

Neutrino and X-ray Round Table Meeting

2025/09/22

Yu Miyazato

Chiba University

24wm2106@student.gs.chiba-u.jp

Introduction:

Why X-ray Search for Neutrinos Is Important

Mainly from

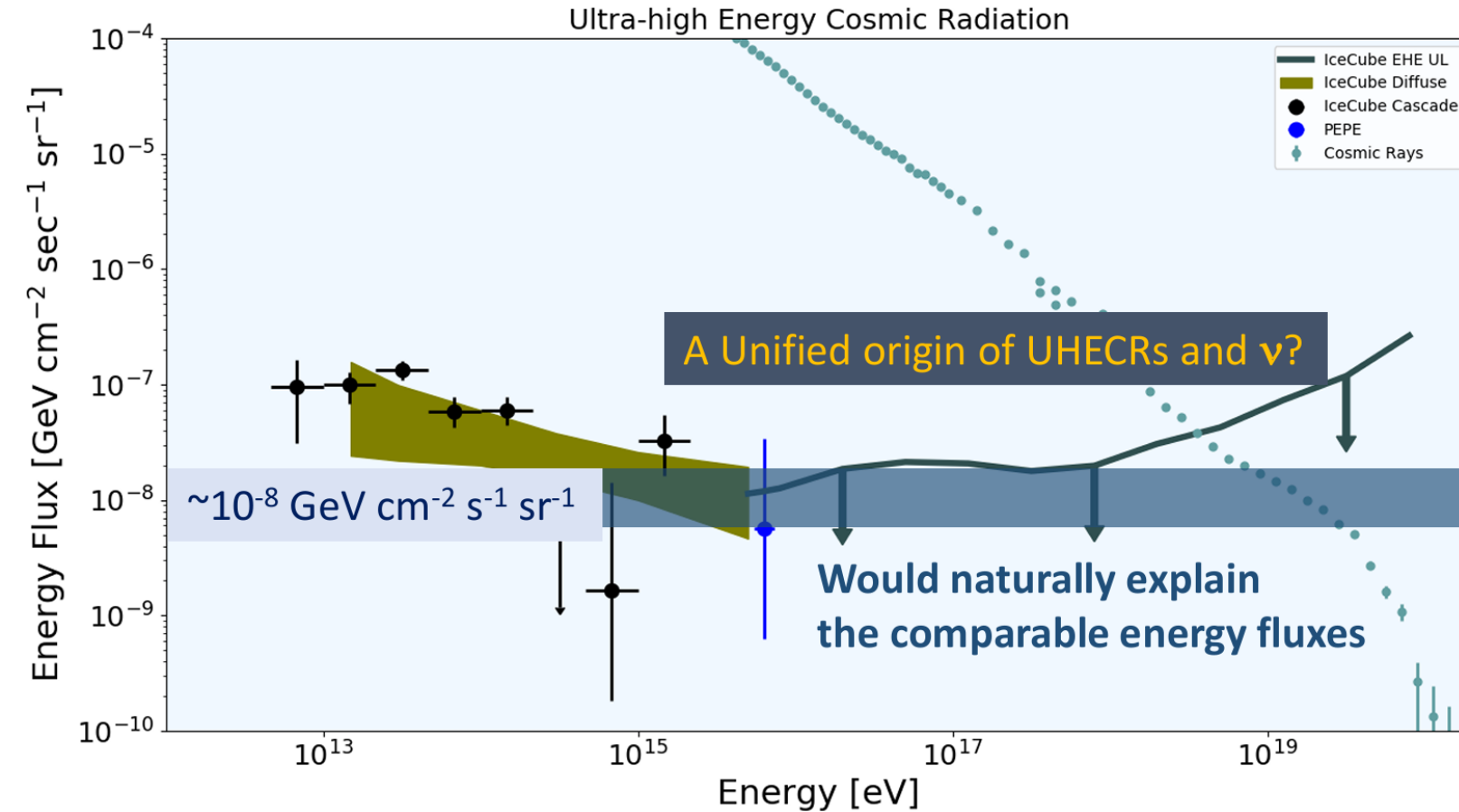
Yoshida & Murase (PRD 2024)

[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 $> \sim 100 \text{ TeV}$ and CRs $> \sim 10^{19} \text{ eV}$ have comparable energy flux**



A unified origin of ν and UHECRs?

Build **generic** unification models by $p\gamma$ process

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

Generically given

- $p\gamma$ optical depth

$$\tau_{p\gamma}(\varepsilon_p) \approx \tau_{p\gamma 0} \left(\frac{\varepsilon_p}{\varepsilon_{\text{UHECR}}^{\text{FID}}} \right)^{\alpha_\gamma - 1}$$

$$\approx \frac{B'}{\Gamma^2} \sqrt{\frac{L'_\gamma}{\xi_B}} \beta^{-1} C(\alpha_\gamma) \left(\frac{\varepsilon_p}{\varepsilon_{\text{UHECR}}^{\text{FID}}} \right)^{\alpha_\gamma - 1}.$$

- magnetic field loading factor

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



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

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

- Neutrino flux requirements

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

- Acceleration of UHECRs

$$\xi_B \geq \frac{1}{2} c \eta^2 \beta^2 L_\gamma'^{-1} \left(\frac{\varepsilon_i^{\text{max}}}{Ze} \right)^2$$

$$\gtrsim 1.7 \eta^2 \beta^2 \left(\frac{L_\gamma}{10^{46} \text{ erg/s}} \right)^{-1} \left(\frac{\Gamma}{10^{0.5}} \right)^2 \left(\frac{\varepsilon_i^{\text{max}}}{Z 10^{11} \text{ GeV}} \right)^2$$

- Escape of UHECRs

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

- Nuclei survival

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

$$\lesssim 0.4 \left(\frac{A}{56} \right)^{-0.21},$$

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_γ^{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^{eff} [Mpc $^{-3}$]	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-6}$	$\sim 10^{-7}$
n_0^{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
ξ_B	~ 1	~ 1	~ 1	~ 100
$\tau_{p\gamma 0}$ by Eq. (1)	$\sim 10^{-5}$	$\gtrsim 10^{-3}$	$\sim 10^{-4}$	~ 1
ξ_{UHECR} : Eq. (6)	$\sim 10-100$	$\sim 10-100$	$\sim 1-10$	$\sim 1000-10000$
ξ_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
ξ_B	~ 1	~ 1	~ 1	~ 1
$\tau_{p\gamma 0}$ by Eq. (1)	~ 0.1	~ 0.03	~ 1	~ 0.03
ξ_{UHECR} : Eq. (6)	~ 100 – 1000	~ 1 – 10	~ 10 – 100	~ 0.1 – 1
$\tau_{p\gamma 0}$ by ν flux: Eq. (9)	$\gtrsim 0.1$	$\gtrsim 0.1$	$\gtrsim 0.03$	$\gtrsim 0.03$
ξ_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

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

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

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

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

condition of the Δ resonance

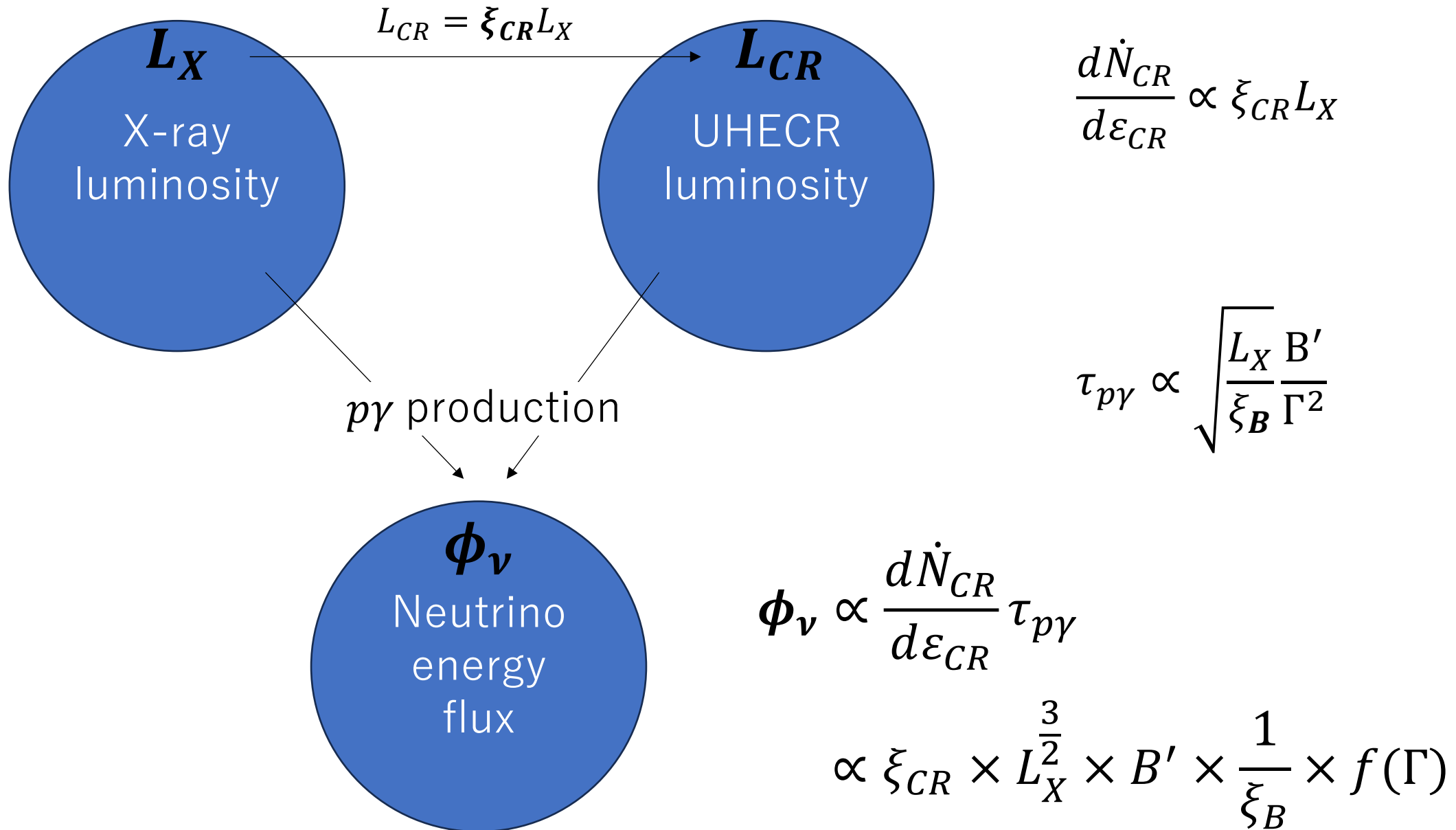
$$\varepsilon_\gamma \gtrsim 15.5 \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\varepsilon_p}{1 \text{ PeV}}\right)^{-1} \text{ keV},$$

Γ : bulk Lorentz factor in plasma

$\sim$ X-ray region

X-ray counter part search is meaningful !!

