# 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

Extreme Transients 2024/08/05-09





# Shigeo S. Kimura Tohoku University

Collaborators:

- Kohta Murase, Peter Meszaros (Penn State)
- Ali Kheirandish (UNLV)
- Seiji Toshikage, Masaomi Tanaka (Tohoku U.)
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UNUNU UNIVERSITY

- Tomoki Morokuma (Chiba Tech), Nozomu Tominaga (NAOJ) - Iwakiri, Shigeru Yoshida, Nobuhiro Shimizu (Chiba U.)



FRIS

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

# Outline

## **Cosmic-Rays (CRs)**  : High-energy atomic nuclei filling the Universe



## **Origin of CRs have been unknown for a century**









### **Detection of Cosmic High-energy Neutrinos** *A combined fit of IceCube's high energy neutrino data* EHE Gold TIC F



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- 
- Soft spectrum:  $F_{E_{\nu}}$  @ TeV >  $F_{E_{\nu}}$  @ PeV
- **• Origin of cosmic neutrinos are a new big mystery Examine 15 and 15**  $\frac{1}{4}$   $\frac{1}{4}$ REFERENCES Aartsen, M., Ackermann, M., Adams, J., et al. 2018a, —. 2017a, JINST, 12, P03012,



1450m

2450m  $2820r$ 



## **High-energy neutrino production**

• Photomeson production (pγ)





- $p + y \rightarrow p + \pi$
- $\bullet$   $\pi^{\pm} \rightarrow 3v + e$
- 
- -
- 

## Interaction between CRs & photons/nuclei  $\rightarrow$  Neutrino production **Gamma-rays inevitably accompanied with neutrinos**

## •  $\pi^0 \rightarrow 2\gamma$



Manheim & Biermann 1989 Halzen & Zas 1997

### **• Cosmic-ray Accelerators**

•Gamma-ray Bursts



• Blazars

- pγ **• Cosmic-ray Reservoirs** 
	- •Galaxy Clusters

• Starburst Galaxies



pp





 $\begin{array}{cc} \mathbb{C}^{\mathcal{D}} & \mathbb{C}^{\mathcal{D}} \end{array}$  and  $\begin{array}{cc} \mathbb{C}^{\mathcal{D}} & \mathbb{C}^{\mathcal{D}} \end{array}$  are confined in reservoirs CRs are escaping from accelerators  $\rightarrow$  CRs are producing neutirons via pp channel



## **Neutrino Source Candidates in Pre-IceCube Era**

## **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**

Biermann 1989 Halzen & Zas 1997



### **• No neutrinos from the** <u>UNCTRINING</u> WARDS **direction & timing of GRBs**

ν

γ

ν

### **No neutrinos from direction of γ-ray detected blazars**





Manheim & Biermann 1989 **Halzen & Zas 1997** The Astrophysical Journal, 736:131 (22pp), 2011 August 1 Abdo et al., 736:131 (2011 August 1 Abdo et al., 736:131 (2012), 2011 August 1 August 1 August 2 Abdo et al., 736:131 (2012), 2012 (2013), 2012 (

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pp



 $\begin{array}{cc} \begin{array}{ccc} \hline \mathbb{C} & \mathbb{C} \end{array} & \mathbb{C} \end{array} \end{array}$   $\begin{array}{cc} \mathbb{C} & \mathbb{C} \end{array}$ CRs are escaping from accelerators  $\rightarrow$  CRs are producing neutirons via pp channel





## **Neutrino Source Candidates in Pre-IceCube Era**

## **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  $\rightarrow$  fit theory to neutrino data  $\rightarrow$  y-ray theory >> y-ray data
- **• γ-ray needs to be absorbed inside the sources (hidden source)**  *γ* + *γ* →  $e^+$  +  $e^-$
- **•** γ rays freely escape from reservoirs **=> contradict with γ-ray data**

i<br>⊡e∑

 $E^2\Phi$ 

12



Manheim & Biermann 1989 **Halzen & Zas 1997** The Astrophysical Journal, 736:131 (22pp), 2011 August 1 Abdo et al., 736:131 (2011 August 1 Abdo et al., 736:131 (2012 August 2 Abdo et al., 736:131 (2012 August 2 Abdo et al., 736:131 (2013 August 2 A

