宇宙ニュートリノ追観測による電磁波対応天体探索

Tohoku University

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References:
- SSK, Tanaka M, Toshikage et al. in prep.
- Toshikage, SSK, Tanaka M et al. 2025 (arXiv:250.404741)

Exploring Extreme Transient 2025
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2025/08/05 - 2025/08/08

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Outline

- Introduction to High-energy Neutrino Astrophysics
- Optical Follow-up Observations to IC230724A

  - SSK, Tanaka M, Toshikage et al. in prep.
- Follow-up analysis of ZTF data for IceCube multiplet events

  - Toshikage, SSK, Tanaka M et al. 2025 (arXiv:250.404741)
- Summary & Discussion

High-energy Neutrino Astrophysics

Cosmic-ray production at distant sources

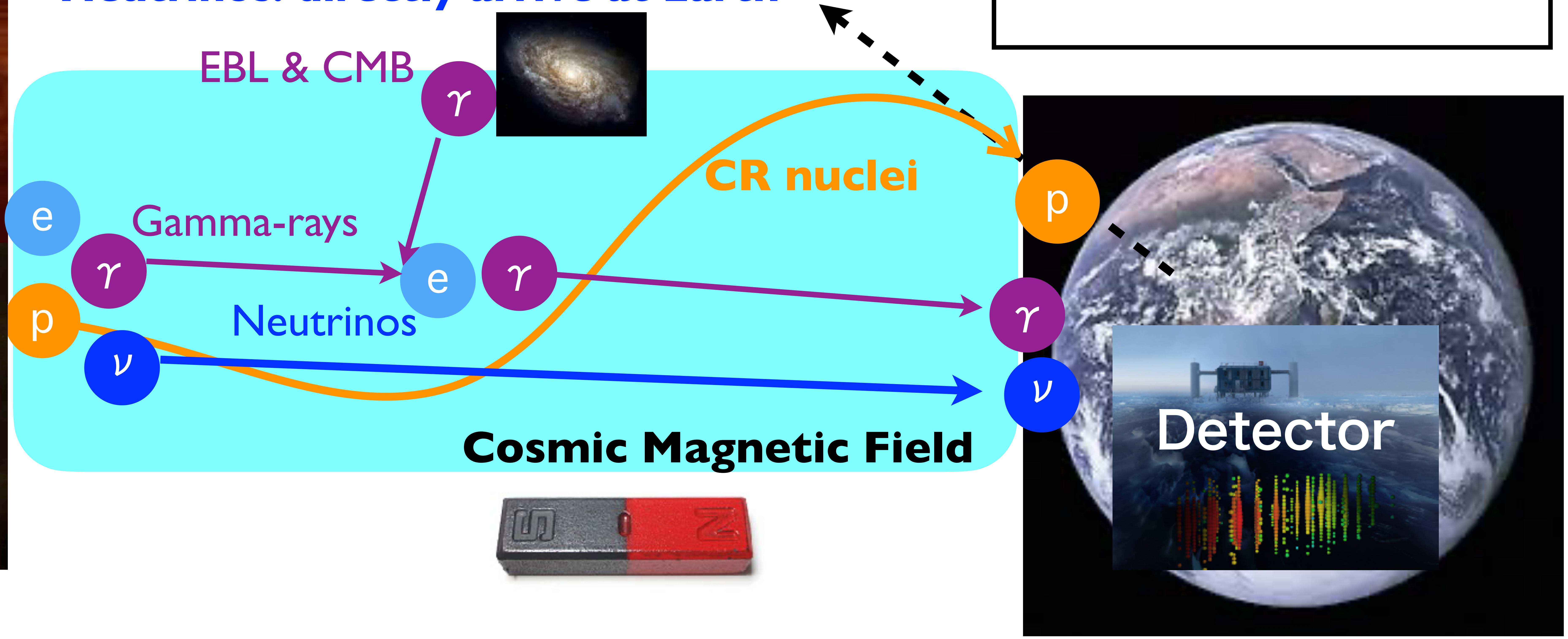
Propagation of intergalactic medium

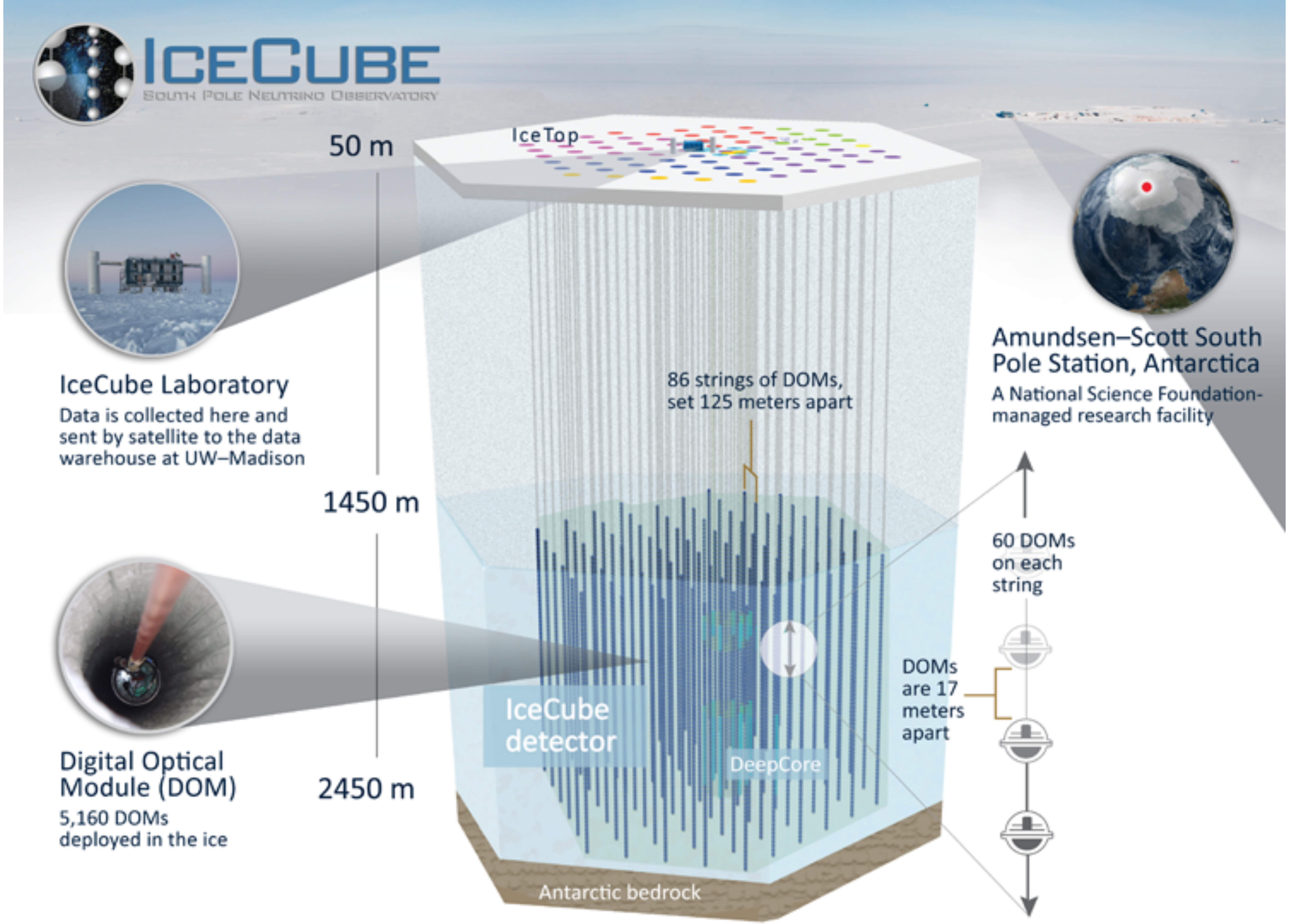
CR nuclei : deflected by B-field

Gamma-rays : attenuated by soft photons

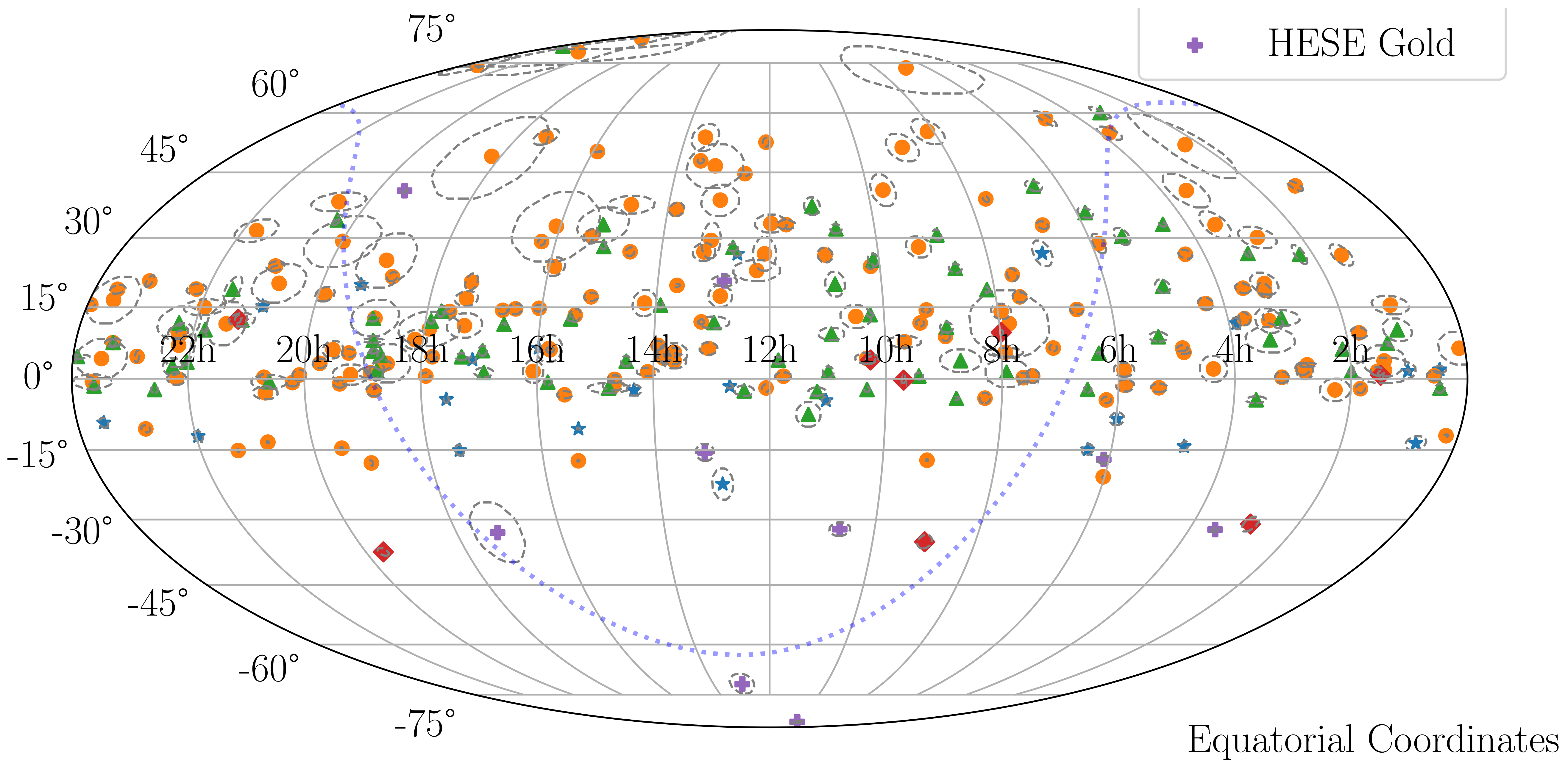
Neutrinos: directly arrive at Earth

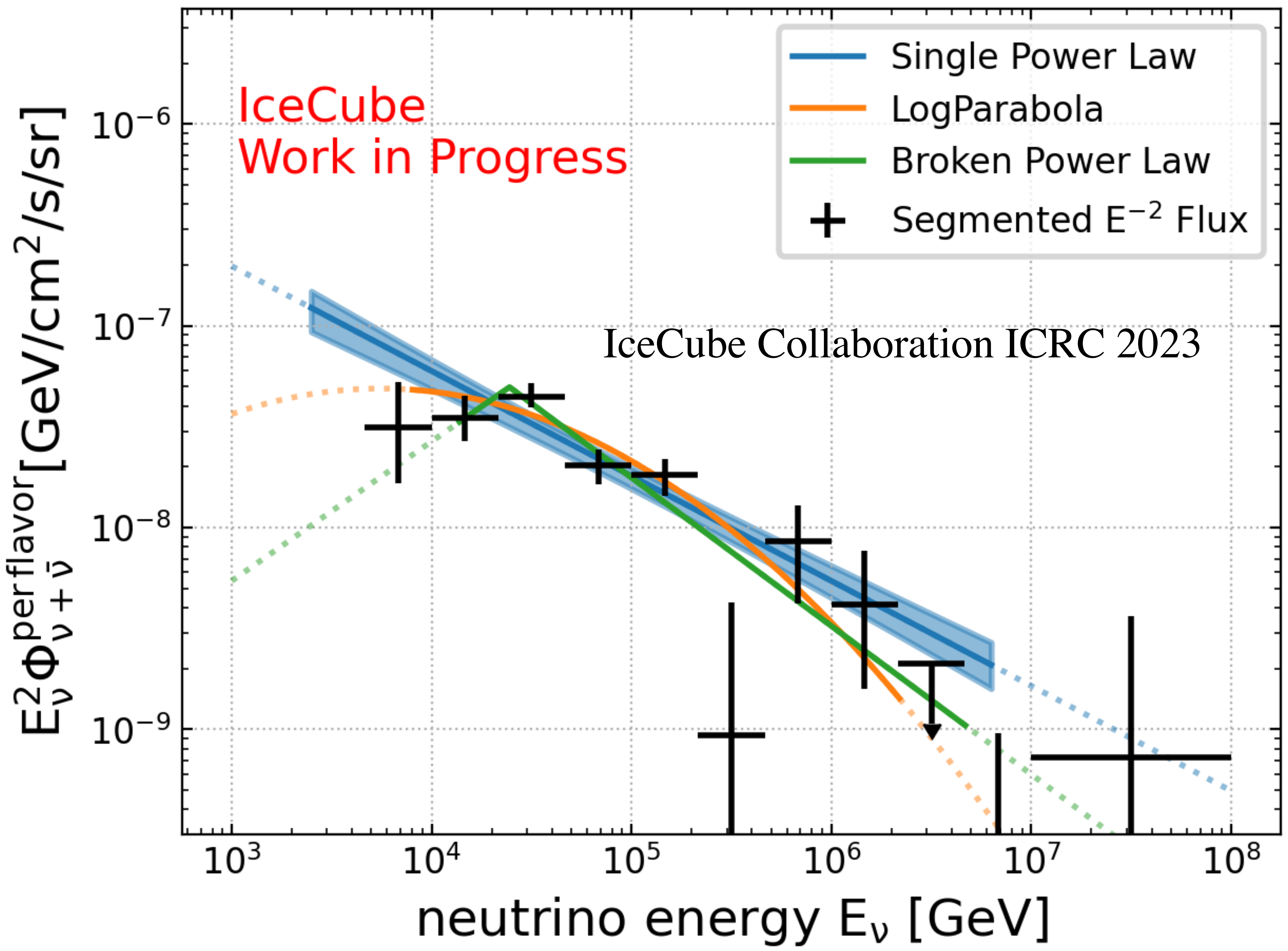
Detection at Earth



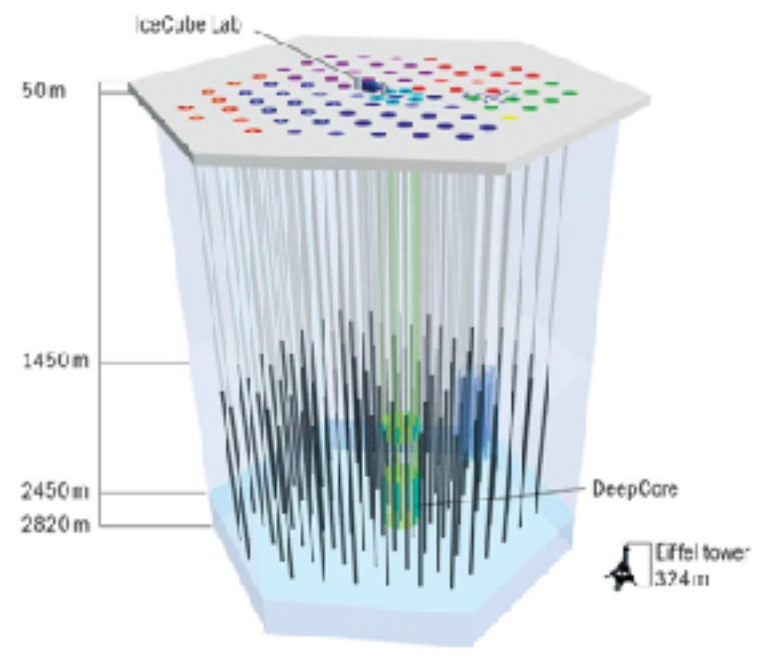

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
2450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

