Connections between high-energy neutrinos and MeV-energy photons: What will IceCube do once the MeV window opens?

(my personal views)

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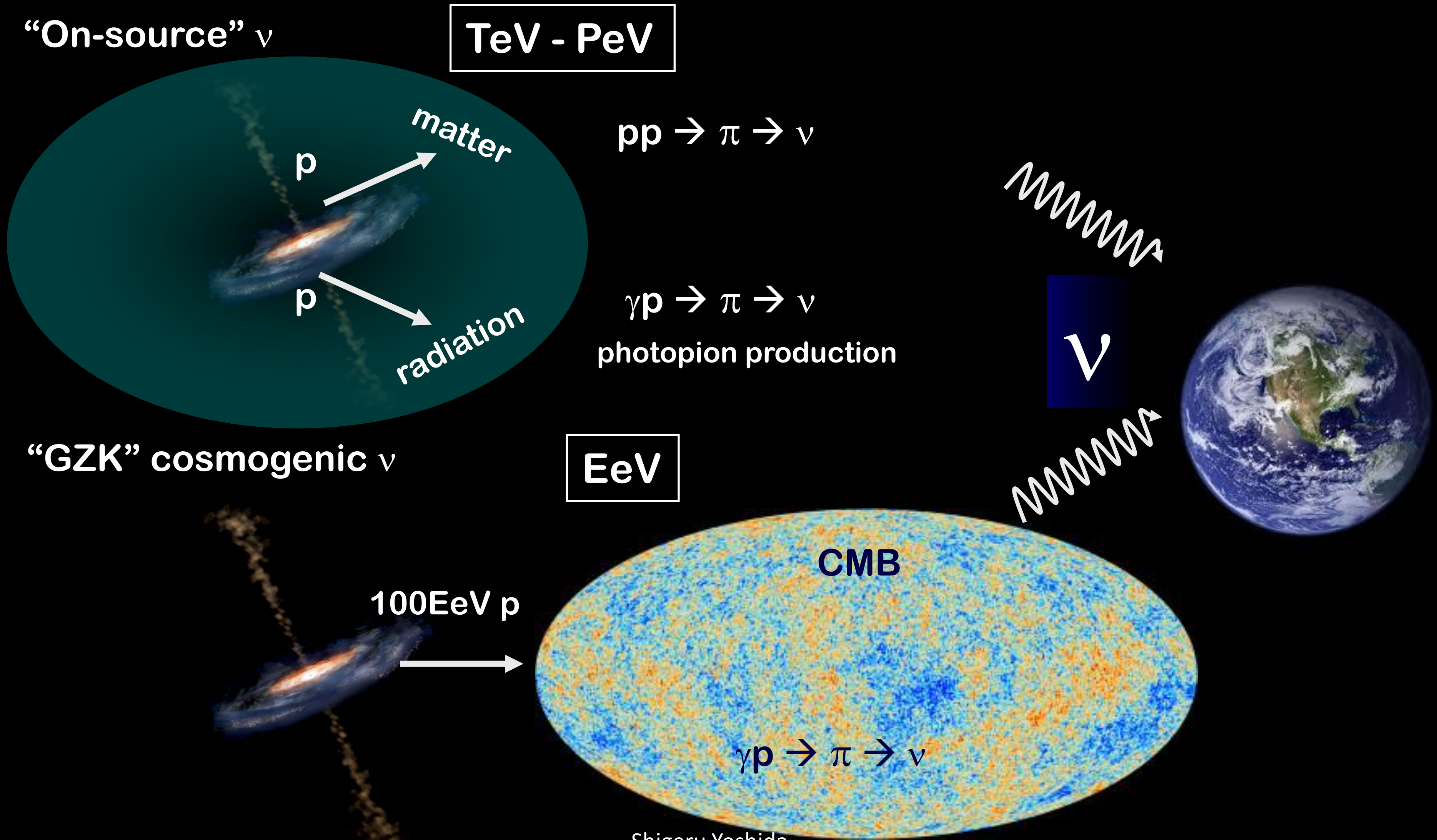
The Cosmic Neutrinos
Production Mechanisms



