IceCubeを軸としたマルチメッセンジャー天文観測の戦略

(Strategies for multi-messenger astronomical observations with IceCube)

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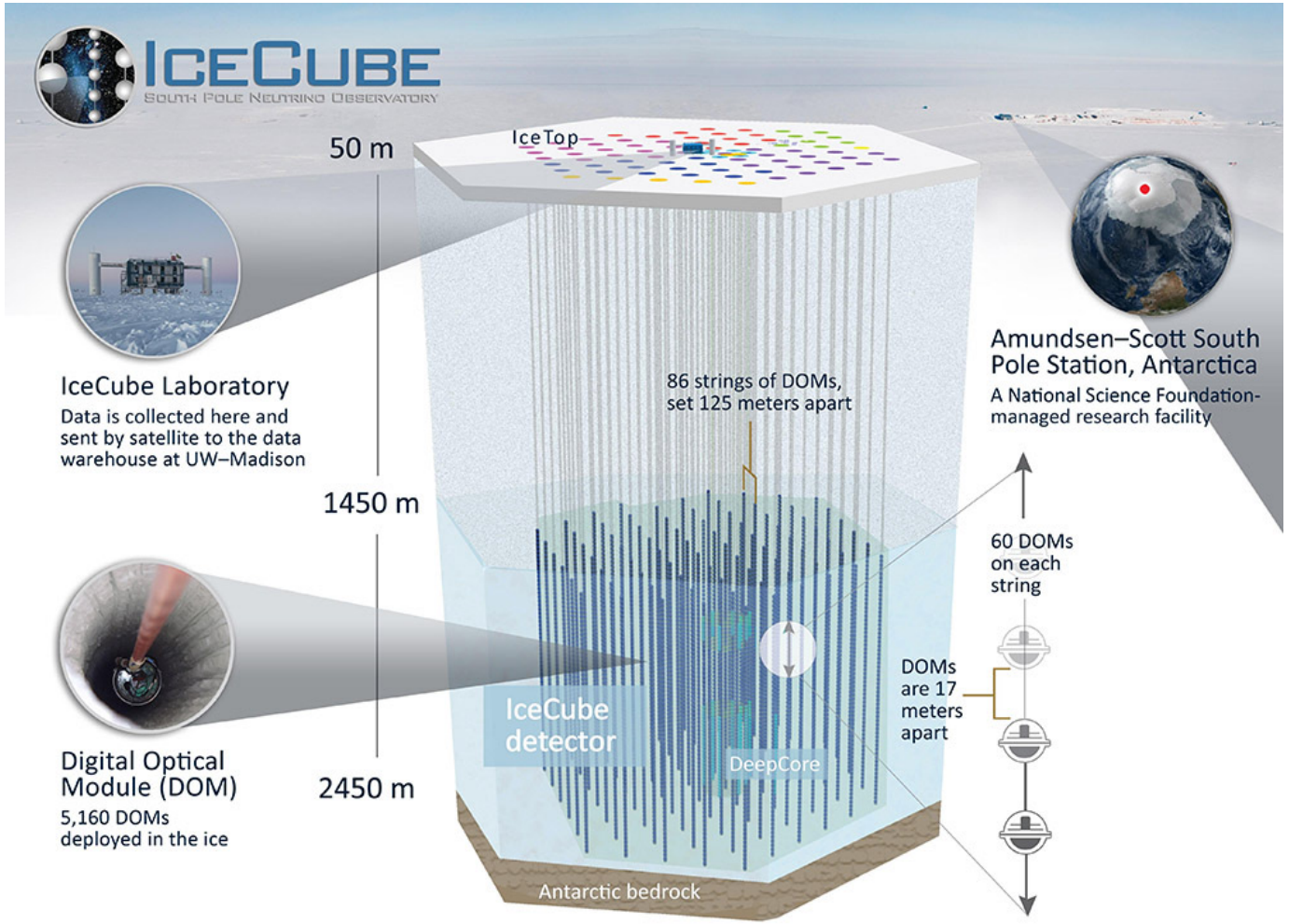
Credit: J. Werthebach, IceCube/NSF

Outline

1. Introduction
2. New IceCube Alert Study
   - Multiplet alert
   - neutrino – X-ray combination alert
3. IceCube upgrade and Gen2

Focusing on research being performed by Chiba University

IceCube

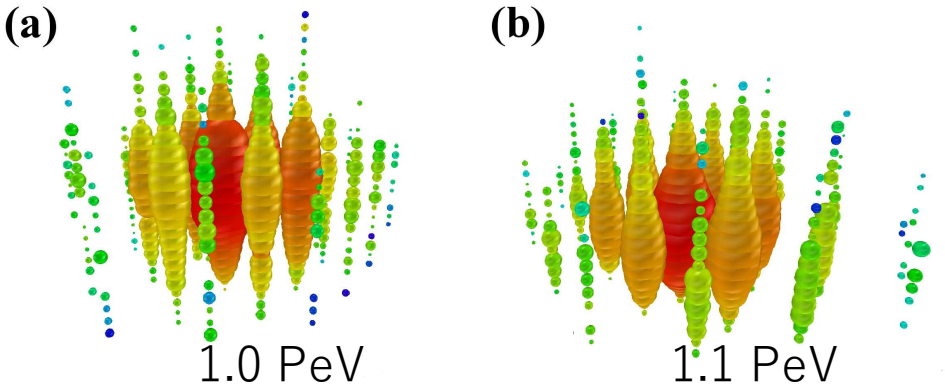


Digital Optical Module (DOM)

- Built at the South Pole
- 5160 DOMs buried within 1 km^3 of underground
- Cherenkov light from charged particles generated by neutrino interaction detected by DOM
- 86 strings in operation (IC-86) since April 2011.

IceCube : astrophysical diffuse neutrino

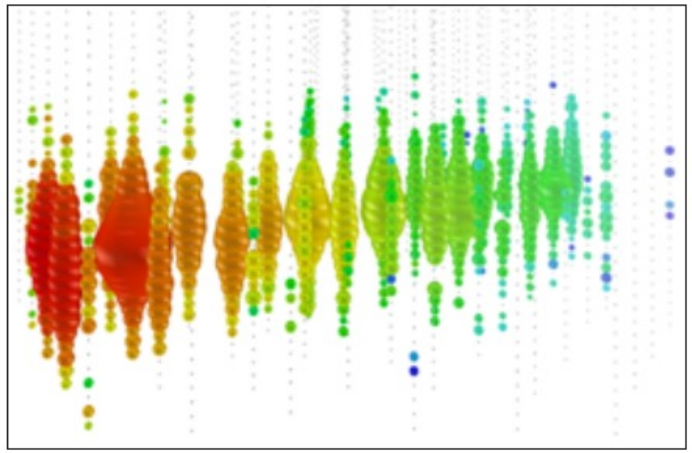
Cascade $\nu_e + N \rightarrow e + X$



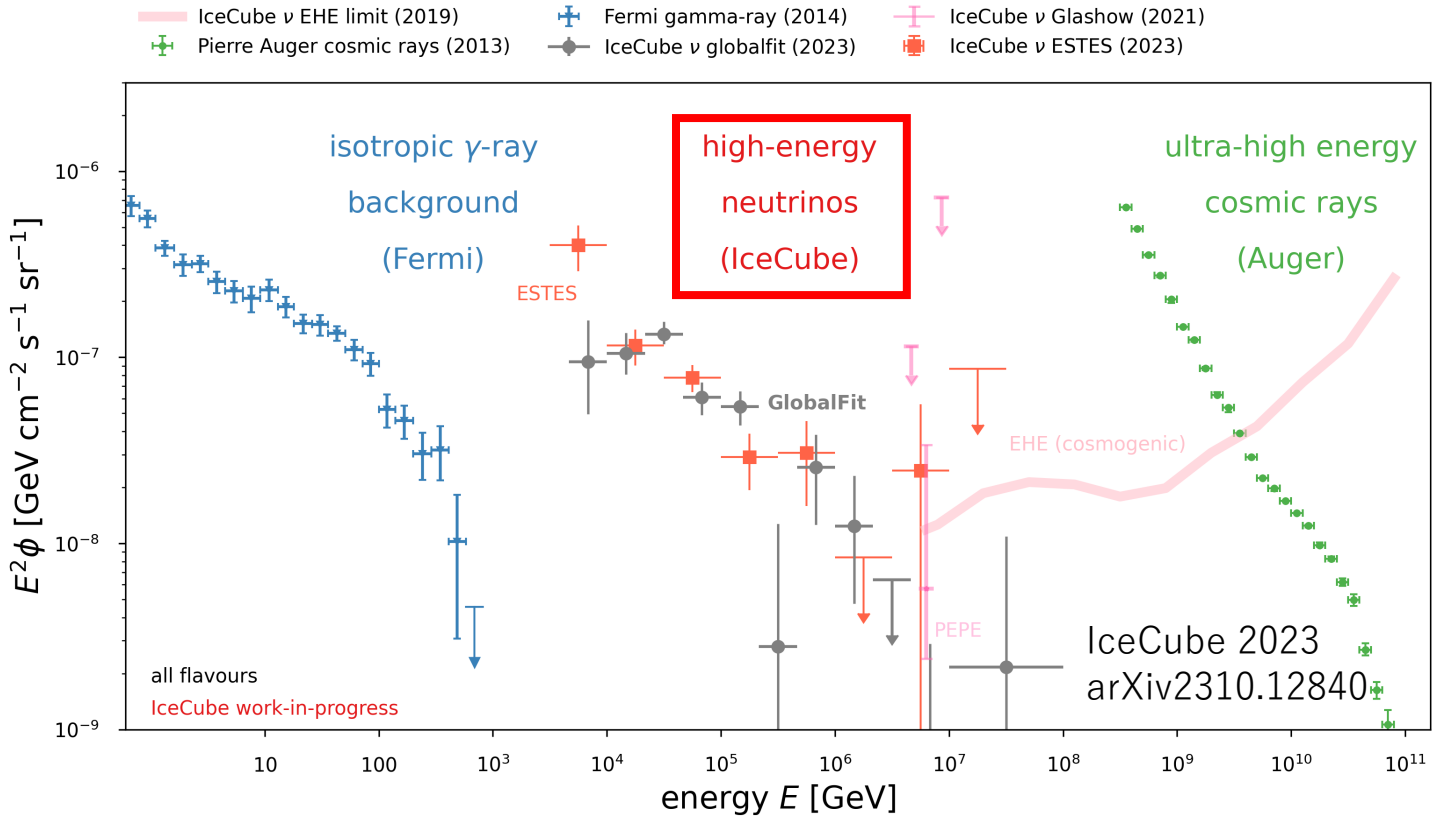
First Observation of PeV-Energy Neutrinos with IceCube