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### •Gamma-ray Bursts



### • Blazars



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







 $c_{\text{waves}}$  and  $c_{\text{max}}$  are confined in reservoirs CRs are escaping from accelerators → CRs are producing neutirons via pp channel



## **Neutrino Source Candidates in Pre-IceCube Era**

• Seyfert Galaxies (Radio-quiet AGN)

# **Current Source Candidates**

### • Tidal Disruption Events

(TDEs)

• Peculiar Supernovae (hypernova; Interacting supernova)





- No observational evidence
- Theory-motivated





• Strong evidence of neutrino signals from NGC 1068

IceCube 2022

• 2 possible association

## reported from ZTF team

Stein+ 2021 Reusch+(incl. SSK) 2022

# How to find neutrino sources?

15

- - Integrated Neutrino data + Catalogued sources by EM → Identify neutrino sources



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



# How to find neutrino sources?







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

### • Peculiar Supernovae (hypernova; Interacting supernova)

• Seyfert Galaxies (Radio-quiet AGN)

### • Tidal Disruption Events

(TDEs)



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Murase, SSK+ 2020 Winter+ 2020





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## **Current Source Candidates**

- 
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- 
- $\bullet\;$  y-ray, CR & v productio of both components is shown in gray and the data in black. This representation of the result ignores the

between 1.5 and 15 and 15 tev, where the flux measurement is well constrained (26). Two theoretical predictions is well constrained (26). The flux measurement is well constrained (26). The flux measurement of the flux meas



 $\rightarrow$  Optically thick disk + Corona



Hoshino 2013, 2015; Riquelme et al. 2014; Kuntz et al. 2014; Kuntz et al. 2014; Kuntz et al. 2016; Kuntz et •高エネルギー天体のエネルギー源

turbulence



### **Magnetic reconnection → relativistic particle production** lines in the background at Y 1.91 and X 1.91 and X  $\mu$  in the background at Y  $\mu$ high-density regions as reddish curved planes. Panels (b) and (c) are at the same time stage. Panel (f): The energy spectra during the MRI **Interaction with Turbulence → further energization**

銀河(白)

 $\mathcal{L}_\text{c}$ 



law

/8π, the current density Jz along the mean magnetic

the 3D simulation with our decay of 10,  $\alpha$  simulation with our decay of 1, and L/de0  $\alpha$  and  $\alpha$ 

Note also that in the 3D case the magnetic energy decays faster show that this leads to a reduced particle acceleration rate at late times. shown by the blue line peaking at *H* \_ 1 1 0.6 *Hth*<sup>0</sup> . At late times, when most of the turbulent energy has decayed, the  $\mathsf{on}$  it perconduction is evolving (orange and red lines): it is peaks at  $\mathsf{on}$  $\mathbf{v}$   $\mathbf{u}$   $\mathbf{v}$   $\mathbf{$ tail of ultrarelativistic particles that can be described by a power-described by a power-described by a powerfield in units of end the bulk dimensionless four-velocity Γβ, and note that the particle density ratio n/n0 a<br>The color bars for Γβ and n/n0 are in logarithmic scale. And n/n0 are in logarithmic scale. And n/n0 are in lo animation showing the current density Jz in different x-y slices can be found at https://doi.org/10.7916/d8-prt9-kn88. simulation in Figure 2. At late times, the spectrum displays a power-law tail waxaa dogaala waxaa duuqdada w **have a 15 at children peak of the peak** per divide production of the magnetization of the scaling of the sc for a σ0-independent domain size L/de<sup>0</sup> = 820. Figure 11. Relation between particle injection and electric current density from

power-law index p for increasing magnetization of increasing magnetization of  $\sigma$ 

### •ブラックホールに引きつけられたガスは, 回転しながらブラックホールに 吸い込まれる (降着円盤 or 降着流). •ガスの重力エネルギーが変換され, 明るく輝き, 場合によってはジェット Particle Acceleration in Turbulence

### Particle-In-Cell Simulations in the shing box  $\Box$  $\begin{array}{c|c|c|c} \hline \quad \textbf{p} & \quad \textbf{p} \end{array}$

