Model Based Observational Study of Black Holes

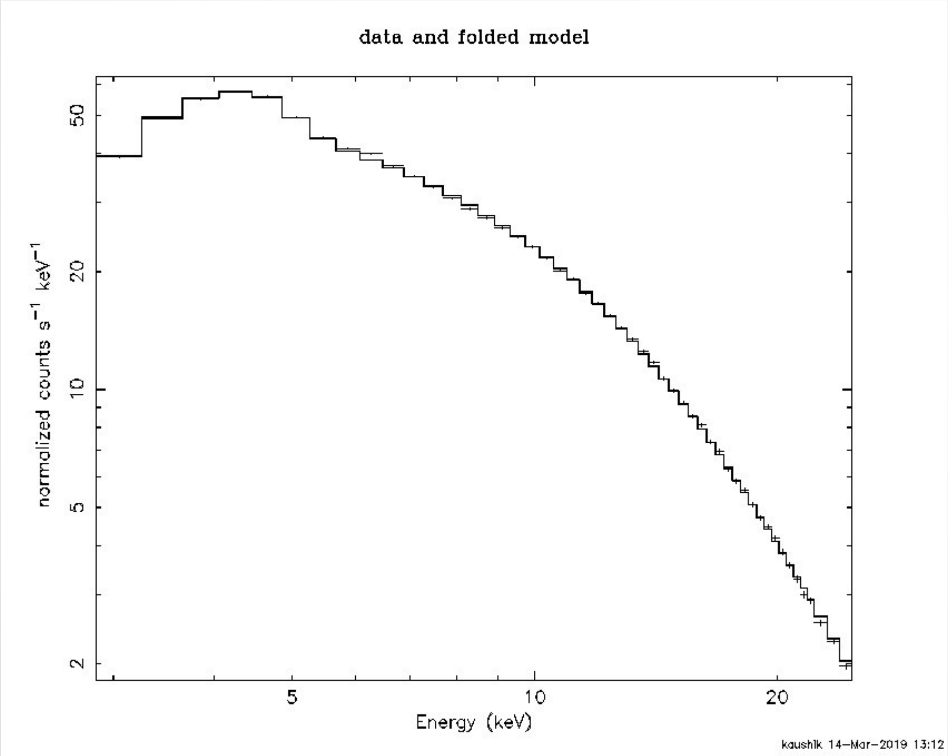
Kaushik Chatterjee
Postdoc
SWIFAR, Yunnan University
(kaushik@ynu.edu.cn)

Milky Way Group Meeting
March 8, 2024
Room 2111 @ 9 A.M.

Contents

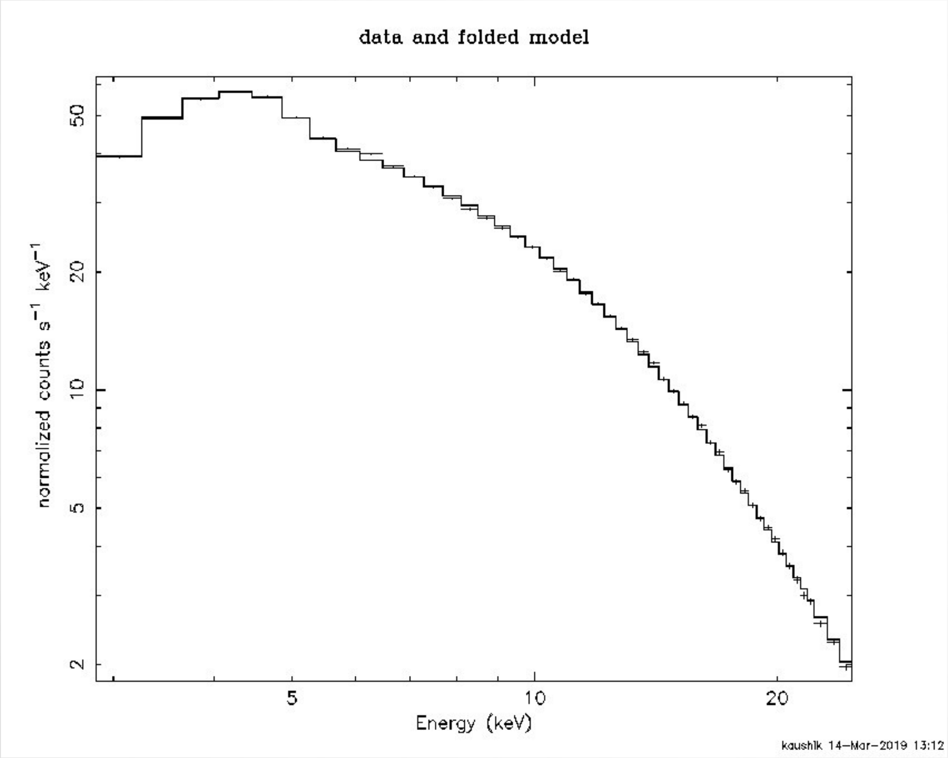
- Models of Accretion
- TCAF model, Spectral States and Change of Flux
- TCAF model and QPOs
- Estimation of Mass from QPO study
- TCAF model and jets/outflows
- Coclusions
- Future Plan

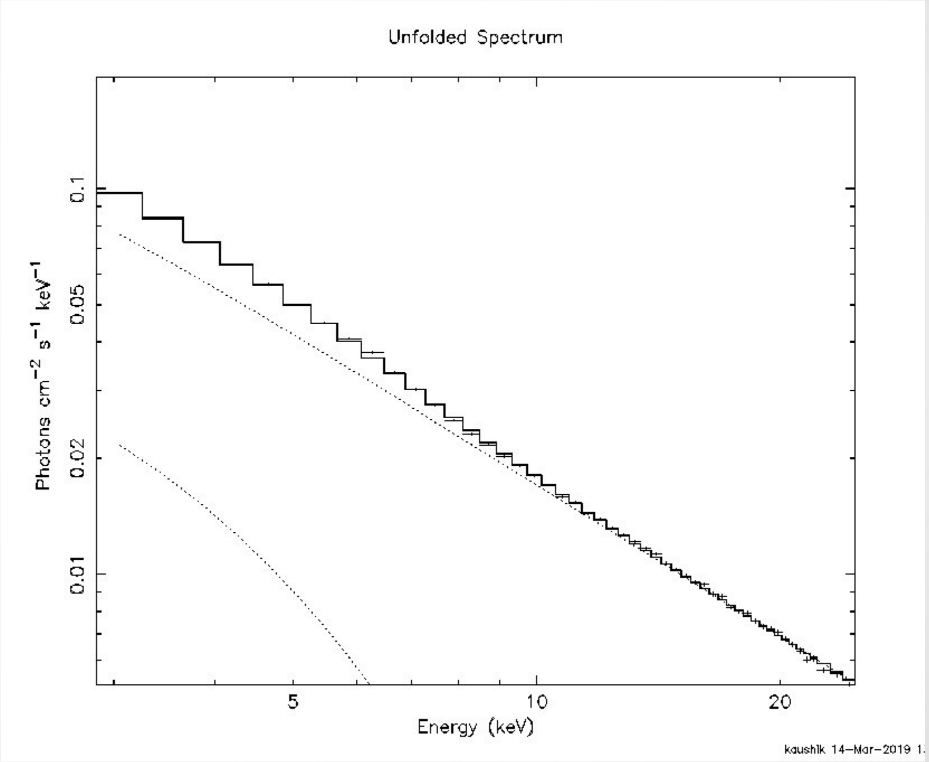
Radiation Spectrum of a BH



Figures taken from the Thesis of Kaushik Chatterjee

Radiation Spectrum of a BH





Figures taken from the Thesis of Kaushik Chatterjee

Change of Flux with Spectral States

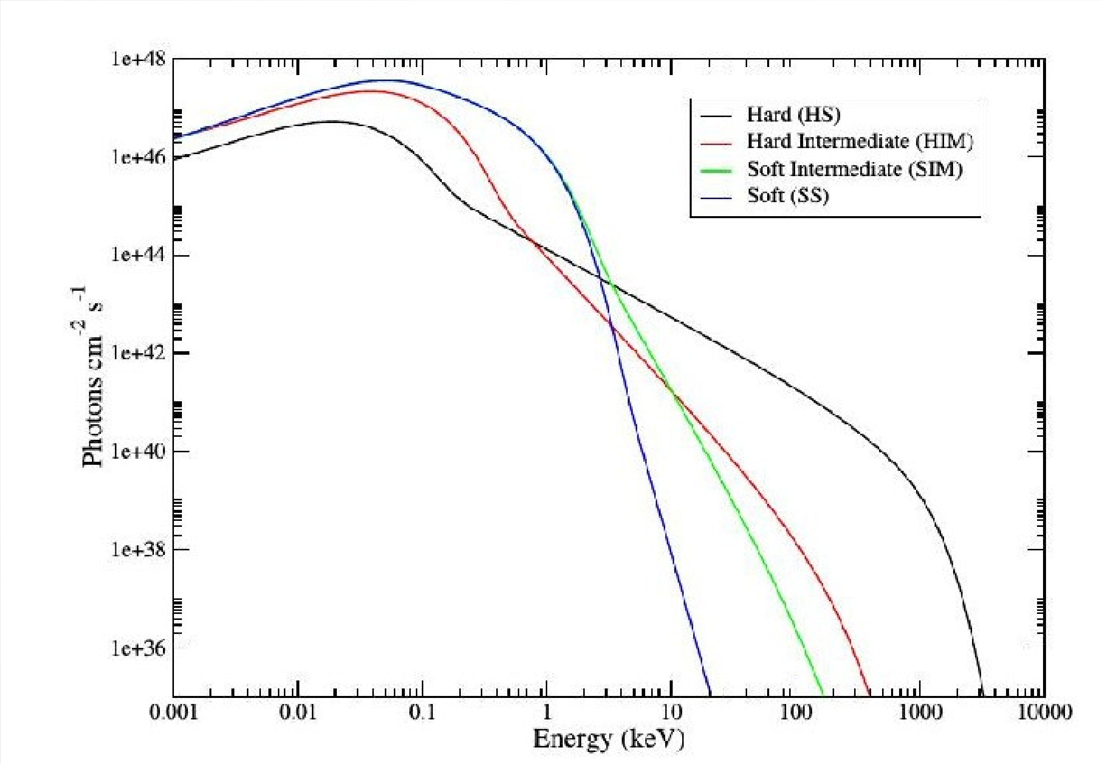


Figure taken from the Thesis of Arghajit Jana

Models of accretion

- To describe the spectra properly many astrophysicists came up with various models of accretion over the years -

  1) Bondi Flow

  2) Standard disk model

  3) Thick disk model

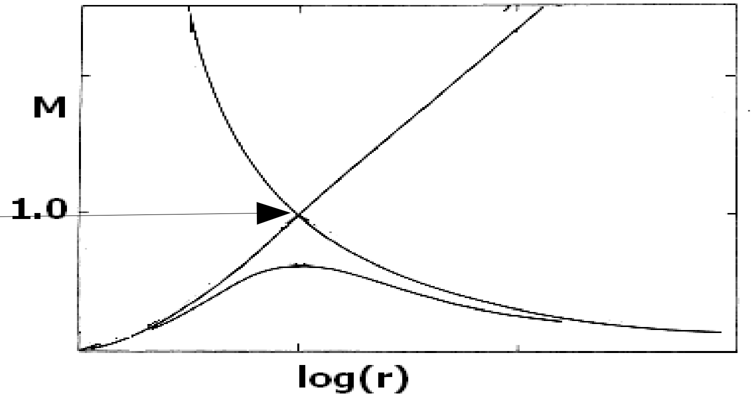
  4) Two component advective flow model (TCAF)

Bondi Flow Model

- This is a spherically symmetric flow around a compact object of mass M.
- Accretion rate :

$$\dot{M} = 4\pi r^2 \rho v$$ (*Bondi, 1952*)

- Crosses a sonic point.



