Multi-messenger astronomy with high energy neutrinos

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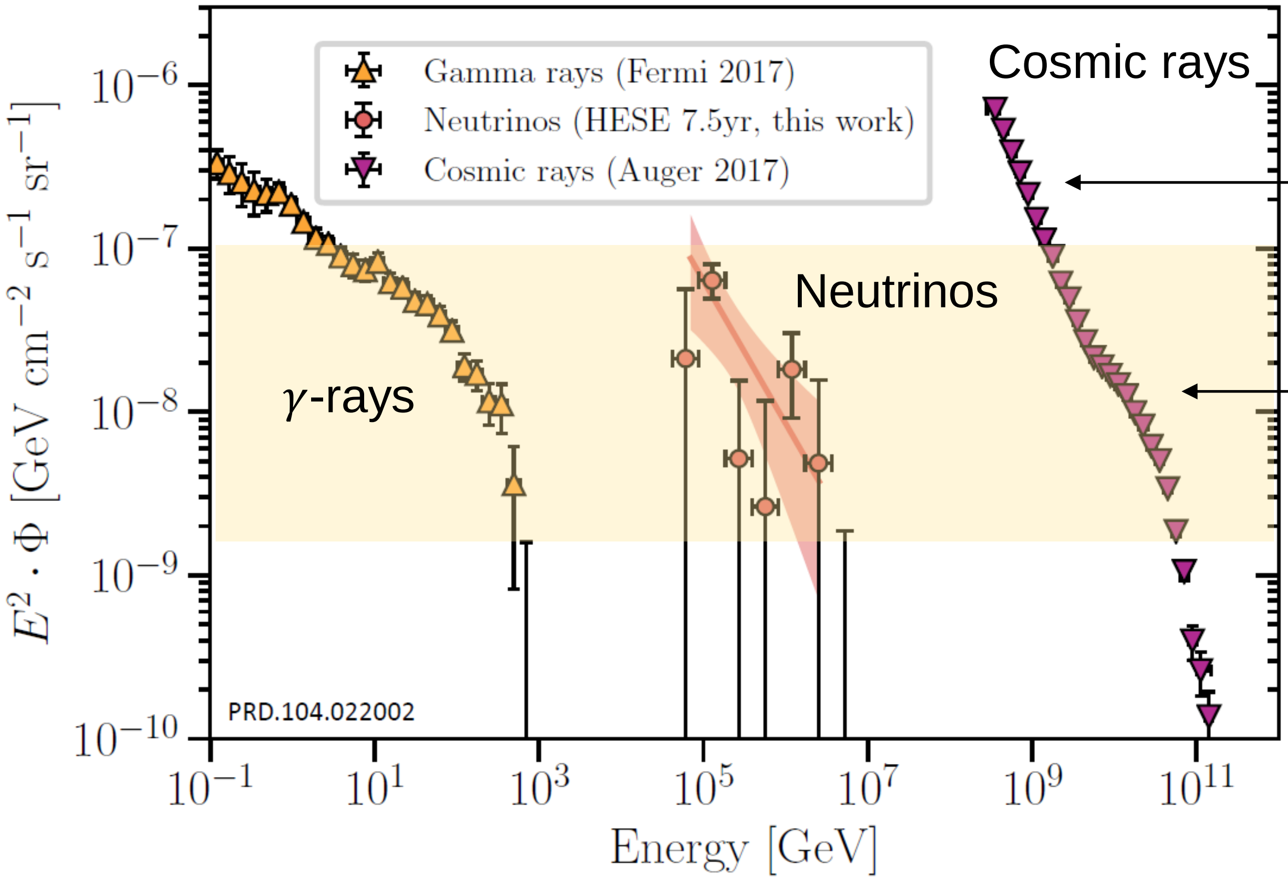
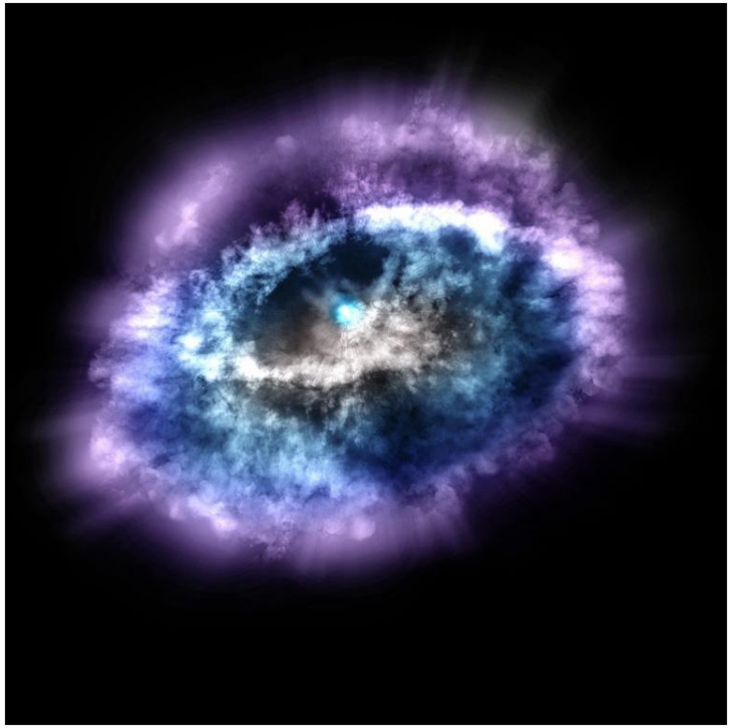
ICEHAP – international center for Hadron Astrophysics

High energy messengers



inter galactic?

extra galactic?



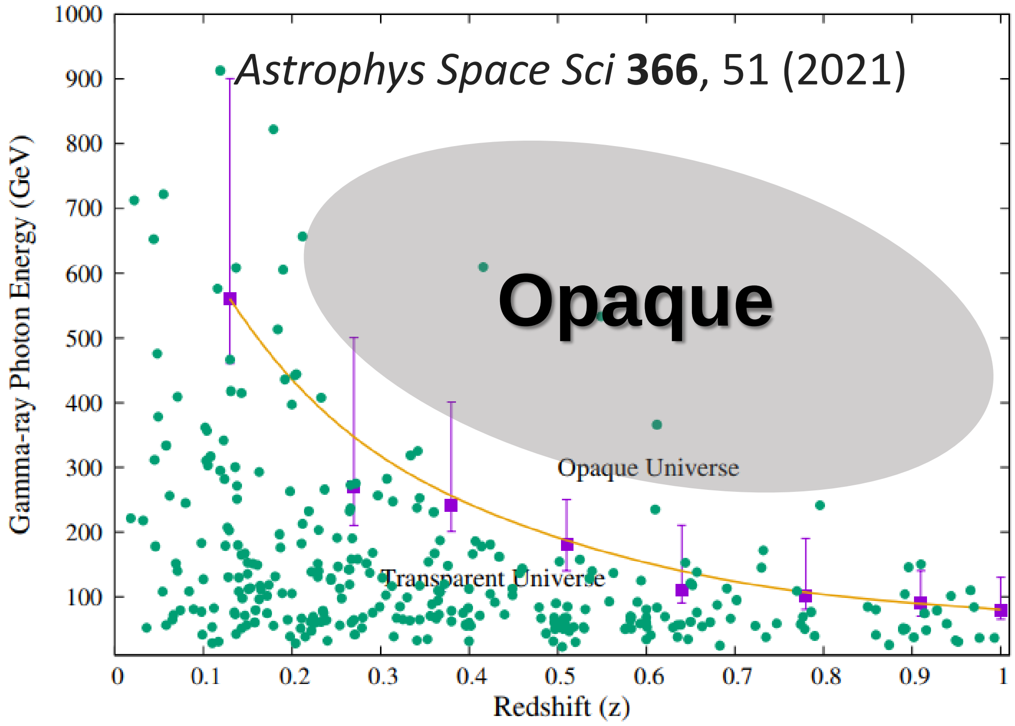
$E^2\phi \sim 10^{-8}$

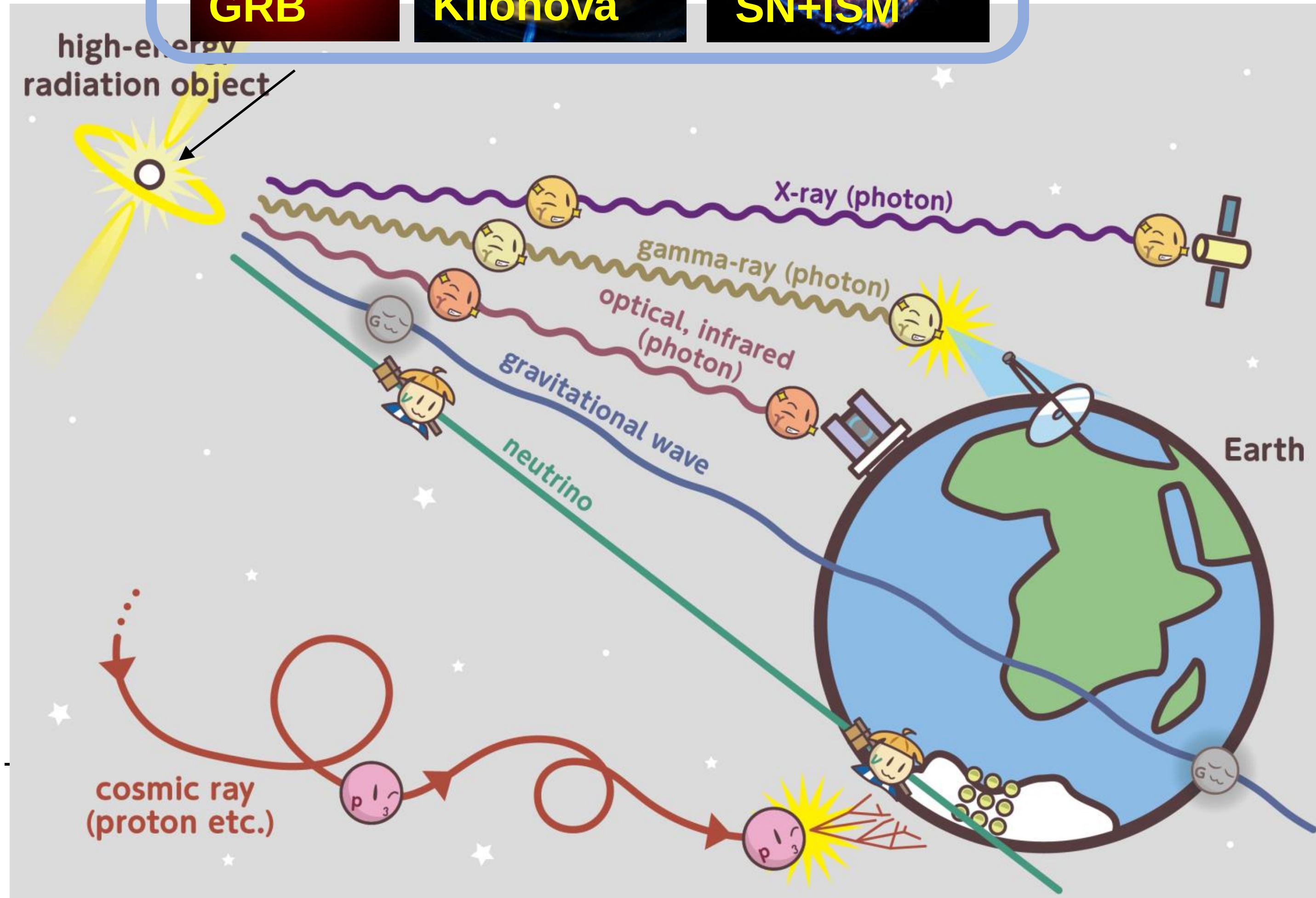
GeV$\cdot$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$

MM observations could imply
γ-rays, neutrinos, and cosmic ray sources could be common.

Neutrino astronomy

Fermi γ-ray sources: redshift vs energy

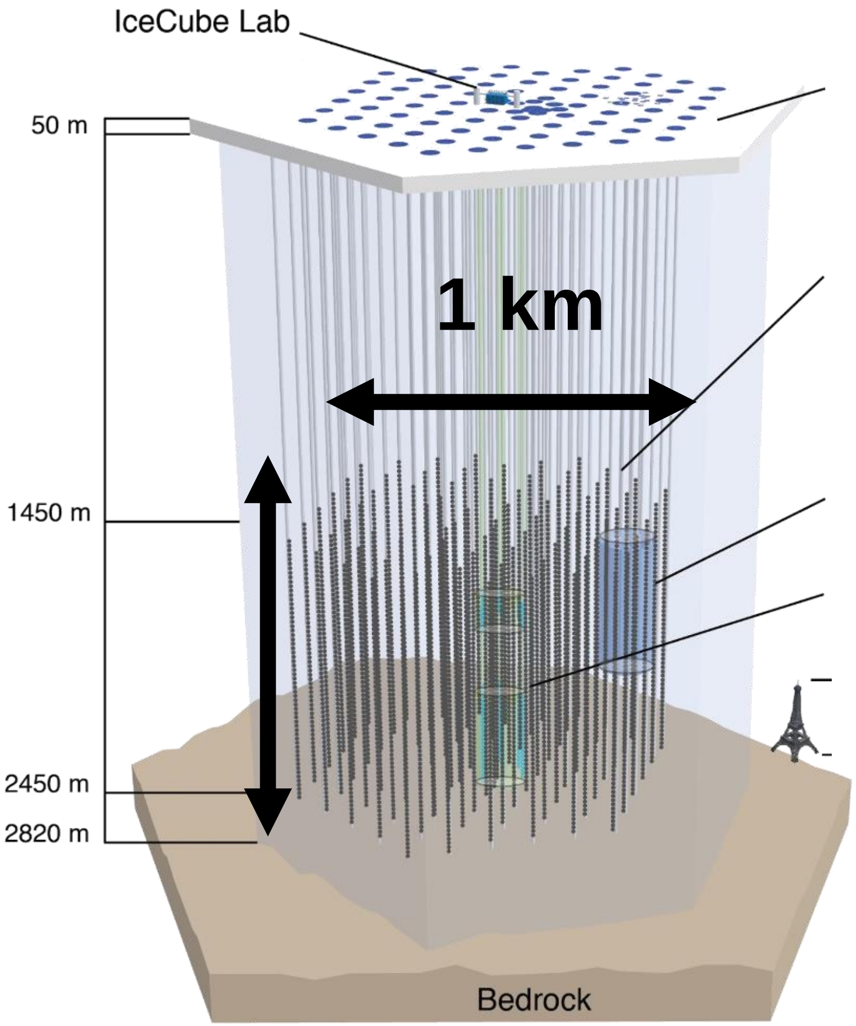




- High energy photons scatter via $\gamma\gamma \to e^+e^-$
- Cosmic rays are deflected by B-field
- **Neutrinos**
  - ➢ no absorption in the propagation
  - ➢ no deflection in magnetic field

Neutrinos are smoking gun of
the high energy phenomena of universe.

