEGO-X explorer proposed.
- e-ASTROGAM not selected at the moment.

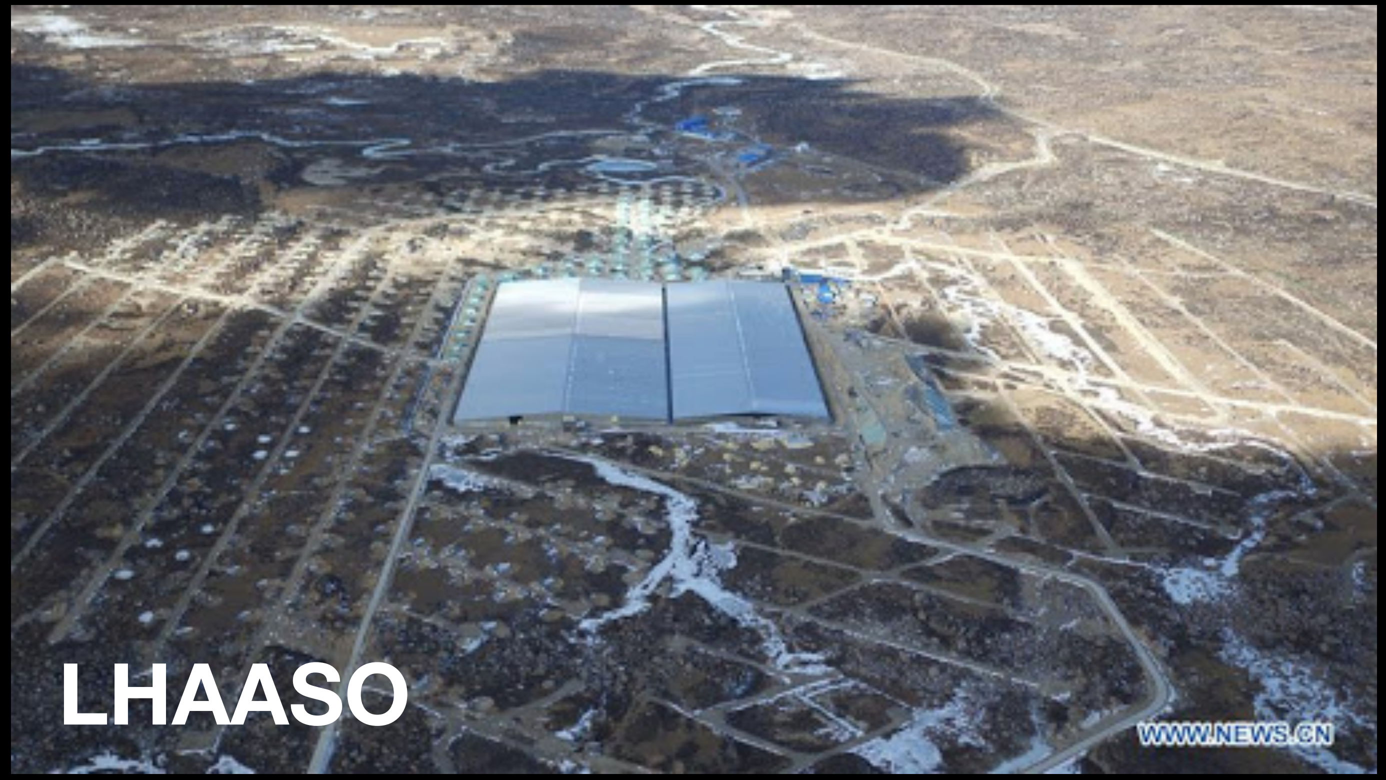
# COVERAGE IN THE VERY-HIGH-ENERGY RANGE




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.

# WISHLIST FOR GLOBAL STUDIES OF 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 $4\pi$ instruments, you need **wide-field, continuous, broad-band, sensitive coverage across the EM spectrum**. Even ULs are useful!
- Streamline the notification of neutrino detections under a unified scheme for all telescopes. Need to enable the computational and software infrastructure to do so.
- Merging data from multiple neutrino telescopes to reach detection will become a **must** as detectors go online to enable discoveries.

