Optical Counterpart search for a Month-timescale IceCube Neutrino Multiplet Event

Seiji TOSHIKAGE in collaboration with

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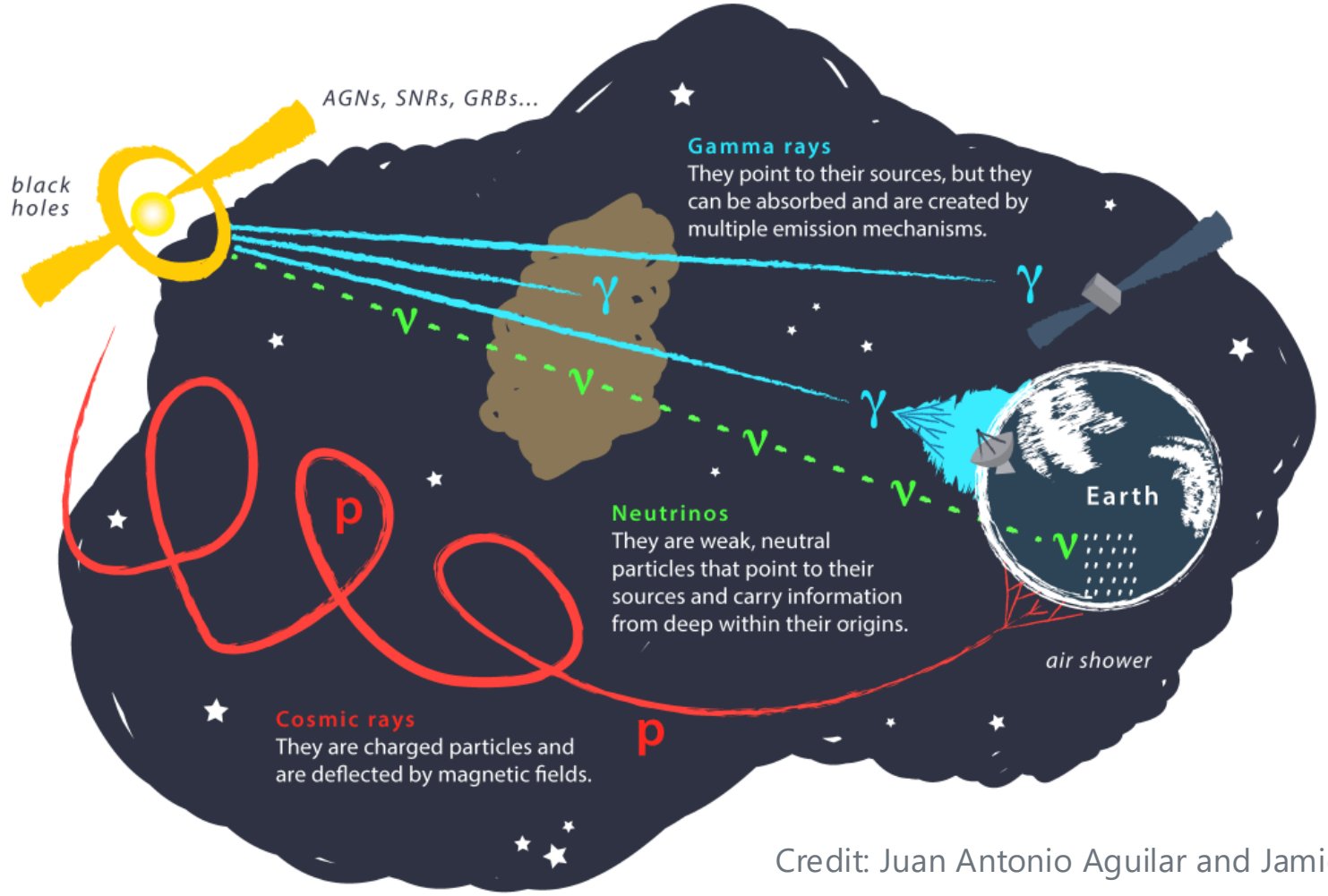
Tomoki Morokuma (Chiba Tech), and IceCube follow-up team

Origin of high-energy particles



Credit: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Neutrino as a probe of high-energy particle origins

Optical transient as neutrino sources

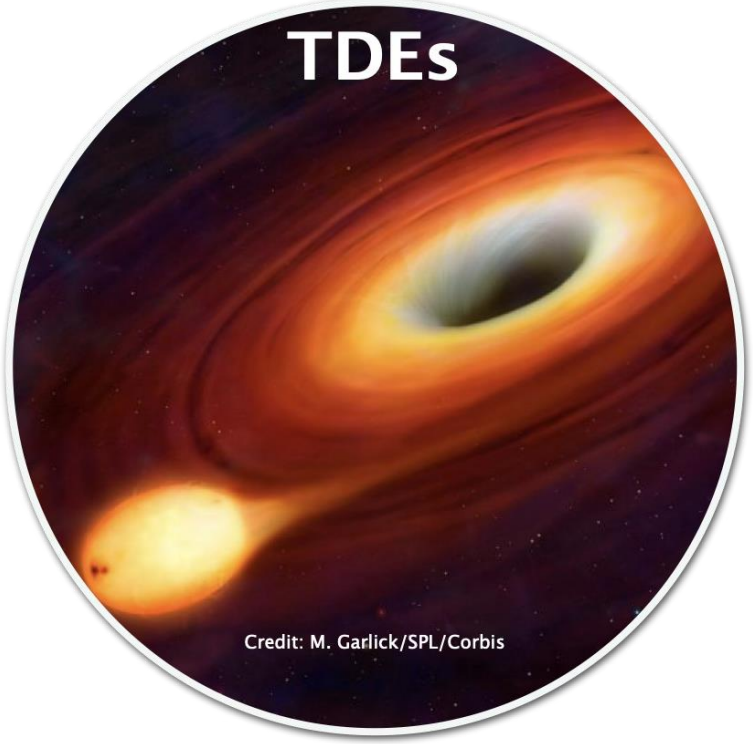
Theoretical predictions

Choked jets/CSM interaction

e.g., Razzaque+ 2004, Murase+ 2011

Jetted TDEs/Corona

e.g., Wang+ 2011



Possible Associations ??

Type Ibn: Stein+ 2025
Type IIn: Lu+ 2025, Garrappa+ 2025

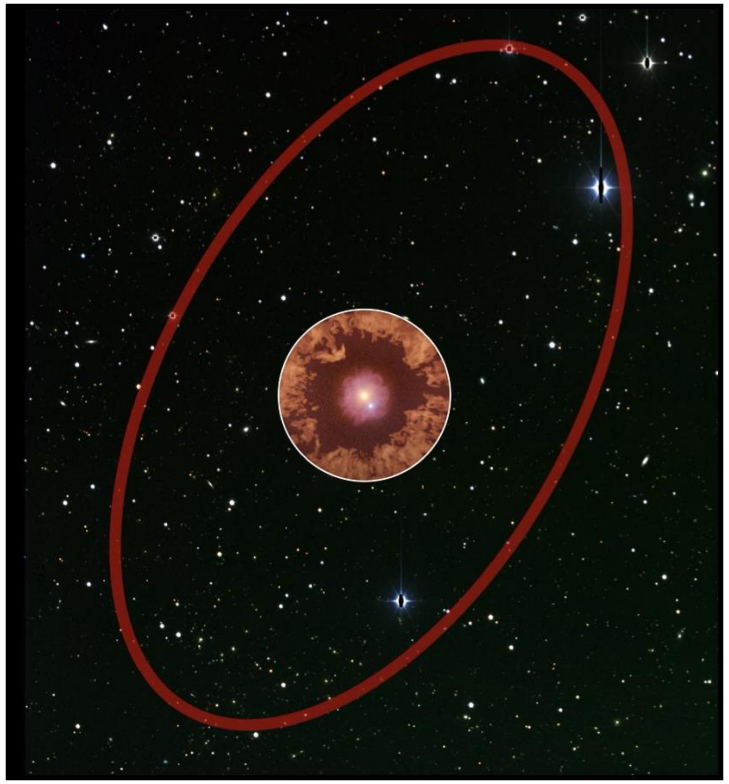
Stein+ 2021, Reusch+ 2022, Jiang+ 2023,
van Velzen+ 2024, Yuan+ 2024, Li+ 2024, …

Talk by Mainak (SLSNe, yesterday), Yosuke (Ibn, tomorrow)

Optical follow-up observations

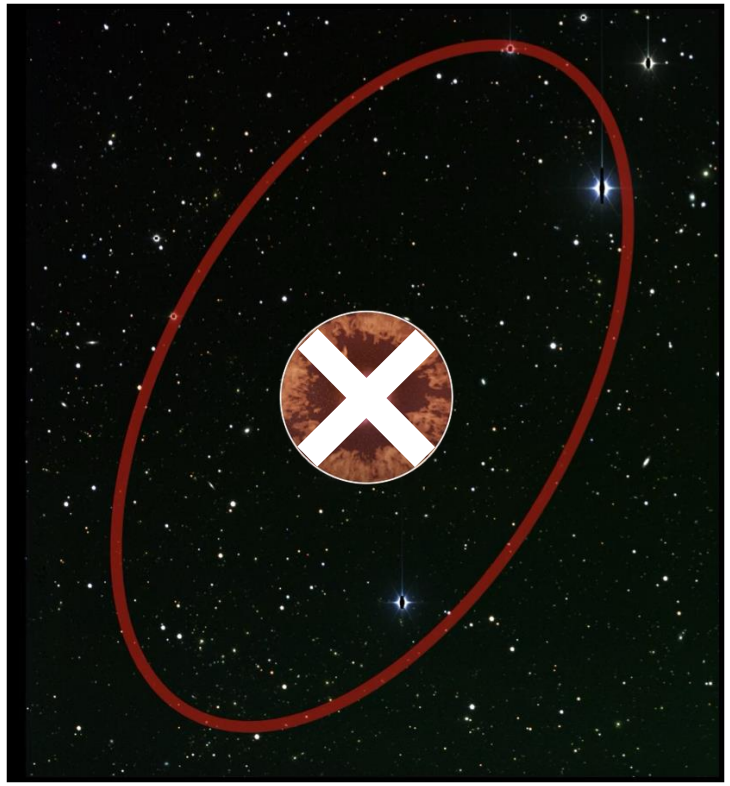
To put it very simply,

Find a candidate!



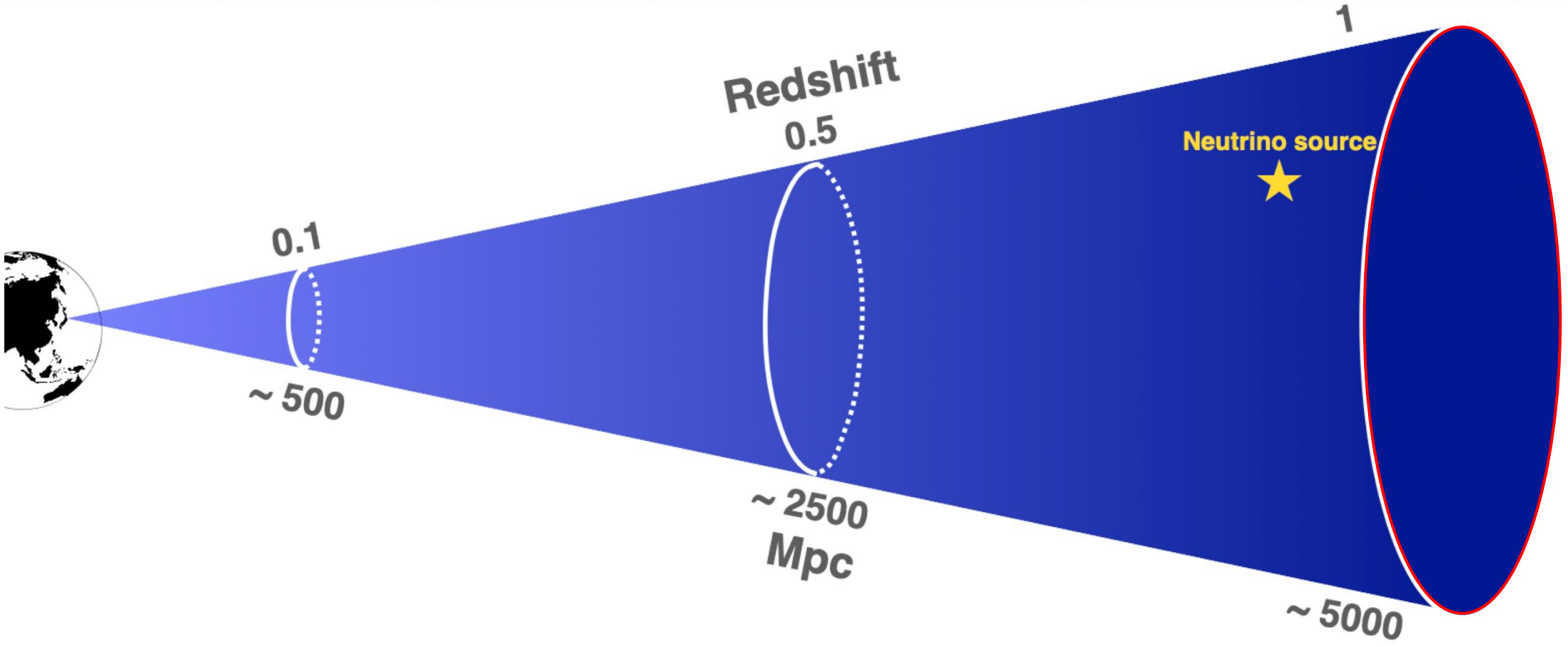
Identify neutrino source!

