Follow-up observations of IceCube events using ZTF data: Lessons learned

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in collaboration with
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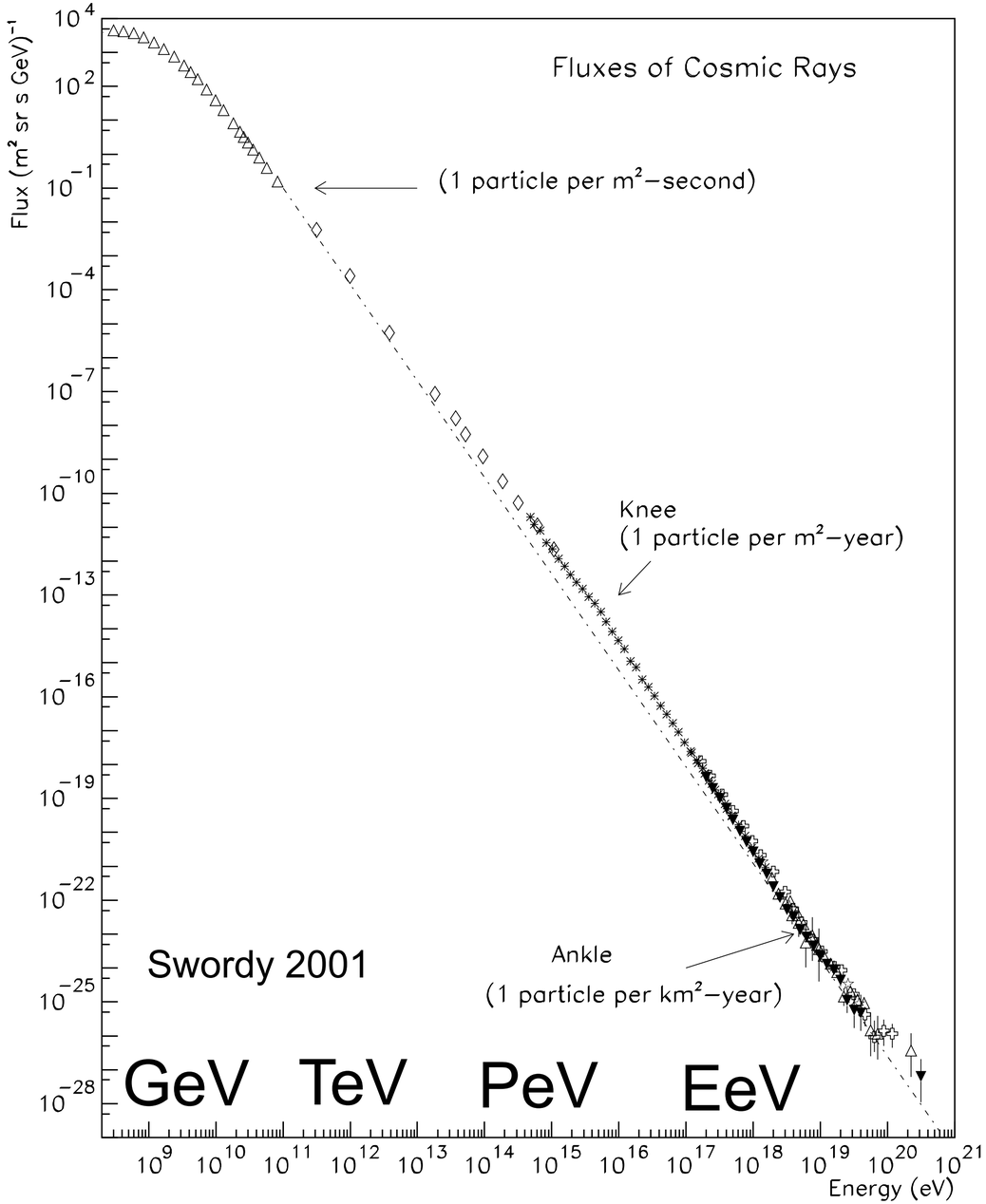
Tomoki Morokuma (Chiba Tech), and IceCube follow-up team

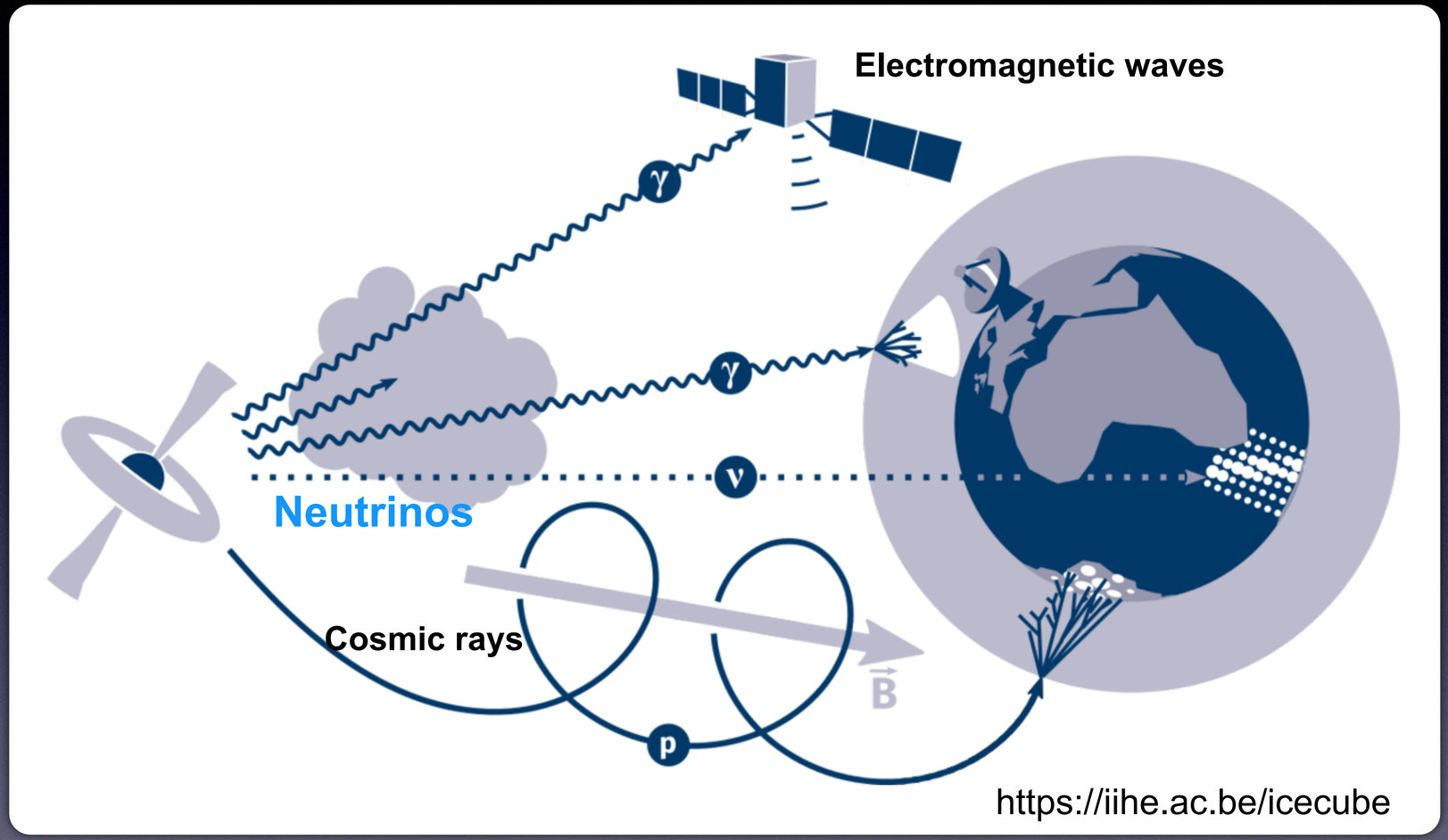
High-energy cosmic rays



Origin of such high-E particles?

