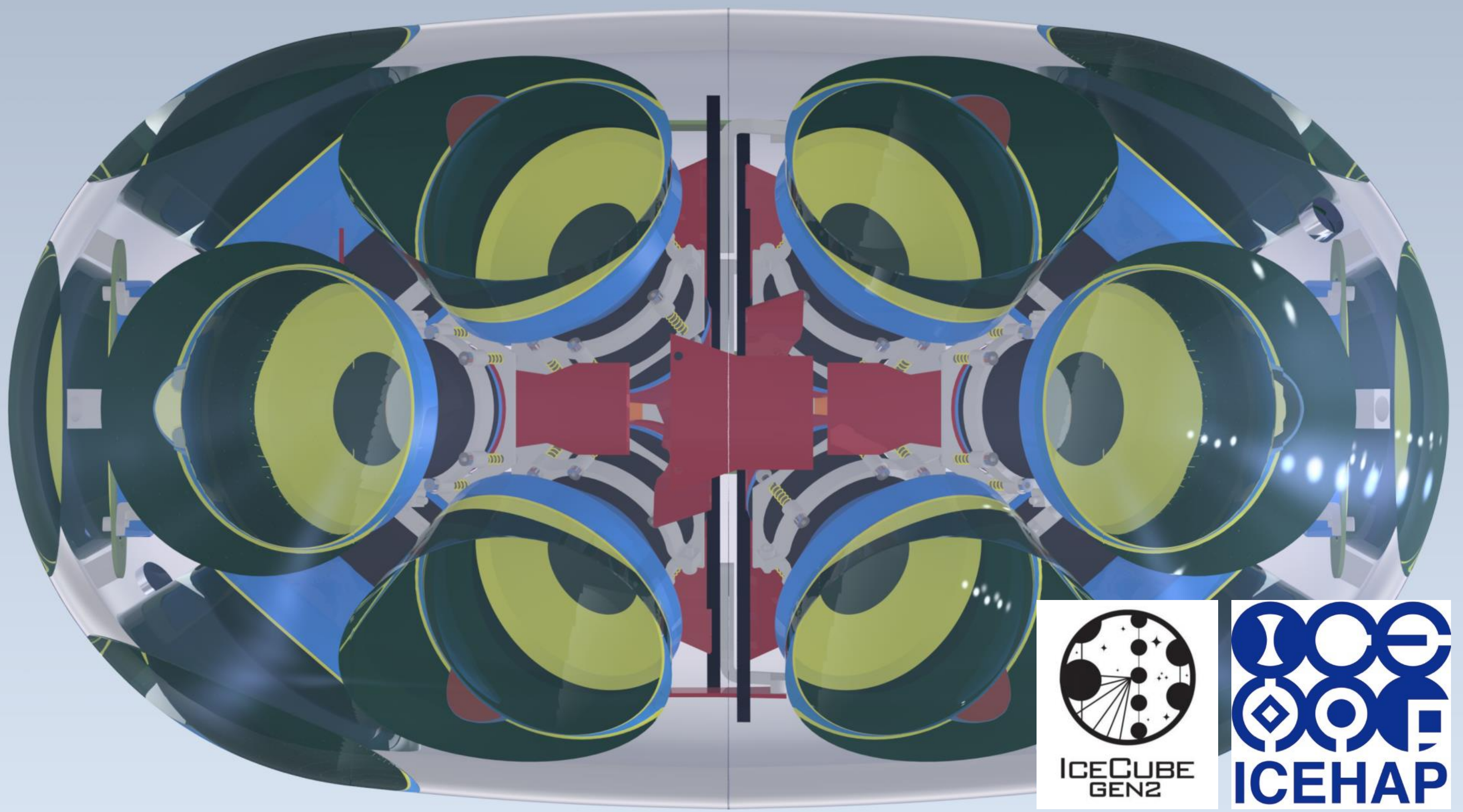
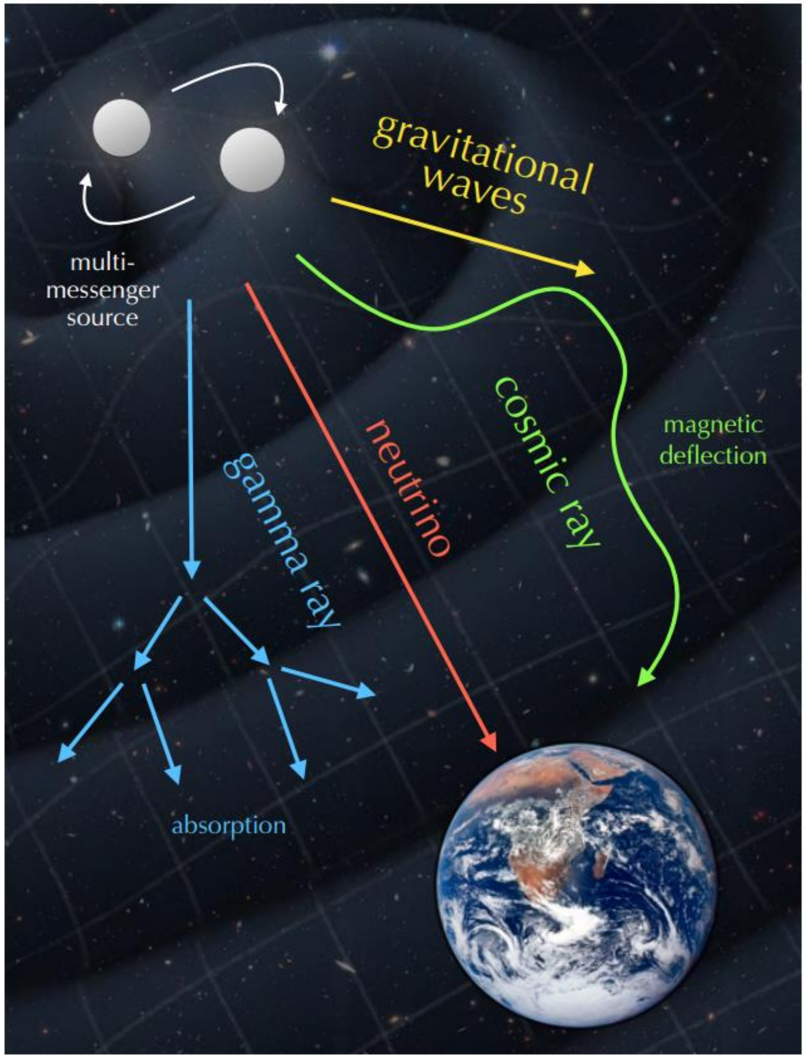


IceCube experiment

Nobuhiro Shimizu (Chiba University)

宇宙線シャワー研究会＠名古屋大学　2022 March 23rd

Neutrino astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

coincident with
photons and gravitational waves

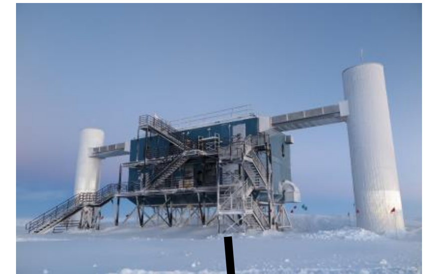
no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

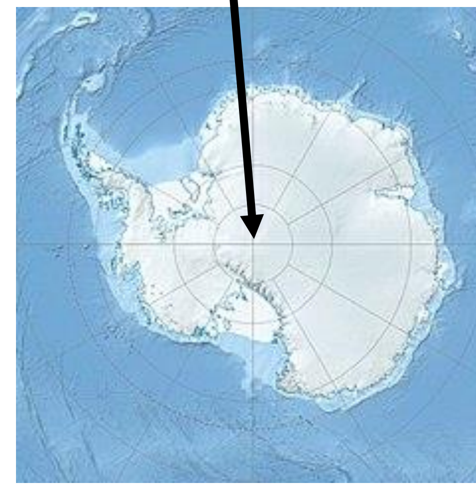
BUT, very difficult to detect!

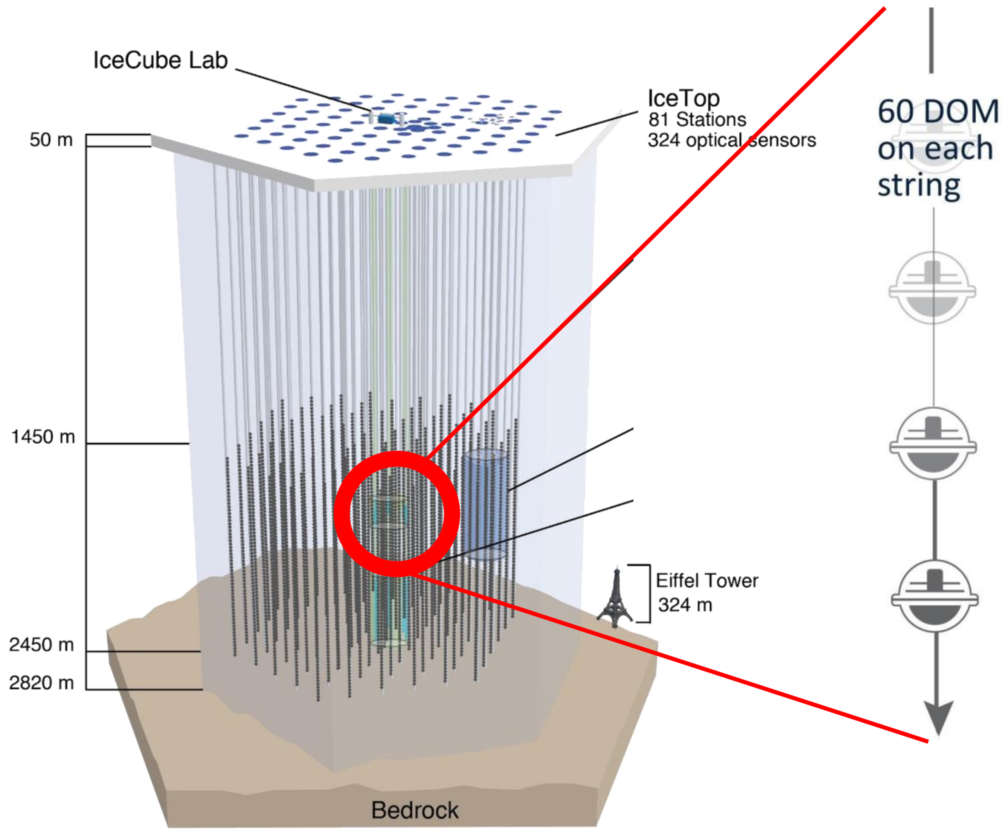
Slide from Markus Ahlers

IceCube experiment

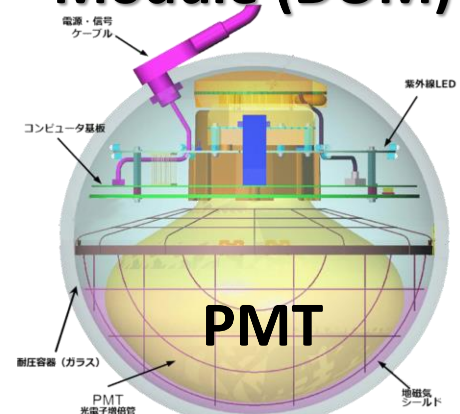


Neutrino telescope operated in Antarctica



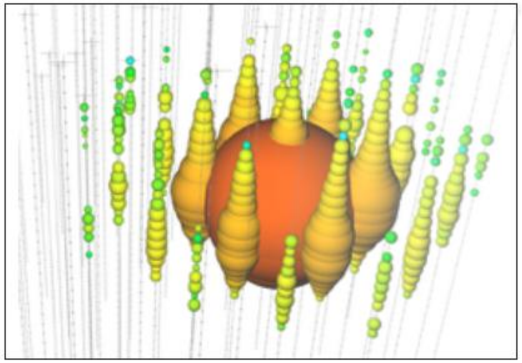


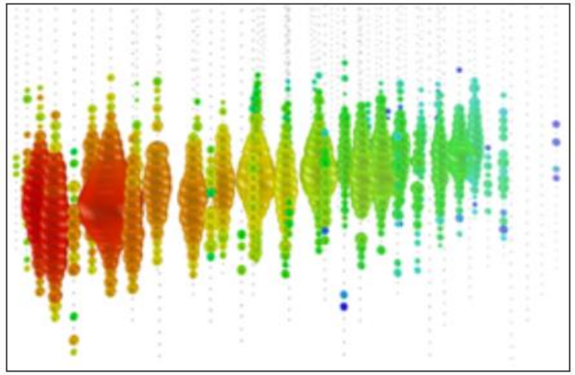
Digital Optical Module (DOM)

