Astrophysical neutrinos and their counterparts

13 Dec 2024

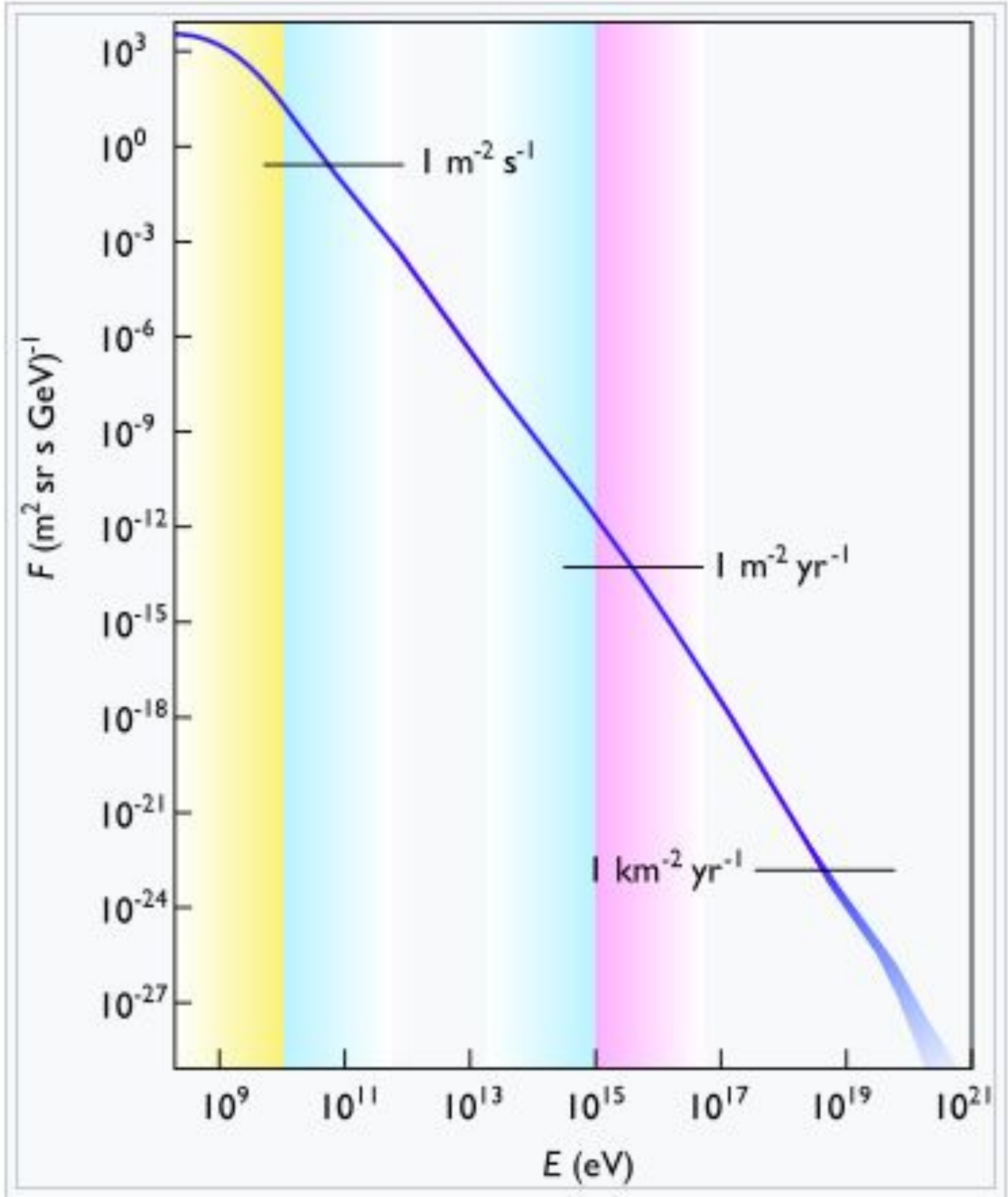
Kalyani C K Mehta
PhD candidate,
Department of Particle Interactions and Detection Techniques,
AGH University of Krakow, Poland

Overview

- **Part - I**: Master's project - Multiwavelength analysis of radio loud AGNs
    - AGNs - Active galactic nuclei and spectral energy distribution
    - Observatories
    - Source selections
    - X-ray and multiwavelength analysis
    - Results and summary
- **Part - II**: Strategy of PhD project - Acoustic detection of ultra high-energy neutrinos using KM3NeT

Motivation - Master thesis

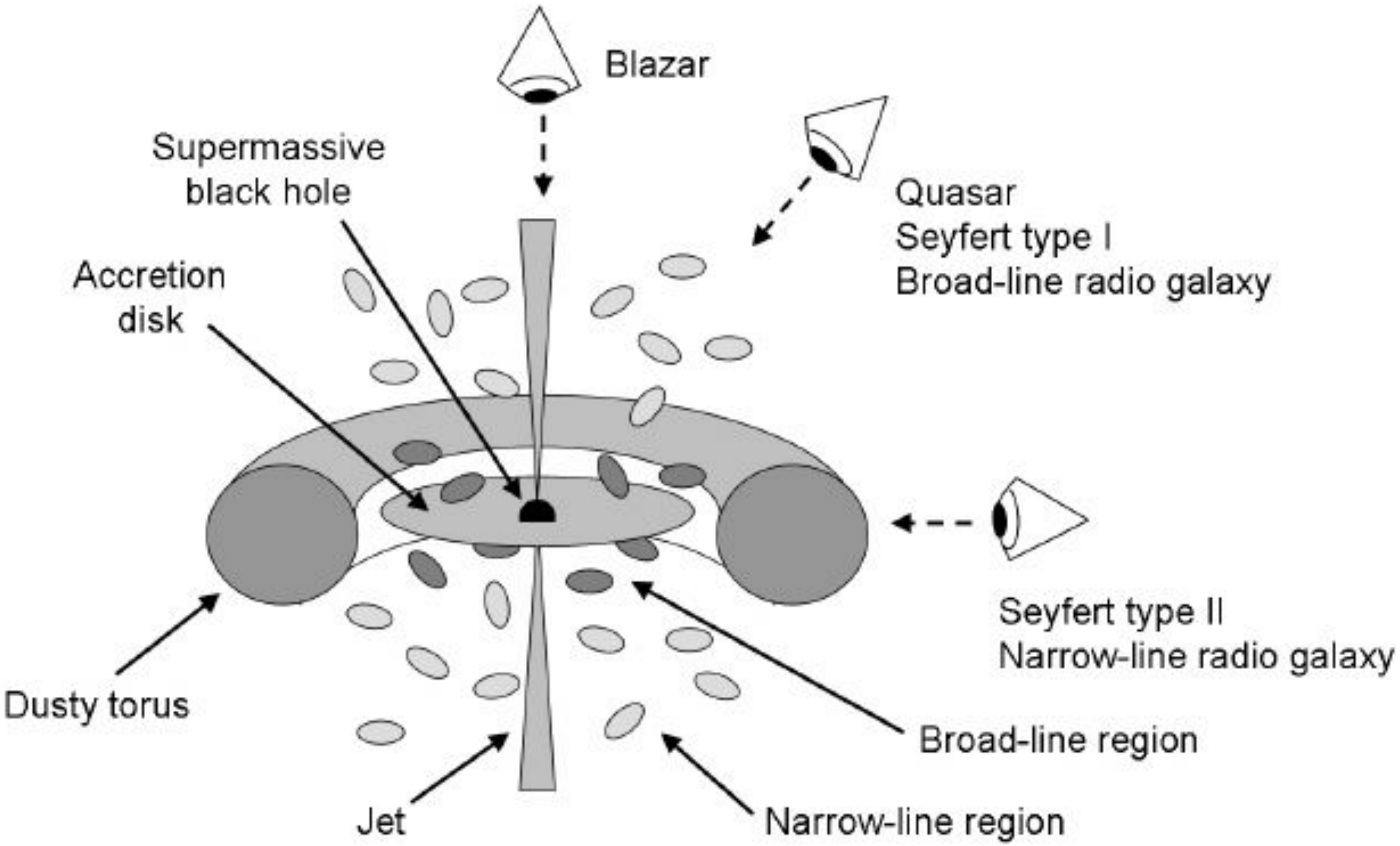
- V. Hess was awarded the 1936 Nobel Prize in Physics for cosmic ray discovery
- Cosmic rays (CR): composition of 90% protons, 9% α particles, and 1% are the nuclei of heavier elements.
- What are the origin of high-energy CR?
- What are the mechanisms behind production of the high-energy CR?



Source: Muzio & Globus, 2023, arXiv:2308.16225

Active Galactic Nuclei (AGNs)

- Extremely bright object, unification model:
  - Radio-loud AGN: radio flux $f_r \geqslant 1$mJy †
  - Radio-quiet AGN: radio flux of $f_r \leqslant 1$mJy
- Blazar relativistic jets at extremely small angles line of sight:
  - BL Lac equivalent line width < 5Å
  - Flat spectrum radio quasar (FSRQ), spectral index (α) $>$ -0.5

