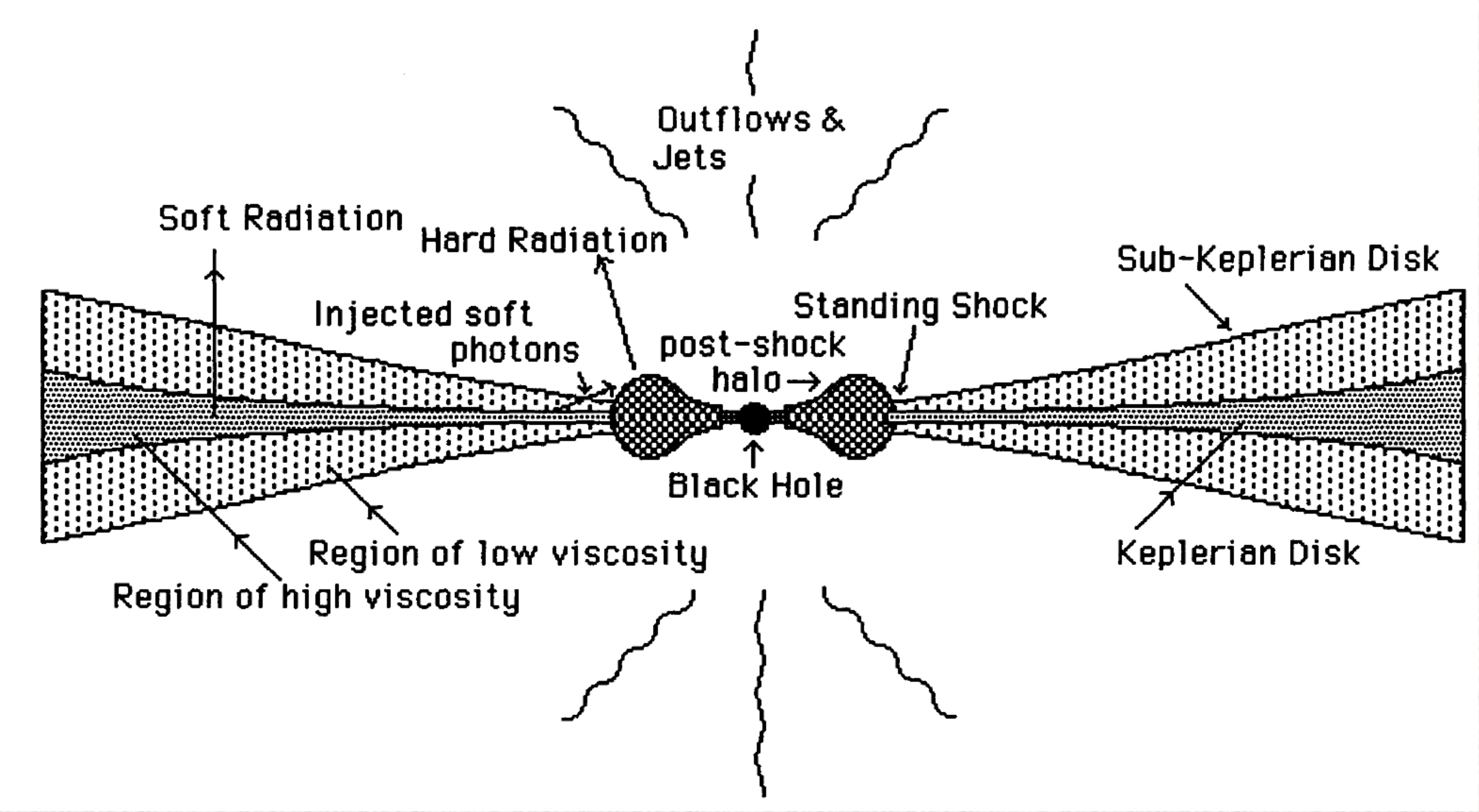
TCAF Solution in XSPEC : An Efficient Model to Study Accretion Flow Properties of Black Hole Sources

Dipak Debnath
Indian Centre for Space Physics, Kolkata, India

Collaborators: Prof. Sandip K. Chakrabarti, Dr. Sanatnu Mondal, Md. Aslam Ali Molla, Mr. Arghajit Jana, Mr. Debjit Chatterjee, Mr. Shreeram Nagarkoti, Mr. Ayan Bhattacharjee, Mr. Anuvab Banerjee, Dr. Indrani Banerjee, Ms. Bandy Shang, Prof. H. K. Chang

Two Component Advective Flow (TCAF) Model



A Schematic diagram of the accretion flow around the black hole.

Chakrabarti & Titarchuk 1995

Generating TCAF model fits file :

Took Chakrabarti & Titarchuk 1995 (CT95) original code as a basic program to generate TCAF model fits file to include as a local addtitive table model for fitting black hole spectra.

To fit spectra from all possible spectral states, several modifications are made in original CT95 code

i)Variation of compression ratio R is allowed from 4 (strong) to 1 (weak). CT95 assumed only strong shocks for illustration purpose.

ii) Computation of temperature of post-shock region using this R.

iii) Radial velocity of a rotating flow as in Chakrabarti (1997).

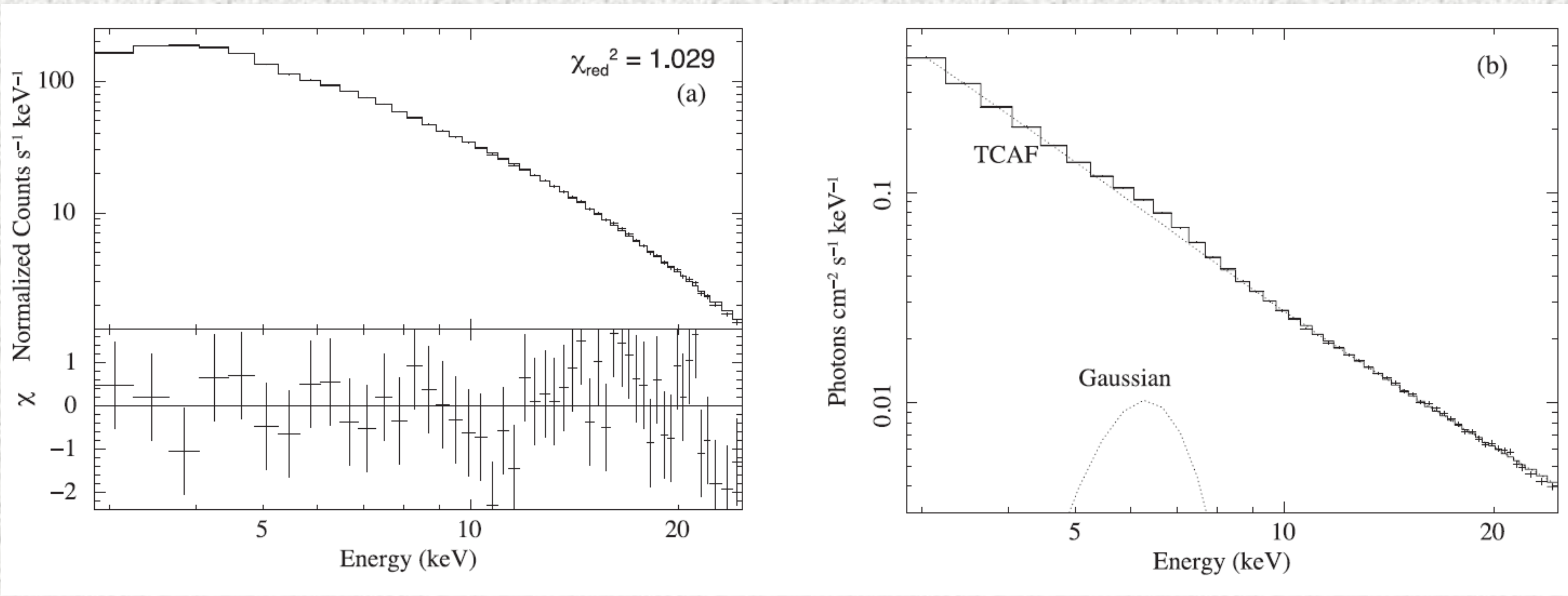
iv) Spectral hardening correction of Shimura & Takahara (1995), which depends on the accretion flow rate. We uniformly consider the correction factor (f) to be 1.8 to calculate effective temperature in emitted spectrum.

