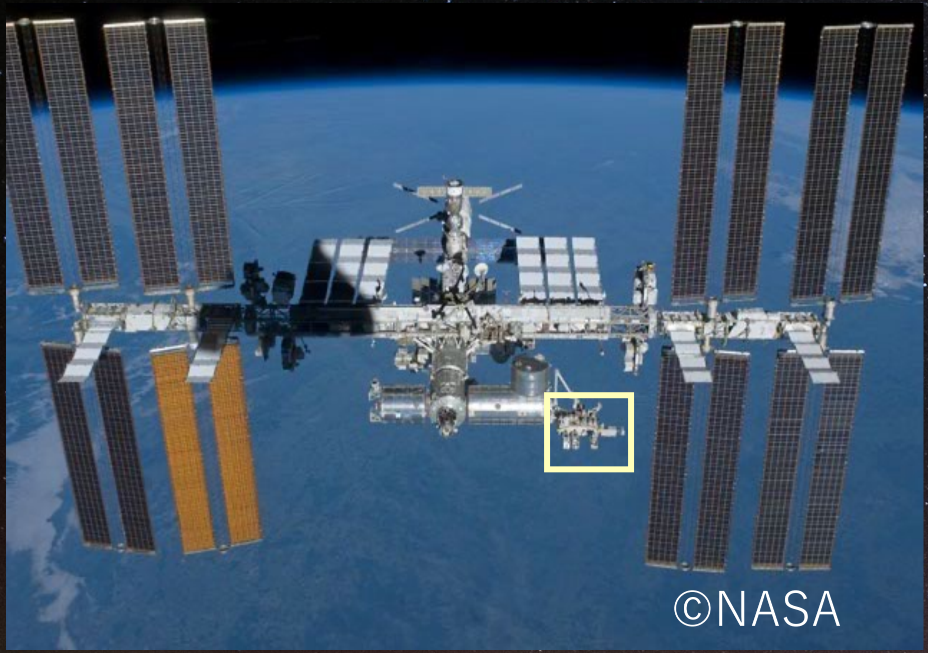


A MAXI search for the sub-threshold X-ray emission associated with the neutrinos detected by IceCube

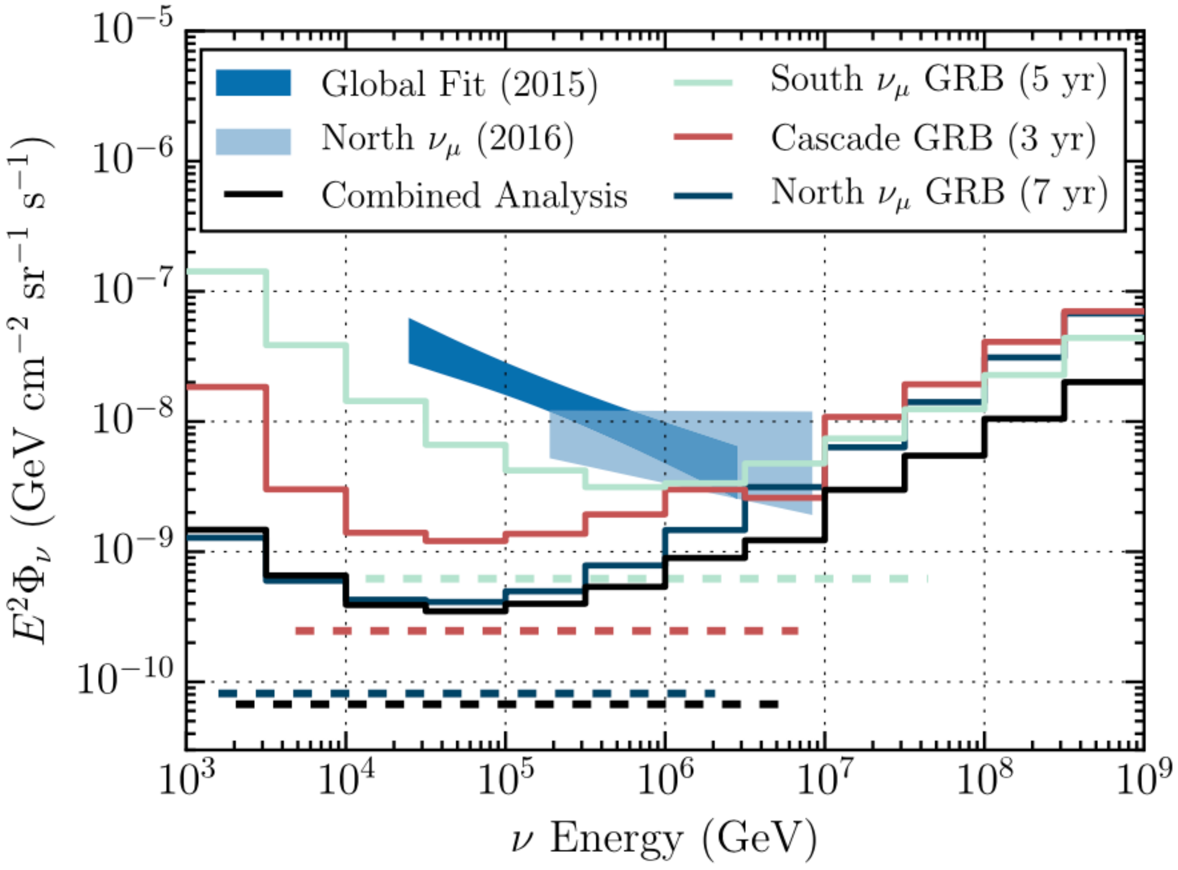
Wataru Buz Iwakiri (Chiba University)

CHIBA UNIVERSITY

ICEHAP

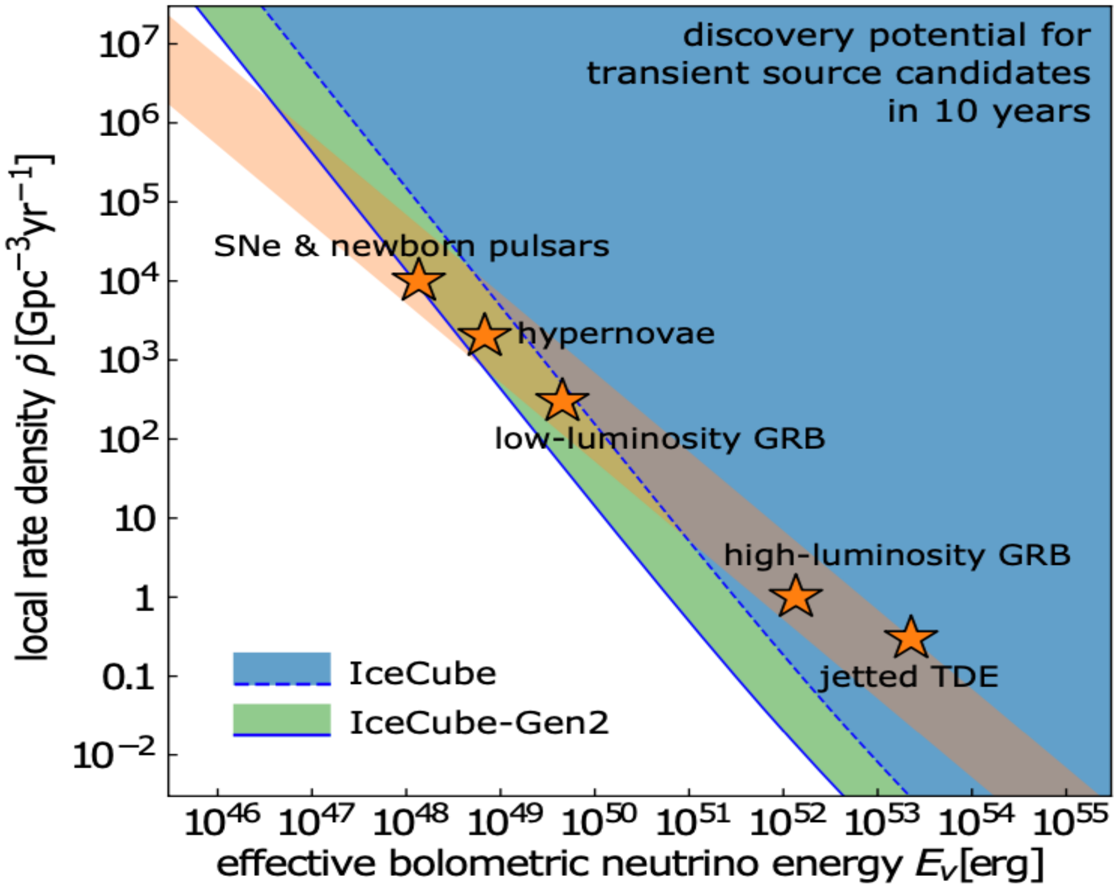
Credit: J. Werthebach, IceCube/NSF

What is the origin of the diffuse neutrino emission?



