Development of a new IceCube realtime alert using multiplet signal for optical follow-up

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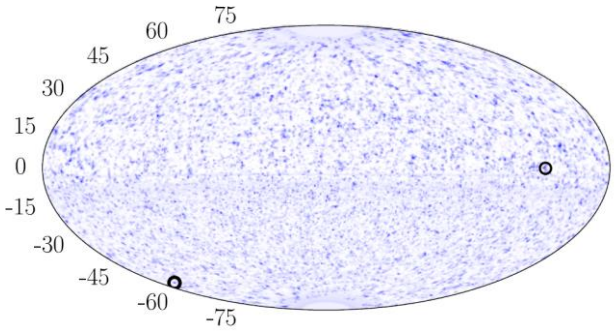
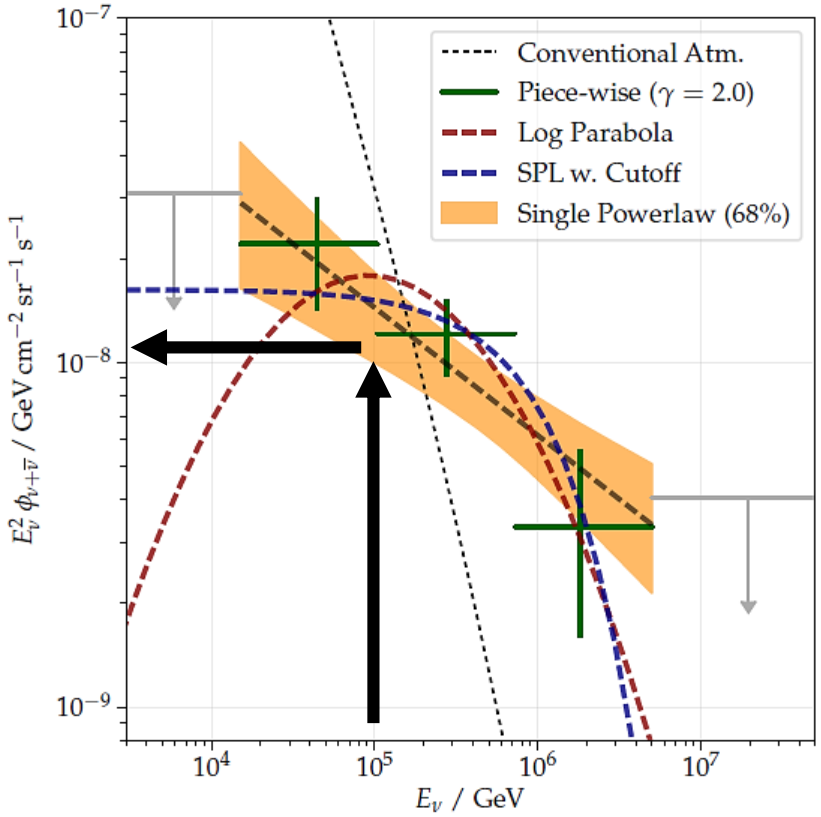
Picture: Y. Makino

Cosmic ν background

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

$$E^2\phi_\nu \sim \mathbf{10^{-8}} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.4}$$

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

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 neutrino

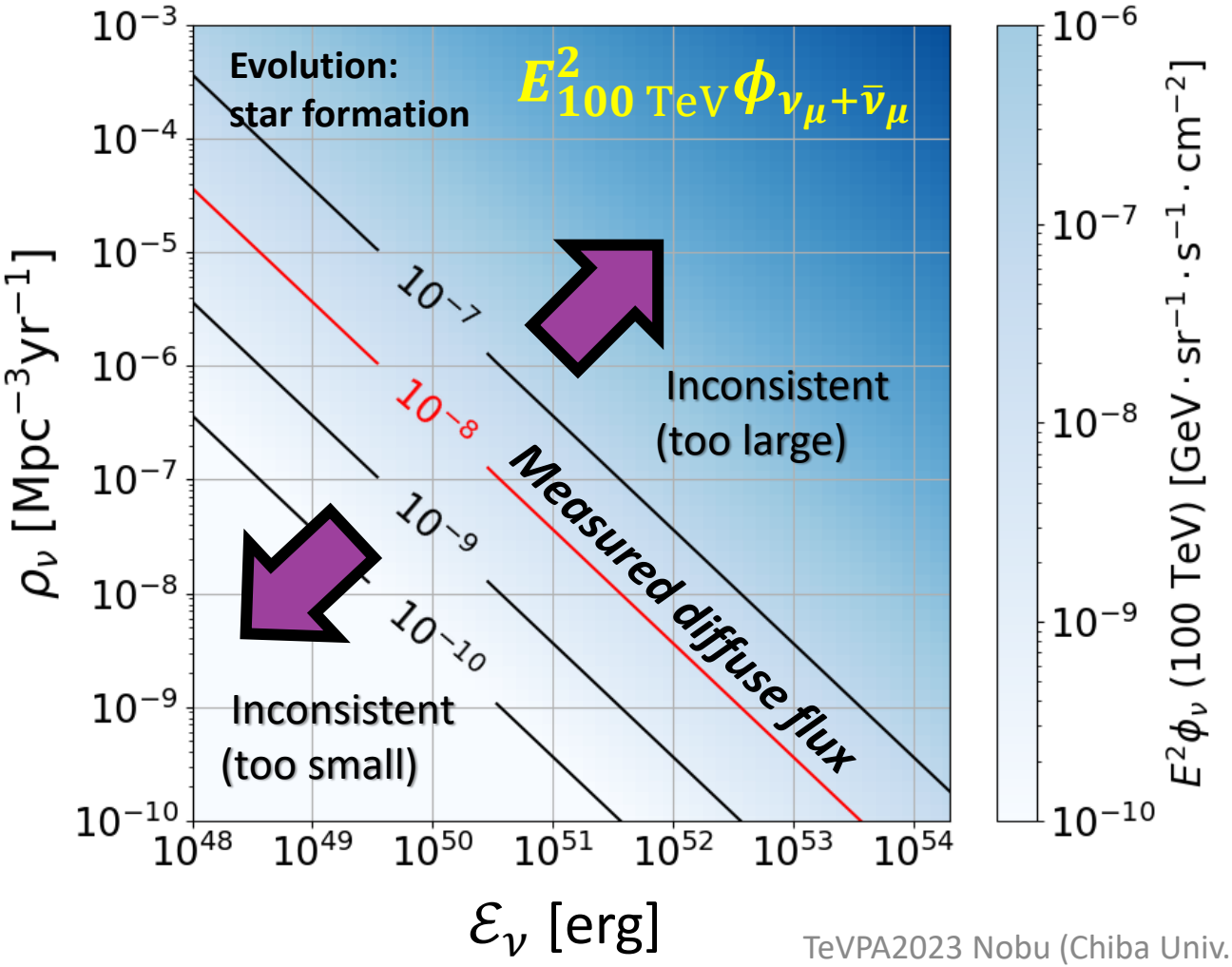
Bright (high $\mathcal{E}_\nu$) & Rare (small ρ_ν)

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}]

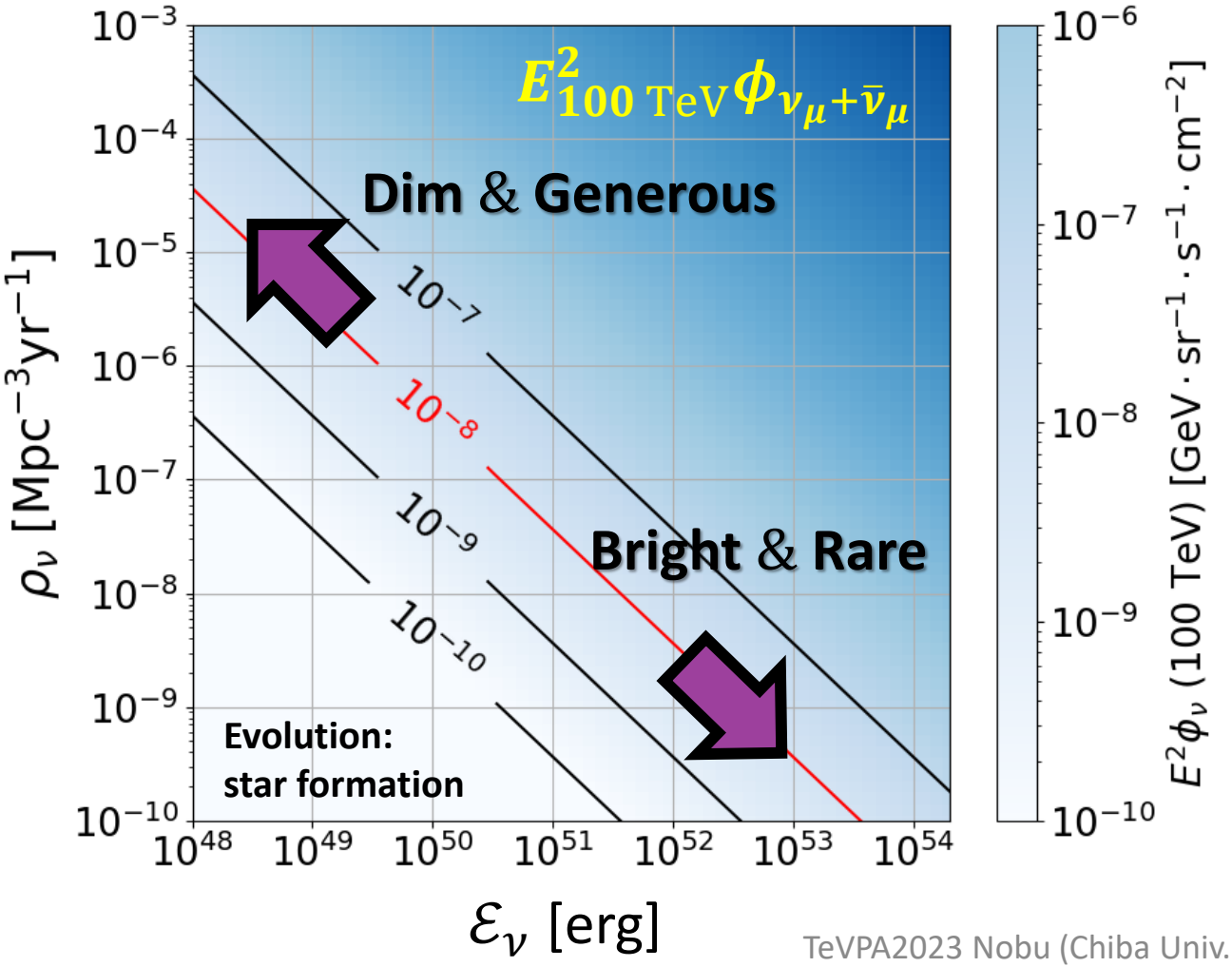


Diffuse energy flux on ($\mathcal{E}_\nu$, ρ_ν) plane

[Source characterization]

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

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



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

[Which sources can be considered?]

