

X-Ray Constraints on a Common Transient Origin of Ultra-High-Energy Cosmic Rays and High-Energy Neutrinos

X-rays

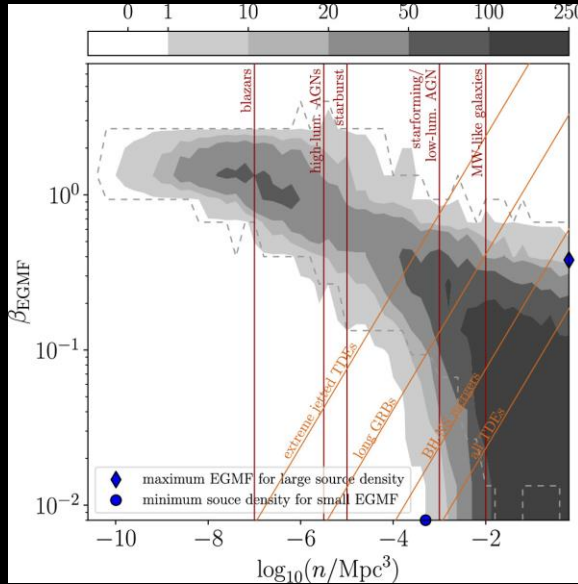
UHECRs

Neutrinos

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UHECR sources are likely transients



UHECRs anisotropy

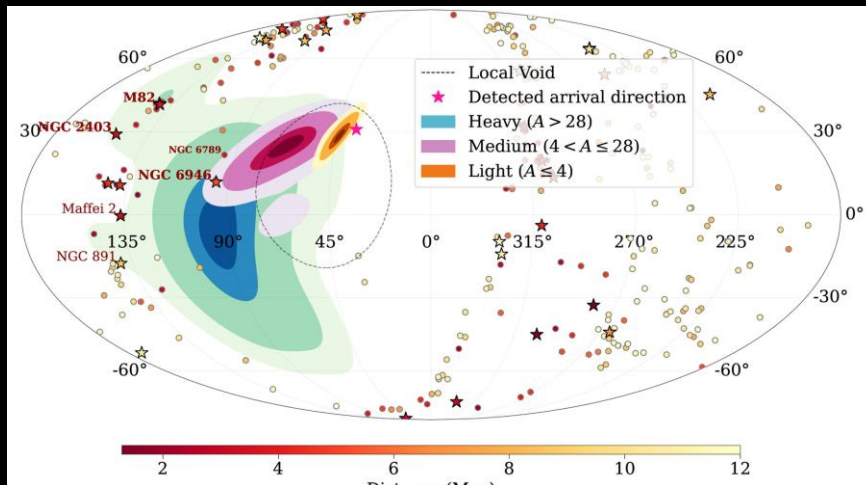
$$n_s \gtrsim 10^{-3} \text{Mpc}^{-3}$$

no powerful steady sources
in this range

$$\gtrsim 10^{-3} \left(\frac{\rho_s}{3 \times 10^{-8} \text{Mpc}^{-3} \text{yr}^{-1}} \right) \left(\frac{\beta_B}{0.1 \text{G}} \right)^2 \text{Mpc}^{-3}$$

Bister & Farrar ApJ 2024

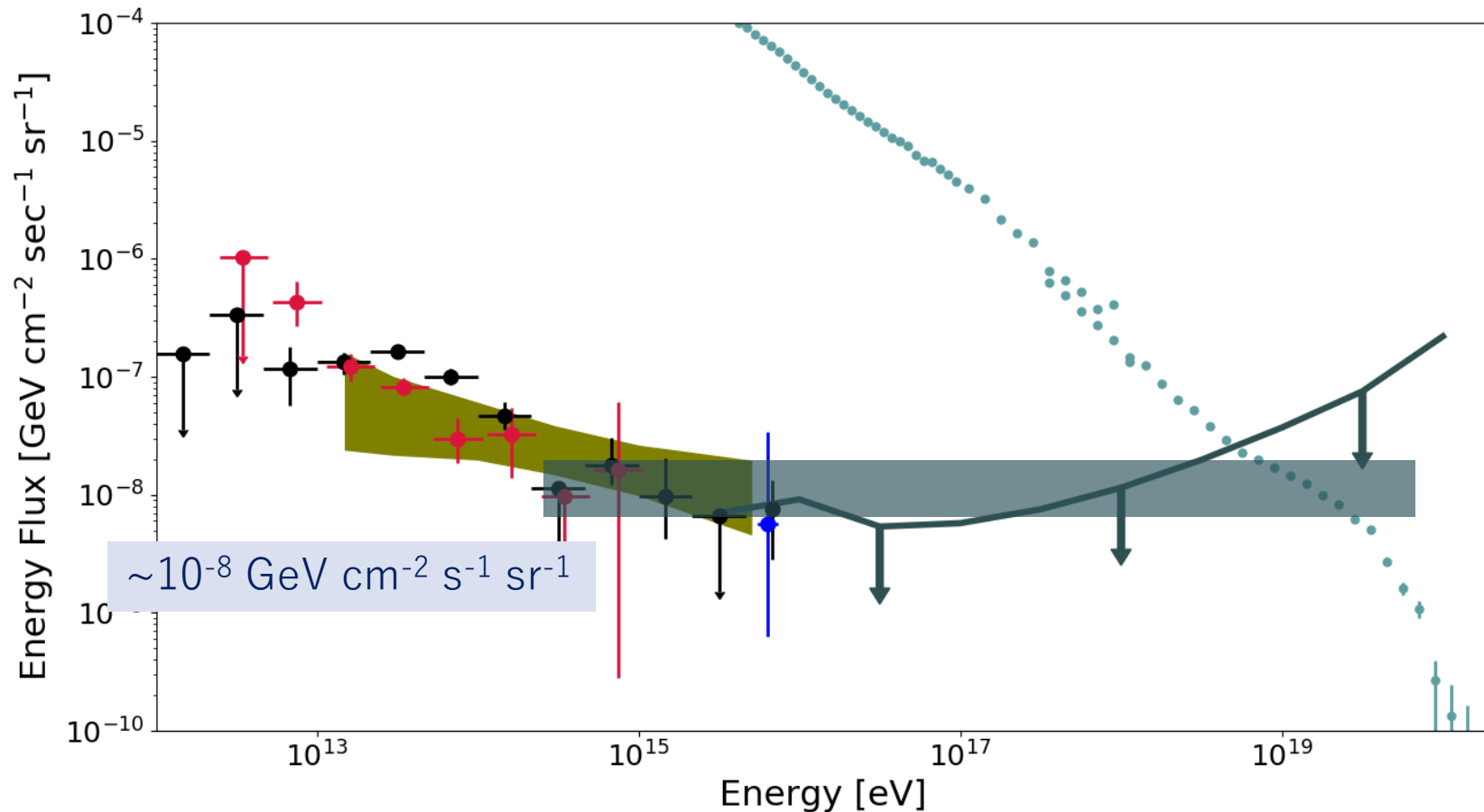
plenty of transient source candidates



The highest energy CR appears to come
from the local void

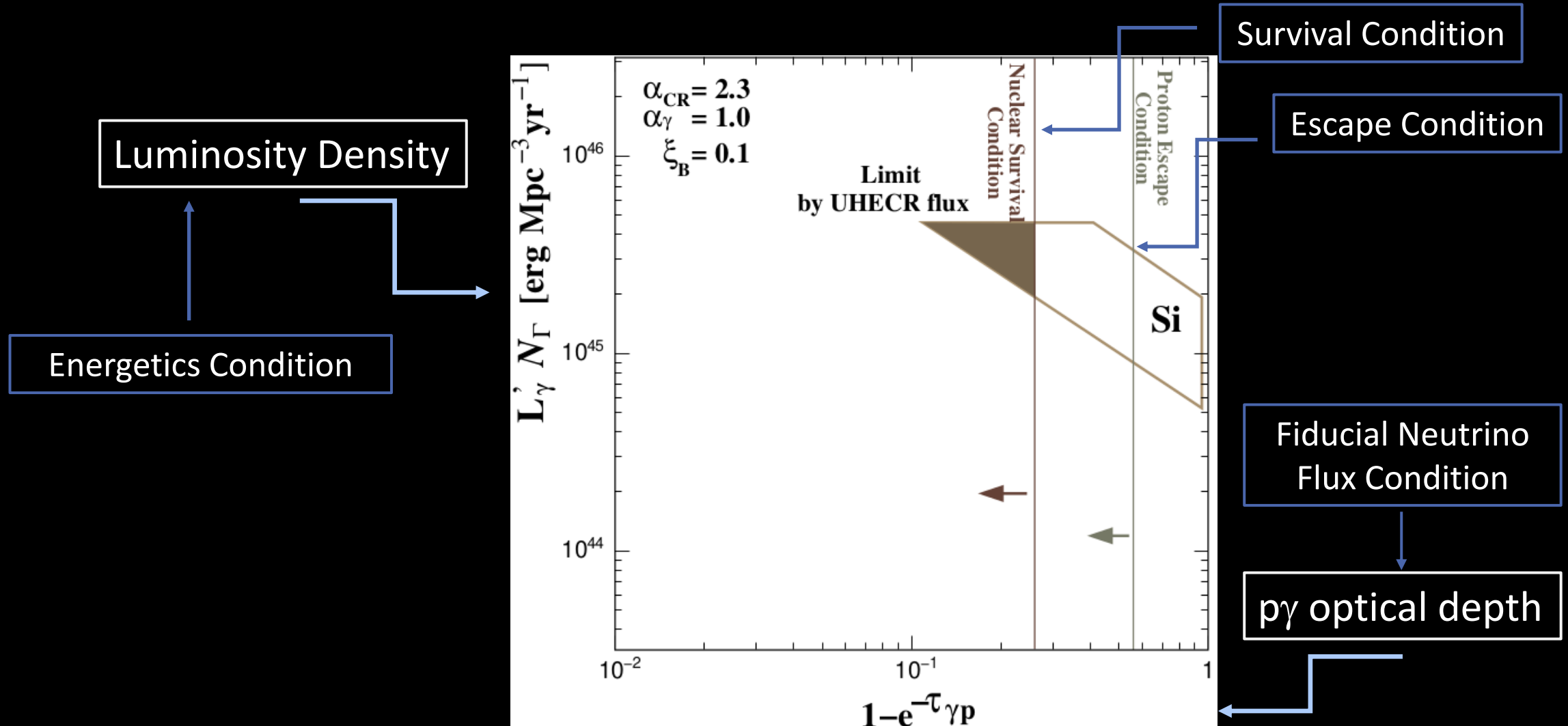
Bourriche & Capel ApJ 2026

UHECRs and high-E neutrinos may share the common origin



The conditions the Common Sources must meet

The valid parameter space is clear!



Yoshida & Murase PRD (2020)

Are they UHECR and PeV ν sources?

The scorebook of individual **transient** astronomical object classes

	Energetics	Fiducial ν flux	Acceleration	Escape	Survival $\tau_{p\gamma} \lesssim 0.4(A/56)^{-0.21}$
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jetted TDE Biehl+ 2018	Challenging $\xi_{CR} = 100 - 1000$	OK $\tau_{p\gamma} \gtrsim 0.1$	OK with nuclei $\xi_B \gtrsim 10^{-2}(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 1 (A/2Z)^4$	Maybe
TDE wind Murase+ 2020	OK $\xi_{CR} = 1 - 10$	Challenging $\tau_{p\gamma} \gtrsim 0.1$	Maybe $\xi_B \gtrsim 1(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 3 (A/2Z)^4$	OK
Low L GRB Murase+ 2006	Maybe $\xi_{CR} = 10 - 100$	OK $\tau_{p\gamma} \gtrsim 0.03$	OK with nuclei $\xi_B \gtrsim 10^{-2}(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 1 (A/2Z)^4$	OK
Engine-driven SN Zang+ 2019	OK $\xi_{CR} = 0.1 - 1$	Challenging $\tau_{p\gamma} \gtrsim 0.03$	Maybe $\xi_B \gtrsim 1(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 3 (A/2Z)^4$	OK