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**

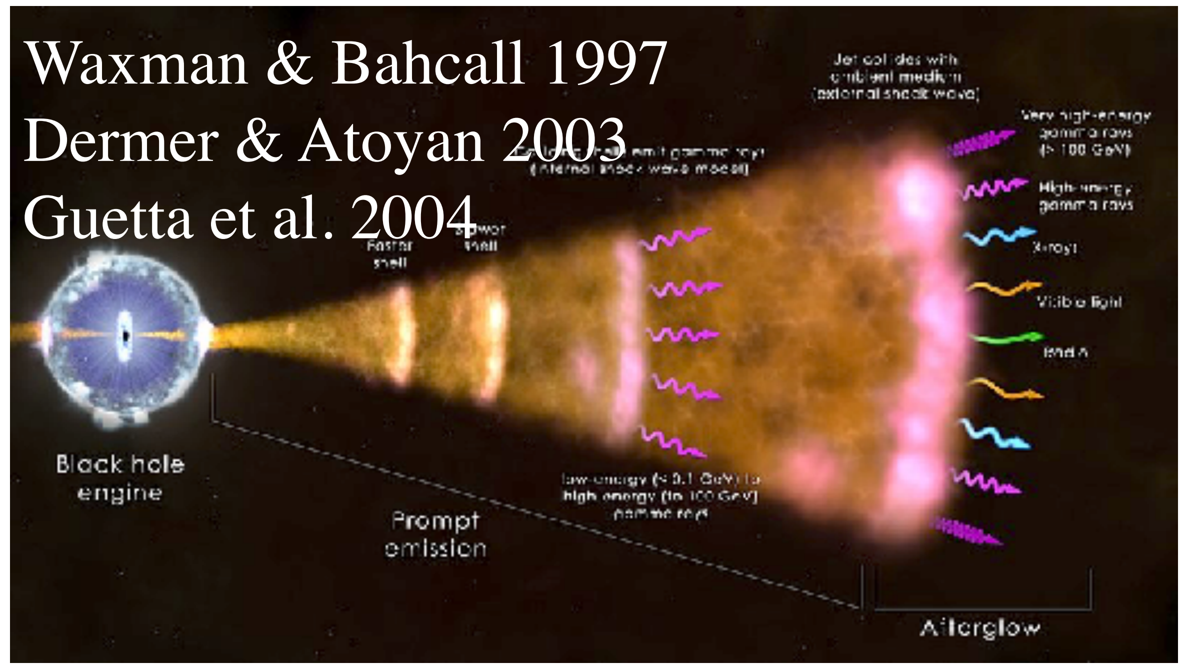


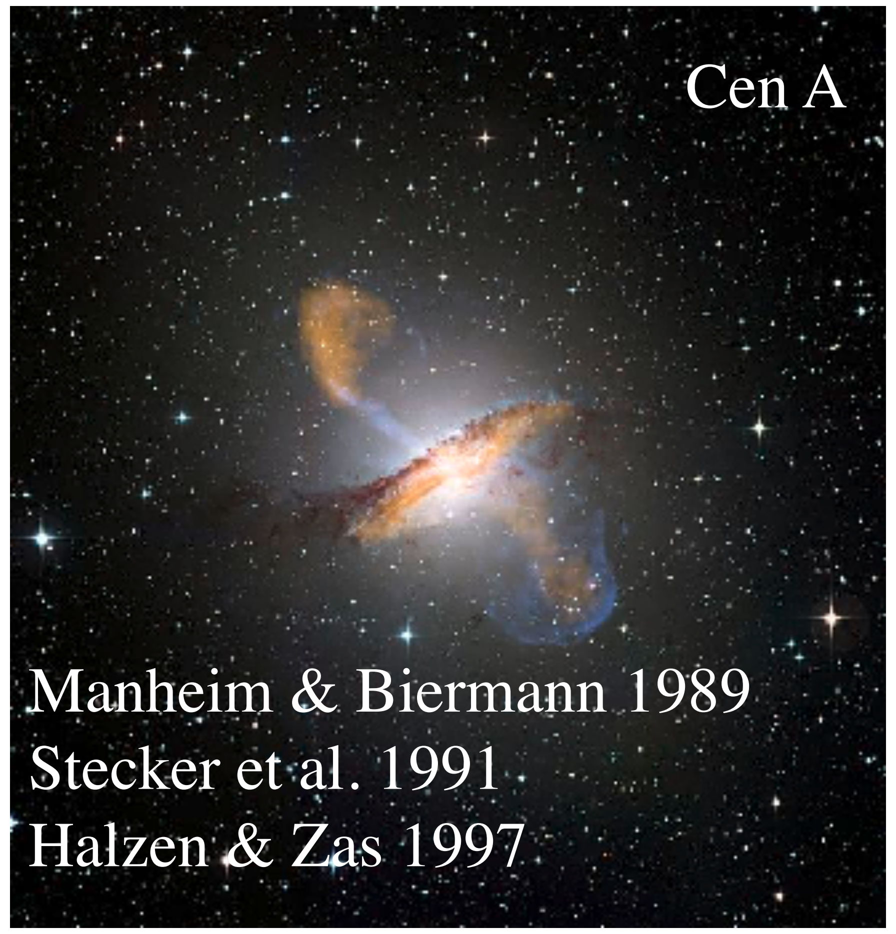
Pre-IceCube Neutrino Models

- **Cosmic-ray accelerators**

mainly pγ channel

- Gamma Ray Bursts (GRBs)





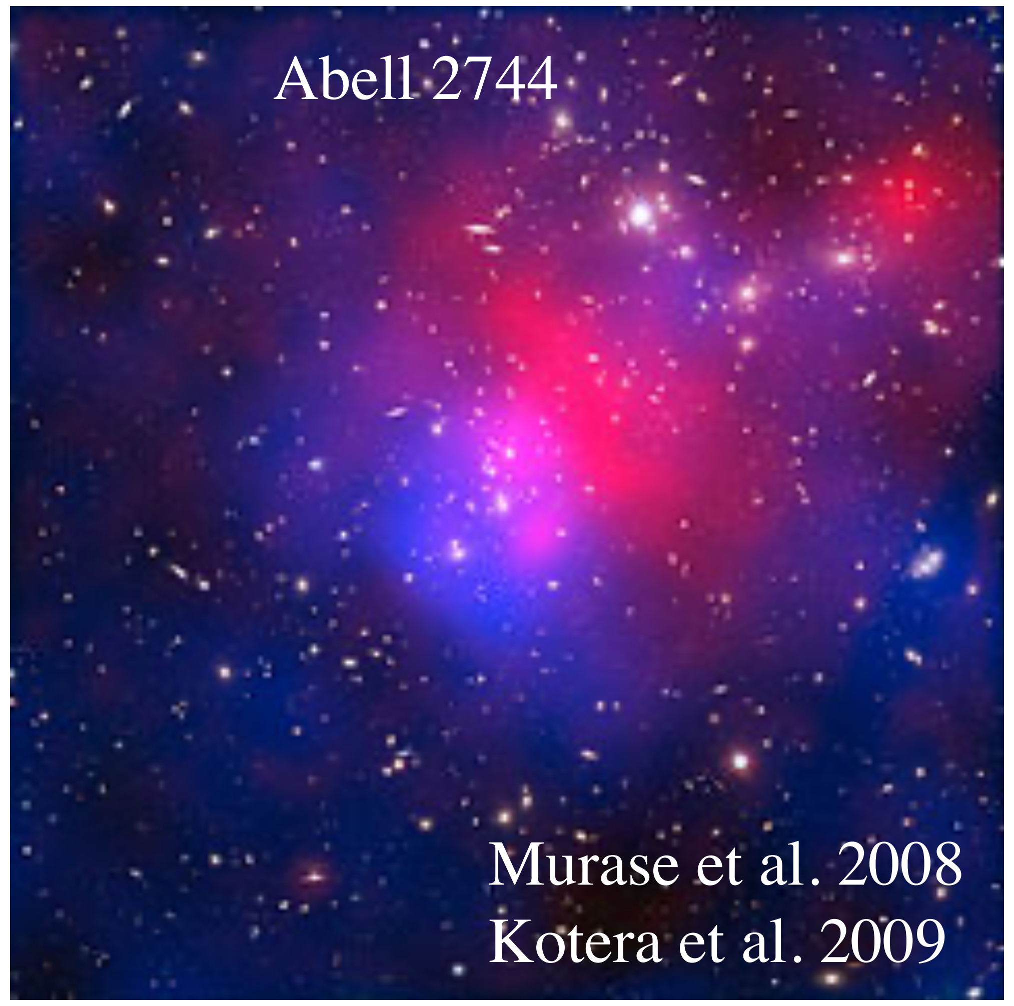
Especially Blazars

- Active Galactic Nuclei (AGN)

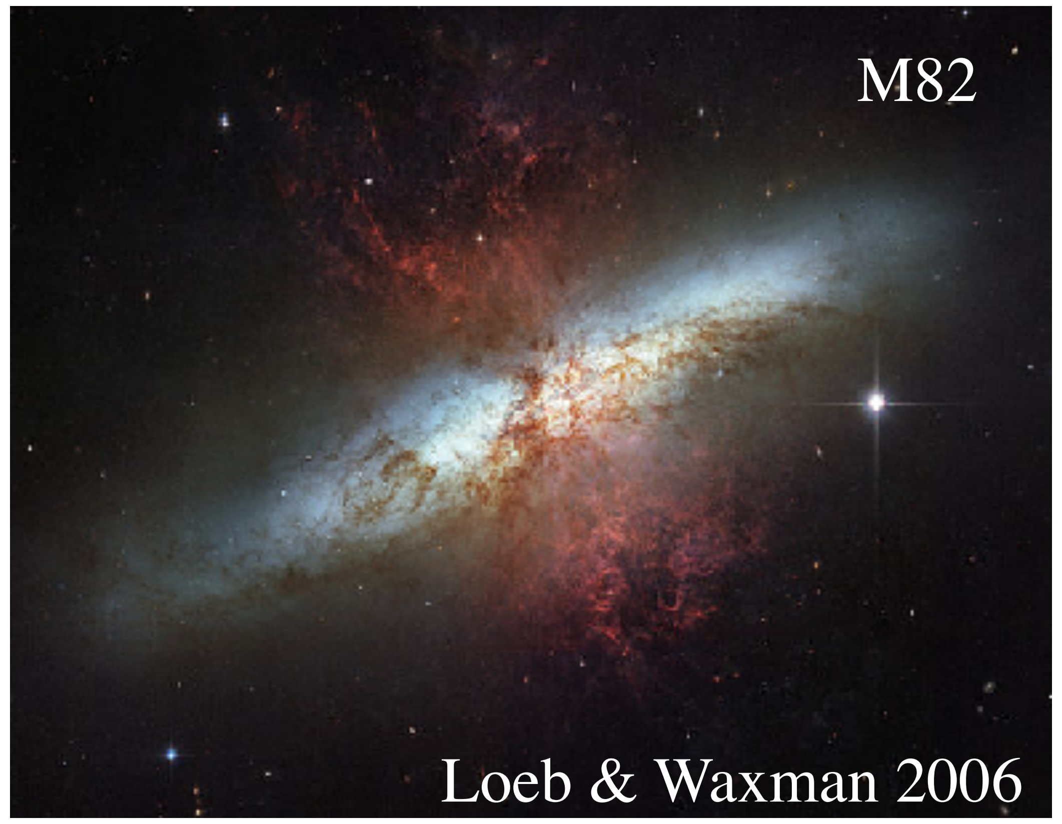
- **Cosmic-ray reservoirs**

mainly pp channel

- Galaxy Groups/Clusters



- Star Forming Galaxies (SFG)

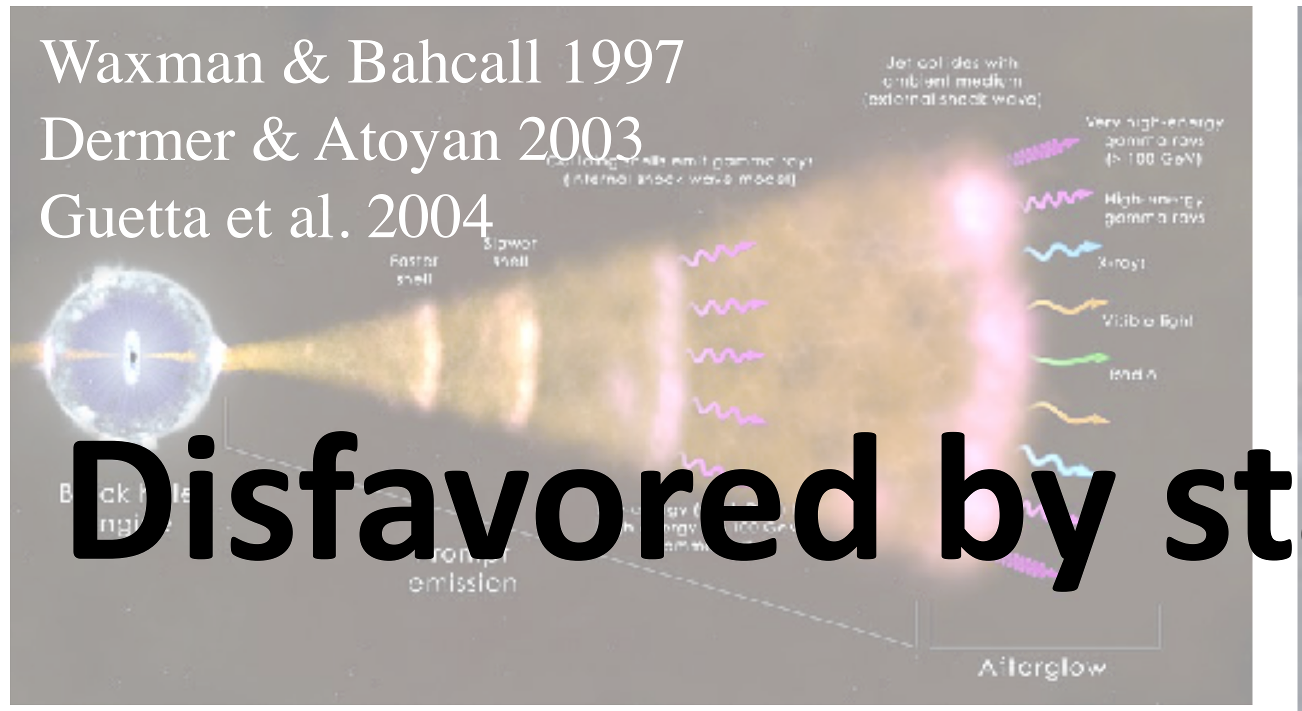


- Cosmic-rays are accelerated in the sources & produce neutrinos inside the sources