- Mass accretion produces luminosity ~ 10^{31} erg/sec(which is only ~ 1 % of Solar luminosity)

So, the flow is **Radiatively inefficient**!

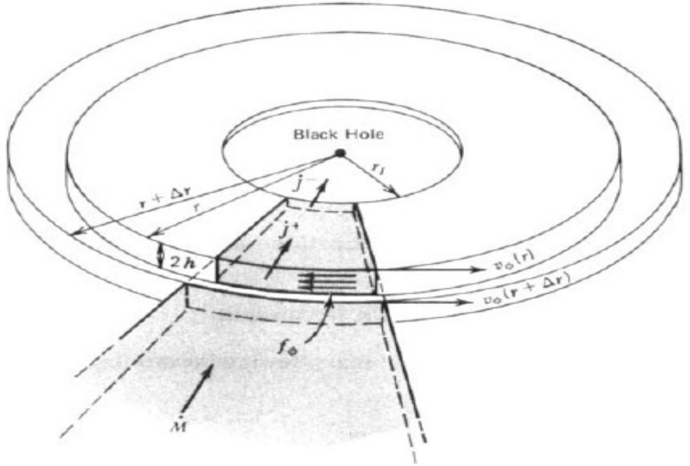
Standard Disk Model

- Also known as Shakura-Sunyaev Disk.
- Accreted matter forms geometrically thin disk which has **Keplerian** angular momentum distribution.
- Radial velocity of accretion is small here.
- Viscous torques transports angular momentum outside to make accretion possible. The efficiency of the mechanism of transport is characterized by the viscosity parameter **α.**
- This model is radiatively efficient.

(*Shakura & Sunyaev, 1973*)

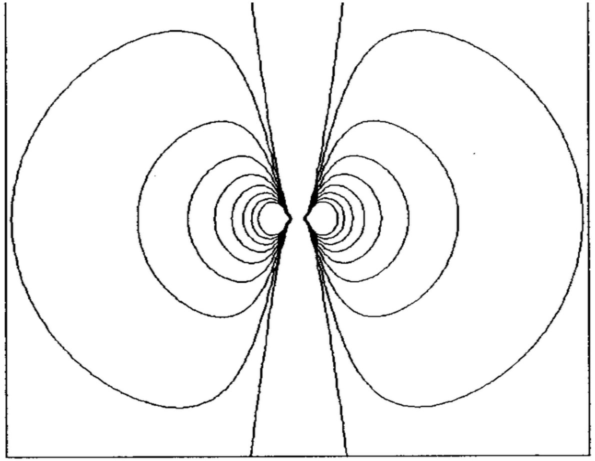
This model was able to explain the soft Blackbody spectra. But!

1) No explanation for energies > 10 keV.
2) This model does not explain what happens below $3r_s$.



(*Shapiro & Teukolsky 1983*)

Thick Disk Model



(Abramowicz et al. 1978)

- Radiation & ion pressure dominated.
- Angular momentum has a deviation from **Keplarian** value.
- Height of the disk is comparable to radial distance(that’s why the name **thick disk**).

(*Paczynski & Wiita, 1980*)

- This model could give explanation of the hard state and jets.

But!

- This model has no advection.
- Doesn't give any idea about the physical properties and their evolution.

TCAF Model

Has two component

Kelperian

(has higher viscosity, higher angular momentum and lower radial velocity as compared to the sub-Keplerian component. Moves in viscous time scale.)

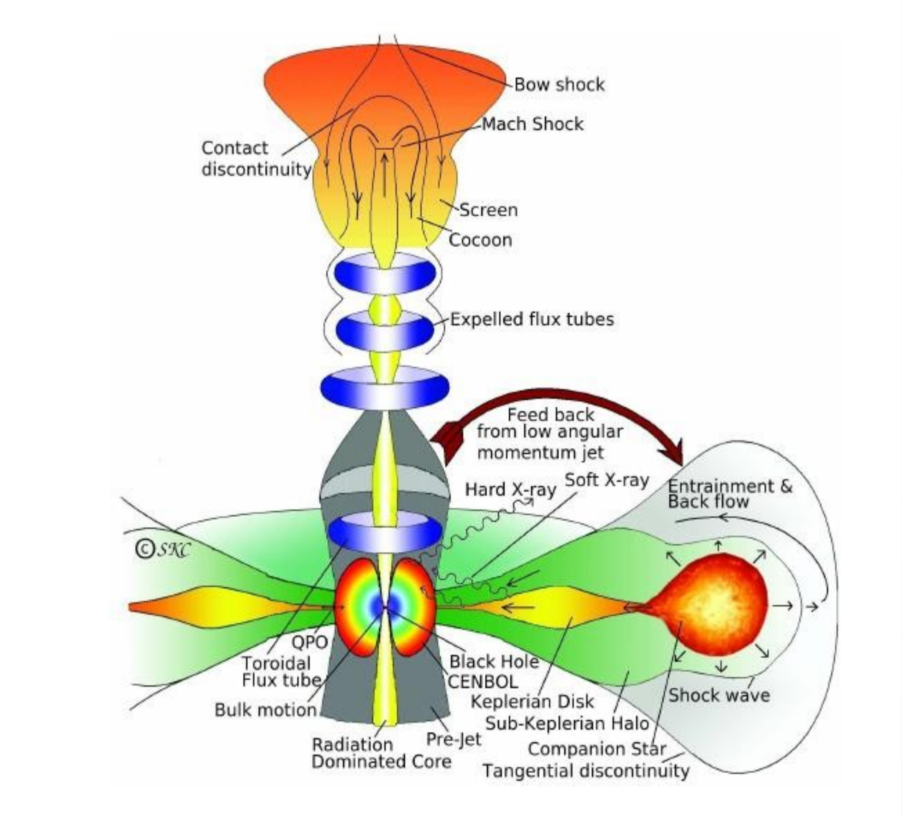
Sub-Keplerian

(has lower viscosity, lower angular momentum and higher radial velocity as compared to the Keplerian component. Moves in free fall time scale.)

- Due to higher viscosity Keplerian component resides at the euatorial plane while the Sub-Kep comp flows above and below it.

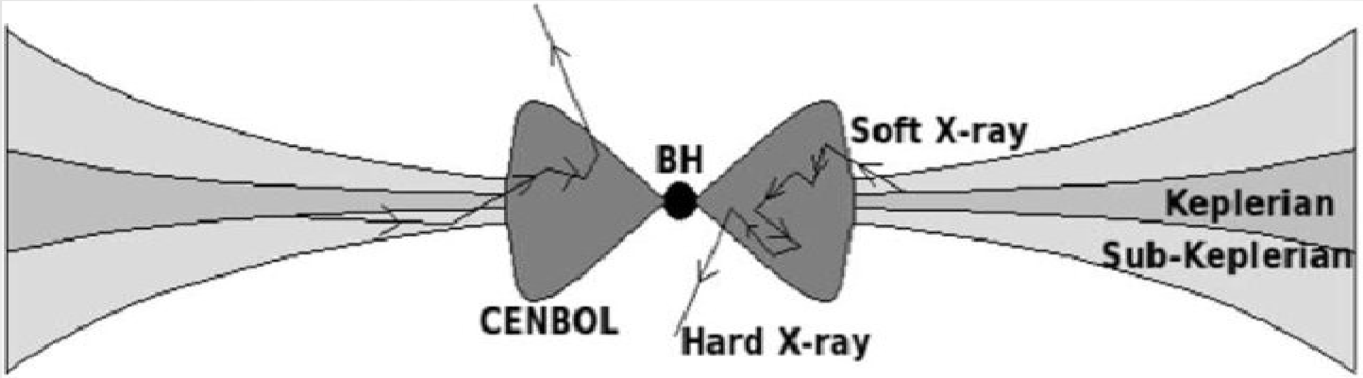
(*Chakrabarti & Titarchuk, 1995*)