IceCube 2013 PRL

Track $\nu_\mu + N \rightarrow \mu + X$



$\sigma_\psi \sim 0.5°$

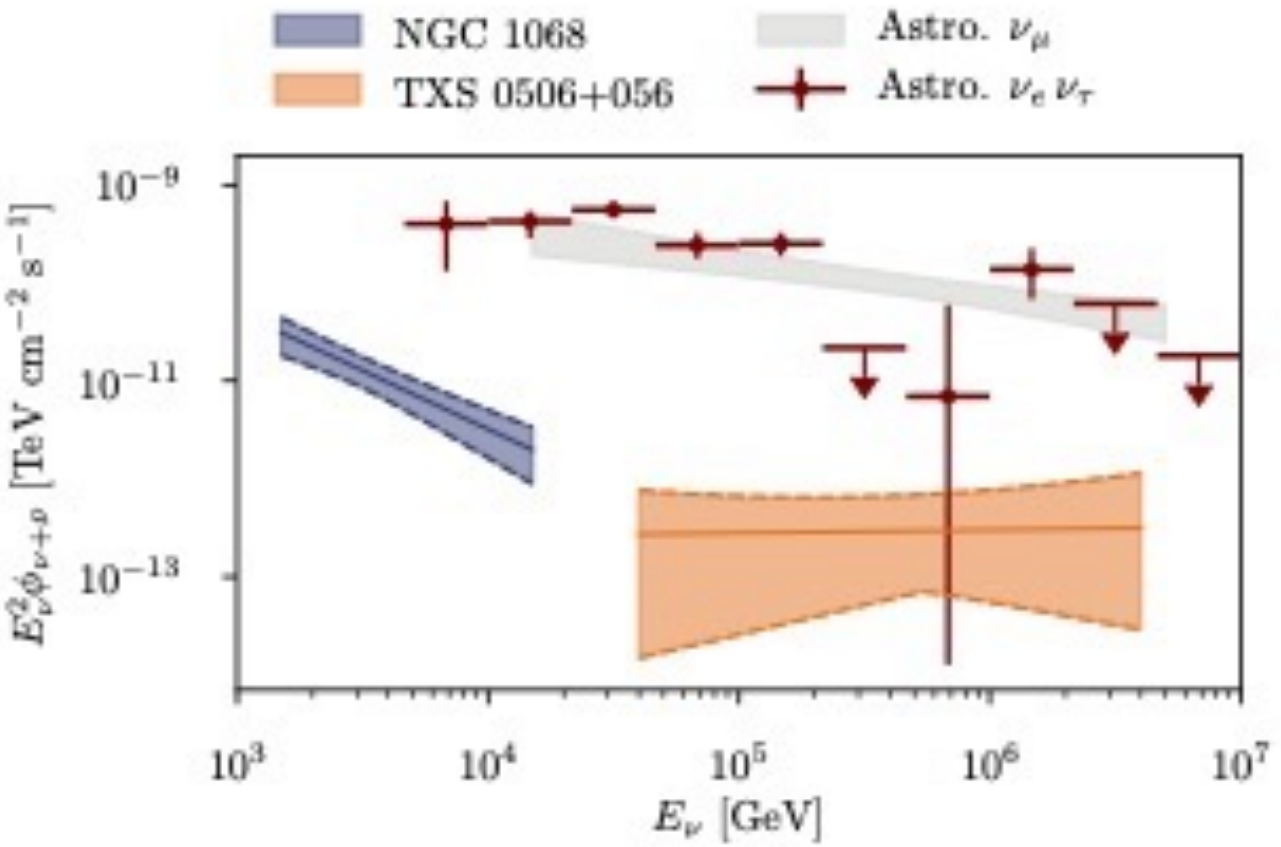


Diffuse astrophysical neutrinos (cosmic neutrino background)

- $E^2\,\phi_\nu \sim 10^{-8}$ @10 TeV
- Same level of cosmic ray flux near the ankle

IceCube : astrophysical diffuse neutrino

Three objects identified as neutrino emitter



TXS 0506+056 (IceCube 2018)

- blazar (AGN with jets ejected to point at Earth)
- first candidate identified by multi-messenger observations on 2017
- this class of AGN alone would not explain diffuse neutrino flux(~20%)

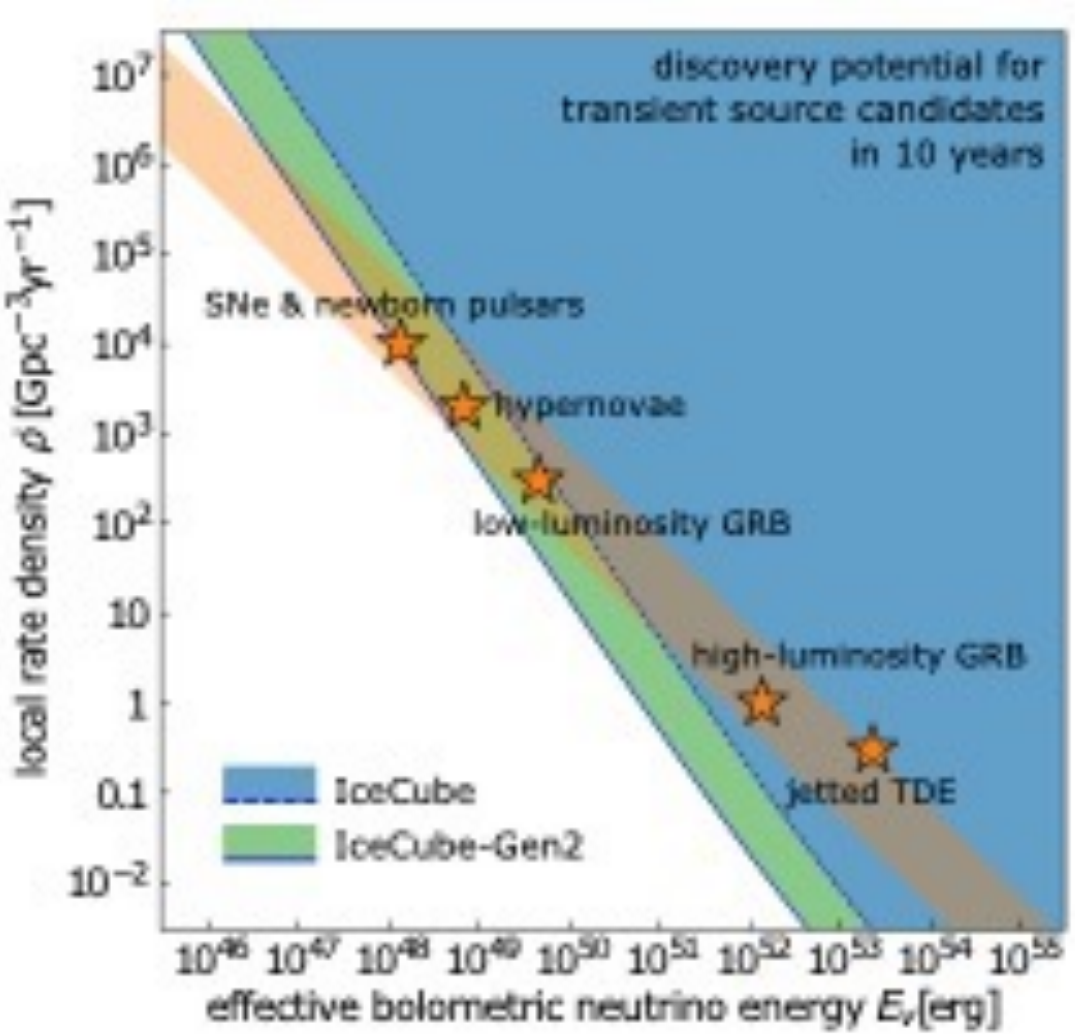
NGC 1068 (IceCube 2022)

- Seyfert galaxy (AGN with weak jets)
- Significance of 4.2 σ by stacking analysis for about 10 years
- Particle acceleration in the corona around SMBH is important
- Origin of diffuse neutrino? → Kimura-san's talk

Galactic Plane (IceCube 2023)

- Progress in analyzing the cascade events has led to the discovery (4.5 σ level)
- consistent with modeled diffuse emission, but could also unresolved point sources.
- Contribution to the diffuse flux is a few%.

How much does the transient contribute?

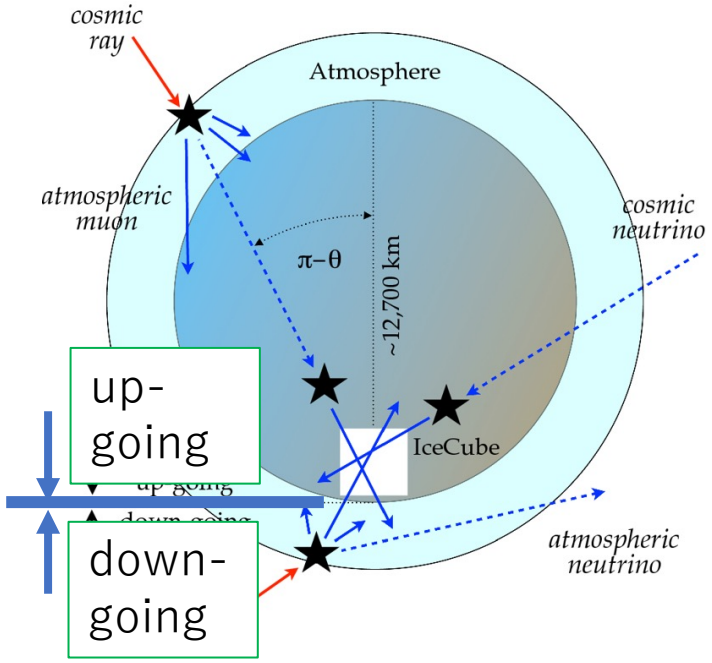


arxiv.org/abs/2008.04323

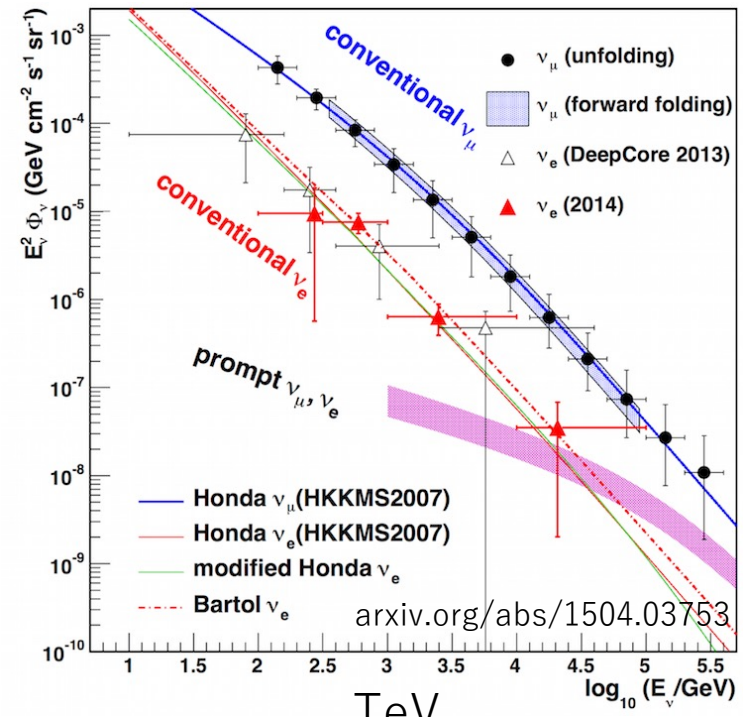
GRBs were a highly expected event as a source of high-energy neutrinos
→ the non-detection of neutrinos in spatial and temporal coincidence with GRBs over several years
→a strict upper bound of 1% for the maximum contribution (IceCube 2017)

Strange supernovae (+circumstellar material)?
Nearby TDE?
Low-luminosity GRBs?

How much does the transient contribute?