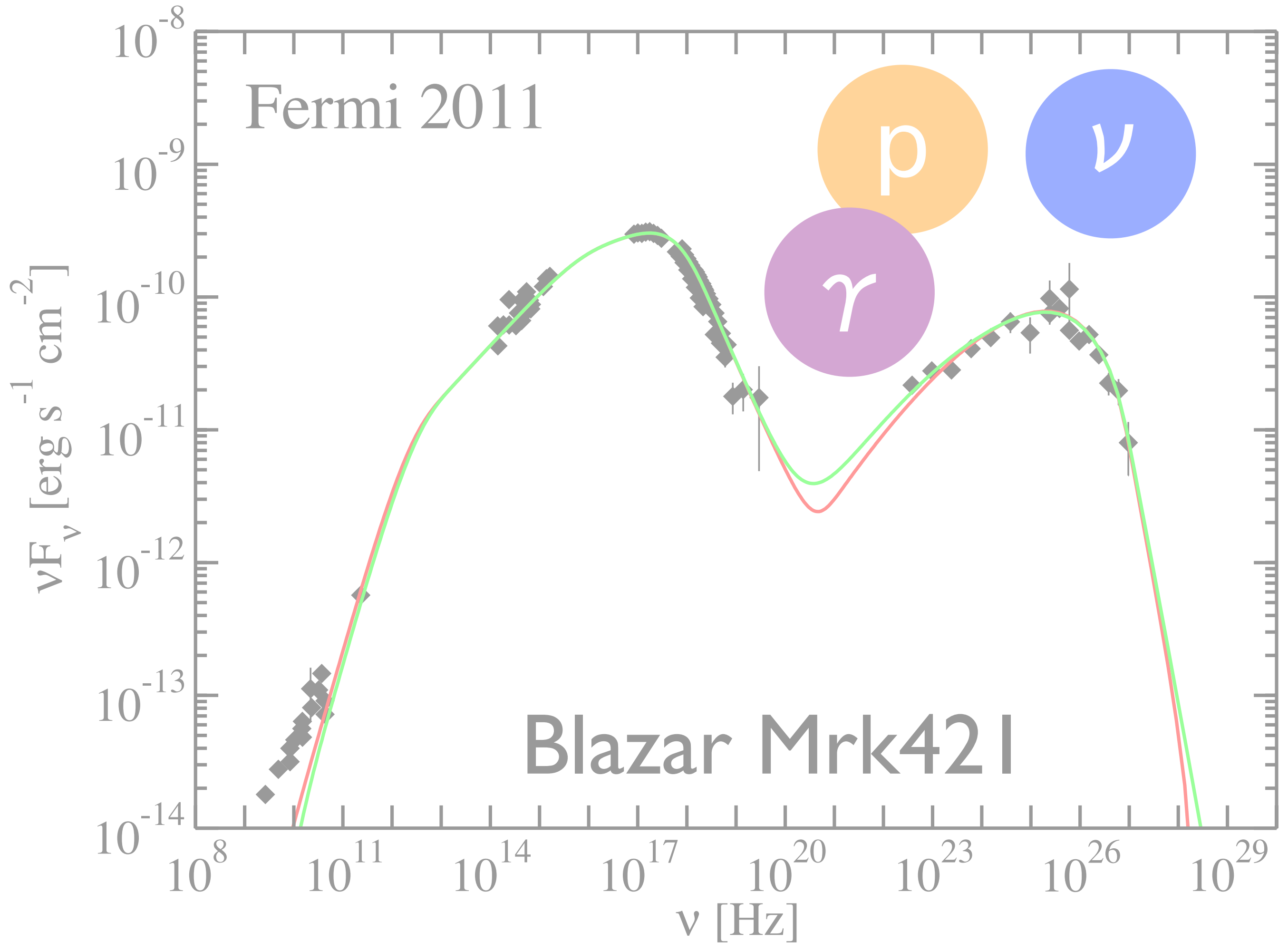
- Cosmic-rays are accelerated at accelerators in the reservoir
- Cosmic-rays are confined in the reservoir and produce neutrinos there

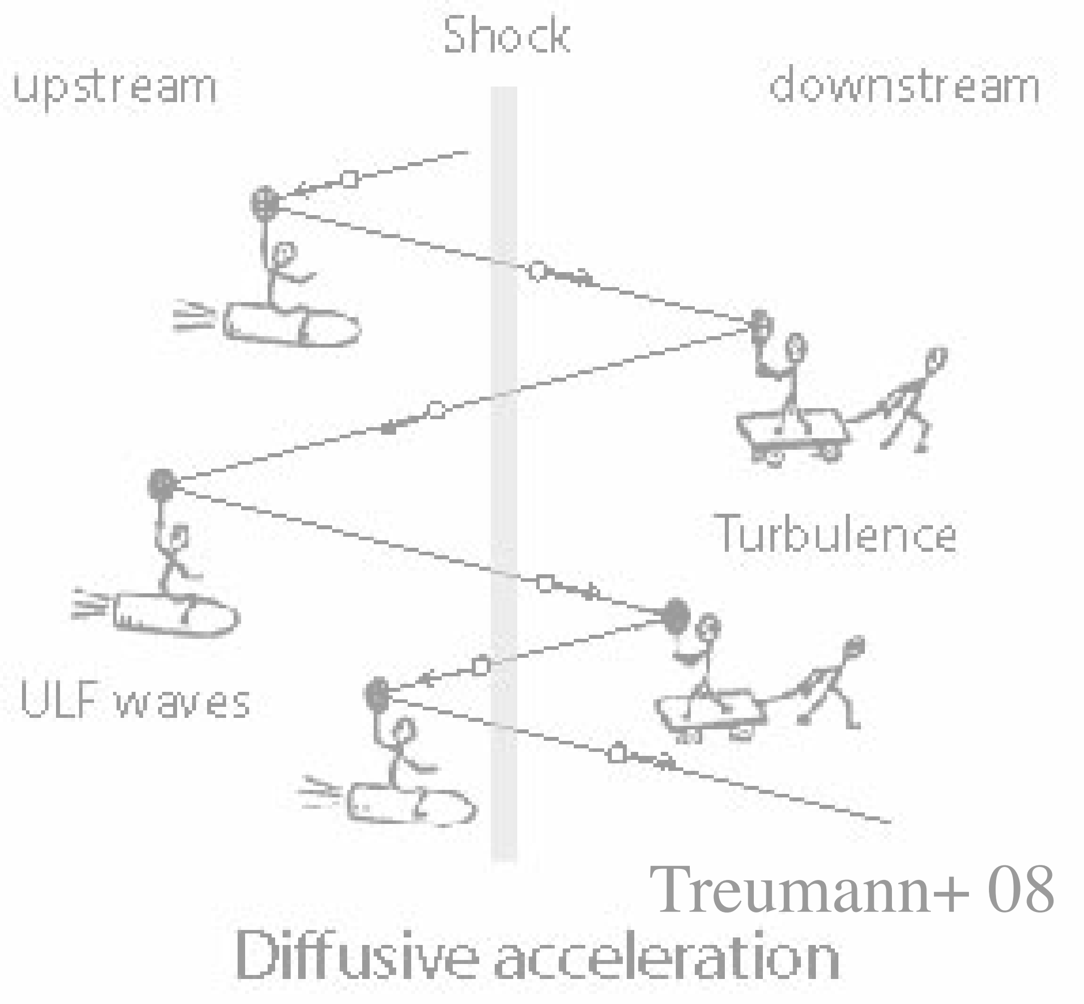
Neutrino Source Candidates in Pre-IceCube Era

- **Cosmic-ray Accelerators** $p\gamma$
  - Gamma-ray Bursts
  - Blazars

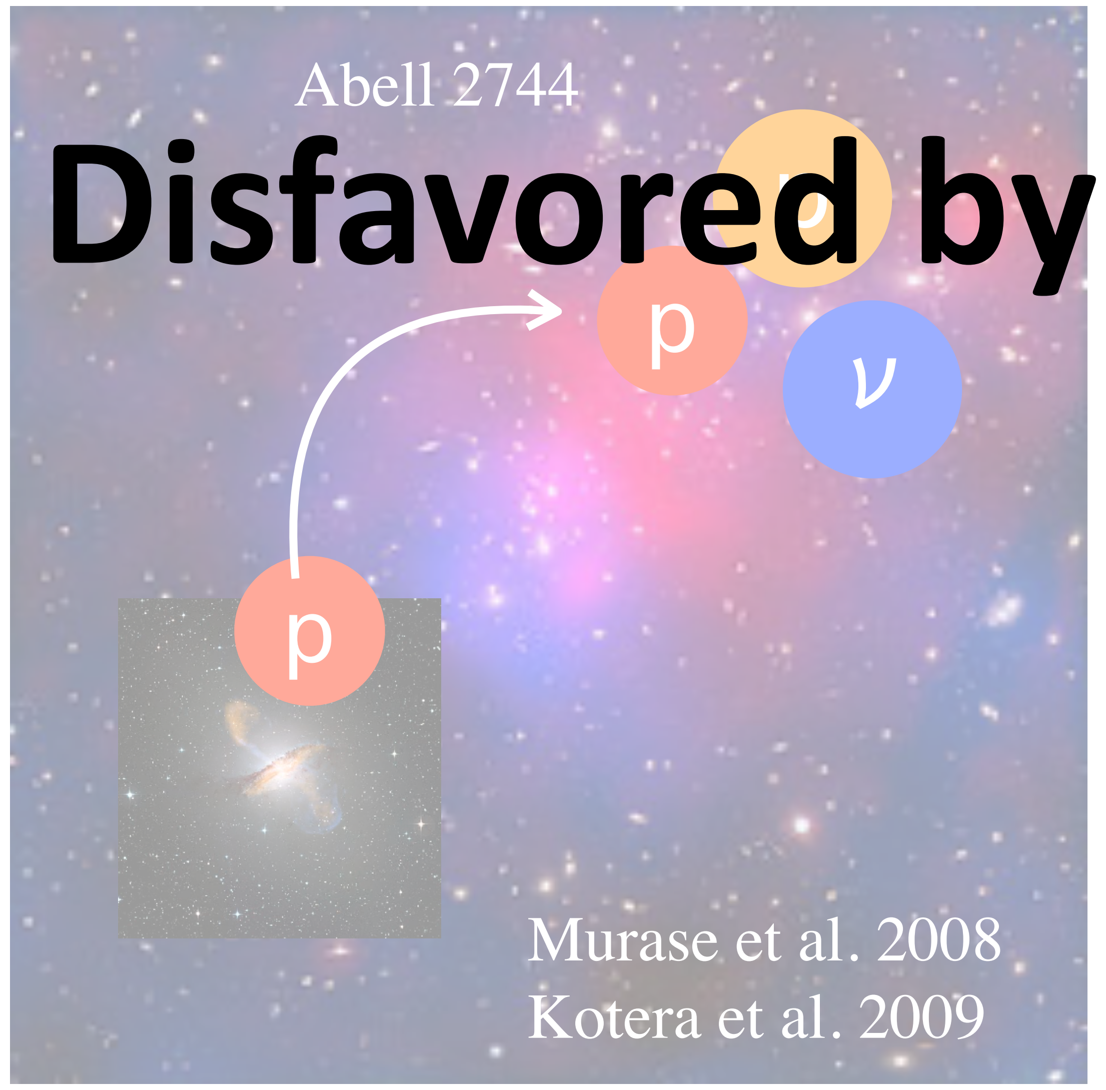


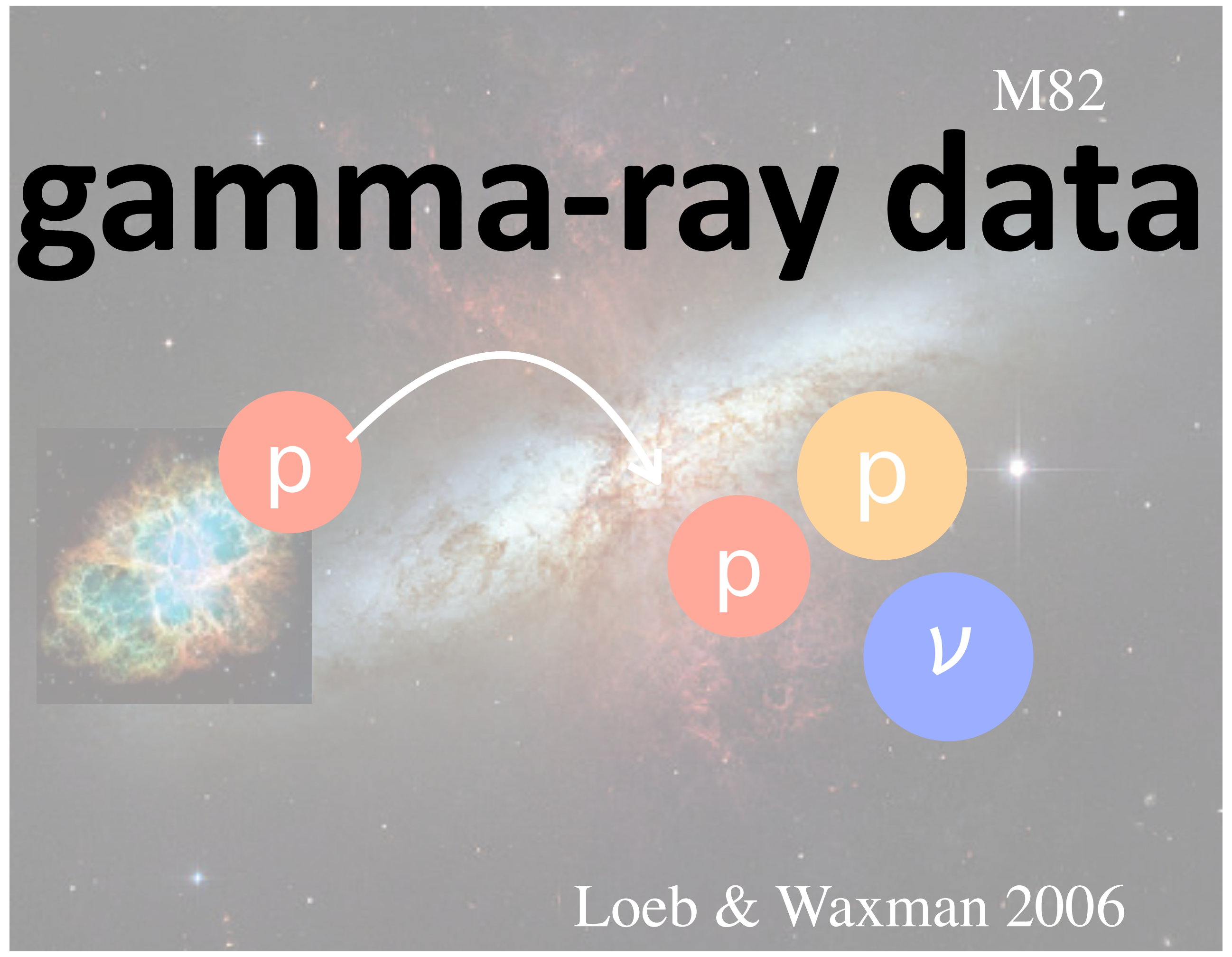
Disfavored by stacking analysis





- **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 neutrinos via pp channel