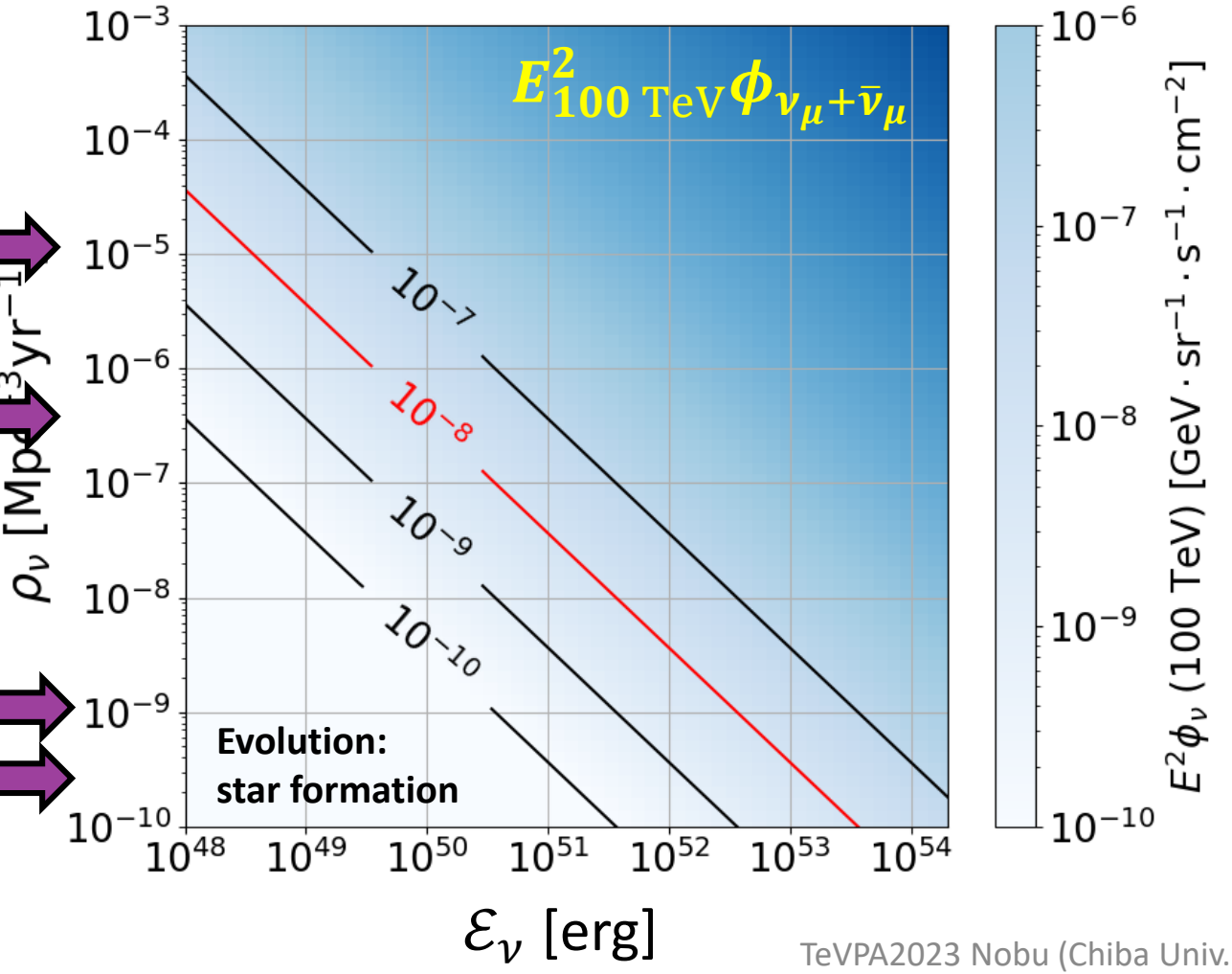
$E^2\phi_\nu \sim 10^{-8}$ (100 TeV)
[GeV· $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$]

SNe

Low Lum. GRB

High Lum. GRB

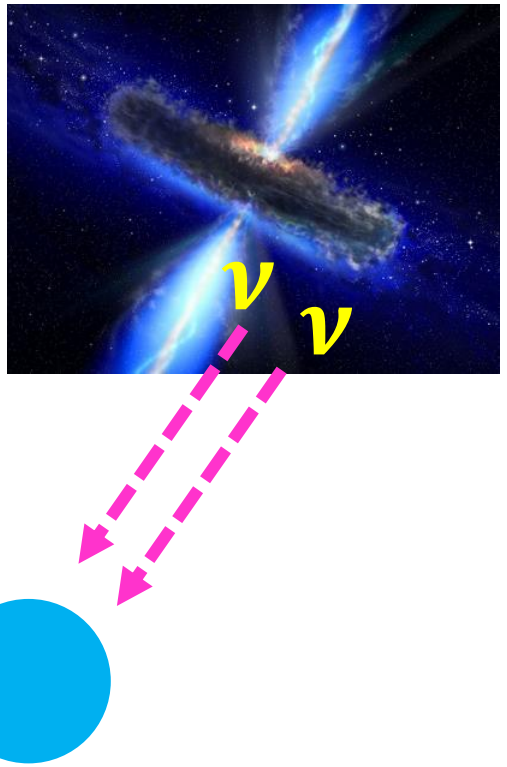
TDE



ν-multiplet as a probe of bright sources

What is multiplet?

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

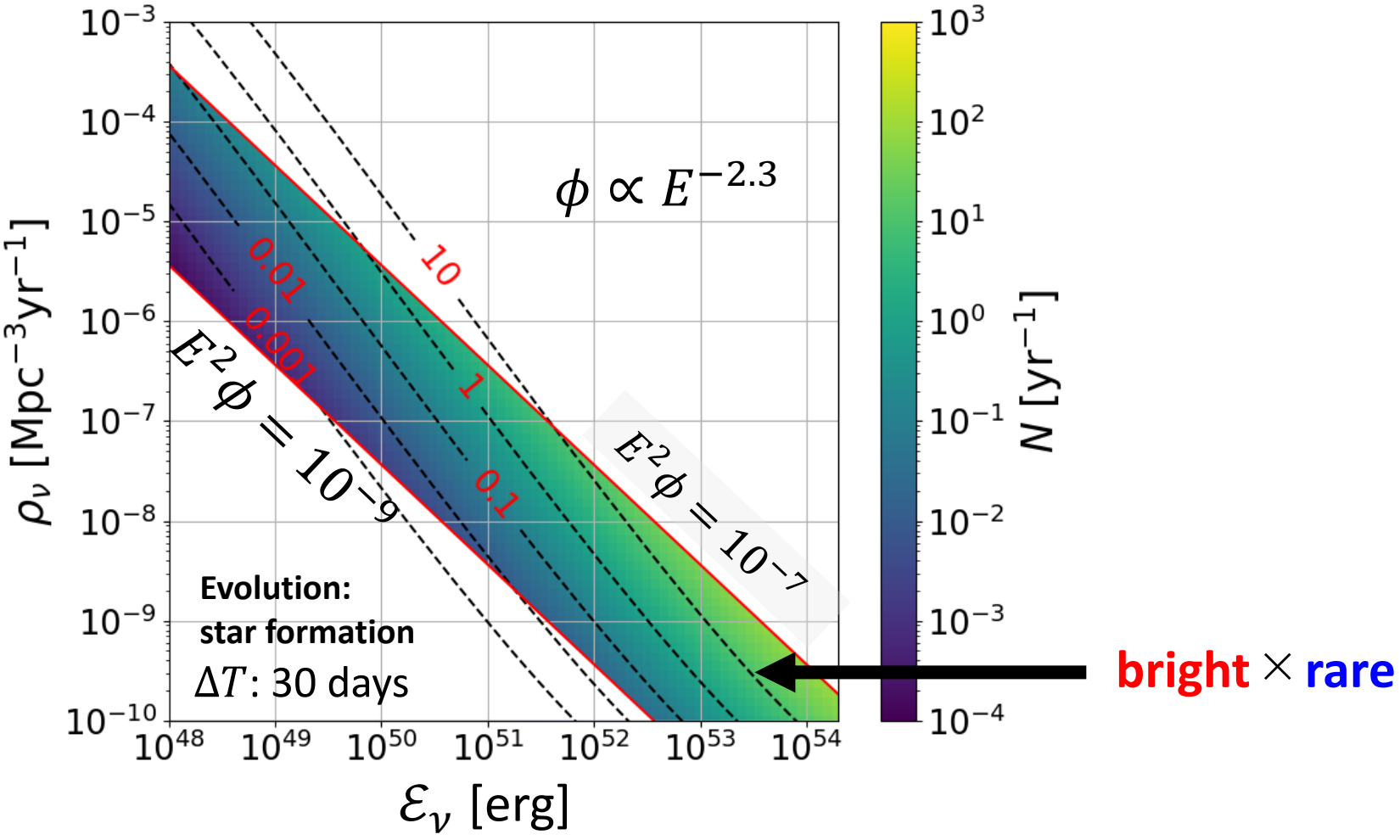


In terms of rate

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

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

Expected number of ν-Multiplet signal

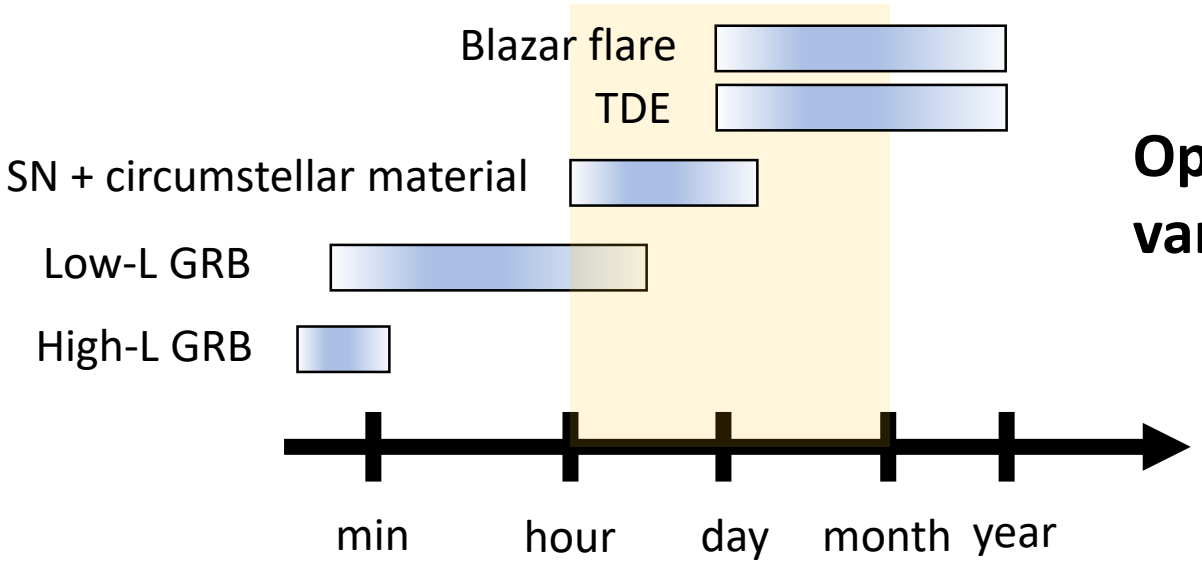


This is a pure number of detections.