Acceleration mechanism?

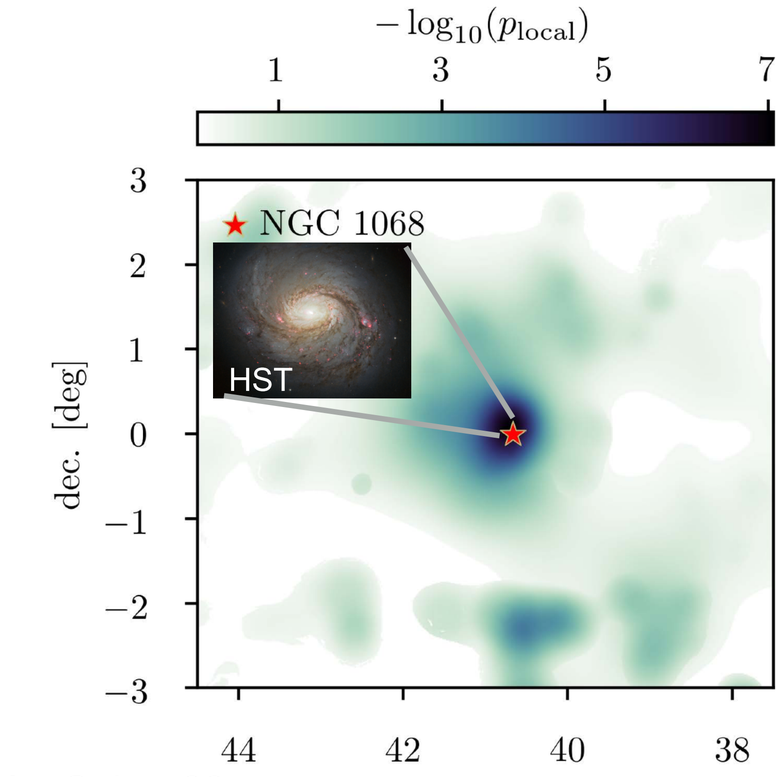
Power of multi-messenger astronomy



Identification of neutrino source
=> Origin of high-energy cosmic rays

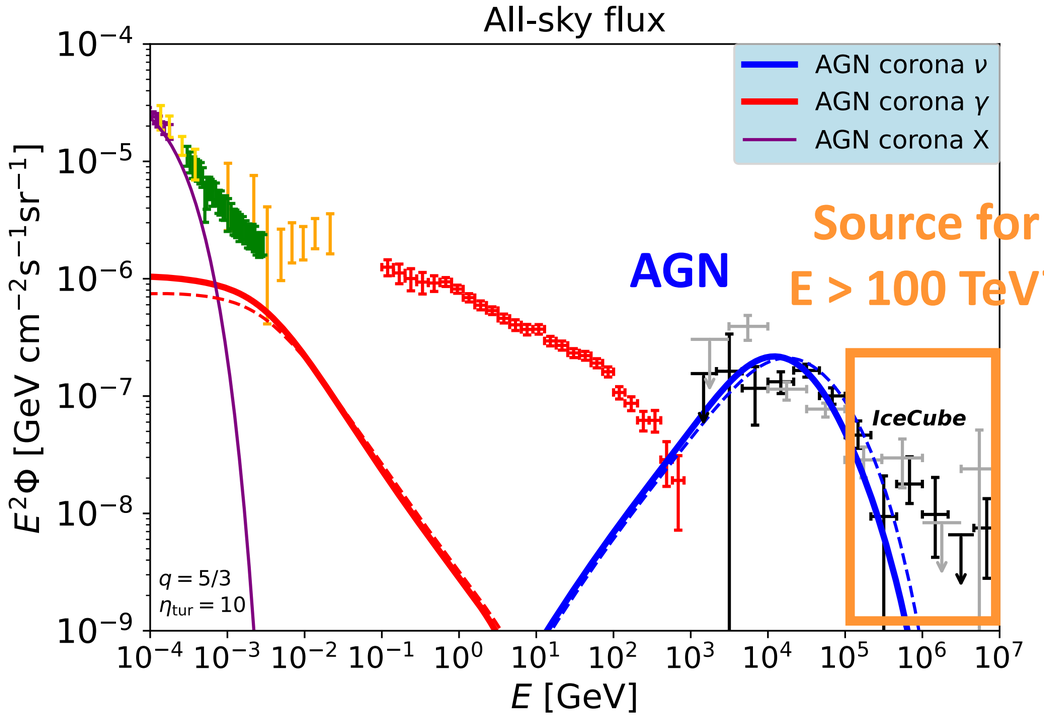
What is the source for high-E neutrino?

NGC 1068 (Seyfert galaxy)



IceCube+22

Contribution to the background flux



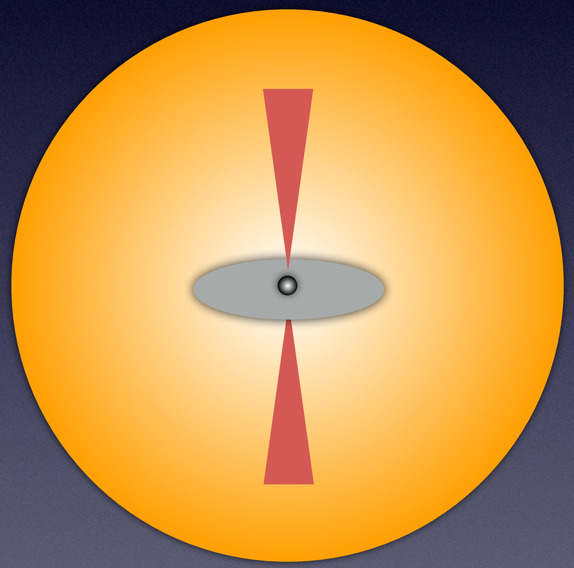
Murase+26

Search for explosive transients as possible sources
(IceCube provides real-time alerts)

Explosive transients as neutrino sources

Chocked jet in the stellar envelope?? (p + γ)

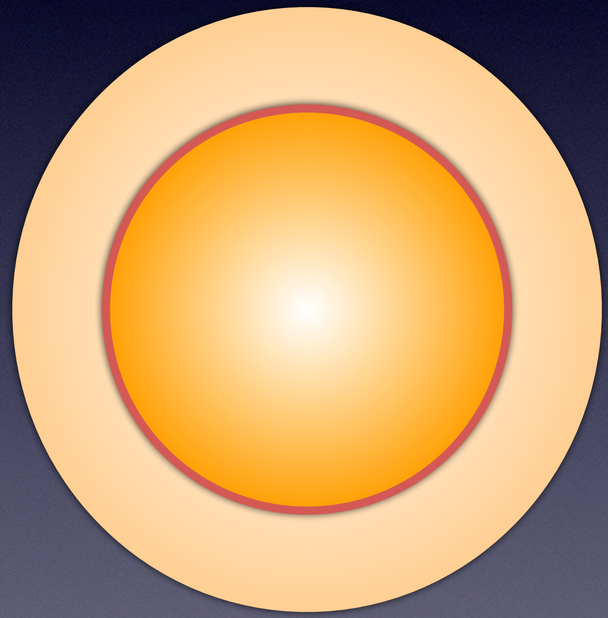
e.g., Murase & Ioka 2013
Senno+2016



Energetic supernovae?
(t < hr)

Interaction between supernova and circumstellar metarial? (p + p)

e.g., Murase+2011
Kimura & Moriya 2025



Interacting supernovae?
(t ~ 30 d)

Challenges in neutrino follow-up observations

Unknown source

interacting SNe ?