20

### Some gain E, others lose E →diffusion in E space of the particles are shown by the stars and circles are shown by the stars and circles, respectively. In the b panel, the cyan circle and black arrows indicate the initial ring *R* = *R*ini and

 $\partial F_p$ ∂*t* = 1 *E*2  $\partial$  $\frac{\partial}{\partial E}\Bigg(E^2\Bigg)$  $D_{E}$  $\partial F_p$ ∂*E* )  $F = \begin{pmatrix} 1 & 1 \end{pmatrix}$  is the unit vector of the  $\lambda$  $\mathbf{p} = \mathbf{1} \mathbf{0} \mathbf{0} \mathbf{1} \mathbf{0}$  $\mathcal{L} = \frac{1}{\sigma^2} \mathcal{L} = \frac{1}{\sigma^2$  $\frac{dt}{dt}$  is the energy distribution in the fluid in frame. Note that the particle distribution is slightly anisotropic: the

### MRI **Communism is a controlled turbulence** an important role in this system. This system is natural in this system. This result is natural in the sub-Alfvenic and sub-sonic turbulence. Finally, we discuss the azimuthal power spectra of the turbulence spectra of the turbulence spectra of the turbulence  $\mathcal{L}$  for the dimensional power spectral power spectr

### SSK+ 2016 ApJ, 2019 MNRAS; Sun & Bai 2021  $\sim$  correlation. We evaluate the correlation coefficients the correlation coefficients of  $\sim$  $\Delta$   $S$  $K$  +  $2010$   $A$  $p$ J,  $2019$  MIN associated with the area in the meridion of the meridion area in the meridion of the meridional plane. The resulting



### by MHD Turbulence 21  $\mathbf{B}_\text{max}$  is created the spiral structure as seen in the figure. We can see the figure. We can see that  $\blacksquare$  that  $\blacksquare$  the magnetic field energy density. The faster modes are a sub-dominant component in the MRI turbulence.  $T = T \cdot \frac{1}{2}$  the importance of the modes of the MHD waves (fast, fast, fast slow, and Alfven), we evaluate the Pearson correlation coefficients between the fluctuations of the density, δρ(*R,* θ*,* φ) = ρ − ⟨ρ⟩*L*,

### $MHD +$  Test Particle Simulations and the magnetic energy, <sup>δ</sup>*B*2(*R,* <sup>θ</sup>*,* <sup>φ</sup>) <sup>=</sup> *<sup>B</sup>*<sup>2</sup> − ⟨*B*<sup>2</sup>⟩*L*. According to the linear MHD was modeled wave the fast model in the fast model in the fast model in the fast model in the f correlation, the slow mode has a negative correlation, and the Alfvender correlation, and the Alfv



frozen in the differentially rotating fluid elements that fall to the

coefficients in distribution in density and magnetic energy are weakly and magnetic energy are weakly are weakly

anticorrelated: the value of the coefficient is  $\mathbf{1} \mathbf{1}$  in the discrete is  $-1.2$ 

region (10.45) for runs have resolution runs have resolution runs have resolution run A. The lower resolution higher coefficients, i.e. the anticorrelations are weaker, but no run are weaker, but no run are weaker, but n

has a positive correlation. The fast modes do not play the fast modes do not play the fast modes do not play t



Fourier transformation in the azimuthal direction,

<sup>√</sup>2<sup>π</sup>

!

where *m* = *k*φ*R* (*k*<sup>φ</sup> is the wavenumber in the φ direction). Then,

we take the average of the average of the power spectrum over the power spectrum over the disc region:







$$
\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2} \frac{\partial}{\partial \varepsilon_p} \left( \varepsilon_p^2 D_{\varepsilon_p} \frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\text{cool}}} F_p \right) - \frac{F_p}{t_{\text{esc}}} + D_{\varepsilon_p} \approx \frac{\zeta c}{H} \left( \frac{V_A}{c} \right)^2 \left( \frac{r_L}{H} \right)^{q-2} \varepsilon_p^2,
$$





## 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 & py (with X-rays) contribute to resulting neutrino flux
- **• Cascade emission at 10 MeV —>Testable by MeV γ ray satellites**