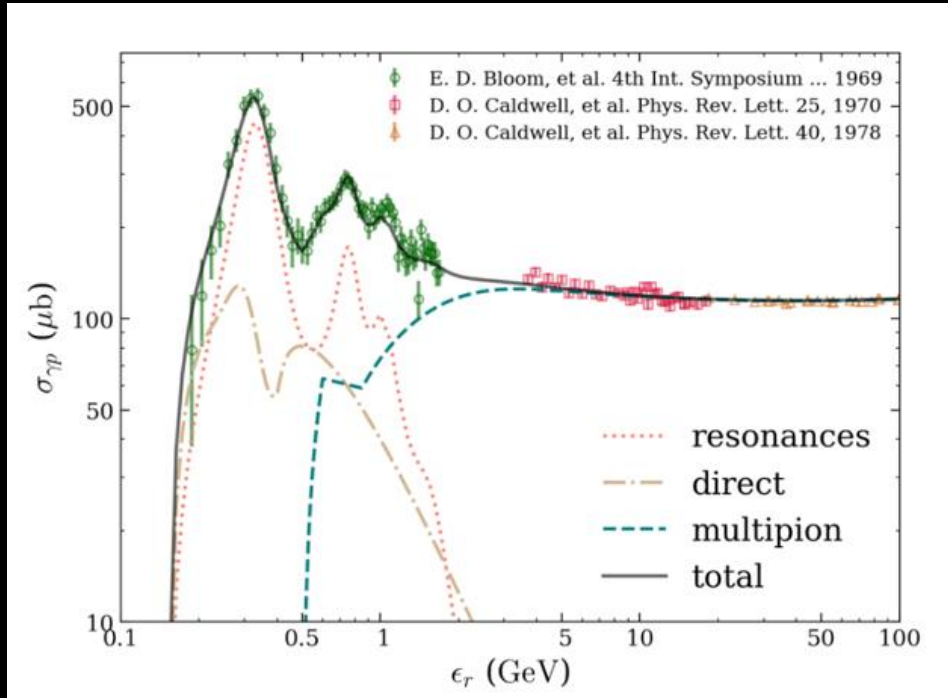
Yoshida & Murase PRD (2024)

Side Note: This is a one-zone model

The most likely target photons are in X-ray range in the **relativistic** plasma flows

Photohadronic interactions

e.g. $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$



$$\varepsilon'_{\gamma 0} \approx \frac{(s_{\Delta} - m_p^2)}{4} \frac{\Gamma}{\varepsilon_{p0}}.$$

$$\longrightarrow \varepsilon_X = 15 \left(\frac{\Gamma}{10} \right)^2 \left(\frac{\varepsilon_p}{1 \text{ PeV}} \right)^{-1} \text{ keV}$$

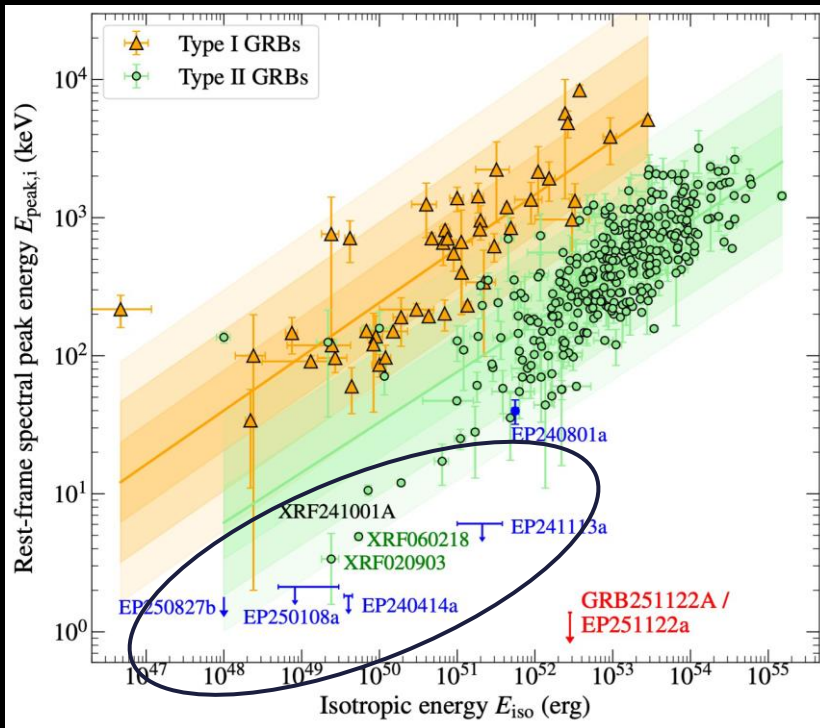
Γ Lorentz factor of
(jet) plasma

So... the prime candidates are (soft) X-ray transients

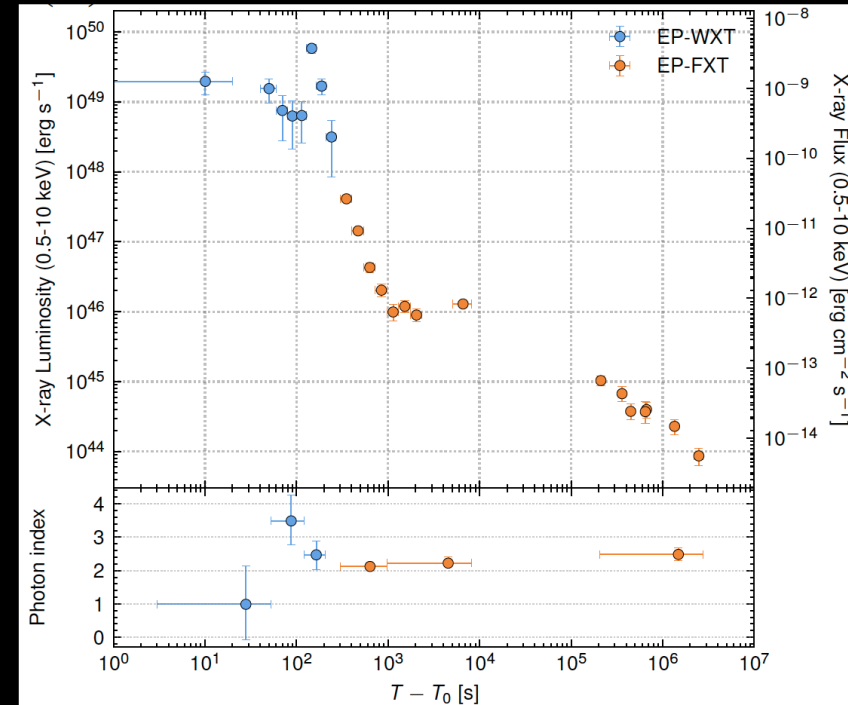
Low Luminosity GRBs, TDEs..., but many unknown!

many new **fast** and **soft** X-ray transients emerged

EP 241113a: No GRB counterpart

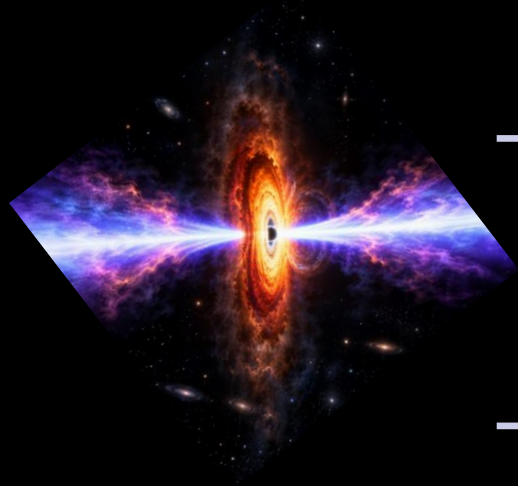


Gotz, TeVPA 2026



Liu, TeVPA 2026

X-Rays + Neutrinos + UHECR multimessenger study



X-rays

$$\longrightarrow L_X$$

UHECRs

$$\longrightarrow L_{\text{UHECR}} = \xi_{\text{CR}} L_X$$

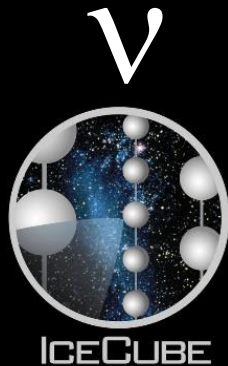
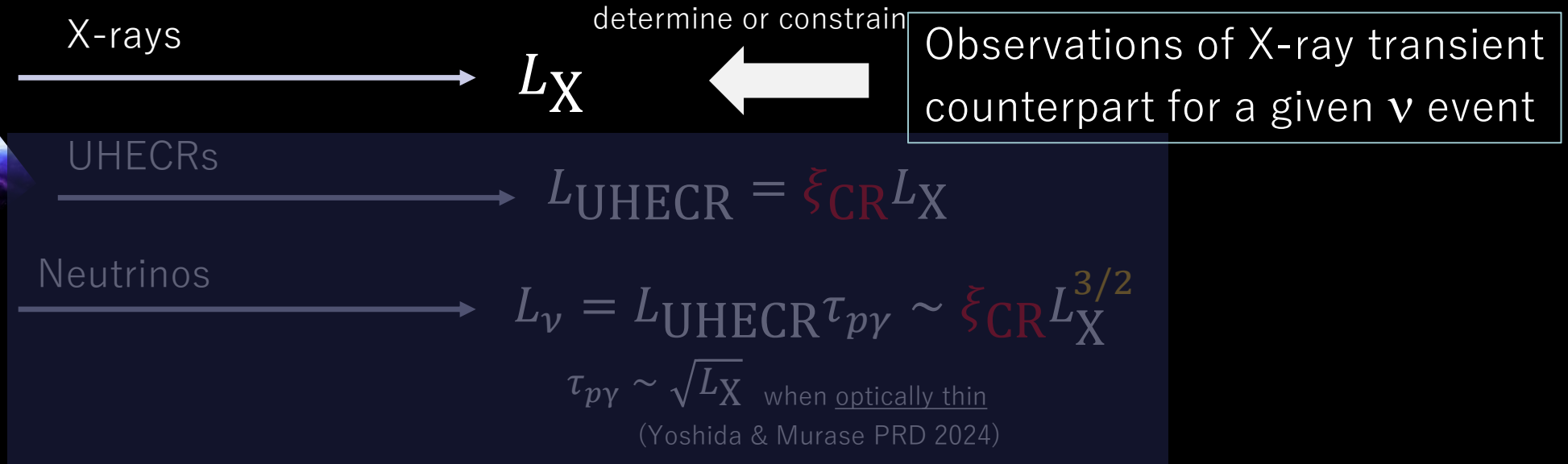
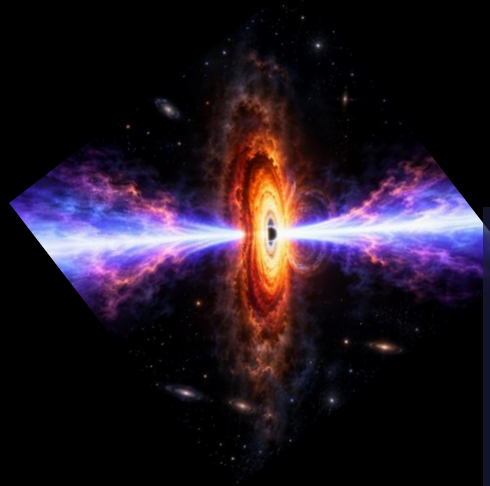
Neutrinos

$$\longrightarrow L_\nu = L_{\text{UHECR}} \tau_{p\gamma} \sim \xi_{\text{CR}} L_X^{3/2}$$

$$\tau_{p\gamma} \sim \sqrt{L_X} \text{ when } \underline{\text{optically thin}}$$

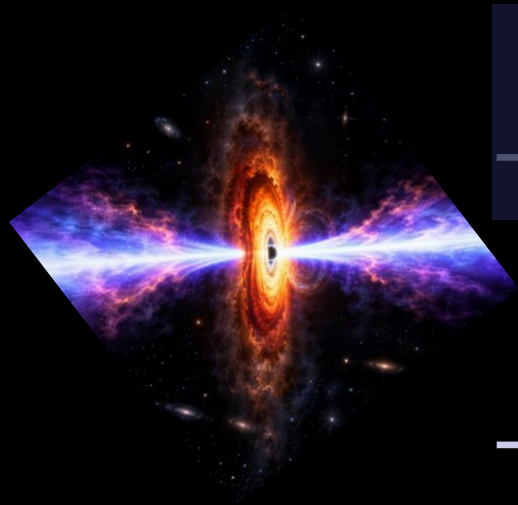
(Yoshida & Murase PRD 2024)

X-Rays + Neutrinos + UHECR multimessenger study



愛因斯坦探針
einstein probe

X-Rays + Neutrinos + UHECR multimessenger study



UHECRs $\rightarrow L_{\text{UHECR}} = \xi_{\text{CR}} L_X$

Neutrinos $\rightarrow L_\nu = L_{\text{UHECR}} \tau_{p\gamma} \sim \xi_{\text{CR}} L_X^{3/2}$