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 multiplets signal

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

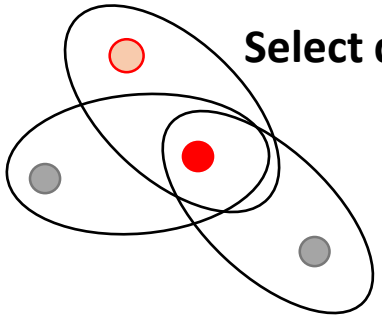
[Doublet case]

Rate *Energy PDF* *Spatial PDF*

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

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

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



Select most signal-like two ν events 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 year
ΔT	30 days
$N_{\mathrm{expected}}^{\mathrm{doublet}}$	1.2×10^7
$N_{\mathrm{expected}}^{\mathrm{triplet}}$	2.8×10^4

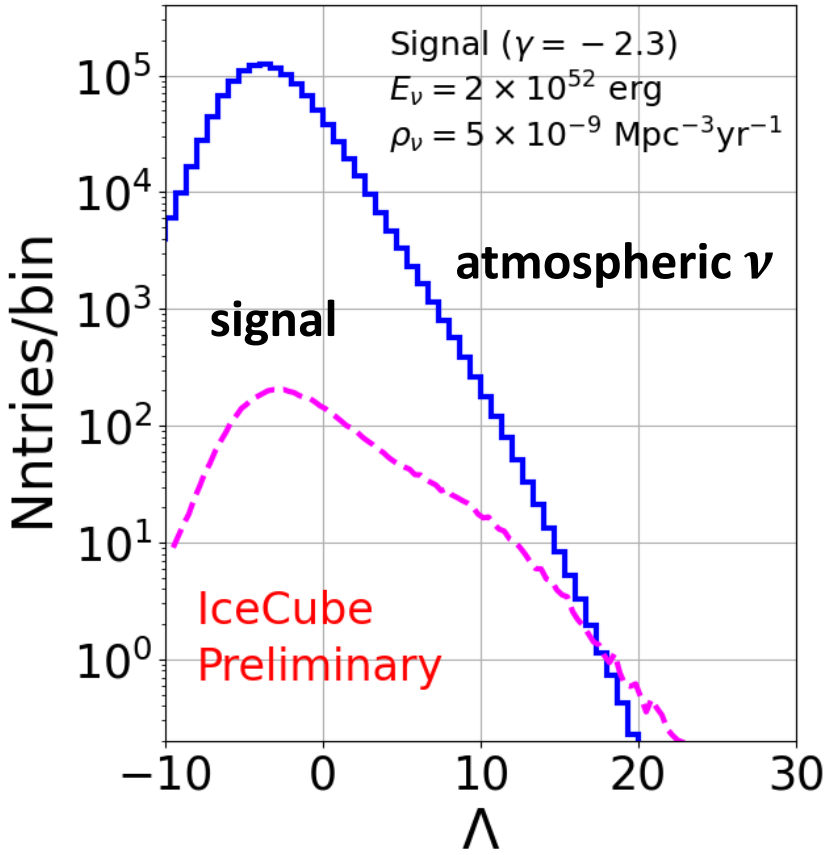
Dataset used for realtime alert

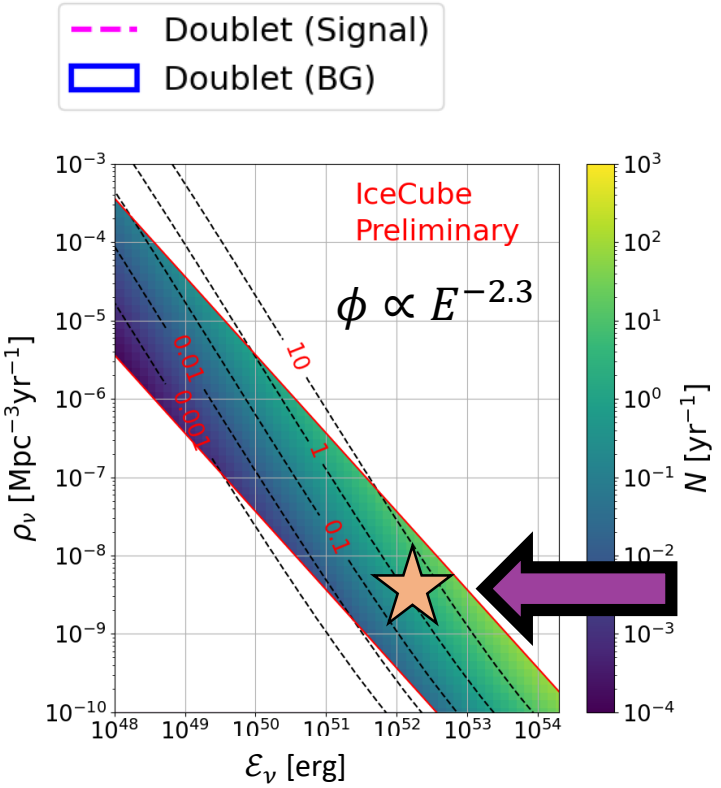
→ this method will be used also for multiplet alert

