Black hole accretion flows

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Modelling the behaviour of accretion flows in X-ray binaries

or

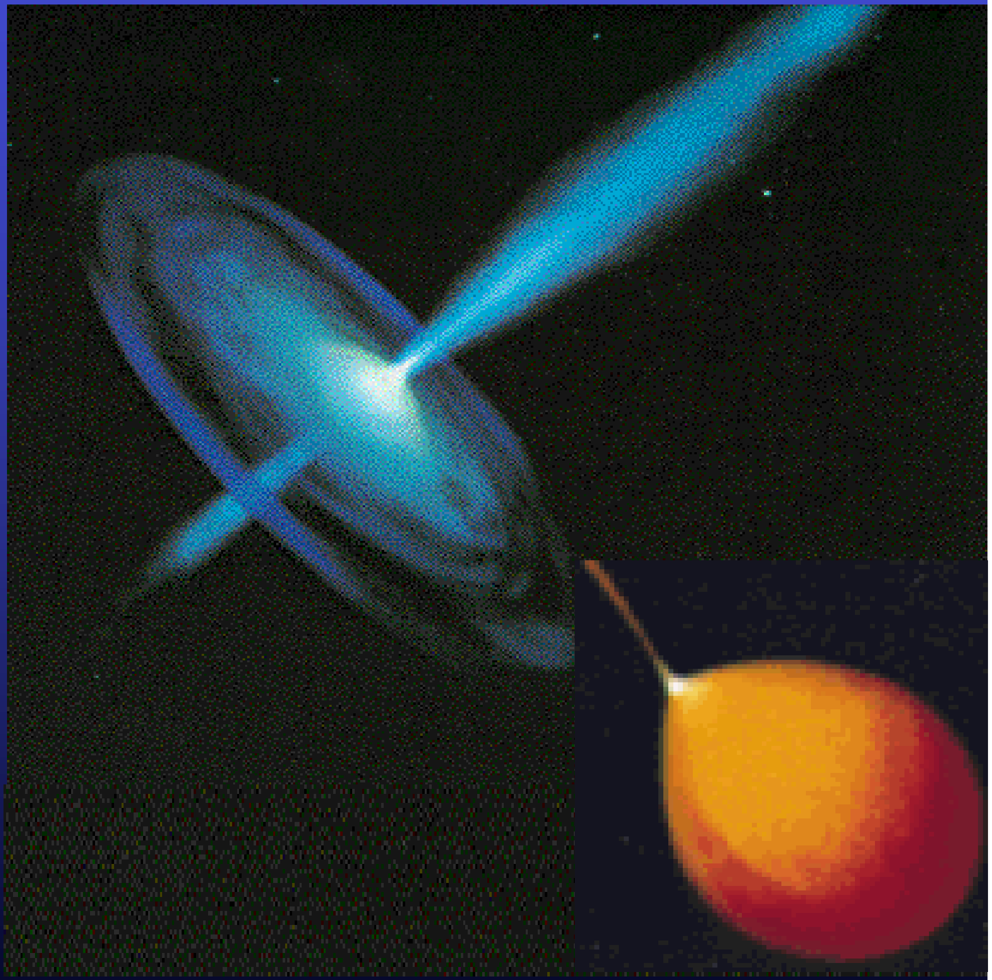
Everything you always wanted to know about accretion but were afraid to ask

Chris Done, Marek Gierlinski, Aya Kubota

Astronomy &Astrophysics Reviews 2007 (DGK07)

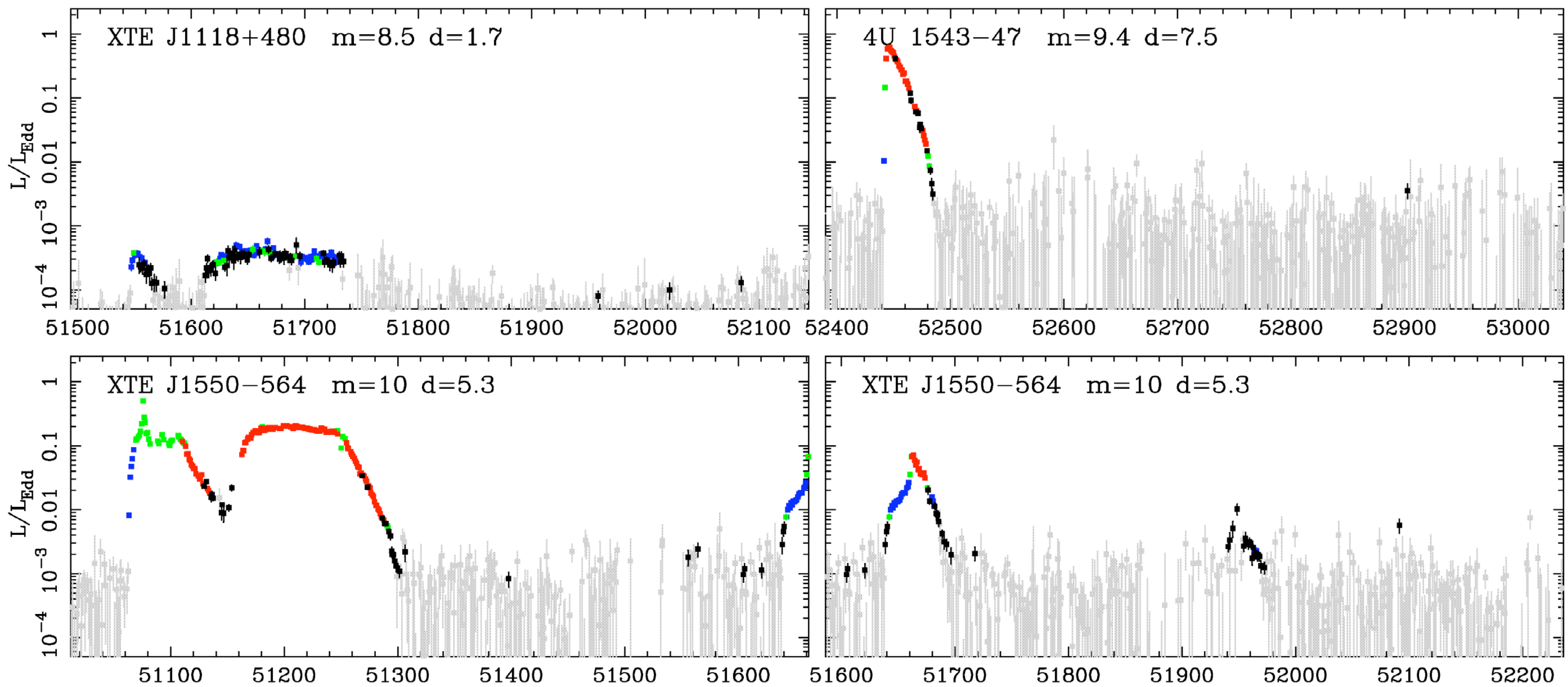
Stellar mass black hole binaries

- Appearance of BH depends only on mass and spin (black holes have no hair!)
- M~3-20 $M_\odot$ (stellar evolution) - very homogeneous
- Plus mass accretion rate, giving observed luminosity L
- Maximum luminosity $\sim L_{\rm Edd}$ where radiation pressure blows further infalling material away
- Get rid of most residual mass dependence by scaling $L/L_{\rm Edd}$
- Form observational template of variation of flow with $L/L_{\rm Edd}$



Transients

- Most transient due to H-ionisation disc instability
- Single object changes L/L_{Edd} by factor of ~10^6 !

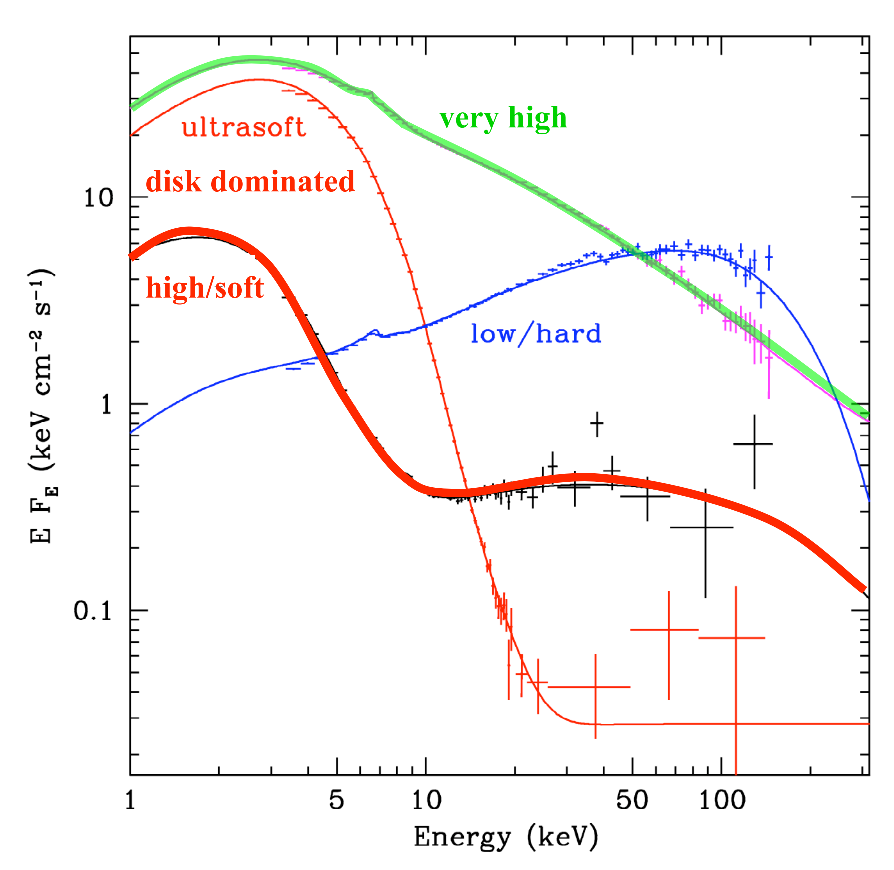


2 years

DGK07

Spectral states

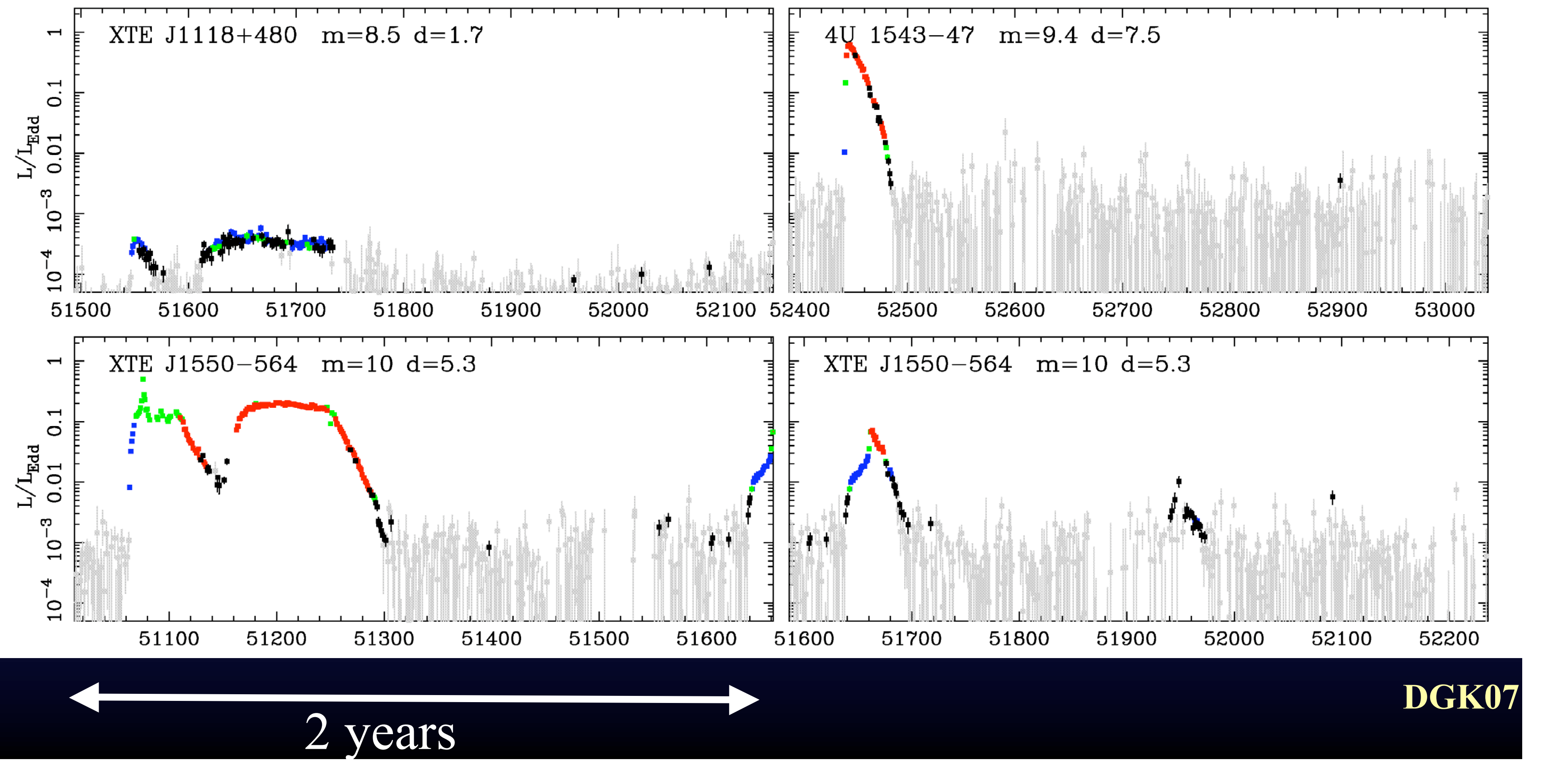
- Dramatic changes in continuum – single object, different days
- Underlying pattern in all systems
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail
- Lower L/L_{Edd}: hard spectrum, peaks at high energies, not like a disc (McClintock & Remillard 2006)



Gierlinski & Done 2003

Transients

- Most transient due to H-ionisation disc instability
- Single object changes L/L_{Edd} by factor of ~10^6 !
- Low L/L_{Edd} outbursts remain hard, high go soft