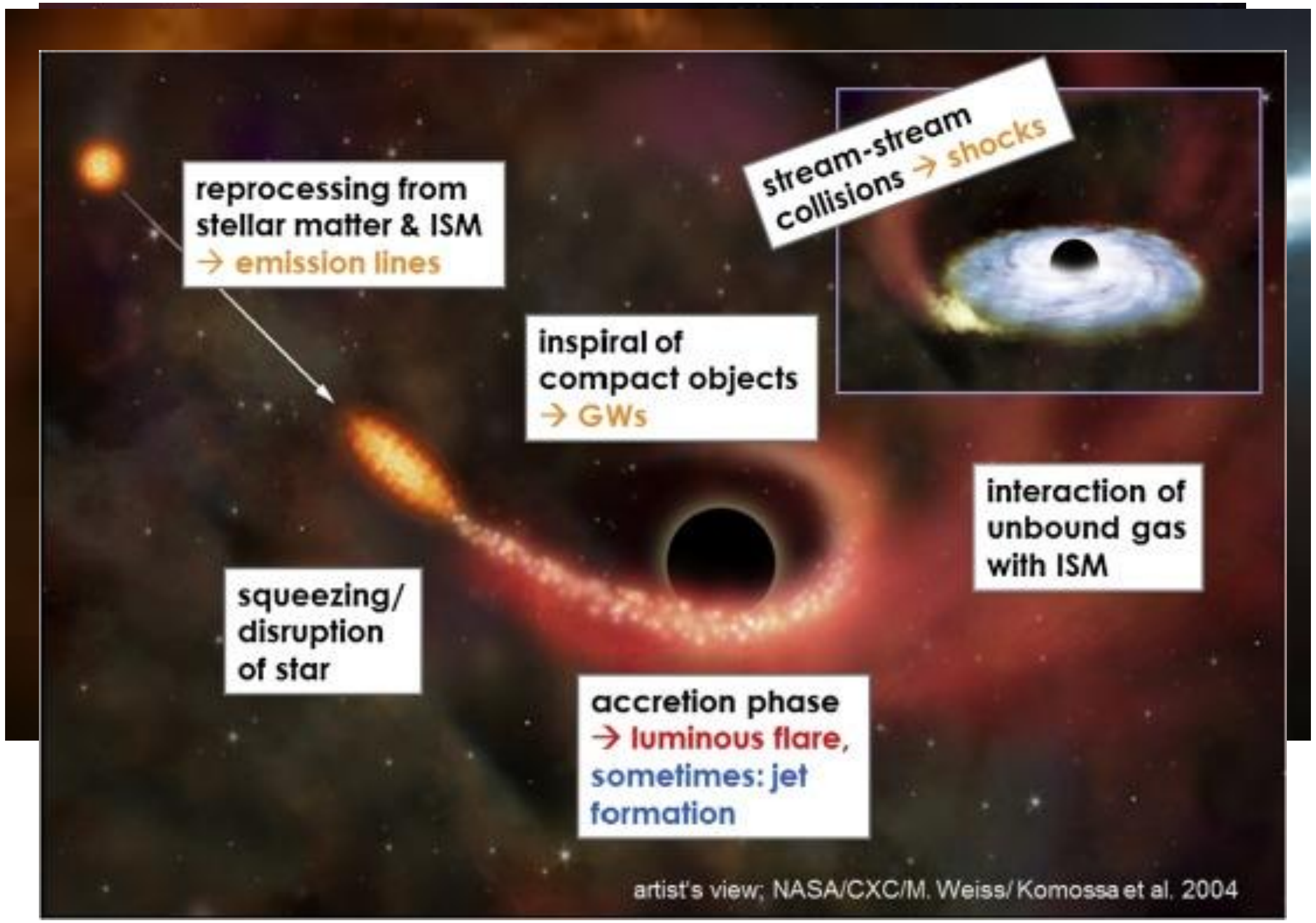


† mJy unit of radio flux density, 1 Jy (jansky) = 10^{-26} W m^{-2} Hz^{-1}

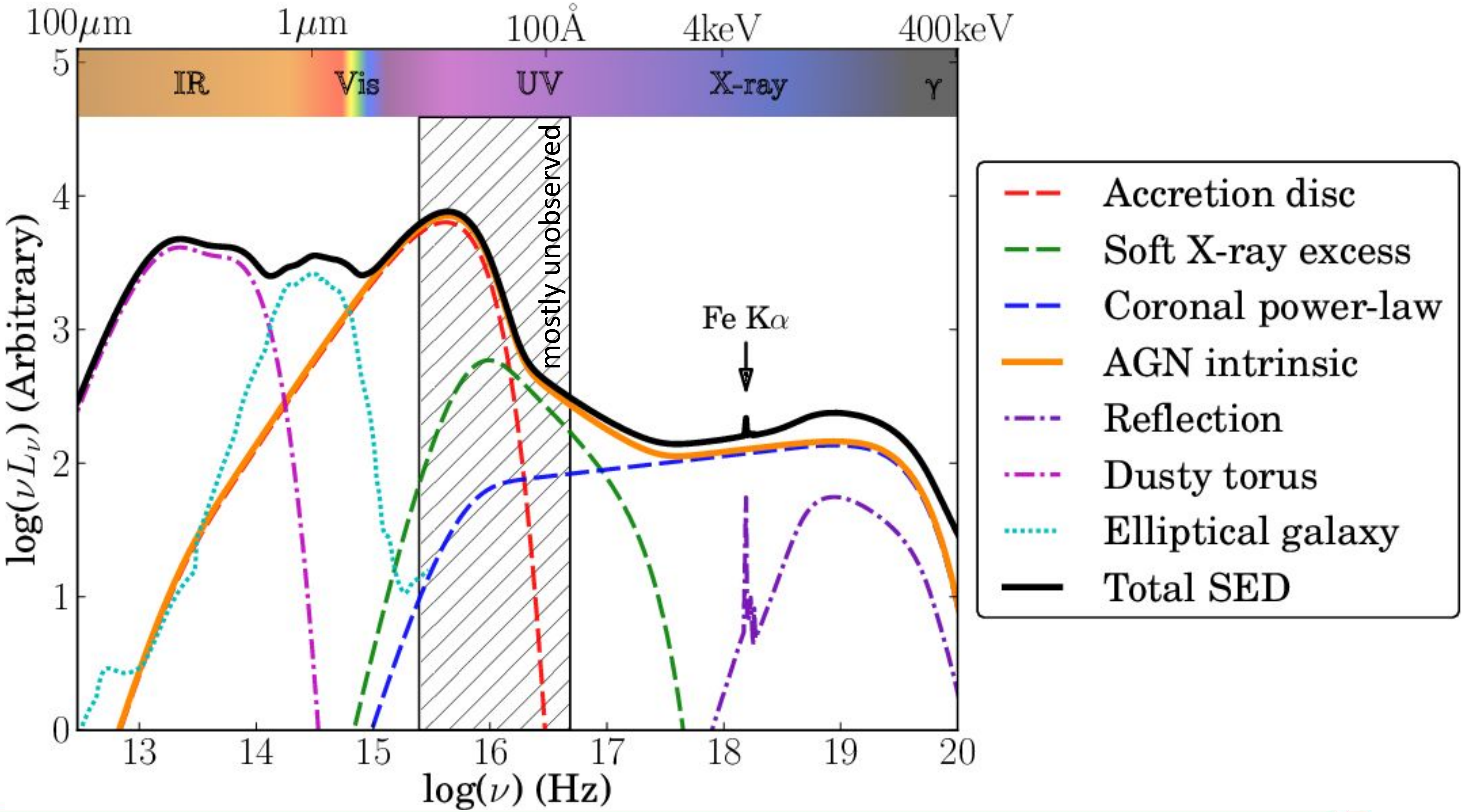
Source: Zackrisson, 2005, Stockholm University

Motivation - Master thesis

- Potential CR source candidates: active galactic nuclei, tidally disrupted events, gamma ray bursts, many other cosmic accelerators
- TXS 0506+056 is the first known evidence of high energy extragalactic neutrinos
- NGC 1068, second evidence of high energy extragalactic neutrinos
- Our galaxy seen through a new lens: neutrinos detected by IceCube

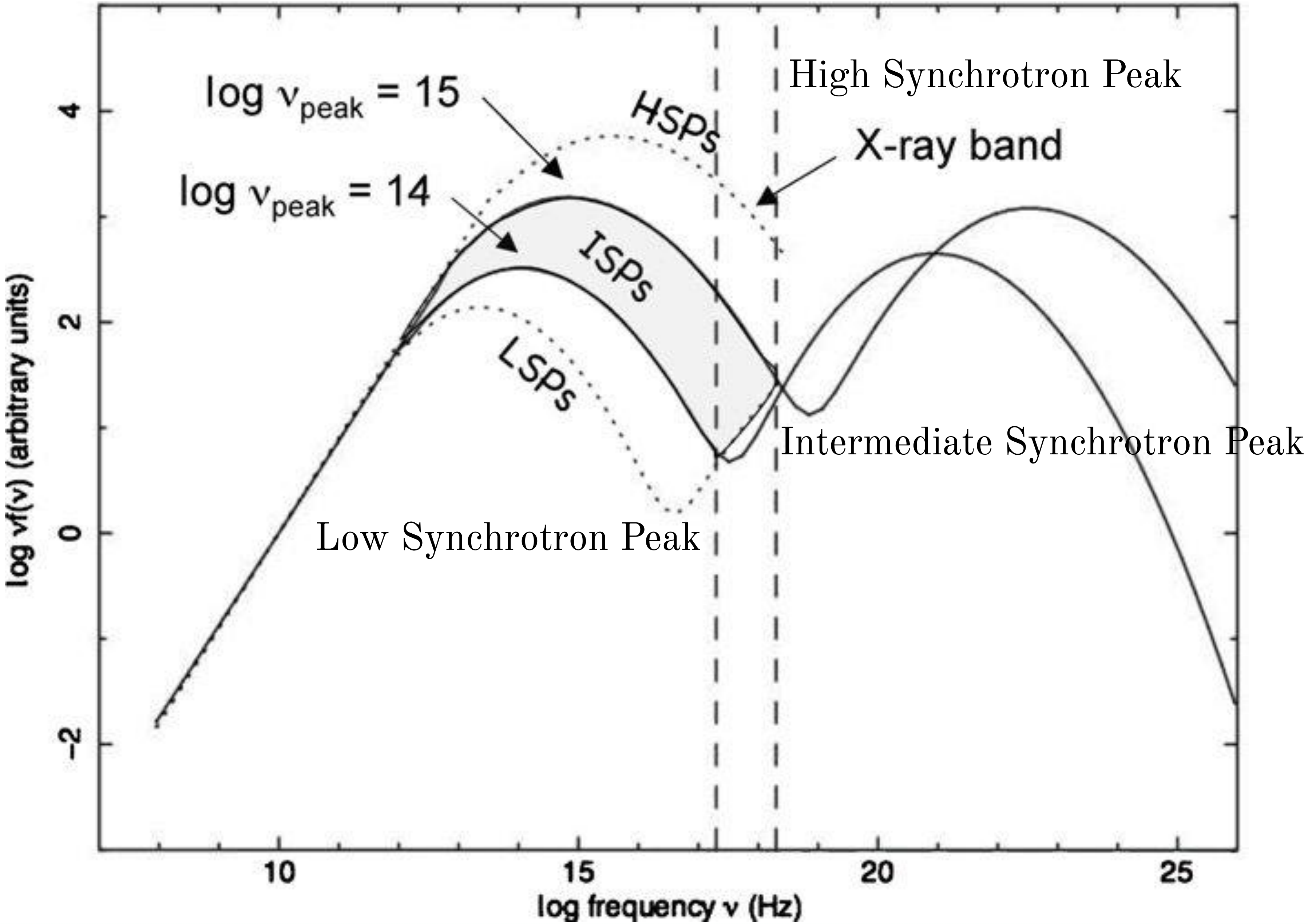


Spectral Energy Distribution (SED)



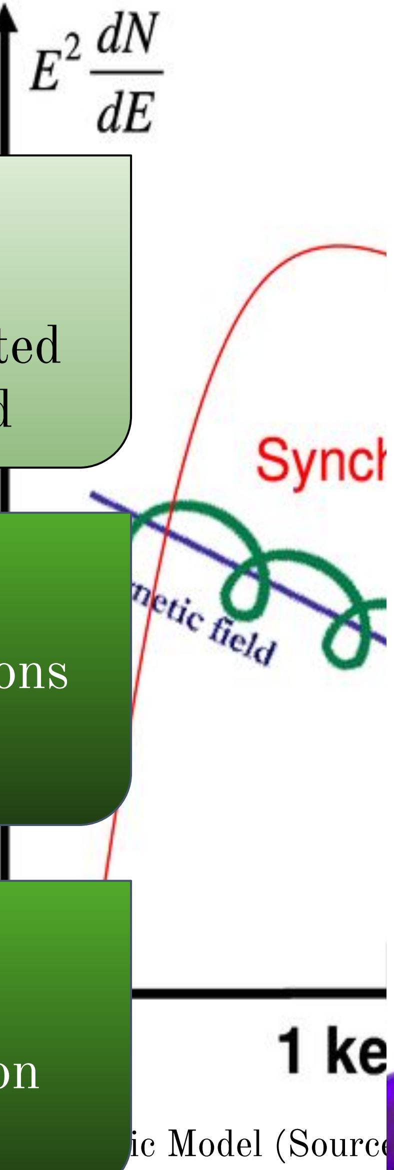
Source: Collinson et al., 2016, MNRAS, DOI: 10.1093/mnras/stw2666

Spectral Energy Distribution (SED)



Source: adlibitum.oats.inaf.it/monaco/Lectures/notes_AGN_18_19.pdf

Leptons and Hadronic models

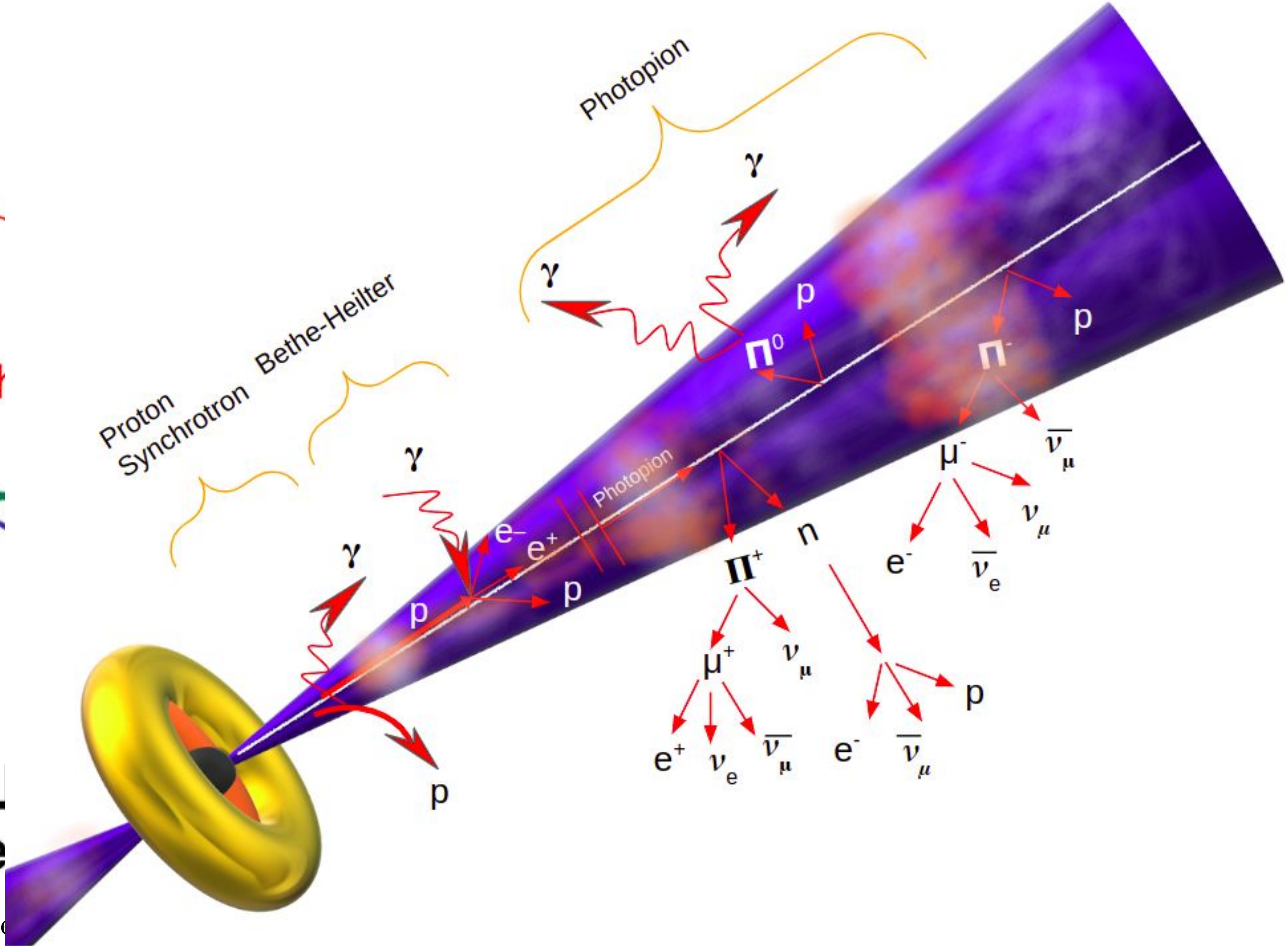


Radiation emitted from a relativistic electrically charged particle accelerated due to high magnetic field

