ACCRETING BLACK HOLES IN X-RAY BINARIES

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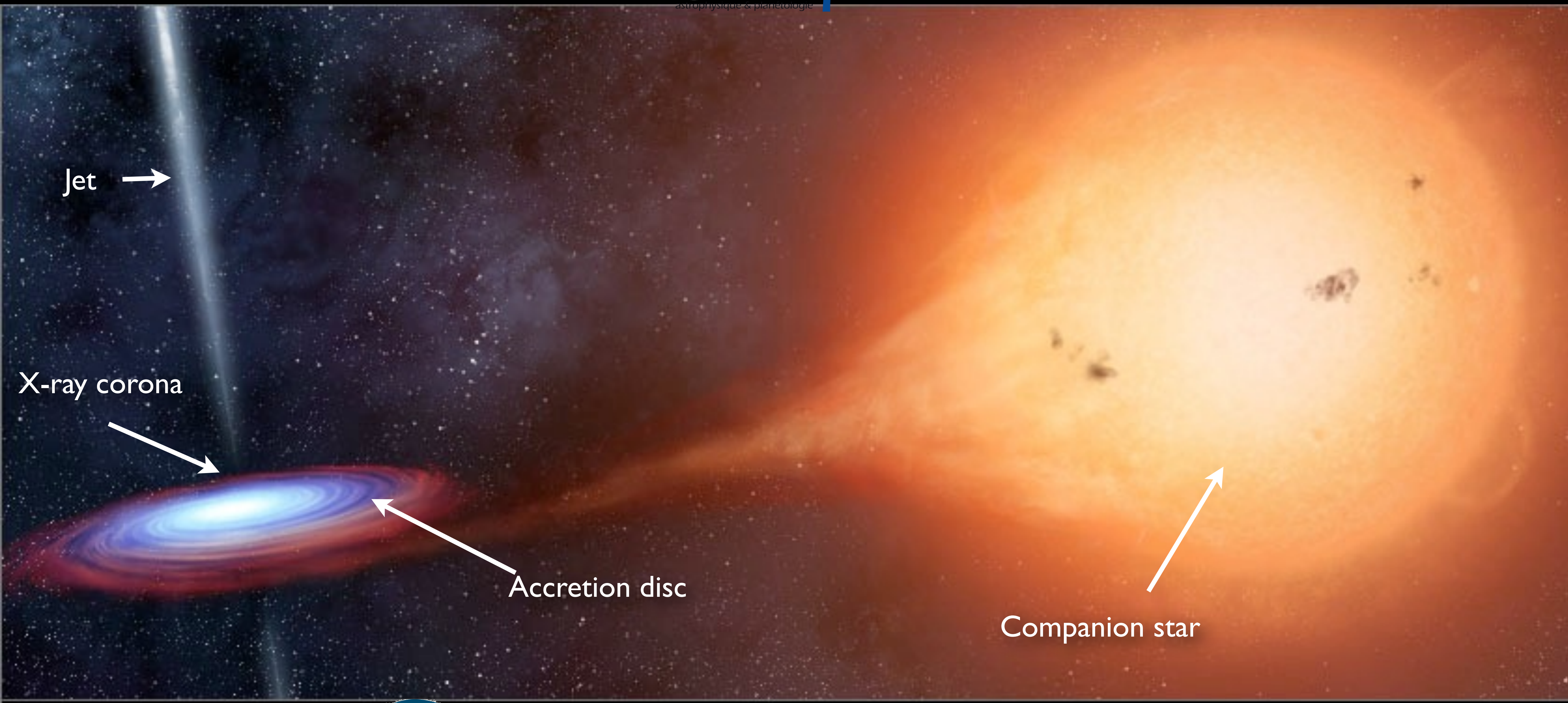
irap
astrophysique & planétologie



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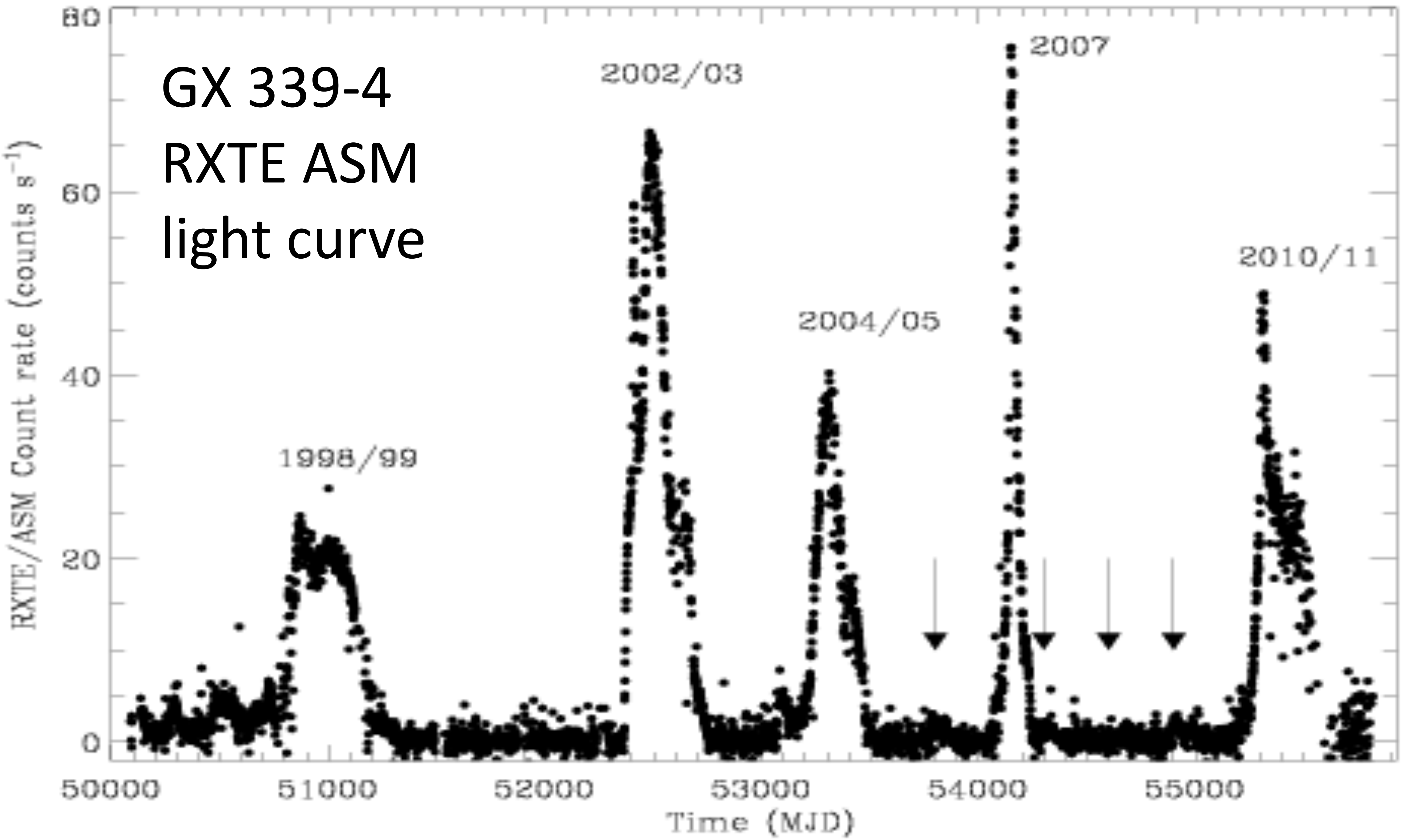
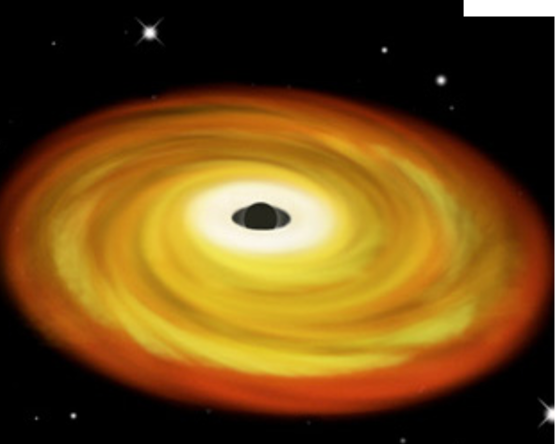
Outbursts

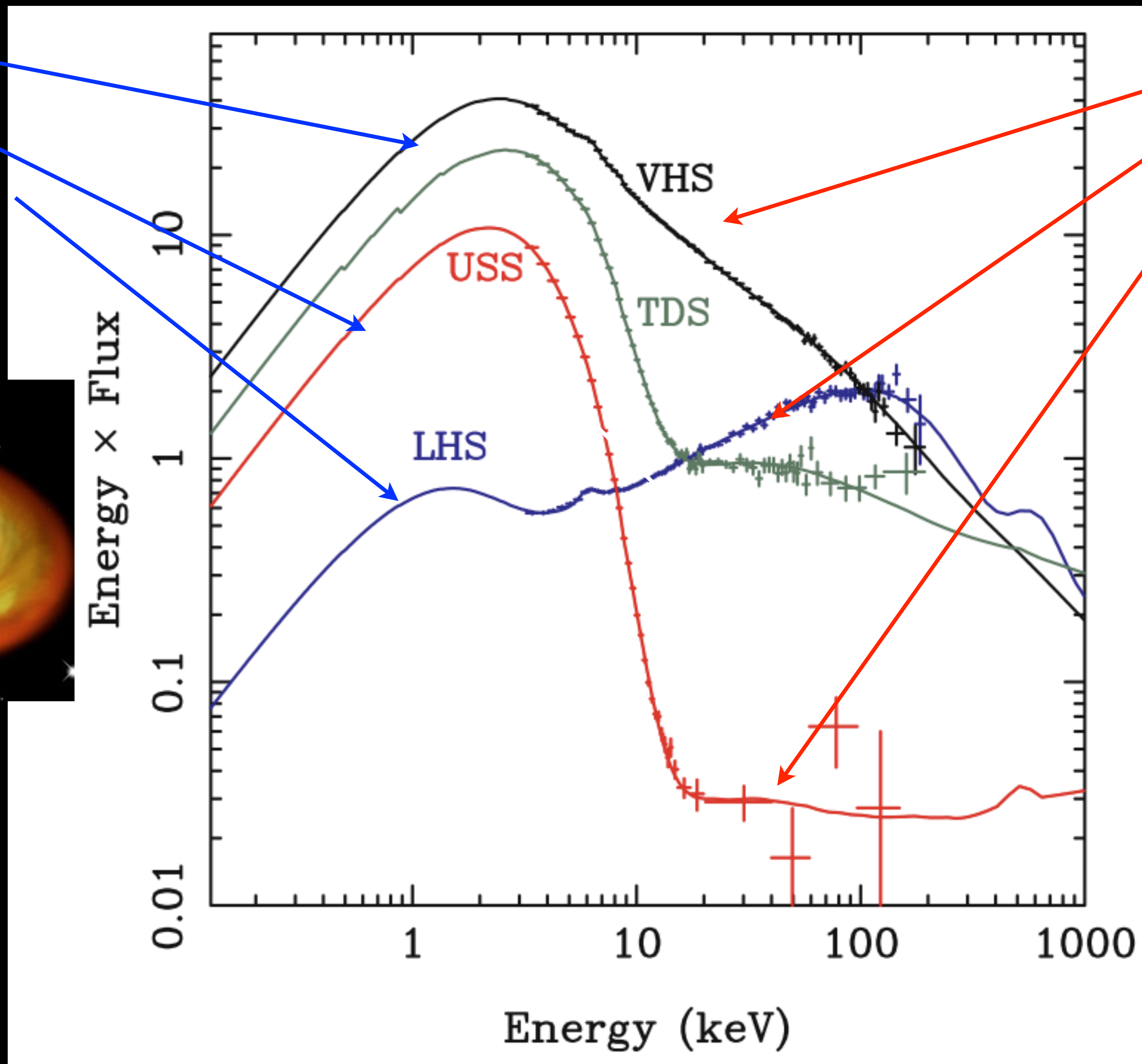


GX 339-4
RXTE ASM
light curve
1998/99
2002/03
2004/05
2007
2010/11
RXTE/ASM Count rate (counts s^{-1})
0
20
40
60
80
50000
51000
52000
53000
54000
55000
Time (MJD)

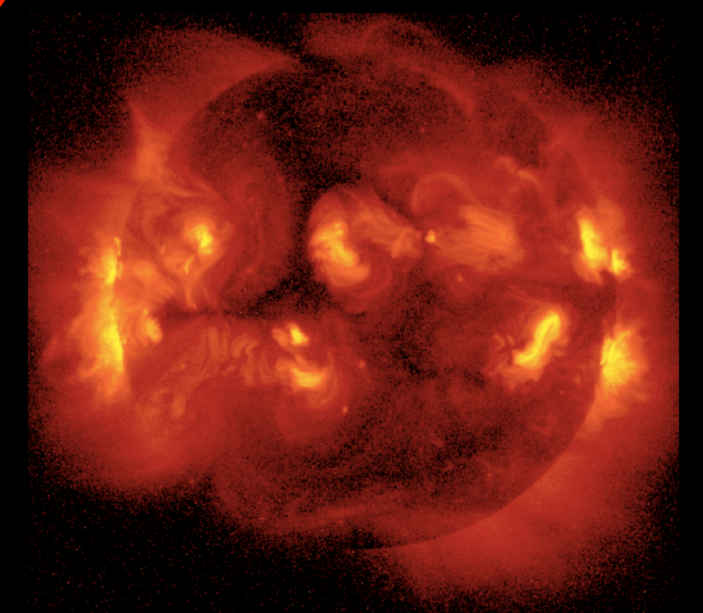
High energy spectra of BH X-ray binaries

Thermal emission: accretion disk





Non-thermal emission: 'the corona'



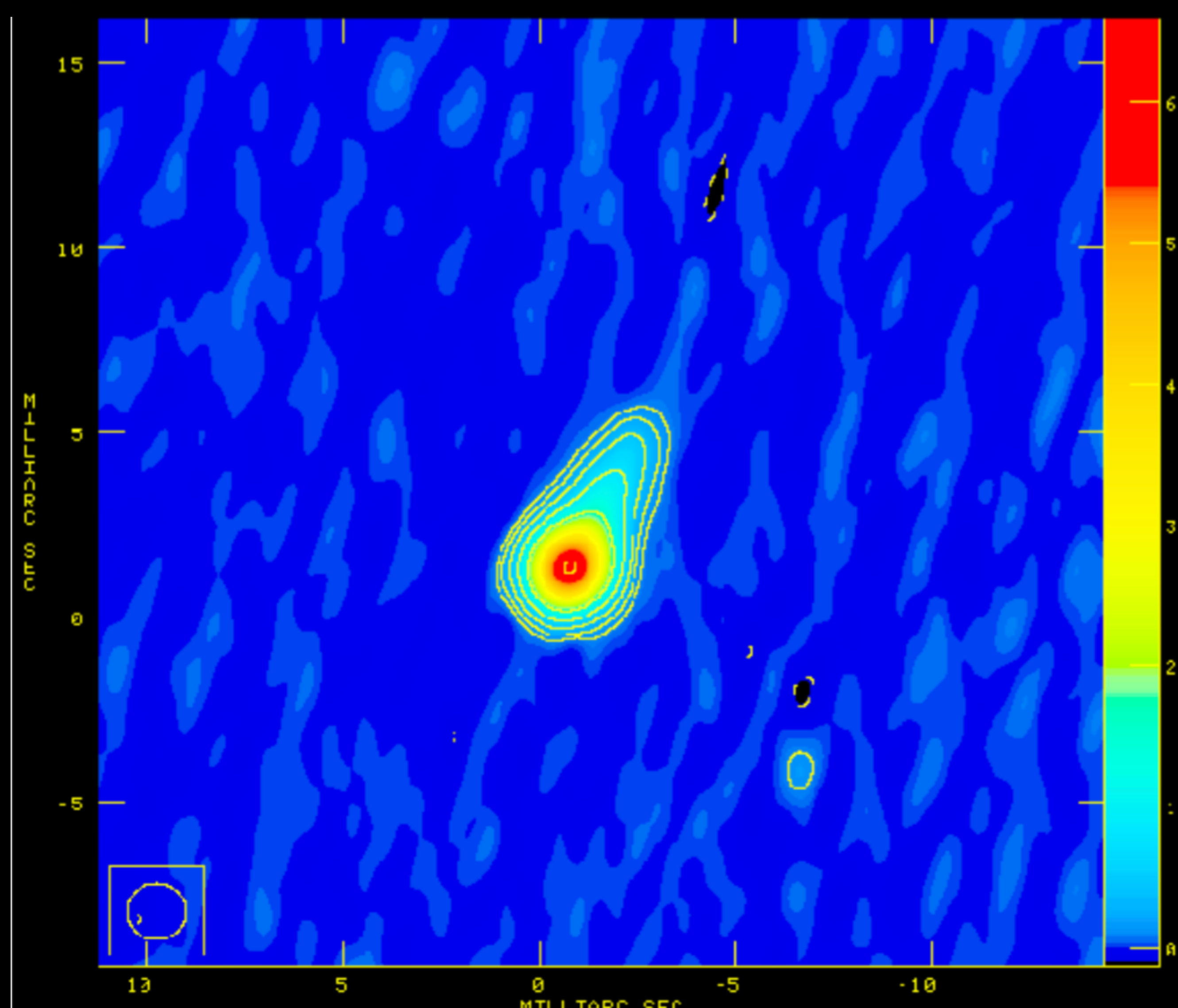
Hot plasma:

- accretion disk corona
- hot accretion flow
- jet

from Done et al. 2007

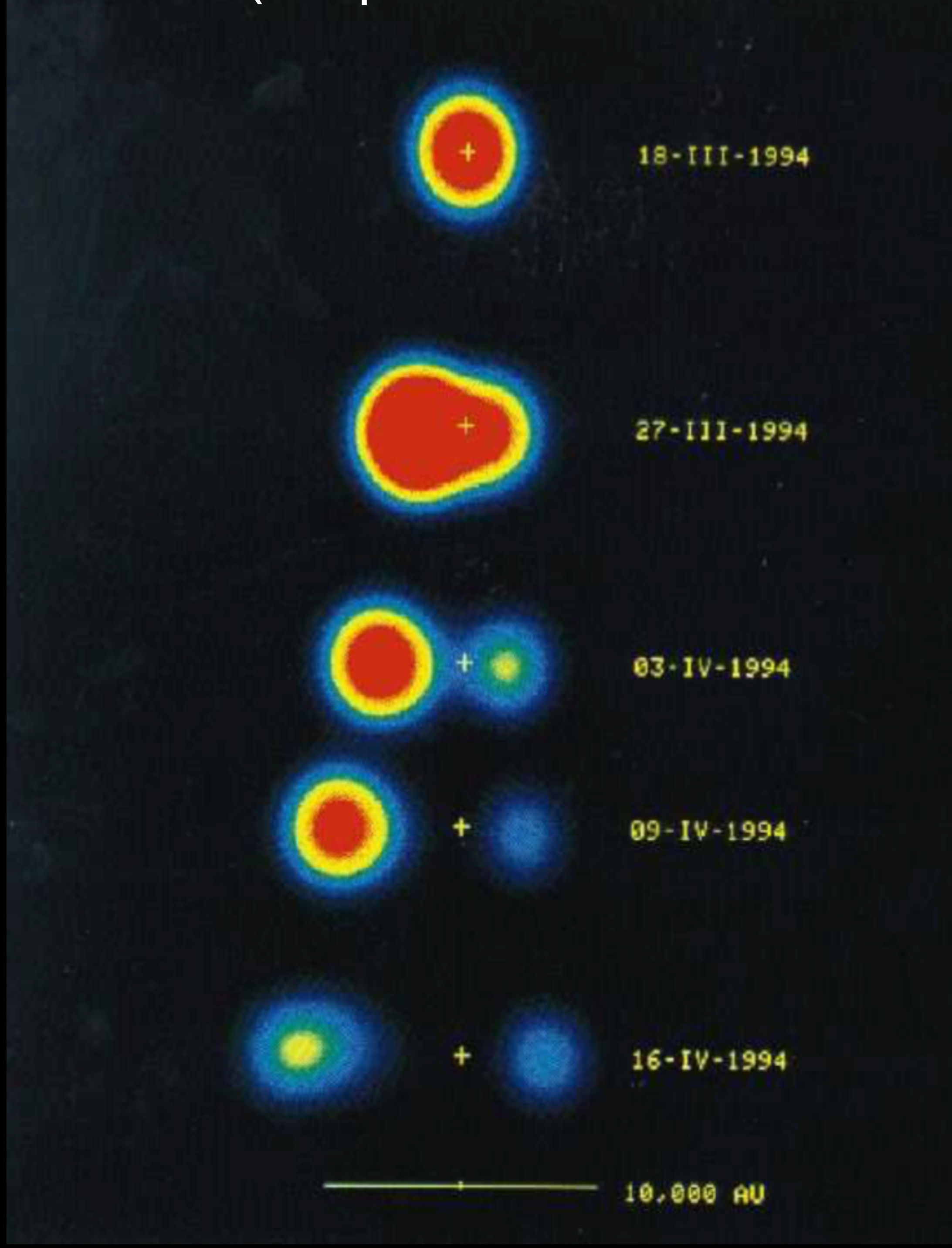
Radio jets

- Compact partially absorbed jets (mas scale)



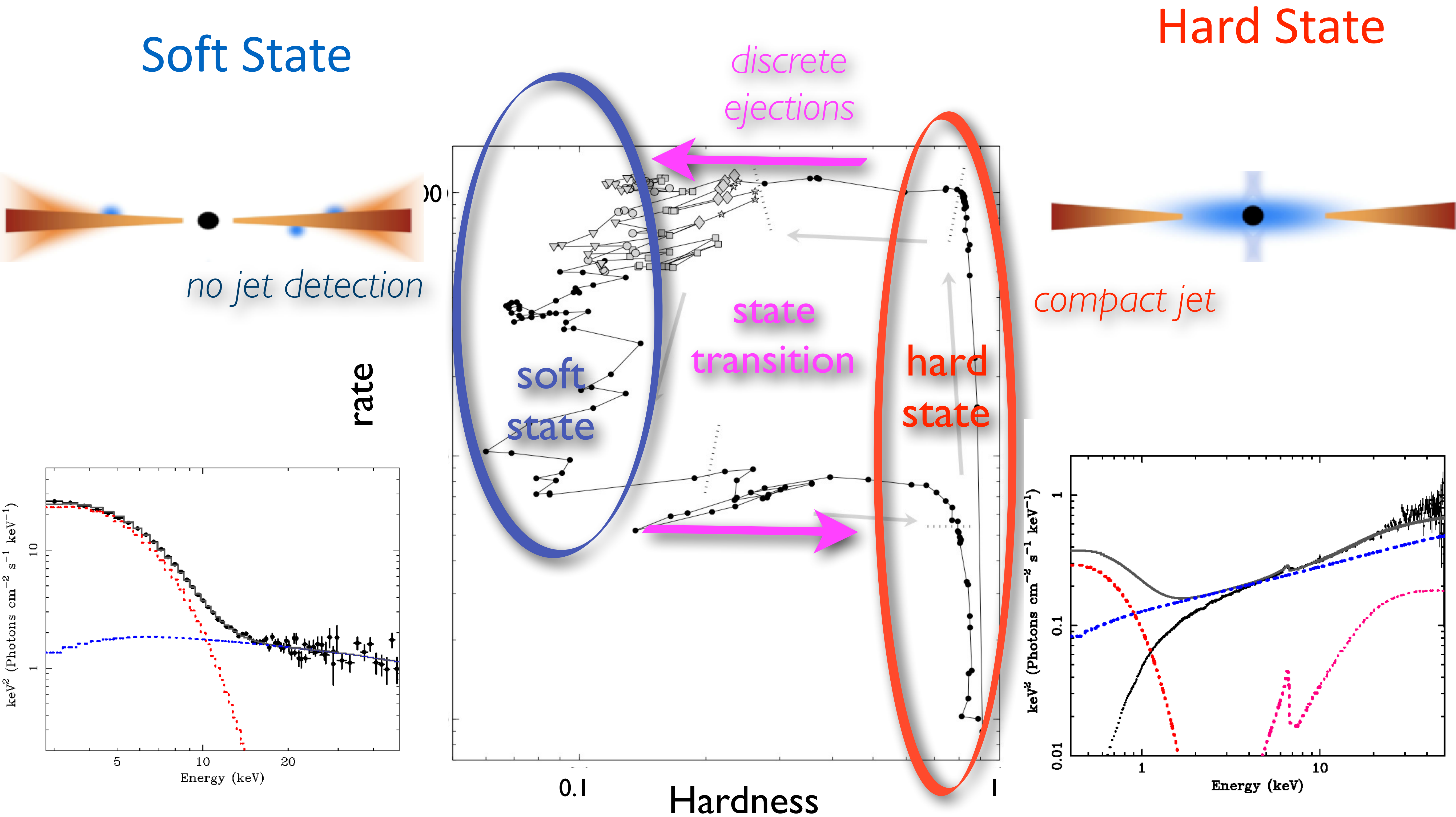
(Stirling et al. 2001)

- Discrete ejections (superluminal,balistic)

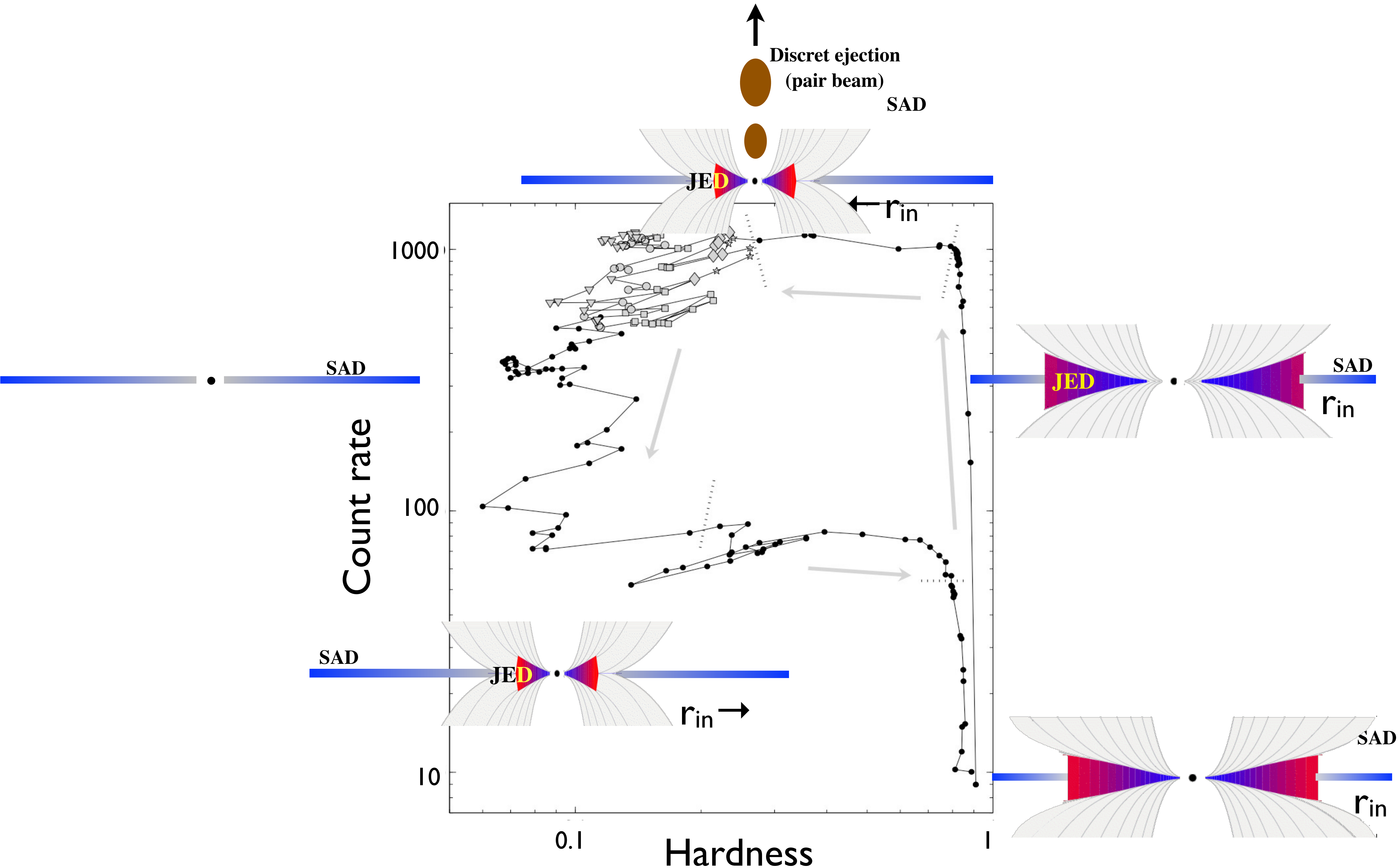


(Mirabel et al. 1994)

Spectral evolution during outbursts of BHBs



Truncated disc model

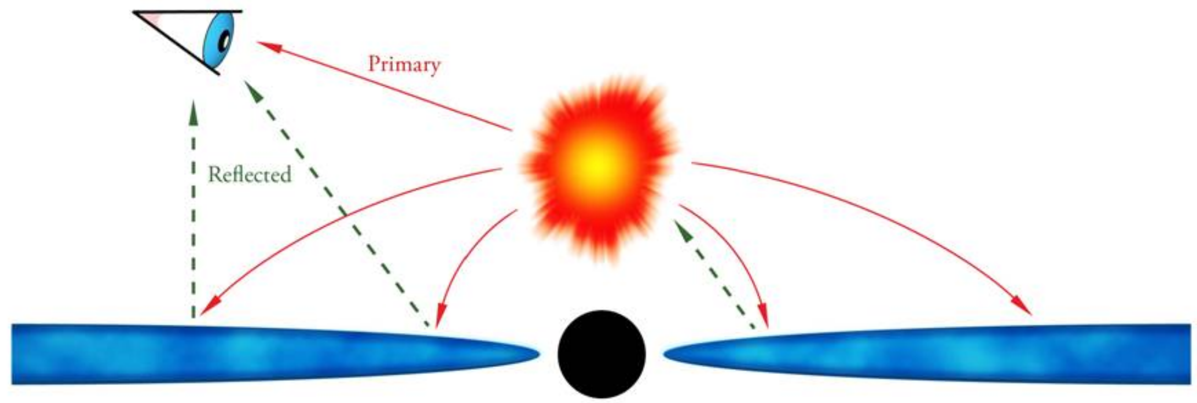


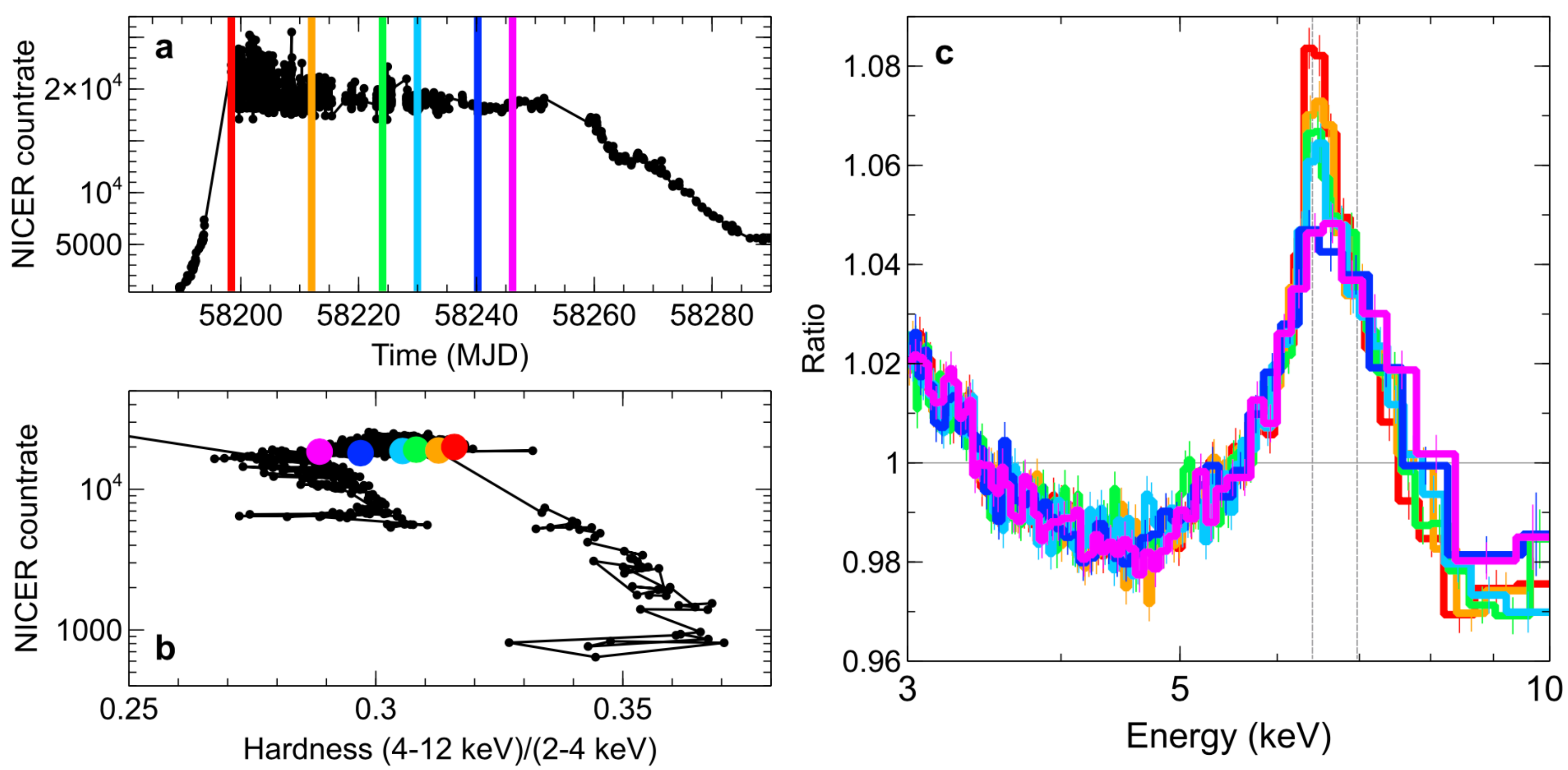
Hot flow = hot Jet Emitting Disc solution

