宇宙ニュートリノ望遠鏡 IceCubeによる新しいアラート マルチプレットチャンネルの開発

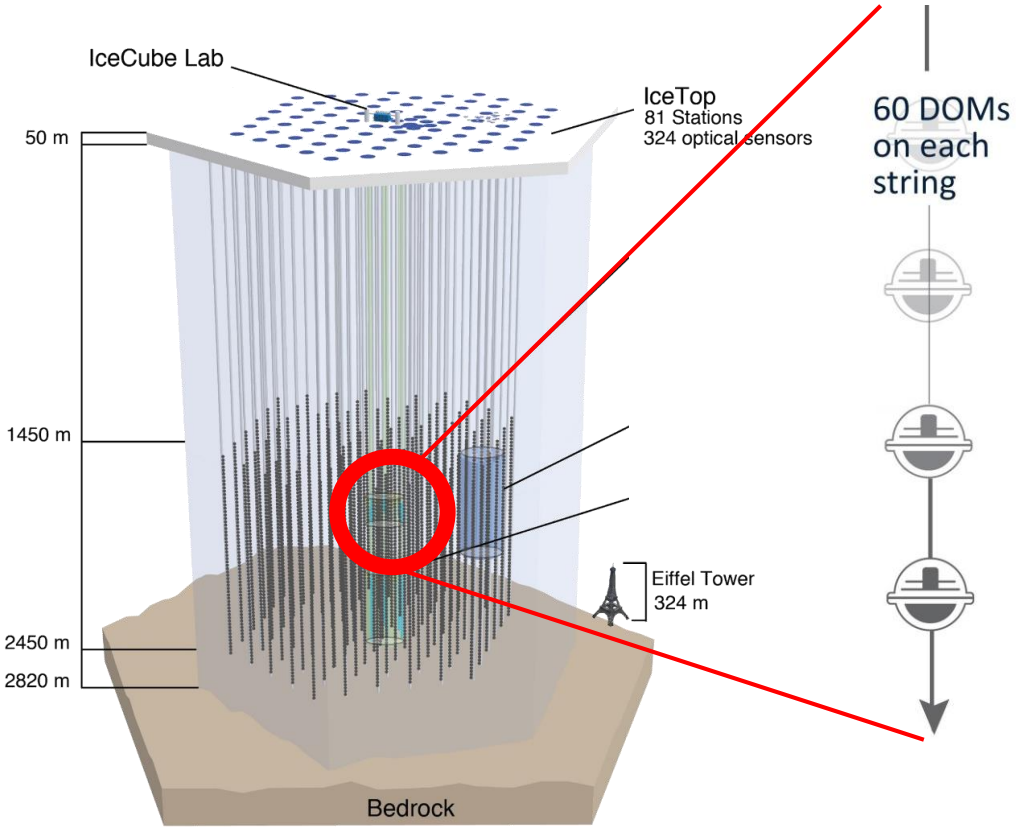
清水 信宏 (千葉大)
for the IceCube collaboration

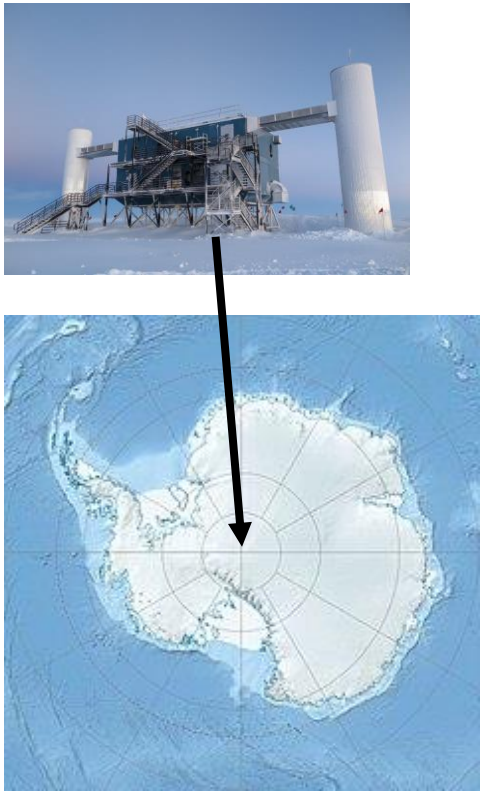
JPS2023 Autumn (Sep. 18th)

Picture: Y. Makino

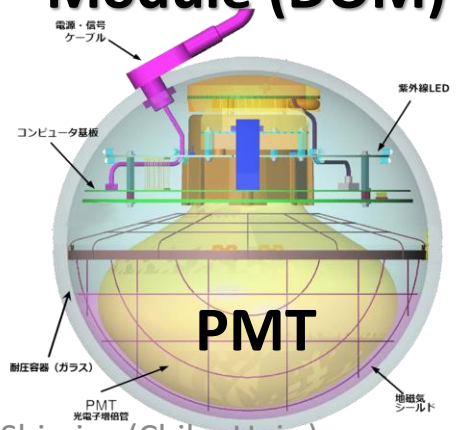
IceCube experiment

Neutrino telescope operated in Antarctica





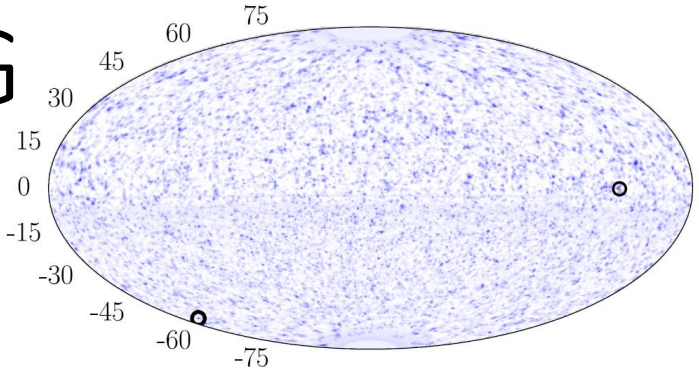
Digital Optical Module (DOM)



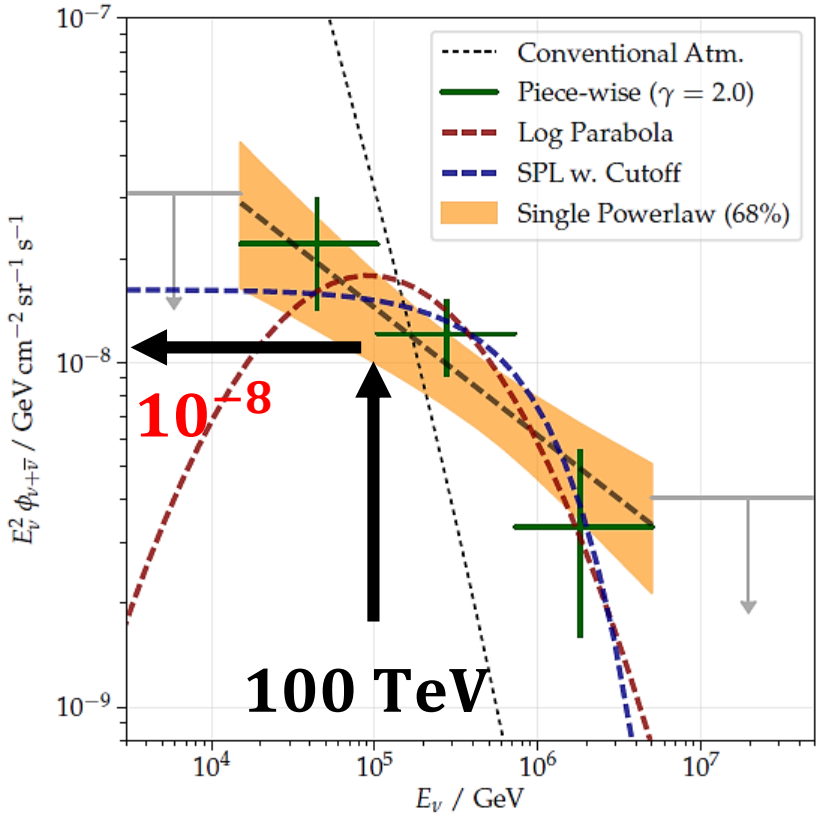
- 5160 optical modules are deployed in ice 1 ㎦
- Cherenkov light from charged particles produced by neutrino interaction is detected by DOM

High energy cosmic ν BG

Our universe is filled with high energy ν !



IceCube collaboration
PRL. **124**, 051103 (2020)



IceCube collaboration
APJ. **928** 50 (2022)

"Diffuse" flux

→ The origin of ν is not specified
= integrated whole the direction

Energy flux

$$E^2\phi_\nu \sim \mathbf{10^{-8}} \left(\frac{E}{100\ \mathrm{TeV}}\right)$$

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

Neutrinos flux characterization

$$\boldsymbol{\phi_\nu} \propto \mathcal{E}_\nu \times \rho_\nu \quad \text{(+ evolution)}$$

ν-flux

Rate density $[\mathrm{Mpc}^{-3} \cdot \mathrm{yr}^{-1}]$

ν emission energy [erg]

Scenarios of the origin of diffuse neutrinos

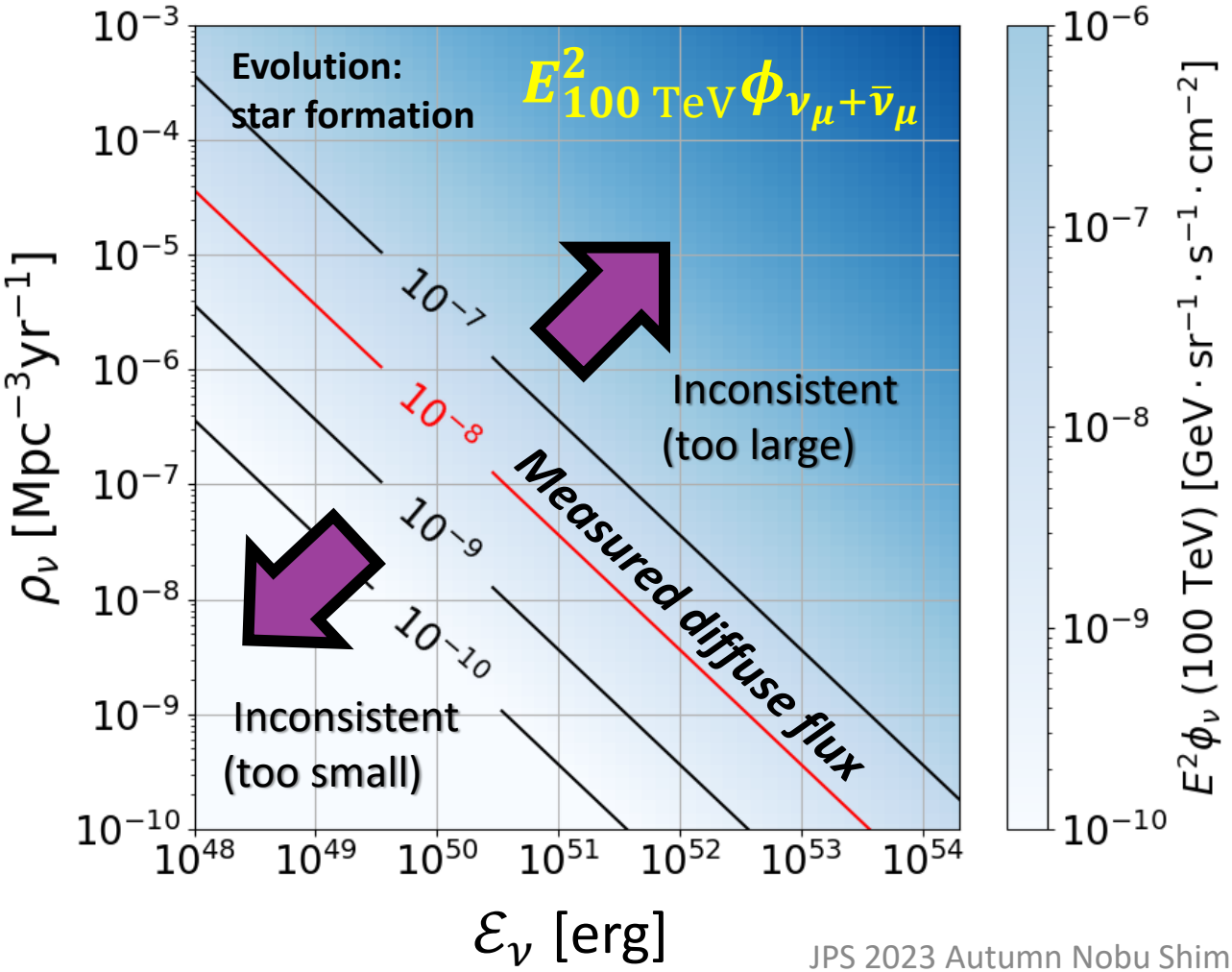
Bright (high $\mathcal{E}_\nu$) & Rare (small ρ_ν)

Dim (small $\mathcal{E}_\nu$) & Generous (high ρ_ν)

Diffuse energy flux on ($\mathcal{E}_\nu$, ρ_ν) plane

[Condition]
Consistency with the diffuse flux

$E^2\phi_\nu \sim 10^{-8}$ (100 TeV)
[GeV$\cdot$ cm$^{-2}\cdot$ s$^{-1}\cdot$ sr^{-1}]