Pair production at low energies; protons & photons collide

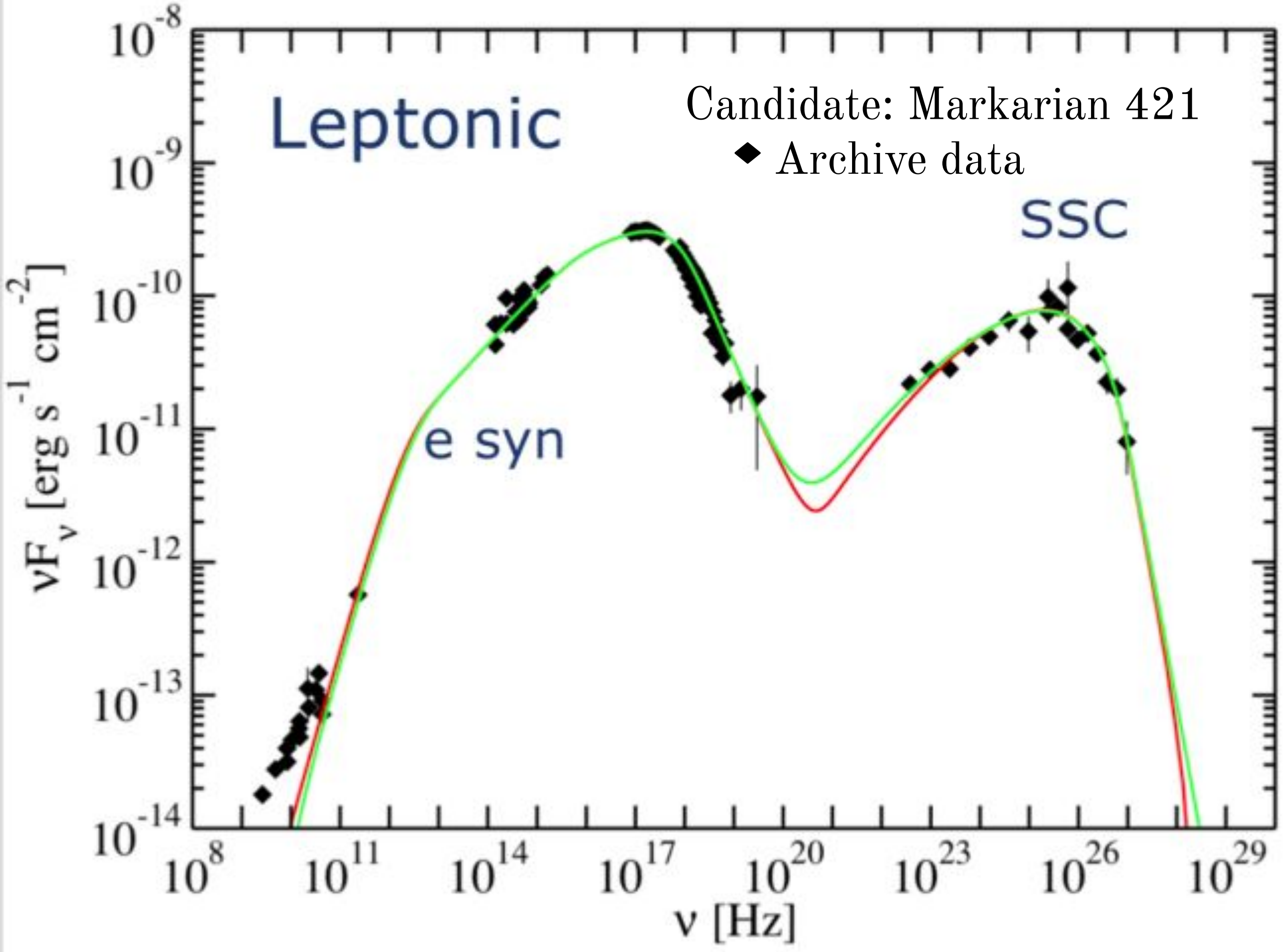
p–γ interaction produces photo-pion or photo-meson

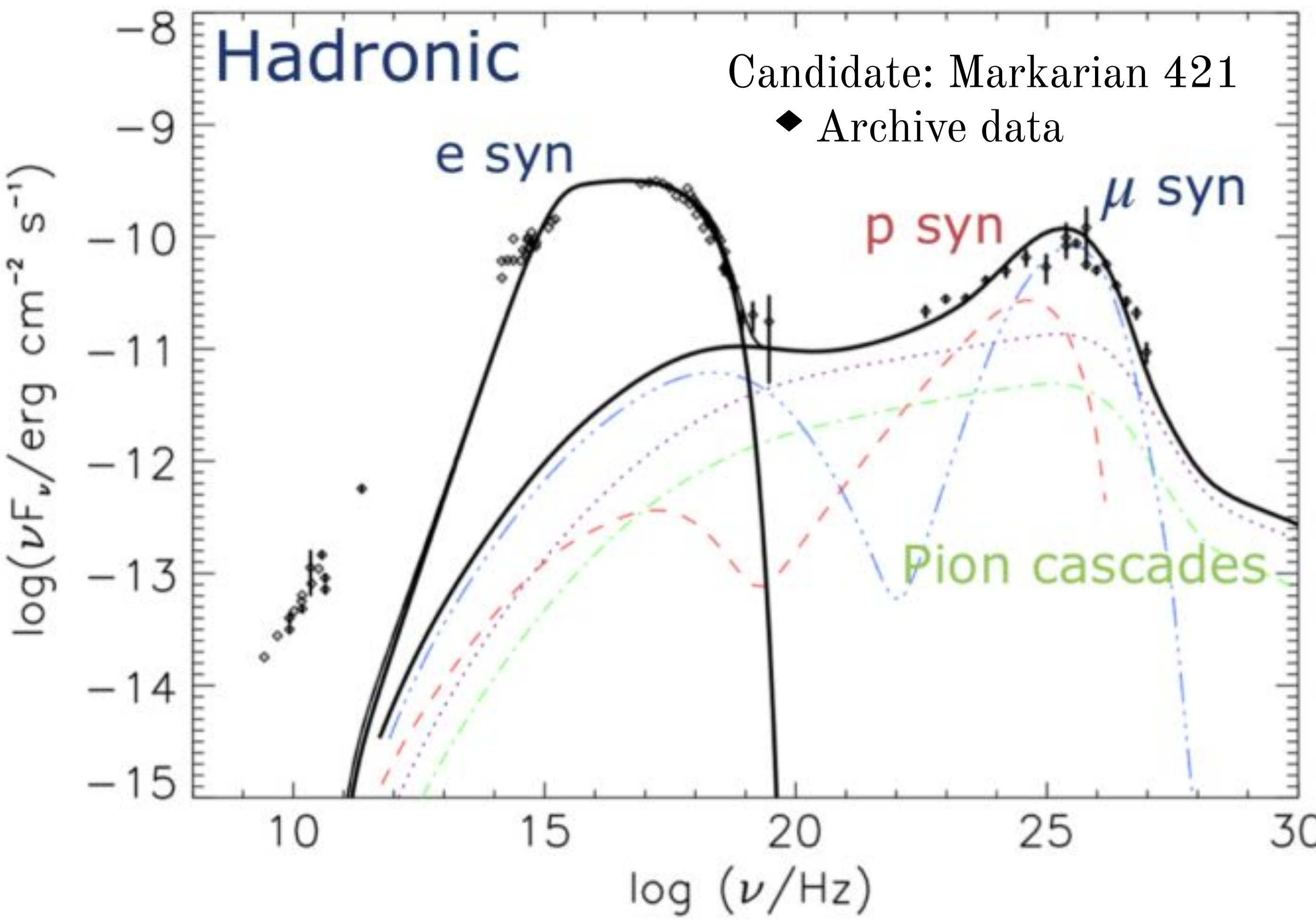
ic Model (Source



Created by: K C K Mehta inspired from Mastichiadis, 2016

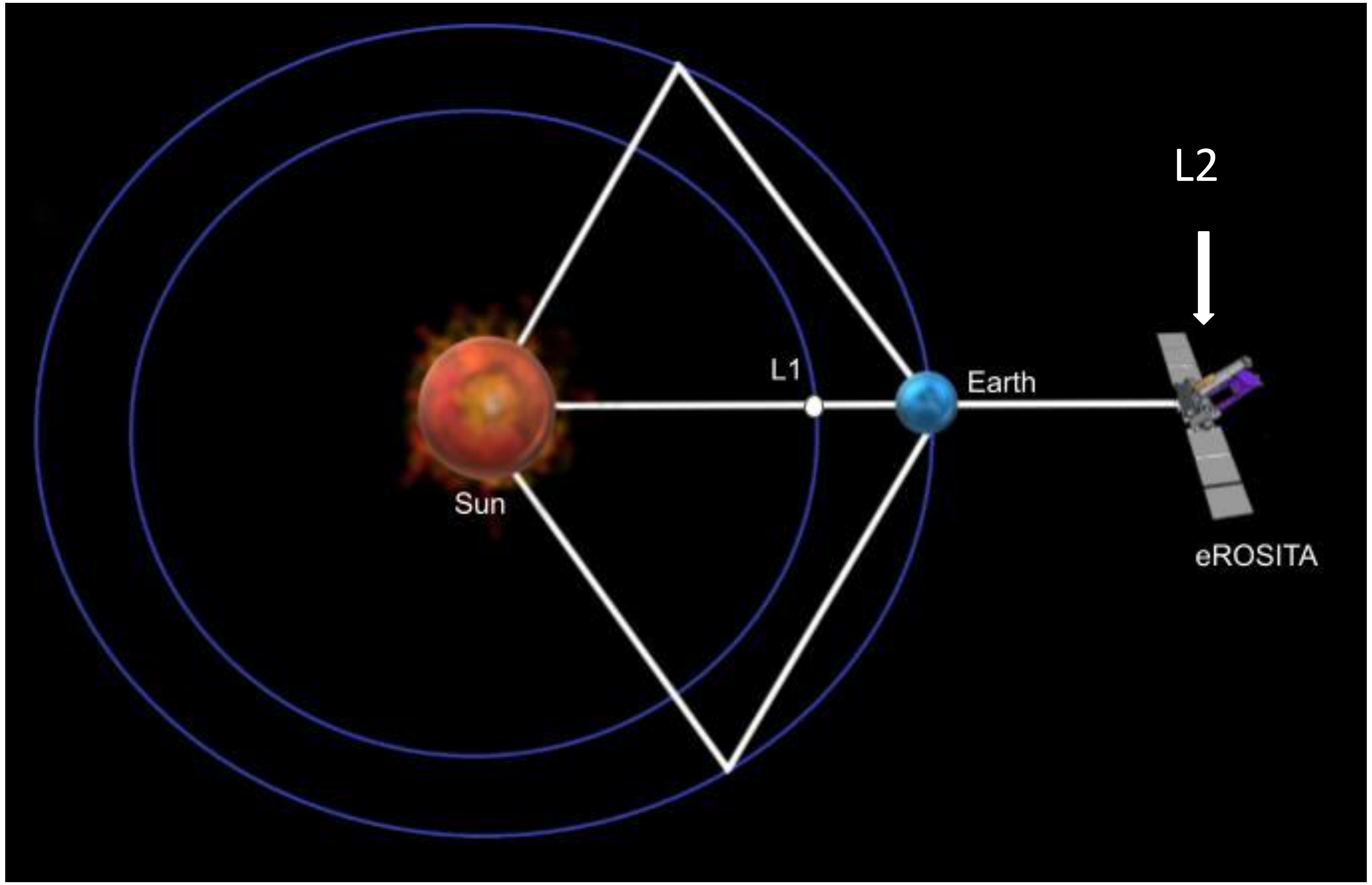
Models of Spectral Energy Distribution





Observatories

- extended ROentgen Survey with an Imaging Telescope Array (eROSITA)
- Sensitivity range: 0.2 - 8 keV and angular resolution: 15 seconds
- eROSITA Final Equatorial-Depth Survey (eFEDS), early releases X-ray data



