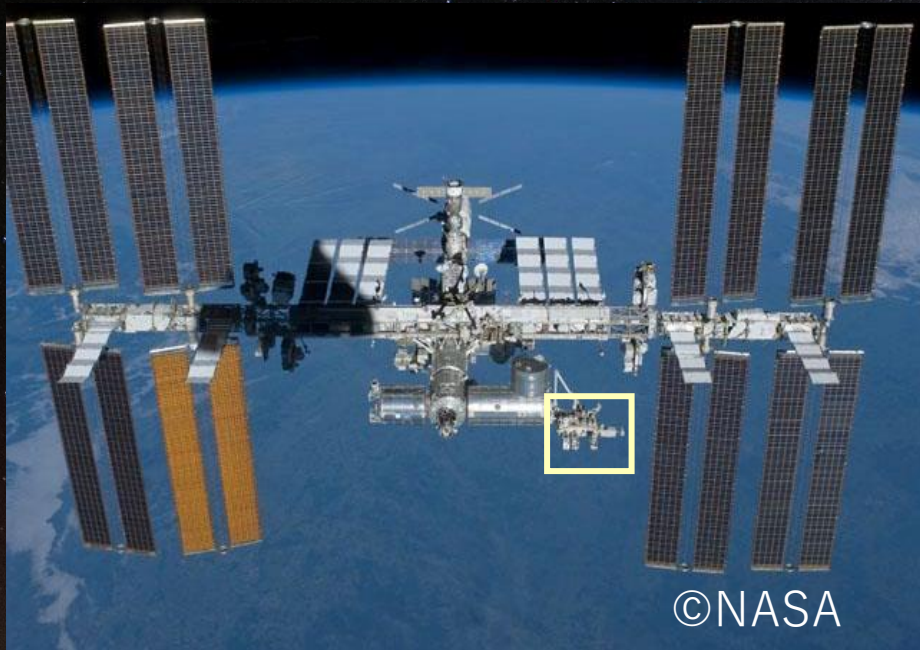


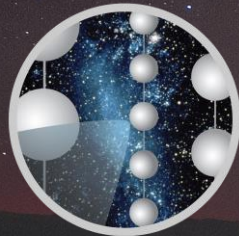


Connecting IceCube to MAXI: Constraining the Origin of Ultra- High-Energy Cosmic Rays with X- ray

Wataru Buz Iwakiri (Chiba University)
for the IceCube Collaboration and
the MAXI team

MMA-CADO TeVPA 2026

Aug 30, 2026

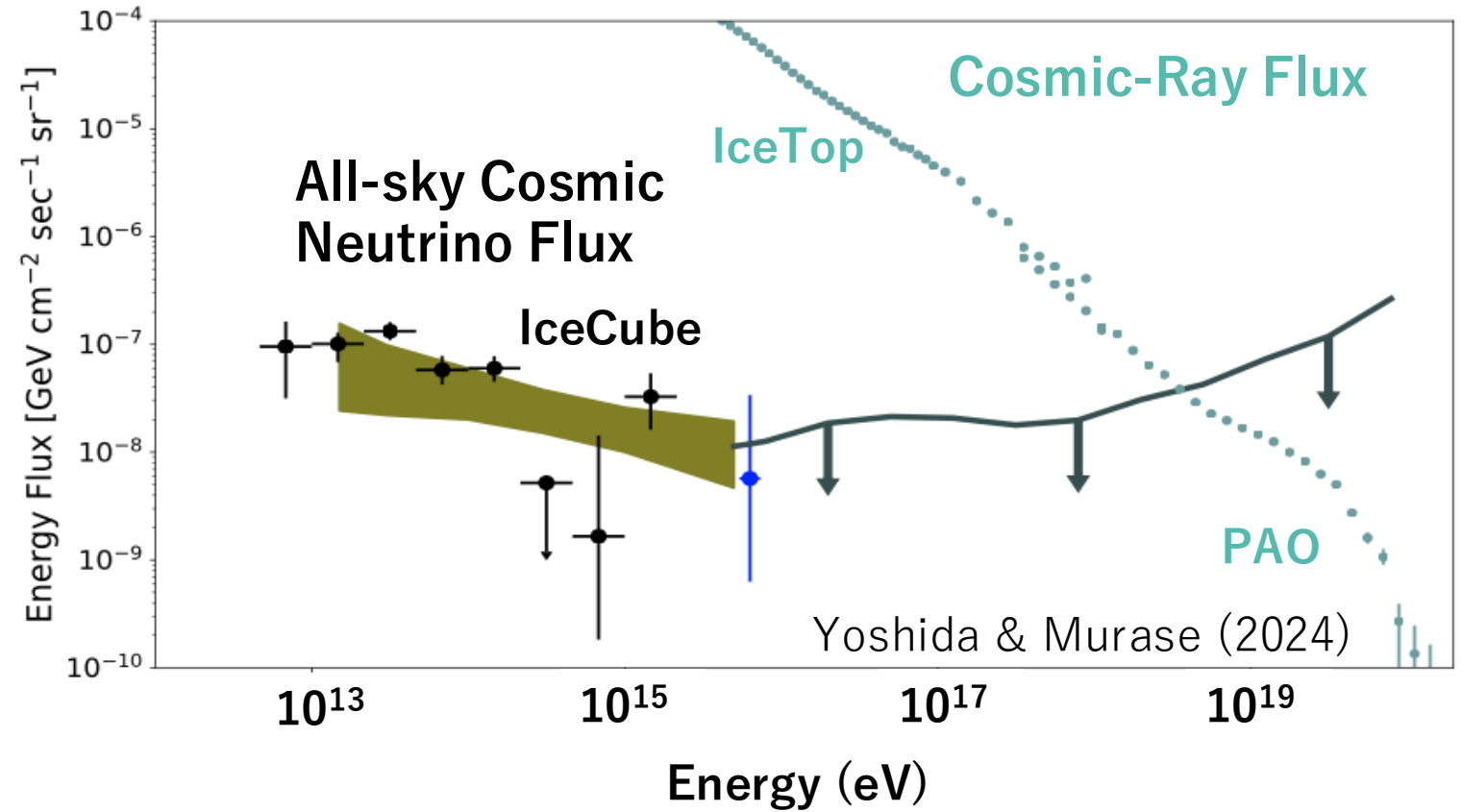
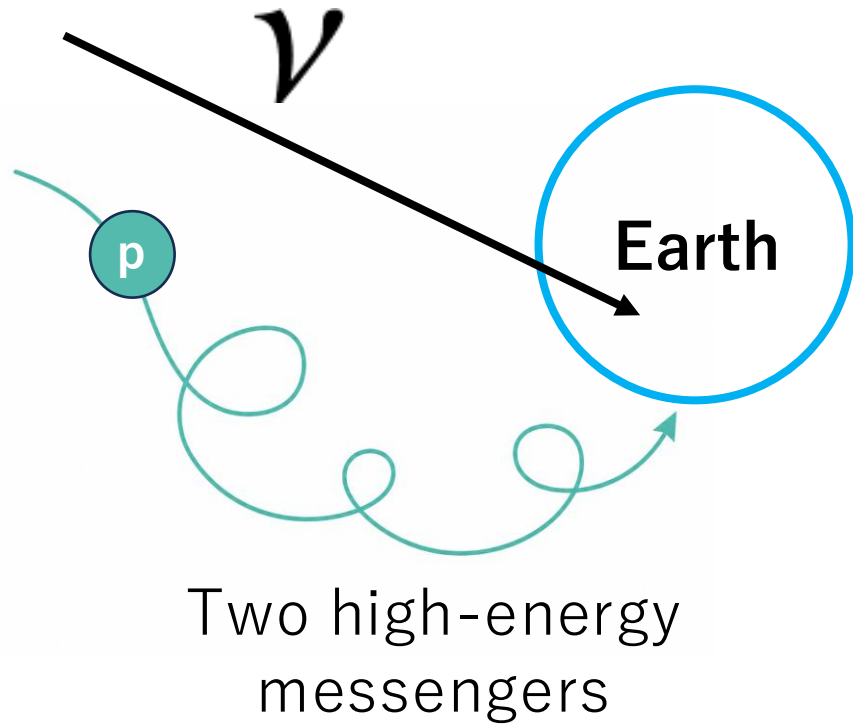


ICECUBE



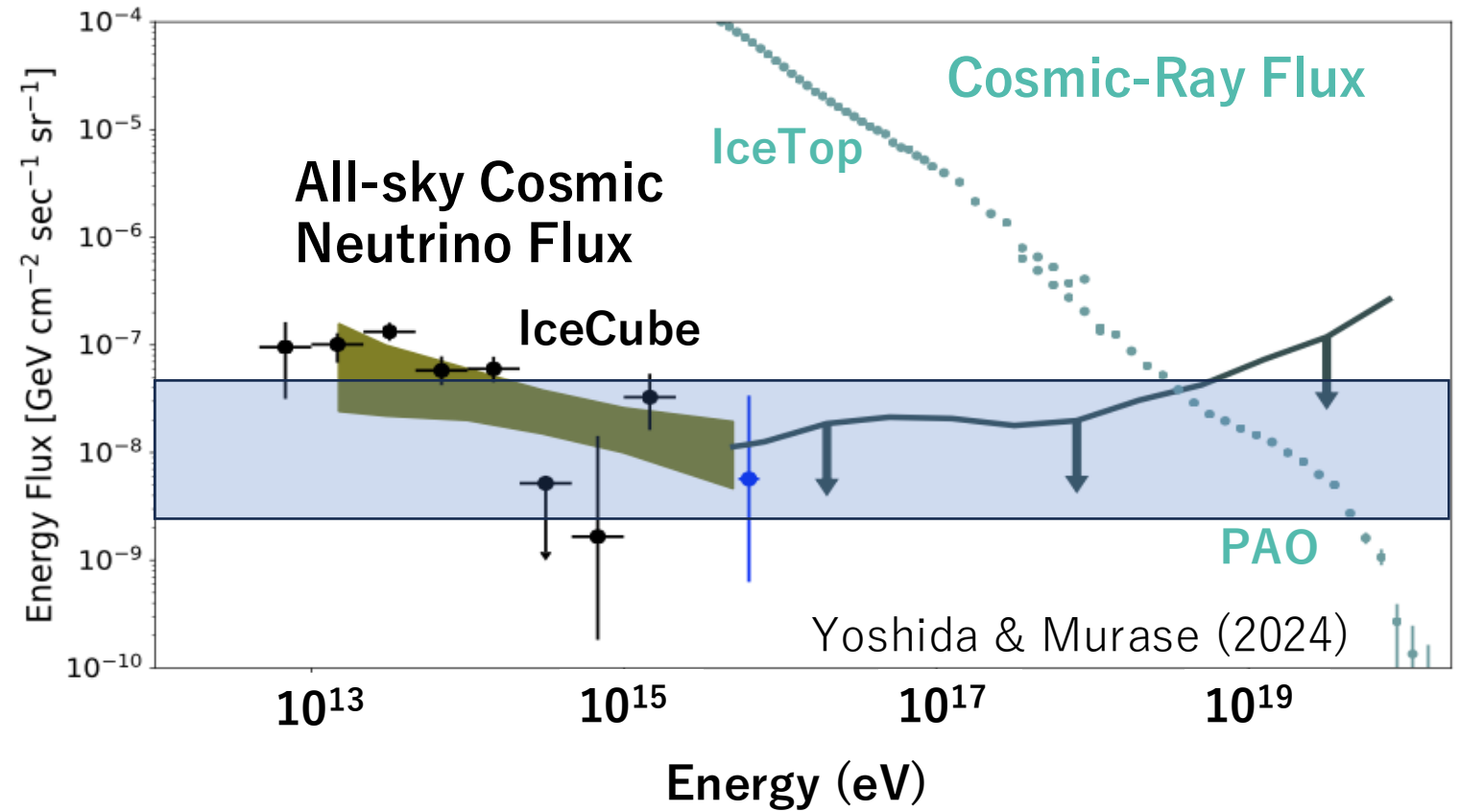
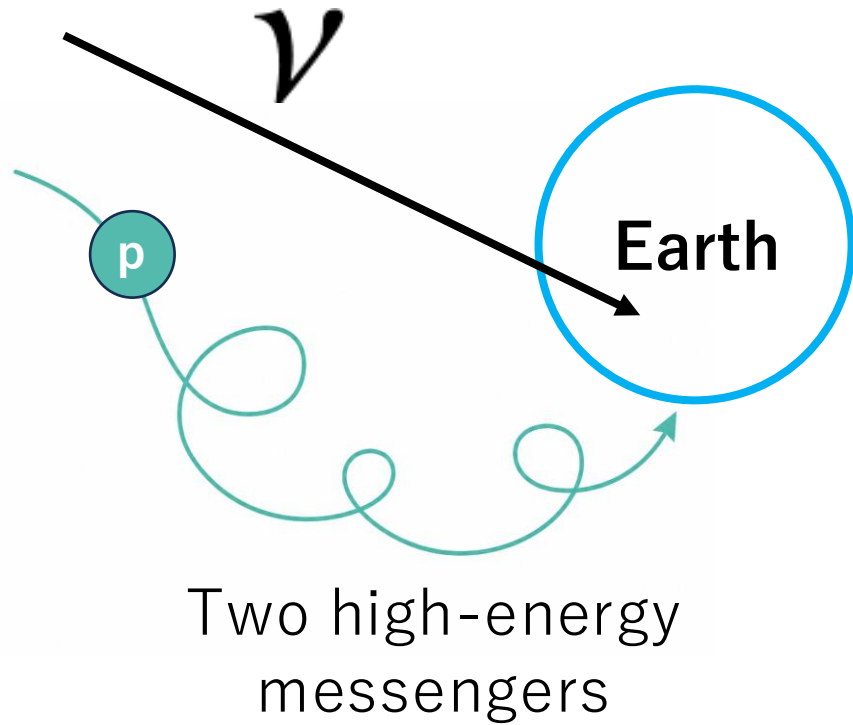
Credit: J. Werthebach,
IceCube/NSF

Where do cosmic neutrinos and UHECRs come from?



Could the same source population produce both cosmic neutrinos and UHECRs?

Where do cosmic neutrinos and UHECRs come from?

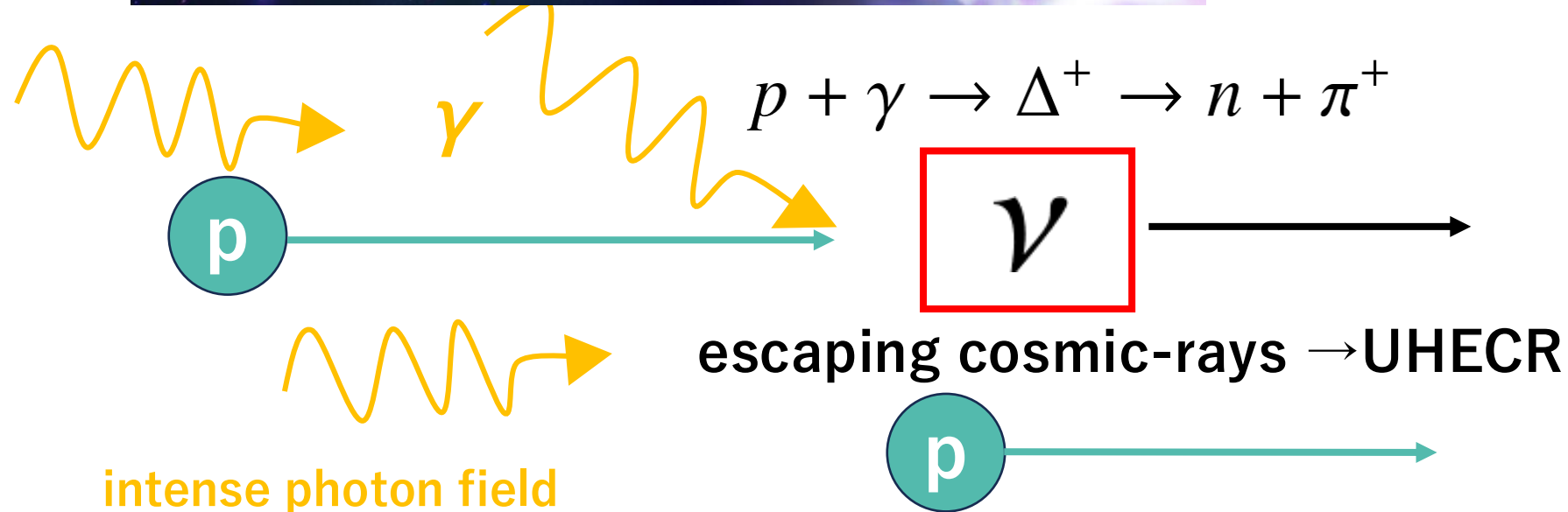


Could the same source population produce both cosmic neutrinos and UHECRs?