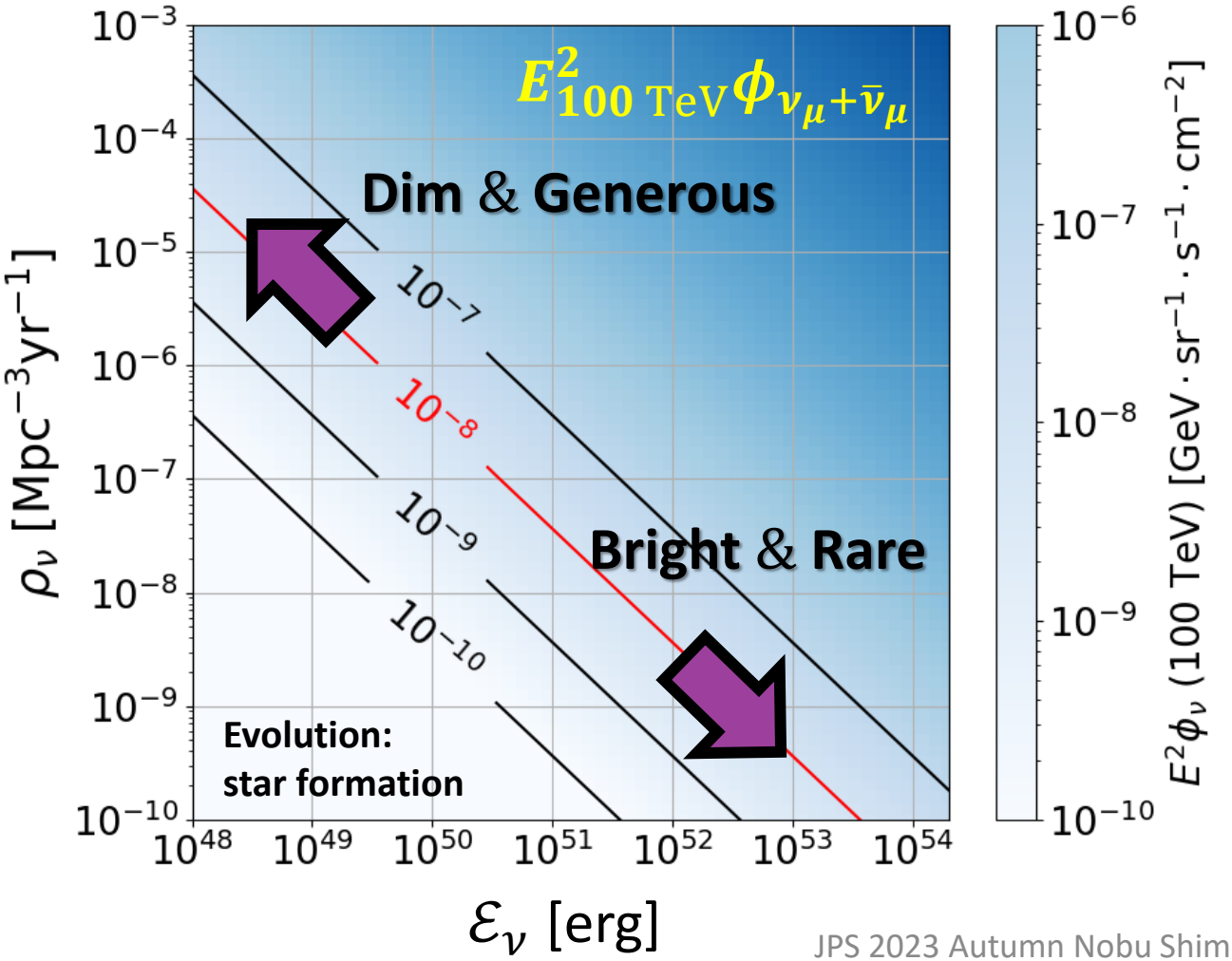


Diffuse energy flux on ($\mathcal{E}_\nu$, ρ_ν) plane

[Source characterization]

$E^2\phi_\nu \sim 10^{-8}$ (100 TeV)

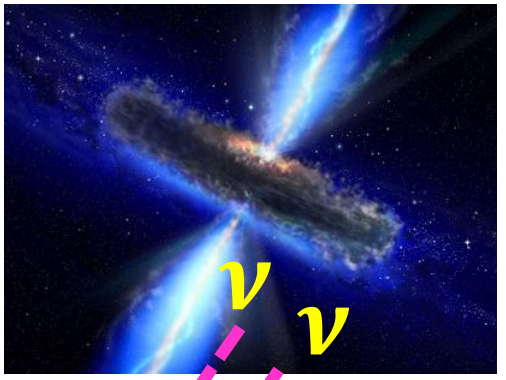
[GeV· $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$]



ν-multiplet as a probe of bright sources

What is multiplet?

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

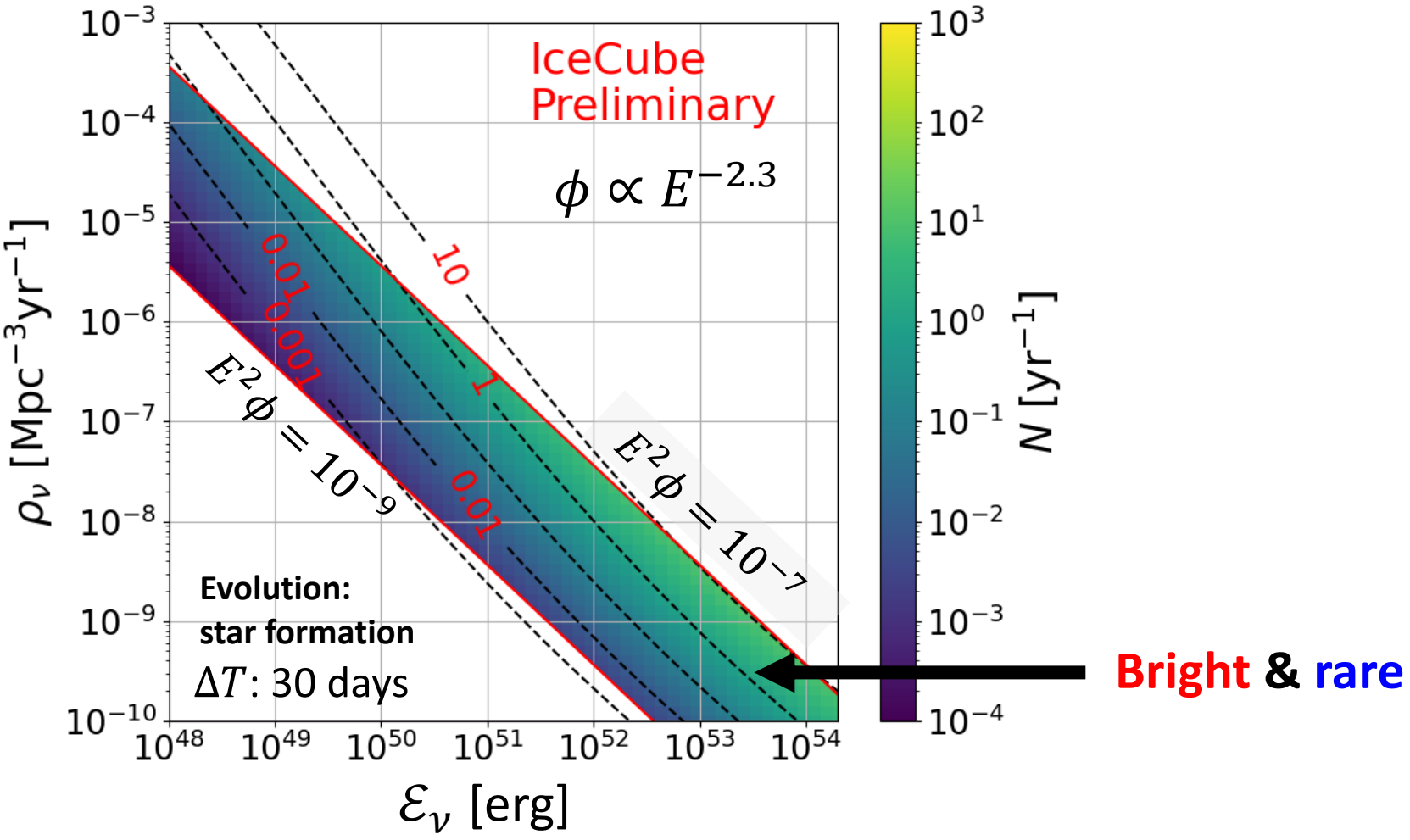


In terms of rate

$$\phi_\nu = R_{\text{signlet}} \propto \mathcal{E}_\nu \times \rho_\nu$$
$$R_{\text{doublet}} \propto (\mathcal{E}_\nu)^2 \times \rho_\nu$$
$$R_{\text{triplet}} \propto (\mathcal{E}_\nu)^3 \times \rho_\nu$$

Multiplets are sensitive to
Bright (high $\mathcal{E}_\nu$) & Rare (small ρ_ν) sources

Expected number of ν-Multiplet signal

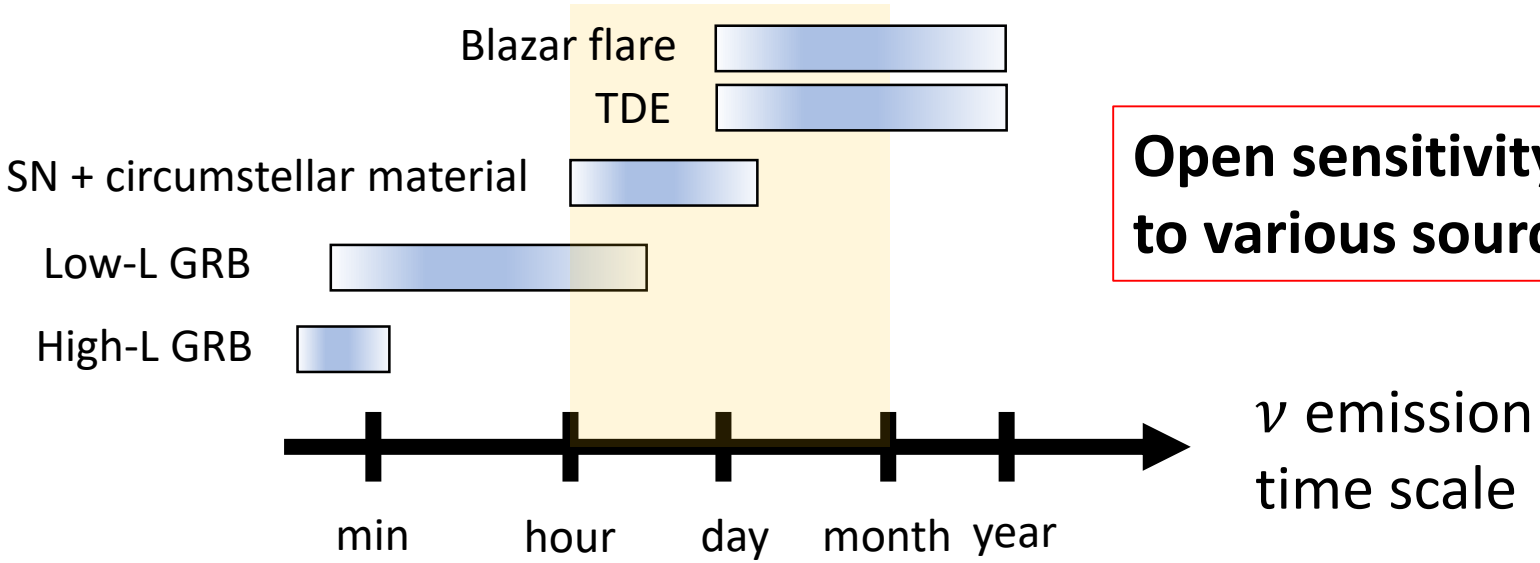


This is a pure number of detections.

In reality, we need to further select multiplets against backgrounds.

Multiplet timing window

- Set ΔT = 30 days.
  → Various sources can have time scale of month!



Open sensitivity to various sources.

- Technical challenge
  - Long ΔT → large # of backgrounds.
  - Previous multiplet study was 100 sec
    → Accommodate 30 days with an improved method of BG rejection

Selection of multiplet signal

- Major background source → **atmospheric neutrinos**
- Focus only on **doublets** and **triplets**
- *Construct a **test statistic Λ** from signal and background likelihoods: $\mathcal{L}_{sig}, \mathcal{L}_{bg}$*

[Doublet case]

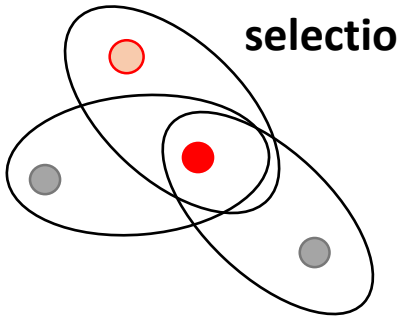
Rate *Energy PDF* *Spatial PDF*

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

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

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

In the case of Double selection



Select most signal-like ν combinations using Λ

Search for multiplets in 12 years data

Performed a multiplet search with the new method.