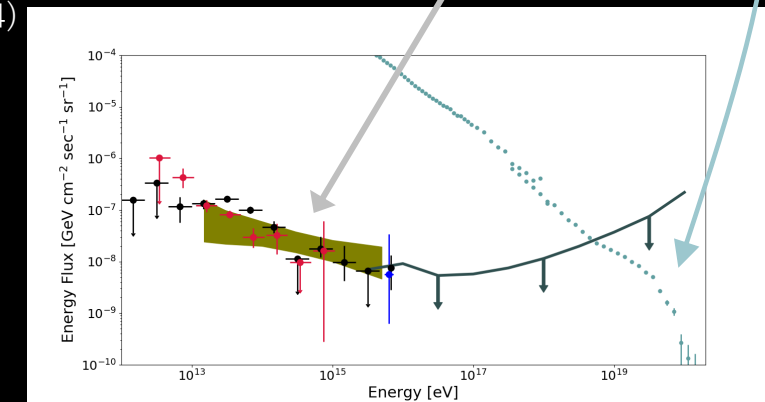
$\tau_{p\gamma} \sim \sqrt{L_X}$ when optically thin
(Yoshida & Murase PRD 2024)

Constraints by

UHECR flux

all-sky (diffuse)
neutrino flux

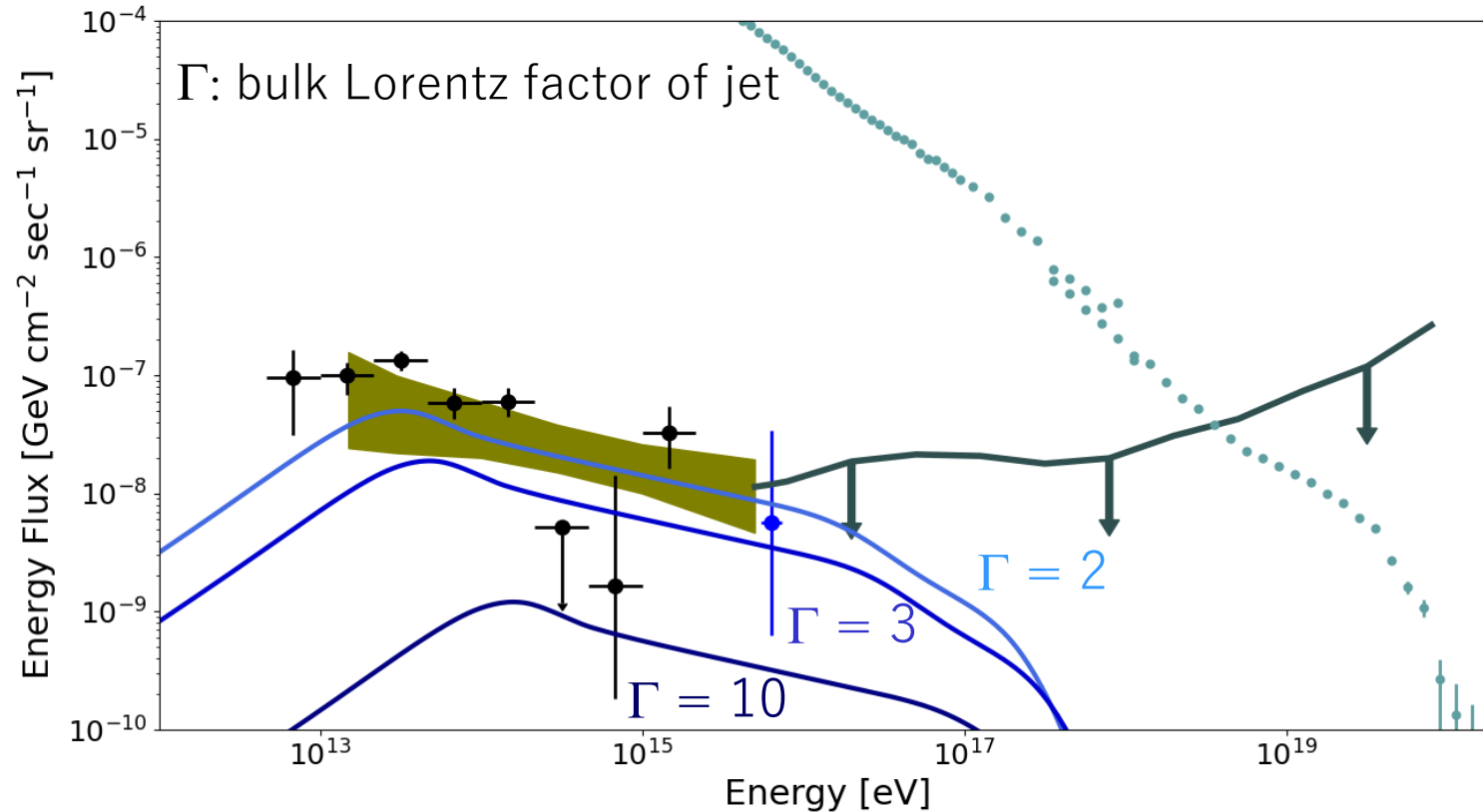
But How?



X-Rays + Neutrinos + UHECR multimessenger study

Introducing a **generic** neutrino-Xray source model

$$\xi_{CR}=10 \quad L_x=5 \times 10^{45} \text{ erg/s} \quad n_0=3 \times 10^{-11} \text{ Mpc}^{-3}$$



For a given Γ and n_0

you can tell whether

$\xi_{CR} = 10$ is okay or not

if we know L_x



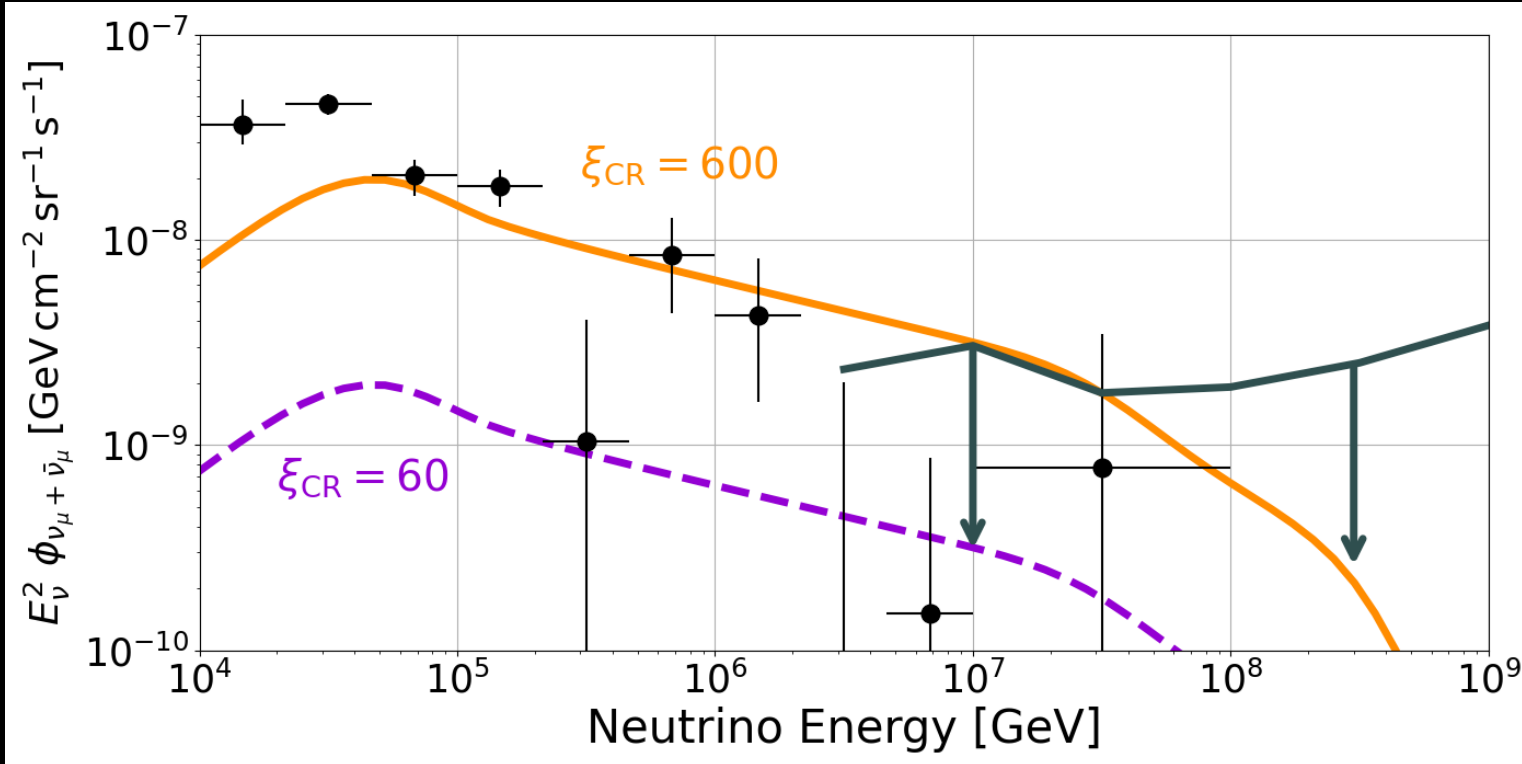
Yoshida & Murase PRD (2024)

X-Rays + Neutrinos + UHECR estimating CR loading factor ξ_{CR}

An example

$$L_x = 2 \times 10^{46} \text{ erg/s} \quad \Gamma = 3, \quad n_0 = 2 \times 10^{-11} \text{ Mpc}^{-3}$$

For a given Γ and n_0



If  $\rightarrow$  爱因斯坦探针
einstein probe

tells $L_x = 2 \times 10^{46} \text{ erg/s}$

Then

$$\xi_{\text{CR}} = 600$$

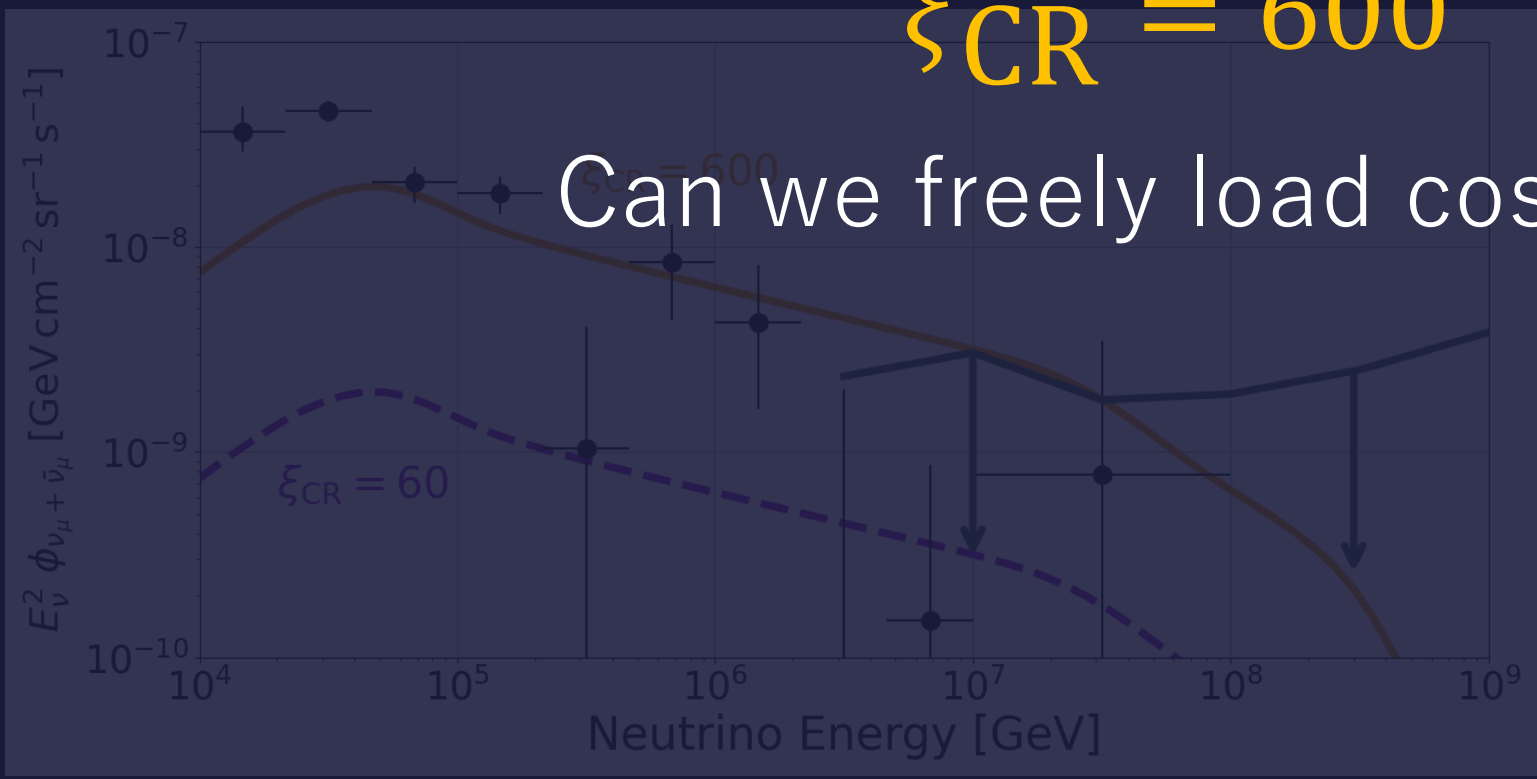
can explain the all-sky ν flux

X-Rays + Neutrinos + UHECR estimating CR loading factor ξ_{CR}

An example

$L_x = 2 \times 10^{46} \text{ erg/s}$ $\Gamma = 3$, $n_0 = 2 \times 10^{-11} \text{ Mpc}^{-3}$
 $\xi_{\text{CR}} = 600$

Can we freely load cosmic rays?



