Subaru observations for IC230724A

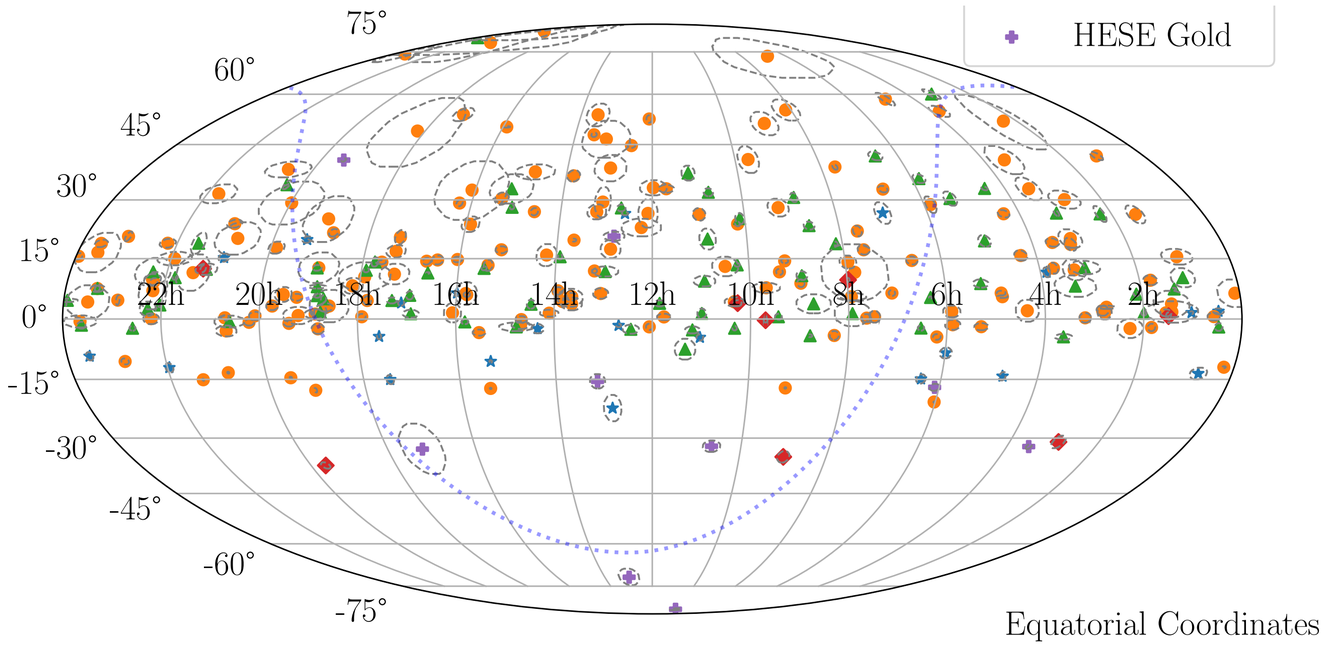
Tohoku University

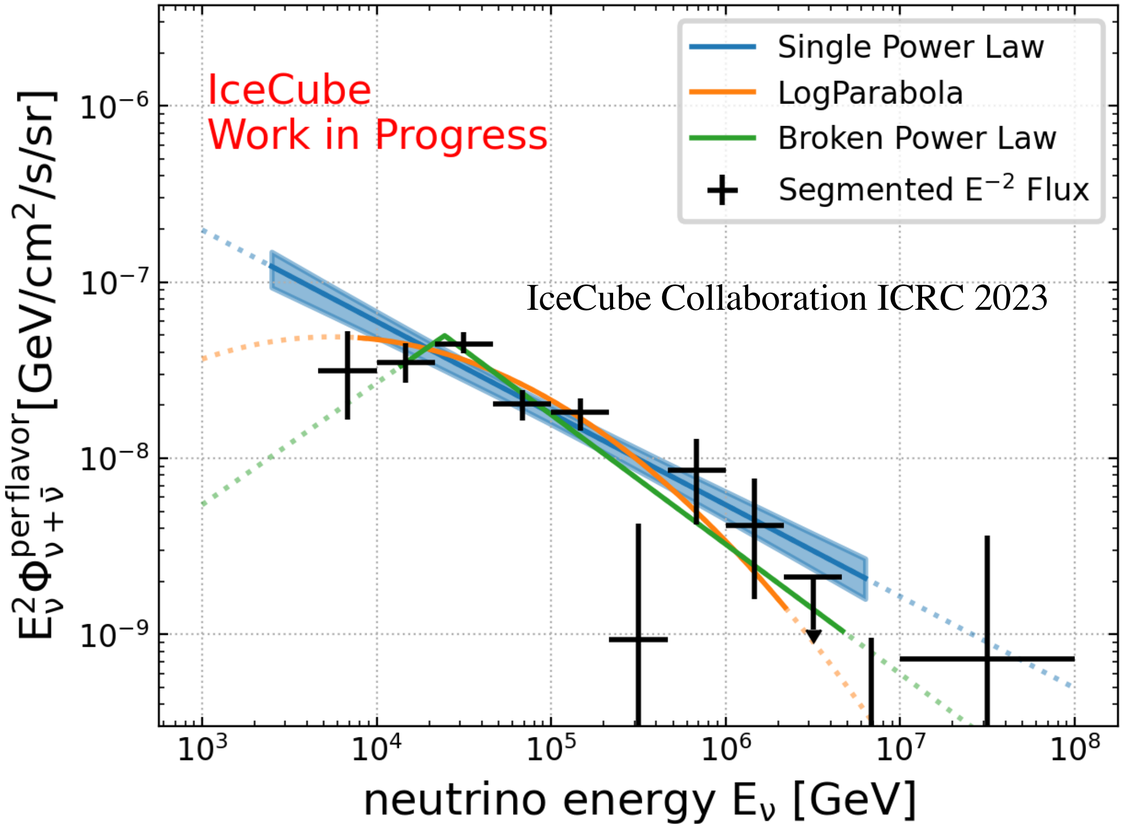
Shigeo S. Kimura

References: SSK, Tanaka M, Toshikage et al. in prep.

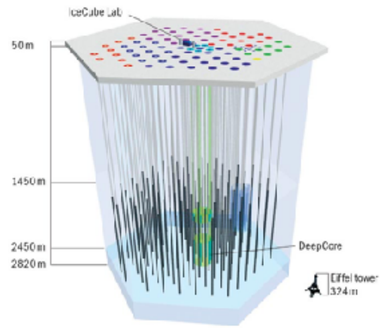
Multi-messenger Annual Conference 2025
2025/11/18 - 2025/11/20

Detection of Cosmic High-energy Neutrinos





- IceCube has been detecting astrophysical neutrinos
- Arrival direction: consistent with isotropic —> cosmic HE neutrino background
- Soft spectrum: F_{E_ν} @ TeV > F_{E_ν} @ PeV
- **Origin of cosmic neutrinos are a new big mystery**

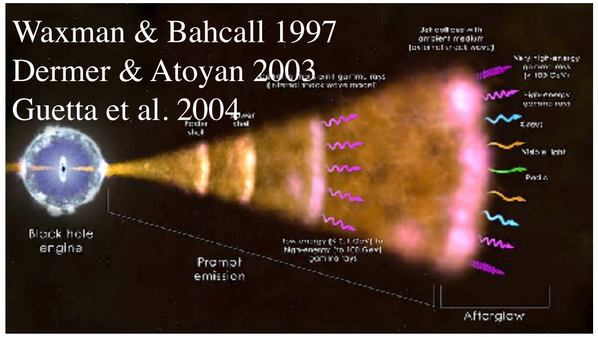


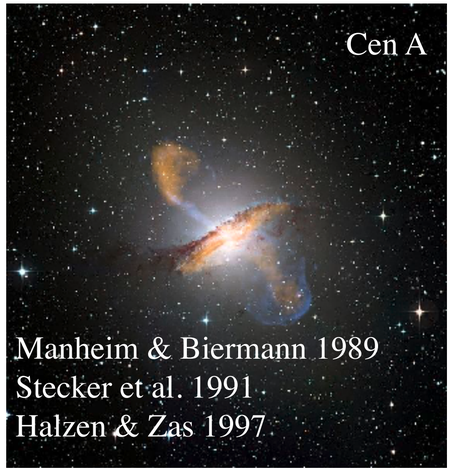
Pre-IceCube Neutrino Models

- **Cosmic-ray accelerators**

mainly pγ channel

- Gamma Ray Bursts (GRBs)





Especially Blazars

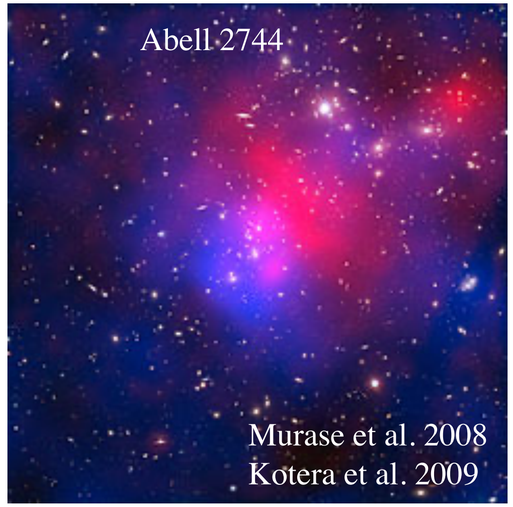
- Active Galactic Nuclei (AGN)

- Cosmic-rays are accelerated in the sources & produce neutrinos inside the sources

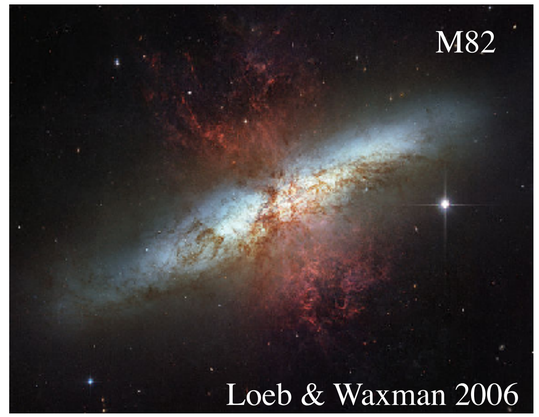
- **Cosmic-ray reservoirs**

mainly pp channel

- Galaxy Groups/Clusters



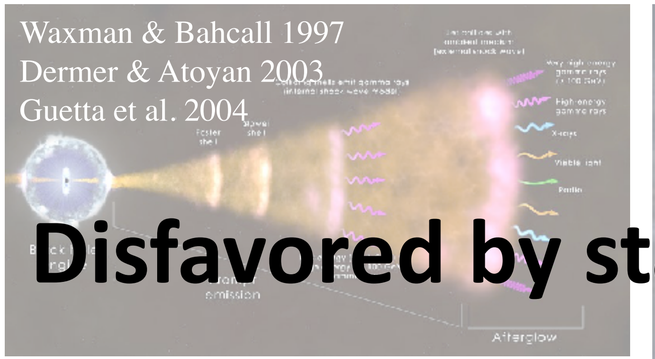
- Star Forming Galaxies (SFG)



