Search for X-ray transient counterparts for IceCube neutrino events with Swift-XRT

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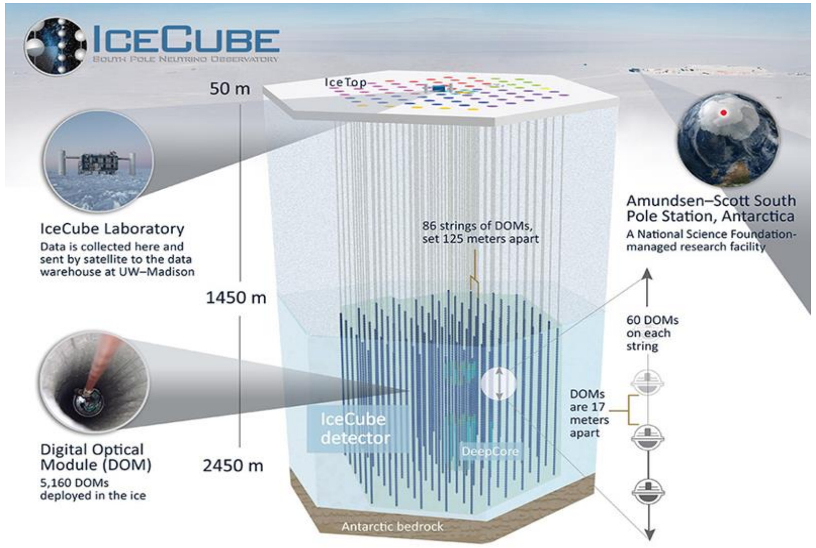
Neutrinos for UHECR Source Search

The source of the **Ultra High Energy Cosmic Rays (UHECRs)** are not well known

$p \sim \begin{matrix} p \\ \gamma \end{matrix} \to \pi \to \nu$

IceCube experiment

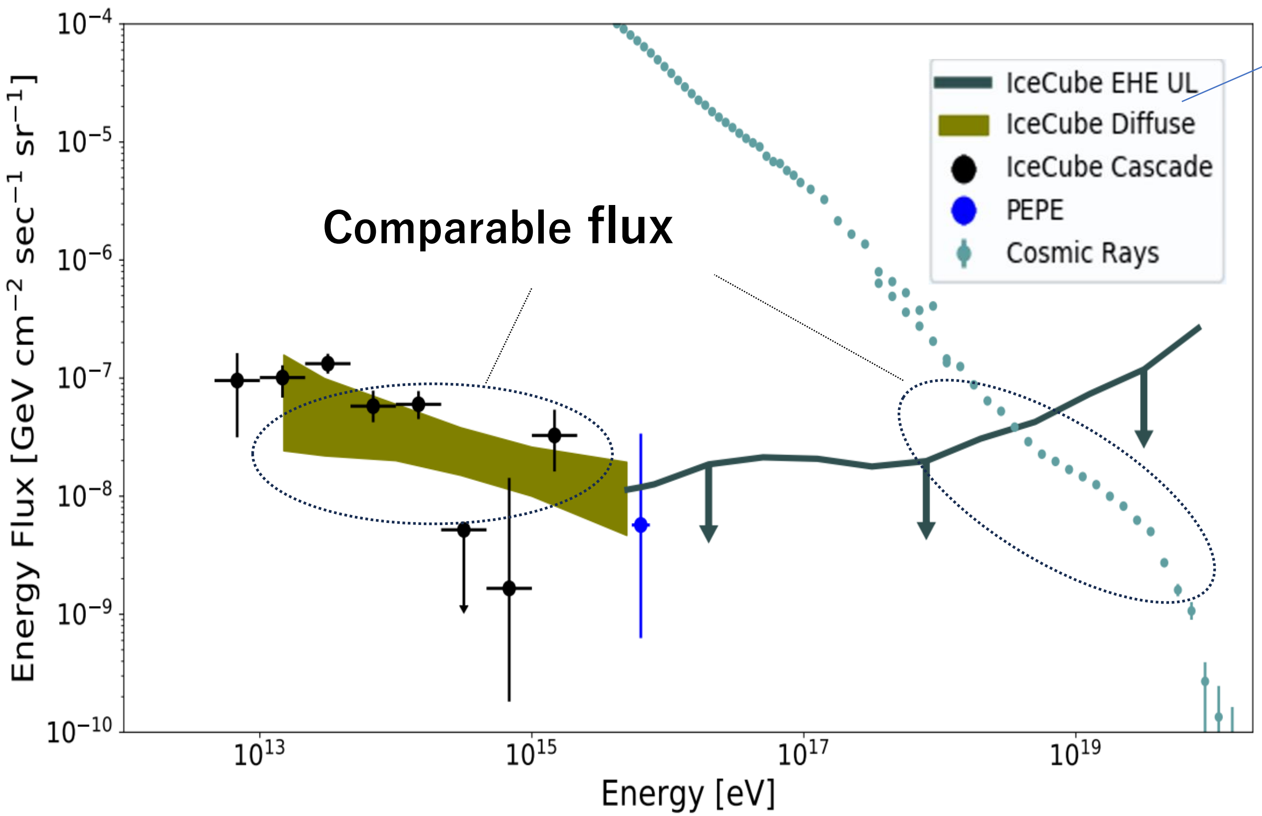
High energy neutrino searches are a key to reveal the mystery



IceCube:
Observes high energy neutrinos in 1 km^3 ice under the south pole

Unified Source Model of ν and UHECRs

Neutrinos and UHECRs Energy Flux



Diffuse flux:
neutrino flux from the entire sky (nearly isotropic)

- This observation implies unified sources of ~100 TeV ν and $\sim 10^{19}$ eV CR

Yoshida + Murase 2024

Astrophysical phenomena comparison in $p\gamma$ **scenario**

✓ Optical depth? ✓ CR acceleration? ✓ …

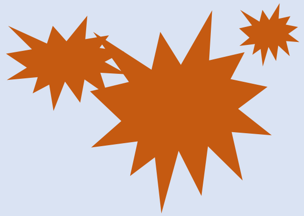
Most likely unified source candidate

X-ray transient sources（ex: LLGRB）

Constrains by X-ray Counterpart Search

Considering the observed flux of UHECRs and neutrinos, the seed photon's energy is ~X-ray

→ **Search for X-ray transients including LLGRB is meaningful**



Ex) LLGRB

L_{X}, L_{CR} → $p\gamma$ production → $\Phi_\nu \propto \frac{dN_{CR}}{d\varepsilon_{CR}} \tau_{p\gamma} n_0 \propto \xi_{\mathrm{CR}} L_{\mathrm{X}}^{\frac{3}{2}} f(\Gamma) n_0$

Cosmic Ray Loading Factor

$L_{\mathrm{CR}} = \xi_{\mathrm{CR}} L_{\mathrm{X}}$

- If we can know L_{X}, this constrains important factors of the neutrino source such as ξ_{CR} and L_{CR}
- Even for 'non-detection', we can get a lower limit of ξ_{CR}

Good analysis leads to a higher sensitivity, and a stronger constrain!

X-ray Follow Up for Neutrinos has been already done

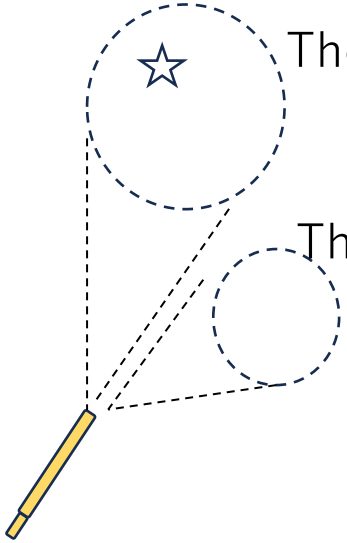
Swift XRT

- Rapid slewing
  →starts follow up ~2h after IceCube alert
- Sensitive to $5 \times 10^{-13}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$ in $1\ \mathrm{ks}\ (0.3 - 10\ \mathrm{keV})$

- **Has already Followed up (FU) ~40 alerts**

IC NAME	found sources?
IC250406A	1
:	:
IC110326A	7

Problems of the current style



There may be something in this case..

There may be nothing in this case..

- Event by event analysis
- Serendipity? Counterpart?

My research

- Stacked analysis (Combine all the previous FU observations)
- Evaluate statistical significance by simulation

Goal and Strategy

Goal

- Develop a method to find X-ray counterparts in the previous ~40 observations for IceCube neutrino alerts with Swift XRT
- Evaluate its sensitivity and constrain the physics parameters

Strategy

Define Test Statistics (TS) to the combined FU dataset : how likely to be the unified source..?

Use real information

ICECUBE

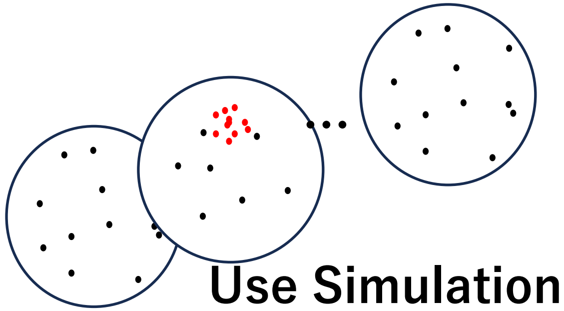
IC***
Energy
ra
dec

IC***
Energy
ra
dec

…

IC***
Energy
ra
dec

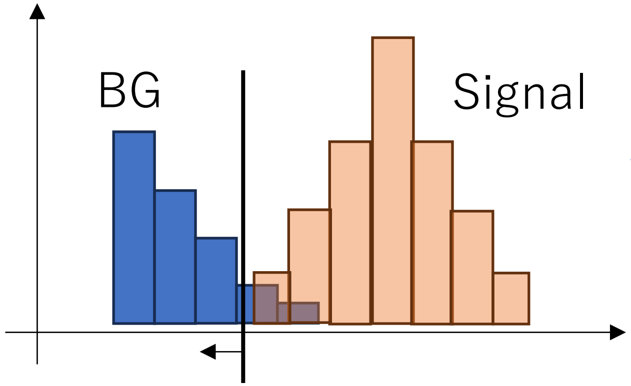
$TS(\Pi_{k=1}^{k=40})$ →



Use Simulation data

Evaluate the sensitivity

TS histogram



→ **Unblind** XRT observations

Test Statistics Construction

$$TS = 2\log\left(\frac{\mathcal{L}^{tot}_{sig+bg}(\vec{x})}{\mathcal{L}^{tot}_{bg}(\vec{x})}\right)$$

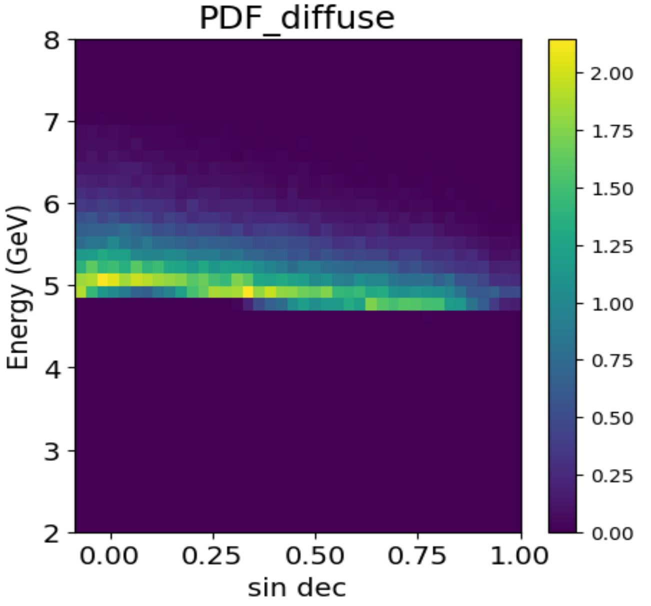
FU 1 … FU 40

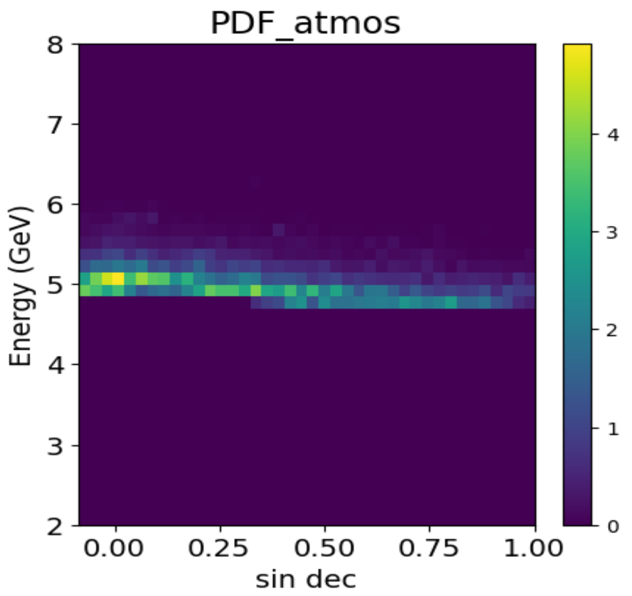
$$\underbrace{\mathcal{L}^{1}_{\text{sig+bg}} \quad \cdots \quad \mathcal{L}^{40}_{\text{sig+bg}}}$$

$$\mathcal{L}^{\text{tot}}_{\text{sig+bg}}(\vec{x}) = \prod_{k=1}^{k=40} \max_{\vec{n}^{k}_{\text{src}}, n^{k}_{X_{\text{sig}}}} \mathcal{L}^{k}_{sig+bg}$$

$$\mathcal{L}_{sig+bg} = P^{\nu}_{\text{diffuse}}(\vec{x}_\nu, E_\nu) P^{X}_{\text{sig}}(\vec{x}_X, N_X) + P^{\nu}_{\text{diffuse}}(\vec{x}_\nu, E_\nu) P^{X}_{\text{bg}}(\vec{x}_X, N_X) + P^{\nu}_{\text{atmos}}(\vec{x}_\nu, E_\nu) P^{X}_{\text{bg}}(\vec{x}_X, N_X)$$

$P^{\nu}_{\text{diffuse}}(\vec{x}_\nu, E_\nu)$ & $P^{\nu}_{\text{atmos}}(\vec{x}_\nu, E_\nu)$: by IceCube MC simulation

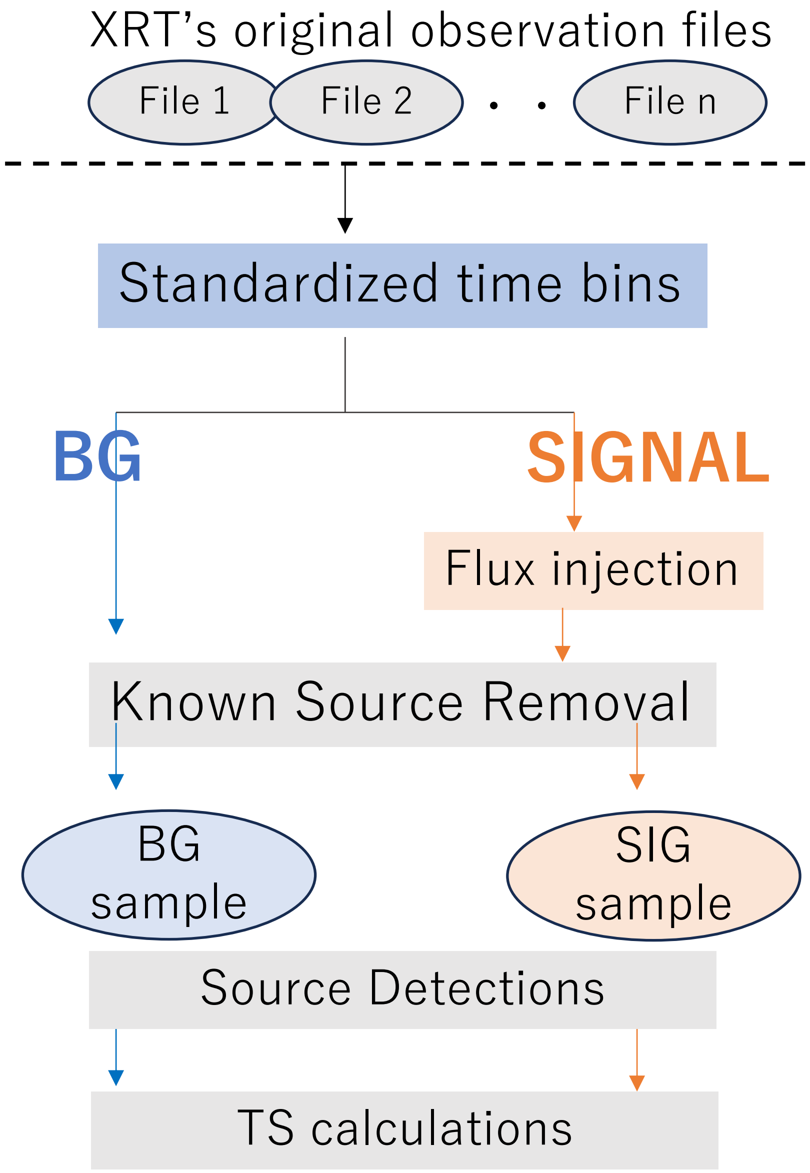




$P^{X}_{\text{sig}}(\vec{x}_X, N_X)$:
by XRT Point Spread Function

$P^{X}_{\text{bg}}(\vec{x}_X, N_X)$:
by assuming BG X-rays are uniformly spread

Simulation Flow



Galactic Plane Cut: remove b<5°

Standardized Exposure Time:
- Analysis sensitivity largely depends on the exposure time
- For statistic analysis, **we unify all of the exposure time to 200 s**

