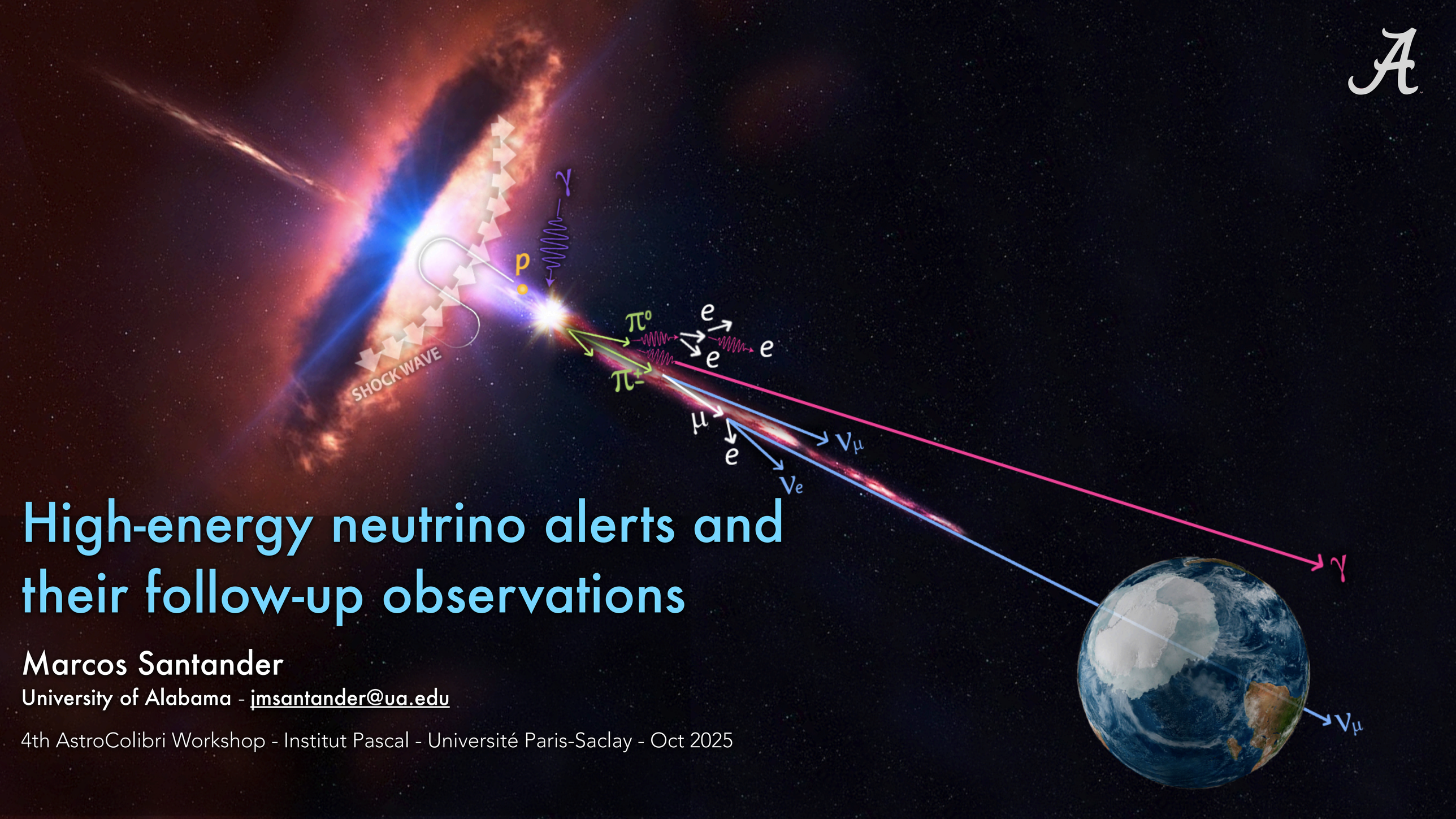
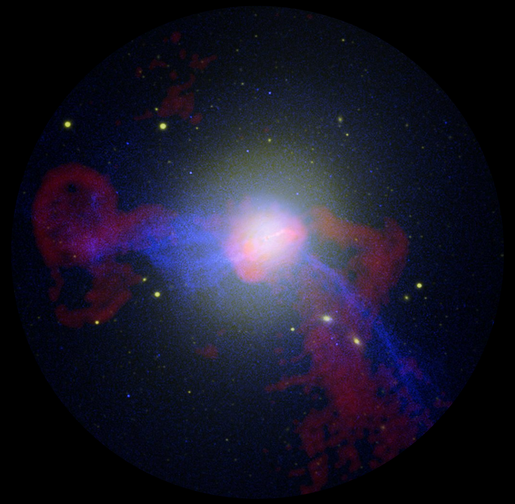


High-energy neutrino alerts and their follow-up observations

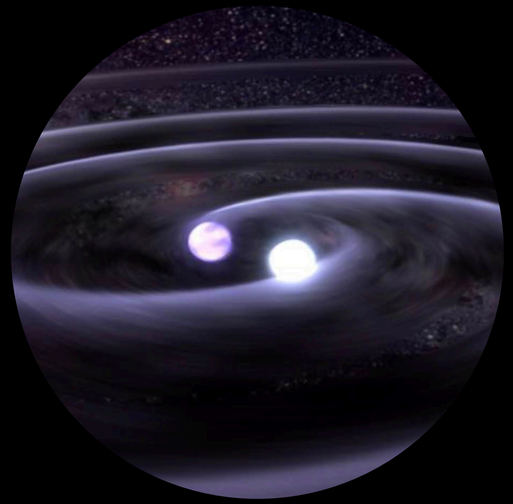
Marcos Santander
University of Alabama - jmsantander@ua.edu

4th AstroColibri Workshop - Institut Pascal - Université Paris-Saclay - Oct 2025

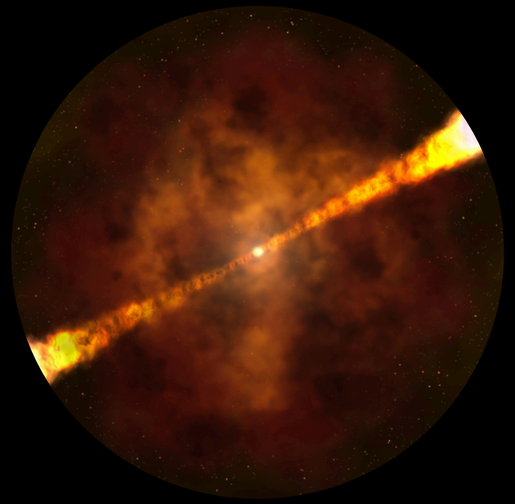
NEUTRINOS FROM TRANSIENT ASTROPHYSICAL SOURCES



Active galaxies

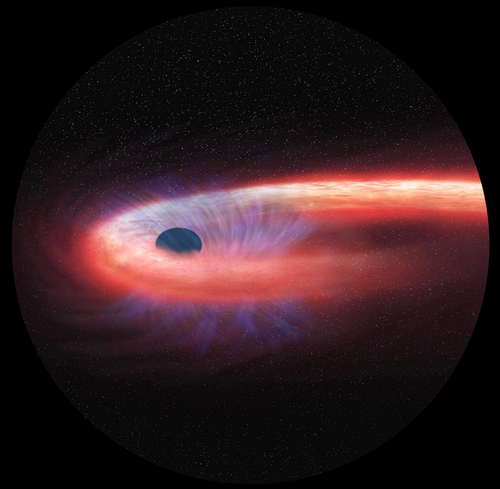


Compact object mergers



Gamma-ray bursts

Core-collapse supernovae



Tidal disruption events

- Transient and highly-variable persistent astrophysical sources display high-energy non-thermal emission potentially from hadronic processes.
- **Realtime neutrino alerts** identified in correlation with MM signals can provide direct insights into particle acceleration processes in these sources.
- Broad range of timescales (seconds to weeks/months)

EVENT TOPOLOGIES IN NEUTRINO TELESCOPES

Early  Late

Examples from IceCube

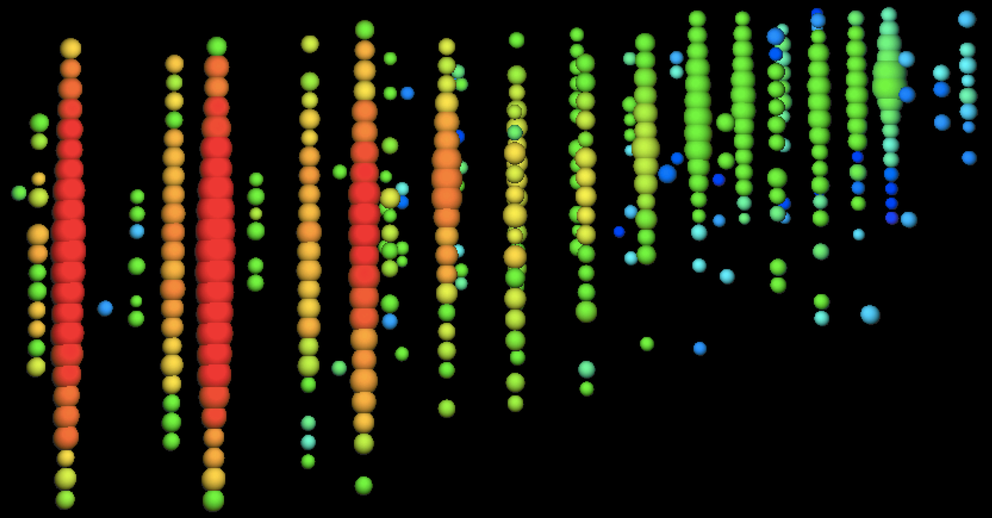
EVENT TOPOLOGIES IN NEUTRINO TELESCOPES

Early — Late

Examples from IceCube

Muon tracks

CC ν_μ interactions



Angular resolution **O(0.1°) - O(1°) at a few TeV**

Angular resolution better suited for correlating with pointed instruments

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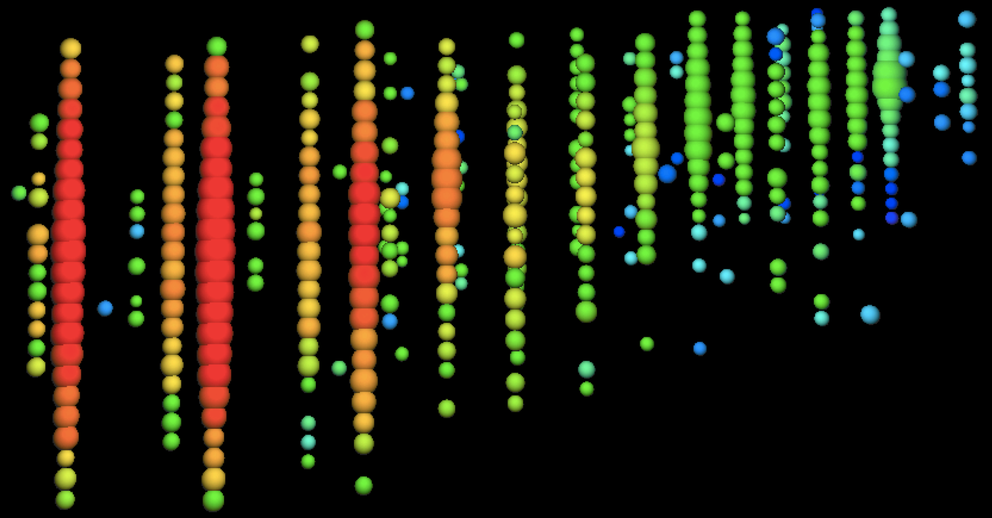
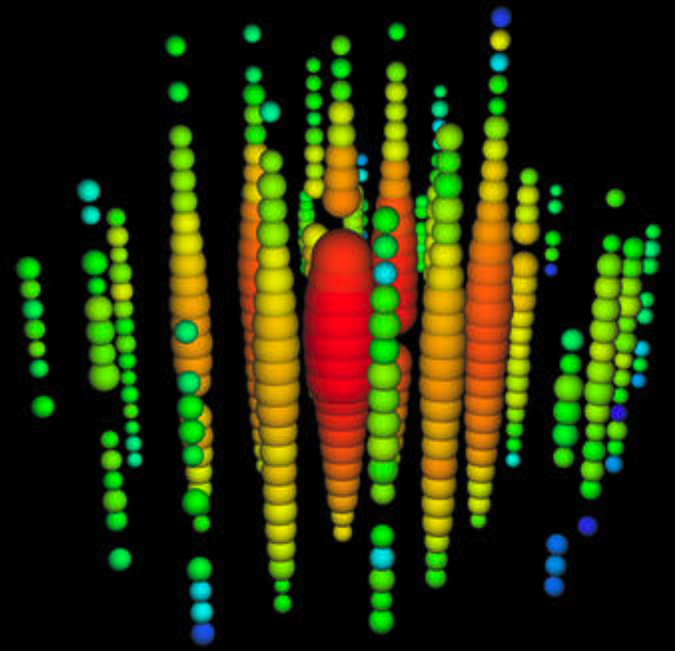


Angular resolution **O(0.1°) - O(1°) at a few TeV**

Angular resolution better suited for correlating with pointed instruments

Cascades

NC / CC ν_e, most ν_τ



Angular resolution O(1°) - O(10°)

