Recent results of the IceCube

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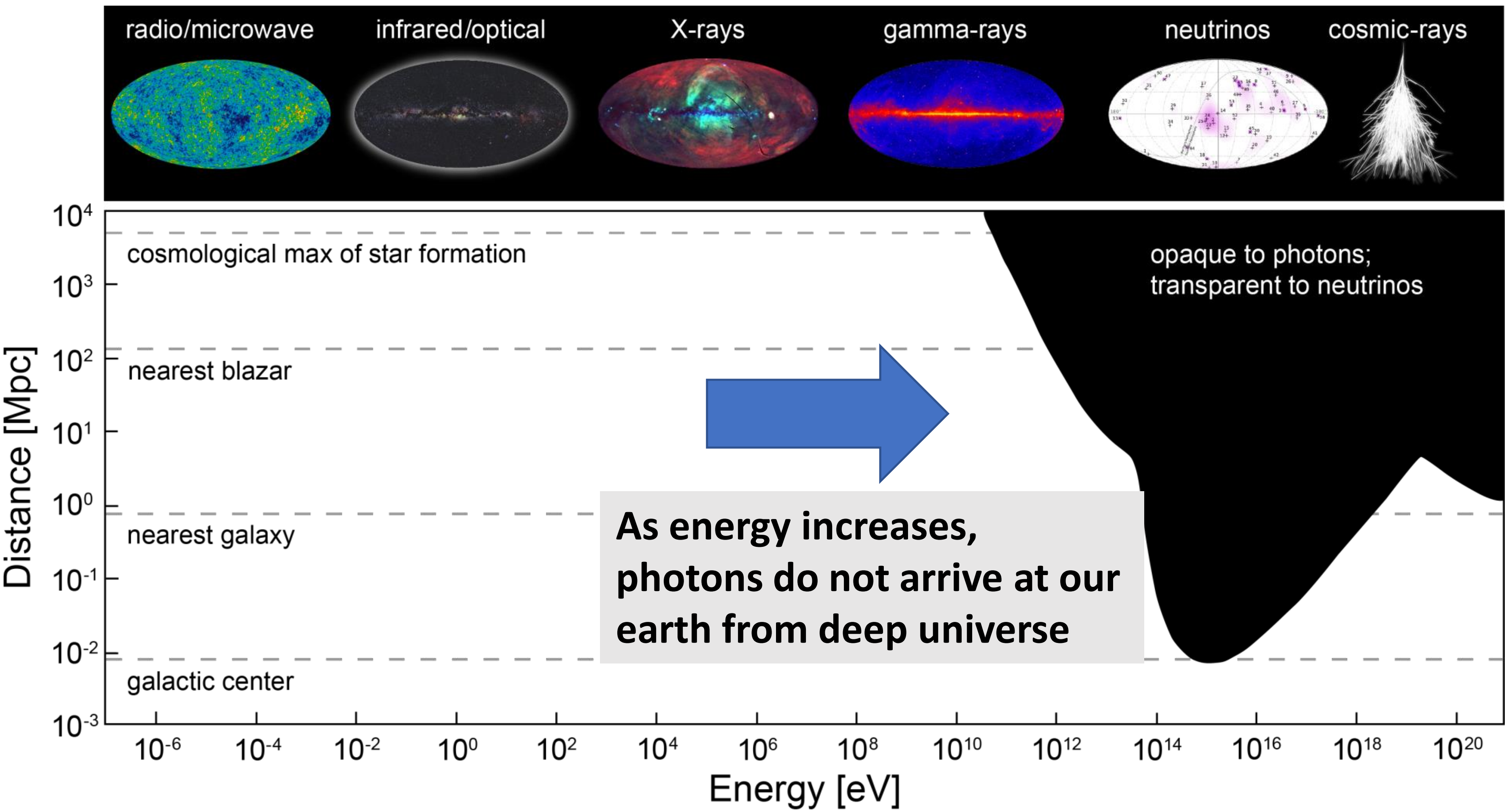
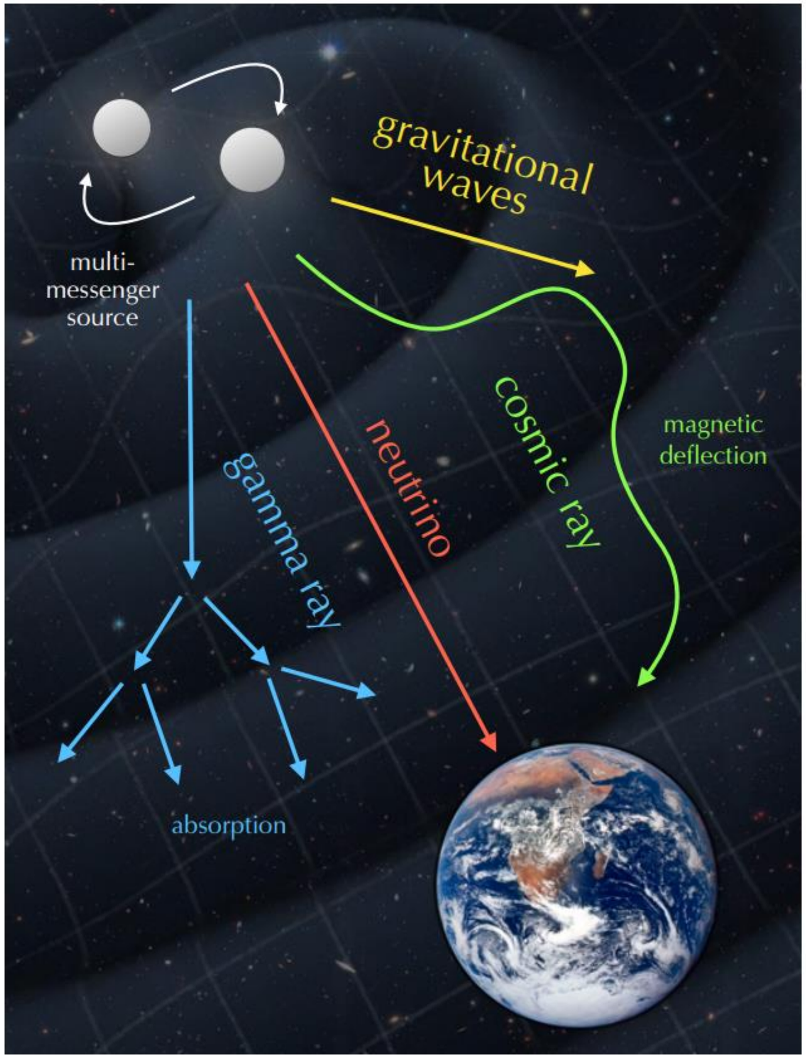
ICRR workshop 2024 Feb. 20th

Neutrinos as messenger

J. Phys. G **48**, 6, 060501 (2021).



Neutrino astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

Slide from Markus Ahlers

Hadron production of neutrino

$p + \gamma \rightarrow n + \pi^+$ $\quad \boldsymbol{E_p/5}$

$\boldsymbol{E_p}$

$\quad \hookrightarrow \mu^+ + \nu_\mu$ $\quad \boldsymbol{E_p/20}$

$\quad\quad \hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$ $\quad \boldsymbol{E_p/20}$

