Accretion flows onto black holes

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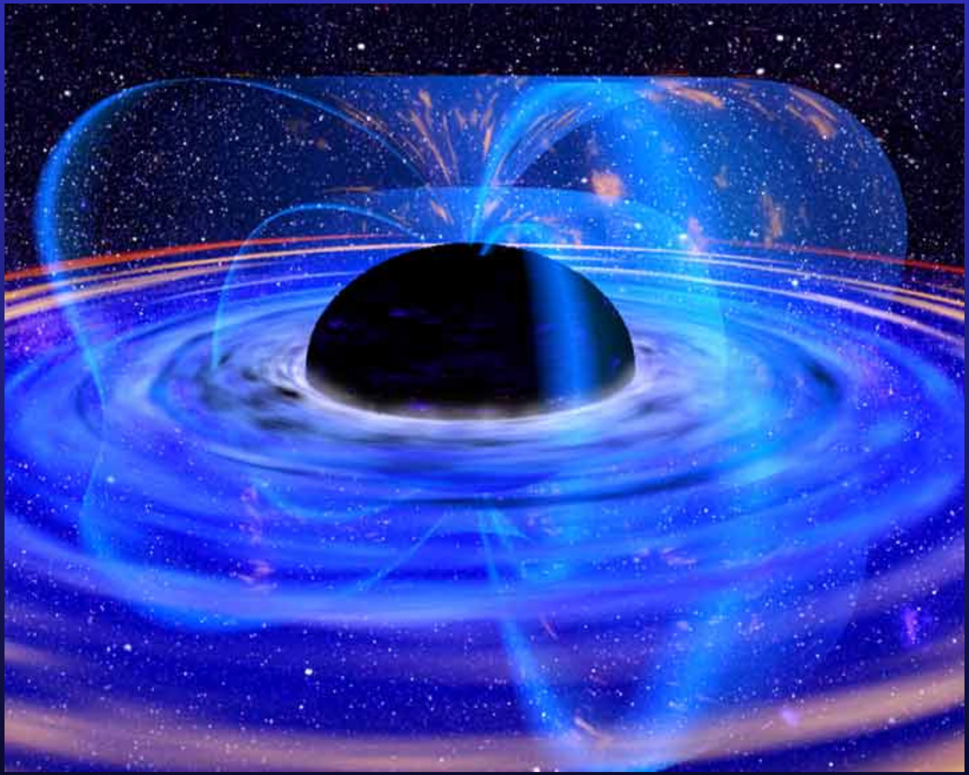
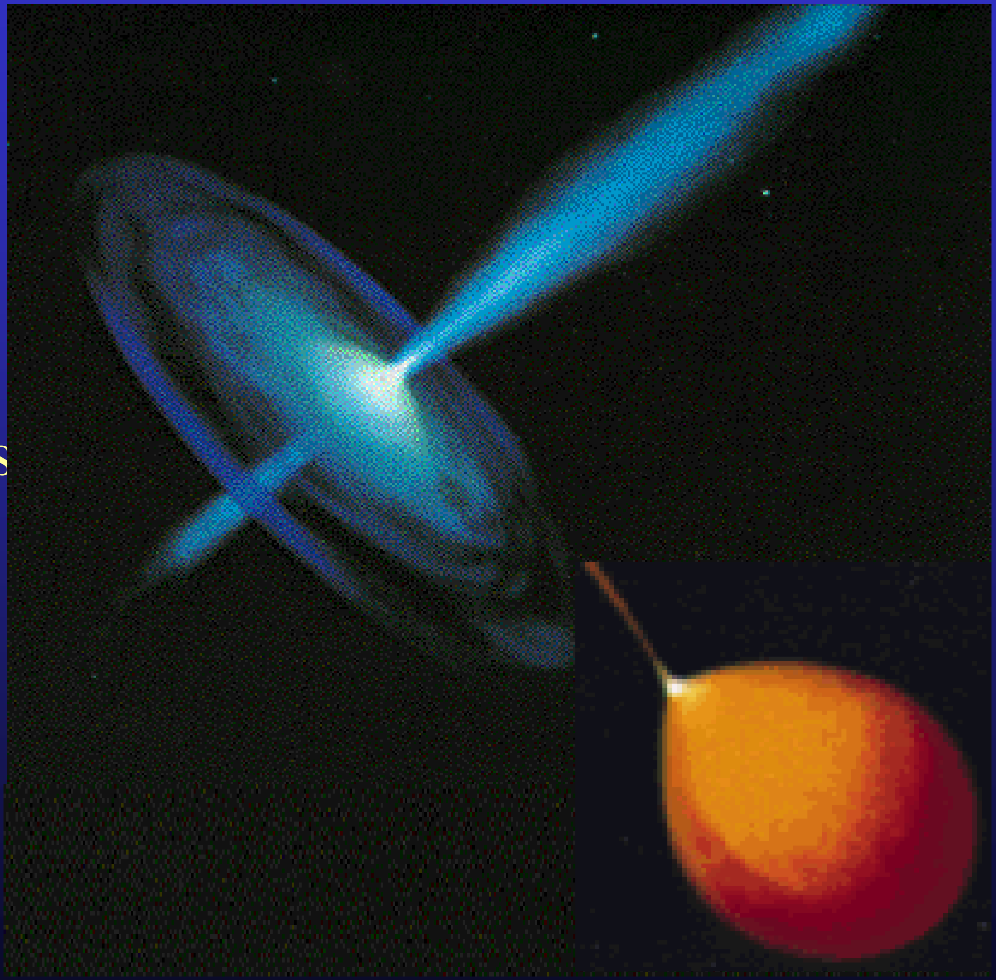
Accretion

- Accreting BH: huge X-ray luminosity close to event horizon R_s
- Emission from region of strong spacetime curvature
- Observational constraints on strong gravity **if** we can understand accretion!



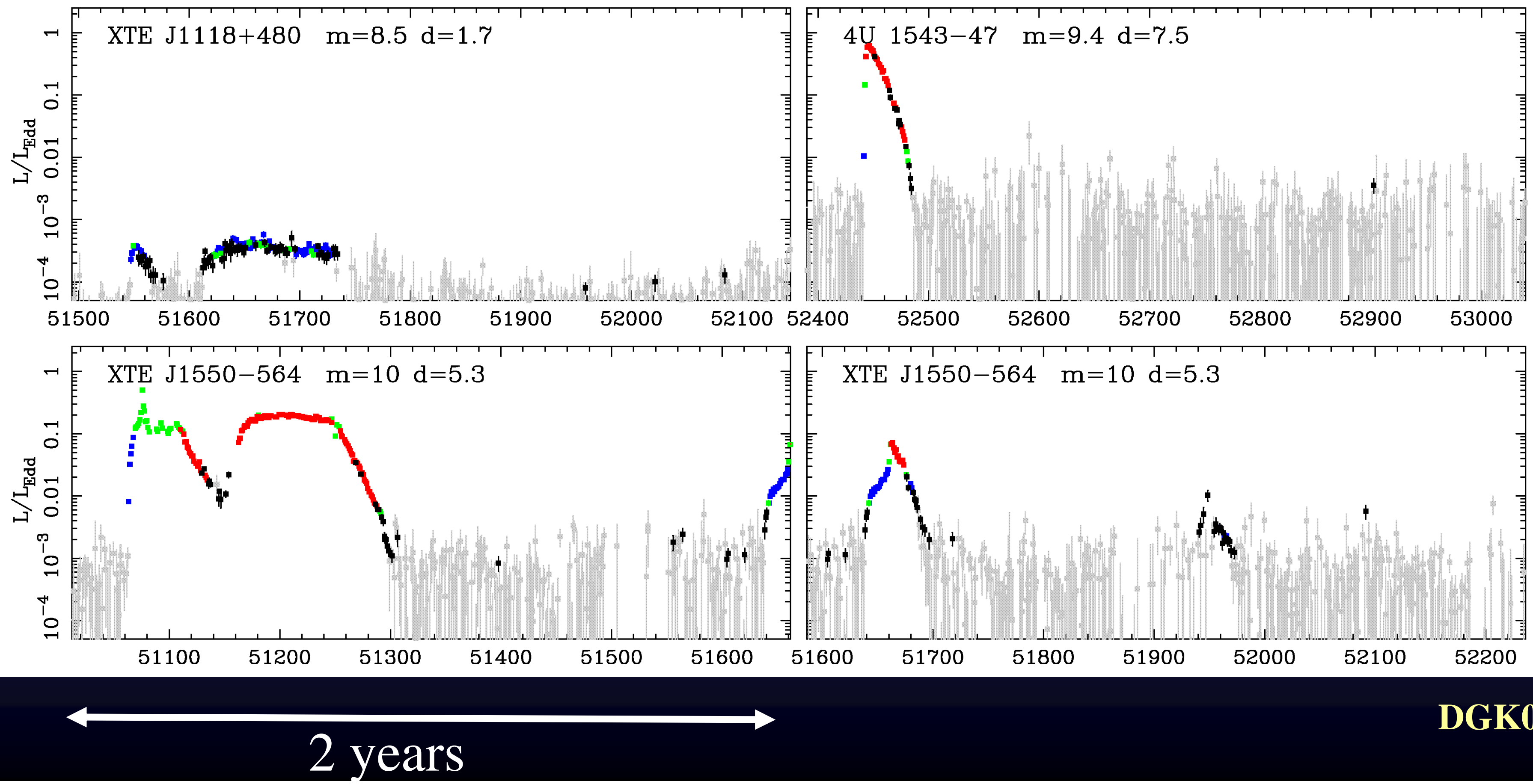
Black holes

- Appearance of BH should depend only on mass and spin (black holes have no hair!)
- Plus mass accretion rate, giving observed luminosity *L*
- Maximum luminosity ~L_{Edd} where radiation pressure blows further infalling material away
- Get rid of most mass dependance as accretion flow should scale with L/L_{Edd}
- 10^4-10^{10} $M_\odot$: Quasars
- 10-1000(?) $M_\odot$: ULX
- 3-20 $M_\odot$: Galactic black holes



Transients

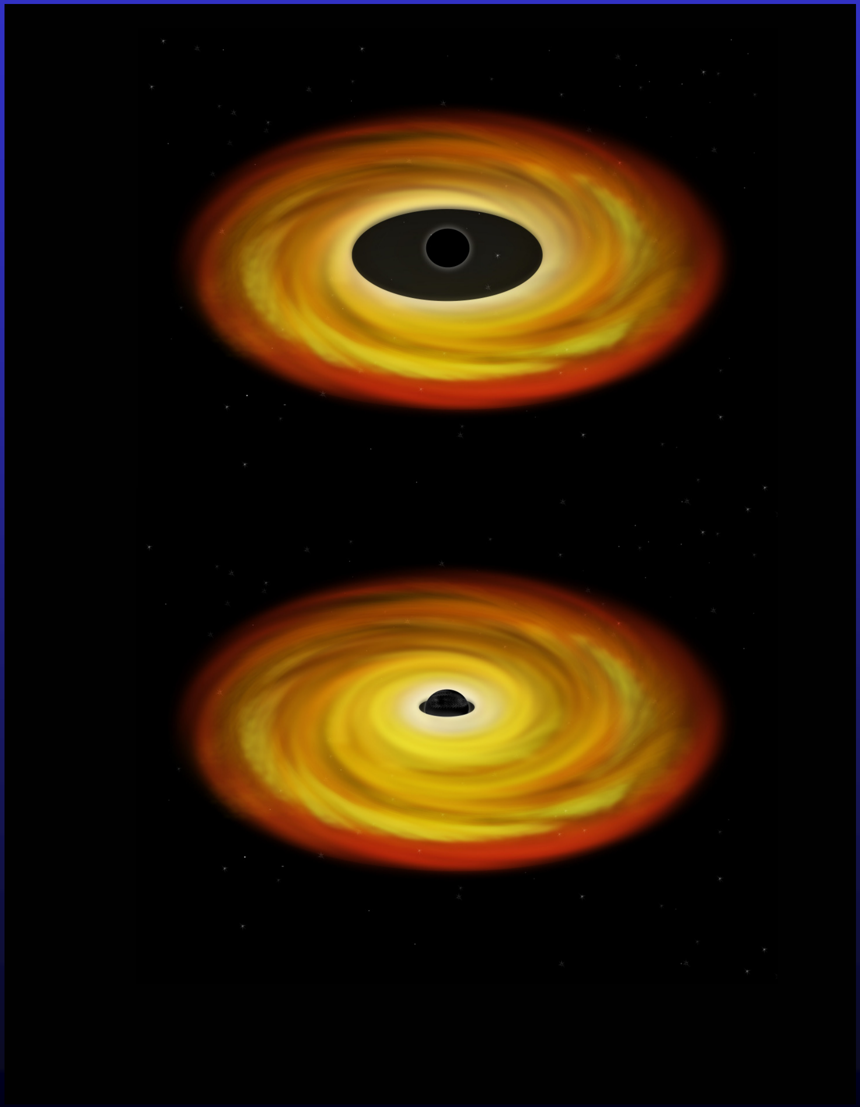
- Huge amounts of data, long term variability (days –years) in mass accretion rate (due to H ionisation instability in disc)
- Observational template of accretion flow as a function of $L/L_{\rm Edd}$ onto ~10 $M_\odot$ BH



