Probing a unified model for the origin of UHECRs and neutrinos with X-ray observations

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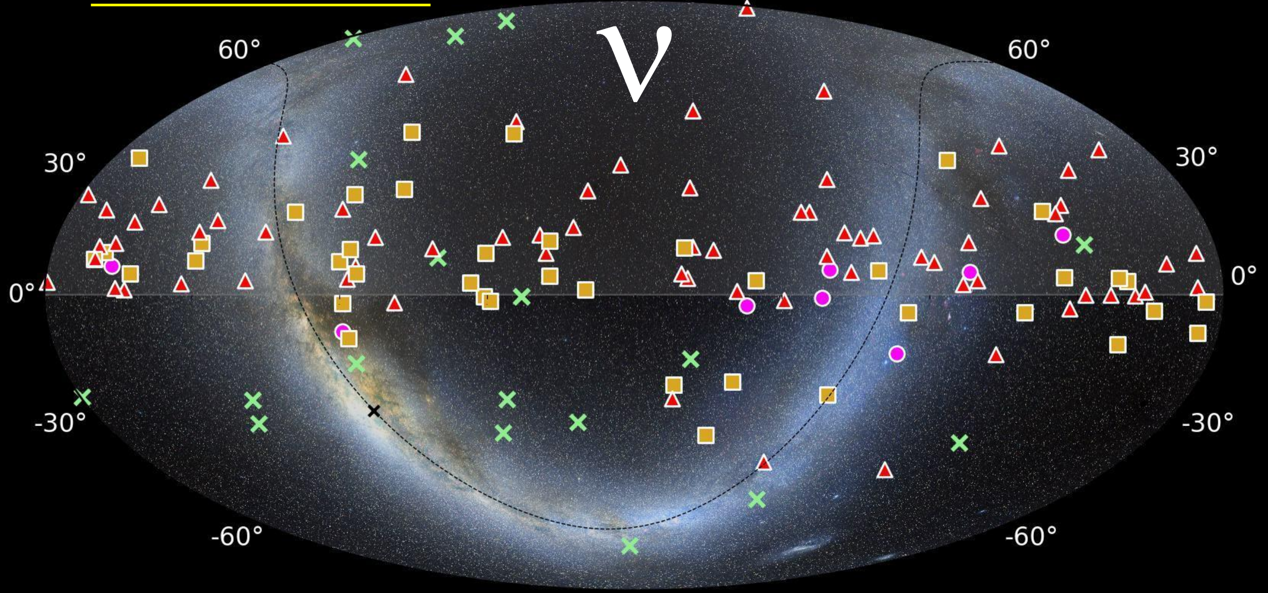
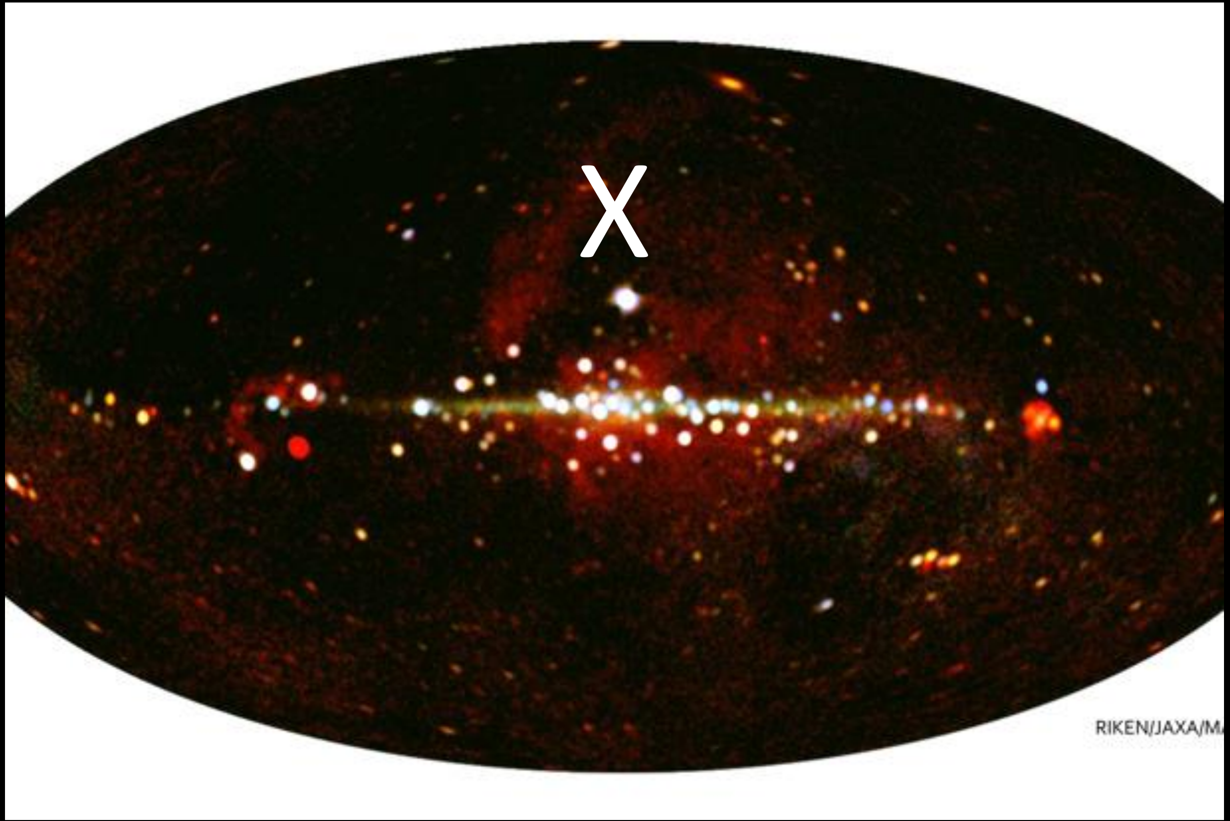
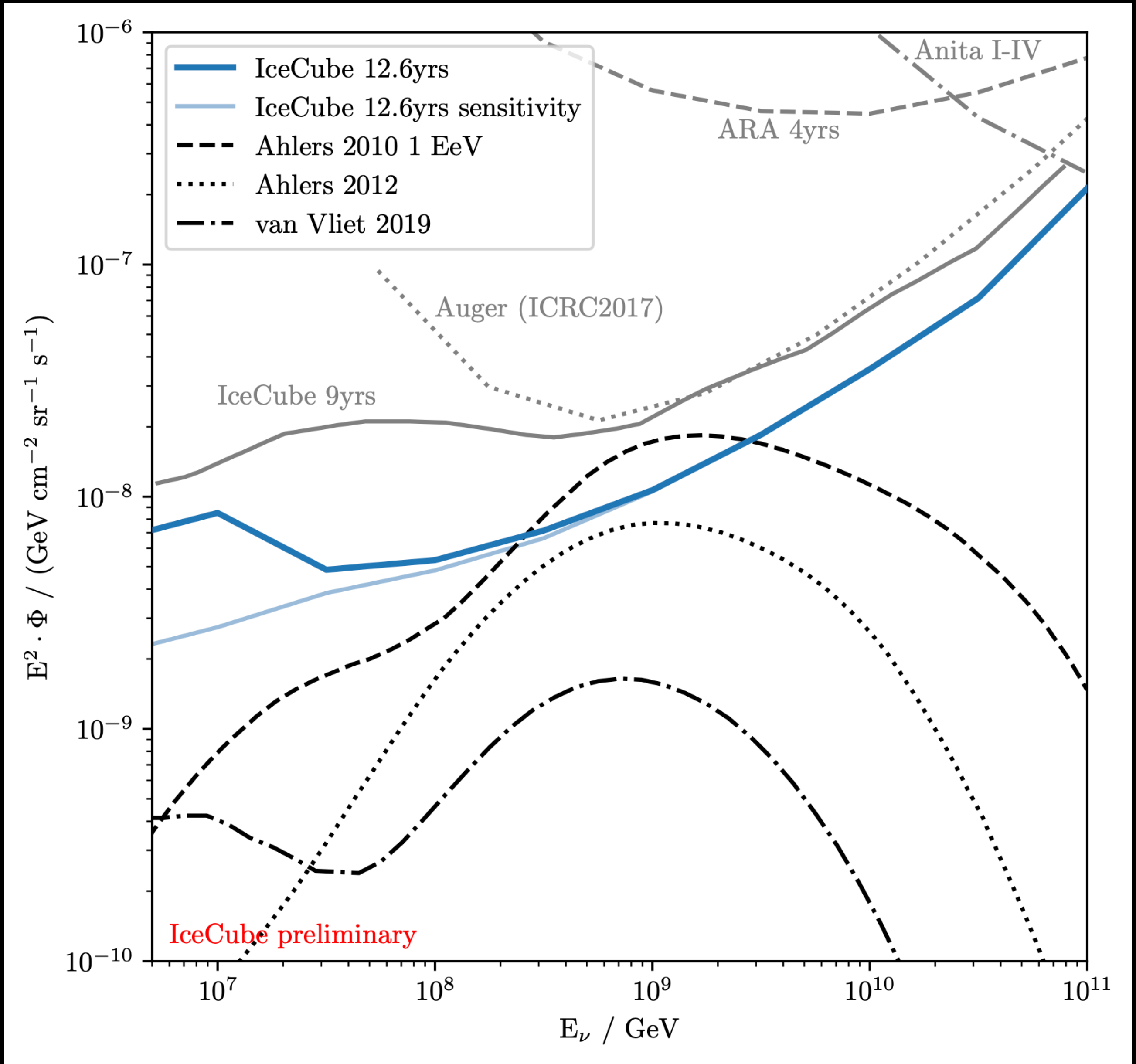
For detalis
Yoshida and Murase
arXiv 2406.10944





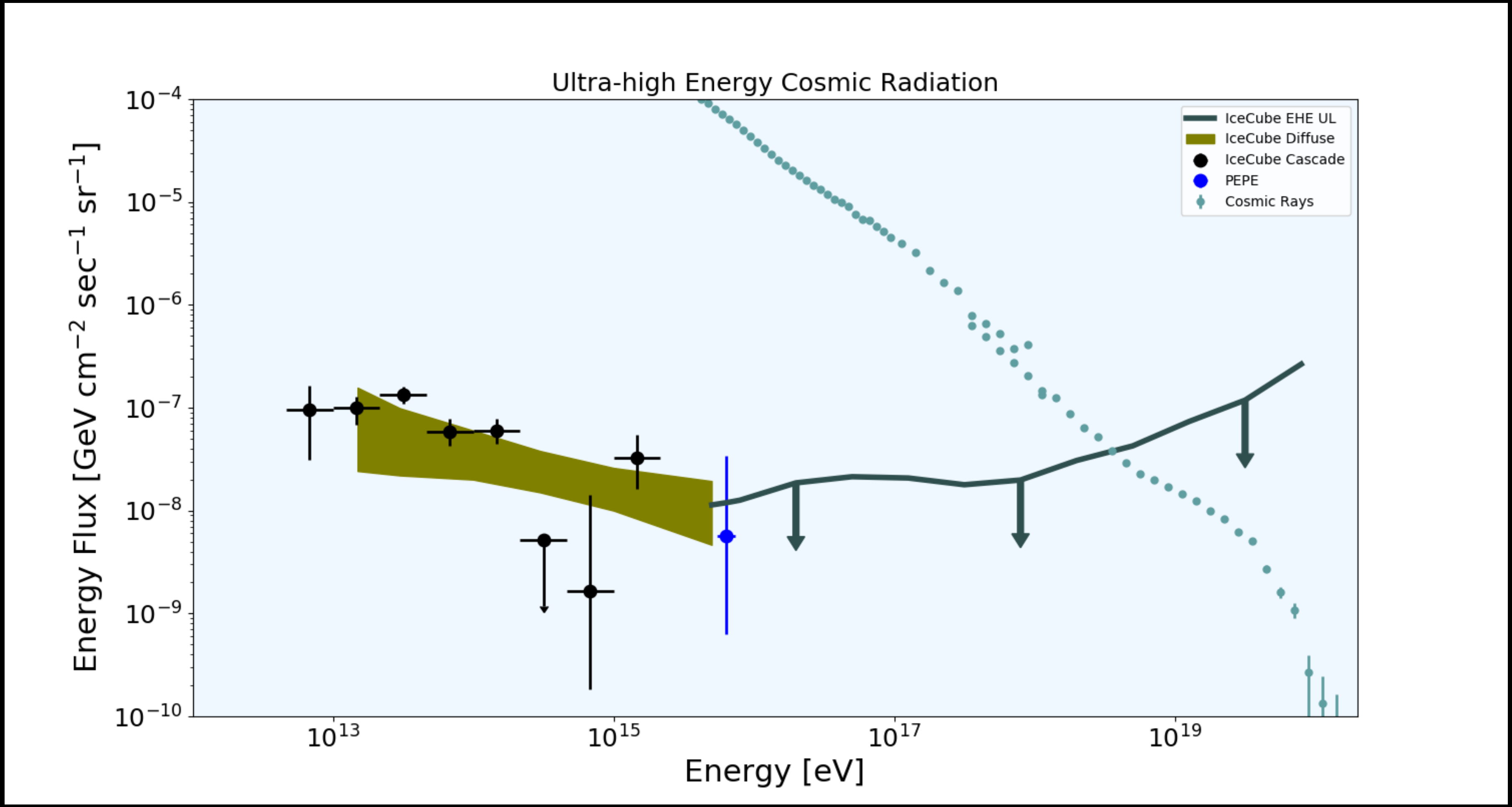
Before start…..