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



Constraints by Neutrino Diffuse Flux -Yoshida & Murase 2024

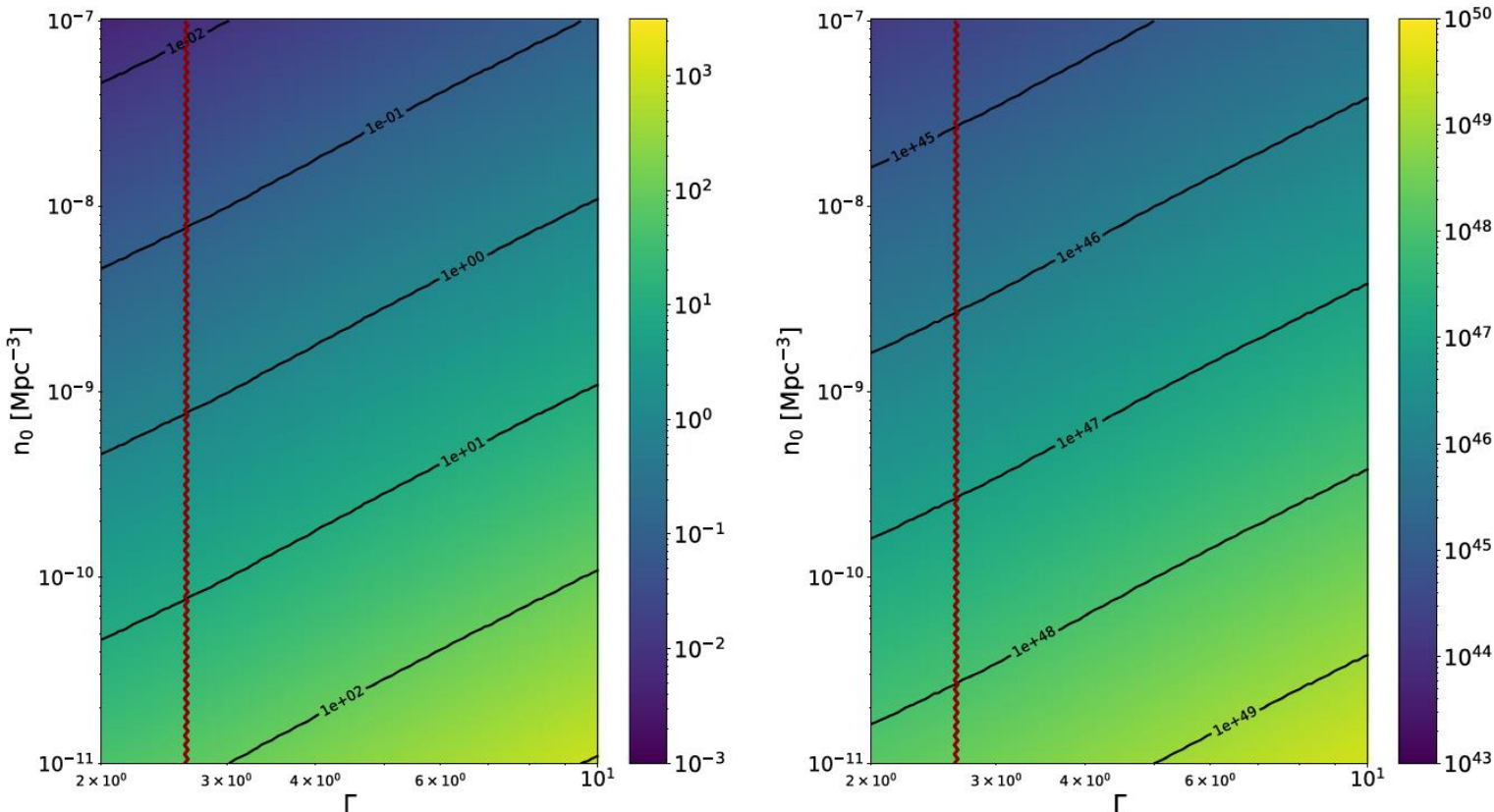
Neutrino diffuse flux

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

➡

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

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

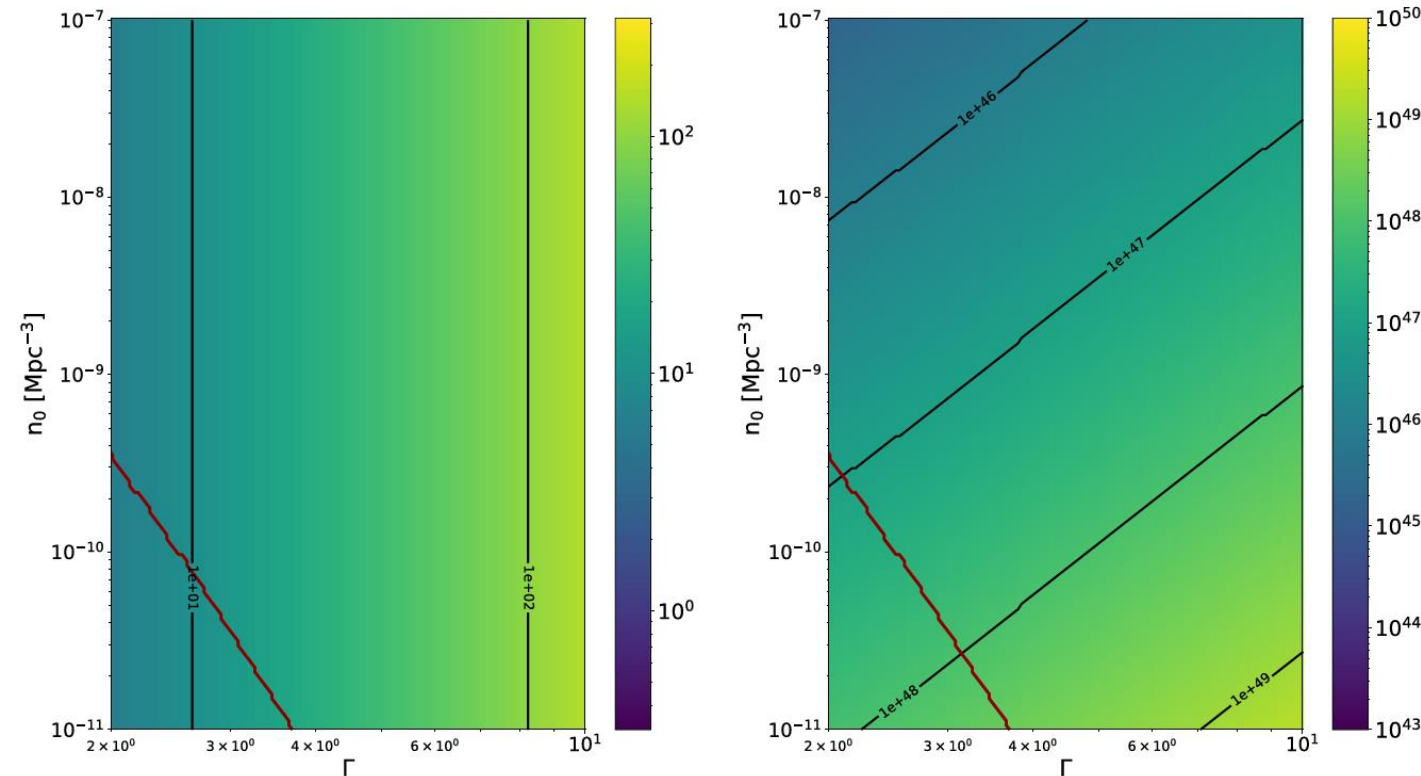
Constraints by X-ray Search -Yoshida & Murase 2024

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 = 3×10^{45} erg/s for 5.2×10^{-9} Mpc⁻³ (density for LL GRB-like source)

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

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

X-ray Detector's Sensitivity is Important

Constrains from no X-ray counterpart detection by MAXI

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

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

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

Higher sensitivity

More chances to find the counter-parts

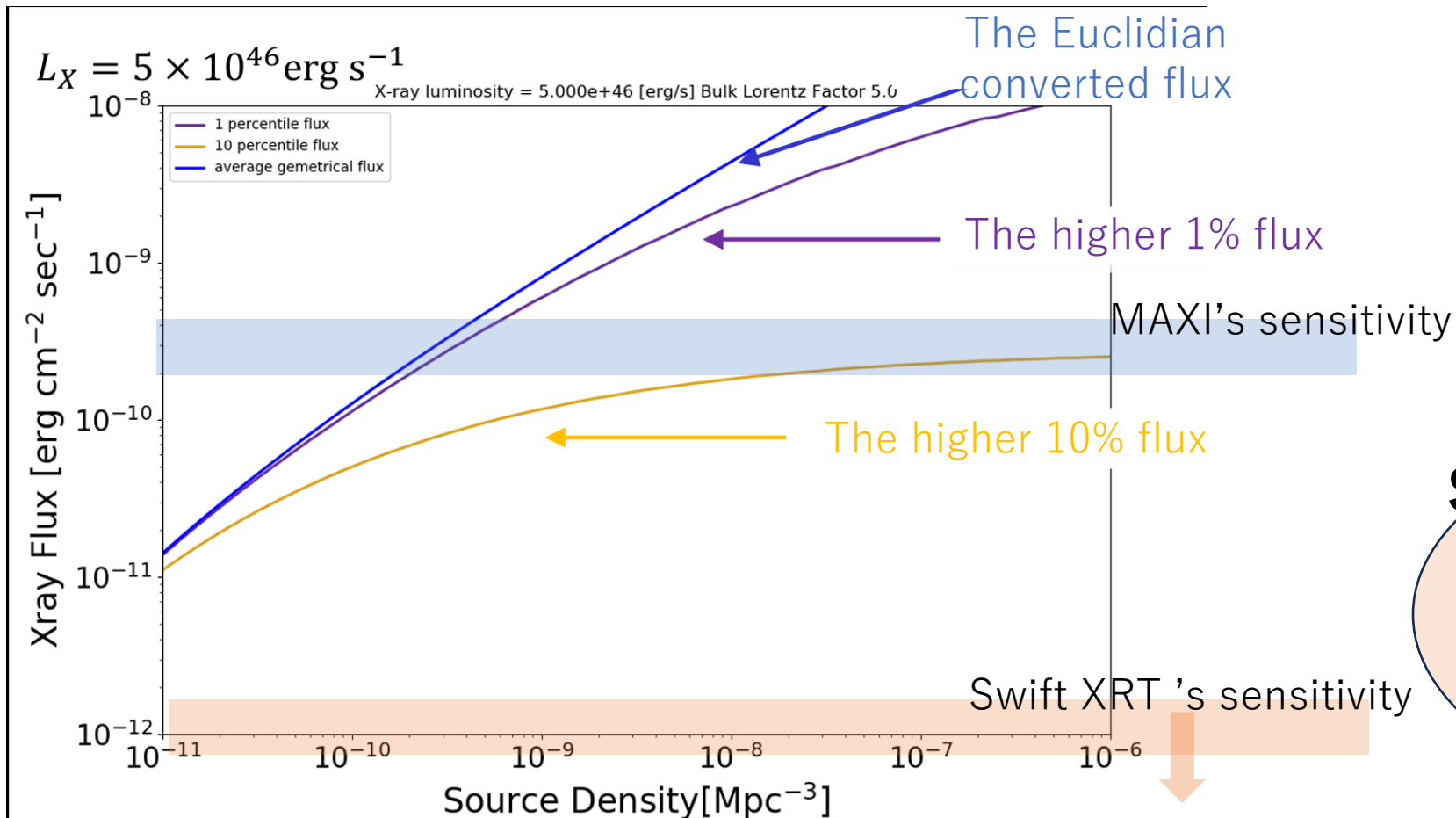
Stronger constrain for ξ_{CR} or L_{UHECR}

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?

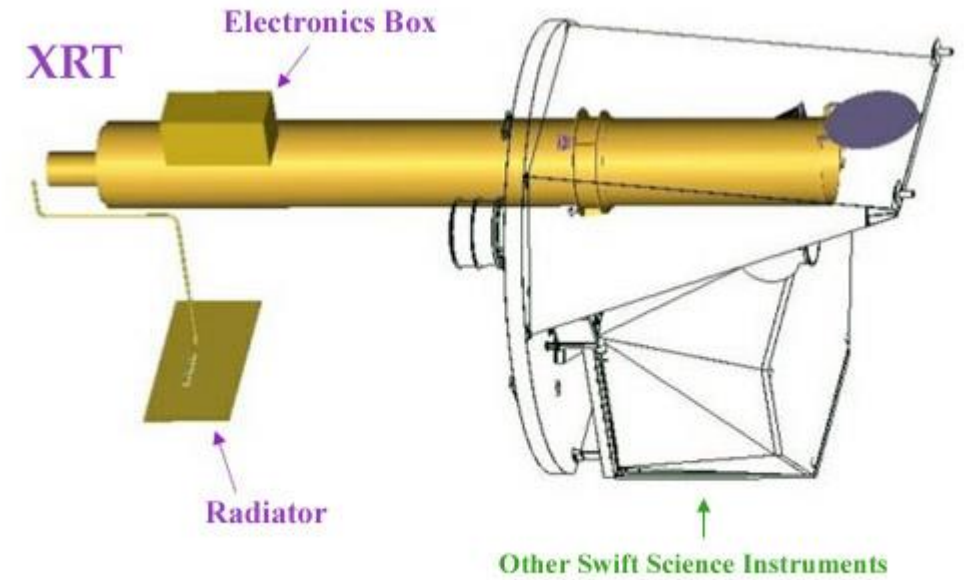
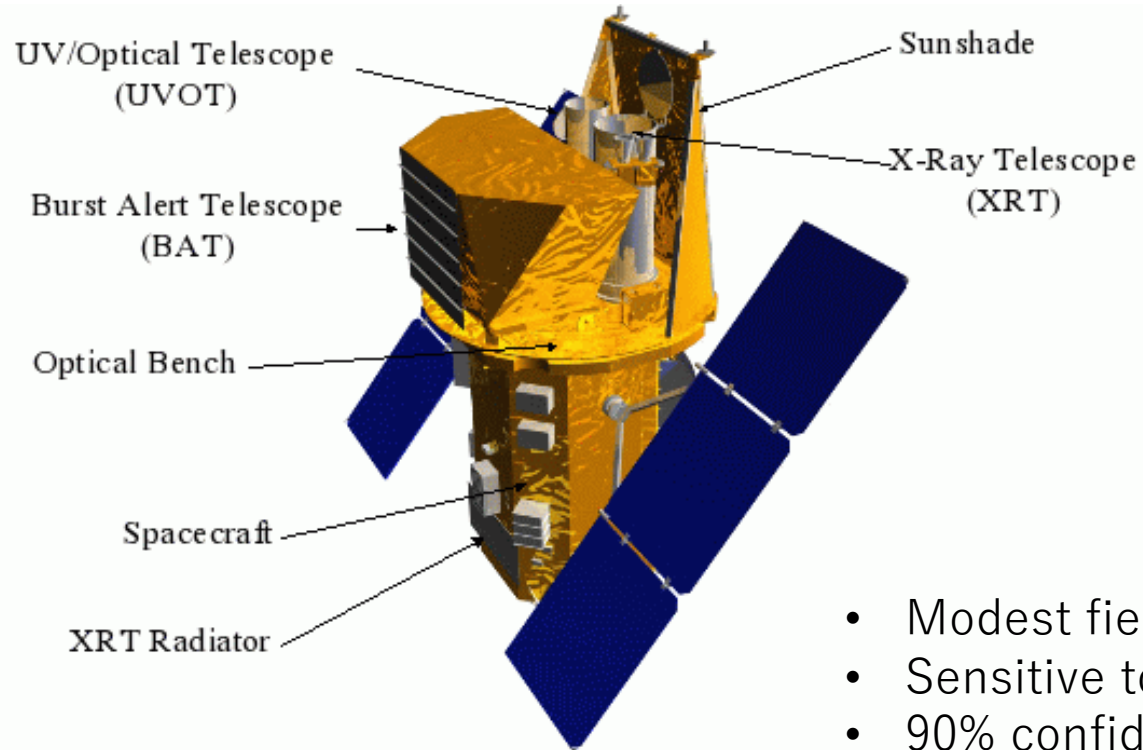
- X-ray monitors such as MAXI has a wider field of view but lower sensitivity
- Many of ν sources are far away so 'cosmological distance effect' makes their Flux smaller
→ It needs lots of follow up to provide good constrains



Swift/XRT

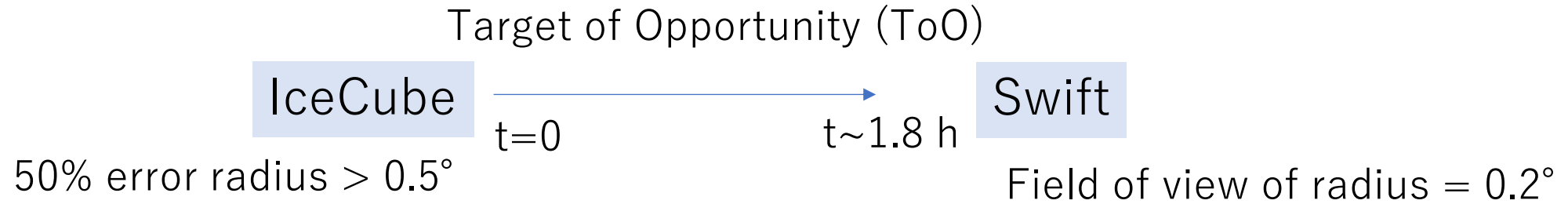
Only a few times follow up bring good sensitivity!