DGK07

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 $L{\sim}L_{Edd}$ T_{max} is
  - 1 keV (10^7 K) for 10 $M_\odot$
  - 10 eV (10^5 K) for 10^8 $M_\odot$
  - big black holes luminosity scales with mass but area scales with $mass^2$ so T goes down with mass!
- Maximum spin T_{max} is 3x higher

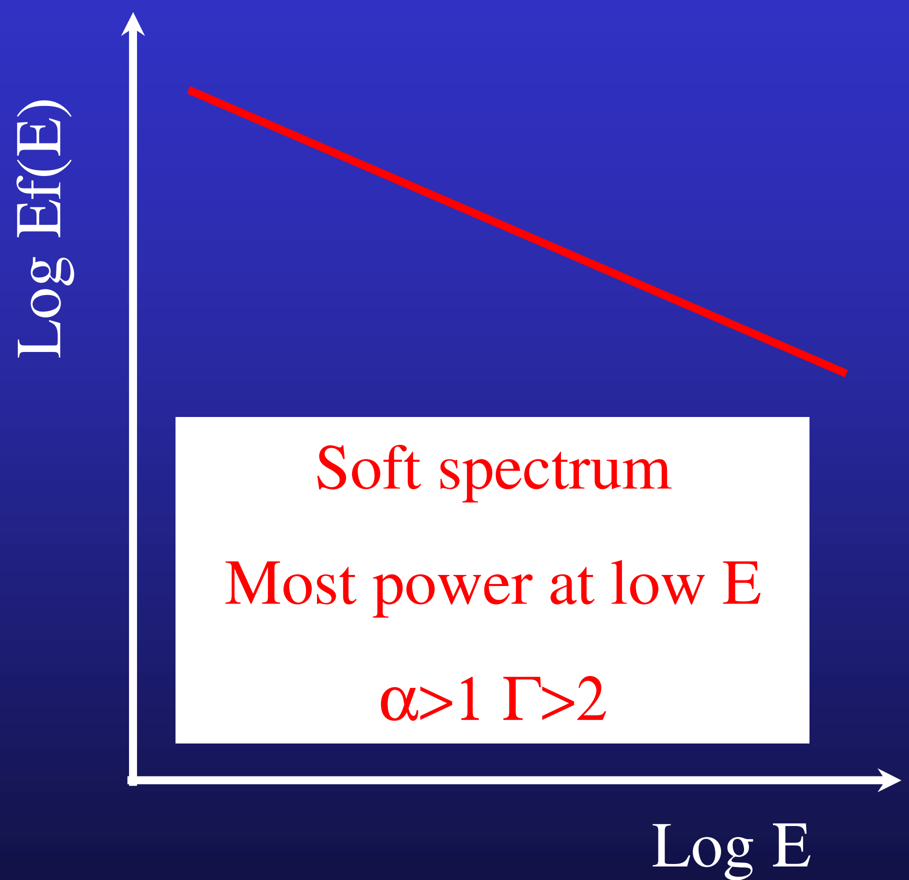


Spectra

- Differential photon number
- dN/dE=photons / s / keV
- $dN/dE=N_0\ E^{-\Gamma}$ power law
  photon index Γ
- $E\ dN/dE$ = flux $f(E)\ E^{-\alpha}$

  energy / s / keV

  energy index $\alpha=\Gamma-1$
- $E^2\ dN/dE = Ef(E) = \nu f(\nu)$
- Plot $\nu f(\nu)$ as this peaks at energy where power output of source peaks.



$$dL = F(E)\ dE = EF(E)\ dE/E = EF(E)\ d\log E$$

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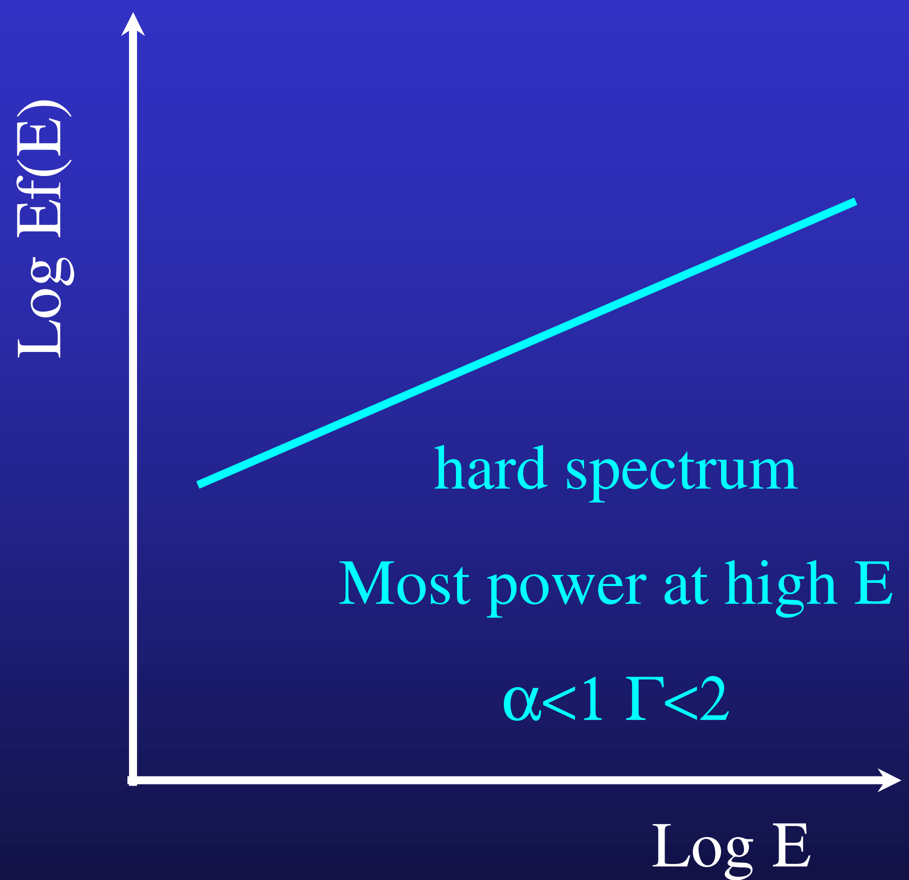

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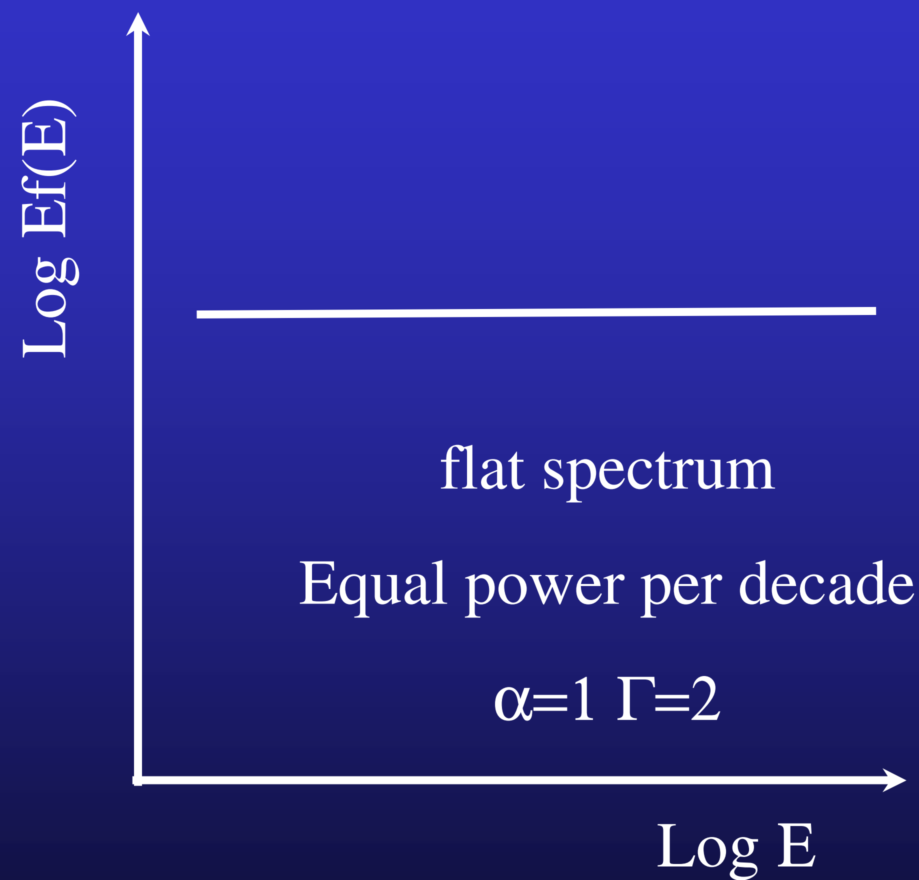
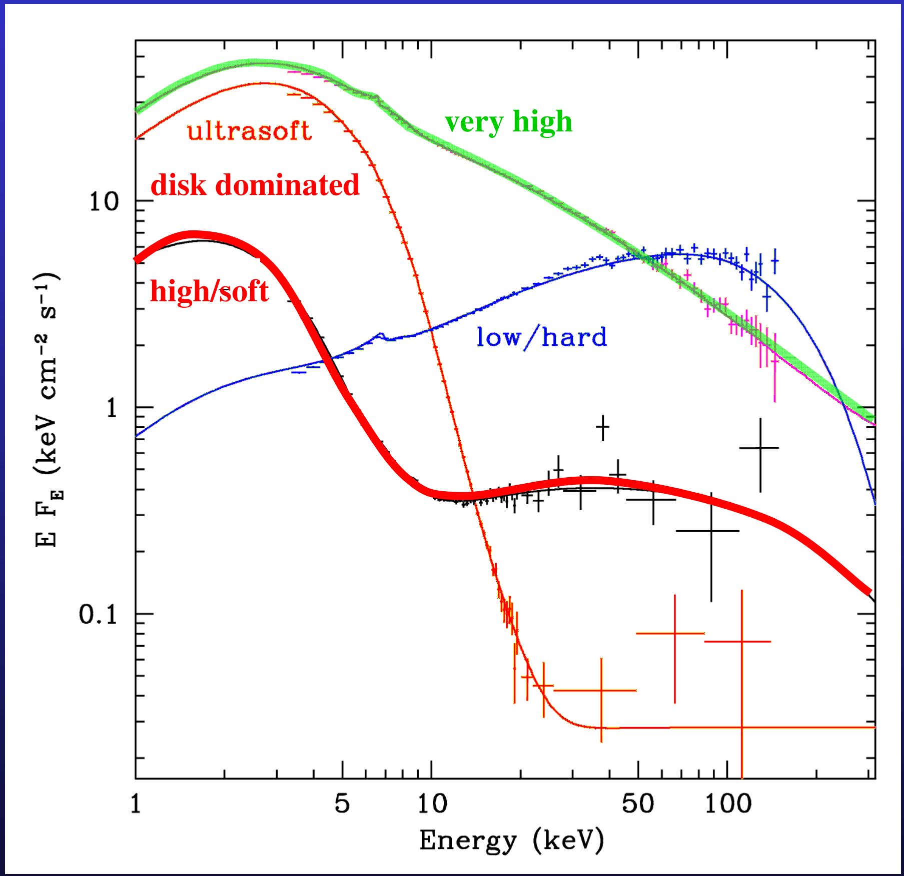


