

Constraining optical transients as cosmic neutrino sources



Tohoku University

Shigeo S. Kimura



TI-FRIS



TOHOKU
UNIVERSITY

References

- SSK, M. Tanaka, Toshikage et al. 2026, ApJ re-submitted, (arXiv: 2606.01158)
- Toshikage, SSK, M. Tanaka et al. 2025, ApJ, 993, 23



IceCube Particle Astrophysics Symposium
2026/10/14-2026/10-16

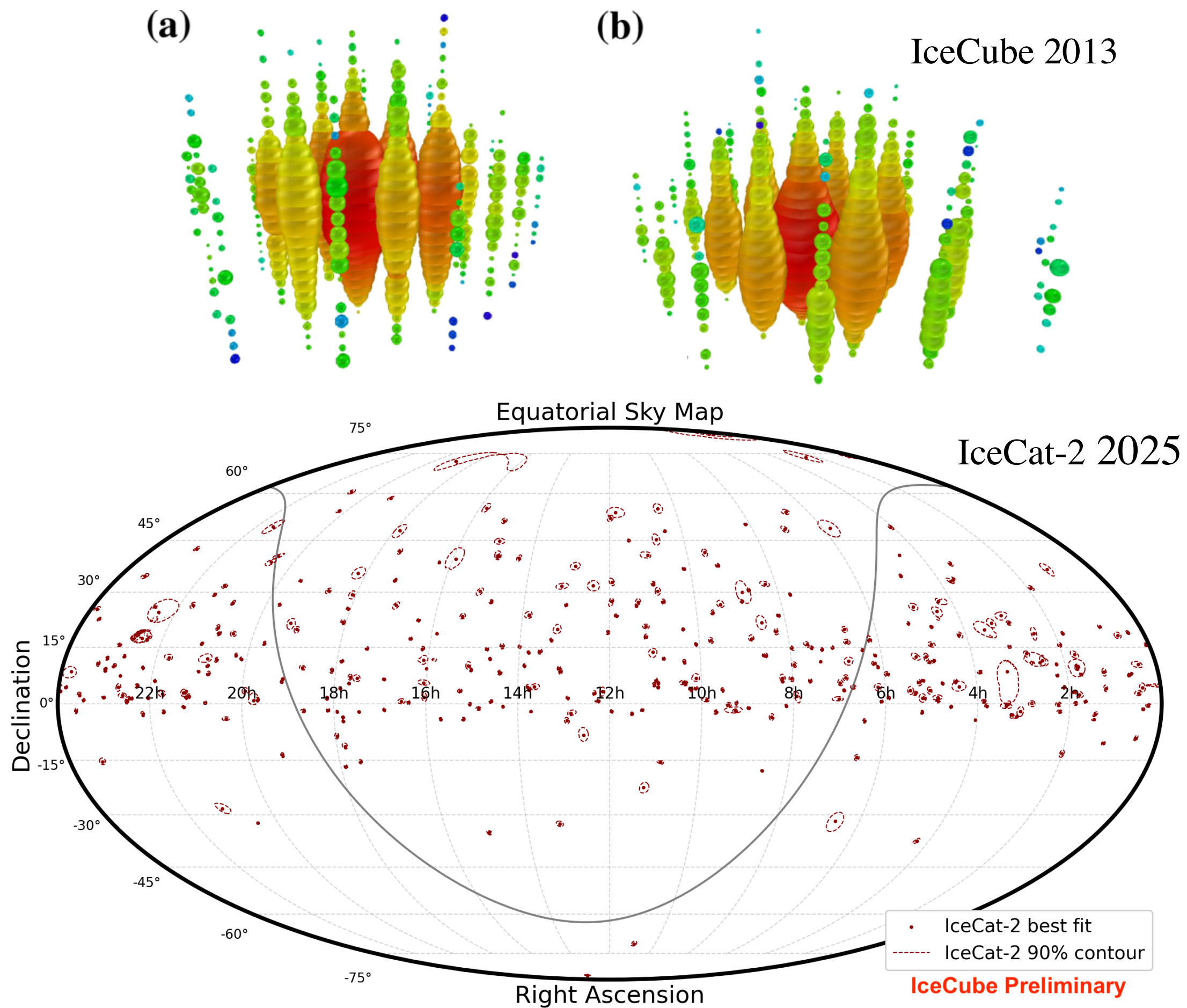
Index

- Introduction
- Follow-up observation to singlet
 - Subaru follow-up to IC 230724A
 - Future prospects with Rubin/LSST
- Follow-up analysis to multiplet event
- Summary

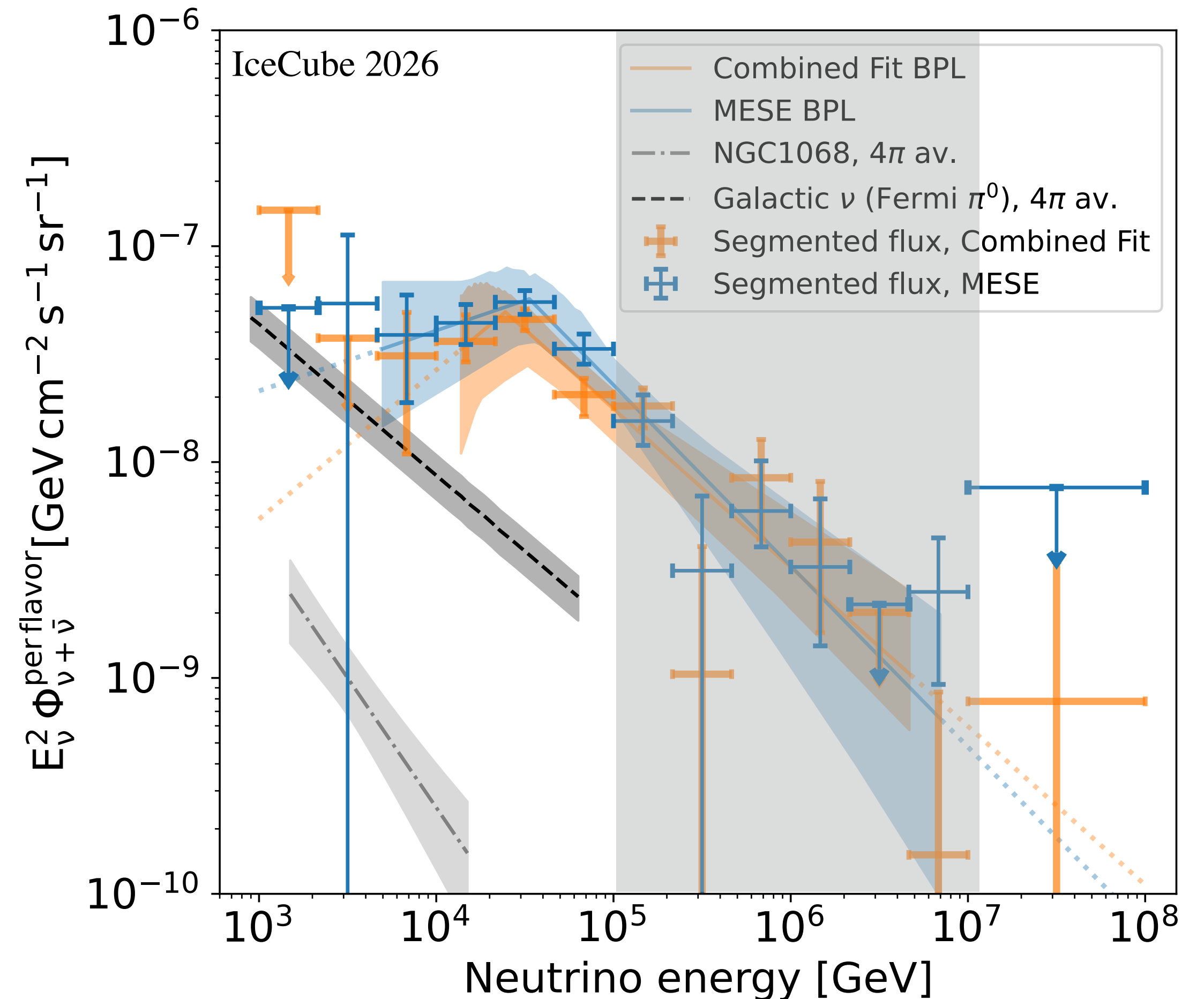
Index

- Introduction
- Follow-up observation to singlet
 - Subaru follow-up to IC 230724A
 - Future prospects with Rubin/LSST
- Follow-up analysis to multiplet event
- Summary

Cosmic high-energy neutrinos



IceCube has established
cosmic TeV–PeV neutrinos



Sources @ $E < 100$ TeV: Seyfert galaxies?

e.g., IceCube 2022, 2025; Murase, SSK+2026, Fiollaro+2024

Sources @ $E > 100$ TeV is under debate

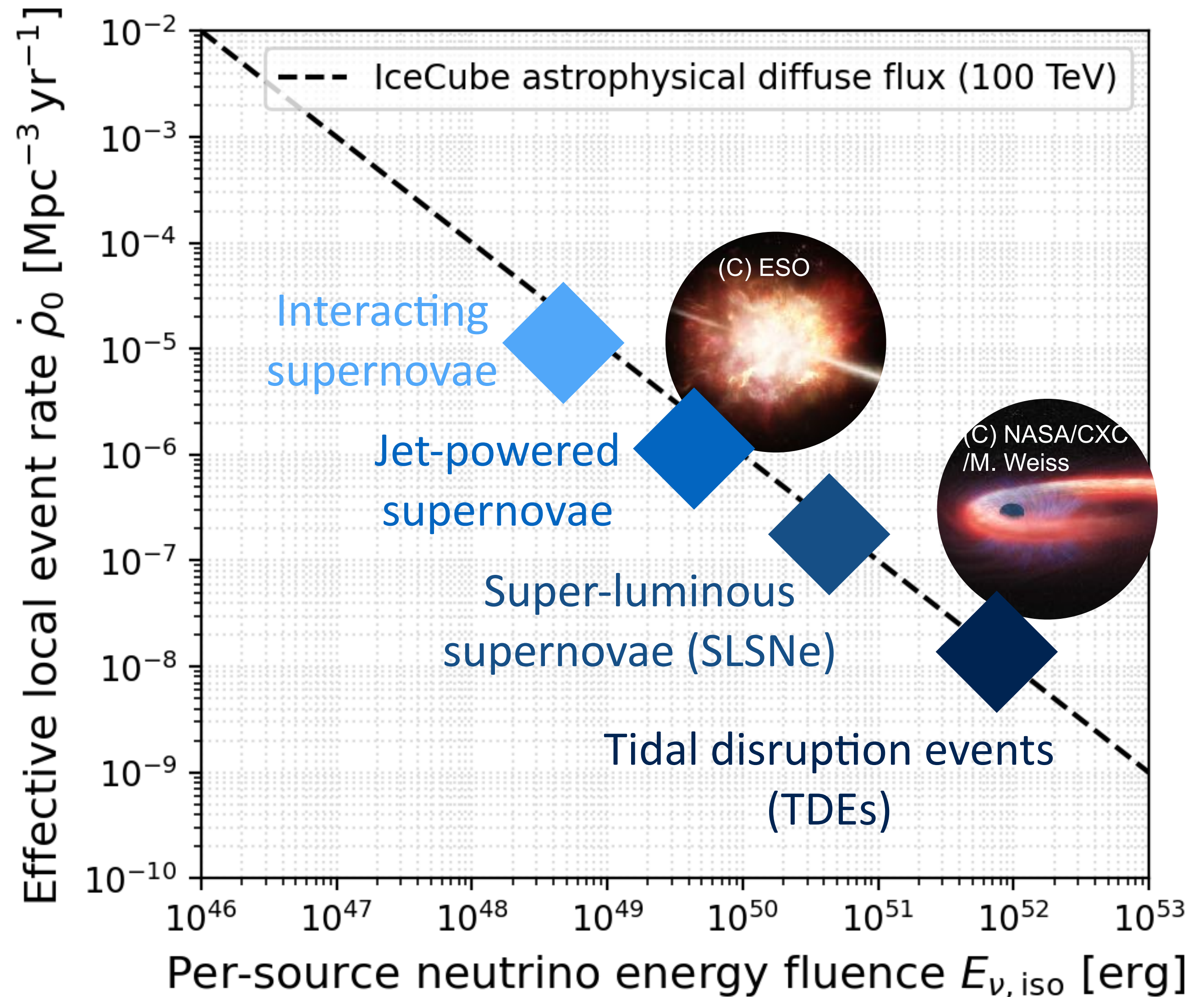
Transient neutrino sources

- Energetics:

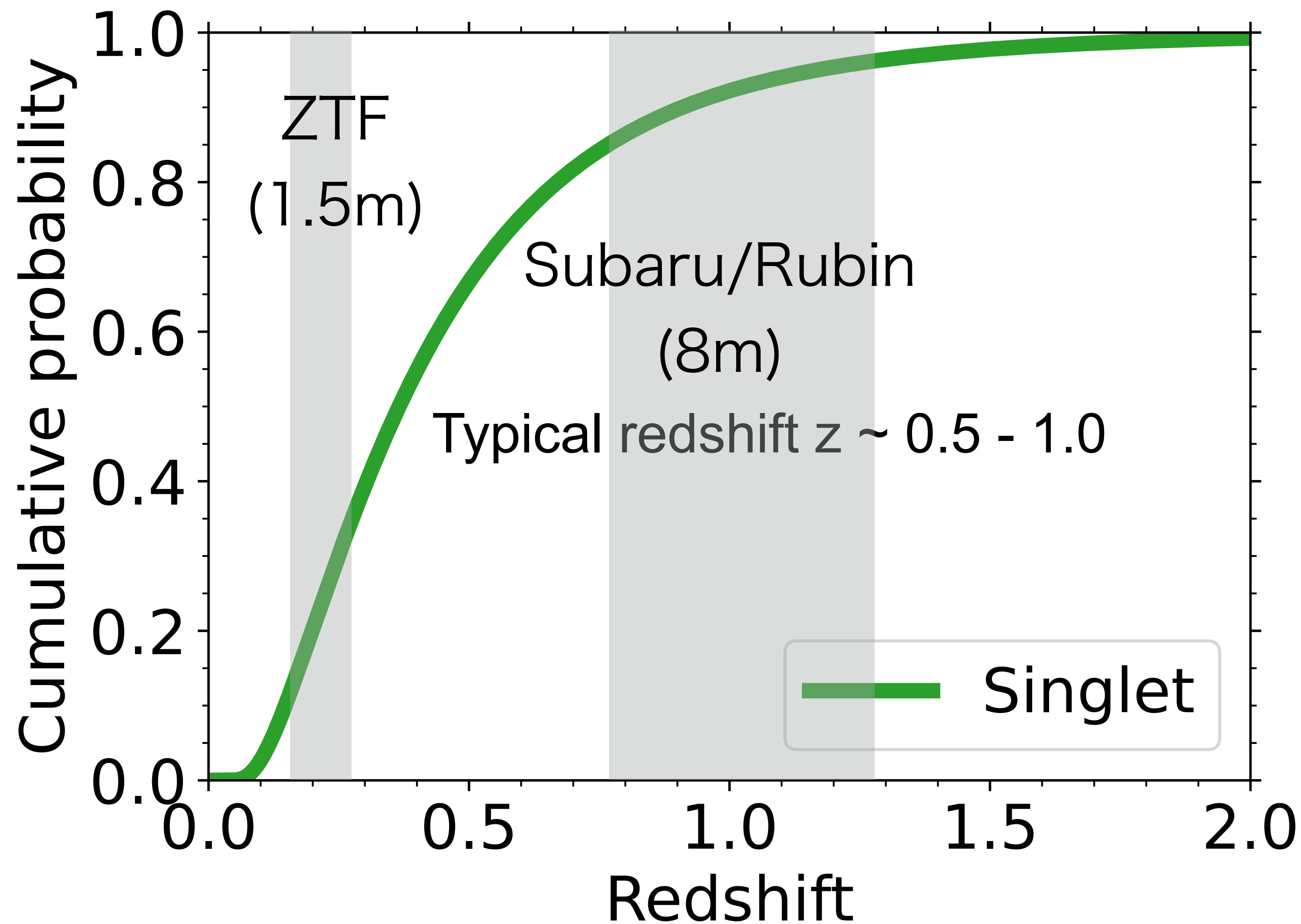
$$E_\nu^2 \Phi_\nu \sim \frac{c}{4\pi H_0} \rho_{\text{eff}} L_{\nu, \text{eff}}$$

$$\rightarrow \rho_{\text{eff}} \propto L_{\nu, \text{eff}}^{-1} \text{ (dashed line)}$$

- Various optical transients are feasible neutrino source candidates



Expected distance to Sources



- ZTF: too shallow to detect v -source TDE

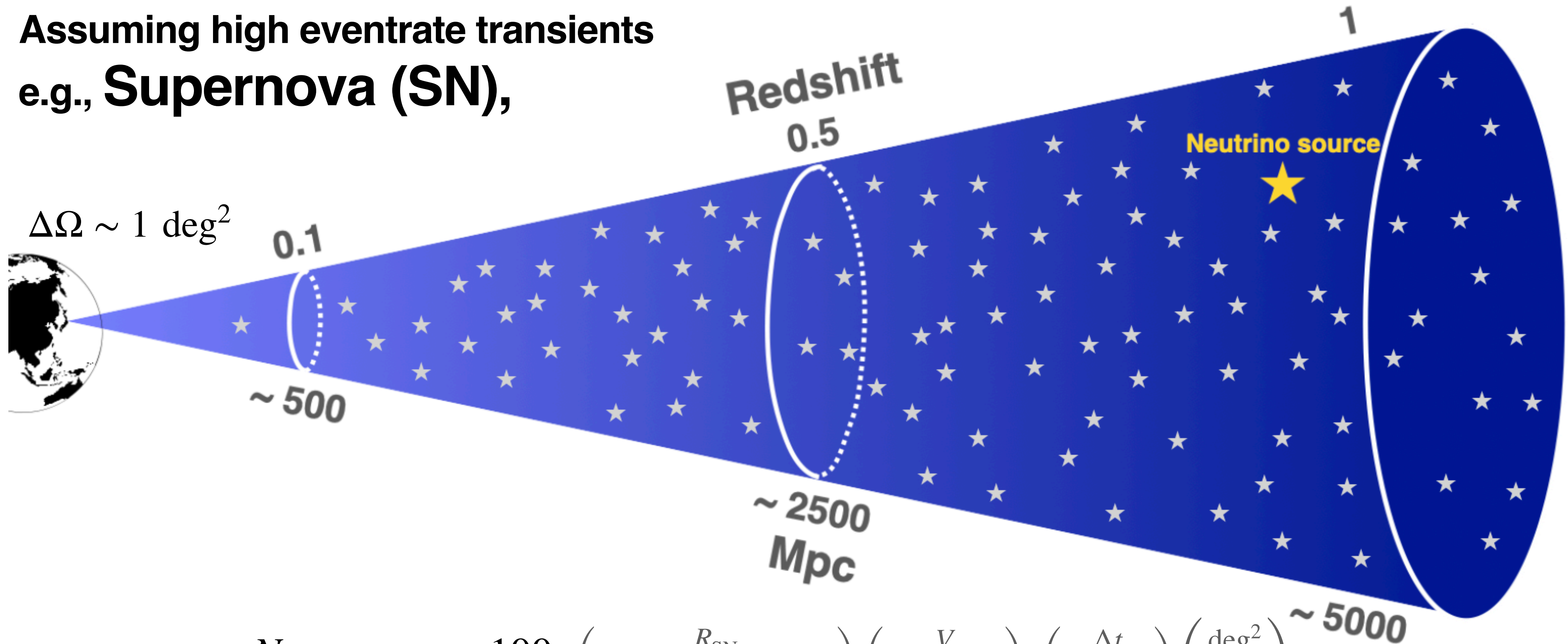
- **Subaru/Rubin: deep enough to detect v -source TDE**