The updated limit of neutrino flux in PeV-EeV range with IceCube



The UHE Cosmic Background Radiations

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



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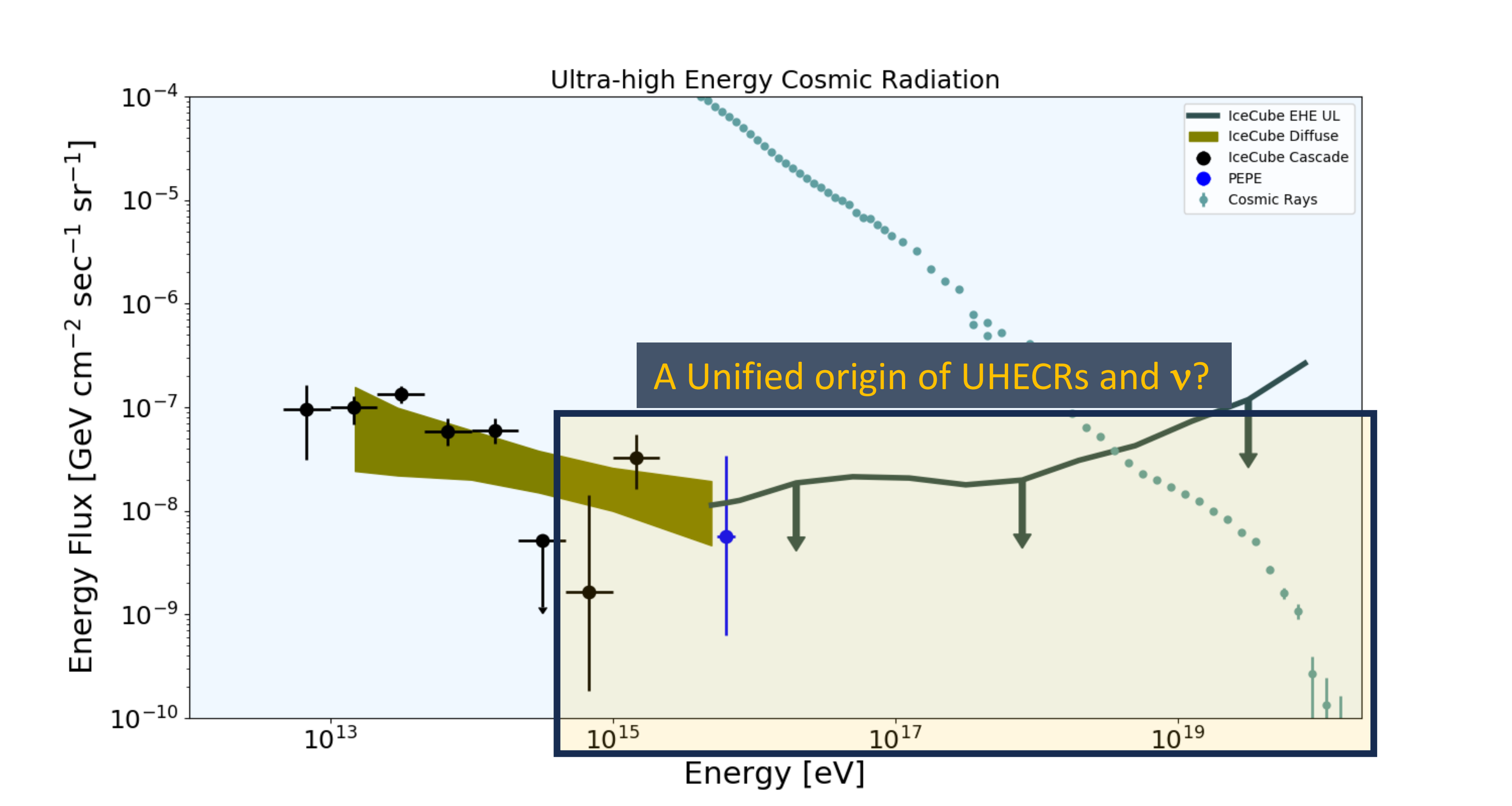

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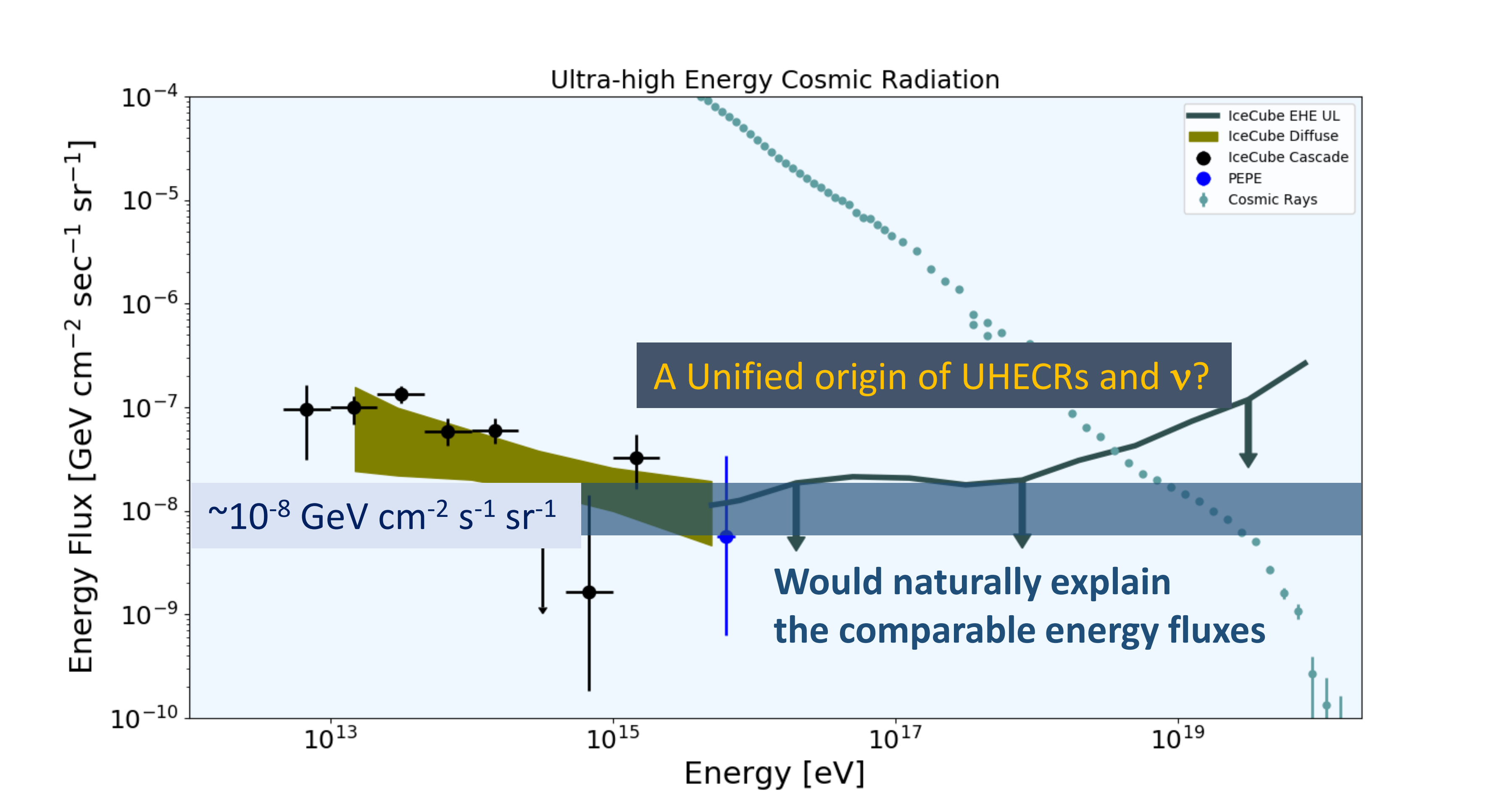


Are they UHECR and PeV ν sources?

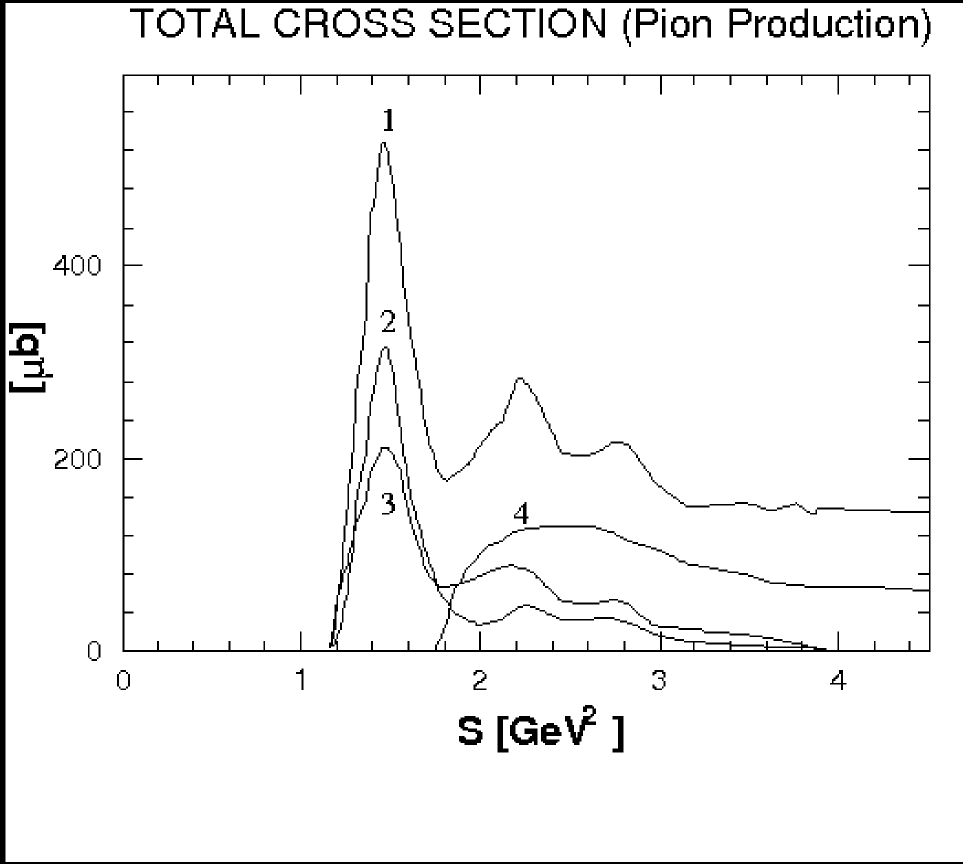
The scorebook of individual transient astronomical object classes