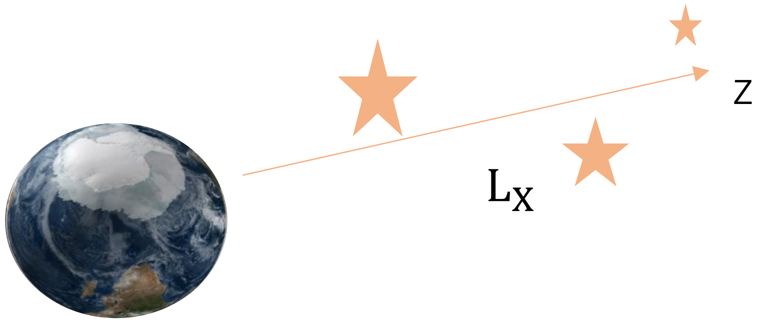
Inject Pseudo X-ray of Assumed Flux

Steady Known Source Removal :
- we made original steady source catalog by crossmatching Swift catalog & ROSAT catalog
- ROSAT catalog is sensitive enough for 200 s XRT data

Source Detection and TS calculations

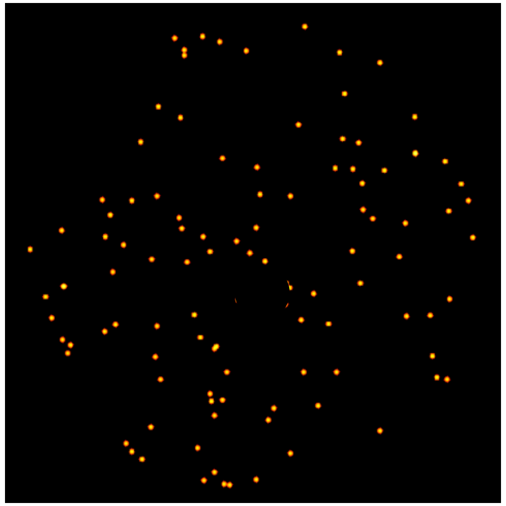
Simulations

We already know (RA, Dec, Neutrino Energy) of the IceCube events
→ **Only X-ray side simulation**



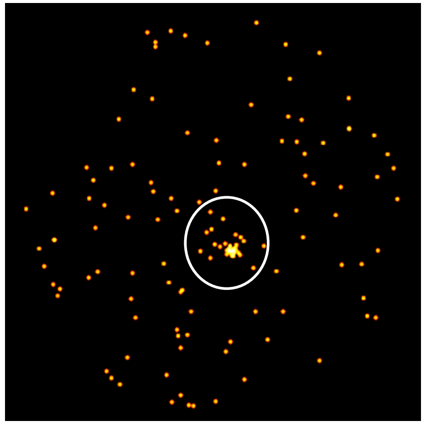
BG simulation

Real XRT bg data

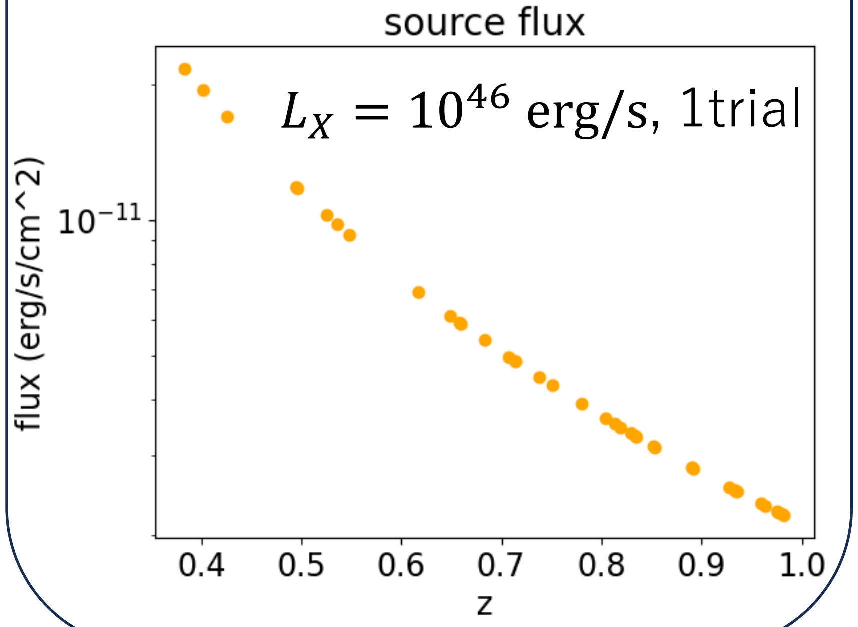


Signal simulation

- Assume all the sources are the unified sources of X and ν
- Assign z $(0 \leq z \leq 1)$ to each assuming the Star Formation Rate $1/(\Omega_M(1+z)^3+\Omega_\lambda)$
- Set common L_X (erg s^{-1})
- Calculate each source's flux and inject corresponding photons



Flux (erg/s/cm^2) ←z→ flux model L_X (erg/s)

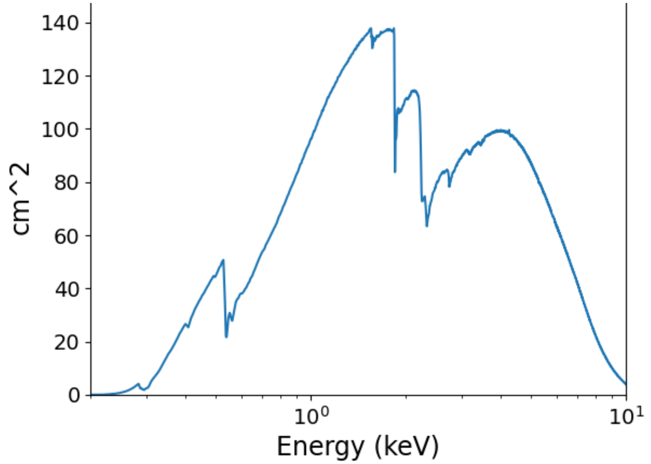


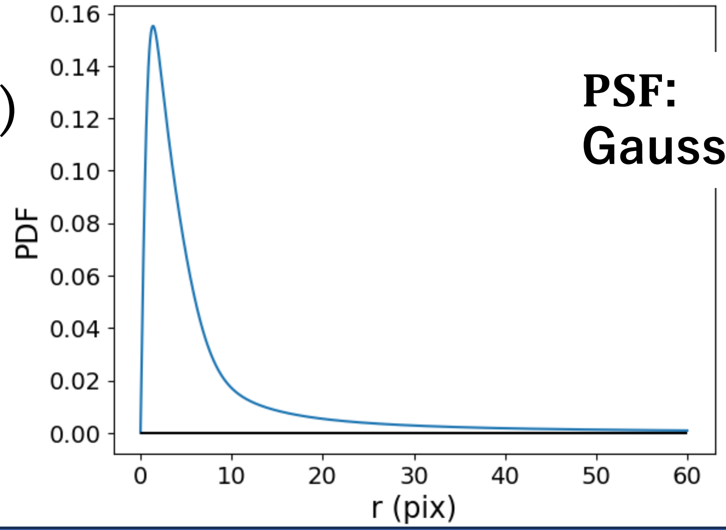
Details of the pseudo photon injection

- We know the Effective Area and PSF of XRT
- **We assume Power law**

AE^{-2} **(/keV/s/cm^2)**

Effective Area $(E, \text{offaxis})$

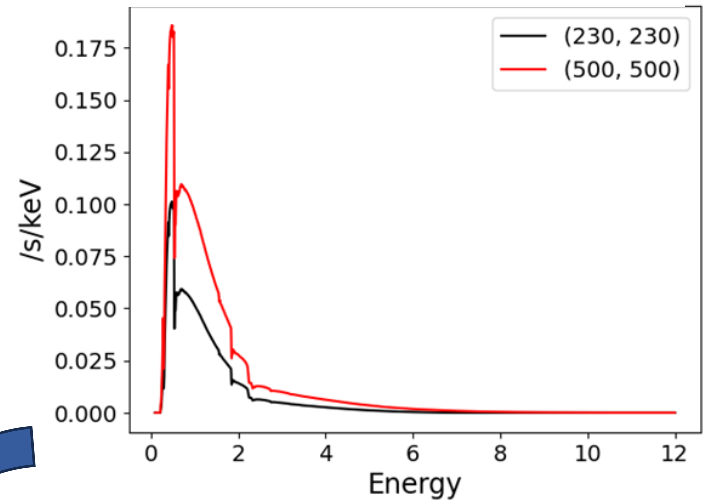


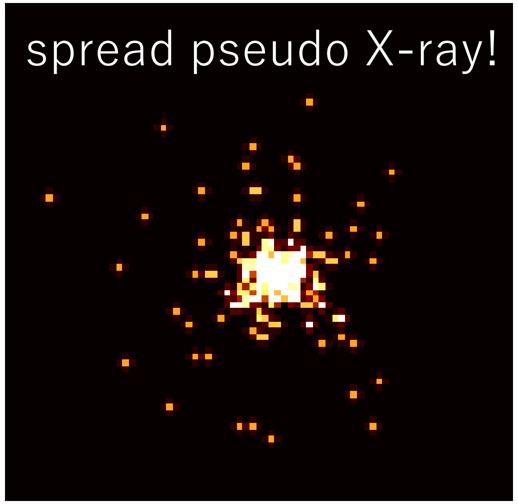


PSF: Gauss+King

w/ calculated X-ray flux

count rate /s/kev



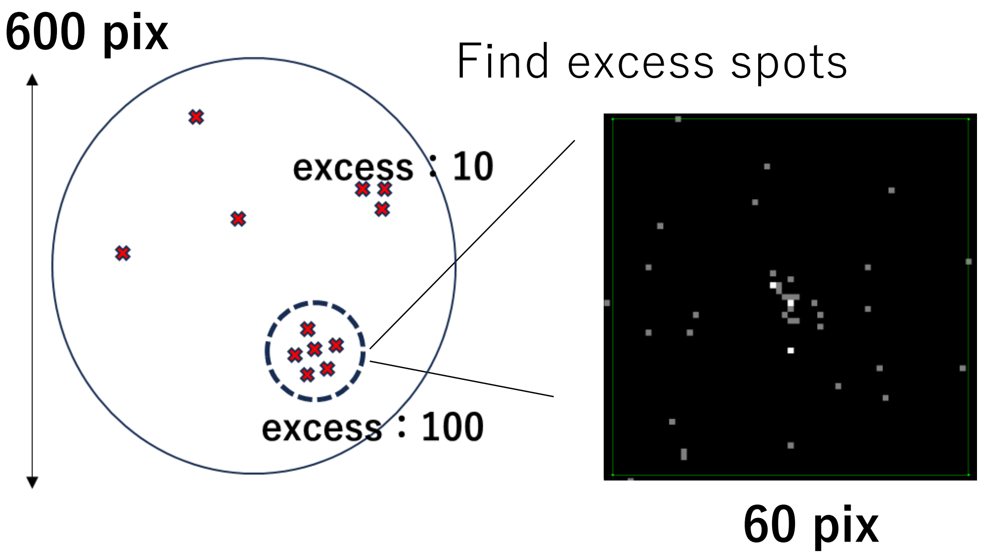


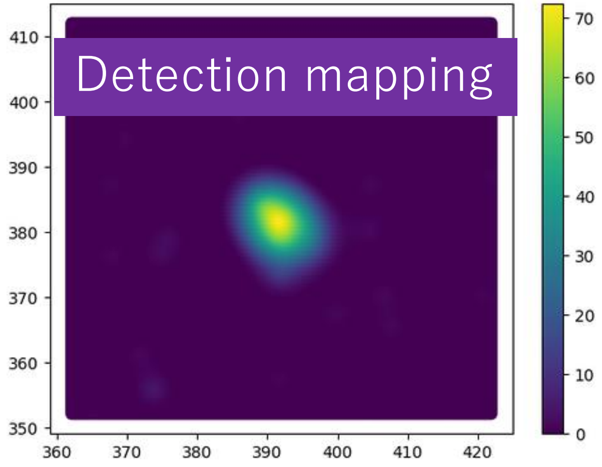
Test Statistic Calculation

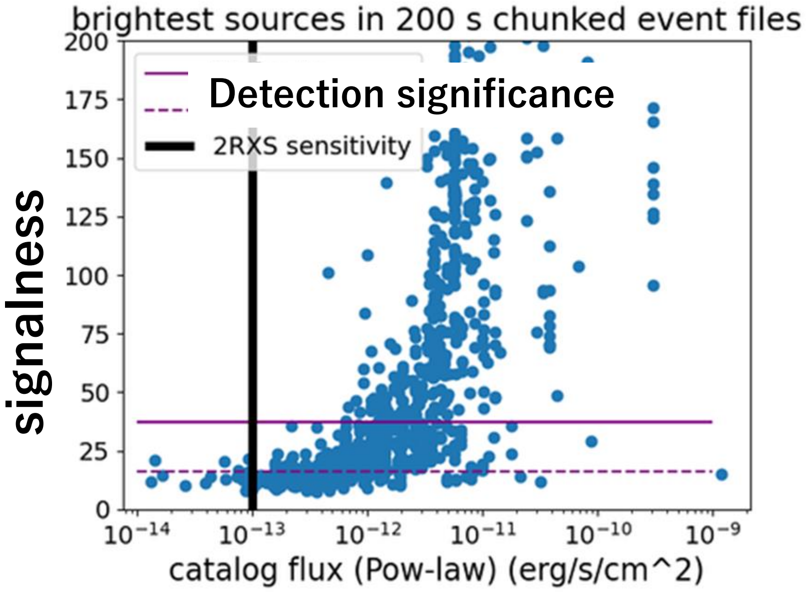
X-ray Source Detection

A standard tool (*ximage*) is a black box, so we developed an original method using likelihood

$$P_X^{\mathrm{sig}}(x_0, y_0, N_X) = \prod_i \left\{ \frac{N_X}{N_{tot}} \, \mathrm{PSF}\left(r_i(x_i, y_i | x_0, y_0)\right) \right\} + \left(\frac{N_{tot} - N_X}{N_{tot}}\right) \frac{1}{\Omega_{tot}}$$