$\quad\quad\quad \hookrightarrow$ radiations

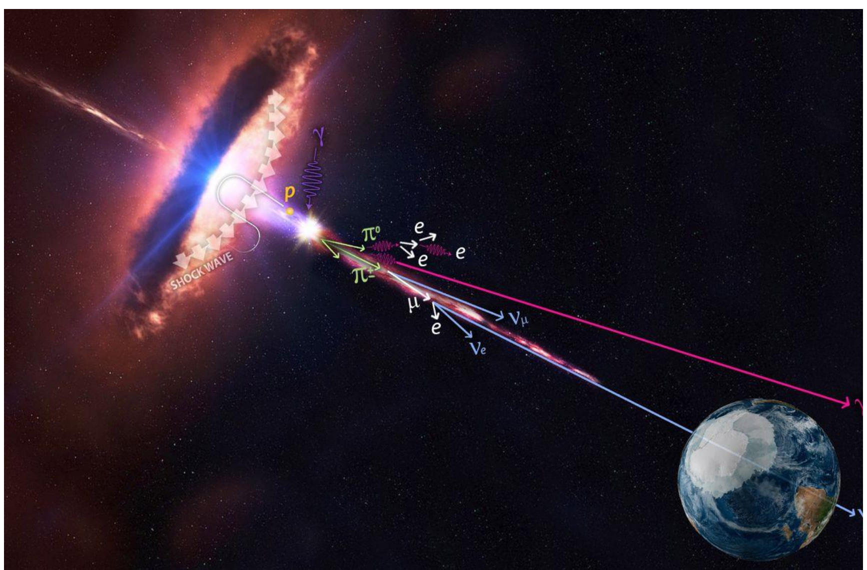
$\rightarrow p + \pi^0$

$\quad \hookrightarrow \gamma\gamma$

$\boldsymbol{E_p/10}$

Neutrinos

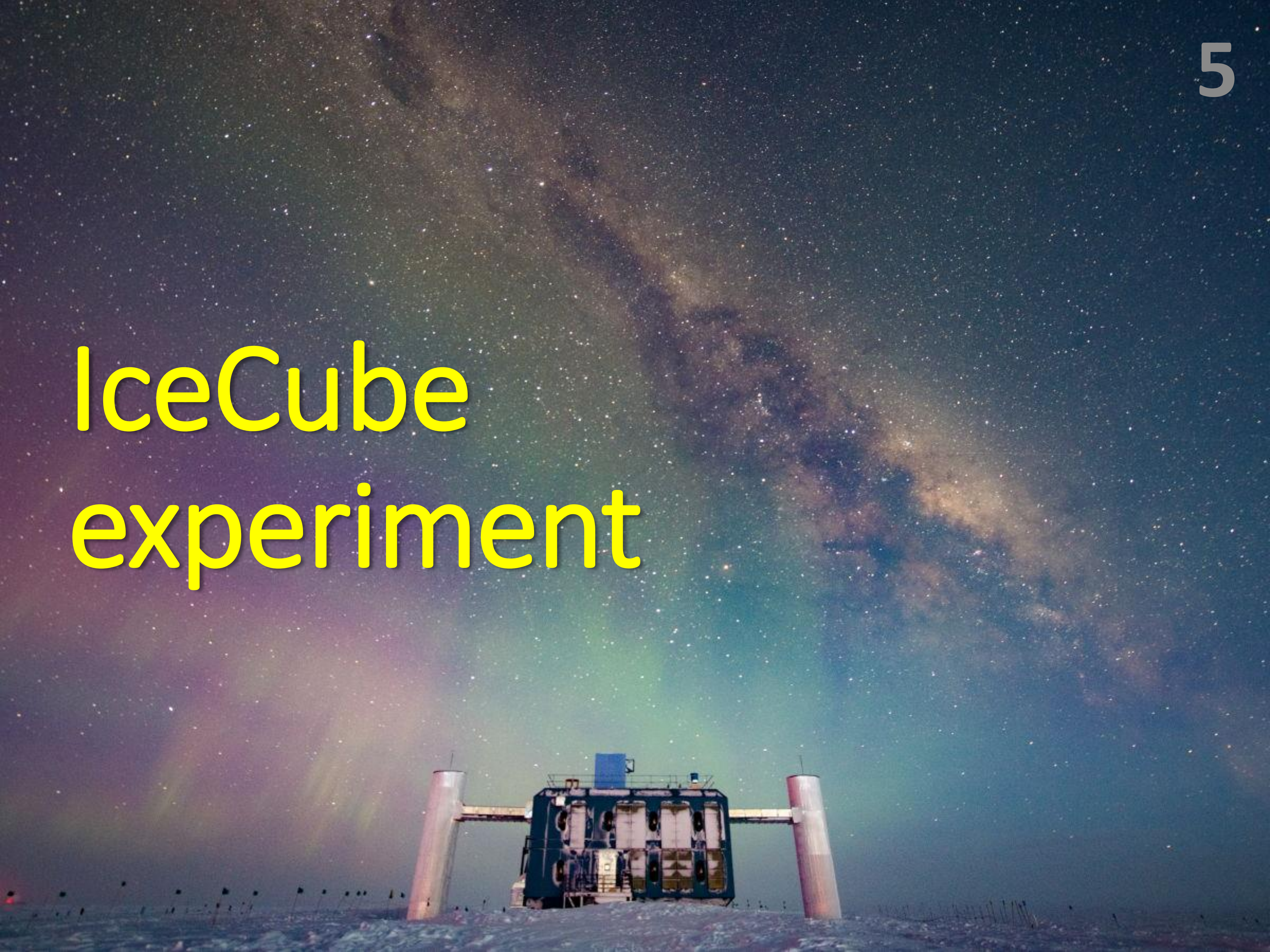
γ



Neutrinos accompany with various partners

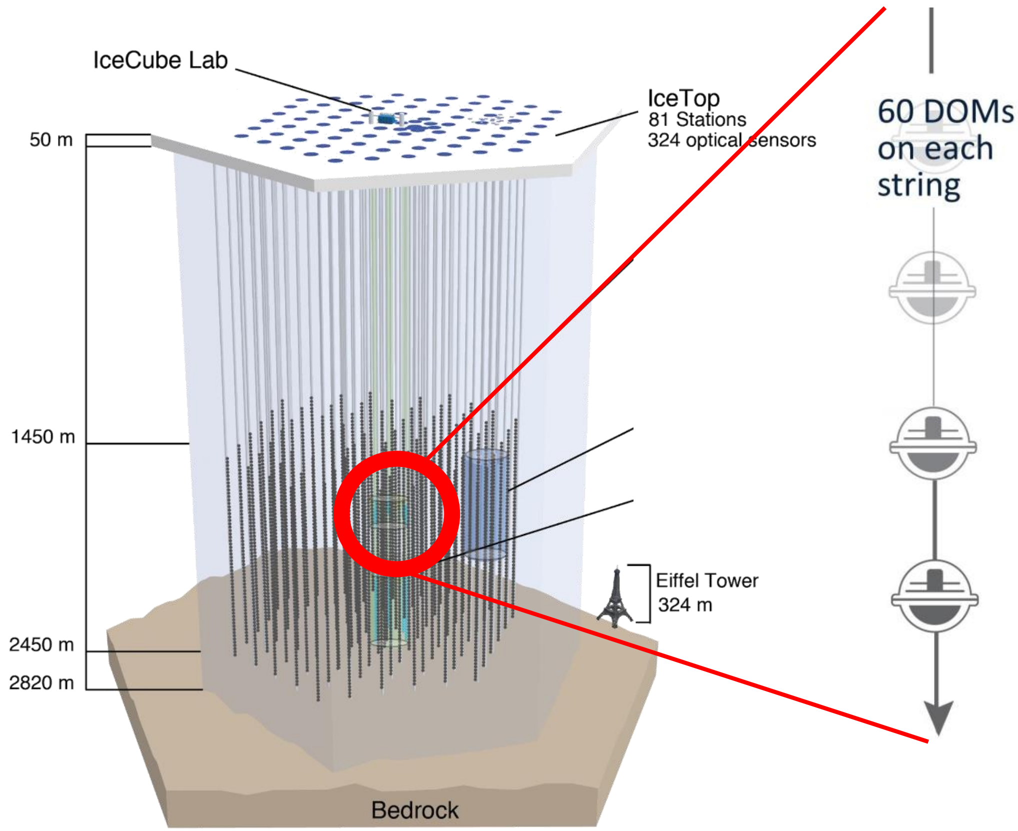
Multi-messenger astronomy to understand the mechanism of astrophysical objects

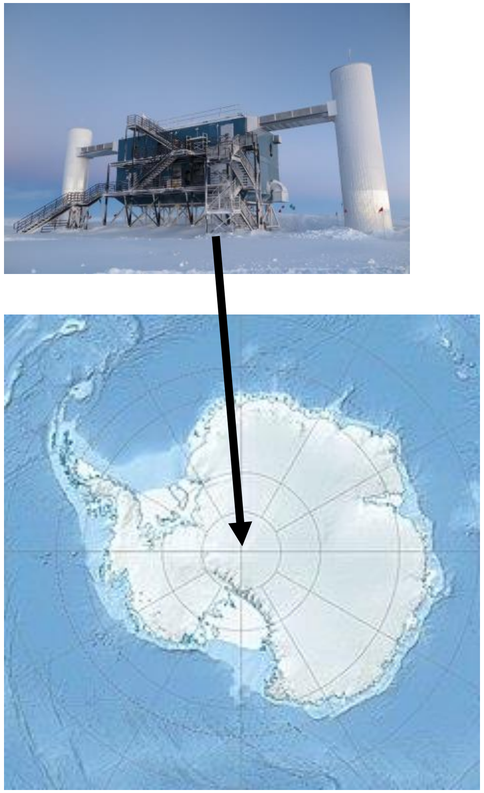
IceCube experiment



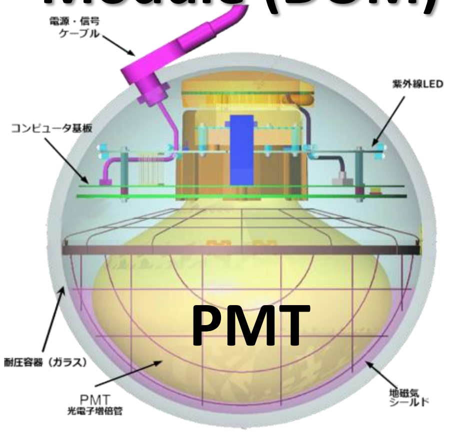
IceCube experiment

Neutrino telescope operated in Antarctica



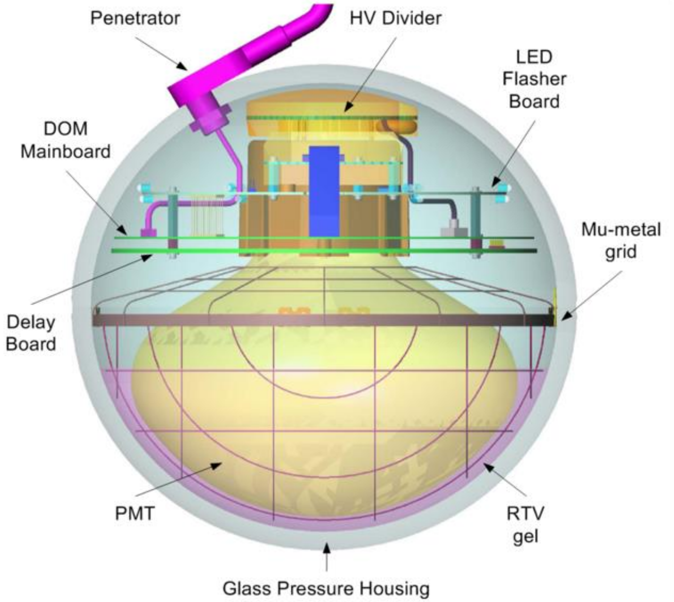


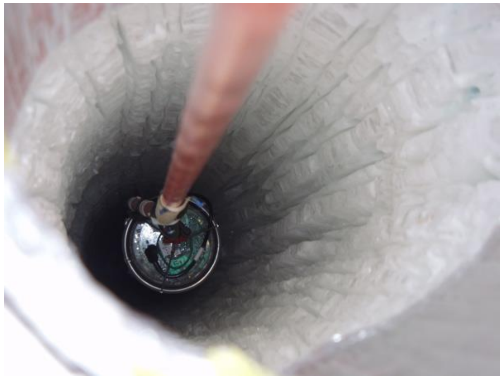
Digital Optical Module (DOM)



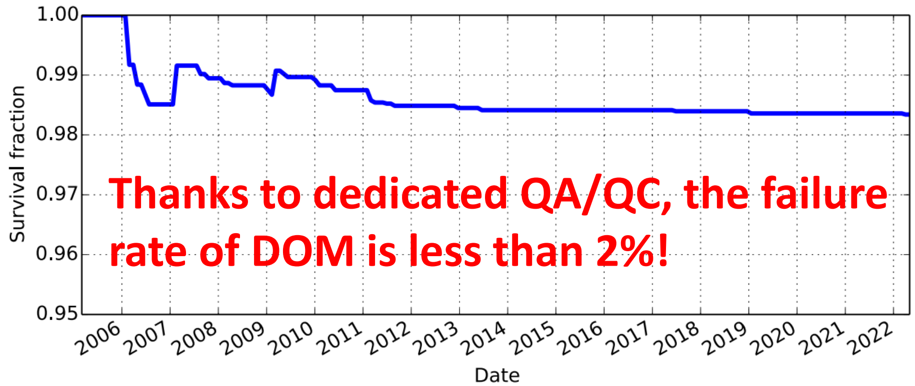
- 5160 optical modules are deployed in ice 1 ㎦
- Cherenkov light from charged particles produced by neutrino interaction is detected by DOM

Digital Optical Module (DOM)



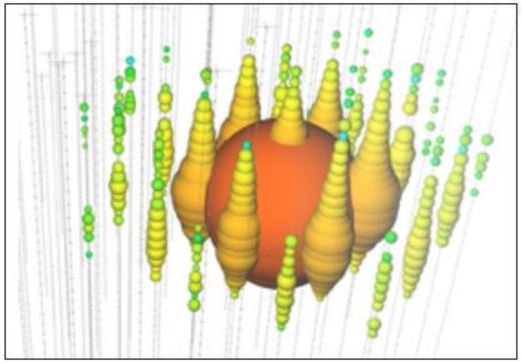


- Glass
  - UV transparent
  - Small radioisotope contamination
  - Pressure resistant 70 MPa! (7000 m deep sea
- PMT
  - 10'' Hamamatsu PMT (QE=25%)



IceCube neutrino reconstruction

Event topology of neutrino signal



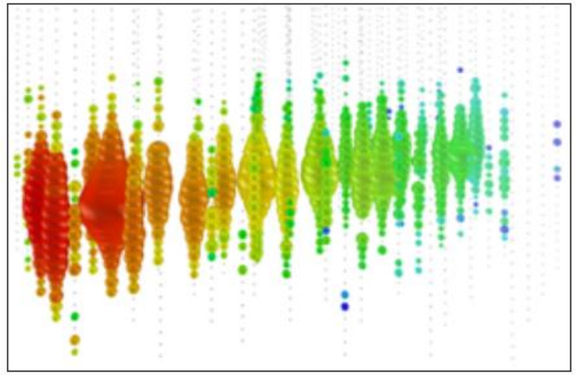
cascade

$\nu_e + N \rightarrow e + X$

$\nu + N \rightarrow \nu + X$

$\sigma_\psi \sim 15°$

$\sigma_E/E \sim 15\%$

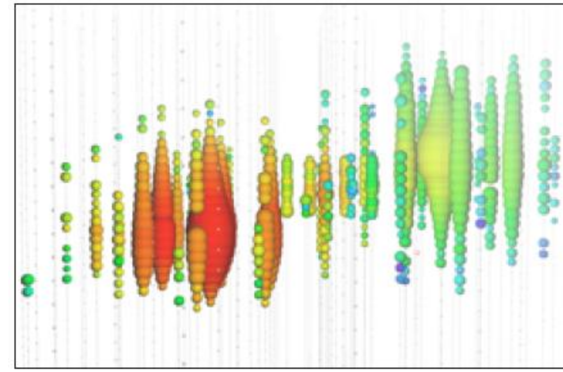


"Track-like"

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

$\sigma_\psi \sim 0.5°$

$\sigma_E/E \sim 25\%$



"Double-bang"

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

→ decay

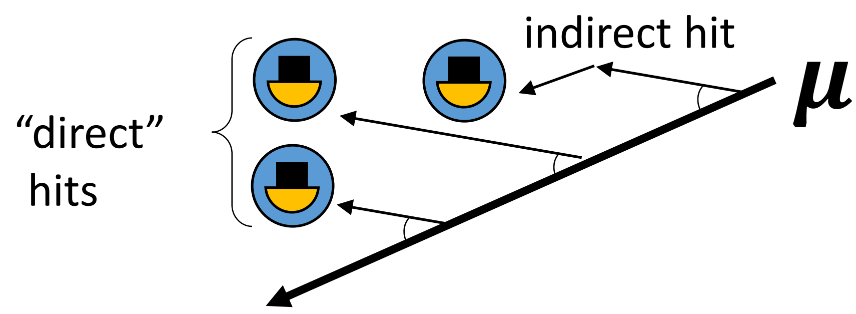
Flight length ~ 50 m/PeV

High tracking resolution is important for the follow-up.

