Search for X-ray transient counterparts for the IceCube neutrino events with MAXI

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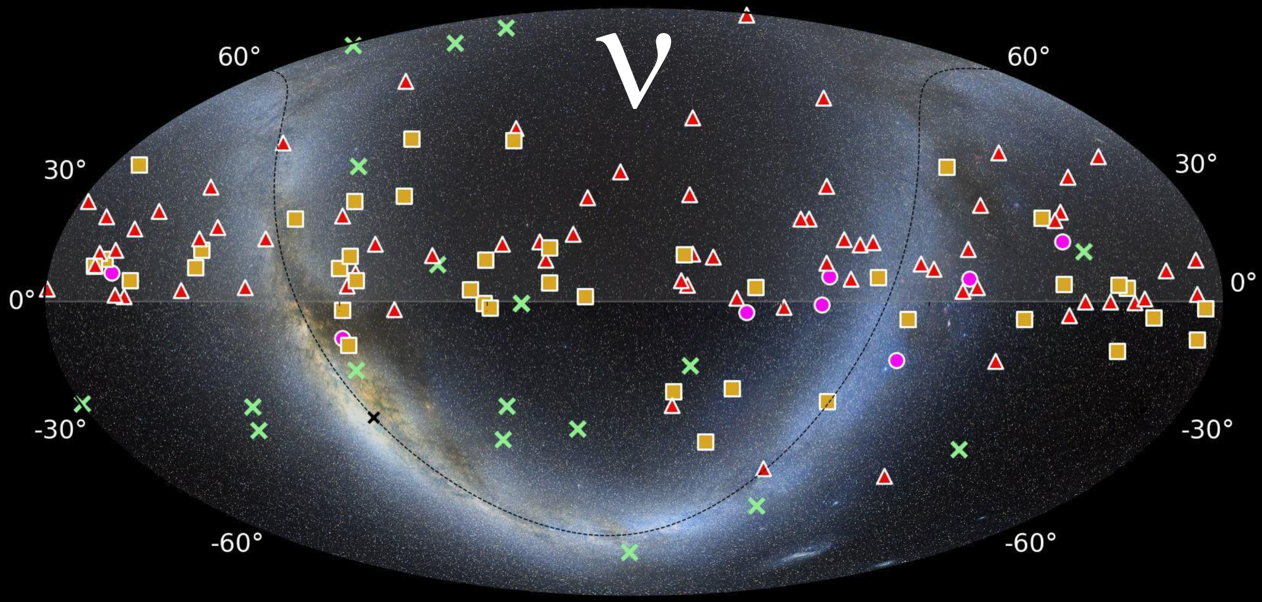
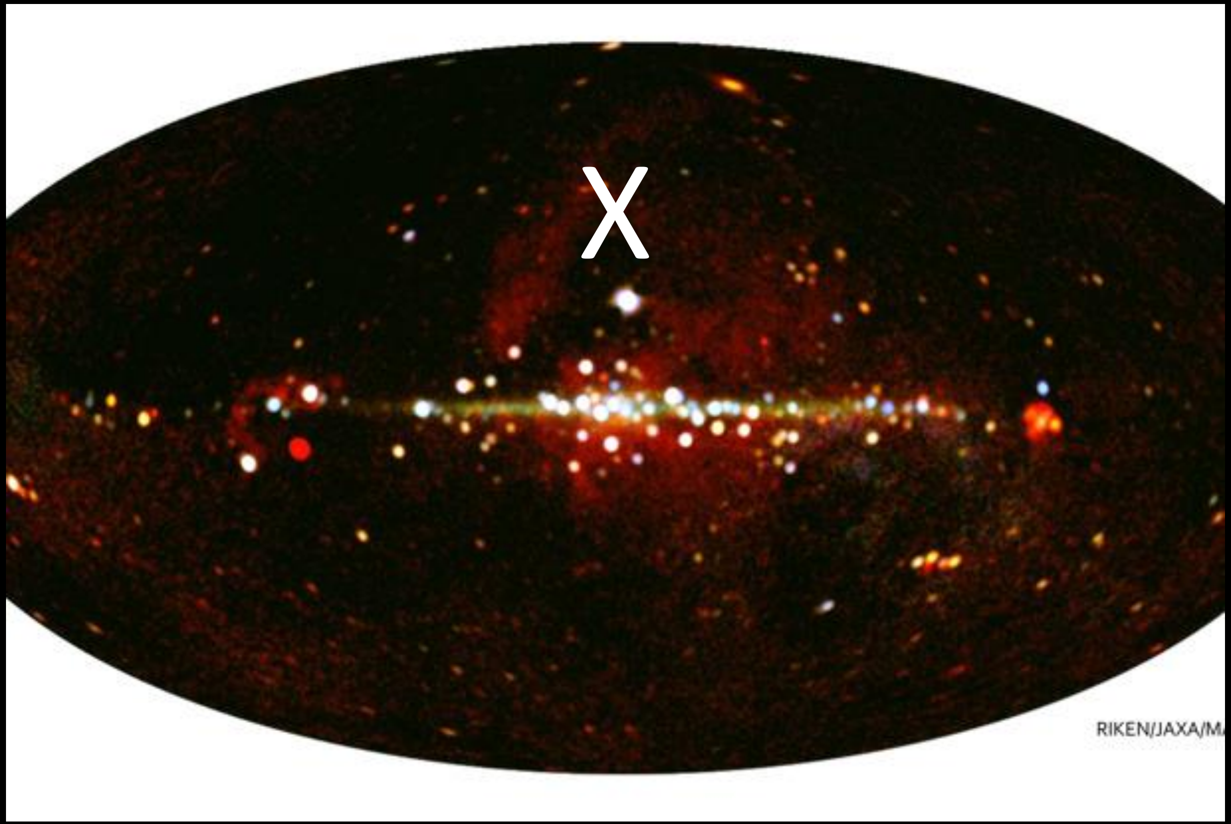
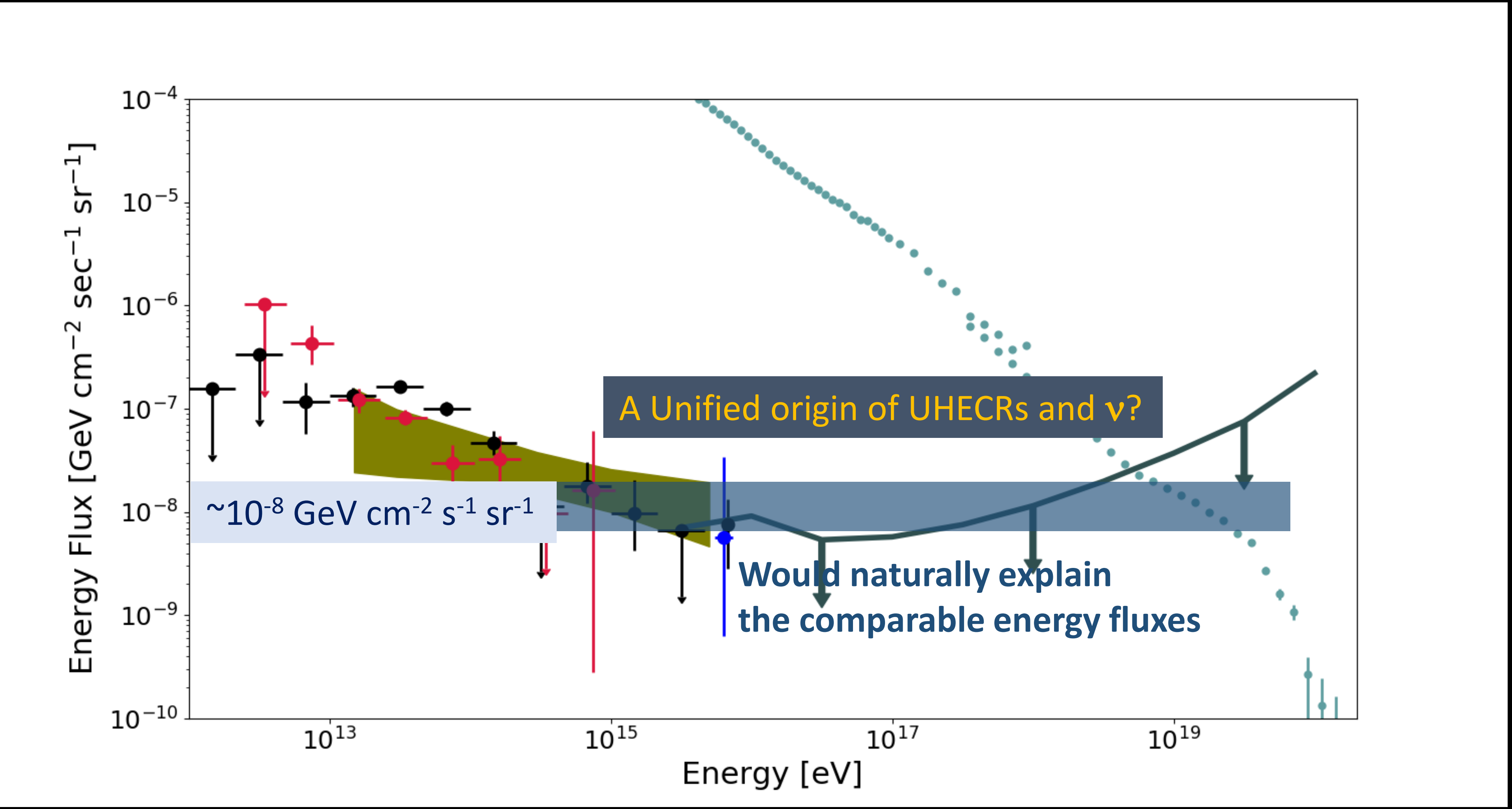




The UHE Cosmic Background Radiations

The UHE Cosmic Ray + **Neutrino** **Energy** Fluxes



The conditions the Common Sources must meet

The only narrow parameter space is allowed!