(C) NASA/SDO

tidal disruption events (TDEs)?

(C) NASA/CXC/M. Weiss

energetic SNe ??

(C) ESO

variable blazars?

(C) NASA

(c.f. gravitational waves)

Large distance

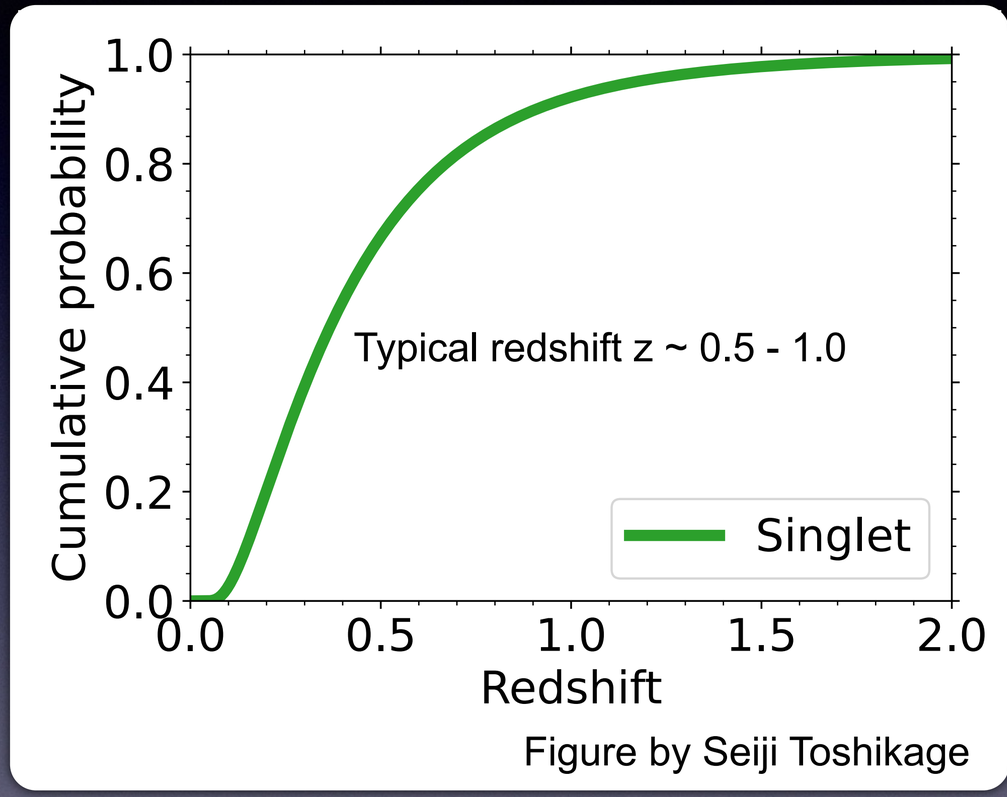


Figure by Seiji Toshikage

Search for “something special”

Large distance is a big challenge for follow-up

1 m class, mall telescope

~20 mag

(ZTF, Pan-STARRS, Kiso)

Insufficient sensitivity
=> needs many trials

8 m class, large telescope

~25 mag

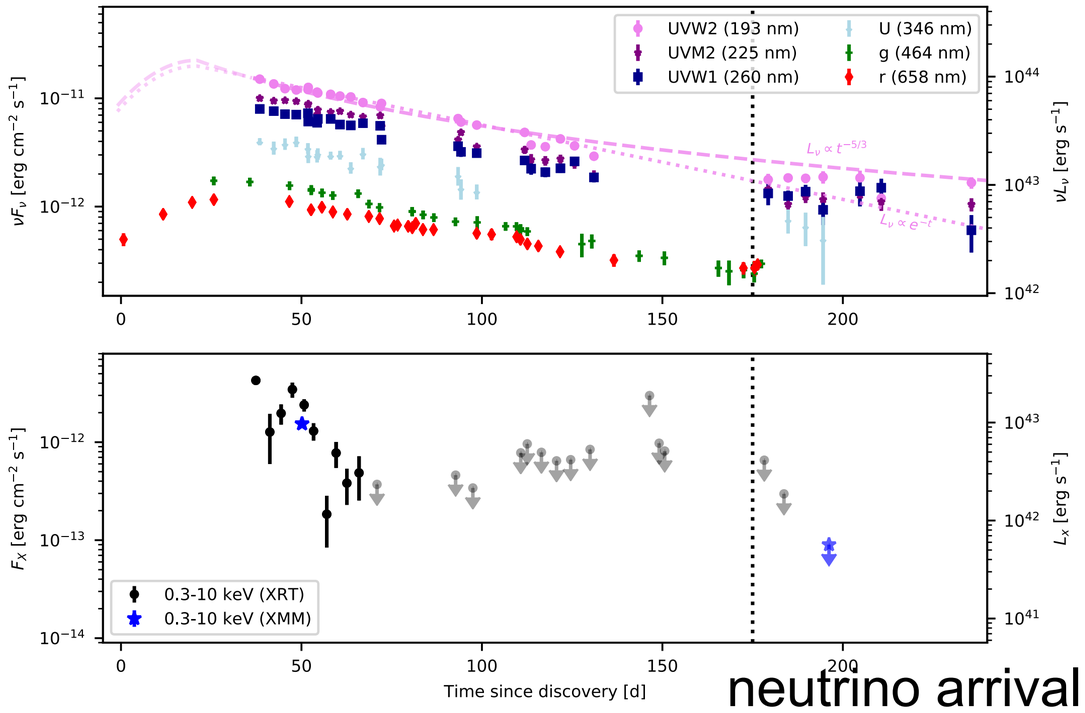
(Subaru, Rubin)

Too many (unrelated) background SNe

Past neutrino follow-up search

ZTF sensitivity => Need many trials (low recovery rate)

