超巨大ブラックホール周囲からの高エネルギーニュートリノ放射

Tohoku University

Shigeo S. Kimura

Collaborators:

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- Seiji Toshikage, Masaomi Tanaka (Tohoku U.)
- Tomoki Morokuma (Chiba Tech), Nozomu Tominaga (NAOJ)
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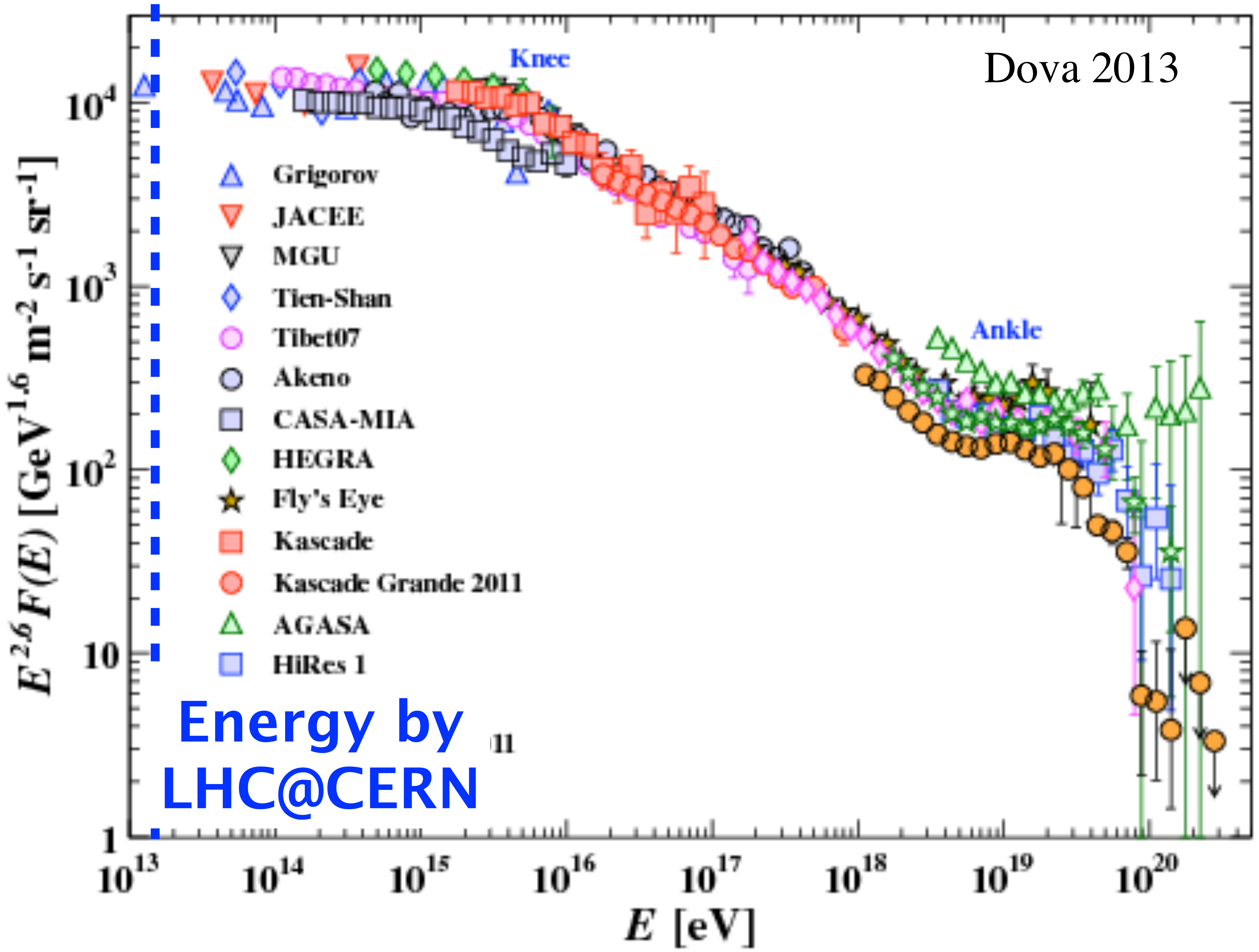
Extreme Transients 2024/08/05-09

Outline

- Introduction
- High-energy Neutrinos from Accretion Flows onto SMBHs
- Optical Follow-up Observations to Cosmic Neutrino Events
- Summary

Cosmic-Rays (CRs)

：High-energy atomic nuclei filling the Universe

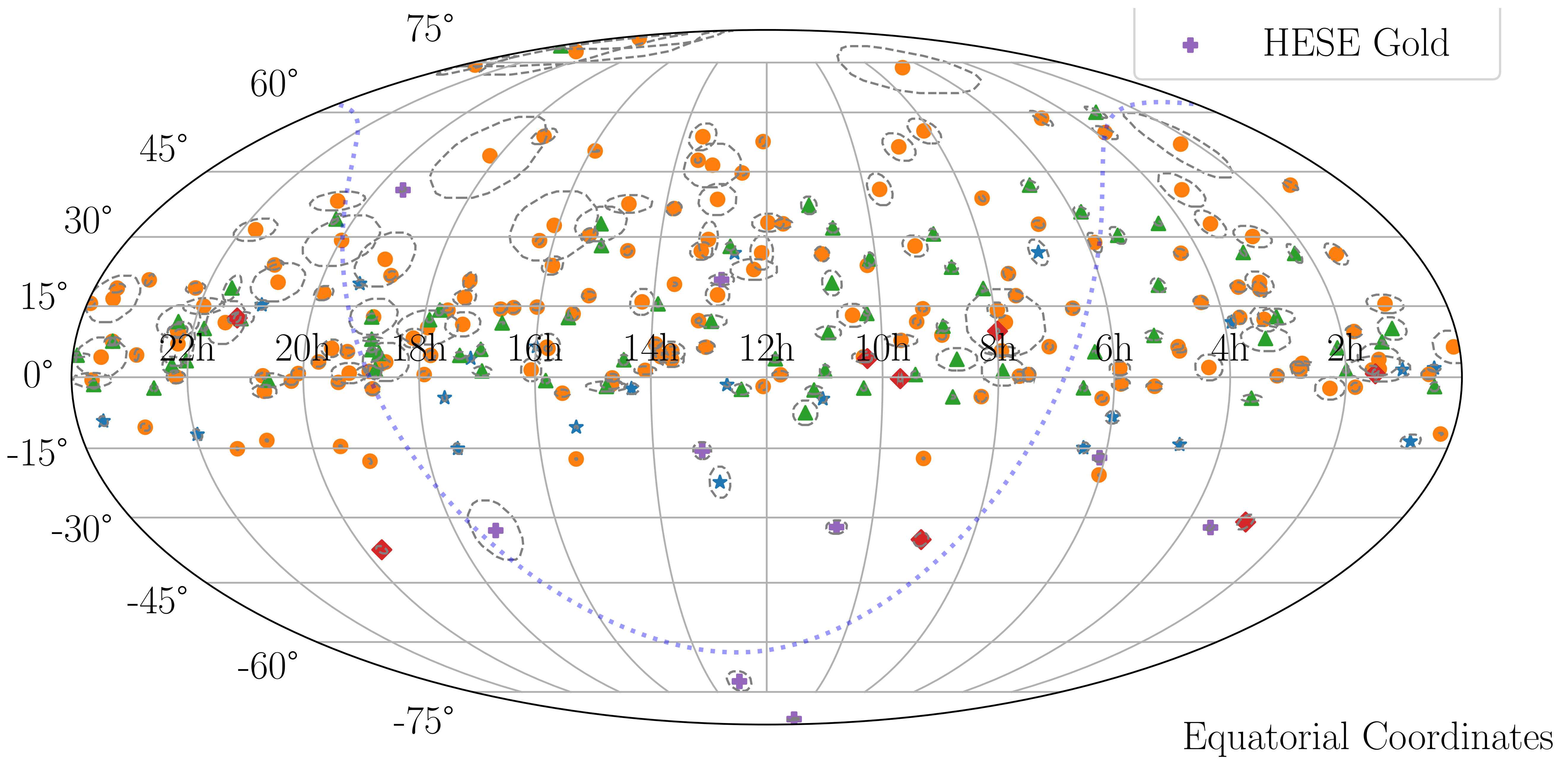


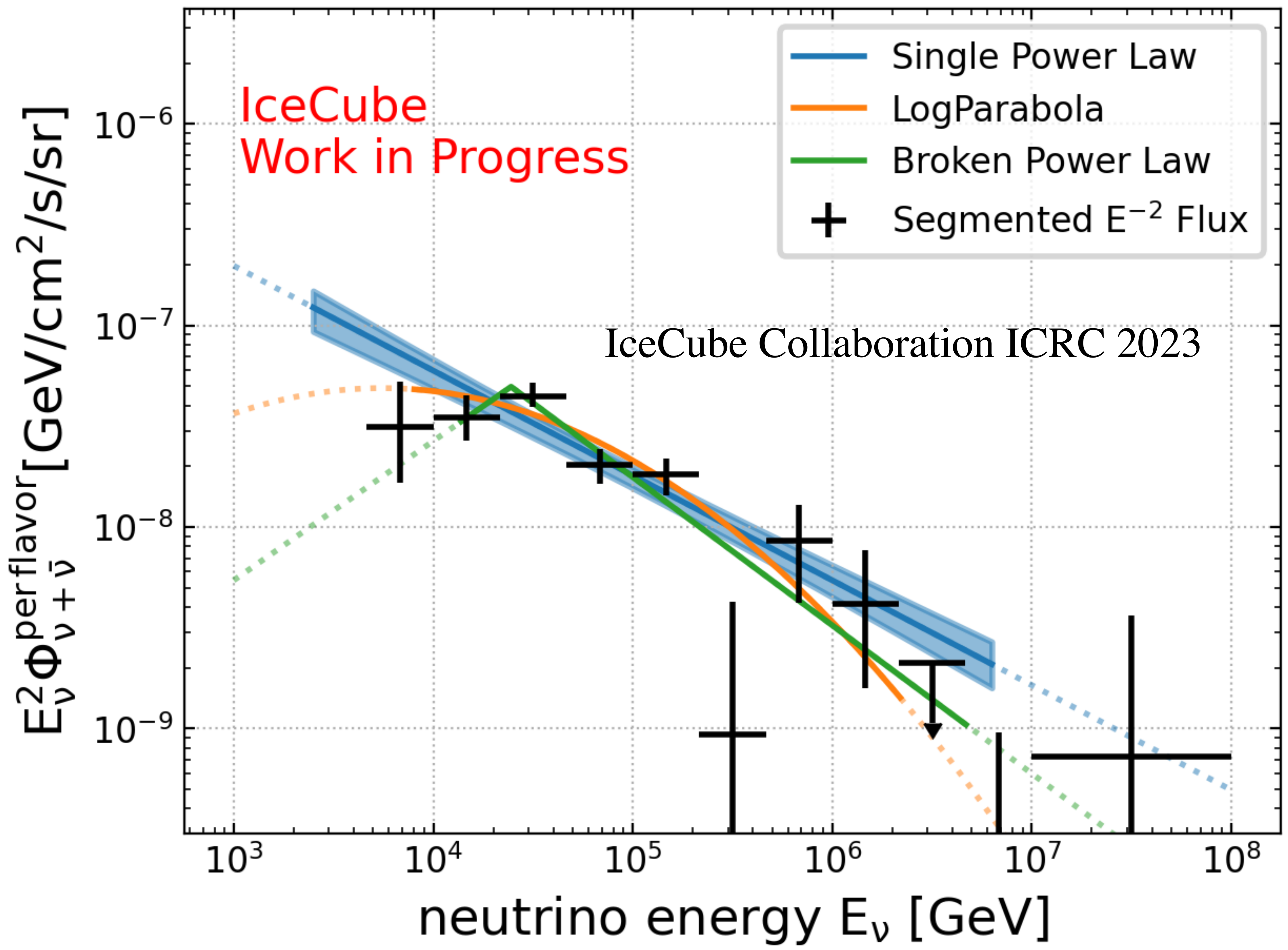
Origin of CRs have been unknown for a century

Challenges to identify cosmic-ray sources

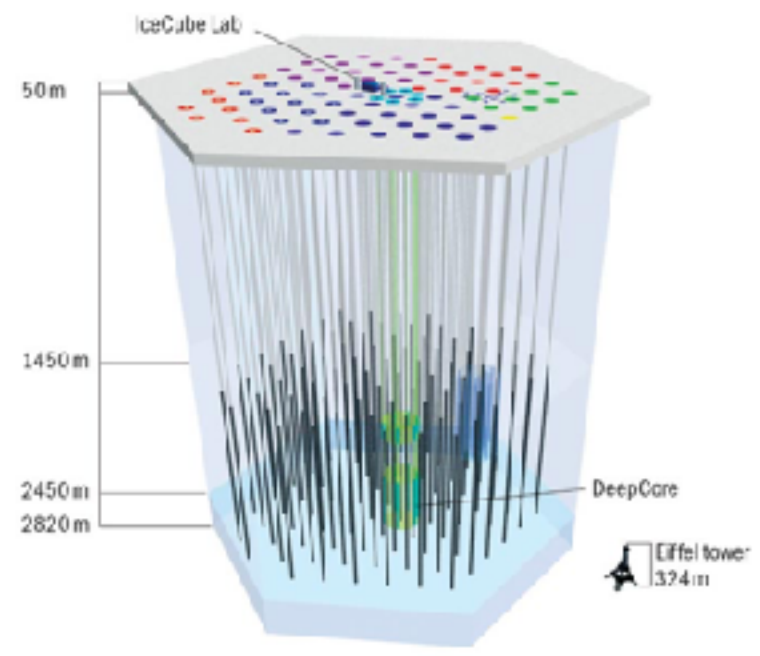
Multi-messenger Astrophysics

Detection of Cosmic High-energy Neutrinos



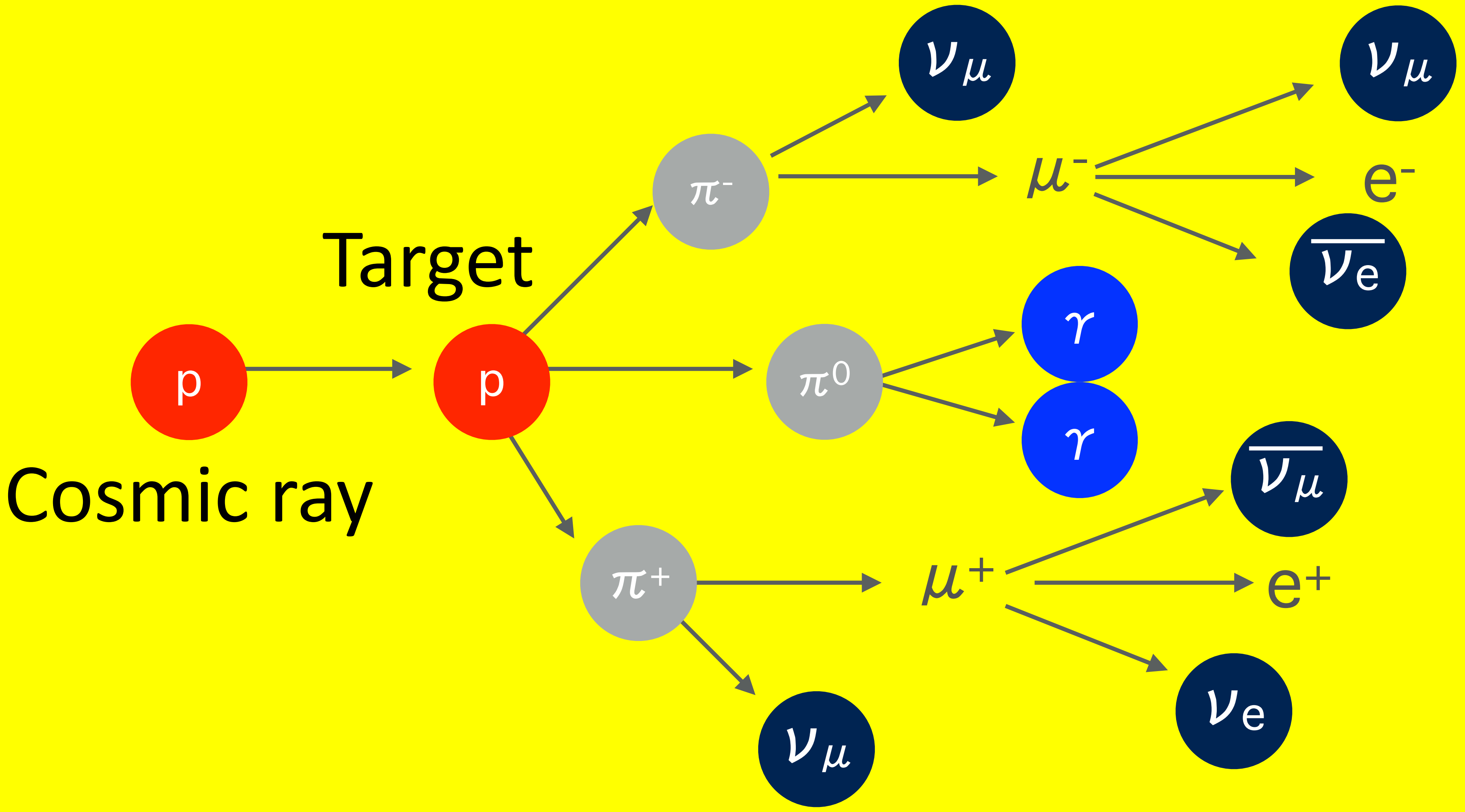


- IceCube has been detecting astrophysical neutrinos
- Arrival direction: consistent with isotropic —> cosmic HE neutrino background
- Soft spectrum: F_{E_ν} @ TeV > F_{E_ν} @ PeV
- **Origin of cosmic neutrinos are a new big mystery**



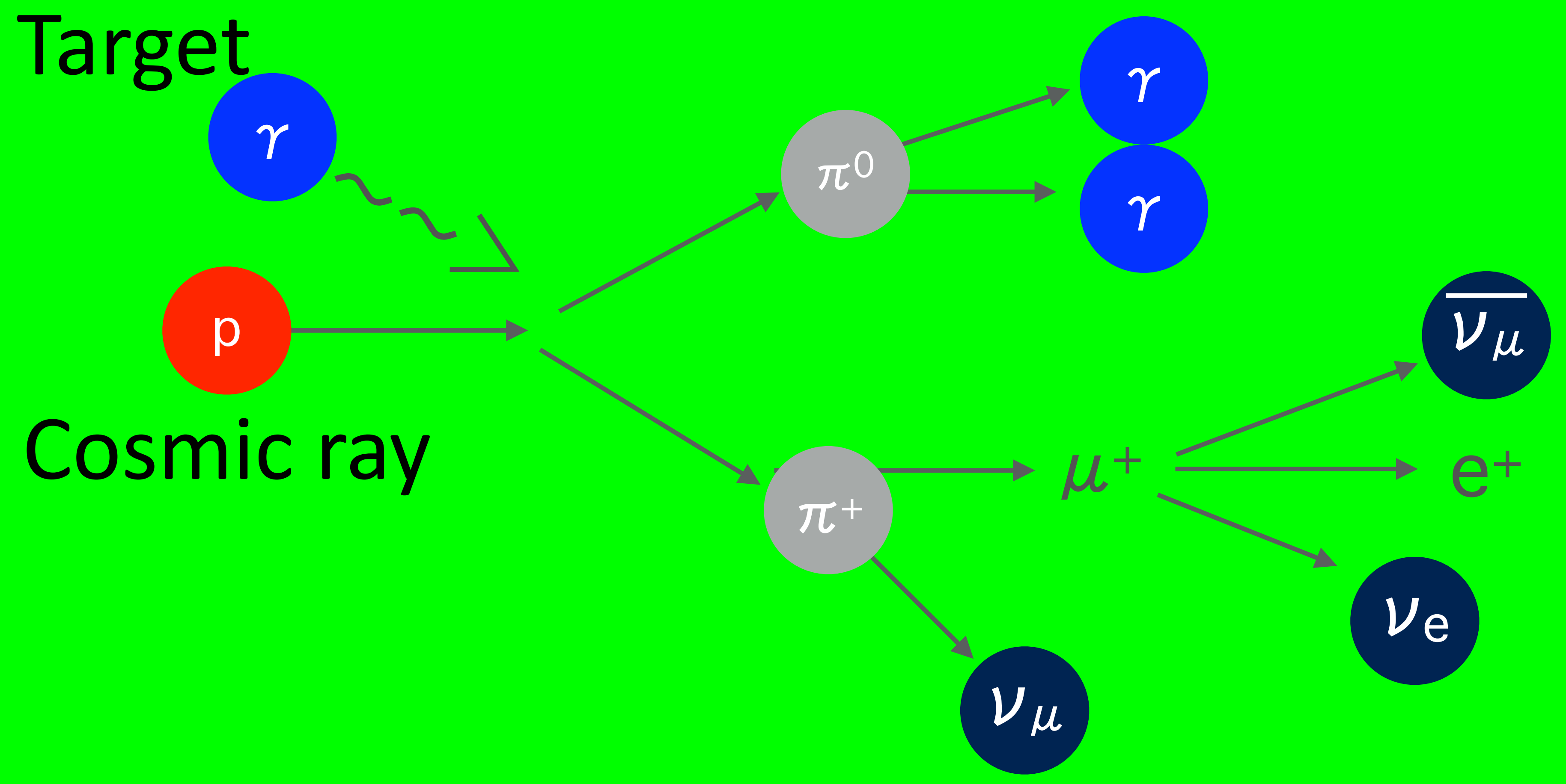
High-energy neutrino production

- pp inelastic collision



- $p+p \rightarrow p+p+\pi$
- $\pi^{\pm} \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

- Photomeson production ($p\gamma$)



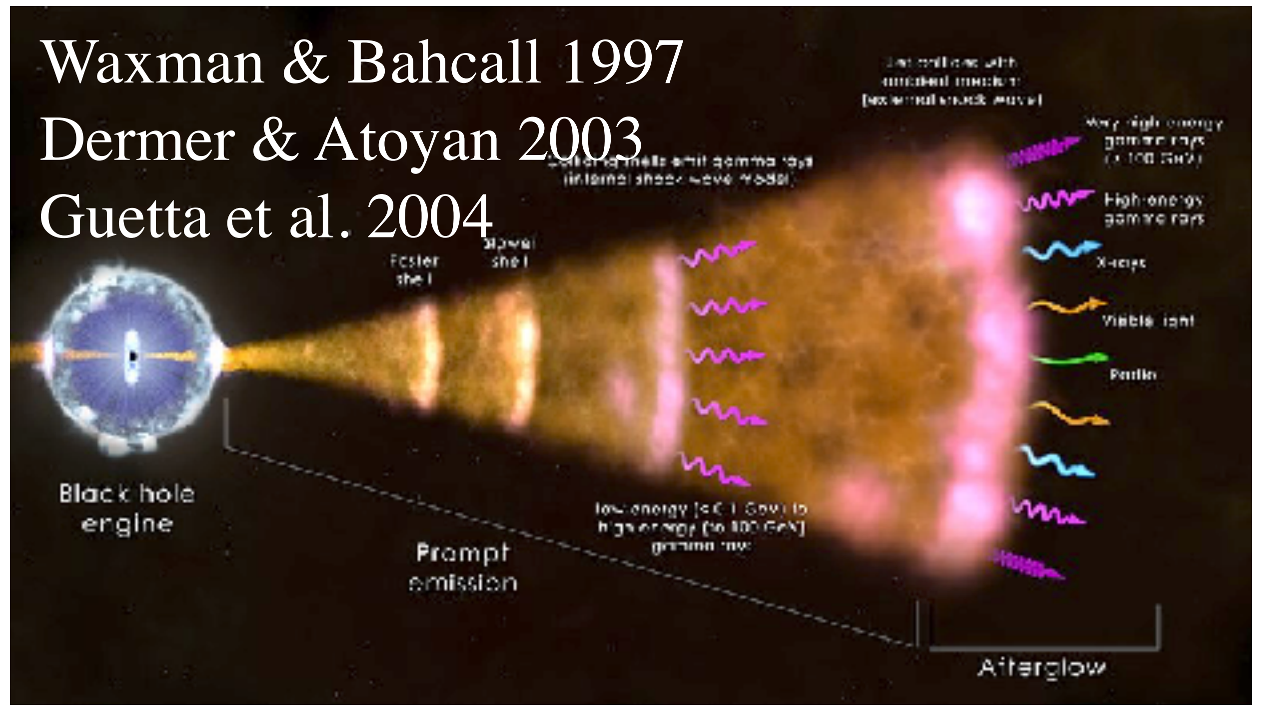
- $p+\gamma \rightarrow p+\pi$
- $\pi^{\pm} \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

Interaction between CRs & photons/nuclei → Neutrino production

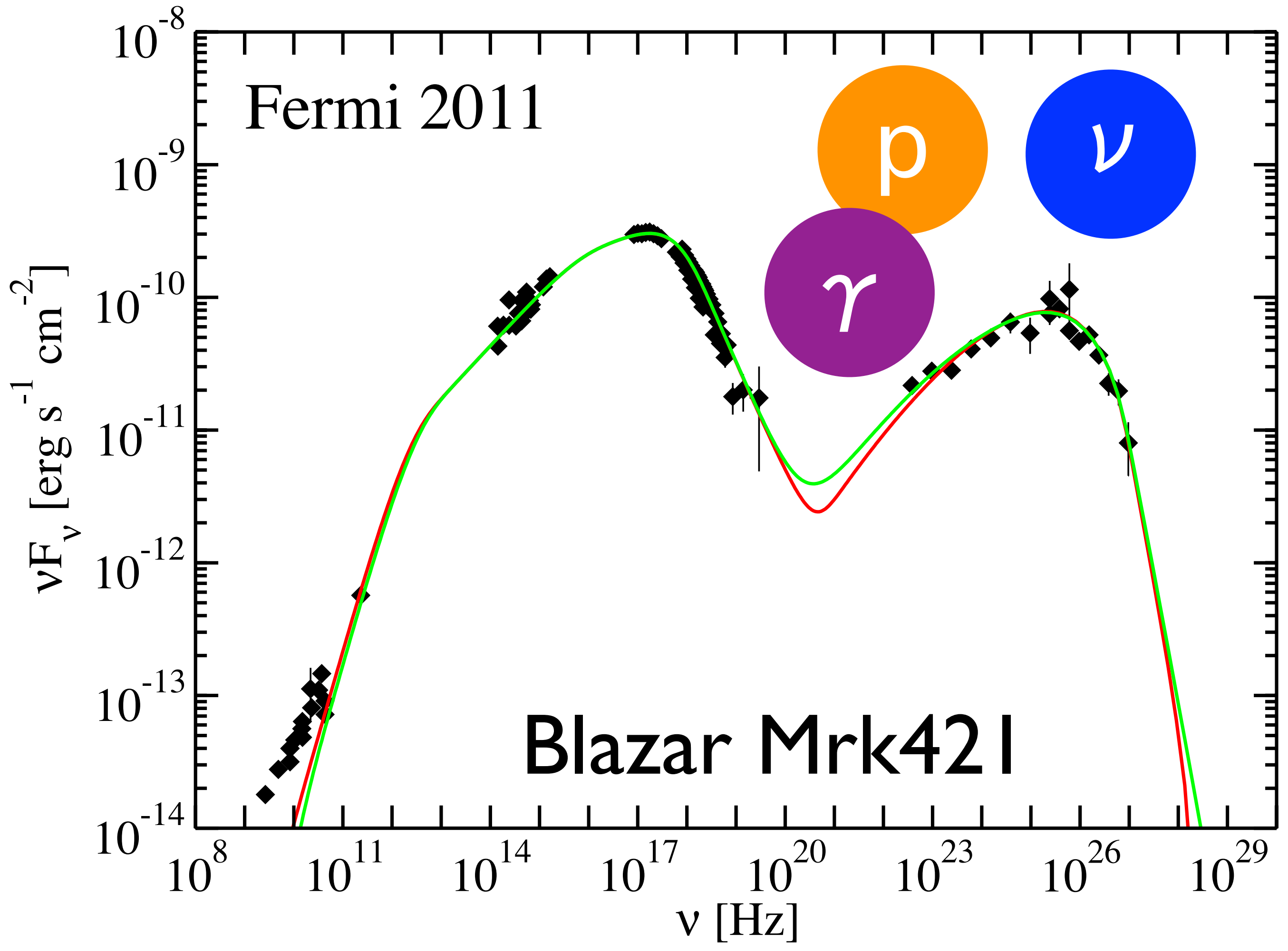
Gamma-rays inevitably accompanied with neutrinos

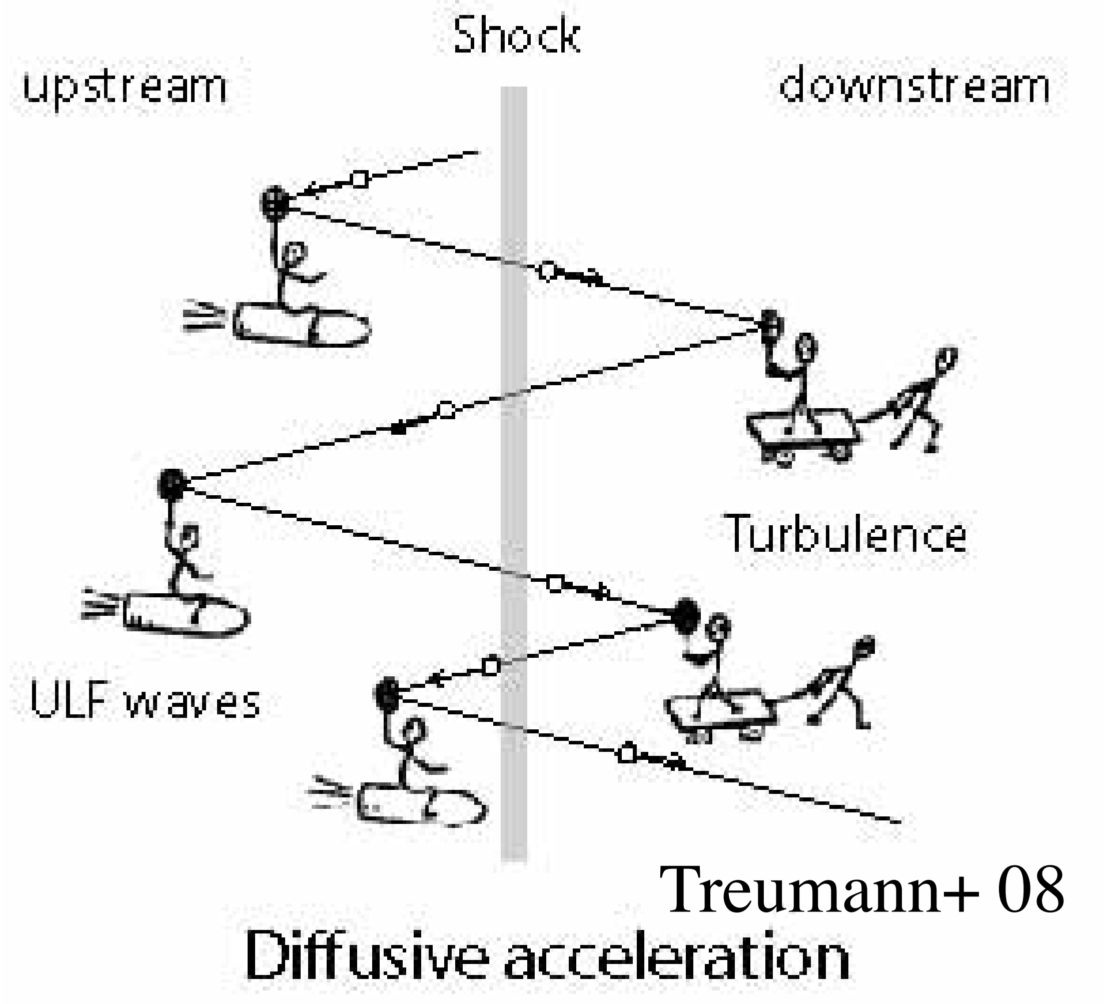
Neutrino Source Candidates in Pre-IceCube Era