Luminosity Density

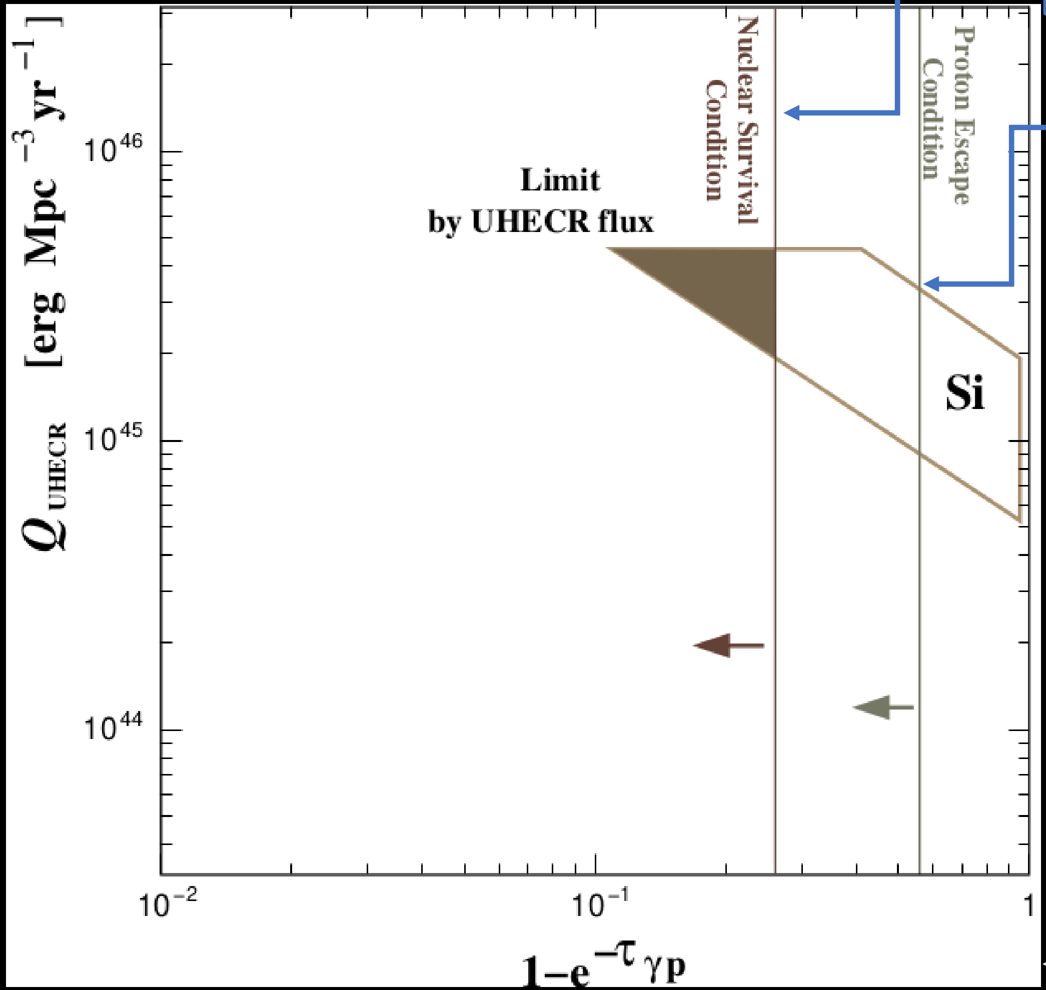
Energetics Condition

Survival Condition

Escape Condition

Fiducial Neutrino Flux Condition

pγ optical depth



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 $\tau_{p\gamma} \lesssim 0.4(A/56)^{-0.21}$
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

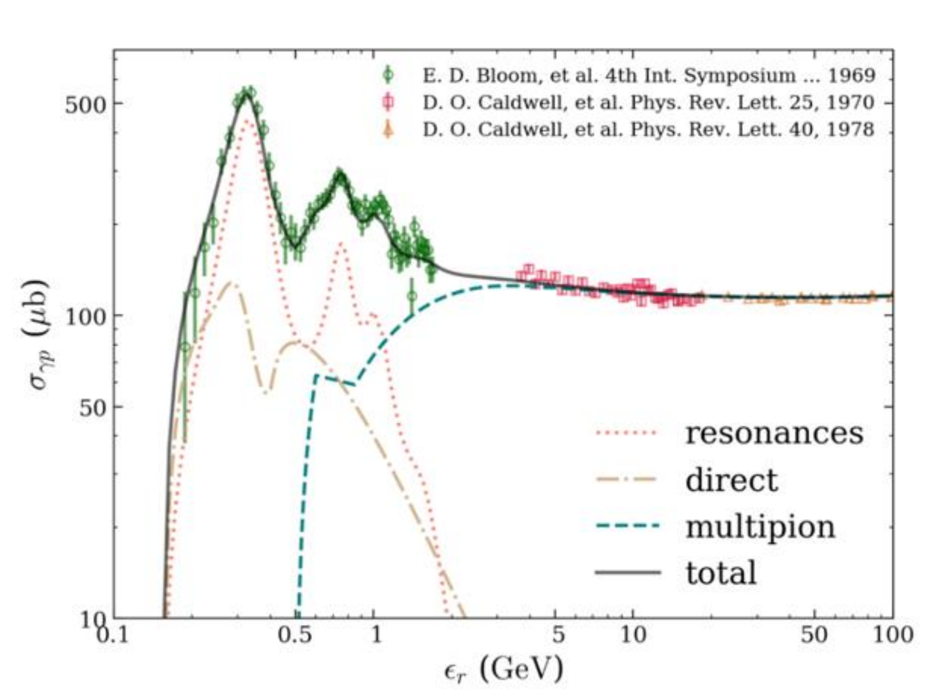
Yoshida & Murase PRD (2024)

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

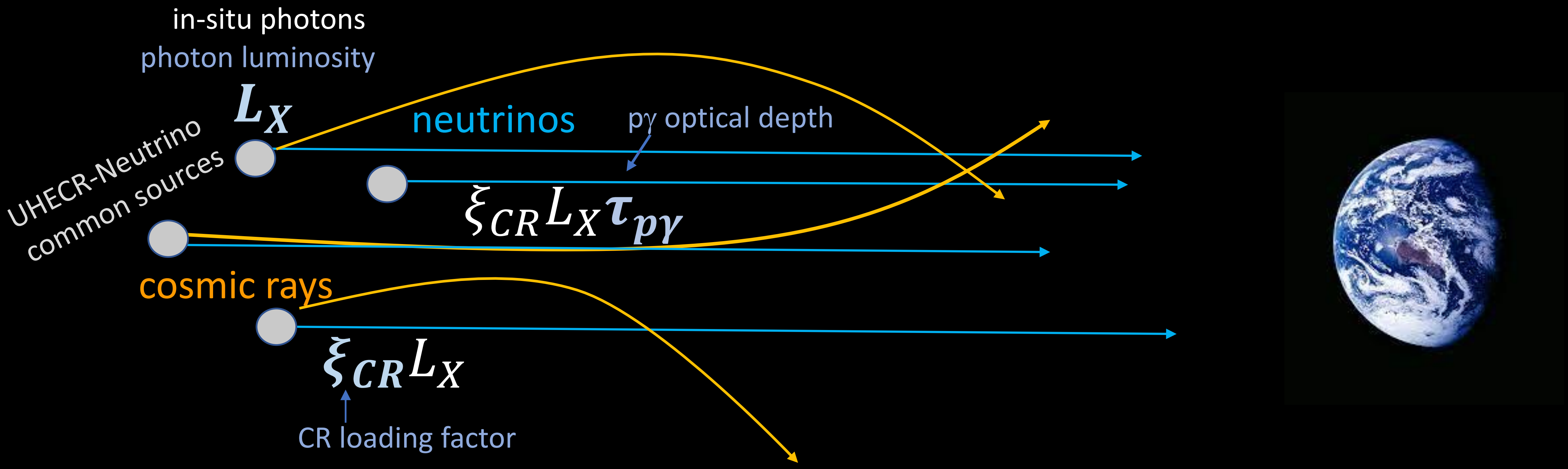


$$\varepsilon'_{\gamma 0} \approx \frac{(s_\Delta - m_p^2)}{4}\frac{\Gamma}{\varepsilon_{p0}}.$$

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

Γ Lorentz factor of (jet) plasma

The generic **neutrino source scheme** via photo-hadronic framework

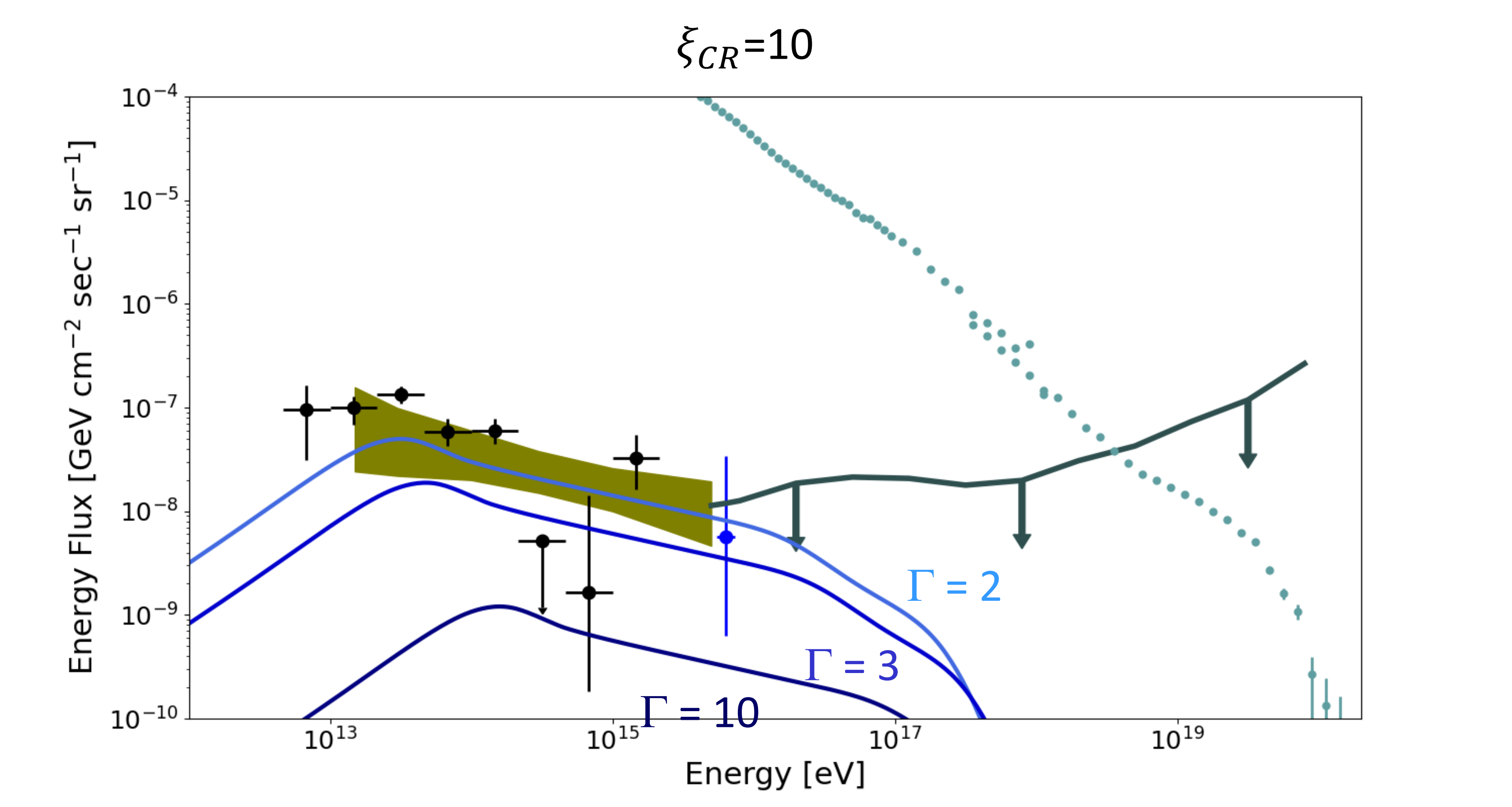


The **in-situ photon luminosity**
- A gauge of the source power
- The gauge of the neutrino emission power via **the optical depth**
- The gauge of the UHECR emission power via **the CR loading factor**