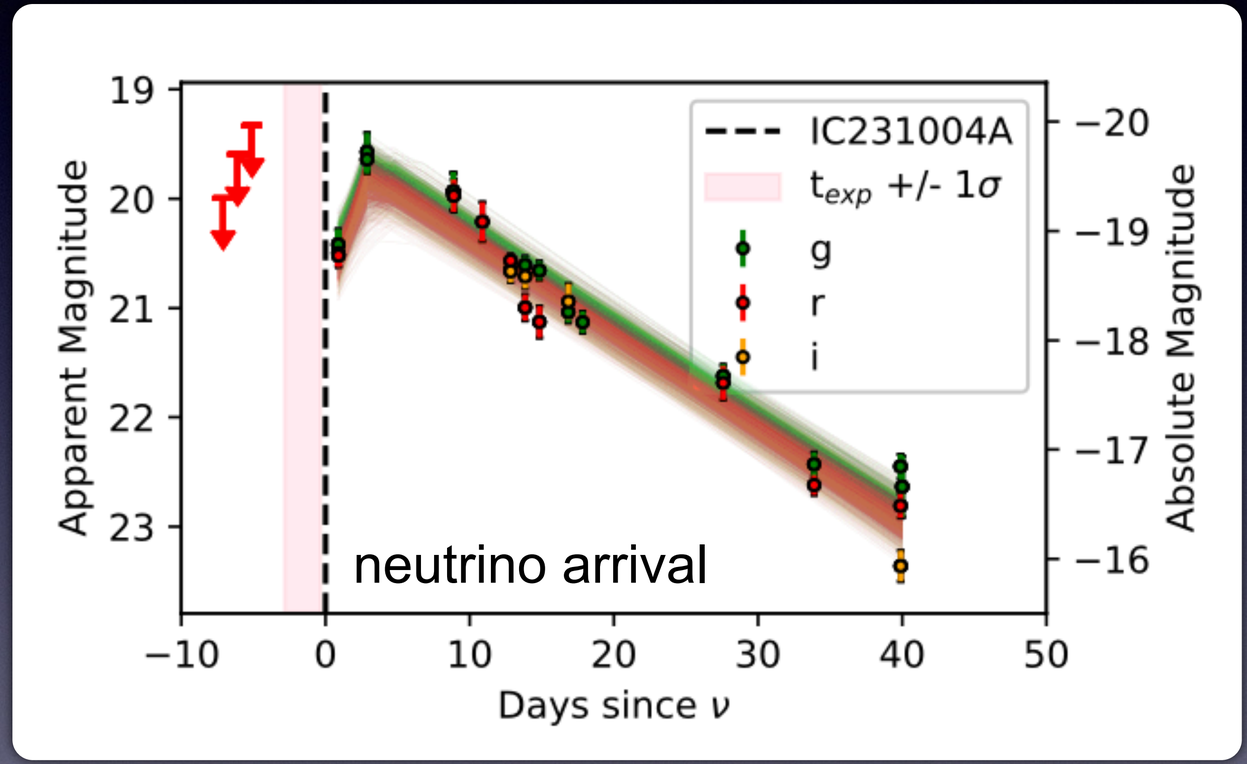
Tidal disruption event (AT2019dsg)



Stein et al. 2022 (with ZTF)
see also Reusch et al. 2022

Estimated chance coincidence ~ 0.5 %

Interacting SN (Type Ibn, SN 2023uqf)