→ *Use the track type events for generating alert signals.*

Reconstruction of track

◆Direction



- **Single Photo Electron (SPE) fit**
  → uses information of direct hits

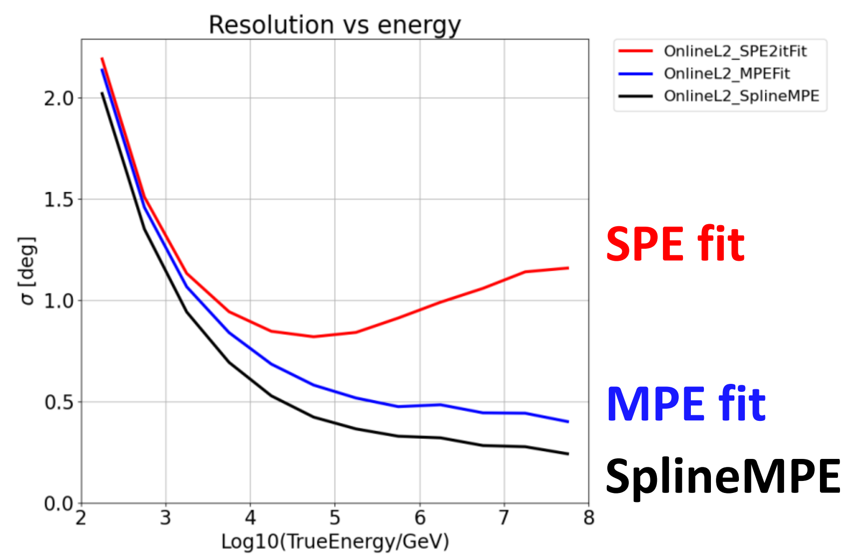
$$\mathcal{L}^{SPE} = \prod_{\text{1st hits}} P(t_{\text{obs}} - t_{\text{expected}})$$

- **Multi Photo Electron (MPE) fit**
  → uses information of multiple hits

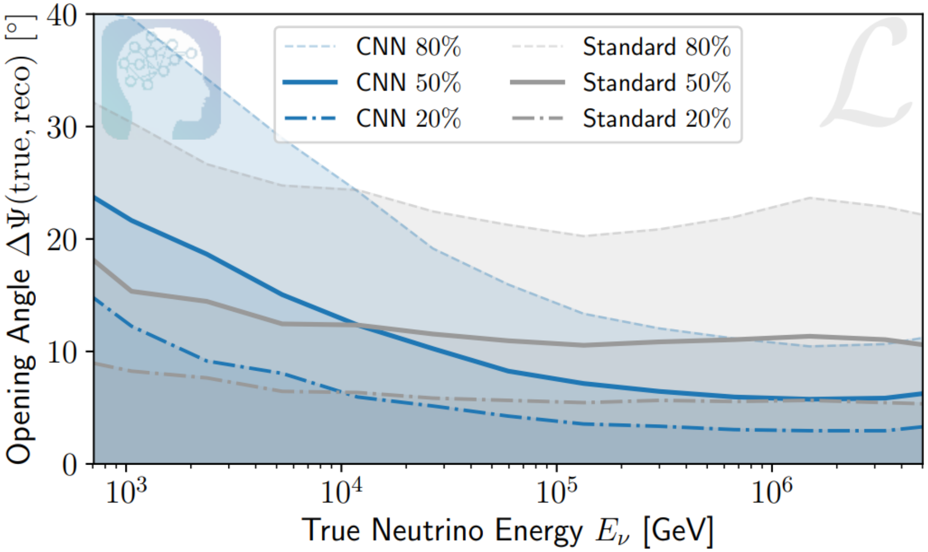
$$\mathcal{L}^{MPE} = \prod_{\text{1st } N \text{hits}} P(t_{\text{obs}} - t_{\text{expected}})$$

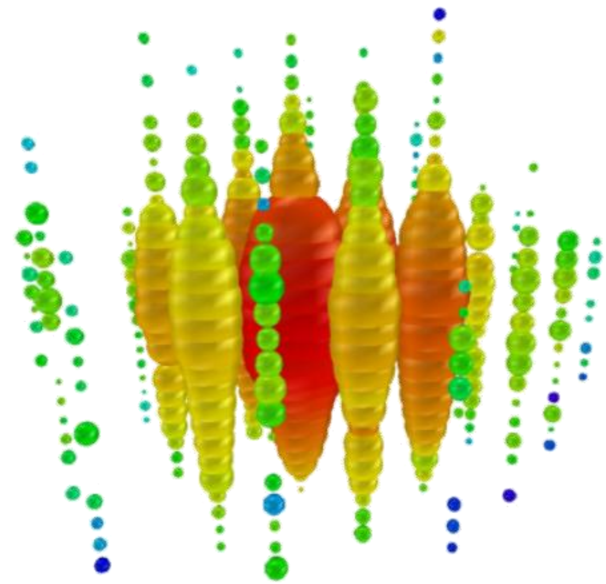
- **SplineMPE fit**
  → uses information of multiple hits and ice properties

$$\mathcal{L}^{\text{SplineMPE}} = \prod_{\text{1st } N \text{hits}} P(t_{\text{obs}} - t_{\text{expected}}; ice)$$



Reconstruction of cascade

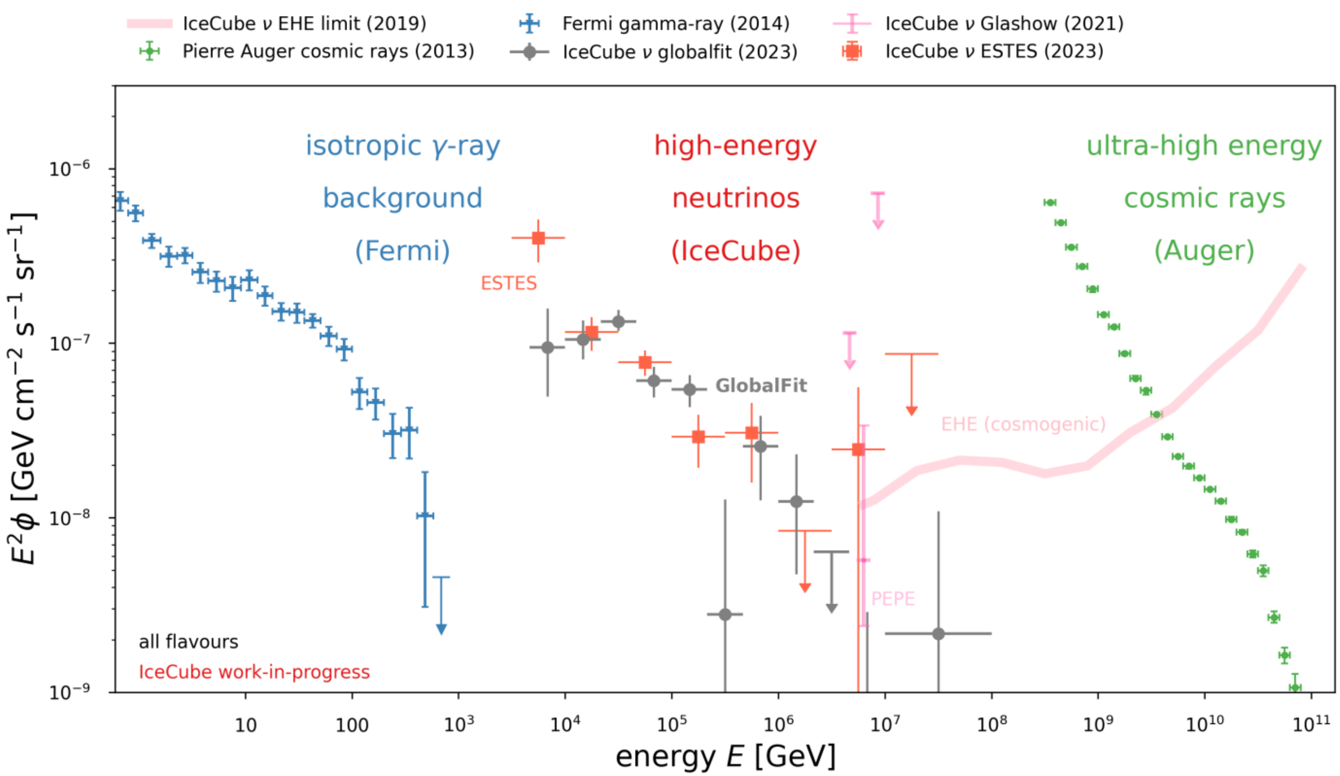




With (convolutional) neural net work, the pointing resolution of the cascade event is less than 10°.

IceCube diffuse neutrino flux

Diffuse neutrino flux



"Diffuse" flux → The origin of ν is not specified

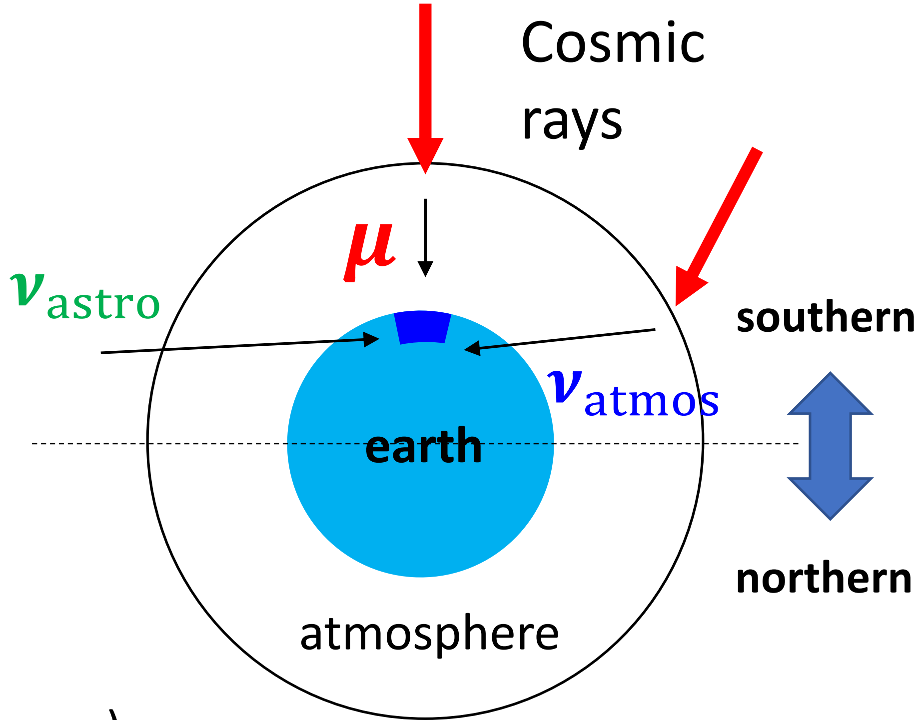
= integrated whole the direction

$$E^2\phi_\nu \sim \mathbf{10^{-8}} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.4} \quad [\mathrm{GeV}\cdot \mathrm{cm}^{-2}\cdot \mathrm{s}^{-1}\cdot \mathrm{sr}^{-1}]$$

Backgrounds for IceCube events

□ μ muon

- atmospheric muon
- mostly not single but coincident hits called "muon bundle"
- serious for "southern" events
- $\propto E^{-3.7}$

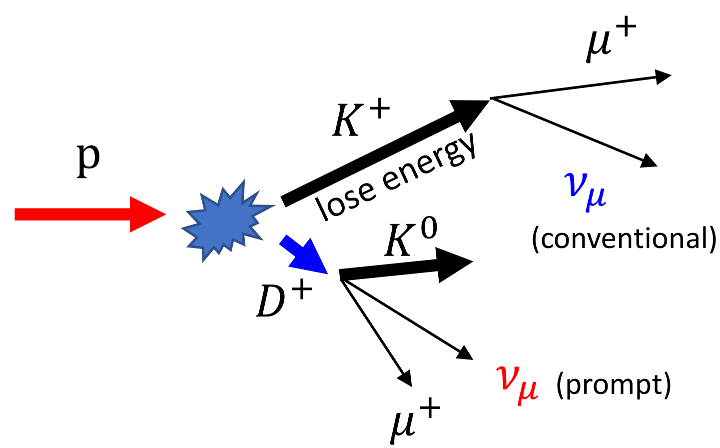


□ $\nu_{\rm atmos}$

- atmospheric neutrino caused by hadron/muon decays
- $\nu_\mu : \nu_e$ = 20 : 1 (for IceCube energy range)