- Standard long GRBs origin has been ruled out by MM analysis of over 1000 events between soft gamma-rays and neutrinos

<u>Potential transients</u>

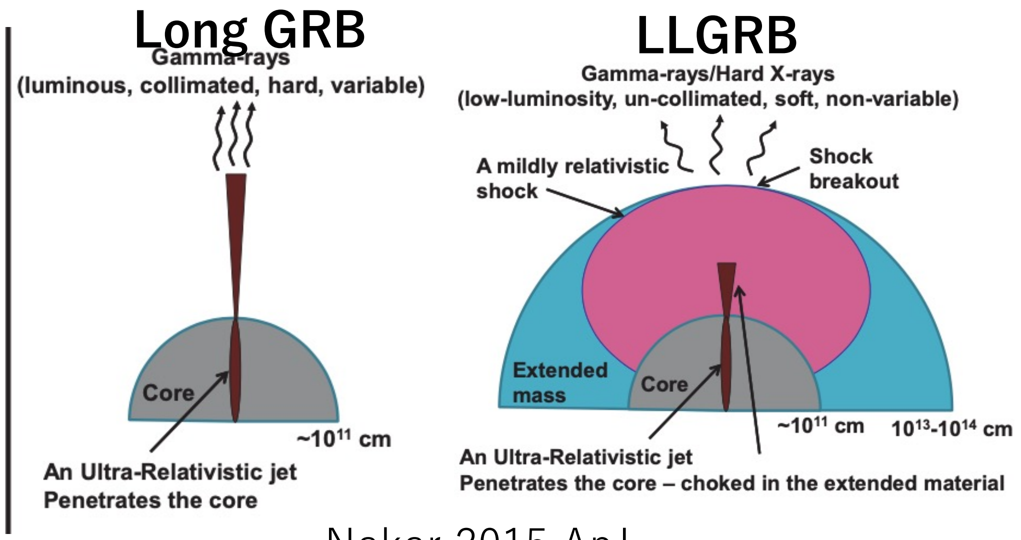


Evaluate the contribution of the more nearby, numerous, and dimmer transients are the next key ← Neutrino - X-ray analysis

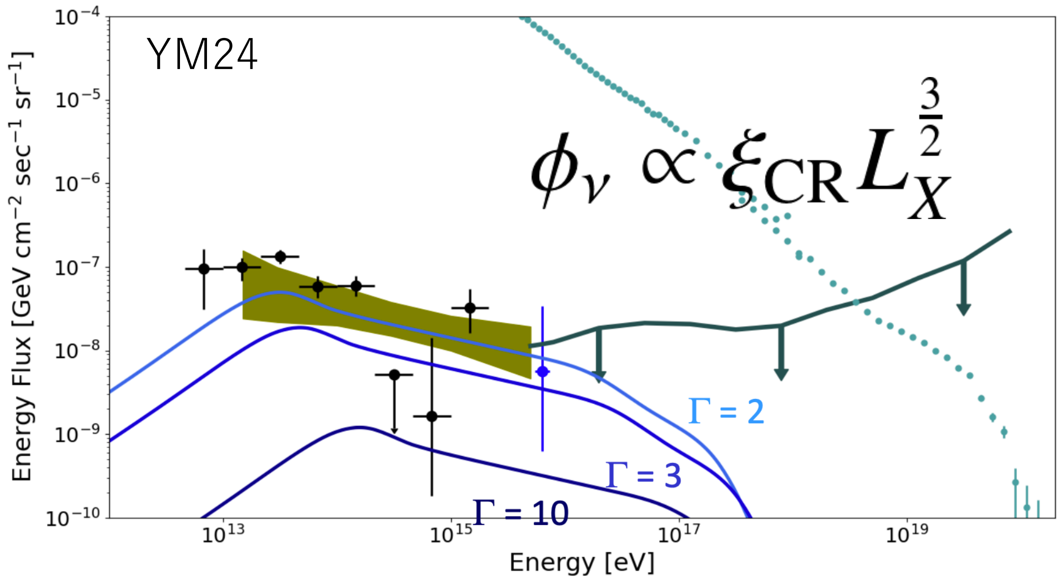
Soft X-ray transients

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

Δ resonance in p γ interactions requires photon energy of ~keV in the relativistic flow (Γ ~2-10)



Nakar 2015 ApJ



Low Luminosity GRBs (LLGRB)

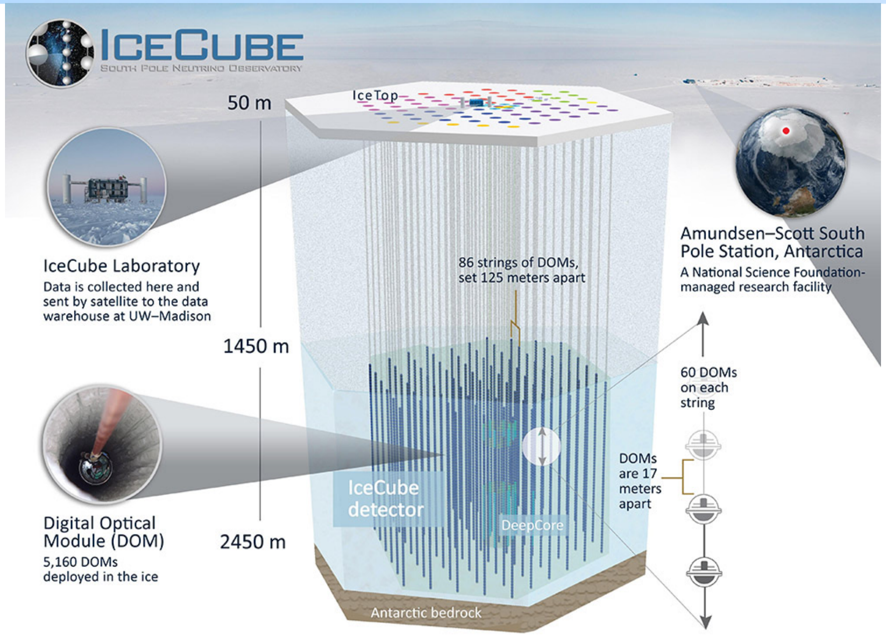
- compared with ordinary long GRBs, low-luminous ($10^{45\text{-}48}$ erg/s), closer(z~0.1), softer (brighter in X-rays than in γ-ray), longer duration
- If the plasma bulk Lorentz factor Γ=3 ~10, PeV protons interact with X-ray photons and generate TeV – PeV neutirino →one of the prime candidates of the neutrino sources (cf, Yoshida & Murase PRD 2024, YM24)

X and ν MM analysis essentially important

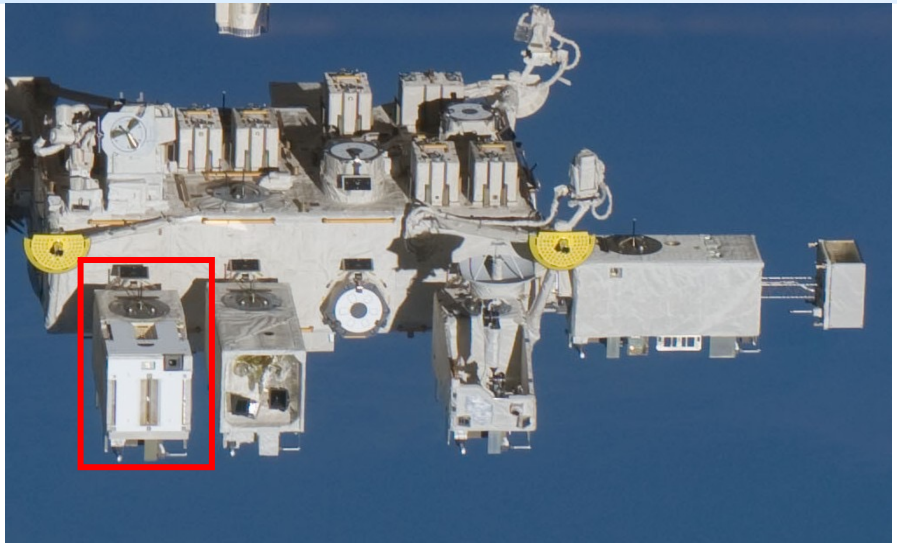
MAXI —good probe for searching "soft" transient

- X-ray all sky monitor onboard ISS from 2009
- Overlap of more than 12 years already
- PSF : 1.5 deg (similar resolution of track events)
- better detection of soft transients than Swift/BAT and Fermi/GBM

IceCube and MAXI



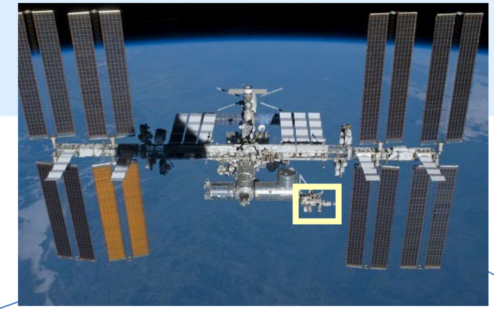
MAXI (Monitor of All-sky X-ray Image)



	IceCube	MAXI
Energy range	TeV – PeV (ν)	2 – 20 keV (photon)
FOV	All sky	All sky (80% in 92 min orbit)
Start date	April 2011 (IC86)	Aug 2009
Angular resolution	~1.0 deg (90% for track events)	1.5 deg (FWHM)
Data processing	Real-time@South pole	Real-time@TKSC via TDRSS

- **All sky monitor**
- **Overlap of more than 13 years already**
- **Similar angular resolution**
- **Real-time data processing and sending alerts**

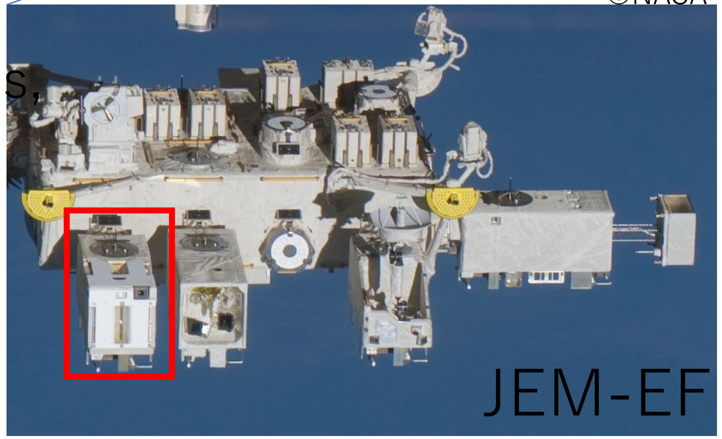
MAXI (Monitor of All-sky X-ray Image)