	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 2020
Yoshida & Murase 2024

Side Note: This is a one-zone model

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

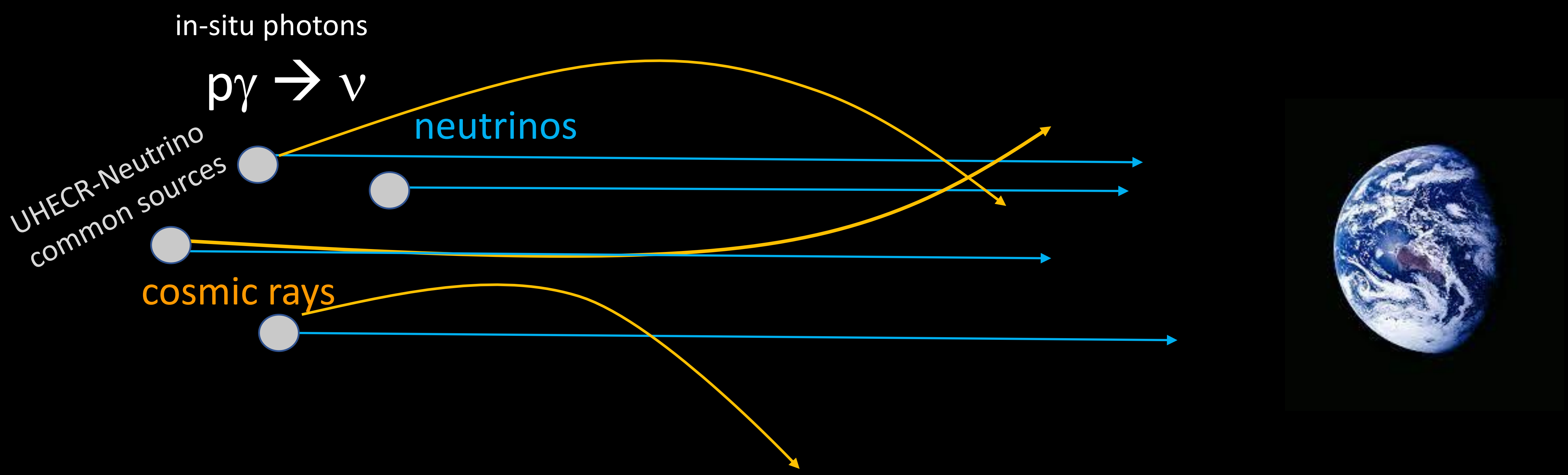


$$\varepsilon'_{\gamma 0} \approx \frac{(s_\Delta - m_p^2)}{4} \frac{\Gamma}{\varepsilon_{p0}}.$$

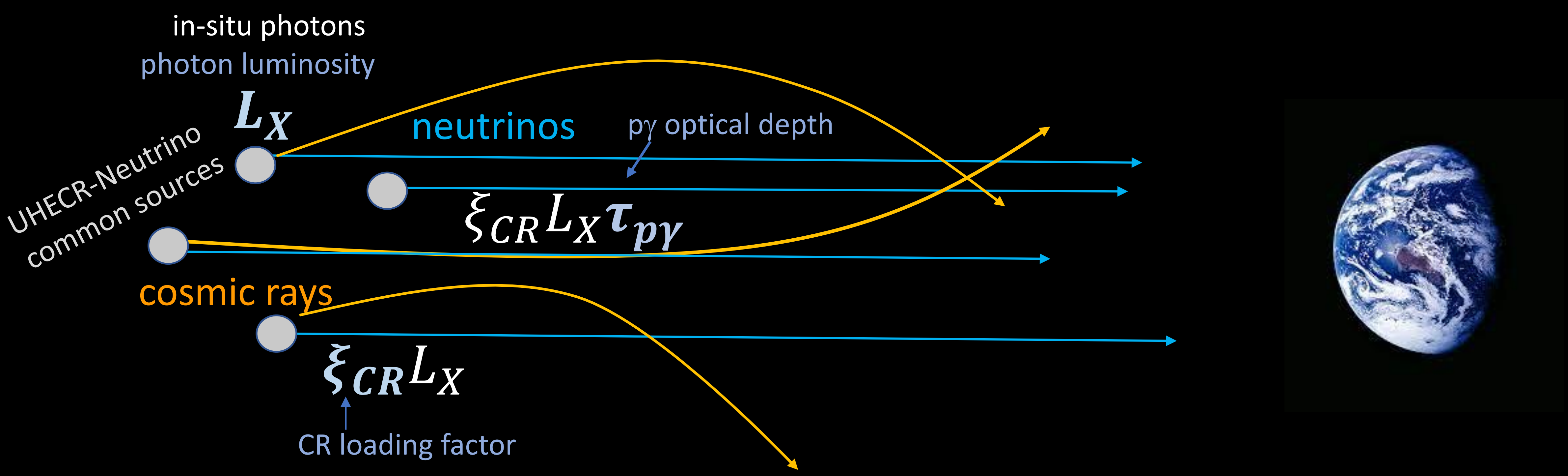
$$\varepsilon_X = 15 \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\varepsilon_p}{1PeV}\right)^{-1} \text{keV}$$

Γ Lorentz factor of (jet) plasma

The generic neutrino source scheme via photo-hadronic framework



The 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**

Here is the issue – the *degeneracy*

Neutrino flux

based upon Yoshida & Murase PRD (2020)

$$\propto \boxed{\xi_{CR}} \times B \times L_X \times (\sqrt{L_X}, 1) \times f(\Gamma)$$

We want to know this

MW observation/ theory could tell

This could be any value!
We need to determine/constrain this

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This could be any value!
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Search for X-ray signals associated with neutrino events!

