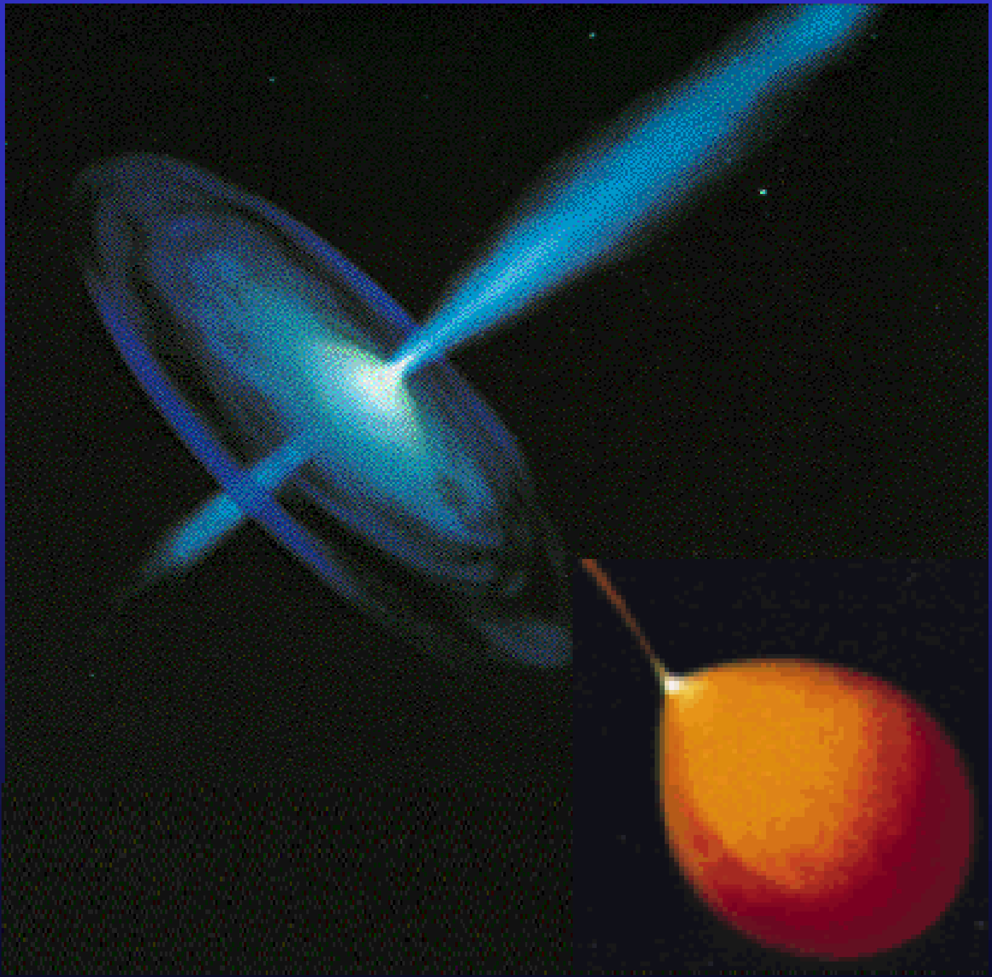
Spectra and variability properties of accretion flows

Chris Done
University of Durham

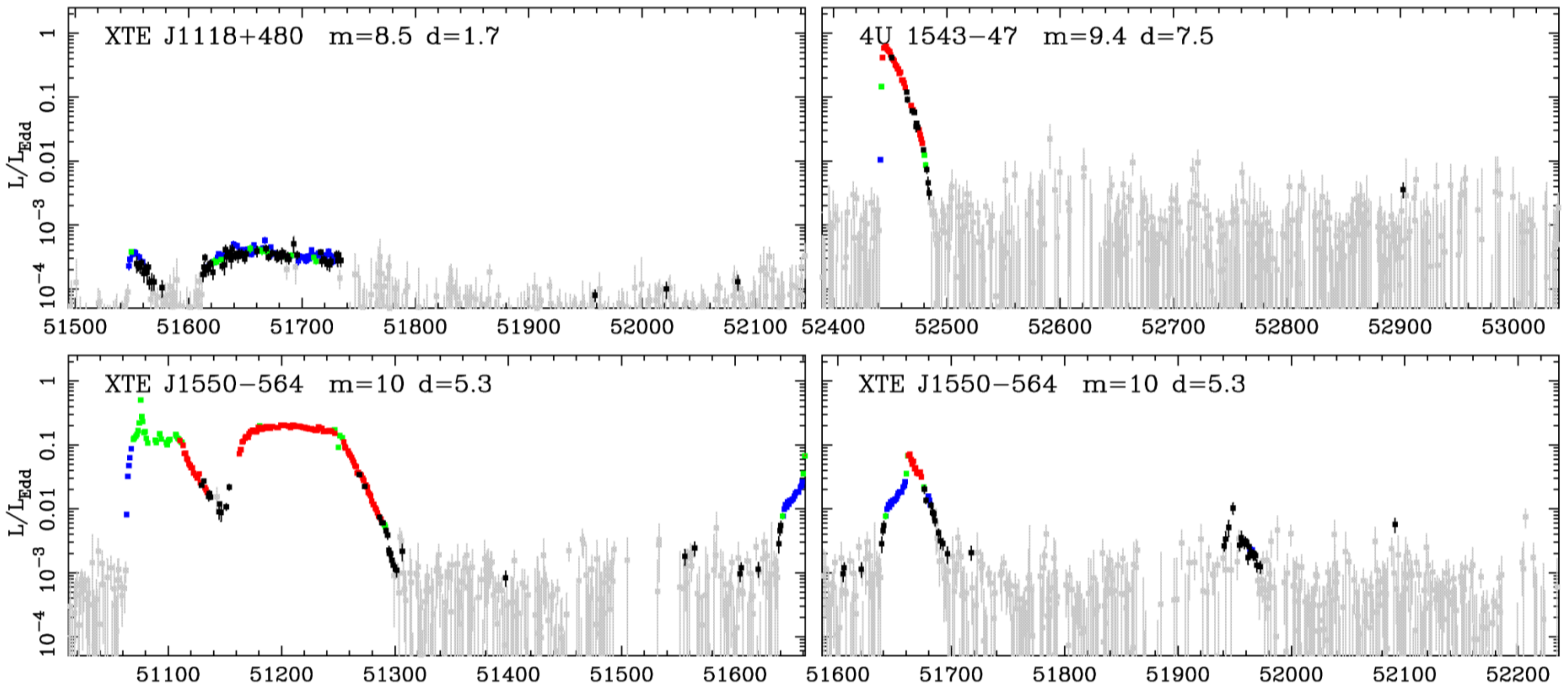
Black holes

- A quick review of black hole spectral states
- Nature of the low/hard state
- Truncated disc/hot inner flow to explain spectra
- Supported by quantatitve model for the low frequency QPO and broadband variability (Adam Ingram and Chris Fragile)



Transients

- Huge amounts of data, long term variability (days –years) in mass accretion rate (due to H ionisation instability in disc)
- Observational template of accretion flow as a function of L/L_{Edd} onto ~10 $M_\odot$ BH (very homogeneous!)

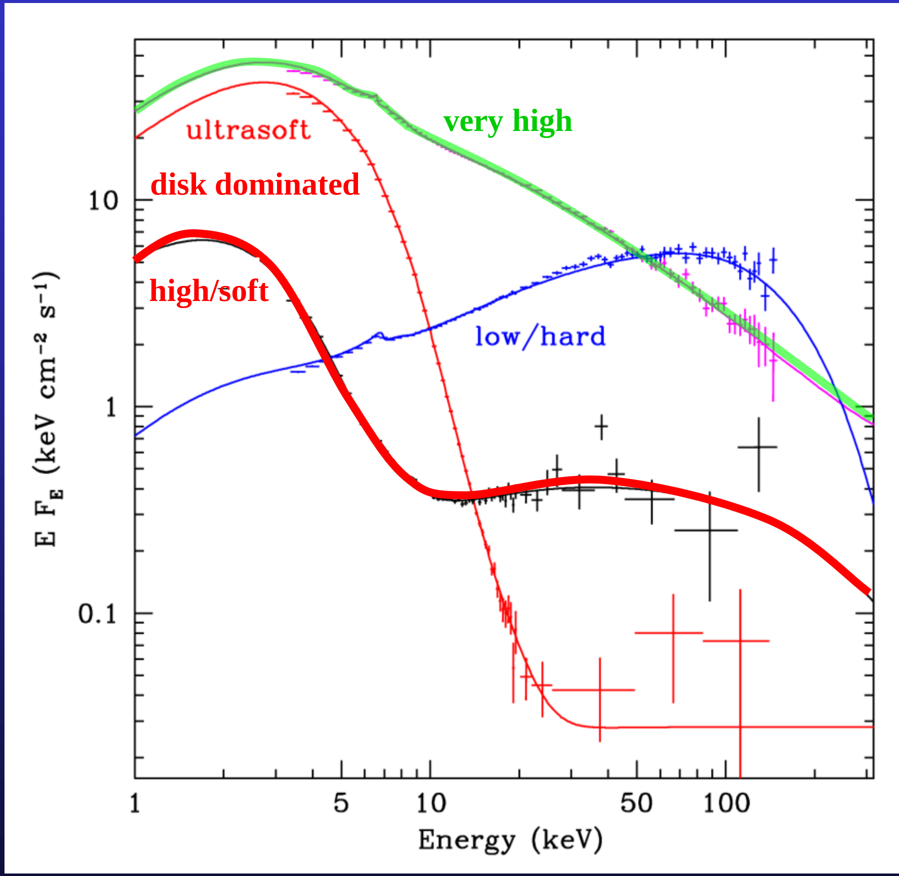


2 years

DGK07

Spectral states

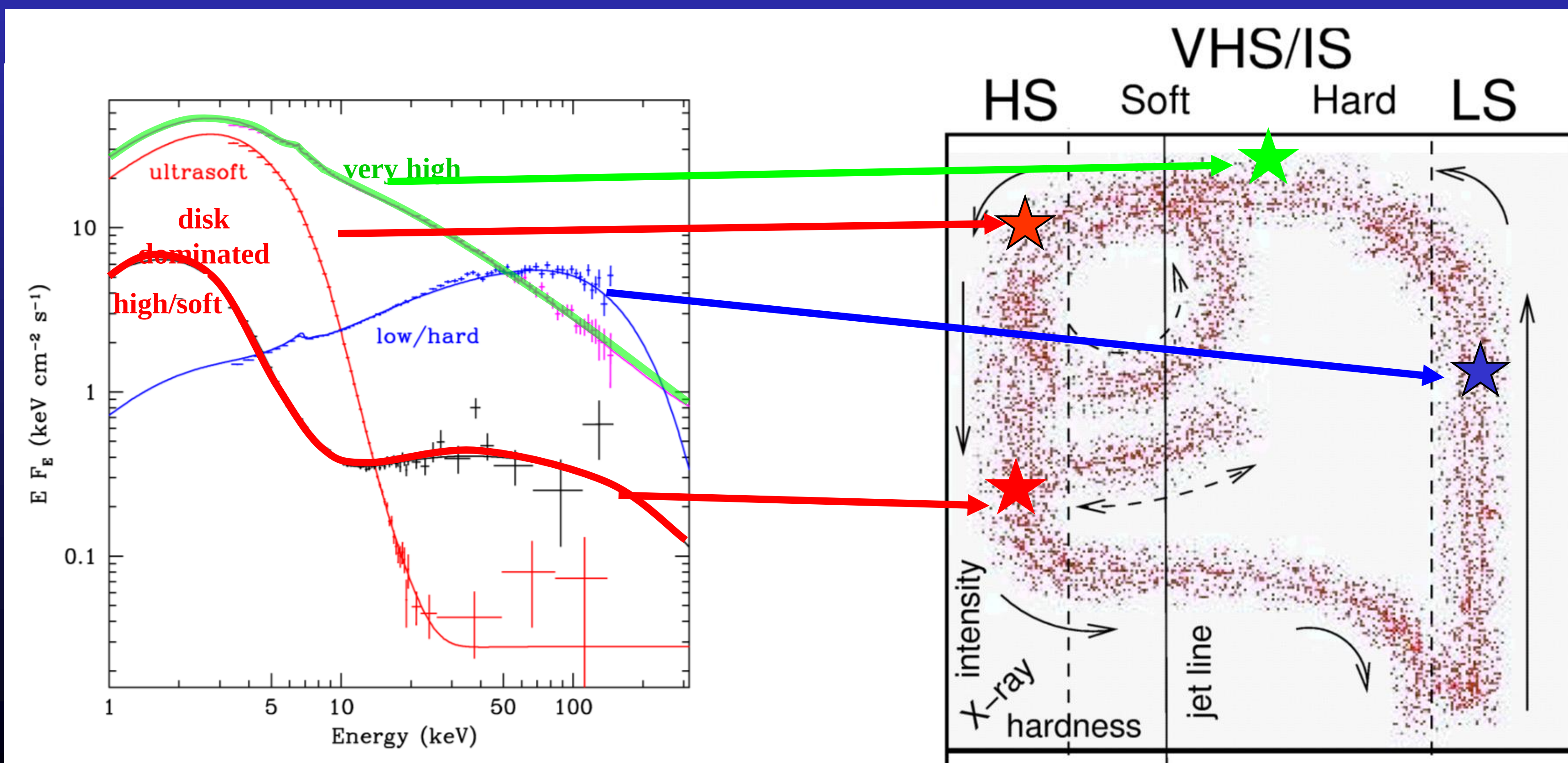
- Dramatic changes in continuum – single object, different days
- Underlying pattern in all systems
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail
- Lower L/L_{Edd}: hard spectrum, peaks at high energies, not like a disc (McClintock & Remillard 2006)



Gierlinski & Done 2003

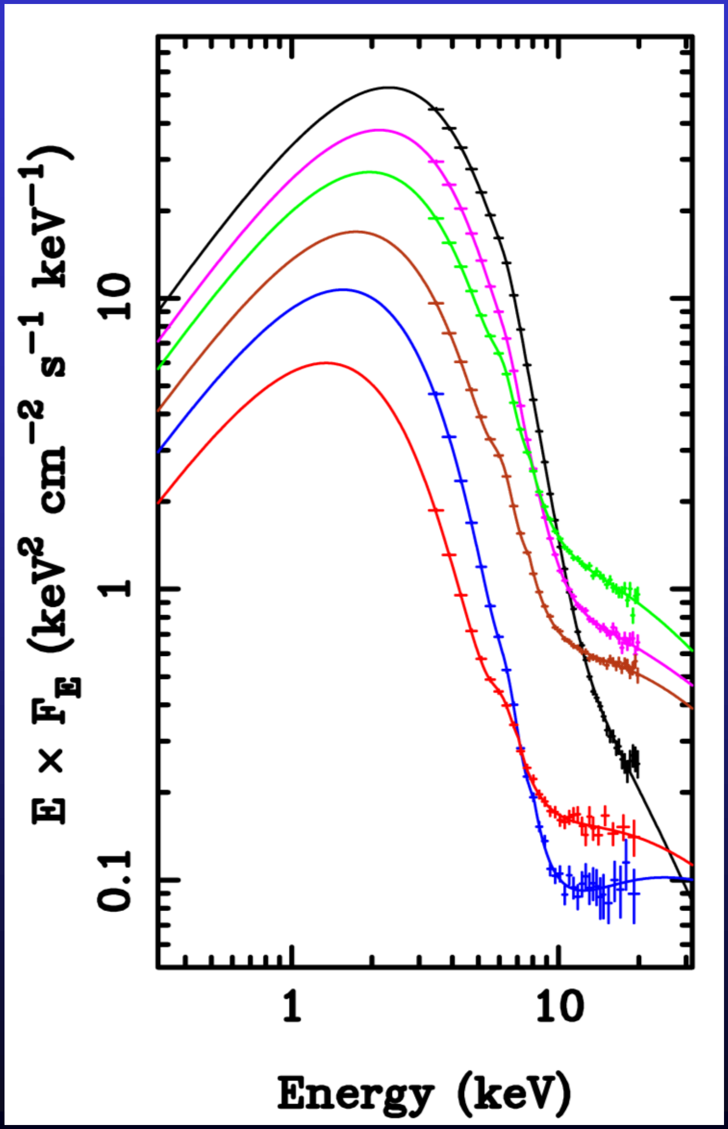
Hardness – intensity diagram

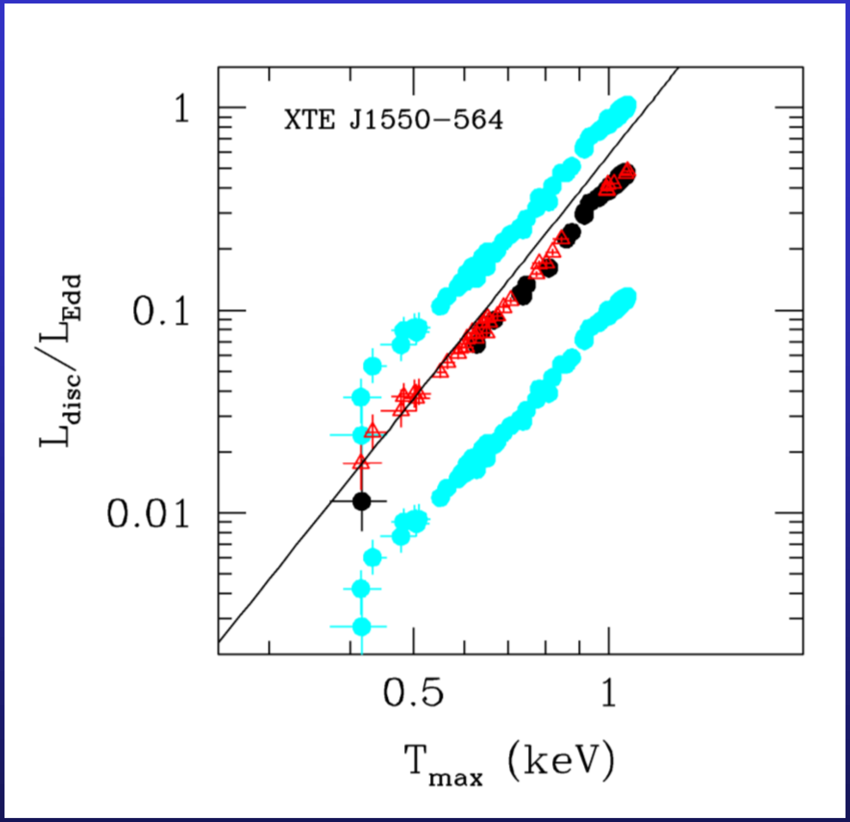
- Outburst starts hard, source stays hard as source brightens
- Then softens to intermediate/very high state/steep power law state major hard-soft state transition
- Then disc dominated, then hardens to make transition back to low/hard state – hysteresis as generally at lower L



Fender Belloni & Gallo 2004

Variability of disc:long timescale

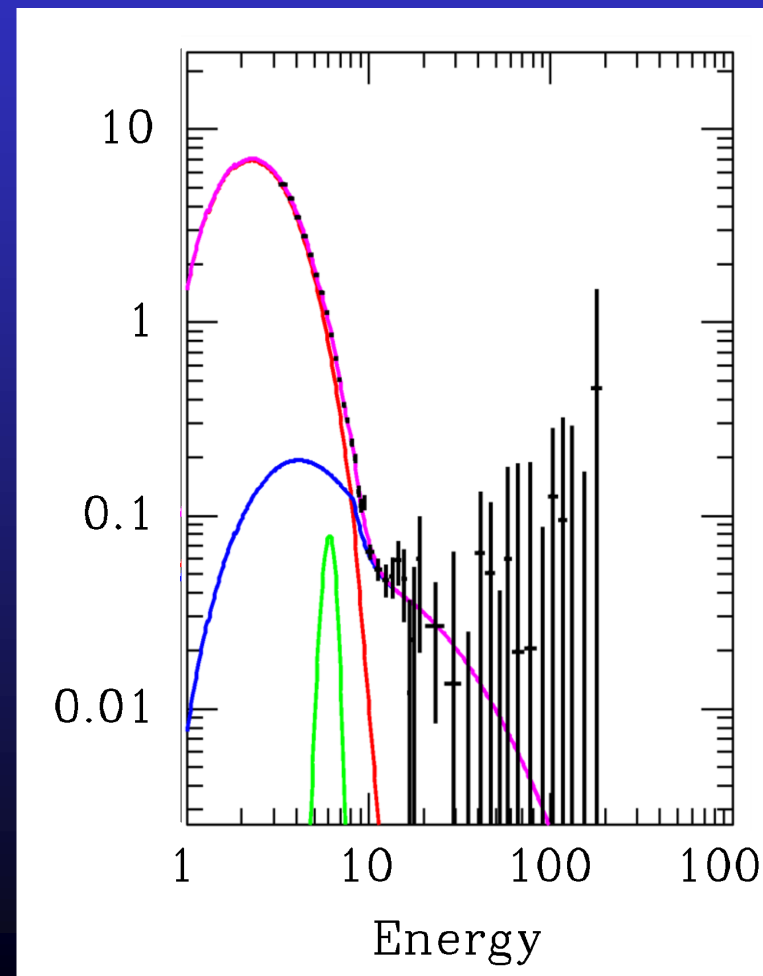


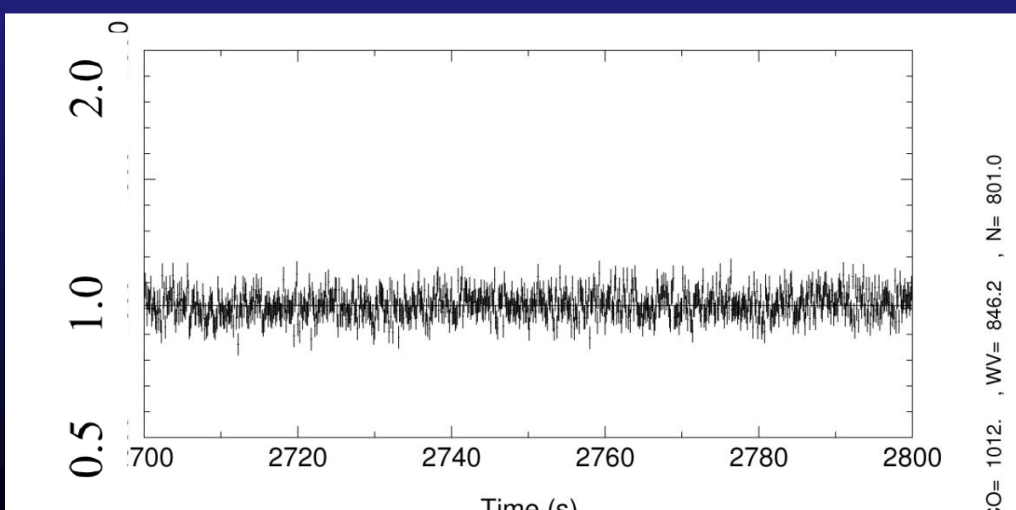


- $L/L_{Edd} \propto AT^4_{max}$ (Ebisawa et al 1993; Kubota et al 1999; 2001)
- Constant size scale – last stable orbit!! BH spin

Variability of disc:short timescale

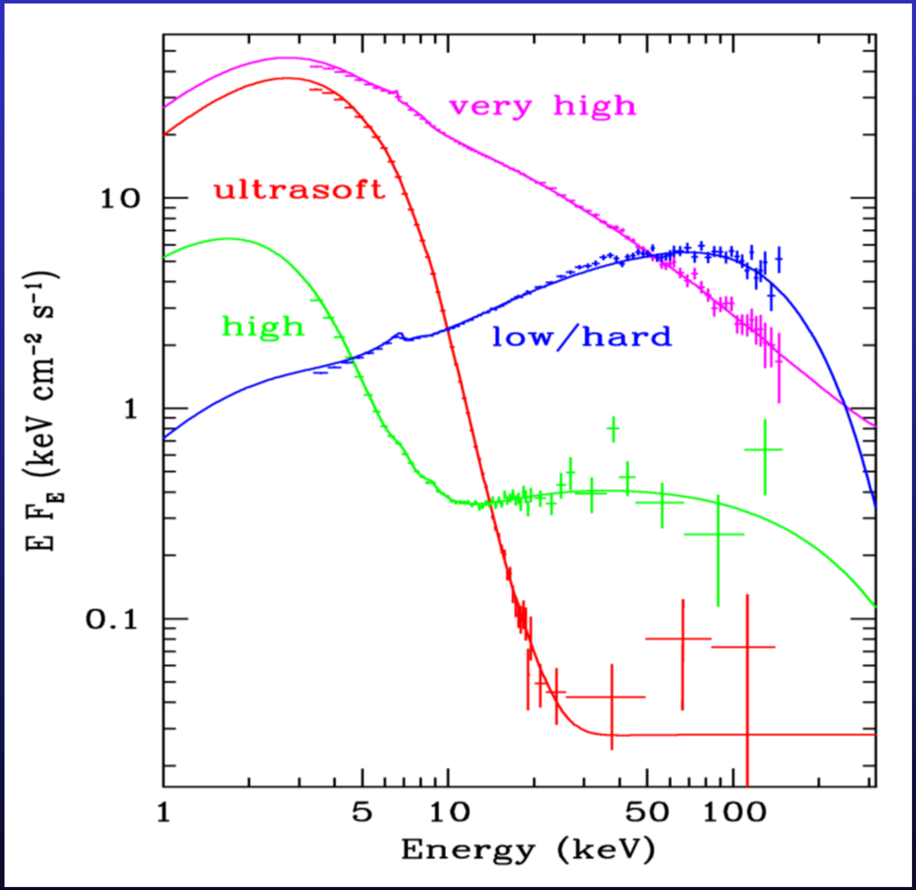
- Accretion rate through disc changes on timescales of days
- tvisc= α^{-1} (H/R)$^{-2}$ tdyn = 5 α^{-1} (H/R)$^{-2}$ (r/6) $^{-3/2}$ ms ~ 500s even at last stable orbit for 10M BH
- No rapid variability of disc in disc dominated states!





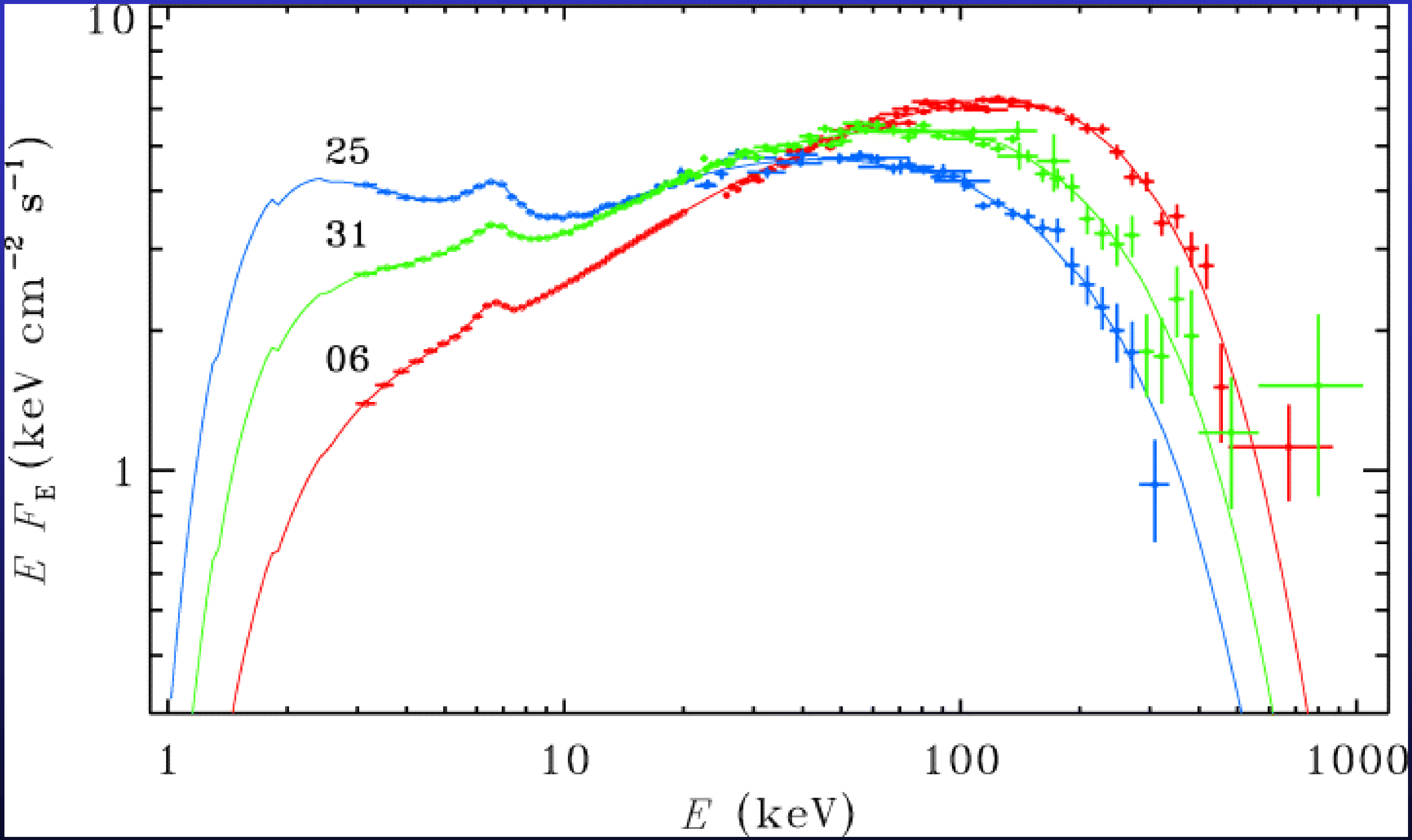
But what about the rest??

- Disc dominated look like a disc and vary like a disc on both long (L-T^4) and short (nothing) timescales
- Very high at least knows something about a disc
- Low/hard state look really different, not at all like a disc!