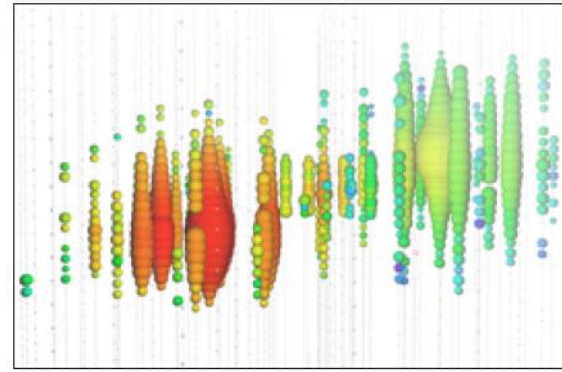


- 5160 optical modules are deployed in ice 1 ㎦
- Cherenkov light from charged particles produced by neutrino interaction is detected by DOM

Event topology of neutrino signal





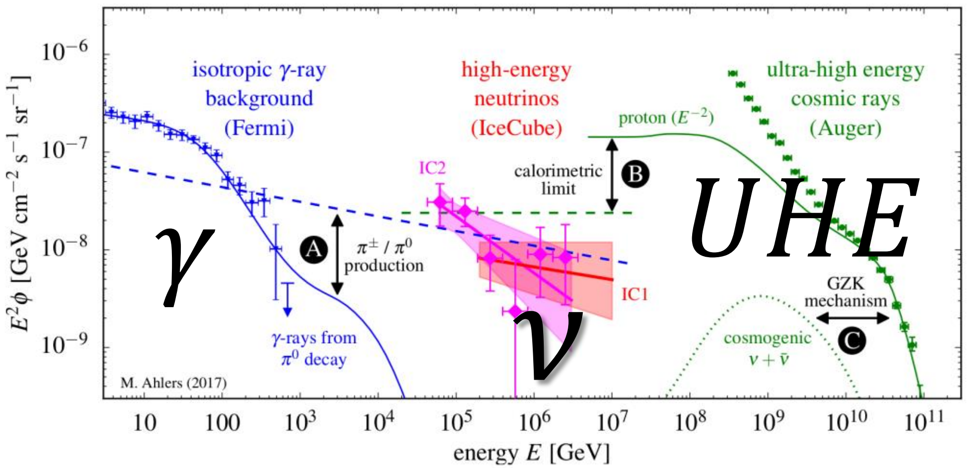


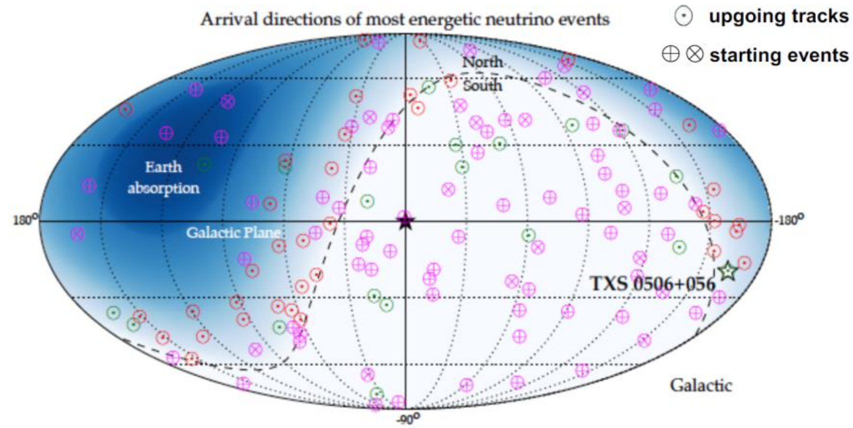
cascade	*"Track-like"*	*"Double-bang"*
$\nu_e + N \rightarrow e + X$ $\nu + N \rightarrow \nu + X$	$\nu_\mu + N \rightarrow e + X$	$\nu_\tau + N \rightarrow \tau + X$ decay
$\sigma_\psi \sim 15°$	$\sigma_\psi \sim 0.5°$	
$\sigma_E/E \sim 15\%$	$\sigma_E/E \sim 25\%$	Flight length ~ 50 m/PeV

High tracking resolution is important for the follow-up.

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

Diffuse neutrino flux

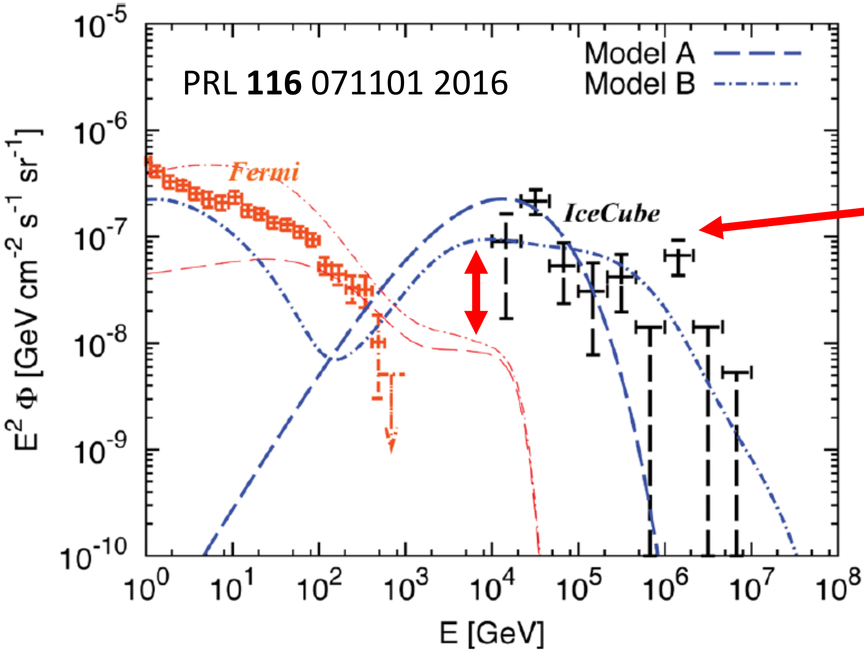


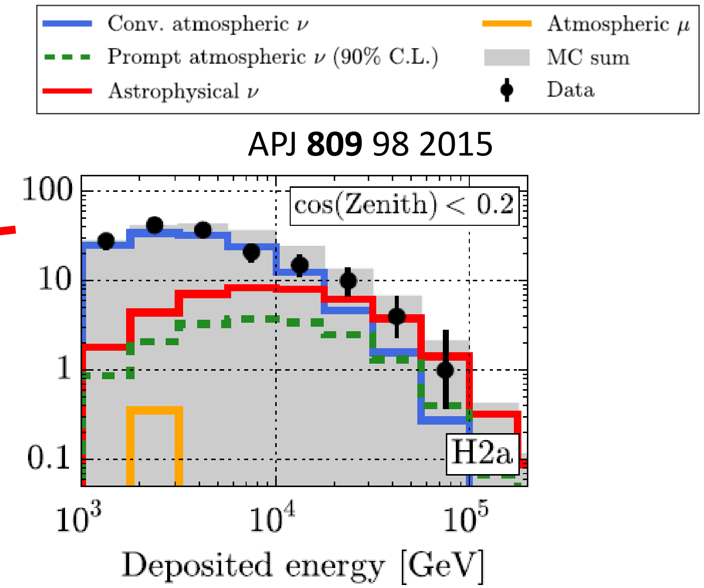


- Consistent with isotropic distribution
- $E_\nu^2 \phi^2 \in [10^{-9}, 10^{-7}]$ GeV $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$
  - A: a source of CR is common between γ and ν
  - B: a source of CR is common between UHE and ν

Where is the origin of high energy ν?

Tension in low energy ν flux

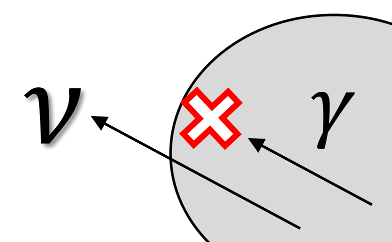




Parameter	Best Fit	68% C.L.	90% C.L.
ϕ_{conv}	1.10	0.94–1.31	0.87–1.49
ϕ_{prompt}	0.00	0.00–1.04	0.00–2.11
ϕ	6.7	5.5–7.8	4.6–8.6
γ	2.50	2.41–2.59	2.35–2.65

- Combined analysis of low energy (10 TeV -100 TeV) neutrino ⇨ $\phi \propto E^{-2.5}$, $E^2\phi = 2 \times \mathbf{10^{-7}}$ GeV $\mathrm{cm^{-2}s^{-1}sr^{-1}}$
- If ν source is transparent to γ ray, there is a 2-3σ tension from the theoretical estimate based on Fermi γ ray survey

→ **implication of some accelerators opaque to γ**



Galactic origin of neutrinos?

APJL **868** L20 (2018).

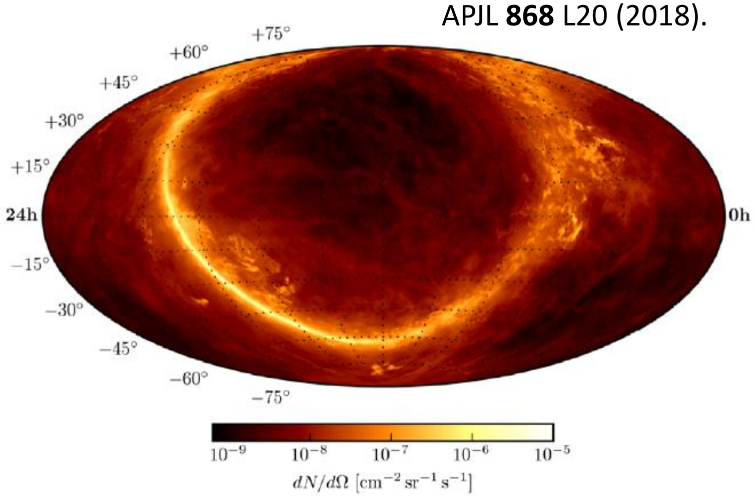
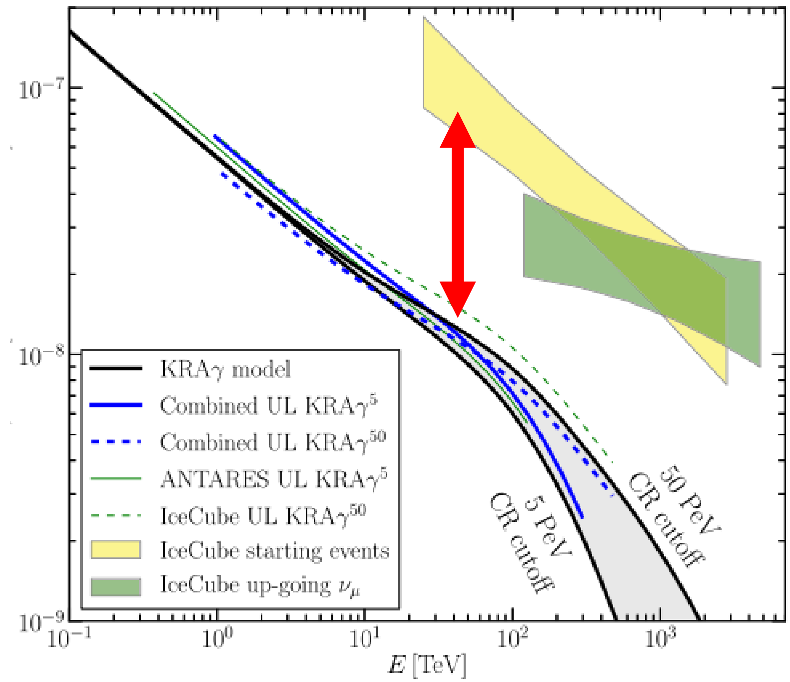


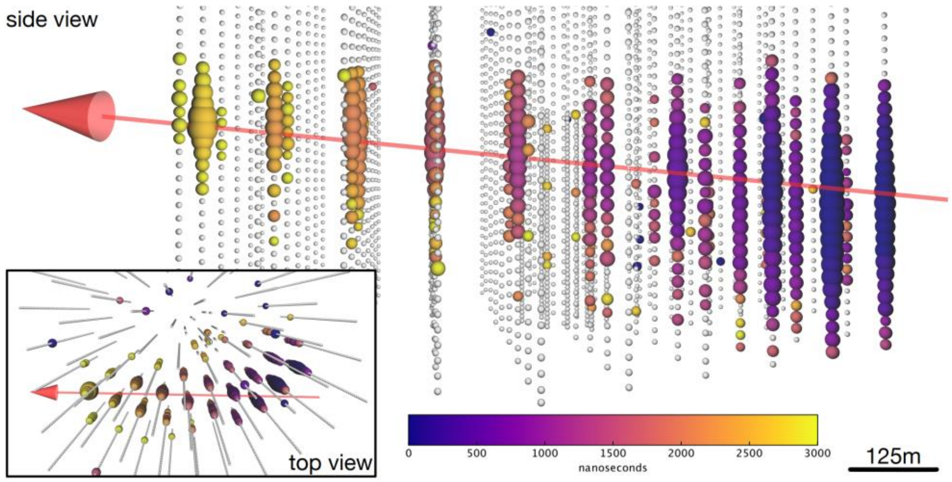
Figure 1. Neutrino flux per unit of solid angle of the KRA_γ^5 model (Gaggero et al. 2015a), shown as a function of direction in equatorial coordinates (Hammer projection).



