LORENTZ FACTORS OF COMPACT JETS IN BLACK HOLE X-RAY BINARIES

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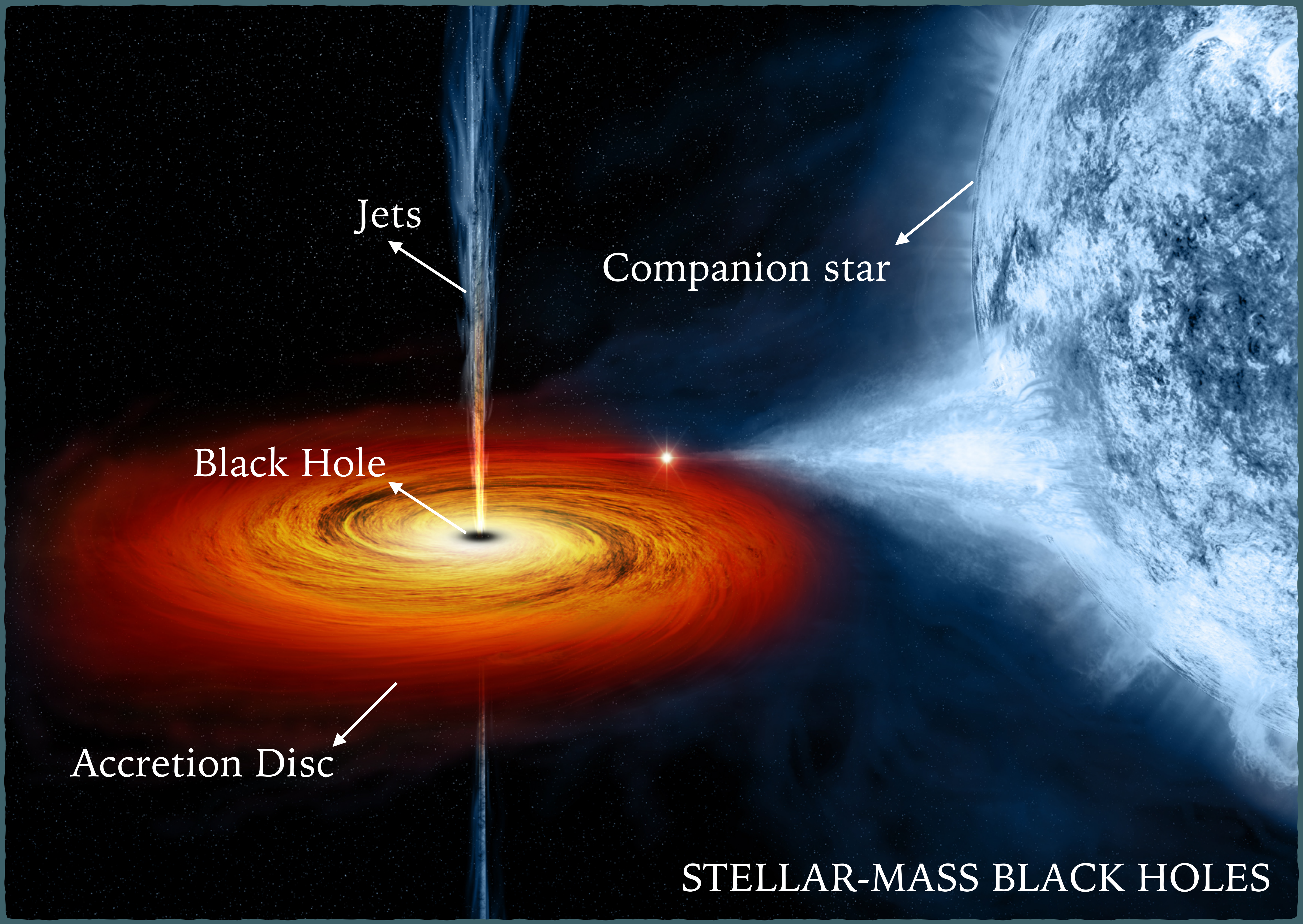
PAYASWINI SAIKIA

DAVE RUSSELL, MARIA CRISTINA BAGLIO, DANIEL BRAMICH,
JAMES MILLER-JONES, NATHALIE DEGENAAR

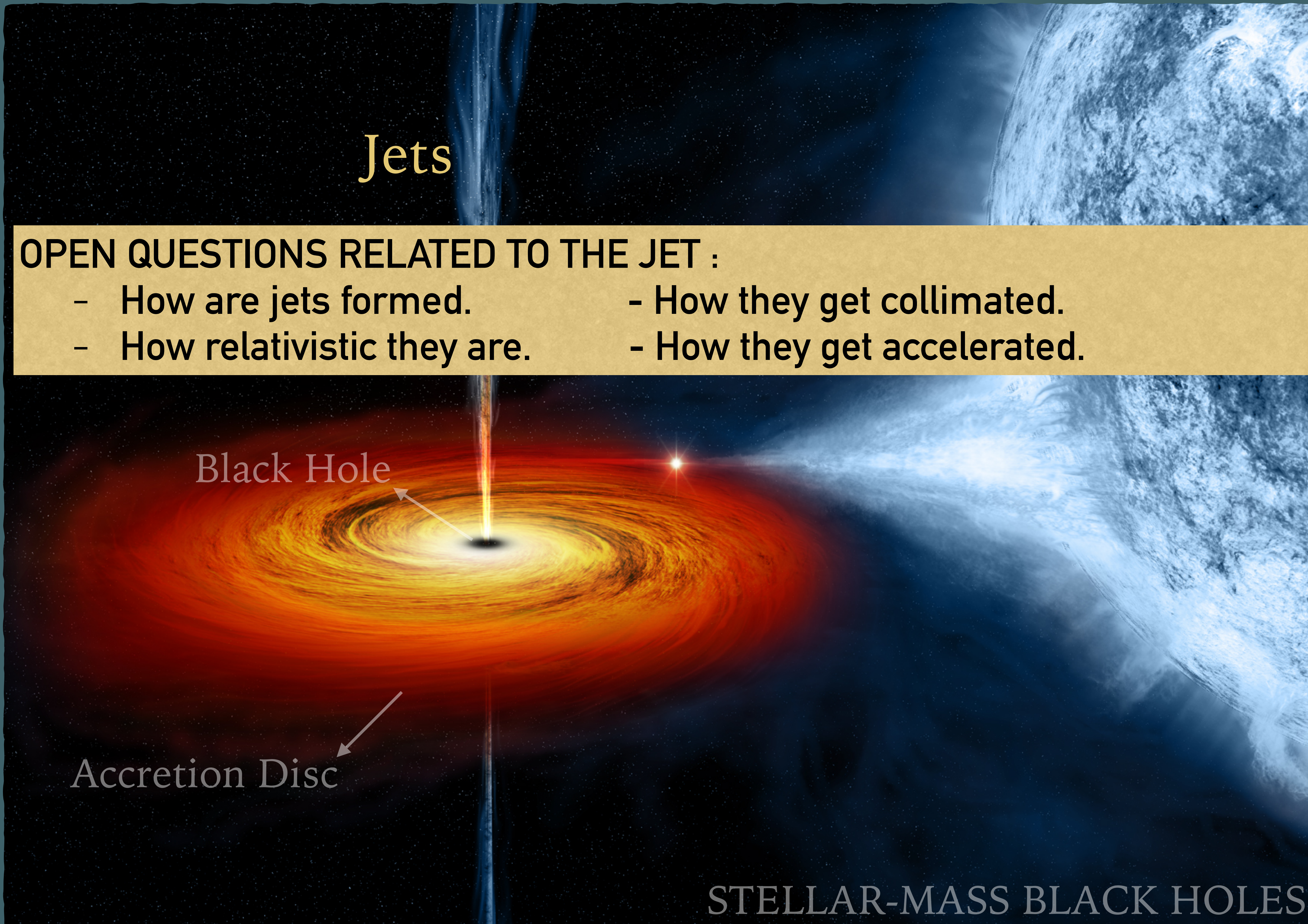
BLACK HOLE X-RAY BINARIES (BHXRB)



JETS IN BHXRB

- Jets are some of the fastest outflows of matter in our galaxy
- They energize the galaxy, spewing matter and energy into the surrounding
- They travel close to speed of light - but the exact speed is still unknown.

JETS IN BHXRB



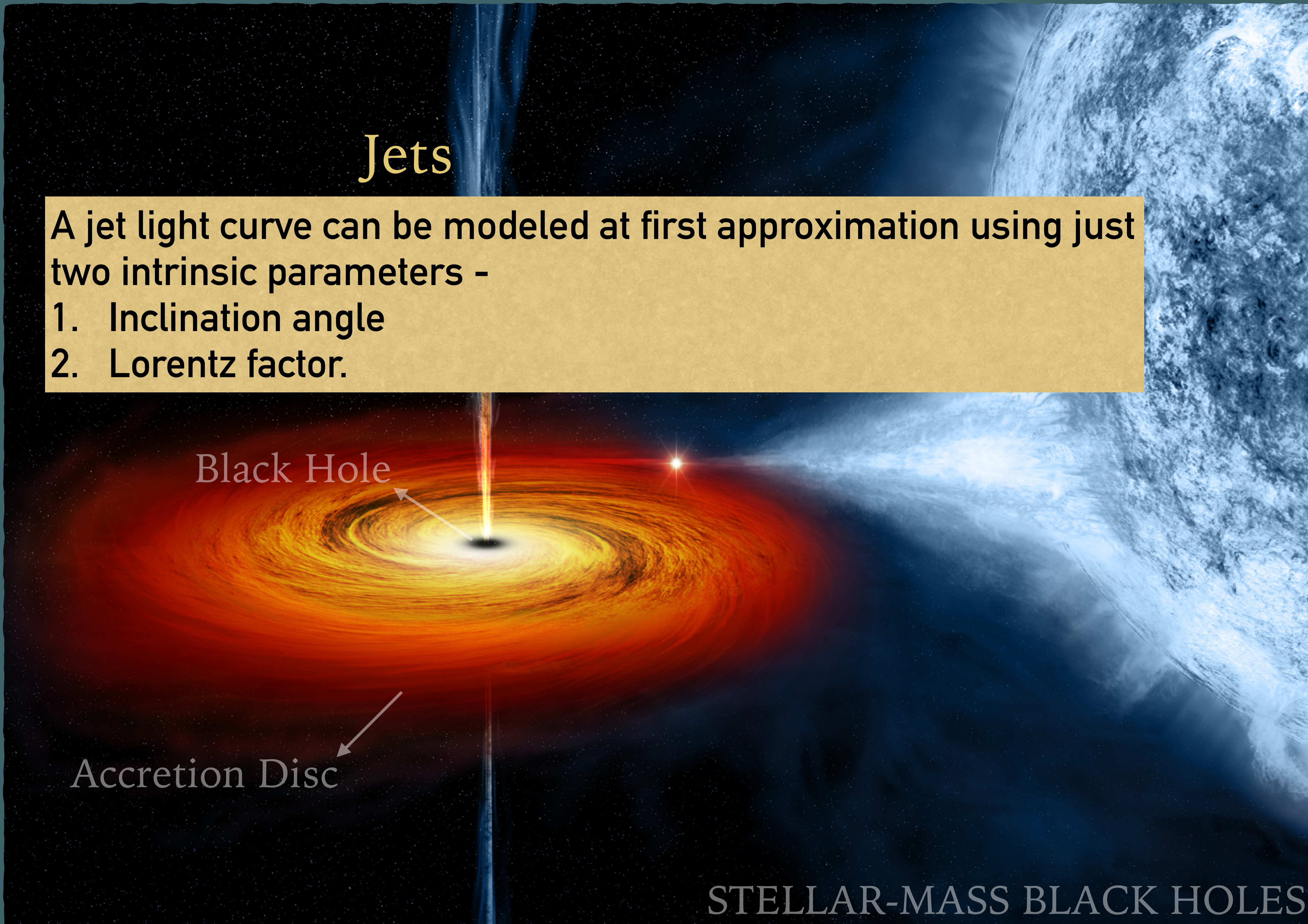
OPEN QUESTIONS RELATED TO THE JET :

- How are jets formed.
- How they get collimated.
- How relativistic they are.
- How they get accelerated.

