IceCube実験による
これからの宇宙ニュートリノ即時同定

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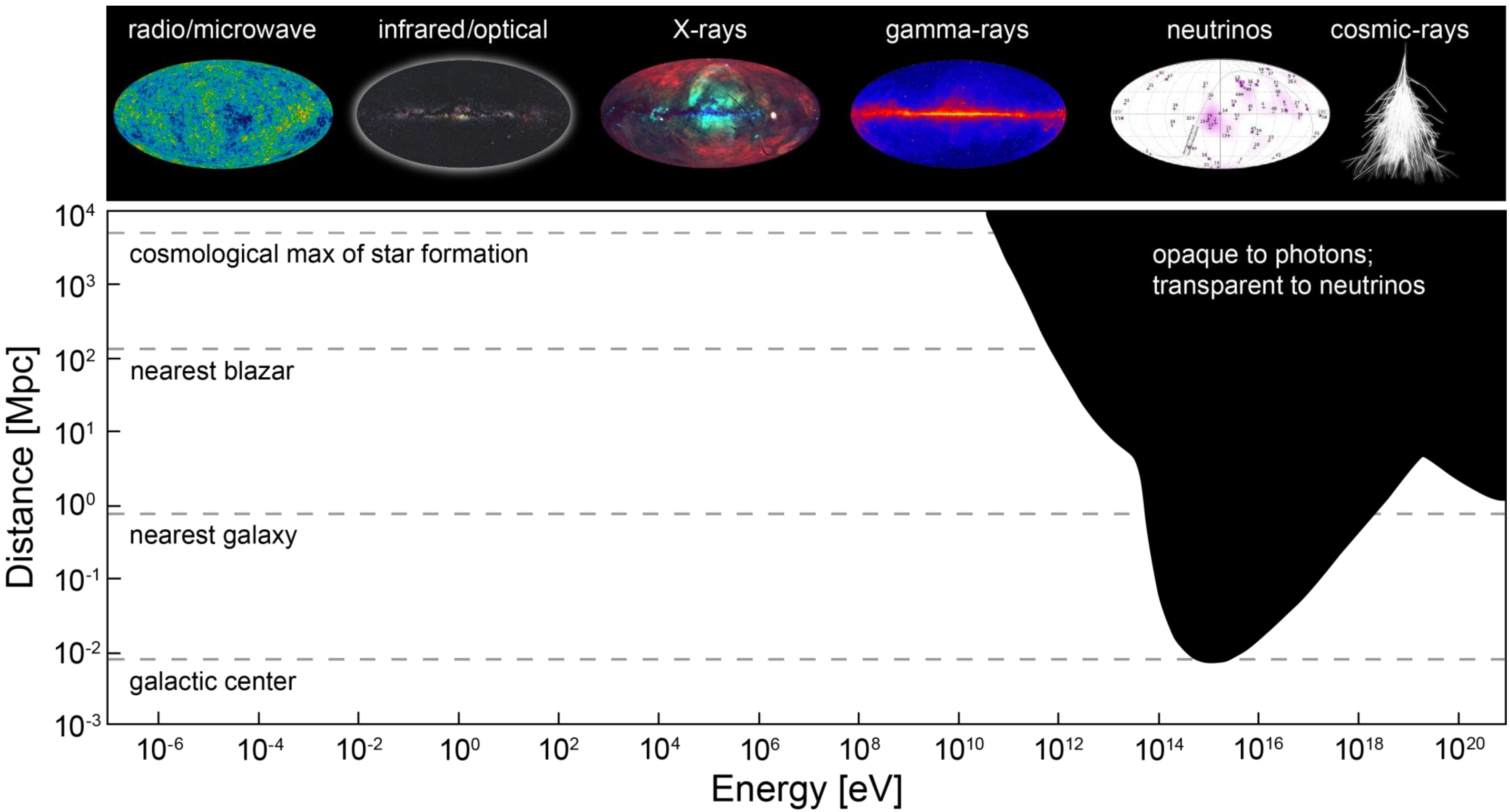
17aW1-5　日本物理学会　2021年　秋大会

シンポジウム 「ニュートリノ・重力波時代のマルチメッセンジャー観測の展望」

Neutrinos as messenger

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



Neutrinos from burst object

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

$\boldsymbol{E_p}$

$\quad \llcorner\!\to \mu^+ + \nu_\mu$ $\boldsymbol{E_p/20}$

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

$\quad\quad\quad \llcorner\!\to$ radiations

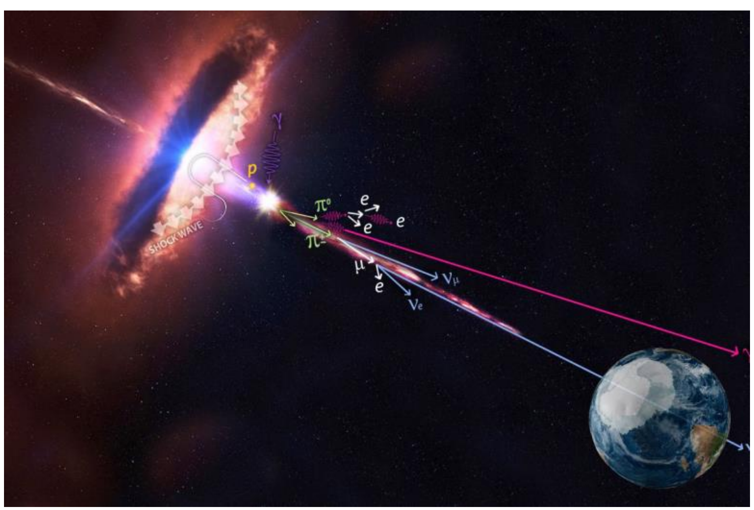
$\to p + \pi^0$

$\quad \llcorner\!\to \gamma\gamma$

$\boldsymbol{E_p/10}$

Neutrinos

γ

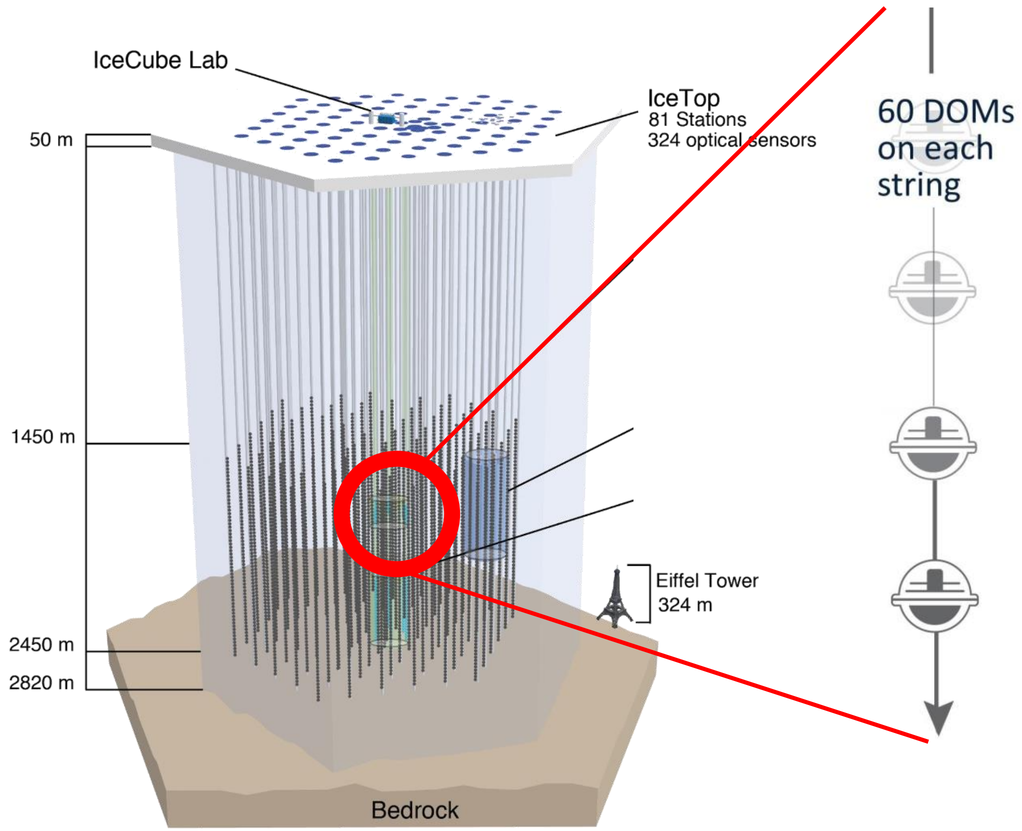


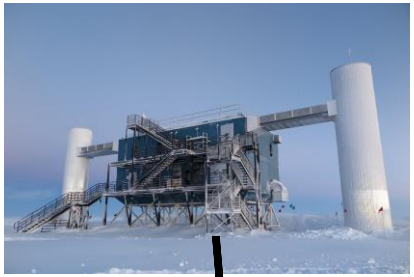
Neutrinos accompanies with various partners

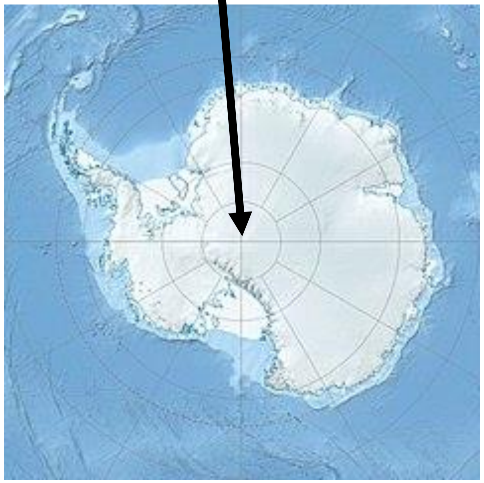
Multi-messenger astronomy to understand the mechanism of astrophysical objects

