Results in Multimessenger Astronomy from ICEHAP

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IceCube 15th year symposium
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CREATION OF MULTI-MESSENGER ASTROPHYSICS

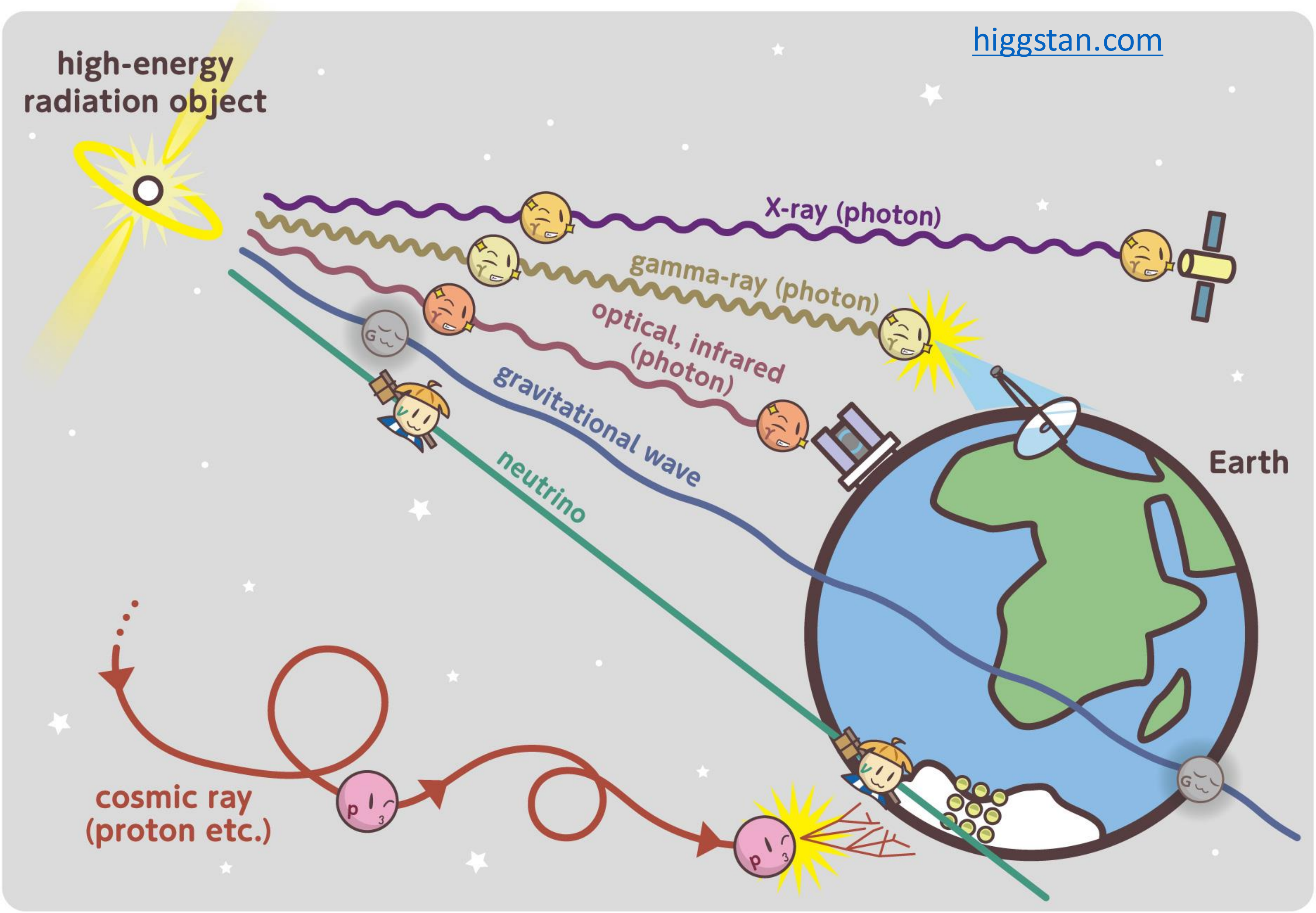
CHIBA UNIVERSITY

ICEHAP

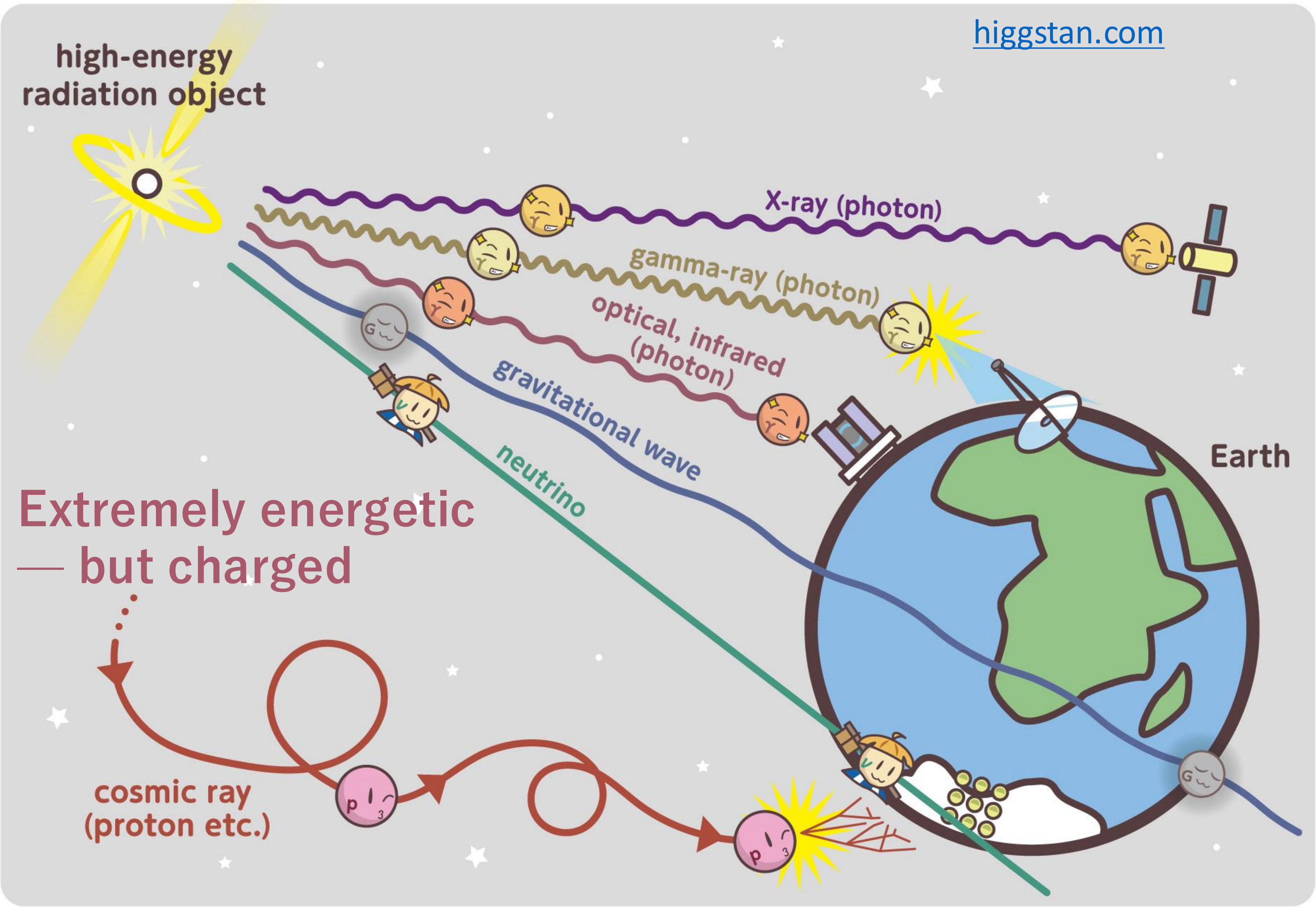
ICECUBE

Credit: J. Werthebach, IceCube/NSF

Messengers from the High-Energy Universe

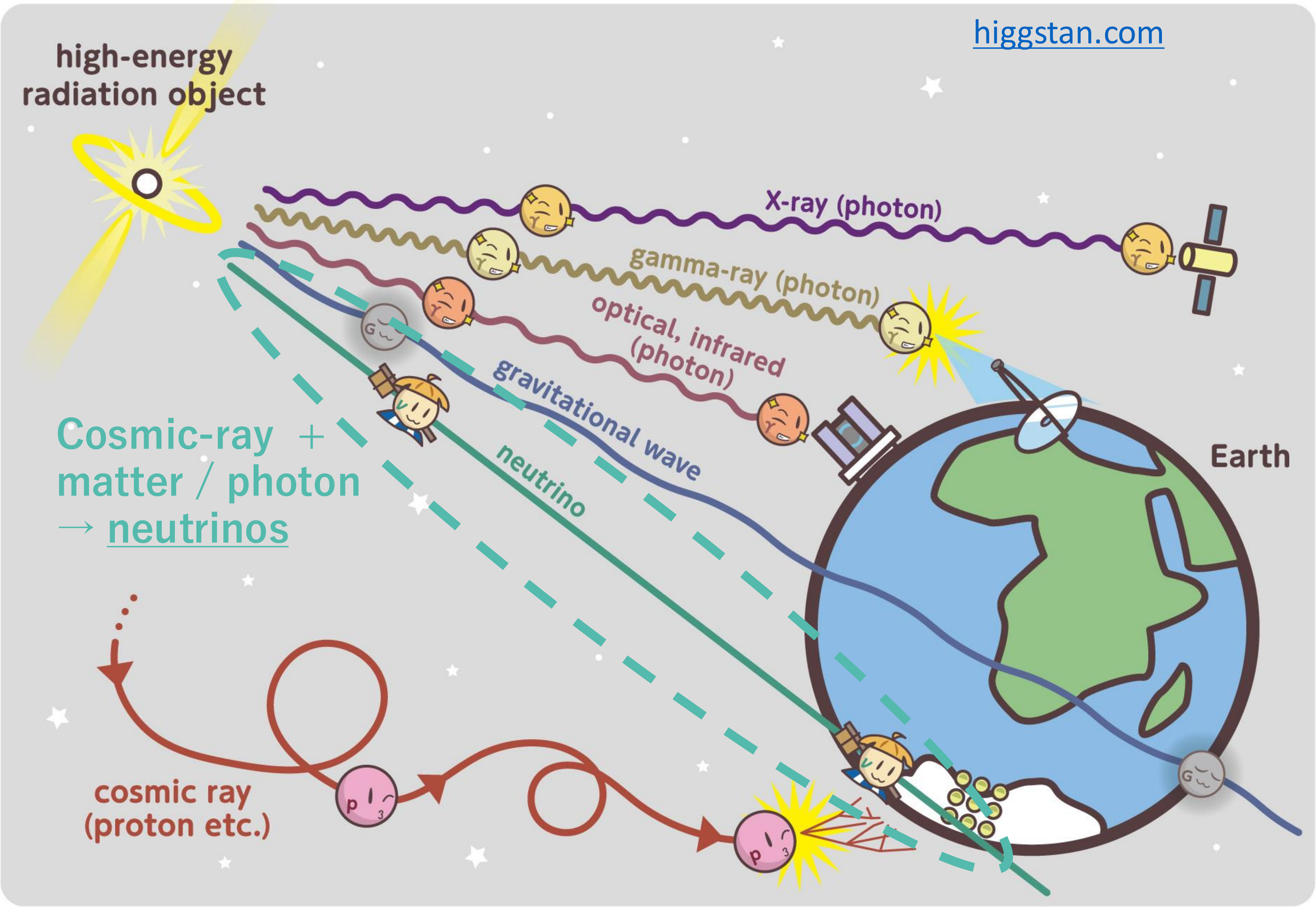


Messengers from the High-Energy Universe



Where and how are cosmic rays accelerated?

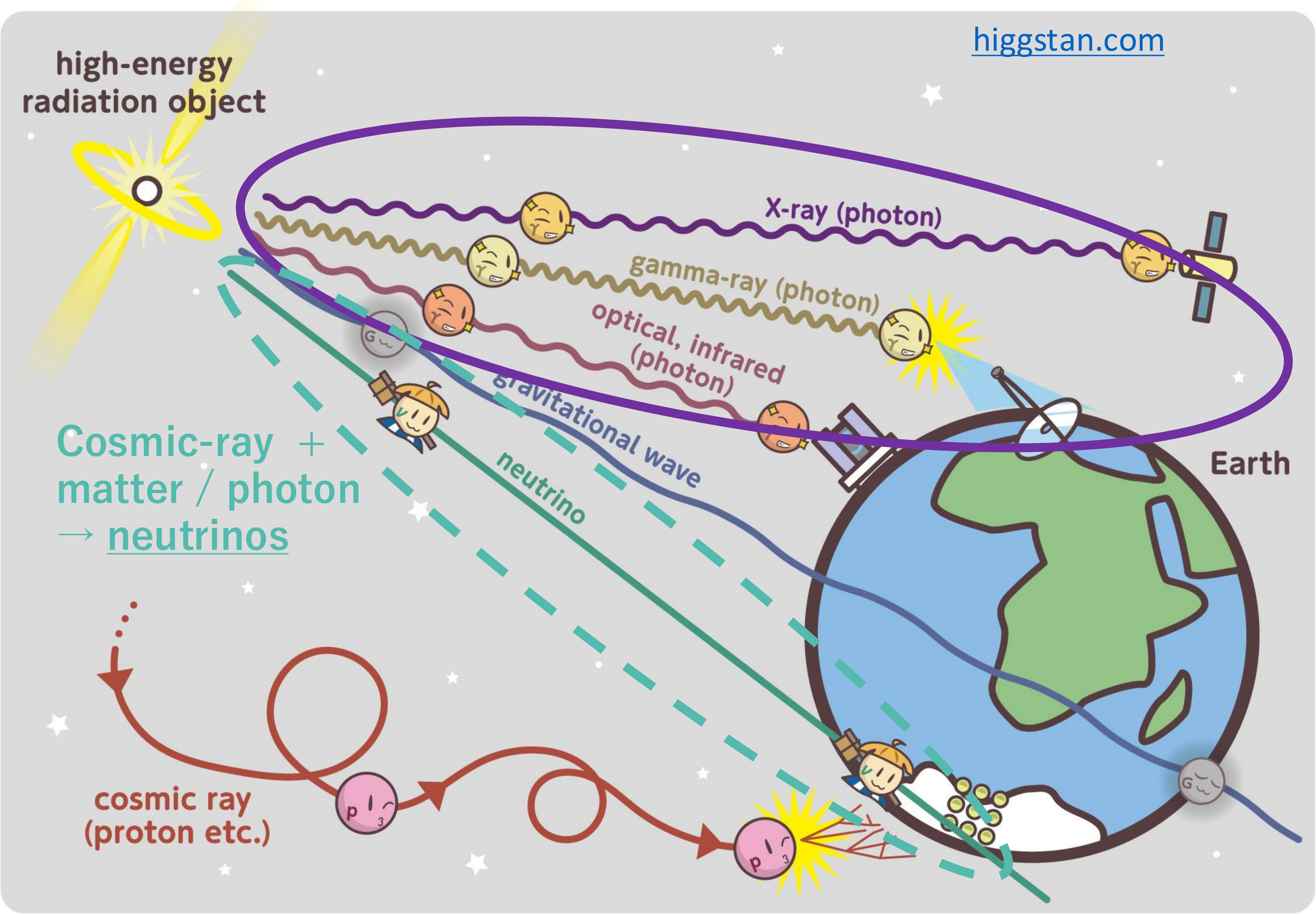
Messengers from the High-Energy Universe



Where and how are cosmic rays accelerated?

Neutrinos can tell us where to look.

Messengers from the High-Energy Universe

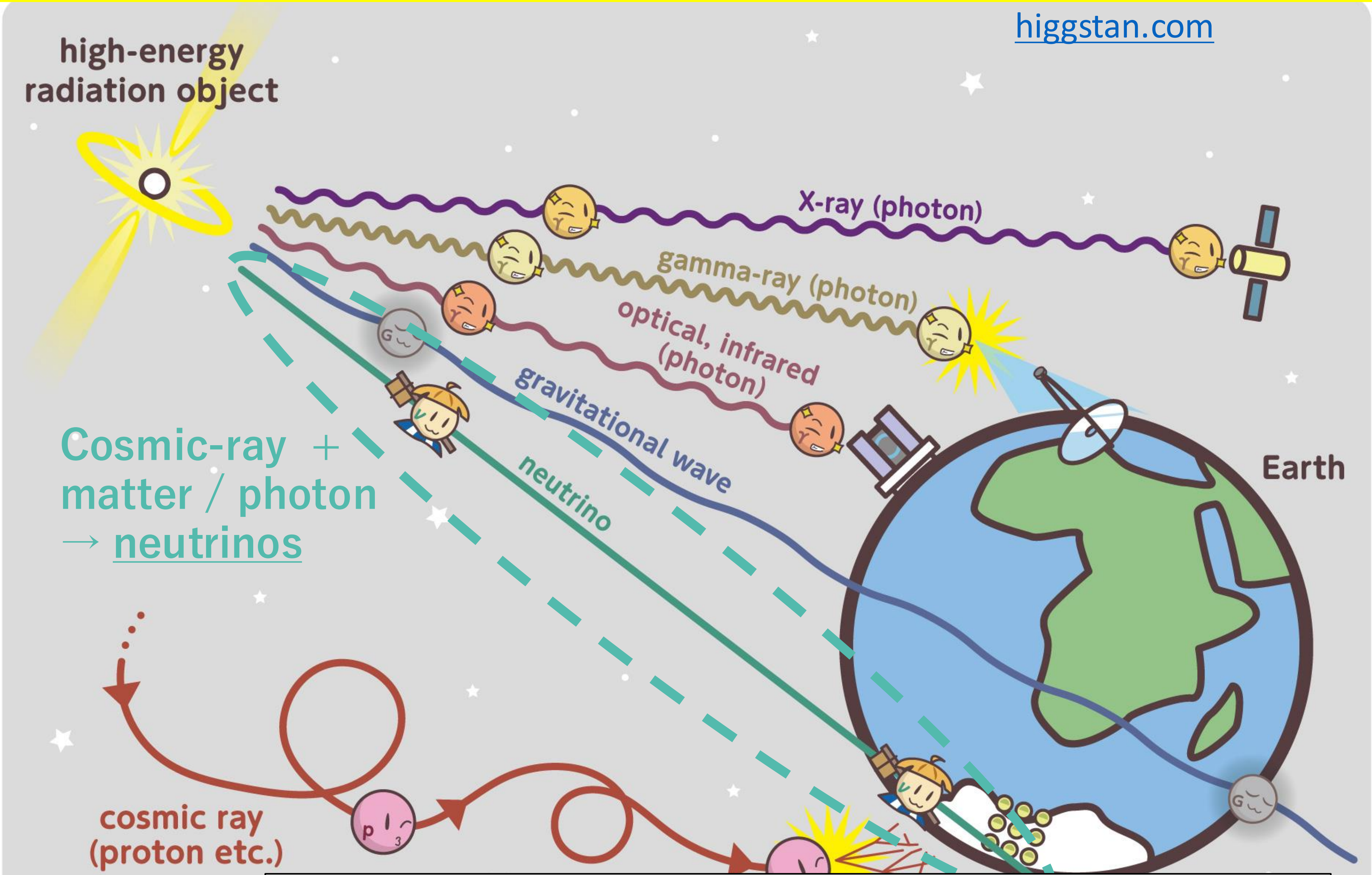


Where and how are cosmic rays accelerated?

Neutrinos can tell us where to look.

Photons can tell us what is happening there.

Messengers from the High-Energy Universe



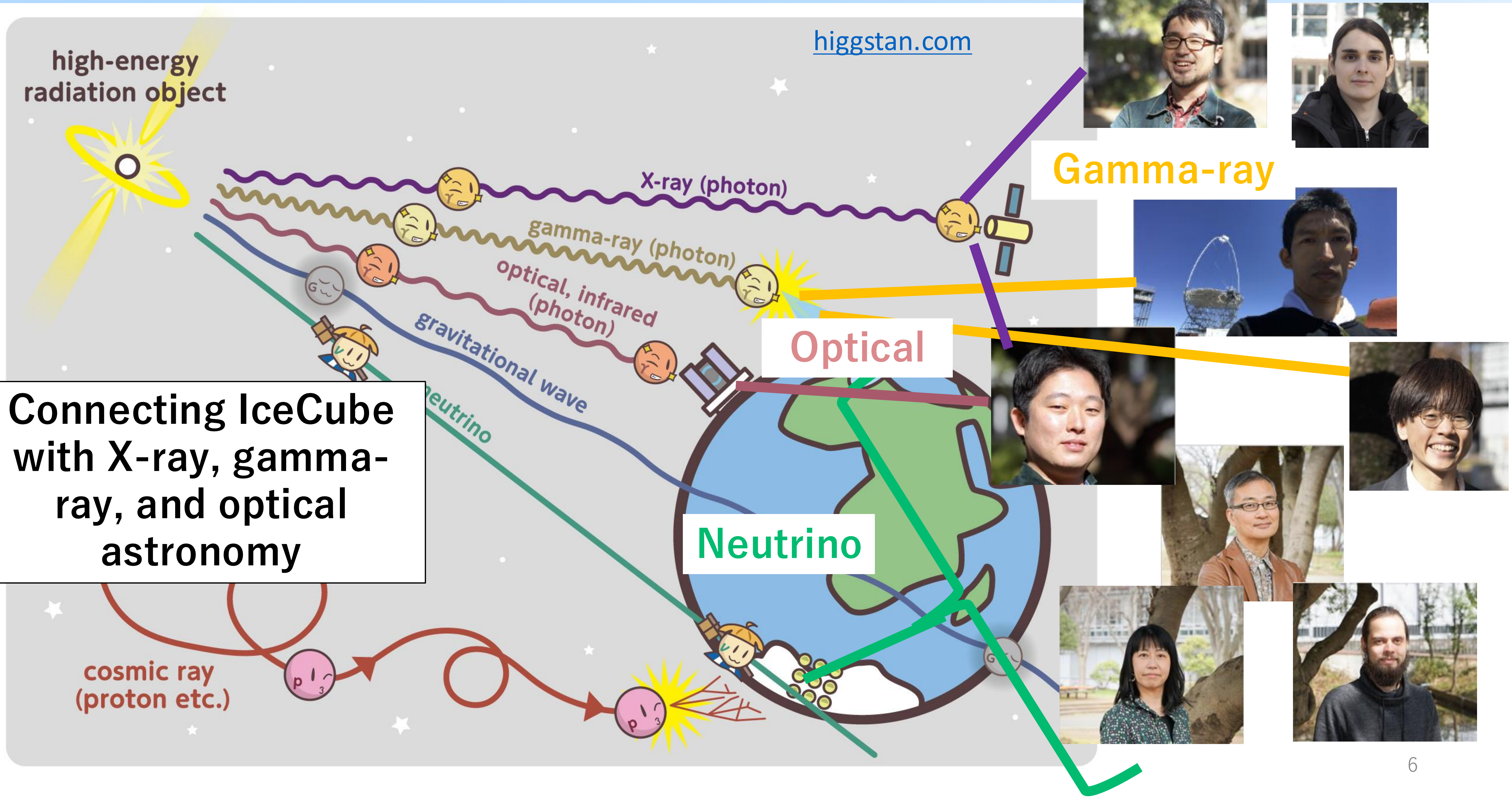
Multi messenger astronomy

Where and how are cosmic rays accelerated?

Neutrinos can tell us where to look.

Photons can tell us what is happening there.

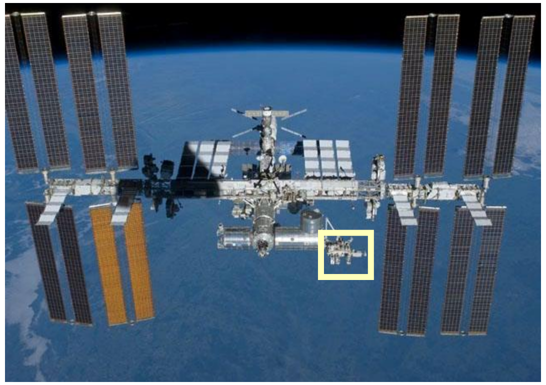
ICEHAP: a hub for multimessenger astronomy



Connecting IceCube with X-ray, gamma-ray, and optical astronomy

New scientific value from multimessenger information

1. Find counterparts
Neutrinos tell us when and where to look
→ **MAXI–IceCube / OMMLET ×Optical**



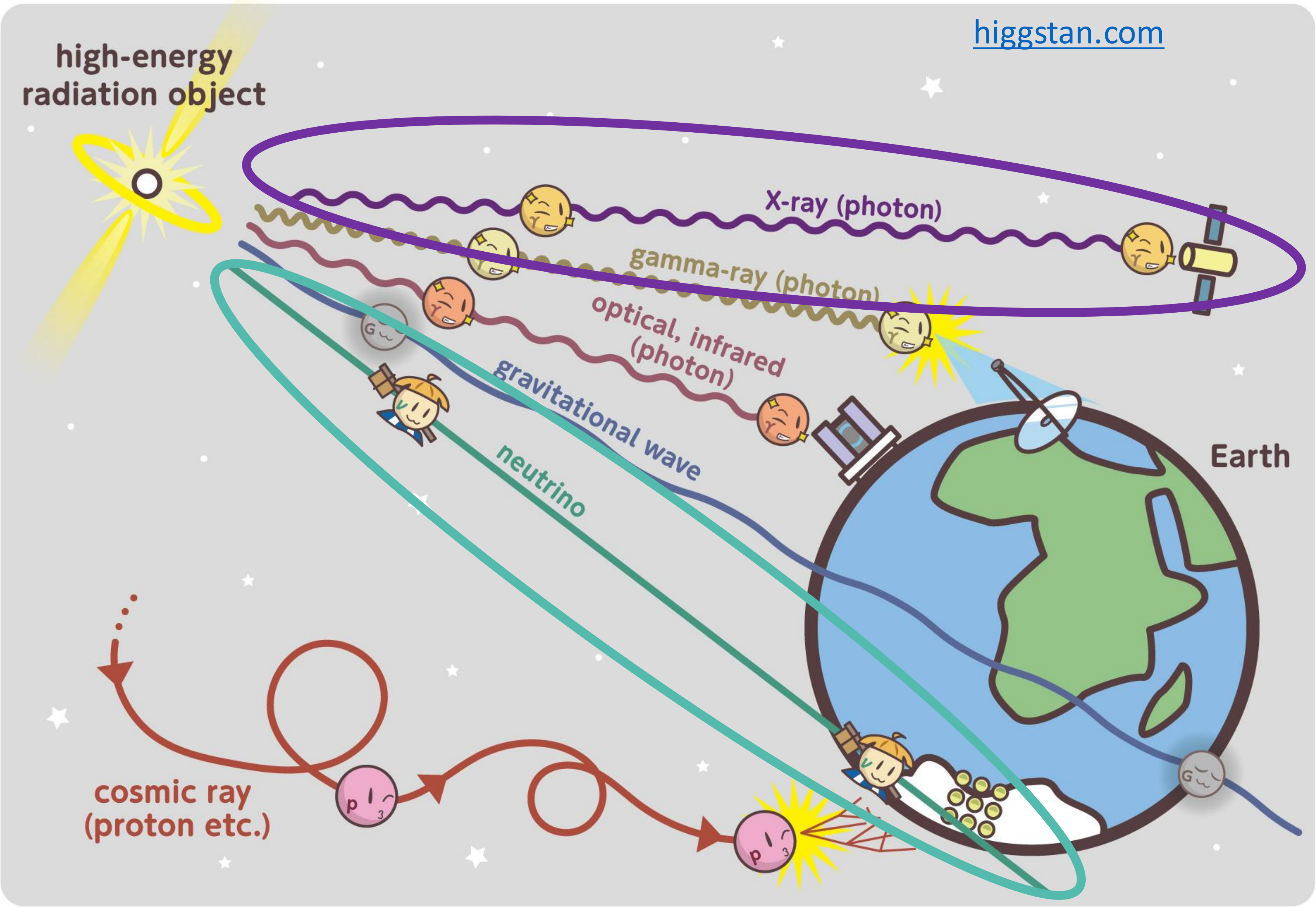
2. Understand the source
X-rays tell us about the source environment
→ **Seyfert coronae**

3. Find promising high-energy sources
Gamma-rays and neutrinos can come from the same particle interactions→ **IceCube × CTAO**

4. Guide neutrino searches
Other messengers tell us when and where to look
→ **Upgrade GeV neutrinos**

IceCube neutrinos give new meaning to existing observations

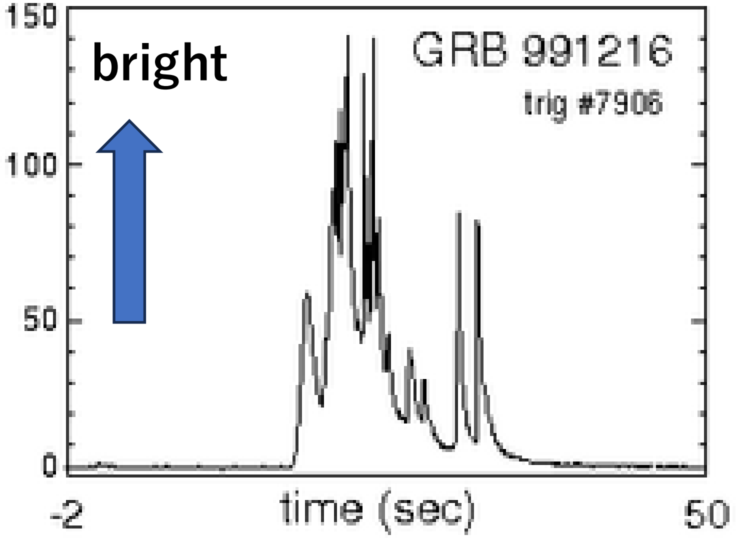
Messengers from the High-Energy Universe



Example 1:
Neutrino
+
X-ray

Why search for X-ray transients?