Single neutrino detection = “Singlet”

Credit: Seiji Toshikage

7

Assuming high eventrate transients
e.g., **Supernova (SN)**,



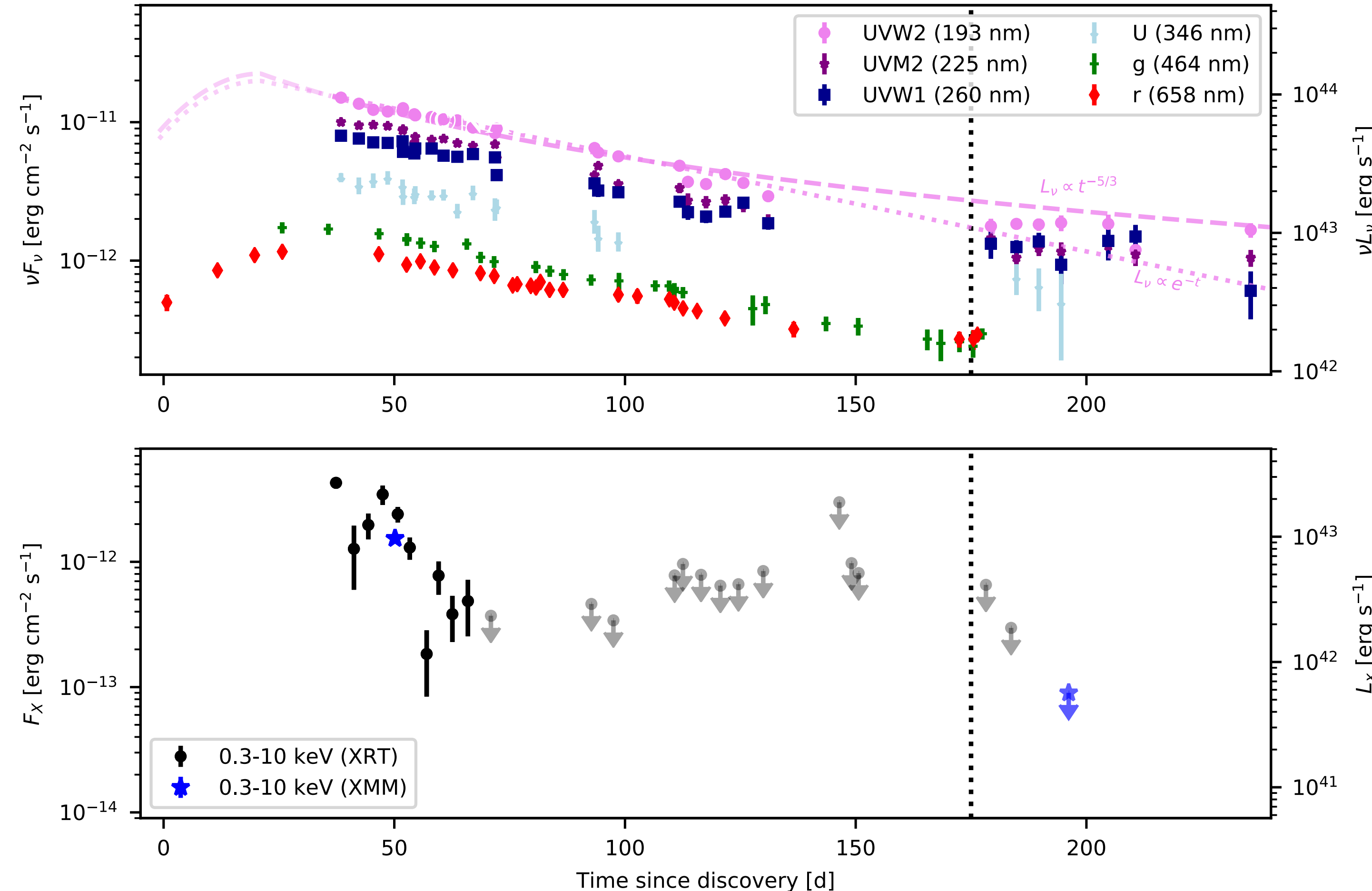
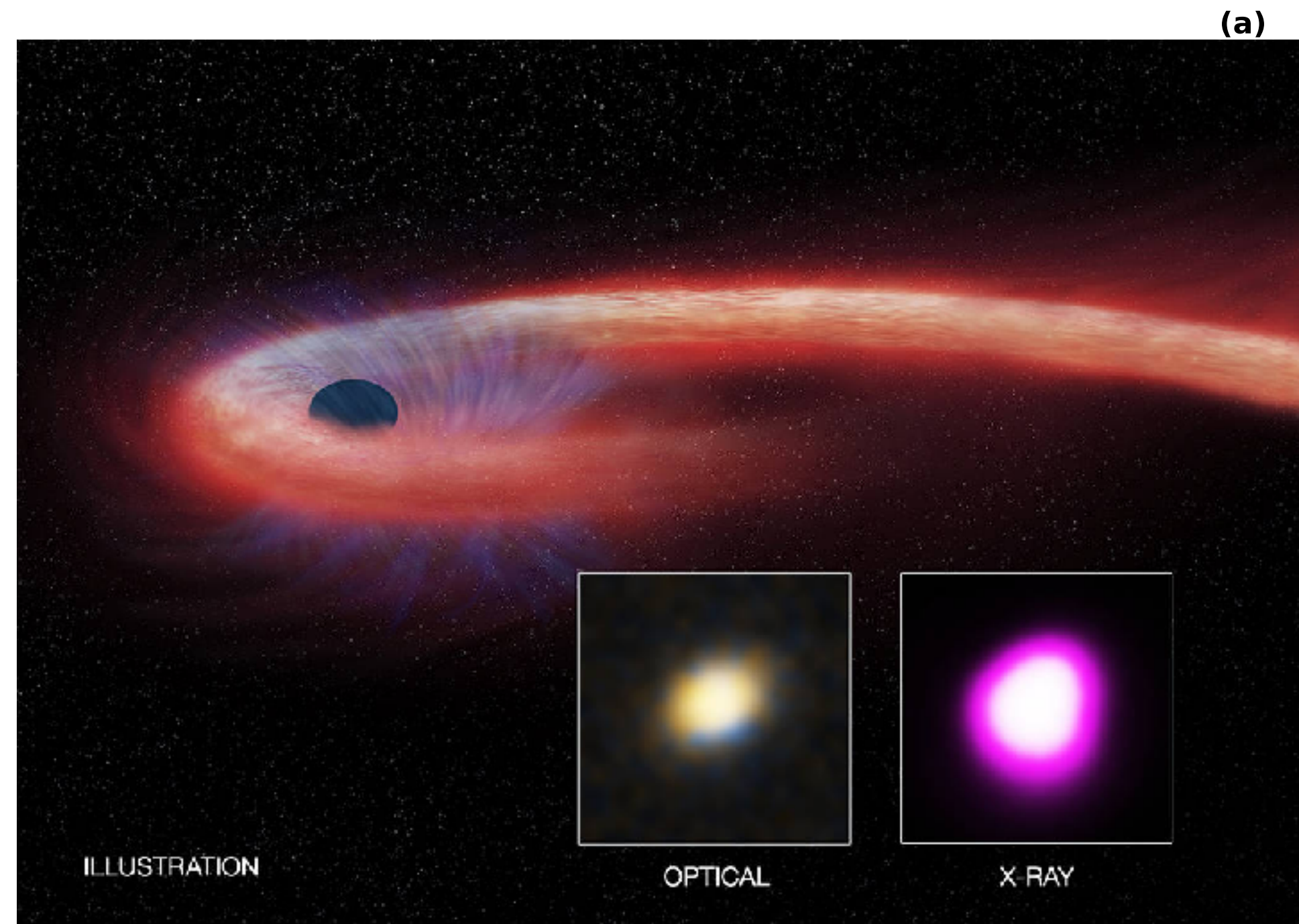
$$N_{\text{SN,unrelated}} \sim 100 \left(\frac{R_{\text{SN}}}{4 \times 10^5 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right) \left(\frac{V}{10^2 \text{ Gpc}^3} \right) \left(\frac{\Delta t}{30 \text{ day}} \right) \left(\frac{\text{deg}^2}{1} \right) \sim 5000$$

Need to distinguish a neutrino-emitting object from 100s of transients/variables
=> Rare transients could be identified as neutrino counterparts

Tidal Disruption Event (TDE)

8

Stein+ 2021; Reusch+2022

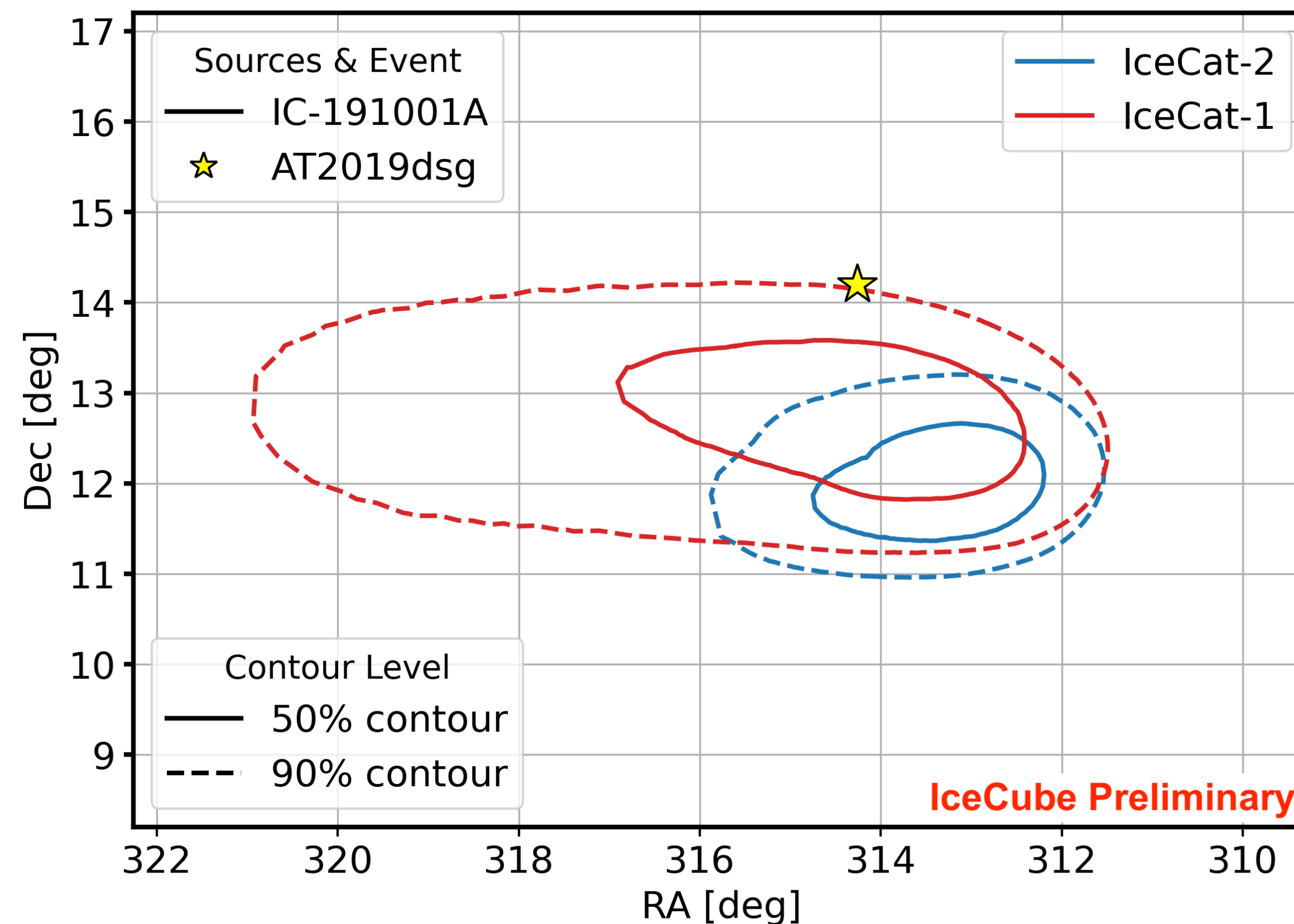
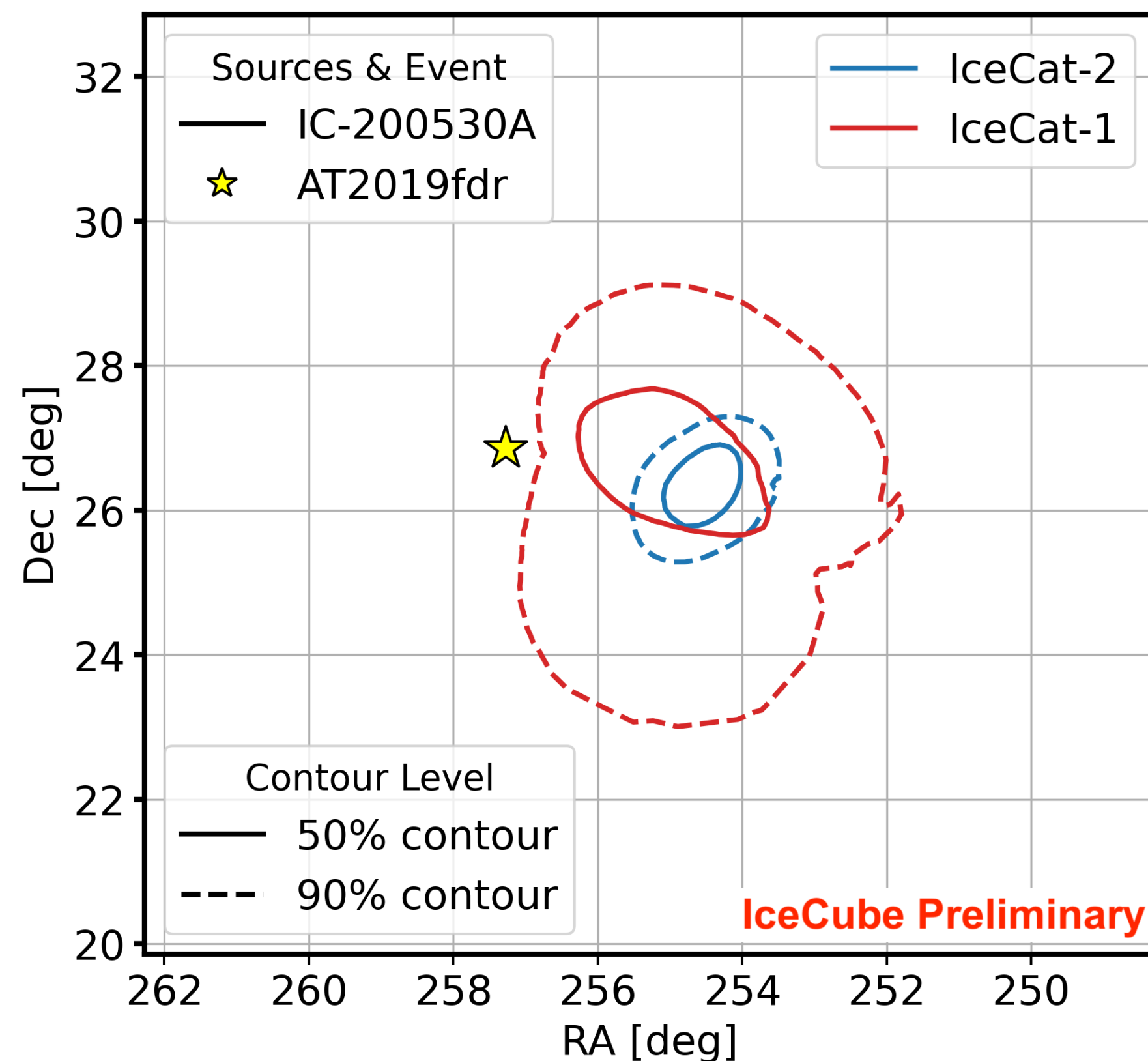


- Stars are torn apart by supermassive black holes
=> luminous ($\sim 10^{43}$ erg/s) & long ($\sim$ year) optical & X-ray transients
- Several TDEs are reported as possible associations with cosmic neutrino events

Tidal Disruption Event (TDE) ?

9

IceCube ICRC 2025



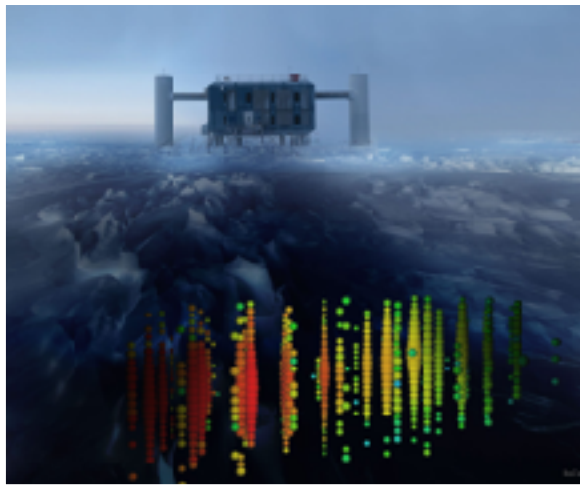
- Using the updated IceCube data, some TDEs are not within the error regions
- **Dedicated analysis is demanded to further examine TDE-neutrino paradigm**

Blind analysis policy

Credit: Masaomi Tanaka

10

Conventional method in astronomy



(1) Neutrino alert!



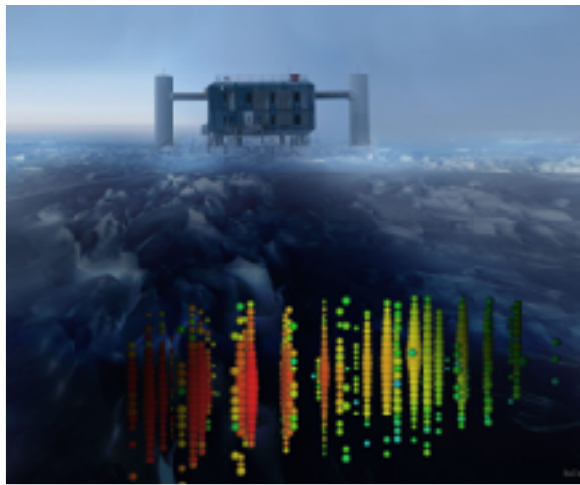
(2) Let's perform follow-up

Blind analysis policy

Credit: Masaomi Tanaka

11

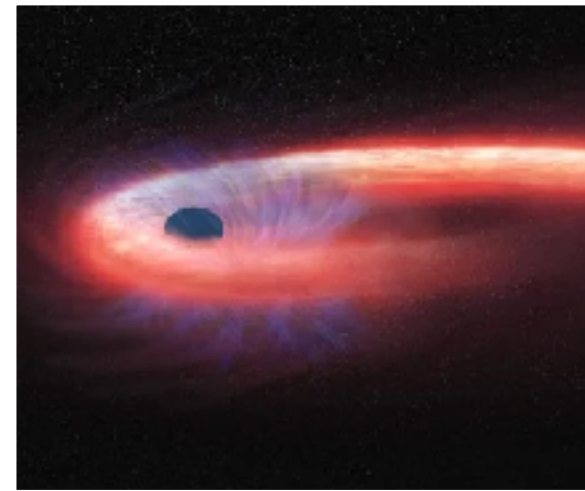
Conventional method in astronomy



(1) Neutrino alert!