IceCube experiment

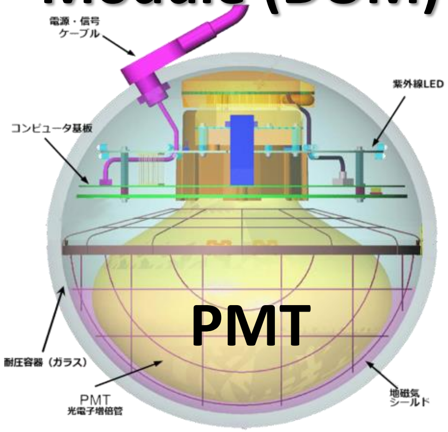
Neutrino telescope operated in Antarctica





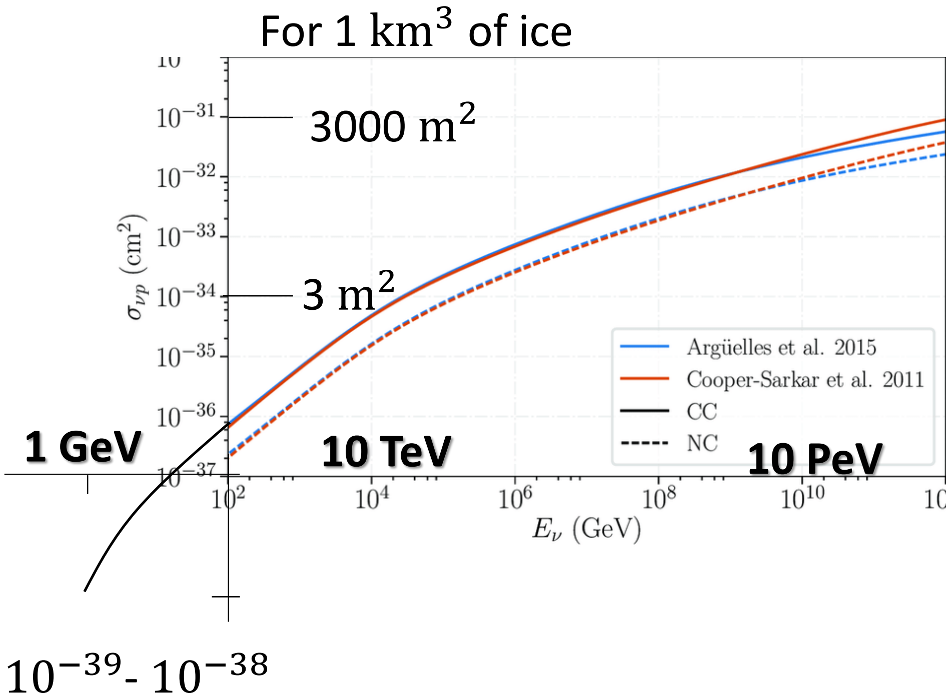


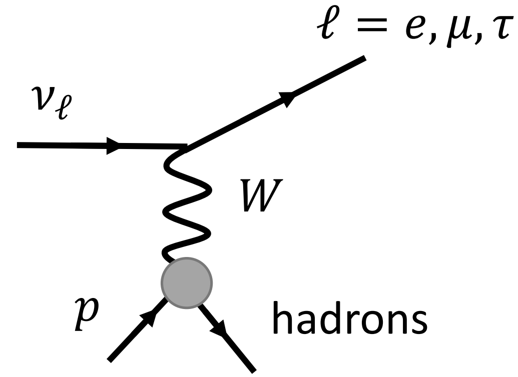
Digital Optical Module (DOM)



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

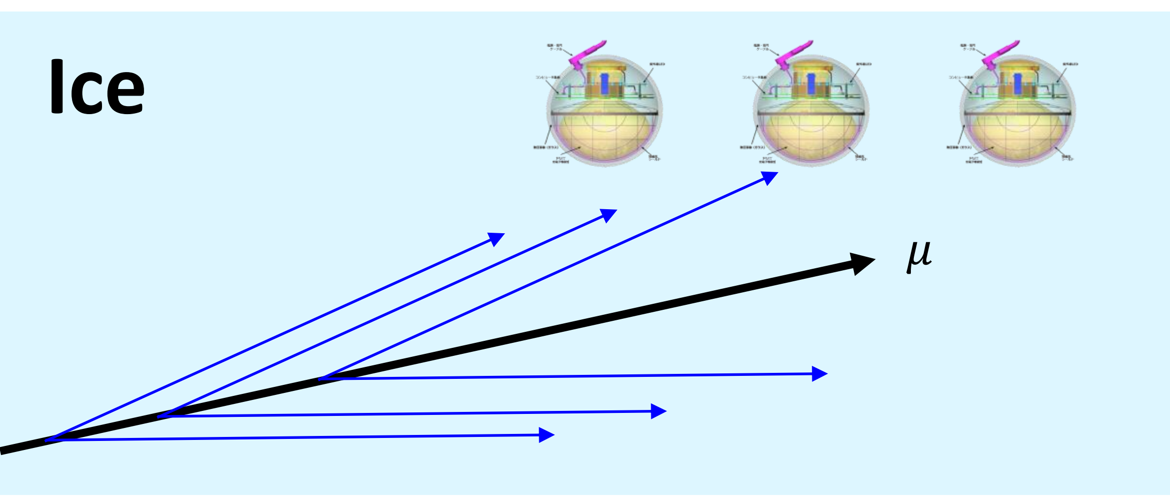
Neutrino detection in IceCube





σ increases as the energy of ν increases (very roughly) $\sigma \propto \sim E^{0.5}$
Astrophysical neutrino flux $\propto E^{-2.3}$

→ This cancellation provides wide range of physics programs

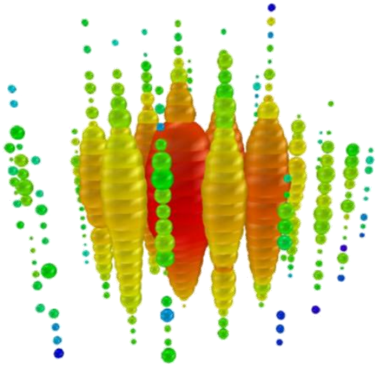


Cherenkov photons from charged particles are detected by sensitive photo detectors.

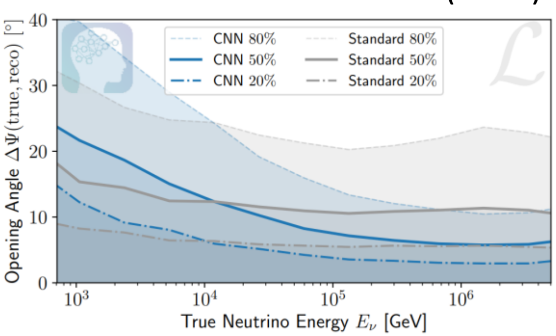
Event topologies and resolution

Cascade

ν_e



JINST 16 P07041 (2021)

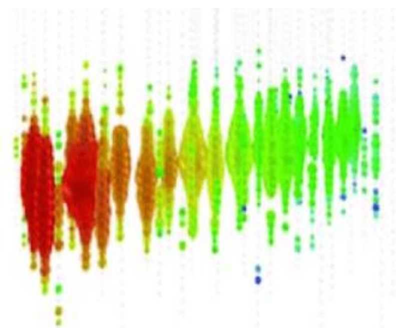


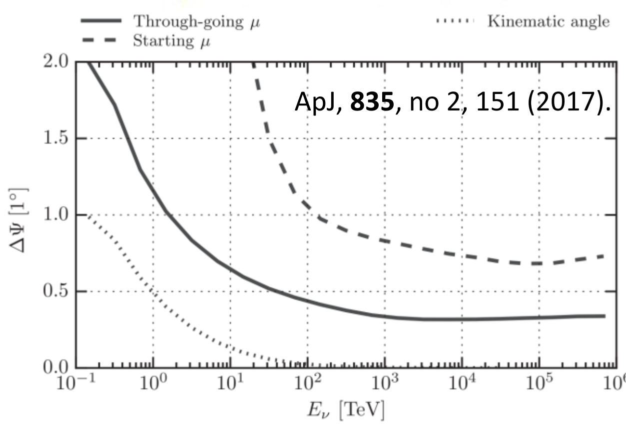
$\sigma_{dir} \sim 10°$

$\sigma_E/E \sim 10\%$

Track

ν_μ



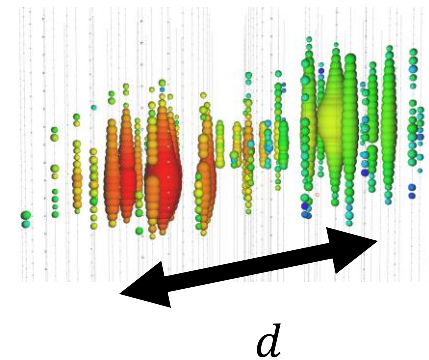


$\sigma_{dir} \sim 1°$

σ_E/E → factor of 2

"Double-bang"

ν_τ

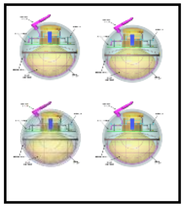


$d \sim 50$ m/PeV

Not observed yet

Neutrino alert

South pole



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

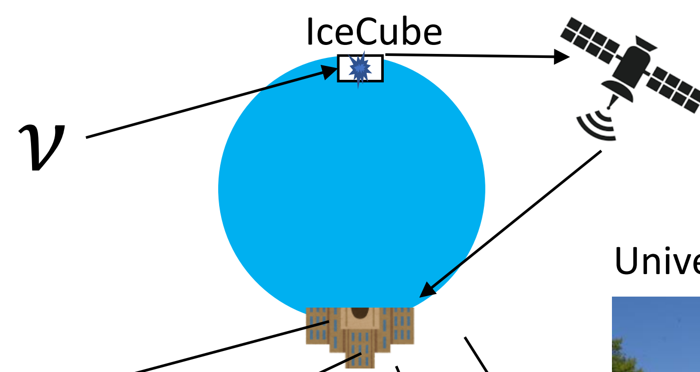
University of Madison

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.