➢ **"Conventional" $\boldsymbol{\nu_{atmos}}$**
originates from light hadrons (π/K)
$\propto E^{-3.7}$

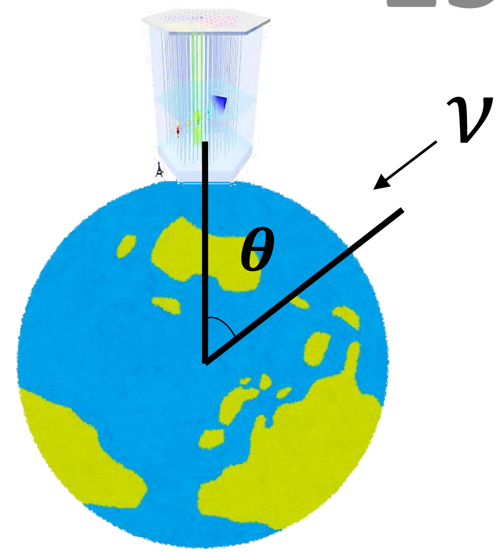
➢ **"Prompt" $\boldsymbol{\nu_{atmos}}$**
originates from charm mesons ($D, J/\psi$)
$\propto E^{-2.7}$

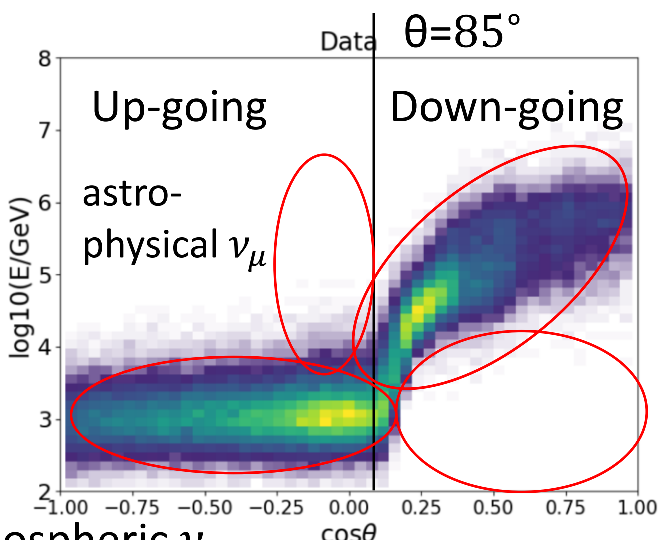


Basics of IceCube event

- **☐ Down-going (θ< 85°)**
  - ➢ large contamination from atmospheric muon
  - ➢ need veto at top layer (bottom right figure)
  - ➢ small efficiency due to tight cuts

- **☐ Up-going (θ > 85°)**
  - ➢ for large angles, contamination of μ is negligible but less sensitive for large energy (>1 PeV) due to absorption by the earth
  - ➢ For track events, major BG comes from atmospheric ν_μ

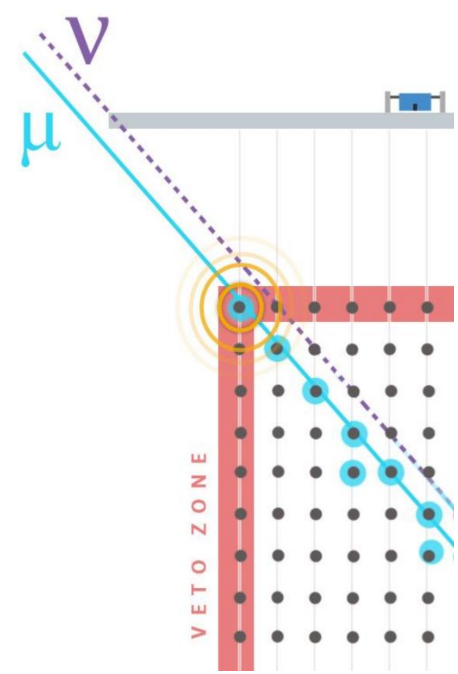




μ

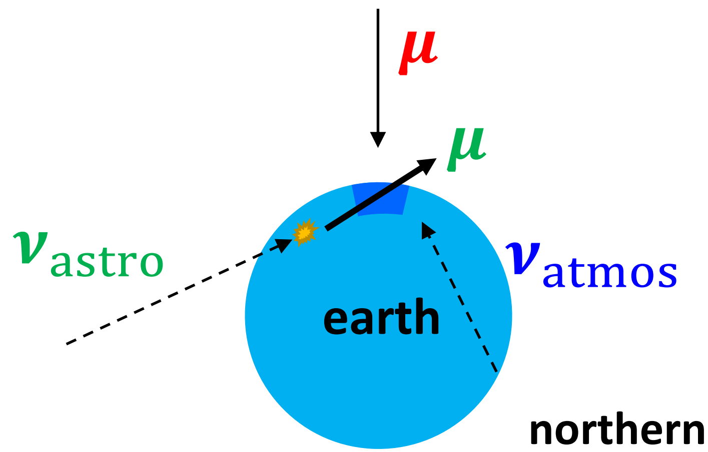
abundant μ
but less efficient due to
tight cuts

atmospheric ν_μ



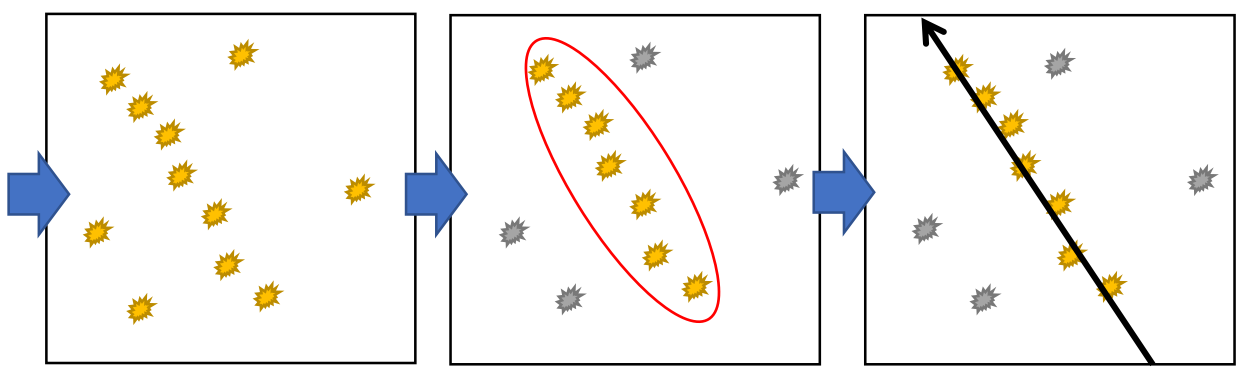
Purification neutrino events (example of up-going analysis)

- Upgoing analysis
  - Target: northern track
  - Down-going μ is almost completely suppressed
  - Even if μ is not produced in IceCube, this can be detected
  - Major background is ν_{atmos}



- Event selection

Precuts
✓ Large charge
✓ Long hits
etc..



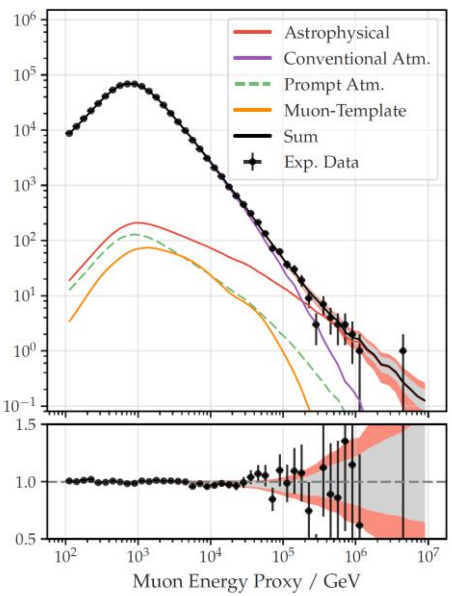
Topological split

Fit track and evaluate goodness of fit

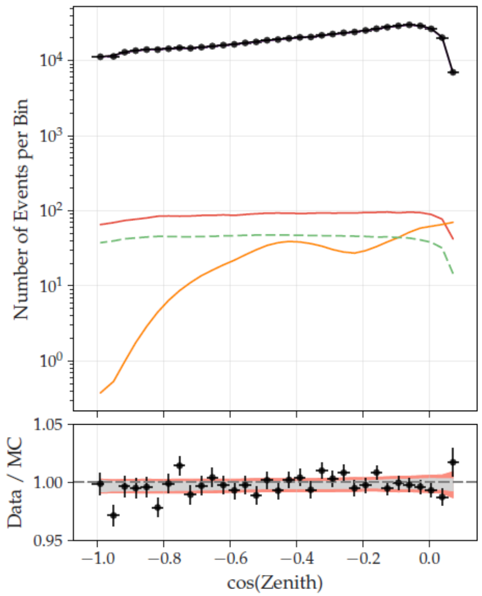
Flux measurement w/ upgoing tracks

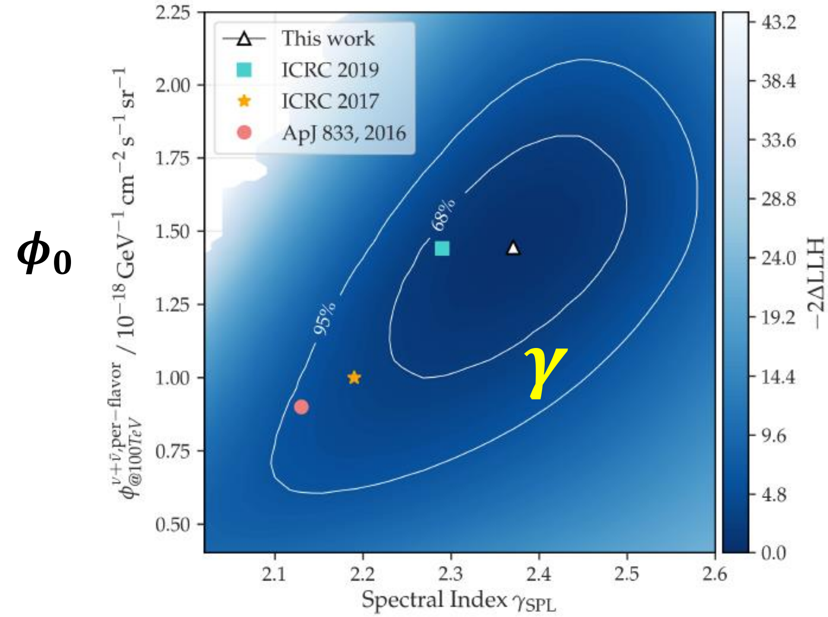
APJ. **928** 50 (2022)

Muon Energy



CosZenith





- Mainly sensitive to upgoing through-going track
- Astrophysical neutrino flux was consistent with a single power law

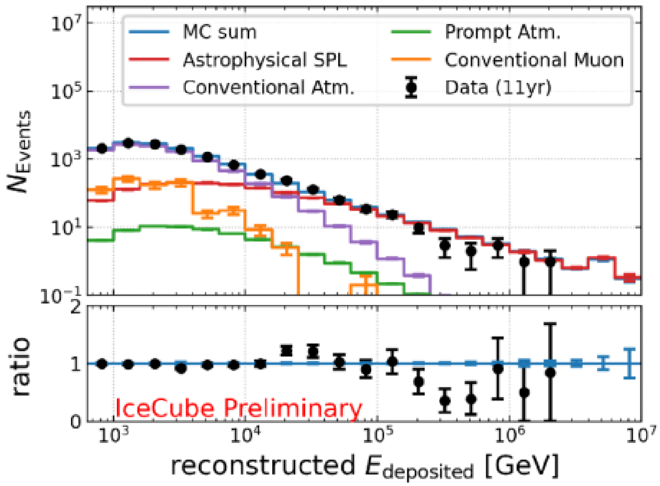
$$\phi = \frac{dN}{\mathrm{d}E\mathrm{d}A\mathrm{d}\Omega\mathrm{d}t}$$

$$= 10^{-18}\phi_0\left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\gamma} \quad [\mathrm{GeV}^{-1}\cdot\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{sr}^{-1}]$$