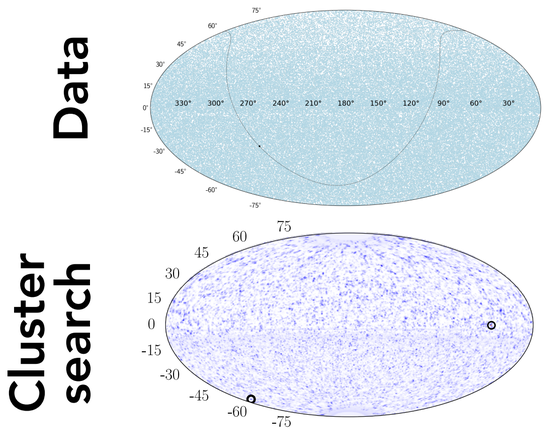
Added statistics at high energies

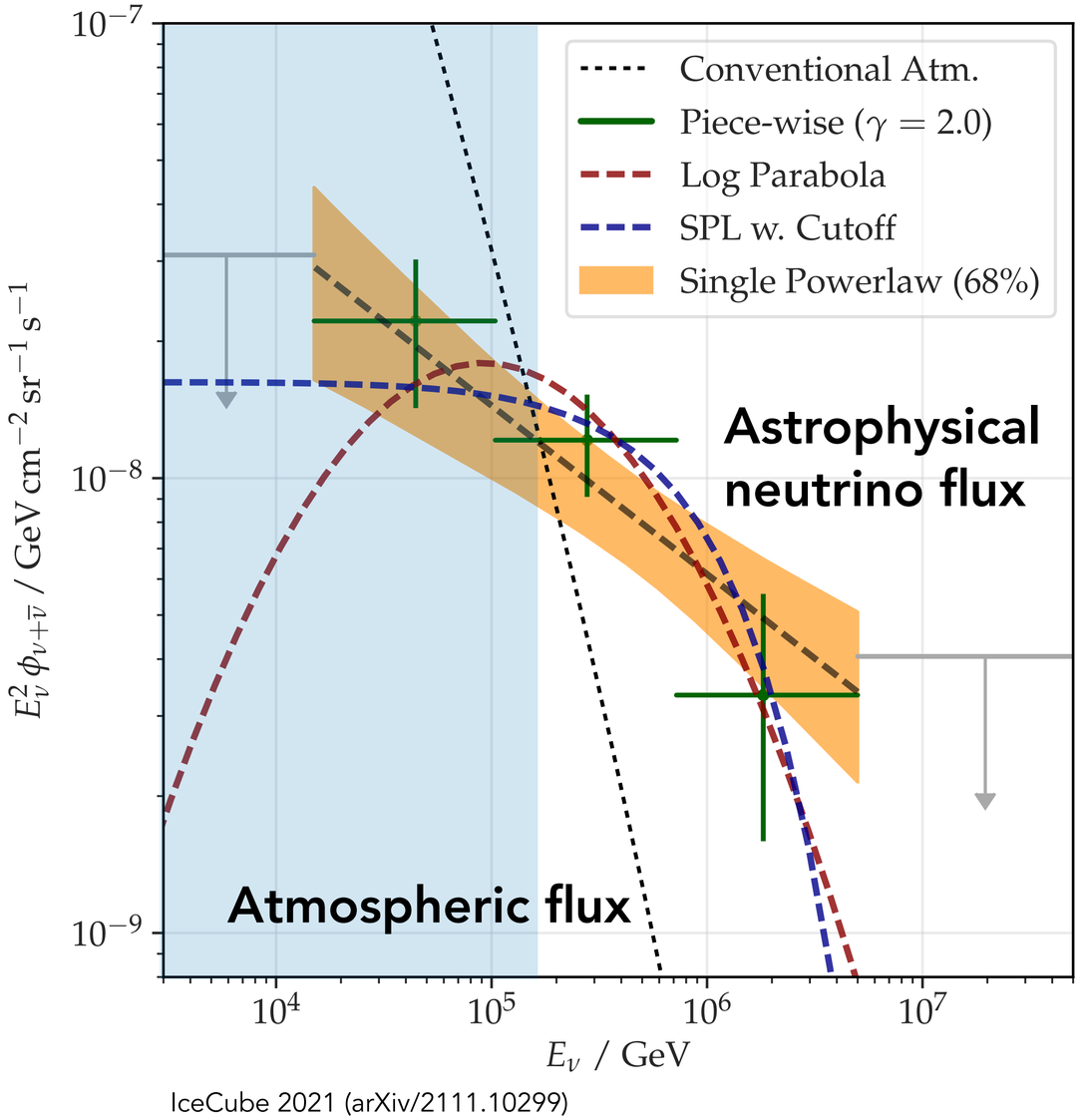
ALERT GENERATION CHALLENGES

ALERT GENERATION CHALLENGES

Low-energy regime

- Background dominated
- Sensitivity roughly ∝ PSF²
- **Search for neutrino clusters in spatial/ temporal correlation.**
- All-sky or using a catalog of known positions (e.g. MM sources)





IceCube 2021 (arXiv/2111.10299)

ALERT GENERATION CHALLENGES

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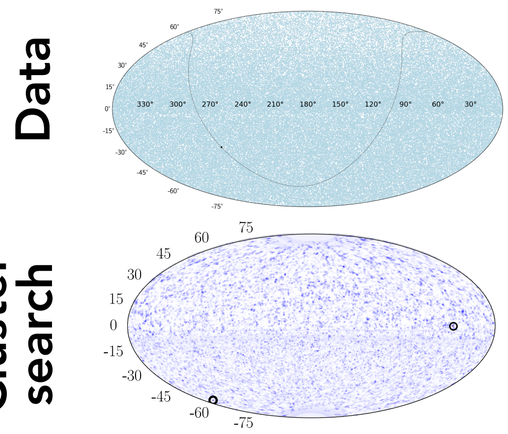
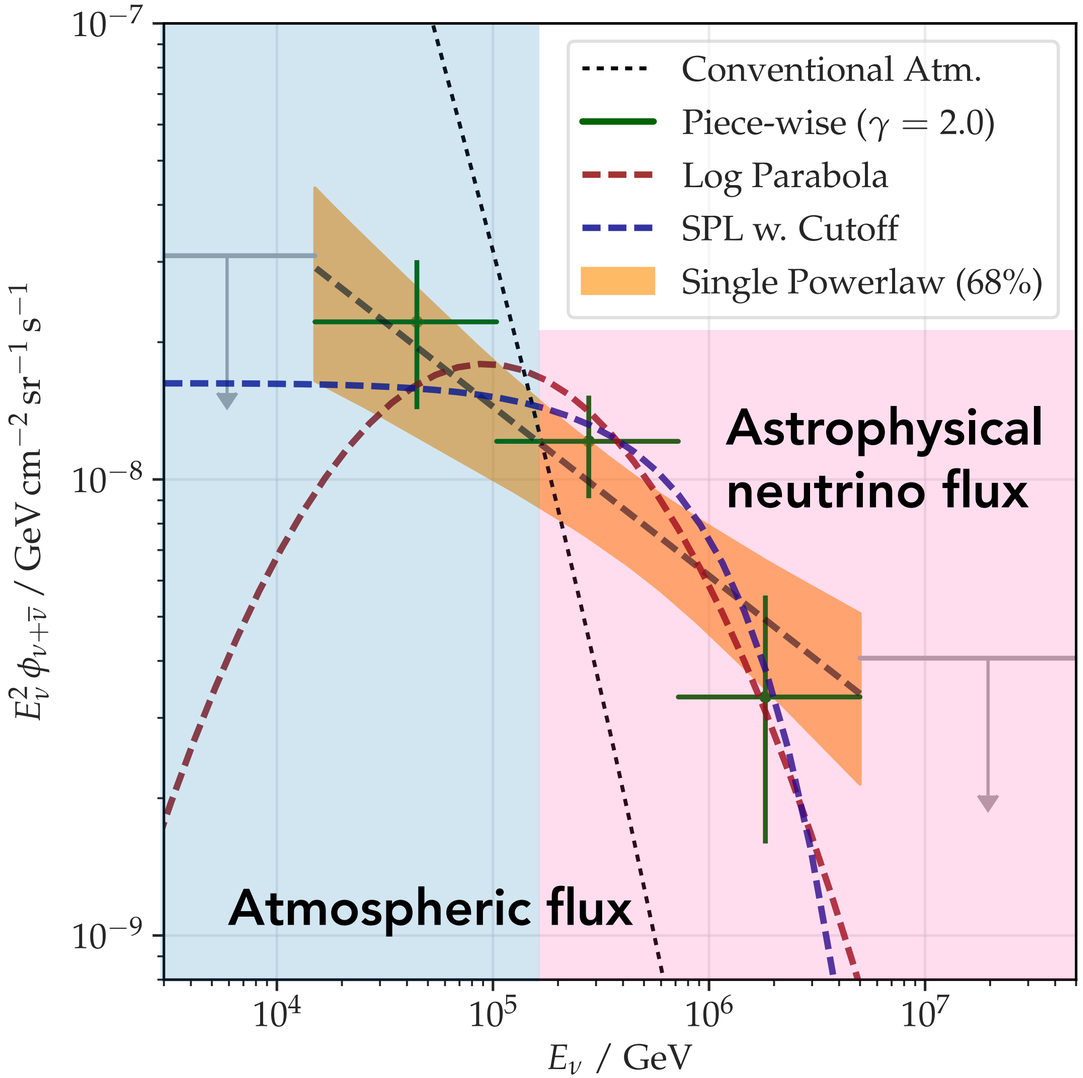
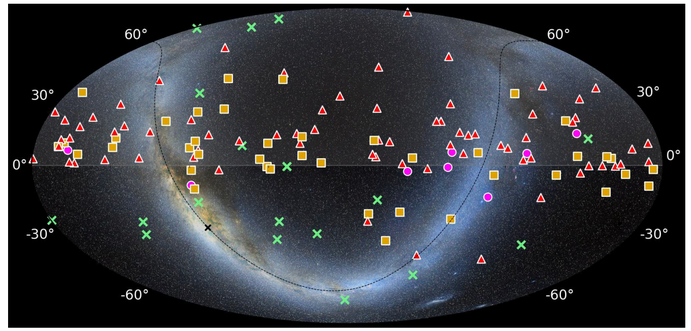




IceCube 2021 (arXiv/2111.10299)

High-energy regime

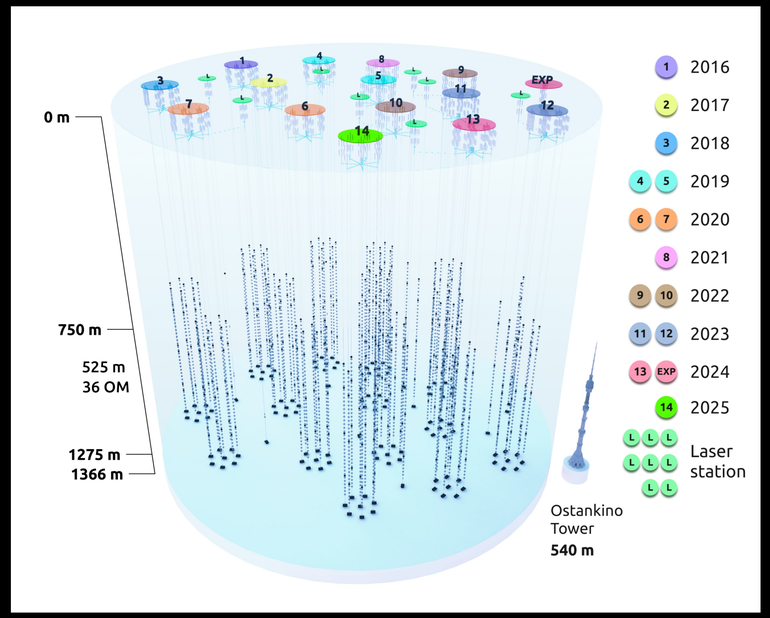
- Signal dominated
- **Very low event rate** (*O*(10) events per year across the sky per km³)
- **Realtime follow-ups. Correlation studies.**



IceCube track alerts

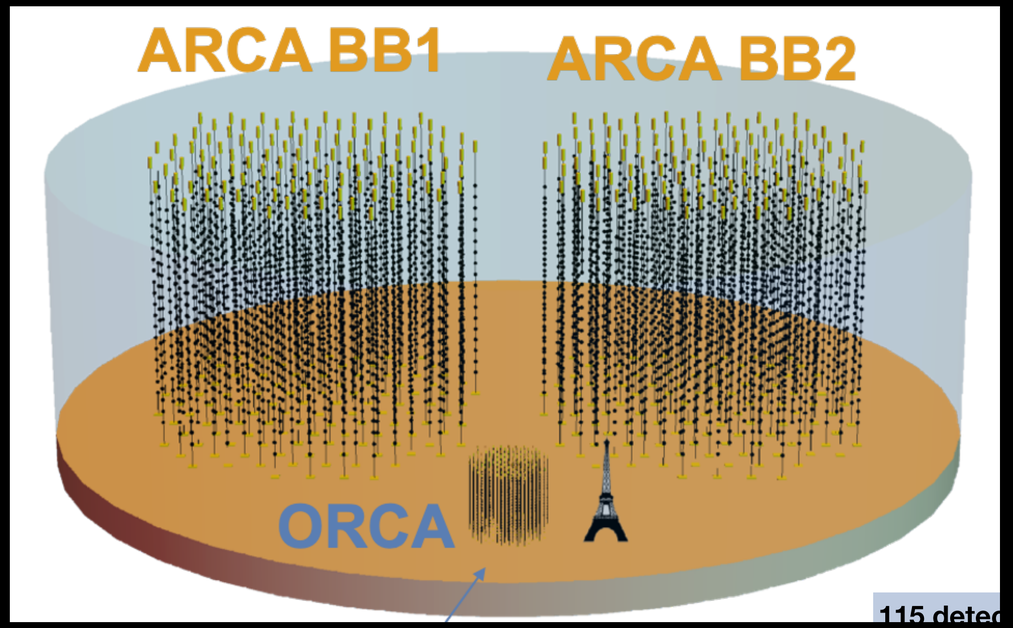
CURRENT GENERATION OF NEUTRINO TELESCOPES