Neutrino and γ-ray stacking search

A simple and solid approach to bridge EM emissions and neutrinos

ν

γ

Swift

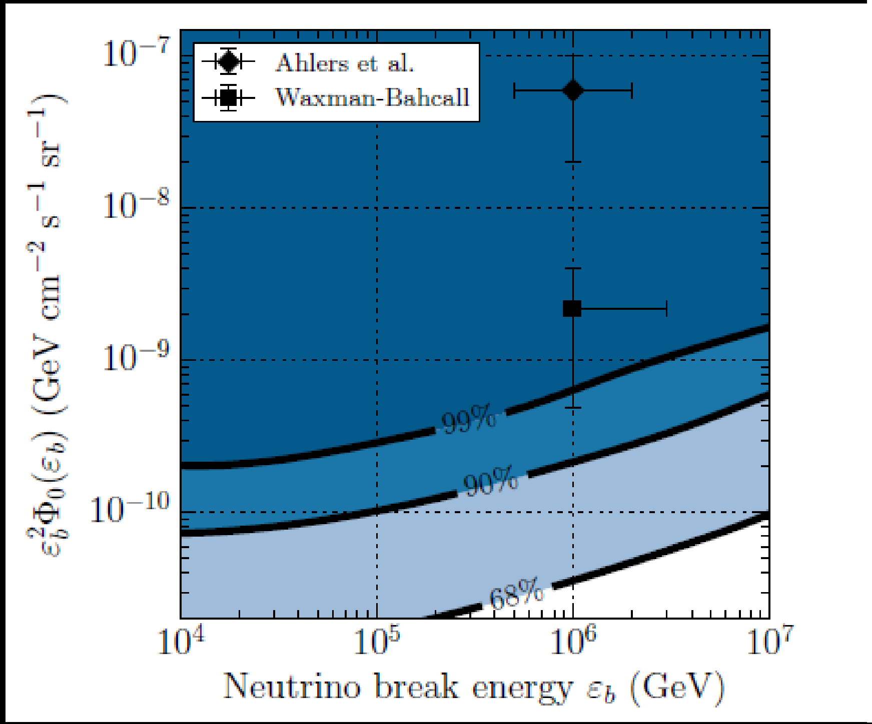
Fermi

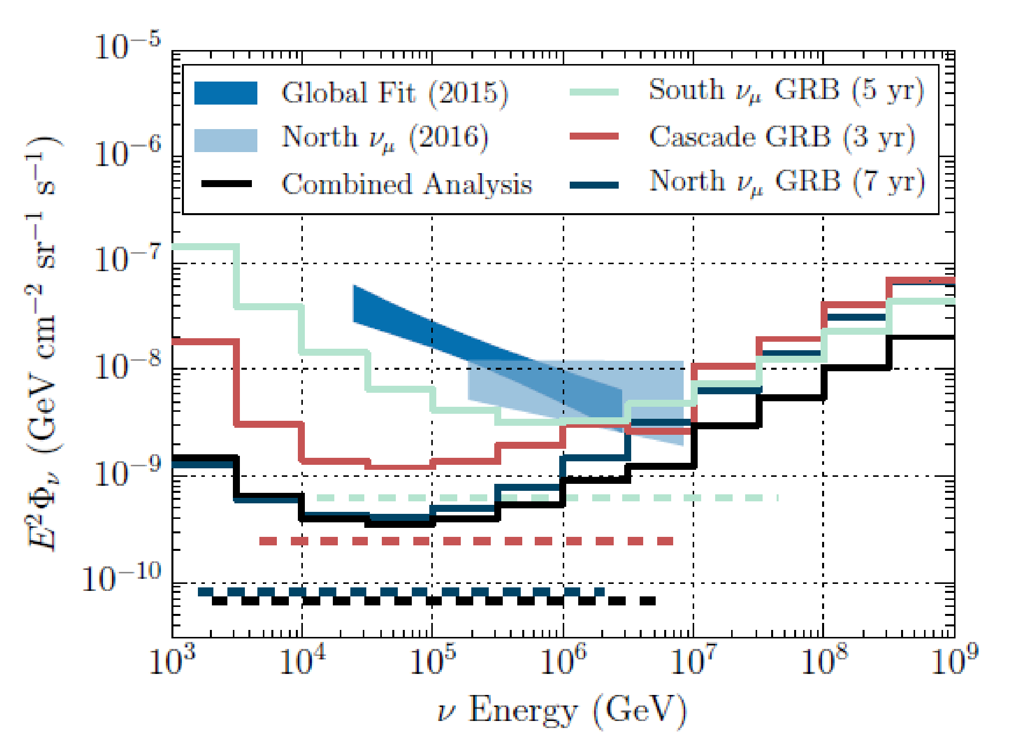
An example : Stacking of GRBs

No neutrinos associated from GRBs

Based on 1172 GRBs

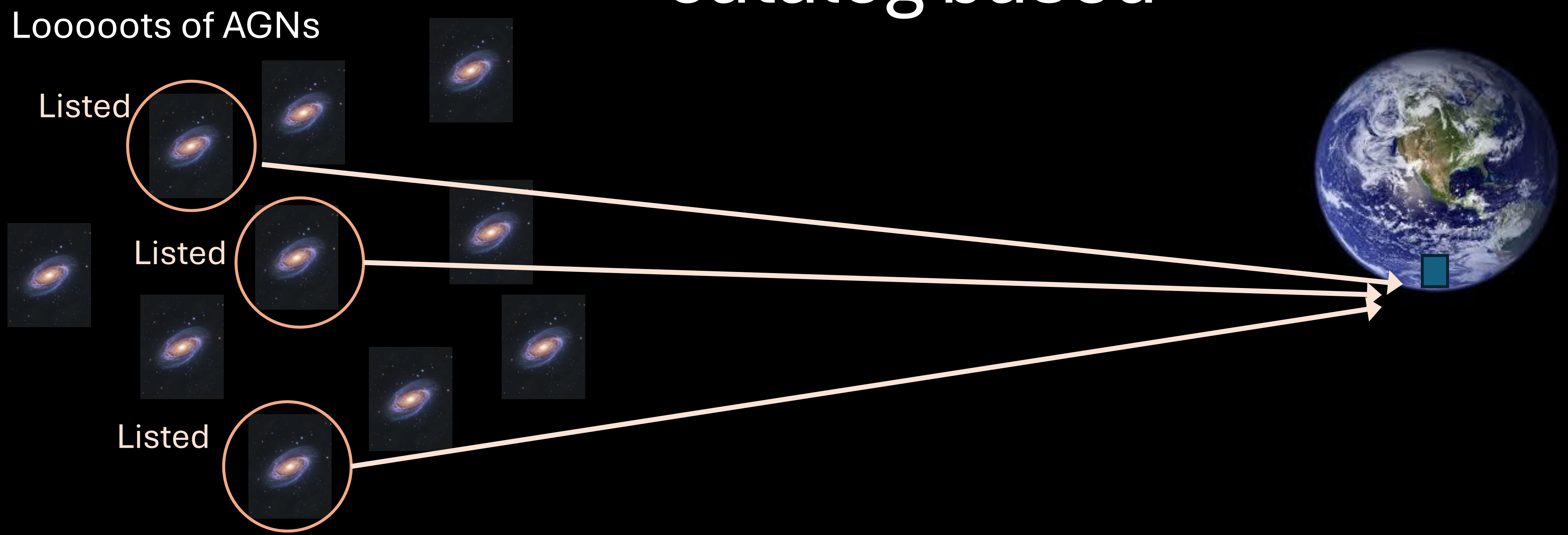
IceCube Collaboration ApJ (2017)





Significant constraints on single-zone fireball models of GRB neutrino and UHECR production

Just Another Way of stacking/source searches – catalog based –



Pre-selection → You make your source catalog based on *your belief*

Biasing to ….

- a certain AGN class (“Blazars” for example)
- bright objects in a certain wavelength band(s)
- objects with higher detectability to IceCube (spectral hardness, declination coordinates…)

The recent examples : looking at X-ray bright AGNs

“Hard” X-ray AGNs based on the BASS catalog made by Swift-BAT hard X-ray survey

IceCube Collaboration, ApJ **981** 131 (2025)

Why hard?

expecting hard spectrum, if photons are cascading down to MeV/hard X-rays

(I’m coming back to this later)

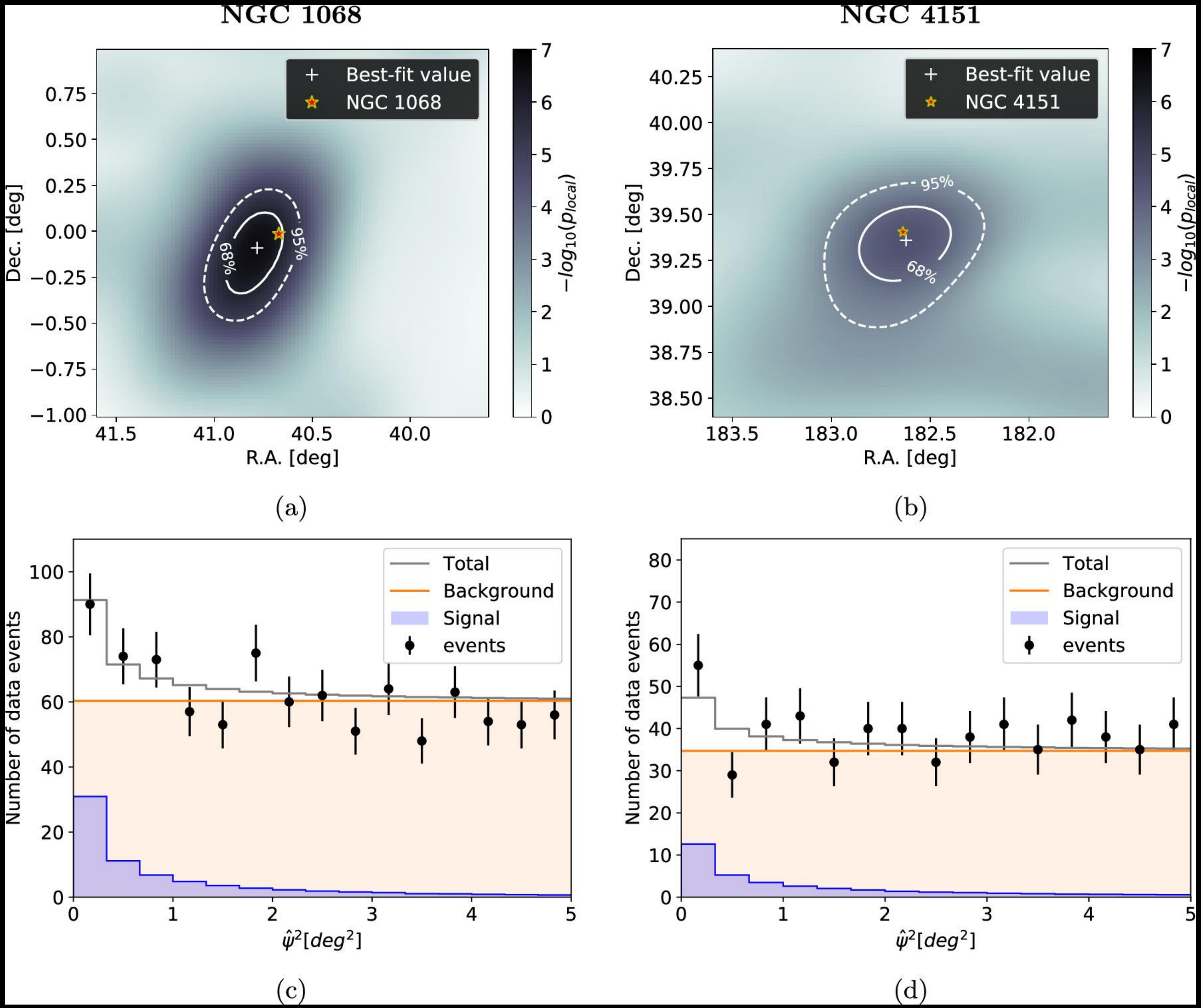
X-ray “Bright” Seyfert Galaxies based on the BASS catalog

IceCube Collaboration, ApJ **988** 141 (2025)

Why “bright” Seyfert?

providing rich X-ray targets to produce neutrinos (in vicinity of central BH)

Emission from Seyfert galaxies



NGC 4151

~ 2.9 σ post-trial

Found in the "hard" X-ray AGNs analysis

among the 43 AGNs pre-selected

IceCube Collaboration ApJ (2025)

Also found in a search for emissions from X-ray bright Seyfert galaxies

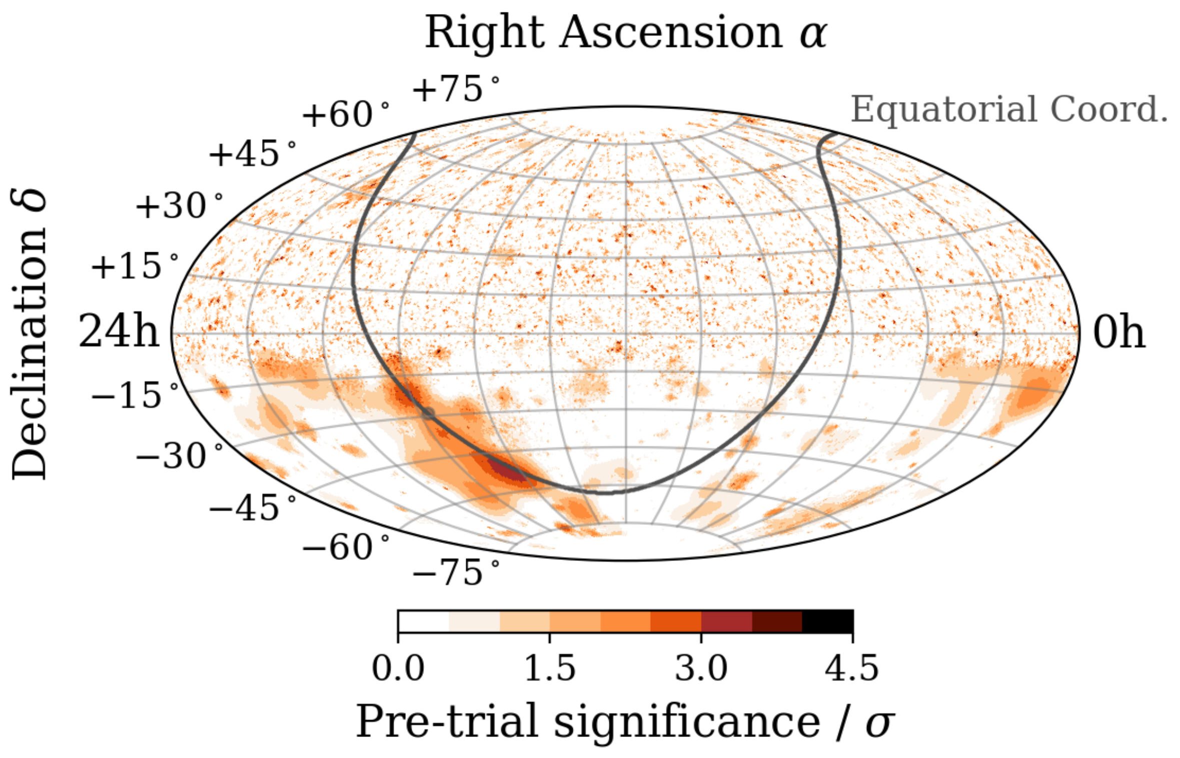
IceCube Collaboration ApJ (2025)