No transient…



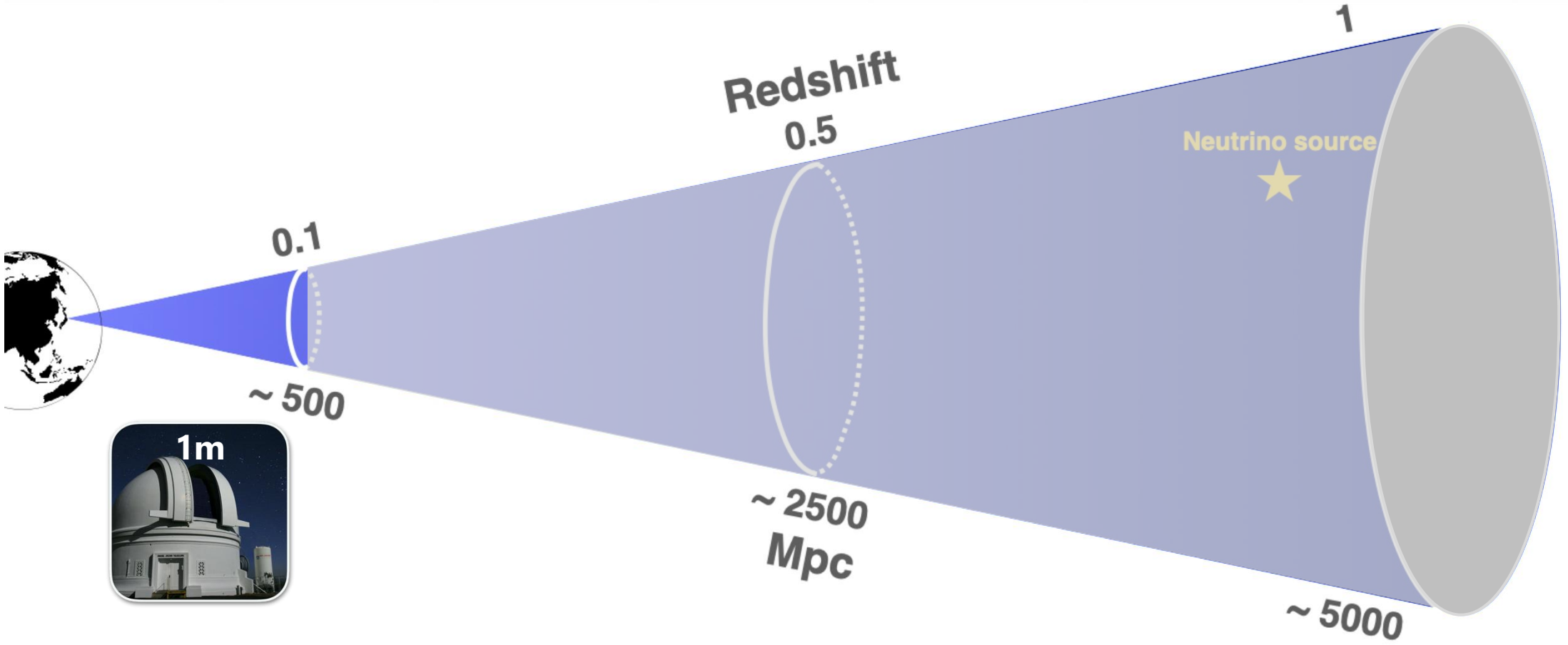
Constrain transient scenario

Issue: Difference of sensitivity



IceCube is sensitive to neutrino sources up to redshift ~ 1-2

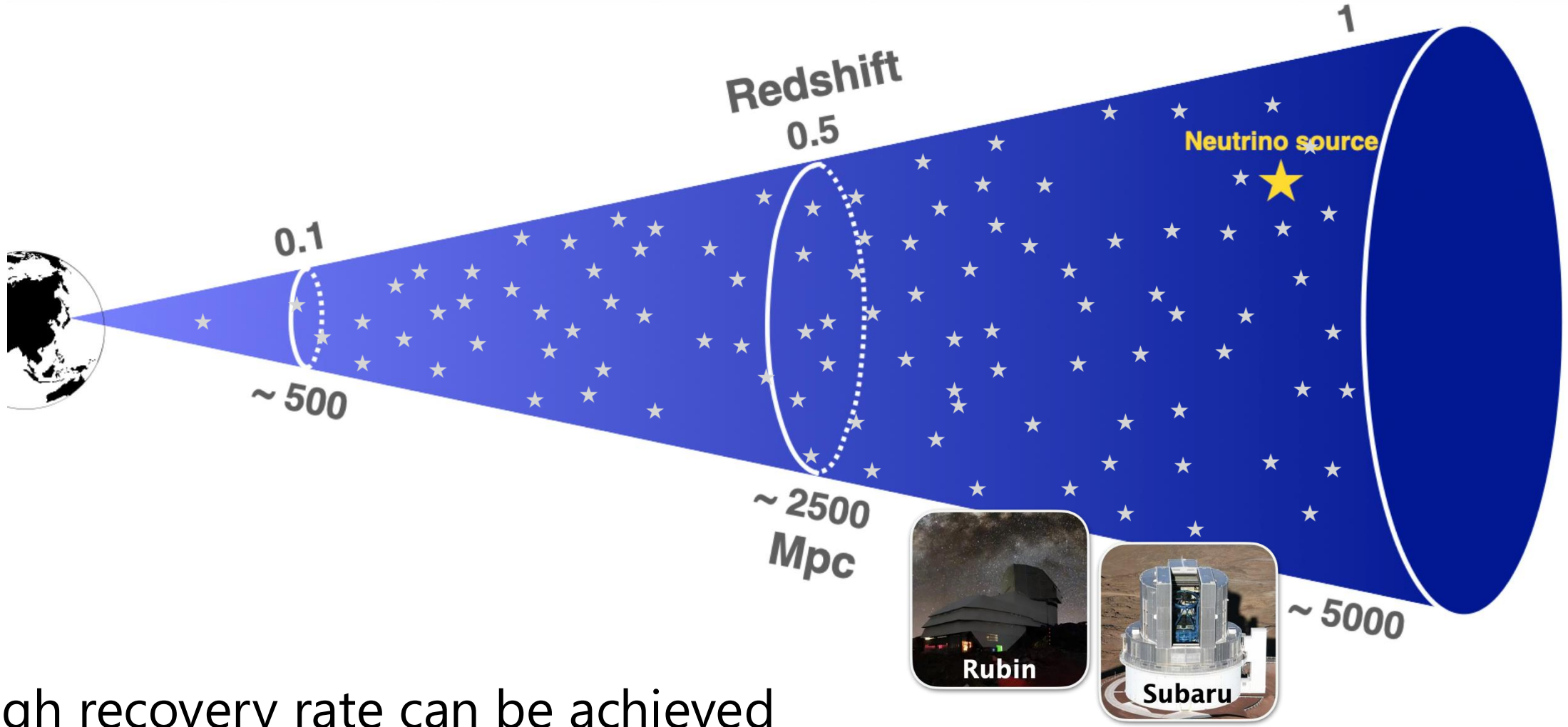
Issue: Difference of sensitivity



Optical counterparts are easily missed by small telescope

High “recovery rate” is needed

Solution 1: Use large telescope



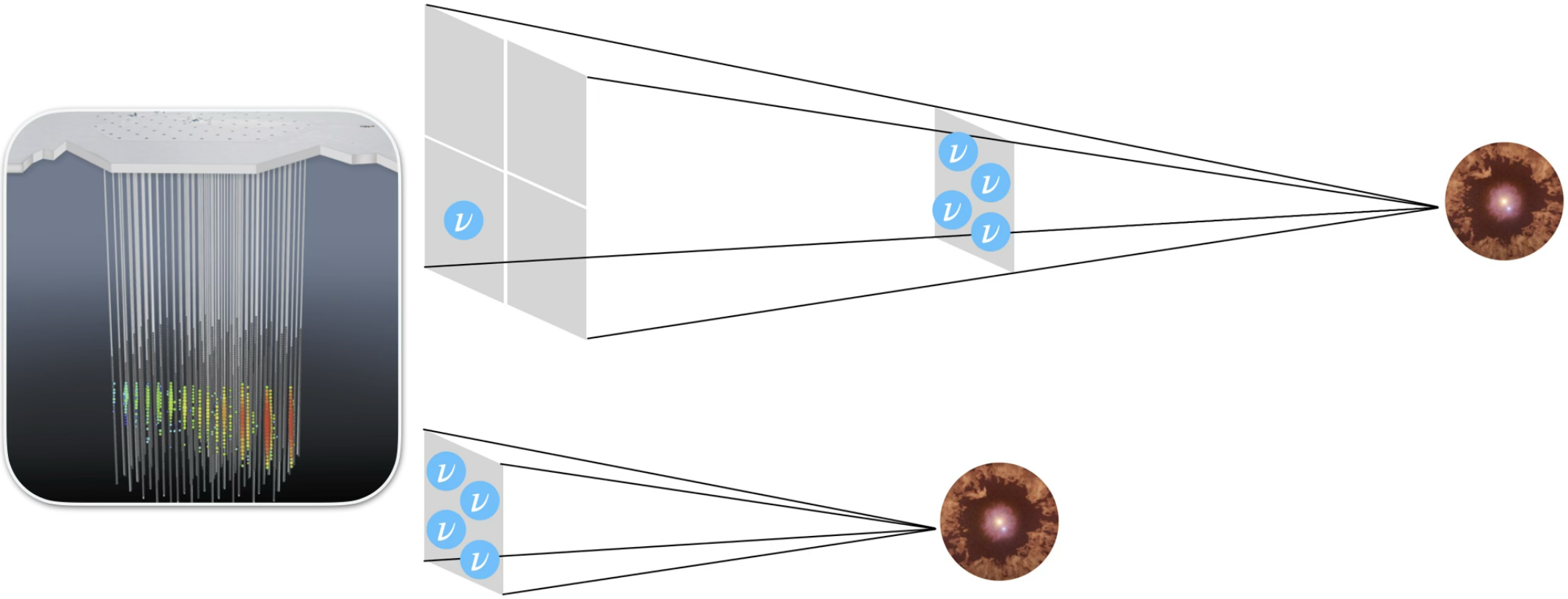
High recovery rate can be achieved

BUT, high background (unrelated SNe/TDEs) …

Solution 2: Neutrino “multiplet”

“Multiplet”: multiple neutrino detections coincident in both space and time

Yoshida+ 2022, IceCube collaboration 2025



*In reality, many neutrinos arrive, and only a tiny fraction are detected by IceCube.

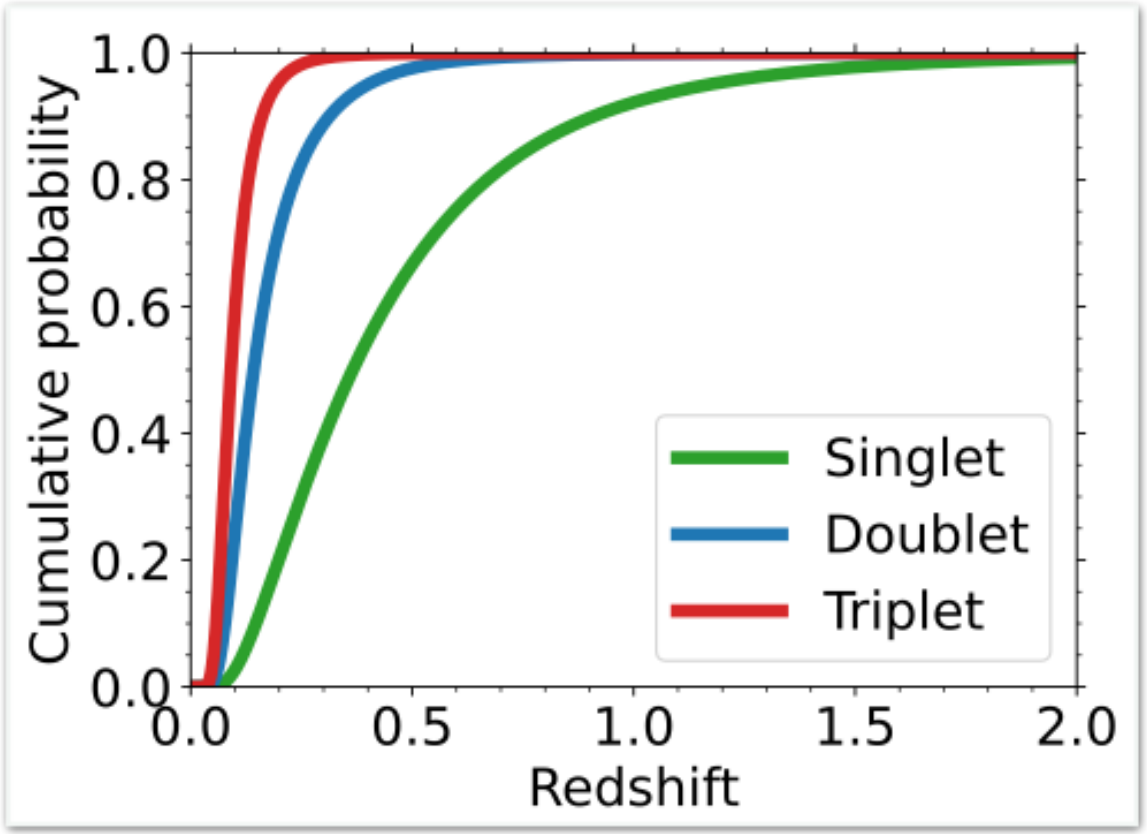
Solution 2: Neutrino "multiplet"

e.g., Assume SLSNe are the dominant high-energy neutrino sources

Total ν fluxes Event rate

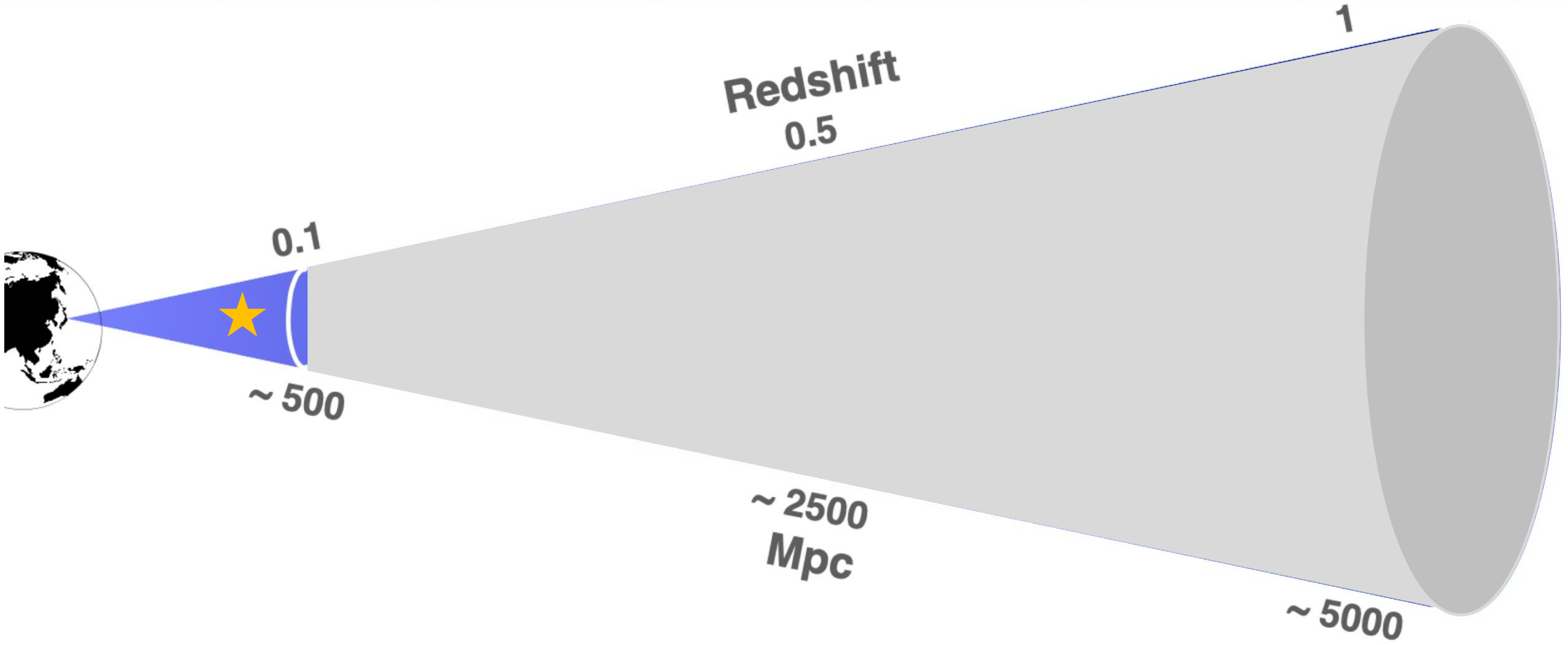
$$\phi_\nu \propto \varepsilon_\nu \times R$$

Neutrino emission energy per object



We can focus on nearby events

Solution 2: Neutrino “multiplet”



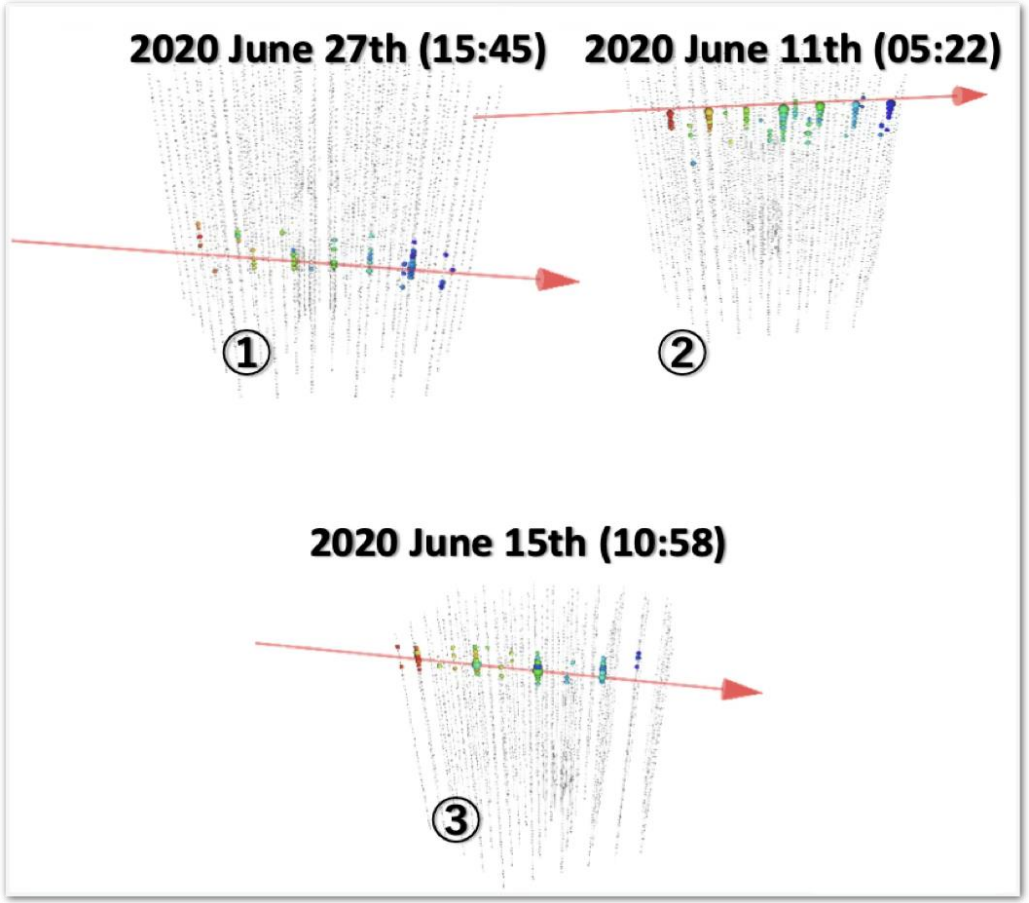
High recovery rate

AND Low-background rate can be achieved!