Test statistic Λ distribution

Doublet

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

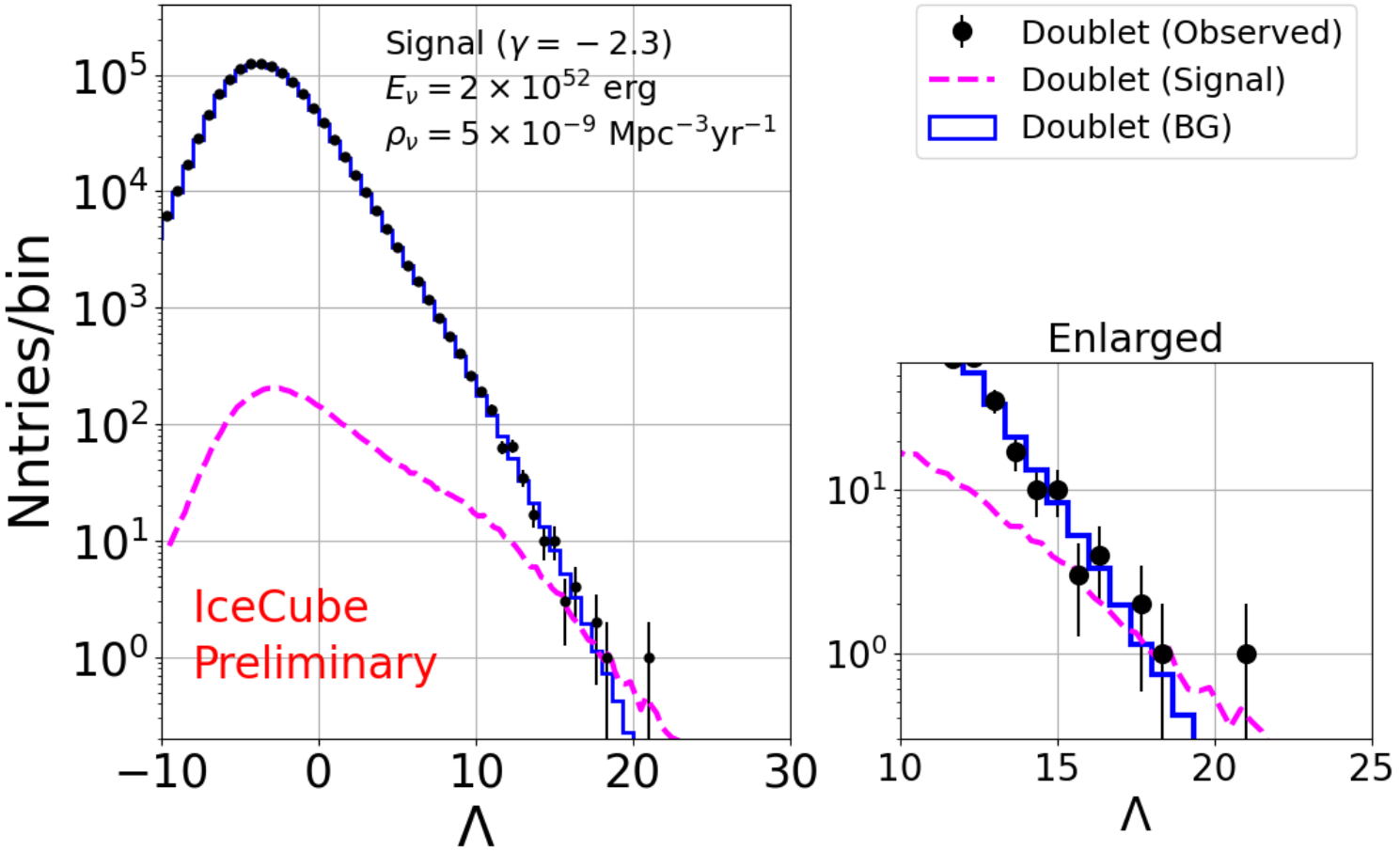




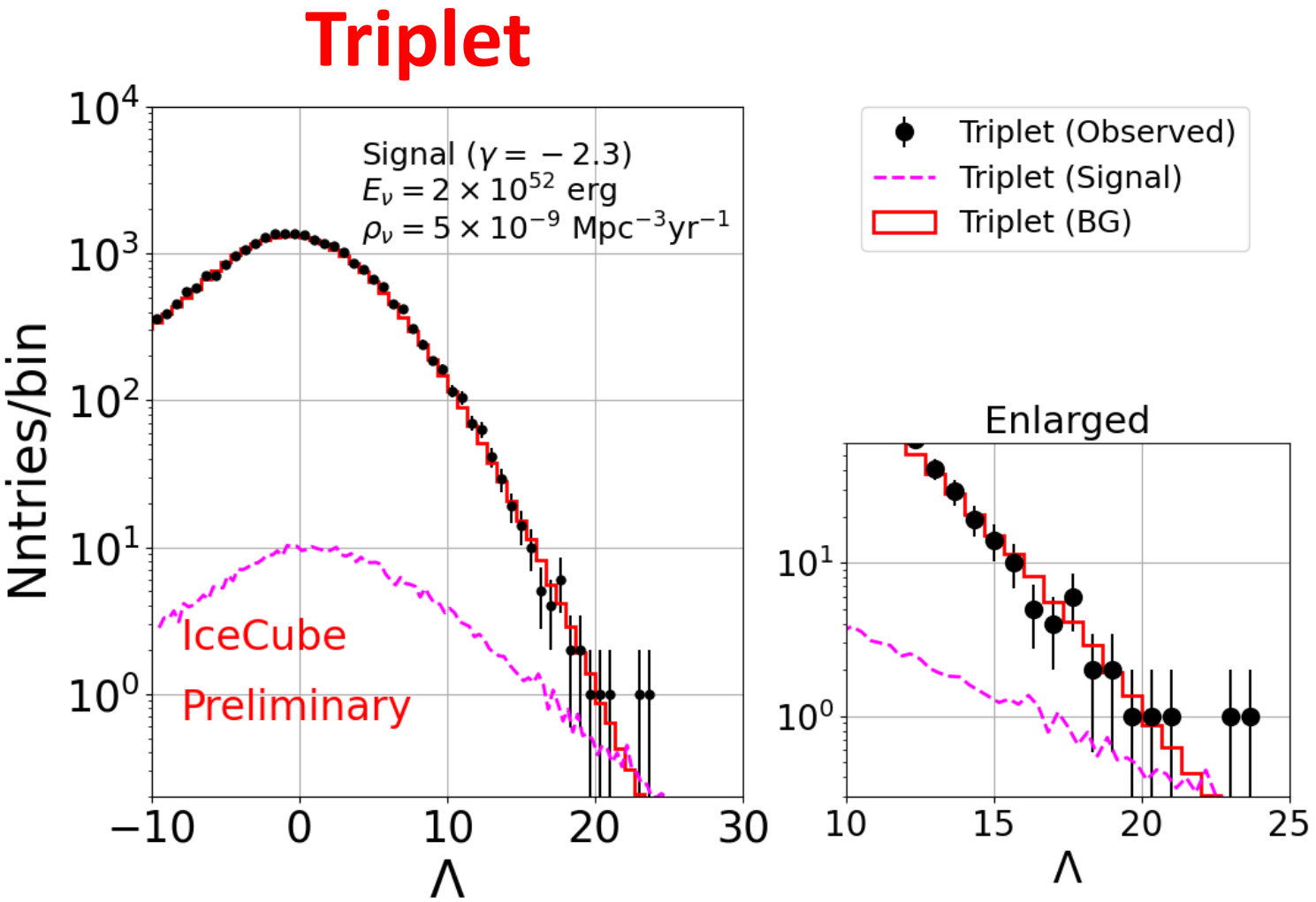
Assumed signal

Result

Doublet



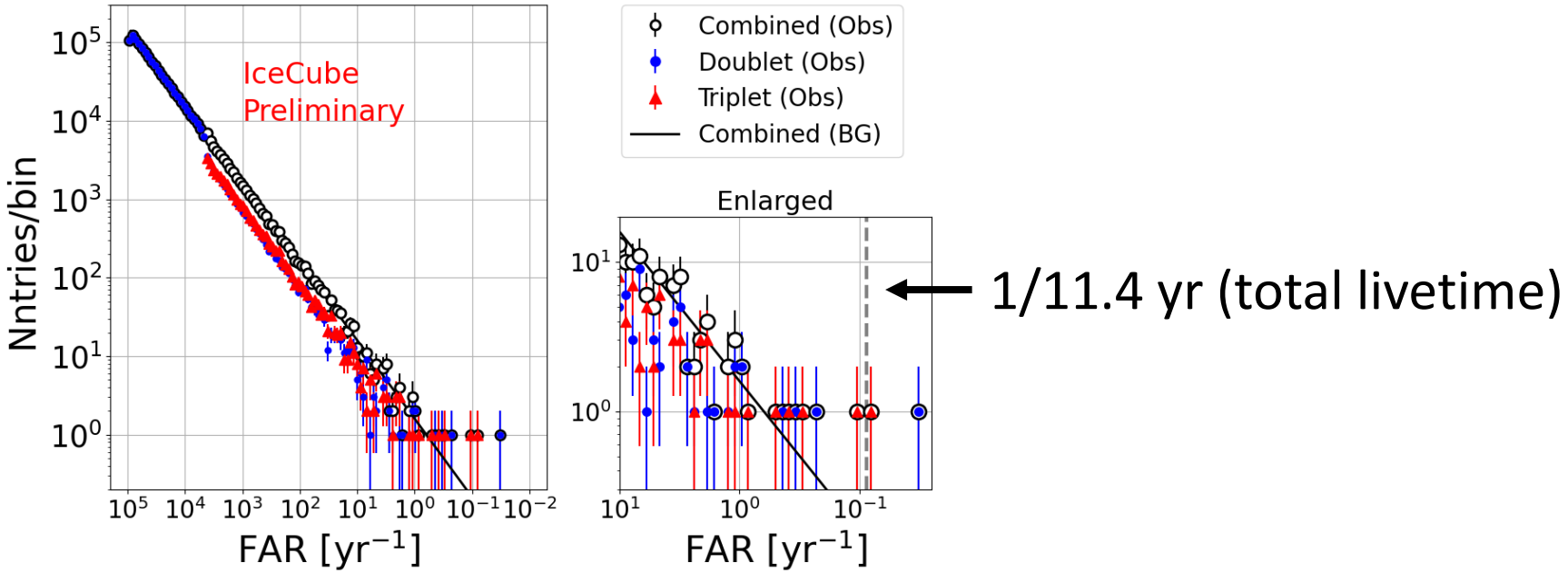
Result


Triplet
Signal ($\gamma = -2.3$)
$E_\nu = 2 \times 10^{52}$ erg
$\rho_\nu = 5 \times 10^{-9}$ Mpc^{-3}yr^{-1}
Nntries/bin
10^4
10^3
10^2
10^1
10^0
IceCube
Preliminary
−10
0
10
20
30
Λ
Triplet (Observed)
Triplet (Signal)
Triplet (BG)
Enlarged
10^1
10^0
10
15
20
25
Λ

Is this consistent with background?

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

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



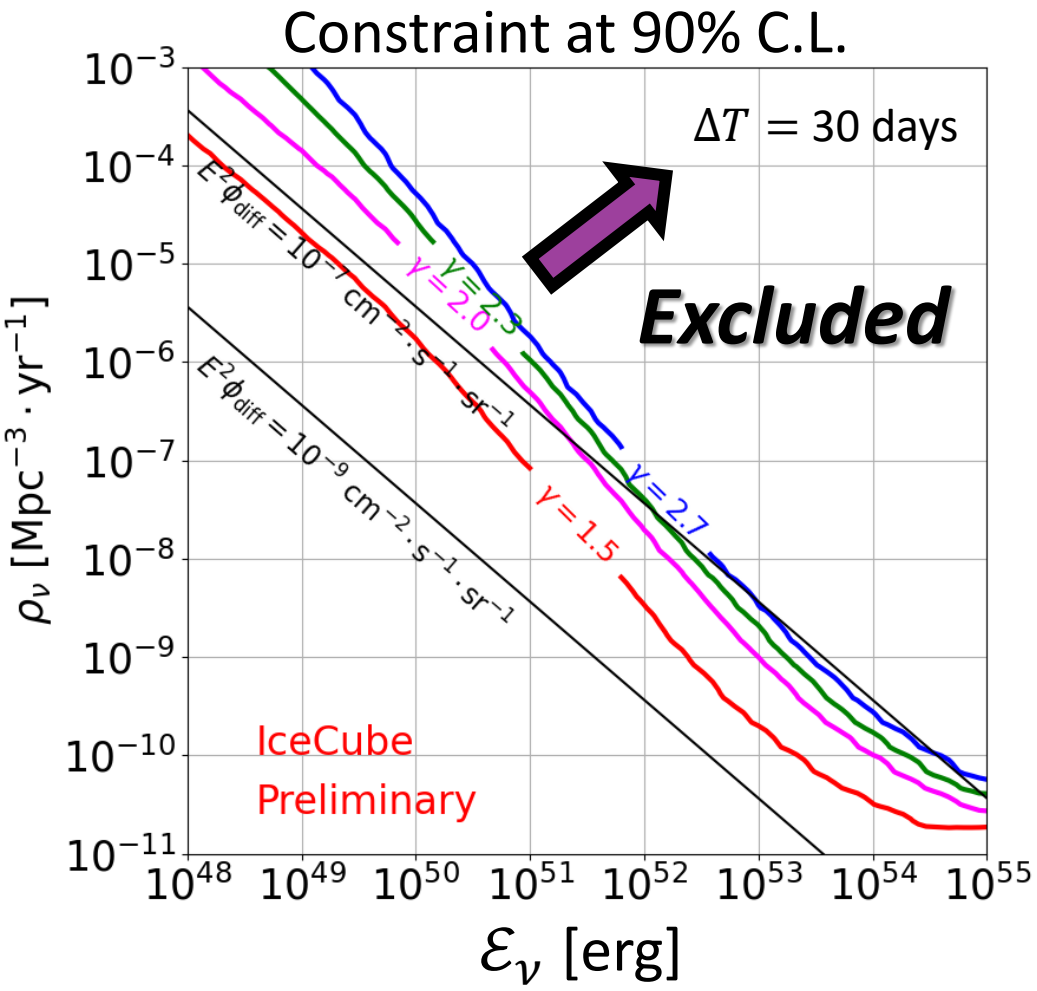
As a whole dataset, the observation was consistent with BG-only hypothesis.