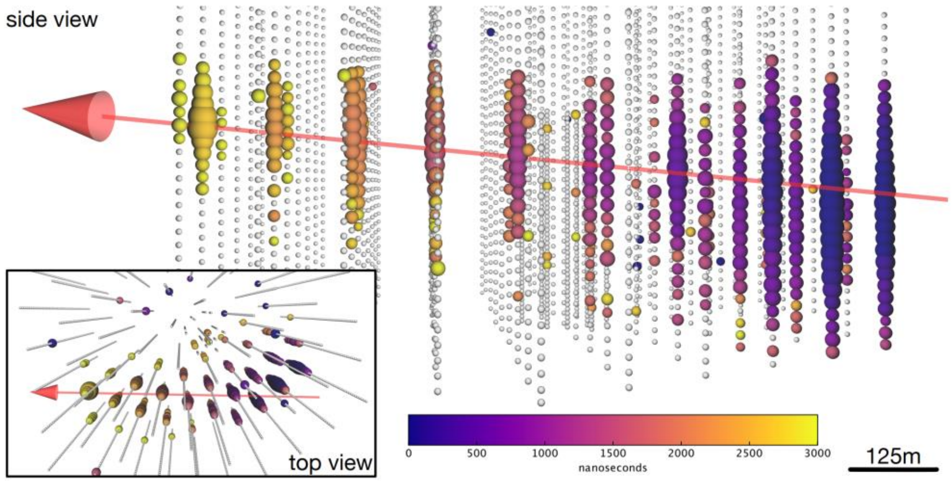
The latency is within a few minutes

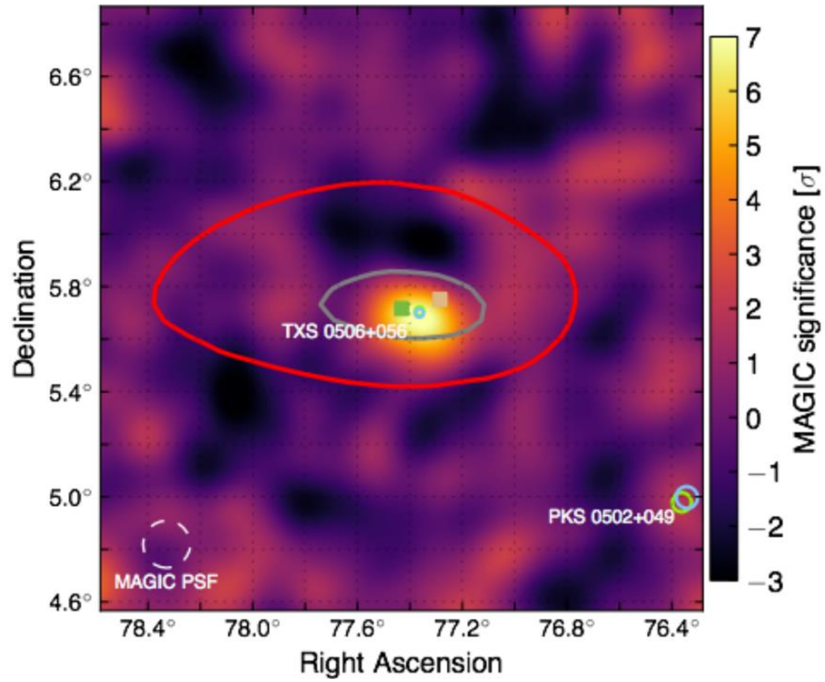


University of Madison

EHE-170922A

Science 361, eaat1378 (2018)





"EHE" alert

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

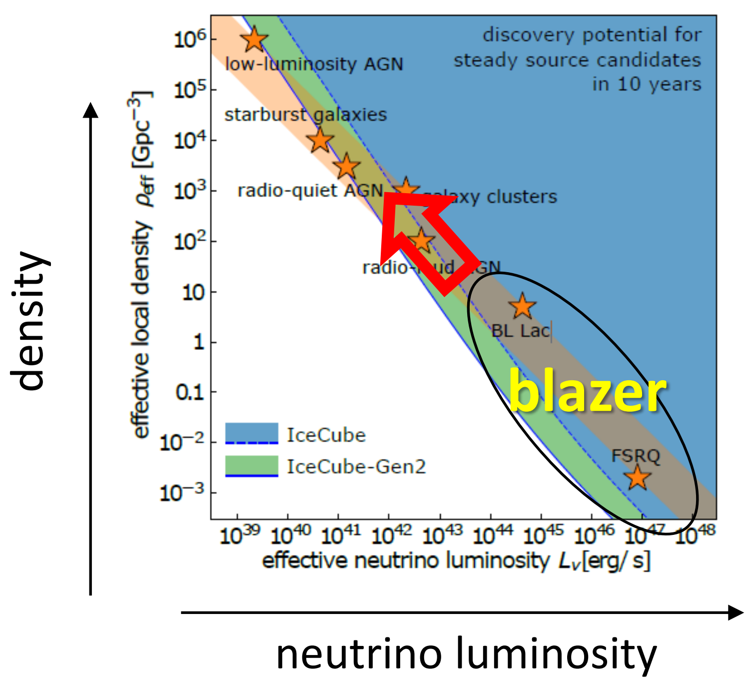
Kanata Telescope followed up it and found a "***blazer***" TXS 0506+056 showed an increase of luminosity. Fermi/MAGIC confirmed an increase of γ ray activity as well.

Parameter space of the neutrino source objects

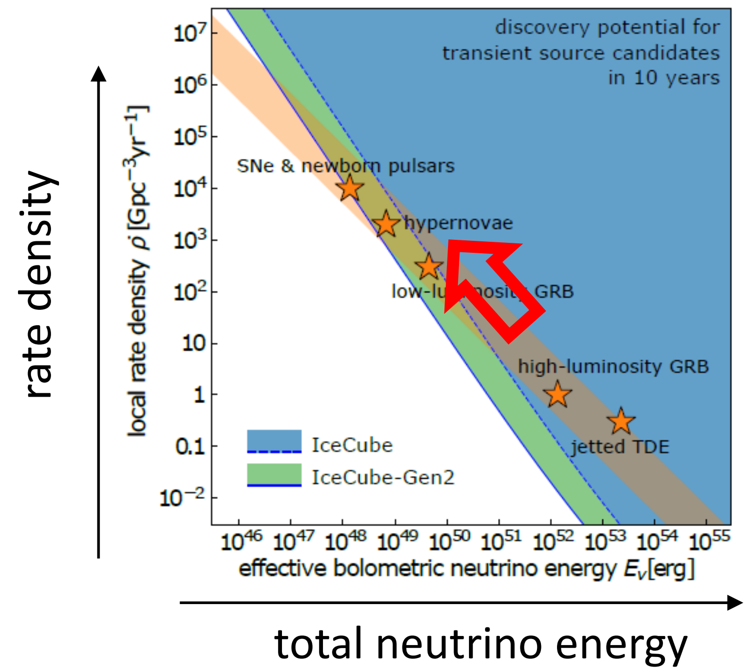
$$n_{obs} \propto n_0 L_\nu$$

n_0: density
L_ν: luminosity

Steady source



Transient source



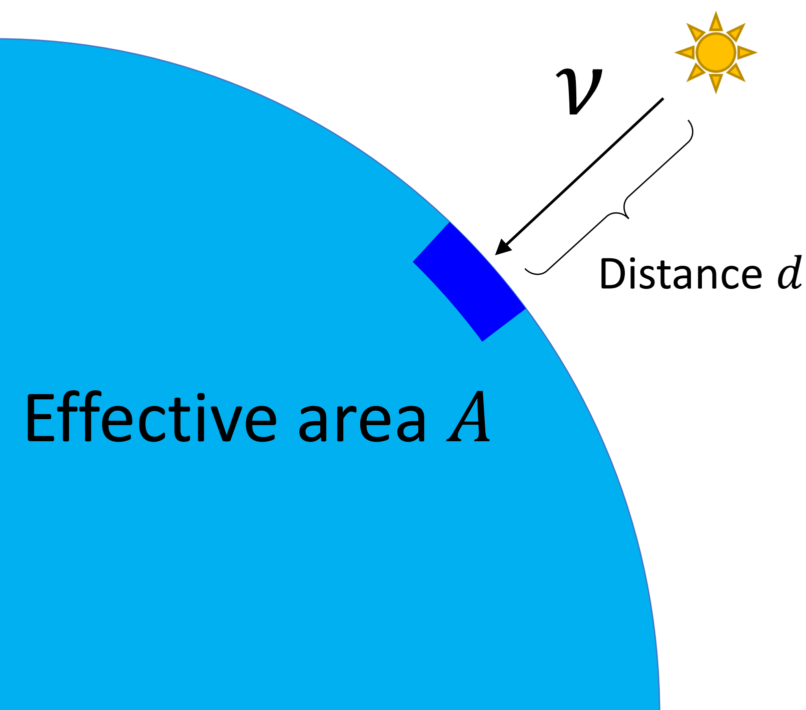
Energetic but minority ⇨ Less energetic but majority = nearby objects

Optical alert using "multiplet" signal

Multiplet signal

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** $\Delta\psi$.

Why multiplet?