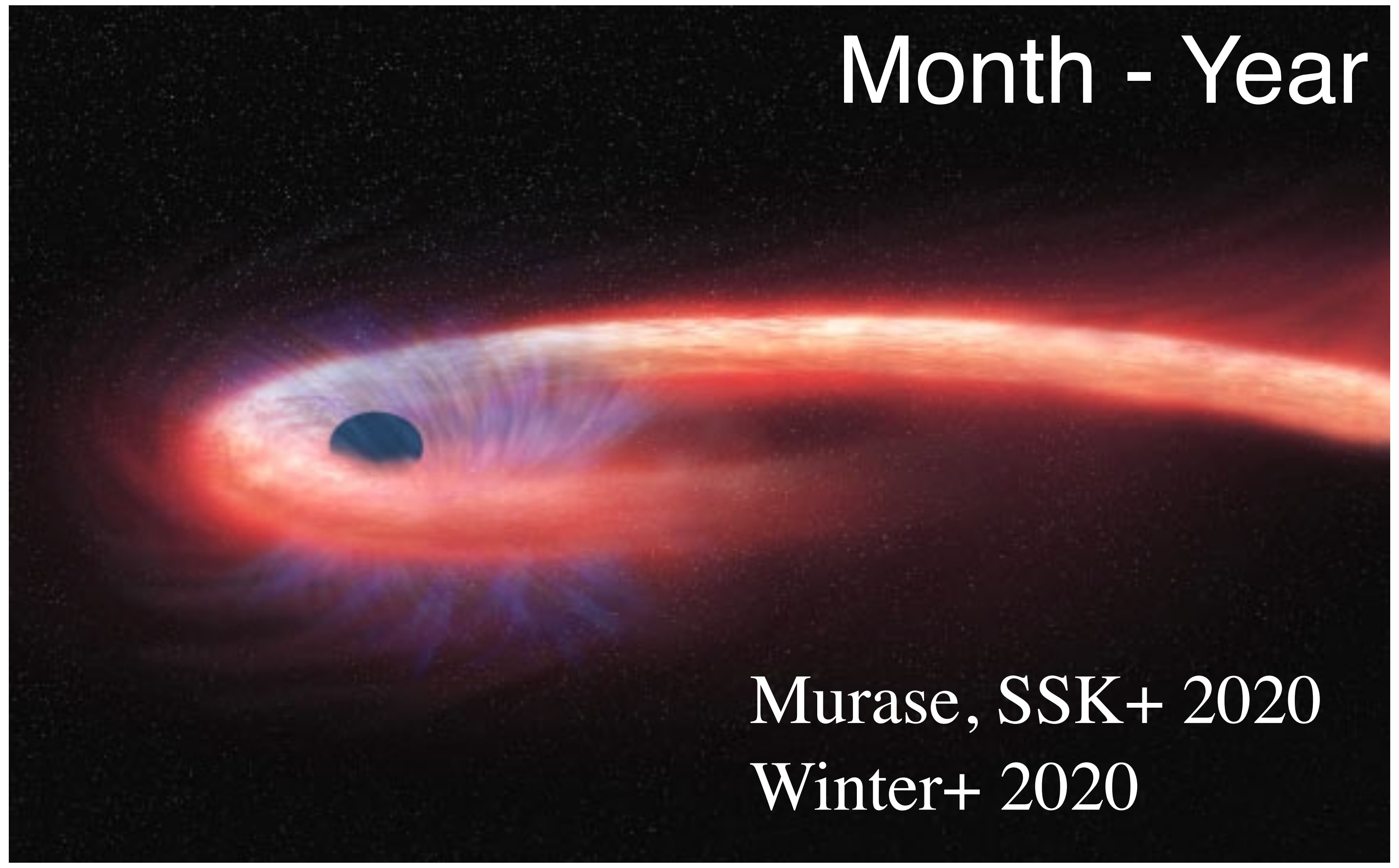
Current Source Candidates

- 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

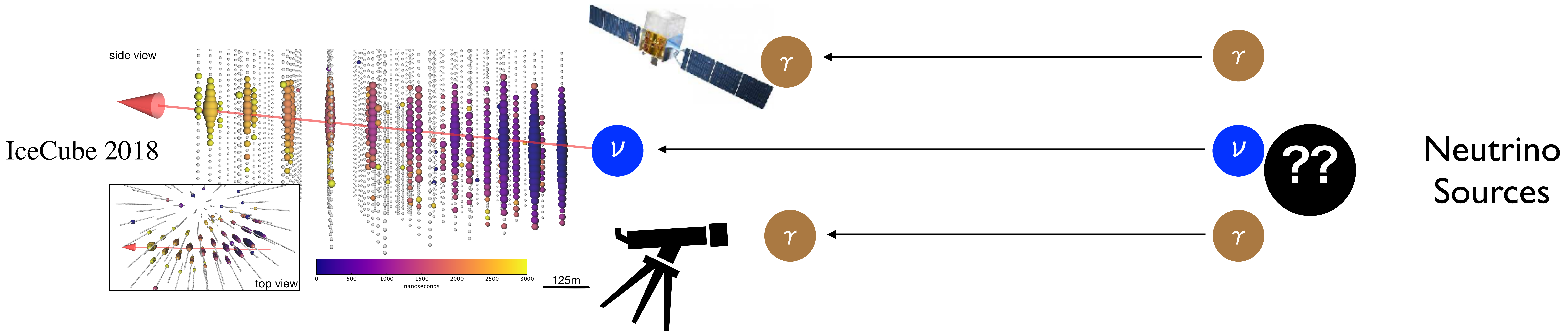
- Peculiar Supernovae (hypernova; super-luminous supernova)

- 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



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  - Neutrino Alerts
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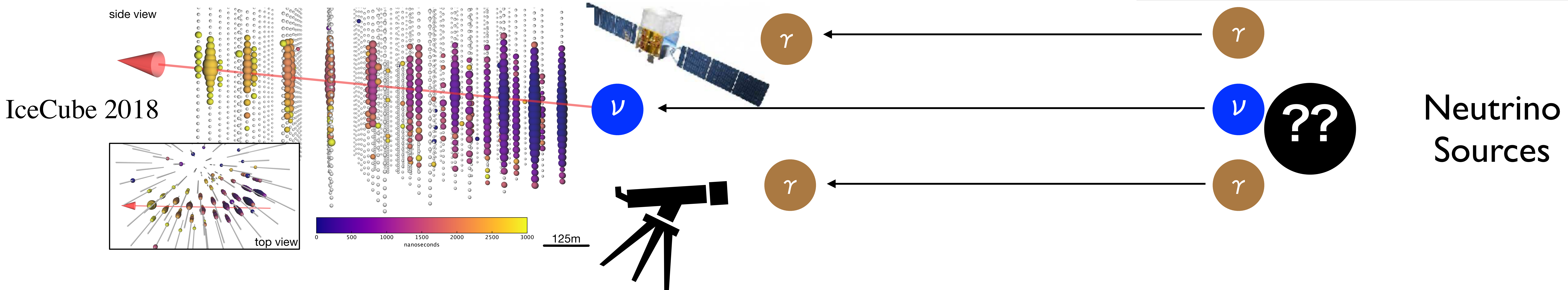
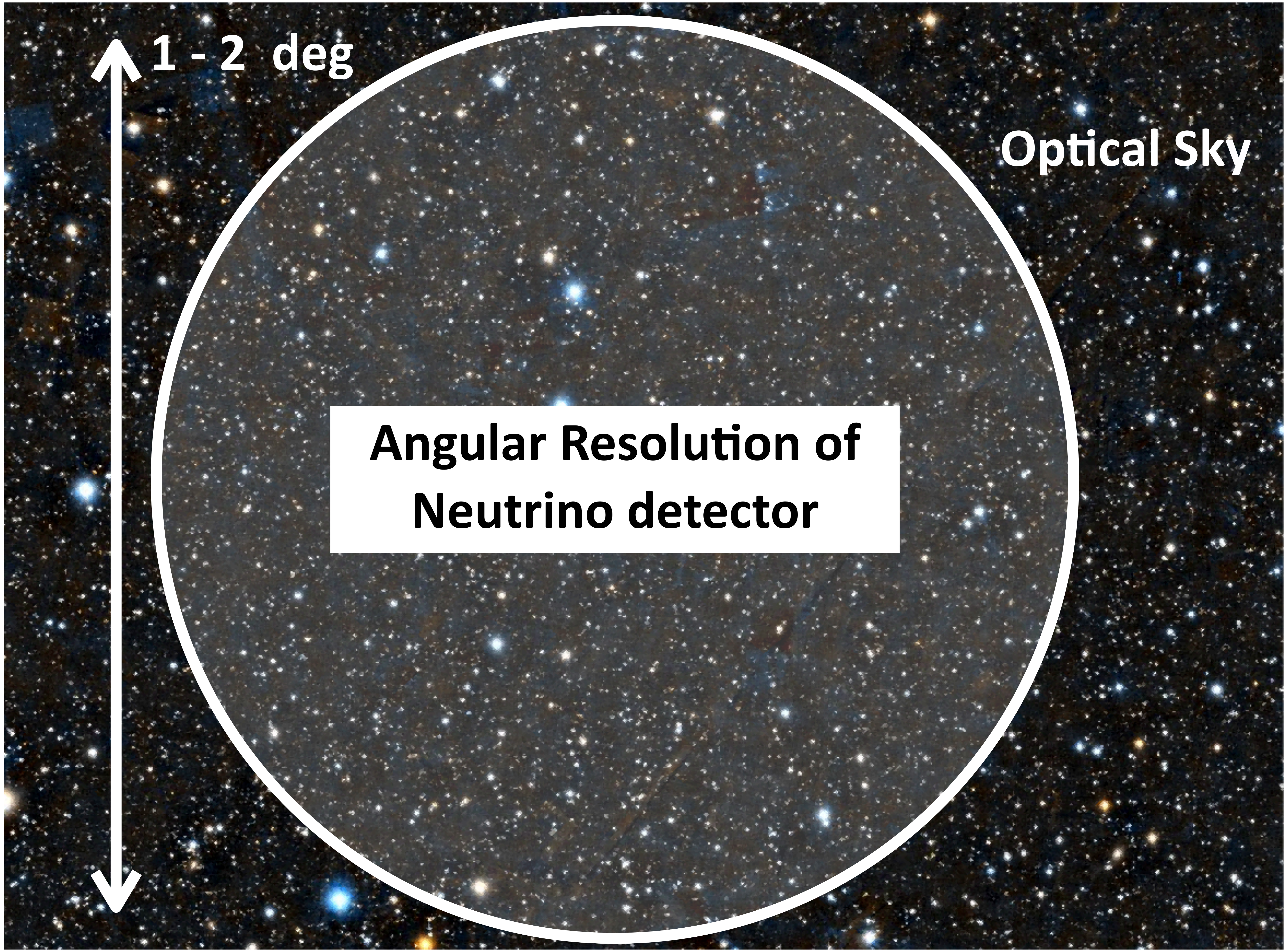
    → Identify neutrino sources
  - Only works for transients
  - **We will have better EM data**

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



Challenge to identify neutrino sources

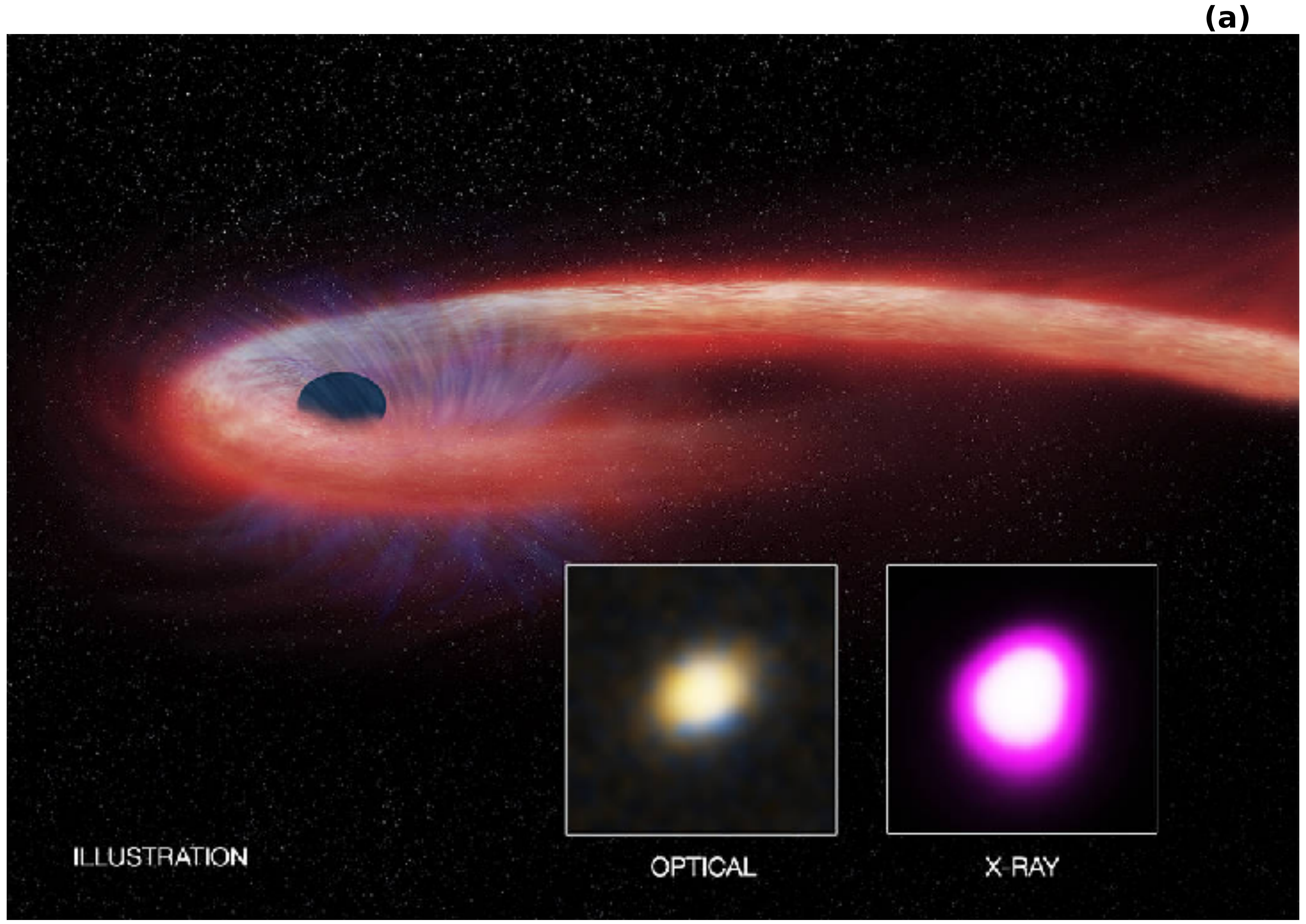


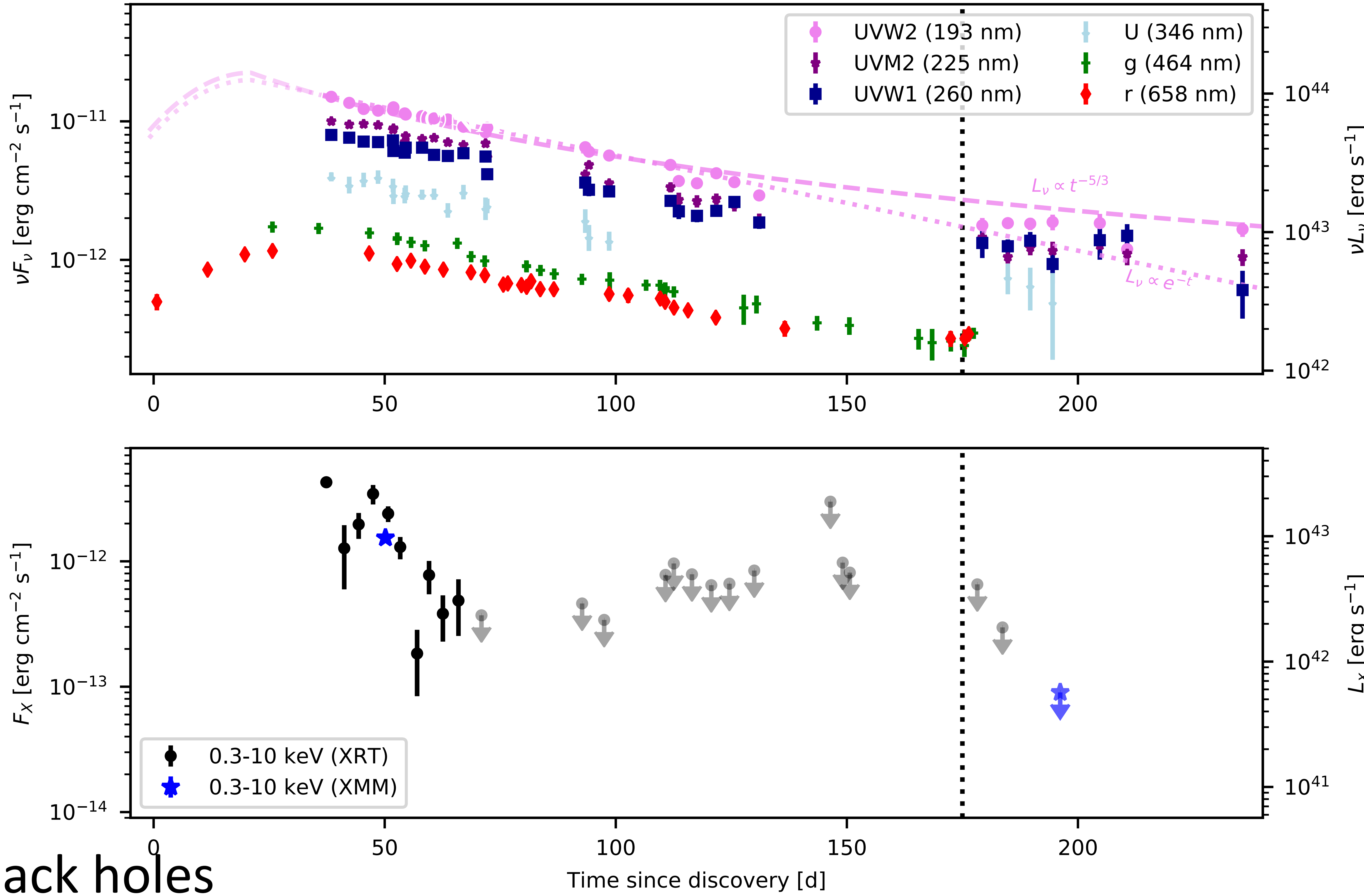
- Angular resolution for optical: $\sim 0.1 - 1$ sec
- Angular Resolution for neutrino: $\sim 0.5 - 3$ deg
- **Number of unrelated transients:** $\gtrsim 100$
- we cannot identify neutrino-emitting object…