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 $\phi \propto E^{-\gamma}$



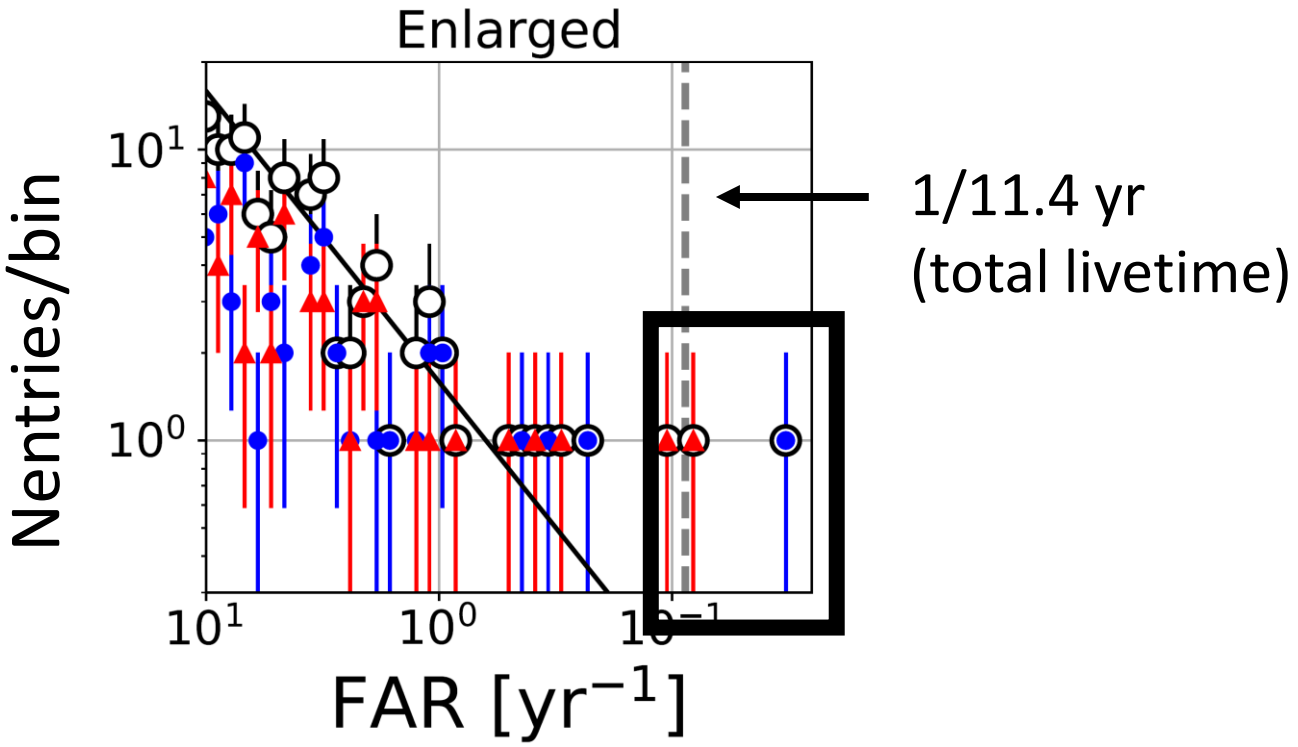
Eg., for $\gamma = -2$ case,

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

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

is excluded at 90% C.L.

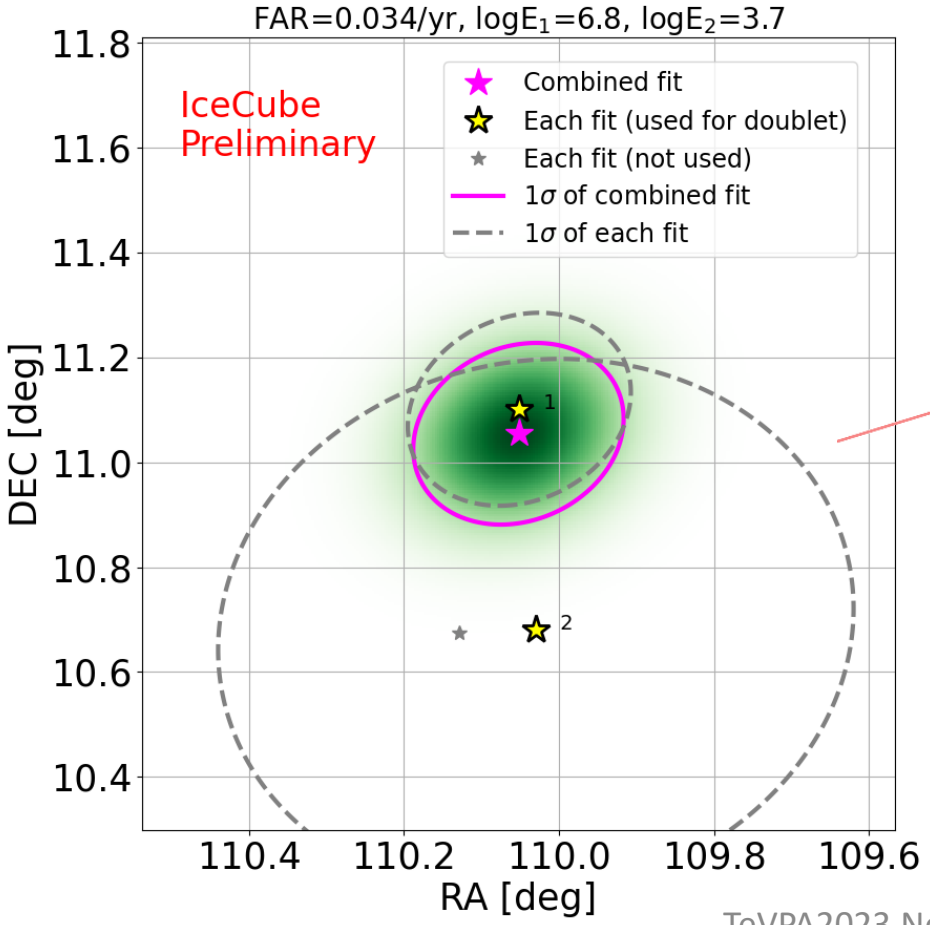
What do the rare multiplets look like?

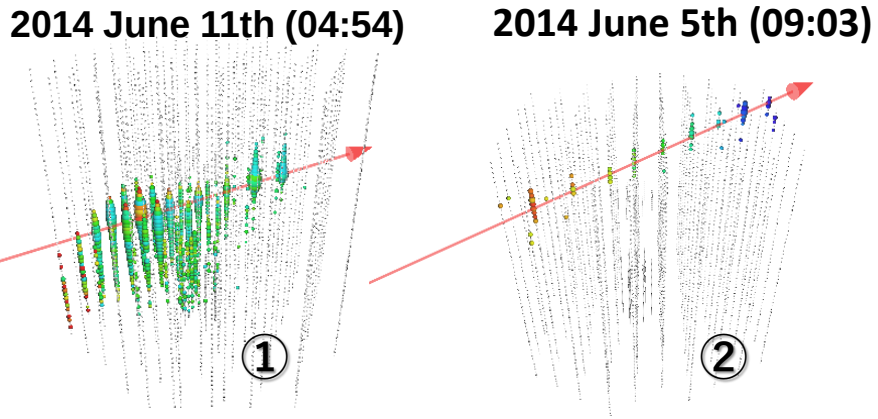


Though global p-value=0.14 was 1.1σ, significant multiplets are still interesting.
With the criteria of FAR<1/11.4 [yr^{-1}], **two multiplets were found**.

The most significant multiplet

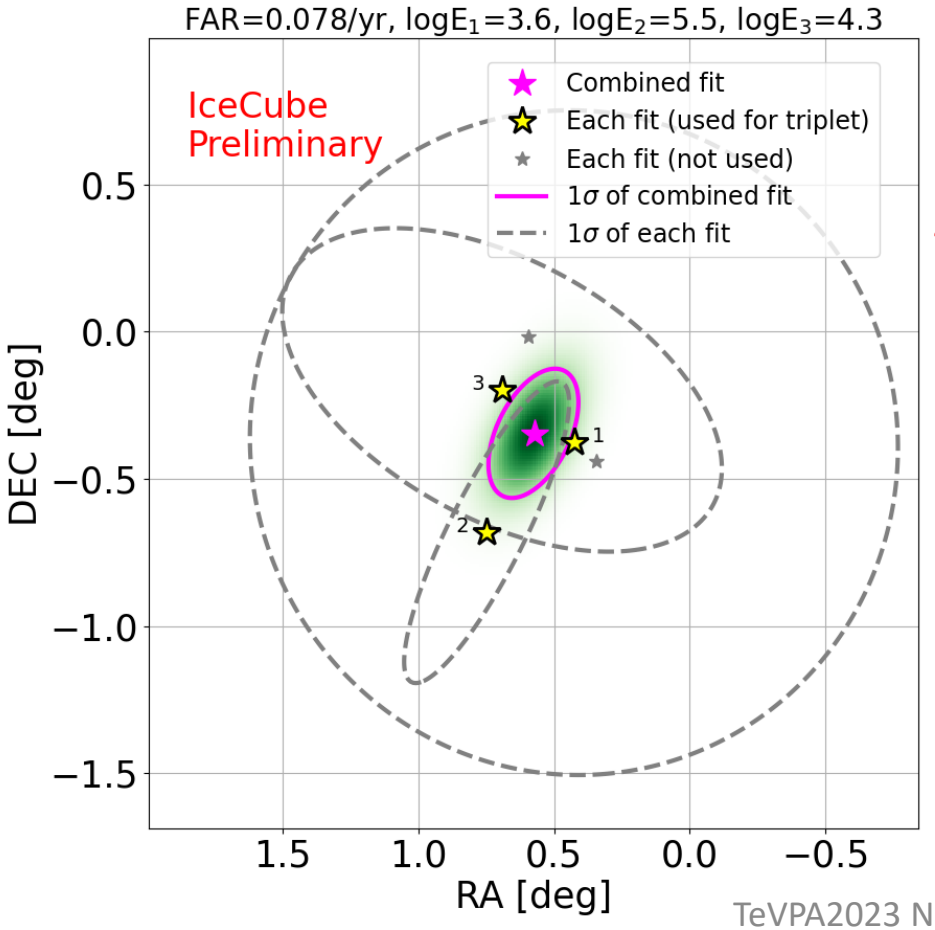
Type: **Doublet**, (RA, DEC)=(110.05 deg, 11.05 deg)
Energy: E=(6 PeV, 6 TeV), $\Delta T = 5.8$ days,
local p-value=3.2×10^{-7}, FAR= 1/29 [1/yr]