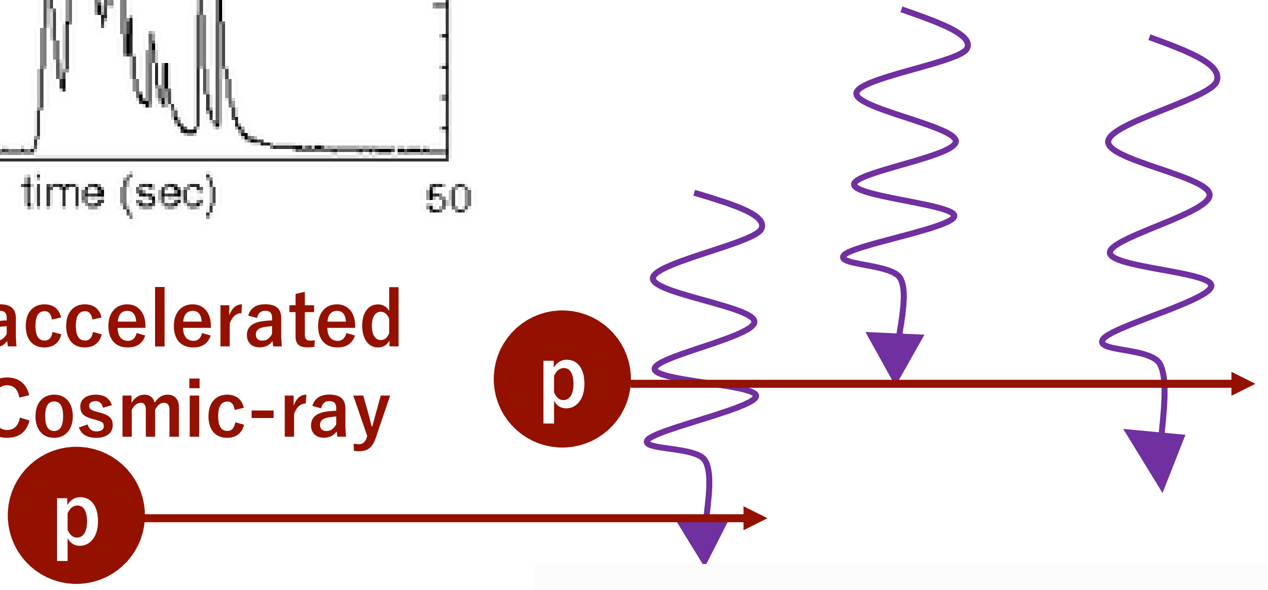
Some high-energy sources are bright only for a short time → transients



photon field

X-ray transient model :
Yoshida & Murase PRD 2024

accelerated
Cosmic-ray



ν

$$p + \gamma_X \rightarrow \pi \rightarrow \nu$$

X-ray photons

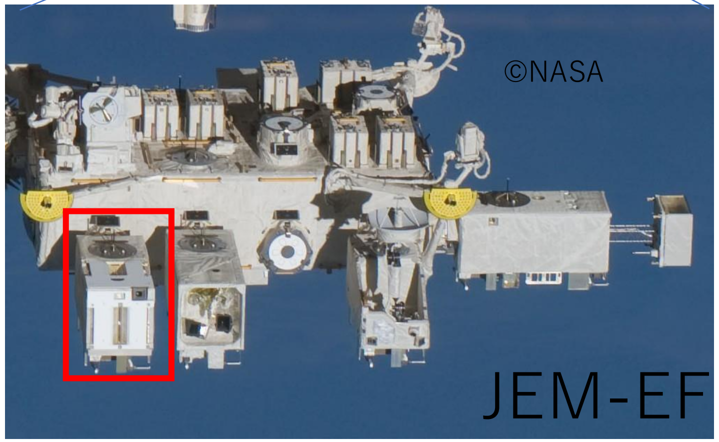
One way to produce neutrinos

X-ray transients are promising neutrino-source candidates

Example 1: IceCube gives new value to the MAXI X-ray archive

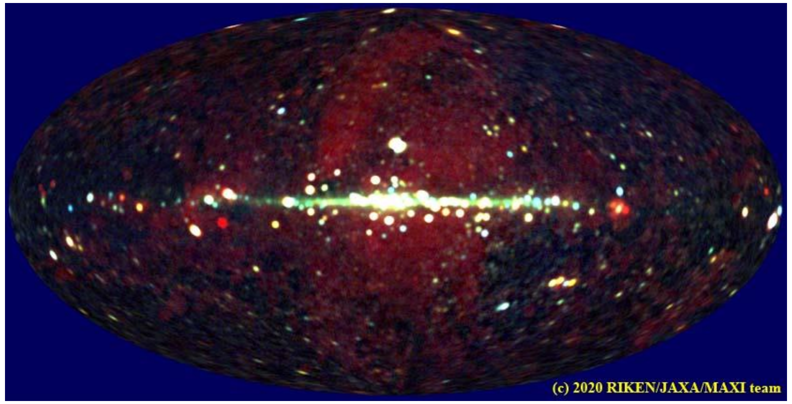
- **MAXI: all-sky X-ray monitor on the ISS**
- **2–20 keV, scans the whole sky every 90 min**

A long-term all-sky X-ray archive since 2009



MAXI alone

Most blank-sky data simply stay in the archive



IceCube + **MAXI**

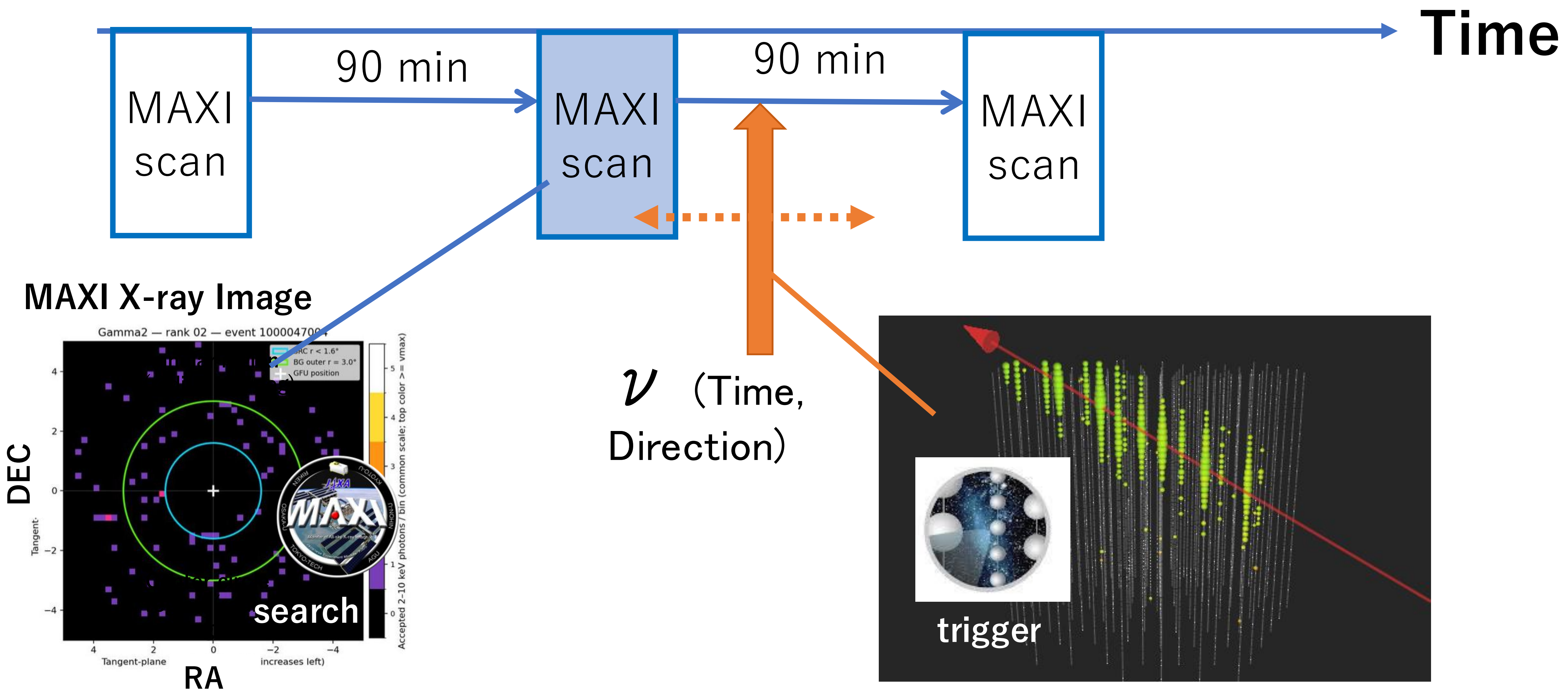
time + direction

⇩

The same data can be searched for an X-ray counterpart

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

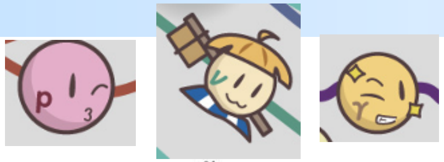
For each neutrino, search the MAXI data at the same time and position

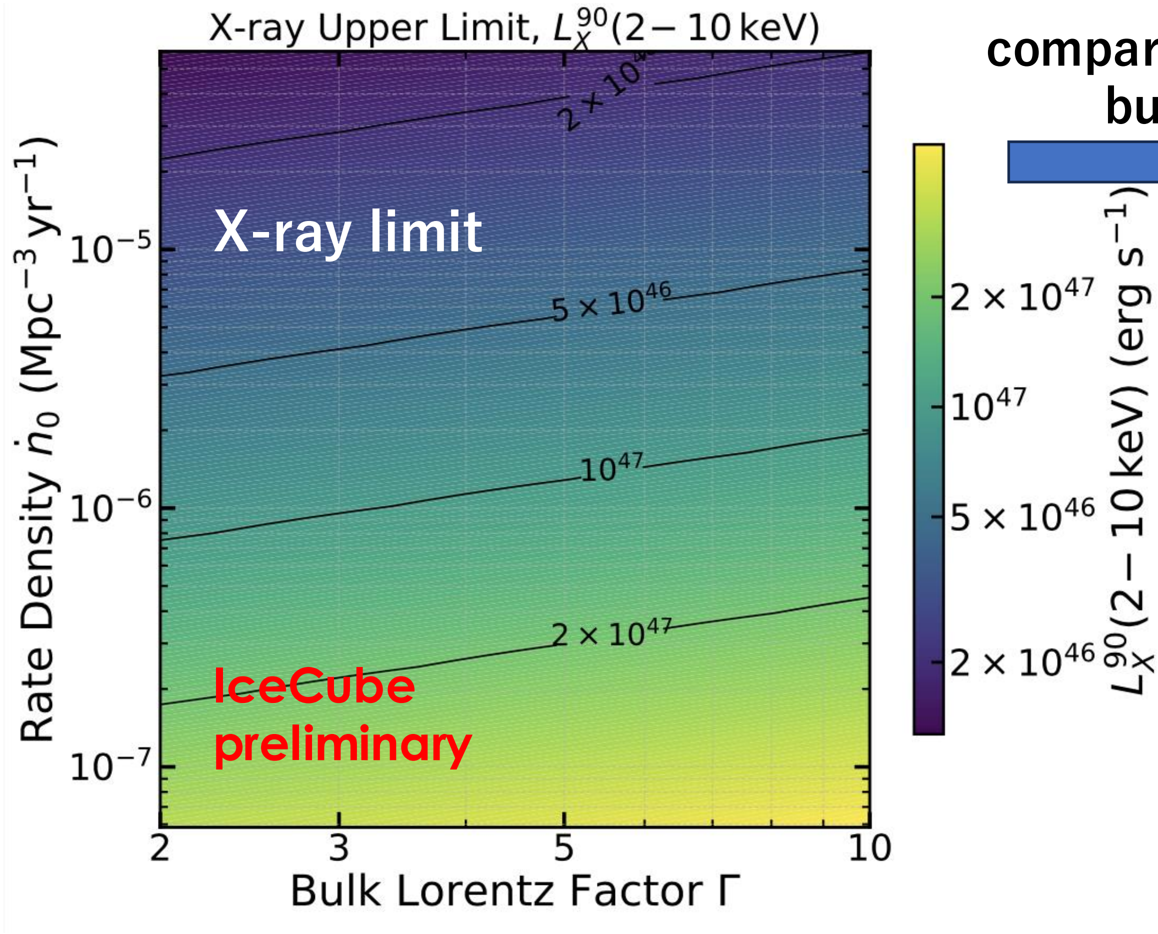


Repeat for 14.5 years → **~200,000 neutrino events with usable MAXI data**

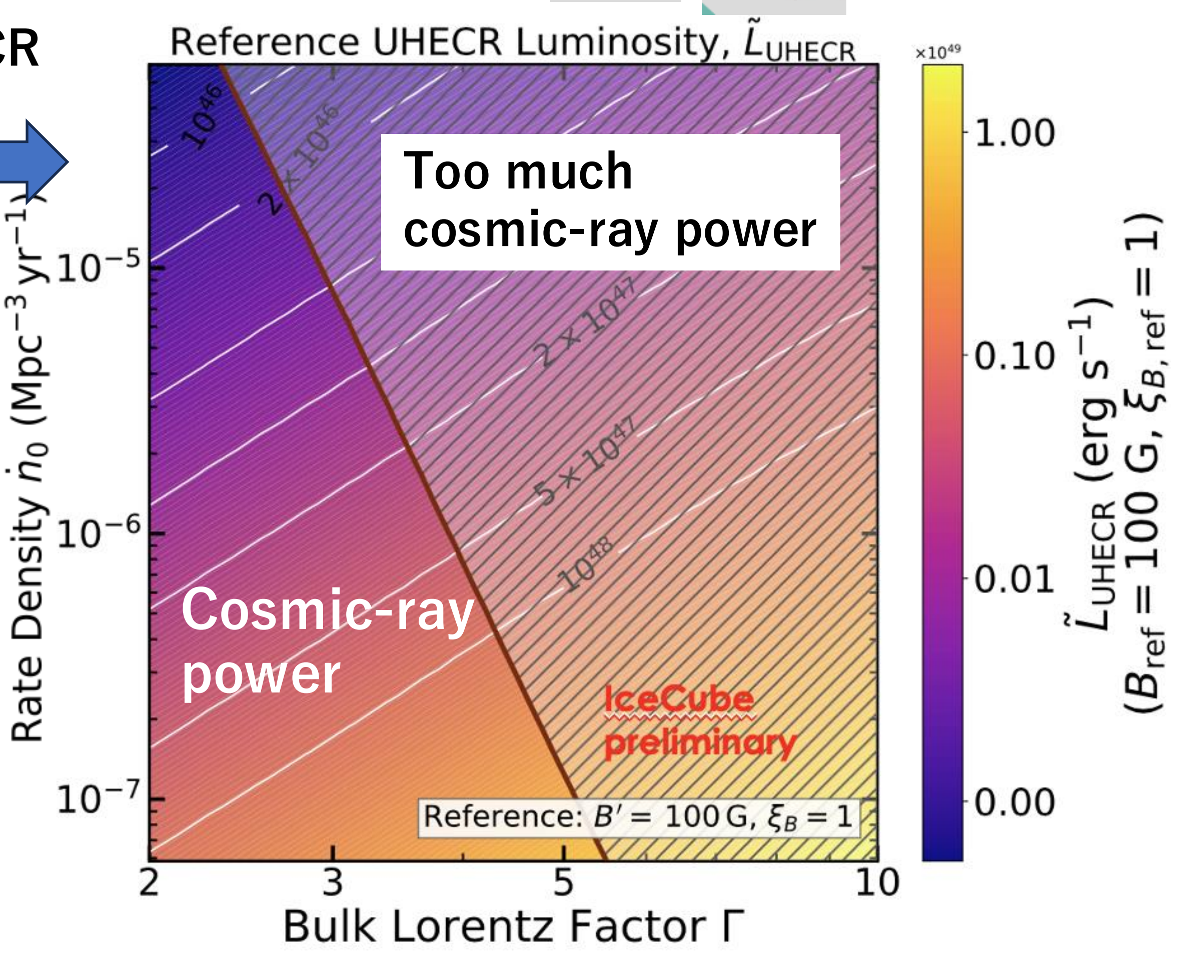
Can X-ray transients be major cosmic-ray sources?

No significant X-ray counterpart excess in 14.5 years





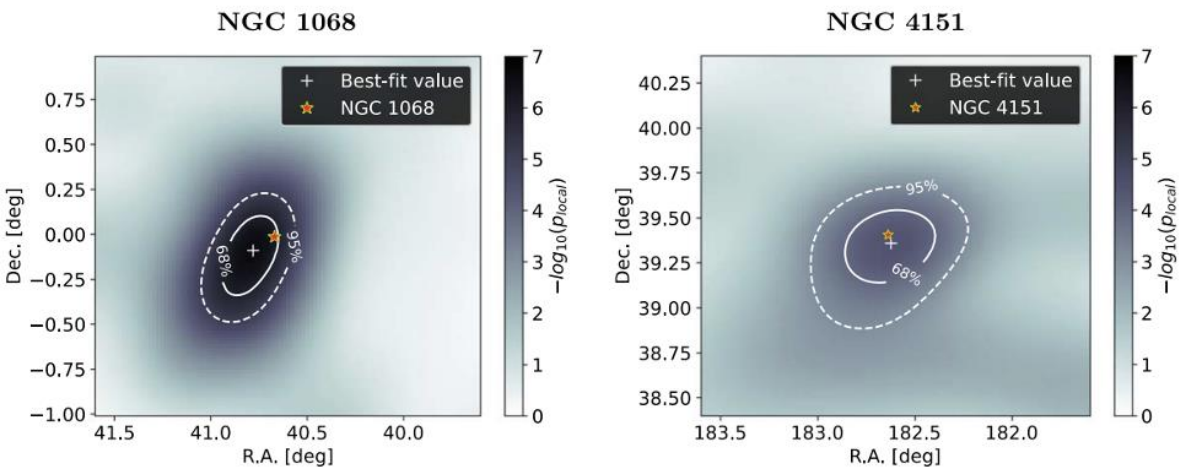
compare with CR budget



Some X-ray-transient models cannot explain both neutrinos and cosmic rays.

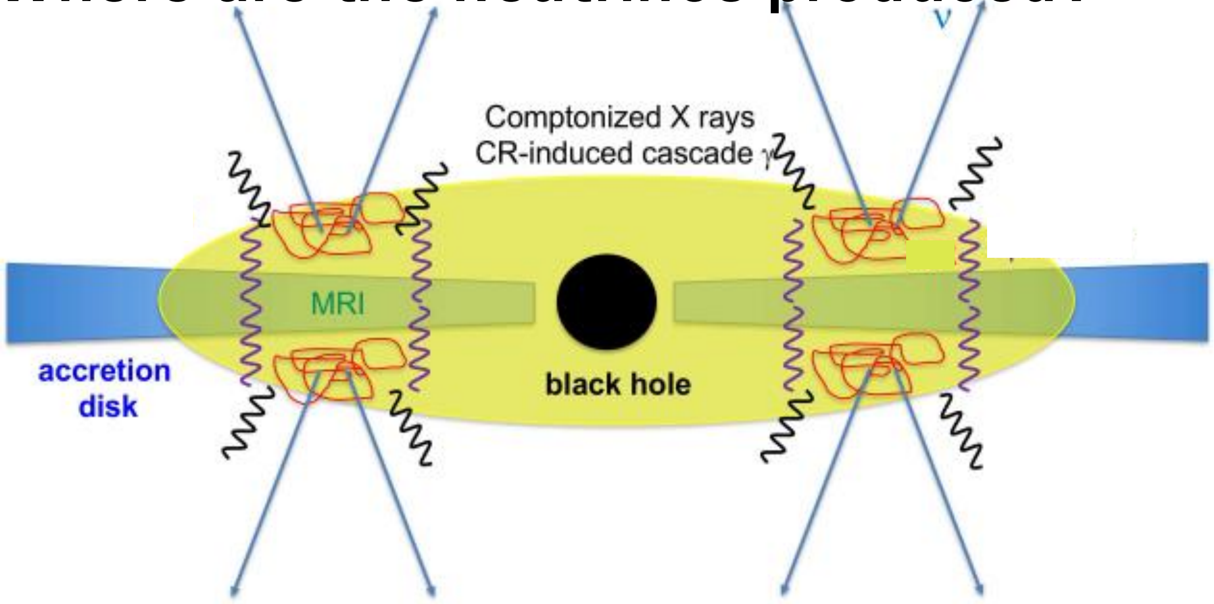
Without IceCube, many of these MAXI observations would simply remain blank-sky data in the archive.

Example 2: Neutrino results give new questions to X-ray observations



IceCube: nearby galaxy NGC 1068
+ indication from NGC 4151

Where are the neutrinos produced?



Possible site: hot X-ray corona close to the black hole

Previous neutrino modeling

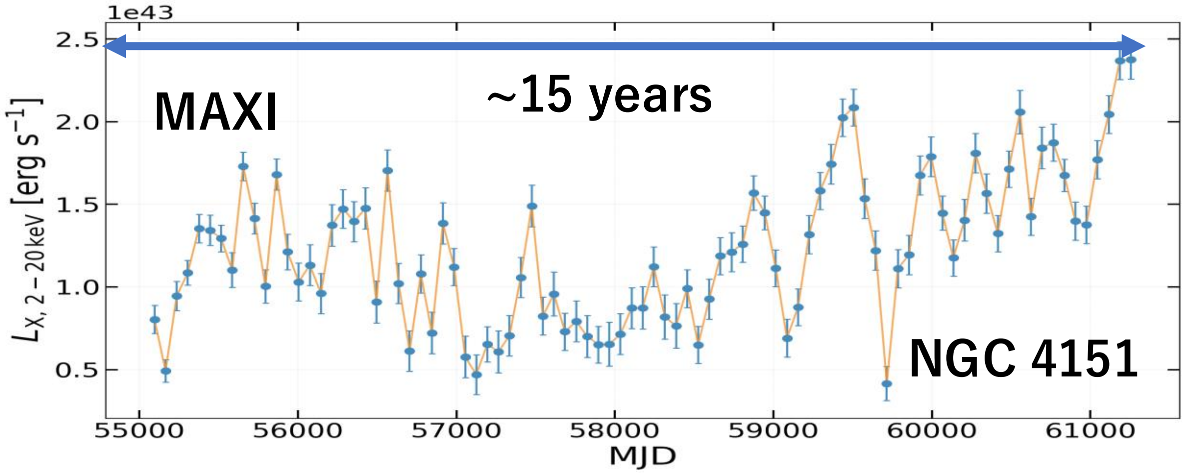
- One representative X-ray luminosity
- Other coronal parameters mostly fixed

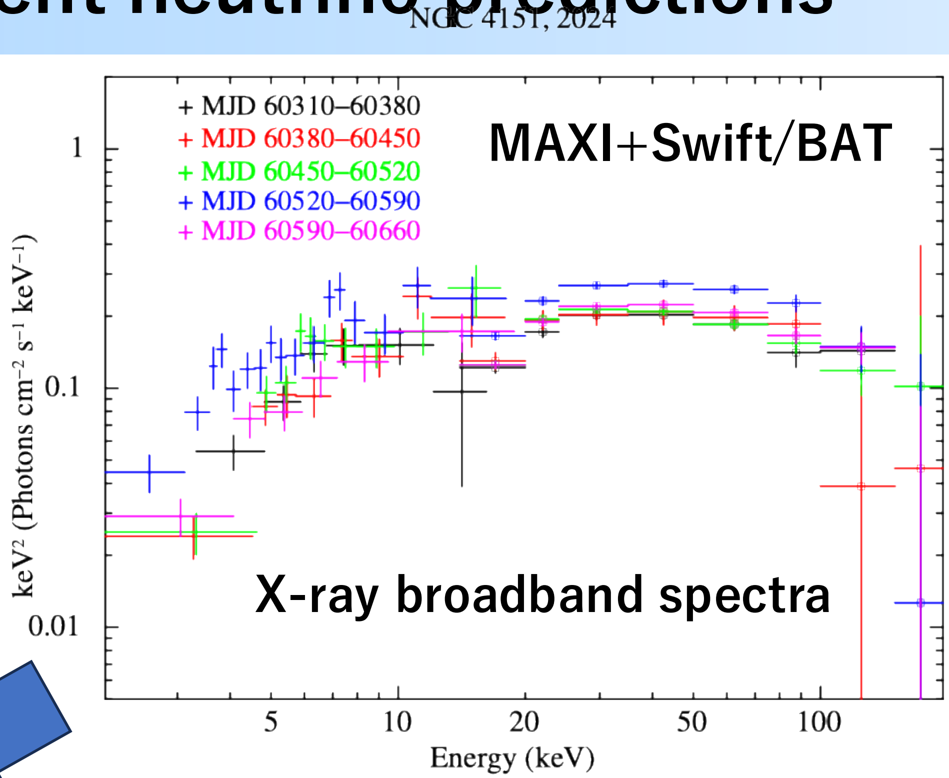
Our ongoing work

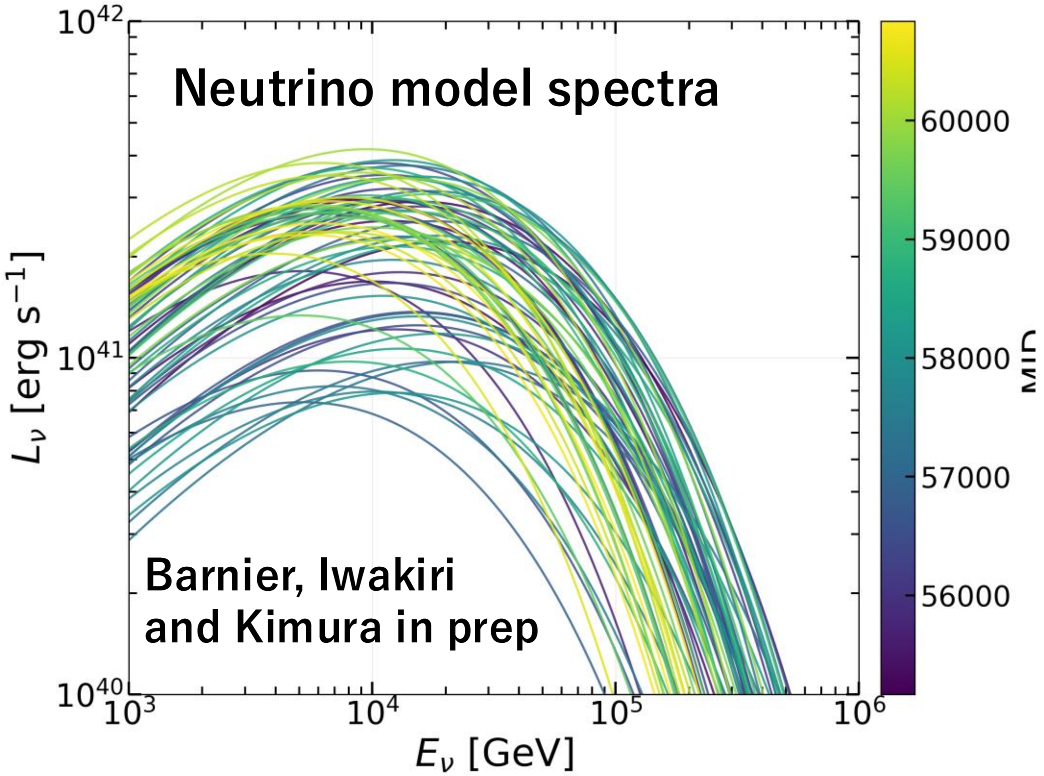
- Time-dependent broadband X-ray spectra
- Source-specific coronal parameters