Explanation of Radiation Spectrum

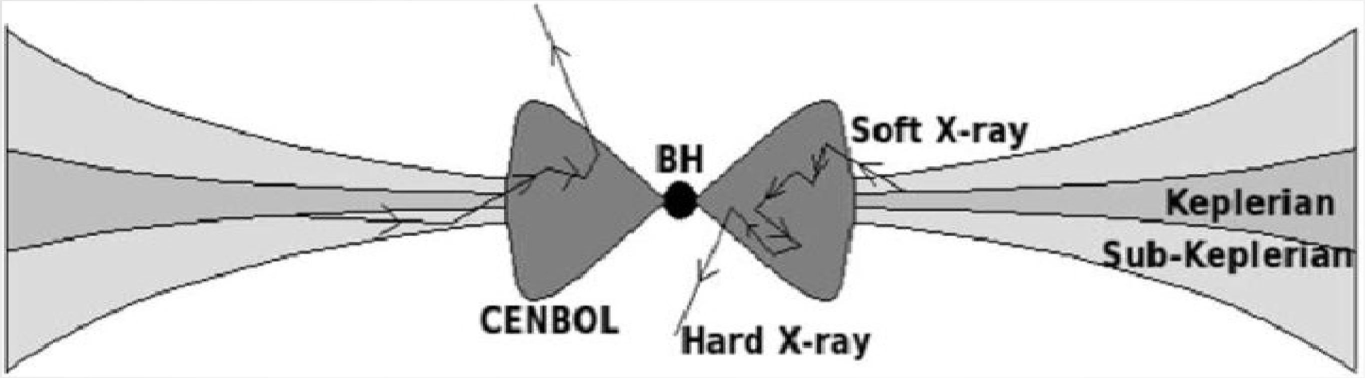


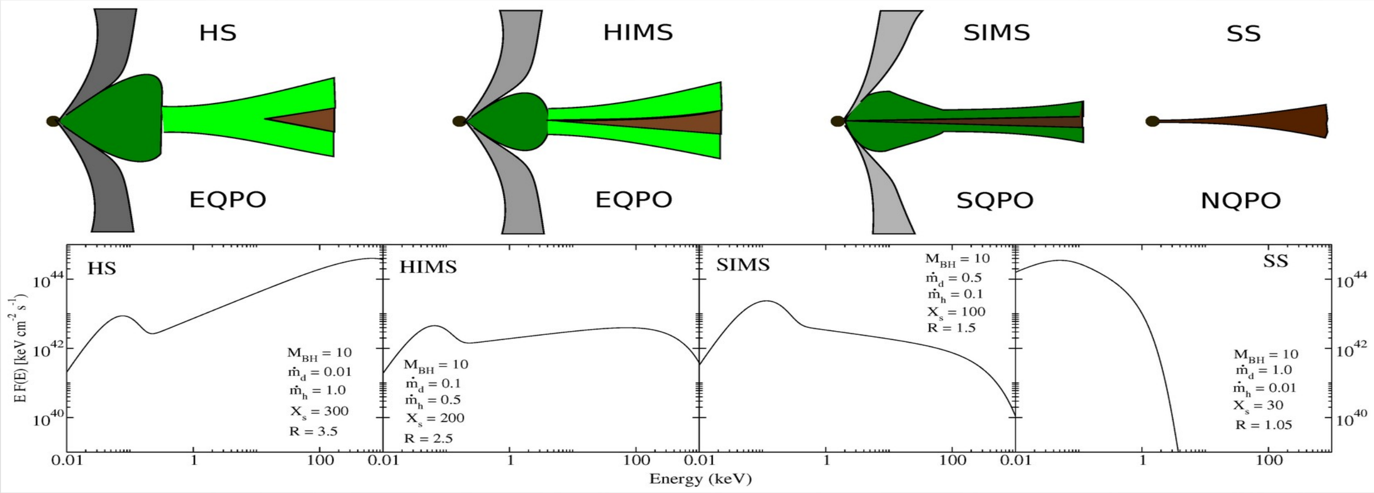
Chakrabarti (2013)

TCAF Cartoon Diagram



Spectral States and the configuration





Spectral Properties

Parameters

diskbb

1) Inner disk temperature ($\boldsymbol{T_{in}}$)

2) Normalization, given as -

$(R_{in}/D_{10})^2 \cos\theta$

where, R_{in}= inner disk radius

D_{10} = source distance in *10 kpc* unit.

PL

1) Photon index of powerlaw ($\boldsymbol{\Gamma}$)

2) Normalization ***k*** in photons $cm^{-2}\ s^{-1}\ keV^{-1}$

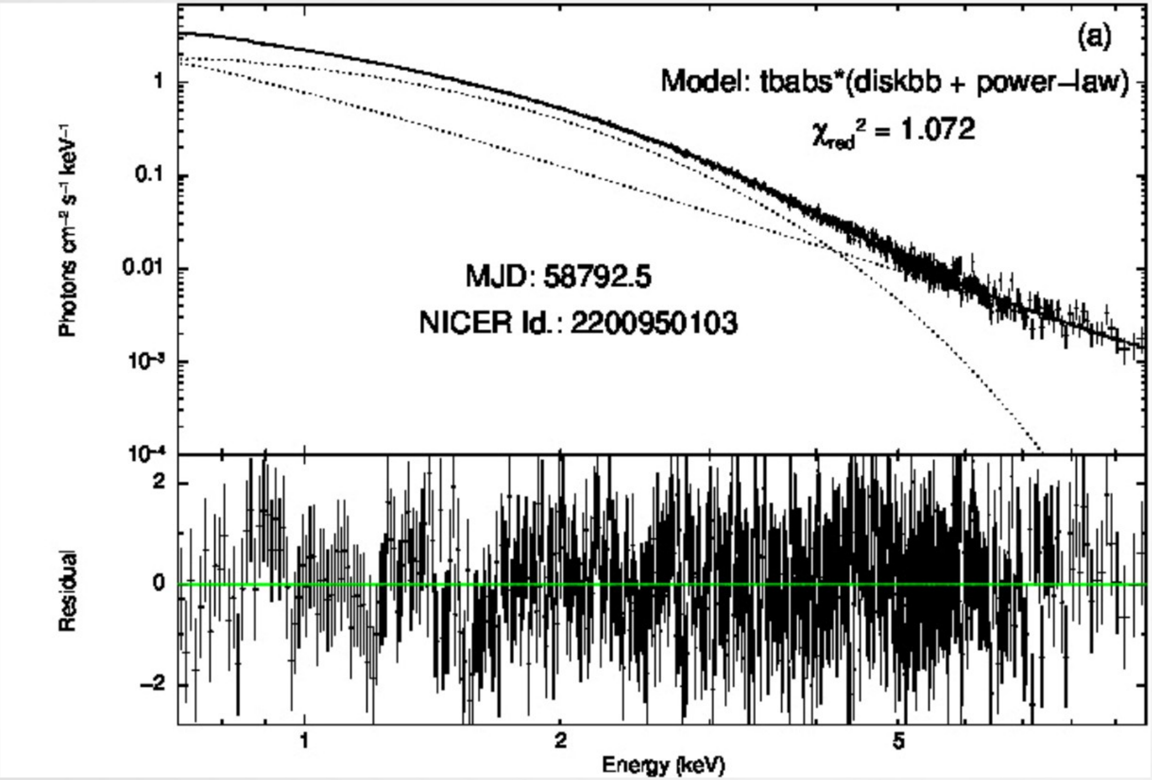
- But, due to ***iron line emission***, to fit the spectra properly (to have the best fit) we need to add a ***Gaussian***
- ***Parameters***

1) $\boldsymbol{E_l}$, line energy (in keV)

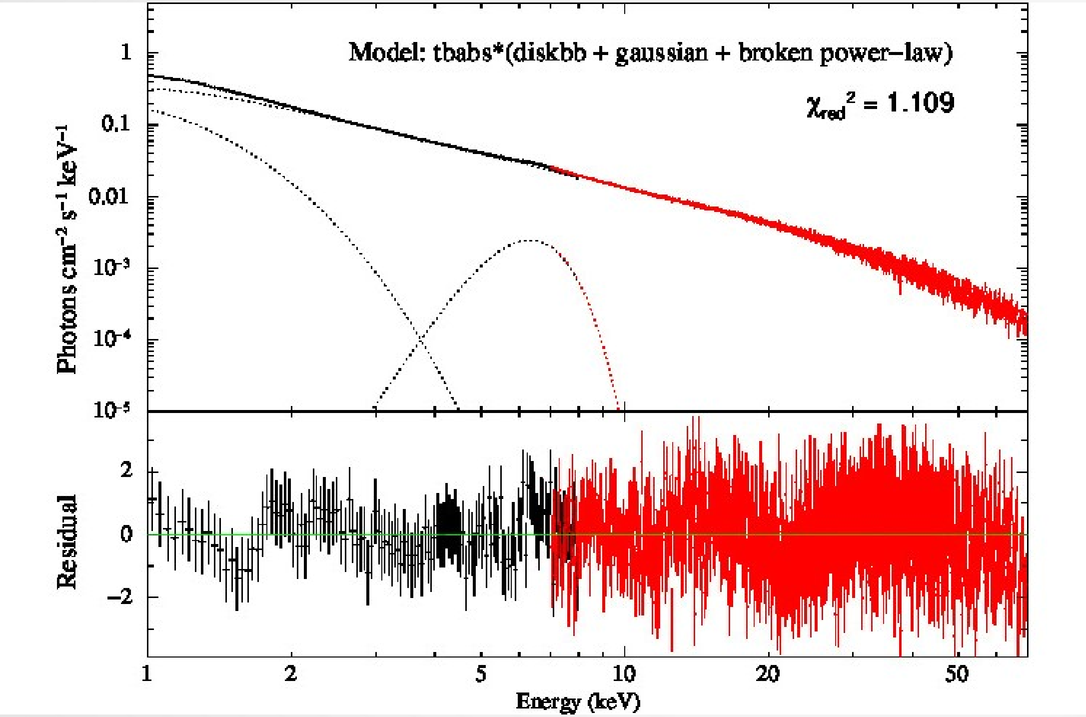
2) $\boldsymbol{\sigma}$, line width in keV

3) Normalisation ***K*** which is total photons $cm^{-2}\ s^{-1}$

Spectral Analysis



Spectral Analysis



Chatterjee et al. (in preparation)