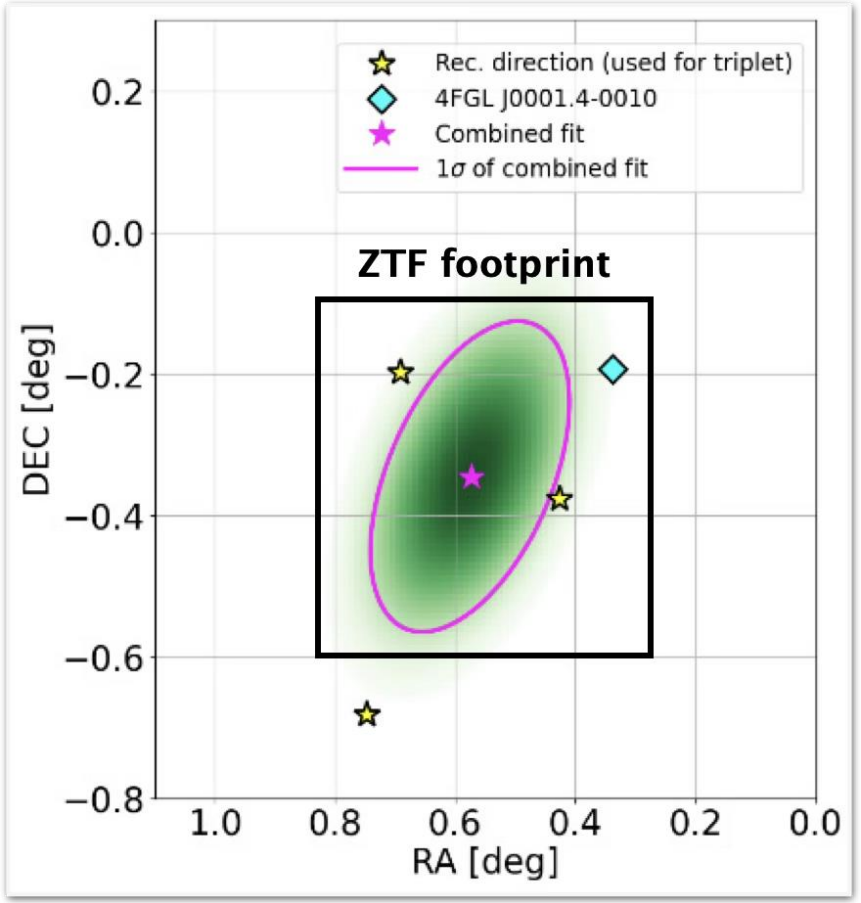
A neutrino triplet event in June 2020

IceCube collaboration 2025

Month-timescale neutrino triplet!



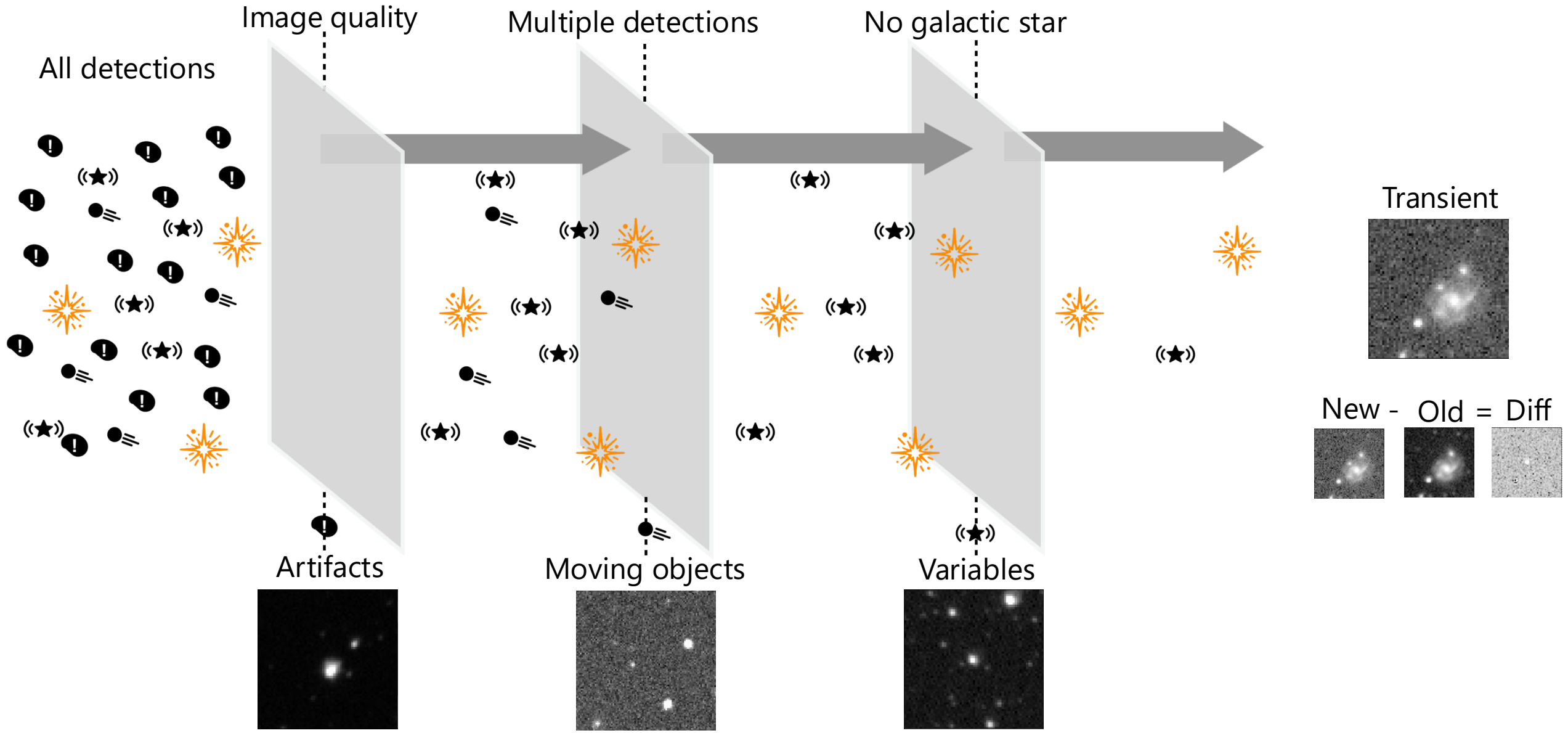
Serendipitous ZTF observations!



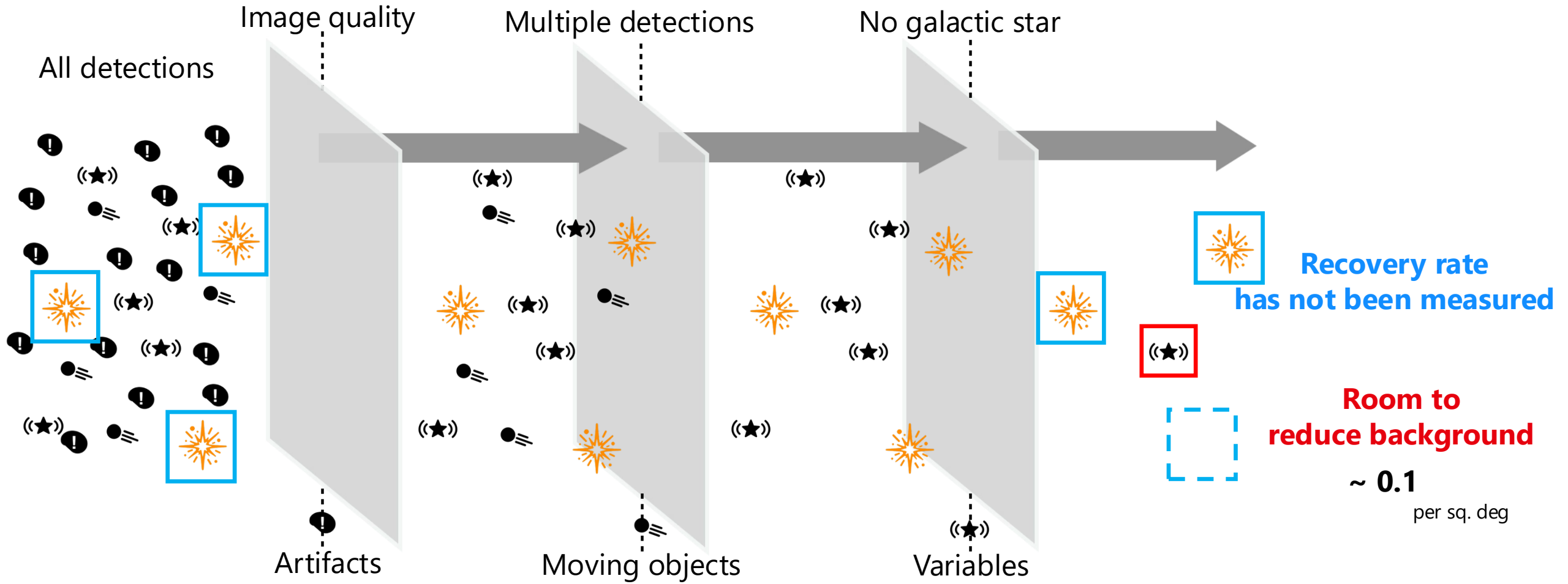
From Nobu Shimizu's slide

First opportunity to search for an optical counterpart to a neutrino multiplet!

Data analysis: ZTF general filtering procedure

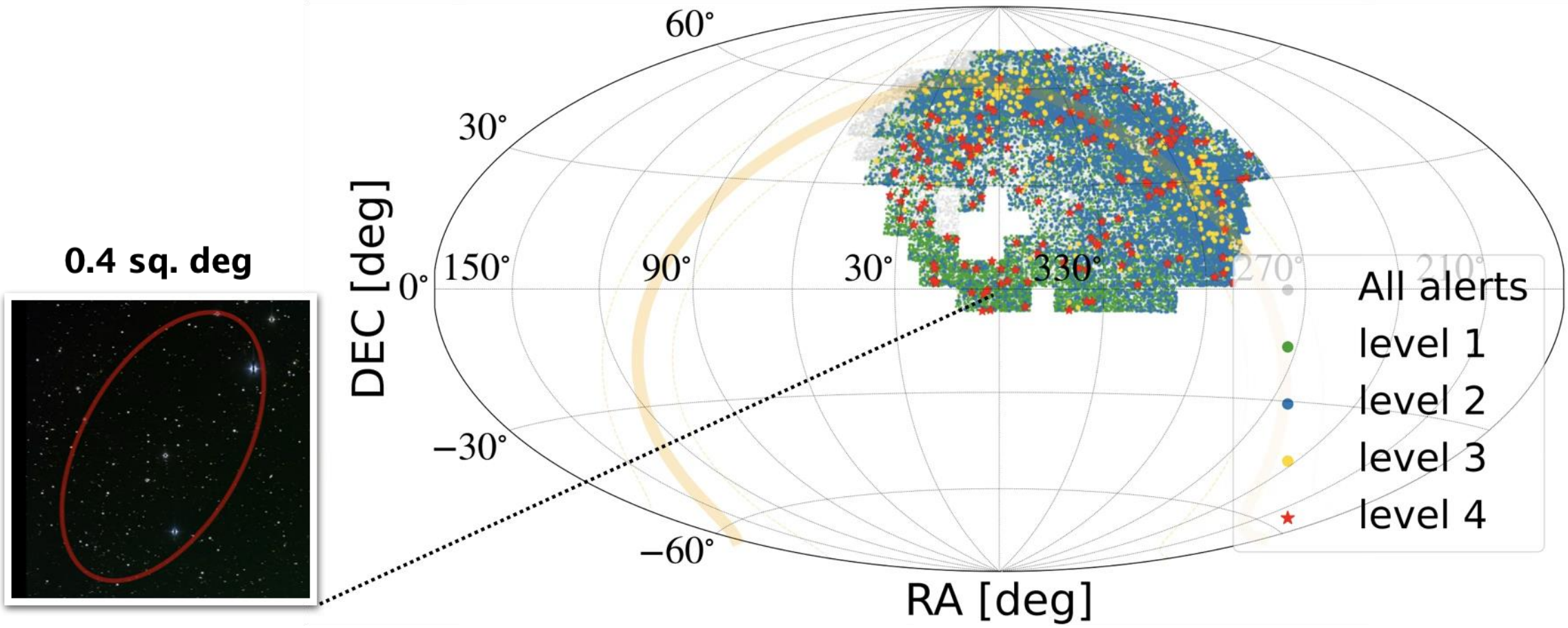


Data analysis: ZTF general filtering procedure



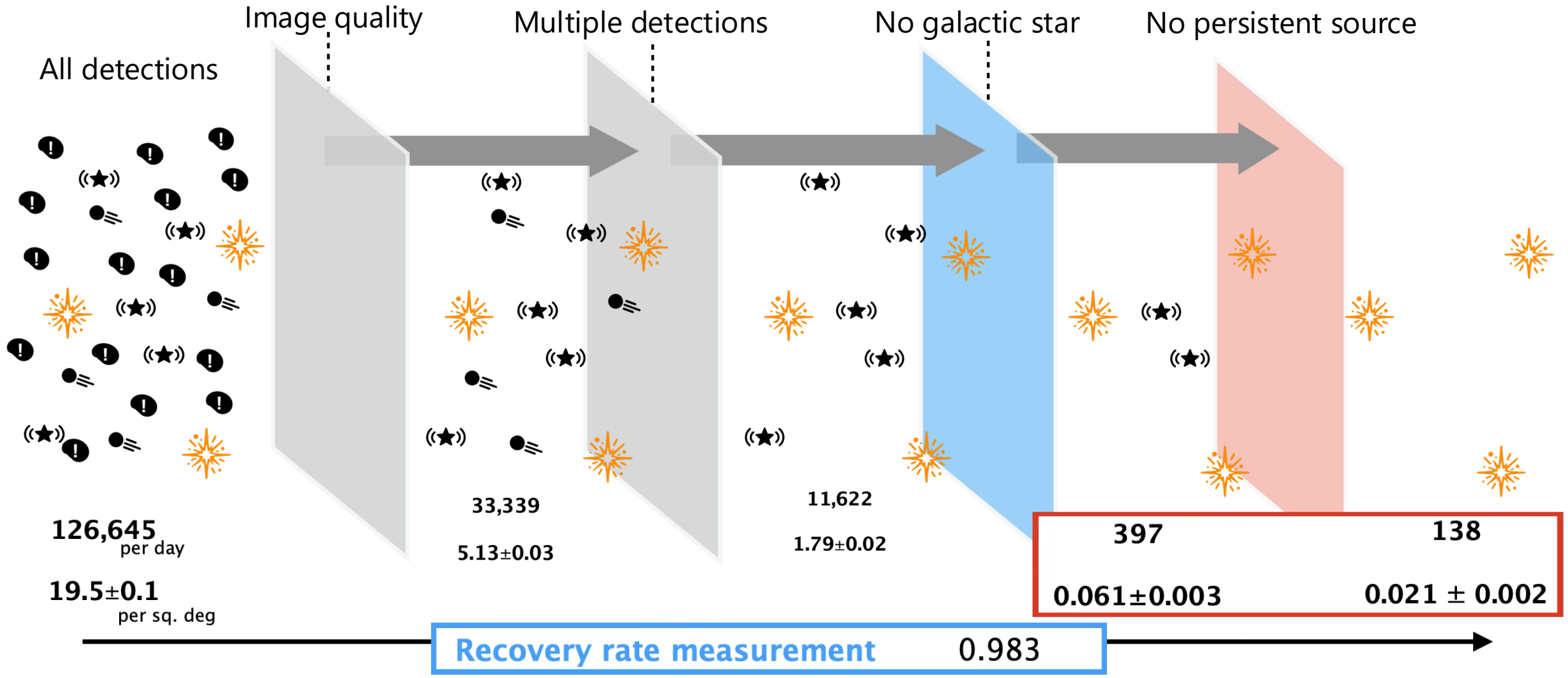
Optimize for month-timescale optical counterpart search