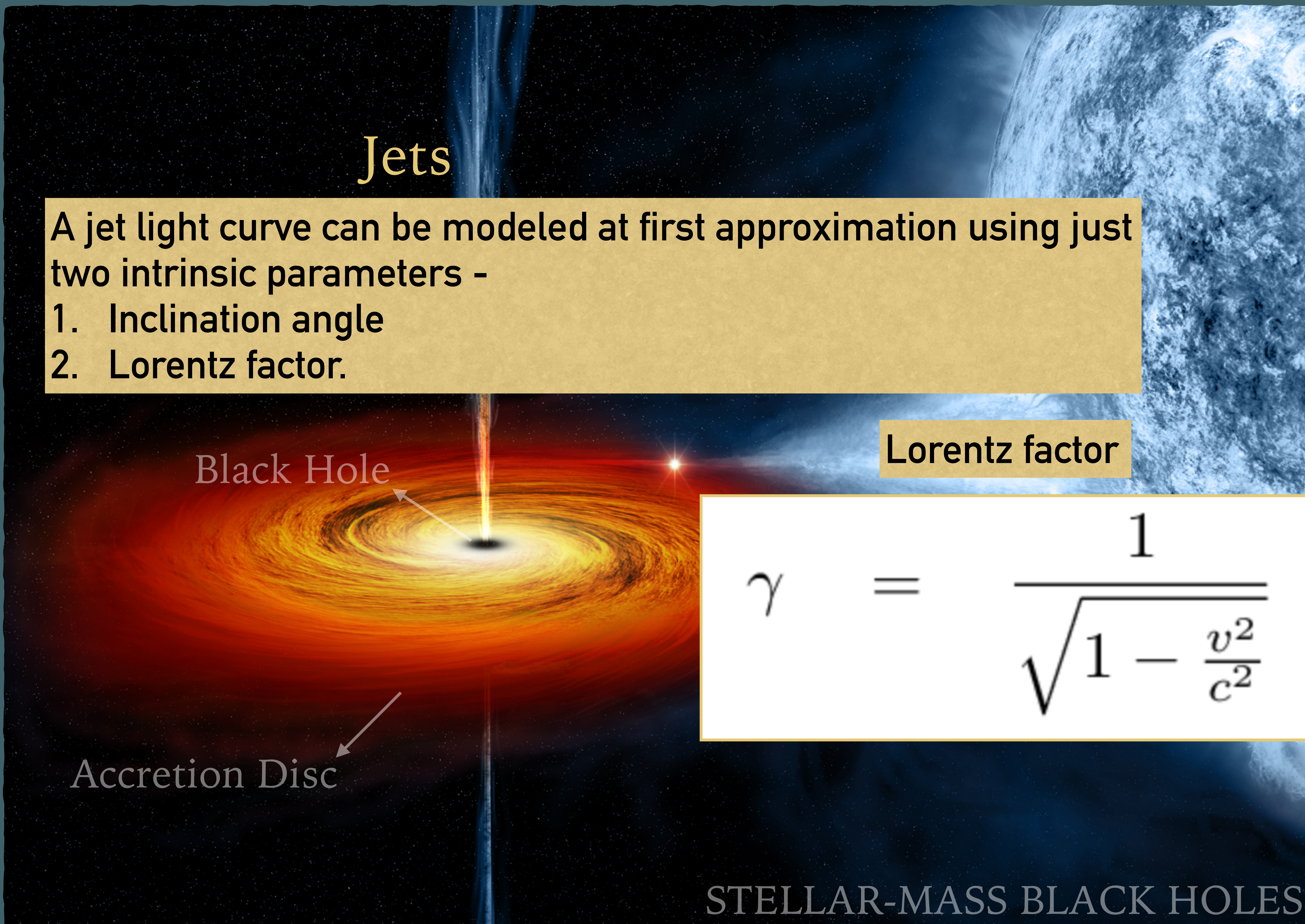
JETS IN BHXRB

A jet light curve can be modeled at first approximation using just two intrinsic parameters -

1. Inclination angle
2. Lorentz factor.



JETS IN BHXRB



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1. Inclination angle
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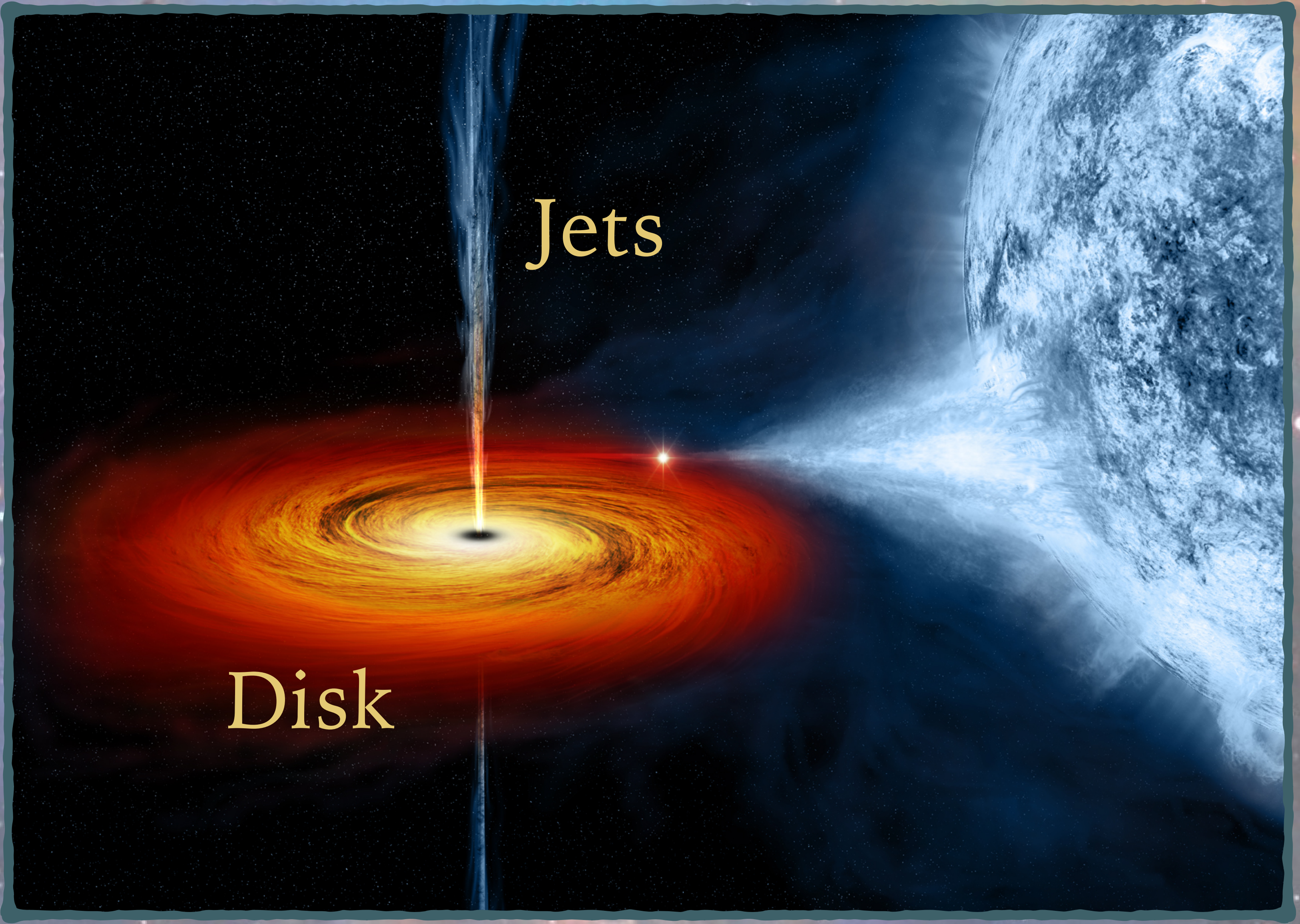
Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

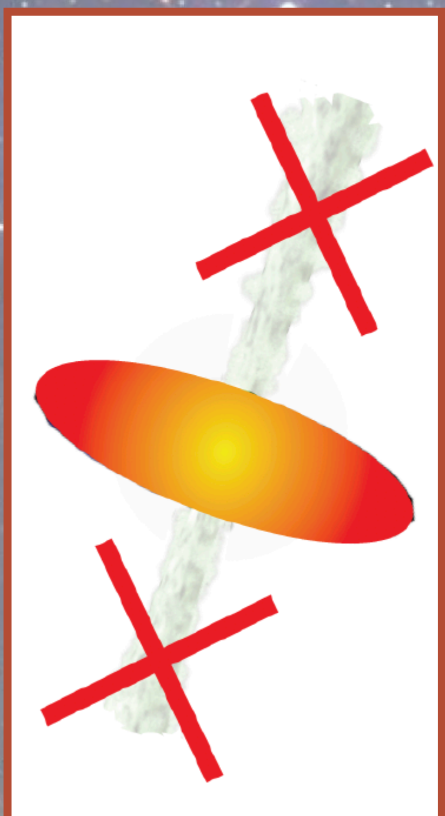
INFRARED WAVELENGTH OBSERVATIONS.



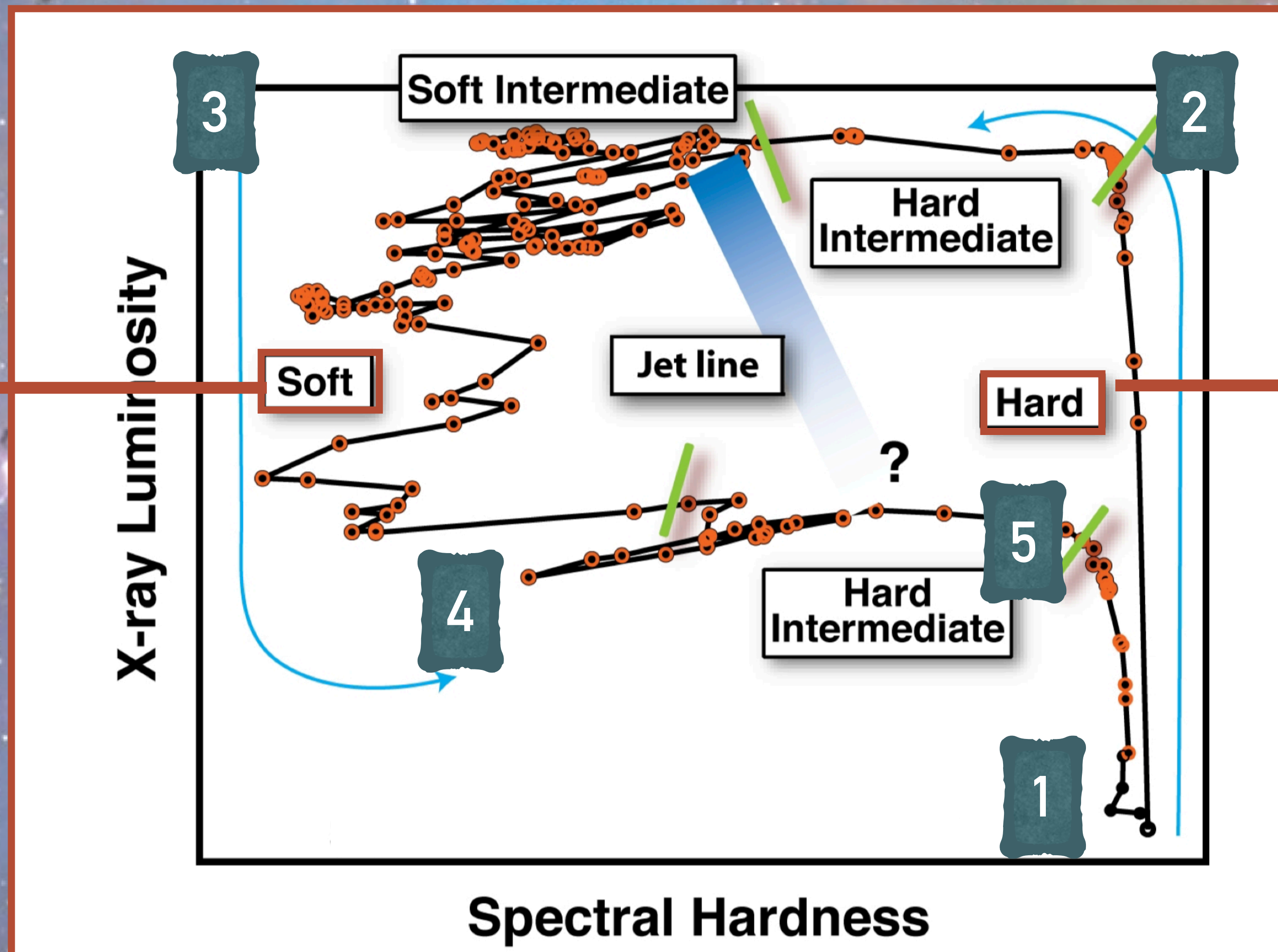
Both the jet and the disk emits in Infrared.

But BHXRBs jets are present only in certain “states”.