➢ "**TCAF_V0.3.fits**" file was created by using around 1 million (~10^6) model spectra. The spectra were generated by varying five model input parameters.

➢ For spectral with current TCAF model fits file, one needs to supply 6 initial input parameters:

i) M_{BH} (black hole mass in solar mass unit),
ii) $\dot{m}_d$ (Keplerian or disk rate),
iii) $\dot{m}_h$ (sub-Keplerain or halo rate),
iv) X_s (shock location in Schwarzschild radii r_g,
v) R (shock compression ratio,
vi) Normalization (which depends on source mass (M_{BH}), distance (D in 10 kpc unit) and disk inclination angle ('*i*') with line of sight).

GX 339-4 spectra fitted with TCAF Model:

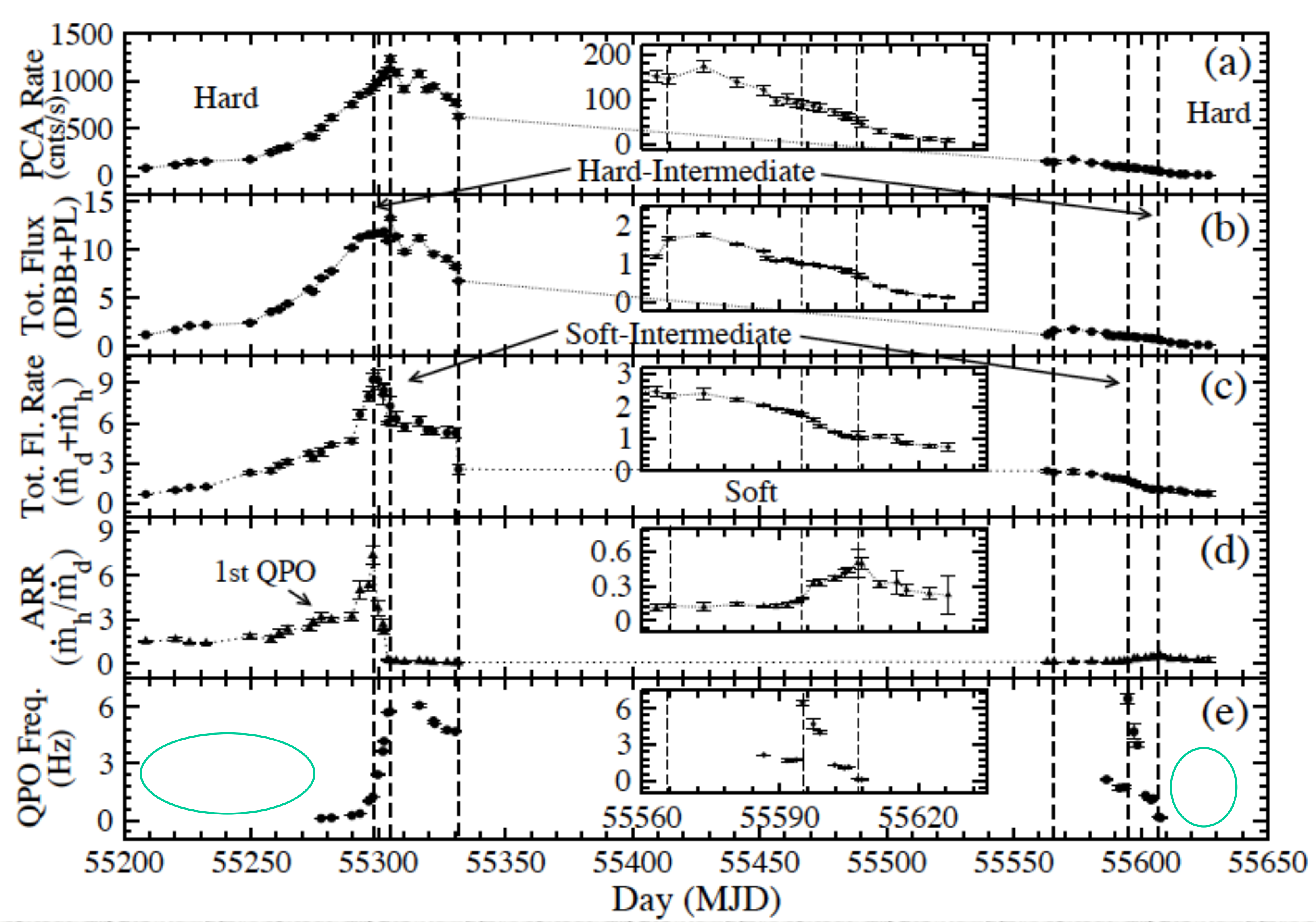


(a) TCAF model fitted 2.5–25 keV PCA spectrum of GX 339-4 (observation ID = 95409-01-14-04; MJD = 553 00, UT Date = 14/04/2010) with variation of $\Delta\chi$ is shown. (b) The unfolded model components of the spectral fit are show.

Debnath, Chakrabarti & Mondal, 2014, MNRAS, 440, L121

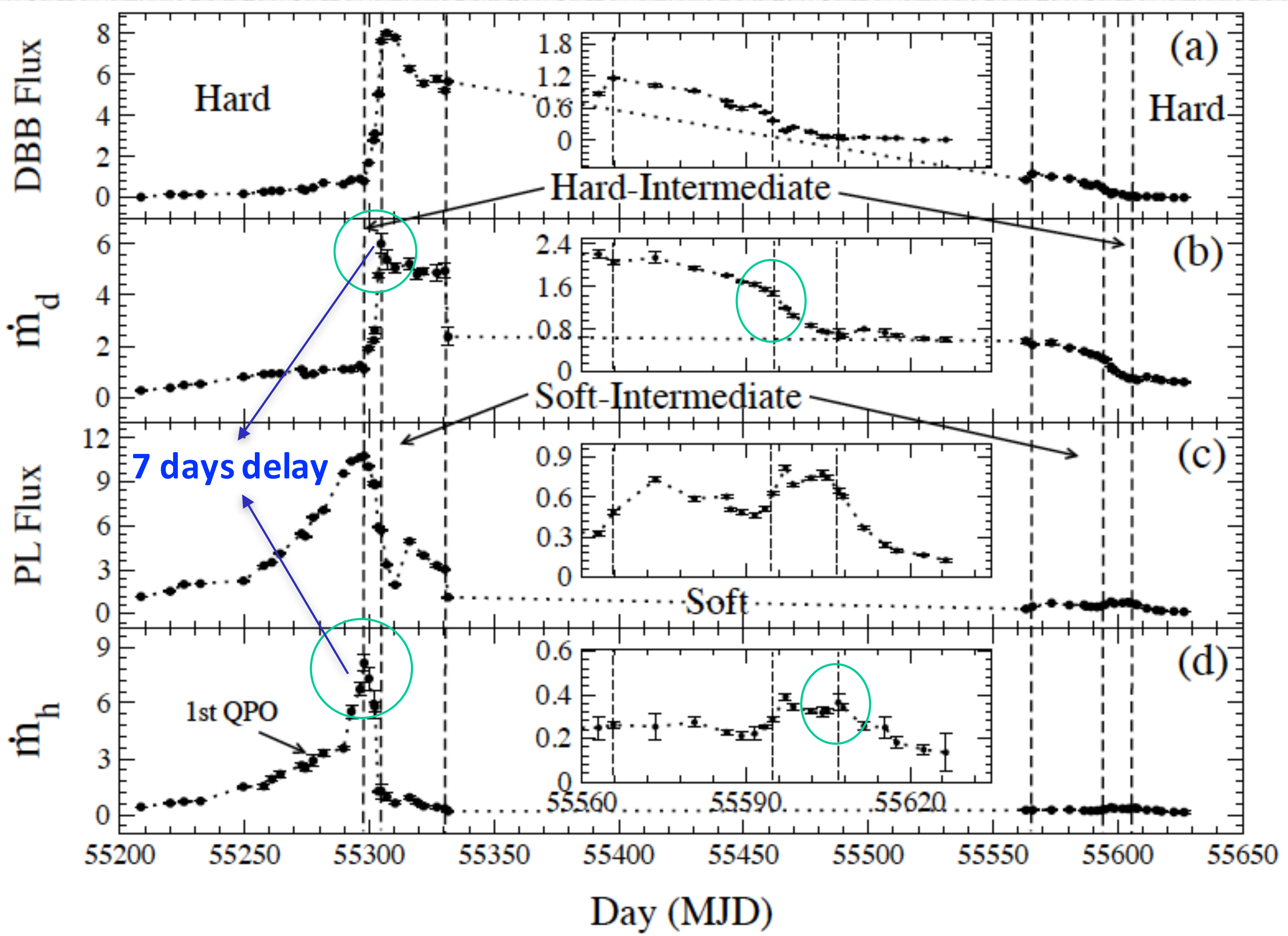
Characterization of BHCs during their X-ray outbursts with TCAF Solution