Dedicated search strategy is necessary

Tidal Disruption Event (TDE)

Stein+ 2021; Reusch+2022



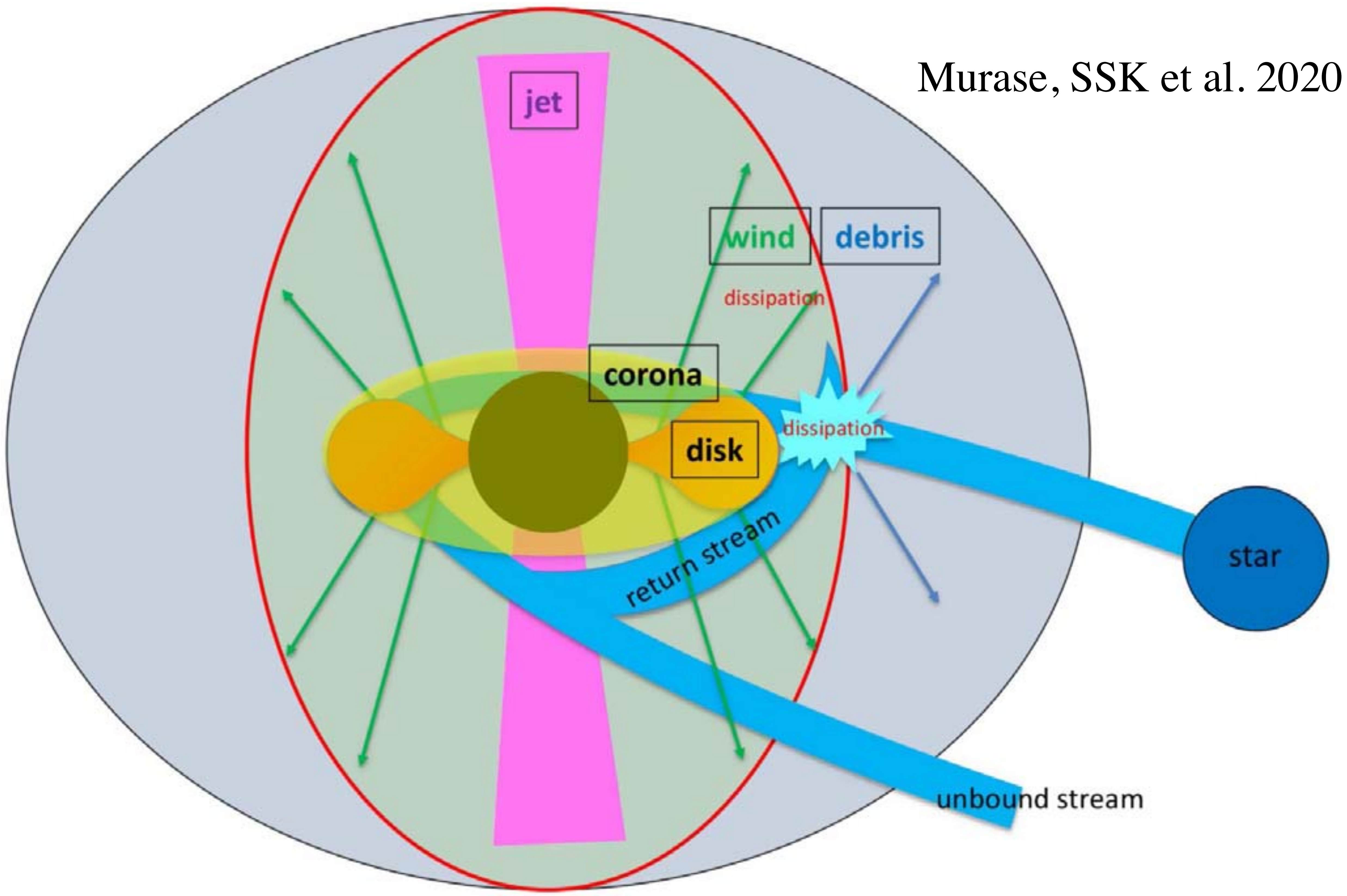


- Stars are torn apart by supermassive black holes
  => luminous (~10^{43} erg/s) & long (~year) optical transients
- Several TDEs are reported as possible associations with cosmic neutrino events
- All the associations have a neutrino signal ~ 100 days after the optical/X-ray peak

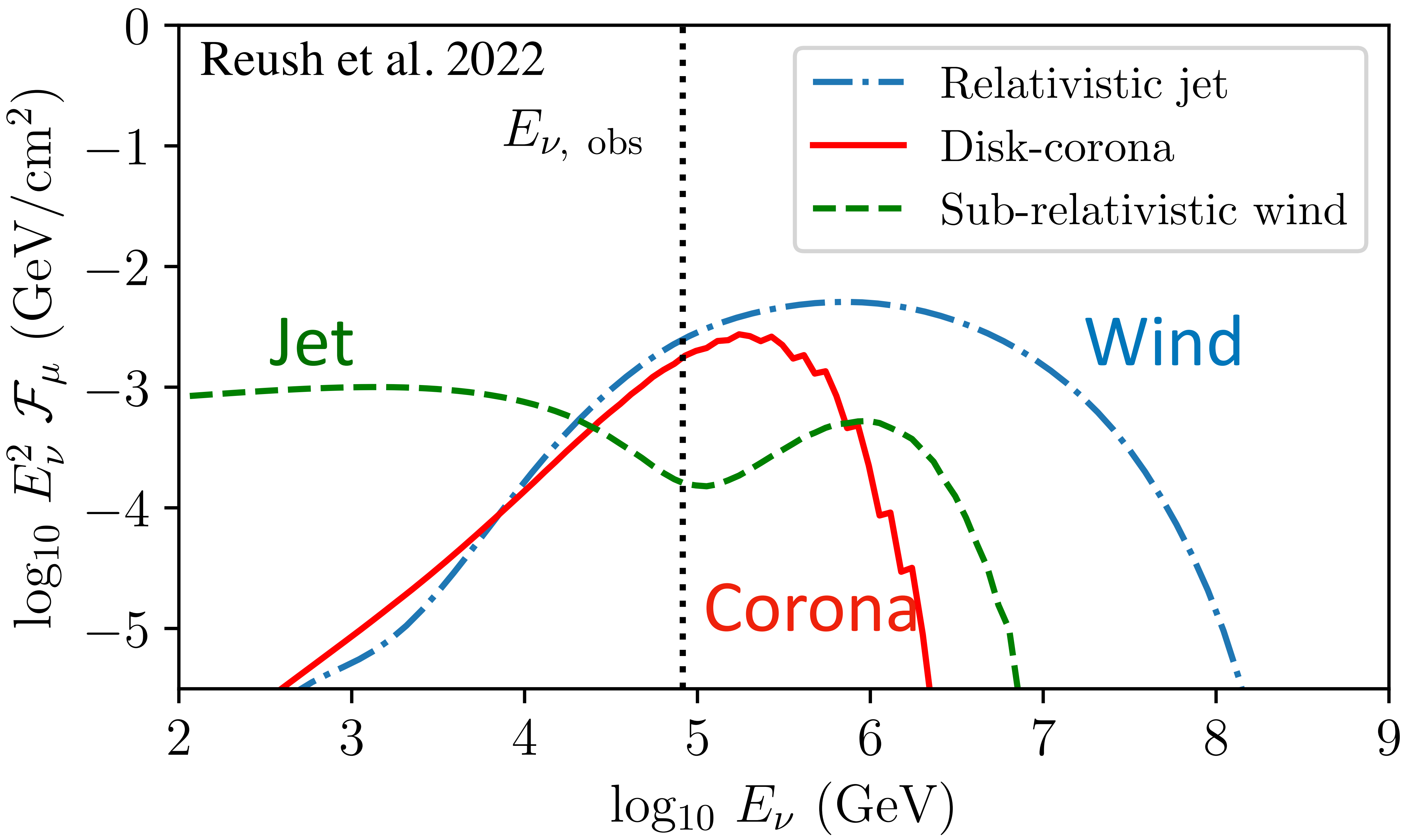
Stein+ 2021; Reusch+2022; van Velezen+2024; Jiang+2024; Yuan+2024; Li+2024