Top3 – NGC1068, NGC4151, CGCG420-015

Why is the catalog-based search "*powerful*"?

All-sky point-source-like emission search

(with **no** referring to any catalog)



IceCube Collaboration ApJ (2025)

Looking for any enhancement from the isotropic (mostly atmospheric) backgrounds over right-ascension band

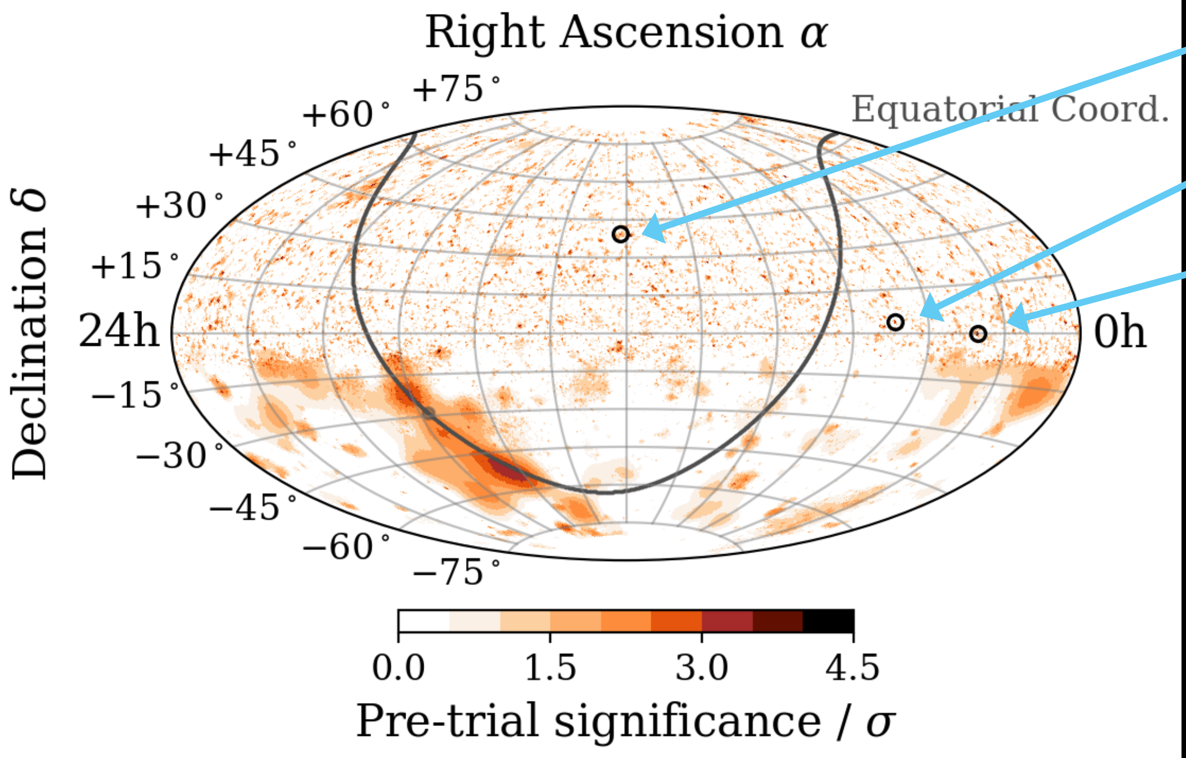
Upward fluctuations can occur *anywhere*

→ Limiting the sensitivity

(trial factor correction is huge)

Why is the catalog-based search "*powerful*"?

All-sky point-source-like emission search
(with **no** referring to any catalog)



NGC 4151

CGCG 420-015

They would not be significant unless you select them *a-priori*

NGC 1068

Yes, this position is certainly the hottest in northern sky → No biasing due to the catalog

Limiting the number of positions you look for by selecting sources based on *your bias* improves the sensitivity of the search

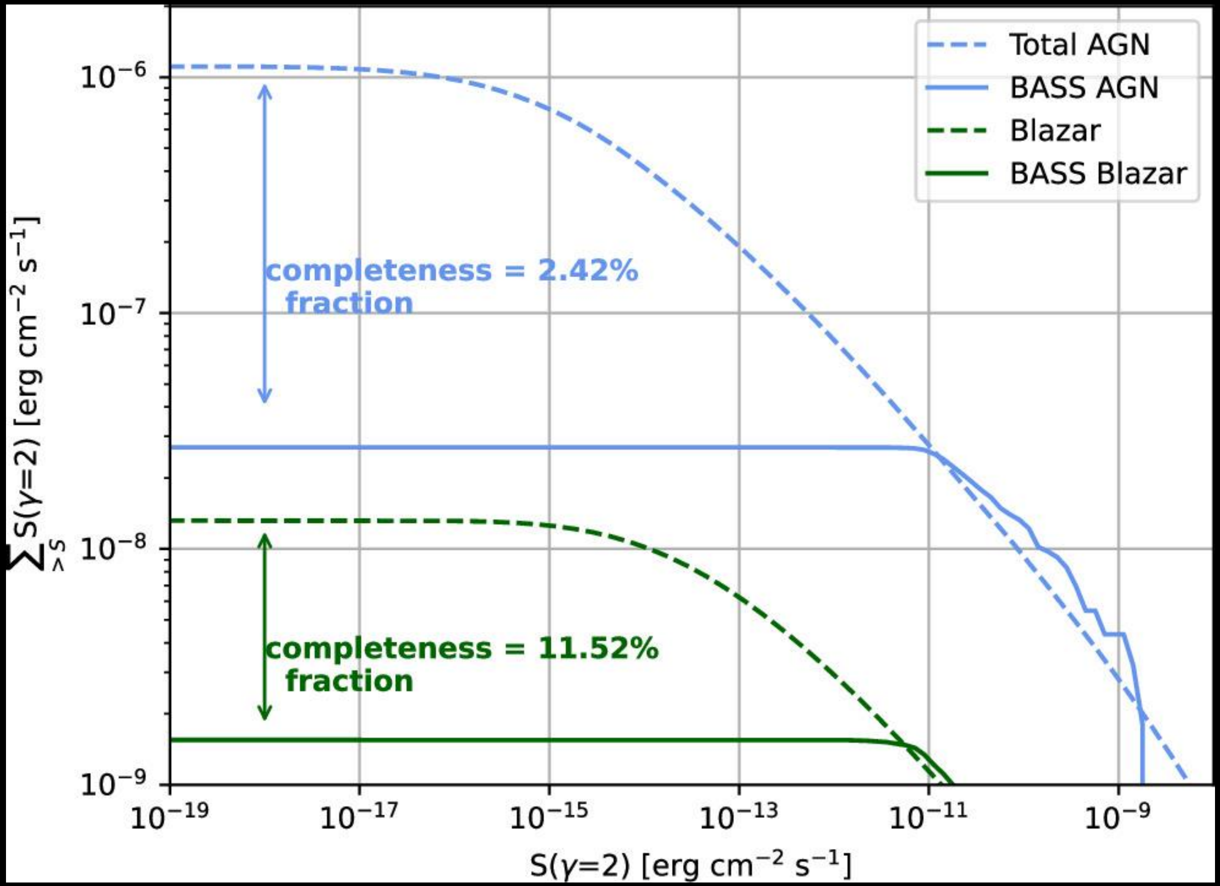
You may not like it, but probably we cannot avoid this approach to search for ν emissions from MeV-bright objects

IceCube Collaboration ApJ (2025)

(Thanks Riya Shah for making this plot for me)

Source-catalog-based stacking flux → all sky background flux

Catalog completeness factor correction



IceCube Collaboration ApJ (2025)