# A PAGE FROM THE HISTORY OF GAMMA-RAY ASTRONOMY

Credit: Naoko Kurahashi Neilson

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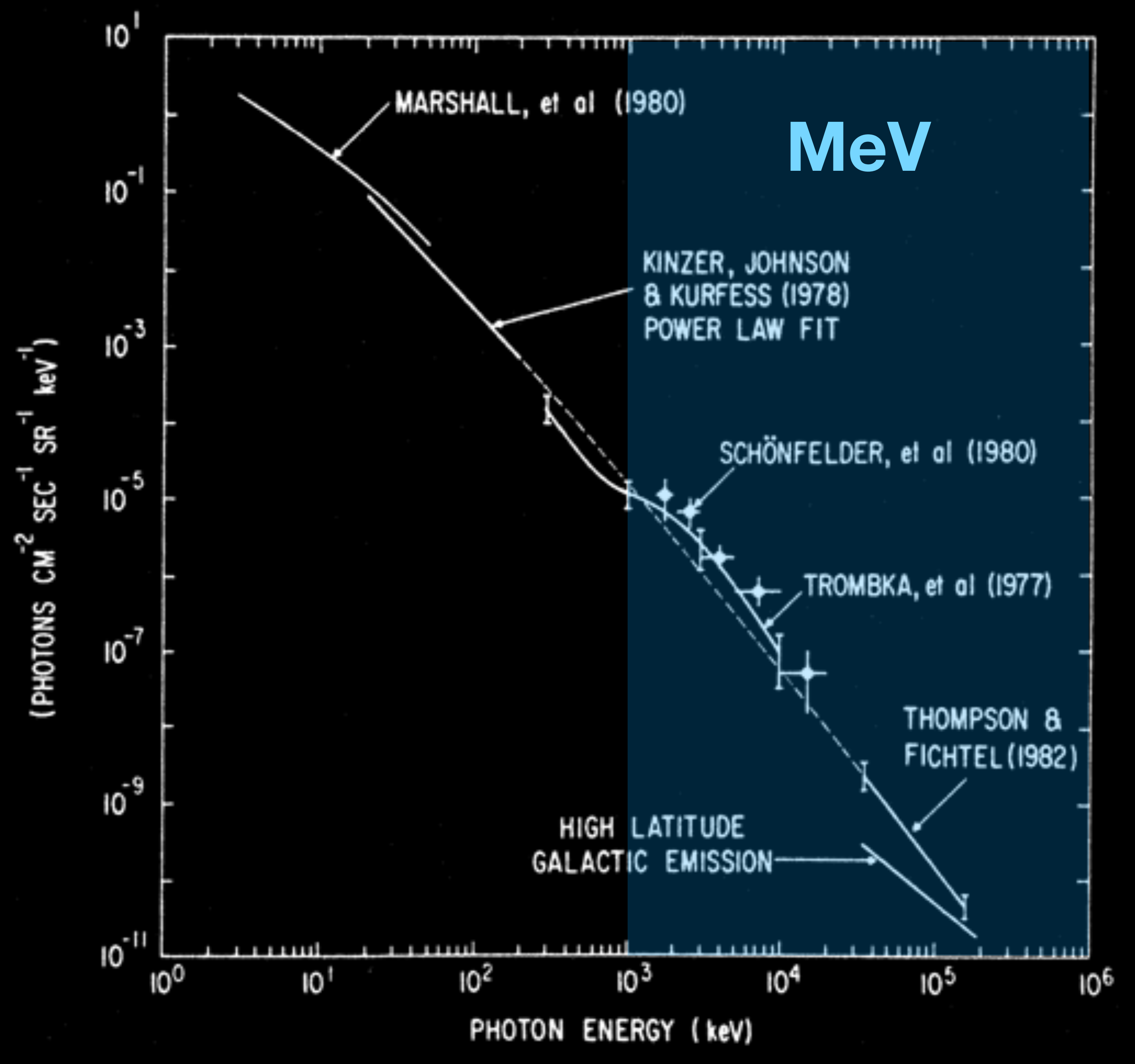