GRBs as Cosmic Accelerators

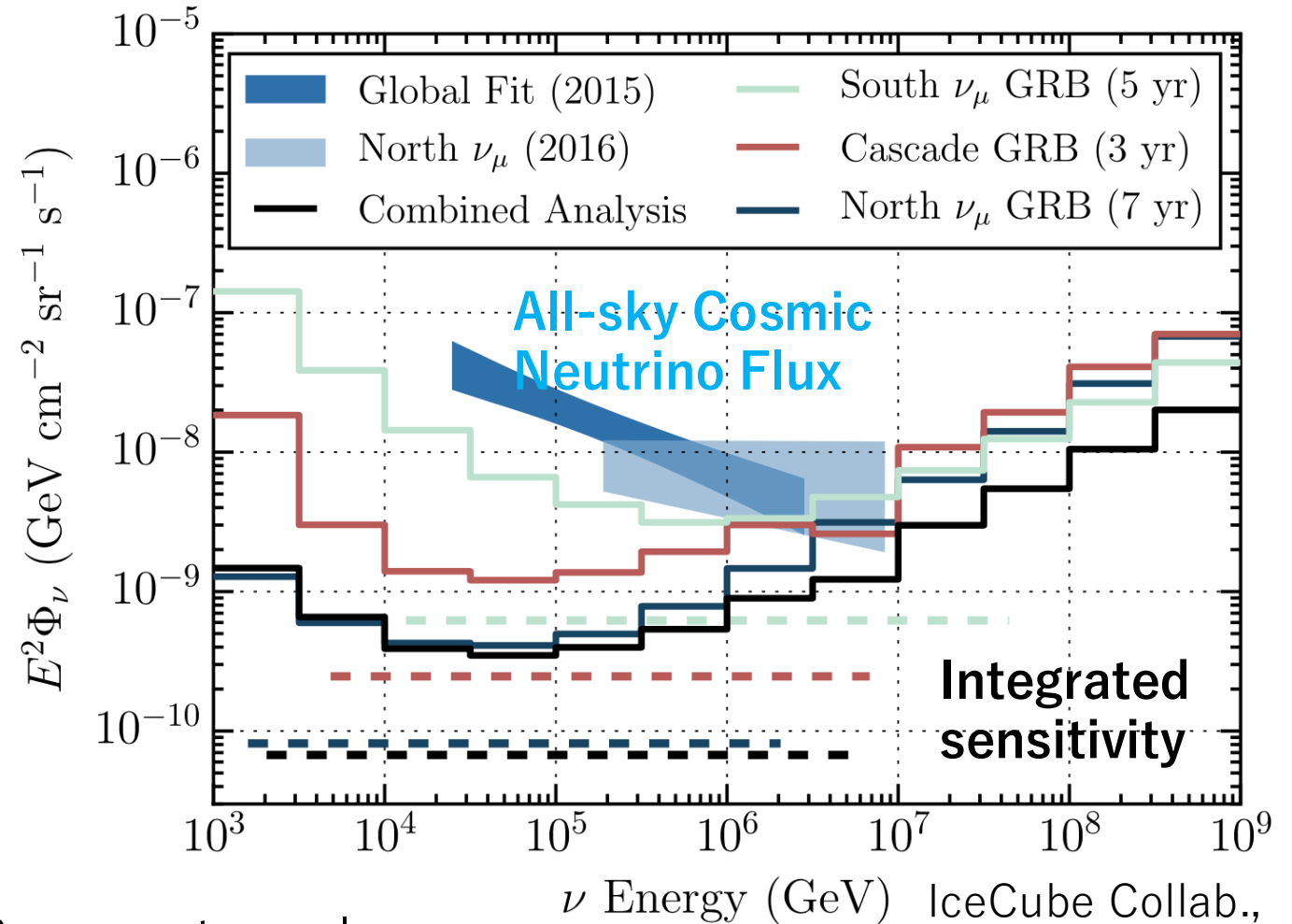
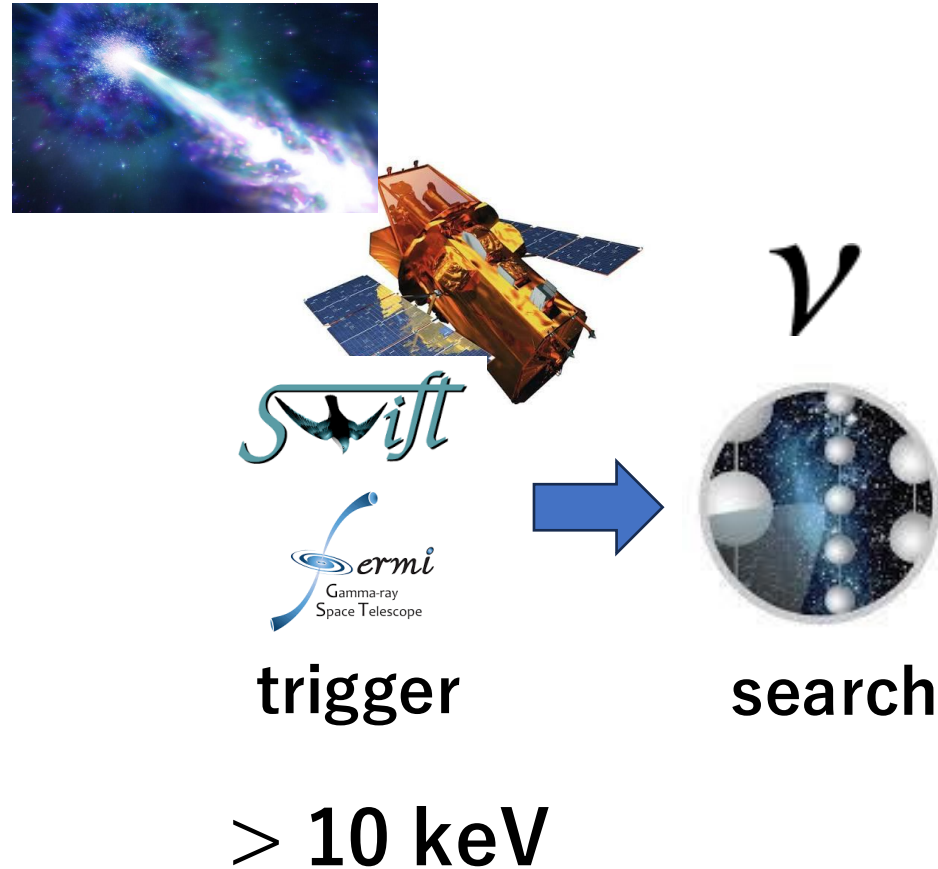


- Gamma-ray Burst (GRB)
- Relativistic Jet ($\Gamma \sim 100$)
- Prompt γ -rays
 $\sim 100 \text{ keV} - 1 \text{ MeV}$



Neutrinos can directly test the GRB-UHECR connection

IceCube Strongly Constrains Classical GRBs



Classical, gamma-ray-bright GRBs are strongly constrained

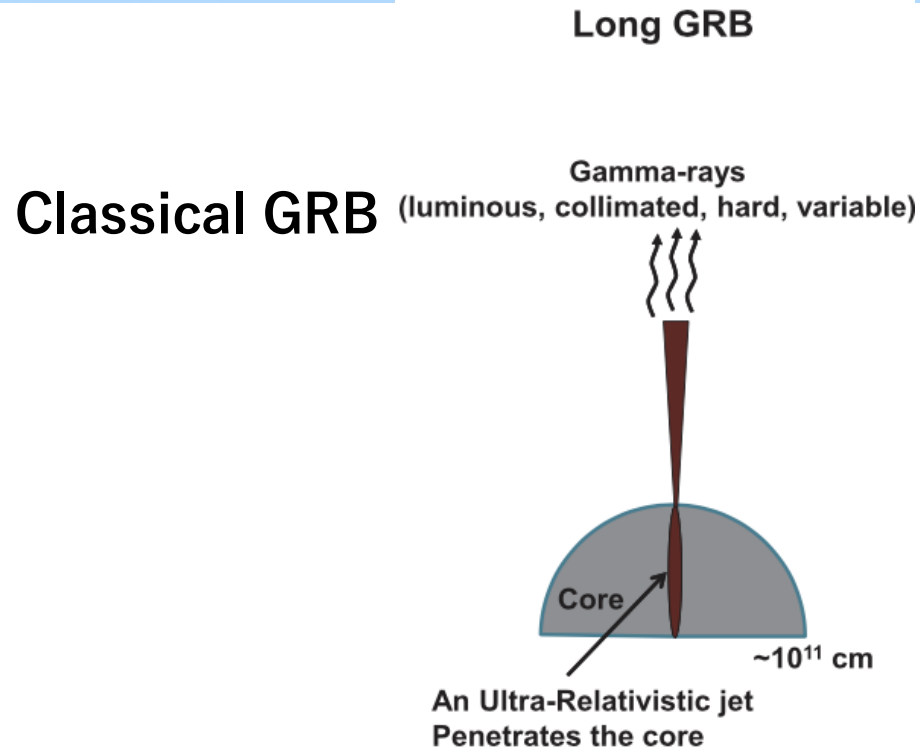
— but this does not exclude other $p\gamma$ transient populations.



Where should we look?



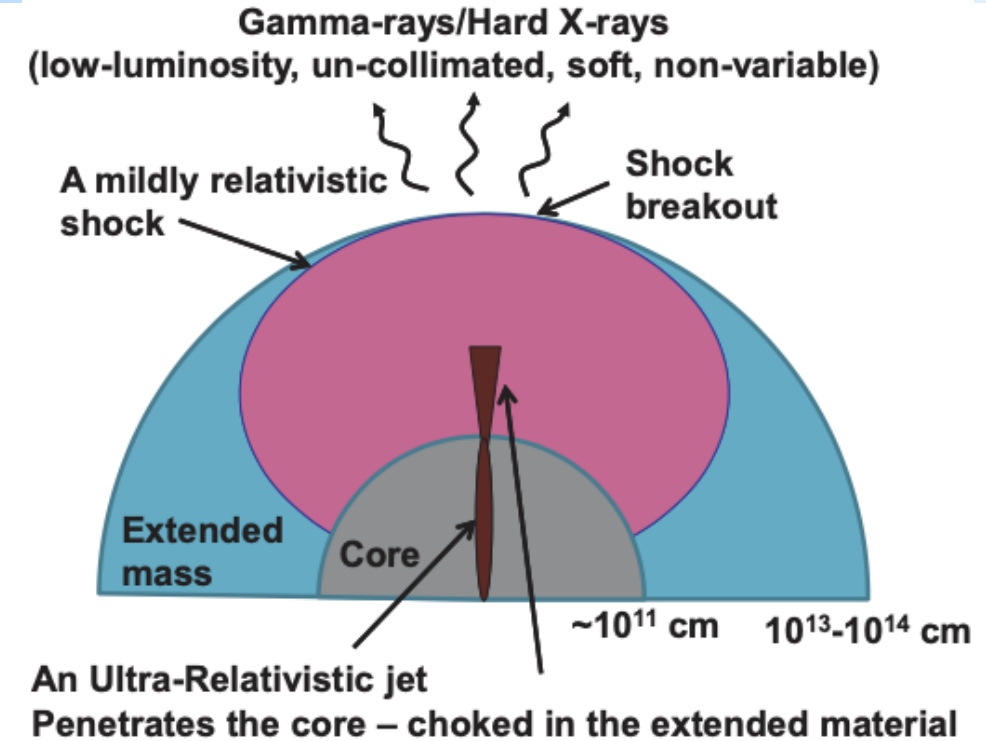
Beyond Classical GRBs: Why Soft X-rays?



Soft X-ray Transients (SXTs)

Example:
Low-luminosity GRB

Nakar 2015 ApJ



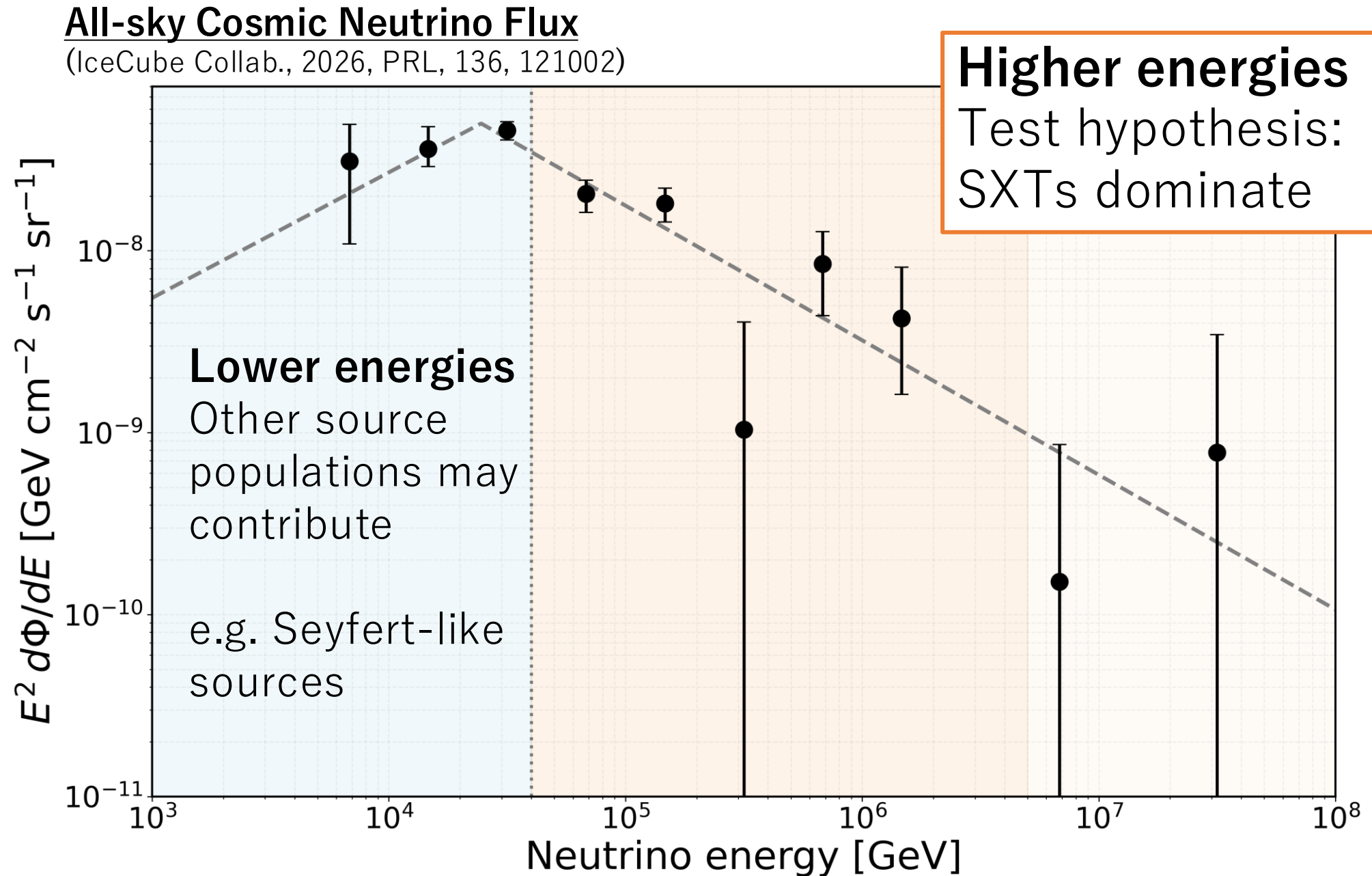
p γ target photon energy
 ϵ_X

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

Γ : bulk Lorentz factor of the plasma

Lower- Γ transients naturally shift the target photons into the soft X-ray band.

A working two-component picture

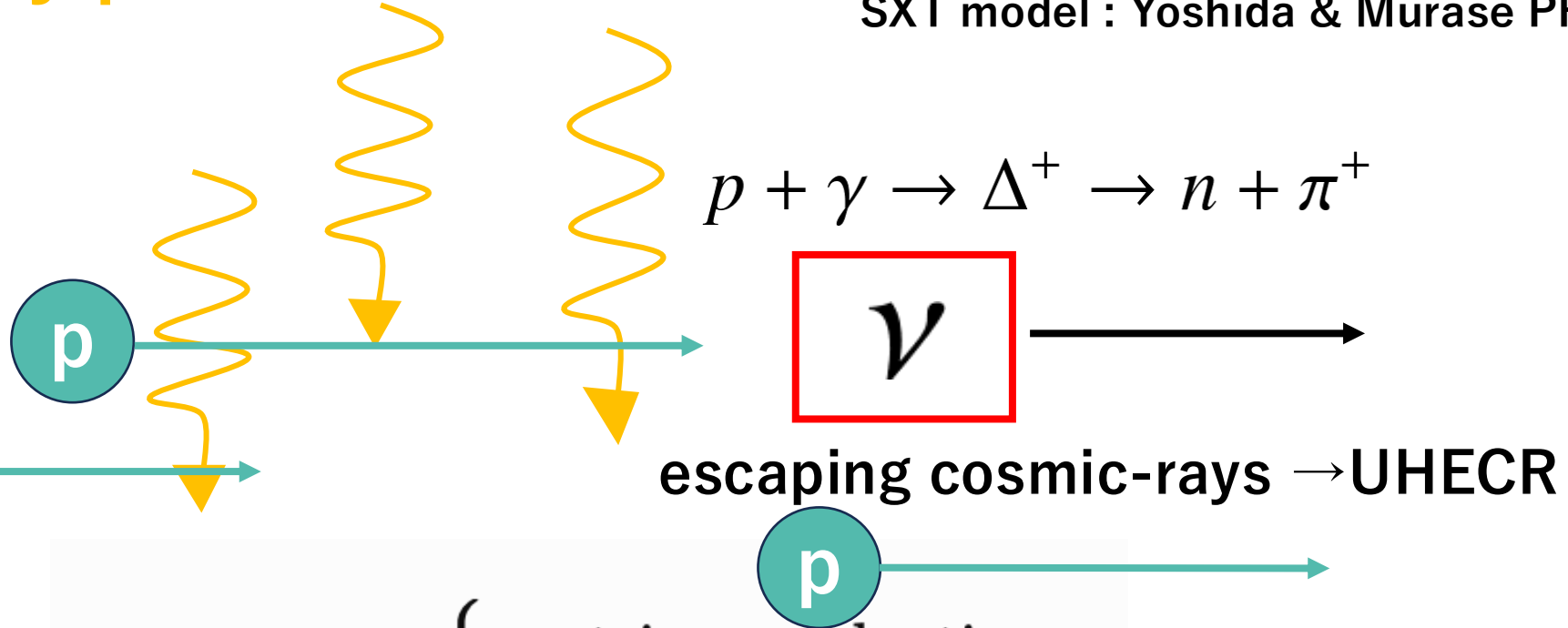


The X-ray Photon Field Controls Neutrino Production and CR Escape

X-ray photon field (L_X)

SXT model : Yoshida & Murase PRD 2024

CR
injection



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

CR loading factor

$$\tau_{p\gamma} \Rightarrow \begin{cases} \text{neutrino production} \\ \text{CR escape} \end{cases}$$

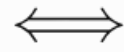
$$\text{Population flux} \propto n_0$$

$$\Phi_\nu = \Phi_\nu(L_X, \Gamma, n_0, \xi_{\text{CR}})$$

For fixed Γ and n_0 , the neutrino flux determines the required ξ_{CR} for a given L_{X7}

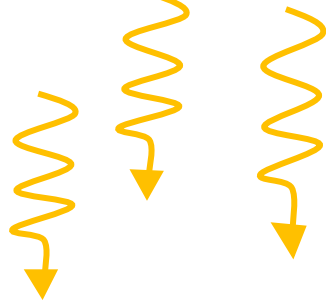
What Does the CR Loading Factor (ξ_{CR}) Mean?