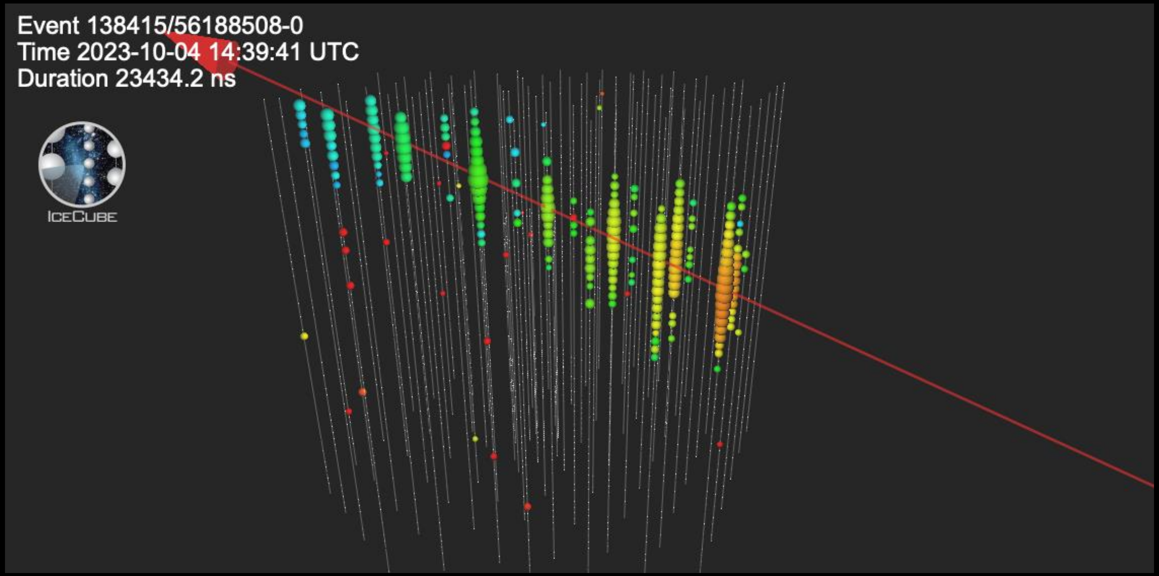
Neutrino and X-ray stacking search

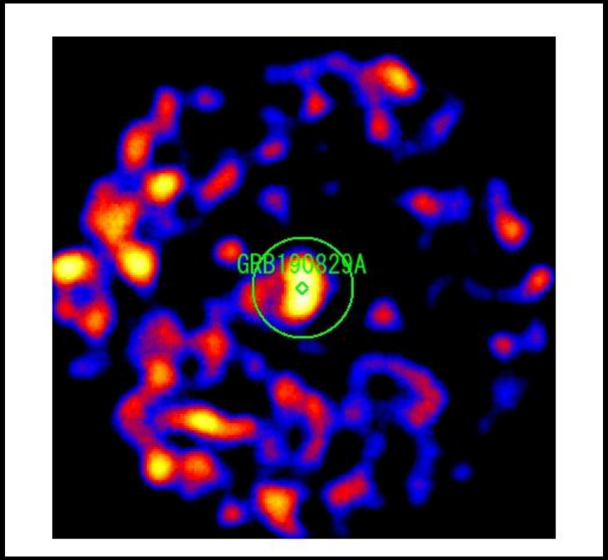
ν

X

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

A neutrino event





2keV-10keV

Neutrino and X-ray stacking search

ν

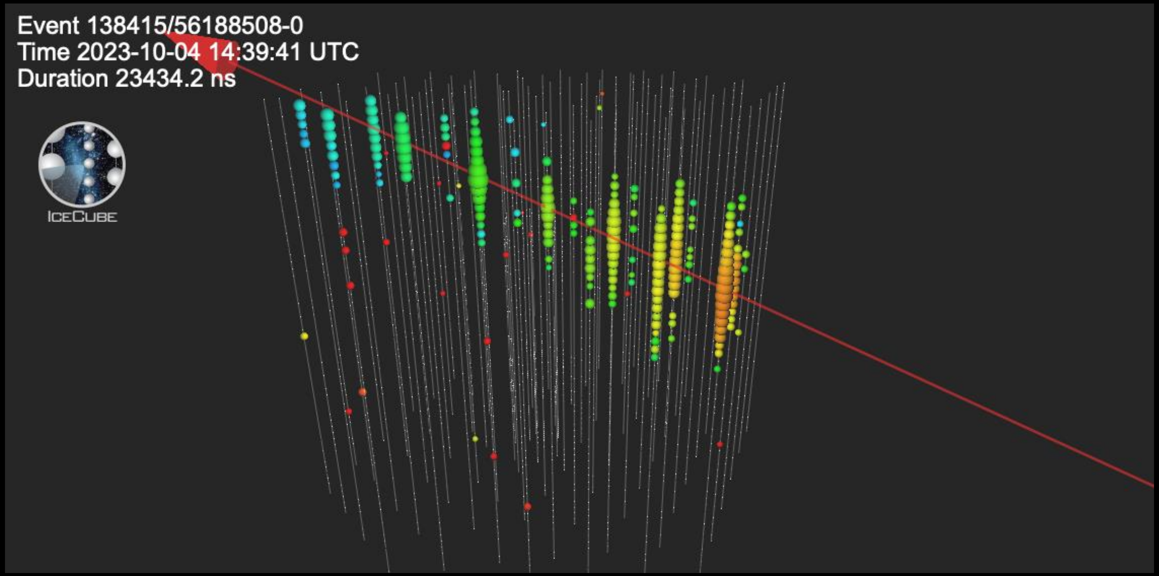
X

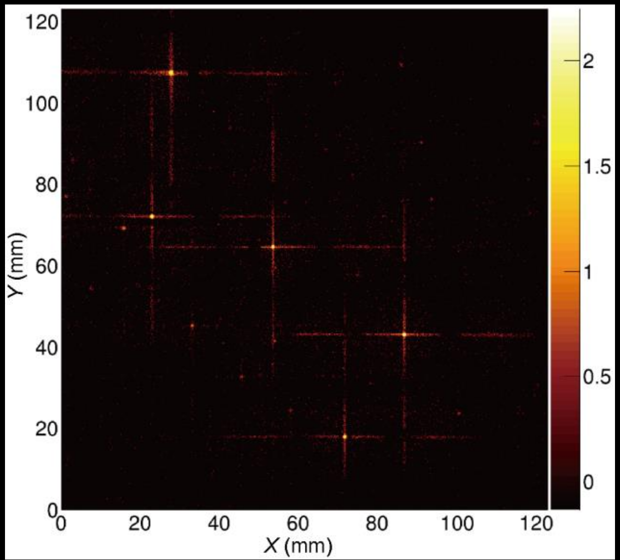
the both facilities monitor all-sky

ICECUBE

爱因斯坦探针
einstein probe

A neutrino event



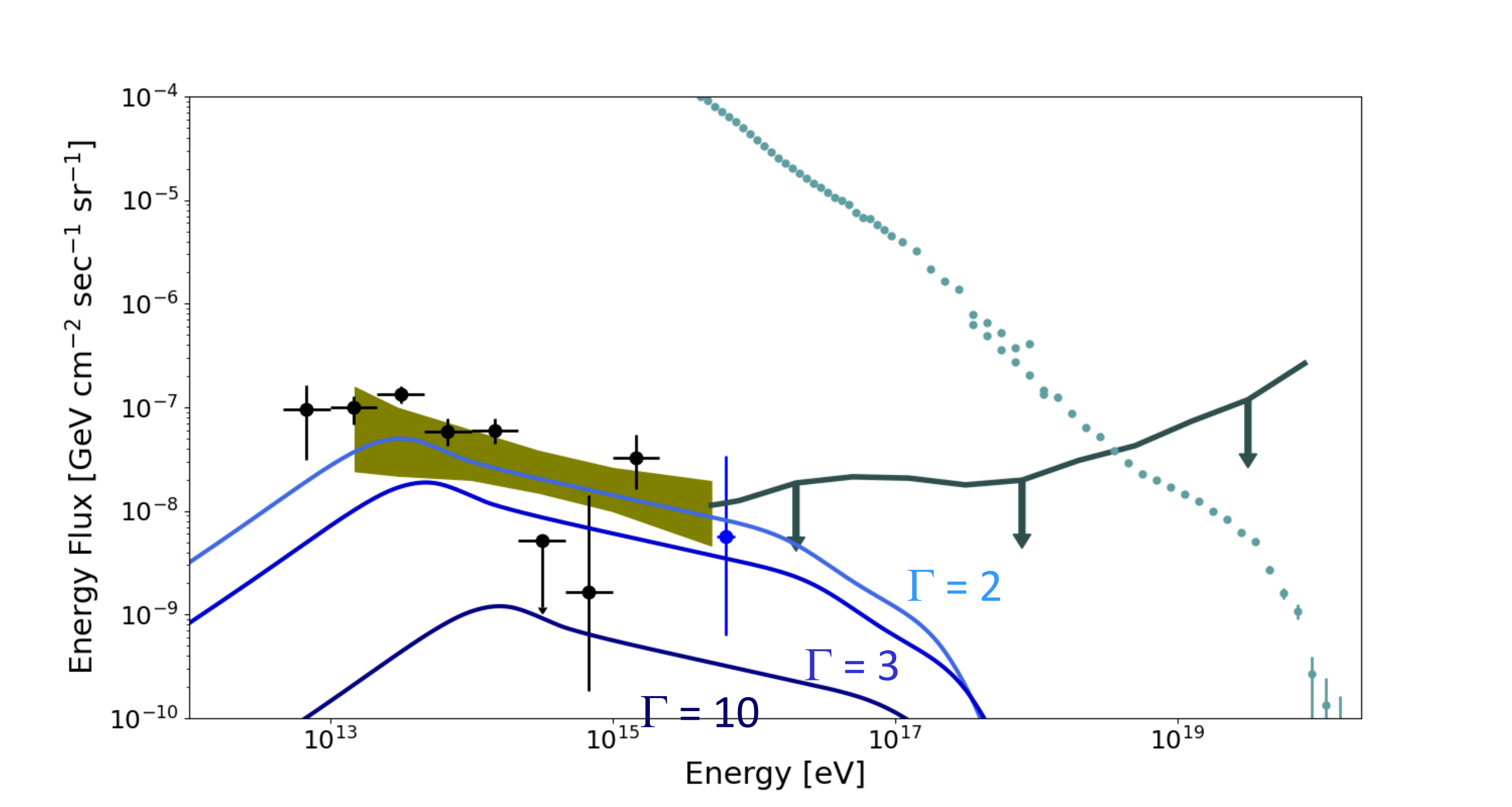


0.5keV-4keV

The UHE Cosmic Background Radiations

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

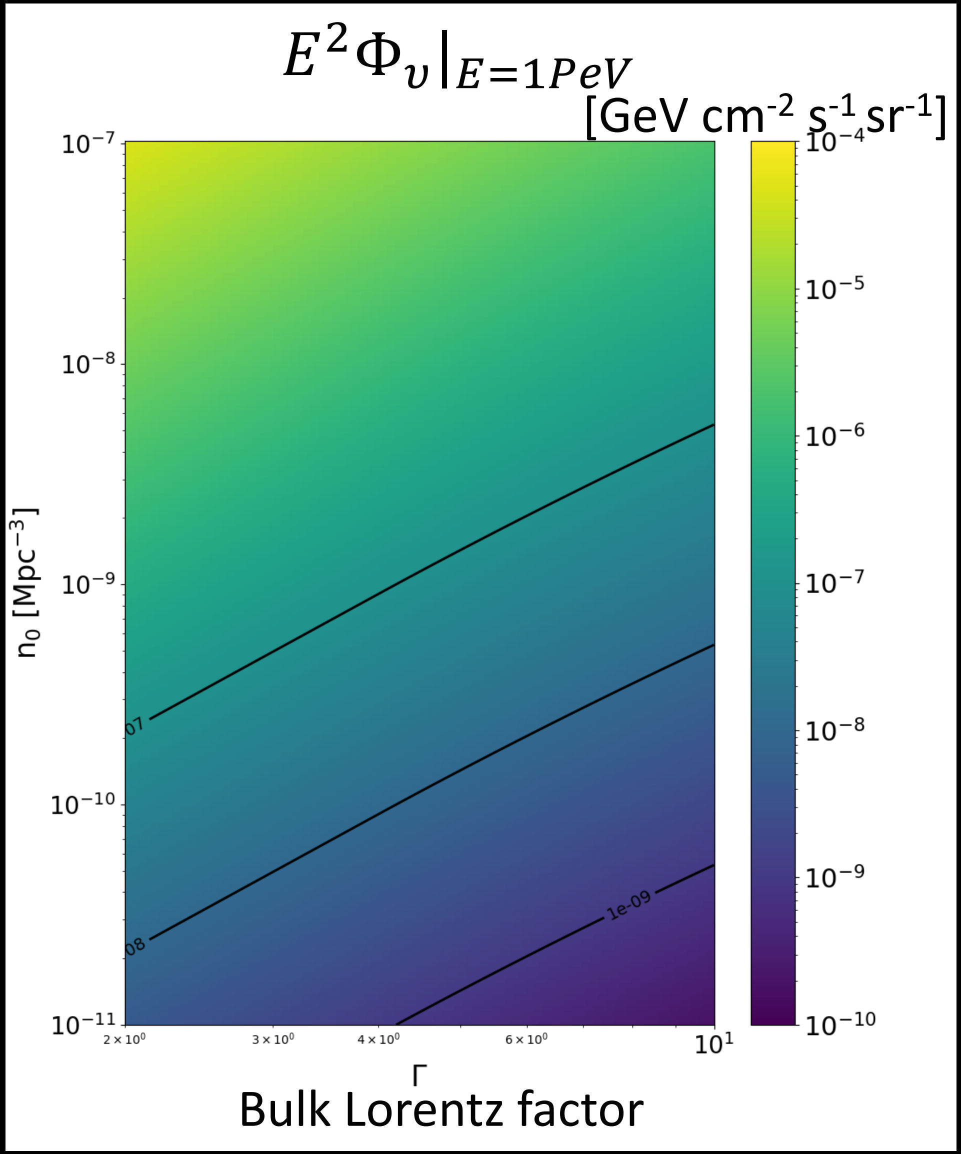
The expected neutrino diffuse flux



The parameter dependence of the diffuse flux

ξ_{CR}=10

local source number density



For a given n_0 [Mpc^{-3}] and Γ

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

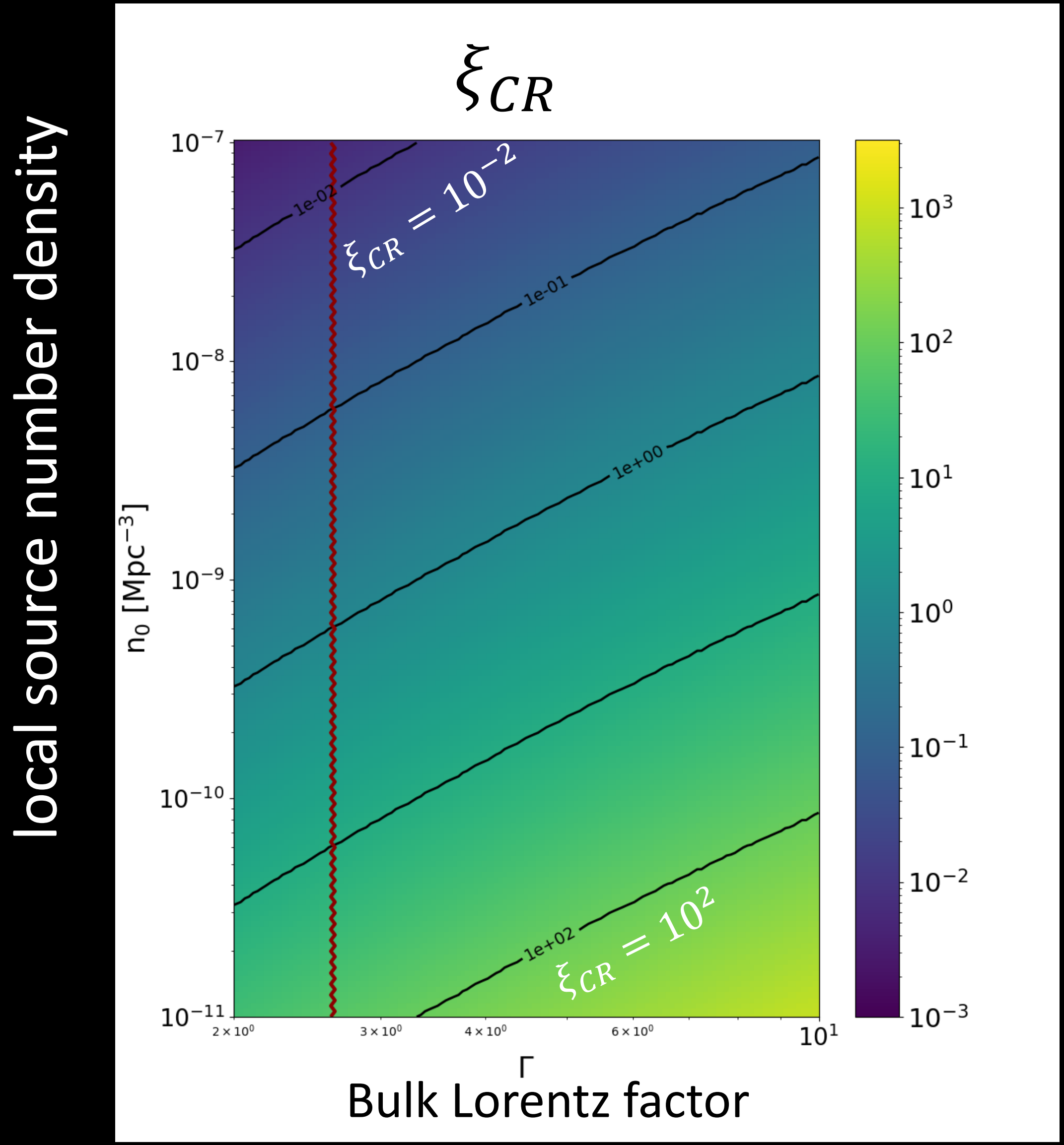
We know this by the I[3] diffuse data

You can determine this!

Now we know this by the stacking analysis

The most likely CR loading factor

favored by the diffuse flux data



For a given n_0 [Mpc^{-3}] and Γ

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

We know this by the I^3 diffuse data

You can determine this!