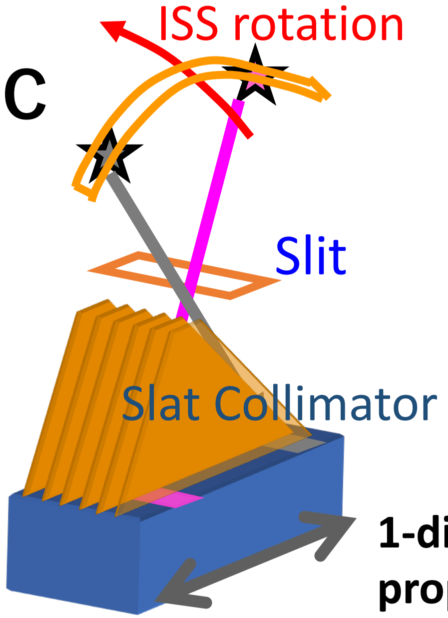
- First astronomical mission on ISS
- Operated since 2009 August 15 (over 15 years)
- Scans all-sky every 92 minutes with ISS rotation

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

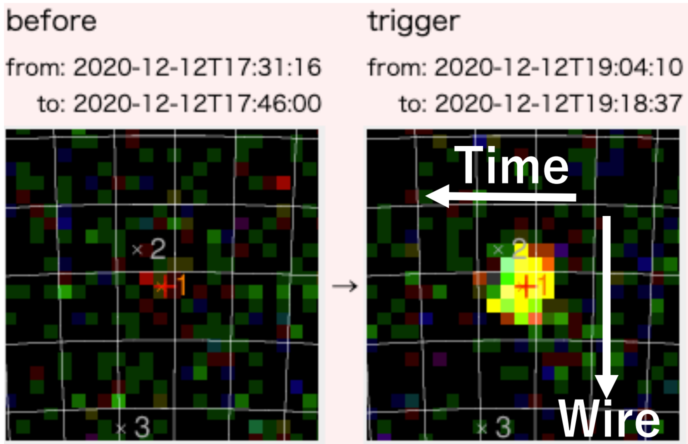
- All data are public http://maxi.riken.jp
- Data downlinked in real time via TDRSS → Real time alert

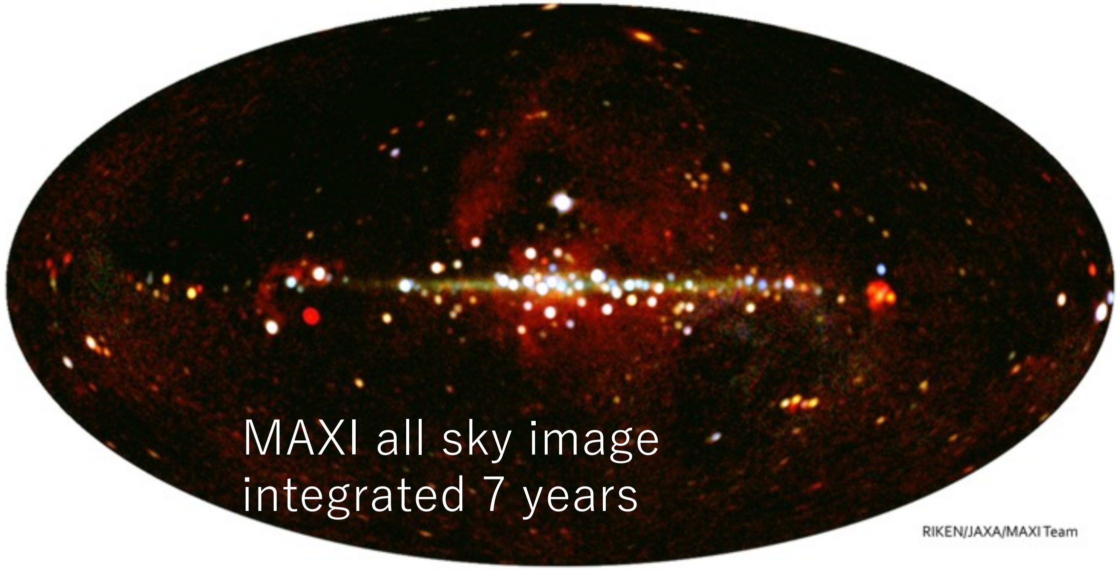


GSC



1-dimensional position sensitive proportional counter





MAXI all sky image integrated 7 years

MAXI has higher sensitivity for LLGRBs

LLGRBs are expected to have softer energy spectra ← **MAXI has higher sensitivity**

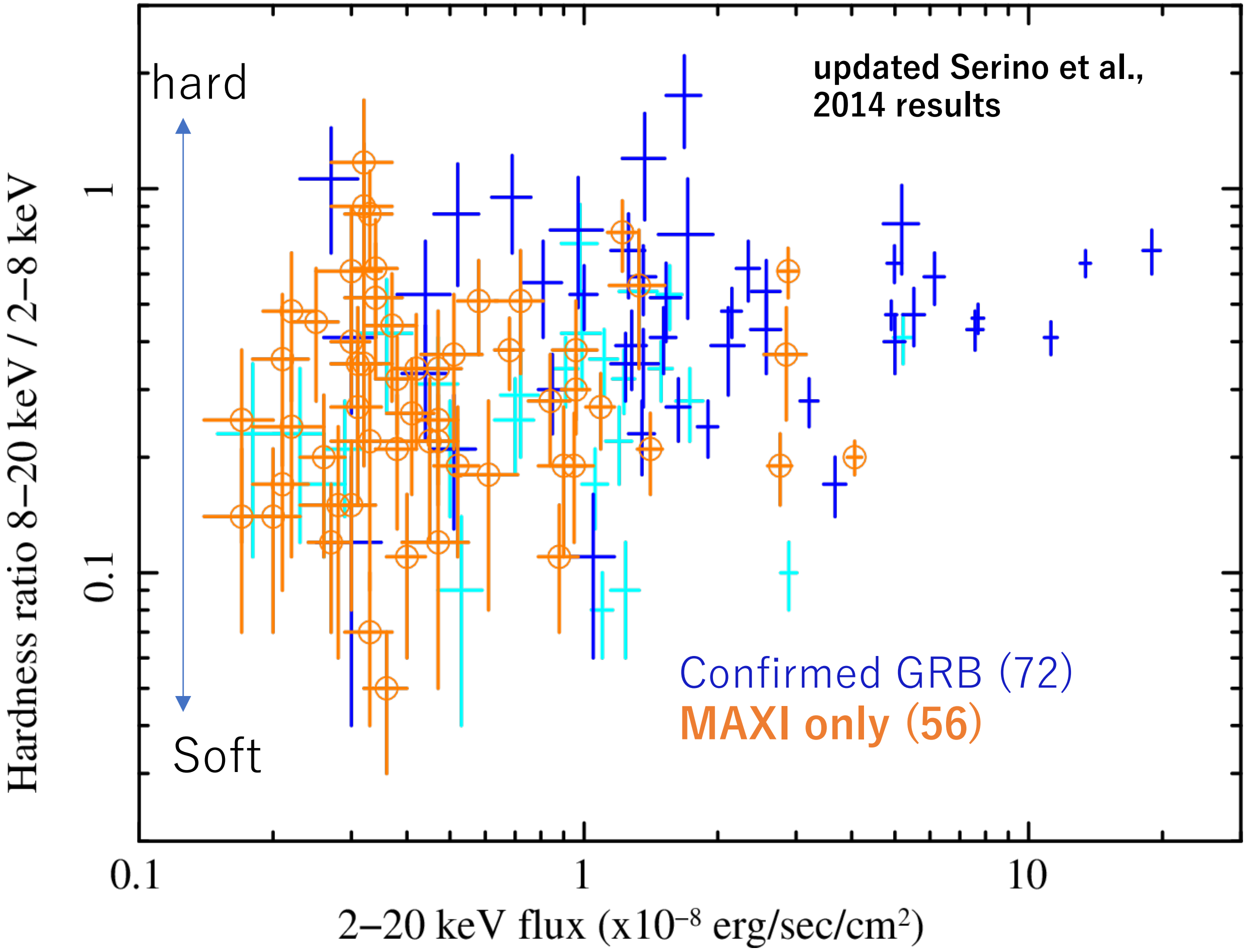
56 soft transients (MAXI GRBs) significantly detected only at MAXI over the past 13 years
→ the rate is 4 / year