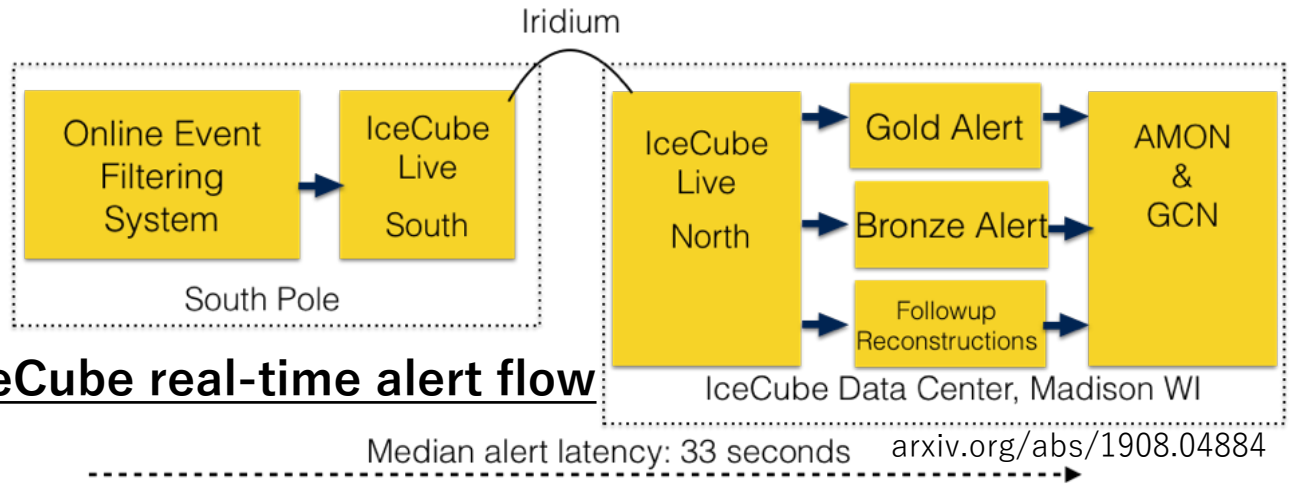
Up-going, Down-going



TeV Atmospheric neutrino spectra PeV

Example of GFU filter flow (upgoing)

Cut Level	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times 10^{-3}$ (mHz)
0	1010.5	1523.81	7.166	6.23
1	282.49	504.44	5.826	5.62
2	8.839	22.01	3.076	4.06
3	1.124	4.30	2.313	3.69
4	0.100	2.15	1.899	3.26
5	0.080	2.08	1.880	3.25
6	0.075	2.06	1.875	3.24



IceCube real-time alert flow

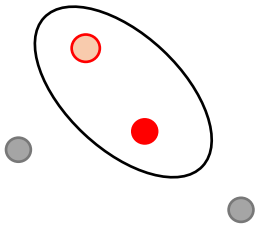
Develop new alerts for:
Long duration (~month) transients
← neutrino multiplet alert

Short duration (~$10^{3\text{-}4}$ sec)
← neutrino – X-ray combination alert

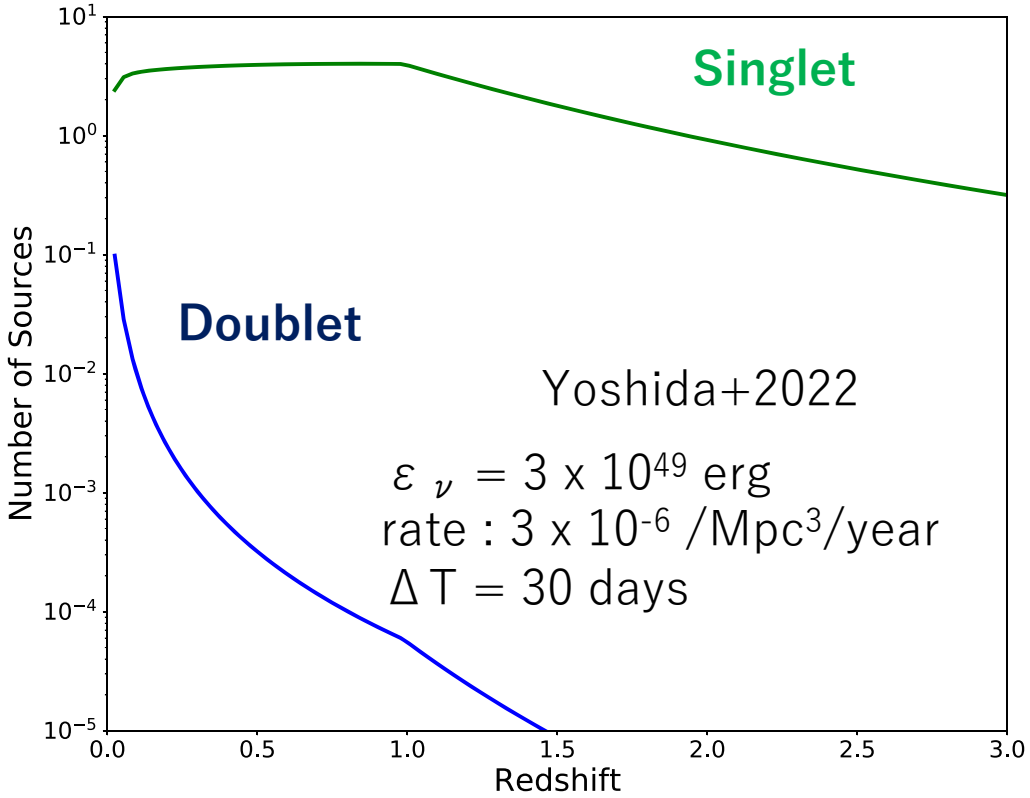
Multiplet alert

The study is lead by Nobu Shimizu @Chiba Univ.

Multiplet

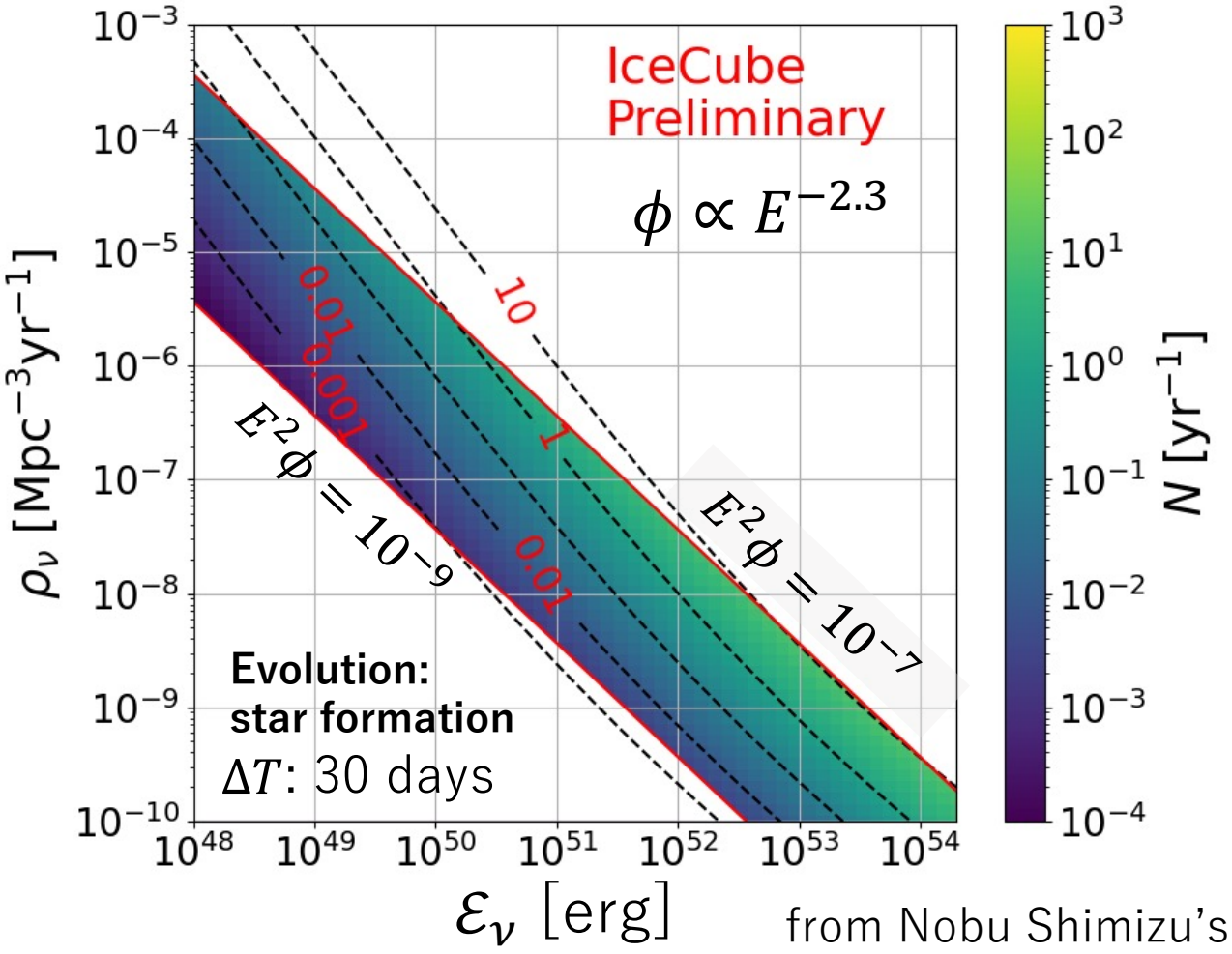


$N \geq 2$ coincident ν-signals
in ΔT from the same direction



SNe→

TDE →



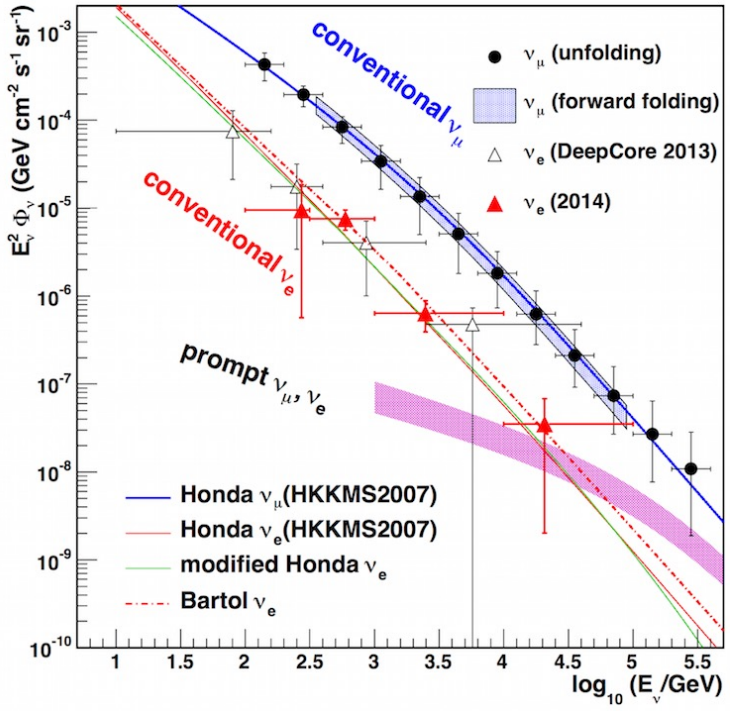
from Nobu Shimizu's ASJ 2023 slides

- Multiplet allows selection of nearby events (z~0.1)→ advantageous for EM follow-ups
- Allows limiting the parameter in the ρ_ν - ε_ν plane from the upper limit of the archive analysis.