Now we know this by the stacking analysis

example

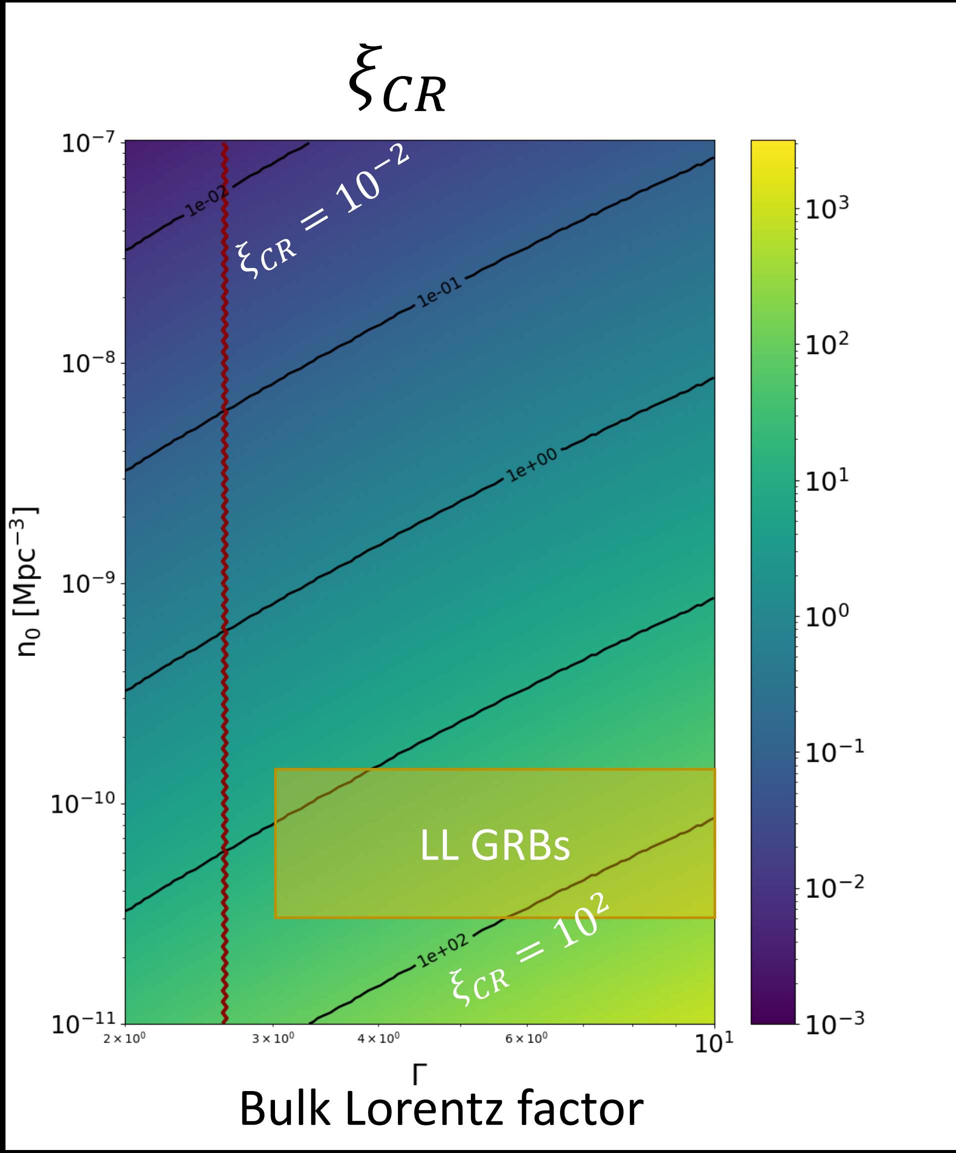
L_X = 5 x 10^{46} erg/s

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

The most likely CR loading factor

favored by the diffuse flux data

local source number density



For a given n_0 [Mpc^{-3}] and Γ

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

We know this by the I³ diffuse data

You can determine this!

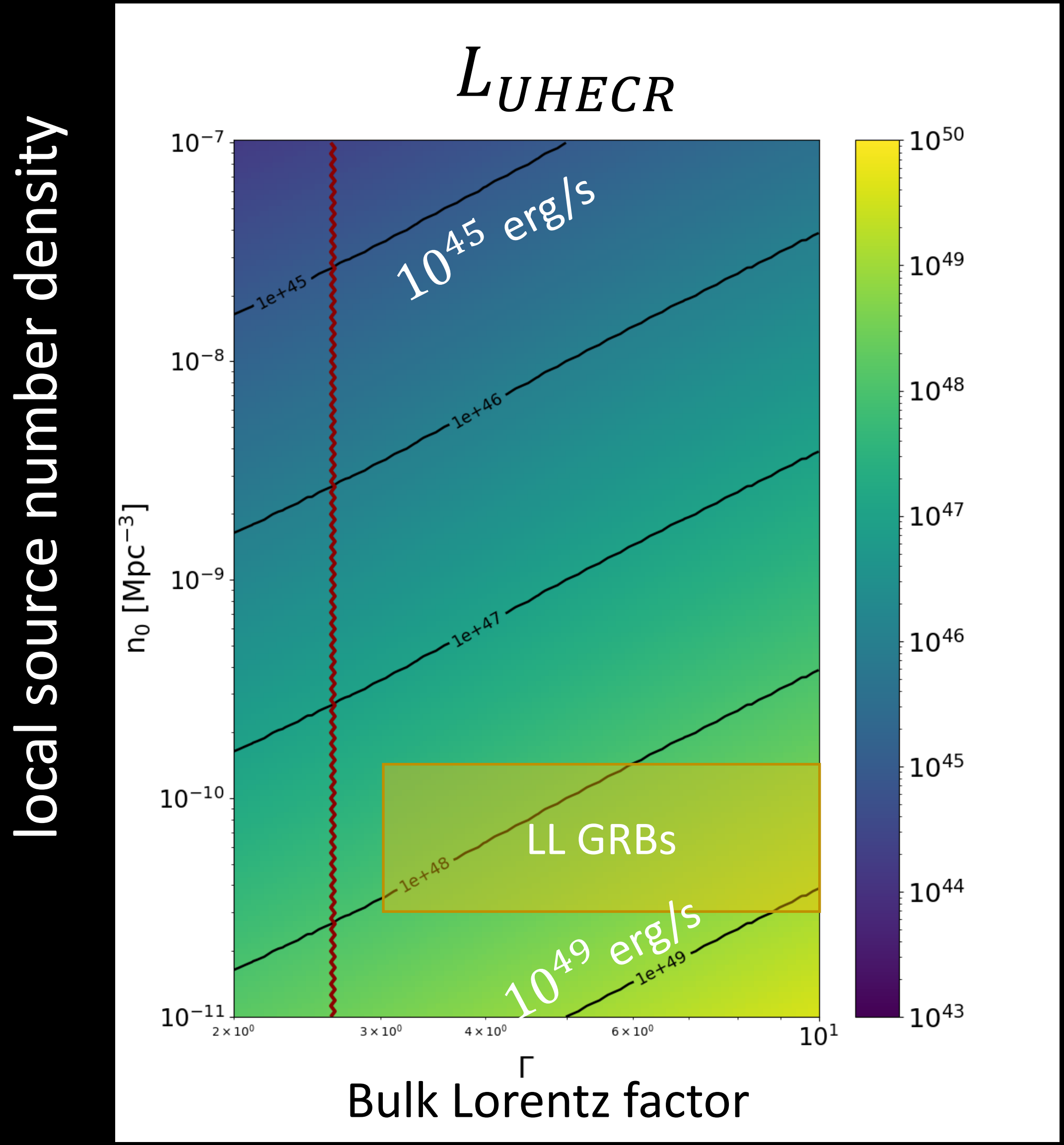
Now we know this by the stacking analysis

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

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

The most likely UHECR Luminosity

favored by the diffuse flux data



For a given n_0 [Mpc^{-3}] and Γ

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

We know this by the I^3 diffuse data

You can determine this!