Gierlinski & Done 2003

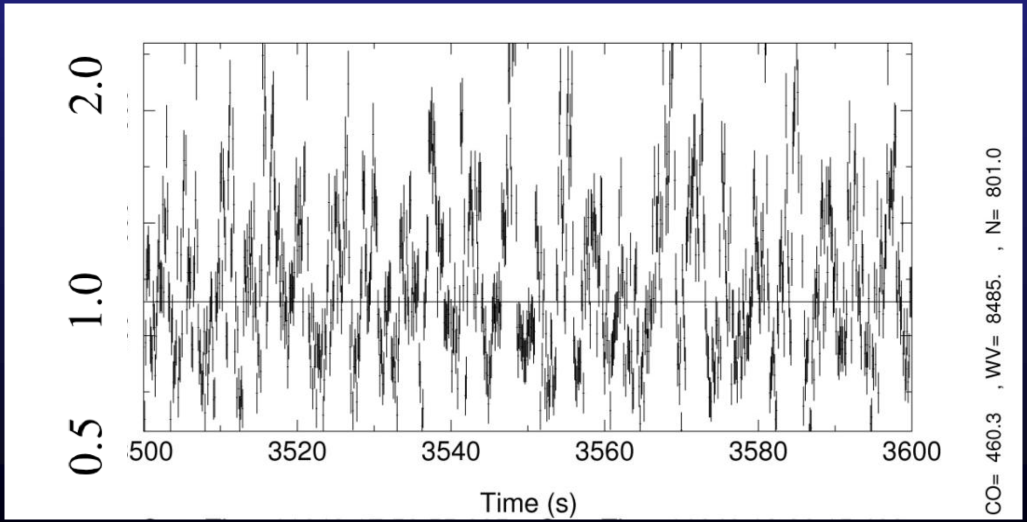
But what about the rest? Low/hard state

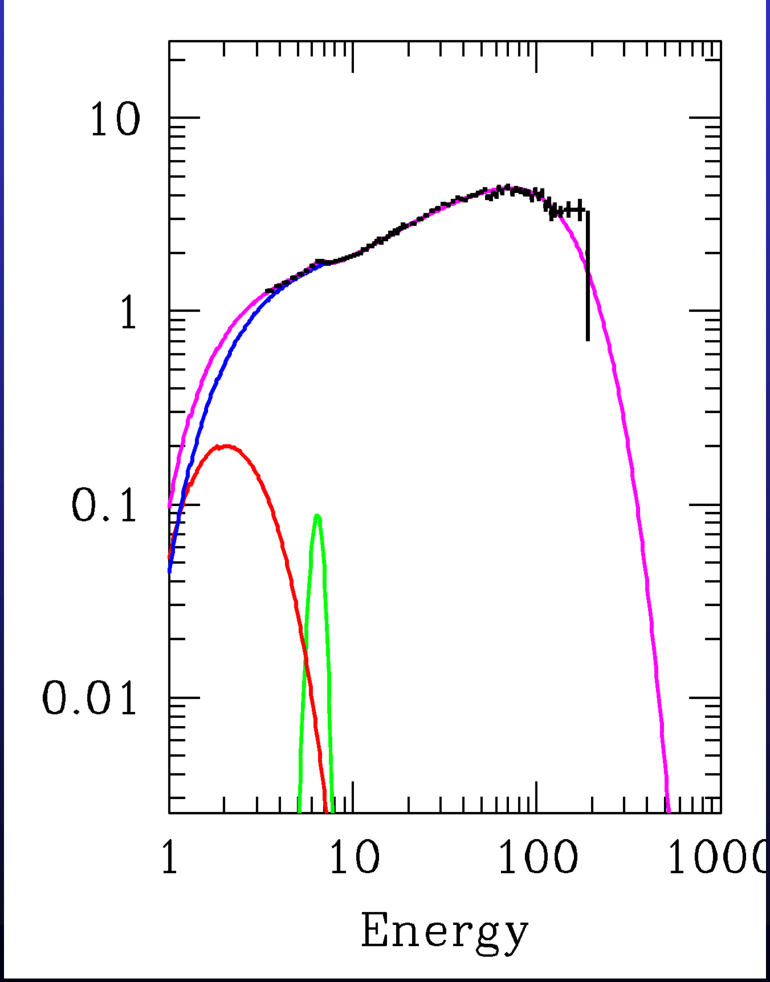


Ibragimov et al 2005

Low/hard state variability

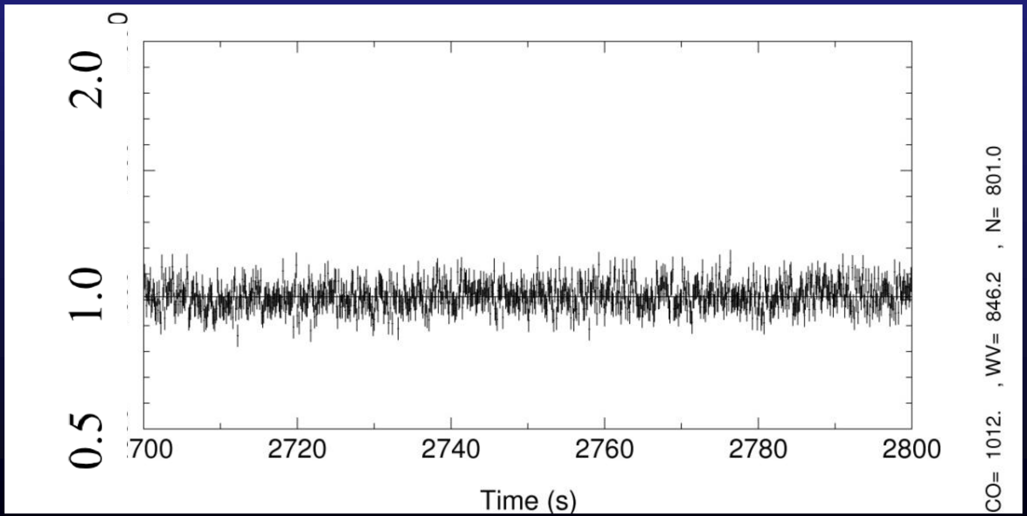
- Hard X-rays show much more dramatic change on short timescales down to few ms
- tvisc= α^{-1} (H/R)$^{-2}$ tdyn = 5 α^{-1} (H/R)$^{-2}$ (r/6) $^{-3/2}$ ms
- IF viscous timescale then H/R~1

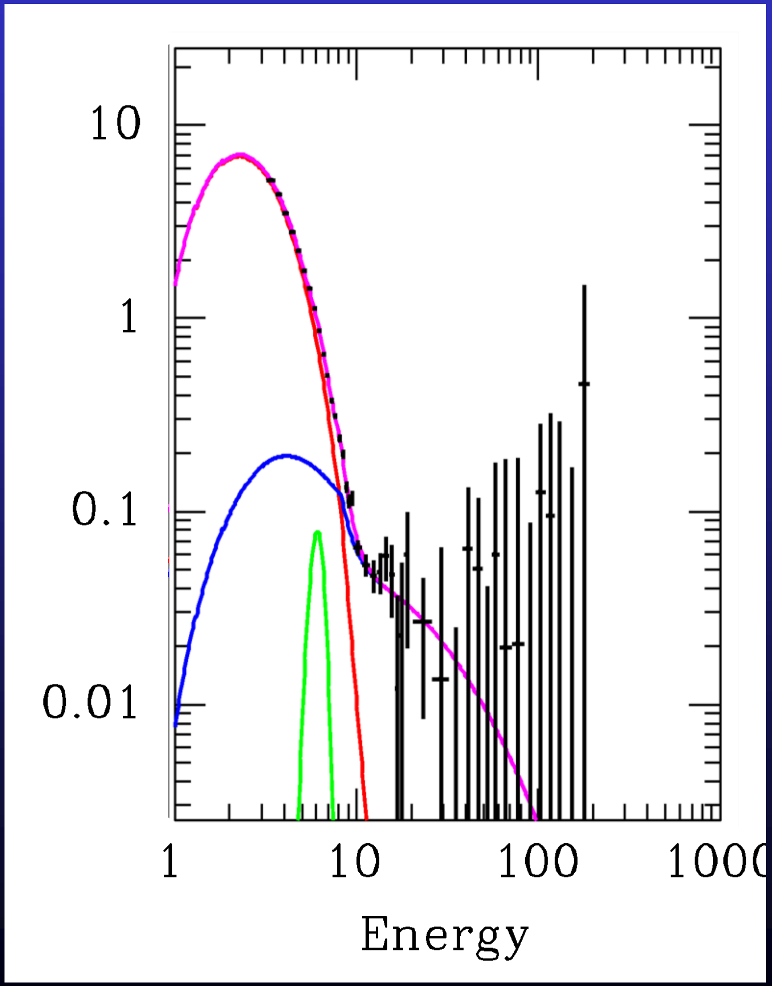




Observed disc variability

- Accretion rate through disc changes on timescales of days
- tvisc= α^{-1} $(H/R)^{-2}$ tdyn = 5 α^{-1} $(H/R)^{-2}$ $(r/6)^{-3/2}$ ms ~ 500s even at
- But low/hard compton tail very variable on short timescales (0.05s)
- If viscous timescale then H/R~1





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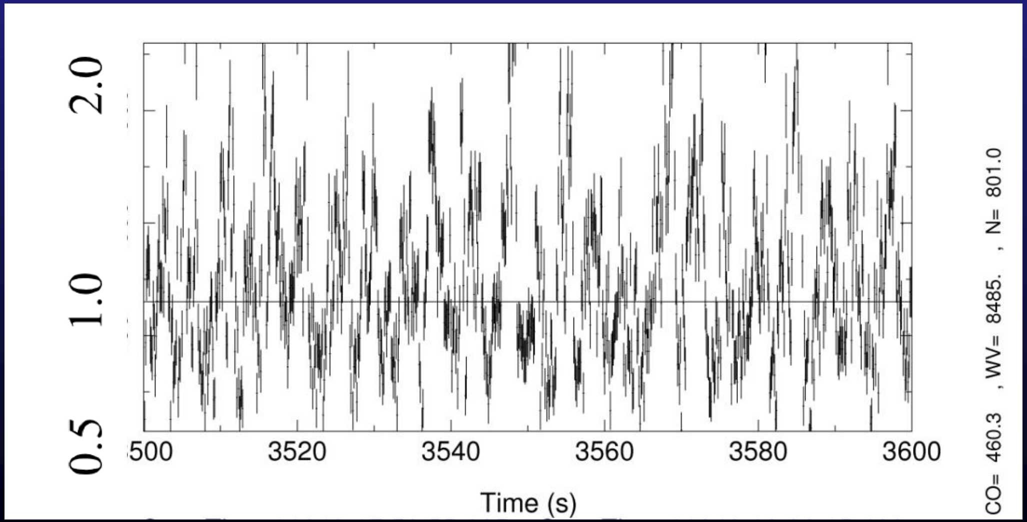
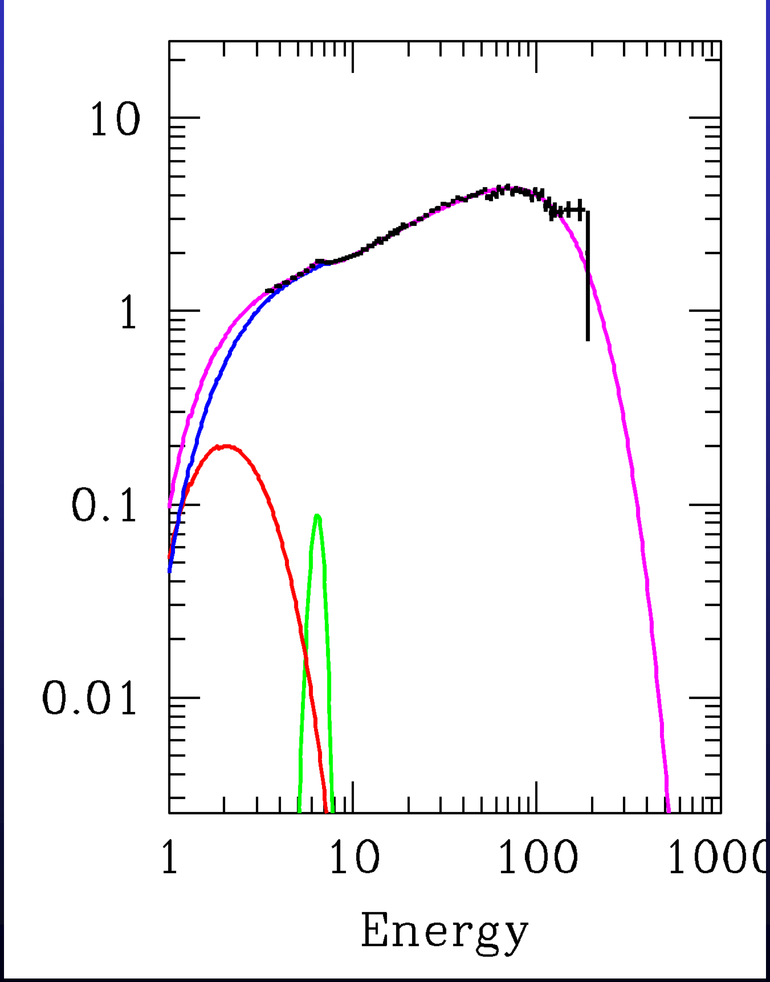
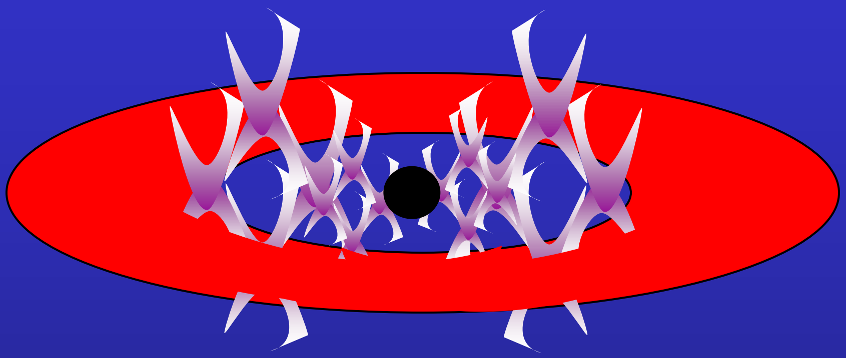
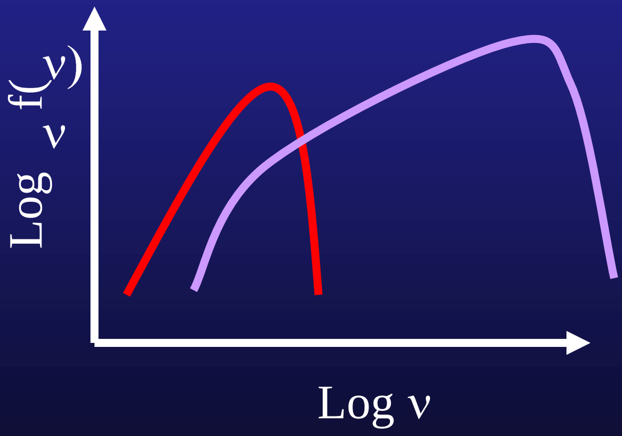




Accretion flows without discs

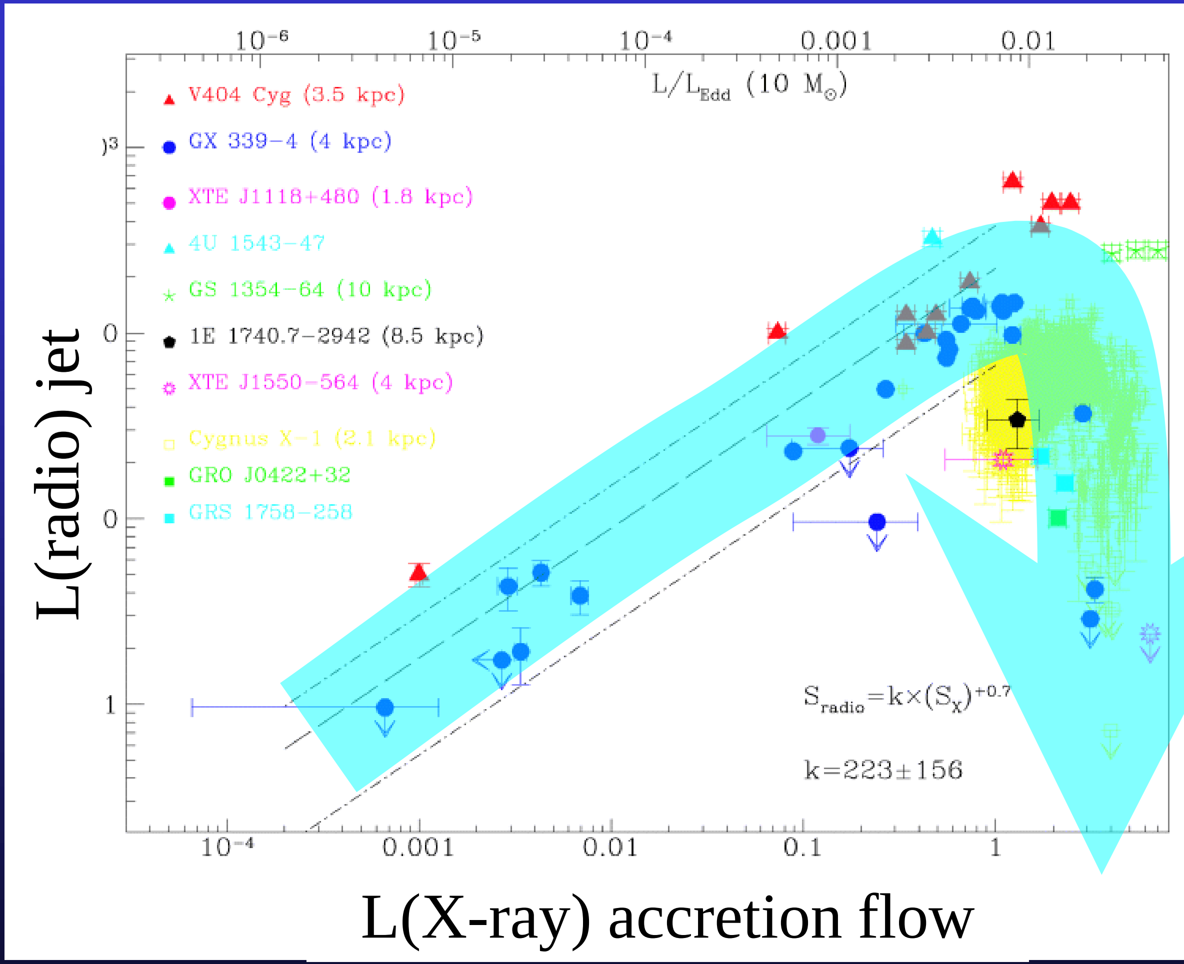
- Disc models assumed thermal plasma – not true at low L/L_{Edd}
- Instead: hot, optically thin, geometrically thick inner flow replacing the inner disc (Shapiro et al. 1976; Narayan & Yi 1995)
- Hot electrons Compton upscatter photons from outer cool disc
- Few seed photons, so spectrum is hard
- Jet from large scale height flow





And the radio jet… link to spin?

- No special μQSO class – they ALL produce jets, consistent with same radio/X ray evolution
- Jet links to spectral state – hard state has steady radio jet which gets brighter as the hard X-rays get brighter
- Then collapses as make transition to disc
- (Fender et al 2004)



Gallo et al 2003

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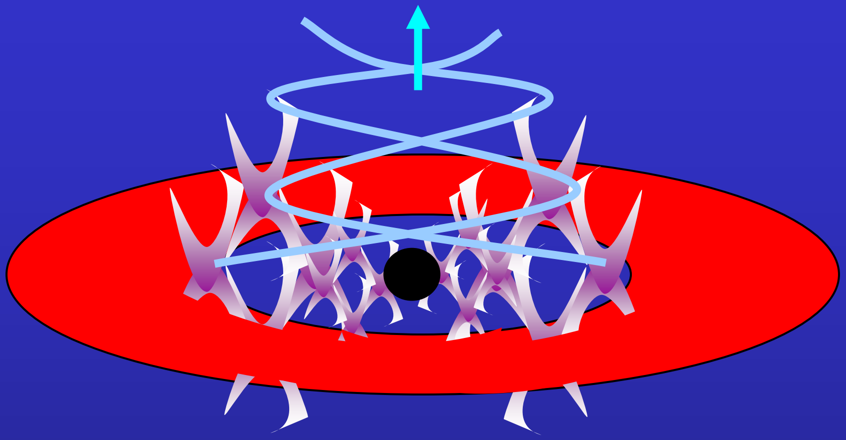
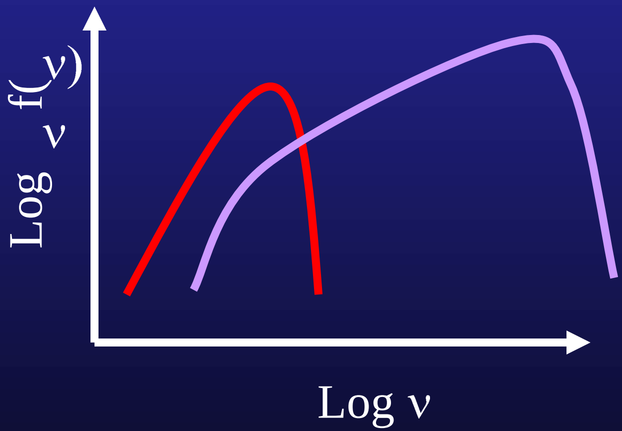
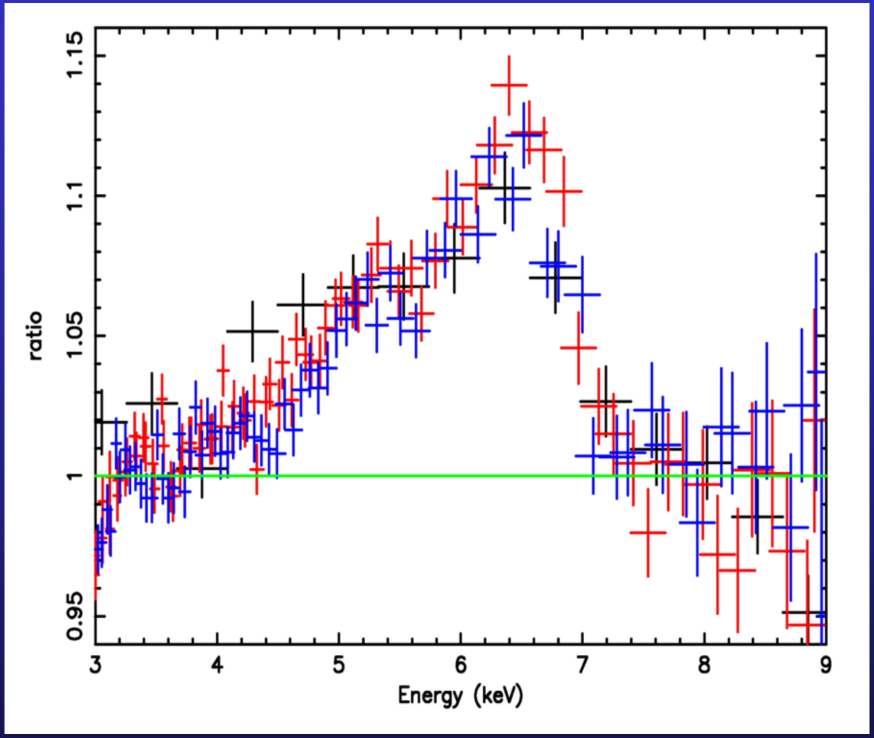




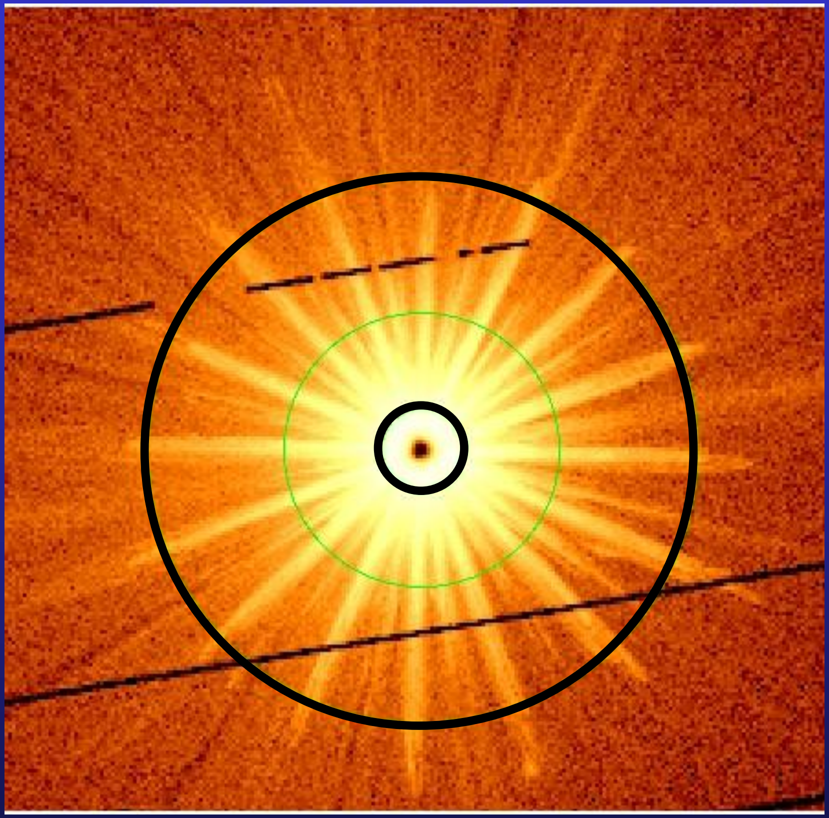
GX339-4 hard state

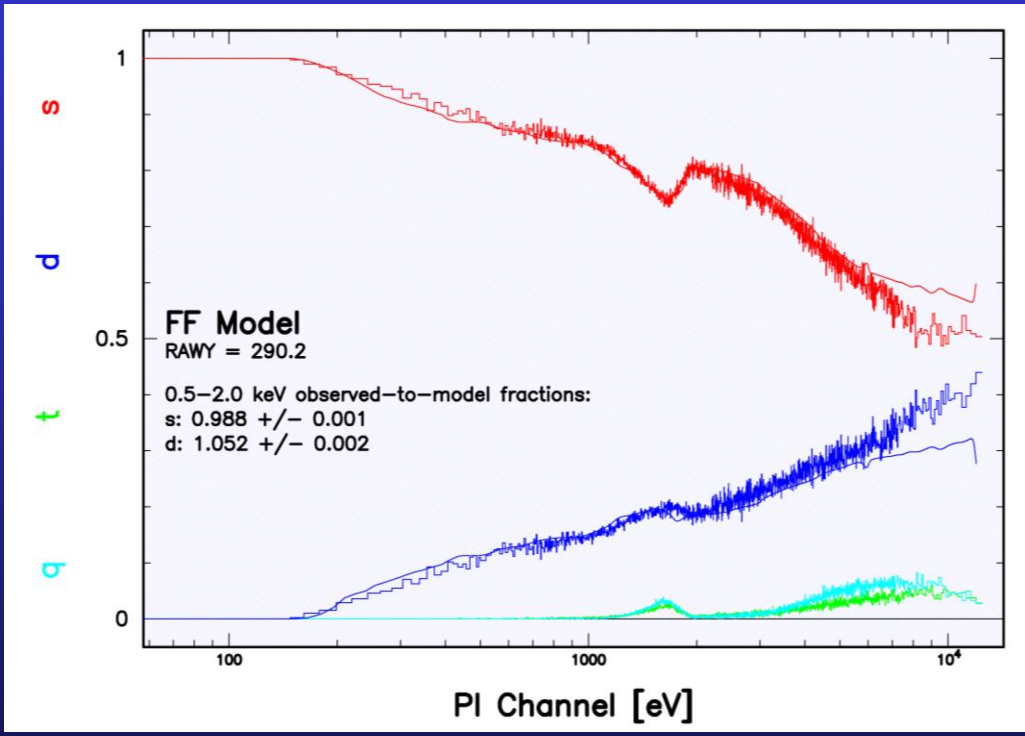
- MOS data from XMM observation is by far the most convincing extreme broad iron line seen in the low/hard state: Miller et al 2006; 2008; Reis et al 2008; 2009; 2010