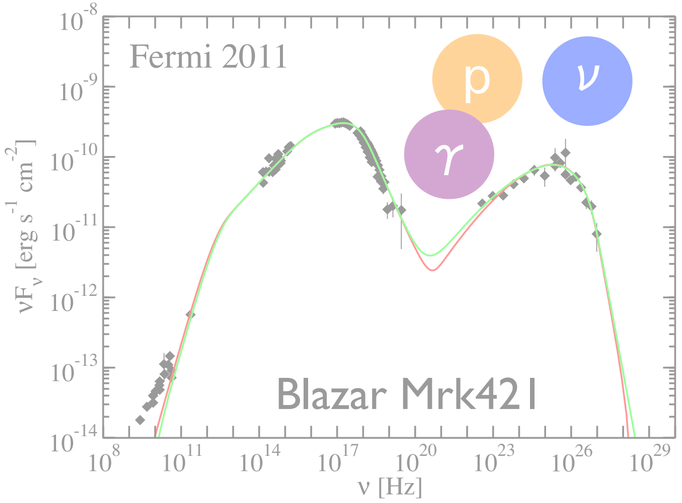
- Cosmic-rays are accelerated at accelerators in the reservoir
- Cosmic-rays are confined in the reservoir and produce neutrinos there

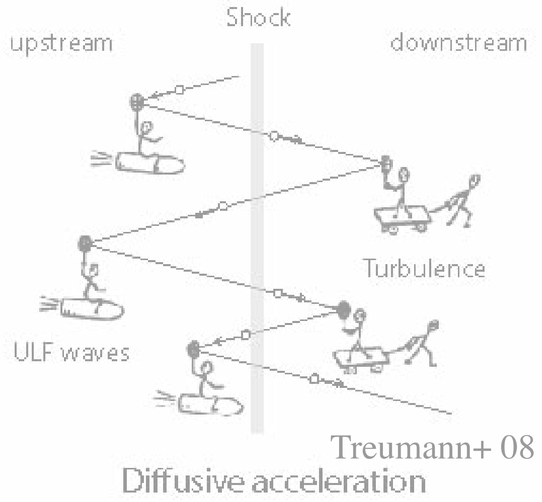
Neutrino Source Candidates in Pre-IceCube Era

- **Cosmic-ray Accelerators** pγ
  - Gamma-ray Bursts
  - Blazars

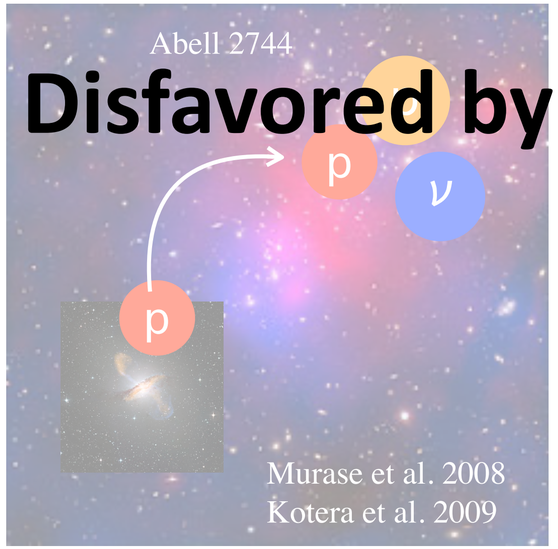


Disfavored by stacking analysis

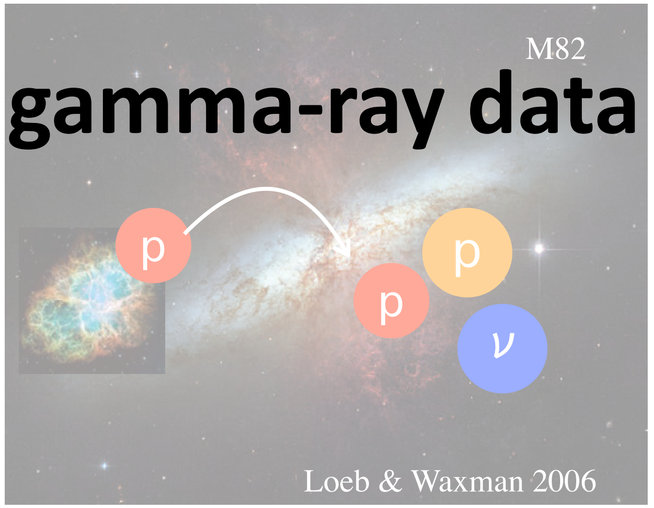




- **Cosmic-ray Reservoirs** pp
  - Galaxy Clusters
  - Starburst Galaxies



Disfavored by gamma-ray data



CRs are escaping from accelerators
→ CRs are confined in reservoirs
→ CRs are producing neutirons via pp channel

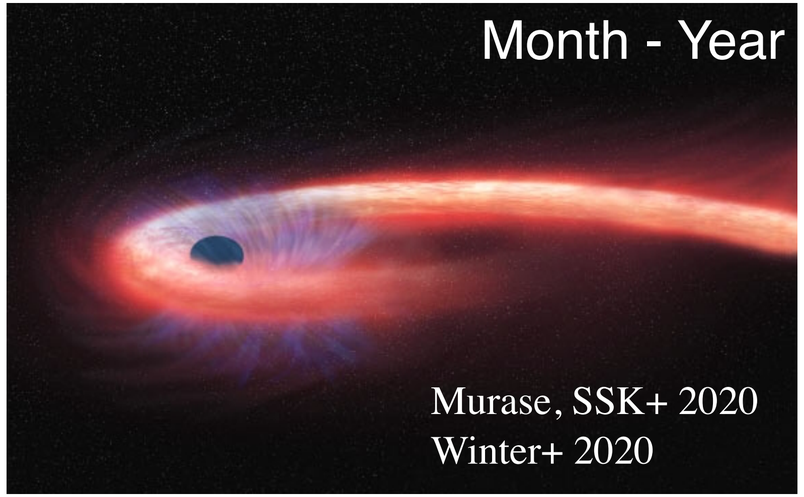
Current Source Candidates

- Seyfert Galaxies (Radio-quiet AGN)

- Strong evidence of neutrino signals from NGC 1068

IceCube 2022

- Tidal Disruption Events (TDEs)



- 2 possible association reported from ZTF team

Stein+ 2021
Reusch+(incl. SSK) 2022

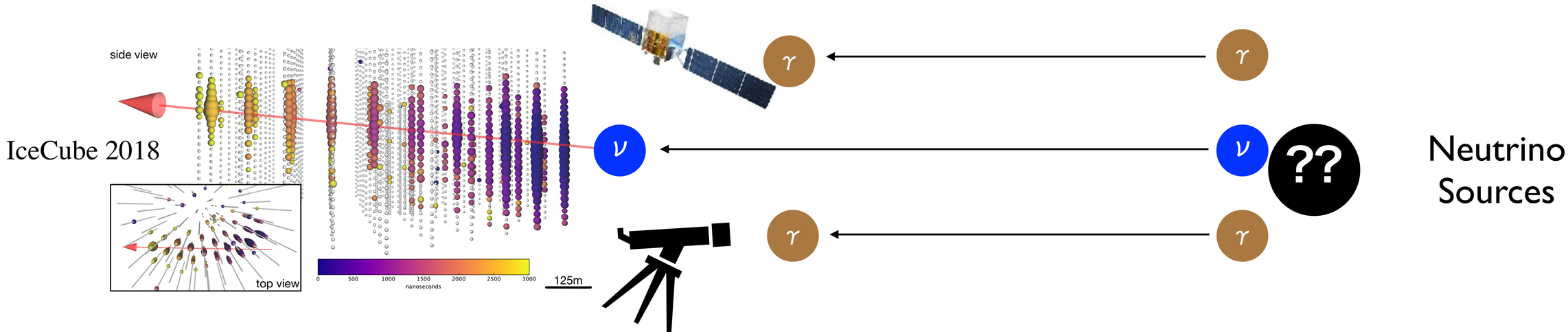
- Peculiar Supernovae (hypernova; super-luminous supernova)

- No observational evidence
- Theory-motivated

How to find neutrino sources?

- Stacking analysis ($\gamma \rightarrow \nu$)
  - Integrated Neutrino data
    + Catalogued sources by EM
    → Identify neutrino sources
  - We can find steady sources
  - Only sensitive to
    the catalogued sources

- Follow-up Observations ($\nu \rightarrow \gamma$)
  - Neutrino Alerts
    + Follow-up observations by EM
    → Identify neutrino sources
  - Only works for transients
  - We will have better EM data

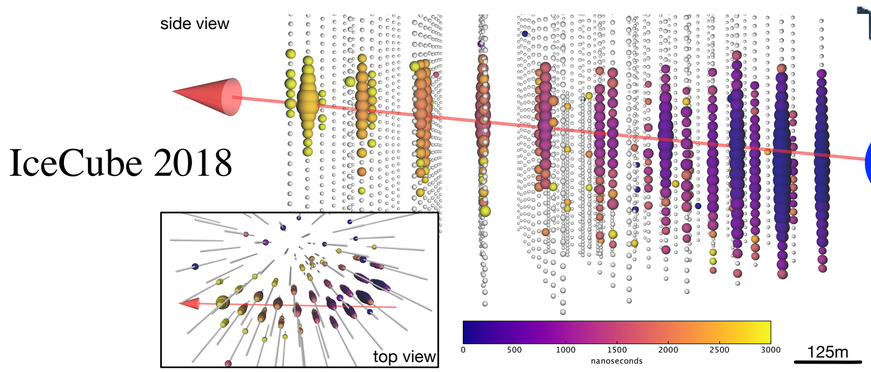


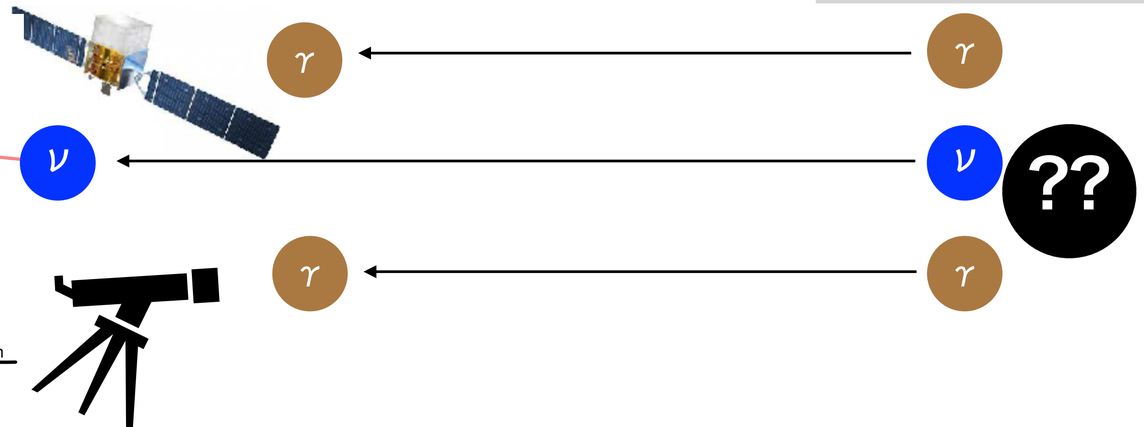
How to find neutrino sources?