For a given Γ and n_0

If  $\rightarrow$  爱因斯坦探针
einstein probe
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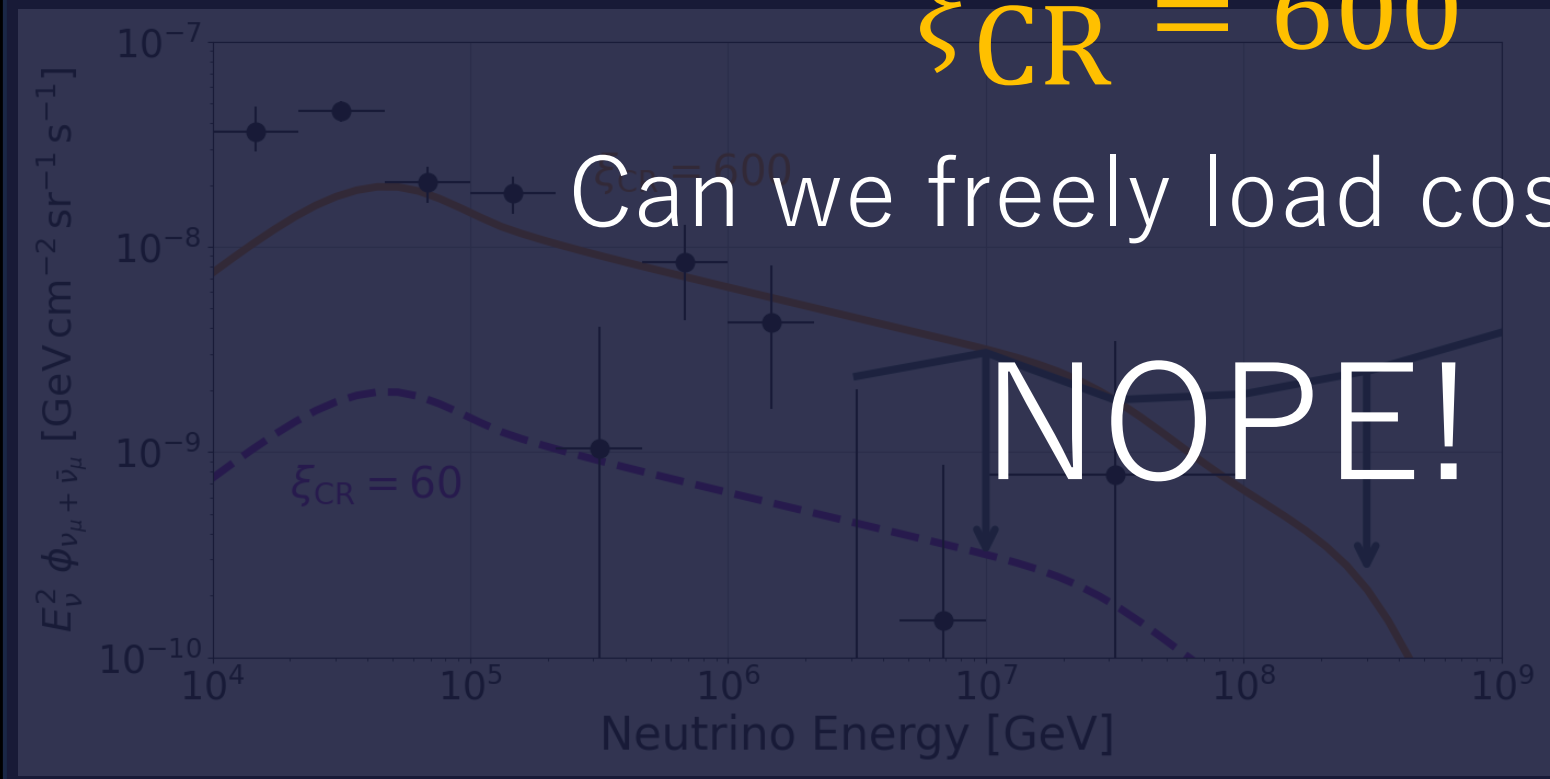
X-Rays + Neutrinos + UHECR estimating CR loading factor ξ_{CR}

An example

$L_x = 2 \times 10^{46} \text{ erg/s}$ $\Gamma = 3$, $n_0 = 2 \times 10^{-11} \text{ Mpc}^{-3}$
 $\xi_{\text{CR}} = 600$

Can we freely load cosmic rays?

NOPE!



For a given Γ and n_0



tells $L_x = 2 \times 10^{46} \text{ erg/s}$

Then

$\xi_{\text{CR}} = 600$

can explain the all-sky ν flux

The power of introducing a genetic model with parameterization

Neutrino flux

based upon [Yoshida & Murase PRD \(2020\)](#)
[Yoshida & Murase PRD \(2024\)](#)

$$\phi_{\nu}^{\text{allsky}} \propto n_0 \times \boxed{\xi_{\text{CR}}} \times \underbrace{L_X \times \sqrt{L_X}}_{\text{observed or upper-limit}} \times B \times f(\Gamma) \quad \leftarrow \tau_{p\gamma}$$

We know this $\Rightarrow \xi_{\text{CR}} > n_0^{-1} \phi_{\nu}^{\text{allsky}} L_X^{-3/2} B^{-1} f(\Gamma)^{-1}$ Lower bound!! $\leftarrow \text{Bulk Lorentz factor of the plasma (jet)}$

UHECR energetics

$$n_0 L_{\text{UHECR}} = n_0 \xi_{\text{CR}} L_X$$

$$\sim \phi_{\nu}^{\text{allsky}} \frac{1}{\sqrt{L_X}} B^{-1} f(\Gamma)^{-1} \lesssim Q_{\text{UHECR}} [\text{erg/s}]$$

$\uparrow$
We know this

The power of introducing a genetic model with parameterization

Neutrino flux

based upon [Yoshida & Murase PRD \(2020\)](#)
[Yoshida & Murase PRD \(2024\)](#)

$$\xi_{\text{CR}} > n_0^{-1} \phi_{\nu}^{\text{allsky}} L_{\text{X}}^{-3/2} B^{-1} f(\Gamma)^{-1} \quad \boxed{\text{Lower bound!!}}$$

UHECR energetics

$$\begin{aligned} n_0 L_{\text{UHECR}} &= n_0 \xi_{\text{CR}} L_{\text{X}} && \boxed{\text{Upper bound!!}} \\ &\sim \phi_{\nu}^{\text{allsky}} \frac{1}{\sqrt{L_{\text{X}}}} B^{-1} f(\Gamma)^{-1} \lesssim Q_{\text{UHECR}} [\text{erg/s}] \end{aligned}$$

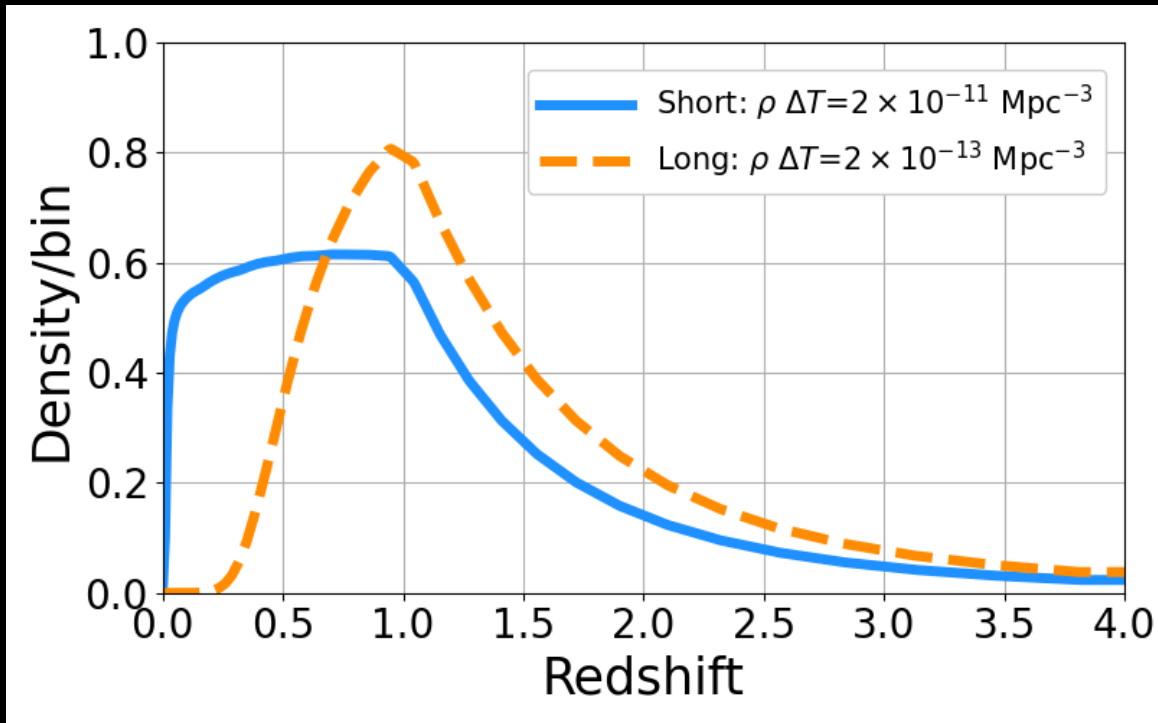
If L_{X} is too dim (upper limit is too tight)

ξ_{CR} becomes too large and overproduce UHECRs

➡ nearly model-independent solid constraints

We need to measure L_x [erg/s] **not** F_x [erg/cm² s]

We cannot estimate source distances by neutrino observations
but **probability distribution** of the distance



If too close, we should have detected multiple ν events
If too distant, we should not have detected any ν events

In the parameter space of

$$\rho [\text{Mpc}^{-3}\text{yr}^{-1}] \quad \text{or} \quad n_0 = \rho \Delta T [\text{Mpc}^{-3}]$$

we can simulate X-ray data for a given L_x
by sampling the redshift from the probability distribution

The methodology (primarily for multiplet) is discussed by
Yoshida, Murase, Tanaka, Shimizu, Ishihara, ApJ(2022)

Neutrino $\rightarrow$ Xray **unified** Likelihood function



$$\mathcal{L} = \mathcal{L}^{X \rightarrow \nu}(E_\nu, \sin \delta, N_X, \vec{n}_\nu, \vec{n}_X) + \mathcal{L}^{\text{a.o.} \rightarrow \nu}(E_\nu, \sin \delta, N_X) + \mathcal{L}^{\text{atm}}(E_\nu, \sin \delta, N_X)$$

Yes, this icecube event came from an X-ray transient

Well, it is astrophysical ν but came from somewhere else

This is a boring atmospheric ν

- detected X-ray photon number N_X is predicable by $P(N_X | L_X, \rho \Delta T, \Gamma)$
- relative weights of $\mathcal{L}^{X \rightarrow \nu}, \mathcal{L}^{\text{a.o.} \rightarrow \nu}, \mathcal{L}^{\text{atm}}$ are determined by the generic X+ ν model (SY+Murase 2024) all-sky diffuse flux data, and the atmospheric neutrino model (or RA-scrambled control data)