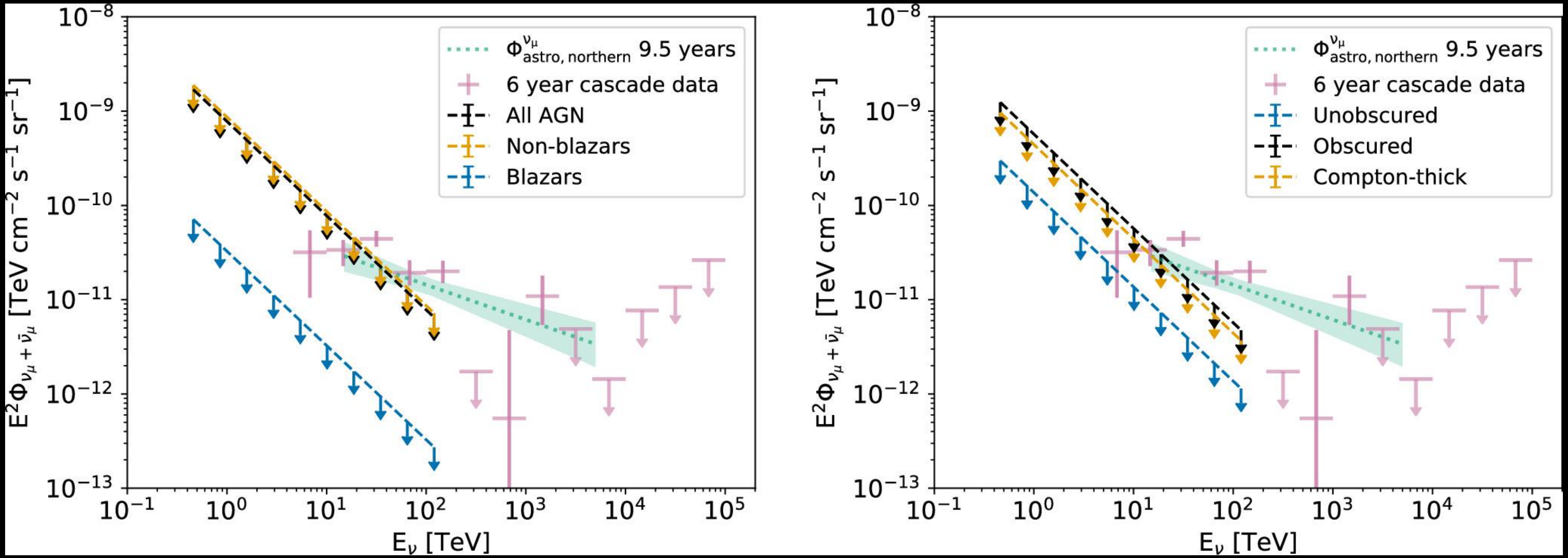
$$S_X^{\rm obs} = \int dL_X dz\, d\Omega F_X^{\rm source} (1+z)^{-\gamma} \phi_L(L,z,\gamma) \frac{dV}{dz d\Omega}$$

Luminosity function

Requests to theorists/astronomers

We need luminosity function, or cosmological evolution function for doing this

Converting the stacking limit to the all-sky flux limit



It allows us to run source population study!

IceCube Collaboration ApJ (2025)

You can do the same in MeV. But why does MeV matter?

Because the proton-photon collision sites are optically so thick at very high energies

$\tau_{\gamma\gamma} \simeq 10^3 \tau_{p\gamma}$ The secondary photons from pγ collisions are converted to e^+e^-!

γ-rays are cascading down until reaching to the pair creation threshold energy.

A typical photon energy in the pγ interactions $\varepsilon_\gamma^{p\gamma} \simeq \frac{s_\Delta - m_p^2}{4\varepsilon_p}\Gamma^2$

Energy threshold for the e^+e^- production $(2m_e c^2)^2 \leq 4\varepsilon_\gamma \varepsilon_\gamma^{p\gamma}\Gamma^{-2}$

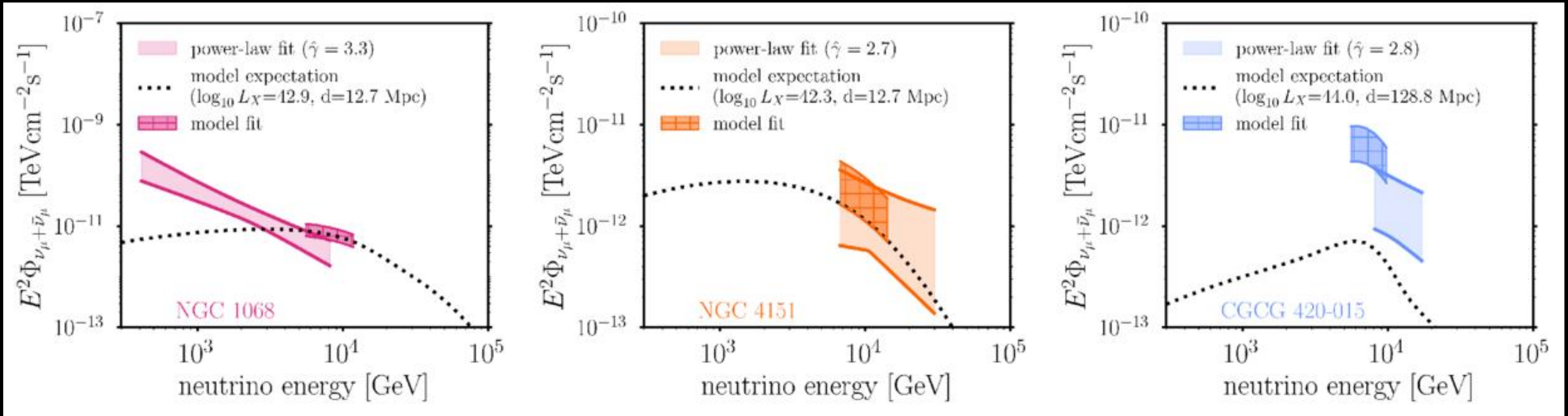
$$\varepsilon_\gamma \geq 4\frac{(2m_e c^2)^2 \varepsilon_p}{s_\Delta - m_p^2} \sim 0.6\left(\frac{\varepsilon_p}{100\mathrm{TeV}}\right)\mathrm{GeV}$$

Becomes transparent in MeV

A remark for the AGN model builders

The best fitted flux and the disk-corona model (Murase+ 2020, Kheirandish+ 2021) predictions

NGC1068 (marginally) OK | NGC4151 OK | CGCG420-015 Terrible



IceCube Collaboration, ApJ **988** 141 (2025)

We rely on the model prediction and its scaling law $L_\nu \propto L_X$ in the stacking analysis

→ Inaccurate theoretical models degrade detection sensitivity

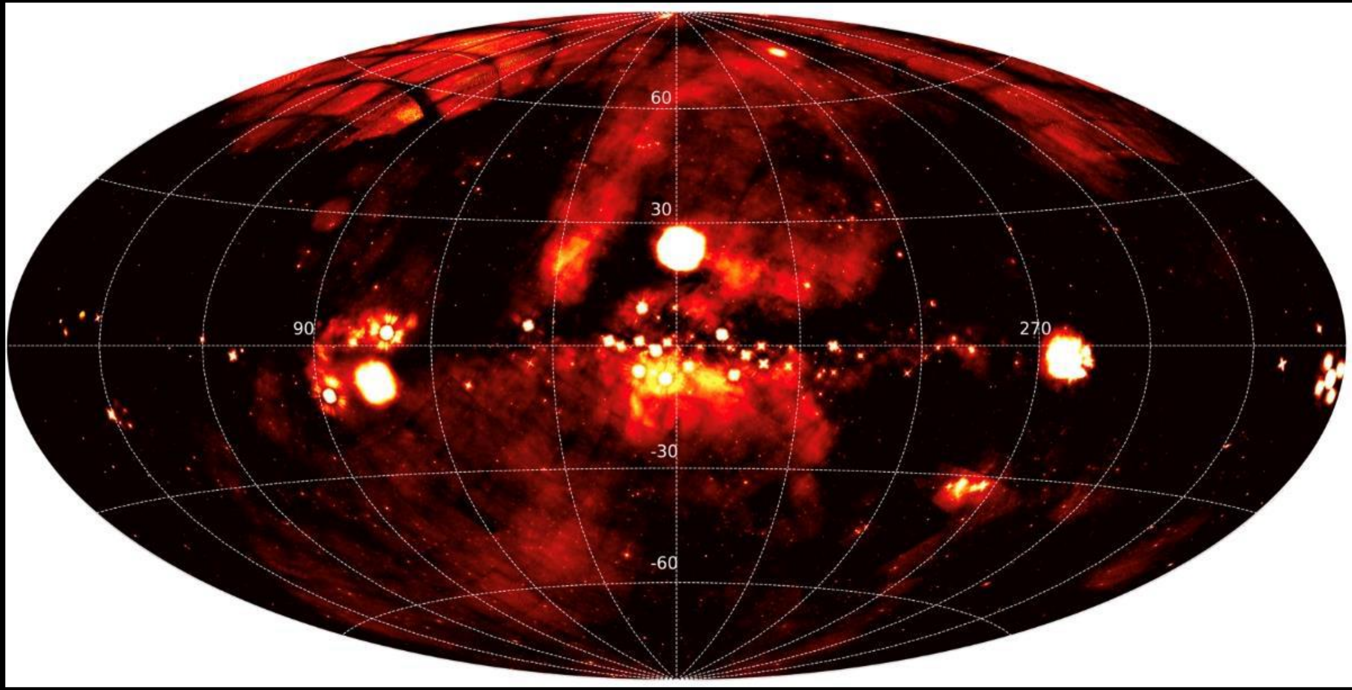
(Acknowledgements : Ty DeYoung @MSU brought this issue to my attention)