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

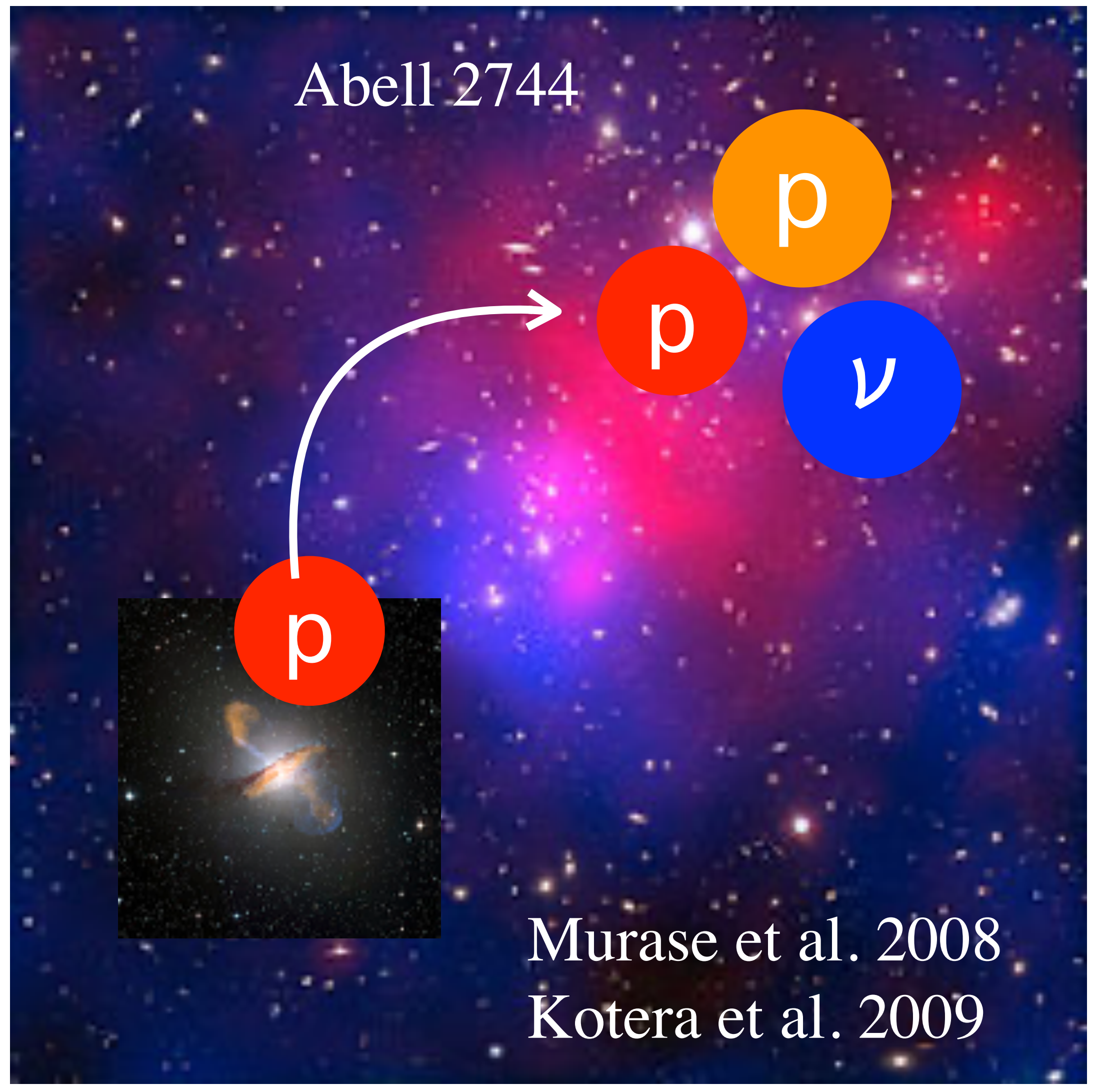


  - Blazars

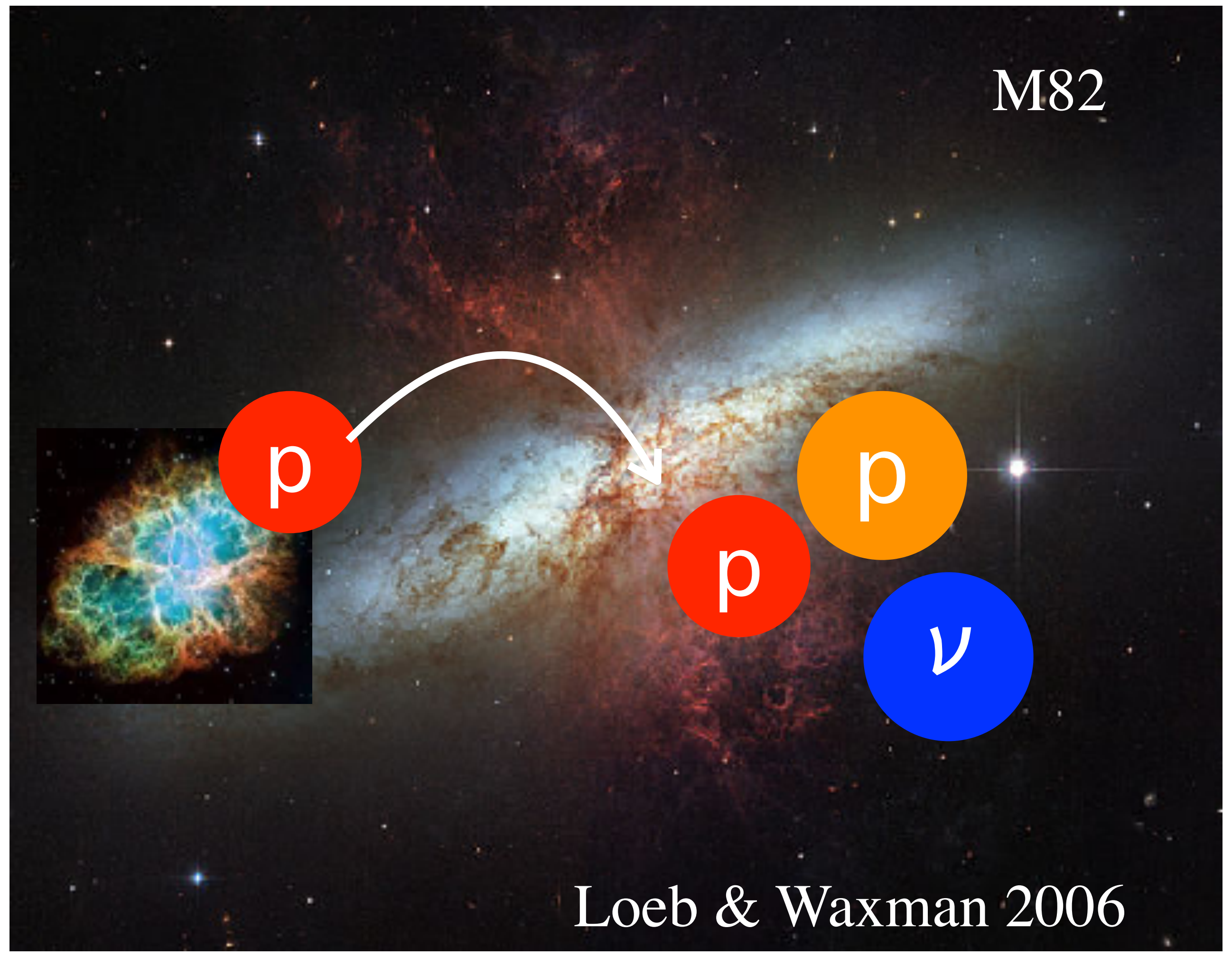




- **Cosmic-ray Reservoirs** pp
  - Galaxy Clusters



  - Starburst Galaxies



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

Neutrino Source Candidates in Pre-IceCube Era

- **Gamma-ray Bursts**
- **Jetted AGN (Blazars)**

- Very bright non-thermal gamma-rays
  => Existence of cosmic-ray electrons
- **If protons are also accelerated, they will emit neutrinos**

Neutrino Source Candidates in Pre-IceCube Era

- **Gamma-ray Bursts**
- **Jetted AGN (Blazars)**

No neutrinos from the direction & timing of GRBs

No neutrinos from direction of γ–ray detected blazars

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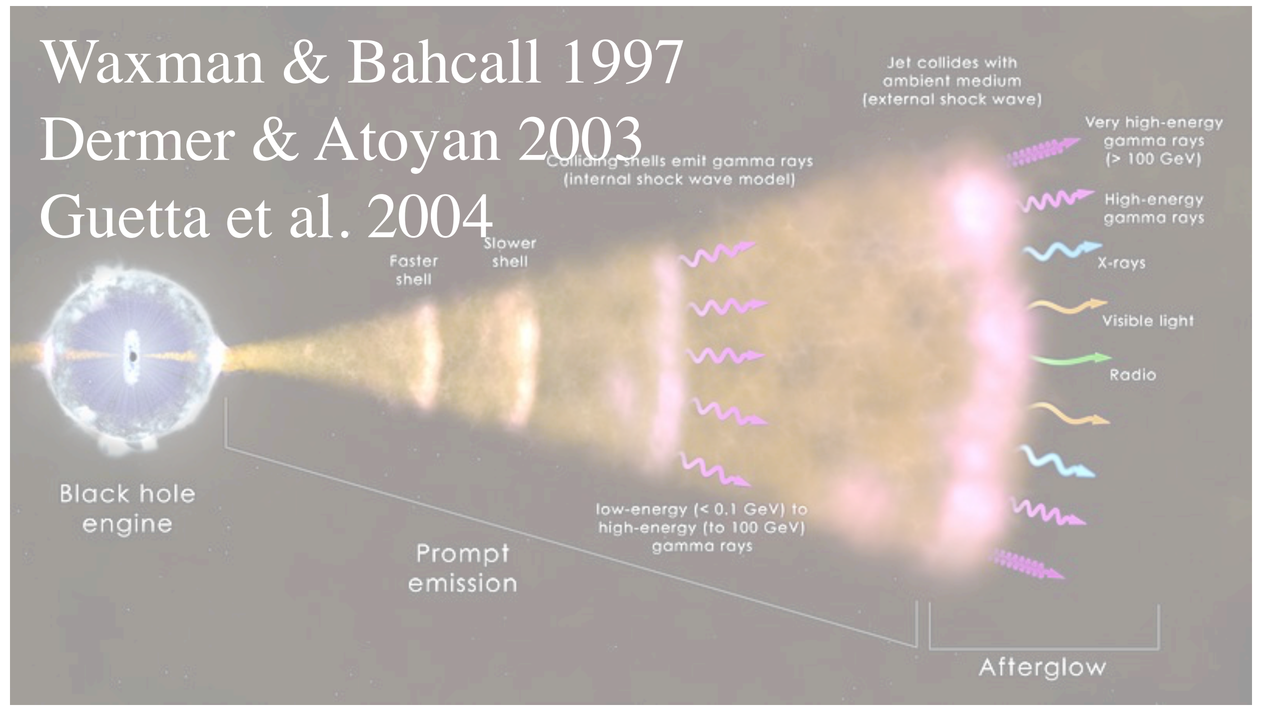

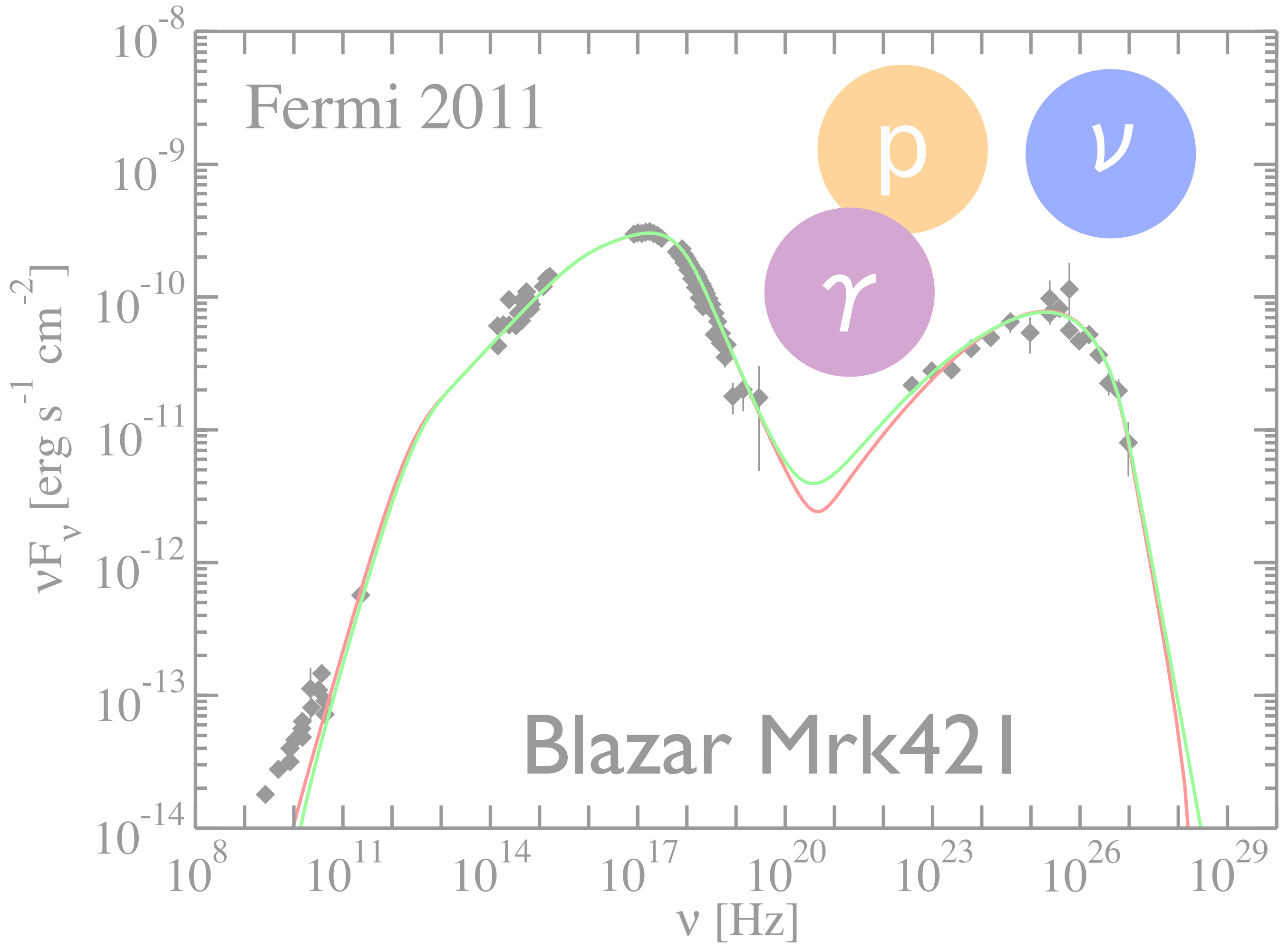

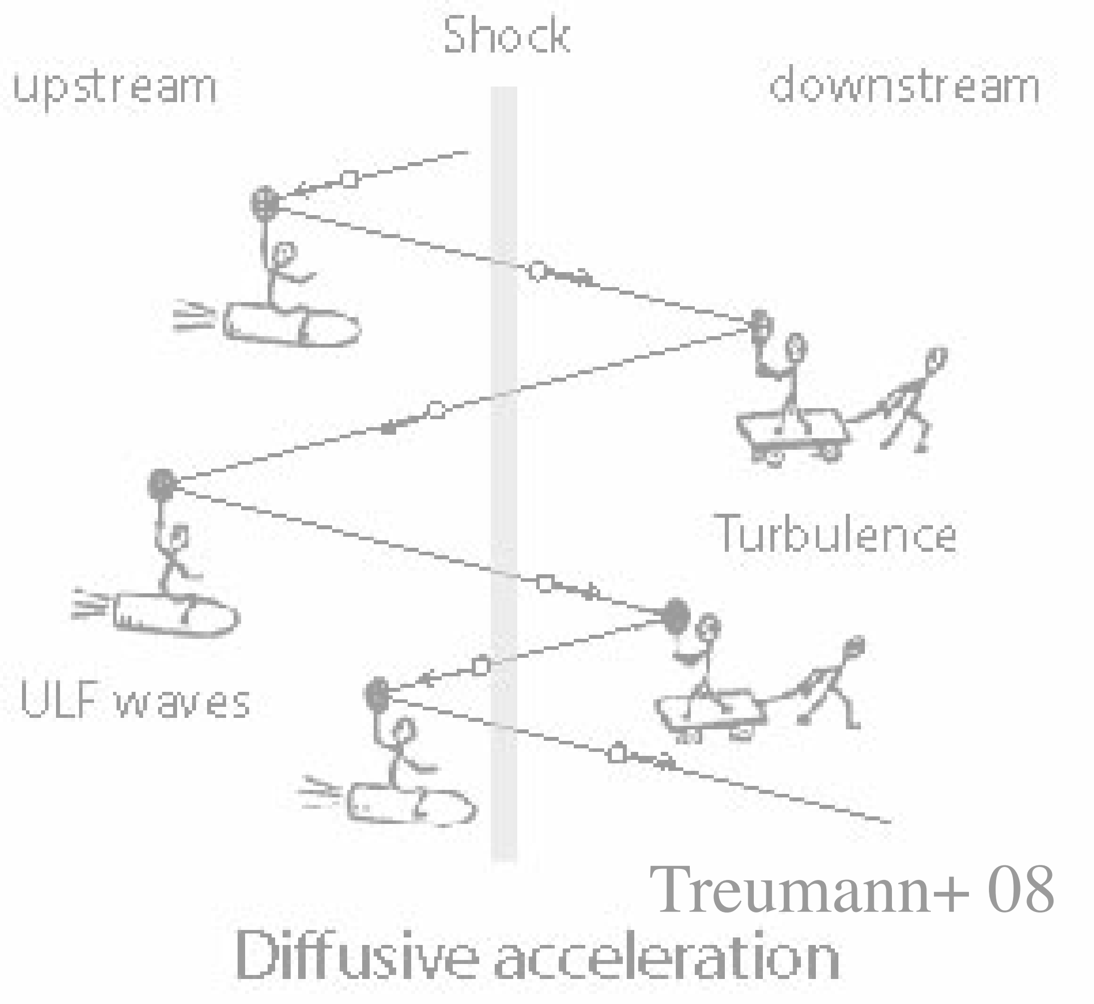

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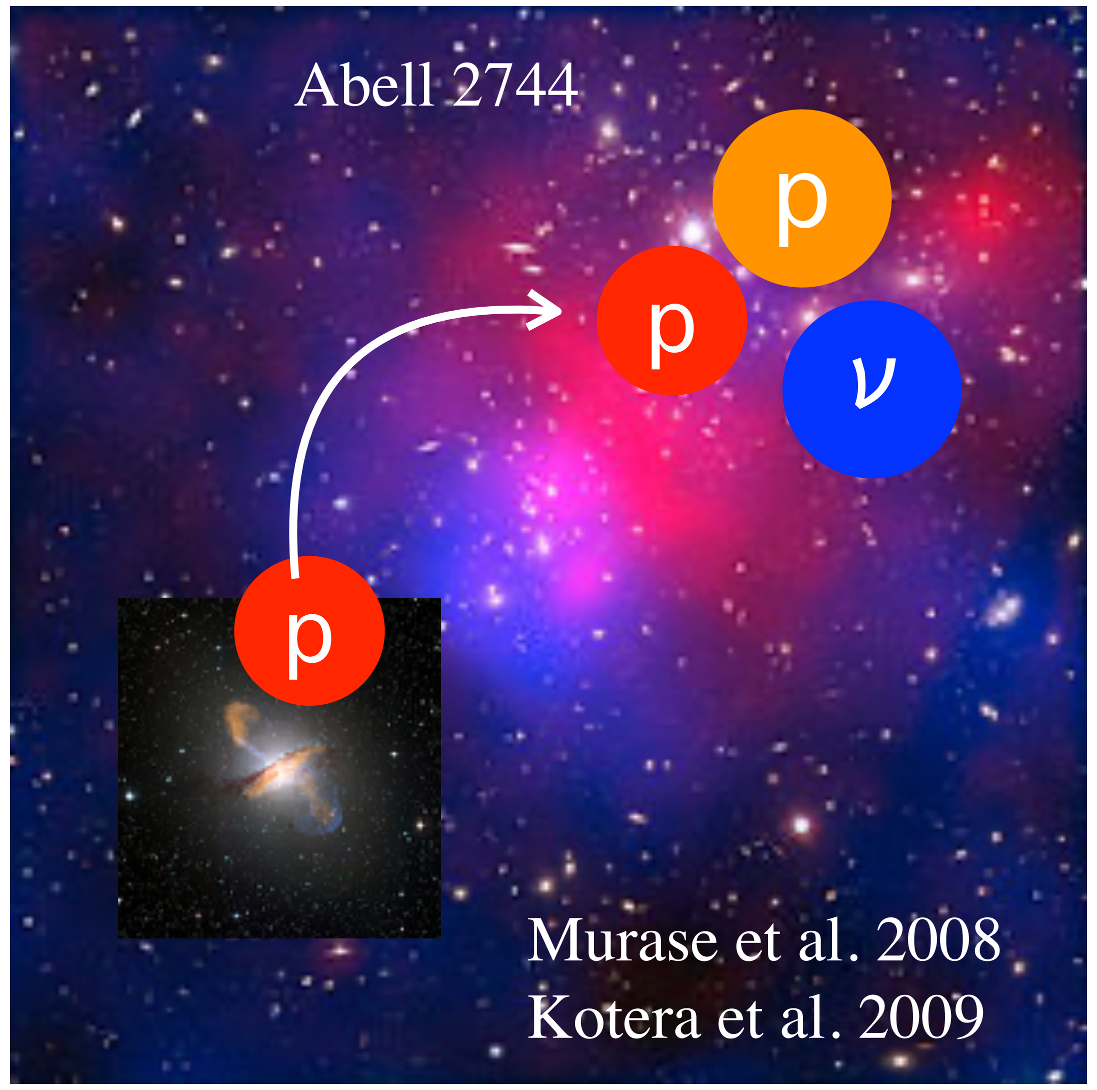

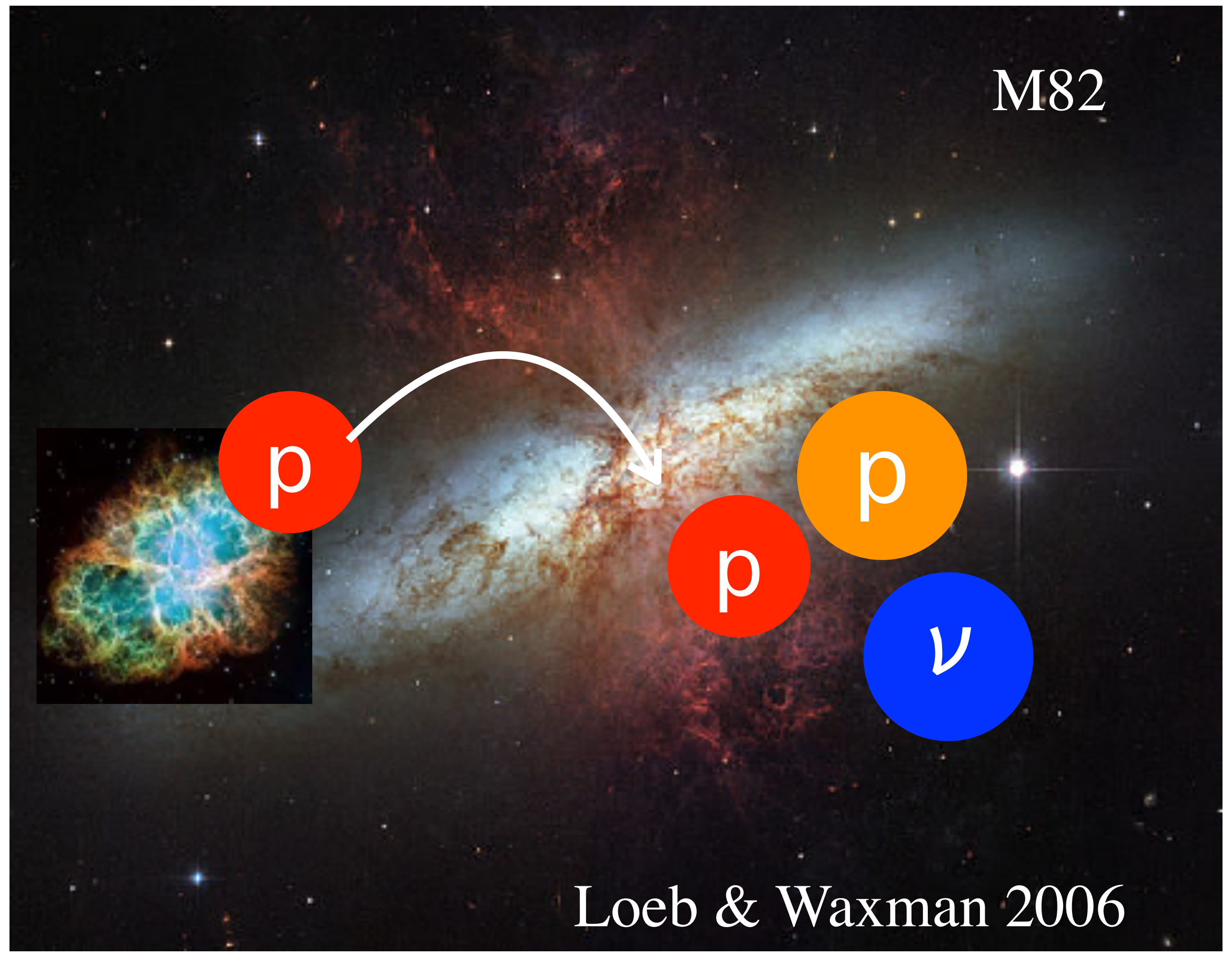

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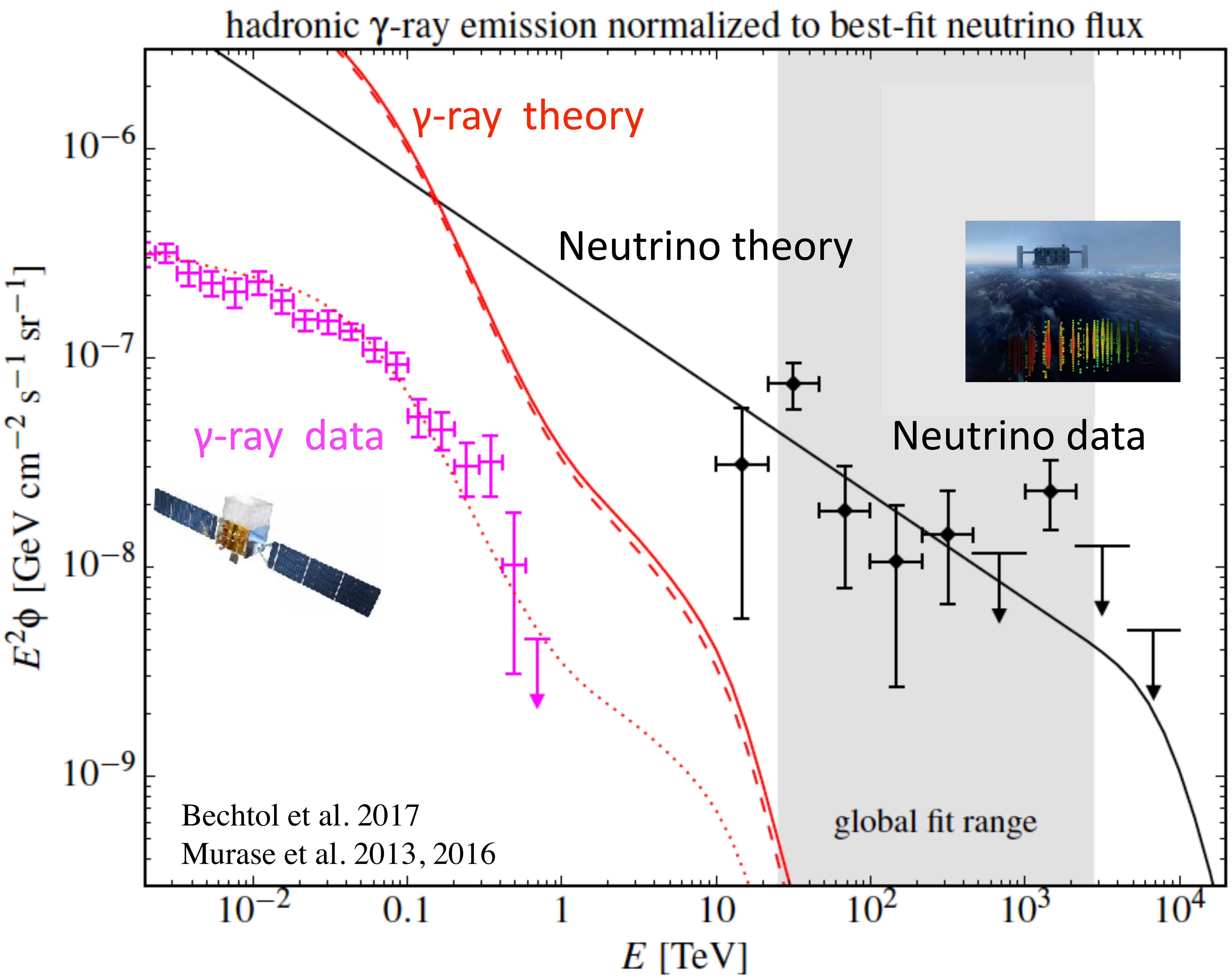
Gamma-ray Constraint on Neutrino Sources

- Fermi Satellite is measuring cosmic gamma-ray backgrounds
- ν flux@10 TeV > γ-ray flux@100 GeV
- Consider sources from which both γ & ν can easily escape
  → fit theory to neutrino data
  → γ-ray theory >> γ-ray data
- **γ-ray needs to be absorbed inside the sources (hidden source)**
  $\gamma + \gamma \rightarrow e^+ + e^-$
- γ rays freely escape from reservoirs
  => contradict with γ-ray data



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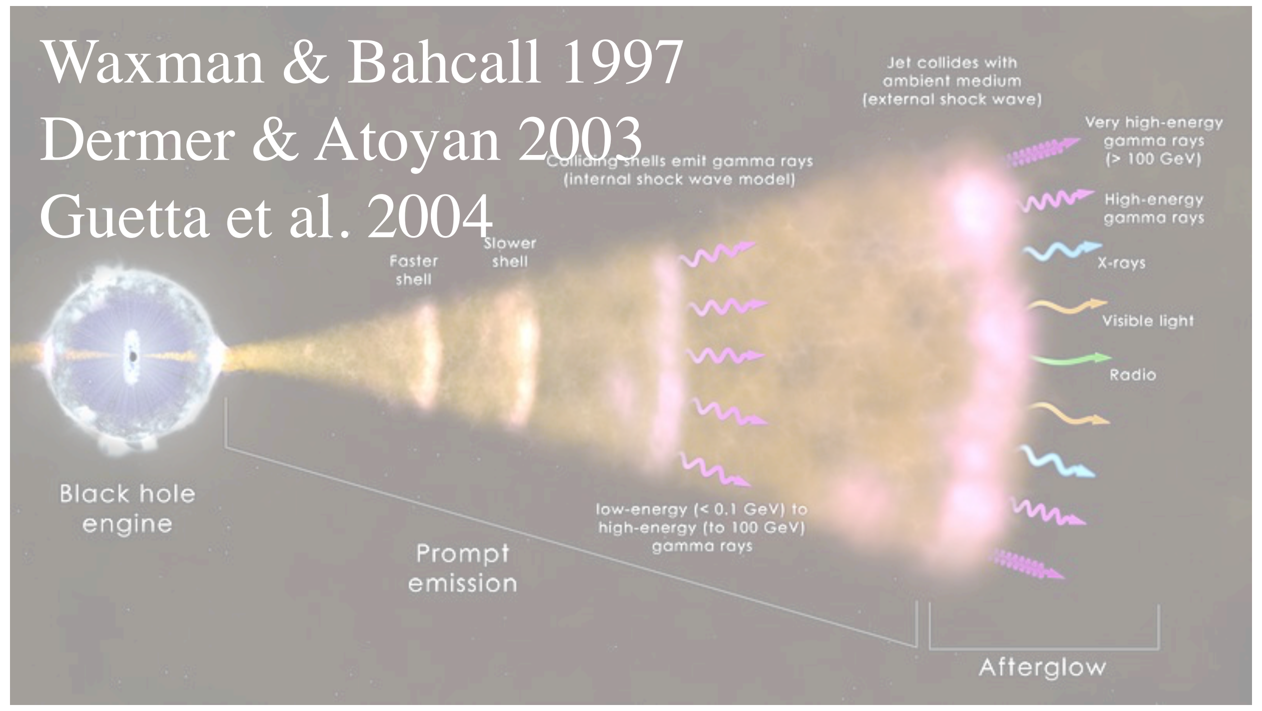
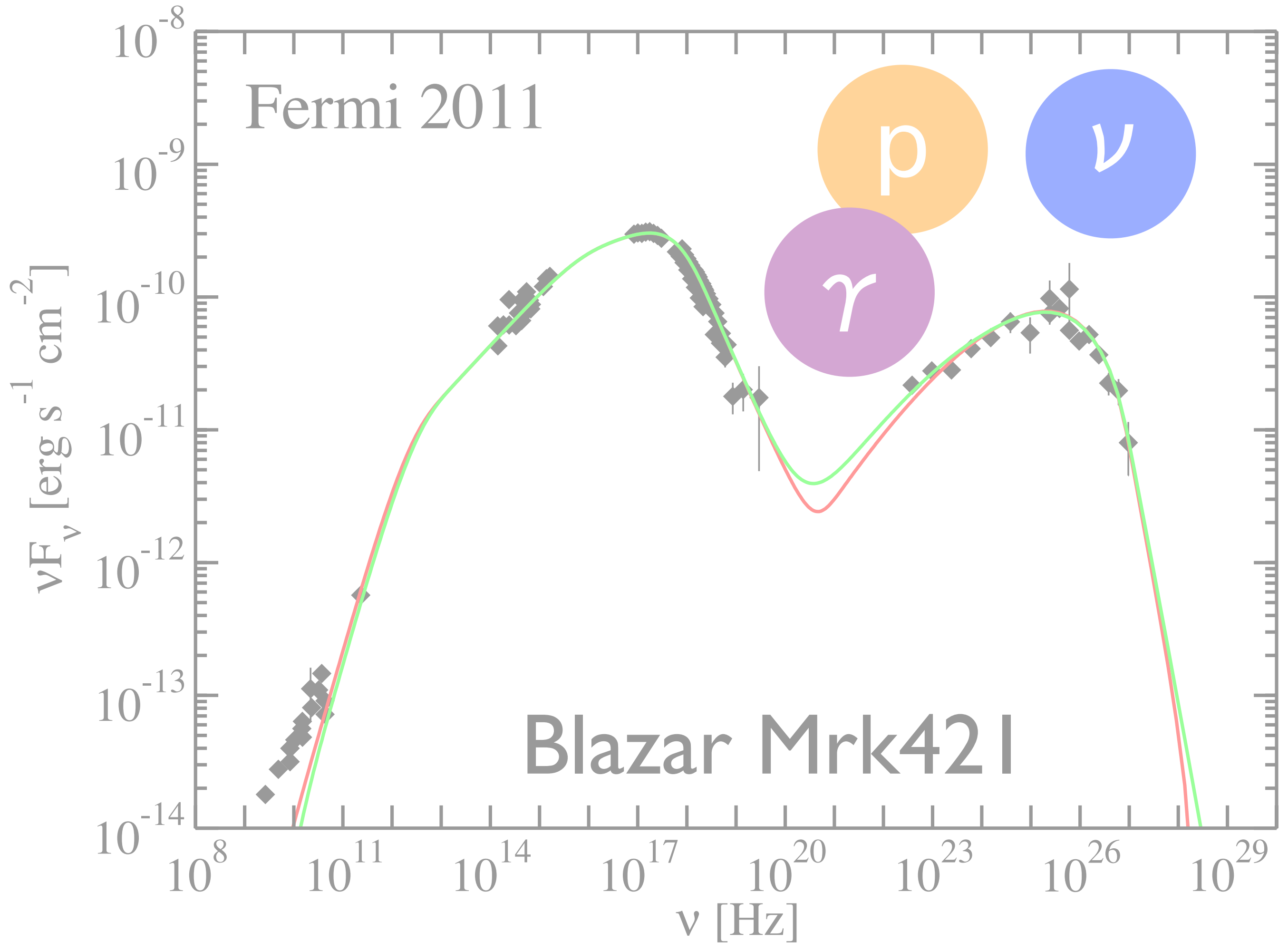
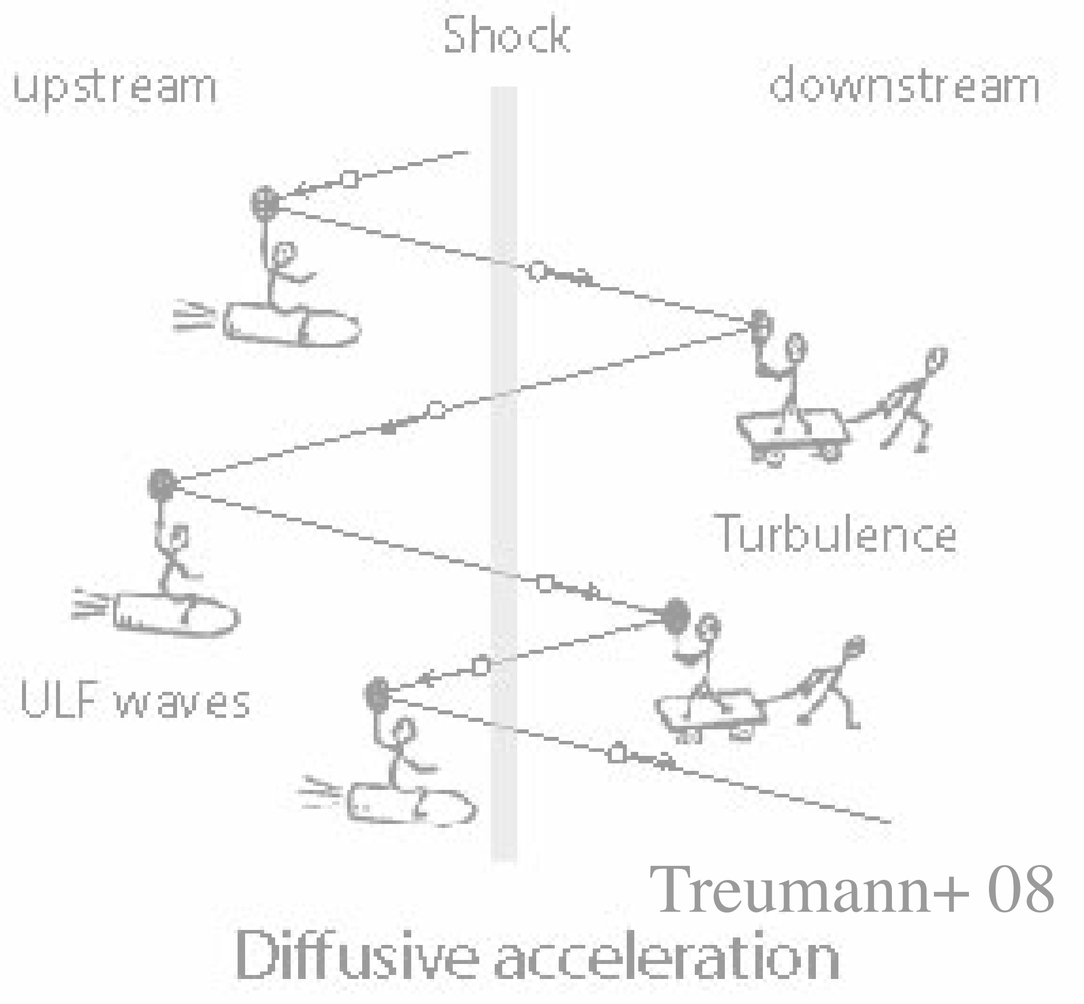