Multiplet : method

from Nobu Shimizu's ASJ 2023 slides

- Major background source → **atmospheric neutrinos**
- Focus only on **doublets** and **triplets**
- Set long time window $\Delta T = 30$ **days** to access various sources
- Construct a **test statistic** Λ from signal and background likelihoods: $\mathcal{L}_{sig}, \mathcal{L}_{bg}$



arxiv.org/abs/1504.03753

Atmospheric neutrino spectra

[Doublet case]

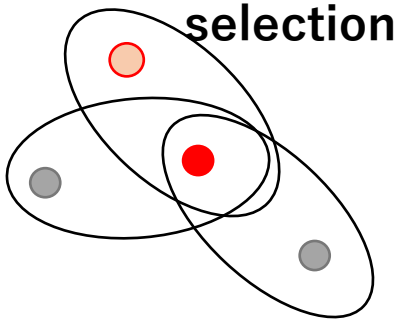
Rate *Energy PDF* *Spatial PDF*

$$\mathcal{L}_{\mathrm{sig}}^{\mathrm{doublet}} = R_{\mathrm{sig}}(\vec{n}_{obs}) \prod_{i=1}^{2} \frac{1}{N_{\mathrm{sig}}} \frac{dN_{\mathrm{sig}}(E_{obs})}{dE} \cdot \frac{1}{N_{\mathrm{sig}}} \frac{dN_{\mathrm{sig}}(\vec{n}_{obs};\vec{n}_{sig})}{d\Omega}$$

$$\mathcal{L}_{\mathrm{bg}}^{\mathrm{doublet}} = R_{\mathrm{bg}}(\vec{n}_{obs}) \prod_{i=1}^{2} \frac{1}{N_{\mathrm{bg}}} \frac{dN_{\mathrm{bg}}(E_{obs})}{dE} \cdot \frac{1}{N_{\mathrm{bg}}} \frac{dN_{\mathrm{bg}}(\vec{n}_{obs})}{d\Omega}$$

$$\Lambda_{\mathrm{doublet}} = 2\log\left(\frac{\mathcal{L}_{\mathrm{sig}}^{\mathrm{doublet}}}{\mathcal{L}_{\mathrm{bg}}^{\mathrm{doublet}}}\right)$$

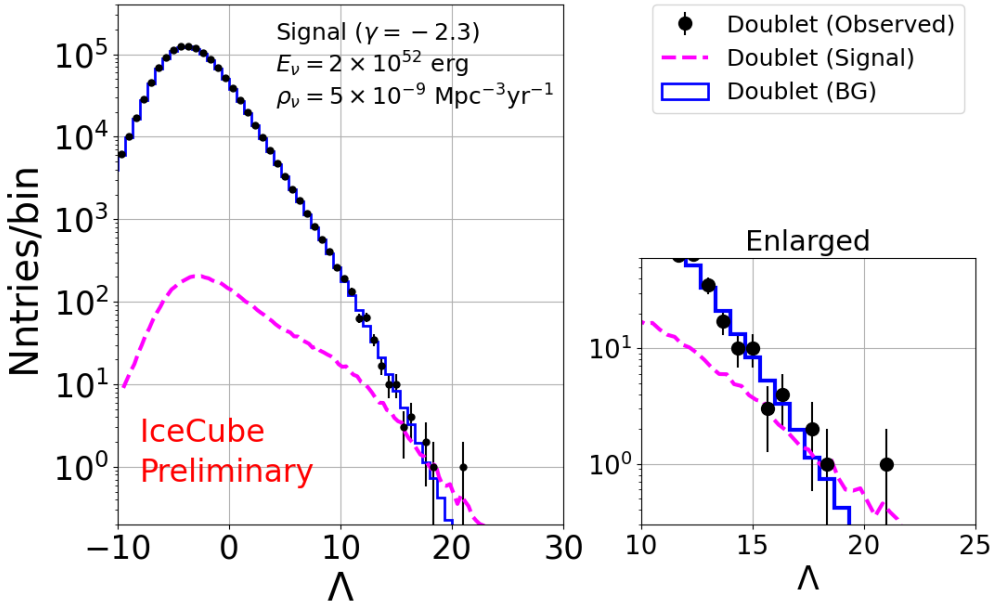
In the case of Double selection

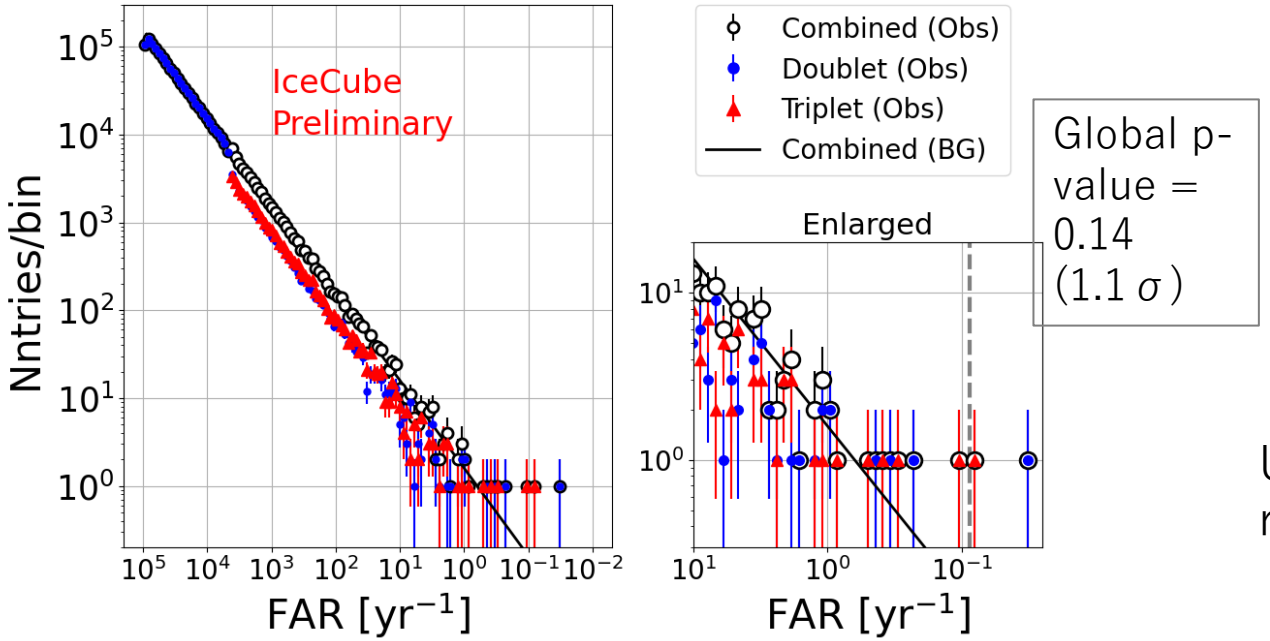


Select most signal-like ν combinations using Λ

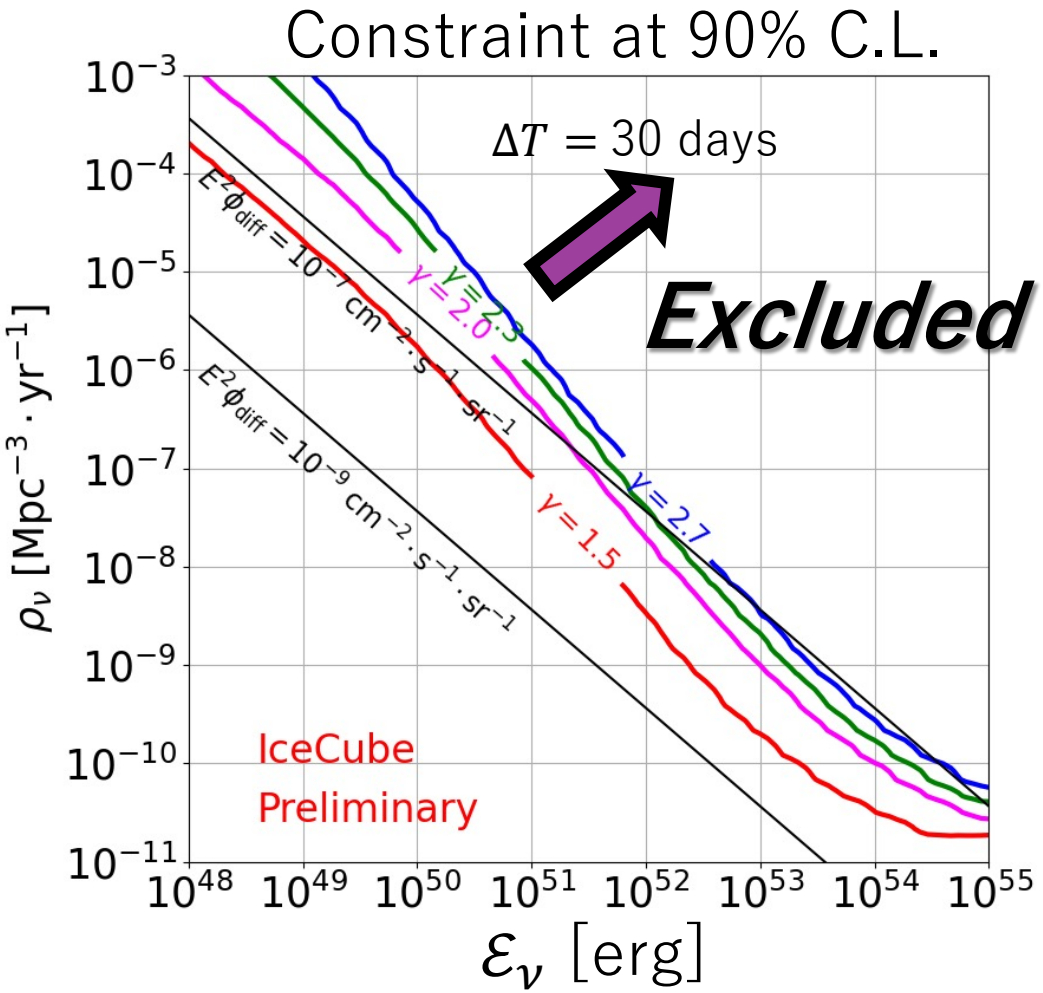
Multiplet archival data (~11 years) analysis results

from Nobu Shimizu's ASJ 2023 slides





Global p-value = 0.14 (1.1 σ)

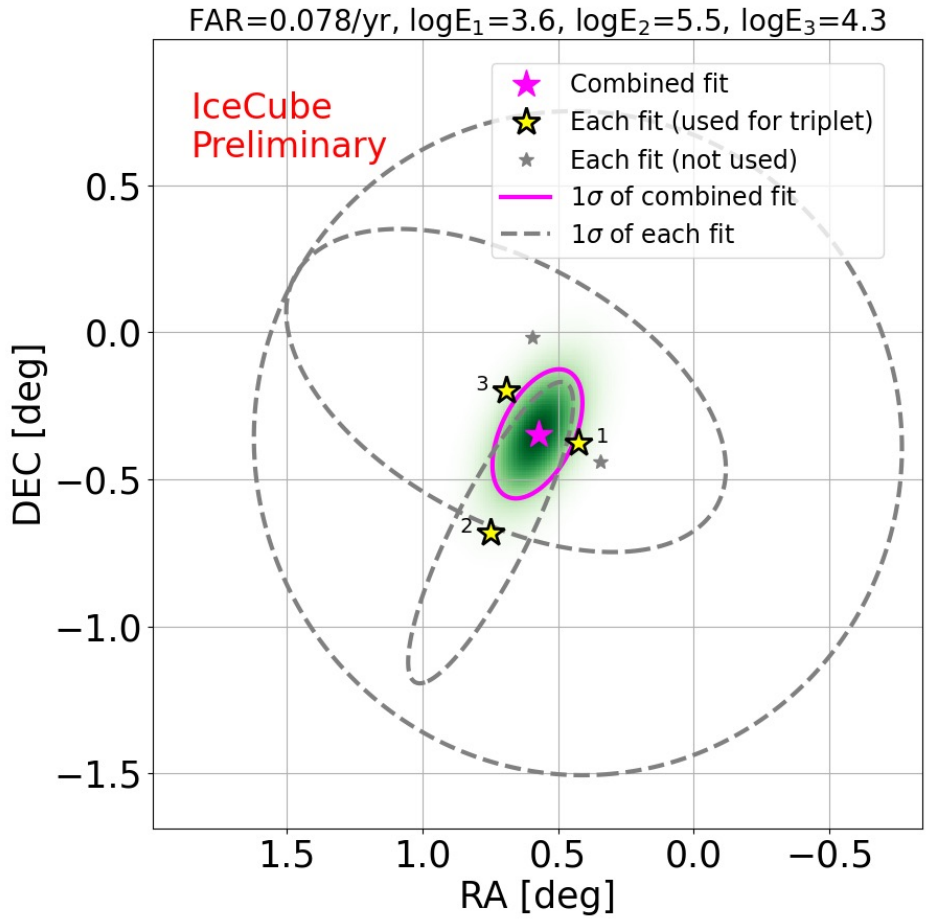


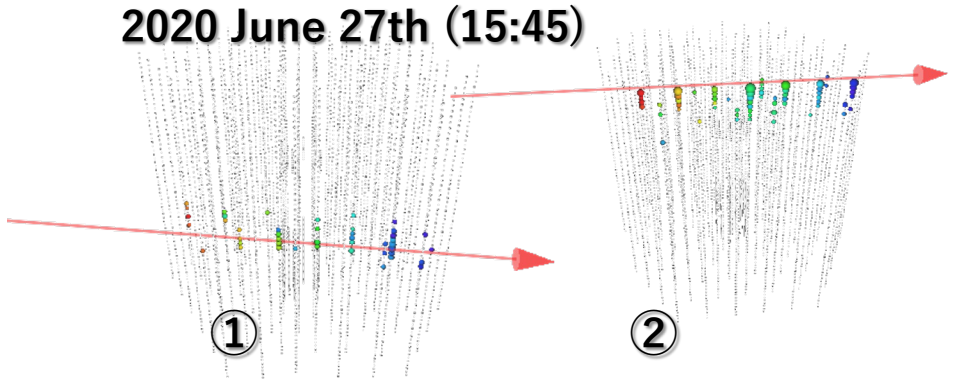
Using the largest $\boldsymbol{\Lambda}$, we scanned the consistent region of ($\mathcal{E}\_\nu$,ρ_ν).