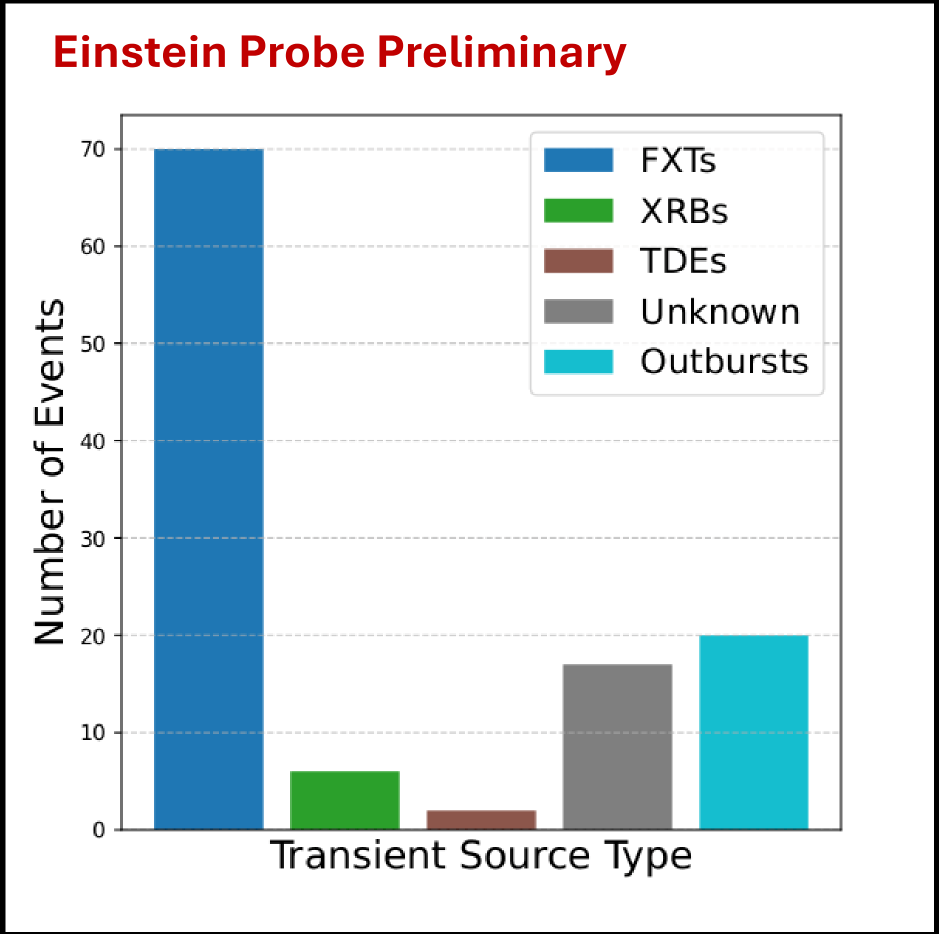
What about transient objects with MeV-energies?

Yes – The canonical GRBs (mostly detected in 100 keV range) may appear again

But you never know if any new classes will emerge !

New soft X-ray transient sky monitored by Einstein Probe - WXT

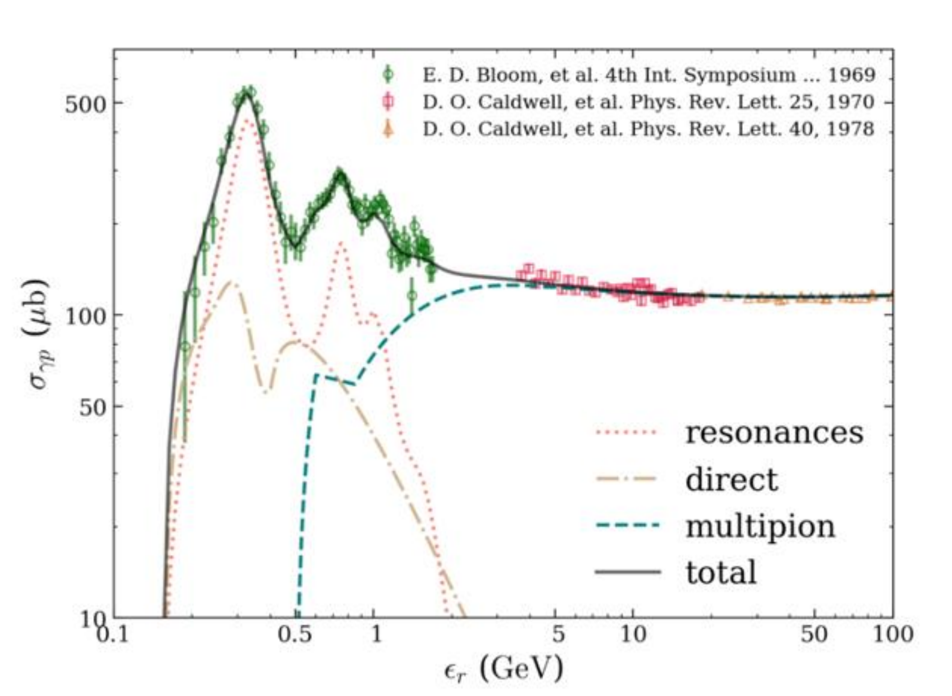




What we will see in neutrino sky if unknown new MeV transients are discovered

Photohadronic interactions

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



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

Γ Lorentz factor of (jet) plasma

$$\varepsilon_\gamma = 1.5\left(\frac{\Gamma}{10}\right)^2\left(\frac{\varepsilon_p}{10\mathrm{TeV}}\right)^{-1} \mathrm{MeV}$$

~500 GeV ν

Even the present IceCube could see them if the source yields multiple detectable ν's

Reminder: The canonical GRB case

$$\varepsilon_\gamma = 1.5\left(\frac{\Gamma}{300}\right)^2\left(\frac{\varepsilon_p}{10\mathrm{PeV}}\right)^{-1} \mathrm{MeV}$$

~500 TeV ν

Neutrino and γ-ray stacking search

ν γ

THE MeV mission
?

This is what we have been talking about

(Yes, this is promising)

Neutrino and γ-ray stacking search

ν γ

THE MeV mission ?

A reversed sequence would probe CR sources in a more generic way

What we have been doing in X-ray band

Neutrino and X-ray stacking search for transients

ν

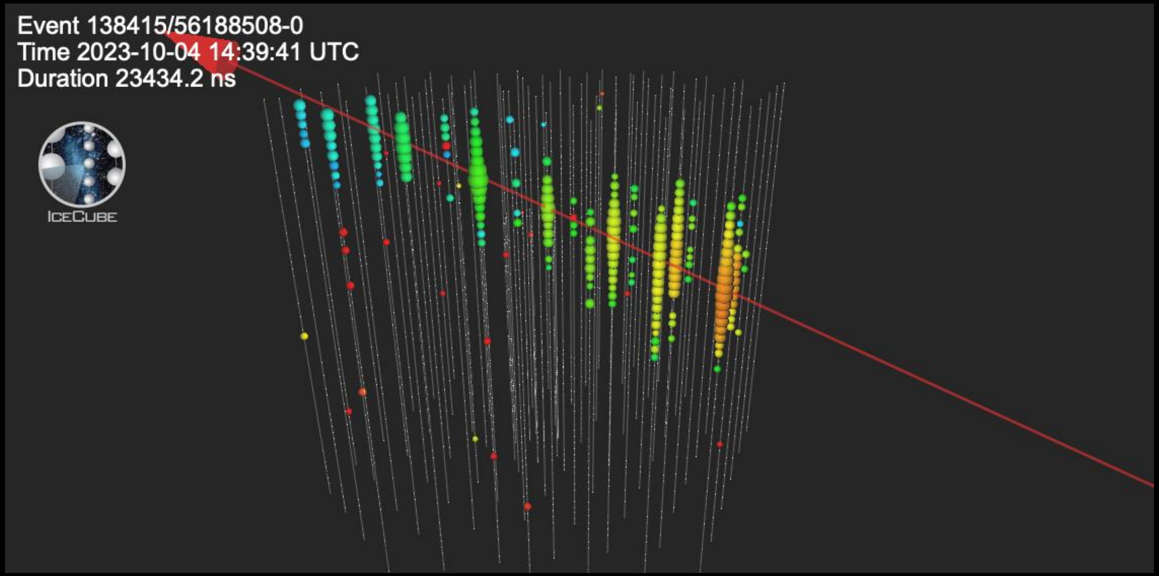
X

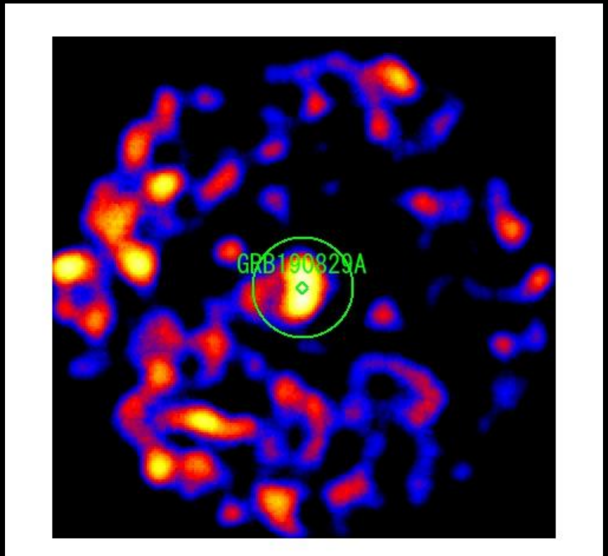
the both facilities monitor all-sky and
the data has been archived