→ **Time-dependent neutrino predictions**

From X-ray variability to time-dependent neutrino predictions



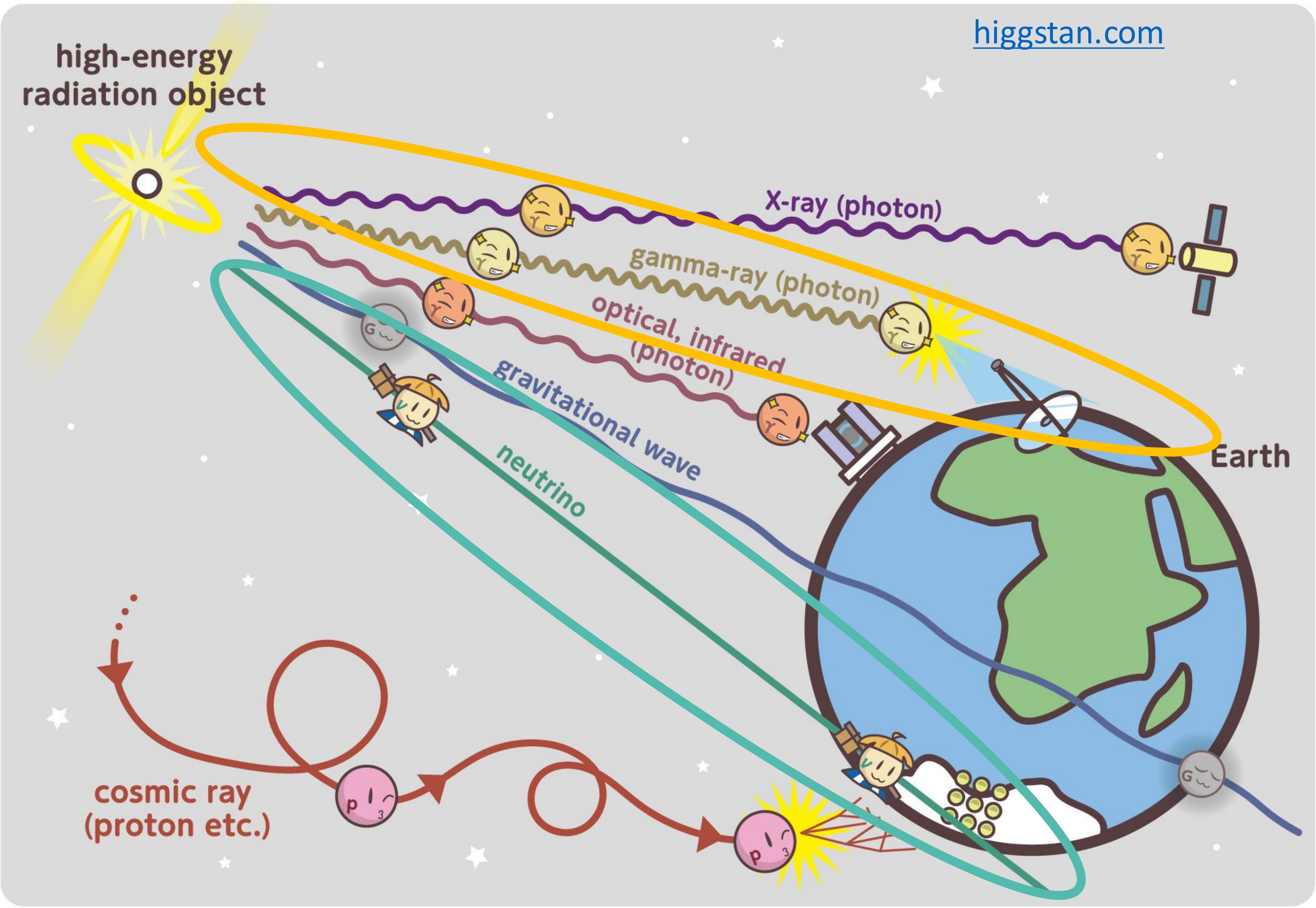




First observation-driven prediction of time-dependent neutrino spectra from a Seyfert corona

Future : test the time-dependent prediction with IceCube data

Messengers from the High-Energy Universe



Example 3:
Neutrino
+
Gamma-ray

Example 3: Gamma rays help us find promising neutrino sources

$$p + p \rightarrow \pi^0, \pi^\pm$$

$$\pi^0 \nearrow \gamma \qquad \pi^\pm \searrow \nu$$

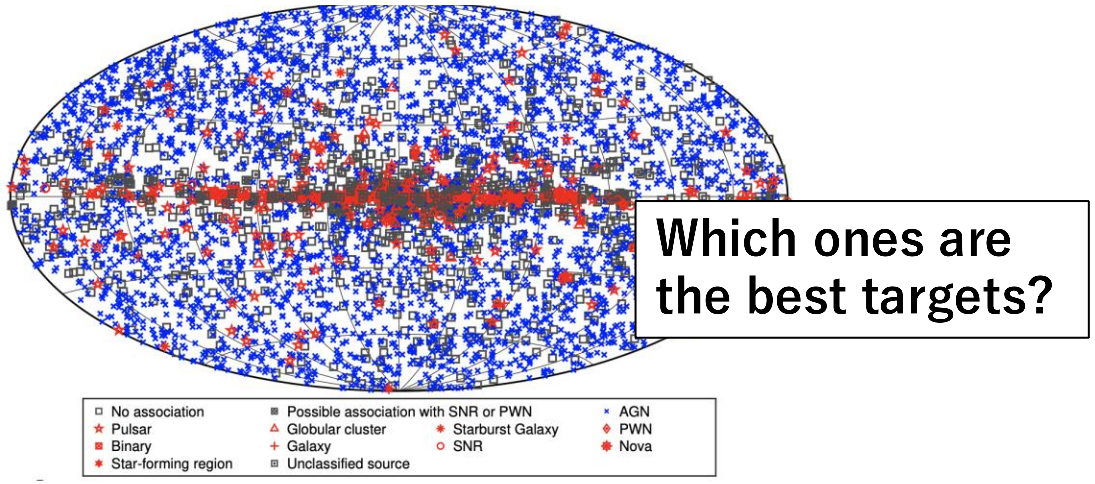
IceCube: TeV–PeV neutrinos
→TeV gamma rays probe the same high-energy particle population

CTAO: next-generation ground-based gamma-ray observatory in 20 GeV – 300 TeV

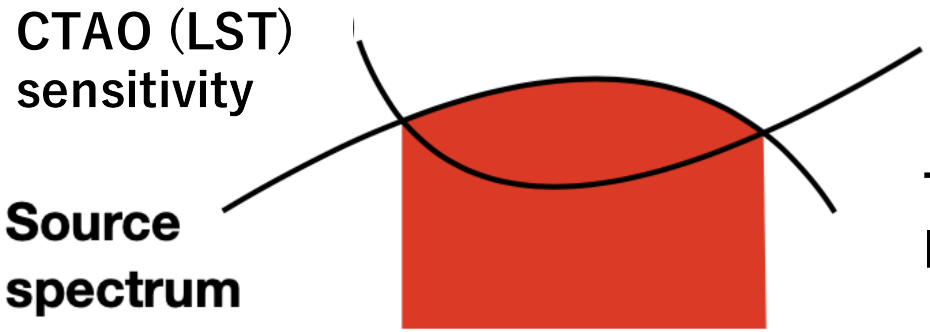
IceCube + CTAO
→ search for the same cosmic-ray accelerators

Selecting promising targets for IceCube × CTAO

Fermi-LAT GeV all-sky map

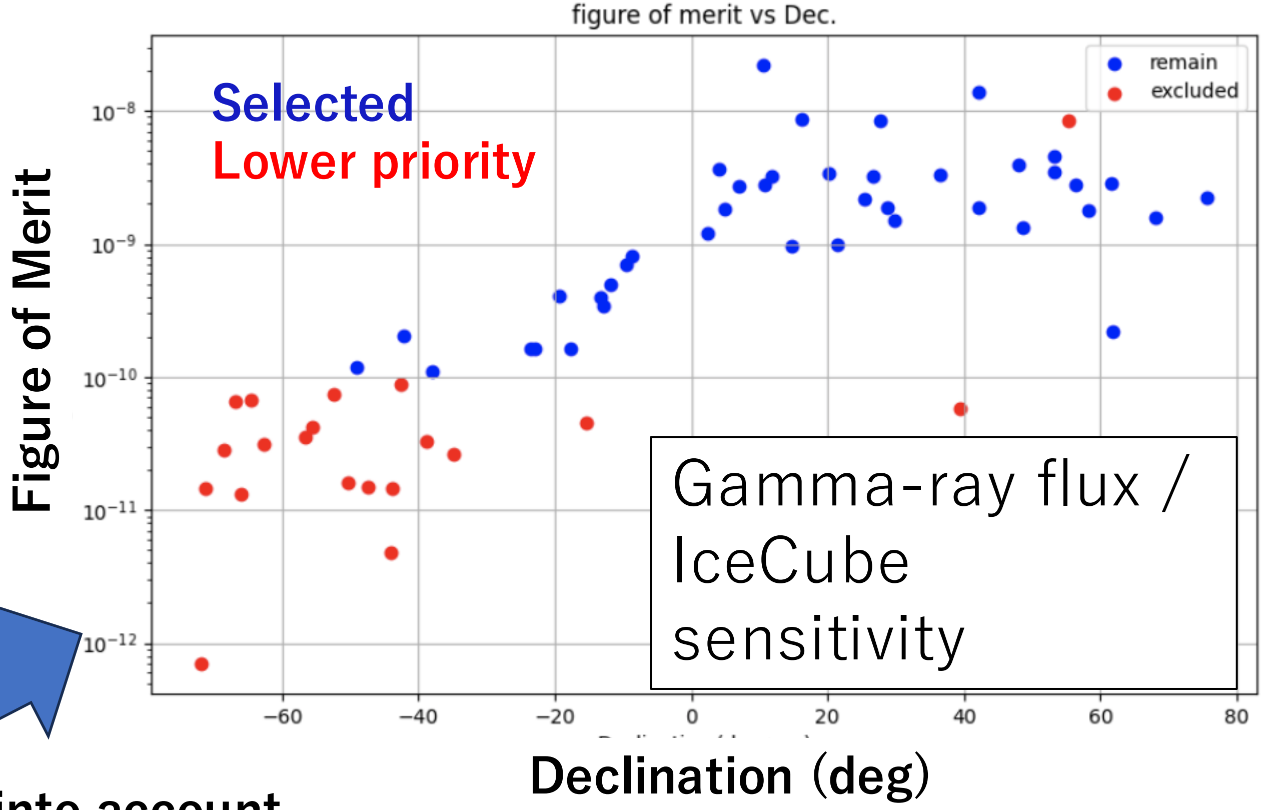


Can CTAO detect the source?



Taking into account IceCube sensitivity

Example: Fermi-based selection

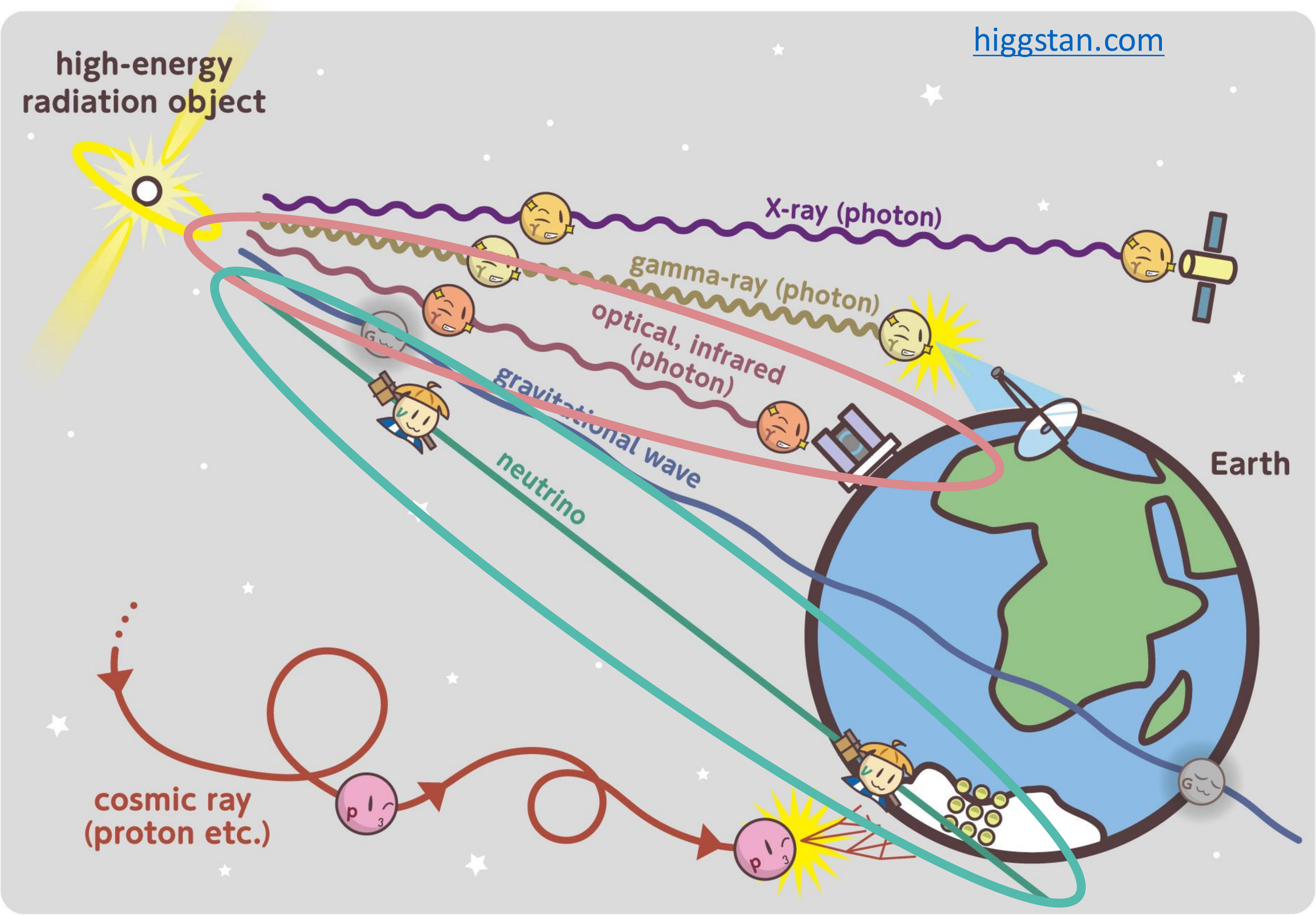


Prioritize sources promising for both gamma rays and neutrinos

ICEHAP contribution

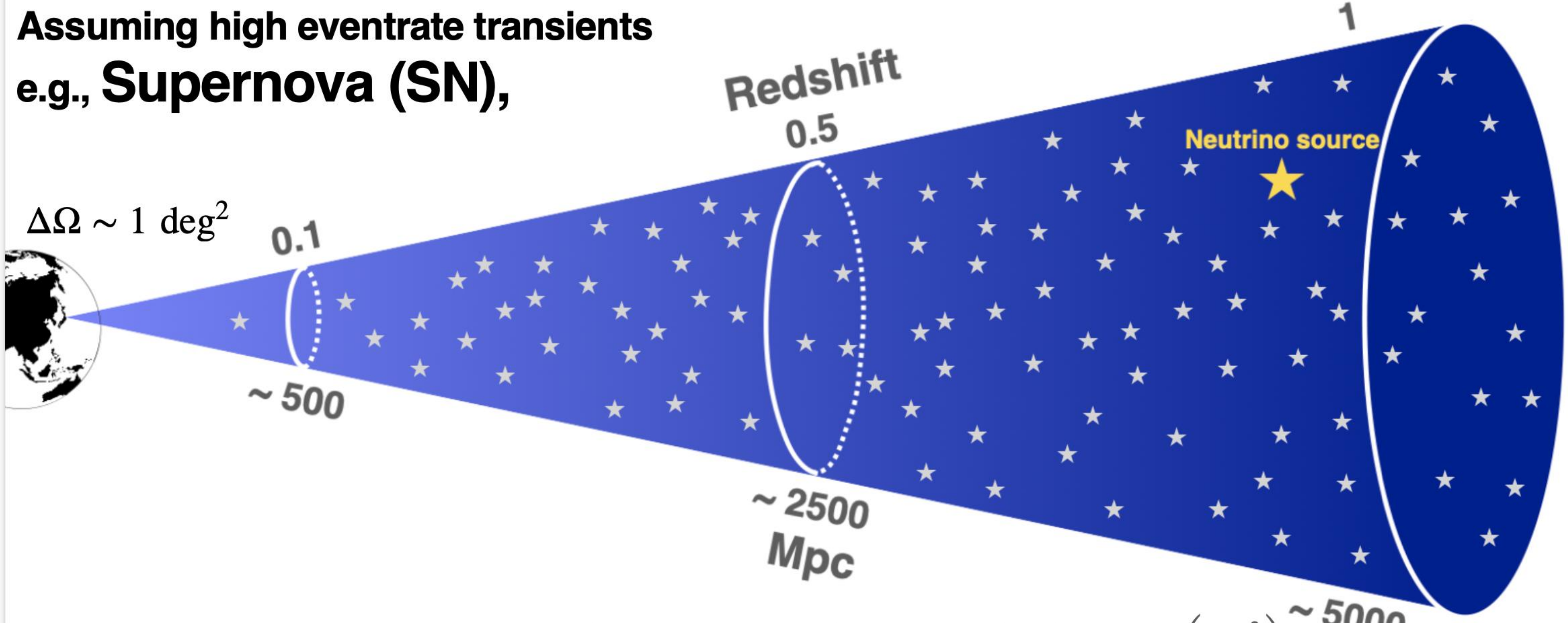
- TeV-oriented selection led by **Koji Noda (ICEHAP)**
- List is being refined for CTAO x IceCube follow-up

Messengers from the High-Energy Universe



Example 4:
Neutrino
+
Optical

Example 4: One neutrino can leave too many optical candidates



$$N_{\mathrm{SN,unrelated}} \sim 100 \left(\frac{R_{\mathrm{SN}}}{4\times10^5\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}}\right)\left(\frac{V}{10^2\ \mathrm{Gpc}^3}\right)\left(\frac{\Delta t}{30\ \mathrm{day}}\right)\left(\frac{\mathrm{deg}^2}{1}\right)$$

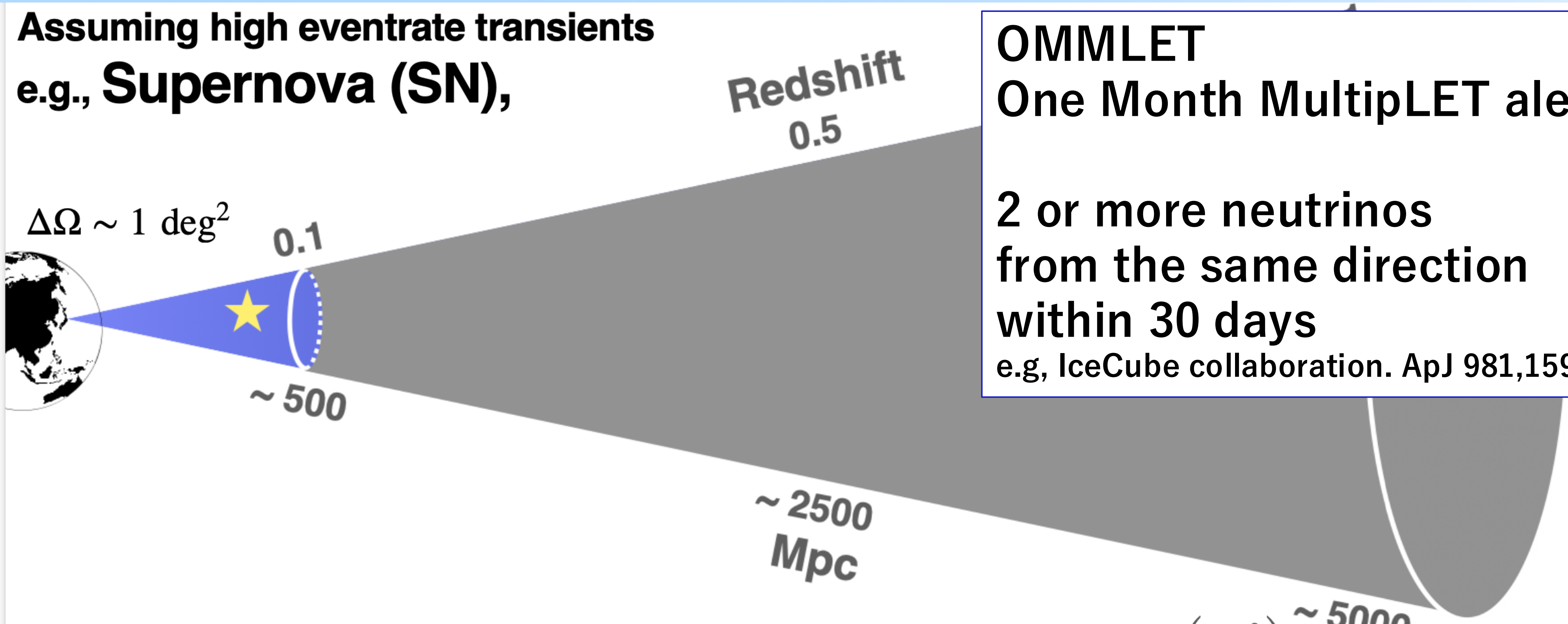
courtesy of S.Toshikage (Tohoku Univ)

IceCube direction: ~1 deg^2
30-day optical search
→ ~100 unrelated supernovae

Which one is the neutrino source?

Neutrino multiplets make optical follow-up practical

Assuming high eventrate transients
e.g., Supernova (SN),



$$N_{\mathrm{SN,unrelated}} \sim 0.01 \left(\frac{R_{\mathrm{SN}}}{4\times10^5\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}}\right)\left(\frac{V}{0.1\ \mathrm{Gpc}^3}\right)\left(\frac{\Delta t}{30\ \mathrm{day}}\right)\left(\frac{\mathrm{deg}^2}{1}\right)$$

courtesy of S.Toshikage (Tohoku Univ)

OMMLET
One Month MultipLET alert

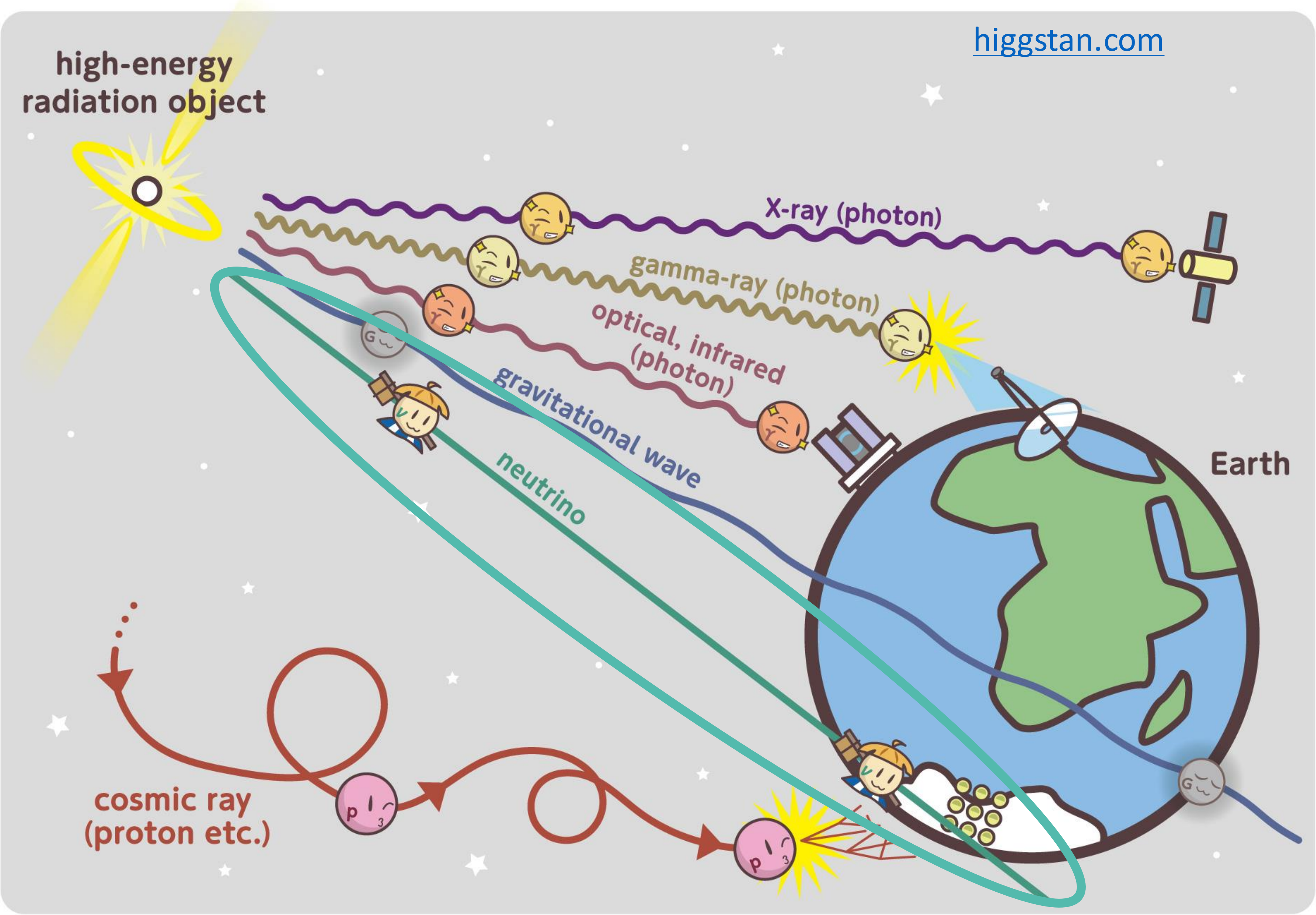
2 or more neutrinos from the same direction within 30 days
e.g, IceCube collaboration. ApJ 981,159 (2025)

Nearby alerts open multimessenger follow-up to a wider range of telescopes.

Already tested with archival data
IceCube triplet × ZTF **Toshikage et al. ApJ 993, 23 (2025)**

Developed at ICEHAP
Led by Nobu Shimizu
Optical follow-up with
Seimei 3.8-m telescope and partners

Messengers from the High-Energy Universe



Neutrino

→ UpGrade

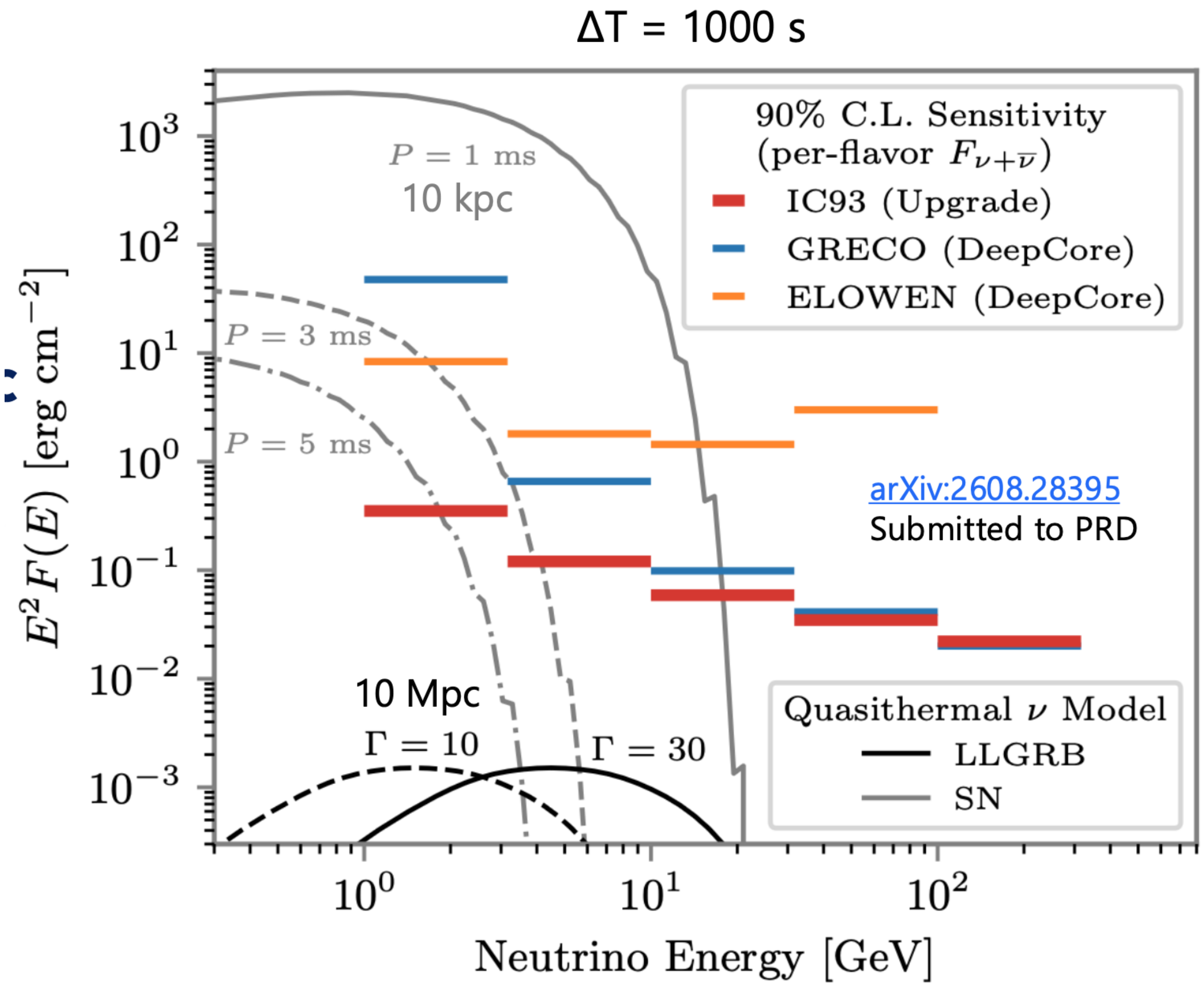
→Next Generation

Multimessenger triggers can reveal astrophysical GeV neutrinos

IceCube Upgrade: 1–10 GeV neutrinos
~10× better sensitivity than current low-energy IceCube capability

At GeV energies, the atmospheric-neutrino background is large

→ time + direction info from photons strongly reduce the neutrino-search background



ICEHAP contribution
GeV transient study led by Yukiho Kobayashi

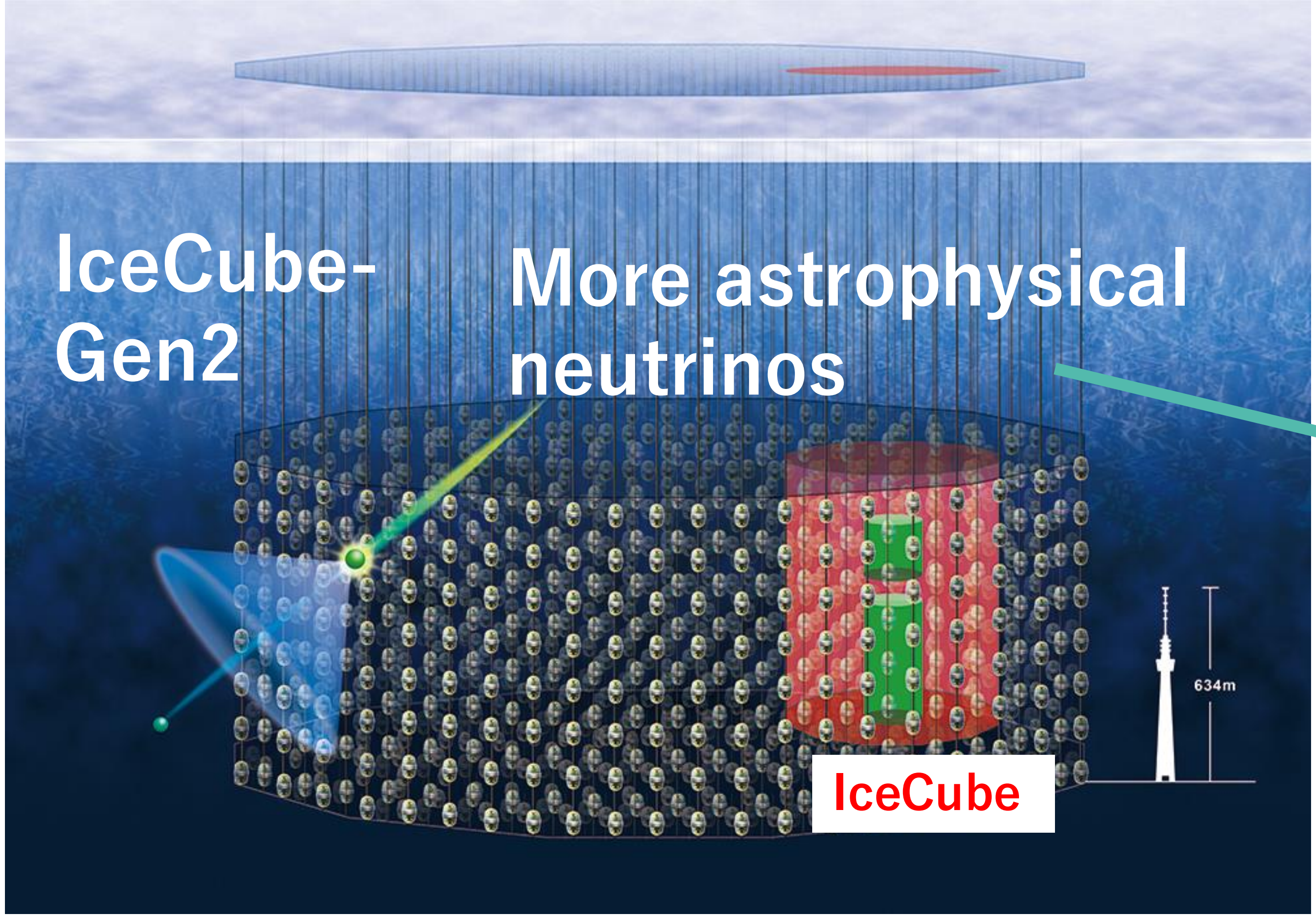
IceCube-Gen2: A Multimessenger Science Multiplier

X-ray → archival counterpart searches / source-state studies

Gamma ray → CTAO joint targets

Optical → multiplet follow-up

Photons triggers → targeted neutrino searches



More counterparts

More source tests

More follow-up opportunities

IceCube-Gen2 will multiply the scientific power of multimessenger astronomy.
→Gen2 is not only a neutrino project. It can increase the scientific return of many observatories that already exist.