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

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

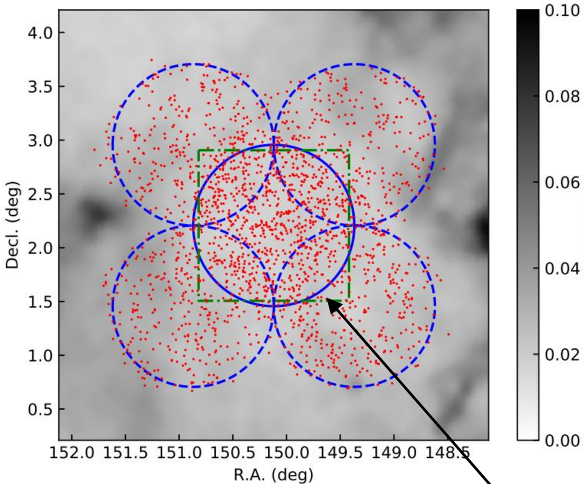
Prob. detected as **Multiplet** $\propto d^{-2N}$

→ *Multiplet signal picks up neutrinos from nearby objects*

= *Useful for optical follow up*

Why multiplet?

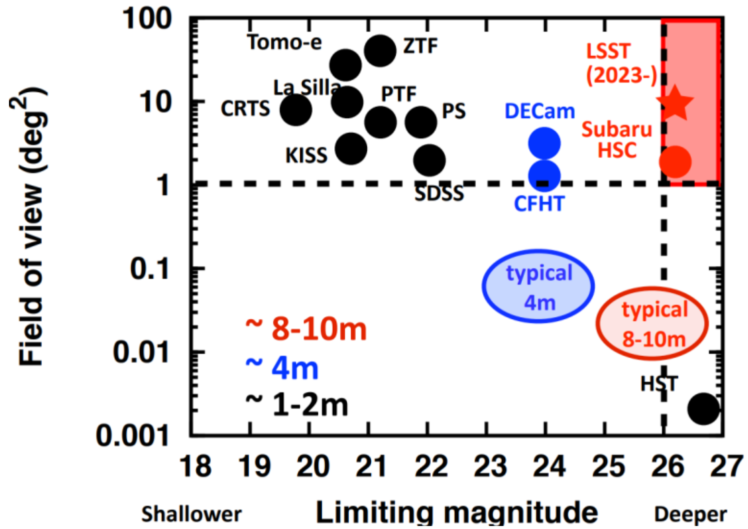
N. Yasuda, *et al*. ApJS, **71**, 74 (2019).



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),

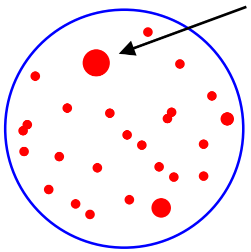
rate/density of SNe = $\dfrac{\mathcal{O}(10)\ SNe}{\mathrm{deg}^2 \cdot 20\ \mathrm{days}}$ → Too many optical counterparts in the distant universe!

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

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

Strategy to identify ν source

Field of view (FoV)



M = number of observation

To achieve large significance, we choose the closest object in field of view.

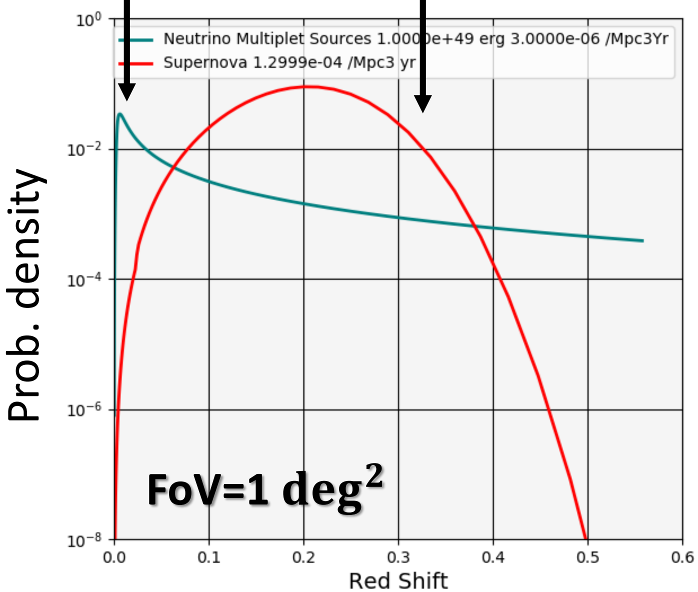
p.d.f of z for a neutrino source: $S(z) = \frac{1}{N_2}\frac{dN_2}{dz}$

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



$$\frac{\rho_{SN}(z)}{\mathrm{Mpc^{-3}yr^{-1}}} = \begin{cases} 1.3\times10^{-4} & d > 100\ \mathrm{Mpc} \\ \text{from Catalog} & d < 100\ \mathrm{Mpc} \end{cases}$$

Difference in z distribution

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

Current scheme and target sensitivity

	Current program		*New scheme*
Alert type	**Private**	→	**Public**
Timing window ΔT	**100 s**	→	**30 days**

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}	...

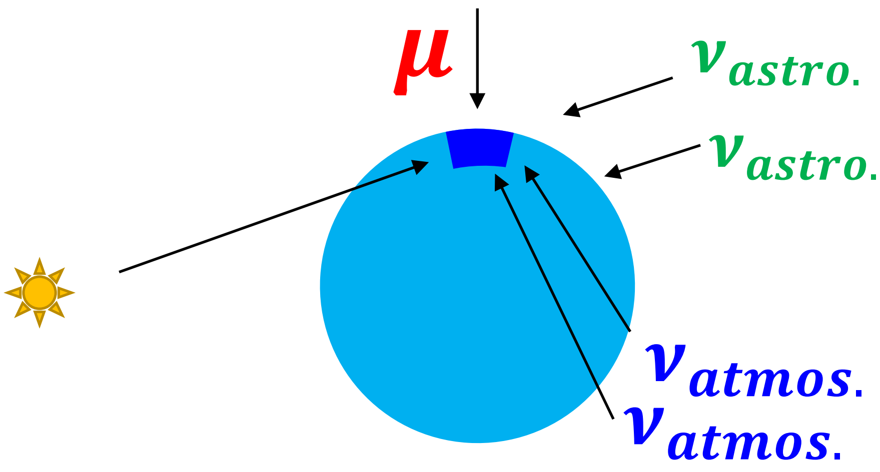
For $\Delta T = 30$ days, and the opening angle of $\psi = 1$ deg,
how many events μ_{sig} can be followed up by optical telescopes?

1 year → $\mathcal{O}(1)$ event
30 days → 12 trials
$1 \times 1\ \mathrm{deg}^2$ → 6500 patches in the half sky

$$\mu_{sig} \sim \frac{1}{12 \times 6500} = 1 \times 10^{-5}$$

Target sensitivity is
$\mu_{sig} \sim 1 \times 10^{-5}$ in each observation.

Backgrounds at IceCube (track type)



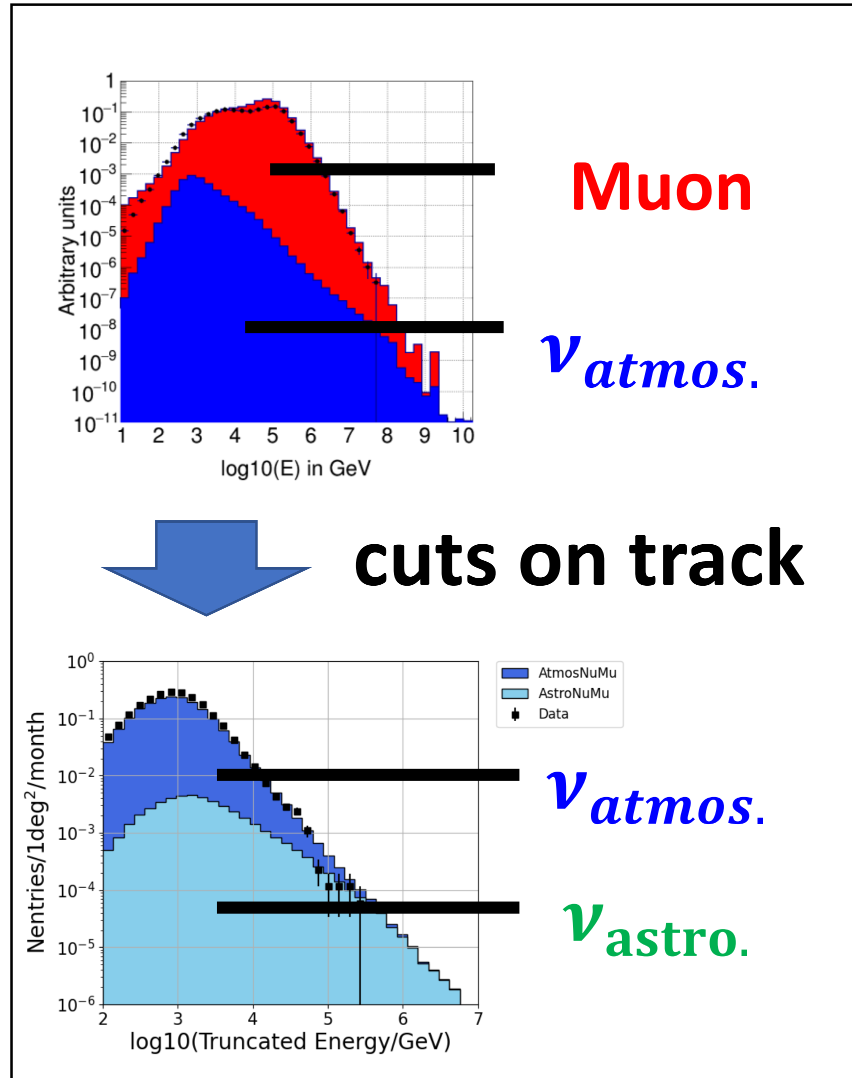
Down-going events are suffered from large contamination from **muon**

Up-going type is relatively pure but still **muon** contribution is huge

Dedicated cuts on the track removes **muon** but **atmospheric ν** still remains.