**Diffuse background measurements**
(1968-1972)

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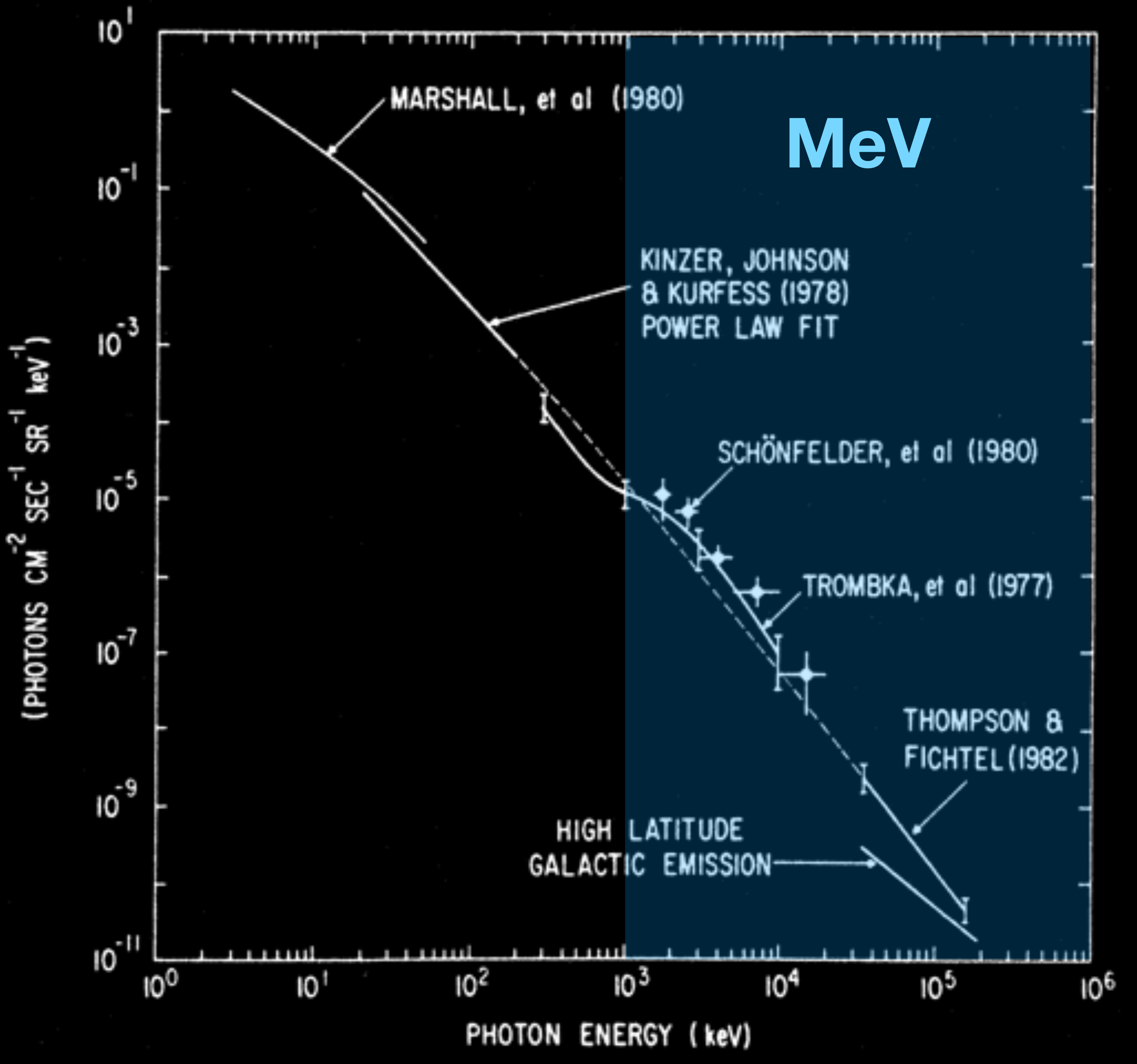