Characterization of GX 339-4 with TCAF Model:



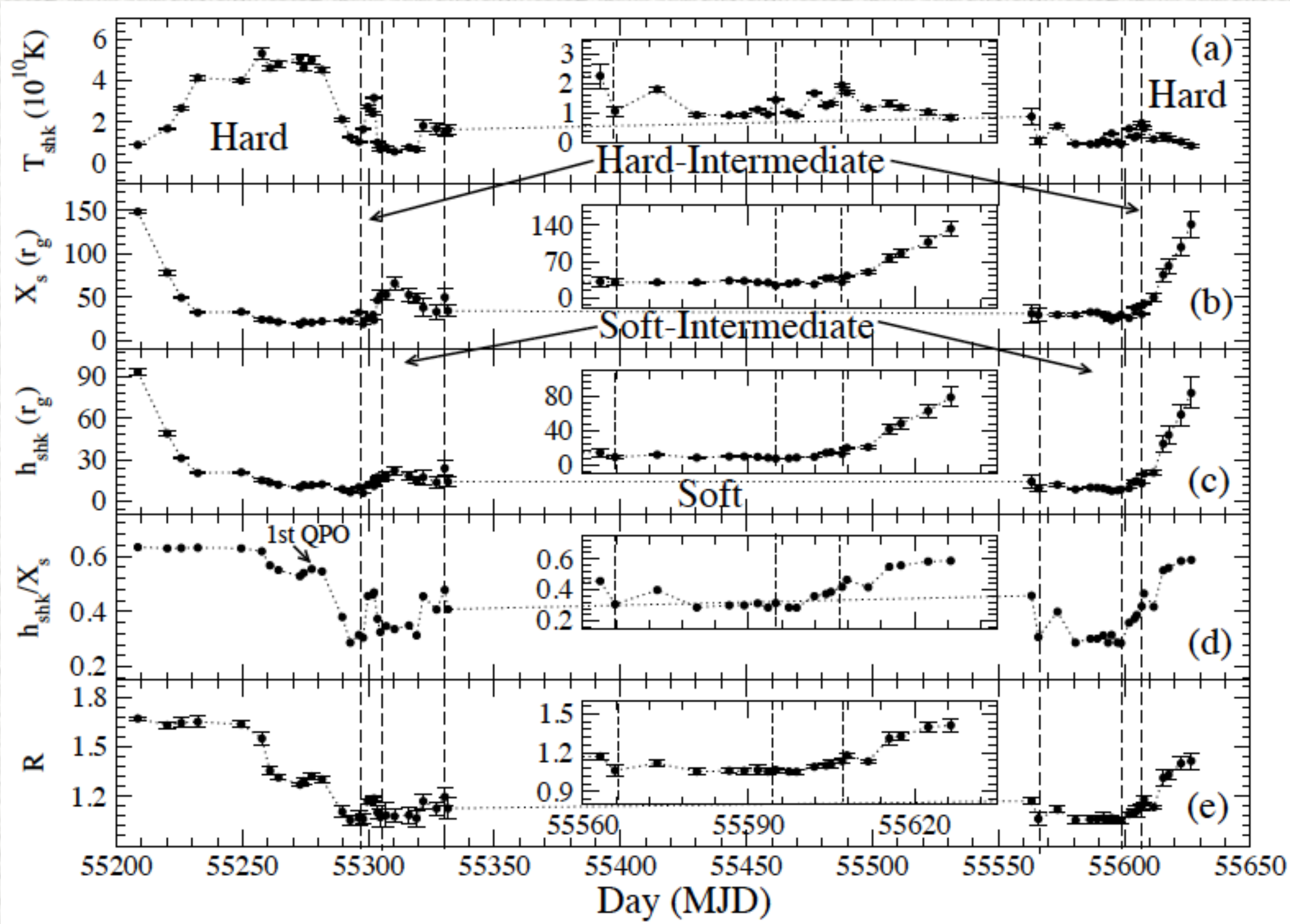
Debnath, Mondal & Chakrabarti, 2014, MNRAS, 447, 1984

Characterization of GX 339-4 with TCAF Model:



Debnath, Mondal & Chakrabarti, 2014, MNRAS, 447, 1984

Characterization of GX 339-4 with TCAF Model:



Debnath, Mondal & Chakrabarti, 2014, MNRAS, 447, 1984

Characterization of BHCs with the TCAF Solution so far…

TCAF model implementation paper : Debnath, Chakrabarti & Mondal, 2014, MNRAS Letters

- ✓ **GX 339-4** : 2010-11 (Debnath et al. 2015)
- ✓ **H 1743-322** : 2010 (Mondal et al. 2014); 2010 & 2011 (Molla et al. 2017); 2004 (Bhattacharjee et al. 2017); 2003 (Chakrabarti et al. 2017)
- ✓ **MAXI J1659-152** : 2010 (Debnath et al. 2015)
- ✓ **MAXI J1836-194** : 2011 (Jana et al. 2016)
- ✓ **MAXI J1543-564** : 2011 (Chatterjee et al. 2016)
- ✓ **Swift J1753.5-0127** : 2005 (Debnath et al. 2017; Jana et al. 2017)
- ✓ **XTE J1118+480** : 2000 (Chatterjee et al. 2017)
- ✓ **Cygnus X-1** : 1998 – 2003 (Banerjee et al. 2017)
- ✓ **IGR J17091-3624** : 2011 (Iyer et al. 2015)

Accretion Rate Intensity Diagram (ARRID) :

A correlation to spectro-temporal properties

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ACCRETION FLOW DYNAMICS OF MAXI J1836-194 DURING ITS 2011 OUTBURST FROM TCAF SOLUTION

ARGHAJIT JANA[1], DIPAK DEBNATH[1], SANDIP K. CHAKRABARTI[1,2], SANTANU MONDAL[1], AND ASLAM ALI MOLLA[1]
[1] Indian Center for Space Physics, 43 Chalantika, Garia St. Rd., Kolkata, 700084, India;
argha@csp.res.in, dipak@csp.res.in, chakraba@bose.res.in, santanu@csp.res.in, aslam@csp.res.in
[2] S. N. Bose National Centre for Basic Sciences, Salt Lake, Kolkata, 700098, India
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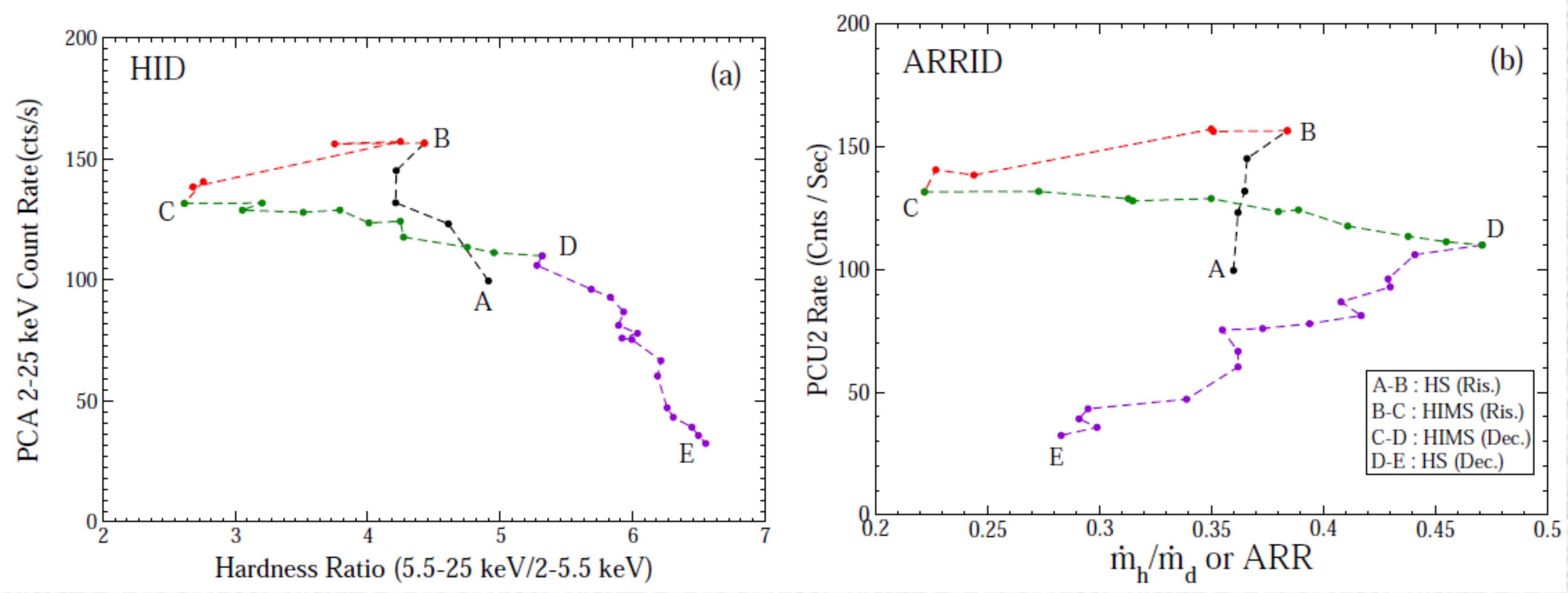
ARRID for 2011 outburst of MAXI J1836-194:



Jana, Debnath, Chakrabarti et al., 2016, ApJ, 819, 107

Prediction of dominating QPO frequency : Using TCAF model fitted shock parameters

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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Advance Access publication 2014 March 12

Implementation of two-component advective flow solution in XSPEC

Dipak Debnath,[1★] Sandip K. Chakrabarti[1,2] and Santanu Mondal[1]

[1] *Indian Centre For Space Physics, 43 Chalantika, Garia Station Road, Kolkata 700084, India*
[2] *S. N. Bose National Center for Basic Sciences, JD-Block, Salt Lake, Kolkata 700098, India*

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Prediction of dominating QPO frequency from TCAF model fitted shock parameters:

From TCAF model fit, location (r_s) and compression ratio (R) of the sock wave can be extracted.

ν_{QPO} **= C/ [R $r_s(r_s-1)^{1/2}$] ,** where C is a constant = M_{BH} x 10^{-5}.

Source	Obs. Id	$\dot{m}_d$ ($\dot{M}_{Edd}$)	$\dot{m}_h$ ($\dot{M}_{Edd}$)	X_s (r_g)	R	χ^2/DOF	ν^*_{QPO} (Obs.)	ν^*_{QPO} (Predic.)
H 1743−322	X-02-01	0.516 ±0.013	0.189 ±0.081	320.0 ±20.04	1.250 ±0.012	60.1/42	1.045 ±0.007	1.228 ±0.293
GX 339−4	Y-14-04	6.883 ±0.003	6.087 ±0.349	147.9 ±1.13	4.000 ±0.075	43.2/42	2.374 ±0.006	2.356 ±0.265
GRO J1655−40	Z-01-00	6.987 ±0.273	1.733 ±0.232	153.8 ±13.36	3.449 ±0.433	64.78/41	2.313 ±0.010	2.172 ±0.529

Notes. Here, X = 95360-14, Y = 95409-01 and Z = 90704-04. DOF means degrees of freedom.* Only frequency of the primary dominating QPOs (in Hz) in mentioned.

Debnath, Chakrabarti & Mondal, 2014, MNRAS, 440, L121

Prediction of dominating QPO frequency of MAXI J1543-564 (2011 outburst) using TCAF & POS models:

Table 2: QPO evolution in initial rising phase: Fitted with POS Model

Obs.	Id.	MJD	ν_{Obs} (Hz)	ν_{POS} (Hz)	X_s (r_g)	V (cm/s)	R	ν_{TCAF} (Hz)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	X-01-00	55691.09	$1.05^{\pm 0.02}$	1.04	210.0	2450.0	2.44	$0.85^{\pm 0.06}$
2	X-01-01	55692.09	$1.75^{\pm 0.02}$	1.65	163.4	2105.7	2.24	$1.12^{\pm 0.05}$
3	X-01-02	55693.09	$2.98^{\pm 0.02}$	2.82	132.0	1760.1	1.81	$2.49^{\pm 0.14}$
4	X-02-00	55694.10	$4.38^{\pm 0.05}$	4.56	115.9	1411.5	1.36	$4.67^{\pm 0.27}$
5	X-02-01	55694.89	$5.70^{\pm 0.09}$	5.89	114.1	1139.0	1.08	$7.68^{\pm 1.11}$
6*	X-02-02	55695.67	$5.08^{\pm 0.17}$	—-	—-	—-	—-	—-
7	X-02-03	55696.68	—–	—-	—-	—-	—-	—-

Here 'X'=96371-02 signifies the initial part of an observation Id.

Chatterjee, Debnath, Chakrabarti, Mondal & Jana, 2016, ApJ, 827, 88

Mass Estimation : Using TCAF & POS Models

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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Advance Access publication 2016 April 15

Estimation of the mass of the black hole candidate MAXI J1659−152 using TCAF and POS models

Aslam Ali Molla,[1] Dipak Debnath,[1★] Sandip K. Chakrabarti,[1,2] S. Mondal[1] and A. Jana[1]

[1] *Indian Centre For Space Physics, 43 Chalantika, Garia Station Road, Kolkata 700084, India*
[2] *S. N. Bose National Center for Basic Sciences, JD-Block, Salt Lake, Kolkata 700098, India*

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QPO Freq. - Photon Index Correlation Method

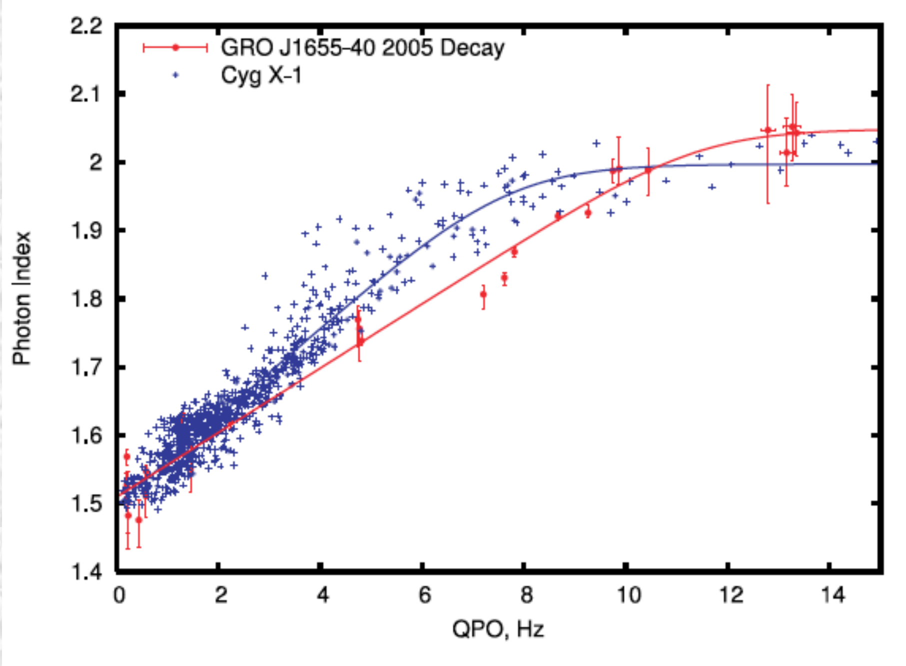
$$f(\nu) = A - DB \ln\left[\exp\left(\frac{\nu_{tr} - \nu}{D}\right) + 1\right]. \qquad (1)$$

where

$$f(\nu) = A + B(\nu - \nu_{tr}) \quad \text{for } \nu < \nu_{tr}$$

$$f(\nu) = A \text{ for } \nu > \nu_{tr}$$

Here 'A' is a value of the index saturation level, 'B' is a slope of the low-frequency part of the data, and 'ν_{tr}' is the frequency at which index-QPO dependence levels off. The parameter 'D' controls how fast the transition occurs.