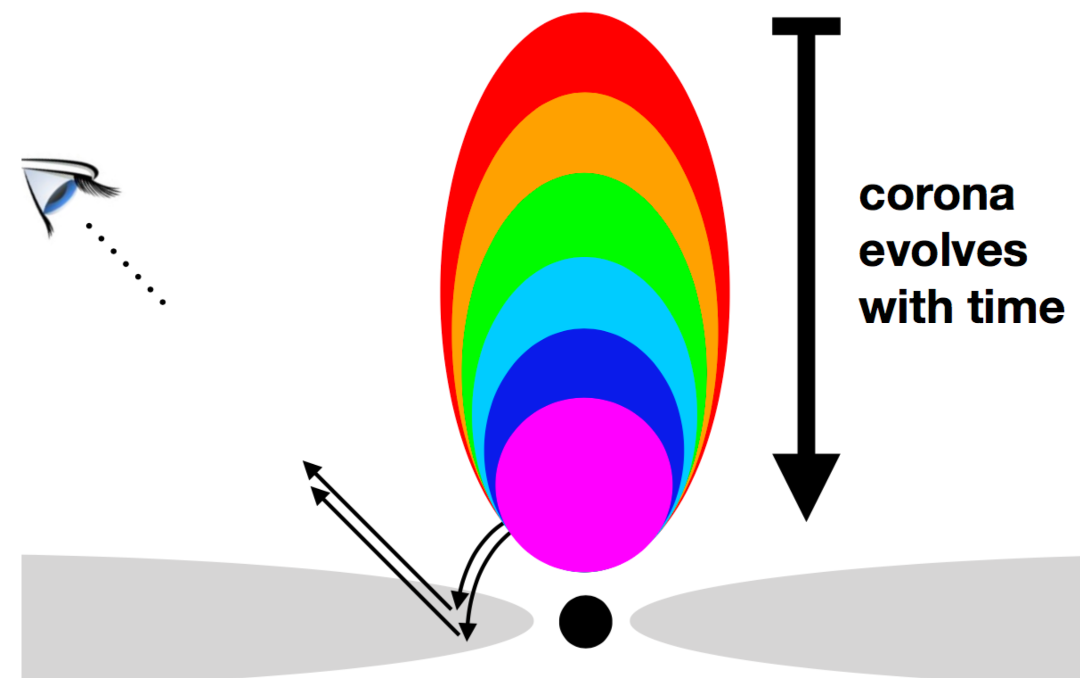
Ferreira et al. 2006; Petrucci et al. 2008; Petrucci et al. 2010; Marcel et al. 2018a, 2018b, 2019

(see talk by Petrucci)

Alternative accretion geometry in hard state: compact ‘lampost model’







Maxi 1820+070 in hard state:

Only narrow iron core emission (from large radii) changes significantly

→ Inner disk radius does not change

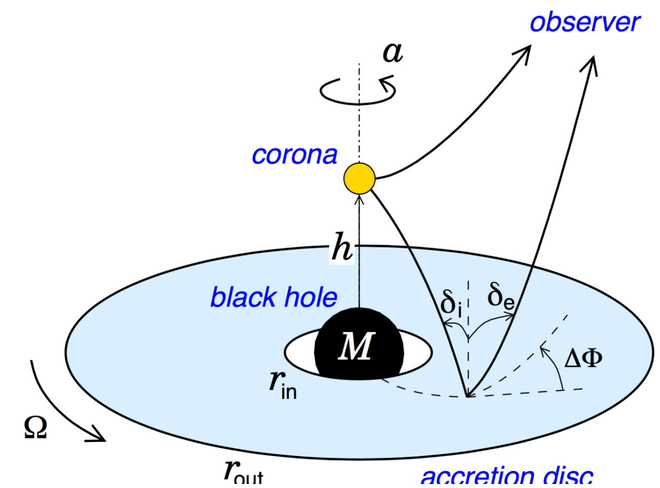
→ change in the extension of the corona is inferred

Kara et al. 2019

Constraints on geometry from X-ray polarisation measurements

- PoGO+ balloon observations of Cyg X-1, constrains polarization degree <8.6% in 20-180 keV band and alignment of the polarisation angle with radio jet axis

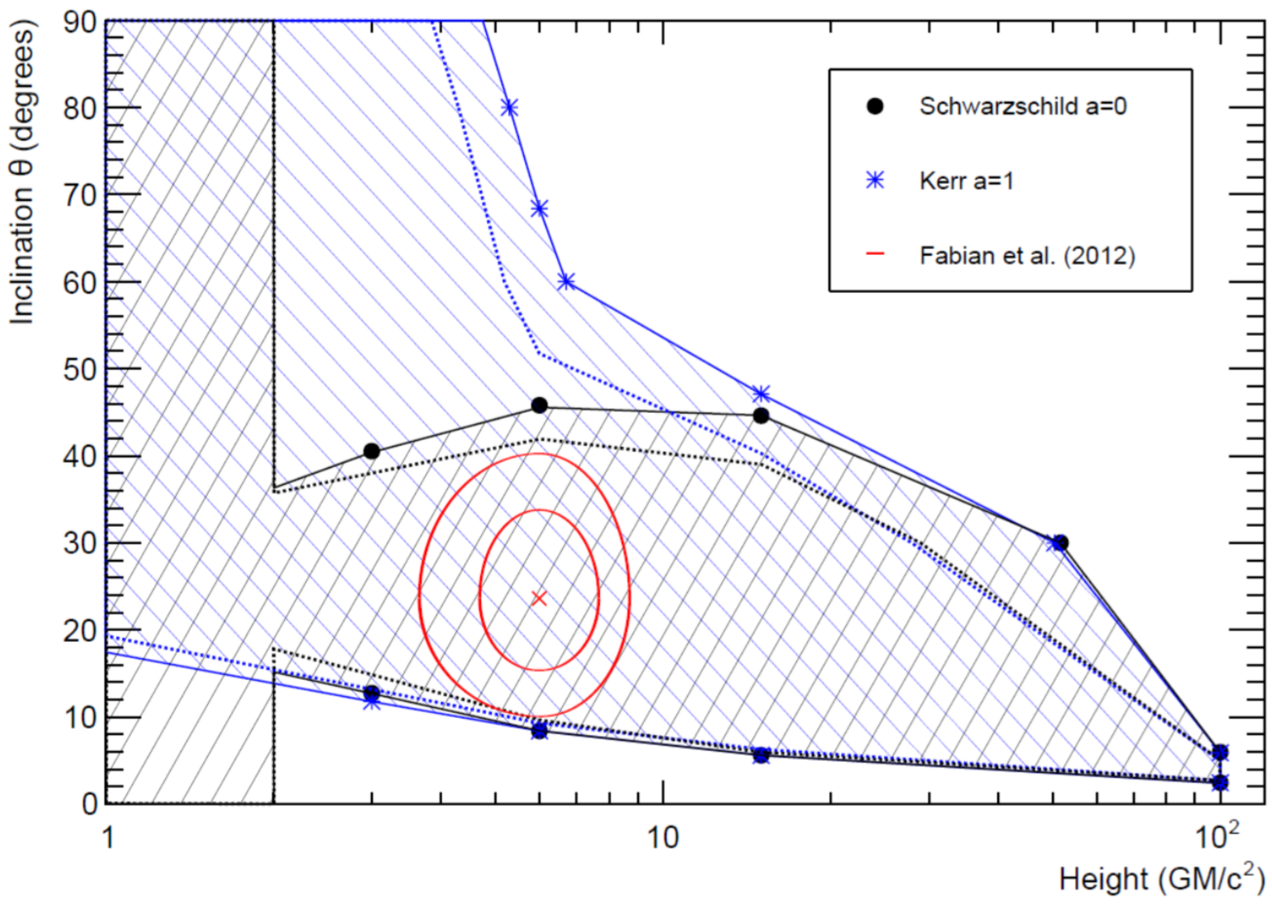
- Consistent with predictions from a truncated disc model with transition radius ~15 Rg (see e.g. Schnittman & Krolik 2010)



- Parameters obtained from spectral fits with lamp-post model are not consistent with low observed polarisation degree (see e.g. Dovciak et al. 2010, 2011).

  -Large lamp-post height is required.

  -Observed polarisation angle not explained in the lampost model.

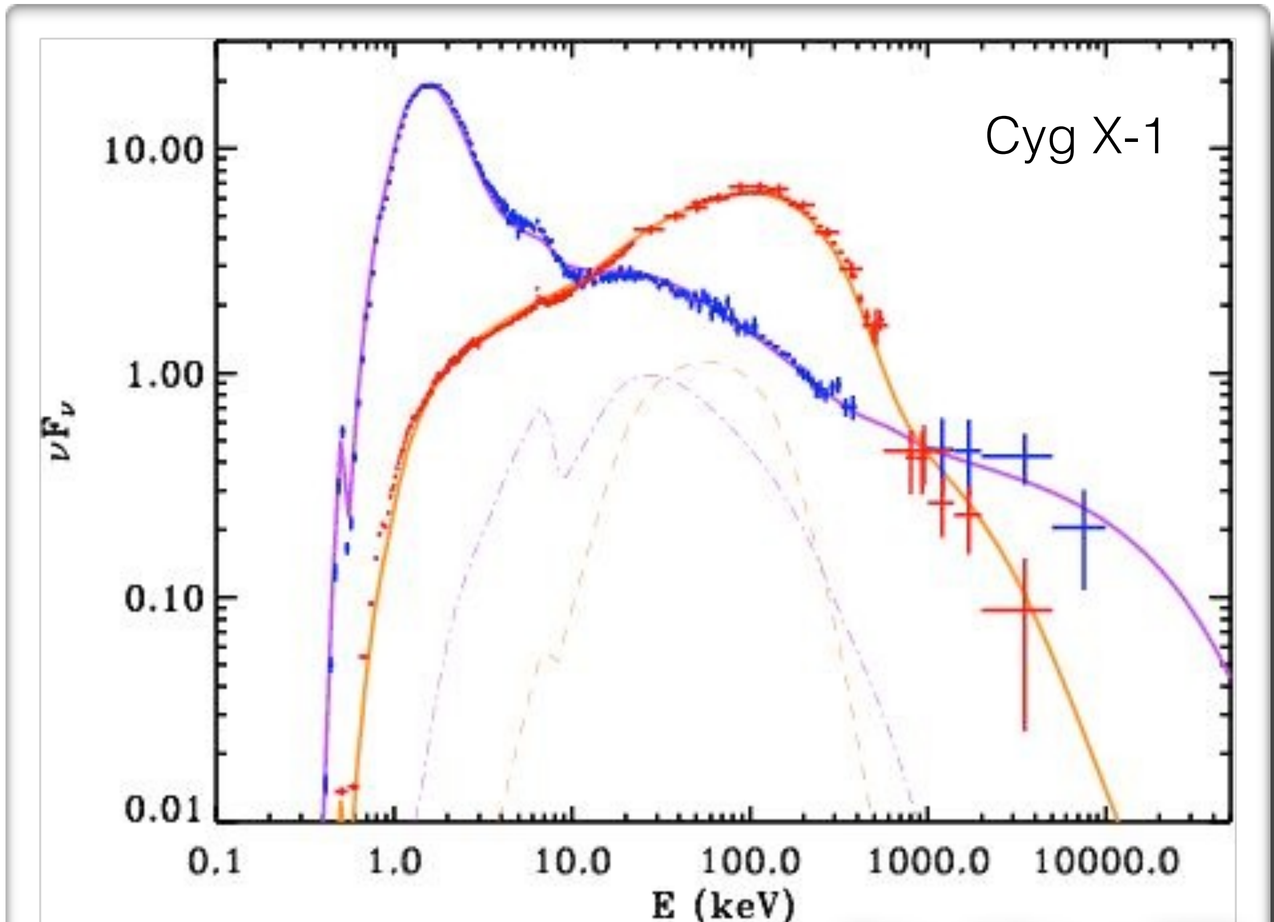


Chauvin et al. 2018

Nature of the MeV excess

- Emission in excess of thermal comptonization detected in several sources in hard state. (Mc Connell et 2002; Del Santo et al. 2008)

- IC emission from non-thermal electrons in the corona (hybrid thermal/ non thermal models) (Coppi & Poutanen 1998)

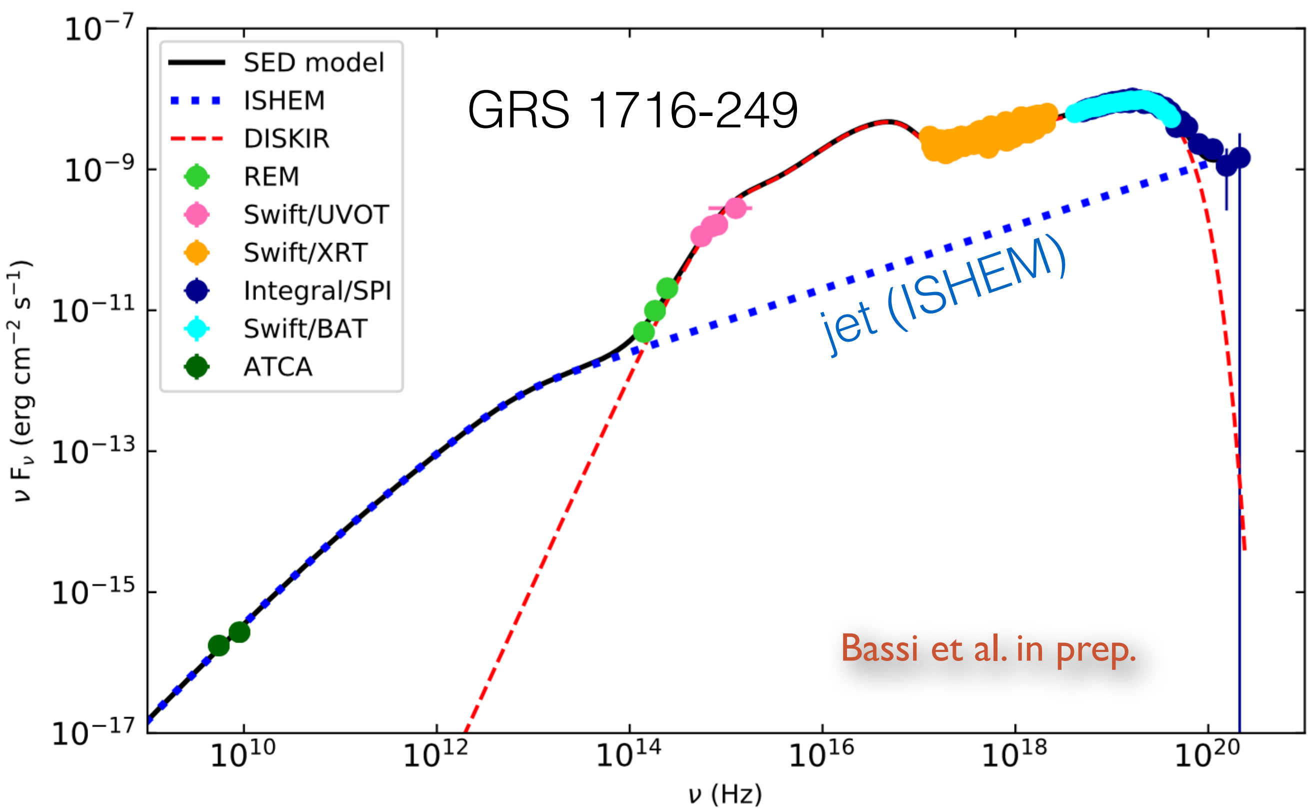


(Malzac & Belmont 2009)

- INTEGRAL polarization measurements in Cyg X-1 suggests excess is strongly polarized (PD: 76%+/-15% above 230 keV).

- Jet synchrotron emission ?