Future: P-ONE, TRIDENT, HUNT, NEON



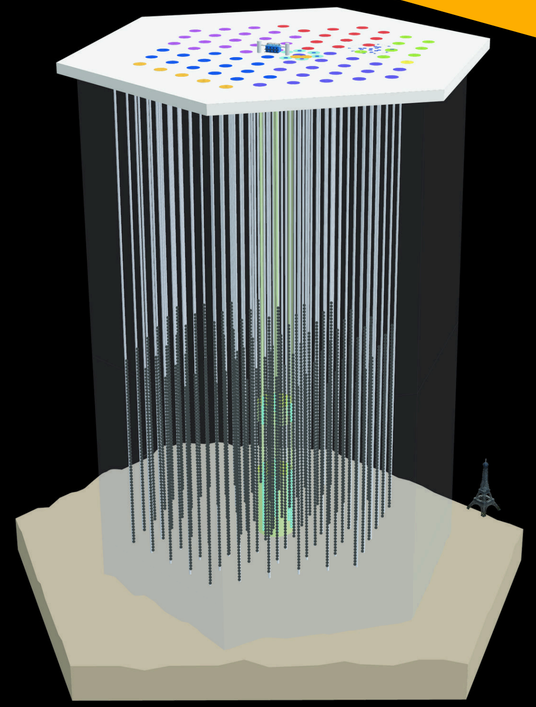
Baikal-GVD

- Lake Baikal (Russia)
- Under construction, targeting 1 km^3
- As of June 2025, ~0.6 km^3 (14 clusters with 4392 sensors)



KM3NeT

- Mediterranean Sea (Italy/France). Successor of ANTARES.
- Under construction, targeting 1 km^3
- Current status: 28/115 detector units (ORCA) + 51/230 detector units (ARCA) as of July 2025.



IceCube

- South Pole glacier. 2010.
- 5160 PMTs in 1 km^3
- 7 new lines (Upgrade) to be deployed 2025-26

ICECUBE HIGH-ENERGY ALERT STATUS (SINGLE EVENTS)

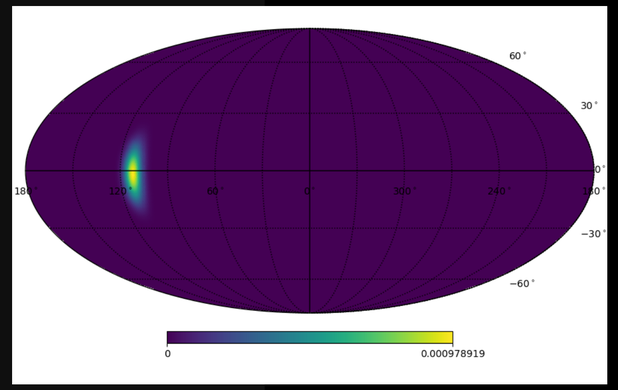
- **High-energy tracks (~30 / year):**
  - Selection of single high-energy muon tracks with high average astrophysical probability (Bronze: 30% - Gold: 50%). Started in 2016, upgraded in 2019 and 2024).
  - Fast reconstruction (at Pole) circulated to the community via GCN Notice / Kafka within ~30 s of detection. Followed by updated position based on more advanced reco algorithm (likelihood scans of reconstruction)
- **Cascade events (~8 / year):**
  - Alert issued through GCN Notice / Kafka. Healpix skymap automatically available.

Gold/Bronze track

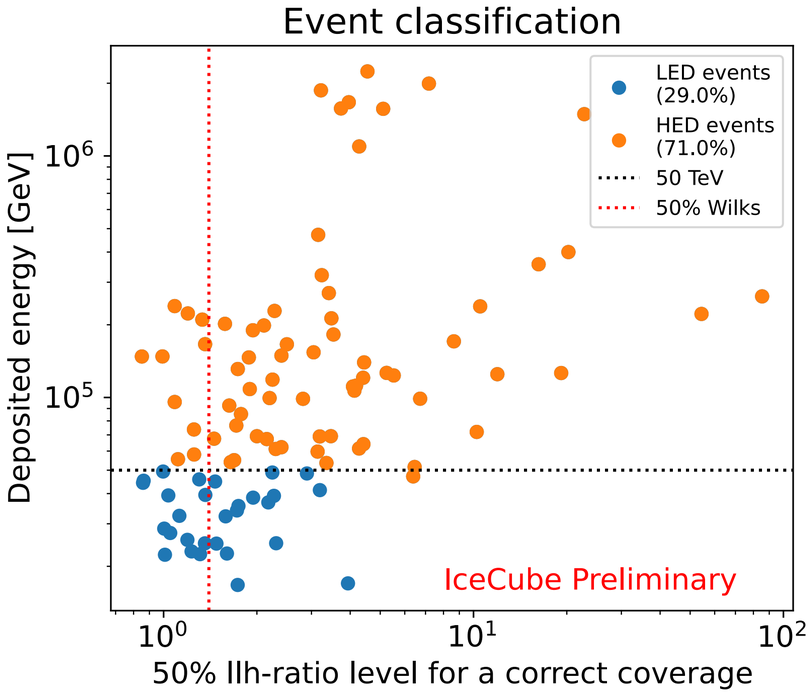
```
////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Sat 18 Oct 25 05:06:32 UT
NOTICE_TYPE:      ICECUBE Astrotrack Gold
STREAM:           24
RUN_NUM:          141495
EVENT_NUM:        22018019
SRC_RA:           321.3077d {+21h 25m 14s} (J2000),
                  321.5651d {+21h 26m 16s} (current),
                  320.8093d {+21h 23m 14s} (1950)
SRC_DEC:          +39.1859d {+39d 11' 09"} (J2000),
                  +39.2982d {+39d 17' 53"} (current),
                  +38.9694d {+38d 58' 10"} (1950)
SRC_ERROR:        161.22 [arcmin radius, stat-only, 90% containment]
SRC_ERROR50:      62.80 [arcmin radius, stat-only, 50% containment]
DISCOVERY_DATE:   20966 TJD;   291 DOY;   25/10/18 (yy/mm/dd)
DISCOVERY_TIME:   18342 SOD {05:05:42.97} UT
REVISION:         0
ENERGY:           1.9226e+02 [TeV]
SIGNALNESS:       6.0730e-01 [dn]
FAR:              0.2566 [yr^-1]
SUN_POSTN:        203.24d {+13h 32m 57s}   -9.70d {-09d 42' 14"}
SUN_DIST:         117.95 [deg]   Sun_angle= -7.9 [hr] (East of Sun)
MOON_POSTN:       169.21d {+11h 16m 50s}   +4.60d {+04d 35' 58"}
MOON_DIST:        129.24 [deg]
GAL_COORDS:        85.11, -8.10 [deg] galactic lon,lat of the event
ECL_COORDS:       342.29, 50.57 [deg] ecliptic lon,lat of the event
COMMENTS:         IceCube Gold event.
COMMENTS:         The position error is statistical only, there is no systematic added.
```

Cascade

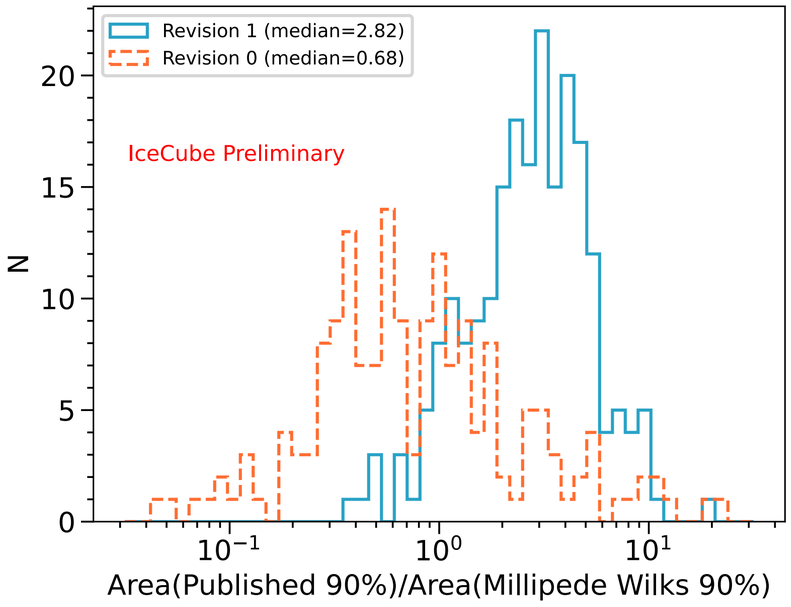
```
////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Thu 11 Sep 25 05:47:53 UT
NOTICE_TYPE:      ICECUBE Cascade
EVENT_NAME:       IceCubeCascade-250911a
STREAM:           26
RUN_NUM:          141344
EVENT_NUM:        29341777
SRC_RA:           111.9776d {+07h 27m 55s} (J2000),
                  112.3027d {+07h 29m 13s} (current),
                  111.3448d {+07h 25m 23s} (1950)
SRC_DEC:          -1.7676d {-01d 46' 02"} (J2000),
                  -1.8215d {-01d 49' 16"} (current),
                  -1.6648d {-01d 39' 52"} (1950)
SRC_ERROR:        13.28 [deg radius, stat+systematic, 90% containment]
SRC_ERROR50:      7.28 [deg radius, stat+systematic, 50% containment]
DISCOVERY_DATE:   20929 TJD;   254 DOY;   25/09/11 (yy/mm/dd)
DISCOVERY_TIME:   16117 SOD {04:28:37.14} UT
REVISION:         0
ENERGY:           96.63 [TeV]
SIGNALNESS:       9.0012e-01 [dn]
FAR:              0.3110 [yr^-1]
SUN_POSTN:        169.66d {+11h 18m 39s}   +4.45d {+04d 26' 52"}
SUN_DIST:          57.65 [deg]   Sun_angle= 3.8 [hr] (West of Sun)
MOON_POSTN:        32.17d {+02h 08m 40s}  +17.03d {+17d 01' 59"}
MOON_DIST:         81.12 [deg]
GAL_COORDS:       218.70,  7.29 [deg] galactic lon,lat of the event
ECL_COORDS:       114.05,-23.39 [deg] ecliptic lon,lat of the event
SKYMAP_FITS_URL:  https://roc.icecube.wisc.edu/public/hese_cascades/hese_60929_run00141344.evt000029341777.fits
SKYMAP_PNG_URL:   https://roc.icecube.wisc.edu/public/hese_cascades/hese_60929_run00141344.evt000029341777.png
COMMENTS:         IceCube Cascade event.
COMMENTS:         The position error is the combined statistical and the systematic.
```



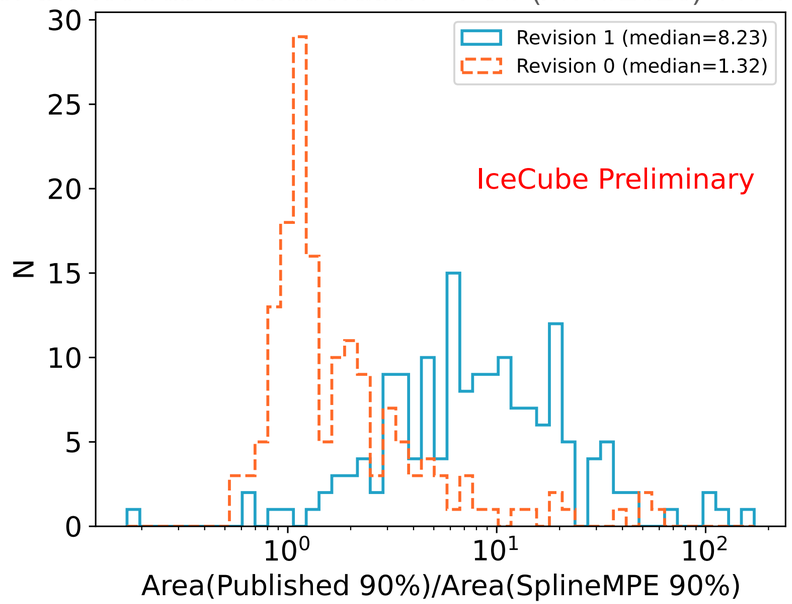
LATEST UPDATE TO ICECUBE TRACK EVENT ALERTS