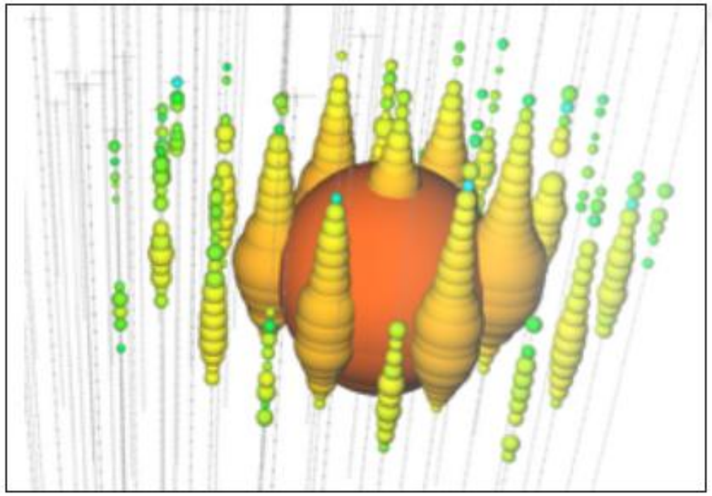
IceCube experiment



DOM

- 5160 optical sensors in 1 km^3 regions
- The world largest Cherenkov detector
- Full operation started from 2011

Neutrino event morphology

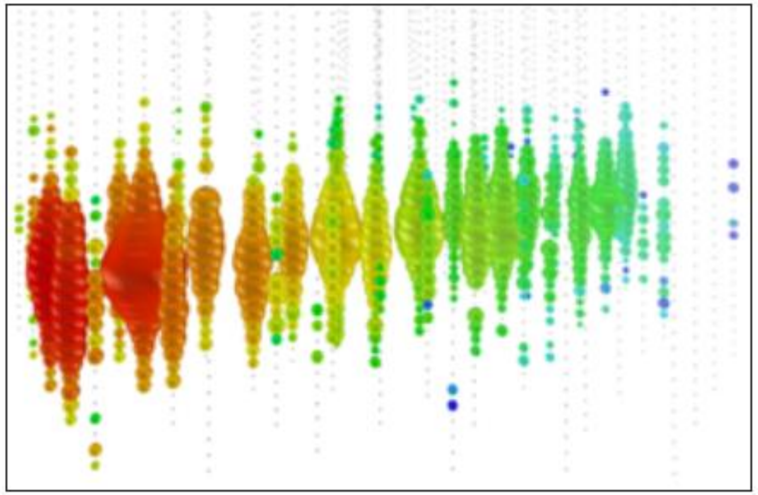


cascade

$\nu_e + N \rightarrow e + X$

$\sigma_\psi \sim 15°$

$\sigma_E/E \sim 15\%$

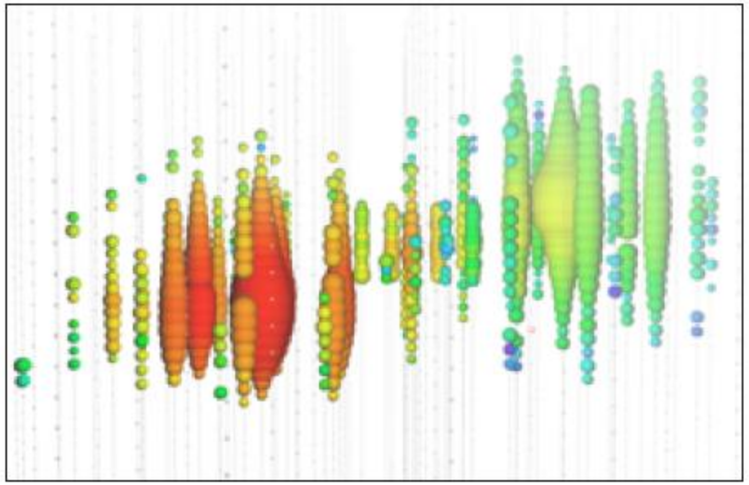


Track

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

$\sigma_\psi \sim 0.5°$

$\sigma_E/E \sim 25\%$



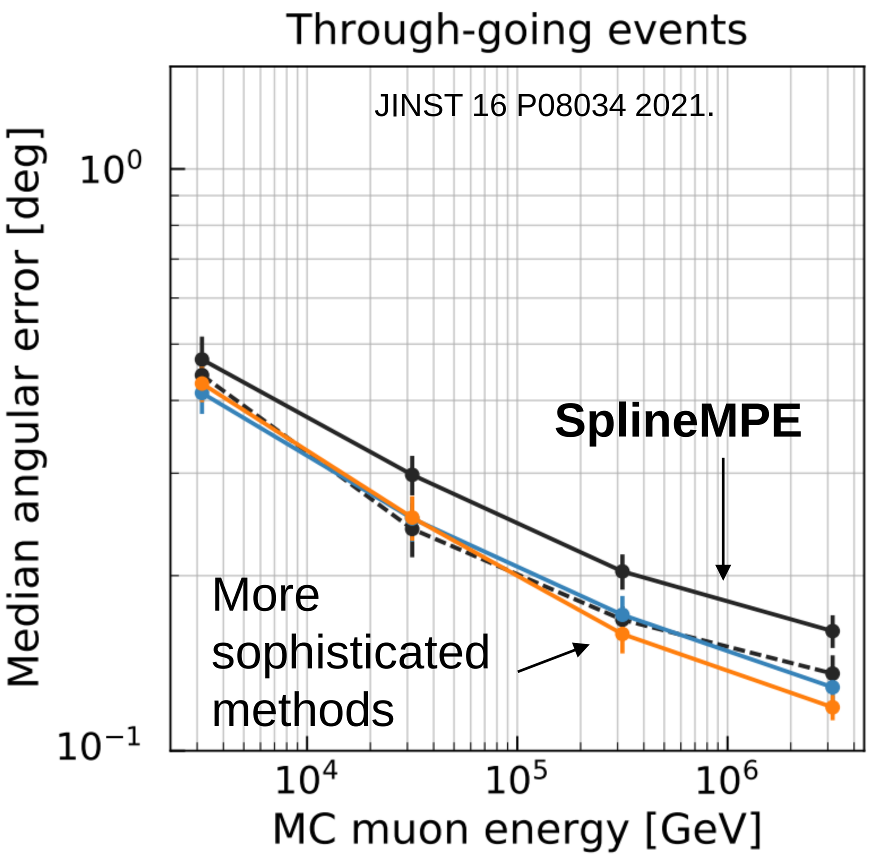
Double-bang

$\nu_\tau + N \rightarrow \tau + X$

decay

Visible only for high energy ν_τ

Reconstruction of direction in track events

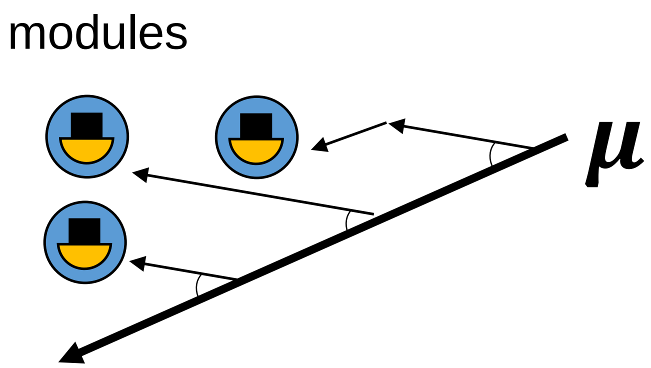


Various reconstruction methods are currently available (e.g. ML-based reco.)

However, current realtime prompt reports still use **"spline-MPE"** fit

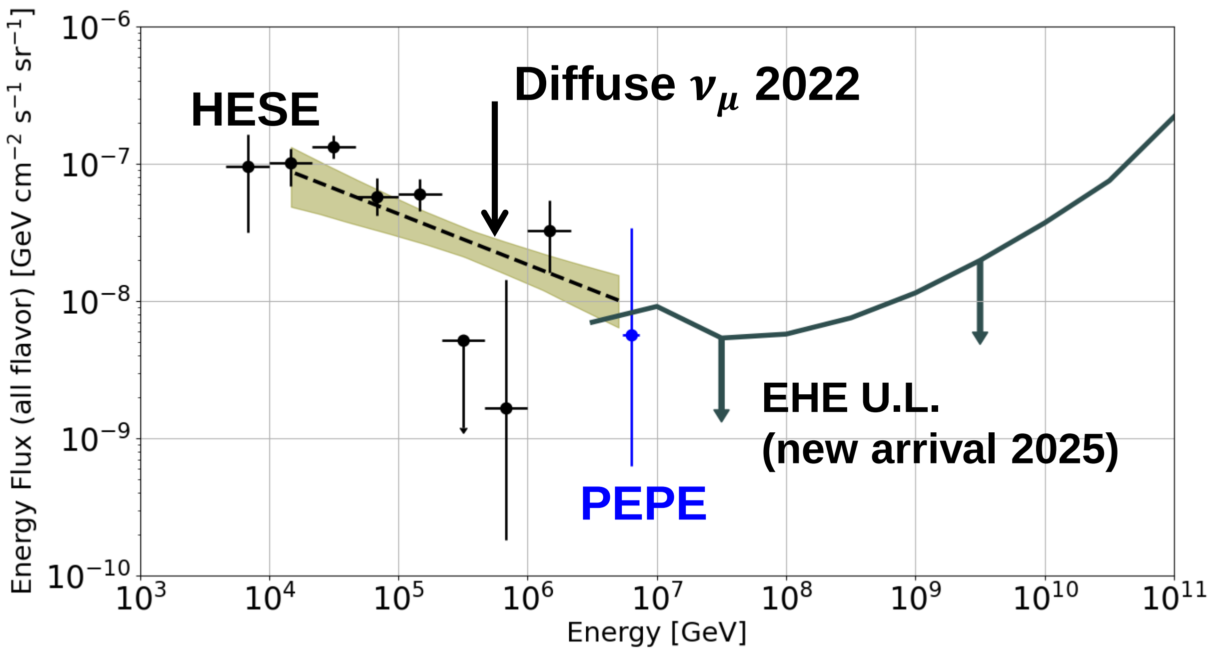
→ uses information of multiple hits and ice properties

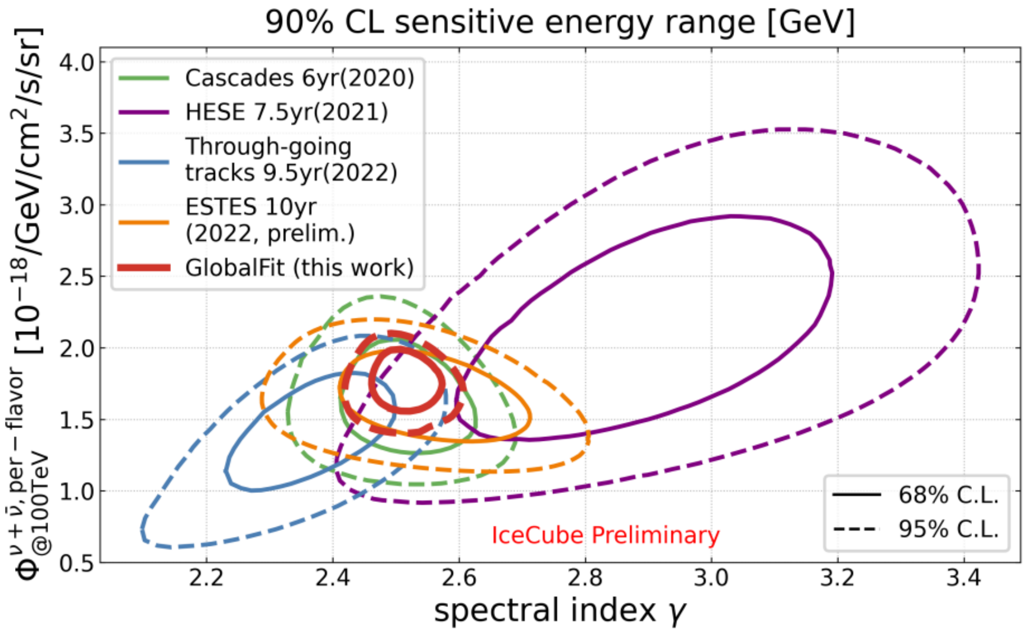
$$\mathcal{L}^{\mathrm{SplineMPE}} = \prod_{N_{\mathrm{mod}}} \underbrace{P(q_{\mathrm{obs}} | q_{\mathrm{expected}}; ice)}_{\text{LLH of charge}} \underbrace{P(t^{\mathrm{1st}}_{\mathrm{obs}} - t^{\mathrm{1st}}_{\mathrm{expected}}; ice)}_{\text{LLH of time for 1st hit}}$$



$$\sigma \sim 0.5^\circ$$

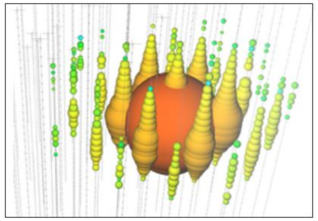
What IceCube told us: diffuse $\boldsymbol{\nu}$ flux



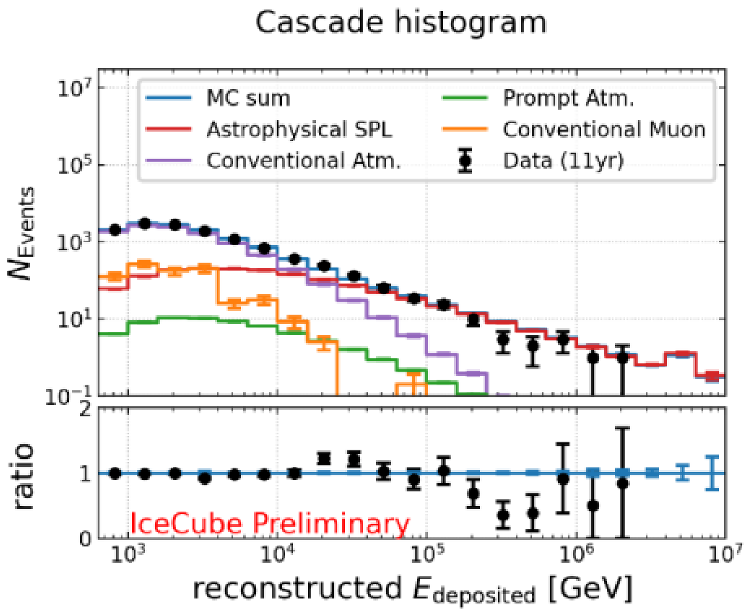


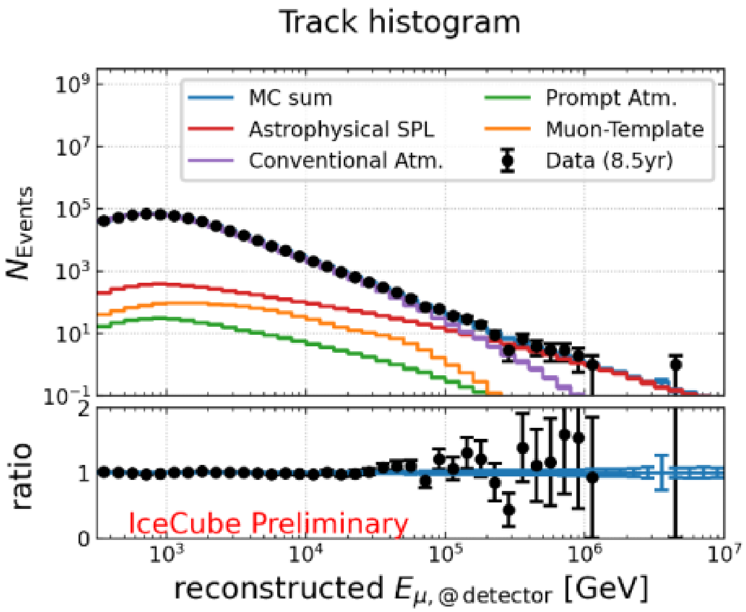
- Strong evidence of the astrophysical background $\boldsymbol{\nu}$ (a.k.a. diffuse $\boldsymbol{\nu}$ flux)
- $E^2\phi_\nu \sim \mathbf{10^{-7} - 10^{-8}}$ GeV$\cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$ in 10-100 TeV
- $dN/dE \propto E^{-\gamma}$ with $\gamma \sim 2.3 - 2.7$
- Consistent with isotropic distribution