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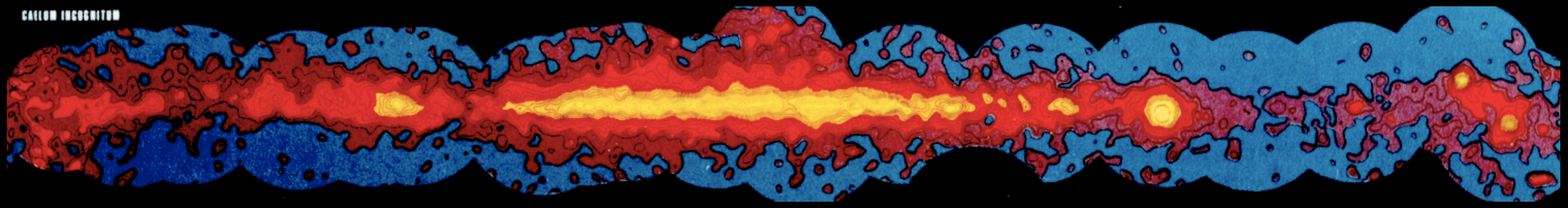

**Galactic emission and few point sources** (COS-B 1975-1982)

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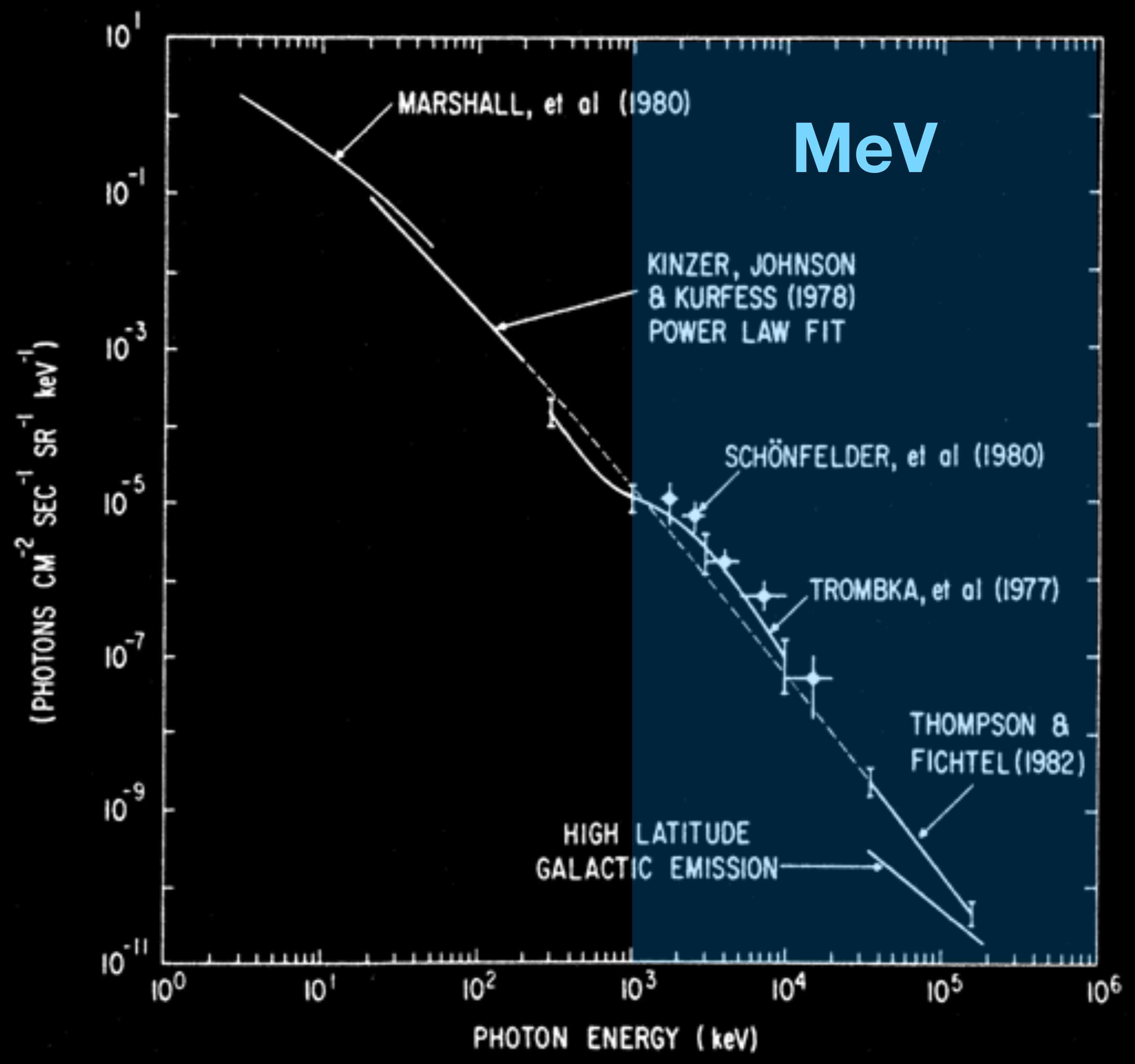