Sommani and Yuan for the IceCube Collaboration - PoS (ICRC2025) 1184



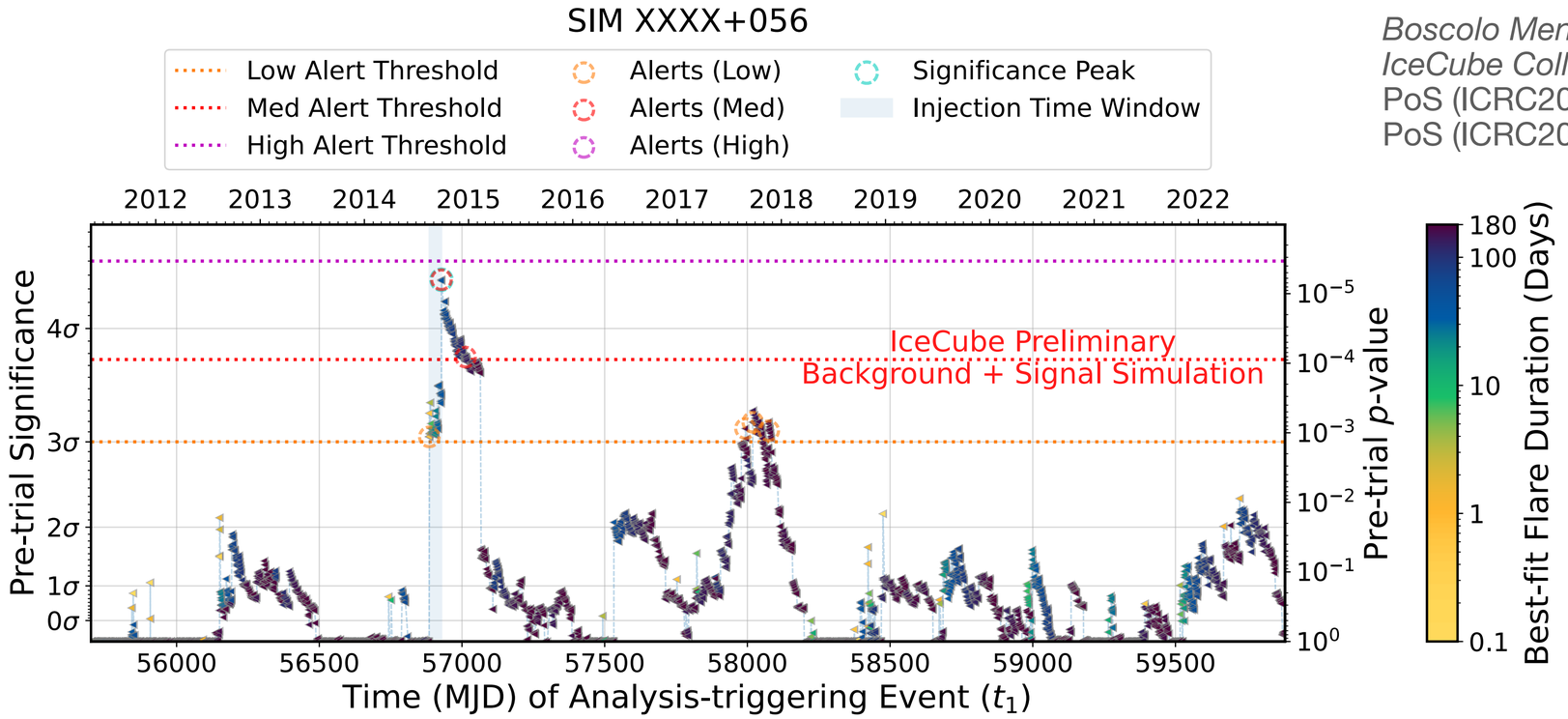
(a) Millipede Wilks



(b) SplineMPE with likelihood scan

- Improving angular resolution and statistical coverage of event uncertainties. Combining two event reconstructions (Millipede Wilks and SplineMPE scans).
- **Improvements of a factor of 5 (4)** in the area of the 50% (90%) containment region.
- IceCat-2 being released soon including 365 tracks between May 2011 and Jan 2025 (Zegarelli et al. for the IceCube Collaboration - PoS(ICRC2025)1224, **see Angela's talk!**)

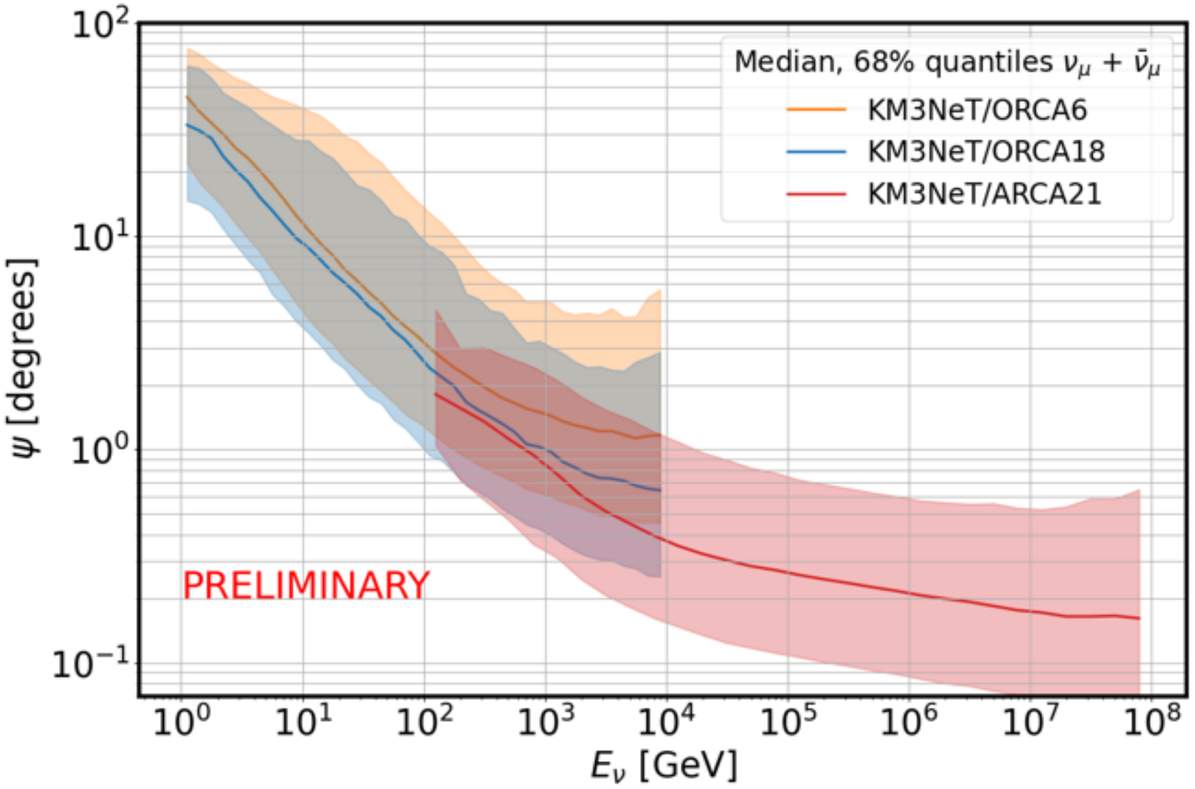
UPCOMING UPDATE TO GAMMA-RAY FOLLOW-UP ALERTS



Boscolo Meneguolo et al. for the IceCube Collaboration
PoS (ICRC2025) 949
PoS (ICRC2025) 919

- **Current status:** IceCube monitores a list of gamma-ray sources agreed upon with IACT telescopes under MoU. If a cluster of neutrino candidate events crosses a significance threshold, a **private** alert is shared with the IACT.
- **Next step:** common list of monitored sources, expanded energy bands (keV/GeV/TeV). Public alerts circulated via NASA GCN. ETA: by end of the year.

KM3NET EVENT RECONSTRUCTION



Del Rosso and Illuminati for the KM3NeT Collaboration - PoS (ICRC2025) 1026

- Data collection to reconstruction in ~7 s.
- Expected median angular resolution for tracks < 0.1° (>1 PeV) and 2° for cascades above 100 TeV.
- Less light scattering in liquid water leads to improve reco.
- Chance probability of correlation goes with PSF^2. Enable sensitive searches of neutrino counterparts with EM instruments.

KM3NET ALERT STATUS

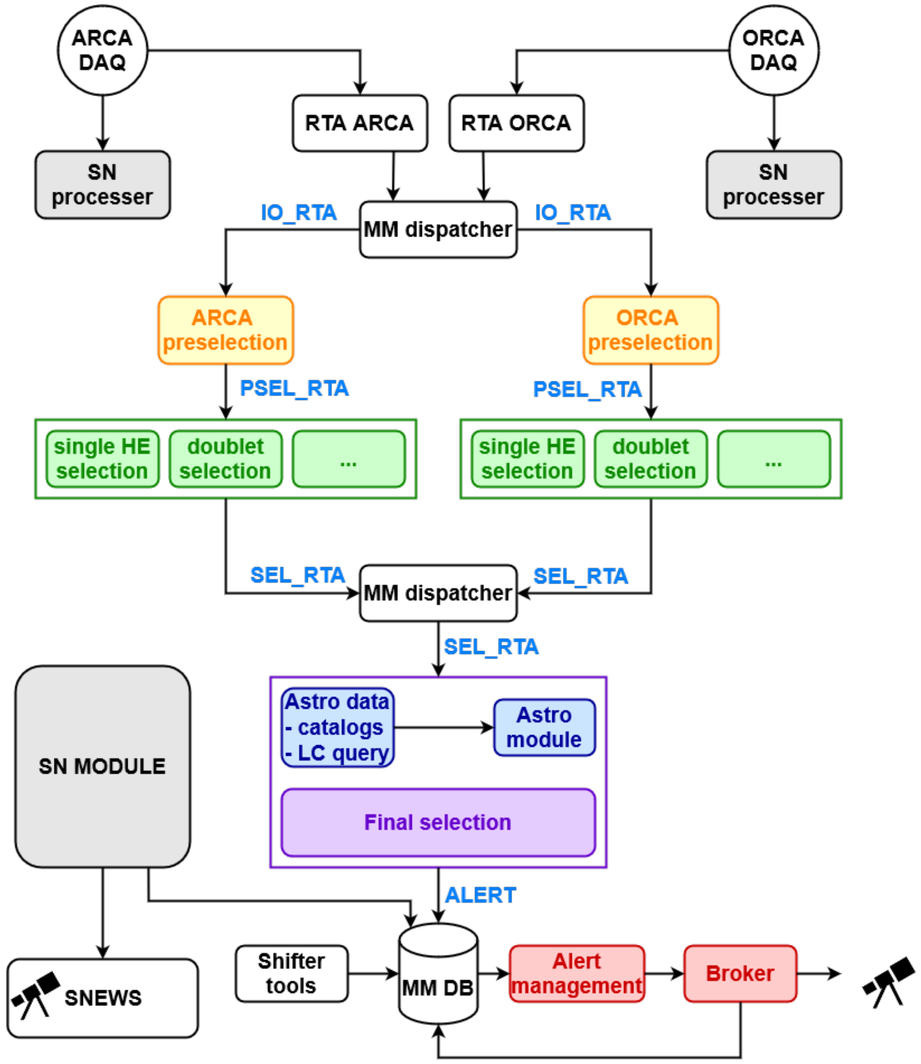
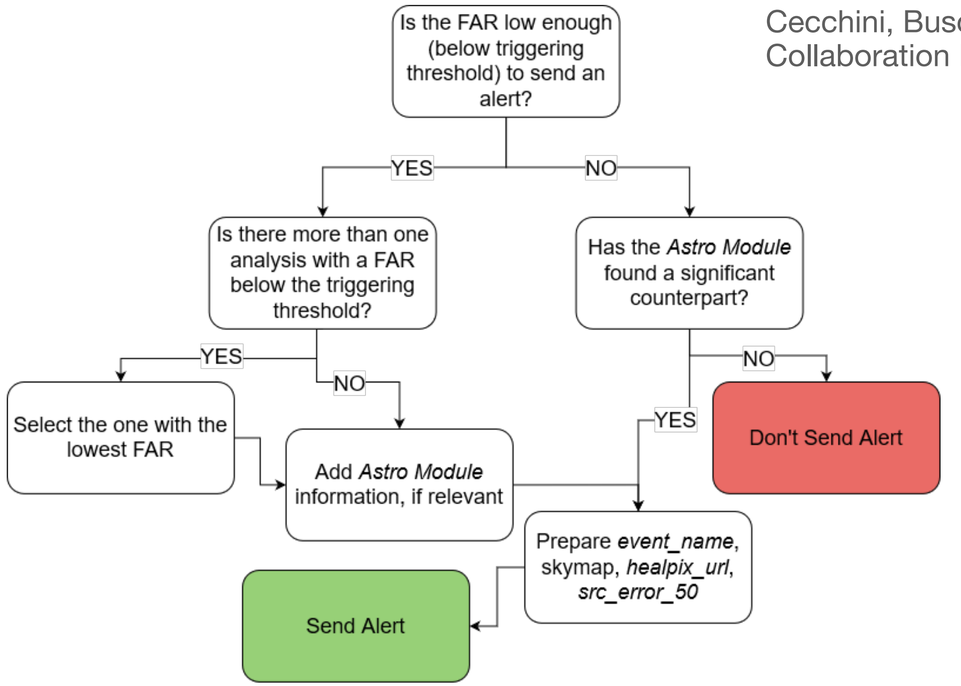


Figure 1: Overview of the KM3NeT alert sending system dataflow. *Credit: M. Marconi.*