Neutrino emissions from TDEs

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



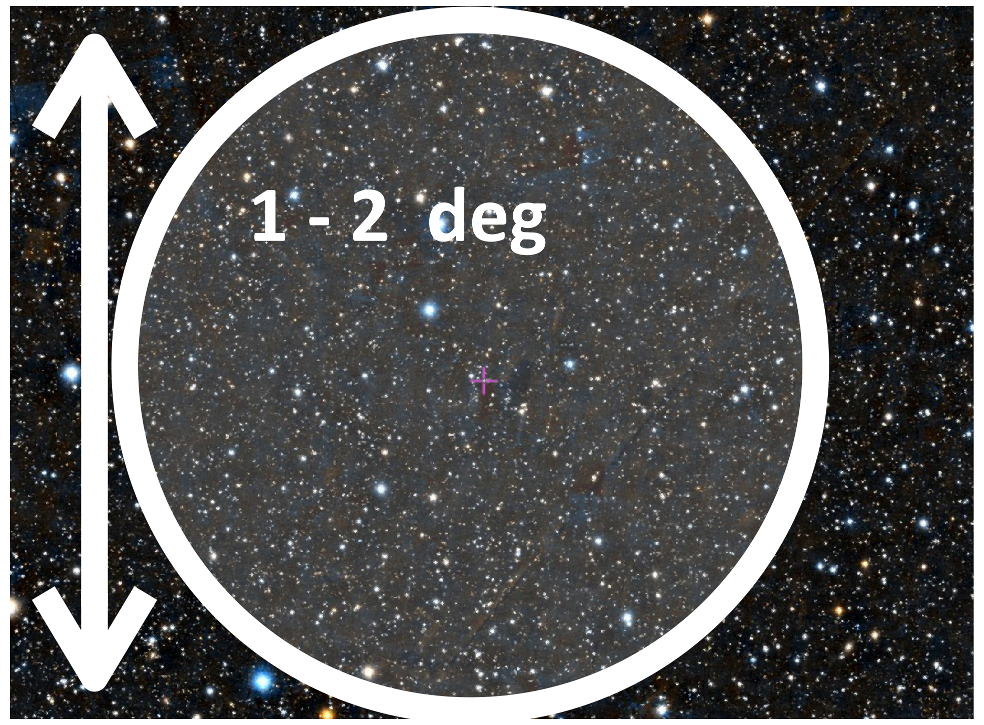
Murase, SSK et al. 2020

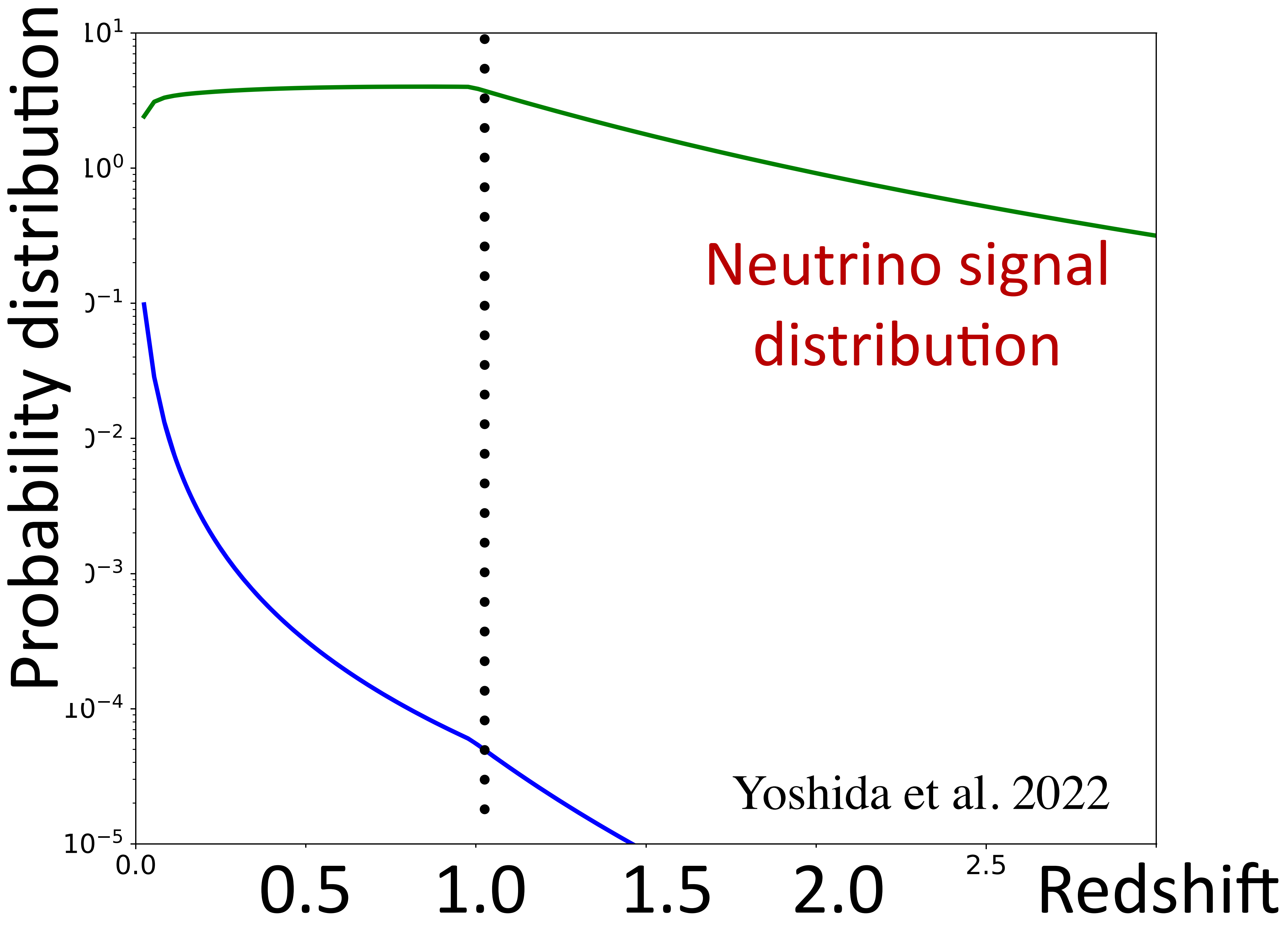


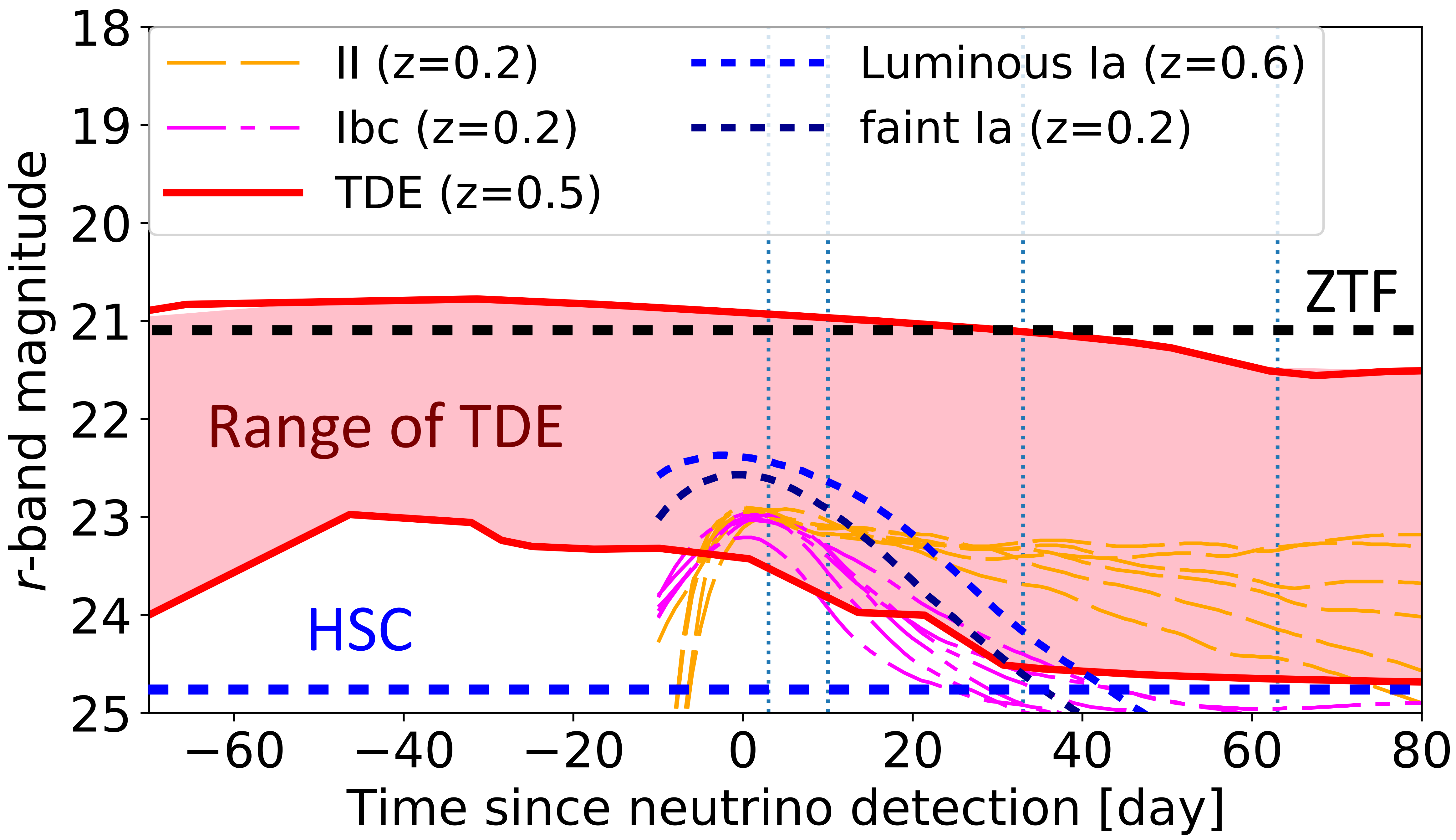
- Several possible sites of neutrino emissions: jets, winds, corona …
- Our best-guess scenario: **accretion disk & corona** Murase, SSK et al. 2020
- Energetics: > 10% of accretion energy needs to be converted to non-thermal protons
- Many models are proposed => **We need more observations to test scenario**

Neutrino Follow-up with Subaru/HSC

- Angular error of neutrino: 1 deg^2 **==> Wide-field survey (1 deg^2)**
- 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