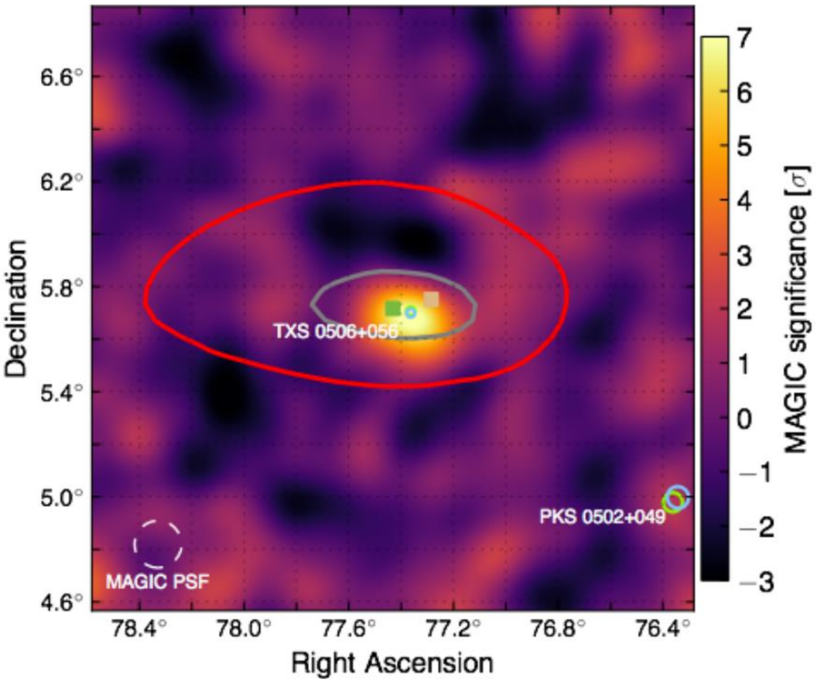
ϕ_ν predicted based on galactic CRs by KRA model

The contribution of the galactic diffuse ν does not explain the observation of the IceCube.

Extraglactic origin?



Science 361, eaat1378 (2018)



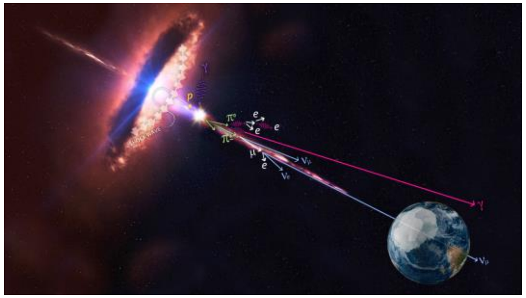
EHE-170922A

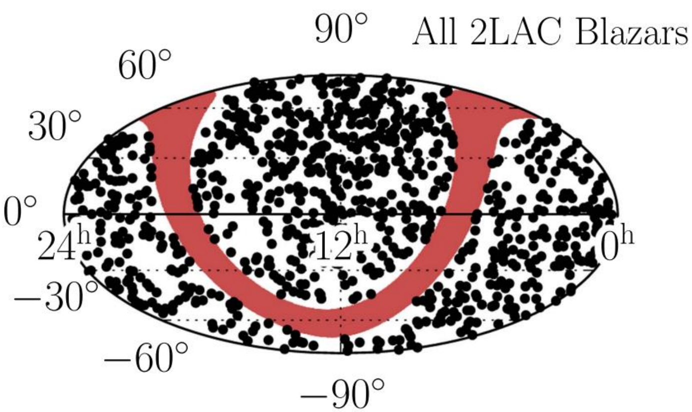
An alert issued when an "extremely high energy" event is observed.
Chiba University lead this development.

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.

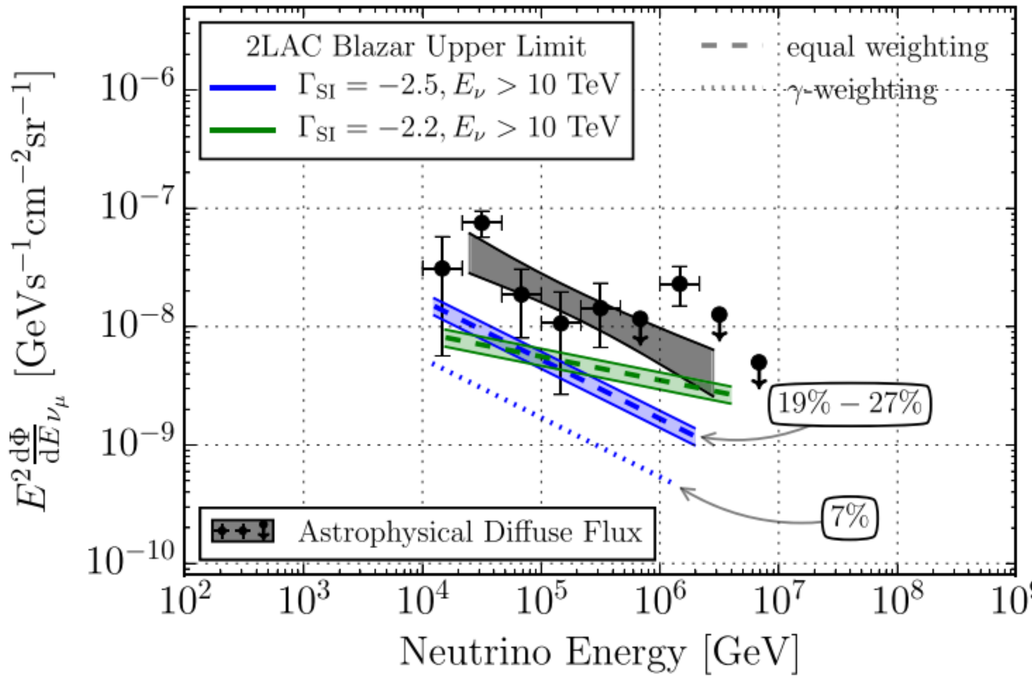
Scenario of blazar





Fermi-LAT AGN catalog

ApJ **835** 45 (2017)

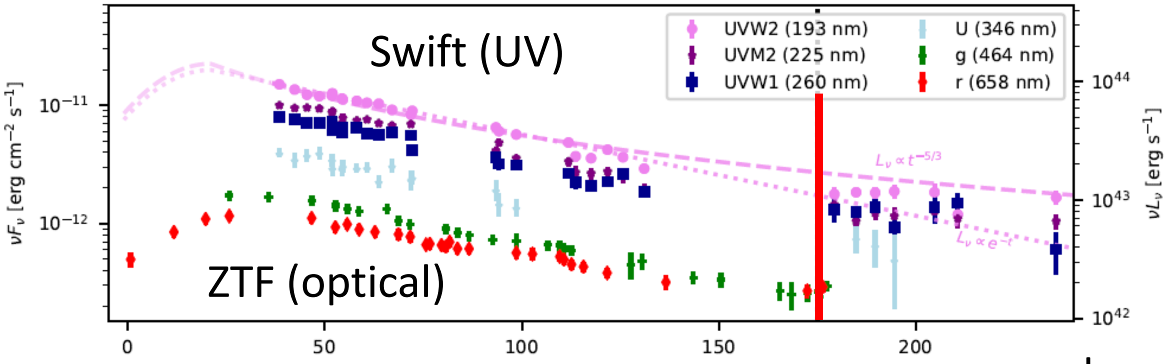


- Analysis of the significance of neutrino flux to every location of Fermi catalog → Blazar contribution was up to 27%.

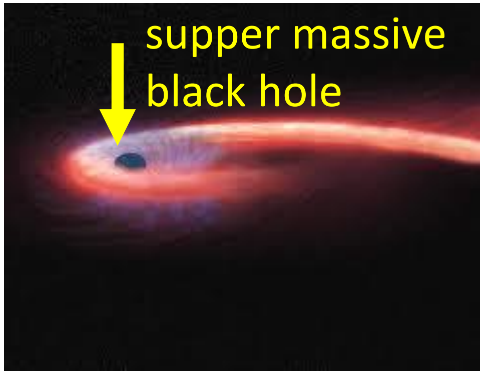
Blazer is not a majority of the mothers of ν

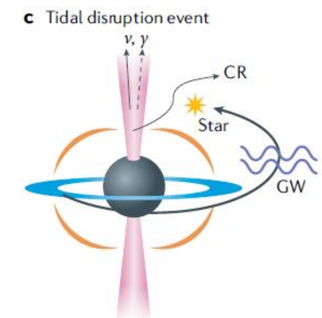
Correlation with TDE

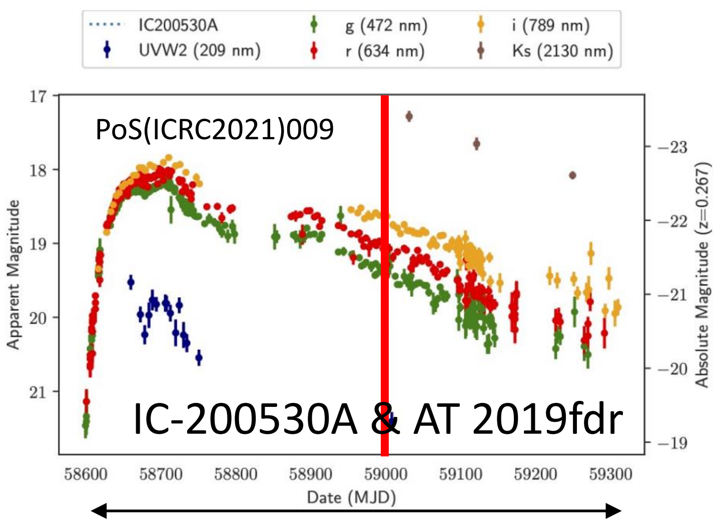
Stein, R., Velzen, S.v., Kowalski, M. *et al.* *Nature Astronomy* **5,** 510 (2021)



IC-191001A & AT 2019dsg







IC-200530A & AT 2019fdr

O (year)

- ◆Suggested correlations between neutrino signal and radio-emitting tidal disruption event (TDE).
- ◆Chance coincidence 0.5%
- ◆ The duration of flare is long (>months)