Background estimation



Using background area ~ 16,000 times larger than target area

Data analysis: Optimized for ν counterpart



Predefined criteria optimized through data-driven measurements

Finally, unblind the data!

Applied pre-fixed criteria

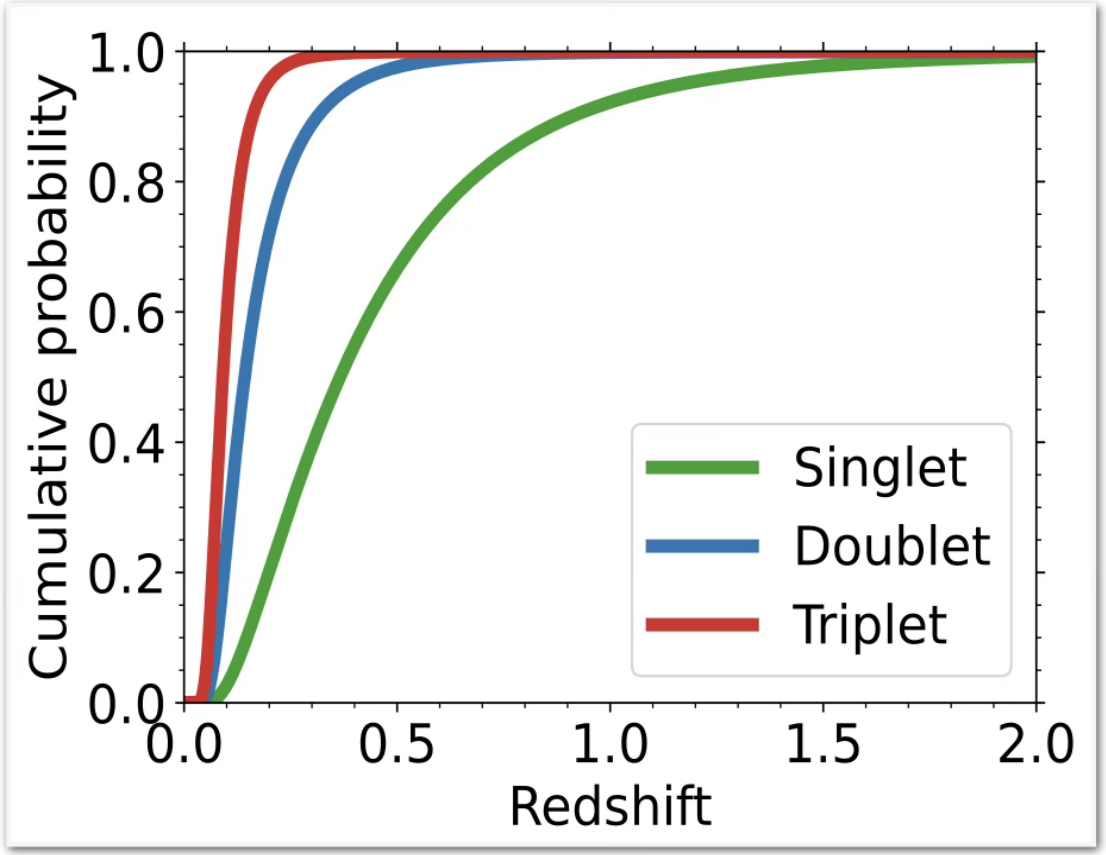
No candidate was found in the multiplet direction

Constraints on source properties

Distance Distribution Inferred from Neutrinos

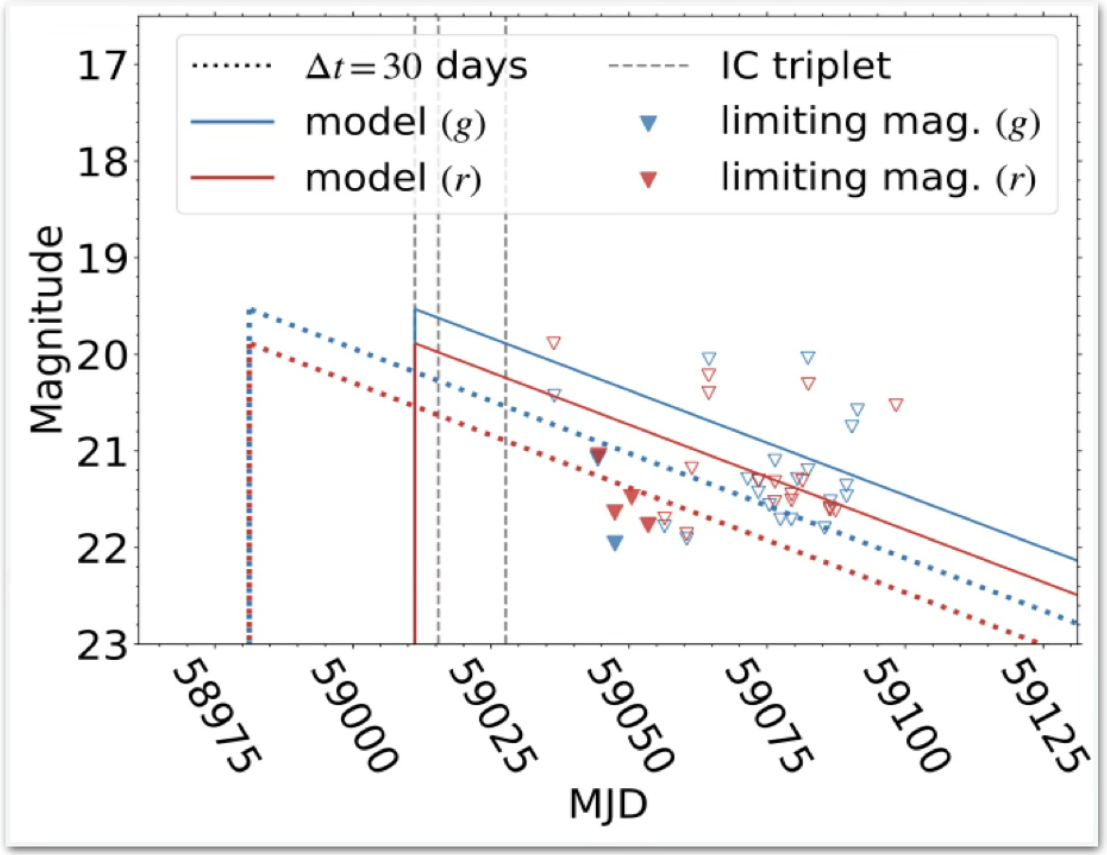
$$\phi_\nu \propto \varepsilon_\nu \times R$$

$$R_{\rm SLSN} : R_0 \sim 1 \times 10^{-7}\ {\rm Mpc}^{-3}\ {\rm yr}^{-1}$$
$$R_{\rm TDEs} : R_0 \sim 3 \times 10^{-7}\ {\rm Mpc}^{-3}\ {\rm yr}^{-1}$$



Simple optical light curve model

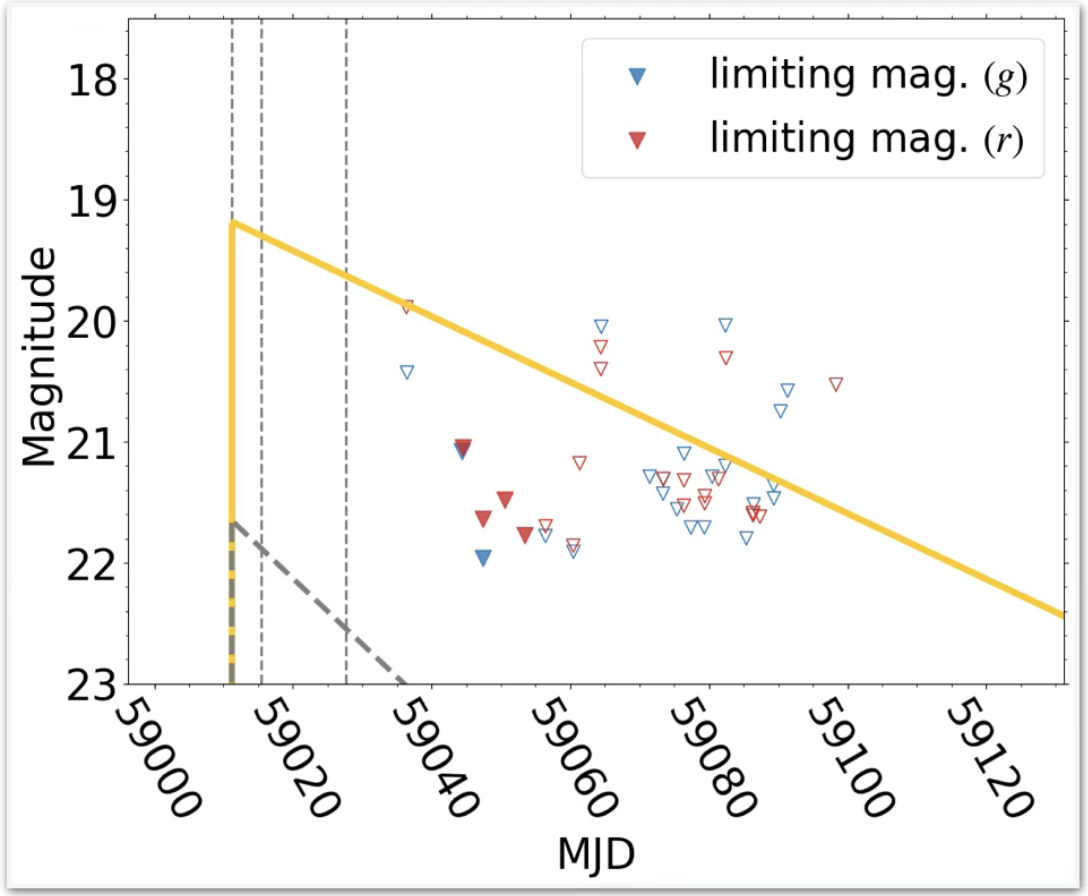
$$L_\nu(t) = L_{\rm peak} \frac{B_\nu(T)}{\sigma T^4/\pi} \exp\left(-\frac{|t - t_{\rm peak}|}{t_{\rm decay}}\right)$$