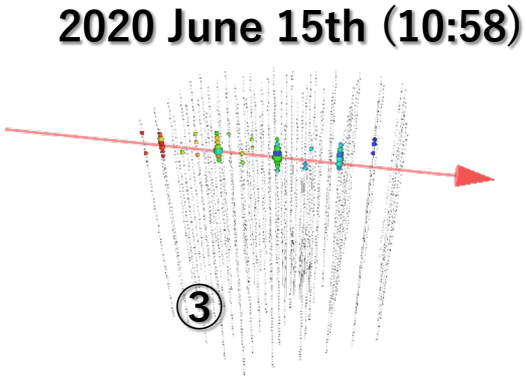
example of multiplet event

from Nobu Shimizu's ASJ 2023 slides

Type: **Triplet**, (RA, DEC)=(0.58 deg, -0.35 deg)
Energy: E=(4 TeV, 30 TeV, 20 TeV), $\Delta T = 16.4$ days,
local p-value=7.4×10^{-7}, FAR= 1/13 [1/yr]

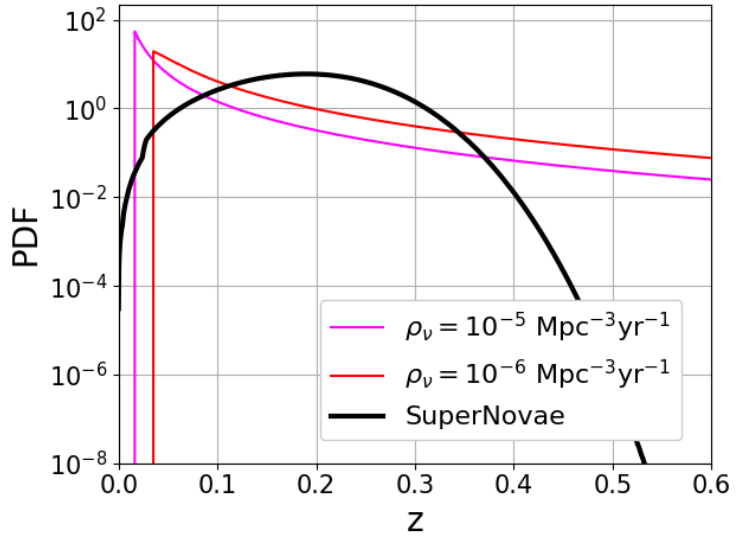


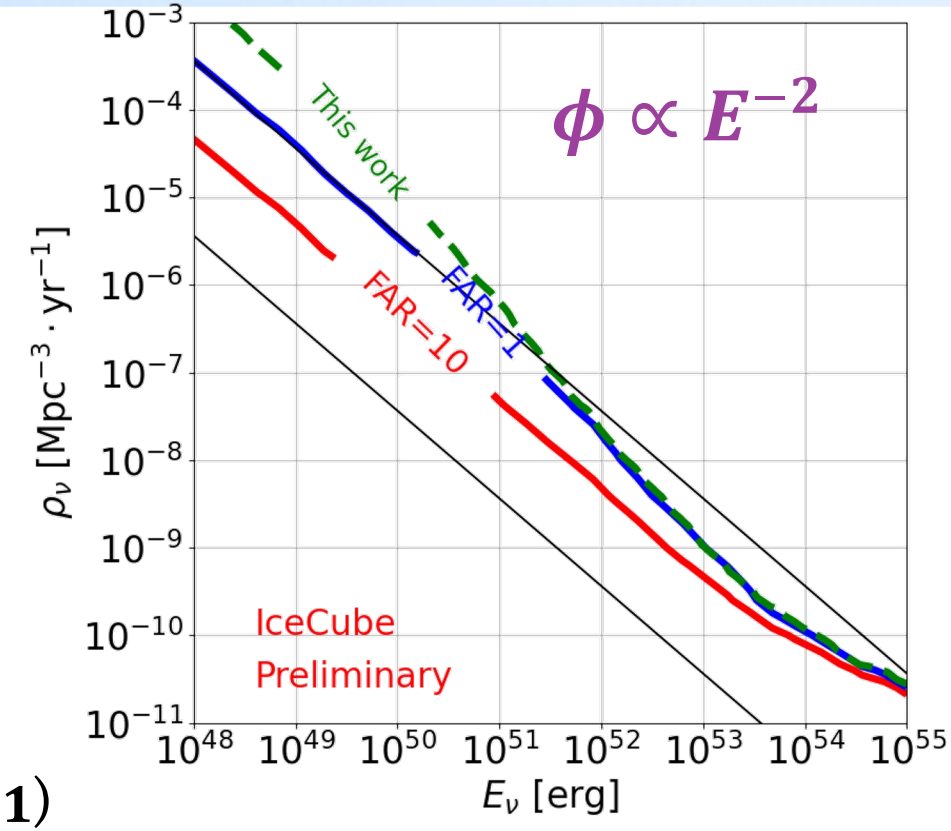




Multiplet alert

z distribution of multiplet from ν-source and supernovae





- multiplet signal gives bias on **close sources** ($z < 0.1$)

  close sources are easy to observe by EM(e.g, when following up with gamma rays, the EBL is less affected.)

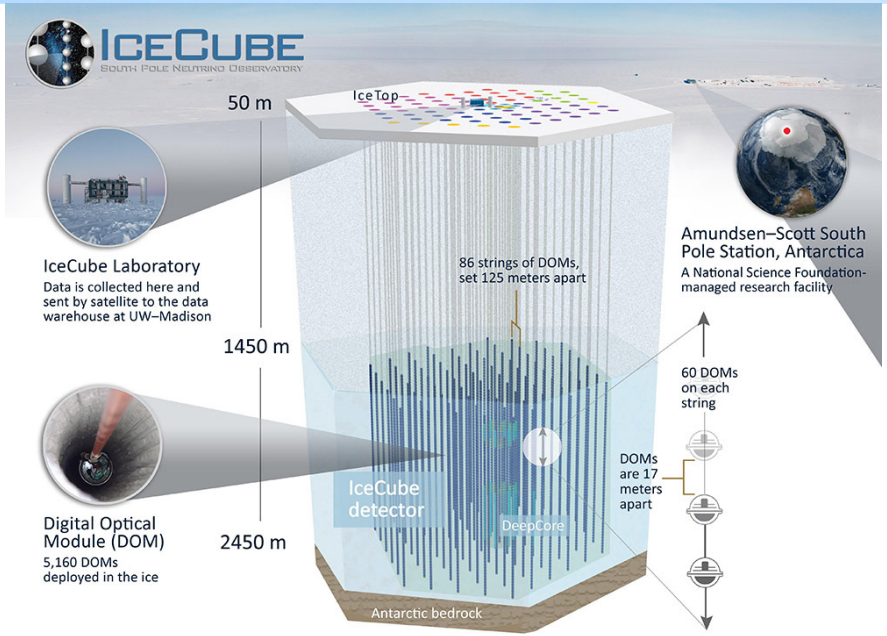
- **Higher angular resolution** than the usual singlet signal ($\sim 1°$)

  $\Delta\psi \sim 0.3°$ at 90% containment

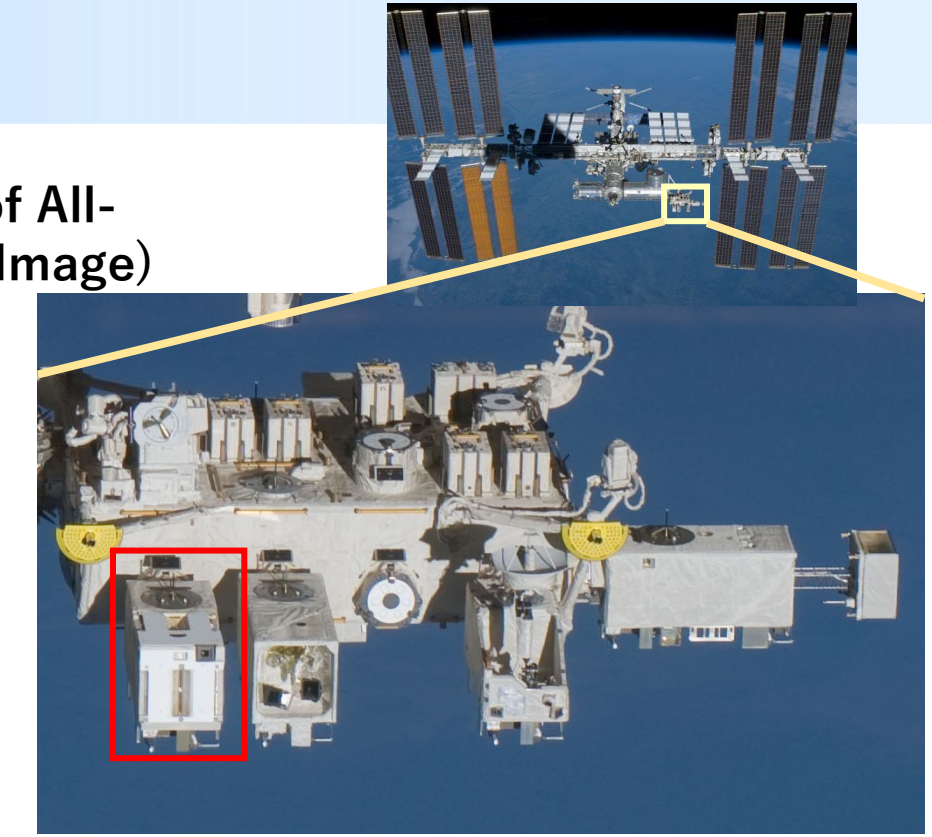
Preparing to send out a new Multiplet Alert by the end of this fiscal year

neutrino – X-ray combination alert

IceCube and MAXI



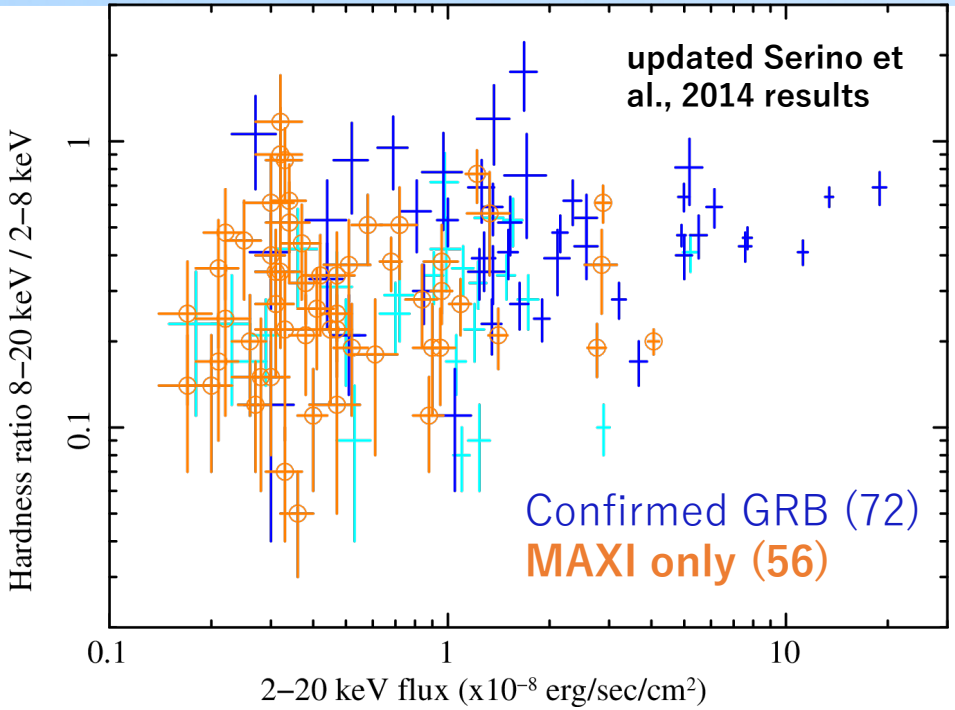
MAXI (Monitor of All-sky X-ray Image)