Swift

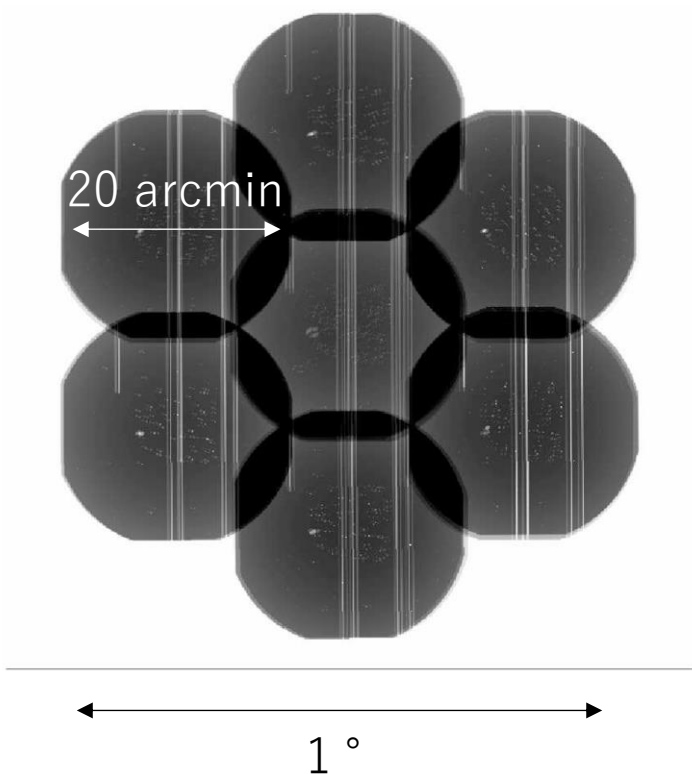


- Modest field of view (radius $\sim 0.2^\circ$) but rapid slewing
- Sensitive to $5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 1 ks (0.3 – 10 keV)
- 90% confidence radius of 3.5 arcsec (1.4 arcsec for brighter sources)
- Followed up on ~ 40 IceCube events so far

Swift Observing Strategy



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 $\sim 96\text{min}$ (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

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

-
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.

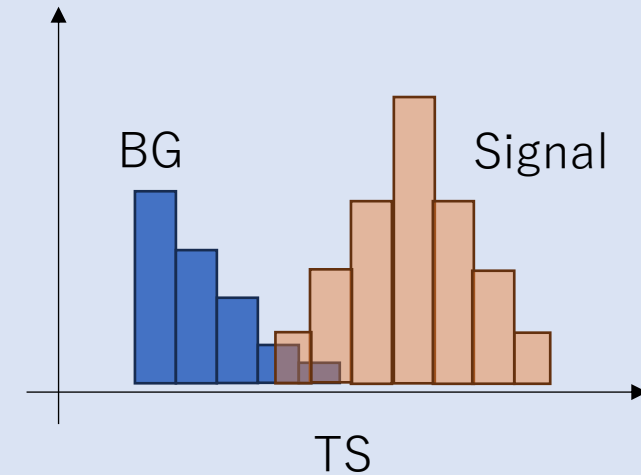
[About the analysis.](#)

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

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

- 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



We don't use HEASoft in analysis part

HEASoft

HEASoft:

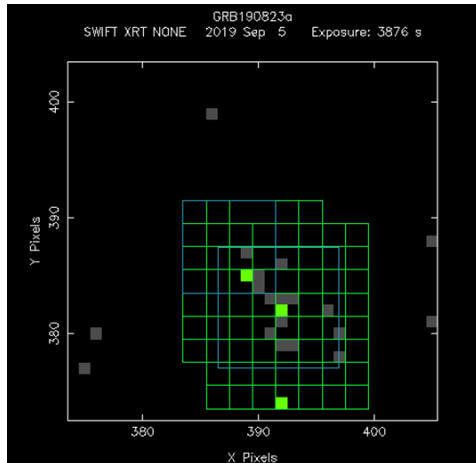
- X-ray analysis software package
- Sophisticated for X-ray analysis
- Contains many tools that can help my analysis

Ximage

BG computation

Excess search

Source finding with SNR



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

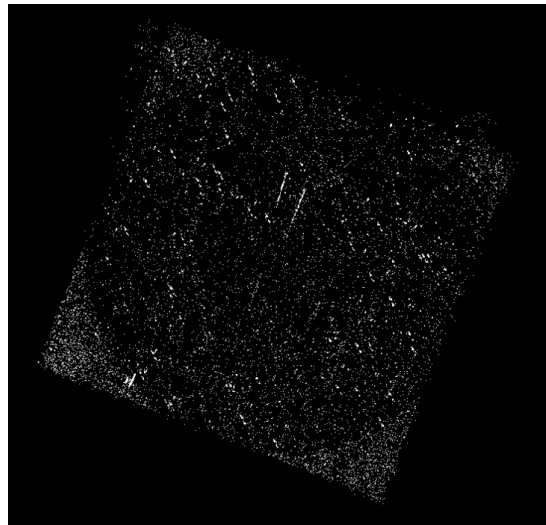
```
1 - x/ypix      388.500000      388.500000
1 - local bg (cnts/img pix)  4.95605450E-03  Imgpix in box  256.000000
1 - PSFco       1.49023223      Back    1.26874995      Tot Cnts      18
1 - S/N         3.94359374      Prob    3.44169138E-15

snr threshold =      2.00000000
bgnd fluctuation probability limit =  9.99999975E-05
```

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

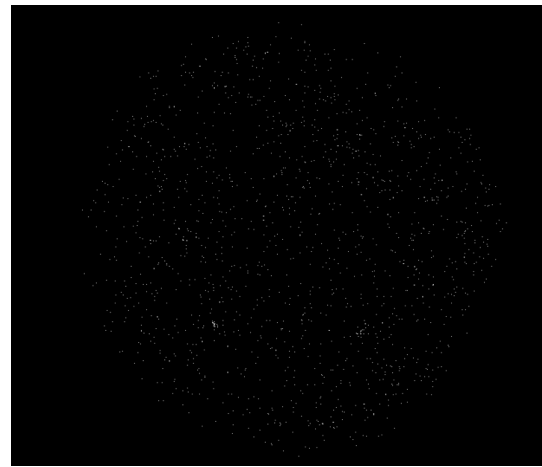
0. event file I use

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

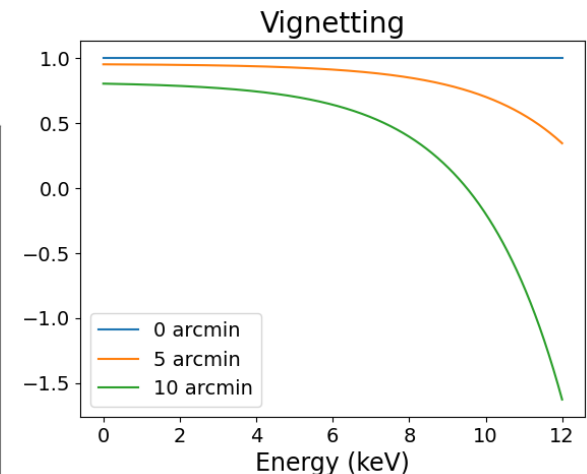
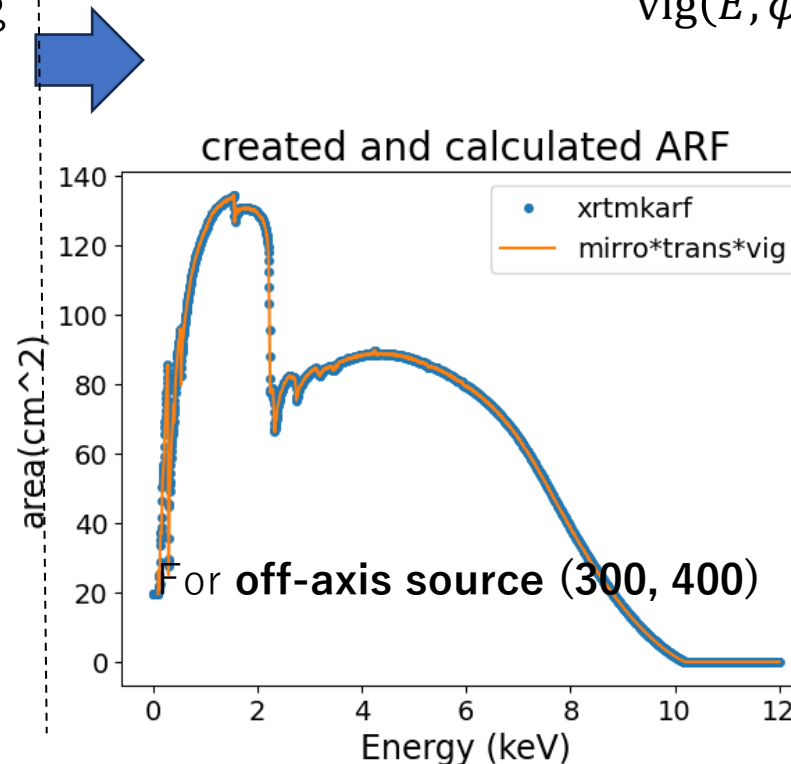
In the calibration database

My method

I somehow found

ARF = mirror_file * filter_file * vignetting

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

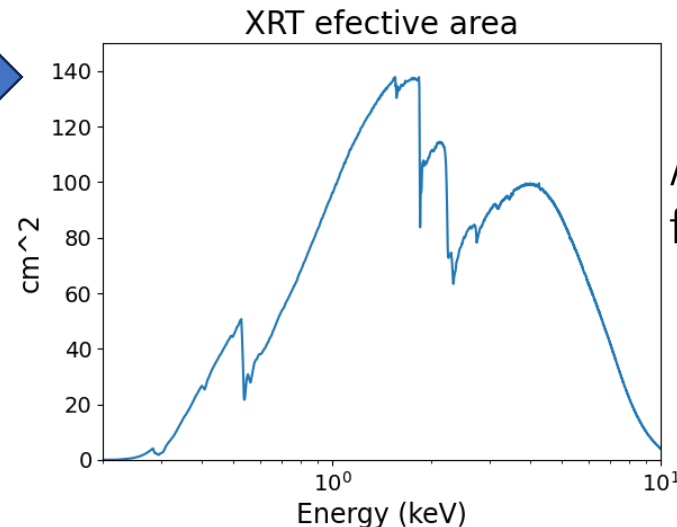
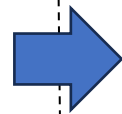


Analysis w/o HEASoft... is it OK?

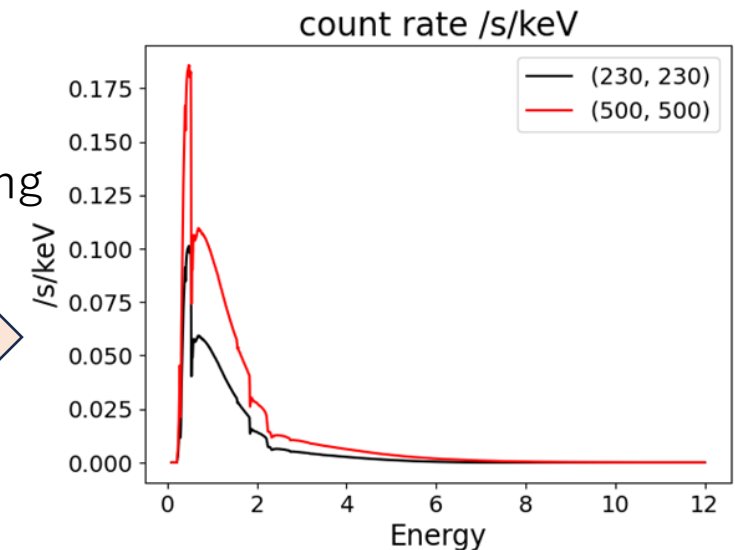
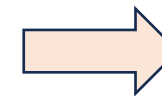
2. Compute count rate for given fluxes

2.1 calculate count rate

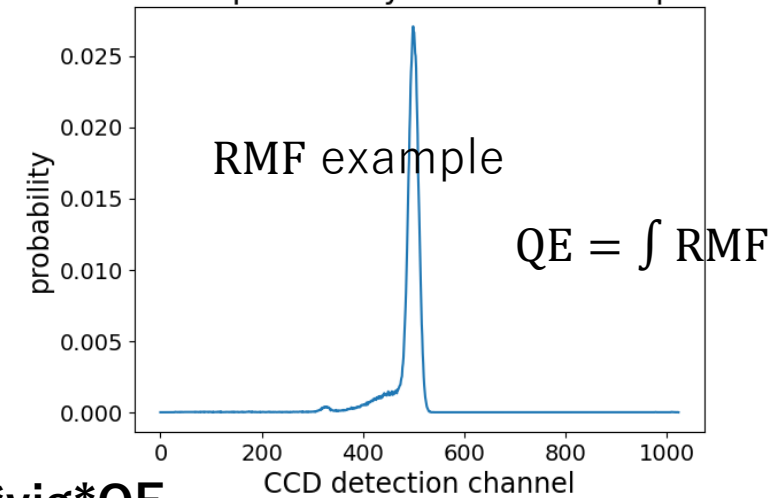
xspecc
(input: pha file/ arf file/ rmf file)
Select flux model → Calculate
count-rate



Assuming
flux



detection probability of 5-5.005 keV photon



check

The XRT effective area is 135 cm² at 1.5 keV
and 20 cm² 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
- 'xrtime-tag' o — Not for PC mode
- 'fselect' on XF — Not for PC mode
- 'xrtpdcorr' on — Not for PC mode
- 'xrwtcorr' on — Not for PC mode
- 'xrtevtrec' on — Cal PI using PHA & gain file
- 'xrtcalcp' on — Events screening using filter file
- 'xrtscreen' on — We don't need image
- 'xrtime' on — Not for PC mode
- 'swiftxform' o — We don't need level 3 and more products
- 'xrtproducts' (