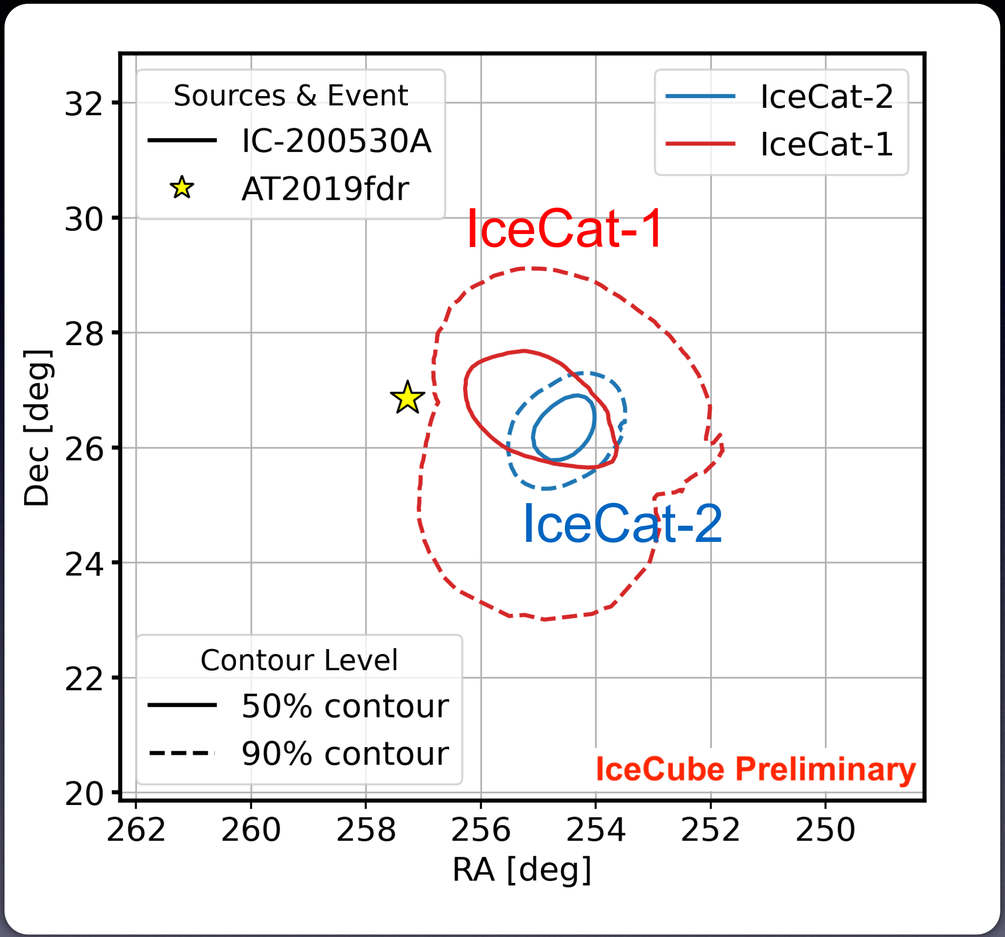


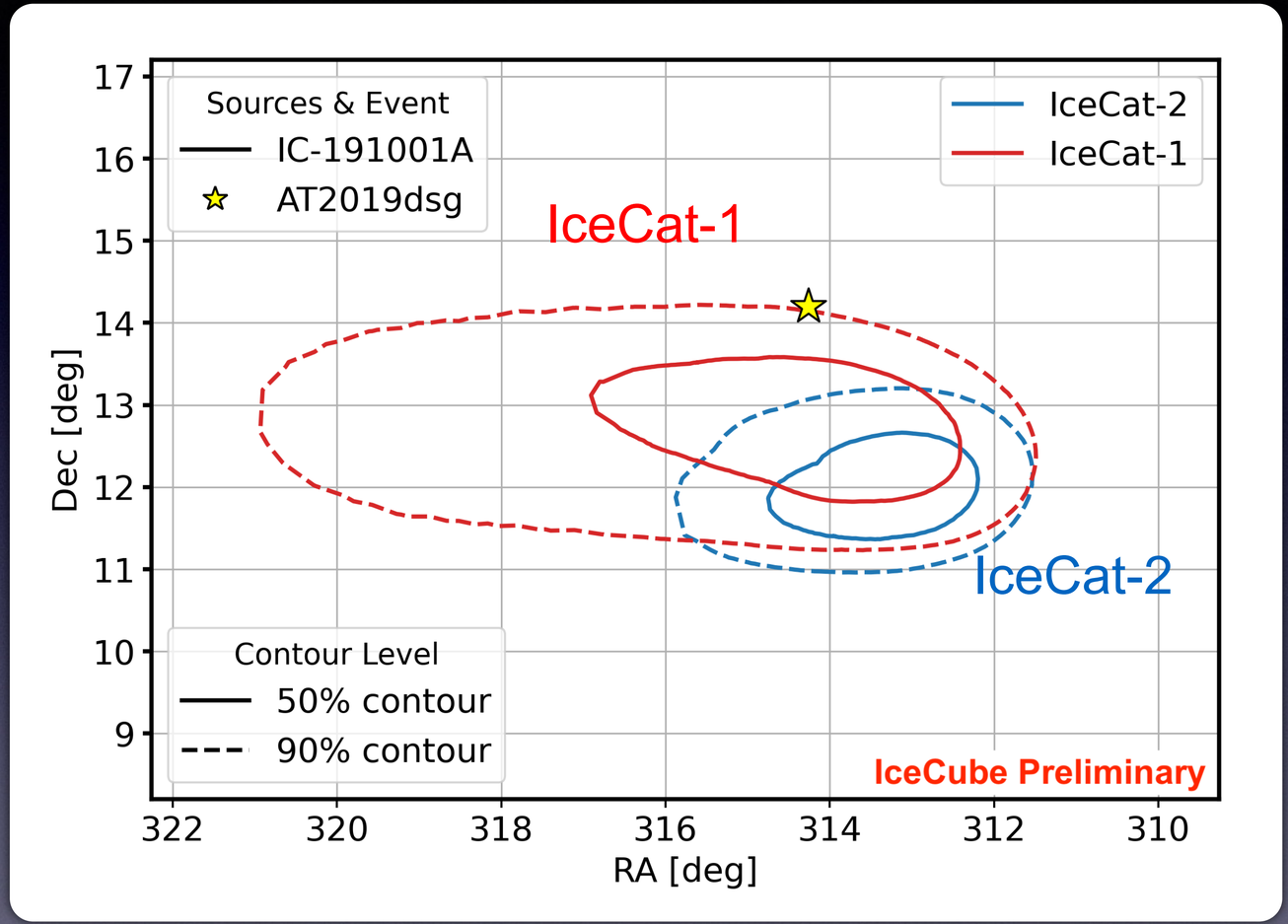
Stein et al. 2025

Estimated chance coincidence ~ 0.3 %

Updated neutrino localization

IceCube+2025



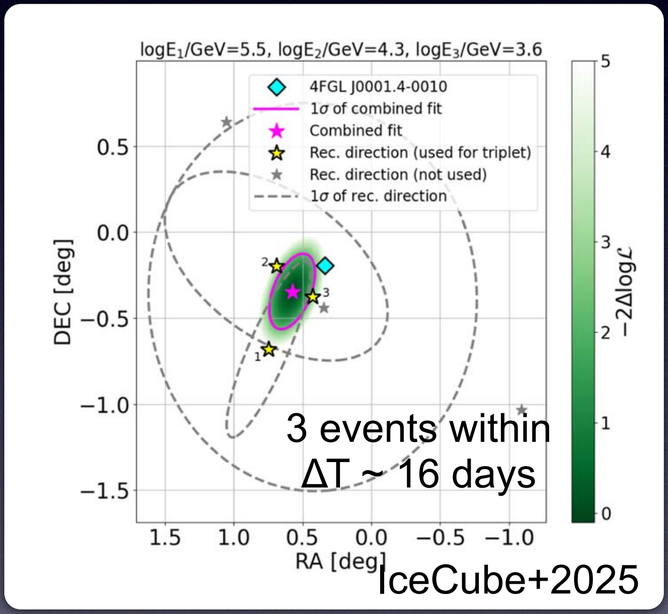


TDE association is no more robust…
=> how can we improve our search??

Our strategies

(1) Use of neutrino “multiplet” signals

Multiple neutrino detections
within a certain time window



High “flux” => close distance
+ Better localization (multiple estimates)

see Yoshida+2022
(also Aartsen+2017)

(2) Extensive background analysis

- Astrophysical background (unrelated transients)
- Non-astrophysical background (fake detections)

Blind analysis
Fix the search criteria and background estimates
BEFORE searching candidates

See Seiji Toshikage’s talk

(1) Neutrino “multiplet”

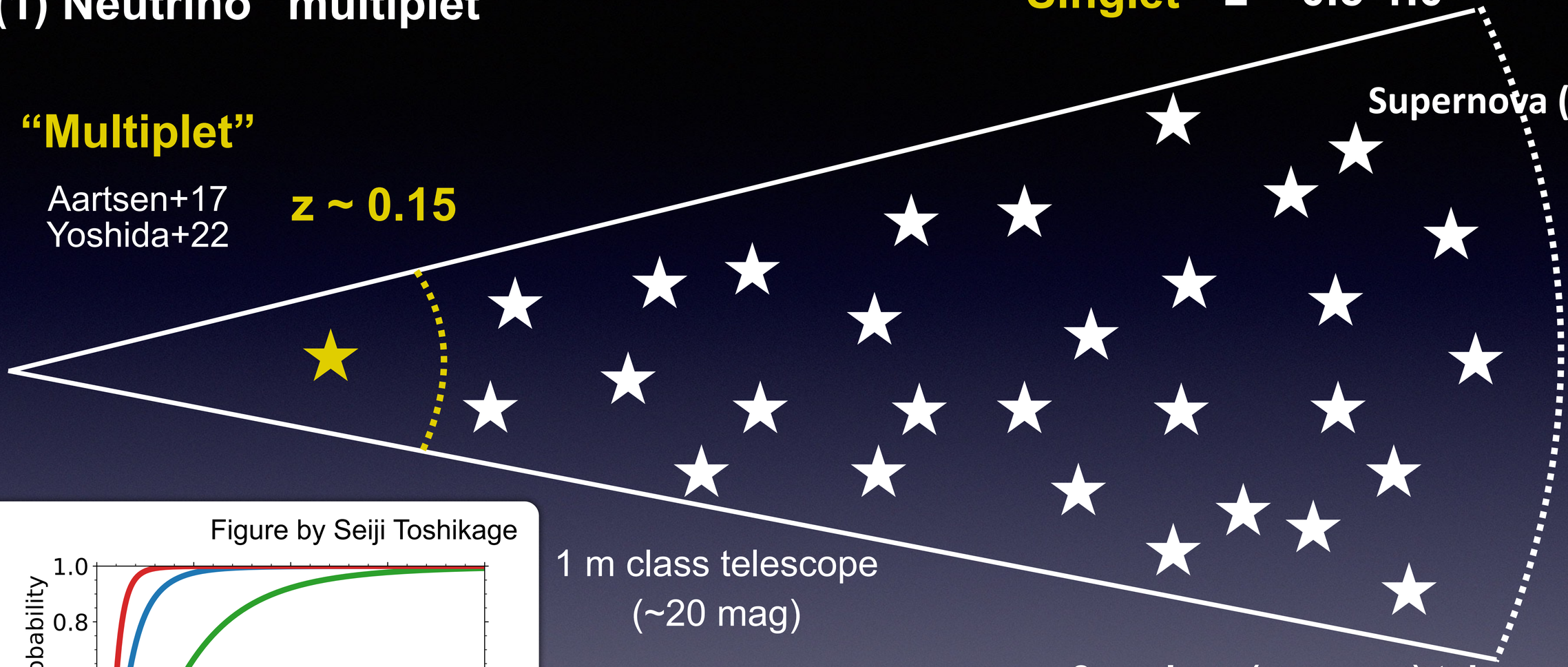
Singlet z ~ 0.5-1.0

Supernova (SN)

“Multiplet”

Aartsen+17
Yoshida+22

z ~ 0.15

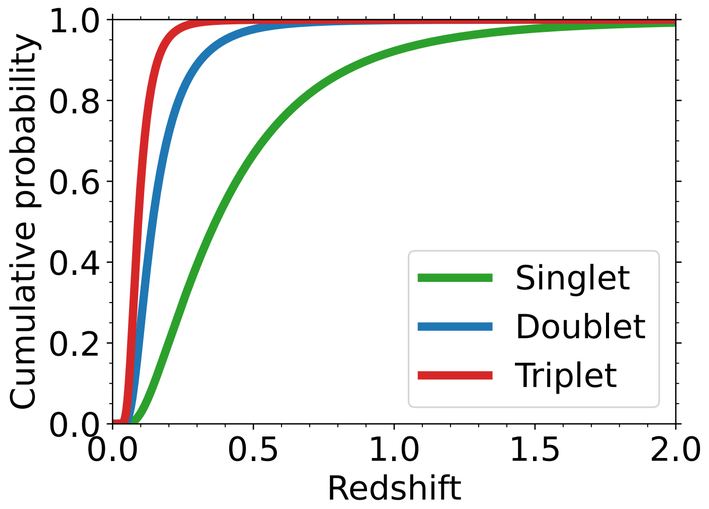


1 m class telescope
(~20 mag)