$dL= F(E)\ dE = EF(E)\ dE/E = EF(E)\ d\log E$

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

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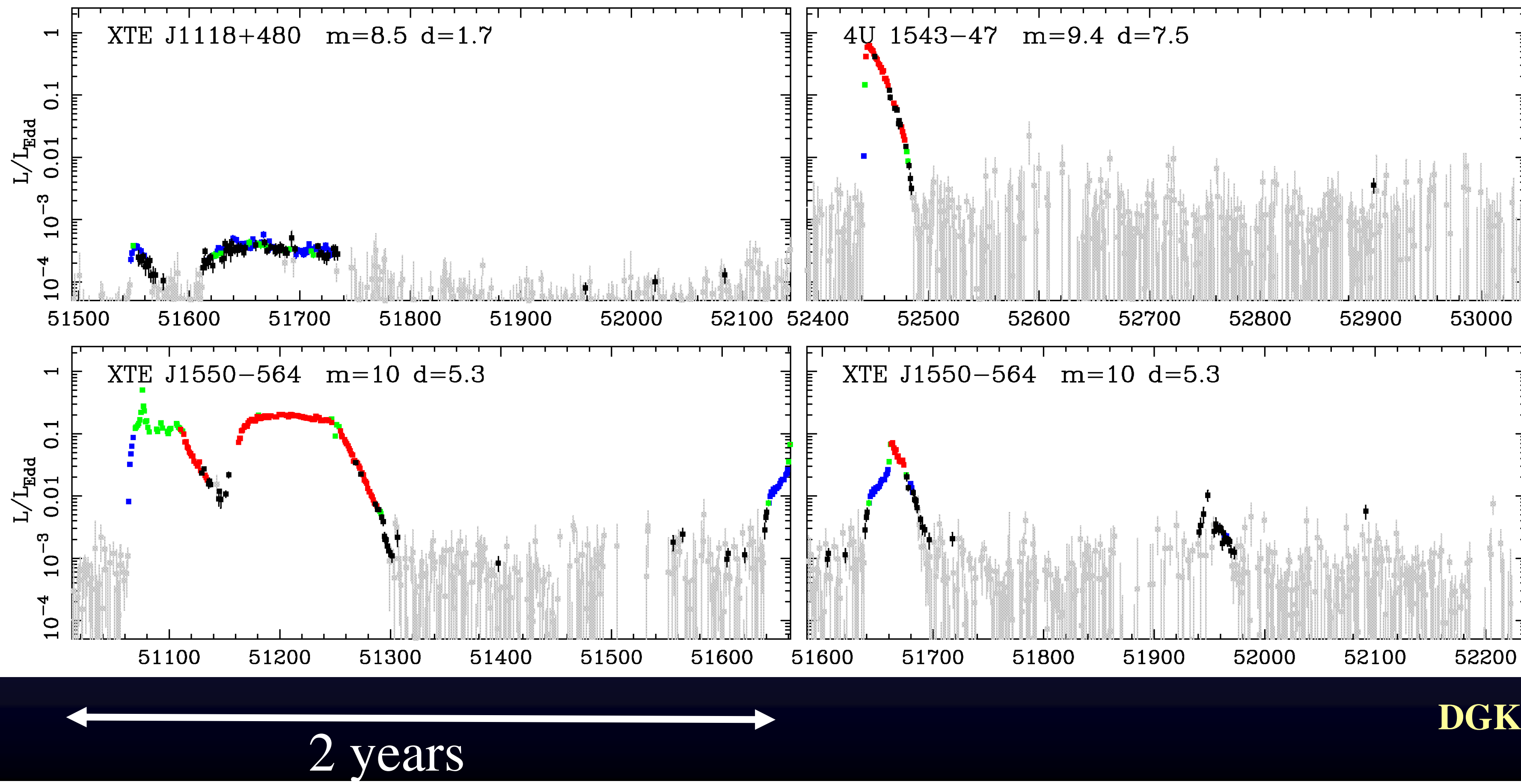
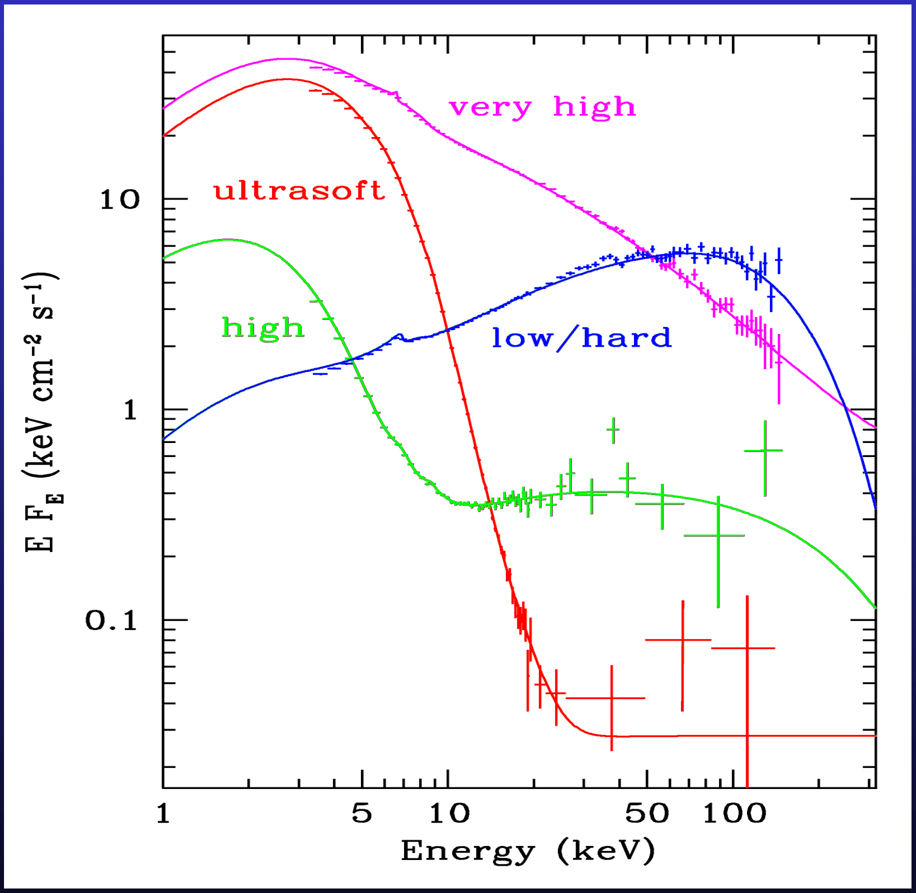


DGK07

Disc spectra: last stable orbit

- Bewildering variety
- 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 spin **nor** extreme versions of higher dimensional gravity - braneworlds (Gregory, Whisker, Beckwith & Done 2004)



Gierlinski & Done 2003

Observed disc spectra

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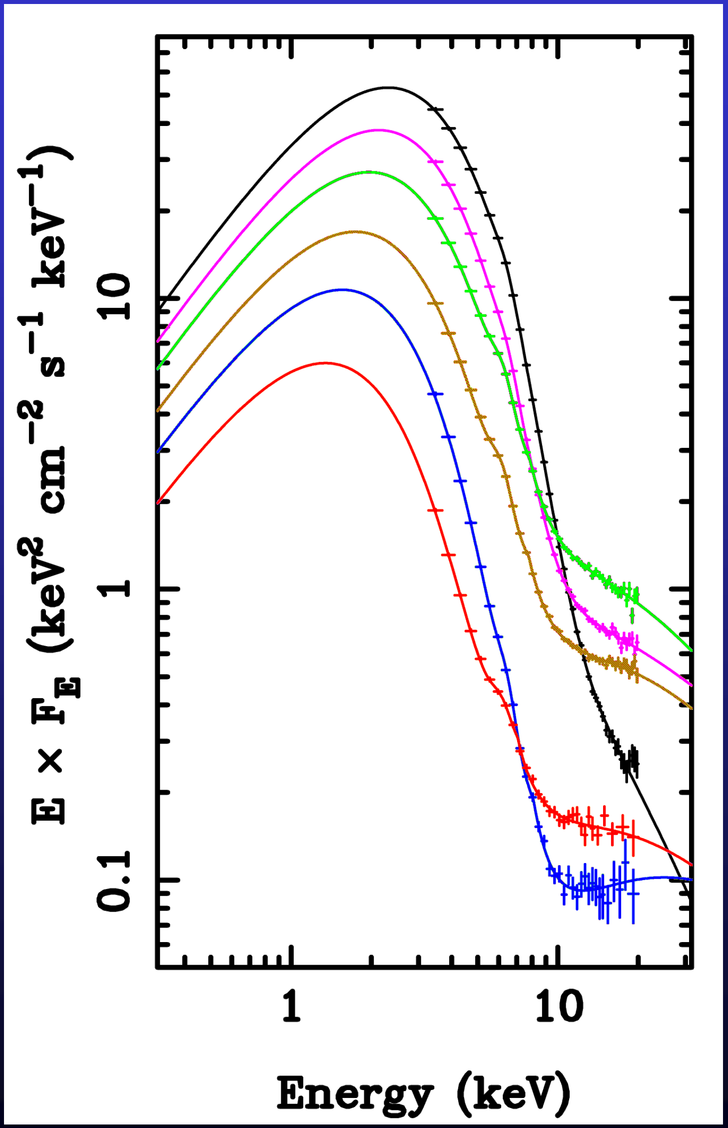

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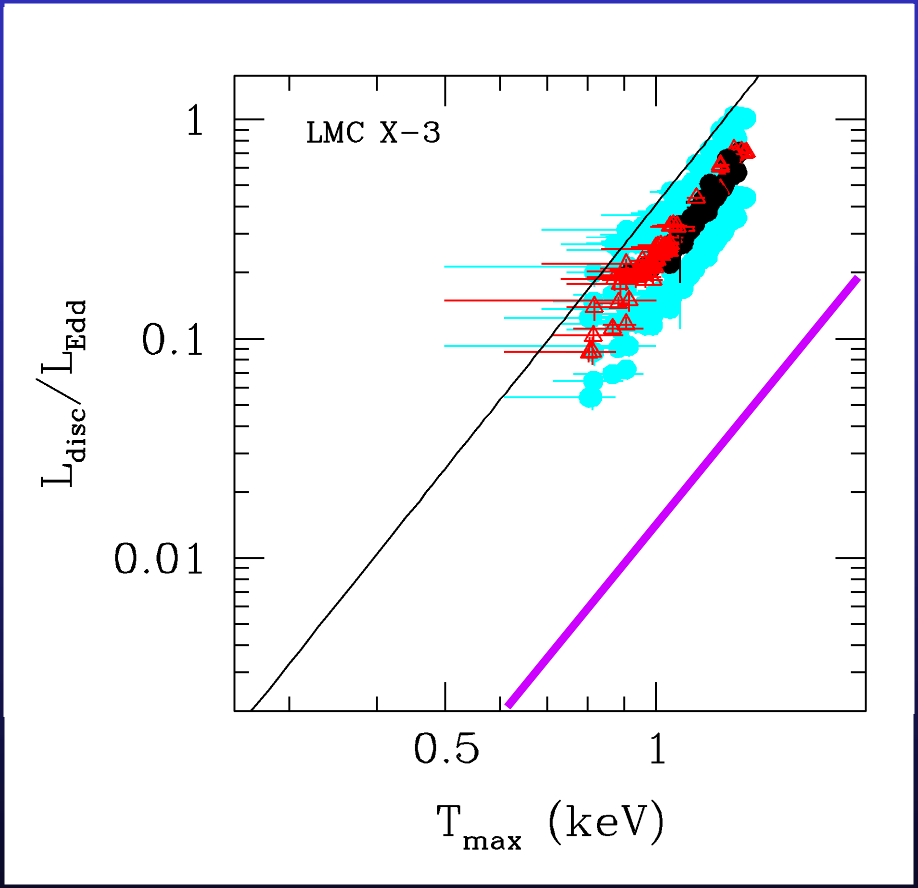
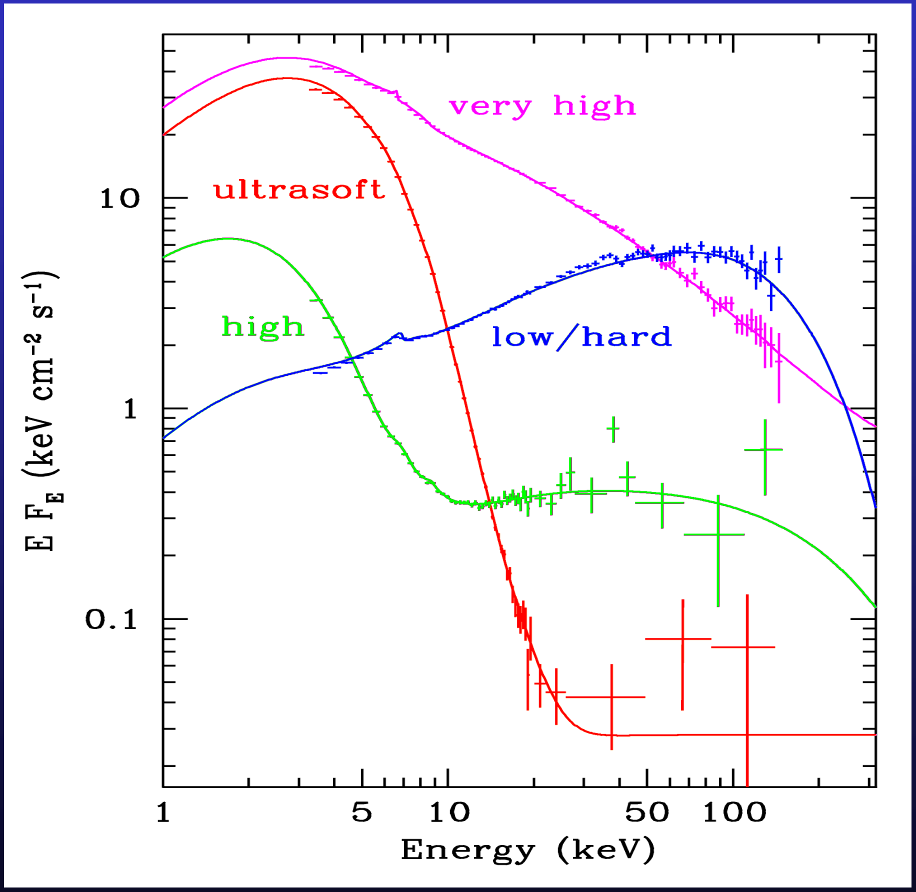