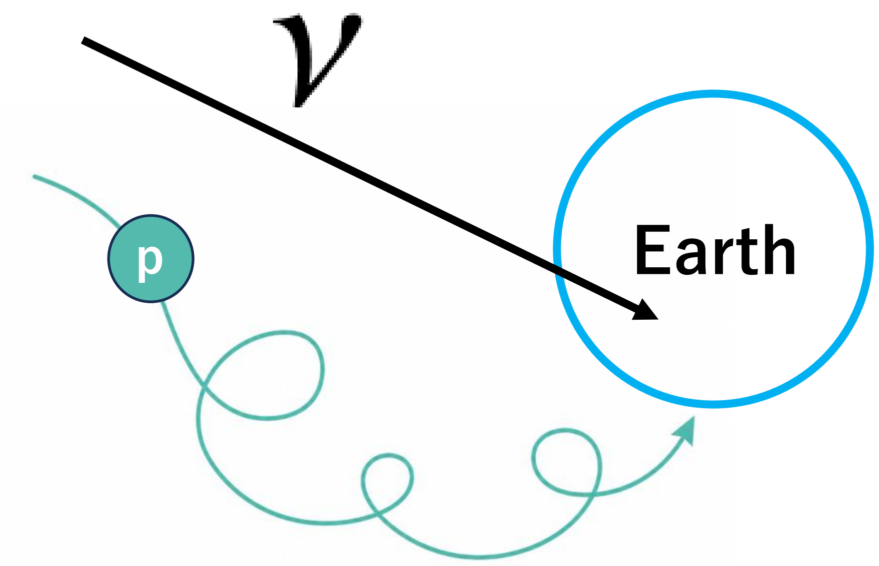
Take-home messages

1. IceCube neutrinos give new scientific meaning to existing observations.
   - MAXI archive → search for X-ray counterparts and test cosmic-ray source models
   - X-ray monitoring → time-dependent neutrino predictions
2. Different messengers help us in different ways.
   - Gamma rays → select promising IceCube × CTAO targets
   - Neutrino multiplets → make optical follow-up practical
   - Photon triggers → reduce background in Upgrade GeV-neutrino searches
3. IceCube-Gen2 will create many more multimessenger opportunities.
   - More astrophysical neutrinos → more counterparts, source tests, and follow-up opportunities

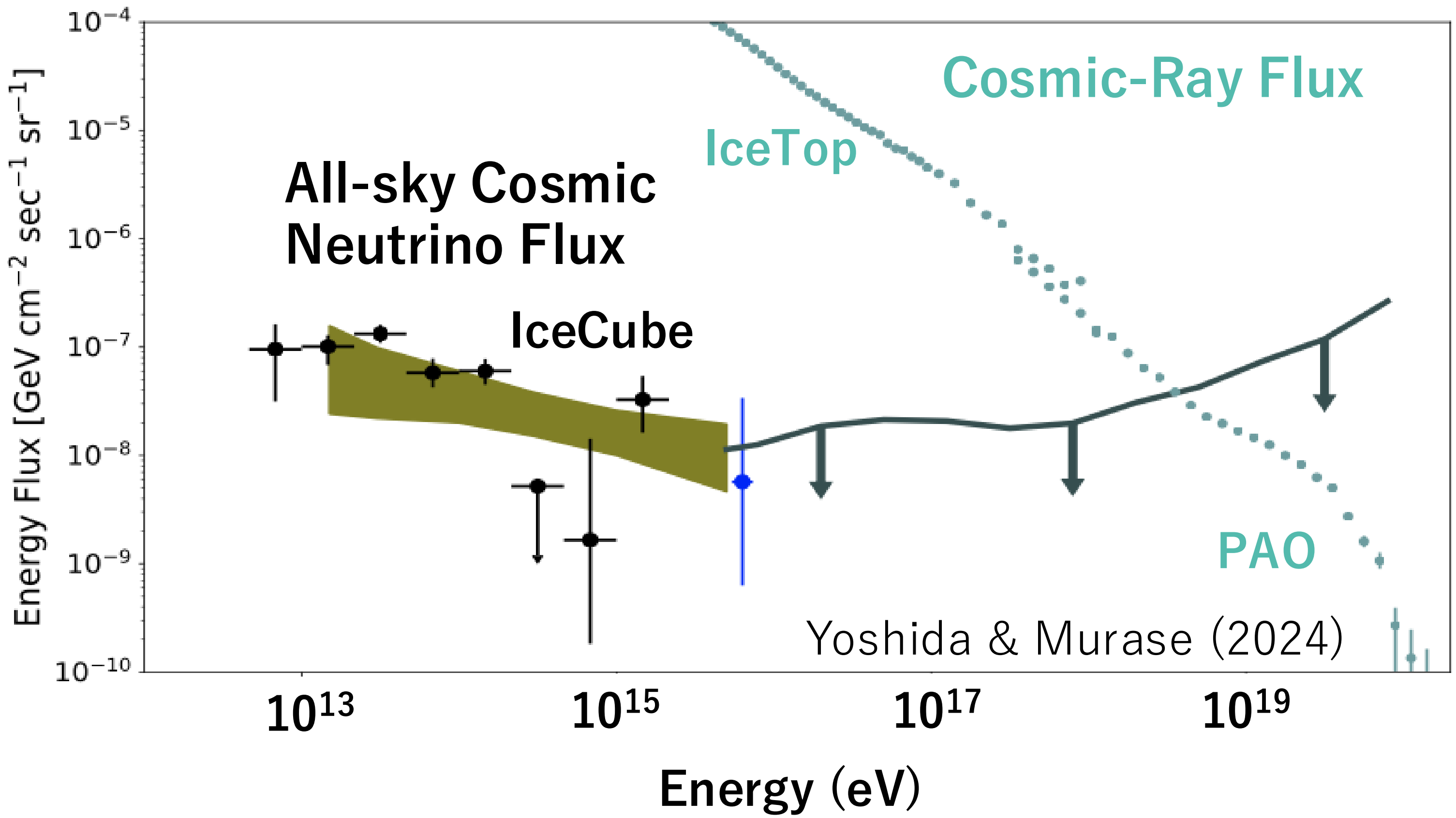
IceCube neutrinos give new meaning to existing observations — and other messengers give new opportunities to IceCube.

backup

Where do cosmic neutrinos and UHECRs come from?

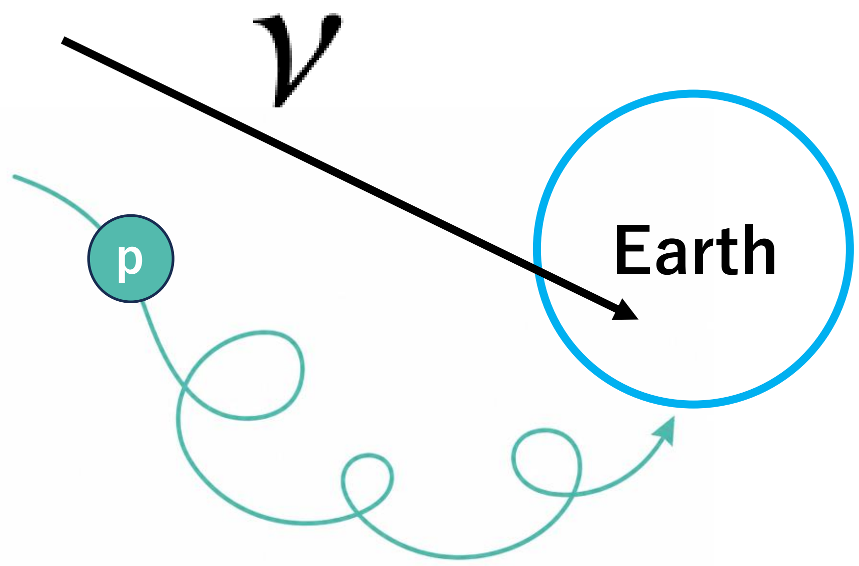


Two high-energy messengers

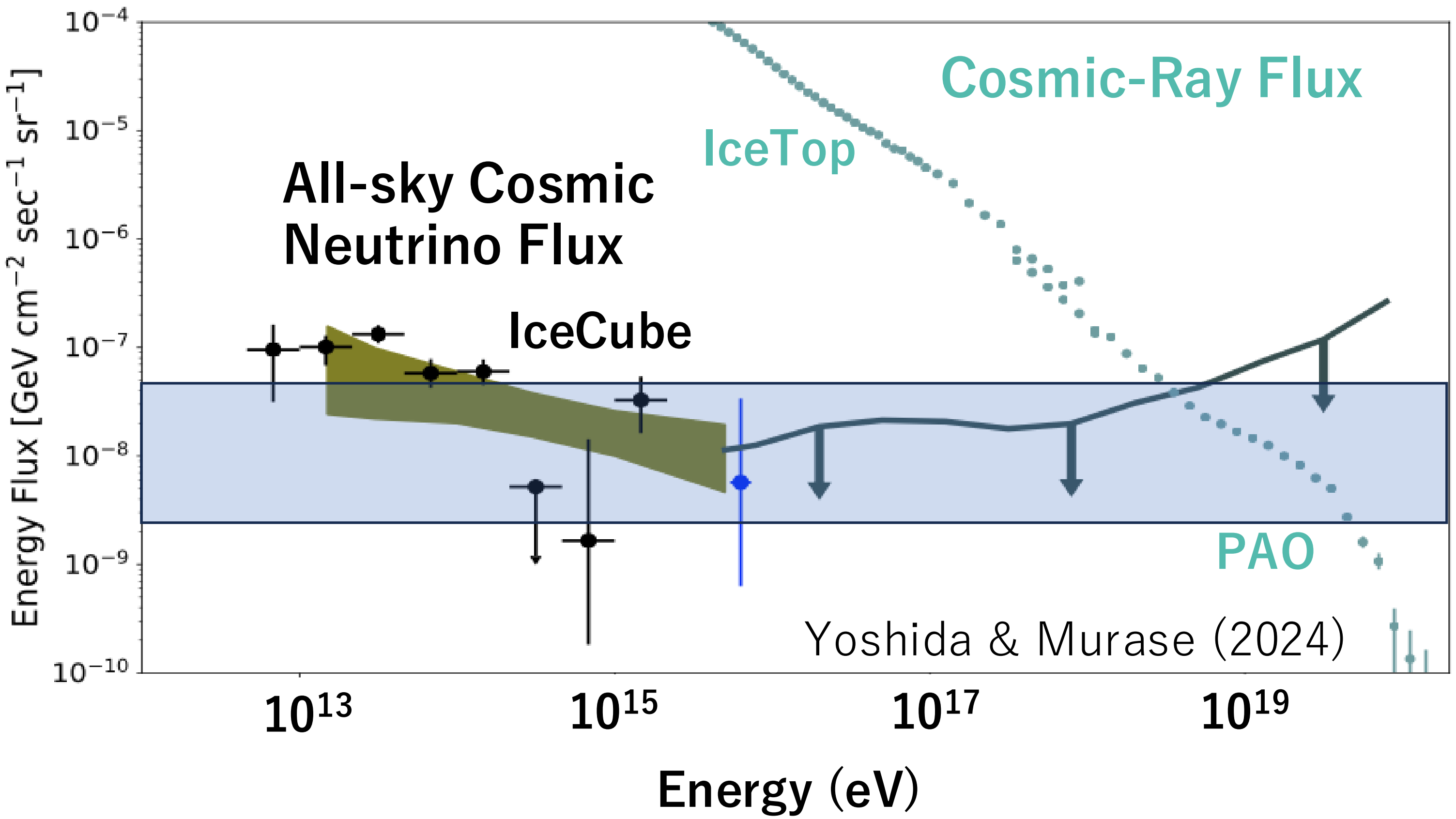


Could the same source population produce both cosmic neutrinos and UHECRs?

Where do cosmic neutrinos and UHECRs come from?



Two high-energy messengers

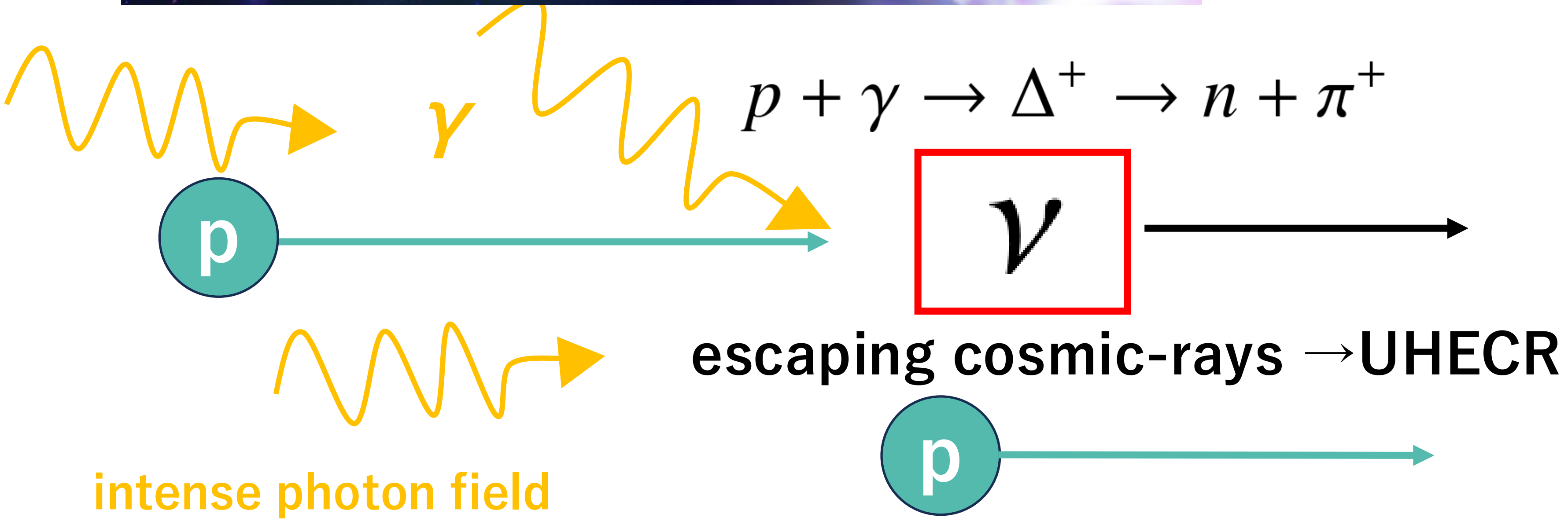


Could the same source population produce both cosmic neutrinos and UHECRs?

GRBs as Cosmic Accelerators

- Gamma-ray Burst (GRB)
- Relativistic Jet ($\Gamma \sim 100$)
- Prompt γ-rays

$\sim$ 100 keV – 1 MeV



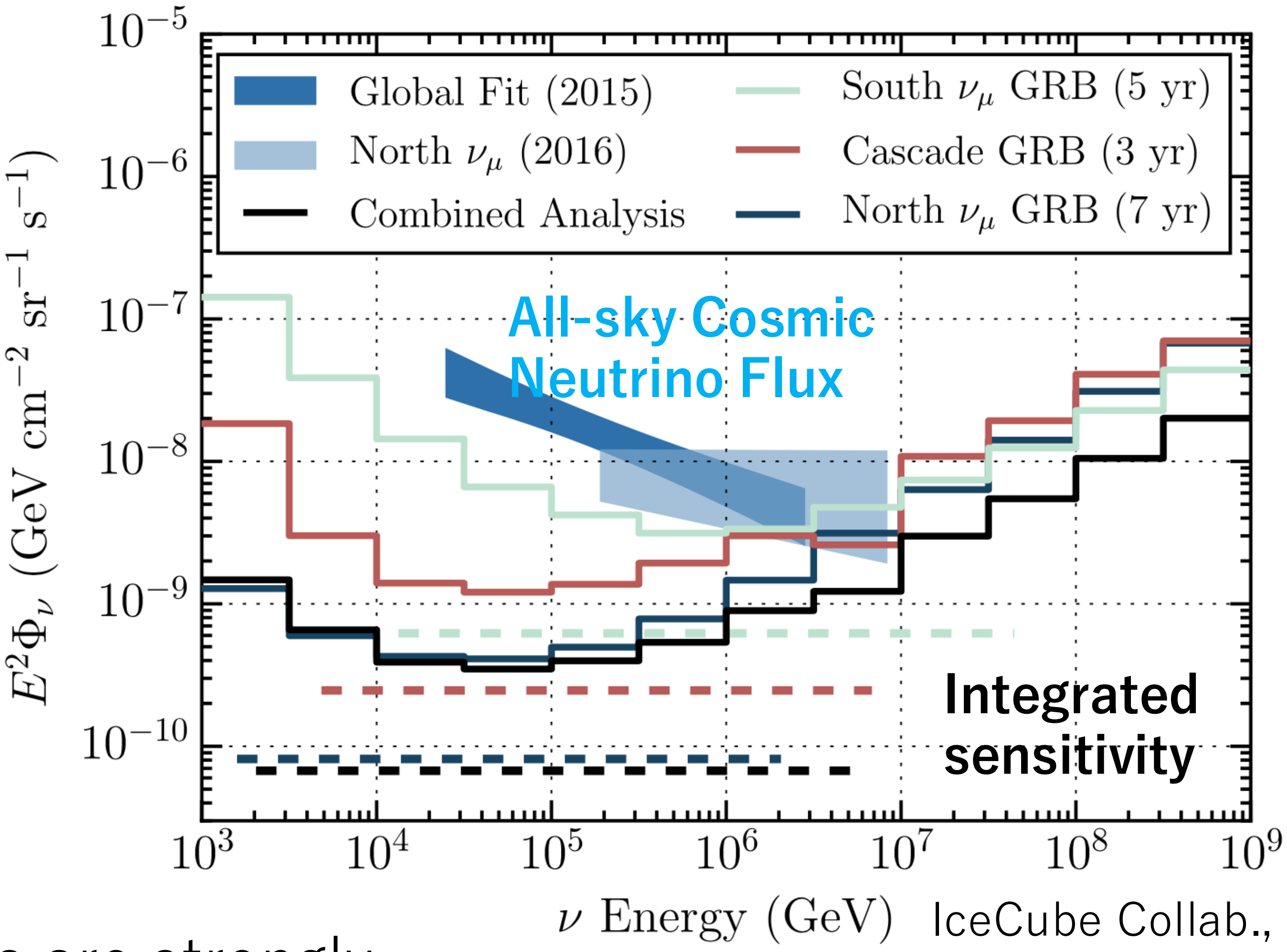
$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

Neutrinos can directly test the GRB–UHECR connection

IceCube Strongly Constrains Classical GRBs

trigger → search

> 10 keV



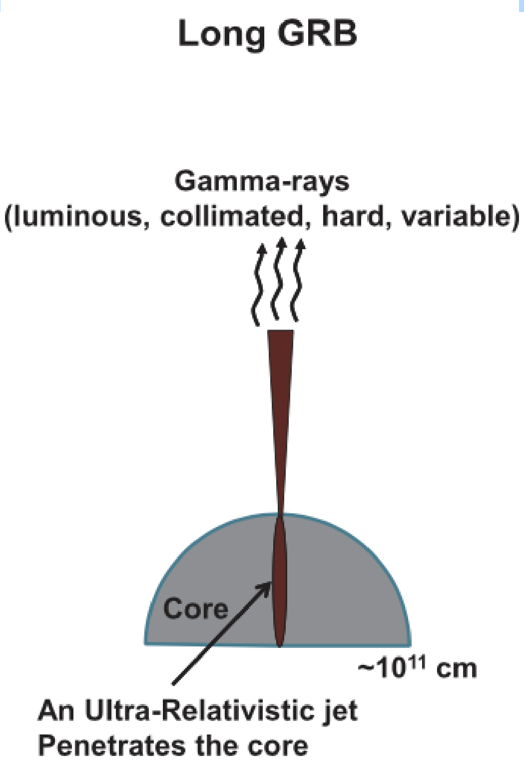
IceCube Collab., ApJ 824, 115 (2016)

Classical, gamma-ray-bright GRBs are strongly constrained
— **but this does not exclude other p γ transient populations.**

→ **Where should we look?**

Beyond Classical GRBs: Why Soft X-rays?

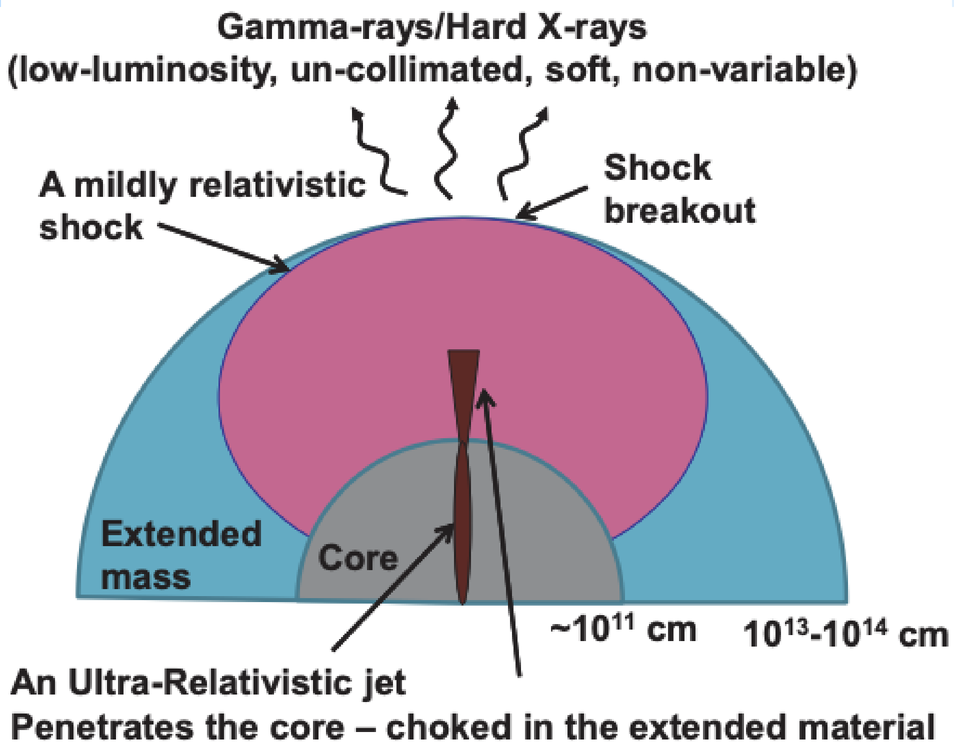
Classical GRB



Soft X-ray Transients (SXTs)

Example: Low-luminosity GRB

Nakar 2015 ApJ



pγ target photon energy ε_X

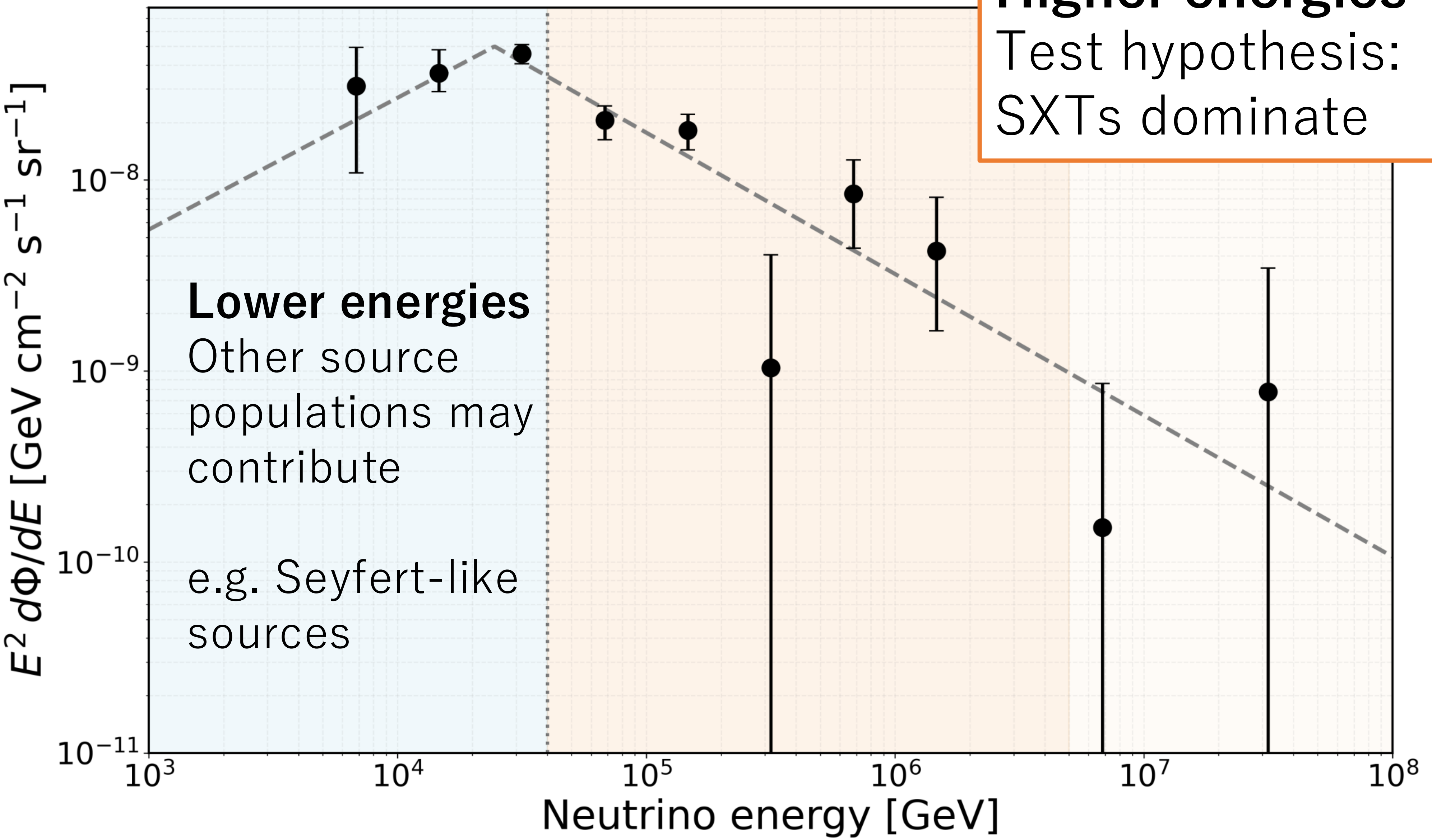
$$\varepsilon_X = 15\left(\frac{\Gamma}{10}\right)^2\left(\frac{\varepsilon_p}{1\ \mathrm{PeV}}\right)^{-1}\ \mathrm{keV}$$