Item	Values
Dataset	Northern track* (DEC > $-5°$)
Duration	2011-May to 2022-Dec.
Livetime	11.4 years
ΔT	30 days
$N_{\text{expected}}^{\text{doublet}}$	1.2×10^7
$N_{\text{expected}}^{\text{triplet}}$	2.8×10^4

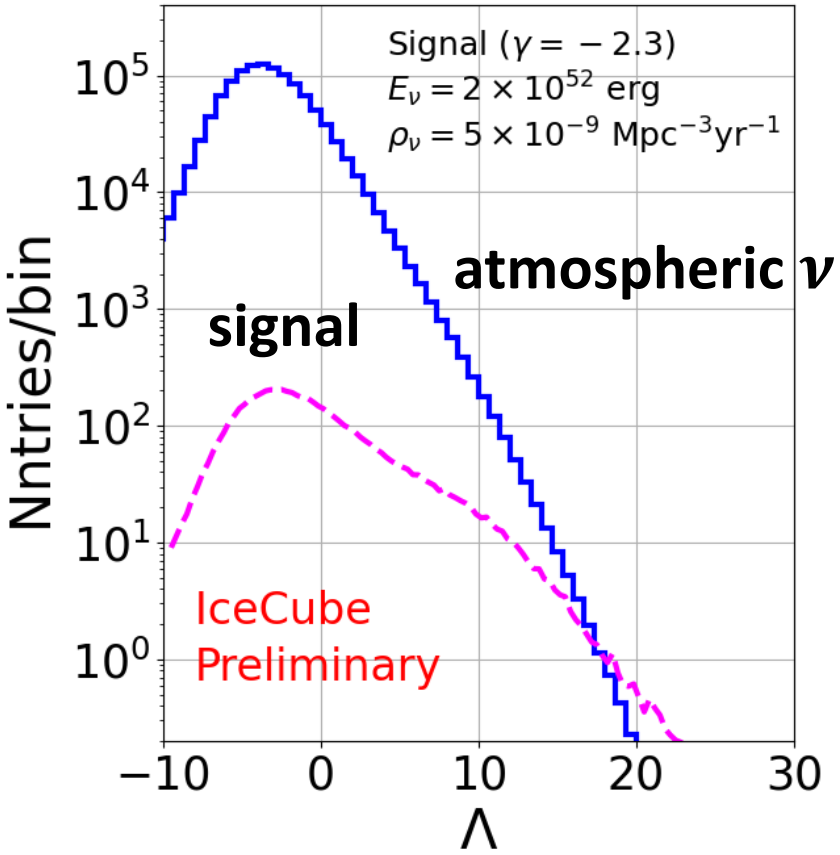
*Common dataset used for realtime alert

→ this method will be used also for multiplet alert

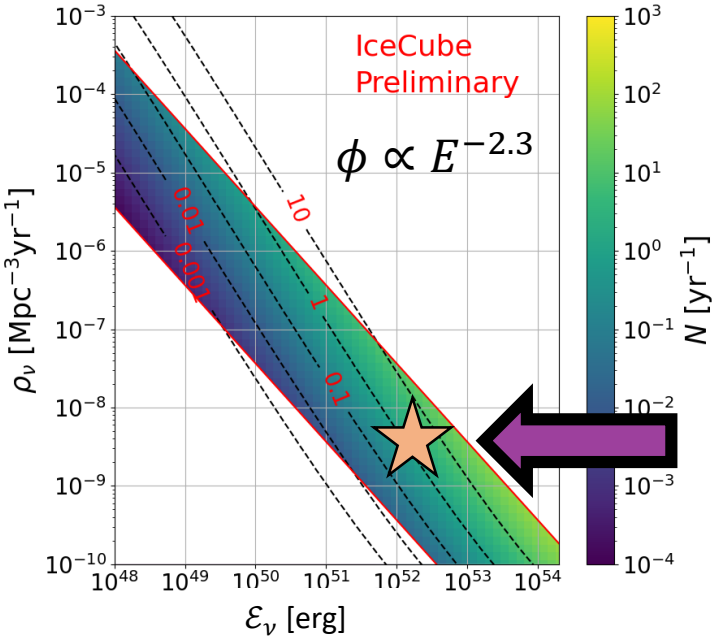
Test statistic Λ distribution

Doublet

$$N_{\text{expected}}^{\text{doublet}} = 1.2 \times 10^{7}$$



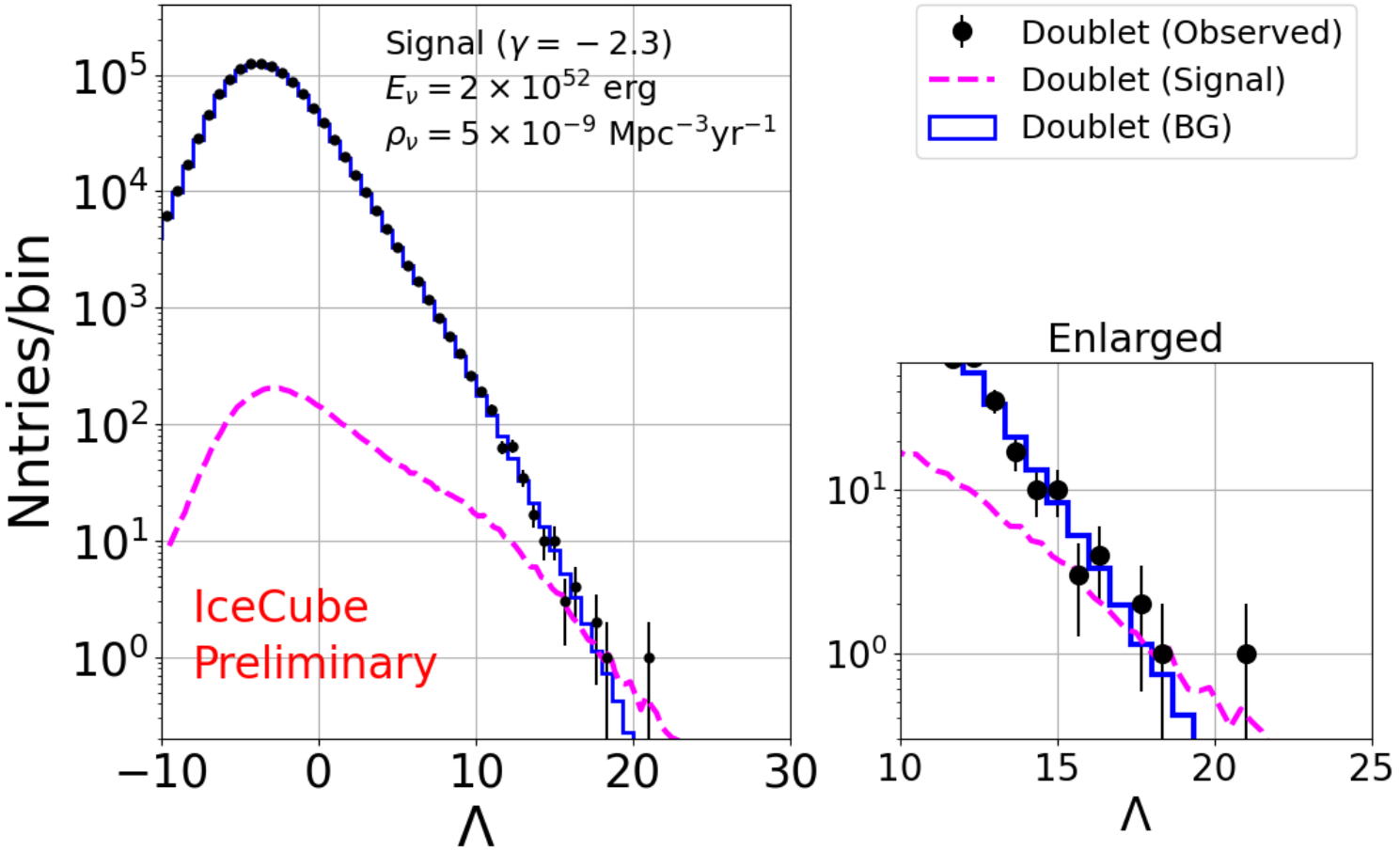
More signal like ⟶



Assumed signal

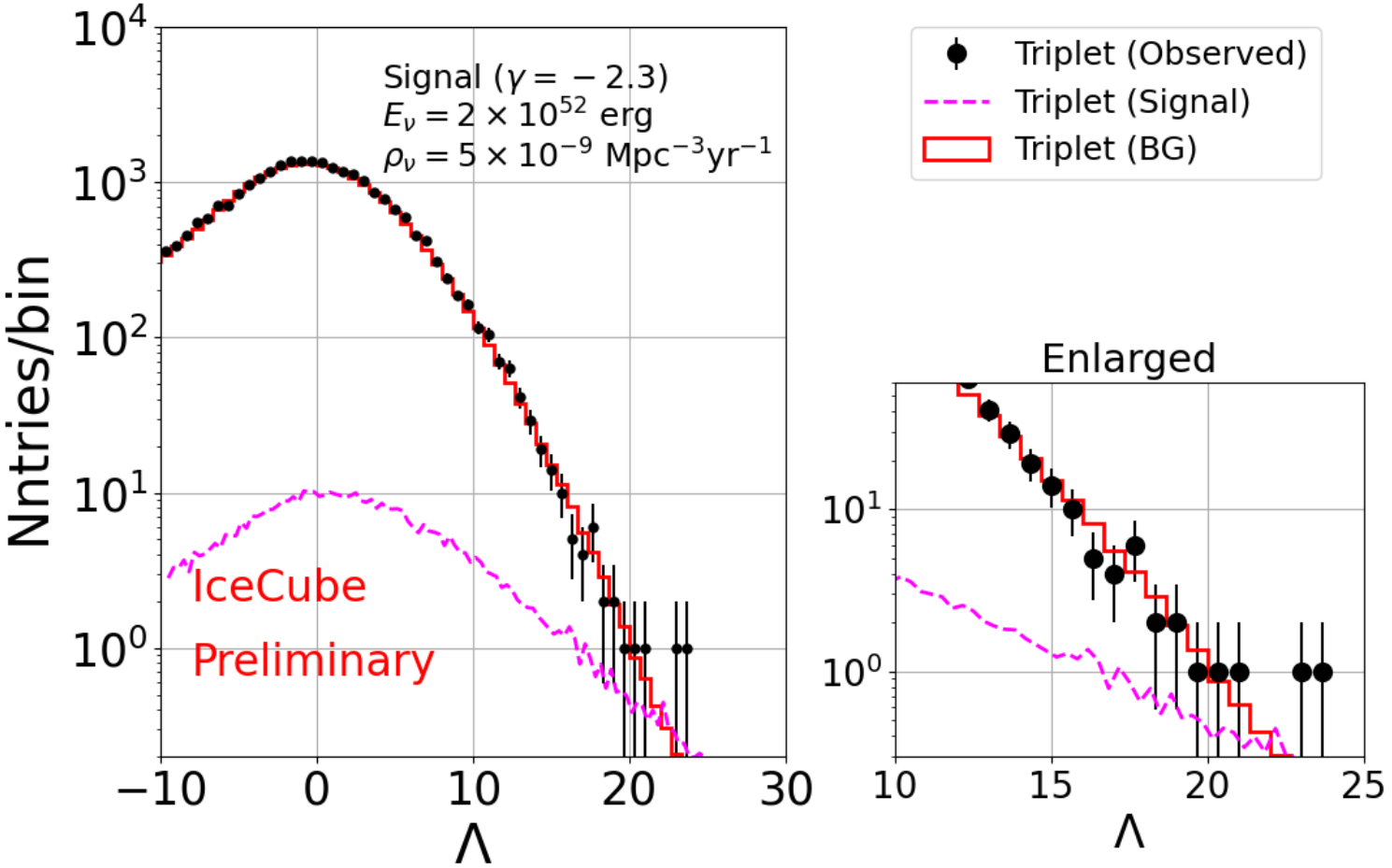
Result (12 years data)

Doublet



Result (12 years data)

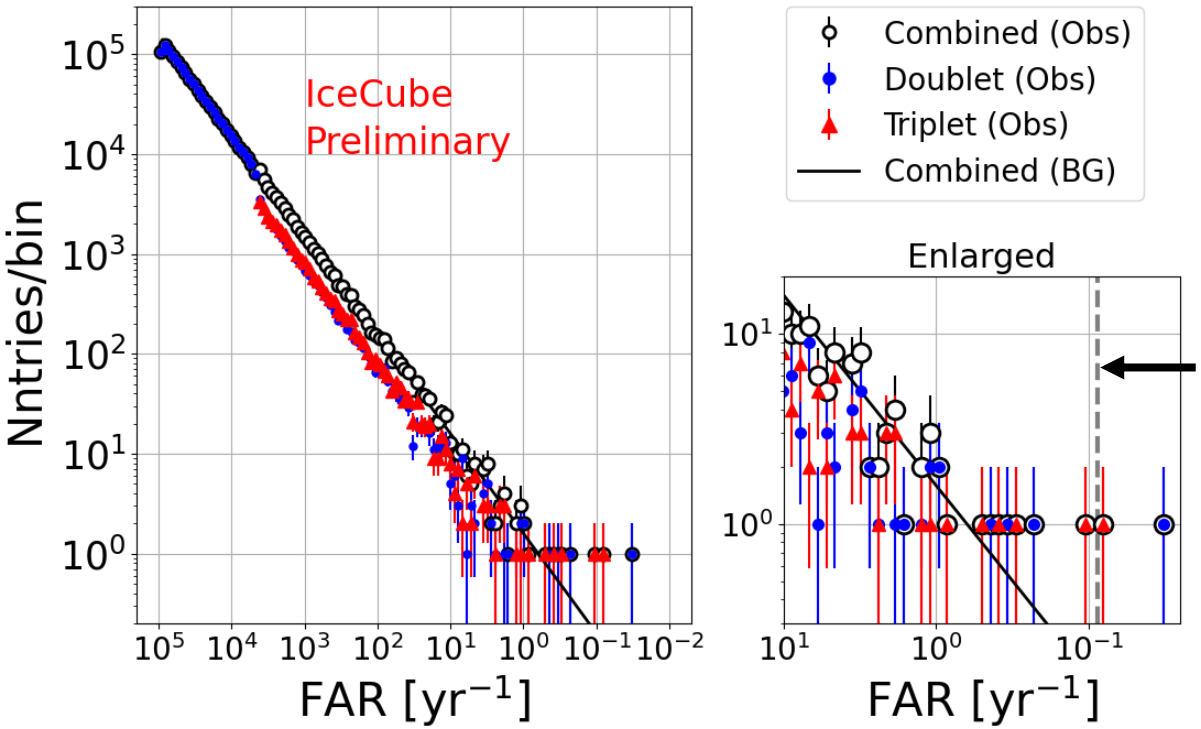
Triplet



Is this consistent with background?