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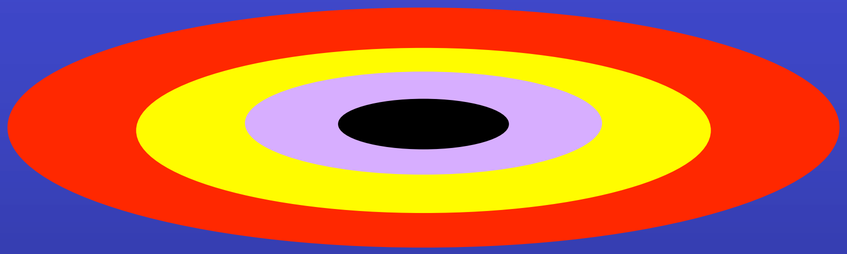
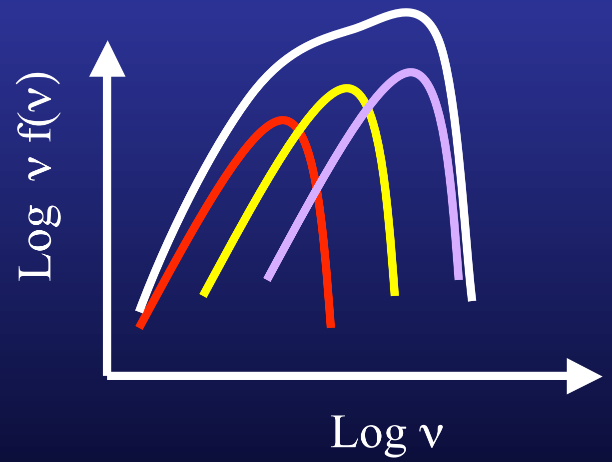
Spectra of accretion flow: disc

- Differential Keplerian rotation
- Viscosity B: gravity → heat
- Thermal emission: $L = A\sigma T^4$
- Temperature increases inwards until minimum radius $R_{lso}(a_*)$
  For a_*=0 and $L \sim L_{Edd}$ $R_{lso} = 6R_g$
  $T_{max} \sim 1$ keV (10^7 K) for 10 $M_\odot$
- Extreme Kerr a*=0.998 (ang. mom of photons from disc spins down from maximal a*=1)
  $R_{lso} = 1.23\ R_g$ T_{max} is 2.2x higher





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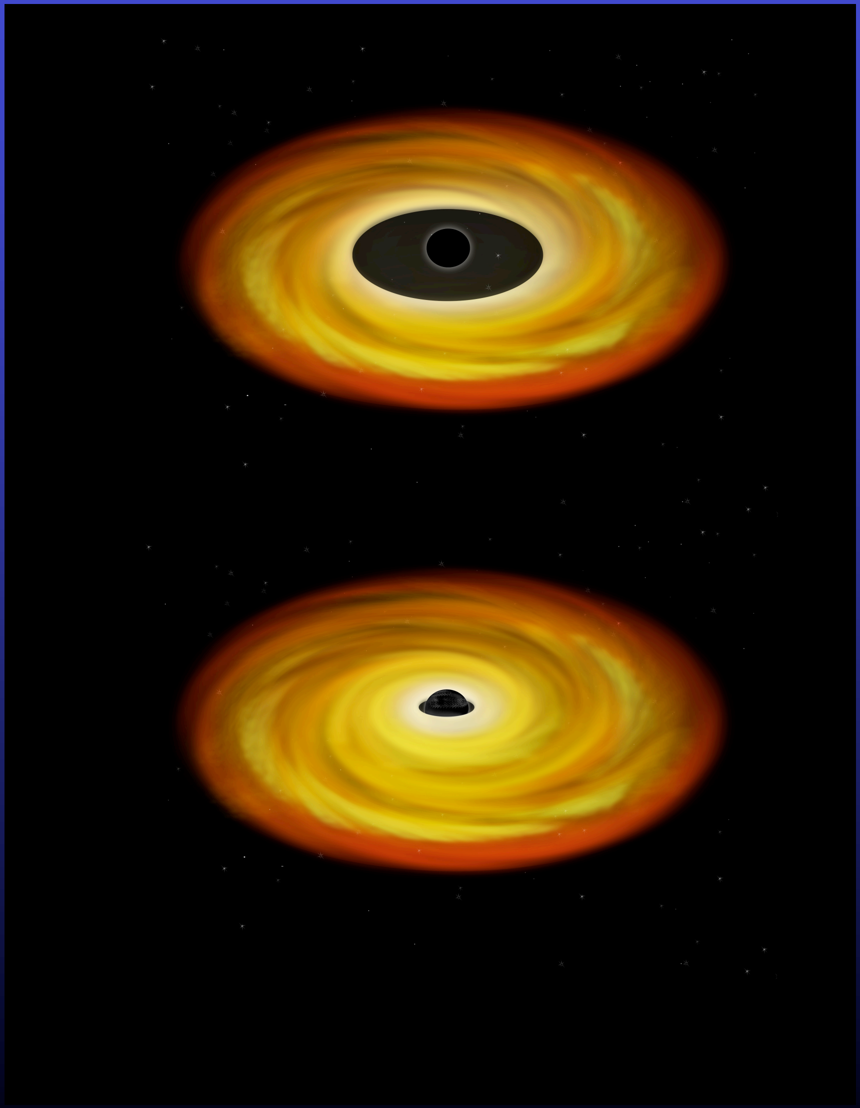
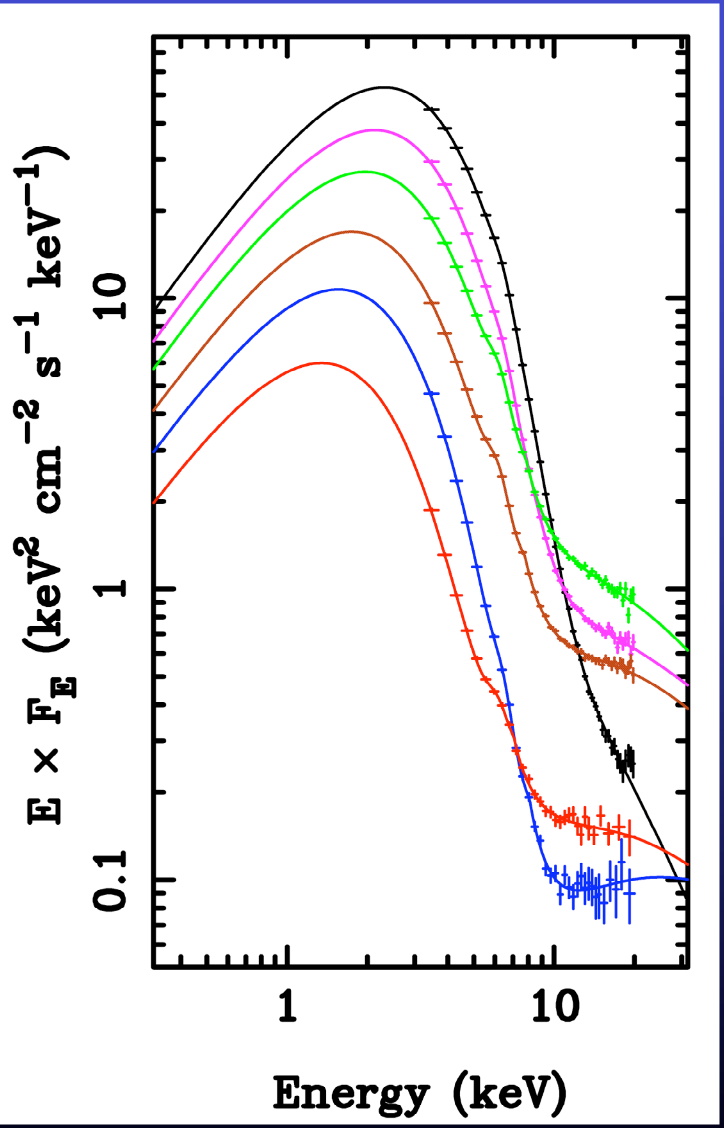


Observed disc spectra

- Pick ONLY ones that look like a disc!
- $L/L_{Edd} \propto T^4_{max}$ (Ebisawa et al 1993; Kubota et al 1999; 2001)
- Constant size scale – last stable orbit!!
- Proportionality constant gives a measure R_{lso} i.e. spin
- Consistent with low to moderate spin **not** extreme/maximal Kerr (see also Shafee et al 2006)



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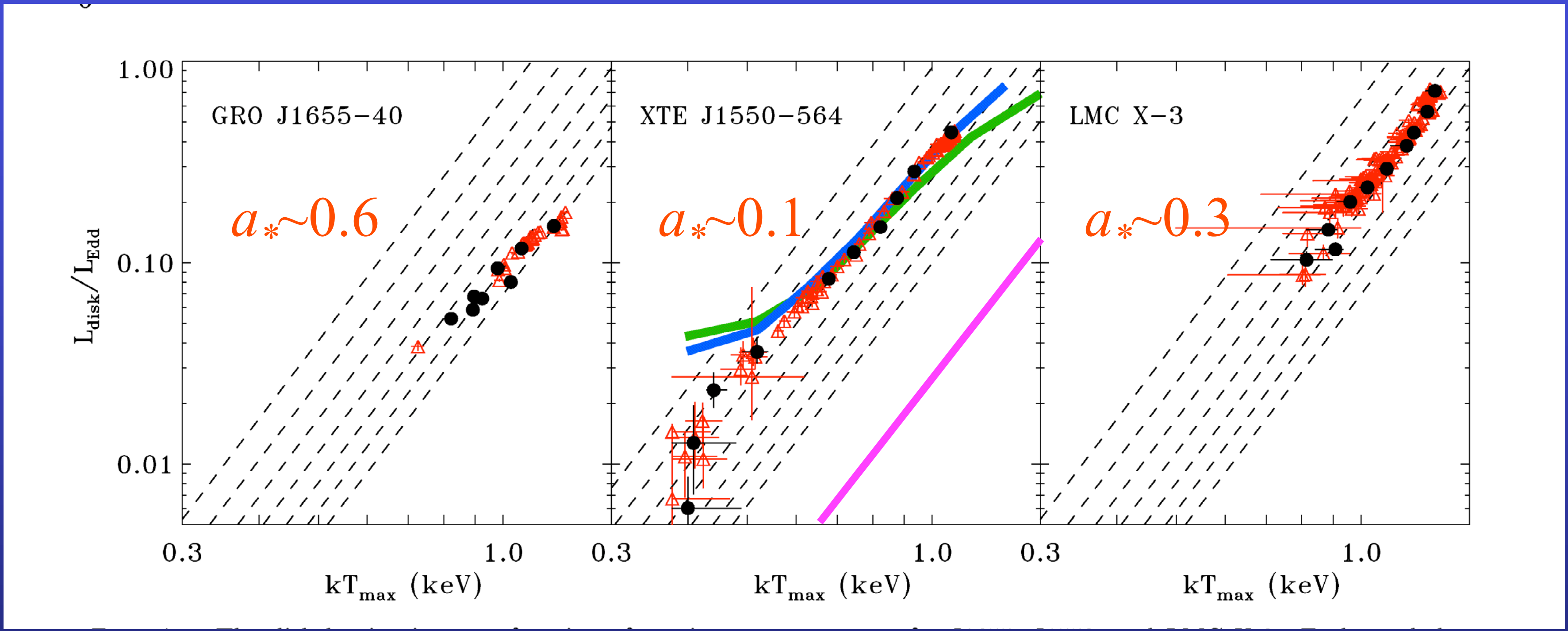
Observed disc spectra

Done Gierlinski Kubota 2007

Observed disc spectra



Davies, Done & Blaes 2005

- Quantify by fitting with best models of disc including vertical structure of disc and GR radiation transport (Davis et al 2006)
- Depends on system parameters distance, mass etc. – inclination not necessarily same as binary! Also depends on viscosity....(???)
- Nonetheless, very difficult to get maximal spin

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)
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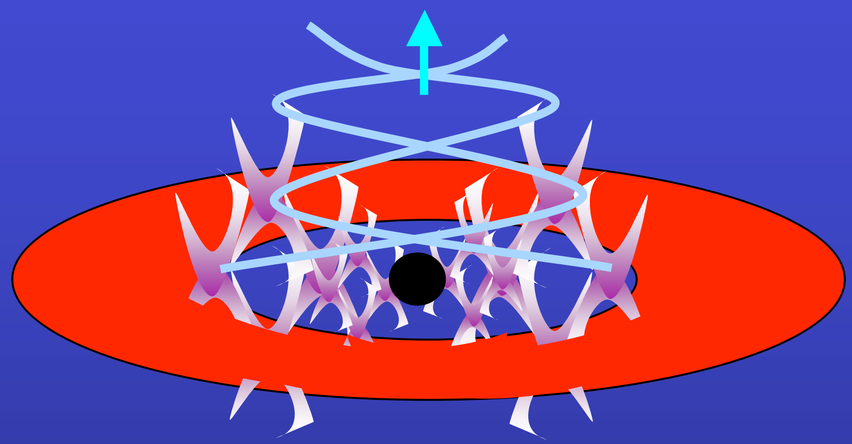

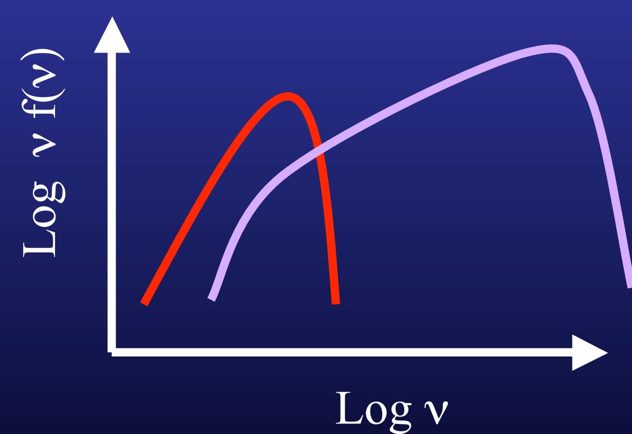

Truncated disc model at low L/L_{Edd}

- Truncated disc/hot inner flow geometry very successful in explaining:
  - Range of low/hard spectra