ICECUBE

ΔT $10^{3\text{-}4}$ sec

A neutrino event





2keV-10keV

Neutrino and X-ray stacking search for transients

ν

X

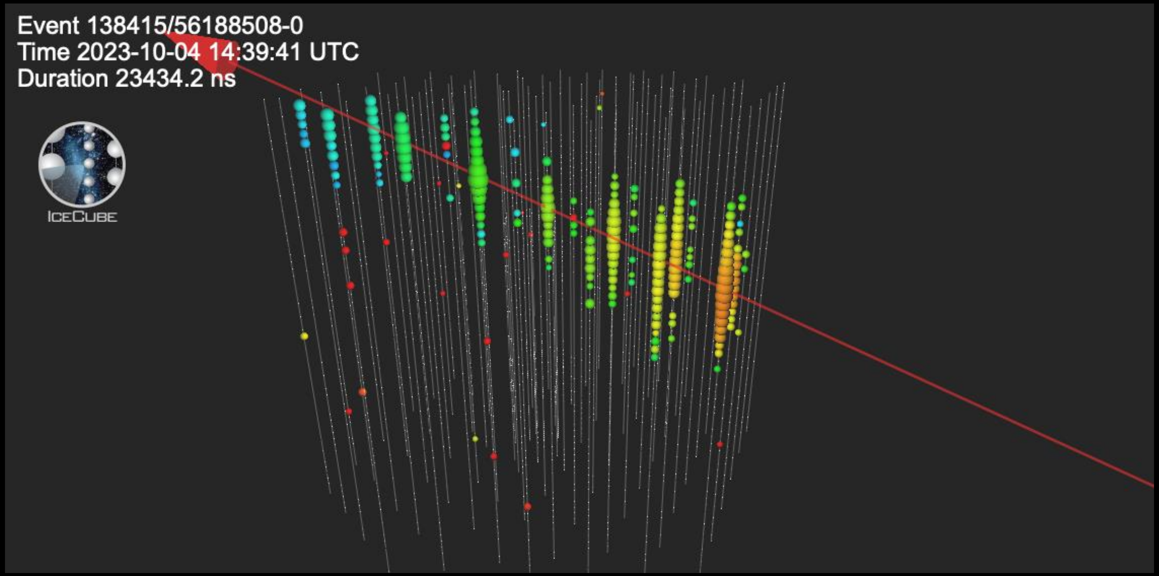
IceCube

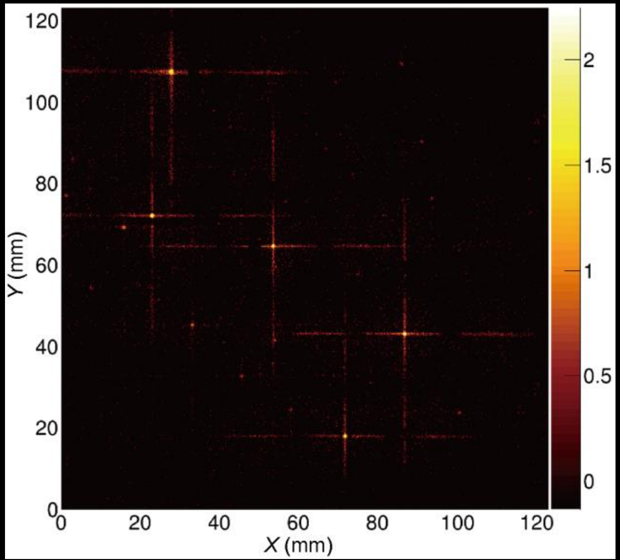
the both facilities monitor all-sky and the data has been archived