Gierlinski & Done 2003

But rest are not simple…

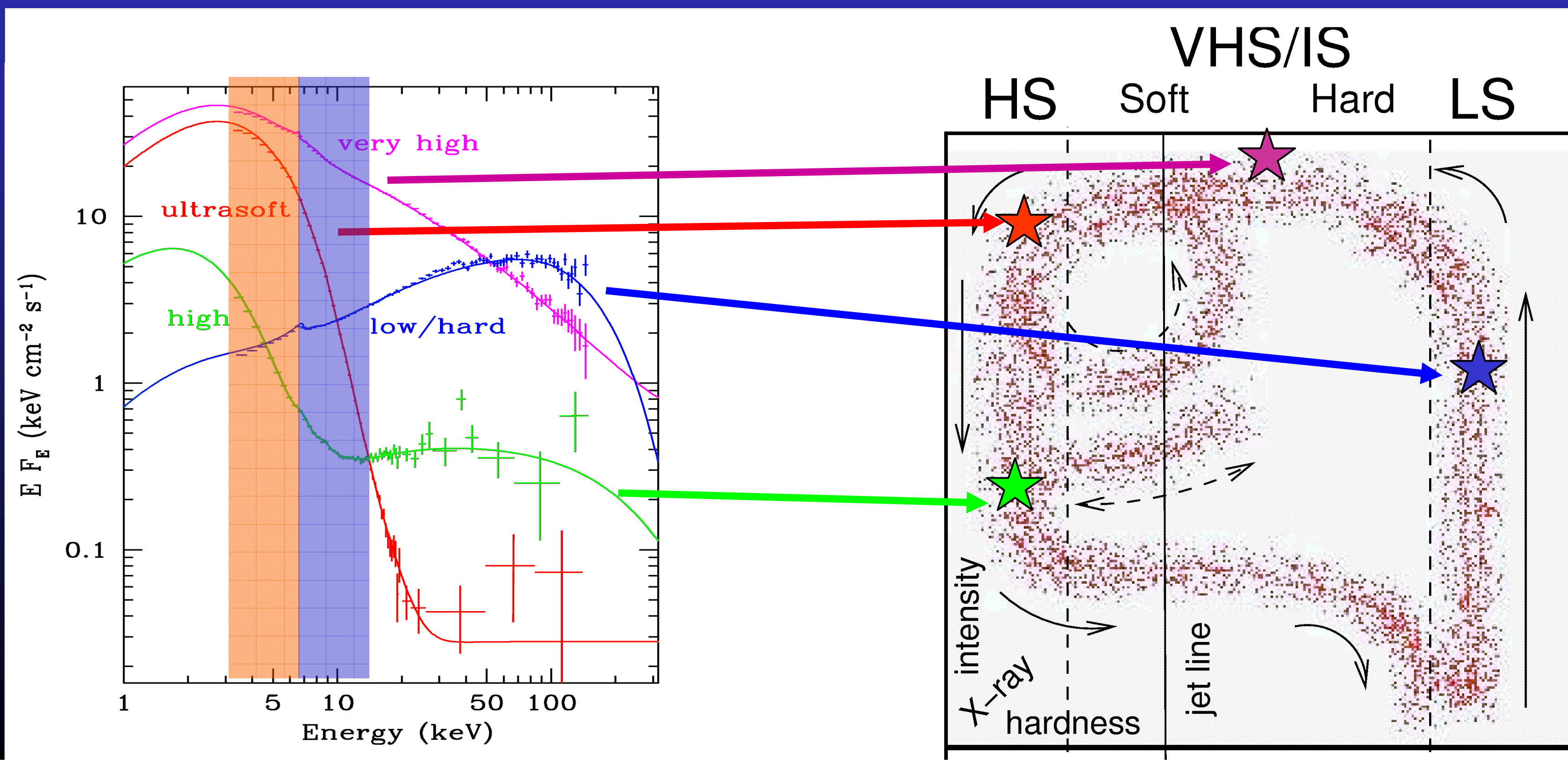
- Bewildering variety of spectra from single object
- Underlying pattern
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail
- Lower L/L_{Edd}: hard spectrum, peaks at high energies, not like a disc



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

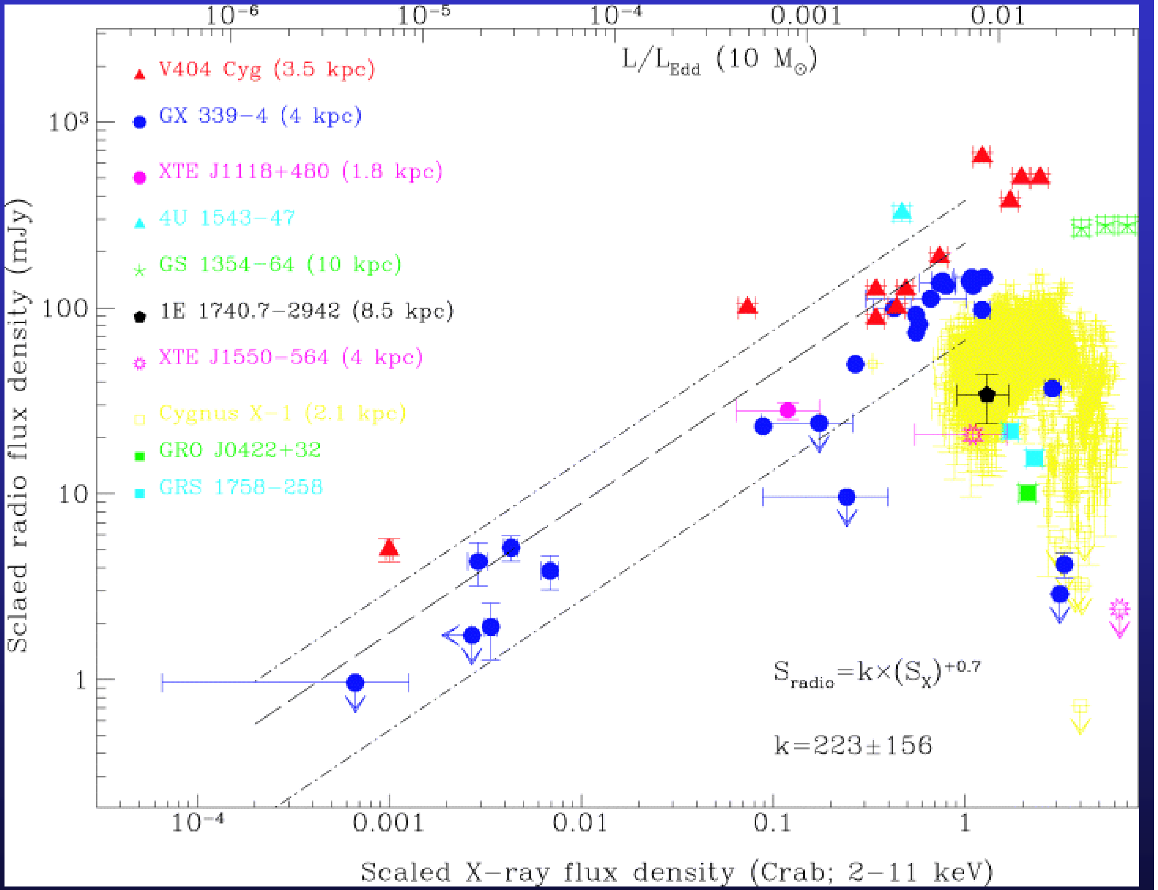


Fender Belloni & Gallo 2004

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
- Steady jet in low/hard state, power depends on accretion rate! i.e. L/L_{Edd} (Merloni et al 2003; Falke et al 2004)

  so jet powered by mass accretion rate ie gravity
- Bright radio flares in rapid low/hard to high/soft associated with outbursts. (Fender et al 2004)



Gallo et al 2003

Accretion flows without discs

- Disc models assumed thermal plasma – not true at low $L/L_{\rm Edd}$
- 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
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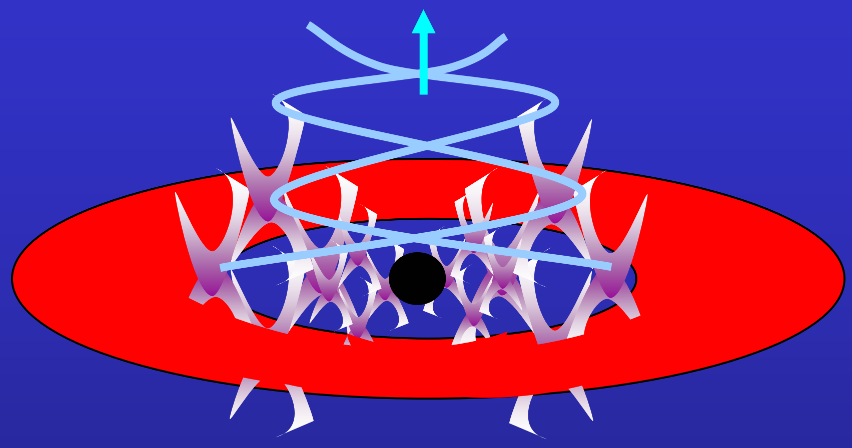
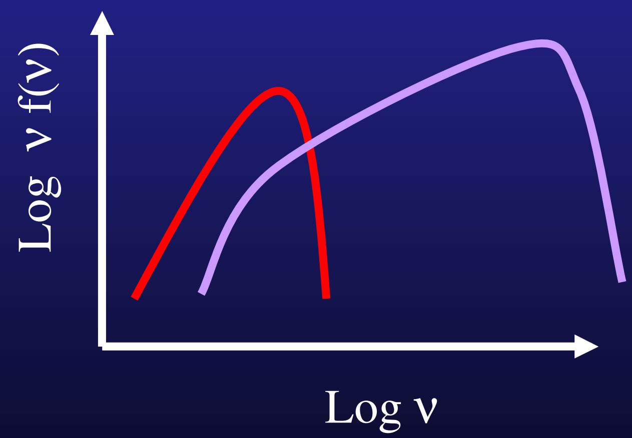
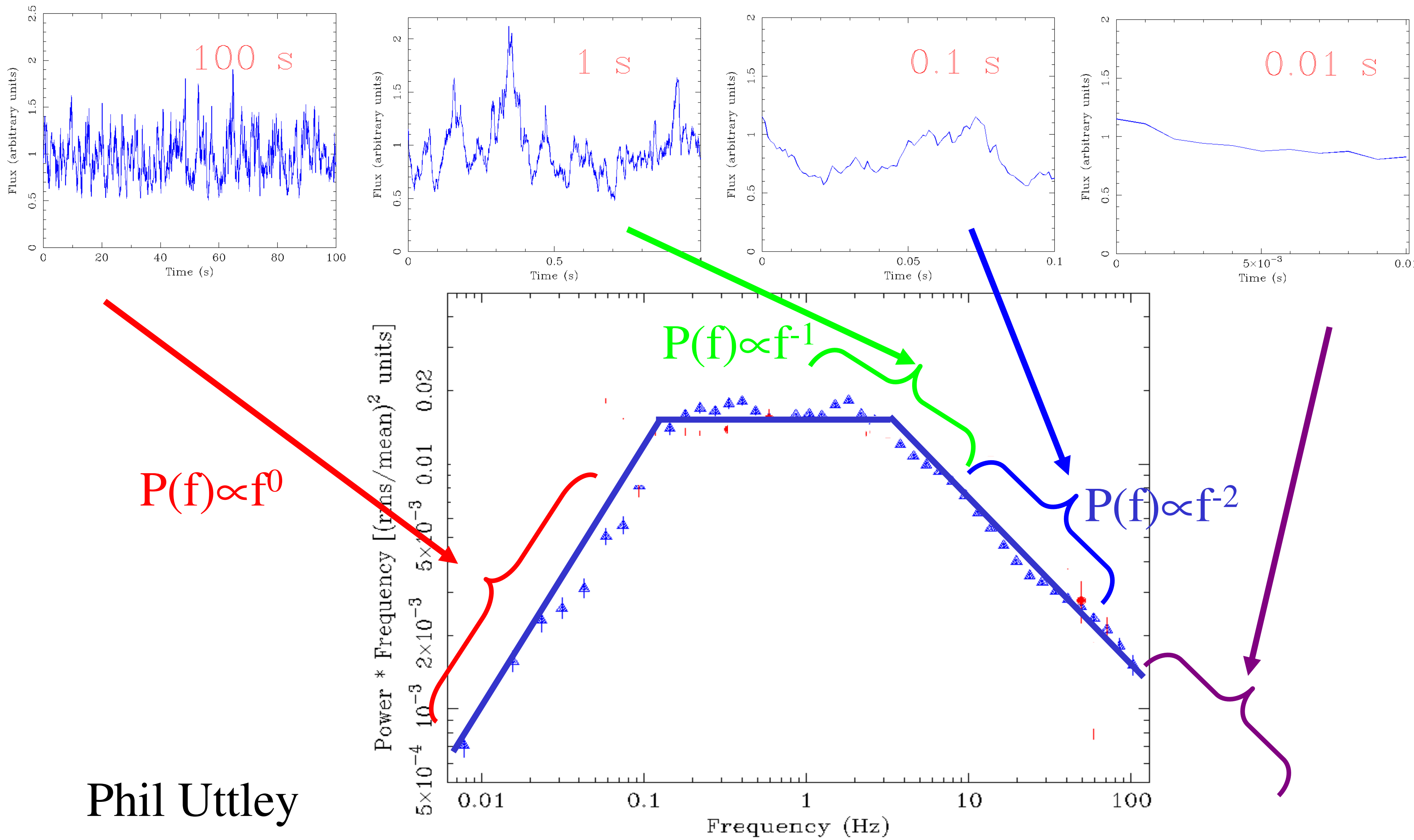