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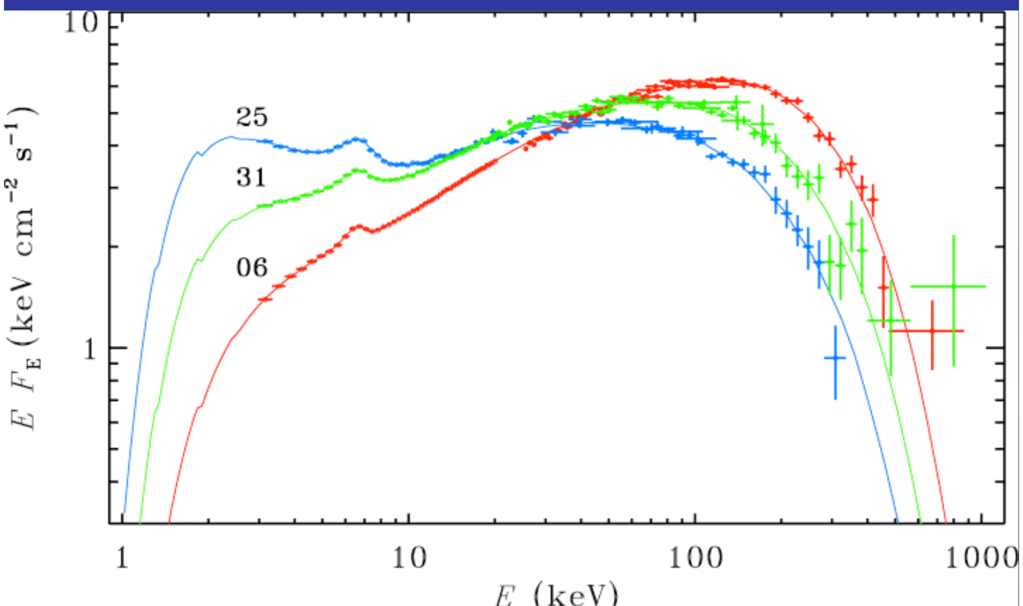
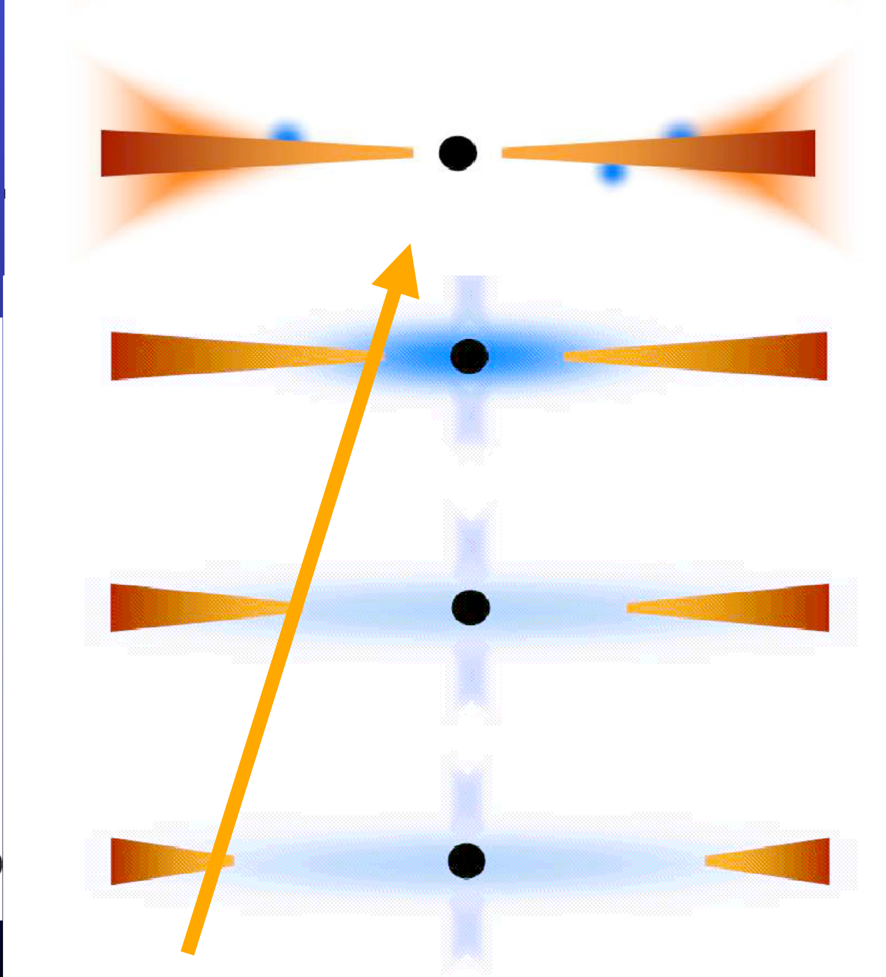


Ibragimov et al 2005



Truncated disc model at low L/L_{Edd}

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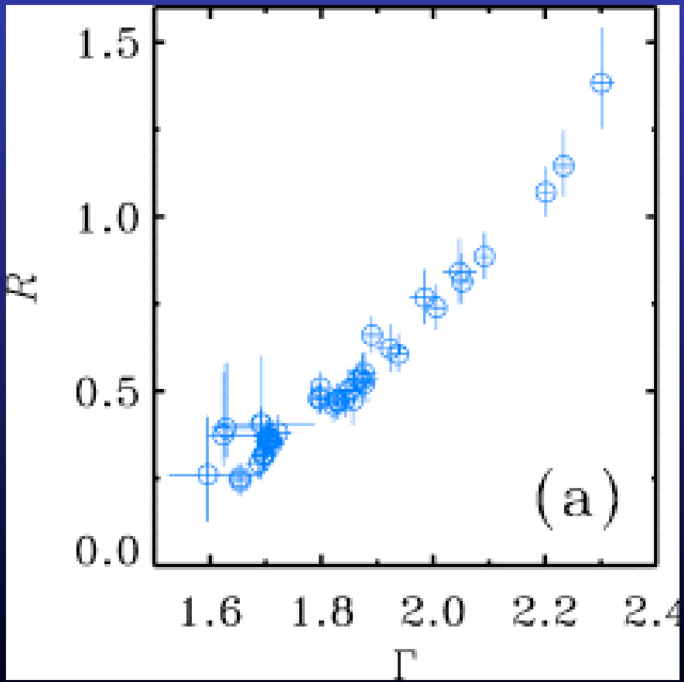
  - Correlated change in reflection strength (Fe EW)



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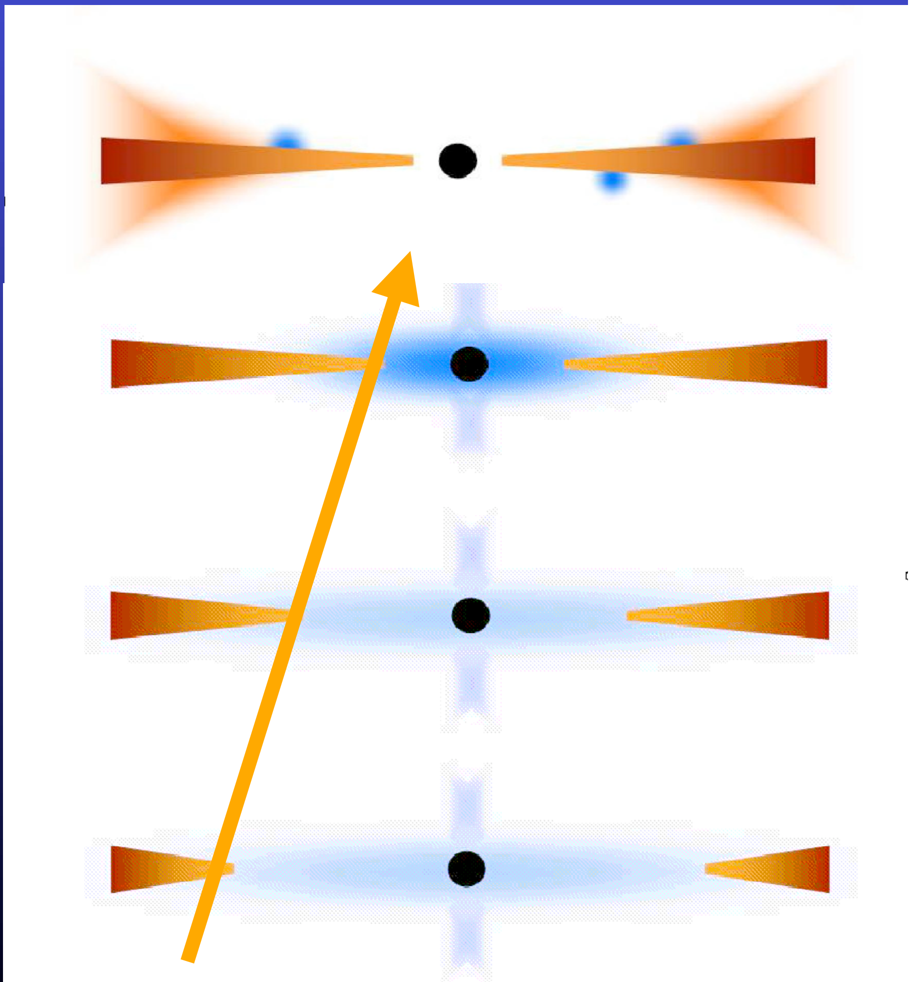

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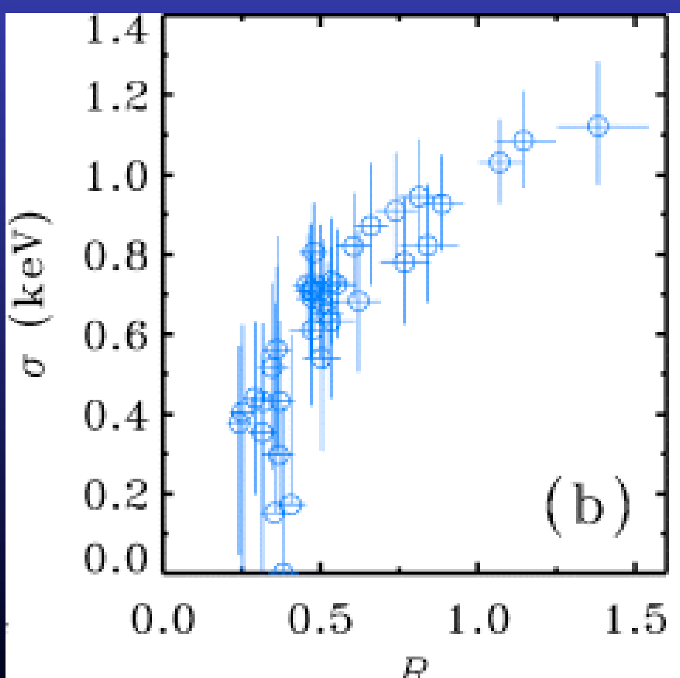
  - Correlated change in Fe width relativistic smearing



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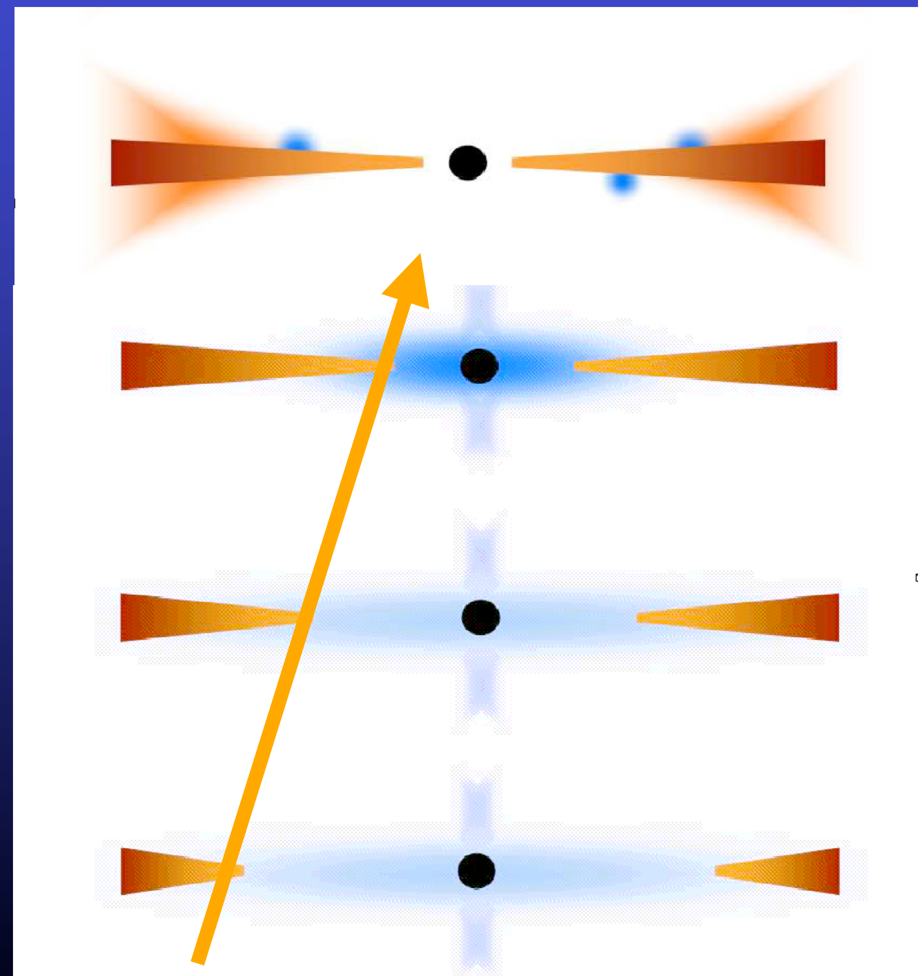

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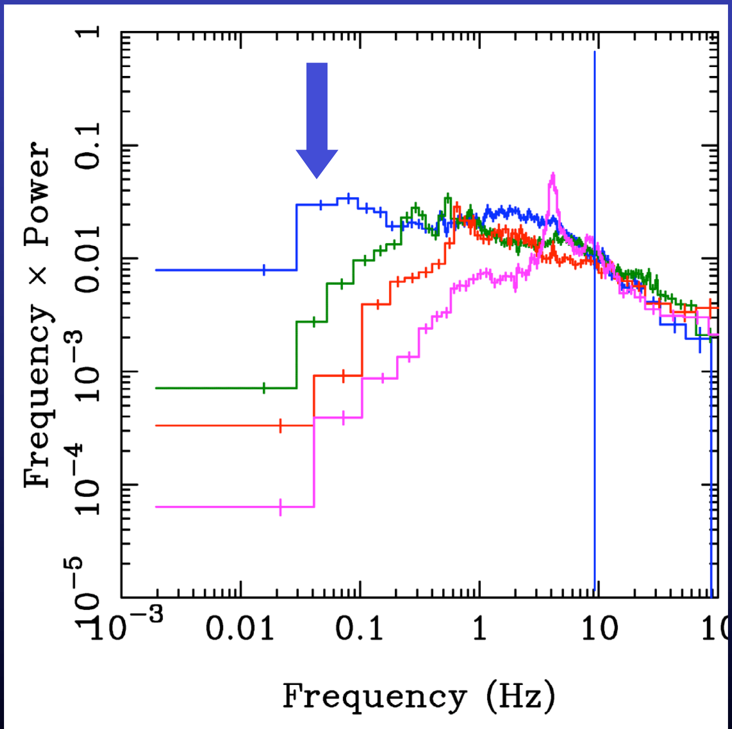
  - Correlated change in PDS frequencies