- 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

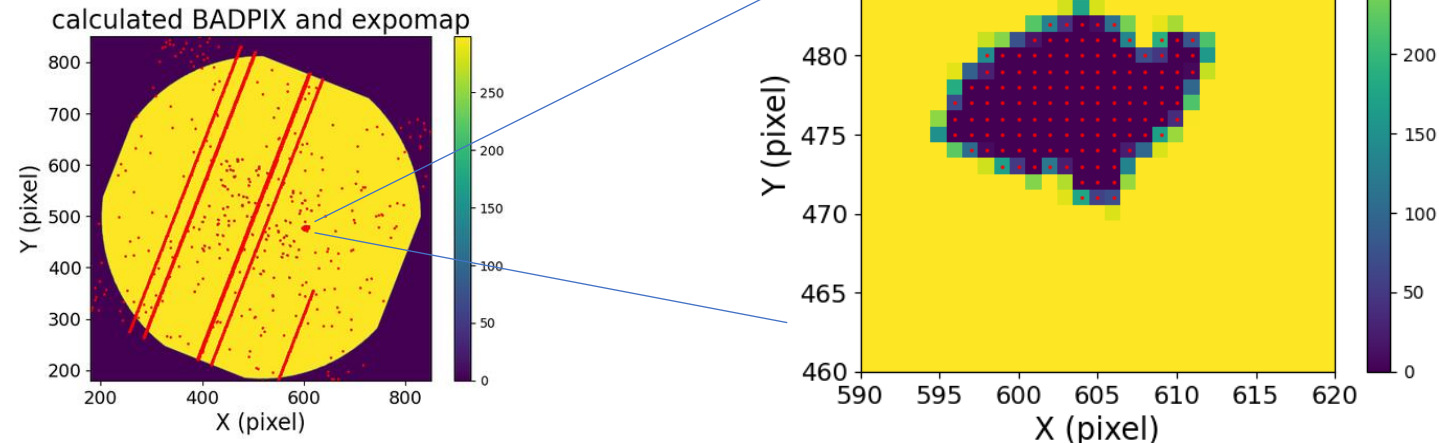
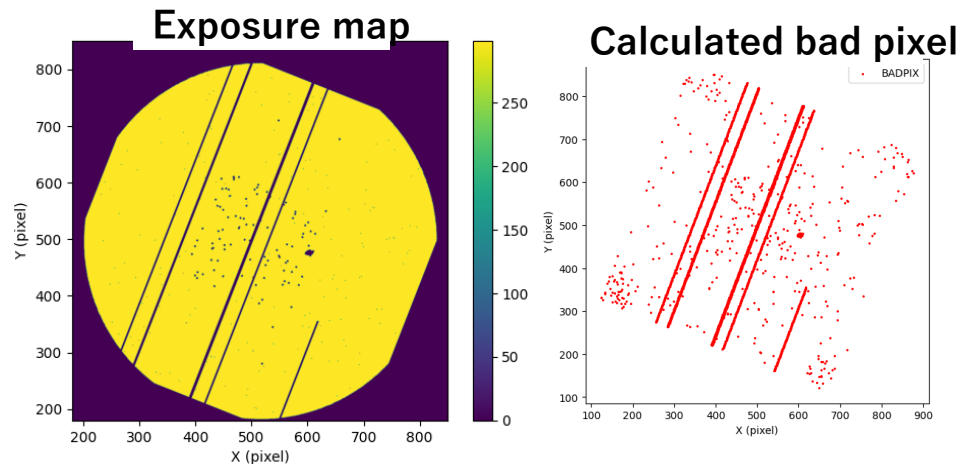
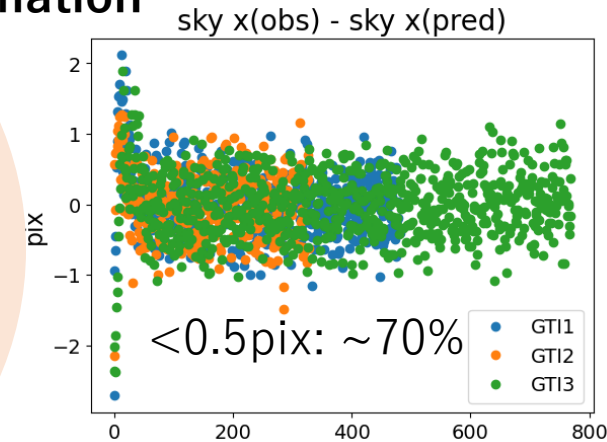
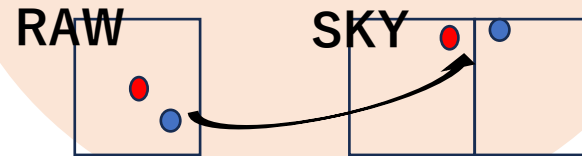
- Detector attitude parameters
- Earth's velocity

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

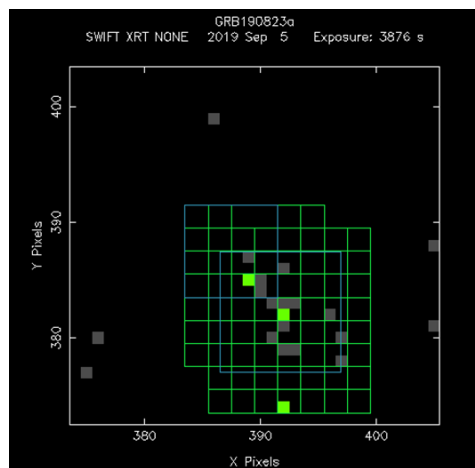
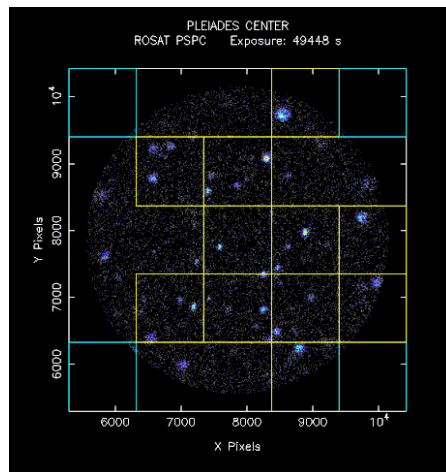
Excess

Find regions containing many photons

Search

Judge 'sourceness' with psf & vignetting

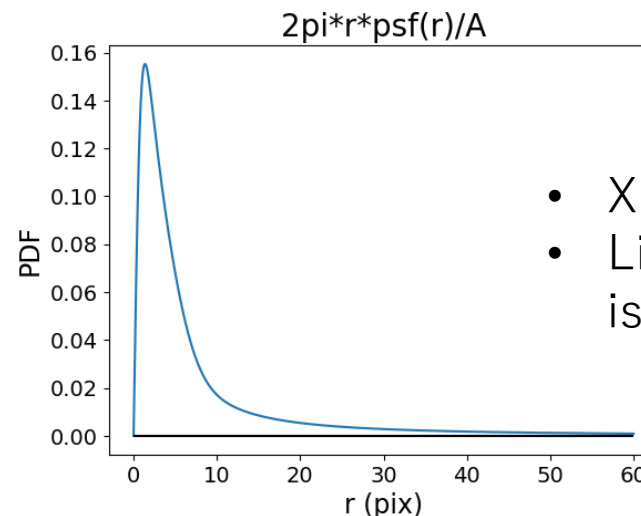
Black box
Low availability



My method

V006(the latest)
$$\text{PSF}(r) = 0.075 \exp\left(-\frac{r^2}{2(3.15)^2}\right) + 0.925 \left[1 + \left(\frac{r}{1.581}\right)^2\right]^{-1.305}$$

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



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

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

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

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

Conclusion about 'Analysis w/o HEASoft'

HEASoft

Helpful tools

Unnecessary work and files, low availability

Xselect

Selection and extraction of the event file

Xrtrmkarf & 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)

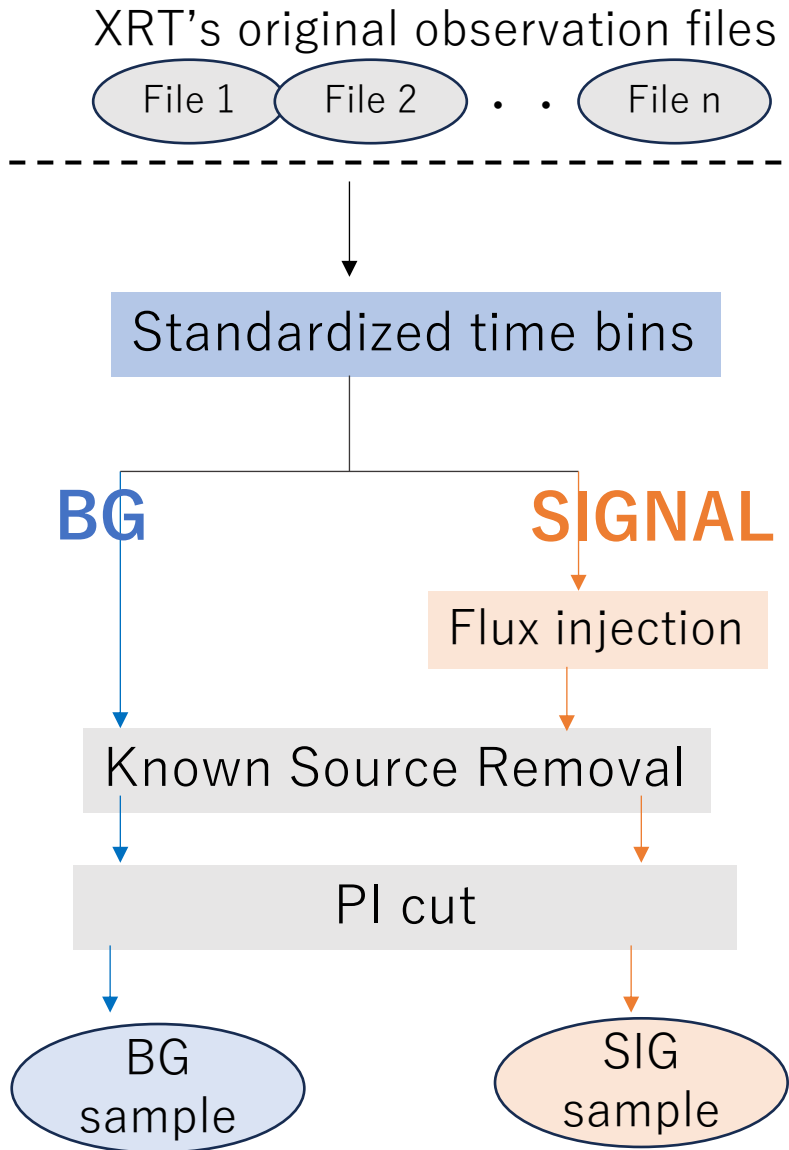
Base-file = cl.evt by ***Xrtpipeline***

Filter BADPIX by RAW to SKY

approx.conversion using the header of cl.evt

Newly designed TS

Dataset for Simulations



Galactic Plane Cut: remove $b < 5^\circ$

Unify Exposure Time:

- Analysis sensitivity largely depends on the exposure time
- For statistic analysis, I unify all of the exposure time

Inject Pseudo X-ray of Assumed Flux:

- Spread with psf function
- Remove events on bad pixels

Known Source Removal :

- We search for transient counterparts
- I use the Swift XRT Point Source (SXPS) catalogue

PI cut:

BG has a relatively high ratio of the counts of $E < 0.3$ keV

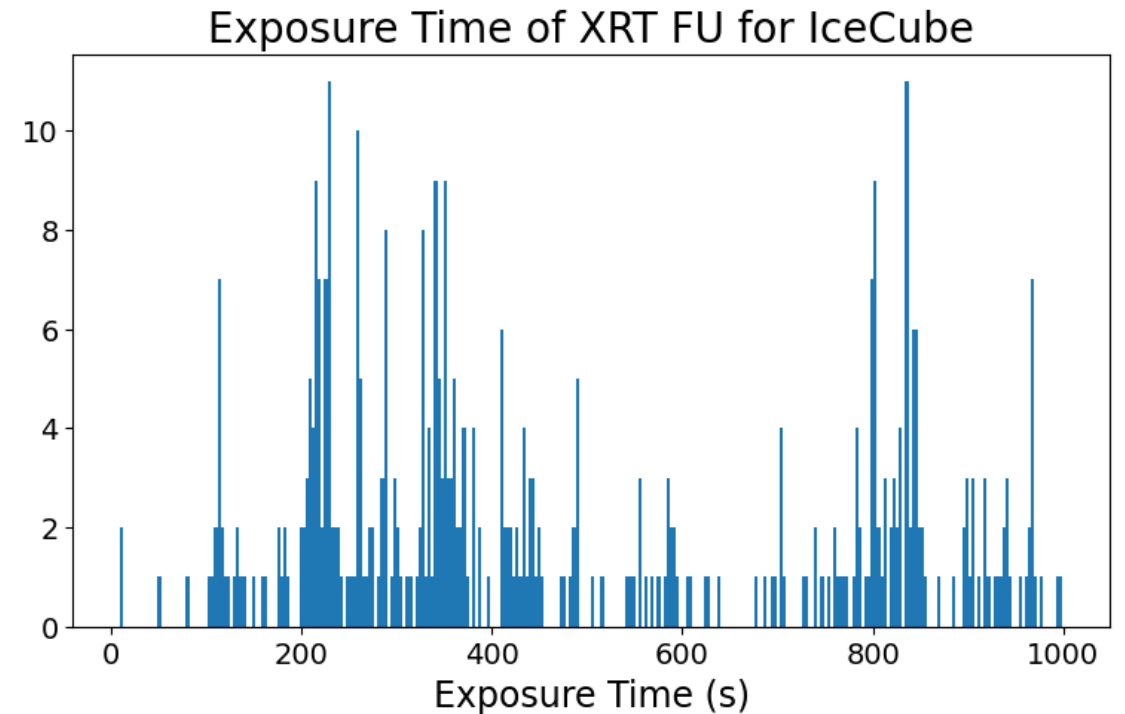
Unify Exposure Time

Ideally, we want to estimate the sensitivity for each observation time but for now, we haven't decided how we make it

For now...