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

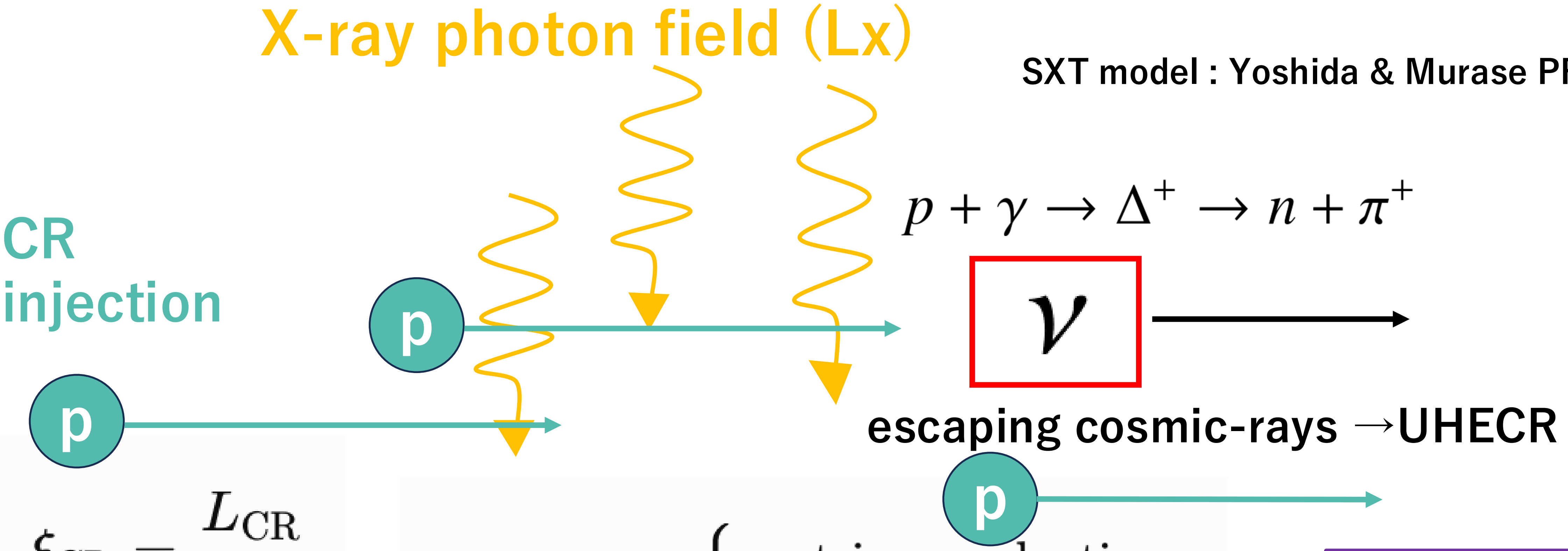
All-sky Cosmic Neutrino Flux
(IceCube Collab., 2026, PRL, 136, 121002)



Higher energies
Test hypothesis:
SXTs dominate

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

SXT model : Yoshida & Murase PRD 2024



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

CR loading factor

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

Population flux $\propto n_0$

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

For fixed Γ and n_0, the neutrino flux determines the required $\xi_{\rm CR}$ for a given Lx

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

$$\boxed{\xi_{\rm CR} \equiv \frac{L_{\rm CR}}{L_X}} \quad \Longleftrightarrow \quad L_{\rm CR} = \xi_{\rm CR} L_X$$

X-ray photon field (Lx)

$\xi_{CR} = 1$

CR injection

$L_{CR} = 1 \times Lx$

modest proton power

Same X-ray luminosity Lx

X-ray photon field (Lx)

$\xi_{CR} = 100$

CR injection

$L_{CR} = \mathbf{100} \times Lx$

enormous proton power

More CR power

↓

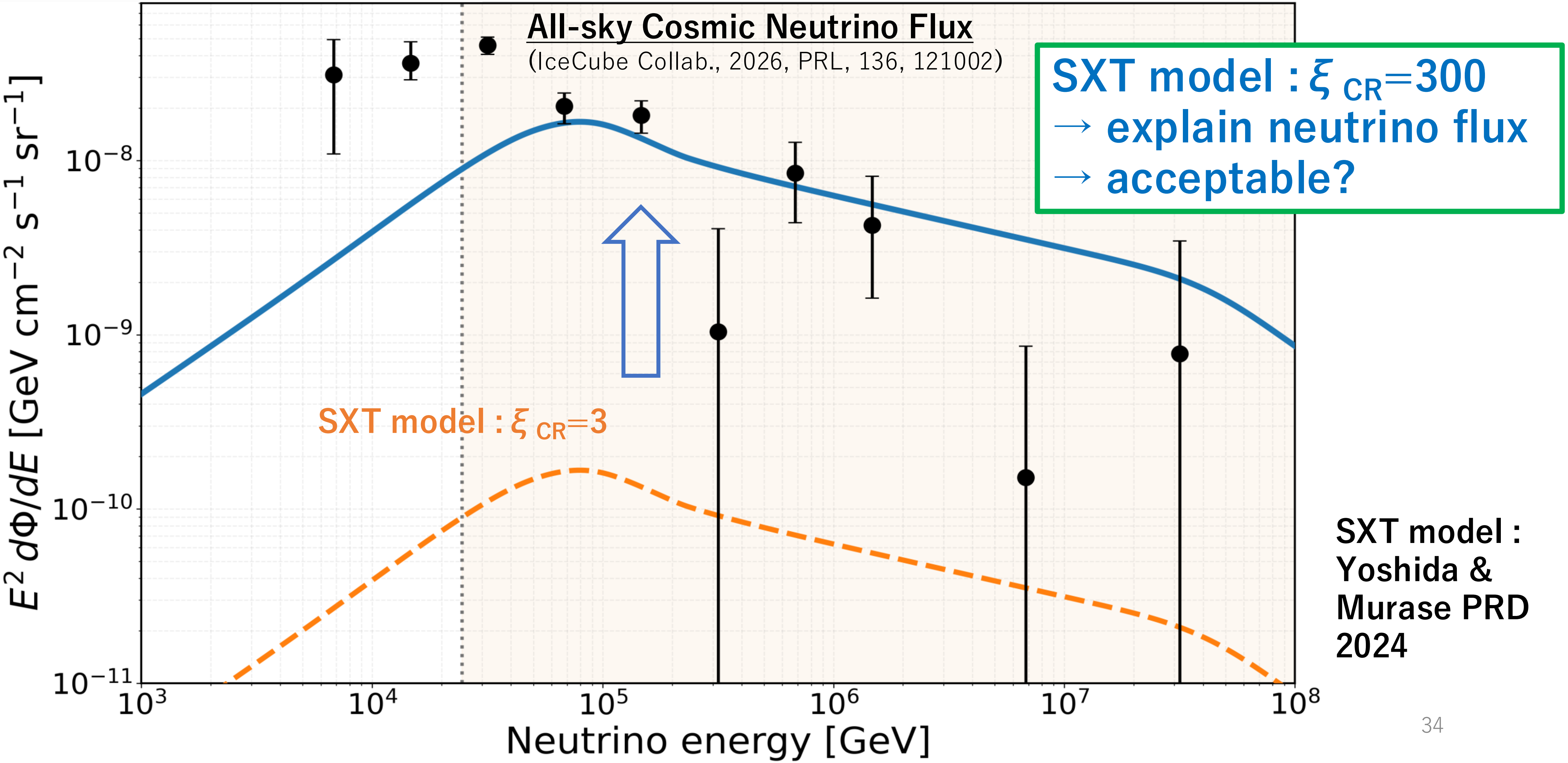
More escaping UHECRs

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

How Much CR Loading Is Required by Neutrinos?

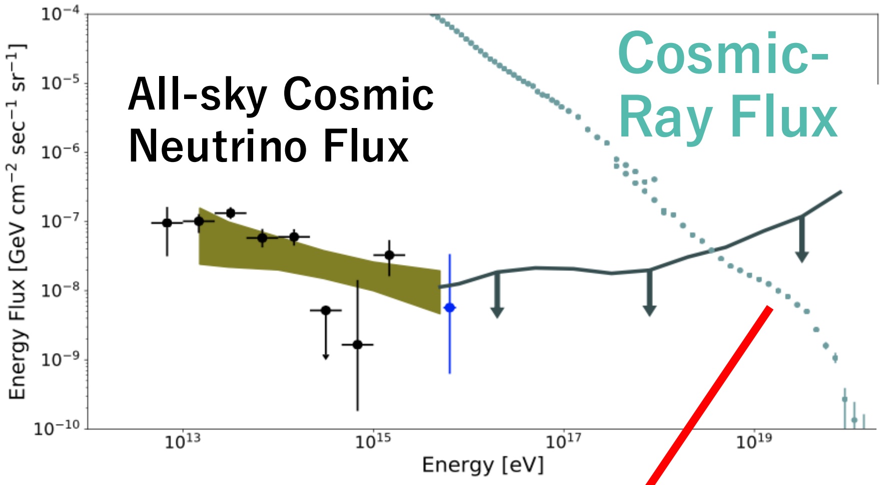
$$\Phi_\nu = \Phi_\nu(L_X, \Gamma, n_0, \xi_{\rm CR})$$

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



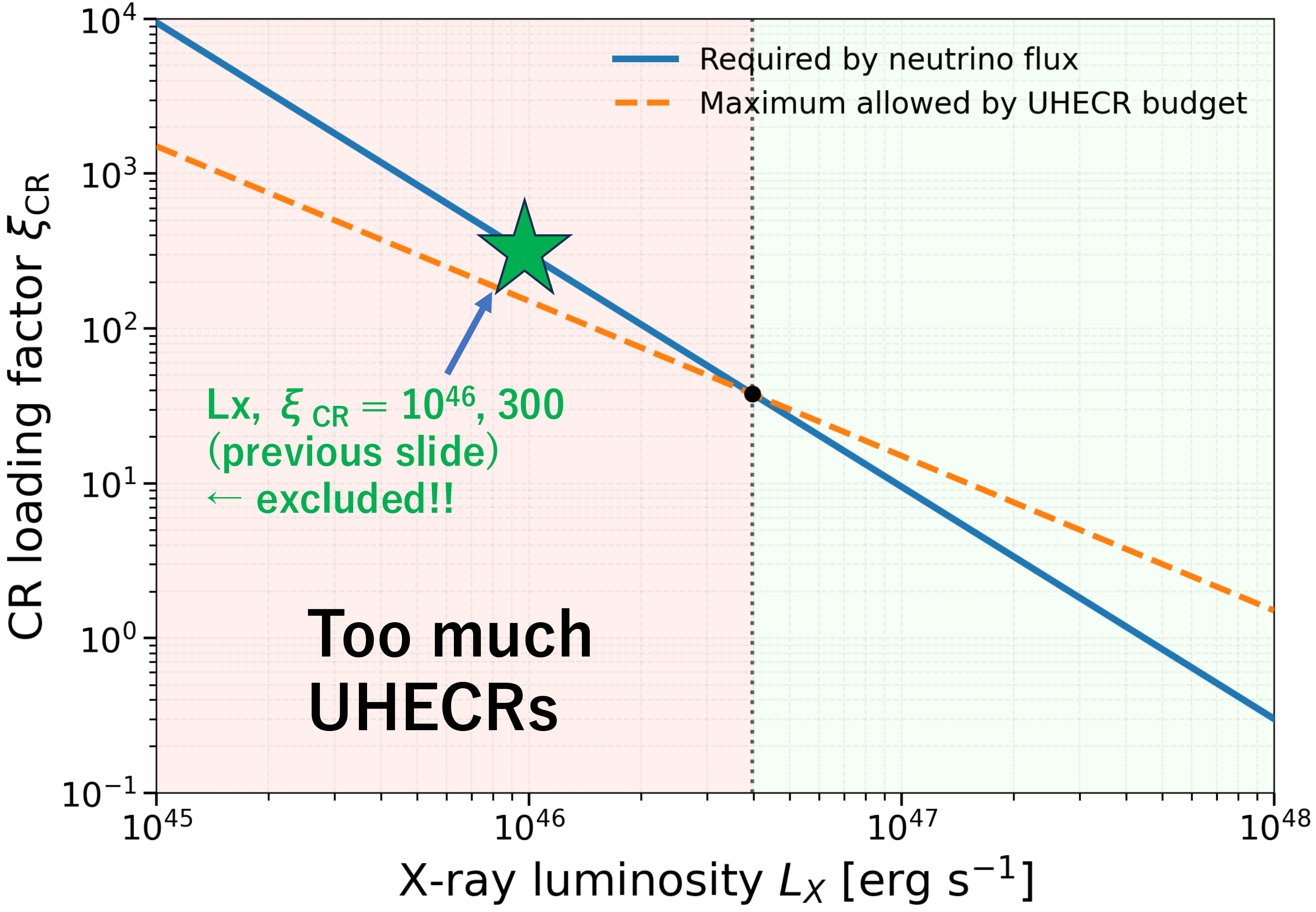
SXT model : Yoshida & Murase PRD 2024

Neutrino Requirement vs. UHECR Budget



ξ_{CR} limit by observed UHECR flux

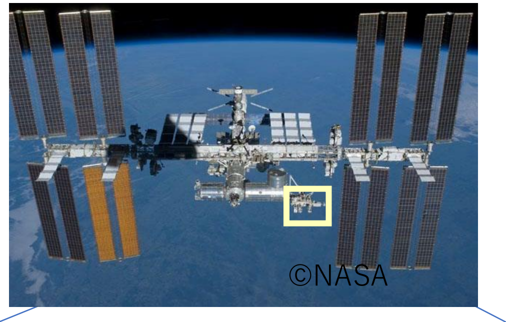
We need an observational constraint on Lx, but how?

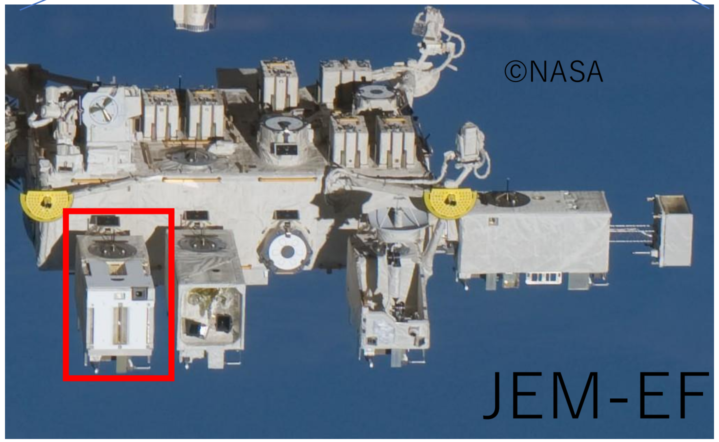


IceCube Turns the MAXI Archive into a Multimessenger Probe

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

Continuous all-sky X-ray monitoring from 2009





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

MAXI alone

all-sky X-ray archive

⇩

no predefined target

IceCube + **MAXI**

time + direction

⇩

targeted MAXI search

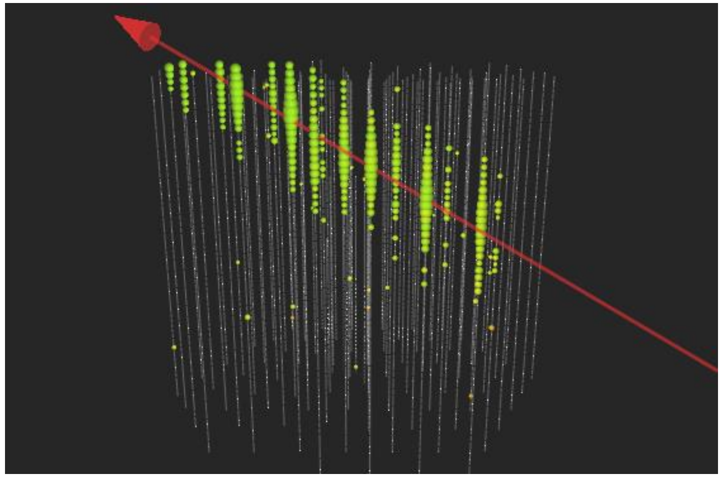
14.5 Years of Simultaneous MAXI–IceCube Observations

IceCube high-energy track sample

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

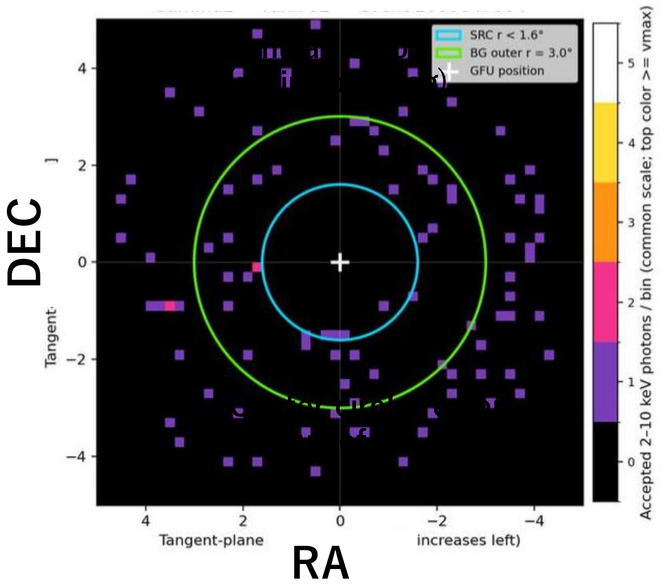
MAXI

- Photon-counting observations



Targeted multimessenger search

MAXI X-ray Image



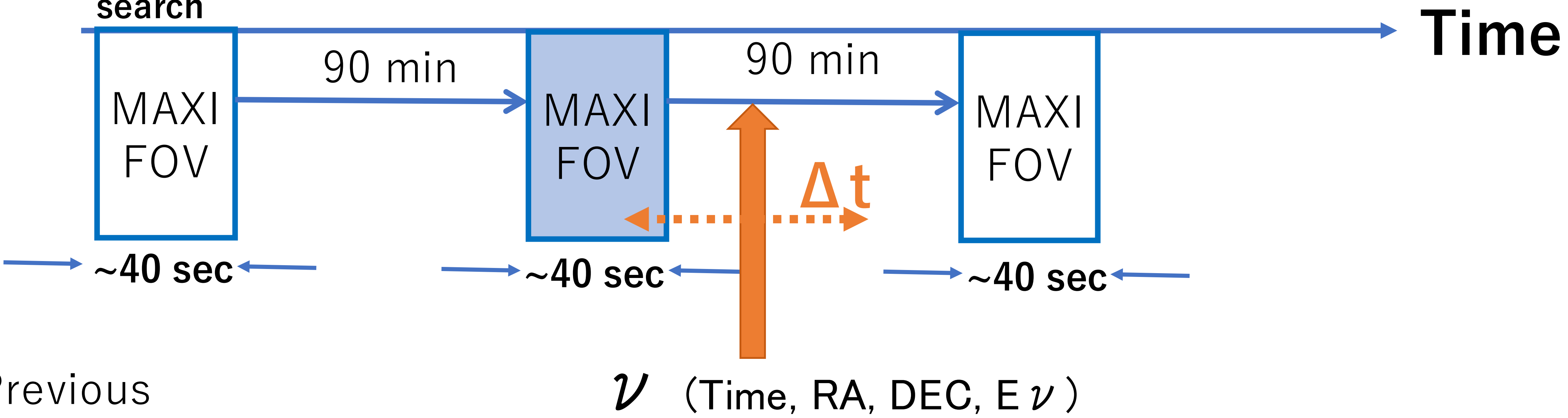
Final analysis sample : ~2 × 10^5 IceCube events with simultaneous MAXI coverage in 14.5 years

For Each Neutrino, Search the Corresponding MAXI Scan

< 10 keV

trigger → search

MAXI data were already recorded
— this is an archival reverse-trigger search.



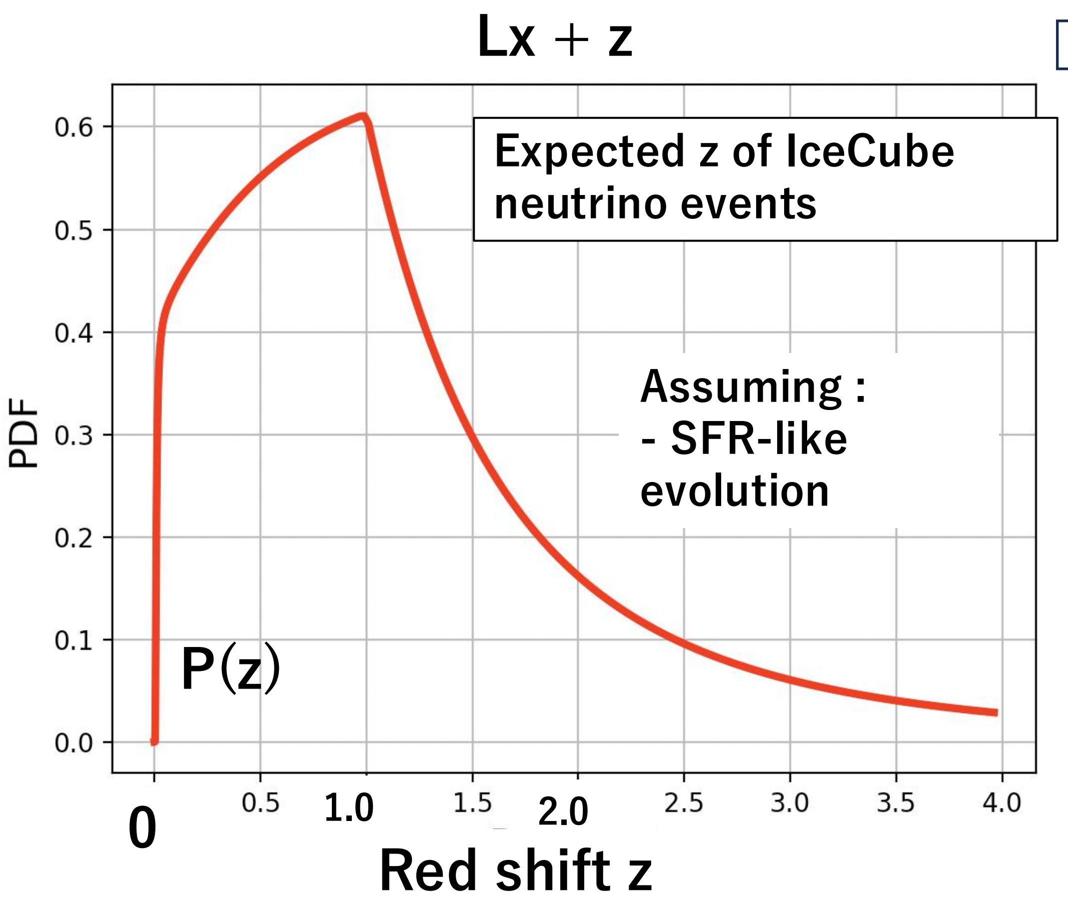
Previous

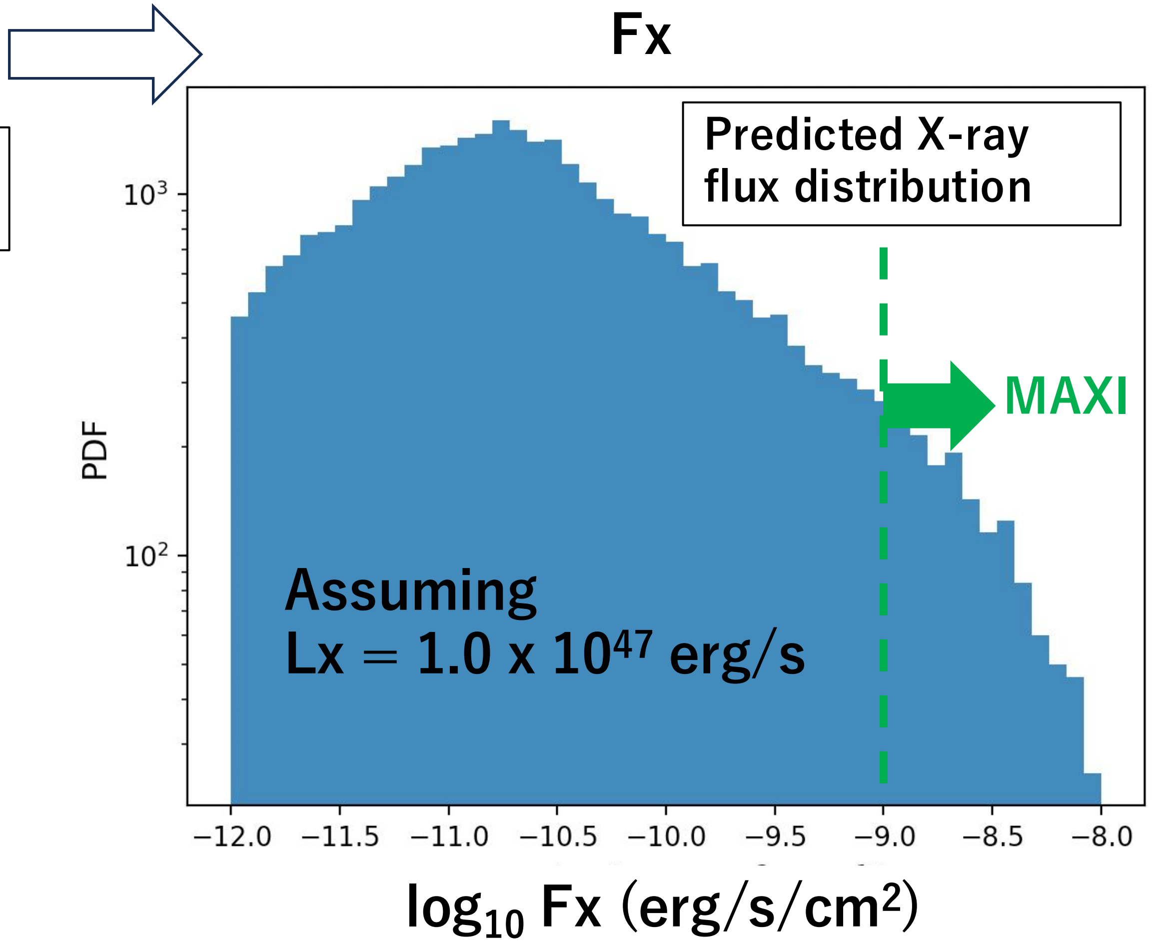
> 10 keV

trigger → search

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

How Can MAXI Constrain Lx Without Knowing the Distance?





Assume a common Lx for the SXT population

Individual source distances are unknown → use the expected P(z)

How Do We Test a Trial Lx?