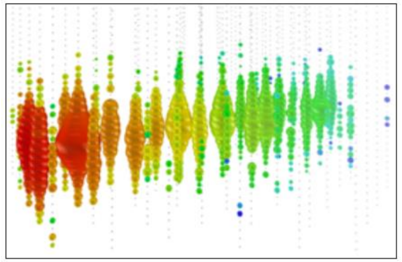
Flux measurement w/ track + cascade combined fit



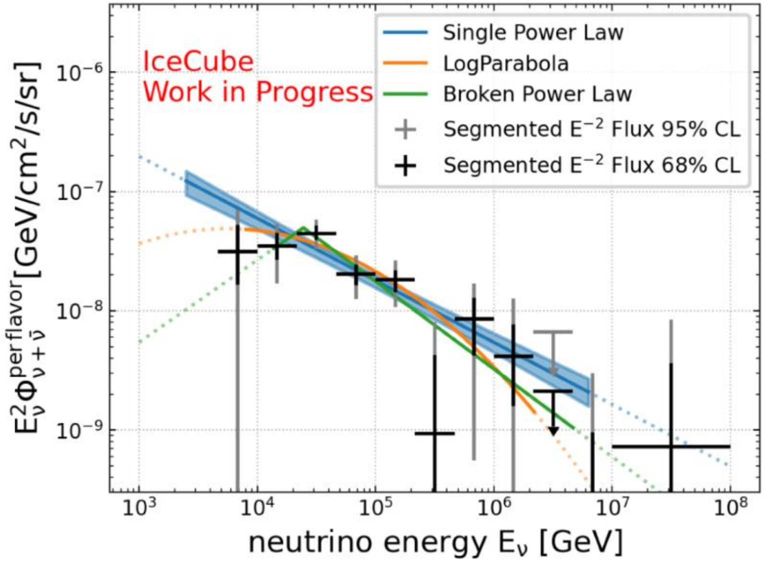
cascade





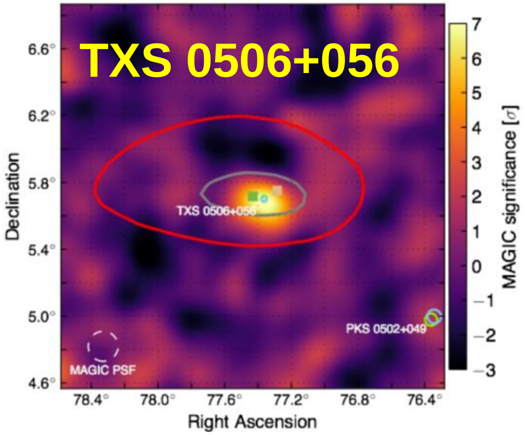


track

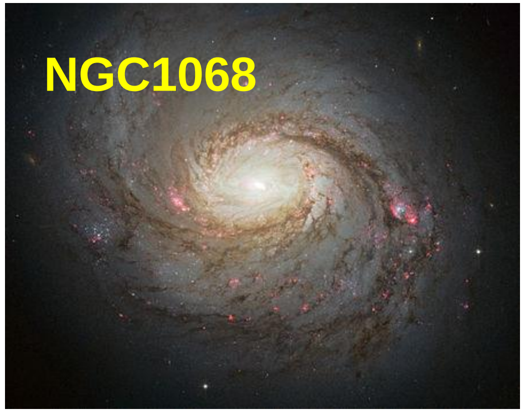


- Efforts to combine cascade + track channel
  w/ consistent systematic uncertainty treatment
- Broken power law shows better agreement.
  We might see some structure beyond the single power law.

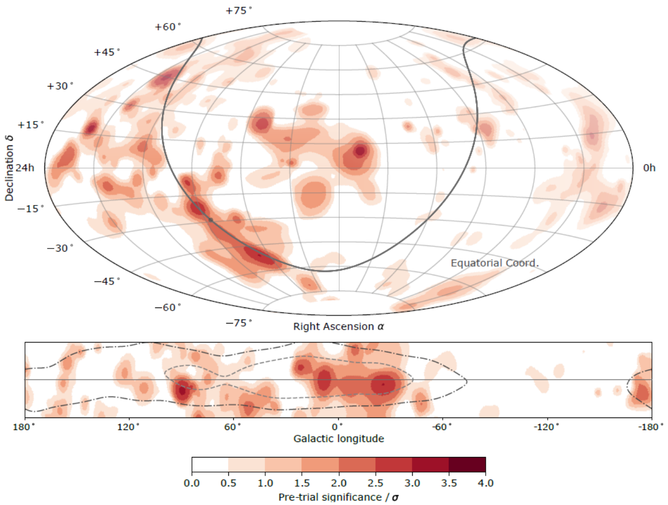
Where is the origin of the neutrinos?



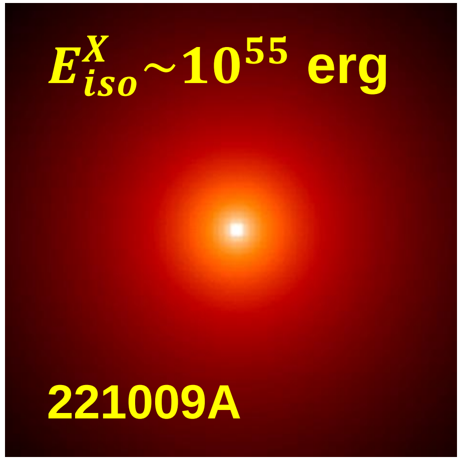
Identification of a blazar as a ν-source (2017)



Observation of ν by Seyfert galaxy (2022)



Observation of ν from galactic plane (2023)



NO observation of ν from BOAT GRB (2022)

Several objects are possible sources of neutrinos. However,
they are not sufficient to account for the magnitude of the total diffuse flux.

Updated point source analysis 2022

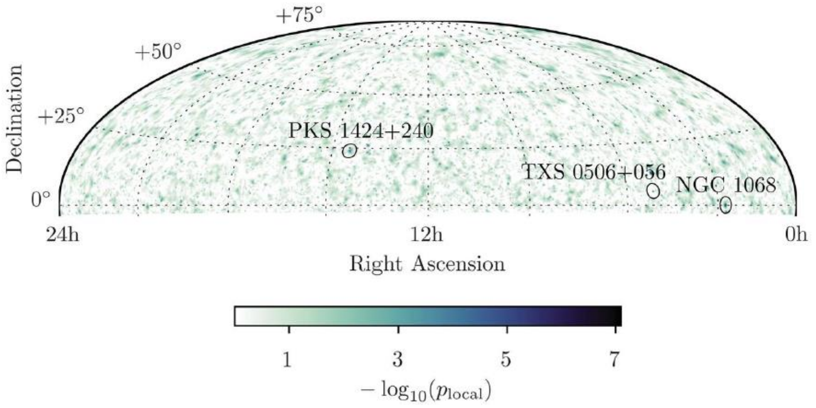
- Northern sky scan w/ improved method of the angular uncertainty estimate
- Two types of analysis performed

  ① Unbiased scan under hypotheses of γ: float, γ=2.0, and γ=2.5

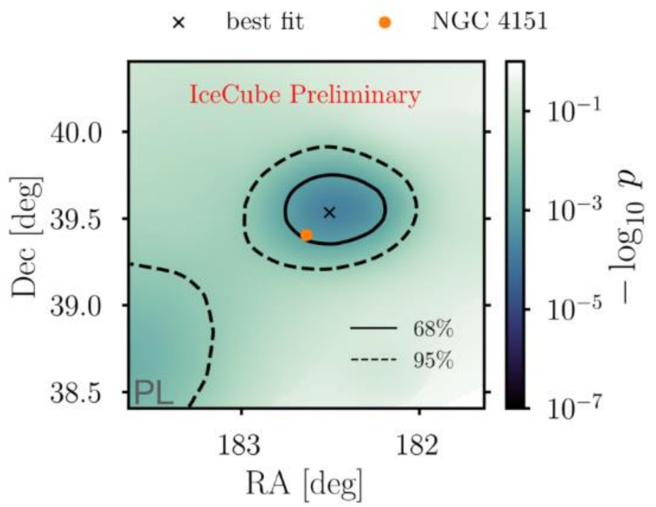
  The 4th hottest spot is coincident to NGC4151.

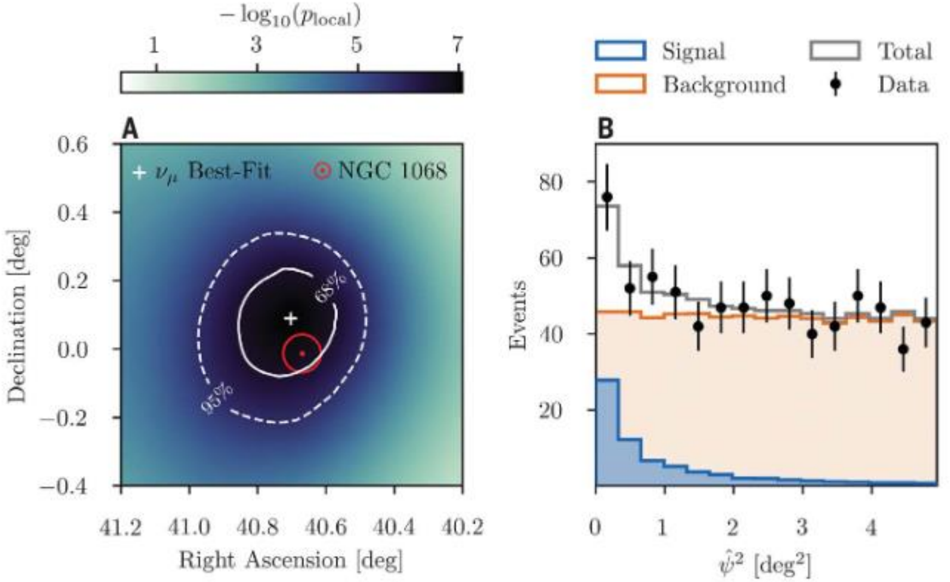
  ② Time-integrated analysis for 110 directions of preselected galaxies.

  The hottest candidate (NGC1068) shows the significance of 4.2σ.



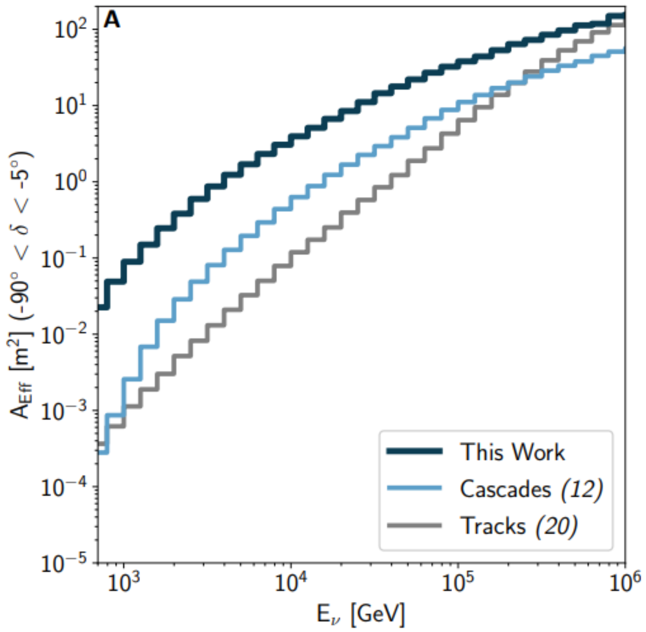
Science **378**, 538–543 (2022)



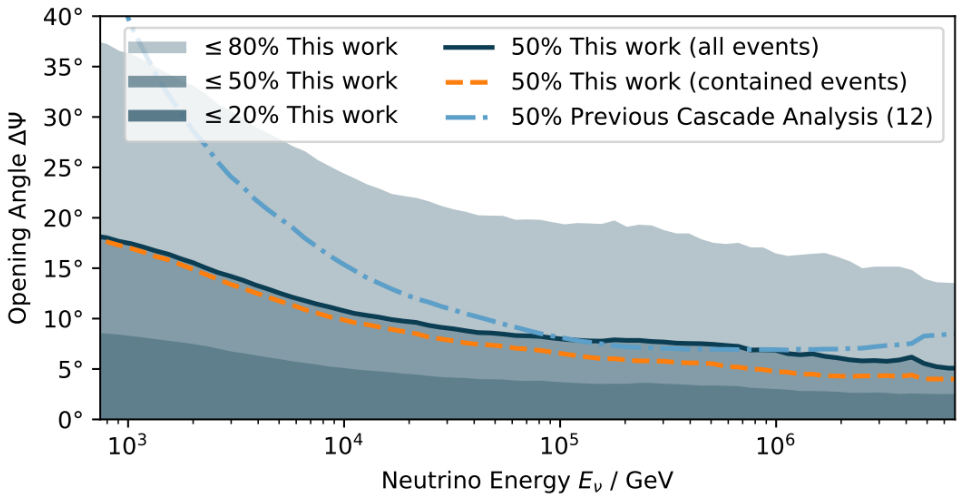


Neutrinos from the galactic plane

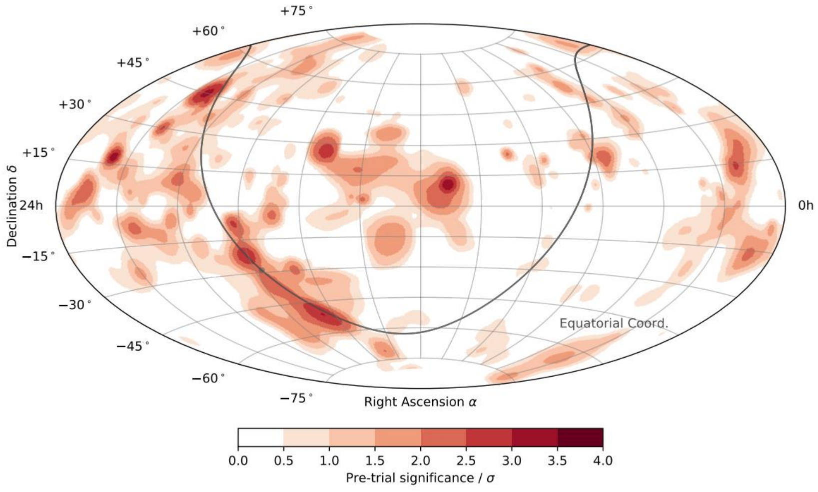
Science **380**, 6652, 1338 (2023)