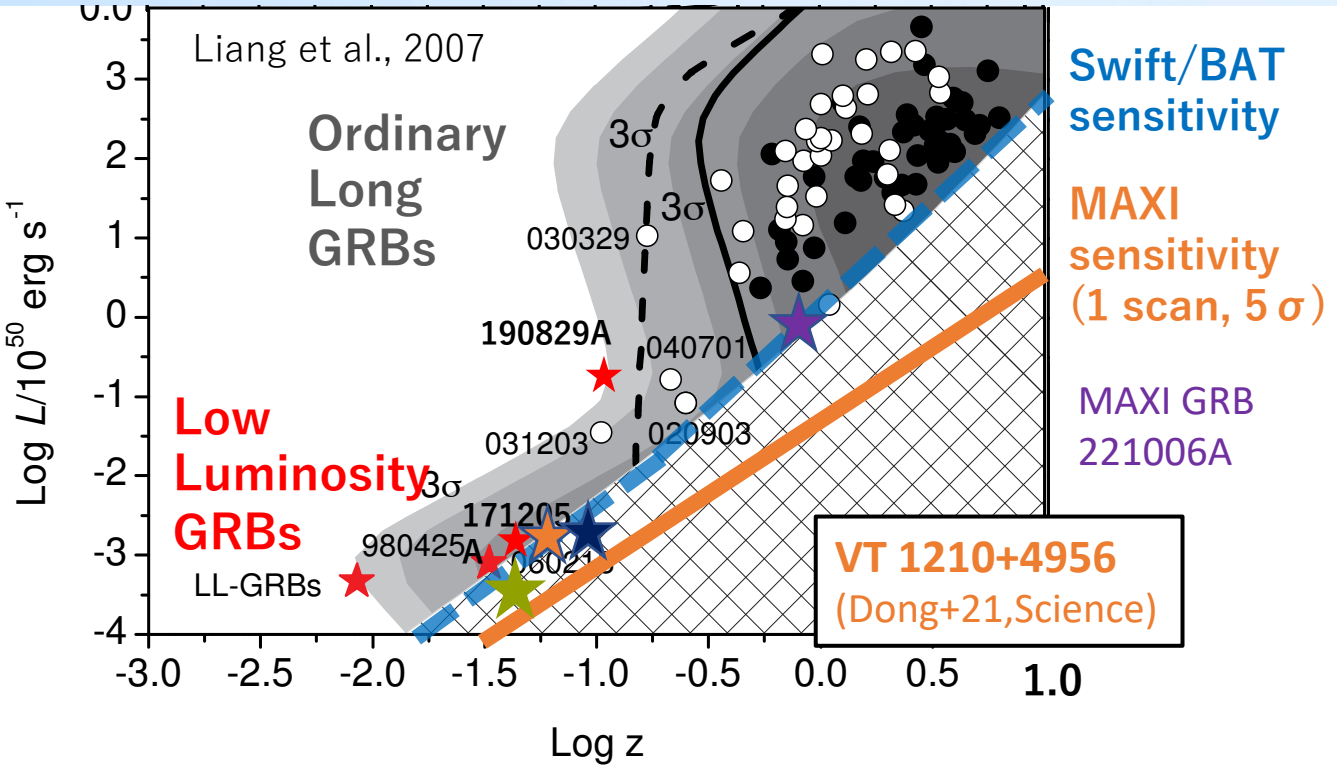


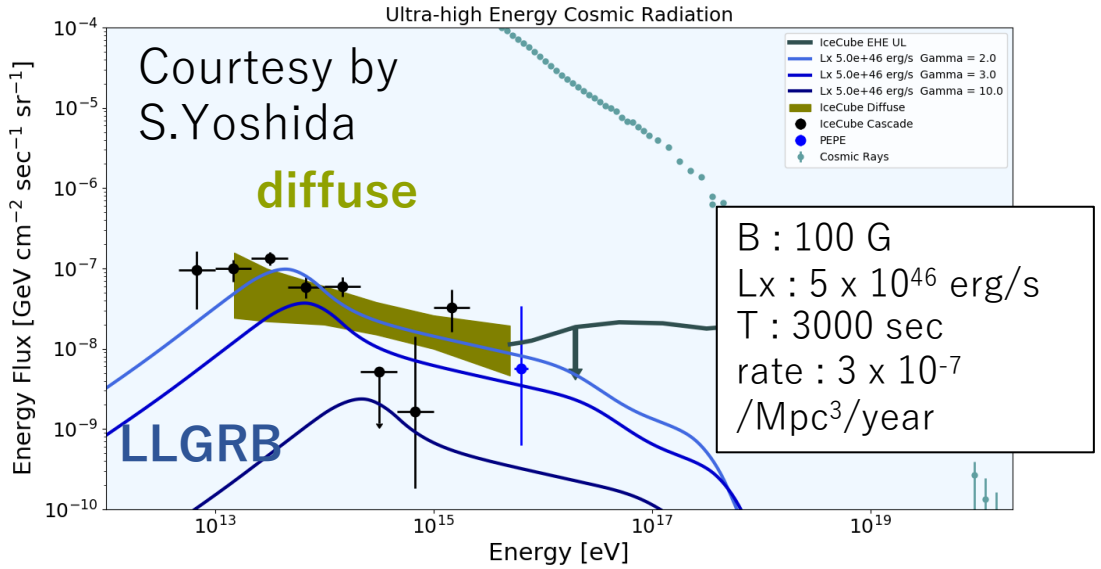
	IceCube	MAXI
Energy range	TeV – PeV (ν)	2 – 20 keV (photon)
FOV	All sky	All sky (80% in 92 min orbit)
Start date	April 2011 (IC86)	Aug 2009
Angular resolution	~1.0 deg (90% for track events)	1.5 deg (FWHM)
Data processing	Real-time@South pole	Real-time@TKSC via TDRSS

- **All sky monitor**
- **Overlap of more than 12 years already**
- **Similar angular resolution**
- **Real-time data processing and sending alerts**

IceCube and MAXI – LLGRBs are common science case







- There are 56 soft transients (MAXI GRBs) observed only at MAXI over the past 13 years
  - → the rate is 4 / year
- at z=0.1, a burst of 1 x 10^{47} erg/s is observable
- LLGRB rate ~100 /Gpc³/year
  - at z=0.1, the rate is ~10 events / year

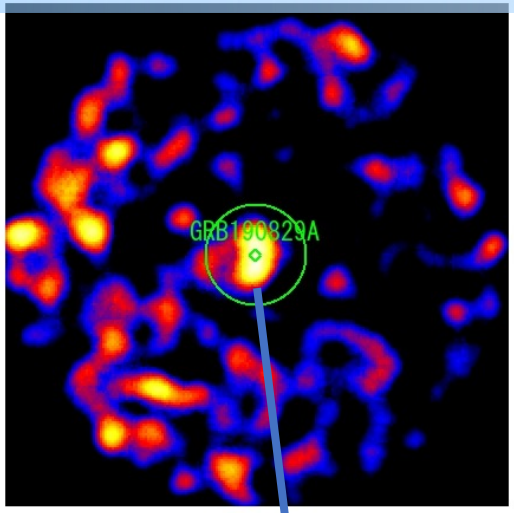
→ consistent with the MAXI GRBs rate

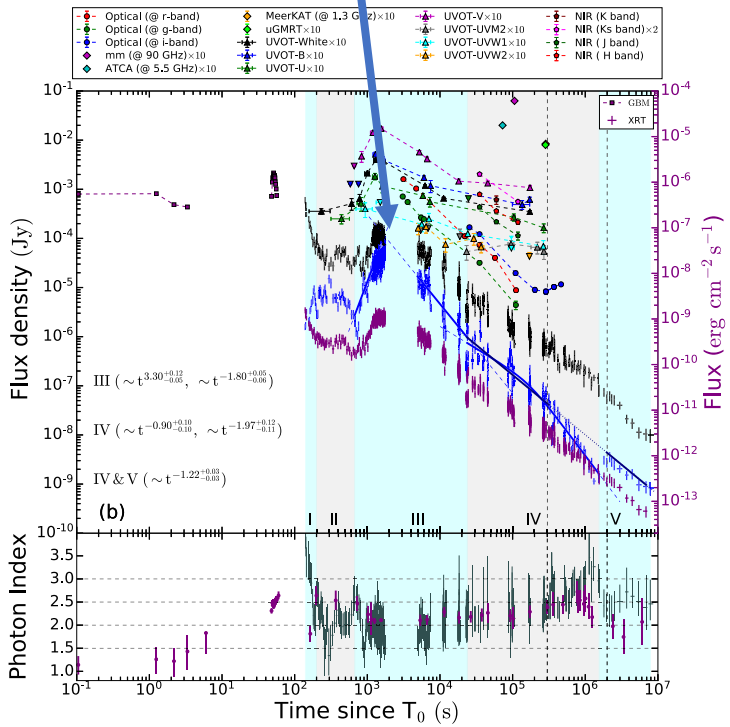
IceCube and MAXI combined analysis is important

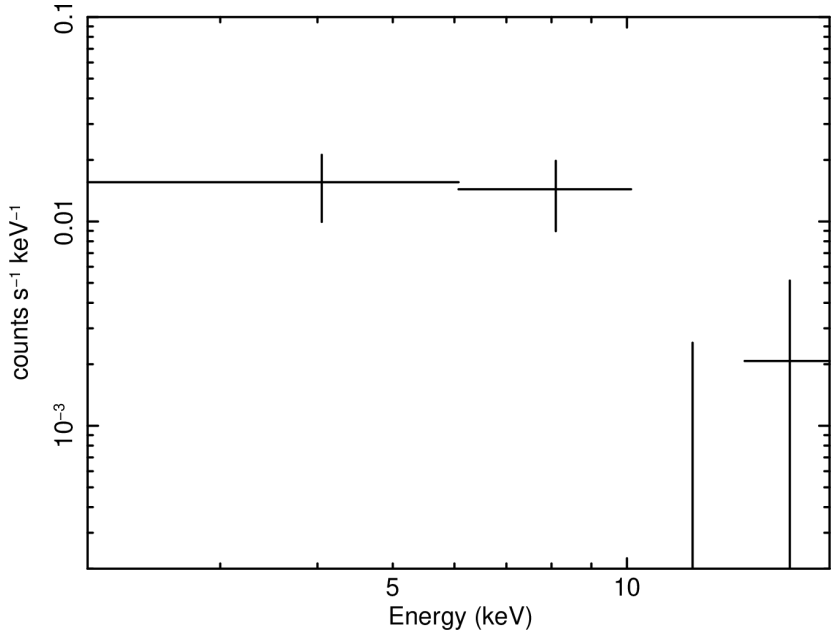
Example of MAXI transient event at the edge of detection limits

GRB 190829A (LLGRB) afterglow

z = 0.0785
358.4 Mpc







Assuming photn index of 2.0,
Lx = 1.2 ± 0.3 x 10^{46} erg/s
(68%)@358 Mpc
in the 2 - 10 keV band

Such treasure transients may lie in MAXI's subthreshold events.