SOFT STATE

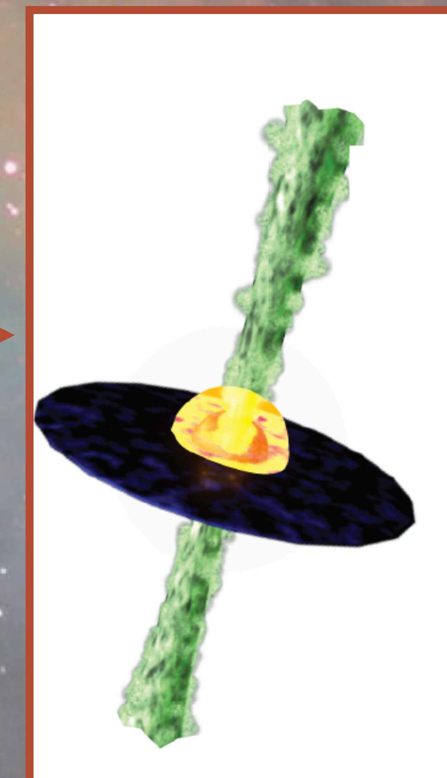


Accretion Disc
Soft spectrum
No jet
No/low radio



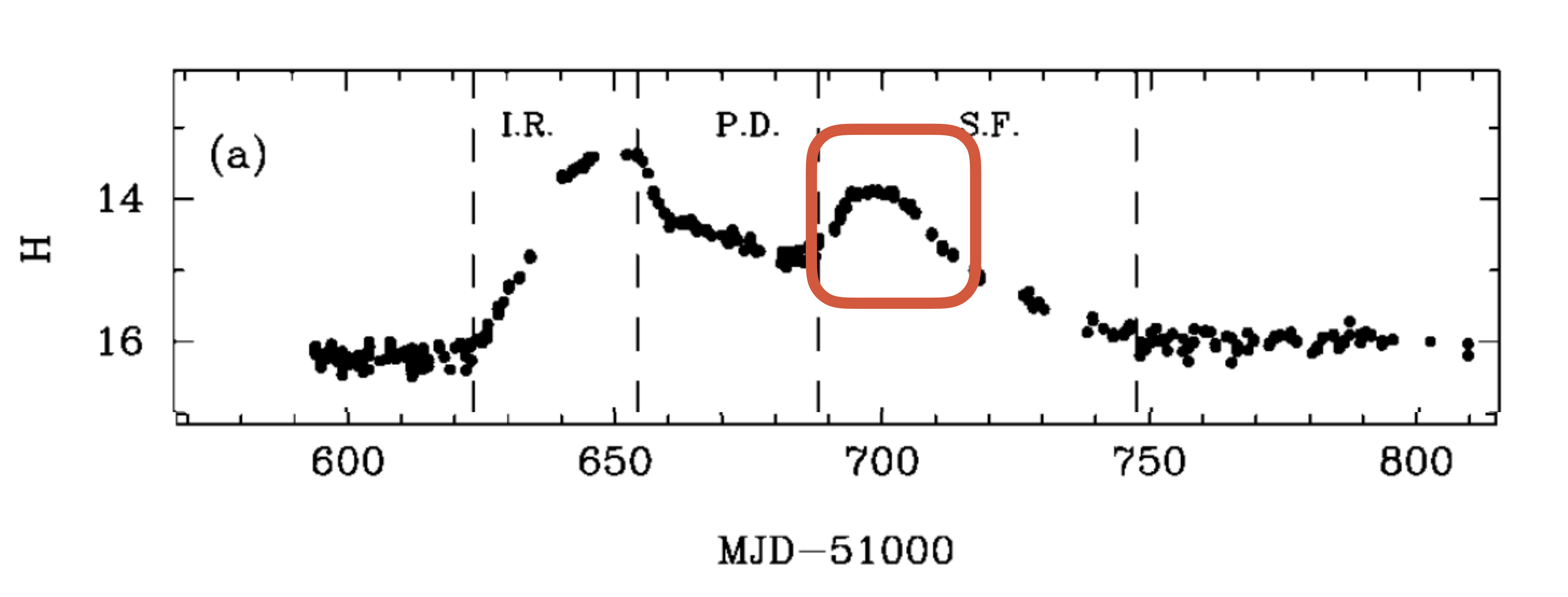
HARDNESS INTENSITY DIAGRAM

HARD STATE



Hot corona
Hard spectrum
Compact jet
Radio emission

INFRARED LIGHT CURVE OF XTE J1550-564 DURING OUTBURST



X-AXIS : MJD = modified Julian day
Y-AXIS : H-Band magnitude (IR emission at 1.65 μm wavelength)

I.R., P.D., and S.F. denote the initial rise, primary decay, and secondary flare.

Jain et al. 2001

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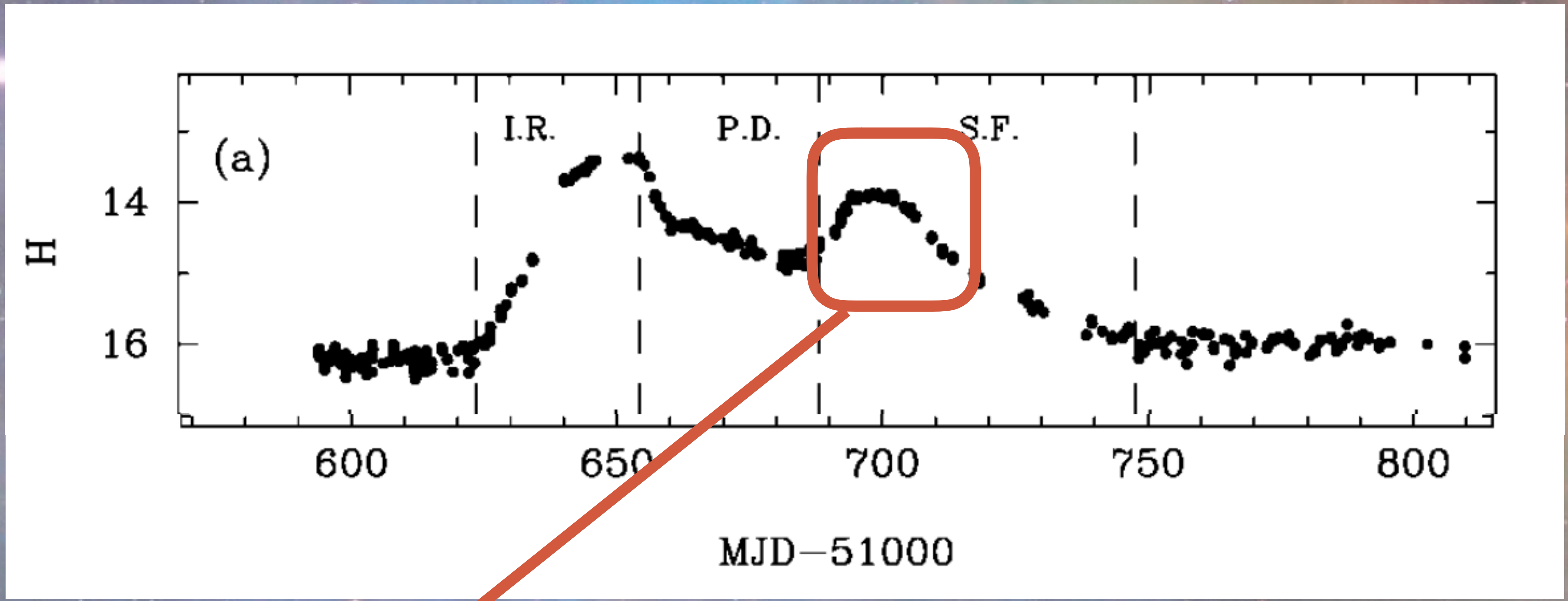

Amplitude of IR excess = (Flux_jet + Flux_disc) / Flux_disc

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INFRA RED EXCESS AND INCLINATION

Amplitude of IR excess = (Flux_jet + Flux_disc) / Flux_disc

- Small inclination angle
- Jet pointing at us
- Relativistic Beaming
- Disc face on

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- Increasing inclination angle
- Less synchrotron emission

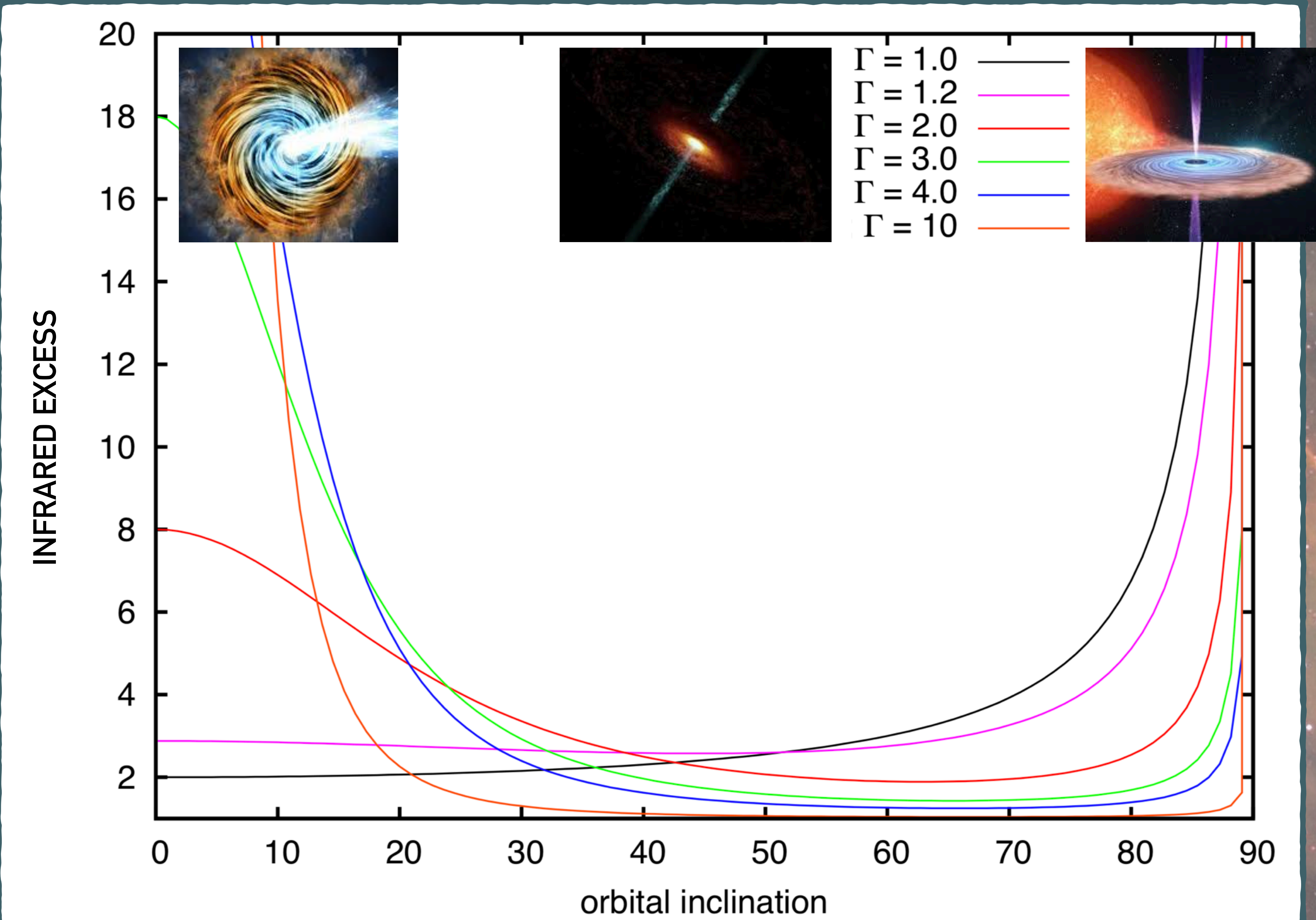
INFRA RED EXCESS AND INCLINATION

Amplitude of IR excess = (Flux_jet + Flux_disc) / Flux_disc

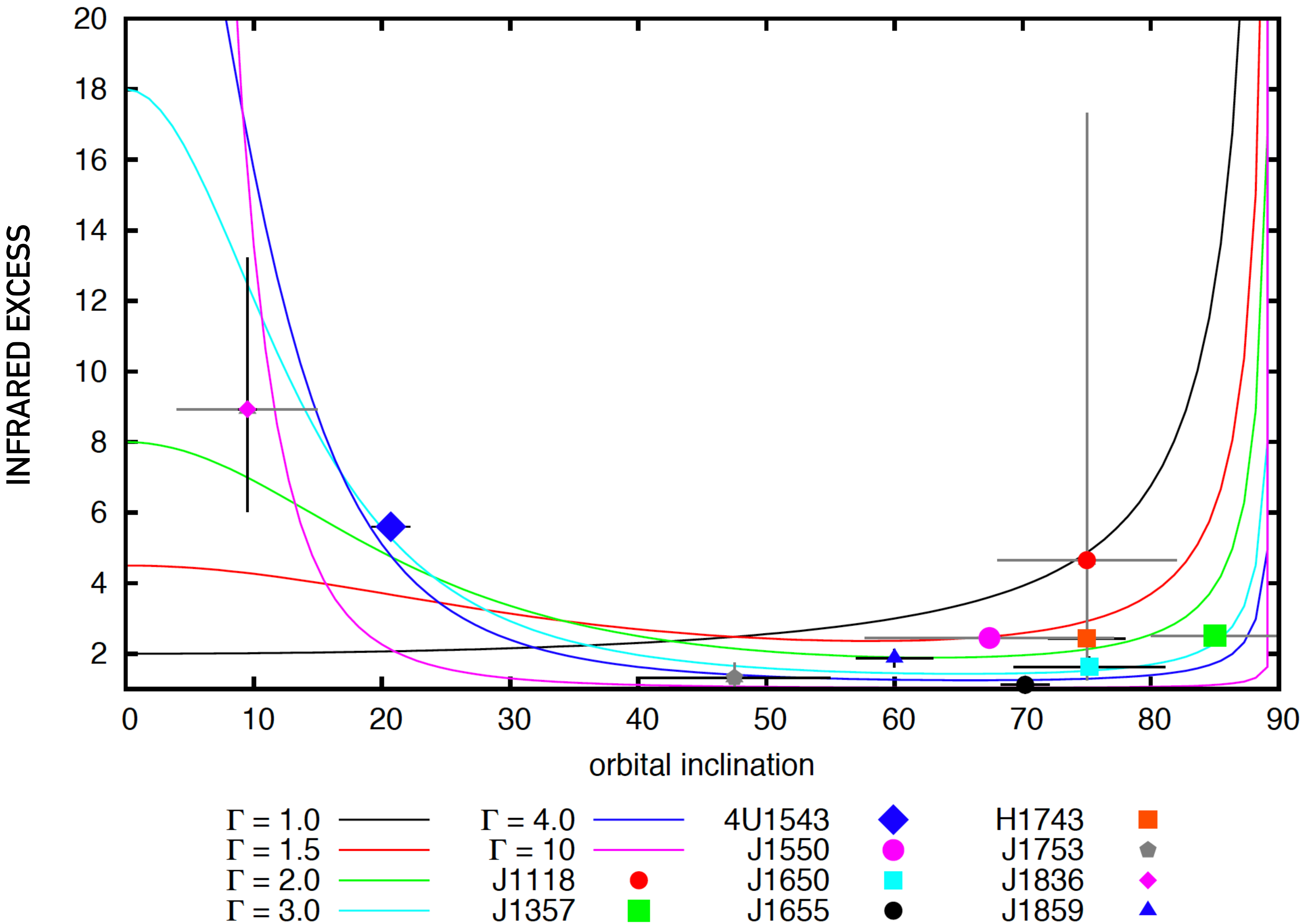
- Small inclination angle
- Jet pointing at us
- Relativistic Beaming
- Disc face on