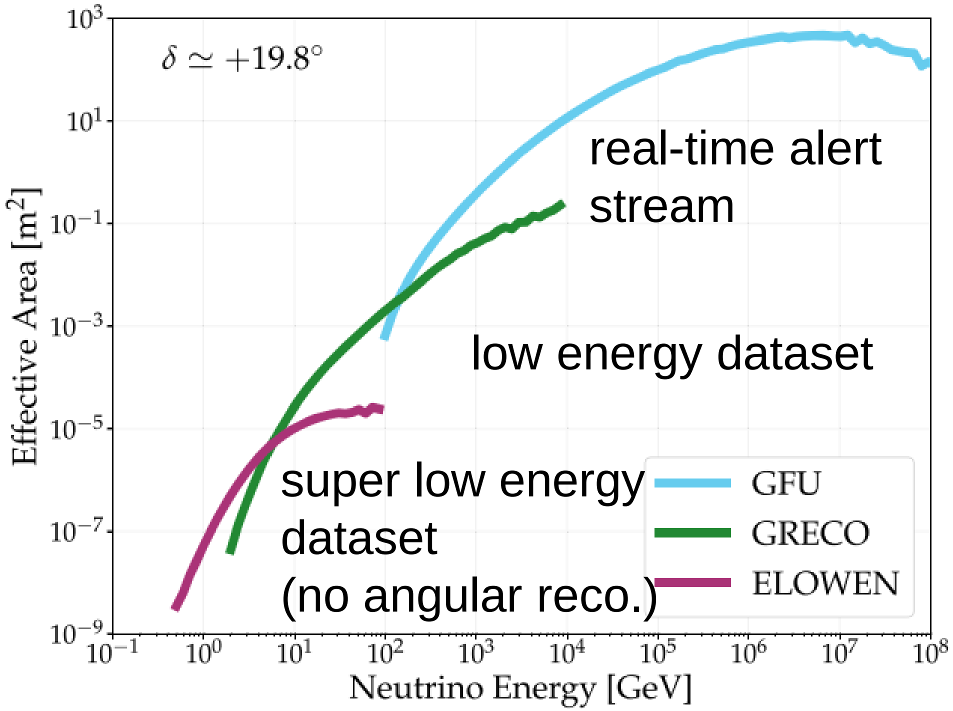
- Southern sky from the galactic plane
- Cascade selection w/ convolutional neural network
  - ✓ higher purity of astrophysical neutrinos than track sample
  - ✓ x20 times higher effective area than the conventional method
  - ✓ angular uncertainty of ~ 10° fit to spatial distribution of galactic plane

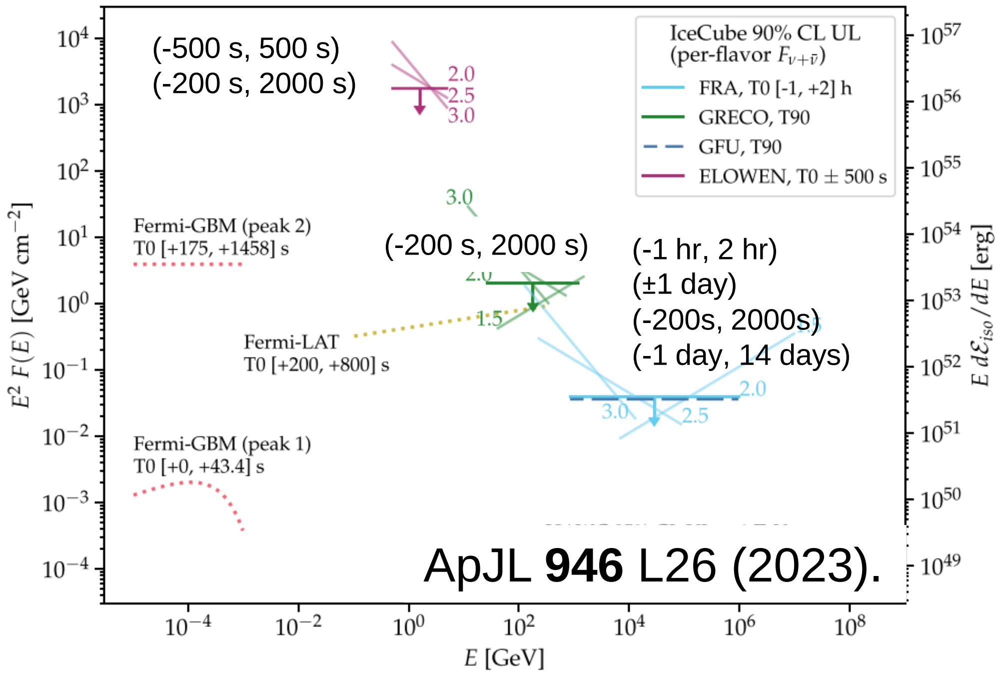


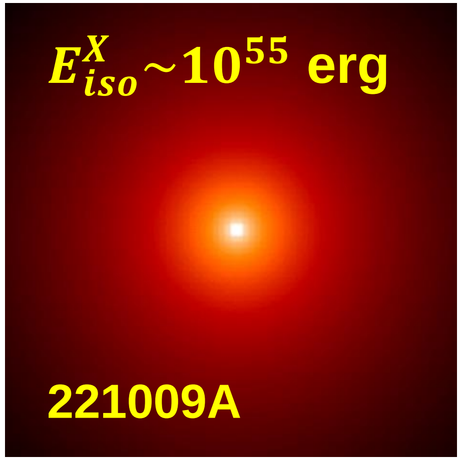
Observation of the neutrino emission from the galactic plane at the 4.5σ C.L.



Follow-up analysis of BOAT GRB







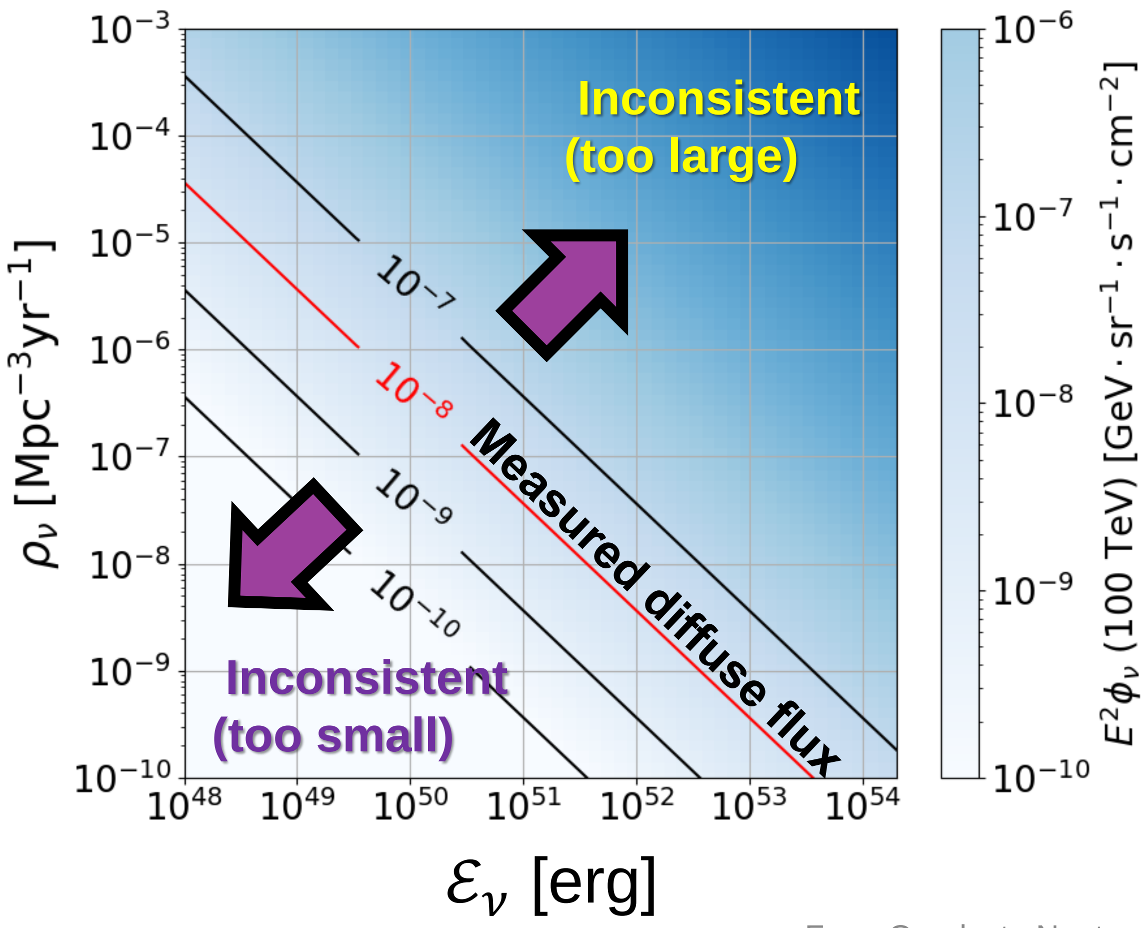
- Brightest of all time (BOAT) GRB observed in 2022 : >100 brighter than the previous brightest GRB (once per 1000 yrs).
- Ideal direction for IceCube
- Dedicated follow-up were performed in various channels and time window
  GFU (300 GeV –), GRECO (10 GeV – 1 TeV), ELOWEN (1 GeV – 10 GeV)
  → No significant detection of neutrinos

Characterization of neutrino sources (transients)

$\boldsymbol{\phi_\nu} \propto \mathcal{E}_\nu \times \rho$

$\mathcal{E}_\nu$: Neutrino emission energy per source

ρ : Source rate density



Complementary hypotheses

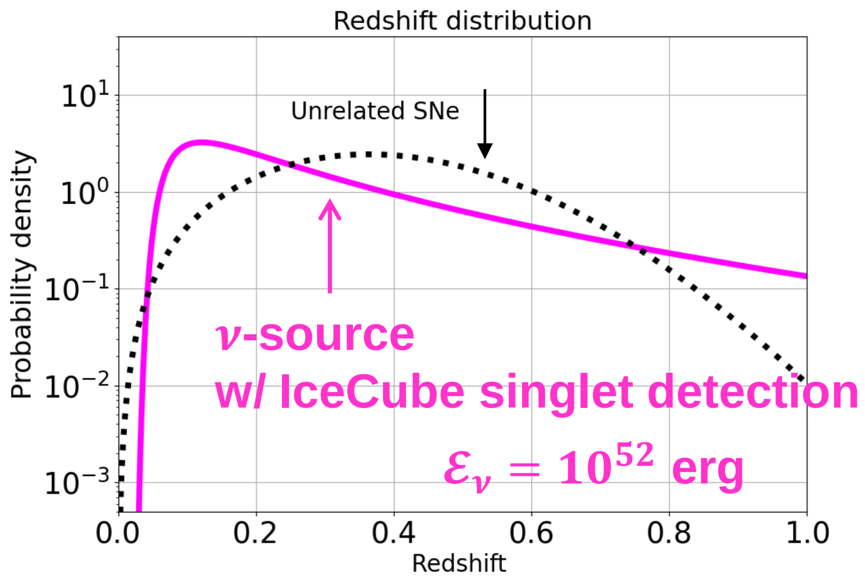
Bright but rare: *e.g.*, GRB, Jetted TDE

Dim but frequent: *e.g.*, SNe, LLGRB

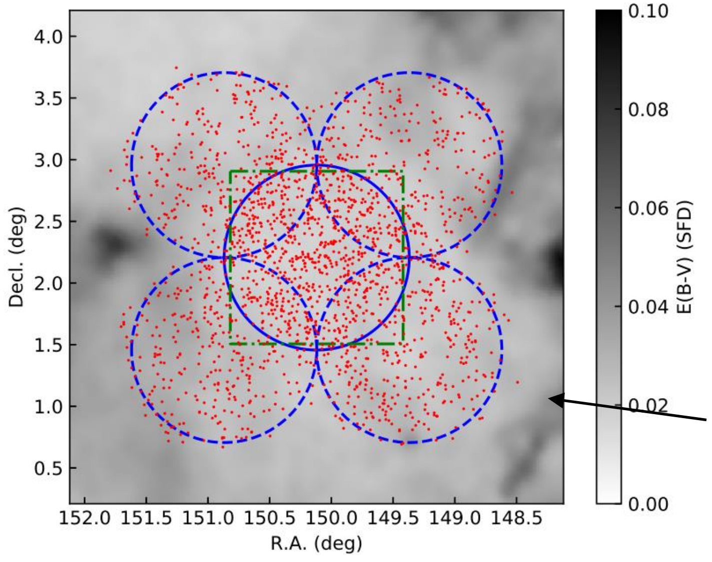
Follow-up observation of neutrino sources

Neutrino comes from distant universe ▶ **a big challenge for follow-up observations**

- An observation of distant sources requires big (good) telescopes
- ν-angular resolution $\sigma \sim 1^\circ$ (90%)→ significant contaminations from unrelated transients



SNe = $\dfrac{\mathcal{O}(10)\ \mathrm{SNe}}{\mathrm{deg}^2 \cdot 20\ \mathrm{days}}$