Quantifying variability: the power spectral density (PSD) of Cyg X-1

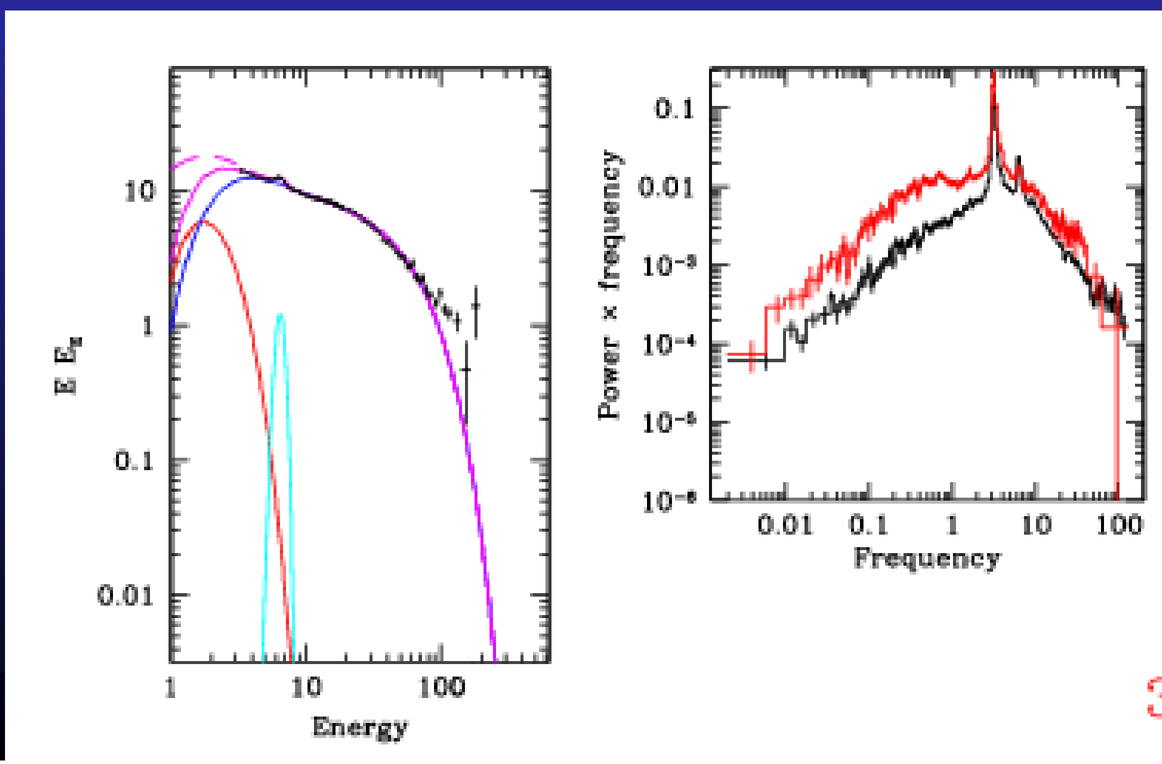


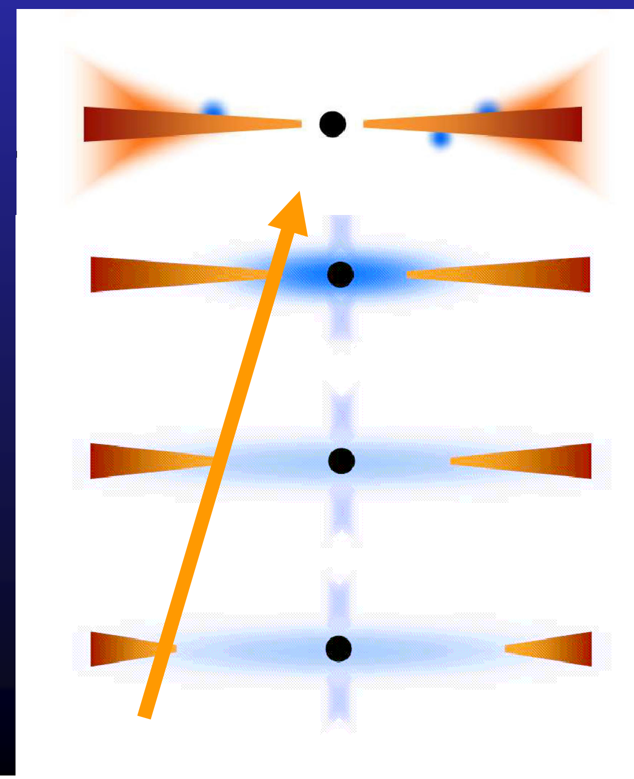
Phil Uttley

Moving disc – moving QPO

- Low frequency QPO – very strong feature at softest low/hard and intermediate and very high states (disc+tail)
- Moves in frequency: correlated with spectrum
- Moving inner disc makes sense of this. Disc closer in, higher f QPO. More soft photons from disc so softer spectra (di Matteo et al 1999)

DGK07





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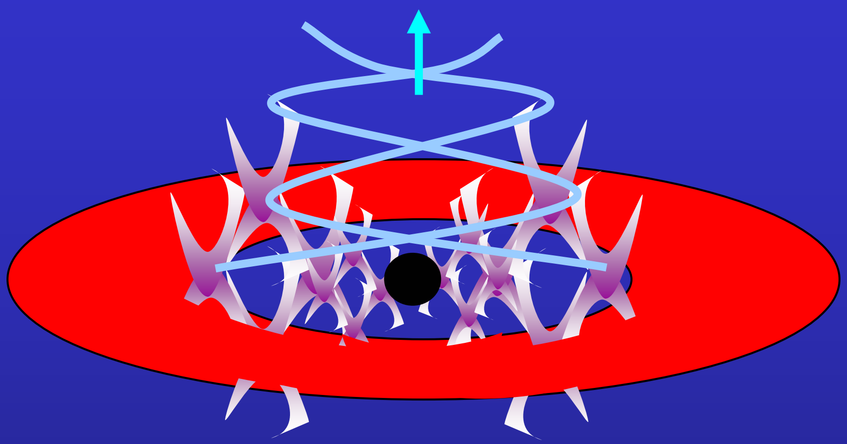

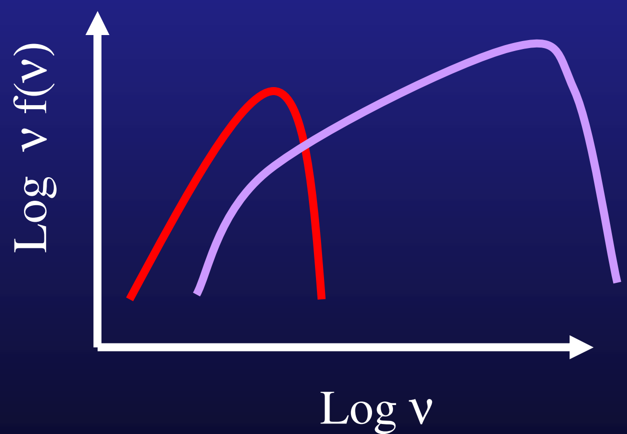

No inner disc

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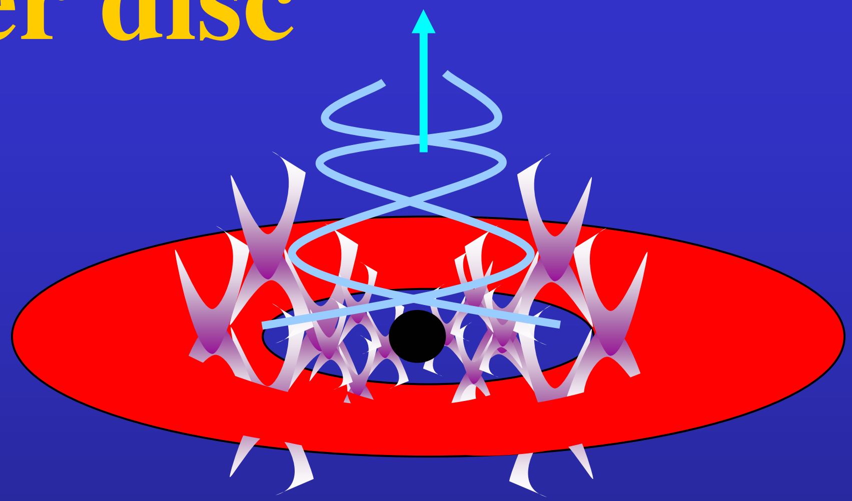

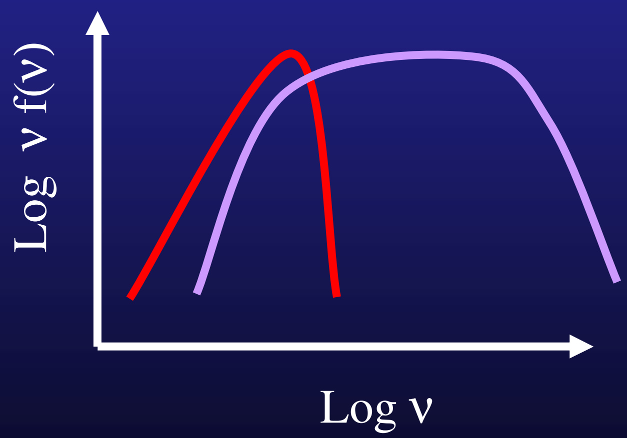

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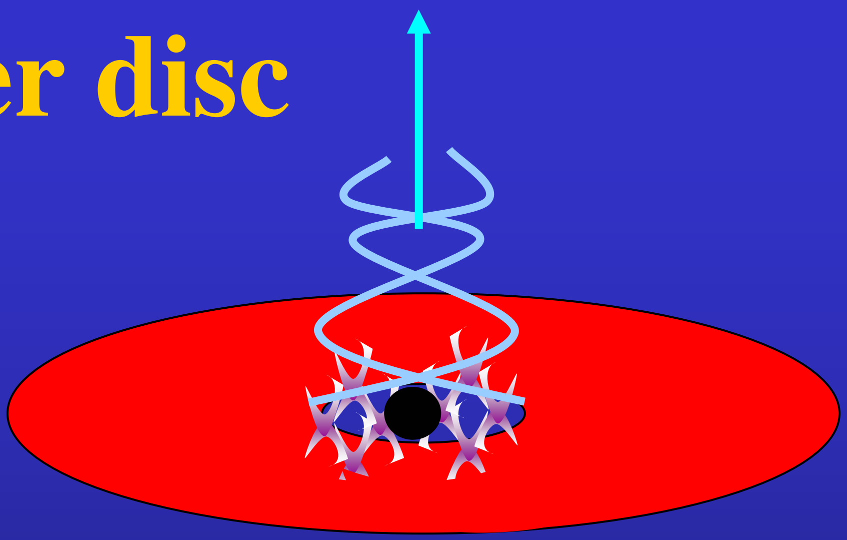