Now we look into the X-ray data

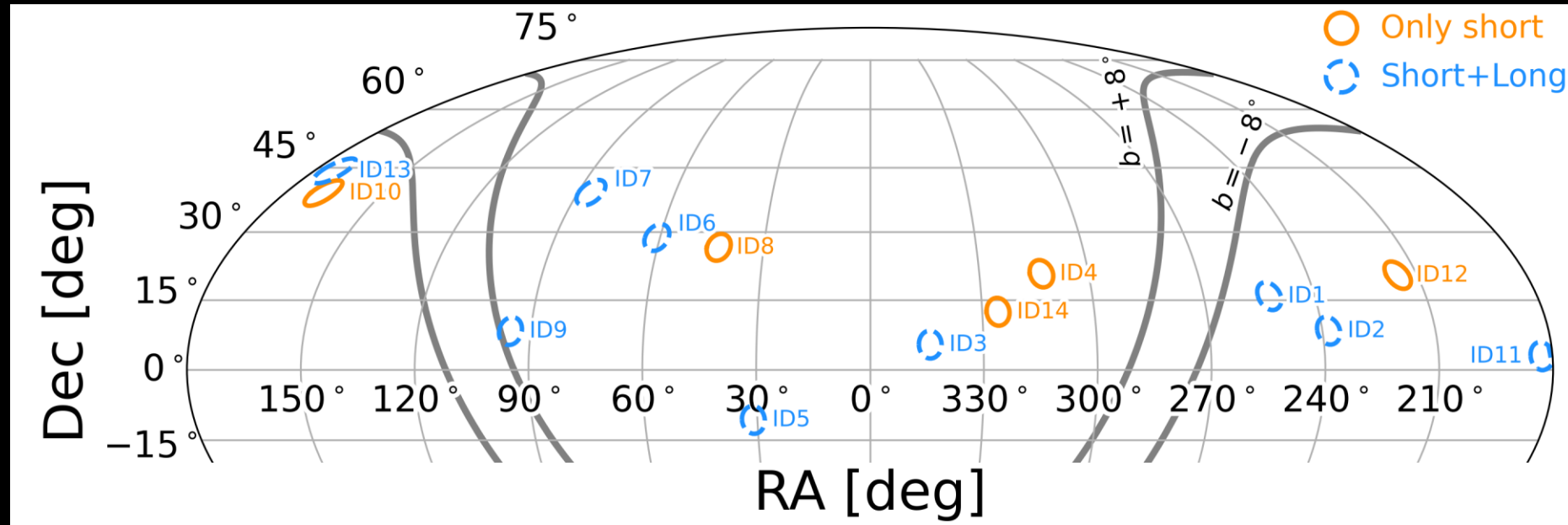


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Jan 2024 – Mar 2026

14 gold and bronze ν alert events

5 events with EP-EXT coverage at $\Delta T \pm 10^3 \text{ sec}$ “Short” – can cover low-luminosity GRBs-like
14 events $\Delta T \pm 10^{4.5} \text{ sec}$ “Long” – can cover TDE-like



Now we look into the X-ray data



Analysis check-points

- Bright known source (mostly AGNs) masking
with ROSAT (1RX, 2RX) and MAXI source catalogues
- Evaluate (unknown) dim AGN contamination effects
implement fake AGNs in the pseudo-data
- Validation of the EP-EXT simulation with control data samples
- Filtering of direct CR hits

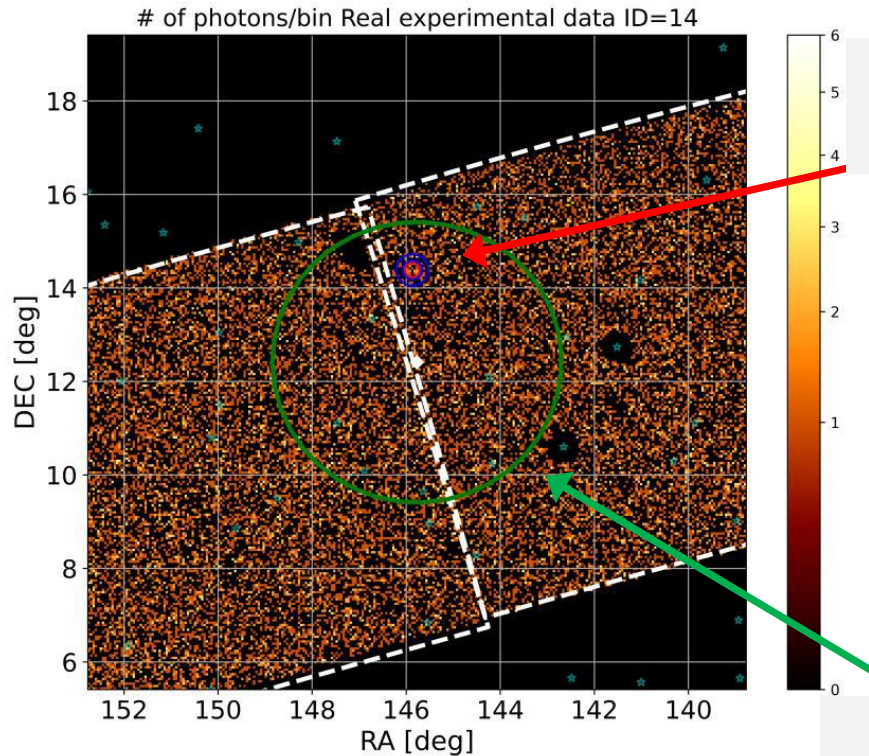
Now we look into the X-ray data

“Short” – can cover low-luminosity GRBs-like



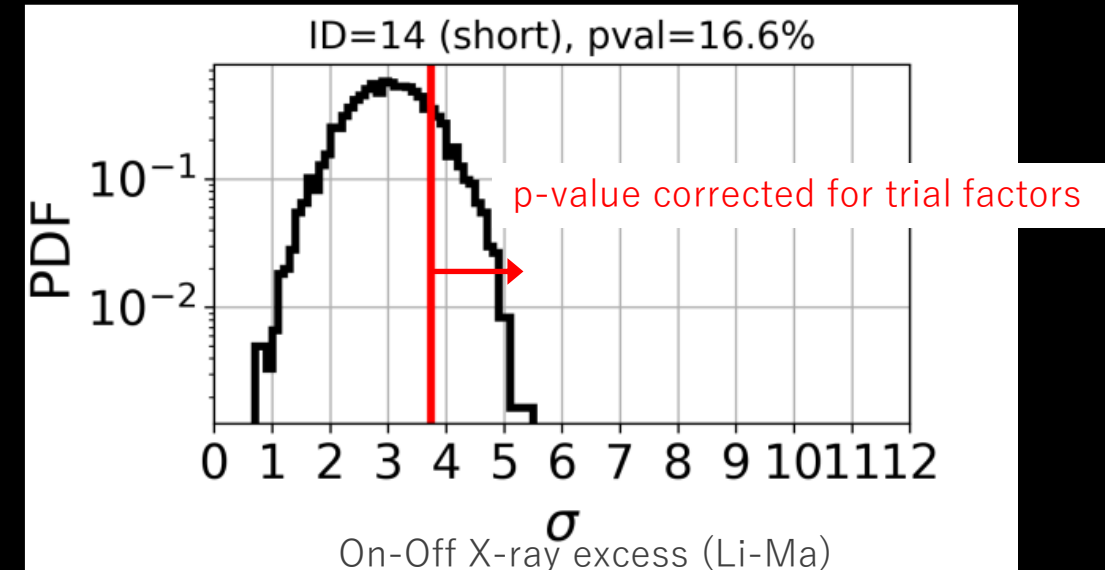
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EP-WXT data for IC160115a X-ray observation exposure time 782.6 sec



location to see
the “excess”

X-ray search
region (3 deg radius)



p-value = 0.166

Not statistically significant

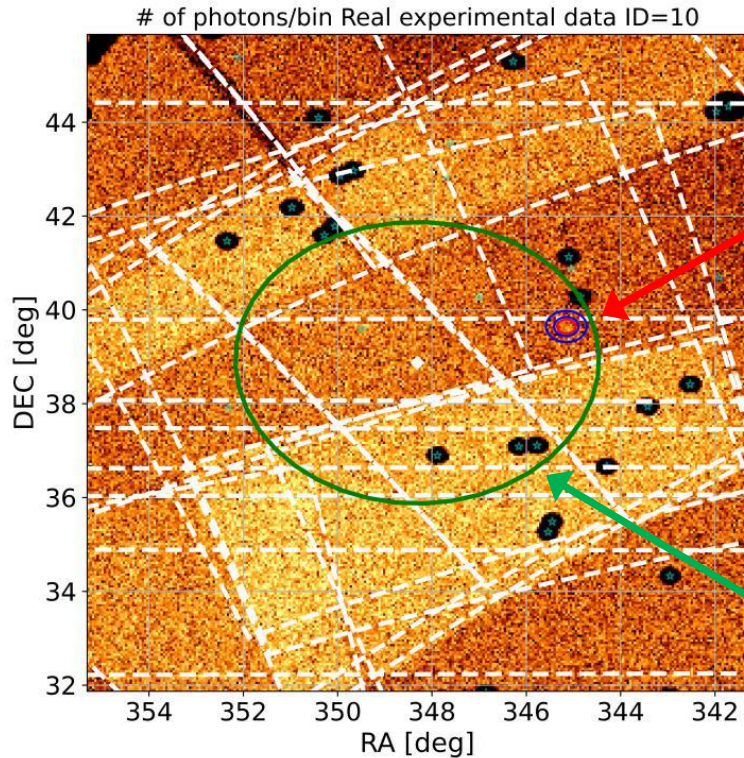
Now we look into the X-ray data



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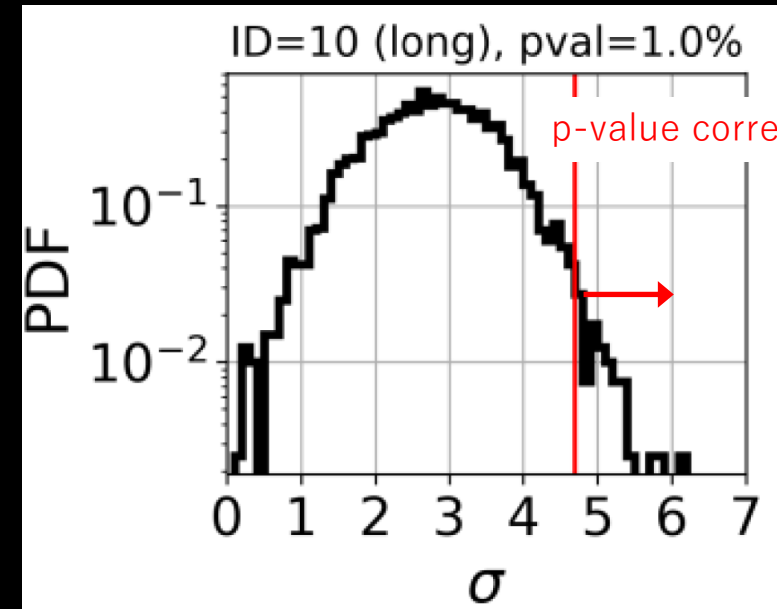
“Long” – can cover TDE-like

EP-WXT data for IC250905a X-ray observation exposure time 9146 sec



location to see
the “excess”

X-ray search
region (3 deg radius)



p-value corrected for trial factors

$$p\text{-value} = 8.8 \times 10^{-3}$$

Not statistically significant
(when 14 events trial factor is considered)