- Stacking analysis ($\gamma \rightarrow \nu$)
  - Integrated Neutrino data
    + Catalogued sources by EM
    → Identify neutrino sources

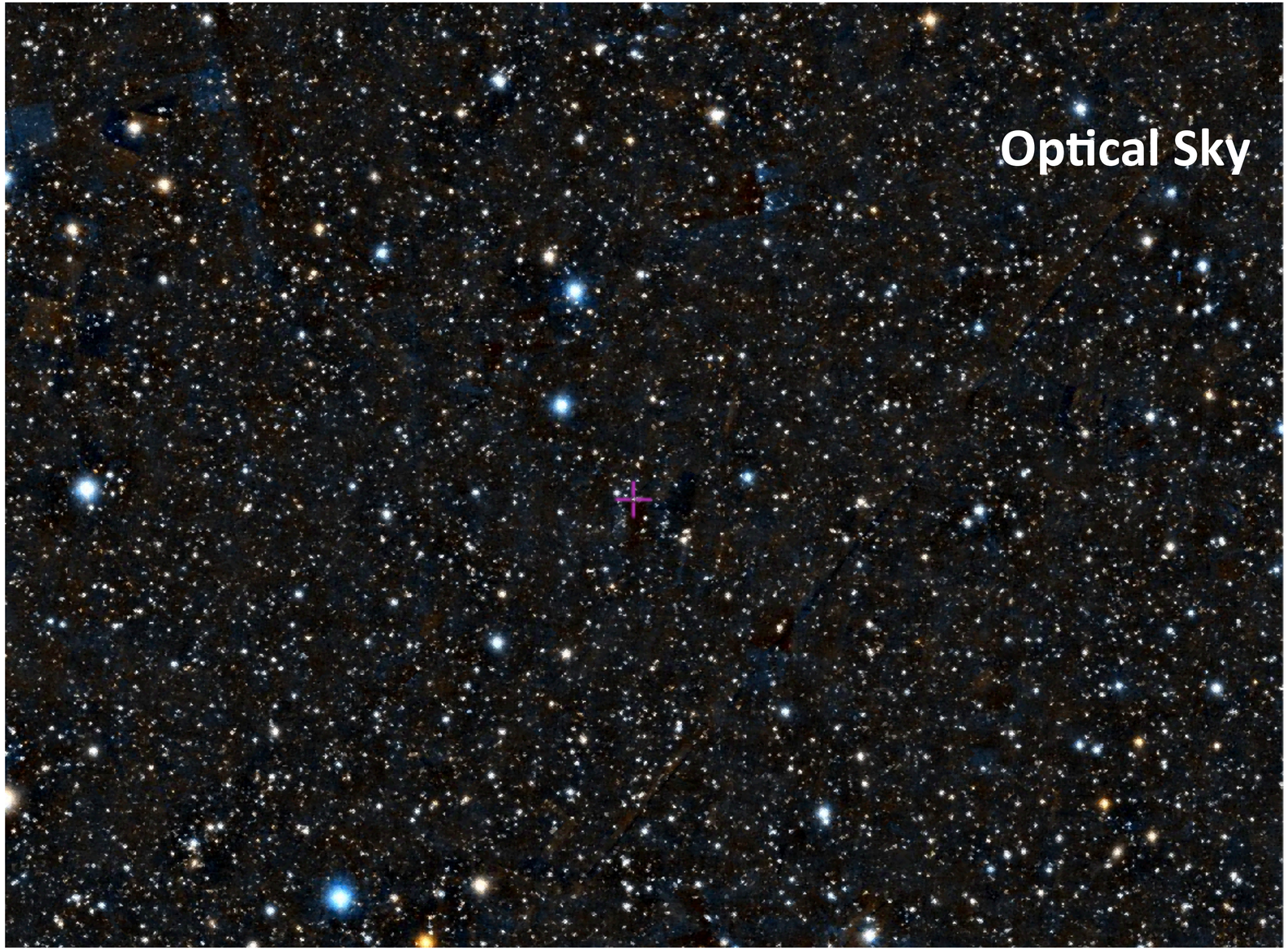
- Follow-up Observations ($\nu \rightarrow \gamma$)
  - Neutrino Alerts
    + Follow-up observations by EM
    → Identify neutrino sources
  - Only works for transients
  - **We will have better EM data**

Neutrino Alert + **Follow-up Observations** → **Neutrino Sourcers**



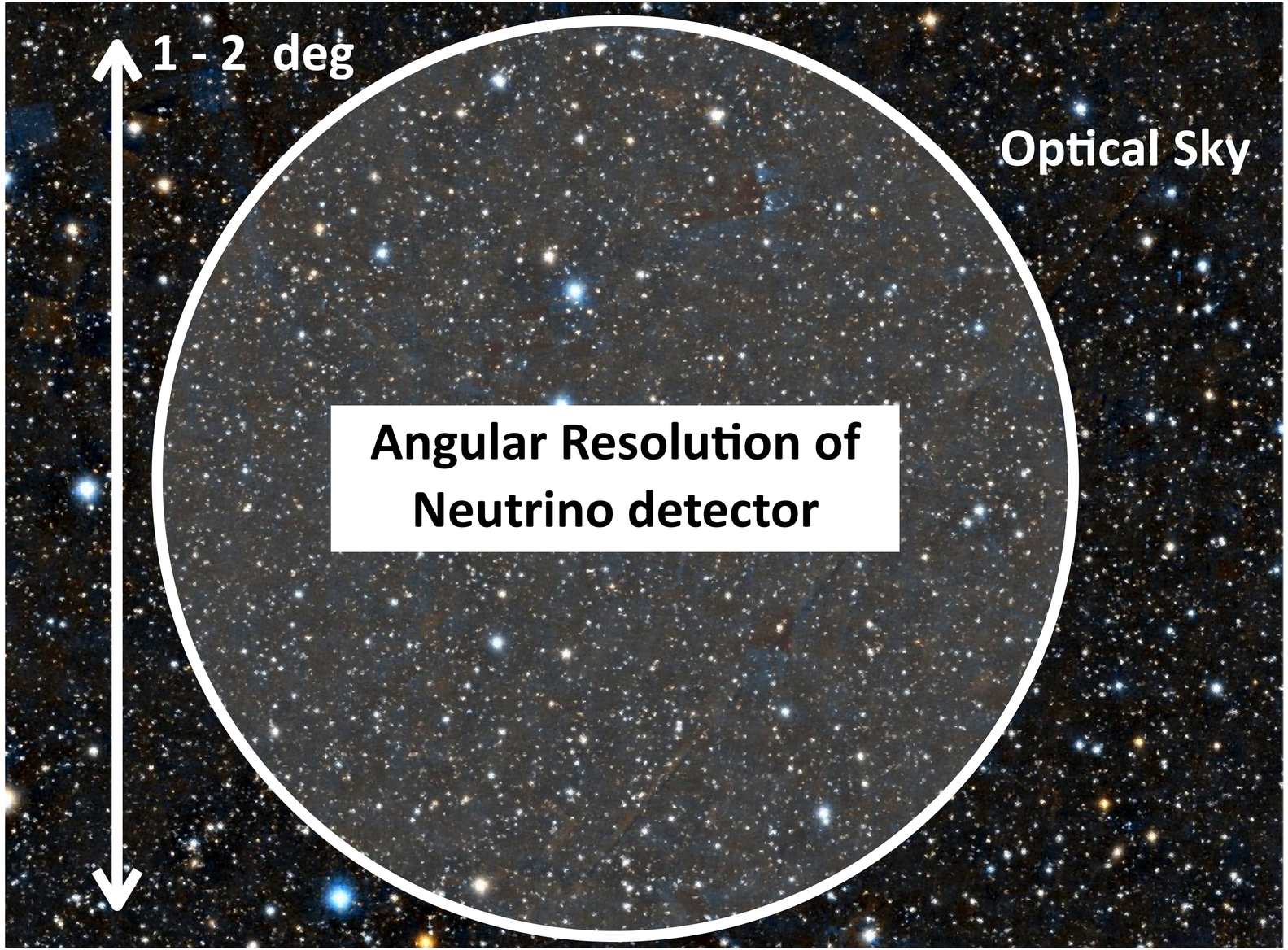


Challenge to identify neutrino sources



- Angular resolution for optical:
  $\sim 0.1 - 1$ sec

Challenge to identify neutrino sources



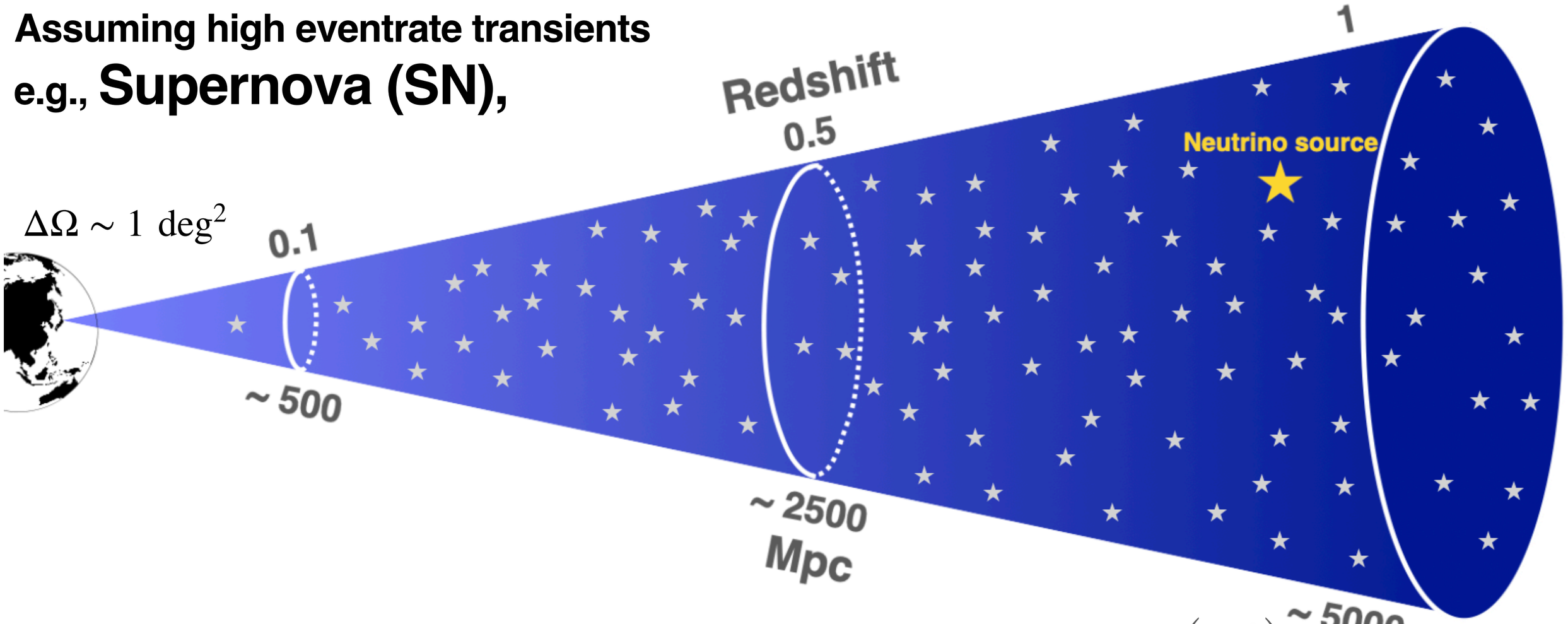
- Angular resolution for optical: $\sim 0.1 - 1$ sec
- Angular Resolution for neutrino: $\sim 0.5 - 3$ deg
- **Number of unrelated transients:** $\gtrsim 100$
- we cannot identify neutrino-emitting object…