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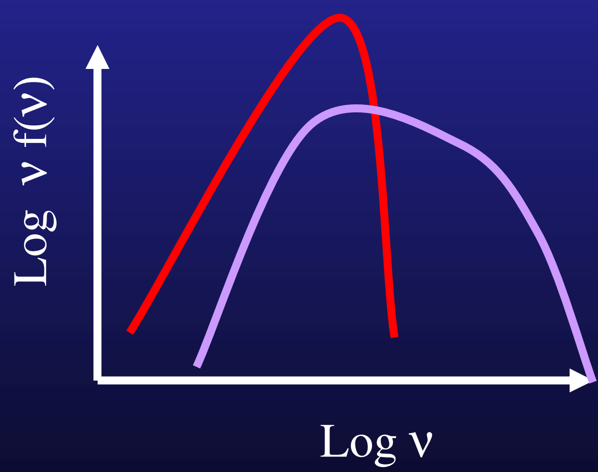

Collapse of hot inner flow

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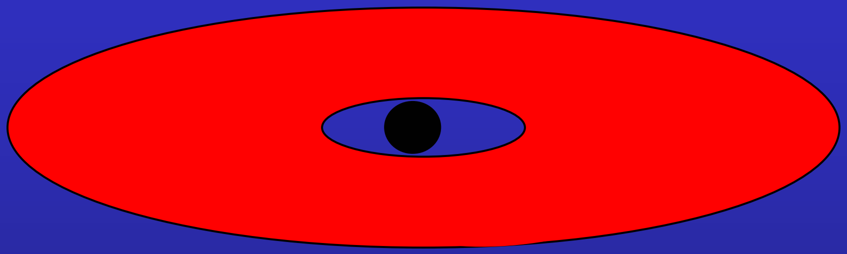
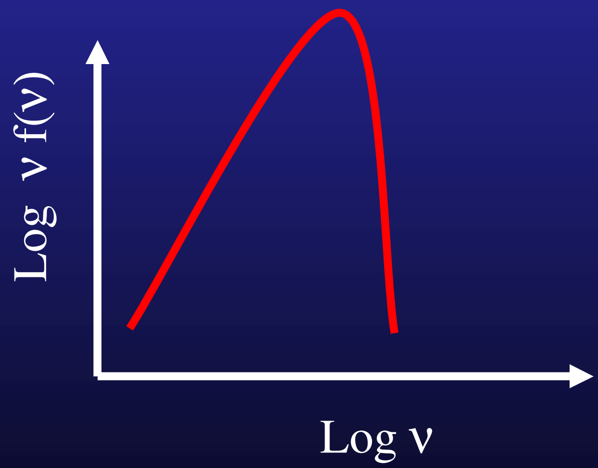
- Hot electrons Compton upscatter photons from outer cool disc
- Few seed photons, so spectrum is hard
- Jet from large scale height flow velocity linked to launch radius collapse of flow=collapse of jet

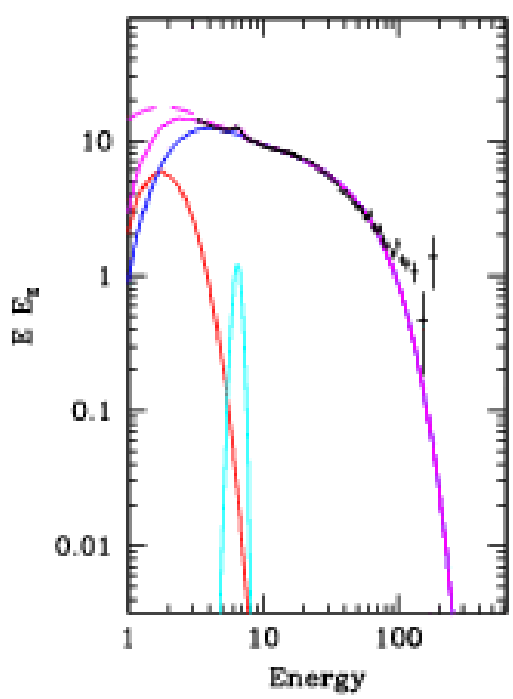


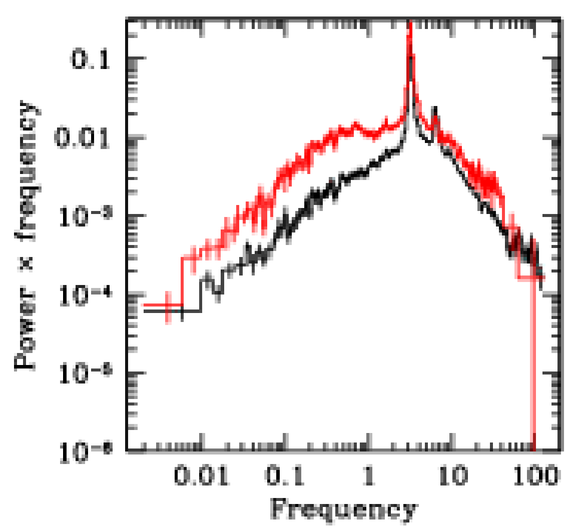


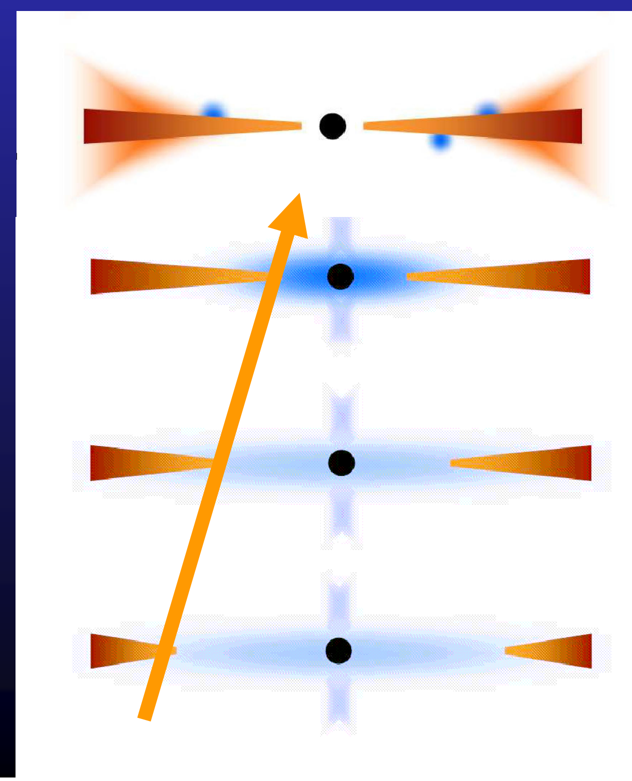
Moving disc – moving QPO

- Spectra need disc to move from 50-6ish Rg as make transition
- This somehow sets QPO (and break) frequency.
- QPO big, must be fundamental.

DGK07

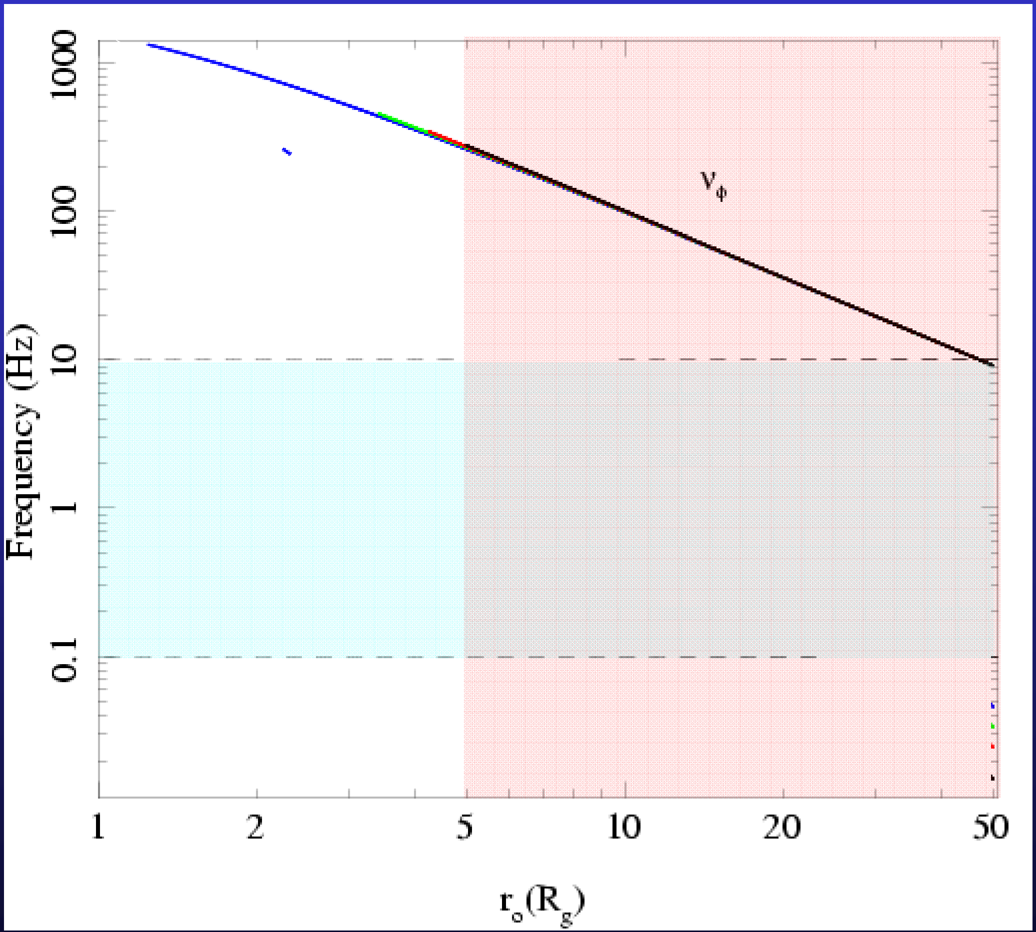






Low frequency QPO

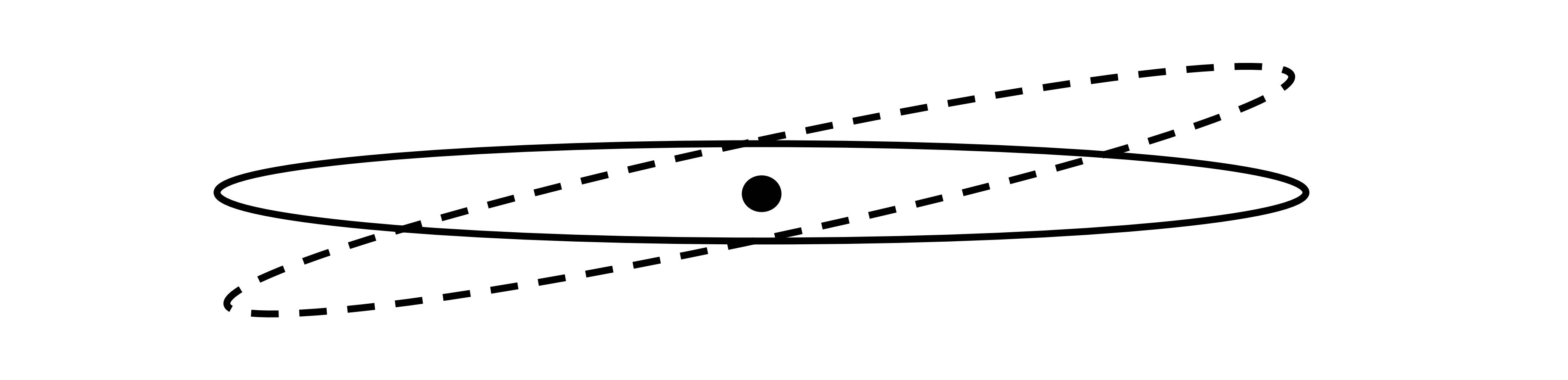
- Observed QPO frequencies go from ~0.1-10 Hz
- See similar range in ALL BHB – so either all BHB have same spin or not much spin dependence on QPO
- Keplarian $\nu(\varphi)$ too fast for reasonable range in radii. Know from spectral change that 50-5R_g



Ingram, Done & Fragile 2009

Low frequency QPO

- Spectra need disc to move from R_{tr} = 50-6ish R_g as make transition
- This somehow sets QPO (and break) frequency.
- QPO big, must be fundamental. Not $\nu(\phi)$ as too fast!
- Stella & Vietri 1998 – GR potential not spherically symmetric so vertically offset circular orbit has $\nu(\theta) \neq \nu(\phi)$
- Lense-Thirring precession $\nu_{LT} = \nu(\theta) - \nu(\phi)$