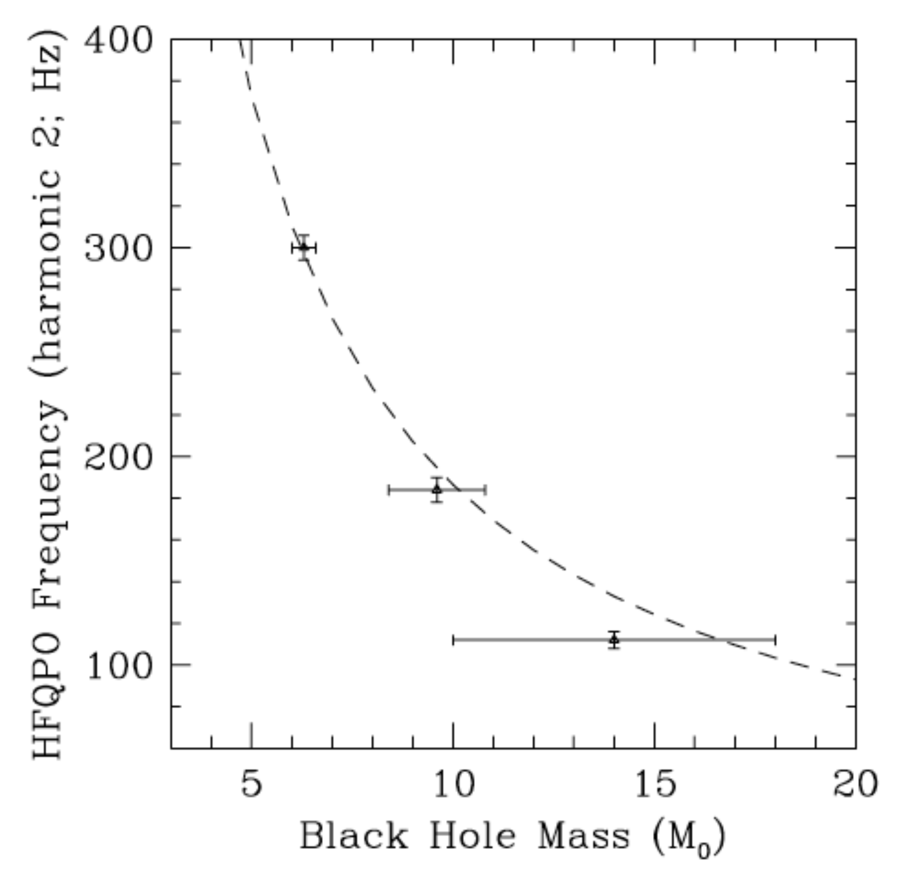


$$M_{\text{Cyg X-1}} = B_{\text{Cyg X-1}} \frac{M_{J1655}}{B_{J1655}} = 8.7 \pm 0.8\ M_{\odot}.$$

By considering reference BH GRO J1655-40 mass = 6.3 $M_{\odot}$

Shaposnikov & Titarchuk, 2007, ApJ, 663, 445

High Freq. QPO Freq. - BH Mass Correlation Method



High Frequency QPOs for different black holes are found to be correlated with BH mass in M^{-1}.

Relationship between HFQPO frequency and BH mass for XTE J1550–564, GRO J1655–40, and GRS 1915+105.. The dashed line shows a relation, ν_0 (Hz) = 931 $(M/M_\odot)^{-1}$.

McClintock & Remillard, 2006

In Molla, Debnath, Chakrabarti et al. (2016), we introduce two independent methods to determine the mass (M_{BH}) of the BH sources.

i) Keeping TCAF fitted normalization parameter in a narrow range

ii) Studying evolution of the Quasi-Periodic Oscillation frequency with time, fitted with the propagating oscillatory shock (POS) model

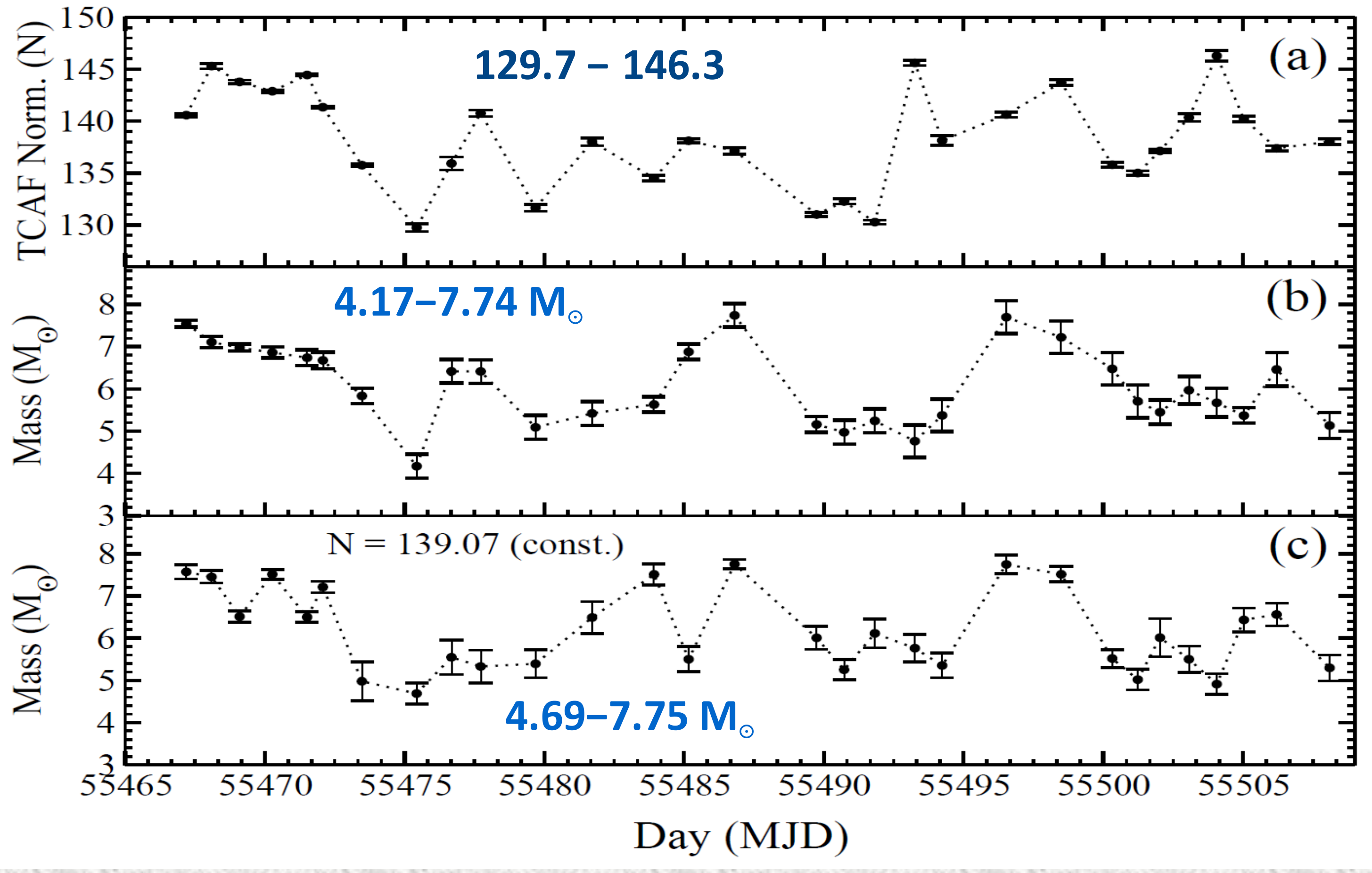
TCAF model normalization (N) should not vary observation to observations, since it only depends on mass (M_{BH}), distance (D), and disk inclination angle (i) of the source, unless there is a precession in the disk or change in the projected surface of effective emission area along the line of sight or there are significant outflow activities that are not included in the TCAF model fits file.

We found high dependence of the mass of BH (M_{BH}) with N, while fitting BH spectra. It helps us to estimate mass of different BHCs.

➢ While studying evolutions of QPOs with POS model, one can calculate frequency of the observed QPOs with following equation, where mass of the BH is an important parameter.