Miller et al 2006

GX339-4 XMM data

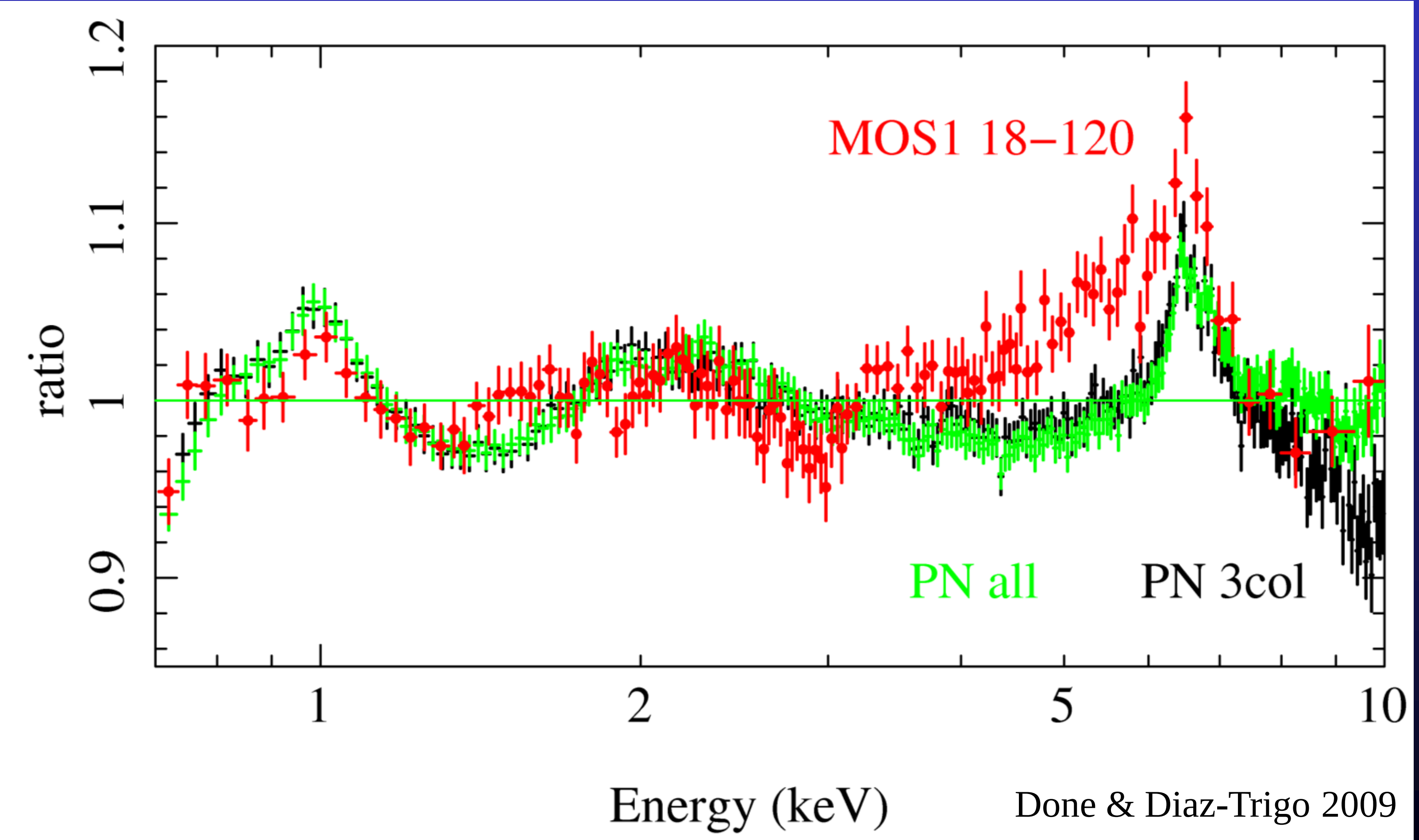




- Flux gives MOS count rate 200x > than pileup limit
- Exclude core. 18-120" singles, data still piled up Done & Diaz-Trigo 2009

Line is much narrower in pn

- Simultaneous PN (timing mode, not piled up) is narrower!
- But timing mode obs. of low/hard state (Reis et al 2010 XTE1752)

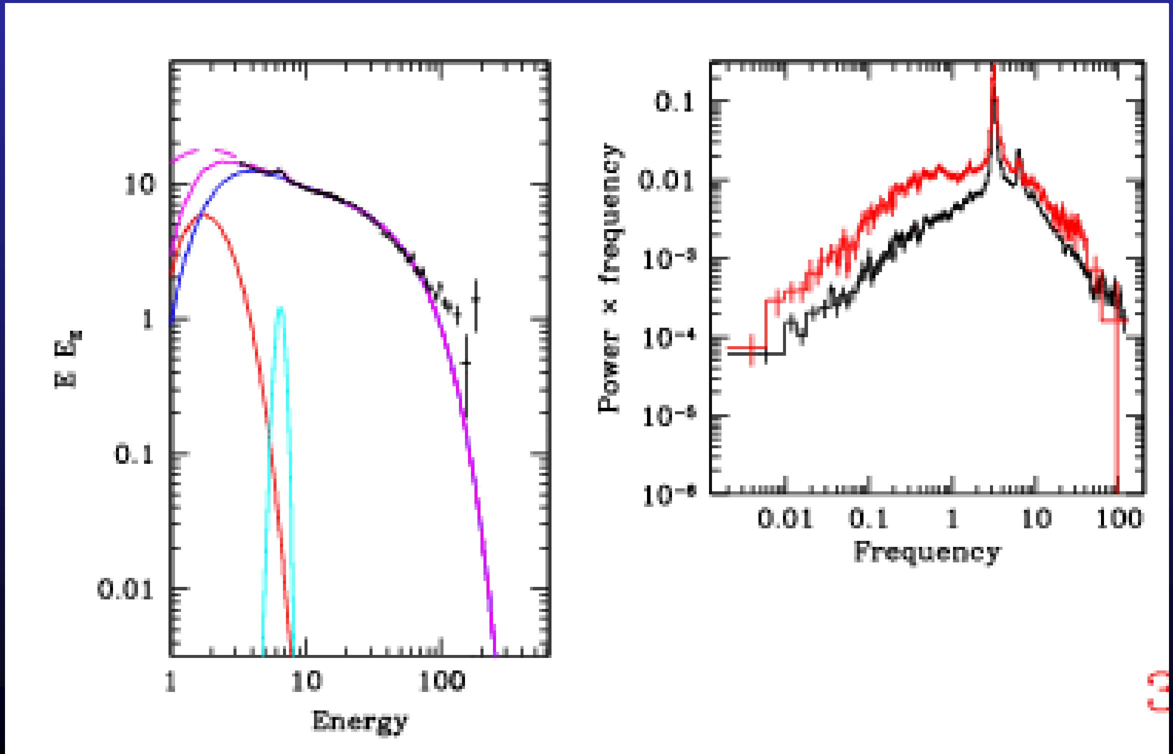


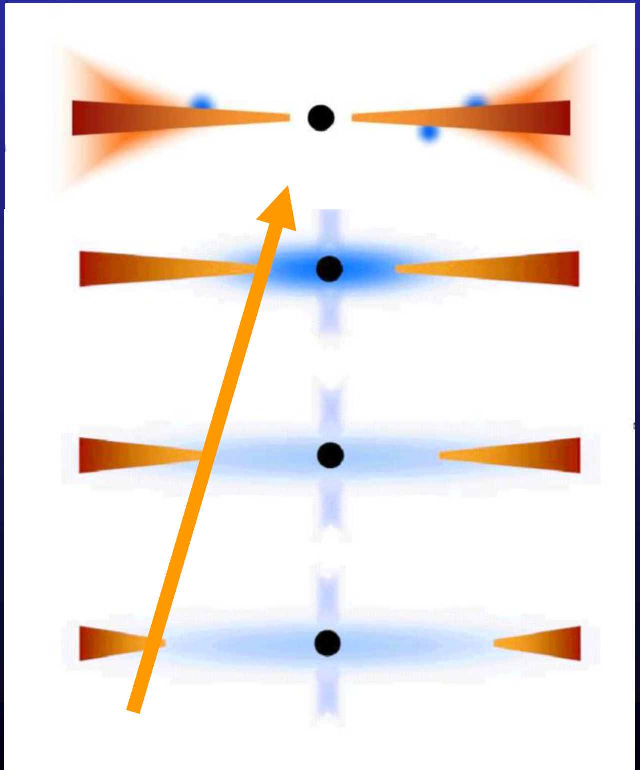
Done & Diaz-Trigo 2009

Moving disc

- Disc closer in, more soft photons from disc so softer spectra
- Especially when overlaps with hot flow. Decrease radius, increase overlap, increases seed photons dramatically
- Disc down to last stable orbit and collapse of hot flow gives physical mechanism for hard/soft transition

DGK07





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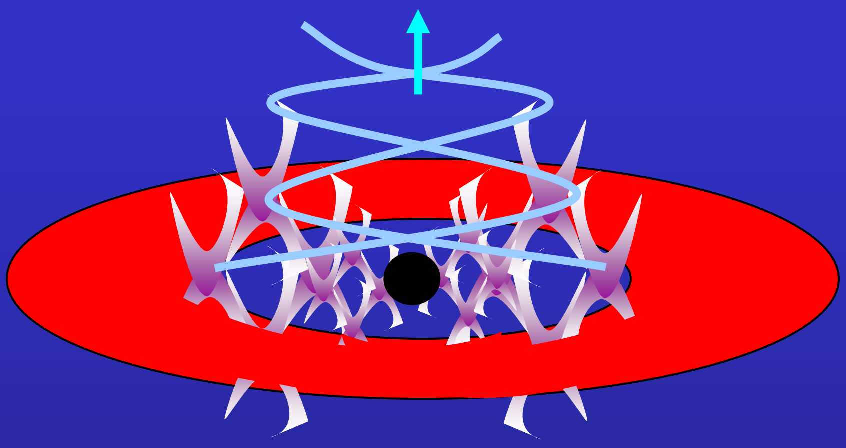

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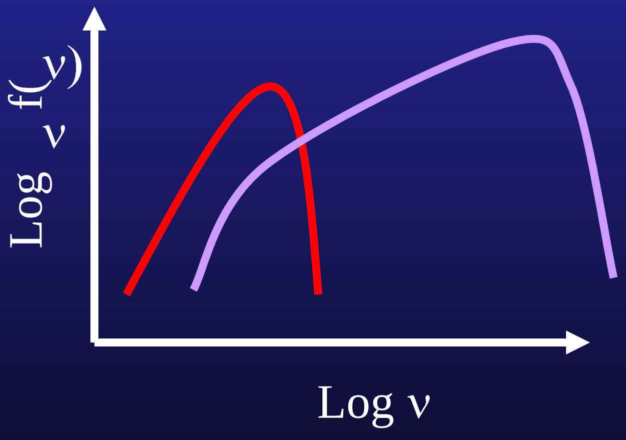
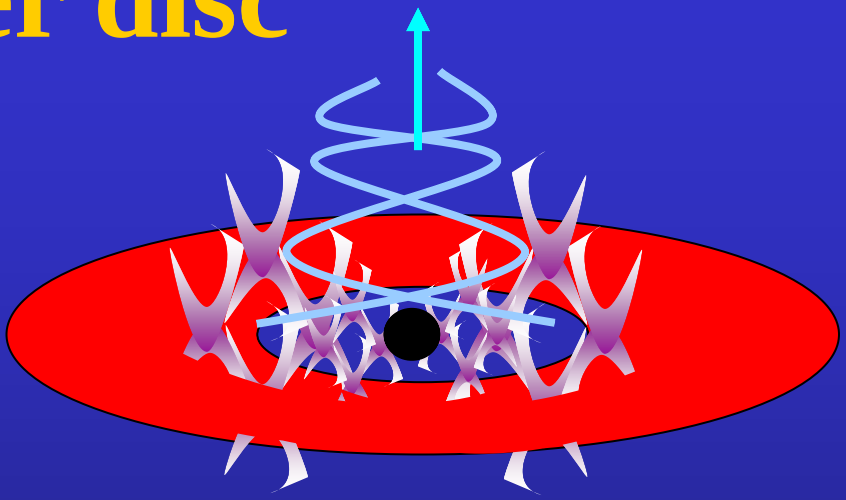


No inner disc



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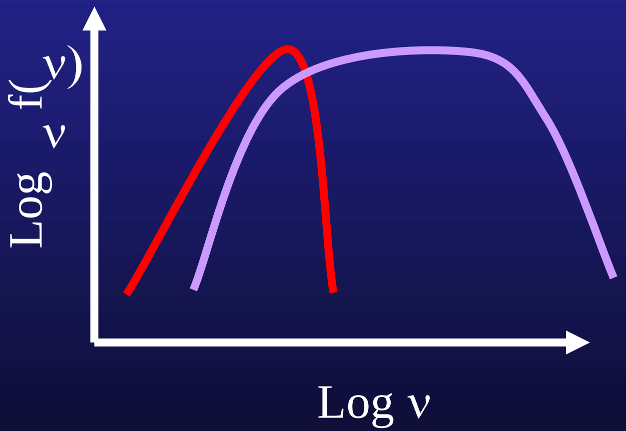

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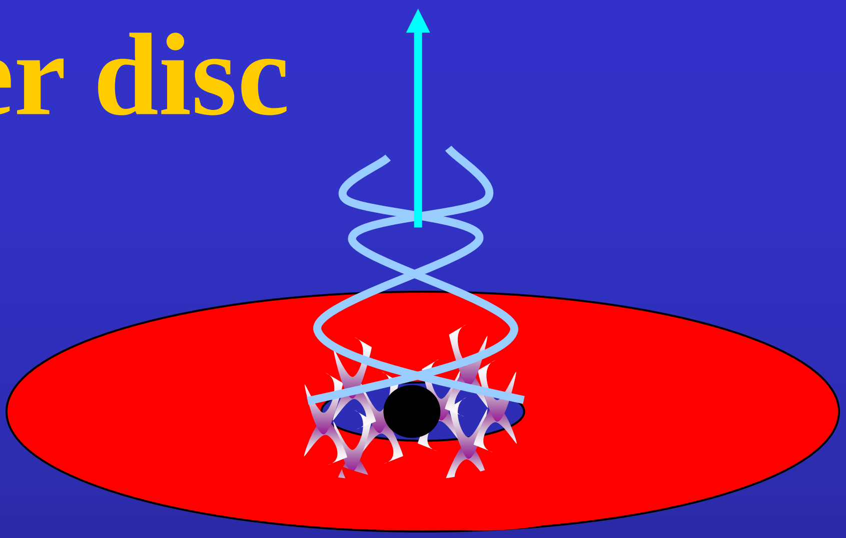

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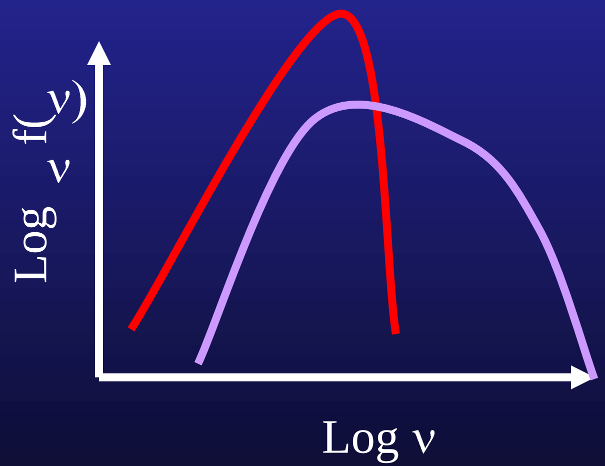

Collapse of hot inner flow

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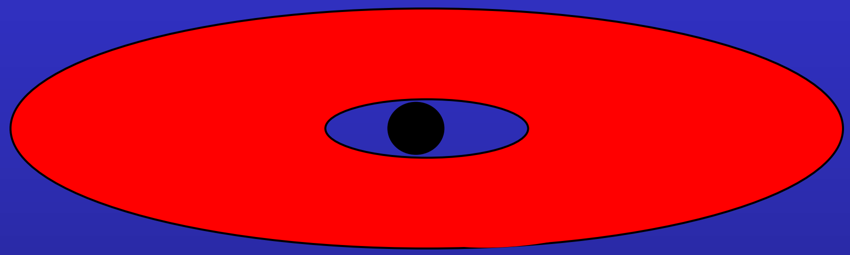
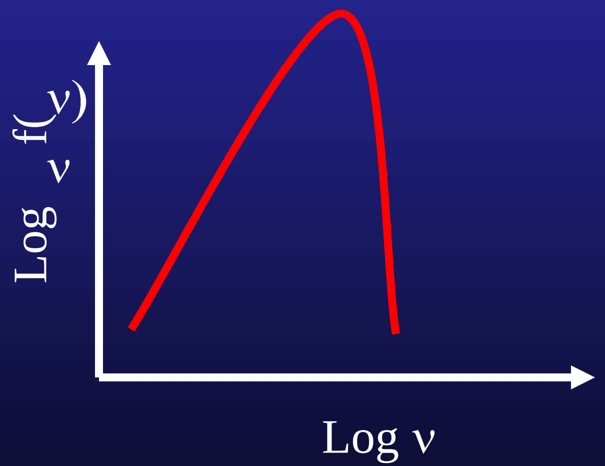
- Hot electrons Compton upscatter photons from outer cool disc
- Few seed photons, so spectrum is hard
- Jet from large scale height flow collapse of flow=collapse of jet

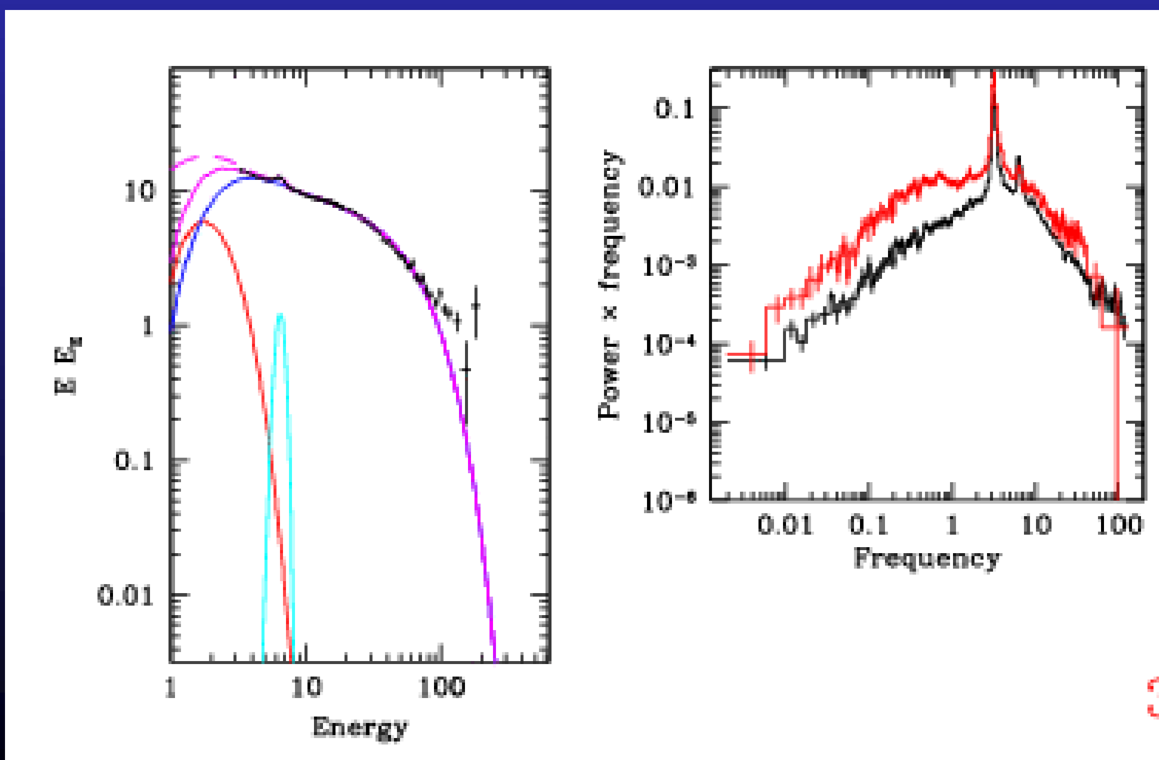


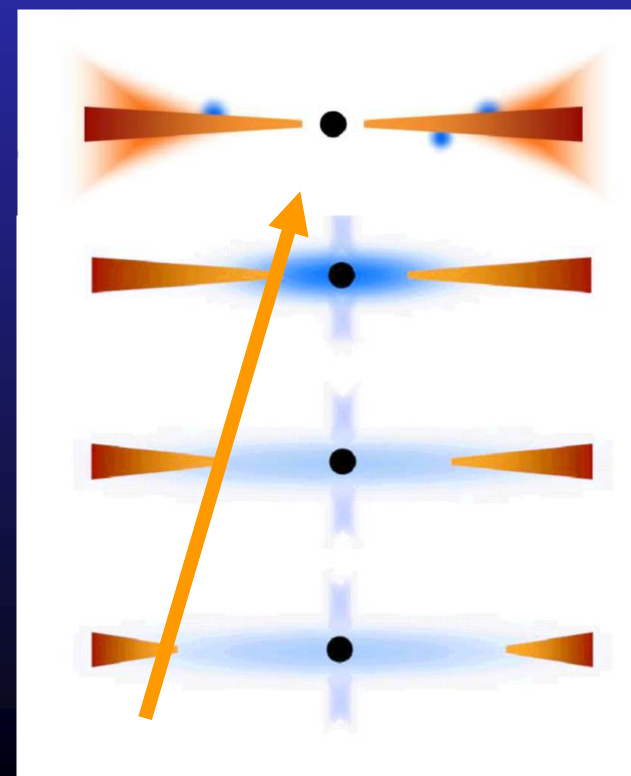


Moving disc – moving QPO

- Energy spectra need disc to move from 50-6ish Rg as make transition
- Power spectra: low frequency break moves, high frequency power more or less constant! Large radius moves, Small radii constant
- Low frequency QPO moves with low frequency break
- QPO big, must be fundamental

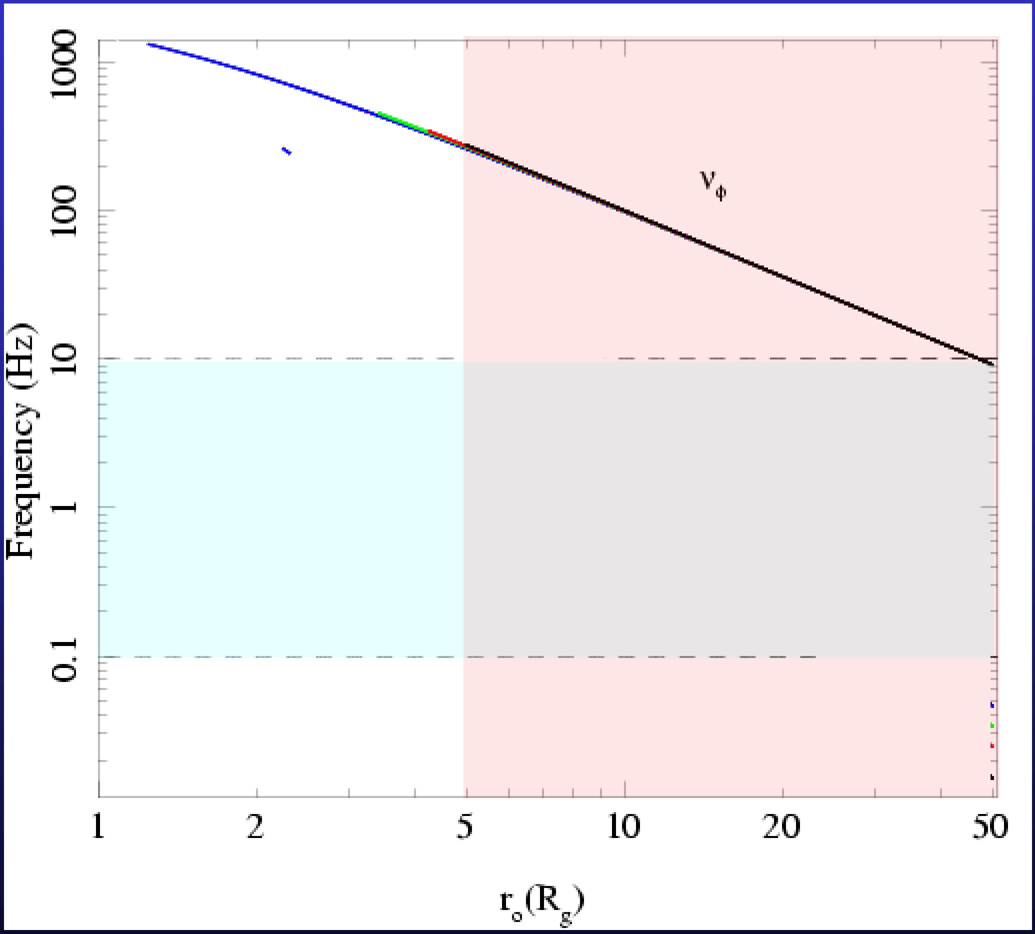
DGK07





Low frequency QPO

- Spectra need disc to move from R_{tr} = 50-6ish R_g as make transition
- Observed QPO frequencies go from ~0.1-10 Hz
- See similar range in ALL BHB – so either all BHB have same spin or not much spin dependence on QPO
- Not $\nu(\varphi)$ as too fast!



Ingram, Done & Fragile 2009

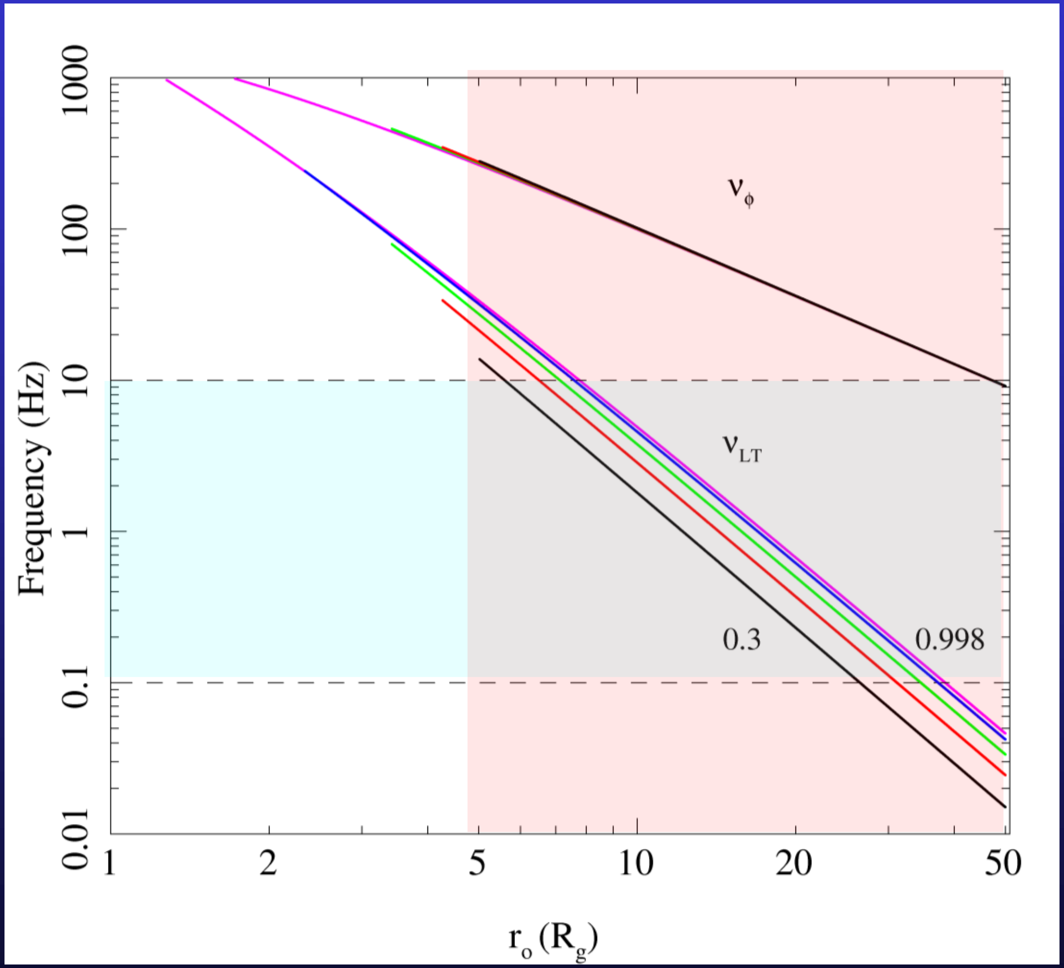
Low frequency QPO

- Stella & Vietri 1998 – GR potential not spherically symmetric so vertically offset circular orbit has $\nu(\theta) \neq \nu(\varphi)$
- Lense-Thirring precession $\nu_{LT} = \nu(\theta) - \nu(\varphi)$

Lamb & Markovic

Does it work ?

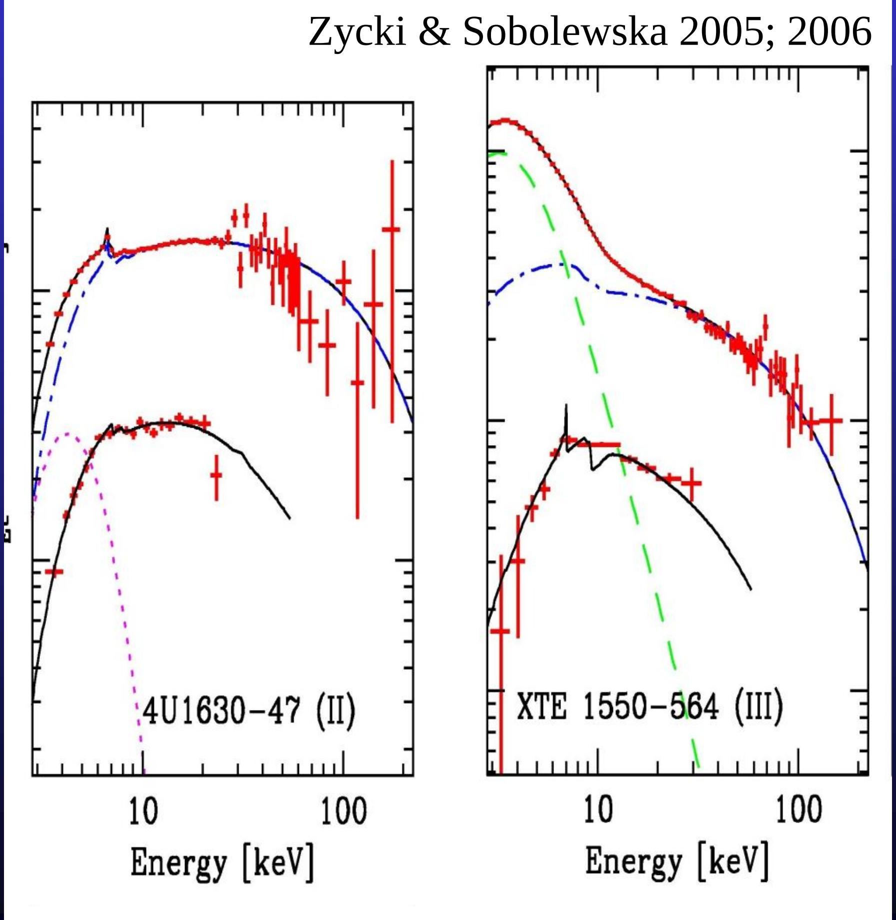
- Not really
- Any moderate spin gives QPO much faster than observed as r → lso
- And edge of disc would have blackbody spectrum. QPO has spectrum of hot inner flow



Ingram, Done & Fragile 2009

How does it modulate?