  - Blazars





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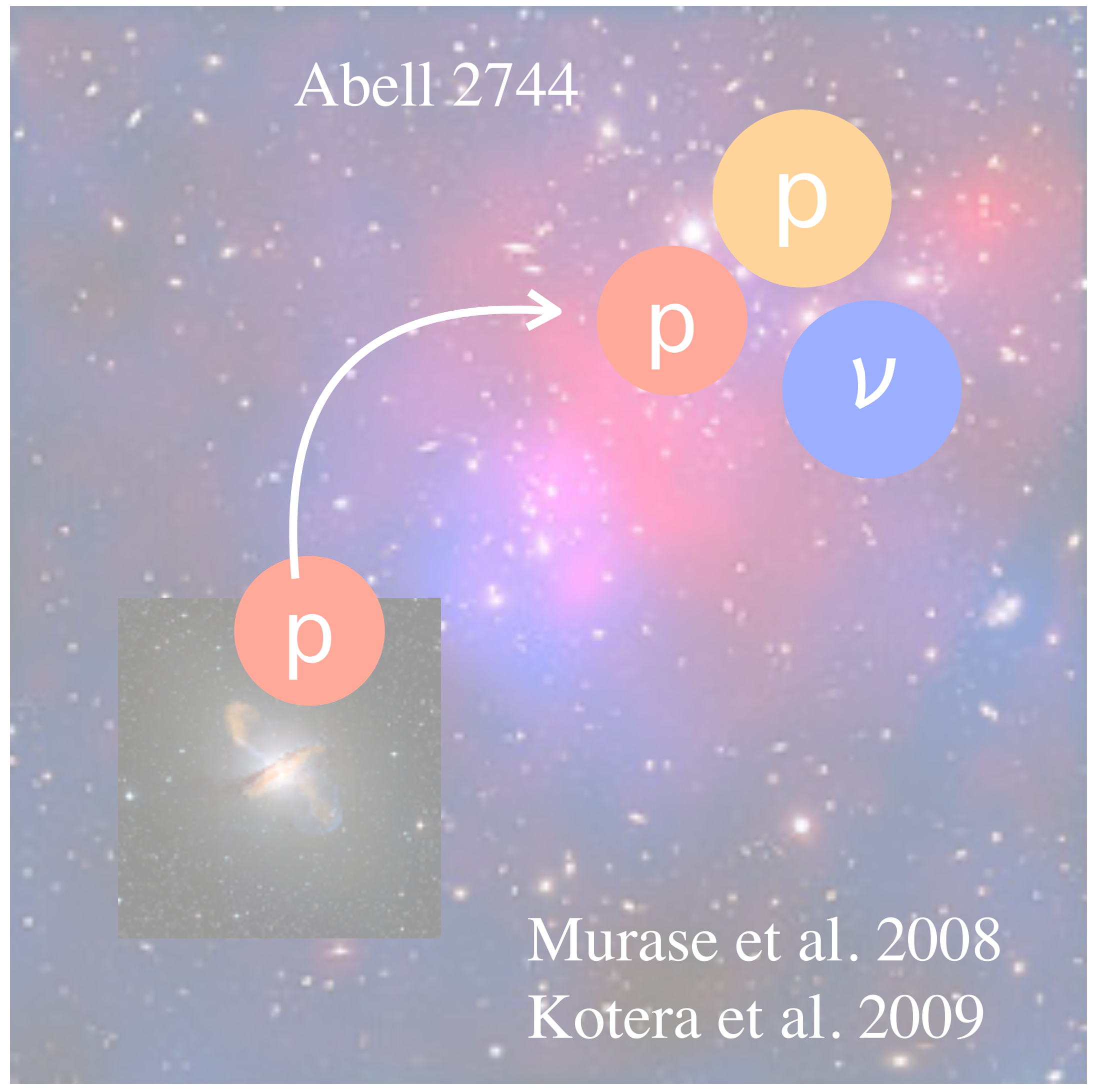

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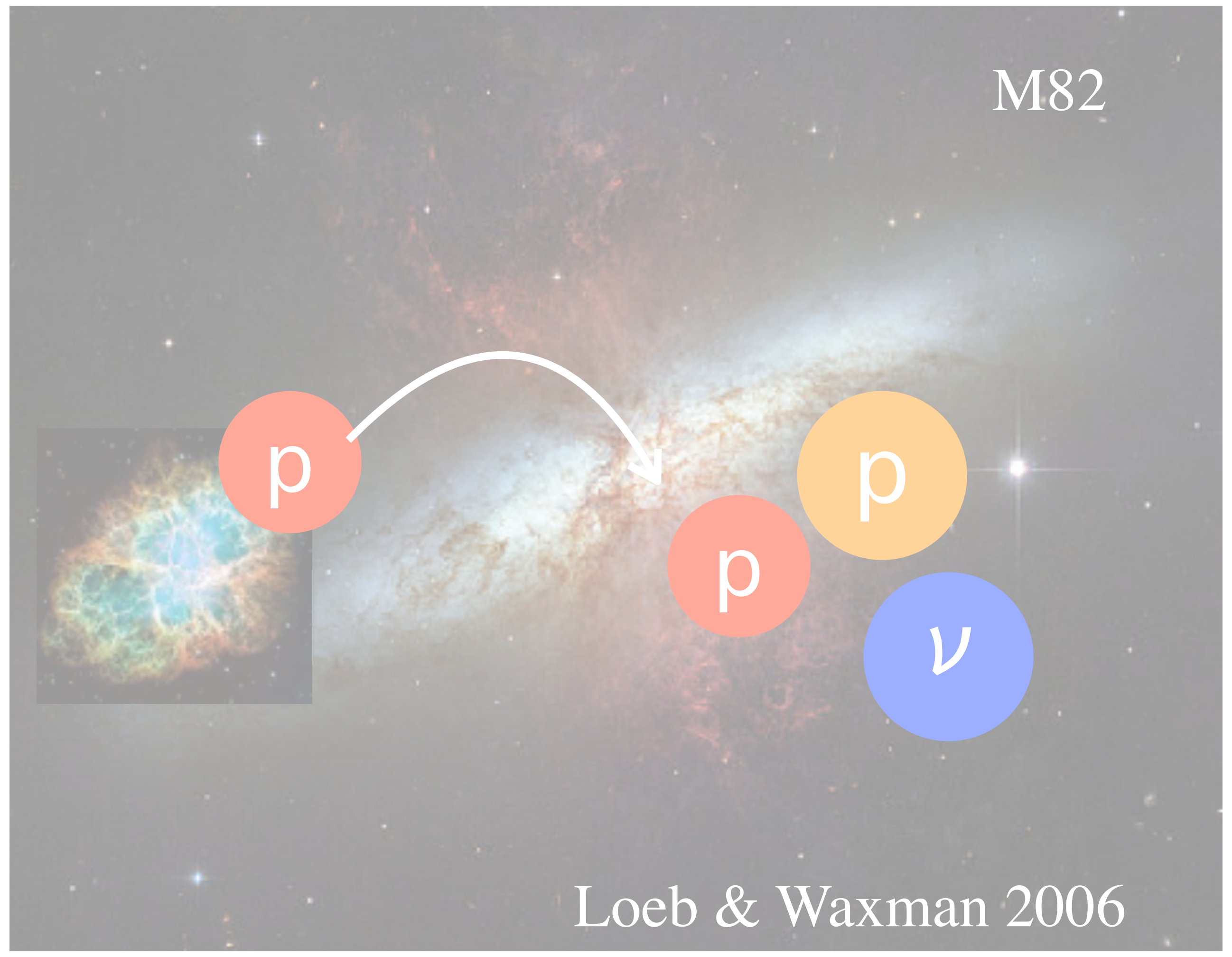

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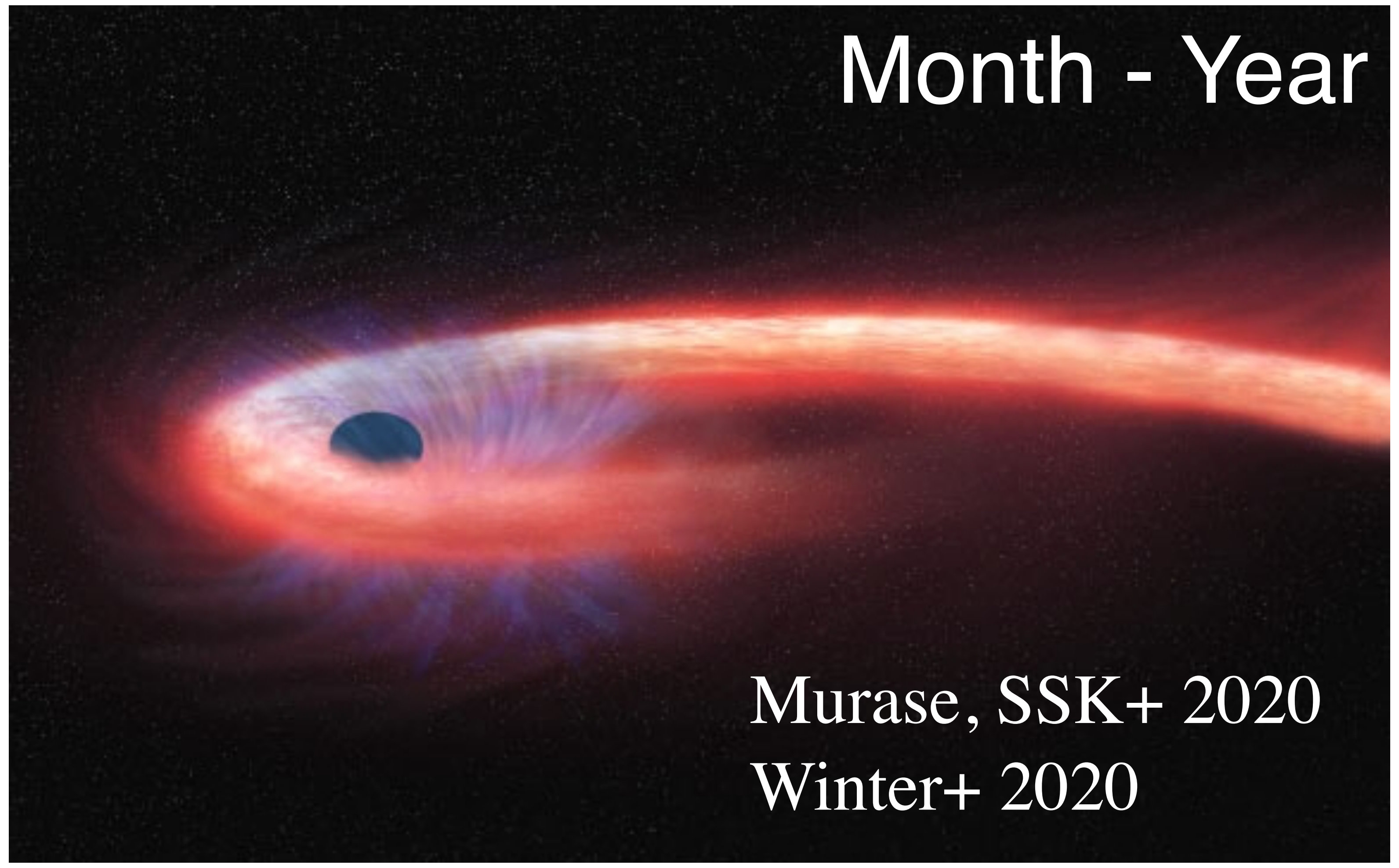
Current Source Candidates

- 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

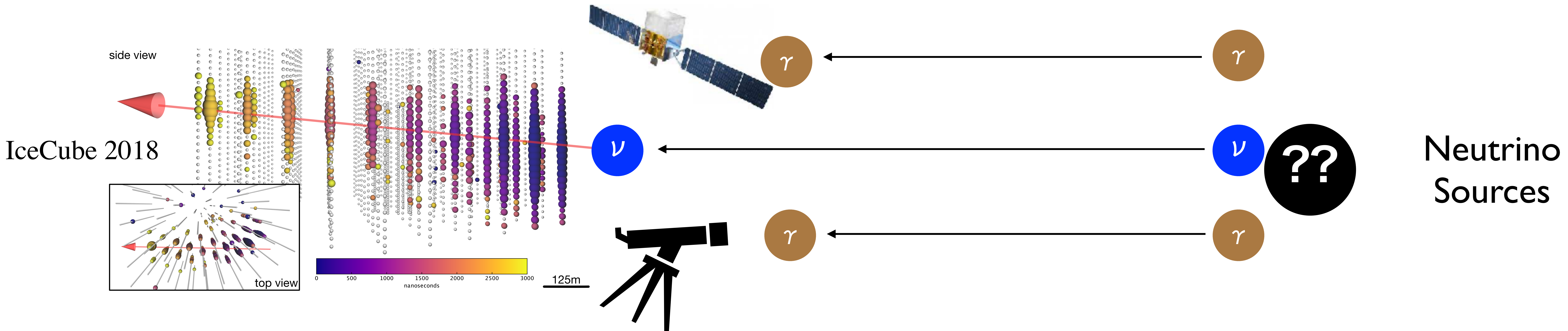
- Peculiar Supernovae (hypernova; Interacting supernova)

- 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

- Follow-up Observations($\nu \rightarrow \gamma$)
  - Neutrino Alerts
    + Follow-up observations by EM
    → Identify neutrino sources

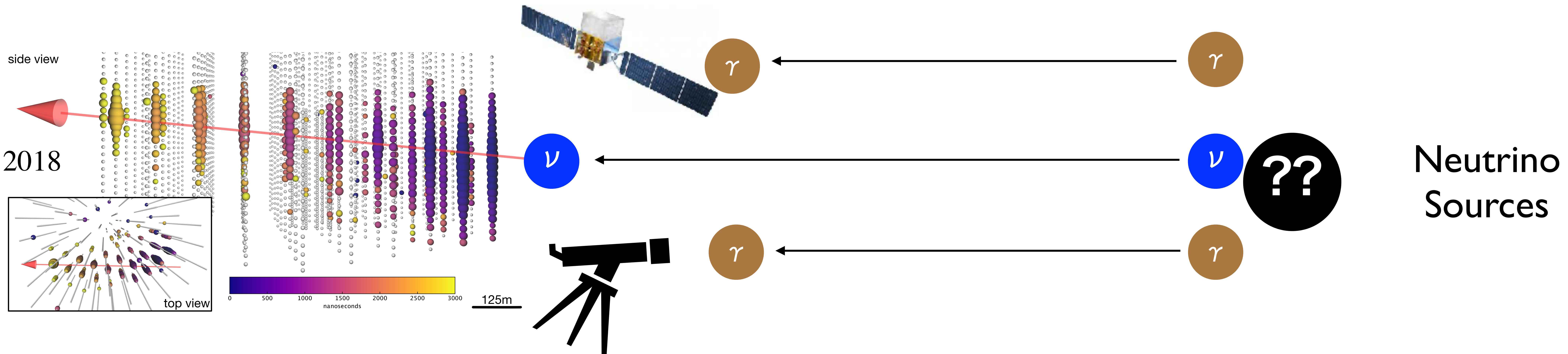


How to find neutrino sources?

- 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

IceCube 2018



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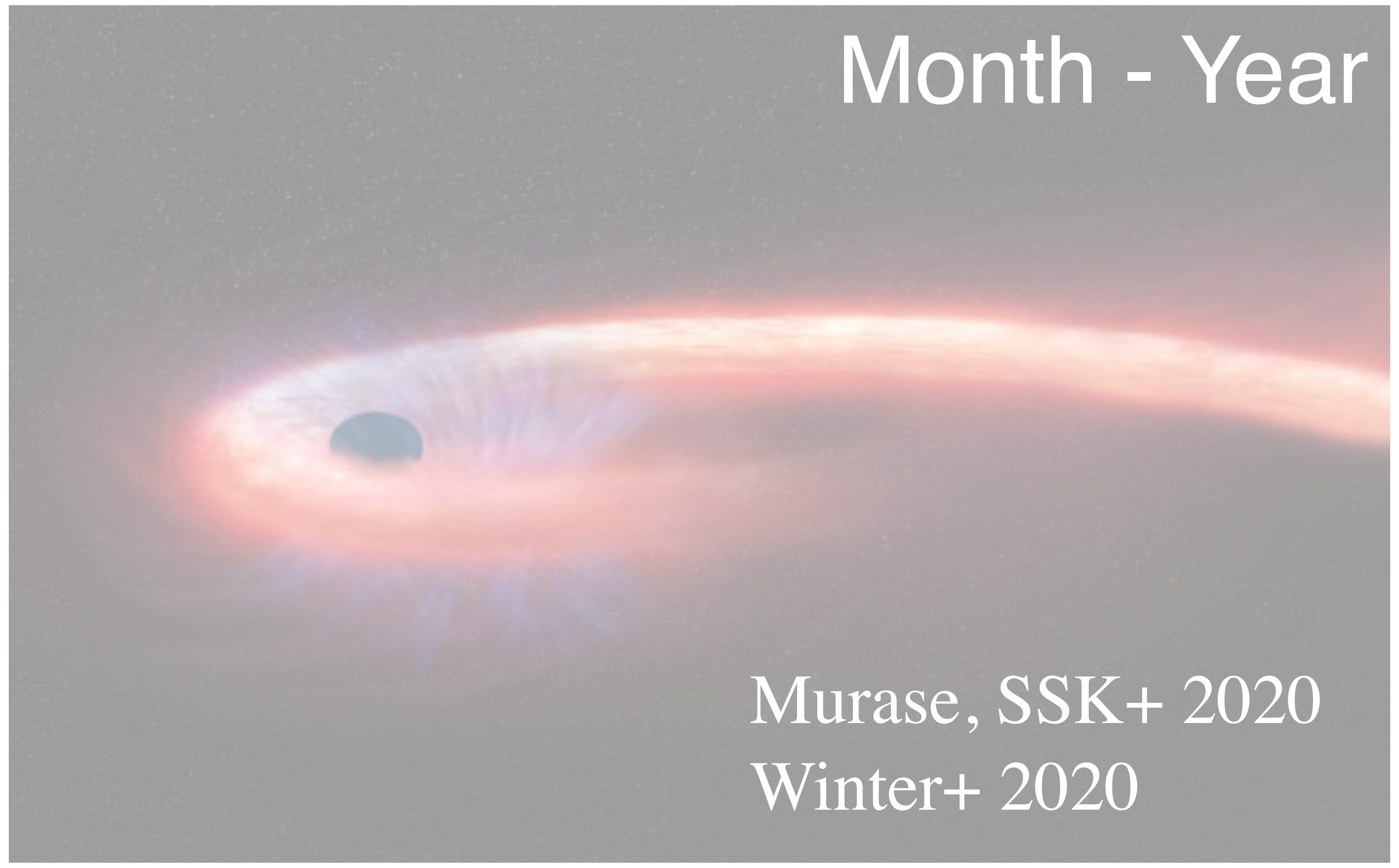

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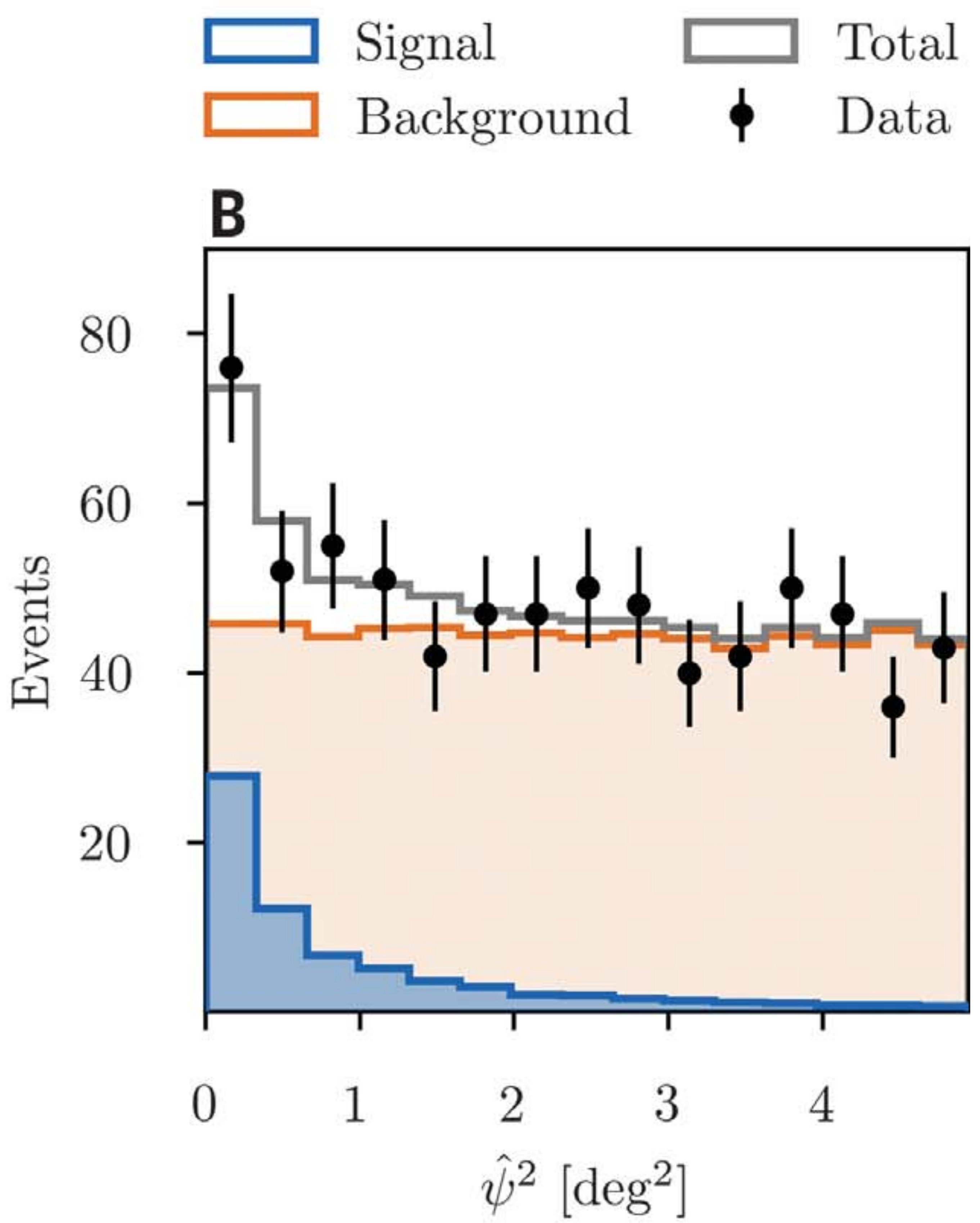
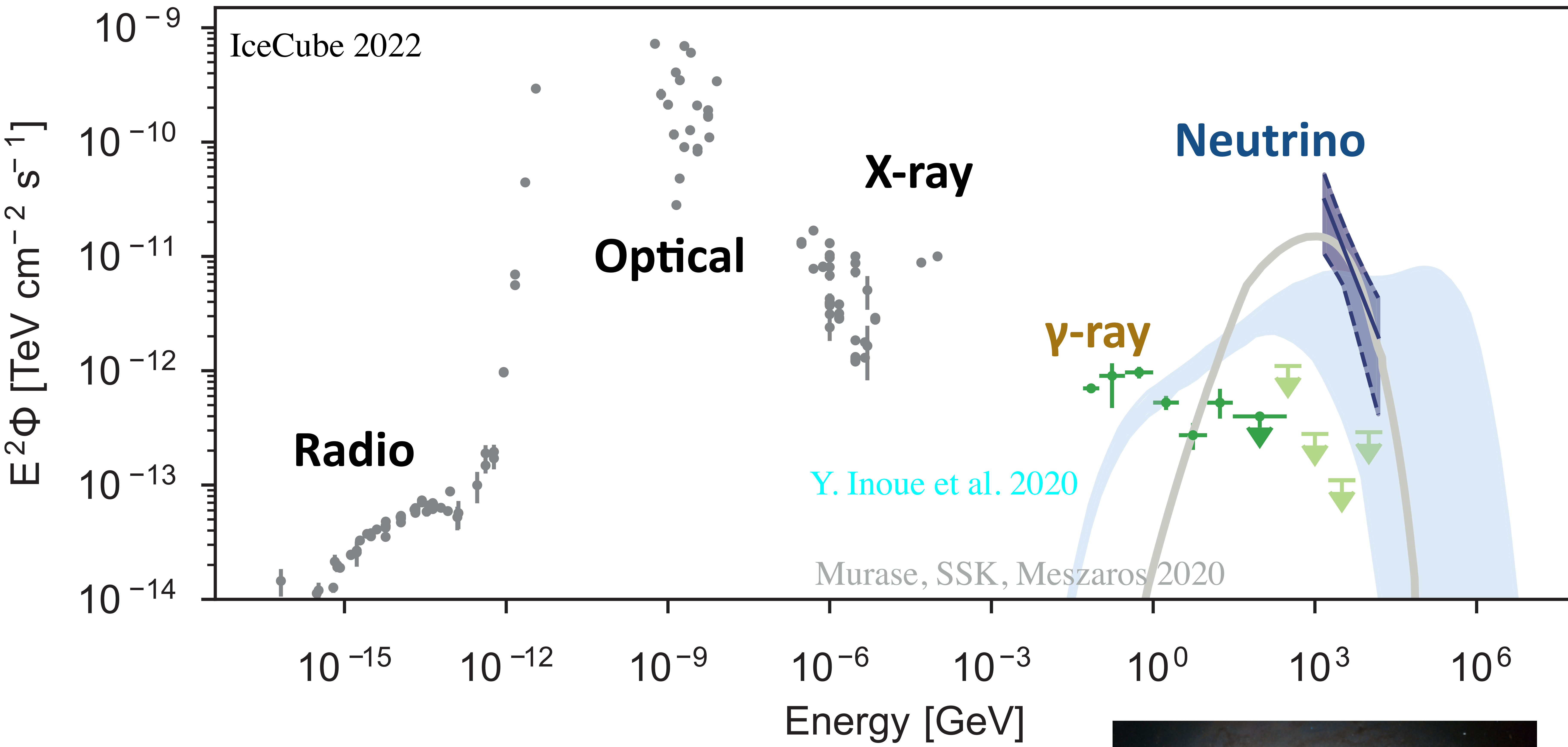
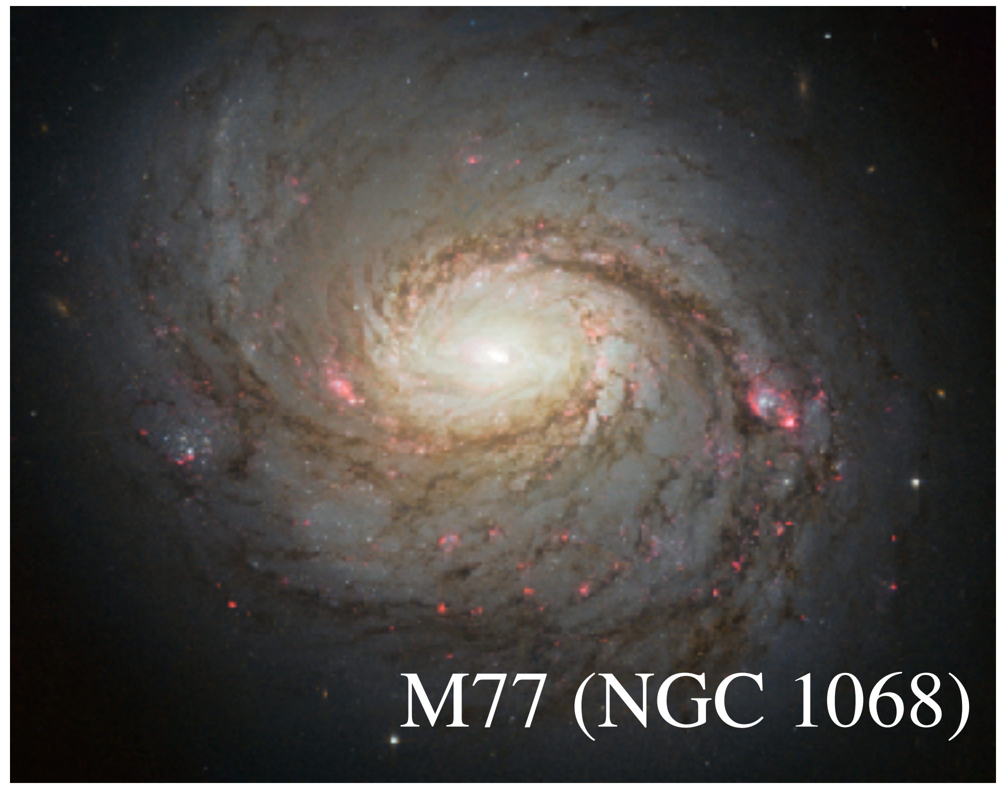
Evidence of Neutrinos from Seyferts



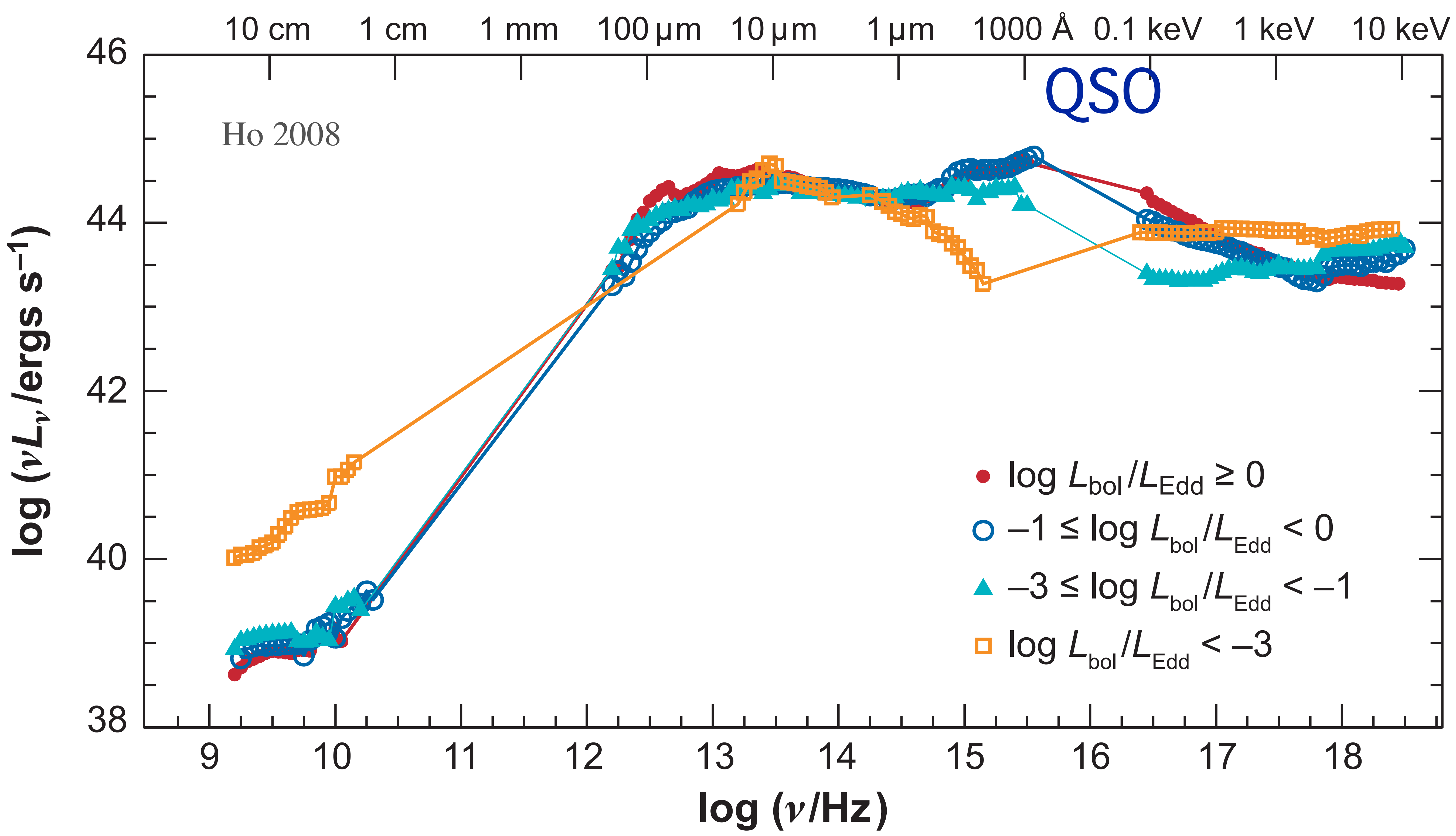


- Point source search with 10-year data set with an improved analysis method
- Cataloged source search result: 2.9σ (2020) —> 4.2σ (2022)
- $F_\nu \gg F_\gamma$ —> Hidden neutrino source
- **γ-ray, CR & ν production sites are under debates. Let's discuss possibilities.**