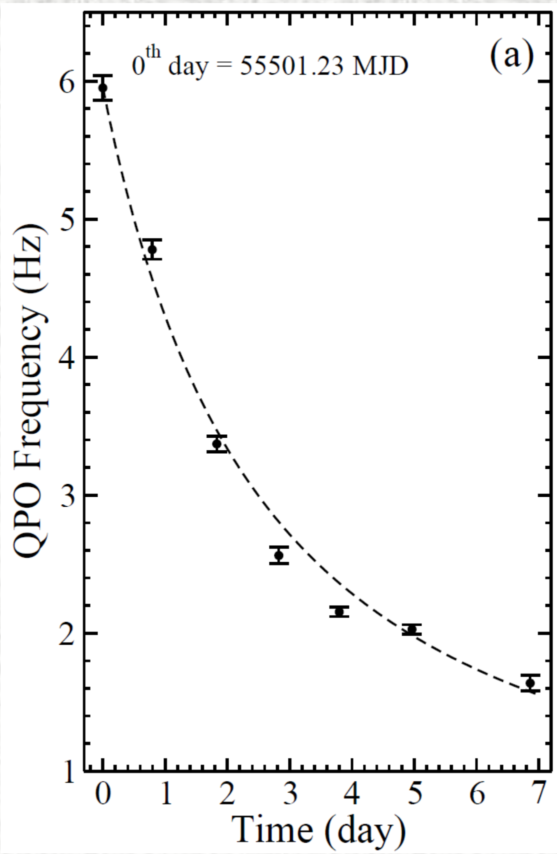
$\boldsymbol{\nu_{QPO} = C/ [R\ r_s(r_s-1)^{1/2}]}$, where C is a constant = $M_{BH} \times 10^{-5}$.

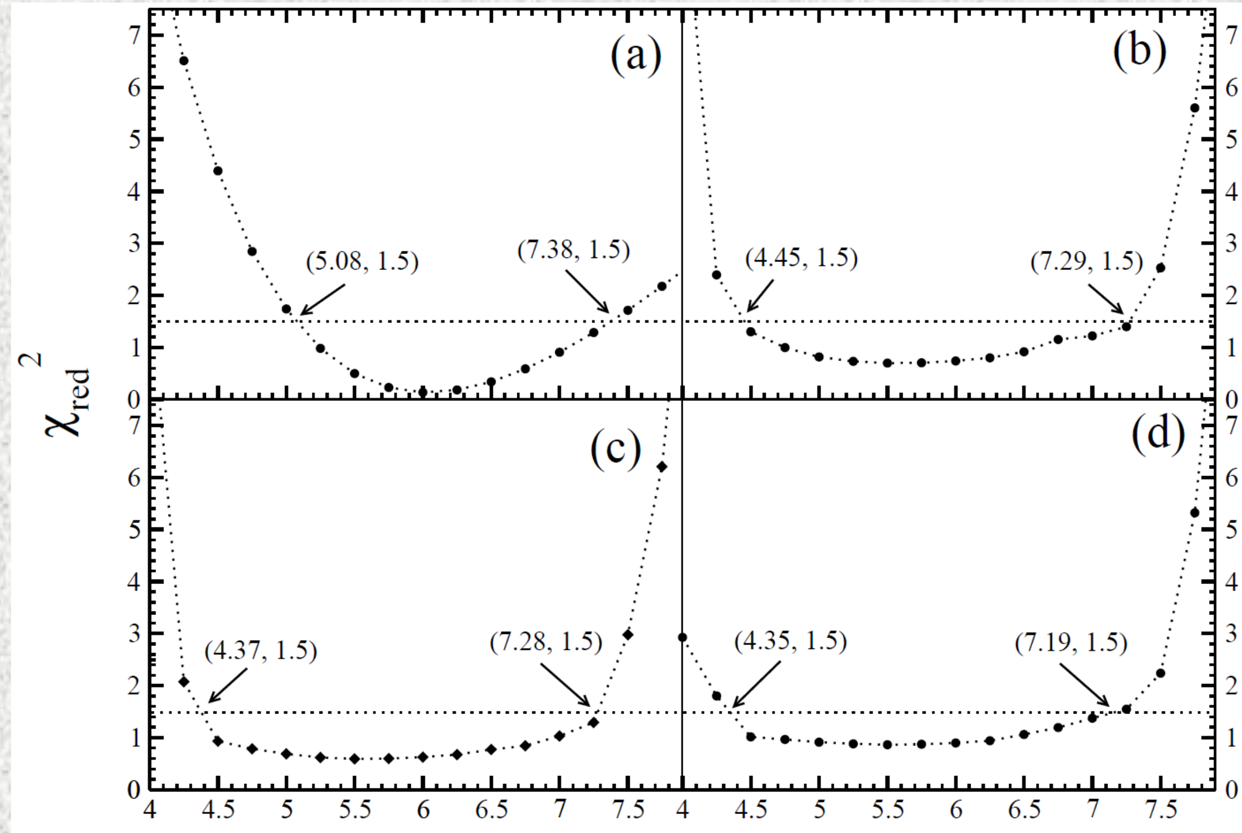
MAXI J1659-152: Mass prediction using TCAF Model fitted Constant Normalization Method



Molla, Debnath, Chakrabarti, et al., 2016, MNRAS, 460, 3163

MAXI J1659-152: Mass prediction using POS Model fitted & Reduced χ^2 Methods





POS Model Fitted Method: **5.08–7.38 $M_\odot$**

M_{BH}-χ^2_{red} Method : **4.35–7.29 $M_\odot$**

Combining three methods: **4.35 – 7.75 $M_\odot$**

or $6^{+1.75}_{-1.65}\ M_\odot$

Molla, Debnath, Chakrabarti, et al., 2016, MNRAS, 460, 3163

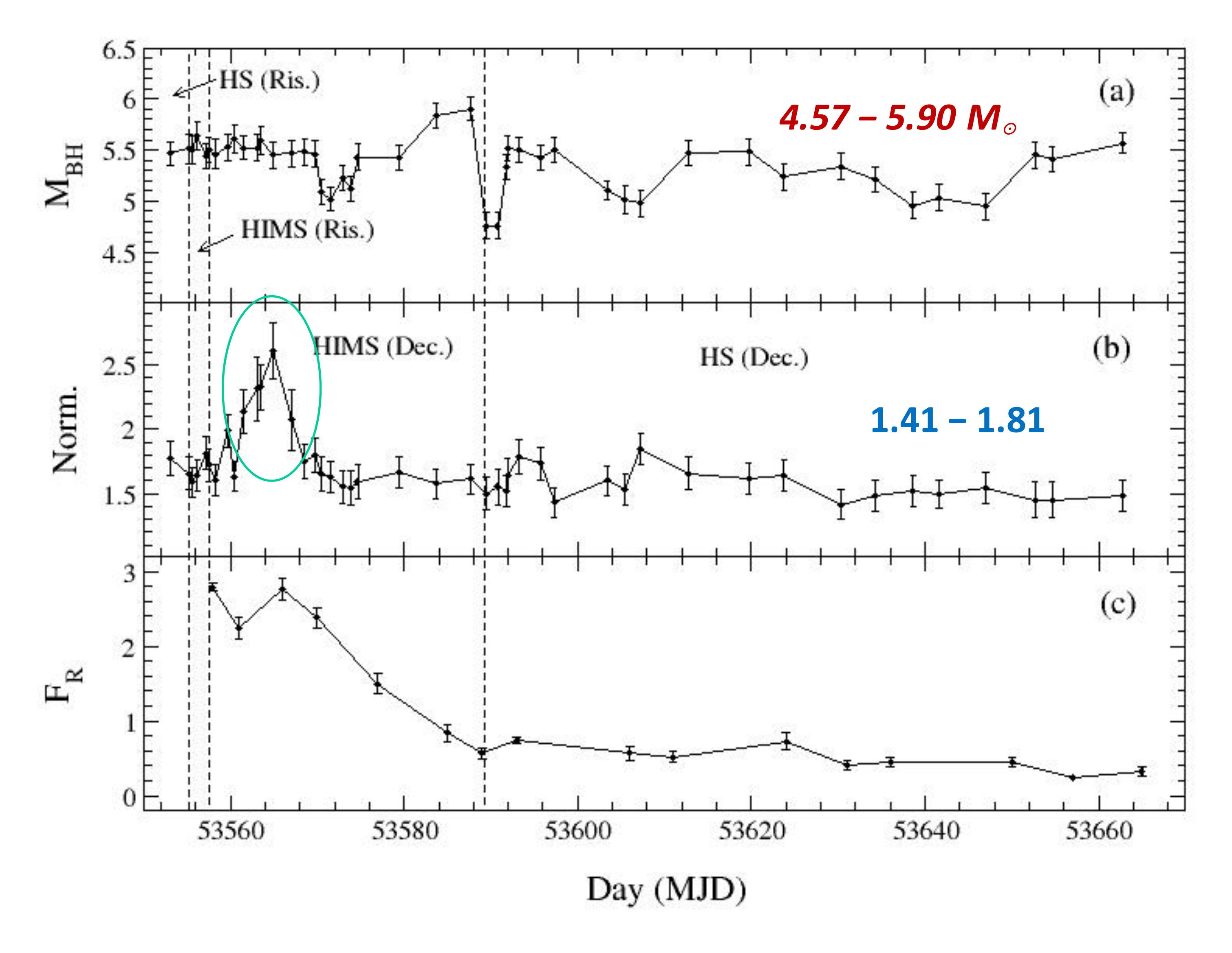
Mass of BHCs Estimated with the TCAF Solution so far…