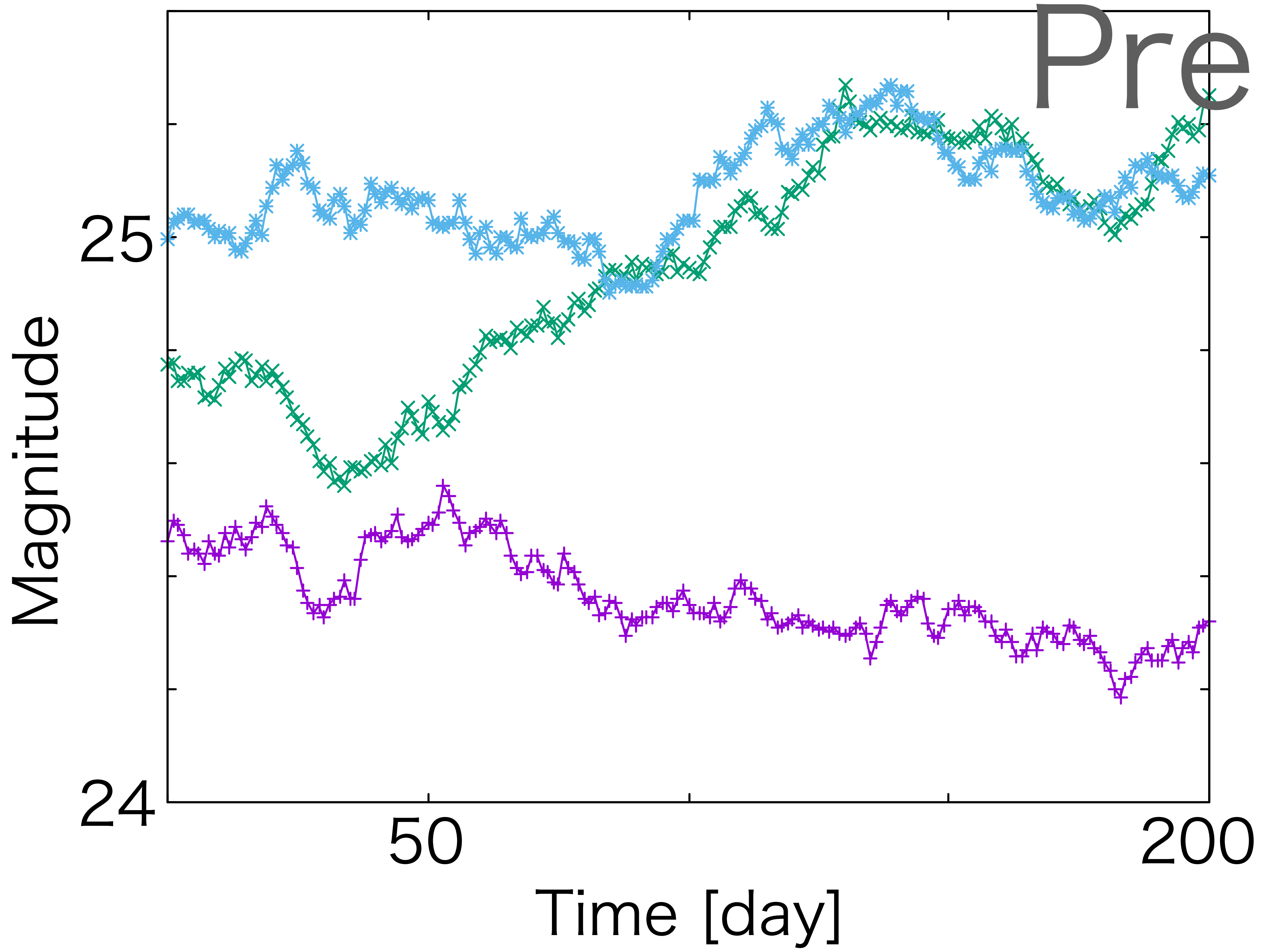




Transient Classification Simulations

- 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

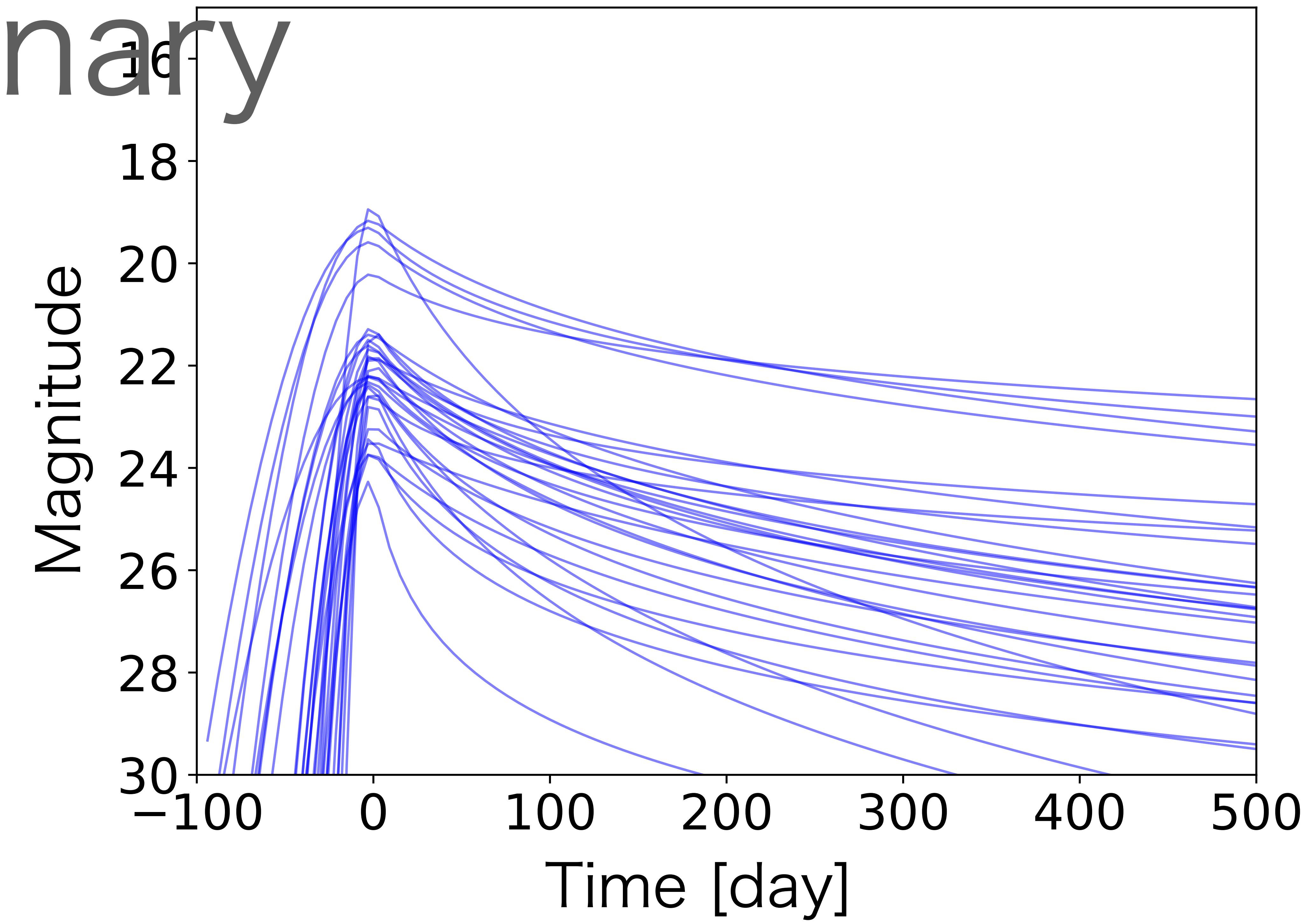
Cf. Y. Kimura et al. 2020



- TDE lightcurve templates

Cf. Hammerstein et al. 2023

Preliminary

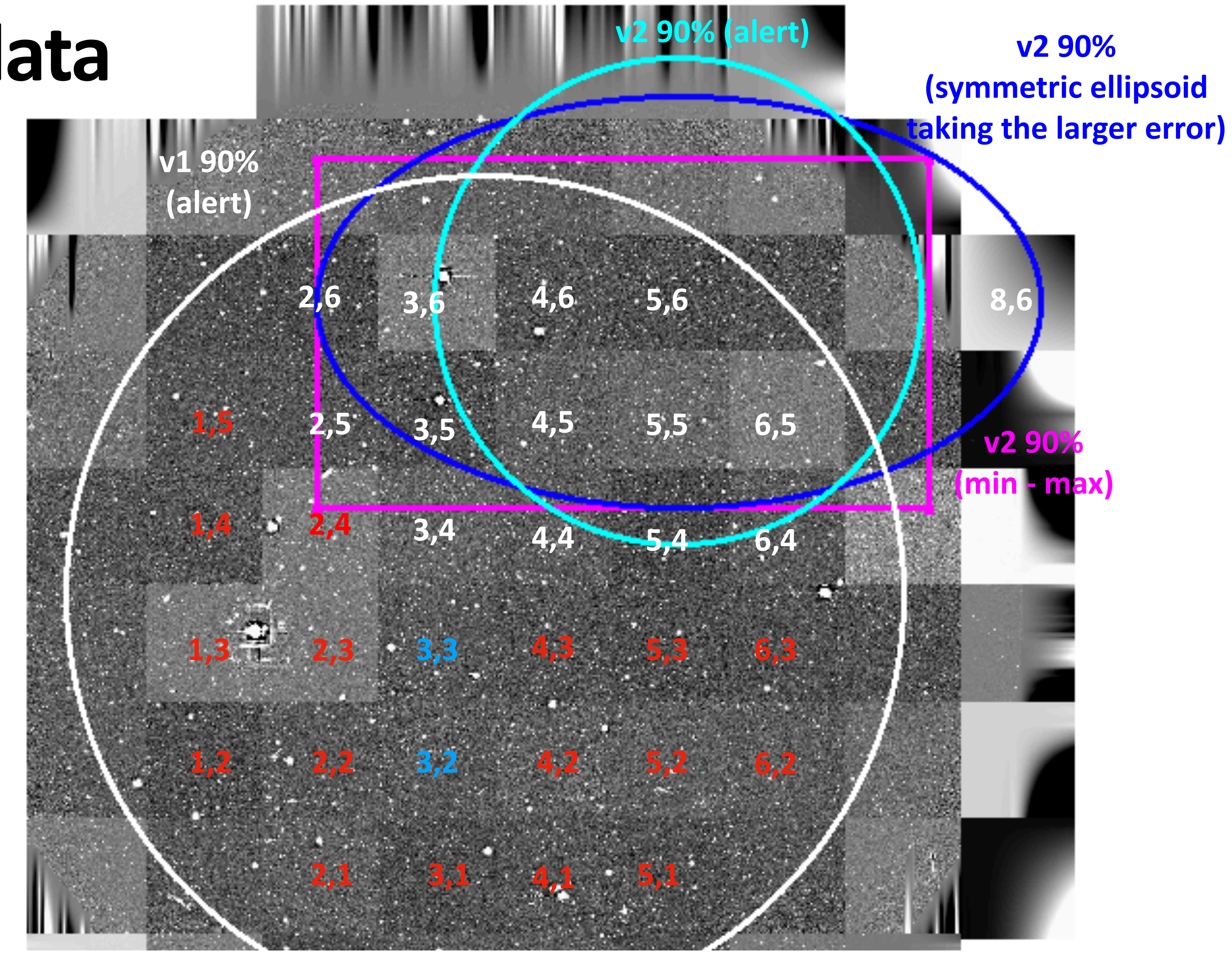


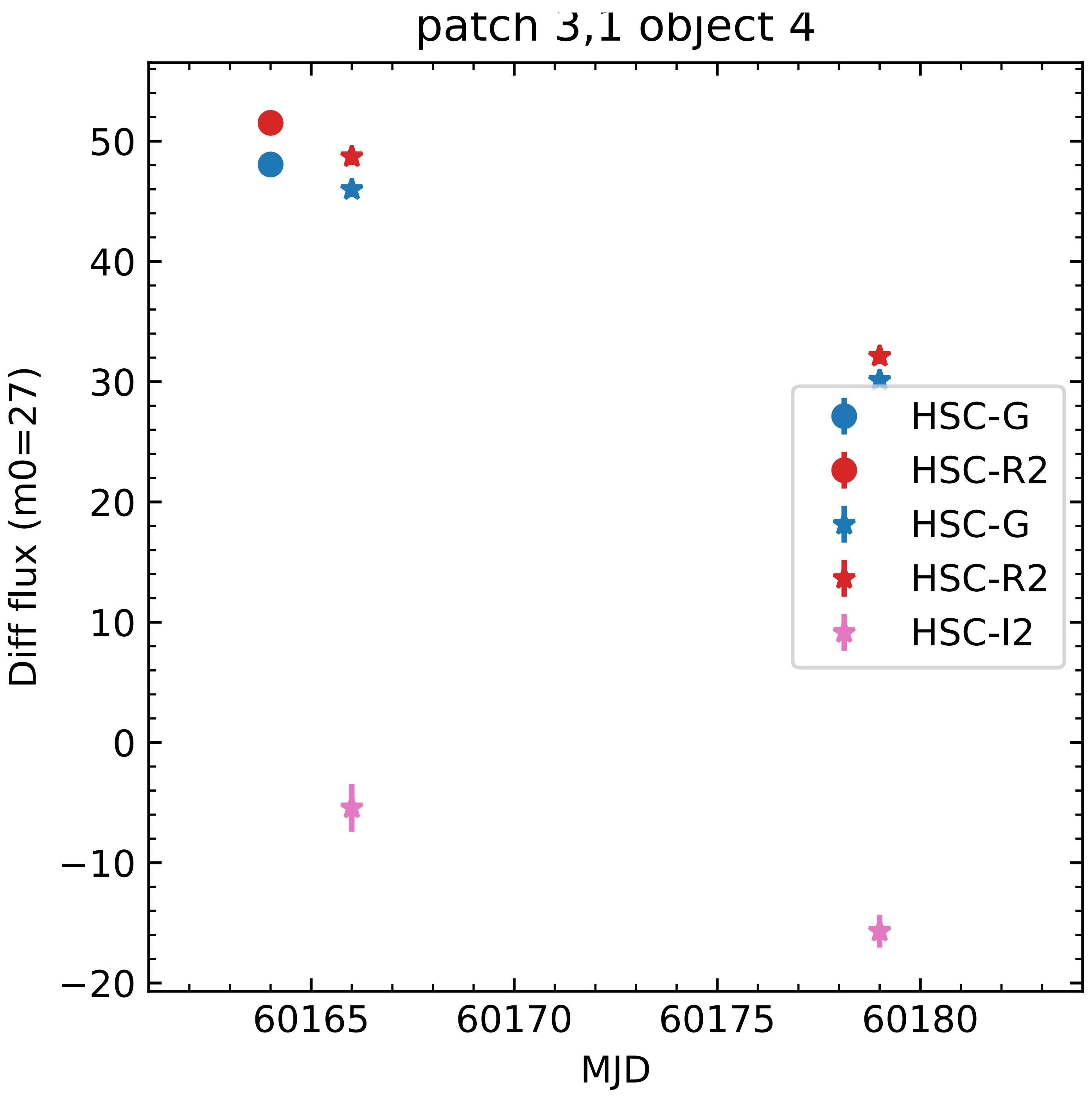
Subaru Follow-up to IC 230724A

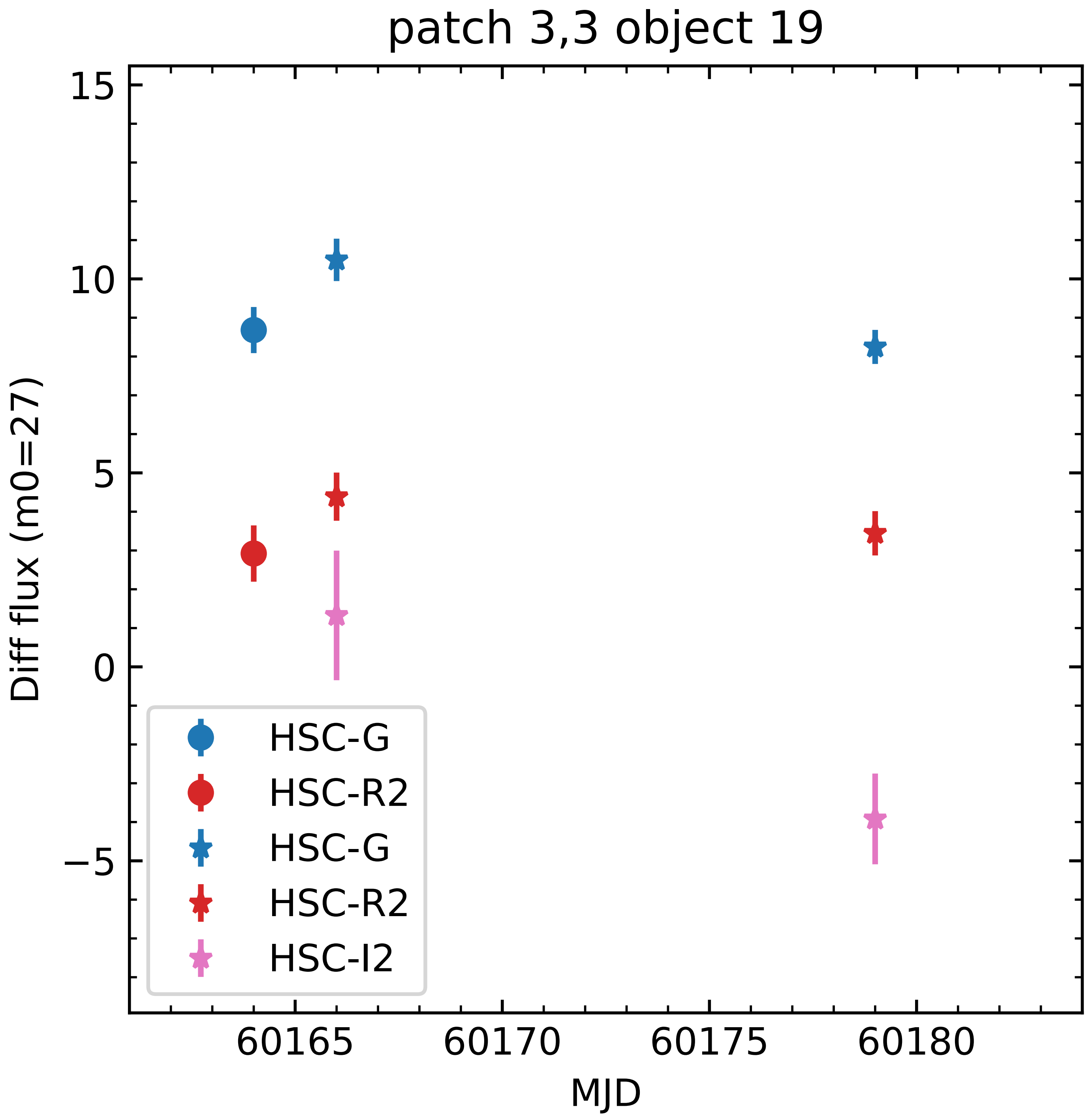
- Excellent IceCube Alert on 2023/07/24 (Angular Error ~ 0.6 deg)
- We performed follow-up observations,
  but only take 2 epoch of data due to the mirror trouble
- **Blind analysis**: Actual data in the error region will be analyzed
  after we have completed estimation of the background number & True positive rate

V1 data

TRACT
9006

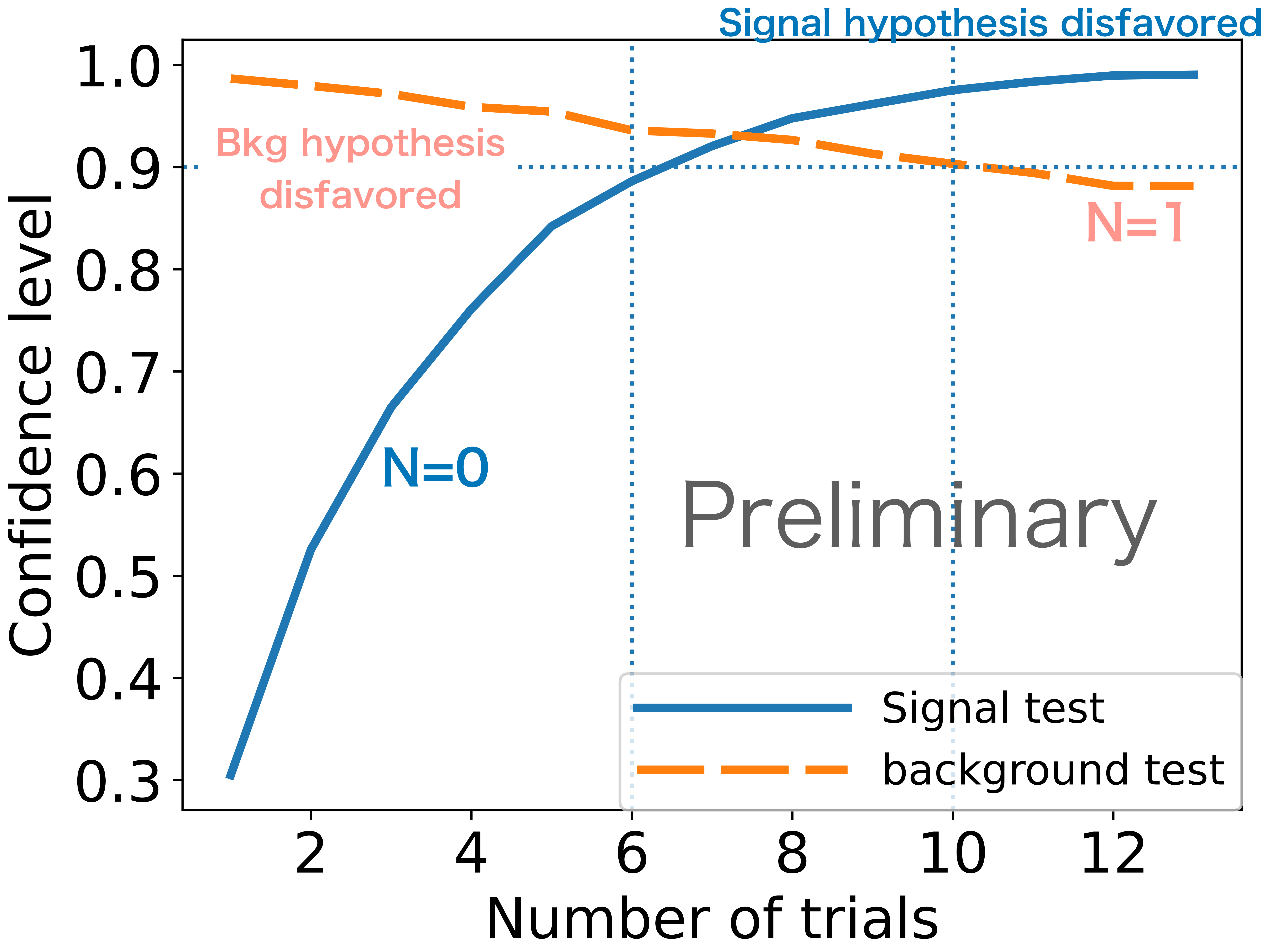






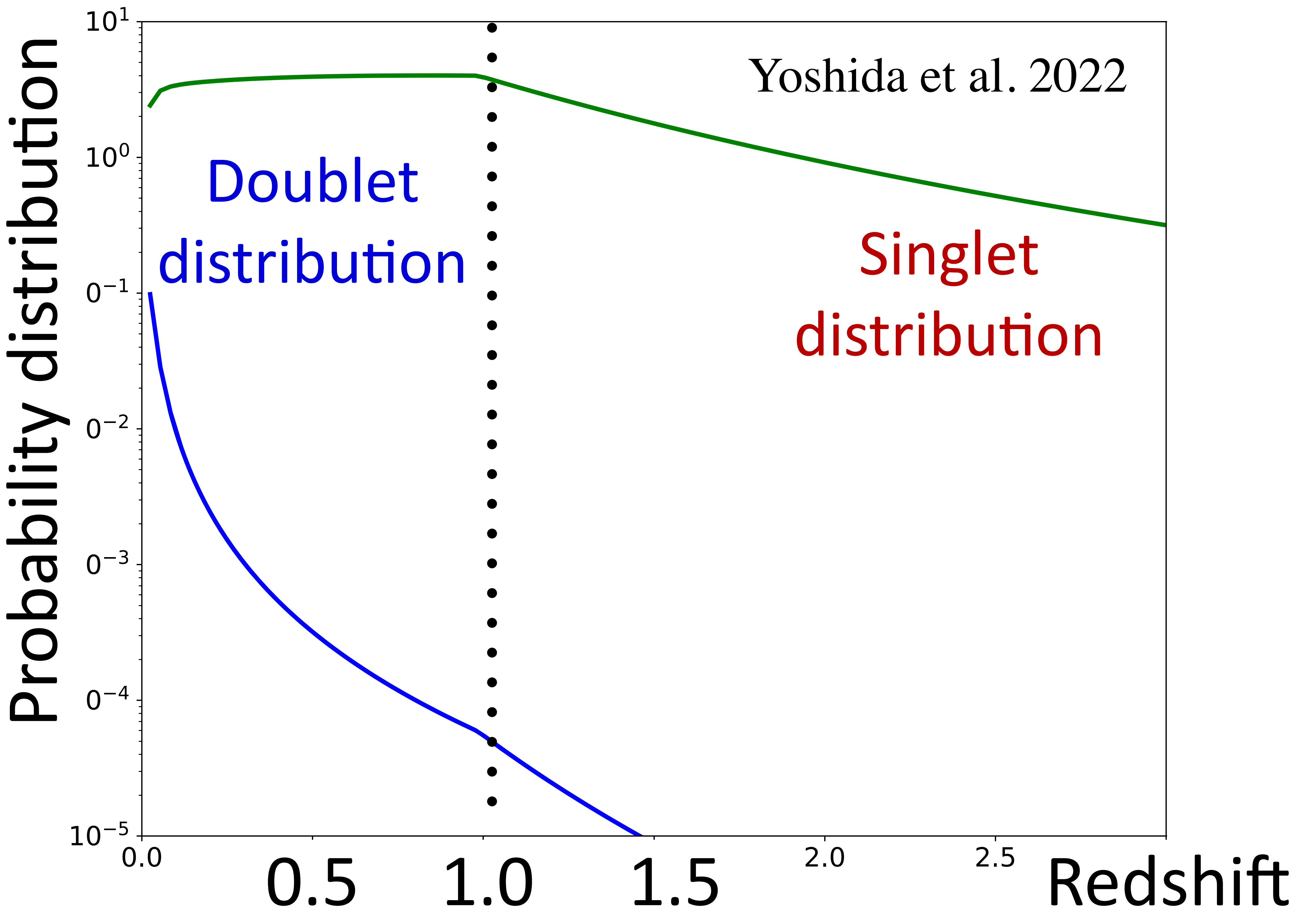
Prospects with Rubin/LSST

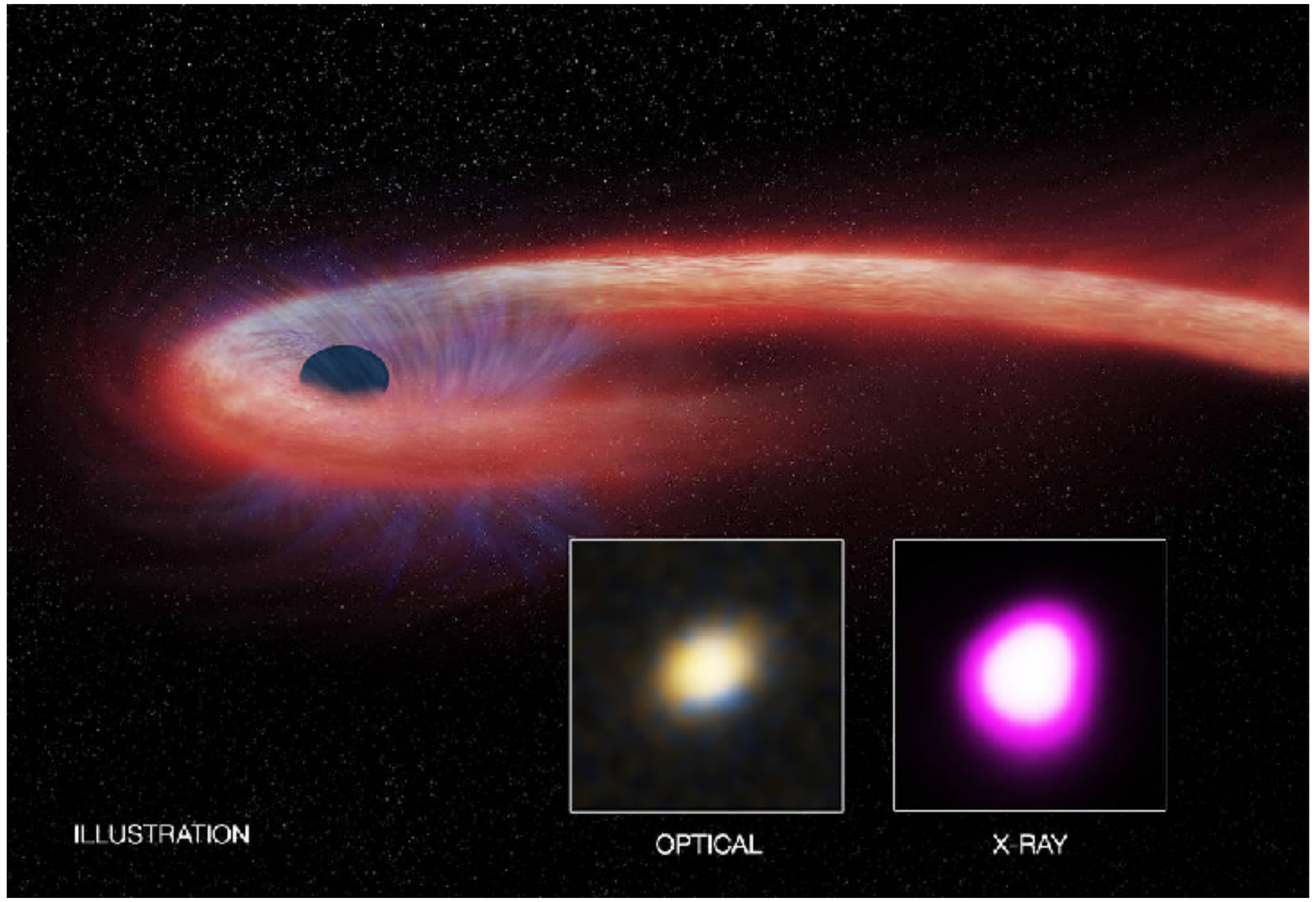
- Rubin/LSST will provide excellent photometric data sets
- Simulations with Rubin/LSST-like photometric data set
- We can achieve TPR ~ 0.3, $N_{\rm bkg} \sim 0.01$
- 1 follow-up cannot say anything
- **We can constrain or support TDE scenario with $N_{\rm trial} \sim 7-9$**