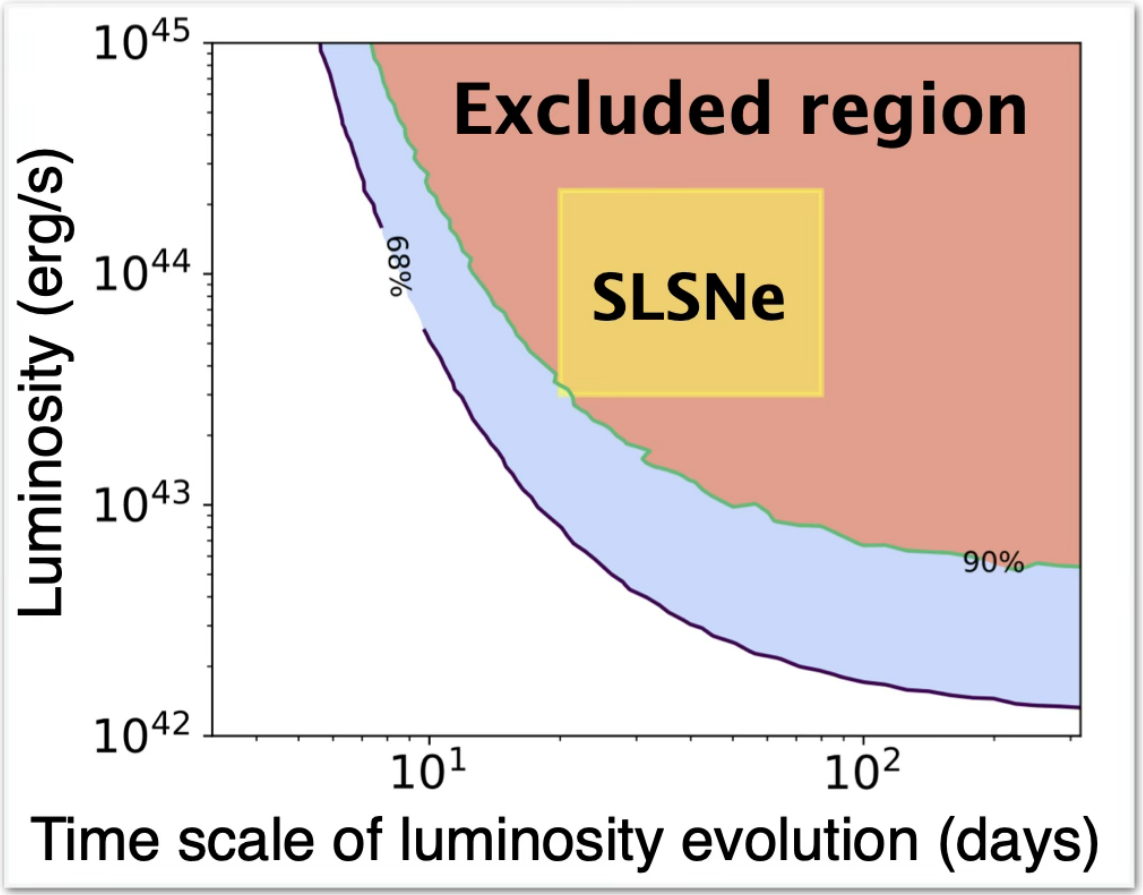


High detectability → Strong constraints

Constraints on source properties

Confirmation of low-background&high-recovery rate a priori



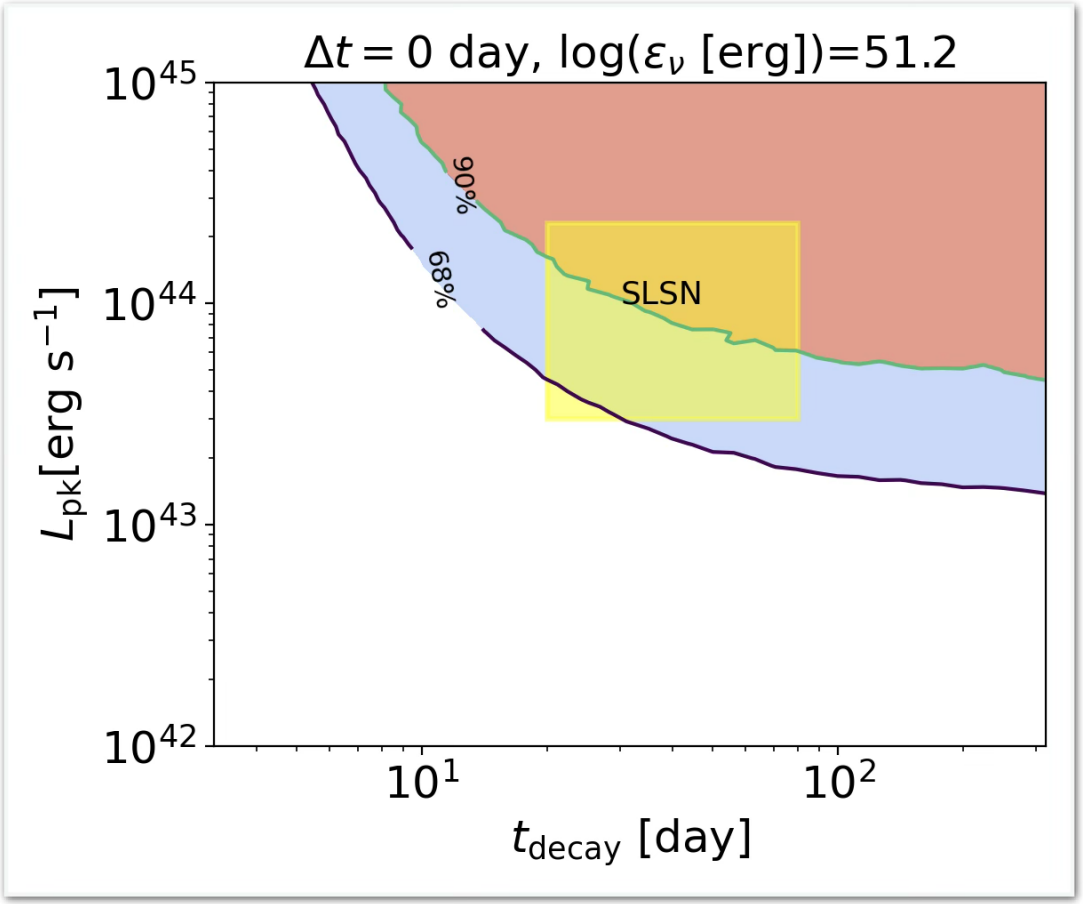


One multiplet search can put meaningful constraints on source properties

For future real time follow-up 1

Real time alerts for IceCube “multiplet” will come

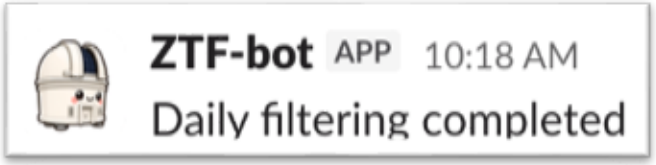
- 3-day cadence, 6 obs.
- limiting mag ~ 19

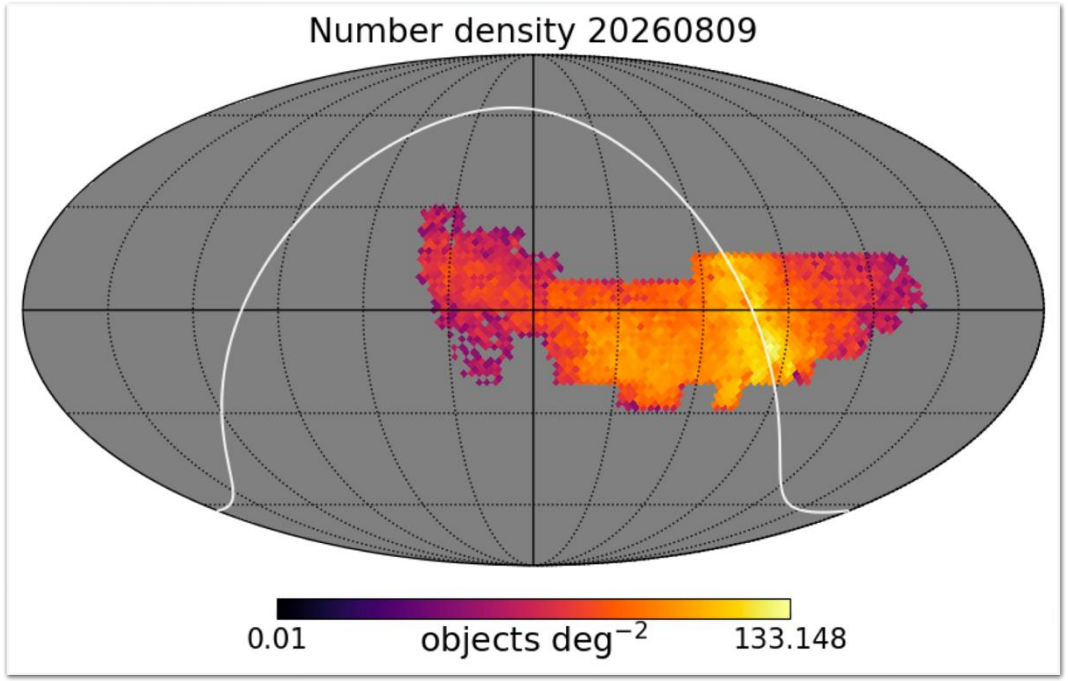


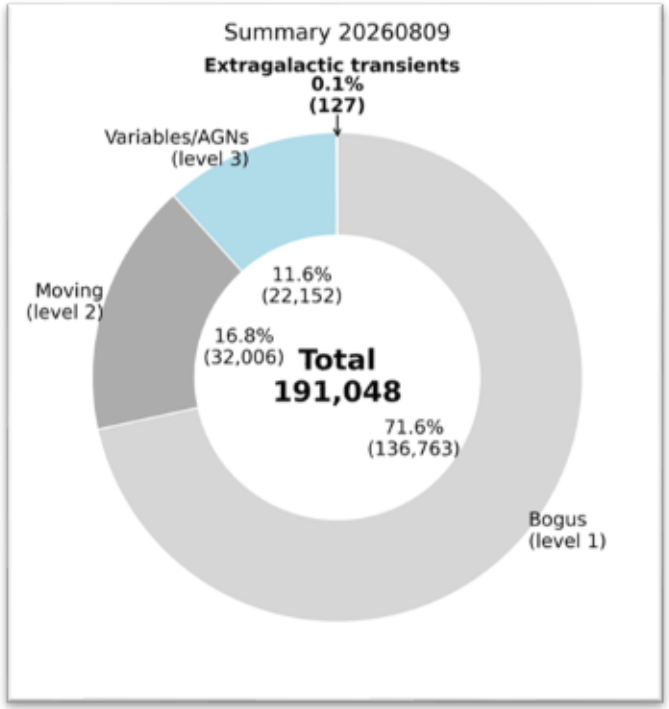
Real time follow-up using Kiso/Tomo-e

For future real time follow-up 2

Background estimation for daily ZTF public data







Daily ZTF data analysis to estimate the background and build up statistics for rapid response

Summary

- **Optical counterpart search for multiplet**
  - Focus on nearby neutrino sources
  - Data-driven background modeling
    - High recovery rate + Low background rate
  - Non-detection puts meaningful constraints
- **Future follow—up**
  - Kiso/ZTF candidate search + Gemini follow-up
  - ZTF background estimate for real-time unblind

Appendix

In real data …

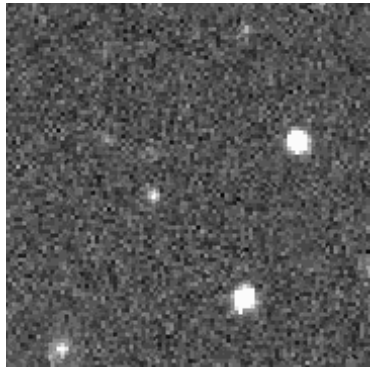
Background in optical transient counterpart search

Astrophysical transient

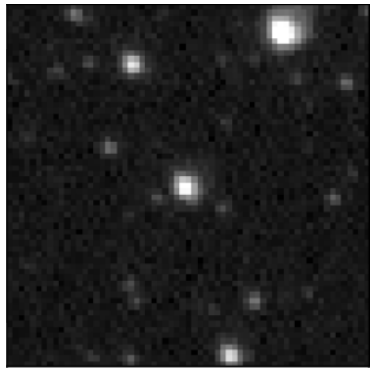
SNe, TDEs

Astrophysical poorly-modeled background

moving objects

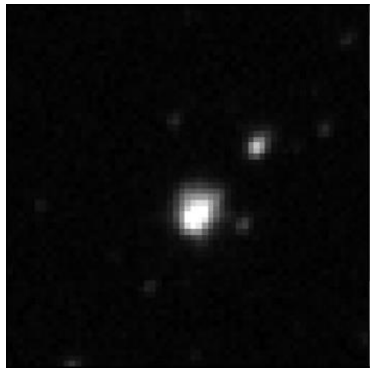


variable stars



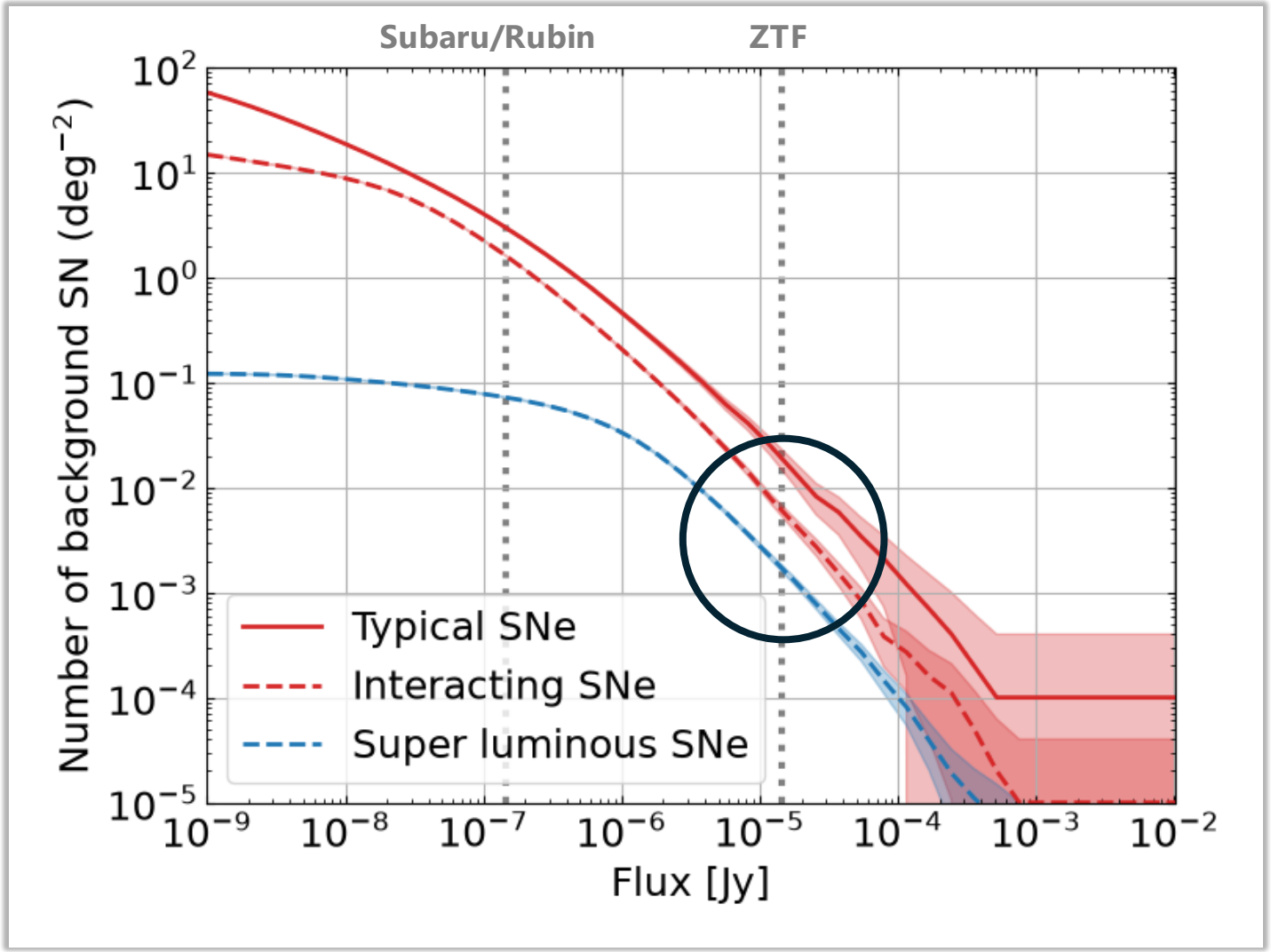
Non-astrophysical background

artifacts



Difficult to simulate (poorly modeled/depend on data quality, instrument,…)
→ Data driven approach !