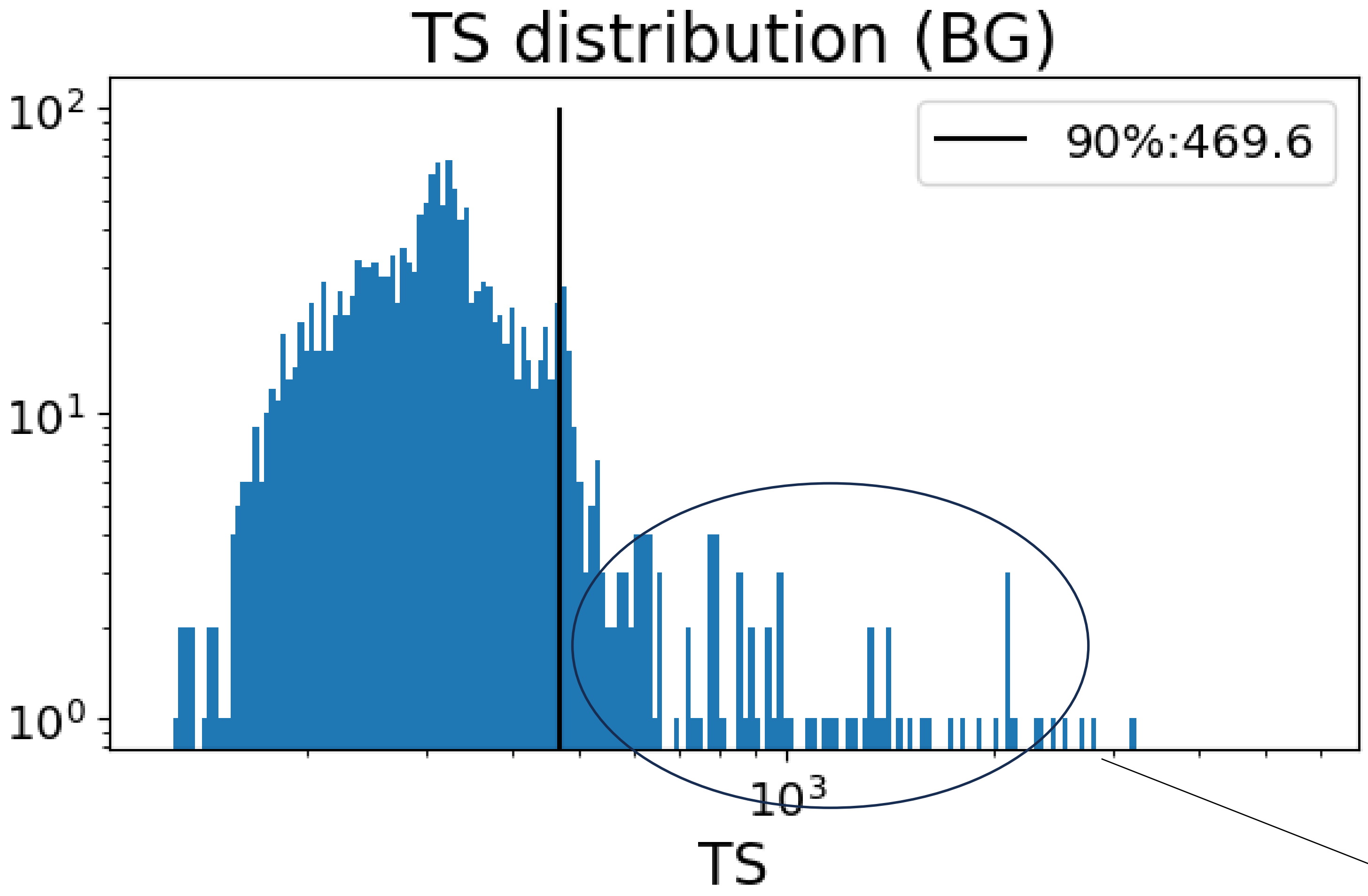
+ neutrino information

Test Statistics

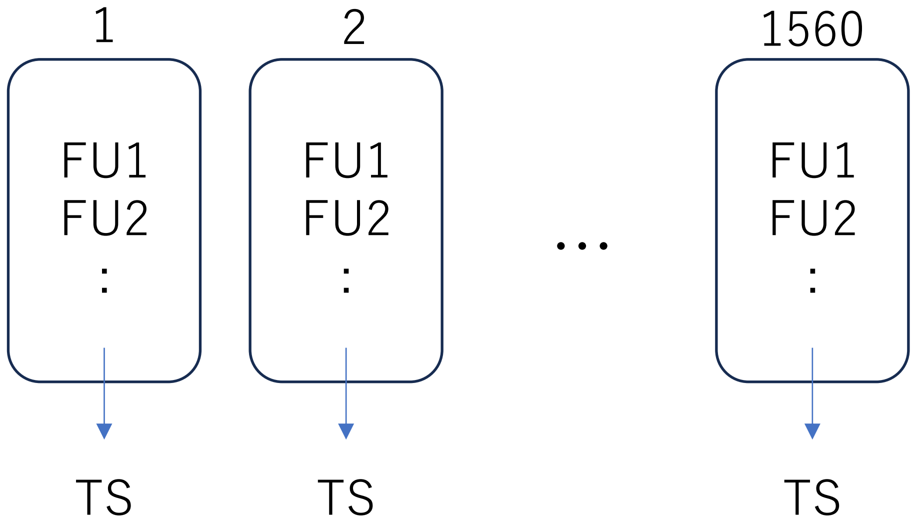
$$TS = 2\log\left(\frac{\mathcal{L}^{tot}_{sig+bg}(\vec{x})}{\mathcal{L}^{tot}_{bg}(\vec{x})}\right)$$

$$\mathcal{L}^{\mathrm{tot}}_{\mathrm{sig+bg}}(\vec{x}) = \prod_{k=1}^{k=40} \max_{\vec{n}^{\mathrm{k}}_{\mathrm{src}}, \mathrm{n}^{\mathrm{k}}_{\mathrm{X_{sig}}}} \mathcal{L}^{k}_{sig+bg}$$

BG Simulation Results



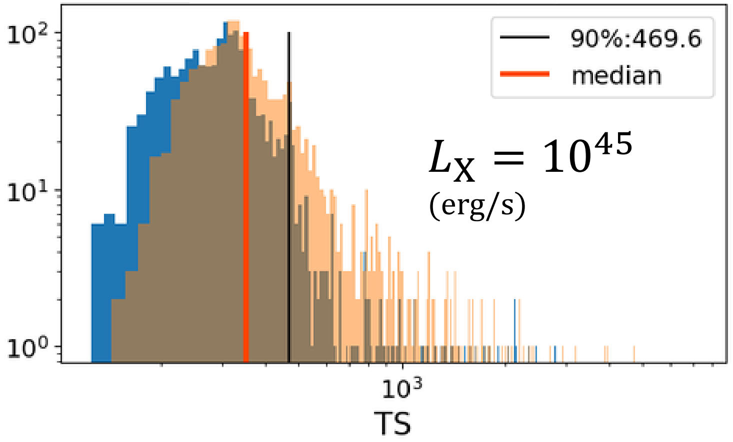
- The Number of Simulations: 1560

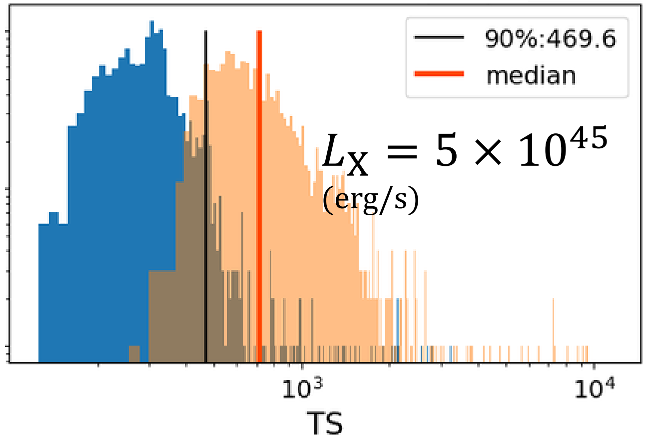


- The effect of Unremoved known sources or serendipities

Signal Simulation & Results

Examples of TS distribution

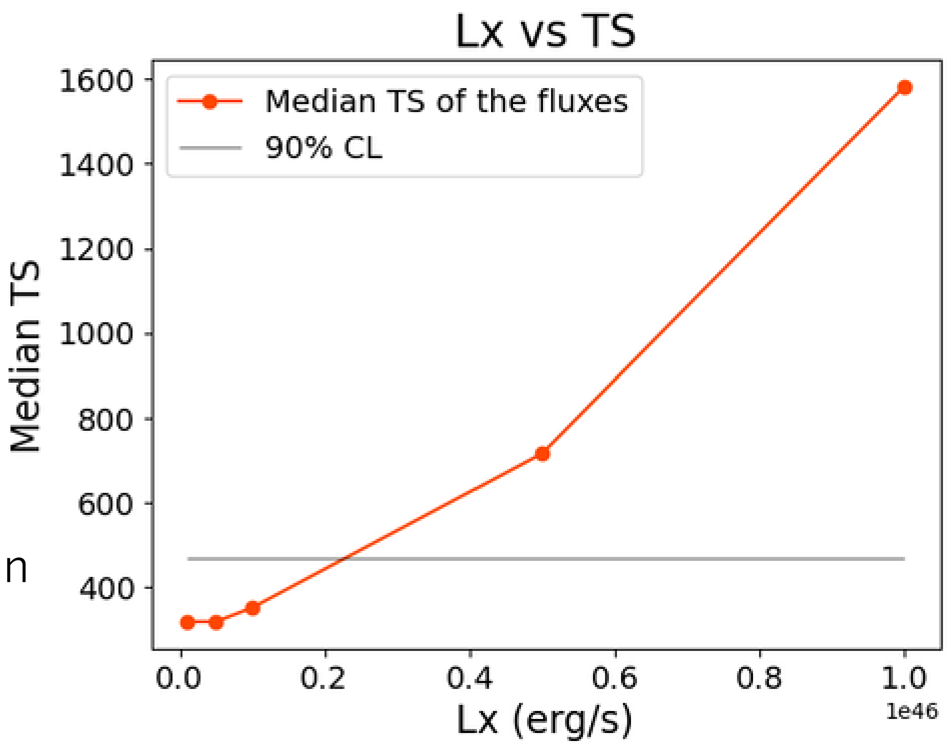




90% confidence level: $L_X \sim 2.3 \times 10^{45}$ (erg/s)

$$\Phi_\nu \propto \xi_{CR} L_X^{\frac{3}{2}} f(\Gamma) n_0$$

This can be an upper limit when we see nothing in unblinding



This sensitivity could place stronger constrains on the UHECRs source model by a further analysis

Future Work / Summary

Future Work

- Consider neutrino point source error
- Constrain physics parameters

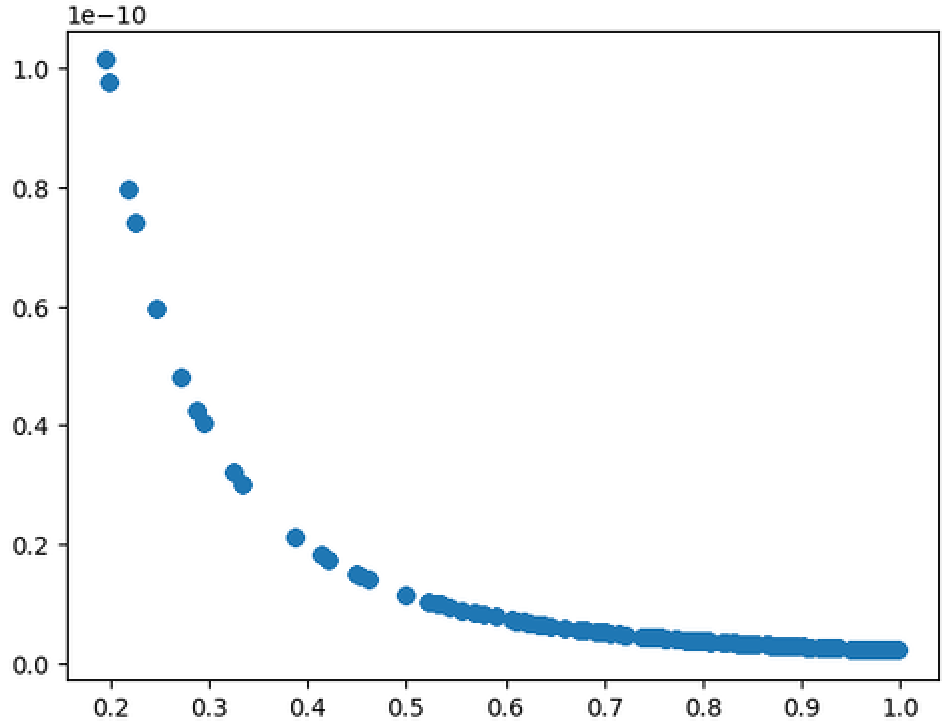
Summary

- Search for X-ray counterpart of IceCube neutrinos such as LLGRBs is meaningful to investigate the origins of UHECRs

- We are developing a method to evaluate Swift-XRT's sensitivity for IceCube follow up by blind analysis method

- $L_X \sim 2.3 \times 10^{45}$ (erg/s) source X-ray luminosity can lead to 90% CL significance detection, which could place stronger constrains on the UHECRs source model

Back up



Introduction:

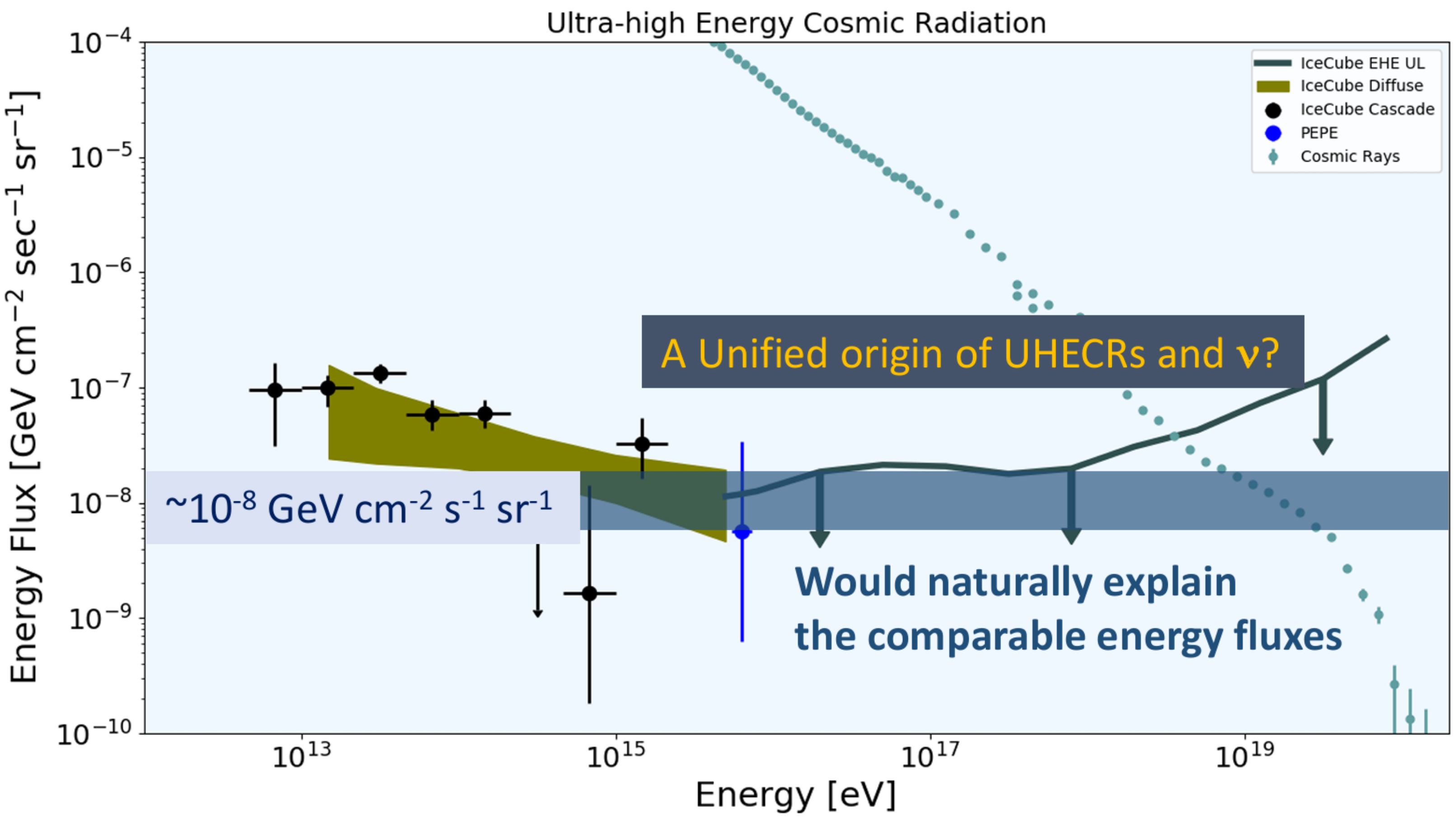
Why X-ray Search for Neutrinos Is Important

Mainly from
Yoshida & Murase (PRD 2024)

[Testing unified models for the origin of ultrahigh-energy cosmic rays and neutrinos: Multimessenger approaches with x-ray observations | Phys. Rev. D]

and Shigeru's slide for X- *ν* meeting
https://indico-icehap.phys.s.chiba-u.ac.jp/event/2/contributions/116/attachments/106/165/NeutrinoXrayRoundTableIntro.pdf

Unified Origin of ν and UHECRs -Yoshida & Murase 2024



- **Neutrinos > ~100 TeV** and **CRs > ~10^19eV** have comparable energy flux

A unified origin of ν and UHECRs?