Dedicated search strategy is necessary

Single neutrino detection = “Singlet”

Assuming high eventrate transients

e.g., Supernova (SN),

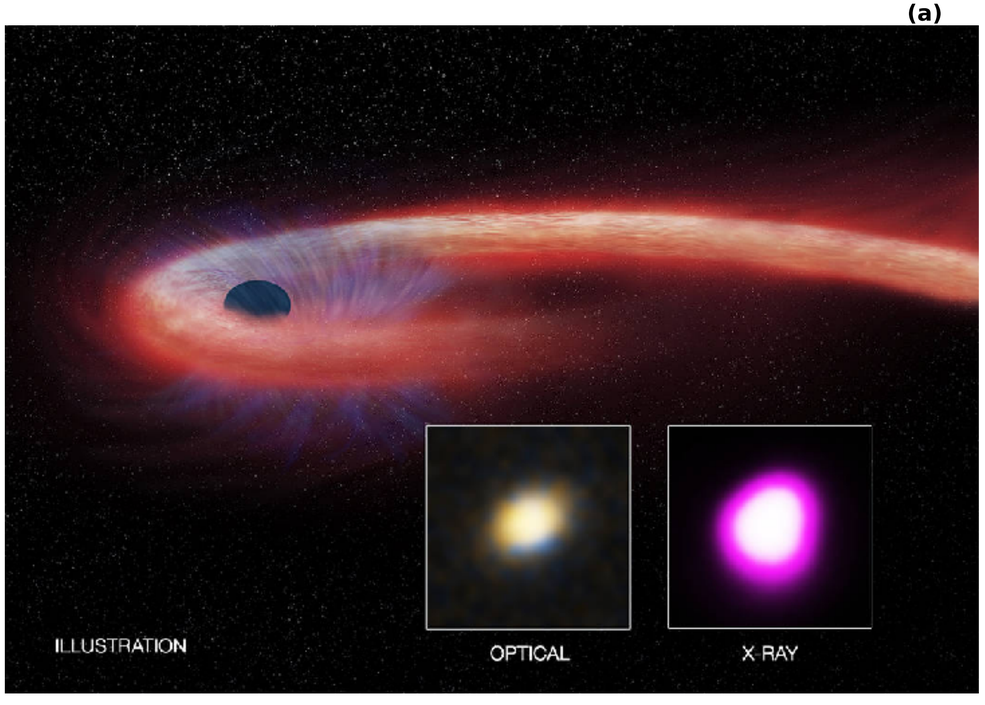


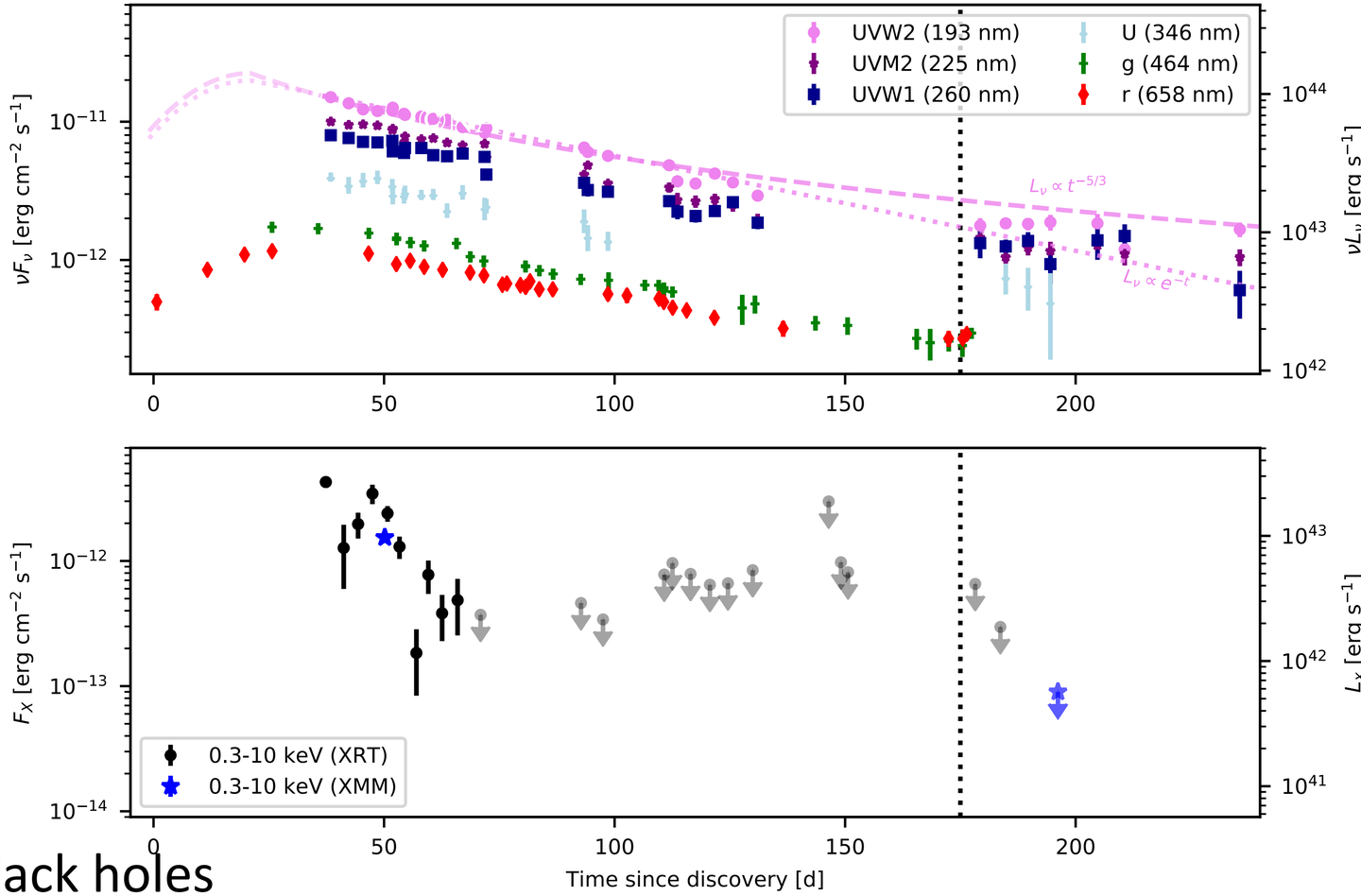
$$N_{\mathrm{SN,unrelated}} \sim 100 \left(\frac{R_{\mathrm{SN}}}{4\times10^{5}\ \mathrm{Gpc^{-3}\ yr^{-1}}}\right)\left(\frac{V}{10^{2}\ \mathrm{Gpc^{3}}}\right)\left(\frac{\Delta t}{30\ \mathrm{day}}\right)\left(\frac{\mathrm{deg}^2}{1}\right)$$

Need to distinguish a neutrino-emitting TDE from 100s of transients/variables

Tidal Disruption Event (TDE)

Stein+ 2021; Reusch+2022



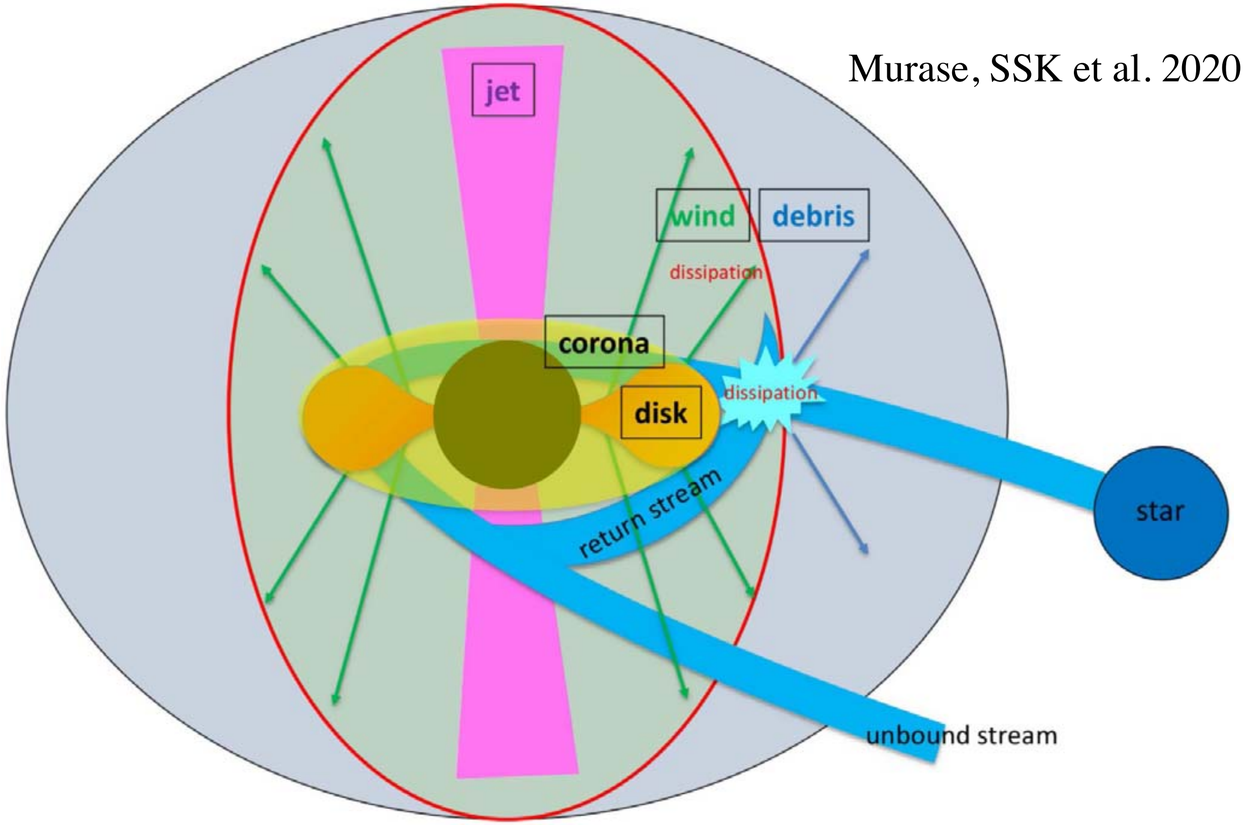


- Stars are torn apart by supermassive black holes
  => luminous ($\sim 10^{43}$ erg/s) & long ($\sim$year) optical transients
- Several TDEs are reported as possible associations with cosmic neutrino events
- All the associations have a neutrino signal $\sim$ 100 days after the optical/X-ray peak