→ *Stay tuned for this new candidate.*

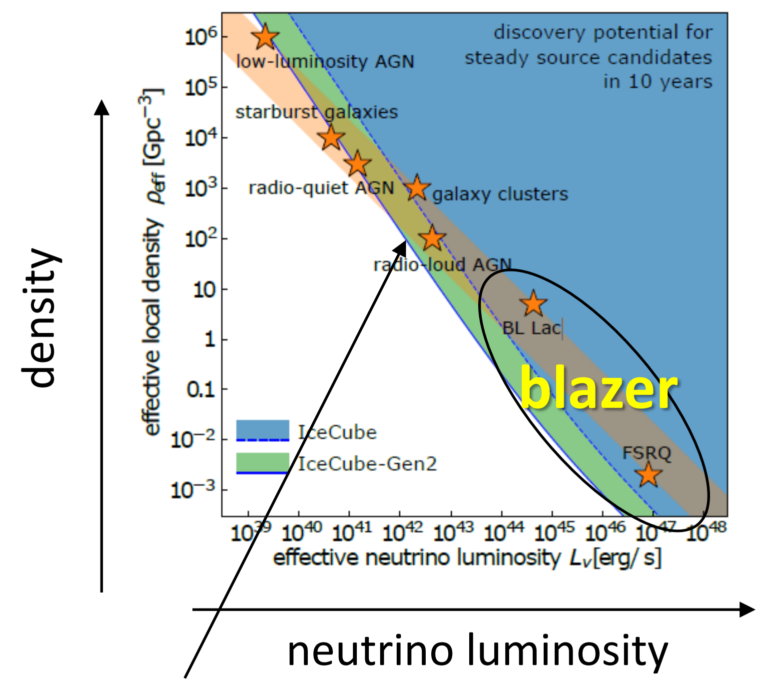
Parameter space of the neutrino source objects

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

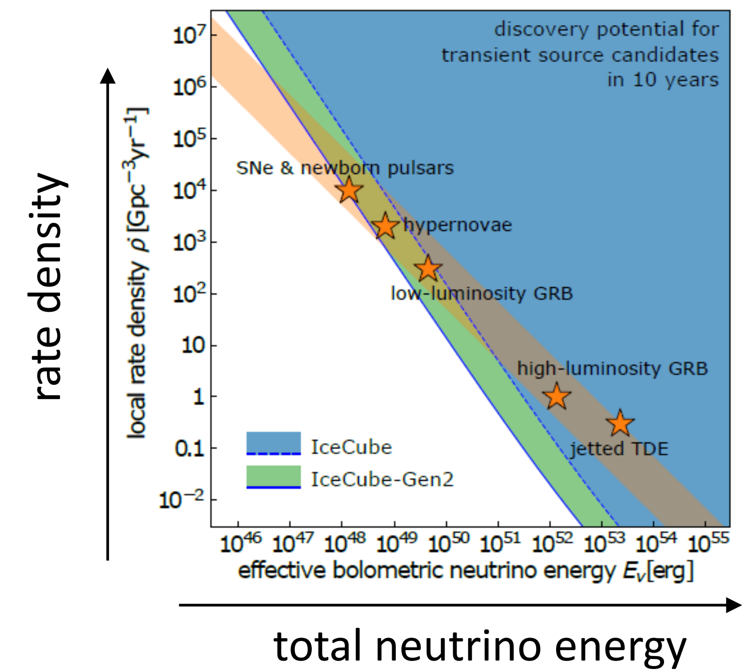
n_0: density

L_ν: luminosity

Steady source



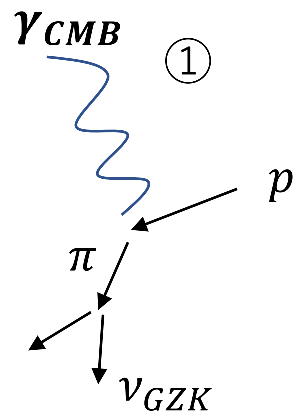
Transient source



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

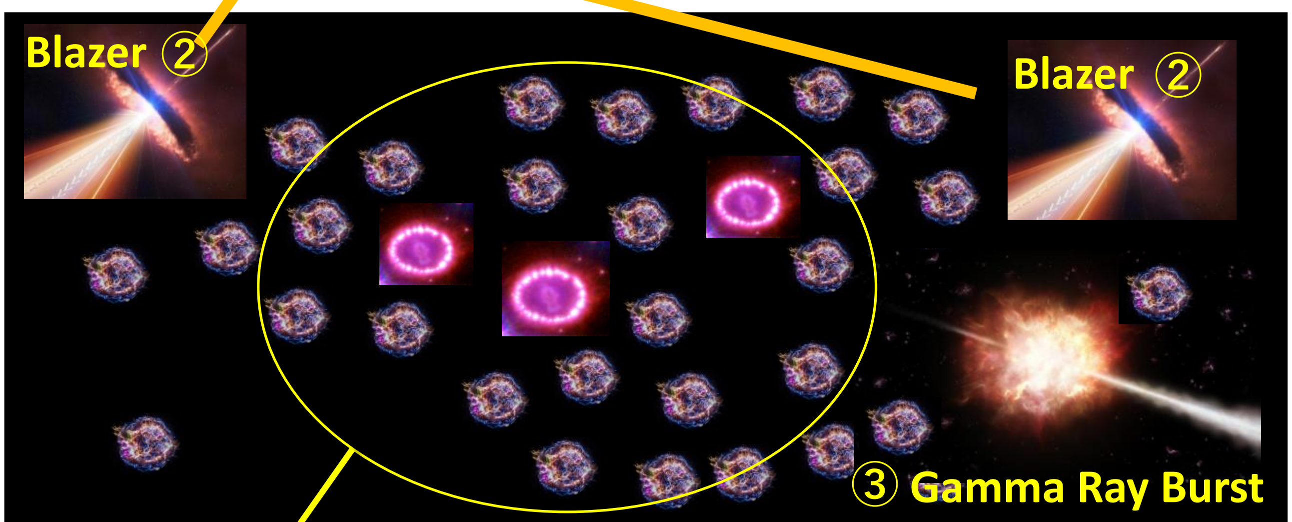
Where is the origin of neutrinos?

① GZK neutrino is not the observed in **EHE** events PRL **117**, 241101 (2016)



② Blazers do not explain all the neutrino flux
(based on study of the correlation with Fermi Catalog) ApJ **835** 45 (2017)

*Experimentally easy to find but **NOT** majority*

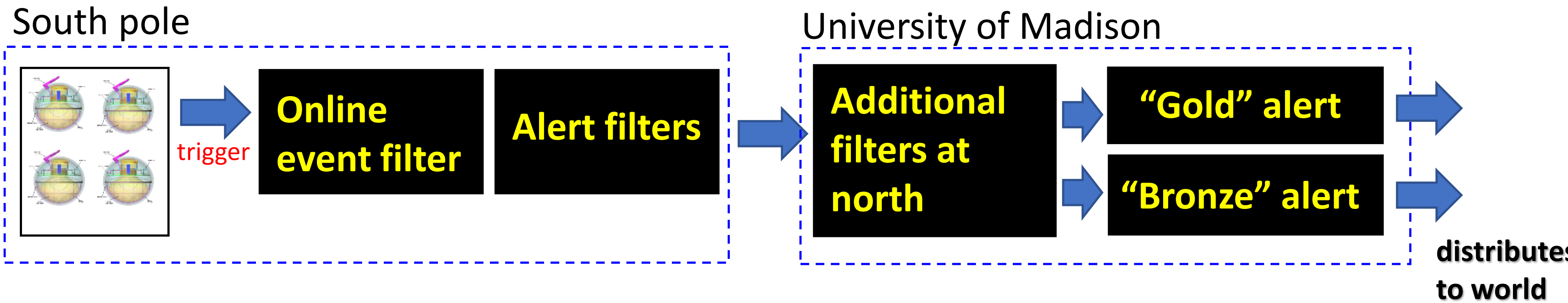


③ No significant correlation between GRB and IceCube data
ApJ **843** 112 (2017)

Next candidates would be in the class of "low luminosity but majority"

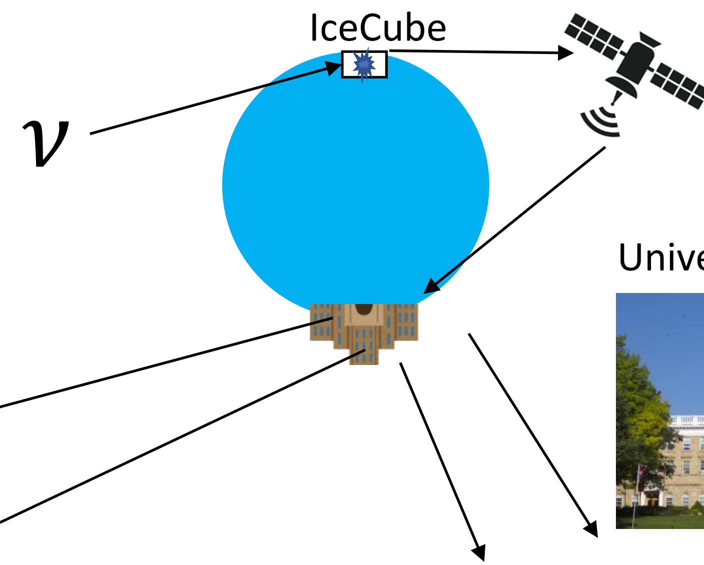
Supernovae, Hypernovae, etc..
Emits optical photons → **Multi messenger astronomy with optical telescopes**.

Neutrino alert program

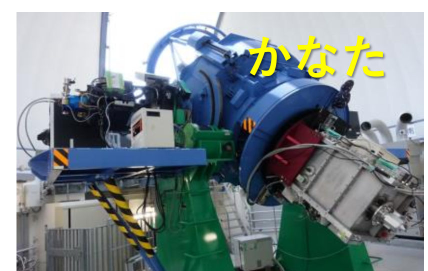


Neutrino event, detected by IceCube, is processed on site, and sent the information of direction, time, significance etc
to other telescopes.

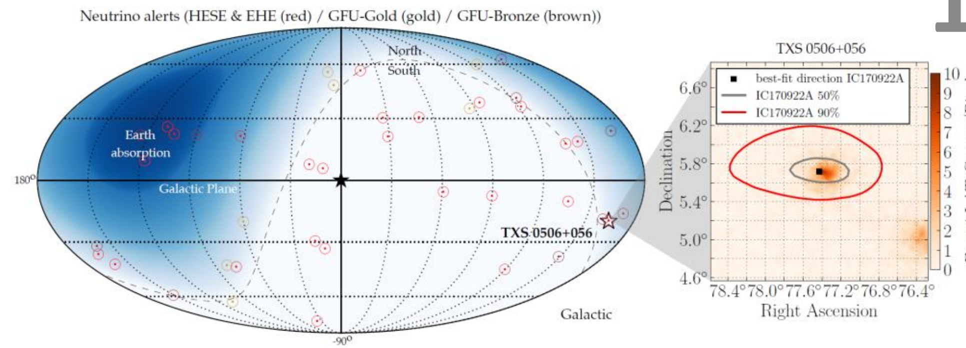
The latency is within a few minutes



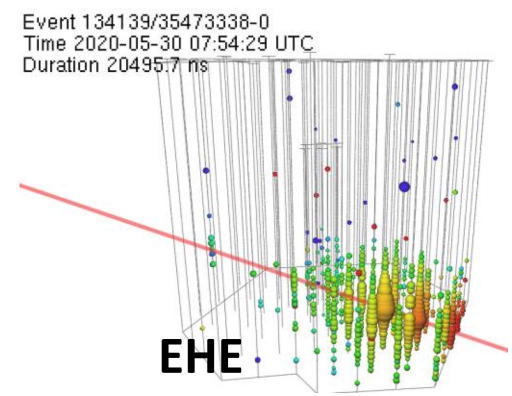
University of Madison

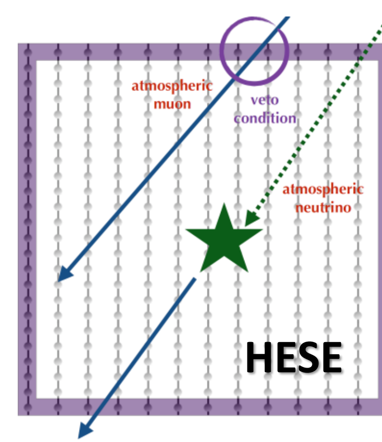


Current alert programs



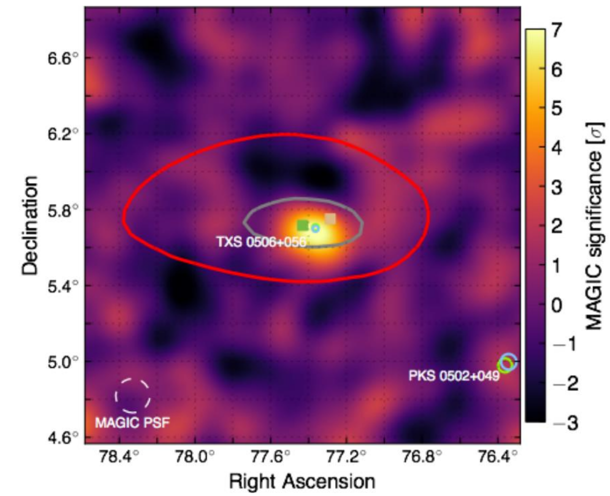
- ◆ EHE (Extremely high energy)
  - ➢ Require large photons: $N_{PE} > 4000$
- ◆ HESE (High energy starting event)
  - ➢ Use outer region of IceCube detector as veto to enhance purity
- ◆ GFU (Gamma-ray follow up)
  - ➢ Limit the FoV to the predefined directions
- ◆ OFU (Optical follow up)
  - ➢ Private alert
  - ➢ Detect coincident hits within $\Delta T < 100\ s$