Low frequency QPO

- Spectra need disc to move from R_{tr} = 20-6ish R_g as make transition
- This somehow sets QPO (and break) frequency.
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- Stella & Vietri 1998 – GR potential not spherically symmetric so vertically offset circular orbit has $\nu(\theta) \neq \nu(\varphi)$
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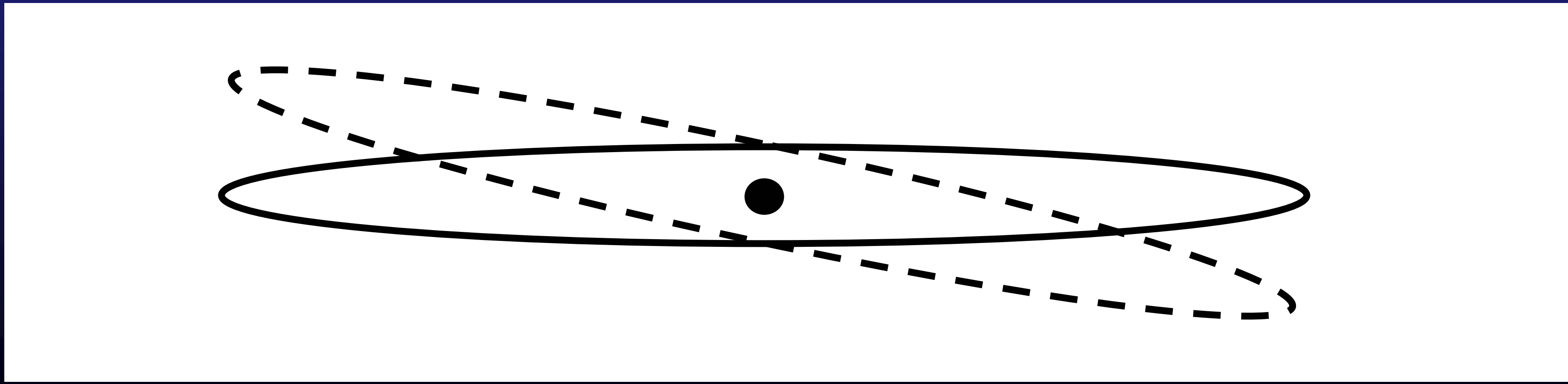
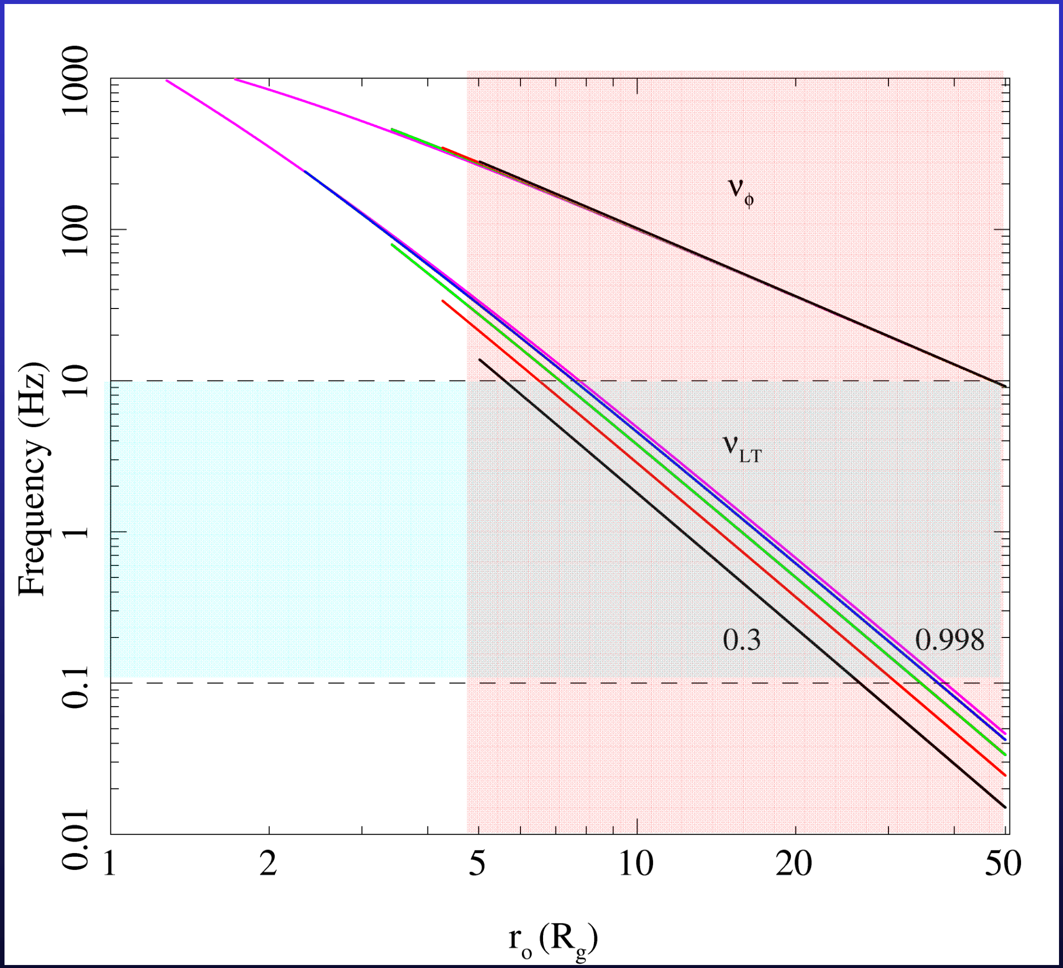


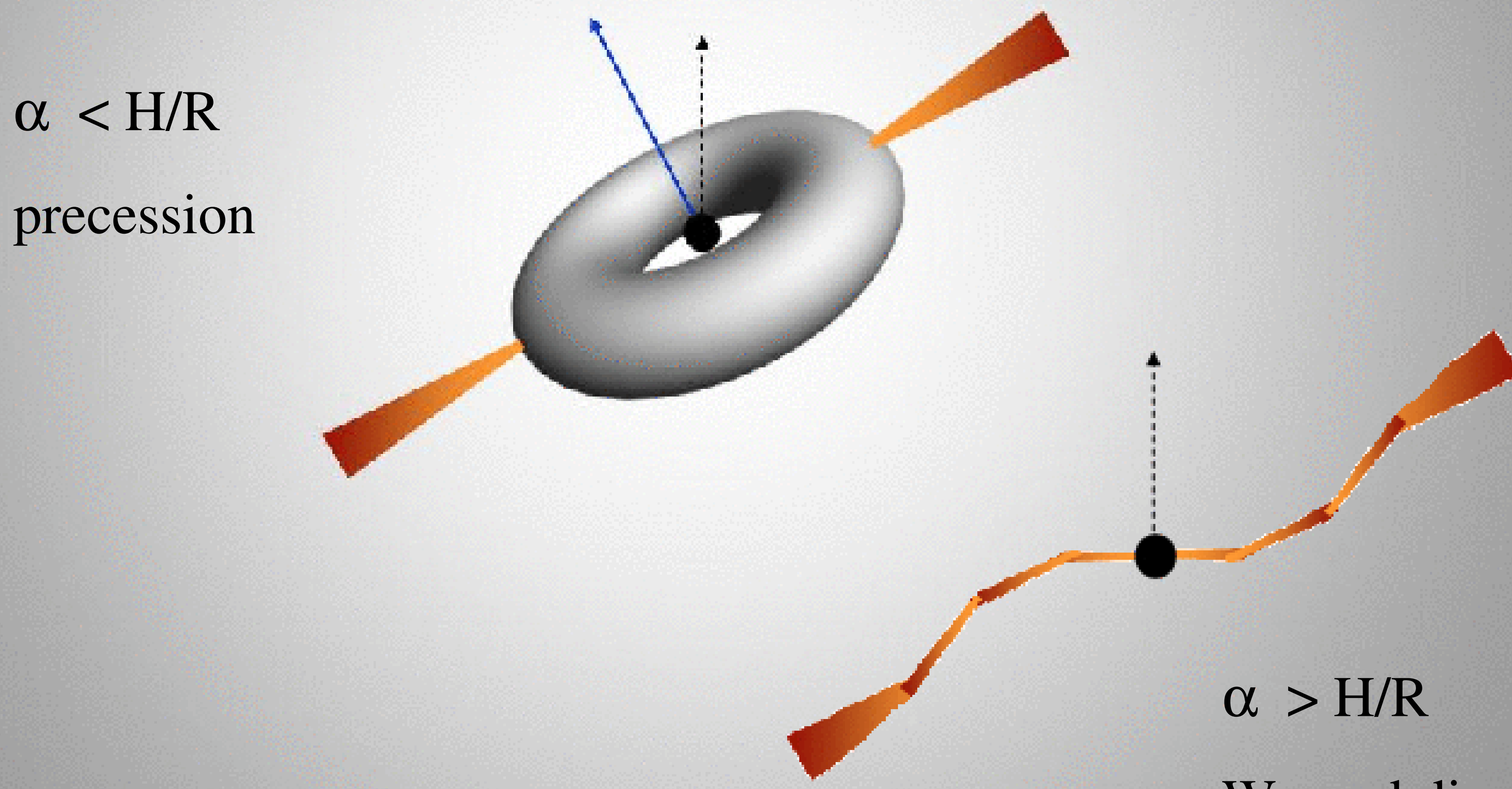
Does it work ?

- No!!
- Data show QPO frequency goes from ~ 0.1-10 Hz for all BHB
- Presumably they have range in spin. LT precession frequency depends on spin but all BHB have similar range in QPO frequencies.
- BUT this is for single radius. Actually expect whole hot inner flow to precess.



Ingram, Done & Fragile 2009

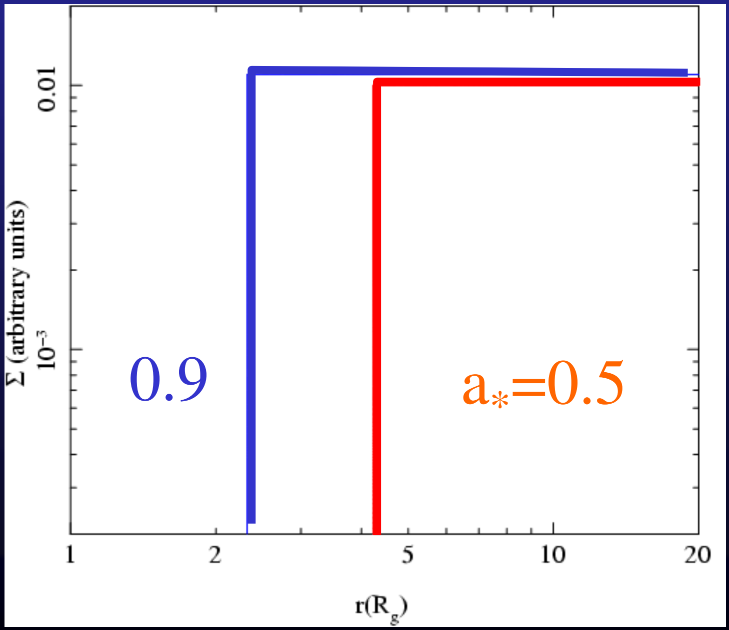
Solid body precession of the flow

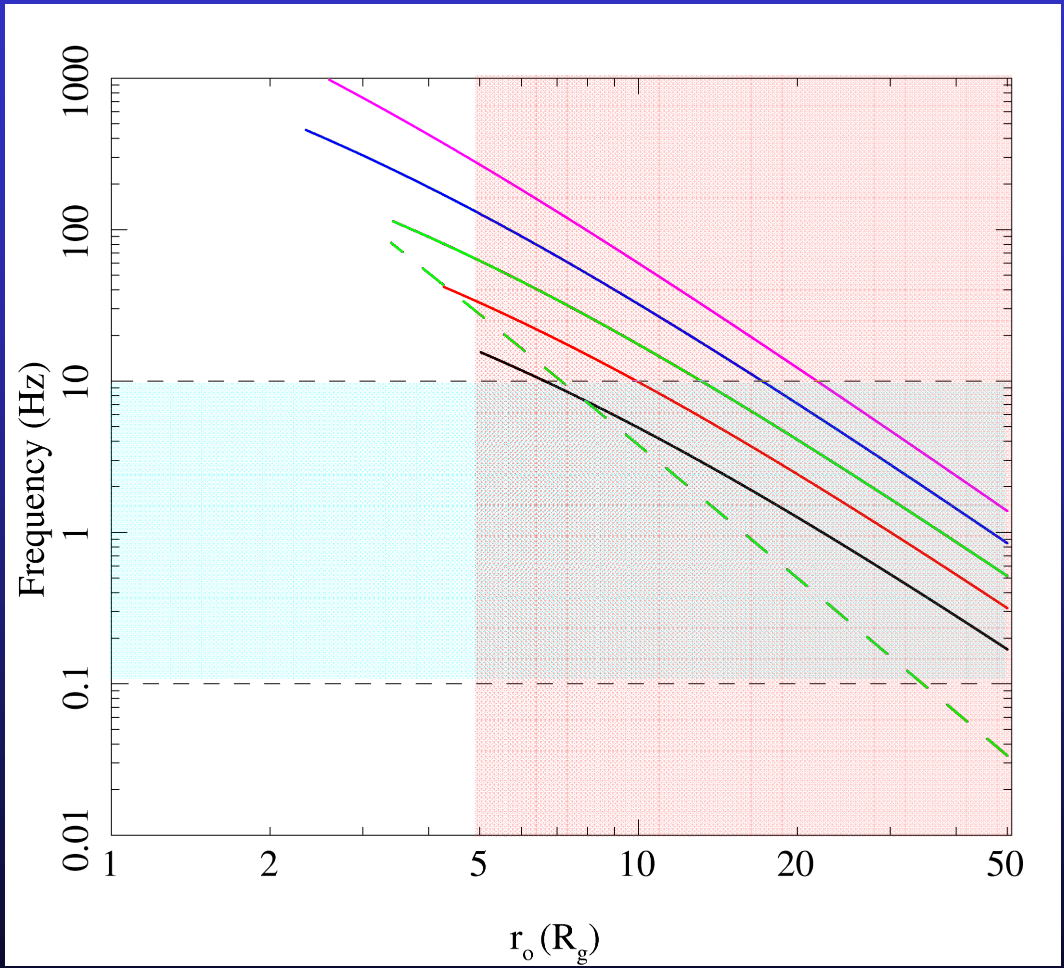


Ingram, Done & Fragile 2009

LT precession of hot flow?