The UHE Cosmic Background Radiations

L_X (2-10 keV) 5x10^{46} erg/s (low luminosity GRB-like)

The expected cosmic neutrino background flux



Yoshida & Murase PRD (2024)

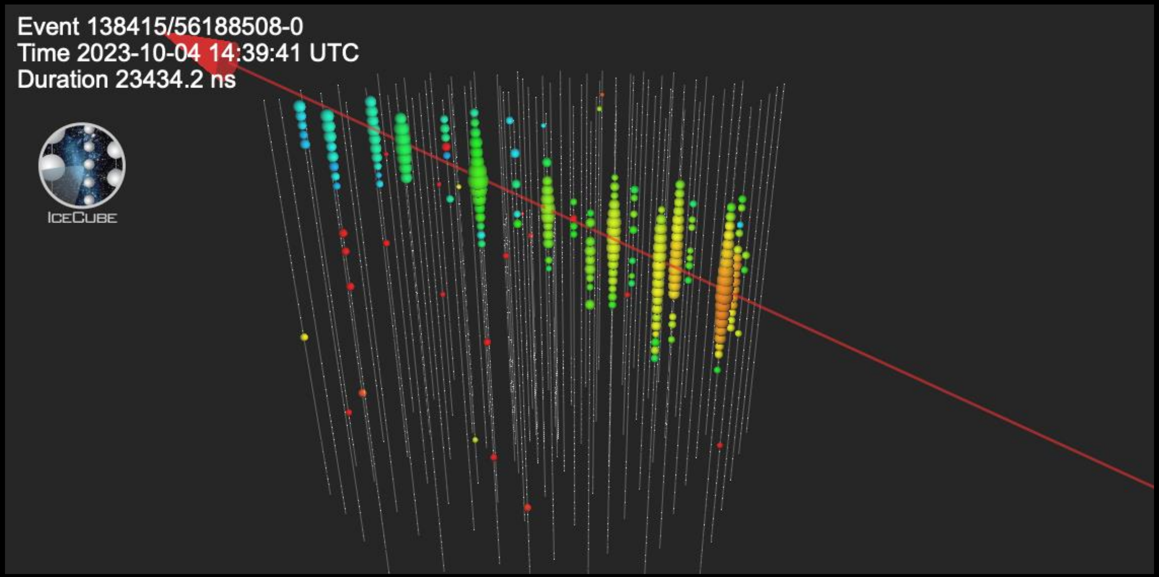
Neutrino and X-ray stacking search

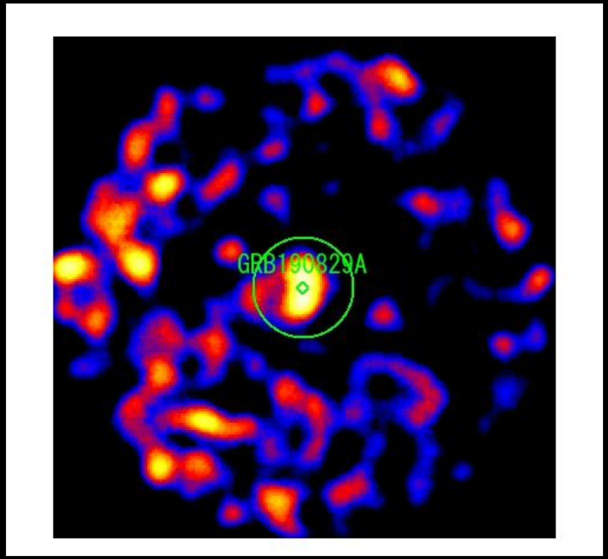
ν X

the both facilities monitor all-sky and
the data has been archived

ΔT $10^{3\text{-}4}$ sec

A neutrino event





2keV-10keV

X-rays! All-sky monitor MAXI is joining the ν campaign

- On board the International Space Station (ISS)
- Scans all-sky every 92 minutes with ISS rotation

searching for X-ray transients, monitoring hundreds of X-ray sources, with Gas Slit Camera (GSC) in 2-20 keV

- Operated since 2009 August 15 (over 15 years)
- The only all-sky X-ray monitor currently in operation
- Data downlinked in real time → Real time alert

→ **Add great synergy to MM astronomy**

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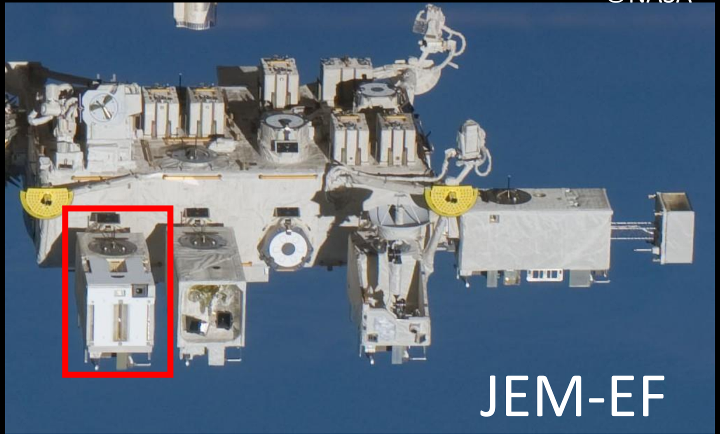
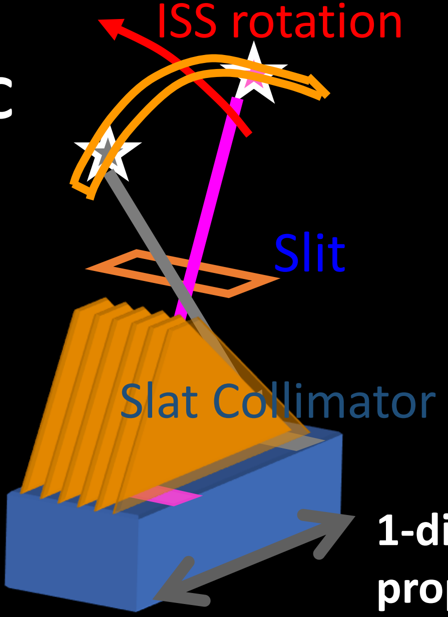
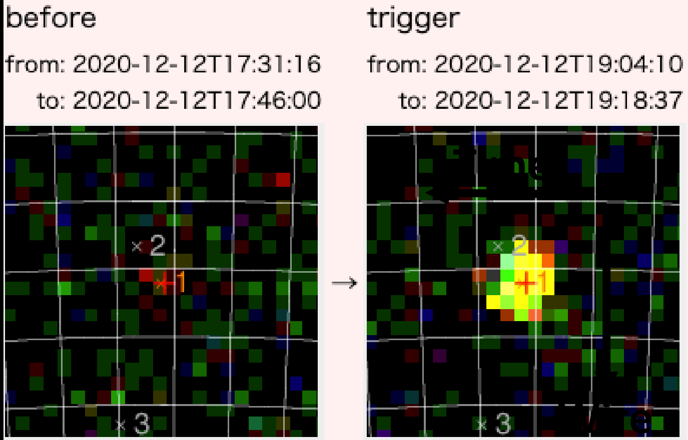
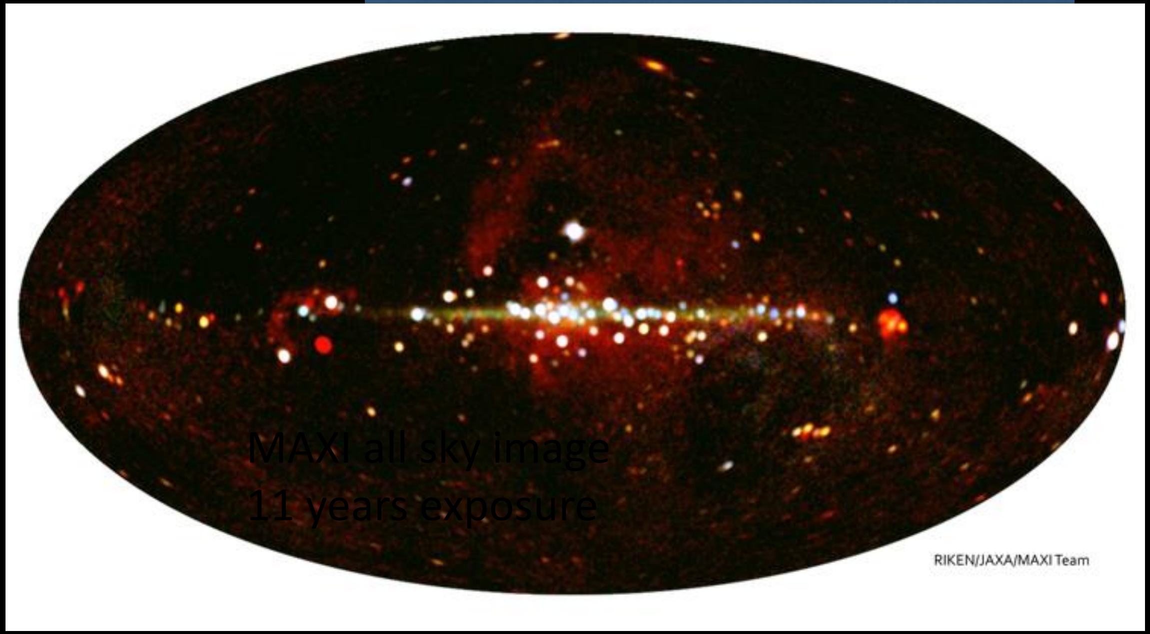