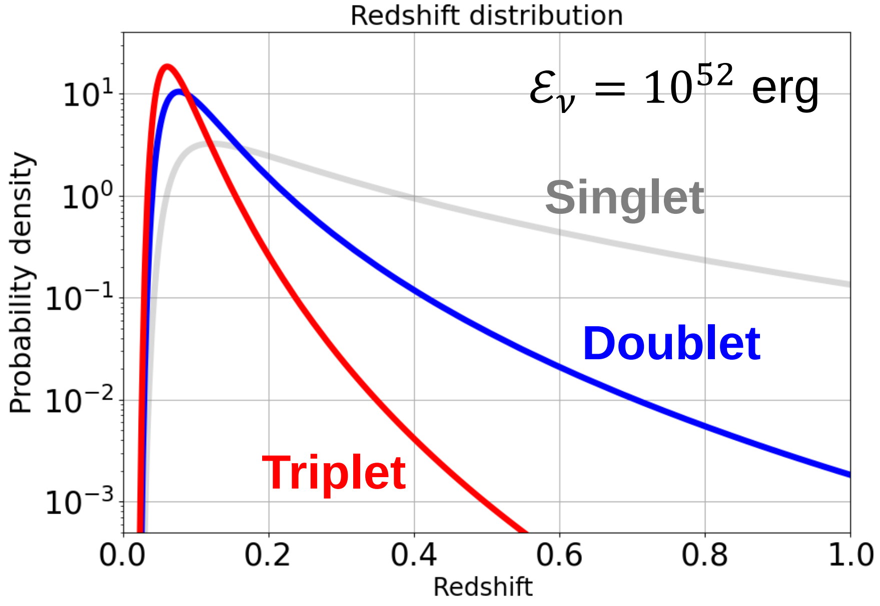


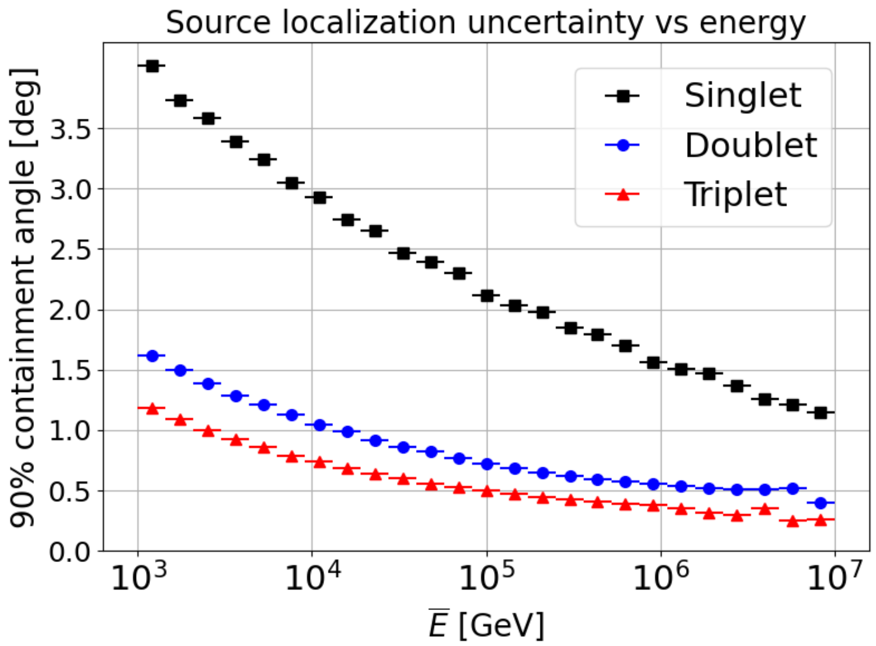
Field of view of Subaru (1.8 deg^2)

- ◆ A constraint of a single neutrino observation shows a wider tail towards high redshifts.
- ◆ Difficult to separate from BGs particularly for long time scale transients such as SNe.

Neutrino multiplets

Multiplets → $\boldsymbol{N \geq 2}$ **coincident** $\boldsymbol{\nu}$**-signals** in $\color{blue}{\Delta T}$ from the same direction

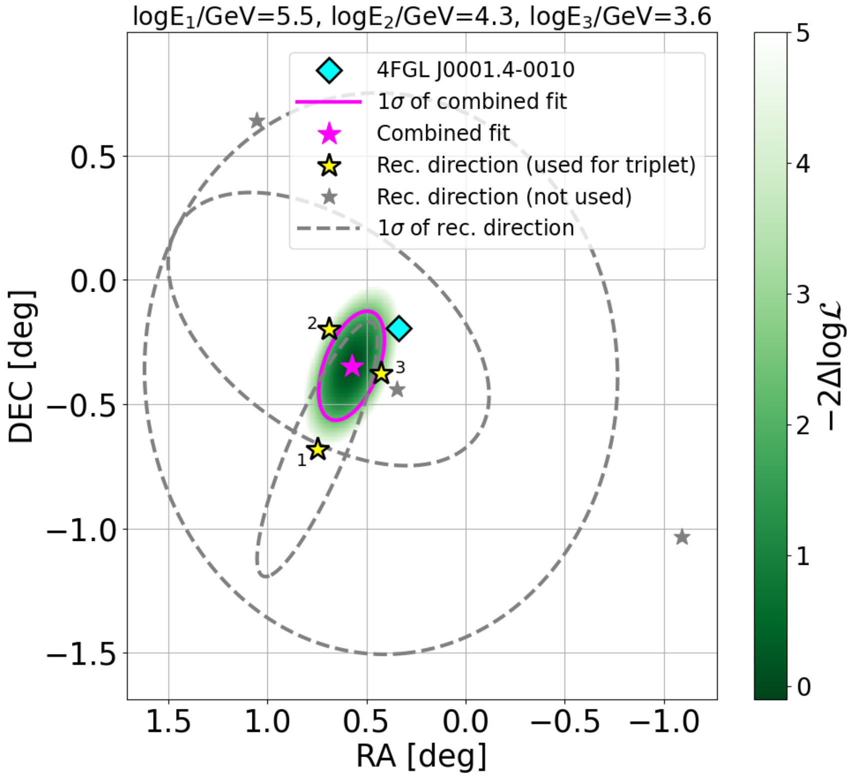


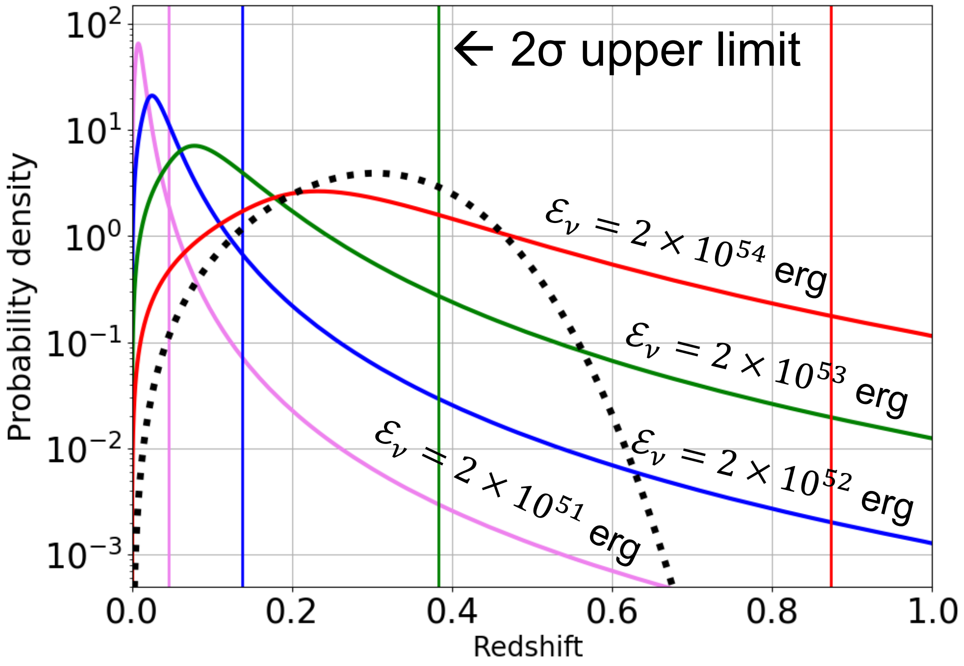


- Multiplet detection limits the distances of sources
  → typically $z \ll 0.1$, which suppresses a contamination of unrelated transients
- Improves angular resolution
  → for alert level, the 90% containment angle is $\psi_{90\%} \sim 0.3°$

Neutrino multiplets are very useful signature for follow-up analysis

One Month MultipLET (OMMLET) alert

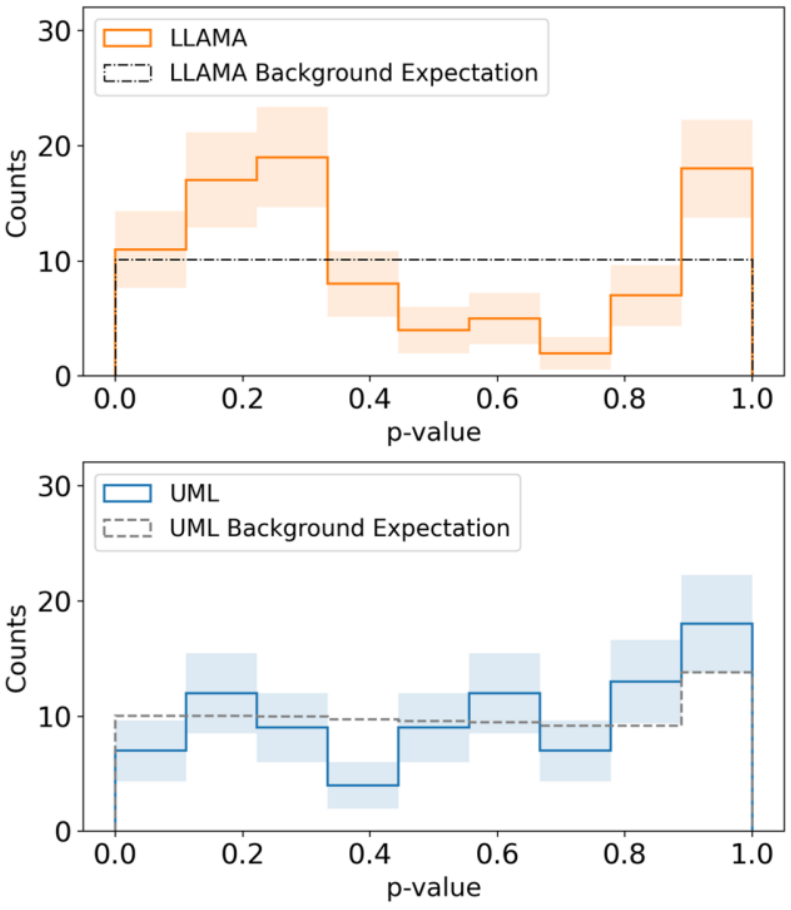




- Plan to issue 30-day-long multiplet alerts → trigger follow-up for long time scale transients
- Biases close sources (z<0.1)
- Particularly, synergies with BNS for small ν-energy hypothesis (d~200 Mpc)

Gravitational follow-up by IceCube

91 GW during O3



ApJ **944** 80 (2023).

GW alerts → ν follow-up

Provides much smaller localization $\sigma \sim 1°$

Two types of follow-up realtime analyses are performed

- Time window: $T_\nu - T_w \in (-500\ \mathrm{s}, 500\ \mathrm{s})$
- Low latency algorithm for MM astrophysics (LLAMA)
  Bayesian style analysis
- Un-binned maximum LLH:
  Frequentist approach

Follow-up for 91 GWs in O3 were performed.
p-values were consistent with uniform distribution.

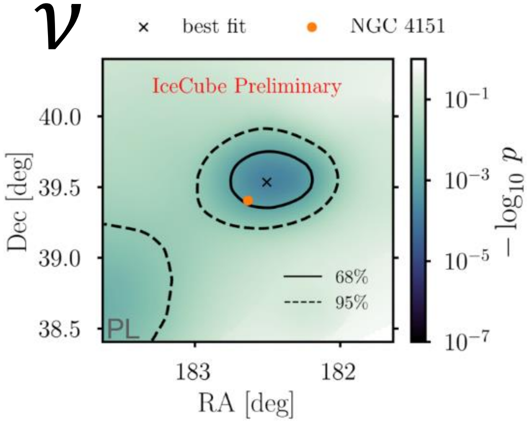
Gravitational follow-up by IceCube (UML)

Unbinned maximum LLH method (UML)

$$\mathcal{L}(n_s) = \frac{e^{-(n_s+n_b)^N}}{N!} \prod_{i=1}^{N} \frac{n_s}{N} \color{red}{S_i} + \frac{N-n_s}{N} \color{blue}{B_i}$$

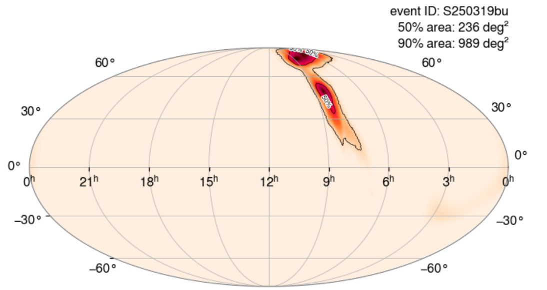
ν-signal PDF $\quad$ ν-BG PDF

ν



GW

$\otimes$



$$TS_\nu = 2\log\left(\frac{\mathcal{L}(n_s)}{\mathcal{L}(n_s=0)}\right)$$

The standard point source metric of significance (test statistics)

$$TS_{\nu+\mathrm{gw}} = 2\log\left(\frac{\mathcal{L}(n_s)}{\mathcal{L}(n_s=0)} \cdot \mathcal{P}_{\mathrm{gw}}(\Omega)\right)$$

GW skymap from GraceDB is adopted as a weight

- The best fit direction is determined by maximizing $TS_{\nu+\mathrm{gw}}$
- Significance of ONLY neutrinos is computed for a given GW skymap $\mathcal{P}_{\mathrm{gw}}(\Omega)$. Should be interpreted as p-value ($\nu|\mathrm{gw}$) and not p-value (ν & gw)
- Two tests of ± 500 s and (-0.1 d, 14 d) are performed.