- ✓ **MAXI J1659-152** : **4.35 – 7.75 M$_\odot$** or $6^{+1.75}_{-1.65}\ M_\odot$ (Molla et al. 2016)
- ✓ **MAXI J1836-194** : **7.5 – 11 M$_\odot$** (Jana et al. 2016)
- ✓ **MAXI J1543-564** : **12.6 – 14 M$_\odot$** or $13^{+1.0}_{-0.4}\ M_\odot$ (Chatterjee et al. 2016)
- ✓ **H 1743-322** : **9.25 – 12.86 M$_\odot$** or $11.21^{+1.65}_{-1.96}\ M_\odot$ (Molla et al. 2017); **10.31 – 14.07 M$_\odot$** (Bhattacharjee et al. 2017)
- ✓ **Swift J1753.5-0127** : **4.75 – 5.90 M$_\odot$** (Debnath et al. 2017)
- ✓ **Cygnus X-1** : **14.30 ± 0.66 M$_\odot$** (Banerjee et al. 2017)
- ✓ **XTE J1118+480** : **7.26 – 7.71 M$_\odot$** (Chatterjee et al. 2017)

- ✓ **IGR J17091-3624** : **11.8 – 13.7 M$_\odot$** (Iyer et al. 2015) ---- Using POS model (Chakrabarti et al. 2005, 2008)

X-ray Jets: Detection and estimation from spectral analysis with the TCAF solution

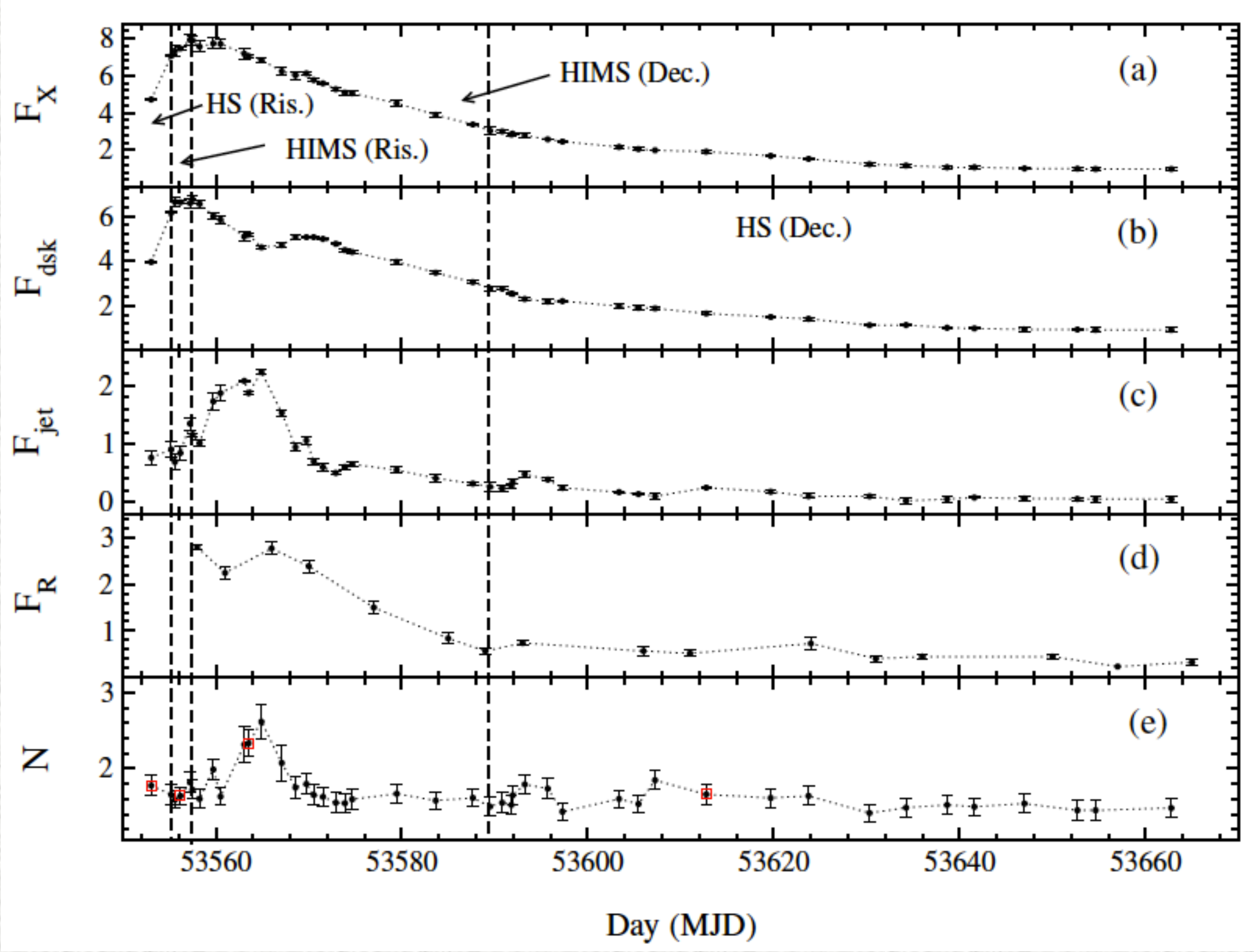
Swift J1753.5-0127: Mass prediction using the TCAF Solution



Debnath, Jana, Chakrabarti, et al., 2017, ApJ (submitted)