ZTF, Pan-STARRS, Kiso

8 m class (or space) telescope
(~25 mag)

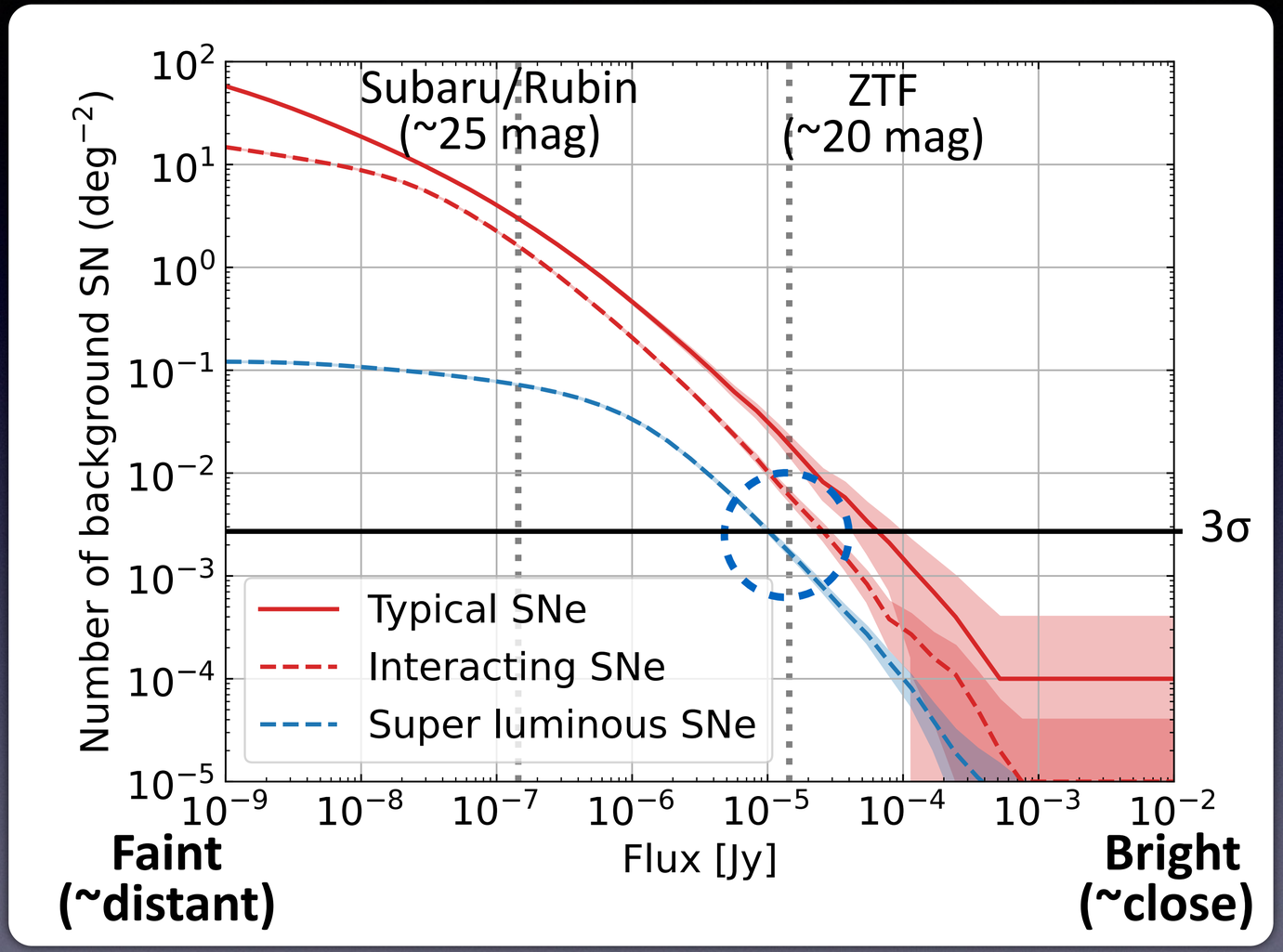
Figure by Seiji Toshikage



Multiplet = High recovery rate
(no sensitivity issue!)

(1) Neutrino “multiplet”

Number of “unrelated” SNe (per 1 deg²)

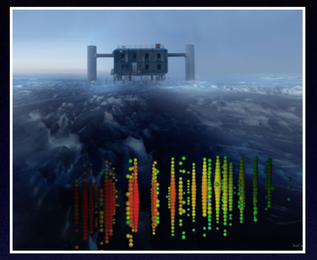


Background simulations
By Seiji Toshikage
(w/ SN light curves and luminosity distributions)

Multiplet = Low (astrophysical) background

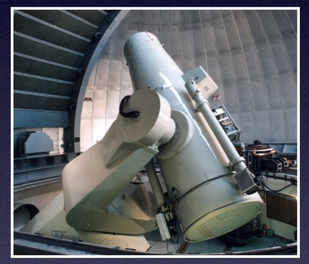
(2) Importance of blind analysis

Conventional method in astronomy



(C) IceCube collaboration

1. Neutrino alert!

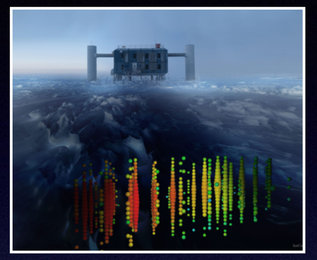


(C) IoA/U. Tokyo

2. Let’s perform follow-up

(2) Importance of blind analysis

Conventional method in astronomy



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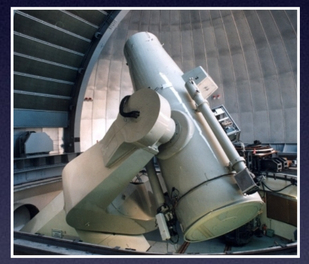

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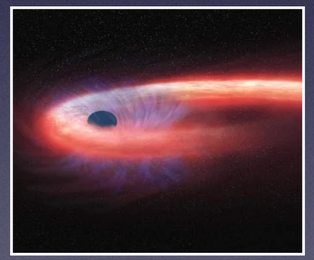

(C) NASA/CXC/M. Weiss

3. I found such an exiting object!

A TDE but radio emitting, A SN but very luminous…

(2) Importance of blind analysis

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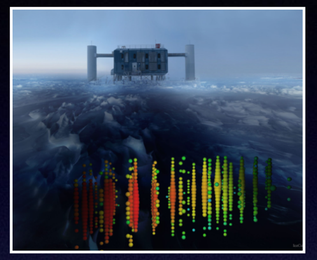

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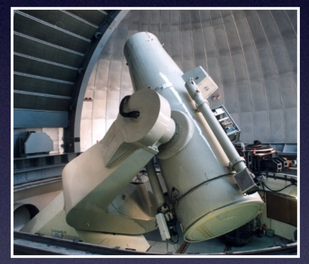

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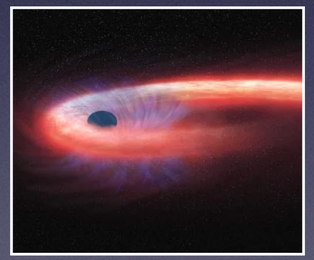


(C) NASA/CXC/M. Weiss

3. I found such an exiting object!

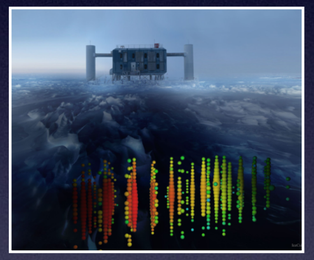
A TDE but radio emitting, A SN but very luminous…

4. Let's estimate how special this object was…

But we already know the "answer"
=> bias in the statistical test

(2) Importance of blind analysis

Blind analysis



(C) IceCube collaboration

1. Neutrino alert!

(C) IoA/U. Tokyo

2. Let’s perform follow-up

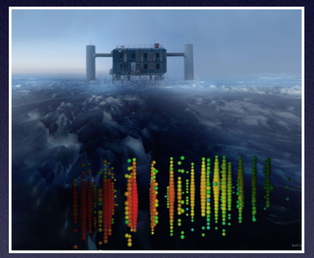
(2) Importance of blind analysis

Blind analysis

0. First let's understand our data

=> Fix the search criteria
and estimate background

=> Likelihood ratios (signal vs background)



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1. Neutrino alert!