GSC

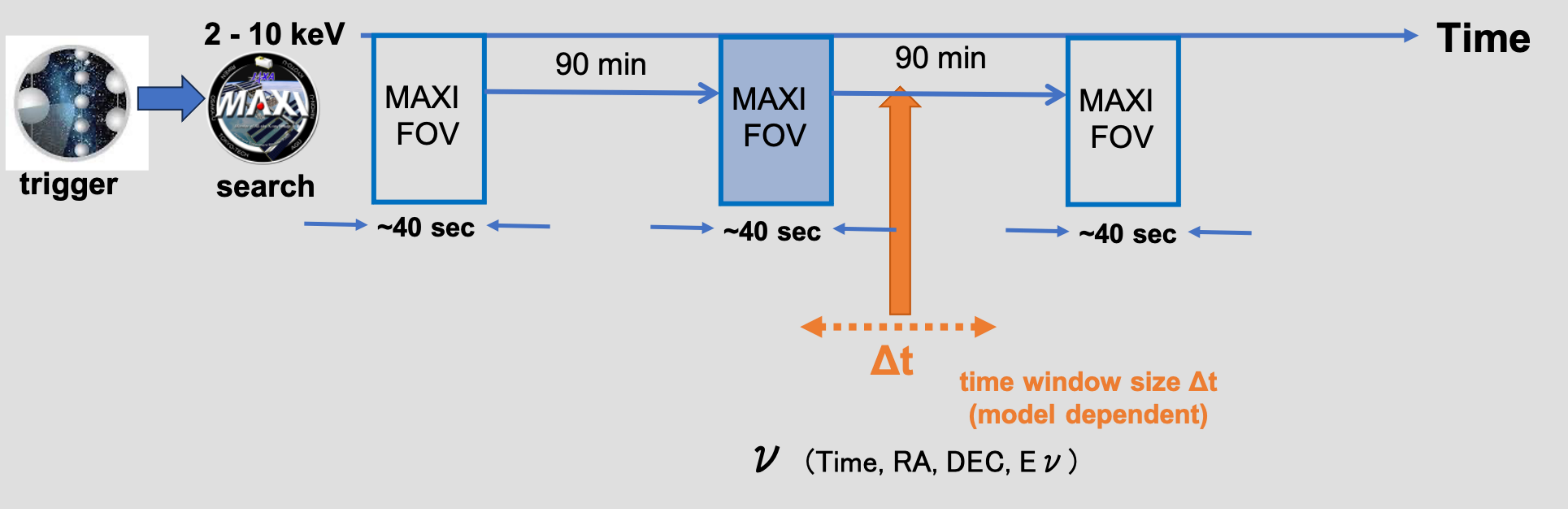


1-dimensional position sensitive proportional counter





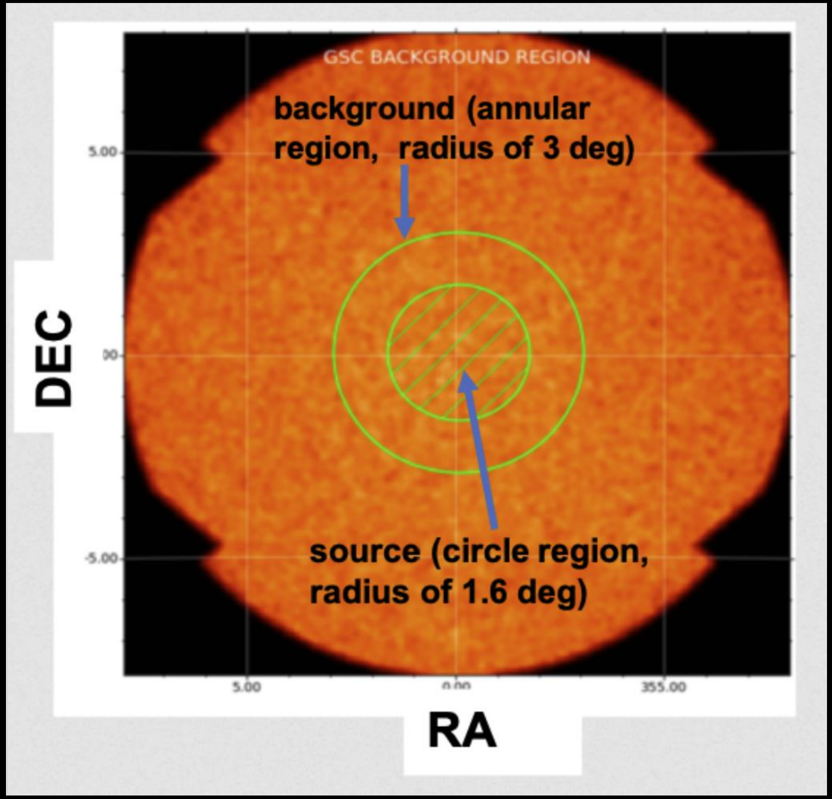
The search scheme

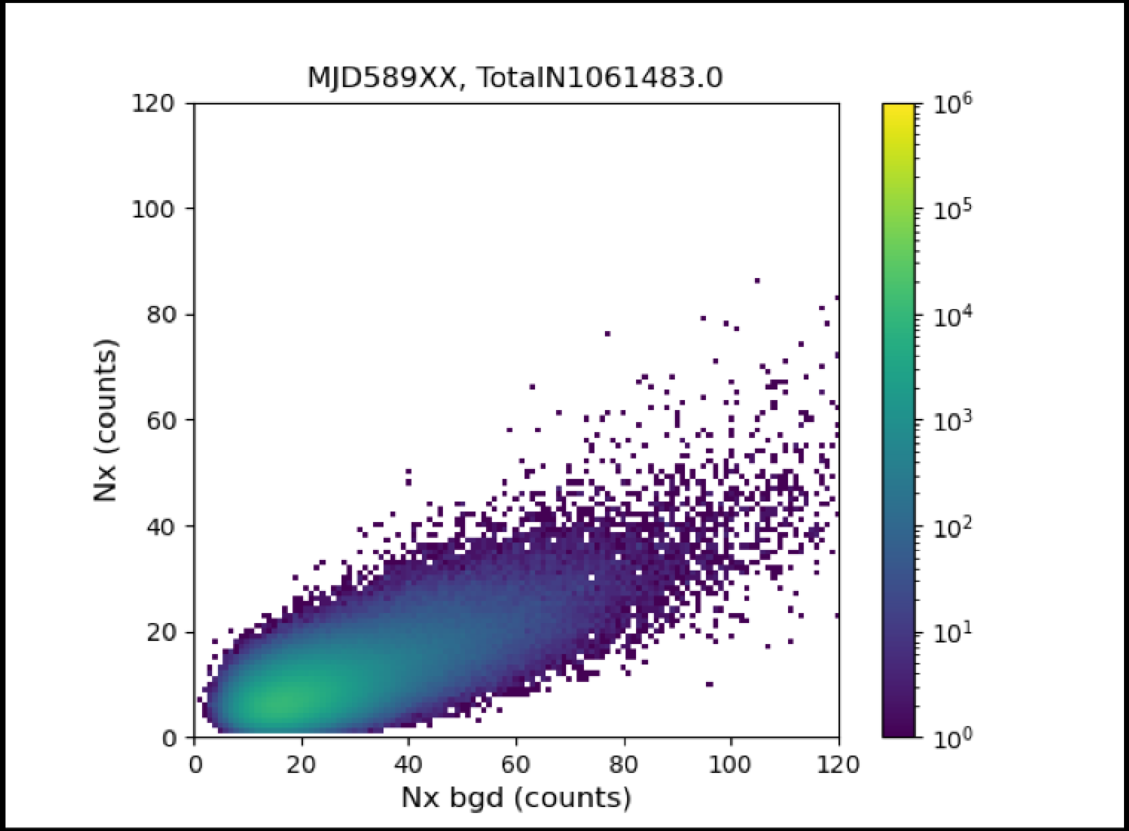


We employed $\Delta T = 10^3$ sec

Looking at excess of X-ray photons

PDF of the photon counts by the data driven approach





Extended Poisson Likelihood Construction

running over all the IceCube – MAXI data pairs

ν signal related X-ray

ν signal “not” related X-ray

$$\mathcal{L}_{sig} = \frac{\mu^{N_{\rm obs}}}{N_{\rm obs}\,!} e^{-\mu} \prod_{i=1}^{N_{\rm obs}} \left(\frac{n_{\rm sig}}{n_{\rm atm} + n_{\rm dif}} P_{\nu}^{\rm sig}{}_{(E_\nu,\delta)} \times P_{\rm X}^{\rm sig}(N_{\rm X}, \mu_{\rm Xsig}(L_{\rm X})) + \frac{1}{n_{\rm atm} + n_{\rm dif}} \left\{ n_{\rm dif} P_{\nu}^{\rm dif}{}_{(E_\nu,\delta)} - n_{\rm sig} P_{\nu}^{\rm sig}{}_{(E_\nu,\delta)} \right\} P_{\rm X_{DB}}^{\rm bgd} + \frac{n_{\rm atm}}{n_{\rm atm} + n_{\rm dif}} P_{\nu}^{\rm atm}{}_{(E_\nu,\delta)} P_{\rm X_{DB}}^{\rm bgd} \right)$$

atmospheric ν bgd “not” related X-ray

N_{obs} : total number of events
μ : total expected numbers
n : expected numbers of each component

N_X : Number of X-ray events
P : Probability Density Function
δ : direction of the events
ϵ_ν : energy of the events

Running Pseudo-experiments

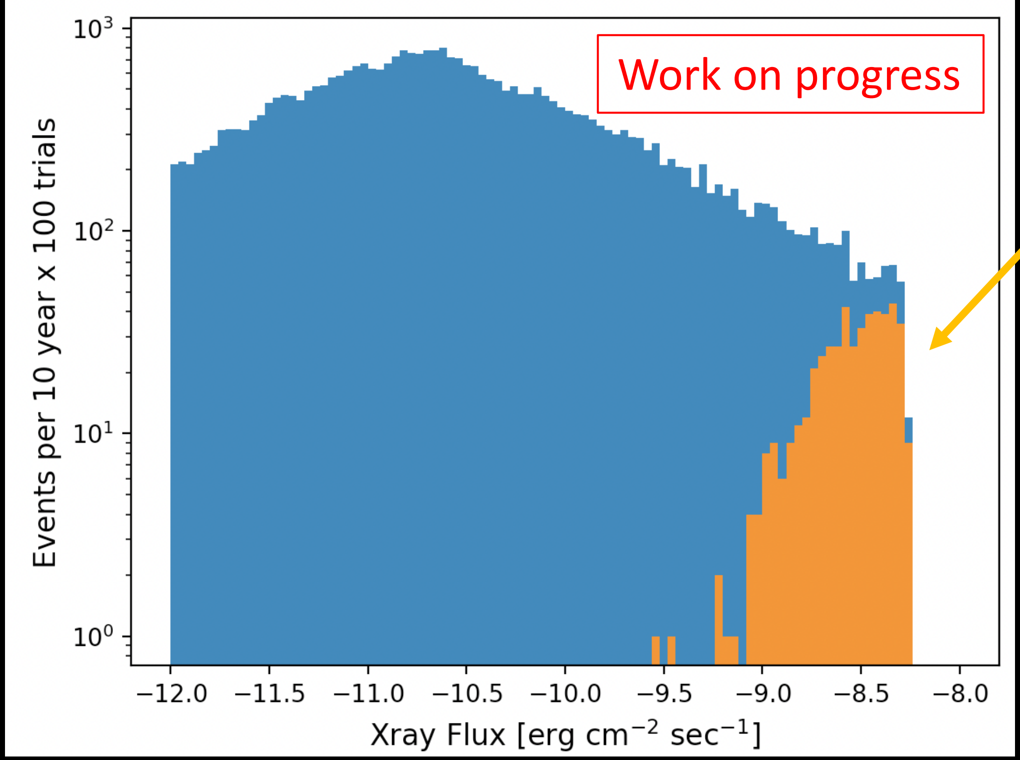
When follow up neutrino direction 200k times