$$\xi_{\text{CR}} \equiv \frac{L_{\text{CR}}}{L_X}$$



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

X-ray photon field (L_X)



$$\xi_{\text{CR}} = 1$$

CR injection

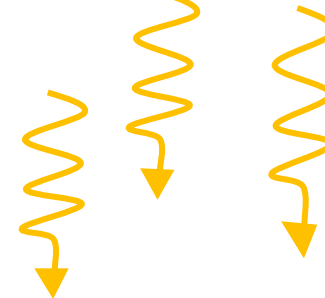


$$L_{\text{CR}} = 1 \times L_X$$

modest proton power

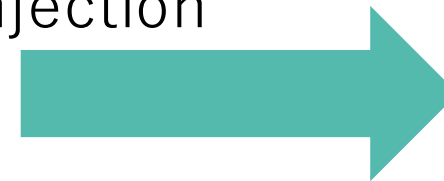
Same X-ray
luminosity L_X

X-ray photon field (L_X)



$$\xi_{\text{CR}} = 100$$

CR injection



$$L_{\text{CR}} = 100 \times L_X$$

enormous proton power

**More CR
power**



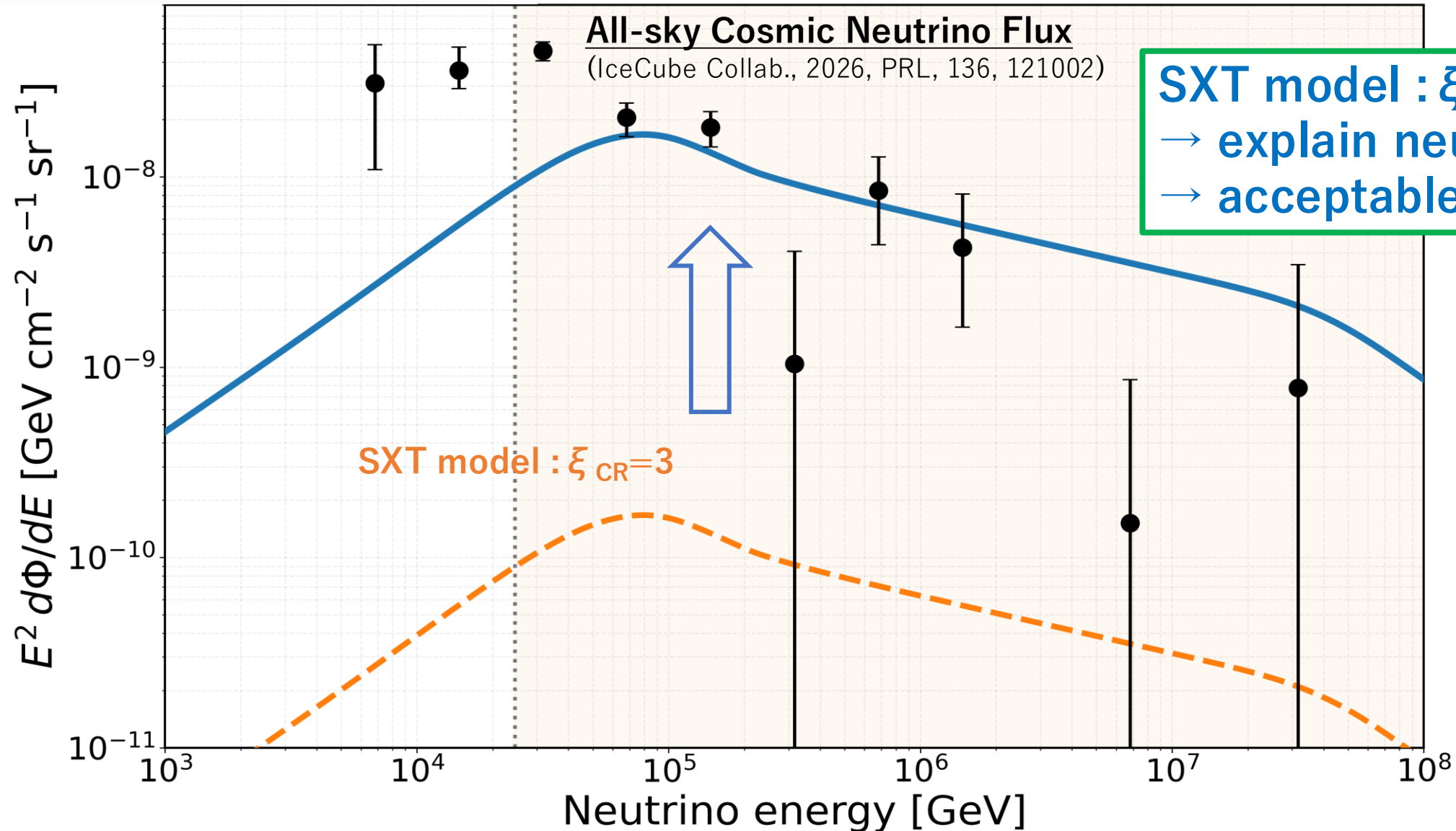
**More
escaping
UHECRs**

Larger ξ_{CR} = more energy injected into cosmic rays for the same X-ray luminosity

How Much CR Loading Is Required by Neutrinos?

$$\Phi_\nu = \Phi_\nu(L_X, \Gamma, n_0, \xi_{\text{CR}})$$

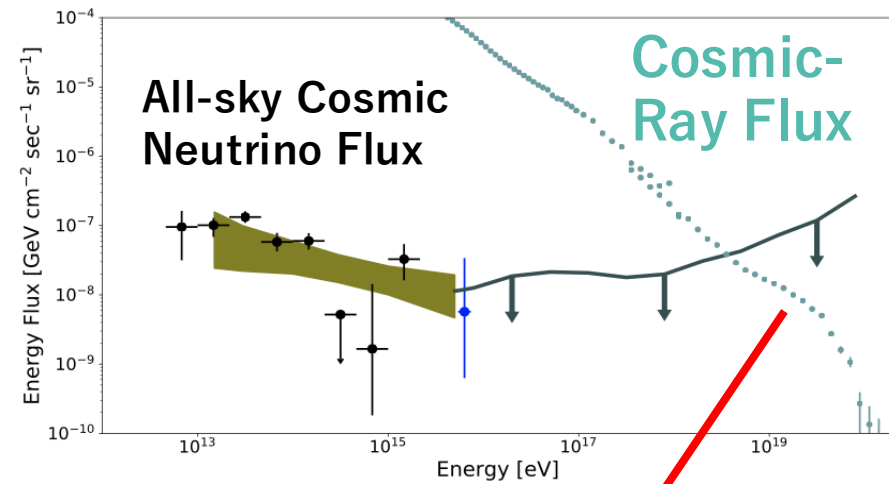
$$L_X = 1 \times 10^{46} \text{ erg/s}, \Gamma = 5, n_0 = 10^{-10} / \text{Mpc}^3$$



SXT model : $\xi_{\text{CR}}=300$
→ explain neutrino flux
→ acceptable?

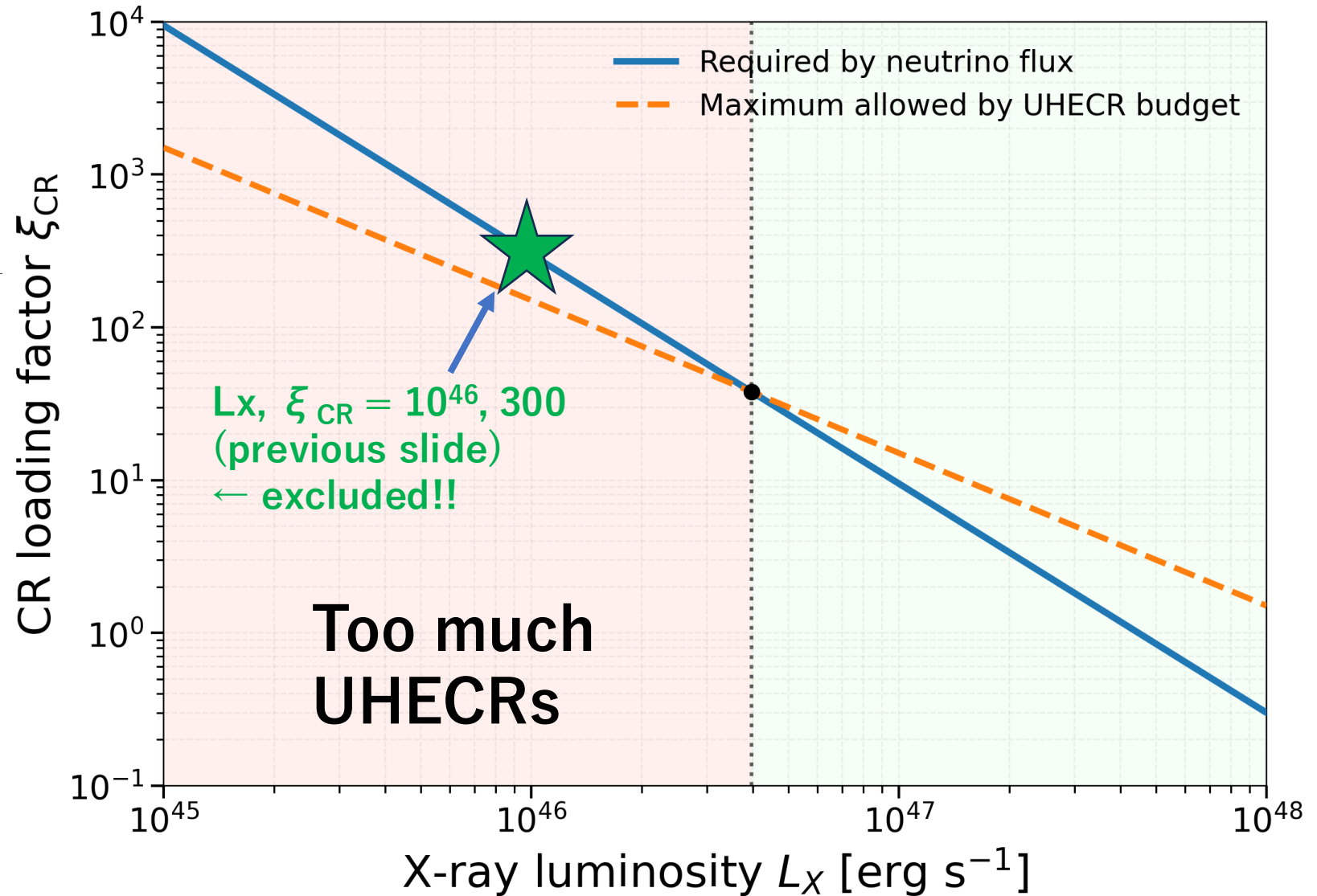
SXT model :
Yoshida &
Murase PRD
2024

Neutrino Requirement vs. UHECR Budget



ξ_{CR} limit by observed UHECR flux

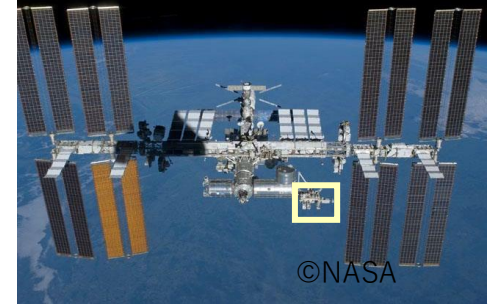
We need an observational constraint on L_x , but how?



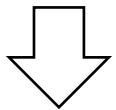
IceCube Turns the MAXI Archive into a Multimessenger Probe

- 2-20 keV soft X-ray band
- All-sky scan every 90 min

Continuous all-sky
X-ray monitoring
from 2009



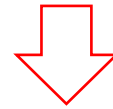
MAXI alone
all-sky X-ray
archive



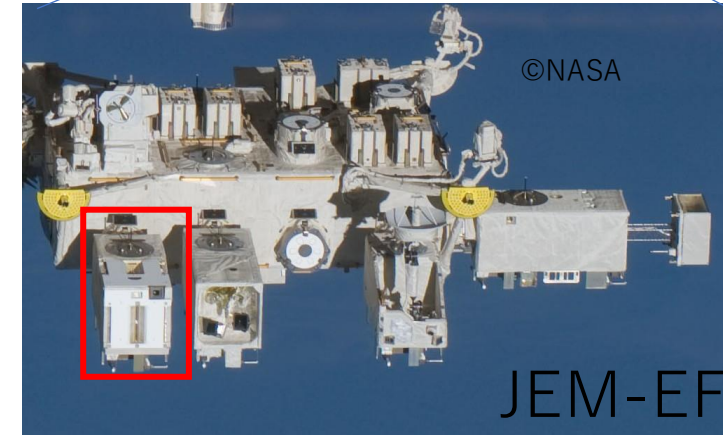
no predefined
target

IceCube + **MAXI**

time + direction



targeted MAXI search



Matsuoka et al.,
PASJ 61, 999 (2009)

14.5 Years of Simultaneous MAXI–IceCube Observations

IceCube high-energy track sample

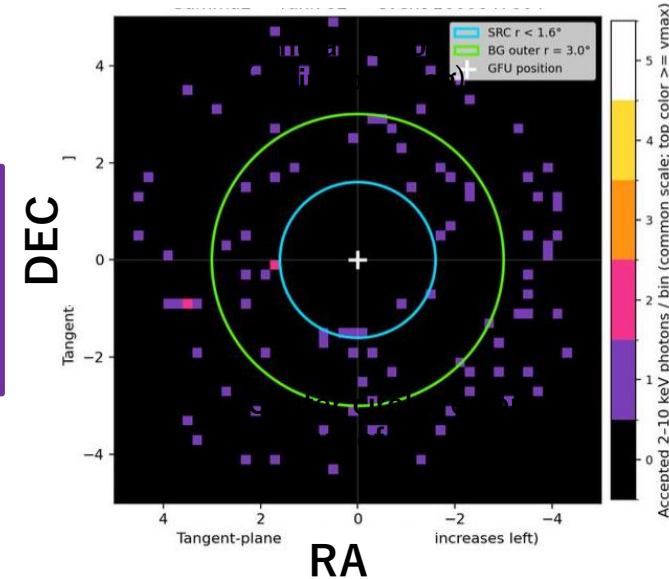
- Northern-sky muon-track events
→ time + direction

MAXI

- Photon-counting observations

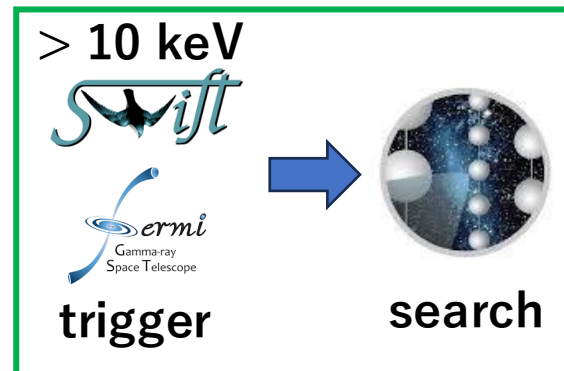
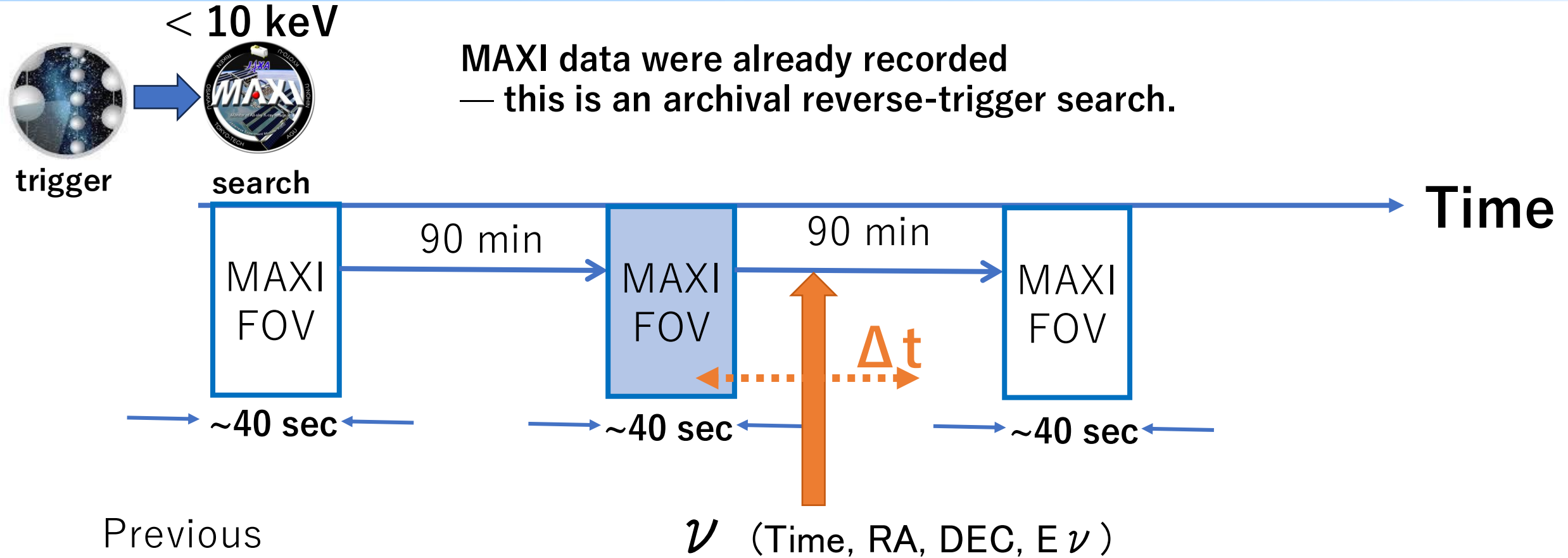
Targeted
multimessenger search

MAXI X-ray Image



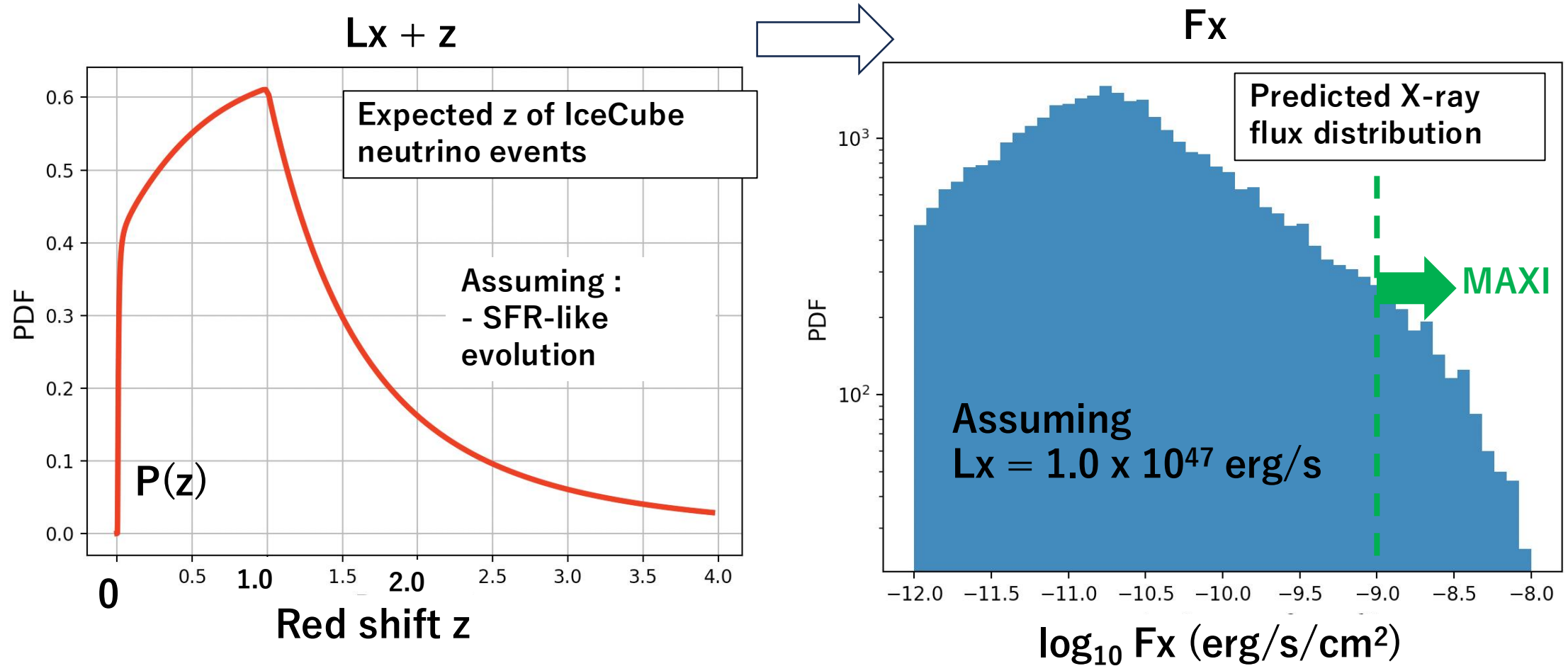
Final analysis sample : $\sim 2 \times 10^5$ IceCube events
with simultaneous MAXI coverage in 14.5 years

For Each Neutrino, Search the Corresponding MAXI Scan



For each IceCube event, search the corresponding MAXI scan within a 90-min window.

How Can MAXI Constrain L_x Without Knowing the Distance?



