Time Correlation between X-rays and Neutrinos from Seyfert Galaxies

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IceCube Experiment

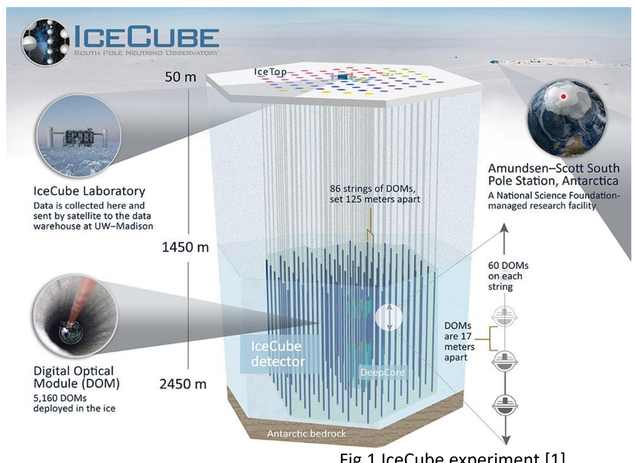


Fig.1 IceCube experiment [1]

Astrophysical neutrinos

- Propagate straight through the universe
- Rarely interact with matter
- Very occasionally interact with nuclei and generate 'Cherenkov light'

Antarctica

- One of the best environments for neutrino detections
  - Large amount of Ice that contains much nuclei
  - Dark in the deep ice
  - Ice with few impurities from high pressure

Since 2011, 5160 PMTs buried in $1\mathrm{km}^3$ under the South pole detect neutrino signals from the universe

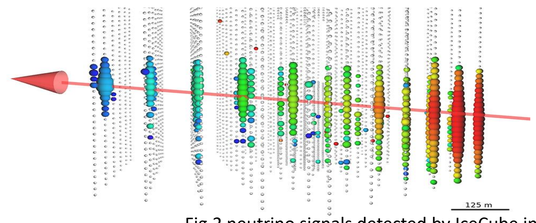


Fig.2 neutrino signals detected by IceCube in 2017 [1]

Seyfert Galaxies as Neutrino Sources

NGC 1068 (Seyfert 2)

- Identified as a possible neutrino source by IceCube (wih 5σ)
  → Seyferts are now getting attentions as the neutrino sources
- Dark in gamma ray

$$p \rightarrow \mathrm{meson}(\pi^{\pm}, \pi^0) \rightarrow \begin{cases} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \pi^0 \rightarrow 2\gamma \quad \text{etc} \end{cases}$$

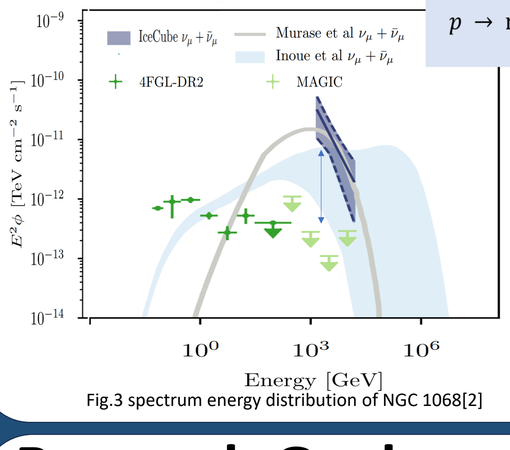


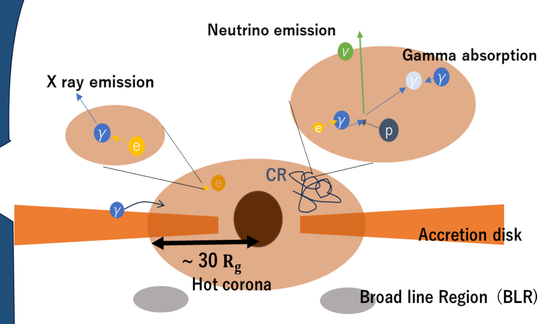
Fig.3 spectrum energy distribution of NGC 1068[2]

Other Seyfert galaxies

Table1. type of Seyfert galaxies and p-value as a neutrino source [3]

	type	p_{local}
NGC 1068	Sey2	5.0 σ
NGC 4151	Sey1	3.2 σ
CGCG 420-015	Sey2	3.5 σ

Possible Mechanism



Dark in gamma-ray → The vicinity of BH ($\lesssim 100\ R_g$) is of particular interest due to effects such as γγ absorption [4]

-Disk Corona Model- [5]

- Plasma turbulences in the corona accelerate CRs
- Can explain neutrino and gamma-ray emissions from Seyferts
- Neutrino emissions are proportional to X-ray

$E_\nu^2 \Phi_\nu \propto \xi_{\mathrm{CR}} L_{\mathrm{X}}$ $\quad \xi_{\mathrm{CR}} = \frac{L_{\mathrm{CR}}}{L_{\mathrm{X}}}$

Problem: Low significance due to fewer ν detections

Approach with multi messenger analysis X-ray and neutrinos!!