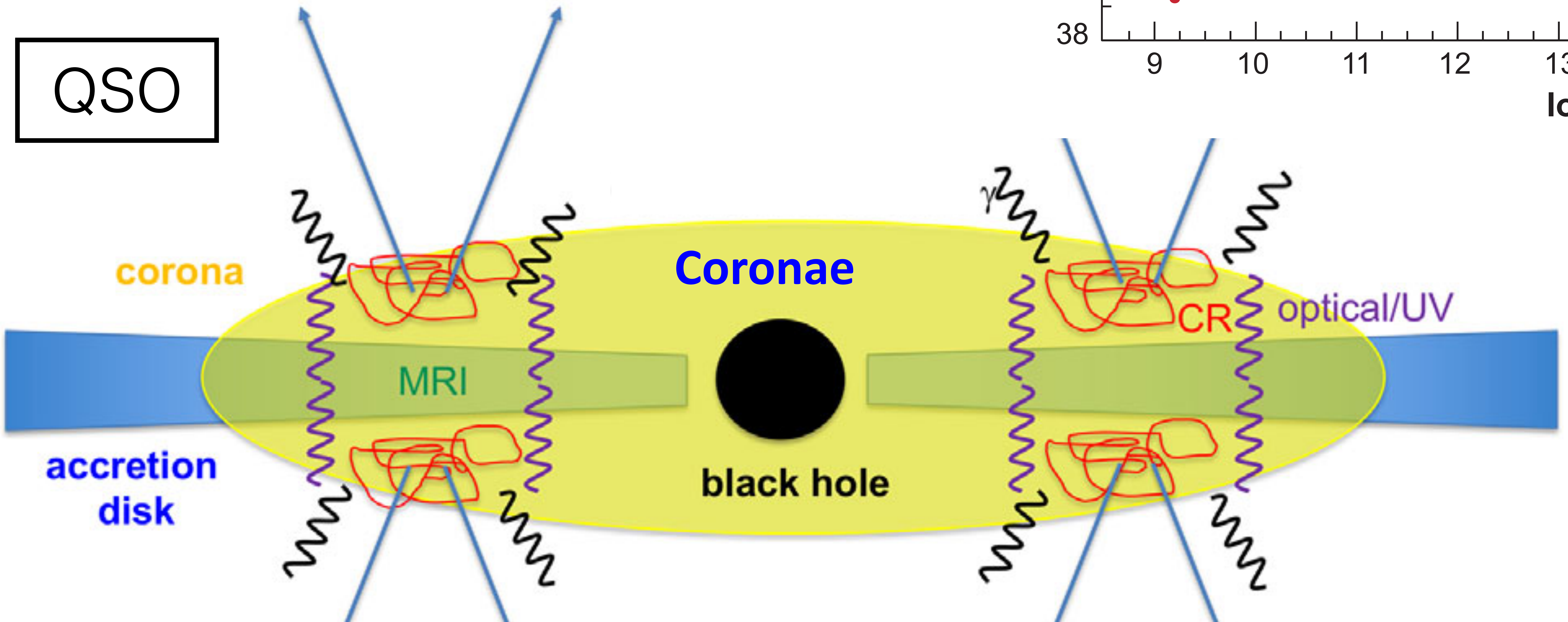


AGN Accretion Flows

- SED: Blue bump & strong X-rays
  → Optically thick disk + Corona



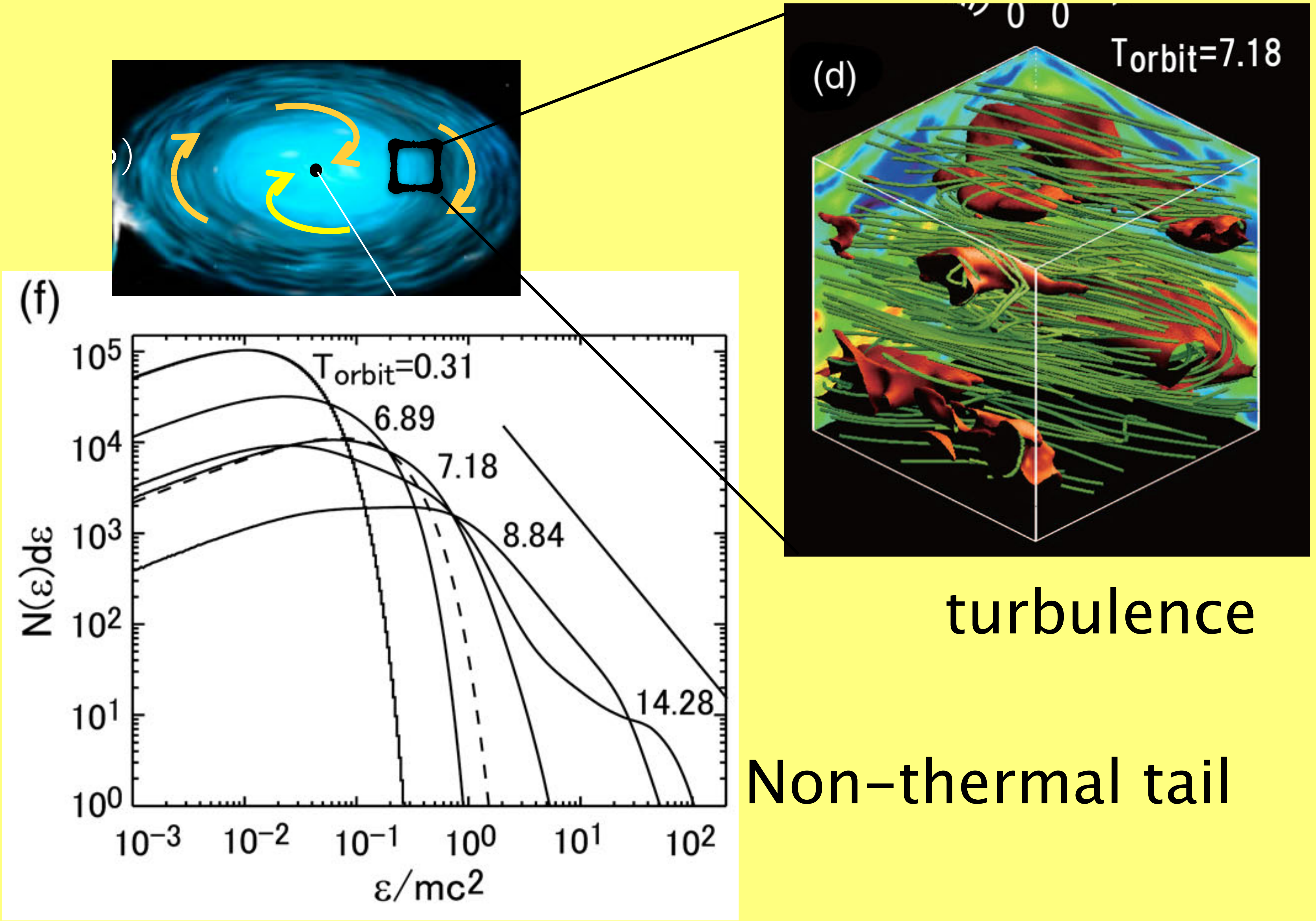
QSO



Particle Acceleration in Turbulence

Particle-In-Cell Simulations in shearing box

Hoshino 2013, 2015; Riquelme et al. 2012; Kuntz et al. 2016

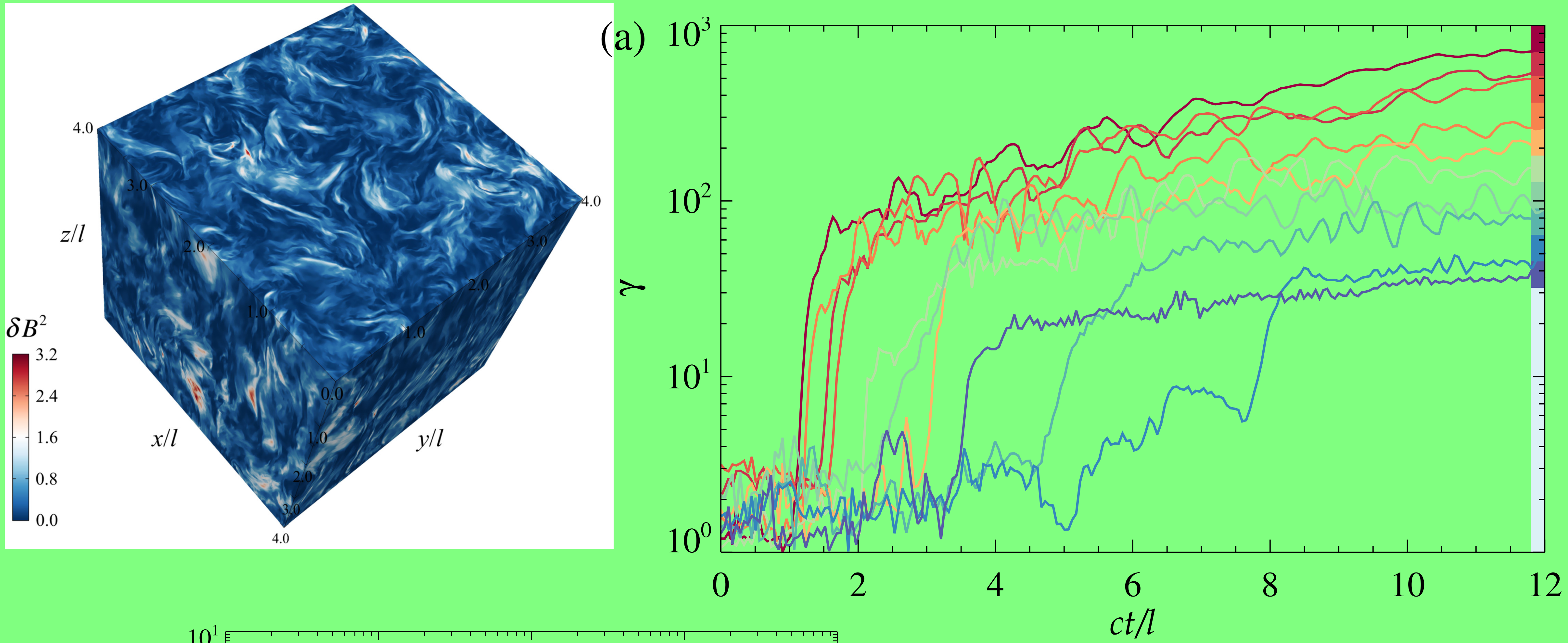


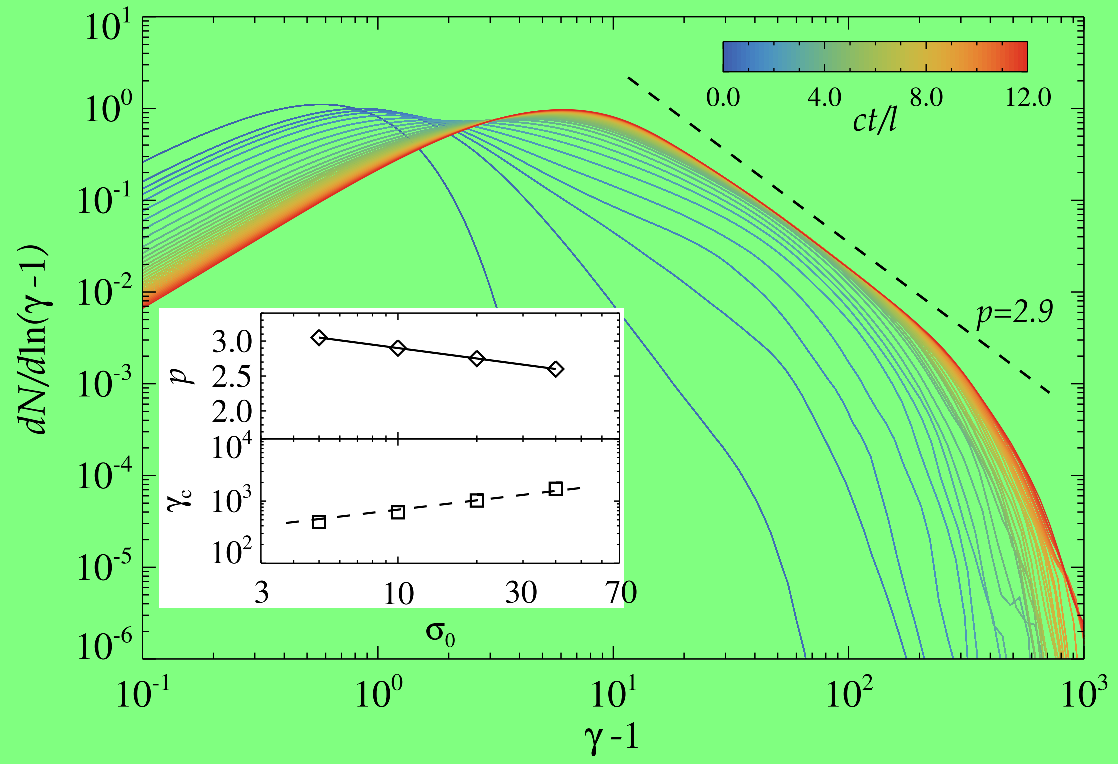
turbulence

Non-thermal tail

Particle-In-Cell Simulations with turbulence

Comisso & Sironi 2018, 2019; Zhdankin et al. 2018





Stochastic acceleration

Power-law tail

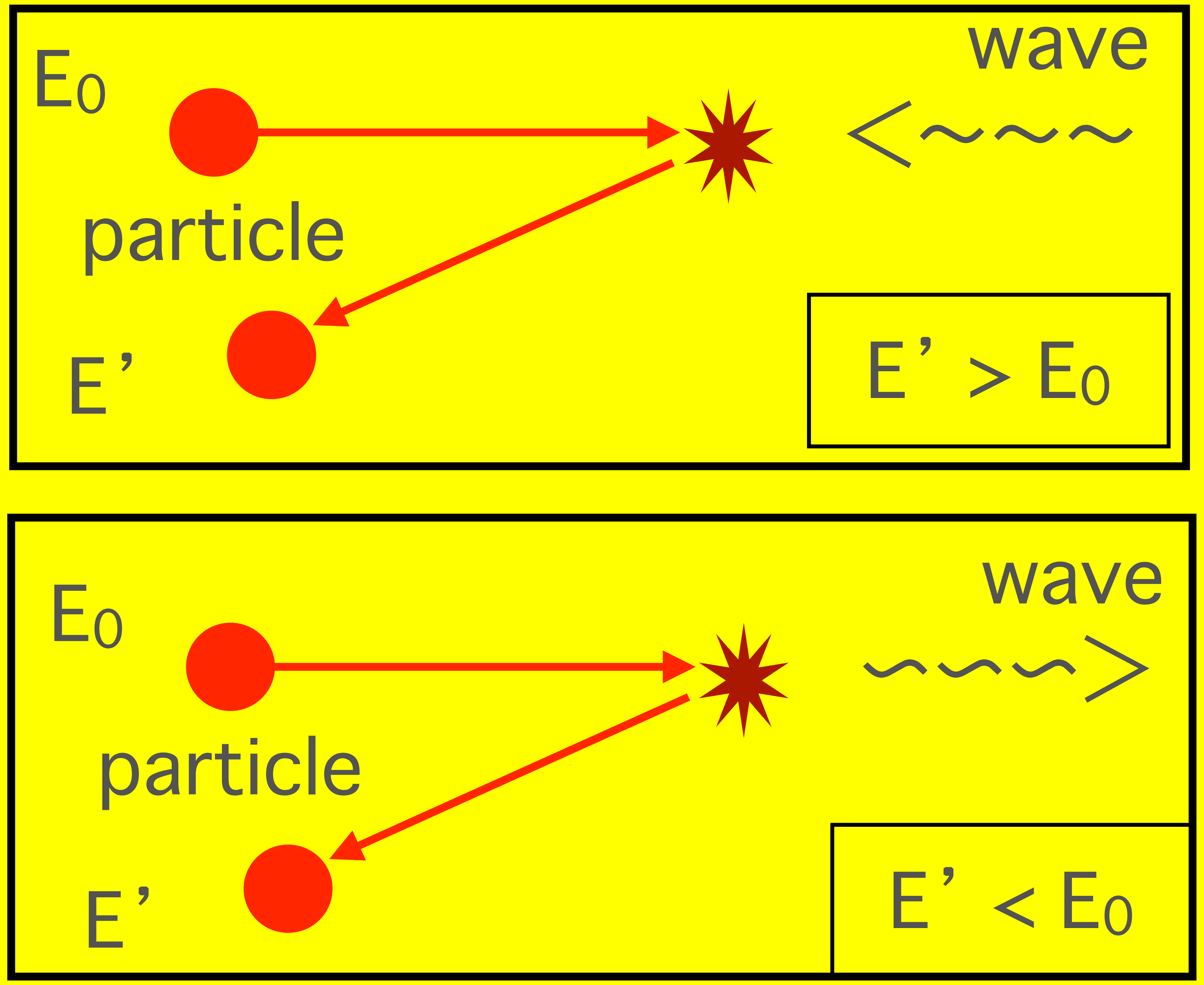
Magnetic reconnection → relativistic particle production

Interaction with Turbulence → further energization

Stochastic Acceleration by MHD Turbulence

CR Acceleration Theory

e.g.) Fermi 1949



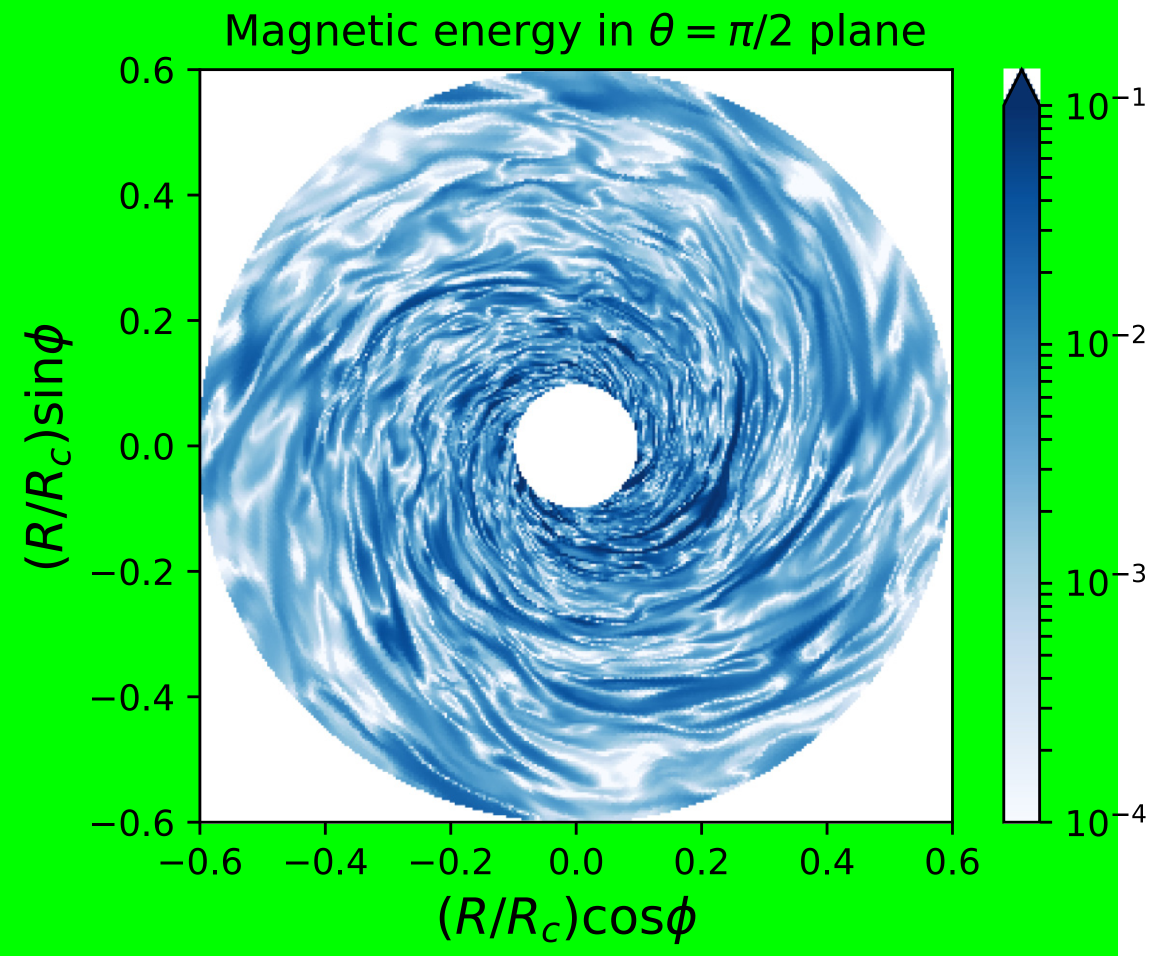
Some gain E, others lose E
→diffusion in E space

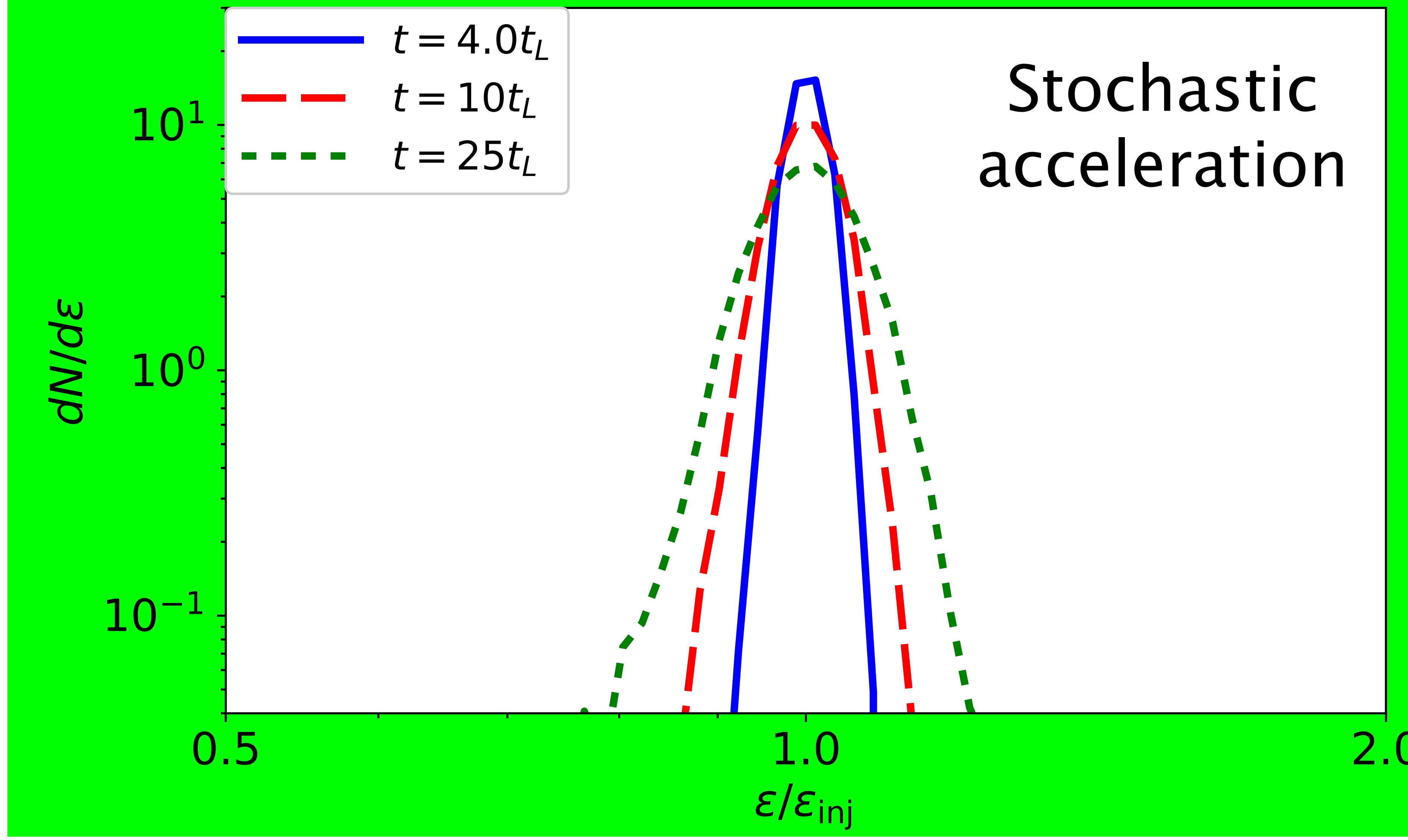
$$\frac{\partial F_p}{\partial t} = \frac{1}{E^2}\frac{\partial}{\partial E}\left(E^2 D_E \frac{\partial F_p}{\partial E}\right)$$

MHD + Test Particle Simulations

SSK+ 2016 ApJ, 2019 MNRAS; Sun & Bai 2021

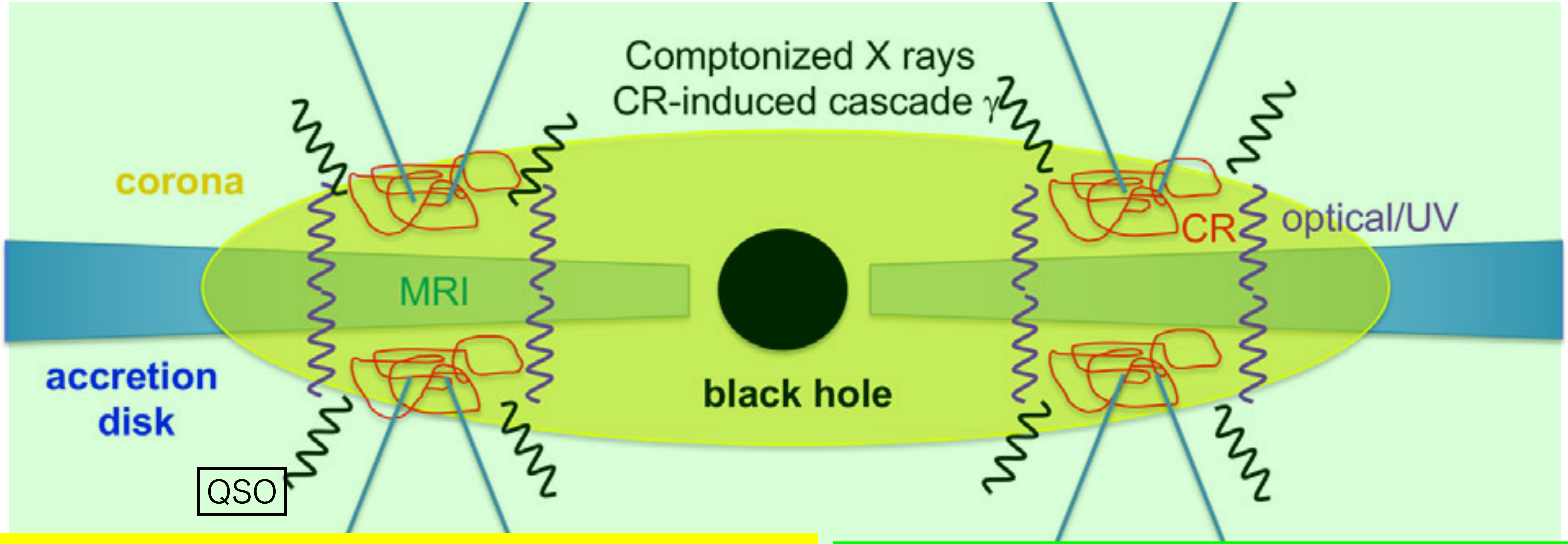
MRI turbulence





AGN Corona Model

Murase, SSK, Meszaros 2020



- Equations for cosmic-ray protons

$$\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\rm cool}}F_p\right) - \frac{F_p}{t_{\rm esc}} + \dot{F}_{p,\rm inj}$$

$$D_{\varepsilon_p} \approx \frac{\zeta c}{H}\left(\frac{V_A}{c}\right)^2\left(\frac{r_L}{H}\right)^{q-2}\varepsilon_p^2,$$

- Equations for electromagnetic cascades

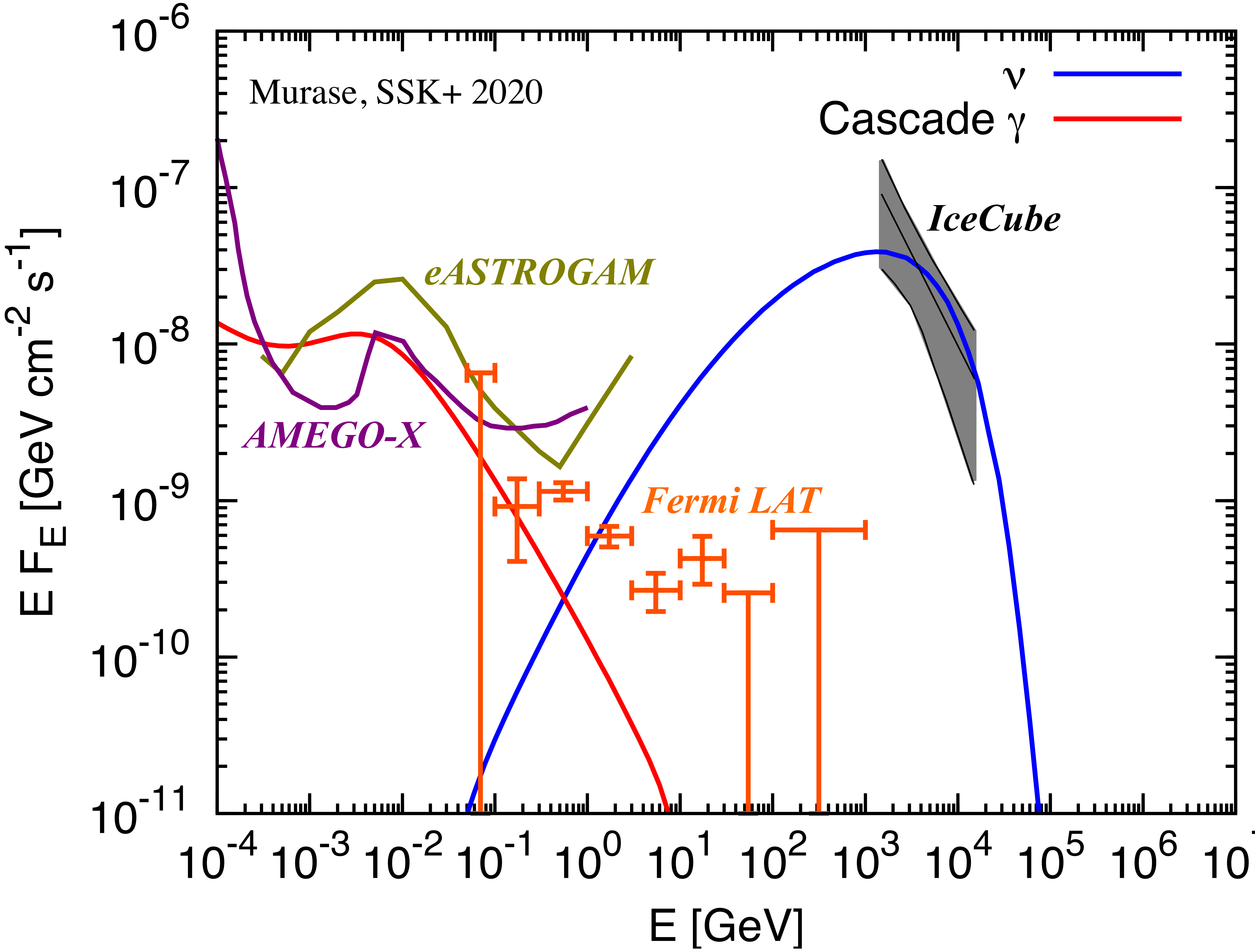
$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\rm esc}} + \dot{n}^{(\rm IC)}_{\varepsilon_\gamma} + \dot{n}^{(\rm ff)}_{\varepsilon_\gamma} + \dot{n}^{(\rm syn)}_{\varepsilon_\gamma} + \dot{n}^{\rm inj}_{\varepsilon_\gamma},$$

$$\frac{\partial n^e_{\varepsilon_e}}{\partial t} + \frac{\partial}{\partial \varepsilon_e}[(P_{\rm IC} + P_{\rm syn} + P_{\rm ff} + P_{\rm Cou})n^e_{\varepsilon_e}] = \dot{n}^{(\gamma\gamma)}_{\varepsilon_e} - \frac{n^e_{\varepsilon_e}}{t_{\rm esc}} + \dot{n}^{\rm inj}_{\varepsilon_e},$$

See also SSK+ 2019; SSK+ 2021; Kheirandish, Murase, SSK 2021

Multi-messenger Spectra from NGC 1068

- Possible to explain IceCube data without overshooting γ-ray data
- CR acceleration is suppressed by Bethe-Heitler process with UV photons
- Both pp & pγ (with X-rays) contribute to resulting neutrino flux
- **Cascade emission at 10 MeV —>Testable by MeV γ ray satellites**