Assume a common L_x for the SXT population
Individual source distances are unknown $\rightarrow$ use the expected $P(z)$

How Do We Test a Trial Lx?

$$\mathcal{L}_{\text{sig+bgd}} = \overbrace{\frac{n_{\text{sig}}}{n_{\text{atm}} + n_{\text{dif}}} P_{\nu}^{\text{sig}}(E_{\nu}, \delta) \times P_X^{\text{sig}}(N_X, \mu_{X\text{sig}}(L_{X\text{ref}}, z))}^{\text{SXT event}} + \overbrace{\frac{1}{n_{\text{atm}} + n_{\text{dif}}} \left\{ n_{\text{dif}} P_{\nu}^{\text{dif}}(E_{\nu}, \delta) - n_{\text{sig}} P_{\nu}^{\text{sig}}(E_{\nu}, \delta) \right\} P_{X_{\text{DB}}}^{\text{bgd}}(N_X)}^{\text{unrelated astrophysical neutrino}} + \overbrace{\frac{n_{\text{atm}}}{n_{\text{atm}} + n_{\text{dif}}} P_{\nu}^{\text{atm}}(E_{\nu}, \delta) P_{X_{\text{DB}}}^{\text{bgd}}(N_X)}^{\text{atmospheric neutrino}}$$

$P_{\nu}(E_{\nu}, \delta)$: neutrino PDF from reconstructed energy and direction

$P_X(N_X)$: MAXI X-ray count (N_X) PDF

$n_{\text{sig}}, n_{\text{dif}}, n_{\text{atm}}$: expected event numbers of the three components

$L_{X,\text{ref}}$: population X-ray luminosity scanned in the likelihood

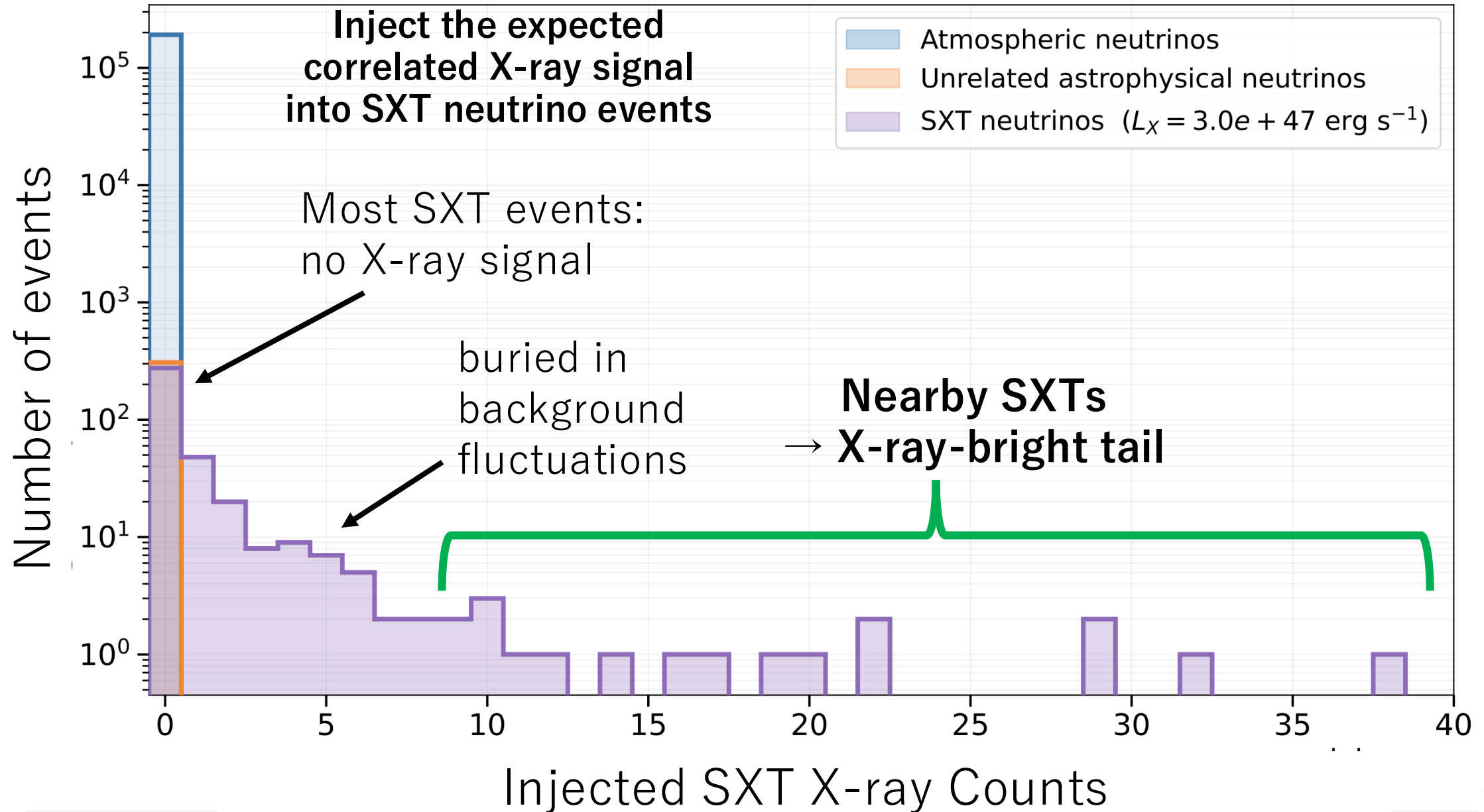
$$\text{LHR}(L_{X\text{ref}}) = \frac{\mathcal{L}_{\text{sig+bgd}}(L_{X\text{ref}})}{\mathcal{L}_{\text{bgd-only}}}$$

$$TS = \max_{L_{X,\text{ref}}} \sum_i \log_{10} \text{LHR}_i$$

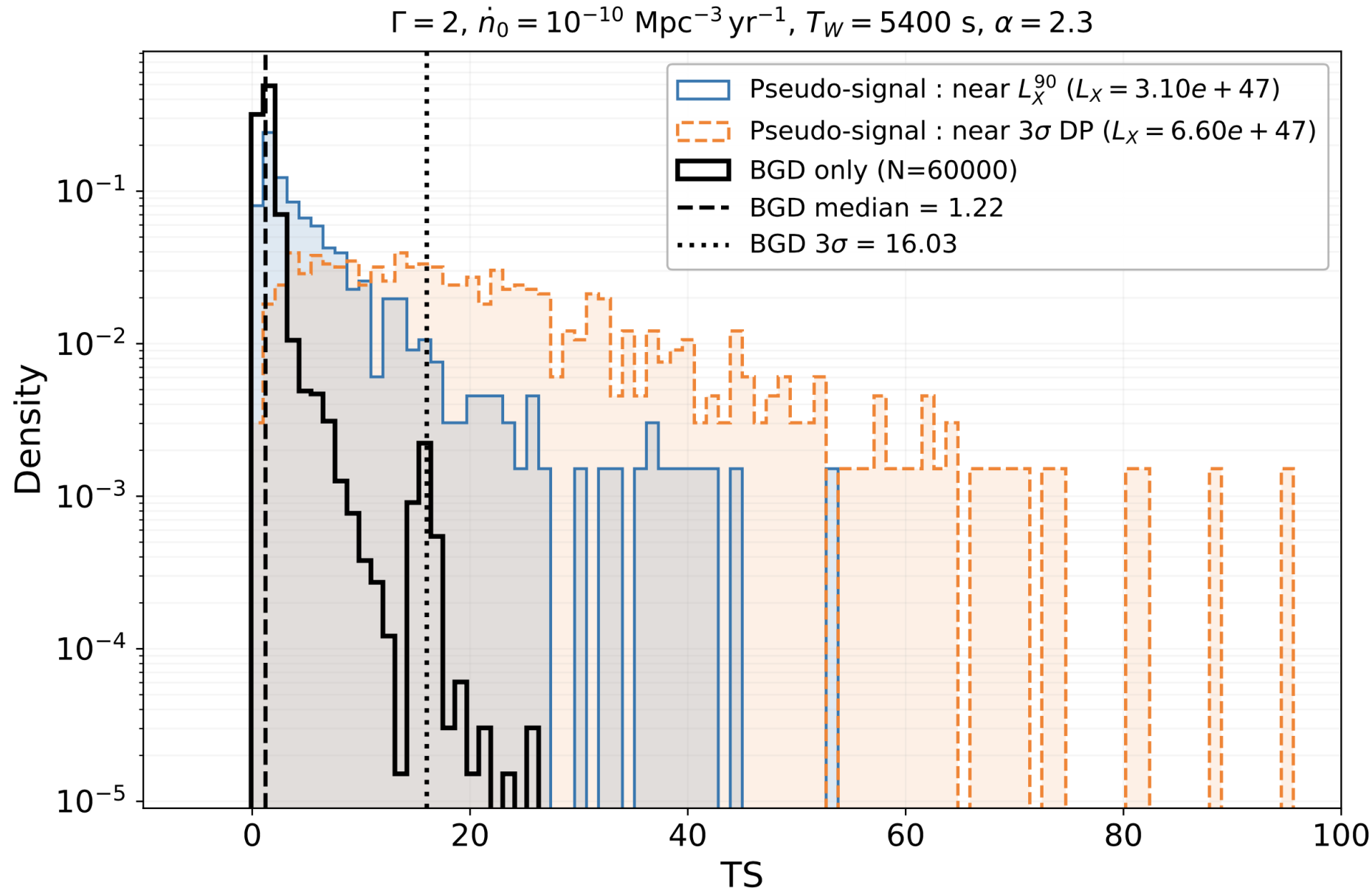
Each coincidence → event-level LHR

14.5 years of coincidences → one population-level TS

What Does a Pseudo-SXT Signal Look Like in MAXI?



Brighter SXT Populations Produce Larger TS



Background only

RA-scrambled

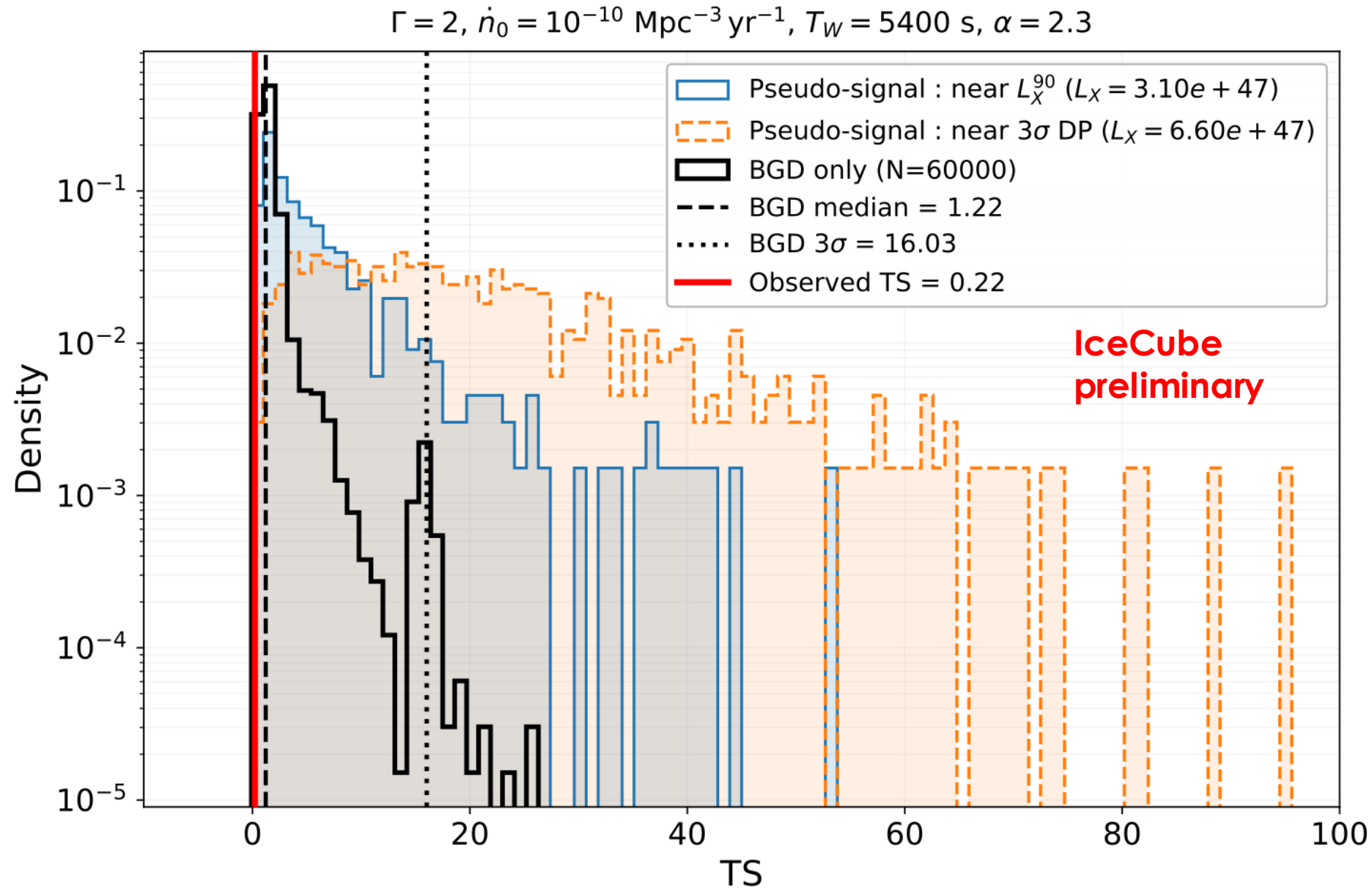
IceCube $\times$ real MAXI

Inject SXT signals

brighter LX

$\rightarrow$ larger TS

No X-ray Counterpart Excess in 14.5 Years



191,925 IC-MAXI
coincident events

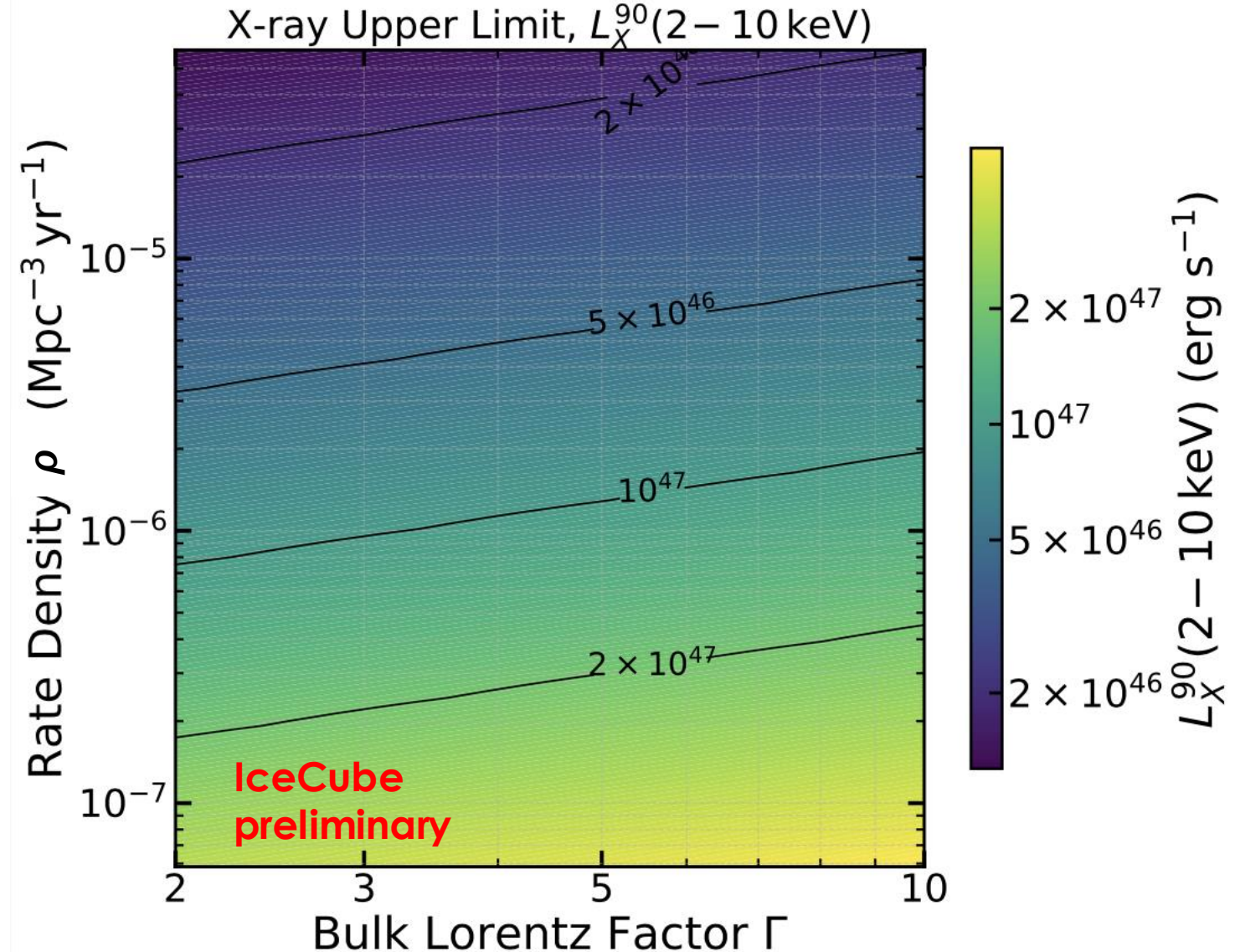
**No X-ray
Counterpart Excess
in 14.5 Years**