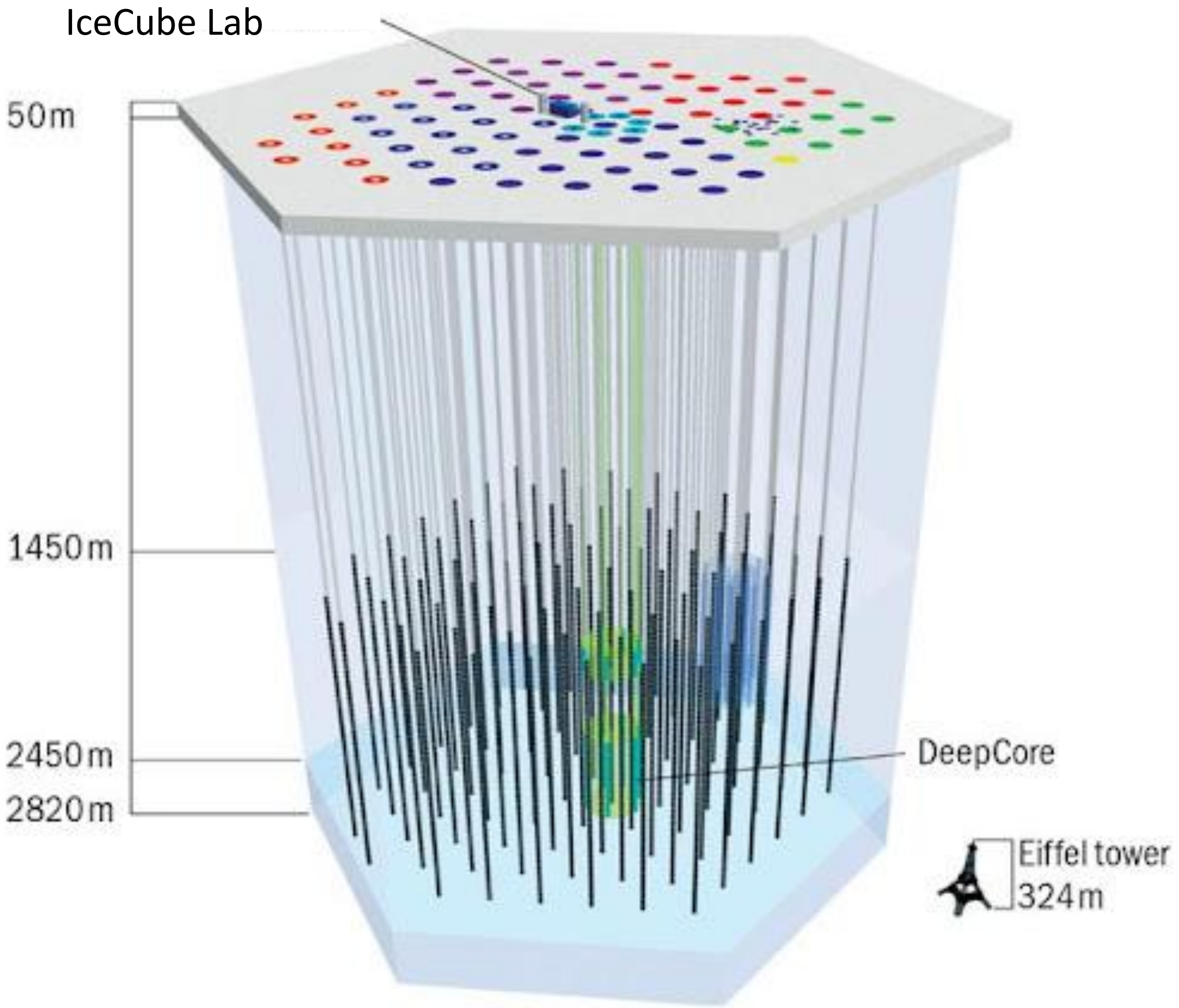
Created by: K. Mehta, inspired by Merloni et al., 2012, arXiv:1209.3114

Observatories

Source: Dr. P. Kalaczyński ICHEP 2022

Observatories

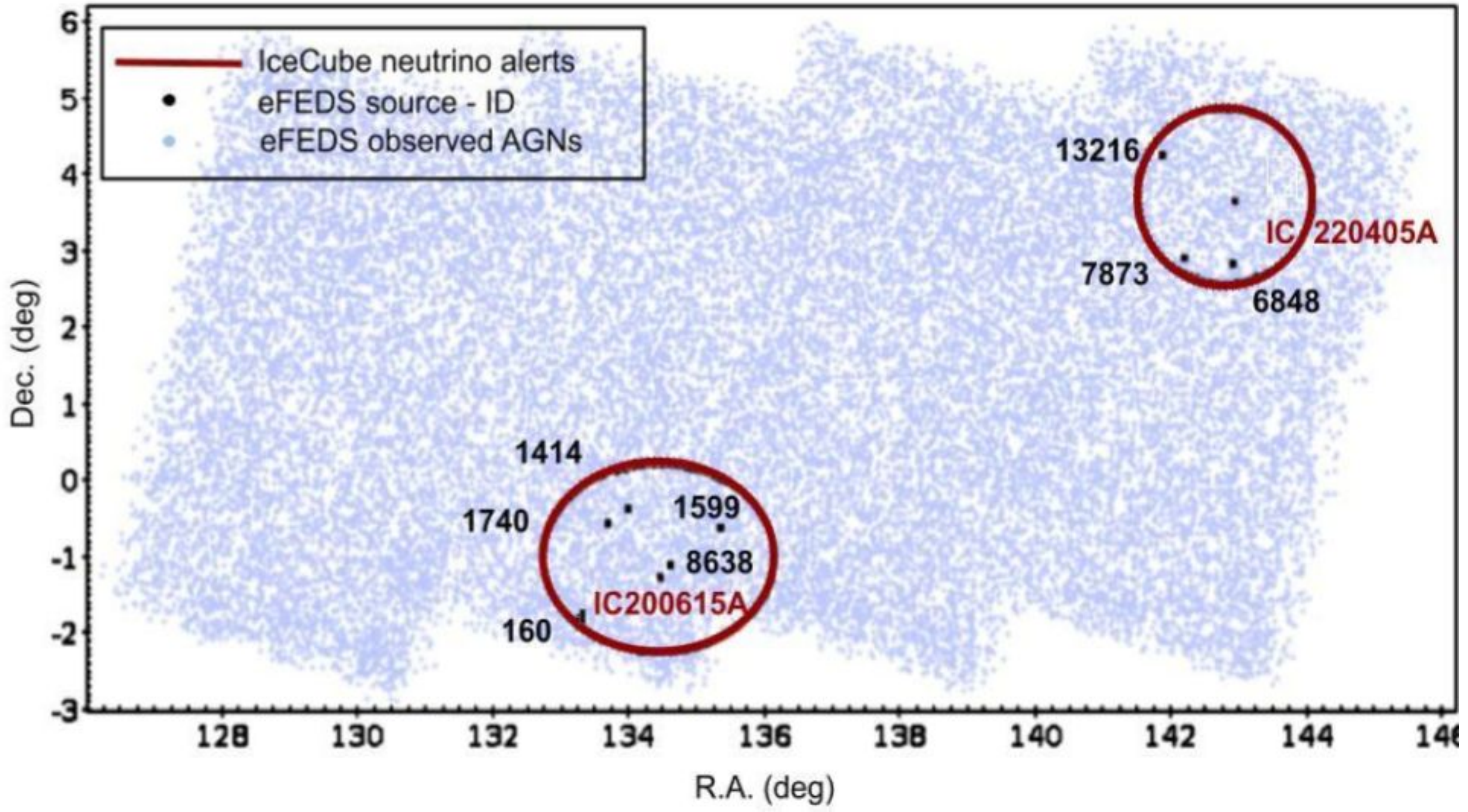
- IceCube neutrino observatory at South Pole, observing in the energy range 10 GeV - PeV
- Signalness $S = N_{signal} / (N_{signal} + N_{background})$
- $N_{background} = N_{atmospheric\ mouns} + N_{atmospheric\ neutrinos}$
  N refers to number of events expected
- Gold alerts: $S > 50\%$



Credit: IceCube Collaboration

Sample Selection

- Two "gold" neutrino alerts of energy above 100 TeV
  - IC220405A: R.A. $134.47^{+1.71}_{-1.72}$ ° & Dec. $-1.27^{+1.45}_{-1.02}$ °
  - IC200615A: R.A. $142.95^{+1.18}_{-1.45}$ ° & Dec. $3.66^{+1.19}_{-1.06}$ °
- Eight radio-loud AGNs in the vicinity of the neutrino events



Sample Selection

Names	eROSITA-ID	R.A. (°)	Dec. (°)	Sep. angle (°)
IC200615A				
5BZQ J0853-0150	160	133.2555	-1.8466	1.34
5BZQ J0855-0021	1414	133.9769	-0.3628	1.03
5BZQ J0901-0037	1599	135.3576	-0.6175	1.10
J085446.24-003348.1	1740	133.6926	-0.5633	1.05
CRATES J085827-010657	8638	134.6216	-1.1177	0.22
IC220405A				
J093141.09+023616.2	6848	142.9212	2.6045	1.06
J092706.83+042722.1	13216	141.7784	4.4561	1.42
CRATES J092810+024118	7873	142.0462	2.6890	1.96

X-ray analysis

Posterior

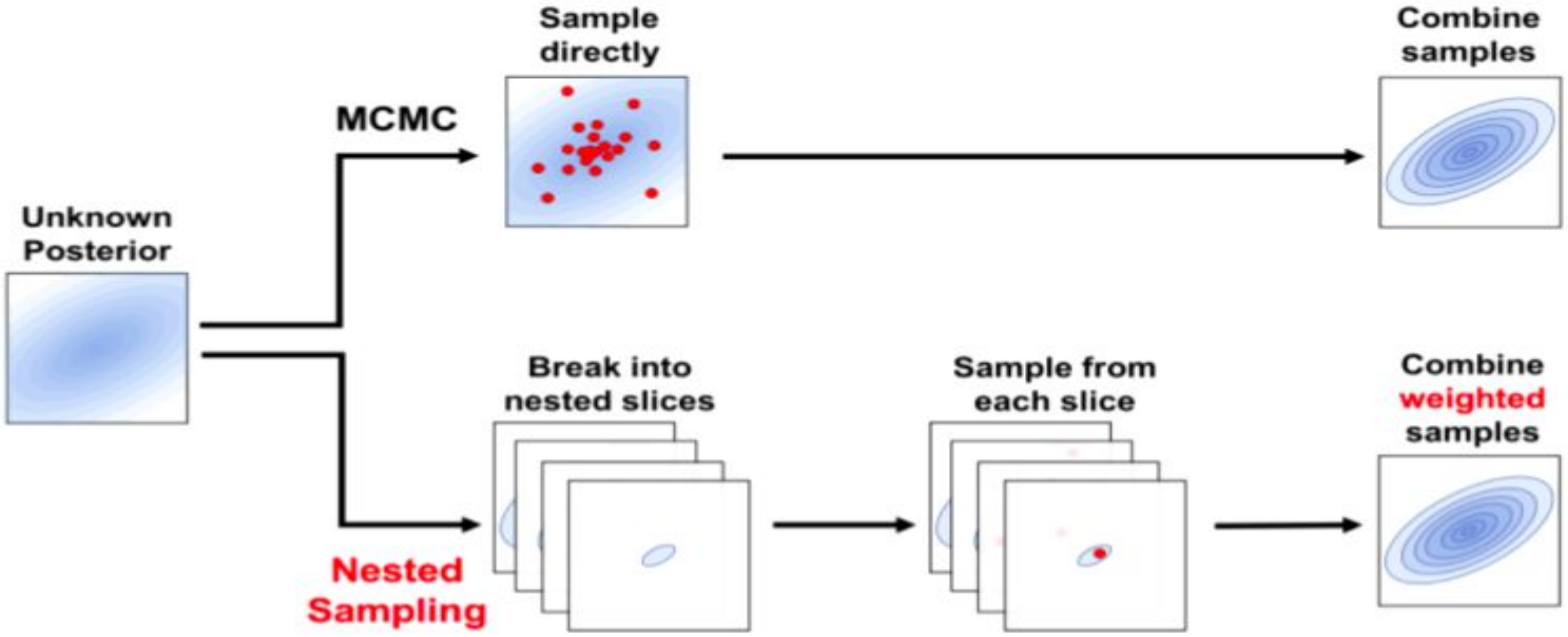
Prior

$$P(\theta|D) = \frac{\pi(\theta)\ P(D|\theta)}{Z(D)}$$

Likelihood

Bayesian evidence

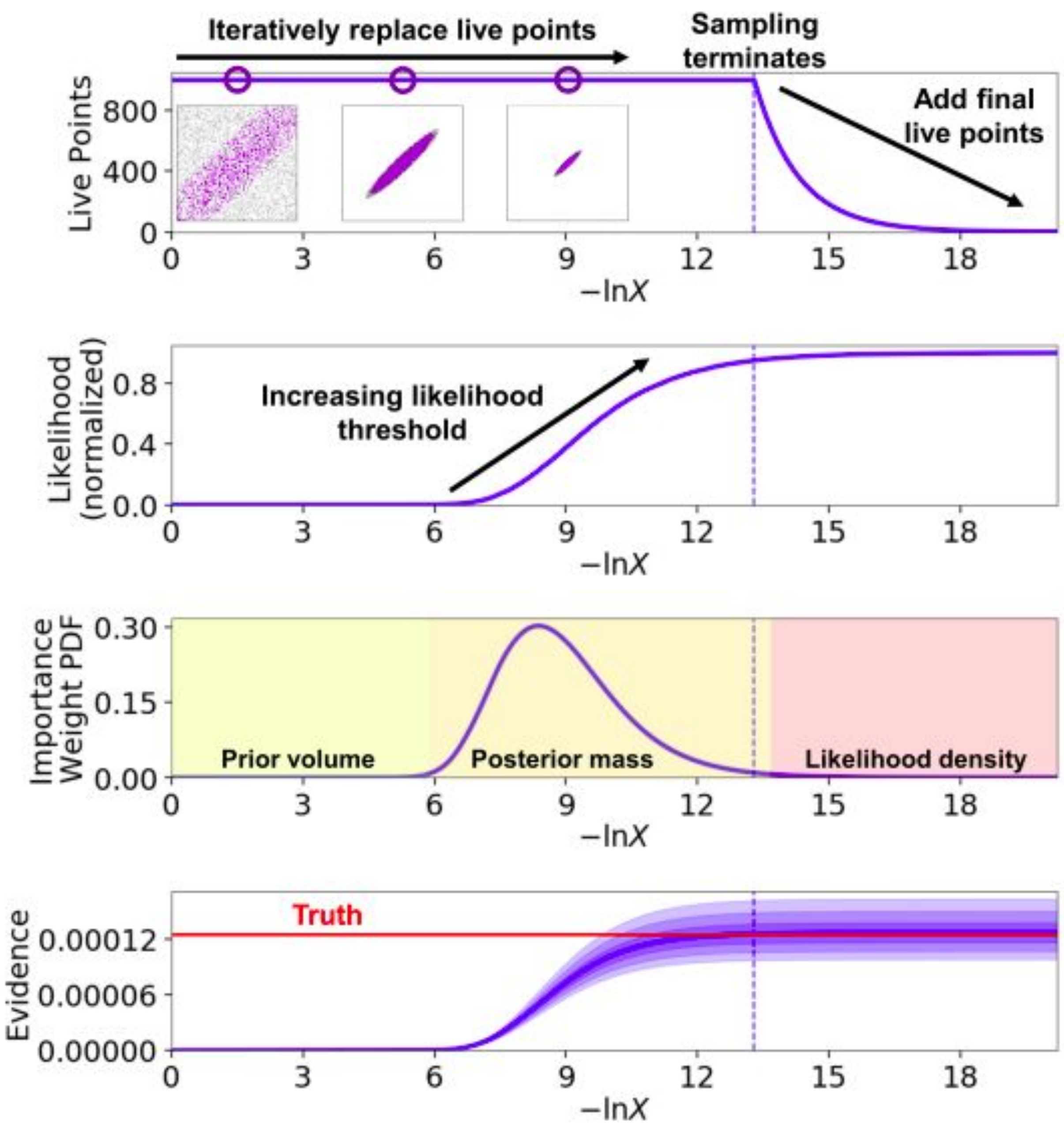
Thomas Bayes



Source: Speagle, 2019, arXiv:1904.02180, and github.com/JohannesBuchner/UltraNest/issues