The observed test statistic Λ is converted to false alarm rate (FAR) [1/year].

FAR (Λ) → expected rate to observe higher Λ only from backgrounds.



1/11.4 yr (total livetime)

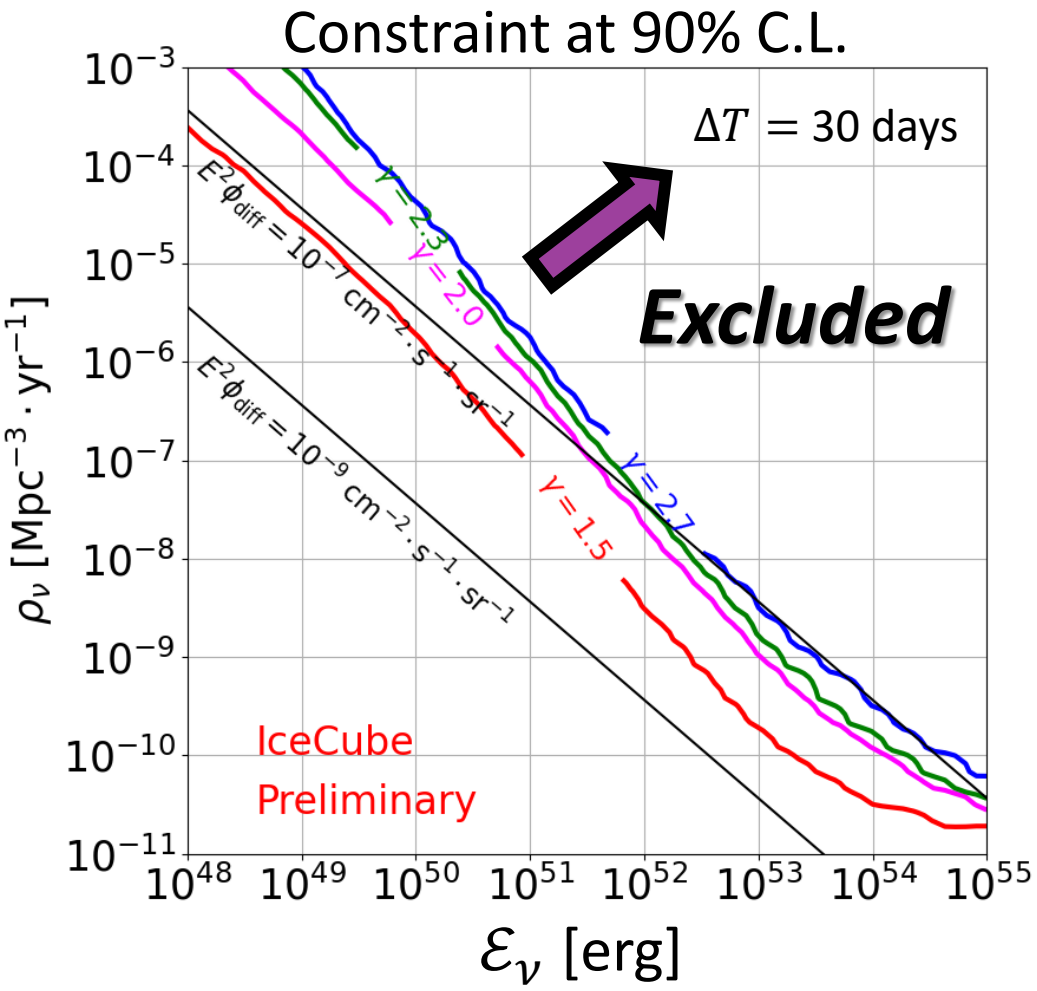
As a whole dataset, the observation was **consistent** with BG-only hypothesis.

Global p-value = 0.14 (1.1σ)

What can we interpret?

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

Assumed several spectral indices $\phi \propto E^{-\gamma}$



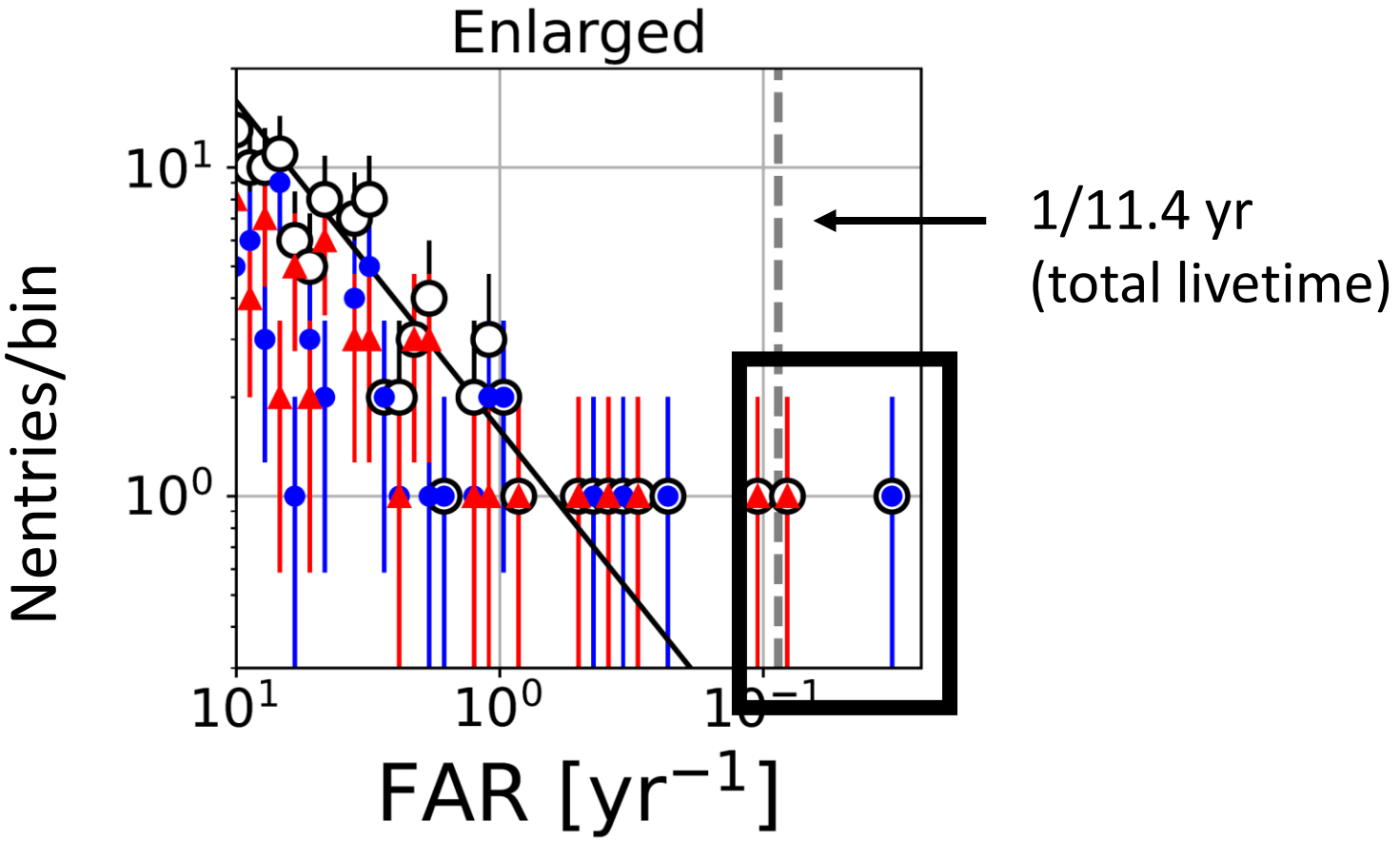
Eg., for $\gamma = -2$ case,

At $\mathcal{E}_\nu = 10^{52}$ [erg]

$\rho_\nu > 3 \times 10^{-8}$ [Mpc$^{-3}\cdot$yr^{-1}]

is excluded at 90% C.L.

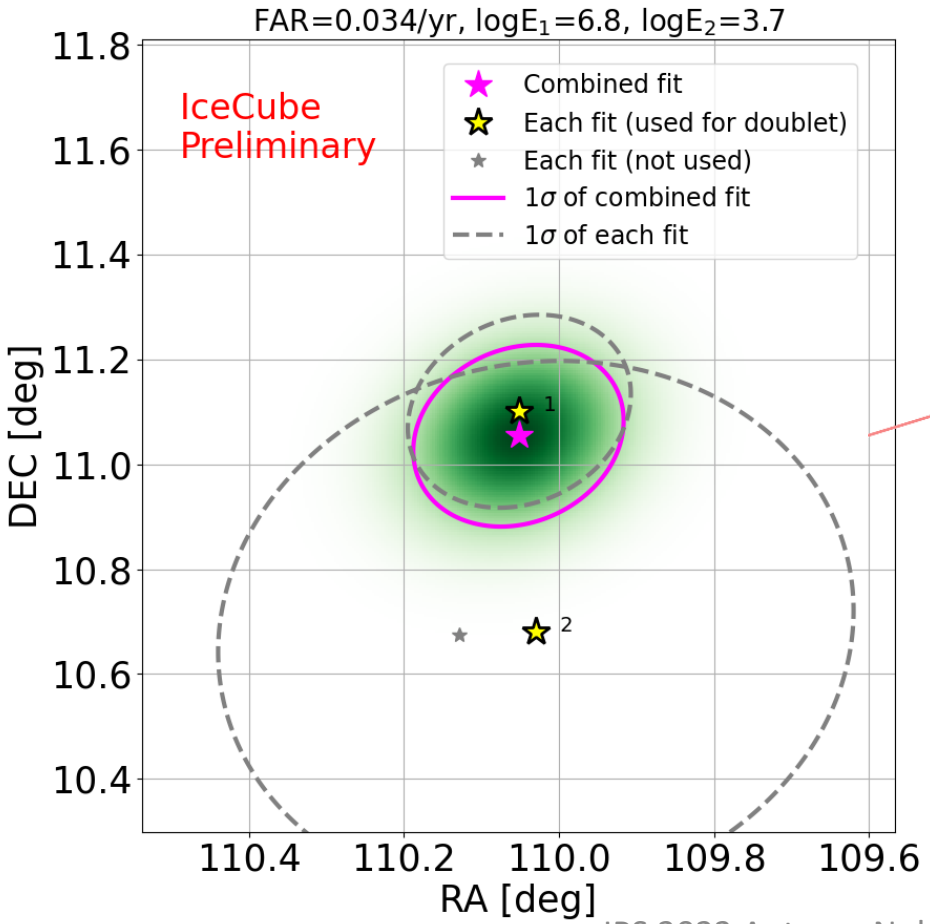
What do the rare multiplets look like?

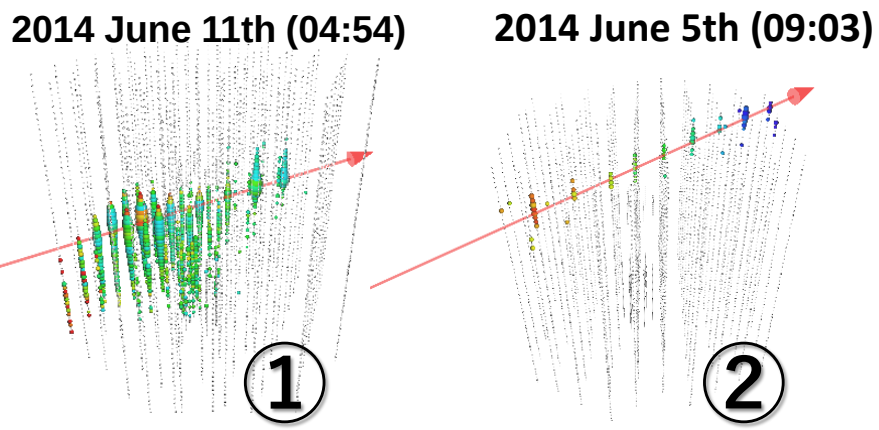


Though global p-value=0.14 was 1.1σ, significant multiplets are still interesting.
With the criteria of FAR<1/11.4 [yr^{-1}], **two multiplets were found**.