Now we know this by the stacking analysis

example

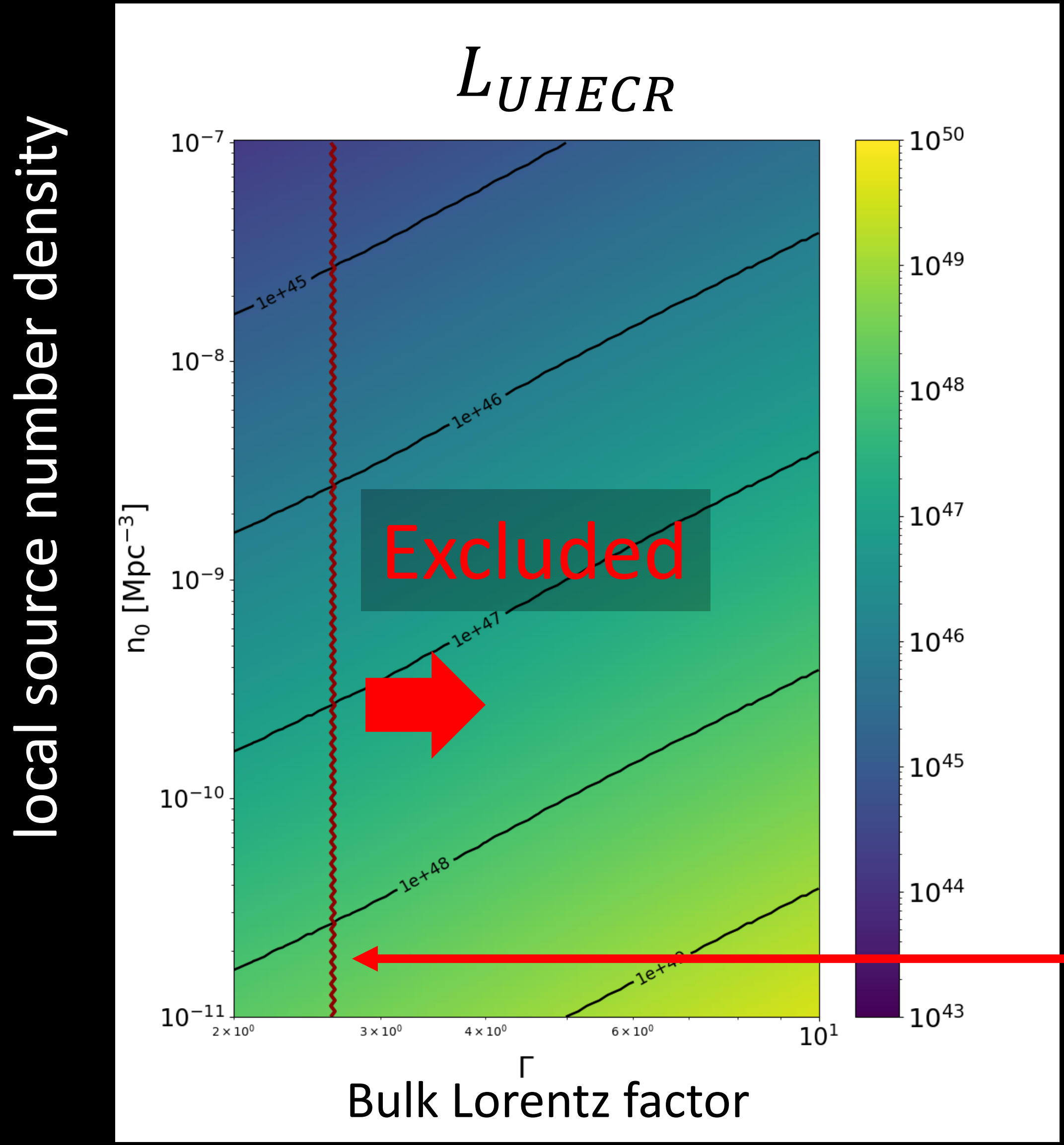
L_X = 5 x 10^{46} erg/s

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



$$n_0 \xi_{CR} L_X \lesssim Q_{UHECR}$$

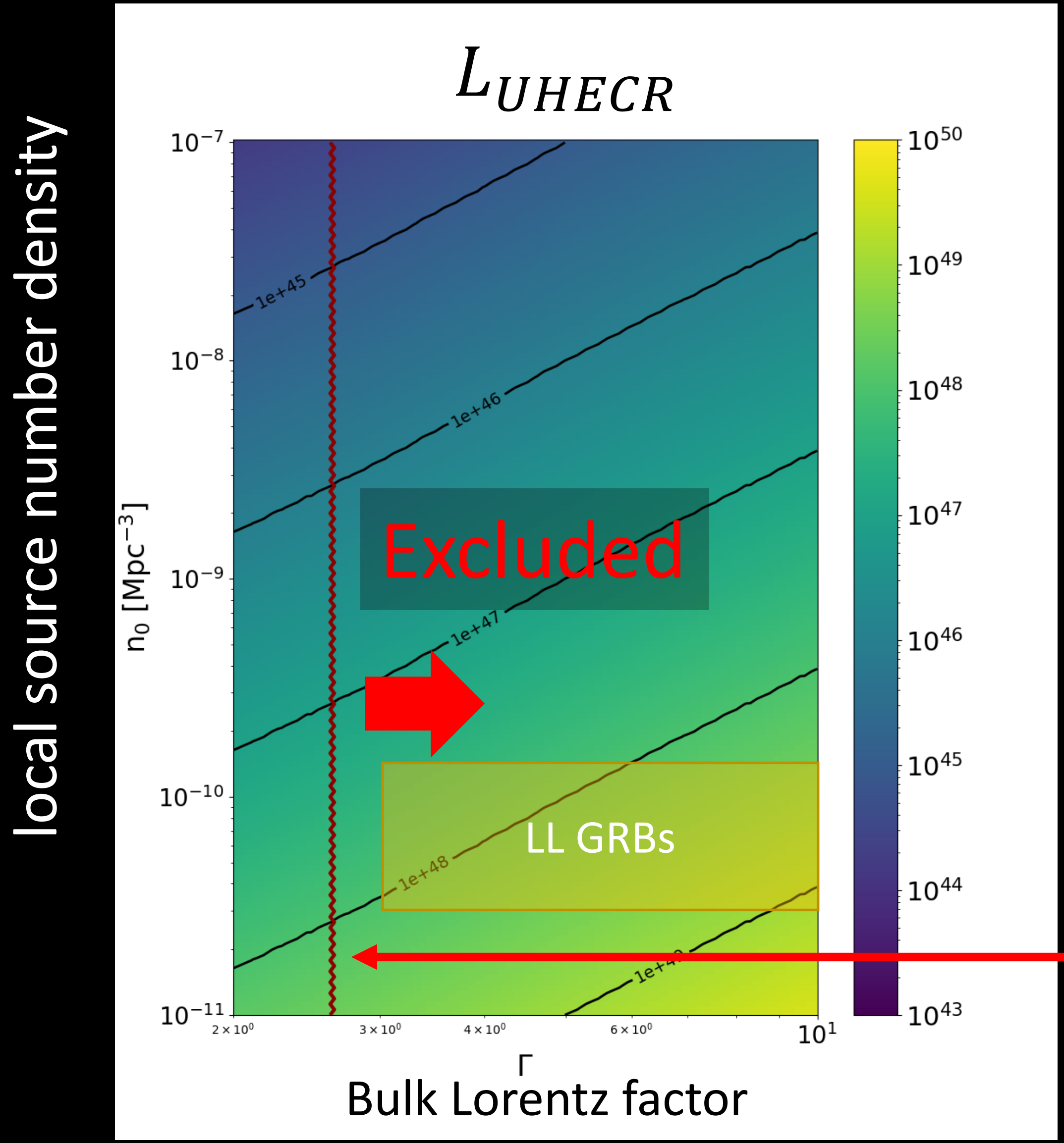
$$\lesssim 9 \times 10^{44} \text{ erg Mpc}^{-3}\text{ yr}^{-1}$$

$$\varepsilon_{CR} \geq 10\ PeV$$

Otherwise these sources would overproduce UHECRs!

The line of Q_{UHECR}

The Excluded parameter space for UHECR sources
determined by UHECR energetics



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The line of Q_{UHECR}

What can we do if we see nothing in X-rays?

Neutrino and X-ray stacking search

X

A conservative scenario

The sub-threshold detection sensitivity by MAXI

2×10^{-10} erg cm^{-2} s^{-1}

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

$$L_X \lesssim 3 \times 10^{45} \left(\frac{n_0}{5.2\times10^{-9} Mpc^{-3}}\right)^{-\frac{2}{3}} \text{erg/s}$$

density of GRB190829A-like sources

ν

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

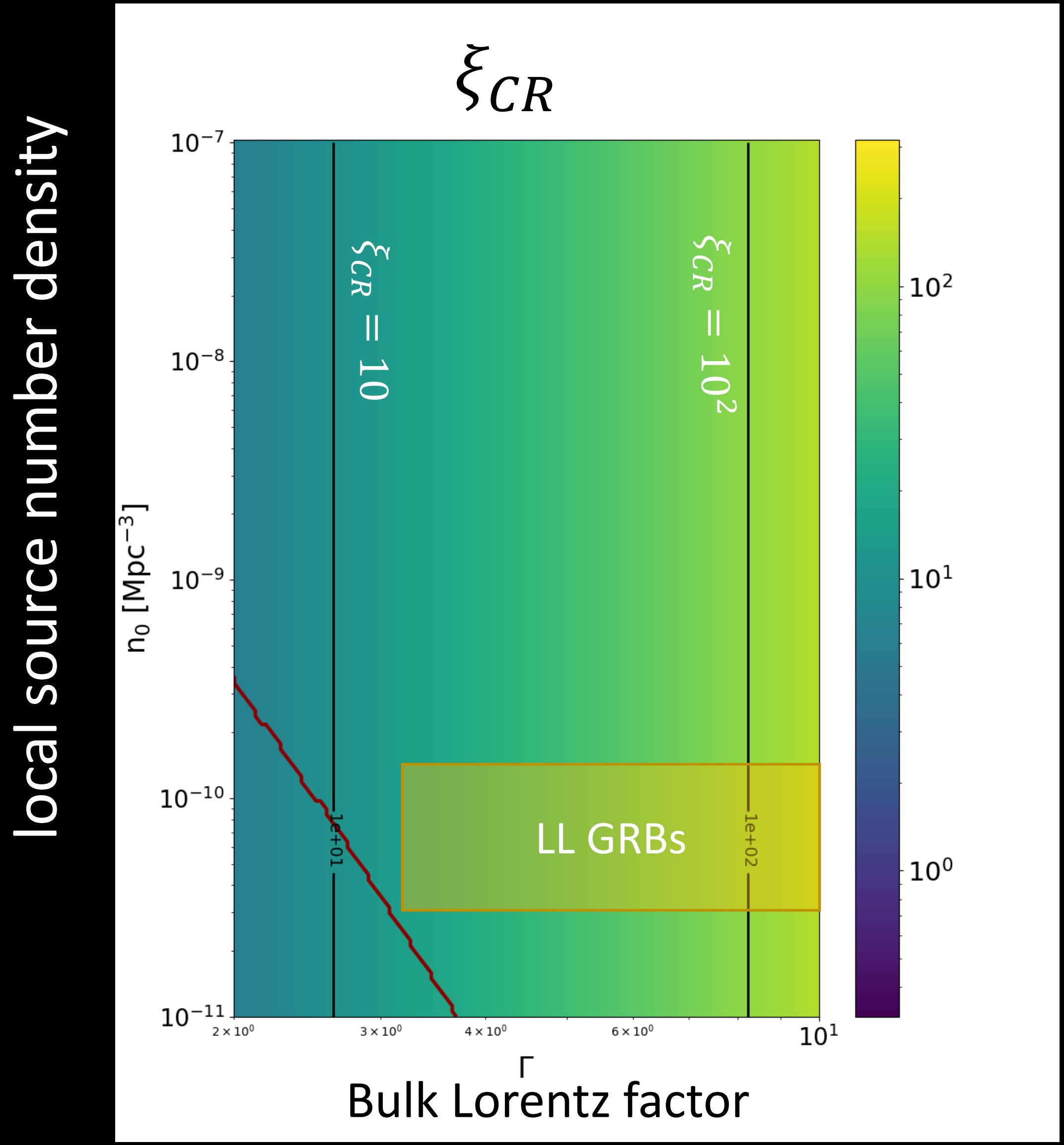
We know this

Yes,now we get Lower Bound!

Now This is the **Upper Limit**

The lower bound of CR loading factor

favored by the diffuse flux data



For a given n_0 [Mpc^{-3}] and Γ

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

We know this by the I³ diffuse data

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

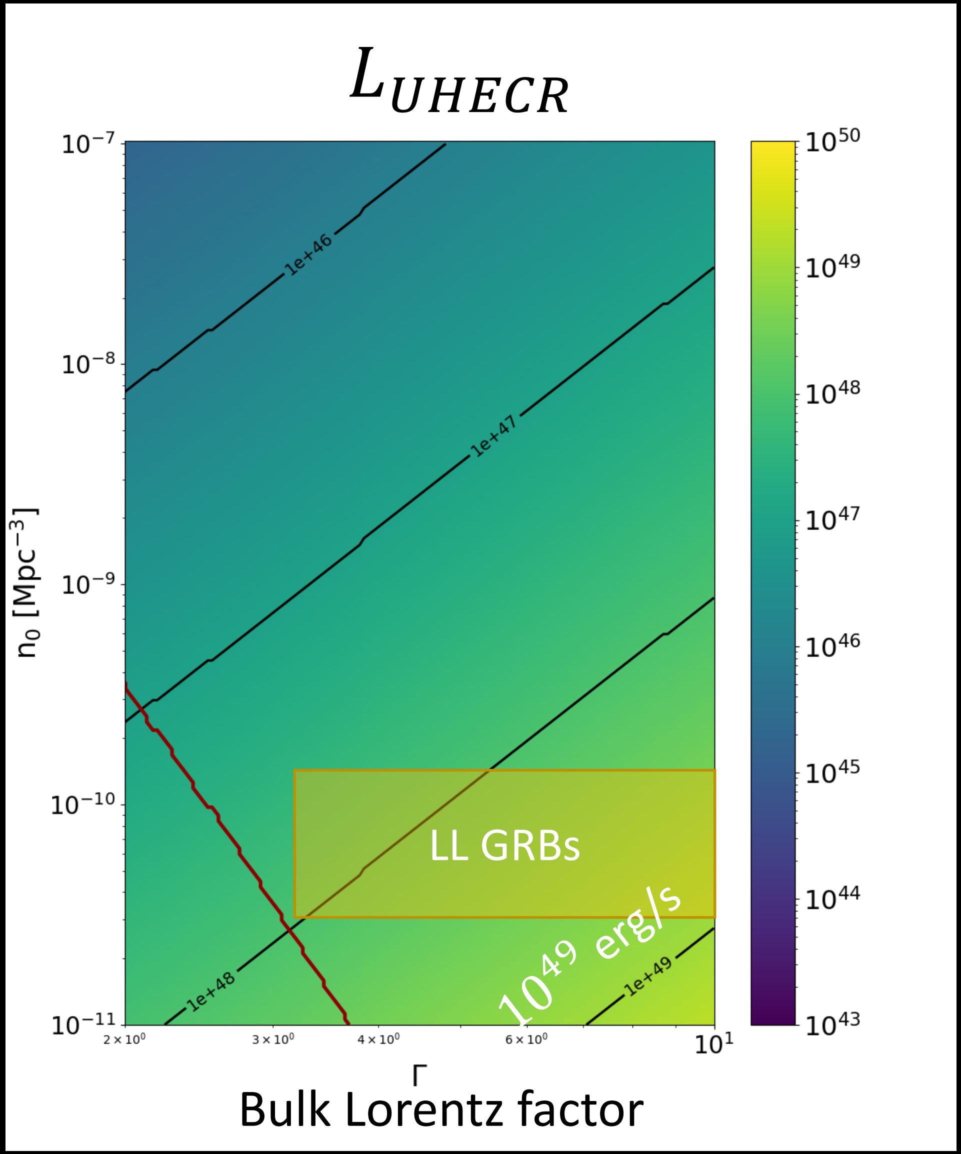
The upper limit is placed by the stacking analysis

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

The lower bound of UHECR luminosity

favored by the diffuse flux data

local source number density



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We know this by the I^3 diffuse data