- Increasing inclination angle
- Less synchrotron emission

- High inclination angle
- Less disc emission
- Jet/disc will increase especially for low velocity jets



Saikia et al. 2019, submitted



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XTE J1118+480	68 - 82	7.3±0.7	0.18±0.07	$4.078414 \pm 5\times10^{-6}$	1.7±0.1	0.24-3.10*
Swift J1357.2-0933	80 - 90	> 9.3	0.4±0.2	2.8±0.3	1.5 - 6.3	1.00±0.13
MAXI J1535-571	–	7.7 - 10.0	–	–	–	2.10±0.16
4U 1543-47	20.7±1.5	9.4±1.0	2.45±0.15	$26.79377 \pm 7\times10^{-5}$	9.1±1.1	1.87±0.03
XTE J1550-564	57.7 - 77.1	9.1±0.6	0.30±0.07	$37.008799 \pm 5.8\times10^{-5}$	$4.38^{+0.58}_{-0.41}$	0.97±0.07
XTE J1650-500	75.2±5.9	4.7±2.2	< 2.36	7.69±0.02	2.6±0.7	0.53±0.18
GRO J1655-40	70.2±1.9	5.4 ±0.3	1.45±0.35	$62.9258 \pm 4.8\times10^{-3}$	3.2±0.5	0.00 - 0.24
GX 339-4	0 - 78	2.3 - 9.5	0.41-1.71	42.14±0.01	8±2	$1.50 - 3.20^{+}$
H 1743-322	75±3	–	–	–	8.5±0.8	0.97±0.12
XTE J1752-223	< 49	9.6±0.9	–	< 22	3.5±0.4	0.35±0.18
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MAXI J1836-194	4 - 15	> 2.0	< 0.65	< 4.9	4-10	2.38±0.43
XTE J1859+226	60±3	10.8±4.7	< 5.41	6.58±0.05	8±3	0.68±0.03
Swift J1910.2-0546	–	> 2.9	–	2.2 - 4.0	> 1.70	0.41±0.28

Table 1. Physical properties and orbital parameters obtained from the literature, for all the BHXBs which have previous measurements/estimates of infrared excess observed during state transitions. For each of the sources, the values obtained from the literature and their references are discussed in the text. We do not include the sources in italics in our analysis. Values in the table have been rounded to a uniform level of precision. ('–' : no measurement is available, '*' : model-dependent values of IR excess explained in the text, '+' : many measurements available in the literature are explained properly in Table 2).

All Black hole X-ray binaries with previous estimates of IR excess seen during state transition.

Saikia et al. 2019, submitted

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OBSERVED INFRARED EXCESS

CALCULATED INFRARED EXCESS

FOR DIFFERENT LORENTZ FACTORS

Calculating/Modeling the IR excess

IR coming from the Disc depends on its projected area :

$$F_{\rm disc} = k_1 D_{\rm pr}$$

$$D_{\rm pr} \propto (M_{\rm BH} + M_{\rm CS})^{2/21} P_{\rm orb}^{4/21} \cos(i)$$

IR coming from the Jet depends on the relativistic beaming and inclination angle :

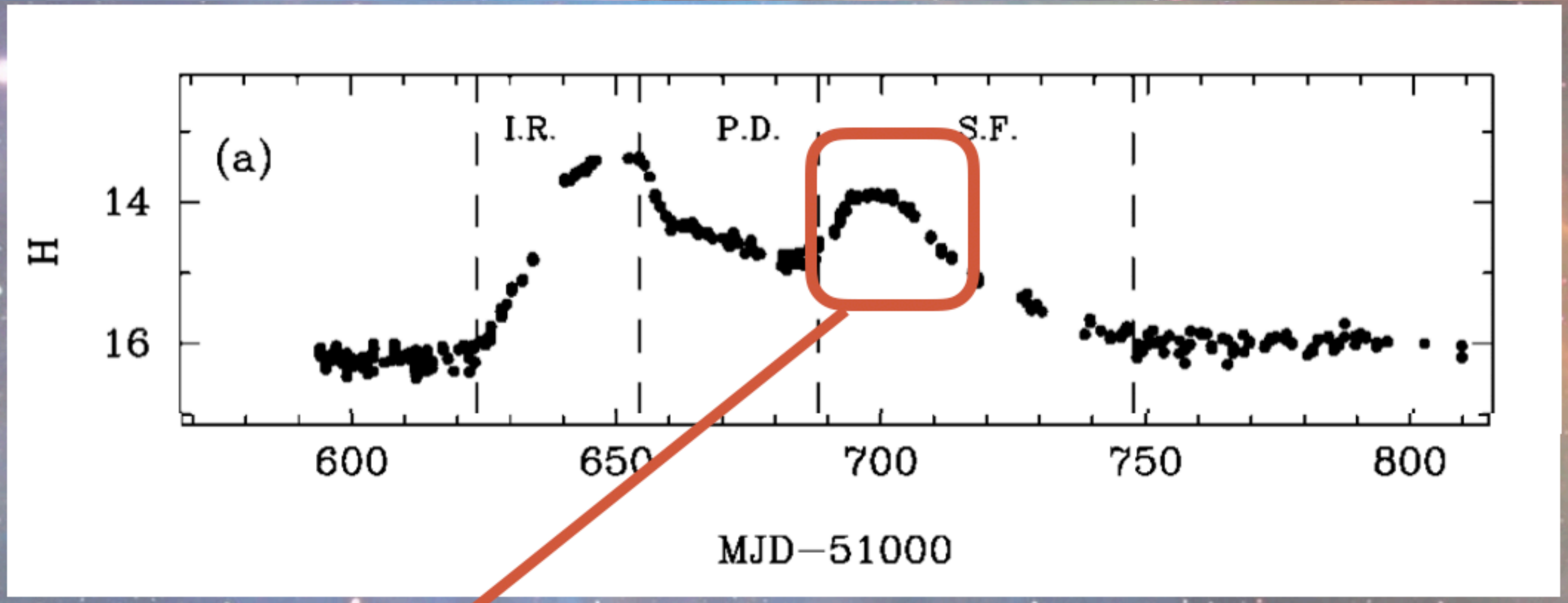
$$F_{\rm jet} = k_2 \Delta_{\rm jet}$$

$$\Delta_{\rm jet} = \frac{(\delta_{\rm app})^2 + (\delta_{\rm rec})^2}{2}$$

where $\delta_{\rm rec/app} = \Gamma^{-1} \times (1 \pm \beta \cos\theta)^{-1}$; $\beta = v/c$

Frank et al. 2002, Paradijs & McClintock 1994; Gallo et al. 2003, Russell et al. 2006, etc.

Calculating/Modeling the IR excess



Amplitude of IR excess = (Flux_jet + Flux_disc) / Flux_disc

So for each source we can calculate the predicted IR excess value :

$$\Delta m_{\mathrm{IR,pred}} = 2.5 \log_{10}\left[\frac{k_1 D_{\mathrm{pr}} + k_2 \Delta_{\mathrm{jet}}}{k_1 D_{\mathrm{pr}}}\right]$$

$$= 2.5 \log_{10}\left[1 + C\frac{\Delta_{\mathrm{jet}}}{D_{\mathrm{pr}}}\right]$$

Saikia et al. 2019, submitted

BAYESIAN ANALYSIS

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OBSERVED INFRARED EXCESS

COMPARE (BAYESIAN ANALYSIS)

CALCULATED INFRARED EXCESS

FOR DIFFERENT LORENTZ FACTORS

Courtesy : Daniel Bramich, NYUAD

Hierarchial Bayesian Inference

Posterior probability density function

$$P(\Phi,\Gamma,\alpha \mid D,M) \propto P(D \mid \Phi,\Gamma,M)\ P(\Phi \mid M)\ P(\Gamma \mid \alpha,M)\ P(\alpha \mid M)$$

Φ : parameters of the black hole system (inclination, mass of compact object, mass of companion star and orbital period)

Γ : Lorentz factors of the individual sources

α : XRB Parent Lorentz factor distribution

D : IR excess data

M : Our model

Hierarchial Bayesian Inference

$$P(\Phi,\Gamma,\alpha \mid D,M) \propto P(D \mid \Phi,\Gamma,M)\ P(\Phi \mid M)\ P(\Gamma \mid \alpha,M)\ P(\alpha \mid M)$$

$P(\Phi,\Gamma,\alpha \mid D,M)$ is the final posterior probability density function for the parameters Φ (inclinations, masses, orbital periods etc), Γ, and α, given the data D and model M

$P(D \mid \Phi,\Gamma,M)$ is the likelihood function of the data D given Φ, Γ and M

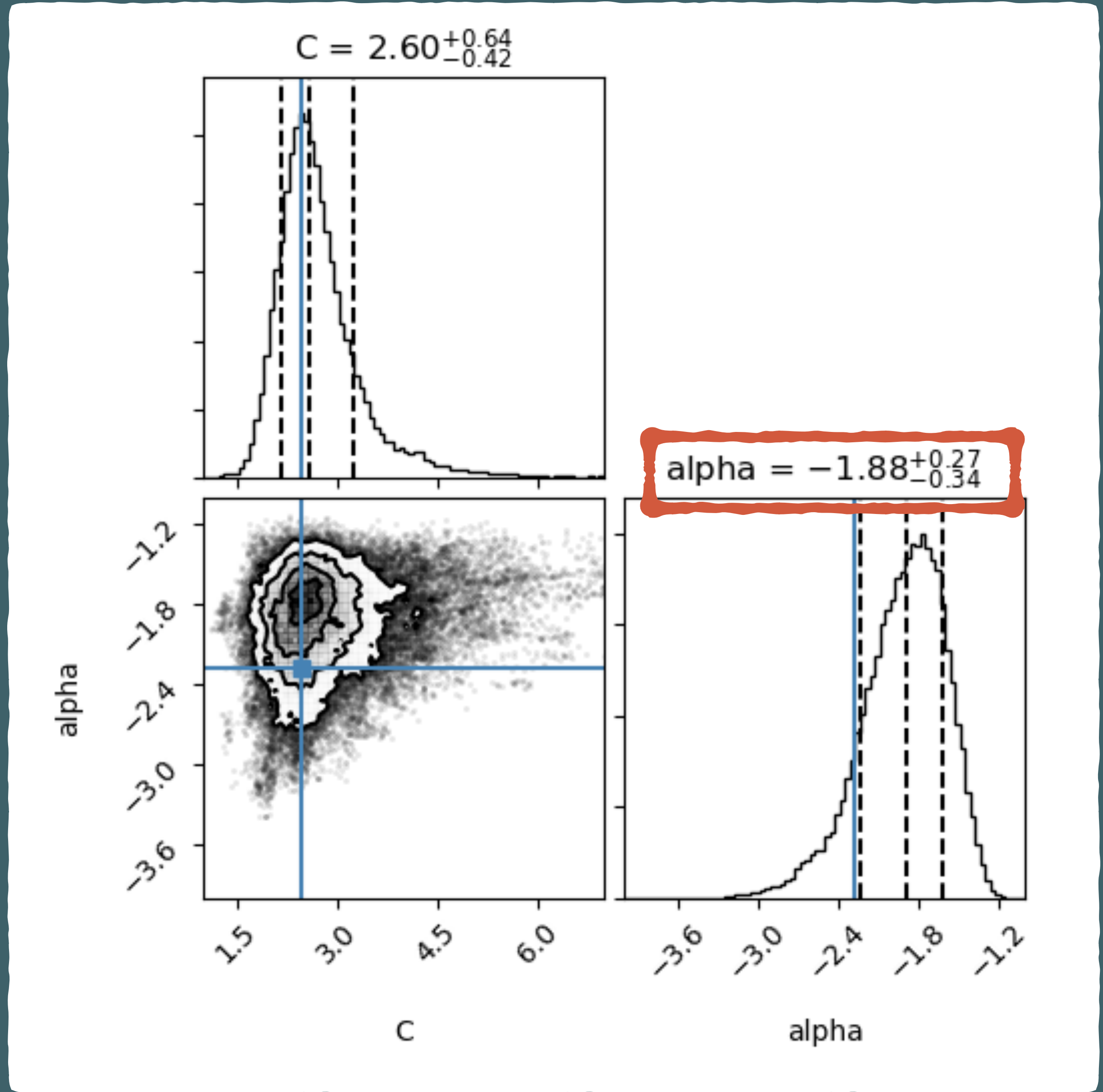
$P(\Phi \mid M)$ is the prior probability density function for Φ given model M (i.e. uniform/gaussian range of the parameters from literature)

$P(\Gamma \mid \alpha,M)$ is parent distribution for Γ (we assume a power-law, like AGN)