- LLGRB rate ~100 /Gpc^3/year
  - at z=0.1, the rate is ~10 events / year

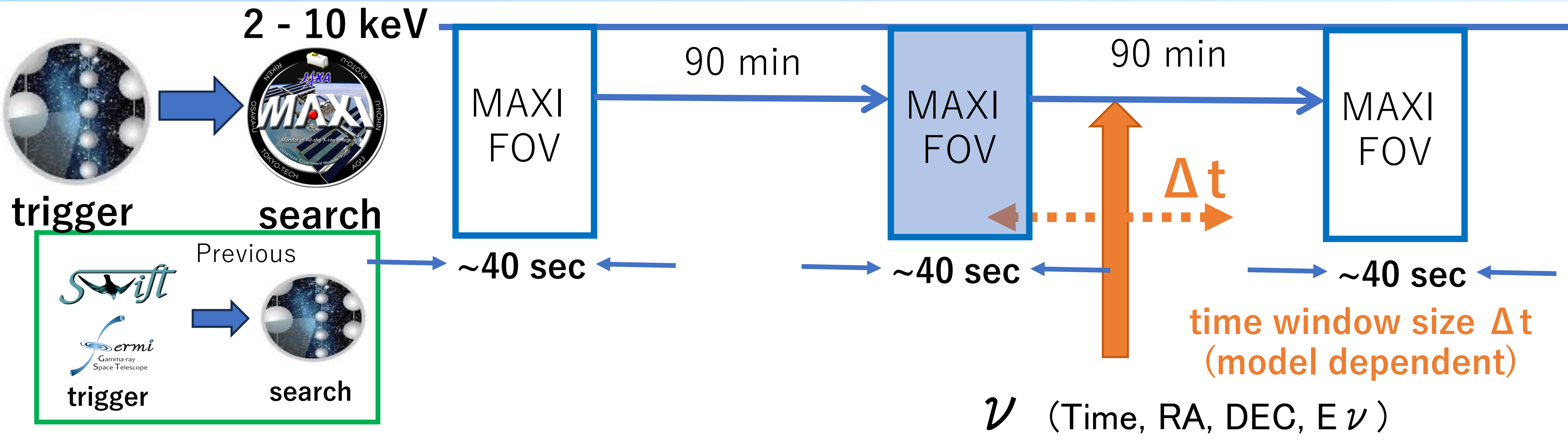
→ consistent with the MAXI GRBs rate

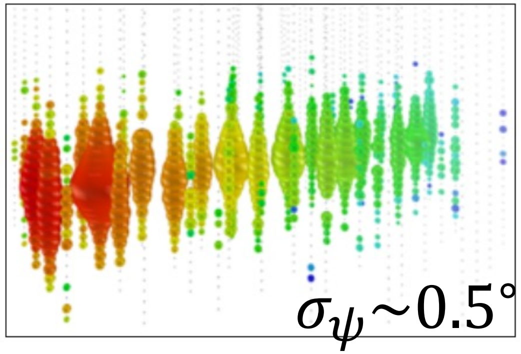
So far, no coincidence between IceCube events and MAXI GRB events has been observed

There is no comparison yet between subthreshold events in MAXI and IceCube



MAXI-IceCube MM analysis strategy





IceCube GFU filter events

	total	μ	Atms. ν_μ	**Astro. ν_μ**
No filter	1.5 Hz	1 Hz	7 mHz	**6 μHz**
After the several cuts (e.g, machine learning)				
GFU	2 mHz	80 μHz	1.9 mHz	**3 μHz**

https://arxiv.org/abs/1610.01814

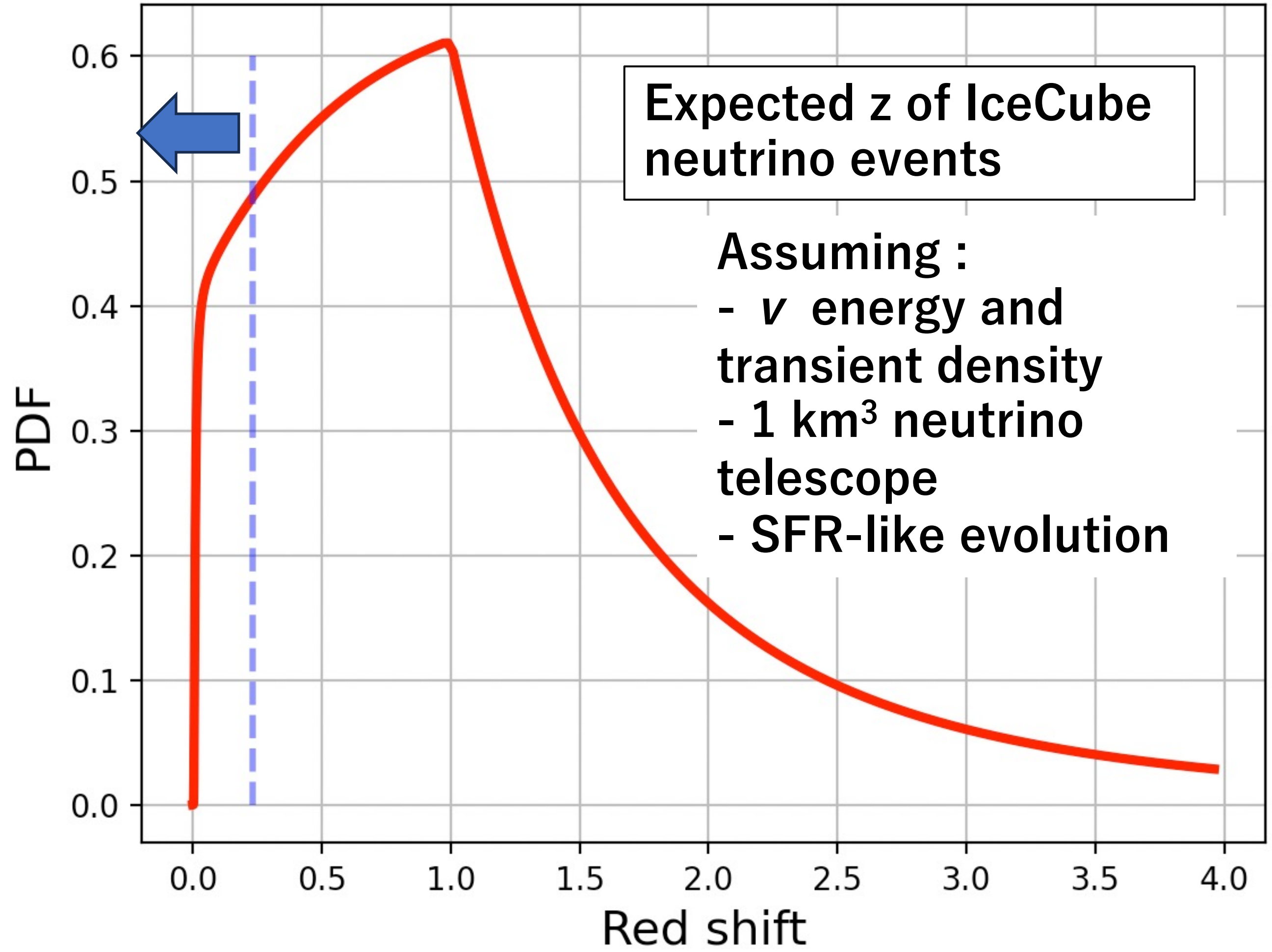
almost neutrino track events are **not** astrophysical

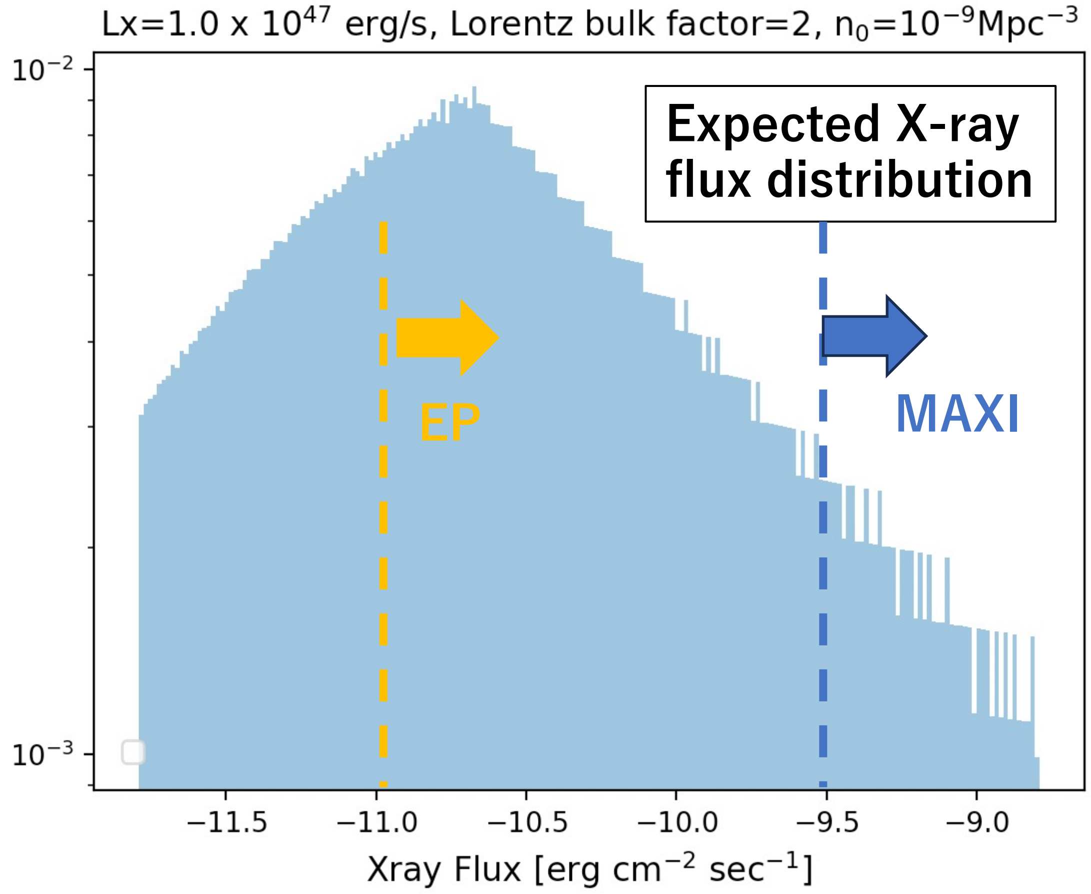
In 10 years :
~6 x 10^5 (~1x10^3) neutrino track events are detected
→with MAXI's detection efficiency and assumed transient duration (5400 sec), ~ 6 x 10^4

It is expected that about ~200 events will coincide with astrophysical neutrinos
but not all of these events will be detected by MAXI, because ν can be detected even at a long distance

Expected distance distribution of the soft transients

It is difficult to measure the distance to each transient, but the distance distribution of neutrino sources can be estimated from the IceCube measurements





MAXI can only observe events at close distances, which is about 10% of the total distribution.

➔ <u>~20 events / 10 year expected</u>

How do we evaluate ~20 signals from 60000 bgd events to limit the luminosity of the X-ray transients?