Build **generic** unification models by pγ process

Parameter-Constrains of the Unified Origin -Yoshida & Murase 2024

Generically given

- pγ optical depth

$$\tau_{p\gamma}(\varepsilon_p) \approx \tau_{p\gamma 0}\left(\frac{\varepsilon_p}{\varepsilon^{\rm FID}_{\rm UHECR}}\right)^{\alpha_\gamma - 1}$$
$$\approx \frac{B'}{\Gamma^2}\sqrt{\frac{L'_\gamma}{\xi_{\rm B}}}\beta^{-1}C(\alpha_\gamma)\left(\frac{\varepsilon_p}{\varepsilon^{\rm FID}_{\rm UHECR}}\right)^{\alpha_\gamma - 1}.$$

- magnetic field loading factor

$$\xi_{\rm B} \equiv U'_{\rm B}\left(\frac{L_\gamma}{4\pi\Gamma^2 R^2 c}\right)^{-1}.$$

We can evaluate the candidate source class with this constrains!

Ex)
A source class has enough optical depth to produce neutrinos
→ But that makes it hard for CRs to escape
→This source class is not favorable

Requirements for ν and UHECRs source

- UHECR energetic argument

$$\xi_{\rm UHECR} \sim 0.7\left(\frac{L_\gamma}{10^{46}\ {\rm erg/s}}\right)^{-1}\left(\frac{n_0^{\rm eff}}{10^{-8}\ {\rm Mpc^{-3}}}\right)^{-1}.$$

- Neutrino flux requirements

$$\tau_{p\gamma 0} \gtrsim 0.04\left(\frac{\xi_z}{2.8}\right)^{-1}.$$

- Acceleration of UHECRs

$$\xi_B \geq \frac{1}{2}c\eta^2\beta^2 L'^{-1}_\gamma\left(\frac{\varepsilon_i^{\max}}{Ze}\right)^2$$
$$\gtrsim 1.7\eta^2\beta^2\left(\frac{L_\gamma}{10^{46}\ {\rm erg/s}}\right)^{-1}\left(\frac{\Gamma}{10^{0.5}}\right)^2\left(\frac{\varepsilon_i^{\max}}{Z10^{11}\ {\rm GeV}}\right)^2$$

- Escape of UHECRs

$$\tau_{p\gamma 0} \lesssim 0.06\frac{2}{1+\alpha_\gamma}\xi_B^{-1}\beta^{-1}\left(\frac{A}{Z}\right)^4\left(\frac{\varepsilon_i^{\max}}{10^{11}\ {\rm GeV}}\right)^{-1}$$

- Nuclei survival

$$\tau_{p\gamma 0} \lesssim A\frac{\int ds \frac{\sigma_{p\gamma}(s)}{s-m_p^2}}{\int ds \frac{\sigma_{A\gamma}(s)}{s-m_A^2}}\left[\left(\frac{s_{\rm GDR}-m_A^2}{s_\Delta - m_p^2}\right)\left(\frac{\varepsilon_p^{10\ {\rm PeV}}}{\varepsilon_i^{\max}}\right)\right]^{\alpha_\gamma - 1}$$
$$\lesssim 0.4\left(\frac{A}{56}\right)^{-0.21},$$

Steady Source Case -Yoshida & Murase 2024

	RL AGN (BL Lac jet)	RL AGN (FSRQ jet)	RQ AGN (jet)	RL AGN (hot disk)
$\Gamma\beta$ of the outflow	~ 10	~ 10	~ 1	~ 0.01
Target photon energy	UV/x-ray	Opt/UV	Opt/UV	IR/opt
$L_\gamma^{\rm eff}$ [erg/s]	A few $\times 10^{45}$	A few $\times 10^{47}$	A few $\times 10^{43}$	A few $\times 10^{41}$
$n_0^{\rm eff}$ [Mpc^{-3}]	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-6}$	$\sim 10^{-7}$
$n_0^{\rm tot}$ [Mpc^{-3}]	$\sim 10^{-7}$–10^{-6}	$\sim 10^{-9}$–10^{-8}	$\sim 10^{-4}$–10^{-3}	$\sim 10^{-5}$–10^{-4}
R [cm]	A few $\times 10^{17}$	A few $\times 10^{17}$	A few $\times 10^{18}$	A few $\times 10^{14}$
B' [G]	~ 0.1	~ 1	~ 0.01	~ 100
$\xi_{\rm B}$	~ 1	~ 1	~ 1	~ 100
$\tau_{p\gamma 0}$ by Eq. (1)	$\sim 10^{-5}$	$\gtrsim 10^{-3}$	$\sim 10^{-4}$	~ 1
$\xi_{\rm UHECR}$: Eq. (6)	~ 10–100	~ 10–100	~ 1–10	~ 1000–10000
$\xi_{\rm B}$ by acceleration: Eq. (10)	$\gtrsim 0.3\eta^2(\frac{Z}{10})^{-2}$	$\gtrsim 0.3\eta^2(\frac{Z}{1})^{-2}$	$\gtrsim 1\eta^2(\frac{Z}{10})^{-2}$	$\gtrsim 0.03\eta^2(\frac{Z}{10})^{-2}$
$\tau_{p\gamma 0}$ by ν flux: Eq. (9)	$\gtrsim 0.3$	$\gtrsim 0.01$	$\gtrsim 0.04$	$\gtrsim 0.3$
$\tau_{p\gamma 0}$ by escape: Eq. (11)	$\lesssim 1(\frac{A}{2Z})^4$	$\lesssim 1(\frac{A}{Z})^4$	$\lesssim 1(\frac{A}{2Z})^4$	$\lesssim 1(\frac{A}{2Z})^4$
$\tau_{p\gamma 0}$ by nuclei survival: Eq. (12)	$\lesssim 0.4(\frac{A}{56})^{-0.21}$	$\lesssim 0.4(\frac{A}{56})^{-0.21}$	$\lesssim 0.4(\frac{A}{56})^{-0.21}$	$\lesssim 0.4(\frac{A}{56})^{-0.21}$

Some may be a dominant unified source, but they are not strongly supported

Transient Source Case -Yoshida & Murase 2024

	Jetted TDE	TDE wind	LL GRB	Engine-driven SN
$\Gamma\beta$ of the outflow	~ 10	~ 0.3	~ 5	~ 0.3
Target photon energy	X-ray	Opt/UV	X-ray	Opt/UV
L_γ[erg/s]	$\sim 10^{47}$	$\sim 10^{44}$	$\sim 10^{47}$	$\sim 10^{44}$
ρ_0[Mpc^{-3} yr^{-1}]	$\sim 10^{-11}$–10^{-10}	$\sim 10^{-7}$–10^{-6}	$\sim 10^{-7}$–10^{-6}	$\sim 10^{-6}$–10^{-5}
ΔT[s]	$\sim 10^{6}$–10^{7}	$\sim 10^{6}$–10^{7}	$\sim 10^{3}$–10^{4}	$\sim 10^{6}$–10^{7}
R [cm]	A few $\times 10^{15}$	$\sim 10^{17}$	A few $\times 10^{15}$	$\sim 10^{17}$
B'[G]	~ 300	~ 1	~ 100	~ 1
$\xi_{\rm B}$	~ 1	~ 1	~ 1	~ 1
$\tau_{p\gamma 0}$ by Eq. (1)	~ 0.1	~ 0.03	~ 1	~ 0.03
$\xi_{\rm UHECR}$: Eq. (6)	~ 100–1000	~ 1–10	~ 10–100	~ 0.1–1
$\tau_{p\gamma 0}$ by ν flux: Eq. (9)	$\gtrsim 0.1$	$\gtrsim 0.1$	$\gtrsim 0.03$	$\gtrsim 0.03$
$\xi_{\rm B}$ by acceleration: Eq. (10)	$\gtrsim 10^{-2}\eta^2(\frac{Z}{10})^{-2}$	$\gtrsim 1(\frac{\eta}{10})^2(\frac{Z}{10})^{-2}$	$\gtrsim 0.01\eta^2(\frac{Z}{10})^{-2}$	$\gtrsim 1(\frac{\eta}{10})^2(\frac{Z}{10})^{-2}$
$\tau_{p\gamma 0}$ by escape: Eq. (11)	$\lesssim 1(\frac{A}{2Z})^4$	$\lesssim 3(\frac{A}{2Z})^4$	$\lesssim 1(\frac{A}{2Z})^4$	$\lesssim 3(\frac{A}{2Z})^4$
$\tau_{p\gamma 0}$ by nuclei survival: Eq. (12)	$\lesssim 0.4(\frac{A}{56})^{-0.21}$	$\lesssim 0.4(\frac{A}{56})^{-0.21}$	$\lesssim 0.4(\frac{A}{56})^{-0.21}$	$\lesssim 0.4(\frac{A}{56})^{-0.21}$

LL GRBs are most possible candidate though ρ_0 and B’ are highly uncertain
Jetted TDE is also possible as a candidate class

Are they UHECR and PeV ν sources?

The scorebook of individual transient astronomical object classes

	Energetics	Fiducial ν flux	Acceleration	Escape	Survival $\tau_{p\gamma} \lesssim 0.4(A/56)^{-0.21}$
jetted TDE Biehl+ 2018	Challenging $\xi_{CR} = 100 - 1000$	OK $\tau_{p\gamma} \gtrsim 0.1$	OK with nuclei $\xi_B \gtrsim 10^{-2}(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 1\ (A/2Z)^4$	Maybe
TDE wind Murase+ 2020	OK $\xi_{CR} = 1 - 10$	Challenging $\tau_{p\gamma} \gtrsim 0.1$	Maybe $\xi_B \gtrsim 1(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 3\ (A/2Z)^4$	OK
Low L GRB Murase+ 2006	Maybe $\xi_{CR} = 10 - 100$	OK $\tau_{p\gamma} \gtrsim 0.03$	OK with nuclei $\xi_B \gtrsim 10^{-2}(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 1\ (A/2Z)^4$	OK
Engine-driven SN Zang+ 2019	OK $\xi_{CR} = 0.1 - 1$	Challenging $\tau_{p\gamma} \gtrsim 0.03$	Maybe $\xi_B \gtrsim 1(z/10)^{-2}$	OK $\tau_{p\gamma} \lesssim 3\ (A/2Z)^4$	OK

Yoshida & Murase PRD (2024)

Side Note: This is a one-zone model

Neutrino Emissions from X-ray Sources -Yoshida & Murase 2024

LL GRBs and jetted TDEs are both X-ray emitters.. This is **NOT** coincident

Neutrino production by $p\gamma$ process

$$p + \gamma \rightarrow \Delta^+ \quad (\Delta \text{ resonance})$$

$$\Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

condition of the Δ resonance

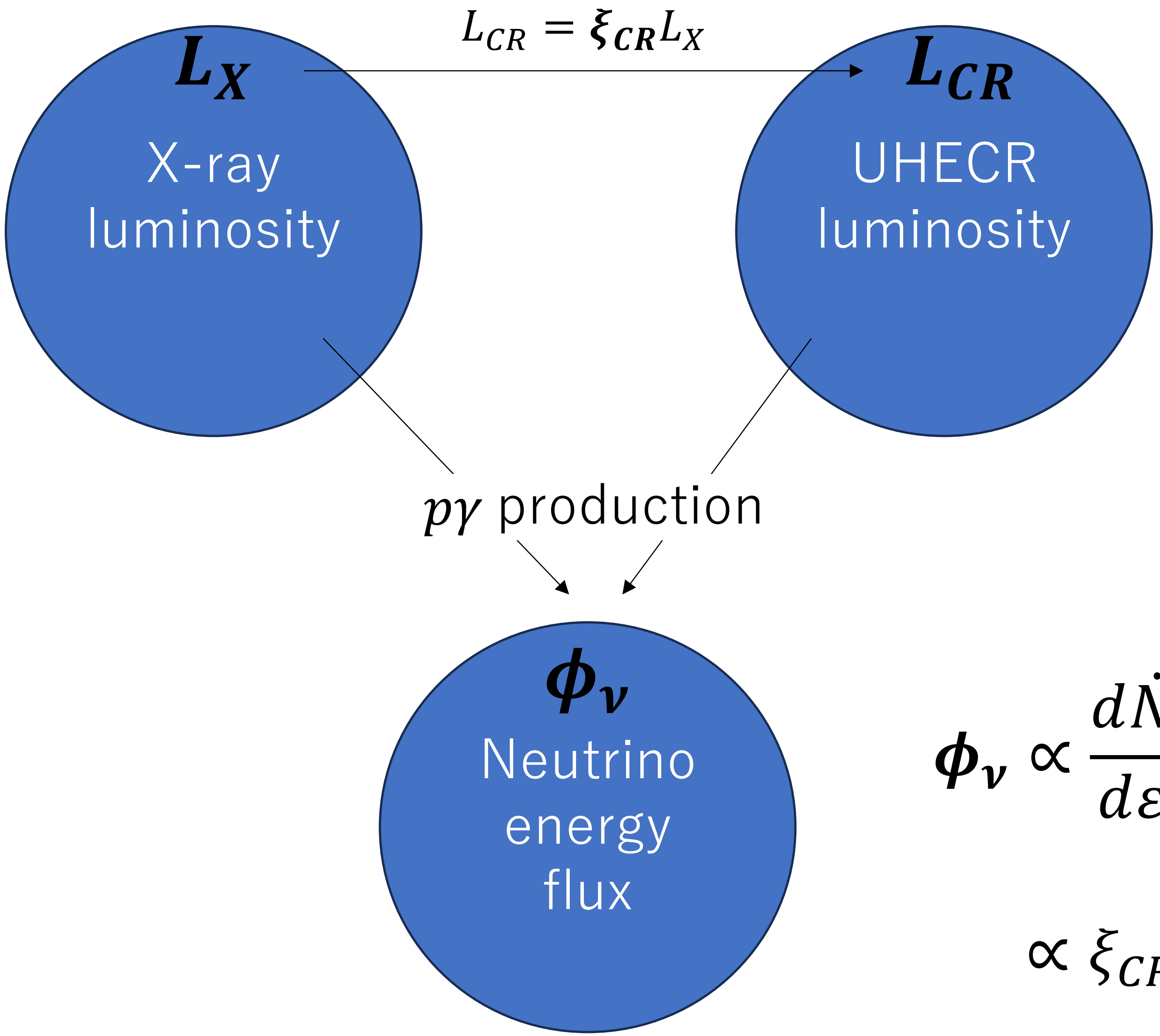
$$\varepsilon_\gamma \gtrsim 15.5 \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\varepsilon_p}{1\ \mathrm{PeV}}\right)^{-1} \mathrm{keV},$$

Γ: bulk Lorentz factor in plasma

~ X-ray region

X-ray counter part search is meaningful !!