SXT event | unrelated astrophysical neutrino | atmospheric neutrino

$$\mathcal{L}_{\mathrm{sig+bgd}} = \frac{n_{\mathrm{sig}}}{n_{\mathrm{atm}} + n_{\mathrm{dif}}} P_{\nu}^{\mathrm{sig}}{}_{(E_\nu,\delta)} \times P_{\mathrm{X}}^{\mathrm{sig}}(N_{\mathrm{X}}, \mu_{\mathrm{Xsig}(L_{\mathrm{X_{ref}}}, z)}) + \frac{1}{n_{\mathrm{atm}} + n_{\mathrm{dif}}} \left\{ n_{\mathrm{dif}} P_{\nu}^{\mathrm{dif}}{}_{(E_\nu,\delta)} - n_{\mathrm{sig}} P_{\nu}^{\mathrm{sig}}{}_{(E_\nu,\delta)} \right\} P_{\mathrm{X_{DB}}}^{\mathrm{bgd}}(N_{\mathrm{X}}) + \frac{n_{\mathrm{atm}}}{n_{\mathrm{atm}} + n_{\mathrm{dif}}} P_{\nu}^{\mathrm{atm}}{}_{(E_\nu,\delta)} P_{\mathrm{X_{DB}}}^{\mathrm{bgd}}(N_{\mathrm{X}})$$

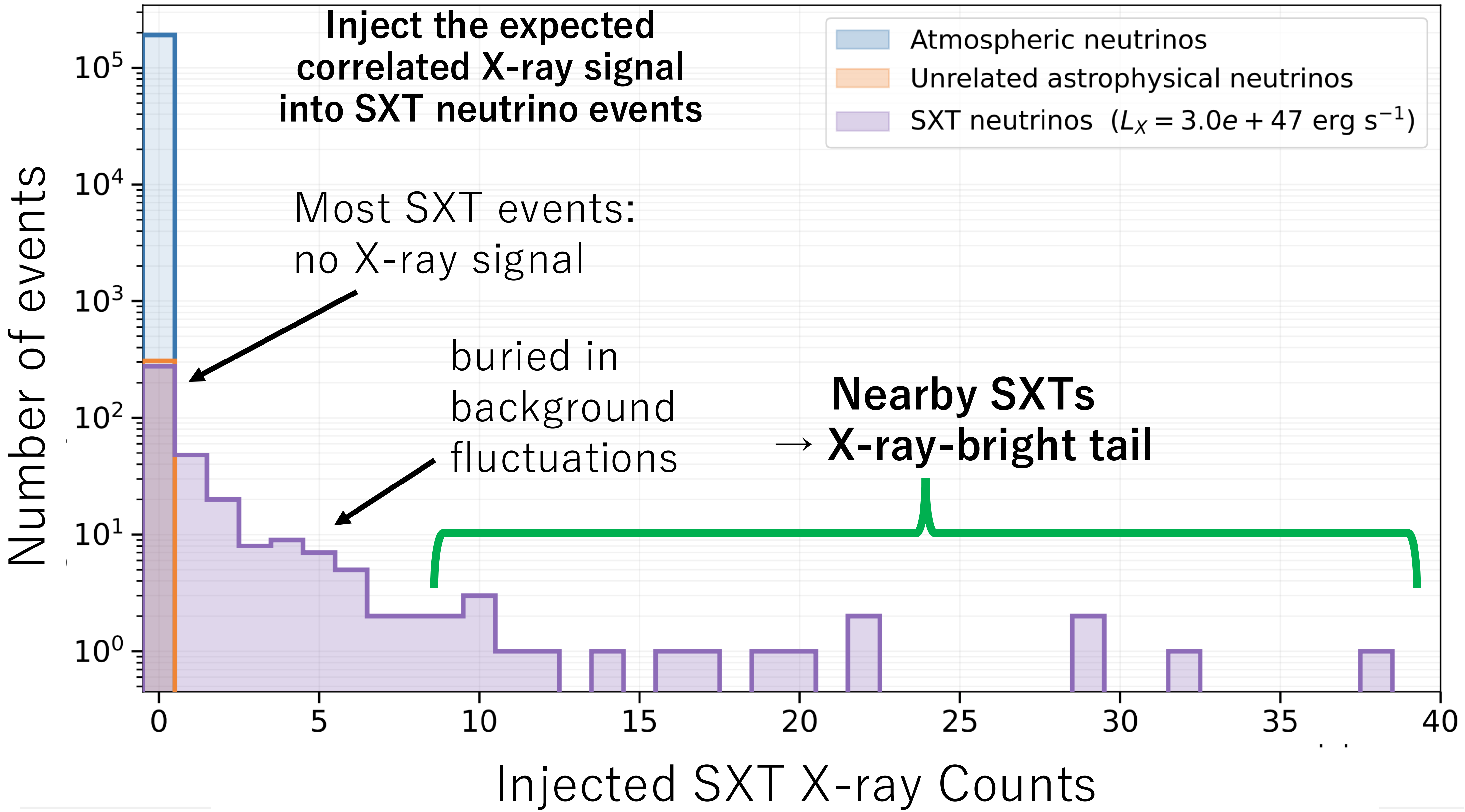
$P_\nu(E_\nu, \delta)$: neutrino PDF from reconstructed energy and direction
$P_X(N_X)$: MAXI X-ray count (Nx) PDF
$n_{\mathrm{sig}}, n_{\mathrm{dif}}, n_{\mathrm{atm}}$: expected event numbers of the three components
$L_{X,\mathrm{ref}}$: population X-ray luminosity scanned in the likelihood

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

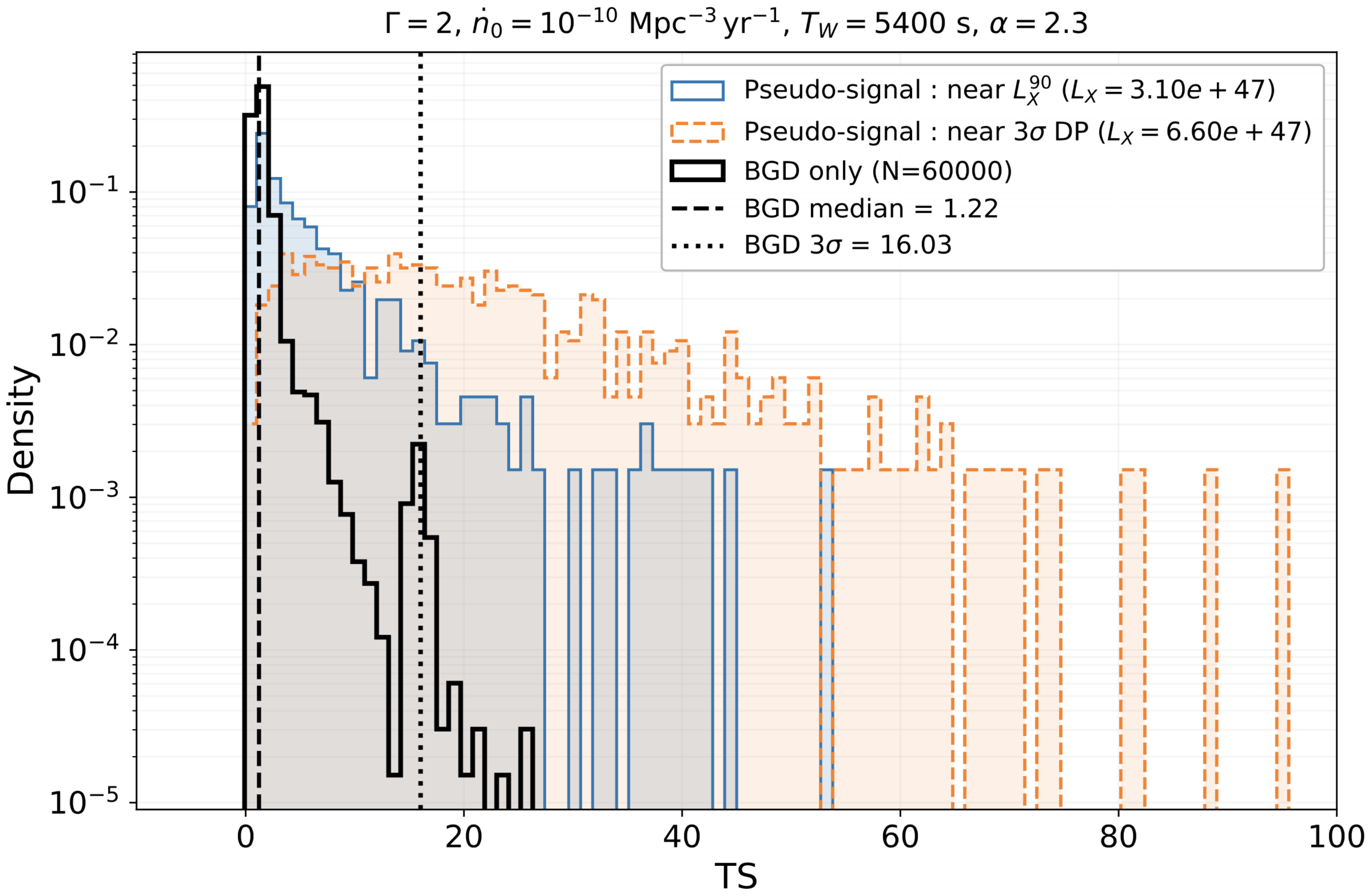
$$TS = \max_{L_{X,\mathrm{ref}}} \sum_i \log_{10} \mathrm{LHR}_i$$

Each coincidence → event-level LHR
14.5 years of coincidences → one population-level TS

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



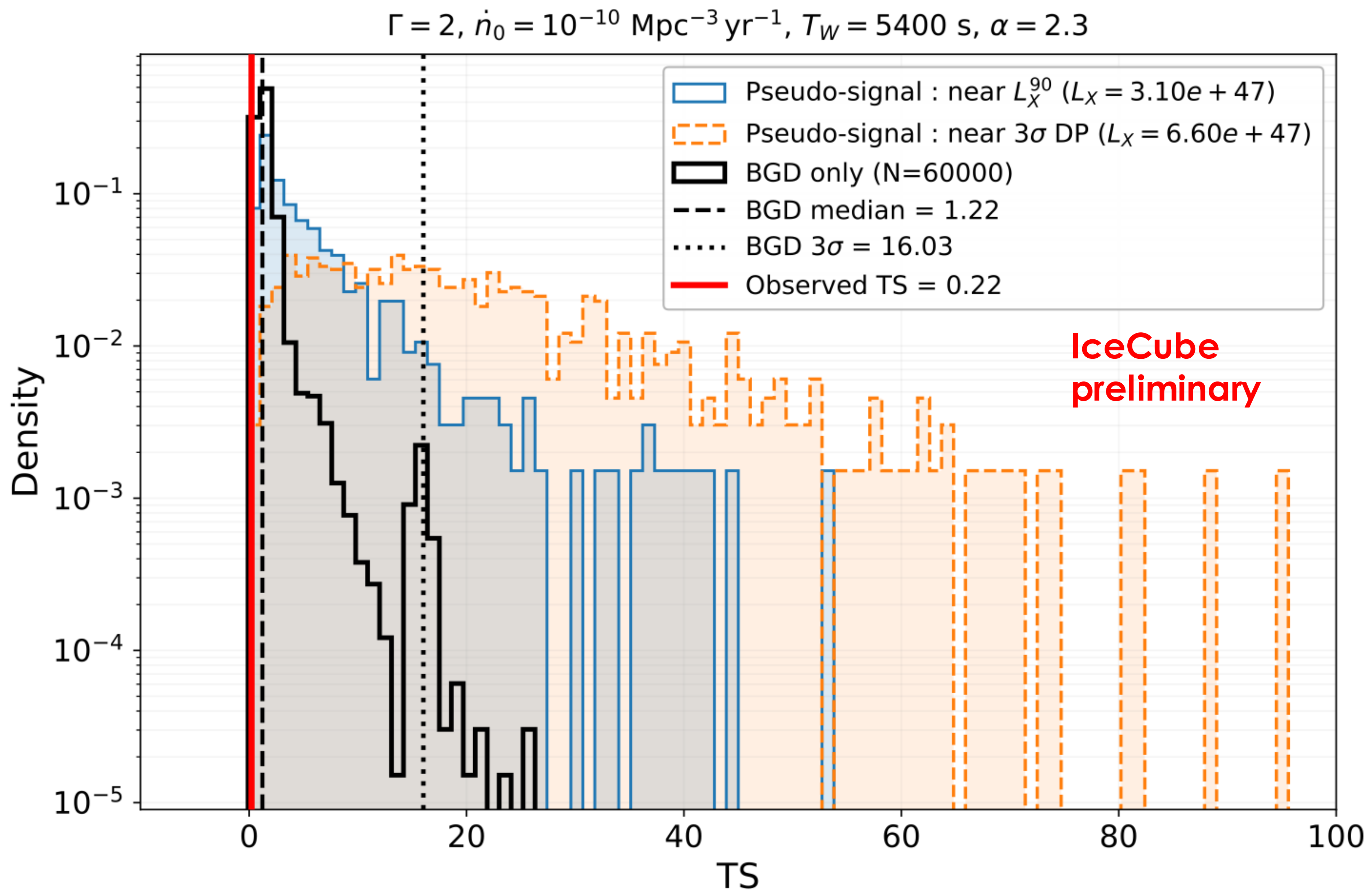
Brighter SXT Populations Produce Larger TS



Background only
RA-scrambled
IceCube × real MAXI

Inject SXT signals
brighter LX
→ larger TS

No X-ray Counterpart Excess in 14.5 Years



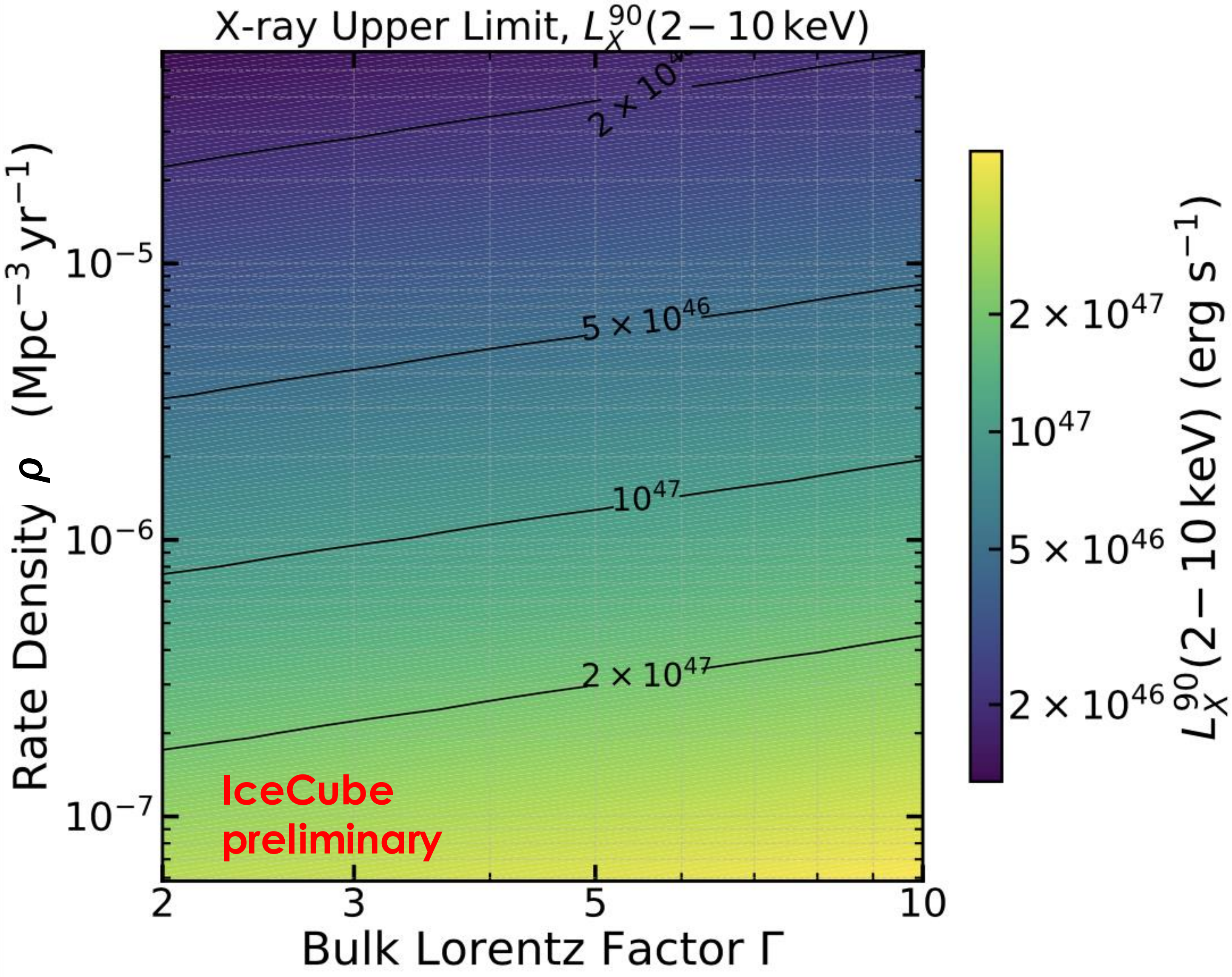
<u>191,925 IC–MAXI</u>
coincident events

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

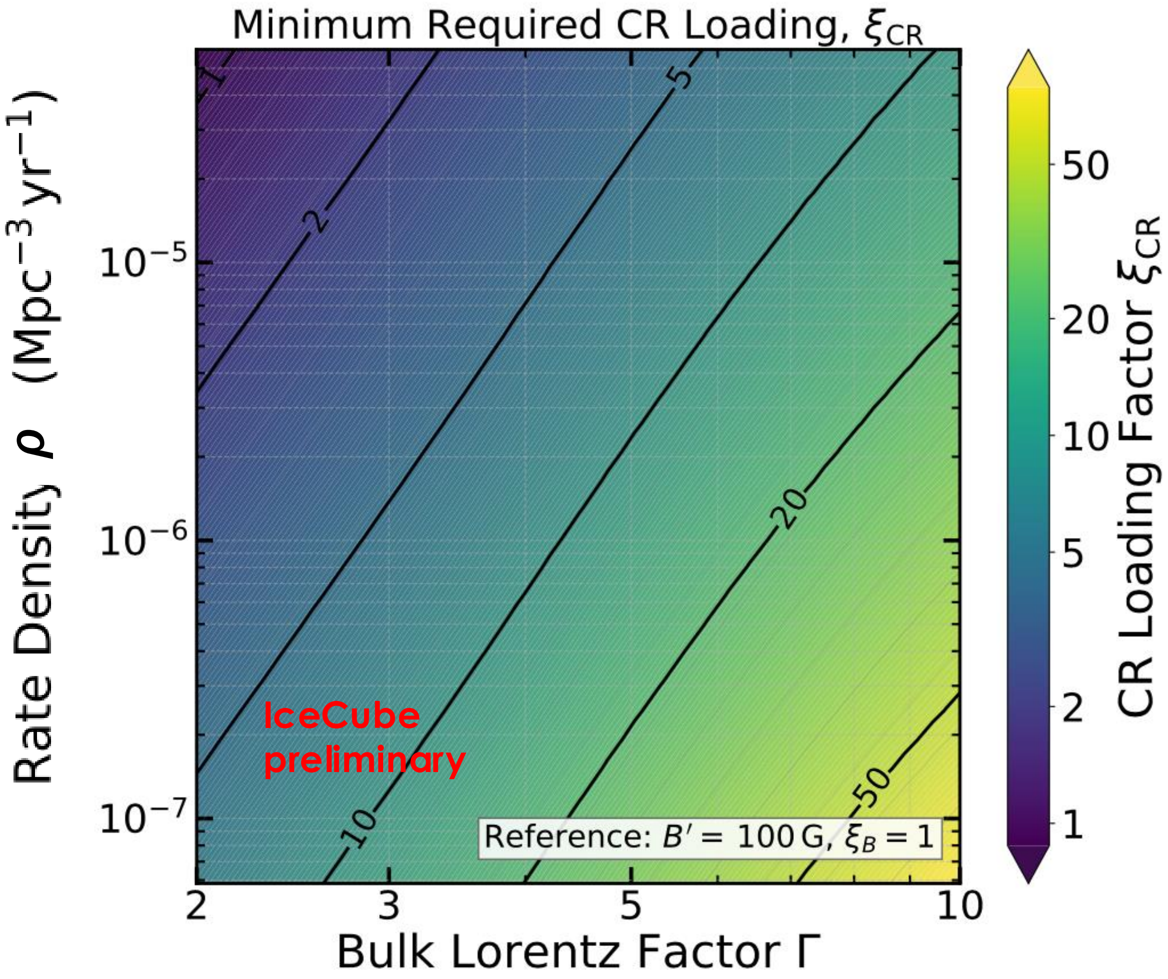
The first systematic constraints are obtained across the $n_0 - \Gamma$ plane using real soft-X-ray data.



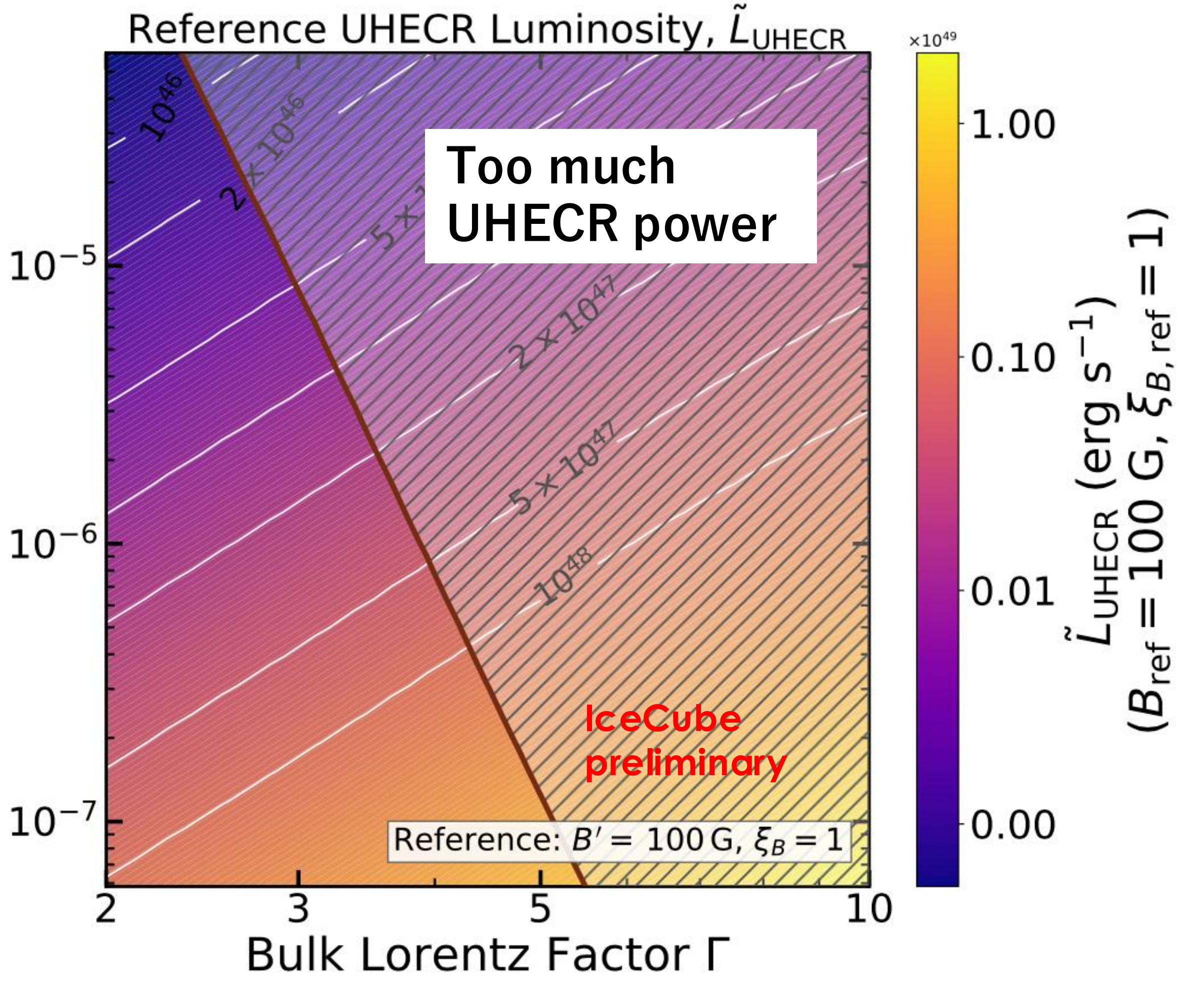
X-ray limits imply a minimum CR loading and constrain UHECR-source models

L_X^{90} from MAXI → $\xi_{\rm CR}^{\rm min}$ from IceCube → UHECR budget

Neutrino requirement

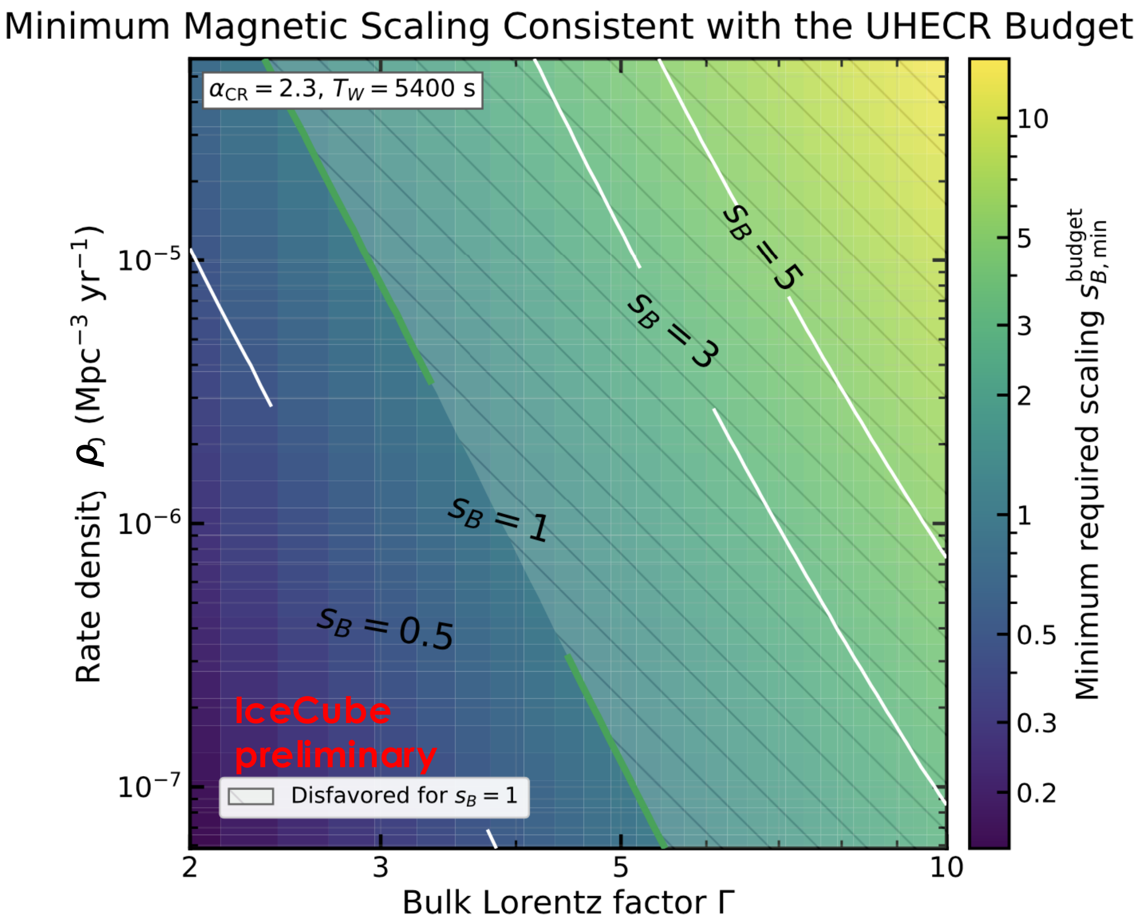


UHECR budget



Robustness of the UHECR interpretation

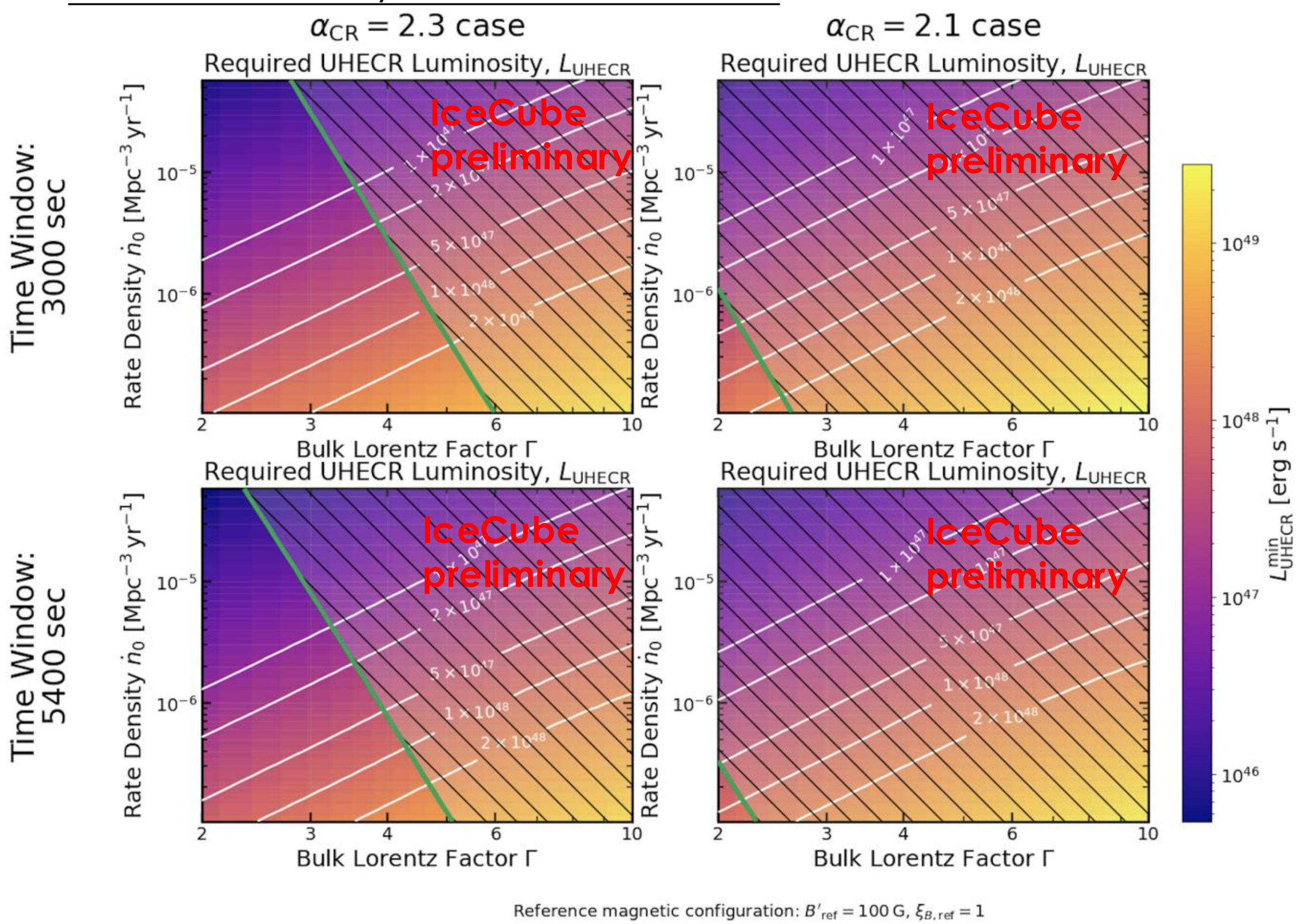
Magnetic environment



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

other environments are described by the scaling s_B

Proton index / source duration



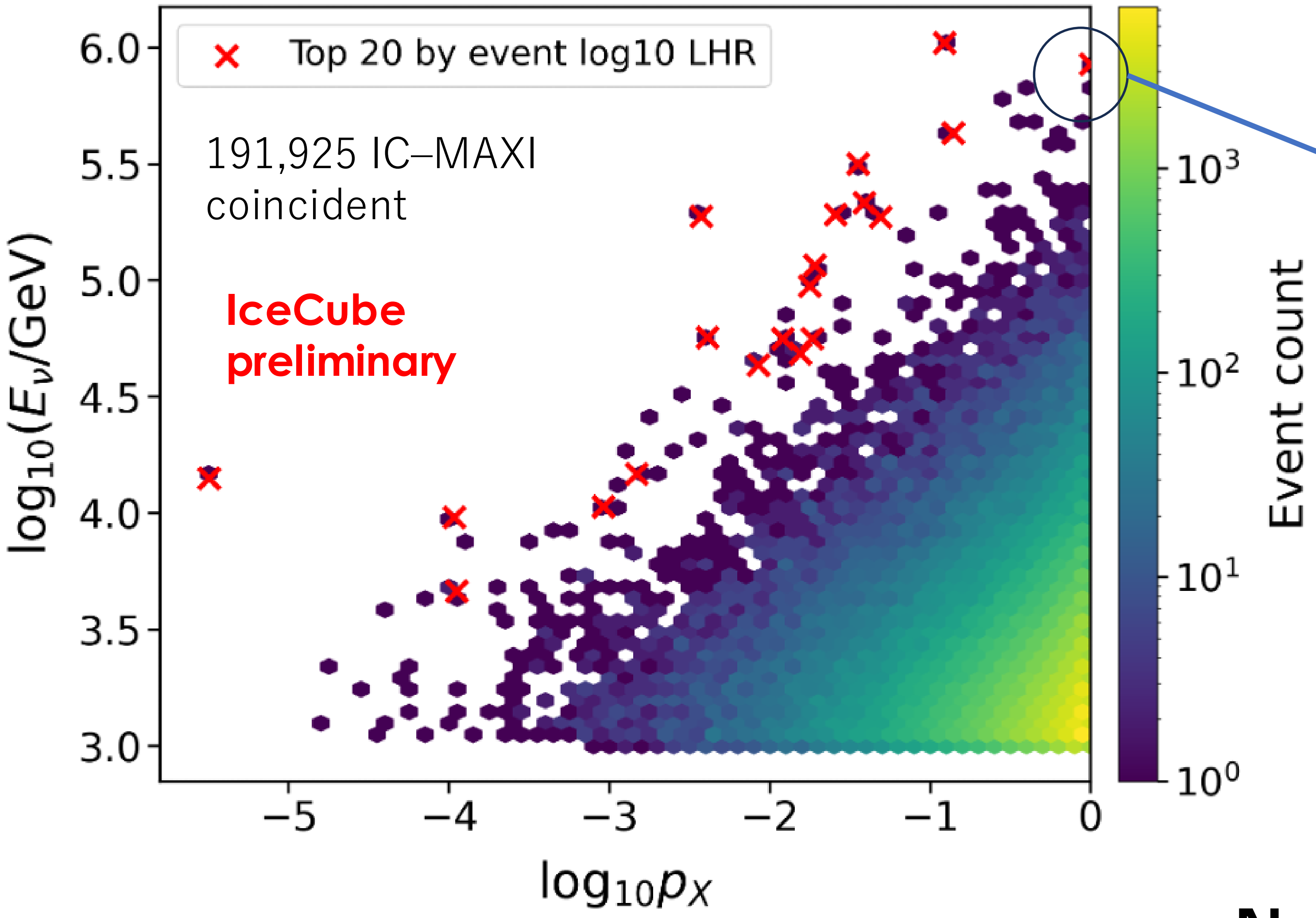
- **Magnetic environment changes the disfavored region**
- **Variations in proton index and duration do not remove the constraint.**