Idea for X-ray-specific semi-real-time alerts

Both IceCube and MAXI process data in real time

IceCube's GFU (Gamma-ray Follow Up) filter :

- event rate is about 6 mHz
- drops most of the muon events
- ~1/500 events is of astrophysical origin

→ MAXI enables us to estimate the significance of the X-rays for all GFU events

Example of GFU filter flow (upgoing)

Cut Level	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times 10^{-3}$ (mHz)
0	1010.5	1523.81	7.166	6.23
1	282.49	504.44	5.826	5.62
2	8.839	22.01	3.076	4.06
3	1.124	4.30	2.313	3.69
4	0.100	2.15	1.899	3.26
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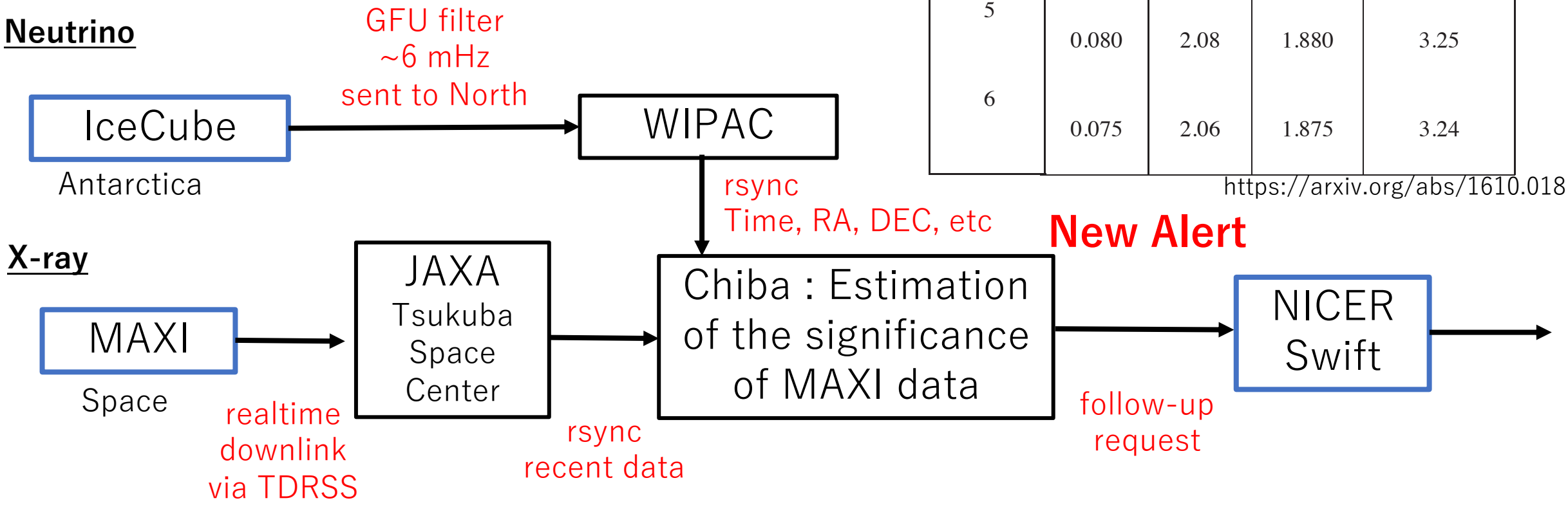
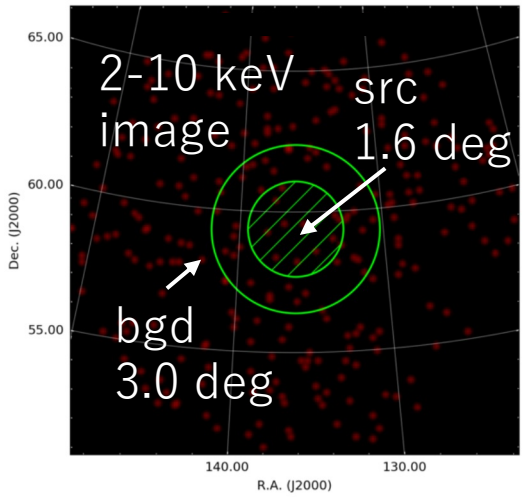
6	0.075	2.06	1.875	3.24

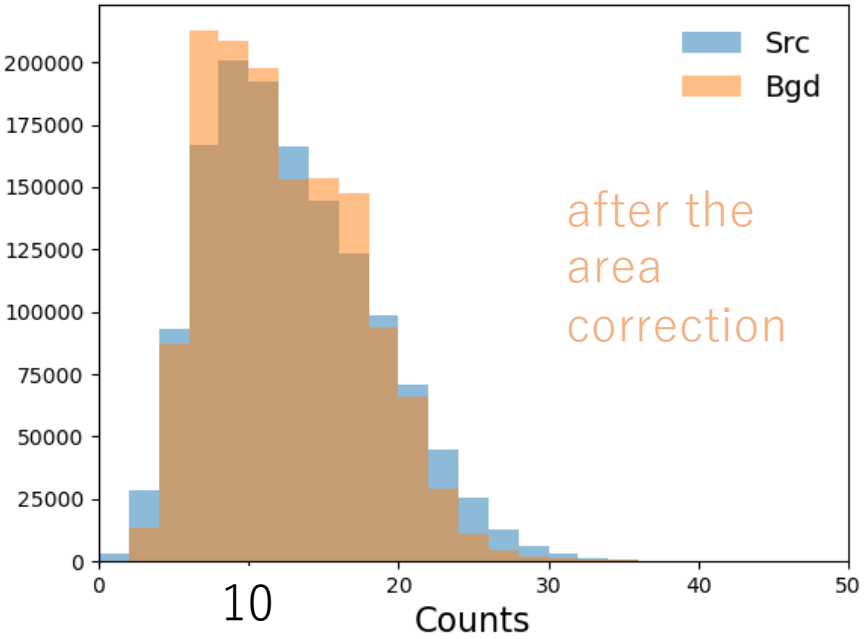
https://arxiv.org/abs/1610.01814



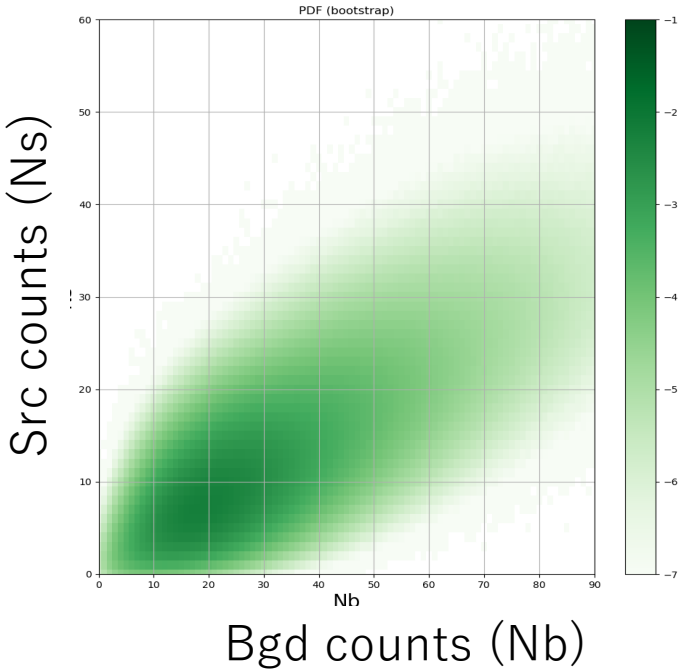
Background estimation on IceCube and MAXI's combined analysis

MAXI data





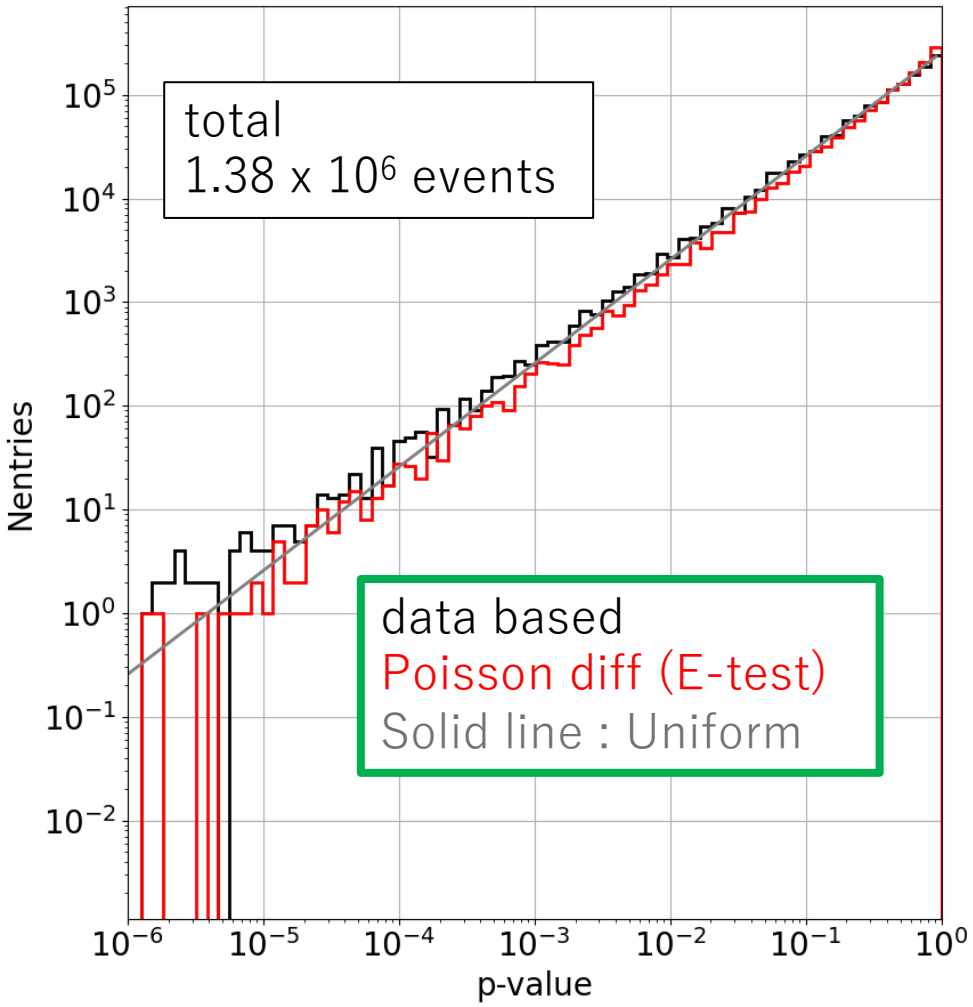
The counts in the region are about 10.
→ We have to test for asymmetry in the Poisson distribution.



method 1 (data driven) : Estimate the PDF from real MAXI data and calculate probability of Ns from observed Nb.