- Spectrum of LF QPO is same as Comptonisation to zeroth order
- NOT the disc - most obvious close to transition



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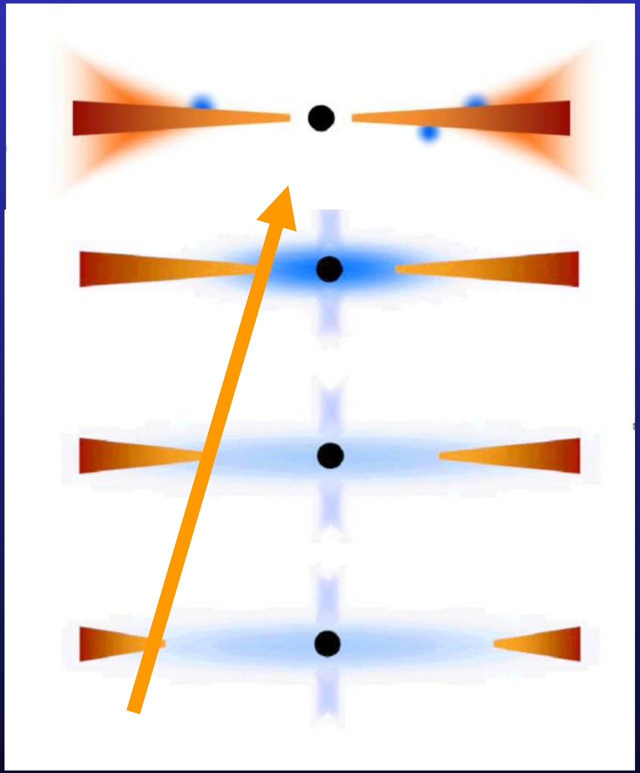
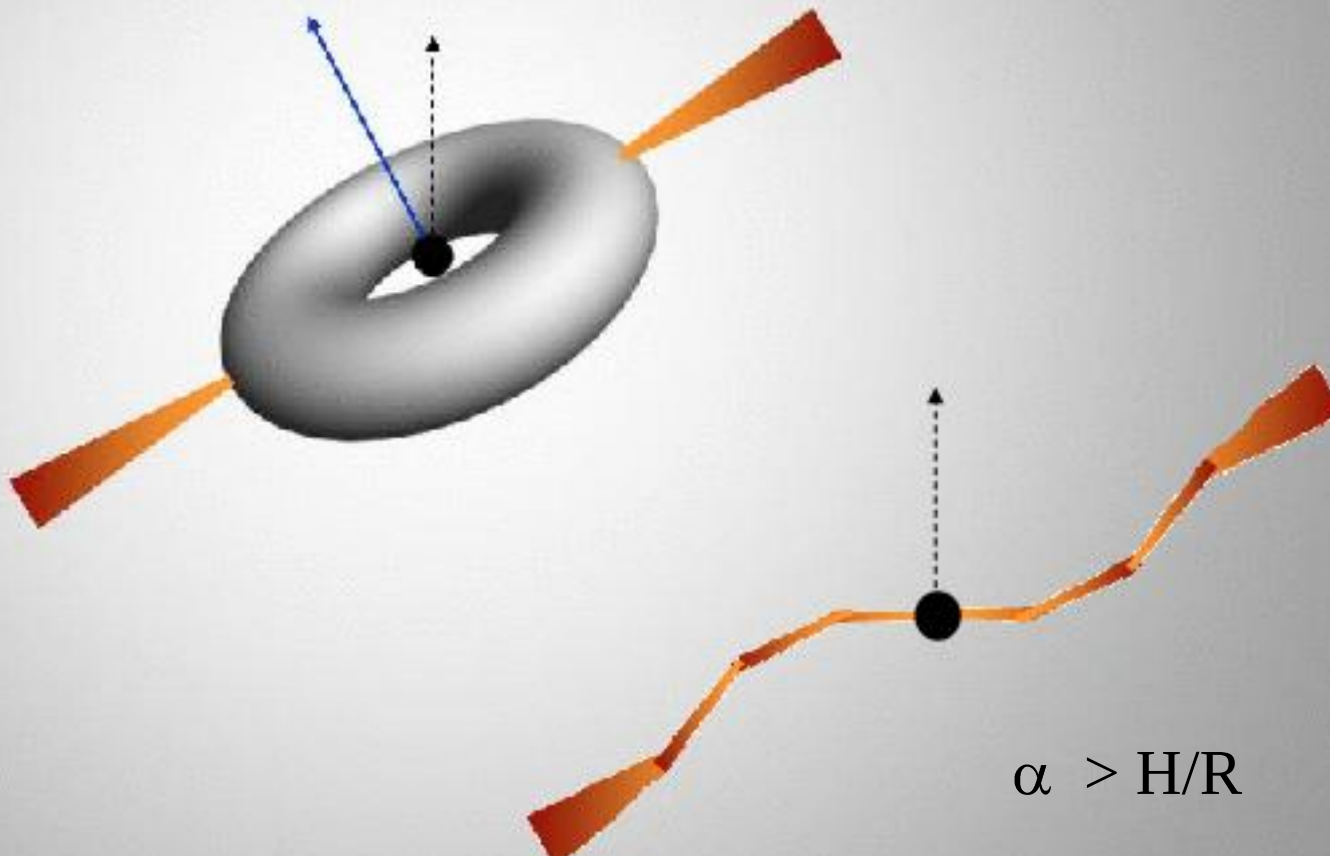


Ingram, Done & Fragile 2009

Solid body precession of the flow

$\alpha < H/R$

precession

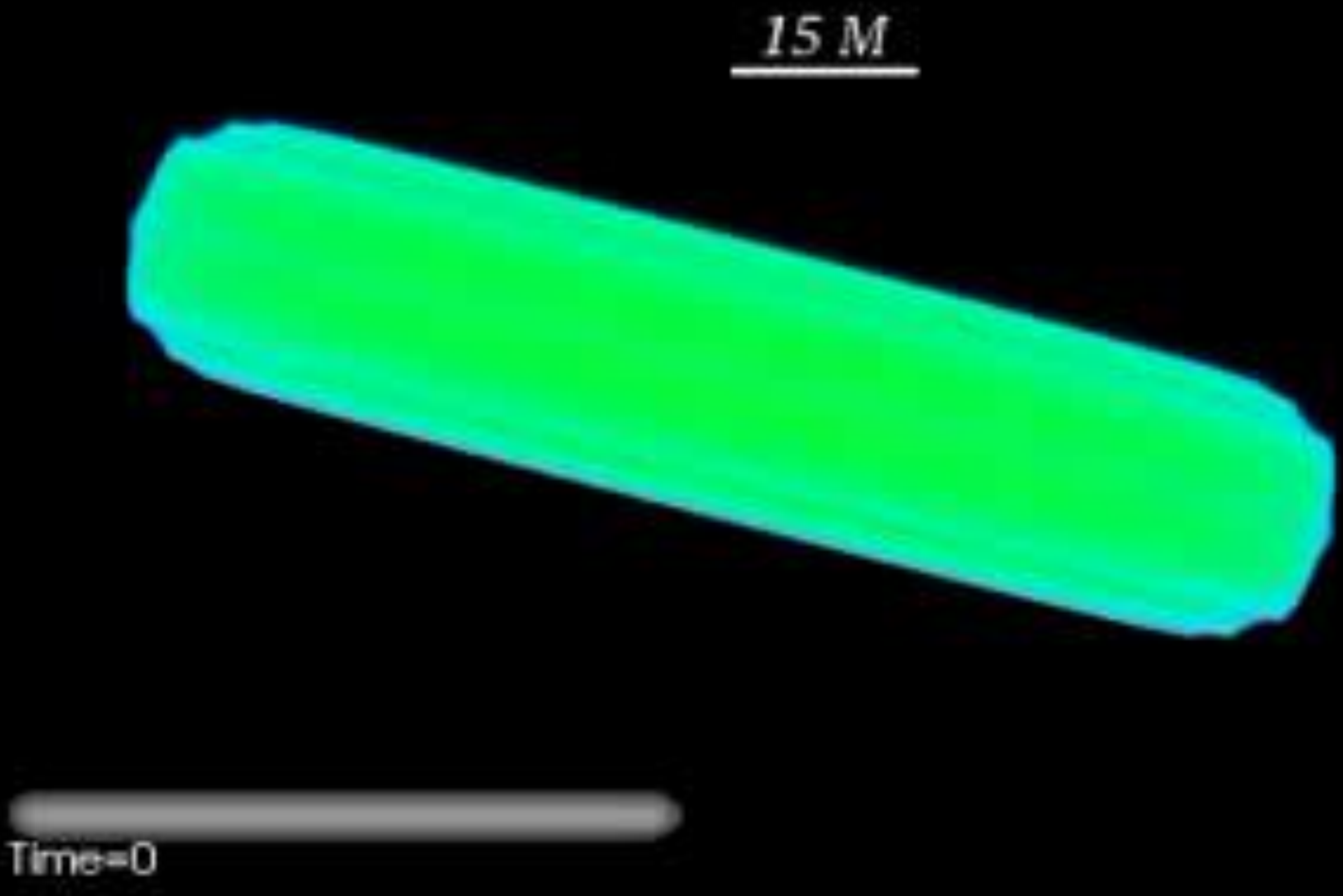


$\alpha > H/R$

Warped disc

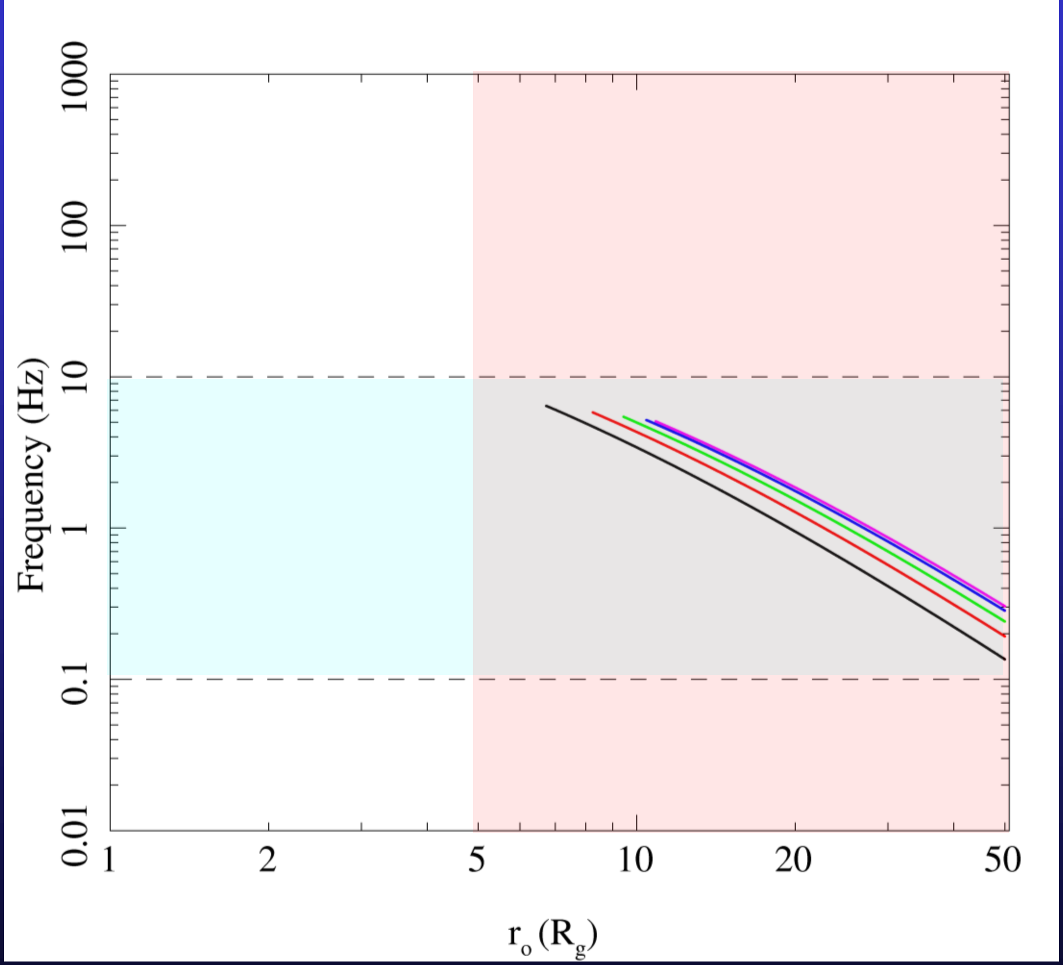
Ingram, Done & Fragile 2009

Chris Fragile 2007



LT precession of hot flow?

- Truncates at ~ bending wave radius



- Modulates Compton region so gets spectrum
- QPO frequency given by weighted average of LT precession frequency over all radii in hot flow
- Gets the frequencies correct!!
- No large spin dependence

Ingram, Done & Fragile 2009

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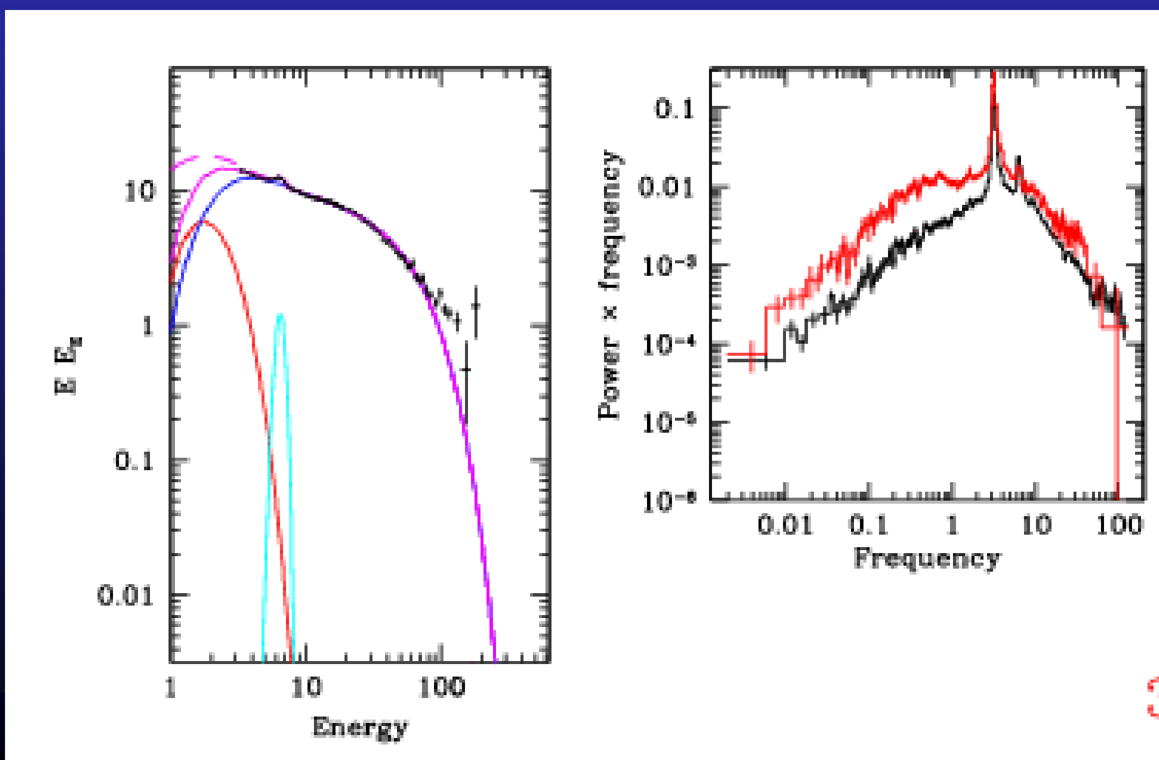
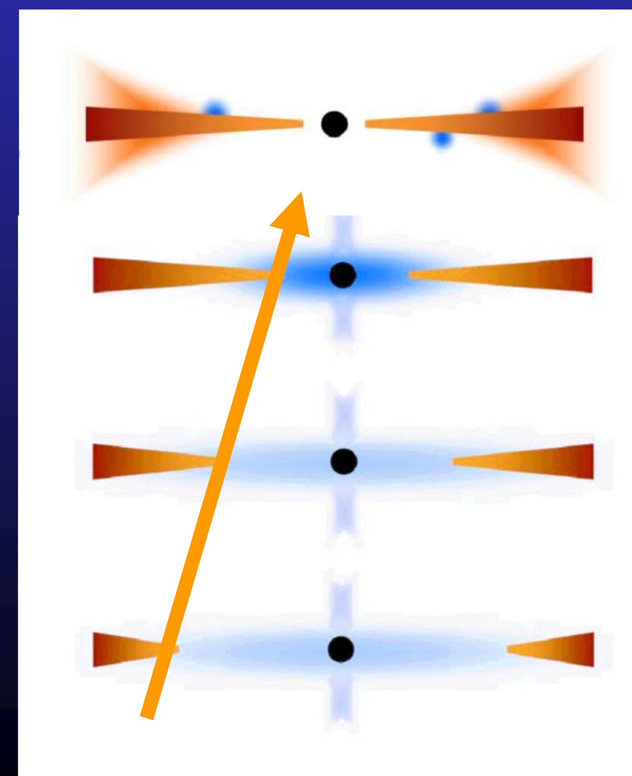
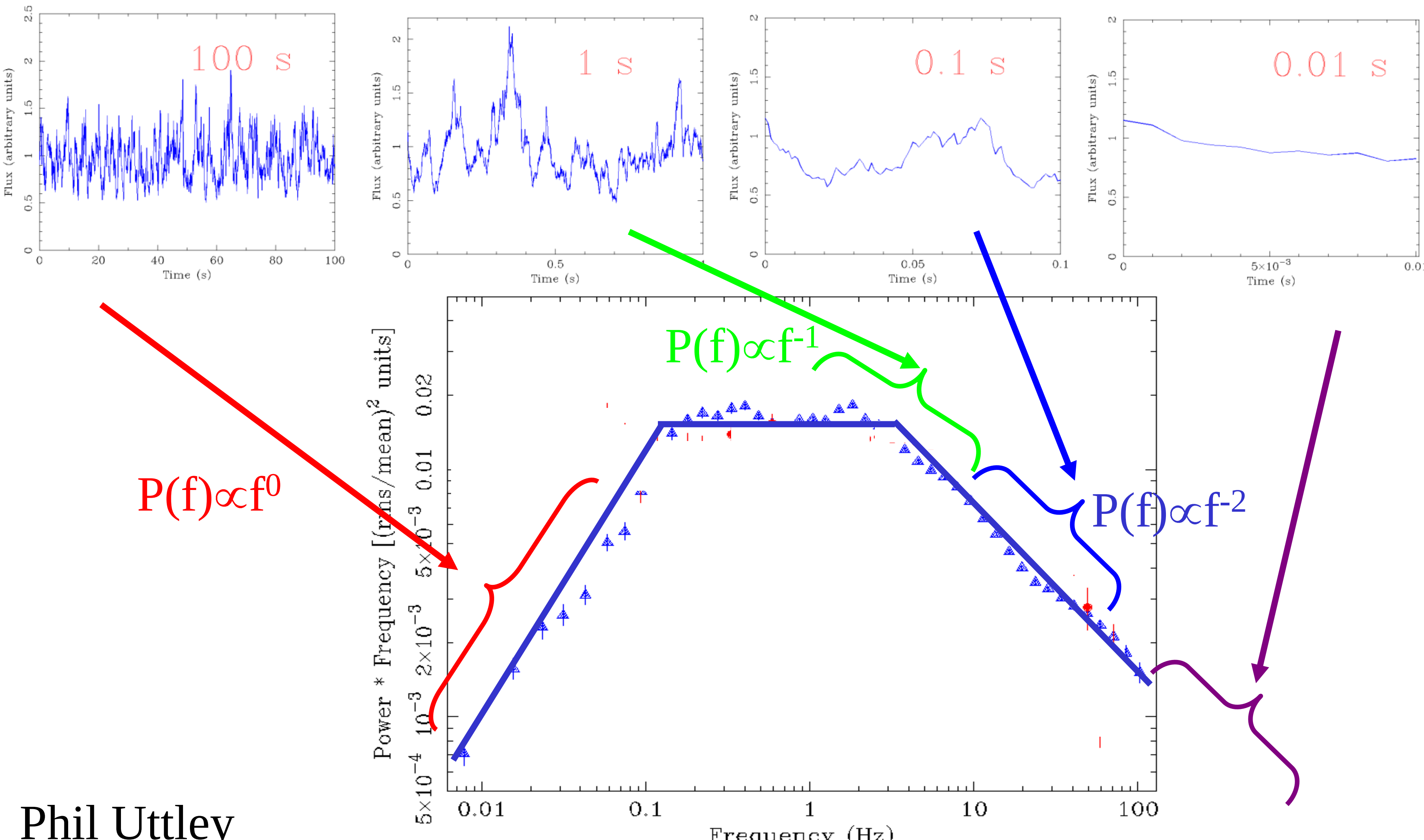


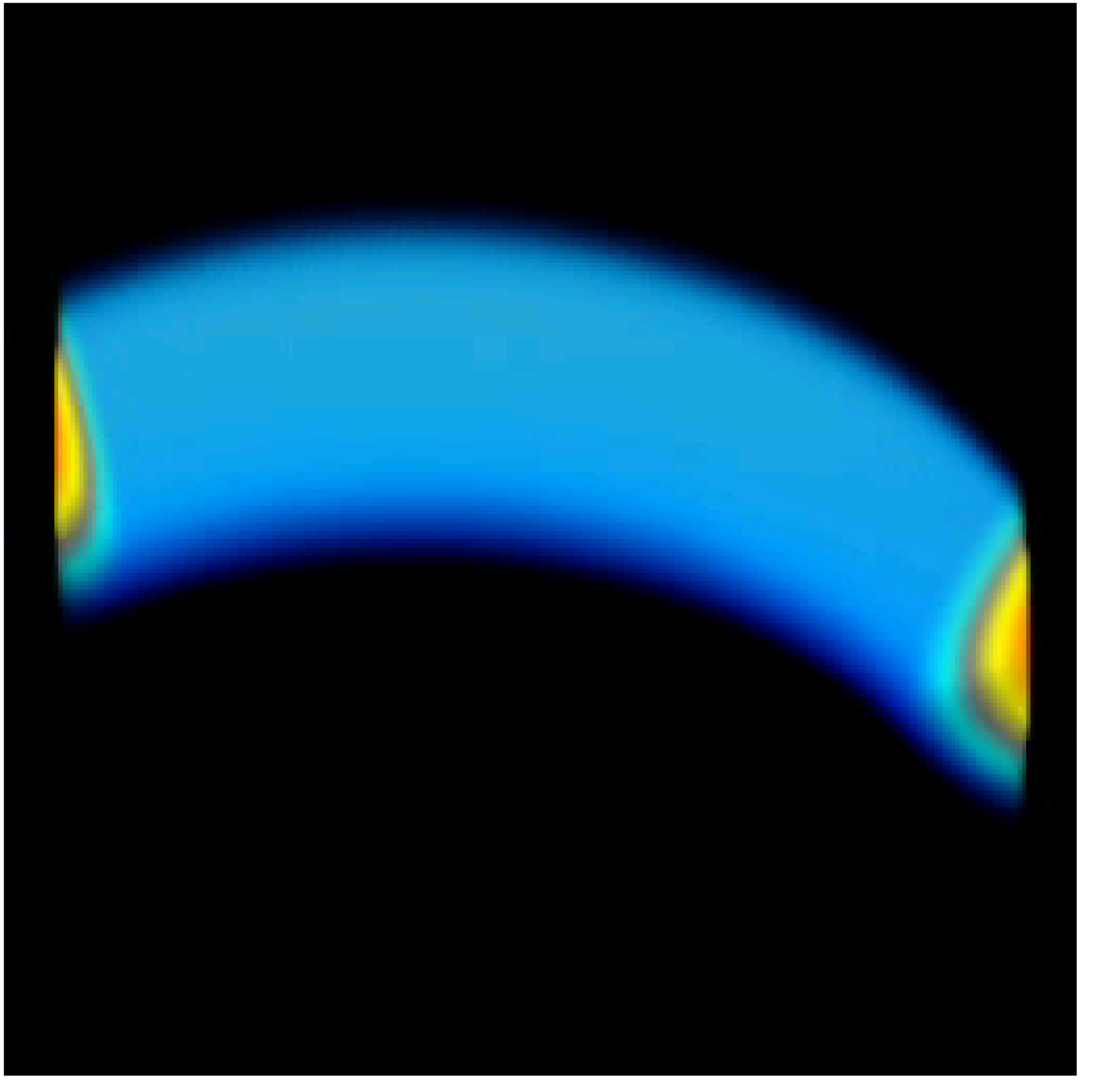


Quantifying variability: the power spectral density (PSD) of Cyg X-1



Phil Uttley

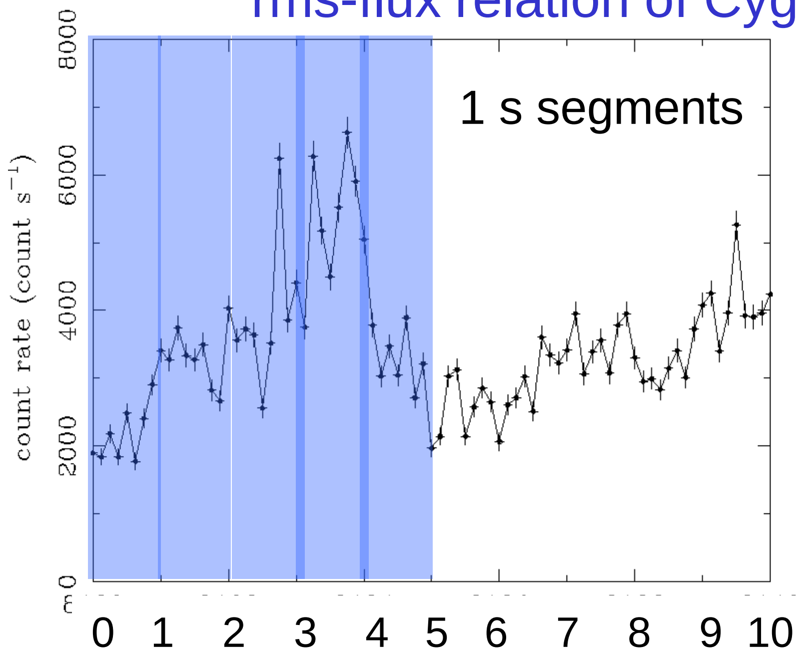
Origin of variability: MRI

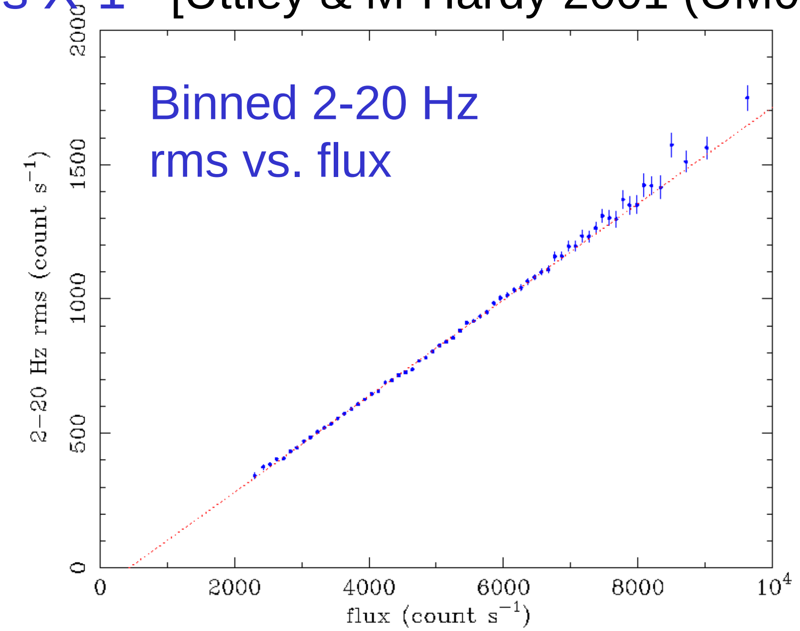


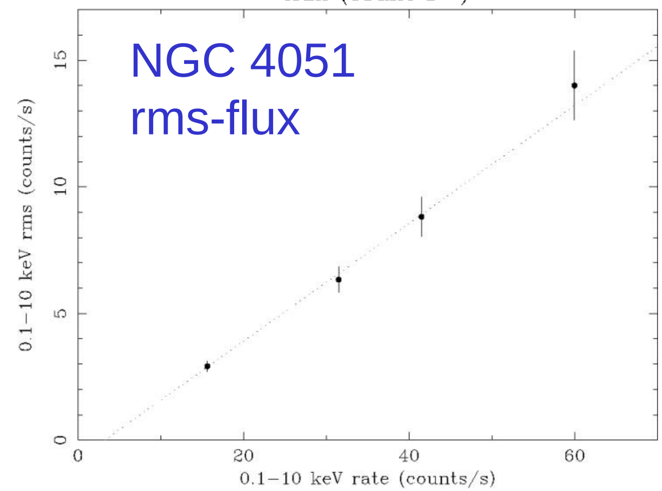
Krolik, de Villiers, Hawley

The rms-flux relation

rms-flux relation of Cygnus X-1 [Uttley & McHardy 2001 (UM01)]