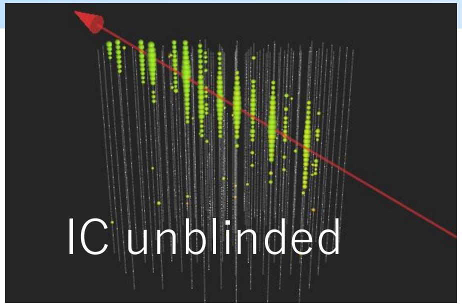
Summary

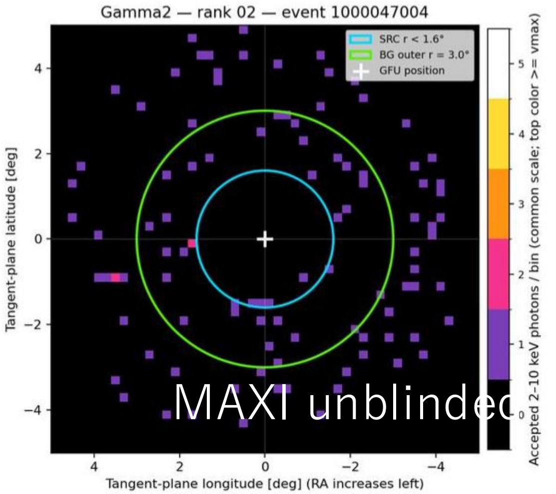
- 14.5 yr of IceCube + MAXI → no correlated X-ray excess
- X-ray-bright SXT populations cannot dominate the high-energy neutrino flux
- First systematic IceCube–MAXI multimessenger constraints on SXT populations using real soft-X-ray data
- The X-ray limits require large CR loading and disfavor part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

appendix

The Most Signal-like Events Are Consistent with Background







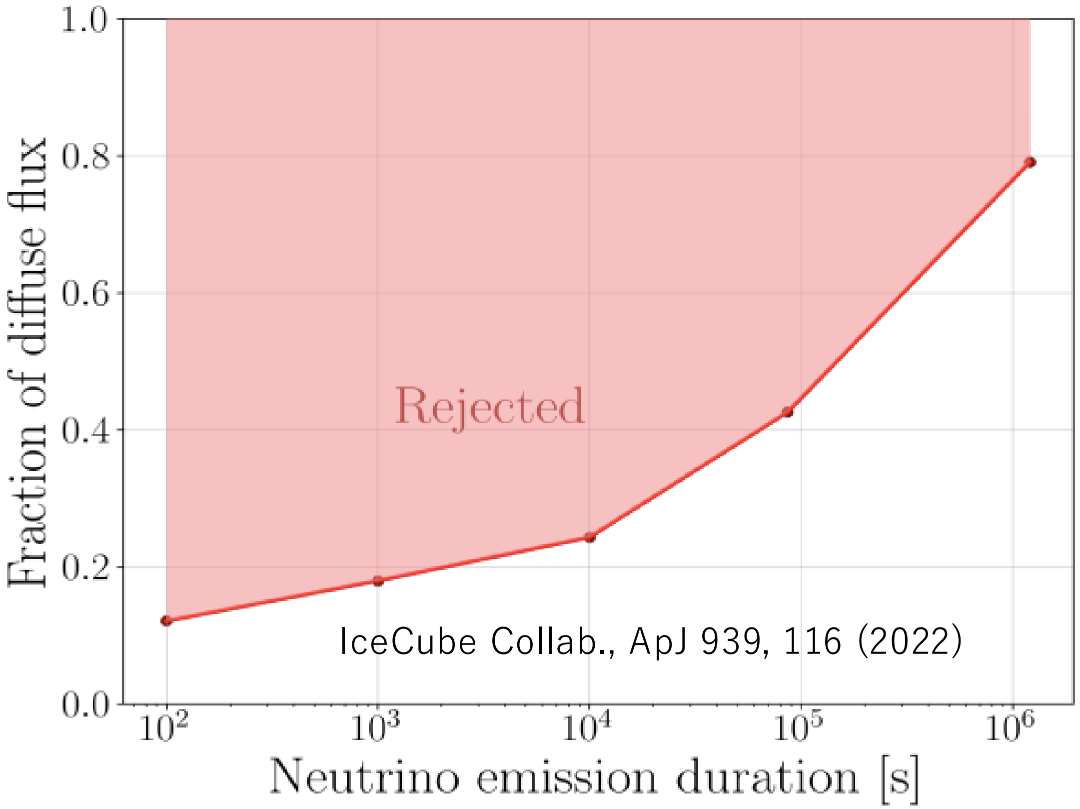
No anomalous X-ray-bright neutrino event

Classical GRBs cannot dominate the diffuse neutrino flux

$>$ 10 keV

trigger

search



Prompt GRB searches: $\mathcal{O}(10^3)$ GRBs, from Northern-sky ν_μ 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 **~10^4 s constrained to <24%** of the diffuse flux

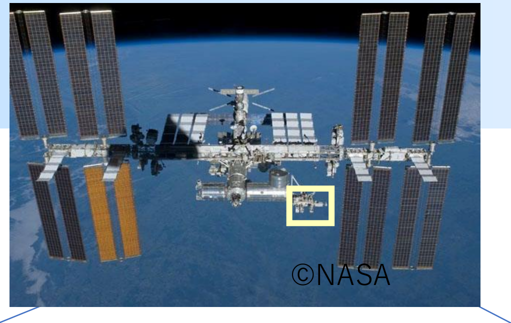
IceCube Collab., ApJ 939, 116 (2022)

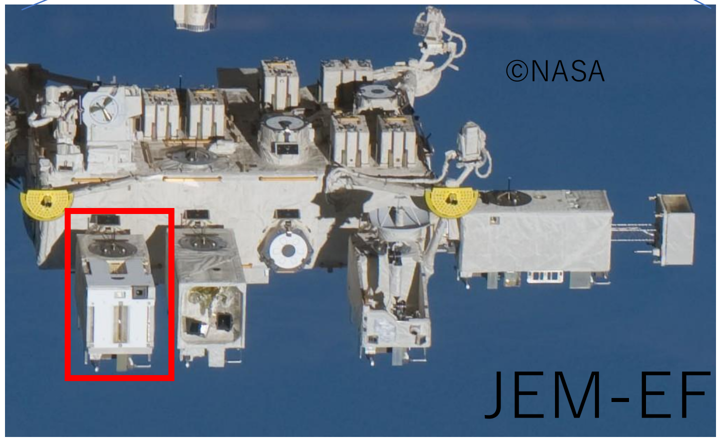
GRB 221009A (BOAT): no significant neutrino detection

IceCube Collab., ApJL 946, L26 (2023)

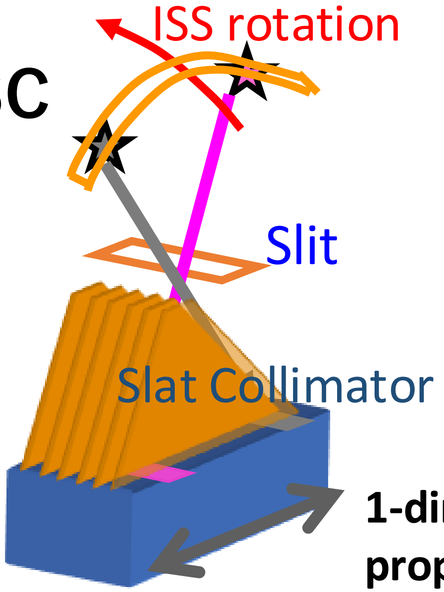
MAXI (Monitor of All-sky X-ray Image)

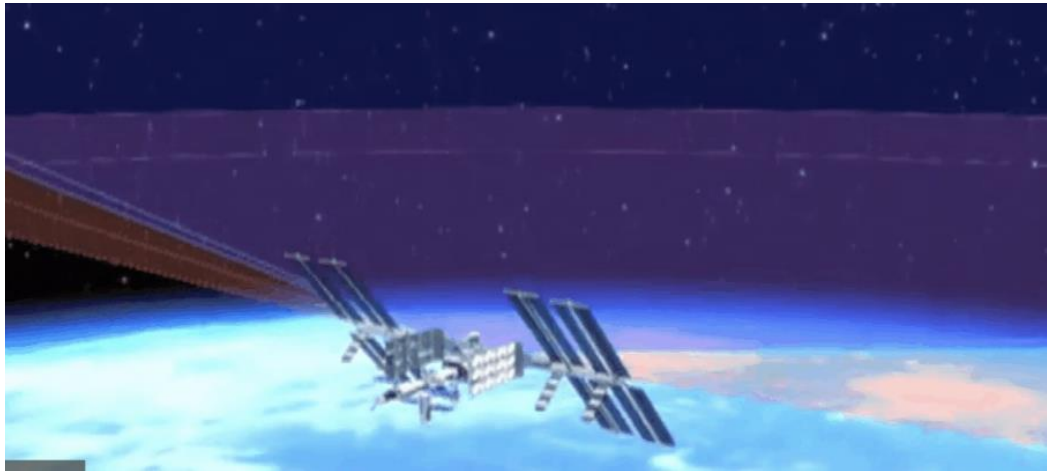
Matsuoka et al.,
PASJ 61, 999 (2009)

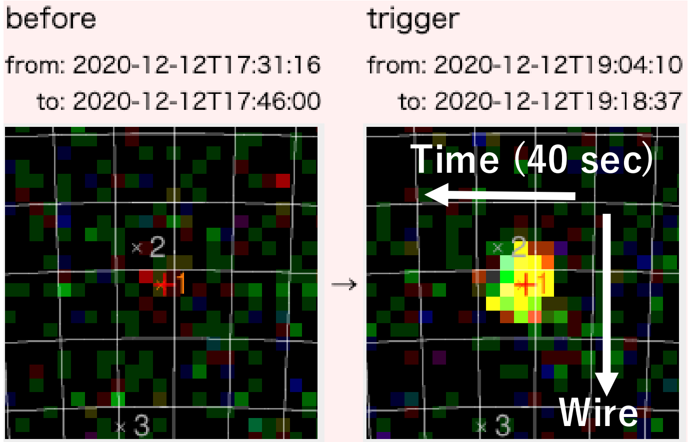




- Operated since Aug 2009, 14.5 years overlap with the IceCube data set
- Scans all-sky every 90 minutes with ISS rotation searching for X-ray transients, monitoring hundreds of X-ray sources, with Gas Slit Camera (GSC) in 2-20 keV
    - Despite its mature proportional-counter technology, the GSC remains 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

ν signal related X-ray | ν signal "not" related X-ray | atmospheric ν bgd "not" related X-ray

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

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

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

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

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

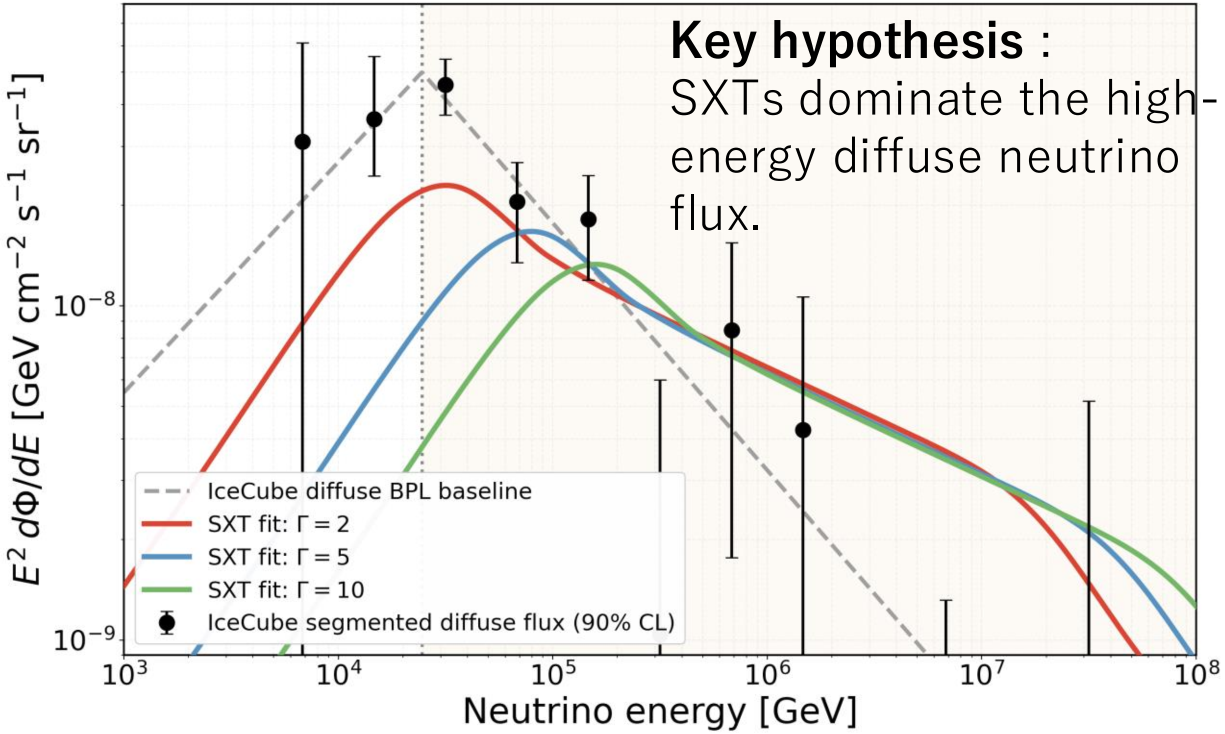
2.Diffuse: BPL baseline − SXT contribution, avoiding double counting

3.Atmospheric: fixed H3a + SIBYLL2.1 template

Statistical test

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

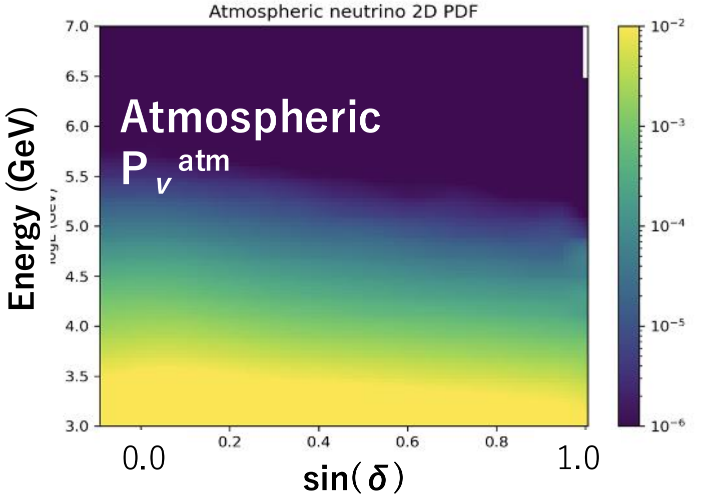
Key hypothesis : SXTs dominate the high-energy diffuse neutrino flux.

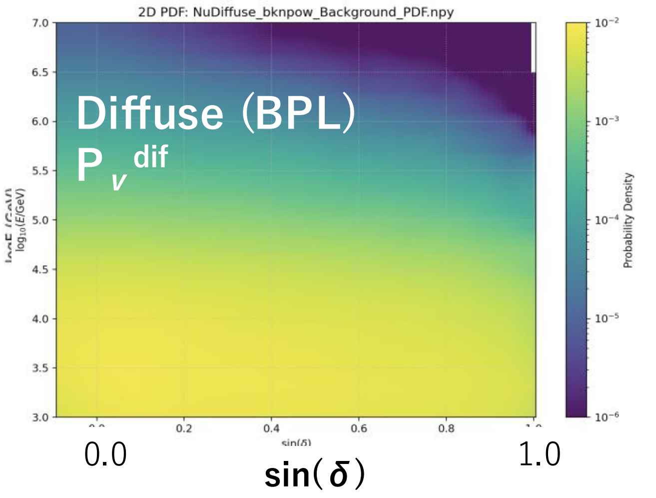


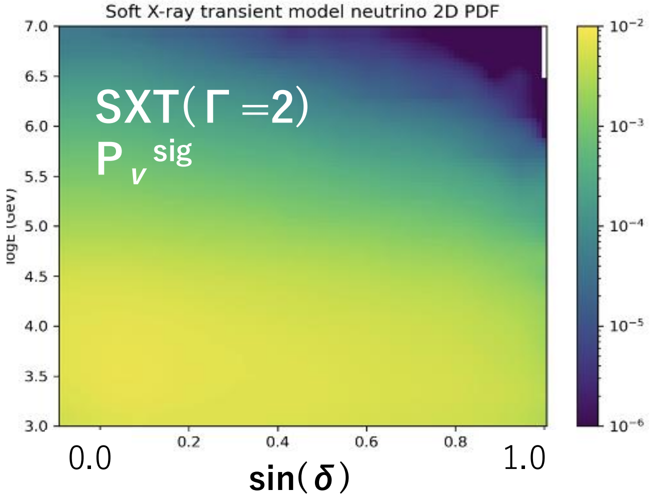
Neutrino PDFs and the MAXI X-ray background PDF

Neutrino PDFs(P ν)

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



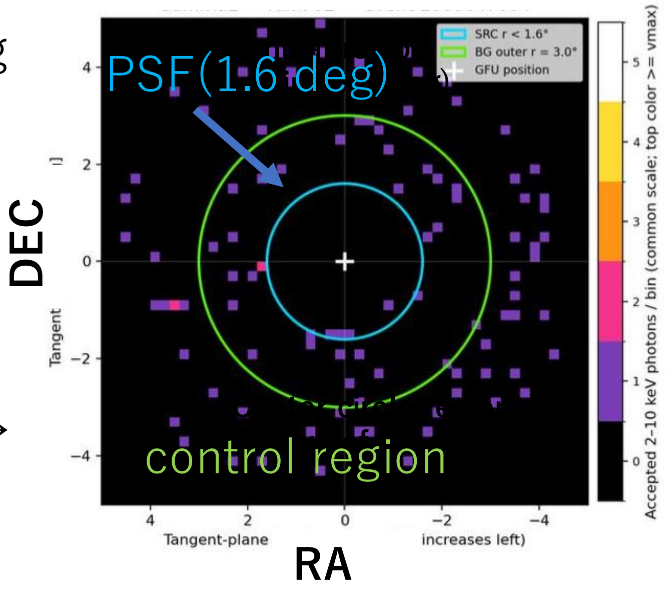




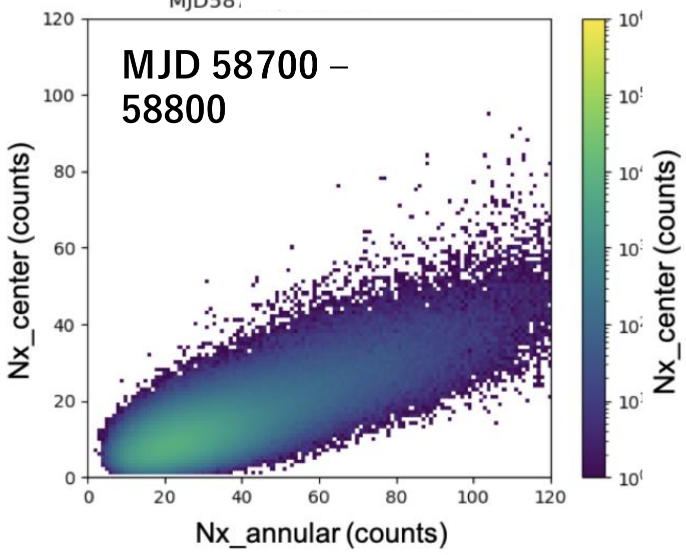
X-ray background PDFs (Pxbgd)

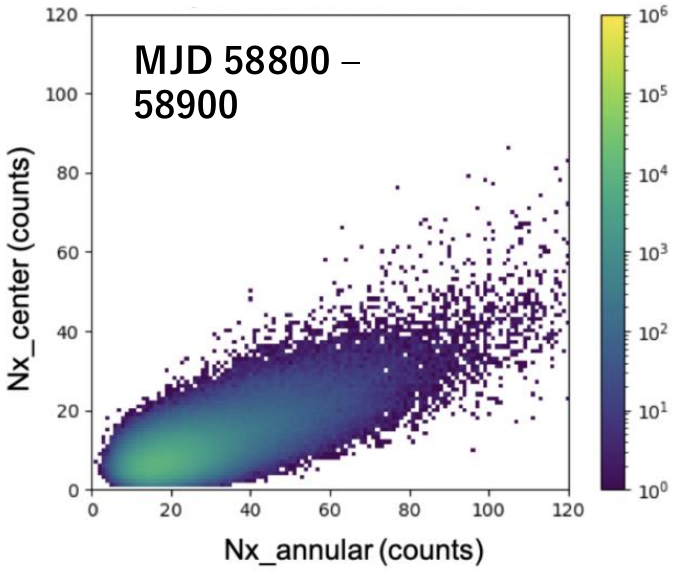
- r~1.6 deg (PSF) source / surrounding bg region → $N_{annular}$ vs N_{center} → event-specific P_{Xbgd}
- Background varies with solar activity → templates updated every 100 days

MAXI X-ray Image



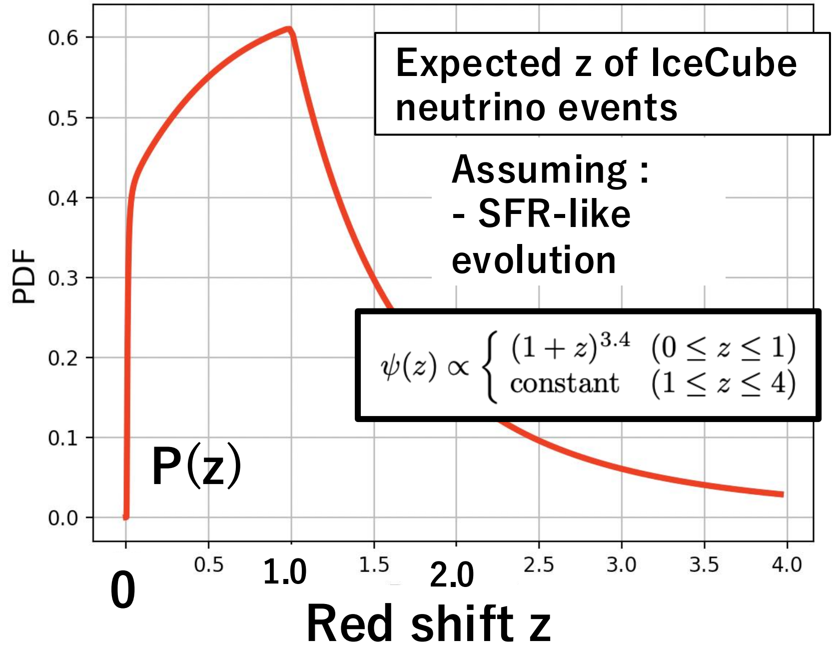
X-ray bgd PDF updated every 100 days

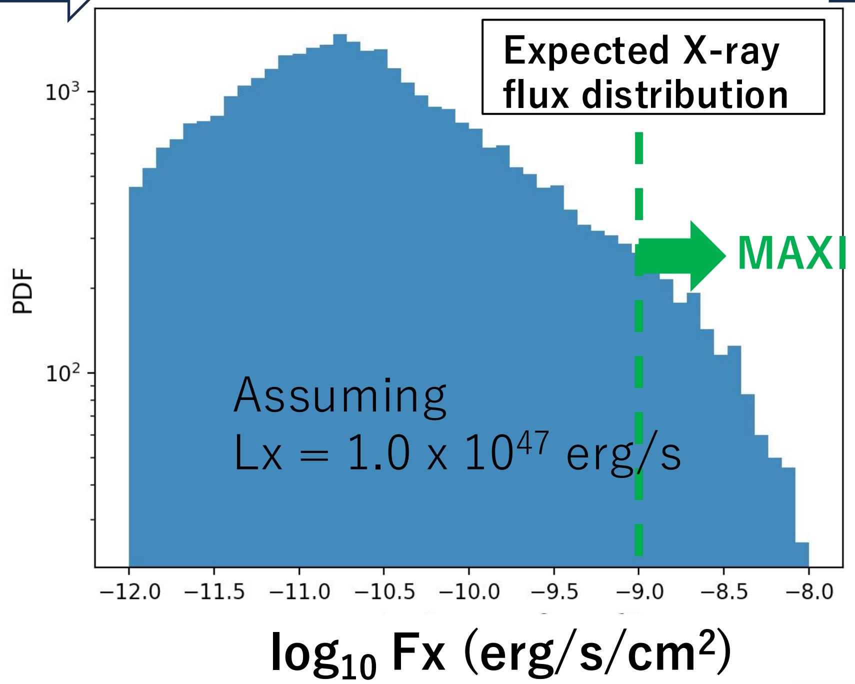


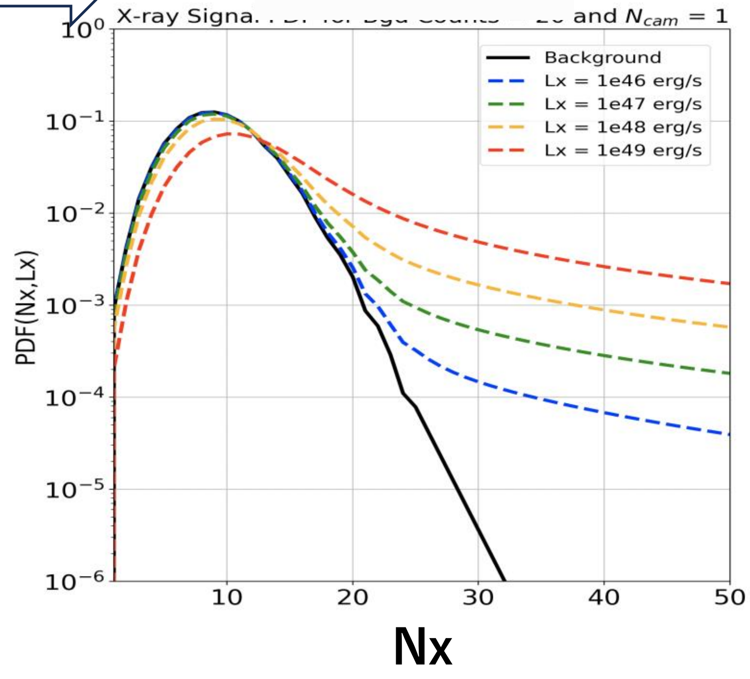


From the source population to the MAXI signal PDF

Lx + z → **Fx** → $P_X^{\mathrm{sig}}(N_X|L_X)$







Source-distance distribution P(z)