(2) Let's perform follow-up



(3) I found such an exiting object!

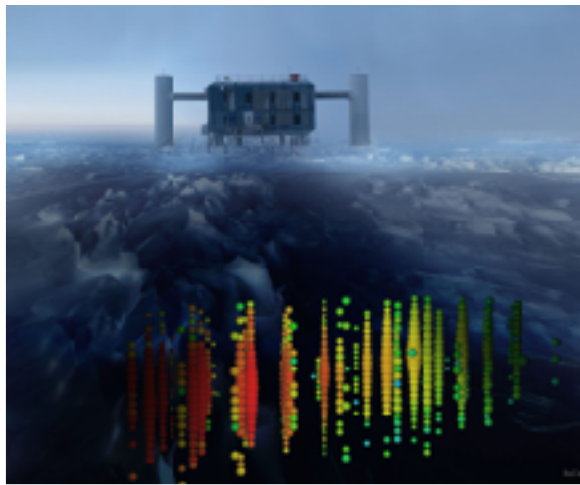
A TDE but radio emitting, A SN but very luminous...

Blind analysis policy

Credit: Masaomi Tanaka

12

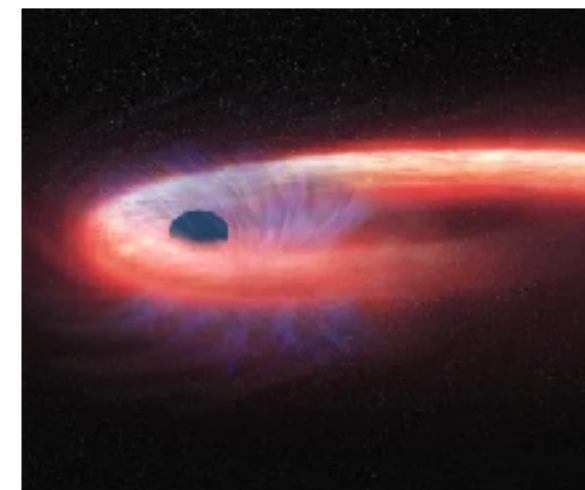
Conventional method in astronomy



(1) Neutrino alert!



(2) Let's perform follow-up



(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...

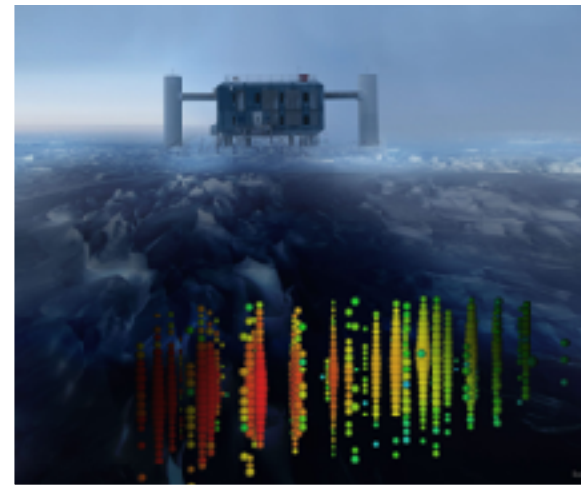
But we already know the “answer”
=> bias in the statistical test

Blind analysis policy

Credit: Masaomi Tanaka

13

Blind analysis



(1) Neutrino alert!



(2) Let's perform follow-up

Blind analysis policy

Credit: Masaomi Tanaka

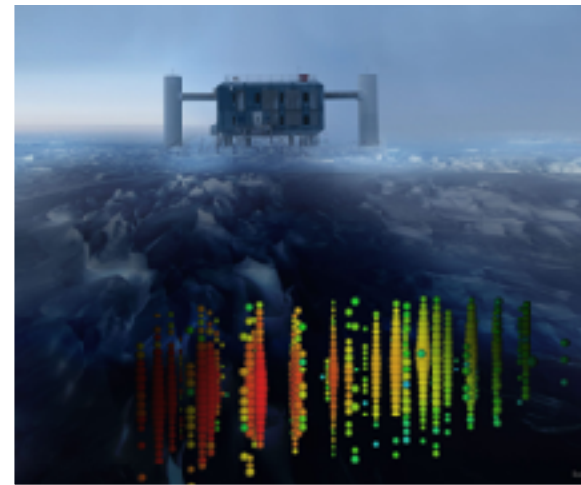
14

Blind analysis



0. First let's understand our data

- => Fix the search criteria
and estimate background
- => Likelihood ratios (signal vs background)



(1) Neutrino alert!



(2) Let's perform follow-up

Blind analysis policy

Credit: Masaomi Tanaka

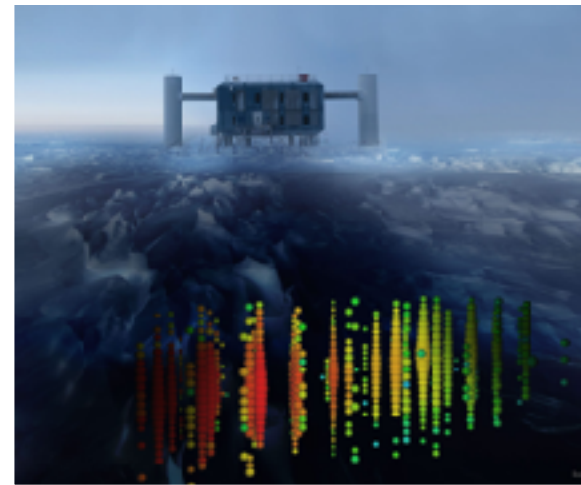
15

Blind analysis



0. First let's understand our data

- => Fix the search criteria and estimate background
- => Likelihood ratios (signal vs background)



(1) Neutrino alert!



(2) Let's perform follow-up



3. Perform “pre-fixed” search

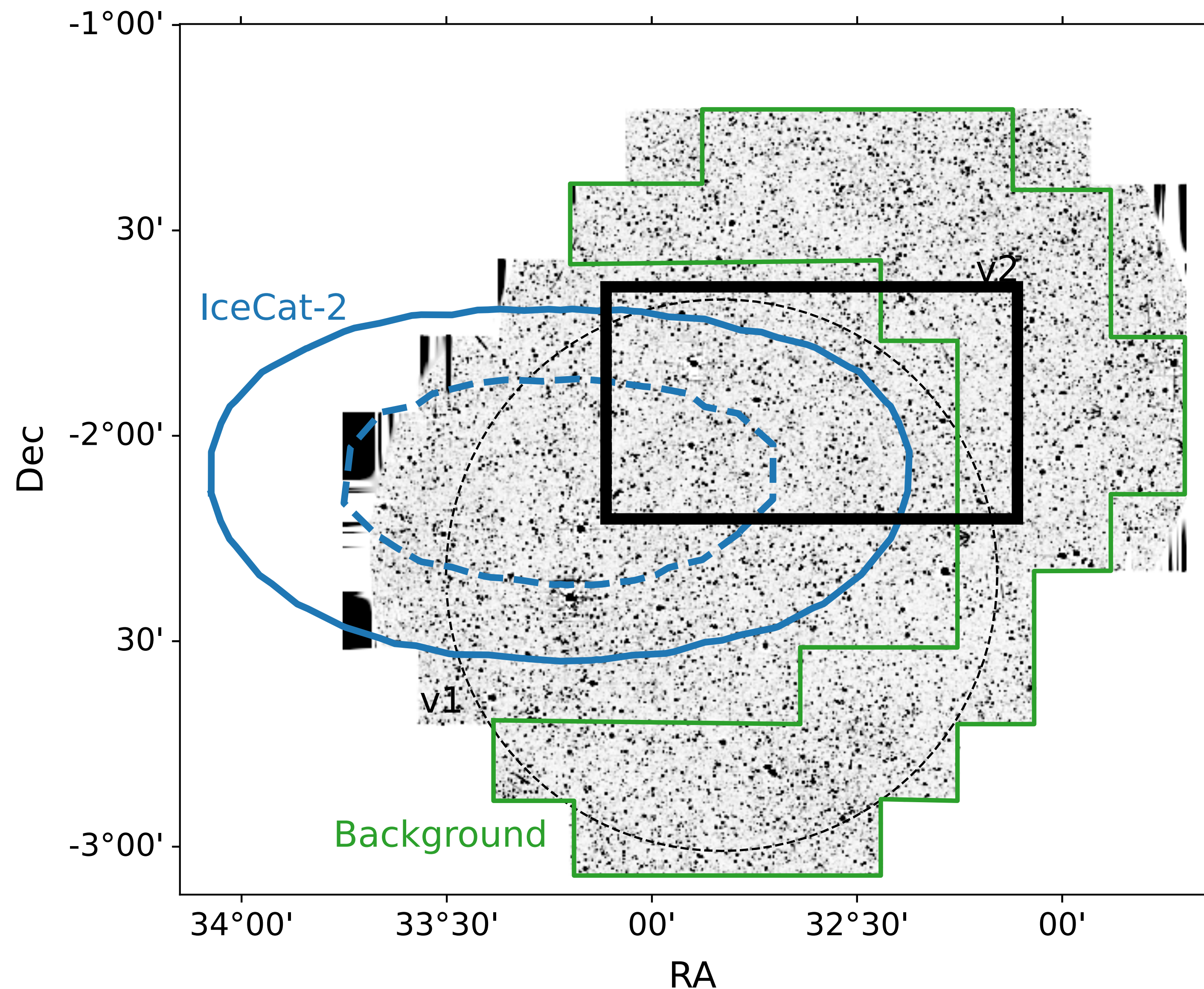
We should not change the selection according to actual findings
(c.f. Hubble constant, cosmological parameters)

Index

- Introduction
- Follow-up observation to singlet
 - Subaru follow-up to IC 230724A
 - Future prospects with Rubin/LSST
- Follow-up analysis to multiplet event
- Summary

Subaru Follow-up to IC 230724A

- Wide ($\sim \text{deg}^2$) & deep ($\sim 25\text{mag}$)
=> Only Subaru/HSC are capable
- Subaru follow-up
on excellent IceCube Alert
IC 230724A
(Angular Error $\sim 0.6 \text{ deg}$)
- ToO observations on
2023/08/10 & 2023/08/23
- Following epochs
canceled by mirror trouble
- New neutrino event reconstruction
=> neutrino position shifted
=> error regions are not fully covered



Blind analysis

- **Blind analysis:**

Actual data in the error region will be analyzed after we have completed estimation of

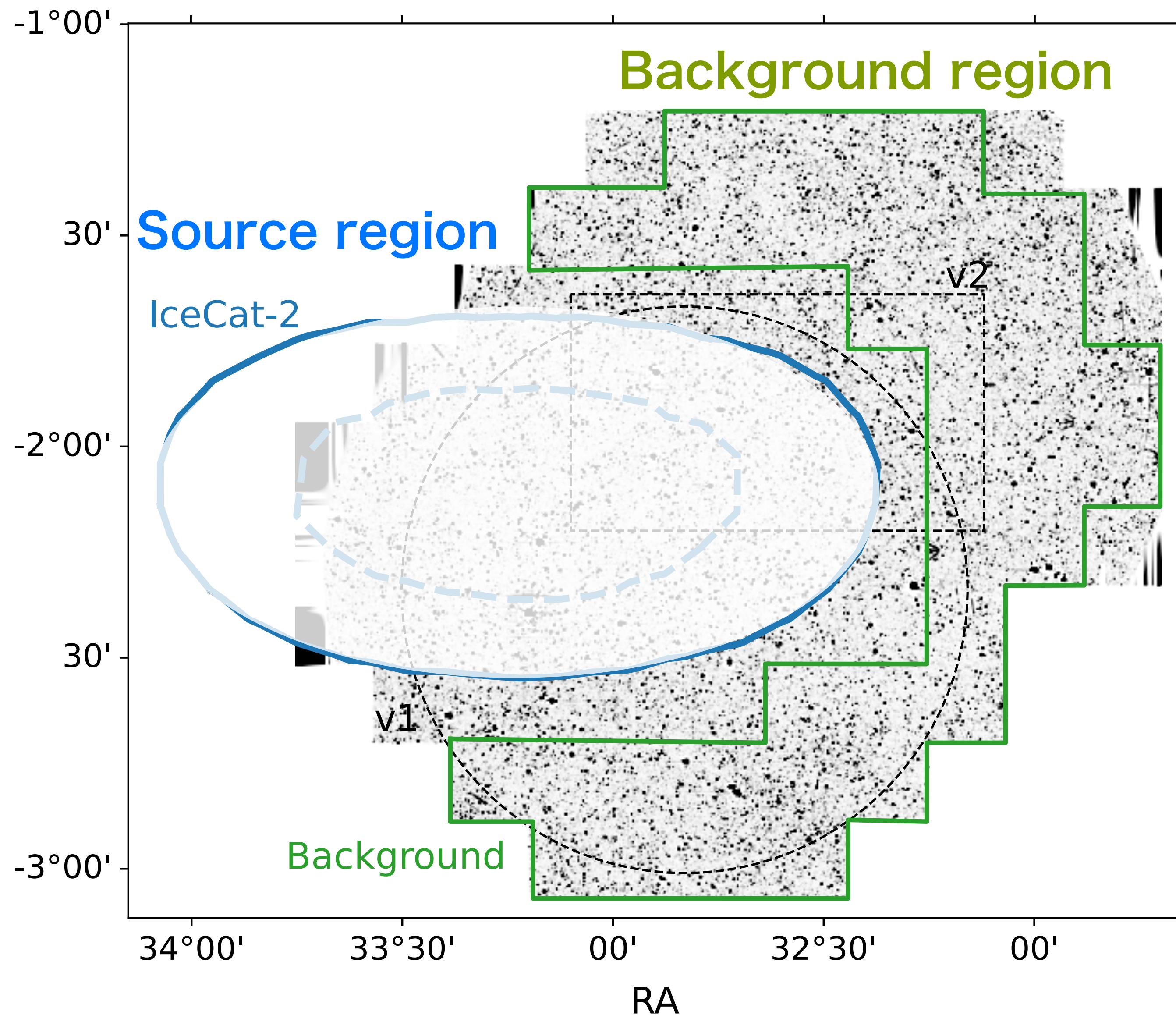
- **Background rate**
- **Recovery rate**

- **Background rate**

- Data-driven method
- Use background region data

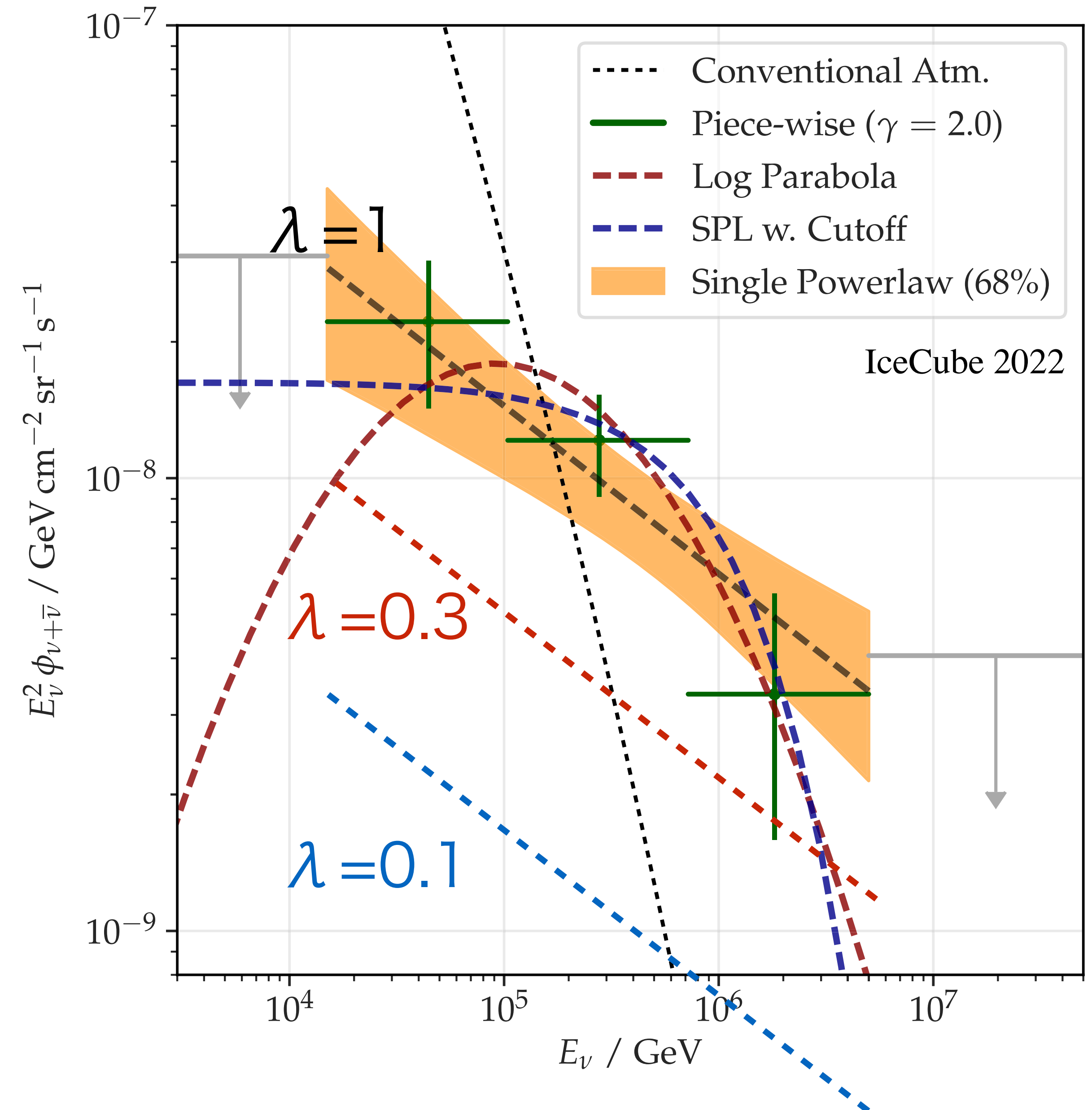
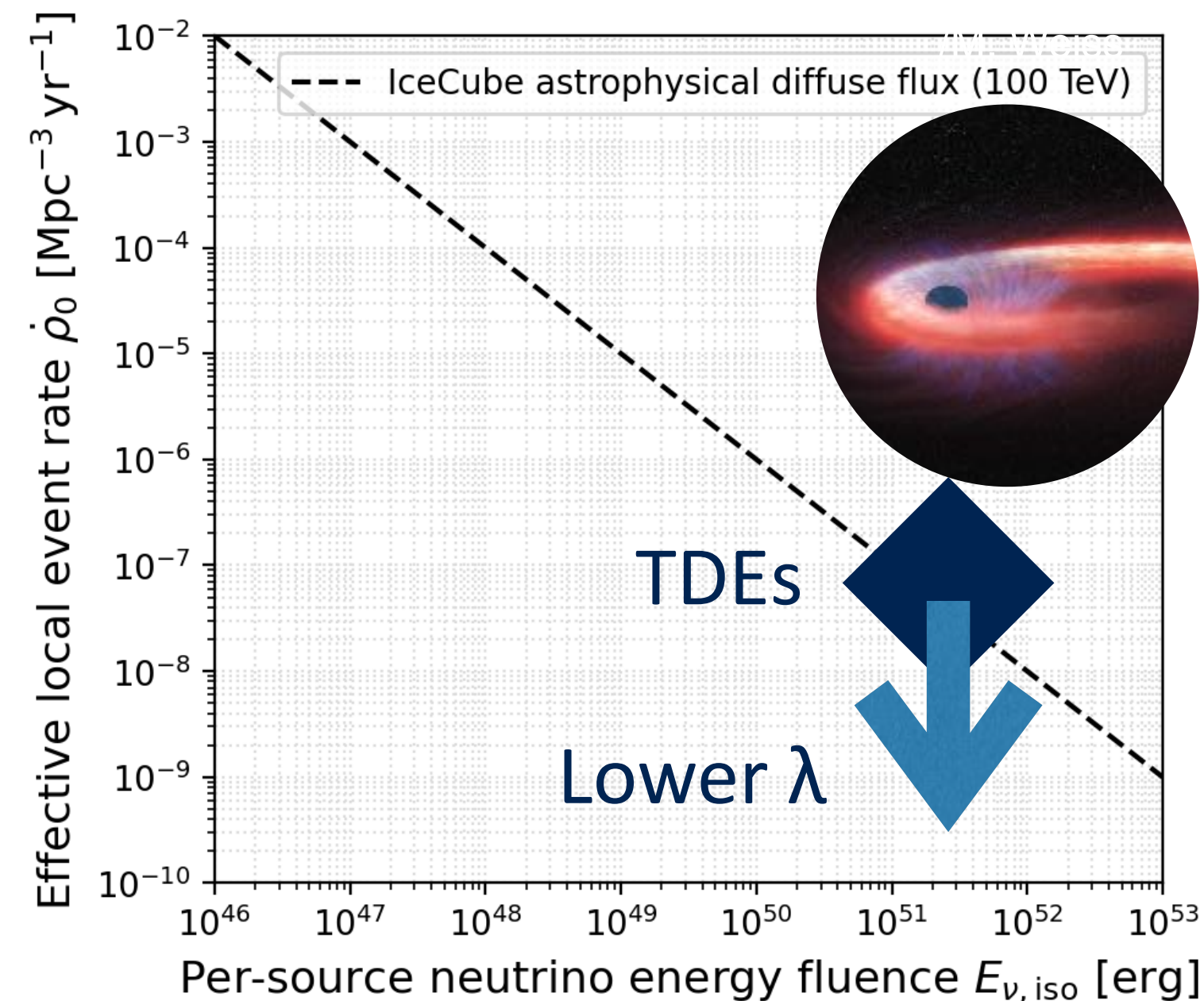
- **Recovery rate**