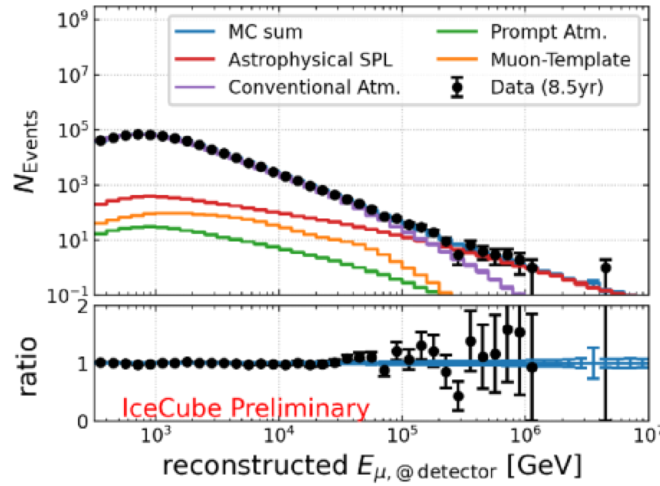
$$\phi_0 = 1.44 \pm 0.25$$
$$\gamma = 2.37 \pm 0.09$$

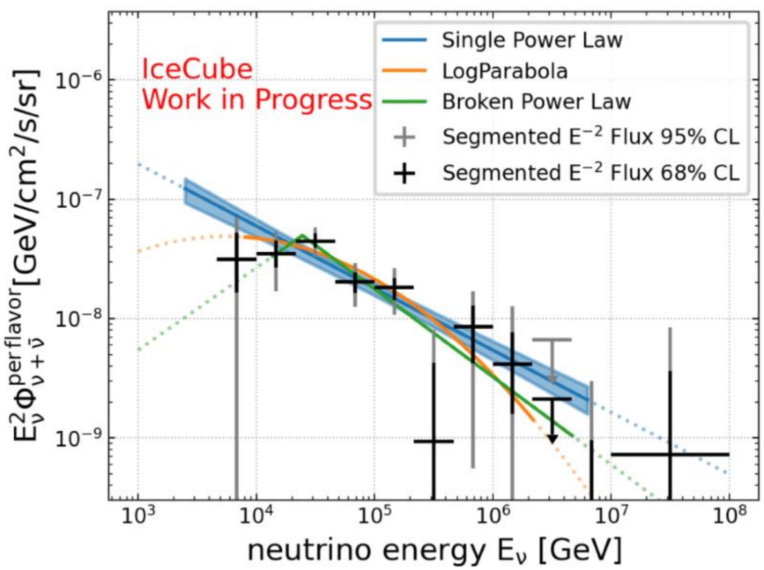
Flux measurement w/ track + cascade combined fit

Cascade histogram



Track histogram





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

→ **Stay tuned!**

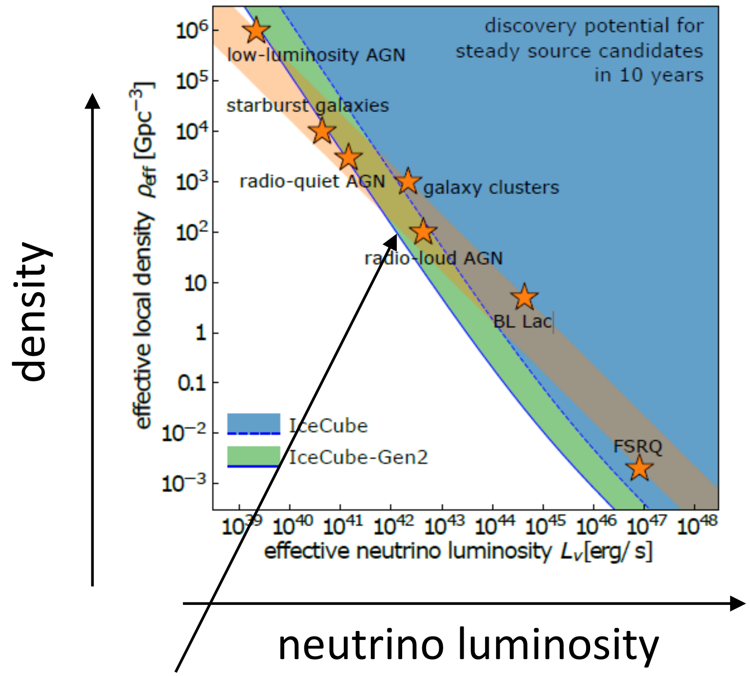
Search for neutrino sources

Parameter space of the neutrino source objects

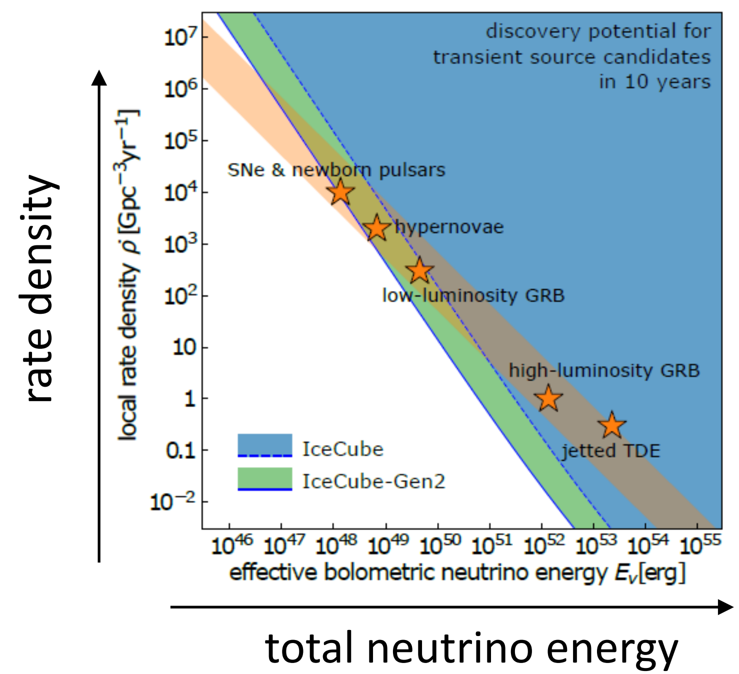
$$n_{obs} \propto n_0 L_\nu$$

n_0: density
L_ν: luminosity

Steady source



Transient source

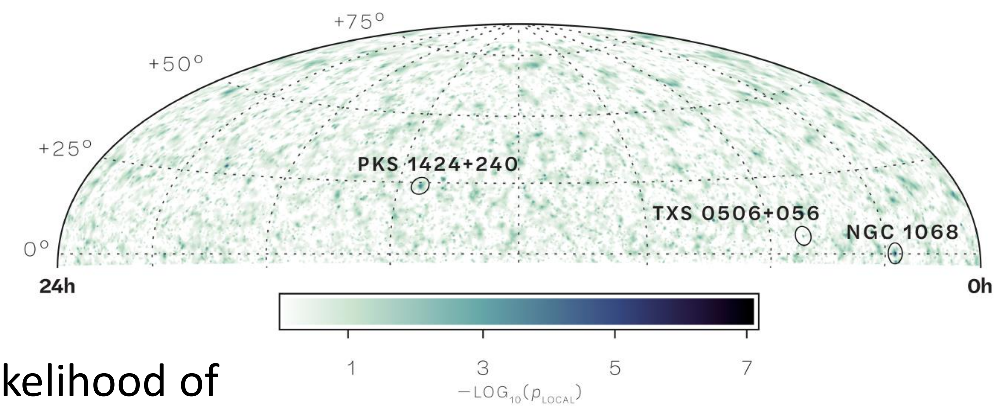


Orange band represents experimental constraint based on the Diffuse ν_μ flux.

Basic method of point source analysis

Goal of the point source analysis

→ Find significant hot spots in the sky



Statistical tool

For observed N events, we construct likelihood of signal parameters: n_s (# of signal), γ (power law index) with a hit spot position $\vec{x}_s$

$$\mathcal{L}(n_s, \gamma : \vec{x}_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S(\vec{x}_i, E_i, \gamma : \vec{x}_s) + \left(1 - \frac{n_s}{N}\right) B(\vec{x}_i, E_i) \right]$$

$\vec{x}_i$: direction in the sky
E_i: energy

- Signal PDF of energy and angle

$$S(\vec{x}_i, E_i, \gamma : \vec{x}_s) = \mathcal{N}(\vec{x}_i : \vec{x}_s) \times \mathcal{E}(E_i, \gamma)$$

$$\mathcal{N}(\vec{x}_i) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}}$$

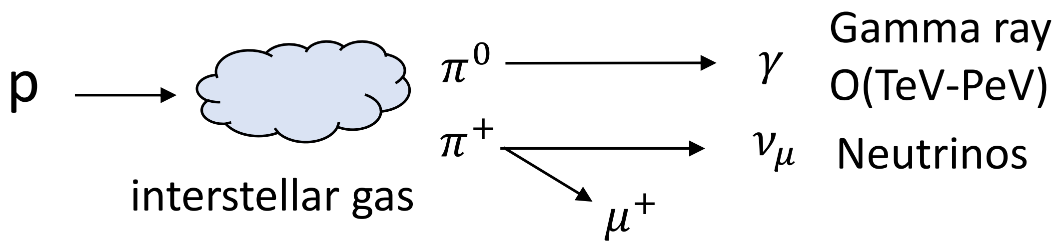
$\mathcal{E}(E_i : \gamma)$ energy PDF evaluated by MC

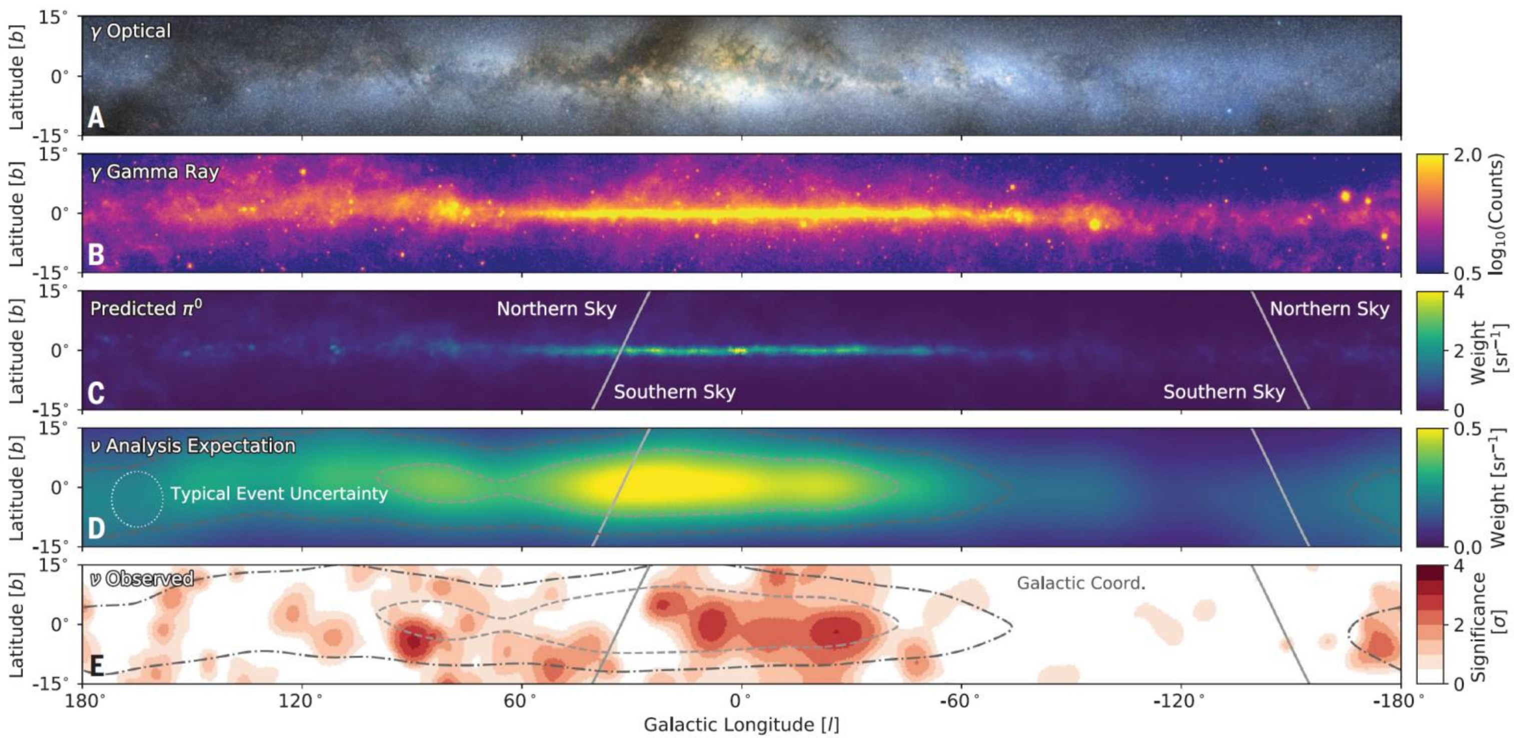
- $B(\vec{x}_i, E_i)$: BG PDF of energy and angle