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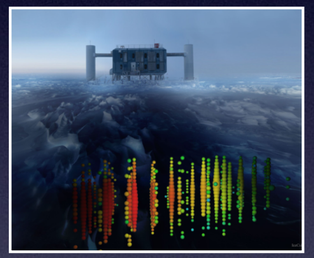


(C) IceCube collaboration

1. Neutrino alert!

(C) IoA/U. Tokyo

2. Let's perform follow-up

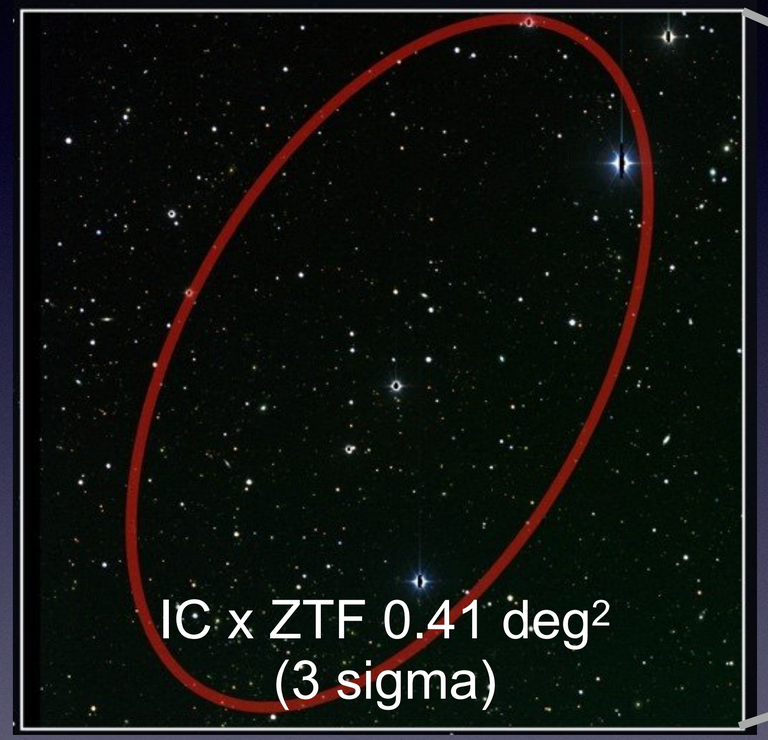
3. Perform "pre-fixed" search

We should not change the selection according to actual findings
(c.f. Hubble constant, cosmological parameters)