Unified Exposure Time: 200s

- In the transient assumption, the first phase of the observation is important
- Typical observation time in an orbit is 200~400 s



Divide a file into 200s chunks

Inject Pseudo X-ray of Assumed Flux

Assume Power-law Flux

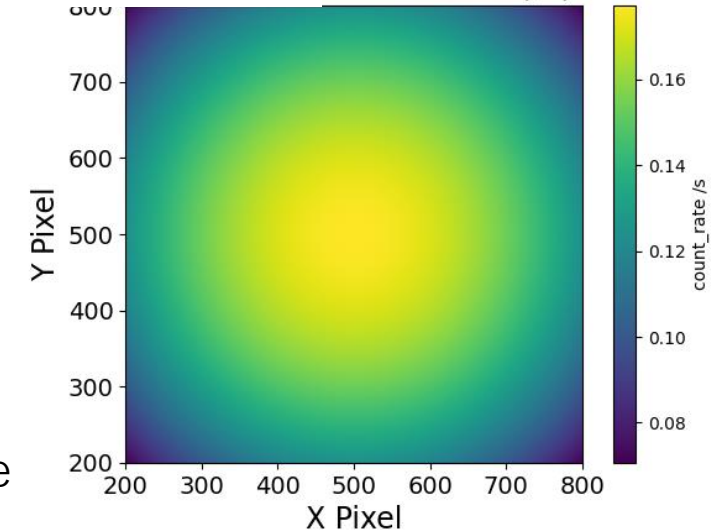
$$AE^{-2} (/keV/s/cm^2)$$

$$A = [0.00001, 0.0005, \dots, 0.001]$$

$$\rightarrow L_X = [7.7 \times 10^{-14}, \dots, 7.7 \times 10^{-12}] (\text{erg/s/cm}^2)$$

$$\begin{aligned} \text{Cnt rate}(\phi, \text{offaxis}) &= \int_E \phi(A, \Gamma, E) \text{eff}(E, \text{offaxis}) dE \\ &\sim 5 \text{ eV} \sum_{0.1 \text{ keV}}^{12 \text{ keV}} \phi(E) \text{mir}(E) \text{fil}(E) QE(E) \text{vig}(E, \text{offaxis}) \end{aligned}$$

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



count rate table

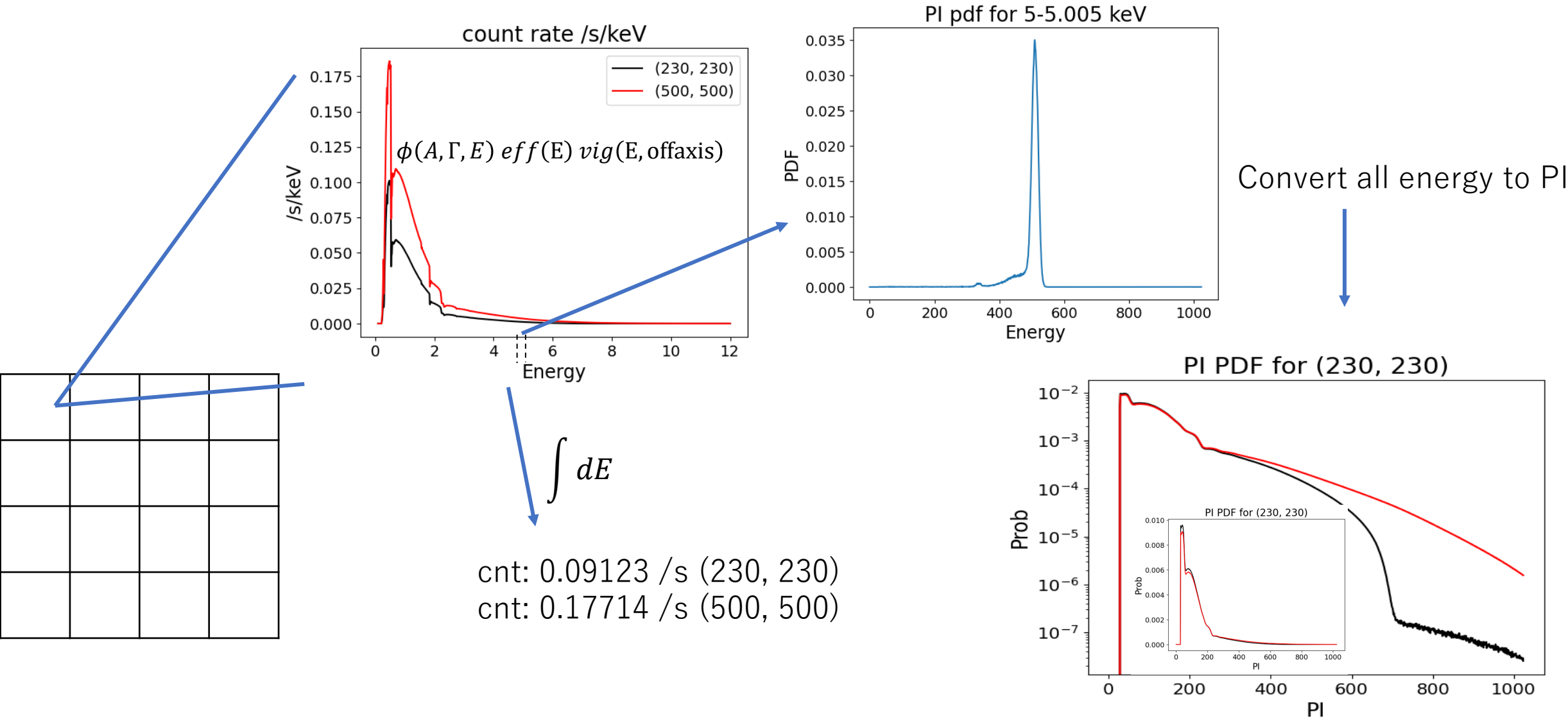
Check: (X, Y) = (700, 500) Original: 0.15368..
Xspec: 0.15364..

When should recreate the table when

- We change flux model
- RMF File in the caldb are updated ex)swxpc0to12s6_20130101v014.rm

PI of The Inject Pseudo X-ray

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



Known Source Removal

Problem: the removal region size is unclear

Table 3

The Radius of the Region Used to Perform PSF Fitting

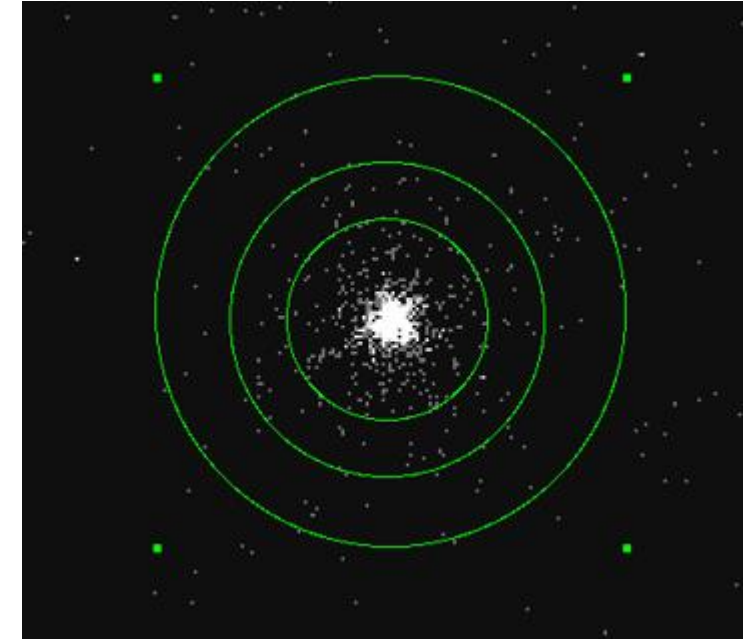
S/N	Radius ^a
$S/N \leq 7$	12 pixels
$7 < S/N \leq 11$	15 pixels
$11 < S/N \leq 40$	20 pixels
$S/N > 40$	30 pixels

Note. ^a 1 pixel = 2''357.

Table 5

The Distance from a Source within Which
Detections are Assumed to be Artifacts

Source Rate (count s ⁻¹)	Radius (pixels)
$R \leq 0.4$	10
$0.5 < R \leq 1$	35
$1 < R \leq 2$	40
$2 < R \leq 8$	47
$R > 8$	70



Swift team when they make 1sxps catalogue: PSF fitting → radius at which cnt rate $< 10^{-6}/\text{s}/\text{pix}$

follow ↓ **Our Strategy:** PSF fitting → find the smallest radius of counts probability $< \text{thr} = 10^{-6}/\text{s}/\text{pix}$

PSF fitting

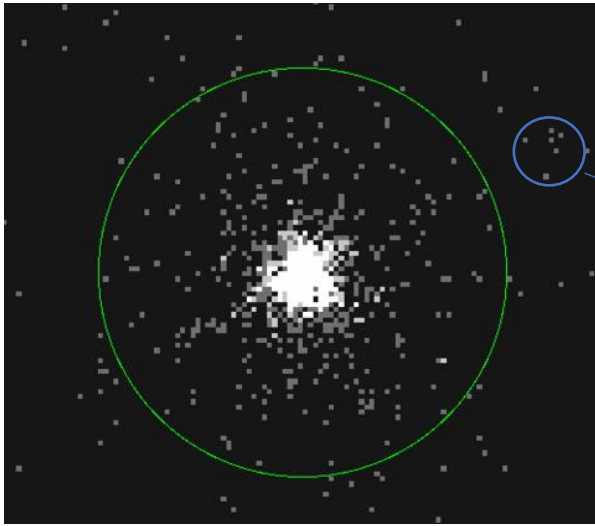
Swift team:

- S/N given by HEASOFT was used to know appropriate size
- HEASOFT can distinguish one from the other on its vicinity

Us:

Need a nice method

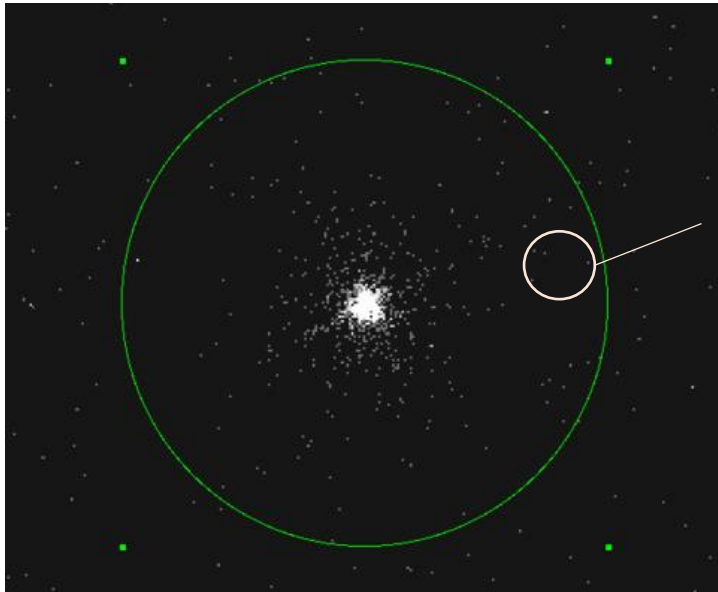
General effect of removal size



If removal region is too small..

artifacts can be appeared

- 3~4 photons cluster makes TS ~20
- sensitivity for lower flux get but



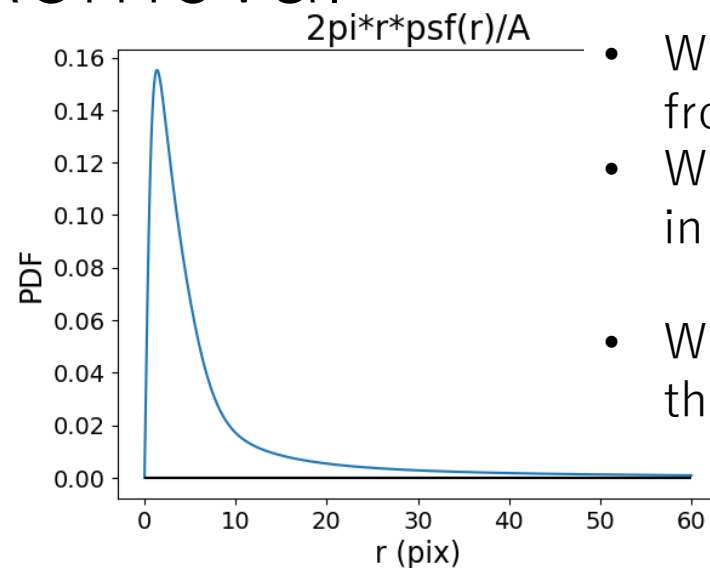
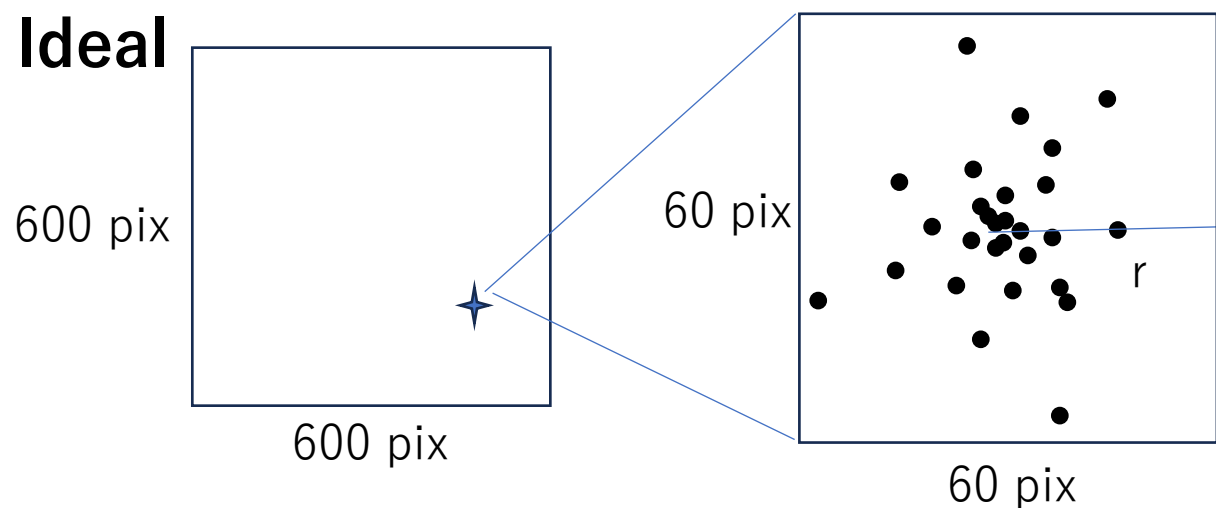
If removal region is too big..