- Both data-driven & simulation-driven
- need to provide source model

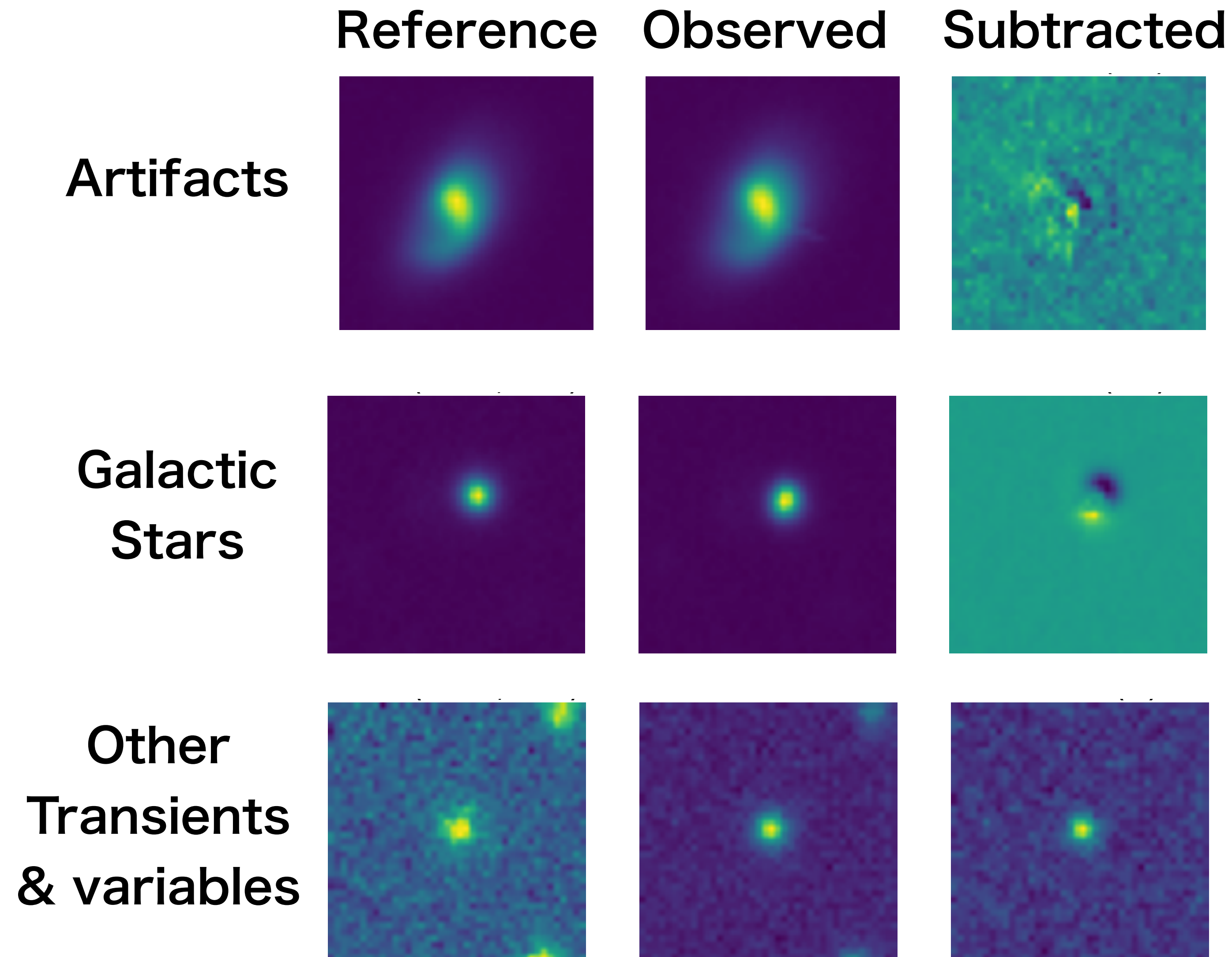


Our strategy: Constrain a population

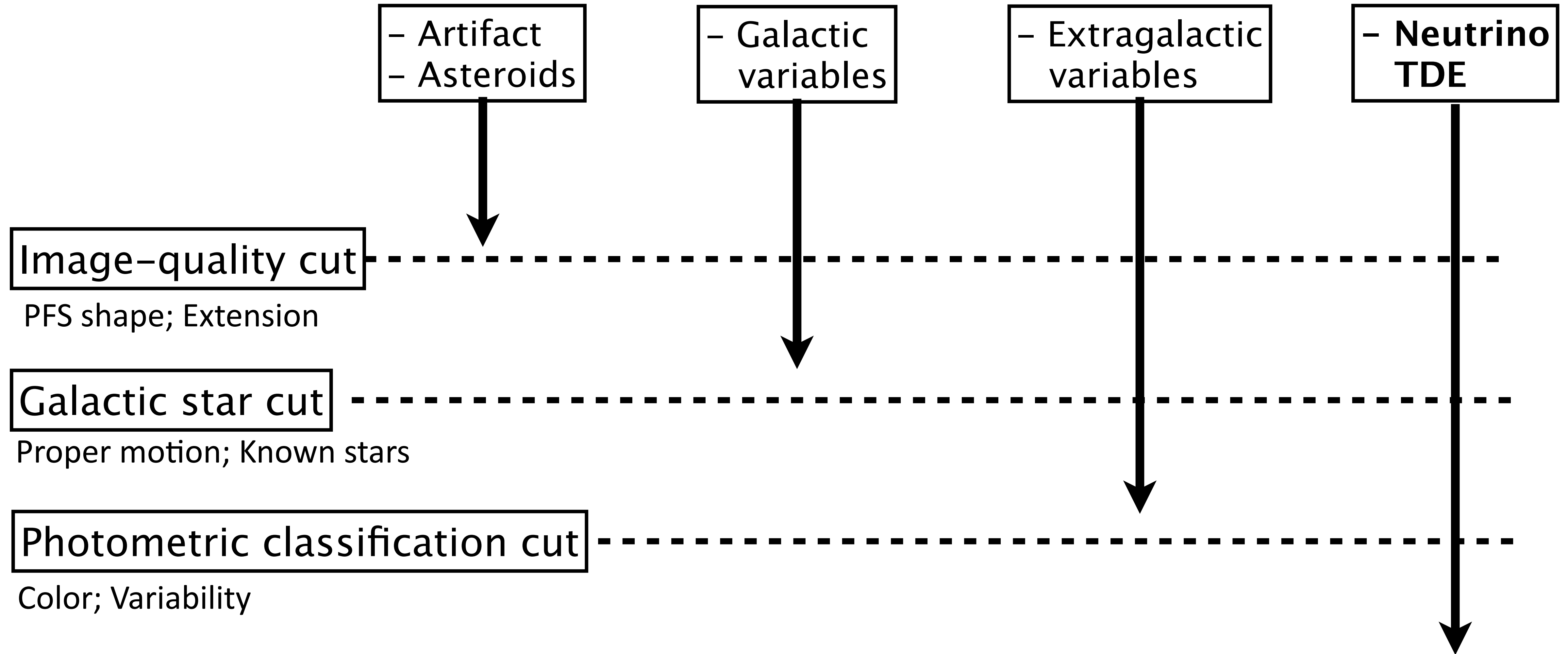
- let us try to constrain a population of transients as neutrino sources
- We assume that a population of TDEs contribute to diffuse flux by a fraction λ
- $\lambda < 1$:
fraction of neutrino-emitting TDE is lower
- We try to constrain the value of λ