Gierlinski et al 2007

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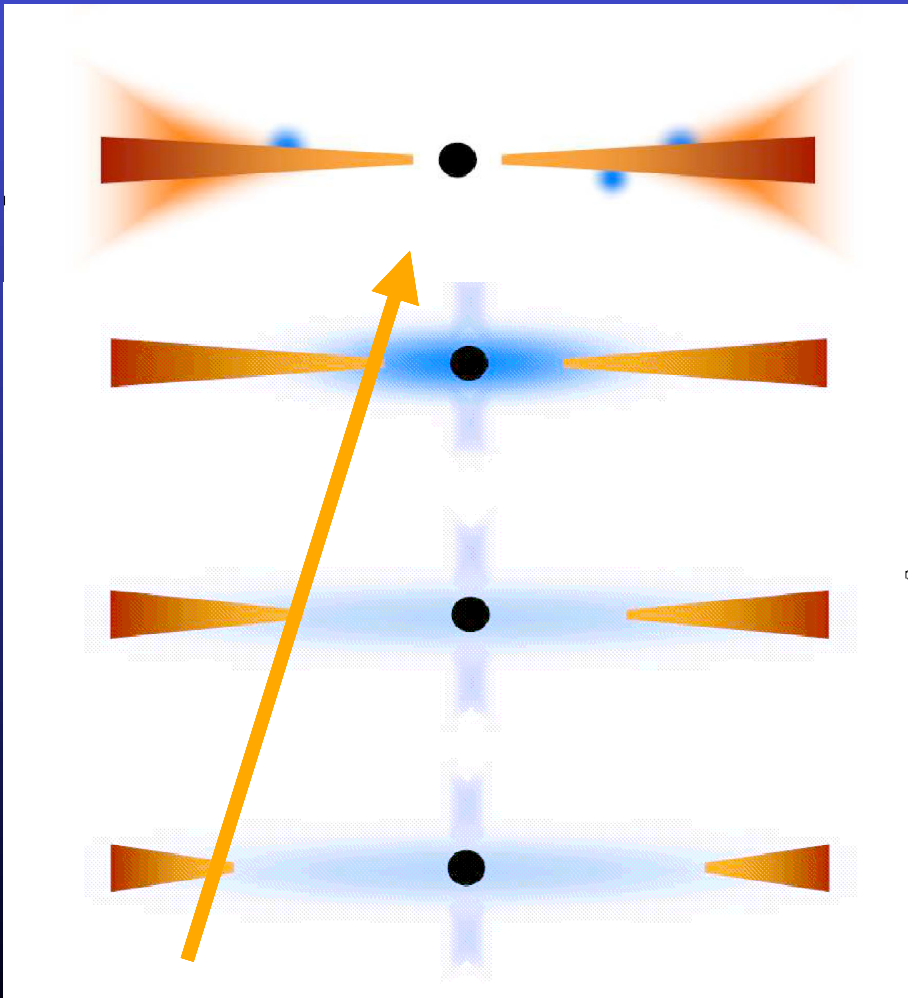
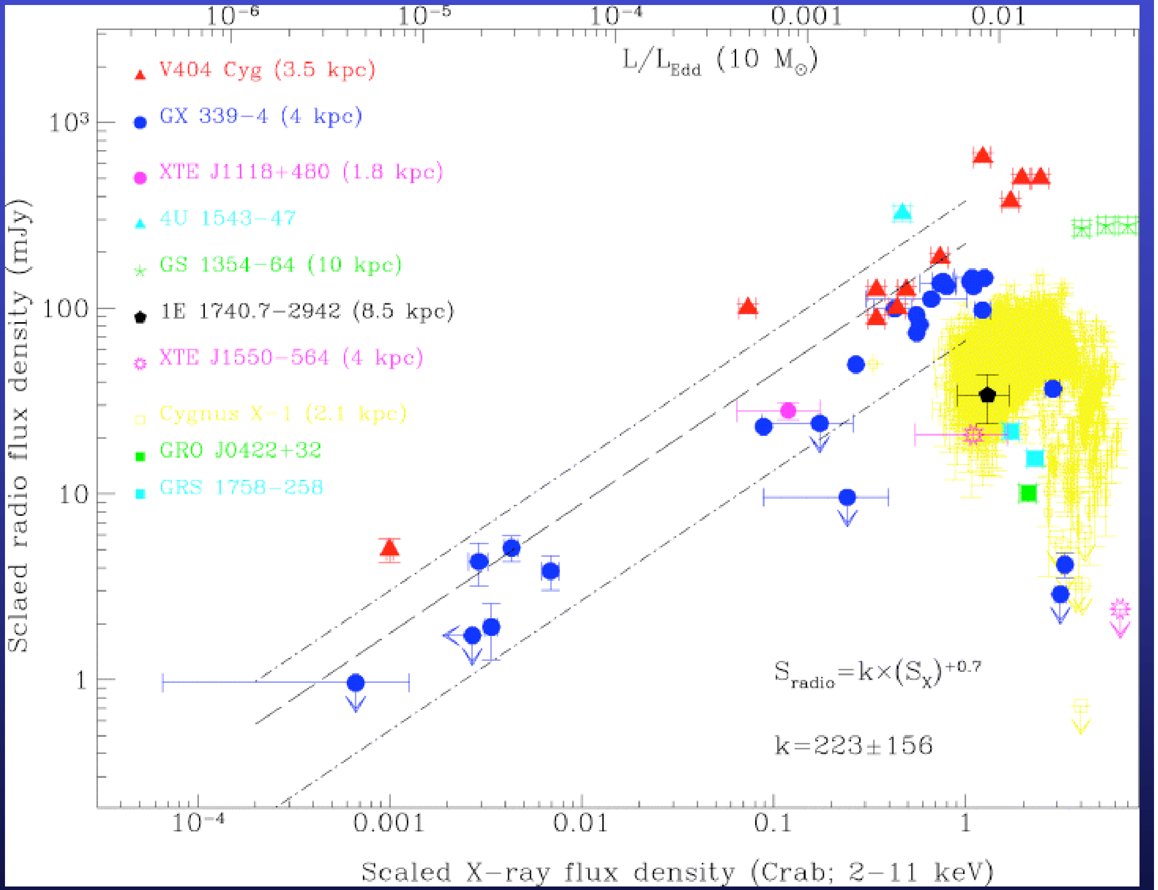


And the radio jet…

- No special µQSO class – they ALL produce jets
- Steady jet in low/hard state, power depends on accretion rate! i.e. L/L_{Edd} (Merloni et al 2003; Falke et al 2004)
- Bright radio flares in rapid low/hard to high/soft associated with outbursts. (Fender et al 2004)
- Jet strongly quenched in high/soft disc dominated spectra….!!
- Need hot inner flow for jet launching – B fields



Gallo et al 2003

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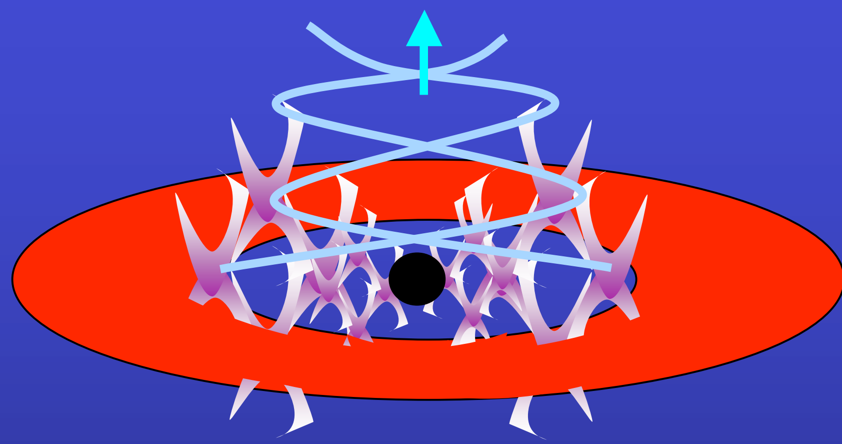
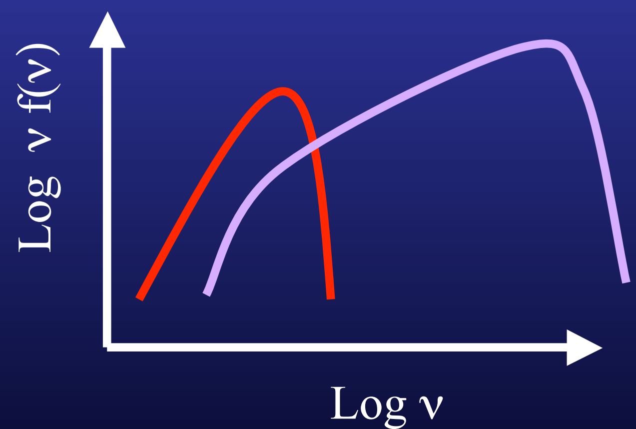
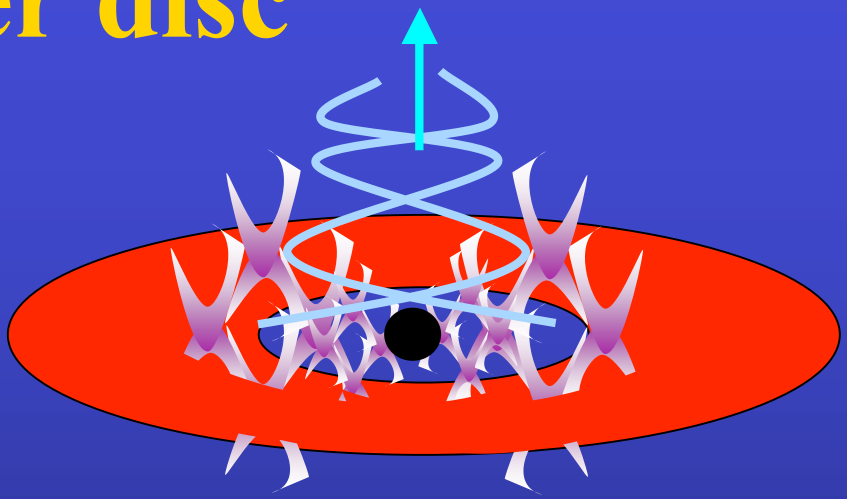




No inner disc



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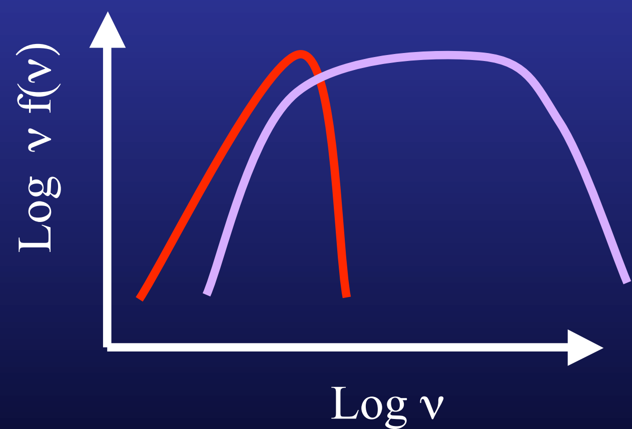
- More seed photons, so spectrum is softer
- Smaller region so higher freq.
- Jet from large scale height flow velocity linked to launch radius



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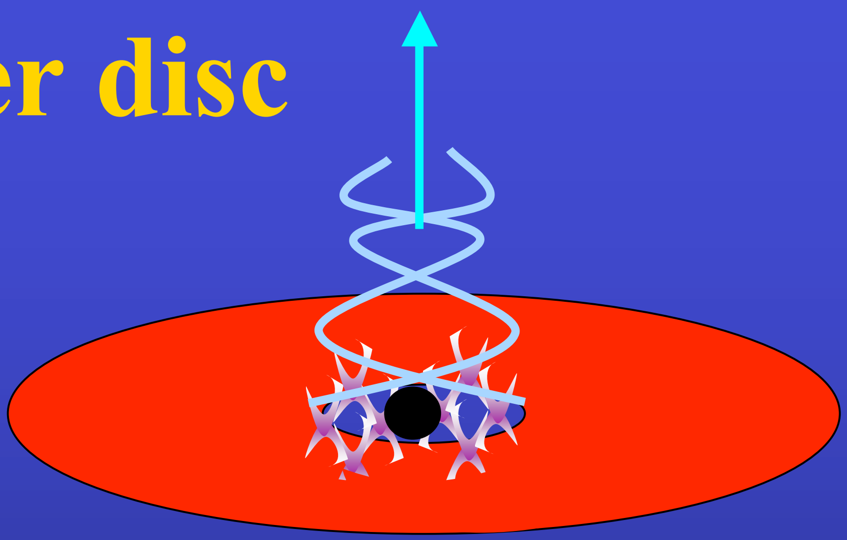

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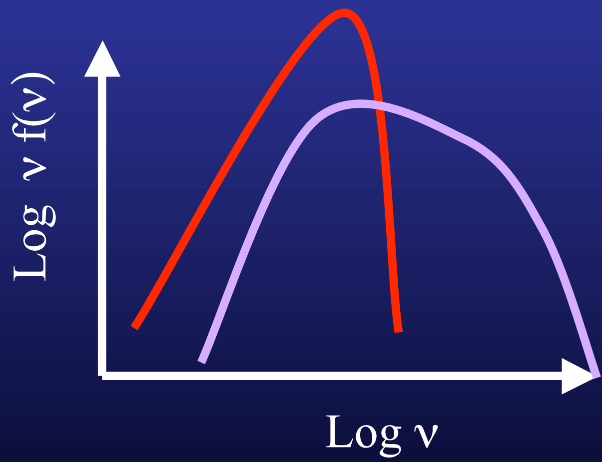