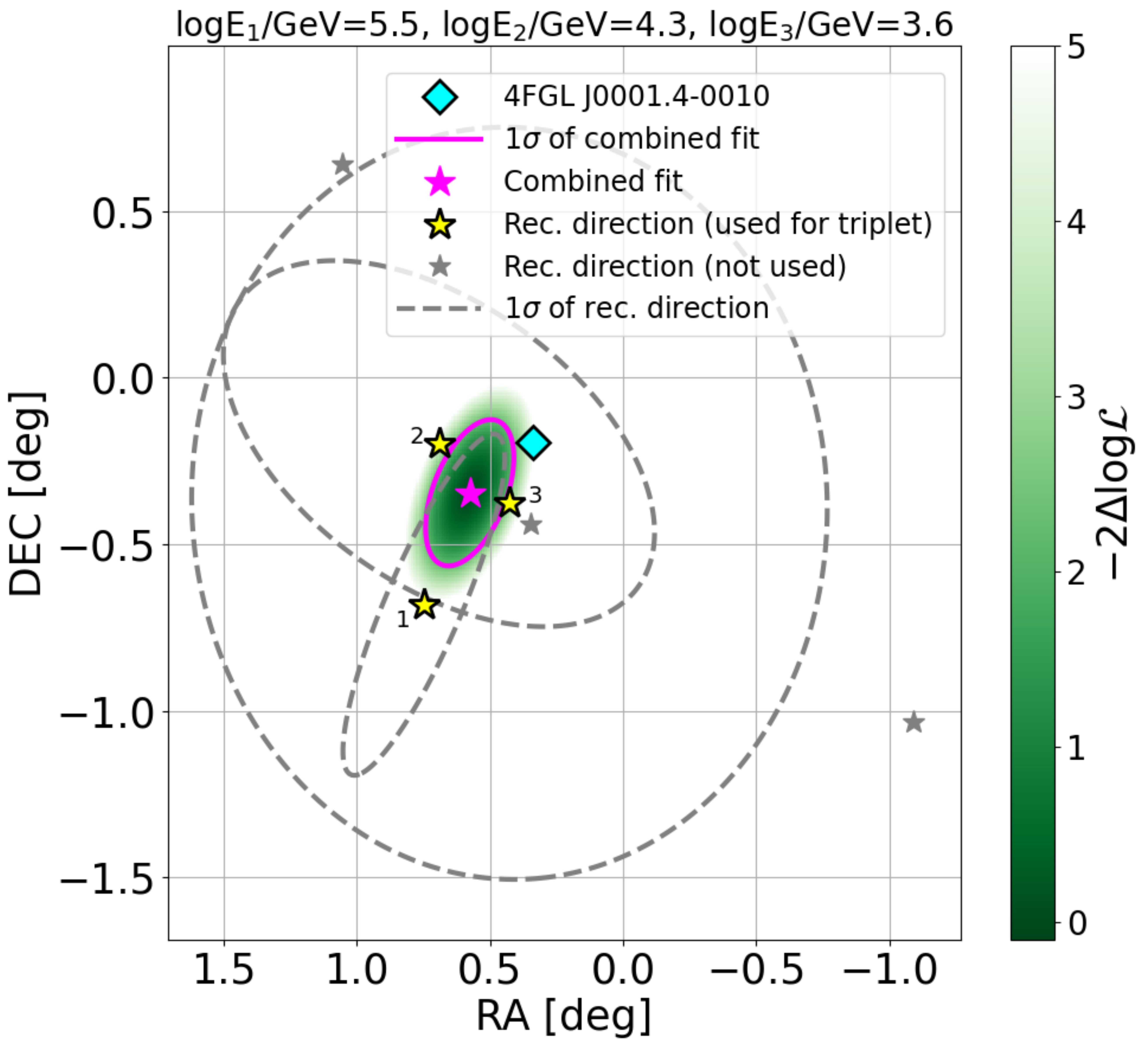
Multiplet Neutrino Alert

- Singlet alert: single neutrino event of high-energy (> 100 TeV)
  => source might be located at a cosmological distance ($z \sim 1$)
- **Multiplet alert**: two neutrino events within a certain time period
  => biased toward the nearby events ($z \lesssim 0.1$)
- Target: Tidal disruption events





Multiplet-alert Candidate



- Long interval (16.4 days)
  => TDE or super-luminous supernovae
- What we can say if we do not find any optical transients
- Perform a **"Blind analysis"** to constrain neutrino-emitting transients

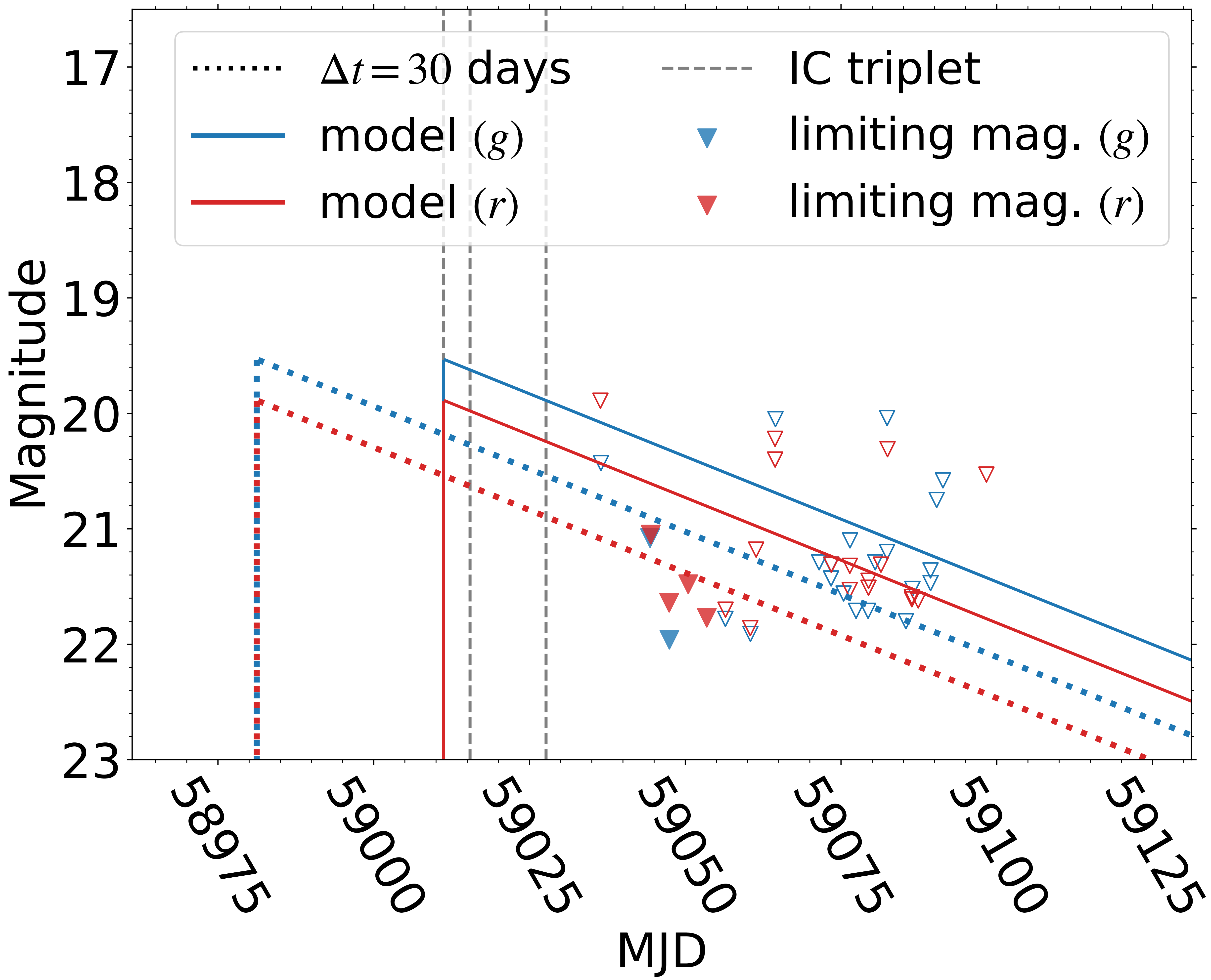
Strategy to constrain transients

- We are trying to obtain "generic" constraint on transients
  => adopt a simple-phenomenological lightcurve

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

- 3 parameters:

$$\boxed{t_{\rm decay},\ \ L_{\rm pk},}\ \Delta t = (t_{\rm pk} - t_{\nu,1})$$

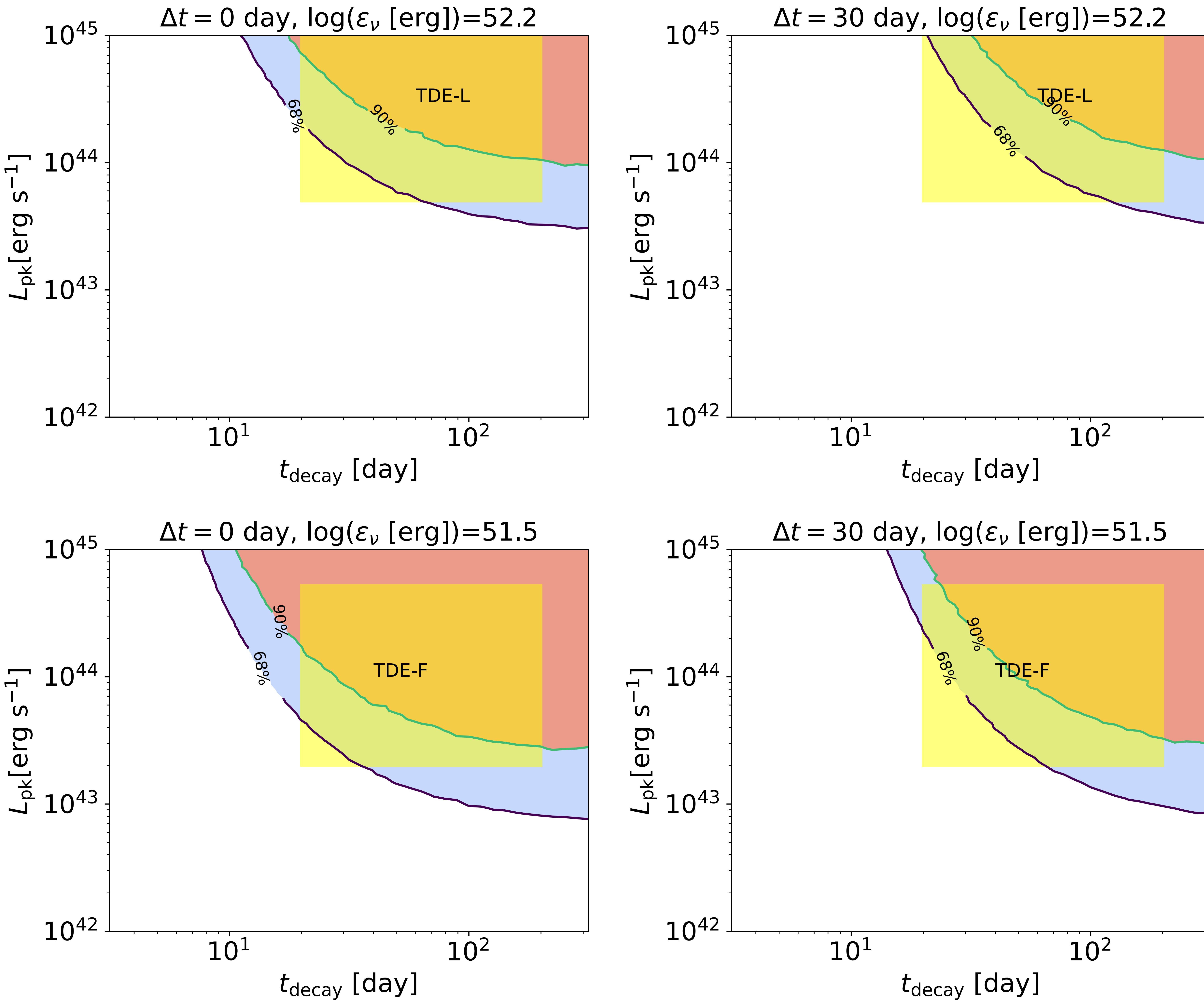


Constraints by ZTF data

- Simplified lightcurve:

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

- 3 parameters:
  $t_{\rm decay},\ \ L_{\rm pk},\ \ \Delta t = (t_{\rm pk} - t_{\nu,1})$
- Use ZTF data to discuss detectability
- Luminous & long-duration transients are strongly disfavored by ZTF data
- If this triplet event is true, we can put very strong constraint on transient neutrino sources



Capability of X-ray Wide-field satellites

- Current multiplet alert (track+track): z ~ 0.1, Error region ~ 0.5 deg^2

  $L_X \sim 10^{44}$ erg/s => $F_X \sim 3.5 \times 10^{-12}$ erg/s/cm^2

  <= easily detectable by XRISM/Xtend for 4 pointing

- Current multiplet alert has high false alarm rate (Signalness ~ 0.3)

- Multiplets with shower+shower: z ~ 0.01-0.1, Error region ~ 10 deg^2

  - lower false alarm rate, but bigger uncertainty range

- EP & HiZ-GUNDAM have sufficiently large FoV & good sensitivity

  => monitoring of error region would provide a better constraints

  (FoV: ~ 3000 deg^2, $F_{\rm sen} \sim 3 \times 10^{-12}$ erg/s/cm^2 for t ~ 10^5 sec)

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
  => Rubin/LSST will enable us to
- Multiplet alert will be key to identify cosmic neutrino sources
  => Report of triplet event candidate in archival data,
  => **we can put strong constraint on SLSN-like & TDE-like transients with archival optical data**
- **X-ray follow-up on multiplets will be useful to constrain X-ray transients as neutrino sources**

Thank you for your attention