Astrophysical transient background



Low astrophysical transient background for multiplet

Optical counterpart search

Background characterization is essential before arrival-direction analysis

1. Astrophysical transient

Explosive transient (SNe, TDEs)

→ **Simulation-driven estimate**

2. Non-transient objects & artifacts

Variables

Moving objects

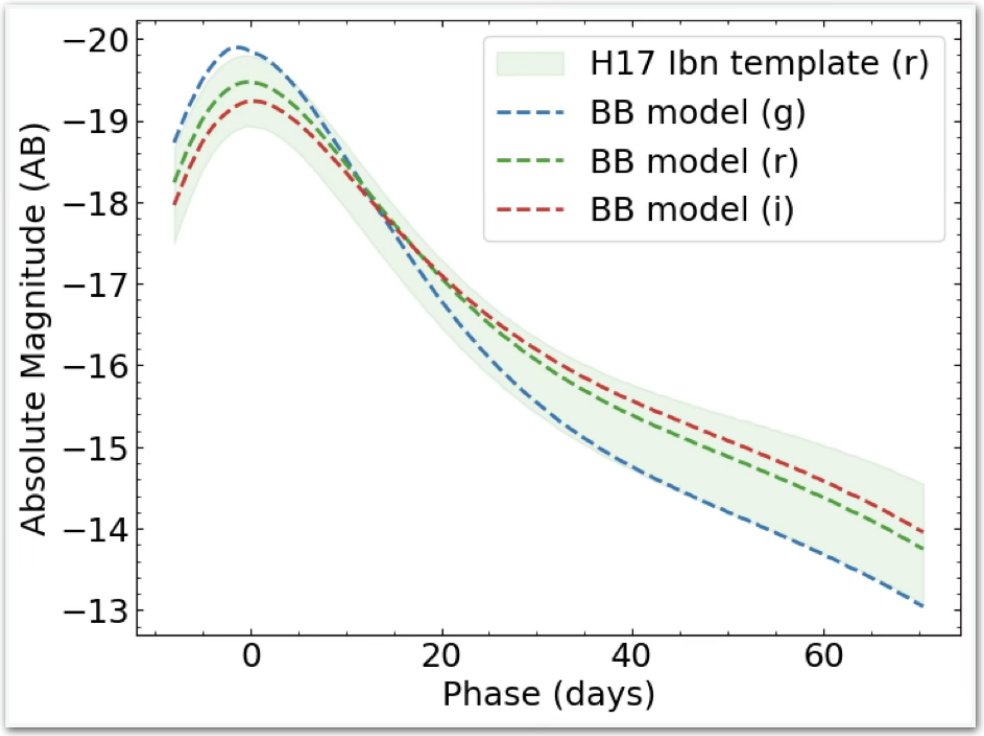
Artifacts

→ **Data-driven measurement**

Simulation-driven estimate 1

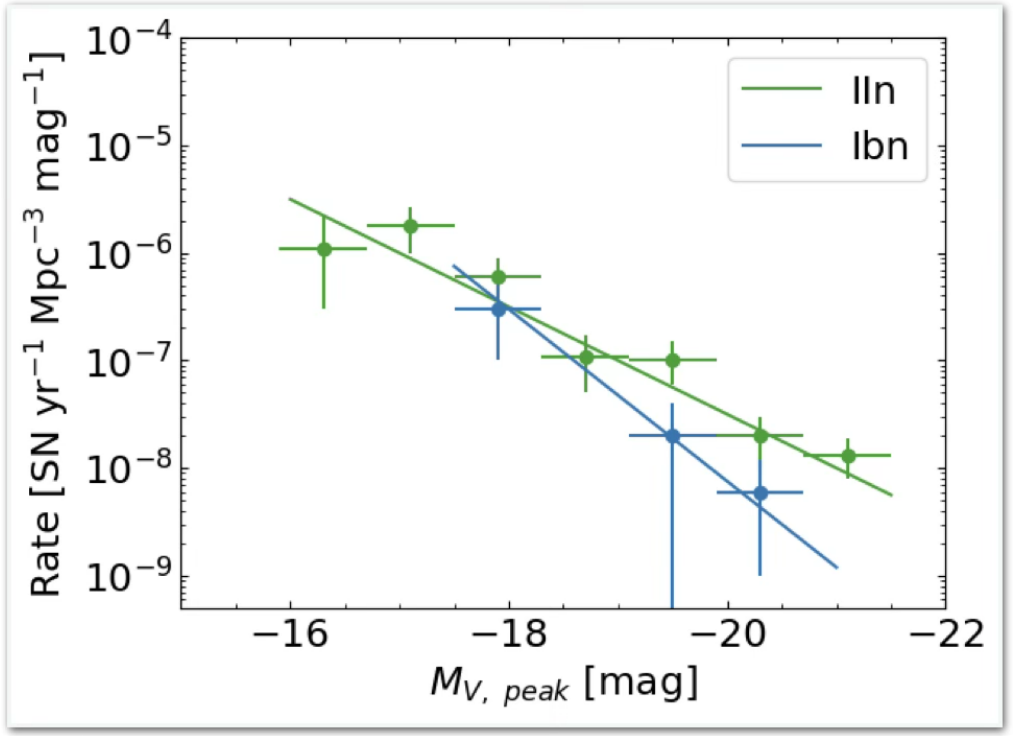
Mock observations using sncosmo A Python Library for Supernova Cosmology based on