X-ray-bright SXT Populations Cannot Dominate the High-energy Neutrino Flux

No X-ray counterpart
excess

$$\Rightarrow L_X < L_X^{90}(n_0, \Gamma)$$

**The first systematic
constraints are obtained
across the $n_0 - \Gamma$ plane
using real soft-X-ray
data.**



X-ray limits imply a minimum CR loading and constrain UHECR-source models

L_X^{90} from MAXI

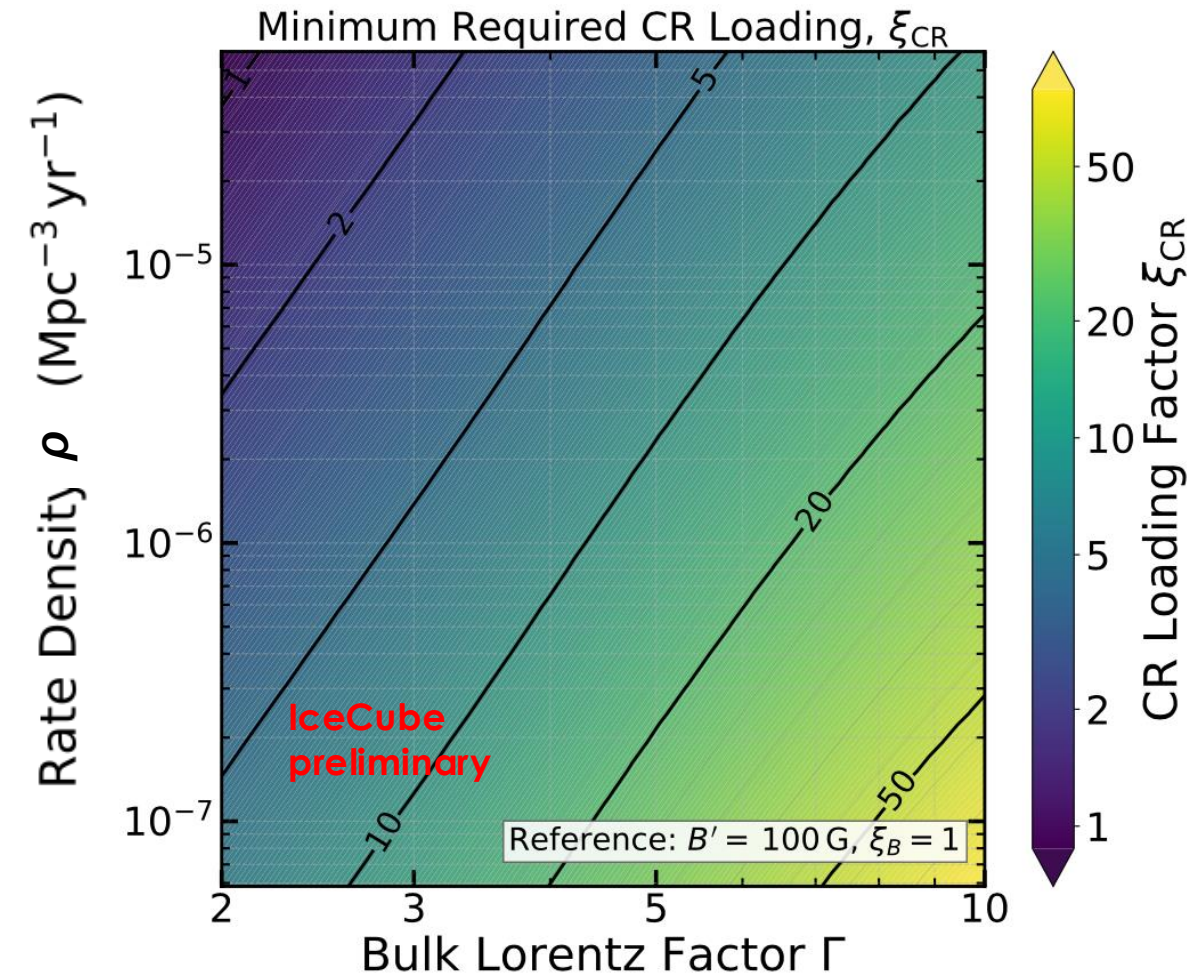
→

$\xi_{\text{CR}}^{\text{min}}$ from IceCube

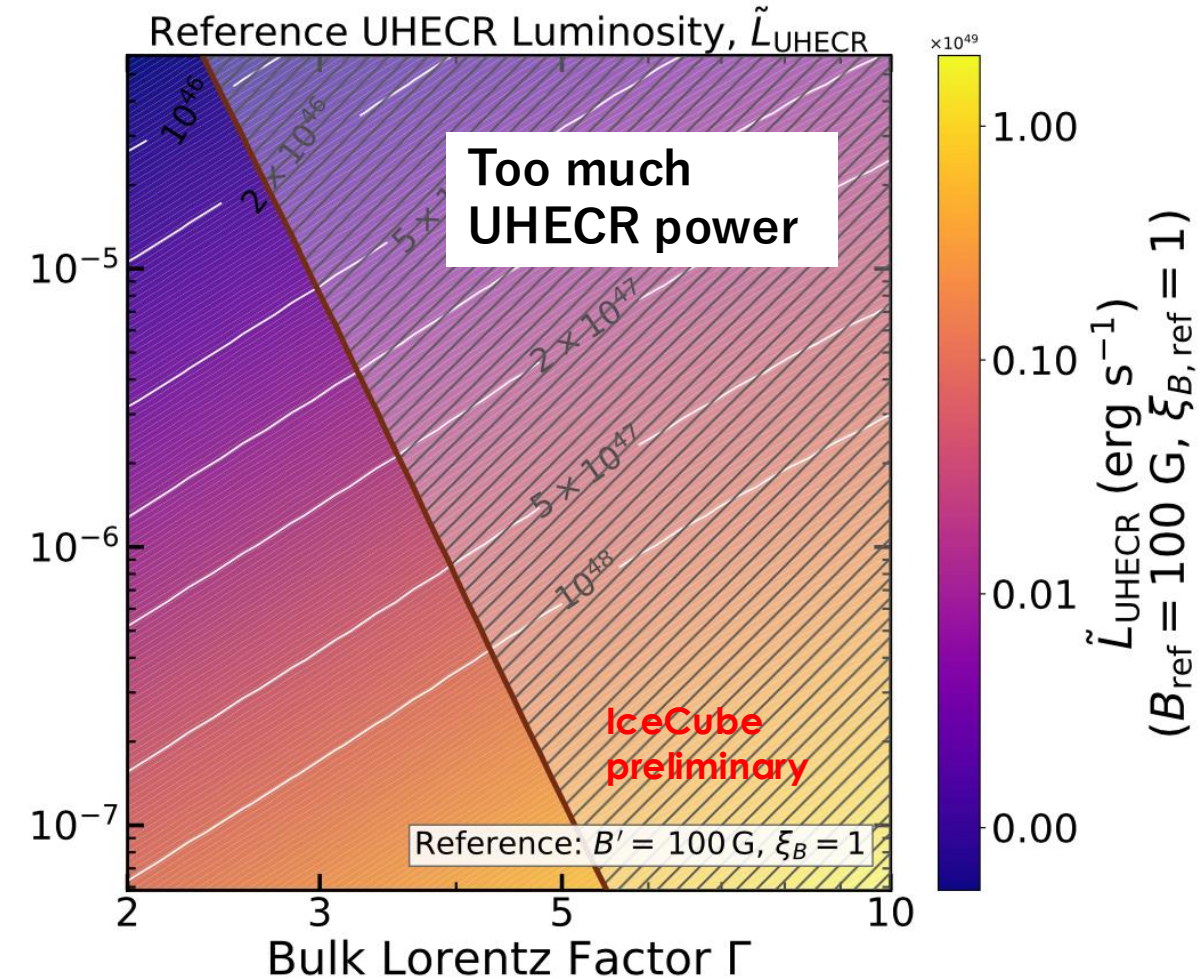
→

UHECR budget

Neutrino requirement



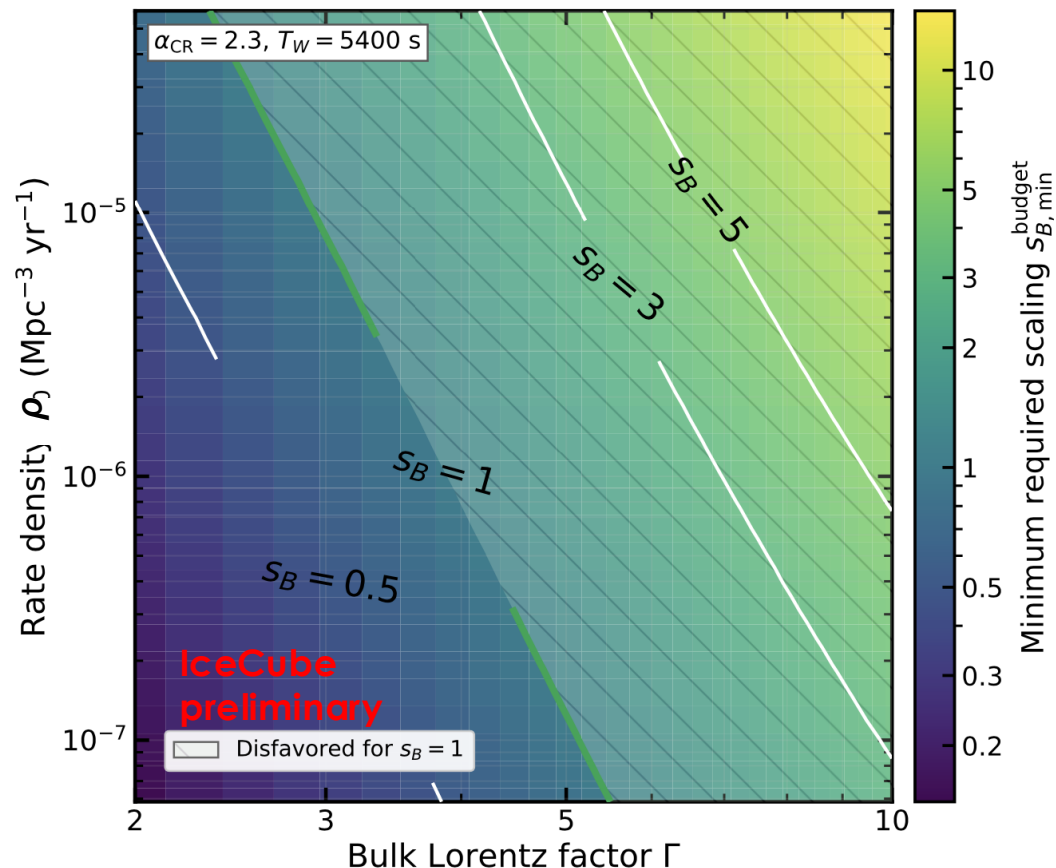
UHECR budget



Robustness of the UHECR interpretation

Magnetic environment

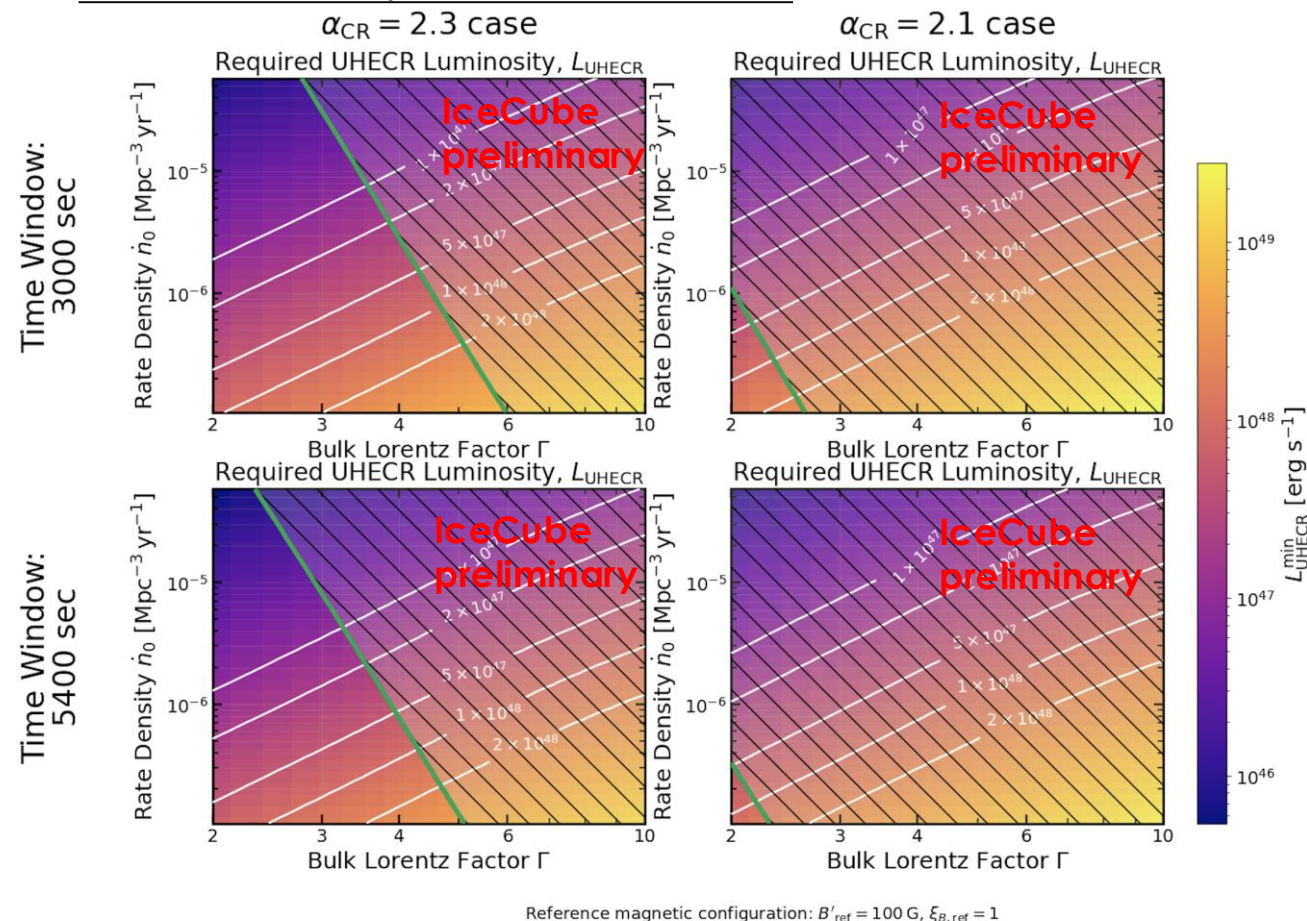
Minimum Magnetic Scaling Consistent with the UHECR Budget



$$\tilde{L}_{\text{UHECR}}^{\text{min}} = L_{\text{UHECR}}^{\text{min}}(B', \xi_B) \underbrace{\left(\frac{B'}{100 \text{ G}} \right) \left(\frac{1}{\xi_B} \right)^{1/2}}_{s_B}$$

other environments are described by the scaling s_B

Proton index / source duration



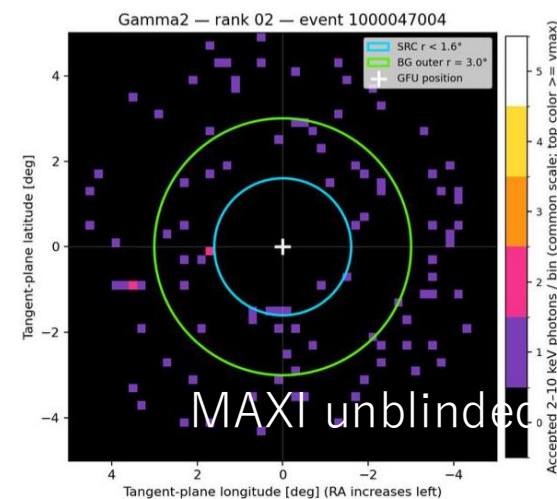
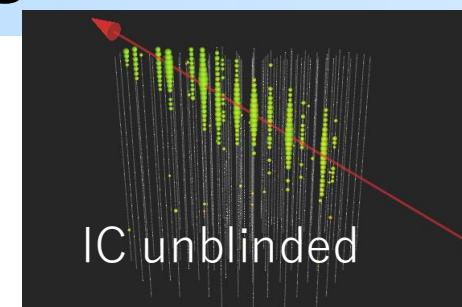
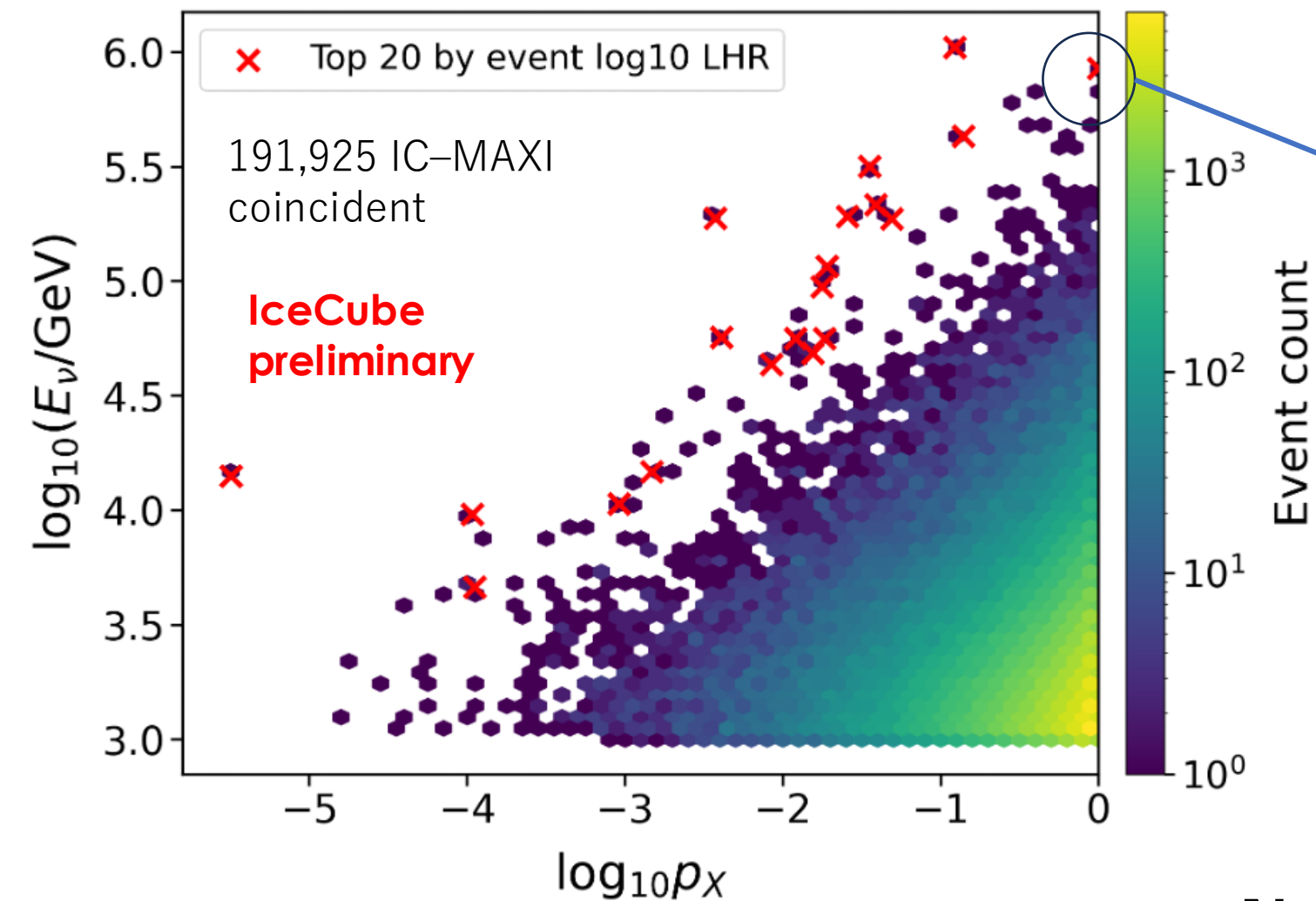
- Magnetic environment changes the disfavored region
- Variations in proton index and duration do not remove the constraint.