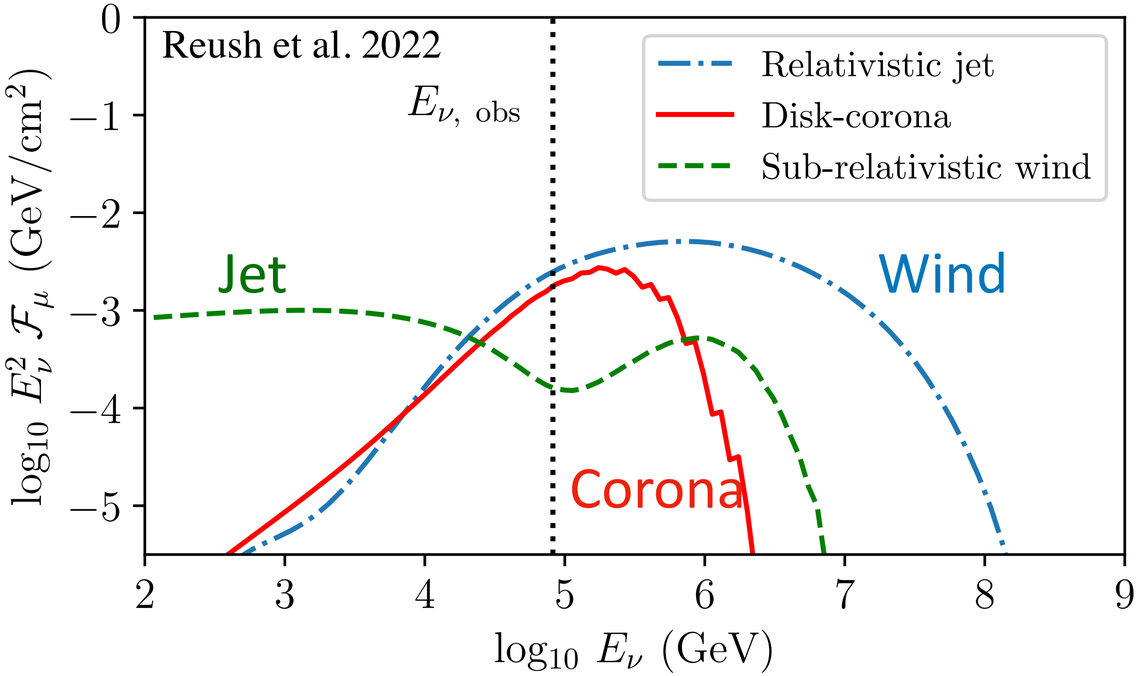
Stein+ 2021; Reusch+2022; van Velezen+2024; Jiang+2024; Yuan+2024; Li+2024

Neutrino emissions from TDEs

e.g., Murase+2020;Winter+2021; Wang+2022; Liu+2021; Zheng+2023;Wu+2024; Mukhopadhyay+2024



Murase, SSK et al. 2020



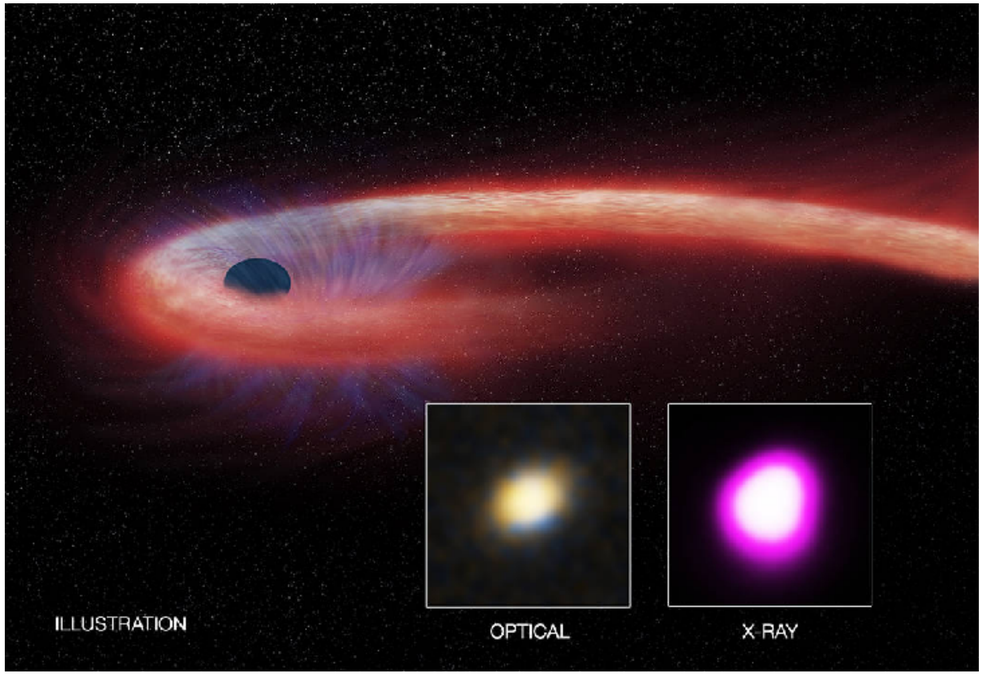
- Several possible sites of neutrino emissions: jets, winds, corona …
- Our best-guess scenario: **accretion disk & corona**

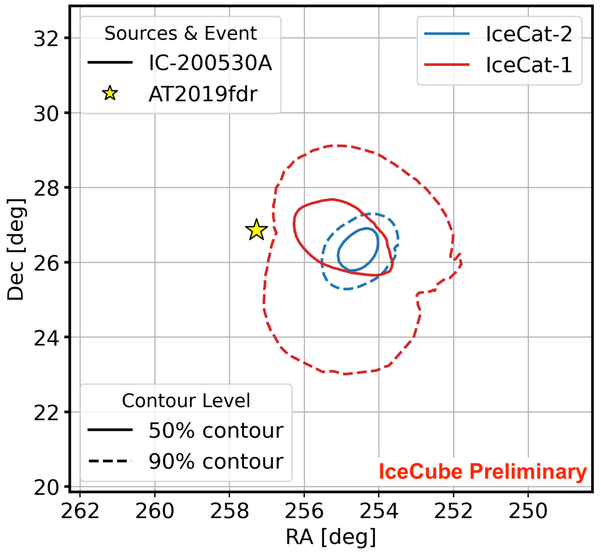
Murase, SSK et al. 2020

- Energetics: > 10% of accretion energy needs to be converted to non-thermal protons
- Many models are proposed => **We need more observations to test scenario**

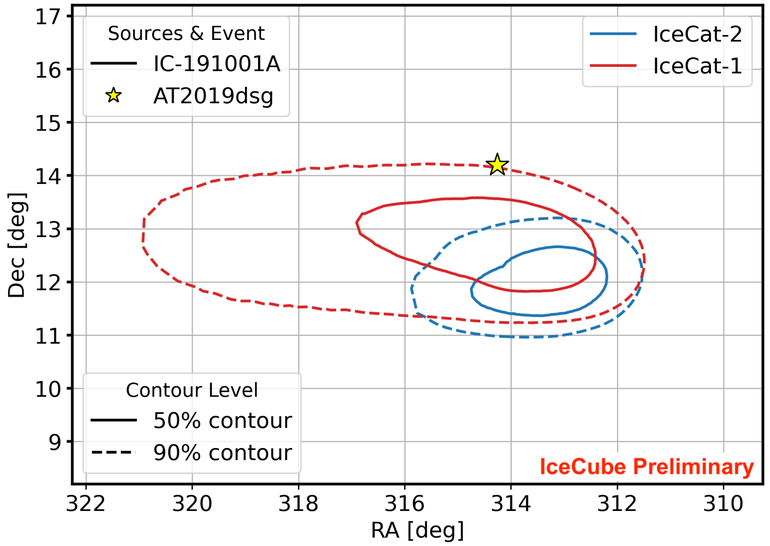
Tidal Disruption Event (TDE)?

Stein+ 2021; Reusch+ (incl. SSK) 2022



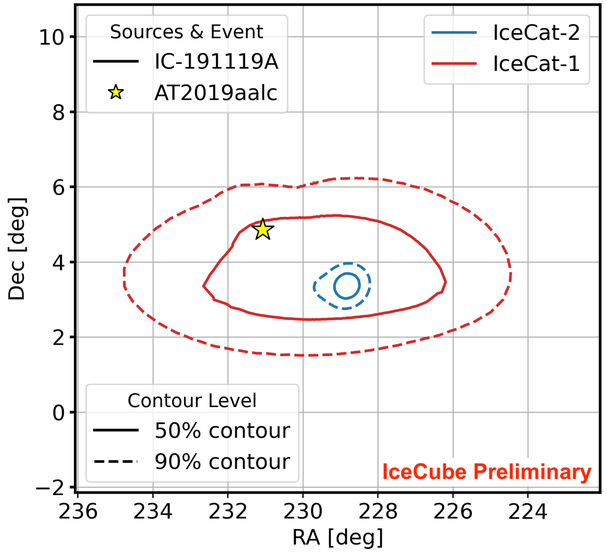


(a) AT2019fdr



(b) AT2019dsg

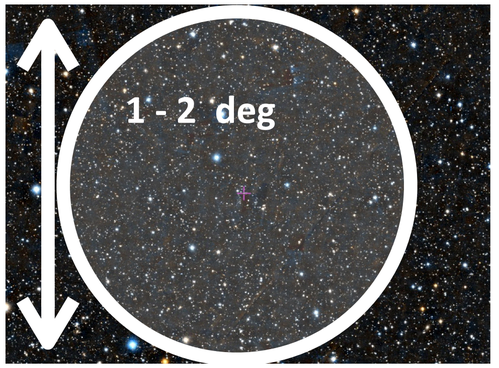
- Using the updated IceCube data,
  TDEs are not within the error regions of IC events
- Needs to examine whether TDEs are emitting
  neutrinos or not with a dedicated search strategy