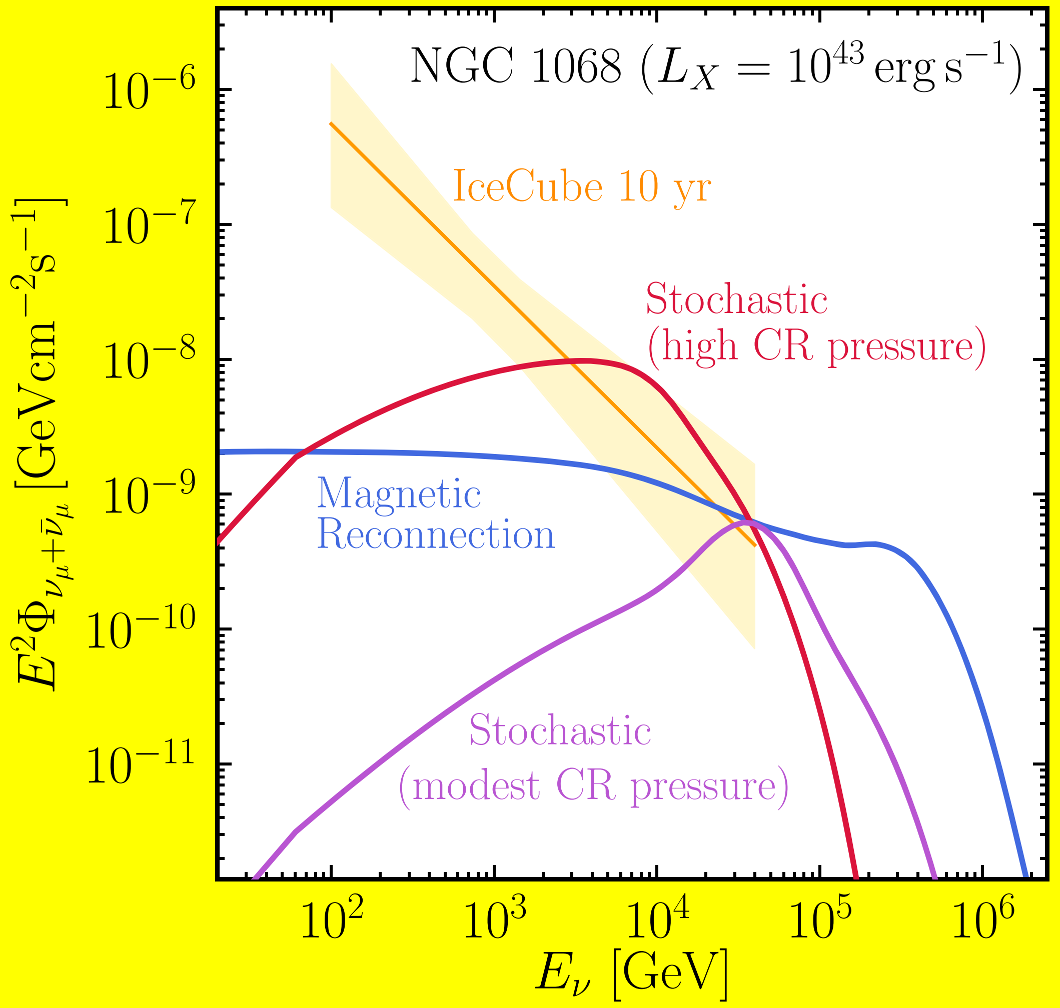


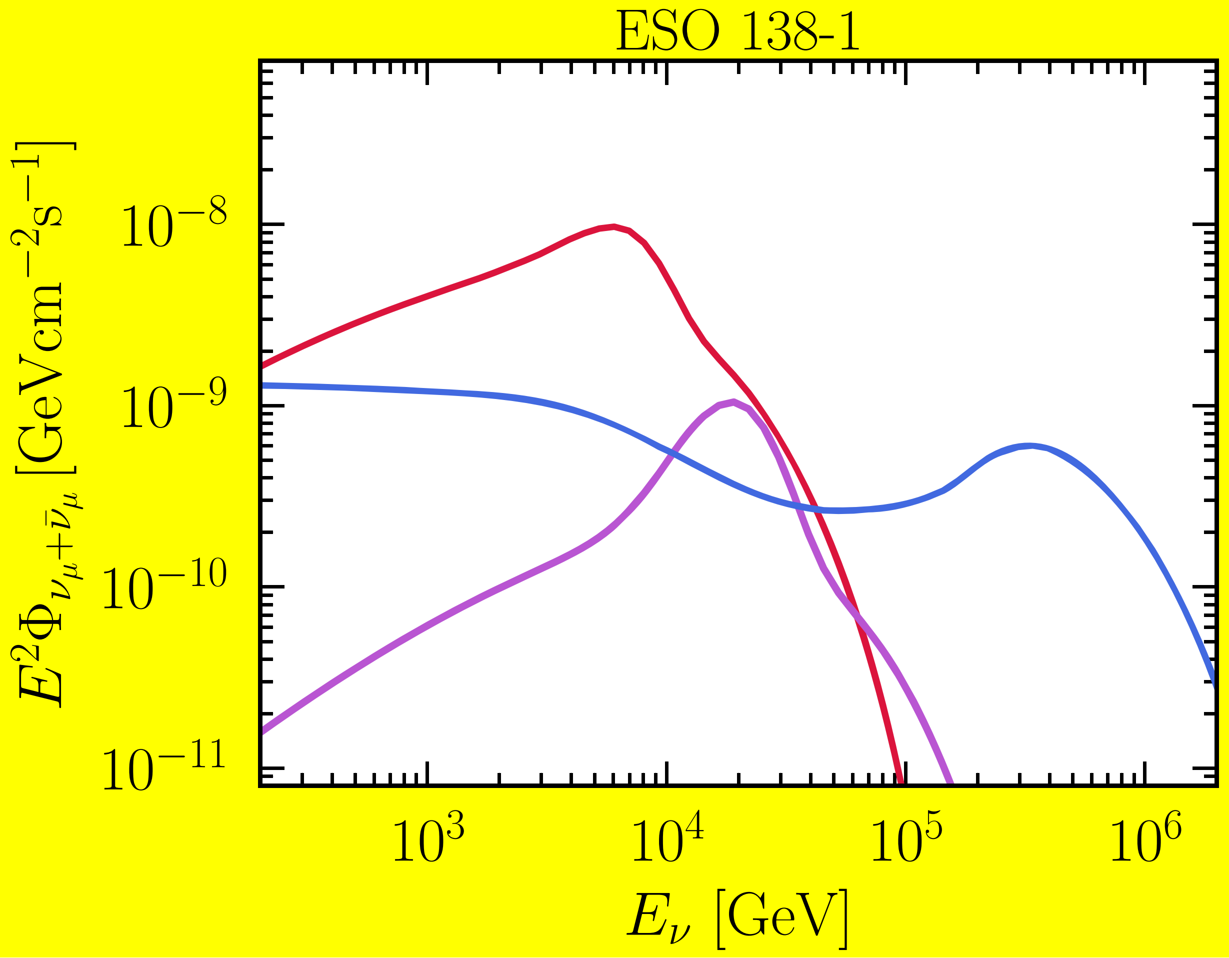
Nearby Seyfert galaxies

Kheirandish, Murase, SSK 2021

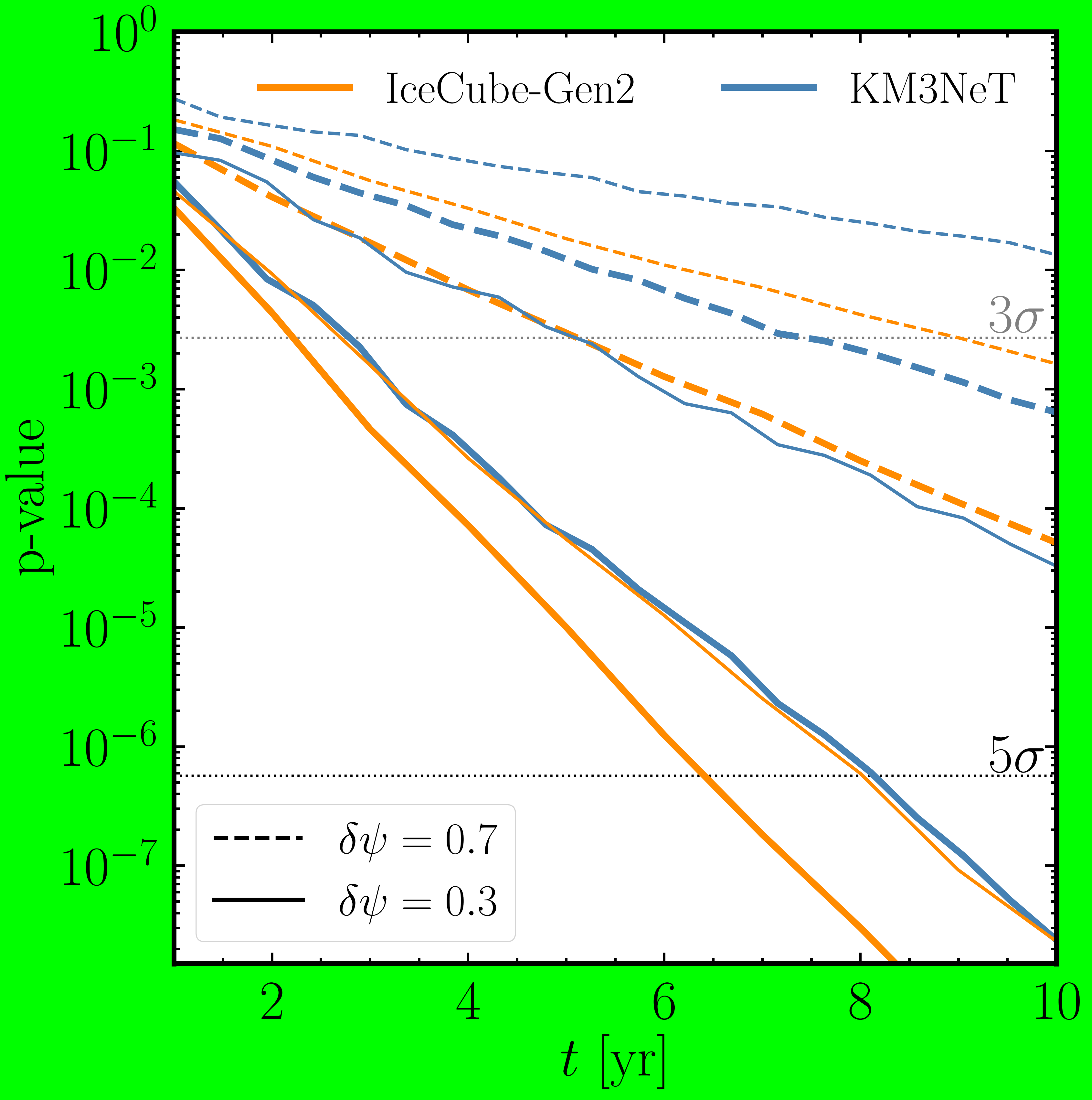
- Our model predicts $L_\nu \propto L_X$
  —> list up bright ν-source candidates

Source
Cen A
Circinus Galaxy
ESO 138-1
NGC 7582
NGC 1068
NGC 4945
NGC 424
UGC 11910
CGCG 164-019
NGC 1275





- Stacking nearby Seyferts

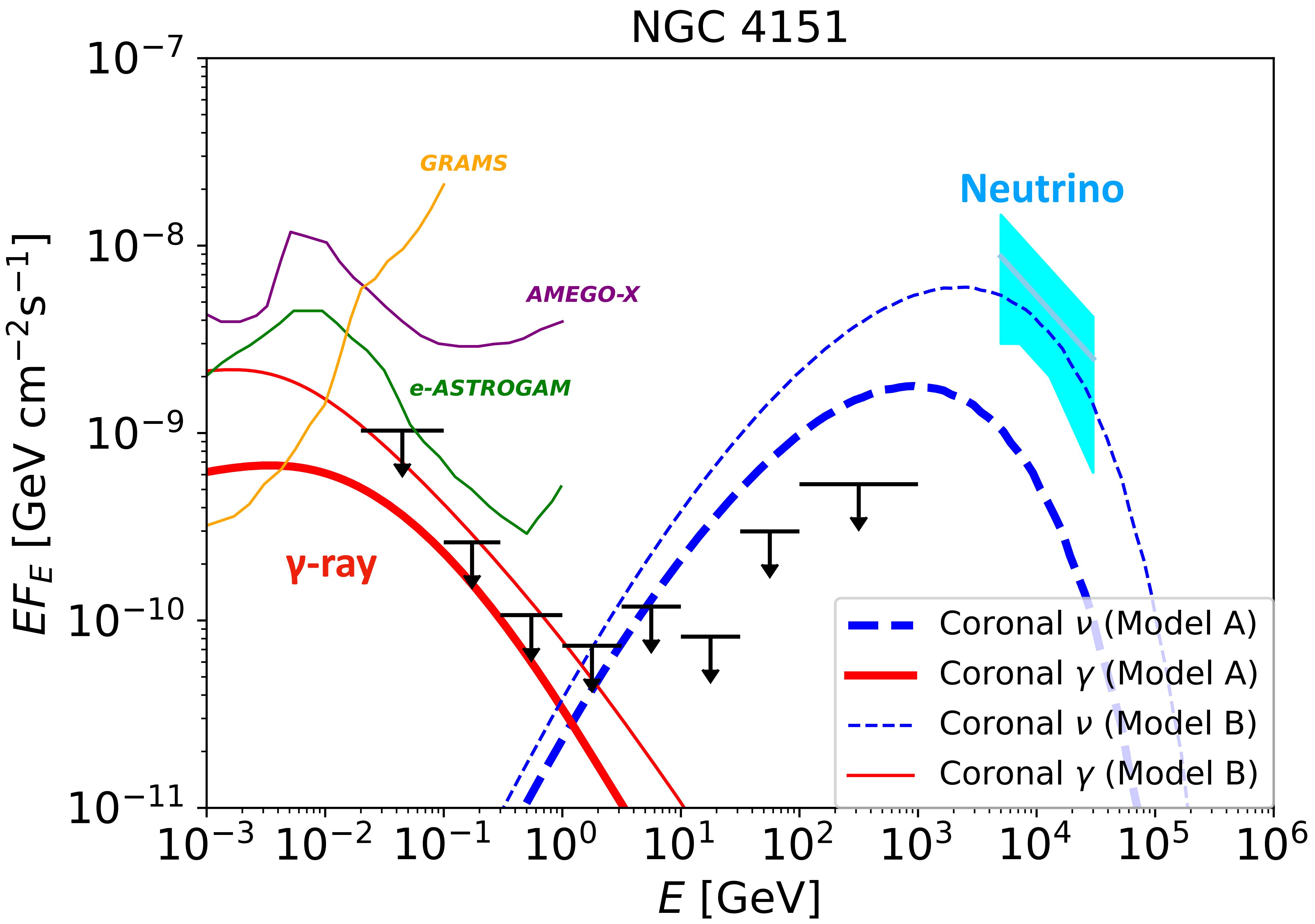


- Future detectors should detect ν from AGN
  —> **testable by future neutrino experiments**

ν & γ from Nearby Seyfert Galaxies

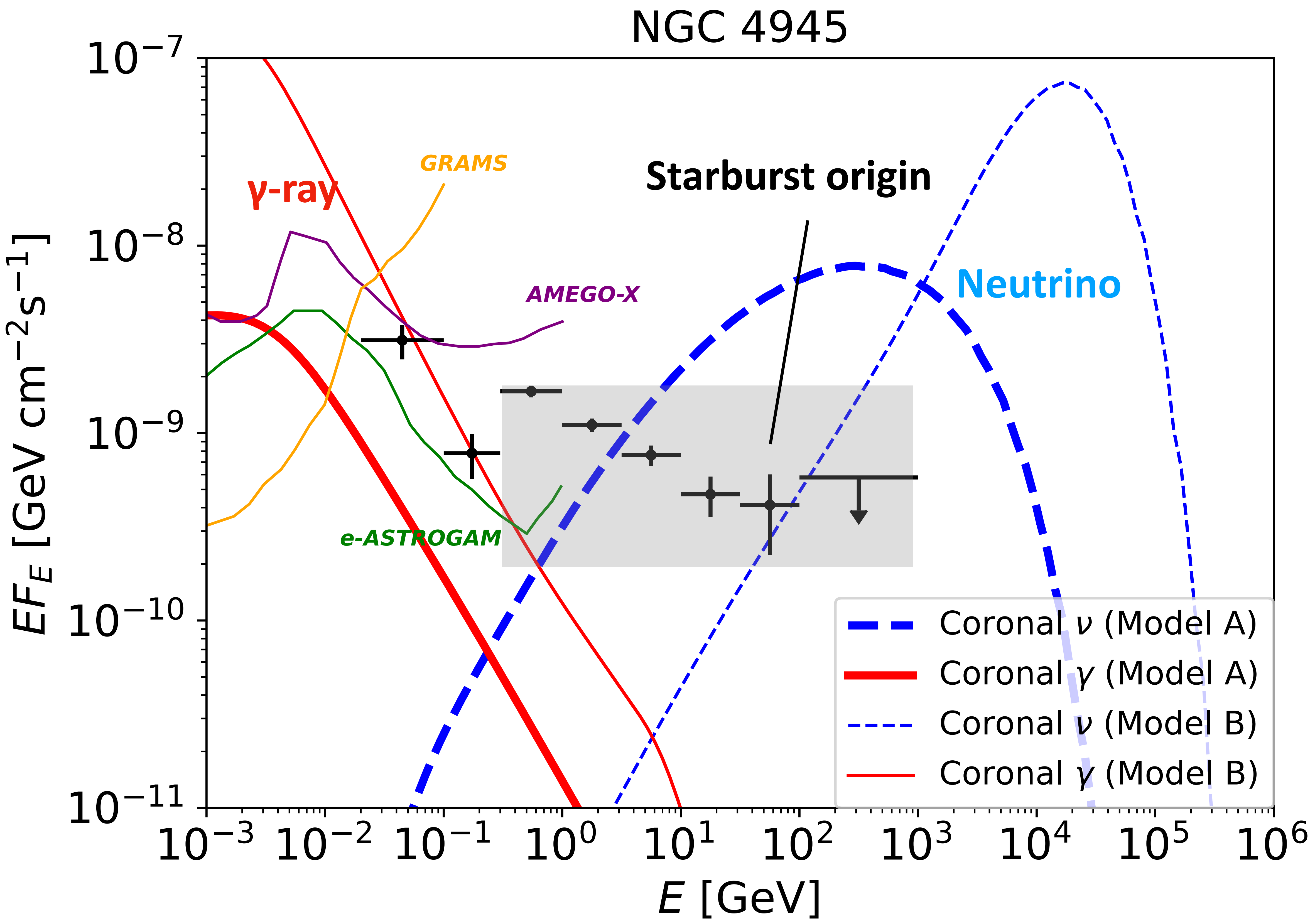
Murase, Karwin, SSK et al. 2024

- NGC 4151: Neutrino source candidate ($\sim 3\sigma$)



- Our model can reproduce the tentative ν data without overshooting γ data

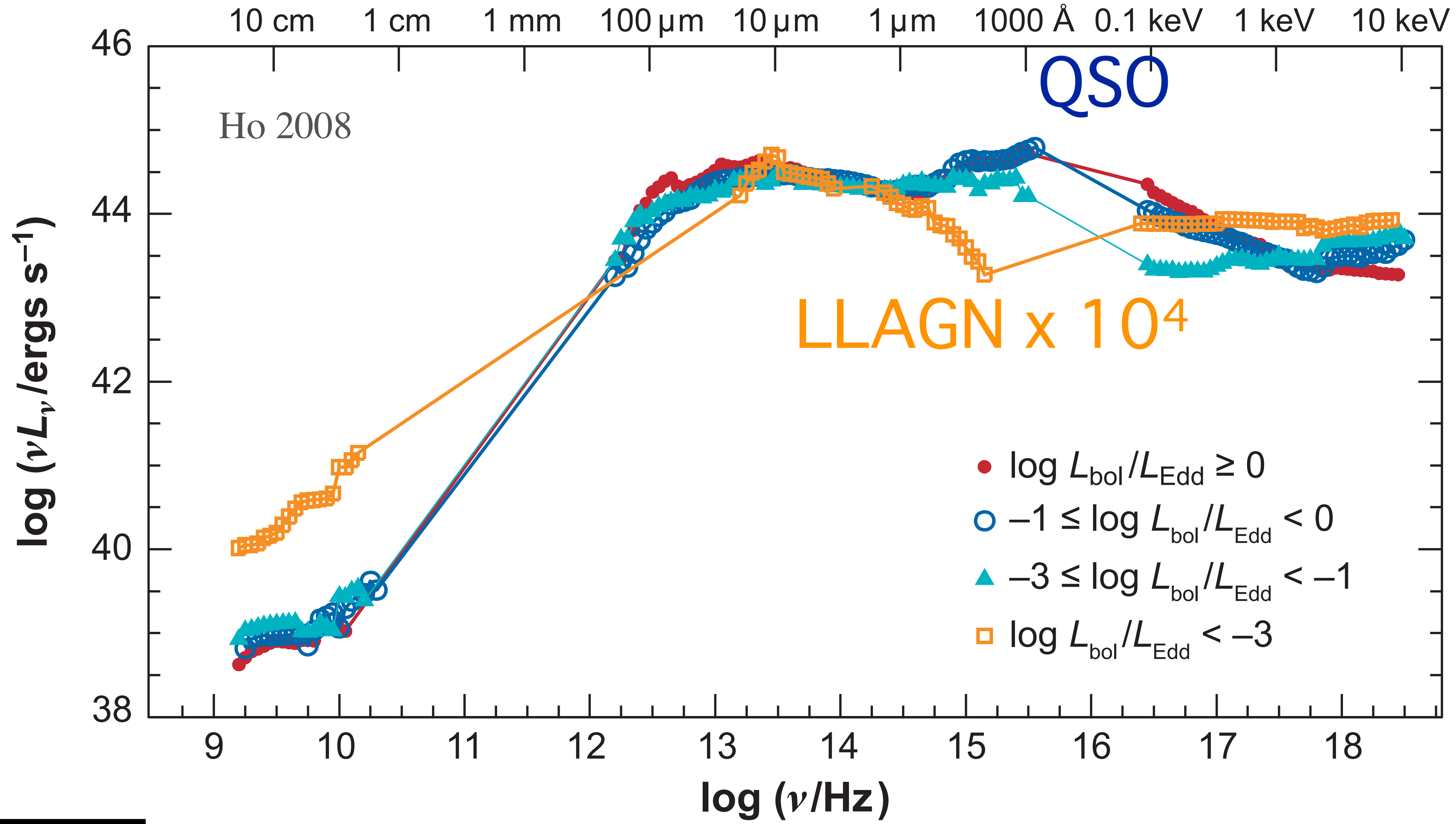
- NGC 4945: γ-ray emitting AGN

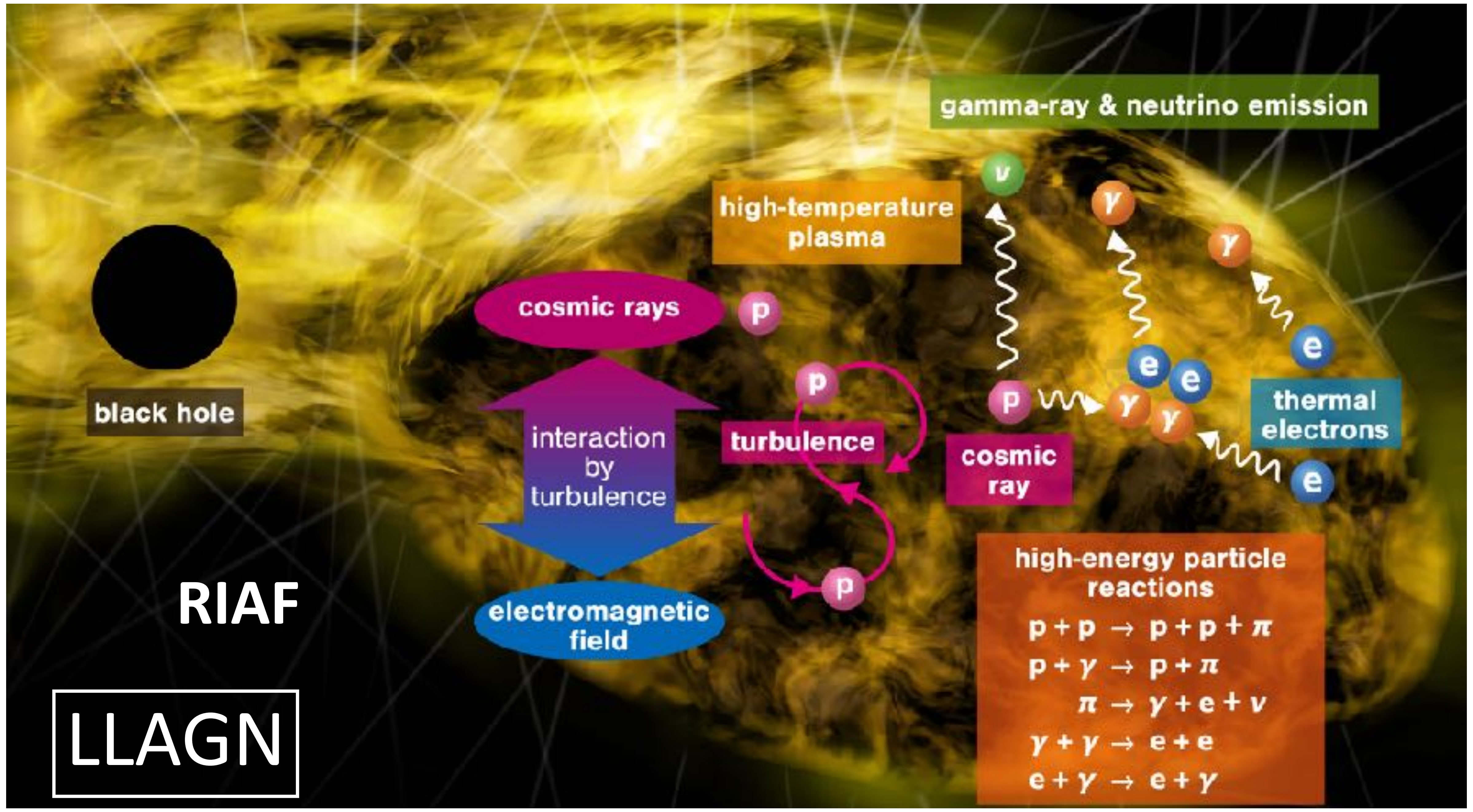


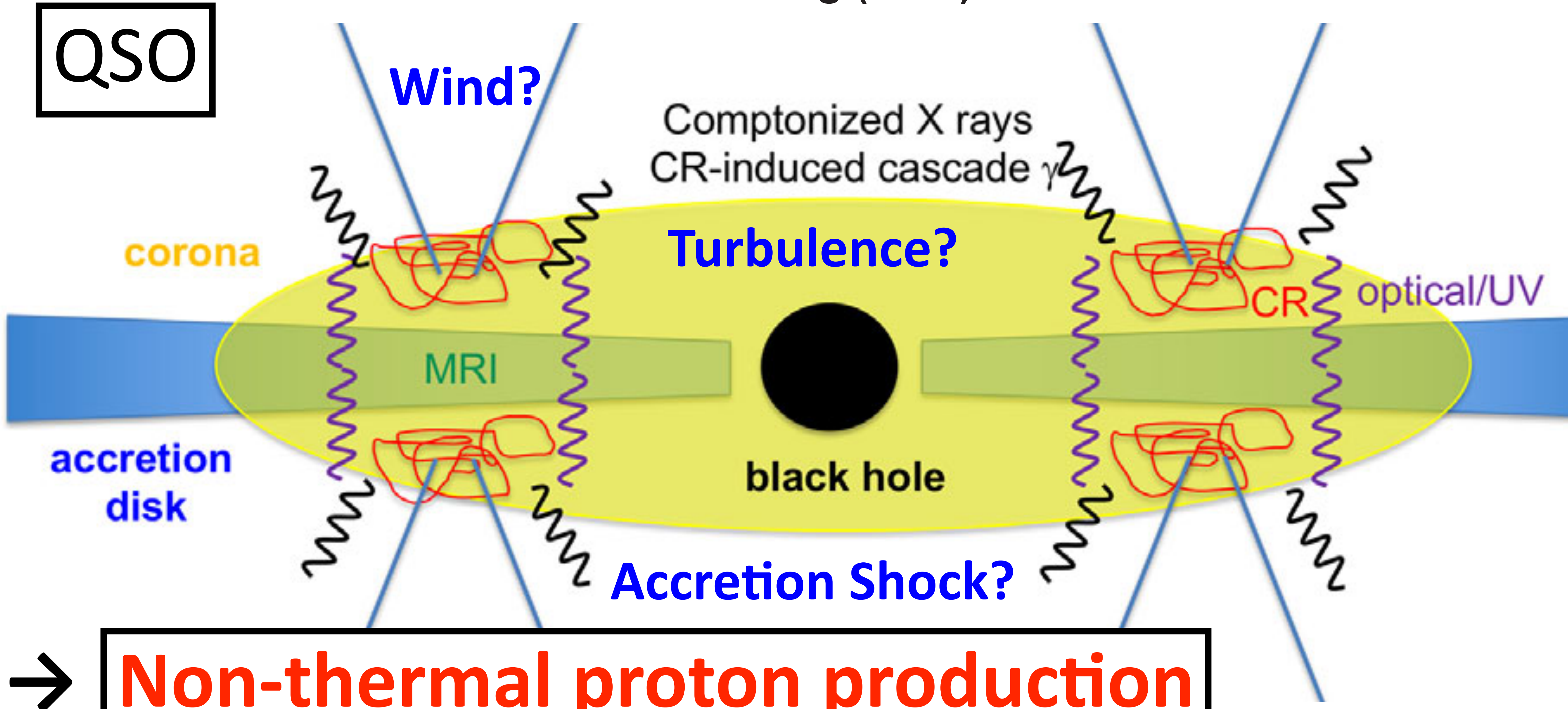
- Our coronal model can explain γ-ray data for $E < 0.3$GeV

RIAFs in LLAGN

- QSO: Blue bump & X-ray
  →Optically thick disk + coronae
- LLAGN: No blue bump & X-ray
  →Optically thin flow
  Radiatively Inefficient Accretion Flow (RIAF)

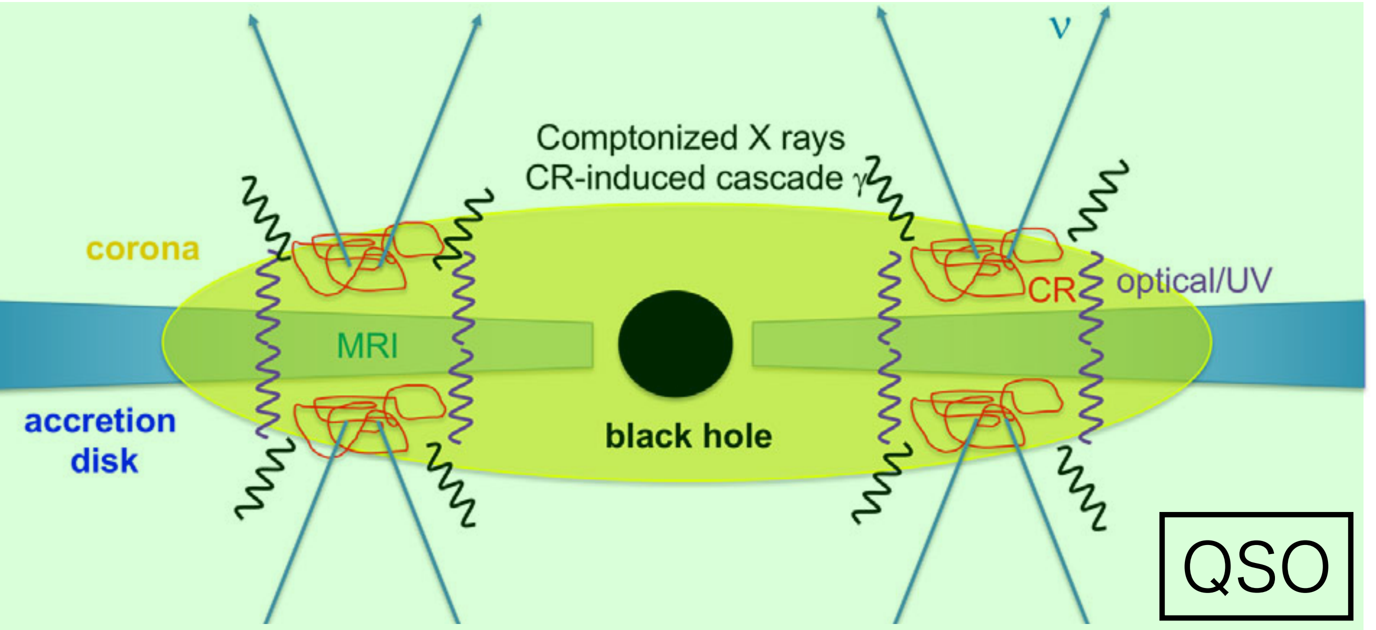




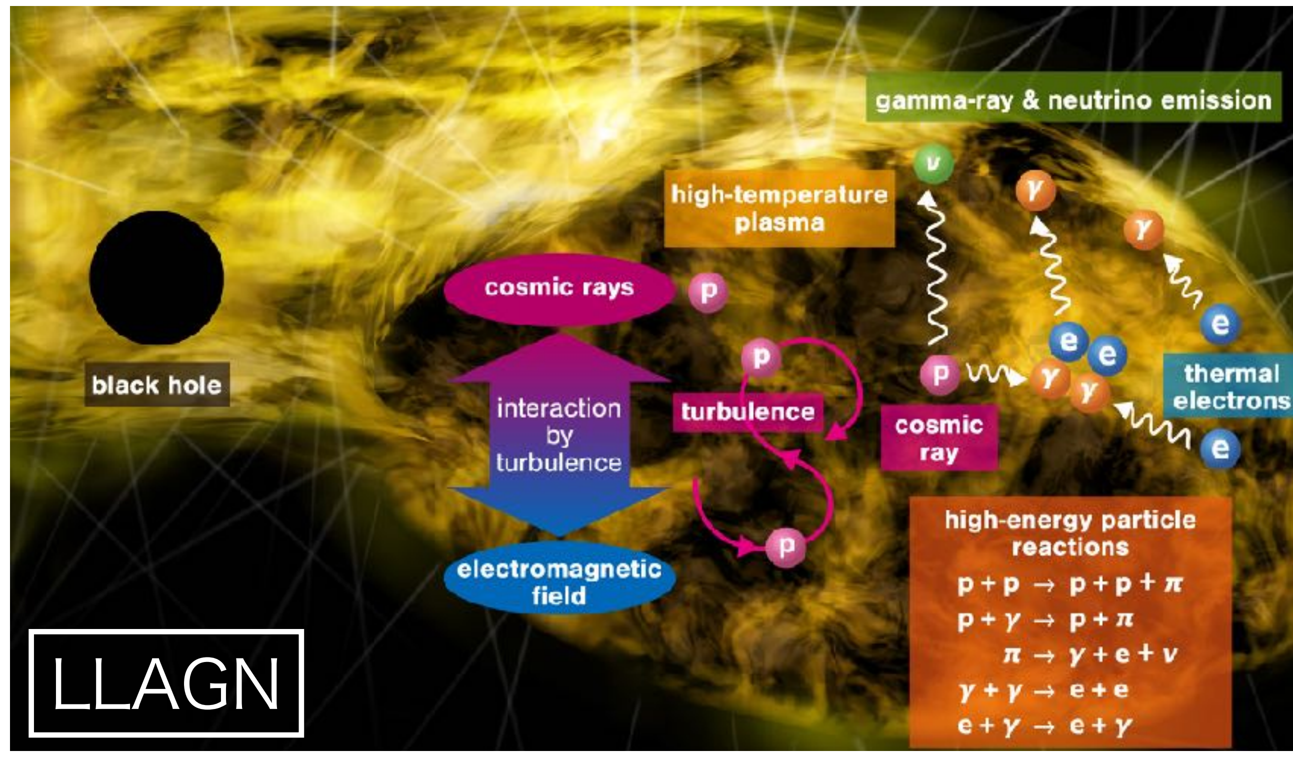


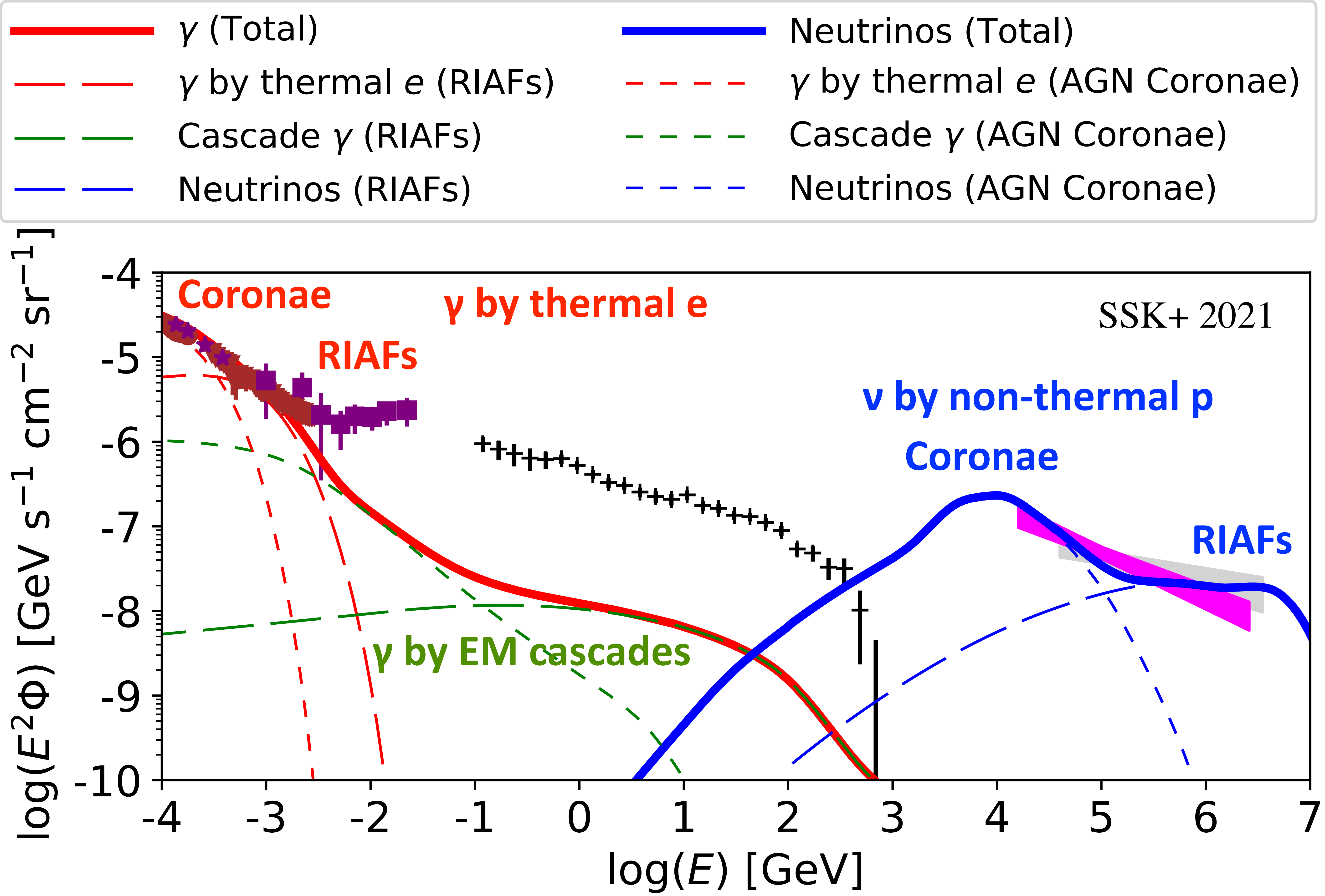
Protons in coronae & RIAFs are collisionless → Non-thermal proton production

Cosmic High-energy Background from RQ AGNs



$$\Phi_i = \frac{c}{4\pi H_0} \int \frac{dz}{\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}} \int dL_{\mathrm{H}\alpha}\rho_{\mathrm{H}\alpha} \frac{L_{\varepsilon_i}}{\varepsilon_i} e^{-\tau_{i,\mathrm{IGM}}},$$





- QSO: X-ray & 10 TeV neutrinos
- LLAGN: MeV γ & PeV neutrinos
- Copious photons
  → efficient γγ —> e+e-
  → strong GeV γ attenuation
  → GeV flux below the Fermi data
- **AGN cores can account for keV-MeV γ & TeV-PeV ν background**