Summary

- 14.5 yr of IceCube + MAXI $\rightarrow$ no correlated X-ray excess
- X-ray-bright SXT populations cannot dominate the high-energy neutrino flux
- First systematic IceCube–MAXI multimessenger constraints on SXT populations using real soft-X-ray data
- The X-ray limits require large CR loading and disfavor part of the UHECR-source parameter space

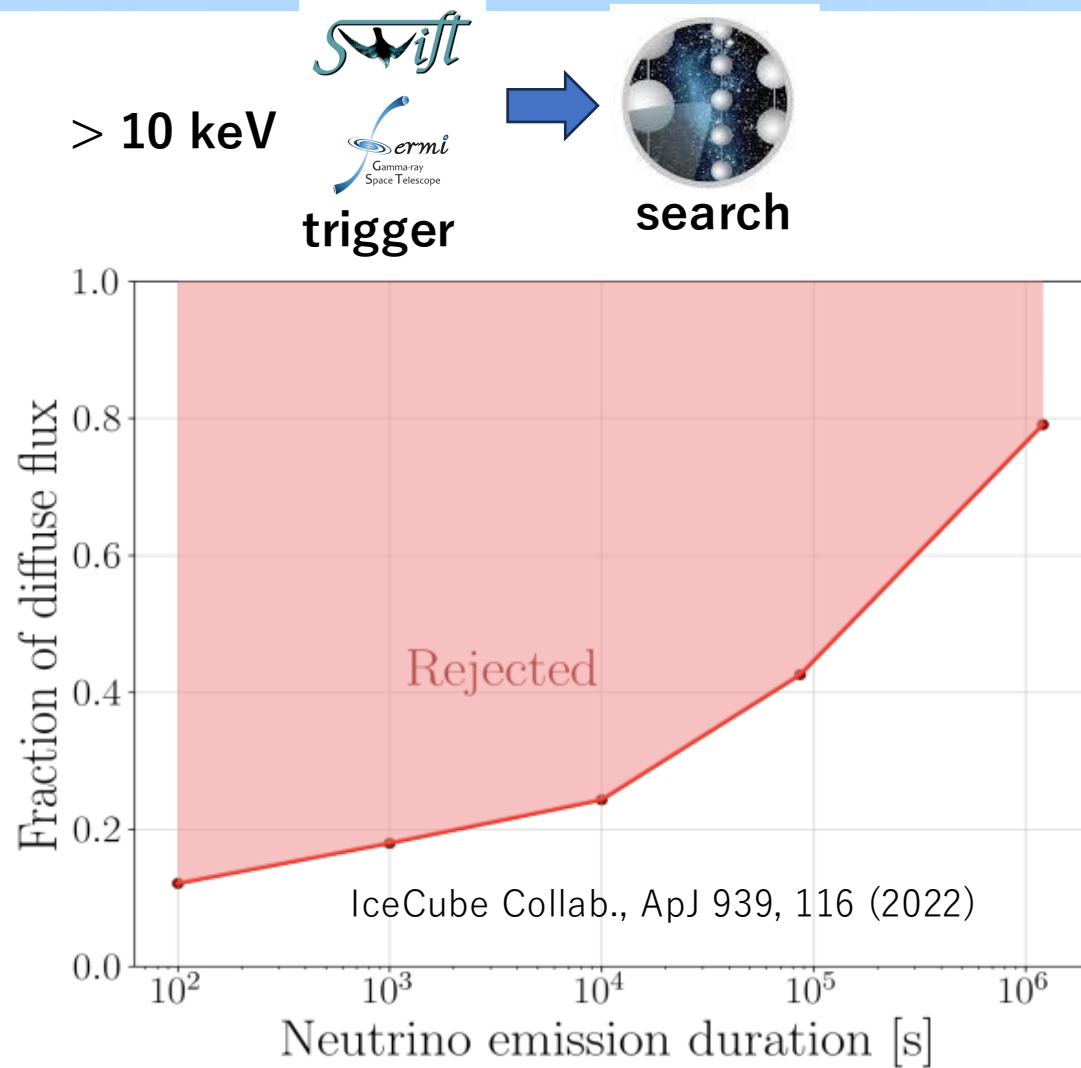
appendix

The Most Signal-like Events Are Consistent with Background



No anomalous X-ray-bright
neutrino event

Classical GRBs cannot dominate the diffuse neutrino flux



Prompt GRB searches: $O(10^3)$ GRBs, from Northern-sky $\nu \mu$ tracks to all-sky, all-flavor searches —no significant neutrino association; contribution $\lesssim 1\%$ of the diffuse flux

IceCube Collab., ApJL 805, L5 (2015); ApJ 824, 115 (2016); ApJ 843, 112 (2017)

Extended time-window search: emission on timescales up to $\sim 10^4 \text{ s}$ constrained to $< 24\%$ of the diffuse flux

IceCube Collab., ApJ 939, 116 (2022)

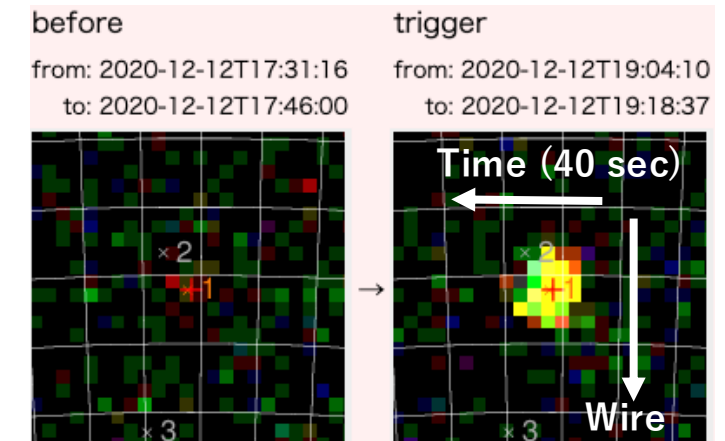
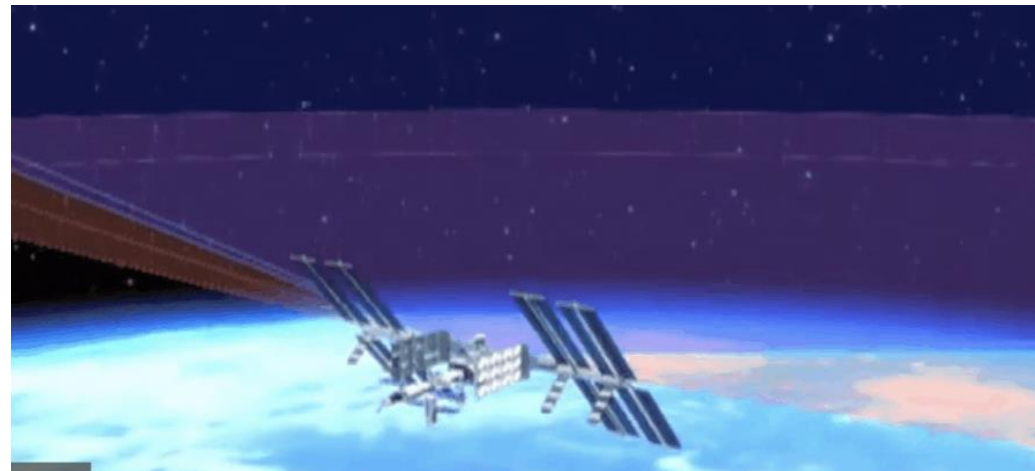
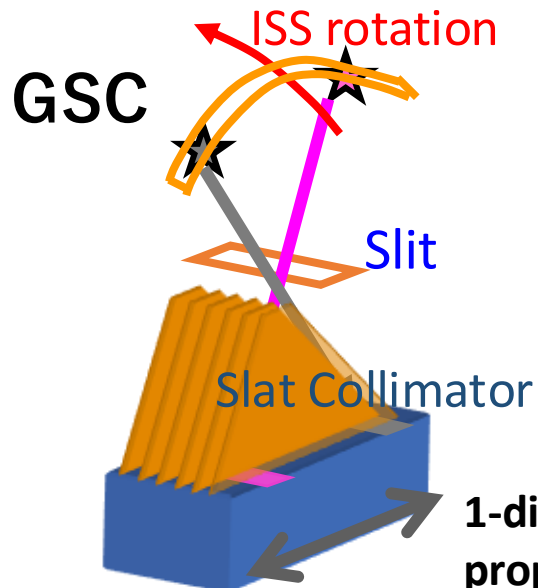
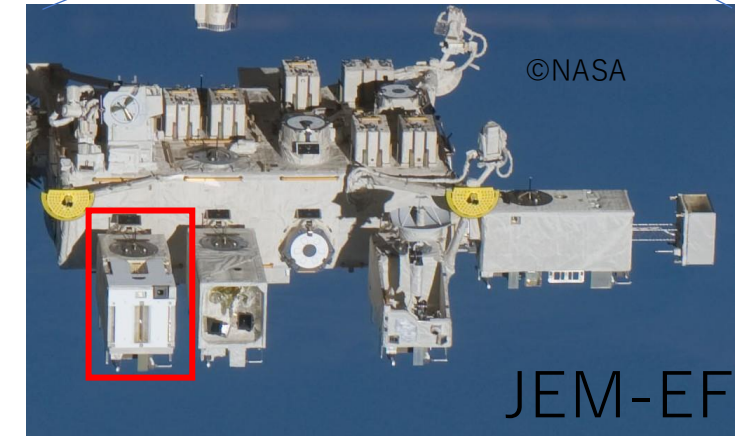
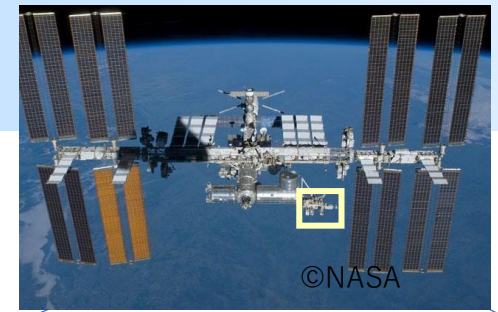
GRB 221009A (BOAT): no significant neutrino detection

IceCube Collab., ApJL 946, L26 (2023)

MAXI (Monitor of All-sky X-ray Image)

Matsuoka et al.,
PASJ 61, 999 (2009)

- Operated since Aug 2009, 14.5 years overlap with the IceCube data set
- Scans all-sky every 90 minutes with ISS rotation searching for X-ray transients, monitoring hundreds of X-ray sources, with Gas Slit Camera (GSC) in 2-20 keV
 - Despite its mature proportional-counter technology, the GSC remains highly effective for all-sky monitoring with a large effective area.
- Typical exposure time for a point source is ~ 40 sec (due to 3 deg FOV)
- All data are public



Testing the SXT hypothesis with a multimessenger likelihood

$$\mathcal{L}_{\text{sig+bgd}} = \underbrace{\frac{n_{\text{sig}}}{n_{\text{atm}} + n_{\text{dif}}} P_{\nu}^{\text{sig}}(E_{\nu}, \delta) \times P_X^{\text{sig}}(N_X, \mu_{X\text{sig}}(L_{X\text{ref}}, z))}_{\nu \text{ signal related X-ray}} + \underbrace{\frac{1}{n_{\text{atm}} + n_{\text{dif}}} \left\{ n_{\text{dif}} P_{\nu}^{\text{dif}}(E_{\nu}, \delta) - n_{\text{sig}} P_{\nu}^{\text{sig}}(E_{\nu}, \delta) \right\} P_{X_{\text{DB}}}^{\text{bgd}}(N_X)}_{\nu \text{ signal "not" related X-ray}} + \underbrace{\frac{n_{\text{atm}}}{n_{\text{atm}} + n_{\text{dif}}} P_{\nu}^{\text{atm}}(E_{\nu}, \delta) P_{X_{\text{DB}}}^{\text{bgd}}(N_X)}_{\text{atmospheric } \nu \text{ bgd "not" related X-ray}}$$

$$\text{LHR}(L_{X\text{ref}}) = \frac{\mathcal{L}_{\text{sig+bgd}}(L_{X\text{ref}})}{\mathcal{L}_{\text{bgd-only}}}$$

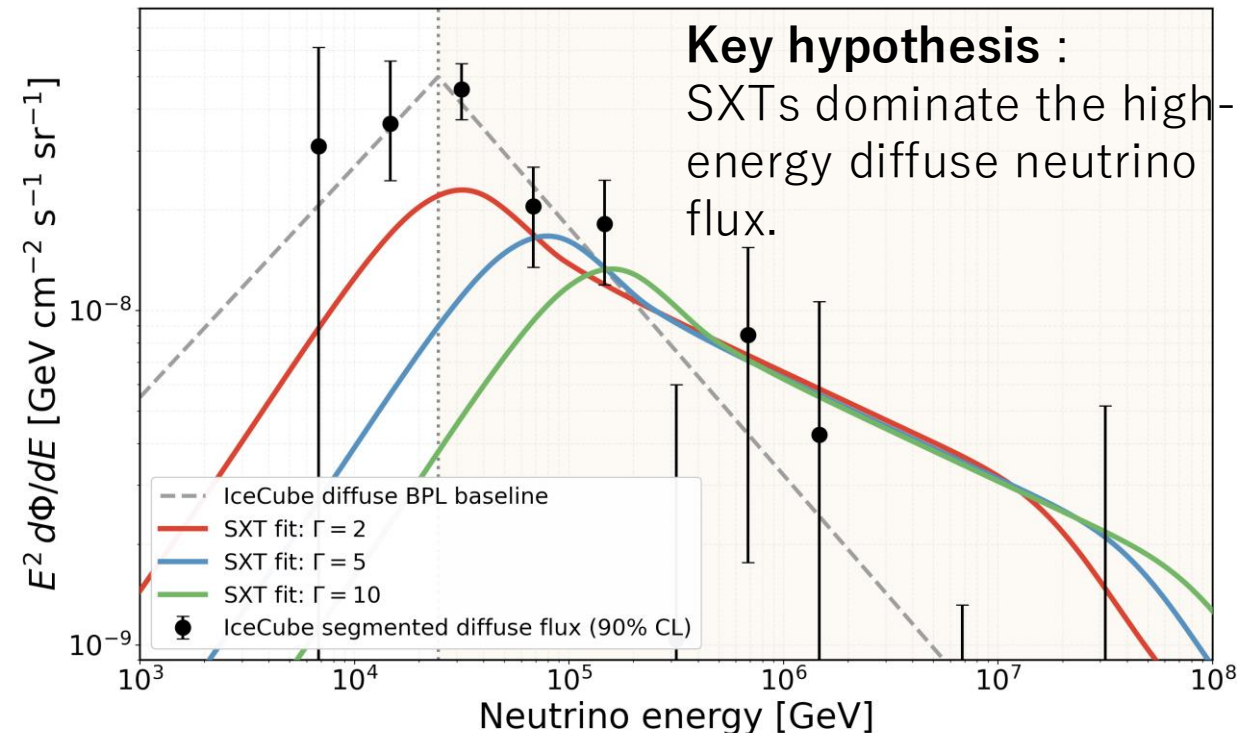
$$TS = \max_{L_{X,\text{ref}}} \sum_i \log_{10} \text{LHR}_i$$

$P_{\nu}(E_{\nu}, \delta)$: neutrino PDF from reconstructed energy and direction
 $P_X(N_X)$: MAXI X-ray count (N_X) PDF
 $n_{\text{sig}}, n_{\text{dif}}, n_{\text{atm}}$: expected event numbers of the three components
 $L_{X,\text{ref}}$: population X-ray luminosity scanned in the likelihood

Likelihood components

- 1.SXT: n_{sig} fixed by fitting the SXT-model normalization to the measured segmented diffuse flux
 - 2.Diffuse: BPL baseline – SXT contribution, avoiding double counting
 - 3.Atmospheric: fixed H3a + SIBYLL2.1 template
- Statistical test

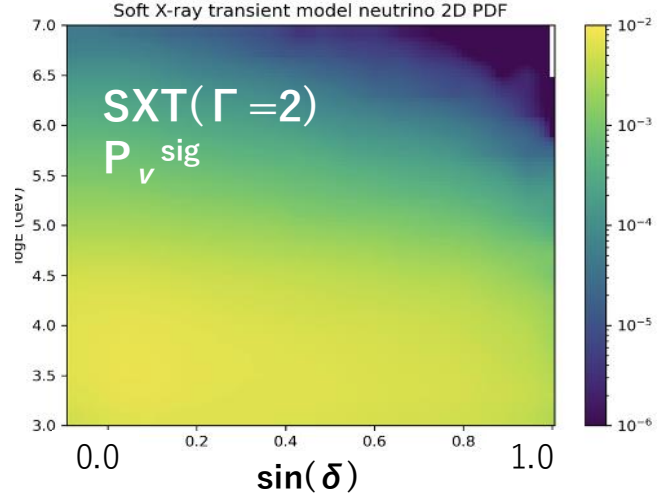
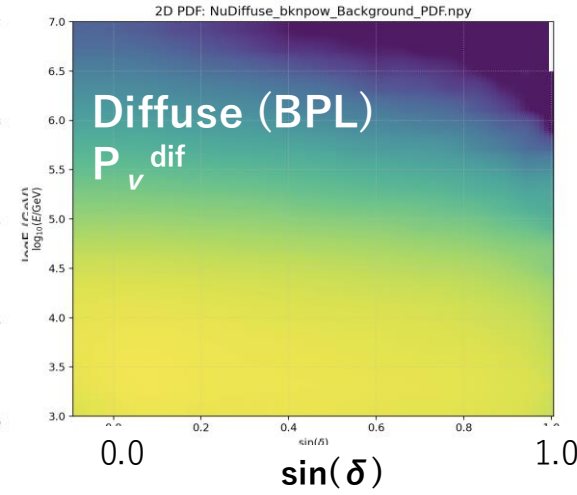
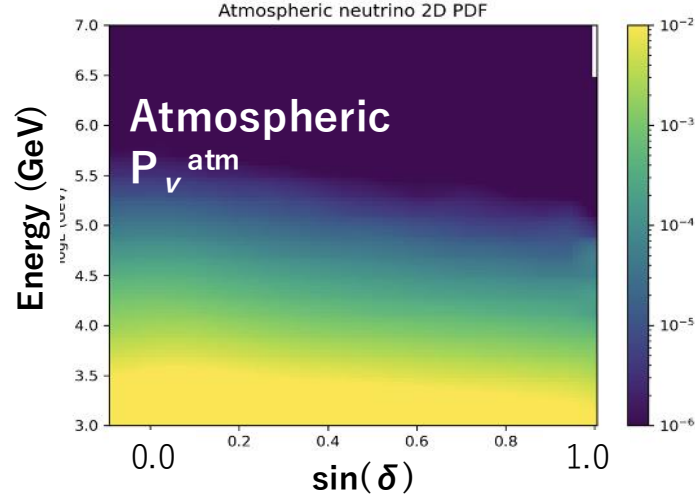
- $n_{\text{sig}}, n_{\text{dif}}, n_{\text{atm}}$ fixed — no event-by-event fitting
- Scan $L_{X,\text{ref}}$ only and maximize the summed LHR over 14.5 years



Neutrino PDFs and the MAXI X-ray background PDF

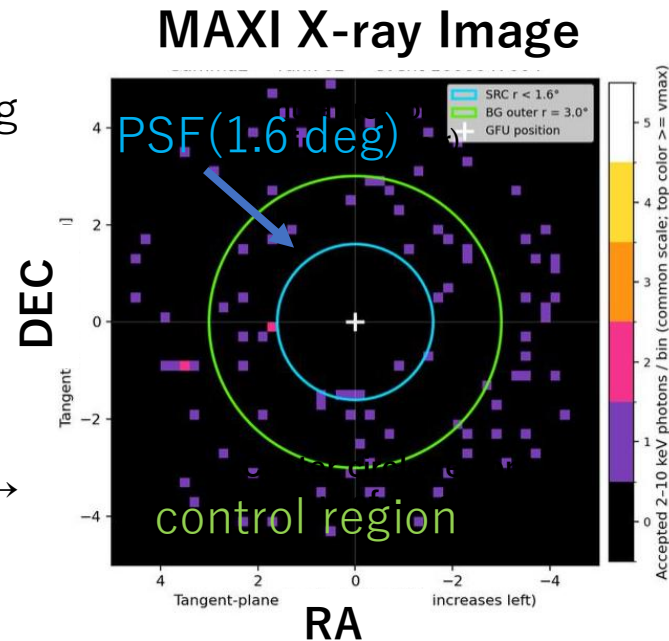
Neutrino PDFs(P_ν)