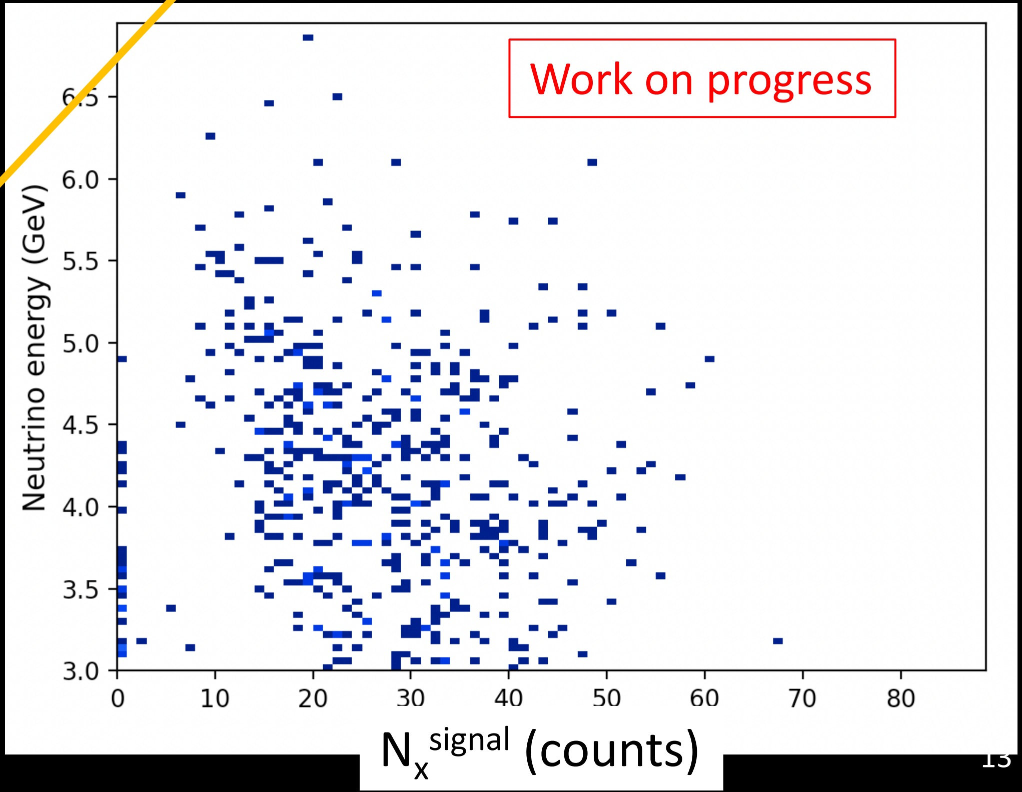
taken from 12yr long IceCube archival data, dominated by atmospheric neutrinos.
Purity of astrophysical neutrinos is $\lesssim 0.1\ \%$

IceCub – MAXI
work on progress

$L_X = 10^{46}\mathrm{erg/s} \quad n_0 = 5\times10^{-9}\mathrm{Mpc}^{-3}$

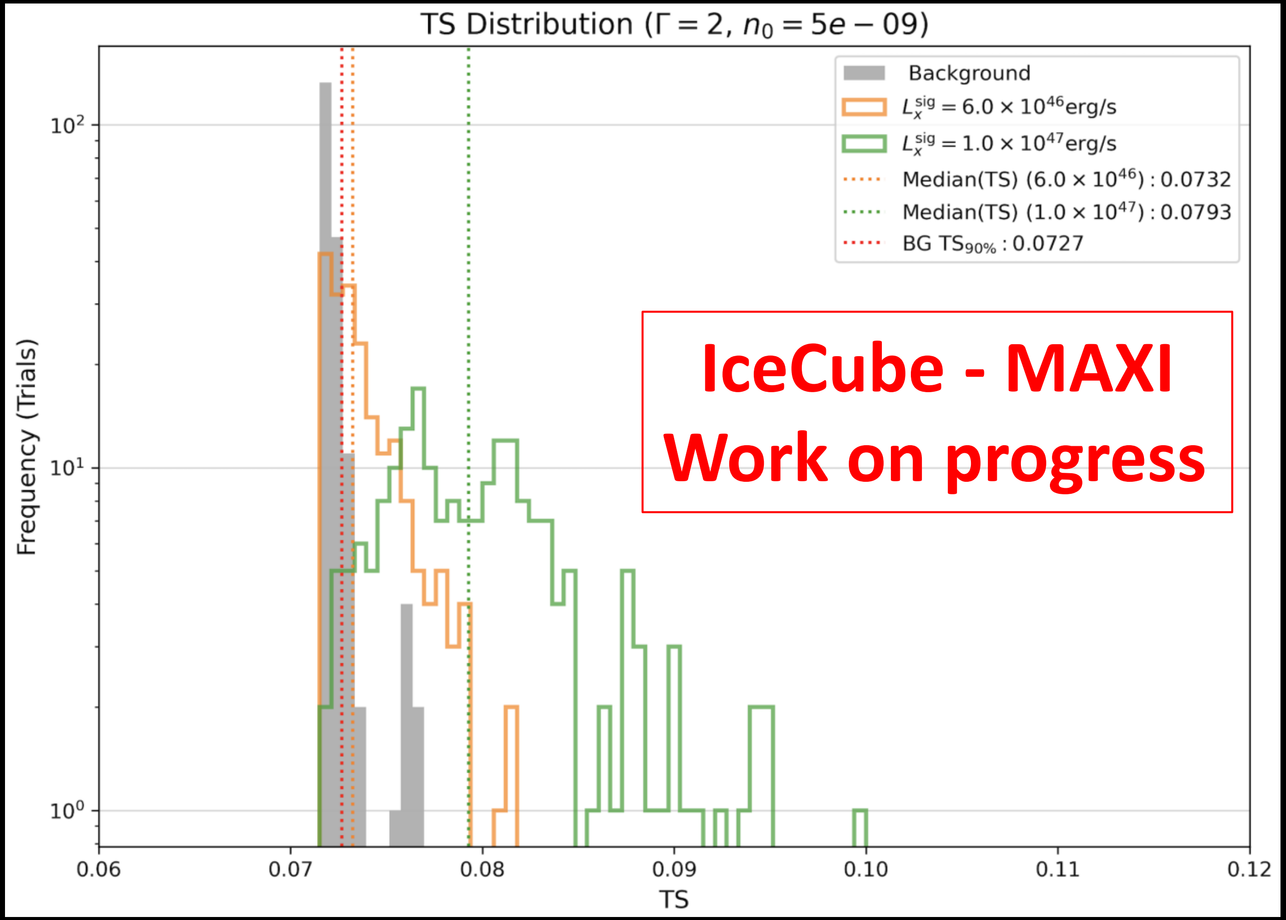
$\frac{\mathcal{L}_{sig}(L_X)}{\mathcal{L}_{bgd}} > 0.5$





The expected sensitivity

$$\boxed{TS = \log \prod \frac{\mathcal{L}_{sig}(L_X)}{\mathcal{L}_{bgd}}}$$



if null detection

$$L_X \lesssim 6 \times 10^{46} \left(\frac{n_0}{5 \times 10^{-9} \mathrm{Mpc}^{-3}} \right)^{-2/3} [\mathrm{erg/s}]$$

Parametrization to describe cosmic-ray/ν emissions

CR loading factor ξ_{CR} determines CR emission power – How *hadronic* you are?

$$L_{CR} = \xi_{CR} L_X$$

X-ray luminosity L_X

decide the target photon density

Lorentz factor of (jet) plasma Γ

$$\tau_{p\gamma} \propto \sqrt{L_X} \frac{B}{\Gamma^2}$$

decide the size of the interaction zone

pγ optical depth $\tau_{p\gamma}$ determines neutrino emission brightness

Yoshida & Murase PRD (2024)

Decompose into the source parameter space

Neutrino flux

based upon Yoshida & Murase PRD (2020)
Yoshida & Murase PRD (2024)

$$\propto \boxed{\xi_{CR}} \times B \times \underbrace{L_X \times (\sqrt{L_X}, 1)}_{\text{Now we are measuring/constraining } L_X} \times f(\Gamma)$$

We want to know this

MW observation/
theory could tell

Now we are measuring/constraining

L_X

Bulk Lorentz factor
of the plasma (jet)

Neutrino and X-ray stacking search

X

When placing Lx upper limit

For a given n_0 [Mpc^{-3}]

$$L_X \lesssim 6 \text{ x } 10^{46} \left(\frac{n_0}{5\times10^{-9} Mpc^{-3}}\right)^{-\frac{2}{3}} \text{erg/s}$$

ν

diffuse

$$\Phi_\upsilon \propto \boxed{\xi_{CR}} \times \underbrace{L_X \times (\sqrt{L_X}, 1)}$$