Fitting with the TCAF Model

Parameters:

i) Keplerian disk rate,

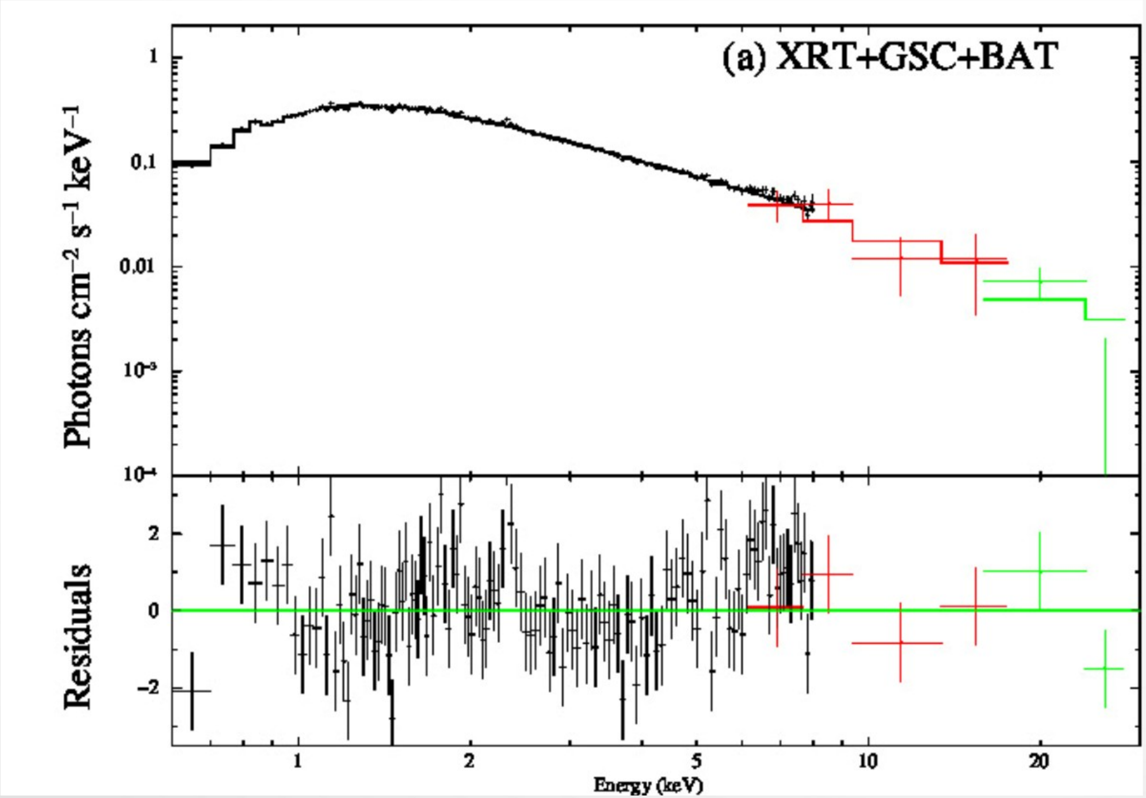
ii) sub-Keplerian halo rate,

iii) shock location (X_s)

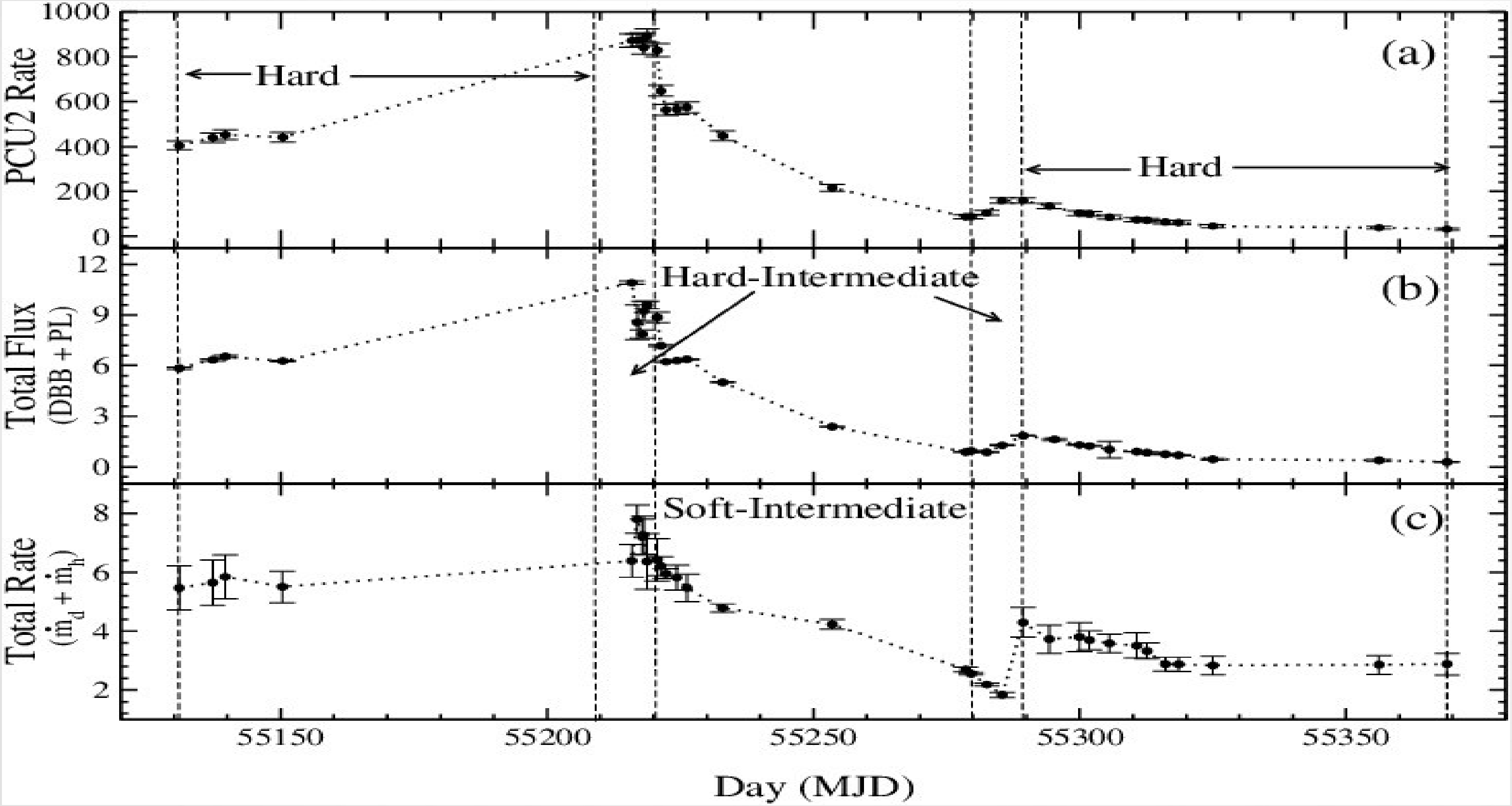
iv) compression ratio (R)

v) mass of the black hole (M_{BH})

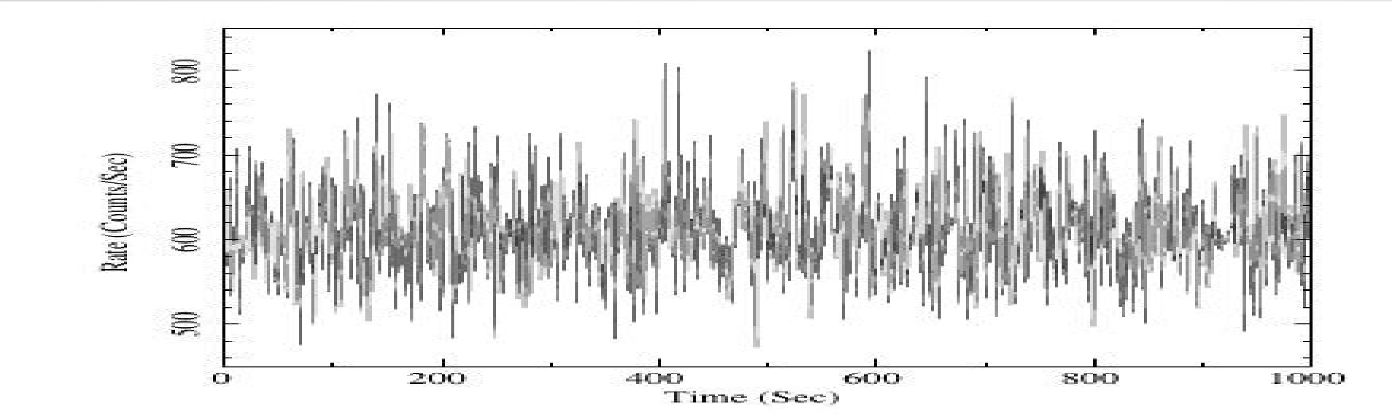
Fitting with TCAF

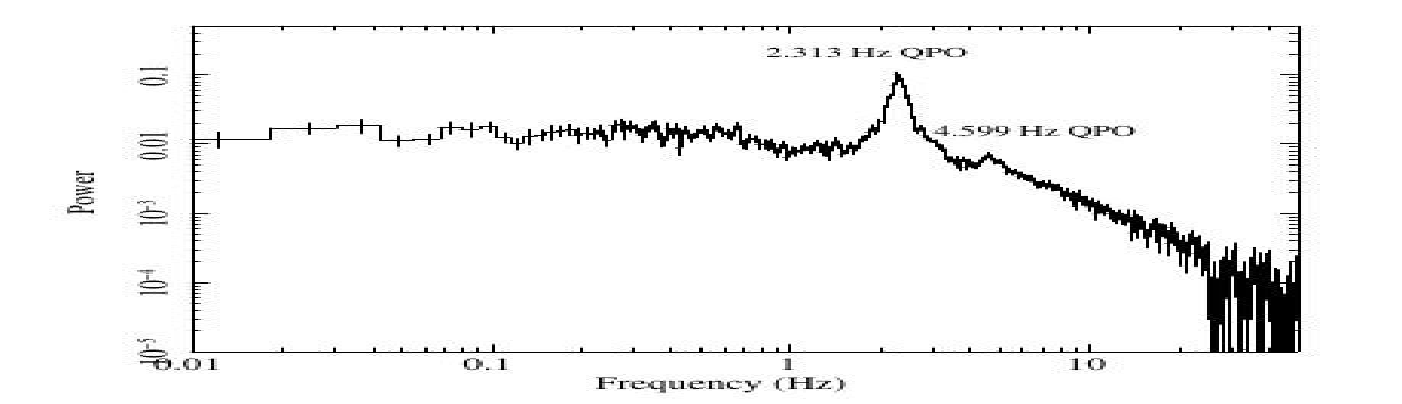


Comparative Result of Model Fitting



Timing Properties



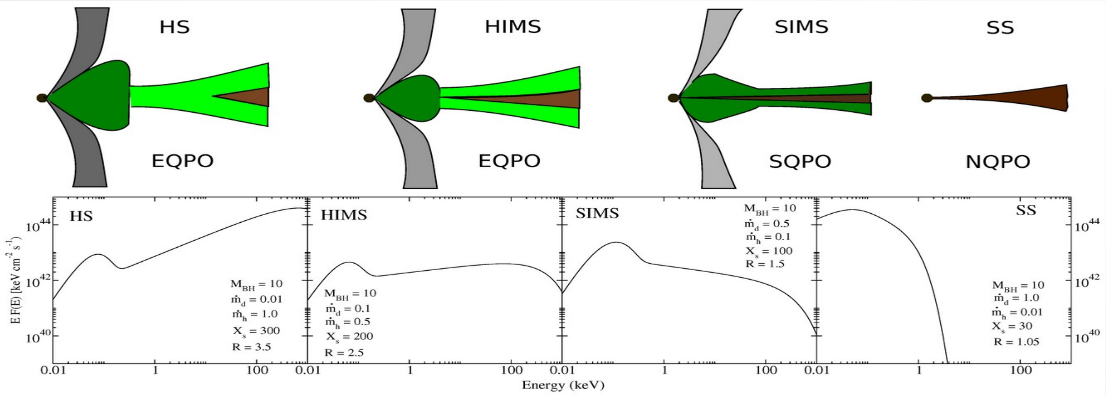


Origin of QPOs

Origin of QPO to occur-

Infall time scale (t_{infall}) of matter and cooling time scale ($t_{cooling}$) of CENBOL are comparable.