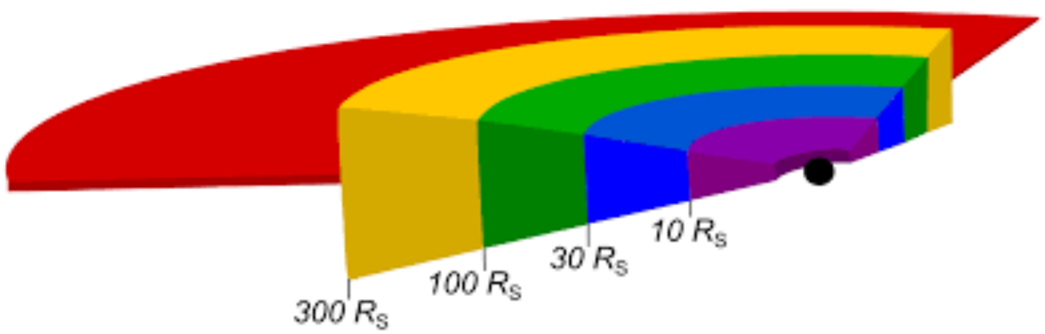
(Jourdain et al. 2012, Laurent et al 2012, but see Zdziarski et al. 2017)

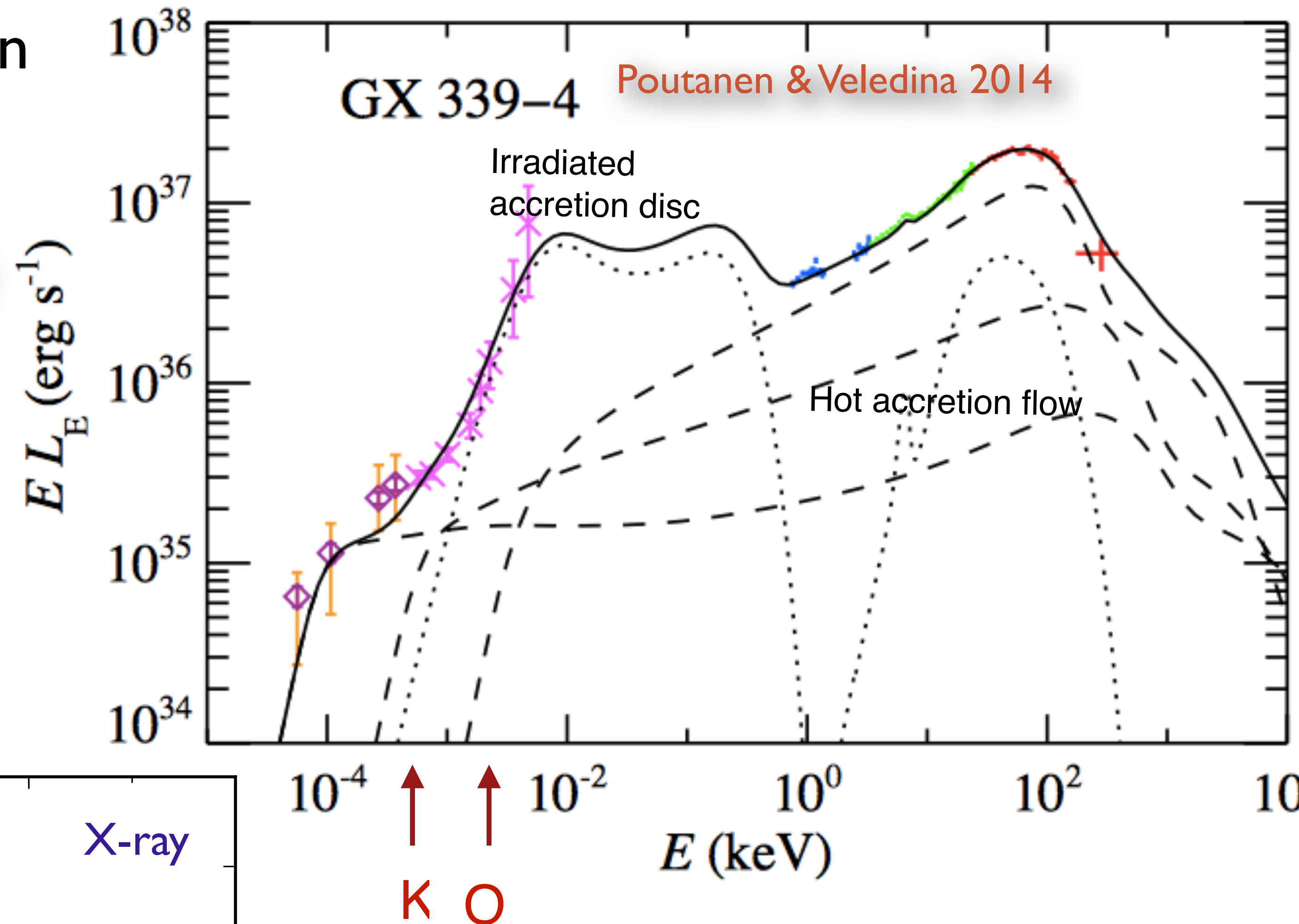


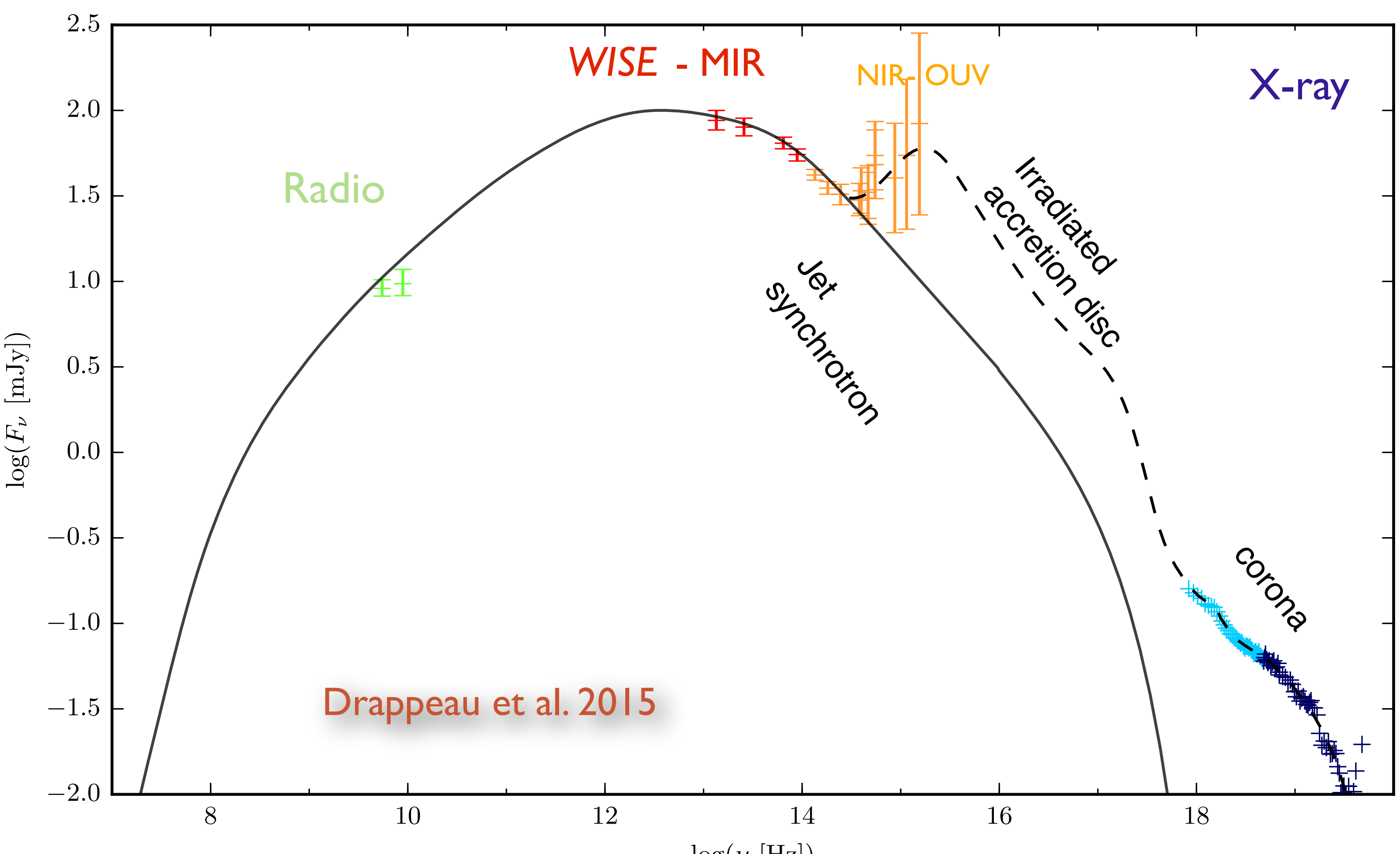
Nature of OIR emission

- Synchrotron from non-thermal particles in hot-flow/corona ?

(Fabian et al 1982; Veledina et al. 2011, Veledina et al. 2018)



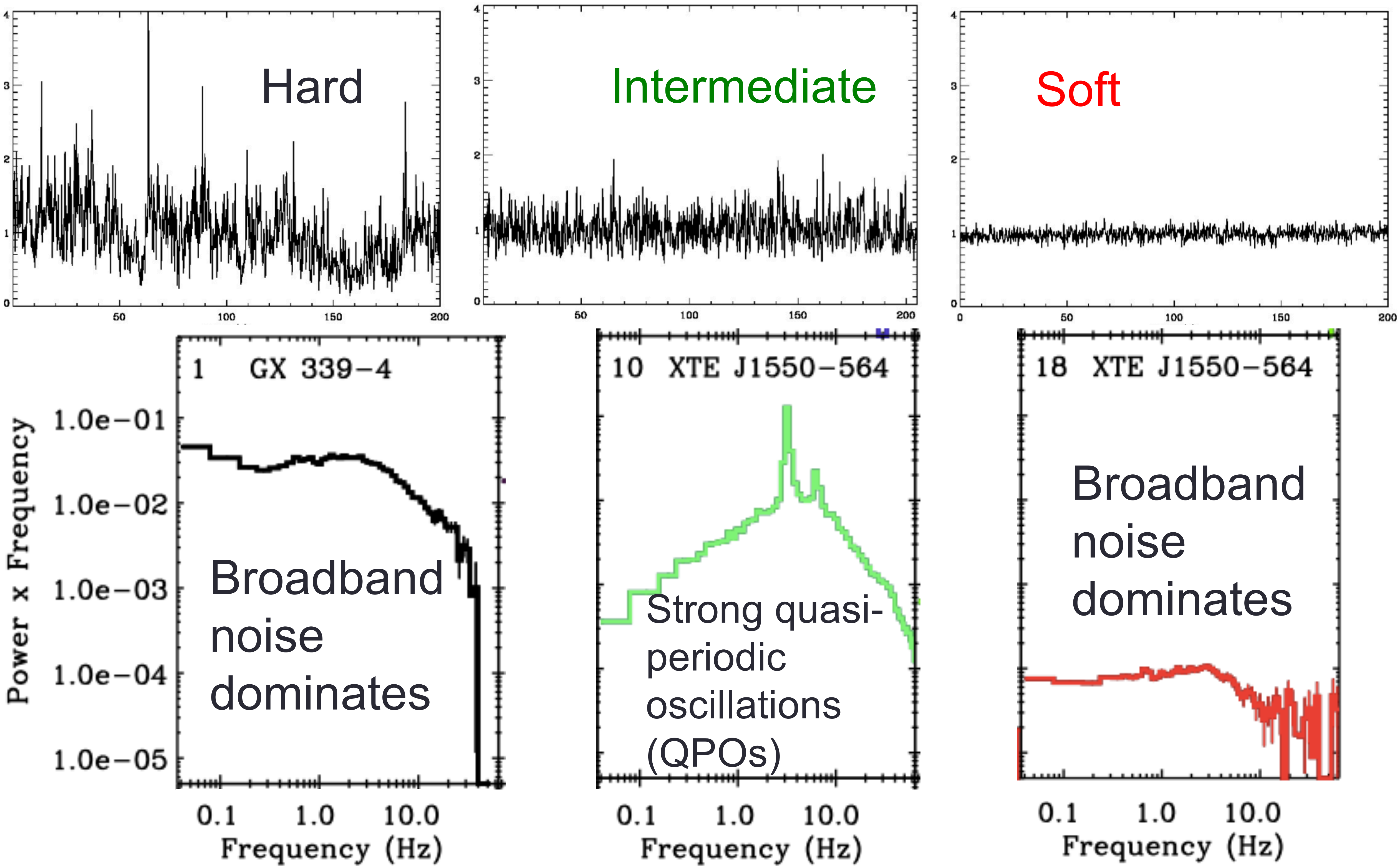




- Synchrotron jet emission ?

(Kanbach et al. 2001; Chaty et al. 2003; Malzac et al. 2004)

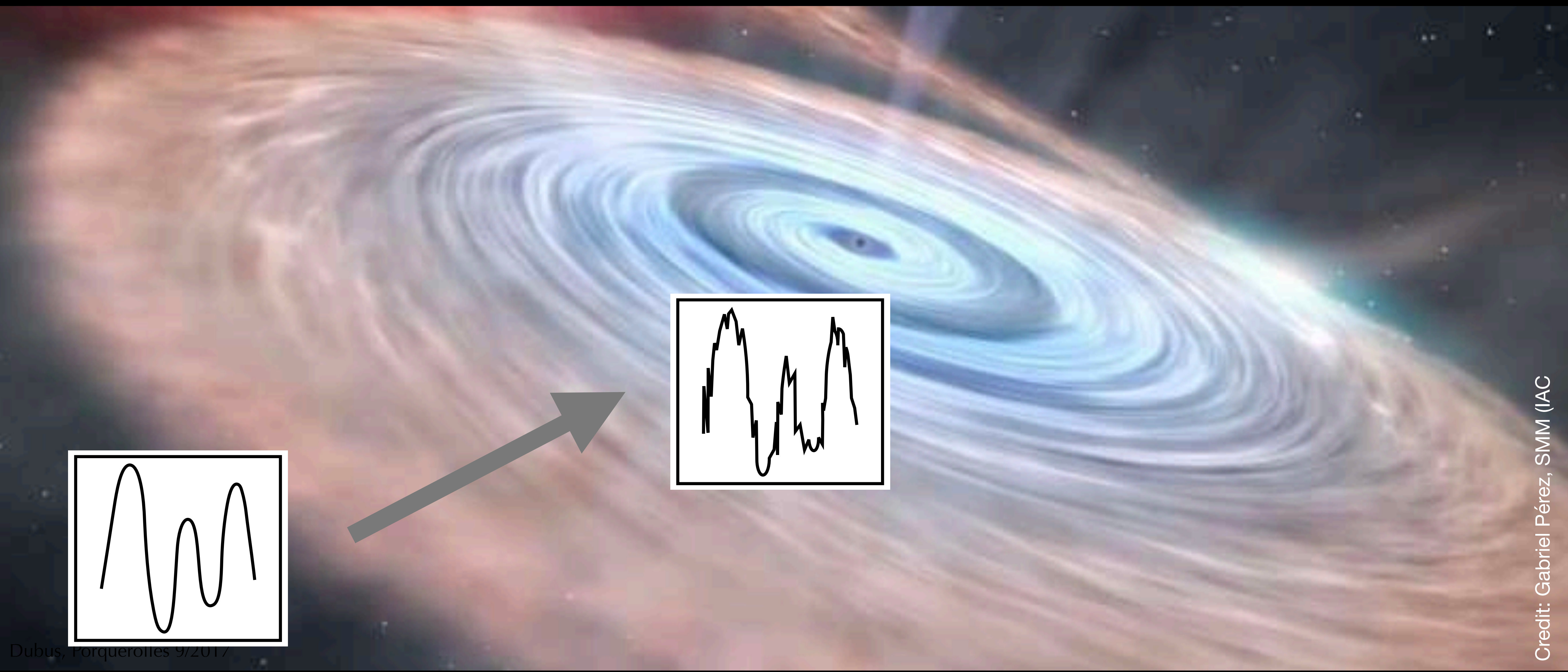
Fast X-ray variability



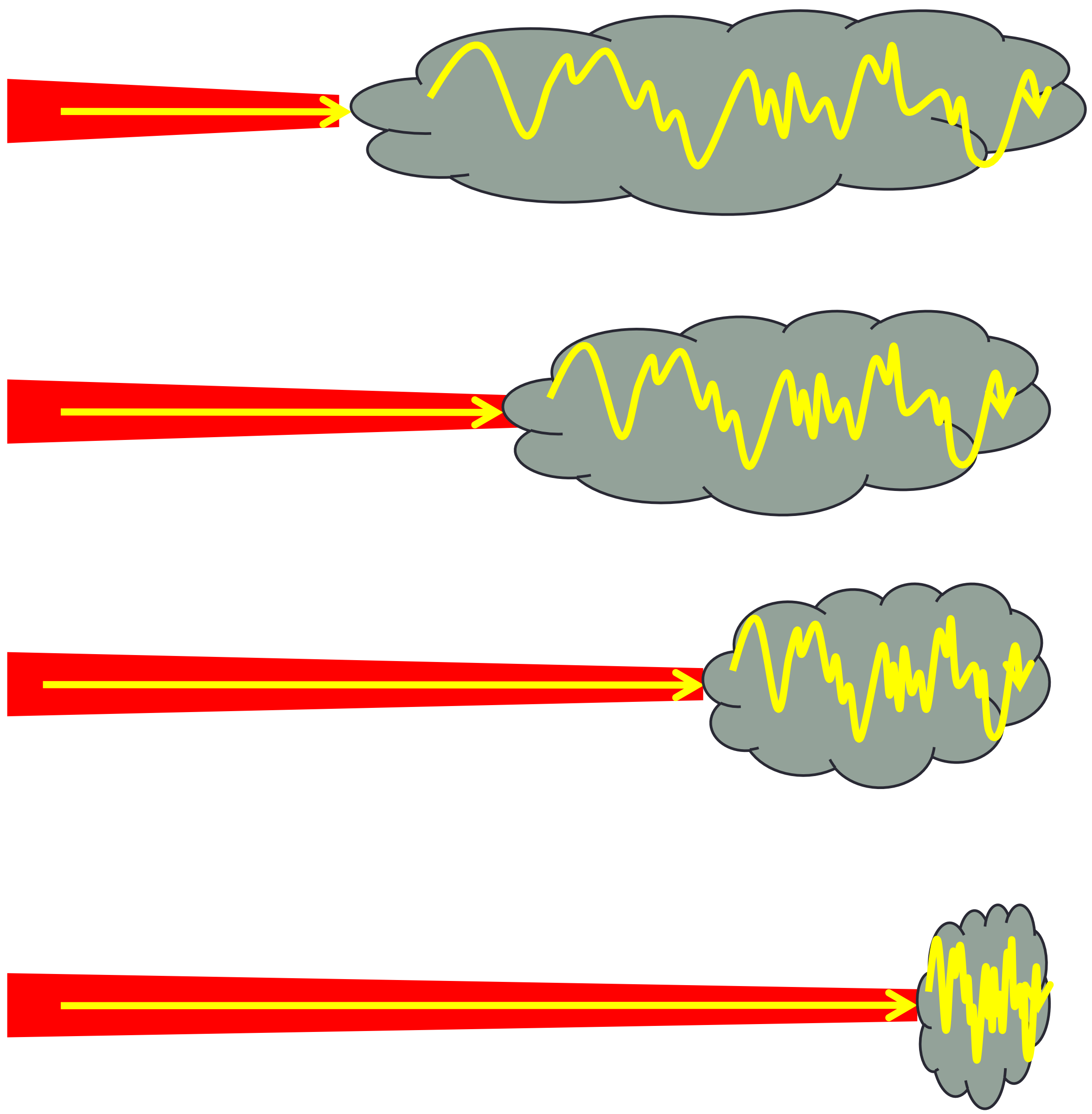
Propagating fluctuations model of variability