Idea for MM likelihood test

$$\mathcal{L}_{sig} = \frac{\mu^{N_{\rm obs}}}{N_{\rm obs}!} e^{-\mu} \prod_{i=1}^{N_{\rm obs}} \Bigg(\overbrace{\frac{\underline{n_{\rm sig}}}{\underline{n_{\rm atm}} + \underline{n_{\rm dif}}} \underline{P_\nu^{\rm sig}(E_\nu,\delta)} \times P_{\rm X}^{\rm sig}(N_{\rm X}, \mu_{\rm Xsig}(L_{\rm X}))}^{\nu\ \text{signal related X-ray}} + \overbrace{\frac{1}{\underline{n_{\rm atm}} + \underline{n_{\rm dif}}} \left\{ \underline{n_{\rm dif} P_\nu^{\rm dif}(E_\nu,\delta)} - \underline{n_{\rm sig} P_\nu^{\rm sig}(E_\nu,\delta)} \right\} P_{\rm X_{DB}}^{\rm bgd}}^{\nu\ \text{signal “not” related X-ray}} + \underbrace{\frac{\underline{n_{\rm atm}}}{\underline{n_{\rm atm}} + \underline{n_{\rm dif}}} \underline{P_\nu^{\rm atm}(E_\nu,\delta)} P_{\rm X_{DB}}^{\rm bgd}}_{\text{atmospheric } \nu \text{ bgd “not” related X-ray}} \Bigg)$$

n : total expected numbers
$N_{\rm obs}$: total number of events

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

Our proposed likelihood function is composed of three components:
1, Astrophysical neutrino signal from the soft X-ray transients (related to the X-ray signal)
2, Astrophysical neutrino signal, but "not related" to the soft X-ray transients (not related to the X-ray signal)
3, Atmospheric neutrino background (not related to the X-ray signal)

Previous studies did not account for the angular dependence of the neutrino PDF and the impact of positional uncertainty on the X-ray PDF.

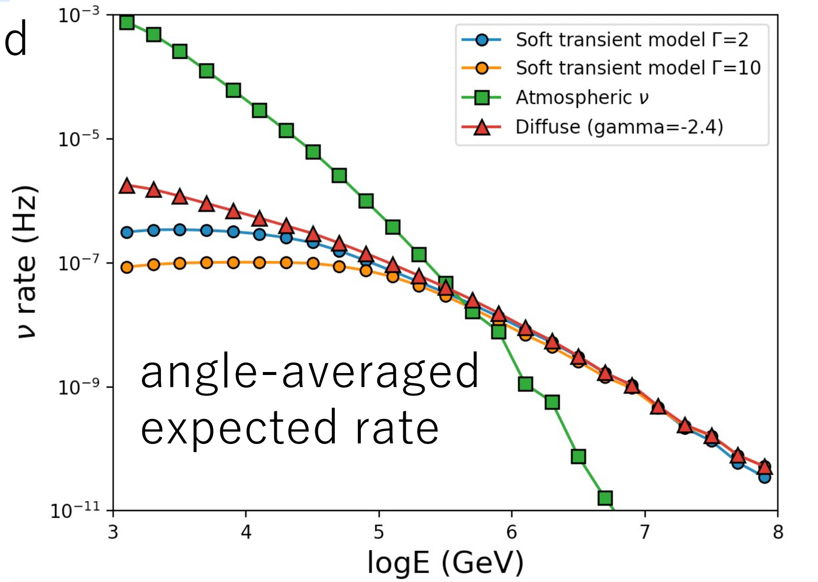
Neutrino PDF $P_\nu(E_\nu,\delta)$

Item	21217
Type	NuMu
Energy	100 GeV - 100 PeV
spectral index	-1.5
ice model	Spice 3.2.1
hole ice model	p0=0.0,p1=0.0
DOM oversize	1
Events/file	10,000
#file used	18,400

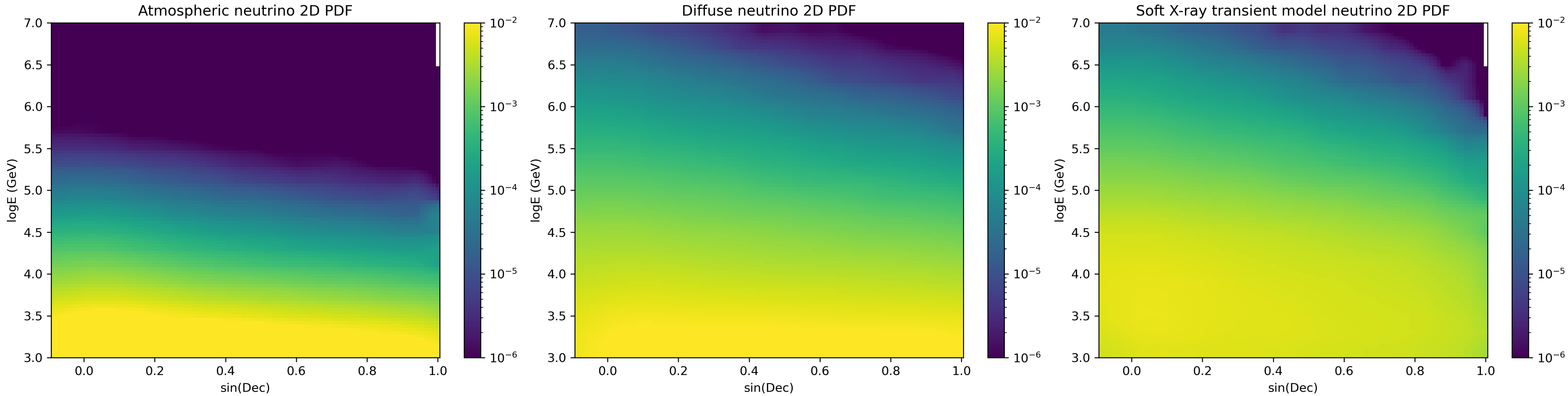
To estimate the PDFs, we use MC samples (detailed are shown in previous slide)

Soft transient model:
- normalization ($\Phi_\nu \propto \xi_{CR} Lx^{3/2}$) is maximized not to exceed the diffuse flux