(c) AT2019aalc

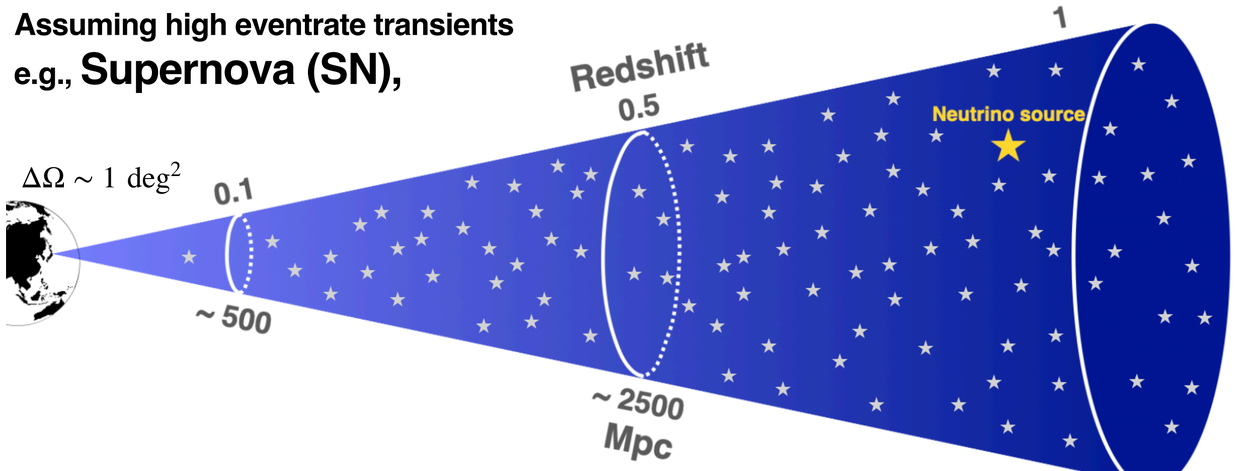
Neutrino Follow-up with Subaru/HSC

- Angular error of neutrino: 1 deg² **==> Wide-field survey (1 deg²)**
- Expected distance: z = 0.5 - 1 ==> **Deep survey (24 - 25 mag)**
- **Only Subaru/ HSC can achieve both criteria**
  => Look for blue & slowly evolving transients using Subaru/HSC
- ToO proposals have been accepted for S23A, S23B, S24A, S25A



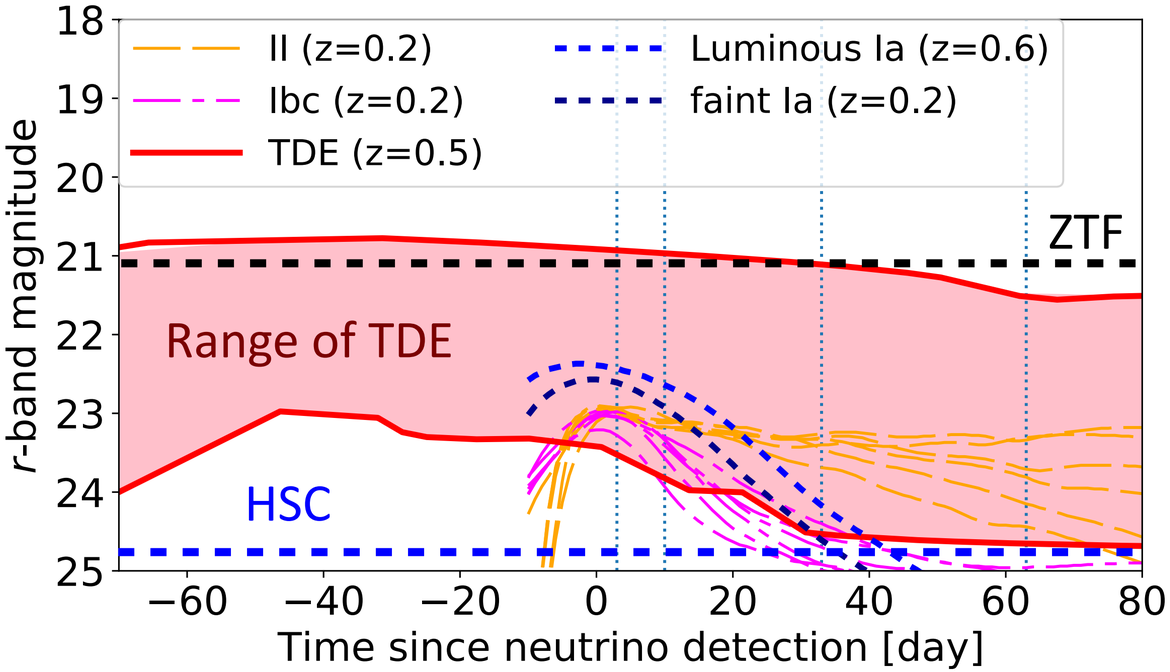
Single neutrino detection = "Singlet"

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



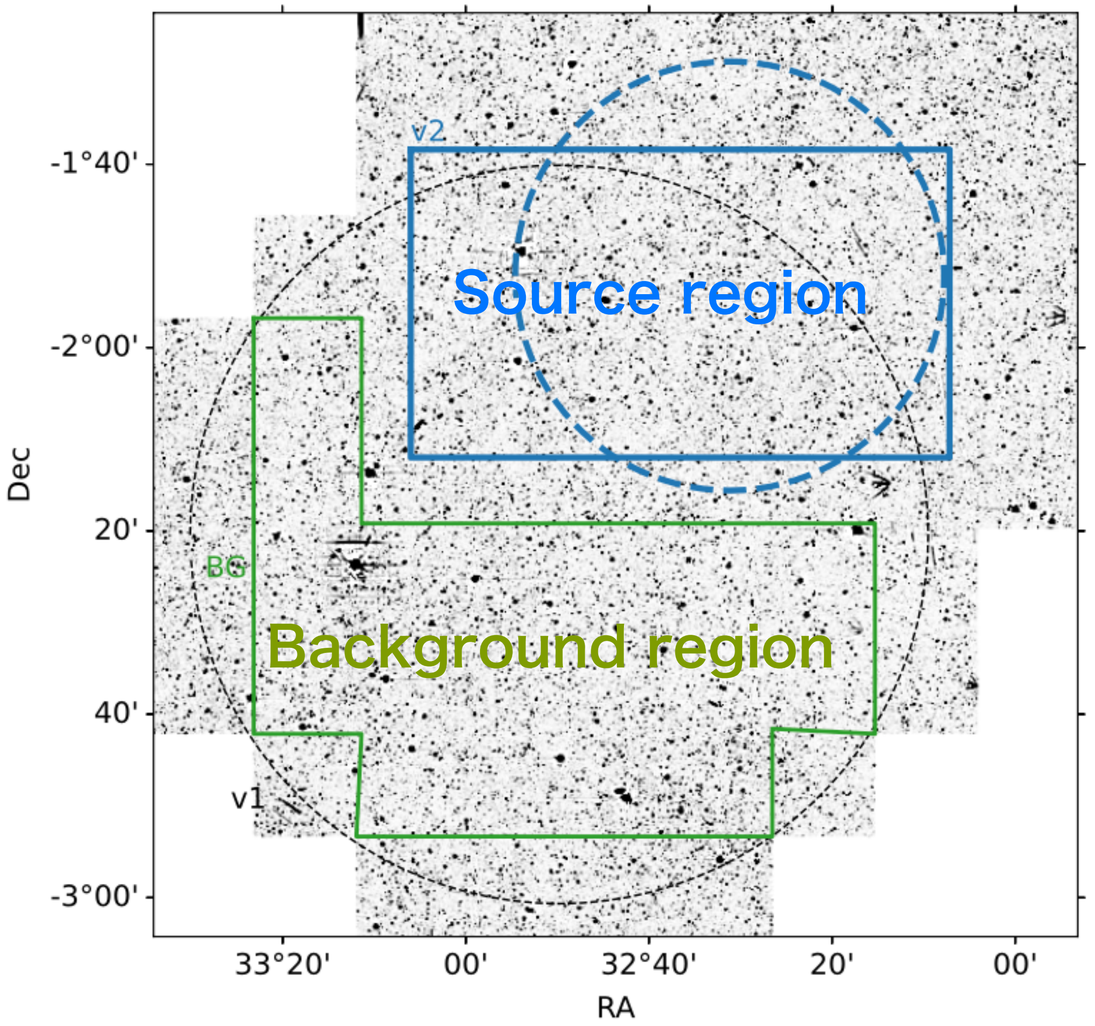
$$N_{\rm SN,unrelated} \sim 100 \left(\frac{R_{\rm SN}}{4\times10^5\ {\rm Gpc^{-3}\ yr^{-1}}}\right)\left(\frac{V}{10^2\ {\rm Gpc^3}}\right)\left(\frac{\Delta t}{30\ {\rm day}}\right)\left(\frac{{\rm deg^2}}{1}\right)$$

Number of unrelated SNe is too large to discuss association



Subaru Follow-up to IC 230724A

- Subaru follow-up on good IceCube Alert
  on 2023/07/24 (Angular Error ~ 0.6 deg)
- ToO observations on 2023/08/10 & 2023/08/23
- **Blind analysis**:
  Actual data in the error region will be analyzed
  after we have completed estimation of
  the background number & True positive rate

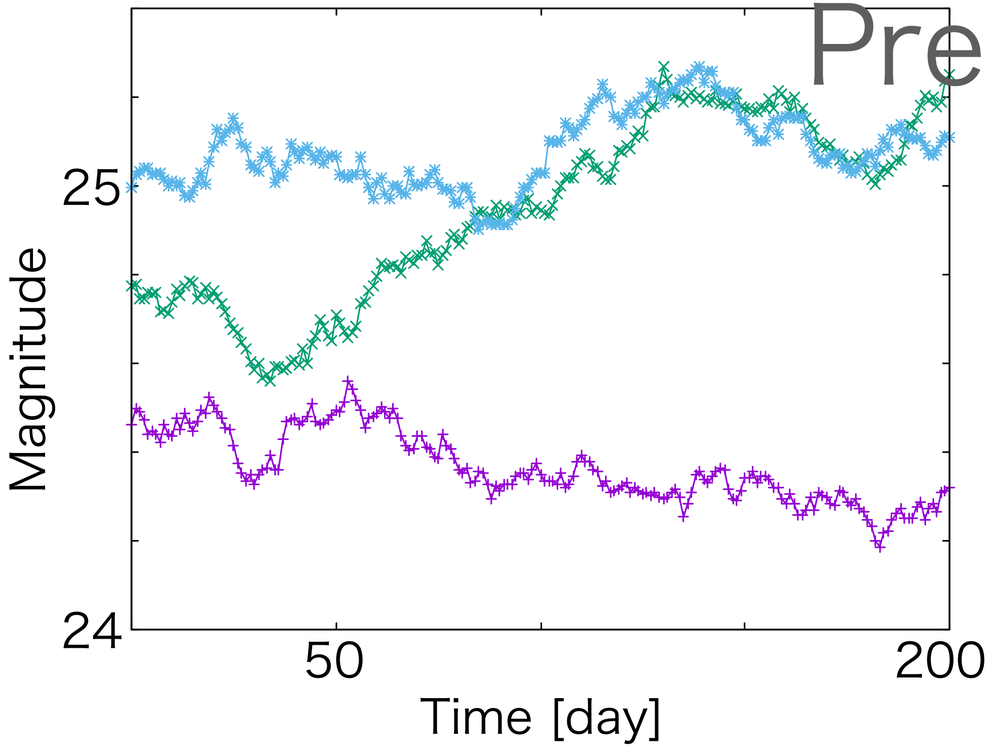


Transient Classification Simulations

- Optical sky includes 200–300 variable objects (supernovae, active galaxies, TDEs)
  => We need to pick up TDE-like optical transient from limited amount of data
  => Optimize the criteria to pick up TDEs using simulations
- We use SNCosmo Package (built-in SNe template) and add TDE & AGN templates