Cecchini, Buson, Celli et al. for the KM3NeT Collaboration PoS (ICRC2025) 920

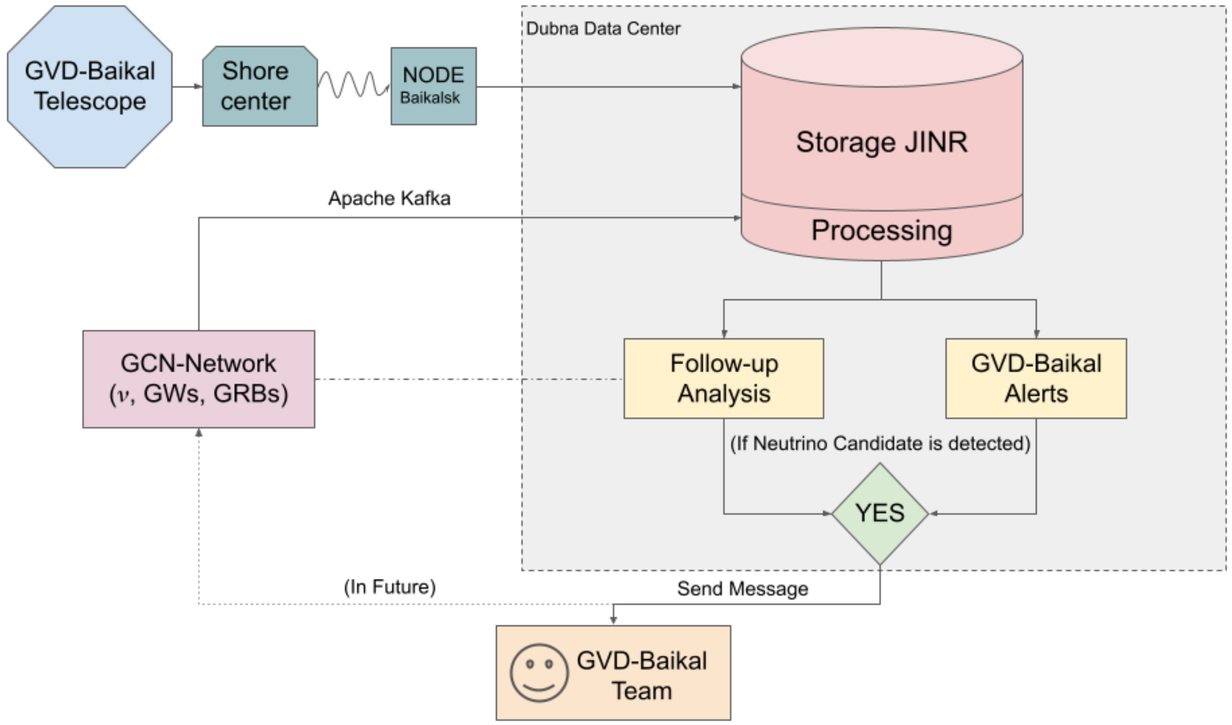
- System searches for potential astro correlations using different catalogs. Selection of O(10)s of events per month.
- Upgrade alert if one or more candidate counterparts have been identified. Rare events are submitted as neutrino only. FAR calculation.
- To be sent via GCN Kafka using VOEvent and JSON. JSON format based on Common Neutrino Format agreed with IceCube. Contains event and counterpart information.
- **ETA: public alerts by end of 2025.**

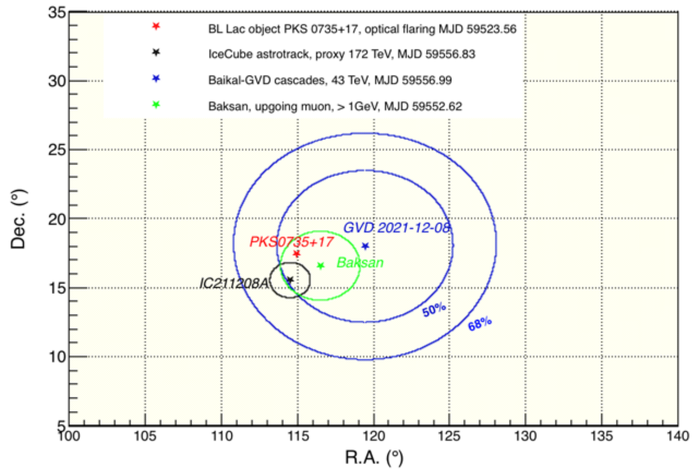
Mastrodicasa et al. for the KM3NeT Collaboration - PoS (ICRC2025) 920

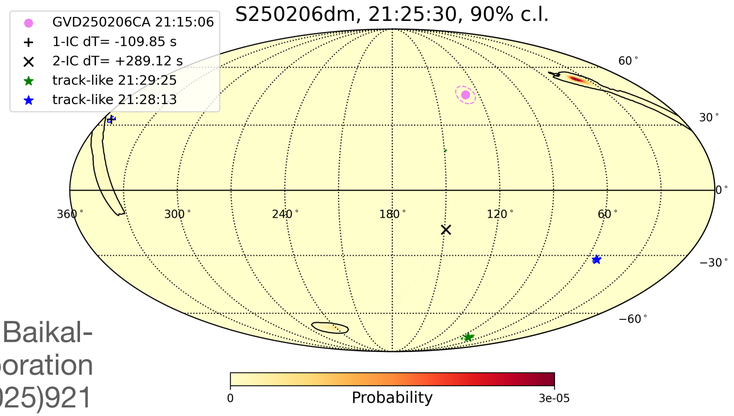
BAIKAL-GVD ONLINE ALERT STATUS

- Ongoing efforts concentrate on online reconstruction and calibration. Most searches concentrate on the follow-up of external MMA triggers (IceCube, LIGO, etc).
- Alerts are received via GCN and data is processed within 5 minutes.