← corresponds to maximized n_{sig} in the likelihood

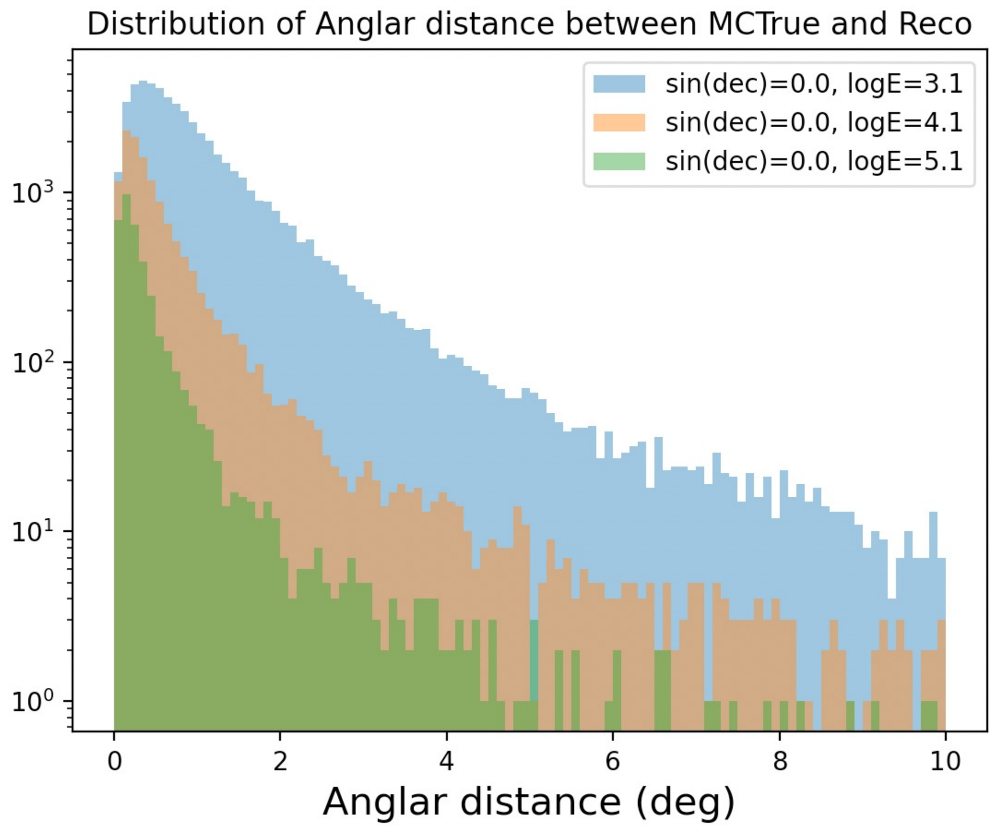


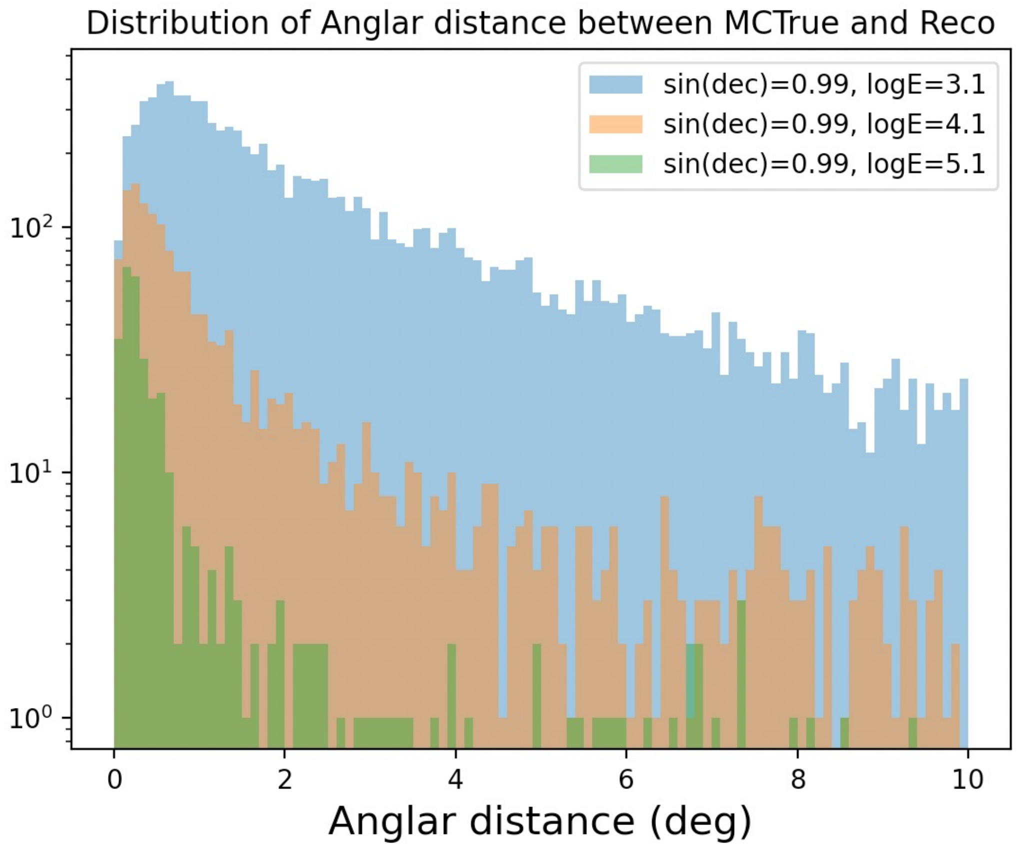
Two-dimensional probability density function of the energy and direction of each neutrino component



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

$$\mathcal{L}_{sig} = \frac{\mu^{N_{obs}}}{N_{obs}!} e^{-\mu} \prod_{i=1}^{N_{obs}} \Bigg(\overbrace{\frac{n_{sig}}{n_{atm}+n_{dif}} P_\nu^{sig}(E_\nu,\delta) \times P_X^{sig}(N_X, \mu_{Xsig(L_X)})}^{\nu \text{ signal related X-ray}} + \overbrace{\frac{1}{n_{atm}+n_{dif}} \left\{ n_{dif} P_\nu^{dif}(E_\nu,\delta) - n_{sig} P_\nu^{sig}(E_\nu,\delta) \right\} P_{X_{DB}}^{bgd}}^{\nu \text{ signal “not” related X-ray}} + \frac{n_{atm}}{n_{atm}+n_{dif}} P_\nu^{atm}(E_\nu,\delta) P_{X_{DB}}^{bgd} \Bigg)$$

n : total expected numbers

N_{obs} : total number of events

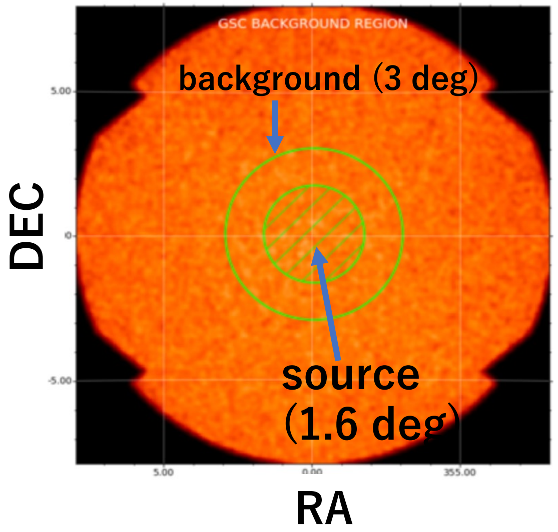
N_X : Number of X-ray events

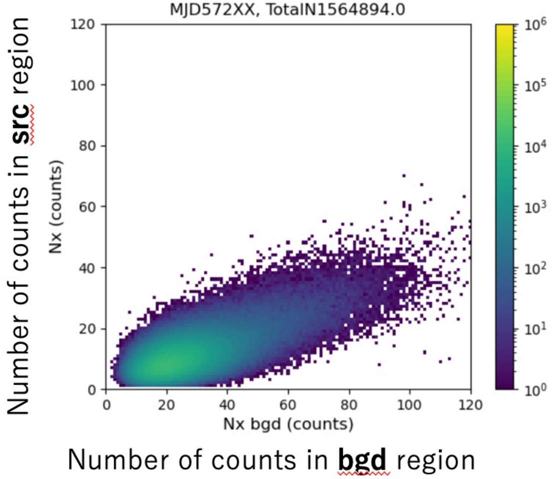
P : Probability Density Function

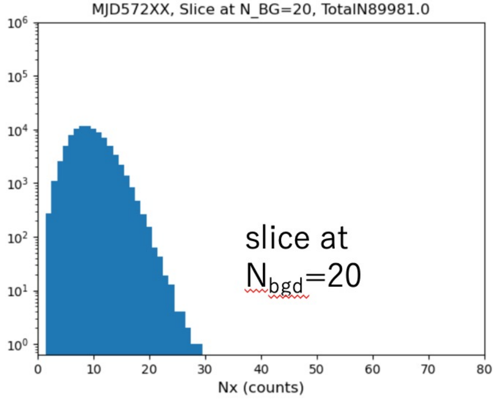
δ : direction of the events

ϵ_ν : energy of the events

MAXI X-ray data





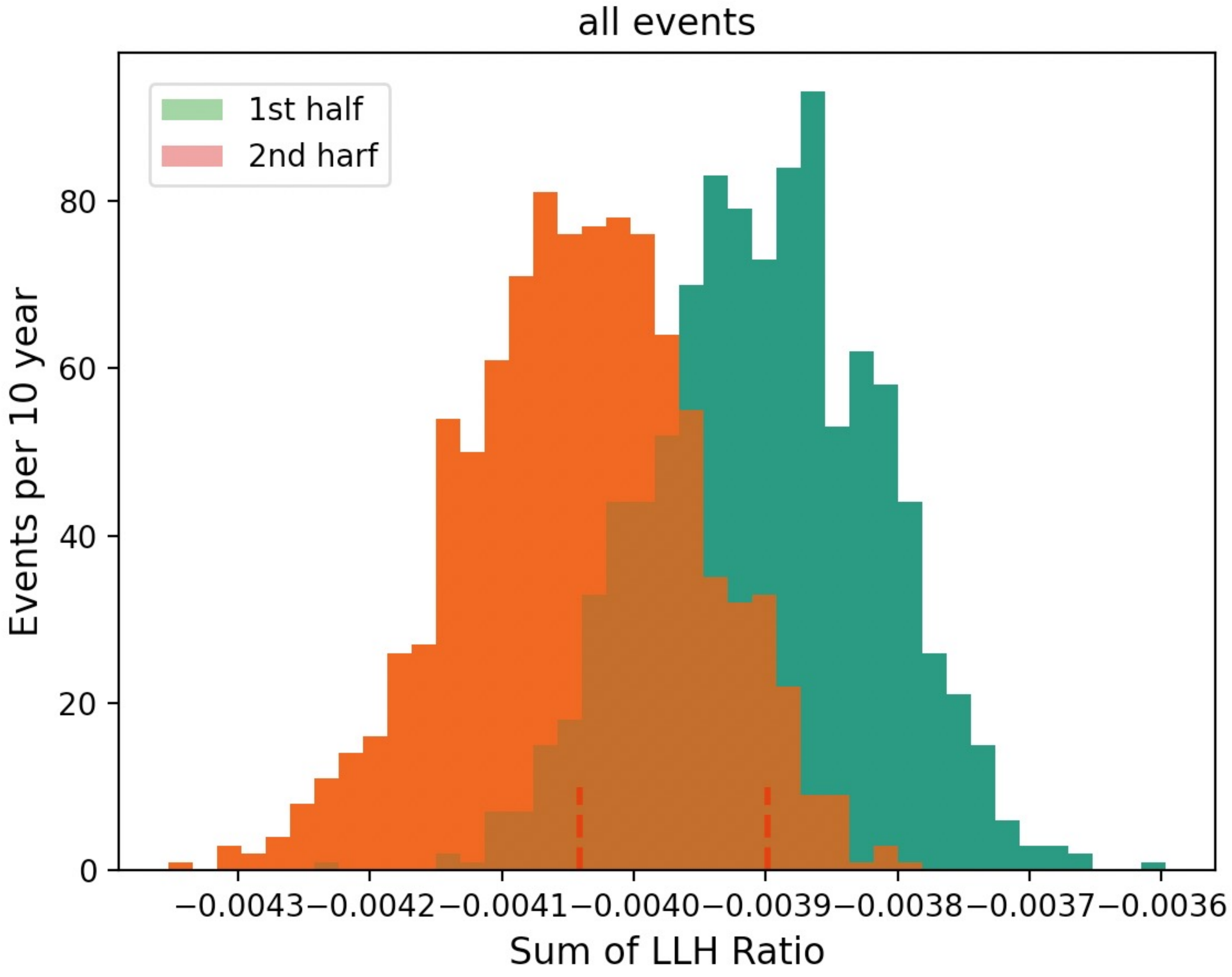


MAXI's source region matches its Point Spread Function (PSF) and is centered on the GFU event.

If the GFU position is misaligned, signal photons can leak into the background region, resulting in an underestimated signal and an overestimated background.