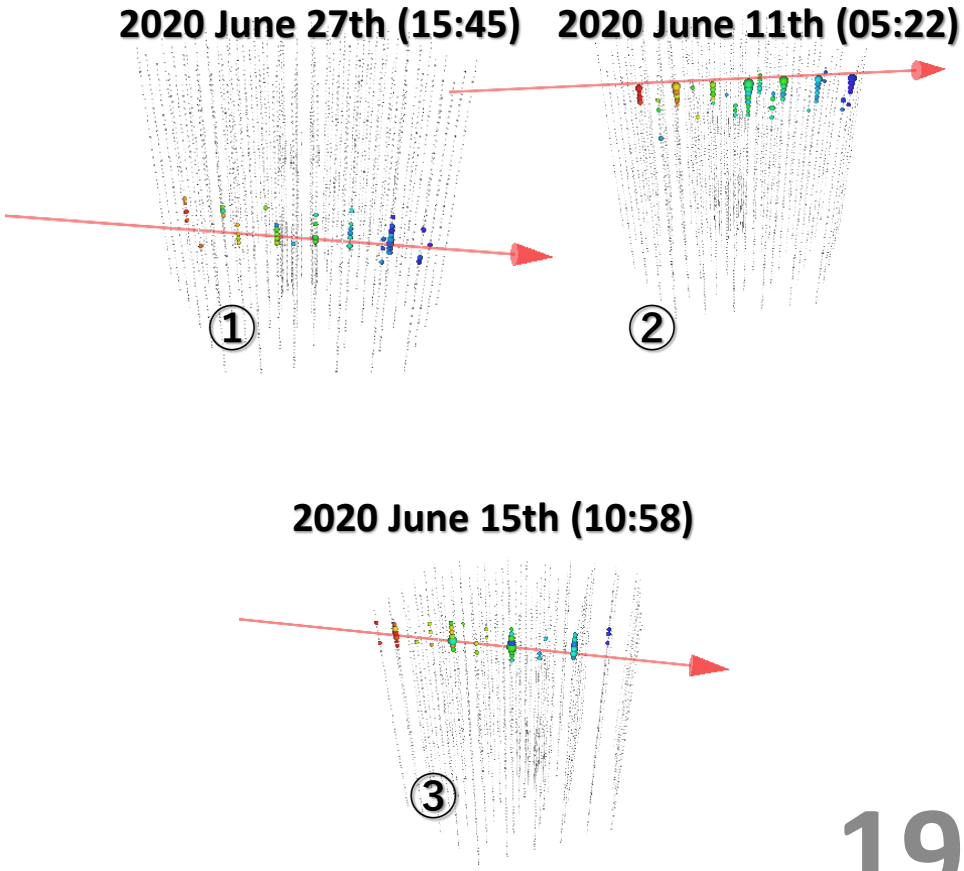




2nd significant multiplet

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]

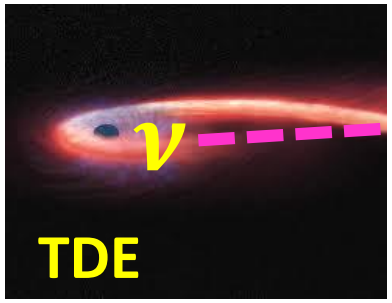


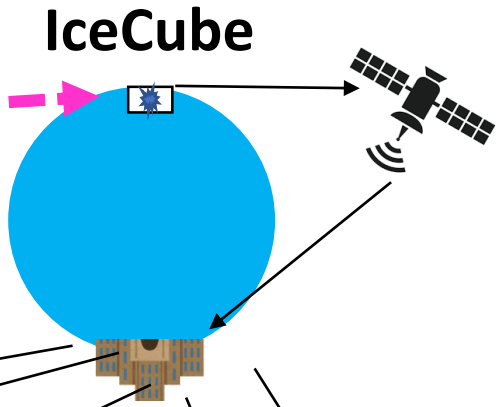


Hunt the origin of the ν-source

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

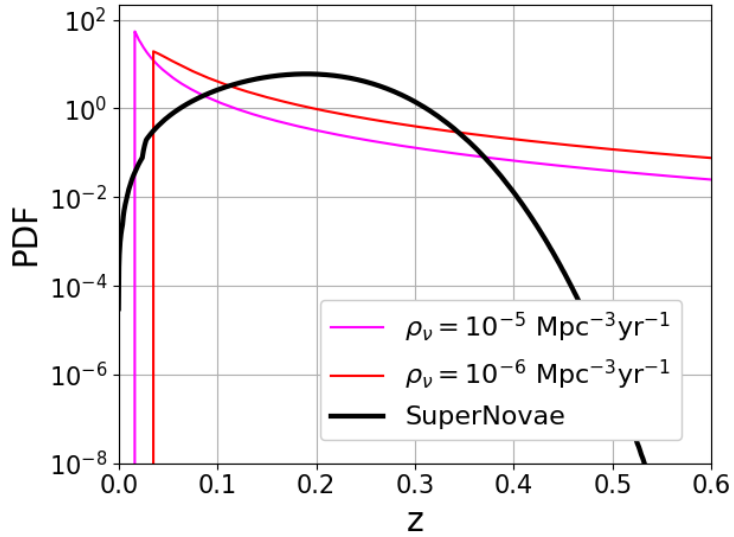
Strategy: issue a public **multiplet** alert to other telescopes

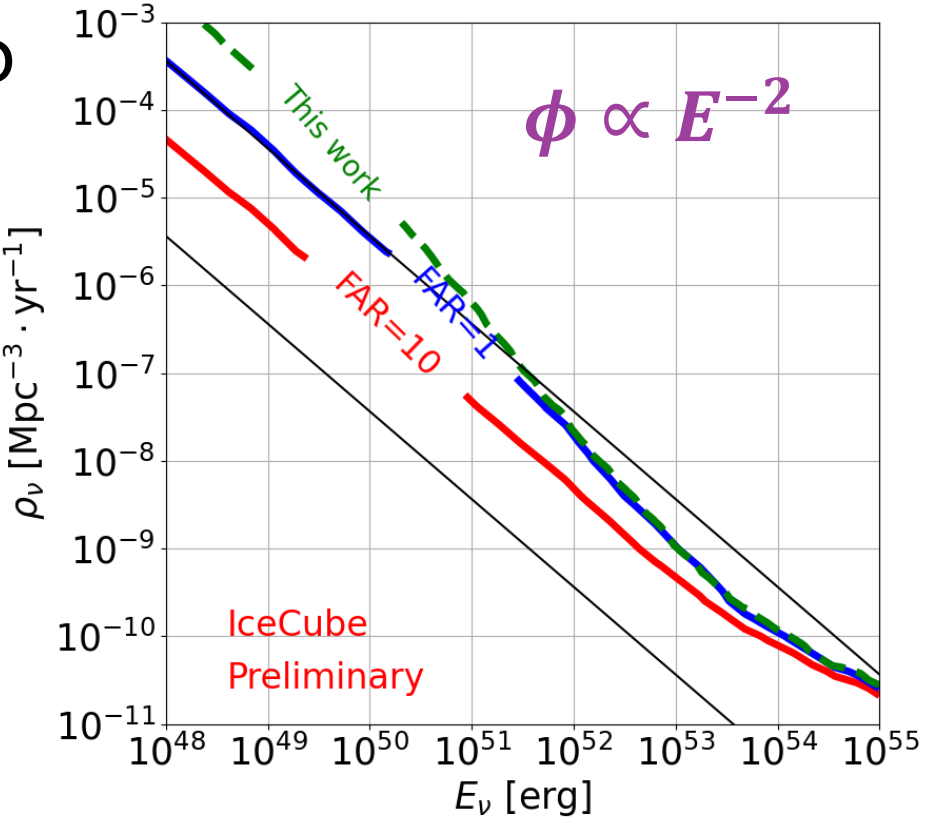




Why multiplet alert?

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 ($\sim 1^\circ$)

$\Delta\psi \sim 0.3^\circ$ 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 unblinded
  - As a dataset, the observed number was 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 for your cooperation of future follow-up!

Backup

Search for multiplets in 12 years data

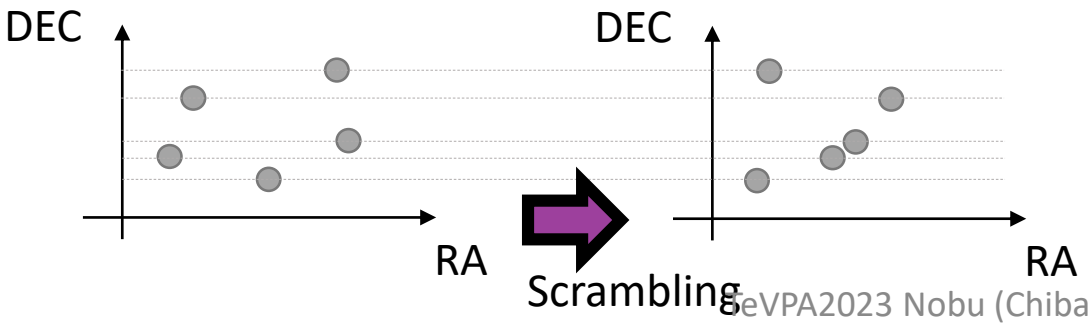
Using the developed method, we performed multiplet search.

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

← the same dataset used for realtime alert

} Atmospheric ν dominates

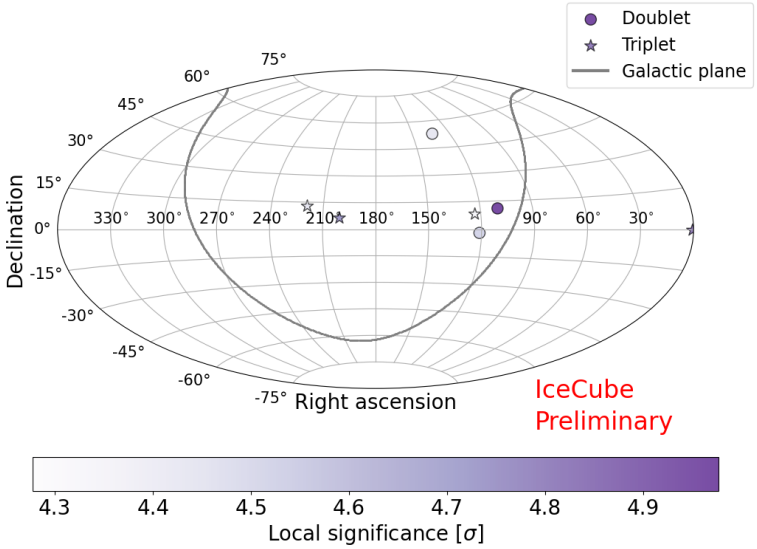
The background contribution is evaluated by data-driven way.



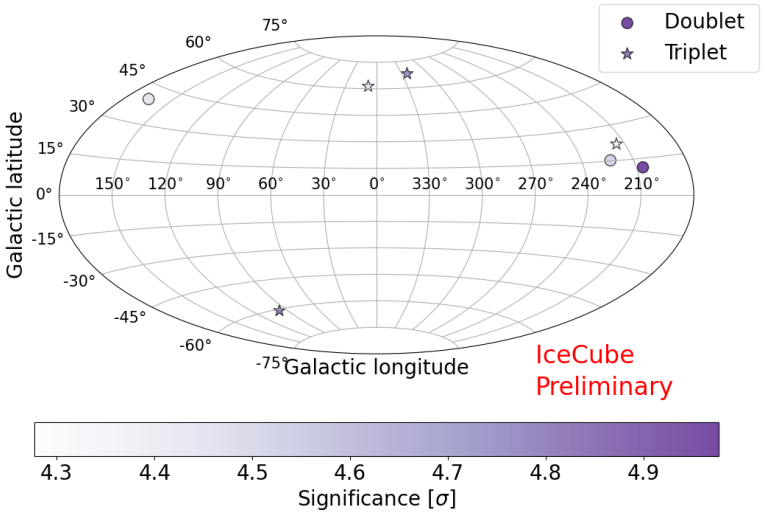
✓ Time and RA are scrambled to increase the effective statistics.