Background objects in Optical data

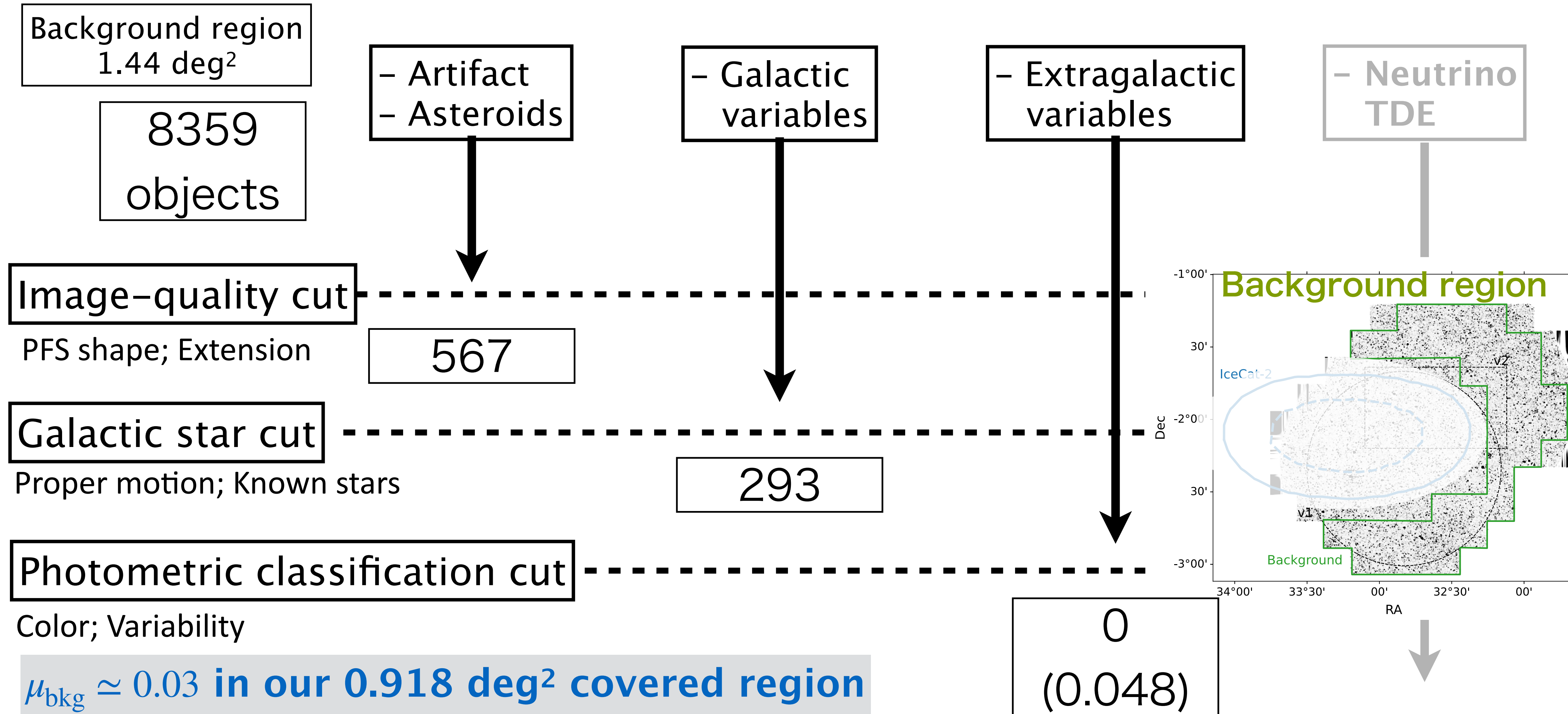


3 filtering processes



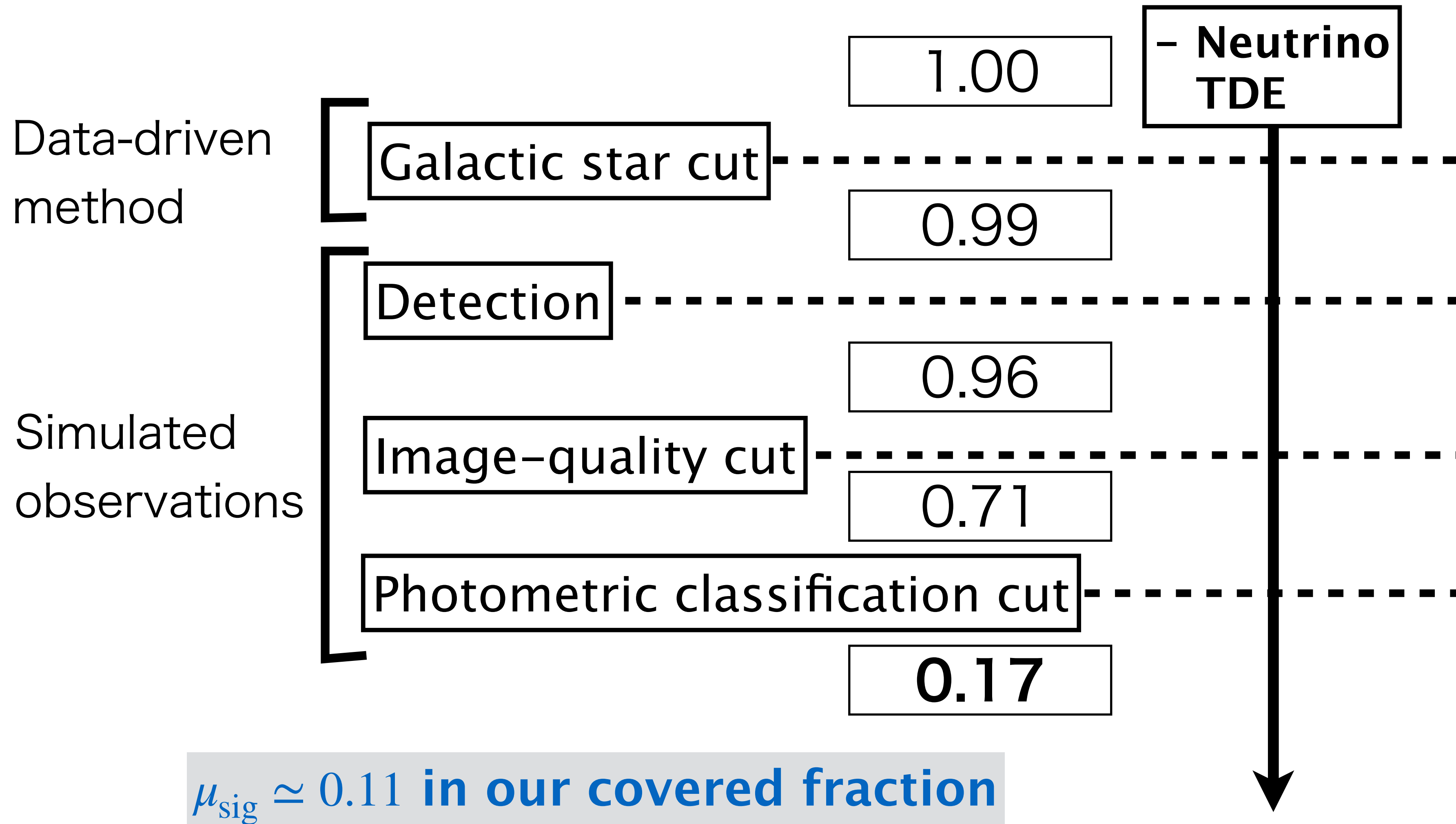
Background Rate: Data-driven method

22

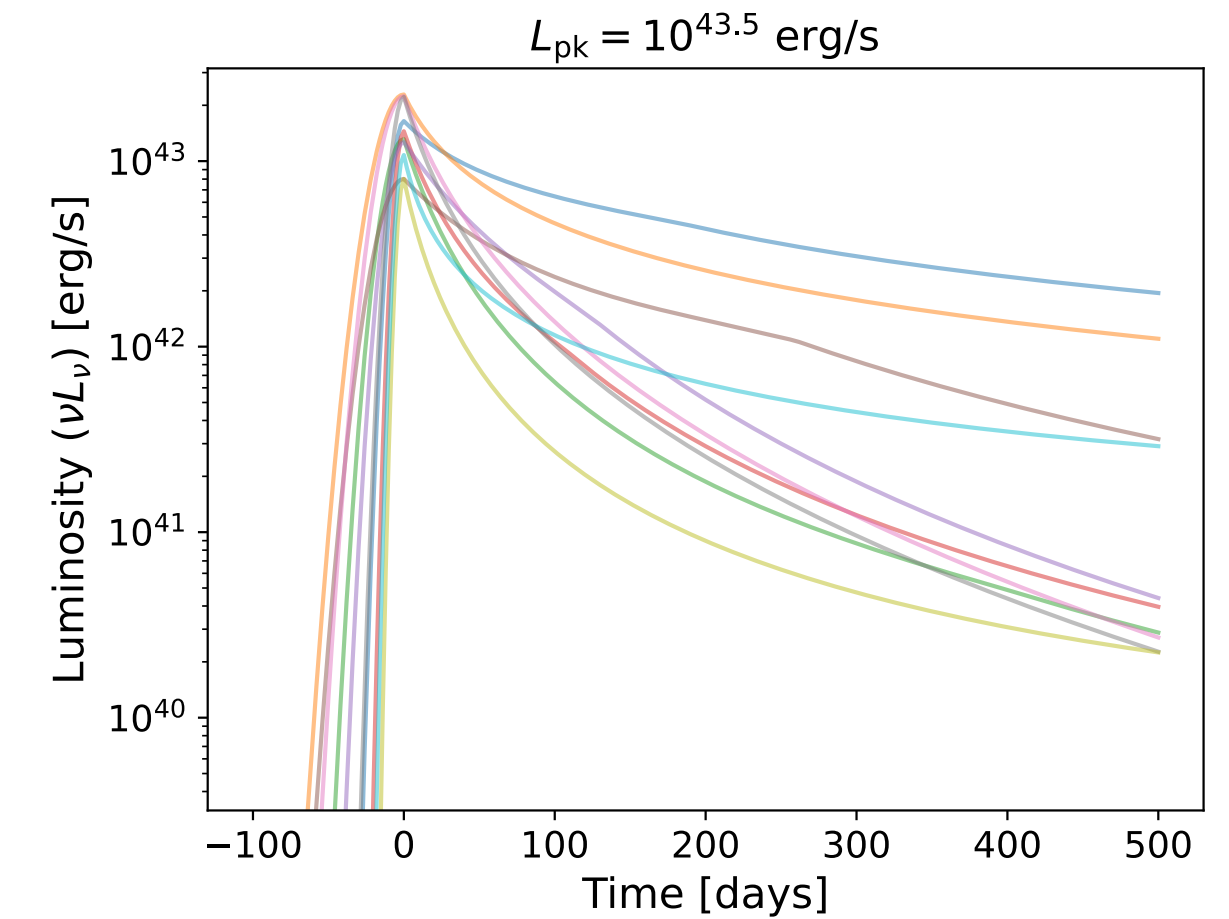


Recovery rate estimate

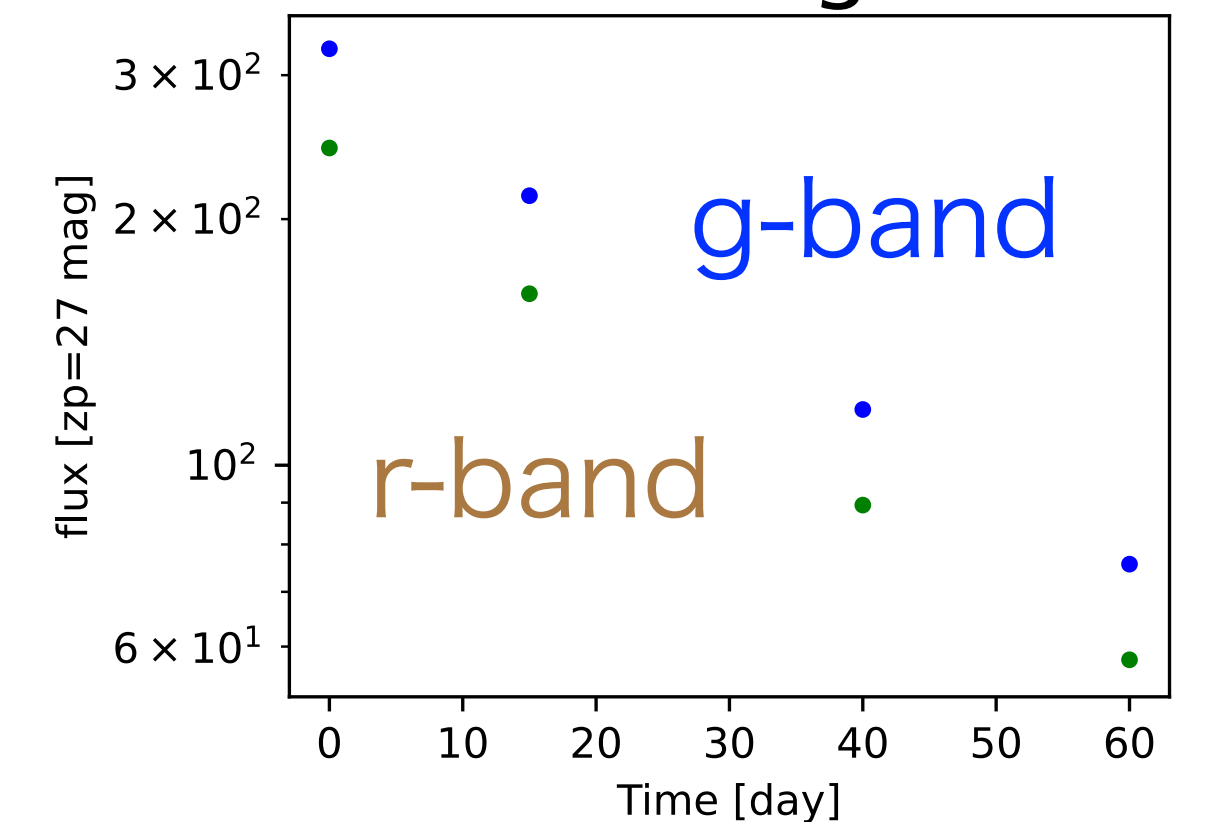
Data-driven method + simulated observations



TDE Lightcurve templates



Simulated lightcurves

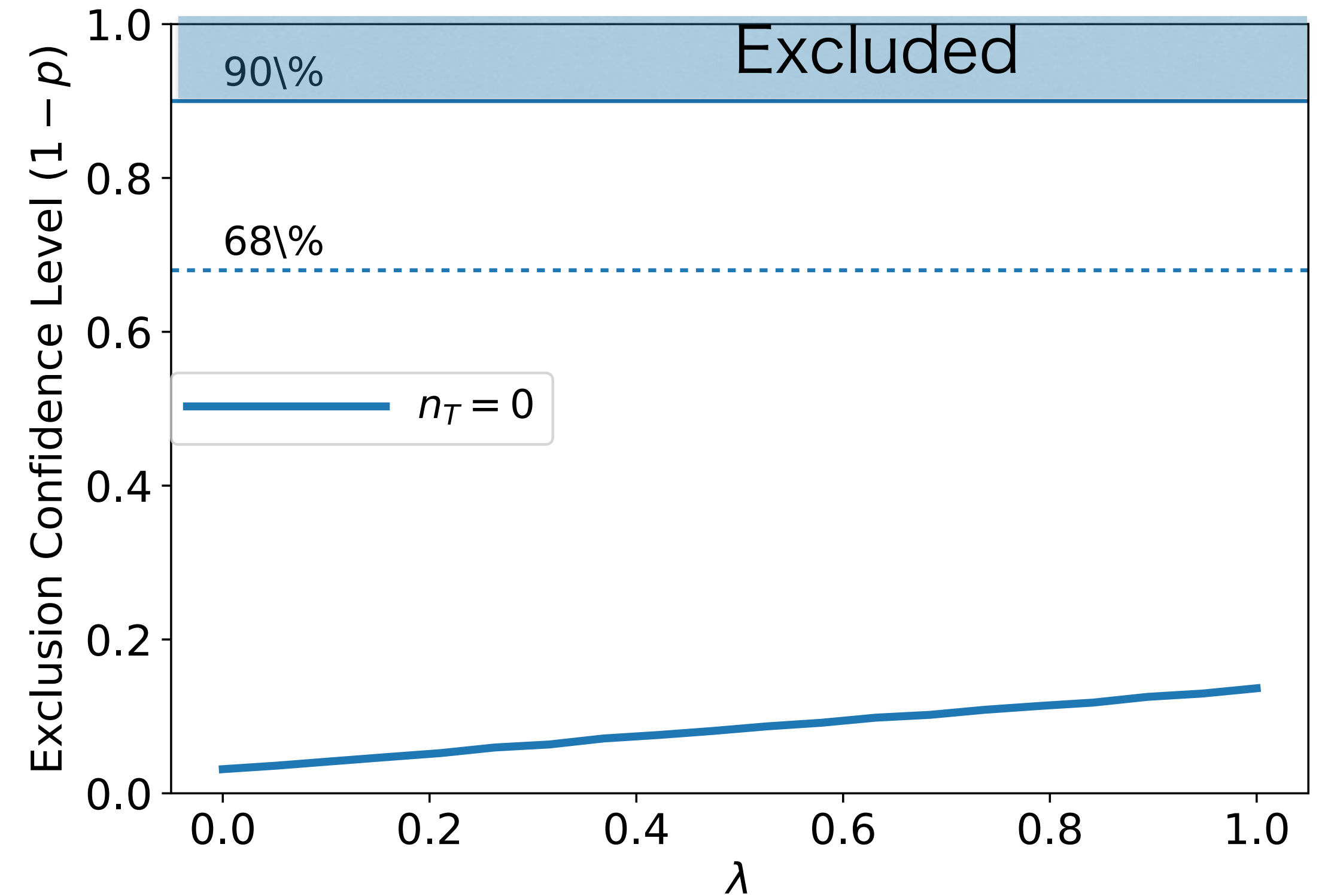
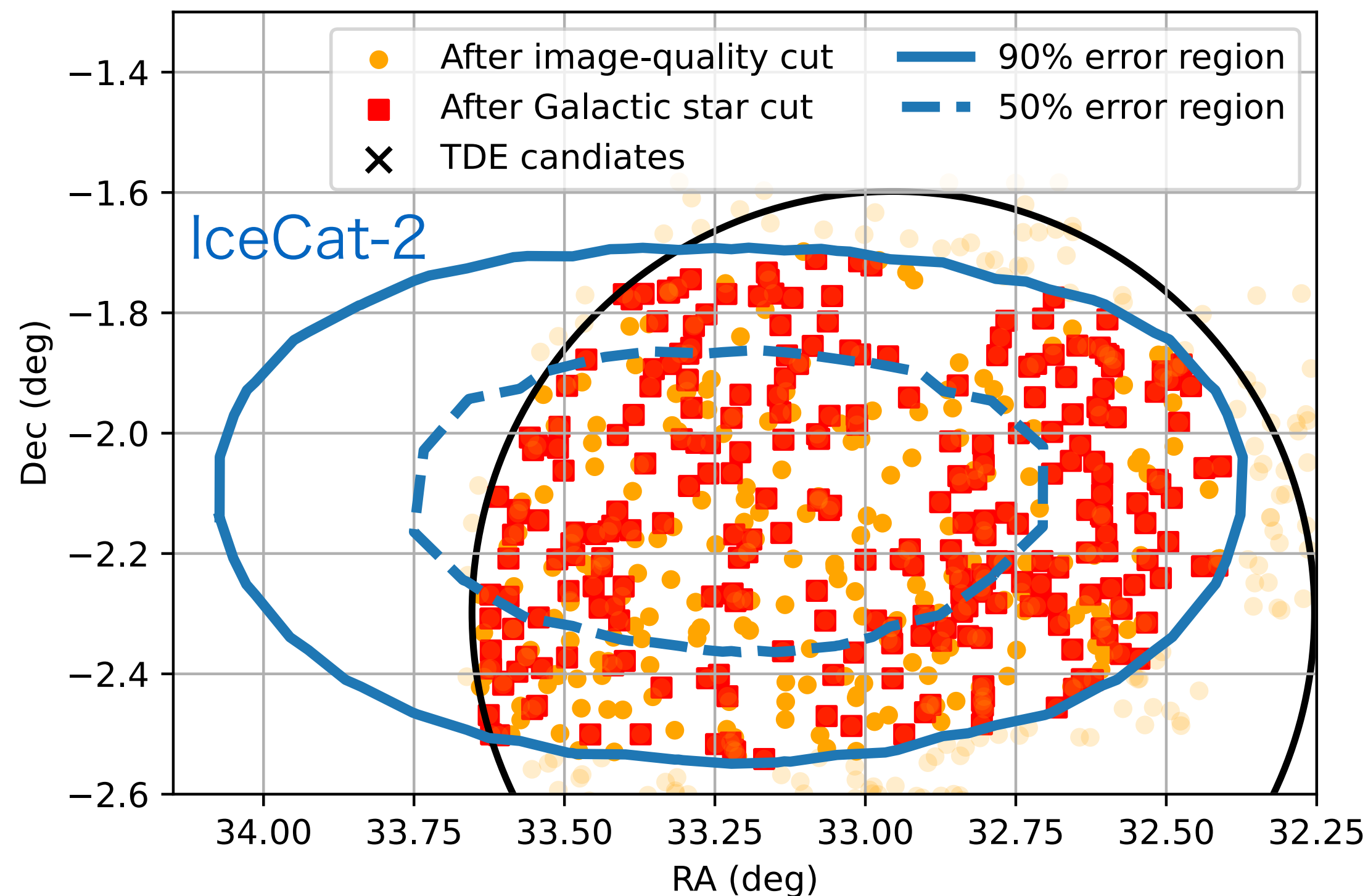


Unblind results

- Apply our filtering processes => No TDE found in the source region
- Try to **constrain the fractional contribution of TDEs, λ**

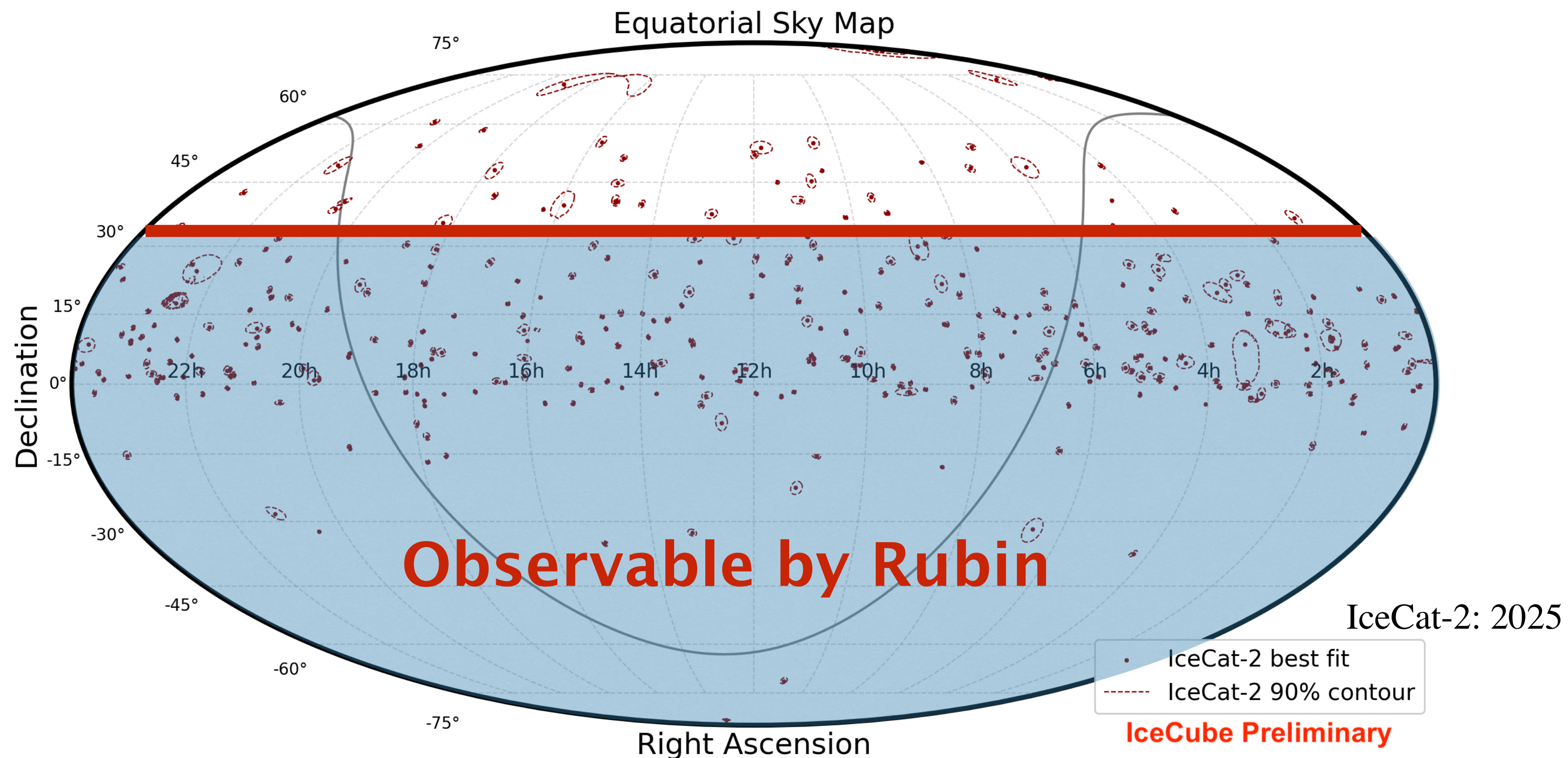
$$\mathcal{L}_{\text{sig}} = \begin{cases} (1 - \lambda \mu_{\text{sig}}) e^{-\mu_{\text{bkg}}} & (n_T = 0) \\ 1 - (1 - \lambda \mu_{\text{sig}}) e^{-\mu_{\text{bkg}}} & (n_T \geq 1) \end{cases}, \quad \mathcal{L}_{\text{alt}} = \begin{cases} e^{-\mu_{\text{bkg}}} & (n_T = 0) \\ 1 - (1 - \mu_{\text{sig}}) e^{-\mu_{\text{bkg}}} & (n_T \geq 1) \end{cases},$$

n_T : number of TDE candidates



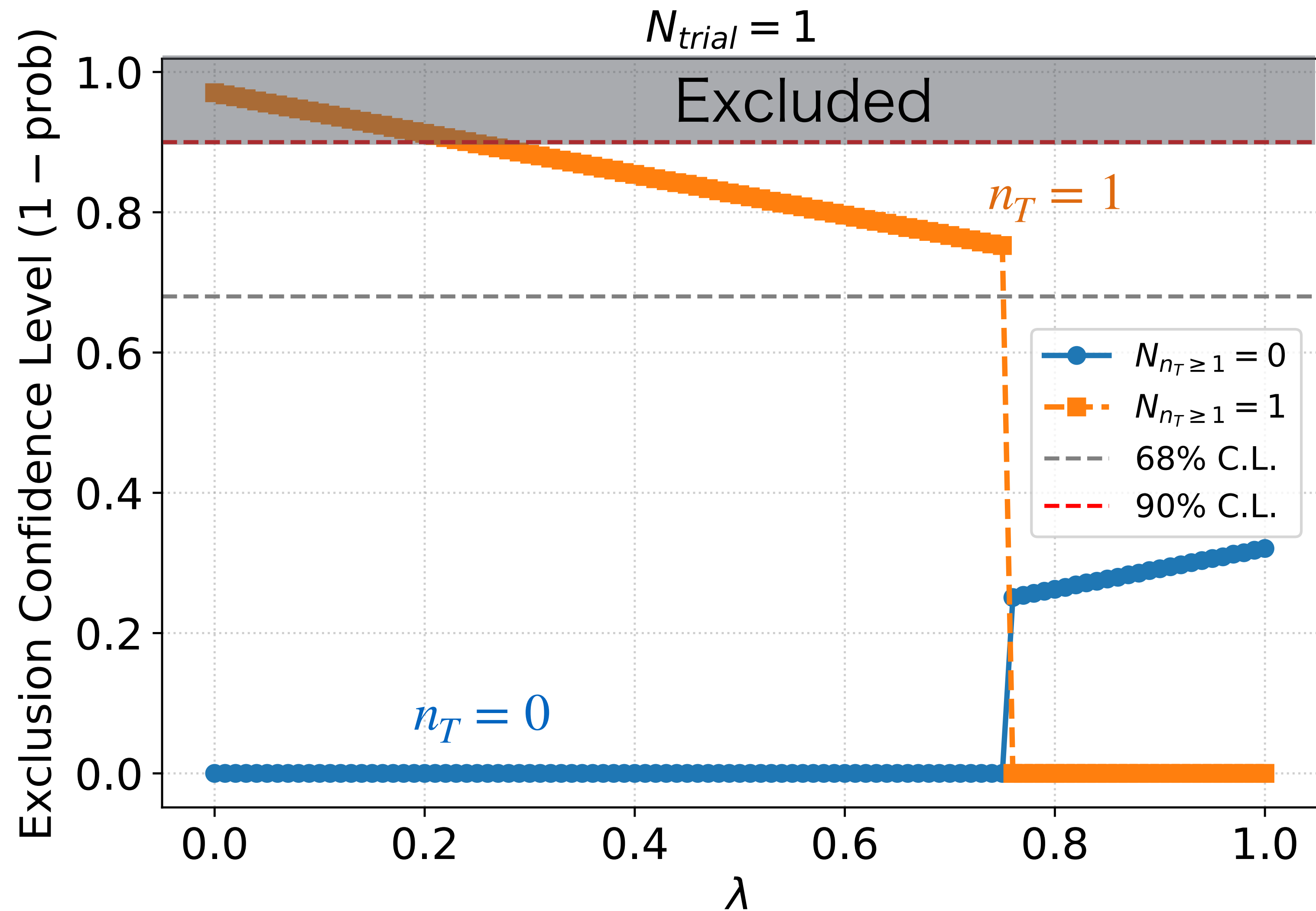
Prospects with Rubin/LSST

- Rubin/LSST will provide excellent photometric data sets
- More than half of neutrino events can be observable from Rubin site