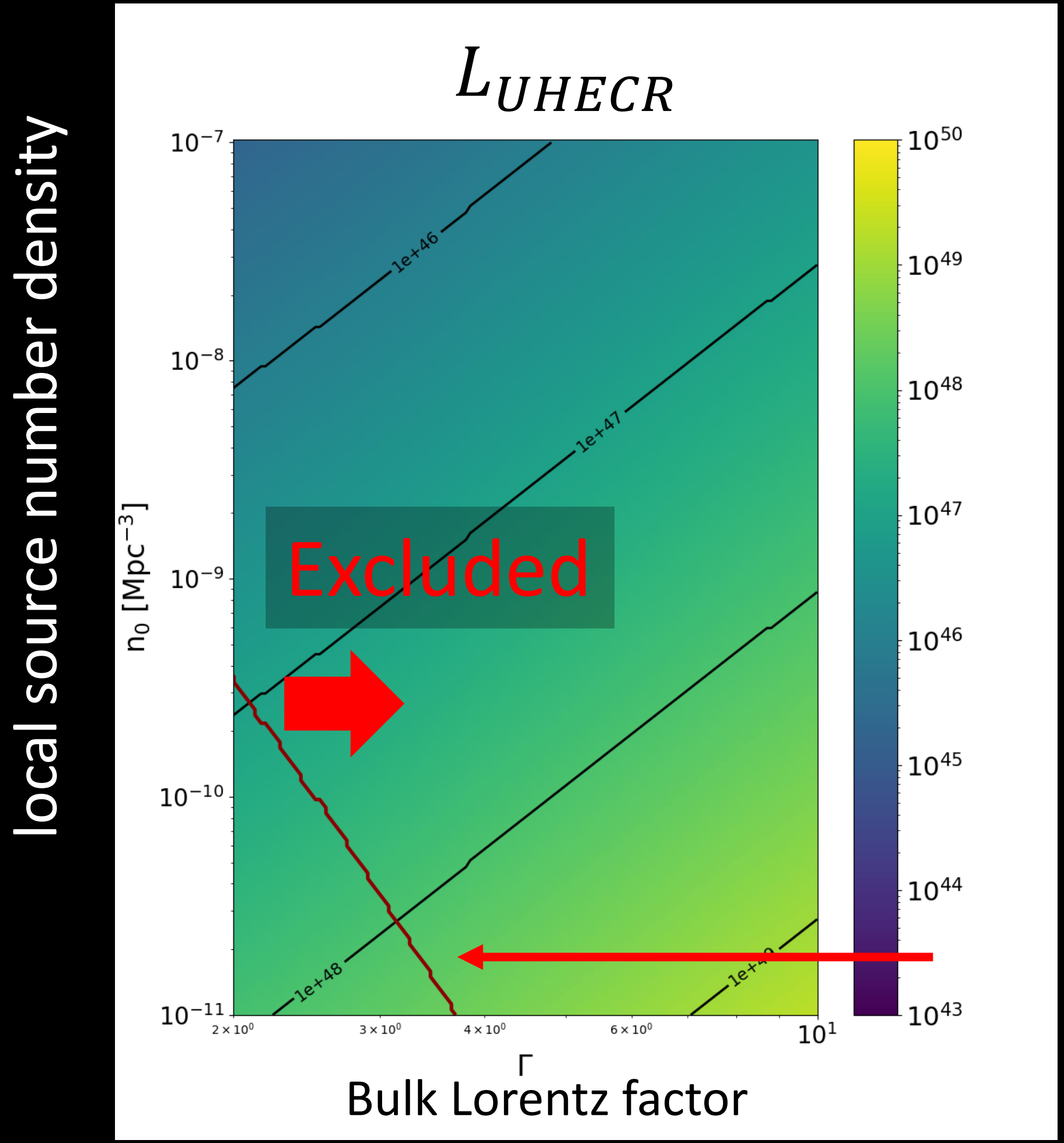
Yes,now we get **Lower Bound**!

The upper limit is placed by the stacking analysis

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**



$$n_0 \xi_{CR} L_X \lesssim Q_{UHECR}$$

$$\lesssim 9 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

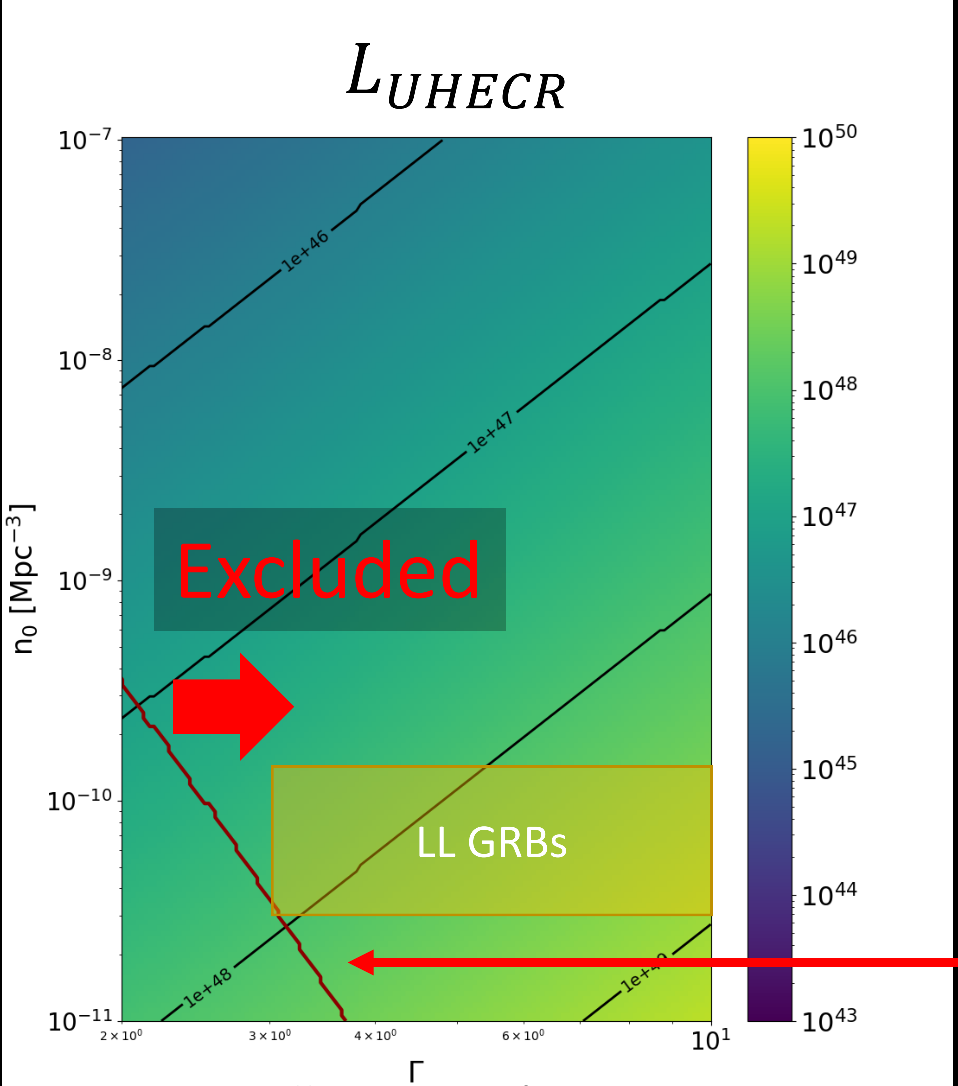
$$\varepsilon_{CR} \geq 10\ PeV$$

Otherwise these sources would overproduce UHECRs!

The line of Q_{UHECR}

The Excluded parameter space for UHECR sources
determined by **UHECR energetics**

local source number density



Bulk Lorentz factor

$$n_0 \xi_{CR} L_X \lesssim Q_{UHECR}$$

$$\lesssim 9 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

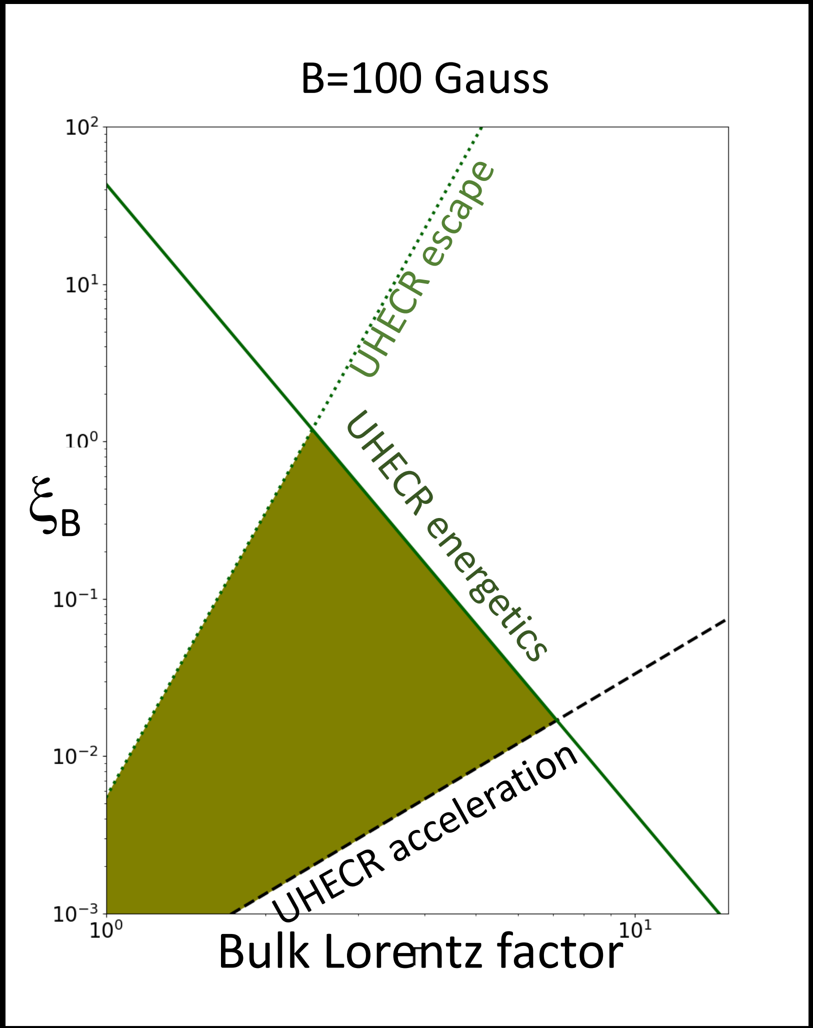
$$\varepsilon_{CR} \geq 10\ PeV$$

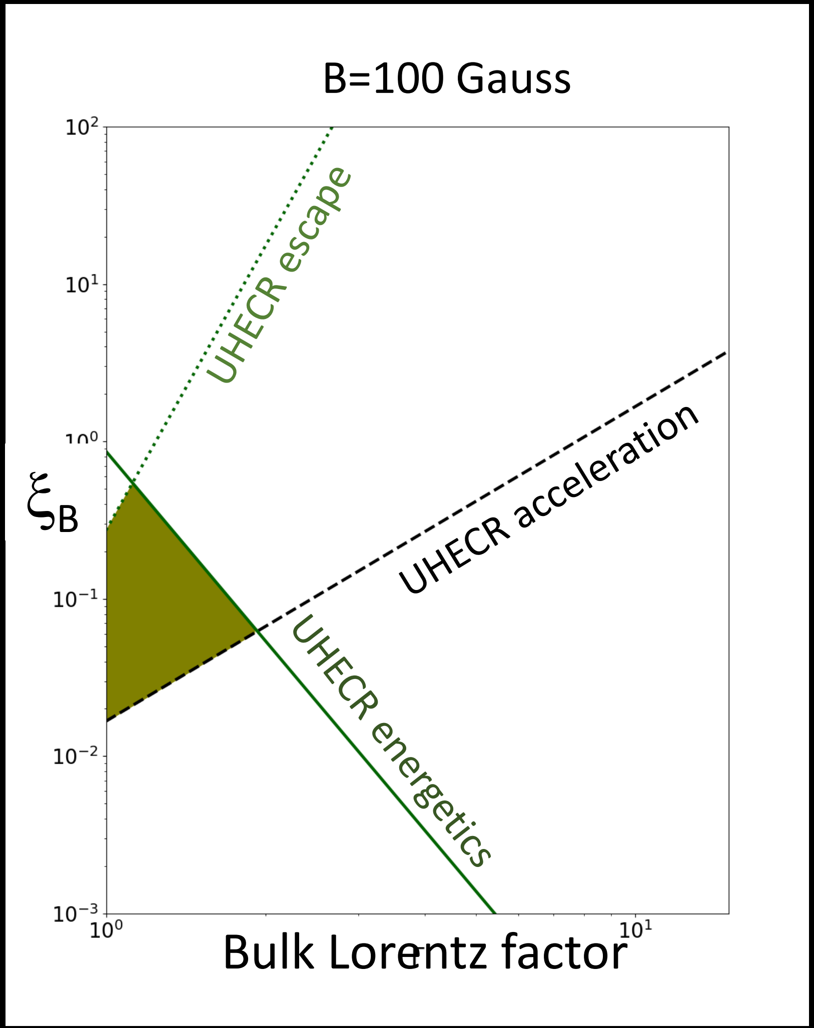
Otherwise these sources would overproduce UHECRs!