Gravitational follow-up by IceCube (LLAMA)

Low Latency algorithm for MM astrophysics (LLAMA)

Phys. Rev. D **100**, 083017

signal

observation

Metric of significance: Bayes factor

$$\mathcal{O}_{\mathrm{gw}+\nu} = \frac{P(H_{\mathrm{s}}|\mathbf{x}_{\mathrm{gw}}, \mathbf{X}_{\nu})}{P(H_0|\mathbf{x}_{\mathrm{gw}}, \mathbf{X}_{\nu}) + P(H_{\mathrm{c}}|\mathbf{x}_{\mathrm{gw}}, \mathbf{X}_{\nu})}$$

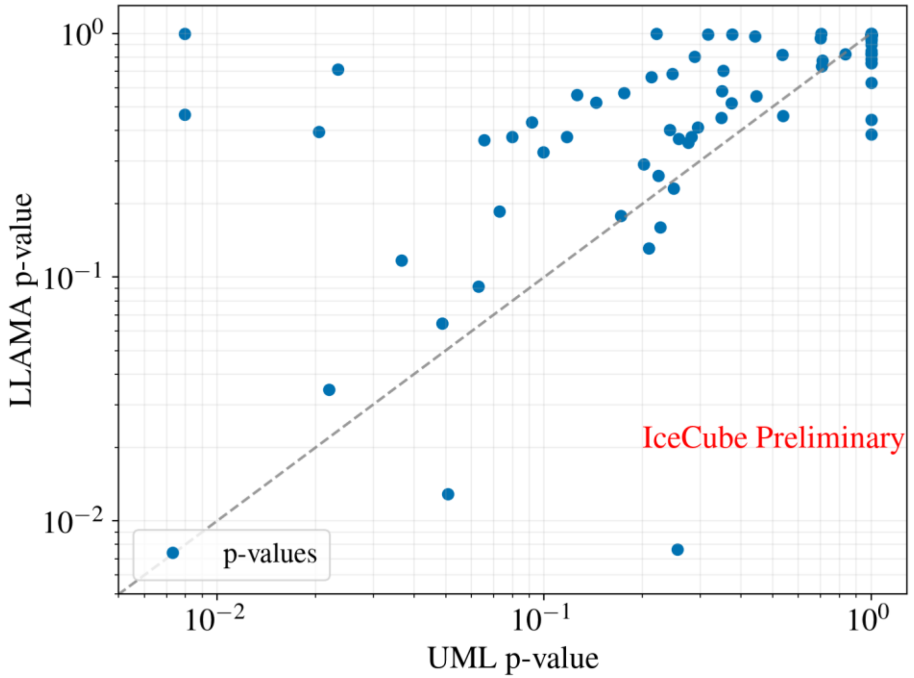
$\mathcal{H}_s$: both GW and ν are signals

$\mathcal{H}_0$: both GW and ν are backgrounds

$\mathcal{H}_c$: either one of GW or ν is signal

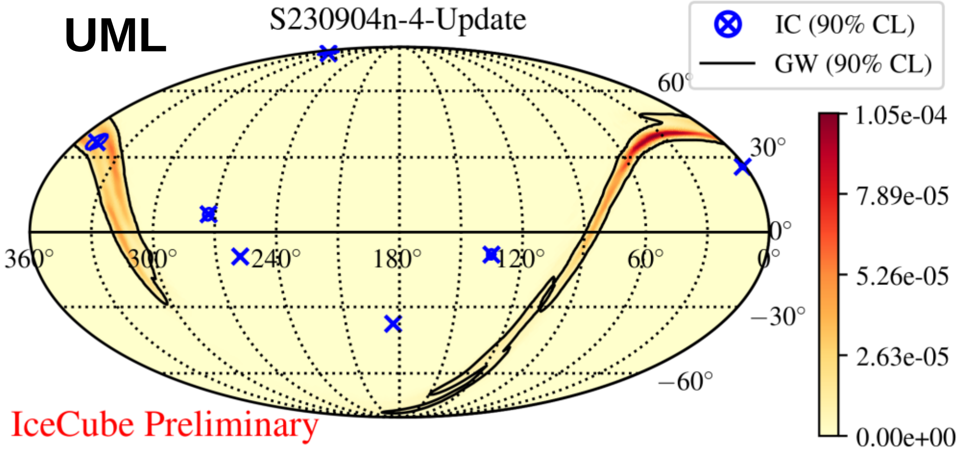
- The p-value can be interpreted as p-value (ν & gw)

→ UML and LLAMA are complementary test
Particularly, LLAMA uses the distance information under its prior distribution (uniform)

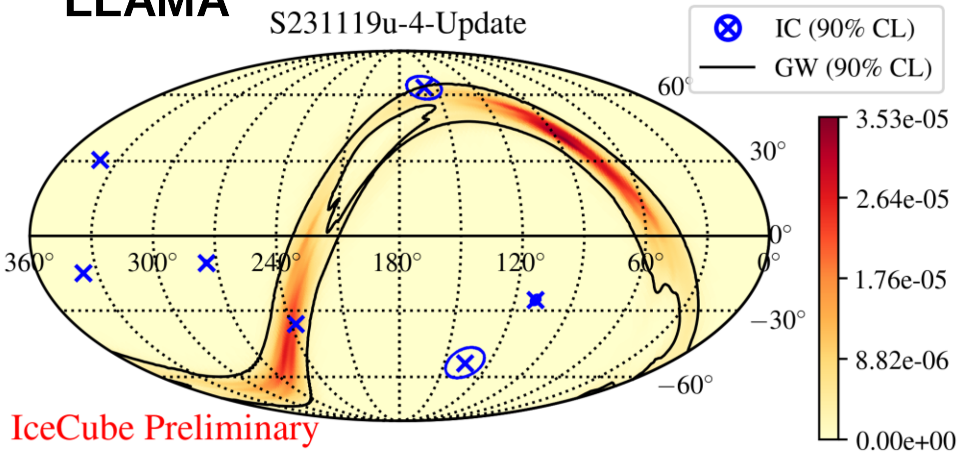


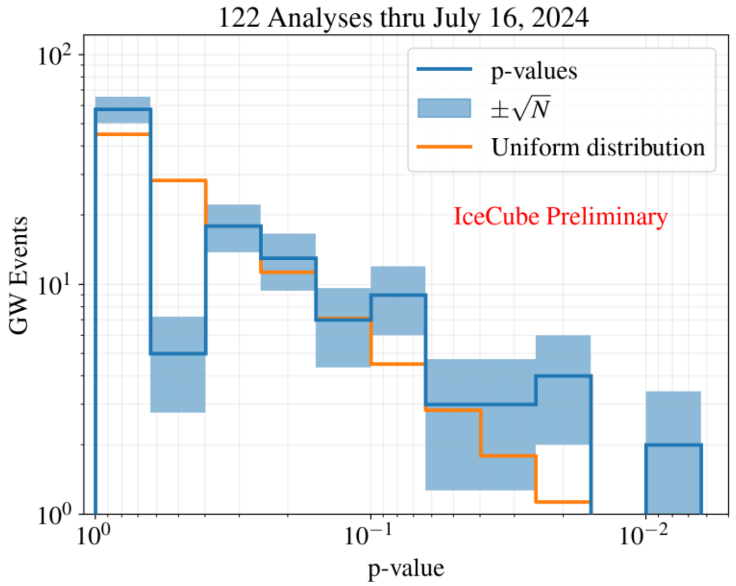
Sky maps GW + ν

UML



LLAMA





The smallest p-value as of last year ~ 0.3%

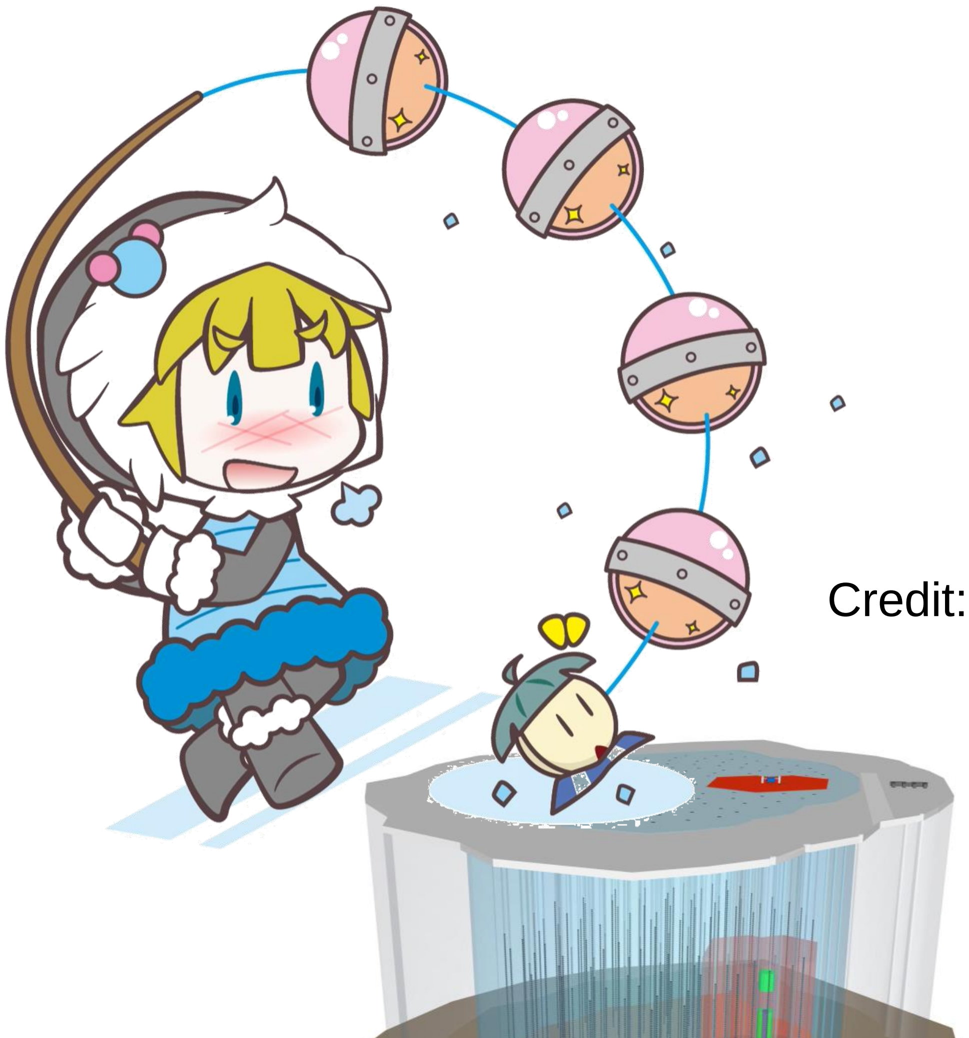
Q. Any requirement on the localization of GW?

A. IceCube is 4π detector.
→ No technical requirements in terms of follow-up.

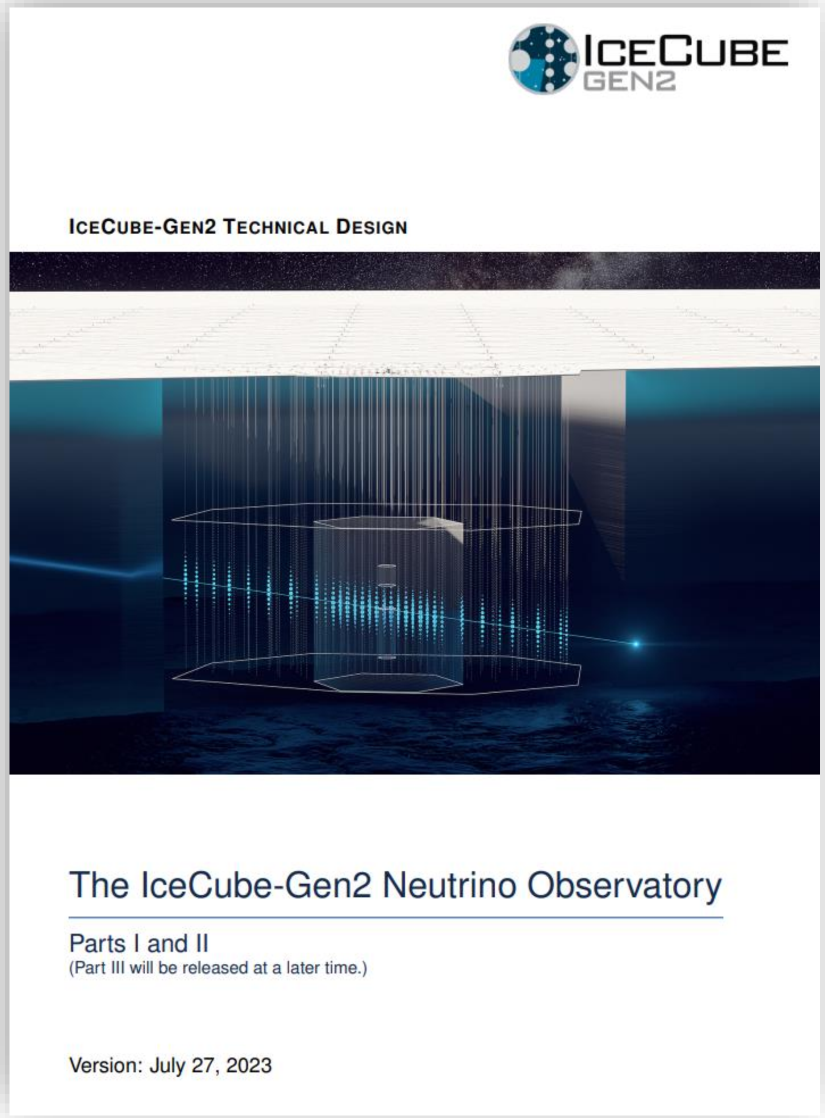
However, if we search for transients in +/- 1 day neutrino BG rate is ~ O(1/30) $\mathrm{deg}^{-2}\ \mathrm{day}^{-1}$

➡ Sensitivity significantly improves if $\Omega_{\mathrm{gw}} \lesssim 30\ \mathrm{deg}^2$

IceCube-Gen2



Credit: Akimoto



ICECUBE GEN2

ICECUBE-GEN2 TECHNICAL DESIGN

The IceCube-Gen2 Neutrino Observatory

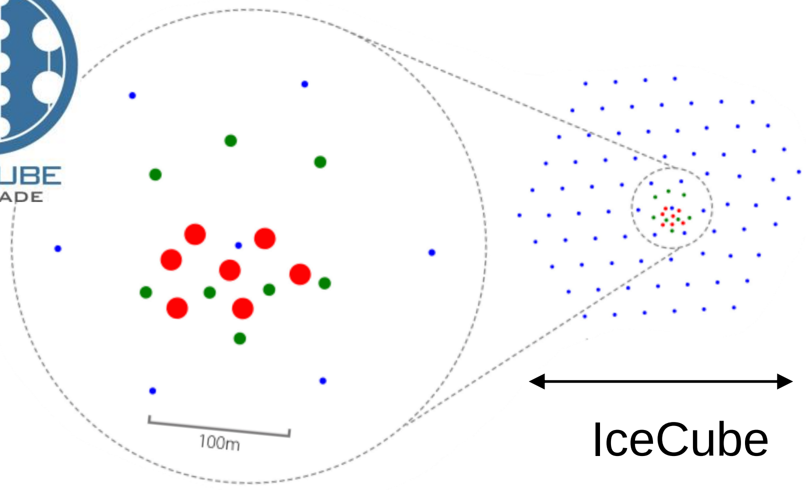
Parts I and II

(Part III will be released at a later time.)