The signals get higher chance to be removed

- Smaller effective area
- Sensitivity for all the flux get bad

Problem of Known Source Removal

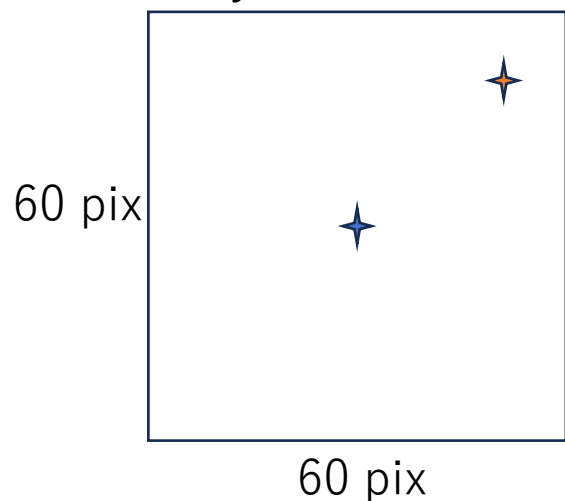
Ideal



- We know (RA,DEC) from the catalogues
- We can estimate N_{sig} in a given region
- We can get r of the threshold

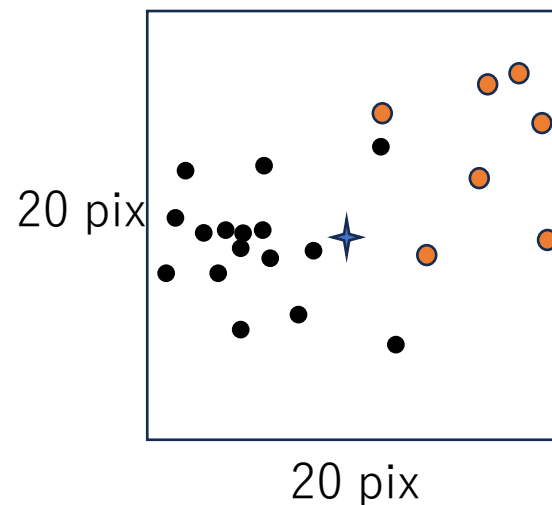
Real

Possibility of 2 source in 1 region



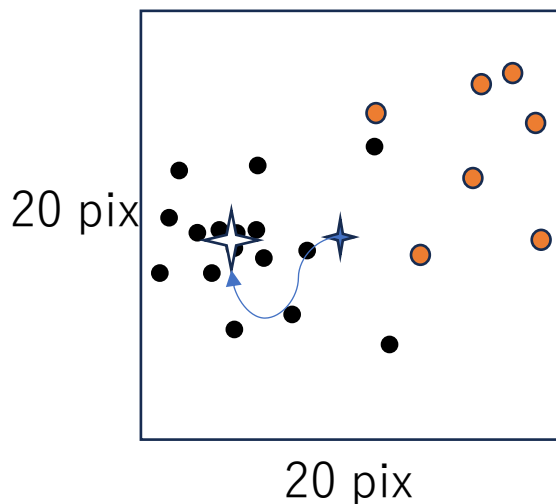
In this situation,
We cannot estimate N_{sig}
→ How about using
smaller region?

Source position slightly differ from catalogue (RA,DEC)



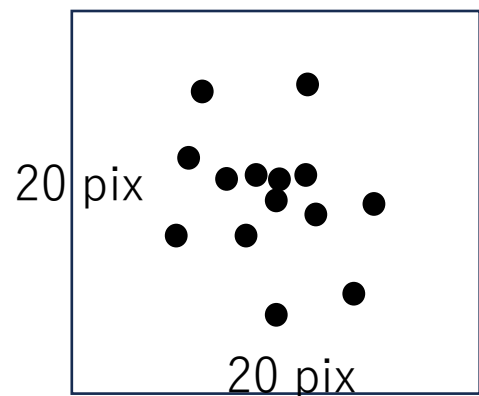
- Too small region can't find the center
- Even in reasonable region, it's difficult to derive the threshold r
- Contaminant can still affect

Known Source Removal Strategy



1. Find the real excess center using catalogue (RA,DEC) and 20pix square region

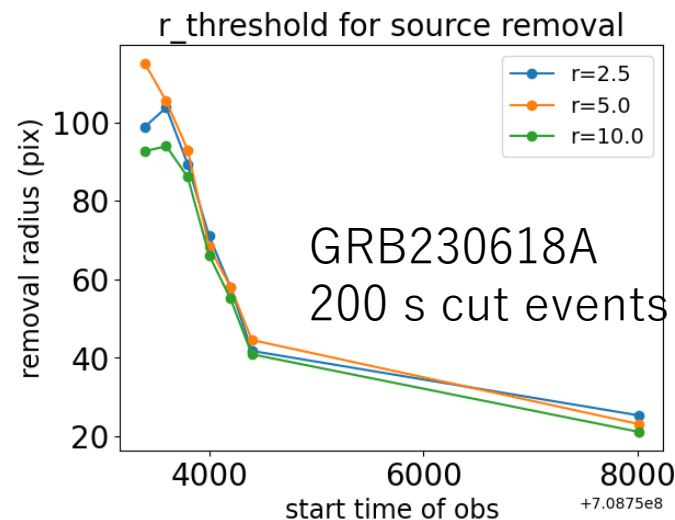
- Use the same method as the one used in TS computing
- This only finds the excess center



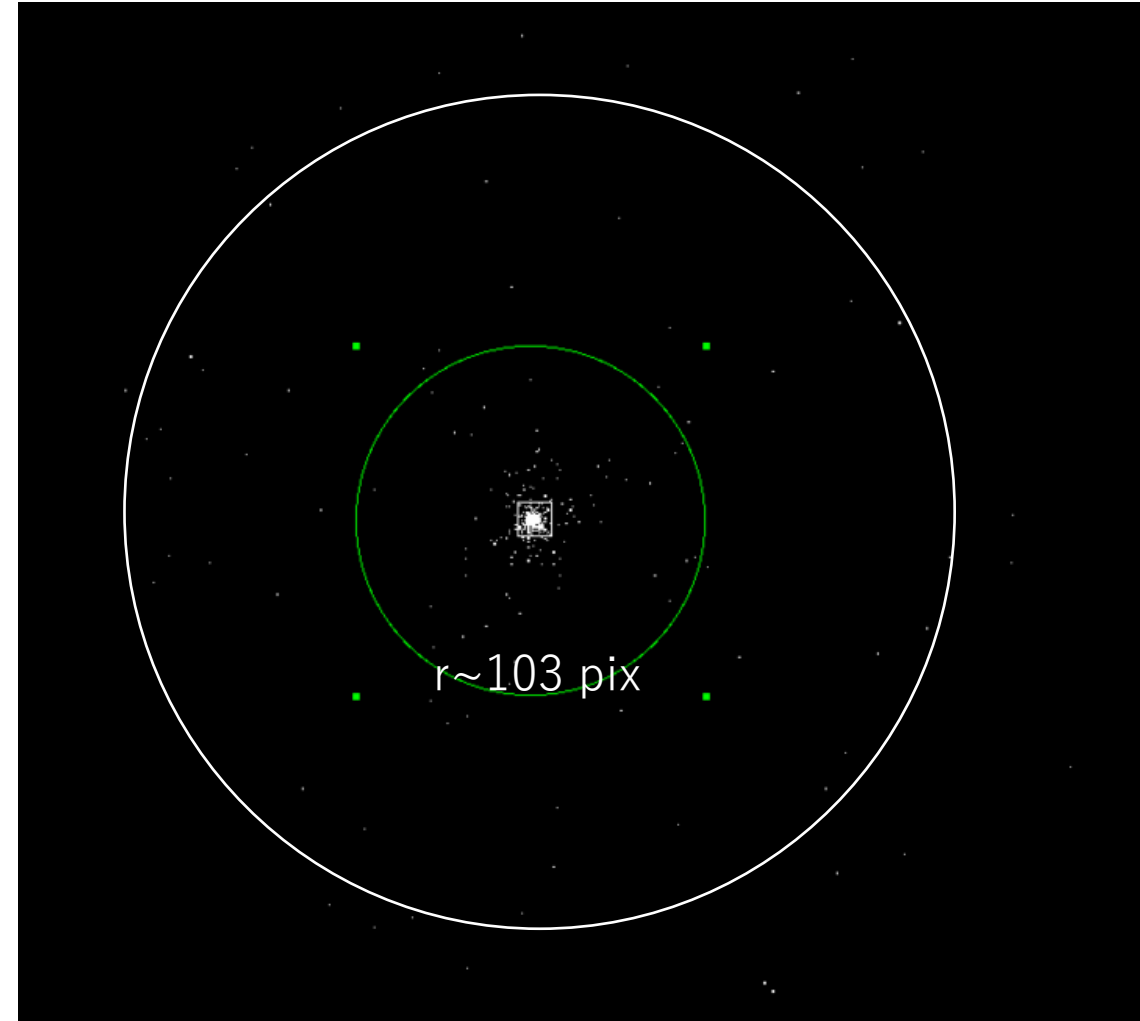
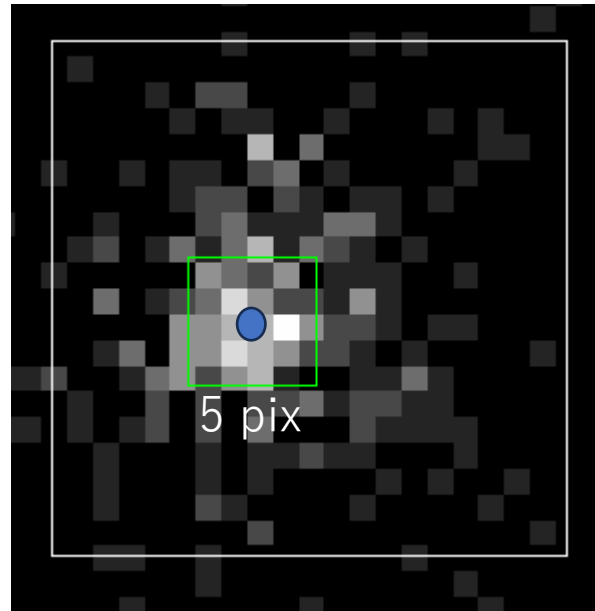
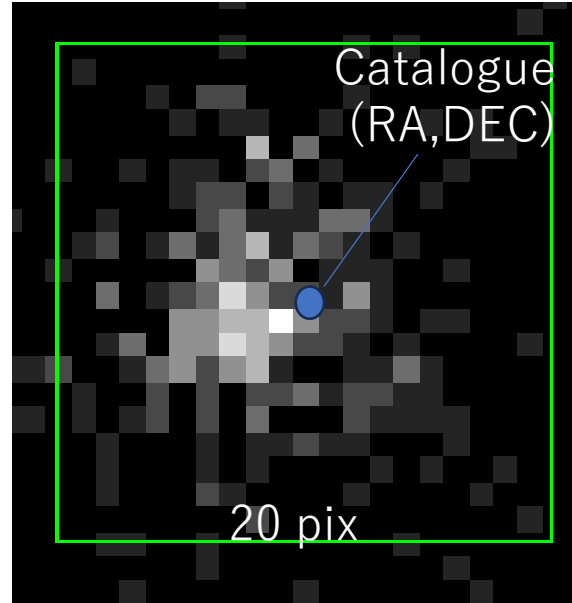
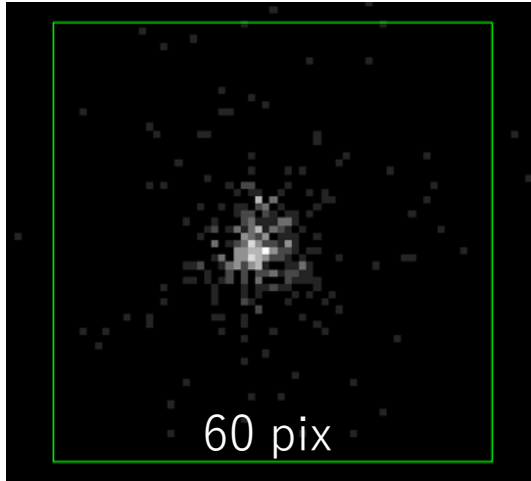
2. Estimate N_{sig} in new 5pix window and convert it to r_{thr}

$$N_{\text{full}}^{\text{tot}} = \alpha N_{5\text{pix}}^{\text{sig}} \left(\frac{\int^{\infty} \text{PSF}}{\int^5 \text{PSF}} \right)$$

$$\frac{N_{\text{full}}^{\text{tot}}}{\text{time}} \text{PDF}(r) = \frac{10^{-6}}{\text{pix s}}$$



Example GRB230618A

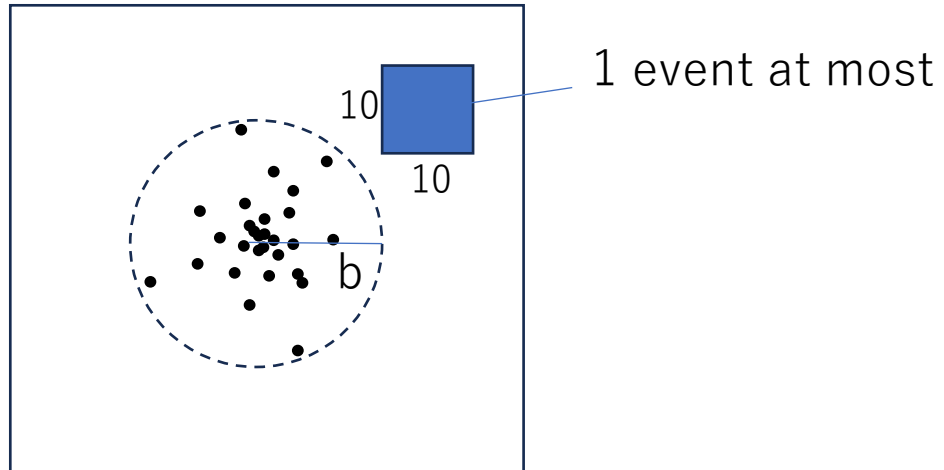


Too big!! Maybe $\text{thr} = 10^{-6}/\text{s/pix}$ was conservative ?