Satisfaction of the above two conditions makes the shock unsteady and as a result the shock starts oscillating, giving rise to ***quasi periodic oscillations***.



QPO-Mass-Shock location & Spectral states

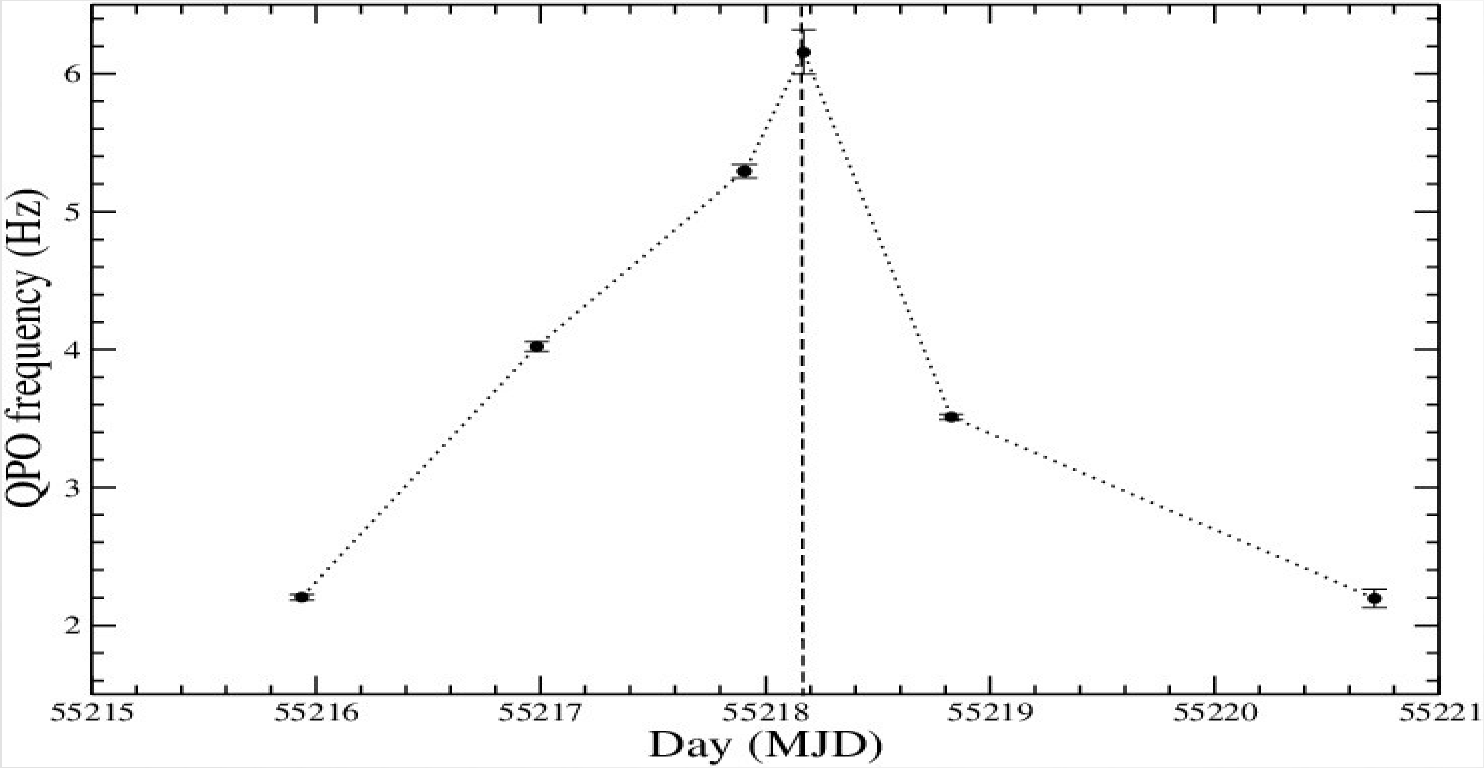
If M_{BH}, X_s & ν_{qpo} represents the mass of the black hole, shock location (CENBOL) & QPO frequency then -

- Instantaneous QPO frequency

$$\nu_{qpo} \sim X_s^{-3/2}$$

- So, in the hard state when X_s was high ν_{qpo} was low.
- When ***cooling*** starts the shock location X_s gets smaller in size and as a result the qpo frequency increases (Intermediate states).
- When the source gets in the soft state, the X_s gets the smallest value due to the ***cooling*** of the **CENBOL**. So, there is no QPOs in the soft states.
- Then when again matter starts coming, the shock forms gradually resulting a decrese in the ν_{qpo}.

QPO Evolution



Determination of mass from QPO frequency

We can measure the mass of black hole candidates from the measured QPO frequencies. We can use

1) **Propagating Oscillatory Shock (POS) model**

- Shock is propating with time satisfying the formula-

$$X_s(t) = X_{s0} \pm Vt/r_s$$

where, V is the velocity of the movement of the shock, and $\mathbf{X_{s0}}$ is the shock location of the first observation.

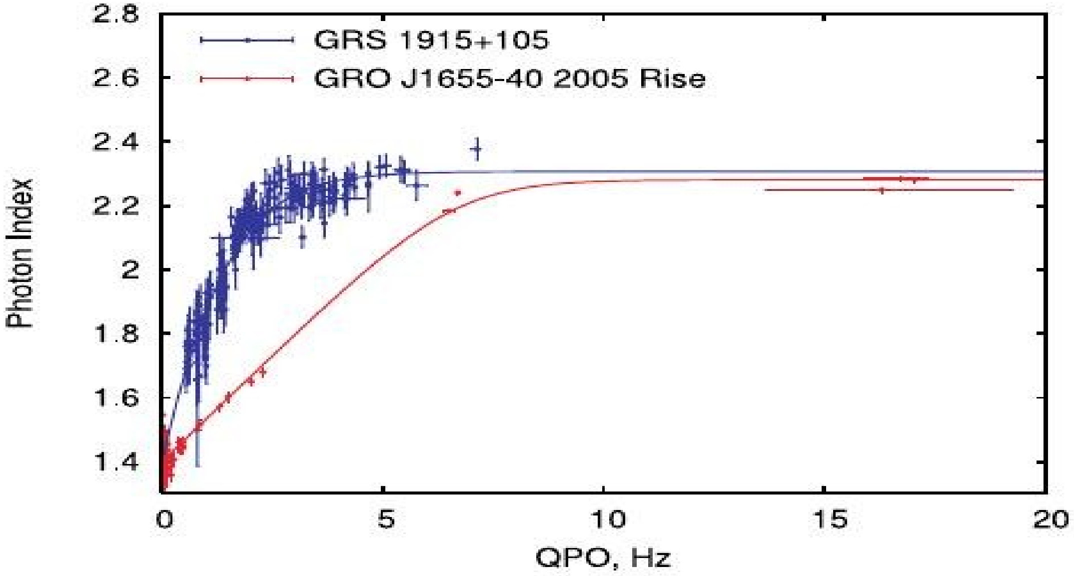
- The ν_{qpo} is given as, $\nu_{qpo} = c^3/2GM_{BH}\,[Rx_s(X_s-1)^{1/2}]$
- Using the evolution of QPO frequency and fitting them with the POS equations, one can get the mass.
- Mass of MAXI J1659-152 was determined using this method which gave a mass value of

M_{BH} ~ **5.1 – 7.4 $\mathbf{M_{Sun}}$** (Molla et al. 2016)

Continued.....

2) **QPO-Photon index correlation**

- Correlation between QPO freq (**ν_{qpo}**) and Photon index of power-law (**Γ**).

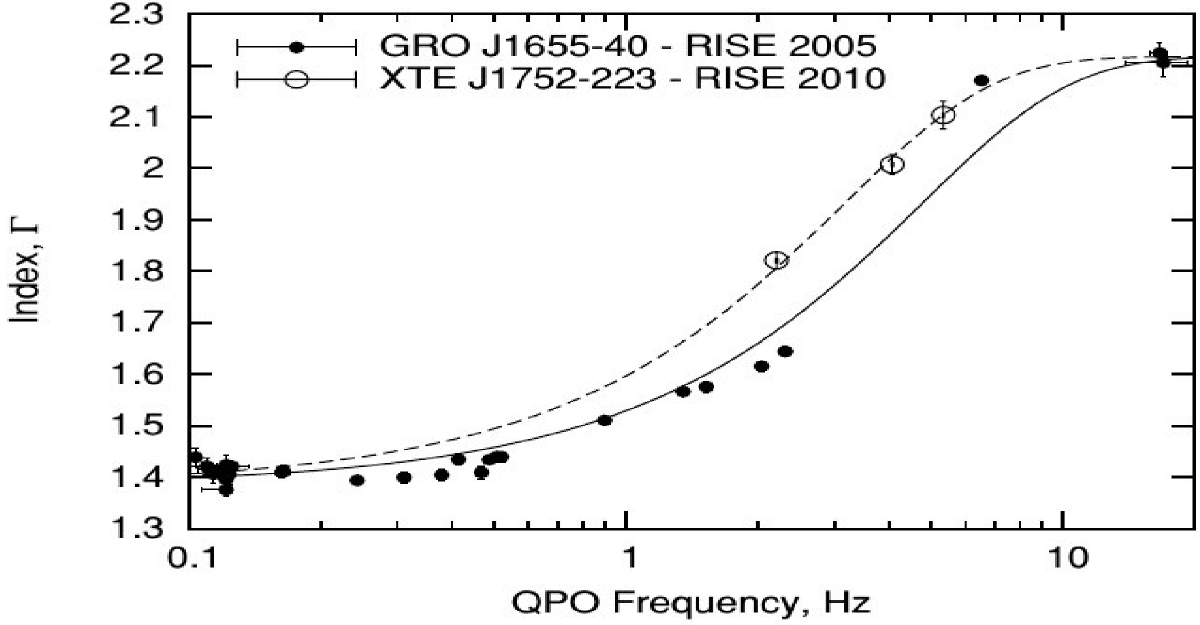


(Shaposhnikov & Titarchuk 2007)