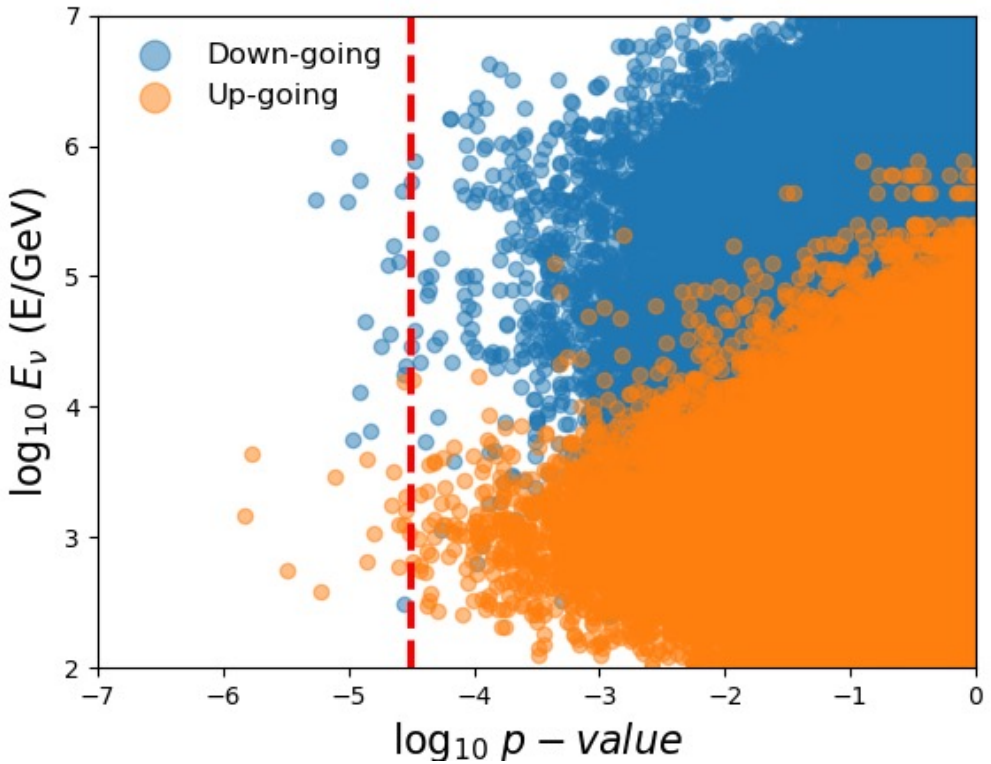
method 2 (analytical) : E-test, for comparing two Poisson means (Krishnamoorthy and Thomson 2004, Journal of Statistical Planning and Inference)

Background estimation on IceCube and MAXI's combined analysis



Background probability distribution is approximately as expected
← Differences between the two methods will be discussed

e.g, GRB 190829A (1 x 10^{46} erg/s @ 358 Mpc)



Background of significance over past GRB 190829A is 19 events in 1 year ← bit high, will consider ways to reduce.

Future works:

- how to multiply the significance of MAXI and IceCube events
- Results of archival data analysis constrain how much LLGRBs contribute to the neutrino diffuse emission

IceCube Upgrade & Gen2

IceCube Upgrade & Gen2

IceCube Upgrade

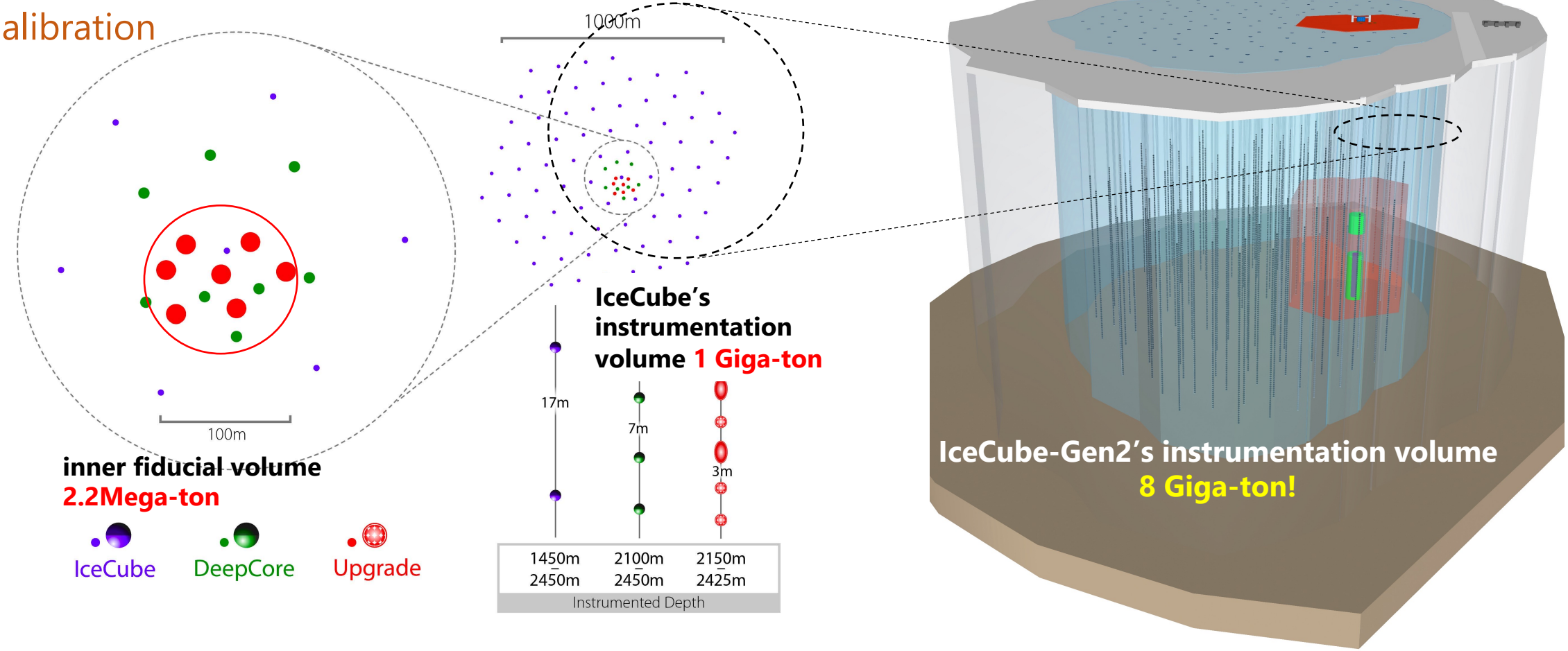
Optimized for
- GeV neutrinos
- Calibration

IceCube (2005-)

Optimized for
- Diffuse high energy cosmic neutrinos

IceCube-Gen2

Optimized for
- Cosmic neutrino point sources



Upgrade : Status

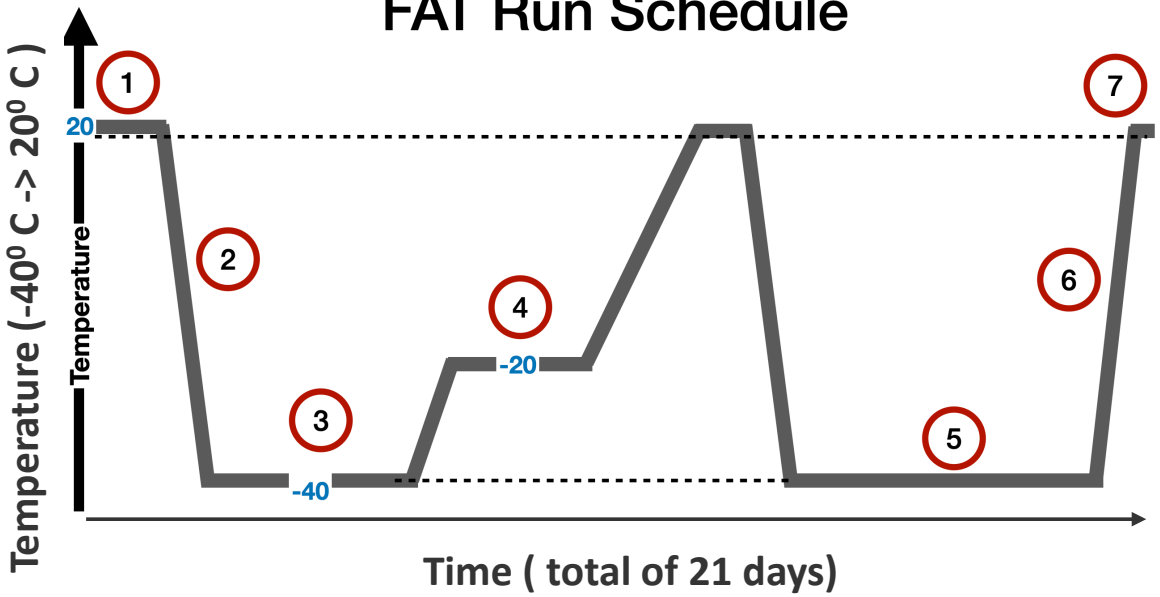
mDOM:402+22
(5.5% spares)

D-Egg: 277 + 15
(5.5% spares)

two 8-inch PMTs
camera module
LED flusher

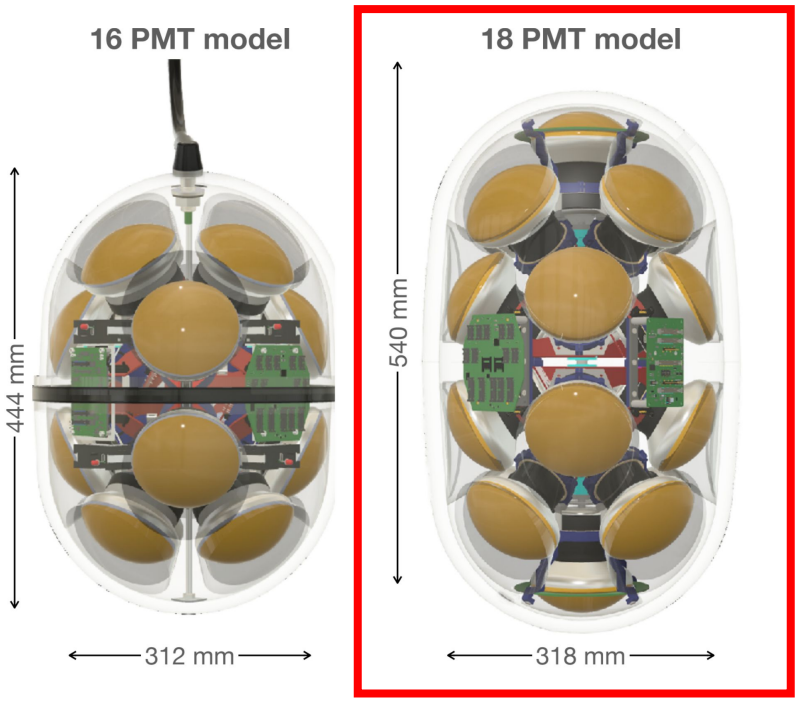
Chiba

FAT Run Schedule



- Final Acceptance Testing –about 3 weeks for each batch of 15 D-Eggs to thoroughly test before in-ice deployment
- FAT of all 309 D-Eggs projected to finish February 2024

Gen2 : Status



Chiba

Gen2 DOM candidates

- Two design candidates, with 16 and 18 PMTs.
- Developed from Upgrade technologies (Mini MainBoard, Optical Gel etc.)
- Use of 4-inch PMTs to maximise photon capture area for given module size

Status:

- Testing the Readout Board
- Gel pad production
- Pressure resistance test

Summary

- Three objects have been identified so far as neutrino emitter (TXS 0506+056, NGC 1068, Galactic Plane).
- The origin of neutrino diffuse emission is still unknown.
- Two new alerts are being developed to identify the origin through multi-messenger observations.
  - Multiplet alert is sensitive to nearby transients with a duration of about 30 days.
  - Combined X-ray and neutrino alert is sensitive to LLGRB-like transients
- The D-egg, which is being fabricated at Chiba University, is currently undergoing FAT. It is scheduled to be transported to Antarctica in FY2024.
- Development of a new DOM for Gen2 is underway.