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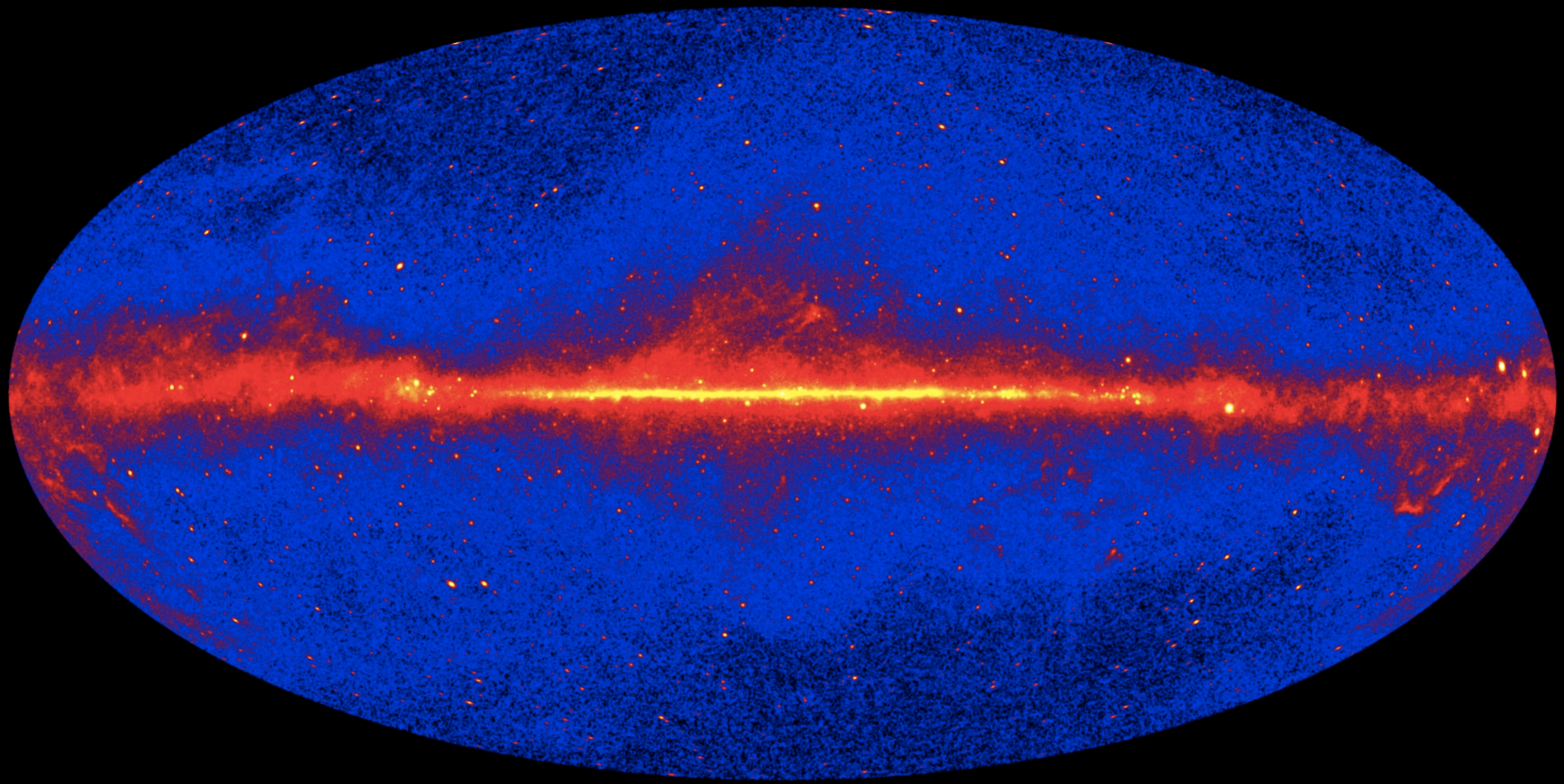
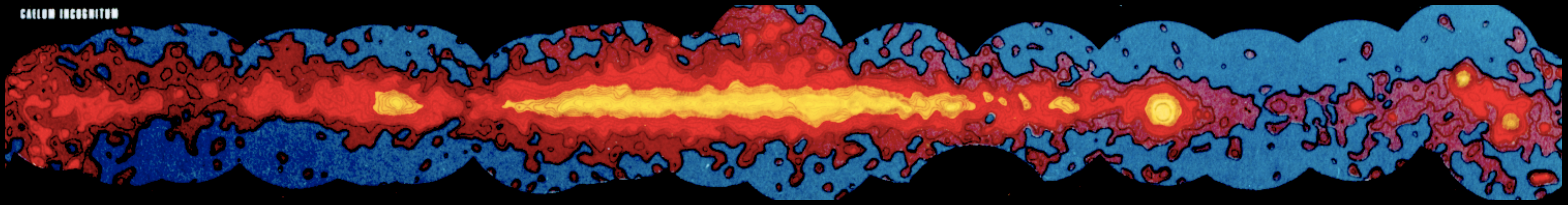