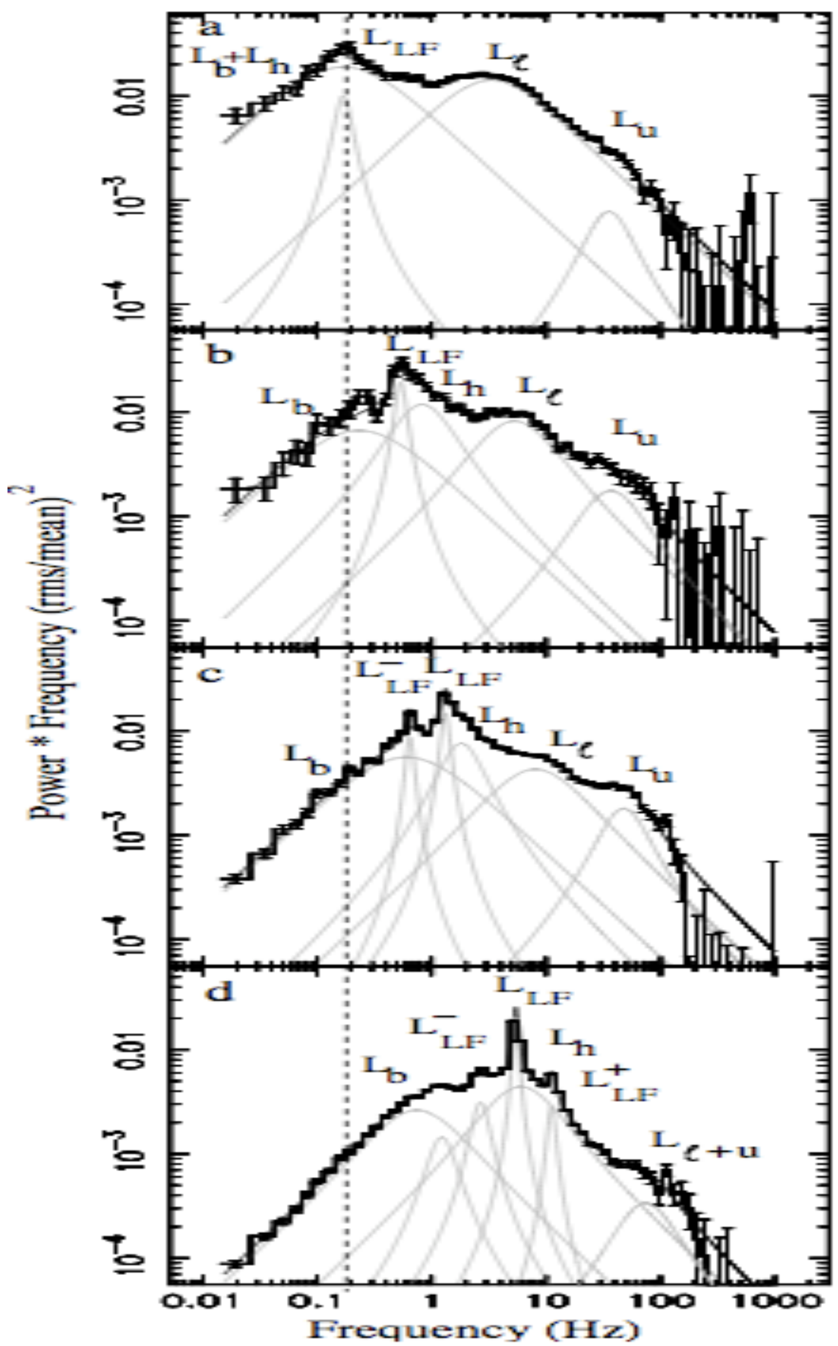
Accretion flow fluctuations propagate inward, modulated at faster times scales at smaller R

(Lyubarskii 1997)



Changing radius of stable disc
+ unstable hot flow ?

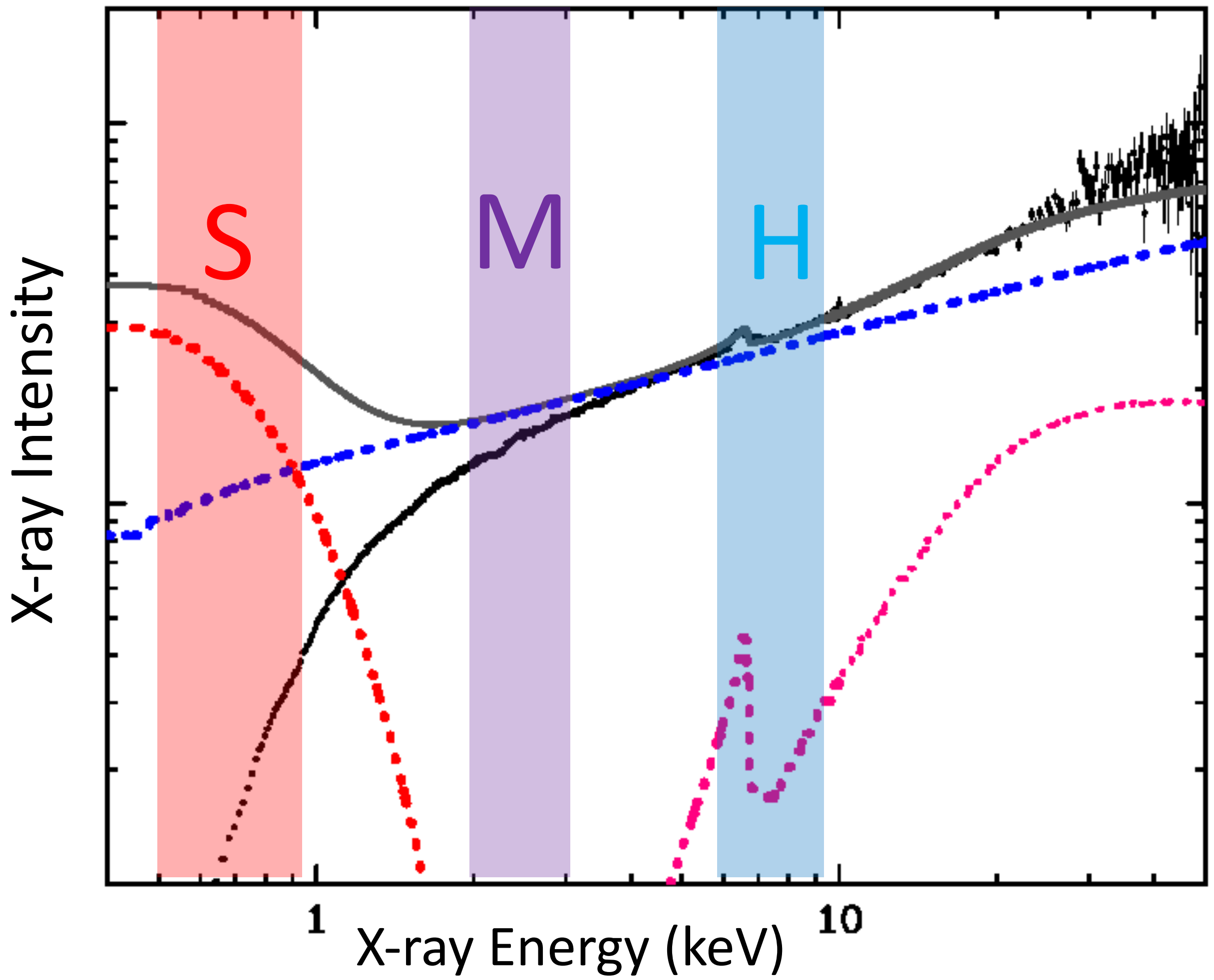


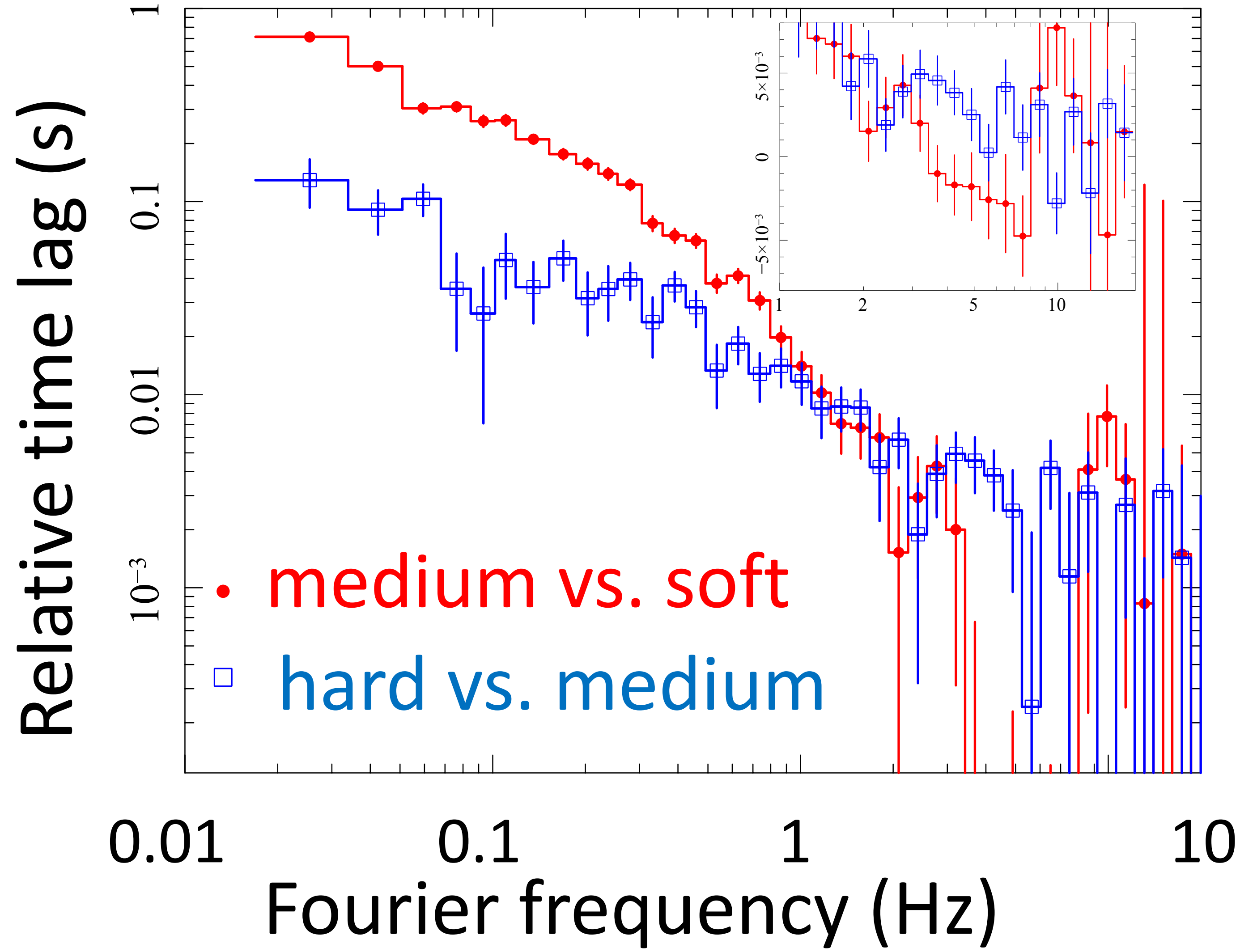


Churazov et al. (2001), Done et al. 2007): disk moves in, variability power concentrates in narrower range of time-scales/frequencies. Can also explain weak variability in disk-dominated soft state.

X-ray time-lags

GX 339-4 hard state: lag vs. Fourier frequency





- **Power-law variations: hard band vs medium band**
  - **- hard photons lag behind variations at softer energies**
  - **- time-lags increase towards lower frequencies (longer time-scales)**
  - **- lag vs energy dependence is approximately log-linear**

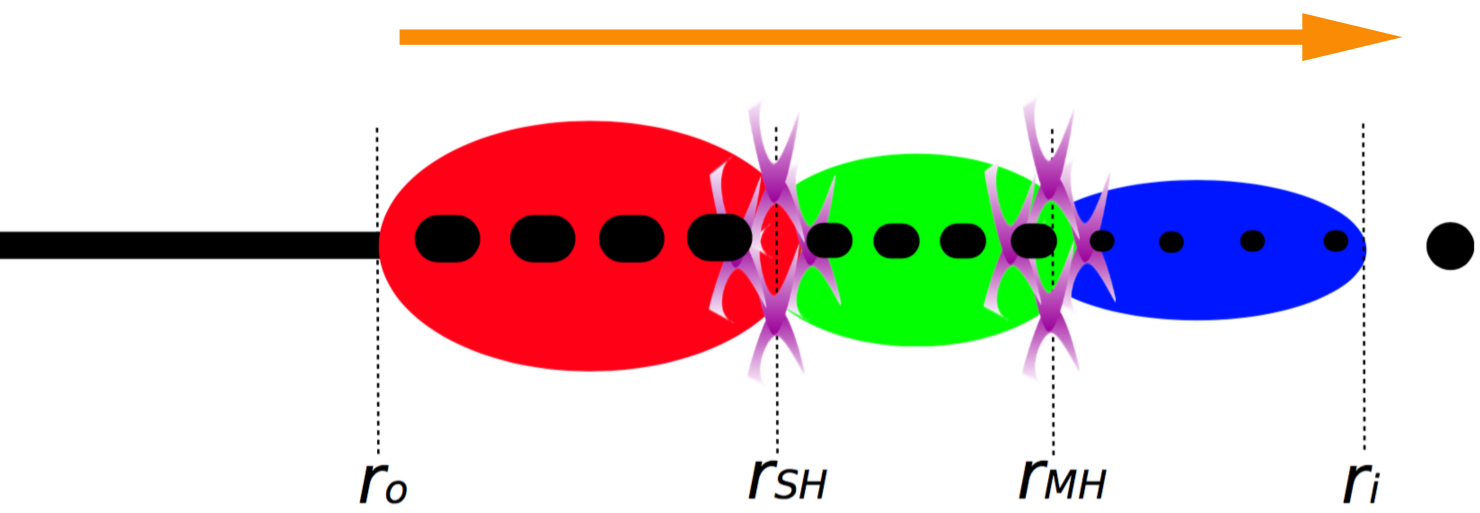
(Nowak et al. 1999; Kotov 2001)

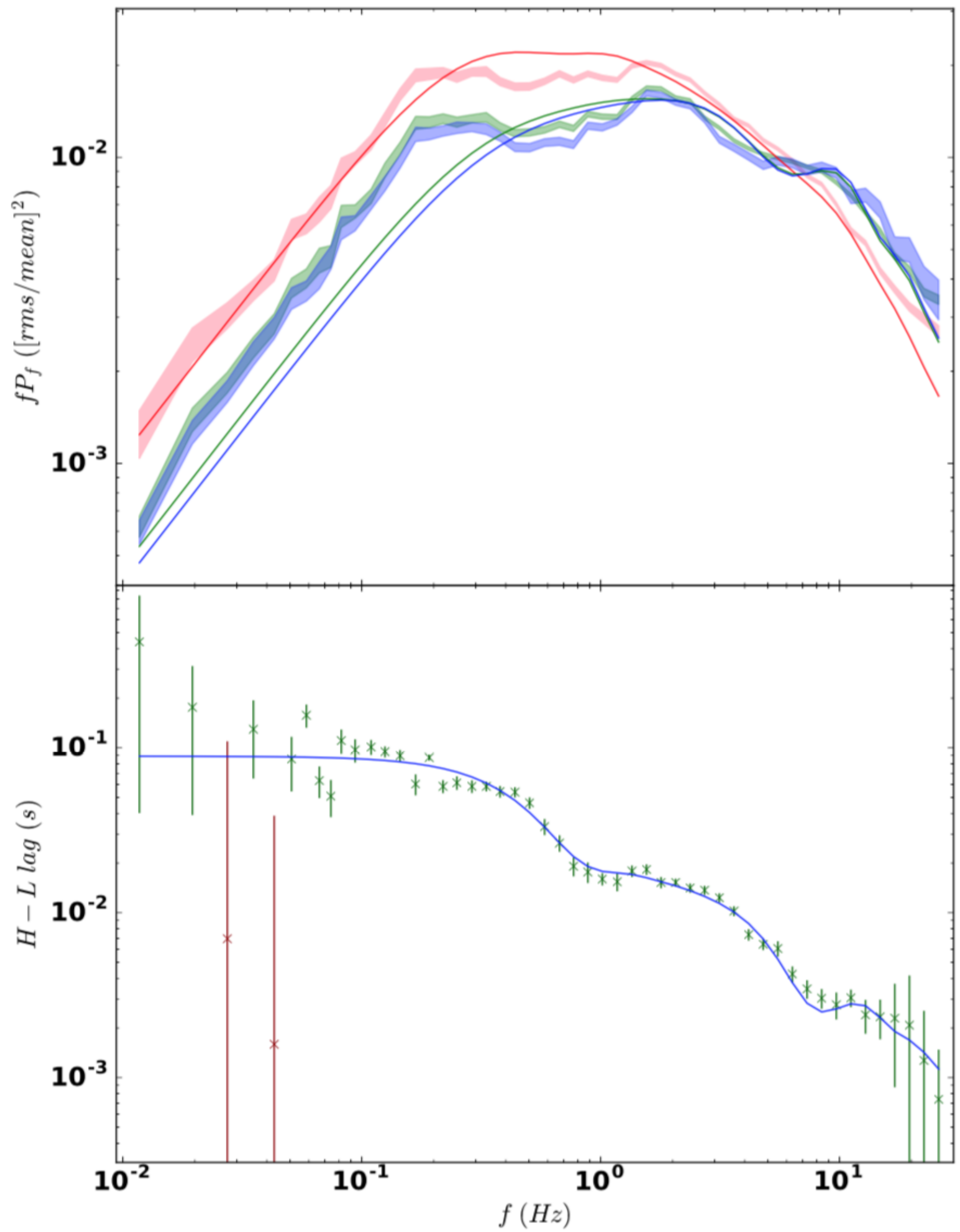
- **Disk vs power-law variations:**
  - **- At low Fourier frequencies, 'disk' leads PL by a few 0.1 s**
  - **- At high Fourier frequencies, 'disk' lags behind PL by a few ms (reverberation lags ?)**