Relation of Neutrino and X-ray -Yoshida & Murase 2024



$$\frac{d\dot{N}_{CR}}{d\varepsilon_{CR}} \propto \xi_{CR} L_X$$

$$\tau_{p\gamma} \propto \sqrt{\frac{L_X}{\boldsymbol{\xi_B}} \frac{\mathrm{B}'}{\Gamma^2}}$$

$$\boldsymbol{\phi_\nu} \propto \frac{d\dot{N}_{CR}}{d\varepsilon_{CR}} \tau_{p\gamma}$$

$$\propto \xi_{CR} \times L_X^{\frac{3}{2}} \times B' \times \frac{1}{\xi_B} \times f(\Gamma)$$

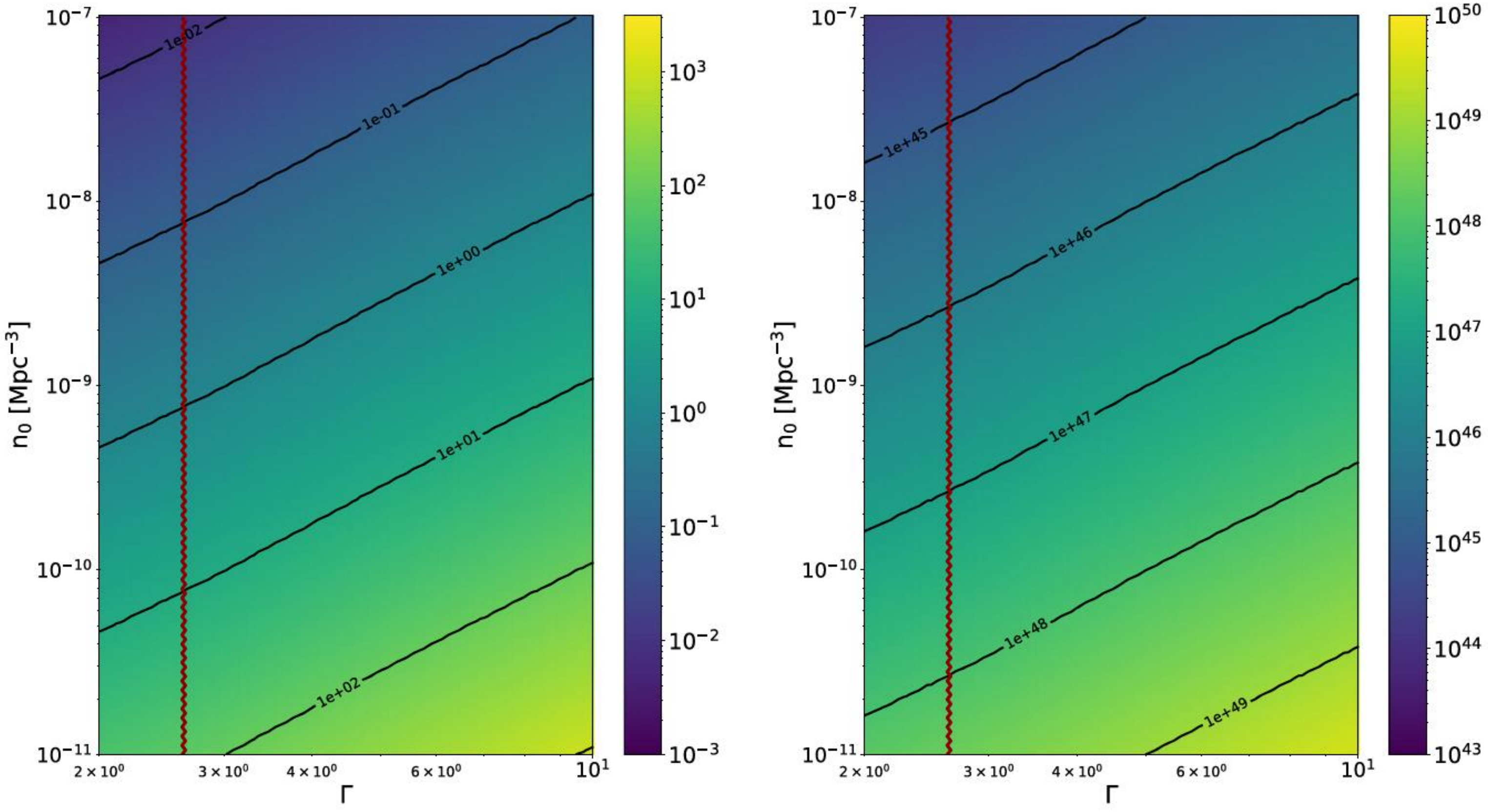
Constrains by Neutrino Diffuse Flux -Yoshida & Murase 2024

Neutrino diffuse flux

$$\Phi_\nu(E_\nu) = \frac{c}{4\pi}\int_{z_{\rm min}}^{z_{\rm max}} dz(1+z)\left|\frac{dt}{dz}\right| \times \frac{d\dot{N}_{\nu_e+\nu_\mu+\nu_\tau}}{d\varepsilon_\nu}\Big|_{\varepsilon_\nu=E_\nu(1+z)} n_0^{\rm eff}\Psi(z)$$

$$\propto \xi_{CR} \times L_X^{\frac{3}{2}} \times (B' \times \frac{1}{\xi_B}) \times f(\Gamma) \times n_0^{\rm eff}$$

MW observation/
theory could tell



By assuming L_X, we can plot the required ξ_{CR} and L_{UHECR} for a given (n_0, Γ) using neutrino diffuse flux

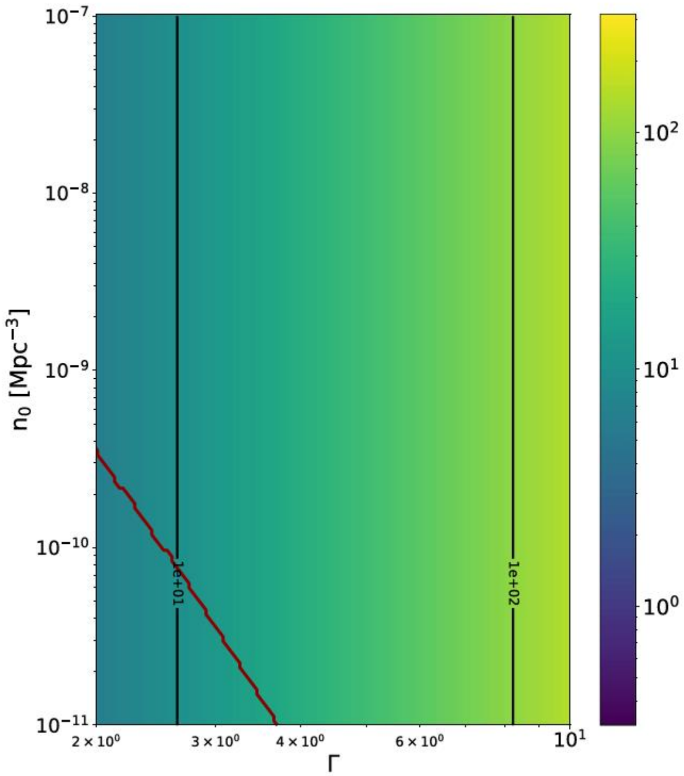
Constrains by X-ray Search -Yoshida & Murase 2024

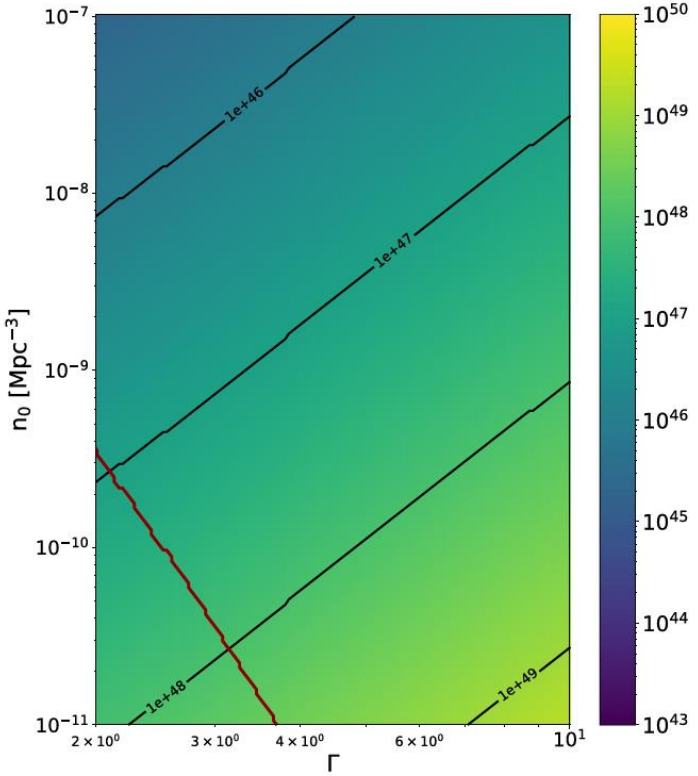
If nothing had been detected by X-ray detector, we can have UL for the X-ray luminosity of the candidates

$$\Phi_\nu \propto \xi_{CR} \times L_X^{\frac{3}{2}} \times f(\Gamma) \times n_0^{\text{eff}}$$

Lower limit   Upper limit

Now we can get a lower limit of CR loading factor!
(and CR luminosity= $\xi_{CR} \times L_X$)





Say MAXI's sensitivity $= 3 \times 10^{45}\mathrm{erg/s}$ for $5.2 \times 10^{-9}\ \mathrm{Mpc}^{-3}$(density for LL GRB-like source)

$$L_X^{\mathrm{REF}} \le L_X^{\mathrm{UL}} \left(\frac{n_0^{\mathrm{eff}}}{5.2 \times 10^{-9}\ \mathrm{Mpc}^{-3}} \right)^{-\frac{2}{3}}$$

$$L_X^{\mathrm{UL}} = 3 \times 10^{45}\mathrm{erg/s}$$

X-ray Detector's Sensitivity is Important

Constrains from no X-ray counterpart detection by MAXI

$$L_X^{\mathrm{REF}} \leq L_X^{\mathrm{UL}} \left(\frac{n_0^{\mathrm{eff}}}{5.2 \times 10^{-9}\ \mathrm{Mpc}^{-3}} \right)^{-\frac{2}{3}}$$

$$\xi_{\mathrm{CR}} \gtrsim 19(14) \left(\frac{L_X^{\mathrm{UL}}}{3 \times 10^{45}\ \mathrm{erg/s}} \right)^{-\frac{3}{2}} \times \left(\frac{B'}{100\ \mathrm{G}} \right)^{-1} \left(\frac{\xi_{\mathrm{B}}}{0.1} \right)^{\frac{1}{2}} \left(\frac{\Gamma}{10^{0.5}} \right)^{2} \beta$$

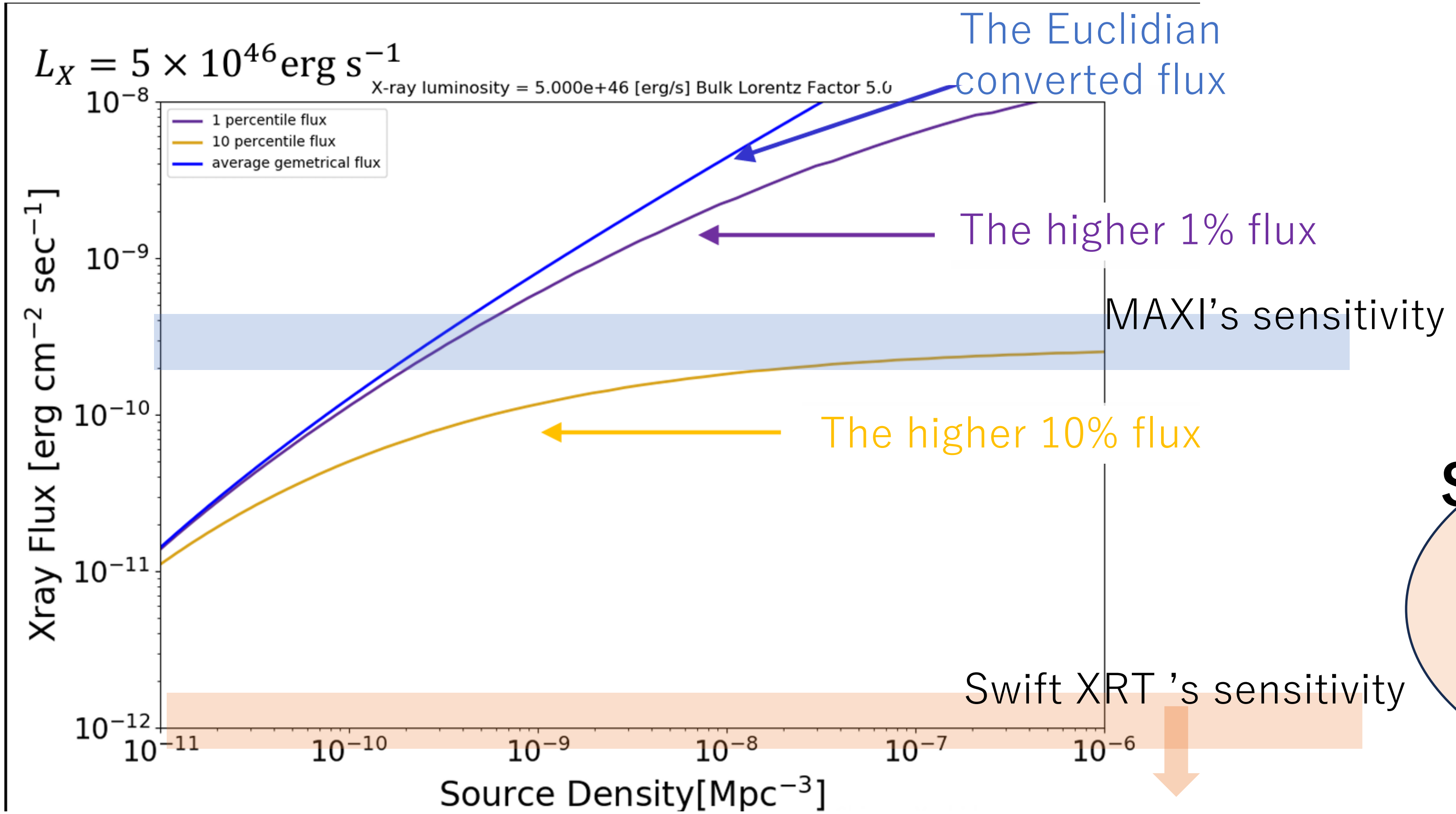
$$L_{\mathrm{UHECR}} = \xi_{\mathrm{CR}} L_X^{\mathrm{REF}} \left(\frac{\varepsilon_{\mathrm{UHECR}}^{\mathrm{FID}}}{\varepsilon_p^{\mathrm{FID}}} \right)^{-\alpha_{\mathrm{CR}}+2} \gtrsim 4.0(4.2) \times 10^{47} \left(\frac{L_X^{\mathrm{UL}}}{3 \times 10^{45}\ \mathrm{erg/s}} \right)^{-\frac{1}{2}} \times \left(\frac{n_0^{\mathrm{eff}}}{10^{-10}\ \mathrm{Mpc}^{-3}} \right)^{-\frac{2}{3}} \times \left(\frac{B'}{100\ \mathrm{G}} \right)^{-1} \left(\frac{\xi_{\mathrm{B}}}{0.1} \right)^{\frac{1}{2}} \left(\frac{\Gamma}{10^{0.5}} \right)^{2} \mathrm{erg/s}$$

Higher sensitivity
- More chances to find the counter-parts
- Stronger constrain for ξ_{CR} or L_{UHECR}

That's why
I am trying to develop a method to search for the X-ray counter-parts of the IceCube neutrinos with good sensitivity

Why Swift XRT?

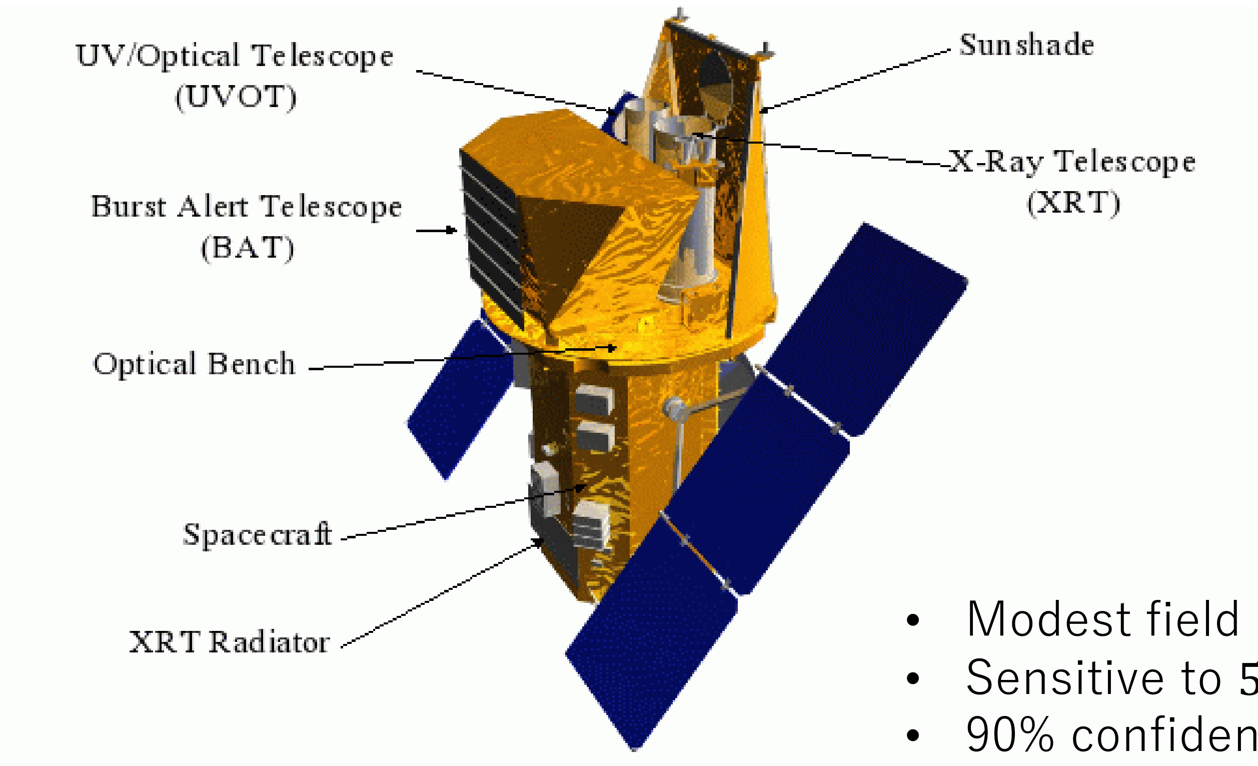
- X-ray monitors such as MAXI has a wider field of view but lower sensitivity
- Many of ν sources are far away so ‘cosmological distance effect’ makes their Flux smaller
  →It needs lots of follow up to provide good constrains