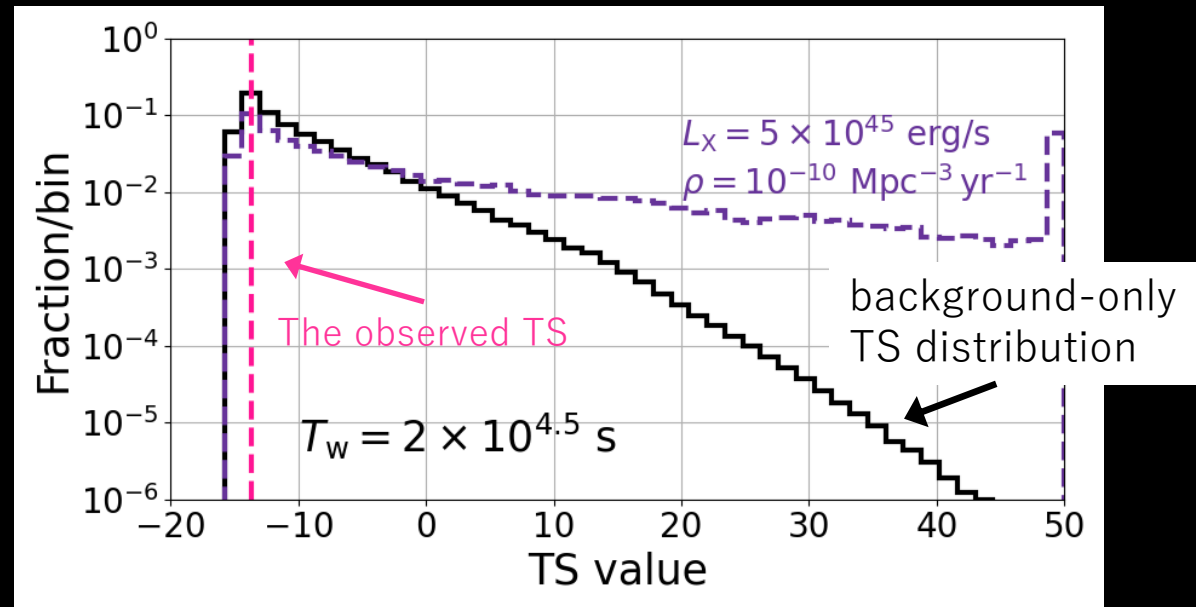
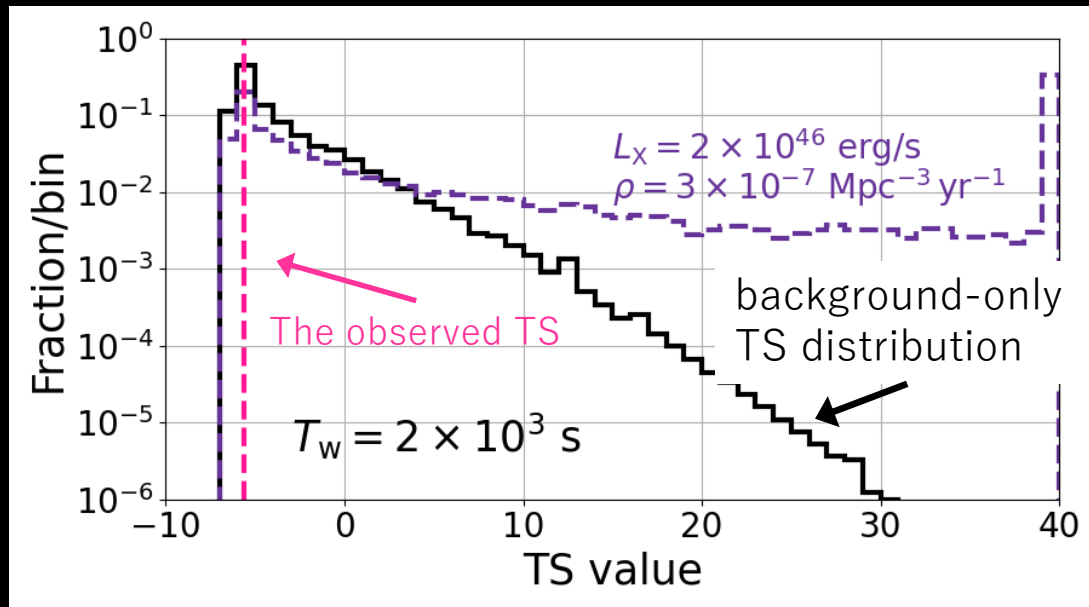
Found no X-ray counterparts



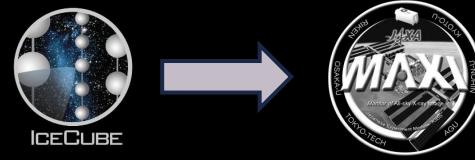
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“Short” – can cover low-luminosity GRBs-like
5 events with EP-EXT coverage at $\Delta T \pm 10^3 \text{ sec}$

“Long” – can cover TDE-like
14 events with EP-EXT coverage at $\Delta T \pm 10^{4.5} \text{ sec}$



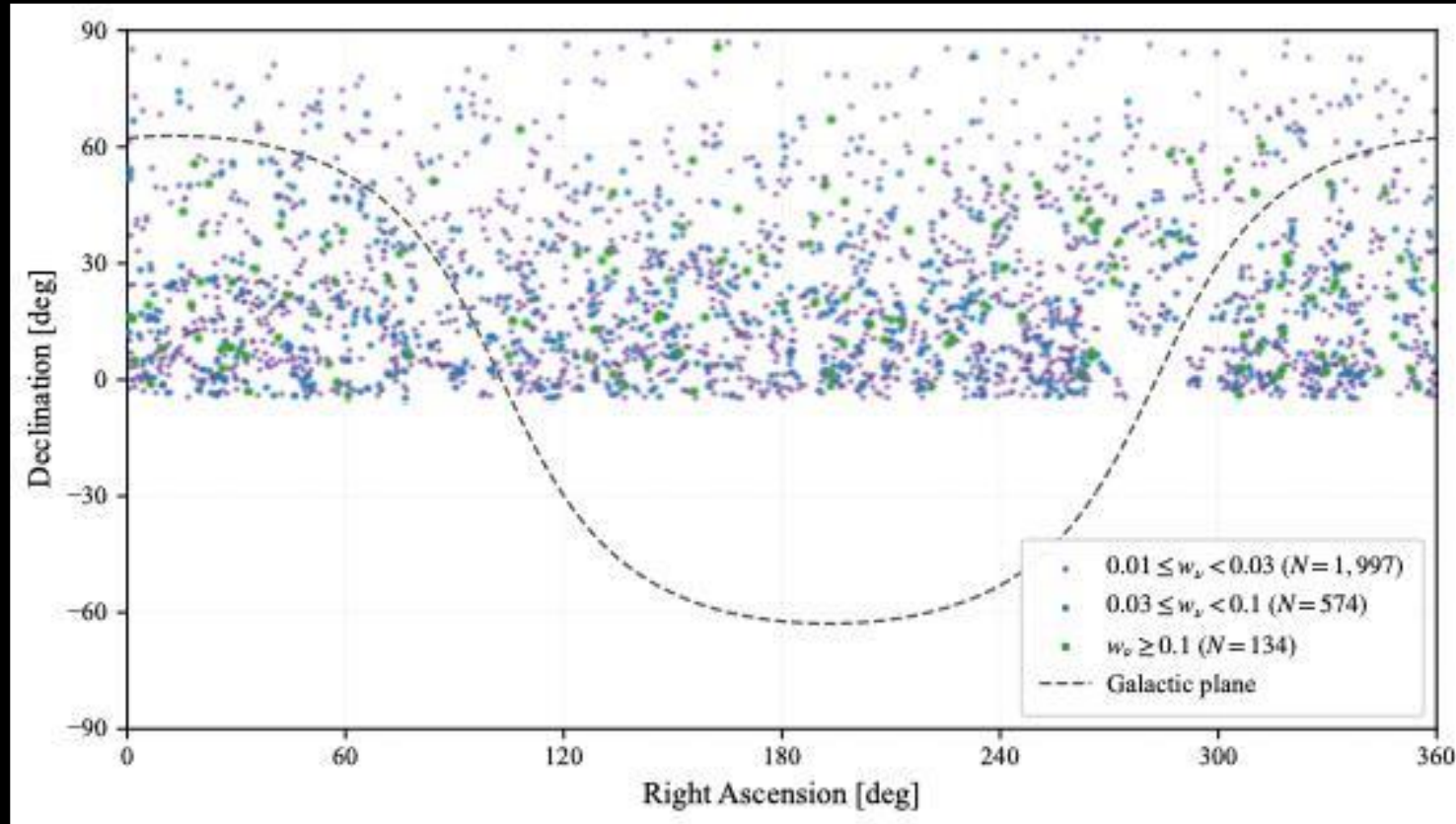
Now we look into the X-ray data



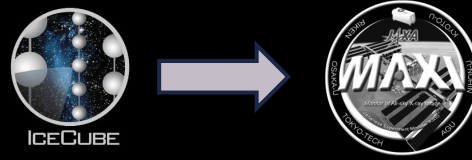
2009 – 2023 (14.5 years)

from IceCube “GFU” sample

191k events with MAXI coverage at $\Delta T \pm 2,700$ sec can cover low-luminosity GRBs-like
(134 events with astrophysical “Signalness” > 0.1)

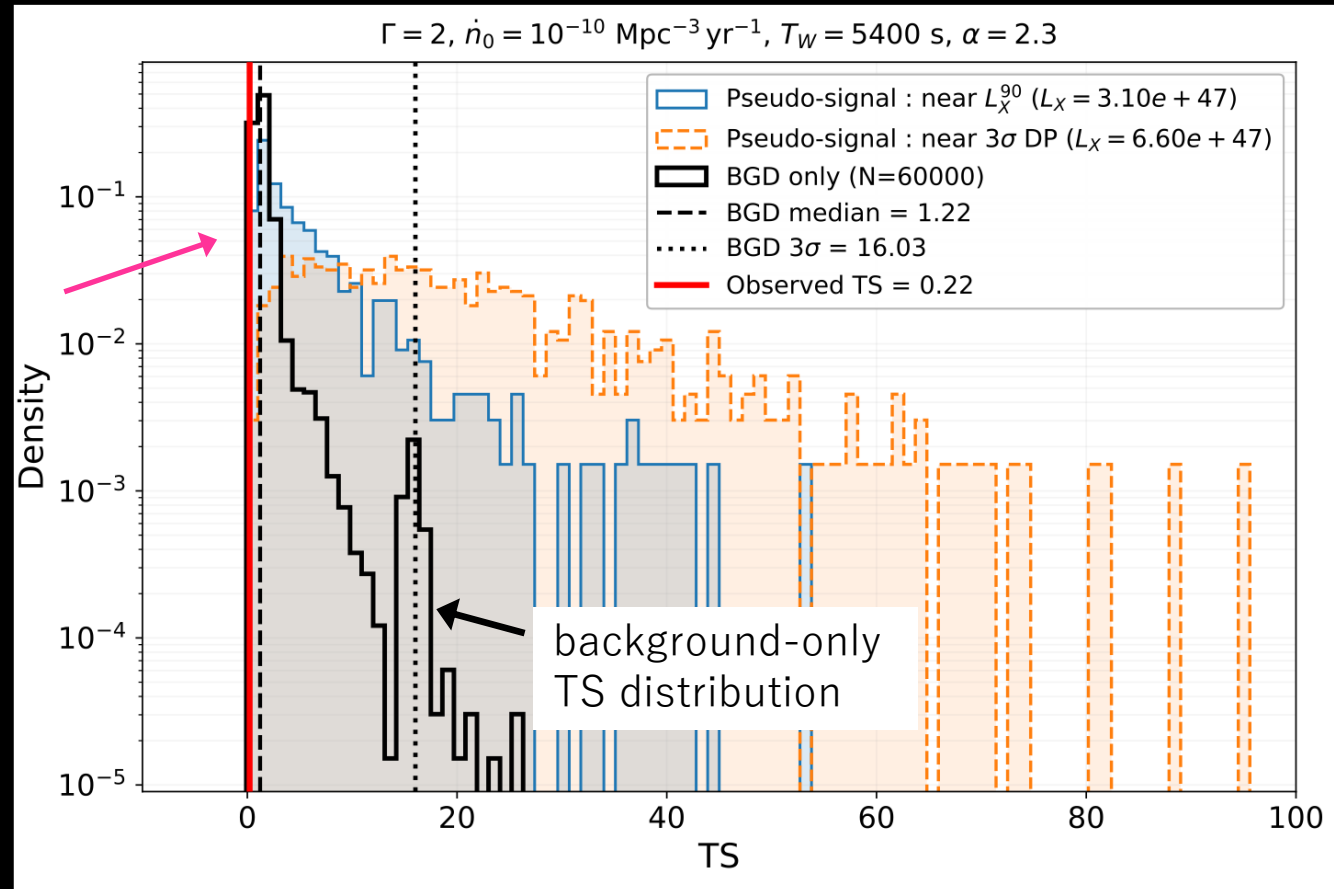


Found no X-ray counterparts



191k events with EP-EXT coverage at $\Delta T \pm 2,700\text{sec}$

The observed TS



X-ray Luminosity UL

X-ray transients (**whatever they are**) responsible for all-sky ν flux must meet