- Derived from MC samples
- Uses reconstructed E and δ
- Separate PDFs for SXT / diffuse / atmospheric

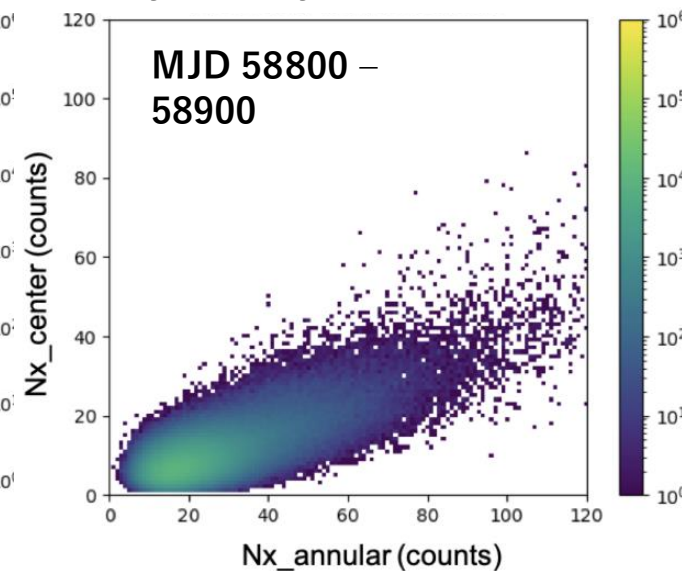
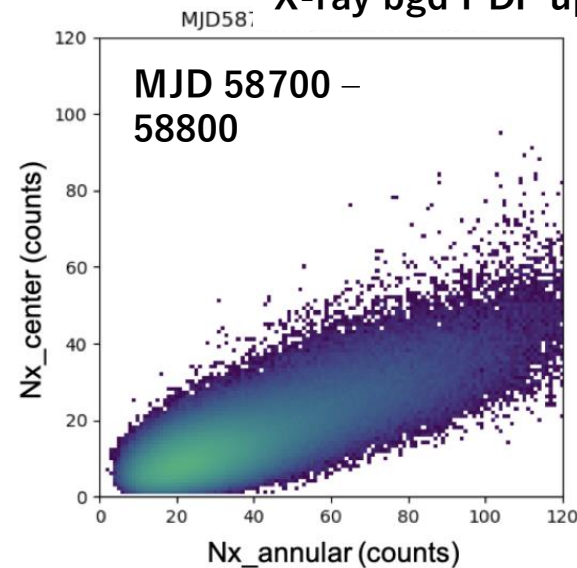


X-ray background PDFs (P_{xbgd})

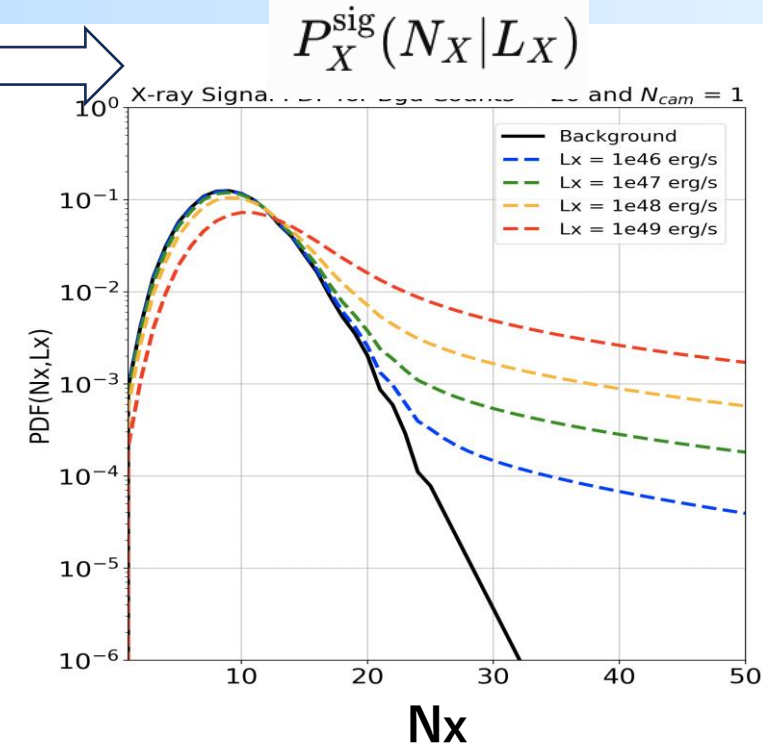
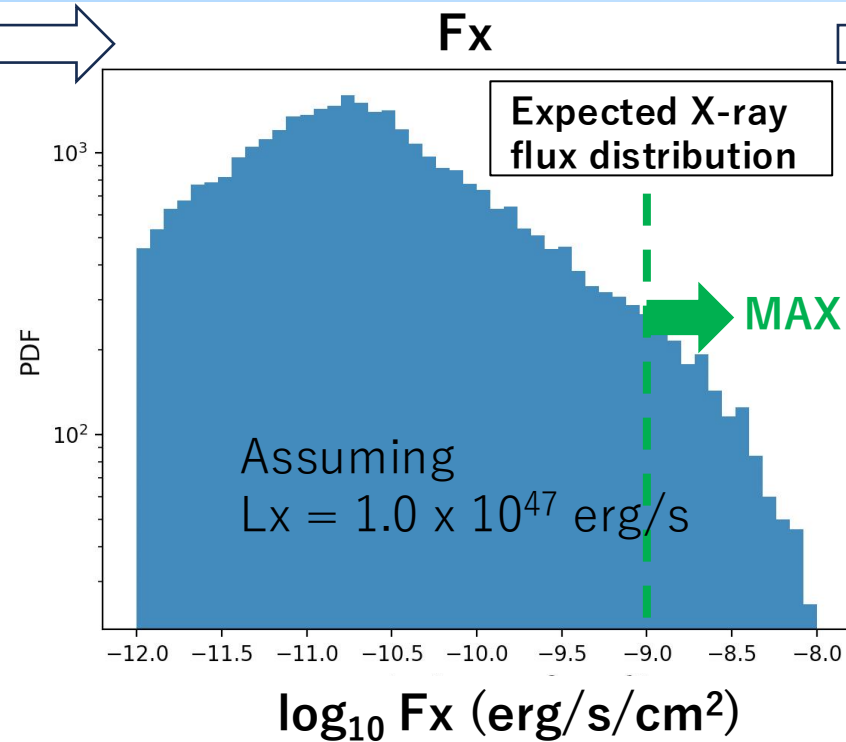
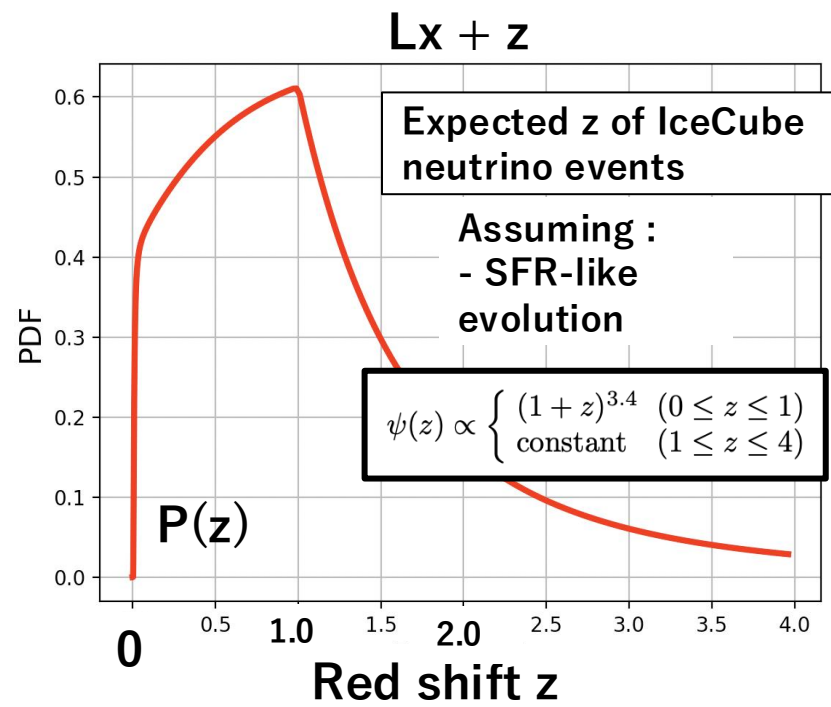
- $r \sim 1.6$ deg (PSF) source / surrounding bg region
→ N_{annular} vs N_{center}
→ event-specific P_{xbgd}
- Background varies with solar activity → templates updated every 100 days



X-ray bgd PDF updated every 100 days



From the source population to the MAXI signal PDF



Source-distance distribution $P(z)$

- Expected redshift distribution of neutrino-producing sources detected by IceCube

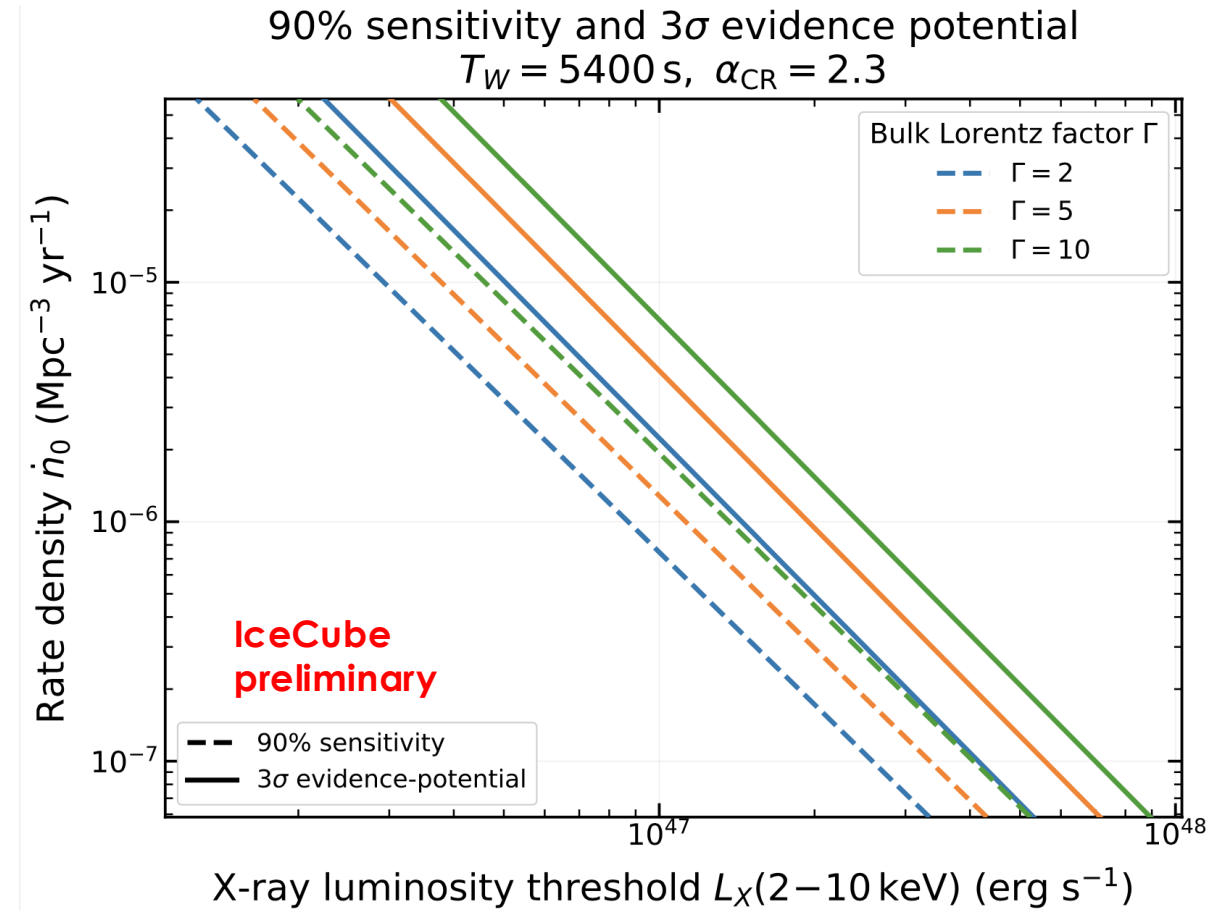
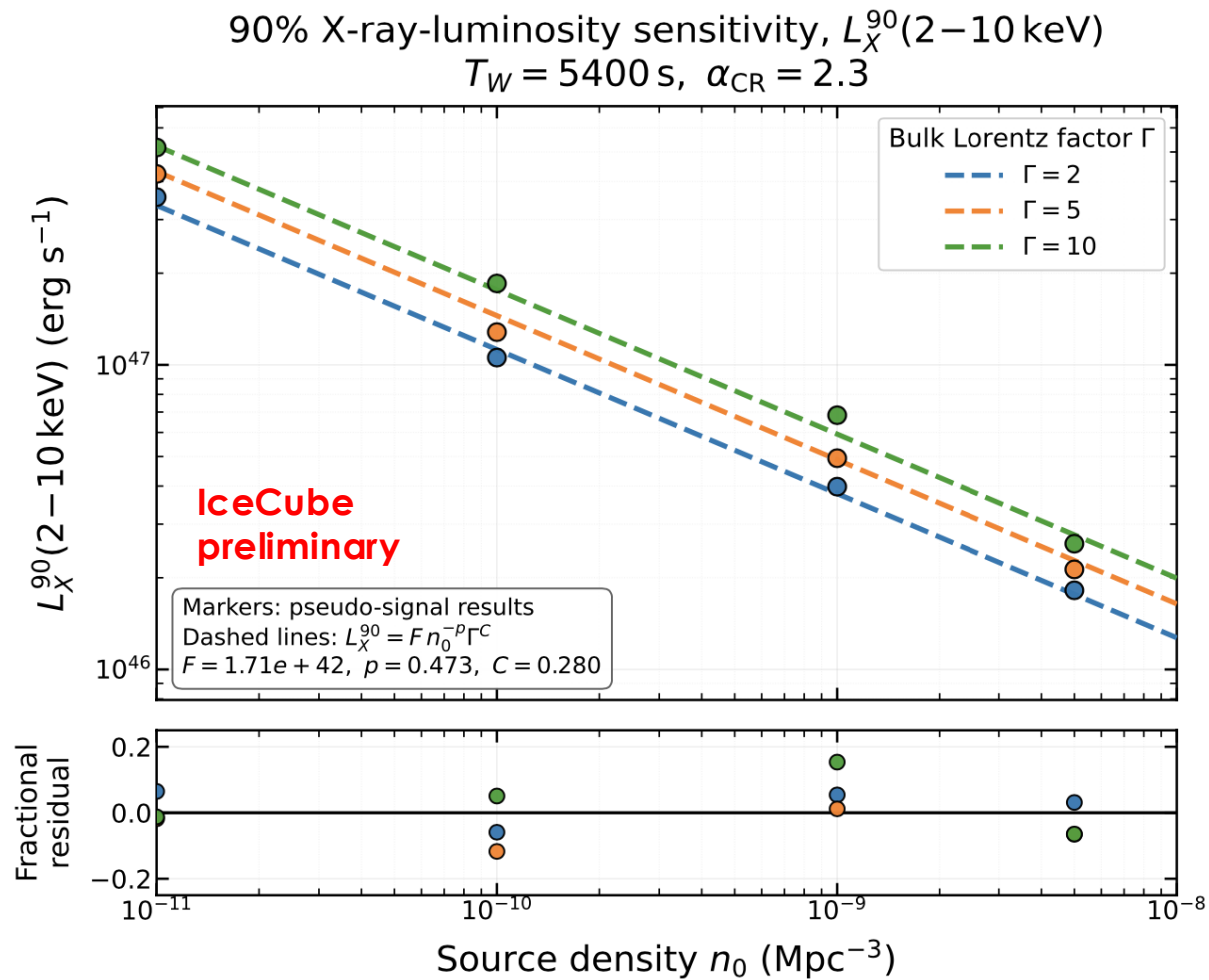
From distance to the signal PDF

- Standard-candle assumption: all SXTs share a common L_X
- Marginalize the expected X-ray counts over $P(z)$
- Convolve the SXT counts with the empirical MAXI background PDF
- MAXI sensitivity is concentrated on the low- z , high- F_X part of the population
→ nearest detectable sources dominate the sensitivity

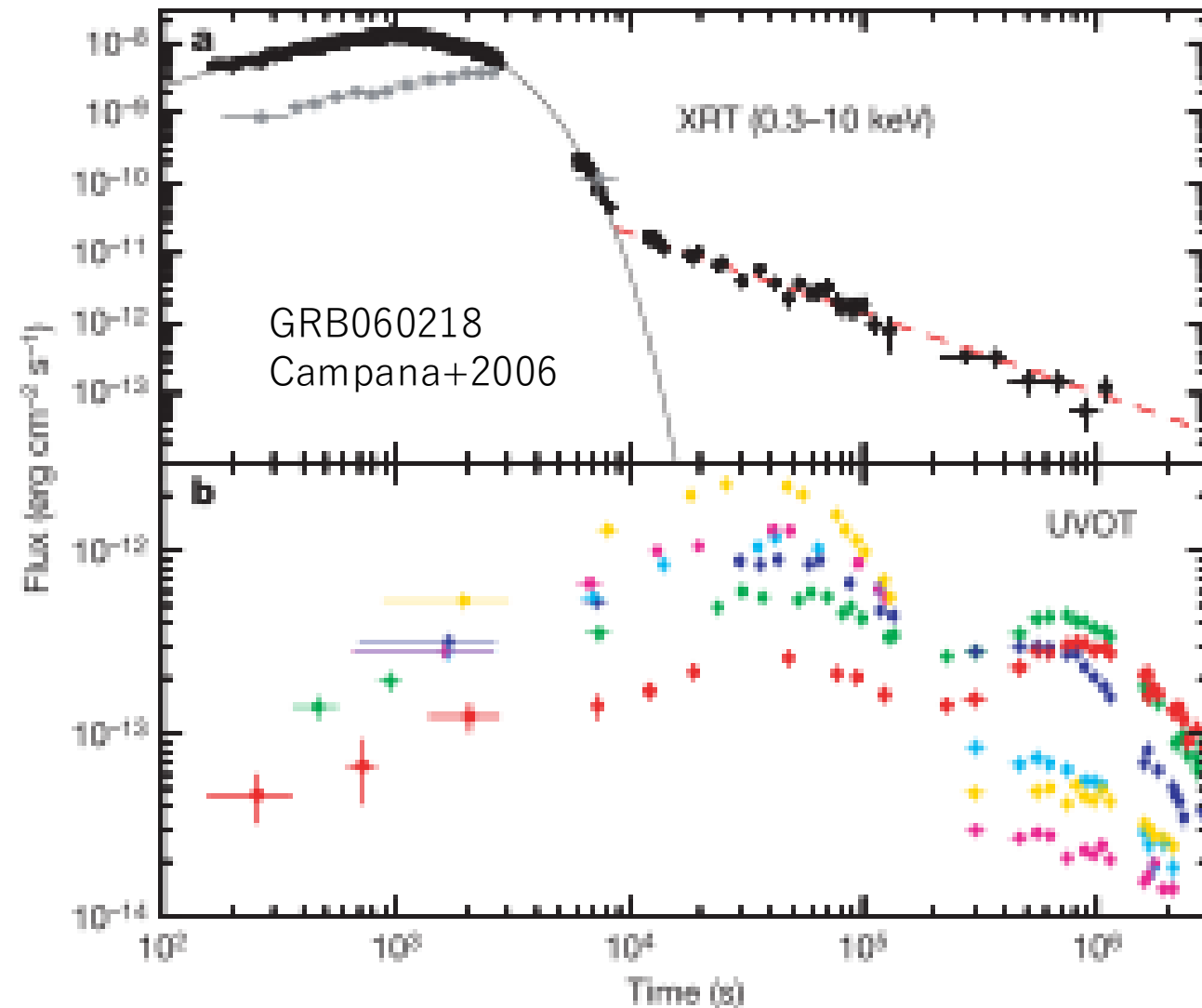
$$P_X^{\text{sig}}(N_X | L_X) = \int dz P(z) P(N_X | L_X, z)$$

$$\sum_{n=0}^{N_X} P^{\text{Poisson}}(N_X - n | \mu_{(L_X)}) P_{X_{\text{DB}}}^{\text{bgd}}(n)$$