X-ray analysis

- Multi-Nested Loops:
  - Initialize live points
  - Main sampling loop
  - number of live points as a function of prior volume X
  - live points remains constant until sampling terminates
  - the estimated evidence Z(X) along with errors



Source: J. S Speagle 2019 arXiv:1904.02180

X-ray analysis

TBabs x zTBabs (powerlaw + constant x spowerlaw)	TBabs x zTBabs x (pow + zbbody)	TBabs x zTBabs x pow	TBabs x pow
TBabs - Galactic absorption, zTBabs - Intrinsic absorption with relativistic effects and double power law model	Galactic absorption, intrinsic absorption, power law, and zbbody: black body model	Galactic absorption, intrinsic absorption, and power law model	Galactic absorption and power law model

Background Fitting

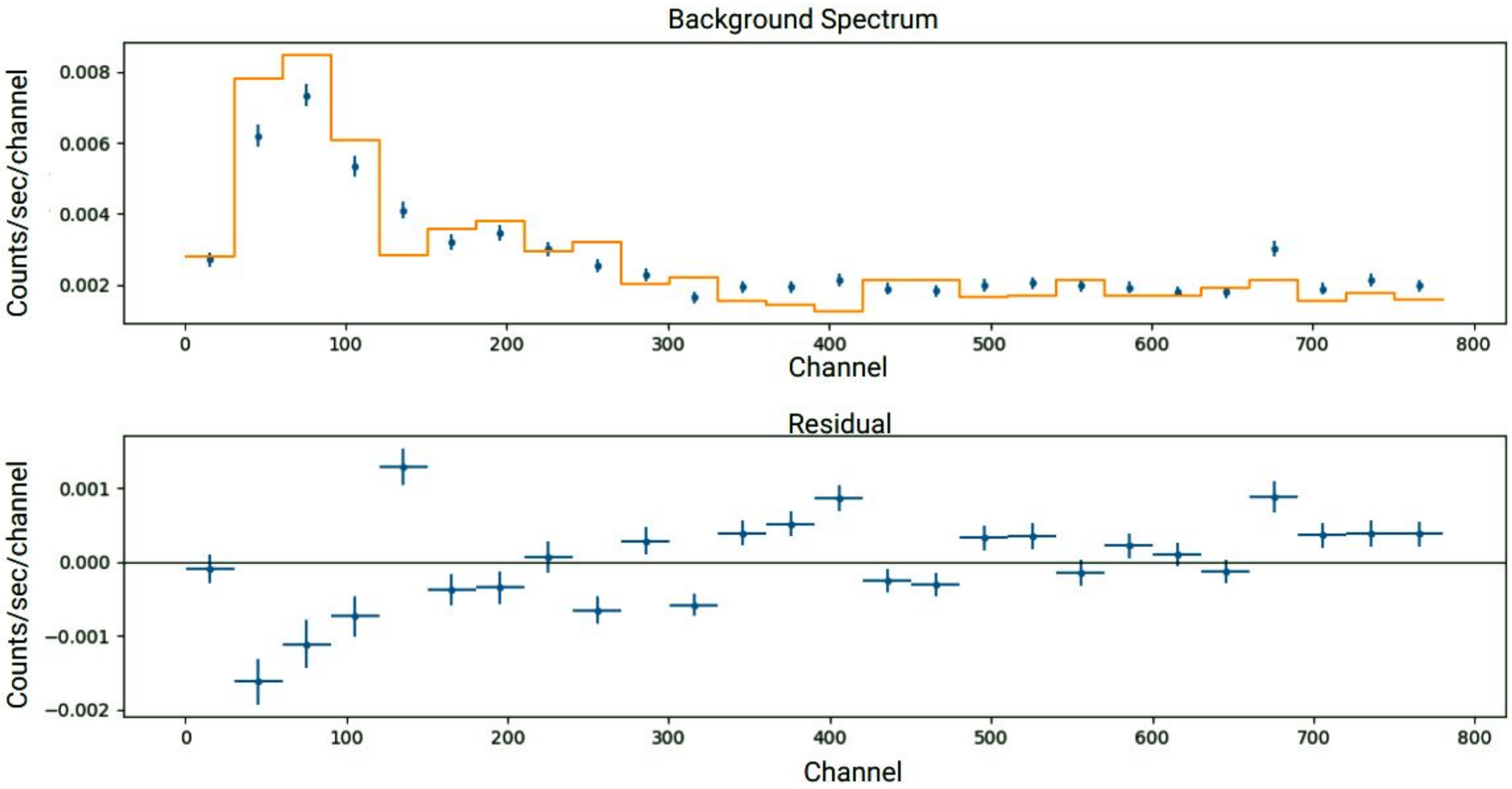
Principal component analysis (PCA) is a reduction of the dimensionality used for the background fitting

How PCA works:

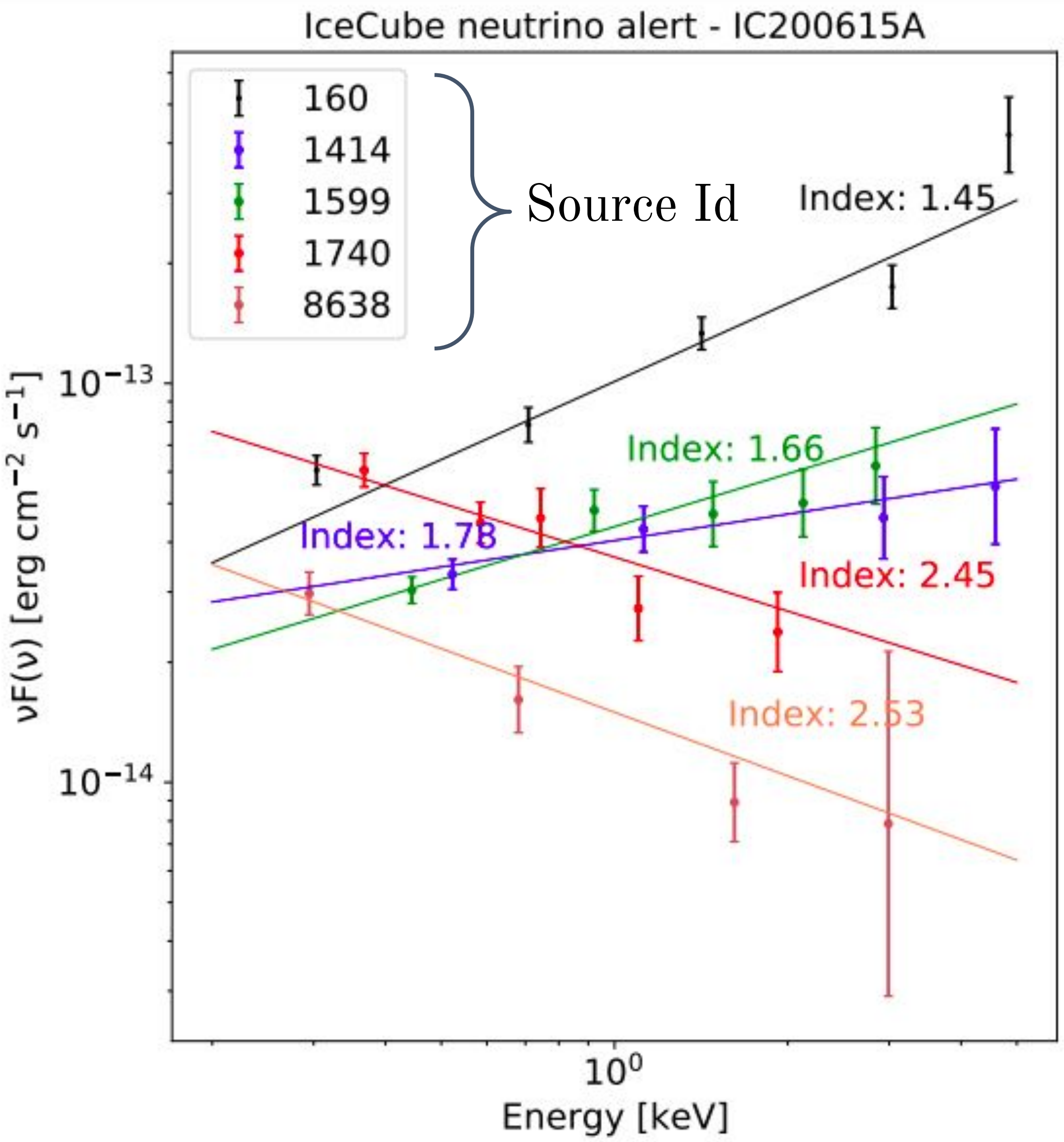
1) Extract the essential information

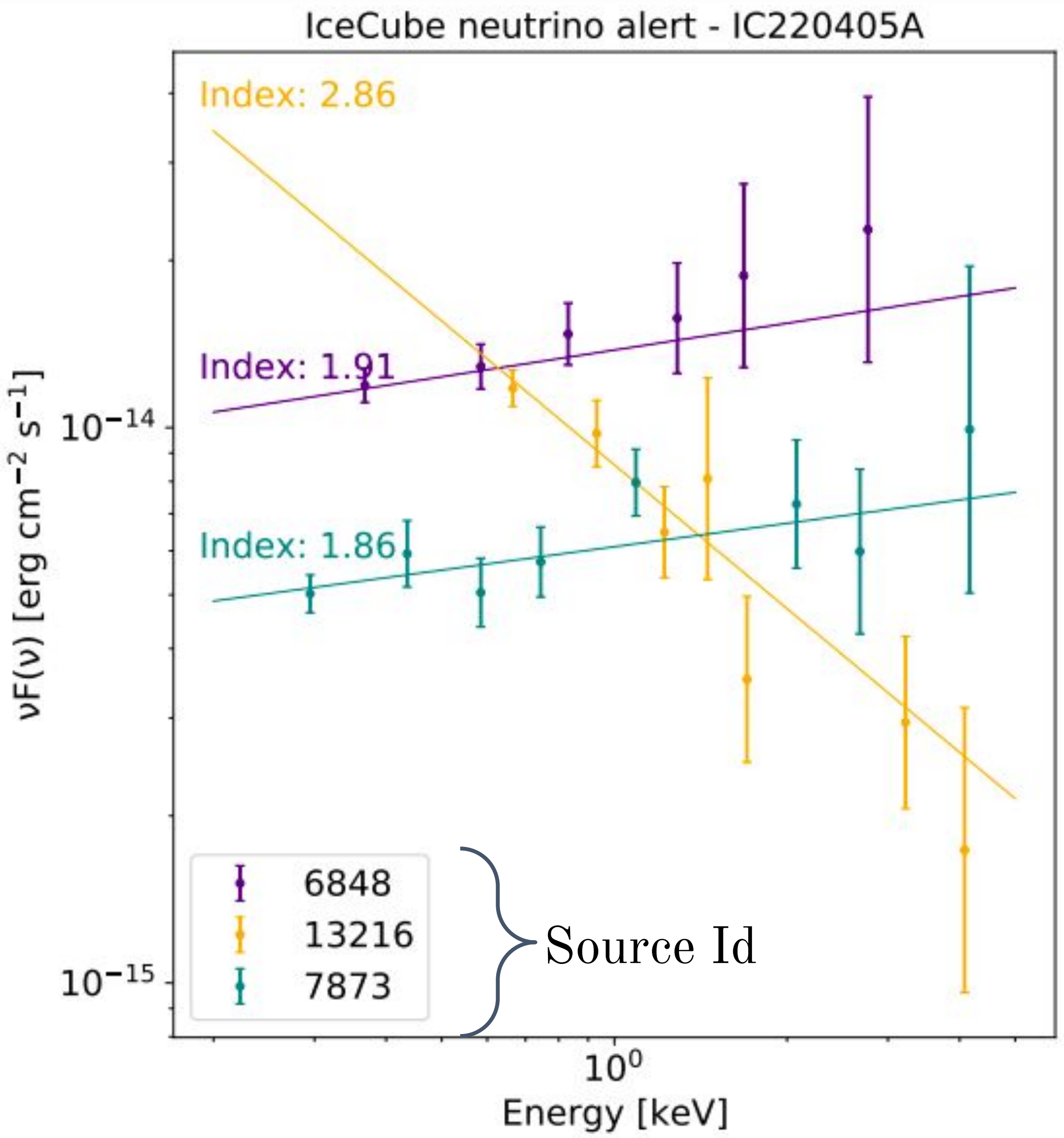
2) Examine the variables

3) Compress the data by reducing the dimensions



Results

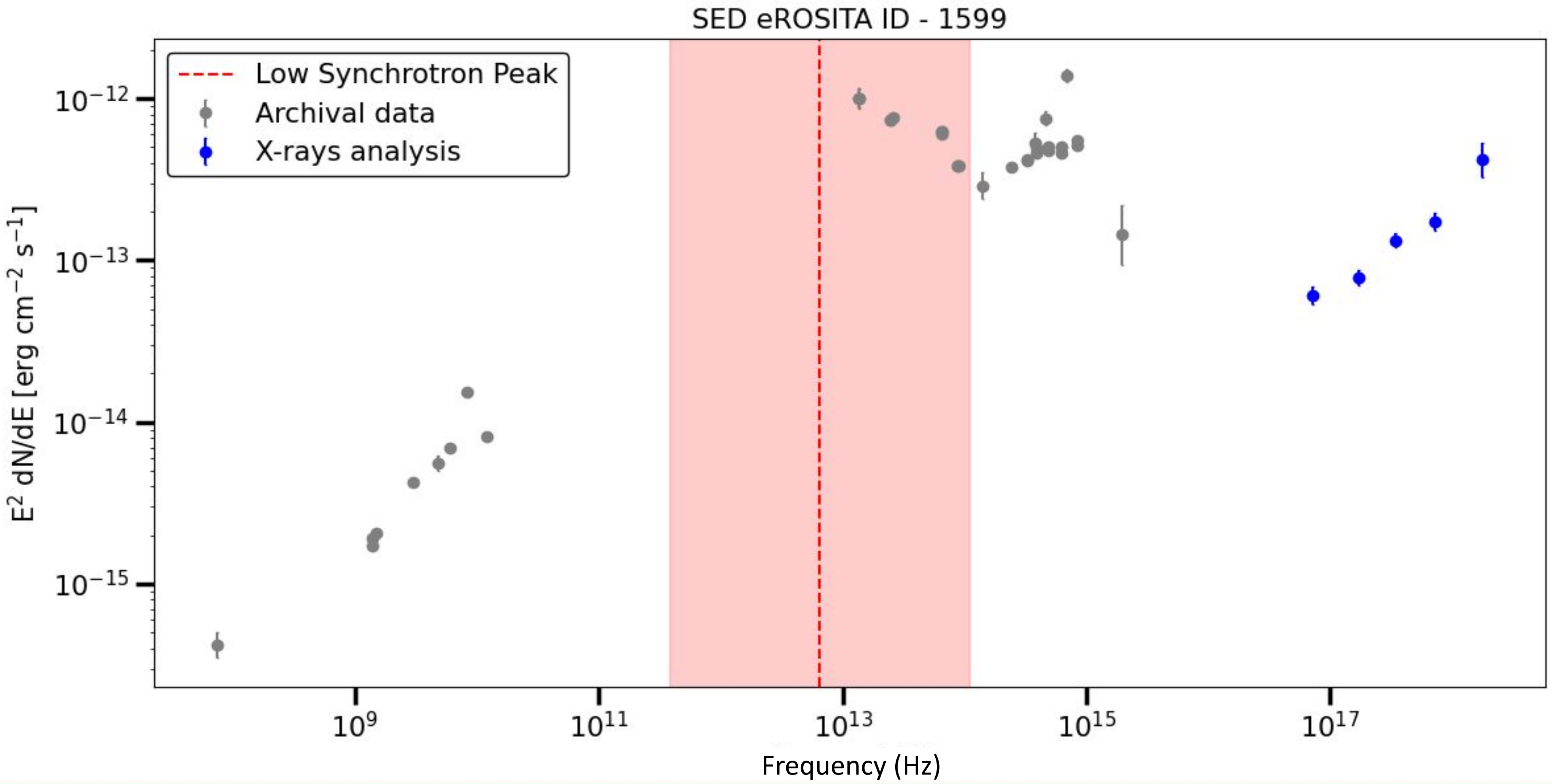




Hard powerlaw index in X-rays: $\Gamma < 2$ and Soft powerlaw index in X-rays: $\Gamma > 2$

Results

- BlaST - A machine-learning estimator for the synchrotron peak of blazars
- Using archival multi-wavelength data used from Space Science data center



Results

- Eddington limit: Maximum luminosity an accreting black hole can reach before radiation pressure halts further infall, limiting its growth

- $L_{emitted} = L_{observed}$ / Doppler Factor^4
- Doppler factor = 2 x Lorentz factor (FSRQ ~ 10)

- $L_{Eddington} = 1.26 \times 10^{38} (M / M_{\odot})$ erg s^{-1}
- Eddington limit = $L_{emitted} / L_{Eddington}$
- Eddington limit < 1 is sub-Eddington Limit

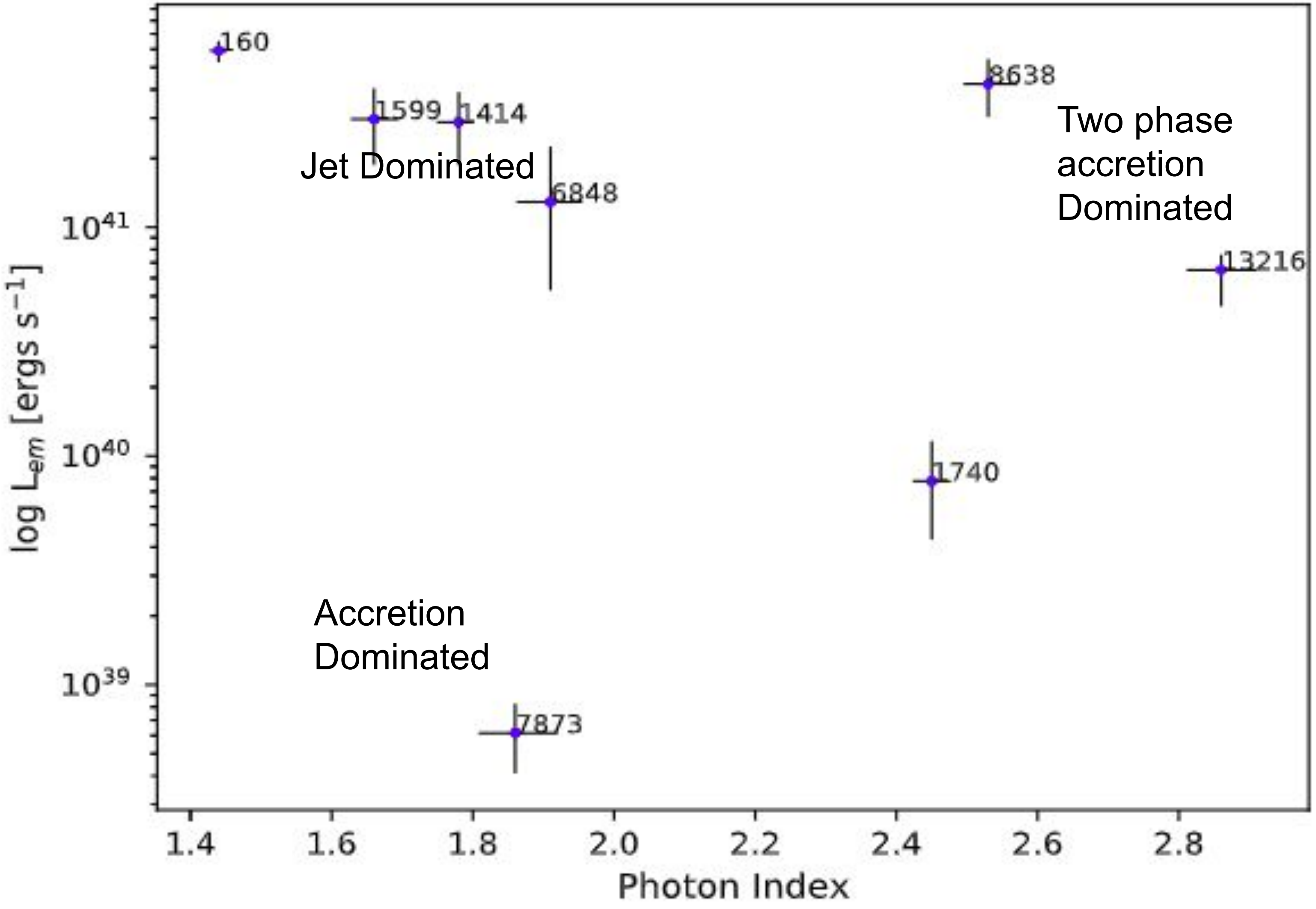
Source	Syn Peak (Hz)	Peak Type	log M_{BH}^{1} ($M_{\odot}$)	L_{em}/L_{Edd}
160	12.99 ± 1.19	LSP	8.99	4.39E-06
1414	13.87 ± 1.20	LSP	9.31	8.09E-07
1599	12.81 ± 1.27	LSP	8.73	4.00E-06
1740	13.99 ± 1.14	LSP	8.69	1.15E-07
8638	14.04 ± 1.41	ISP	9.17	2.08E-06
6848	13.39 ± 1.47	LSP	9.67	2.00E-07
13216	13.94 ± 1.23	LSP	8.63	1.10E-06
7873	13.03 ± 1.34	LSP	10.59^{0}	1.15E-10

Multi-wavelength characteristics of the sources

0) Mass basing for the Eddington limit
1) Source: SDSS DR V and SDSS DR IV: Accessed from https://skyserver.sdss.org/dr5/en/sdss/release/

Results

- Jet dominated: X-ray emission mostly dominated by jets
- Accretion dominated: X-ray emission mostly dominated by hot accretion flows
- Two phase accretion dominated: Disc photons are upscattered by corona (compton scattering) → Produce high-energy X-rays



Summary of master's work

- Sources 160, 1599, 1414, and 6848 have X-ray luminosities mostly emitted by the jets
- The source 7873 X-ray luminosity might be dominated by the hot accretion flows
- Source 8638, 1740, and 13216 might have a huge contribution from two-phase accretion flow (disc-corona)
- All the sources are flat radio spectrum quasars, variability in radio, optical bands and no observation at MeV and higher energies

Inspired by: Yang, Q.-X., Xie, F.-G., Yuan, F., Zdziarski, A. A., Gierliński, M., et al. (2015)

So, which sources produced these neutrino alerts?

We need a better detector!