The most significant multiplet

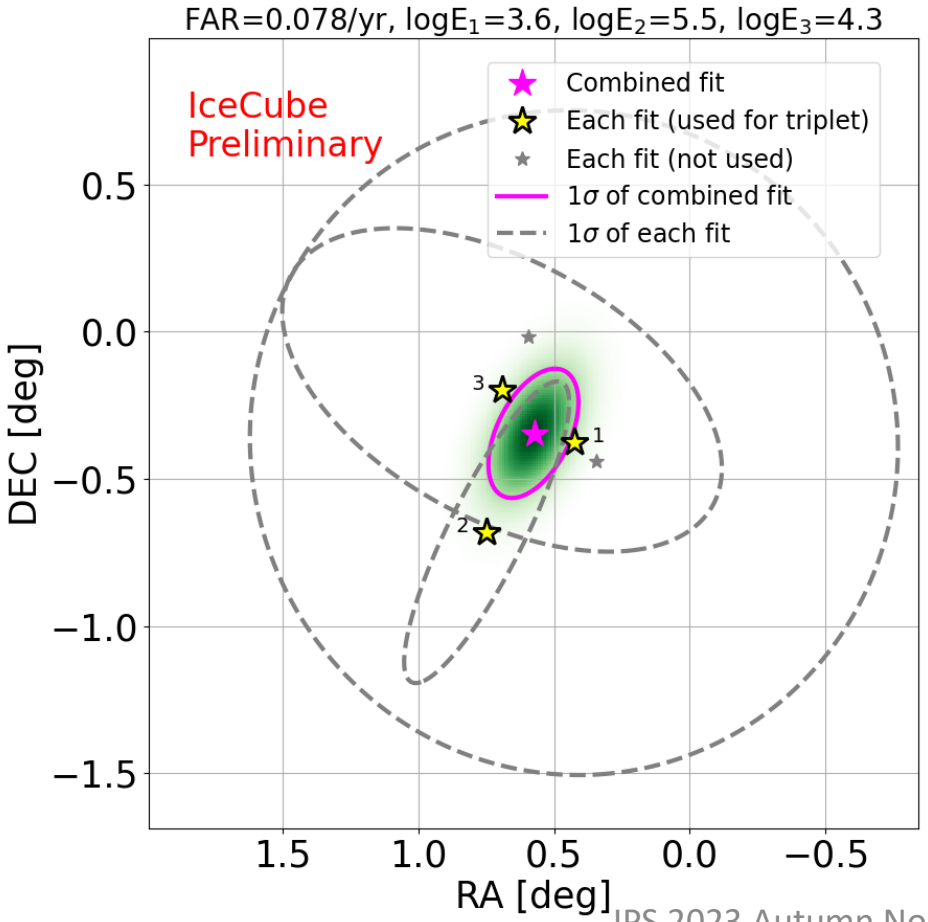
Type: **Doublet**, (RA, DEC)=(110.05 deg, 11.05 deg)
Energy: E=(6 PeV, 6 TeV), $\Delta T = 5.8$ days,
local p-value=3.2×10^{-7}, FAR= 1/29 [1/yr]

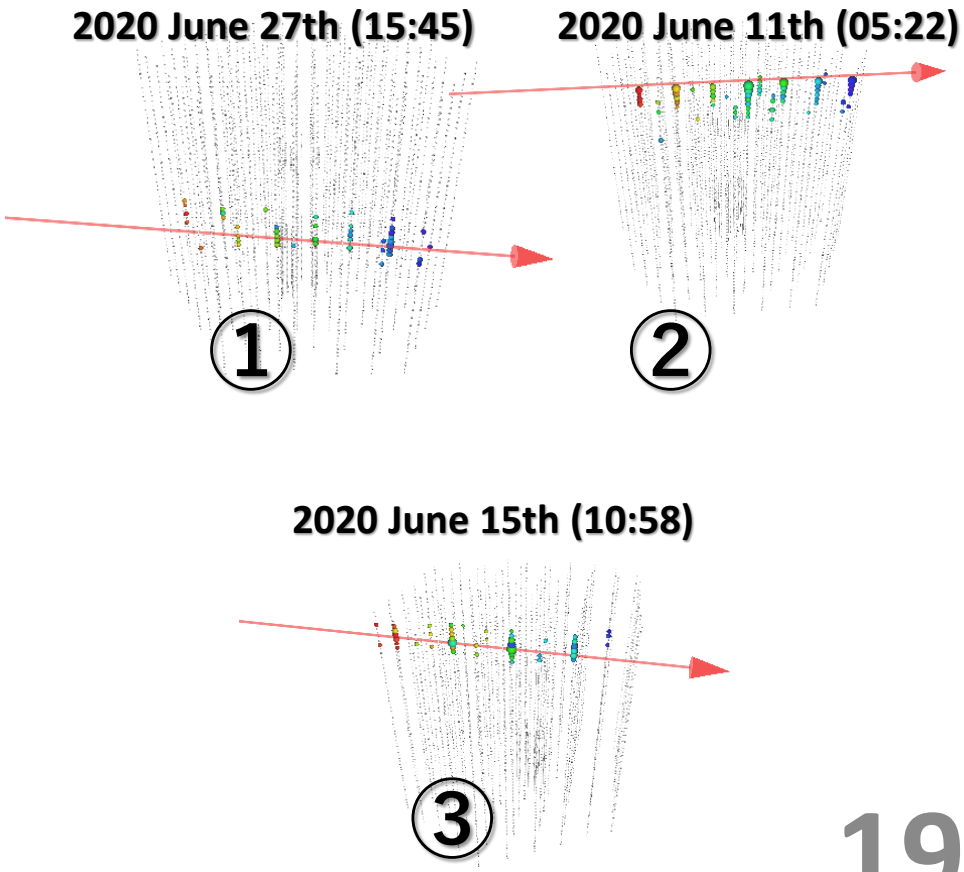




2nd significant multiplet

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

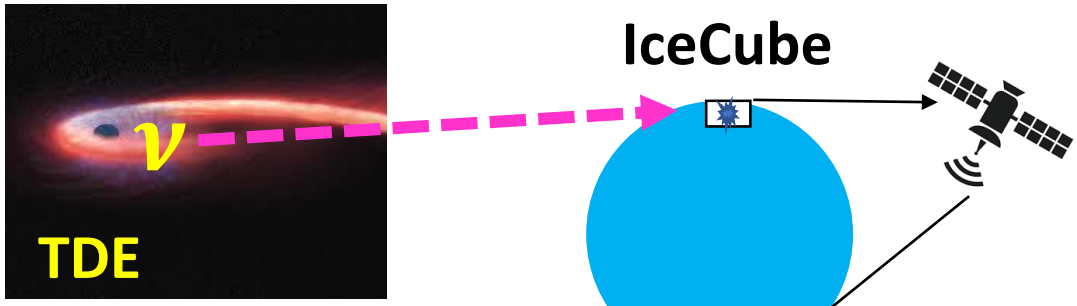




Hunt the origin of the ν-source

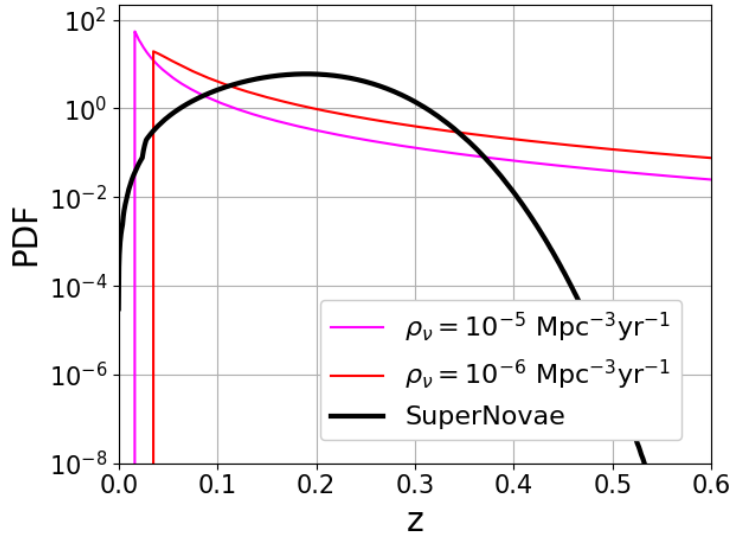
Use multiplet signals to hunt **bright** & **rare** ν-sources

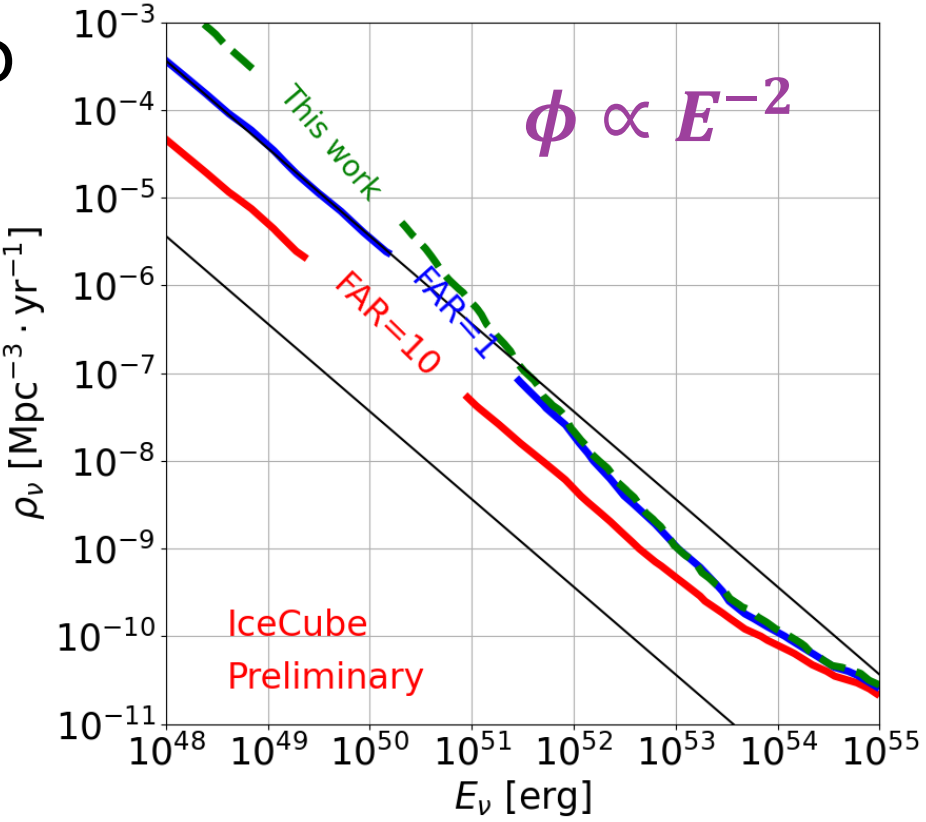
Strategy: issue a public **multiplet** alert to other telescopes



Why multiplet alert?

z distribution of multiplet from ν-source and supernovae





- multiplet signal gives bias on **close sources ($z < 0.1$)**
  - ① close sources are easy to observe with small telescopes
  - ② discriminate irrelevant transients such as SNe.

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

$\Delta\psi \sim 0.3°$ at 90% containment → useful for optical telescope

Summary and plan of the alert operation

- Multiplet signal is a probe of **bright** & **rare** $\boldsymbol{\nu}$-sources

- 12 years archival data was analyzed
  - As a dataset, the observed multiplets were consistent with BG.
  - Two observed multiplets satisfied FAR<1/livetime.
  - Applied constraint on the ν-source parameter

- Intensively working towards the operation of new multiplet alert!
  - Aiming for the start of the operation early in next year

We are happy about your cooperation of future follow-up!

Backup

Diffuse energy flux on ($\mathcal{E}_\nu$, ρ_ν) plane

[Source candidates?]