Light curve template



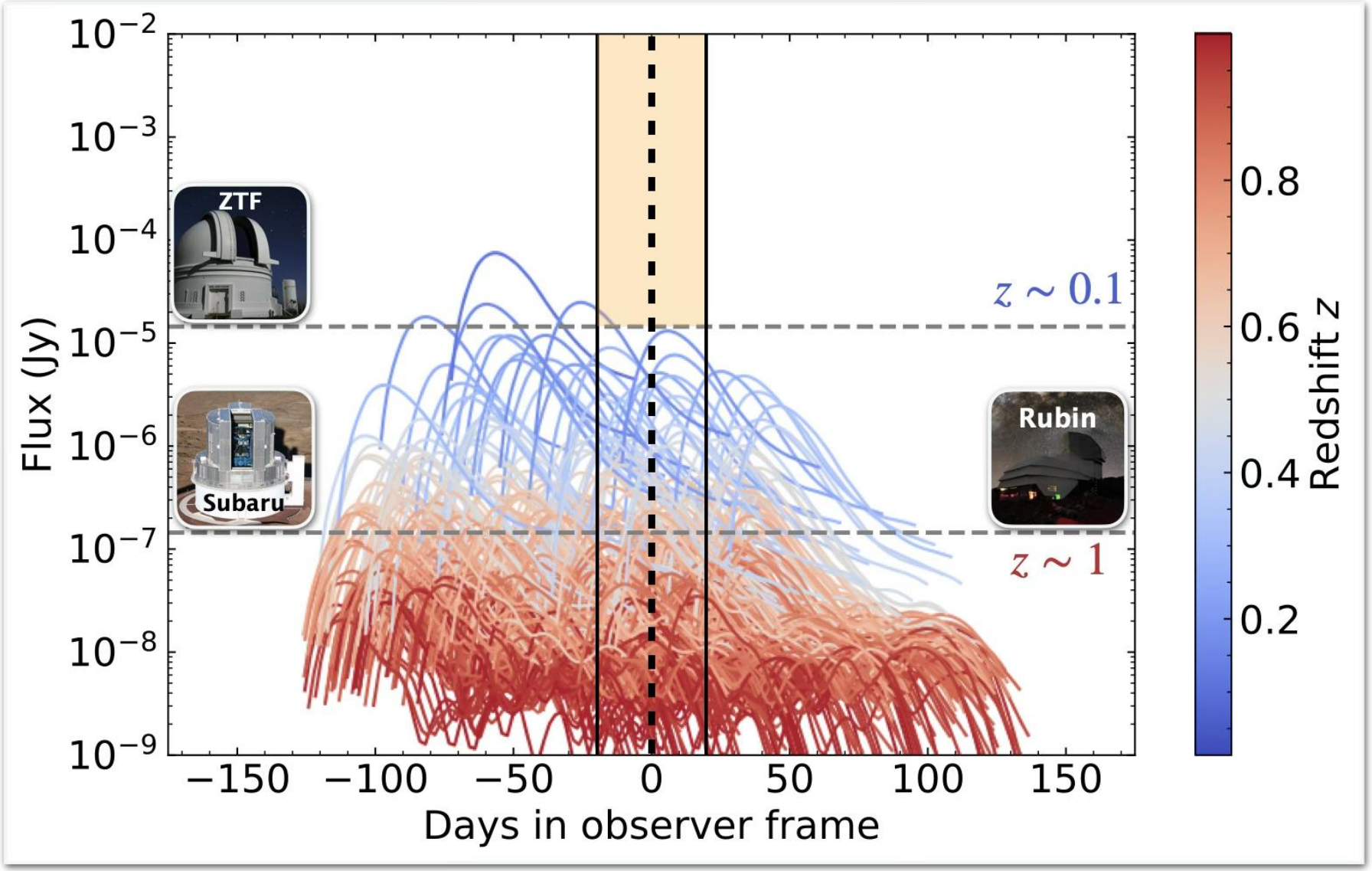
Template example for interacting SNe

Event rate&Redshift evolution

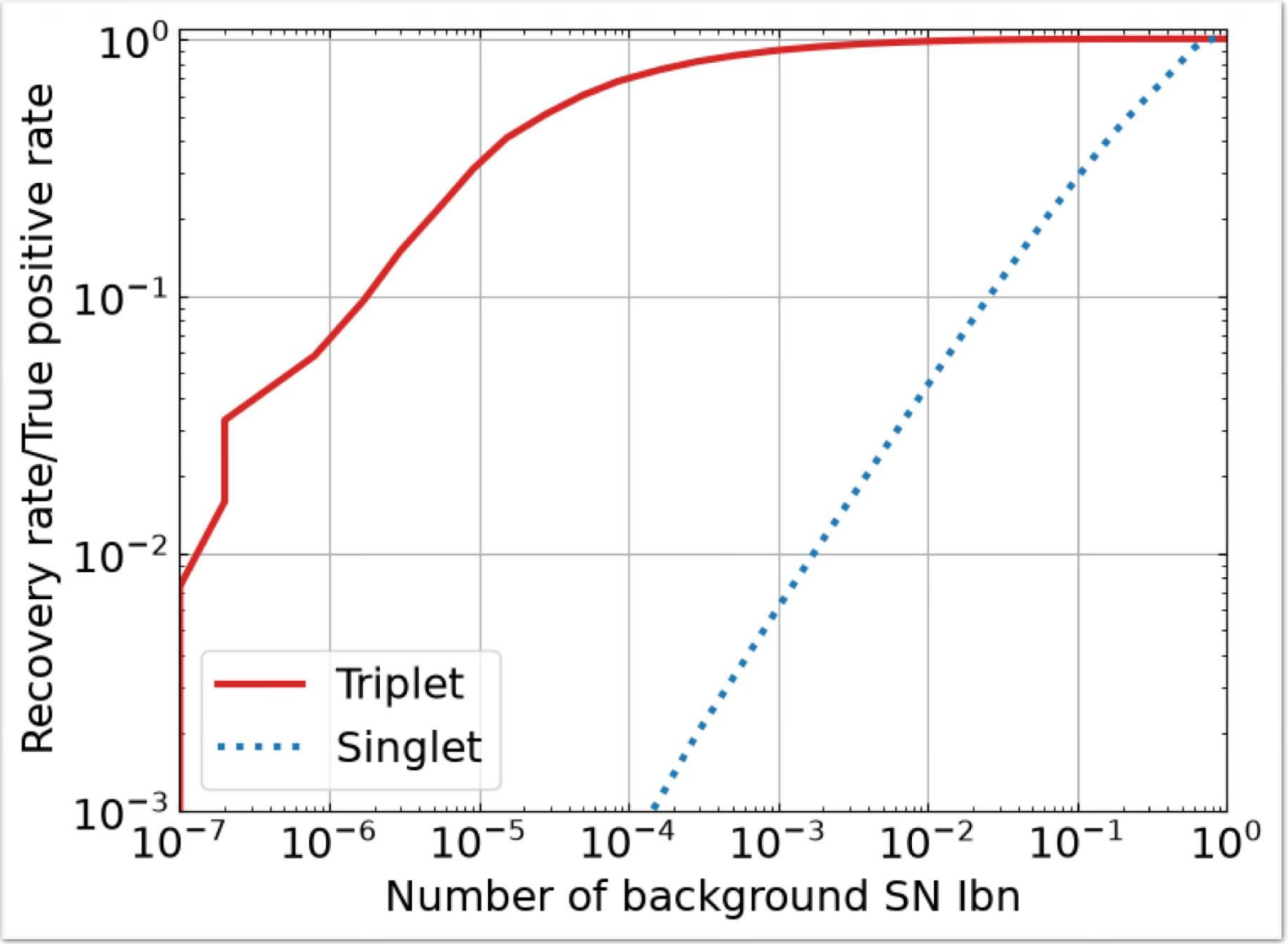


Pessi et al. 2025 + Madau&Fragos 2017

Simulation-driven estimate 2

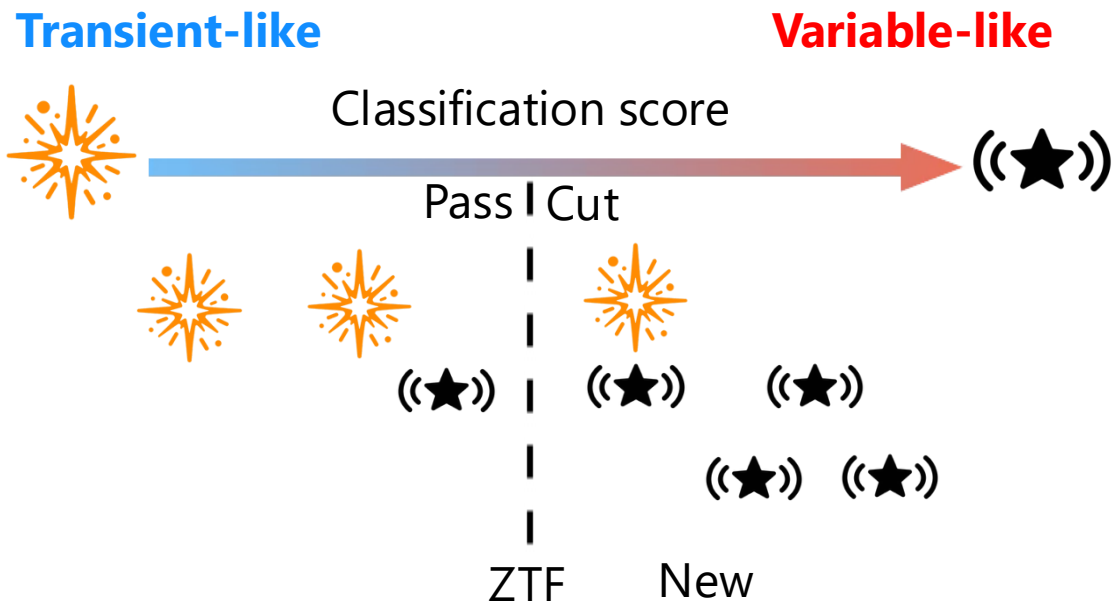


Recovery rate vs Background rate

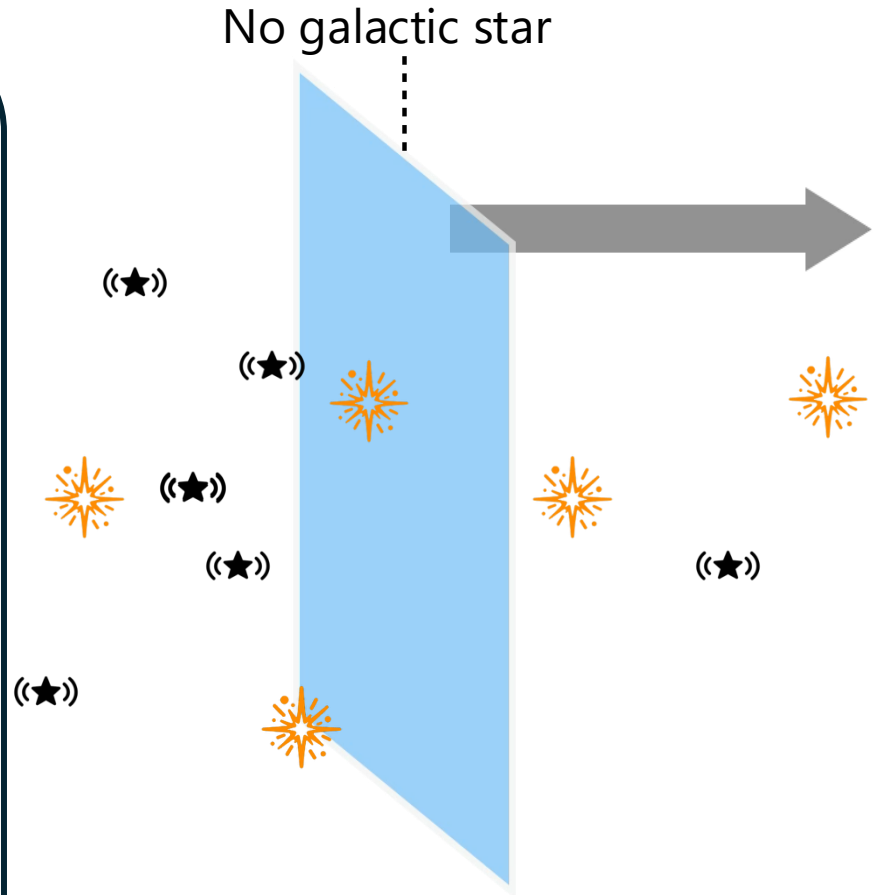


Data analysis: optimized for counterpart

No galactic star criterion

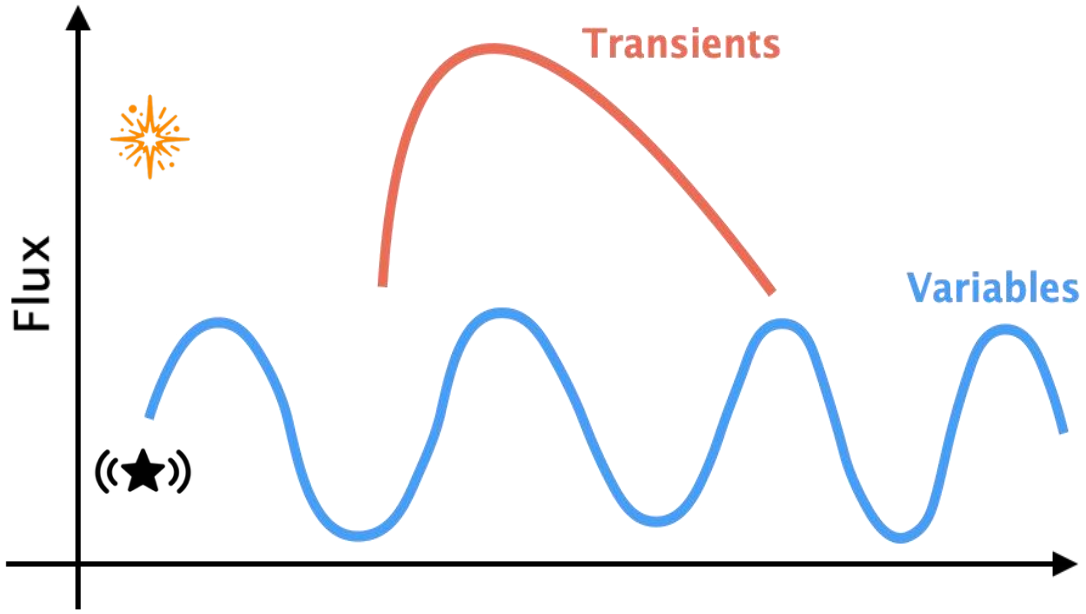


High recovery rate!
BUT, high background rate …

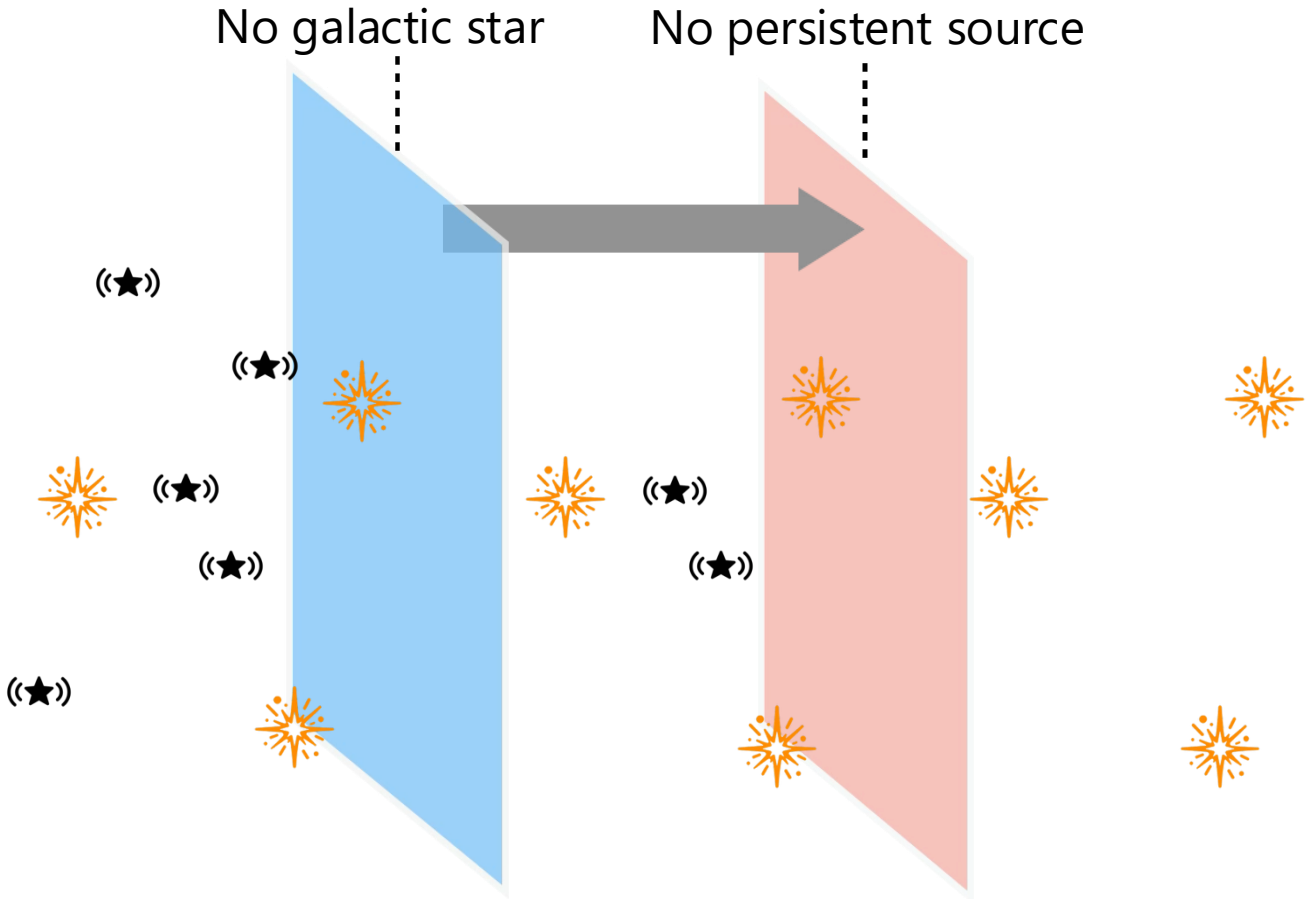


Data analysis: optimized for counterpart

No persistent source

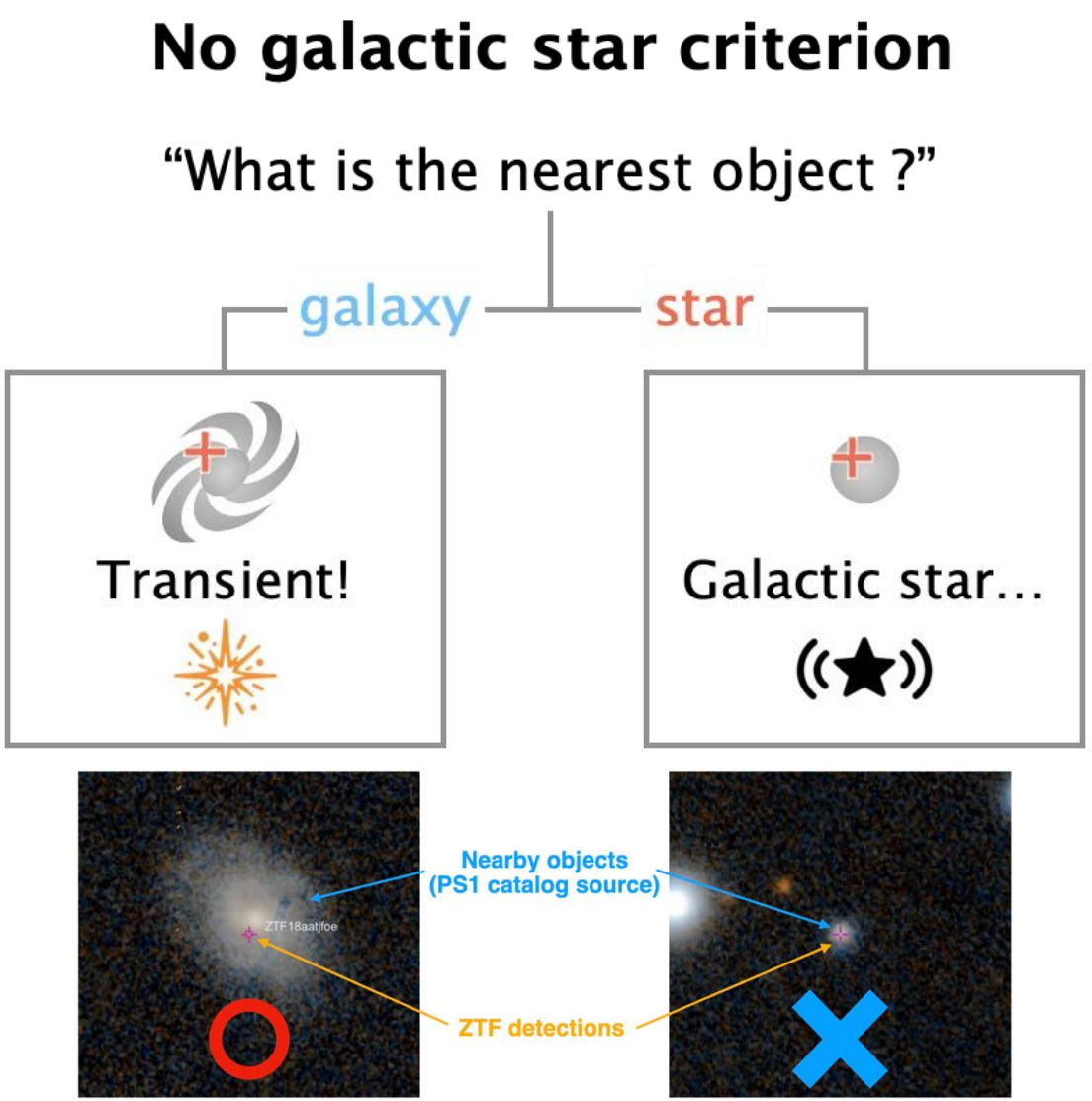


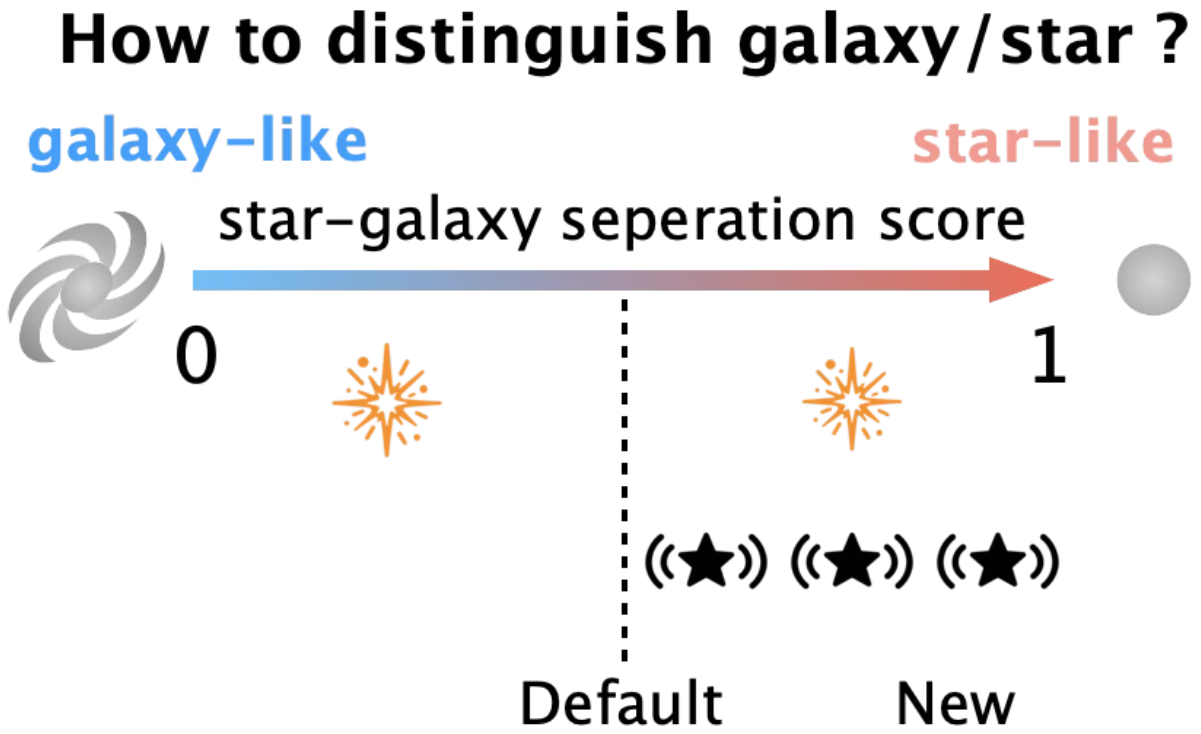
High recovery rate!
AND, low background rate !



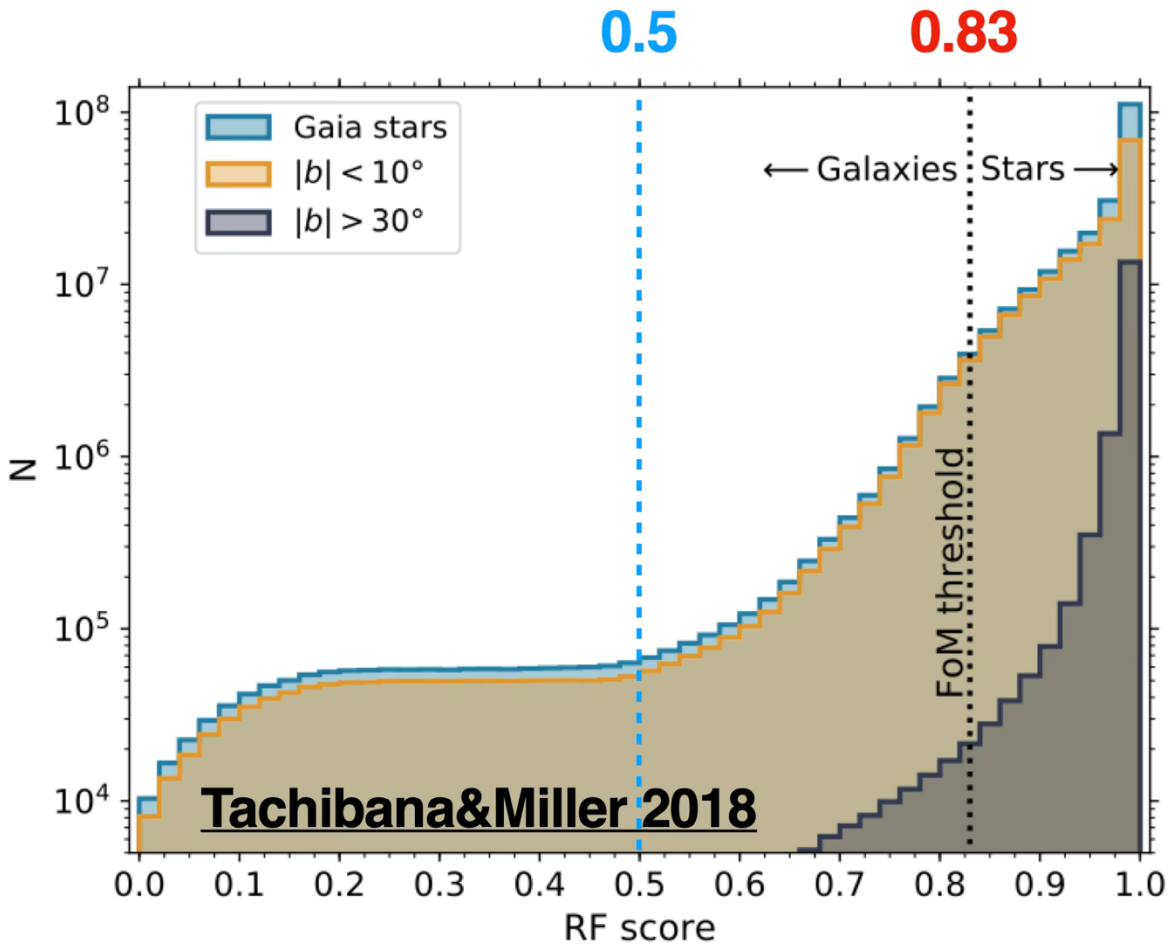
High recovery rate!
BUT, high background rate ...