Energy difference finally discriminates **atmospheric ν** and **astrophysical ν**

Energy distributions for up-going events



Consideration of backgrounds

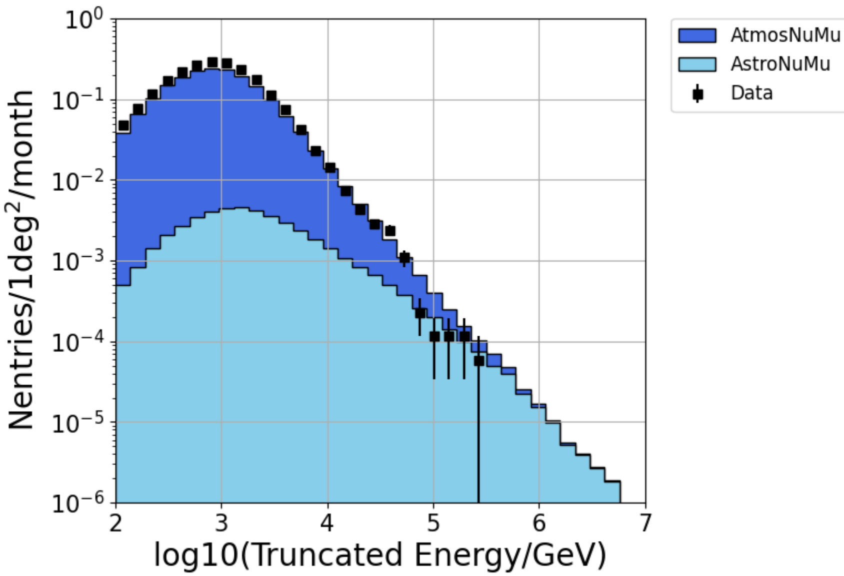
How many BG events μ are practically allowed in 1 deg^2 for ΔT=30 days ?

$1\ \mathrm{deg}^2$ → 6500 patches in the half sky
ΔT=30 days → 12 trials/year

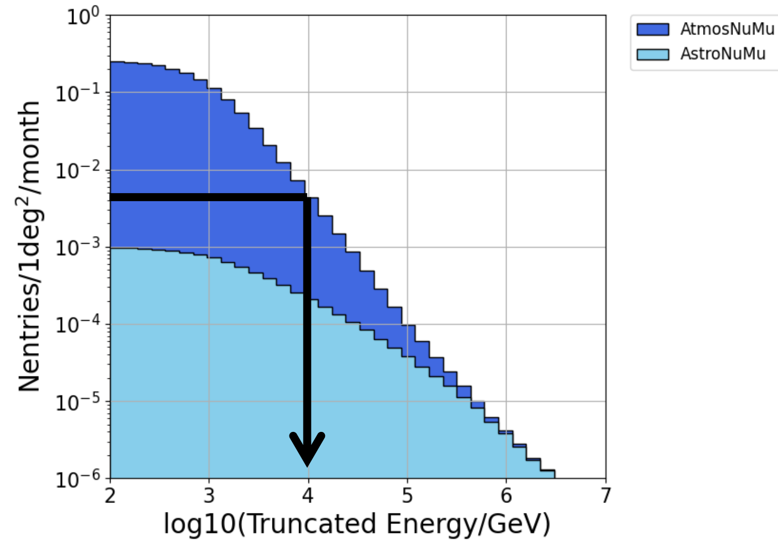
Poisson(n=2|μ)$\times\ 6500 \times 12 = 1$ event

$\mu \sim \mathcal{O}(5 \times 10^{-3})$

Energy distribution



Cumulative distribution function

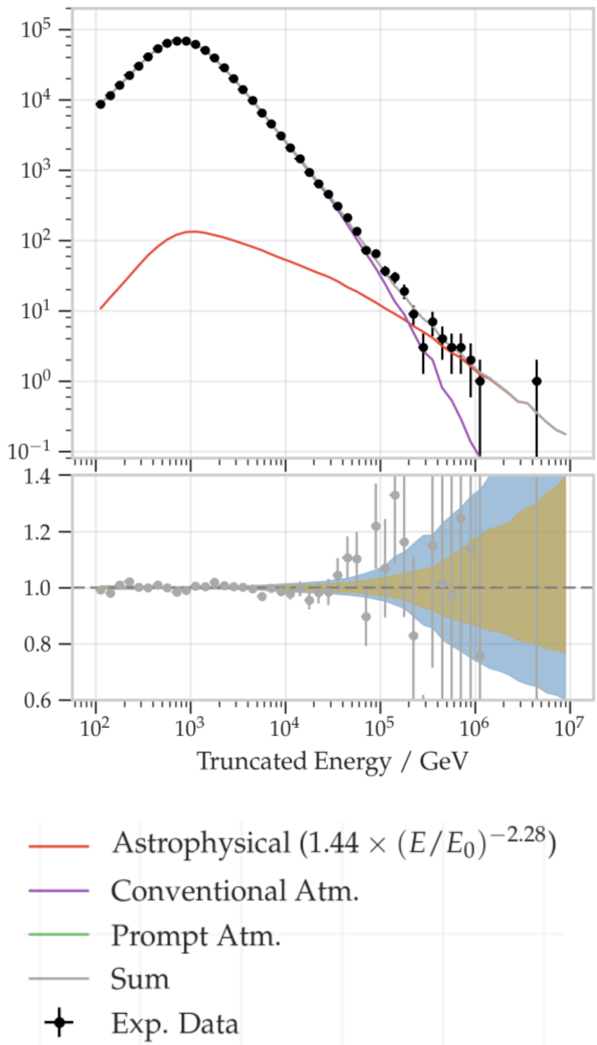


By applying higher energy cut, we can accommodate the background level.

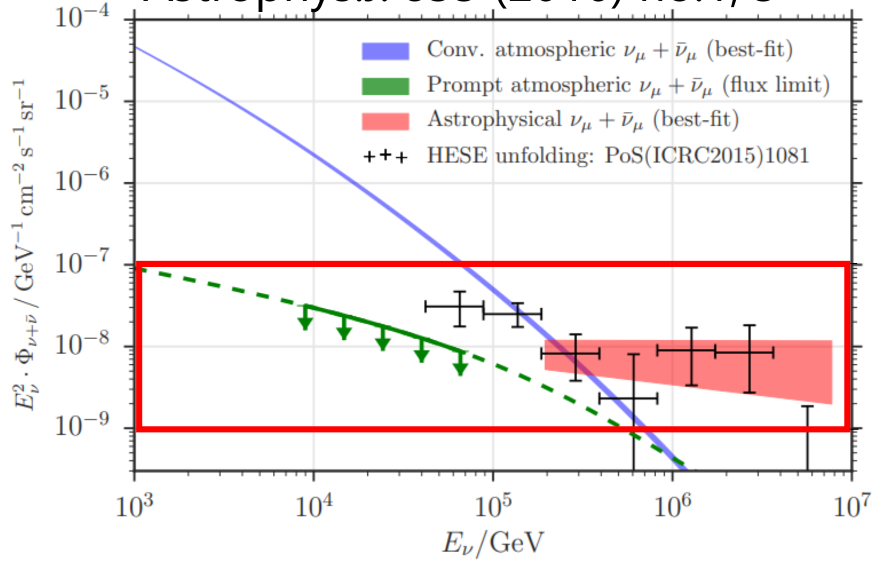
Consideration of Diffuse ν_μ flux

"Diffuse ν_μ" → not specified their source

PoS-ICRC2019-1017



Astrophys.J. 833 (2016) no.1, 3



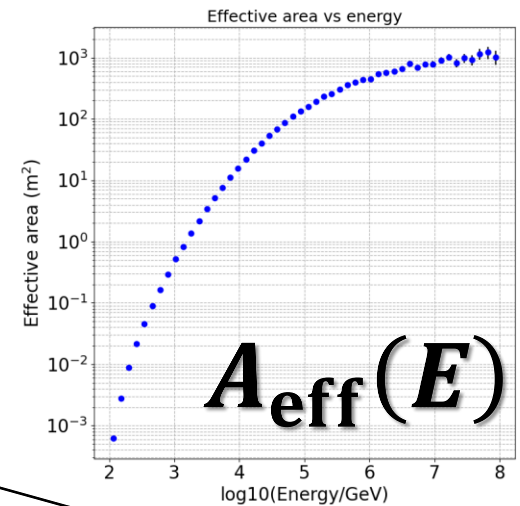
$$10^{-9} < \frac{E^2\phi_{\nu+\bar{\nu}}}{\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}} < 10^{-7}$$