Collapse of hot inner flow

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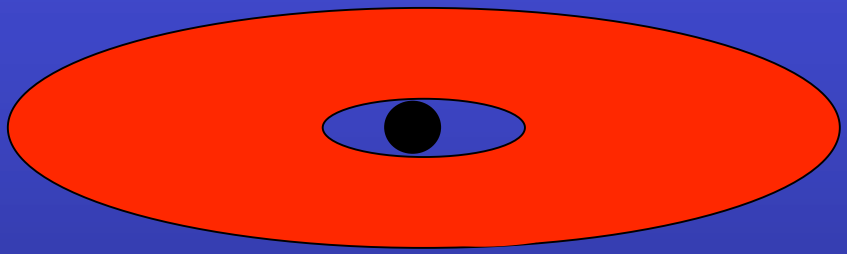
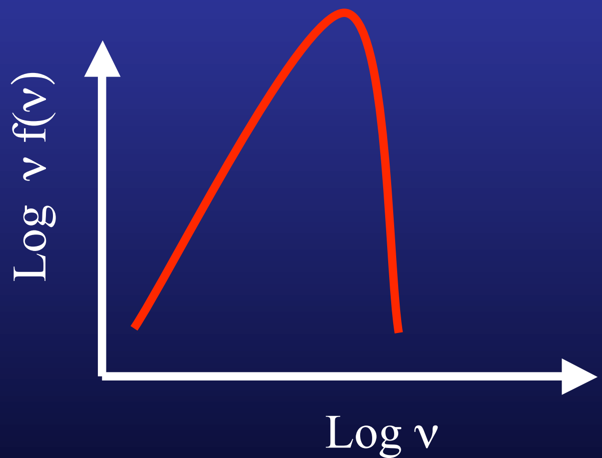
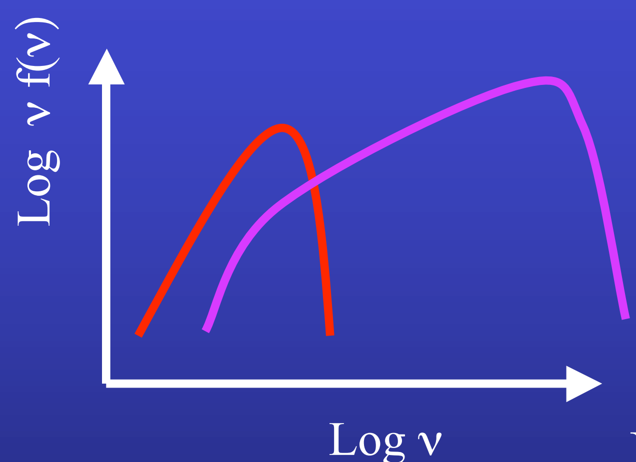
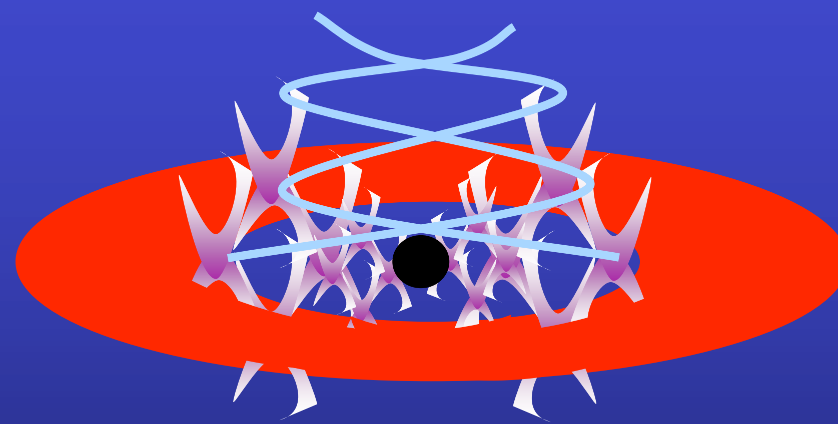
- Instead: hot, optically thin, geometrically thick inner flow replacing the inner disc (Shapiro et al. 1976; Narayan & Yi 1995)
- Flow collapses so no tail
- Disc dominated spectra
- Jet from large scale height flow collapse of flow=collapse of jet
- Do transitions fast enough and get non-steady state flow – hysteresis!





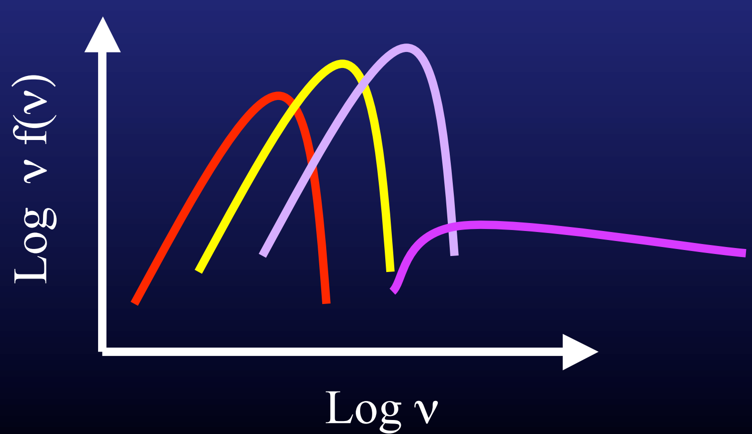
Qualitative and quantitative models: geometry

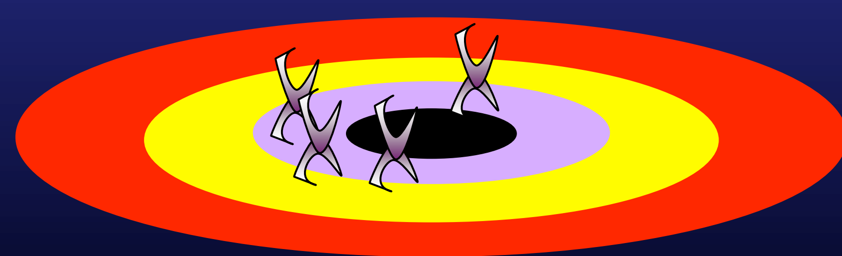




Hard (low L/L_{Edd})

Soft (high L/L_{Edd})

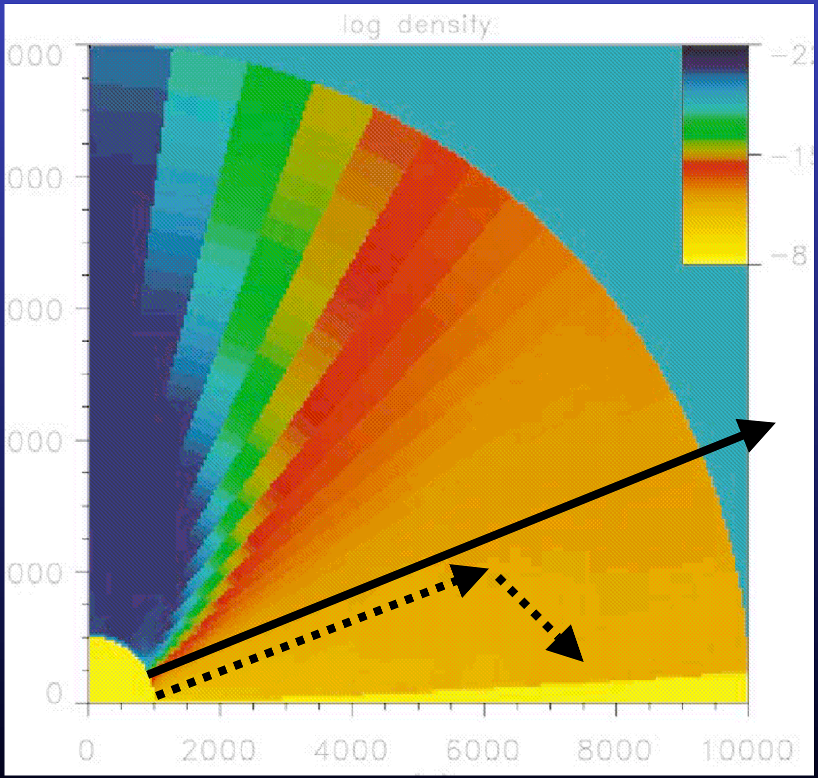




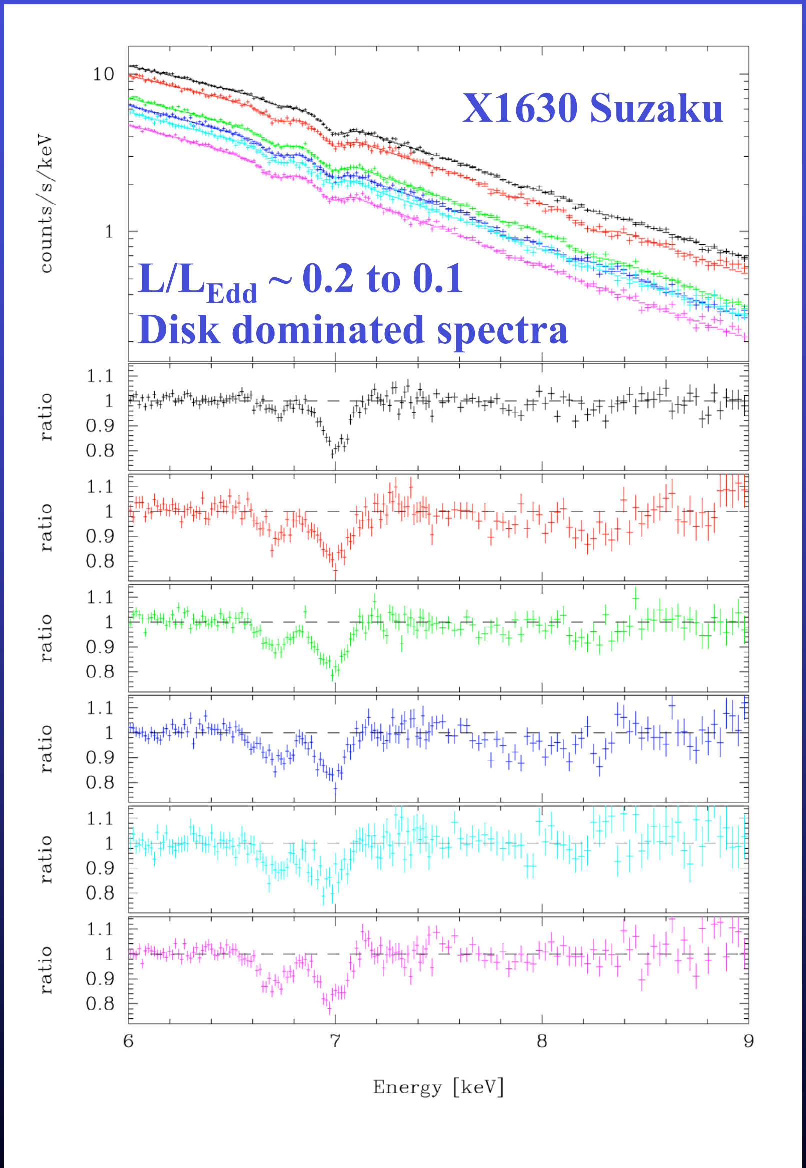
Done & Gierli_ski 2004

Observed disc spectra

- Also see evidence for winds!!
- Highly ionised H and He Fe Ka in BHB and NS systems at high inclination in high states, $N_h \sim 10^{23}$, v~500km/s - accretion disc wind!