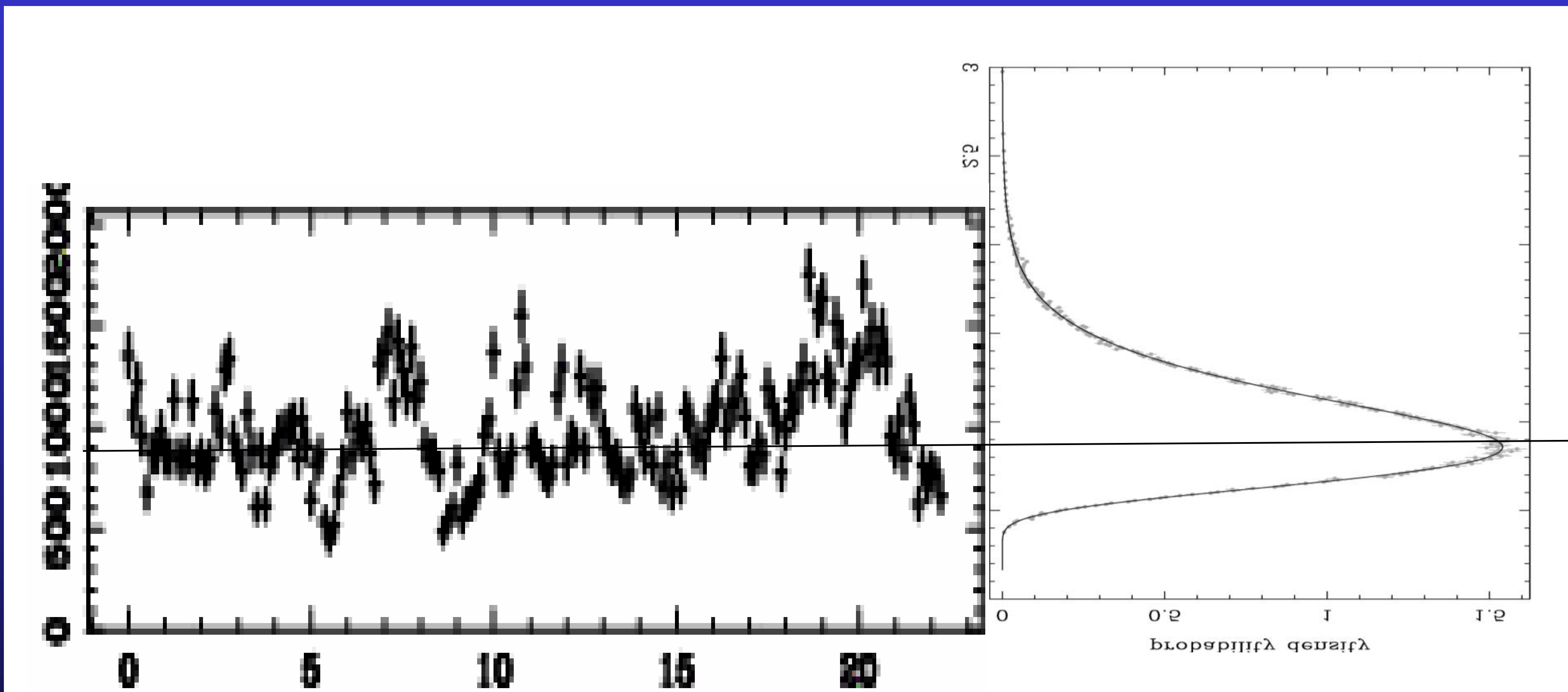


$$\text{rms} = \sqrt{(1/N) \sum_{i=1,N} (\text{flux}_i - \text{mean})^2}$$

Linear rms-flux relations are also seen in AGN, e.g. NGC 4051

(UM01, McHardy et al. 2004)

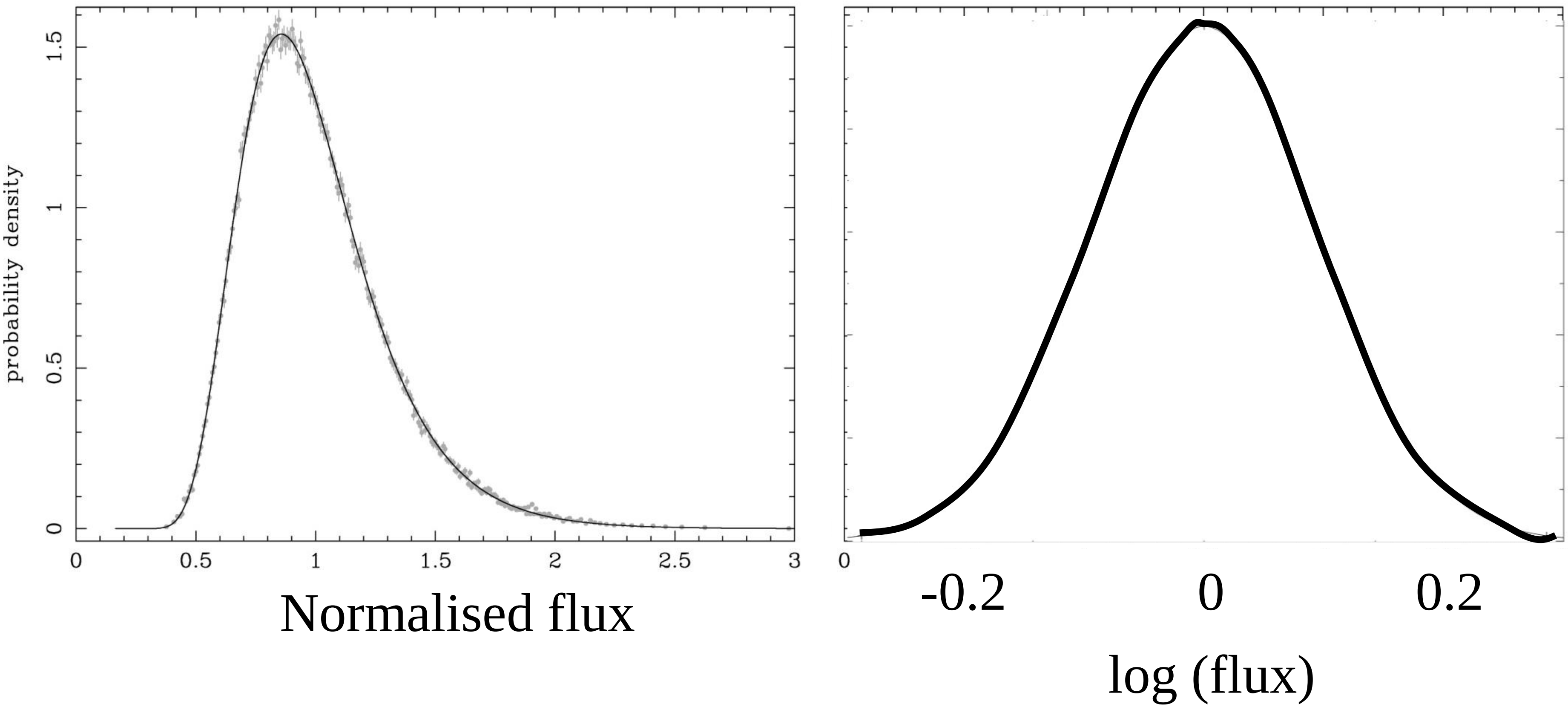
Flux distribution of variability



Has very characteristic shape – not symmetric. Skewed to higher flux levels. Lightcurve is ‘flare-y’

Uttley, McHardy & Vaughan 2005

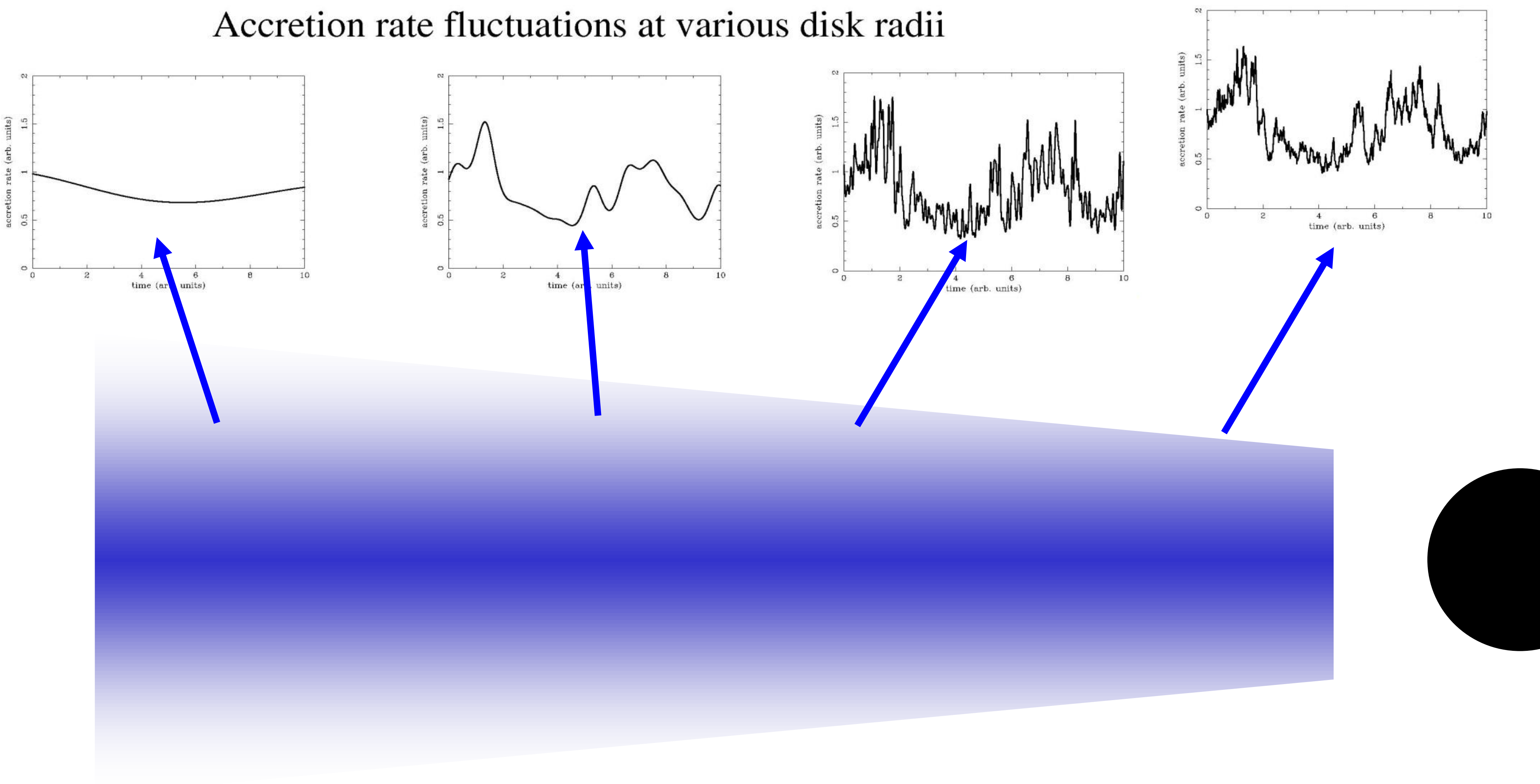
Implies log normal flux distribution



Cannot get this from SHOTS, or any SUM of independent events
Or from self organised criticality (wait till critical value to trigger)

Uttley, McHardy & Vaughan 2005

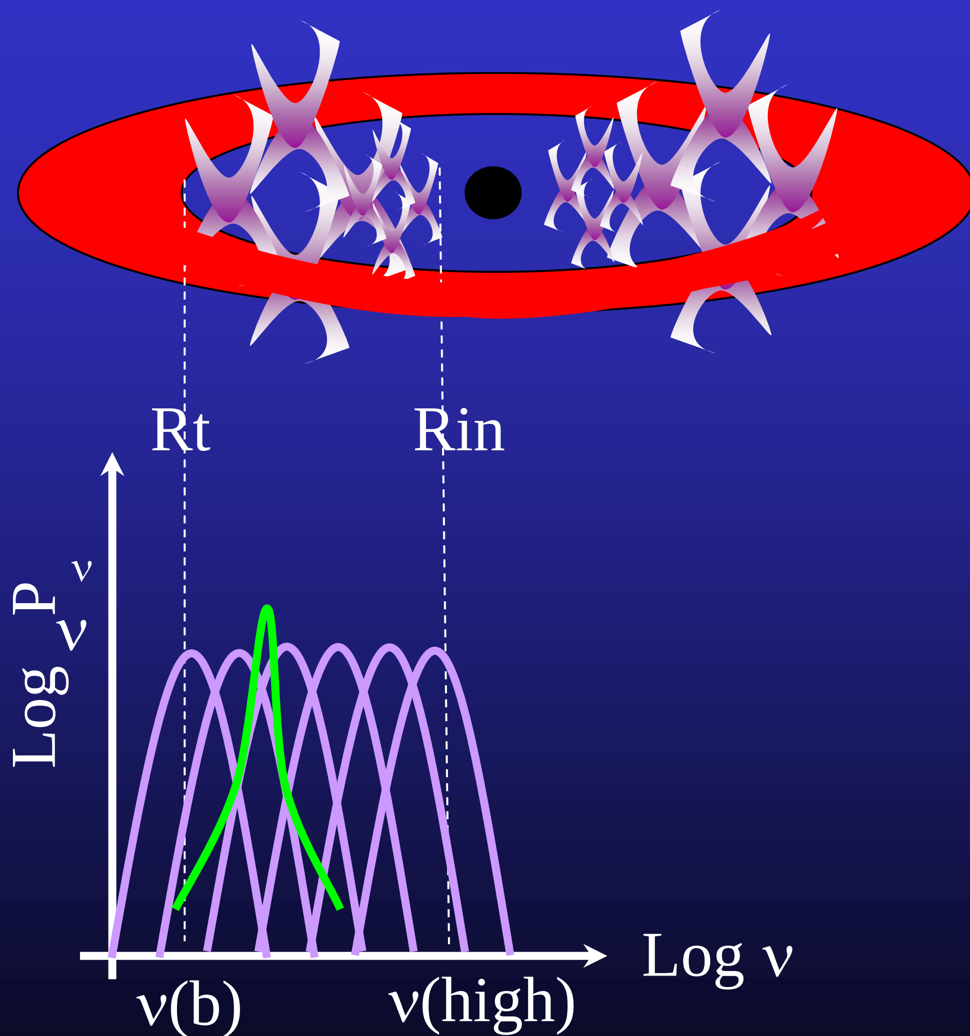
Origin of variability



The model is multiplicative, not additive: fractional mdot variations on different time-scales multiply together: Uttley 2006

And the rest of the variability?

- Broadband noise also produced in hot flow – spectrum of variabilty is hard. Disc constant!
- MRI drives fluctuations
- Equal power from all radii with same H/R
- Rin stays fixed while Rt varies – changes low frequency break ν(b) together with ν(QPO). Wijnands & van der Klis 1999
- SAME flow gives QPO



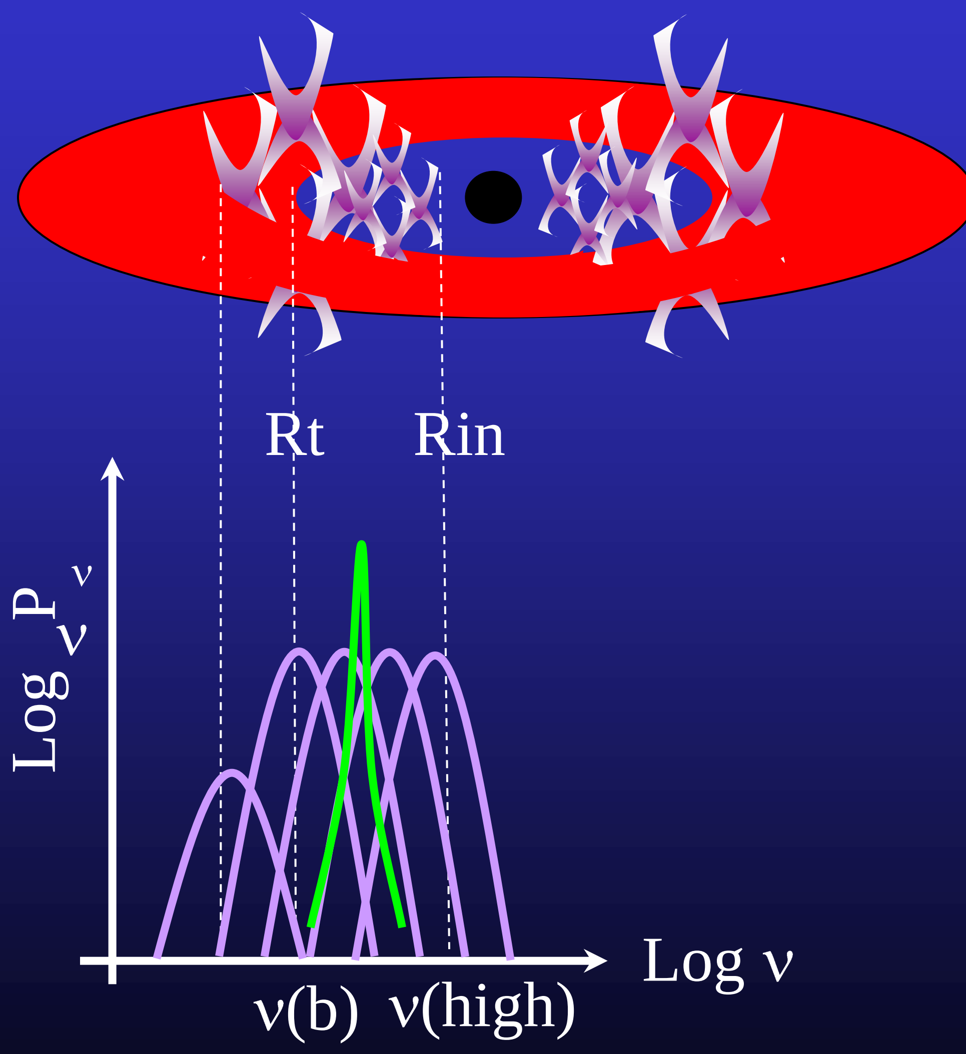
Ingram & Done 2009

So how can we test it?

- Overlap region can be important if Rt small – smaller H/R so smaller normalisation
- Mass accretion rate from each radius propagates down to modulate accretion rate in next annulus
- central region modulated on all timescales

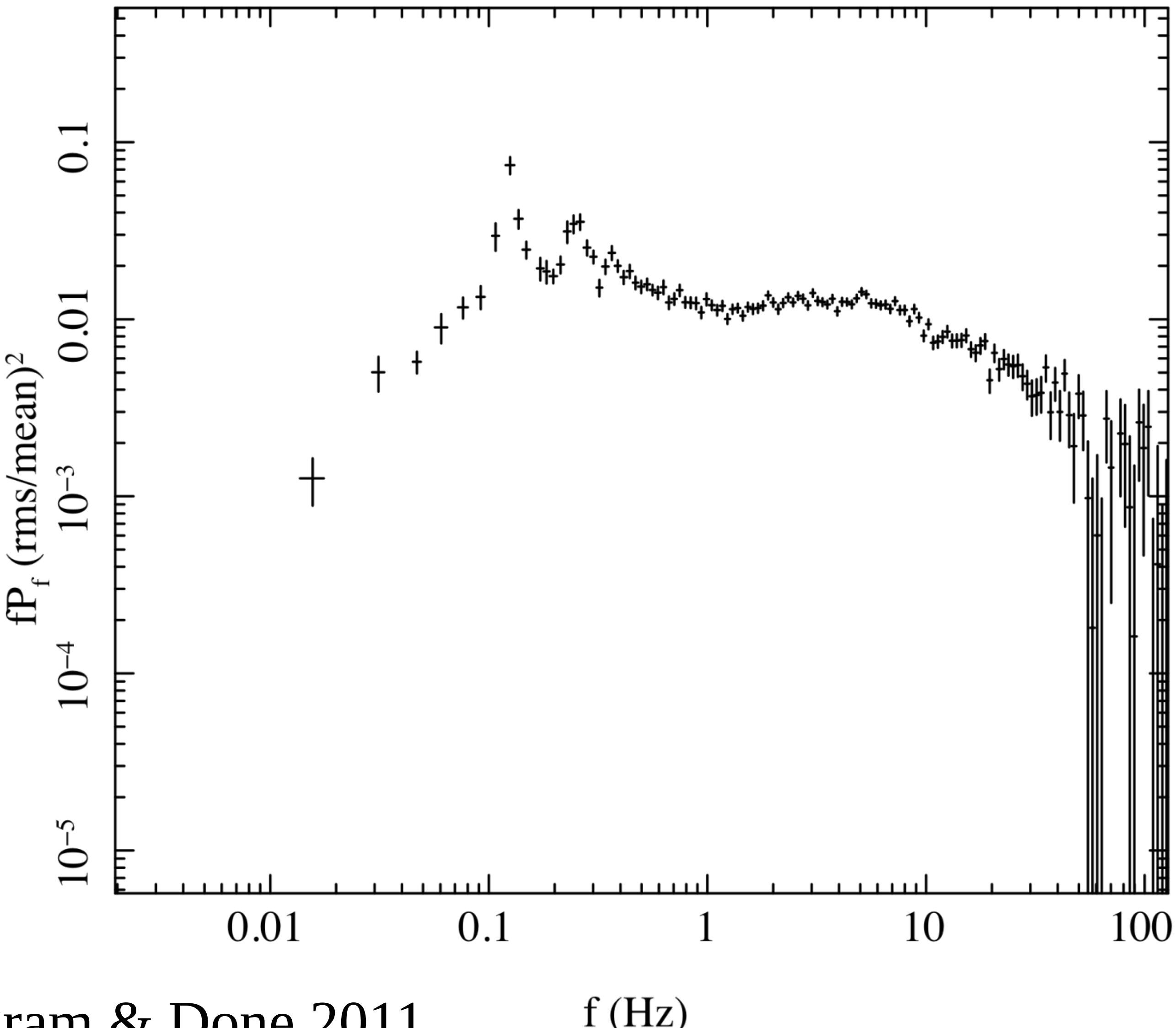
tvisc(Rt) - tvisc(Rin) setting

ν(b) - ν(high)



Ingram & Done 2009

Fitting to observations of XTE 1550-564



Ingram & Done 2011

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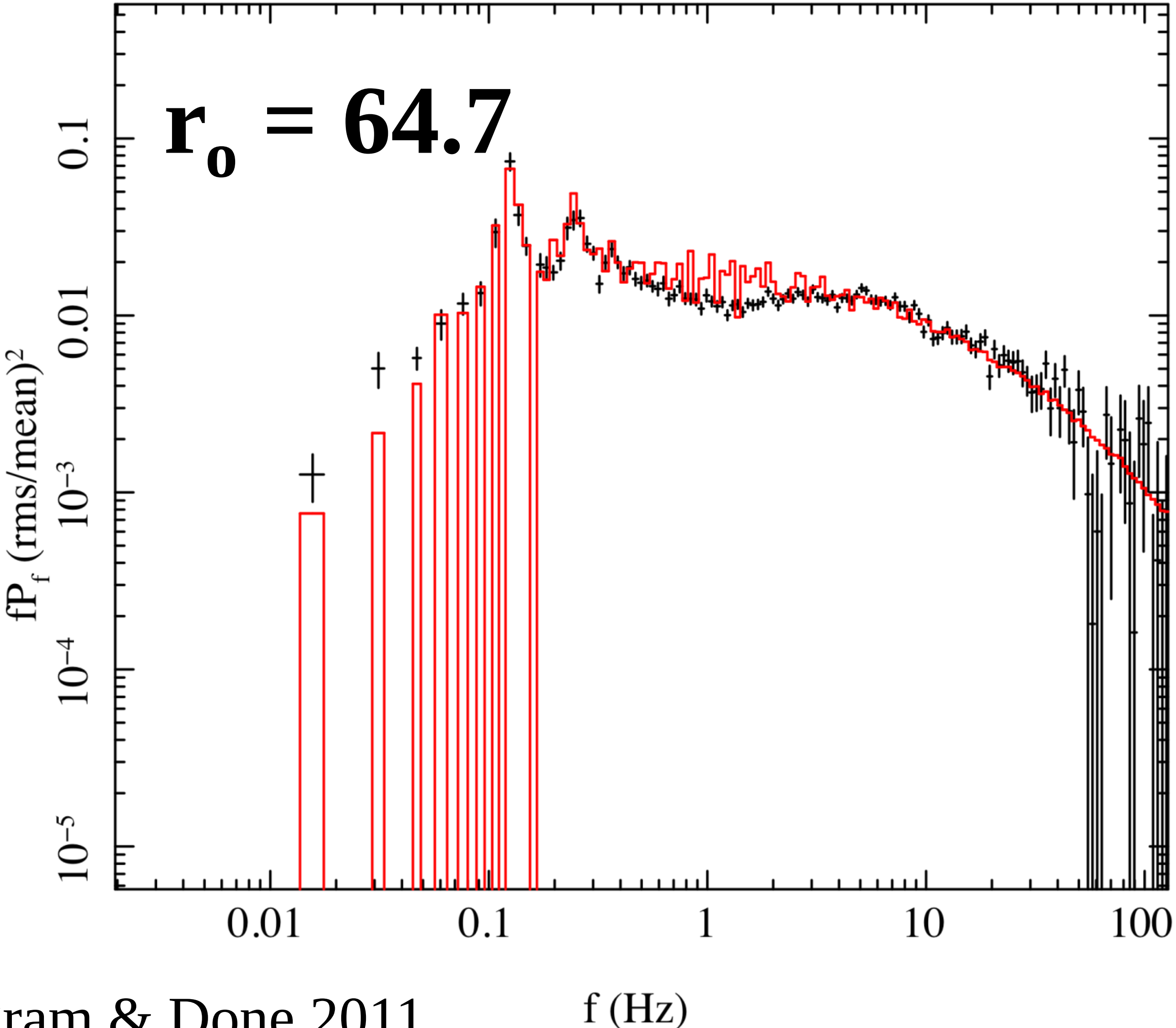

Ingram & Done 2011

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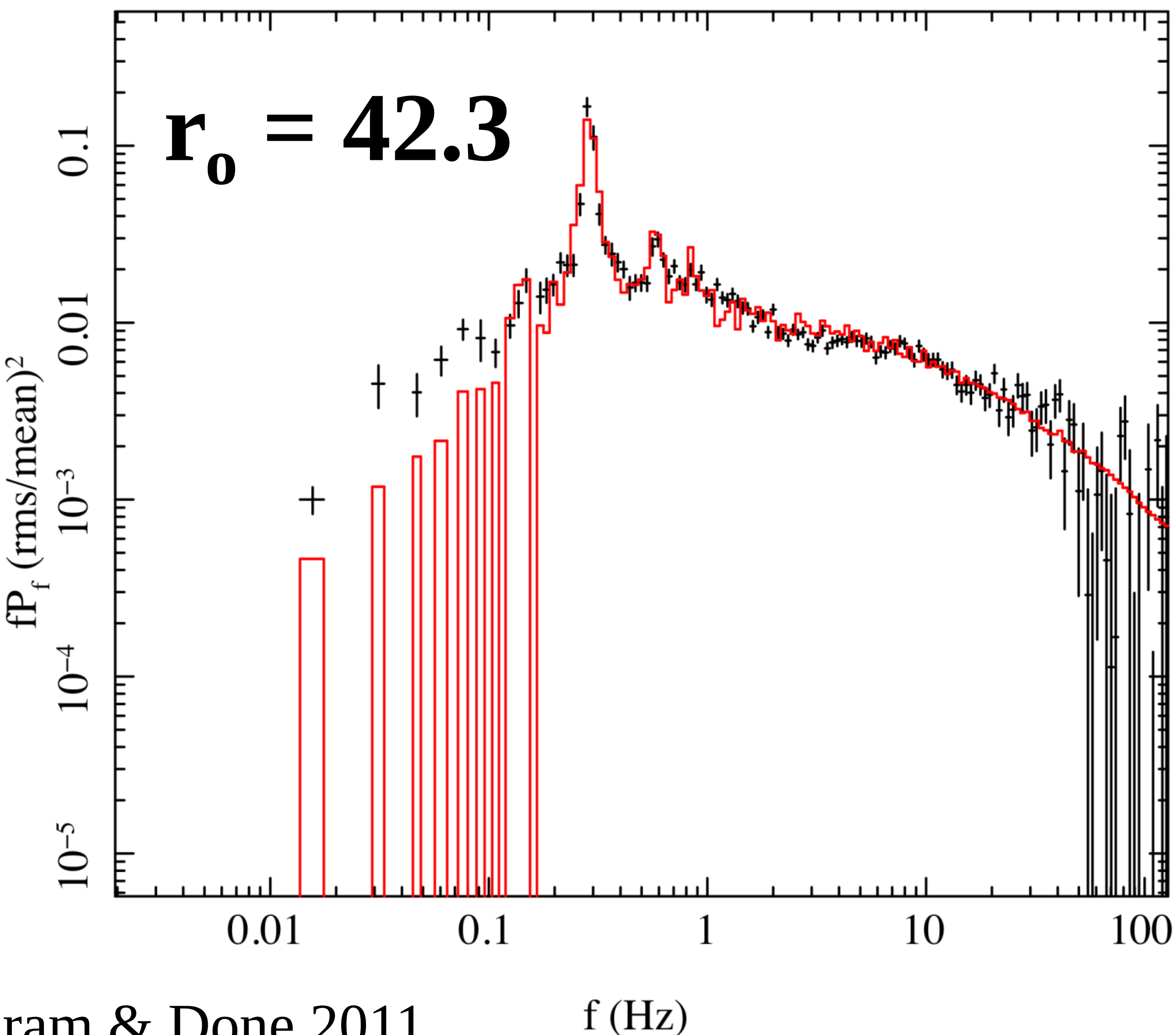