Version: July 27, 2023

https://icecube-gen2.wisc.edu/science/publications/tdr/

IceCube-Upgrade (Gen2-phase1)



D-Egg

- Installation of 700 sensors 25/26 winter
- Targeting "**Low**" energy (GeV) neutrinos

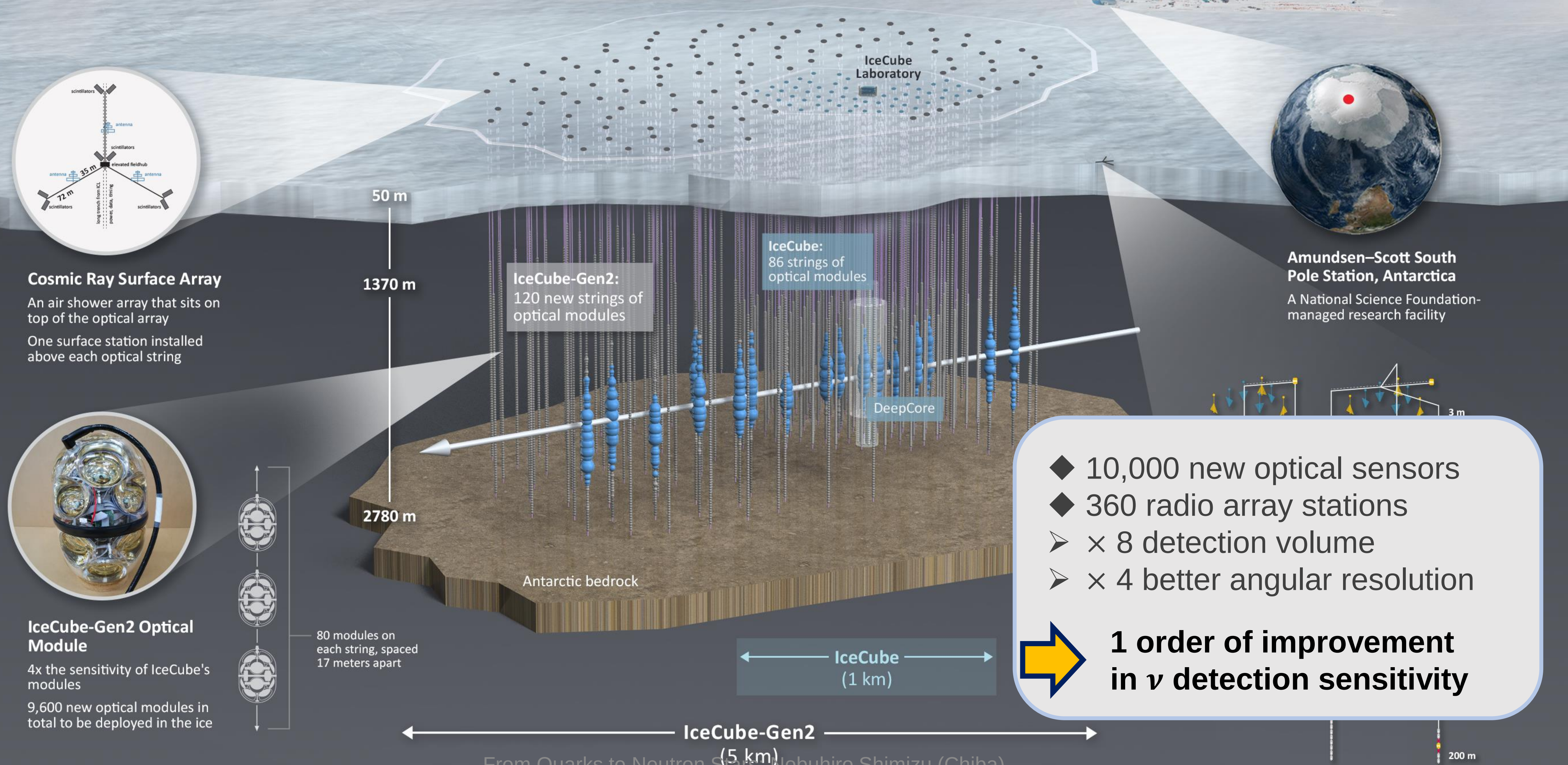
  ν oscillation & GeV-ν astrophysics

- Precise measurement of ice properties

- Chiba produced 300 optical modules (D-Egg)
- "Detectors made-in-Japan" have already arrived at Antarctica!

ICECUBE GEN2 | DETECTORS

SURFACE • RADIO • OPTICAL



- ◆ 10,000 new optical sensors
- ◆ 360 radio array stations
- ➢ × 8 detection volume
- ➢ × 4 better angular resolution

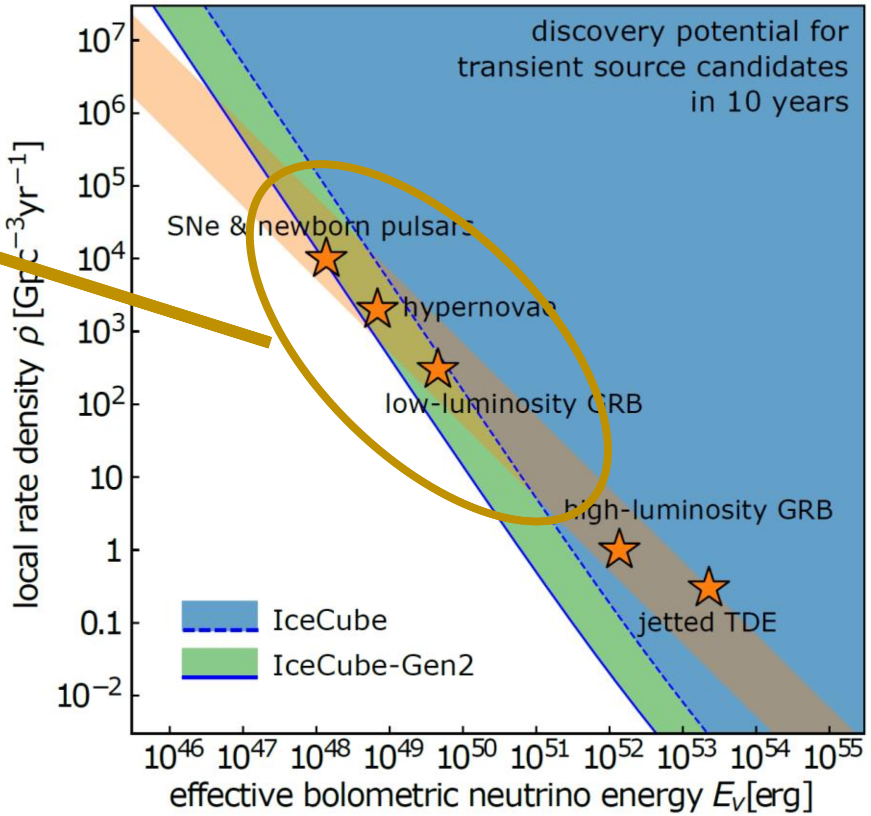
1 order of improvement in ν detection sensitivity

What IceCube-Gen2 delivers

$$\phi_\nu \propto \mathcal{E}_\nu \times \rho$$

$\mathcal{E}_\nu$: Neutrino emission energy per source
ρ : Source rate density

Dim but Frequent

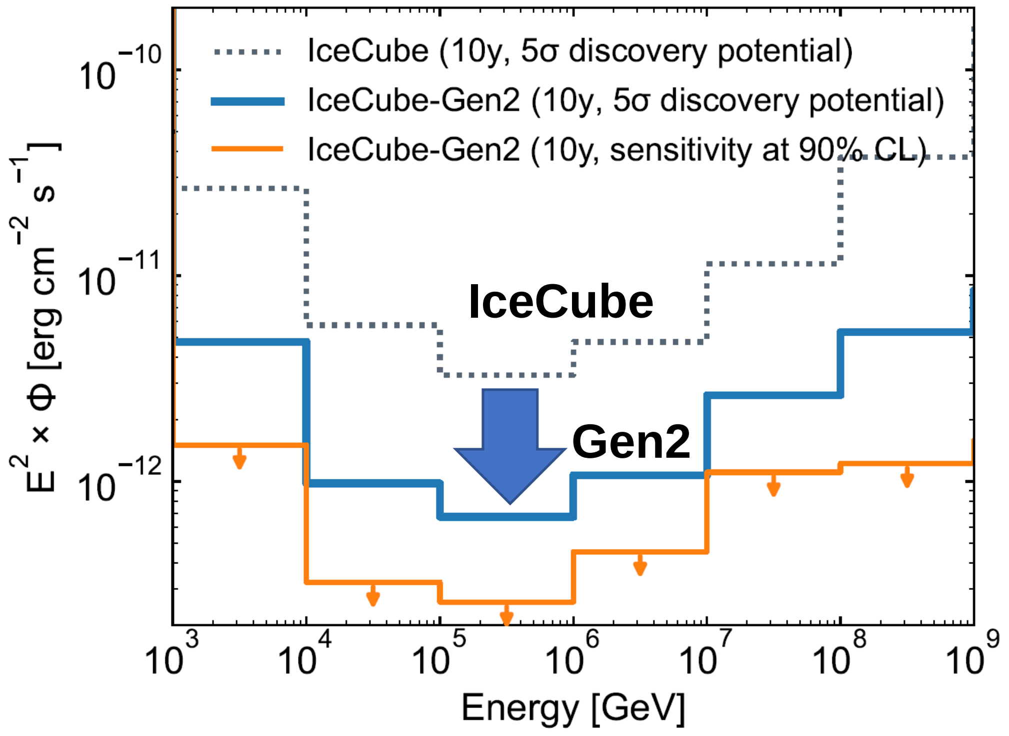


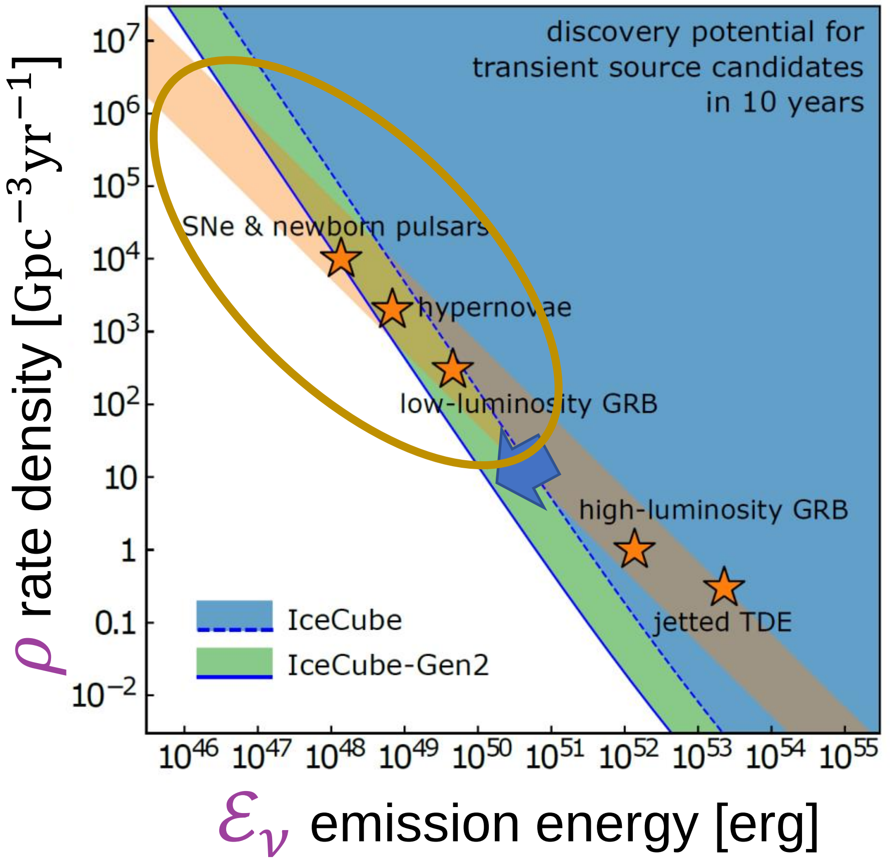
Bright but Rare

There sources are not favored by measurement.

Search for ν-emission sources with Gen2

5σ detection level





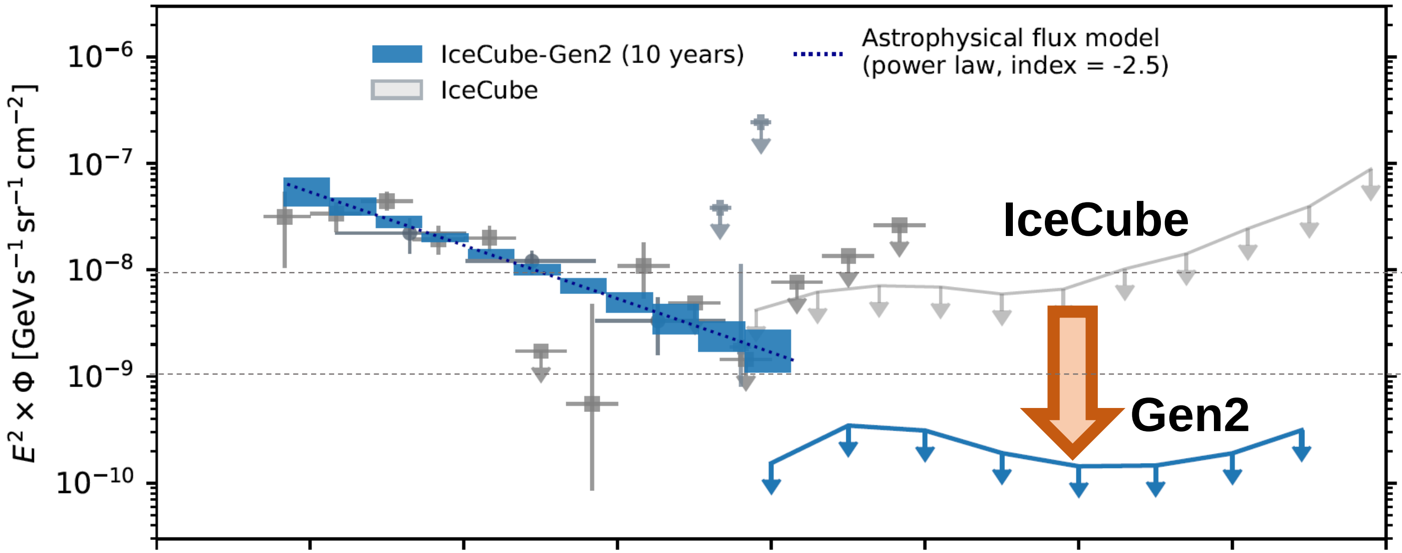
Source detection capability **x 8**

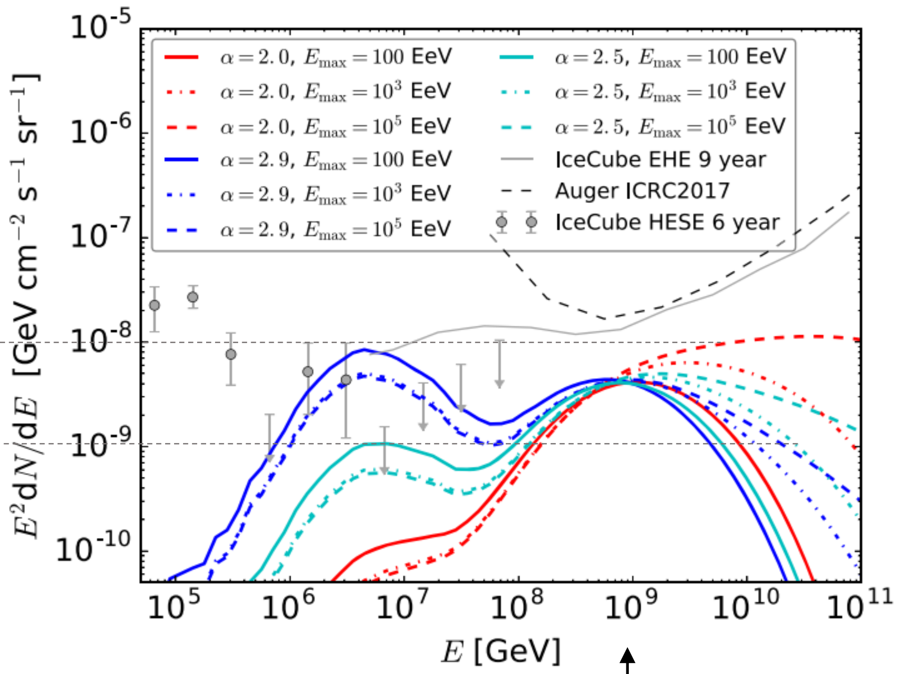
With the updated detectors, we can challenge dim but frequent transients.