Dik for the Baikal-GVD Collaboration - PoS(ICRC2023)1458

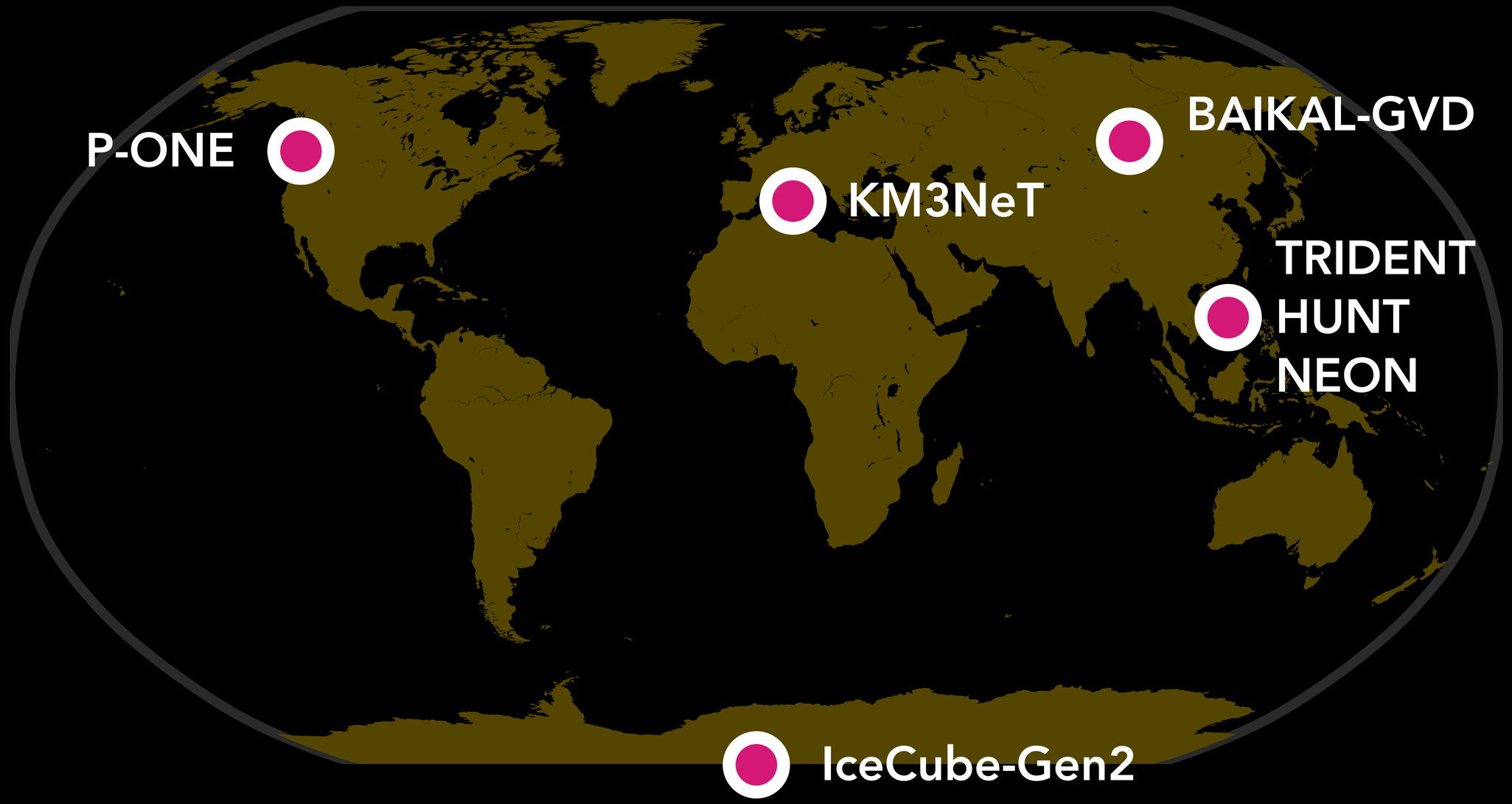




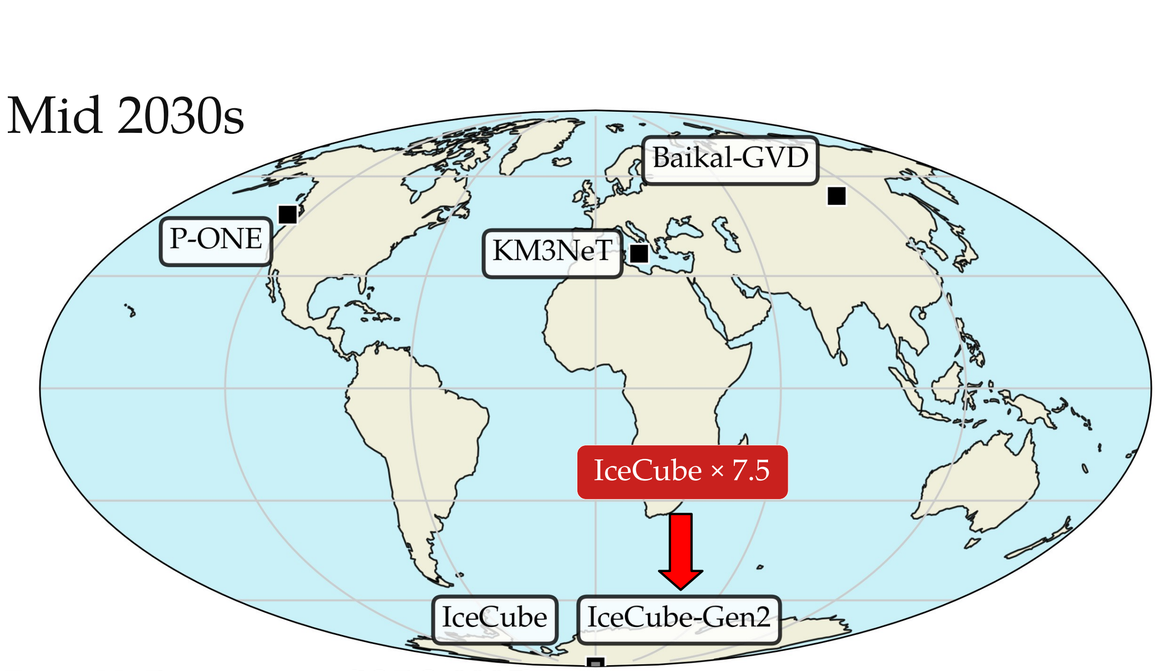


Dik and Suronova for the Baikal-GVD Collaboration PoS(ICRC2025)921

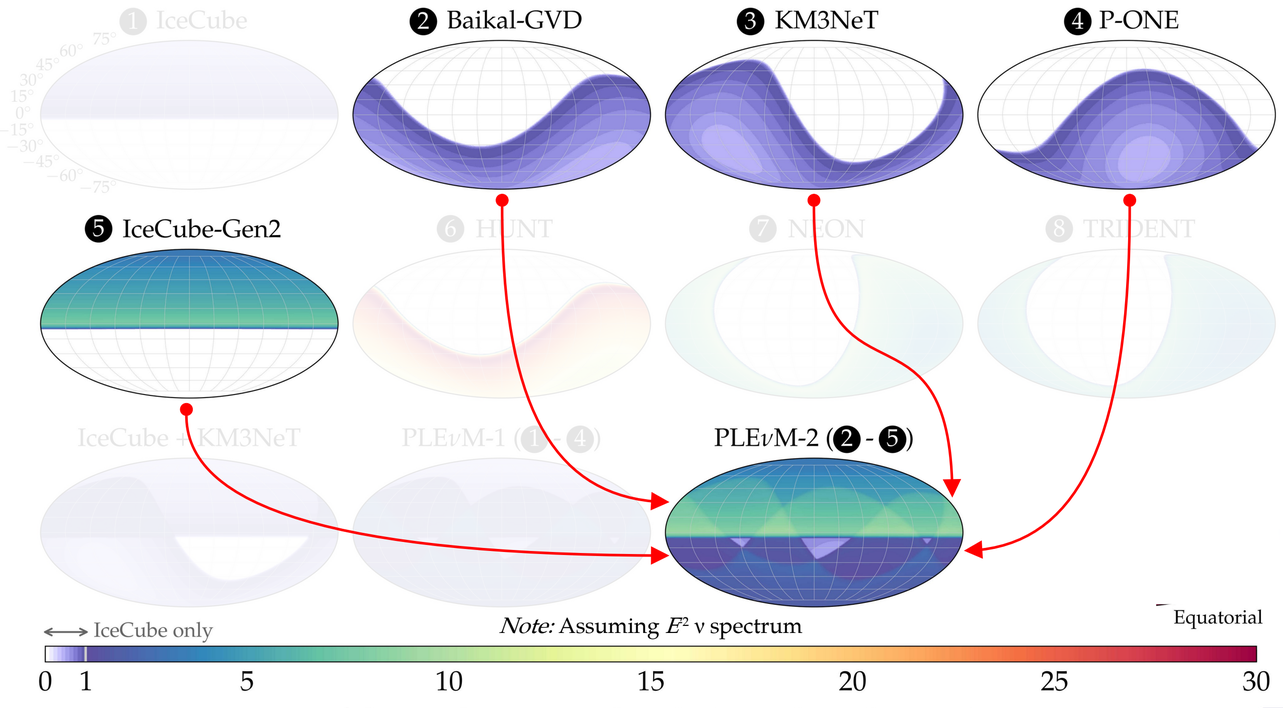
UPCOMING ICE/WATER CHERENKOV TELESCOPES



A GLOBAL NEUTRINO MONITOR



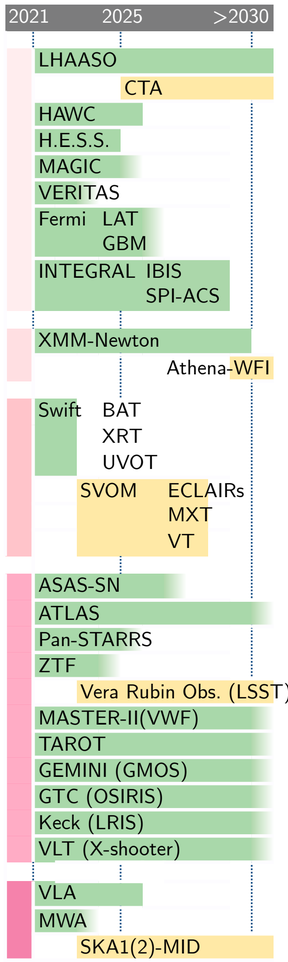
From M. Bustamante (ICRC 2025)



Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

- Rate of muon track detections to increase by x10 wrt IceCube alone by mid 2030s. By x30 or more in mid 2040s with the advent of HUNT/TRIDENT/NEON.
- Coordination of efforts (follow-ups in particular) would be needed. PLENuM approach

RICH MULTIWAVELENGTH LANDSCAPE



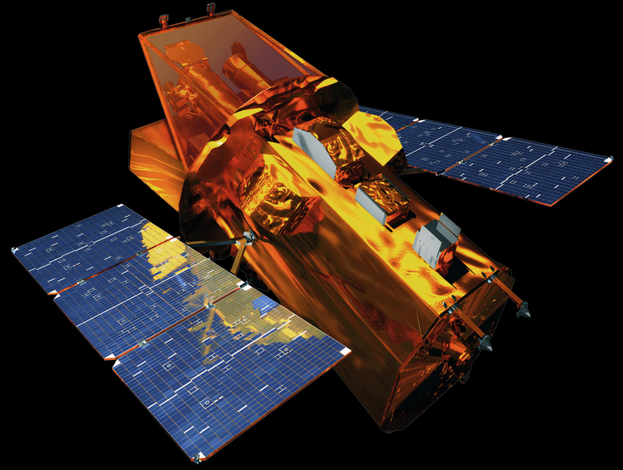
Band Width	Differential sensitivity limit	FoV	ang. res.	slew [survey] speed	resp. delay	ν foll. rate [% alerts] *examples*
100 GeV−1 PeV	5×10^{-14} erg cm^{-2} s^{-1} in 1 yr	2 sr	0.3°	[2/3 sky/day]	-	?
20 GeV−300 TeV	6×10^{-14} erg cm^{-2} s^{-1} in 50 h	10−20°	< 0.15°	180°/20 s	20 s	20 h/yr (2016)
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]
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
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
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
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]
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]
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
100 keV−2 MeV	10^{-3} ph cm^{-2} s^{-1} MeV^{-1} in 10^6 s	4π	-	-	min	and GCN IC alerts]
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*
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]
15−150 keV	6×10^{-10} erg cm^{-2} s^{-1} in 2000 s	1.4 sr	0.4°			
0.2−10 keV	5×10^{-13} erg cm^{-2} s^{-1} in 10^4 s	0.1 deg^2	18”	1°/s	min−h	50% ToO
0.16−0.62 μm	19 mag in 300 s	0.1 deg^2	2.5”			
4−150 keV	7.2×10^{-10} erg cm^{-2} s^{-1} in 10^3 s	2 sr	< 0.2°			first 3 yrs:
0.2−10 keV	2×10^{-12} erg cm^{-2} s^{-1} in 3000 s	1 deg^2	13”	45°/5 min	min−h	15% ToO
0.4−1 μm	22.5 mag in 300 s	0.2 deg^2	< 1”			then: 40% ToO
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]
420−975 nm	19.7 mag in 30 s	29 deg^2	2”	[4×vis. sky/day]	45 s	[no ν alert yet]
400−900 nm	23.1 mag in 904 s	14 deg^2	1.0−1.3”	[vis. sky/week]	h−day	[6 follow ups]
400−650 nm	21.0 mag in 300 s	47 deg^2	2”	[vis. sky/2 days]	h−day	[74% IC Gold alerts]
0.3−1 μm	24.5 mag in 30 s	9.6 deg^2	0.7”	[100 deg^2/5 min]	-	-
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]
350−980 nm	18.5 mag in 180 s	4 deg^2	3.5”	50°/s	s−day	<3% obs. time [70% GCN alerts]
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*
0.365−1.05 μm, spec	27 mag in 1 h	0.02 deg^2	0.127”/pix	obj./min	min	*TXS 0506+056*
0.32−1 μm, spec	23 mag in 20 s	46.8’^{2}	0.135”/pix	1.5°/s	h	*SN PTF12csy*
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*
1−50 GHz	186 μJy in 1 min	0.16 deg^2	0.12”	[20 deg^2/h]	days	*TXS 0506+056, ANTARES events*
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]
350 MHz−15.3 GHz	2(0.1) μJy in 1 h	1(10) deg^2	0.04°−0.7°	?	1 s	?

Guepin, Kotera, Oikonomou - Nature Reviews Physics
arXiv/2207.12205

- Main band for correlation studies unclear.
- Potential hadronic tracers in X-ray, gammas.
- Data analysis of realtime follow-ups not always easy/possible.

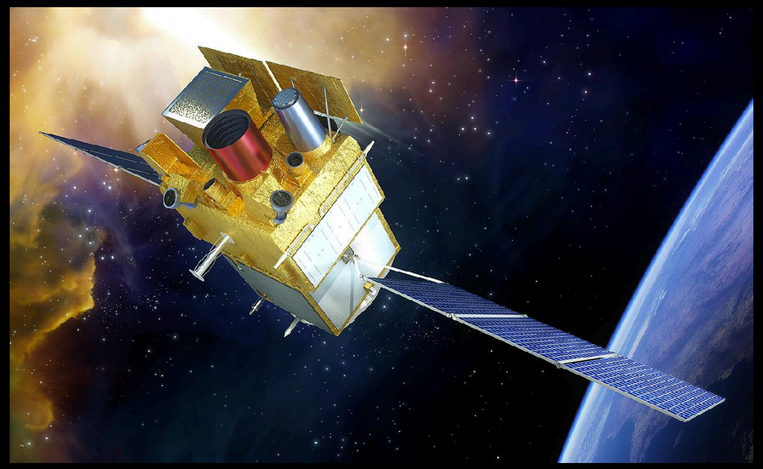
X-RAY COVERAGE

Neil Gehrels *Swift* Observatory



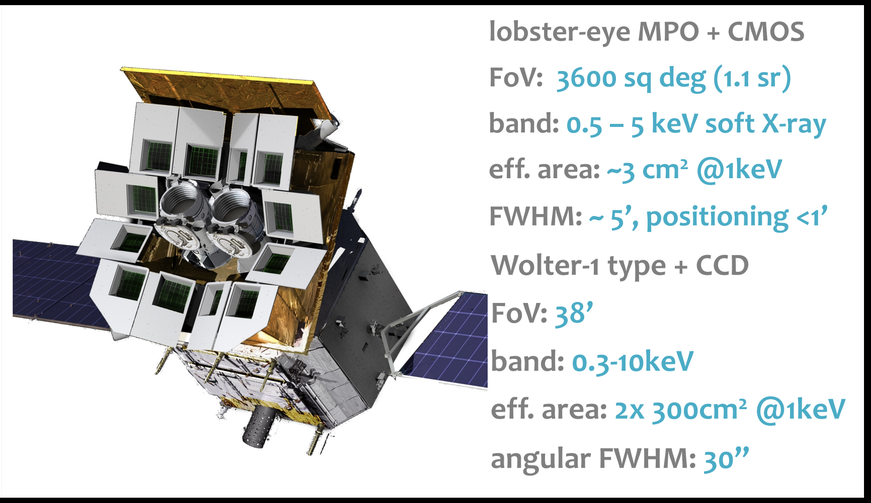
XRT sensitivity in the 0.3-10 keV
Fast response, low overhead.
110 cm^2
~0.4 deg FoV. Launched in 2004.

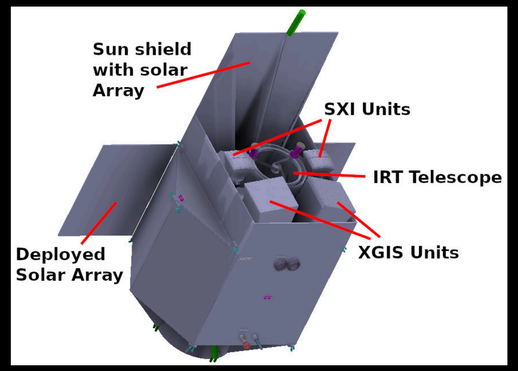
SVOM (China-France)



Rapid follow-ups of GRBs
Launched June 2024
0.2-10 keV
“Lobster eye” optics with 1 deg FoV

Einstein Probe (China-ESA) January 2024 launch





THESEUS (ESA)

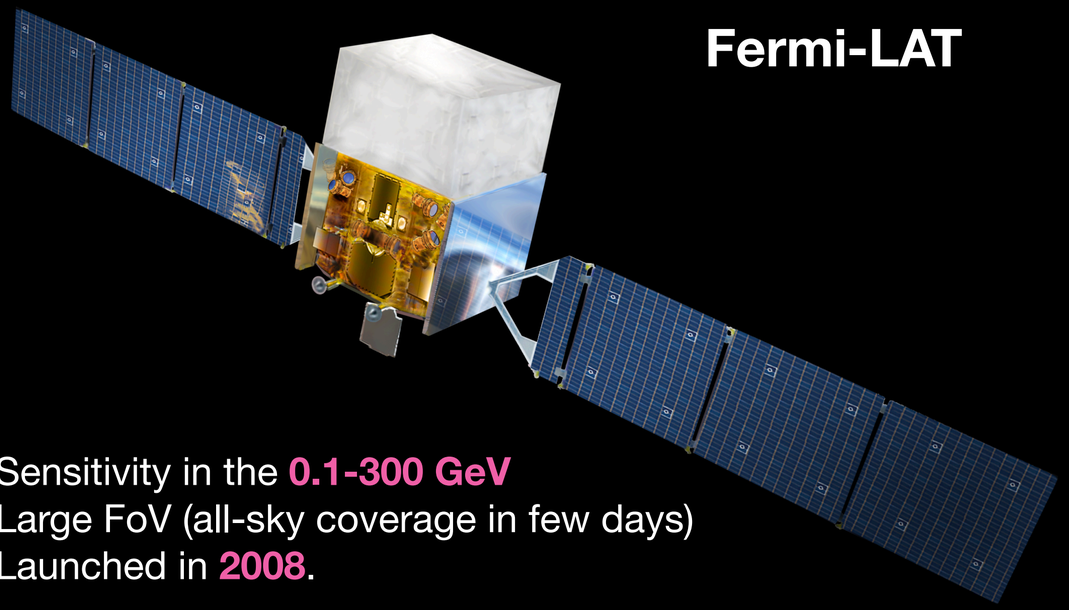
Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2’

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

Being reproposed .

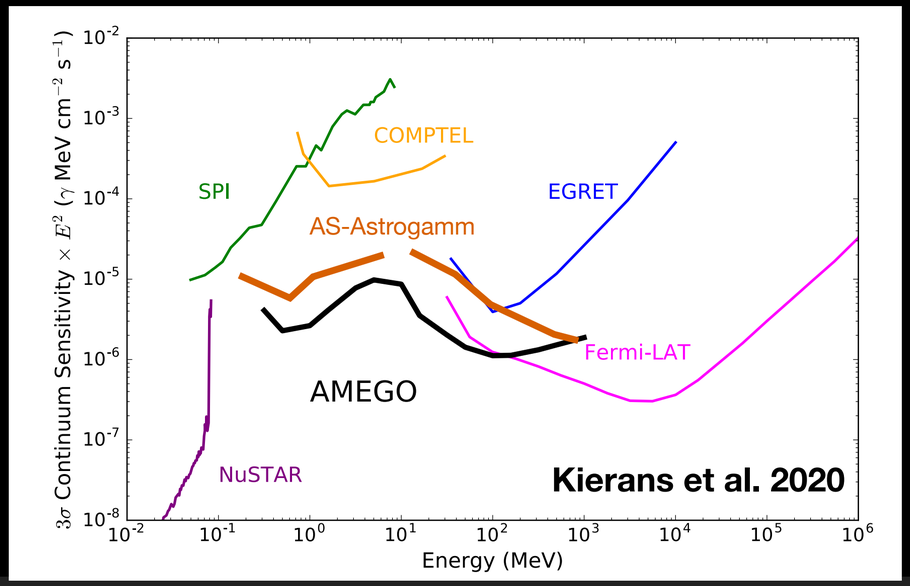
- Critical energy range for the follow-up of neutrino events. Hadronic model testing.
- Main follow-up instrument (Swift XRT) has been >20 years in orbit.