→ Indirect limit of the parameter space in (L_ν, n_0) plane

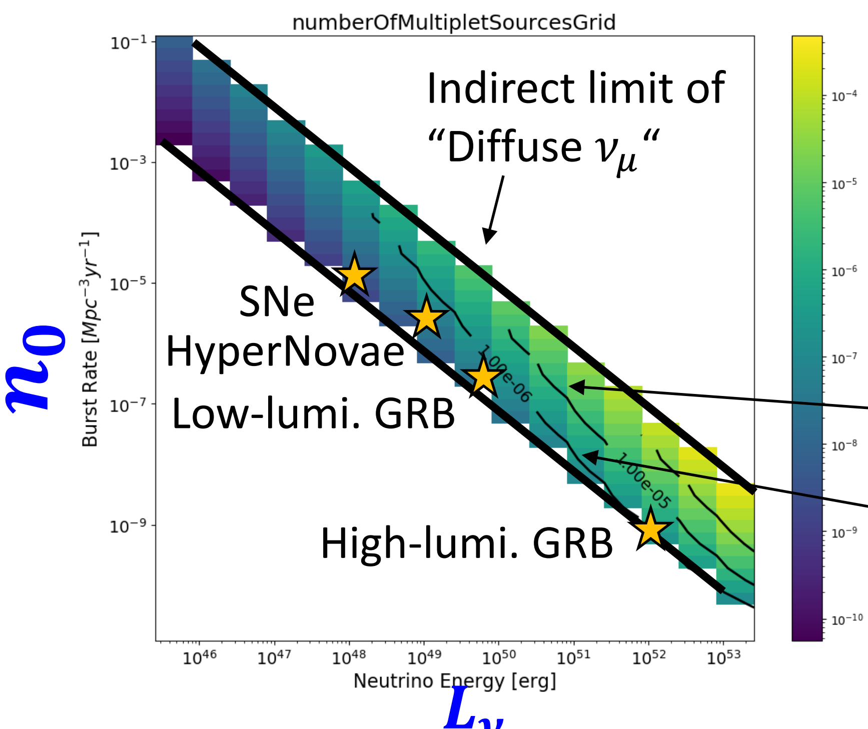
Calculation of the # of multiplet signal

Expected # of detection per single source

$$\mu = \Delta T \int dE \underbrace{A_{\mathrm{eff}}(E)}_{\text{Effective area of IceCube}} \; \underbrace{\phi(r, L_\nu)}_{\text{Neutrino flux from a fixed point source} \propto L_\nu r^{-2}}$$



$$\mu_{sig} = \Delta\Omega \int dr \underbrace{n_0}_{\text{density of burst}} 4\pi r^2 \mathrm{Poisson}(n = 2|\mu)$$



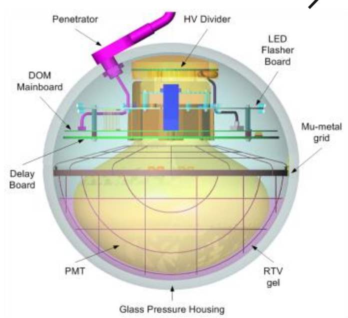
$\mu_{sig} \sim 1 \times 10^{-5}$ ← 1 event/year

$\mu_{sig} \sim 1 \times 10^{-6}$ ← 0.1 event/year

O(1) event can be expected for a few years!

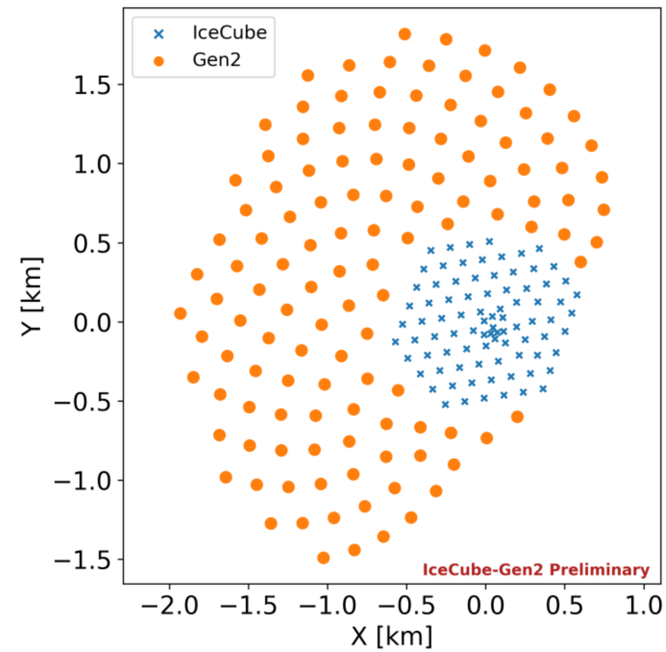
IceCube-Gen2

- Volume of Gen2 → x 8
- Sparse layout: 125 m → 240 m
- Install O(10,000) optical modules



Gen1 DOM

D-Egg **LOM**



$A_{\mathrm{eff}}(E)$ → **x 5**

σ_{dir} → **x 1/3**

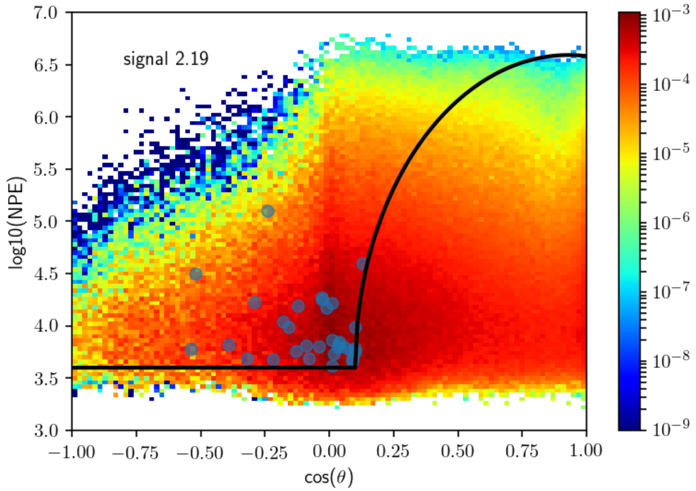
The sensitivity of Gen2 opens a new area of multi-messenger astronomy!

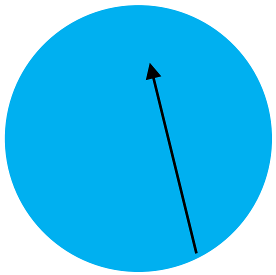
Summary and plan

- High energy neutrinos are one of the unique messengers of the deep universe
- To search for the origin of neutrino source, IceCube issues an alert to the world when it detects neutrino signal.
- To search for the real neutrino source while keeping the significance of observation, the signature of multiplet signal is very useful
- A program of a new multiplet is now being developed and (hopefully) expected to observe 1 events in a few years.

Types of neutrino alerts

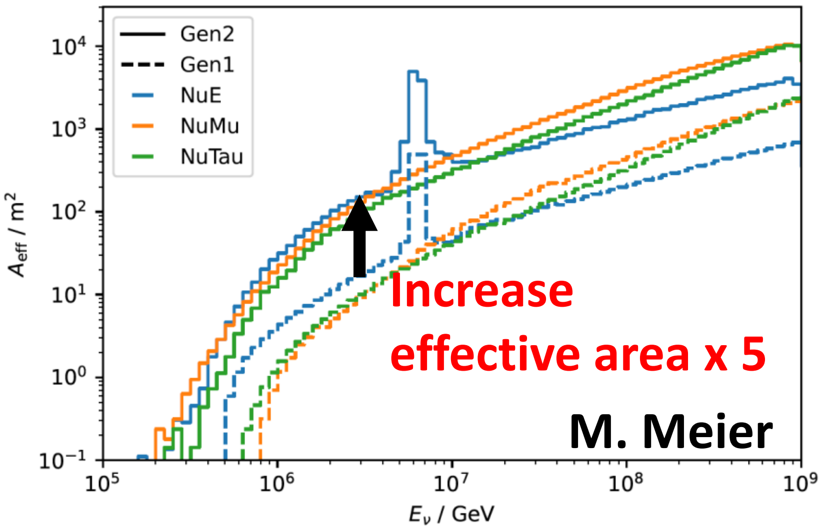
- Extremely high energy (EHE) alert

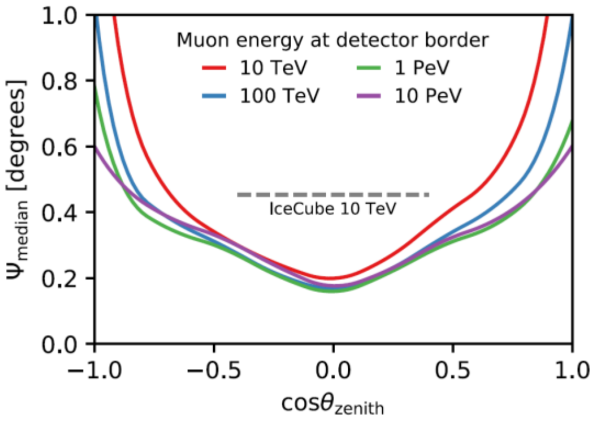




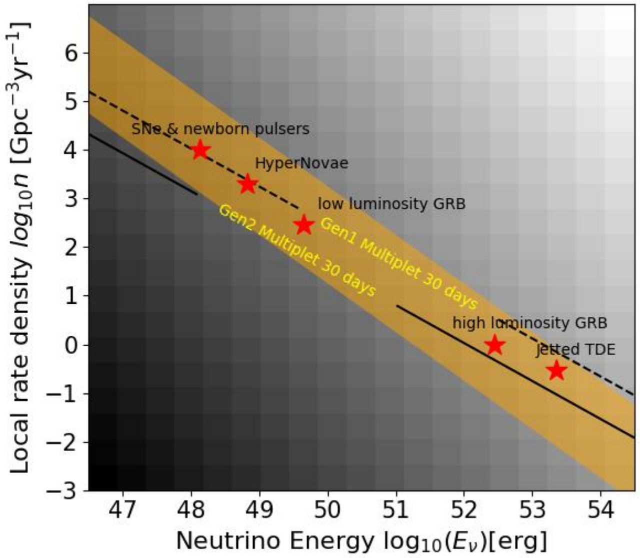
- Optical Follow-up (OFU)

New era of multi-messenger astronomy opened by IceCube-Gen2





Angular resolution improves by x 3



aaa

New optical module for Gen2

Figure of merit of optical modules → sensitivity/cost of deployment
Use a low noise elongated glass vessel.