(IceCube's sensitivity is symmetric in RA for such long time window)

Doublet and triplet in skymap



Equatorial coordinate

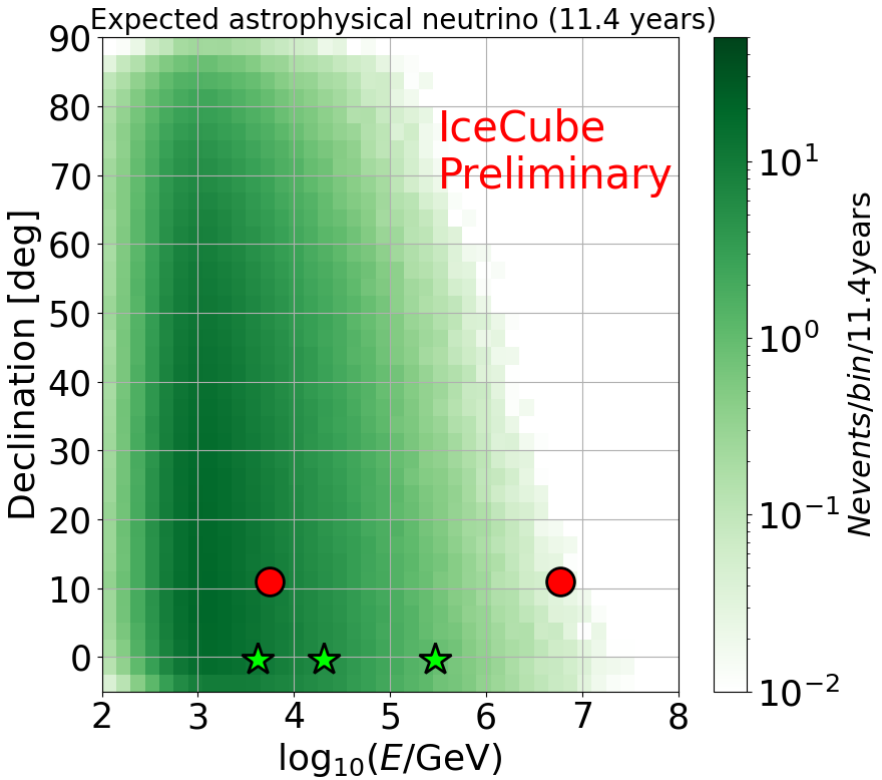


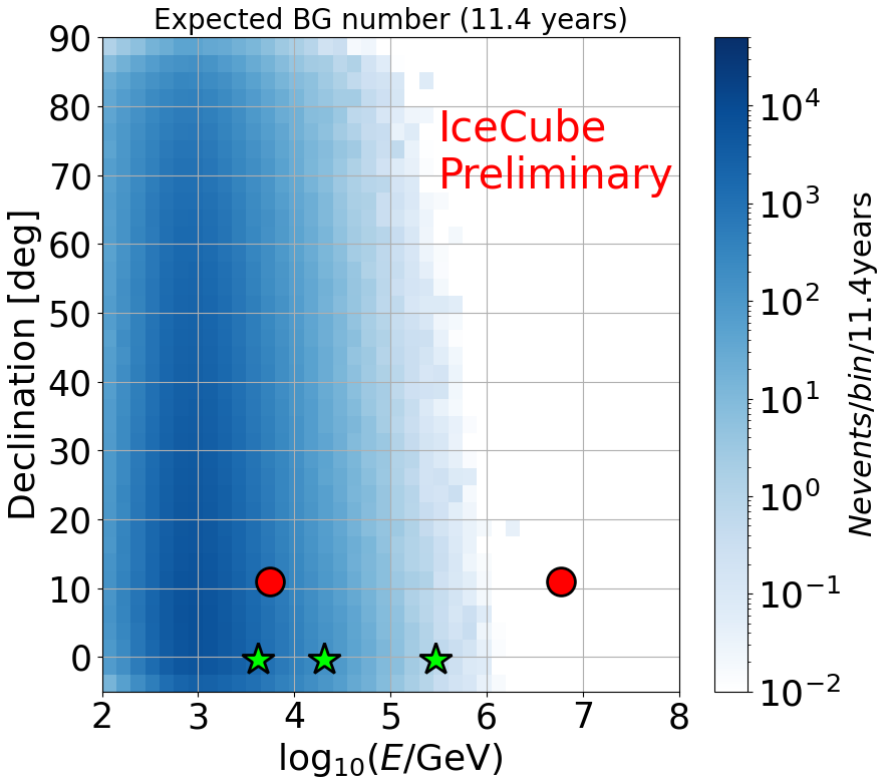
Galactic coordinate

Distribution of energy and declination

Observed doublet

Observed triplet



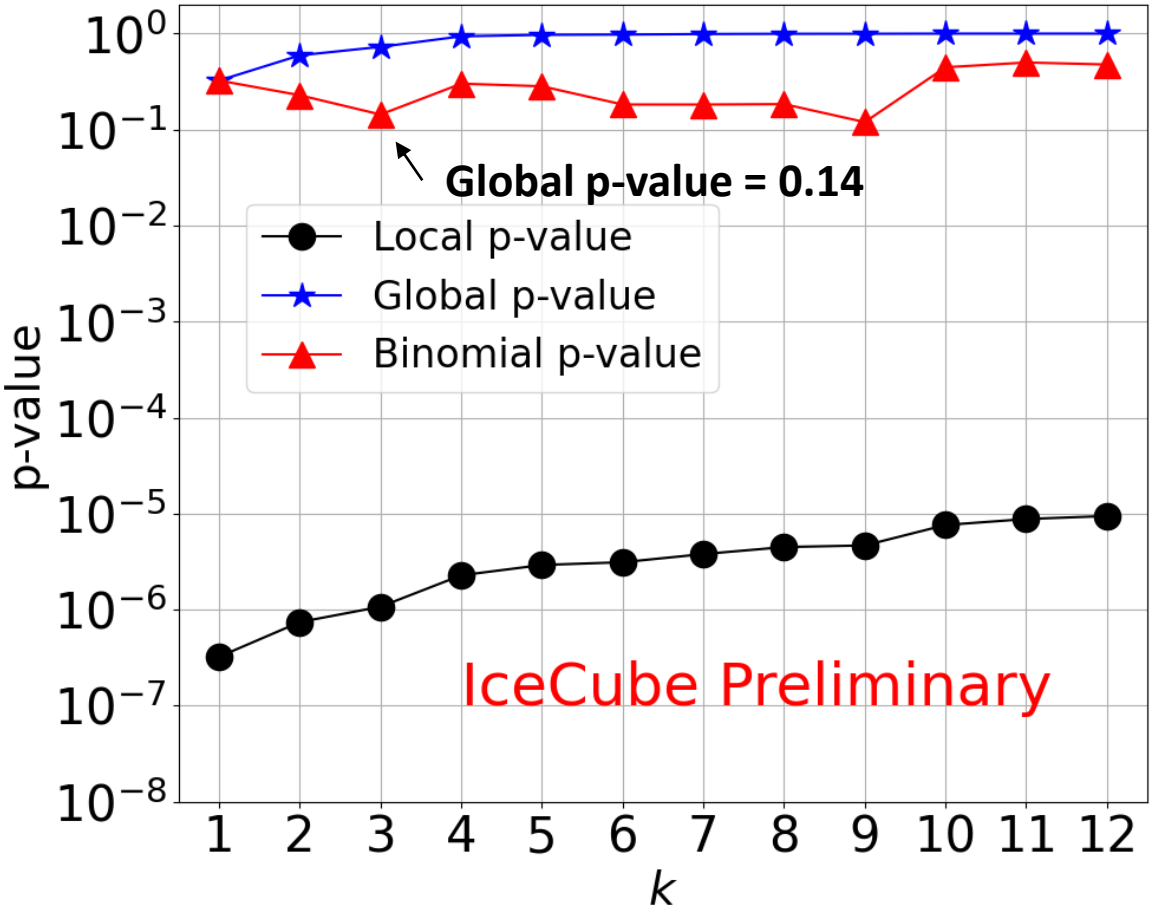


Astrophysical neutrino

Atmospheric neutrino

Binomial tests

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

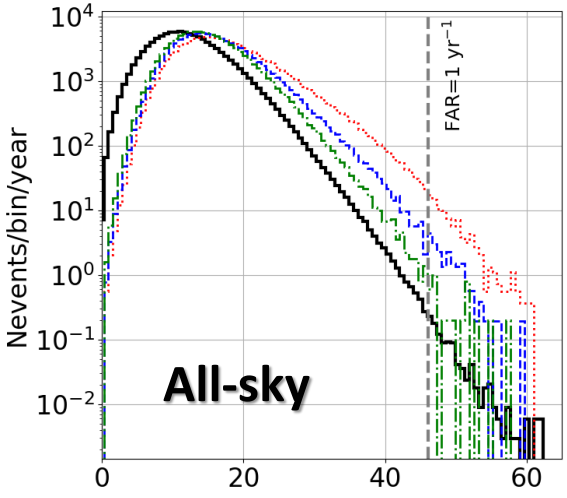


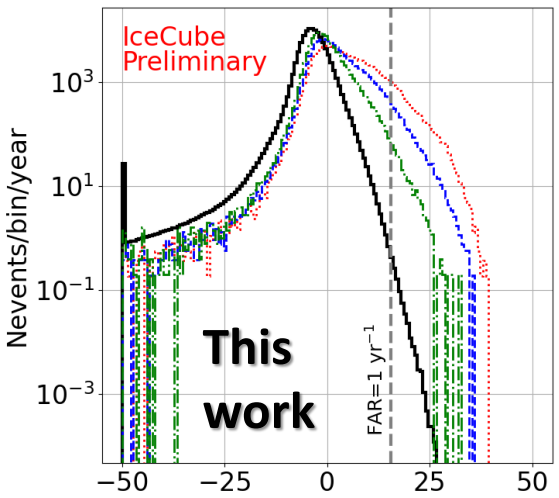
TS distribution

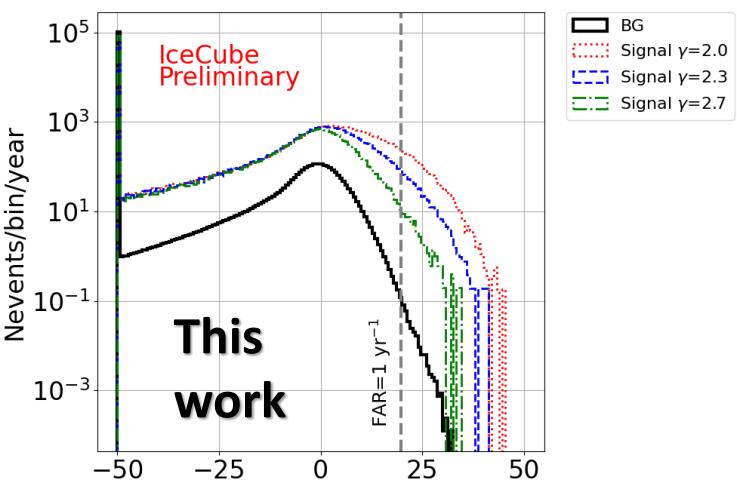
- $dN/dE \propto E^{-\gamma}$
- $N_{\mathrm{det}}^{\mathrm{sig}} = \mathbf{2}$
- $T_{\mathrm{max}} = 30$ days
- Timing distribution of signal → uniform in T_{max}