Opens longer timing window

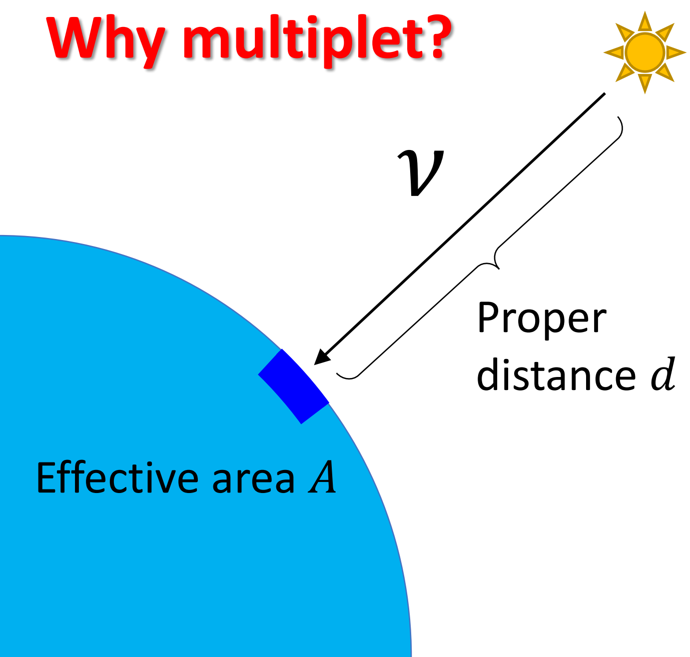
Development of optical alert using “multiplet” signal



Strategy

Issue a public alert to optical telescopes when IceCube observes $\boldsymbol{N \geq 2}$ **coincident signals (multiplet)** in the limited **timing window** ΔT, and **opening angle** ψ.

Why multiplet?



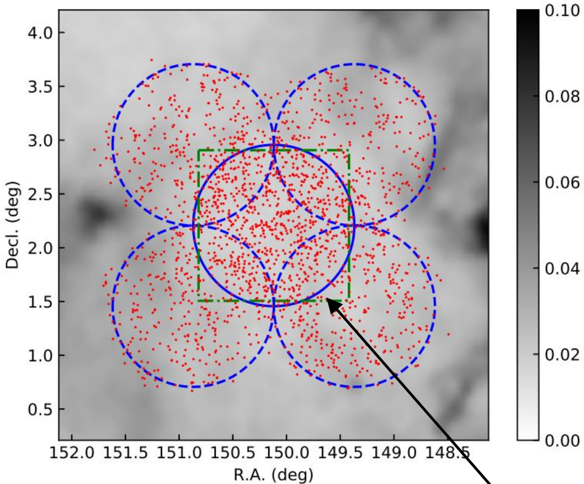
Detection efficiency $\propto \dfrac{A}{4\pi d^2}$

Prob. detected as **Singlet** $\propto d^{-2}$
Prob. detected as **Multiplet** $\propto d^{-2N}$

→ *Multiplet signal picks up neutrinos from nearby objects*

Why multiplet?

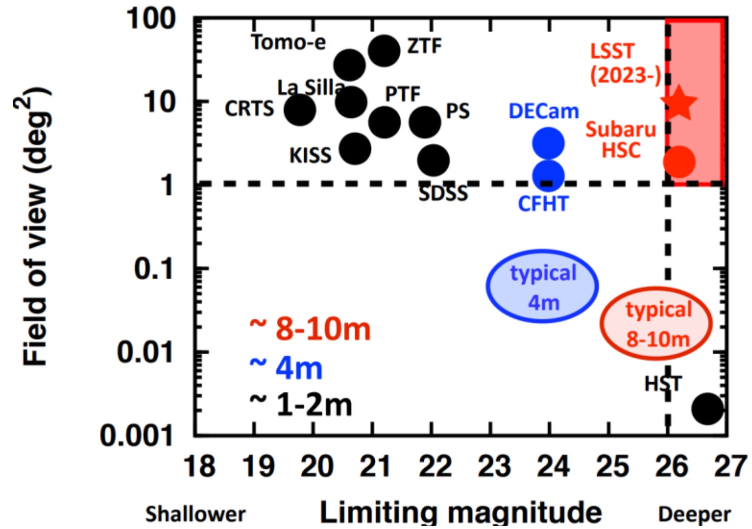
N. Yasuda, *et al*. ApJS, **71**, 74 (2019).



Red: transient objects (mostly SNe)

Field of view by Subaru (1.8 deg^2)

From M. Tanaka (Tohoku)



Wide field of view & large depth mean large BGs

With magnitude brighter than 26 ($z \sim 1$, d=7 Gpc),

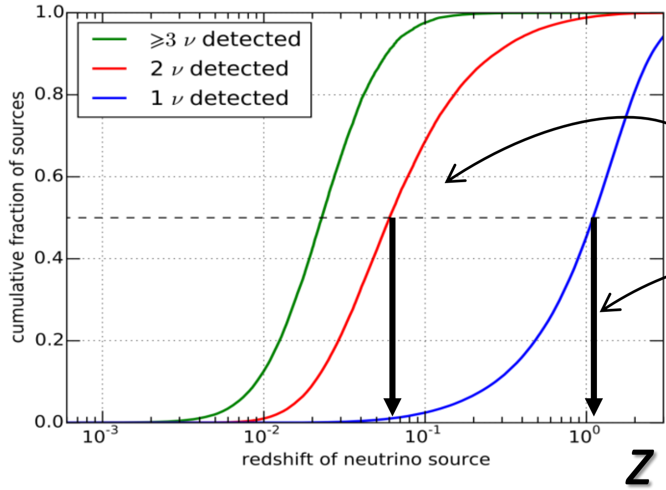
rate/density of SNe = $\dfrac{\mathcal{O}(10)\ SNe}{\mathrm{deg}^2 \cdot 20\ \mathrm{days}}$ → Too many optical counterparts in the distant universe!

Even if we observe a true astrophysical neutrino signal and found a transient source, chance coincidence of other SNe degrades the significance.

To claim a significance large enough, we focus only on close objects $z \ll 1$.

Strategy to identify ν source

M. G. Aartsen *et al*, A&A 607, A115 (2017)



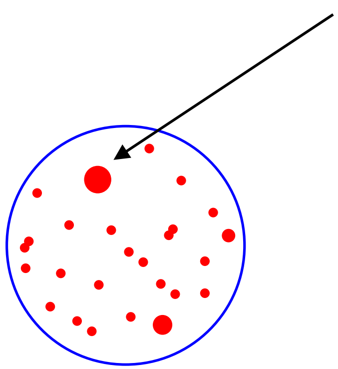
Under the assumption of $n_0 = 10^{-6}\mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$,

Doublet → $\sim$200 Mpc

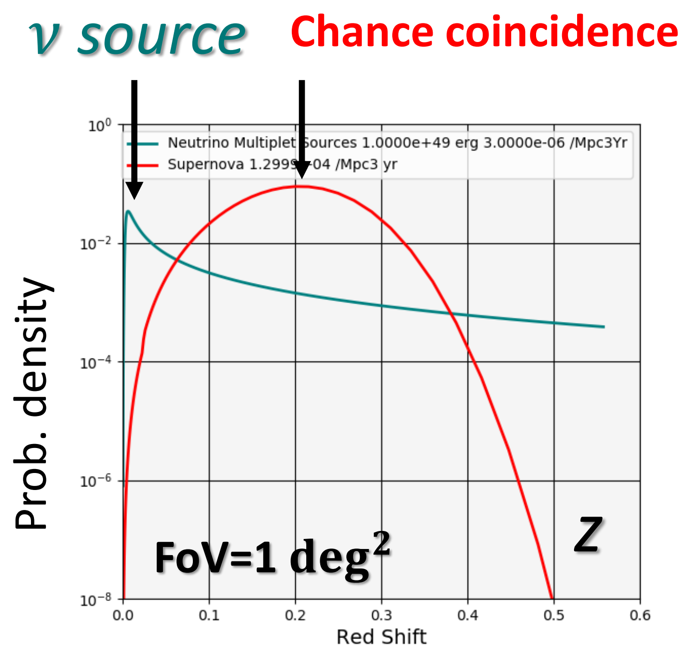
Singlet → $\sim$ 3 Gpc

Strategy

Choose the closest object in the field of view.

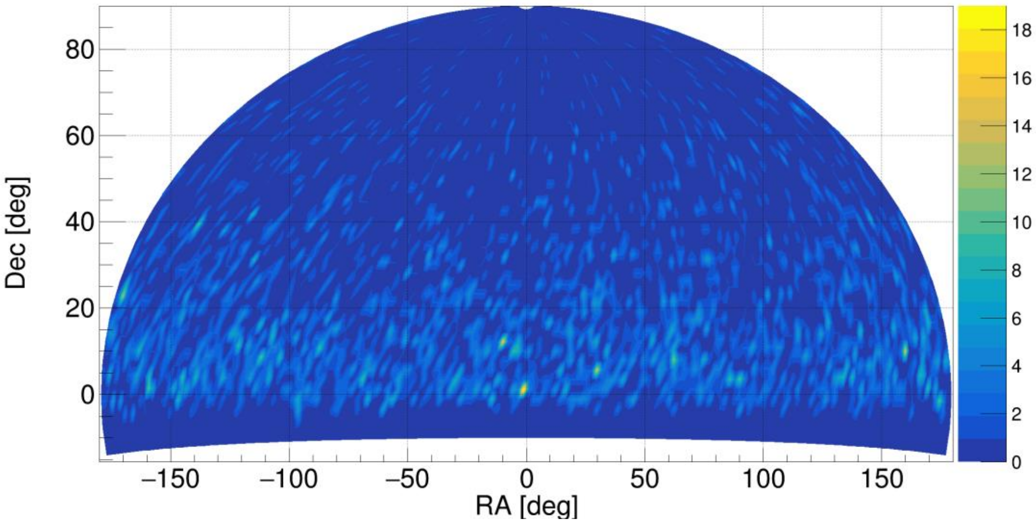


Difference in z distribution is expected between ν *source* and **BG.**



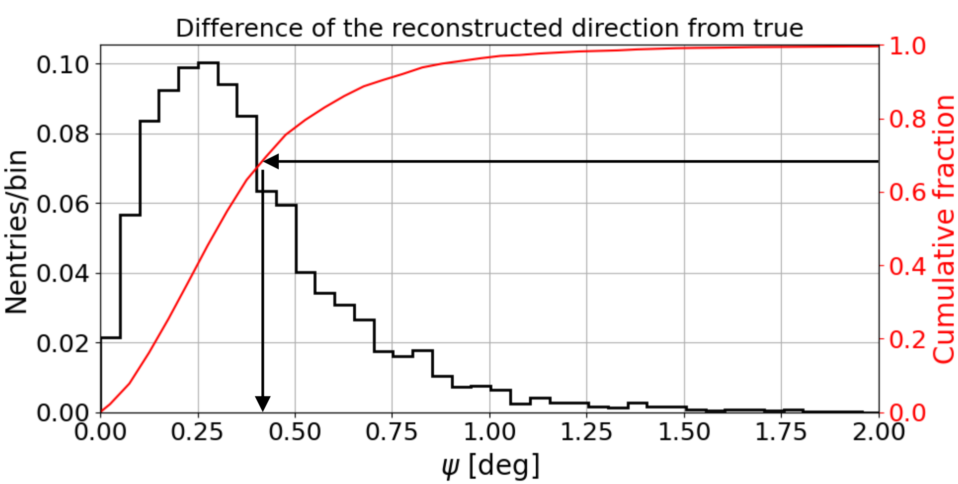
Distribution of the multiplet events

10% of 2016-2021 data



Only 10% of data ("burn" sample) can be compared to simulation.