$E^2\phi_\nu \sim 10^{-8}$ (100 TeV)

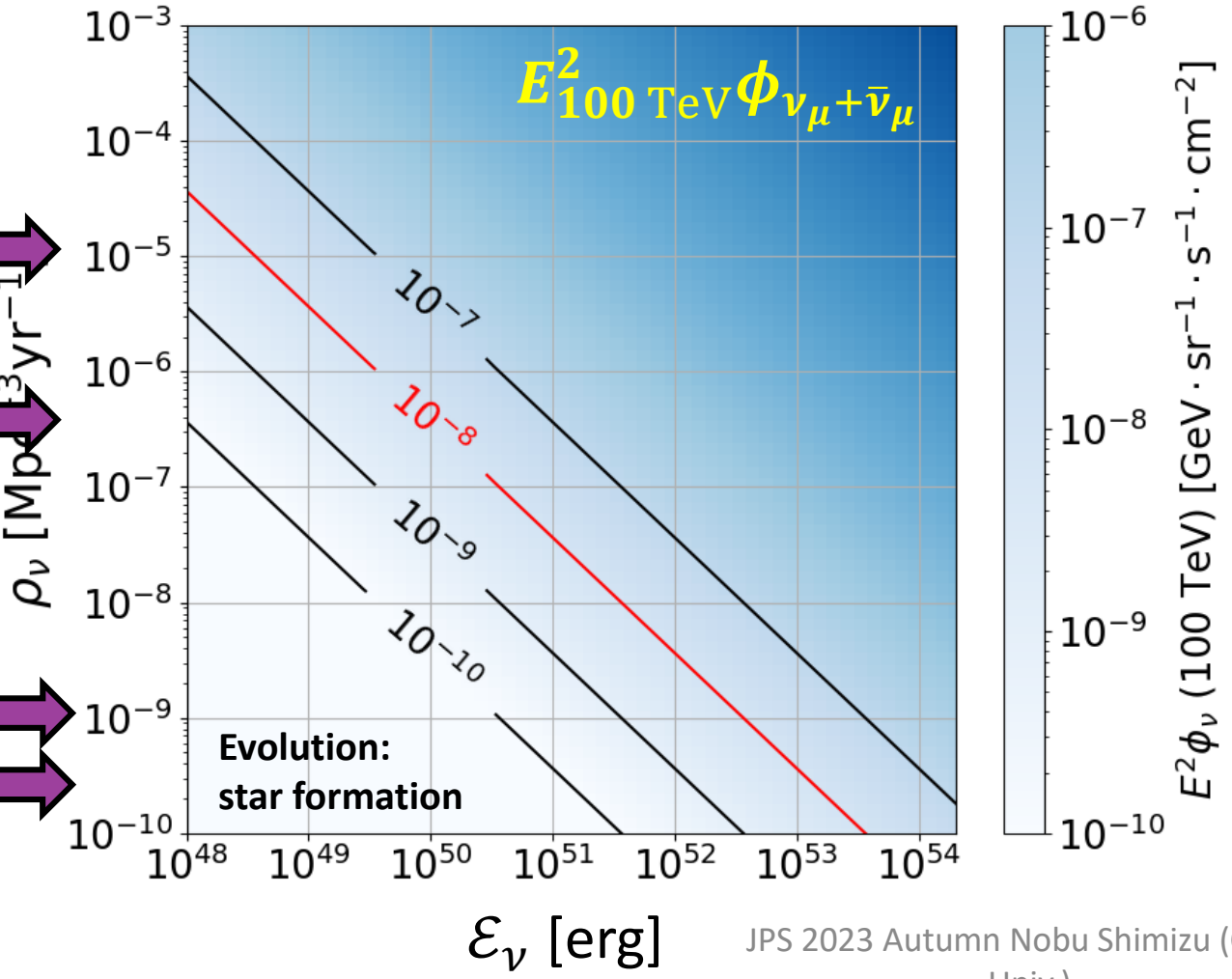
[GeV· $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$]