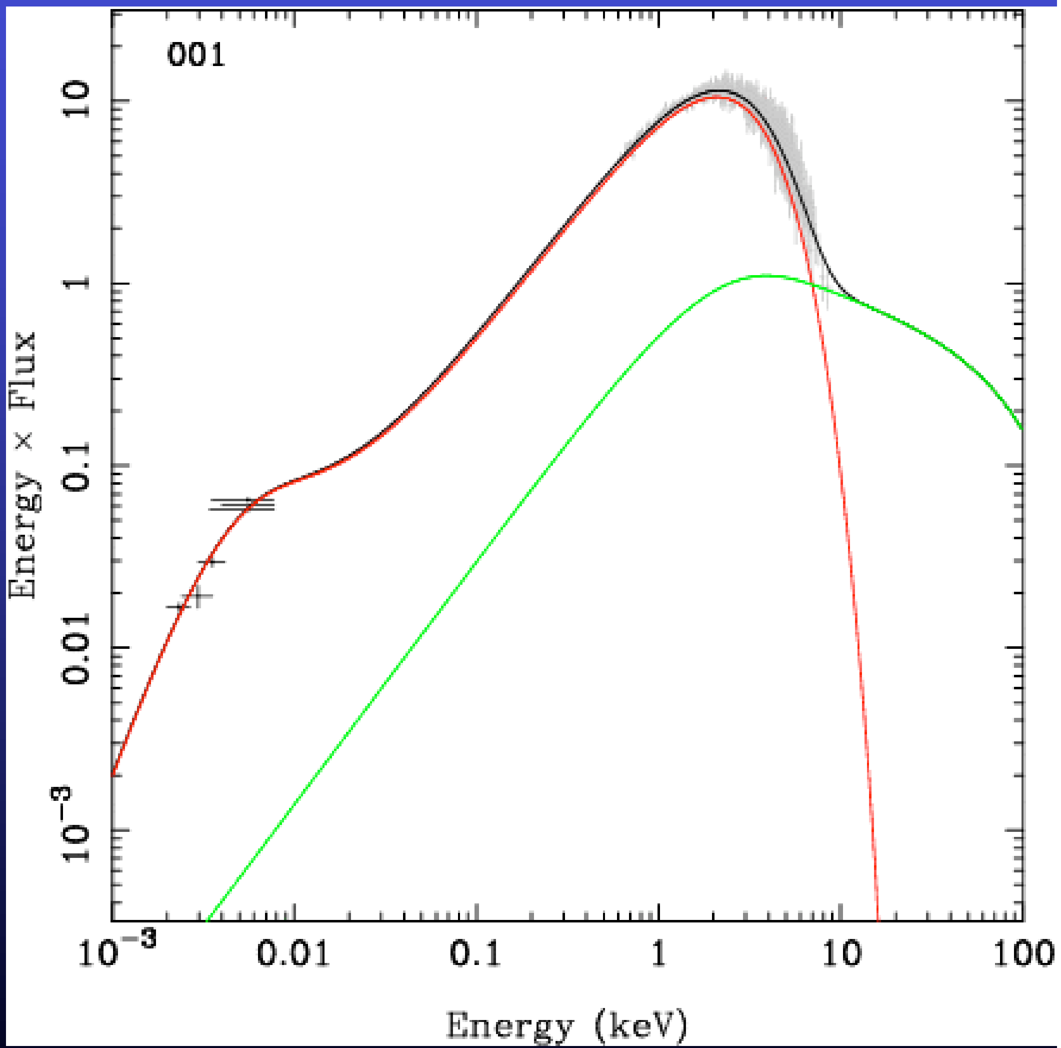
Proga & Kallman 2002



Kubota et al 2007

Modifies optical continuum

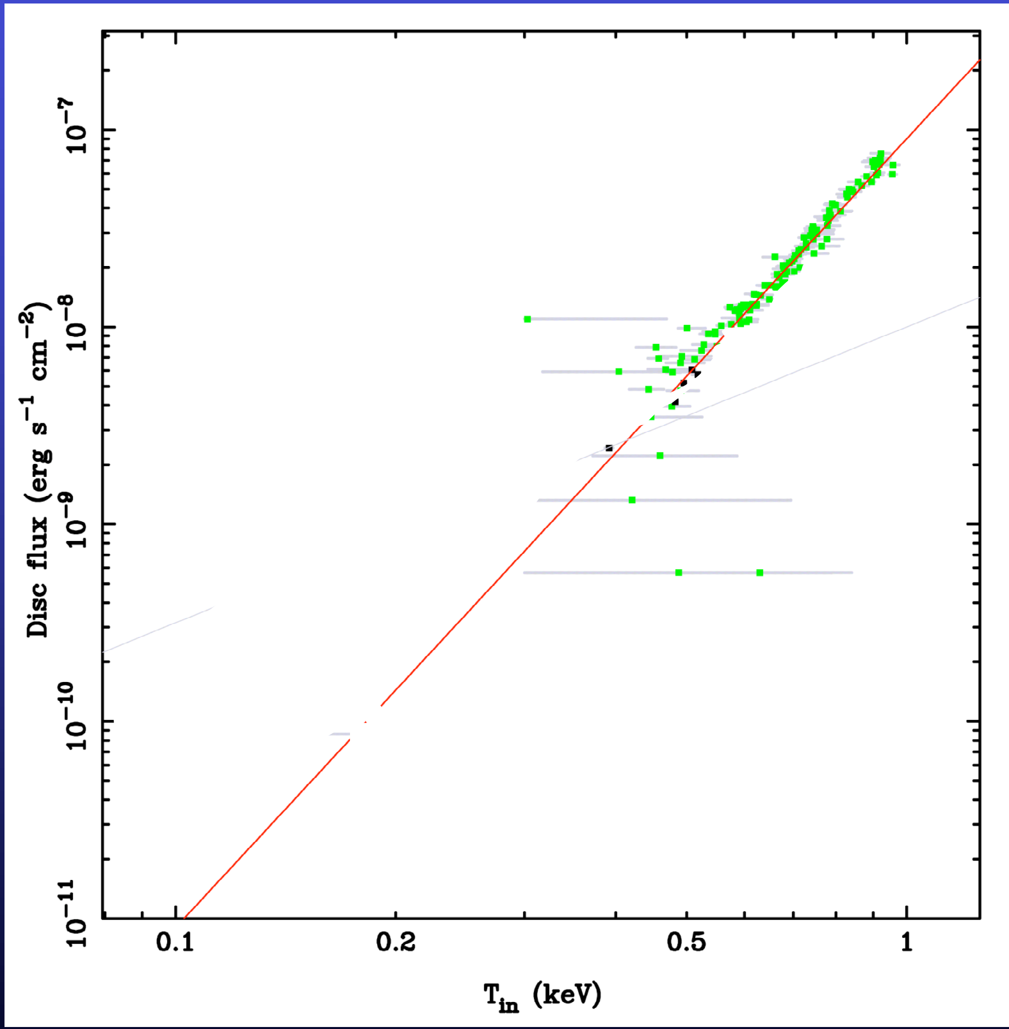
- X-rays illuminate outer disc where intrinsic flux is low so reprocessed can dominate (van Paradijs 1996)
- SWIFT/XMM X-opt simultaneously
- XTE J1817-330 - trace scattered fraction through outburst SWIFT+RXTE
- $L_{opt} \sim 0.002\ L_{disc}$ in high/soft state.
- Big changes at transition to low/hard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



Gierlinski Done & Page 2007

Does the disc radius move out?

- Key aspect of truncated dsic models is radius of disc at last stable orbit in high/soft state, then increases in low/hard
- XTE J1817-330
- RXTE data covering outburst E>3 keV
- Disc dominated state with $L_{disc} \propto T_{in}^4$
- Constant radius
- But disc is out of RXTE band when kT < 0.4keV so no constraint on disc radius in low/hard state



Gierlinski Done & Page 2007

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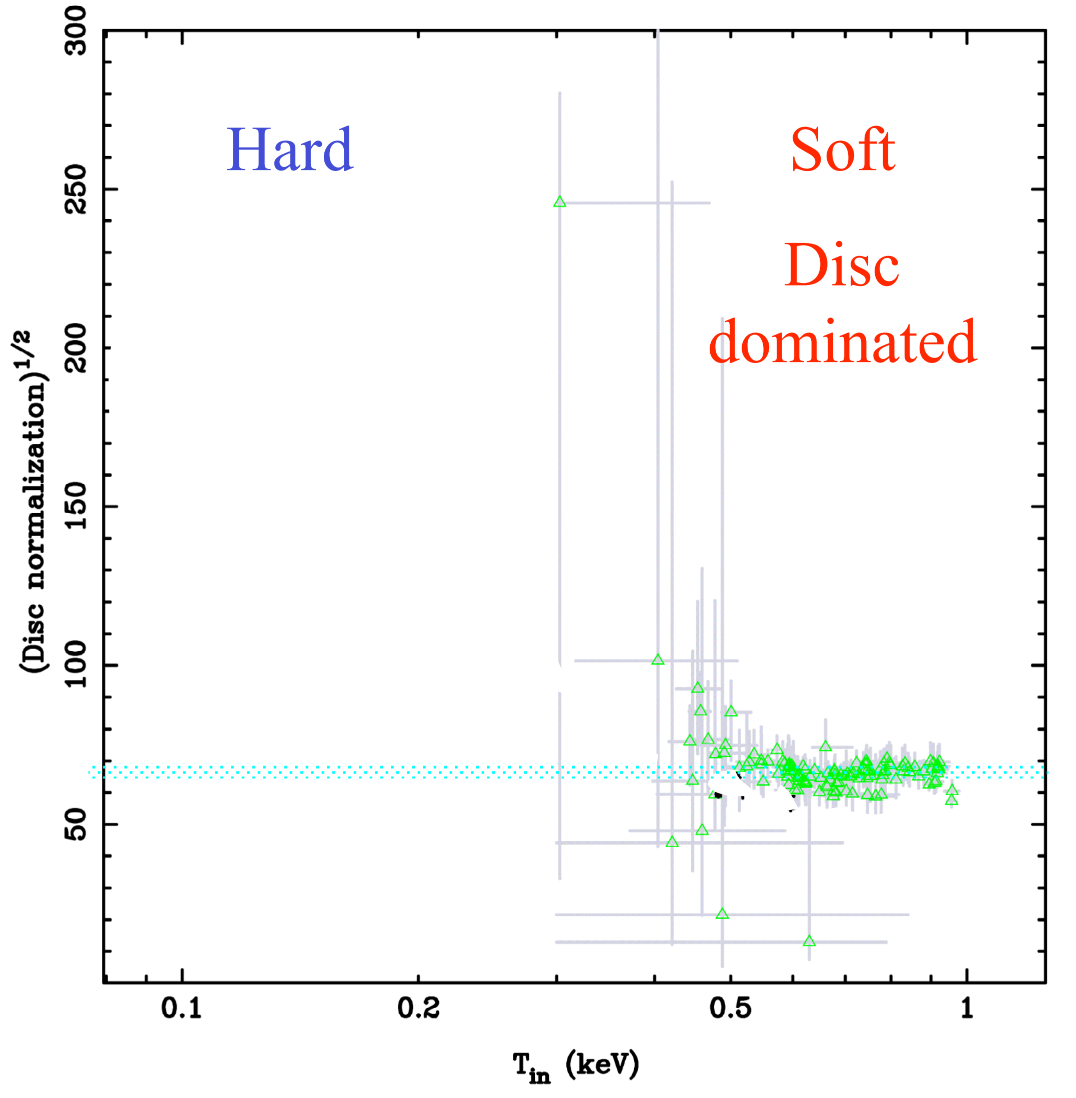
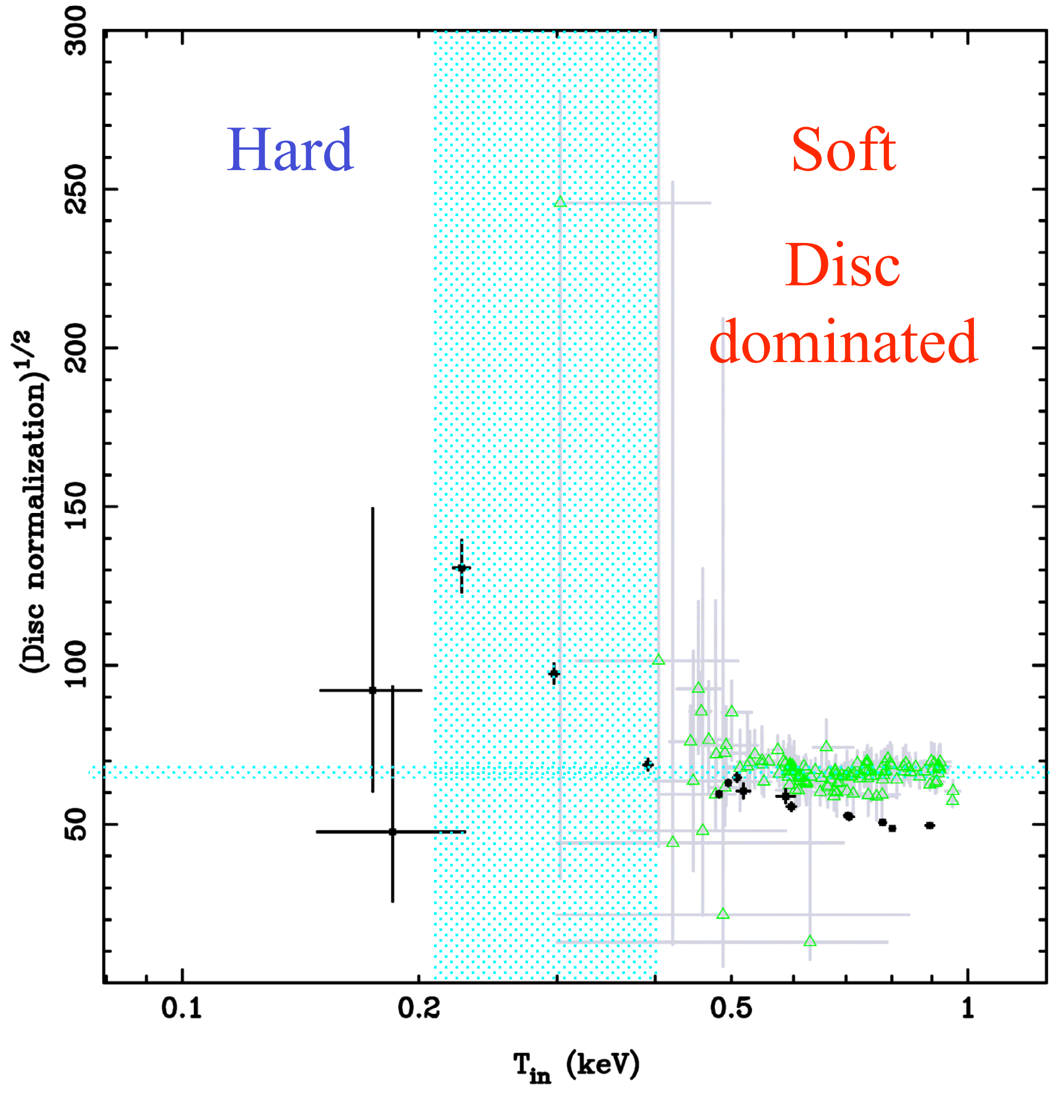


Gierlinski Done & Page 2007

Radius from SWIFT

- Monitoring also with SWIFT E>0.4 keV so can constrain low temperature disc radius
- Fit parameters (diskbb+po or comp) give disc inner radius increasing in transition (Rykoff et al 2007)
- But low/hard state consistent with same inner radius as disc dominated - though errors big so also consistent with truncated disc (Rykoff et al 2007)



Gierlinski Done & Page 2007

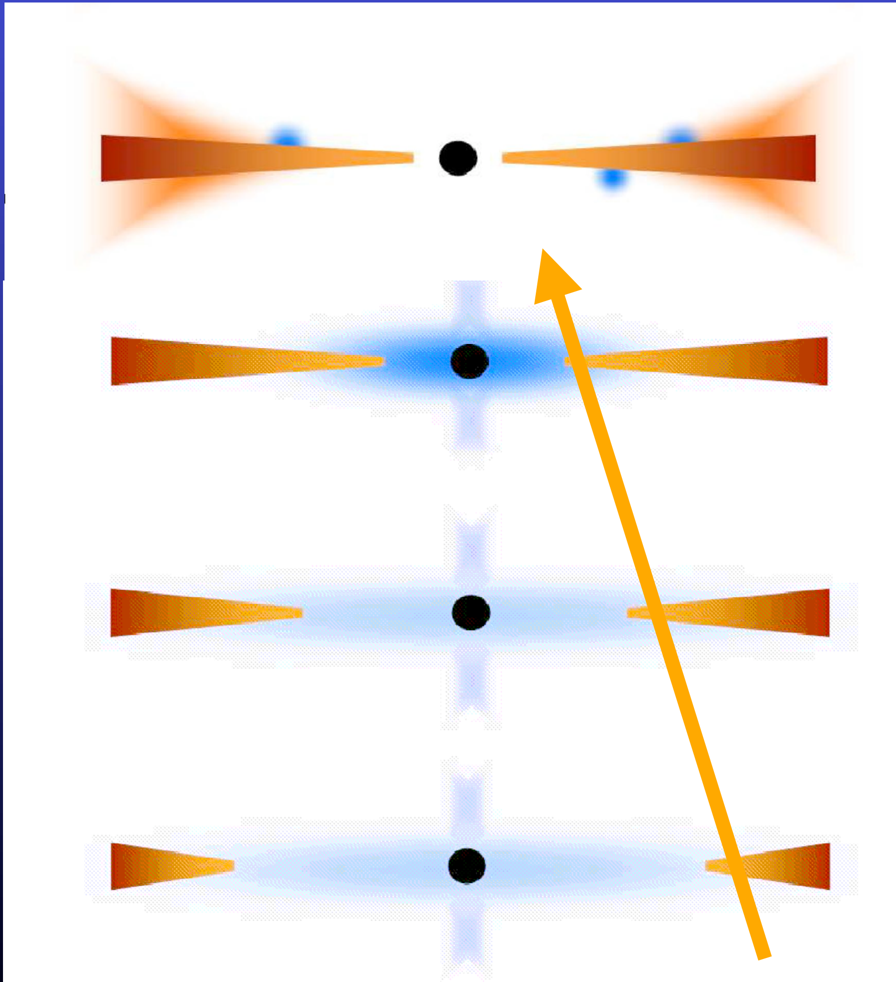
But not simple in low/hard state

- Disk emission DOES NOT dominate bolometric flux
- Irradiation of the inner edge of the truncated disc especially if overlap of disc and hot flow
- Compton models PREDICT overlap for spectra $\Gamma>1.7$ (Poutanen et al 1997)
- Energy $L_{bb} = \Omega/2\pi\ (1\text{-}a)\ L_{comp}$