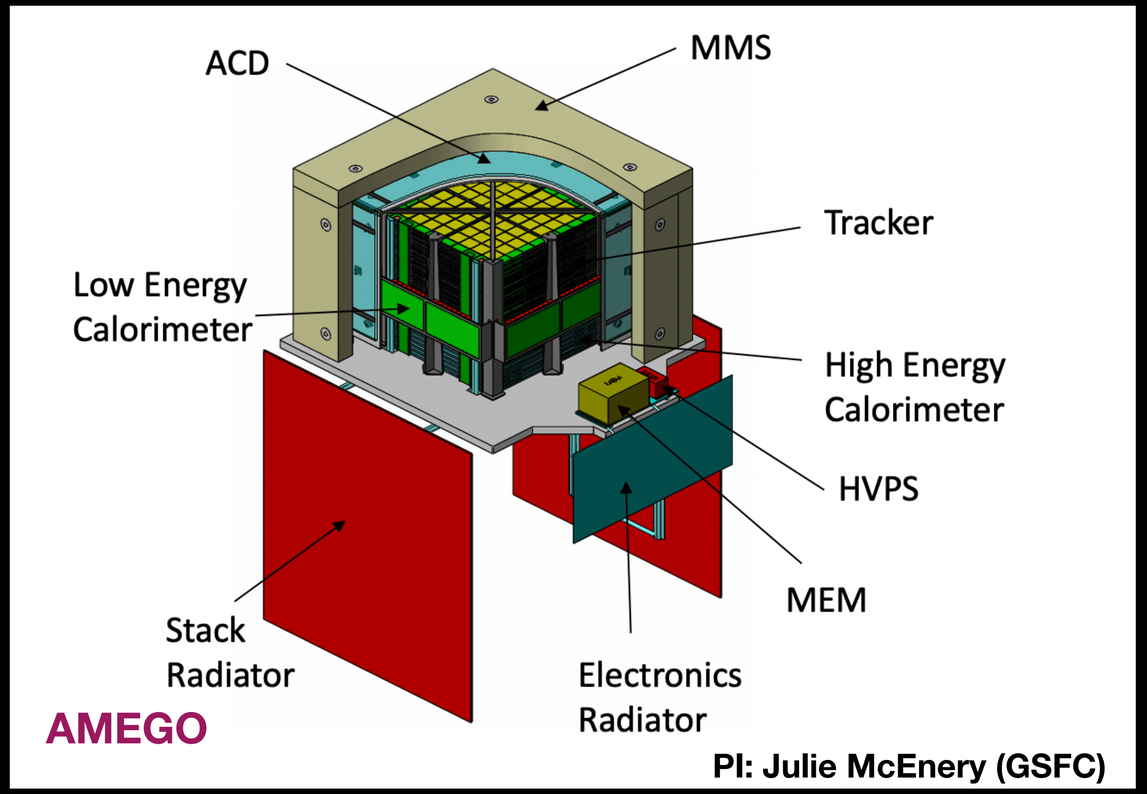
MEV-GEV COVERAGE



Fermi-LAT

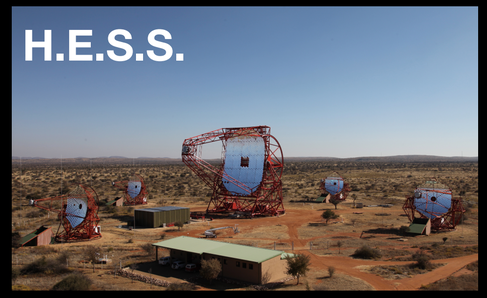
Sensitivity in the **0.1-300 GeV**
Large FoV (all-sky coverage in few days)
Launched in **2008**.

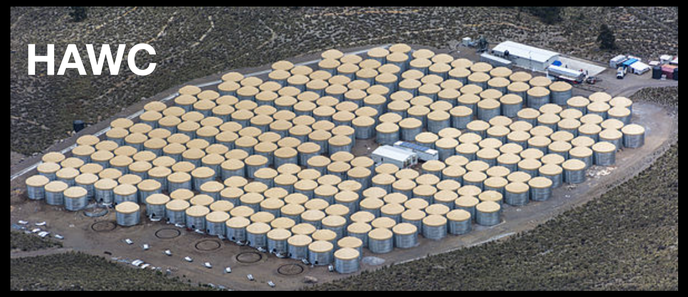




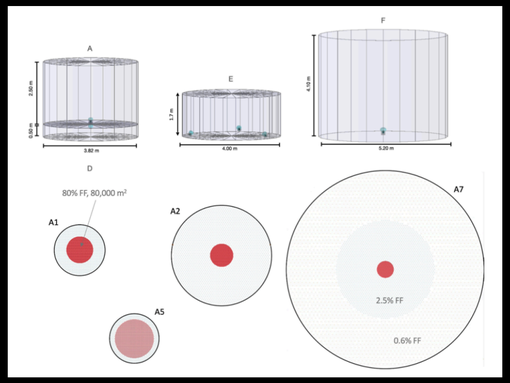
- AMEGO angular resolution: 3° (1 MeV), 10° (10 MeV)
- ComPair prototype for AMEGO.
- AMEGO-X explorer proposed, not selected.
- e-ASTROGAM not selected at the moment.

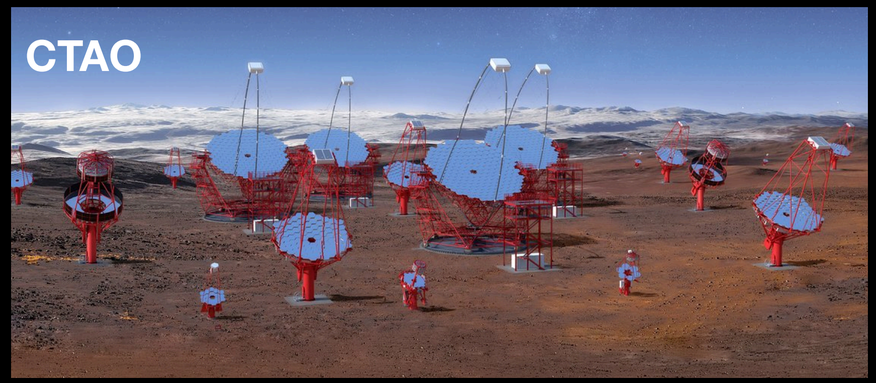
COVERAGE IN THE VERY-HIGH-ENERGY RANGE

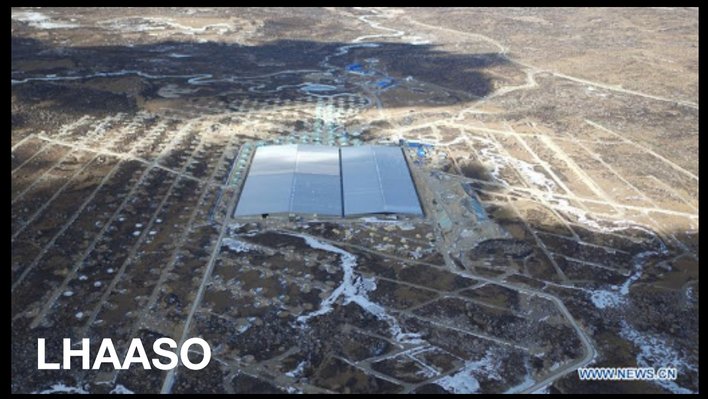




SWGO







- CTAO 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.

FULLY INTEGRATING NEUTRINO TELESCOPES INTO TDAMM

- Work ongoing 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). SciMMA.

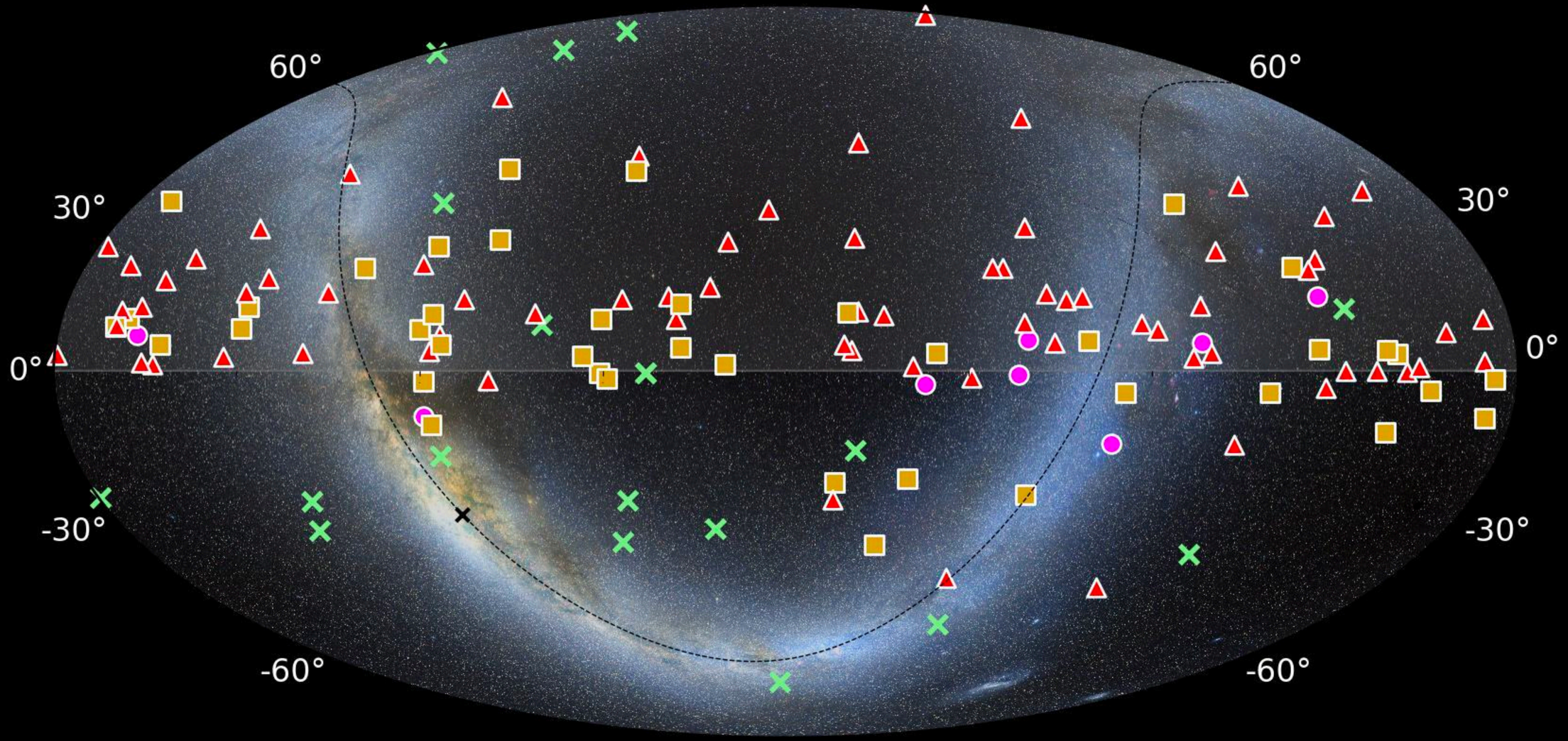
- **Most searches for transient/variable sources should be done in realtime if possible**. Neutrino telescopes already working in that direction.

- EM searches for counterparts should algo go in this direction

- Tools like AstroColibri simplify counterpart identification, follow-up planning.