$P(\alpha \mid M)$ is the prior probability density function for α given the model M

eg. Hogg et al. 2010; Kelly et al. 2012

Parent Lorentz Factor Distribution

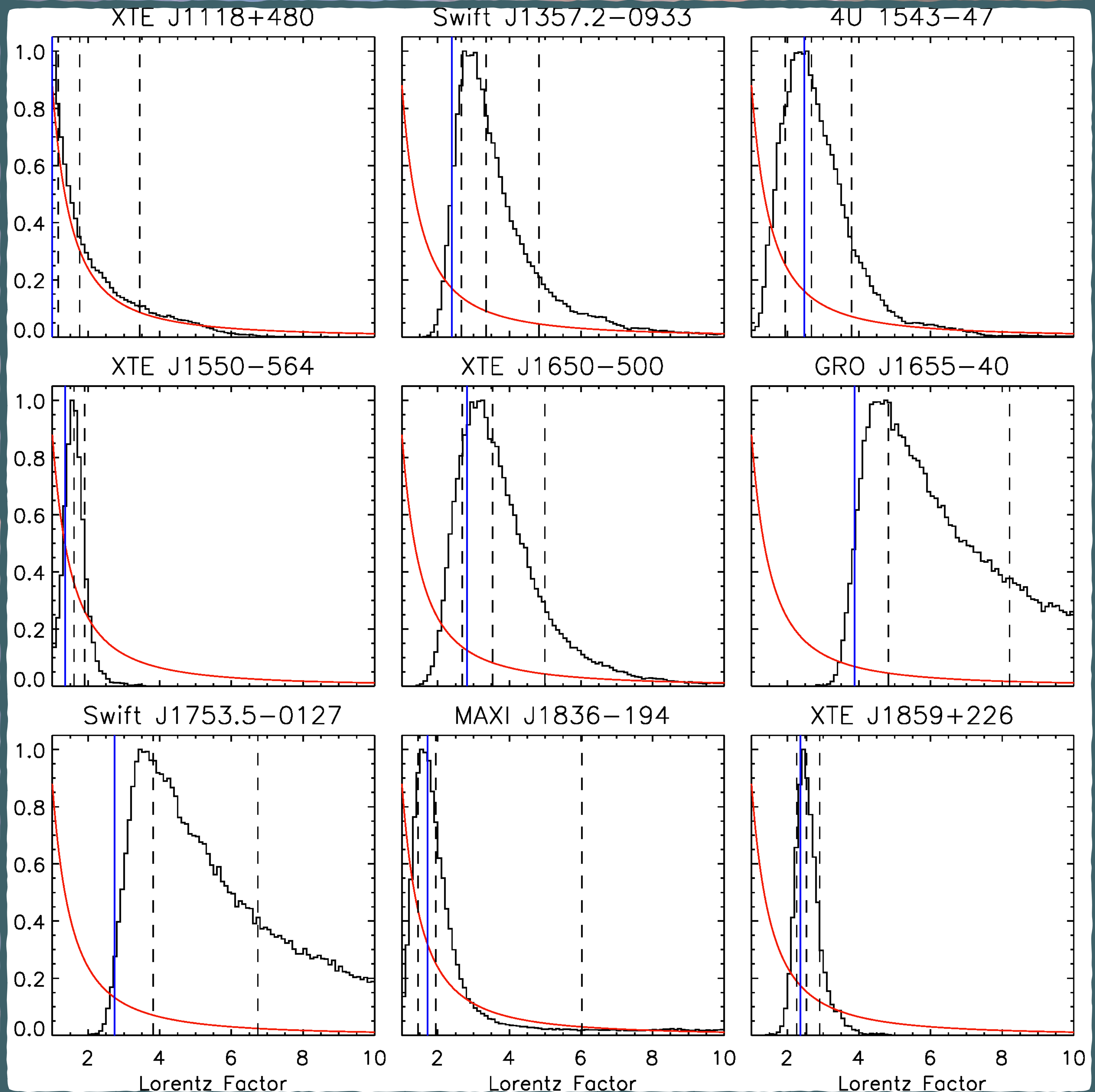


It is interesting to note that the power-law index of the parent Lorentz factor distribution for BHXB obtained from this study (~ -1.88) is quite similar to what is expected for AGN too.

For example, power-law indices of the AGN bulk Lorentz factor distribution from literature:
Padovani & Urry, 1992 : ~ -2.3
Lister & Marscher, 1997 : -1.5 to -1.75
Saikia et al. 2016 : -2.1 +- 0.4

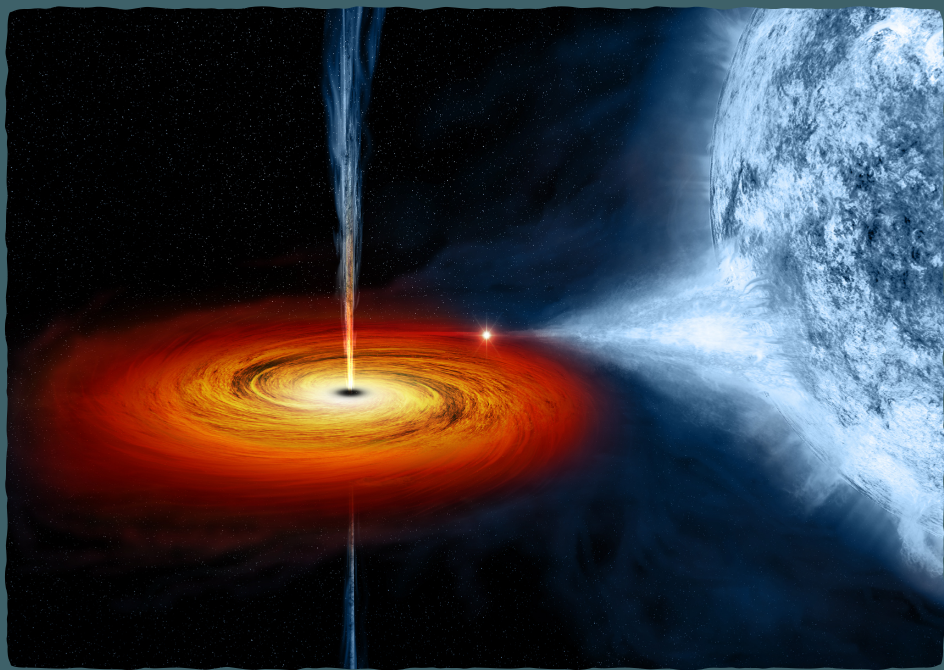
Saikia et al. 2019, submitted

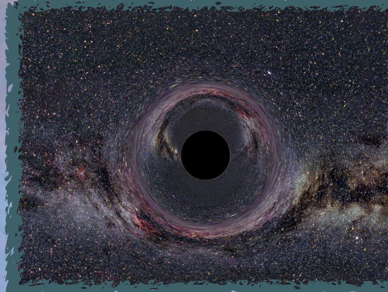
Lorentz factors of individual Black Hole X-ray binaries



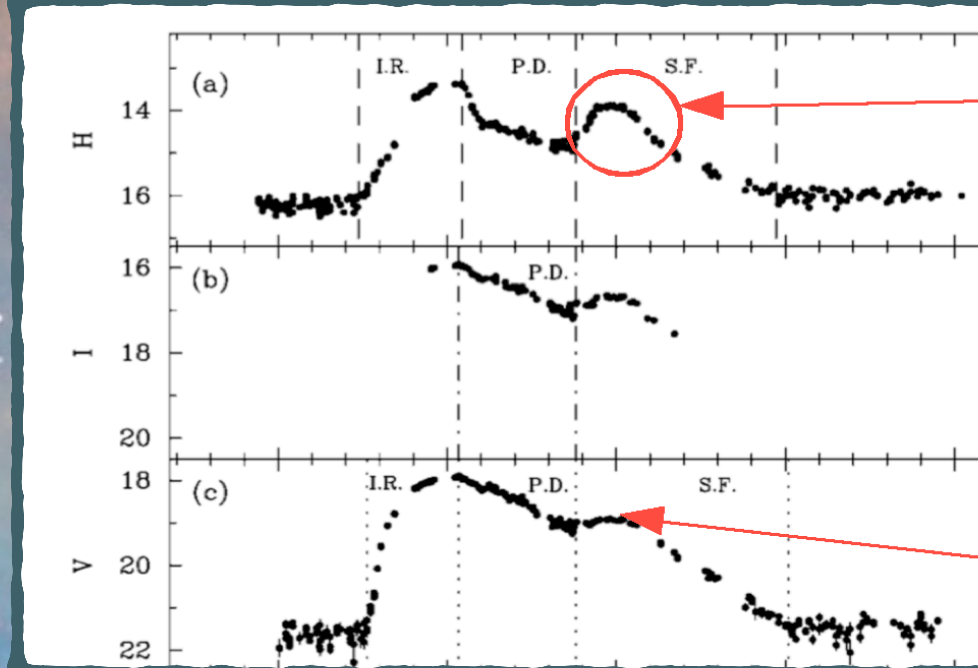
Black curve : Histograms (normalized by peak) of the jet Lorentz factors.
Red curve : Inferred parent distribution for the Lorentz factors of BHXBs .

Vertical blue lines : The best-fit MAP parameter estimates.
Vertical black lines : The 15.9, 50 and 84.1 percentiles.



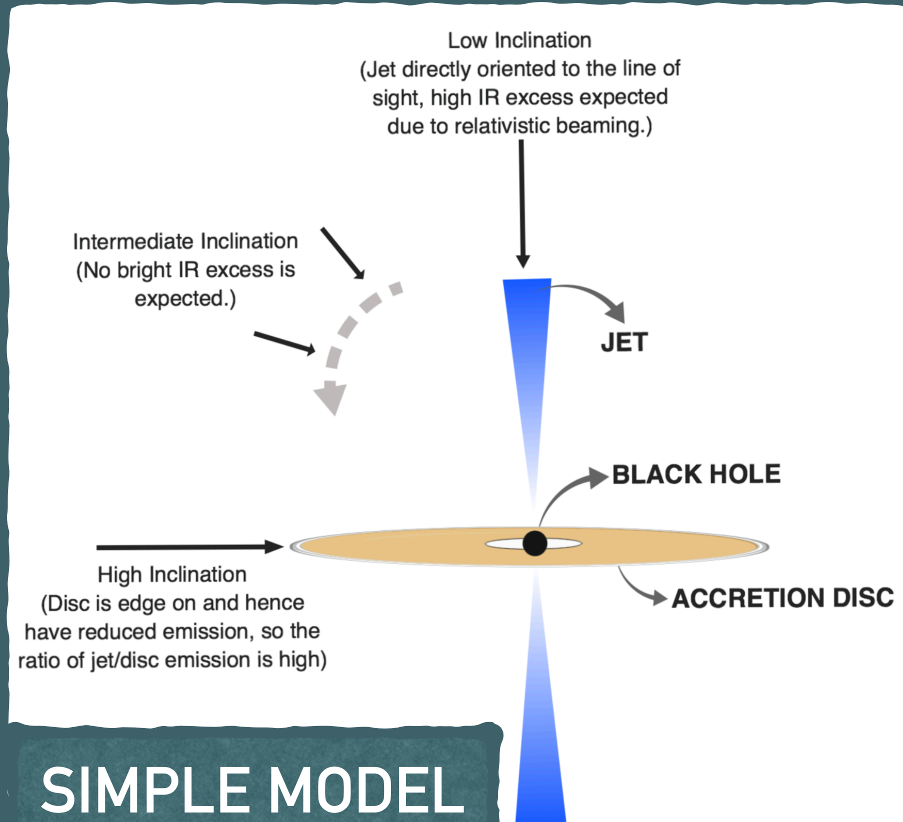


CONCLUSION

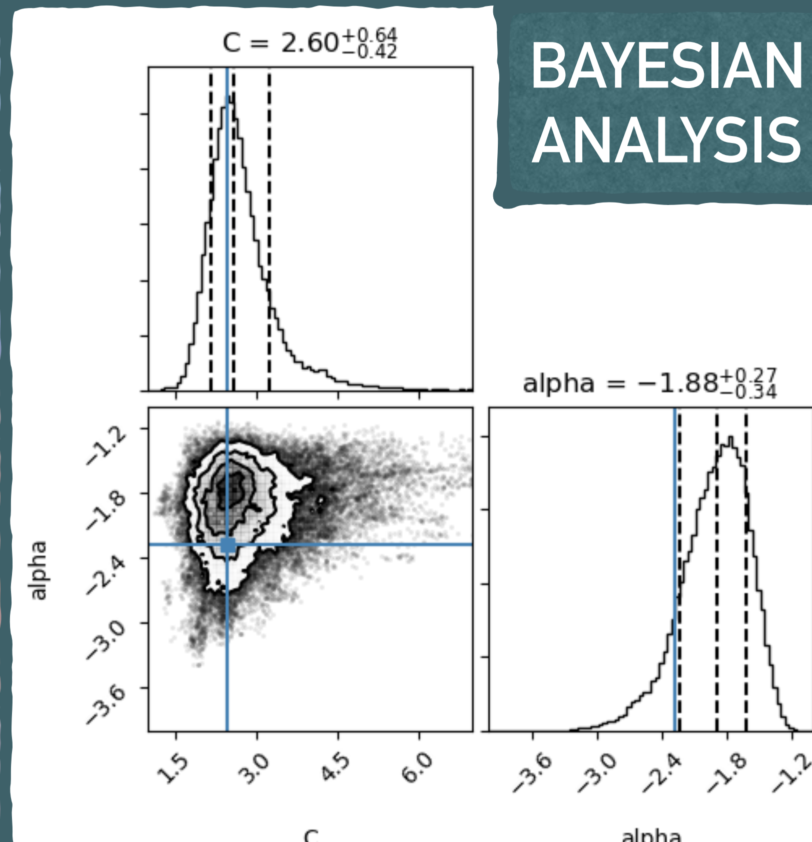


Goal : How fast are the jets of XRBs.