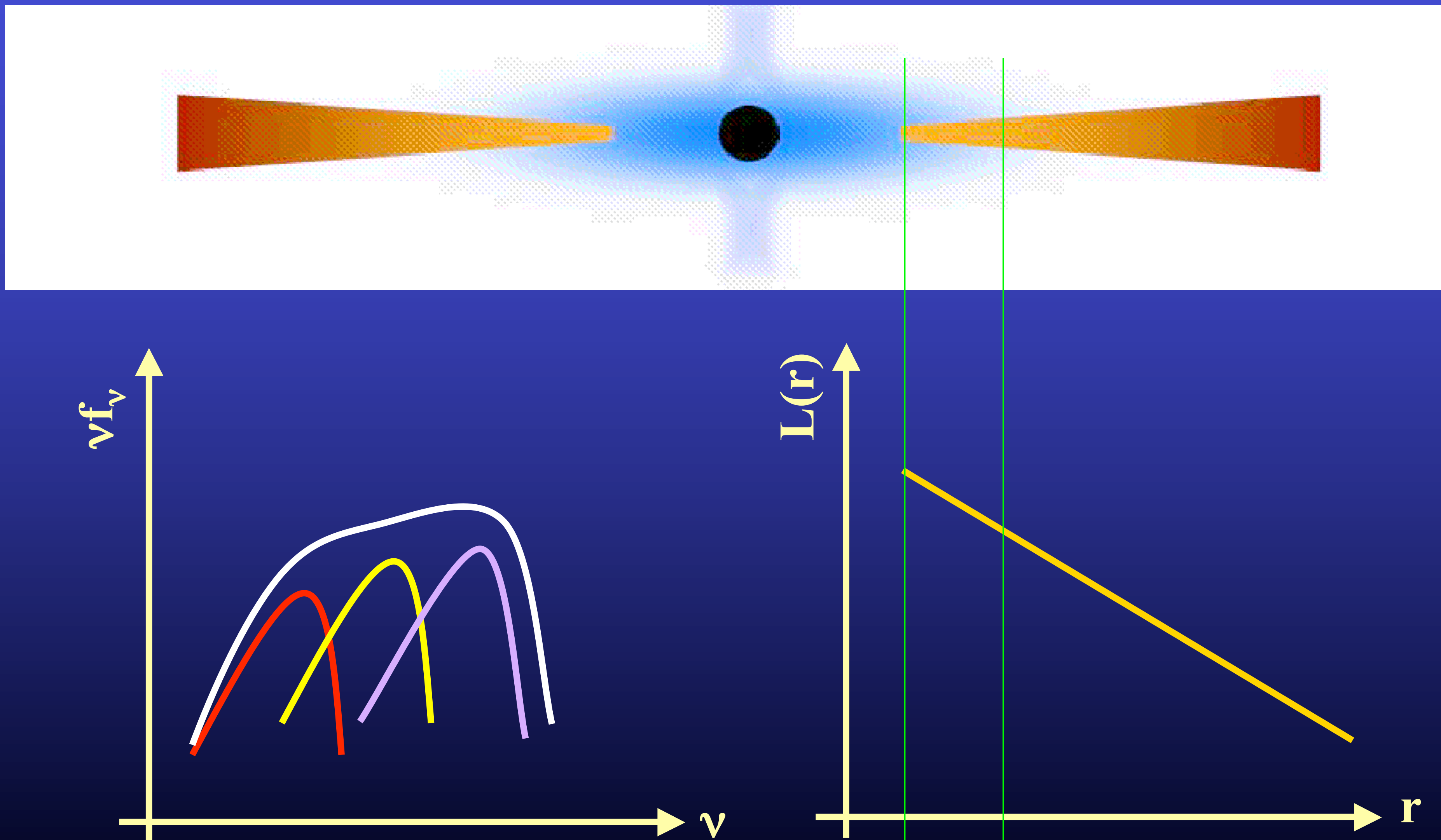
$$= 0.3 \times 0.7\ L_{comp}$$
$$= 0.2\ L_{comp}$$
$$= 0.2 \times 3\ L_{disc} \sim L_{disc}$$

- Irradiation as powerful as intrinsic disc emission

DGK07

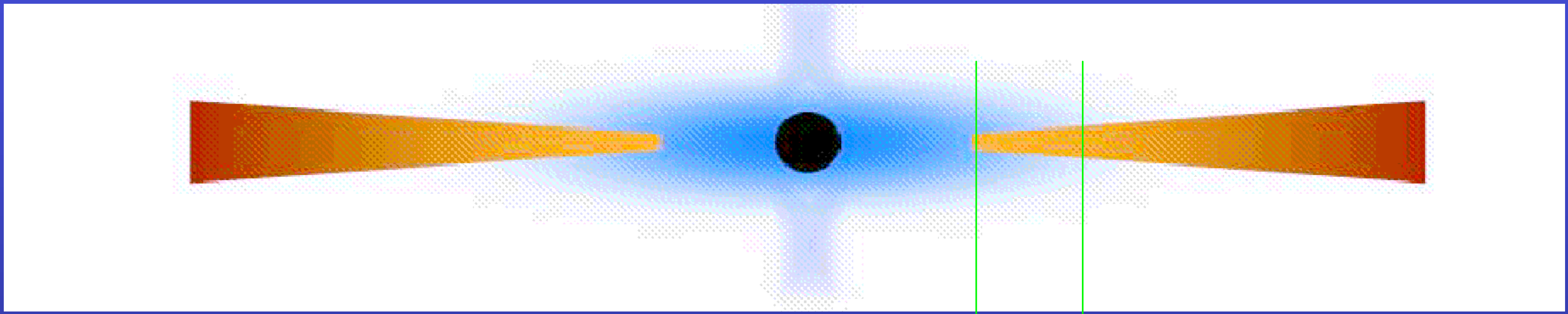


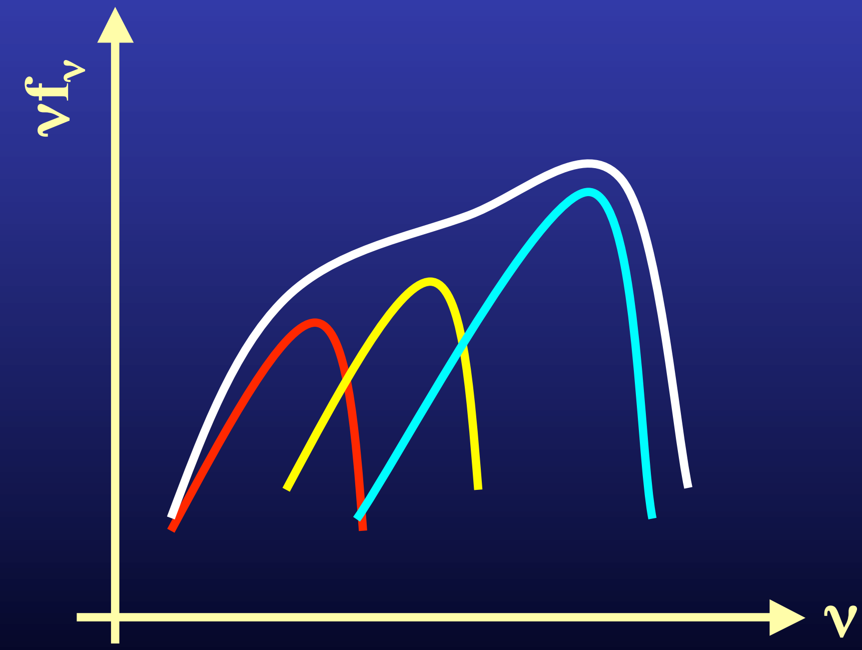
Simple truncated disk

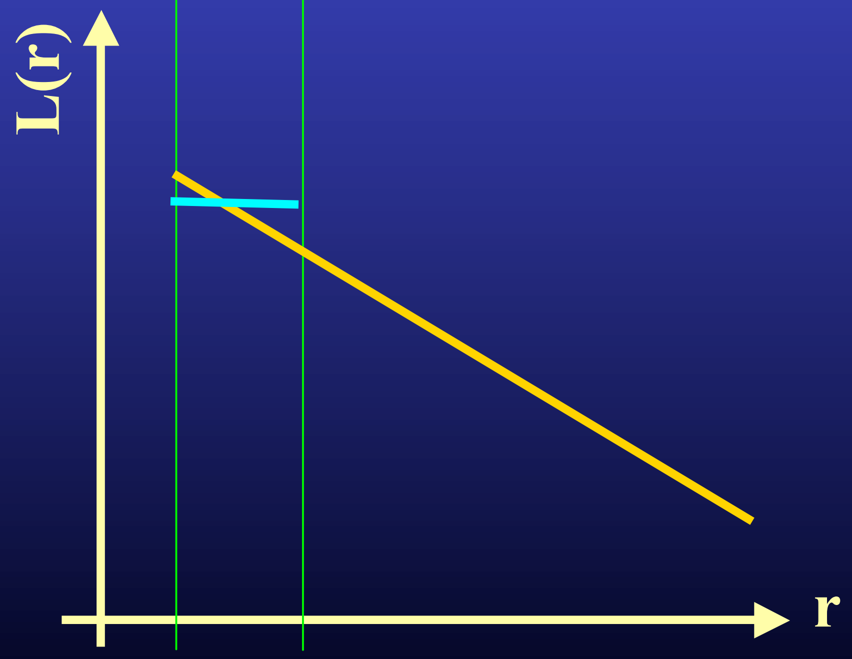


Gierlinski Done & Page 2007

Irradiated truncated disc



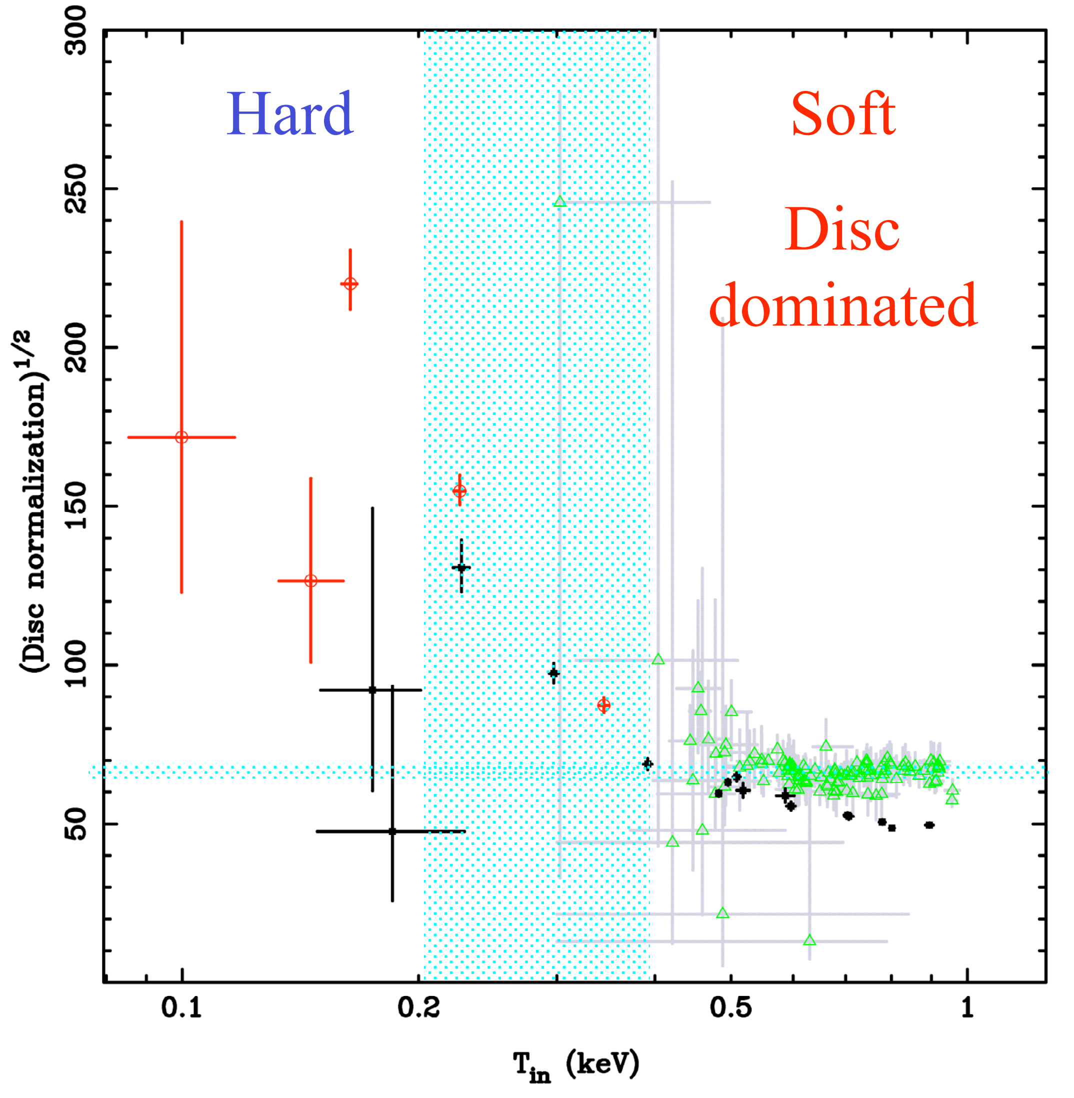




Gierlinski Done & Page 2007

Radius from SWIFT MKII

- Inferred disc radius moves larger with irradiation
- Also same stress-free inner boundary condition
- Still assuming same colour temperature correction – but irradiation (and conduction) from above so may not thermalise.
- Photons in comptonisation come originally from disk
- So real radius larger in low/hard state by some unknown amount…