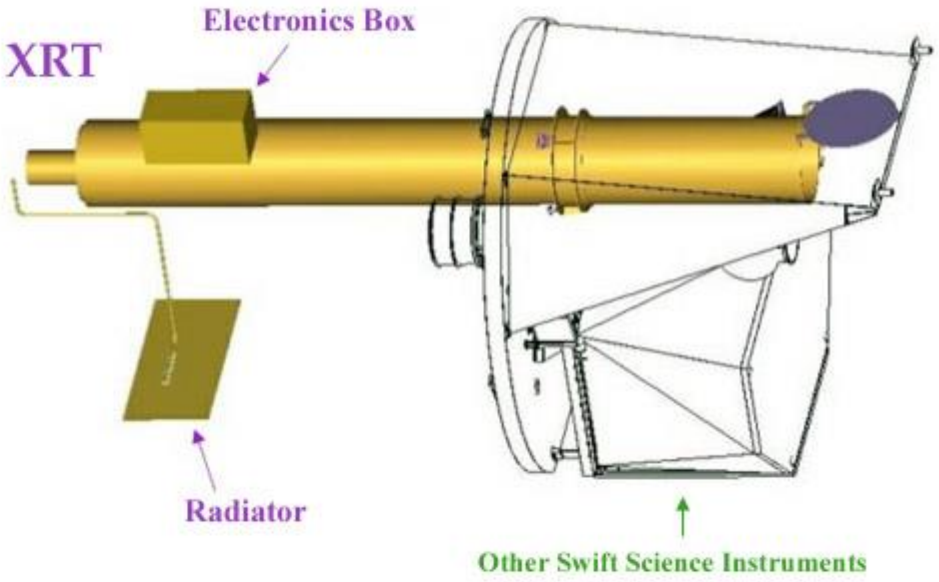


Swift/XRT

Only a few times follow up bring good sensitivity!

Swift





- Modest field of view (radious~0.2°) but rapid slewing
- Sensitive to $5 \times 10^{-13}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$ in $1\ \mathrm{ks}\ (0.3 - 10\ \mathrm{keV})$
- 90% confidence radius of 3.5 arcsec (1.4arcsec for brighter sources)
- Followed up on ~40 IceCube events so far

Swift Observing Strategy

Target of Opportunity (ToO)

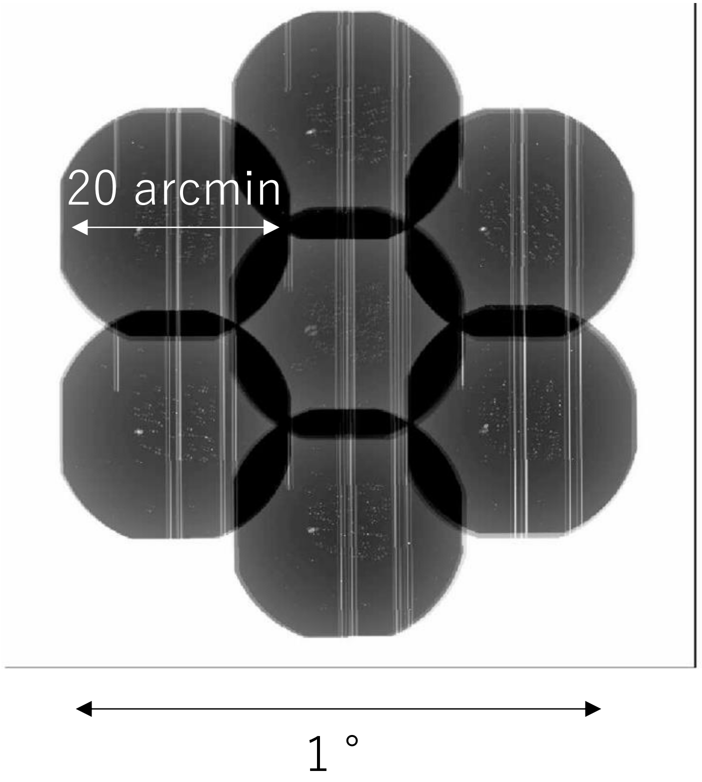
IceCube → Swift

t=0 t~1.8 h

50% error radius > 0.5°

Field of view of radius = 0.2°

Tiling map for a necessary region



Previous

- By manually commanding
- Each tile is consequently observed on a separate spacecraft orbit (1~2 ks for each)

→delay of each tile ~ 96min (Swift orbital period)

After software update

- Automatically divides IceCube region in each spacecraft orbit between 7 and observes that
- Repeat until requested exposure time has been gathered

→7 tiles are observed in one orbit but total time takes longer

My Research:

Evaluation of Swift-XRT's follow up of IceCube neutrino alerts

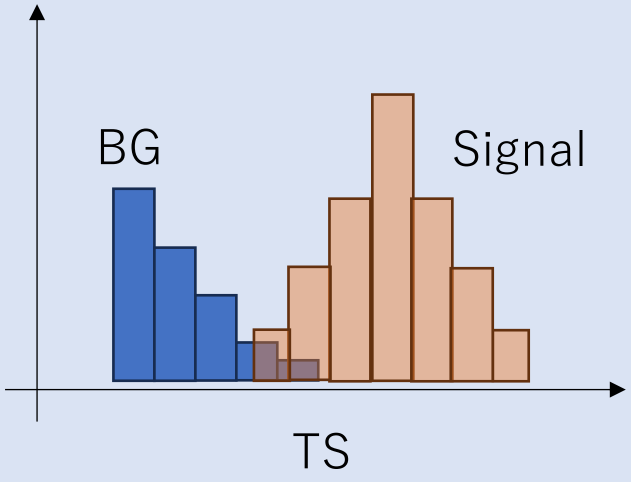
Research Flow

$$TS = 2\log\left(\frac{\mathcal{L}_{\mathrm{sig+bg}}}{\mathcal{L}_{\mathrm{bg}}}\right) \qquad L_{\mathrm{sig+bg}} = L^{\nu}_{\mathrm{sig}} L^{X}_{\mathrm{sig}} + L^{\nu}_{\mathrm{BG}} L^{X}_{\mathrm{BG}}$$

1. Construct Test Statistics
2. BG simulation and Signal simulation
3. Evaluate the sensitivity

- BG control sample: Swift-XRT's observation files
- Inject pseudo signals on the control samples

Compare the median TS of the assumed flux and BG



---

4. Open the Follow Up data

Swift-XRT data products for neutrino follow-up

The table below lists all neutrino triggers observed by Swift to date. Each field name links to the main XRT results page for that trigger.
About the analysis.

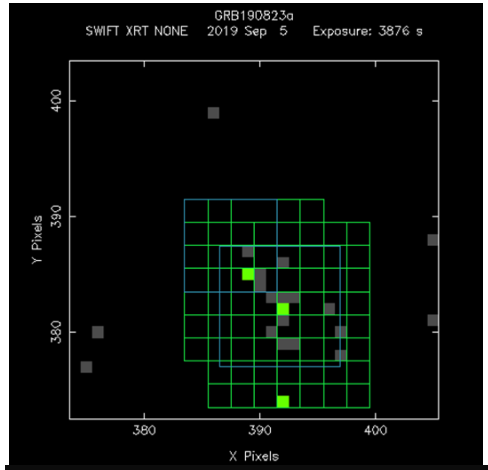
Name	Fields planned/ /processed	Uncatalogued sources (Total sources)	Counterpart candidates	Trigger time	Analysis Updated
ICECUBE J1744.0+3858	10 / 10	5 (2)	0	2025-07-06 13:14:40	2025-07-07 18:11:32
IceCube-250406A	6 / 6	1 (3)	0	2025-04-06 22:50:35	2025-04-08 18:24:39
ICECUBE J1056.4+0523	10 / 10	2 (2)	0	2024-11-27 14:11:14	2024-12-01 04:07:53
ICECUBE J0210.1-0152	7 / 7	3 (0)	0	2023-07-24 01:49:13	2023-07-28 02:07:03
ICECUBE J1756.1-0156	13 / 13	3 (0)	0	2023-07-07 16:58:50	2023-07-10 02:16:39
IceCube 210322A	4 / 4	3 (1)	1	2021-03-22 02:34:09	2023-03-22 11:44:46
IceCube 210210A	2 / 2	4 (3)	0	2021-02-10 11:53:55	2023-03-22 11:45:20
ANTARES 201222A	2 / 2	0 (0)	0	2020-12-22 07:41:08	2023-03-22 11:41:35
IceCube 201222A	3 / 3	3 (0)	0	2020-12-22 00:56:16	2023-03-22 11:45:21
IceCube 201130A	4 / 4	2 (1)	0	2020-11-30 20:21:46	2023-03-22 11:45:32
IceCube 201120A	1 / 1	1 (1)	0	2020-11-20 09:44:40	2023-03-22 11:45:36
IceCube 201114A	4 / 4	1 (1)	0	2020-11-14 15:05:31	2023-03-22 11:45:38
IceCube 201021A	5 / 4	4 (2)	0	2020-10-21 06:37:47	2023-03-22 11:46:07

We don't use HEASoft in analysis part

HEASoft

HEASoft:
- X-ray analysis software package
- Sophisticated for X-ray analysis
- Contains many tools that can help my analysis

Ximage
BG computation
Exsess search
Source finding with SNR




```
         1  - x/ypix     388.500000       388.500000
         1  - local bg (cnts/img pix)    4.95605450E-03  Imgpix in box    256.000000
         1  - PSFco     1.49023223      Back     1.26874995        Tot Cnts          18
         1  - S/N    3.94359374      Prob    3.44169138E-15
 snr threshold =    2.00000000
 bgnd fluctuation probability limit =    9.99999975E-05
```

Xrtmkarf
Response file creation

Xselect
Time, region, energy filtering

Xspec
Count rate computation for a given flux

Merit
- Already developed

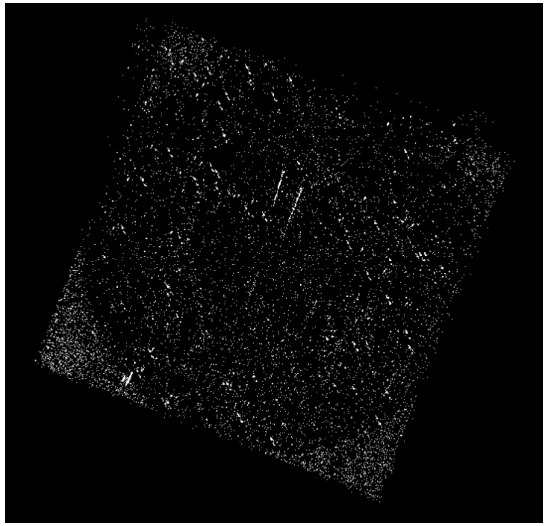
Demerit
- Black Box
- Non-essential files and works

It is ideal if specialized method is developed without reducing heasoft performance

Analysis w/o HEASoft... is it OK?

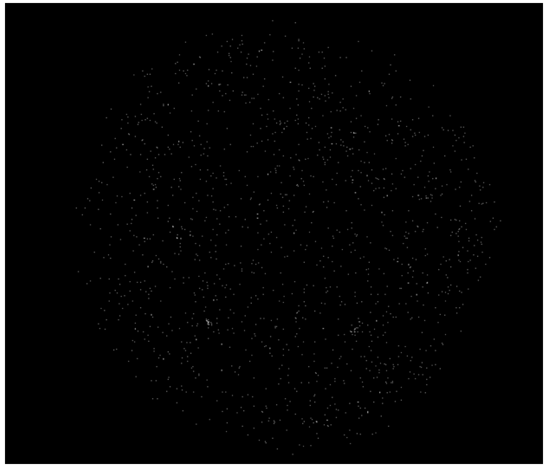
0. event file I use

We use the cleaned event file which is the output of ***XRTPIPELINE***



Unfiltered event
(uf.evt)

XRTPIPELINE



Cleaned event
(cl.evt)

Data calibration

- Hot pixel
- Bad pixel
- 座標変換
- バイアス補正
- Gradeの割り当て
- PIの計算

Data screening

- Calibration sourceの除去
- Bad pixel, earth limb affected pixelの除去
- Saturated pixelの除去
- GRADE 13以上の除去

Analysis w/o HEASoft… is it OK?

1. Extract event file

   We need to edit cl.evt for the time cut, energy cut, etc.

Xselect (input: event file)

Input cl.evt → filter {region, time, energy, etc}

→ extract event file or spectrum file

My method

From astropy import fits

→We can edit the fits file easily

Analysis w/o HEASoft… is it OK?

2. Compute count rate for given fluxes

2.1 mirror response (arf)

xrtmkarf (input: pha file)
Prepare appropriate arf file with vignetting

Output: ARFfile (E, offaxis)

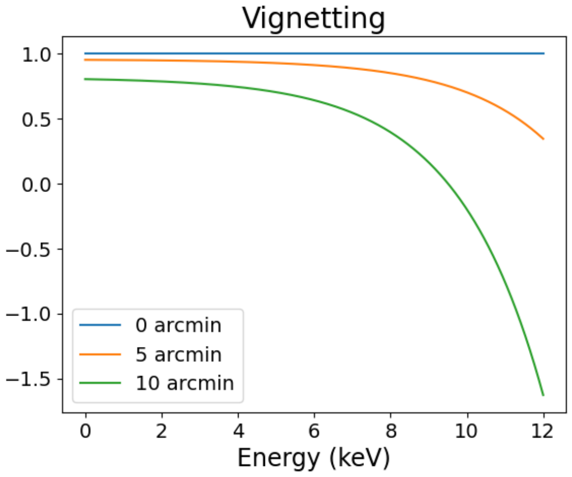
→ Necessary to use this tool many times since we randomly assume the pseudo source positions

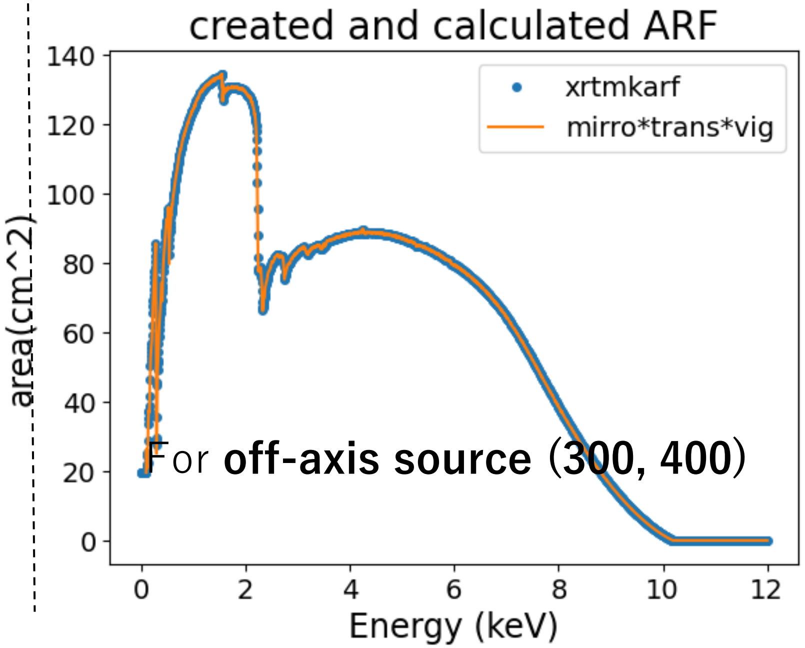
My method

In the calibration database

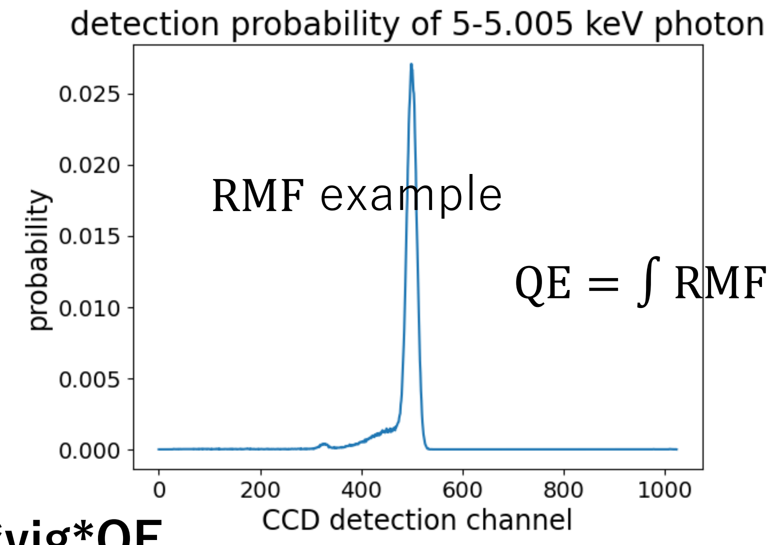
I somehow found
ARF= mirror_file*filter_file*vignetting

$$\mathrm{vig}(E,\phi) = 1-(p_0 p_1^E + p_2)\,\phi^2$$





Analysis w/o HEASoft... is it OK?