Test statistic (significance) is calculated by $TS(\vec{x}_s) = 2\log\left(\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma} : \vec{x}_s)}{\mathcal{L}(n_s = 0 : \vec{x}_s)}\right)$

$\hat{n}_s, \hat{\gamma}$ are the best parameters at each $\vec{x}_s$

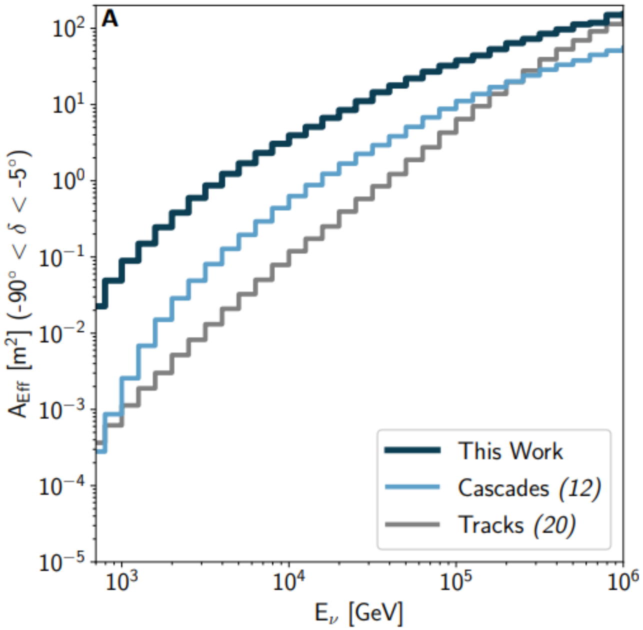
Neutrinos from the galactic plane



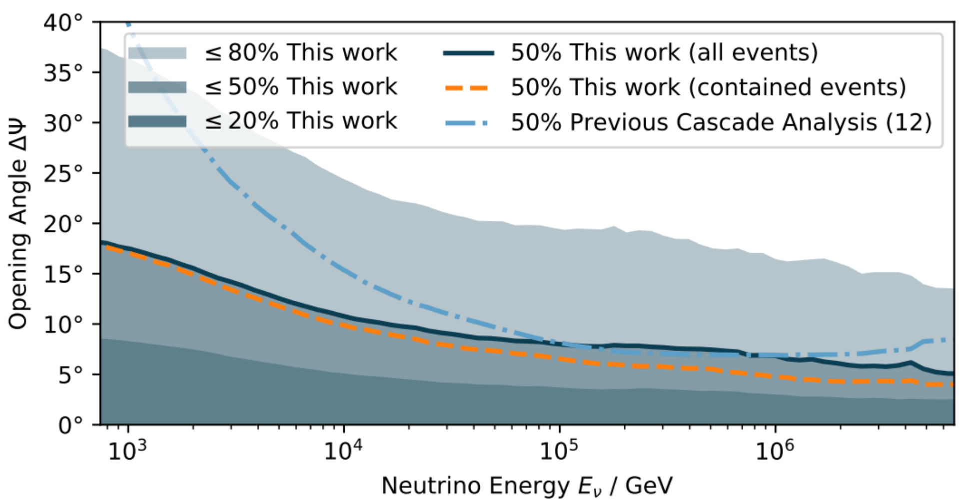


Science **380**, 1338–1343 (2023)

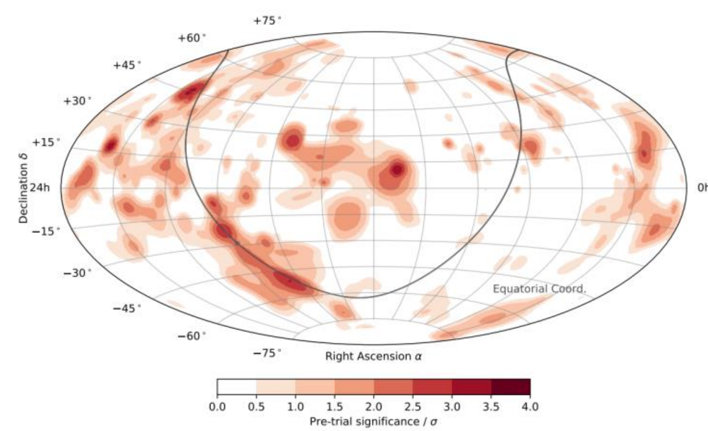
Neutrinos from the galactic plane



- 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 $\sim 10°$ fit to spatial distribution of galactic plane



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



Updated point source analysis (a.k.a. NGC 1068 paper)

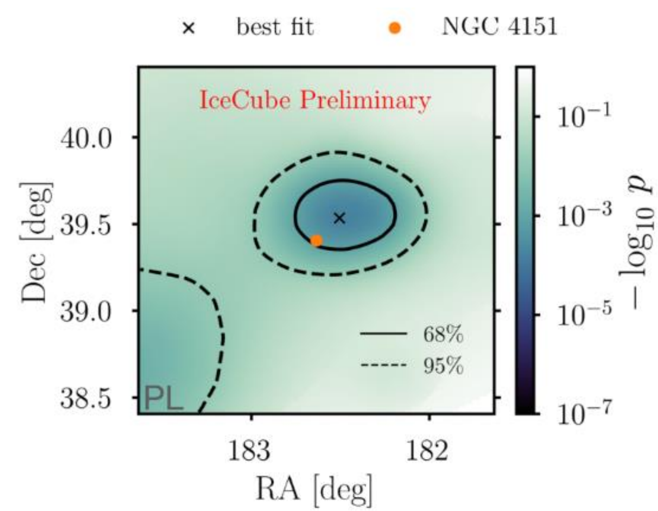
- Northern sky scan w/ improved method of the angular uncertainty estimate
- Two types of analysis performed
  ① Unbiased scan under hypotheses of γ: float, γ=2.0, and γ=2.5

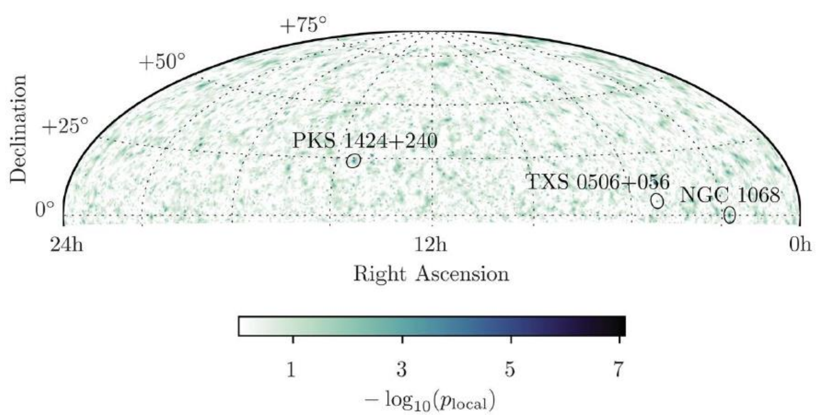
  The 4th hottest spot is coincident to NGC4151.

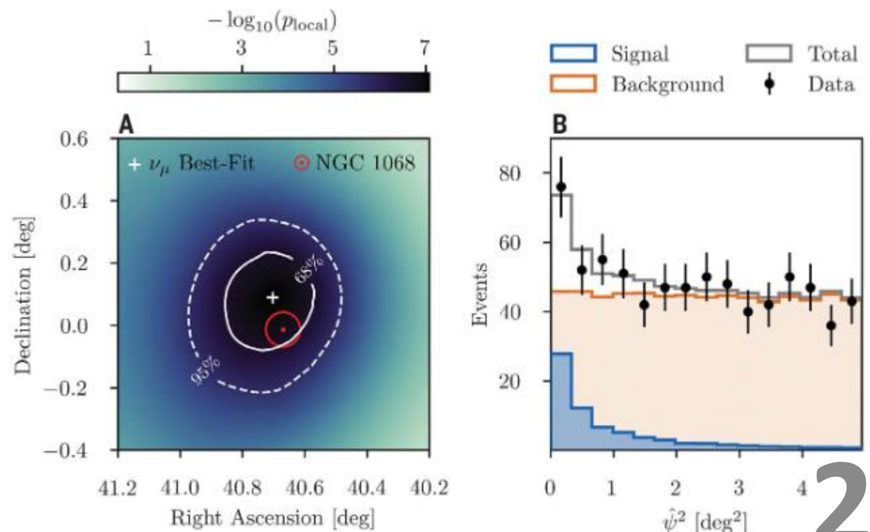
  ② Time-integrated analysis for 110 directions of preselected galaxies.

  The hottest candidate shows the significance of 4.2σ.

Science **378**, 538–543 (2022)

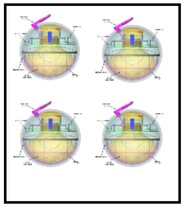






Neutrino alert program

South pole



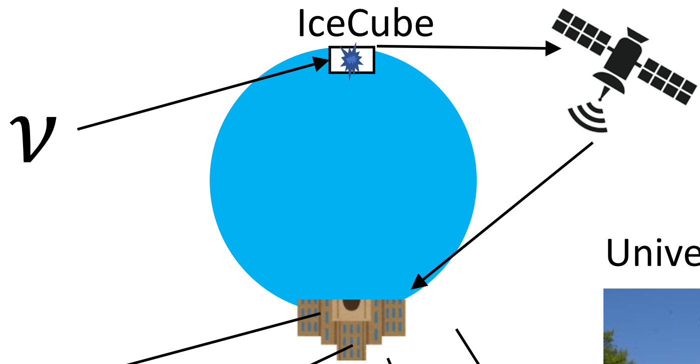
trigger → **Online event filter** → **Alert filters**

University of Madison

Additional filters at north → **"Gold" alert** / **"Bronze" alert** → **distributes to world**

Neutrino event, detected by IceCube, is processed on site, and sent the information of direction, time, significance etc
to other telescopes.