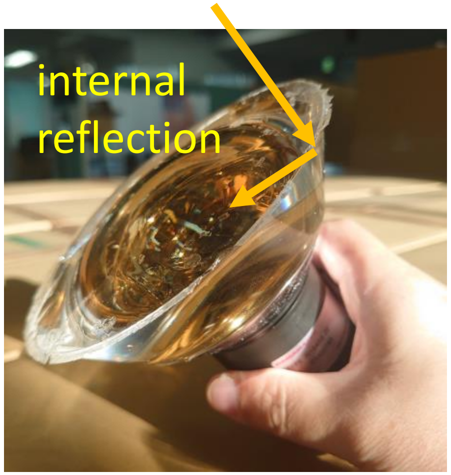
D-Egg

- **Already satisfies the requirement of Gen2!**
- **Sensitivity improves by x 2.8**
- **300 DEggs will be installed as a phase1 of Gen2 (2027)**

Now being produced
270 DEggs now Sep. 10th

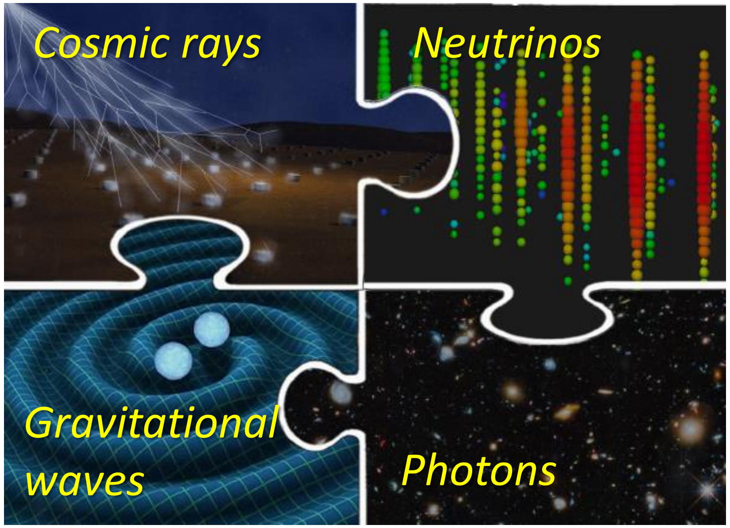
LOM

- **To improve sensitivity further, houses 18 four inch PMTs**
- **Adopt "gel pads" to efficiently lead photons to PMTs**
- **The development of the assembly of difficult structure is ongoing**

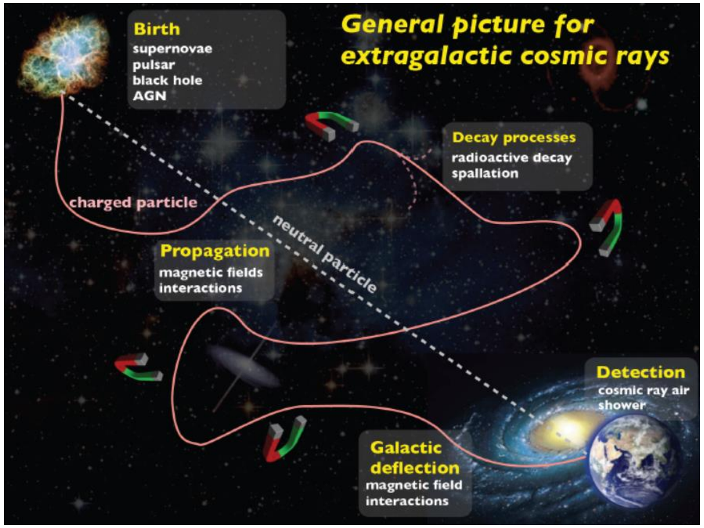


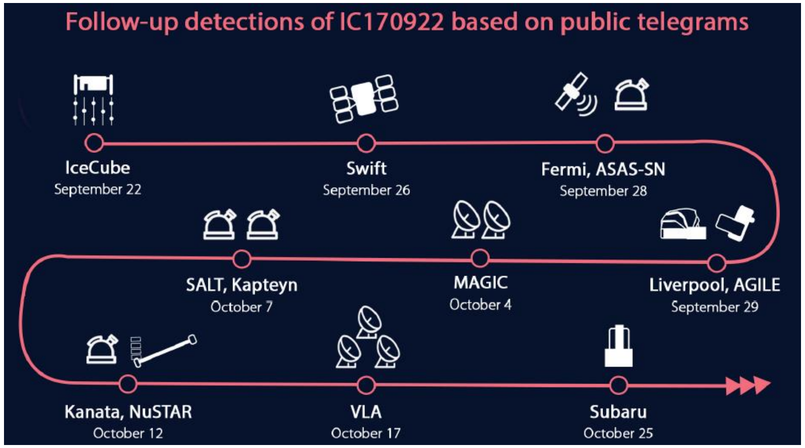
Multi-messenger astronomy

Astrophysical events produce various types of "messengers"



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





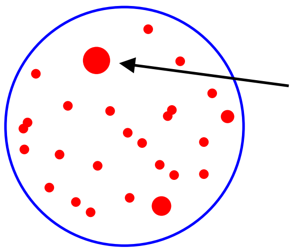
Follow-up observation

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".

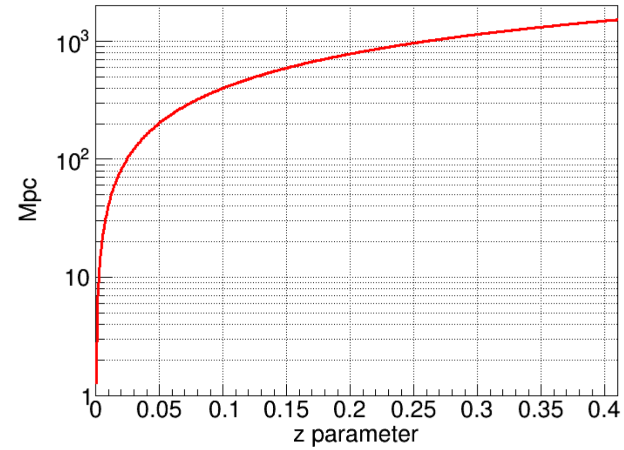
Calculation of redshift distribution

How to find a neutrino source close to the earth?



Once we detect ν multiplet signal and issue an alert, we choose the smallest z object as a astrophysical neutrino sources.

Field of view



Formalism (simplified)

Flux of neutrinos: $\phi(z) = \frac{dN}{dAdtdE} \propto \frac{1}{4\pi d^2}\frac{L}{E_\nu^{-\alpha}}$ (L = luminosity)

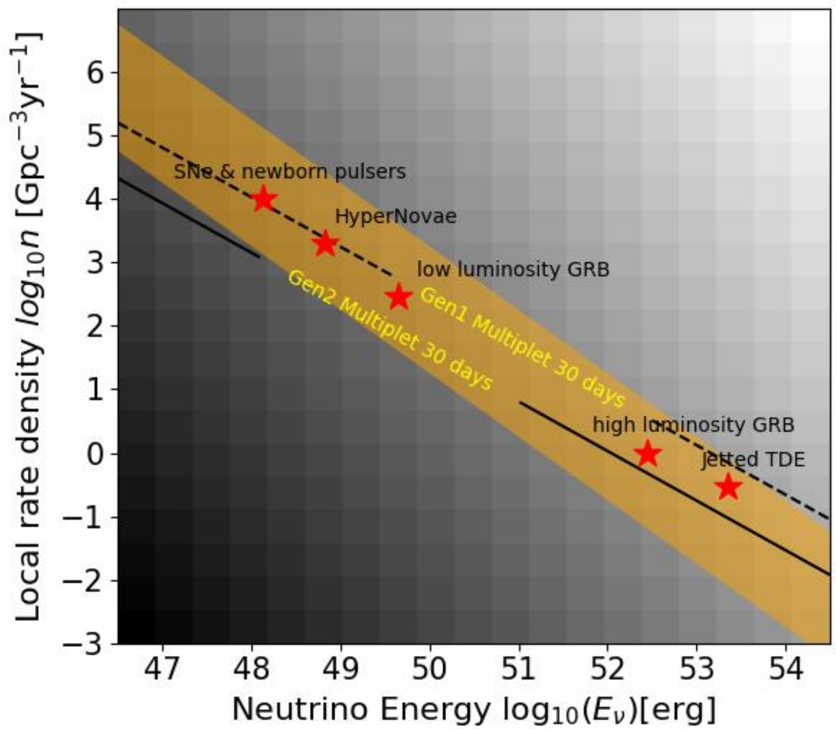
Averaged number of hit in ΔT from a single source: $\mu = \Delta T \int dE\, \boldsymbol{A}_{\mathrm{eff}}(\boldsymbol{E})\, \phi(z)$

Effective area of IceCube telescope

$$\frac{dN(n=2)}{dz} = \int dz\, \mathrm{density}(z) \times \mathrm{Poisson}(n=2|\mu)$$

p.d.f of z parameter for multiplet candidate

Backup


SNe & newborn pulsers
HyperNovae
low luminosity GRB
Gen2 Multiplet 30 days
Gen1 Multiplet 30 days
high luminosity GRB
Jetted TDE
Local rate density $log_{10}n$ [$\mathrm{Gpc^{-3}yr^{-1}}$]
Neutrino Energy $\log_{10}(E_\nu)$[erg]
6
5
4
3
2
1
0
−1
−2
−3
47
48
49
50
51
52
53
54

Comparison between the current scheme

	Current program	*New scheme*
Timing window	**100 s**	**Up to O(week)**
Philosophy of the optimization of sensitivity		**Source-oriented and consider a scheme to select an object in FoV**
Interaction type	**Track + Track**	**Track + cascade** **Track + Track**
Direction	**Northern**	**Northern + expand to southern**

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}	...