Condition: $\Delta T < 30$ days & $\psi < 1^{\circ}$



For the two tracks, determine the direction of source as:

$$\vec{n} = \frac{\vec{n}_1/\sigma_1^2 + \vec{n}_2/\sigma_2^2}{1/\sigma_1^2 + 1/\sigma_2^2}$$

σ: energy dependent tracking resolution

→ Tracking resolution of "doublet" is $\sim 0.4^{\circ}$ at 1σ CL.

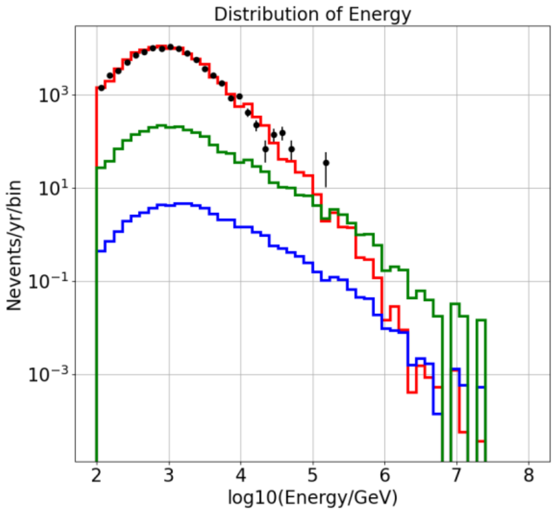
Comparison of the distributions

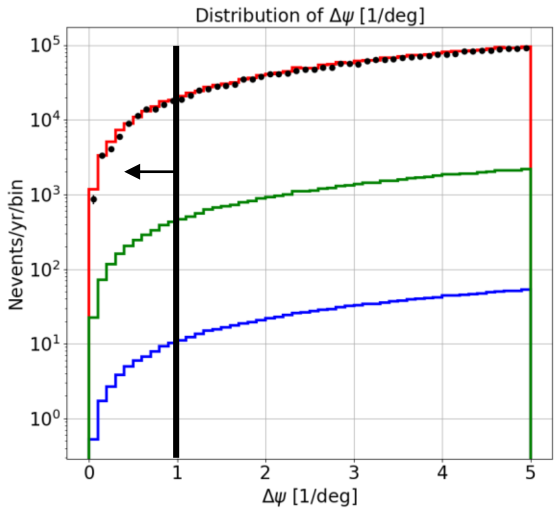
Energy

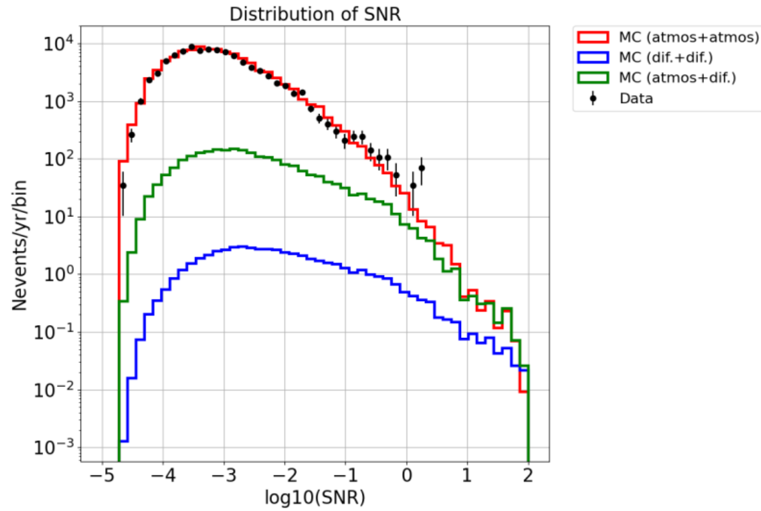
ψ (opening angle)

$$SNR = \frac{\mathcal{L}_{sig}}{\mathcal{L}_{BG}}$$

Atmos. + Atmos.
Atmos. + Diffuse
Diffuse + Diffuse

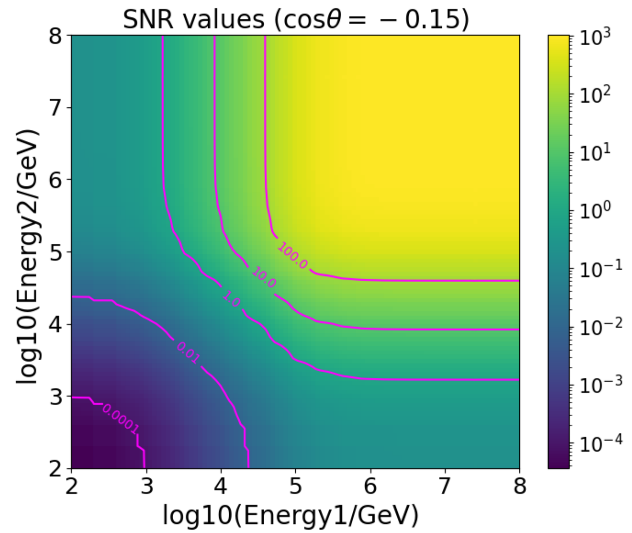




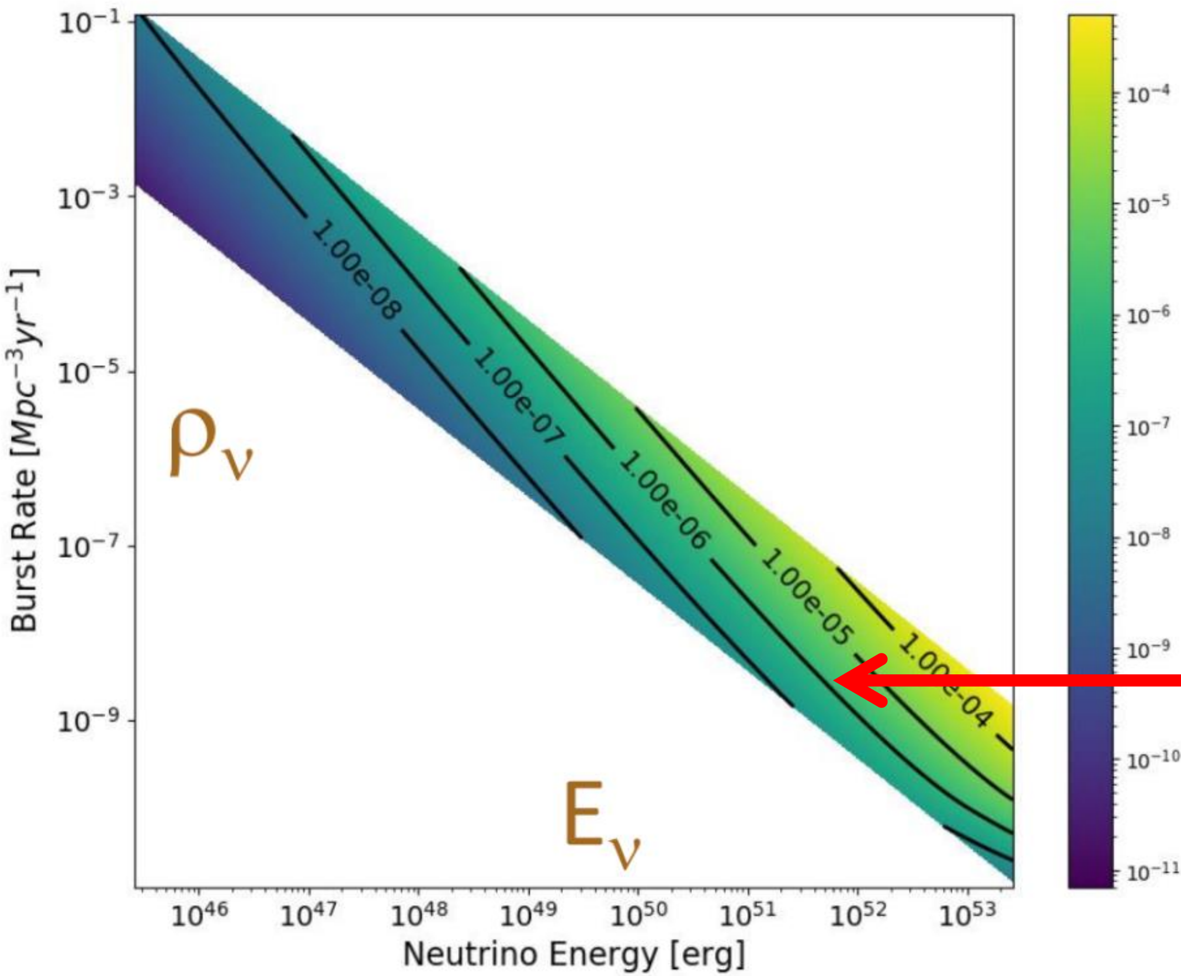


The MC simulation of atmospheric neutrinos well reproduce the experimental distribution.

To keep the false alarm rate < O(1) in a year due to BGs, the SNR needs to be higher than ~10.



Sensitivity for five year's statistics

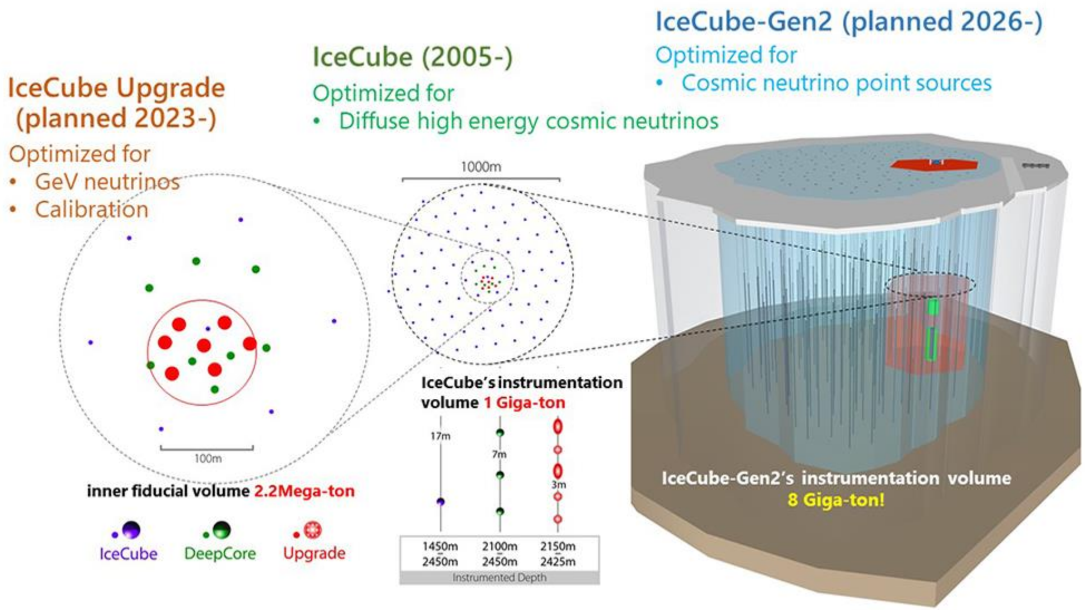


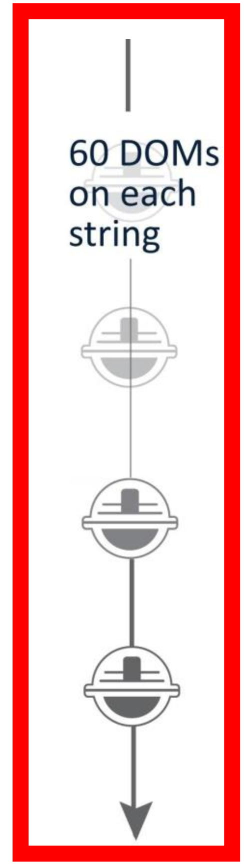
# of multiplets in
$\Delta T = 30$ d and $\Delta\Omega = 1^\circ \times 1^\circ$

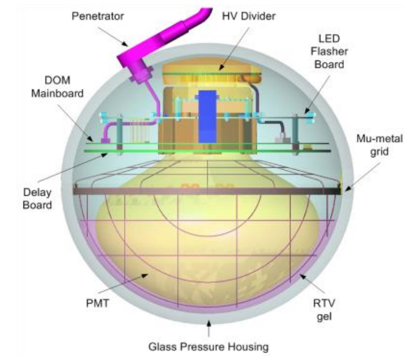
Achievable sensitivity with 5-year data corresponds to $N = 10^{-6}$

For the essential improvement, x 10 is necessary to open the parameter space.