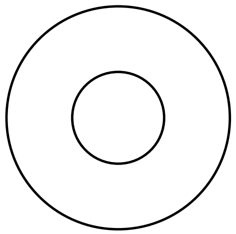
detailed in previous slide

Systematic error

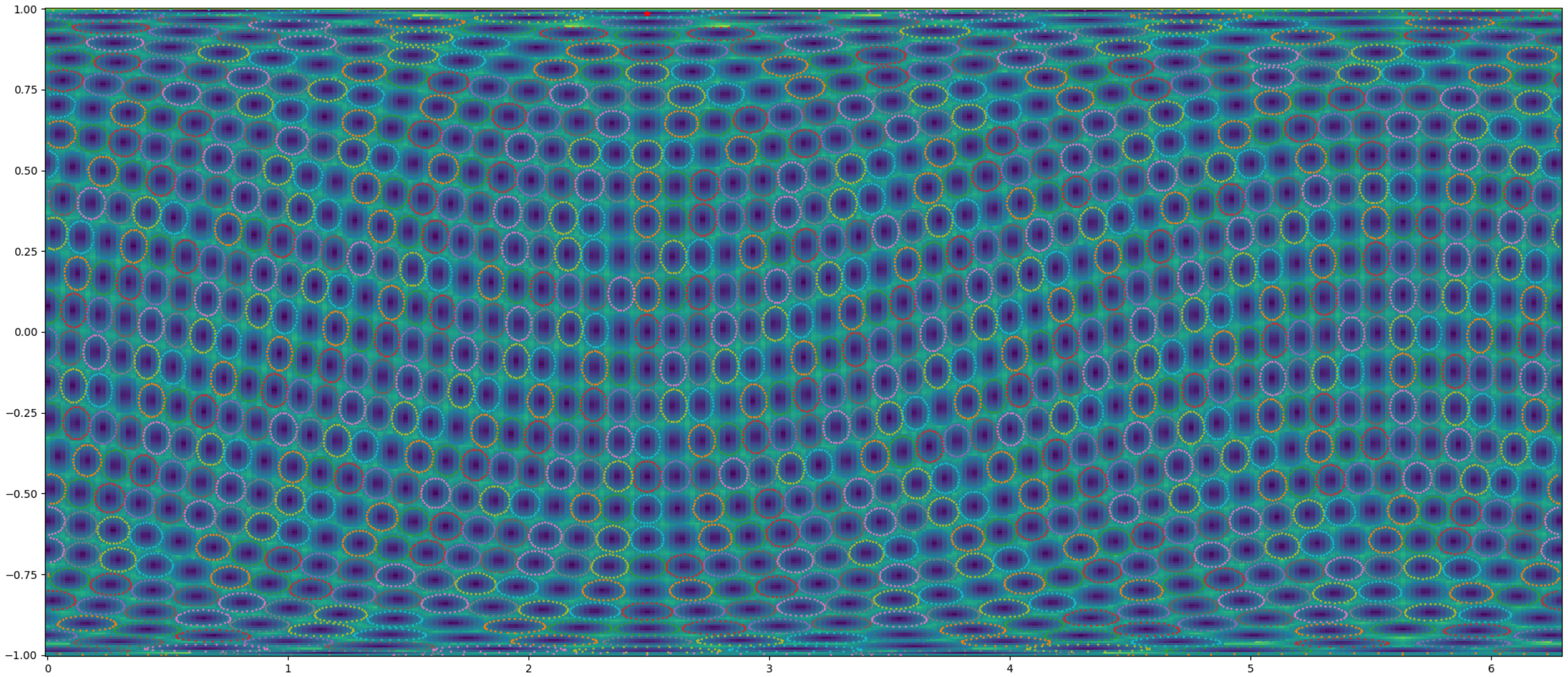


shift of the median value : 0.95

Source/BG regions



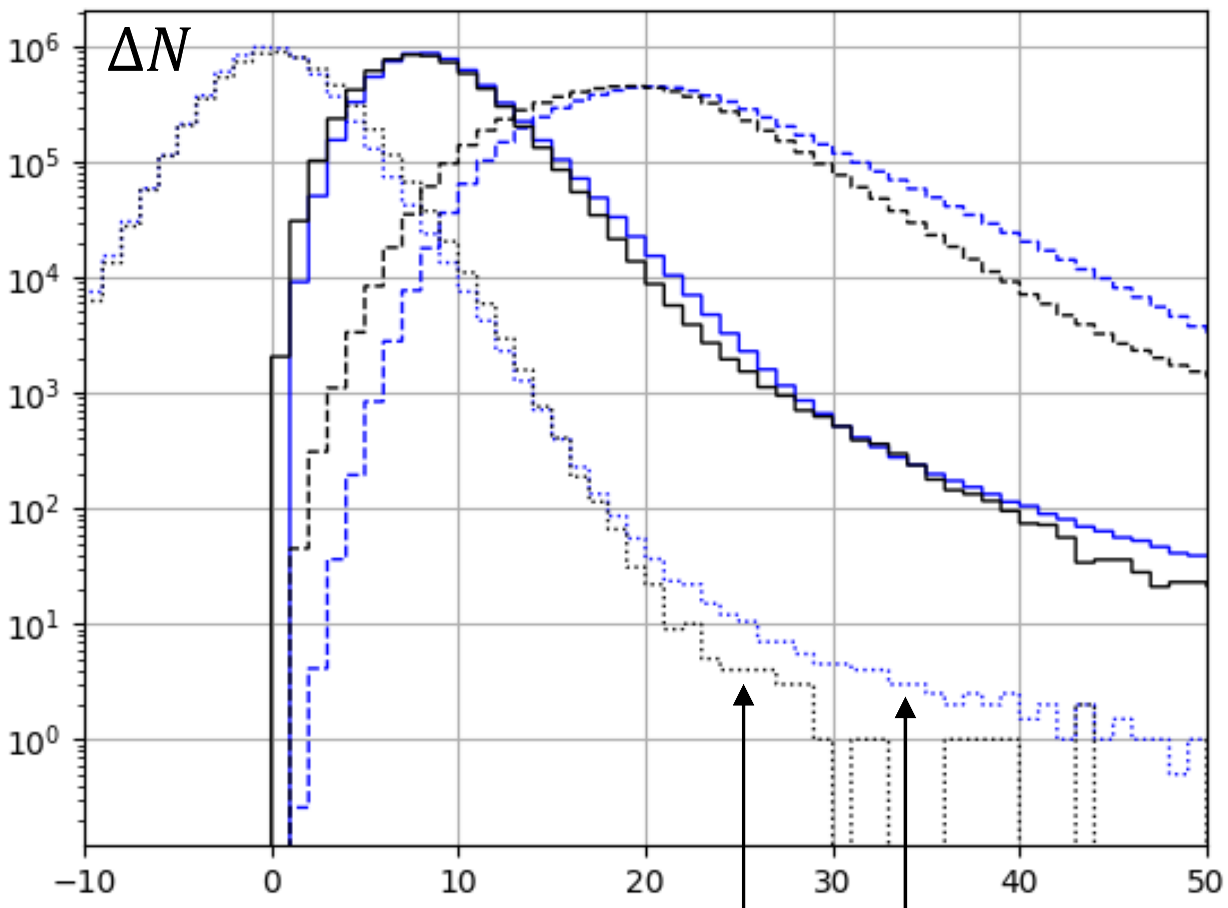
Randomly reconfigure the positions of donuts.
Recycle 10 times.



Statistics about 40 times higher than before

from : discussion_with_serinosan.pdf

N_{SRC} N_{BG}



on demand

this work

Idea for MM likelihood test

$$\mathcal{L}_{sig} = \frac{\mu^{N_{\mathrm{obs}}}}{N_{\mathrm{obs}}!} \mathrm{e}^{-\mu} \prod_{i=1}^{N_{\mathrm{obs}}} \Bigg(\overbrace{\frac{n_{\mathrm{sig}}}{n_{\mathrm{atm}}+n_{\mathrm{dif}}} P_\nu^{\mathrm{sig}}{}_{(E_\nu,\delta)} \times P_{\mathrm{X}}^{\mathrm{sig}}(N_{\mathrm{X}}, \mu_{\mathrm{Xsig}(L_{\mathrm{X}})})}^{\nu \text{ signal related X-ray}} + \overbrace{\frac{1}{n_{\mathrm{atm}}+n_{\mathrm{dif}}} \left\{ n_{\mathrm{dif}} P_\nu^{\mathrm{dif}}{}_{(E_\nu,\delta)} - n_{\mathrm{sig}} P_\nu^{\mathrm{sig}}{}_{(E_\nu,\delta)} \right\} P_{\mathrm{X_{DB}}}^{\mathrm{bgd}}}^{\nu \text{ signal “not” related X-ray}}$$