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

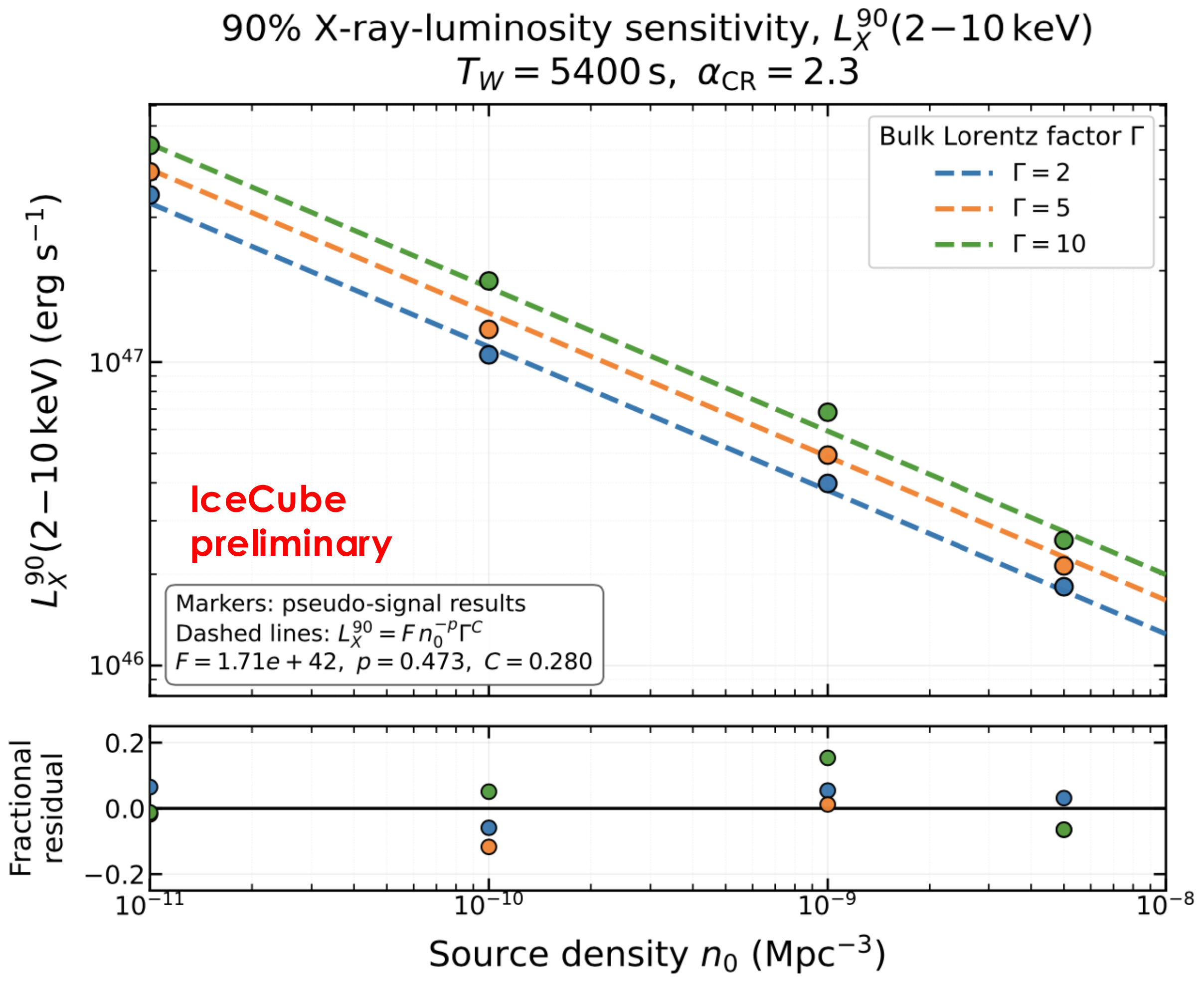
$$P_X^{\mathrm{sig}}(N_X|L_X) = \int dz\, P(z)\, P(N_X|L_X, z)$$

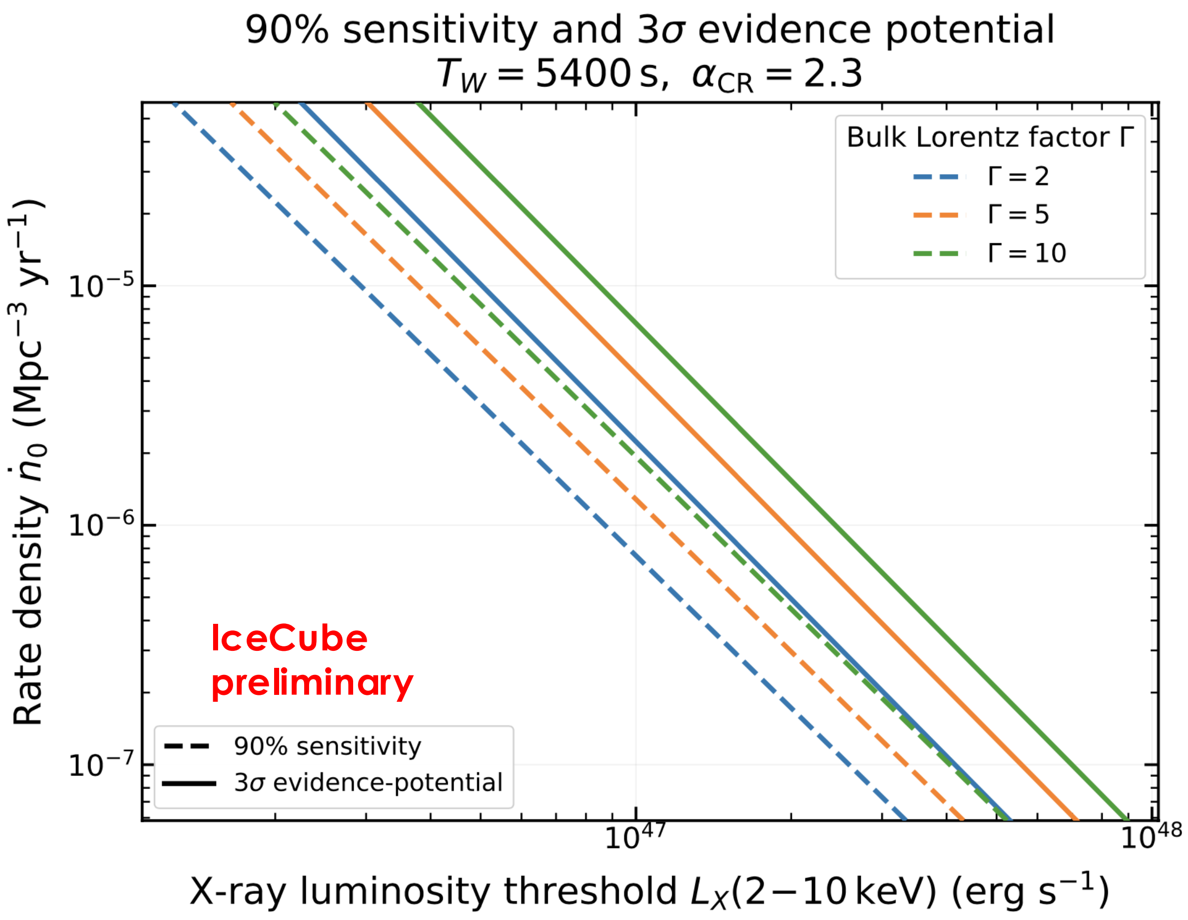
$$\sum_{n=0}^{N_X} P^{\mathrm{Poisson}}(N_X - n \mid \mu_{(L_x)}) P^{\mathrm{bgd}}_{X_{\mathrm{DB}}}(n)$$

From distance to the signal PDF

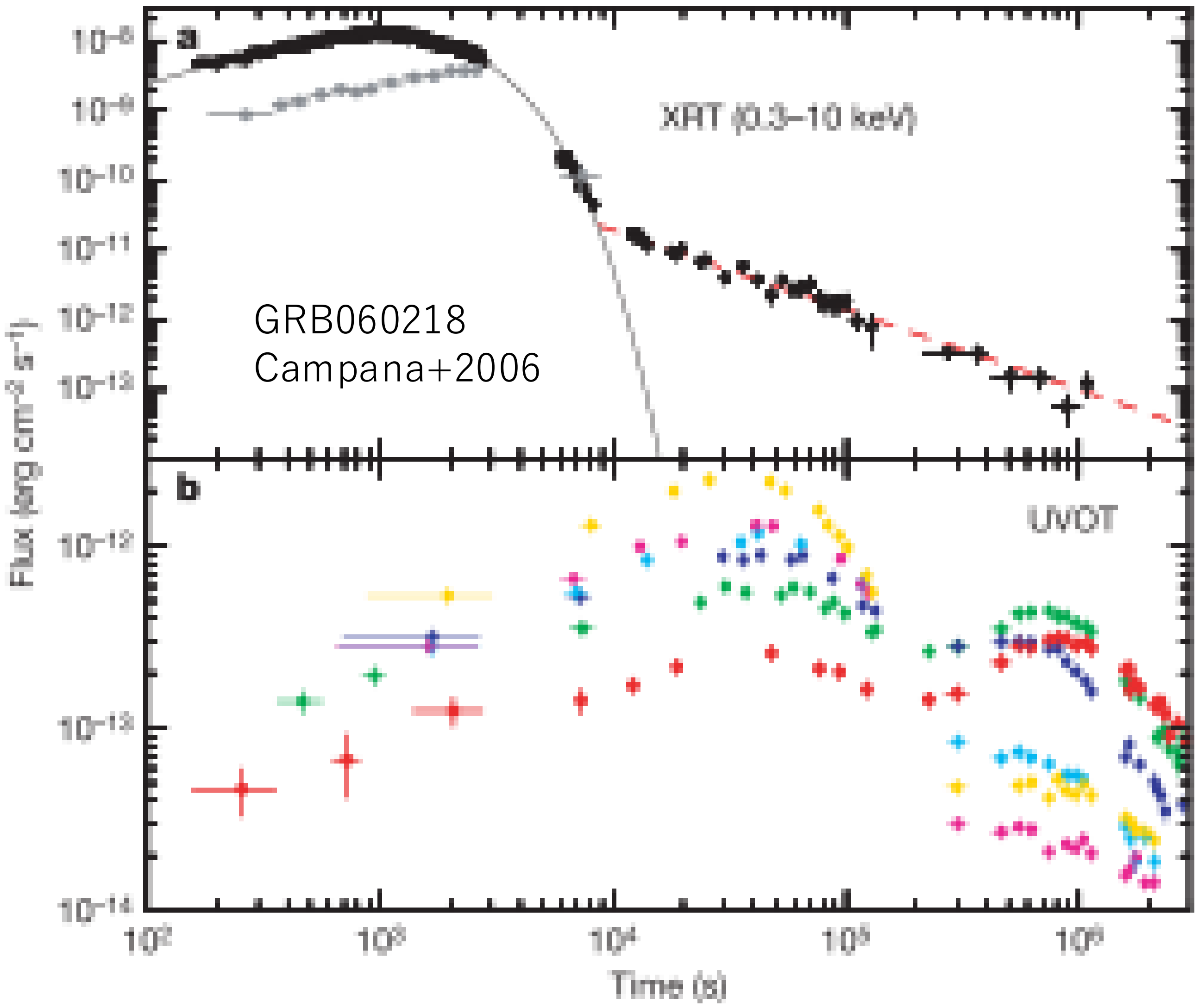
- Standard-candle assumption: all SXTs share a common L_X
- Marginalize the expected X-ray counts over P(z)
- Convolve the SXT counts with the empirical MAXI background PDF
- MAXI sensitivity is concentrated on the low-z, high-FX part of the population → nearest detectable sources dominate the sensitivity

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





LLGRB duration



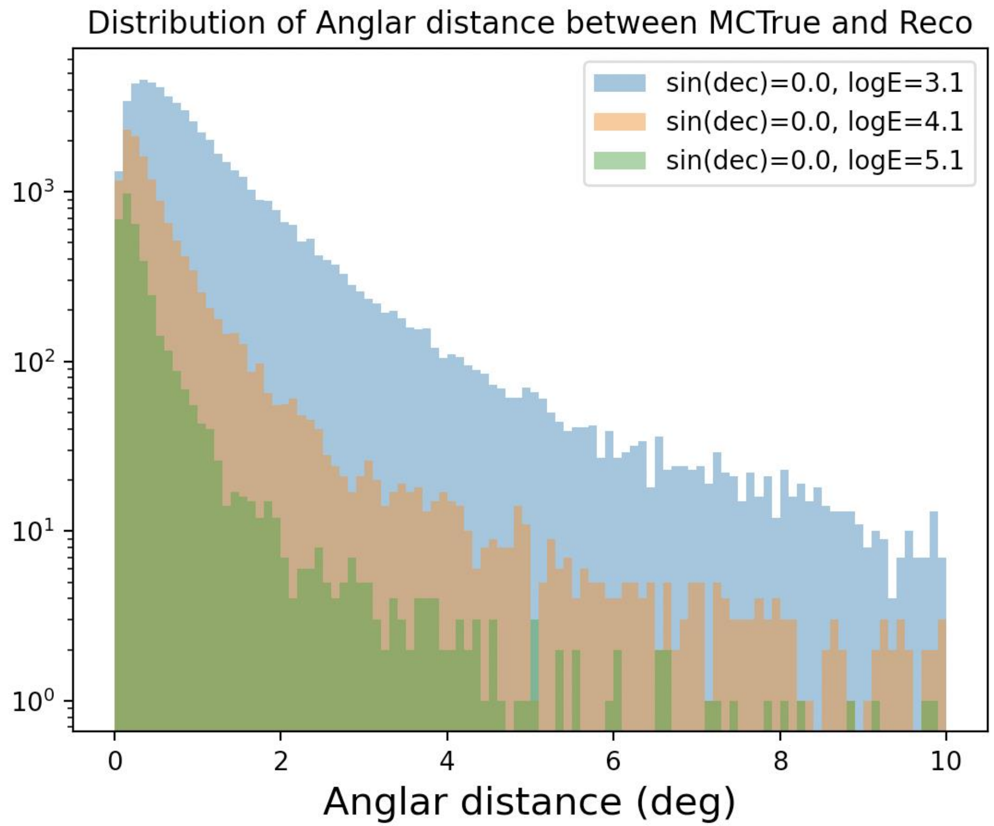
1. Strategic Optimization of Observation:
The baseline ΔT of 5400 s is determined by the ISS orbital period. This duration is the optimal choice to maximize the available photon statistics N_{coin} for a single scan cycle of MAXI.

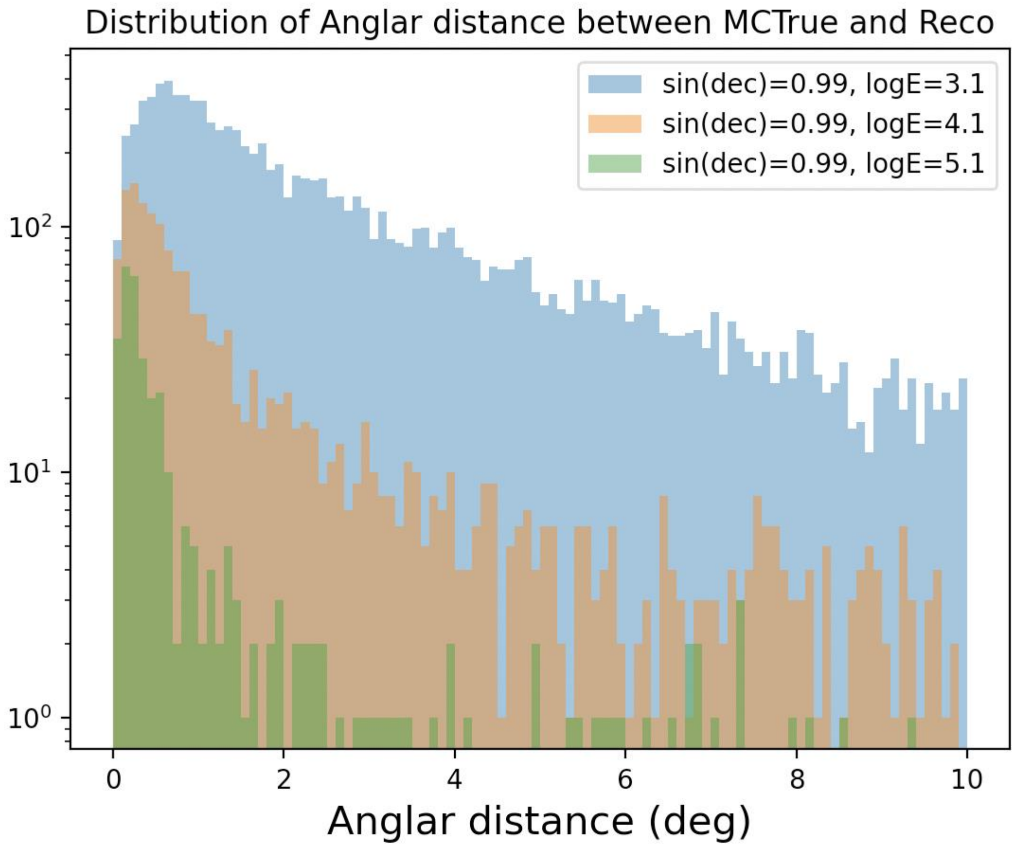
2. Consistency with Science Targets:
This window is well-suited for capturing long-duration transients. For example, the well-known LLGRB 060218 has a duration of ~3000 s, which is fully covered within our 5400 s window, ensuring that the signal integrity is maintained.

3. Risk Assessment & Stability:
Even if ΔT is reduced to 3000 s (e.g., to match a specific burst duration), the resulting decrease in Lx 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

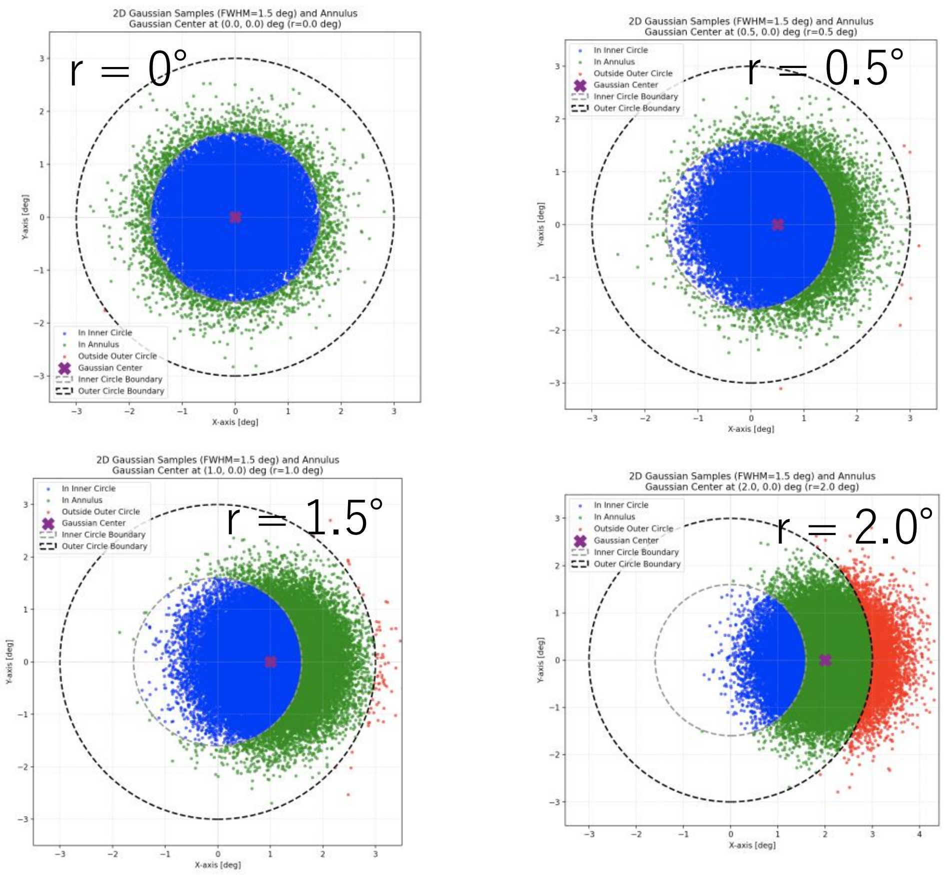




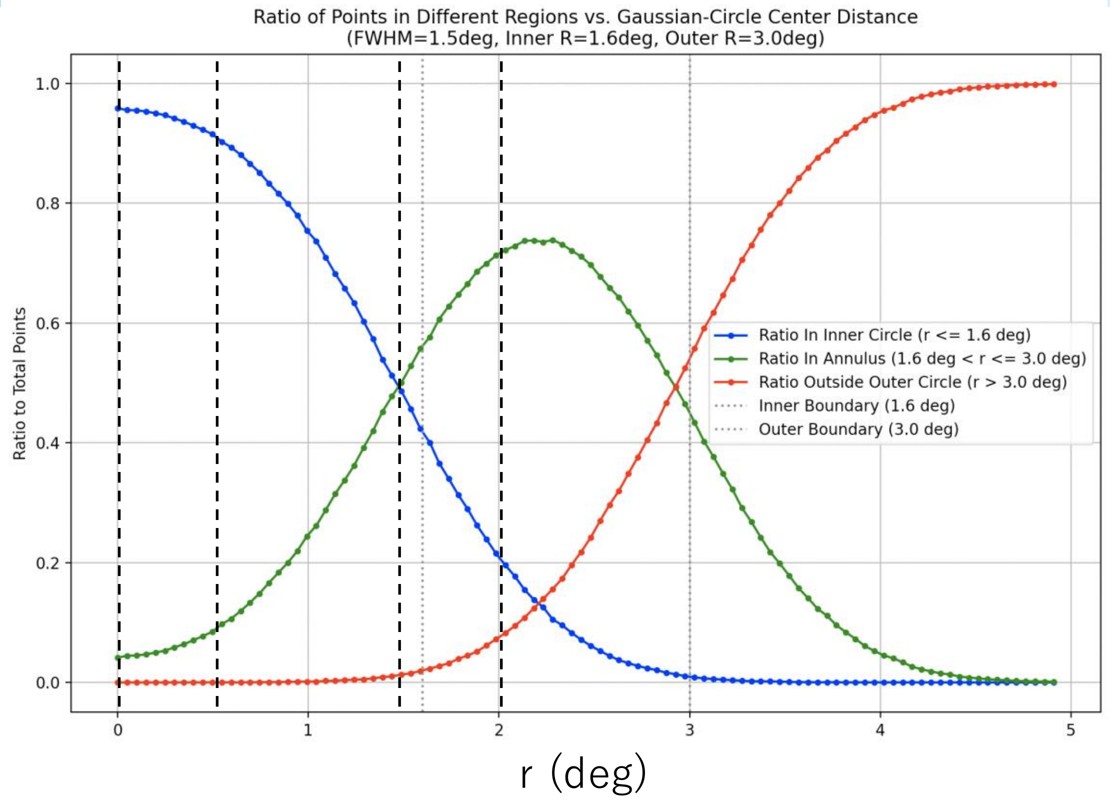
We record the position of events injected in MC simulations (MC True position) and the direction obtained through reconstruction (Reco pisition), treating the angular distance between them as positional uncertainty.
We consider the impact this has on MAXI results.

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 (FWHM = 1.5 deg).
- MAXI's PSF has no dependence on RA or DEC.

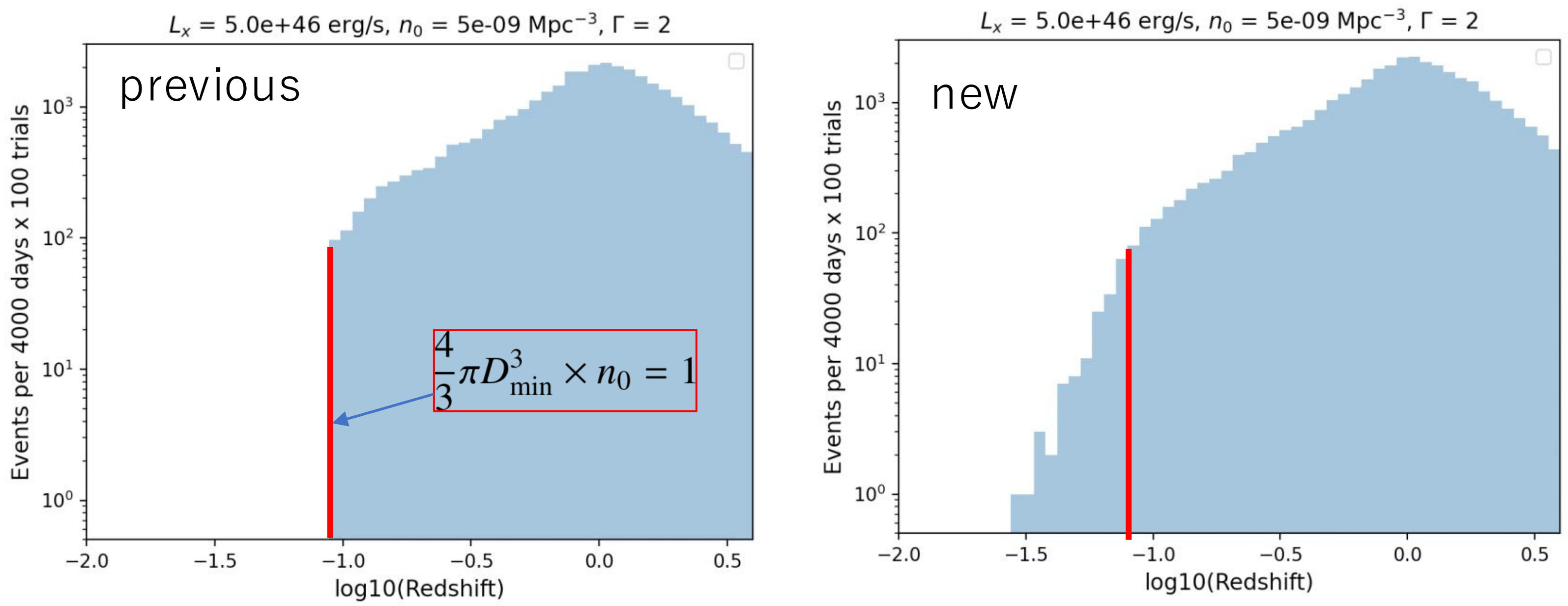
In the pseudo-signal experiment:

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 Lx: 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 Lx 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

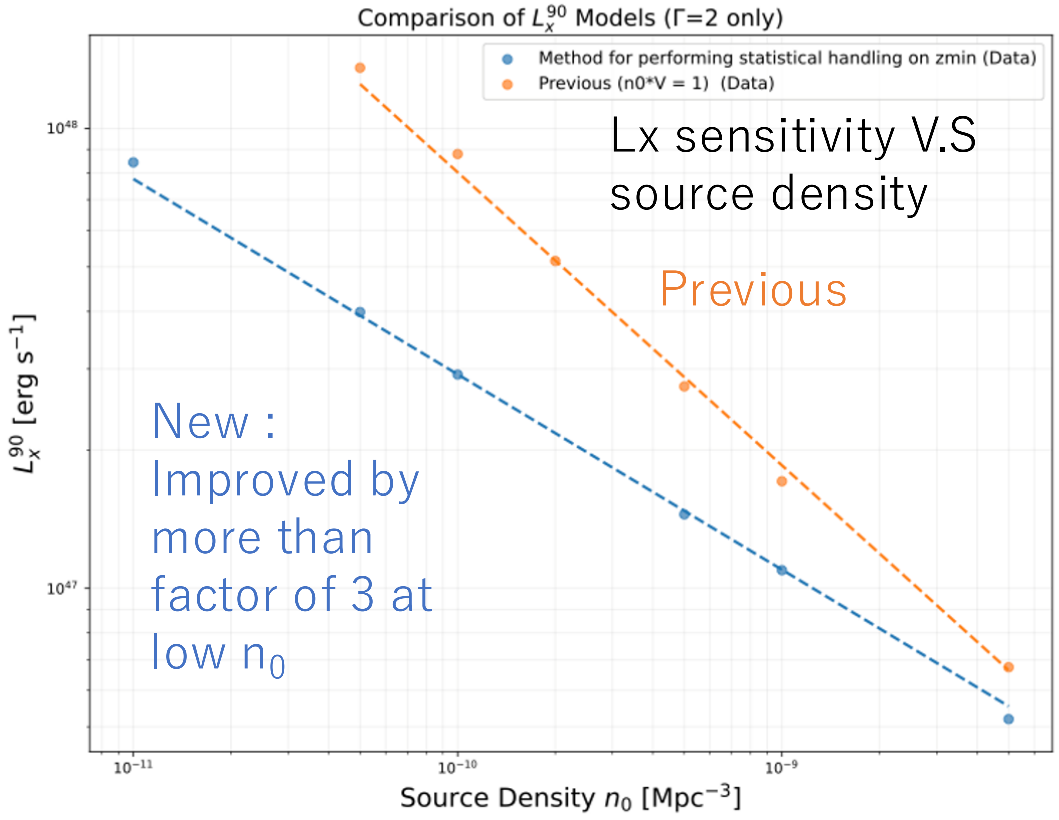
<u>Method for the estimation of the nearest source distance</u>

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

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

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:

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



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_{max} =4
In each simulation trial, the redshifts of the transients in the population are randomly sampled within the range $[z_{min}, z_{max}]$ according to the differential source distribution dN_{tr} / dz .