Future upgrades







Digital Optical Module (DOM) for Gen-1

IceCube Upgrade

- Deploy ~ 700 new optical modules from 2023

IceCube Gen-2

- Deploy O(10,000) new optical modules from 2027

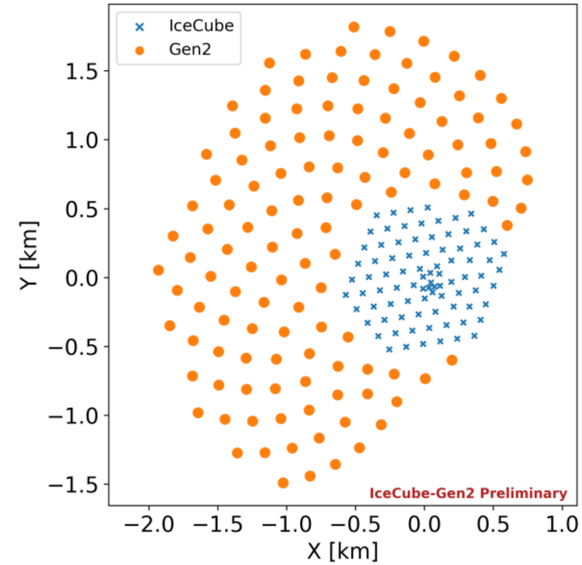
New optical modules for Gen2

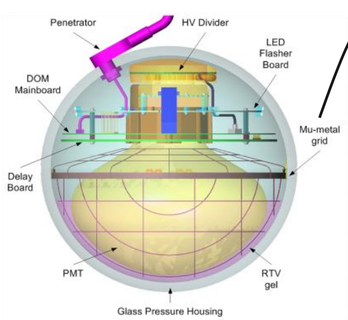
Requirements of new optical modules

- ◆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





33 cm

Gen1 DOM

2023

30 cm

D-Egg

2027

30.5 cm

LOM

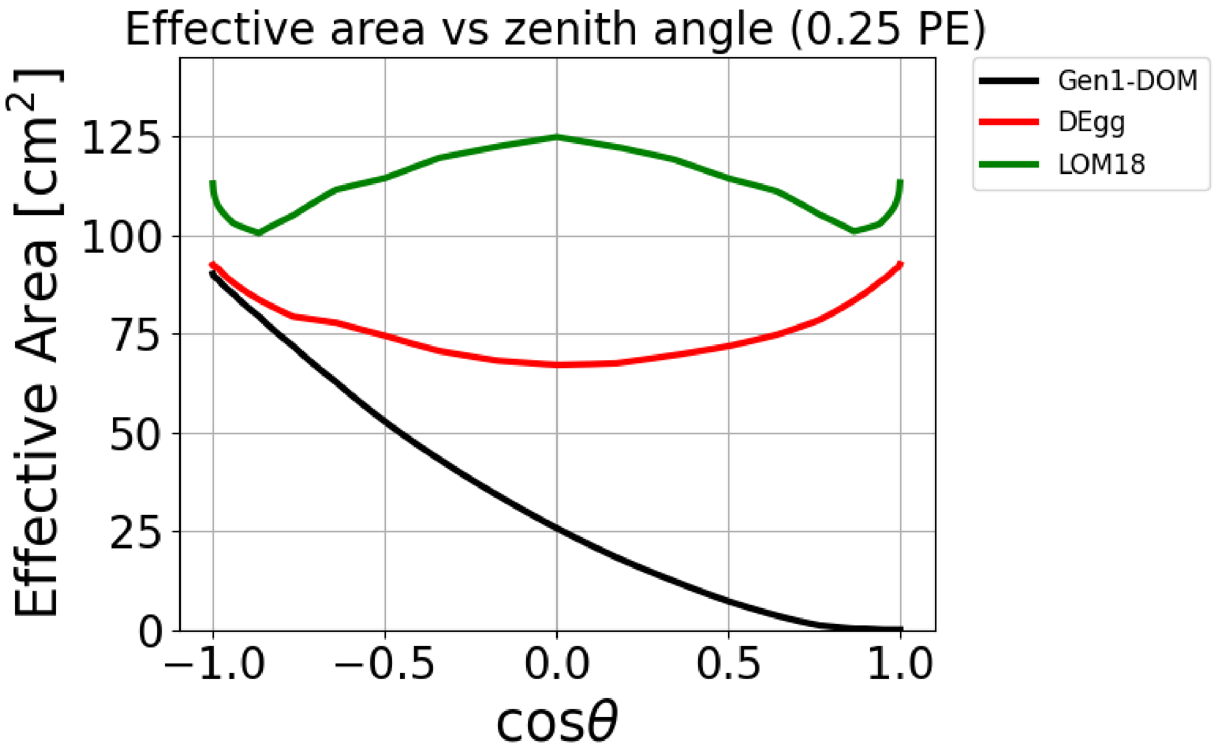
Long optical module (LOM)

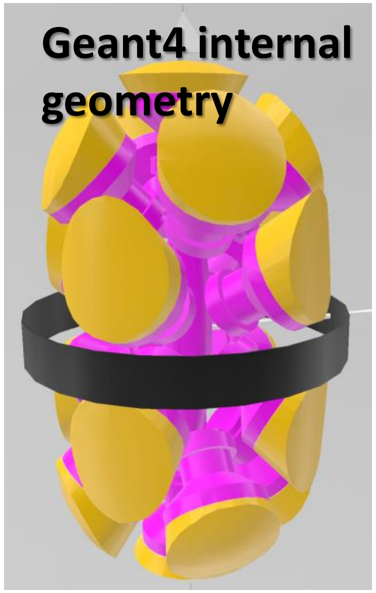
① **Use a low noise elongated glass vessel.**

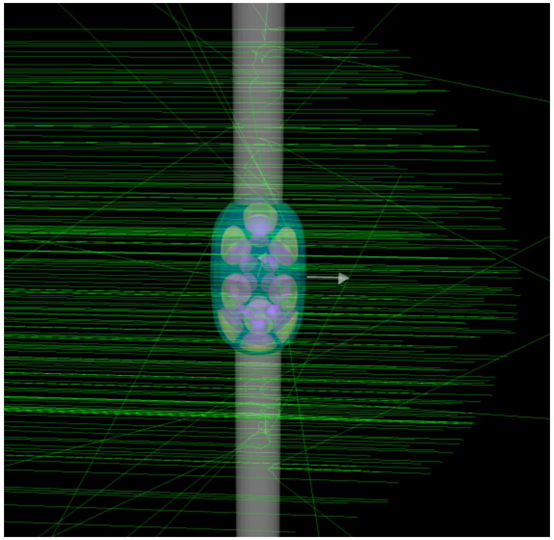
② **House 18 four inch PMTs.**

③ **Adopt a "gel pad" to efficiently lead photons to PMTs**

The performance of the LOM

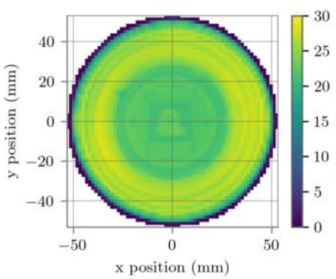


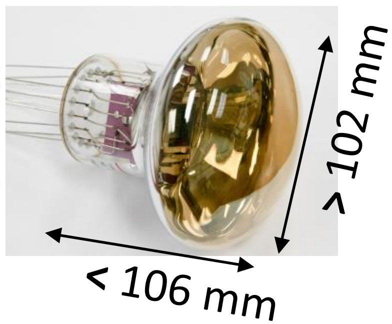




The detailed Geant4 study suggests x 3.6 improvement from the Gen1 optical module.

Long Optical Module (LOM)

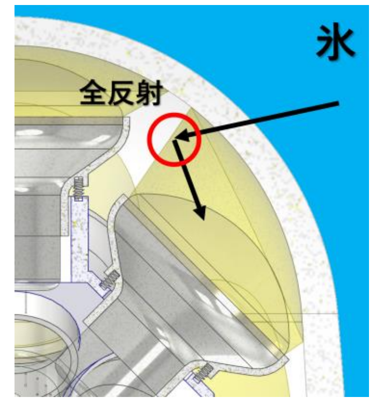


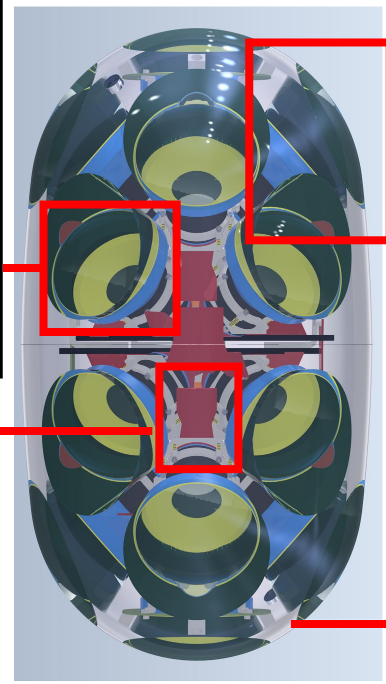


QE vs position

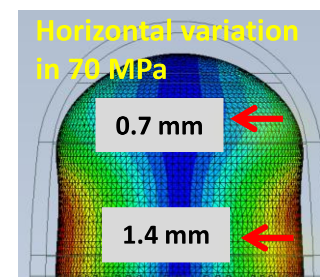
1. A newly developed 4-inch PMTs

2. A gel pad to improve the photon collection efficiency





3. *wuBase*
a new board which digitizes signal on base (w/ small power consumption of 145 mW/PMT)



4. A new extremely low noise pressure-resistant glass

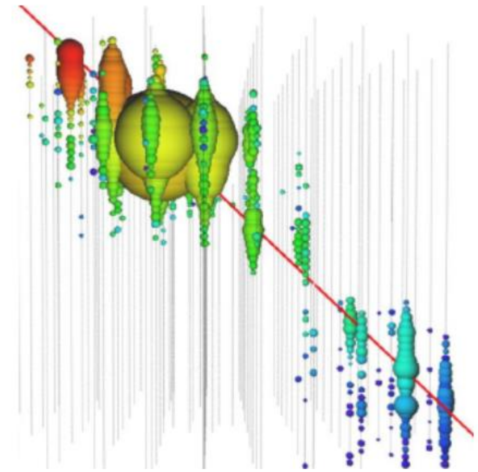
The development of key components have been already established.

Summary

- Shimizu started working in a new world
  - よろしくお願いします。
- IceCube has been measuring ν flux
  - low energy (10 TeV-100 TeV) neutrinos do not accomodate with γ ray spectrum if their source is transparent to γ
  - the source of high energy ν does not seem to be galactic origin
  - blazars were identified with one of their origins, but do not explain all of the contributions (up to 30 %)
  - The correlation with TDE looks interesting.
- Multi-messenger astronomy is important to identify the source of cosmic rays
  - to open new parameter space, new neutrino alert is being developed where the signature of signal is multiplet.
- Development of the new optical sensor LOM is ongoing.