The line of Q_{UHECR}

Constraints on B, ξ_B, and Γ

$L_x = 5 \times 10^{46}$ erg/s ⇒ $L_x < 1 \times 10^{45}$ erg/s





$$\Gamma \lesssim 7 \left(\frac{L_X}{5 \times 10^{46} erg/s}\right)^{\frac{1}{3}} \left(\frac{B}{100G}\right)^{\frac{1}{3}}$$

Exclude sources with $\Gamma \gg 1$

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

- The requirements of UHECR energetics, accelerations, and escape conditions in addition to L_{UHECR} demanded by L_x will provide the solid diagnosis of the UHECR-neutrino unified models.

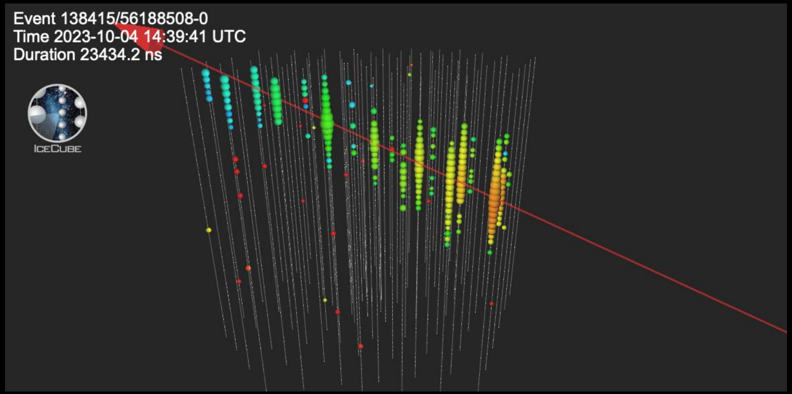
Backup

Neutrino and X-ray stacking search

ν X

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

A neutrino (singlet) event

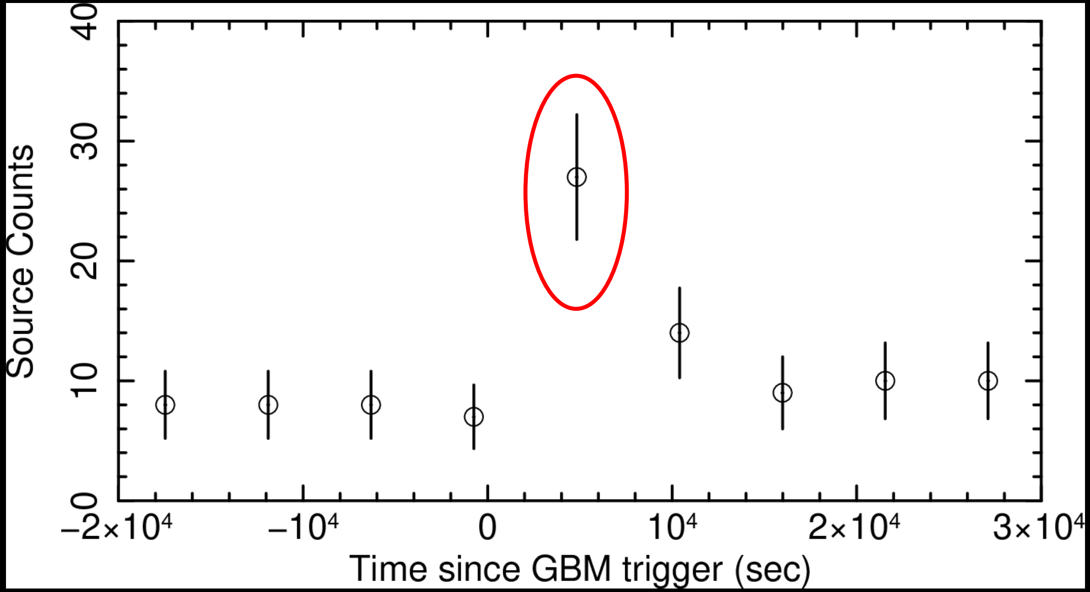


$\Delta T \approx 40\ sec$

this is limited by the ISS orbit cycle

An example – GRB190829A

2keV-10keV

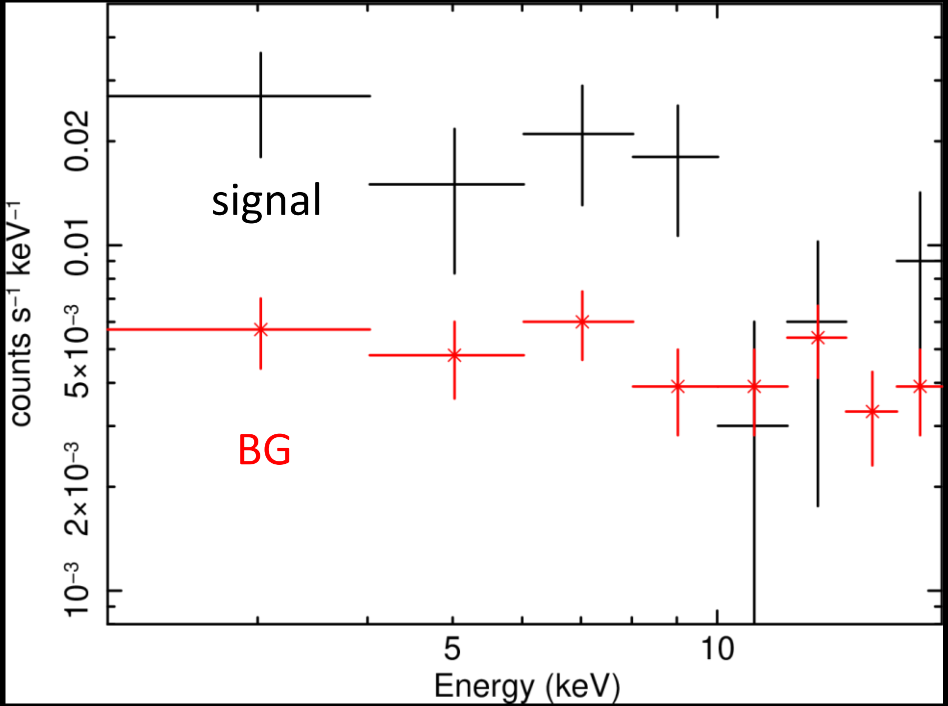


For every each of the astrophysical ν candidates (by GFU?), we look for any X-ray signal enhancement in the same direction

Neutrino and X-ray stacking search

X

An example – GRB190829A



1.2×10^{46} erg/s (R= 358Mpc)

Suppose the stacking **multimessenger** search tells

$$L_X = 5 \times 10^{46} \text{ erg/s}$$

(we expect this number for low luminosity GRBs)

What is our next move?

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

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

Γ Lorentz factor of (jet) plasma

decide the size of the interaction zone

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

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 ... density ...

...ntz factor of (jet) plasma

...ecide the size of the interaction zone

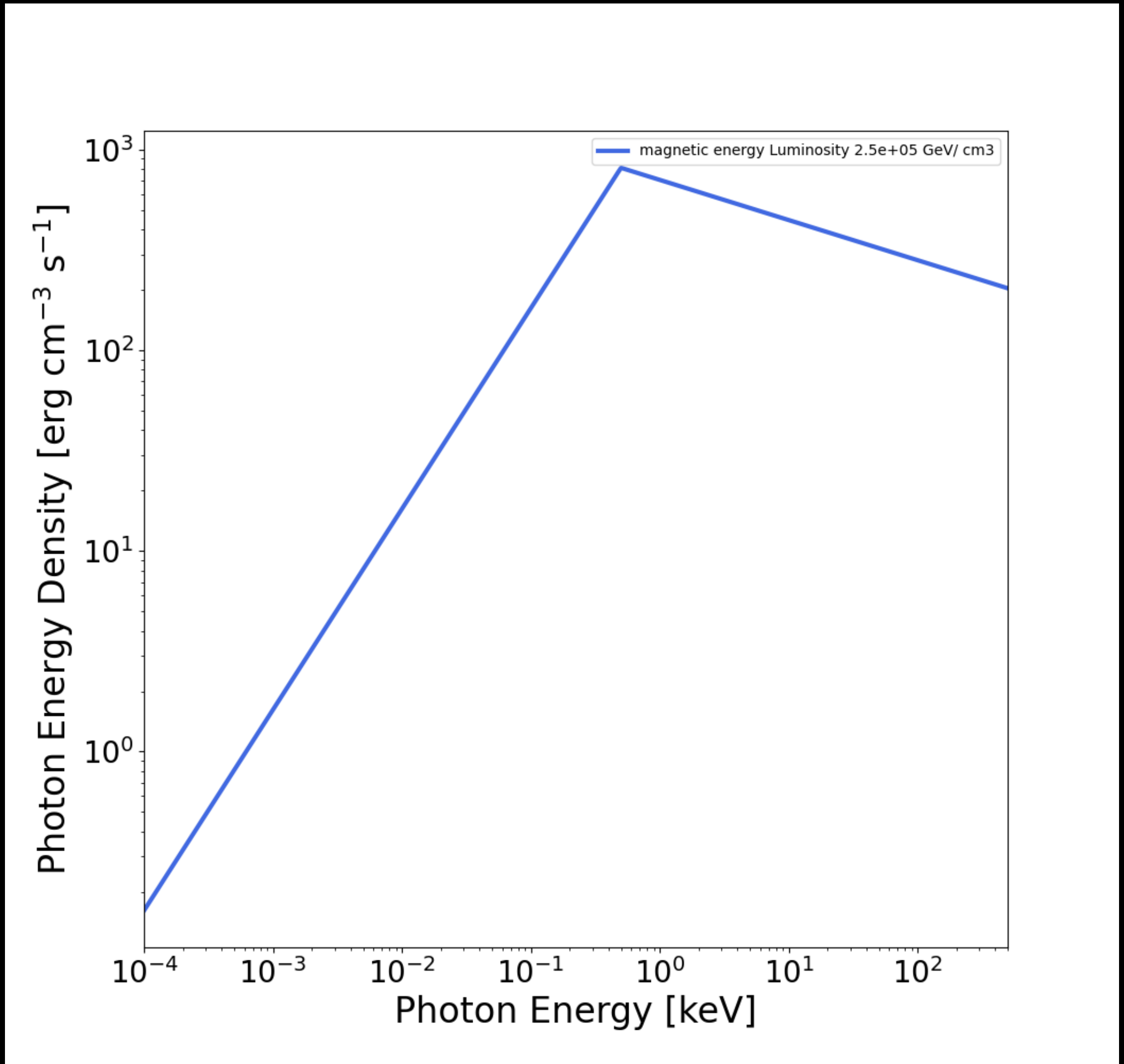
$p\gamma$ determines neutrino emission brightness

The most relevant parameter of the (UHE) Cosmic Ray Origin!
We want to know this for a given source class

Target photon luminosity density

An example when $B' = 100\ [G]$

$\propto \dfrac{B^2}{8\pi}$



Non thermal X-ray spectrum following **broken power-law**

↑

A typical X-ray transient spectrum (e.g. GRB, TDE)