**O($10^3$) points source, spectra, light curves**
(IACTs, Fermi-LAT, 1989-now)

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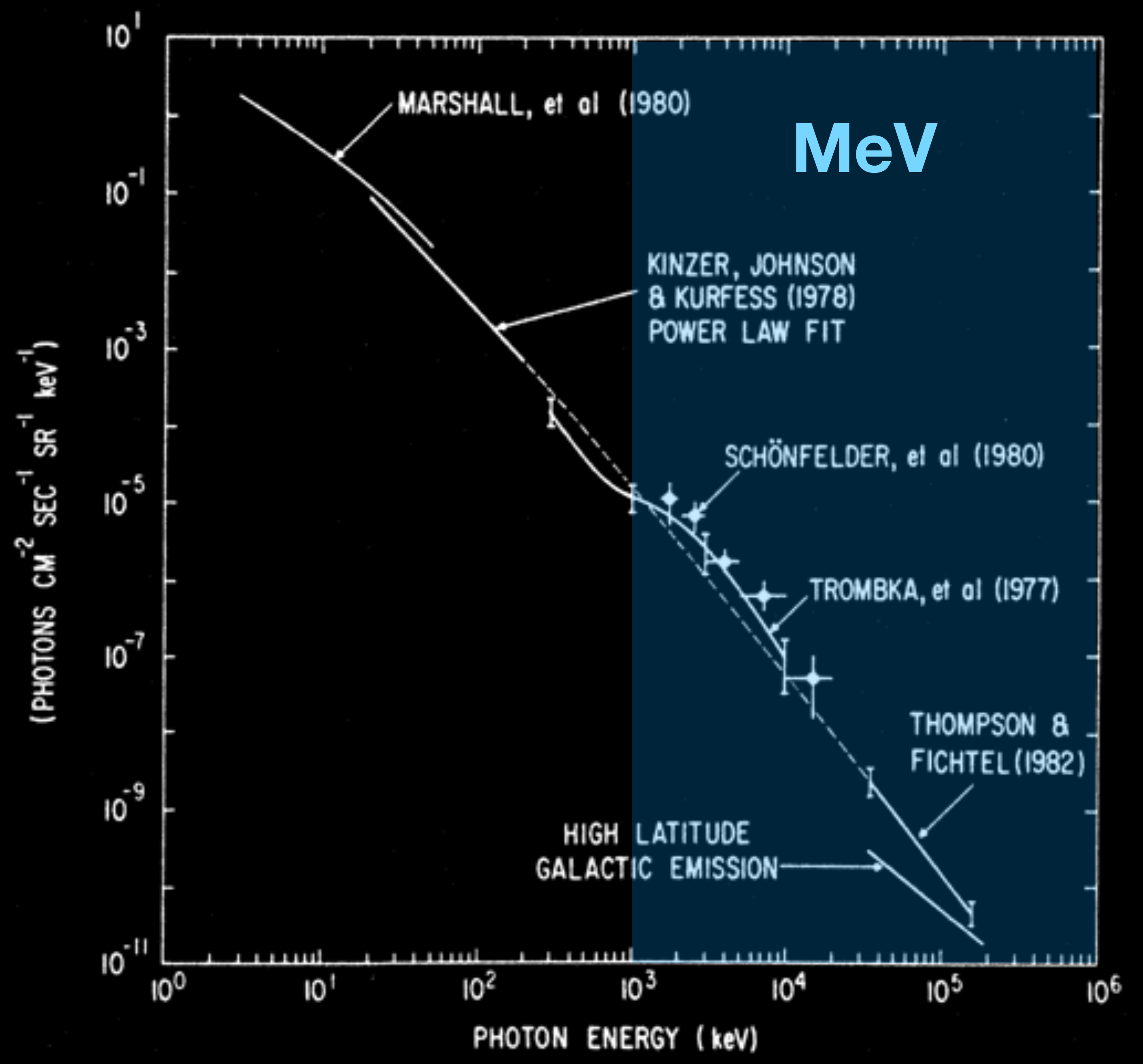