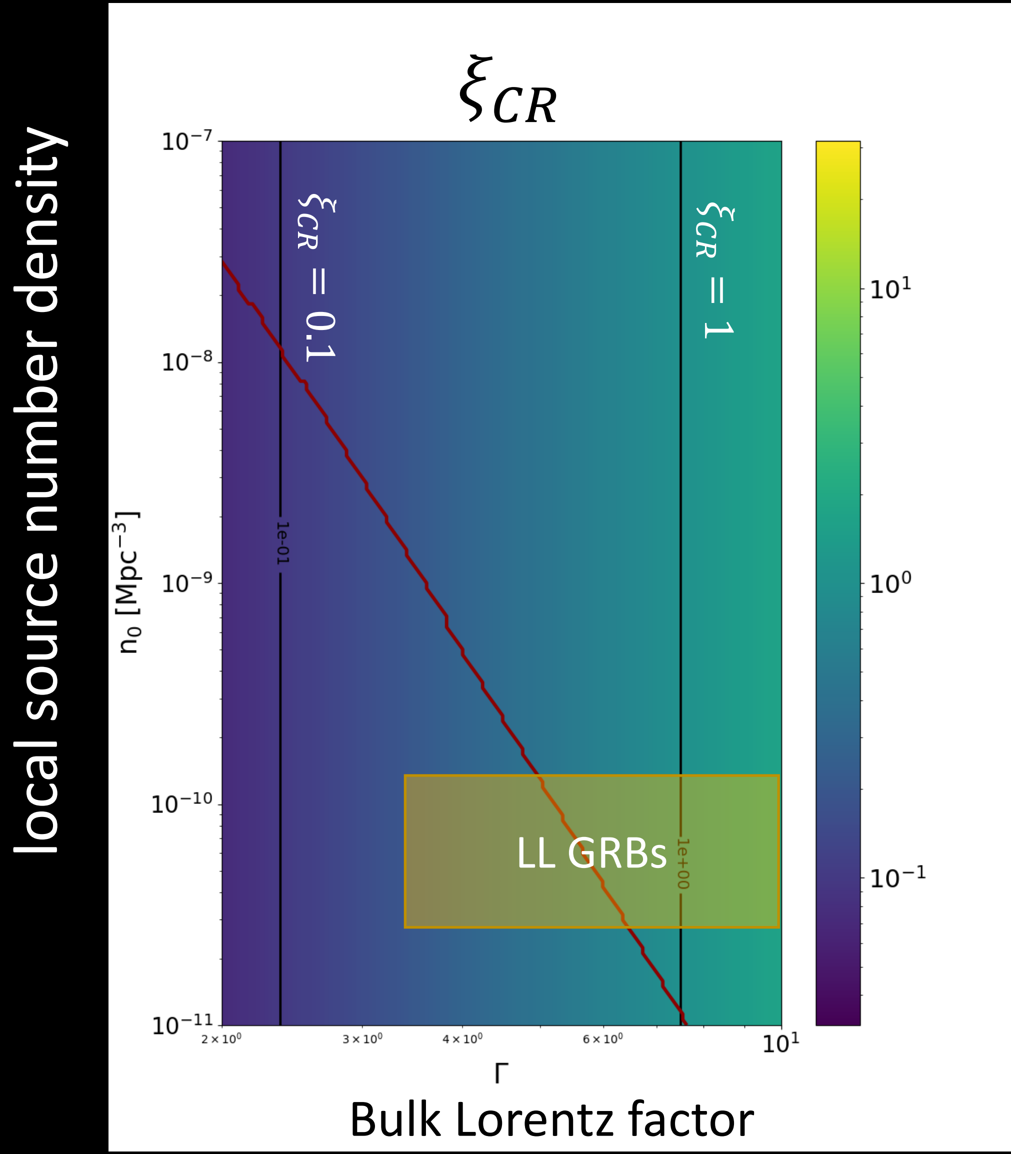
We know this

Yes,now we get
Lower Bound!

Now This is
the **Upper Limit**

The lower bound of CR loading factor

to explain the cosmic background flux data



For a given n_0 [Mpc^{-3}] and Γ

$$\Phi_\upsilon^{\text{diffuse}} \propto \boxed{\xi_{CR}} \times \underbrace{L_X \times (\sqrt{L_X}, 1)}$$

We know this by the I^3 diffuse data

Yes,now we get **Lower Bound!**

The upper limit is placed by the stacking analysis

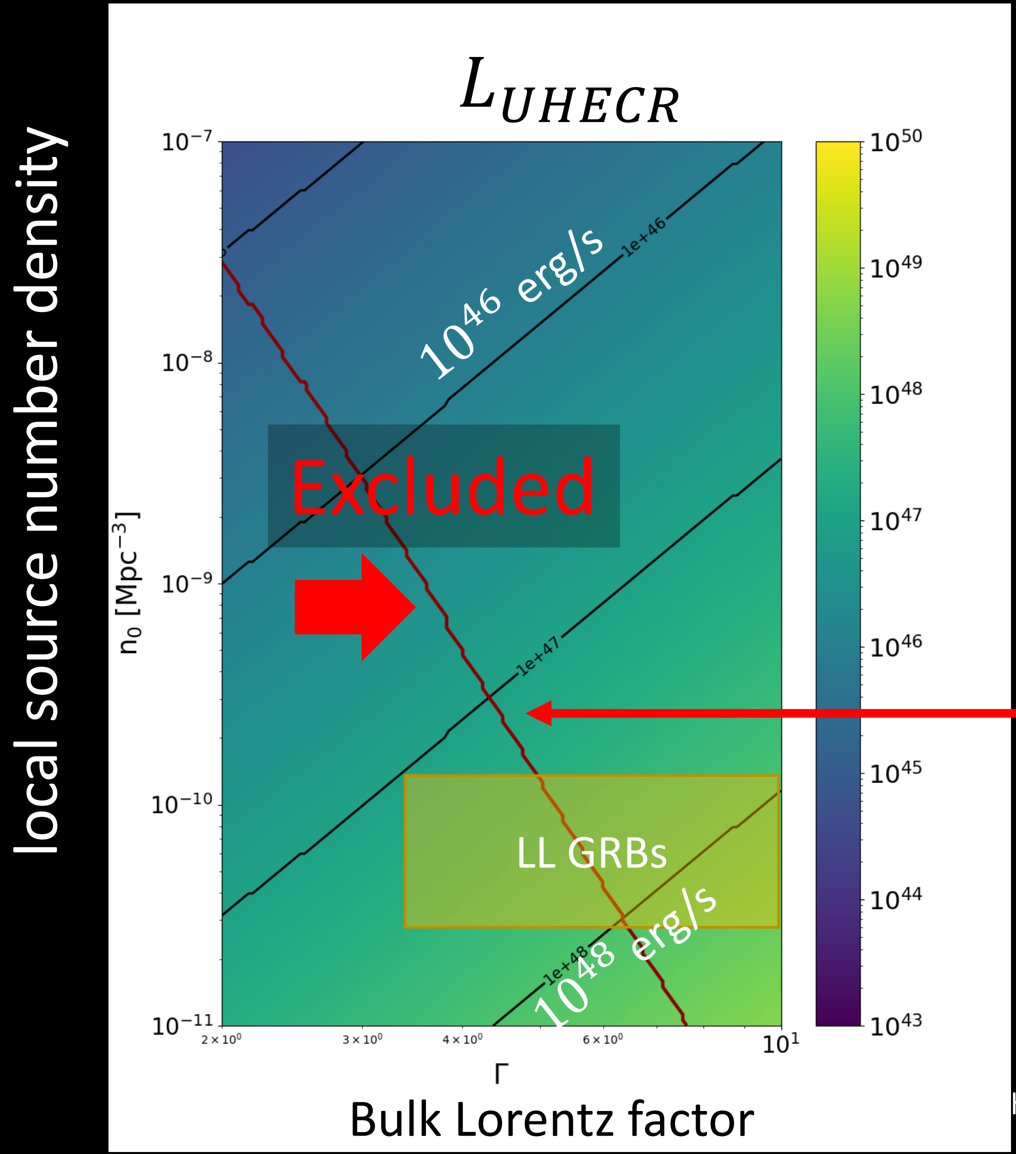
$$L_X \lesssim 6\times10^{46}\left(\frac{n_0}{5\times10^{-9}\mathrm{Mpc}^{-3}}\right)^{-2/3}$$

[erg/s]

We have determined $\xi_{CR}^{LL}(n_0, \Gamma)$

The Excluded parameter space for UHECR sources

determined by **UHECR energetics**



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

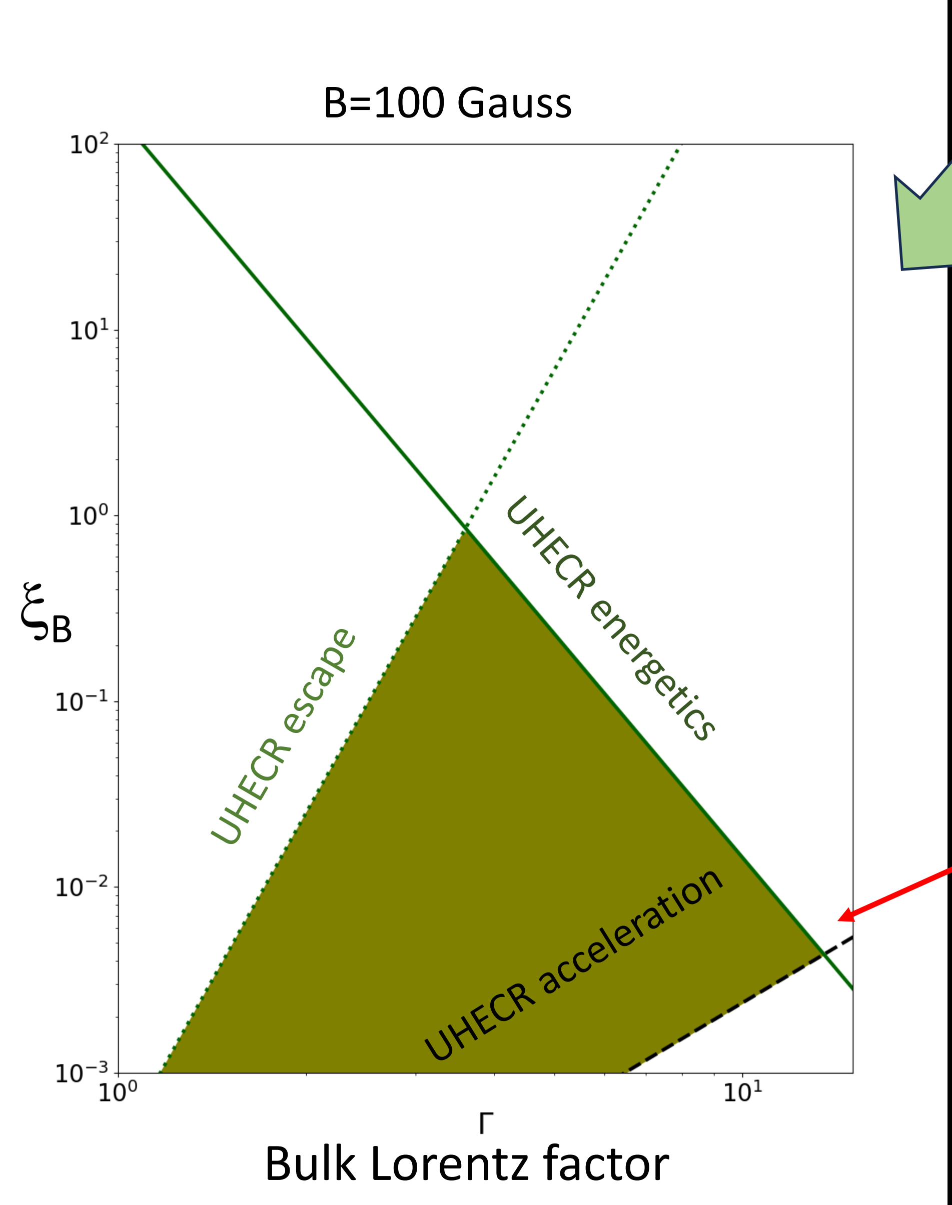
$$n_0\, L_{UHECR} \lesssim Q_{UHECR}$$
$$\lesssim 9 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$
$$\varepsilon_{CR} \geq 10\ PeV$$

Otherwise these sources would overproduce UHECRs!