$$\phi_{\mathrm{PS}} = \frac{dN}{dAdtdE} = \frac{1}{4\pi r^2}(\alpha - 2)L\left(\frac{1}{\epsilon_0}\right)^2\left[\frac{E(1+z)}{\epsilon_0}\right]^{-\alpha}$$

$$\mu_{\mathrm{PS}} = T\int dEA(E,\Omega)\phi_{\mathrm{PS}}$$

$$N^{(n)} = \int dV P(n|\mu_{\mathrm{PS}})n_0(1+z)^3\psi(z),$$

$$dV = \frac{r^2}{(1+z)^2}cdtd\Omega.$$

According to Friedmann model, the equation of motion of the scale factor is calculated to be

$$\frac{dz}{dt} = H_0(1+z)\sqrt{\Omega_\Lambda + (1+z)^2\Omega_k + (1+z)^3\Omega_M},$$

where H_0 is Hubble parameter, Ω_Λ is the normalized cosmology constant, Ω_k is the normalized spatial curvature density, and Ω_M is the normalized matter density. The volume element is finally given as element over solid angle and redshift parameter:

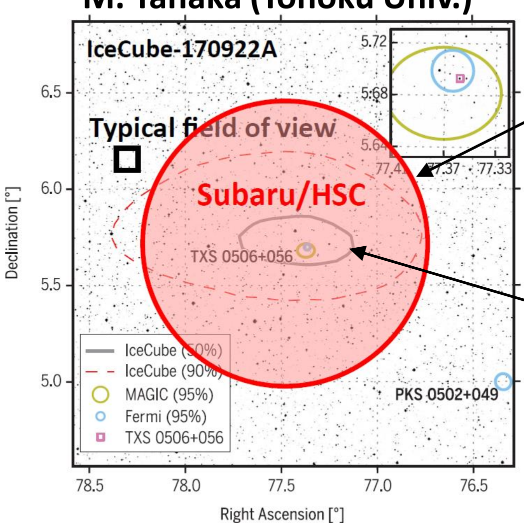
$$dV = \frac{r^2}{H_0(1+z)^3\sqrt{\Omega_\Lambda + (1+z)^2\Omega_k + (1+z)^3\Omega_M}}cdzd\Omega$$

Wide view optical telescopes

These days, many and many wide-field optical telescopes are available.

Kiso/Tomo-e Gozen

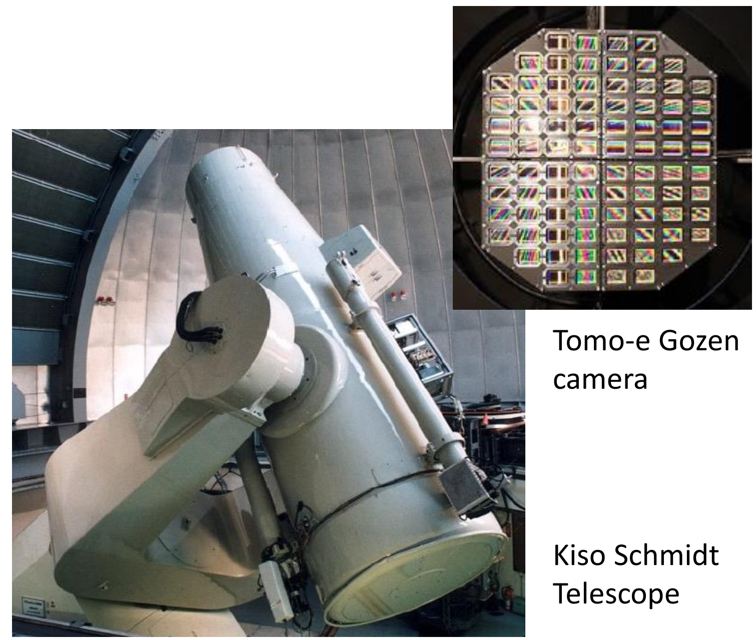
M. Tanaka (Tohoku Univ.)



Subaru

Uncertainty of IceCube (50%)

Tomo-e Gozen project



Tomo-e Gozen camera

Kiso Schmidt Telescope

Started design operation April 2019.
Cover 20 deg^2 at once.
Sub-second /frame

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 $N^{multiplet}/\,N^{BG}$.

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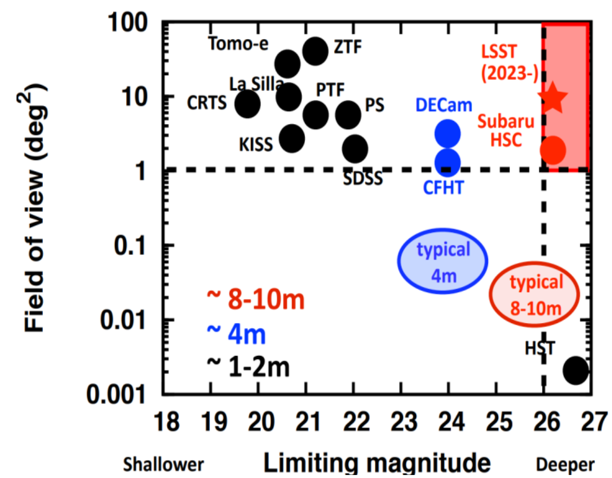
Field of view of various optical telescopes

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

T. Morokuma

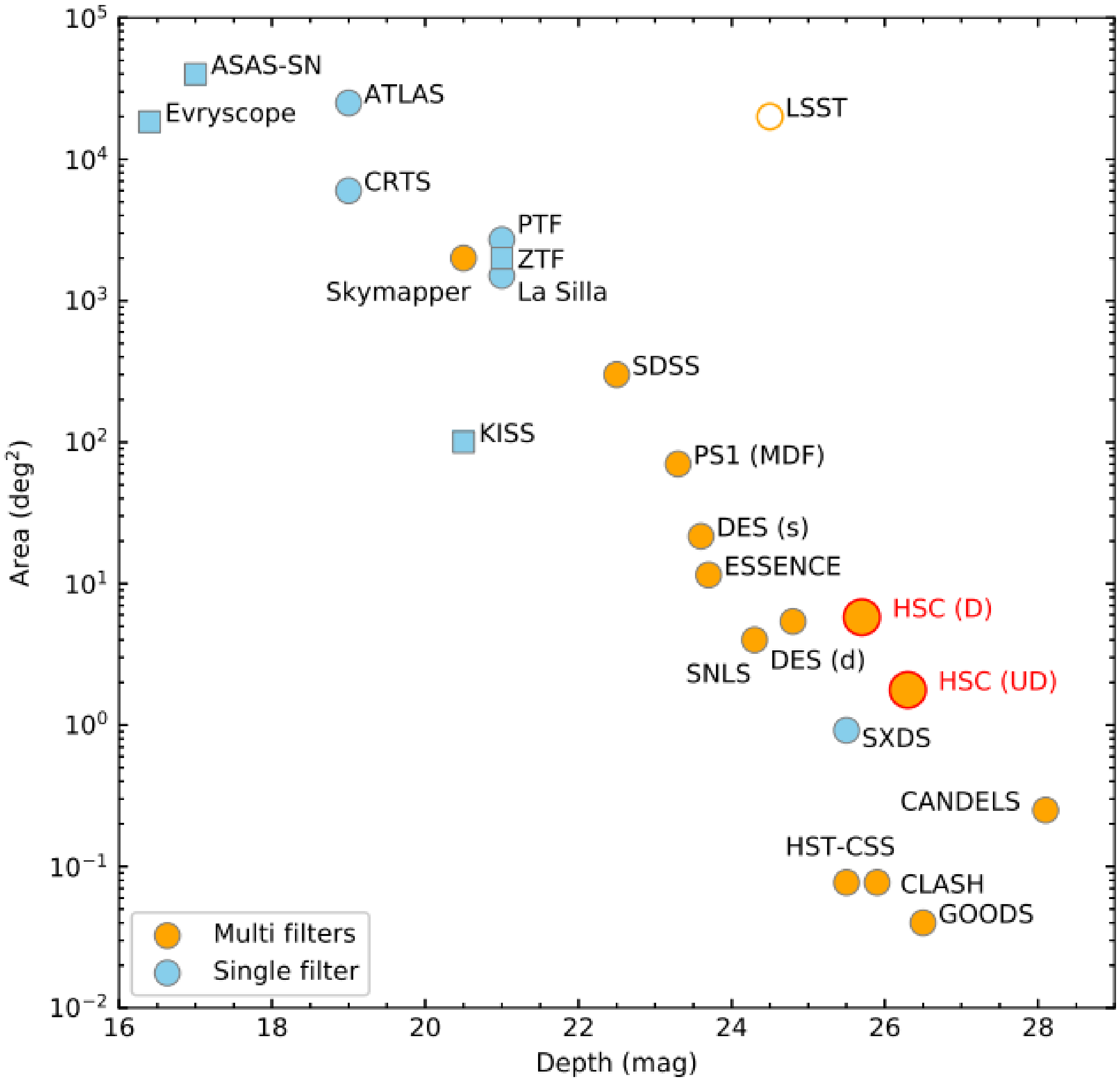
	tel [m]	FoV	area	cadence	depth	detector	note
PTF	1.2	7.3	8,000	5 days	R~20.6	CCD	Palomar 48" Law+2009
ZTF	1.2	47	数1,000?	a few hours	r~21	CCD	Palomar 48" 2018-
ASAS-SN	8 x 0.14	120	20,000	~1 day	~17	CCD	Haleakala & CTIO sites
CRTS	1.5+0.7+0.5	1.2+8.1+4.2	1,200	30 min (x4)	19-20	CCD	2 x USA + Australia
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.



N. Yasuda, *et al*, ApJS **71**, Issue 4, 74 (2019).

arXiv:2008.04323v