Search for cosmogenic ν with Gen2

>PeV neutrinos from interaction between cosmic ray and CMB photons
a.k.a., **GZK neutrinos**

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{+}$$
$$\rightarrow \nu_{GZK}$$

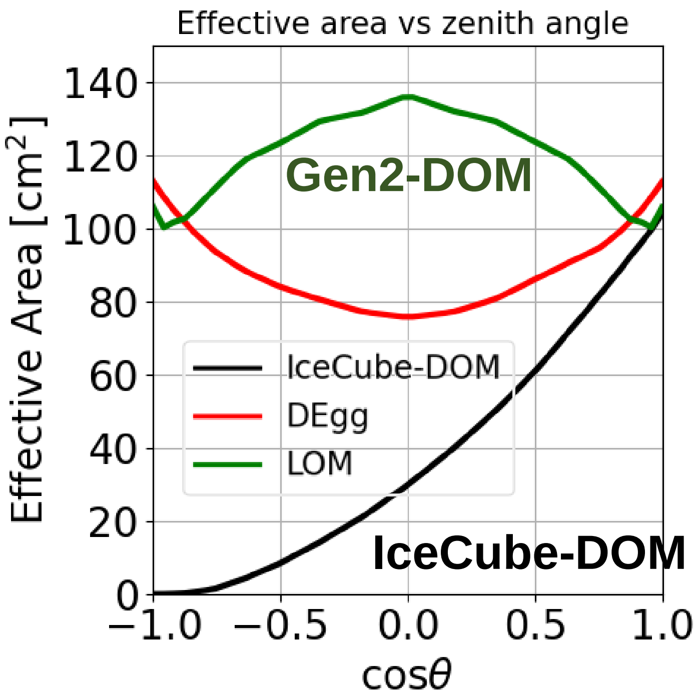


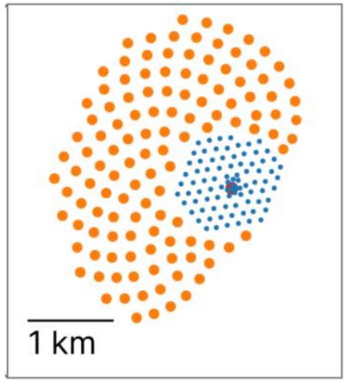


PeV

O(10) or bigger sensitivity reaches flux level of various model predictions!

Sensor for IceCube-Gen2

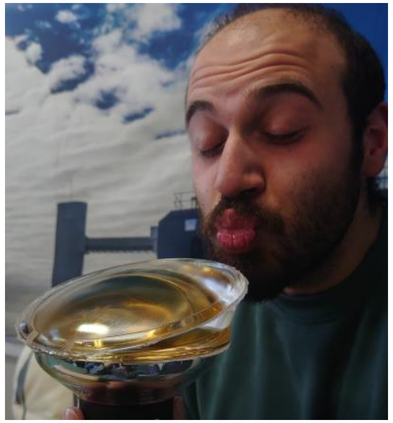


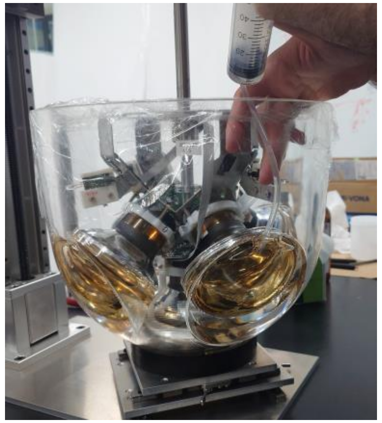


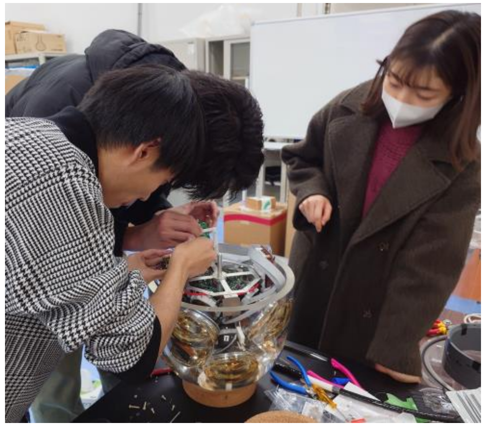
IceCube: 125 m spacing

IceCube-Gen2: 240 m spacing

- Pack multi-PMTs in an egg-shaped glass
- Use silicone elastomer's light guide (gel pad) to efficiently lead photons up to PMTs







A factor of >4 improvement compared to IceCube-DOM

Summary

- Origins of high energy multi-messengers are not yet clarified
- IceCube partially revealed characteristics of neutrinos
  - Energy distribution of flux
  - Sources (though still very much limited)
    Blazer, Seyfert galaxy, Galactic plane
- Follow-up observations are important
  - Need to overcome statistical game on the chance coincidence
  - Follow-ups of GW are on-going
- IceCube-Gen2 project will improve the sensitivity by an order of magnitude.

Backup

IceCube-Extension

◆IceCube-Upgrade (Gen2-Phase1)

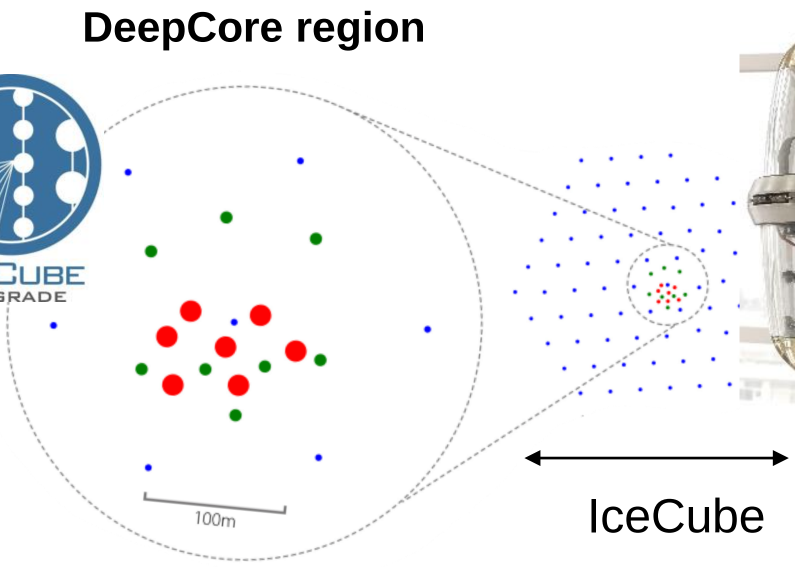
- Installation of 700 sensors
- "Low" energy neutrinos
  - ν oscillation & GeV-ν astrophysics
- Precise measurement of ice properties

⇨ ***Start data collection in 2026***

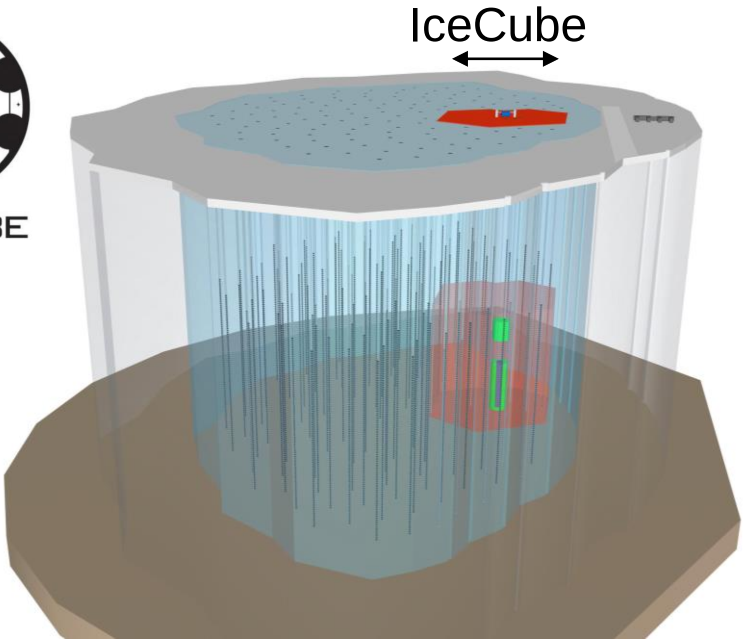
◆IceCube-Gen2

- Installation of new 10,000 sensors
- Aiming for "High" energy neutrinos

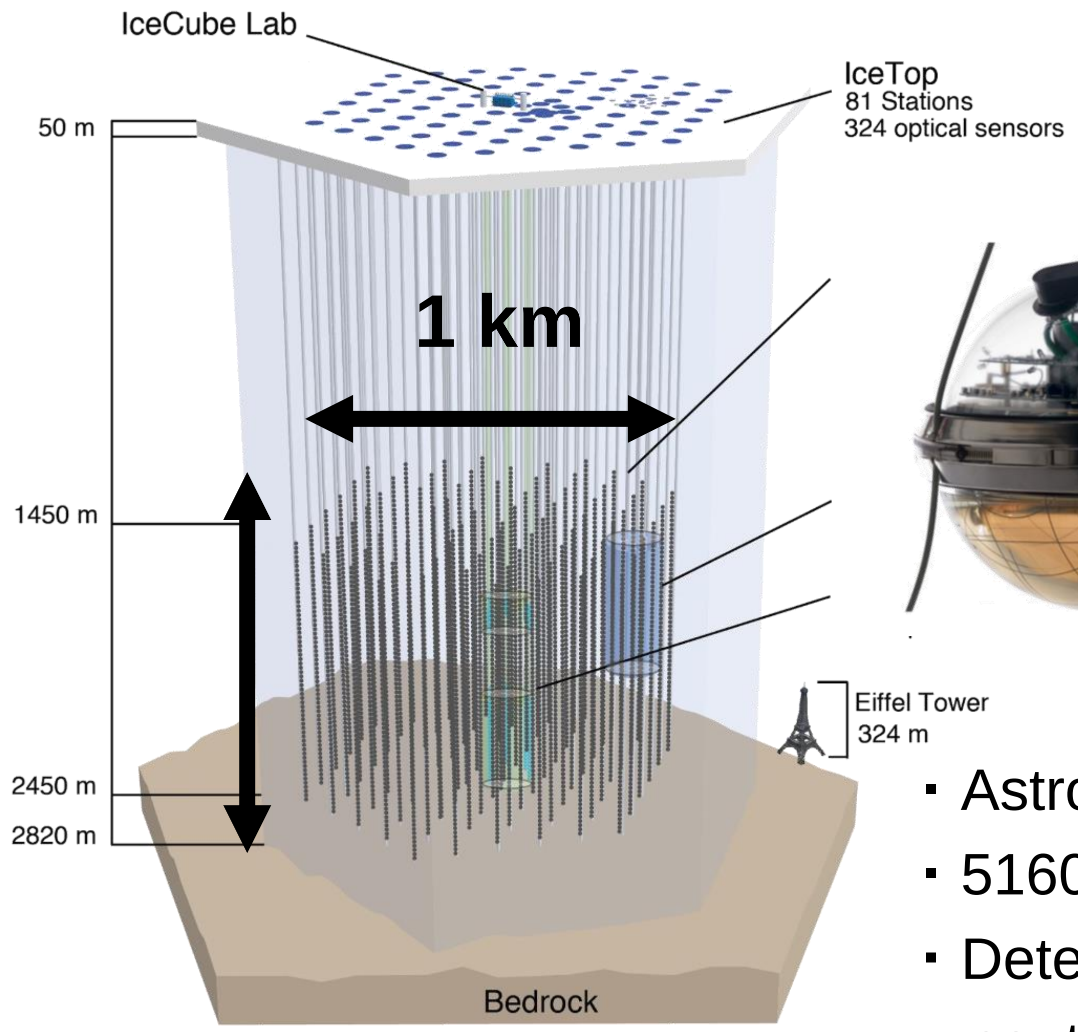
ICECUBE UPGRADE



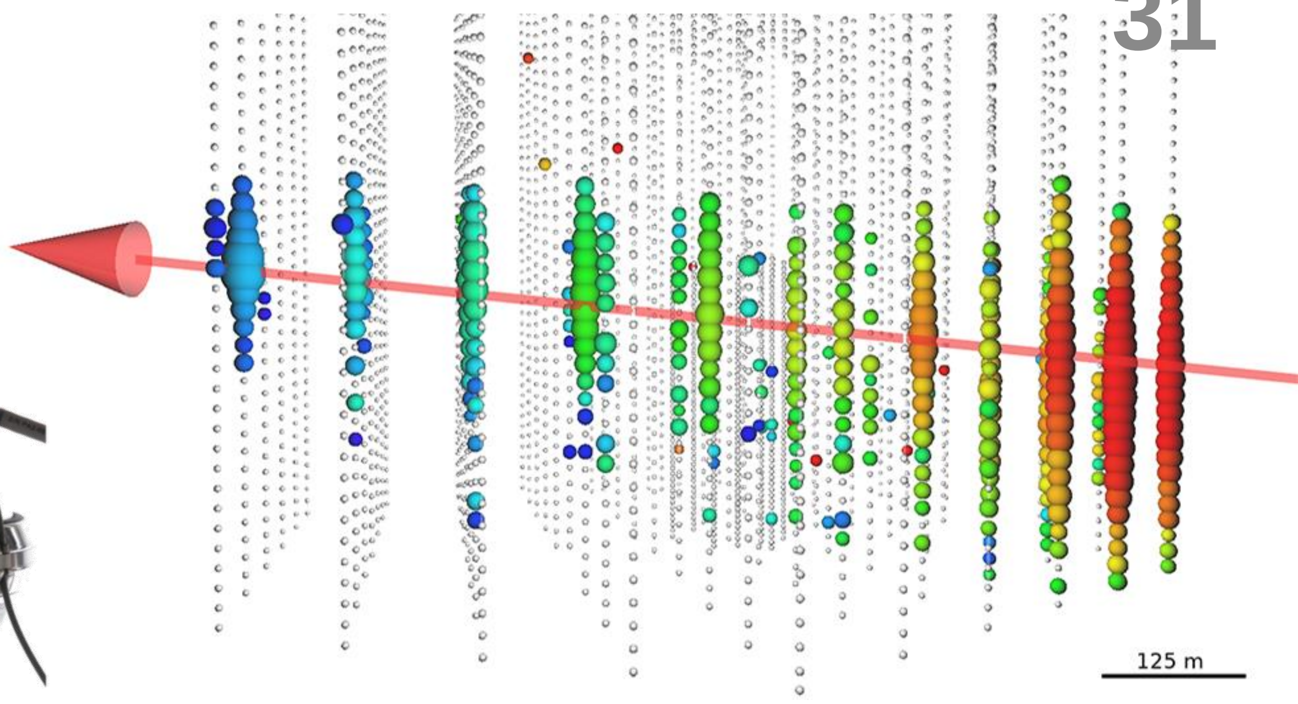
ICECUBE GEN2



IceCube experiment



DOM



- Astrophysical neutrino telescope
- 5160 optical modules (DOM) in the ice of Antarctica 1 km^3
- Detect Cherenkov light from charged particles produced by neutrino interaction