- Follows the analytic formula - $f(\nu) = A - D\ B\ ln[exp(\frac{\nu_{tr} - \nu}{D}) + 1]$

(Shaposhnikov & Titarchuk 2007)

- A = value at the saturation level
- B = slope of the graph
- ν_{tr} = value of frequency at which saturation occurs
- B is proportional to the mass of black hole (M_{BH}).
- So, for two sources, $\boldsymbol{M_{BH2} = M_{BH1} (B_2/B_1)}$



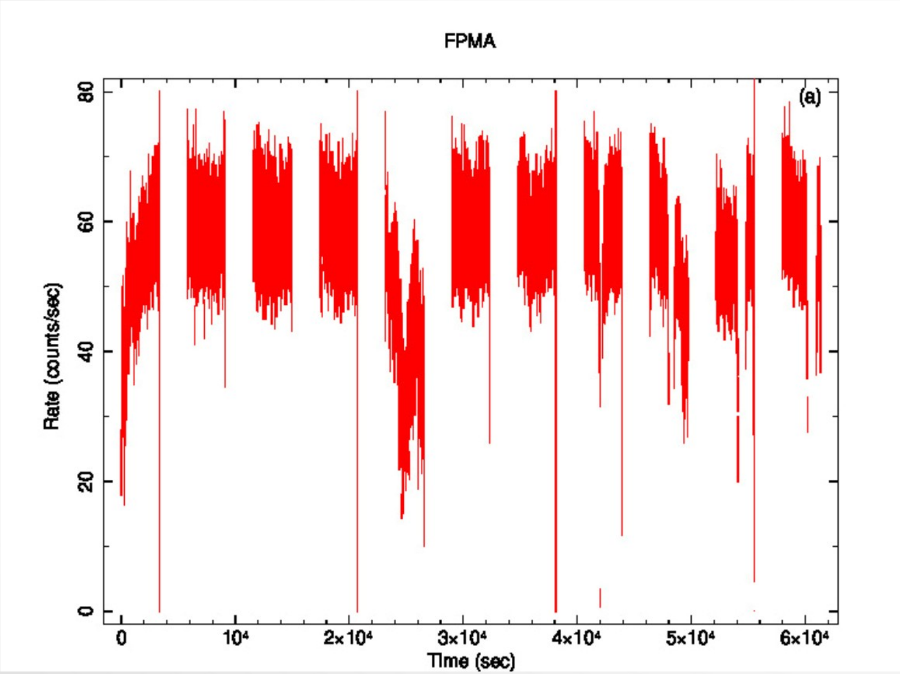
(Shaposhnikov et al. 2010)

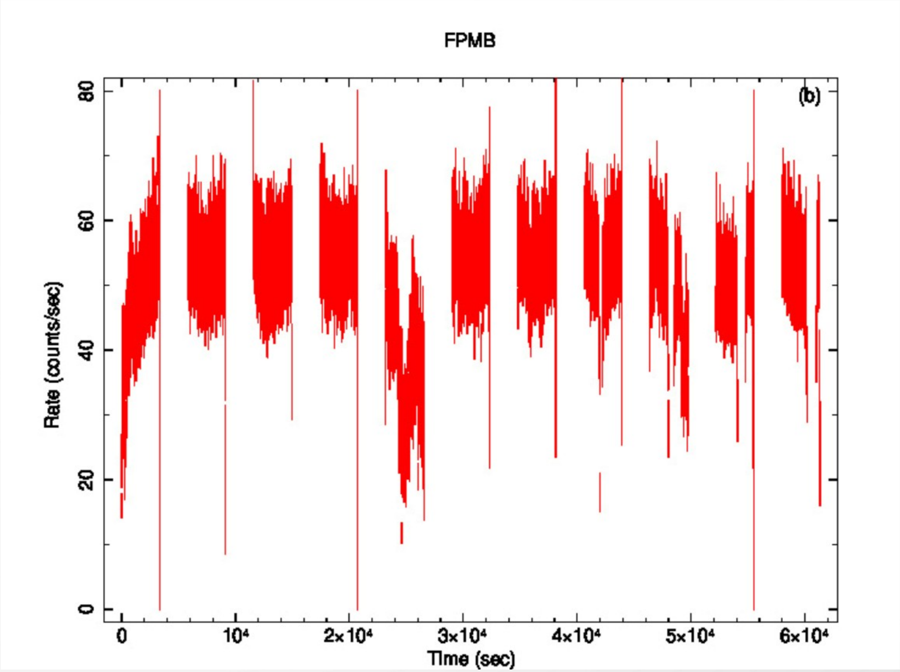
Reference Source : **GRO J1655-40**
Unknown Source: **XTE J1752-223**

$\boldsymbol{M_{J1655\text{-}40} = 6.5 \pm 0.5\ M_{Sun}}$

$\boldsymbol{M_{J1752\text{-}223} = 9.4 \pm 1.0\ M_{Sun}}$

Absorption Dips in light curve (NuSTAR Id: **90702316002)**

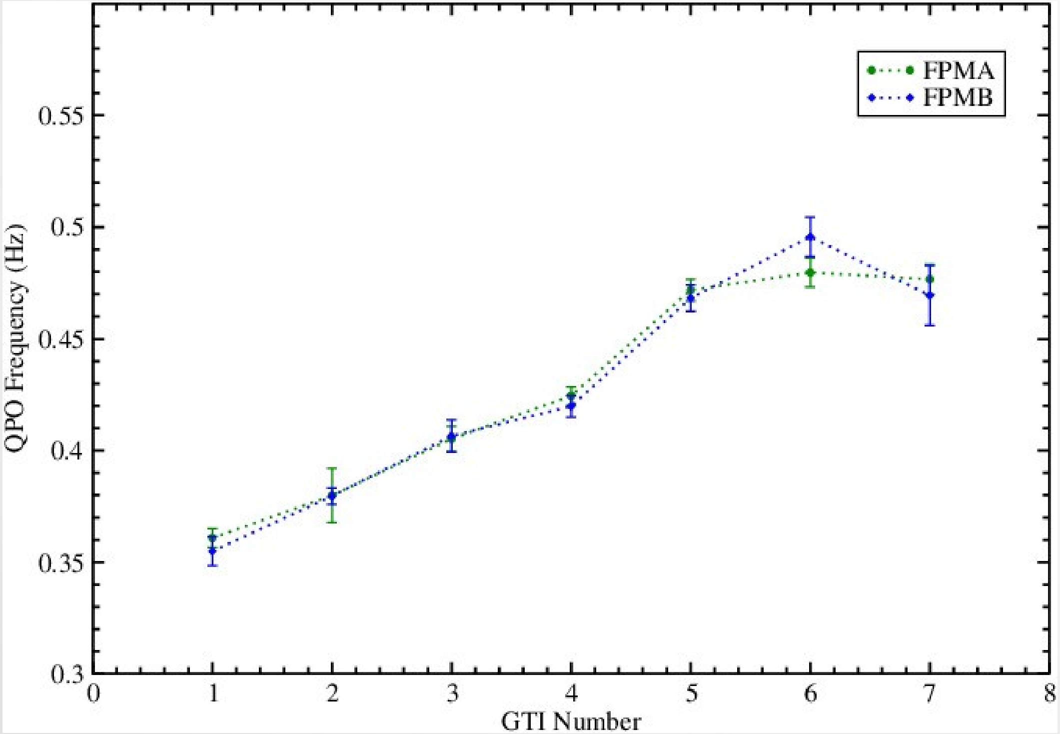




Chatterjee et al. (in preparation)

Timing Analysis

Evolution of QPO Frequency with NuSTAR GTIs

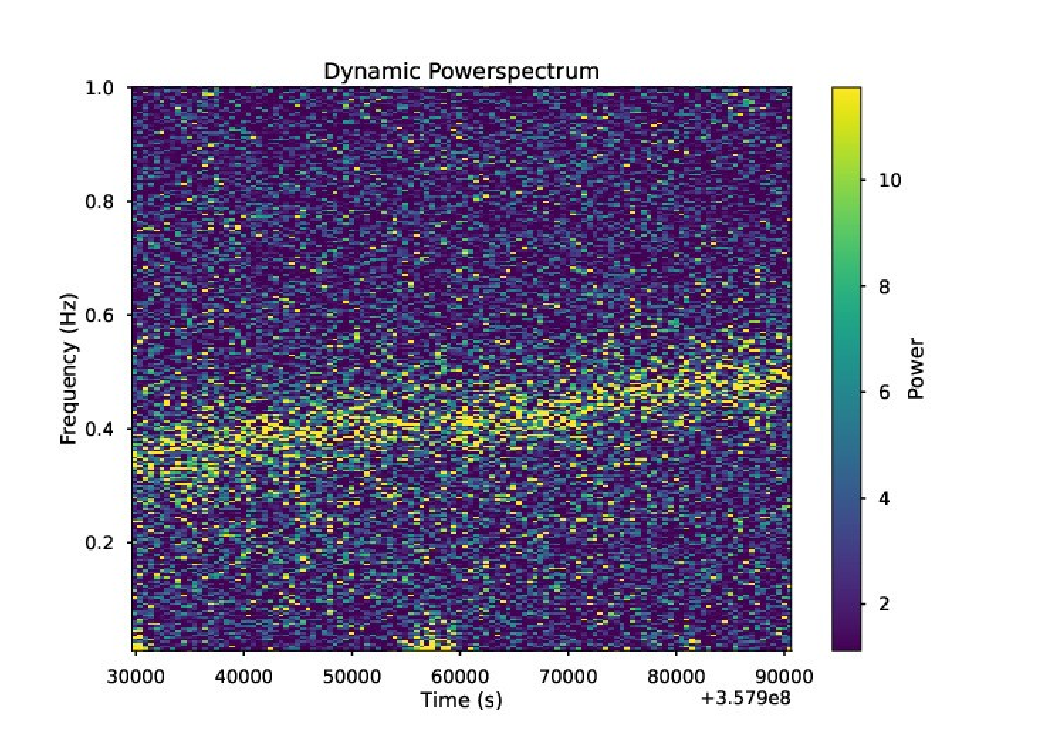


$Freq_{QPO}$ ~ 0.35 – 0.5 Hz

Chatterjee et al. (in preparation)