爱因斯坦探针 einstein probe

ΔT $10^{3\text{-}4}$ sec

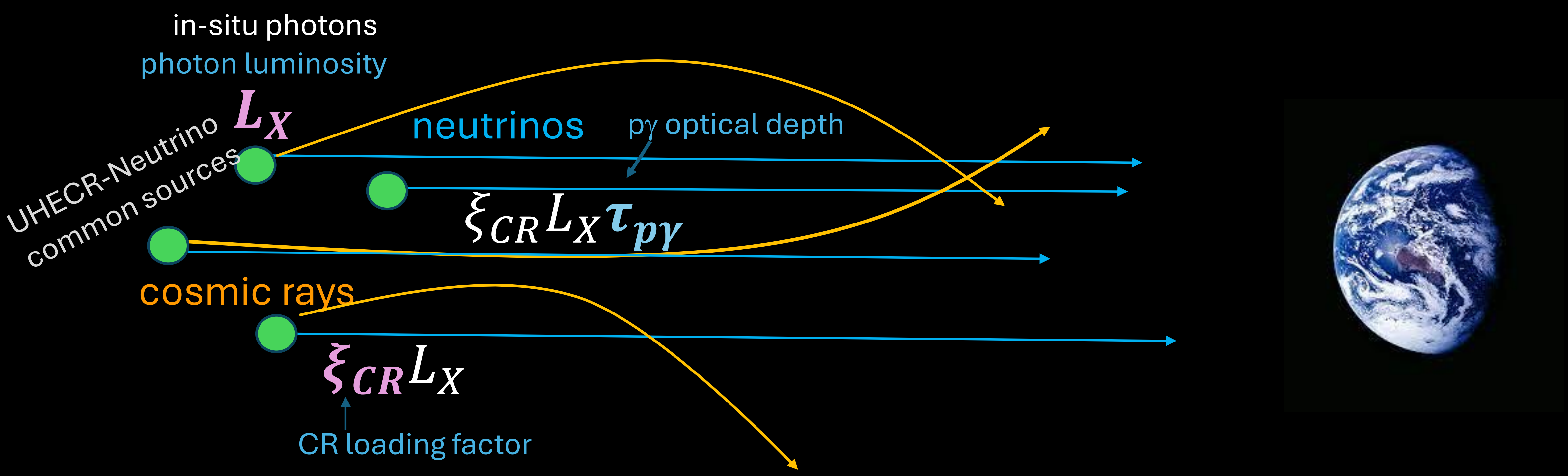
A neutrino event





0.5keV-4keV

The generic neutrino transient source scheme via photo-hadronic framework

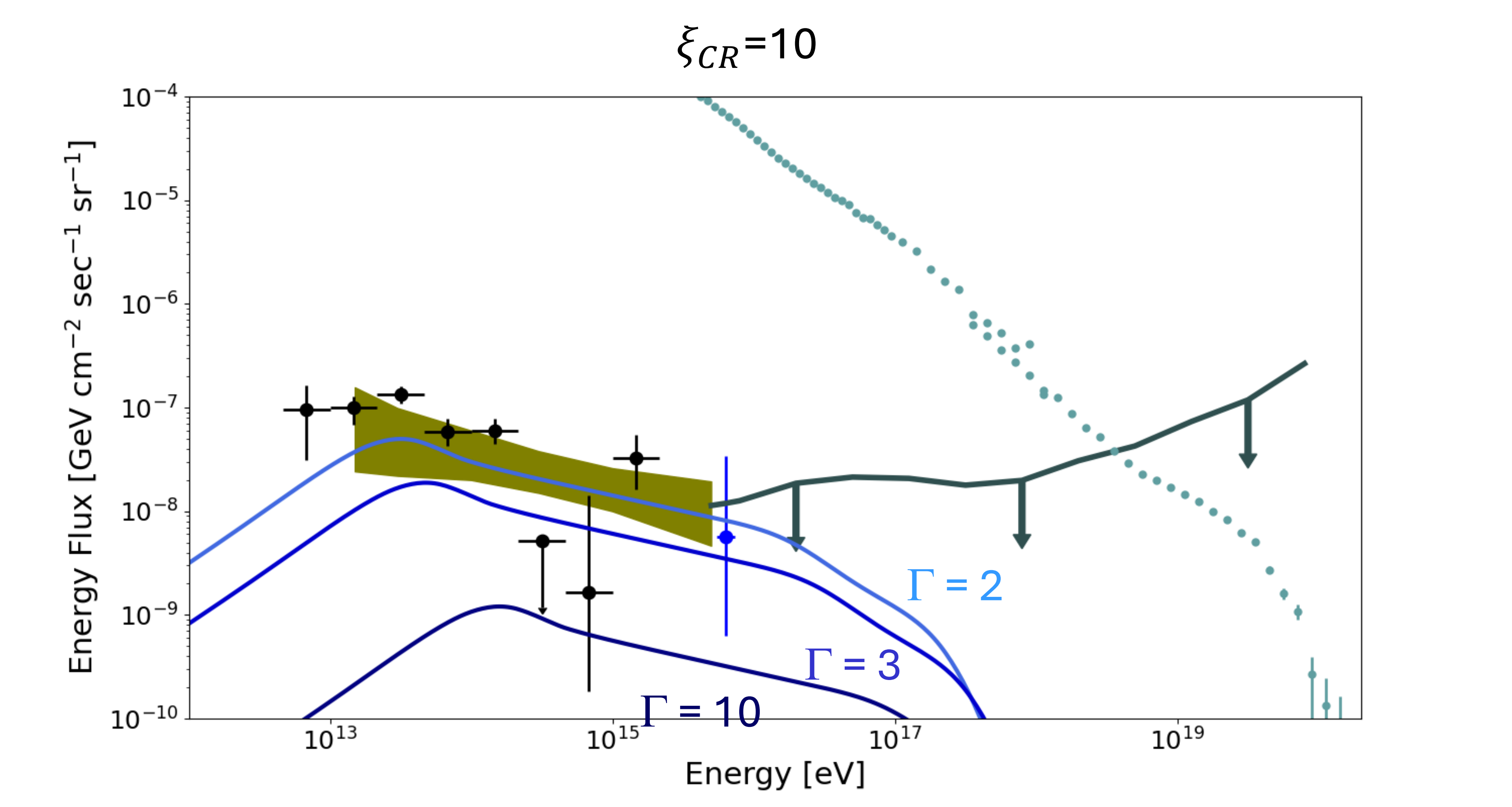


The **in-situ photon luminosity**
- A gauge of the source power
- The gauge of the neutrino emission power via **the optical depth**
- The gauge of the UHECR emission power via **the CR loading factor**

The UHE Cosmic Background Radiations

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

The expected cosmic neutrino background flux predicted by a generic model



Yoshida & Murase PRD (2024)

The conditions the UHECR-Neutrino Common Sources must meet

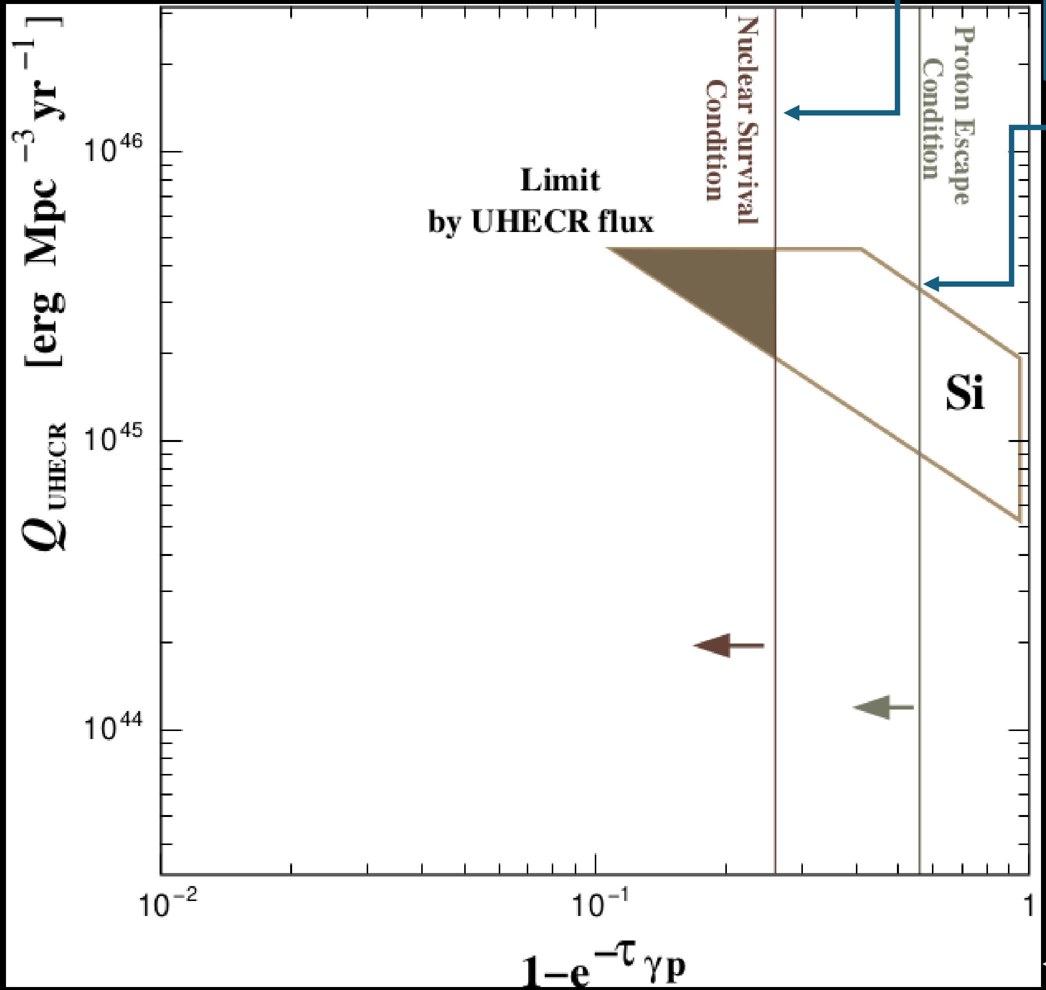
The only narrow parameter space is allowed!

Survival Condition

Escape Condition

Luminosity Density

Energetics Condition



Fiducial Neutrino Flux Condition

pγ optical depth

Yoshida & Murase PRD (2020)

Decompose into the source parameter space

Neutrino flux

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

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

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}]

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

ν

diffuse

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

We know this

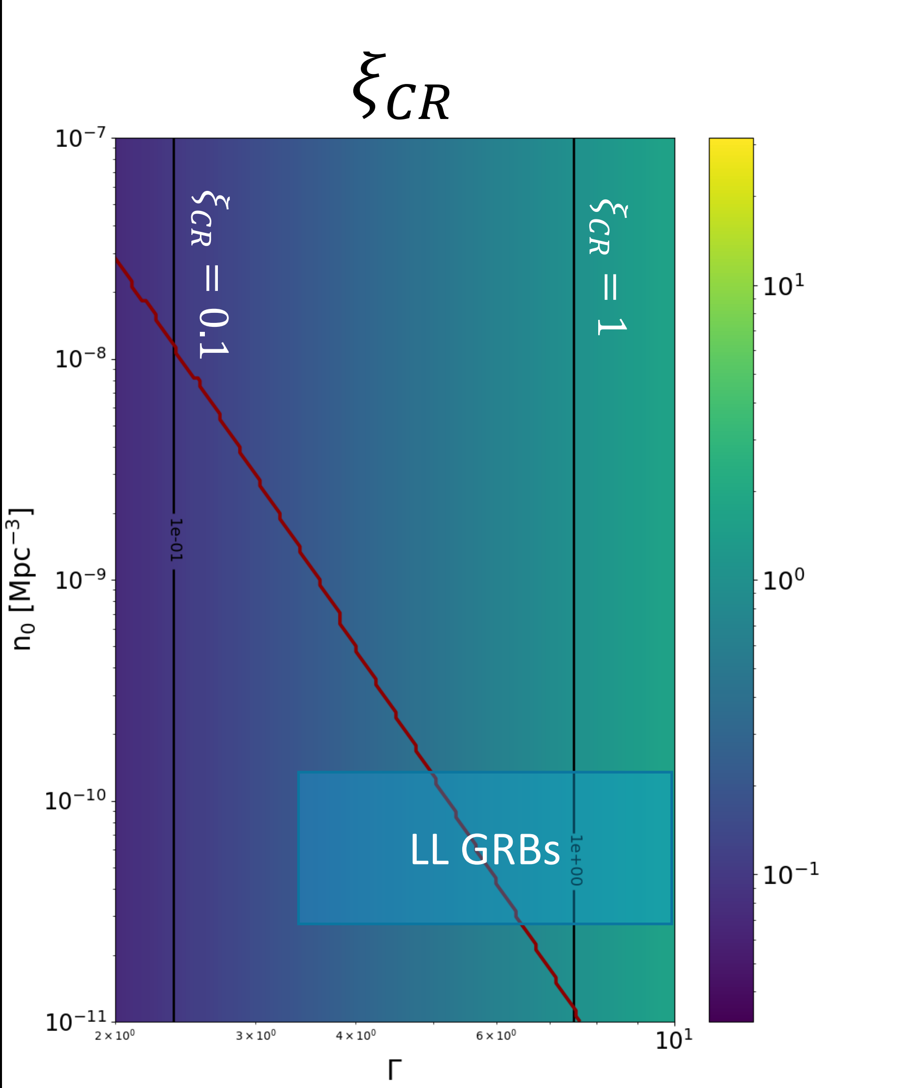
Yes,now we get
Lower Bound!