Acoustic detection of ultra high-energy neutrinos using KM3NeT

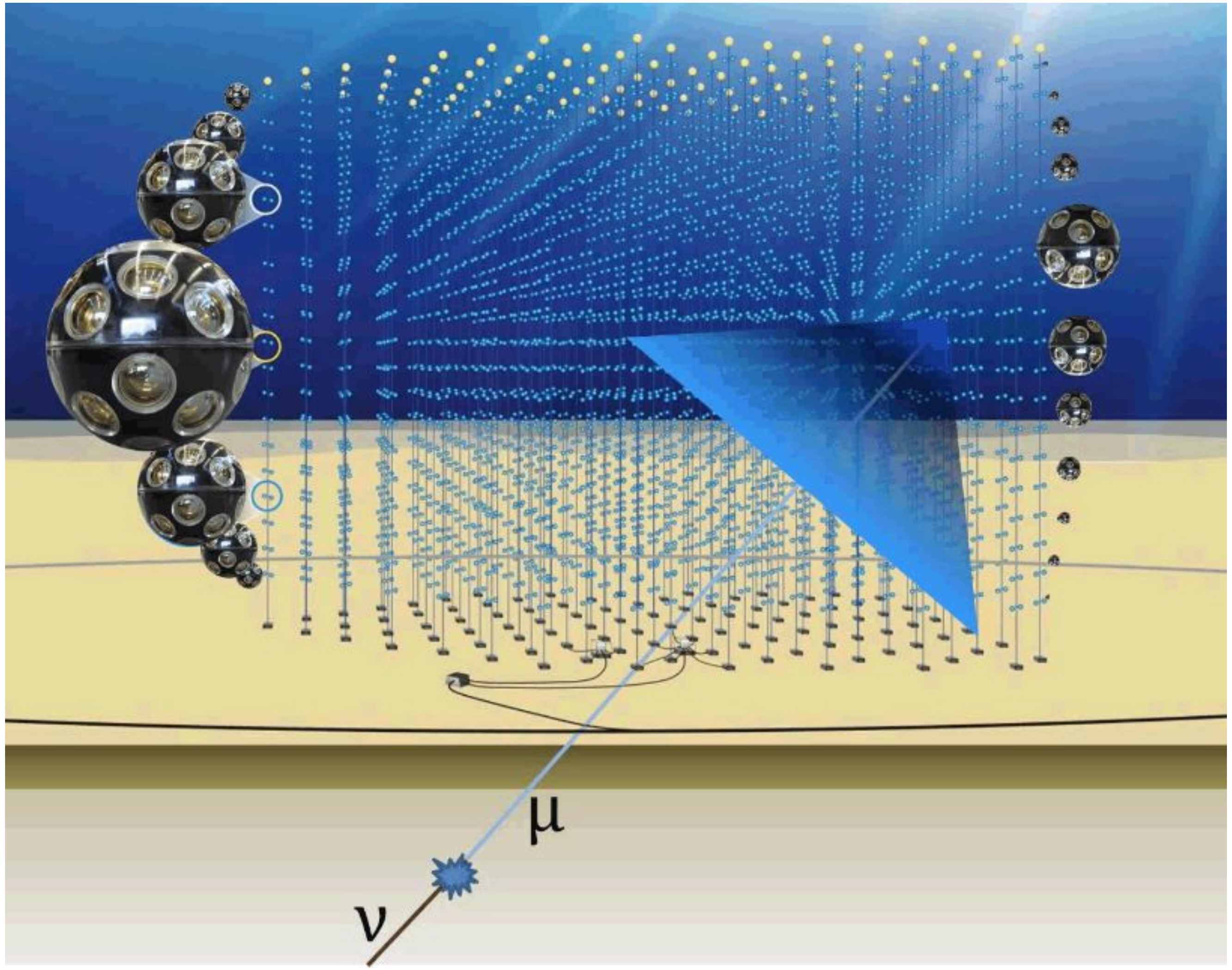
KM3NeT

AGH

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

Cubic Kilometre Neutrino Telescope KM3NeT

- KM3NeT consists of two detection sites:
  - ARCA (Astroparticle Research with Cosmics in the Abyss): Sensitive to TeV-PeV energies
  - ORCA (Oscillation Research with Cosmics in the Abyss): Sensitive to GeV energies
- Sensitivity of the acoustic sensors:
  160 ± 6 dB referenced to 1V/μPa at 50 kHz



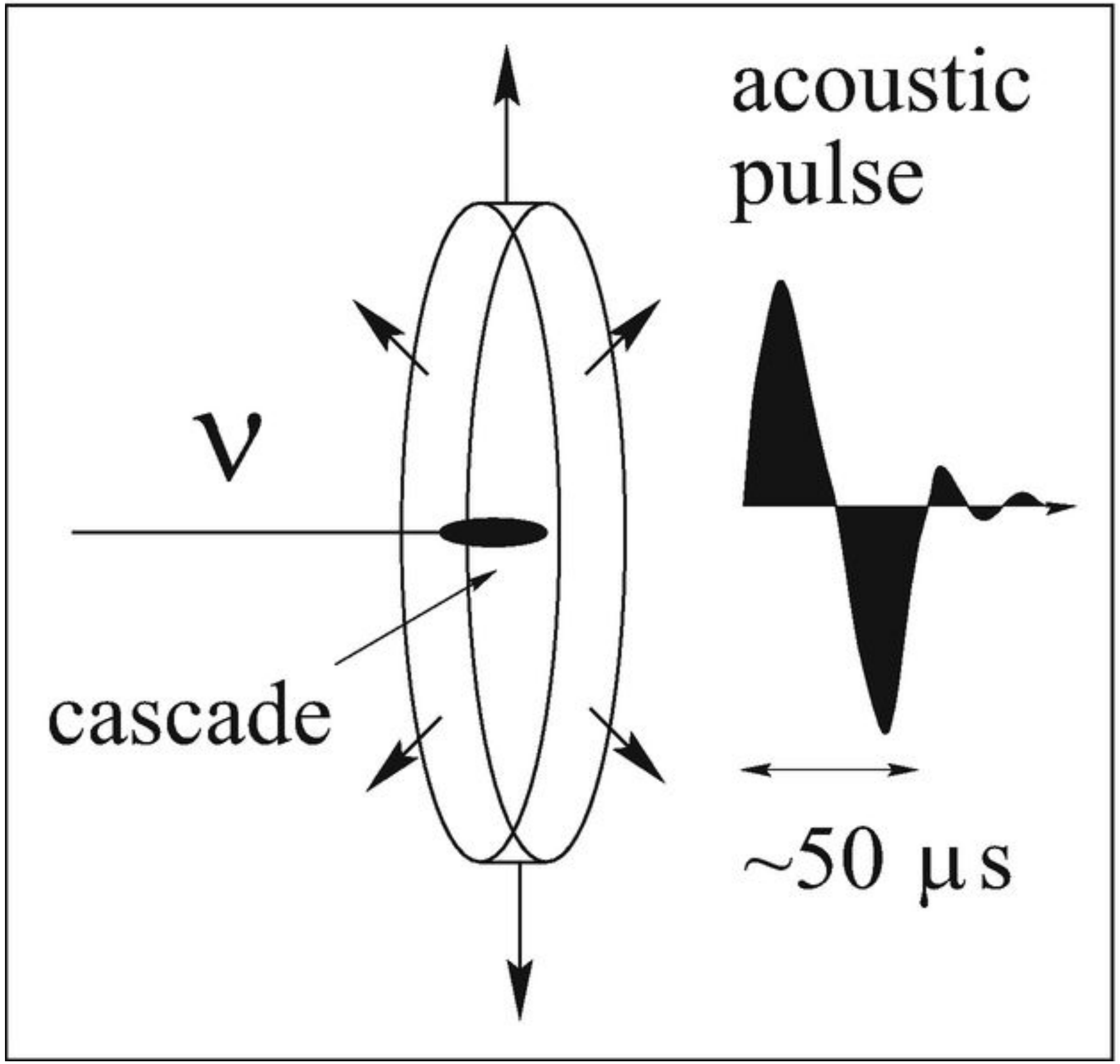
Source: km3net.org

Deployment of digital modules

Source: km3net.org

Phenomenon

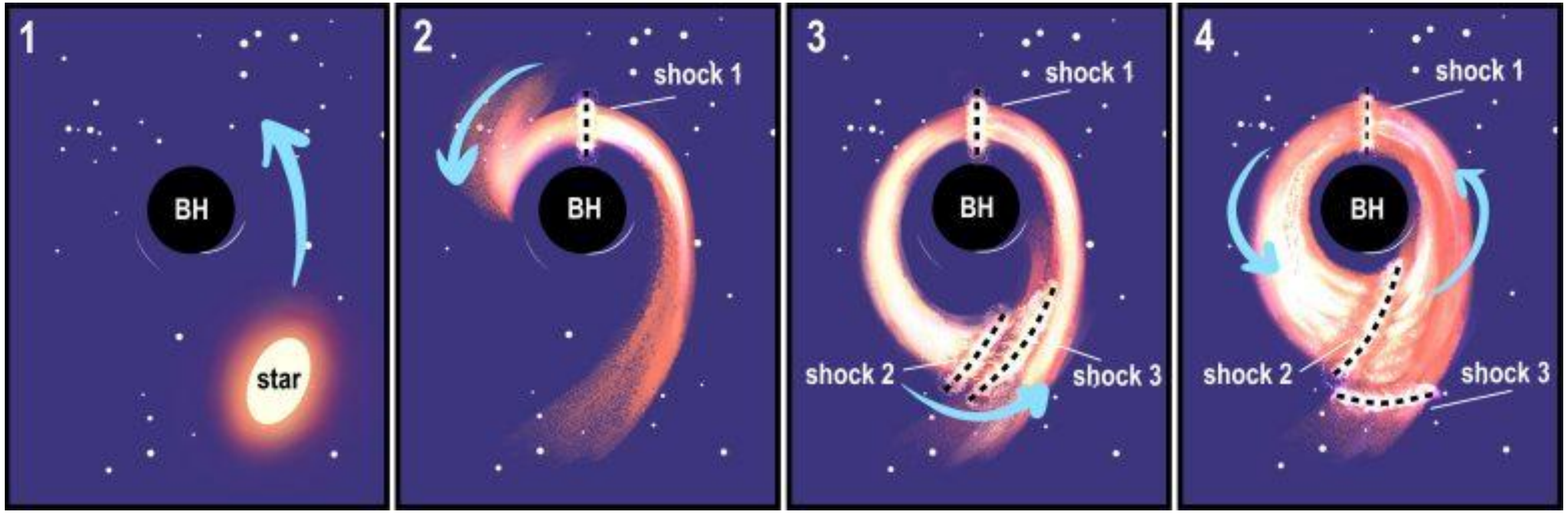
- Acoustic detection:
    - Production of pressure waves by high energy particles passing through a medium
    - Mechanism: Neutrino → hadronic shower in water → energy is deposited heats water up + relaxation pressure → signal (bipolar) by hydrophones sound range in water of few km



Strategy

- Aim: To study acoustic waves produced by ultra-high energy neutrinos and tidal disruption events as potential candidates of these UHE neutrinos

- SMBH (mass - 10^6 - $10^{12} M_\odot$) + Star (mass – 0.3—1$M_\odot$): Stars in the immediate vicinity of supermassive black holes (SMBHs) can be ripped apart by the tidal forces of the black hole.



Source: 10.3847/2041-8213/acc390

Conclusion

- Probing Ultra-High-Energy Cosmic Rays: KM3NeT's neutrino detection offers an unparalleled method to investigate the origins and properties of ultra-high-energy cosmic rays, providing critical insights into their sources and acceleration mechanisms

- Advancing Acoustic Detection Techniques: Research on acoustic detection methods within KM3NeT enhances precision in neutrino detection and opens new avenues for understanding particle interactions in marine environments

- Multidisciplinary Benefits: The integration of neutrino and acoustic studies strengthens KM3NeT's capability to address both fundamental questions in astrophysics

Thank you!

And stayed tuned for upcoming up talk by Amine Masekar in Krakow Epiphany Conference 2025…

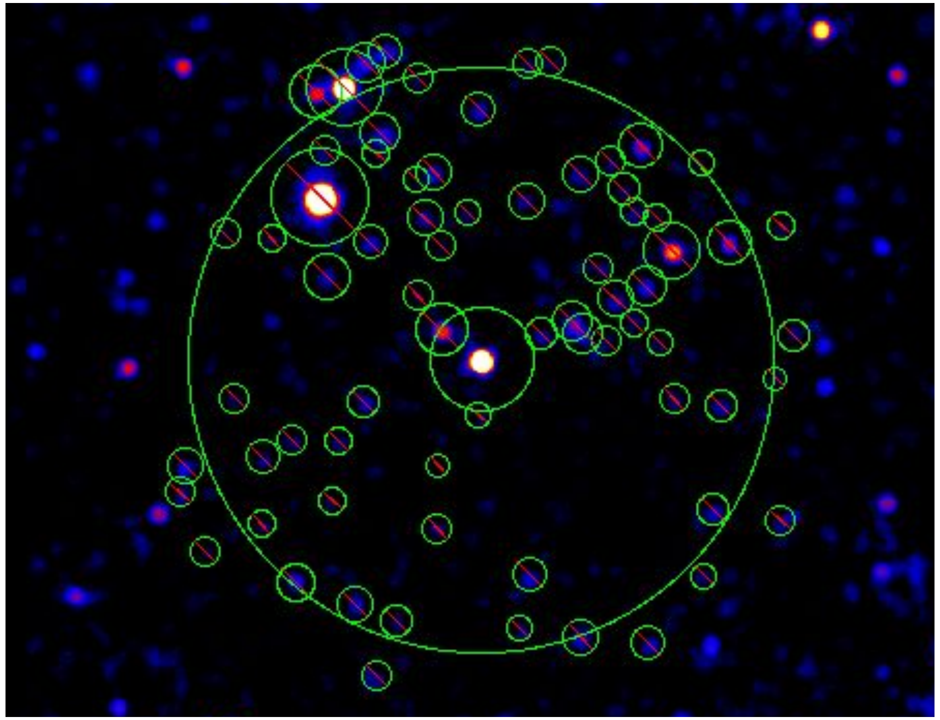
Supplementary Material

Event Files

Filtering, Merging and Image creation = yes

Extracting region file for source using AUTO function.

SRCTOOL: Source spectrum extraction done!