The latency is within a minute



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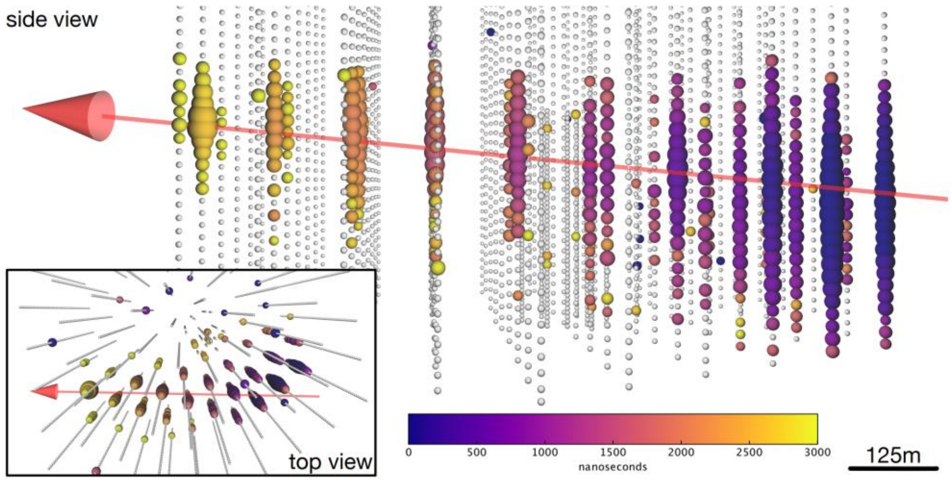
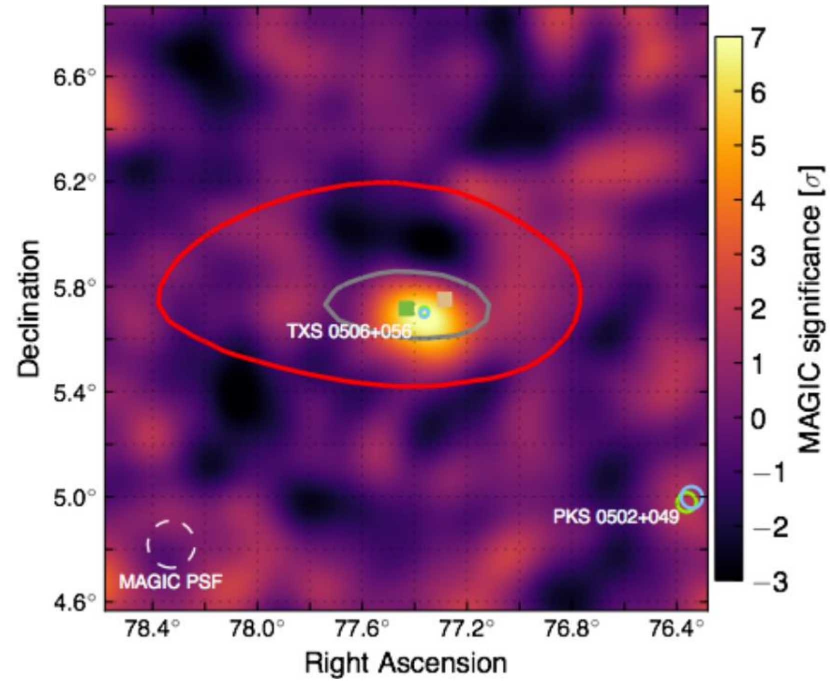
EHE-170922A

Science 361, eaat1378 (2018)





EHE-170922A

An alert issued when an "extremely high energy" event is observed.
Chiba University lead this development.

Event observed at 23nd Sept 2017 5:54:30 JST
→ Issued an alert 43 seconds later

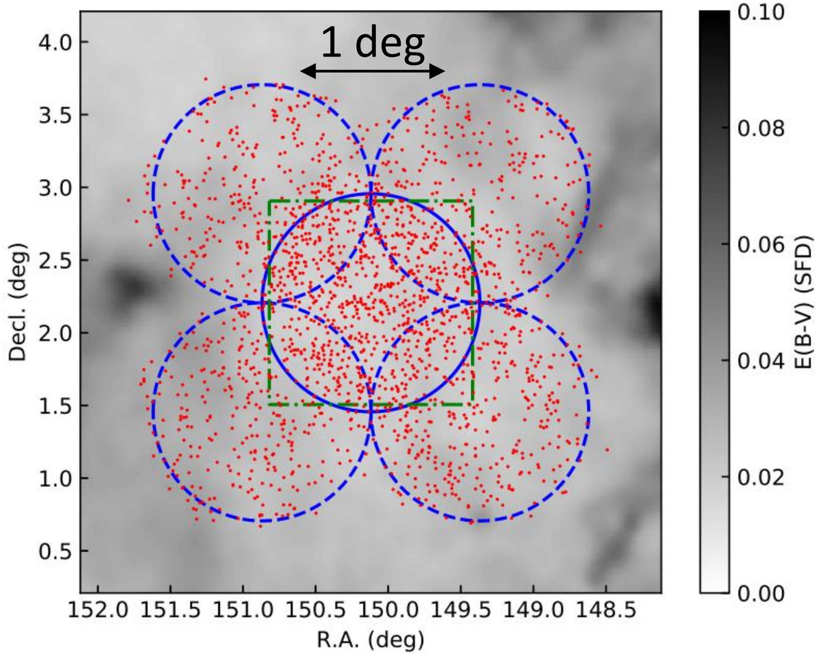
Kanata Telescope followed up it and found a "***blazer***" TXS 0506+056 showed an increase of luminosity. Fermi/MAGIC confirmed an increase of γ ray activity as well.

New optical alert using multiplets

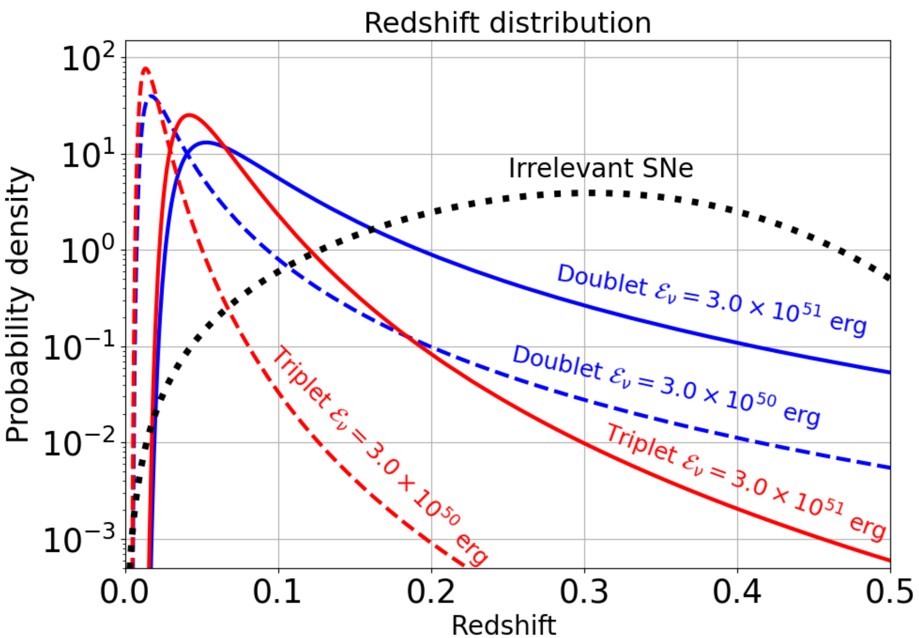
ν angular uncertainty : $\sigma \sim 1°$ → Too many optical counterparts ~50 SNe/30 days/$1\mathrm{deg}^2$ (z<1)
→ Practically impossible to claim physical association for month scale transients (such as interactive SNe)

Introduce multiplets

$N \geq 2$ **coincident signals** in the limited **timing window** ΔT, and **opening angle** ψ.



FoV of Subaru



By imposing multiplets, the z distribution peaks in small redshift → we can perform statistical test on the measured z

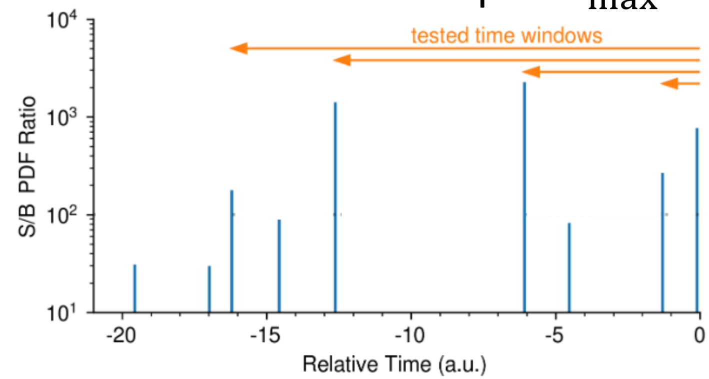
Selection and clustering of multiplets

Conventional algorithm

- Use the conventional point-source LLH
- Define test statistic for variable ΔT

$$TS = \max_{\Delta T} 2\log\left(\frac{\mathcal{L}_{PS}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}_{PS}(n_s = 0)} \cdot \frac{\Delta T}{T_{\max}}\right)$$

Variable ΔT up to $T_{\max}$

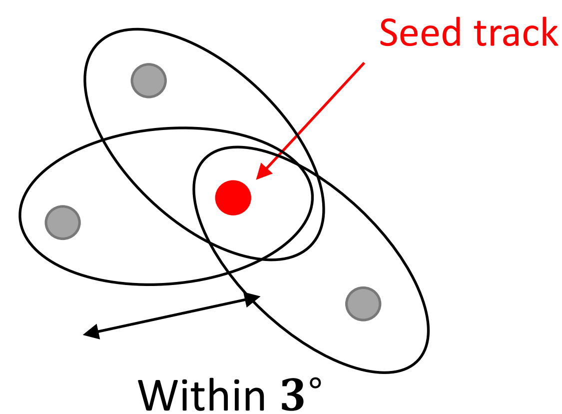


Pick-up algorithm (this new analysis)

- Search tracks within $\mathbf{3}^{\circ}$ and record back to fixed time (ΔT=30 days)
- Calculate a TS for **all the combination of two/three tracks** and select the combination having the maximum TS.

$$\Lambda_{\text{doublet}} = 2\log\left(\frac{\mathcal{L}_{\text{sig}}^{(1)}(\gamma = 2.3)}{\mathcal{L}_{\text{bg}}^{(1)}} \cdot \frac{\mathcal{L}_{\text{sig}}^{(2)}(\gamma = 2.3)}{\mathcal{L}_{\text{bg}}^{(2)}}\right)$$

$$\Lambda_{\text{triplet}} = 2\log\left(\frac{\mathcal{L}_{\text{sig}}^{(1)}(\gamma = 2.3)}{\mathcal{L}_{\text{bg}}^{(1)}} \cdot \frac{\mathcal{L}_{\text{sig}}^{(2)}(\gamma = 2.3)}{\mathcal{L}_{\text{bg}}^{(2)}} \cdot \frac{\mathcal{L}_{\text{sig}}^{(3)}(\gamma = 2.3)}{\mathcal{L}_{\text{bg}}^{(3)}}\right)$$

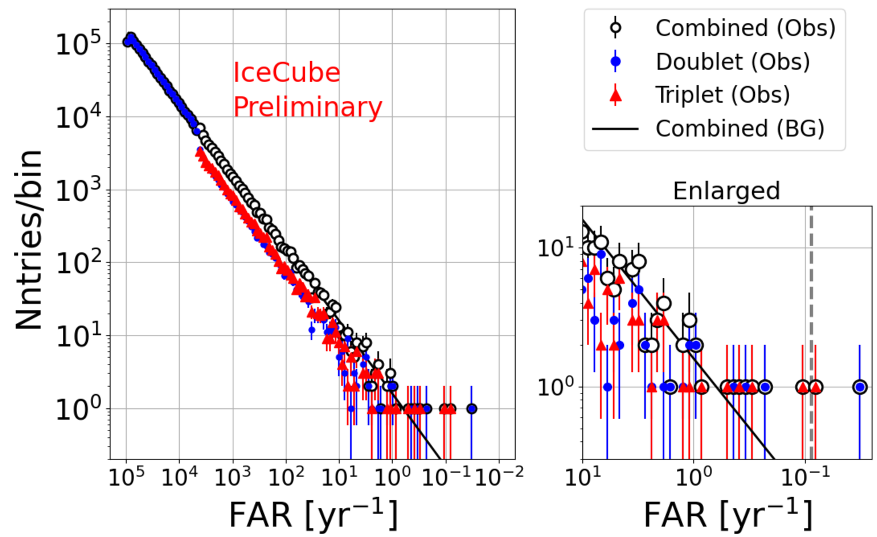


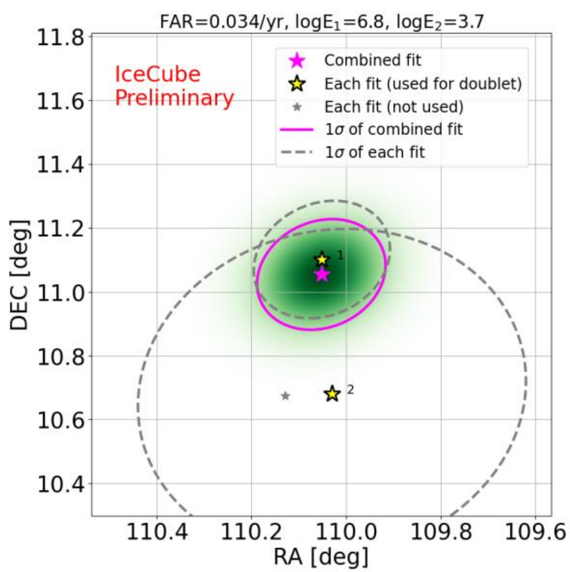
Search for multiplets in 12 years dataset