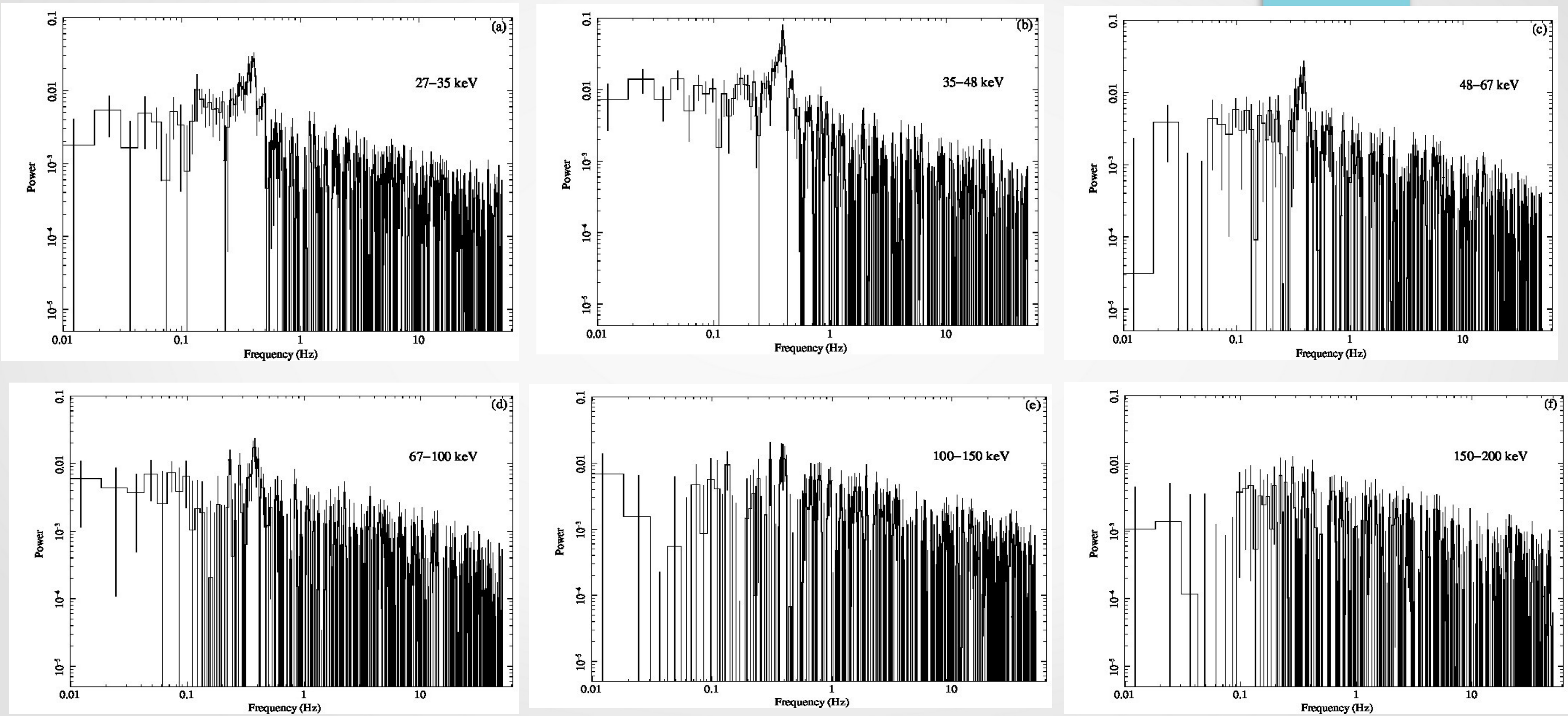
Timing Analysis

Dynamic PDS with the full NuSTAR Light Curve

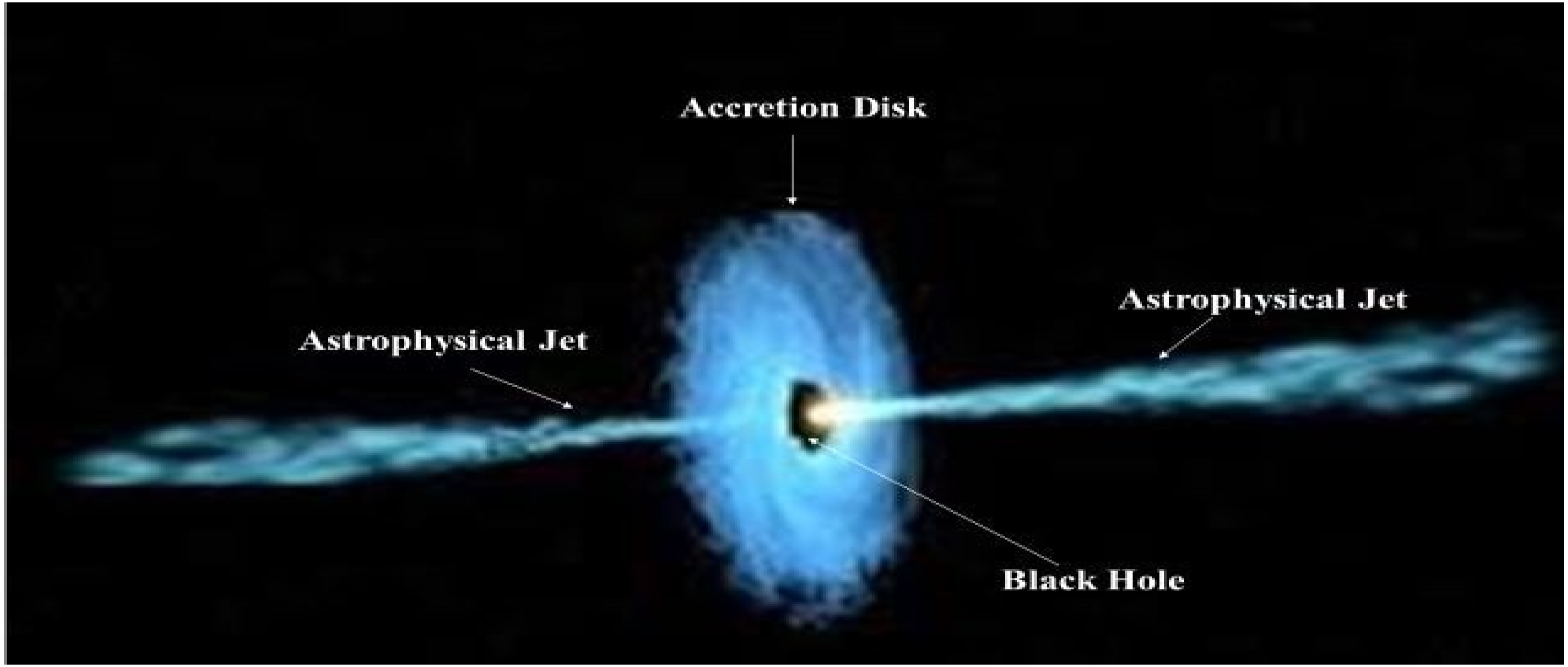


Chatterjee et al. (in preparation)

Energy Dependent PDS (Using HXMT HE Light Curve)



Chatterjee et al. (in preparation)



Astrophysical Jet is a common astronomical phenomena. Ionized matter are emitted along the axis of rotation in this phenomena. Mass, energy, momentum are chanalled from stellar, galactic, extra-galactic sources to the outer medium in these jets. Jets are subsonic close to the black hole and become supersonic when away from the source

- Jets are common in both the Stellar-mass and supermassive black holes. These flows are conical and narrow.
- The most powerful jets are associated with AGNs.
- The structure of jets are same from both the AGNs and SBHs.
- This implies that they both share the same physical origin.
- The jet phenomena covers seven orders of magnitude.

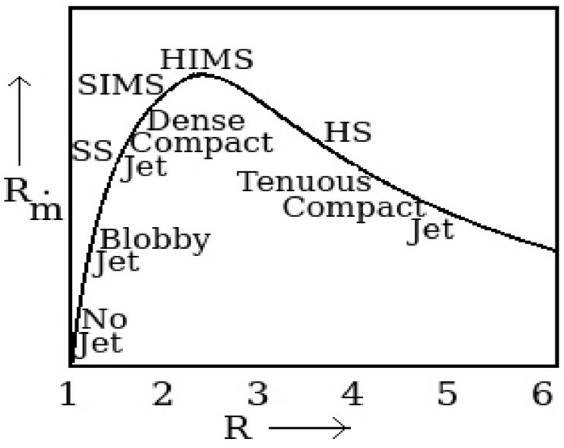
Protostars: (0.1-2) x 10^4 L_{sun} to GRBs with 10^{51-53} erg/sec.

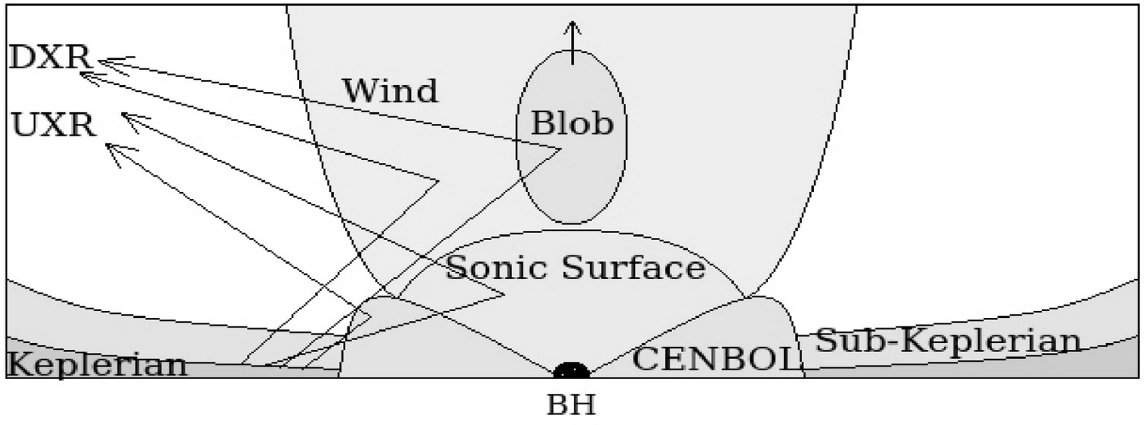
Jet Classification

Two types of jets are there-

- Compact or continuous jets (seen in hard state)
- Discrete or blobby jets (seen in intermediate state)

TCAF model as the base of Jet





Jana et al. (2017)

Variation of outflow rate to inflow rate as a function of compression ratio (R)

$$\frac{\dot{M}_{out}}{\dot{M}_{in}} = \dot{R}_m = \frac{\theta_{out}}{\theta_{in}} \frac{R}{4} \left[\frac{R^2}{R-1}\right]^{3/2} exp\left(\frac{3}{2} - \frac{R^2}{R-1}\right)$$