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.”



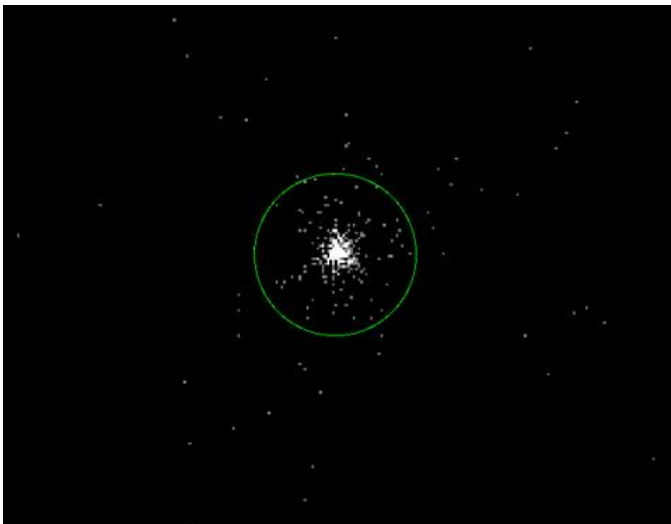
$$\text{total count} = N\alpha \frac{\int_0^\infty dr \text{psf}(r)}{\int_{\text{w size}} dr \text{psf}(r)}$$

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

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

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

(The minimum removal region: 5pix)

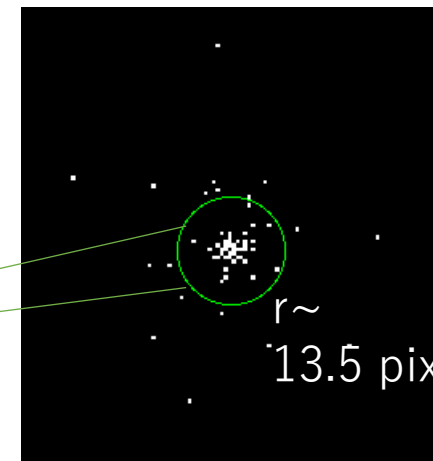
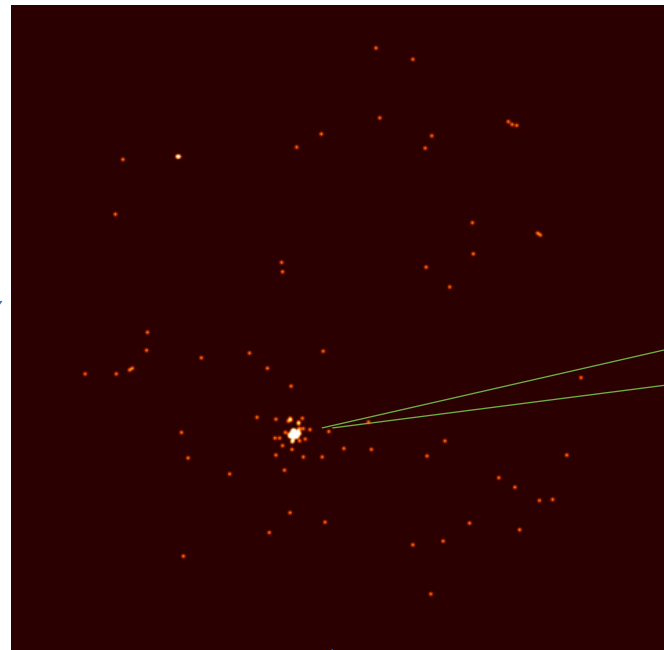
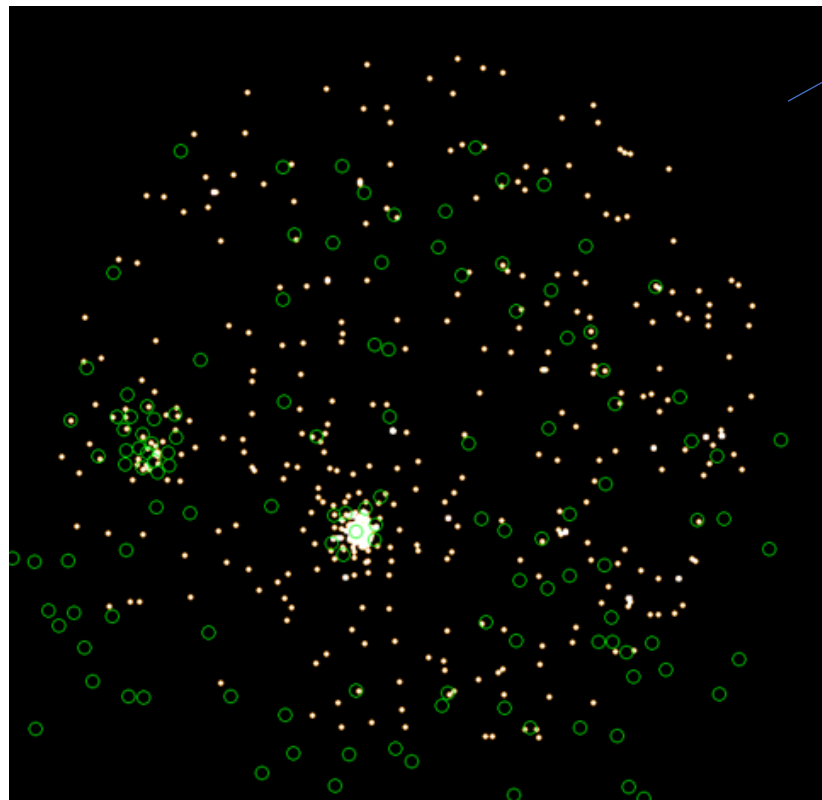


Result of GRB230618A case: 31.62 pixel

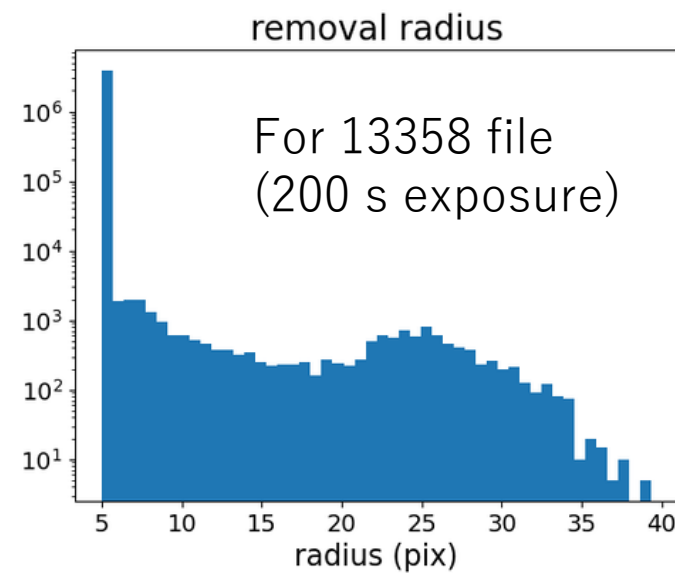
Example

NGC 5548

200 s chunk

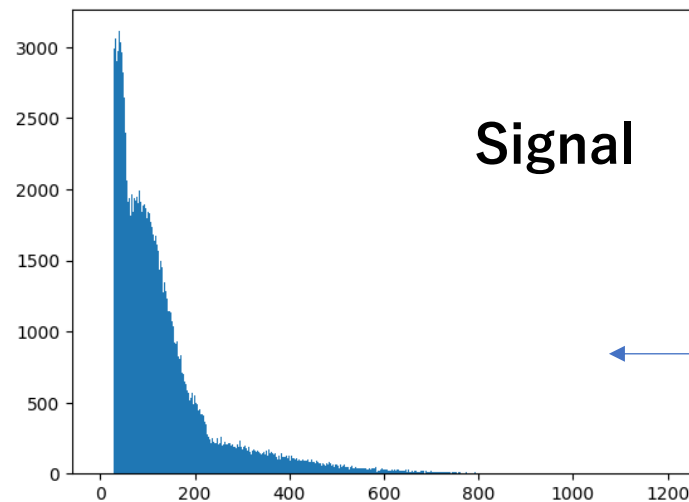
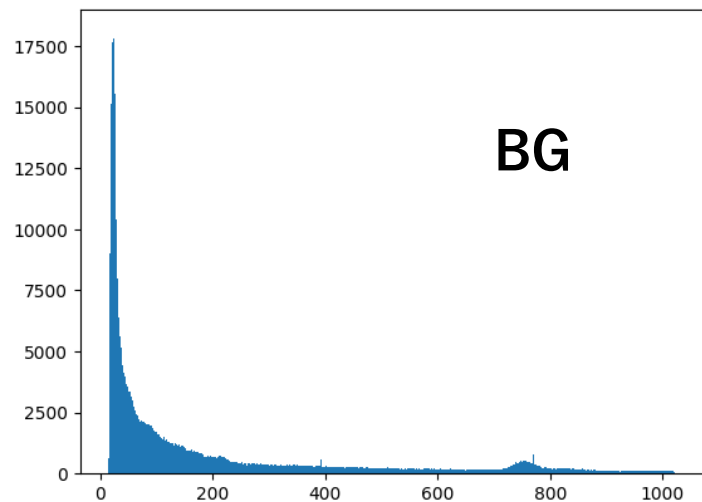


Source removal

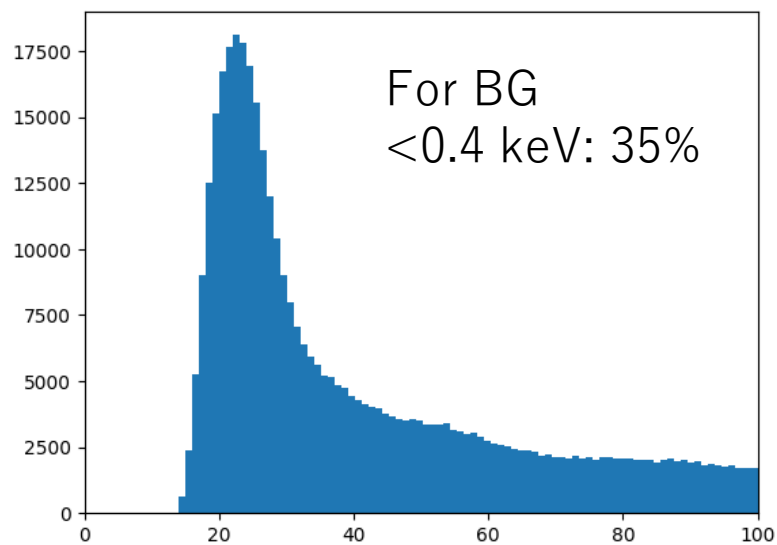
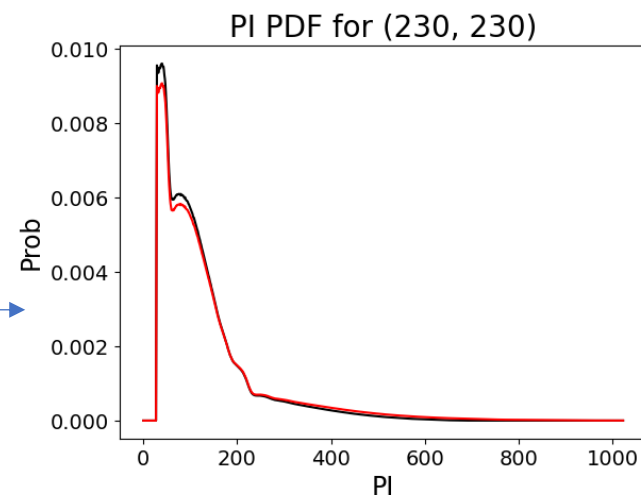


PI cut

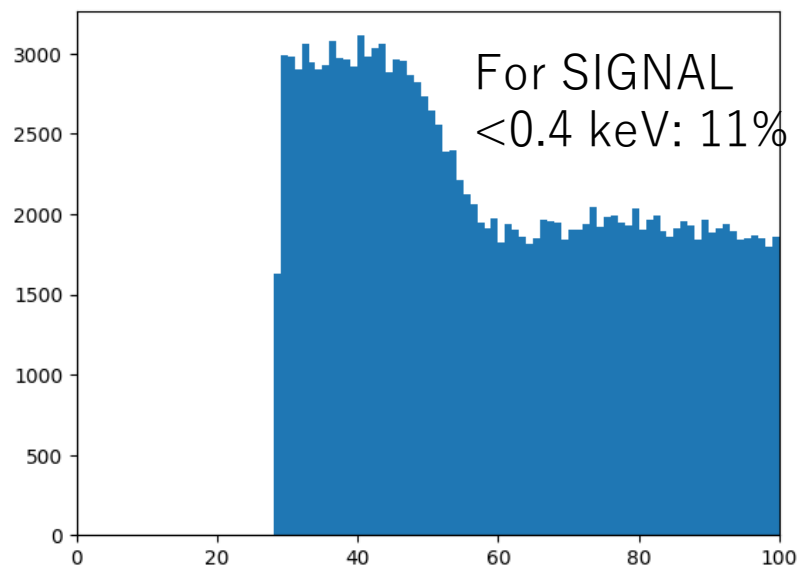
Events energy histogram from data



Theoretical PI



For BG
<0.4 keV: 35%



For SIGNAL
<0.4 keV: 11%

Considering the both shapes of PI,
the cut threshold are set to 0.4 keV

TS computing

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

- How many signal-like and BG-like photons in a region?
- Where is the expected source?