The line of Q_{UHECR}

Based upon Yoshida & Murase PRD (2024)

Constraints on B, ξ_B, and Γ



$$L_X \lesssim 6 \times 10^{46} \left(\frac{n_0}{5\times10^{-9}Mpc^{-3}}\right)^{-\frac{2}{3}} \text{erg/s}$$

$$\Gamma \lesssim 13 \left(\frac{L_X}{7\times10^{47} erg/s}\right)^{\frac{1}{3}} \left(\frac{B}{100G}\right)^{\frac{1}{3}} \left(\frac{n_0}{10^{-10}\mathrm{Mpc}^{-3}}\right)^{-\frac{1}{9}}$$

Exclude sources with $\Gamma \gg 1$

Based upon [Yoshida & Murase PRD (2024)]

Summary

- Xray transients (e.g. LL GRBs) are the most promising candidate of the UHECR – neutrino unified origin

- Neutrino – Xray **multimessenger** search will measure/constrain the cosmic ray target Xray luminosity L_x [erg/s]

- The neutrino flux determines the CR loading factor (or L_{UHECR}) for the obtained/upper limit of L_x

- IceCube – MAXI is sensitive to substantially constrain the LL-GRB scenarios to account the UHE neutrino/cosmic ray sky

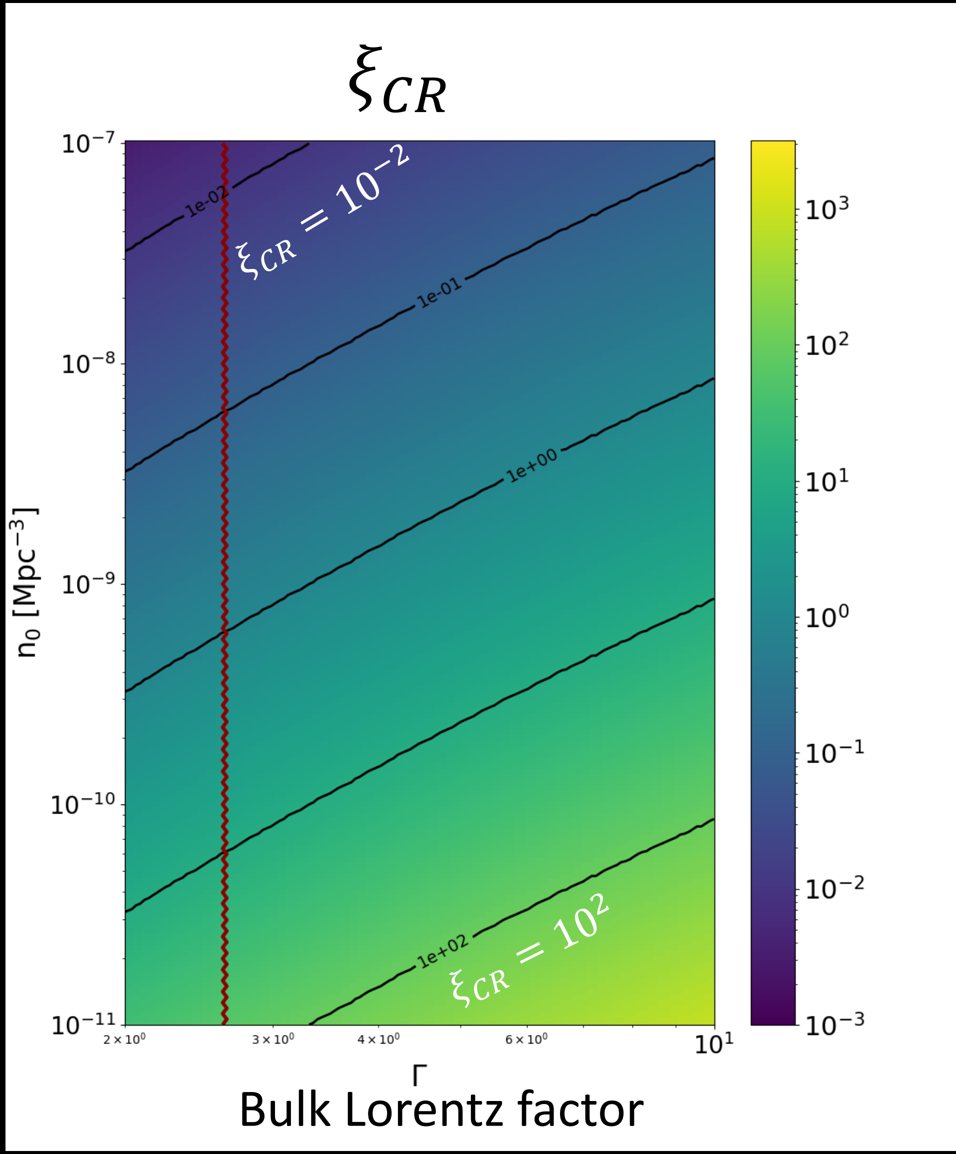
Backup

The most likely CR loading factor

favored by the cosmic background flux data

L_X = 5 x 10^{46} erg/s

local source number density



For a given n_0 [Mpc^{-3}] and Γ

$$\Phi_\upsilon^{\text{diffuse}} \propto \boxed{\xi_{CR}} \times \underbrace{L_X \times (\sqrt{L_X}, 1)}$$

We know this by the I³ diffuse data

You can determine this!

Now we know this by the stacking analysis

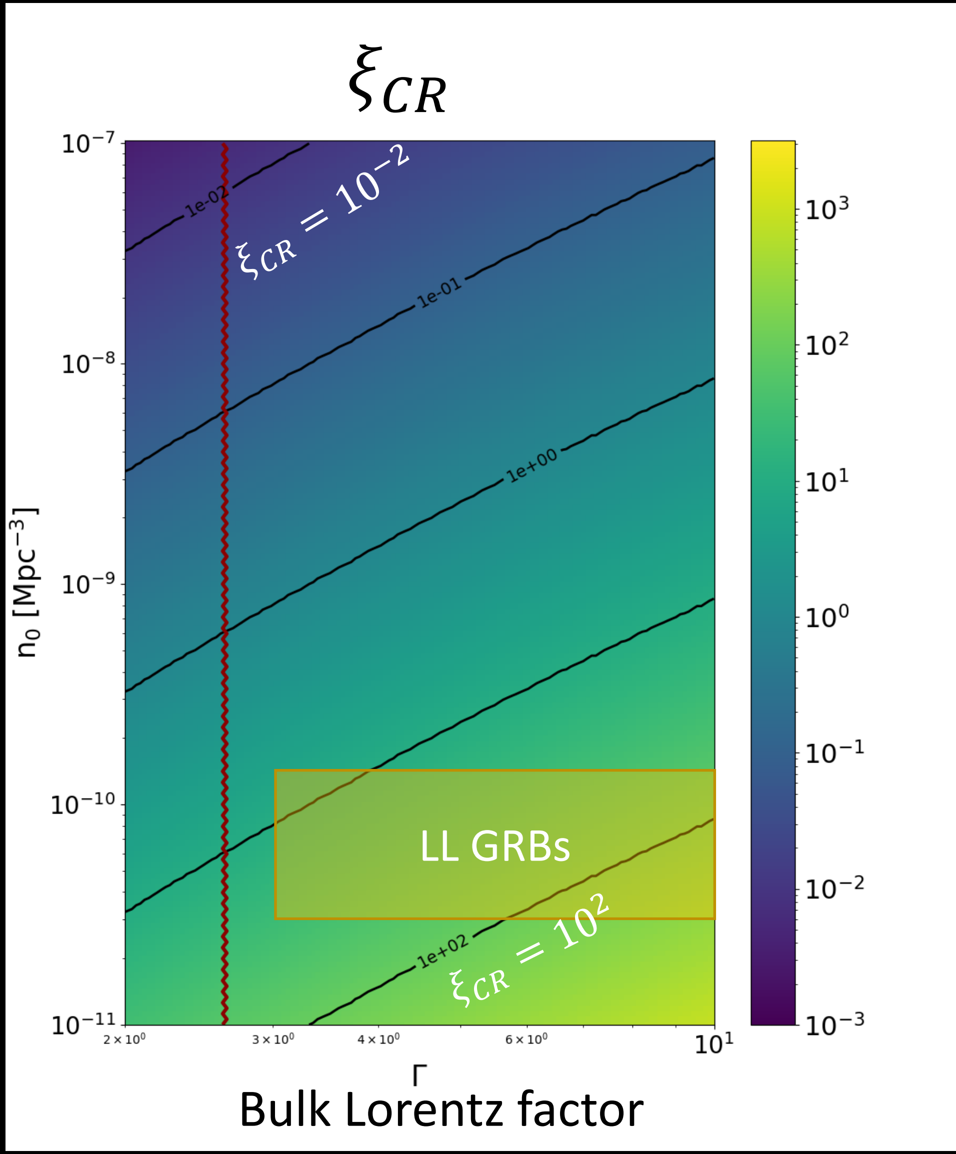
We have determined $\xi_{CR}(n_0, \Gamma)$

The most likely CR loading factor

favored by the cosmic background flux data

L_X = 5 x 10^{46} erg/s

local source number density



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You can determine this!