90% L_X upper limit from the predefined Case-1 procedure



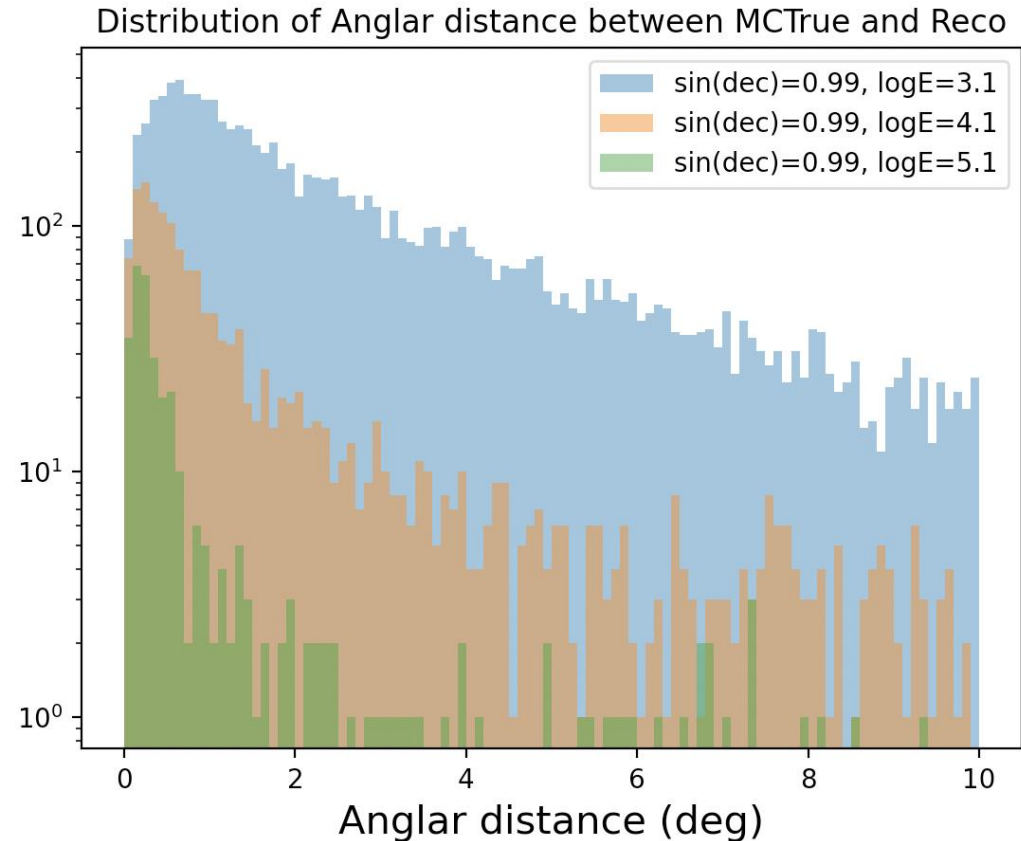
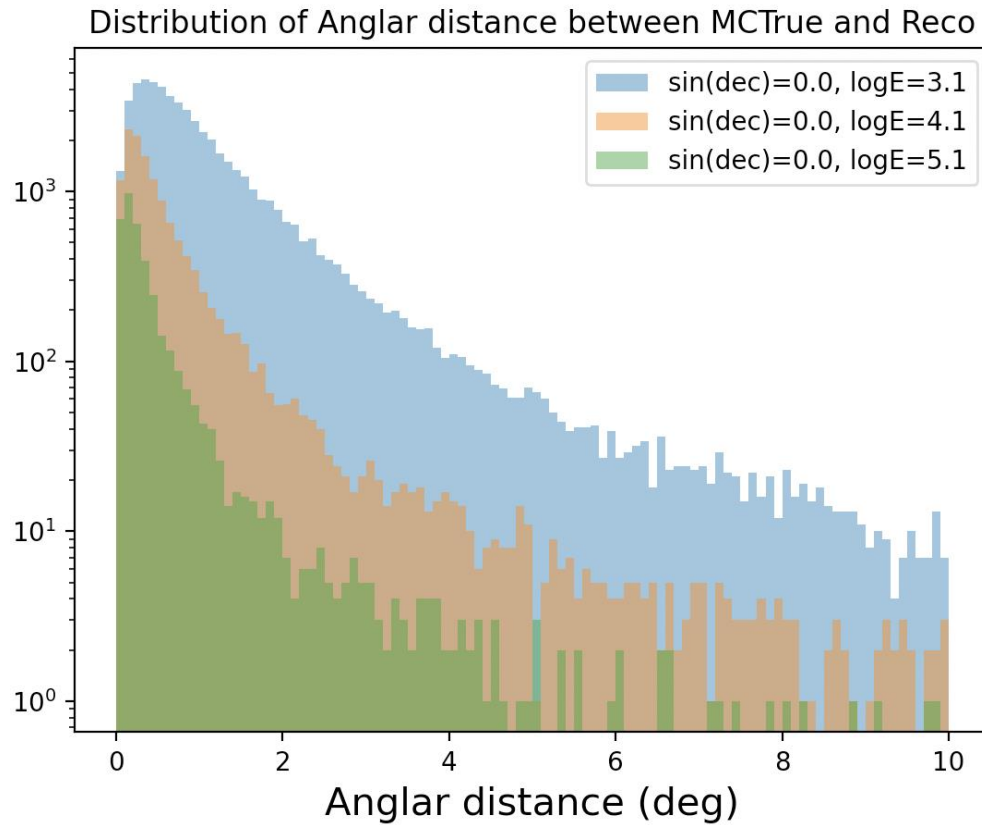
LLGRB duration



1. Strategic Optimization of Observation:
The baseline ΔT of 5400 s is determined by the ISS orbital period. This duration is the optimal choice to maximize the available photon statistics N_{coin} for a single scan cycle of MAXI.
2. Consistency with Science Targets:
This window is well-suited for capturing long-duration transients. For example, the well-known LLGRB 060218 has a duration of ~ 3000 s, which is fully covered within our 5400 s window, ensuring that the signal integrity is maintained.
3. Risk Assessment & Stability:
Even if ΔT is reduced to 3000 s (e.g., to match a specific burst duration), the resulting decrease in L_x sensitivity is approximately 50%. This demonstrates that the methodology remains statistically sound and the physical order of magnitude of the results is preserved, even under more restrictive temporal constraints.

Deviation between the neutrino Reco position and MC True

Angular distance distribution between the MC True position and Reco position

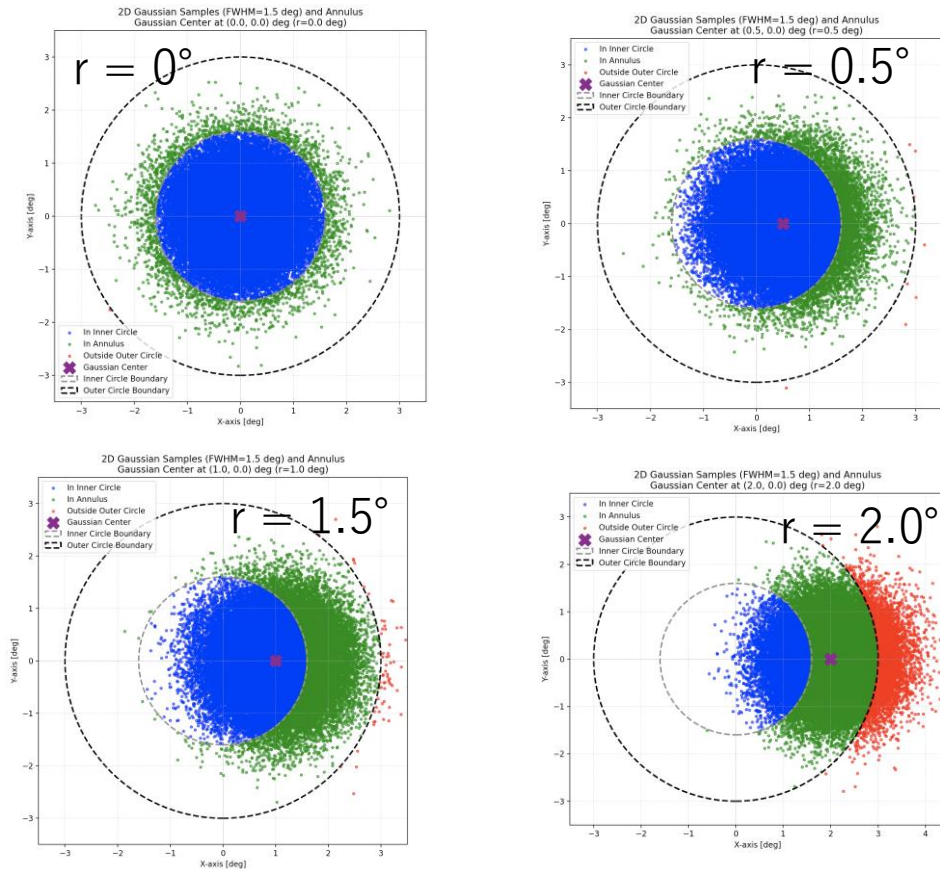


We record the position of events injected in MC simulations (MC True position) and the direction obtained through reconstruction (Reco position), treating the angular distance between them as positional uncertainty.

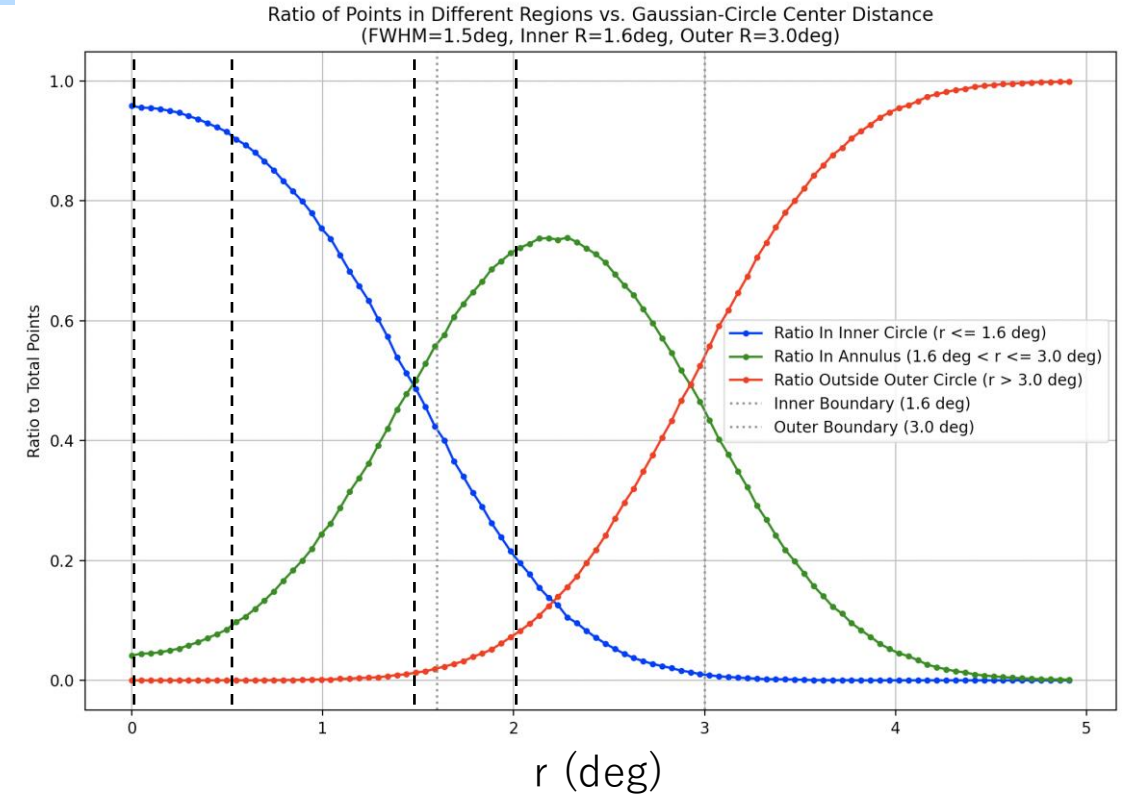
We consider the impact this has on MAXI results.

Effect of neutrino signal position offset on X-ray data analysis

To assess this effect, we conducted Monte Carlo simulations to determine the amount of signal leakage into the annular region when the neutrino position is misaligned.



r : Angular distance between the defined signal region and the actual signal position



- Assume MAXI's PSF can be approximated by a two-dimensional Gaussian ($\text{FWHM} = 1.5$ deg).
- MAXI's PSF has no dependence on RA or DEC.

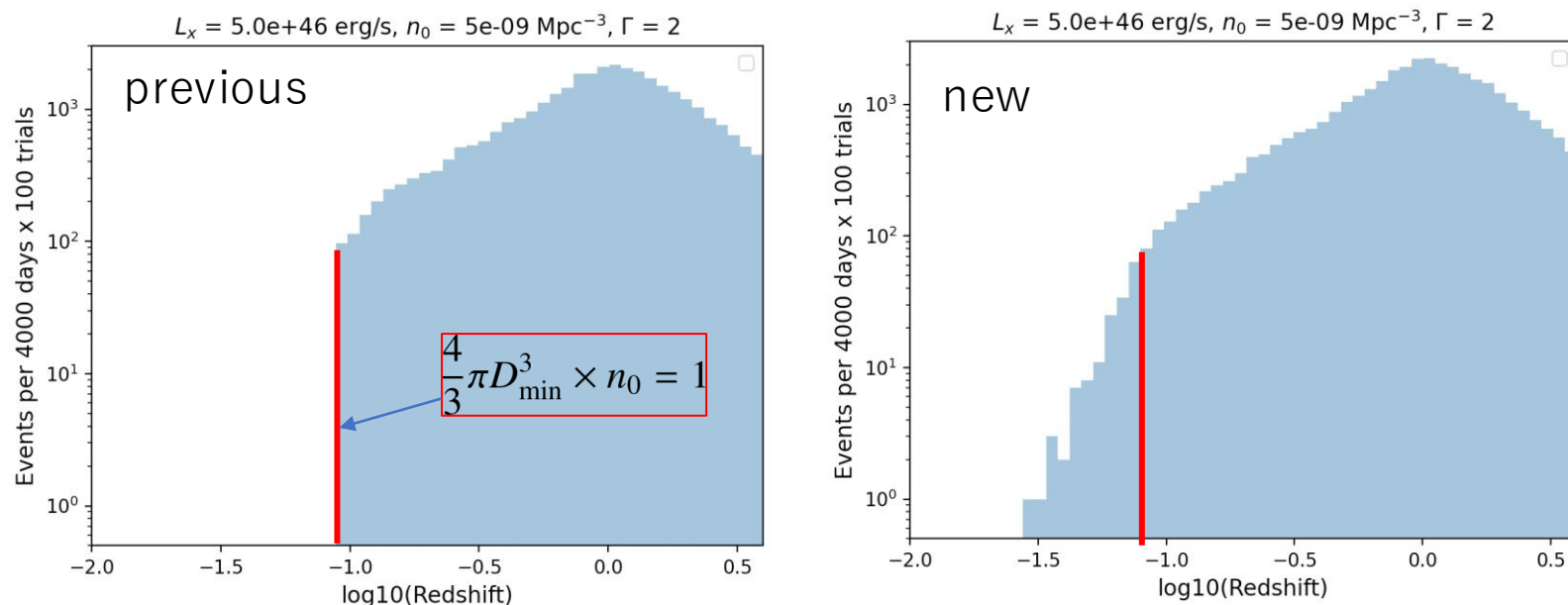
In the pseudo-signal experiment:

1. Select an r value from its distribution obtained from MC simulation results (P5, dependent on neutrino energy and position).
2. Allocate the number of X-ray photons to the signal region and background region according to the selected r value.

Applying statistical treatment to the minimum distance for the transients

We discovered an assumption that has a greater impact on the sensitivity of L_x : the assumption regarding the minimum distance of the transient.

Distance distribution of the sources by the pseudo-signal simulation



Previously, we have defined the minimum distance $D_{\min}$ by

$$\frac{4}{3}\pi D_{\min}^3 \times n_0 = 1$$

where n_0 represents the snapshot density of sources.

However, $D_{\min}$ the average distance for sources distributed at a given n_0 .

The distance to the nearest transient for a specific n_0 should actually vary with fluctuation. MAXI's sensitivity is particularly dependent on the number of nearby transients, which affects its L_x sensitivity. We performed the pseudo-signal experiment again, taking into account the distance distribution to the nearest source.

Applying statistical treatment to the minimum distance for the transients

Method for the estimation of the nearest source distance

The number of sources stochastically distributed within a field of view $\Delta \Omega$ up to redshift z is given by:

$$N_{\text{tr}}(z) = \frac{\Delta \Omega}{4\pi} n_0^{\text{tr}} \int_0^z dz' d_c^2 (1+z') \left| \frac{dt}{dz'} \right| \psi_{\text{tr}}(z')$$

The PDF of minimum z (z_{min}) is derived using Poisson statistics, representing the probability that the nearest source is located at a specific redshift:

$$\rho(z_{\text{min}}) \simeq \exp(-N_{\text{tr}}(z_{\text{min}})) \left. \frac{dN_{\text{tr}}}{dz} \right|_{z_{\text{min}}}$$

Calculation of expected Number: Using n_0 and cosmological parameters, we calculate the cumulative number of sources over the full sky.

Sampling of z_{min} : For each pseudo-signal generation, we sample z_{min} value from the calculated CDF

Redshift range: We set the maximum redshift of the source population to a fixed value of $z_{\text{max}} = 4$

In each simulation trial, the redshifts of the transients in the population are randomly sampled within the range $[z_{\text{min}}, z_{\text{max}}]$ according to the differential source distribution dN_{tr} / dz .