See also Murase, SSK+ 2020 PRL; SSK+ 2019, PRD; SSK+ 2015

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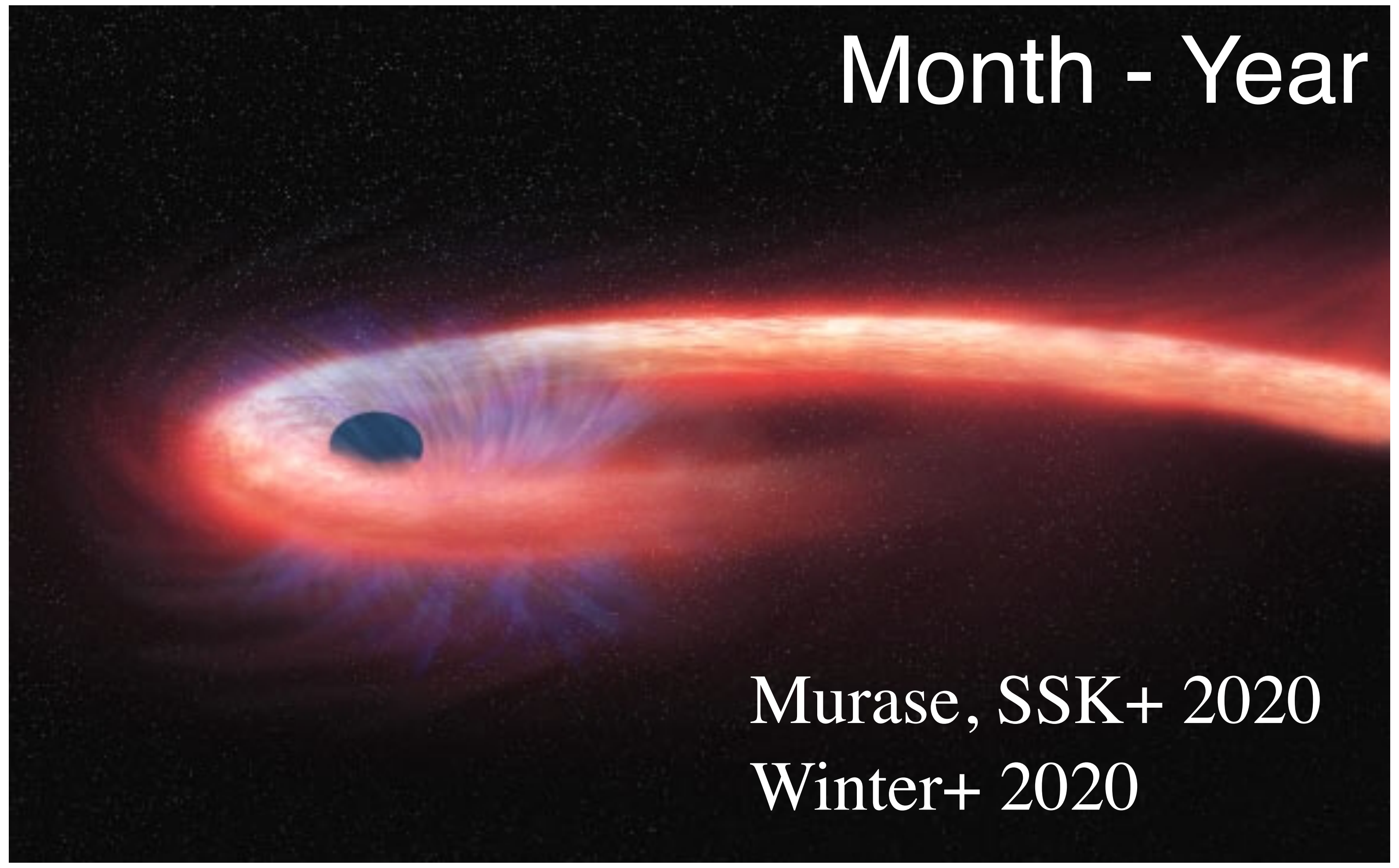
IceCube 2022

- Tidal Disruption Events (TDEs)



- 2 possible association reported from ZTF team

Stein+ 2021
Reusch+(incl. SSK) 2022

- Peculiar Supernovae (hypernova; Interacting supernova)

- No observational evidence
- Theory-motivated

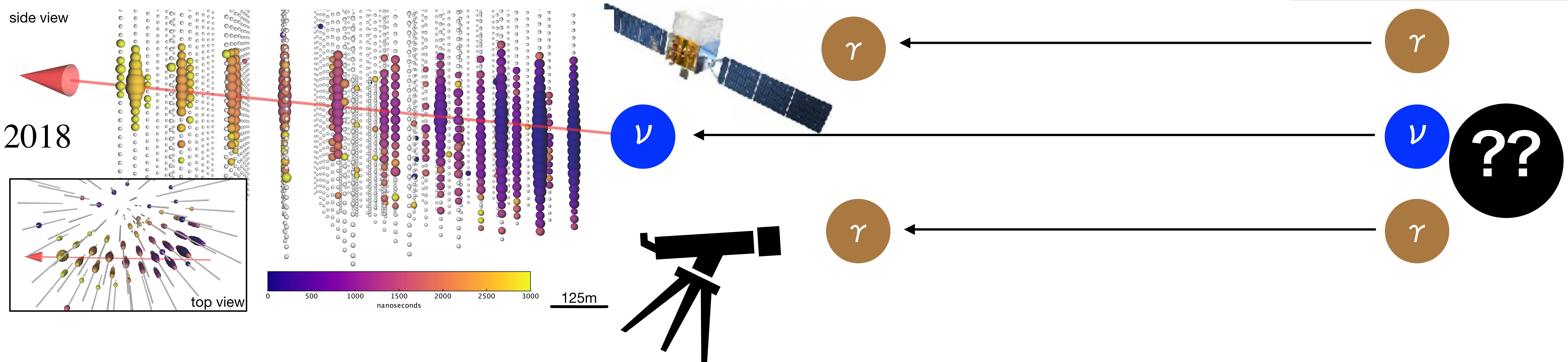
How to find neutrino sources?

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

- 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**

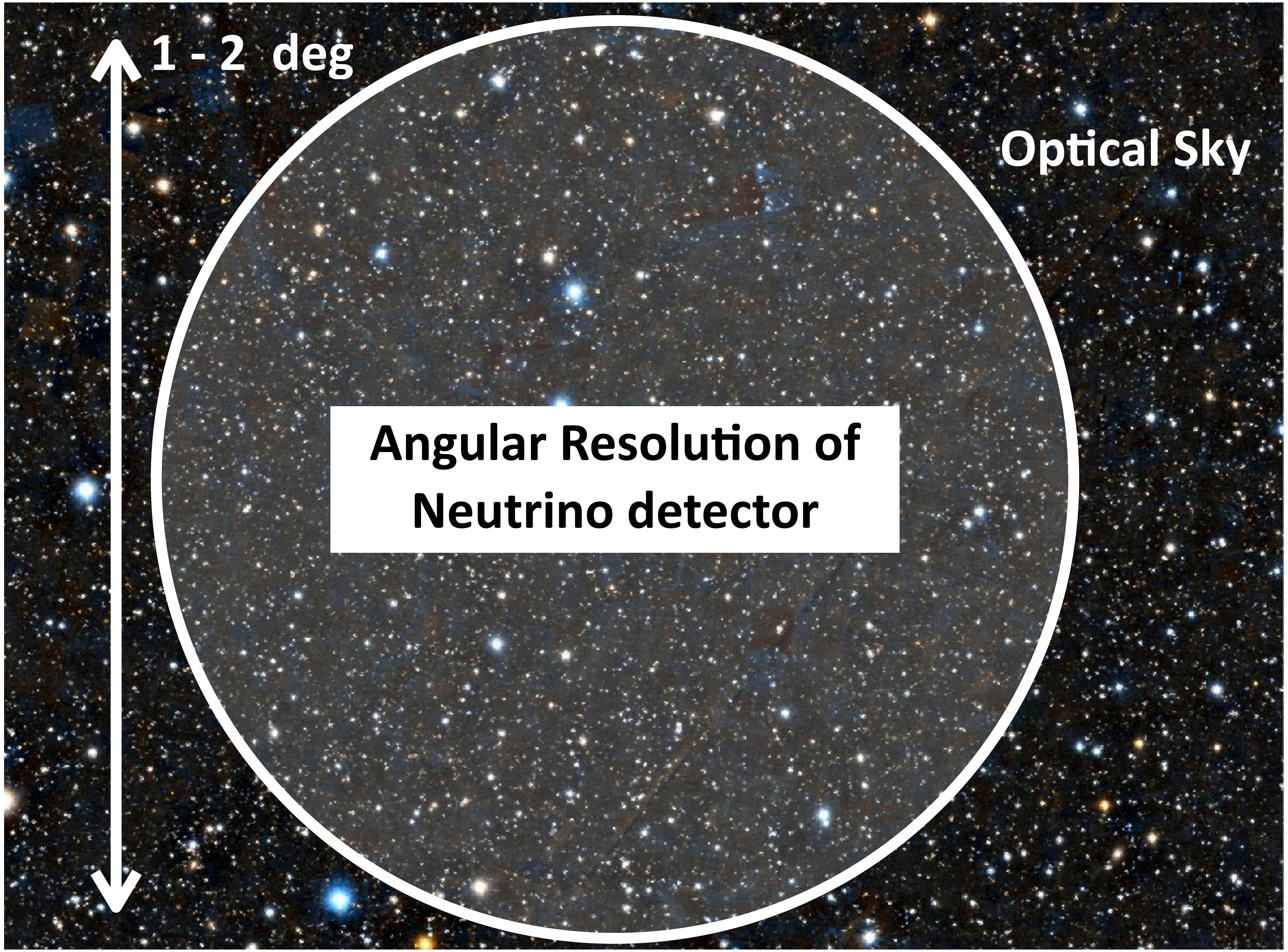
Neutrino Alert + **Follow-up Observations** → **Neutrino Sourcers**

IceCube 2018



Neutrino Sources

Challenge to identify neutrino sources

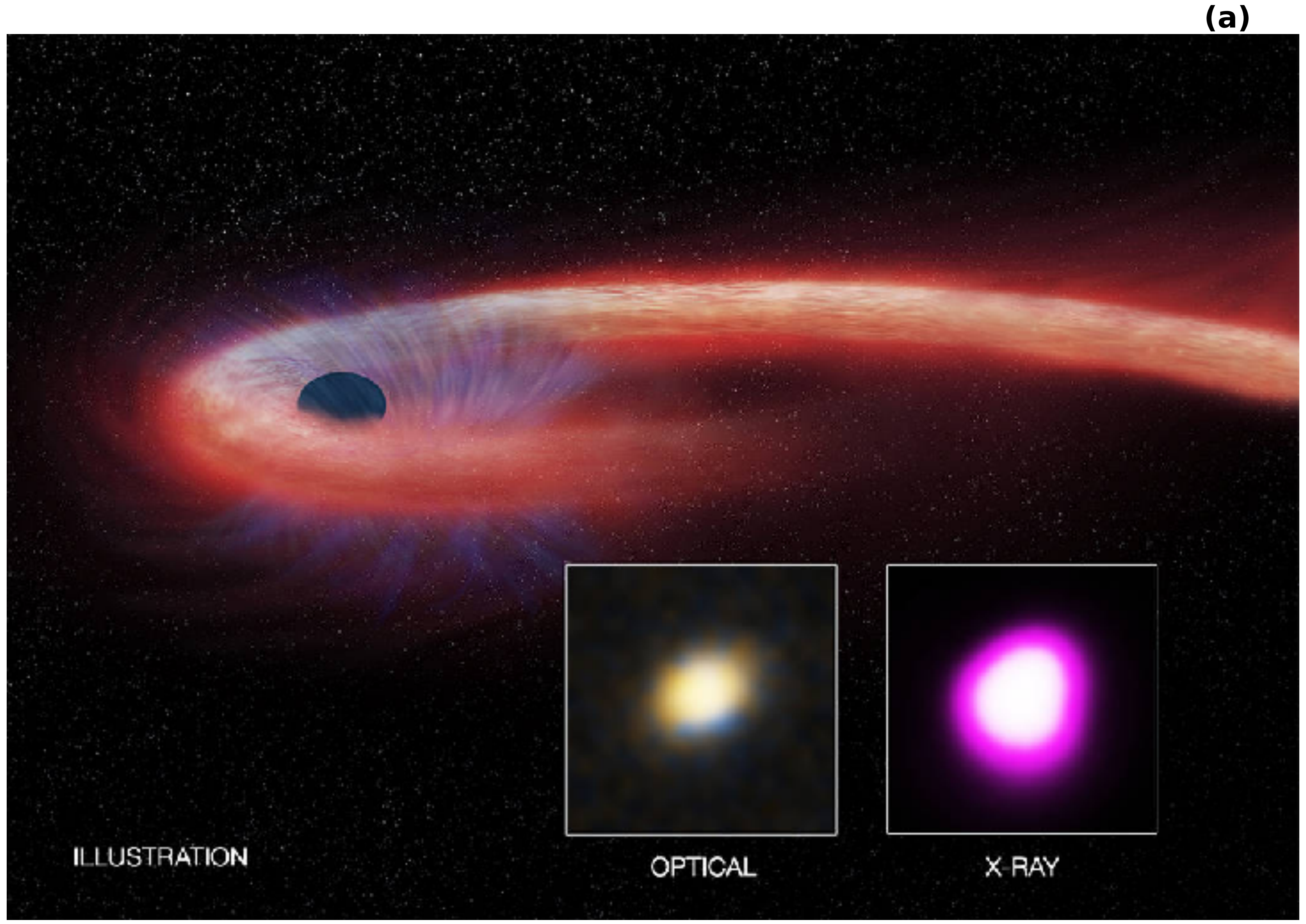


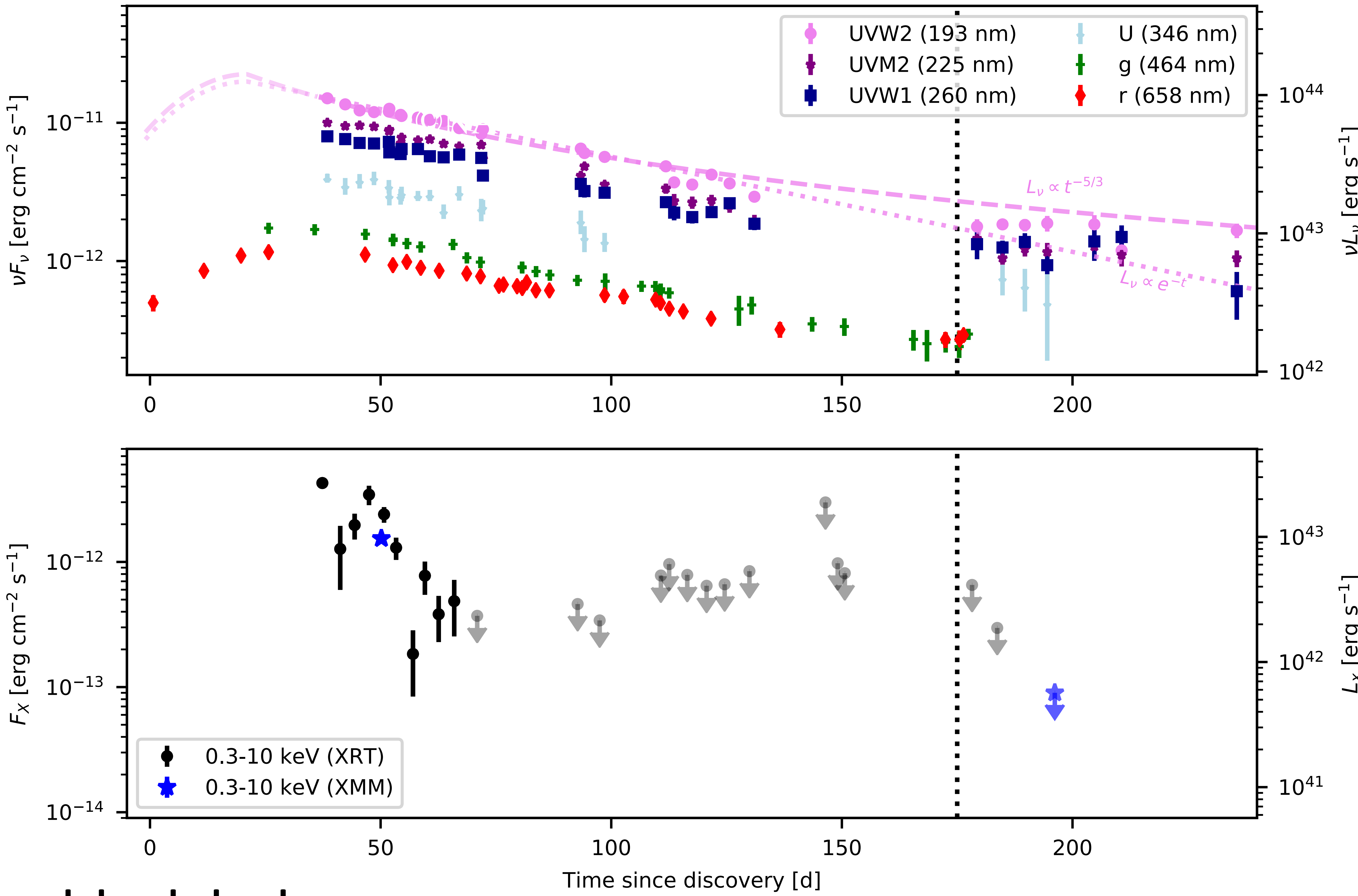
- Angular resolution for optical: $\sim 0.1 - 1$ sec
- Angular Resolution for neutrino: $\sim 0.5 - 3$ deg
- **Number of unrelated transients:** $\gtrsim 100$
- we cannot identify neutrino-emitting object…

Dedicated search strategy is necessary

Tidal Disruption Event (TDE)

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

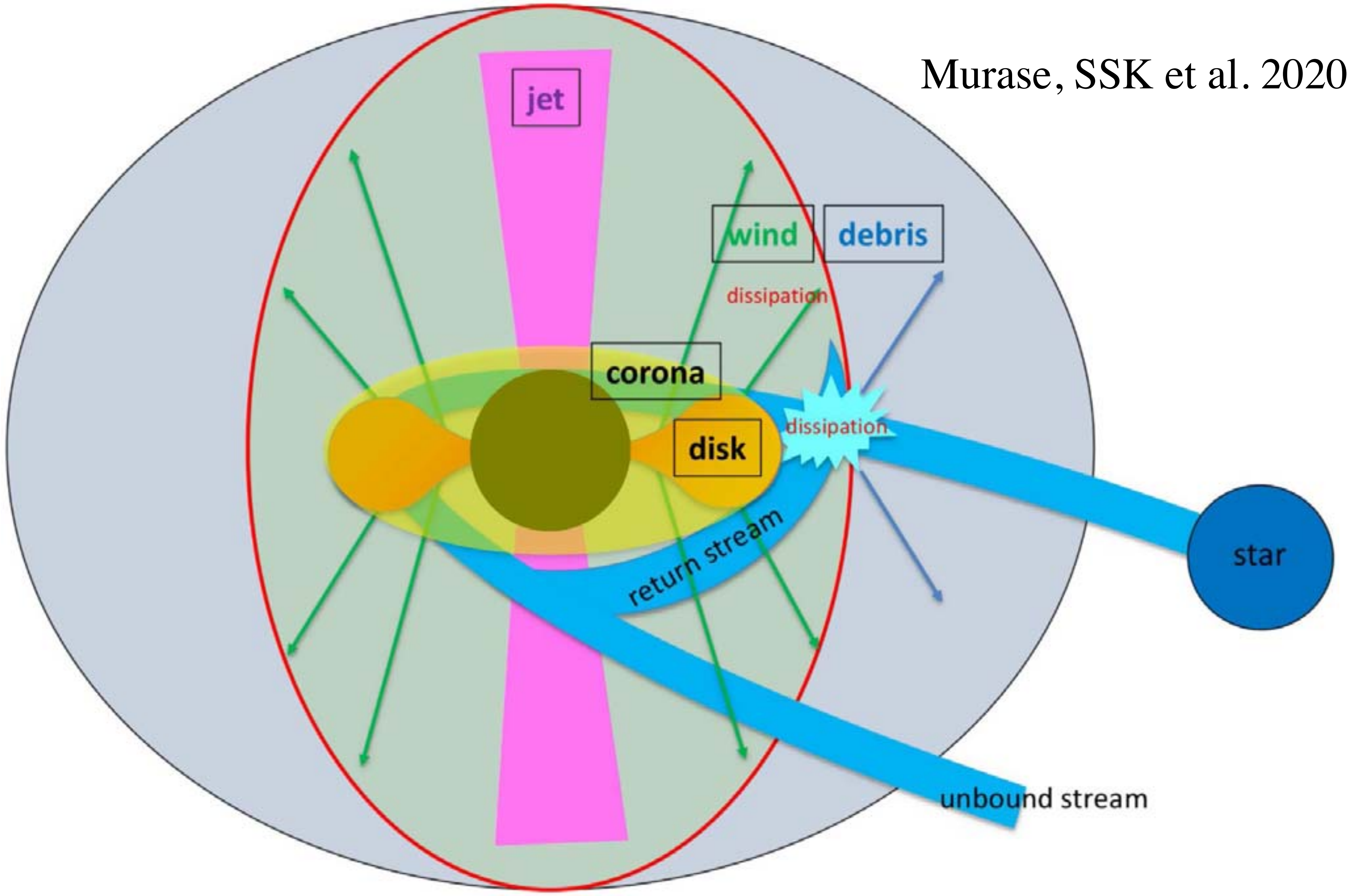




- Stars are torn apart by supermassive black holes
  => luminous (~10^{43} erg/s) & long (~year) optical transients
- 2 TDEs are reported to associate with cosmic neutrino events

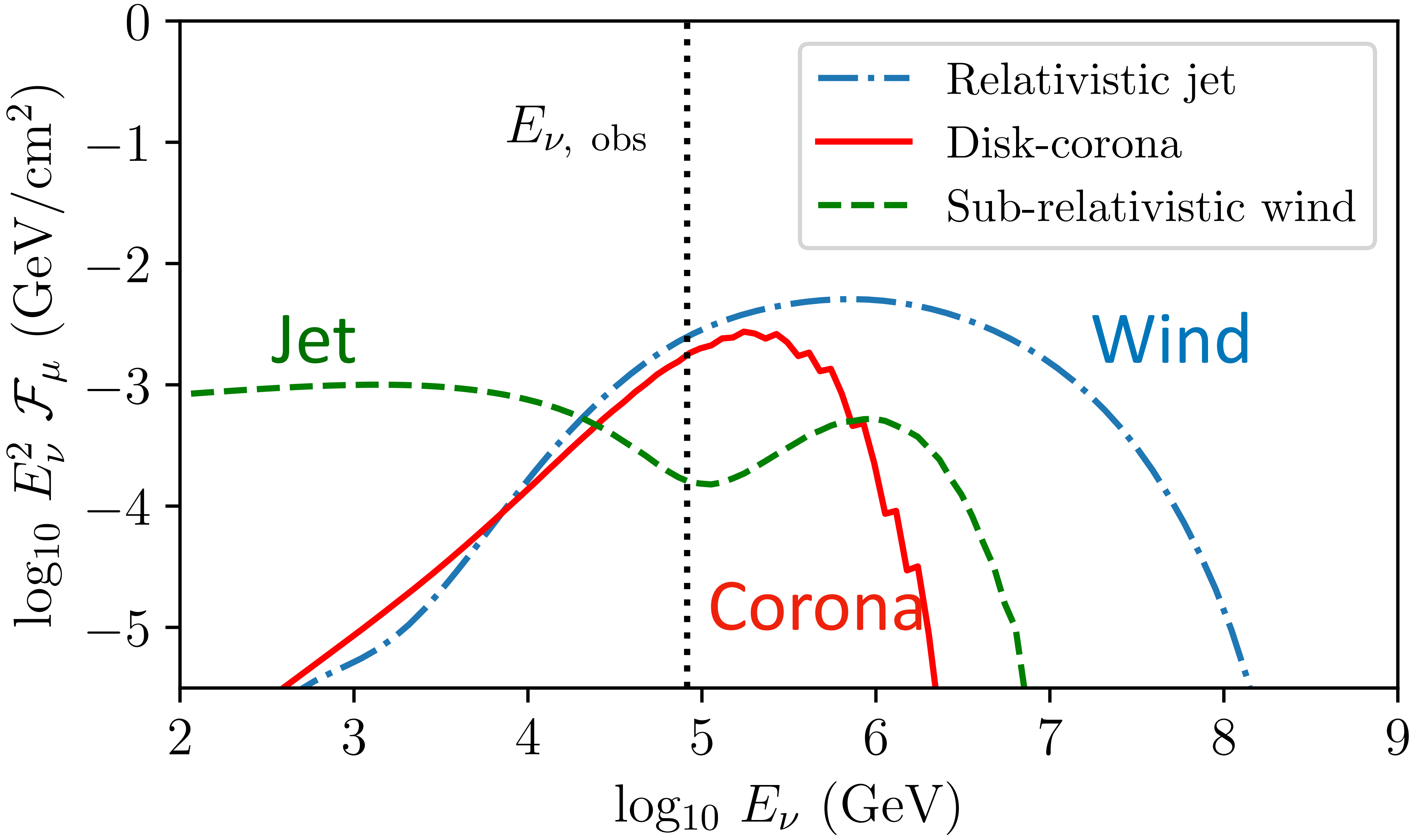
IC191001 <=> AT2019dsg ; IC200530 <=> AT2019fdr

Neutrino emissions from TDEs



Murase, SSK et al. 2020

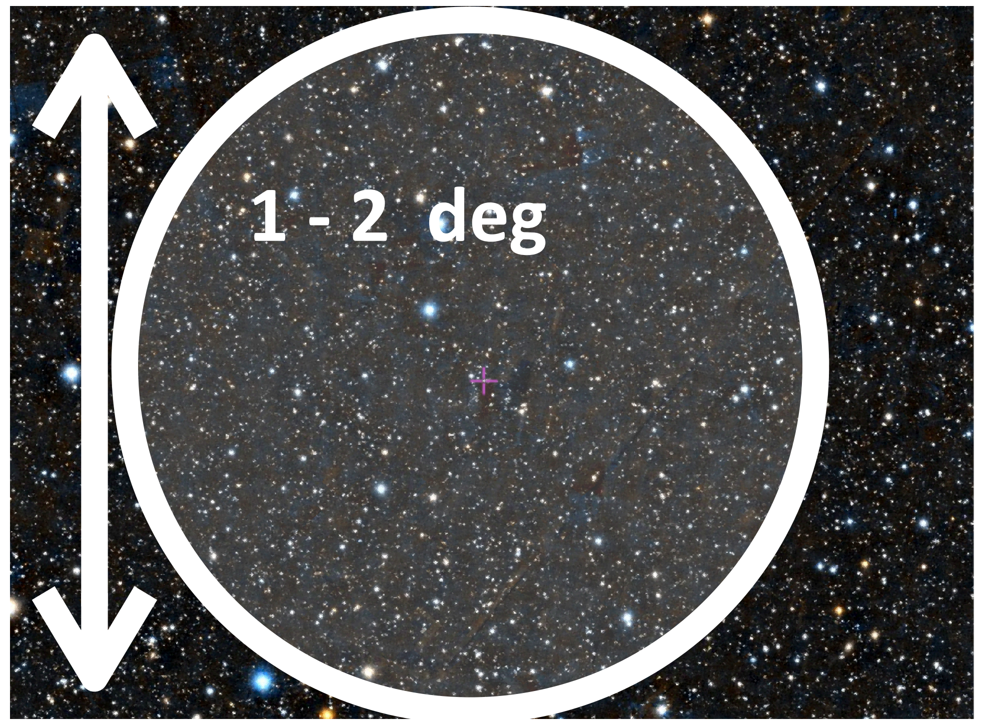
Reush et al. (incl. SSK) 2022

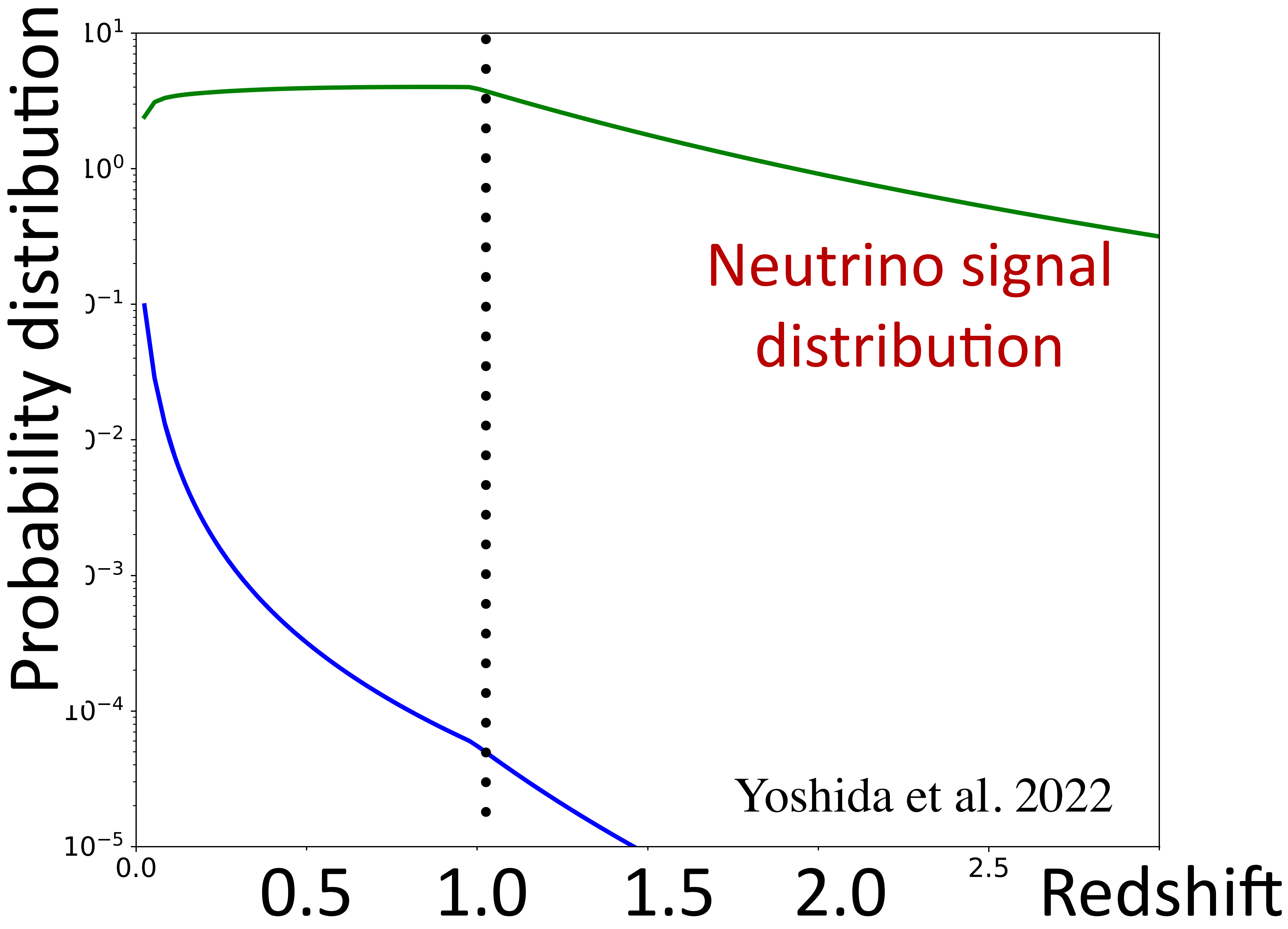


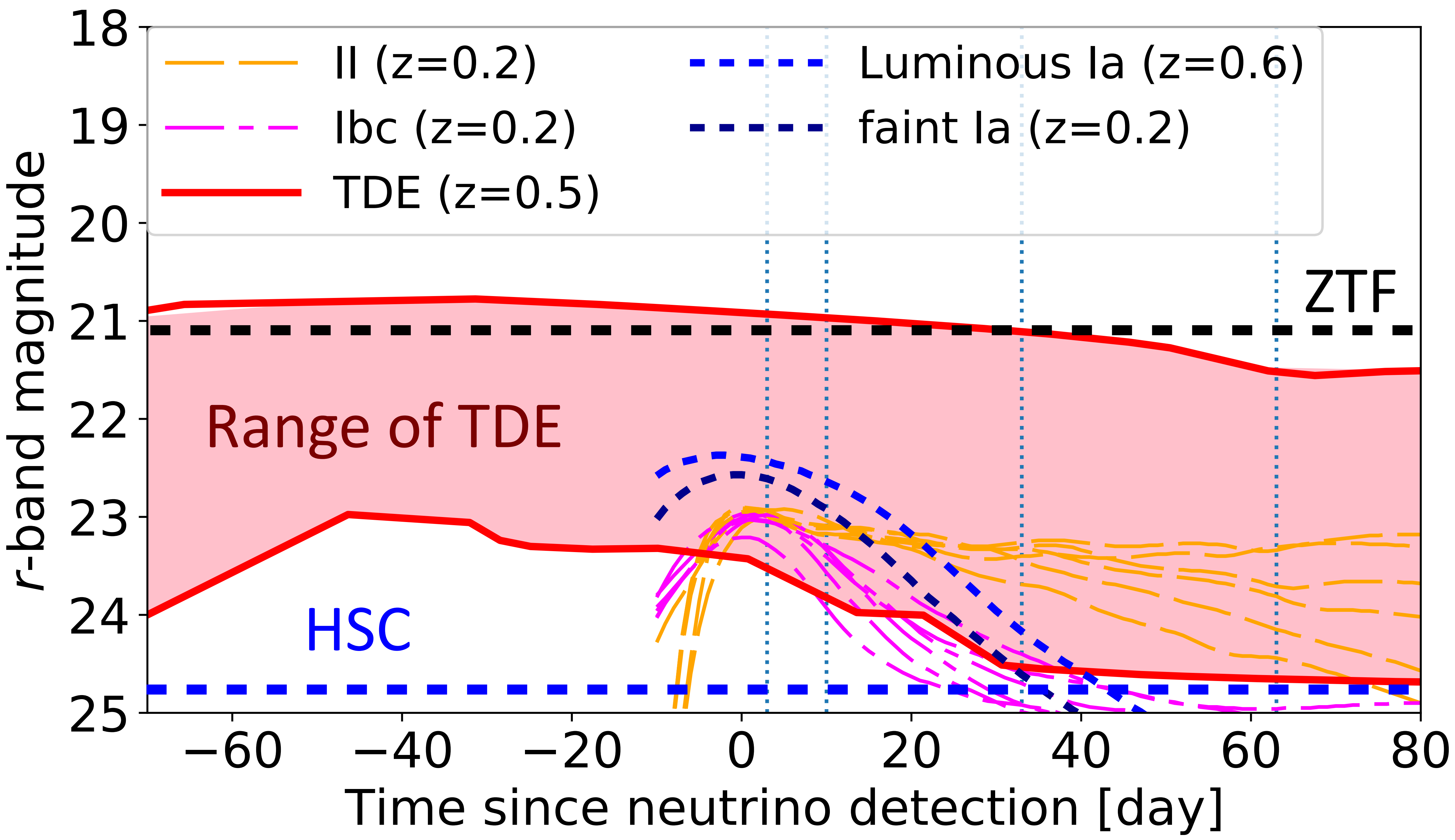
- Several possible sites of neutrino emissions
- Our best-guess scenario: **accretion disk & corona**
- Many models are proposed => **We need more observations to test scenario**