SNe

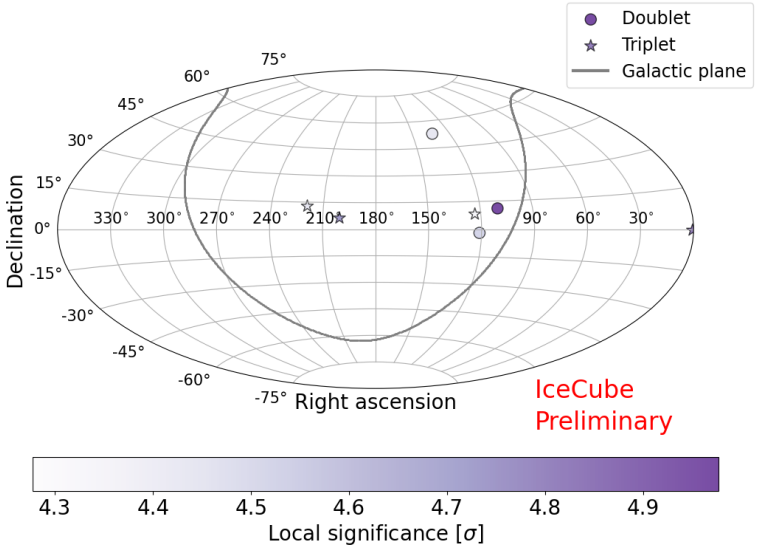
Low Lum. GRB

High Lum. GRB

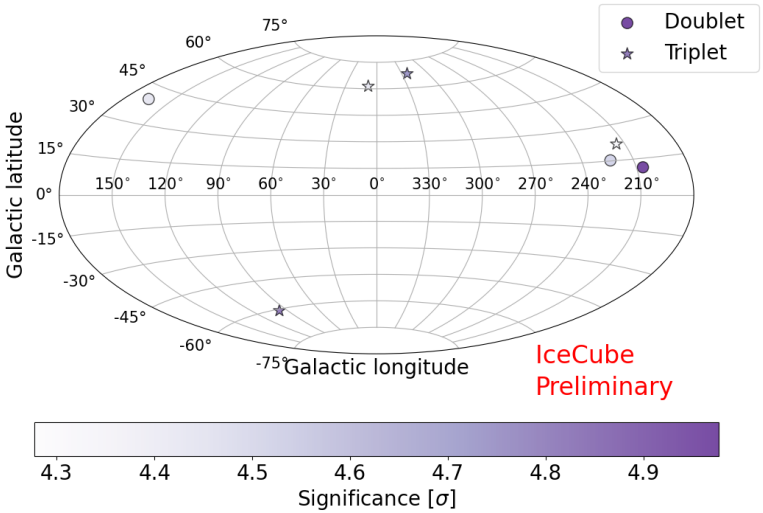
TDE



Doublet and triplet in skymap



Equatorial coordinate

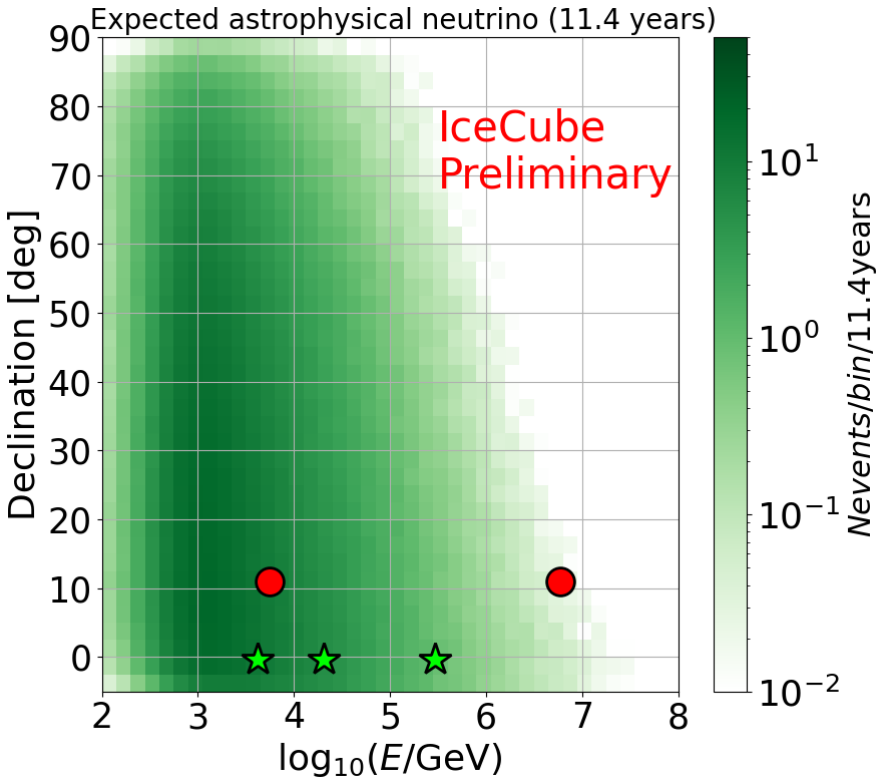


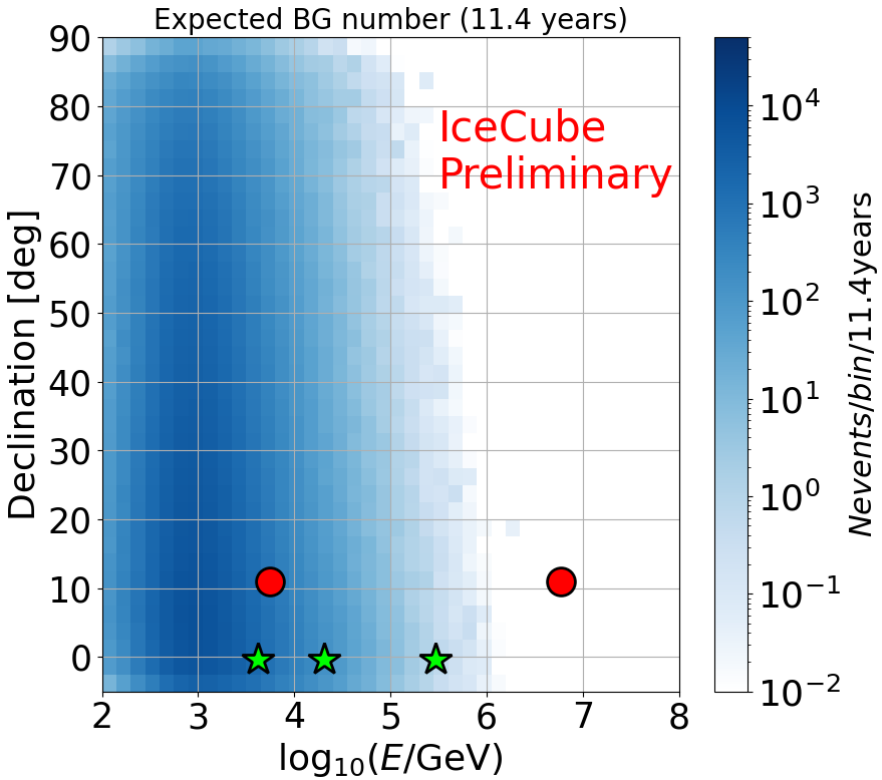
Galactic coordinate

Distribution of energy and declination

Observed doublet

Observed triplet



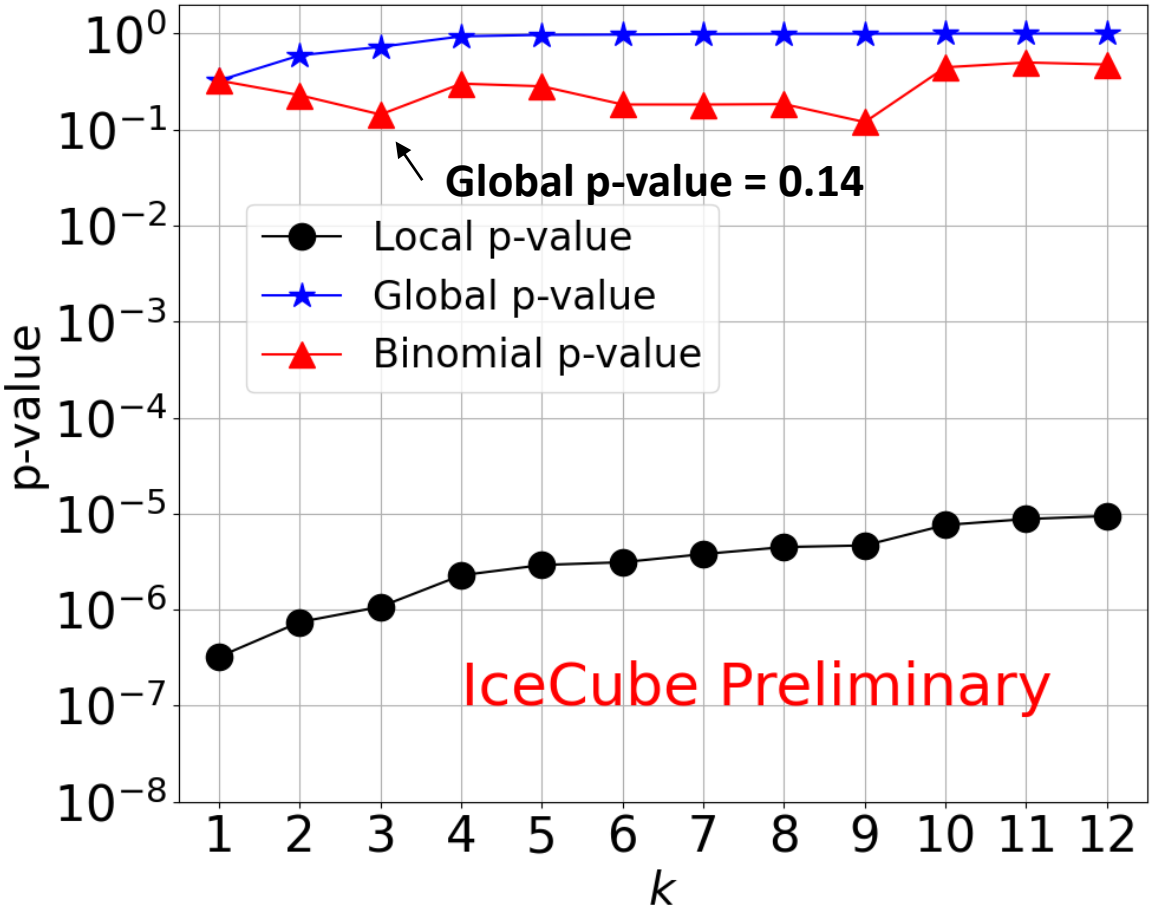


Astrophysical neutrino

Atmospheric neutrino

Binomial tests

Binomial p-value $$P(k) = \sum_{m=k}^{N} \binom{N}{m} p_k^m (1-p_k)^{N-m}$$

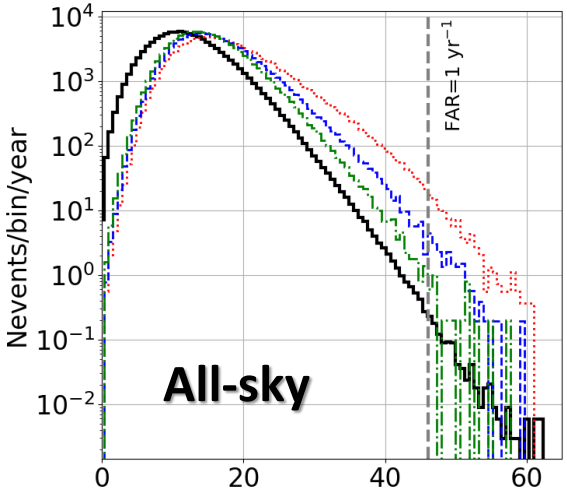


TS distribution

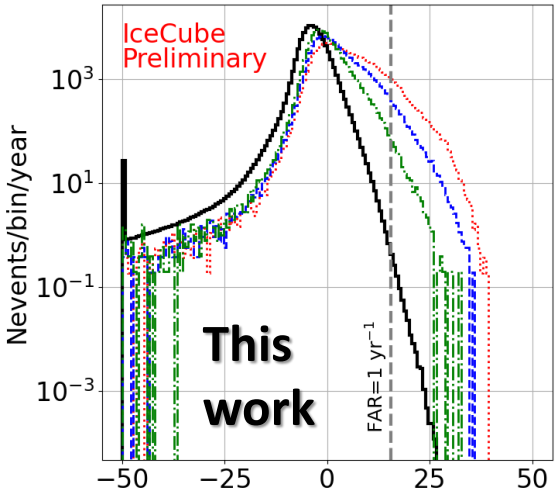
- $dN/dE \propto E^{-\gamma}$
- $N_{\mathrm{det}}^{\mathrm{sig}} = \mathbf{2}$
- $T_{\mathrm{max}} = 30$ days
- Timing distribution of signal → uniform in T_{max}

BG
$\gamma = 2.0$
$\gamma = 2.3$
$\gamma = 2.7$

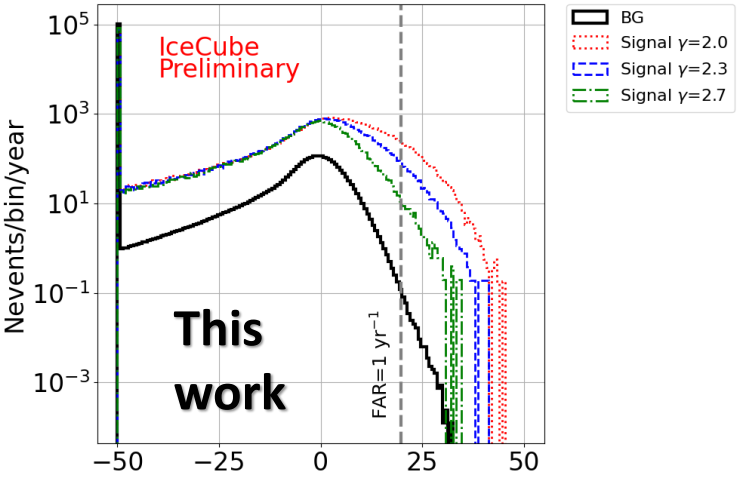
*the lowest bin is underflow (for triplet, no association of three tracks)



$\Lambda_{\mathrm{all-sky}}$



$\Lambda_{\mathrm{doublet}}$



$\Lambda_{\mathrm{triplet}}$

The new proposed method shows higher separation capability between BG and signal than the all-sky method (for such small $N_{\mathrm{det}}^{\mathrm{sig}}$).

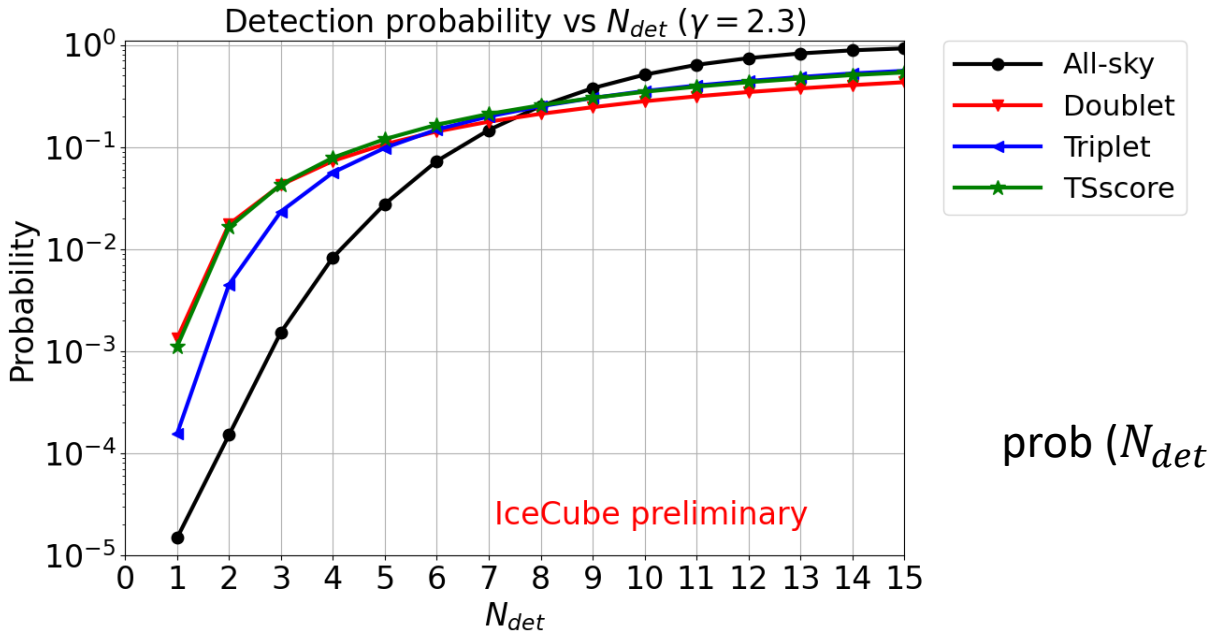
Detection Efficiency of signal

Efficiency: fraction of successive trials which exceeds Λ-threshold at FAR=1/year.

1 trial : addition of N_{det} signal events into 30 days BG events

To unite both $\Lambda_{\mathrm{doublet}}$ and $\Lambda_{\mathrm{triplet}}$, we define TS-score:

TS score = $\max\{-\log_{10}\mathrm{FAR}^{\mathrm{doublet}}(\Lambda_{\mathrm{doublet}}), -\log_{10}\mathrm{FAR}^{\mathrm{triplet}}(\Lambda_{\mathrm{triplet}})\}$

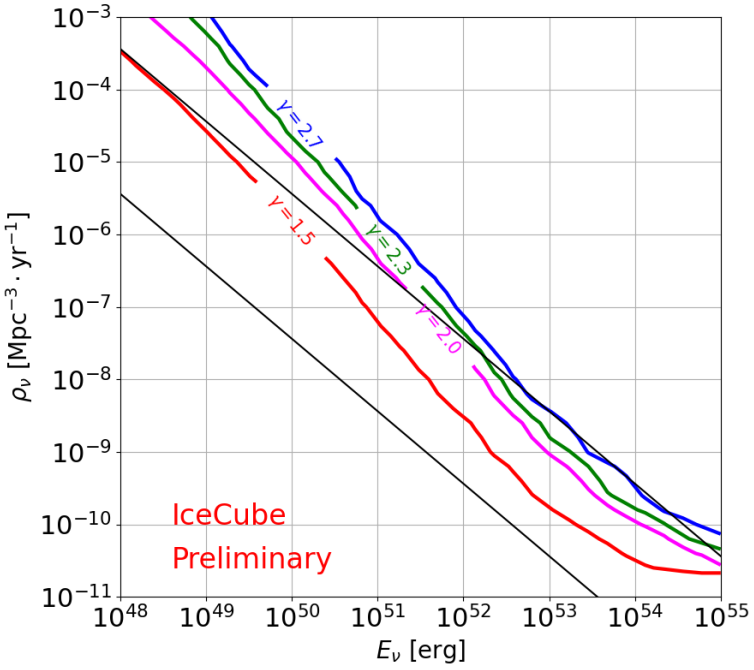


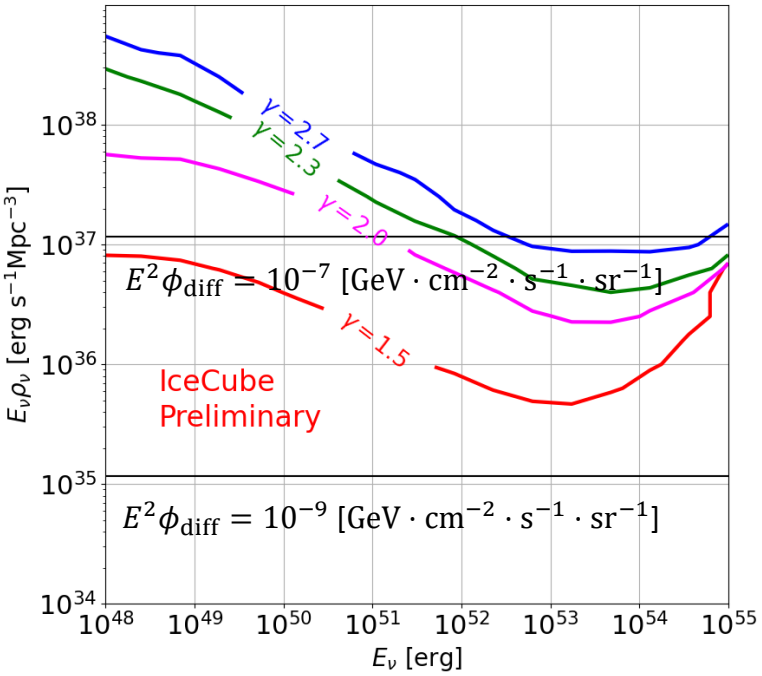
$$\text{prob}\,(N_{det}) = \frac{N_{\mathrm{trial}}^{\mathrm{pass}}}{N_{\mathrm{trial}}}$$

For small number of N_{det},
the new method shows O(100) higher efficiency to signal.

Constraint of ν-source parameter

If we do not have any ν-source (BG-only scenario)





$\gamma = 2.3$ $\gamma = 1.5$

$\gamma = 2.7$ $\gamma = 2.0$

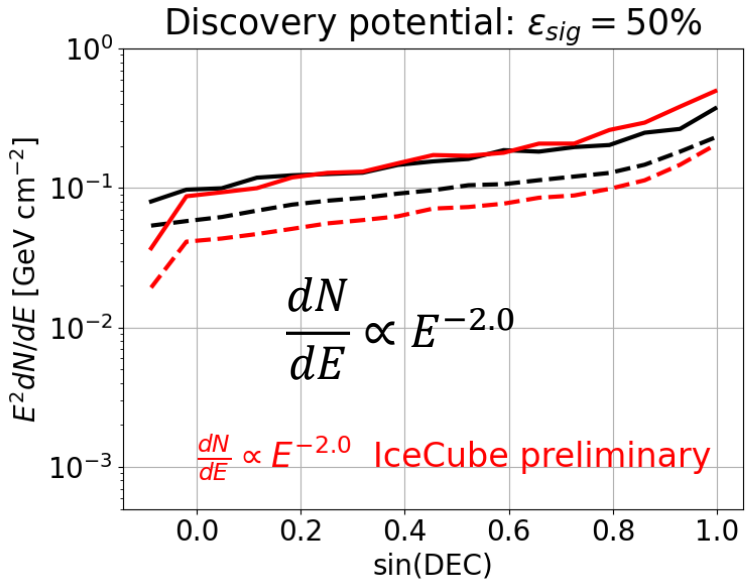
p-value = 10%

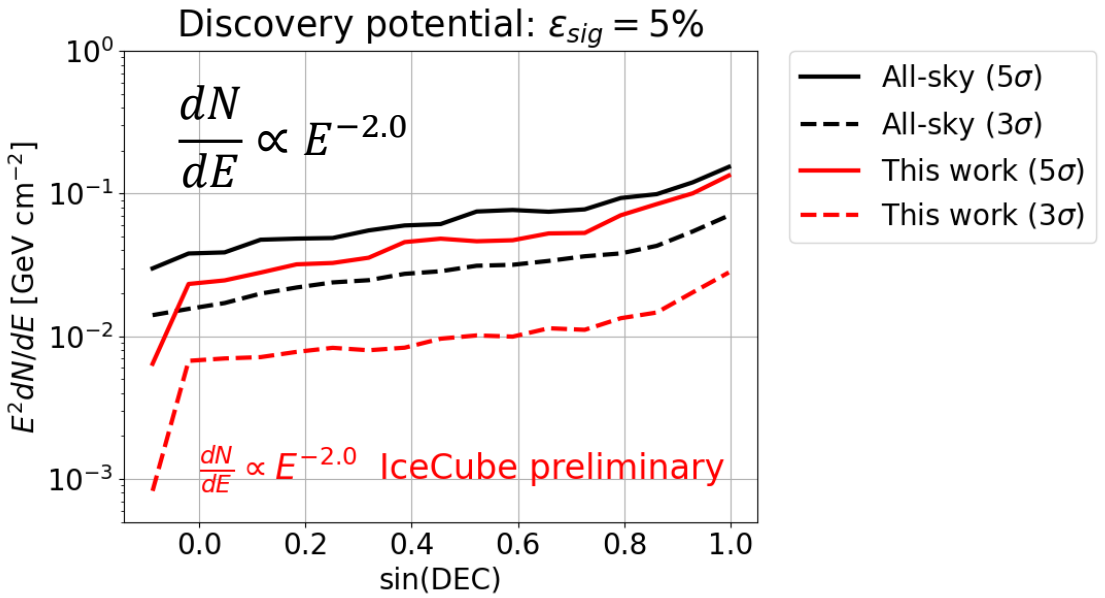
Information to be sent in the alert

- Basic: time, RA, DEC, FAR, angular uncertainty
- Doublet/Triplet
- z-distribution, allowed region in $(\mathcal{E}_\nu, \rho_\nu)$ plane
- Matching information with a galaxy catalog (GLADE+)

Discovery potential

This becomes more apparent if we relax the requirement of signal efficiency.