Prospects with Rubin/LSST

- Simulated observations with Rubin/LSST-like data set
 $\Rightarrow \mu_{\text{sig}} \sim 0.3, \mu_{\text{bkg}} \sim 0.01$
 (conservative choice)
 See e.g. Bardwaj et al 2025 for ML classification
- 1 follow-up cannot say anything unless we luckily find a candidate



Prospects with Rubin/LSST

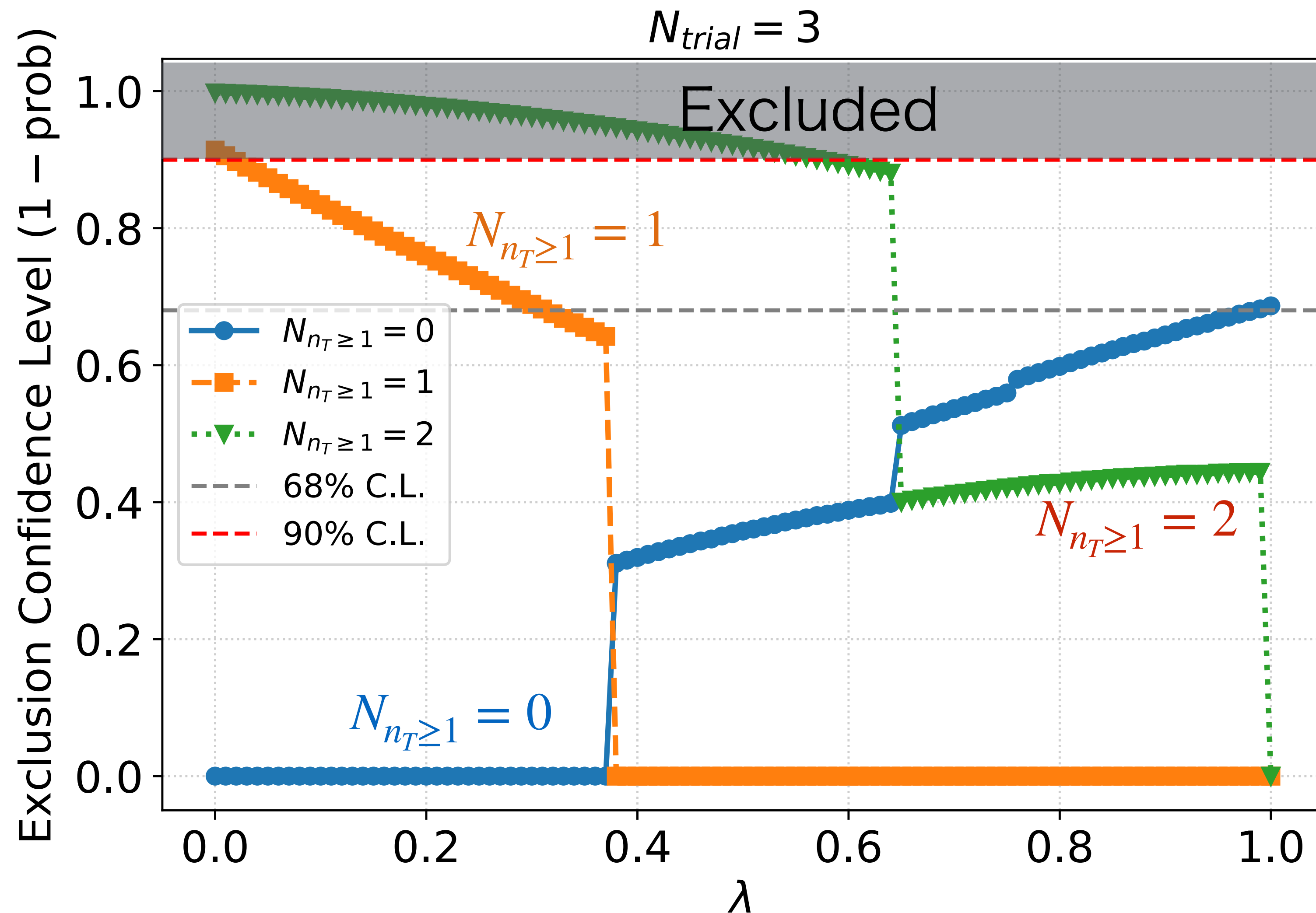
- We extend our analysis to multiple follow-up trials

$$\mathcal{L}_{N,\text{sig}}(N_{n_T \geq 1}; \lambda) = \prod_i^{N_{\text{trial}}} \mathcal{L}_{\text{sig},i}$$

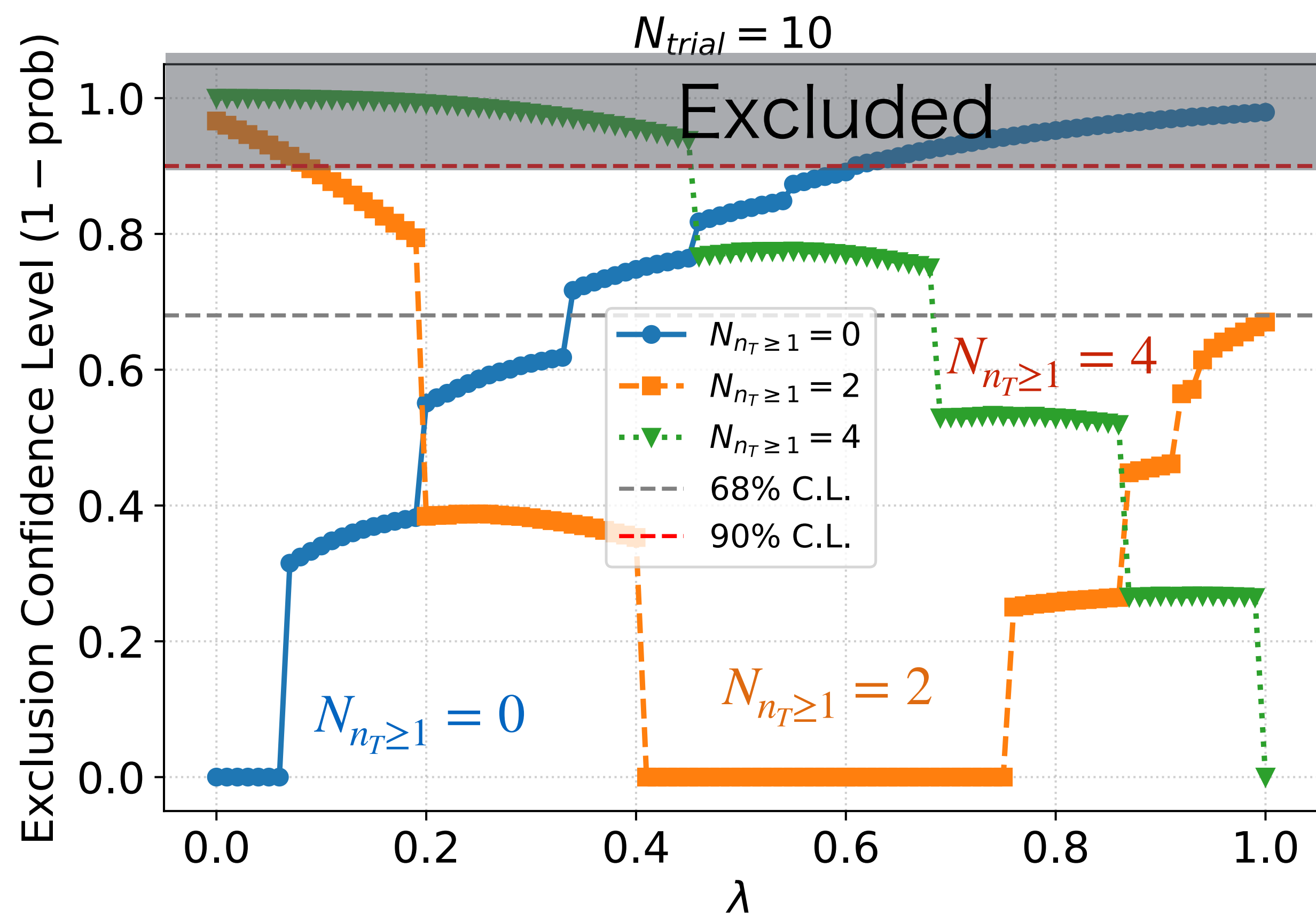
$$\mathcal{L}_{N,\text{alt}}(N_{n_T \geq 1}; \hat{\lambda}) = \prod_i^{N_{\text{trial}}} \mathcal{L}_{\text{alt},i}$$

$$\Lambda_N(N_{n_T \geq 1}) = -2 \ln \left(\frac{\mathcal{L}_{N,\text{sig}}}{\mathcal{L}_{N,\text{alt}}} \right)$$

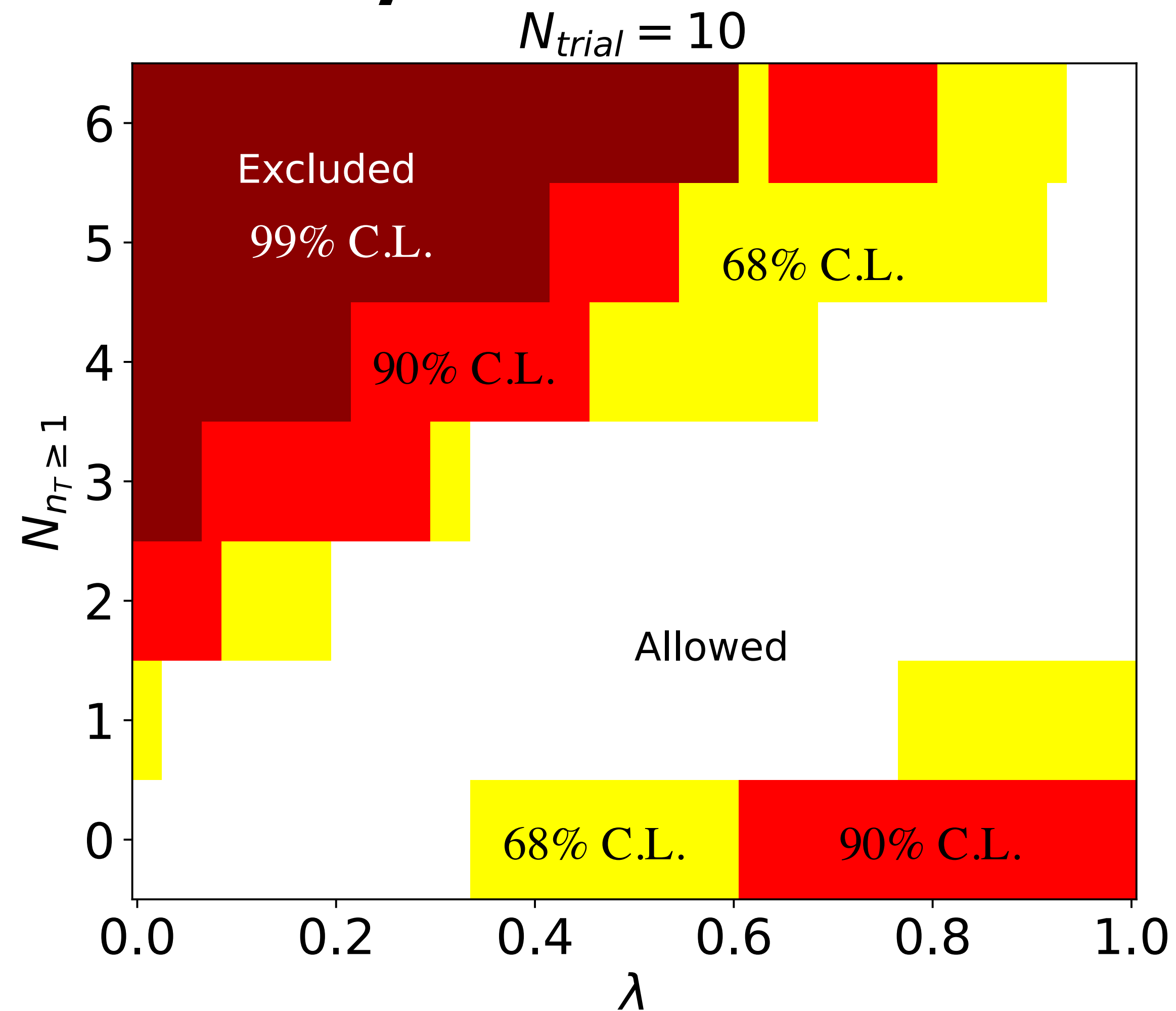
- $N_{n_T \geq 1}$:
Number of trials satisfying $n_T \geq 1$
- 3 follow-up cannot say anything unless we are lucky



Prospects with Rubin/LSST



- With 10 trials, we can constrain λ for most values of $N_{n_T \geq 1}$



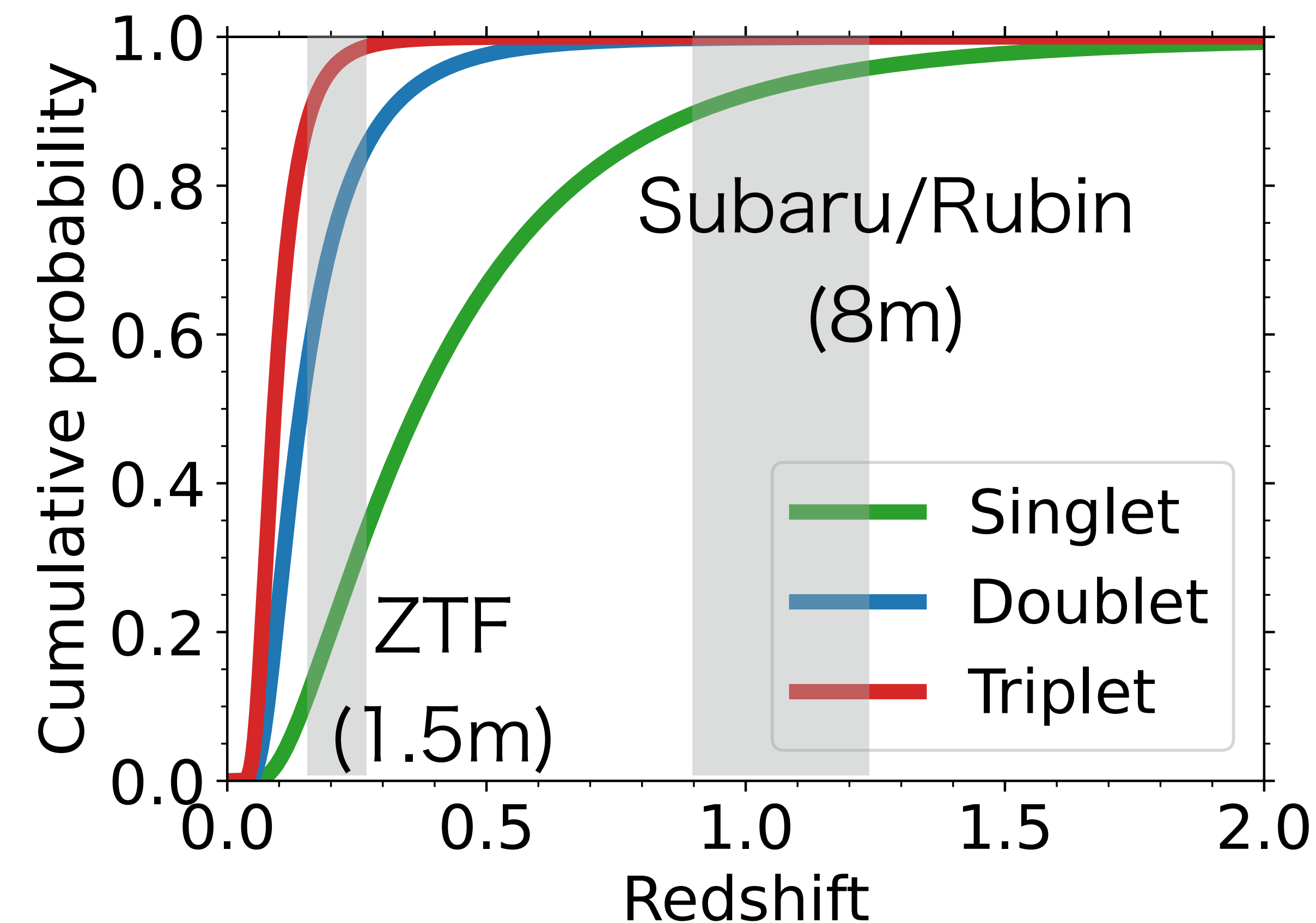
- $N_{n_T \geq 1} = 0 \Rightarrow \lambda > 0.6$ disfavored
- $N_{n_T \geq 1} \geq 3 \Rightarrow \lambda < 0.3$ disfavored