Ingram & Done 2011

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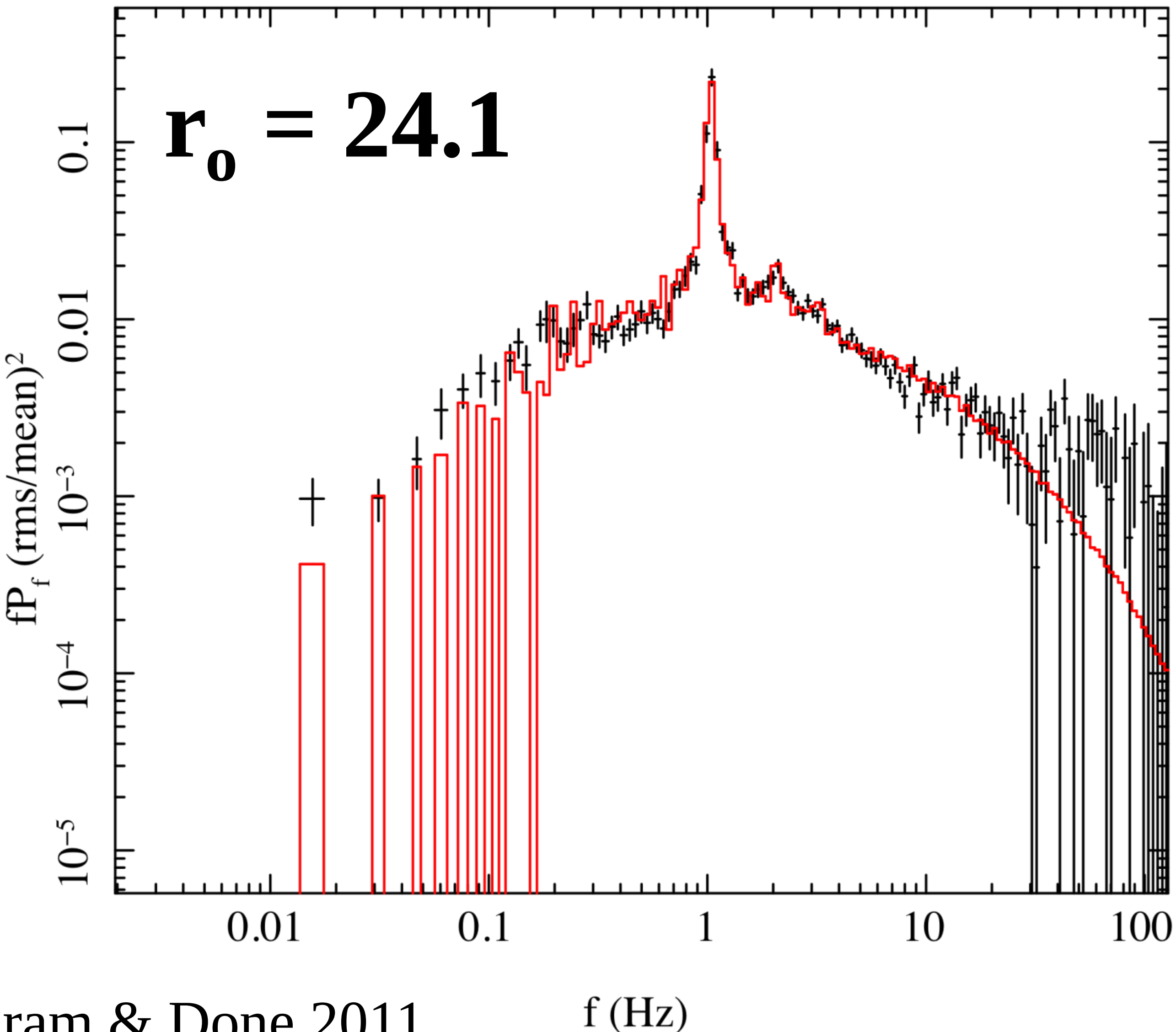

Ingram & Done 2011

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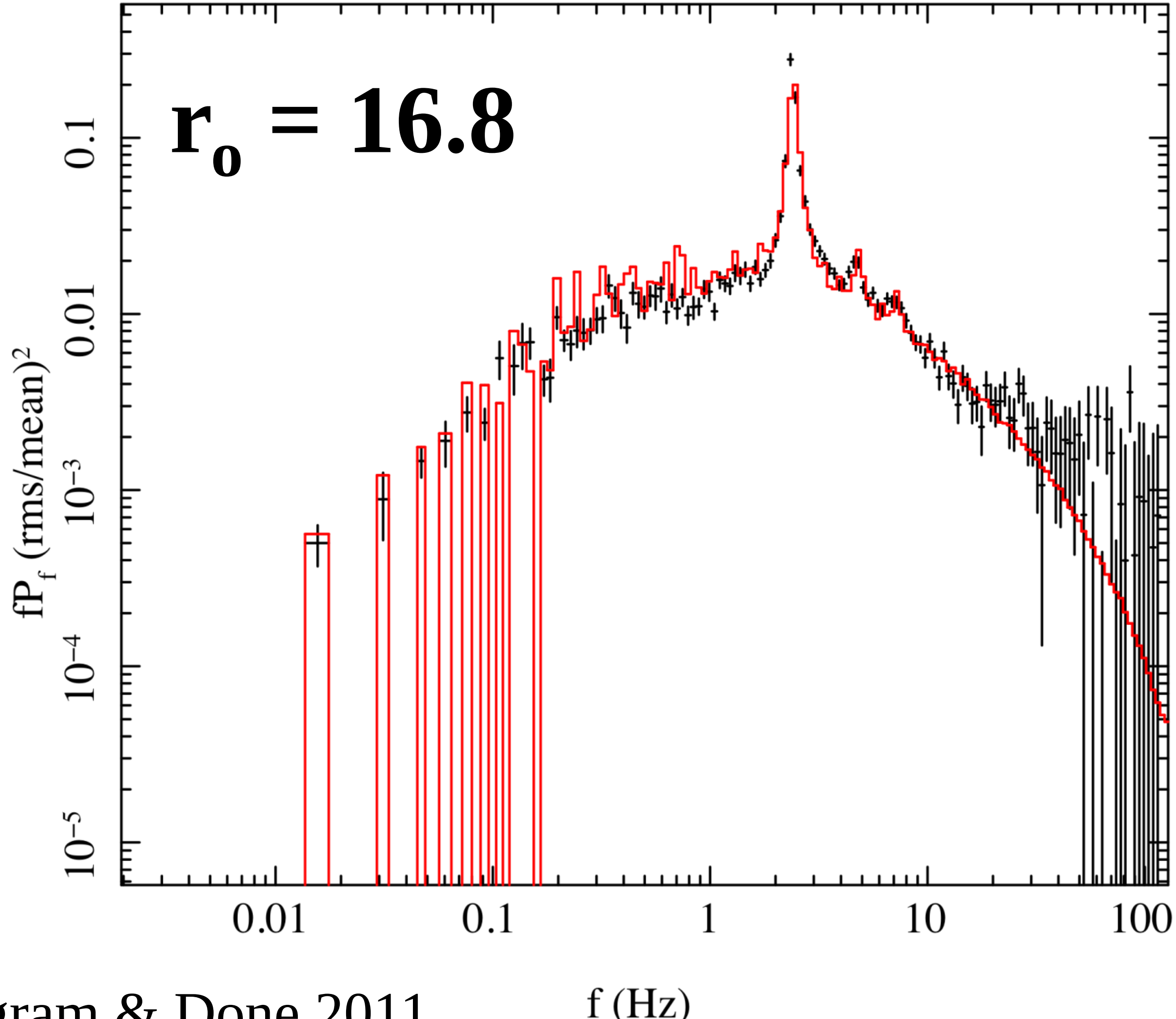

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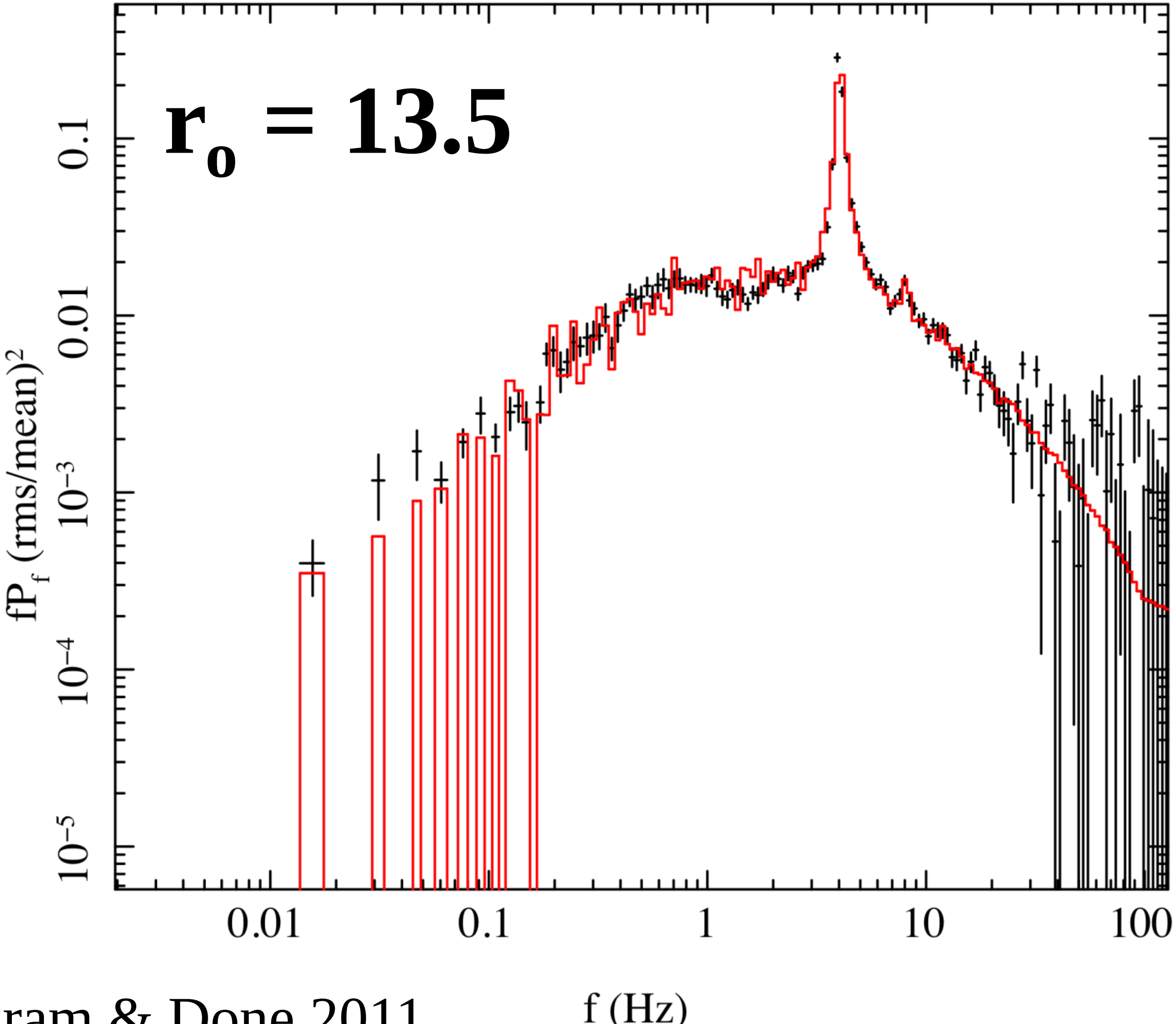
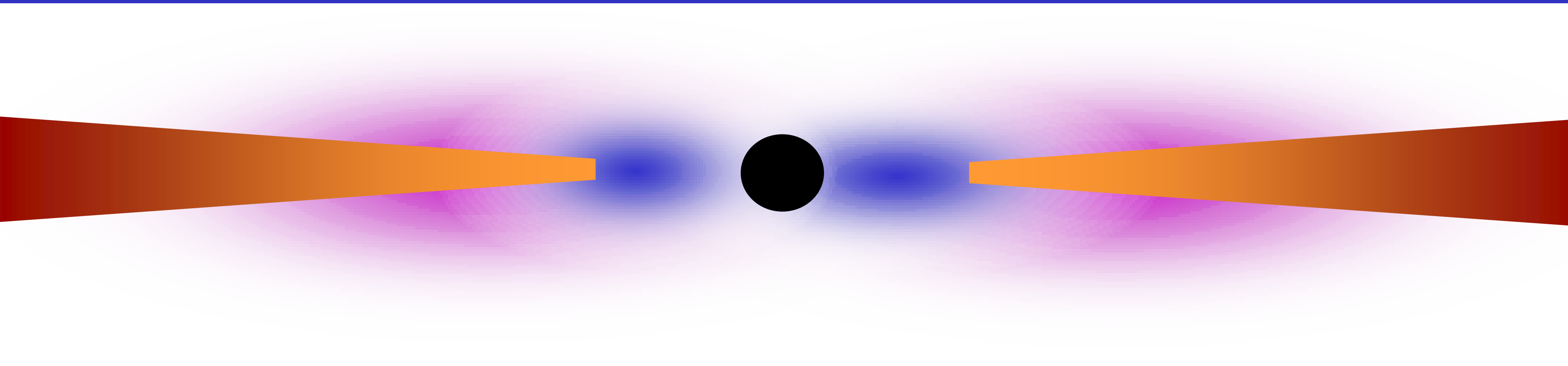
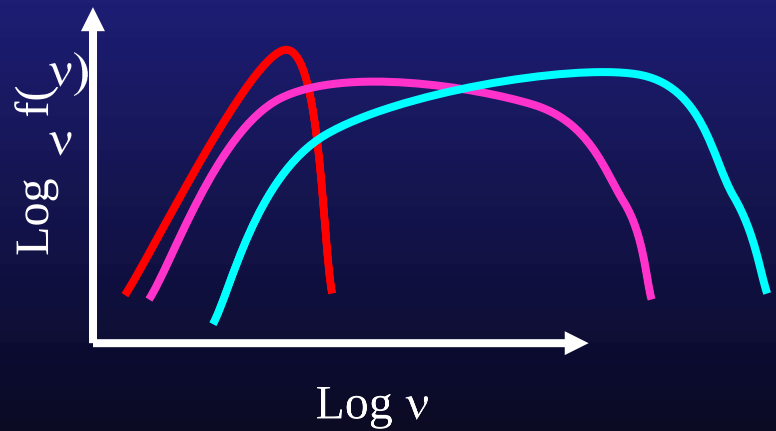


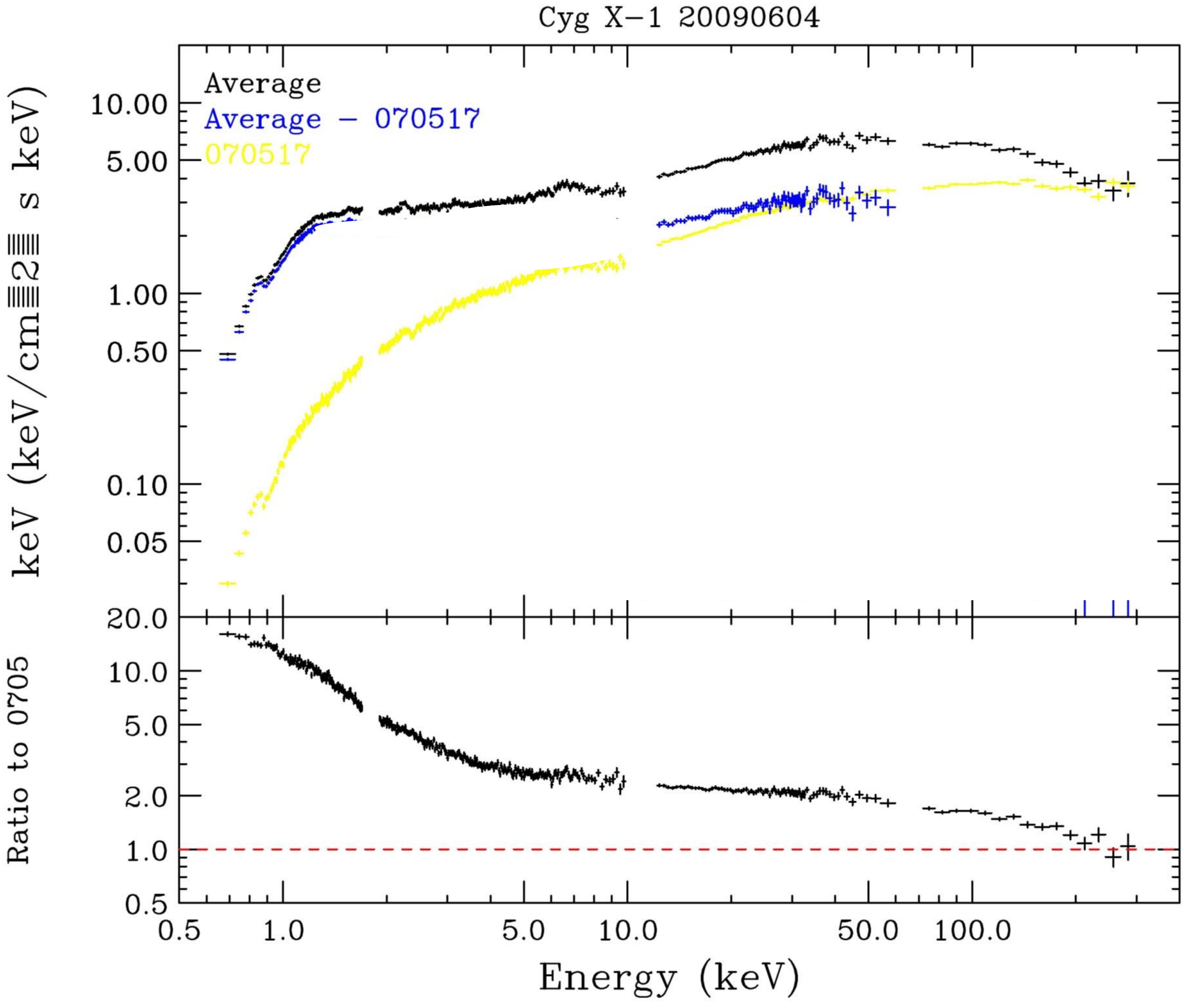
Ingram & Done 2011

Inhomogeneous spectra ?



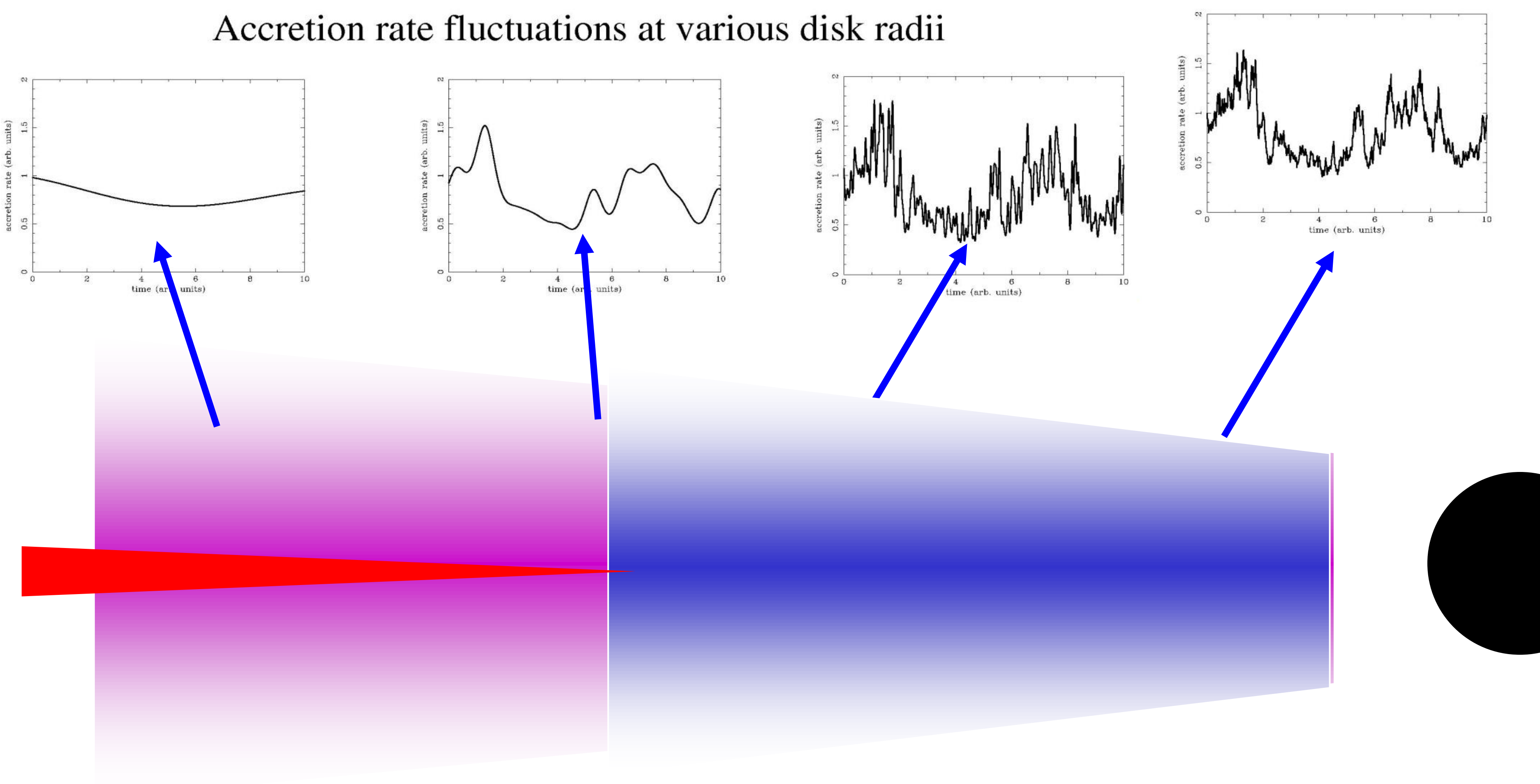


- Overlap softer (and more reflection)
- Inner region harder (and less reflection)
- WE SEE THIS!!



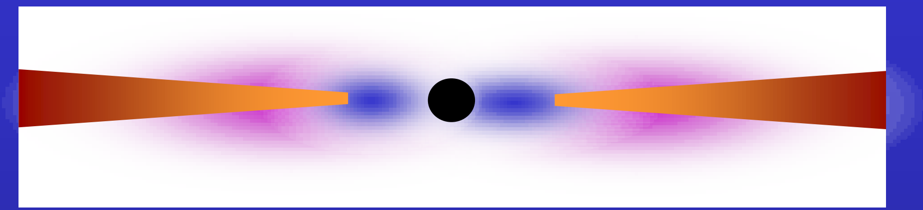
Makishima, Torii, Takahashi…..

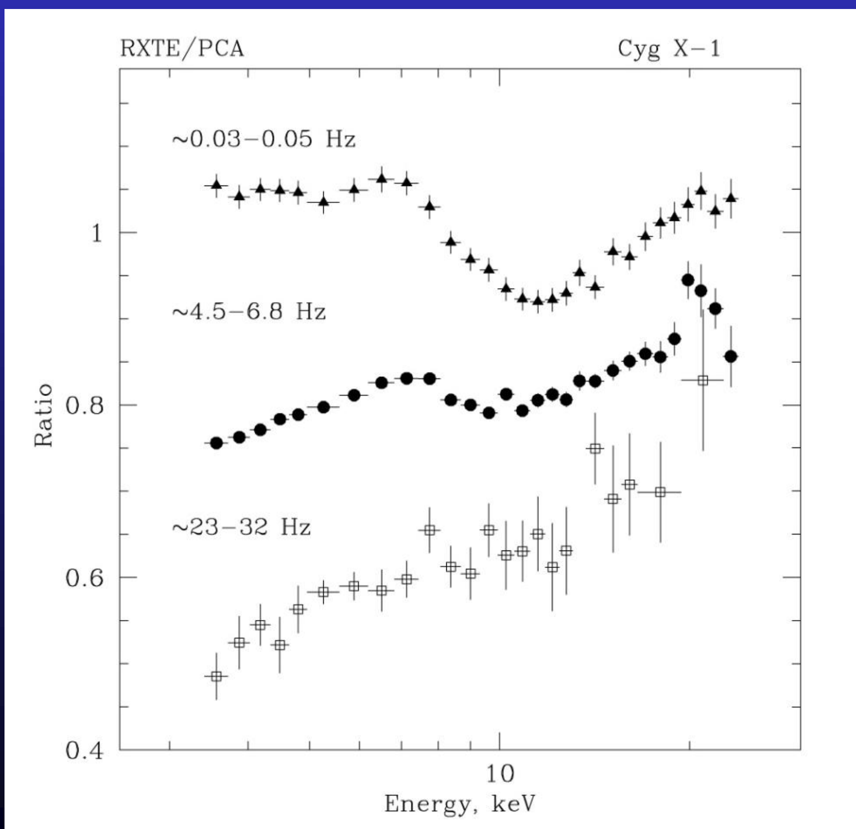
Origin of broad band variability



Fluctuations start at large radii – first, soft and slow with R
propagate down to smaller radii – lagged, harder and faster less R

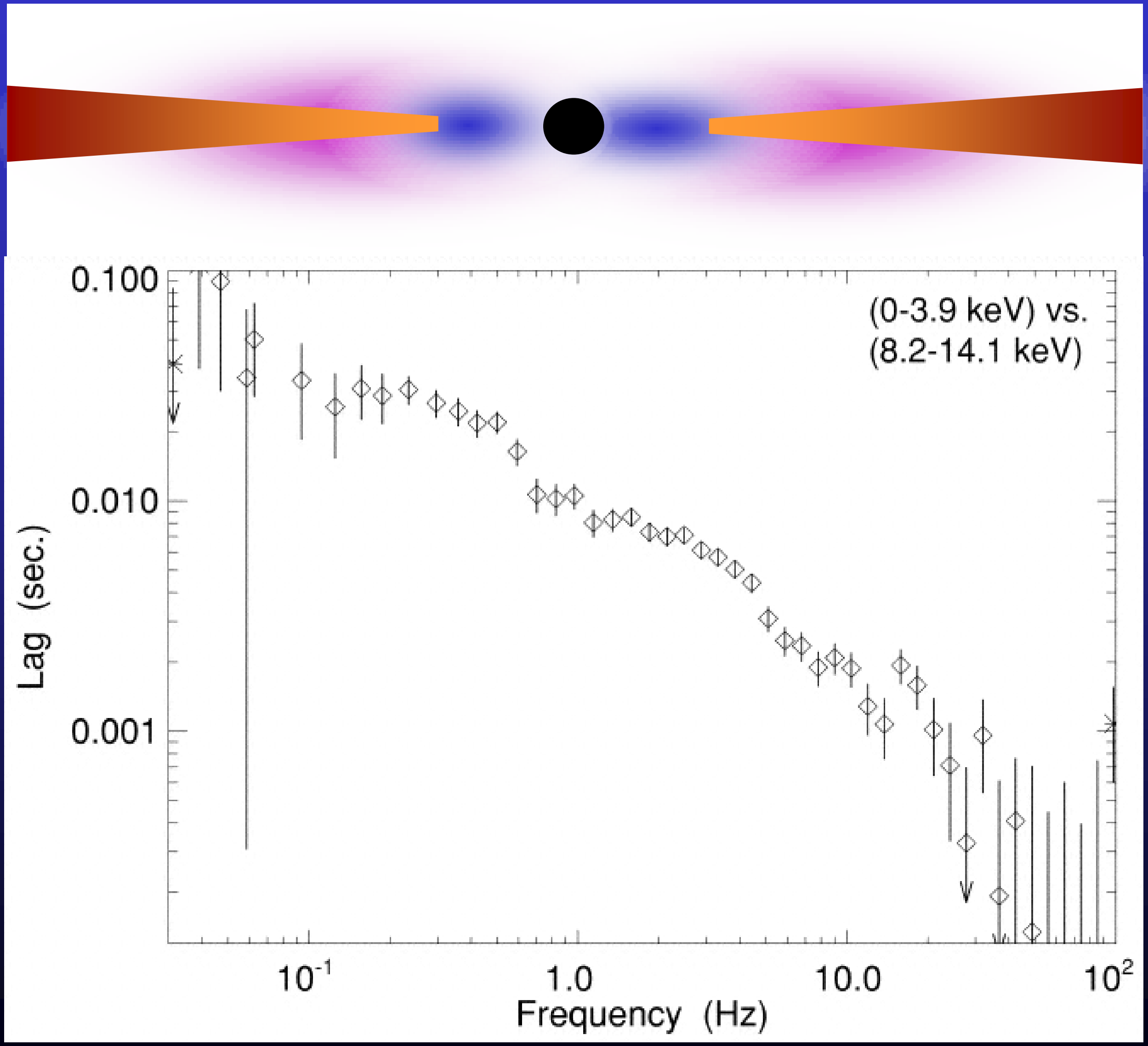
Inhomogeneous close to transition





- Overlap softer, and more reflection, slow variability
- Fluctuations propagate down to inner region – smaller so faster variability. Fewer seed photons so harder spectrum and less reflection
- WE SEE THIS Revnivtsev et al 1999

Inhomogeneous close to transition



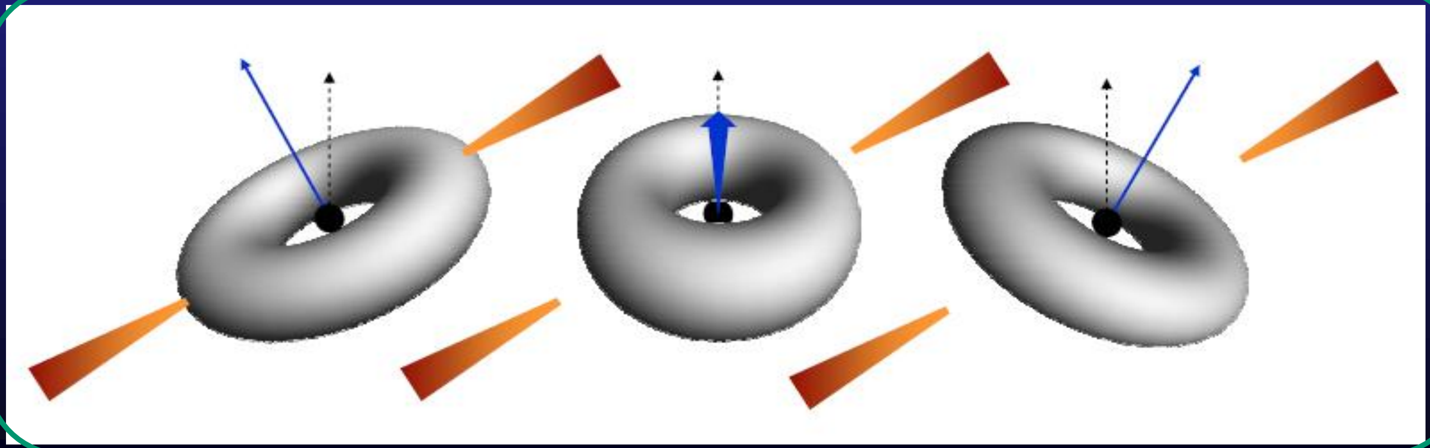
- Overlap softer, slower variability
- Fluctuations propagate down to inner region – lagged. But this has harder spectrum. So hard lags soft. But smaller region so faster variability.
- Miyamoto & Kitamoto 1988; Kotov et al 2001, Nowak et al 1999, Arevalo & Uttley 2006

Conclusions

- Truncated disc/hot inner flow models can explain more or less everything we see in LHS-VHS transition!!!
  - Hard spectra, soften as disc overlaps more with inner flow
  - Spectral transition and jet collapse when disc gets to lso
  - Variability from propagating fluctations (MRI) in hot flow
  - Low frequency break in power spectrum as disc comes in
  - Low frequency QPO from Lense-Thirring precession of entire hot flow – not down to lso as bending waves truncate it
- Challenges!
  - High frequency QPO from some other mode!
  - Broad iron line in low.hard state? (XTEJ1752 Reis et al 2010)

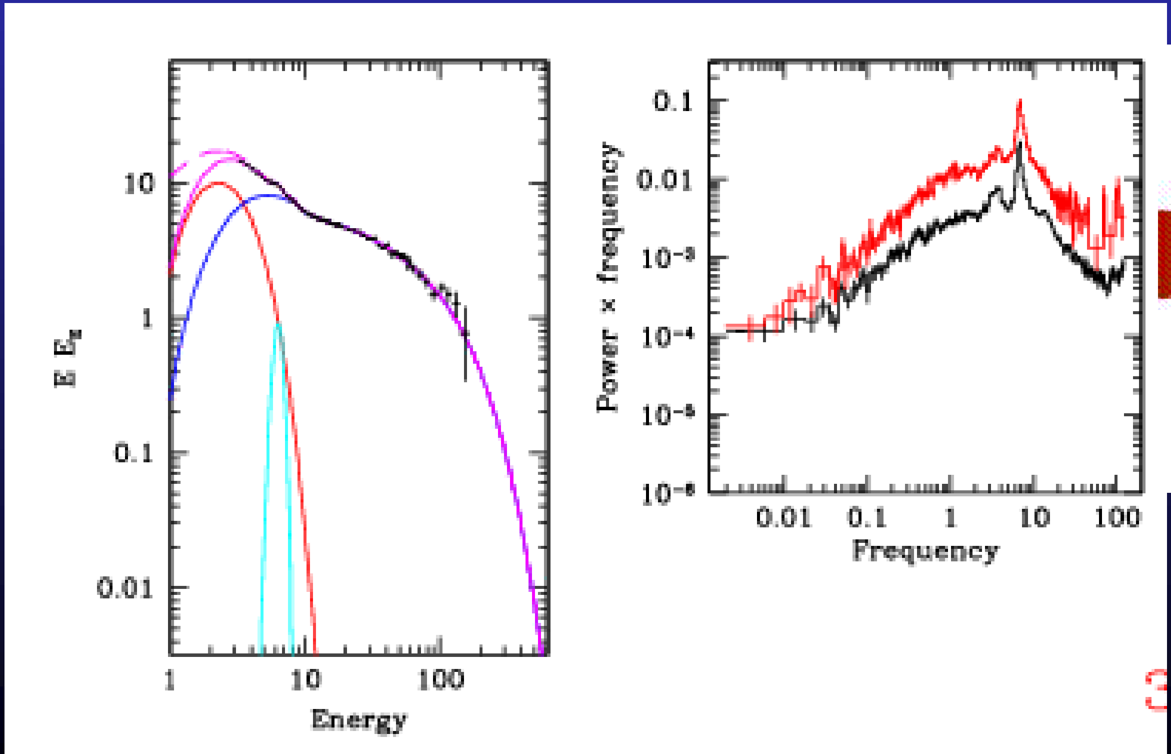
How does it modulate?