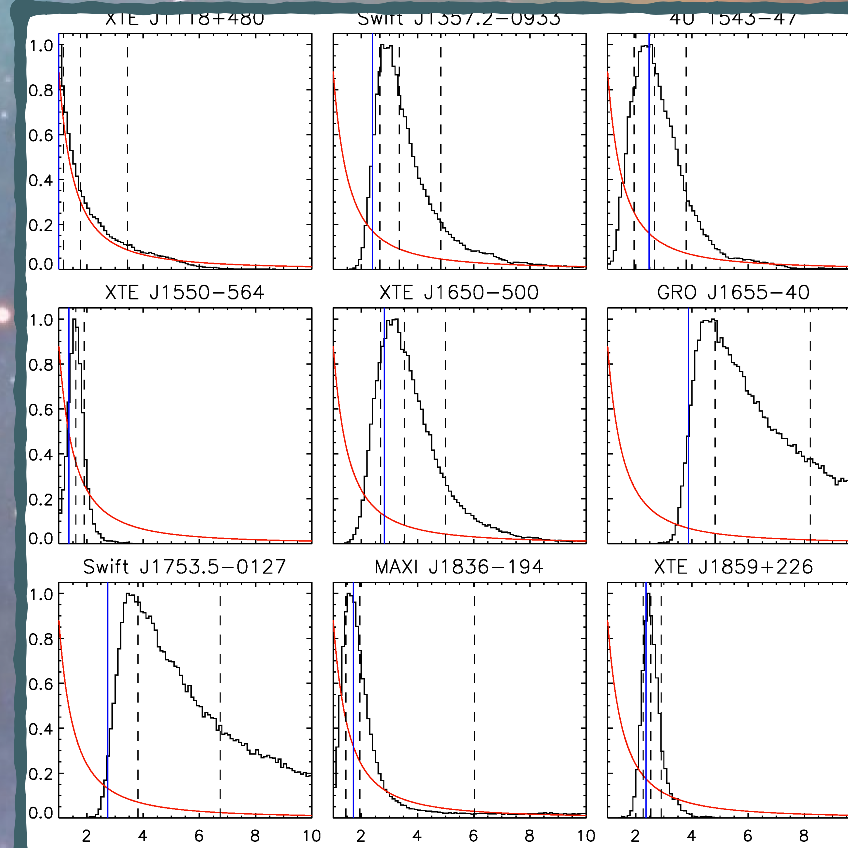
Tool : Infrared excess when jet starts.



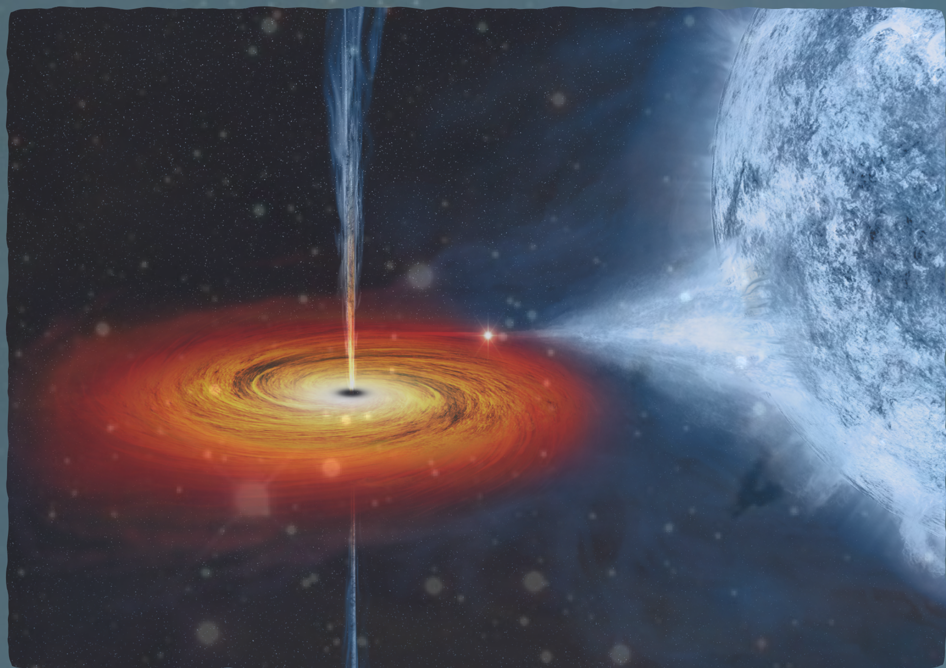
SIMPLE MODEL



BAYESIAN ANALYSIS

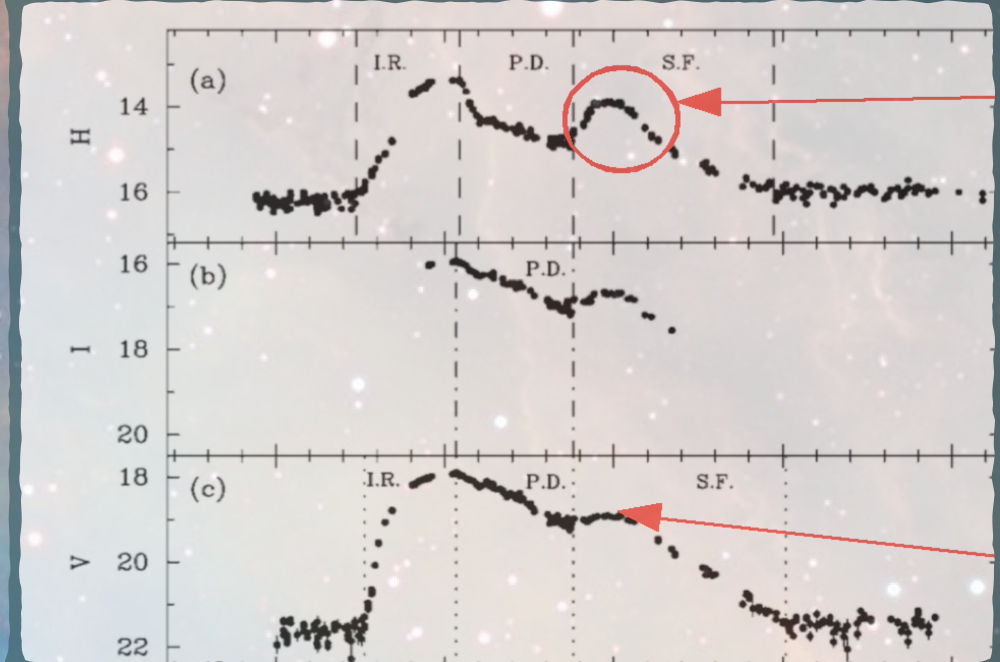


Result : For the first time, we constrain the Lorentz factors for several XRBs to be ~ 1.5-3.5.



CONCLUSION

THANK YOU



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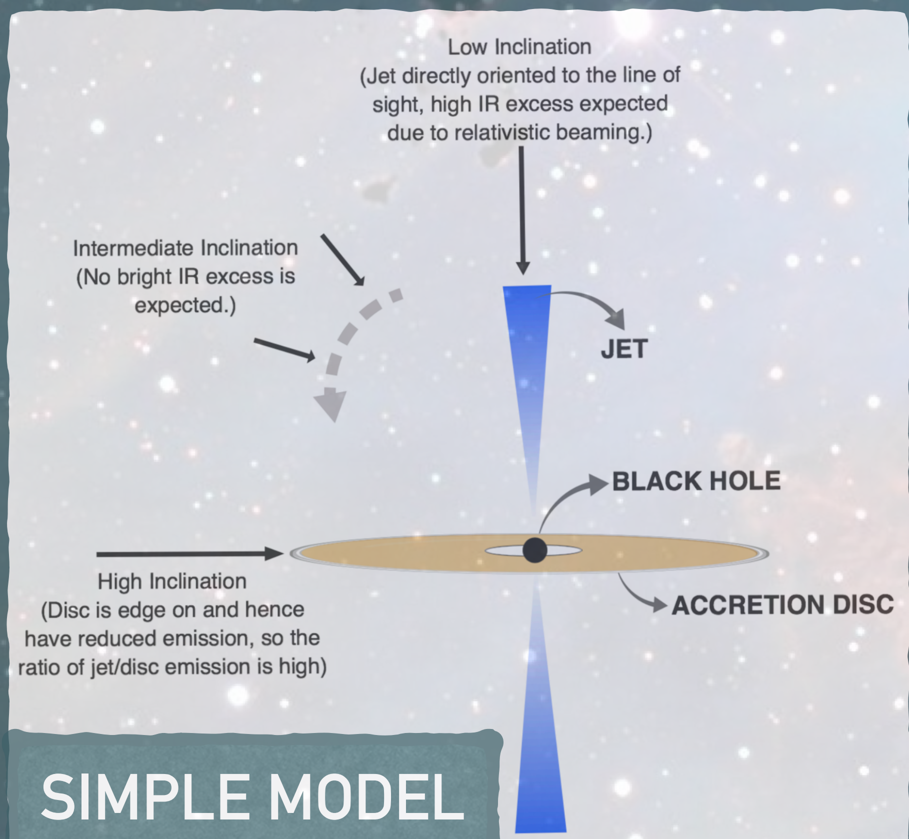
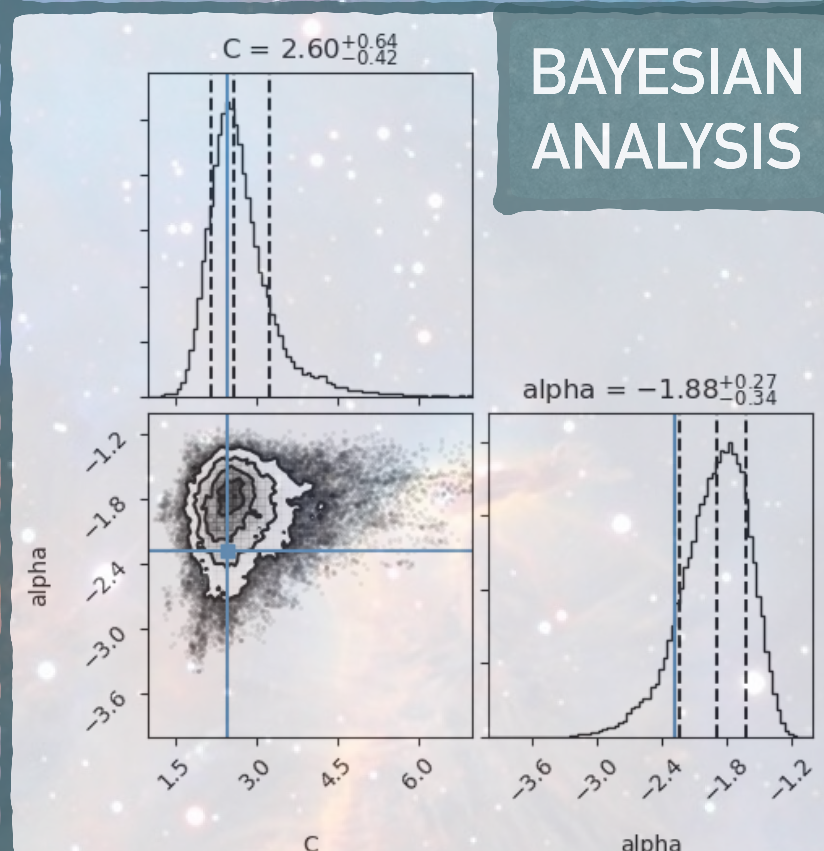
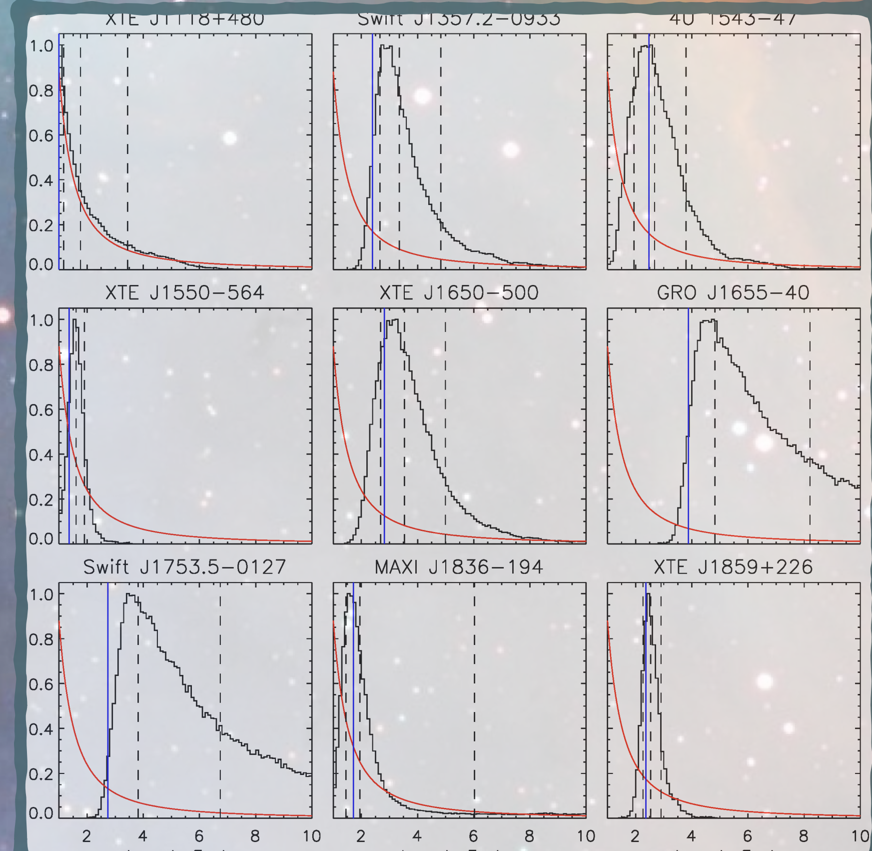