Archival search for optical counterpart of neutrino “multiplet” events

Toshikage+2025

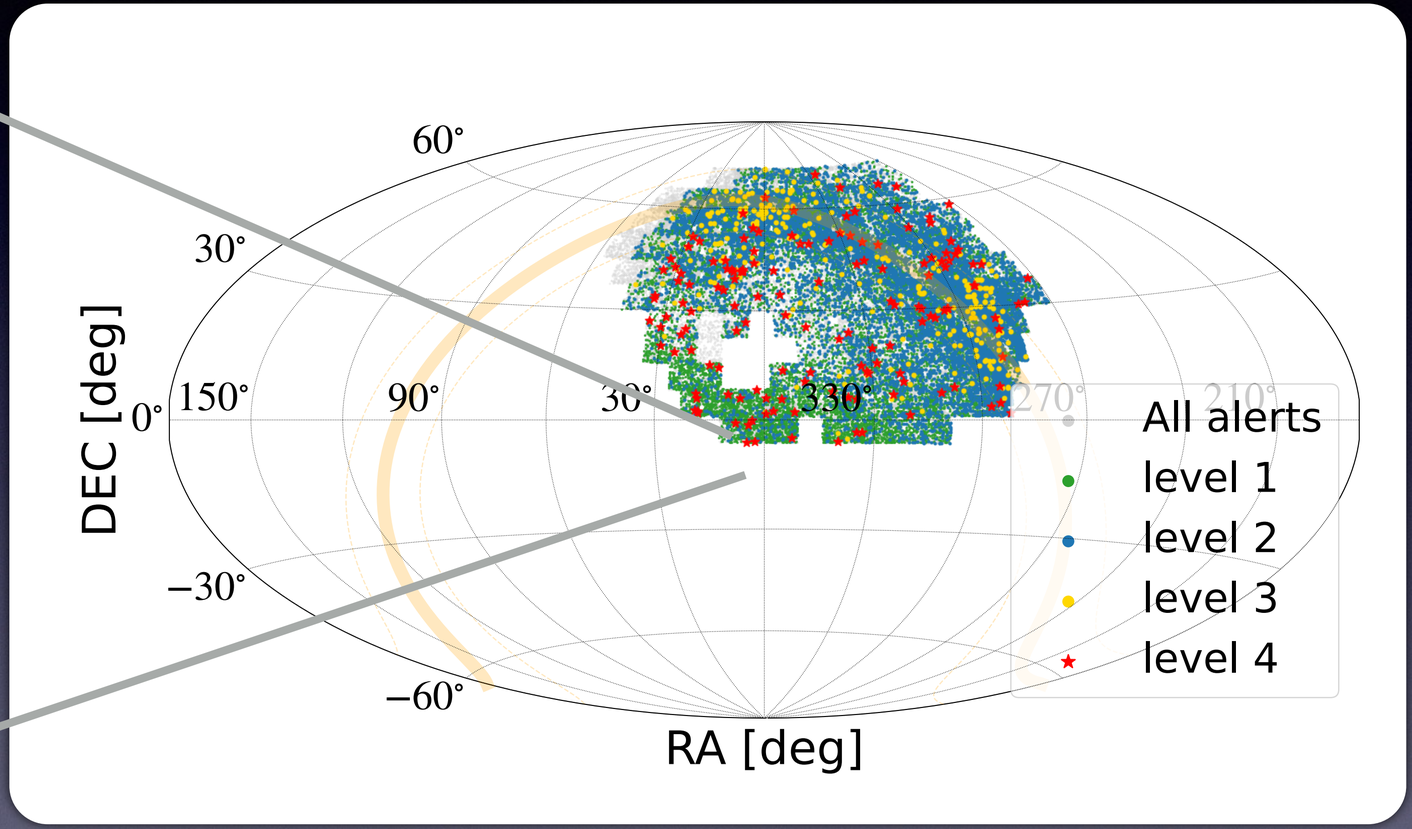
Combined localization area



“Triplet” over 16 days
(E = 295, 20, 4 TeV)
in 2020

IceCube+2026

Transient search with archival ZTF data



Extensive background analysis

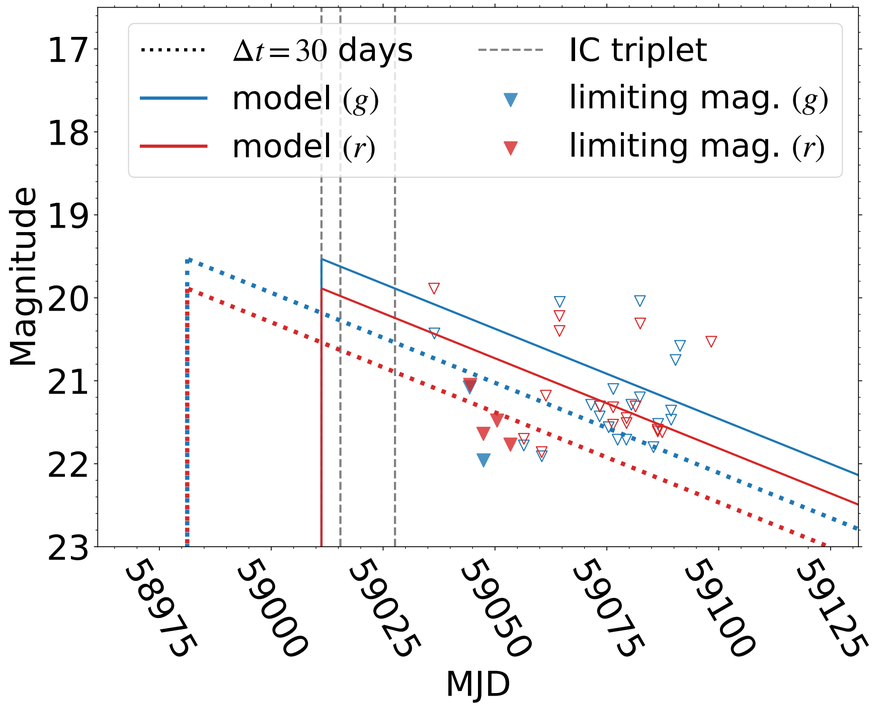
(over 6500 deg2!!)

=> 0.02 objects/deg²

Search for optical counterpart of neutrino “multiplet” events

Toshikage+2025

Light curve

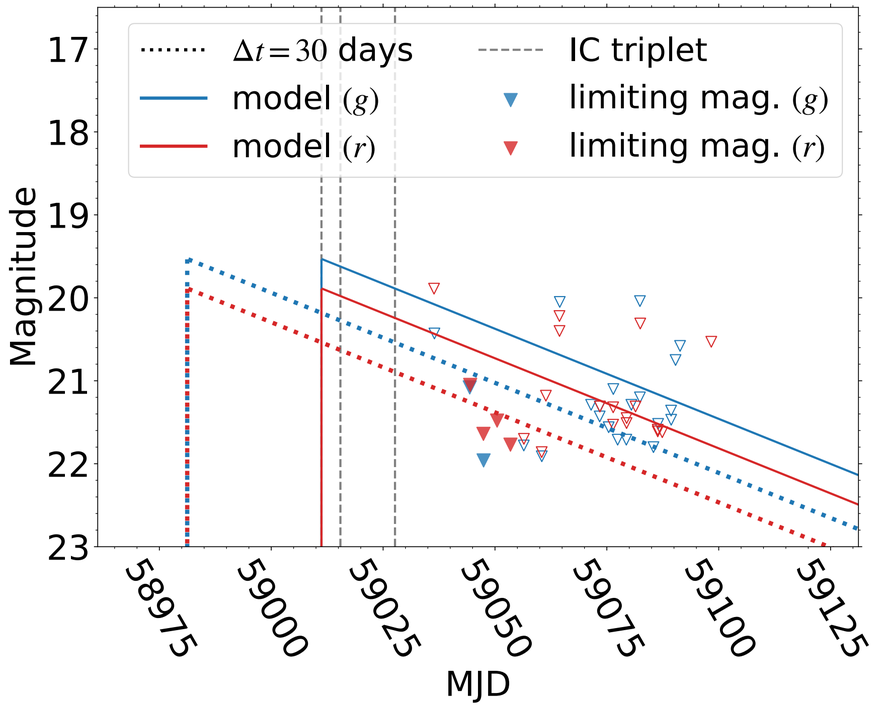


No candidate found

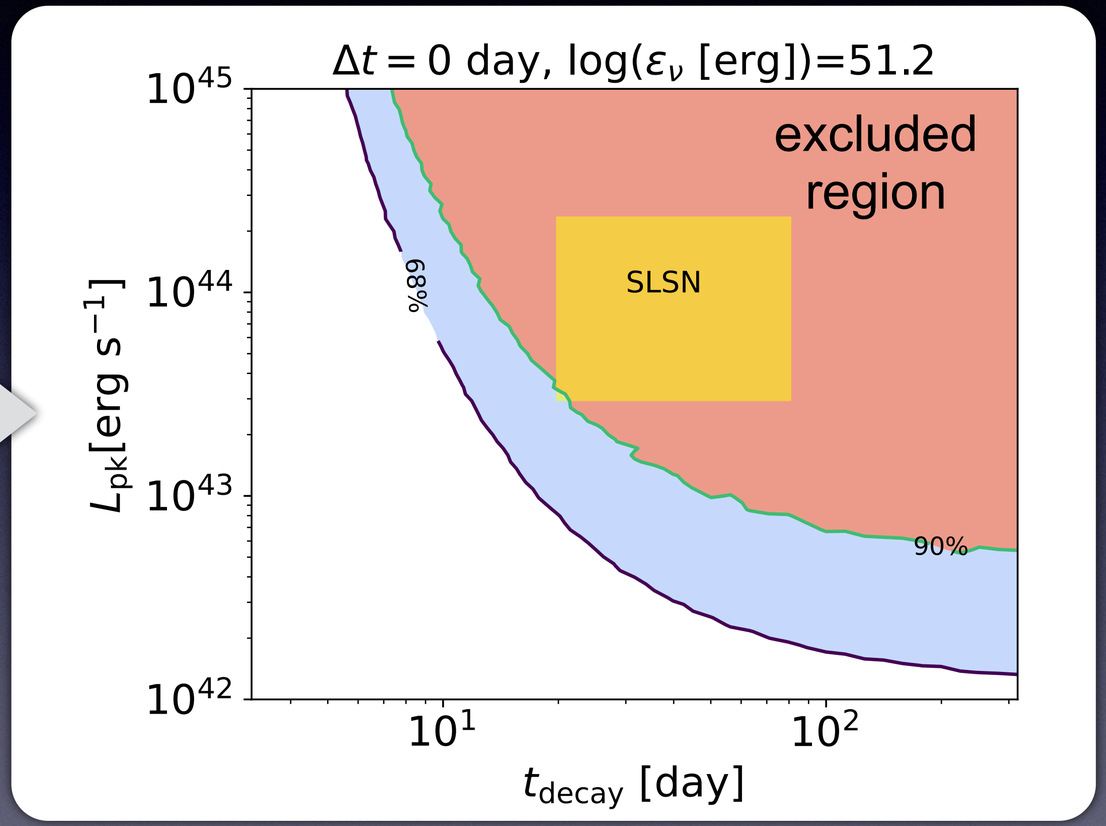
Search for optical counterpart of neutrino “multiplet” events

Toshikage+2025

Light curve



Constraints on transient properties



No candidate found

A single trial rules out luminous objects as a counterpart

(but “signalness” of the multiplet is ~ 0.5)

Summary & Future

- **Our new strategy for neutrino counterpart search**
  1. Use of multiplet events
  2. Extensive background analysis (blind analysis)
- **Lessons from archival search with ZTF**
  - Interesting constraints even with one single event (and even with non detection!)
- **Future?**
  - **Real-time neutrino multiplet alert => real-time follow-up (imaging => spectroscopy)**