Now This is
the **Upper Limit**

The lower bound of CR loading factor

If we place
$L_X \lesssim 6 \times 10^{46} \left(\frac{n_0}{5\times10^{-9}Mpc^{-3}}\right)^{-\frac{2}{3}}$ erg/s
to explain the cosmic background flux data

local source number density



Bulk Lorentz factor

For a given n_0 [Mpc^{-3}] and Γ

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

We know this by the I[3] diffuse data

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

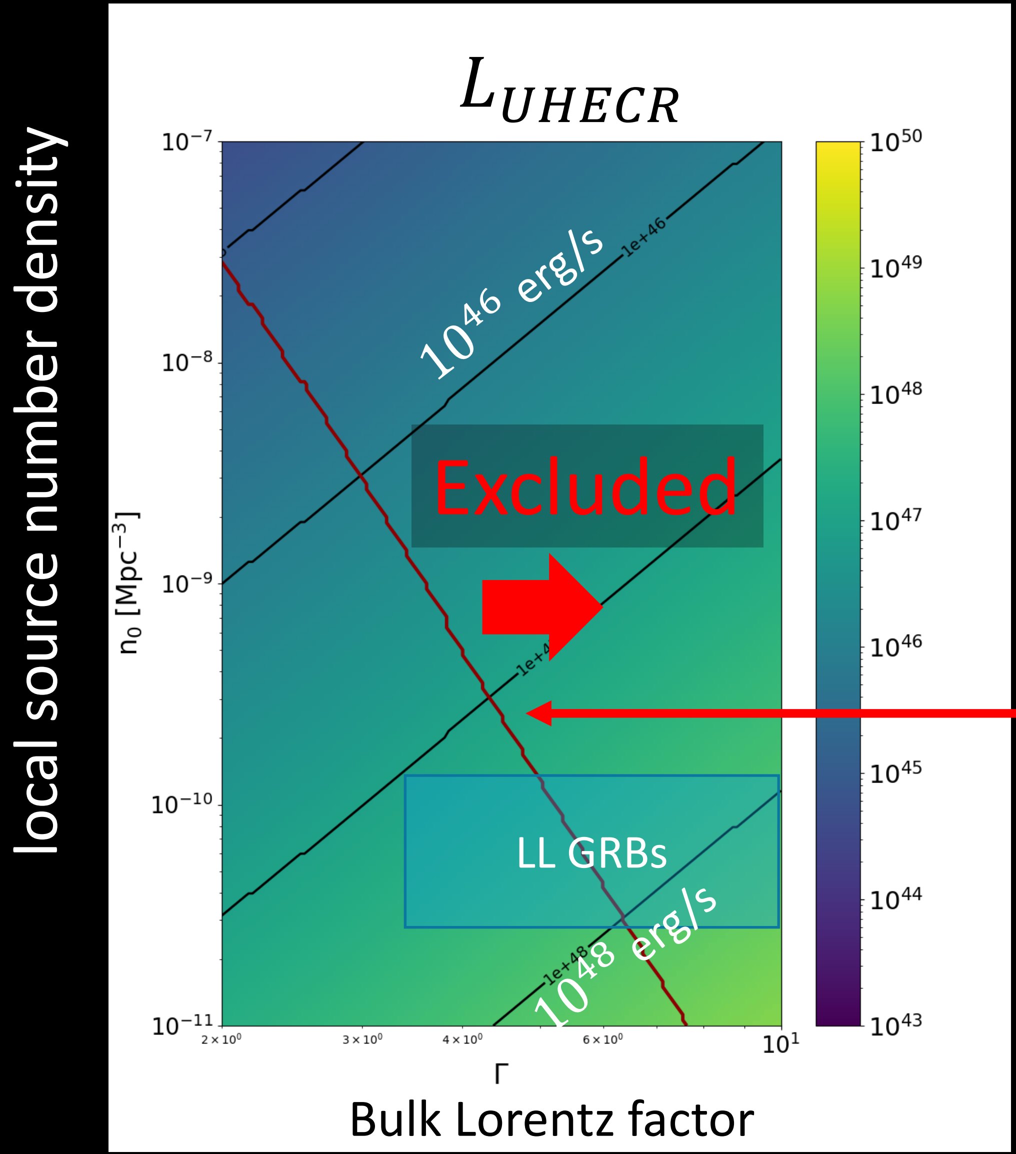
The upper limit is placed by the stacking analysis

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

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

The Excluded parameter space for UHECR sources determined by UHECR energetics

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



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

UHE CR experiments measured this

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

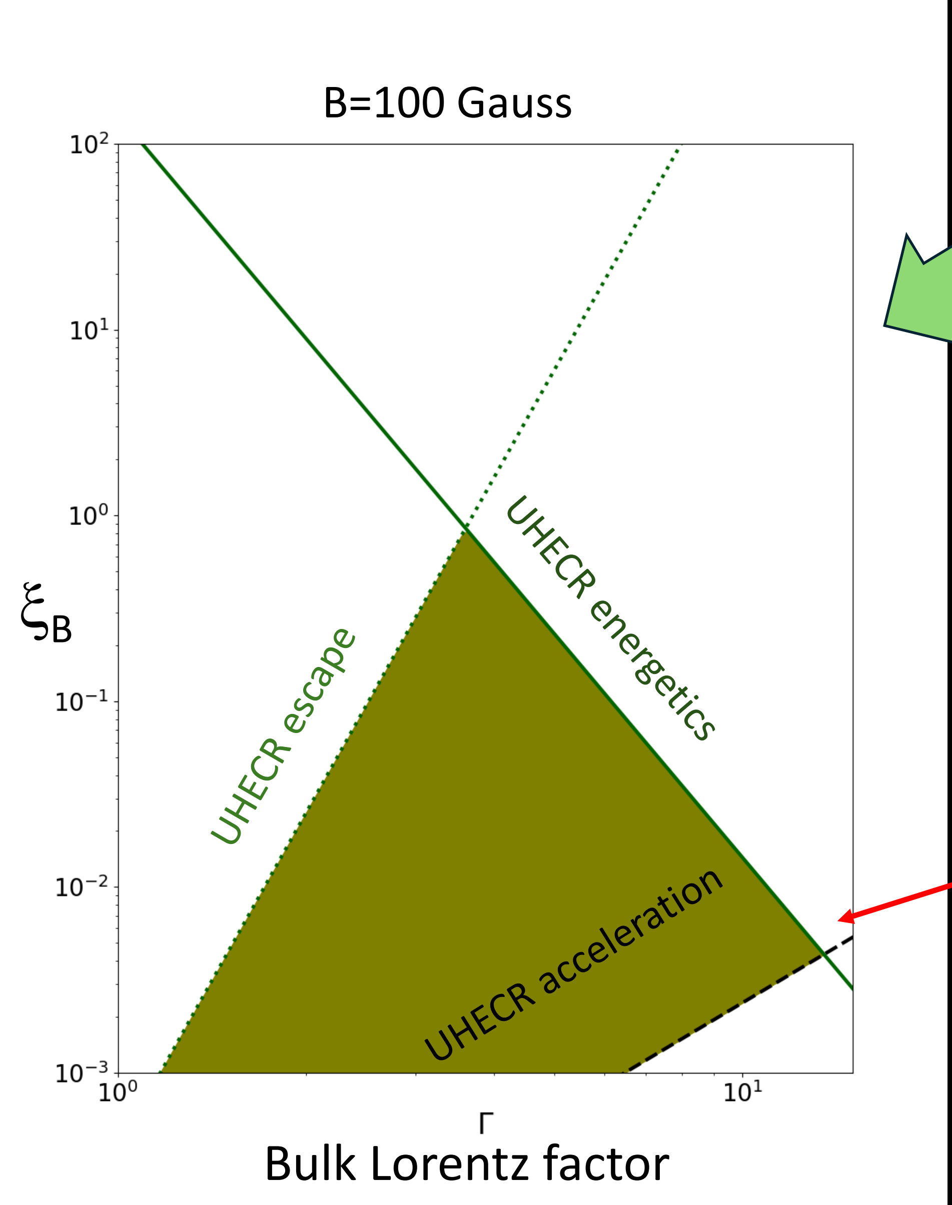
Otherwise these sources would overproduce UHECRs!

The line of Q_{UHECR}

Based upon Yoshida & Murase PRD (2024)

Constraints on B, ξ_B, and Γ

ξ_B B-field equipartition parameter
expect ~1



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

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

Exclude sources with $\Gamma \gg 1$

Based upon [Yoshida & Murase PRD (2024)]

We can do this also in the MeV band

A main difference

$$\varepsilon_\gamma = 1.5 \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\varepsilon_p}{10\mathrm{TeV}}\right)^{-1} \mathbf{MeV}$$

We expect
100 GeV – 1 TeV energy ν

(not 100 TeV – 1PeV energy as we expect from soft X-rays transients)

For this energy range, we may need to detect multiple ν events because of the vast atmospheric ν backgrounds

We trigger ToO once we detect them

Takeaway Messages

- Photon cascading initiated in VHE/UHE energy bands yields MeV emission

  Link between high-energy neutrino and MeV γ-ray observations

- Neutrino emission search by stacking MeV-energy AGNs is a powerful approach

  Having reliable model prediction is a key

- Prompt hadronic emission from MeV transients likely radiates 100GeV-1TeV neutrinos

  ToO MeV observations triggered by multiple TeV ν detections can probe cosmic ray origin in a generic and comprehensive way