Research Goals

- Develop a new method to determine the significance of AGNs
- Constrain ξ_{CR} of the disk corona model
  by observing the time correlation between X-ray & neutrinos flux

→Focus Seyfert 1, NGC 4151

- Seyfert 1 (No torus that reflect X-ray)
- Brightest Seyfert 1 for MAXI
- Continuous observation by MAXI for 15 years

Seyfert 2 (NGC 1068, CGCG420-015)

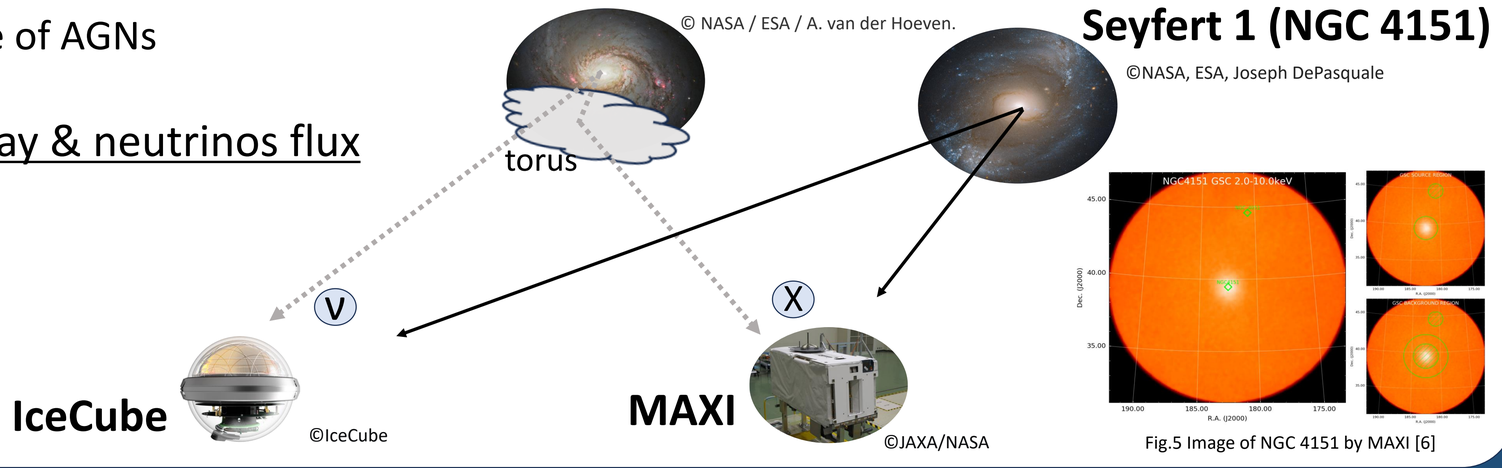


Fig.5 Image of NGC 4151 by MAXI [6]

Methods

Toy simulation before using IceCube data

X-ray luminosity variation of NGC4151 by MAXI (70days bin)

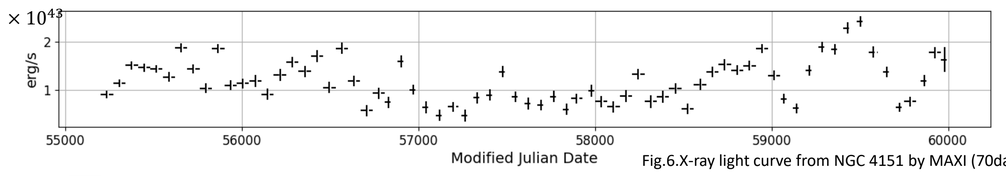


Fig.6.X-ray light curve from NGC 4151 by MAXI (70days bin)[6]

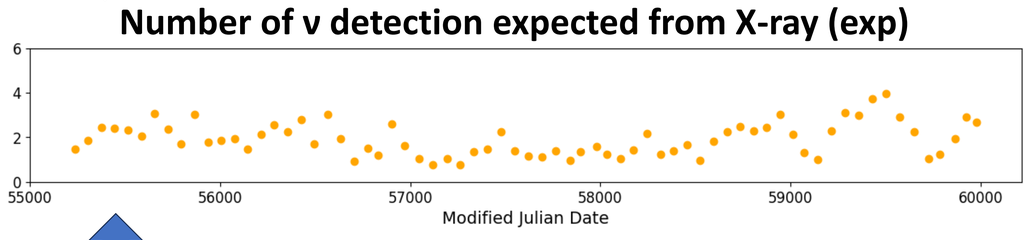
1

- **Transfer function** $f(t-t', C, \Delta T) = \frac{C}{\sqrt{2\pi}\Delta T} e^{-\left(\frac{t-t'}{2\Delta T}\right)^2}$

parameters C: ν ratio to X (corresponds to ξ_{CR})
ΔT: correlation time width (fixed as 10 days)