(Uttley et al. 2011)

Models for the hard lags

- **Fluctuations propagating through hot flow with a radial temperature gradient**
  (Kotov et al. 2001, Arévalo & Uttley 2006, Rapisarda et al. 2016, Mahmoud & Done 2018)





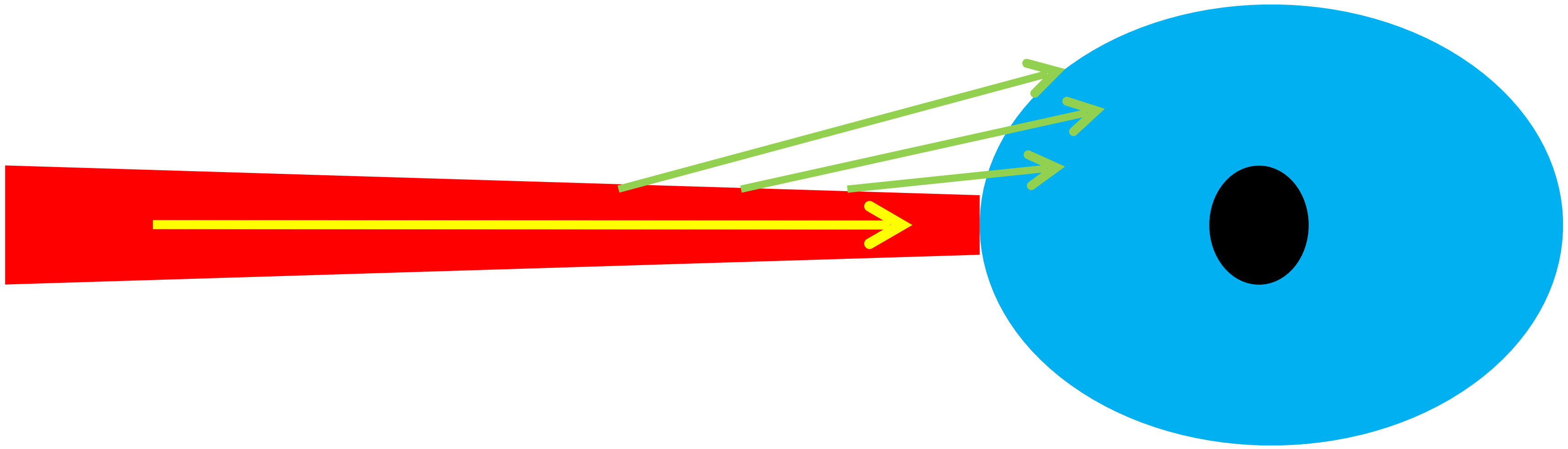
—> Can produce large lags (viscous time-scale) if corona is strongly radially extended

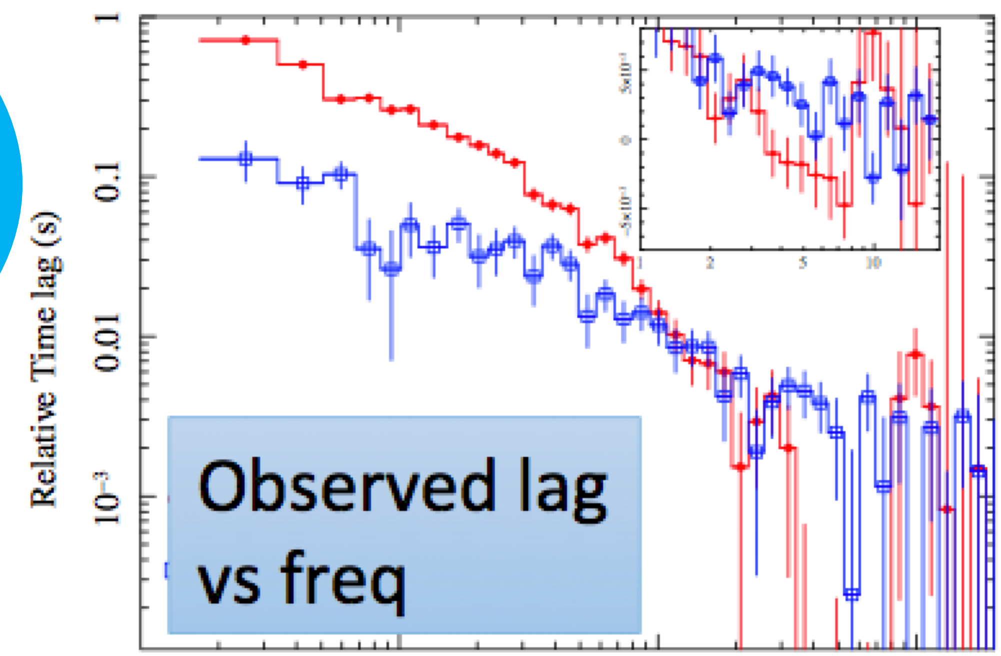
—> Energy dependence of lags is included in an had-hoc way

—> 3 radii in the hot flow with enhanced emission (inner disc, inner hot flow and jet launching radius) Mahmoud & Done 2018

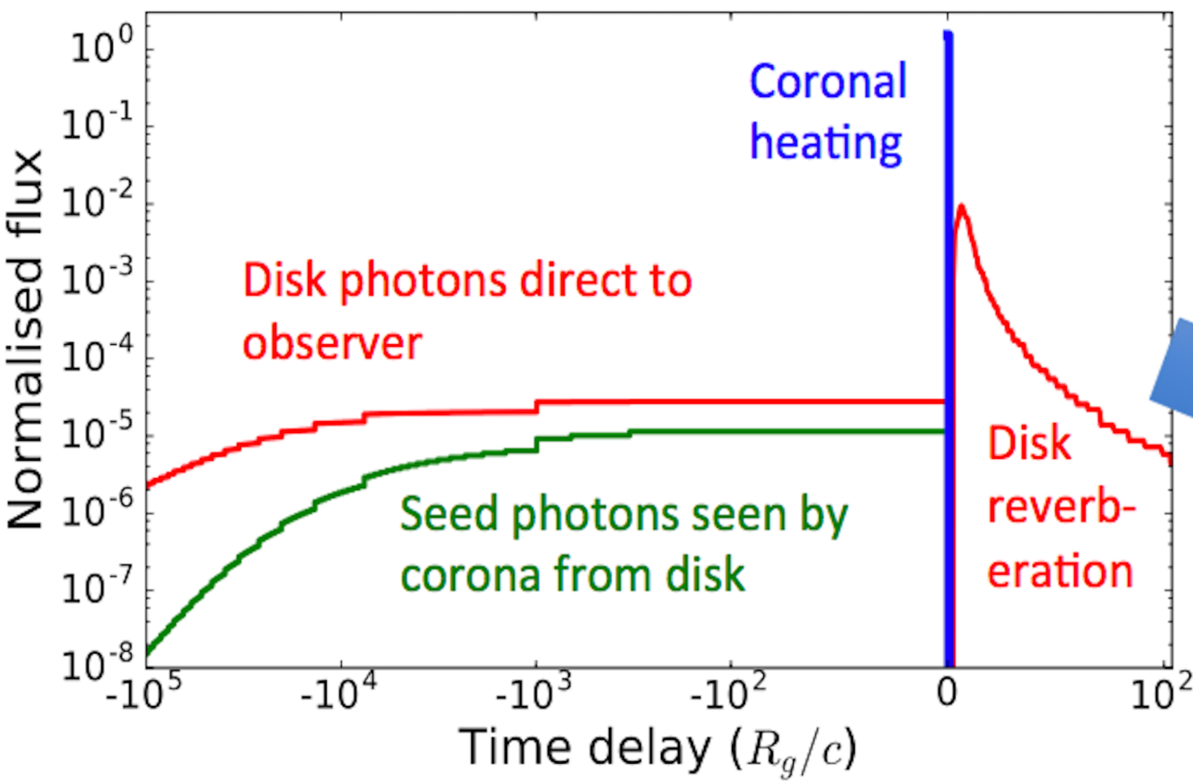
Models for the hard lags

- **Propagation through the disc: accounting for seed photon variability**

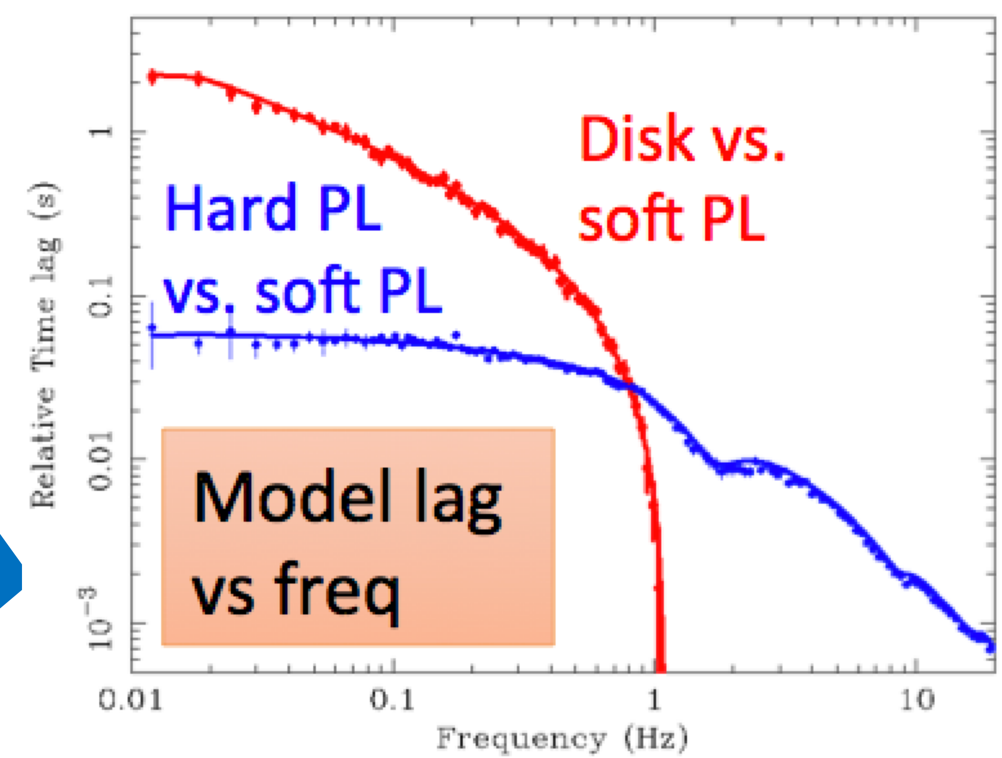




Combined impulse response function model

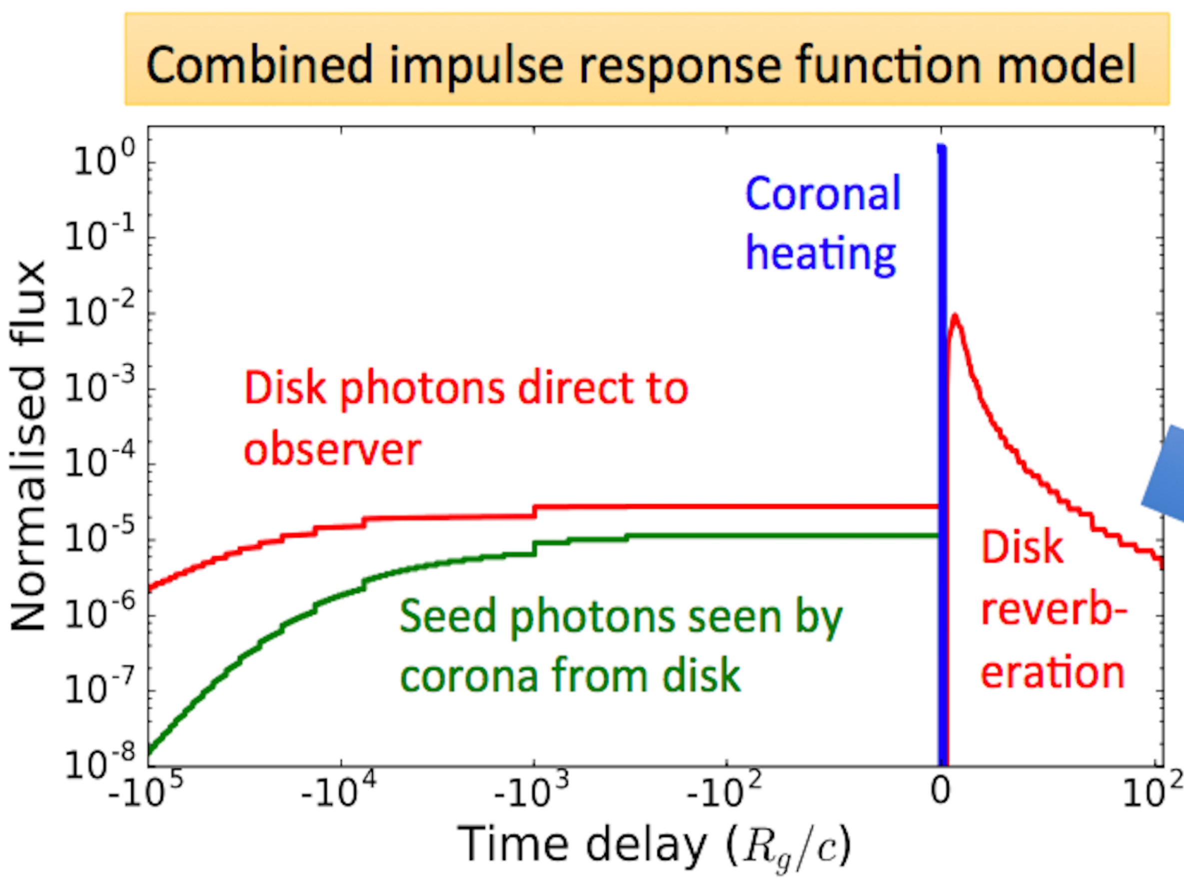


$$\Gamma \propto \left(\frac{L_{\rm seed}}{L_{\rm heat}}\right)^{1/6}$$

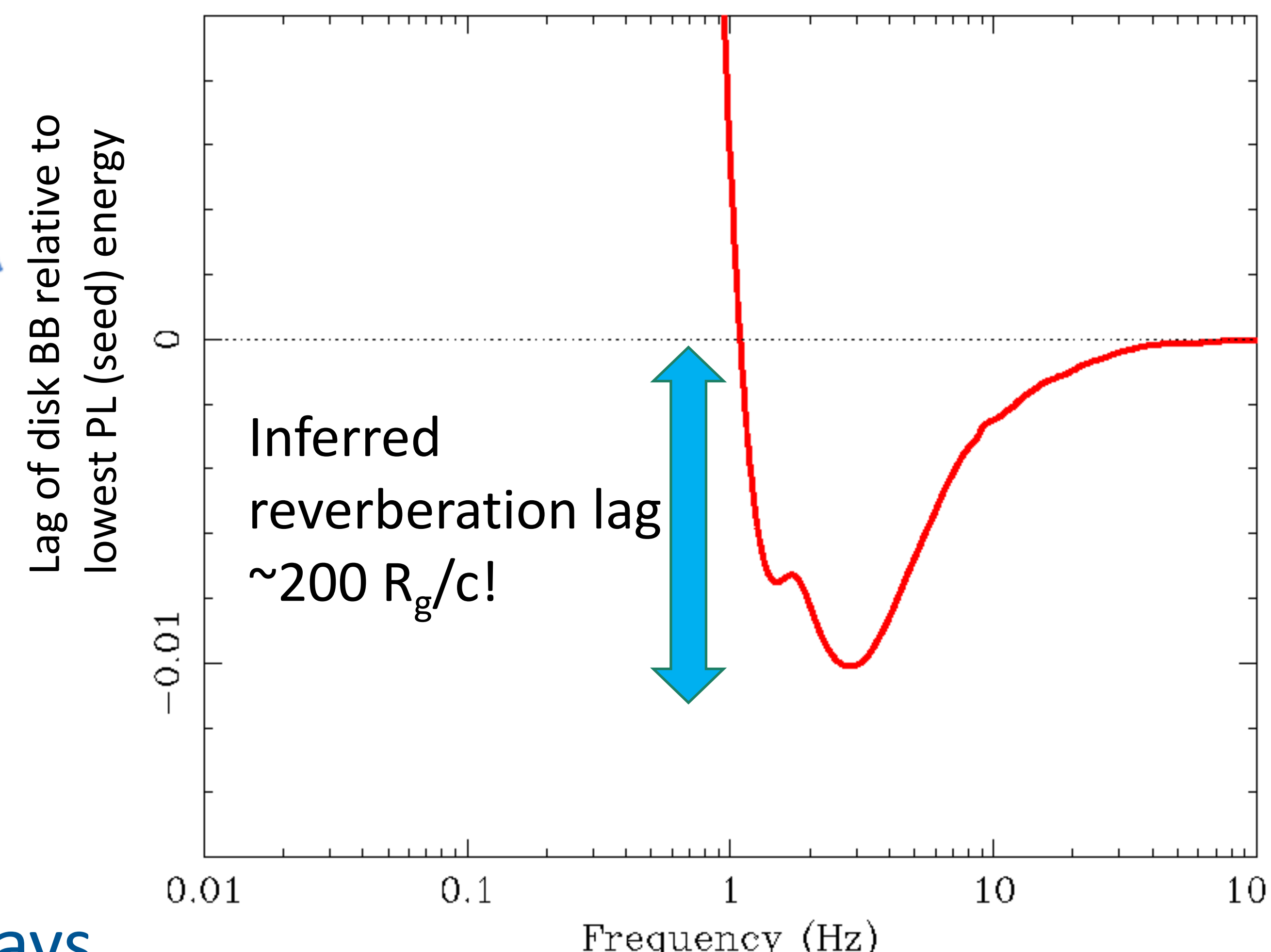


(Uttley & Malzac in prep.)