SIMPLE MODEL



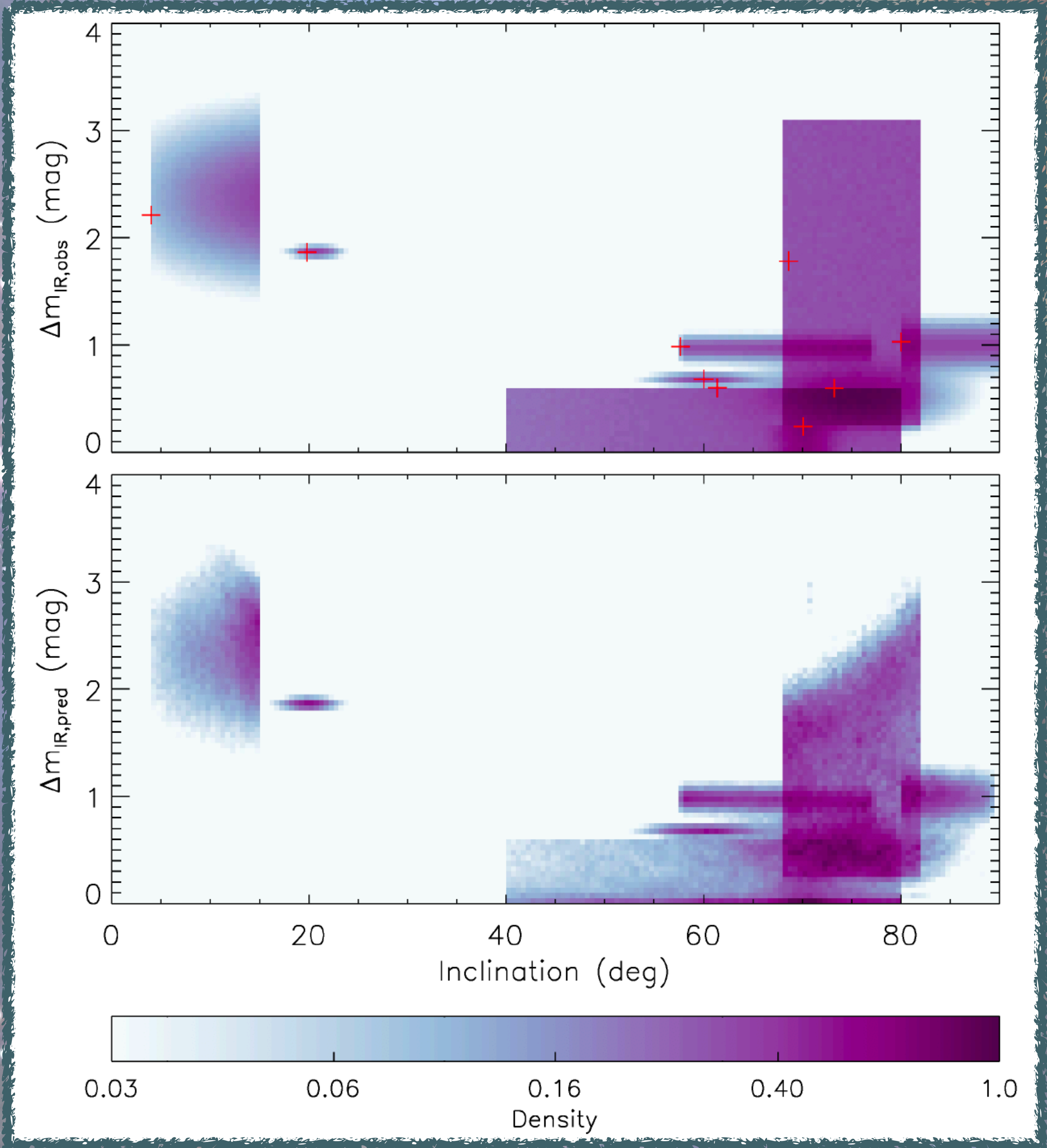
BAYESIAN ANALYSIS



Result : For the first time, we constrain the Lorentz factors for several XRBs to be ~ 1.5-3.5.

EXTRA SLIDES

We maximize the logarithm of the posterior probability density function
⟶ yields a maximum a posteriori (MAP) estimate of the best-fit parameters



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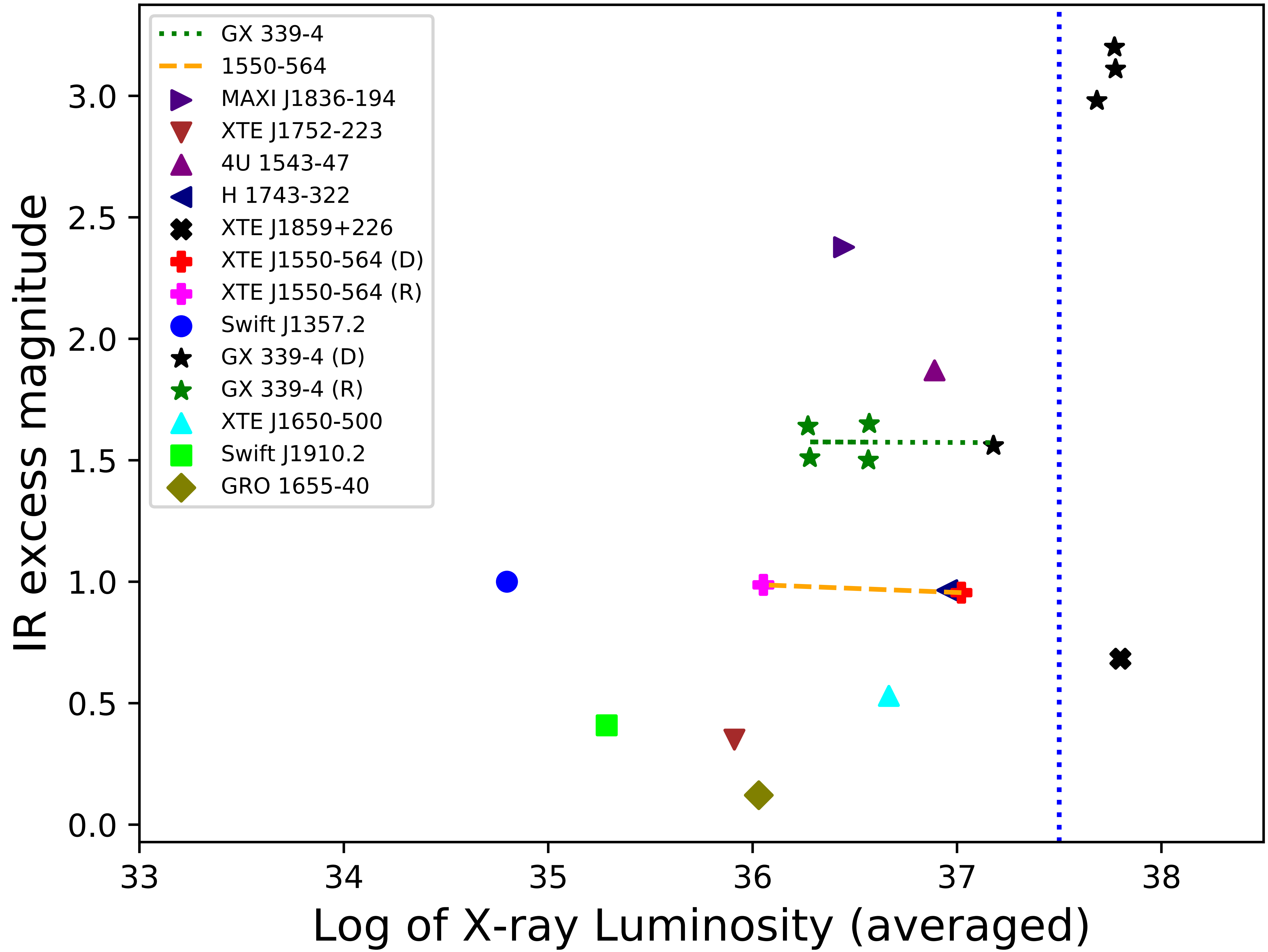
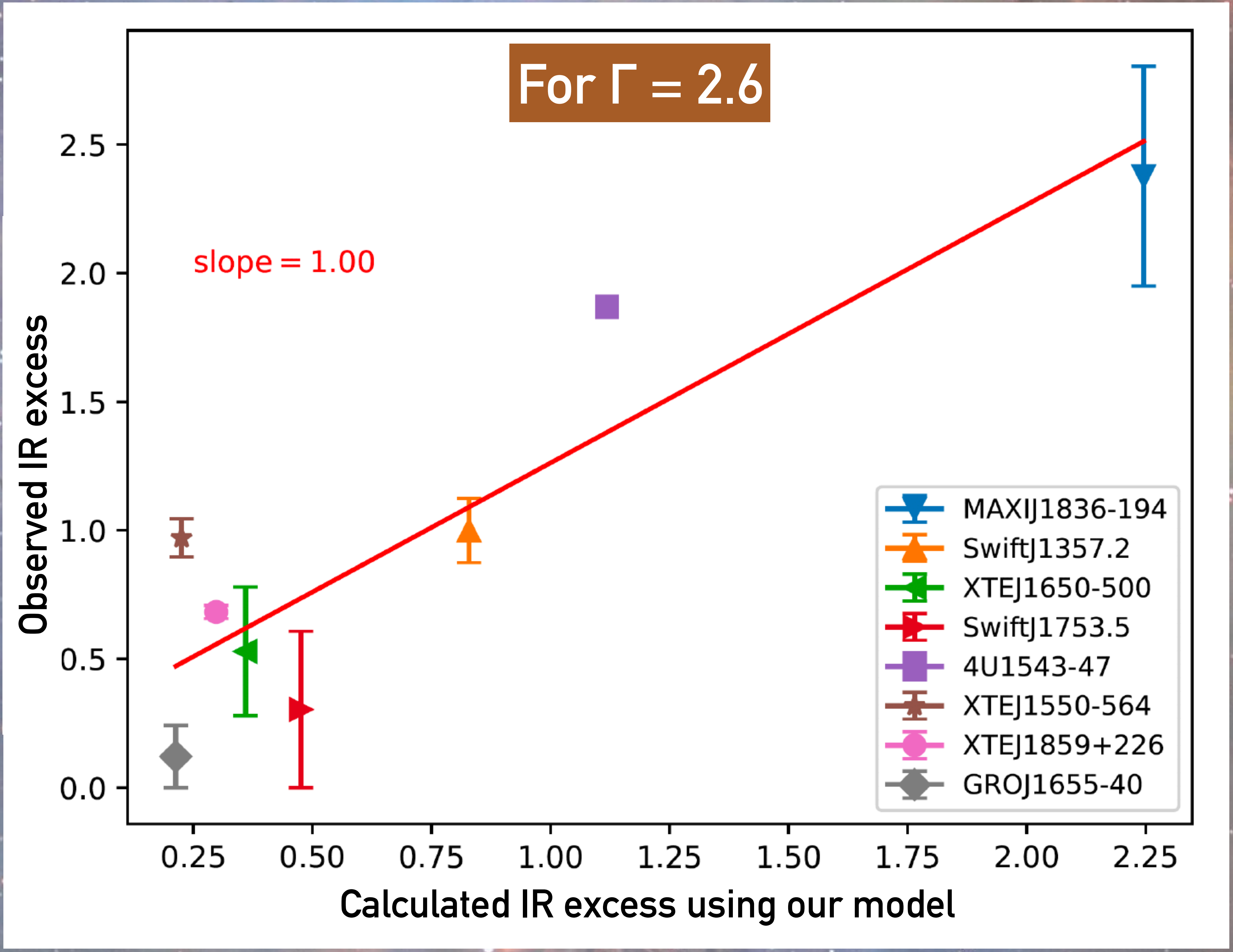
IR excess and X-ray luminosities



Only for the Lorentz factors in the range of 1.3 - 3.5, the predicted IR excesses are in agreement with the observed ones. For example, Γ of 2.6 :