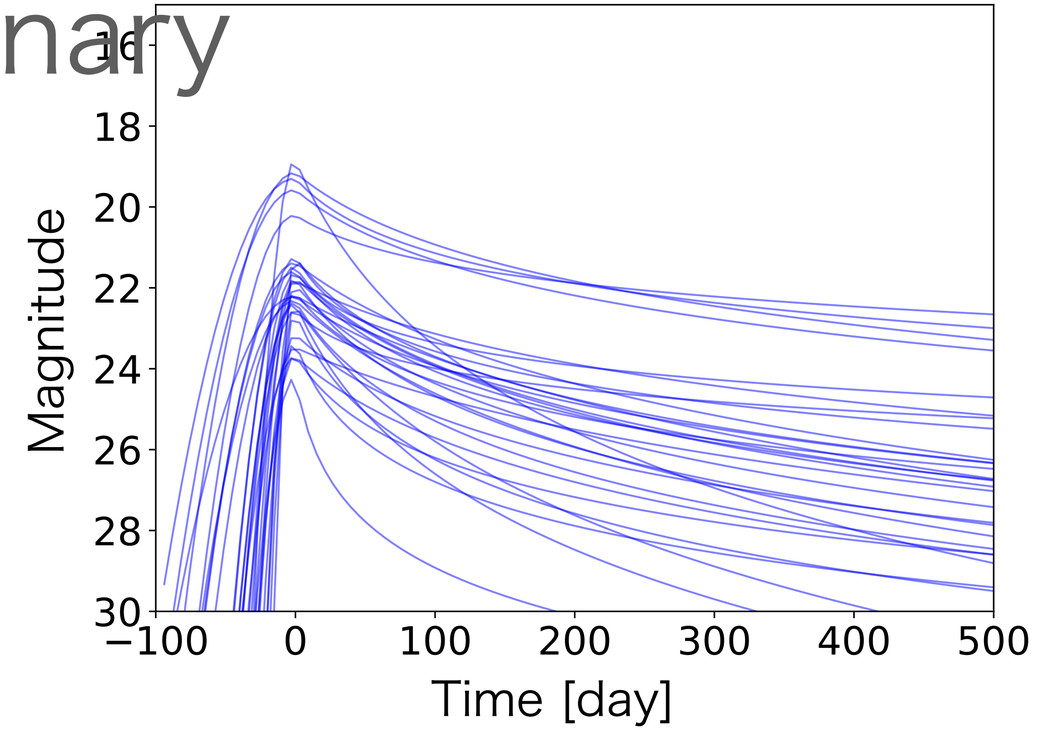
- AGN lightcurve templates

Cf. Y. Kimura et al. 2020



- TDE lightcurve templates

Cf. Hammerstein et al. 2023

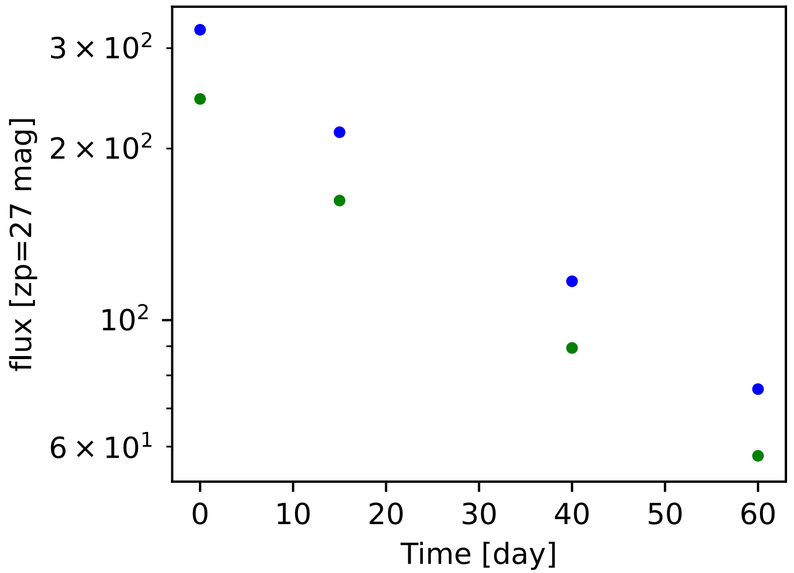


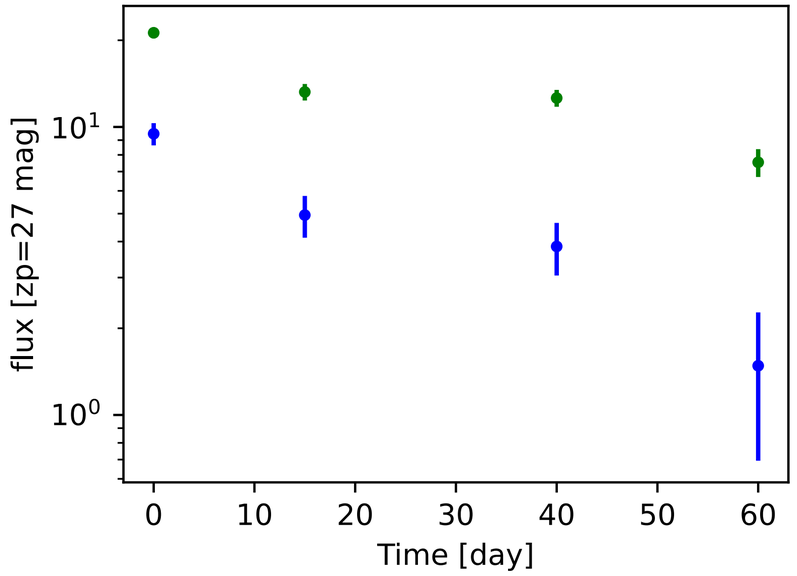
Preliminary

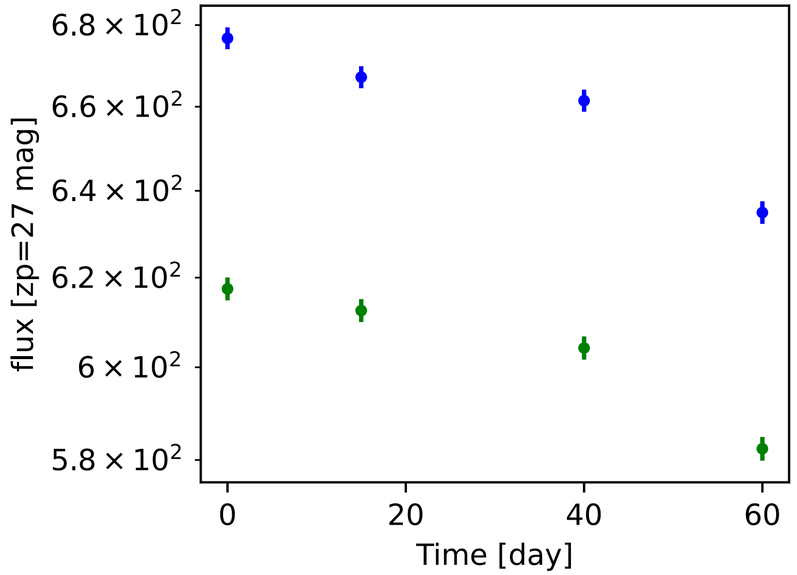
Transient Classification Simulations

SSK et al. in prep.

- Optical sky includes 200-300 variable objects (supernovae, active galaxies, TDEs)
  => We need to pick up TDE-like optical transient from limited amount of data
  => Optimize the criteria to pick up TDEs using simulations
- We use SNCosmo Package (built-in SNe template) and add TDE & AGN templates



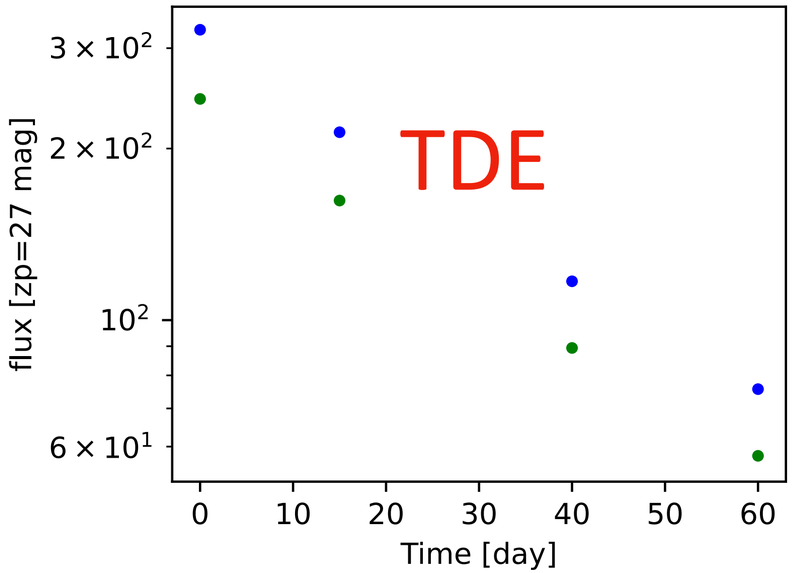


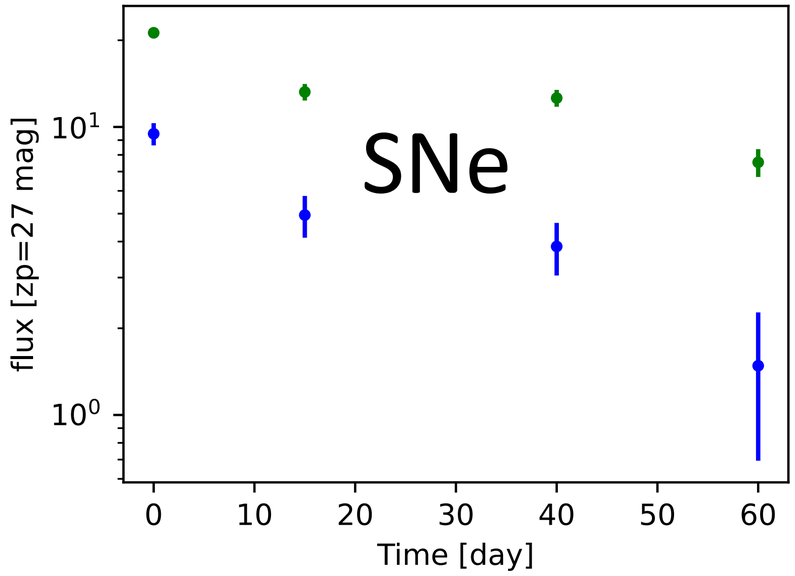


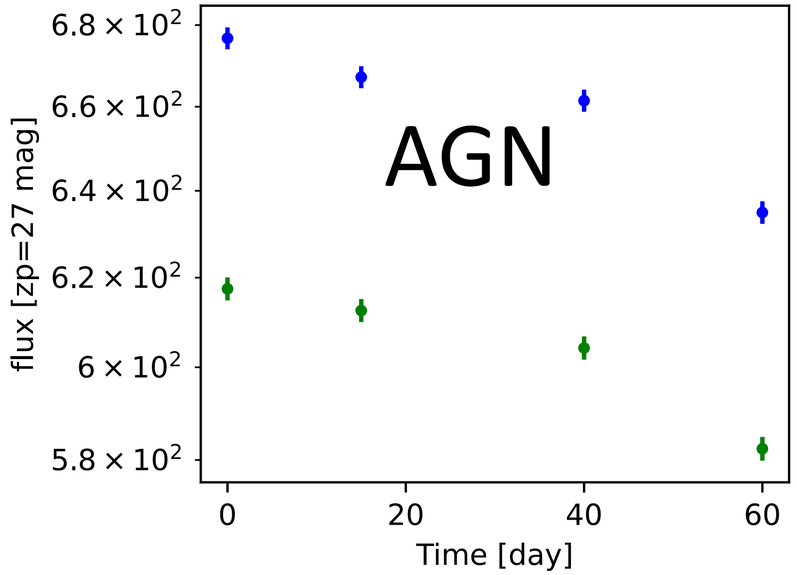
Transient Classification Simulations

SSK et al. in prep.