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

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







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

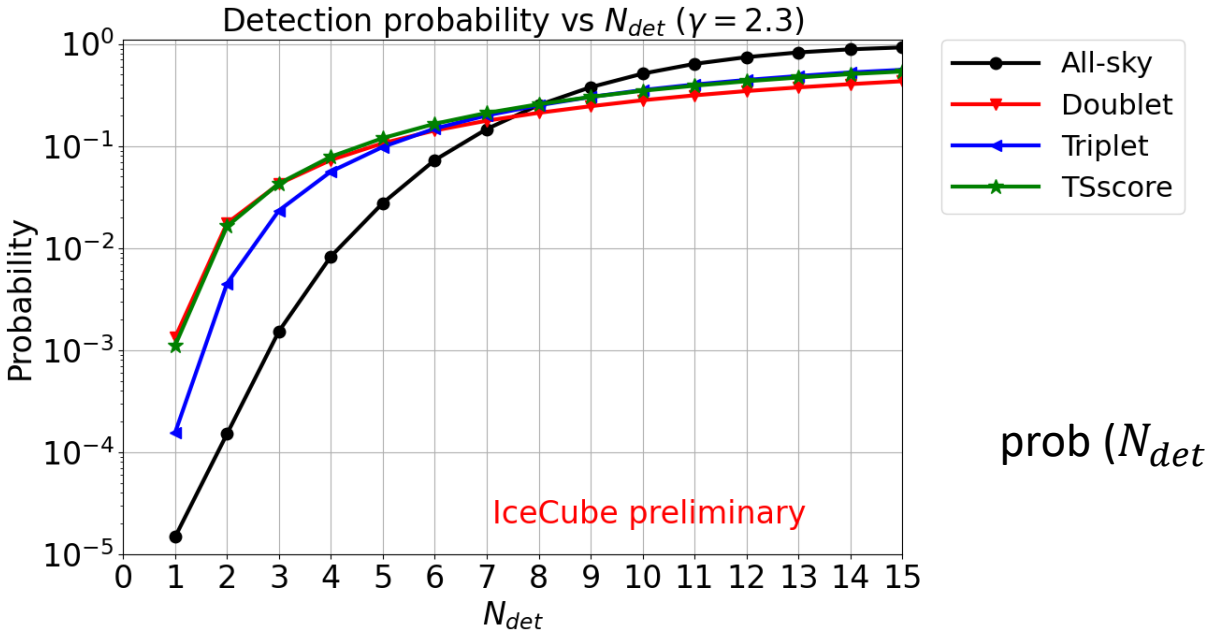
Detection Efficiency of signal

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

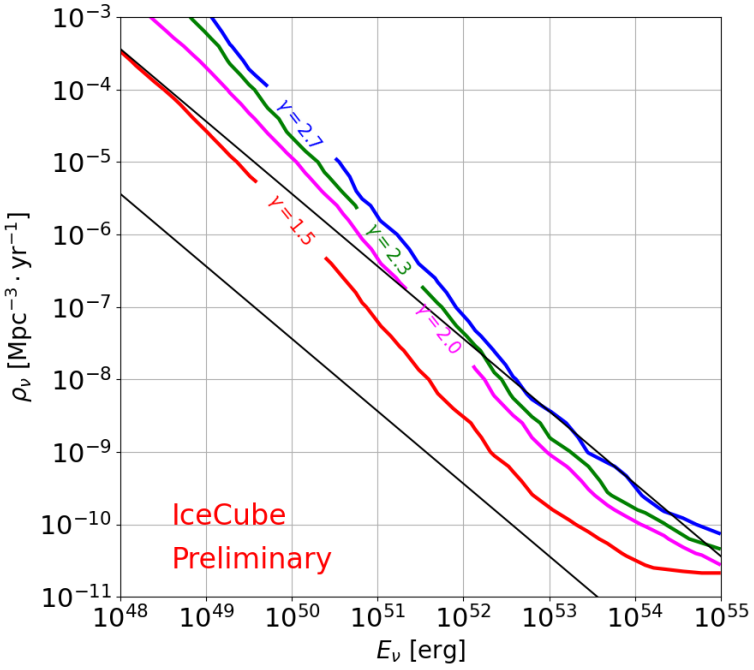


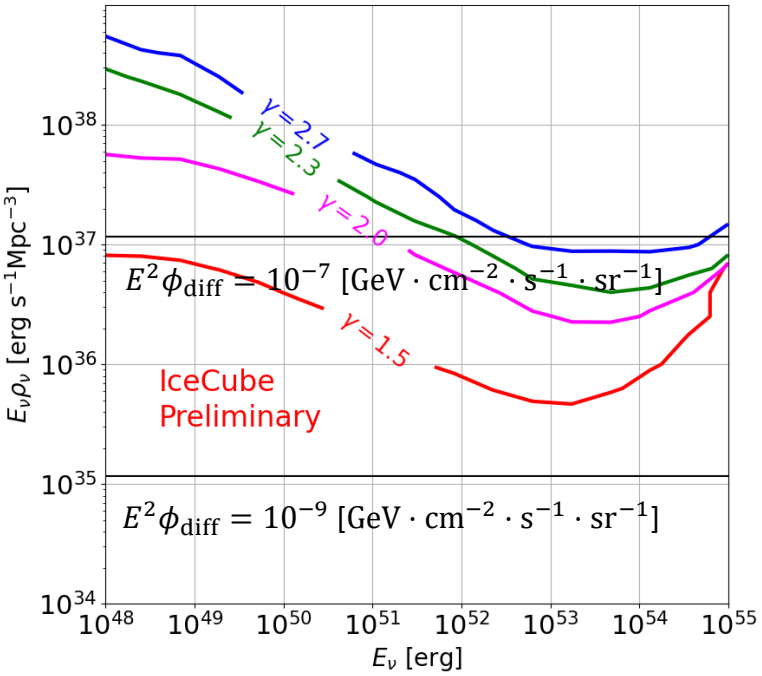
prob (N_{det}) = $\frac{N_{\mathrm{trial}}^{\mathrm{pass}}}{N_{\mathrm{trial}}}$

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)





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

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

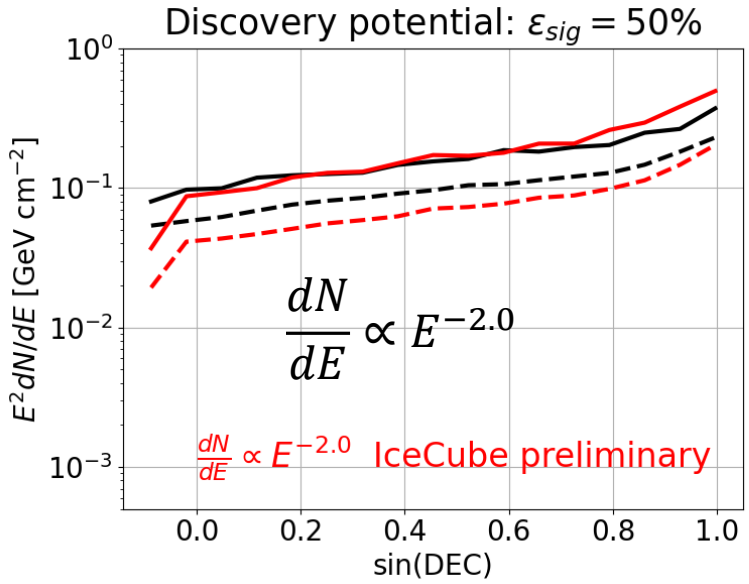
p-value = 10%

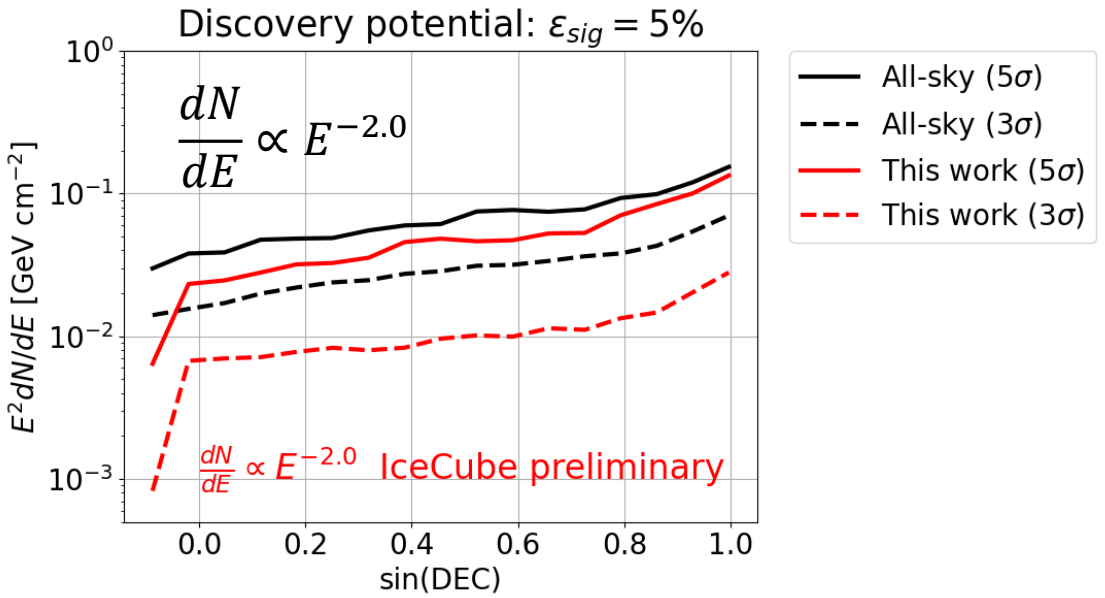
Information to be sent in the alert

- 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.