Pearson r-coefficient = 0.9, p-value = 0.001

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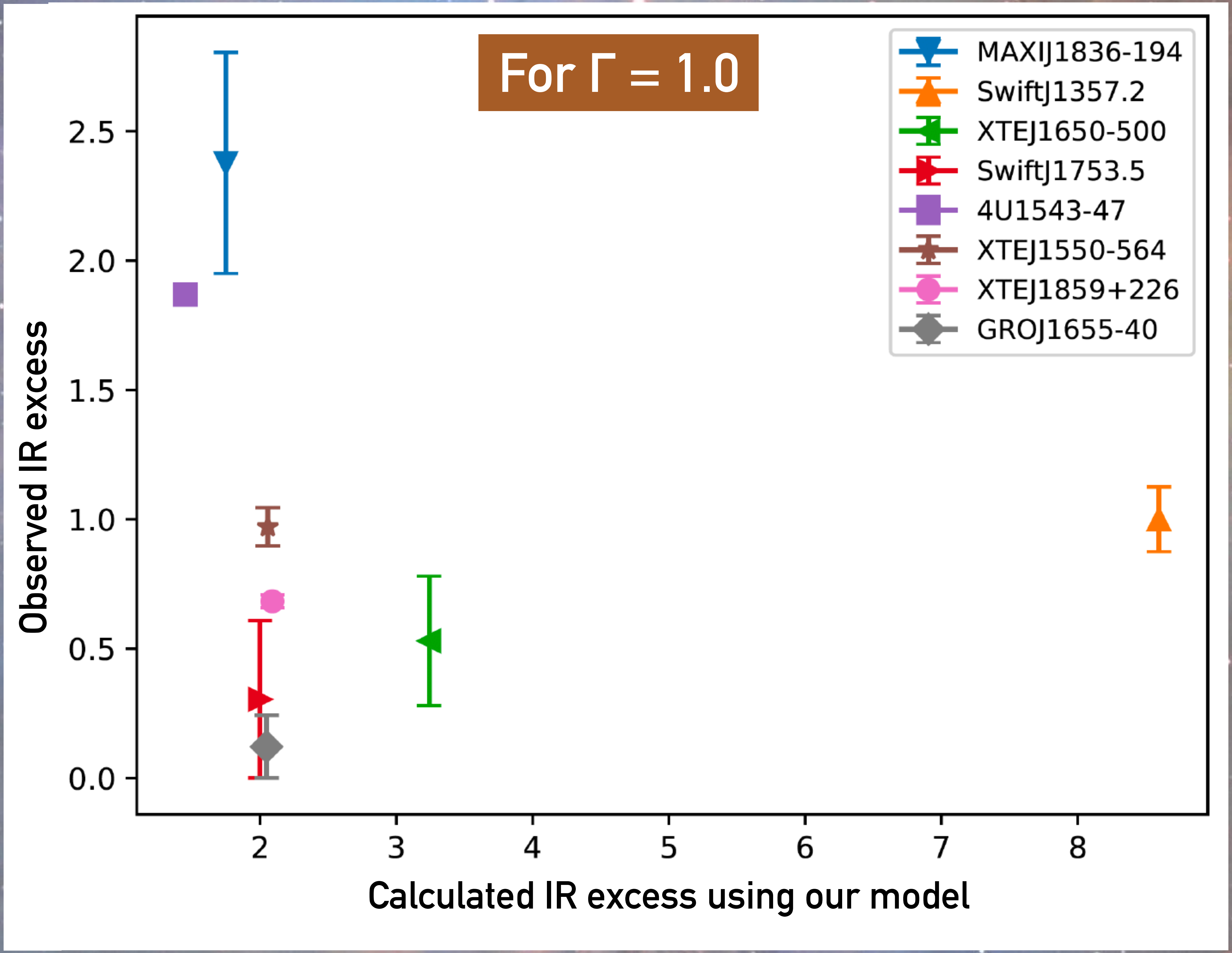
The slope systematically deviates from 1 and the correlation becomes weaker as we move to other Lorentz factors. For example, Γ of 1 :



Pearson r-coefficient = -0.2, p-value = 0.5

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Lorentz factors of individual Black Hole X-ray binaries

Name	Inclination (°)	Γ
XTE J1118+480	68.3, 70.3, **75.2**, 79.9, 81.7	1.02, 1.17, **1.77**, 3.40, 5.37
Swift J1357.2-0933	80.2, 81.1, **83.8**, 87.1, 88.9	2.22, 2.66, **3.40**, 4.92, 8.11
4U 1543-47	16.53, 18.29, **19.92**, 21.44, 22.91	1.38, 1.90, **2.69**, 3.90, 6.24
XTE J1550-564	58.03, 60.07, **66.09**, 73.15, 76.49	1.10, 1.35, **1.61**, 1.92, 2.50
XTE J1650-500	62.21, 68.26, **74.22**, 79.93, 84.85	2.13, 2.70, **3.54**, 5.08, 8.84
GRO J1655-40	66.32, 68.28, **70.15**, 72.01, 74.04	3.92, 4.88, **8.22**, 24.02, 82.68
Swift J1753.5-0127	34.62, 41.98, **49.00**, 55.48, 61.40	3.21, 4.32, **7.65**, 20.90, 64.11
MAXI J1836-194	4.7, 7.7, **11.5**, 14.1, 14.9	1.14, 1.42, **1.86**, 3.06, 10.85
XTE J1859+226	54.01, 56.89, **59.90**, 62.93, 65.97	2.00, 2.26, **2.54**, 2.95, 3.74
C	1.81, 2.17, **2.61**, 3.31, 5.32	
α	−2.73, −2.25, **−1.89**, −1.62, −1.41	

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Possible Lorentz factor values from the slopes

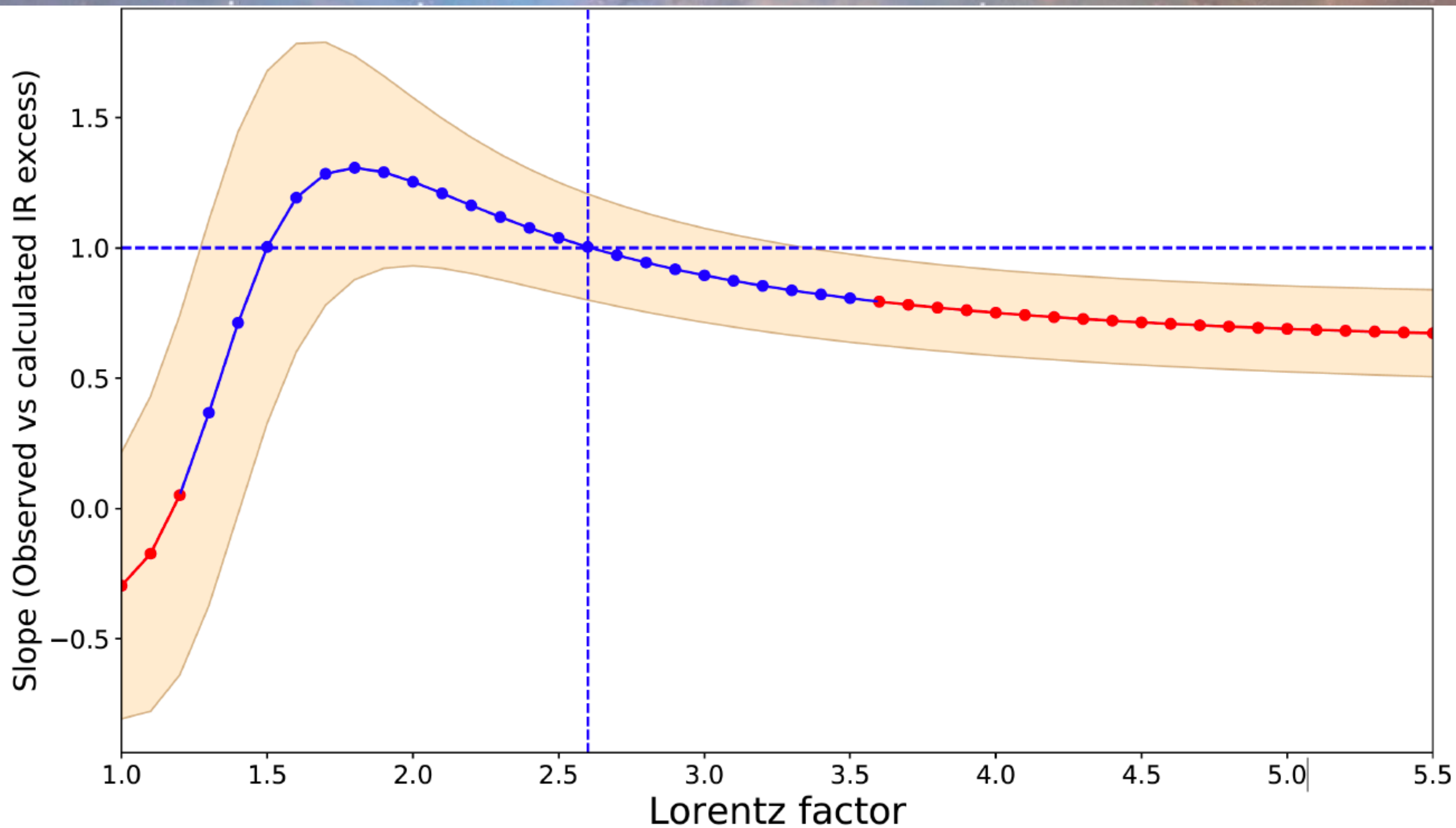

Figure 4. Best Lorentz factor values (when C=1) by looking at the slopes. A slope of 1 (in the Y-axis) implies that the distribution of observed IR excess matches with the predicted one, for that particular Lorentz factor. The shaded region represents the one-sigma error on the value of slope. We see that only the Lorentz factors in the range of 1.3-3.5 (shown here in blue points) are in agreement with having a slope of 1 within the errors.

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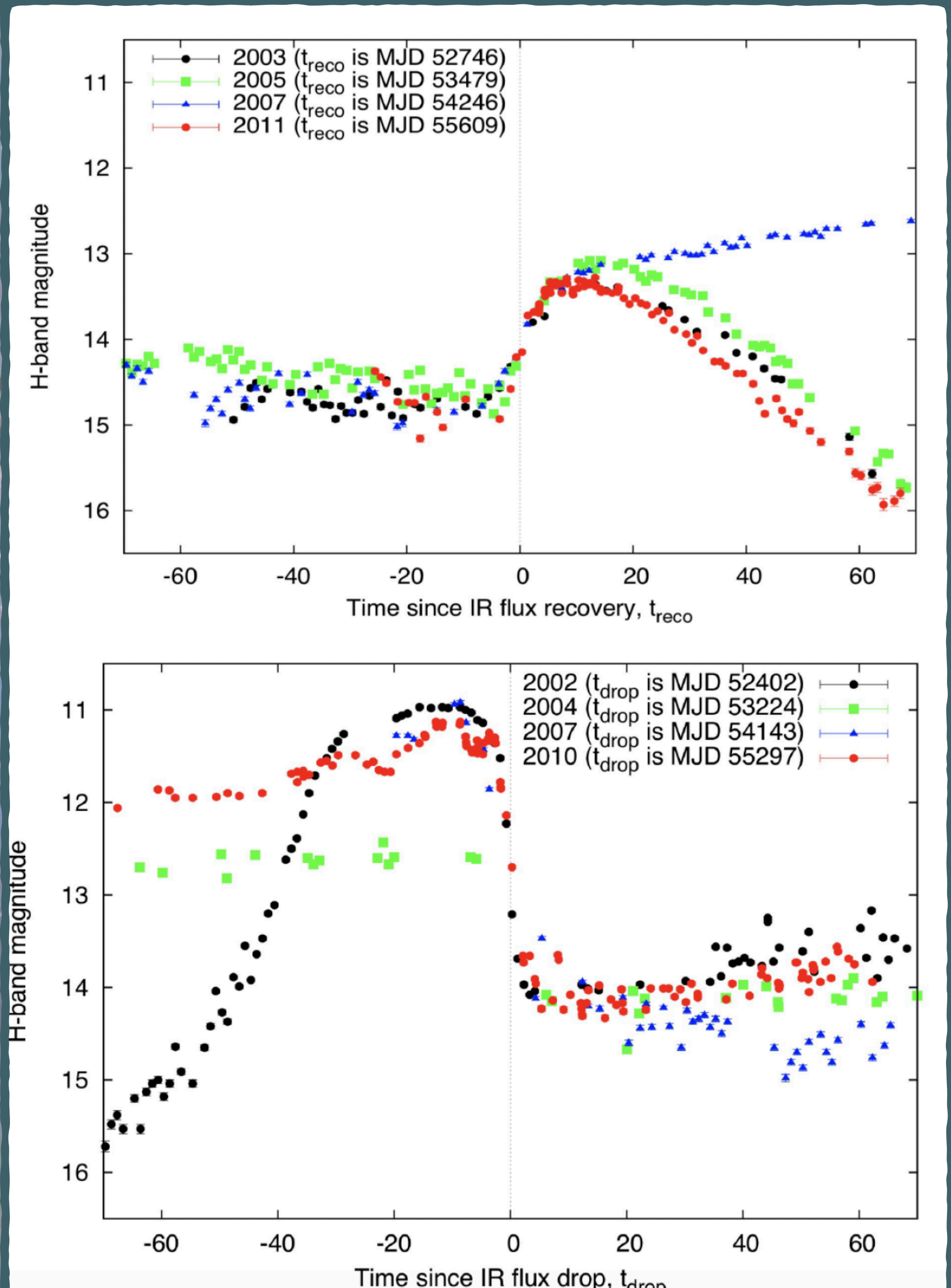
IR drop in GX 339-4



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Previous Lorentz Factors in XRBs

There is no clear consensus on the value of Lorentz factors expected in BHXB jets. Following Mirabel & Rodriguez (1994) it was suggested that BHXB jets would be significantly less relativistic than AGN jets, having $\Gamma \sim 2$. Fender & Kuulkers (2001) placed an upper limit of $\Gamma < 5$, arguing that a value higher than that would probably destroy the observed correlation between radio and X-ray peak fluxes. Furthermore, Gallo et al. (2003) used the scatter in the radio/X-ray relation of BHXB jets to constrain the Lorentz factors of compact jets to $\Gamma < 2$.

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Previous Lorentz Factors in XRBs

There are also studies to estimate the Lorentz factor of compact jets in a few individual BHXBs. For example, Casella et al. (2010) used IR variability of GX 339-4 to constrain the Lorentz factor of the source to be $\Gamma > 2$. Russell et al. (2015) found an unusually steep radio/X-ray correlation for MAXI J1836-194 and argued that the Lorentz factor of this source needs to vary from $\Gamma \sim 1$ at low X-ray luminosities to $\Gamma \sim 3$-4 at high X-ray luminosities to produce the observed correlation. Tetarenko et al. (2019) studied the time lags between the X-ray and radio bands for Cygnus X-1 and found a Lorentz factor value of $2.59^{+0.79}_{-0.61}$.

Saikia et al. 2019, in prep.