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







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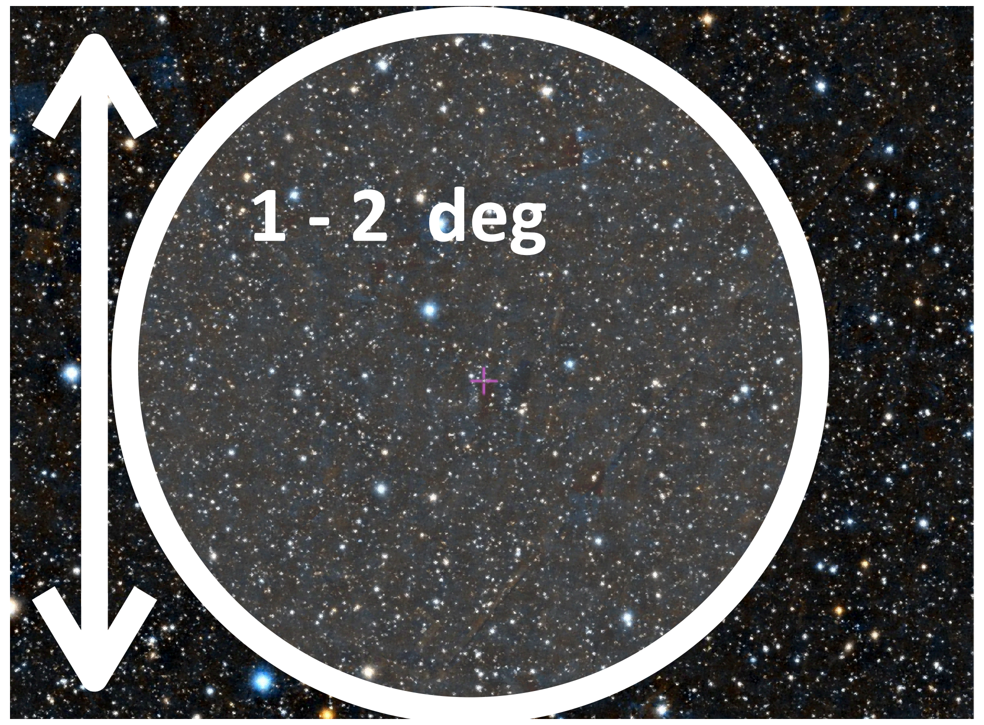
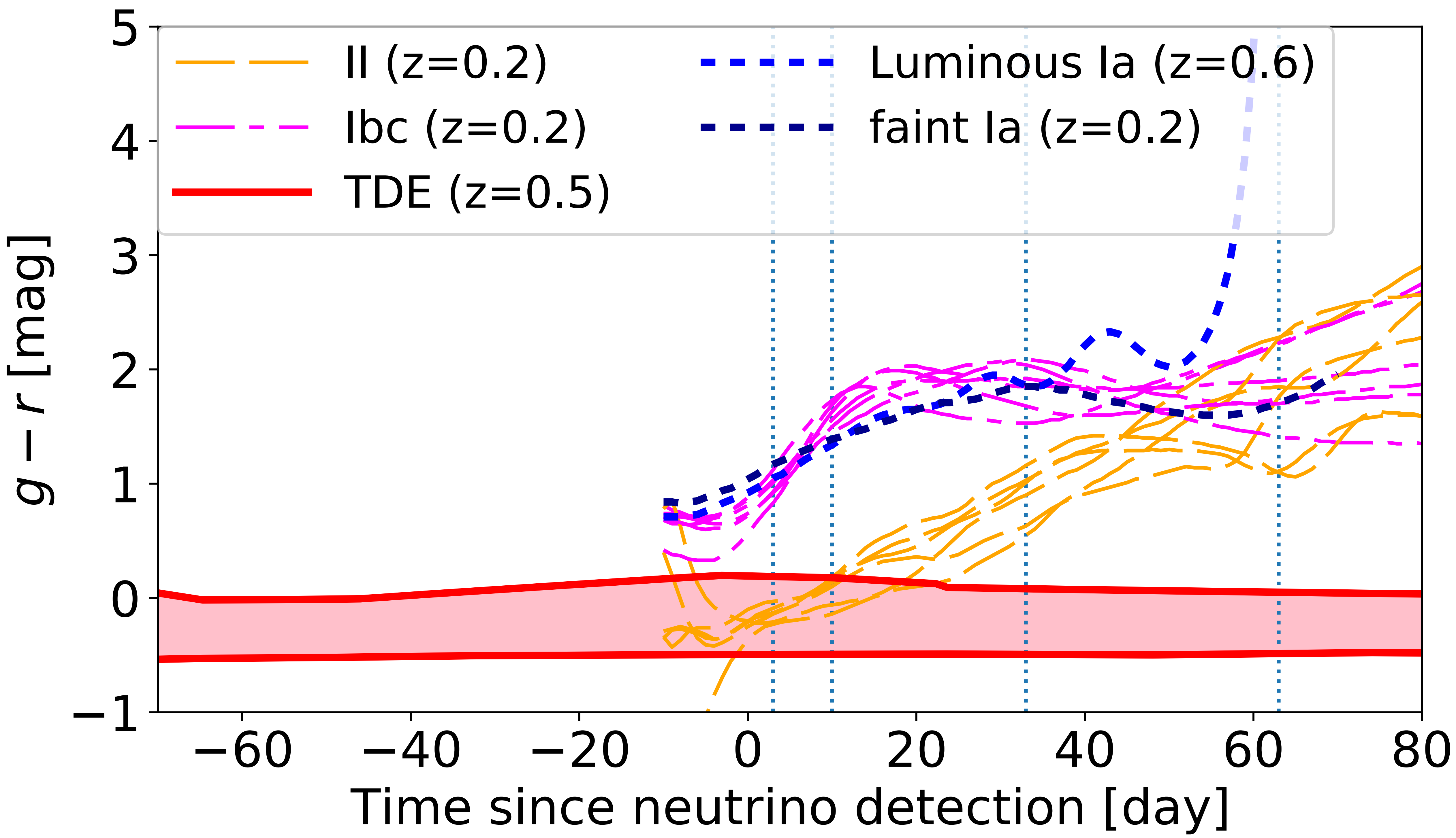
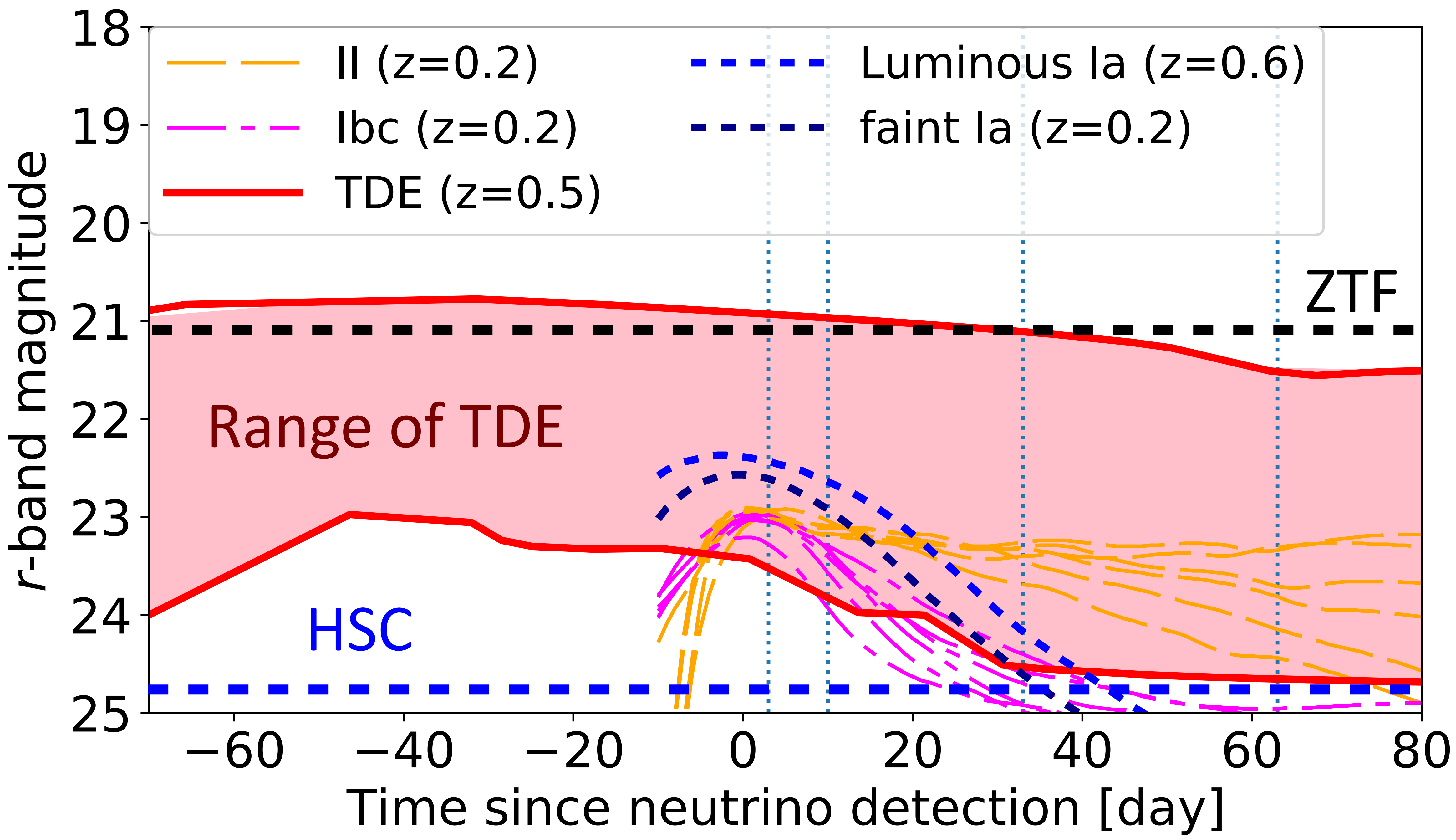






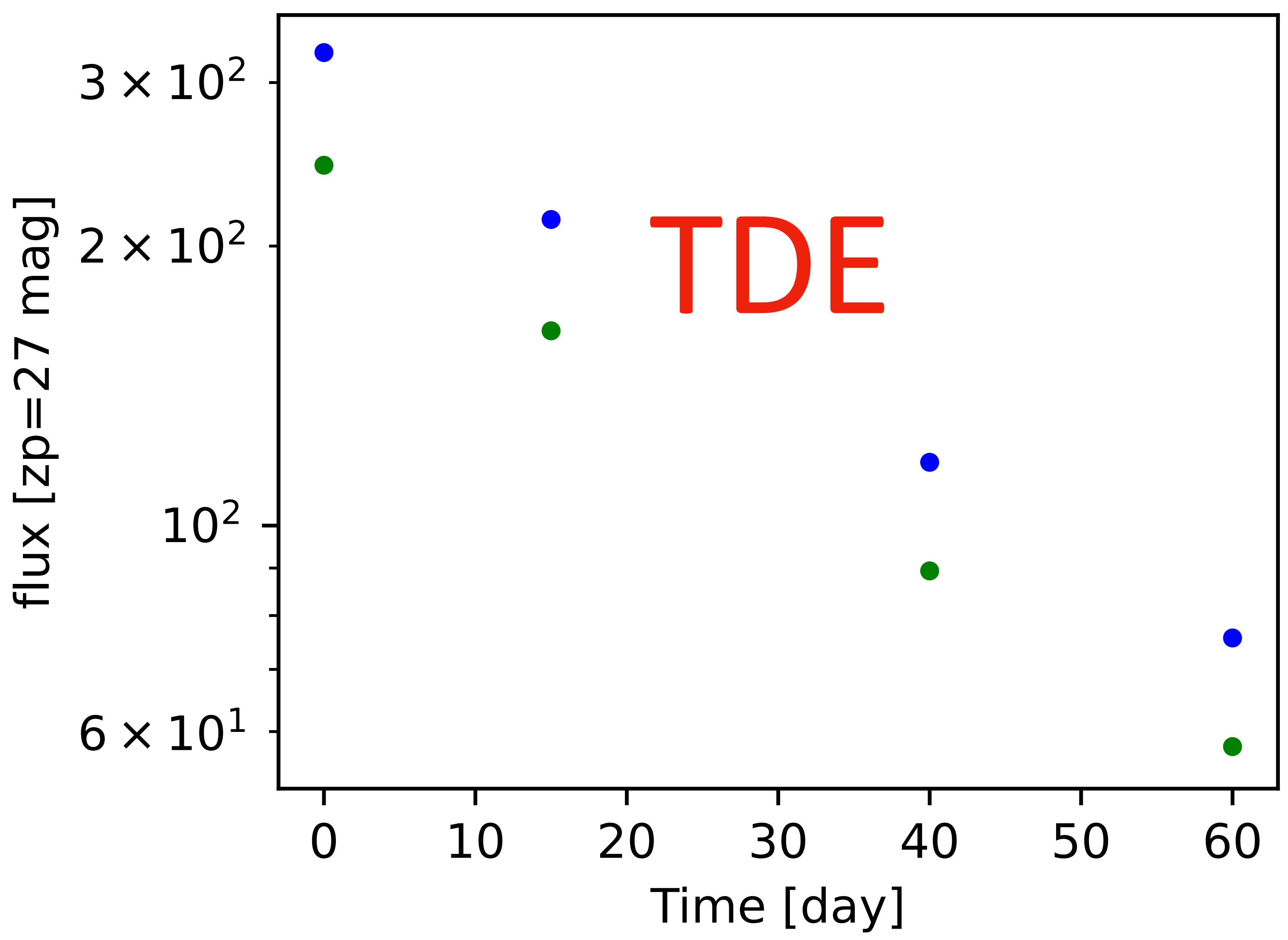
Transient Classification Simulations

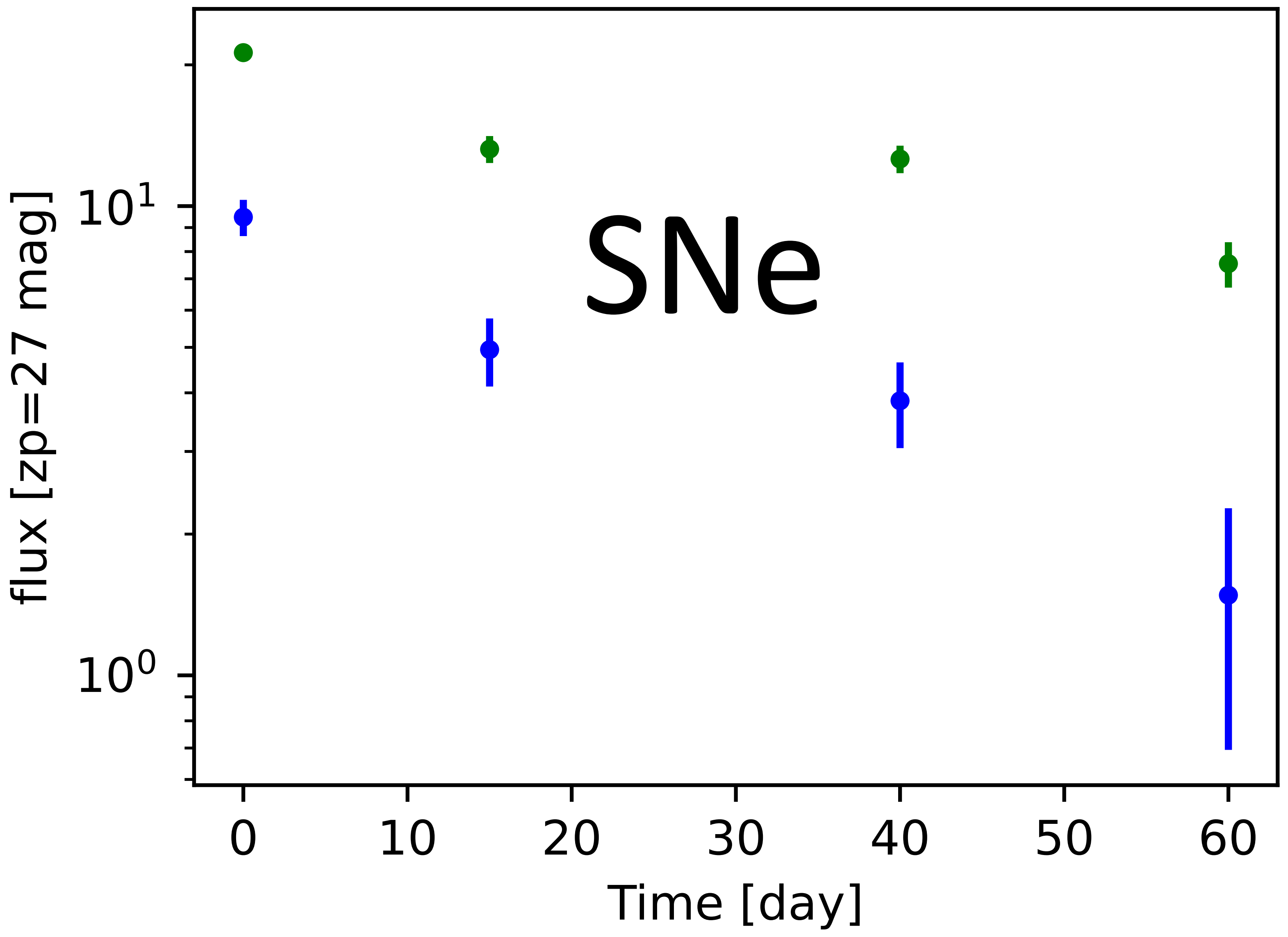
- Optical sky includes a lot of variable objects (supernovae, active galaxies, TDEs)
- We use SNCosmo Package with additional lightcurve templates

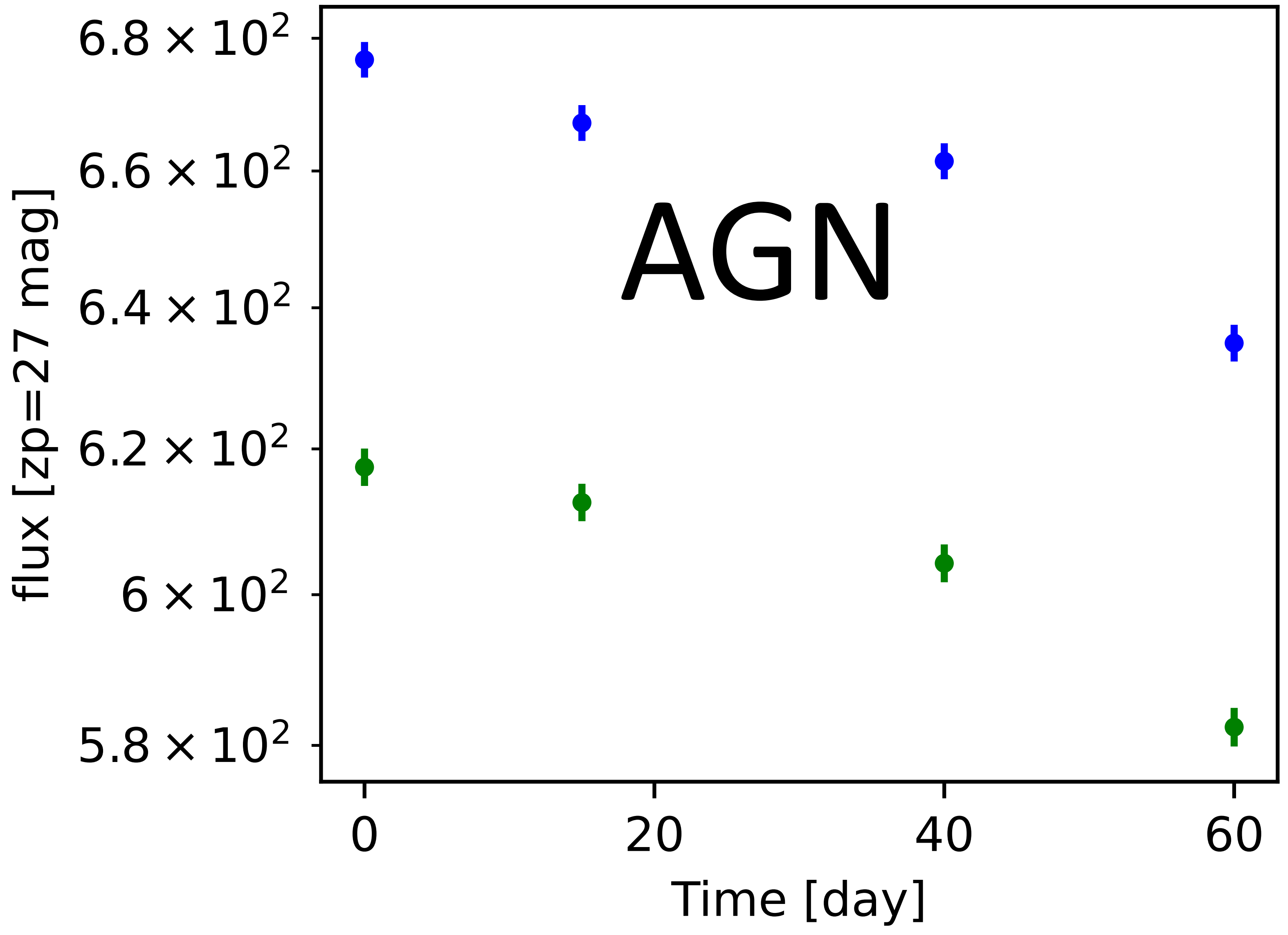
Cf. Kimura et al. 2020; Hammerstein et al. 2023

Transient type	TDE (signal)	CCSN (noise)	SN Ia (noise)	AGN (noise)	TDE (noise)
Number of detected transients	1	80	50	260	0.2

Preliminary







Transient Classification Simulations

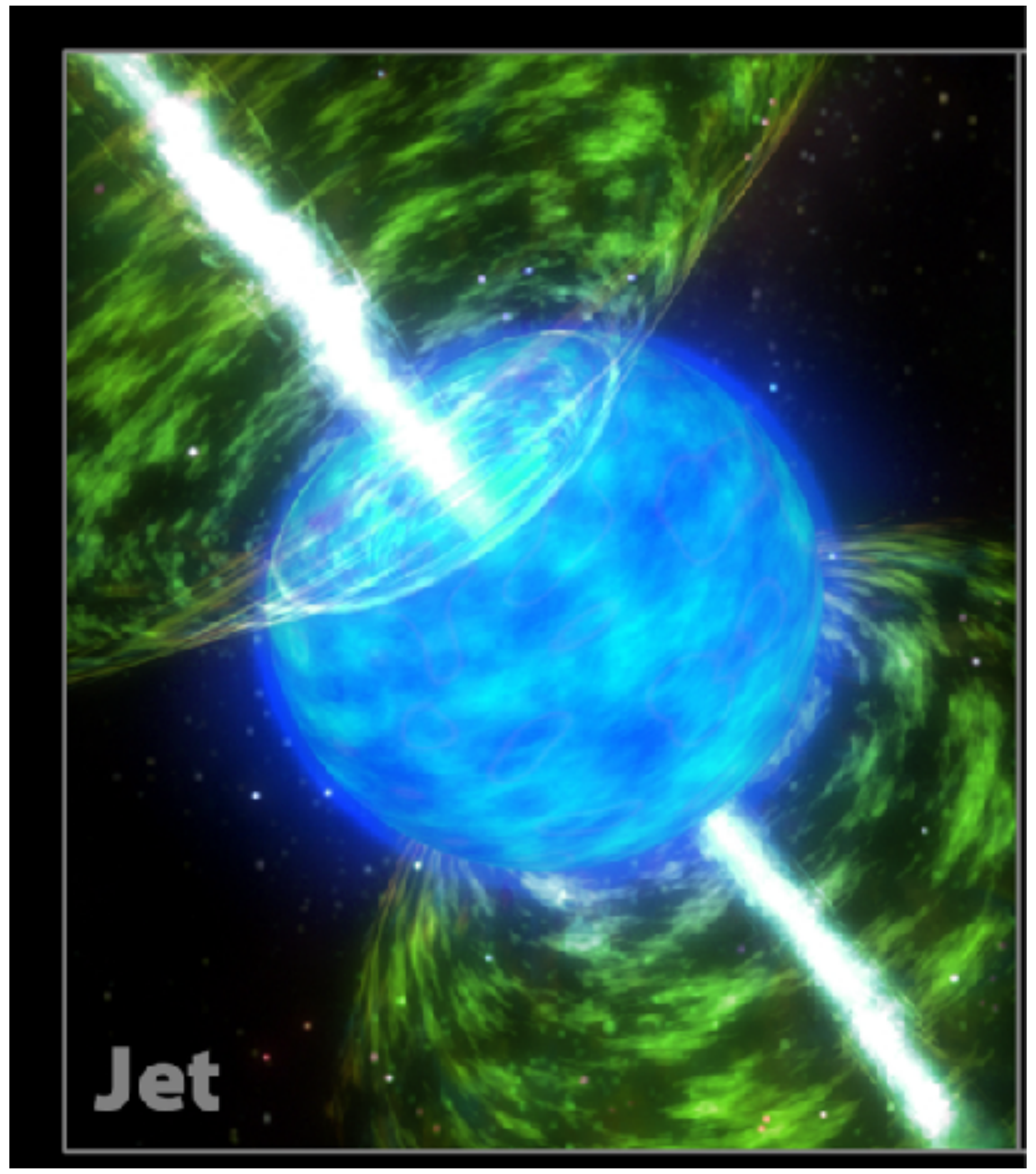
- TDE is rare object => need to reject a lot of AGN, SNe from detected transient
- Lightcurve & color evolution templates => determine criteria to pick up TDE
  - Bluer color (g-r < 0.7)
  - Long duration (Bright for > 45 days)
  - Continuously declining lightcurve with significant variation
- Result of classification simulation (Error region = 1 deg^2, 15-day cadence, 4 ToO observations)

Transient type	TDE (signal)	CCSN (noise)	SN Ia (noise)	AGN (noise)	TDE (noise)
Number of detected transients	1	80	50	260	0.2
Number of source TDE candidates	**0.6**	**< 0.01**	**< 0.01**	**0.01**	**0.04**

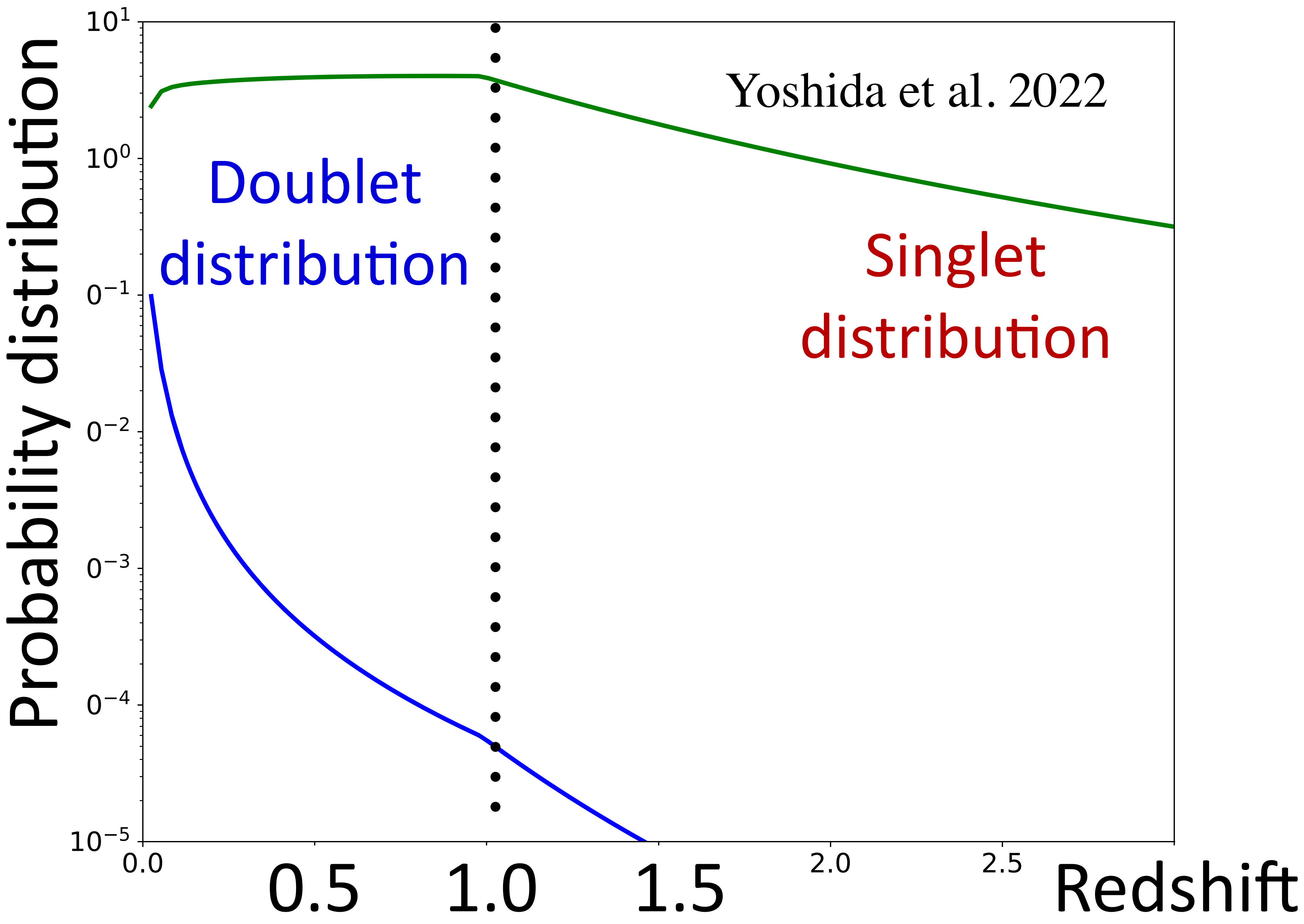
Preliminary

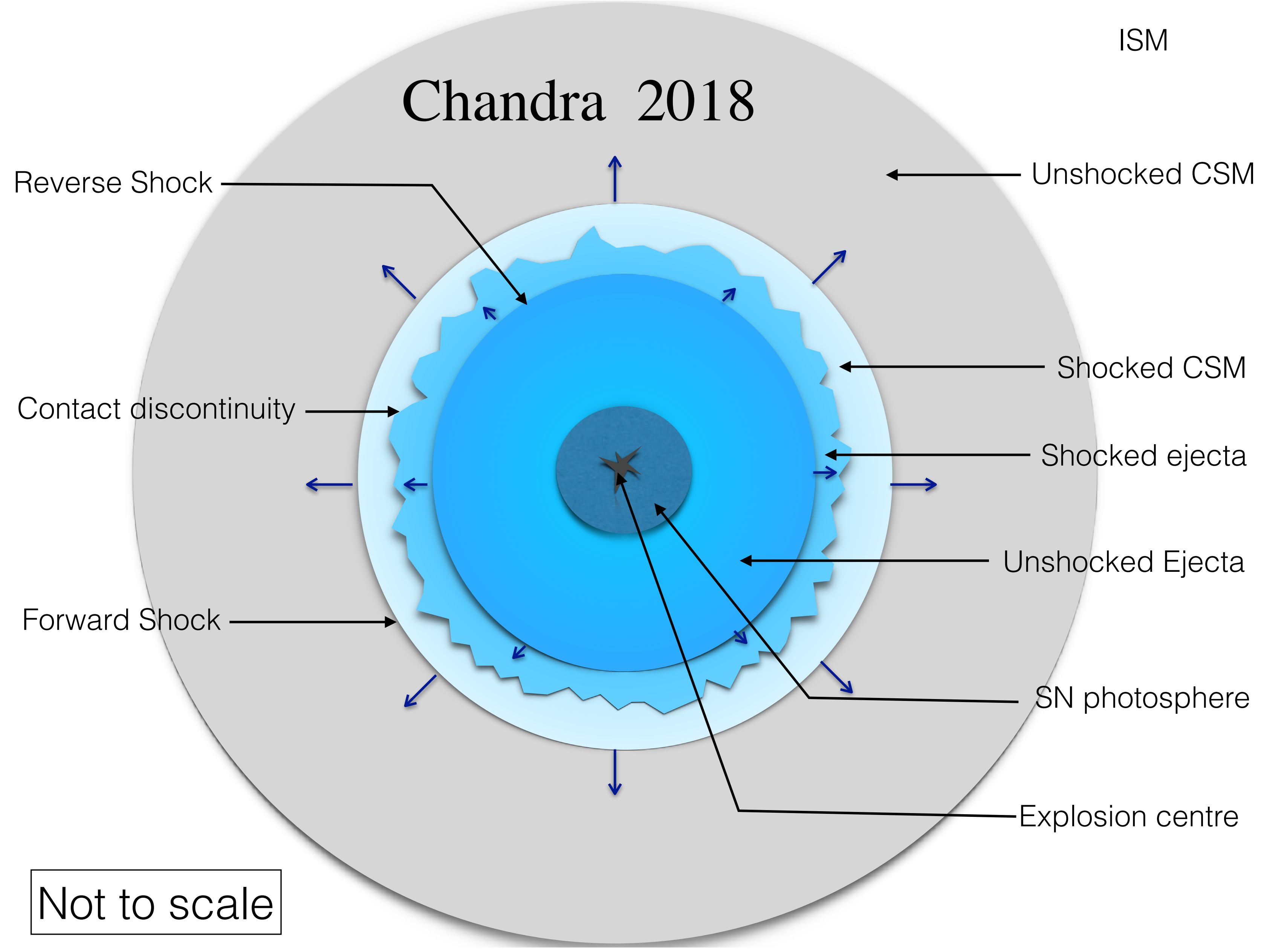
If we find TDEs in neutrino error regions multiple times, we can establish TDEs as neutrino sources

Near Future Neutrino Alert



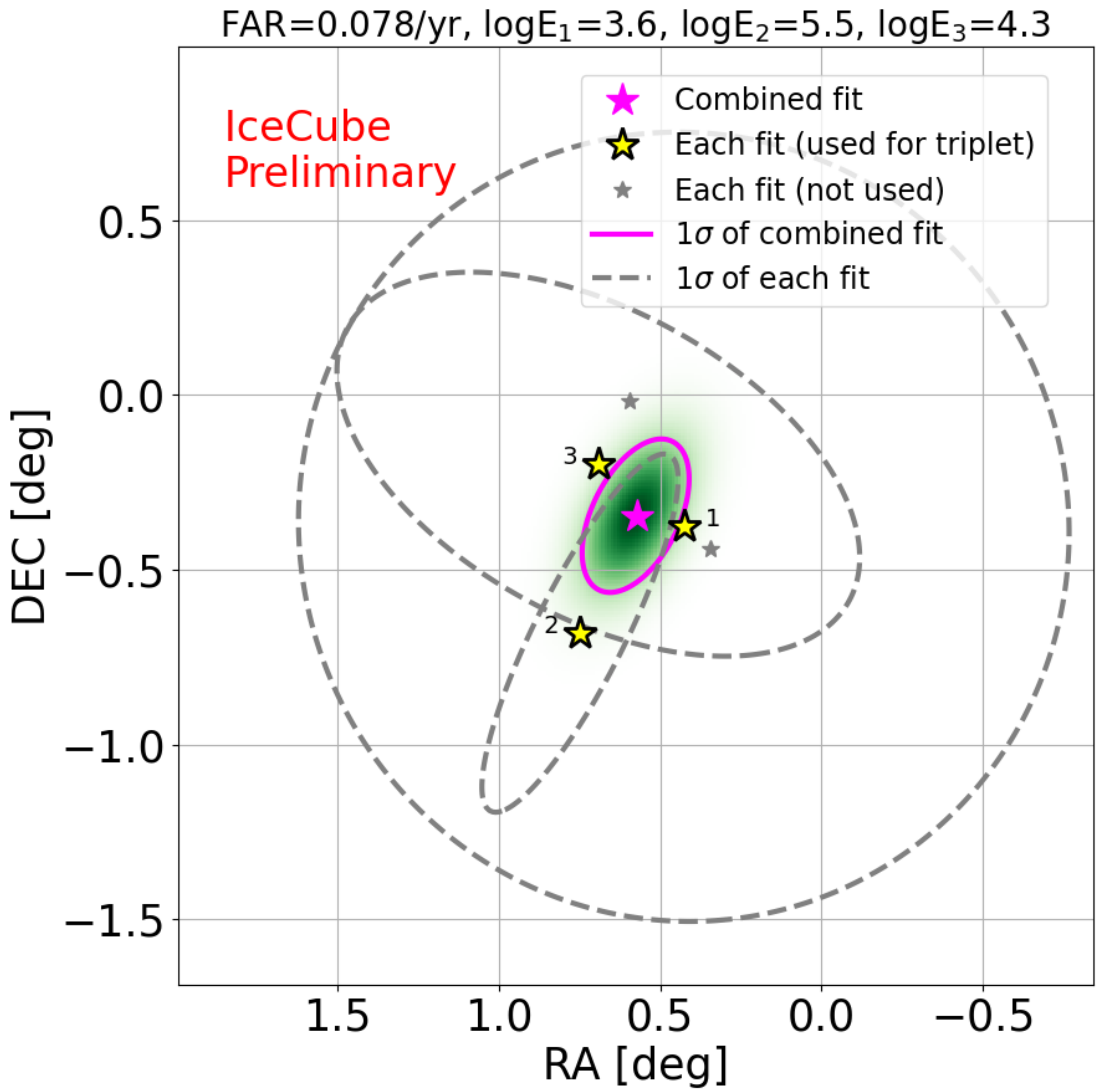
- Target: Peculiar SNe (Interacting SNe; Hypernovae)
- Photometric classification is challenging
  => **need to perform spectroscopic observations**
- **Multiplet alert**: two neutrino signals within a certain time period
  => biased toward the nearby events