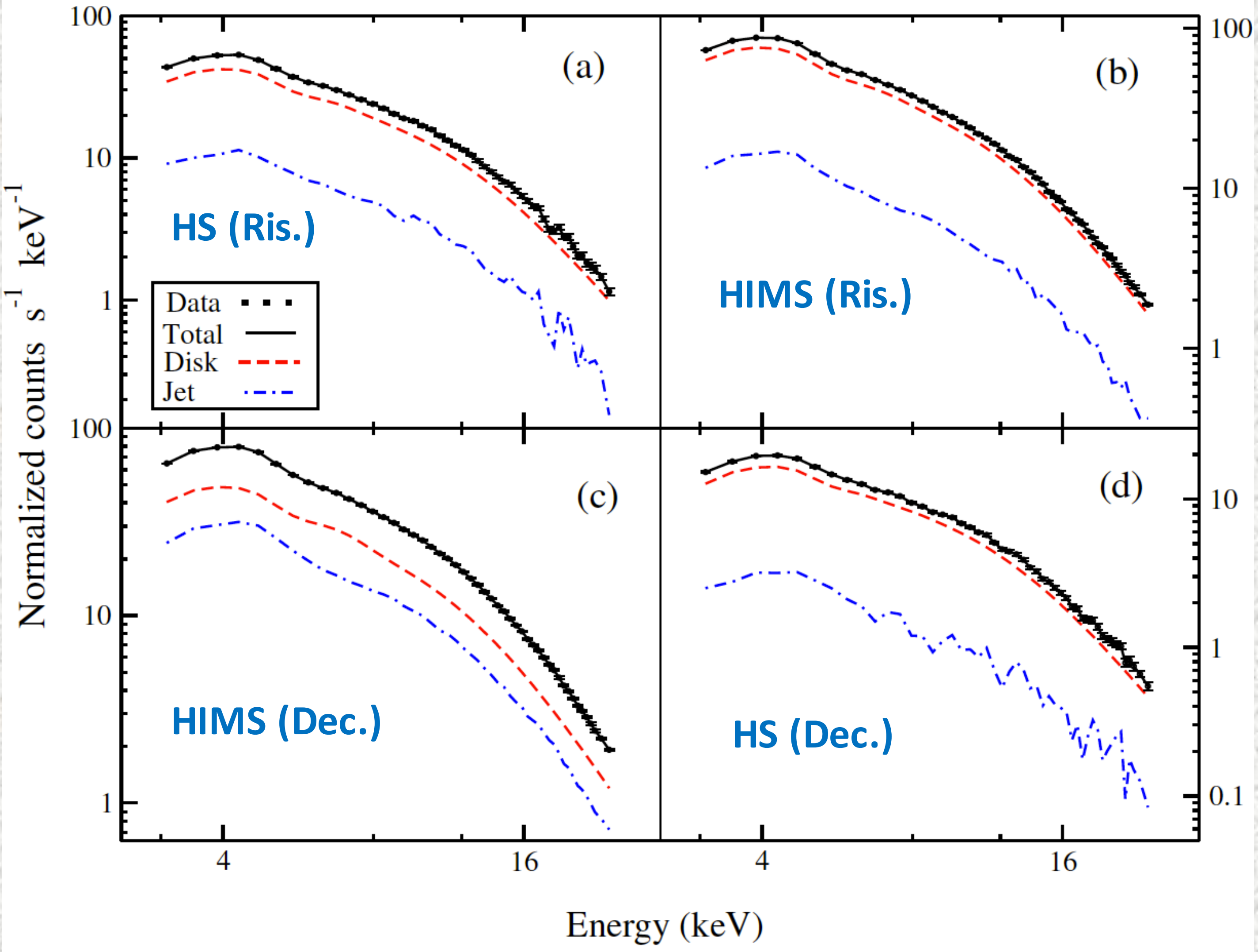
Swift J1753.5-0127: Estimation of X-ray Jet fluxes

$$F_{jet} = F_{tot} - F_{dsk}, \qquad (1)$$



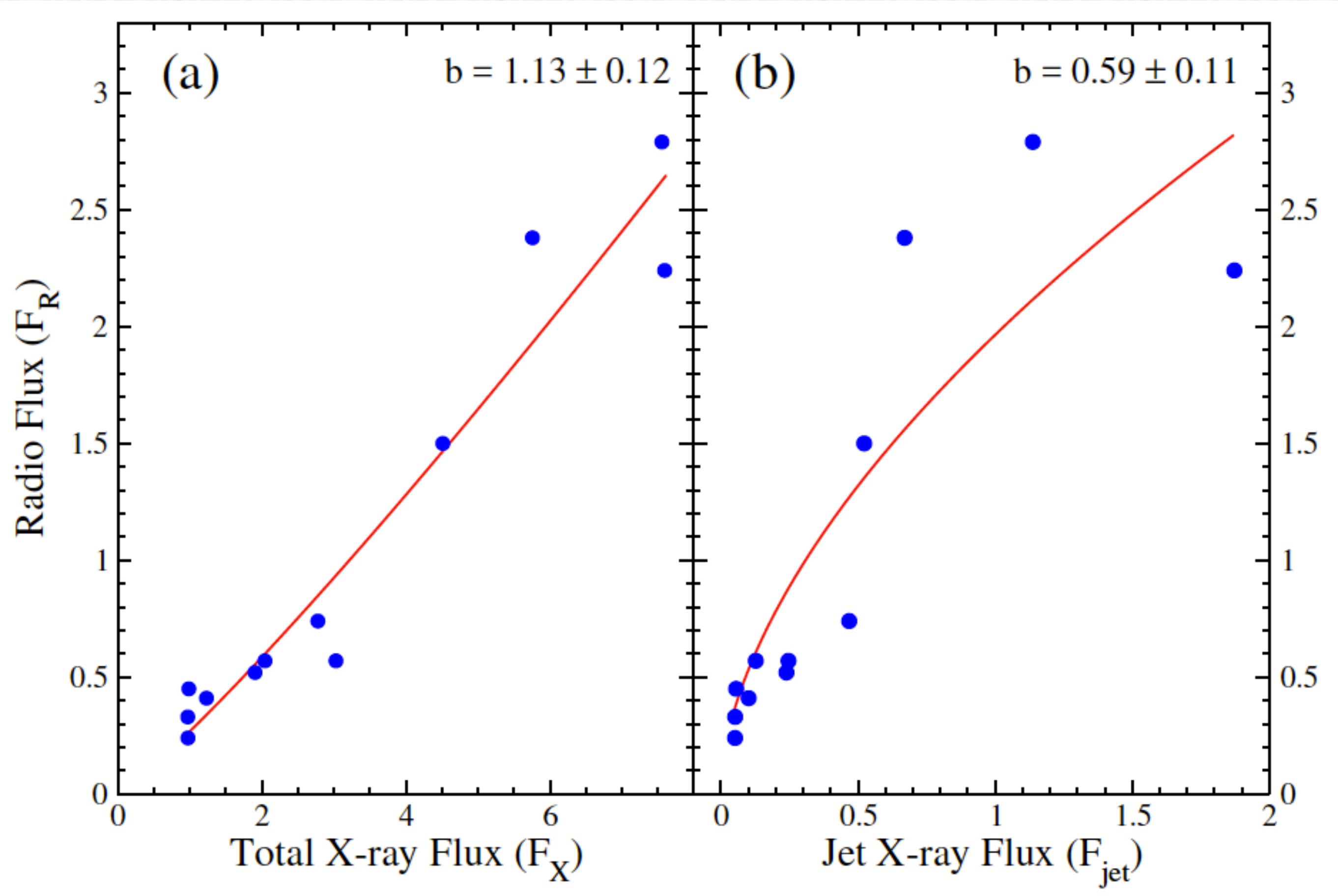
Jana, Chakrabarti & Debnath, 2016, ApJ (submitted)

Swift J1753.5-0127: Fitted with TCAF to separate Jet part



Jana, Chakrabarti & Debnath, 2016, ApJ (submitted)

Swift J1753.5-0127: Correlation between X-ray and Radio fluxes



Radio and X-ray fluxes follows correlation relation

$$\mathbf{F}_{R} \sim \mathbf{F}_{X}^{b}$$

During the 2005 outburst of Swift J1753.5-0127, average jet contribution in total X-ray is about 12.5 %, where as on the day of strongest jet, the contribution is rised upto ~ 32% of the total flux.

Jana, Chakrabarti & Debnath, 2016, ApJ (submitted)

Summary and Concluding Remarks:

1) **Accretion flow dynamics** during outbursts of transient BHCs well understood with spectral studies with Two-Component Advective Flow (**TCAF**) model, as an additive table model in XSPEC.

2) **Classification of spectral states** during outbursts can be well understood based on TCAF model fitted physical parameters (variation of accretion rate ratios, i.e., **ARRs**; ratio between TCAF model fitted sub-Keplerian halo to Kelerian disk rates) and **nature of QPOs** (if present).

3) **Prediction of dominating QPO** frequencies could be done with the TCAF model shock parameters (**location and compression ratio**).

4) **Estimation of mass** of an unknown BH from TCAF & POS model fits.

5) Idea about the **viscous time scale** from peak time differences of disk & halo rates.

6) **ARRID** to find correlation between timing and spectral properties.

7) **Detection of Jets in X-rays** and **estimation** of flux contributions and find its correlation with radio.

8) In future, we will **extend our work to other transient** as well as persistent BHCs(for e.g., GRO J1655-40, XTE J1550-564, GRS 1915+105, IGR J17091-3654, Cyg X-1, LMC X3, 4U 1957+115, etc.) and will also try predict mass of some unknown objects.

9) In future, we also have plan to use **ASTROSAT** and other satellite data of transient BHCs to make a combined study for detailed temporal and spectral properties of those BHCs.

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Thank you