Interpreting the thermal reverberation lags



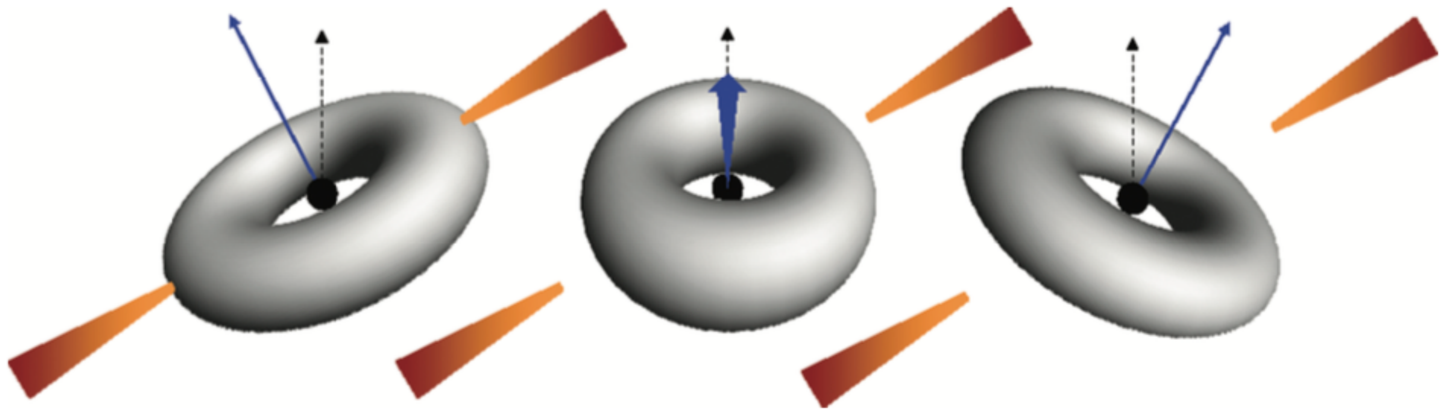
Assuming ***zero intrinsic reverberation lag*** relative to coronal heating:

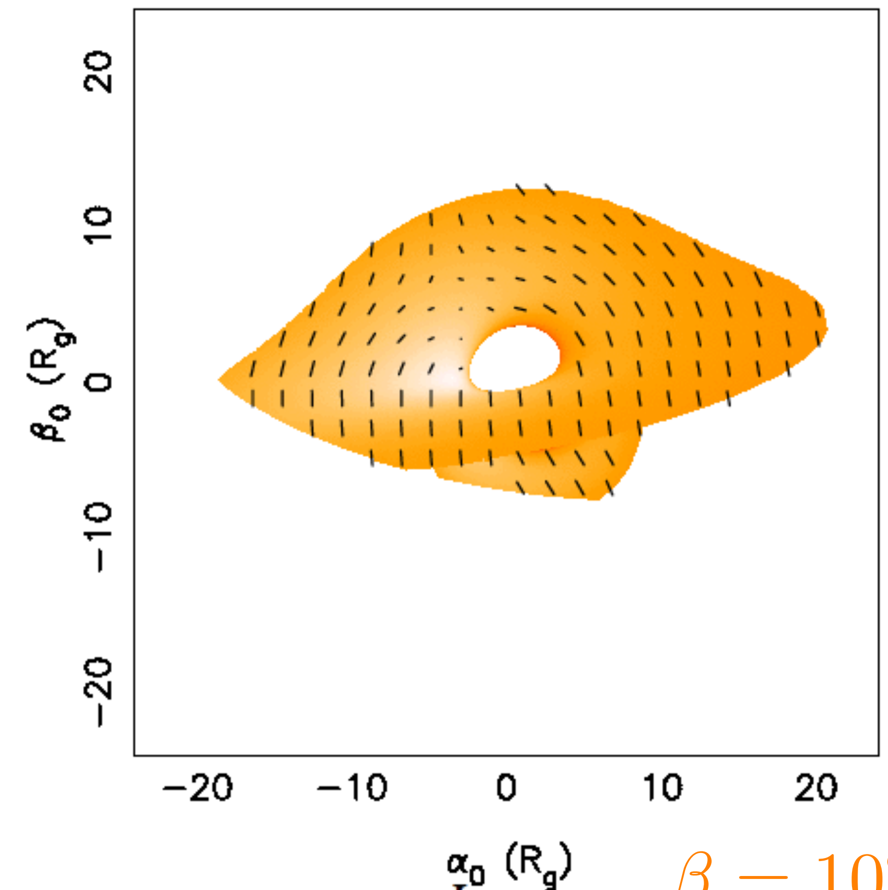


The thermal reverberation lags are relative to seed rather than coronal heating – depend on propagation delays ***and coronal geometry***, not just light-travel time.

(Uttley & Malzac in prep.)

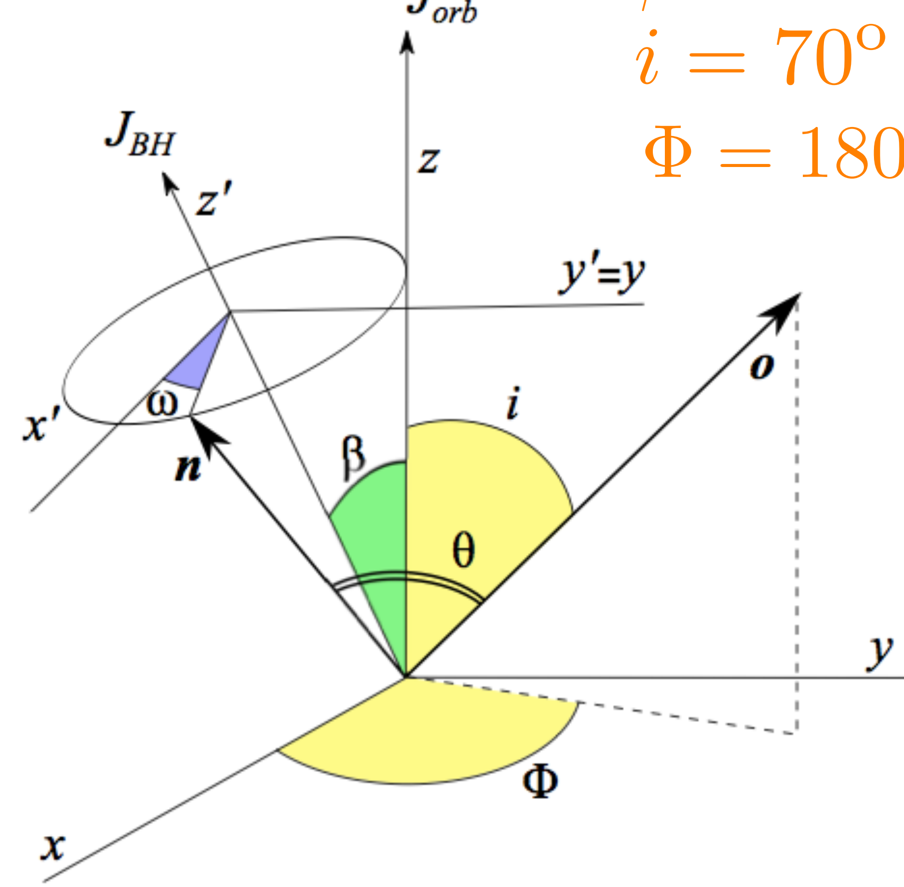
QPO model: precessing hot flow





- Lense-Thirring Precession of the hot inner accretion flow. The flow precesses like a solid body if H/R > alpha.
- Modulation due to relativistic light bending and Compton anisotropy
- QPO rms amplitude up to ~10 %,
- Predict precession frequencies in observed range with little spin dependence
- Modulation of polarisation angle and amplitude predicted

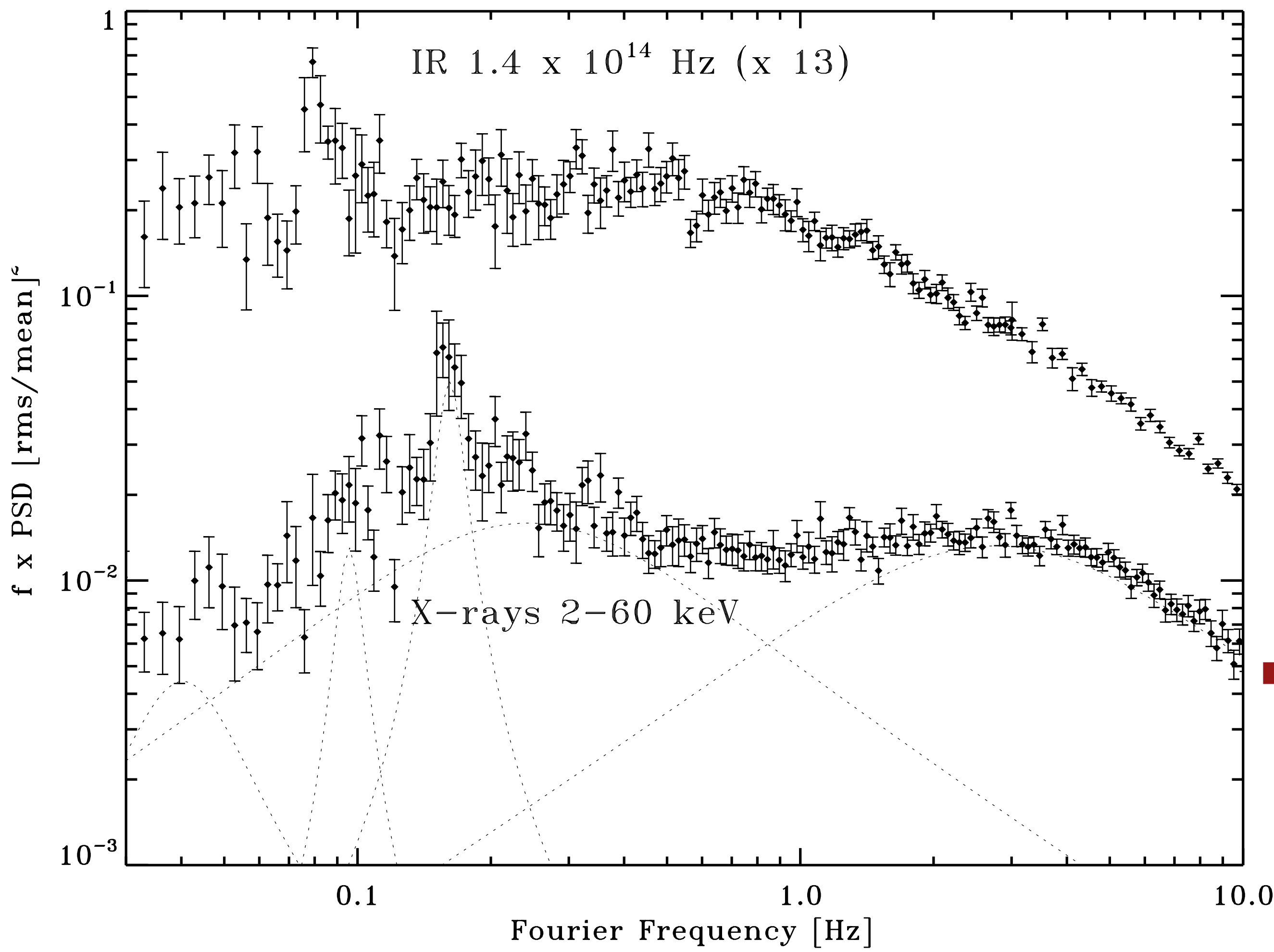
$\beta = 10^o$
$i = 70^o$
$\Phi = 180^o$



Stella & Vieri 2014, Fragile et al. 2007 , Ingram et al. 2009, 2015, 2016; Zycki et al 2016…

QPOs also in optical and infrared

The case of the IR QPO of GX 339-4



- Simultaneous IR / X timing data with VLT/ISAAC and RXTE (Kalamkar et al. 2016)
- IR QPO @ ~0.08 Hz
  X-ray QPO @ ~0.16 Hz

➡ **Main X-ray QPO and IR QPO frequencies are different but in harmonic**

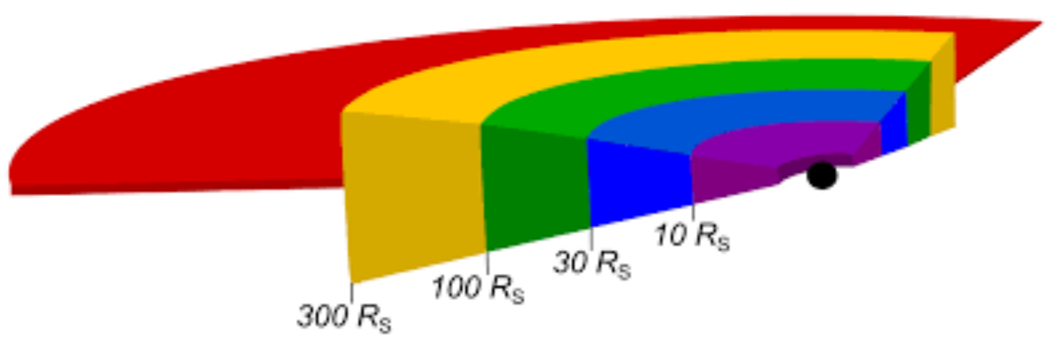
- Precession model: Depending on hot flow geometry, orbital inclination and precession angle, X-ray QPO can be dominated by second harmonic.

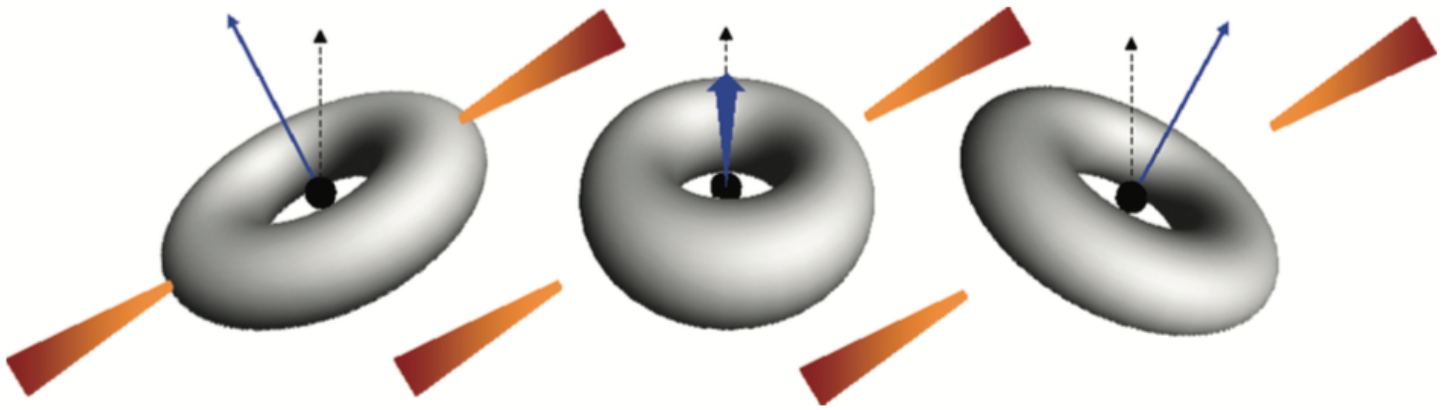
Veledina et al. 2013

Nature of OIR QPOs

- Synchrotron from non-thermal particles in the same precessing hot flow that produces the X-ray QPO.