Figure 10. Prospects for observation of the bright Seyfert galaxies in the next-





absence of a signal from the disk-corona model for Cen A and NGC 1275.

scenarios are the same as in  $\mathbb{E}_{\nu}$  [GeV]. The injected injected in  $\mathbb{E}_{\nu}$ CR, i.e., proton, differential luminosity for the three scenarios



• Future detectors should detect Nfrom AGN **H** > testable by future neutrino experiments (dashed) lines show expectations for 0°. 3 (0°. 7) angular resolution for the <u>identification of the 10 nearbor of the 10 nearby bridge sources in Table 2 in Table 2 in Table 2 in a stacking</u>  $T \sim \Delta$  in Middle sources in the prospects for  $T$ 

### Nearby Seyfert galaxies Kheirandish, Murase, SSK 2021  $\blacksquare$  $\blacksquare$  $\mathbf{M}$  or  $\mathbf{V}$  and  $\mathbf{V}$  and  $\mathbf{V}$  and  $\mathbf{V}$  are  $\mathbf{V}$  and  $\mathbf{V}$  are  $\mathbf{V}$  and  $\mathbf{V}$  and  $\mathbf{V}$  are  $\mathbf{V}$  and  $\mathbf{V}$  are  $\mathbf{V}$  and  $\mathbf{V}$  are  $\mathbf{V}$  and  $\mathbf{V}$  are  $\mathbf{V}$  and  $U_{\rm eff}$  ,  $U_{\rm eff}$  ,



for NGC 1068 by the IceCube Collaboration (Aartsen et al. Inc.) and IceCube Collaboration (Aartsen et al. Inc.<br>In the IceCube Collaboration (Aartsen et al. Inc.) and IceCube Collaboration (Aartsen et al. Inc.) and IceCube

that achieving finer and  $\parallel E_{\nu}[\rm{GeV}]$  and  $\parallel$ 

 $\mathbb{E}_{\nu}$  (severally for its observation is the likelihood for its observation is high,  $\mathbb{E}_{\nu}$  (severally for its observation is in the likelihood for its observation is in the likelihood for its observation is in

### Kheirandish, Murase, SSK 2021

# ν & γ from Nearby Seyfert Galaxies

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

in neutrinos (Glauch et al. 2023; Liu et al. 2023). Sensitivities for *e-ASTROGAM* (De Angelis et al. 2017) and *GRAMS* (Aramaki

Figure 2. Multimese Can reproduce the tentative Constitution of NGC 4151, NGC 4151, NGC 4151, NGC 4945 and Corona model. The magnetic corona model corona model. The magnetic corona model corona model. The magnetic corona m  $\mathsf V$  data without overshooting  $\mathsf V$  data  $\mathsf V$  and  $\mathsf V$ -ray data for  $E < 0.3$  GeV data without overshooting  $\mathsf V$  data  $\mathsf V$ • Our model can reproduce the tentative ν data without overshooting γ data

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





- $\rightarrow$  Optically thick disk + coronae
- →Optically thin flow







 $\sqrt{(1+z)^3\Omega_m+\Omega_\Lambda}$ z<br>Zanada<br>Zanada  $dL_{\rm H\alpha}\rho_{\rm H\alpha}$  $L_{\varepsilon_i}$  $\varepsilon_i$  $e^{-\tau_{i,\mathrm{IGM}}},$ 

 $\gamma$  (Total)  $\Box$   $\Box$  Cascade y (RIAFs)  $\Box$ Neutrinos (RIAFs) **Neutrinos (Total)** , ⌦*<sup>M</sup>* ⇠ 0*.*3, and ⌦⇤ ⇠ 0*.*7.  $\gamma$  by thermal e (AGN Coronae) (⇢⇤*/L*⇤)*/*[(*L*H↵*/L*⇤)*<sup>s</sup>*<sup>1</sup> + (*L*H↵*/L*⇤)*<sup>s</sup>*<sup>2</sup> ], where ⇢⇤ ' <sup>4</sup>*.*<sup>11</sup> ⇥ - - Cascade γ (AGN Coronae) (2010)<br>- - Meutrinos (AGN Coronae) and *s*<sup>2</sup> = 1*.*88. We extrapolate this luminosity func-FIG. 1. Schematic picture of the AGN disk-corona scenario.  $\Box \longrightarrow \Box$  are accelerated by the rmal expected in the  $\Box$  $\zeta = 0$  rascaue  $\gamma$  (inters) and radiations with matter and radiation. The coronal setting in the coronal setting  $\zeta = -1$  in the Neutrinos (AGN Coronae) 10<sup>43</sup> , 10<sup>44</sup> , 1045, and 1046 erg s−<sup>1</sup> (from bottom to top). See text