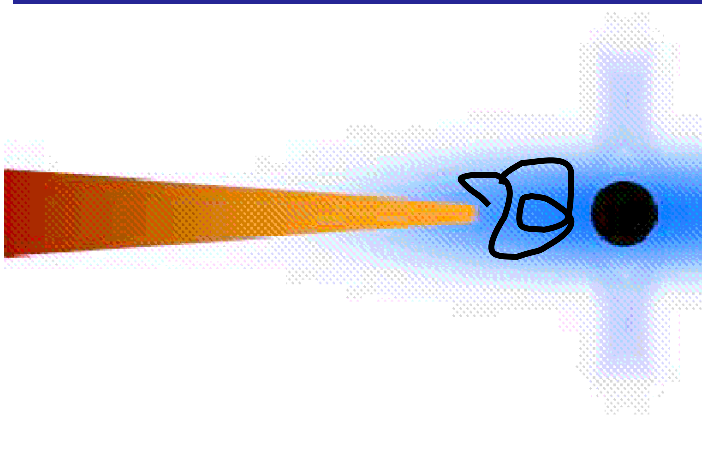
- Optical depth of ~ unity so translucent. Get change in projected area as function of precession
- plus self occultation if inclination within opening angle of torus
- Both these modulate the emission from the hot flow – gives harmonic structure!!



And the LF QPO types?

- Aperiodic variability depends on MRI
- low frequency QPO global mode (Ingram Done & Fragile 2009)
- Global mode can keep going even if MRI suppressed





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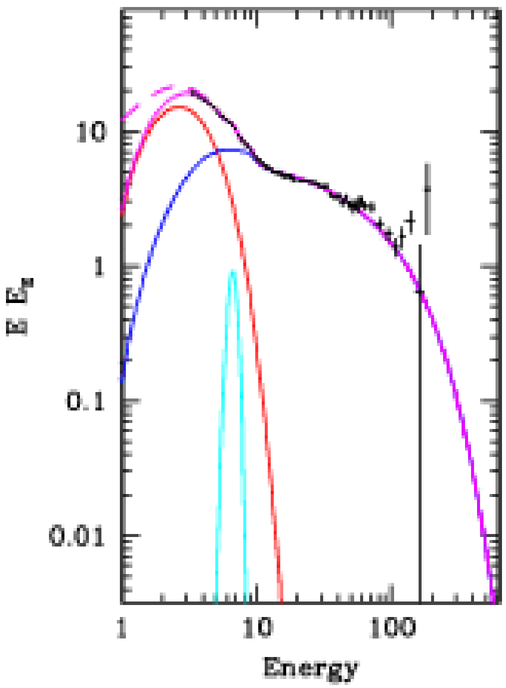

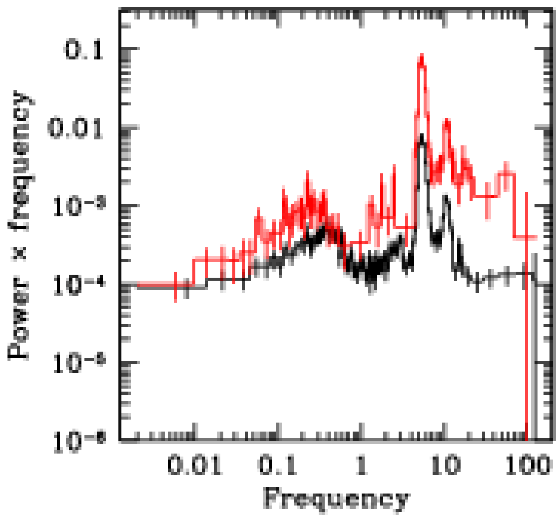

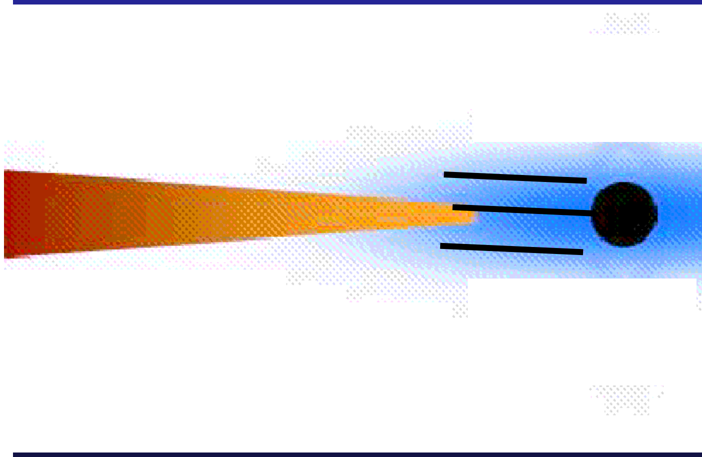

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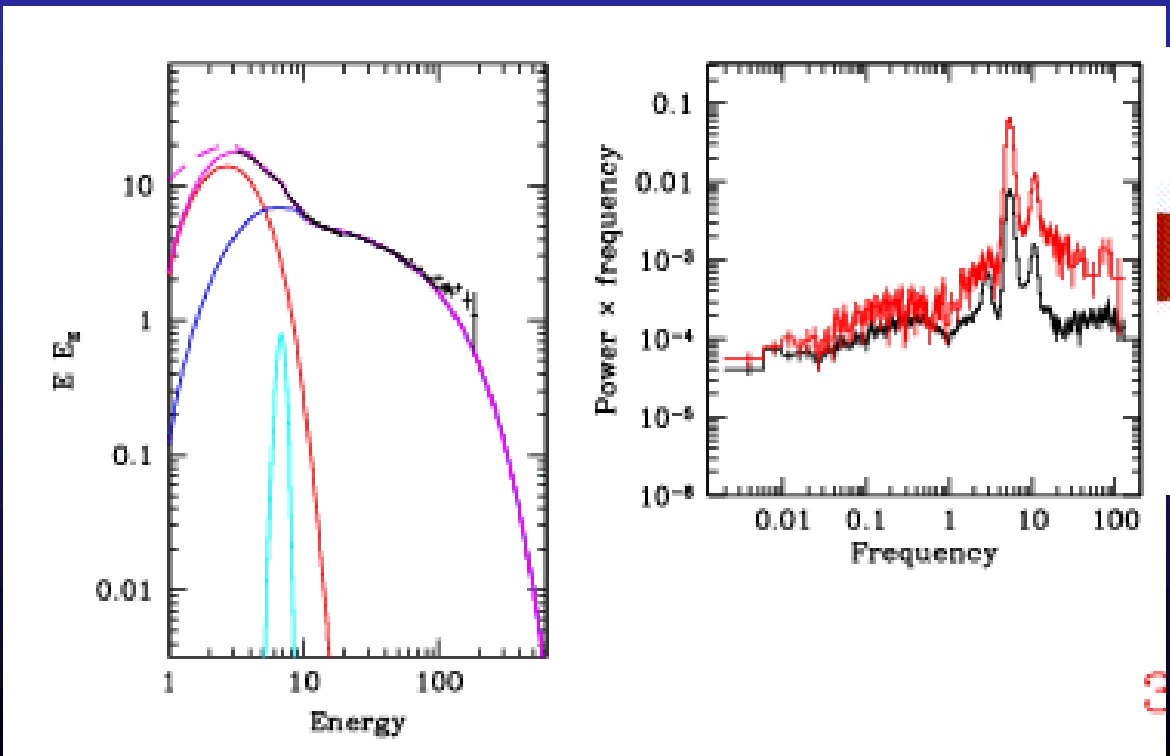
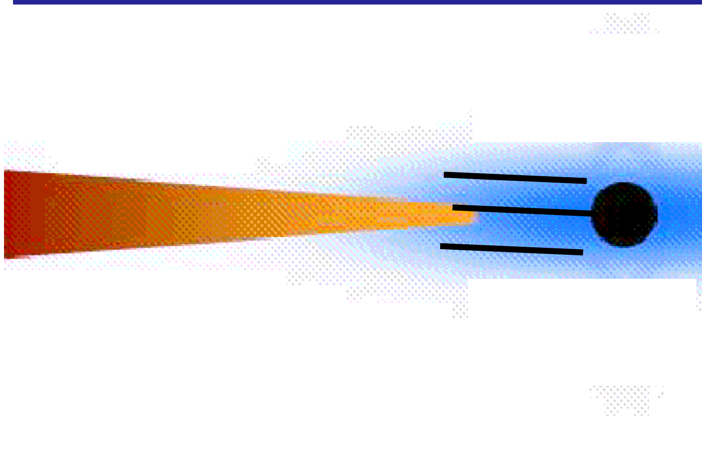
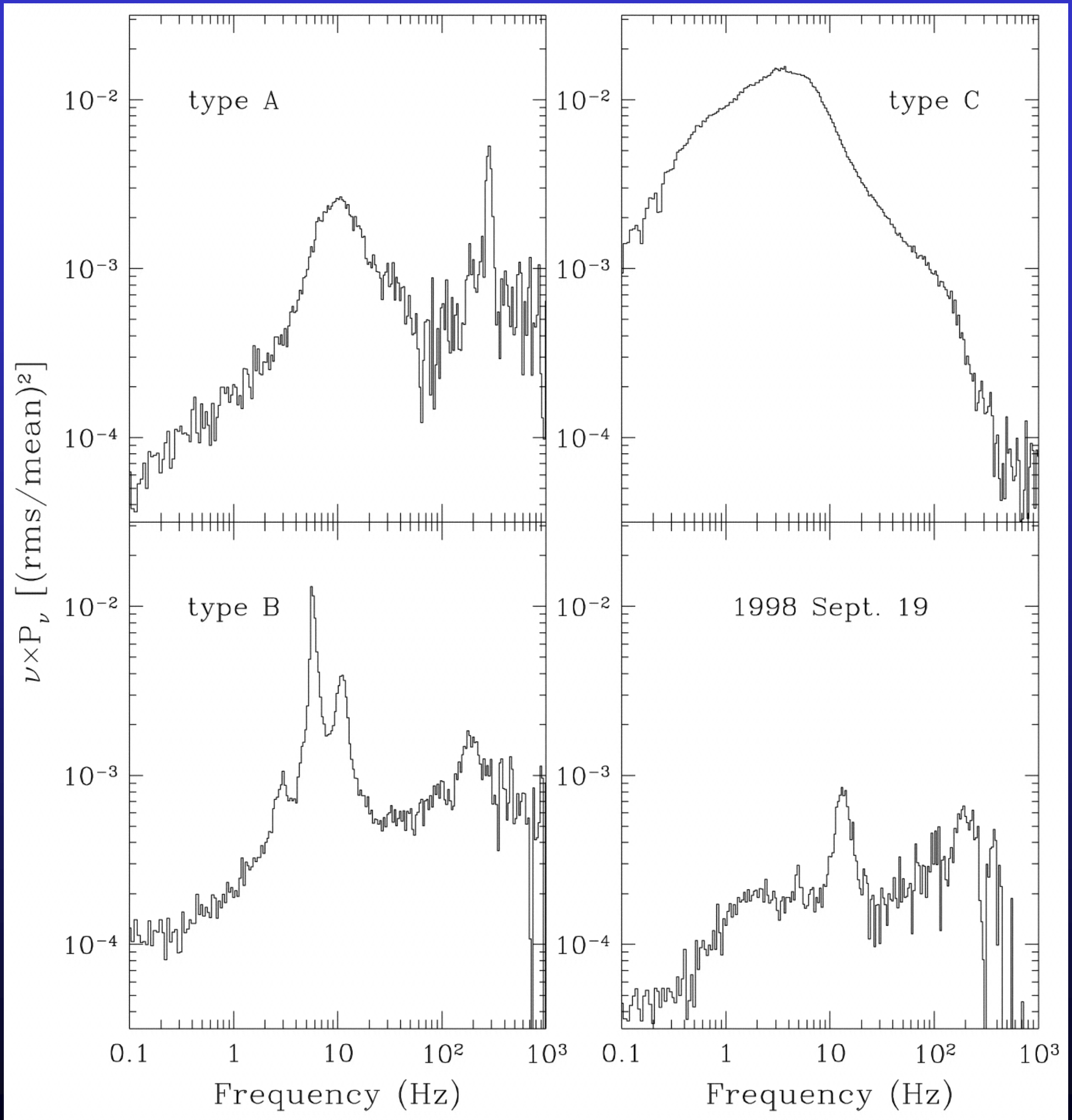
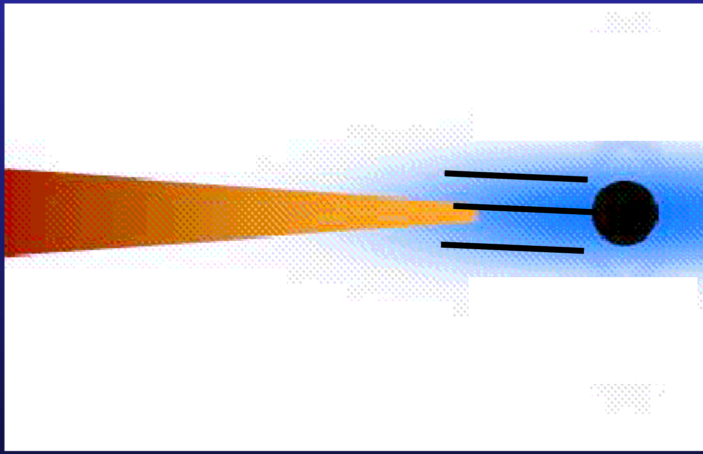




HF QPO origin?



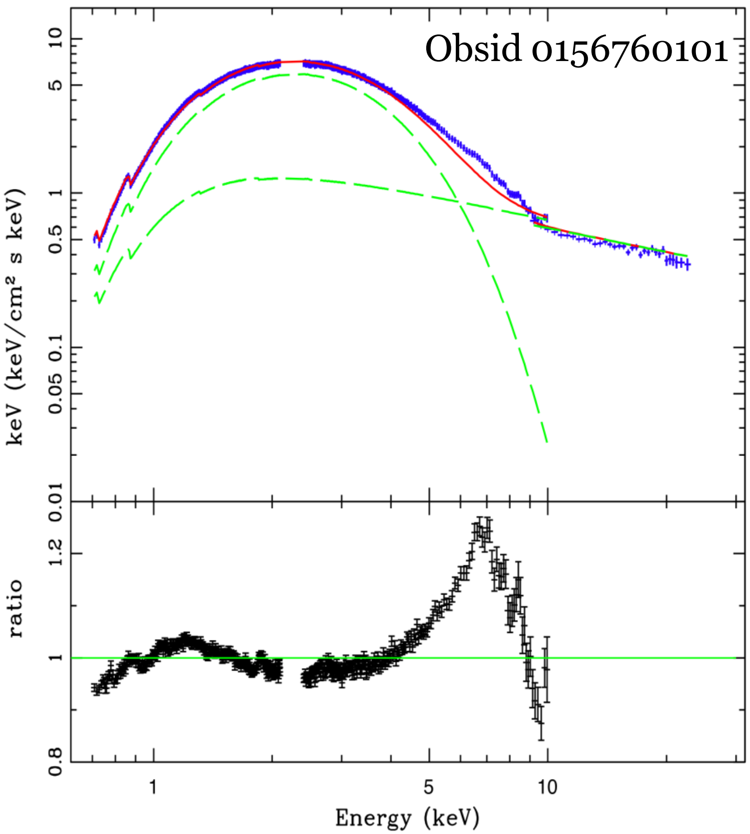


The Fe-line and the BH spin

diskbb+po+reflection

- disc, power law, ionised smeared reflection
- continuum modelled by ignoring 4−7 keV

➔ Residuals show a broad iron line



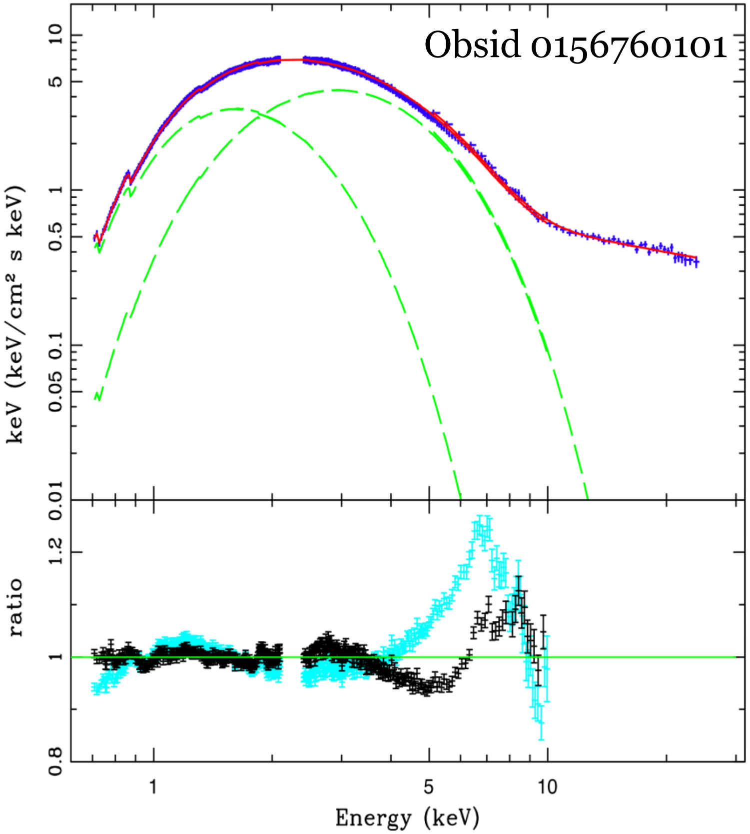
Durham University

The Fe-line and the BH spin

diskbb+compTT+reflection

- convolved disc, compTT, ionised smeared reflection

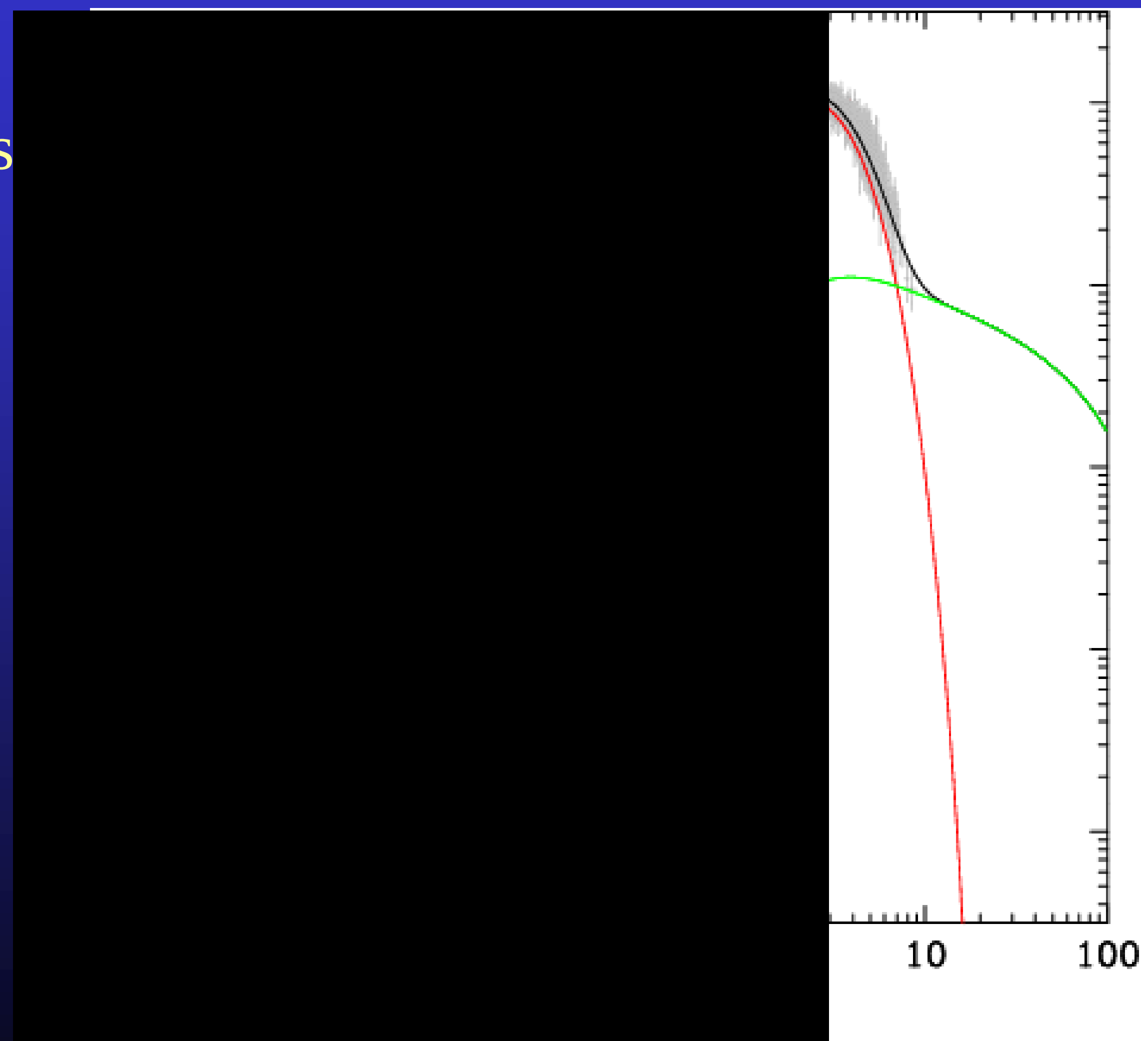
➔ Narrow line does not constrain BH spin



Durham University

Modifies optical continuum

- X-rays illuminate outer disc where intrinsic flux is low so reprocessed can dominate (van Paradijs 1996)
- SWIFT/XMM X-opt simultaneously
- XTE J1817-330 - trace scattered fraction through outburst SWIFT+RXTE
- L_{opt} ~ 0.002 L_{disc} in high/soft state.
- Big changes at transition to low/hard state….