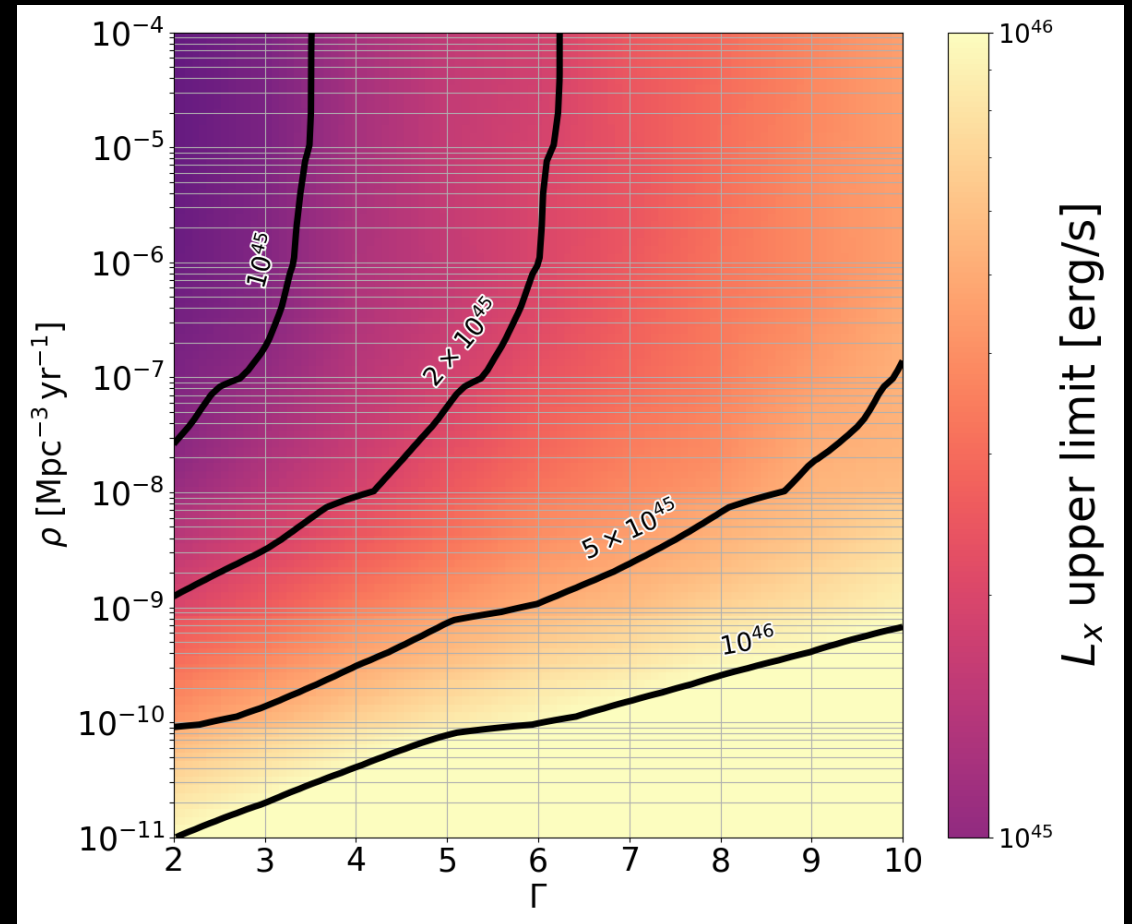
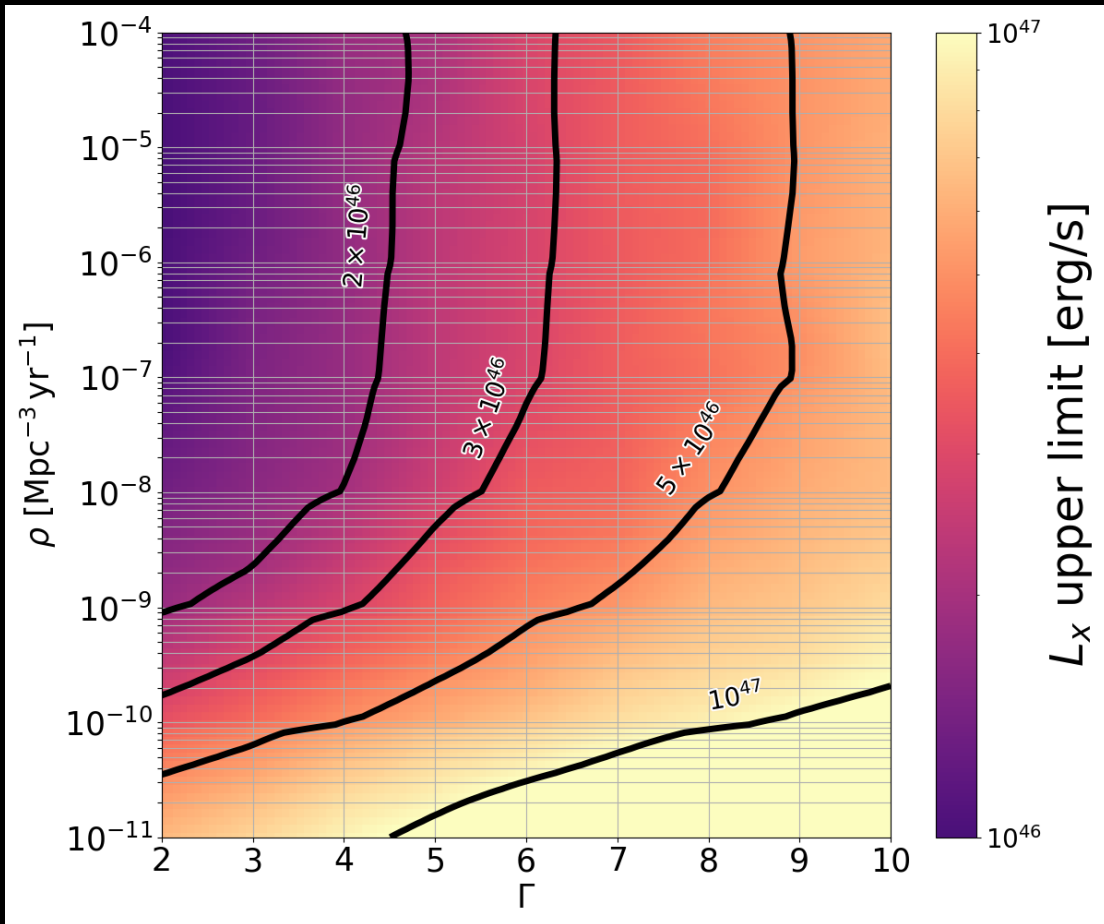
$$L_X \lesssim \mathcal{O}(10^{46}) \text{ erg/s}$$

“Short” $\Delta T \pm 10^3 \text{ sec}$



$$L_X \lesssim \mathcal{O}(10^{45}) \text{ erg/s}$$

“Long” $\Delta T \pm 10^{4.5} \text{ sec}$



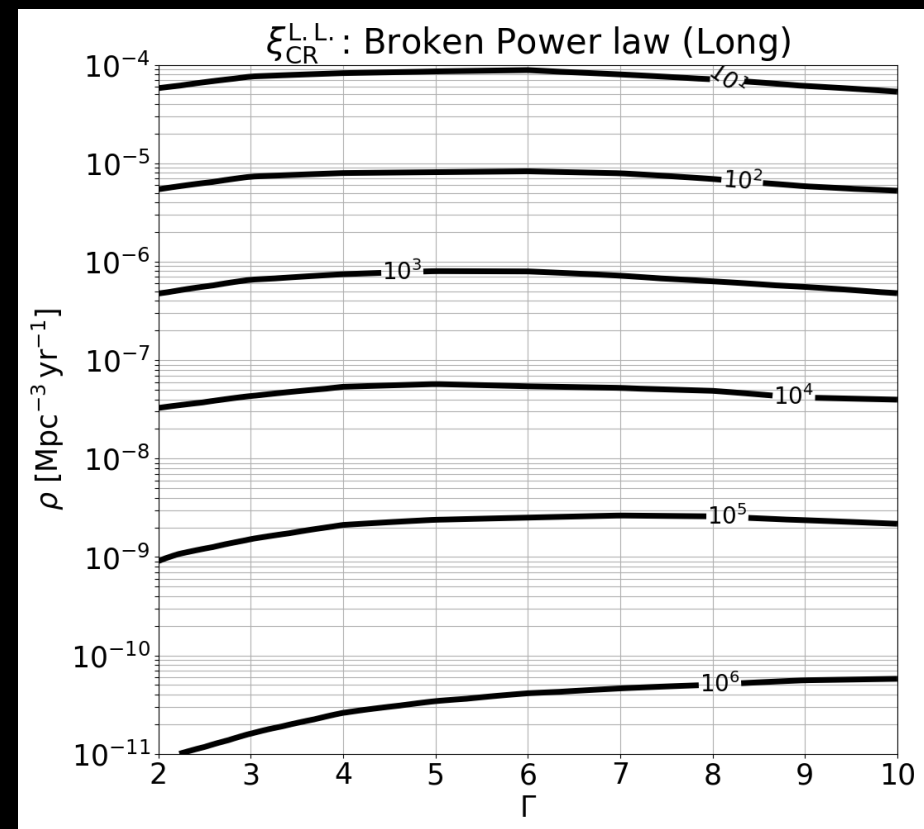
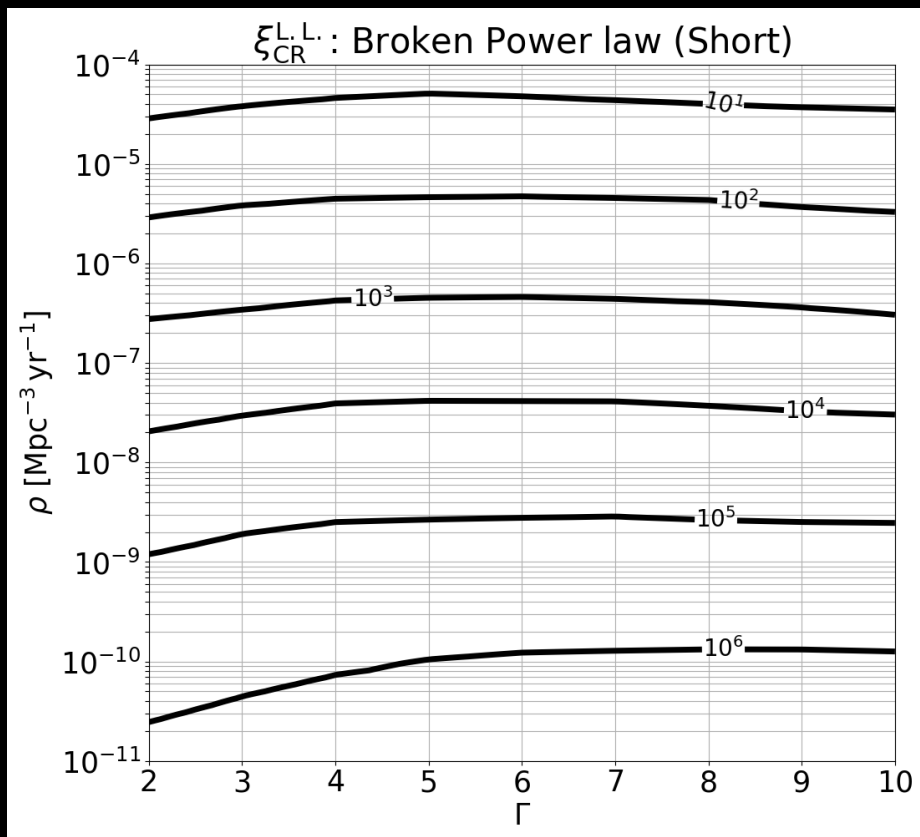
ξ_{CR} CR loading factor LOWER LIMIT

X-ray transients (**whatever they are**) responsible for all-sky ν flux must load at least this much cosmic-rays

$$\xi_{\text{CR}} \gtrsim 1,000 \text{ for } \rho \sim 3 \times 10^{-7} \text{Mpc}^{-3} \text{yr}^{-1}$$