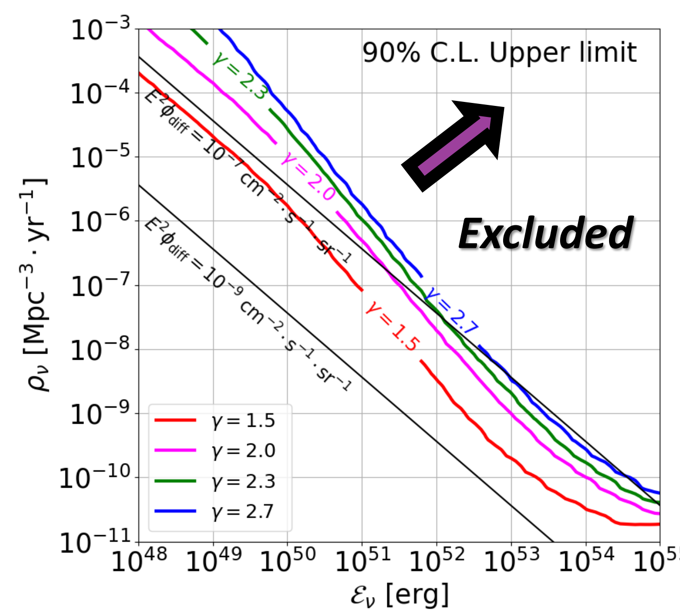
- A search for small multiplicity tracks doublets/triplets
- 12-years northern track
- Long time ($\Delta T = 30$ days) time window

The most significant candidate was a doublet FAR~1/30 [1/yr]

As a whole analysis, the result was consistent with BG-only hypothesis.
→ apply constraint on the ν-source parameters

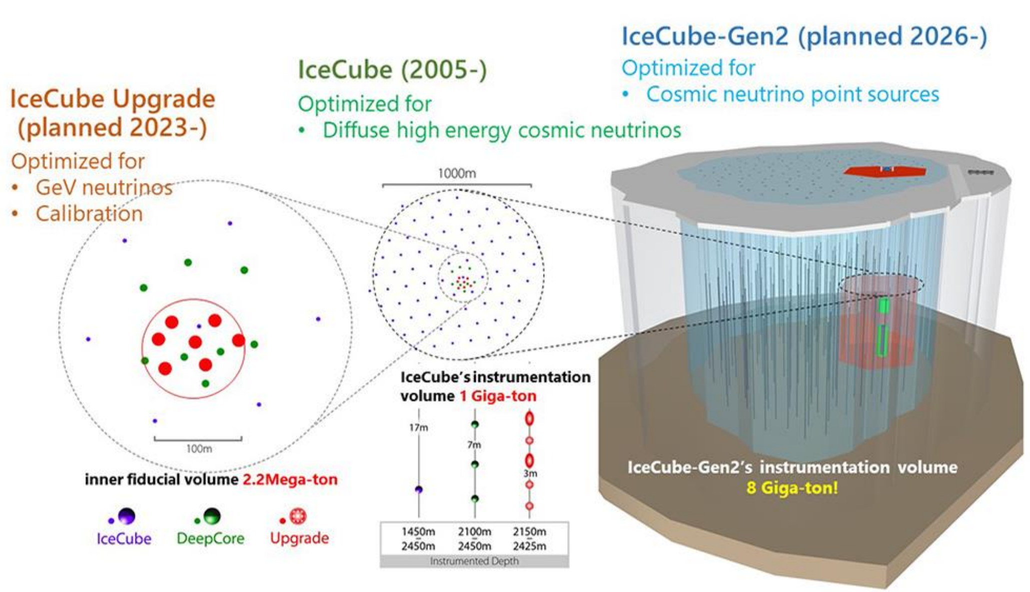


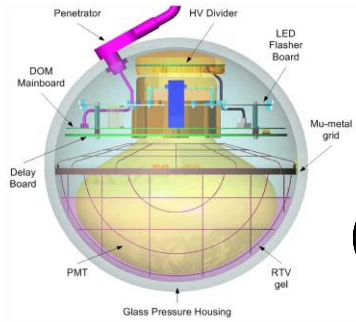




Future upgrades

IceCube-Upgrade, IceCube-Gen2

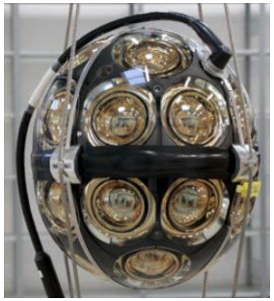




DOM (IceCube-Gen1)

Modules for IceCube-Upgrade

D-Egg



mDOM

IceCube Upgrade

- Deploy ~ 700 **new** optical modules from 2025
- Optimized for low energy physics (1 - 100 GeV)
- Already funded by NSF

IceCube Gen-2

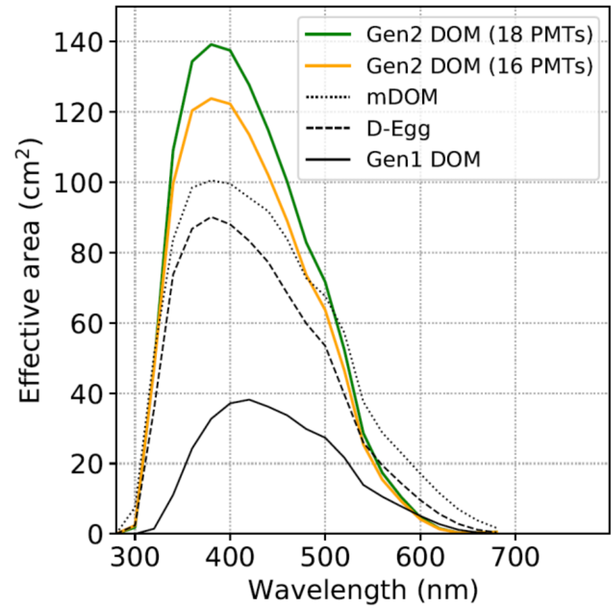
- Deploy O(10,000) further new optical modules
- Optimized for high energy physics (>100 TeV)

New optical modules for Gen2

- ◆Volume of Gen2 → x 8
- ◆Sparse layout: 125 m → 240 m
- ➢ **low cost per optical sensitivity**

Reduce a diameter to save cost of drilling

House as many PMTs as possible

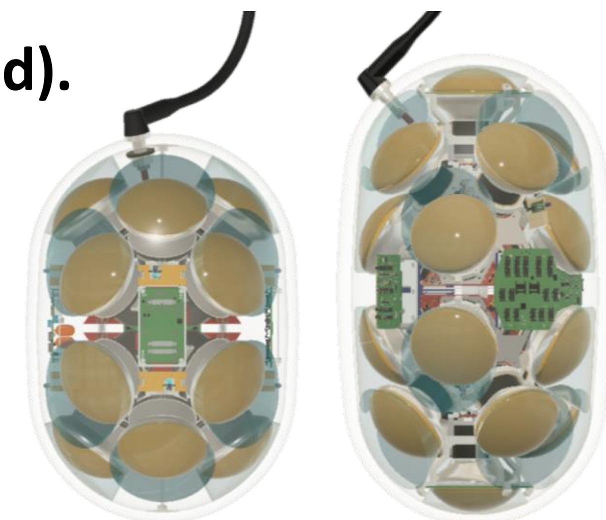


Gen2-DOM

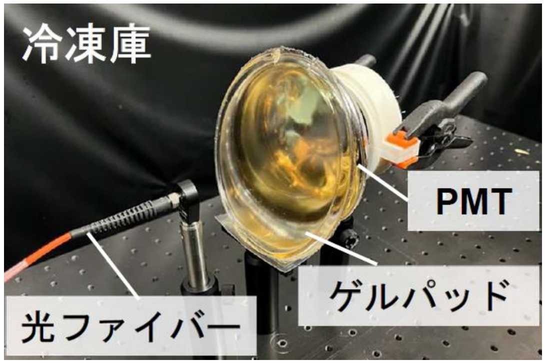
① **Use an elongated glass vessel (egg-shaped).**

② **House many four inch PMTs (16 and 18 options are investigated)**

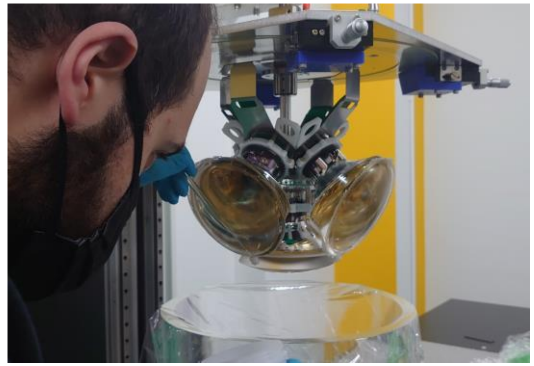
③ **Shows 4-5 times higher photon detection efficiency than Gen1 DOM**



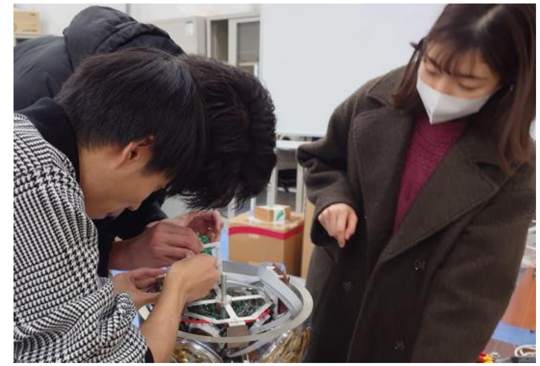
The first functional Gen2-DOM



PMT-by-PMT inspection



PMT installation

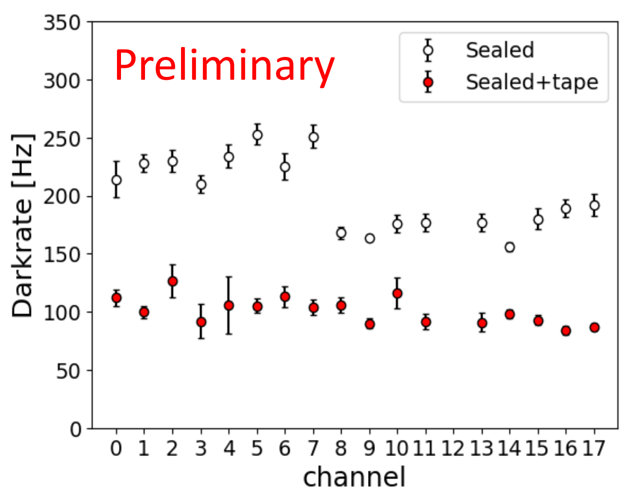


Board installation

The first Gen2-DOM (18 PMT opt.) was constructed in 2023.

Endurance tests will be performed.

- Cold test
- Vibration test
- Photo detection capability test
- Dark rate measurement
  (significantly small dark noise
  per sensitivity)



Very densely packed !

Summary

- IceCube: neutrino telescope installed in the ice of Antarctica
  - High energy neutrino can travel long distance without significant scattering
  - Multi-messenger astronomy is a key to unveil the mystery of high energy phenomena of the universe.
- Diffuse neutrino (background neutrino)
  - Flux are now precisely measured : $\phi \sim 10^{-18}$ [$\mathrm{GeV}^{-1} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$] at 100 TeV
  - Traditional measurement: upgoing ν_μ track. Consistent with single power law
  - Recent effort: cascade + track fit. This may imply something beyond the single power law
- Analysis of neutrino source
  - Observation from galactic plane (4.5σ) using southern cascade dataset
  - w/ updated uncertainty treatment,
    unbiased analysis → 4th hottest spot coincided with NGC4151
    10 years stack for the predetermined source list → significance of 4.2σ from NGC1068
- Multiplet signal can open new window to the search for neutrino sources
- IceCube upgrade projects are ongoing
  - Chiba/Japan group successfully developed a new Gen2-DOM candidate.
    Students played important roles in this construction.