No galactic star criterion

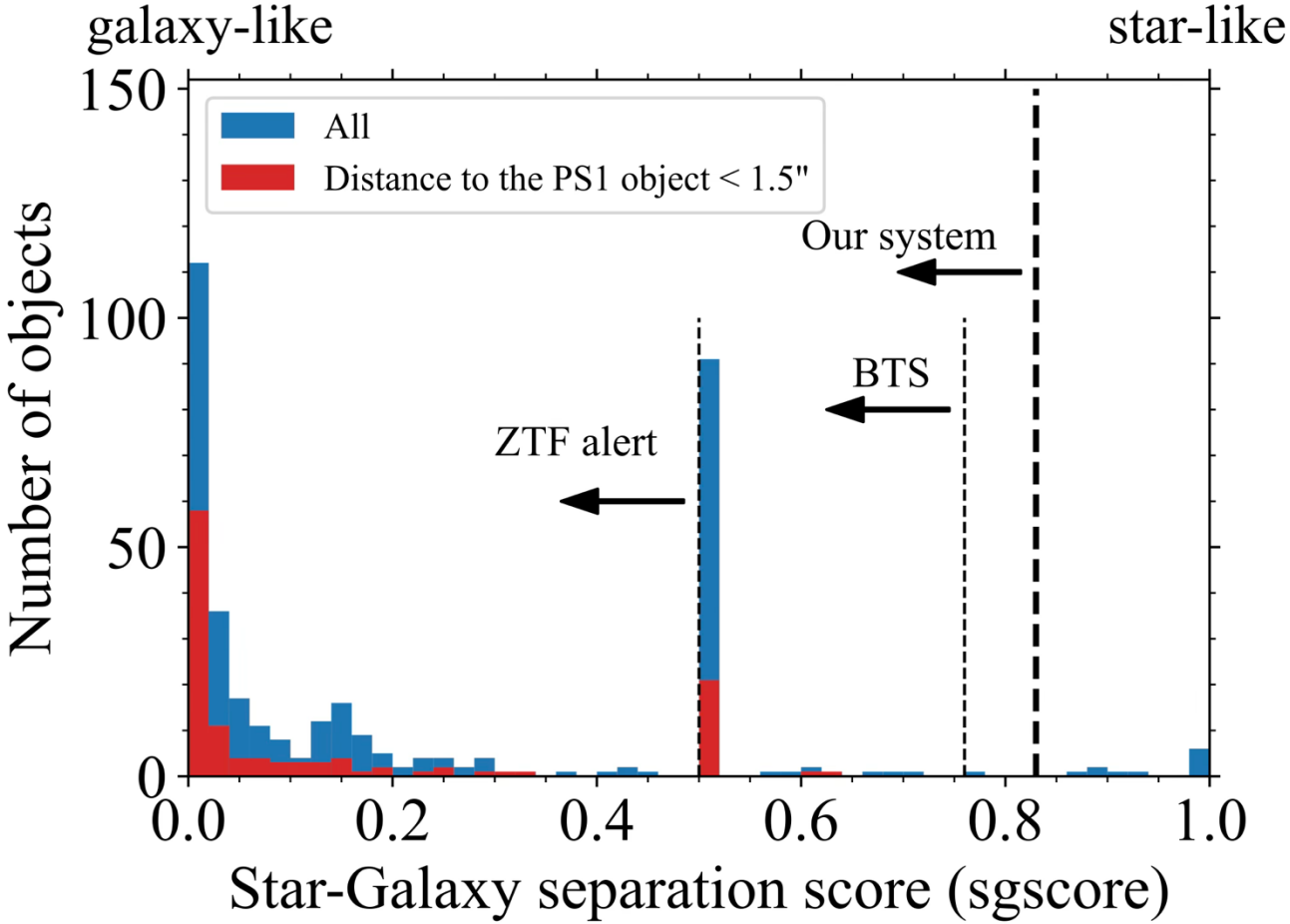




Star-galaxy separation score



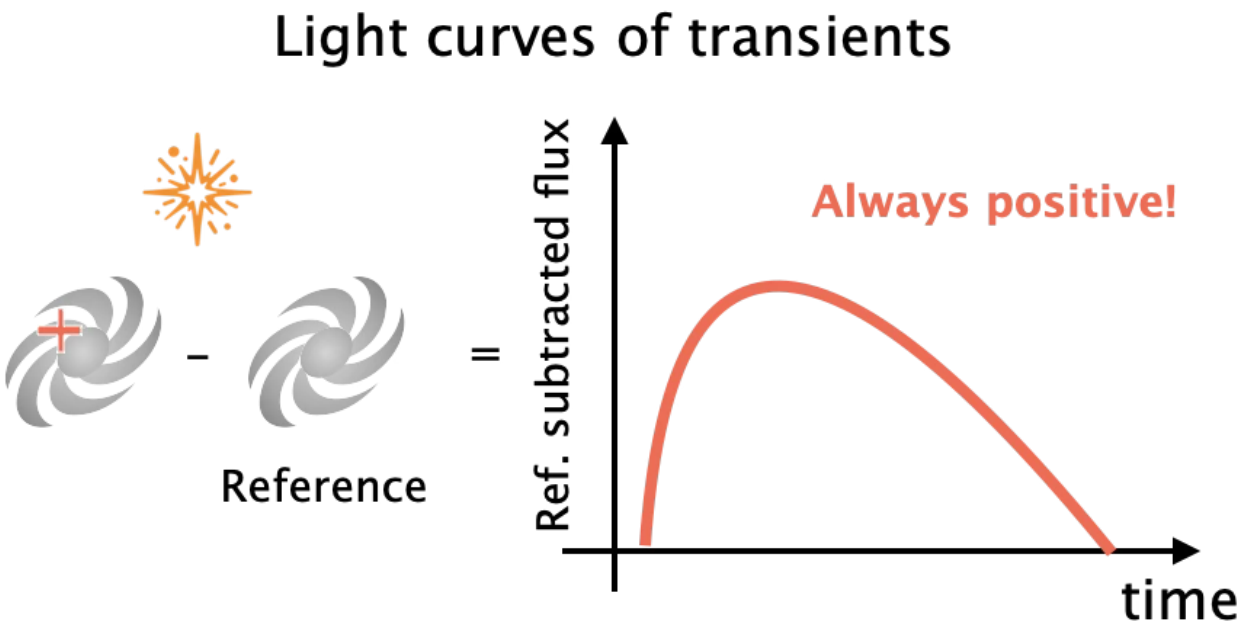
Distribution of sgscore for stars

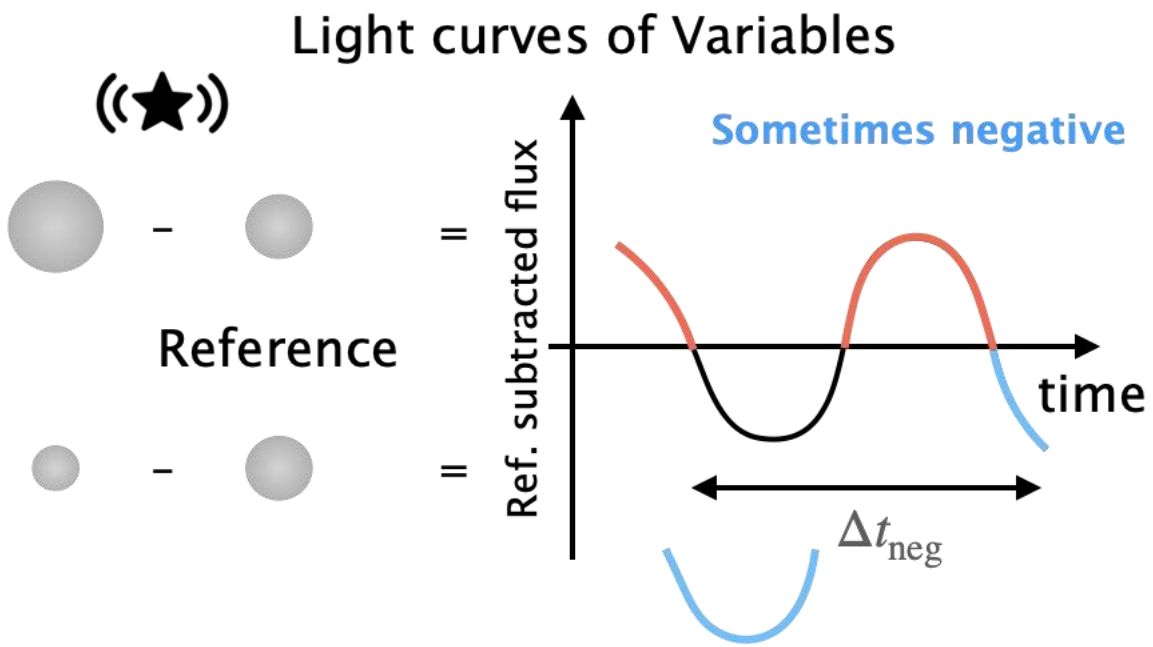


Distribution of sgscore for SNe

Light curve cut

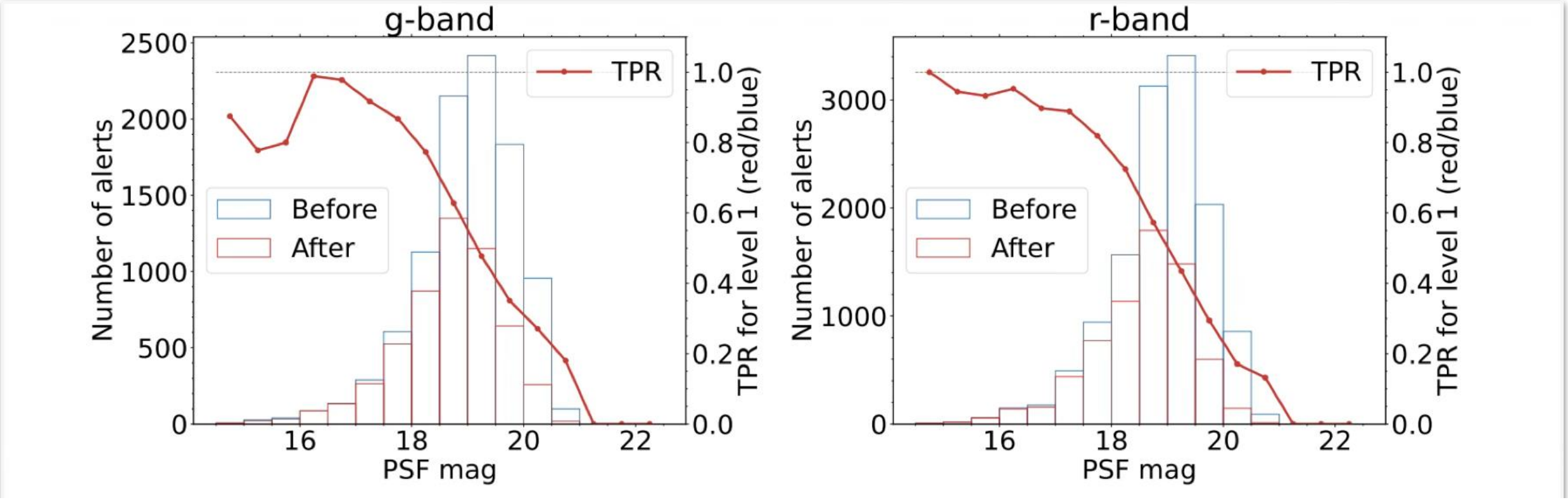
No persistent source criterion



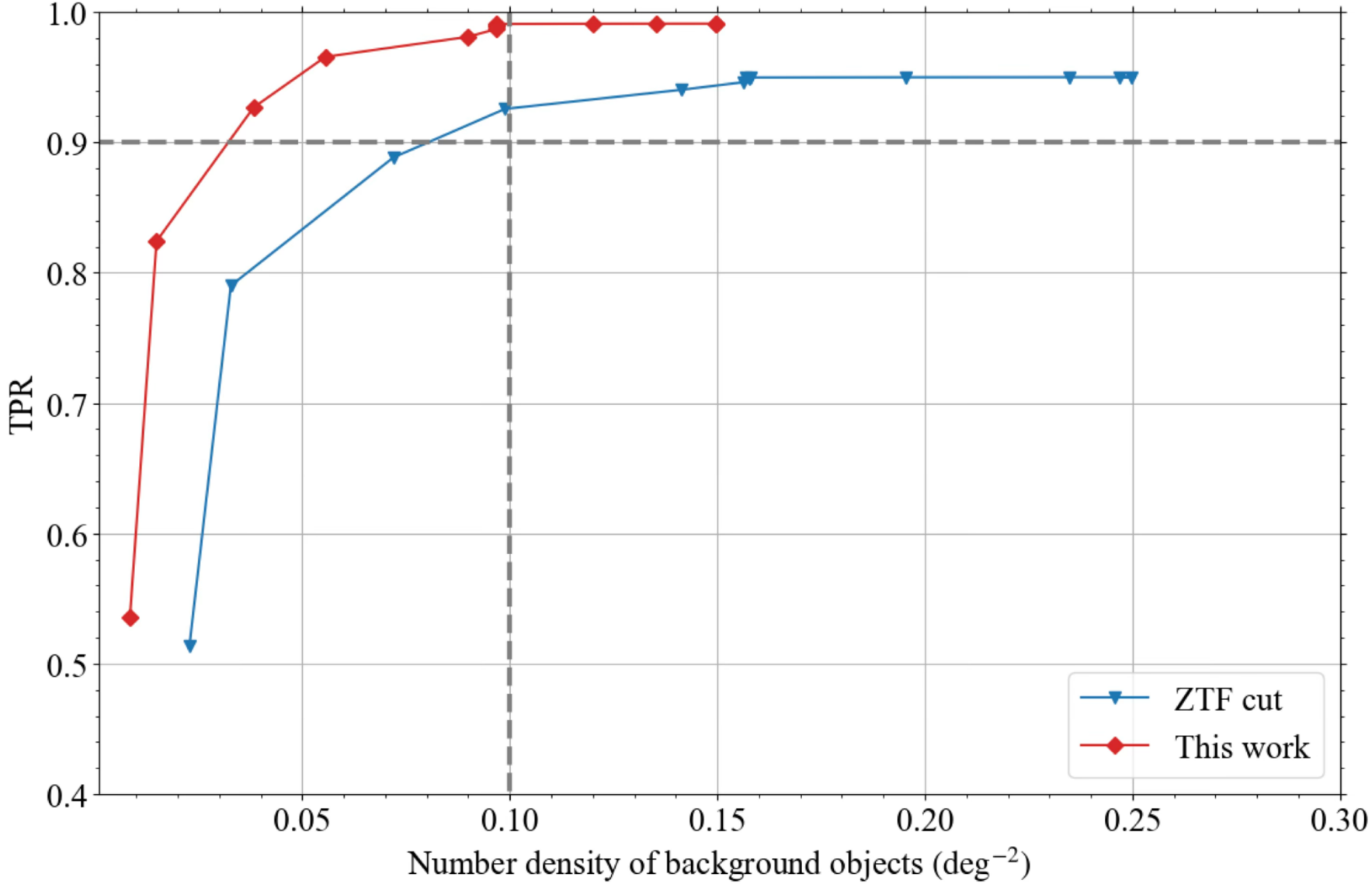


cut objects with negative durations $\Delta t_{neg} > 2$ yr

Flux dependence of recovery rate



Recovery rate vs Background rate



Recovery rate vs background rate