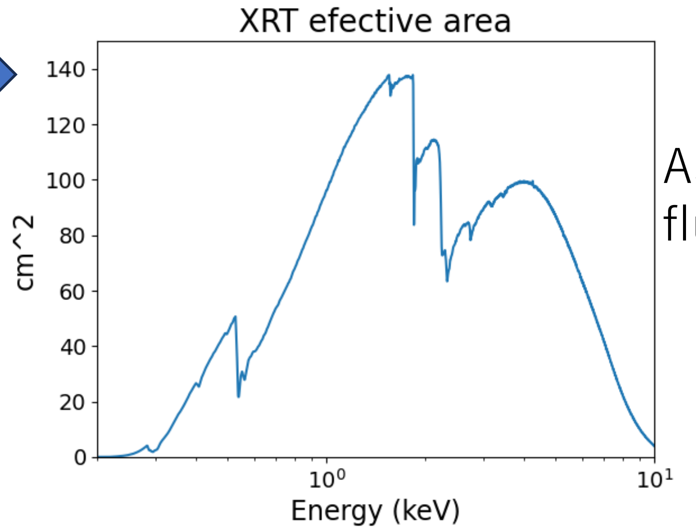
2. Compute count rate for given fluxes

2.1 calculate count rate

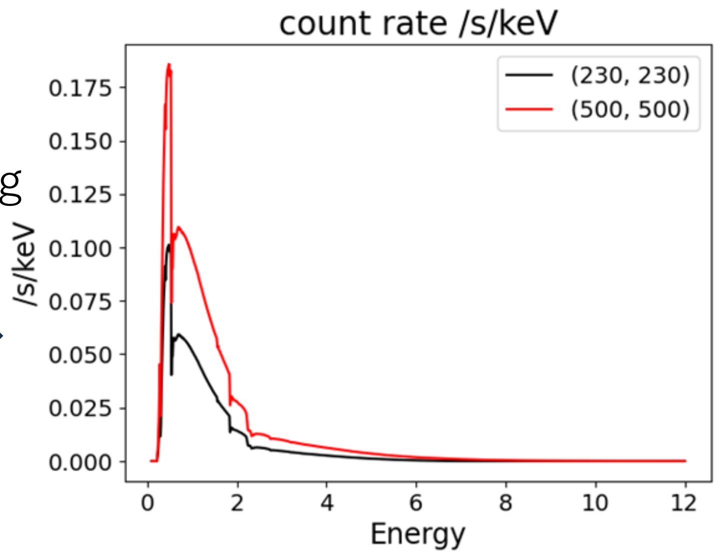
xspec
(input: pha file/ arf file/ rmf file)
Select flux model→Calculate count-rate

My method
I somehow found

Effective Area = mirror*filter*vig*QE



Assuming flux



check

The XRT effective area is 135 cm^2 at 1.5 keV and 20 cm^2 at 8.1 keV.

- w/ arf by xrtmkarf →0.177090
- w/ arf by mir*fil*QE →0.17691

Analysis w/o HEASoft… is it OK?

3. Scanning by XRTPIPELINE
For newly created events, some of them can be removed by XRTPIPELINE

XRTPIPELINE

- 'xrthkproc' on — Not for PC mode
- 'xrtfilter' on X — We already have standard filter file
- 'coordinator' (— Raw coordinate to det & sky coordinate
- 'xrtpcbias' on — Adjusts PHA by correcting bias
- 'xrtflagpix' on — Flag bad pixels using caldb or on-board badpix table
- 'xrtpcgrade' o — Assign GRADE by PHA
- 'xrthotpix' on — Find hot and flickering pixels, but the information was already got
- 'xrttimetag' o — Not for PC mode
- 'fselect' on XF — Not for PC mode
- 'xrtpdcorr' on — Not for PC mode
- 'xrtwtcorr' on — Not for PC mode
- 'xrtevtrec' on — Not for PC mode
- 'xrtcalcpi' on) — Cal PI using PHA & gain file
- 'xrtscreen' on — Events screening using filter file
- 'xrtimage' on — We don't need image
- 'swiftxform' o — Not for PC mode
- 'xrtproducts' (— We don't need level 3 and more products

- What XRTPIPELINE does is only BAD PIXEL scanning
- We have bad pixel information in cl.evt

My method

BAD PIX scanning by a
raw to sky coordinate conversion

Analysis w/o HEASoft… is it OK?

3.1 BAD PIXEL scanning

XRTPIPELINE

Coordinator (input: teldef, event file)

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} \text{raw } x \\ \text{raw } y \end{pmatrix} + \text{offset} = \begin{pmatrix} \text{sky } x \\ \text{sky } y \end{pmatrix}$$

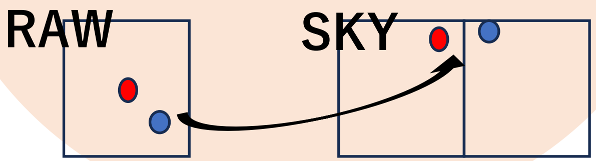
Time dependence term
- Detector attitude parameters
- Earth's velocity

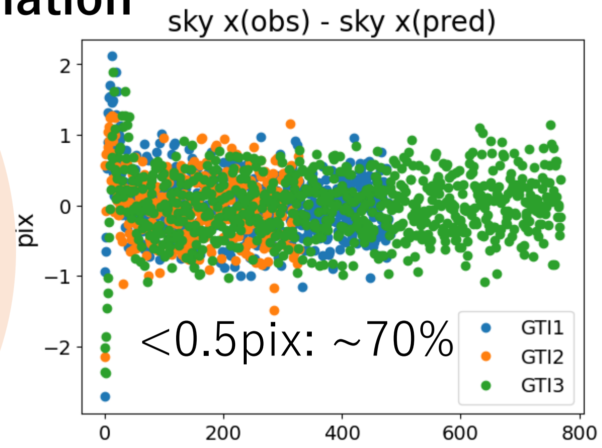
My method

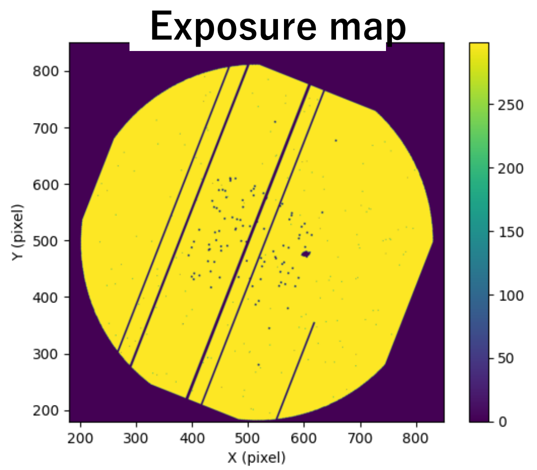
Determine by fit with
time independent approximation

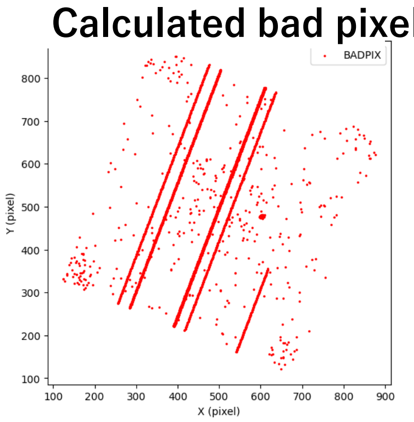
$$\begin{pmatrix} \text{sky } x \\ \text{sky } y \end{pmatrix} = \begin{pmatrix} a & b \\ d & c \end{pmatrix}\begin{pmatrix} \text{raw } x \\ \text{raw } y \end{pmatrix} + \text{offset}$$

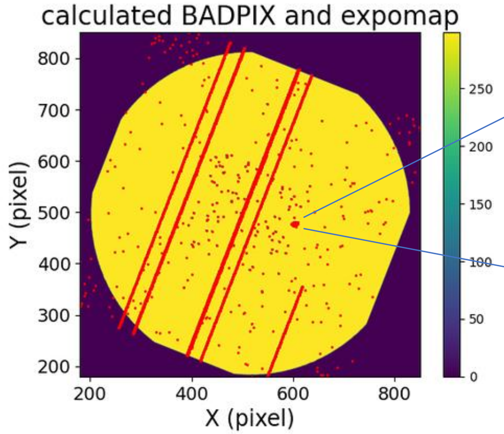
Bad pix in sky coordinate!
Mask 3 × 3 around the pixel

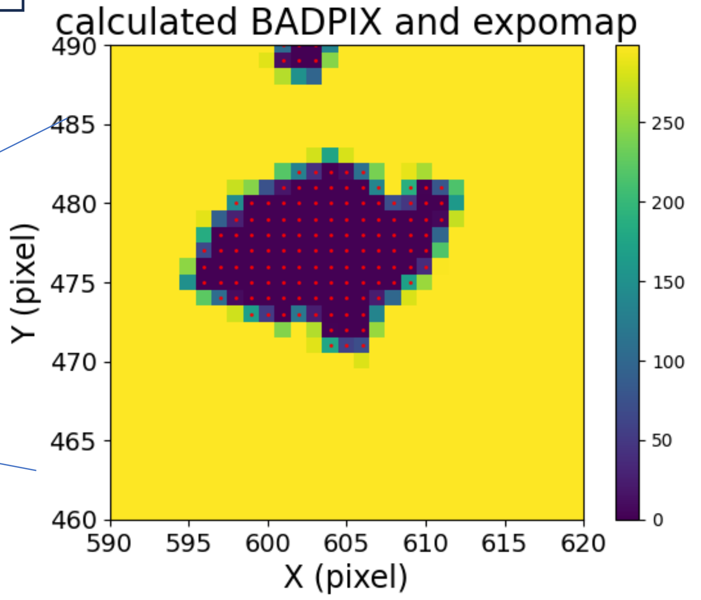












Analysis w/o HEASoft… is it OK?

4. Source detection

Ximage (input: event file)

Background

Calculated Avg.BG

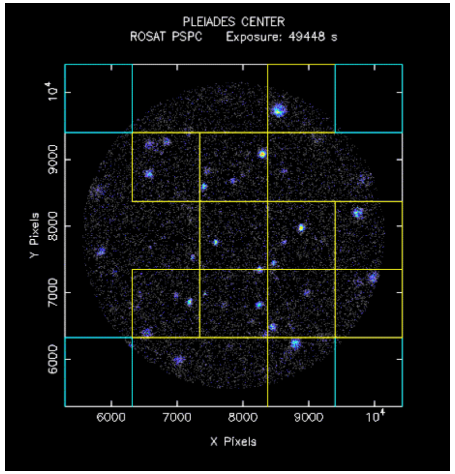
Excess

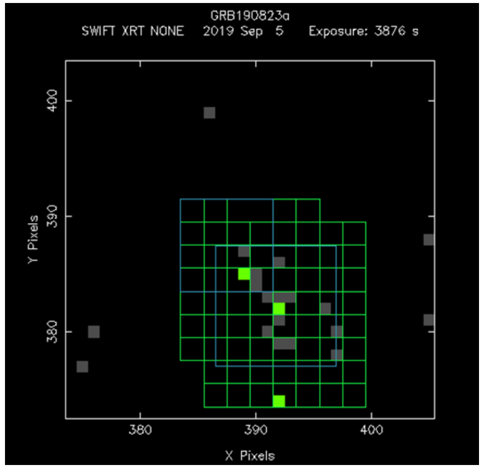
Find regions containing many photons

Search

Judge ‘sourceness’ with psf & vigntting

Black box
Low availability



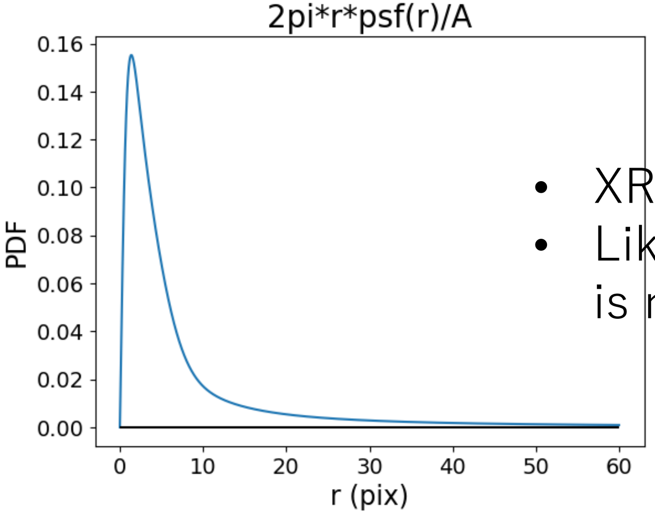


My method

V006(the latest)

$$\mathrm{PSF}(r) = 0.075\exp\left(-\frac{\mathrm{r}^2}{2(3.15)^2}\right) + 0.925\left[1+\left(\frac{\mathrm{r}}{1.581}\right)^2\right]^{-1.305}$$

- Gauss+King
- Independent from E & off-axis



- XRT has a simple PSF
- Likelihood calculation is not so difficult

$$\mathcal{L}_{\mathrm{sig}}(x_0, y_0, \alpha) = \prod_i \left\{\alpha\,\mathrm{PSF}\left(r_i(x_i, y_i | x_0, y_0)\right) + (1-\alpha)\frac{1}{\Omega_{tot}}\right\}$$

$$\mathcal{L}_{\mathrm{BG}} = \prod_i \frac{1}{\Omega_{tot}}$$

$$\mathrm{TS} = 2\ln\left(\frac{\mathcal{L}_{\mathrm{sig}}}{\mathcal{L}_{\mathrm{BG}}}\right)$$

Conclusion about 'Analysis w/o HEASoft'

HEASoft

Helpful tools

Unnecessary work and files, low availability

Xselect
Selection and extraction of the event file

Xrtmkarf & Xspec
Effective area and counts rate calculation

Xrtpipeline
Create the base-file (cl.evt)
Filter the injected events

Ximage
Search for the source

Original method

Simple, robust, efficient method tailored to my analysis

astropy

Caldb (mirror, filter, vignetting, rmf)

Base-file = cl.evt by ***Xrtpipeline***

Filter BADPIX by RAW to SKY
approx.conversion using the header of cl.evt

Newly designed TS

Inject Pseudo X-ray of Assumed Flux

Assume Power-law Flux

AE^{-2}(/keV/s/cm^2)

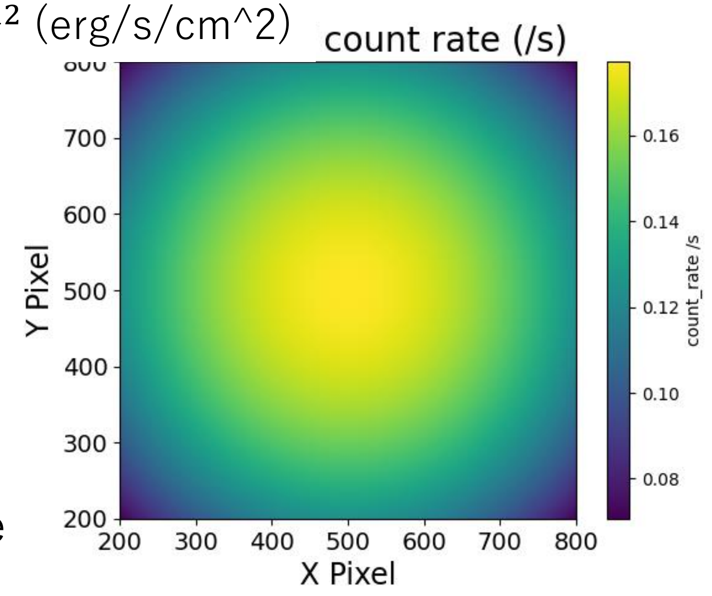
$A = [0.00001, 0.0005, \ldots, 0.001]$
$\rightarrow L_X = [7.7 \times 10^{-14}, \ldots, 7.7 \times 10^{-12}]$(erg/s/cm^2)

$$\mathrm{Cnt\ rate}(\phi, \mathrm{offaxis}) = \int_E \phi(A, \Gamma, E)\, eff(\mathrm{E}, \mathrm{offaxis})\, dE$$

$$\sim 5\ \mathrm{eV} \sum_{0.1\ \mathrm{keV}}^{12\ \mathrm{keV}} \phi(\mathrm{E})\, mir(\mathrm{E})\, fil(\mathrm{E})\, QE(\mathrm{E})\, vig(\mathrm{E}, \mathrm{offaxis})$$