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





### Cosmic High-energy Background from RQ AGNs<sup>27</sup> *<sup>p</sup>/D*"*<sup>p</sup>* , is longer than *<sup>t</sup>*fall for "*<sup>p</sup> <sup>&</sup>gt;* <sup>1</sup>*.*<sup>5</sup> ⇥ <sup>10</sup><sup>4</sup> GeV 26, 67]) PURSICAL REVIEW LETTER



kBTp=mp

- QSO: X-ray & 10 TeV neutrinos
- **LLAGN: MeV γ & PeV neutrinos**
- $\text{Copious photons}$ **Propriet and luminosity** of the luminosity of the luminosi  $\leftarrow$  in the range of  $\rightarrow$  strong GeV γ attenuation → efficient γγ —> e+e-
- **A keV-MeV γ & TeV-PeV ν background • AGN cores can account for**  <sup>¼</sup> ffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffi <sup>p</sup> <sup>¼</sup>  $\Box$



- 
- 
- 

• Seyfert Galaxies (Radio-quiet AGN)

### • Tidal Disruption Events

(TDEs)







Murase, SSK+ 2020 Inoue Y et al. 2019 Inoue S et al. 2022

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## **Current Source Candidates**

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# How to find neutrino sources?

- - Integrated Neutrino data + Catalogued sources by EM → Identify neutrino sources





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



## **Dedicated search strategy is necessary**







## Challenge to identify neutrino sources 30

## **Angular Resolution of Neutrino detector**

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



**1 - 2 deg**



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

IC191001 <=> AT2019dsg; IC200530 <=> AT2019fdr



## coronal radius. The plasma beta, *b p* º 8 *n kT B p p*

• Many models are proposed => **We need more observations to test scenario** duced to estimate the magnetic field strength B. Here, next s

- Several possible sites of neutrino emissions  $\mathbf{f}(\mathbf{r}) = \mathbf{f}(\mathbf{r})$  . Schematic picture of neutrino and gamma-ray production models with  $\mathbf{f}(\mathbf{r})$ • Several possible sites of neutrino emissions
- Our best-guess scenario: **accretion disk & corona**   $\sim$  and disk regions. In the emission regions. In the emission regions,  $\sim$  1.1  $\sim$ • Our best-guess scenario: accretion disk & c • Our best-guess scenario: accretion disk & corona
- collanum adole are proposed -> Ille need me e ividily inducts are proposed  $-\epsilon$  we need ins time, we conservatively estimated their average lifetime at neutrino energy.



### **Neutrino emissions from TDEs** The Astrophysical Journal, 902:108 (13pp), 2020 October 20 Murase et al. No rays were detected by the Fermi large area telescope and the Fermi large area t INGATILIO GIIIISSI interactions, where  $\mathbf{r}$  is a set of  $\mathbf{r}$  and  $\mathbf{r}$  and  $\mathbf{r}$  and  $\mathbf{r}$  accelerated in a set of  $\mathbf{r}$ dis indiri disk corona, a subrelativistic visitivistic visitivistic visitivistic visitivistic visitivistic vis<br>A relativistic visitivistic visitivistic visitivistic in termine visitivistic visitivistic visitivistic visiti



# Neutrino Follow-up with Subaru/HSC 33

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

![](_page_32_Figure_7.jpeg)

![](_page_32_Picture_8.jpeg)

![](_page_32_Figure_5.jpeg)

![](_page_32_Picture_6.jpeg)

![](_page_33_Picture_7.jpeg)

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![](_page_33_Figure_5.jpeg)