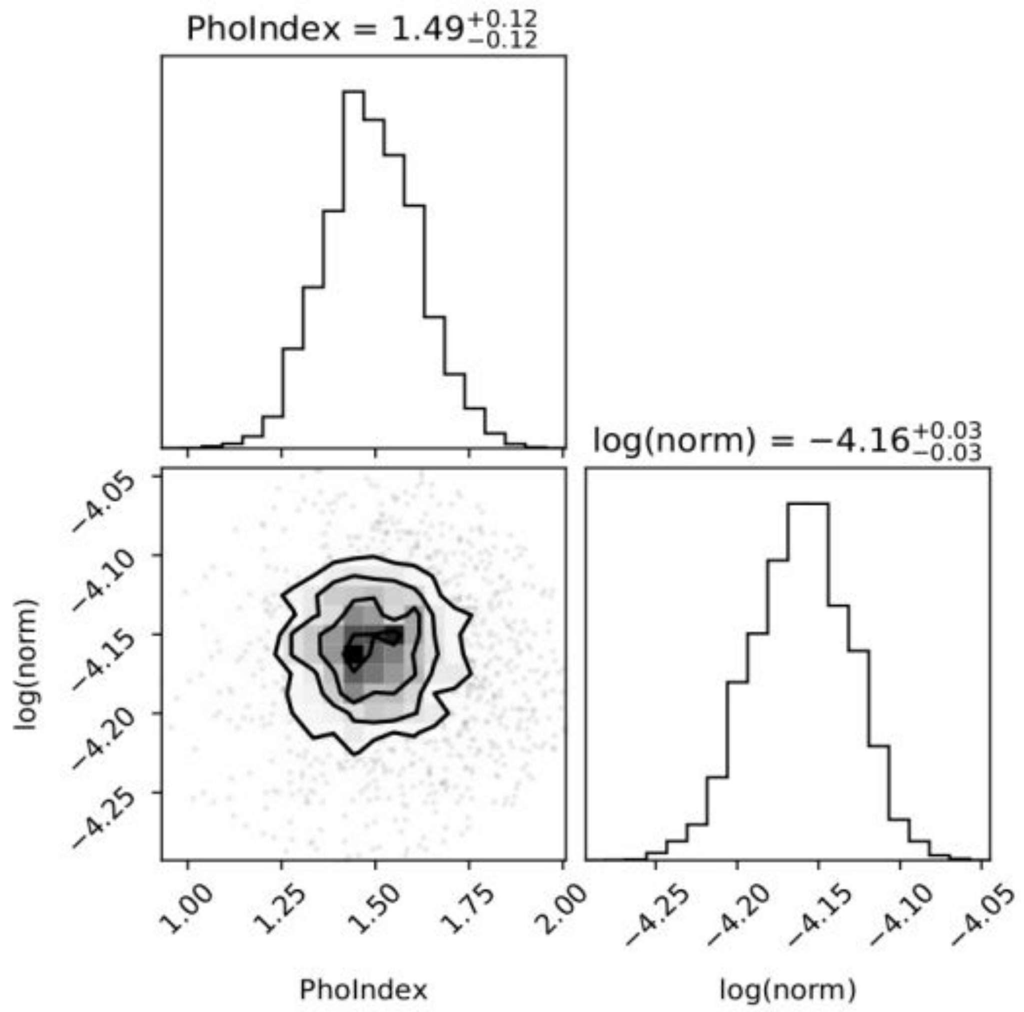


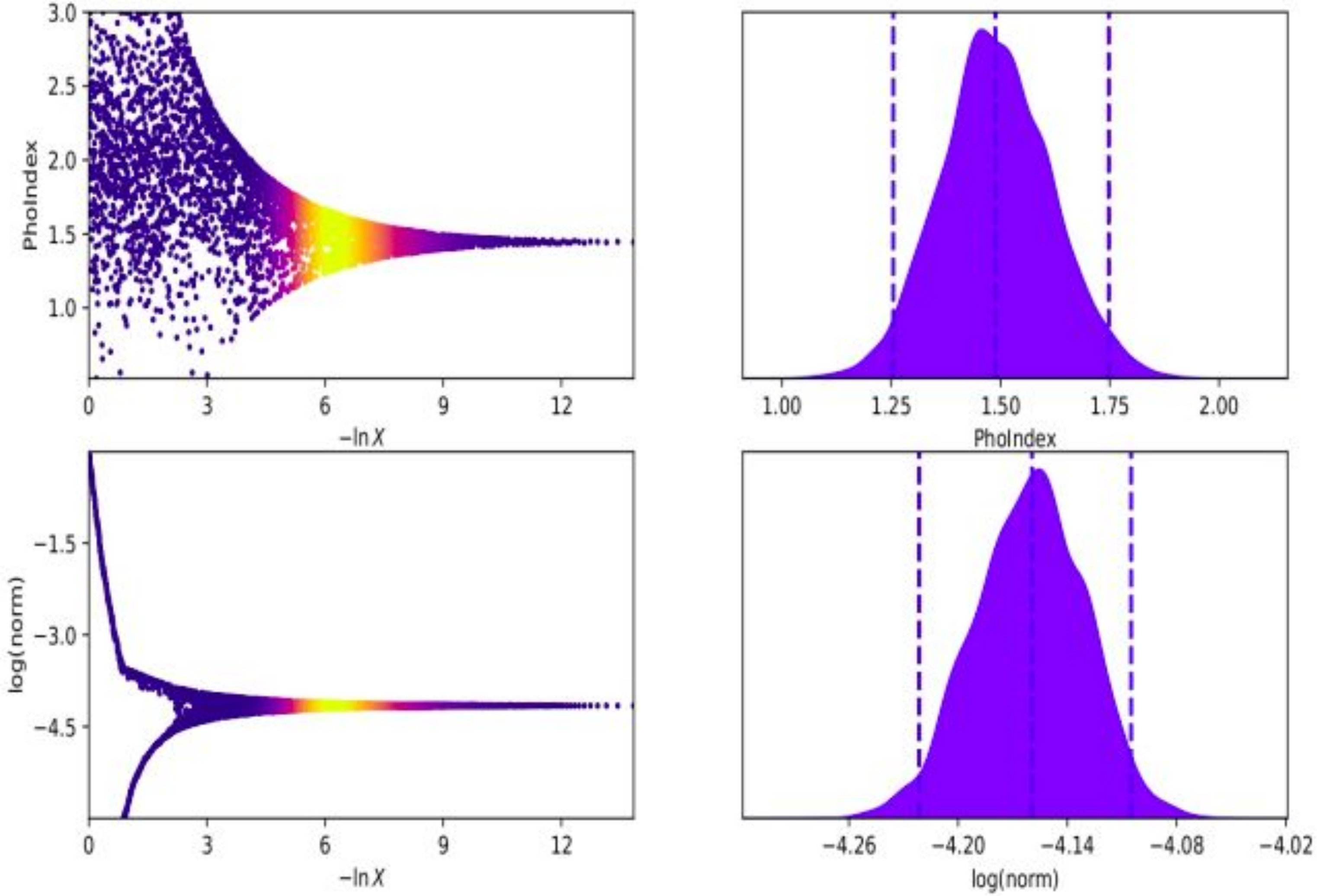
EVTOOL: Merging and FLARE_GTI

Extracting region file for background using AUTO function.

SRCTOOL: Background spectrum extraction done!

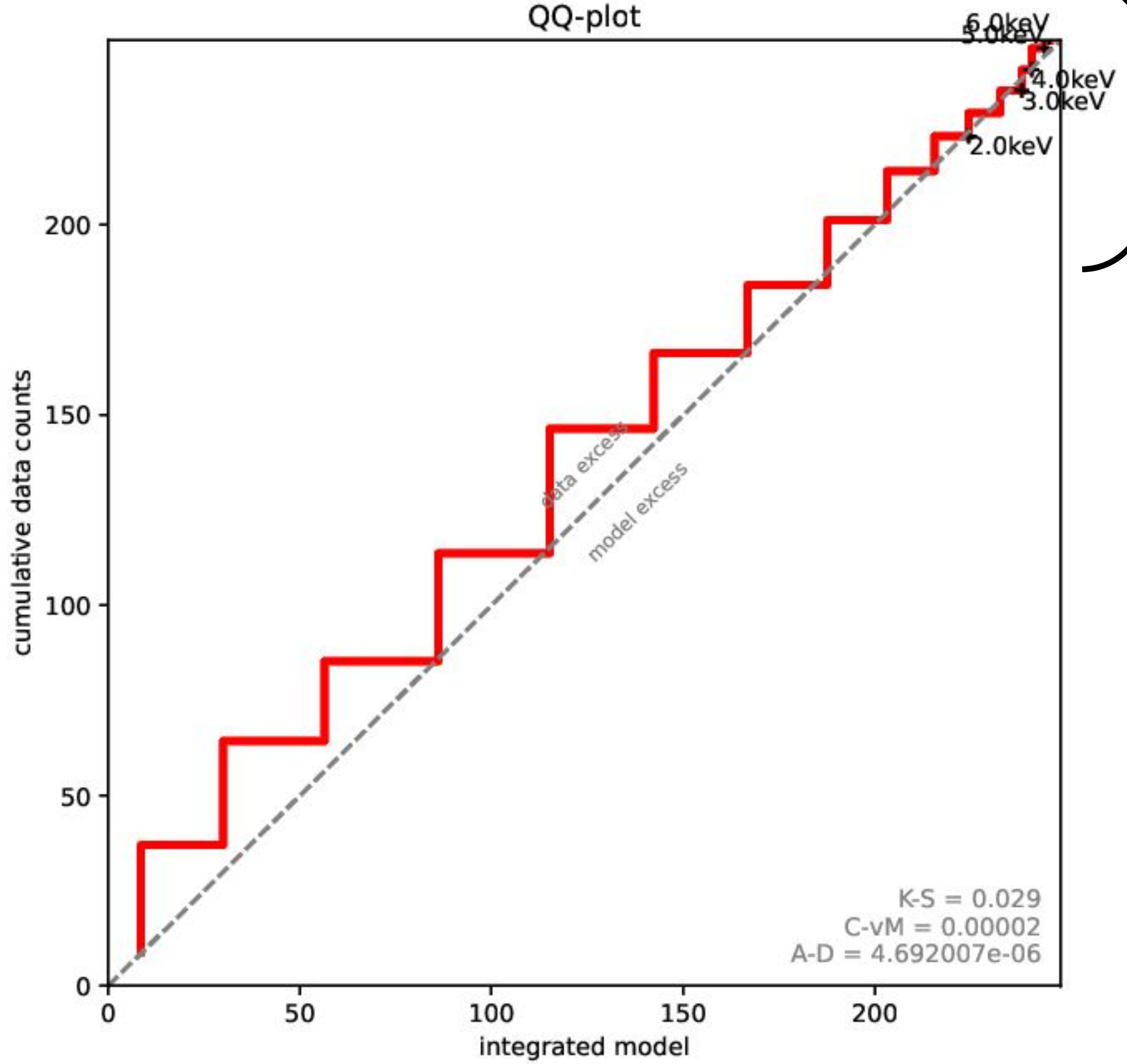
Supplementary Material





Supplementary Material

Quantile- Quantile(QQ): Residual plot for source Id 1599



Less significant detection after 3.0 keV

Supplementary Material

Proton interaction with low-energy radiation fields can produce neutrinos and gamma-ray emissions

Gamma rays may interact with the powerful electric fields in the SSC's powerful radiation field & form electron-positron pairs – shift of spectrum to X-rays and MeV

Tomographic techniques supports the neutrinos and observational importances at X-rays and MeV

Buson, S. et al. (2022); Stathopoulos, S.I. et al. (2022); Murase, K., Guetta, D., & Ahlers, M. (2016); Halzen, F., & Kheirandish, A. (2019); Ando, S., Tamborra, I., & Zandanel, F. (2015)

Supplementary Material

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **447,** 1692–1704 (2015) doi:10.1093/mnras/stu2571

Correlation between the photon index and X-ray luminosity of black hole X-ray binaries and active galactic nuclei: observations and interpretation

Qi-Xiang Yang,[1,2] Fu-Guo Xie,[1★] Feng Yuan,[1] Andrzej A. Zdziarski,[3] Marek Gierliński,[4] Luis C. Ho[5,6,7] and Zhaolong Yu[1]

[1] *Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China*
[2] *University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, China*
[3] *Centrum Astronomiczne im. M. Kopernika, Bartycka 18, PL-00-716 Warszawa, Poland*
[4] *Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[5] *Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China*
[6] *Department of Astronomy, Peking University, Beijing 100871, China*
[7] *The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA*

Accepted 2014 December 3. Received 2014 December 3; in original form 2014 September 18

ABSTRACT

We investigate the observed correlation between the 2–10 keV X-ray luminosity (in unit of the Eddington luminosity; $l_X \equiv L_X/L_{Edd}$) and the photon index (Γ) of the X-ray spectrum for both black hole X-ray binaries (BHBs) and active galactic nuclei (AGNs). We construct a large sample, with $10^{-9} \lesssim l_X \lesssim 10^{-1}$. We find that Γ is positively and negatively correlated with l_X when $l_X \gtrsim 10^{-3}$ and $10^{-6.5} \lesssim l_X \lesssim 10^{-3}$, respectively, while Γ is nearly a constant when $l_X \lesssim 10^{-6.5}$. We explain the above correlation in the framework of a coupled hot accretion flow–jet model. The radio emission always comes from the jet while the X-ray emission comes from the accretion flow and jet when l_X is above and below $10^{-6.5}$, respectively. More specifically, we assume that with the increase of mass accretion rate, the hot accretion flow develops into a clumpy and further a disc–corona two-phase structure because of thermal instability. We argue that such kind of two-phase accretion flow can explain the observed positive correlation.

Supplementary Material

Characteristic	ARCA (Astroparticle Research)	ORCA (Oscillation Research)
Energy Range	Several tens of GeV to PeV	1 GeV to 100 GeV
Energy Resolution	20%-30% at TeV energies	~30% at 5 GeV
Angular Resolution	<0.2° at TeV-PeV energies	~9° at 5 GeV
Effective Area	~1 km^2 for TeV-PeV energies	0.03 km^2 at 5 GeV
Sensitivity	Detecting high-energy cosmic neutrinos, studying astrophysical sources	Determining the neutrino mass hierarchy, oscillation parameters

Source: km3net

Supplementary Material