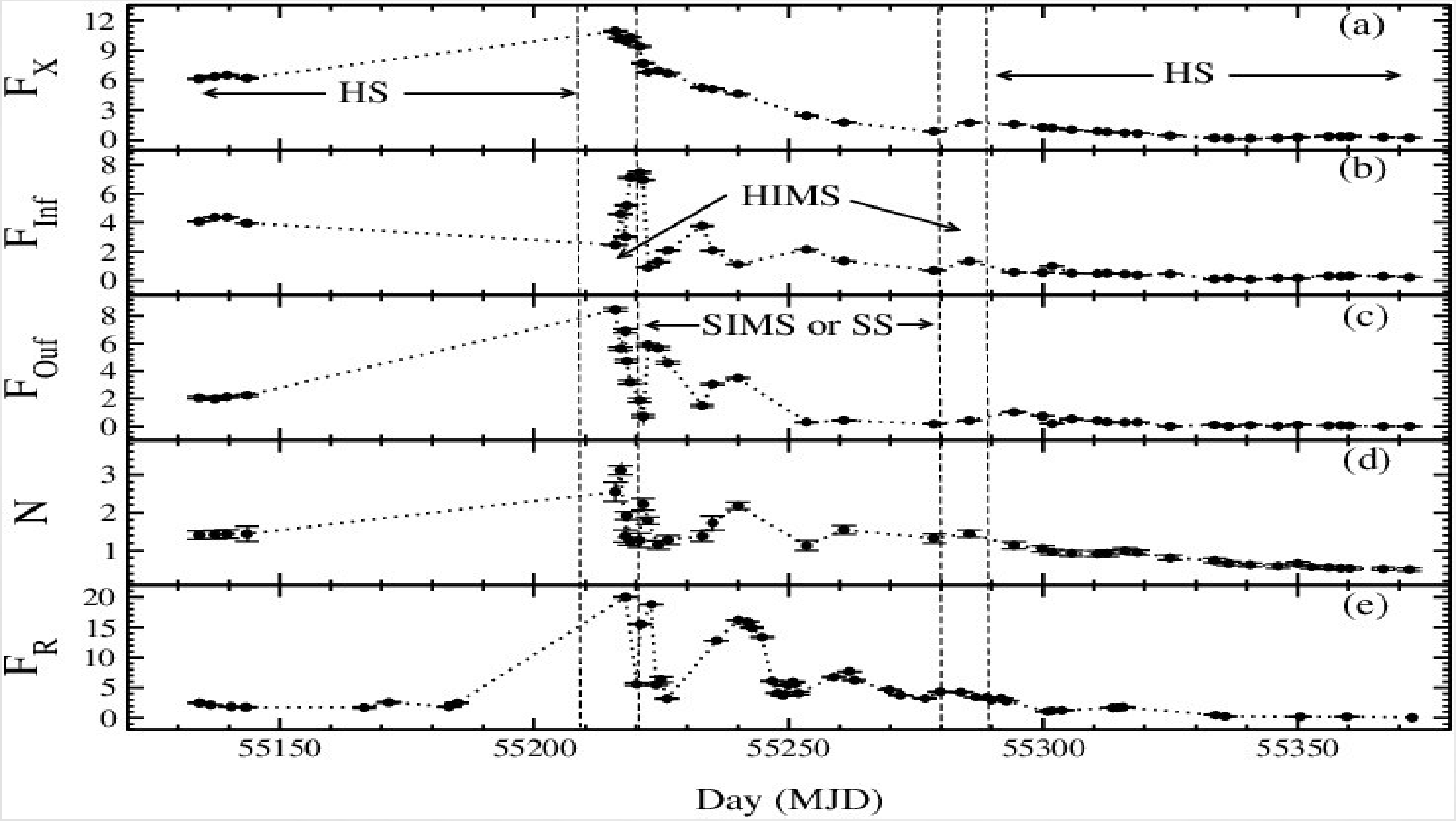
Chakrabarti (1998)

Extracting Jet Contribution

$$F_X = F_{inf} + F_{ouf} \; ,$$

$$F_{ouf} = F_X - F_{inf}$$

Variation of Normalization with radio flux



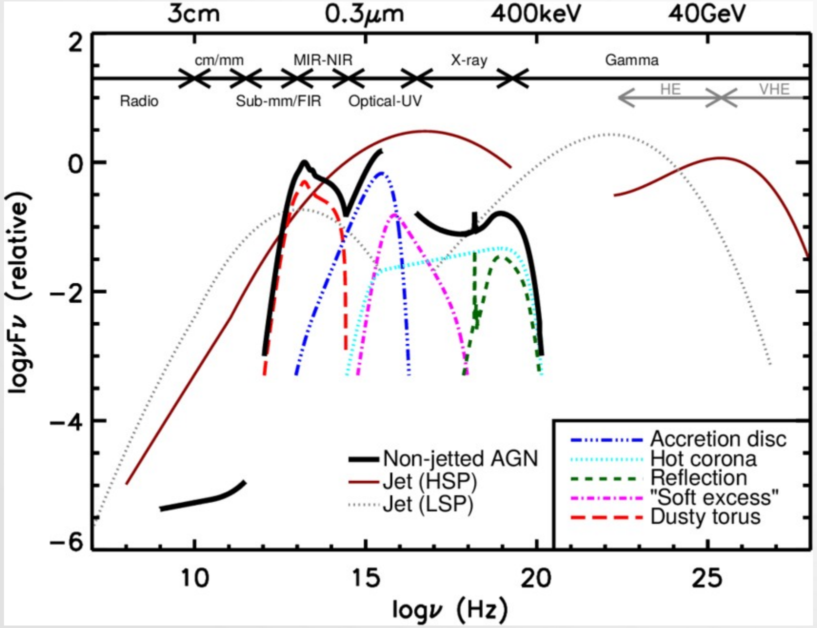
Debnath, Chatterjee et al. 2021, MNRAS, 504, 4242

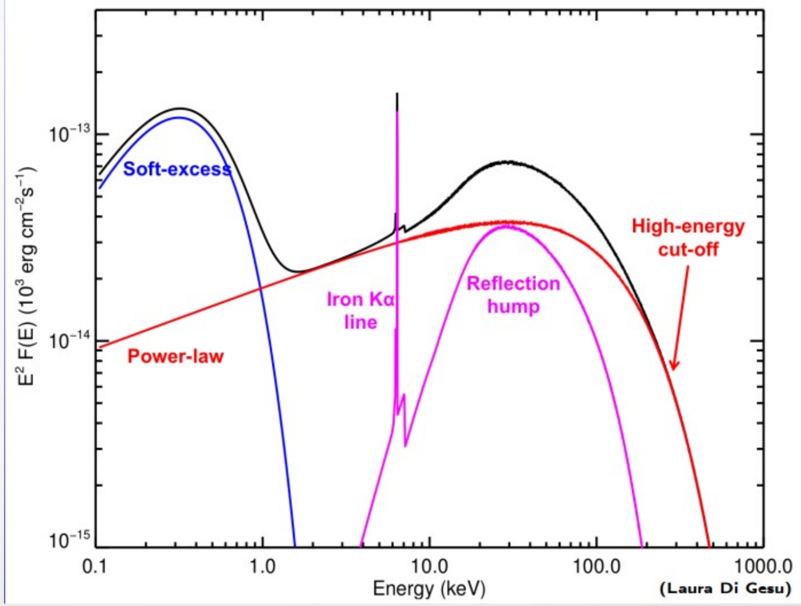
Conclusions

- Studying Spectral properties gives a good detail about the radiation process, going on in the surrounding of BHs.
- The Timing properties give idea about the variabilities and possible distance of those variability.
- The TCAF model can explain the timing, spectral, and jet properties
- We can determine mass from this modelling.

Future Plan

- Develope the jet extraction method.
- Develope ***fits*** file that can fit the composite spectra of AGNs.





References

Brocksopp C., Corbel S., Tzioumis A., et al., 2013, MNRAS, 432, 931
Chakrabarti S., Titarchuk L. G., 1995, ApJ, 455, 623
Chakrabarti S. K., 1998, InJPB, 72, 565
Chakrabarti S. K., 2013, RETCO: Theory and Observation, ASI Conf. Ser., 8, 1
Ghosh A., Chakrabarti S. K., 2019, MNRAS, 485, 4045
Debnath D., Mondal S., Chakrabarti S. K., 2015, MNRAS, 447, 1984
Jana A., Chakrabarti S. K., Debnath D., 2017, ApJ, 850, 91
Jana A., Debnath D., Chakrabarti S. K., Mondal S., Molla A. A., 2016, ApJ, 819, 107
Ratti E. M. et al., 2012, MNRAS, 423, 2656
Shaposhnikov N., Markwardt C., Swank J., Krimm H., 2010, ApJ, 723, 1817
Antia, H. M., et al. 2017, ApJS, 231, 10
Ballet, J., Denis, M., Gilfanov, M., et al. 1993, IAU Circ., 5874
Bharali, P., Chandra, S., Chauhan, J., et al. 2019, MNRAS, 487, 3150
Chakrabarti, S. K., Titarchuk, L., 1995, ApJ, 455, 623
Chatterjee, D., Debnath, D., Jana, A., Chakrabarti, S. K., 2019, Ap&SS, 364, 14
Chatterjee, D., Debnath, D., Jana, A., Chakrabarti, S. K., 2019, Ap&SS, 364, 14

Debnath, D., Chakrabarti, S. K., Mondal, S., 2014, MNRAS, 440, L121

della Valle, M., Mirabel, I. F., Rodriguez, L. F., 1994, A&A, 290, 803

Harmon, B. A., Fishman, G. J., Paciesas, W. S., Zhang, S. N., 1993, IAU Circ.,5900

Jana, A., Debnath, D., Chatterjee, D., Chatterjee, K., et al. 2020b, ApJ, 897, 3

Masumitsu, T. et al., 2016, ATel, 9895, 1

Masetti, N., Bianchini, A., Bonibaker, J., della Valle, M. Vio R., 1996, A&A, 314, 123

Matsuoka, M., Kawasaki, K., Ueno, S., et al. 2009, PASJ, 16, 999

Shakura, N. I., Sunyaev, R. A., 1973, A&A, 24, 337

Sreehari, H., Ravishankar, B. T., Iyer, N., et al. 2019, MNRAS, 487, 928

Thank you!