Index

- Introduction
- Follow-up observation to singlet
 - Subaru follow-up to IC 230724A
 - Future prospects with Rubin/LSST
- **Follow-up analysis to multiplet event**
- Summary

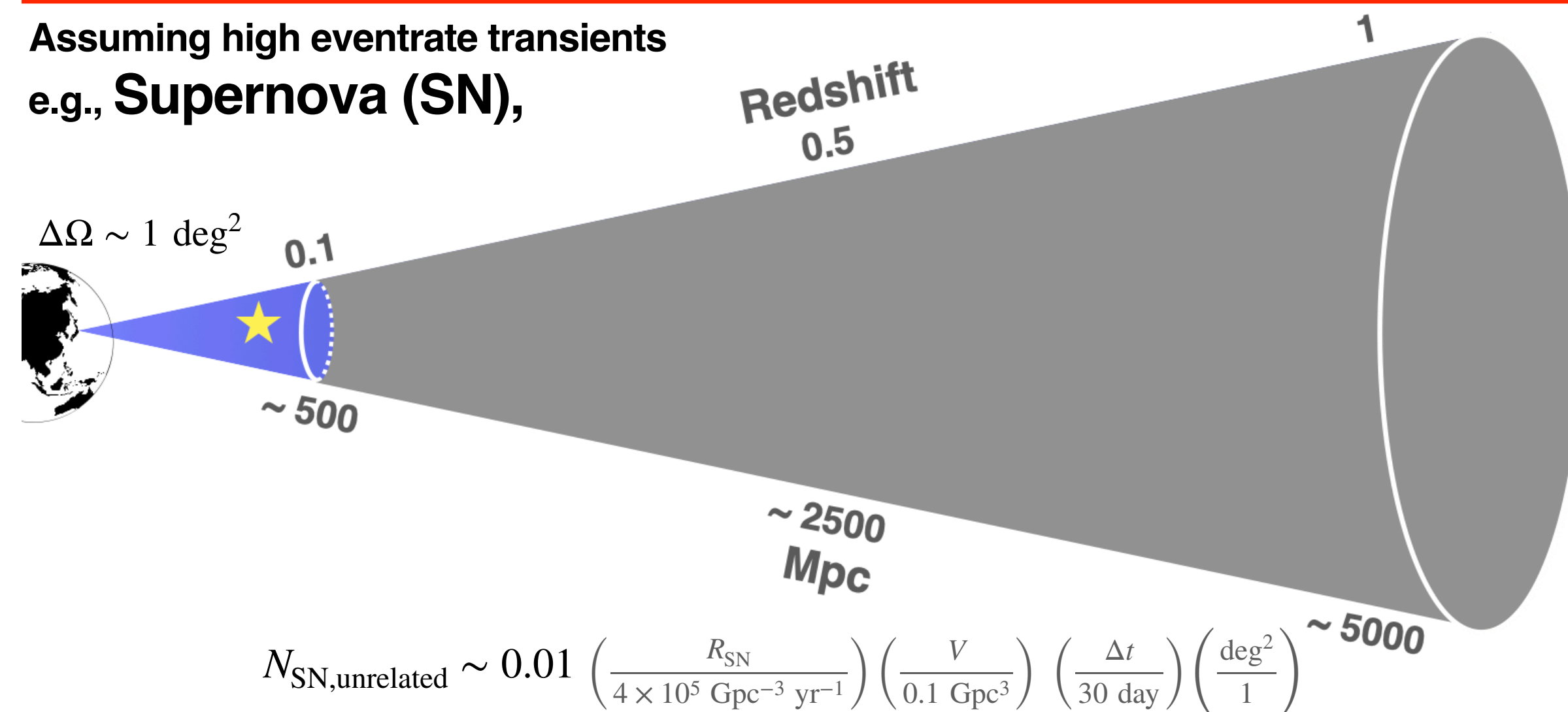
Singlet VS multiplet

Figure by Seiji Toshikage



- **Multiplet**
 - **Low expected distance**
=> **good with small telescopes & almost background free**

Assuming high eventrate transients
e.g., **Supernova (SN)**,

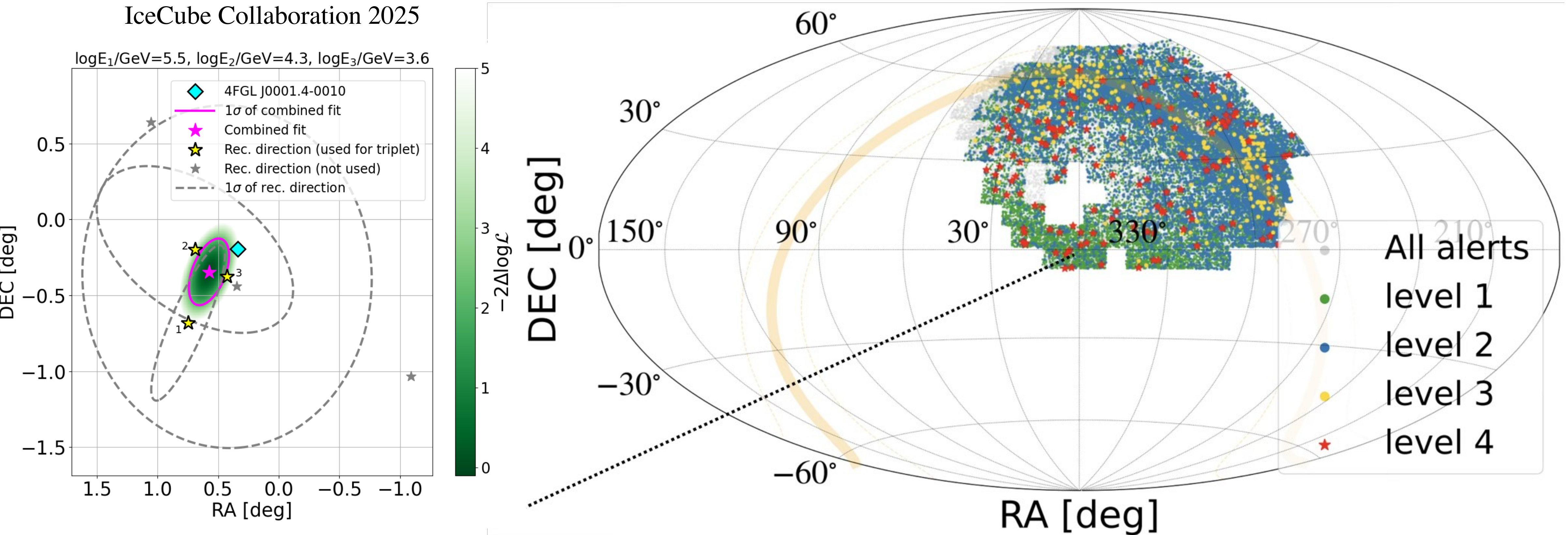


$$N_{\text{SN,unrelated}} \sim 0.01 \left(\frac{R_{\text{SN}}}{4 \times 10^5 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right) \left(\frac{V}{0.1 \text{ Gpc}^3} \right) \left(\frac{\Delta t}{30 \text{ day}} \right) \left(\frac{\text{deg}^2}{1} \right) \sim 5000$$

Number of unrelated objects become **small enough** to discuss association

A triplet event on June 2020

Credit: Seiji Toshikage



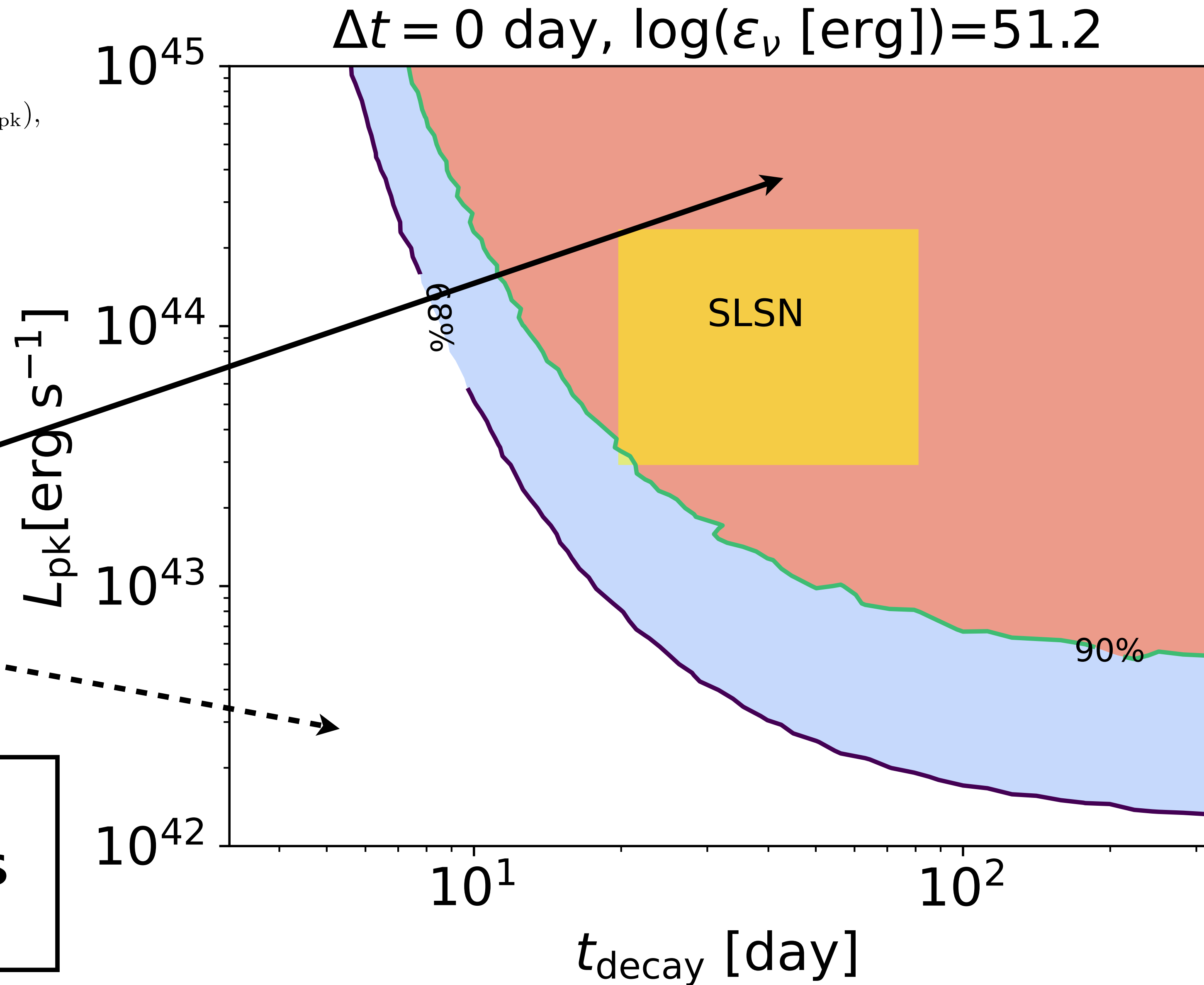
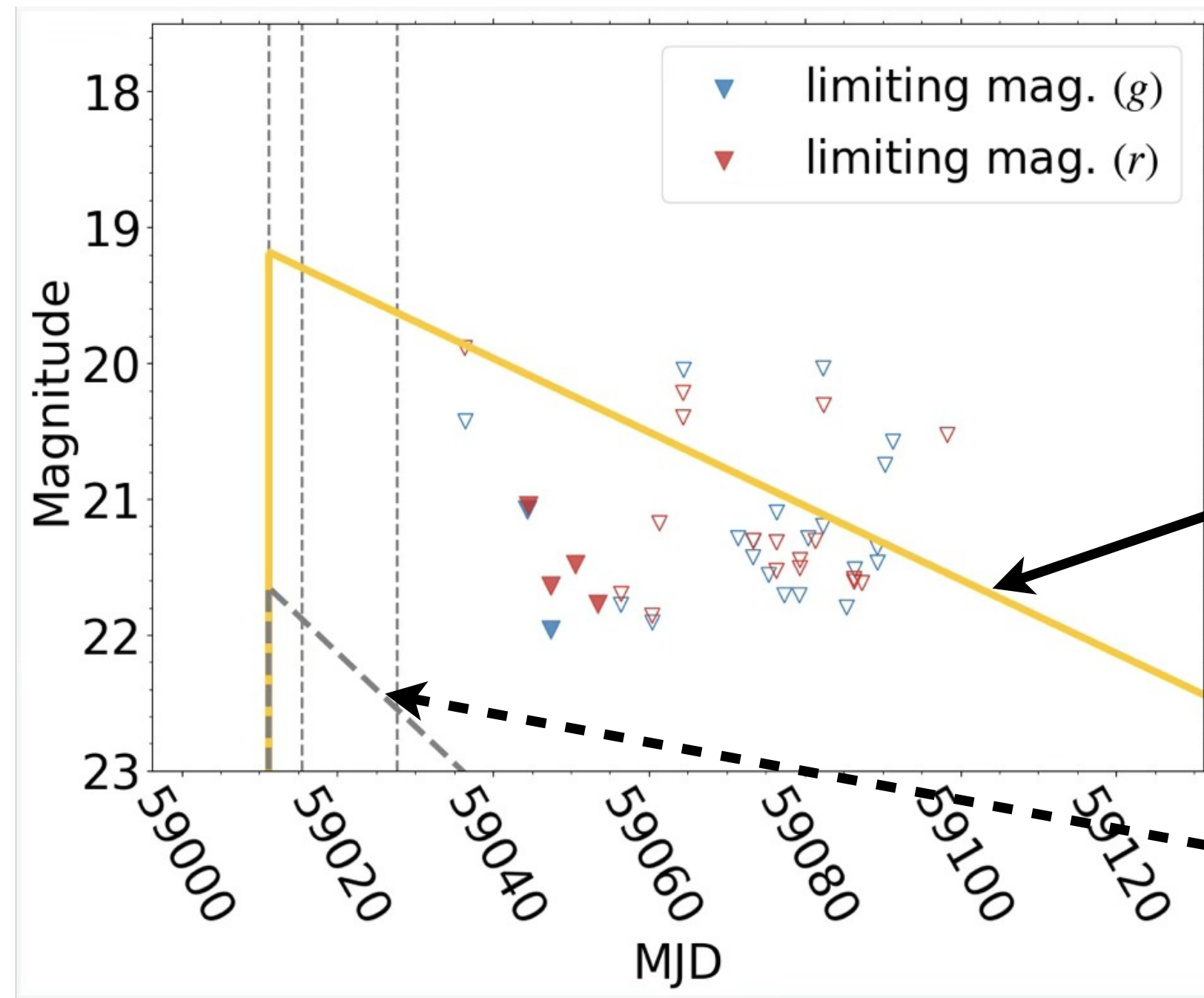
Massive ZTF data available ($A_{\text{bkg}} \sim 16000A_{\text{sig}}$)

Create our own filtering criteria by **fully data-driven way**
=> low background rate (0.02) and high recovery rate (0.98)

Constraints on optical transient sources ³²

- 2 parameters:

$$t_{\text{decay}}, L_{\text{pk}} \quad L_{\nu}(t) = L_{\text{pk}} \frac{B_{\nu}(T)}{\sigma T^4 / \pi} \exp\left(-\frac{|t - t_{\text{pk}}|}{t_{\text{decay}}}\right) \Theta(t - t_{\text{pk}}),$$