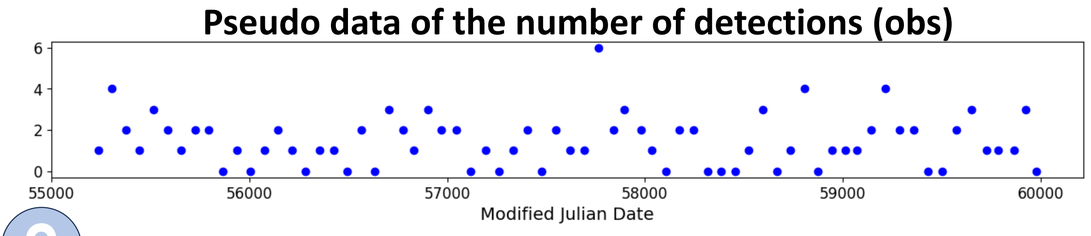
- **Neutrino BG** $\overline{P_\nu^{\mathrm{BG}}}$
- **Spectrum assumption**
- **The Effective area of IceCube**

Number of ν detection expected from X-ray (exp)



2 maximize $\mathrm{TS} = \sum_{\text{data points}} \log \frac{\mathrm{P}(\mathrm{obs}|\mathrm{exp} + \overline{P_\nu^{\mathrm{BG}}})}{\mathrm{P}(\mathrm{obs}|\overline{P_\nu^{\mathrm{BG}}})}$ over C (& ΔT)

Pseudo data of the number of detections (obs)



3 Repeat and fit C (ΔT) for both BG and signal assumption

Sensitivity

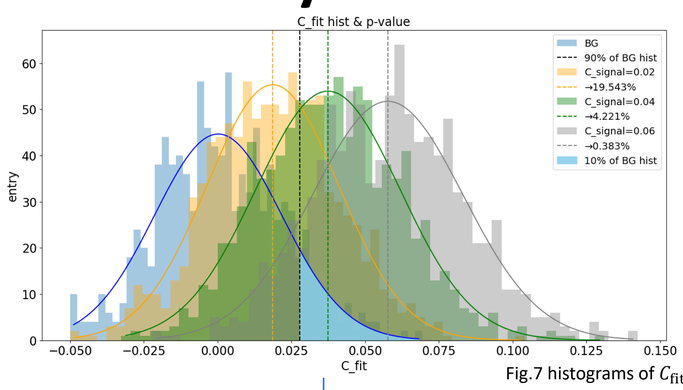


Fig.7 histograms of C_{fit} for BG and some C_{signal}

- Define p-value for each correlation assumption by calculating the level of separation of the C_{fit} hist from BG

A_{eff} of IceCube ν flux assumption → C_{signal} gives the number of expected ν

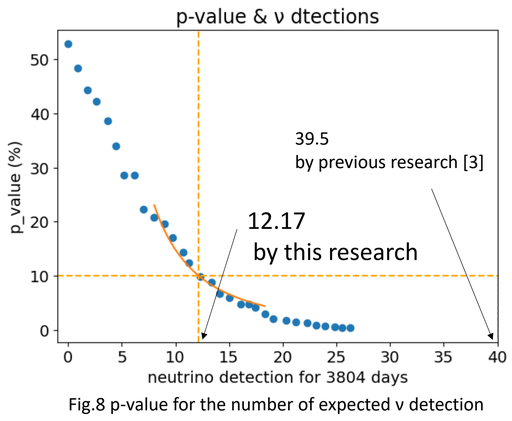


Fig.8 p-value for the number of expected ν detection

- Evaluate p-value for the number of expected ν detections in 10 yrs
- 10% p-value is given by 12.17 ν/3804 days (smaller than 39.5 ν / 10 yr by the previous method!)

Conclusion & Future works

Multi messenger time correlation analysis can

- give a better sensitivity for Seyfert neutrino search
- constrain ξ_{CR} by observations

Next approach will be

- Using 90minutes bin X-ray data to consider time width

References

[1] ICEHAP HP http://www.icehap.chiba-u.jp/icecube/index.html
[2] IceCube collaboration (2022) Science 378, 6619
[3] IceCube collaboration (2024) https://arxiv.org/abs/2406.07601
[4] Murase (2022) Astrophys.J. 941 L17
[5] Murase et.al. (2020) Phys. Rev. Lett. 125, 011101
[6] MAXI on-demand process