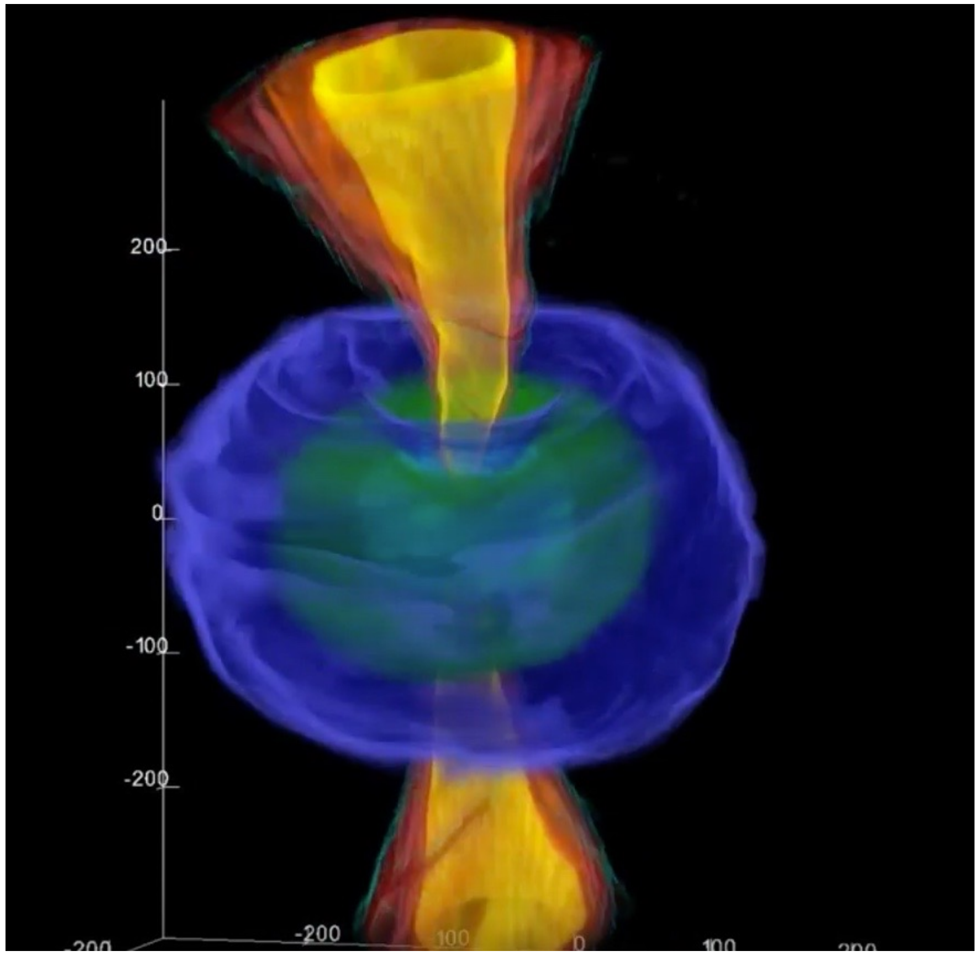
Veledina et al. 2013





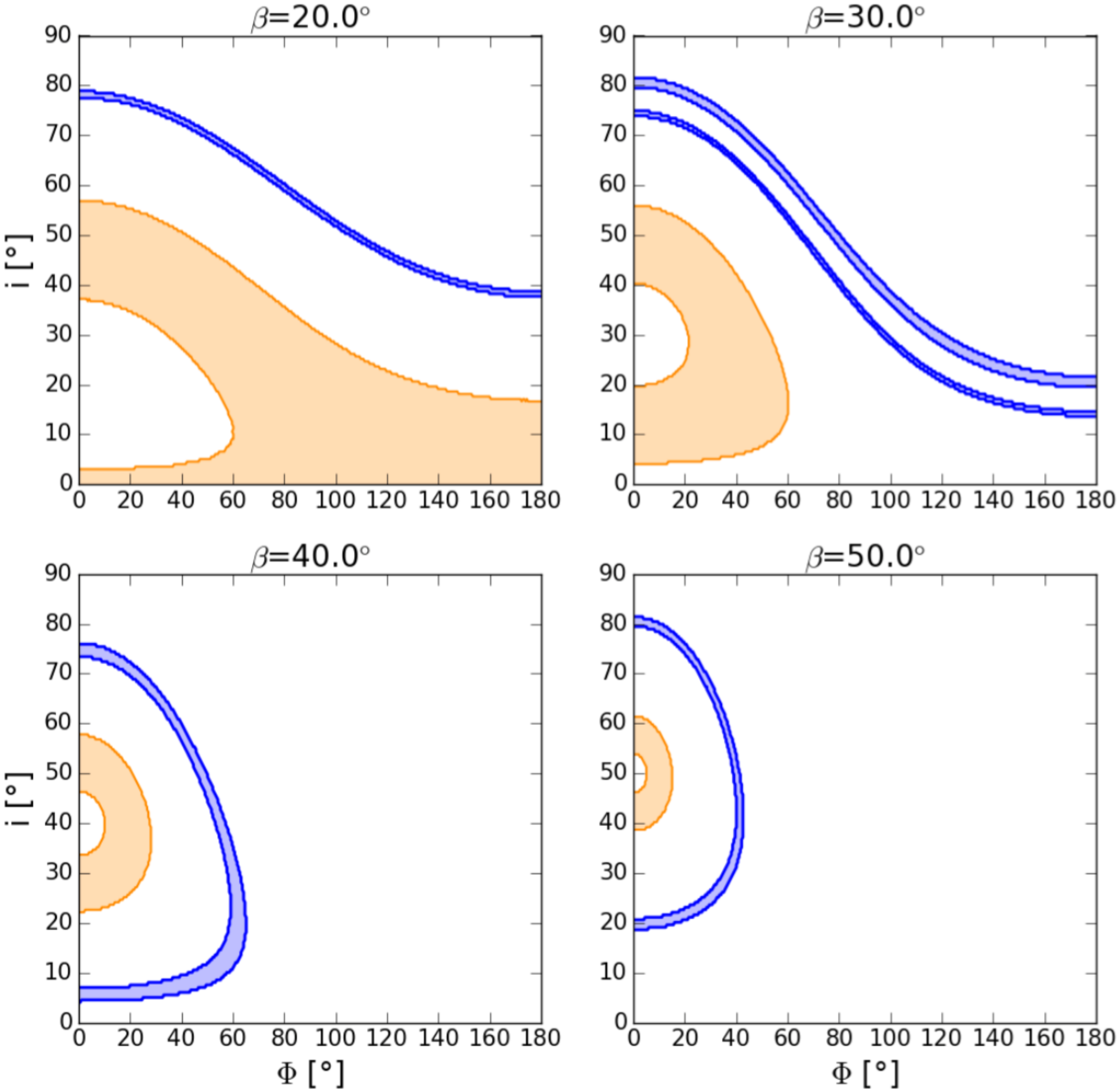
- Synchrotron emission from precessing jet.

Kalamkar et al. 2016; Malzac et al. 2018



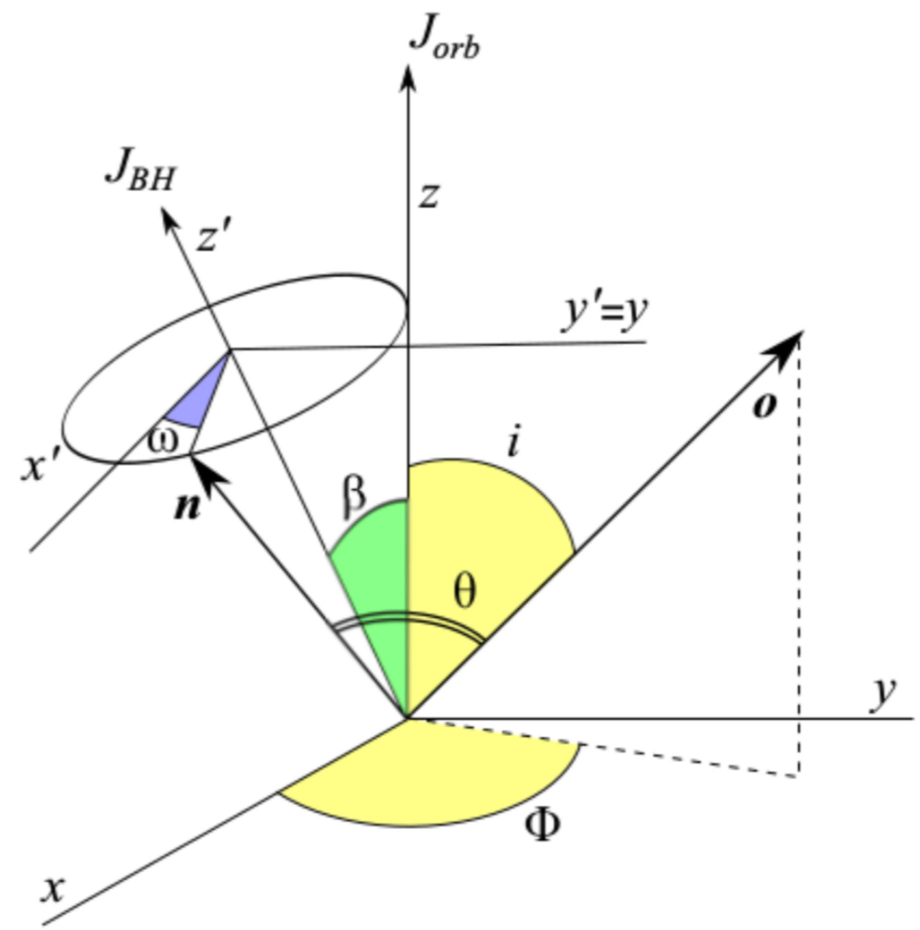
Liska et al. 2018

The case of GX 339-4:
Combining X-ray and IR QPO information



Assuming X-ray and IR emission are both from hot accretion flow

Calculations based on precessing hot-flow model by Veledina et al. 2013



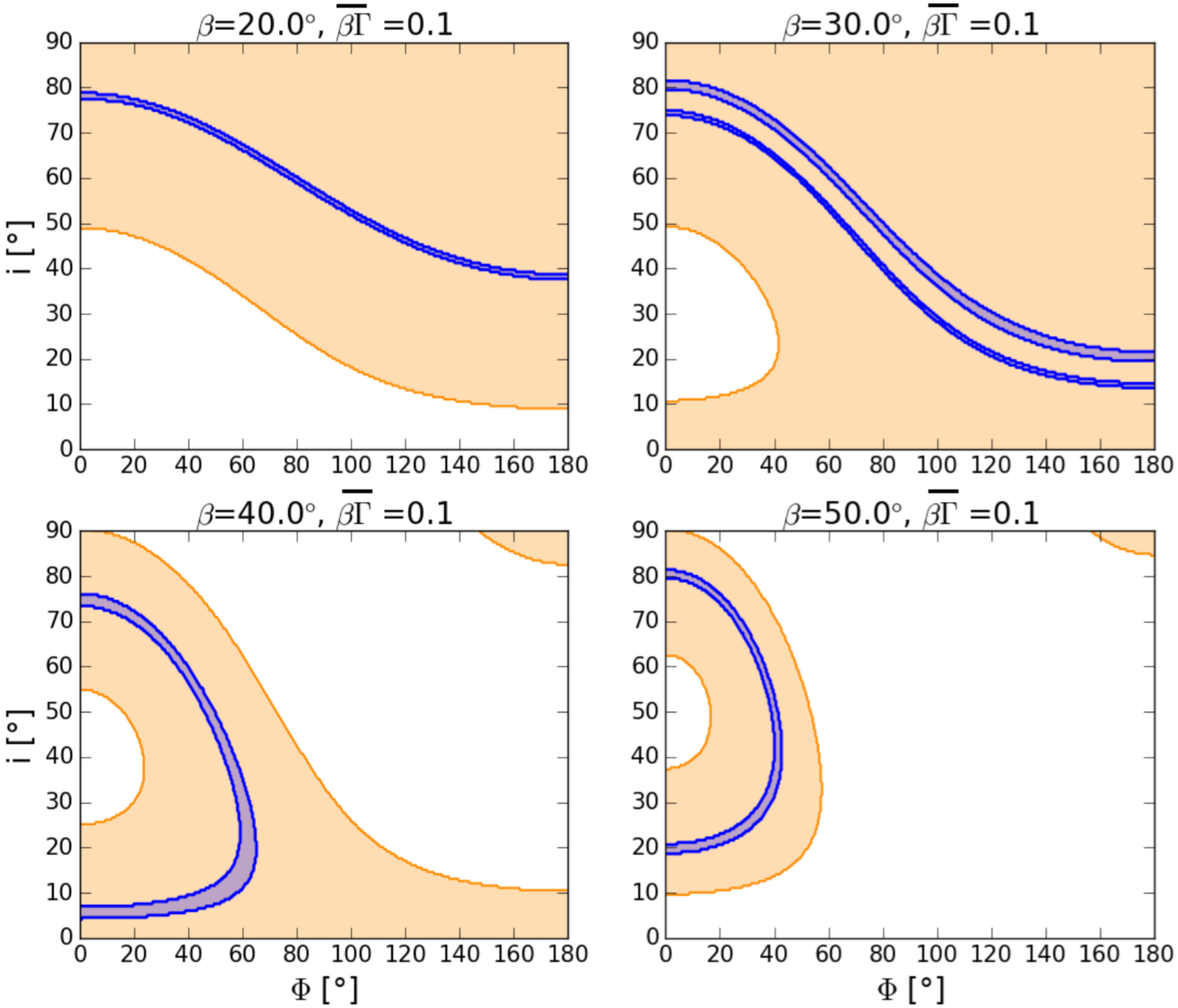
— **Amplitude of both fundamental AND harmonic of X-ray QPOs**

— **Amplitude of IR QPO reproduced by IR synchrotron emission from hot flow**

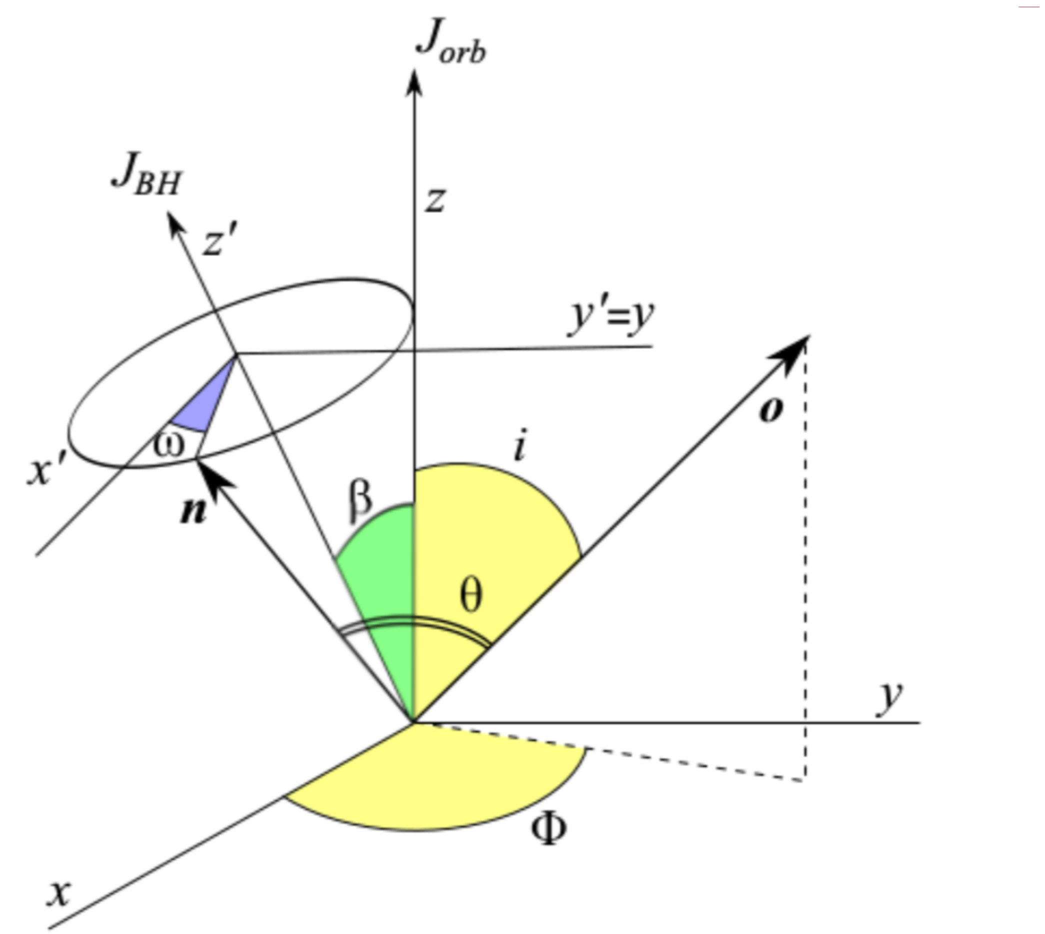
➡ **IR and X-ray QPO amplitudes cannot be reproduced simultaneously**

Boughelilba, Master Thesis

The case of GX 339-4:
Combining X-ray and IR QPO information



Assuming X-ray QPO from hot flow
IR QPO from jet precession



— Amplitude of both fundamental AND harmonic of X-ray QPOs produced

— Amplitude of IR QPO produced by IR synchrotron emission from JET

➡ **both IR and X-ray QPOs amplitudes can be reproduced**

➡ **Jet velocity must be < 0.16 c**

Boughelilba's Master Thesis

Conclusions

- Because accreting black holes in X-ray binaries are bright and strongly variable they constitute a unique laboratory to study relativistic accretion

- The combined use of
  - multi-wavelength observations,
  - spectral,
  - timing,
  - and polarization techniques,

  can disentangle the intricacies of accretion onto a black hole.

- The truncated disc scenario can explain many of the observed spectral, timing and polarization properties. The details need to be worked out. Alternative models must also be explored.

- The future is bright:
  eXTP, IXPE, XRISM, Athena…