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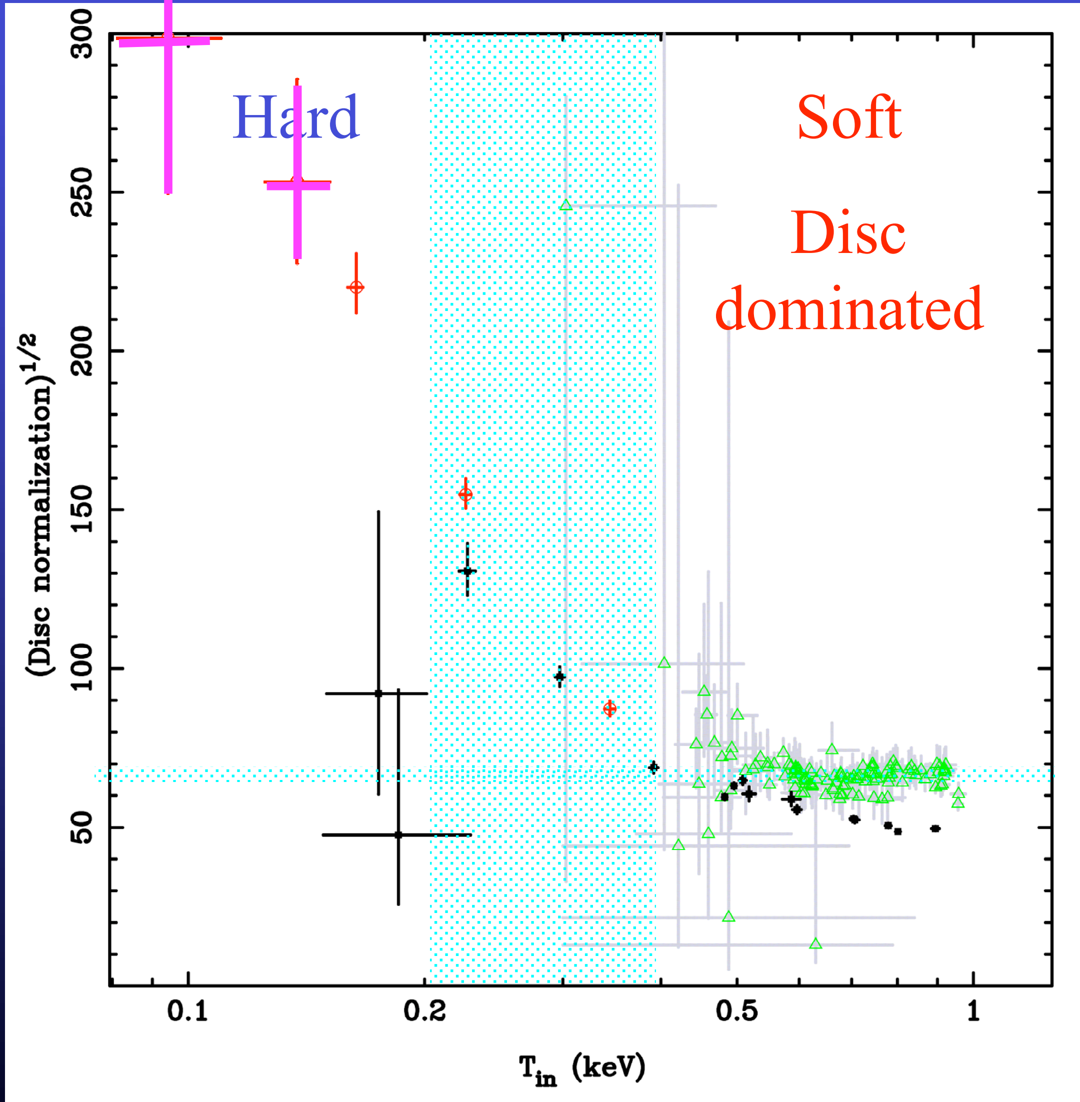

Gierlinski Done & Page 2007

Other low/hard states

Makishima et al 2007

- Complex continuum clearly seen with good data over broad bandpass
- Suzaku (& BeppoSAX)
- Continuum softens at low energies so spectrum concave
- Could be irradiated disc as expected – emission may not thermalise to blackbody
- Makes radius larger….
- L/L_{Edd} ~0.01 and 0.005 respectively

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DGK07

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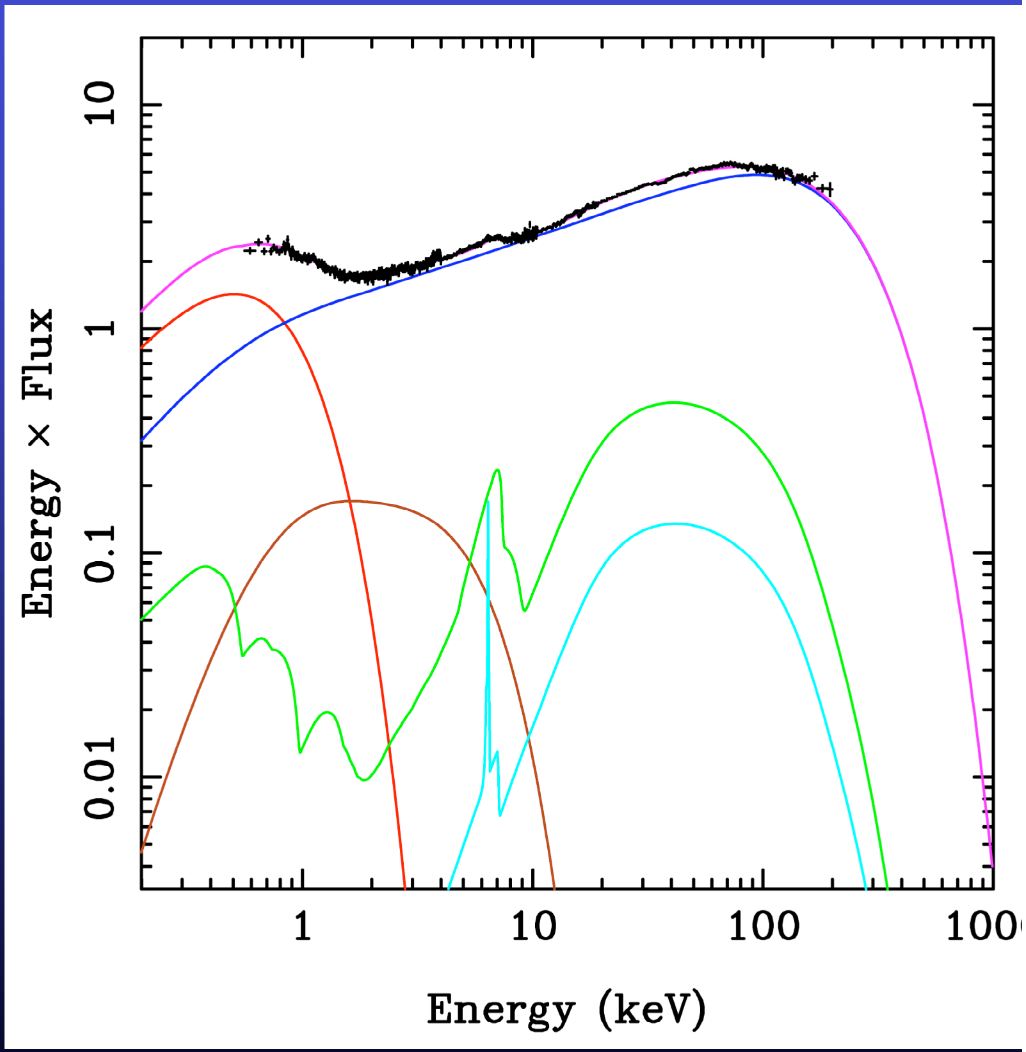
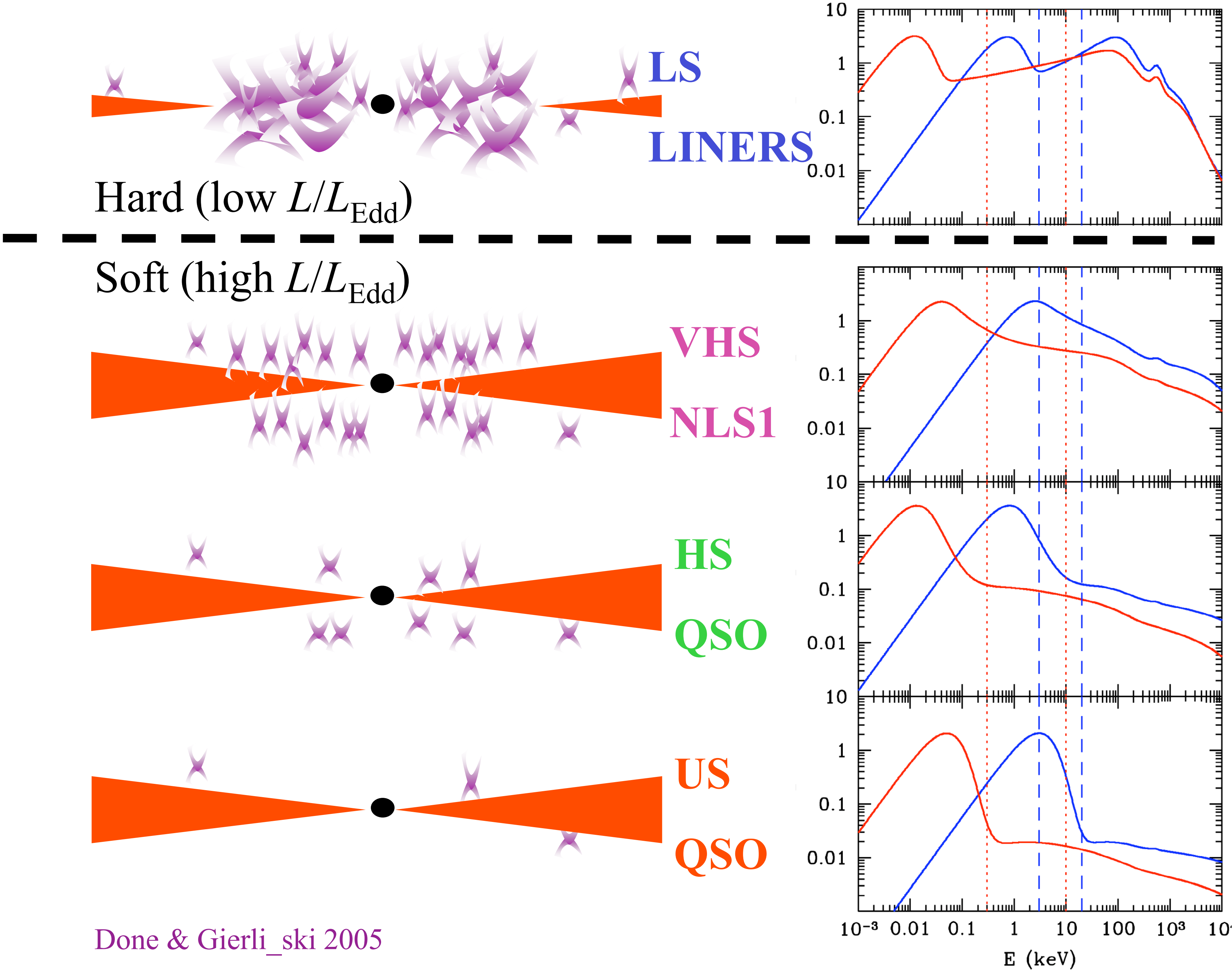


Fe line as inner disc tracer

Makishima et al 2007

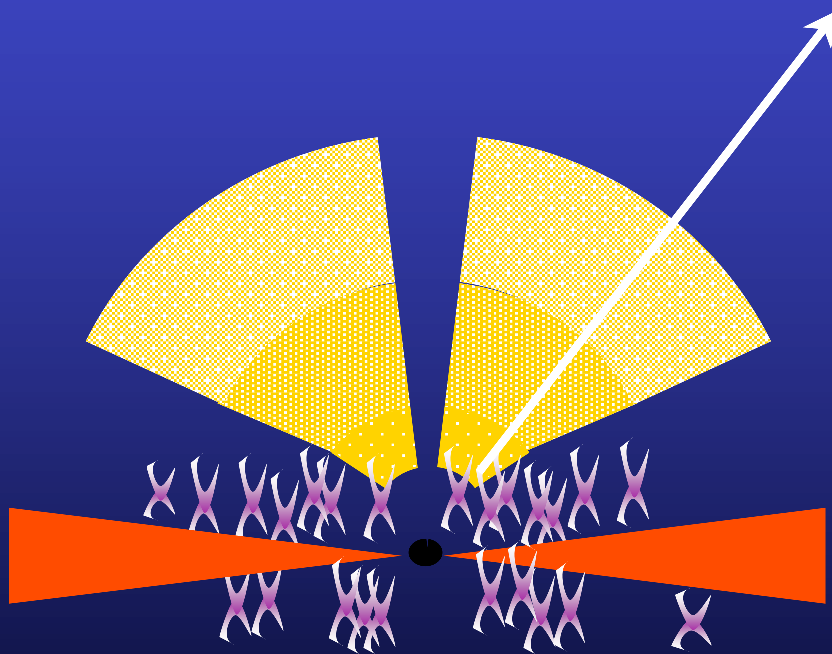
- Fe line width around σ=0.7 keV for Gaussian in Suzaku CCD's for both Cyg X-1 and GRO 1655-40
- Cyg X-1 at 45^o $R_{in}=13^{+6}_{-7}$ R_g
- Consistent with truncated inner disc and so no constraint on spin
- NB diskbb+po+laor to xis gives R_{in}=2.5 ±0.5 R_g



Done & Gierli_ski 2005

Alternative geometries for partially ionised, smeared material

Reflection



Absorption

Conclusions

- LMXB very homogenous at ~10 M_{sun} variable L/L_{Edd}
- Last stable orbit (ONLY simple disc spectra) $L \propto T^4_{max}$
- Low to moderate spin in LMXB as expected
- Accretion flow NOT always simple disc – X-ray tail. Ratio of disc/tail, shape of tail (+ jet) change with L/L_{Edd}
- Hard tail in low/hard state - Hot flow replacing inner disc
- Disc progressively moves outwards to give correlated spectral + variability signatures and state transition as L/L_{Edd} decreases.
- Can track using disk spectrum! See radius increase during transition! Low/hard state consistent with even larger radius as expected when include irradiation.
- Suzaku low/hard state shows complex curvature (irradiation?) and moderately broad Fe line. Consistent with truncated disc.