- Optical sky includes 200-300 variable objects (supernovae, active galaxies, TDEs)
  => We need to pick up TDE-like optical transient from limited amount of data
  => Optimize the criteria to pick up TDEs using simulations
- We use SNCosmo Package (built-in SNe template) and add TDE & AGN templates



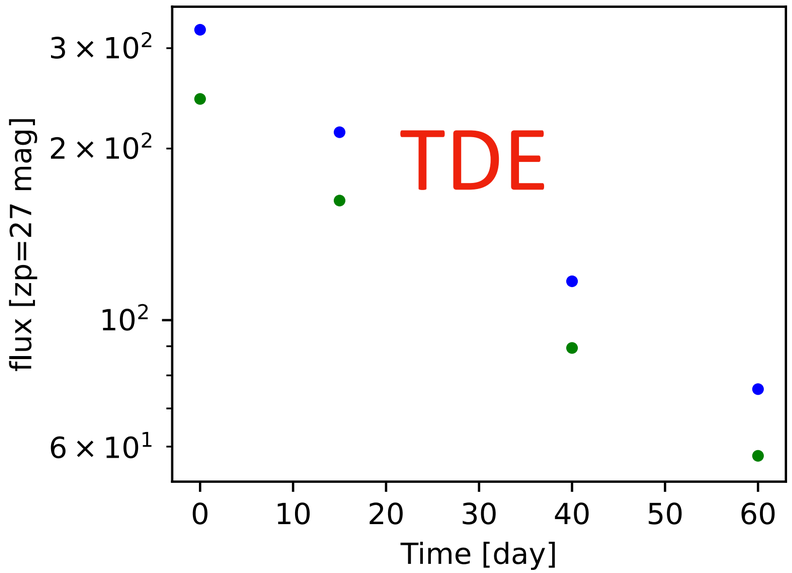


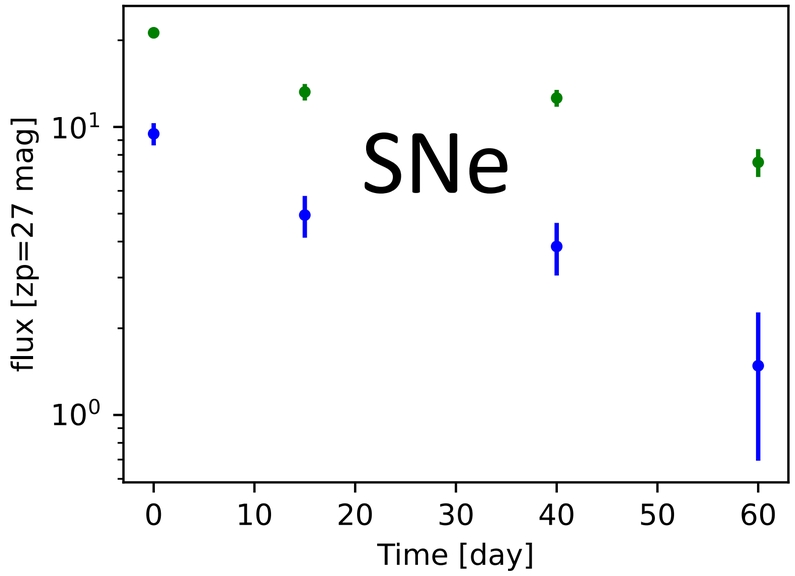


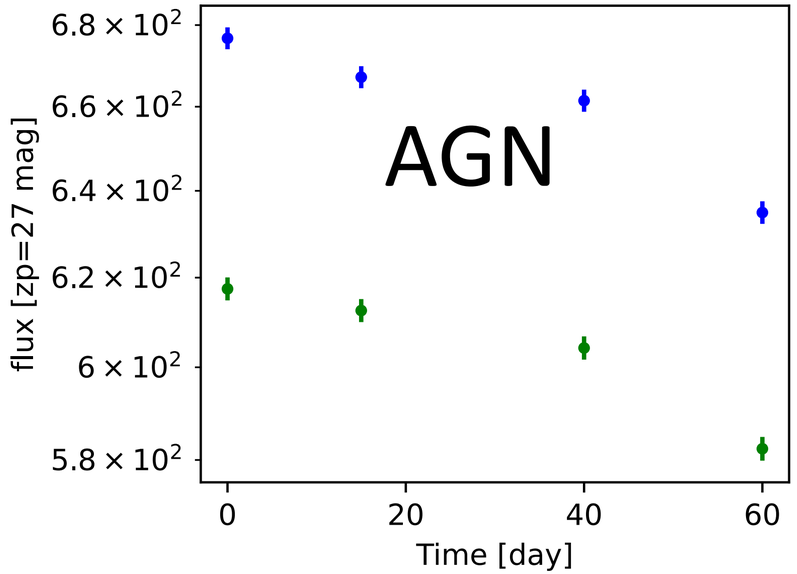
Transient Classification Simulations

SSK et al. in prep.

- Optical sky includes 200-300 variable objects (supernovae, active galaxies, TDEs)
  => We need to pick up TDE-like optical transient from limited amount of data
  => Optimize the criteria to pick up TDEs using simulations
- We use SNCosmo Package (built-in SNe template) and add TDE & AGN templates



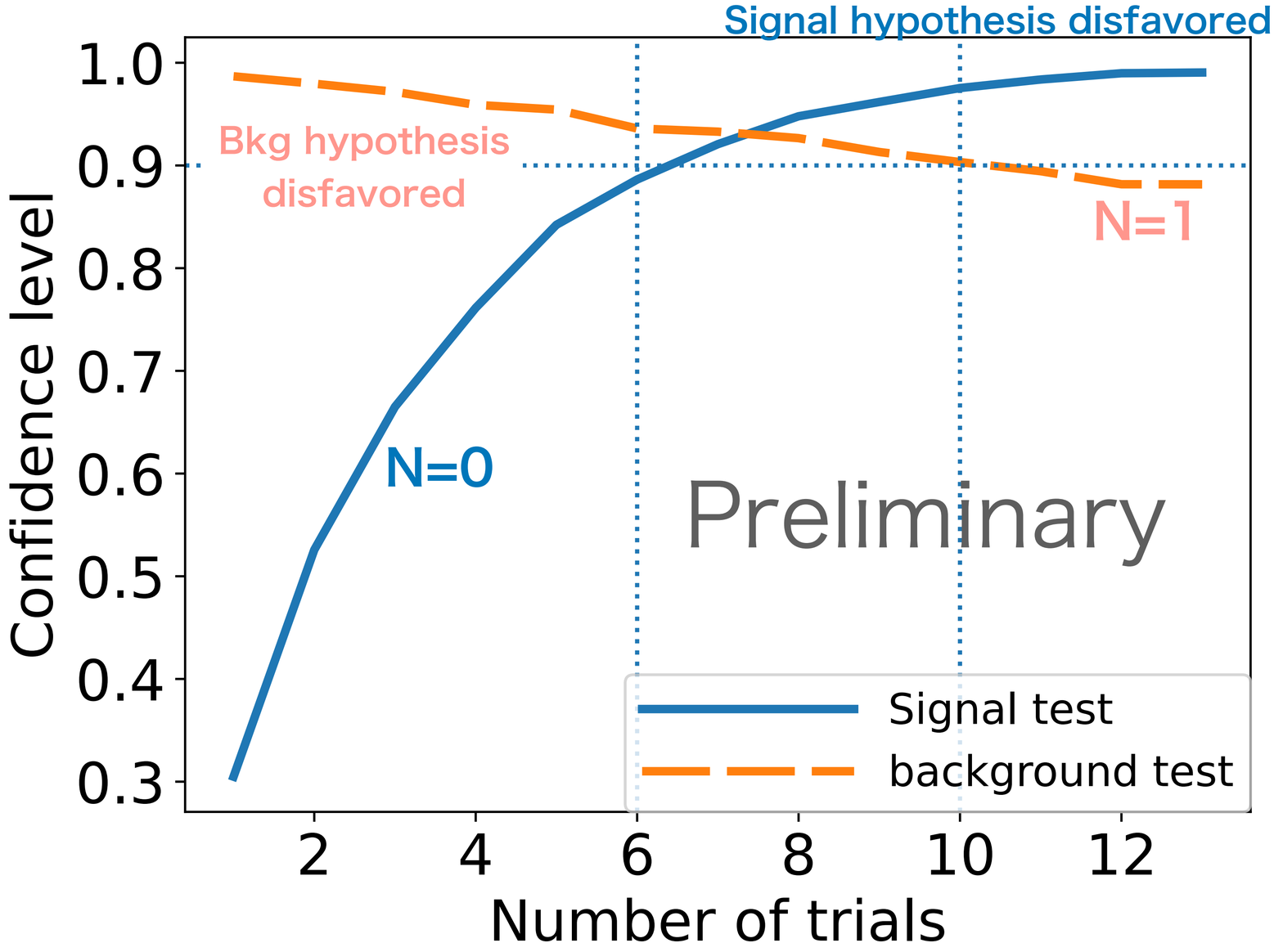




Transient type	TDE (signal)	SN (noise)	AGN (noise)	TDE (noise)
Number of transients	1	270	130	0.2
After classifications	0.2	0	0	0

Prospects with Rubin/LSST

- Rubin/LSST will provide excellent photometric data sets
- Simulations with Rubin/LSST-like photometric data set
- We can achieve
  TPR ~ 0.3, $N_{\mathrm{bkg}} \sim 0.01$
- 1 follow-up cannot say anything
- **We can constrain or support TDE scenario with $N_{\mathrm{trial}} \sim 7-9$**



Summary

- **Cosmic neutrinos are the smoking gun signature to identify cosmic-ray sources**
- Pre-IceCube models are strongly disfavored by current IceCube data
- Follow-up observations to neutrino alerts will be able to identify neutrino sources
- Current our strategy: Search for TDEs using wide & deep survey
  => We have developed a simulation tool which enables us to distinguish TDEs from SNe/AGN
- Single follow-up observations cannot put a meaningful constraint,
  multiple trials with Rubin will enable us to find/rule out TDEs as neutrino sources

Thank you for your attention