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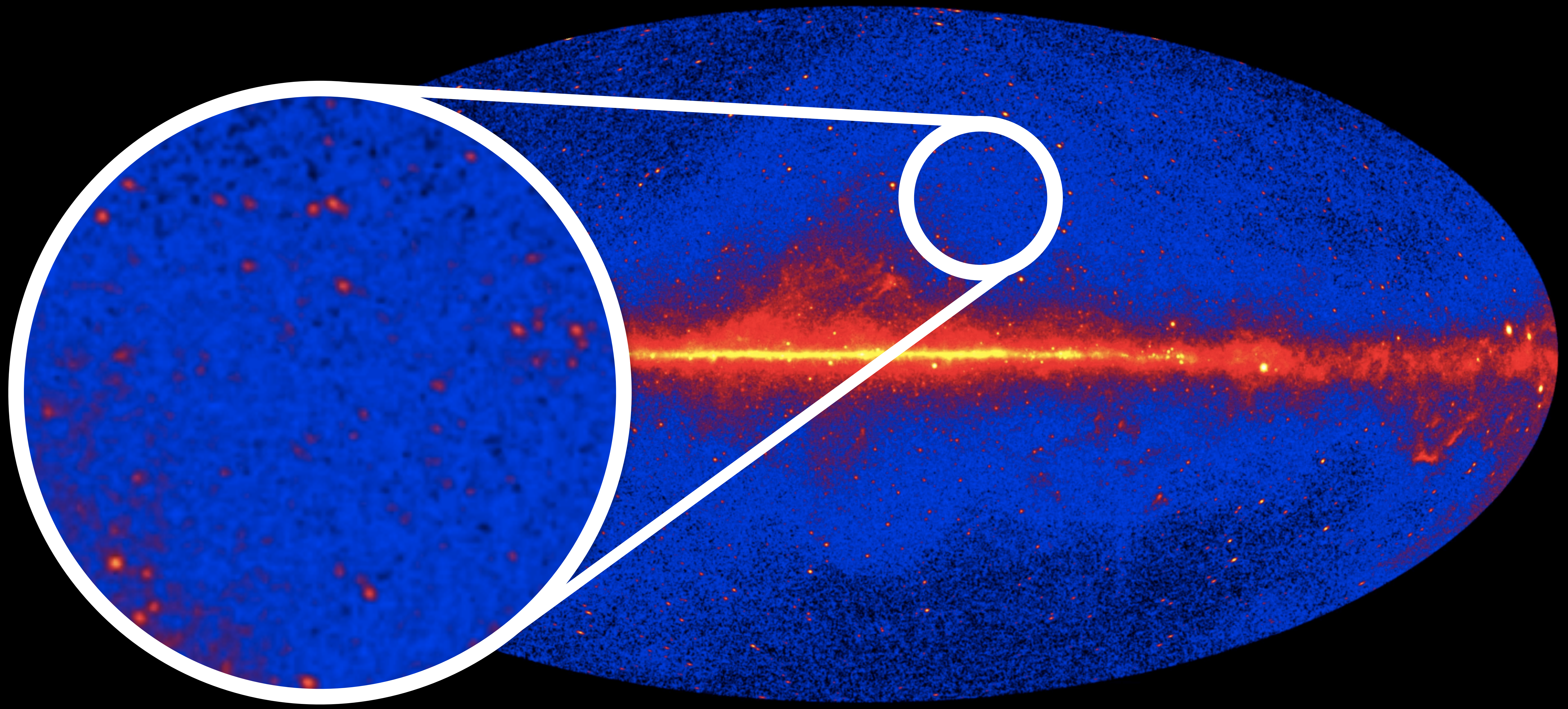

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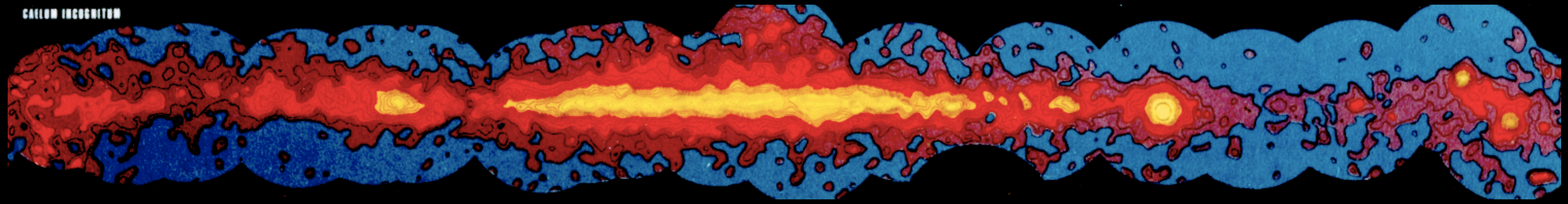


**Galactic emission and few point sources** (COS-B 1975-1982)


Thank you!