Backup

Reconstruction of track

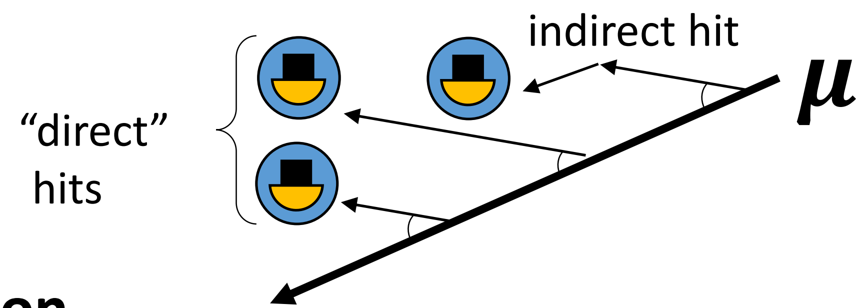


◆ **Energy**

→ adopts an energy deposit of $\boldsymbol{\mu}$ as a proxy of neutrino energy

$\propto$ number of photon

Use a “truncated“ energy, where too high outliers of dE/dx are removed and decrease fluctuation of $\langle dE/dx \rangle$



◆ **Direction**

➢ **Single Photo Electron (SPE) fit**

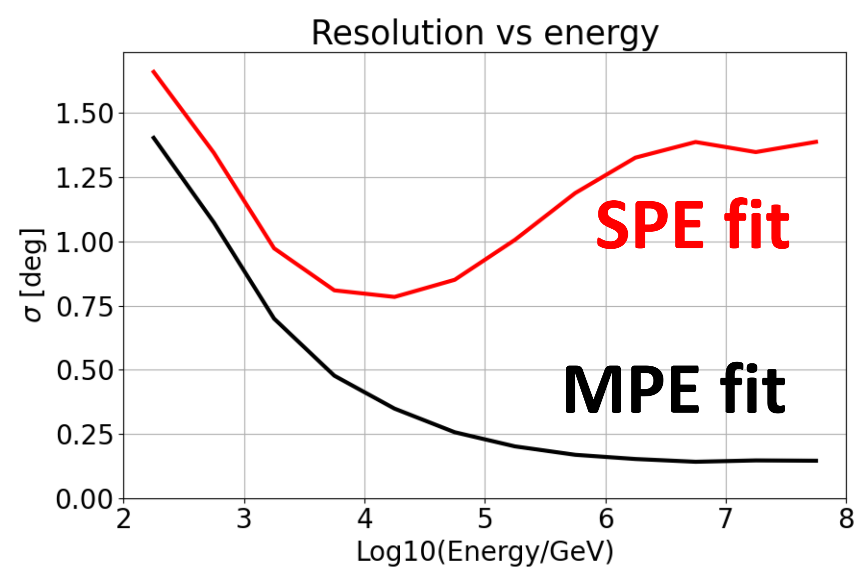
→ uses information of direct hits

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

➢ **Multi Photo Electron (MPE) fit**

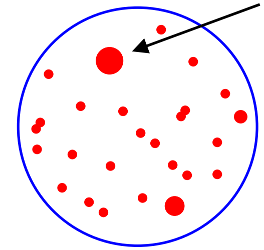
→ uses information of multiple hits

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



Calculation of z-likelihood

Field of view (FoV)



choose the smallest z

M = number of observation

Using the evaluated $A_{\mathrm{eff}}(E)$, z distribution of neutrino sources is calculated.

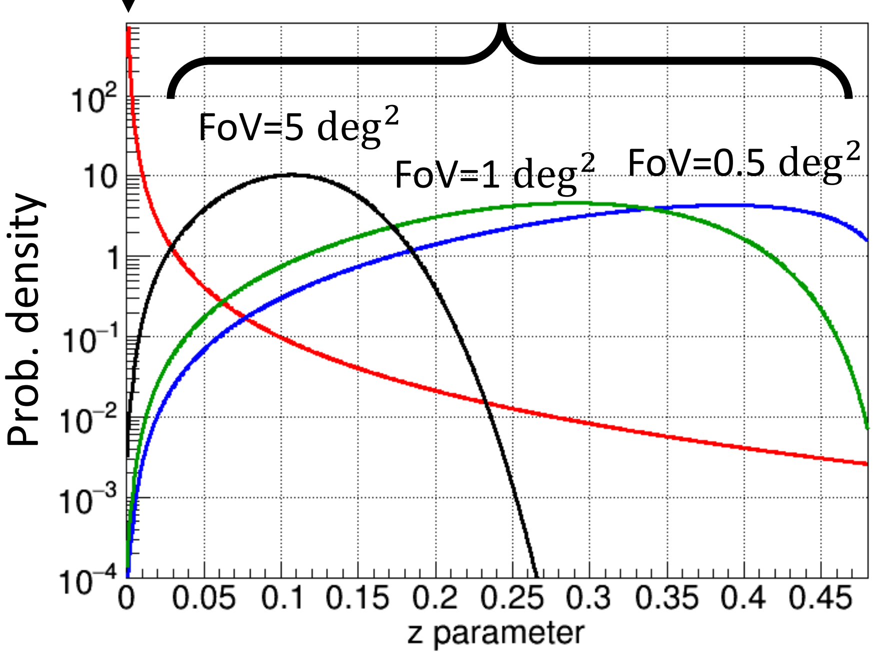
p.d.f of z for a neutrino source: $S(z) = \frac{1}{N(n=2)} \frac{dN(n=2)}{dz}$

p.d.f of z for a chance coincidence: $B(z) = M\rho_{SN}(z)\left[1 - \int_0^z \rho_{SN}(z')dz'\right]^{M-1}$

z density of supernovae

ν source

chance coincidence



Apparent difference in z distribution

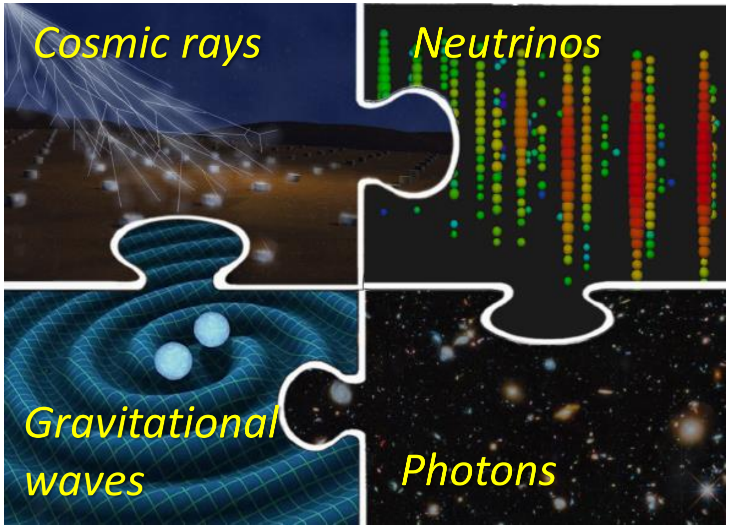
Current strategy is to repeat the follow up observation several times.

→

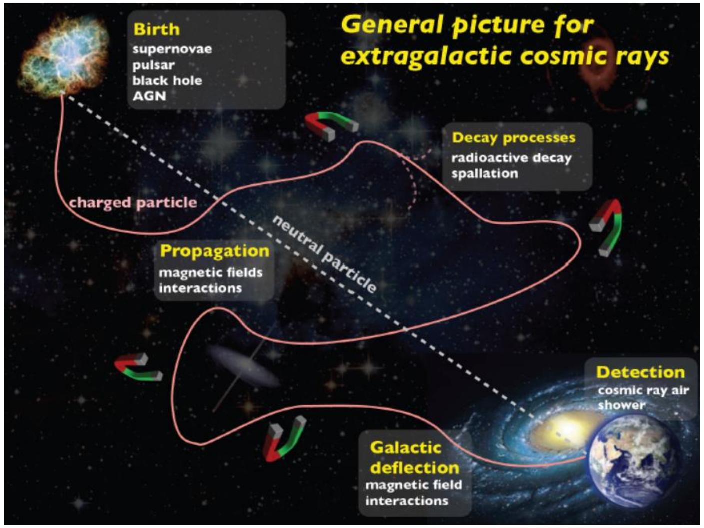
The tendency of z distribution may reveal new type of neutrino sources.

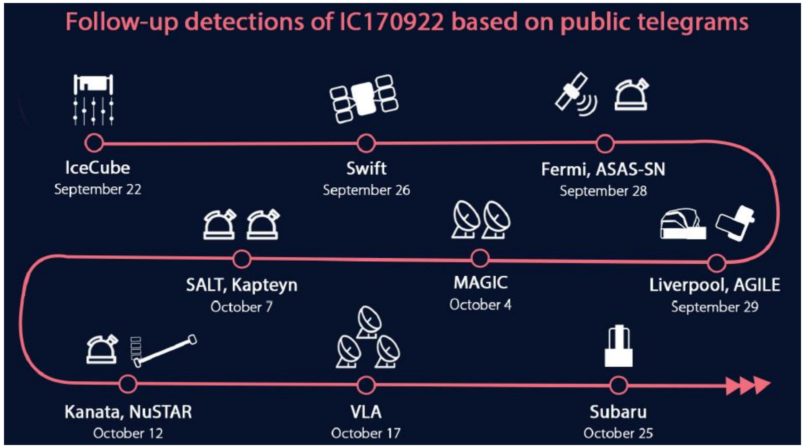
Multi-messenger astronomy

Astrophysical events produce various types of “messengers”



Neutrinos less interacts with particles when they move through the space.





Follow-up observation

When a telescope observes a notable event, issue an alert to other telescopes and see what happens in that direction.

Neutrinos are believed to be one of the earliest “messenger”.

Optimization of sensitivity

For a given flux of transit source of ν, $\phi(L_\nu)$, the averaged number of events from the point source is

$$\mu_{PS} = T\Delta\Omega A\ \phi$$

T: length of timing window,
$\Delta\Omega$: acceptable solid angle,
A: Effective area

Then, the total number of sources, which can be observed as multiplet is

$$N^{multiplet}(L_\nu, n_0, T) = \Delta\Omega \int dV\ n_0(1+z)^3\ P(n=2|\mu=\mu_{PS})$$

where n_0 is a density of the transit sources.

BGs due to diffuse singlet sources and atmospheric muon, can be evaluated as $N^{BG}(L_\nu, n_0, T)$. For a given L_ν, n_0, we maximize $N^{multiplet}/\ N^{BG}$.

TABLE I. Characteristic parameters of the candidate sources of UHECRs and high-energy neutrinos. PRD **102**, 083023 (2020)

	HL GRB	LL GRB	Newborn magnetar	Jetted TDEs	Blazar Flares	Jetted AGN
L_γ [erg s^{-1}]	10^{51-53}	10^{46-48}	10^{42-44}	10^{45-48}	10^{45-48}	10^{43-48}
Γ	100–1000	2–30	?	3–100	3–100	3–100
ρ [Gpc^{-3} yr^{-1}]	0.1–1	100–1000	1000–10000	0.01–0.1	100–1000	...
ΔT [s]	10–1000	100–10000	10^{2-5}	10^{5-7}	10^{5-7}	...

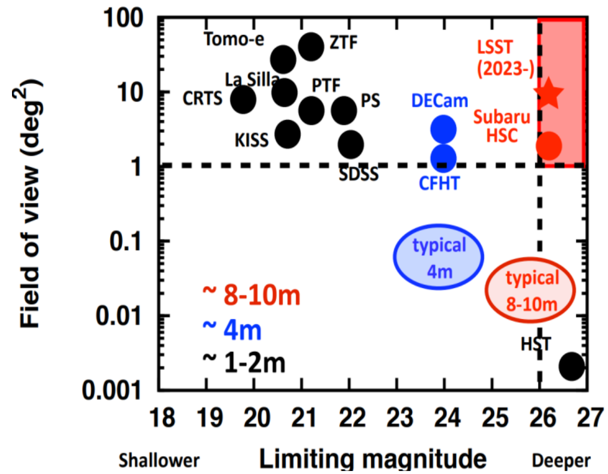
Field of view of various optical telescopes

Field of view ($\mathbf{deg^2}$)

T. Morokuma

	tel [m]	FoV	area	cadence	depth	detector	note
PTF	1.2	7.3	8,000	5 days	R~20.6	CCD	Palomar 48" Law+2009
ZTF	1.2	47	数1,000?	a few hours	r~21	CCD	Palomar 48" 2018-
ASAS-SN	8 x 0.14	120	20,000	~1 day	~17	CCD	Haleakala & CTIO sites
CRTS	1.5+0.7+0.5	1.2+8.1+4.2	1,200	30 min (x4)	19-20	CCD	2 x USA + Australia
TESS	4 x 0.105	2300	2,300	27-day continuous	I~18	CCD	downlink ~2weeks
Evryscope	24 x 0.061	8000	8000?	2 min 1 day	V~16.5 V~19	CCD	CTIO site
KISS	1.05	4	100	1 hr	g~20-21	CCD	Kiso
Tomo-e	1.05	20	10,000	2 hrs 1 day	g~18 g~19	CMOS	Kiso

https://www.nao.ac.jp/study/oao//pdf/reference/um/um16/O22_Morokuma.pdf



Various optical telescopes $\Delta\Omega > 1\mathrm{deg}^2$ are now available and even might be able to cover angular resolution of cascade.

Moreover, not necessary to have large aperture in this proposal.