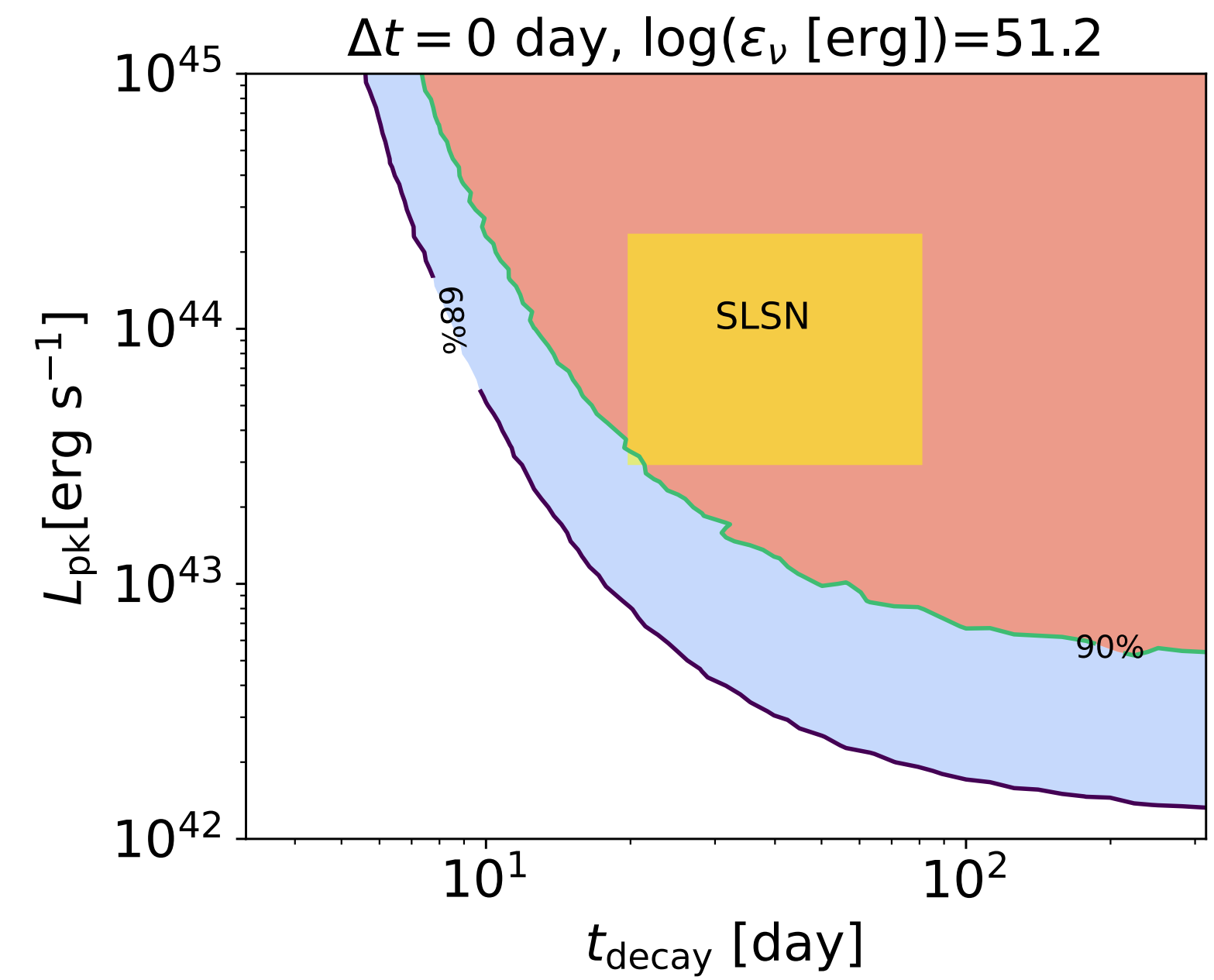
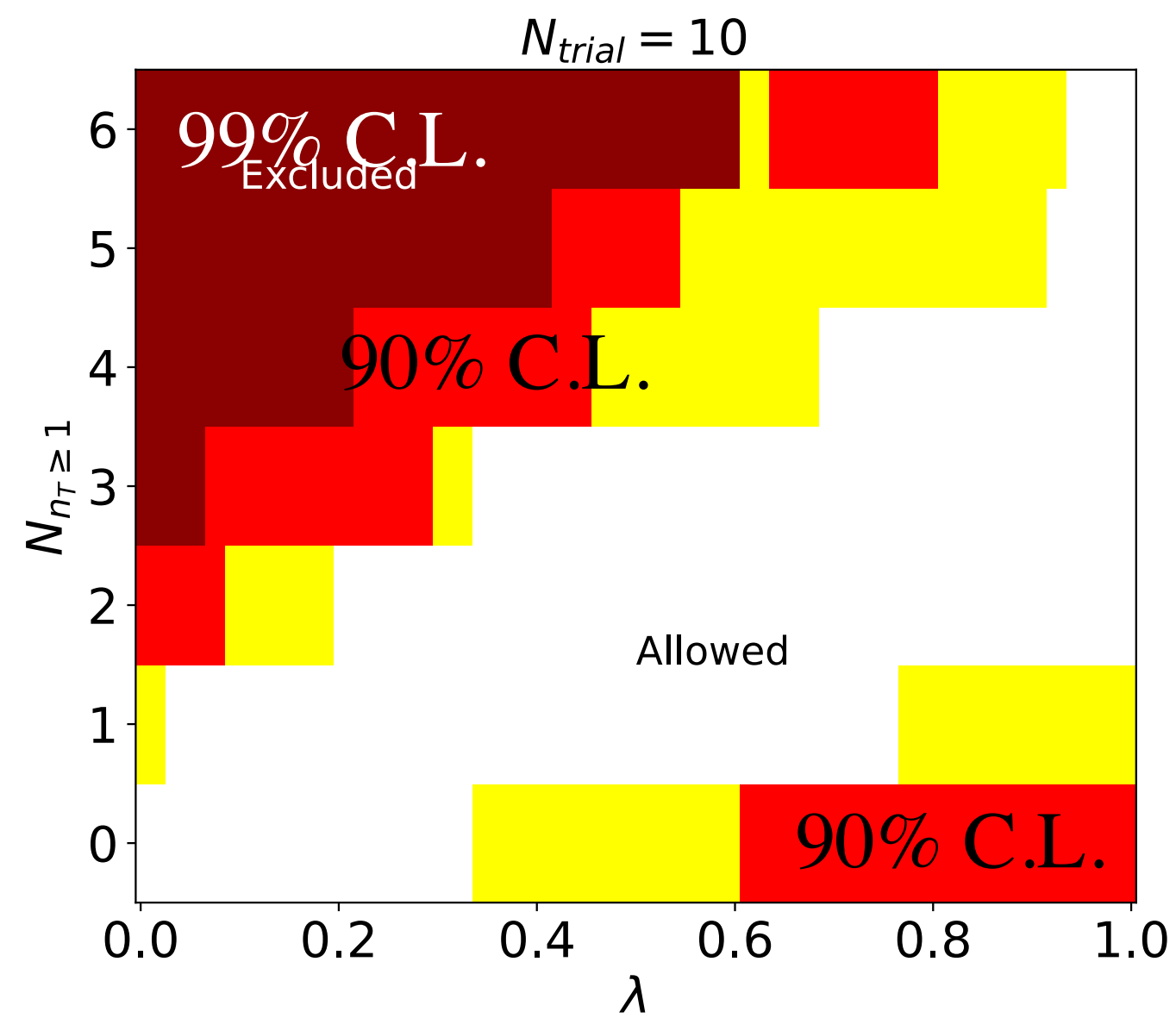
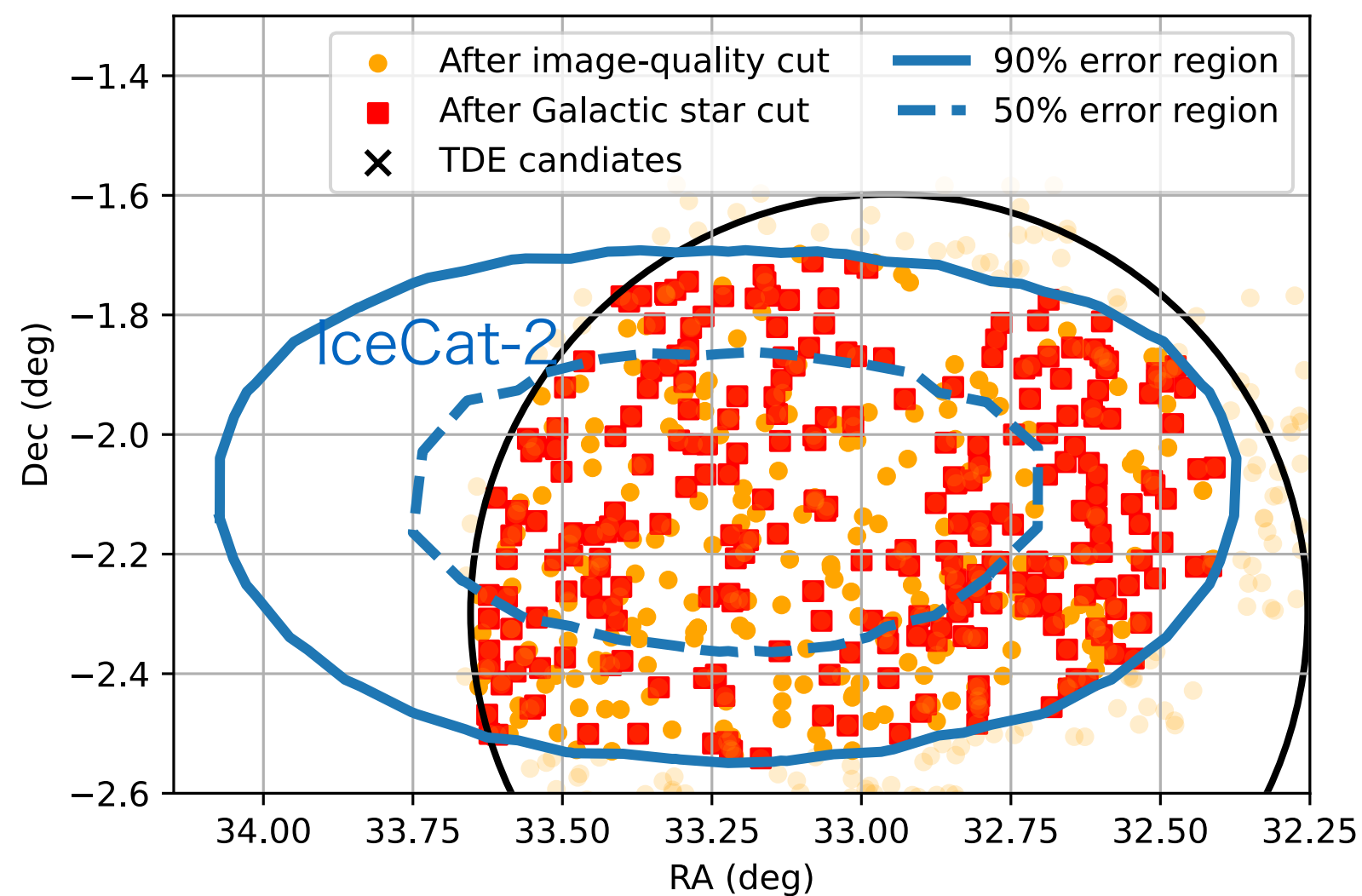
**Single follow-up analysis
can put strong constraints
on physical quantities**

Index

- Introduction
- Follow-up observation to singlet
 - Subaru follow-up to IC 230724A
 - Future prospects with Rubin/LSST
- Follow-up analysis to multiplet event
- **Summary**

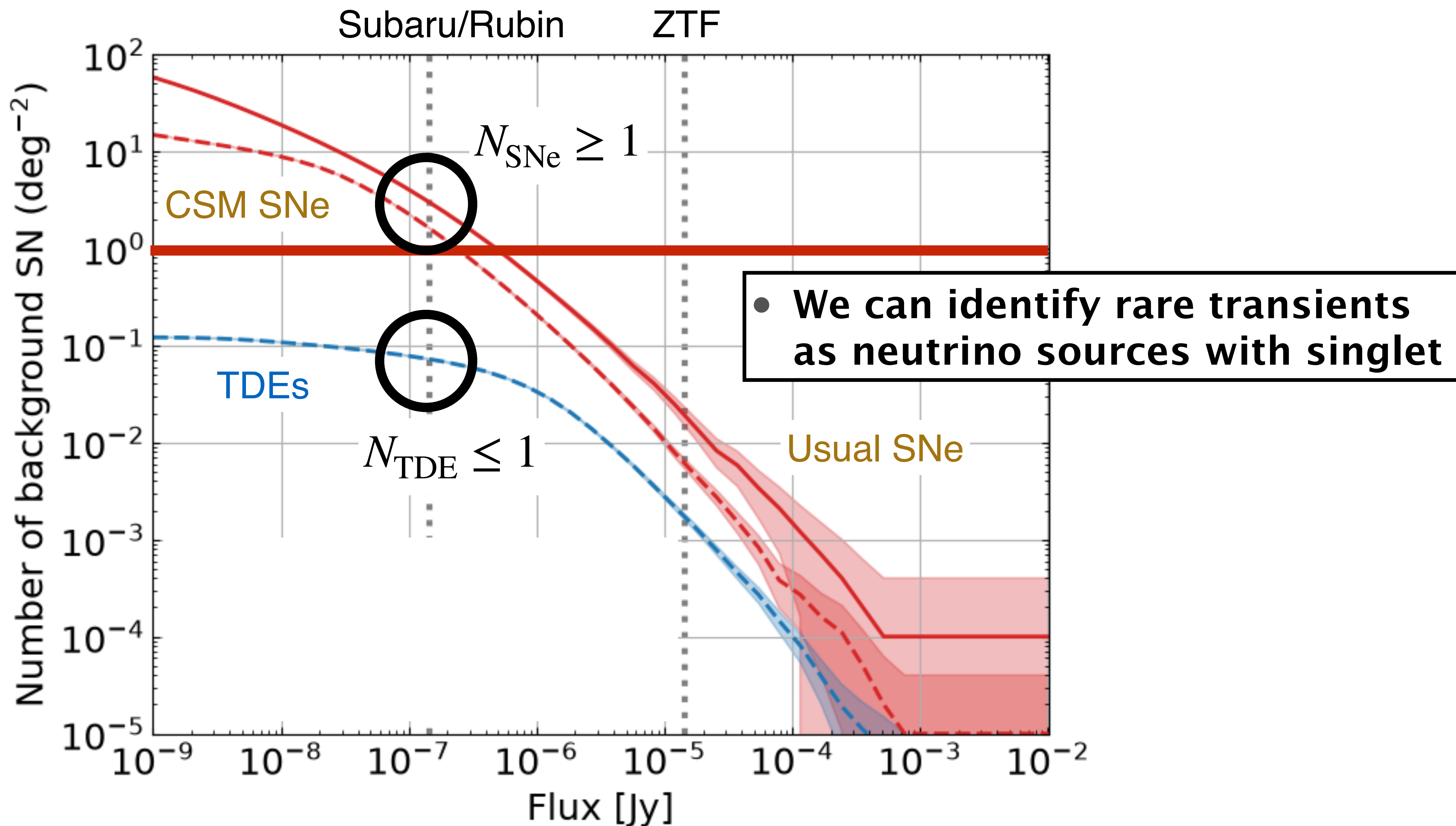
Summary

- Rare transients are easier to identify by optical follow-up to singlet neutrino alerts
=> Let us try to constrain TDE population as neutrino source
- **We developed a blind analysis method** using Subaru follow-up on IC230724A, although we cannot constrain the TDE population
- **Future Rubin/LSST will be able to constrain TDE population with $N_{\text{trial}} = 10$**
- **Multiplet alerts will be able to constrain the optical transients features**



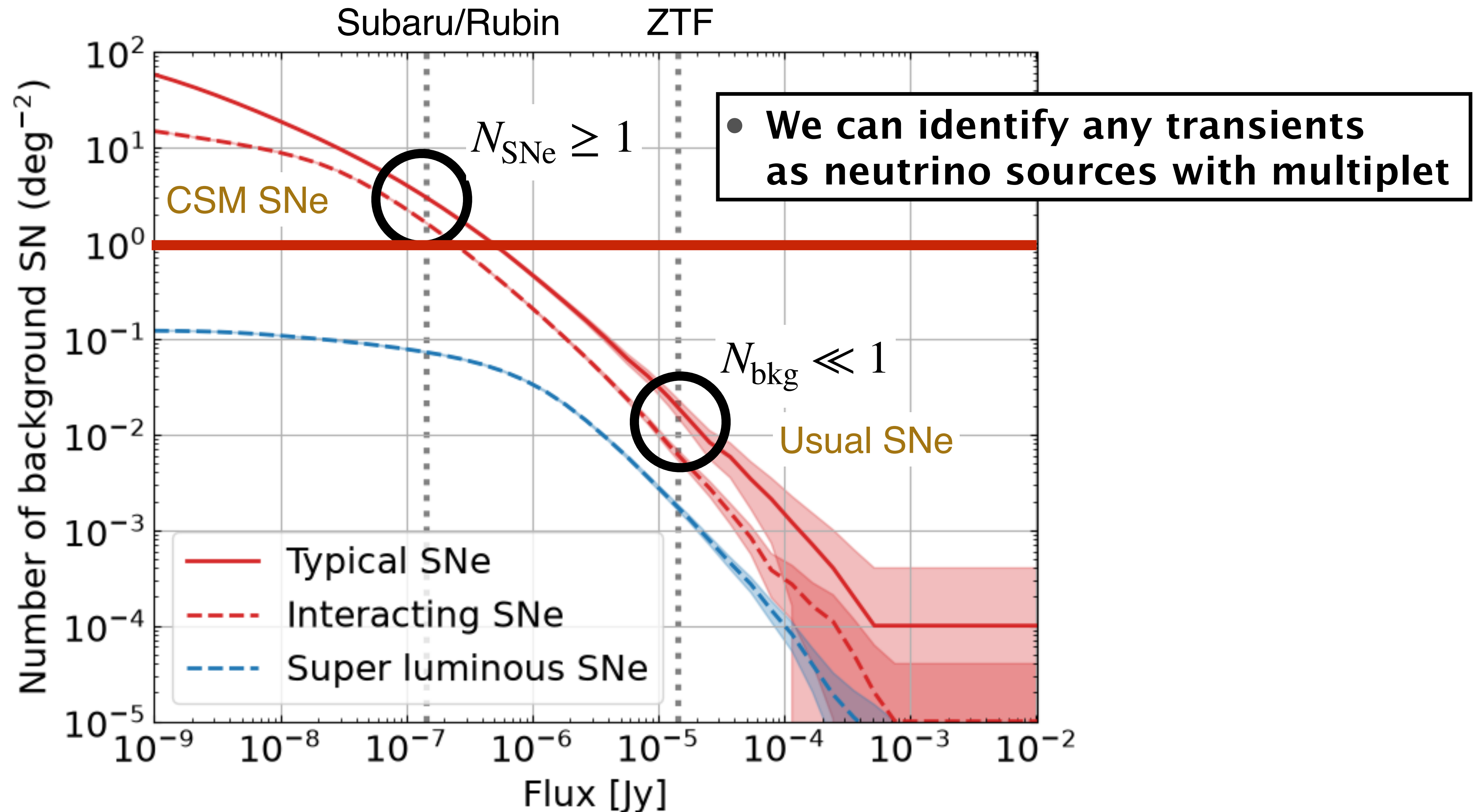
Backup

Targeting rare objects for singlet



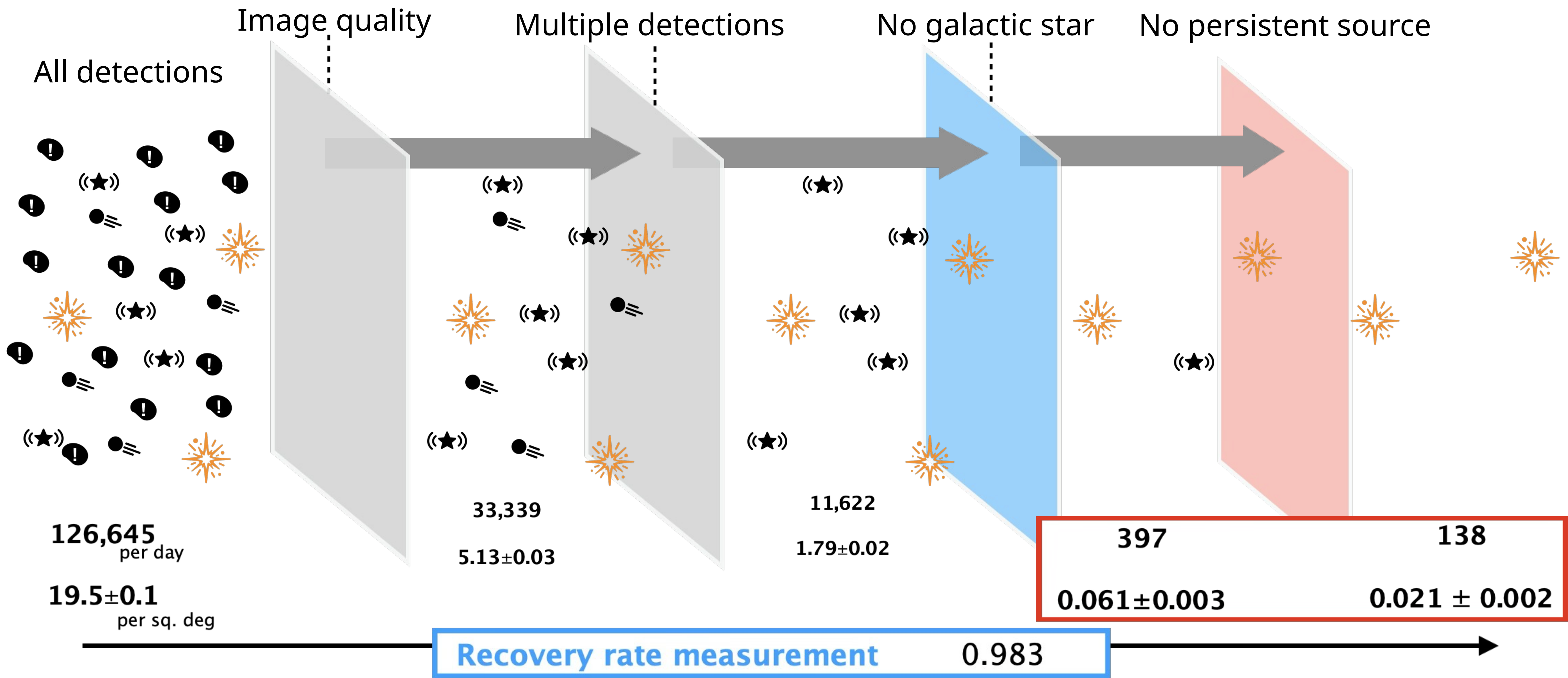
Low background rare with Multiplet

37



Data analysis:

Credit: Seiji Toshikage



Predefined criteria optimized through data-driven measurements