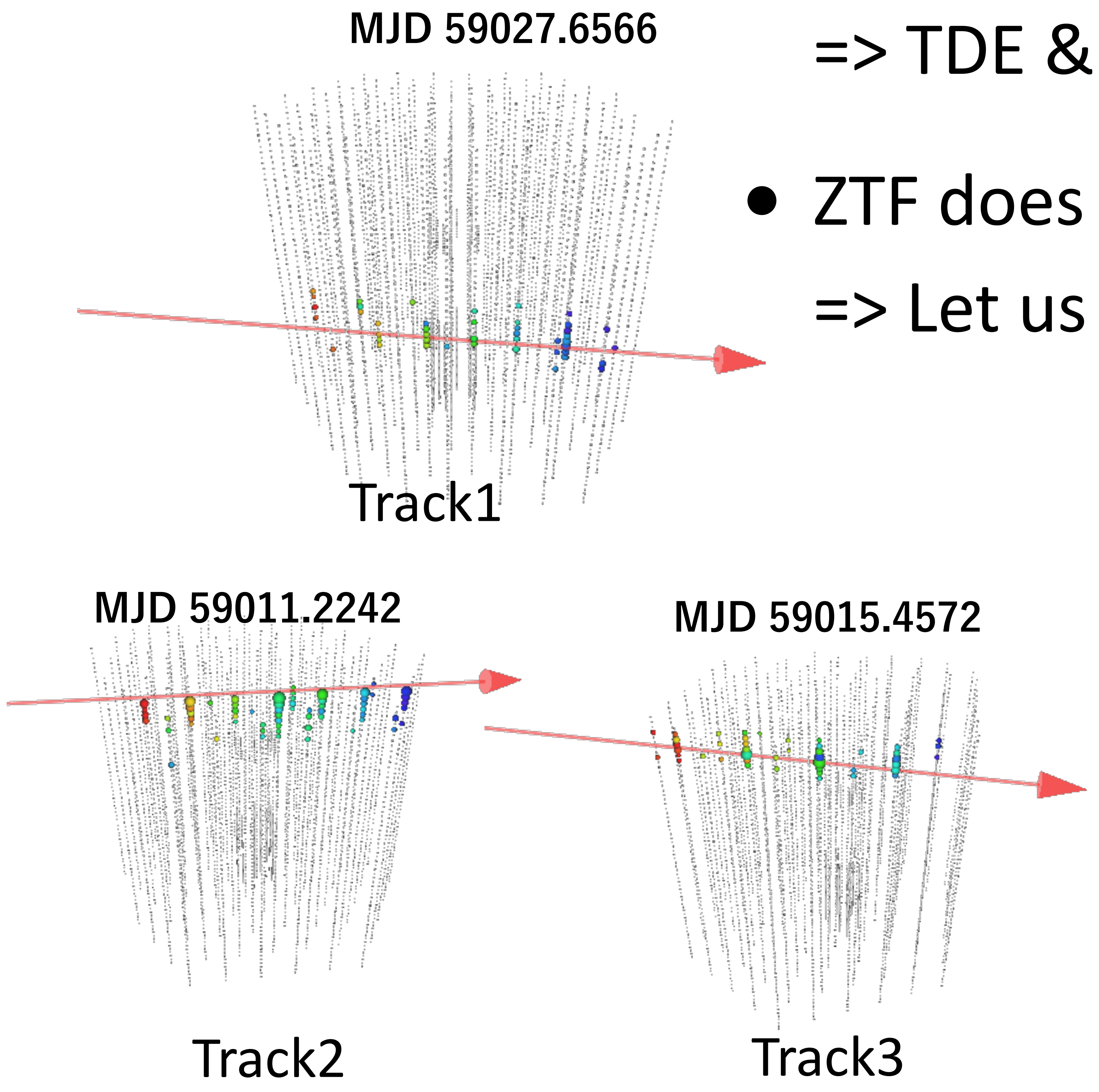




Multiplet-alert Candidate

Type: **Triplet**, (RA, DEC)=(0.58 deg, -0.35 deg)
Energy: logE=(3.62, 5.47, 4.31), $\Delta T = 16.4$ days,
local p-value=7.4×10^{-7}, FAR= 0.078 [1/yr], MAXI p-value=0.283



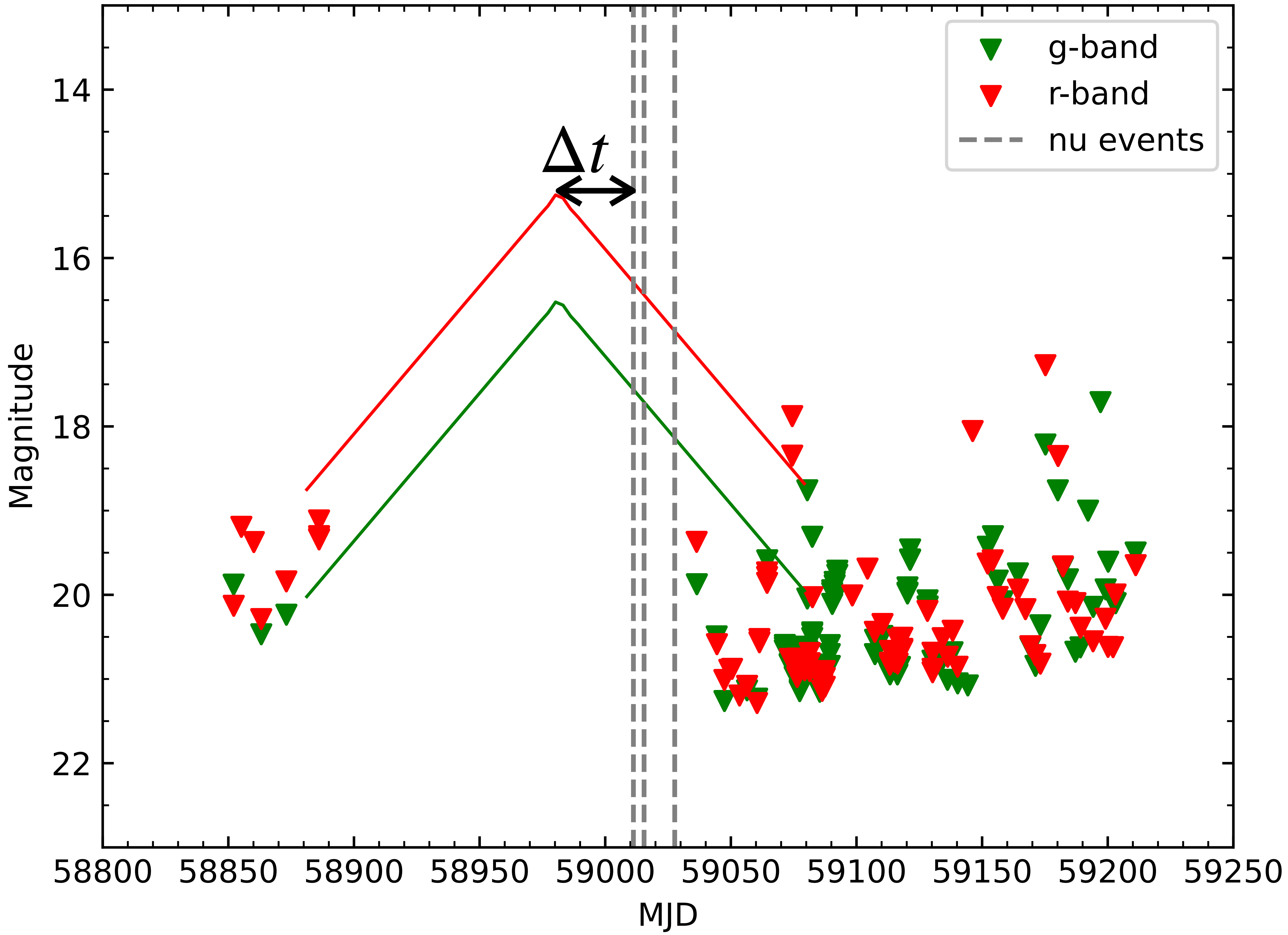


- Long interval (16.4 days)
  => hypernova scenario does not work
  => TDE & interacting SNe are feasible
- ZTF does not report any transient
  => Let us discuss constraint on transients

Strategy to constrain transients

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

$$L(\nu, t) = L_{\rm pk} \exp\left(-\frac{|t - t_{\rm pk}|}{T_{\rm decay}}\right) B_\nu(T_{\rm sn})$$



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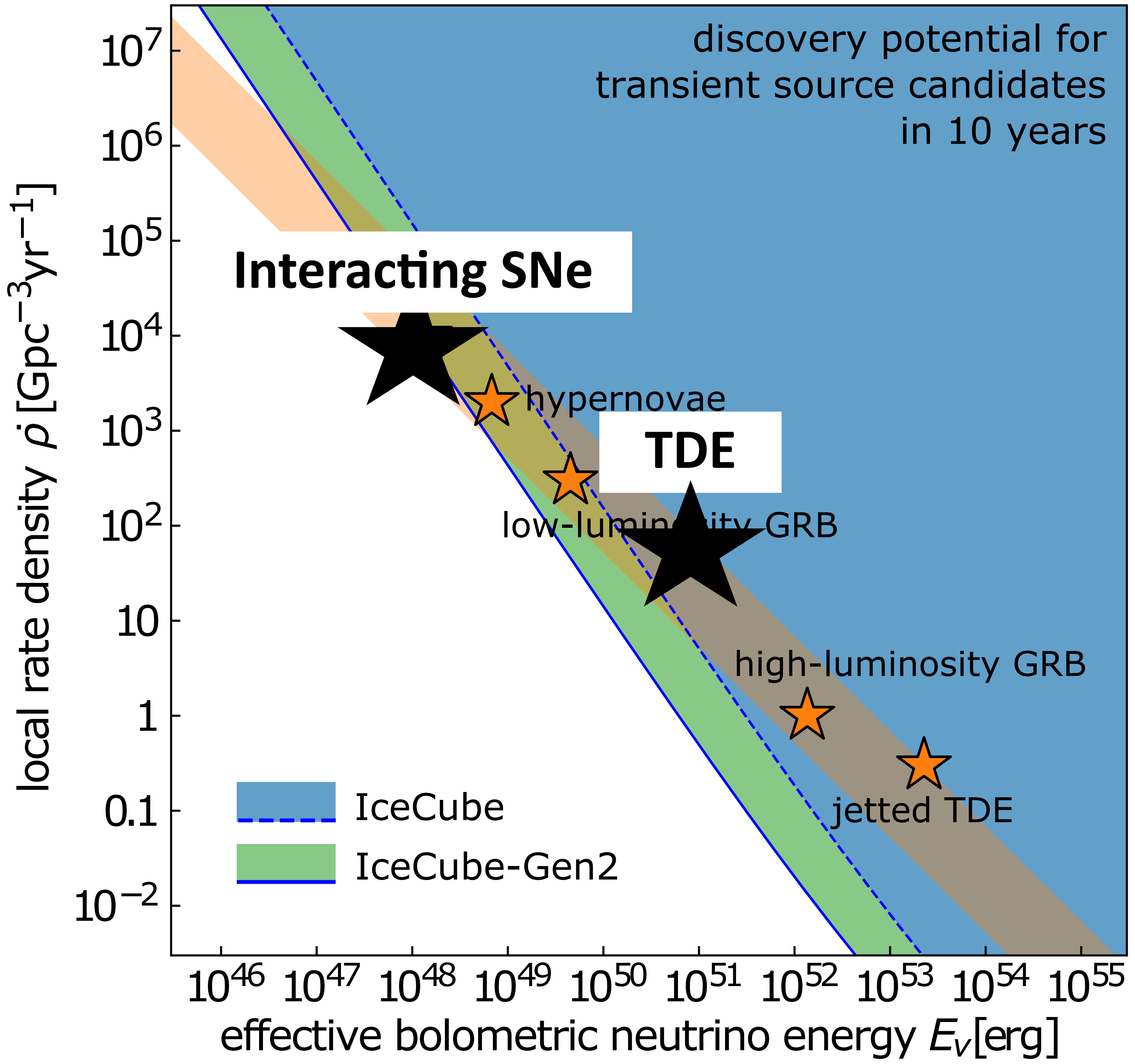
$$L(\nu, t) = L_{pk} \exp\left(-\frac{|t - t_{pk}|}{T_{decay}}\right) B_\nu(T_{sn})$$

- Give total neutrino energy ($\mathscr{E}_\nu$) & time lag btw EM & ν (Δt)
  # We can convert $\mathscr{E}_\nu$ to the event rate, suppose that the transient is the dominant source of the cosmic high-energy neutrino background



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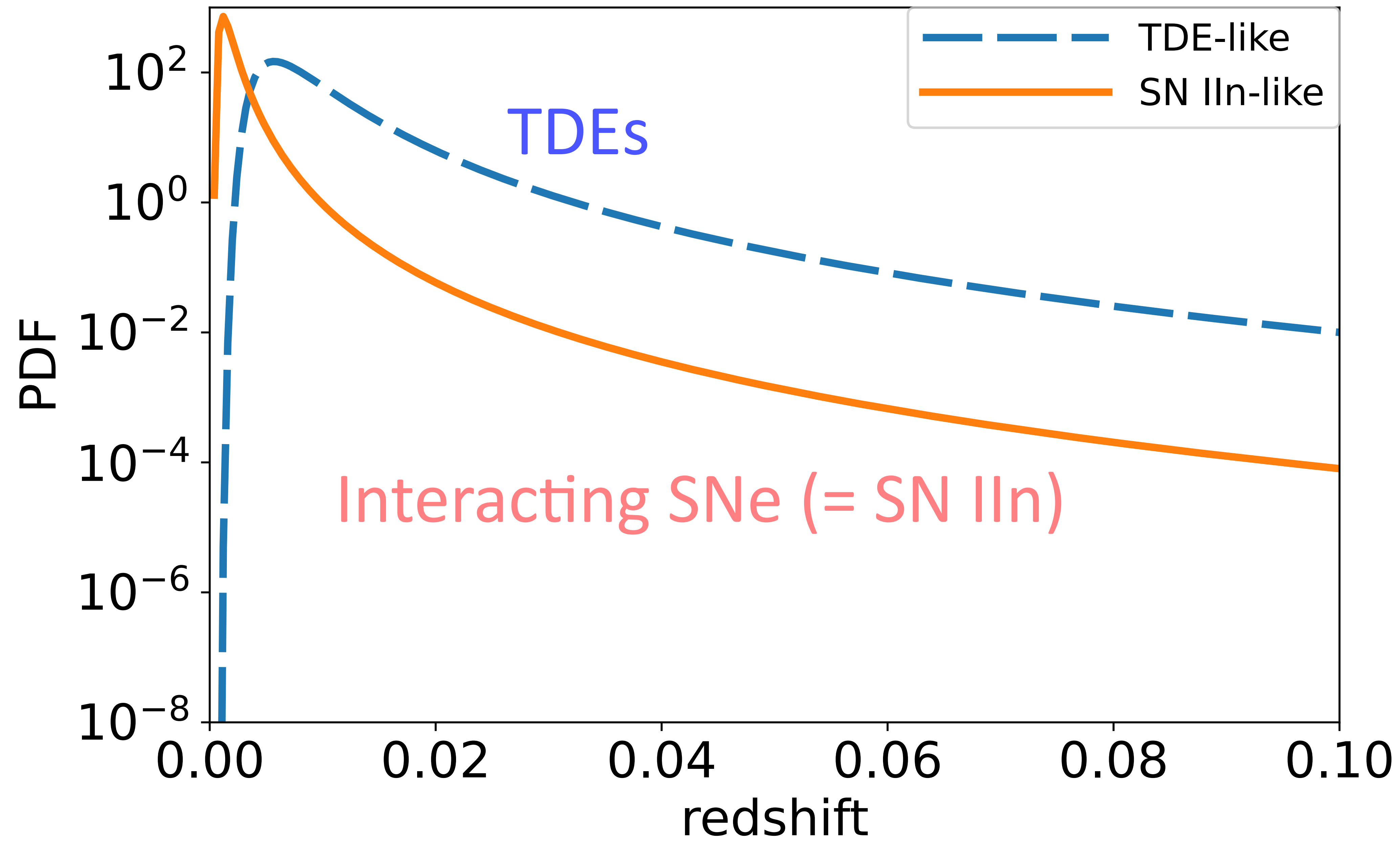
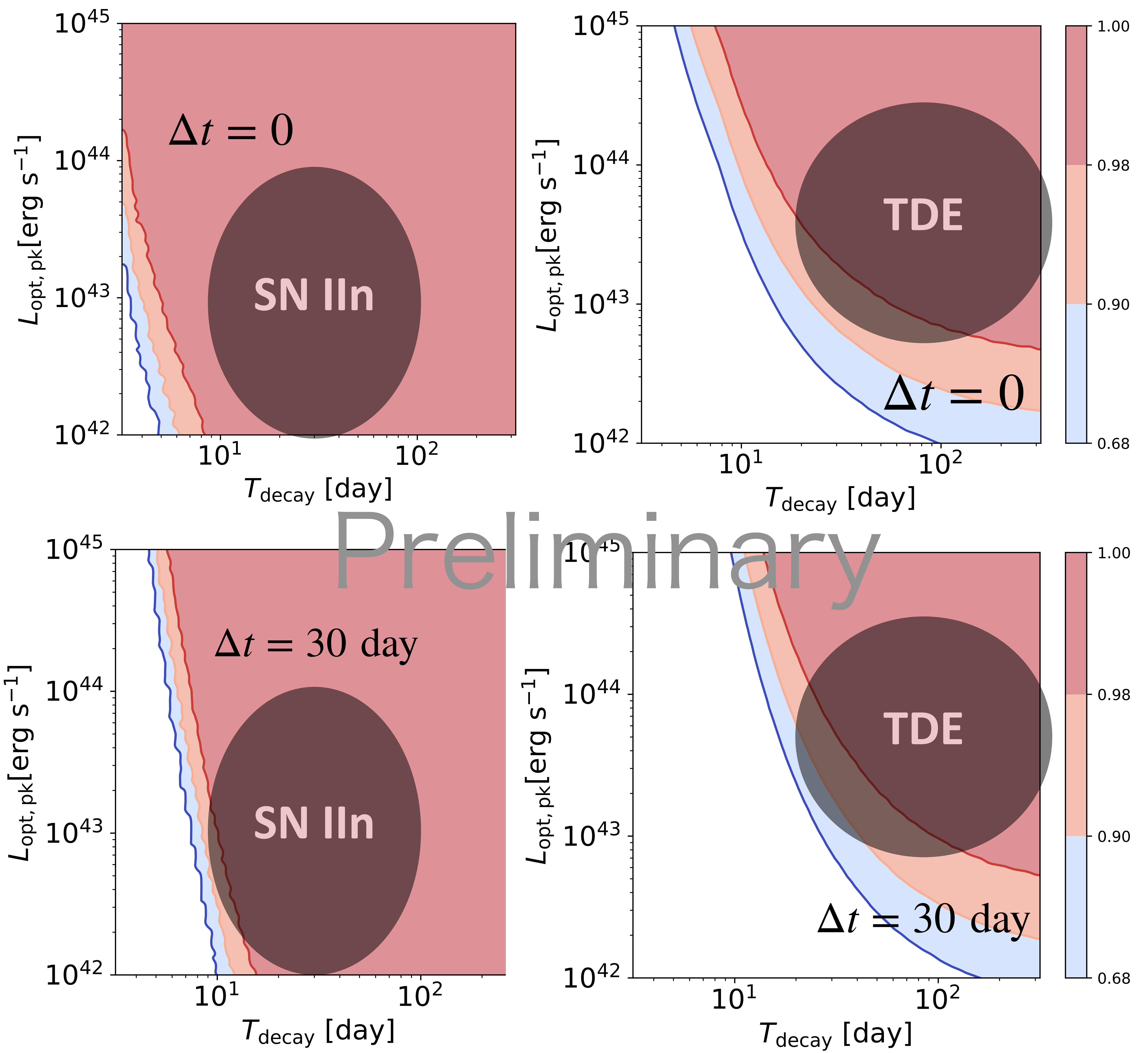
- Give ($T_{\rm decay}$, $L_{\rm pk}$)
  => generate light curve with z-dist. by Triplet alert
  # typical distance: TDE $\sim$ 50 Mpc; SN IIn $\sim$ 10 Mpc
  => evaluate the consistency with respect to ZTF data

- Repeat the procedure by various $T_{\rm decay}$ & $L_{\rm pk}$
  => constrain these two parameters



Constraints by ZTF data

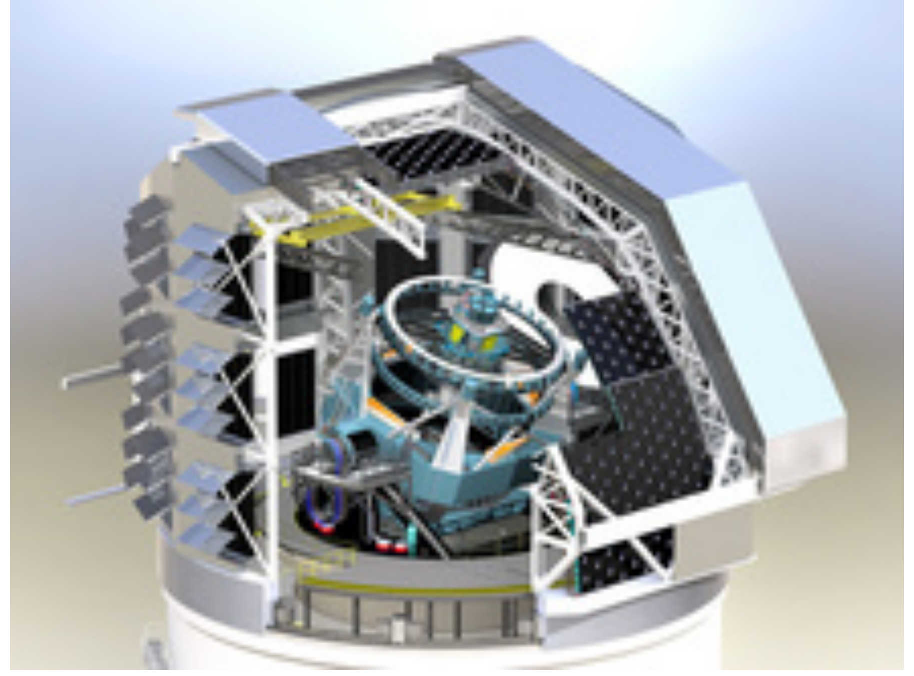
- Both TDE-like & SN IIn-like scenarios are strongly disfavored by ZTF data
- If this triplet event is true, we can put very strong constraint on transient neutrino sources
- Real-time multiplet alert will be implemented in 2024/2025 => various transients will be constrained or discovered near future



Future Optical Follow-up in 2020s

- Follow-up to doublet alert
  => HSC or Vera Rubin: 10 - 30 SNe with ~ 23 mag
  => PFS spectroscopy for all the SNe

- Jet-powered SNe are rare (1% of SNe)
  => number of unrelated SNe < 0.1
  => **identify jet-powered SNe**
  as neutrino sources



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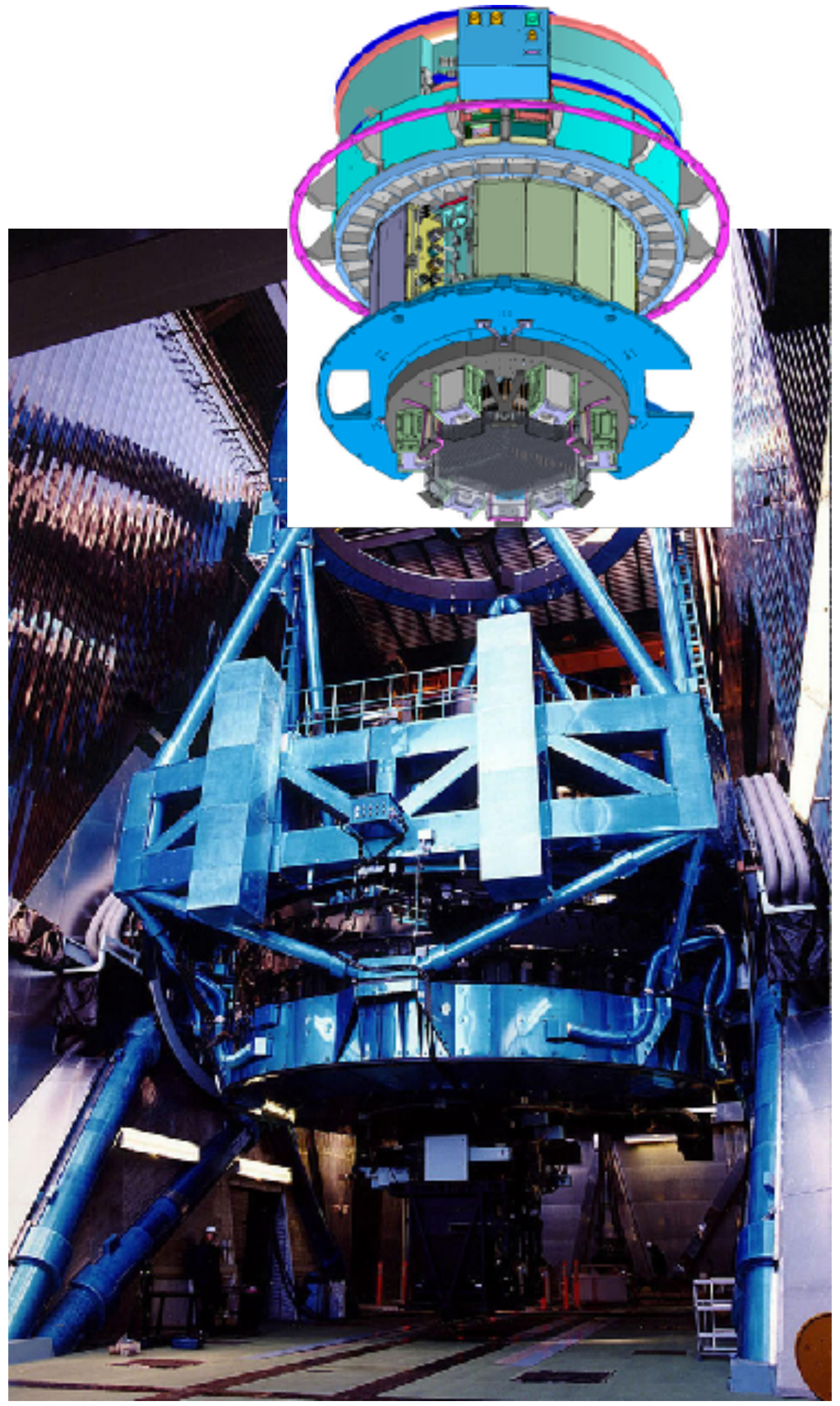

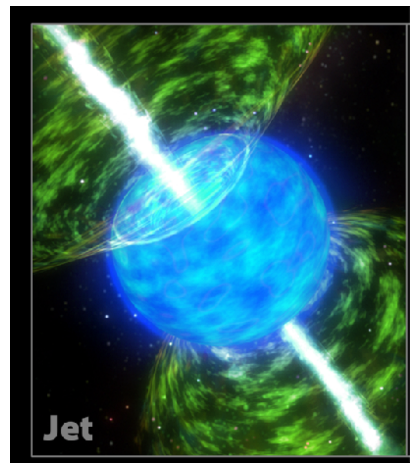

Doublet Neutrino Alert

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Transient Search by HSC or Rubin

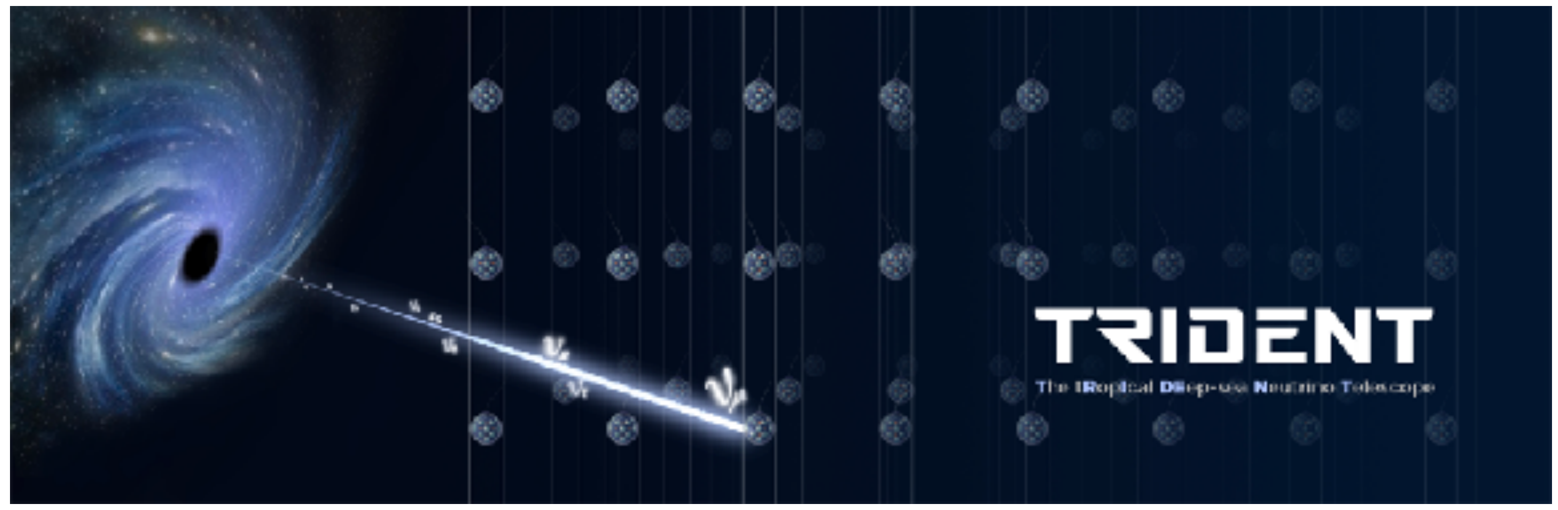
Spectroscopy by PFS

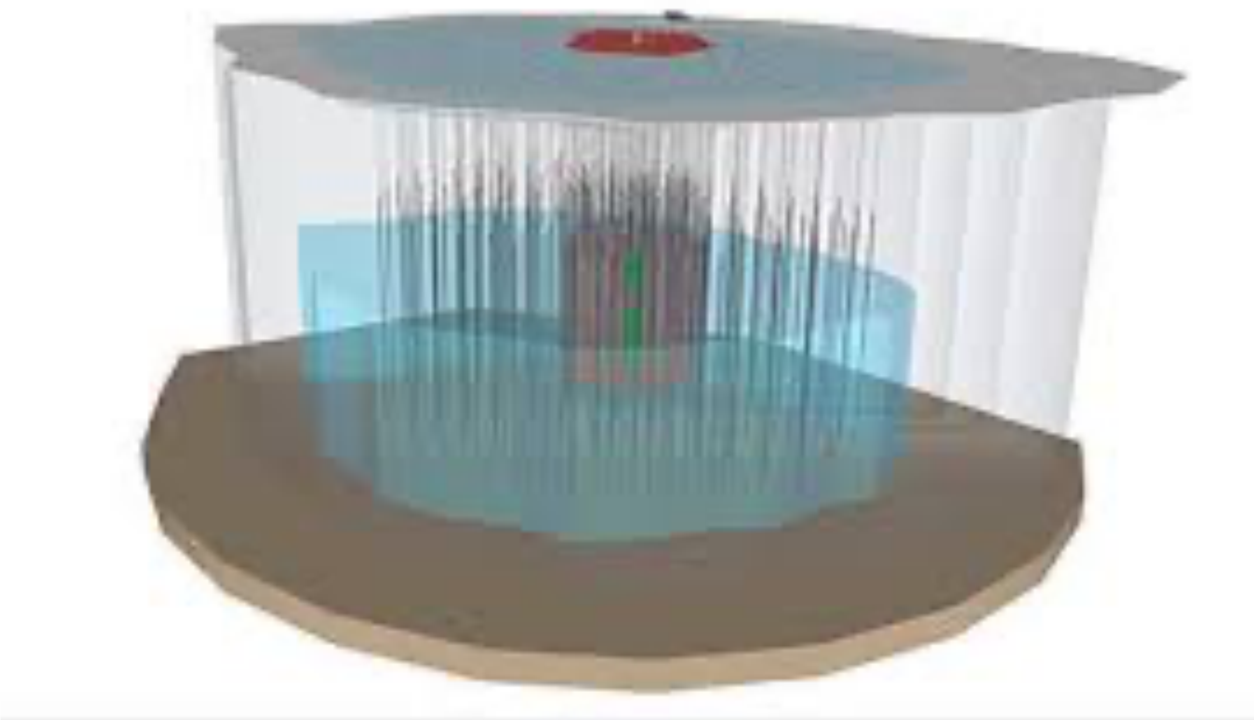
→

Jet-powered SNe as neutrino sources

Future Optical Follow-up in 2030s

- Neutrino detectors will have significant updates (IceCube-Gen2; TRIDENT)
  - Angular error: 0.1 deg
- Singlet alert is more frequent than doublet
- Singlet alert
  => HSC or Rubin: 3 - 10 SNe (25 - 27 mag)
  => Spectroscopy by ELTs
  => **Identify peculiar SNe as neutrino sources**





High-resolution neutrino alert

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Transient Search by HSC or Rubin + **Spectroscopy by ELTs** → **Peculiar SNe as neutrino source**

Summary

- **Cosmic neutrinos are the smoking gun signature to identify cosmic-ray sources**
- Pre-IceCube models are strongly disfavored by current IceCube data
- Accretion flows onto SMBHs are currently most likely sources of cosmic neutrinos
  => **We propose stochastic acceleration scenario, which can explain IceCube data**
- Follow-up observations to neutrino alerts will be able to identify neutrino sources
- Current our strategy: Search for TDEs using Subaru/HSC
  => **We have developed a simulation tool which enables us to distinguish TDEs from SNe/AGN**
- Multiplet alert will be key to identify cosmic neutrino sources
  => Report of triplet event candidate in archival data,
  => **we can put strong constraint on SN IIn- & TDE-like transients with archival optical data**

Thank you for your attention