“Short” $\Delta T \pm 10^3 \text{sec}$

“Long” $\Delta T \pm 10^{4.5} \text{sec}$



$$n_0 L_{\text{CR}} = \rho \Delta T \xi_{\text{CR}} L_X < Q_{\text{UHECR}}$$

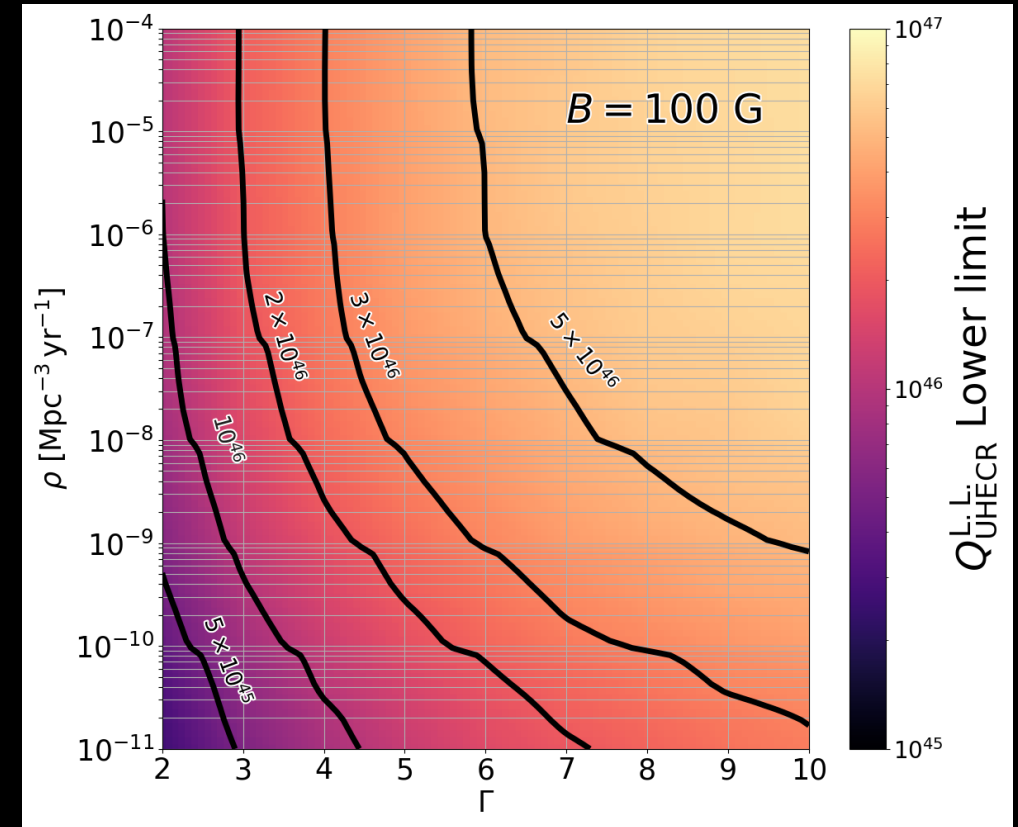
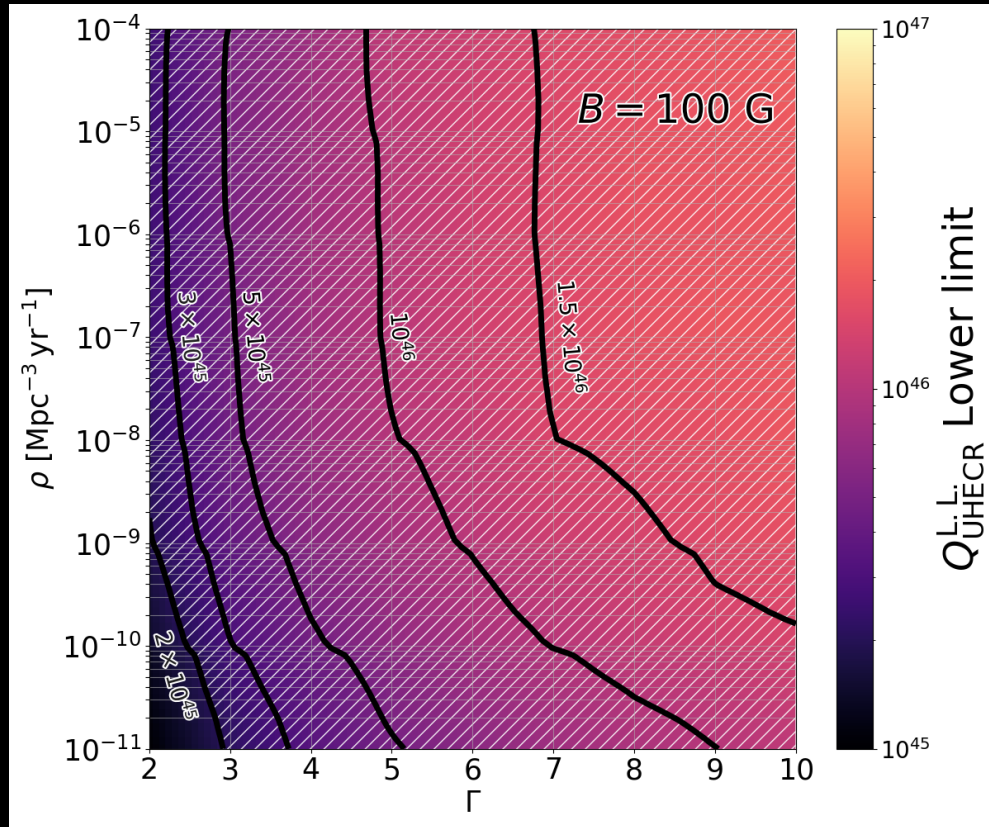
constraints from UHECR energetics

$$Q_{\text{UHECR}}^{>10\text{PeV}} \lesssim 2 \times 10^{45} \text{ erg}^{-3} \text{ yr}^{-1} \leftarrow \text{based on Auger data Murase \& Fukugita PRD 2019}$$

A common transient origin of UHECRs and high-energy ν 's is severely constrained

“Short” $\Delta T \pm 10^3 \text{ sec}$

“Long” $\Delta T \pm 10^{4.5} \text{ sec}$



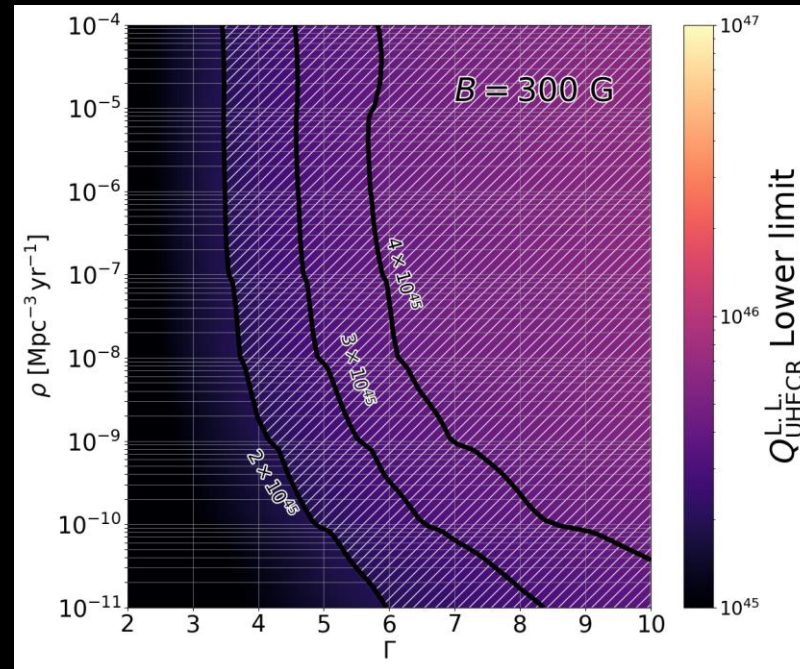
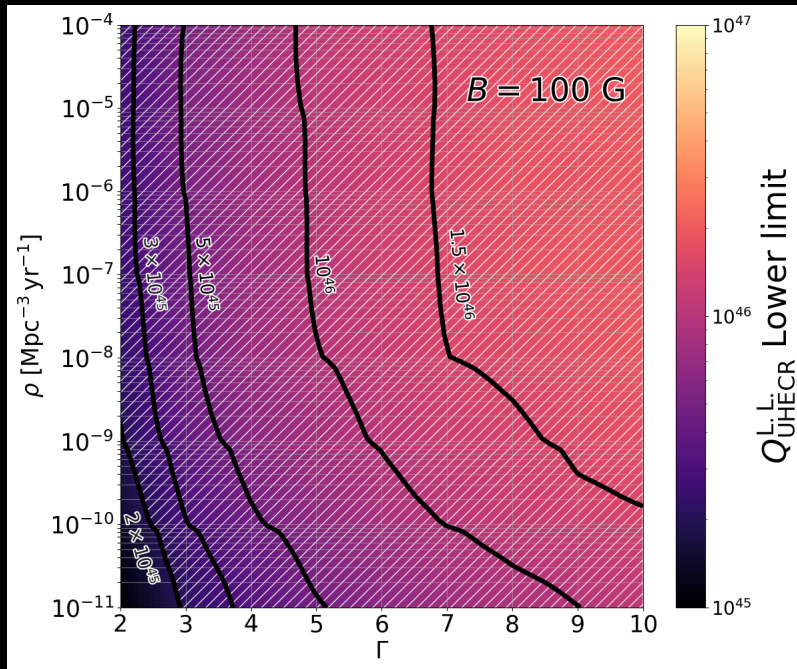
$$n_0 L_{\text{CR}} = \rho \Delta T \xi_{\text{CR}} L_X < Q_{\text{UHECR}}$$

constraints from UHECR energetics

There is some room to relax the constraints by B-field, but not much.

Higher B $\rightarrow$ denser X-ray $\rightarrow$ more efficient ν production $\rightarrow$ you do not have to load CRs so much

“Short” $\Delta T \pm 10^3 \text{ sec}$



Unless $B \gg 500 \text{ Gauss}$

(and $\xi_B \lesssim 1$)

a substantial phase space
is ruled out

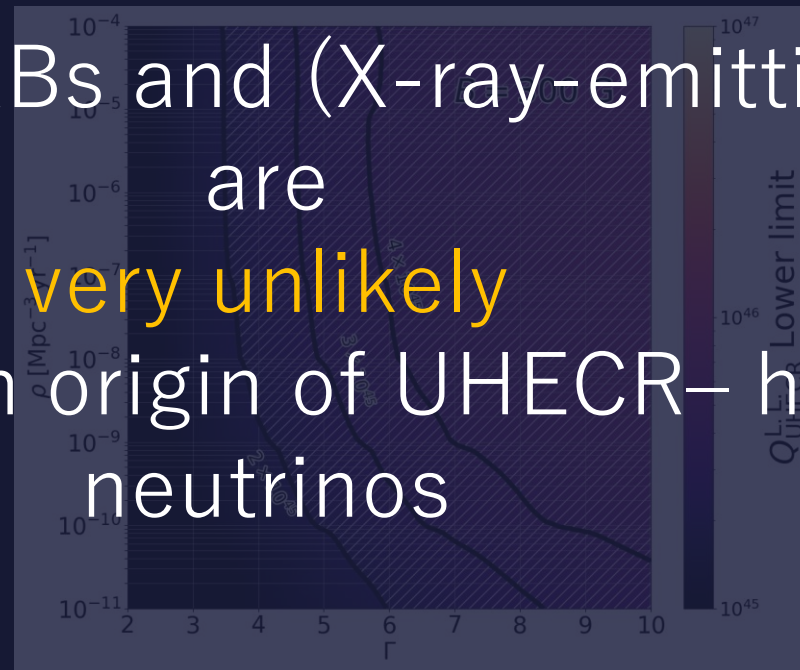
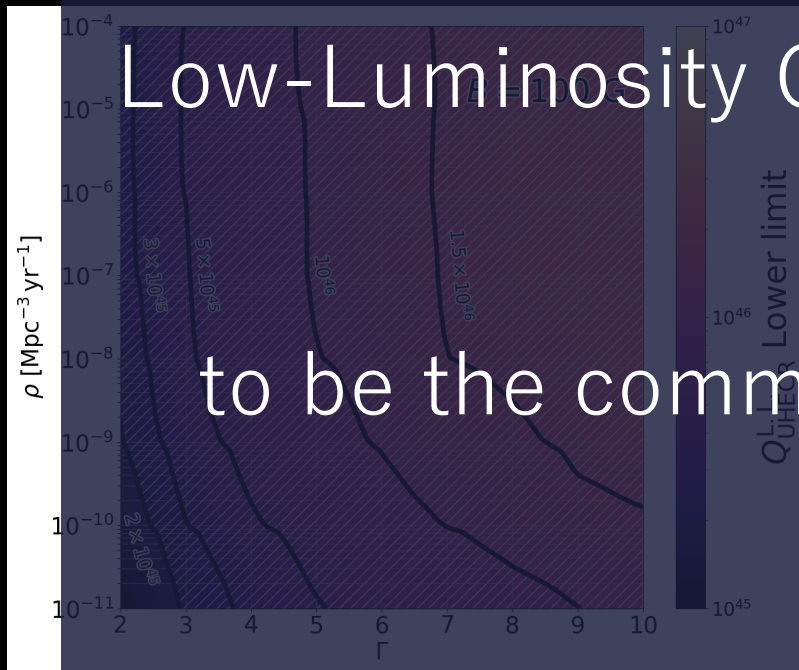
$$n_0 L_{\text{CR}} = \rho \Delta T \xi_{\text{CR}} L_X < Q_{\text{UHECR}}$$

constraints from UHECR energetics

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“Short” $\Delta T \pm 10^3 \text{ sec}$



Low-Luminosity GRBs and (X-ray-emitting) TDE jets
are
very unlikely
to be the common origin of UHECR– high-energy
neutrinos

Unless $B \gg 500 \text{ Gauss}$
(and $\xi_B \lesssim 1$)
a substantial phase space
is ruled out

Summary

- We demonstrate that the neutrinos – X-rays – UHECRs multimessenger probe is a powerful approach to characterize the origin of cosmic rays.
- If the primary origin of the all-sky neutrino emissions with energies above 100 TeV is X-ray transient sources, their X-ray luminosity is lower than 10^{46} erg/s
- Their jet bulk Lorentz factor must be $\lesssim 4$ if they are also UHECR sources
LL-GRBs and jetted TDEs are confronted with a significant challenge.
Even new transients that we have not discovered yet must satisfy this general constraint.

This work was a collaborative effort with

Nobu Shimizu
Wataru Iwakiri
Guojiong Yang
Aya Ishihara
Yuan Liu
Xiang-Yu Wang

and

IceCube Collaboration