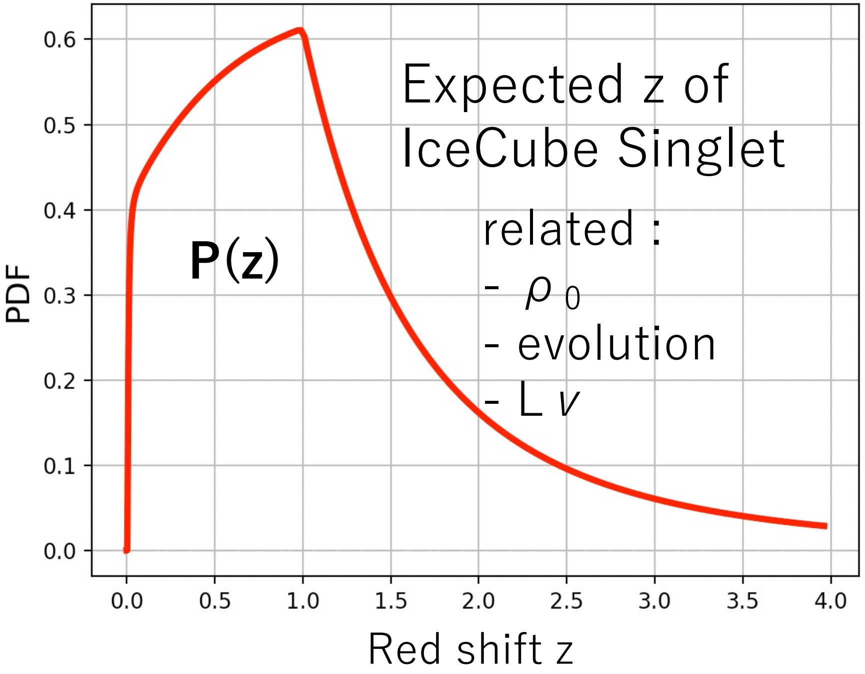
$$+ \underbrace{\frac{n_{\mathrm{atm}}}{n_{\mathrm{atm}}+n_{\mathrm{dif}}} P_\nu^{\mathrm{atm}}{}_{(E_\nu,\delta)} P_{\mathrm{X_{DB}}}^{\mathrm{bgd}}}_{\text{atmospheric } \nu \text{ bgd “not” related X-ray}} \Bigg)$$

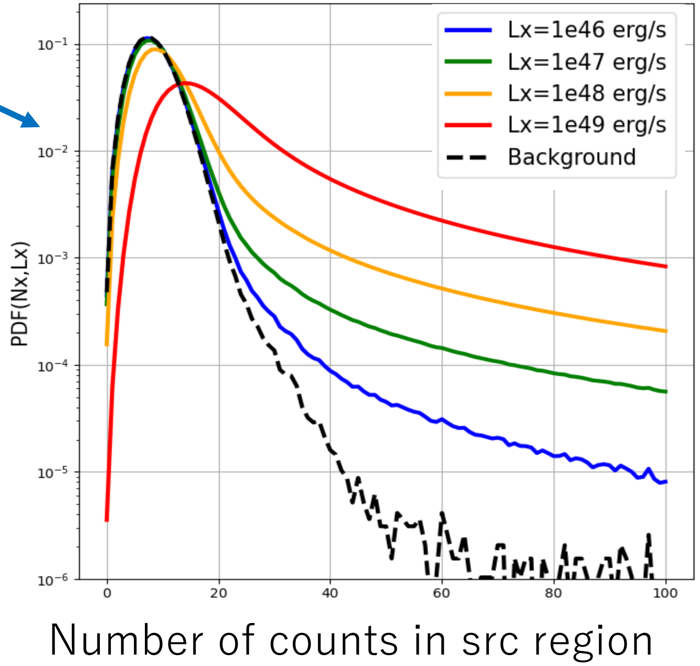
n : total expected numbers
N_{obs} : total number of events

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

$$\int_0^{z_{\max}} P(z)\, P(N_X \mid \mu_{(L_X)})\, dz$$

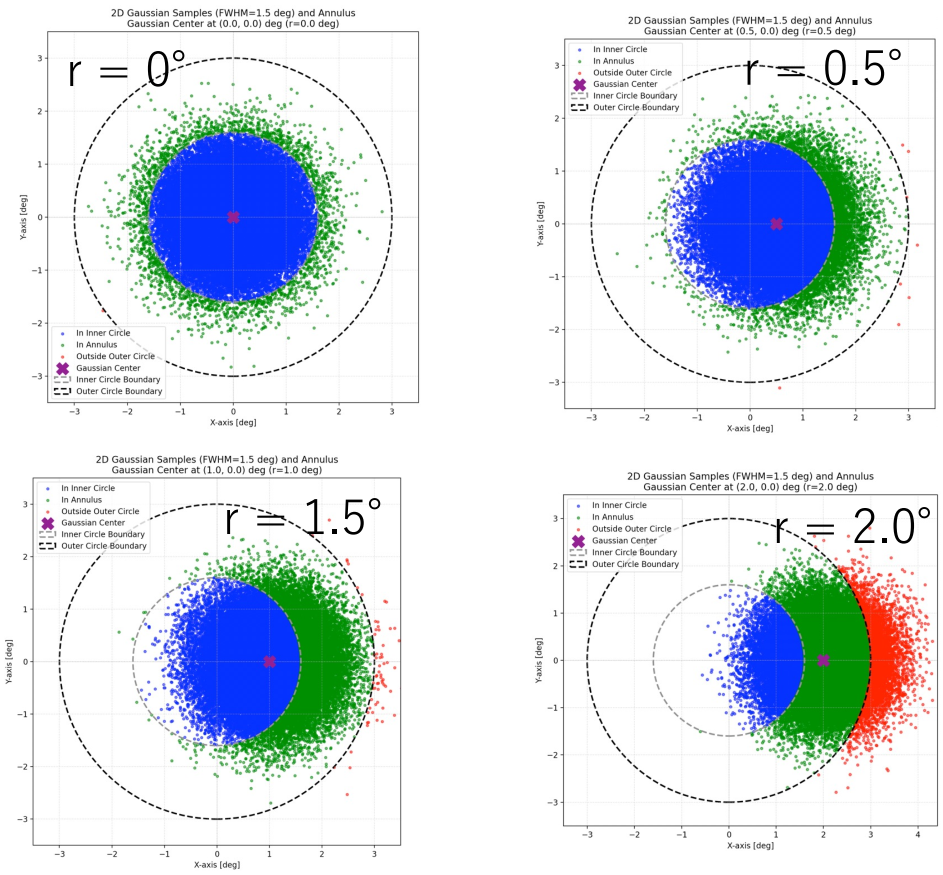
$$\sum_{n=0}^{N_X} P^{\mathrm{Poisson}}(N_X - n \mid \mu_{(L_x)}) P_{\mathrm{X_{DB}}}^{\mathrm{bgd}}(n)$$



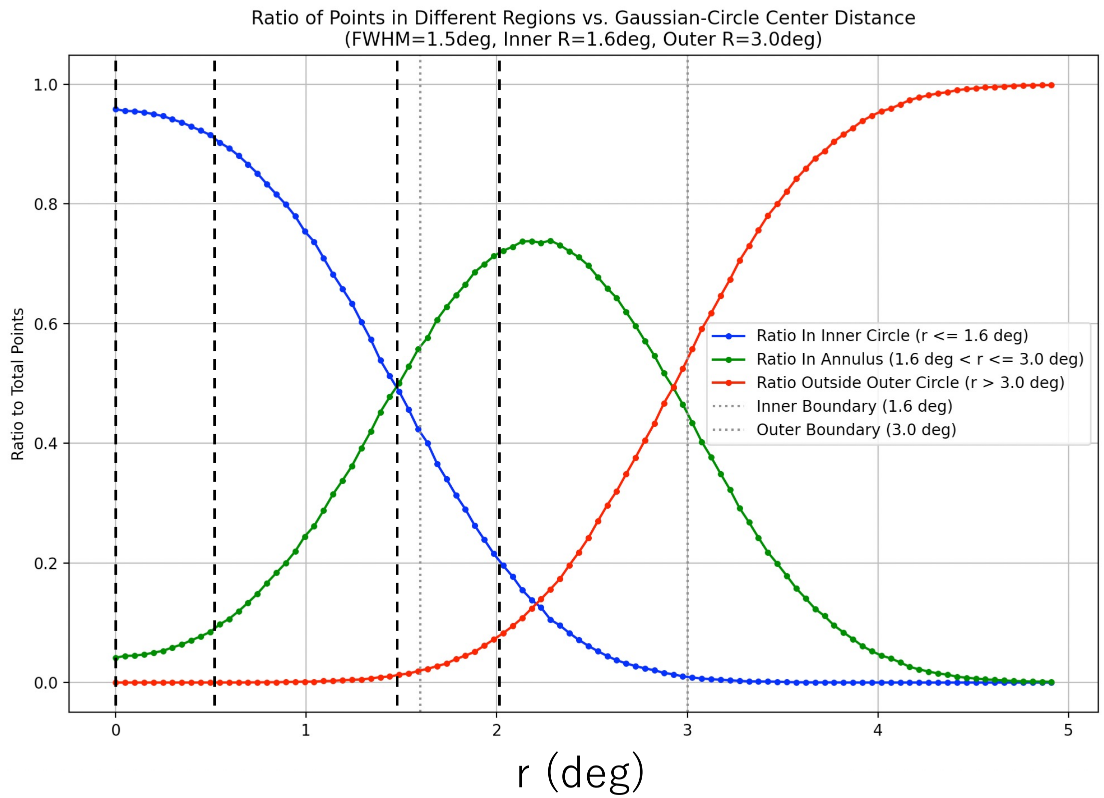


Effect of neutrino signal position offset on X-ray data analysis

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

Summary

- Consider the zenith angle dependence of the neutrino PDF based on MC simulation results
  - To estimate the effect of direction uncertainty of the neutrino event, deviation between the true position and the reconstructed position is recorded.
- A quantitative evaluation was performed to investigate how the offset of the true neutrino position affects the number of X-ray signals
  - This effect is implemented in the pseudo-signal experiment by distributing X-ray photons to the signal and background regions according to the value of r.

To do list :

- The sensitivity of this multi-messenger analysis method to Lx is evaluated by scanning n_0 and Γ.
- Uncertainty in MC simulations (how results change if the diffuse spectrum flux differs) from Steve's comment

Scan a reasonable range to obtain the upper limit of Lx for each n_0 and Γ

$$\Phi_\nu^{\mathrm{Diffuse}} \propto \underline{n_0}\,\underline{\xi_{\mathrm{CR}}}\,\underline{L_X}\,\tau_{p\gamma}[\sqrt{L_X}, B, \underline{\Gamma}]$$

Lower limit derived from constraints on the neutrino diffuse flux

Upper limit by this X-ray counterpart search