![](_page_33_Picture_6.jpeg)

# **Neutrino Follow-up with Subaru/HSC**

# **Transient Classification Simulations**

- Optical sky includes a lot of variable objects (supernovae, active galaxies, TDEs)
- We use SNCosmo Package with additional lightcurve templates<br>Cf. Kimura et al. 2020; Hammerstein et al. 2023

![](_page_34_Figure_3.jpeg)

![](_page_34_Picture_5.jpeg)

![](_page_35_Picture_97.jpeg)

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

![](_page_35_Picture_10.jpeg)

# 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<sup>2</sup>, 15-day cadence, 4 ToO observations)

# **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<br>The Astrophysical Journal, 937:108 (11pp), 2022 October 1 Yoshida et al.

![](_page_36_Figure_4.jpeg)

![](_page_36_Picture_8.jpeg)

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<sup>-7</sup>, FAR= 0.078 [1/yr], MAXI p-value=0.283

![](_page_37_Figure_2.jpeg)

![](_page_37_Figure_3.jpeg)

## **Multiplet-alert Candidat** Multiplet-alert Candidate

![](_page_37_Figure_4.jpeg)

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

![](_page_37_Figure_9.jpeg)

## transients Strategy to constrain transients

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

![](_page_38_Figure_2.jpeg)

- $L(\nu, t) = L_{\text{pk}} \exp\left(-\frac{|t t_{\text{pk}}|}{T_{\text{decay}}}\right)$ • We are trying to obtain "generic" constraint on transients => adopt a simple-phenomenological lightcurve
- Give total neutrino energy  $(\mathcal{E}_\nu)$  & time lag btw EM & v ( $\Delta t$ ) # 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

## transients Strategy to constrain transients

![](_page_39_Figure_3.jpeg)

![](_page_40_Figure_6.jpeg)

- $L(\nu, t) = L_{\text{pk}} \exp\left(-\frac{|t t_{\text{pk}}|}{T_{\text{decay}}}\right)$  $\frac{P^{K}}{T_{\text{decay}}}$   $B_{\nu}(T_{\text{sn}})$ • We are trying to obtain "generic" constraint on transients => adopt a simple-phenomenological lightcurve
- ansiant is  $^{\mathscr{C}_{\nu}}$  ansiant is  $^{\mathscr{C}_{\nu}}$  $2\sigma$ round<sup>b</sup> • Give total neutrino energy  $(\mathcal{E}_\nu)$  & time lag btw EM & v ( $\Delta t$ ) # 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
- Give  $(T_{\text{decay}}, L_{\text{pk}})$ => 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  $T_{\text{decay}} \& L_{\text{pk}}$ => constrain these two parameters

## transients Strategy to constrain transients

![](_page_40_Figure_5.jpeg)

- 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

# Constraints by ZTF data

 $10^{42}$ 

 $10^{45}$ 

 $\frac{1}{10}$  10<sup>44</sup>

 $\frac{12}{9}$  10<sup>43</sup>

 $10^{42}$ 

pk[erg

![](_page_41_Figure_6.jpeg)

- Follow-up to doublet alert  $\Rightarrow$  HSC or Vera Rubin: 10 - 30 SNe with  $\sim$  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**

# **Future Optical Follow-up in 2020s**

**Transient Search by HSC or Rubin**

![](_page_42_Picture_6.jpeg)

![](_page_42_Picture_7.jpeg)

![](_page_42_Picture_9.jpeg)

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![](_page_42_Figure_10.jpeg)

![](_page_42_Picture_11.jpeg)

![](_page_42_Picture_8.jpeg)

**Doublet Neutrino Alert**

- 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**

# **Future Optical Follow-up in 2030s**

**Transient Search by HSC or Rubin**

![](_page_43_Picture_8.jpeg)

![](_page_43_Picture_9.jpeg)

![](_page_43_Picture_10.jpeg)

![](_page_43_Picture_11.jpeg)

## **Peculiar SNe as neutrino source**

![](_page_43_Picture_13.jpeg)

**High-resolution neutrino alert**

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- **• 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**

# Summary

# Thank you for your attention

![](_page_44_Figure_9.jpeg)