5σ discovery potential:
Signal strength: 5σ of BG-only hypothesis
Signal efficiency $\mathbf{0.5}$

relaxed

Signal efficiency $\mathbf{0.05}$

Our proposed method is more optimized to “tasty” events, and shows further high performance when the requirement on the signal efficiency is loosened.

Fermi catalog

0.28°

ID=1 **FBQS J0001-0011**

Select All	Services	name	ra	dec	flux 1 100 gev [photon/cm^2/s]	flux 1 100 gev error [photon/cm^2/s]	detection significance [sigma]	spectrum type	alt gammaray name 1	assoc name	analysis flags	Search Offset ['] from (target)
☐	O R N S D	4FGL J0001.4-0010	00 01 29.2	-00 10 12	1.1773e-10	2.7161e-11	5.2516	PowerLaw		FBQS J0001-0011	000	16.522 (0.58, -0.35)
☐	O R N S D	4FGL J2357.4-0152	23 57 28.2	-01 52 13	2.7596e-10	3.2261e-11	11.5753	PowerLaw	3FGL J2357.3-0150	PKS 2354-021	000	116.670 (0.58, -0.35)
☐	O R N S D	4FGL J0006.4+0135	00 06 26.3	+01 35 54	1.8394e-10	3.3214e-11	7.1257	LogParabola	3FGL J0006.2+0135	NVSS J000626+013611	000	132.203 (0.58, -0.35)
☐	O R N S D	4FGL J0011.4+0057	00 11 25.2	+00 57 53	8.4994e-10	5.2123e-11	28.2453	LogParabola	2FGL J0011.3+0054	RX J0011.5+0058	000	157.651 (0.58, -0.35)
☐	O R N S D	4FGL J2359.3+0215	23 59 19.9	+02 15 37	1.4273e-10	2.9032e-11	8.5776	LogParabola		1RXS J235916.9+021505	000	162.904 (0.58, -0.35)

5 rows retrieved from fermilpsc

Basic data :

2SLAQ J000121.46-001140.2 -- BL Lac

Other object types: **BLL** (2009A&A,[VV2006b]), **Bla** ([MGL2009],[MML2015]), **G** (2014MNRAS), **Q?** (FBQS), ***** (Gaia), **Rad** (FIRST), **Opt** (SDSS)

ICRS coord. *(ep=J2000) :* **00 01 21.4678641576 -00 11 40.314481656 (Optical) [0.5646 0.4355 90] A 2020yCat.1350....0G**

FK4 coord. *(ep=B1950 eq=1950) :* 23 58 47.7070432080 -00 28 22.609194971 [0.5646 0.4355 90]

Gal coord. *(ep=J2000) :* 096.8121710633993 -60.5013808702879 [0.5646 0.4355 90]

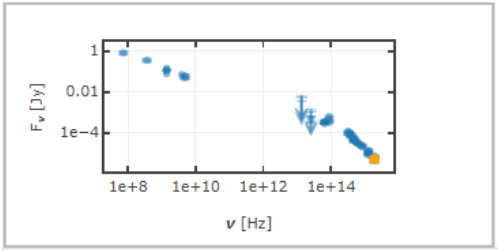
Proper motions *mas/yr* : **-0.773 0.227 [1.269 0.435 90] A 2020yCat.1350....0G**

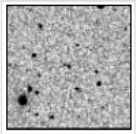
Radial velocity / Redshift / cz : **V(km/s) 108601 [105] / z(spectroscopic) 0.46152 [0.00035] /** cz 138360.2 [104.9]
(Opt) C 2012ApJS..203...21A

Fluxes (8) :
V 19.97 [~] E ~
R 19.1 [~] E 2009A&A...495..691M
G 19.973806 [0.009809] C 2020yCat.1350....0G
u (AB) 20.679 [0.062] C 2012ApJS..203...21A
g (AB) 20.158 [0.018] C 2012ApJS..203...21A
r (AB) 19.619 [0.016] C 2012ApJS..203...21A
i (AB) 19.194 [0.015] C 2012ApJS..203...21A
z (AB) 18.919 [0.041] C 2012ApJS..203...21A

Results for object FBQS J0001-0011 (2SLAQ J000121.46-001140.2)

Overview | Cross-IDs (20) | Coordinates (15) | Redshifts (8) | Distances (0) | Classifications (1) | Galactic Extinctions | Notes (0) | Diameters (4)
Photometry & SED (46) | Spectra (1) | Images (0) | References (21) | External Links | Survey Coverage



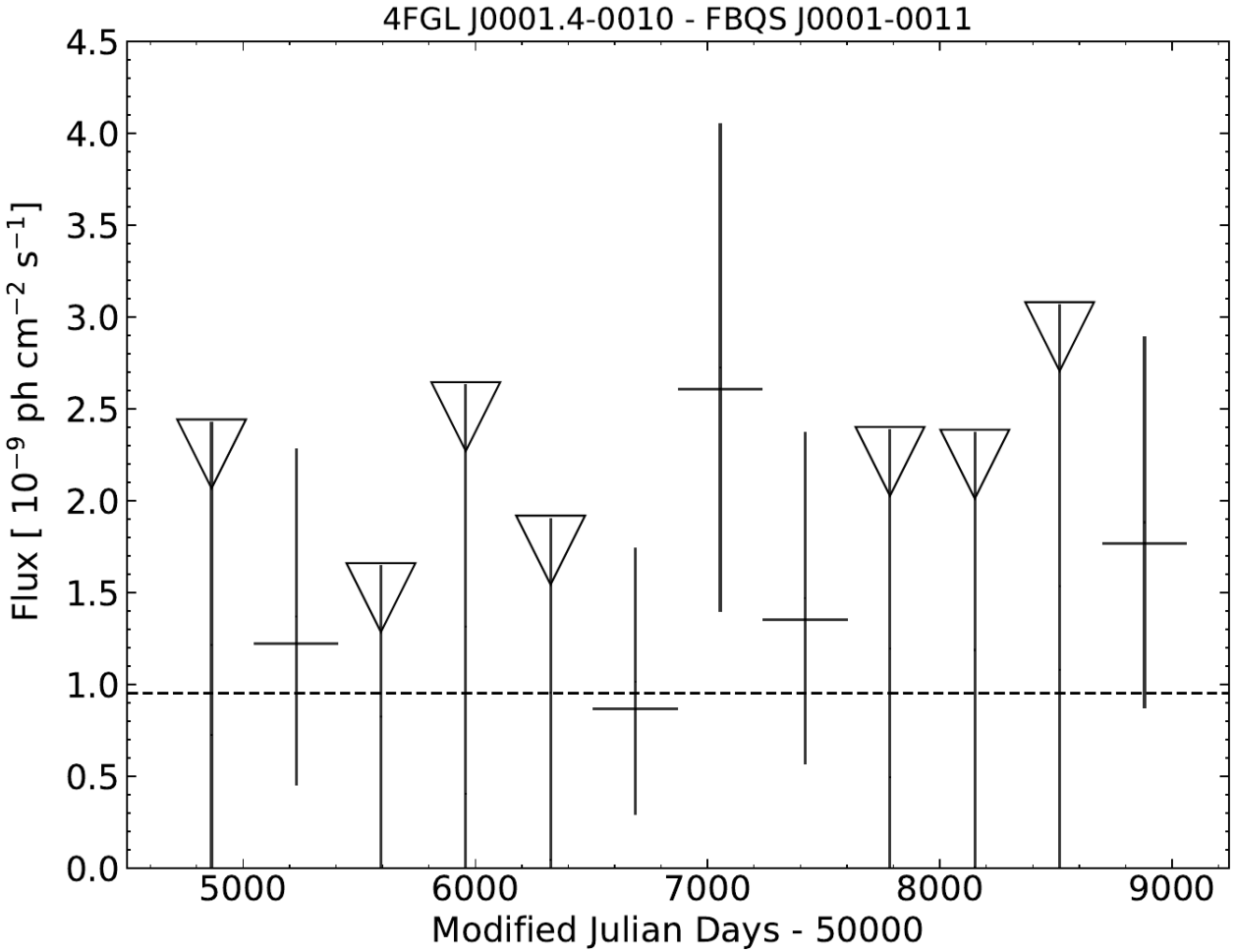


POSS-II F (North), AAO-SES/SERC-ER (South), Red image
View in IRSA Finderchart
Image Credit: Caltech or AAO/ROE

Selected data and derived quantities for FBQS J0001-0011†. More information in the tabs above.

Cross-identifications				**Essential note**	
FBQS J0001-0011; WISEA J000121.50-001140.0; SDSS J000121.46-001140.2; SDSS J000121.46-001140.3; SDSS J000121.47-001140.3				TXS codes: lobes(W)	
Coordinates for Preferred Position					
Equatorial (J2000)					Galactic
RA, Dec	RA, Dec [Deg]	Unc Semi-major,minor ["]	Unc PA [deg]	Reference	Lon, Lat [deg]
00h01m21.469s, -00d11m40.25s	0.339454, -0.194513	5.00E-01, 5.00E-01	0	2007SDSS6.C...0000:	96.812150, -60.501353
Preferred Redshift & Derived Quantities [H_0 = 67.8 km/sec/Mpc, Ωmatter = 0.308, Ωvacuum = 0.692]					**Redshift-independent Dis**
z (Helio)	V (Helio) [km/s]	Reference	V (CMB) [km/s]	Hubble Distance (CMB) [Mpc]	# Measurements
0.46152 +/- 0.00035	138359.035430 +/- 104.327790	2016SDSSD.C...0000:	137999 +/- 107	2035.39 +/- 142.49	
Classifications					
Object Type	Morphology	Reference	Activity Type	Reference	Other
G			BL	2006A&A...455..773V	BLLAC
Quick-look Angular & Physical Diameters				**Foreground Galactic Extinction (2011ApJ...737..103**	
Passband	Diameter ["]	Reference	Diameter [kpc]	A_λ [mag] V	A_λ [mag] K
r (SDSS Isophotal)	6.02	2007SDSS6.C...0000:	59.42	0.093	0.010
Quick-look Photometry & Luminosities (brightest flux in each spectral region)					
Spectral region	Band	Apparent mag or flux	Reference	Absolute Mag or νL_ν [W]	νL_ν [$L_\odot$(bol)]
X-Ray					
UV	NUV (GALEX) AB	21.0549 +/- 0.117164 mag	2012GASC..C...0000S	-21.06 +/- 0.51 [mag]	3.84E+10 +/- 8.73E+09
Visible	z (SDSS CModel) AB	18.757 asinh mag	2007SDSS6.C...0000:	-2.34E+01 [mag]	7.91E+10
Near-IR	W1 (WISE)	14.256 +/- 0.036 mag	2013wise.rept....1C	-27.85 +/- 0.50 [mag]	1.19E+11 +/- 2.42E+10
Far-IR					
Radio	74 MHz (VLA)	0.81 +/- 0.12 Jy	2007AJ....134.1245C	4.99E+34 +/- 1.24E+34 [W]	1.30E+08 +/- 3.23E+07

†Derived quantities are based on the median redshift-independent distance when available, otherwise the preferred redshift is used with the selected cosmological parameters (which can be changed in search options).
Cosmological params can be changed in search options.


4FGL J0001.4-0010 - FBQS J0001-0011
Flux [10^{-9} ph cm^{-2} s^{-1}]
Modified Julian Days - 50000
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5000
6000
7000
8000
9000