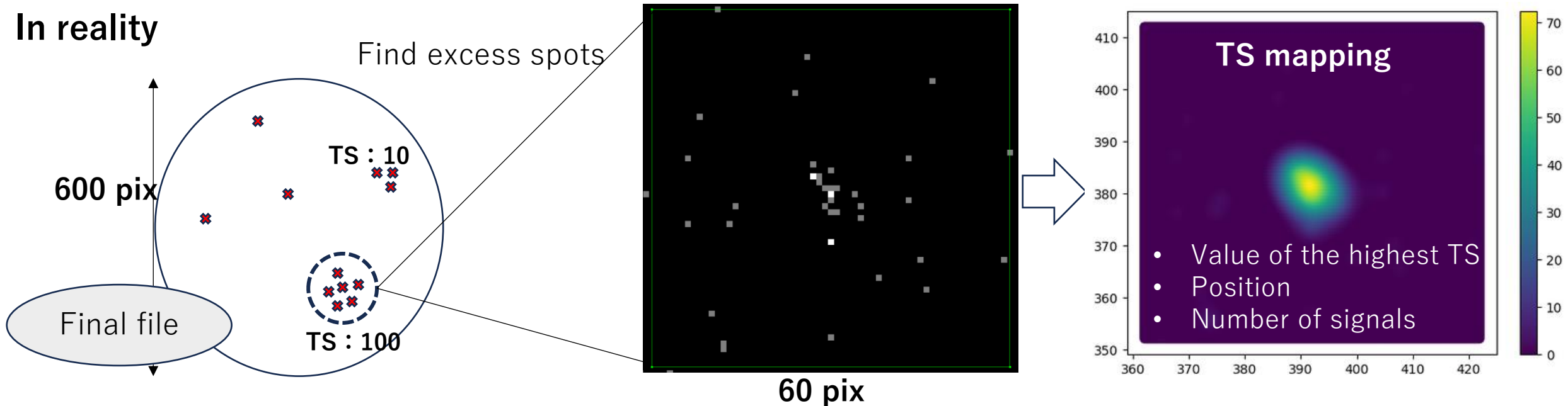
$$\alpha = \frac{n_{\text{sig}}}{n_{\text{sig}} + n_{\text{BG}}}$$

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

How about the
'all from BG' case?

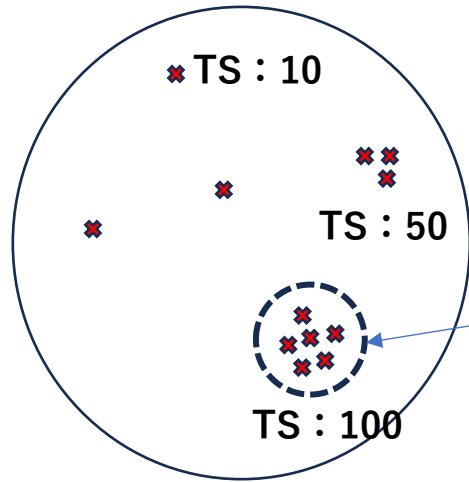
$$\text{TS} = 2 \ln \left(\frac{\mathcal{L}_{\text{sig}}}{\mathcal{L}_{\text{BG}}} \right)$$

In reality



TS computing

Before TS computing is triggered, it is necessary to determine the most likely location of a source



Since TS computing takes time,
want to locate this efficiently!

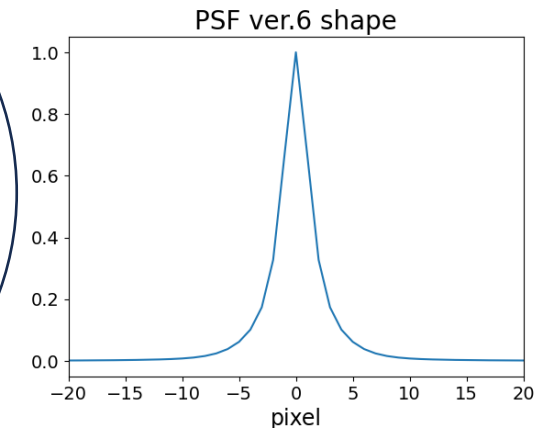
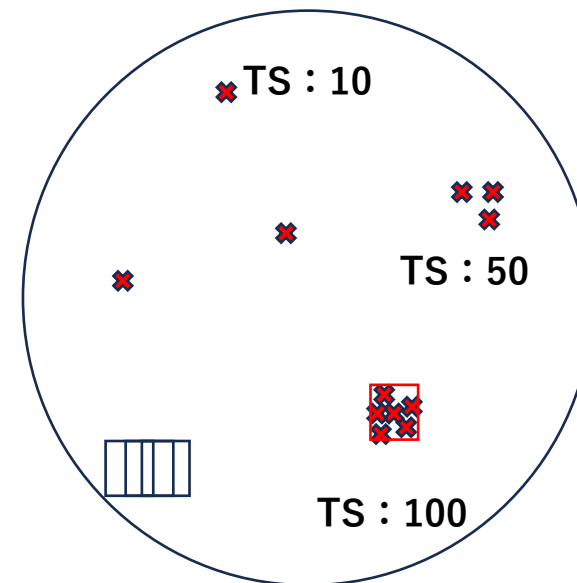
Need a method to find

- larger number
- grater clustering

Method I'm using- **Window Scanning Method**

1. Scan $10 \text{ pix} \times 10 \text{ pix}$ region w/ one pixel step
2. Extract windows that contain the most events
3. If several windows are extracted, select the one whose events have the smallest average distance from the centroid
4. If still multiple windows are extracted, they all will go to TS computation phase

→return centroid of events in the chosen window



BG Simulation

I focused IceCube 180109A and Swift-XRT follow up of it

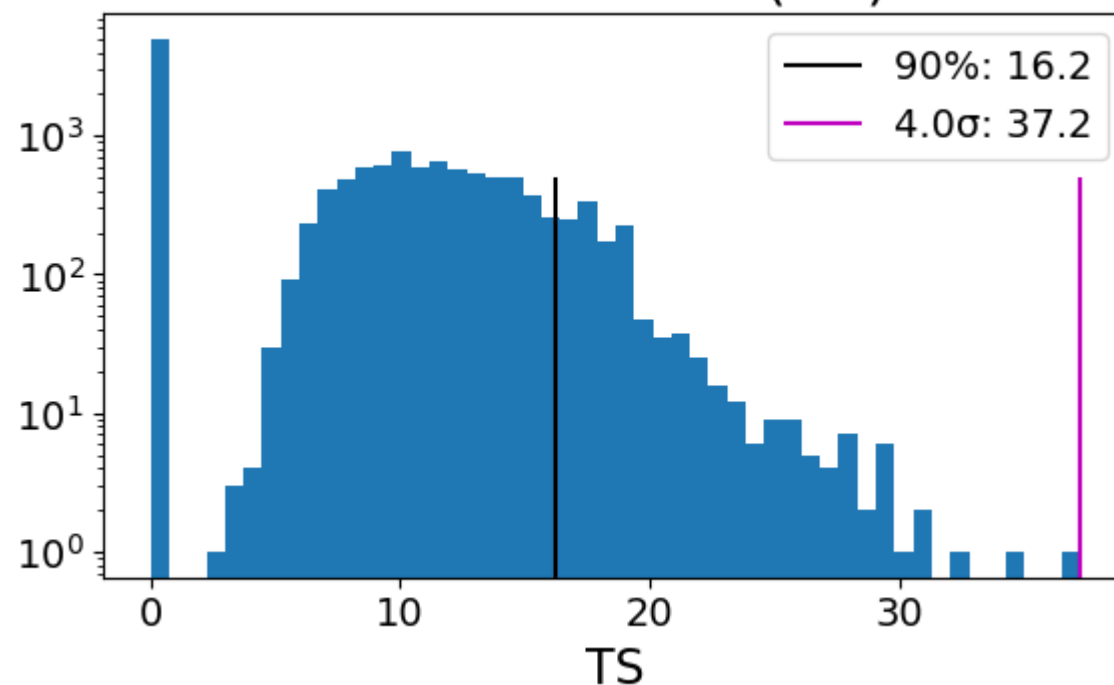
Control sample

All the XRT observations within 2 months before the triggered event / 2865 events

Above $b > 5$ / 2604 events

200s chunk / 13358 events

TS distribution (BG)



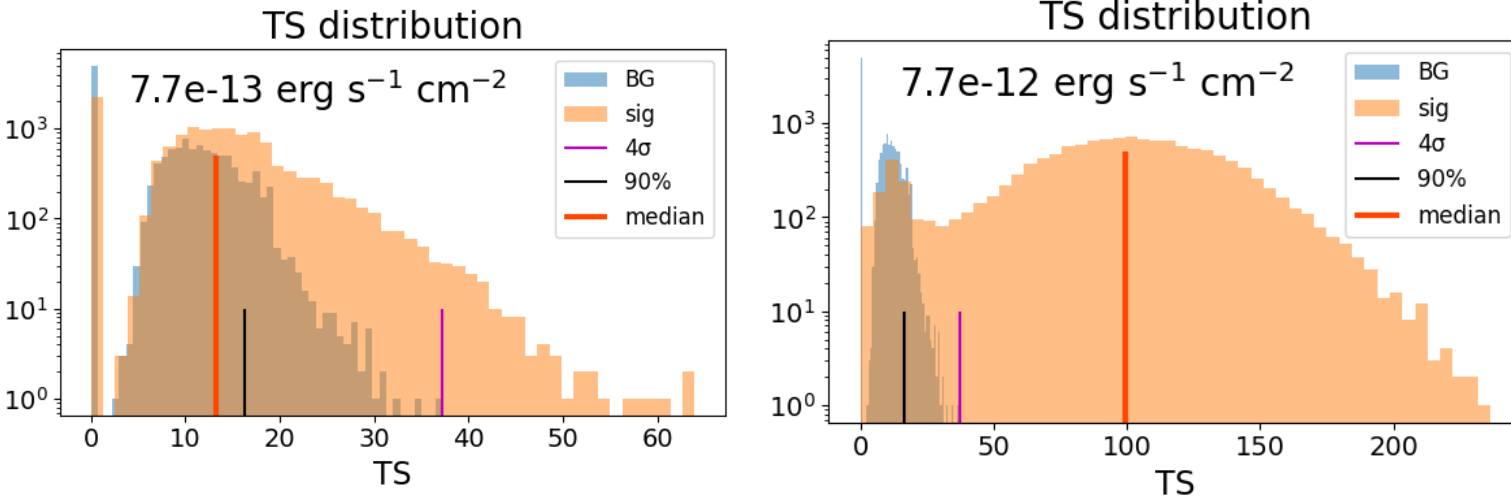
p-value: defined by the amount of the sample

90%: 1336/13358 $\longrightarrow$ **TS: 16.2**

4 σ : 1/13358 $\longrightarrow$ **TS: 37.2**

Signal Simulation & Results

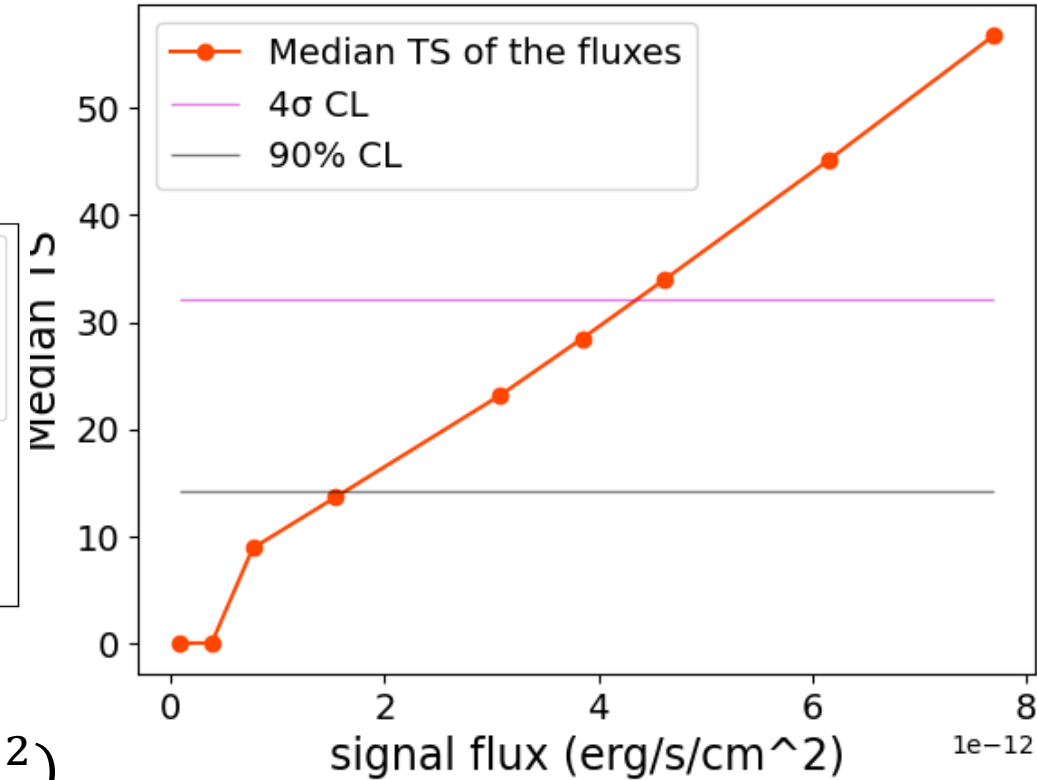
Examples of TS distribution



90% confidence level: $L_X \sim 1.1 \times 10^{-12} \text{ (erg/s/cm}^2\text{)}$

4σ significance: $L_X \sim 2.9 \times 10^{-12} \text{ (erg/s/cm}^2\text{)}$

flux vs TS



For your information,

90% confidence level: $L_X \sim 1.6 \times 10^{-12} \text{ (erg/s/cm}^2\text{)}$

4σ significance: $L_X \sim 4.4 \times 10^{-12} \text{ (erg/s/cm}^2\text{)}$

in the case of PI cut: $< 1 \text{ keV}$

Current Problems

- **It takes time to download original event files (~2.5 h for 2month data)**
 - It even got error for ~4h downloading
 - I'm using 'astroquery.heasarc', 'swifttool, ud.downloadObsData()'
- **SXPS catalog is not perfect**
 - Recent observations are not covered.. Should I use LSXPS?
 - Even LSXPS can miss some known sources

Future Works

- Increase the simulation sample
- Add the neutrino side effect to the current likelihood

Summary

- Search for X-ray counterpart of IceCube neutrinos such as LLGRBs is meaningful to investigate the origin of UHECRs
- I am developing a method to evaluate Swift-XRT's sensitivity for IceCube follow up by blind analysis method
- So far, the source X-ray luminosity $L_x \sim 3 \times 10^{-12}$ (erg/s/cm²) leads 4σ significance detection, which could place stronger constrain to the UHECRs source model
- Catalogs and downloading are the two main problems so far
- Likelihood w/ neutrinos and more control samples are needed as future works