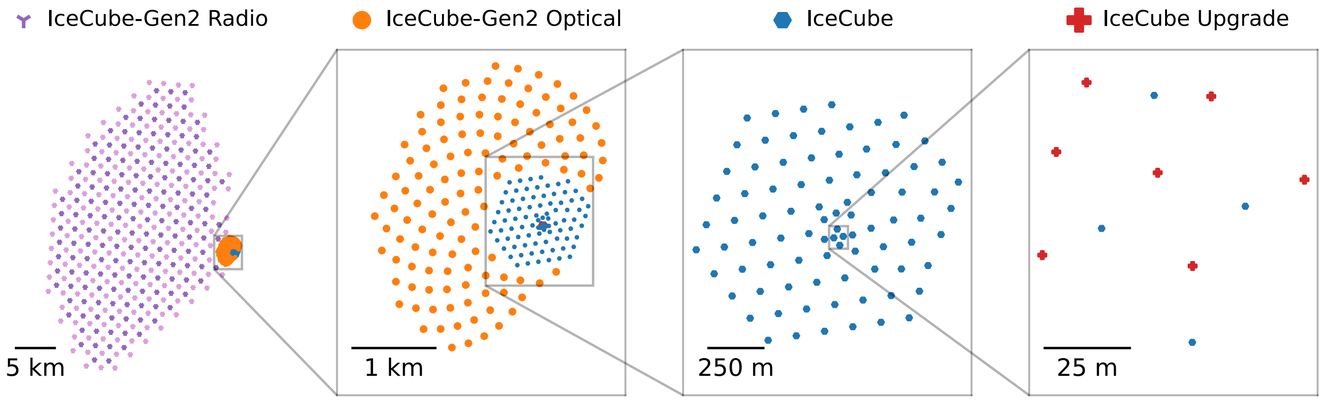
WISHLIST FOR NEUTRINO ALERTS

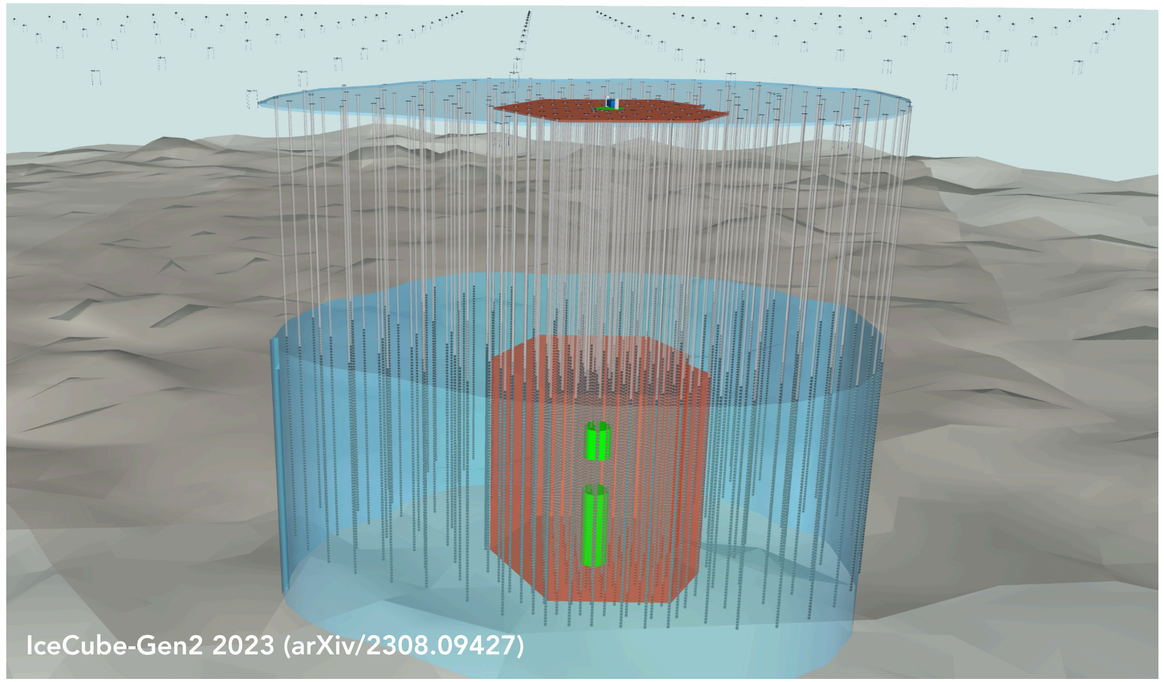
- **Next steps for alerts:**
  - Increase the number of neutrino events >100 TeV (high astrophysical purity)
  - Improve the angular resolution (correlation probability goes with PSF^2)
- As neutrino telescopes are 4π instruments, you need **wide-field, continuous, broad-band, sensitive coverage across 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 with the EM community and continued follow-up tools**



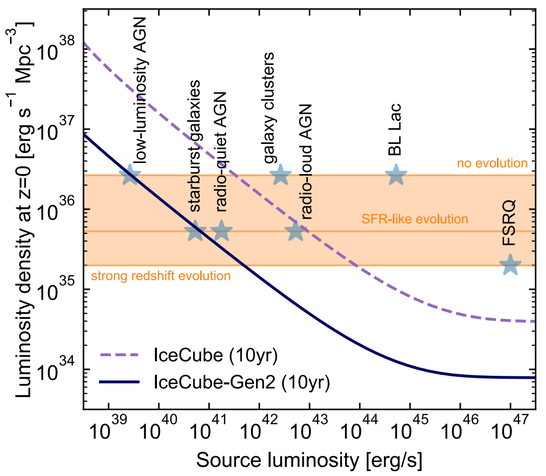
THANK YOU!

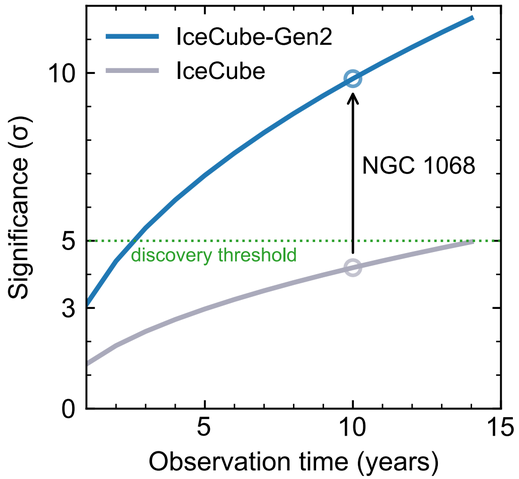
ICECUBE-GEN2



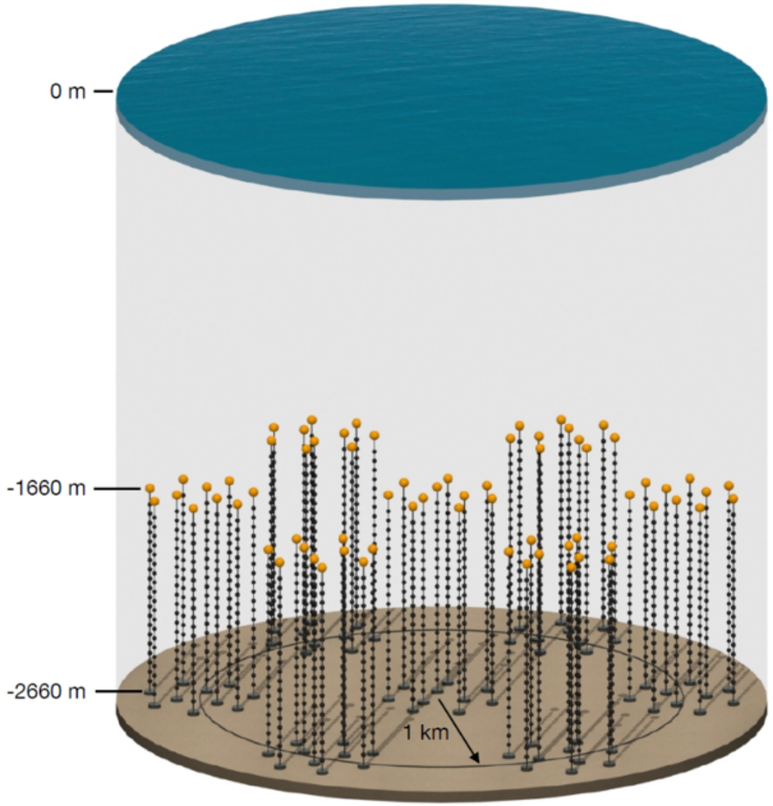


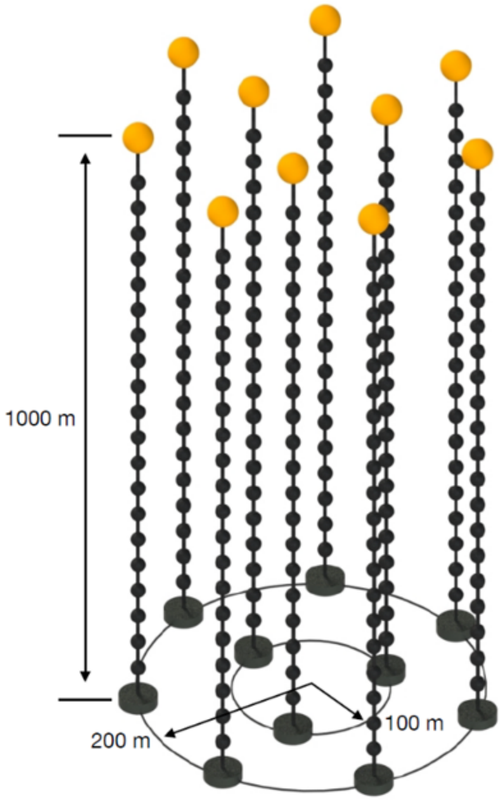
- Detector volume of ~8 km^3. Strings farther apart than in current IceCube, optimized for high energies.
- Angular resolution improved by x3 wrt current IceCube.
- Strong source detections within reach of the first 10 years of operation.
- Endorsed by the Astro2020 Decadal Survey in the U.S.
- IceCube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





P-ONE

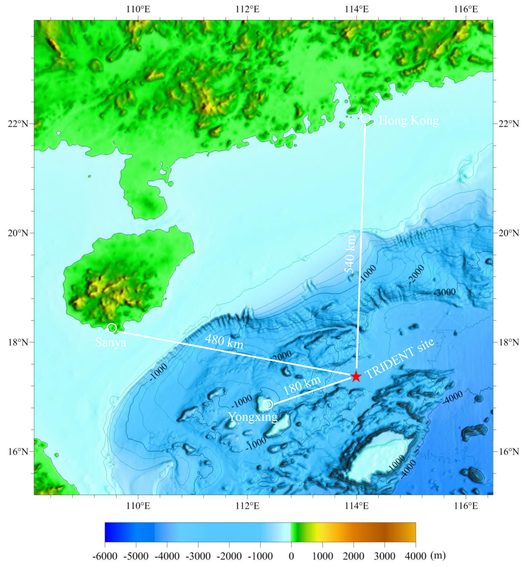


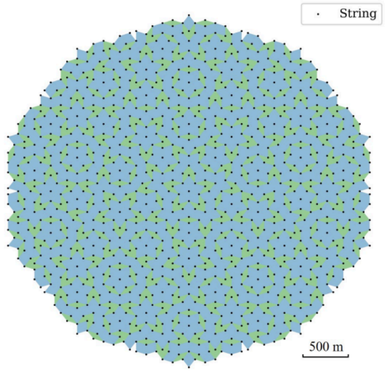


- Cascadia basin off the coast of British Columbia, Canada.
- Deployed two pathfinder lines (STRAW-a/b in 2018 and 2020), currently working on the development of a prototype line.
- **Targeting 1 km³**. 7 clusters of 10 lines each, 20 detectors per line.

P-ONE Collaboration ICRC 2023 (Vol 444 1197)

TRIDENT

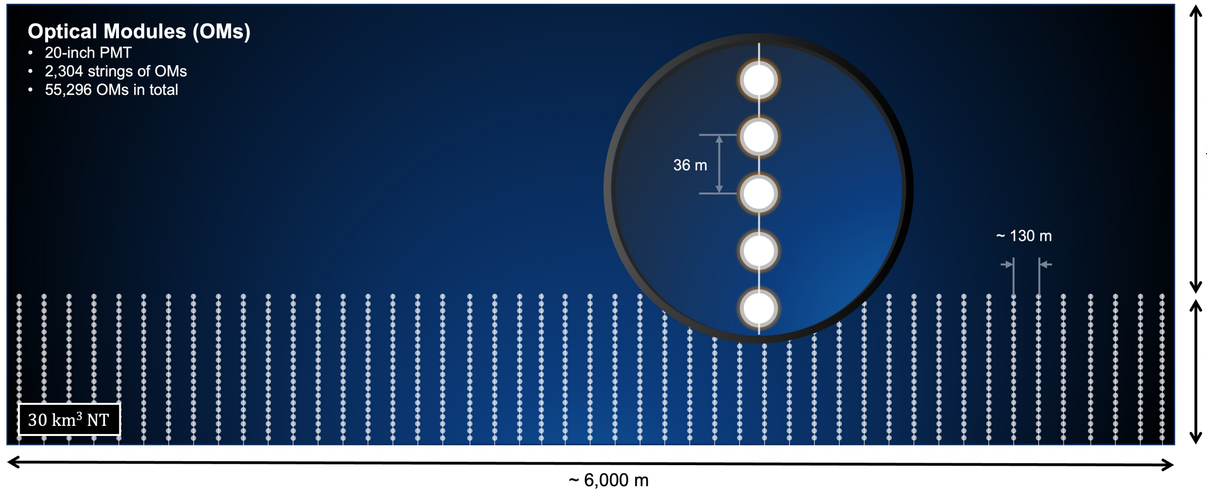




TRIDENT Collaboration (2022, arXiv/2207.04159)

- 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

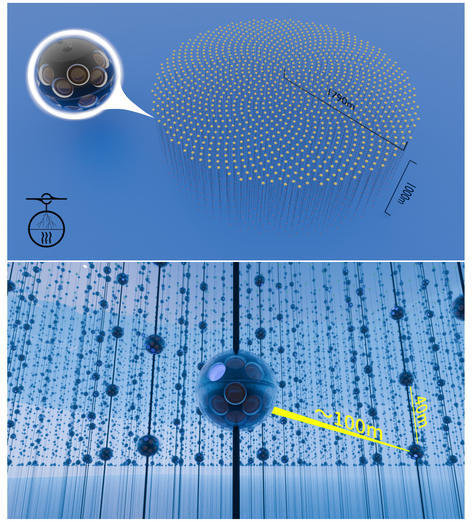


HUNT Collaboration ICRC 2023 (Vol 444 1080)

- 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.

NEON

- Total volume of **10 km^3**. 660k PMTs on 1200 strings
- Main goal is to target PeV neutrino astronomy.



NEON Collaboration (2024, arXiv/2408.05122)