$L_X = 7.7 \times 10^{-12}$ (erg/s/cm^2)

count rate table



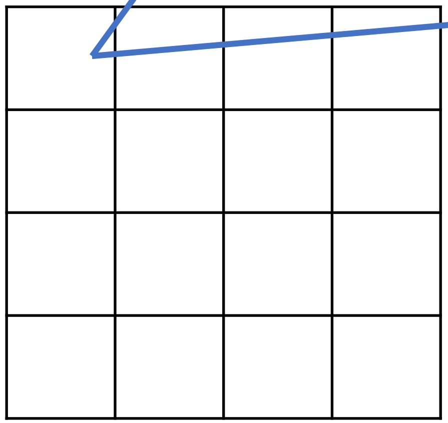
Check: (X, Y) =(700, 500)

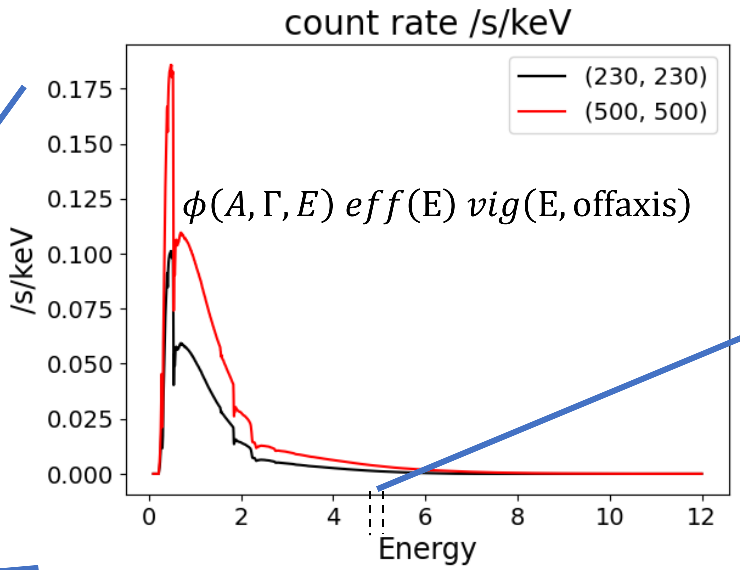
Original: 0.15368..
Xspec: 0.15364..

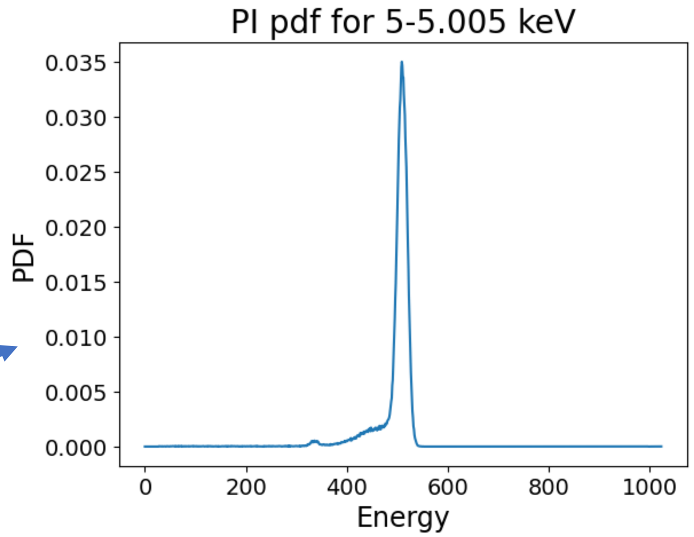
When should recreate the table when
- We change flux model
- RMF File in the caldb are updated ex)swxpc0to12s6_**20130101v014**.rmf

PI of The Inject Pseudo X-ray

Since vignetting depends on the off-axis, energy (PI) pdf should be determined by pixel



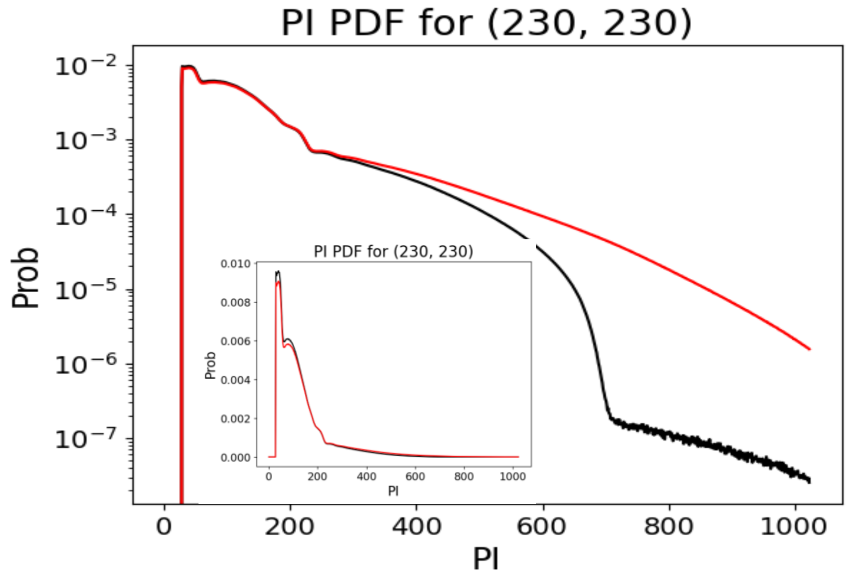




Convert all energy to PI

$$\int dE$$

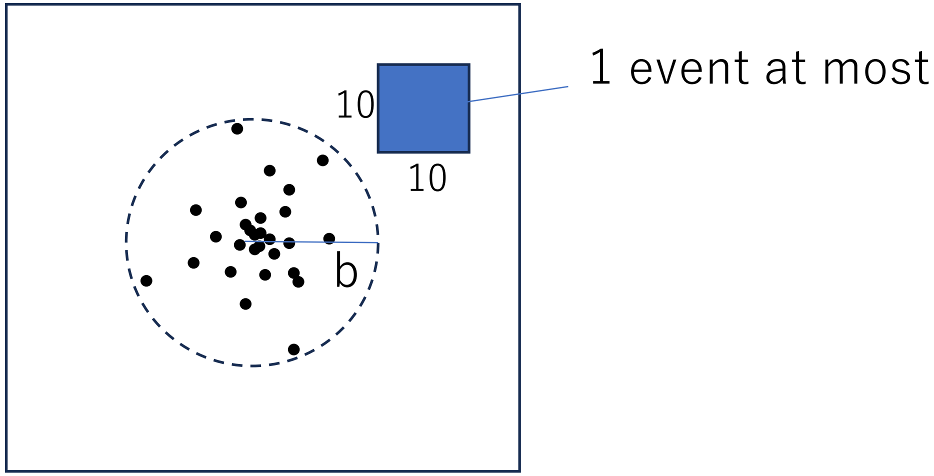
cnt: 0.09123 /s (230, 230)
cnt: 0.17714 /s (500, 500)



Known Source Removal Strategy 2

New definition

"No two or more events are expected to occur within the same 10-pixel by 10-pixel region."



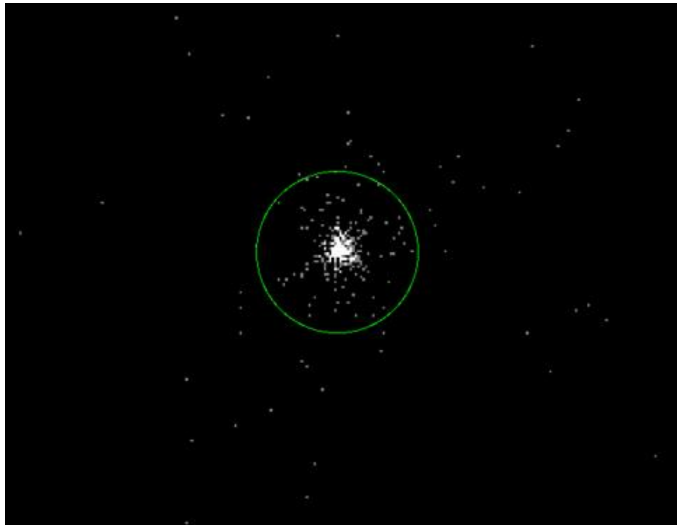
$$\text{total count} = \mathrm{N}\alpha \frac{\int_0^\infty dr\ \mathrm{psf}(r}{\int_{\text{w size}} dr\ \mathrm{psf}(r)}$$

$$\mu = \text{total count} \times \mathrm{PDF(r)} \times \Omega_{10\mathrm{pix}}$$

$$p_{2\mathrm{more}} = 1 - (\mathrm{poisson}(1|\mu) + \mathrm{poisson}(0|\mu))$$

$$N_{\mathrm{window}}^{>2} = \int_b^\infty dr\ (2\pi r\ /\Omega_{10\mathrm{pix}}\ p_{2\mathrm{more}}) < 1$$

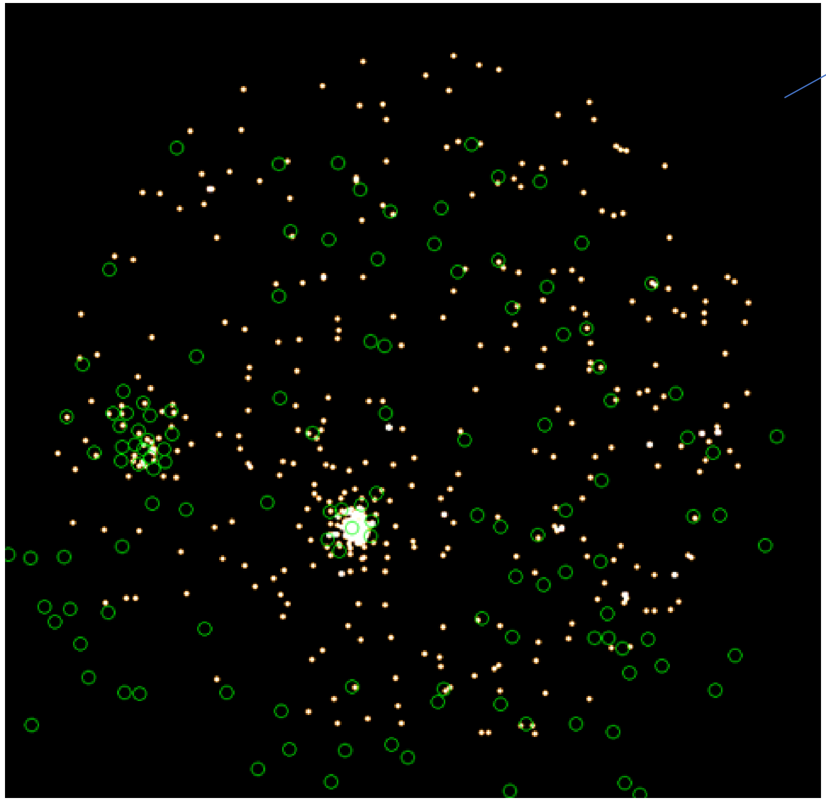
(The minimum removal region: 5pix)



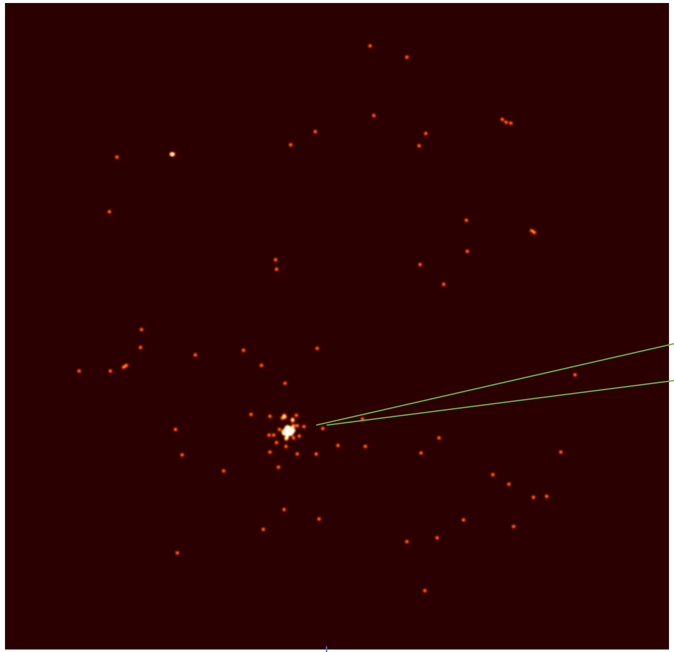
Result of GRB230618A case: 31.62 pixel

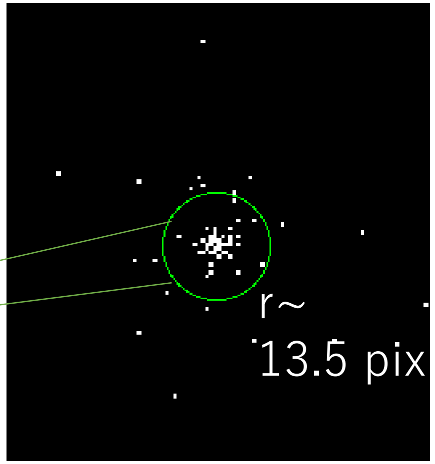
Example

NGC 5548

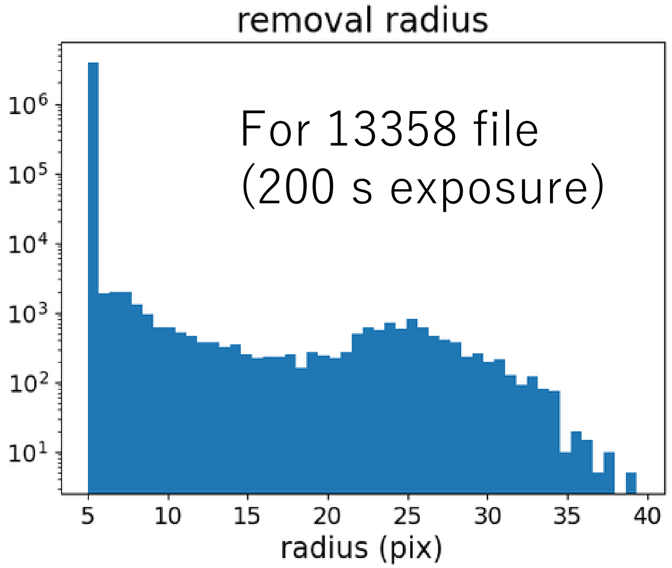


200 s chunk





Source removal



Dataset for Simulation

Steady Source Removal To find the transient counterpart, the steady source should be removed previously

LSXPS

All the source detected by XRT

- **Transient**
- Steady

match

2RXS

List from ROSAT
(90's X-ray all sky survey)

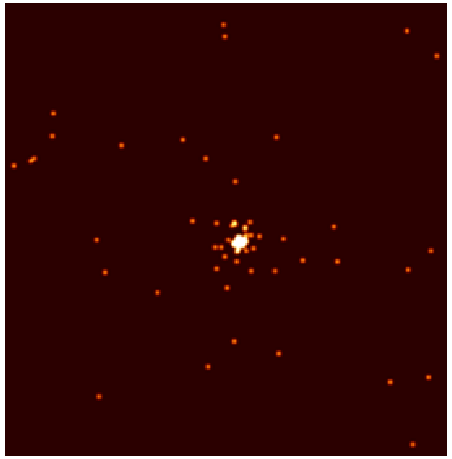
match

GAIA
Optical Source
Potentially X-ray flare

Original catalog

Steady X-ray Source

Stars bright in X-ray



Before removal