We know this by the I^3 diffuse data

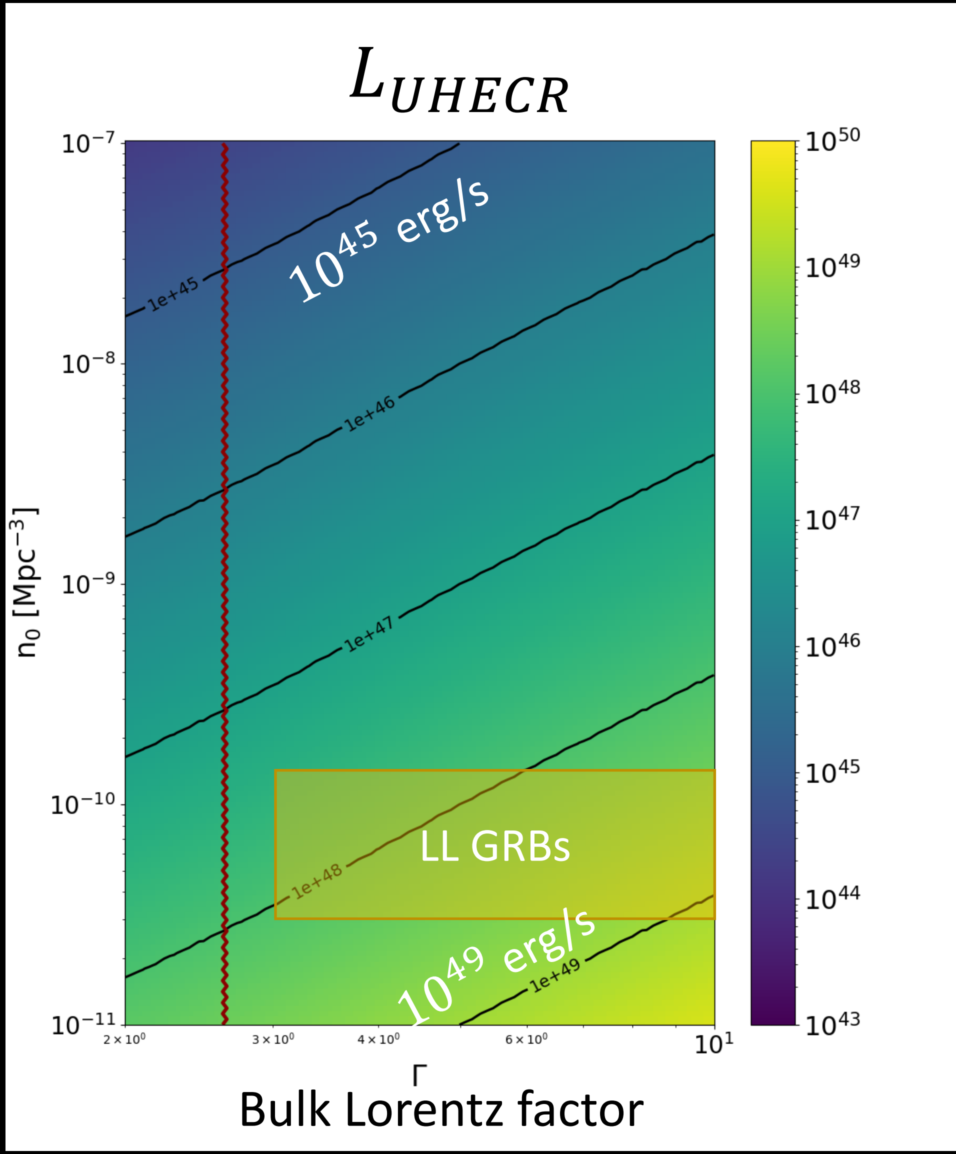
We have determined $\xi_{CR}(n_0, \Gamma)$

The most likely UHECR Luminosity

favored by the cosmic background flux data

L_X = 5 x 10^{46} erg/s

local source number density



For a given n_0 [Mpc^{-3}] and Γ

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You can determine this!

Now we know this
by the stacking analysis

We know this
by the I^3 diffuse data

We have determined

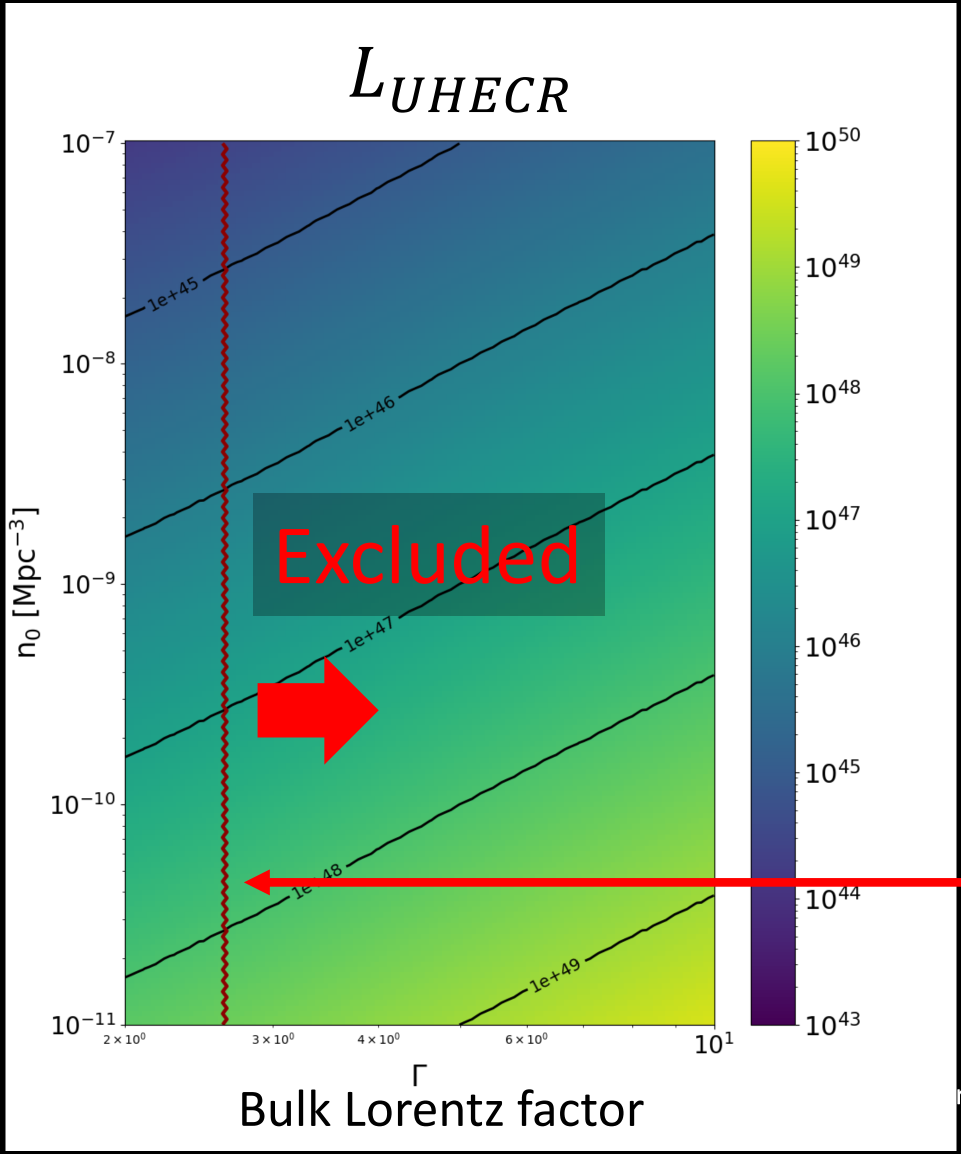
$$L_{UHECR}^{\varepsilon_{CR} \geq 10\ PeV}(n_0, \Gamma) = \xi_{CR} \times L_X$$

The Excluded parameter space for UHECR sources

determined by **UHECR energetics**

L_X = 5 x 10^{46} erg/s

local source number density



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Otherwise these sources would overproduce UHECRs!

The line of Q_{UHECR}

Yoshida & Murase PRD (2024)

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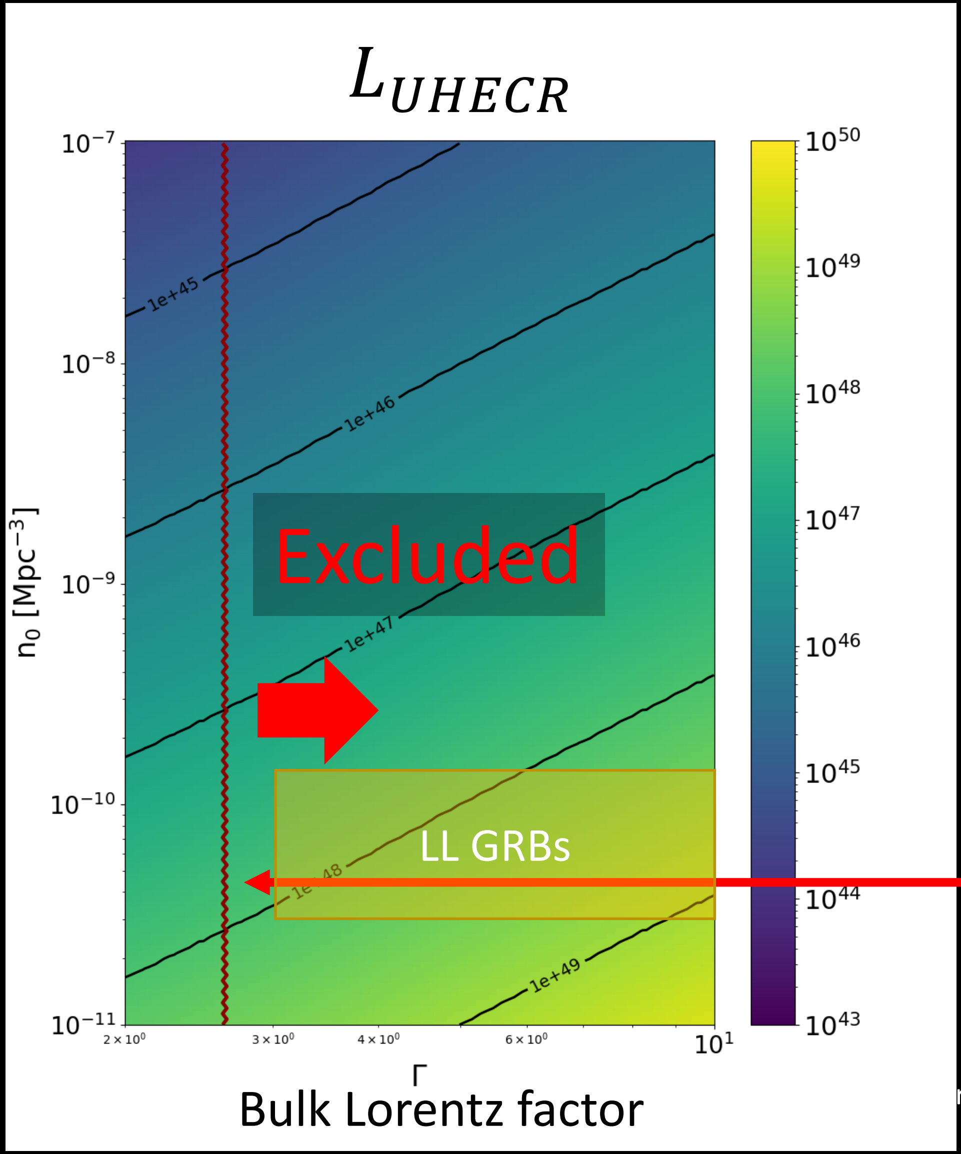

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The line of Q_{UHECR}

Yoshida & Murase PRD (2024)

Needs to search for X-ray counterparts many times!

Then you encounter neayby emitters