Gierlinski Done & Page 2007

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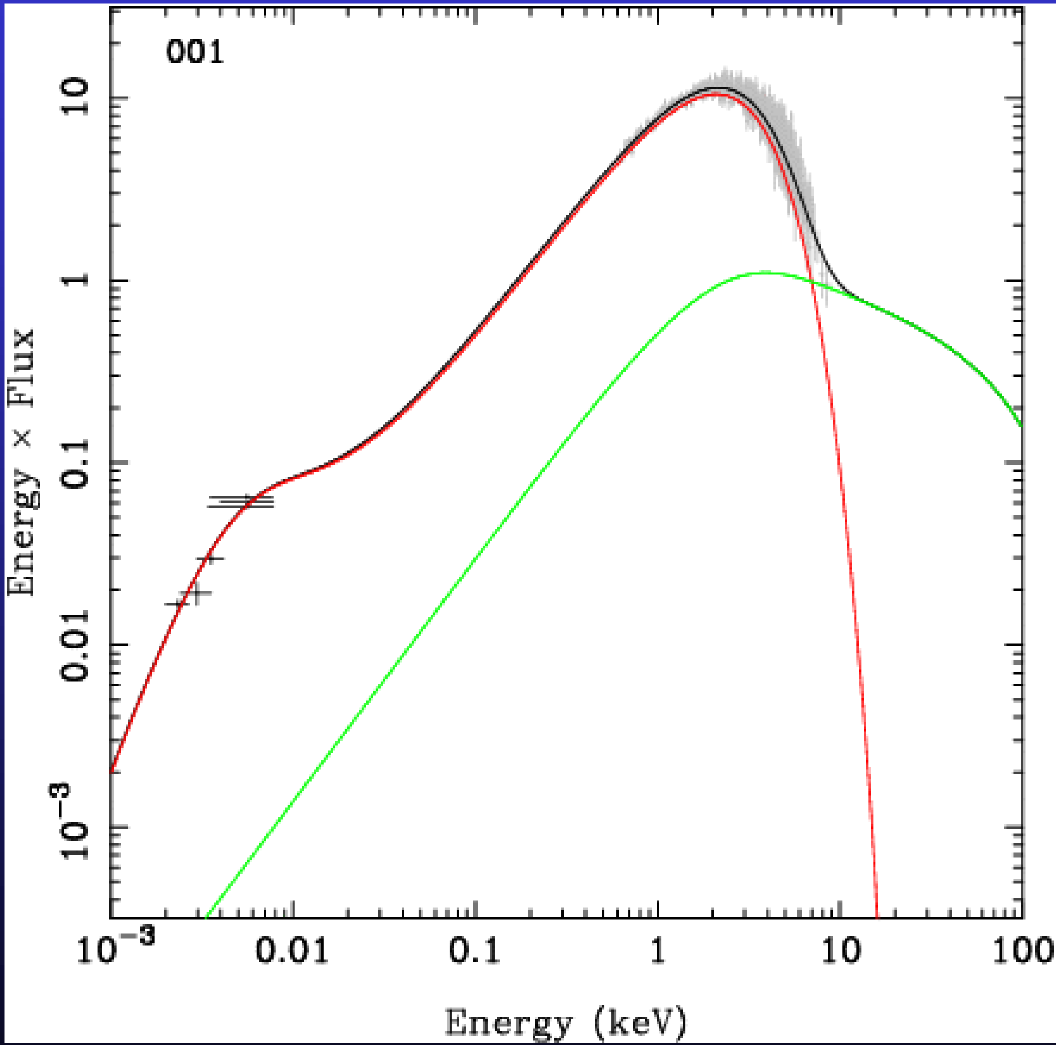
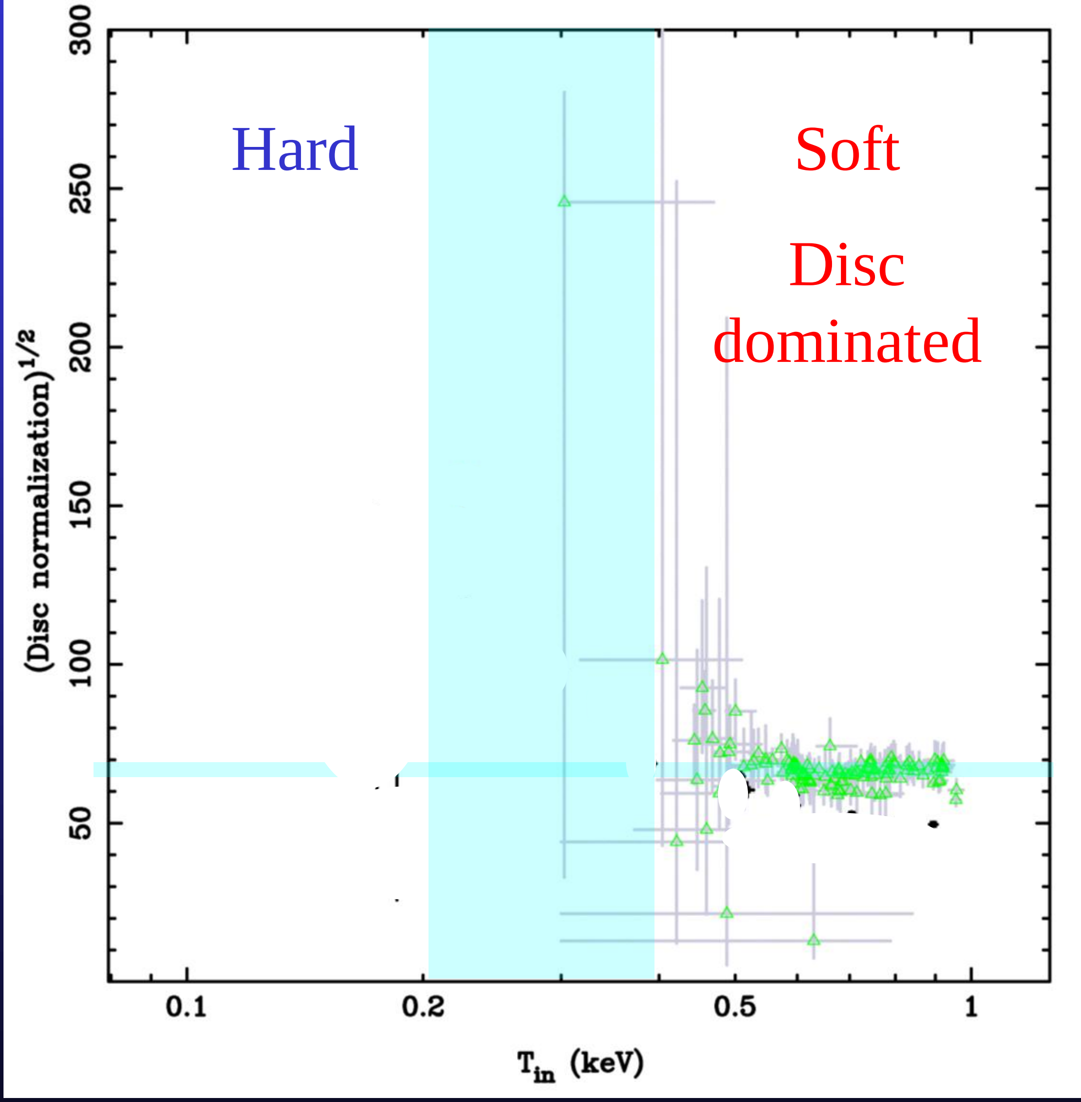


Gierlinski Done & Page 2007

Radius from SWIFT-RXTE

- Clear that SWIFT radius does increase in transition
- Can actually see in Rykoff et al plot as well but much clearer with RXTE data to define radius in disk dominated state
- And their main point is about the disc in the hard state where it does seem small again – but with large errors.



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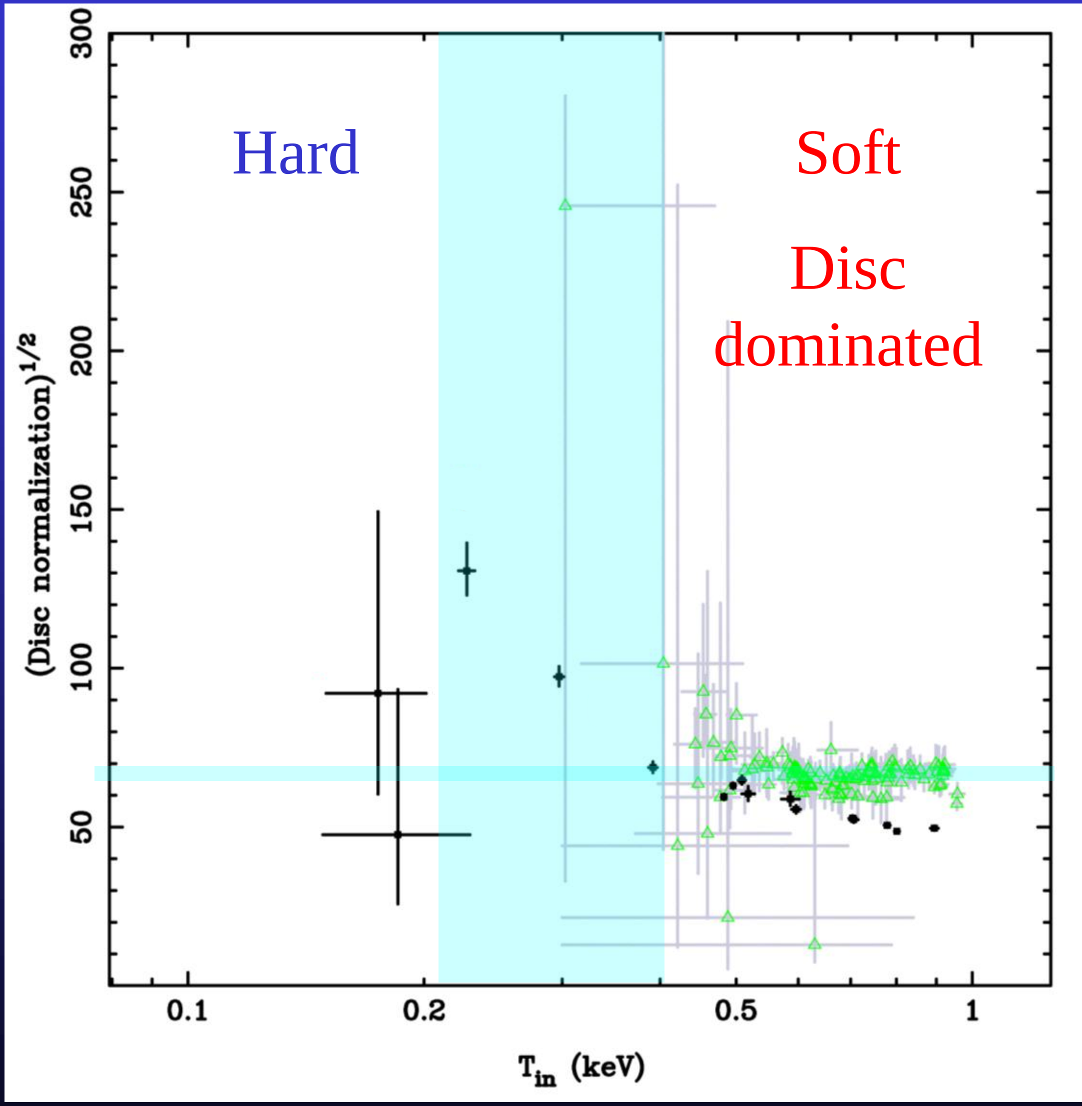
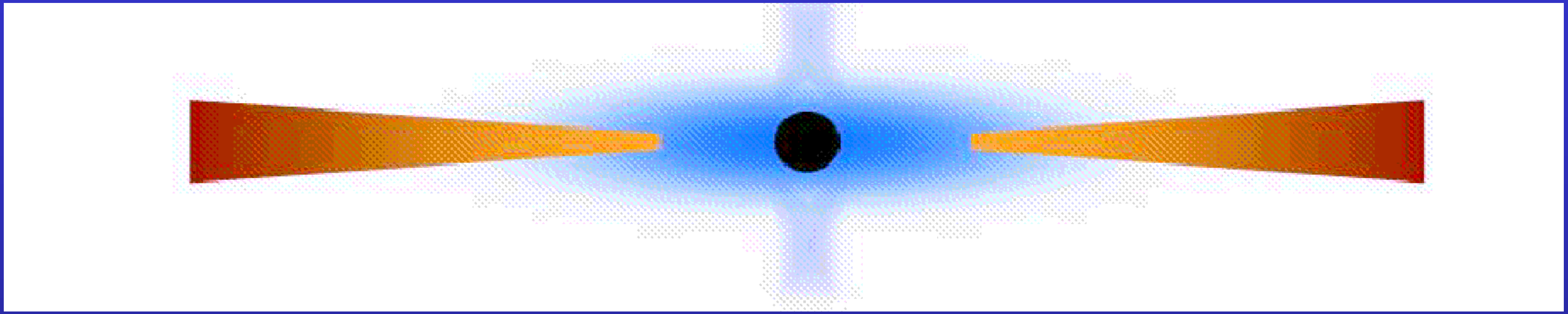
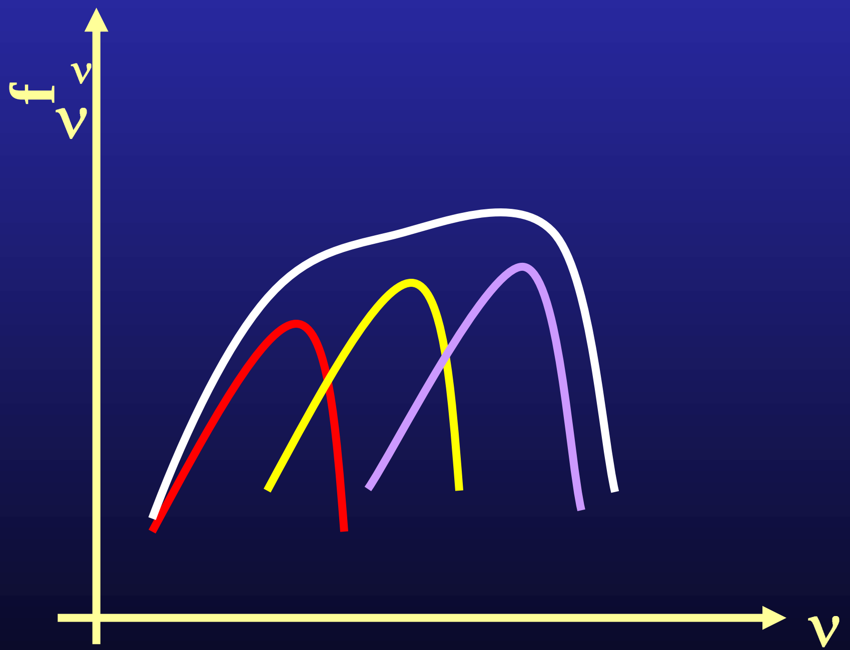
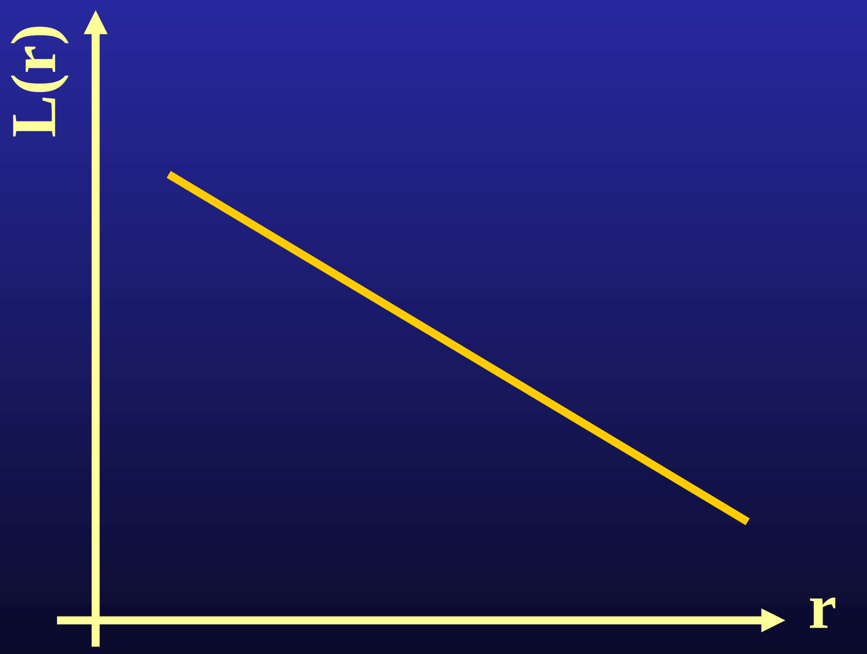


Gierlinski Done & Page 2007

But not simple just after transition







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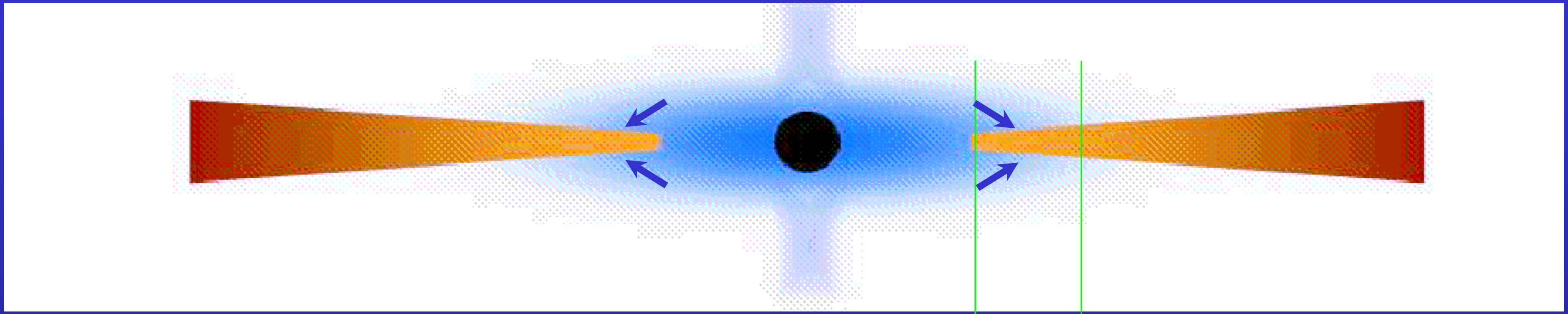
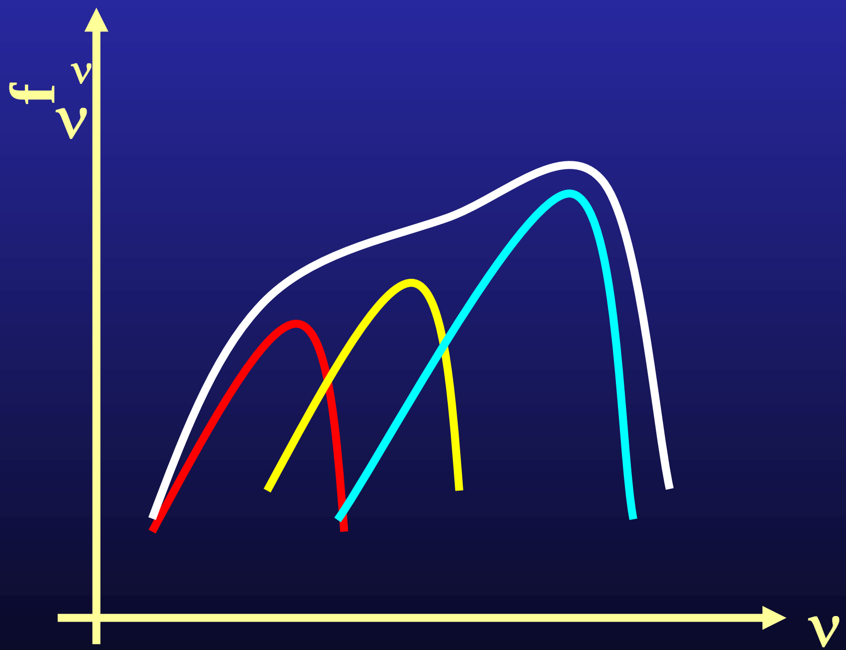
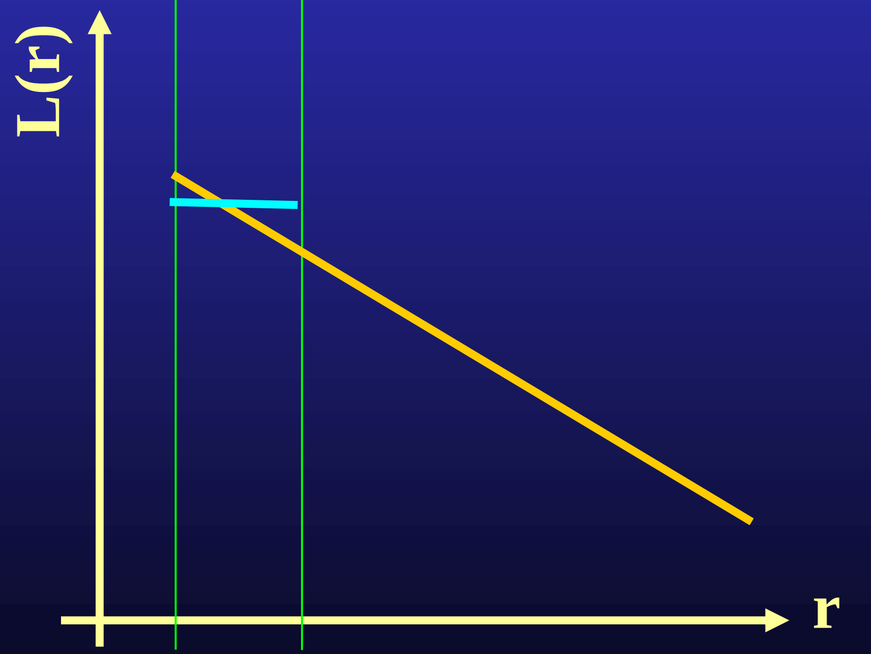


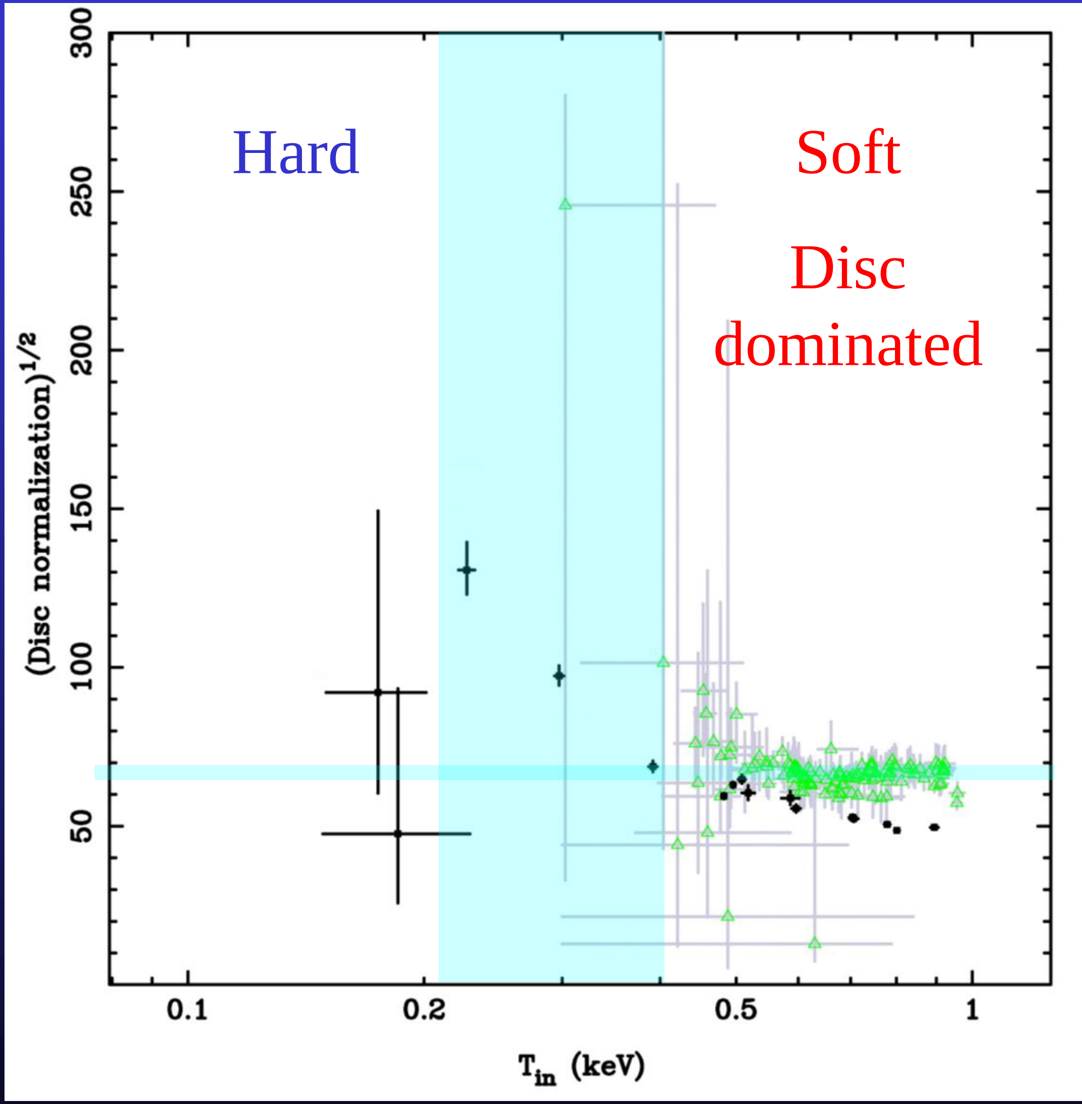




Gierlinski Done & Page 2007

Direct illumination

- Inferred disc radius moves larger with irradiation
- Different stress on inner boundary
- Still assuming same colour temperature correction, radiation thermalises and not correcting for Compton scattering
  Makishima et al 2008



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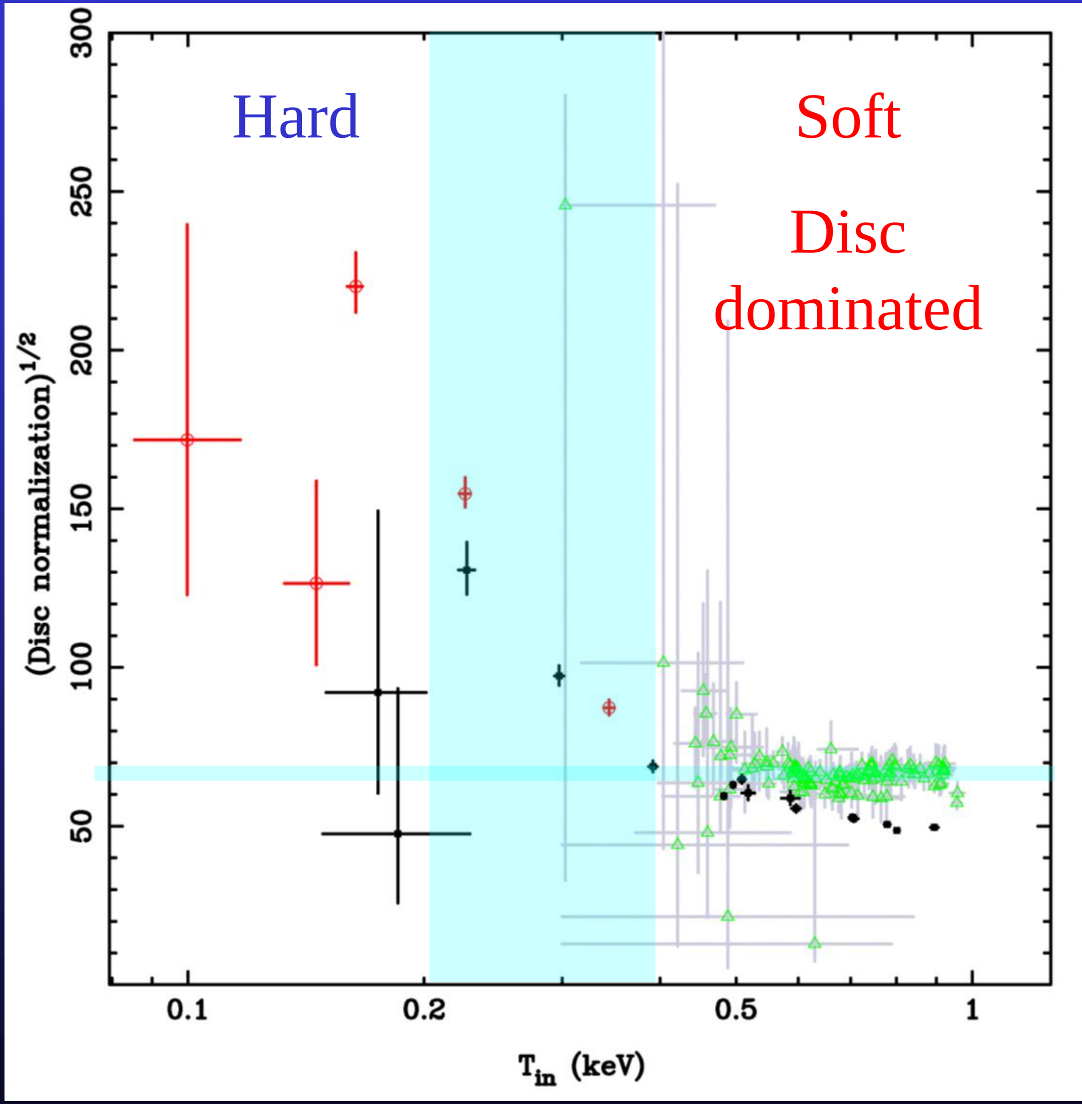

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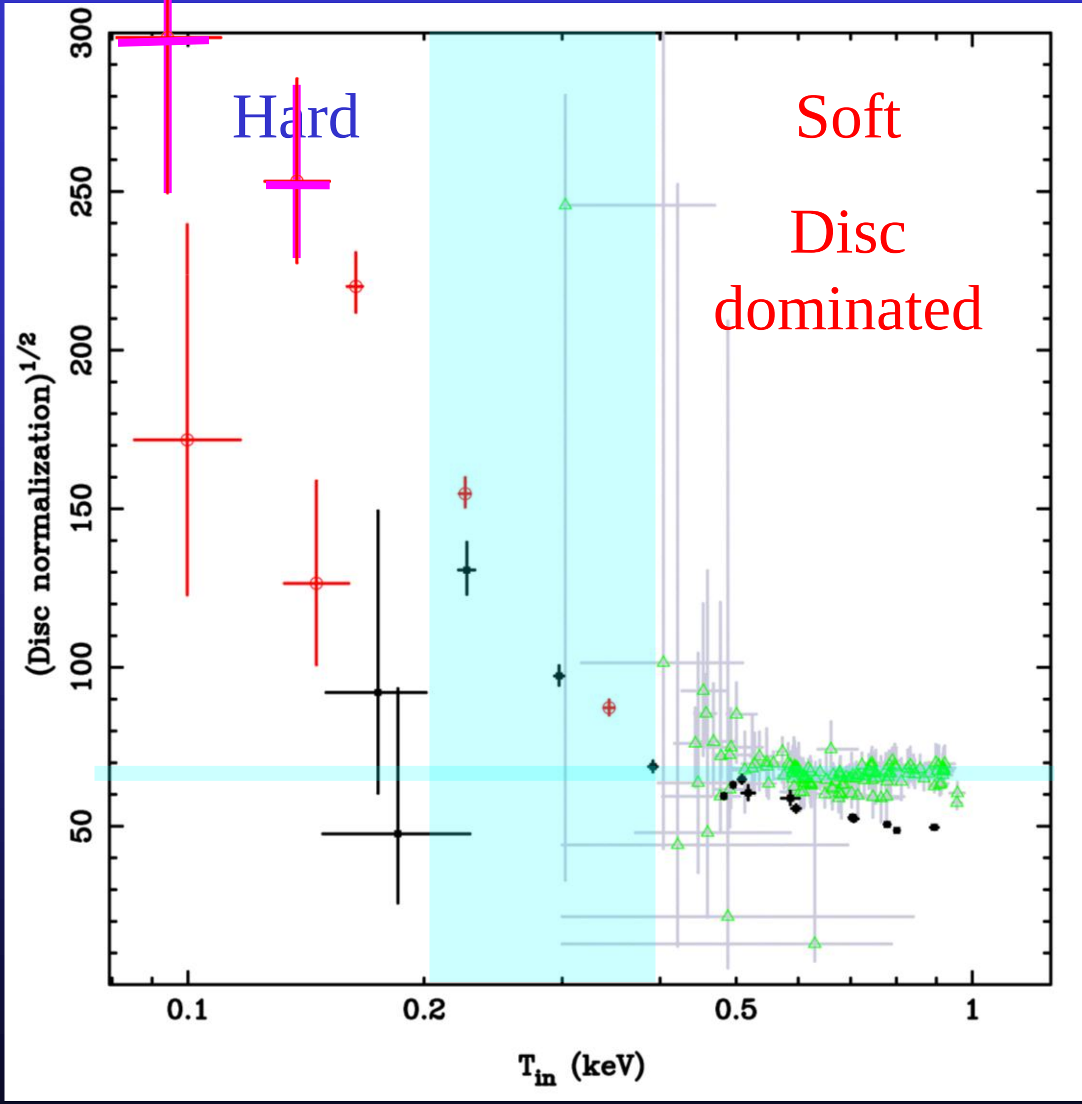

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