- LT frequency depends on distribution of mass in flow. Fragile et al 2007
- Assume constant surface density with radius from Rtr to Rlso

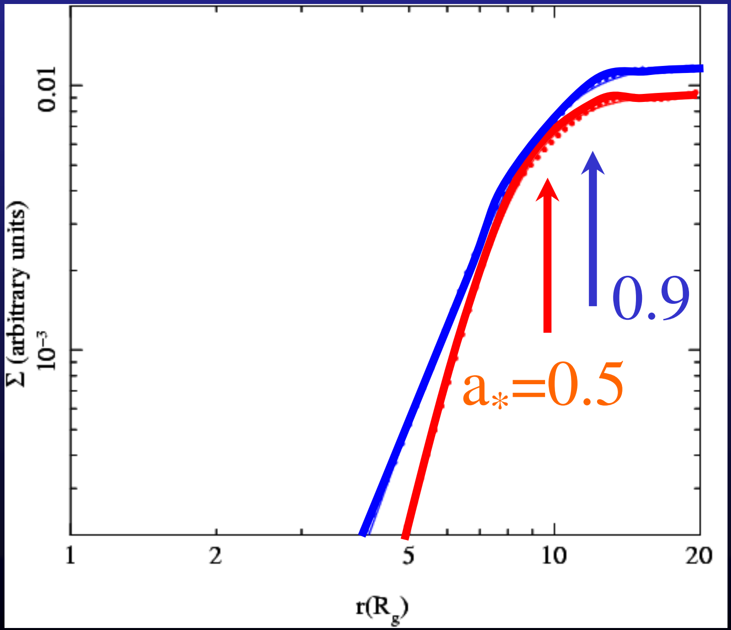




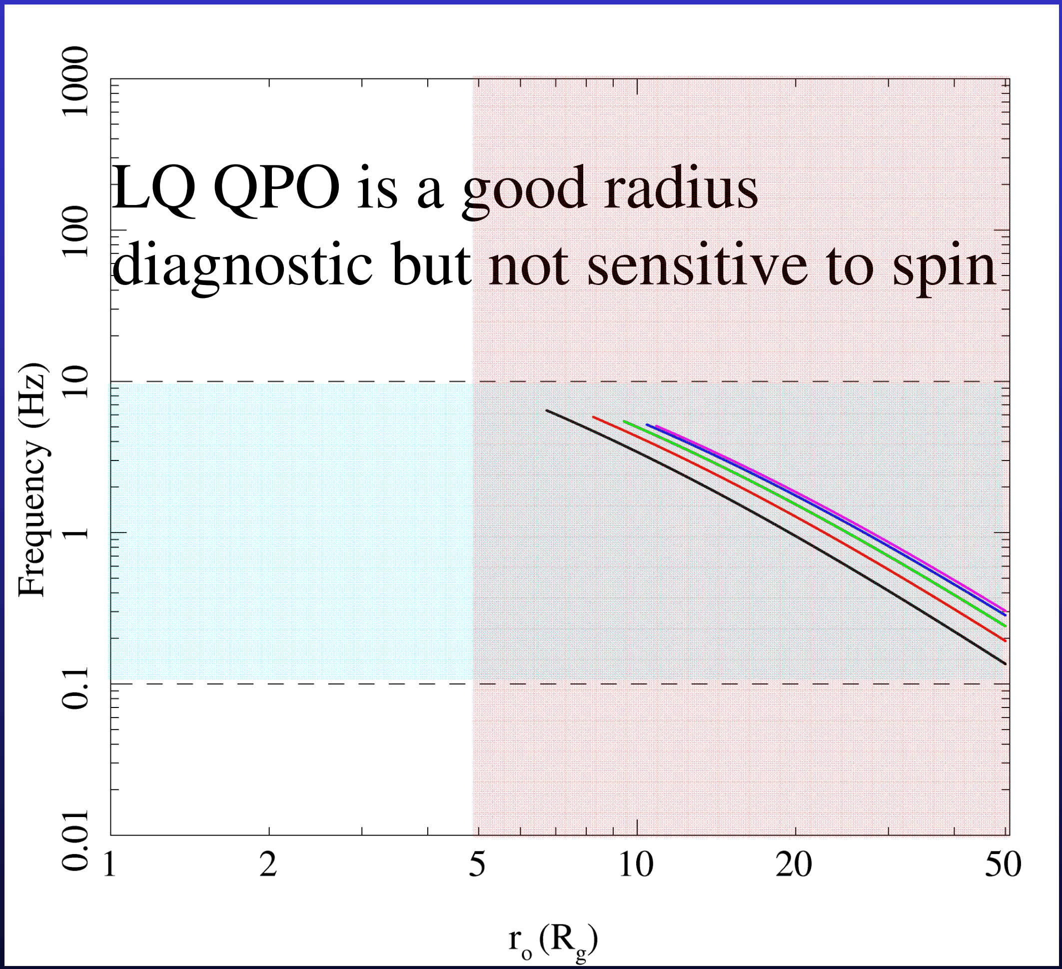
Ingram, Done & Fragile 2009

LT precession of hot flow?

- Extra torque as misalign
- More stress, faster accretion so lower surface density Fragile et al 2007; 2009
- more torque for bigger spin so Rin bigger (opposite to Rlso!)

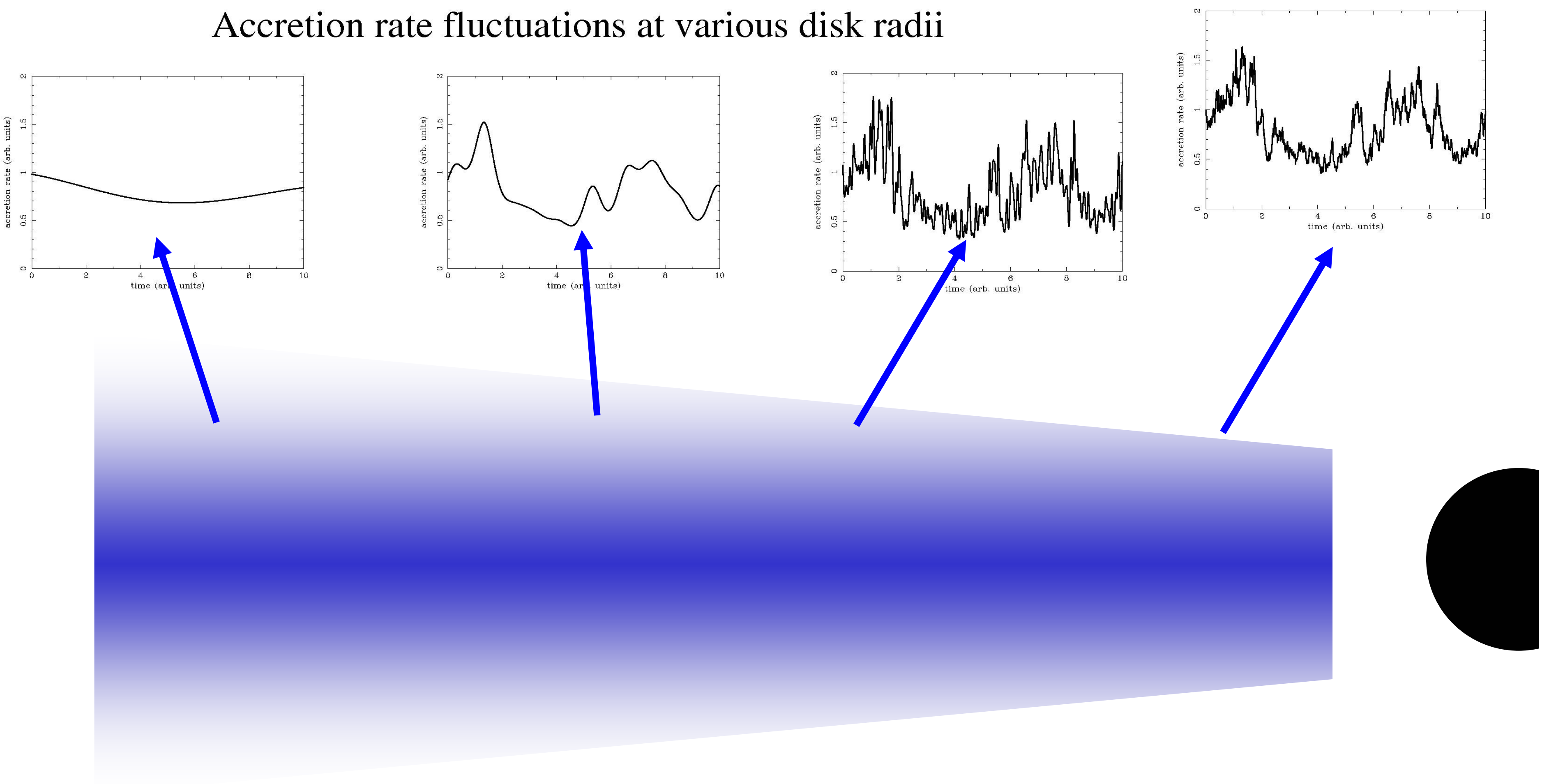


- Truncates at ~ bending wave radius



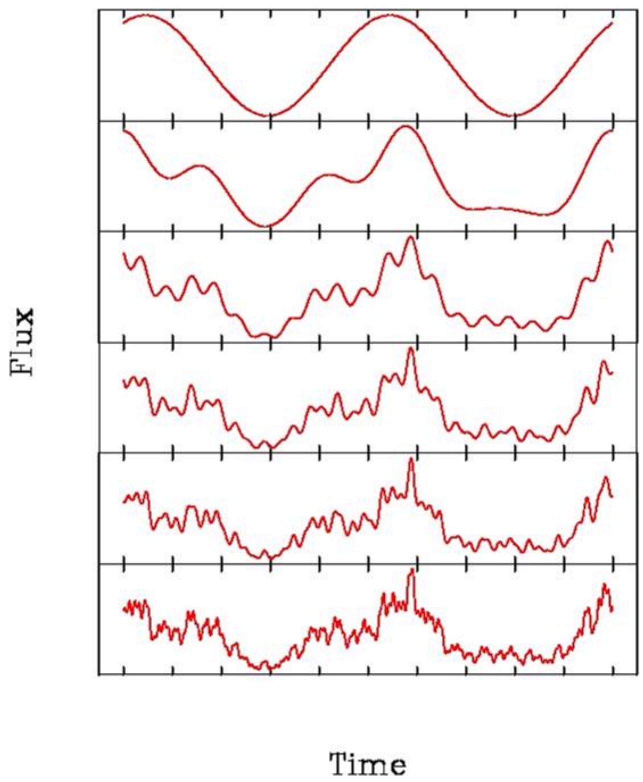
Ingram, Done & Fragile 2009

Origin of variability



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

A simple mathematical model



Linear light curves can be generated by a sum of sine waves:

$$L(t) = 1 + \sum A_\iota \sin(\omega_\iota t + \phi_\iota)$$

But here, we have a product….

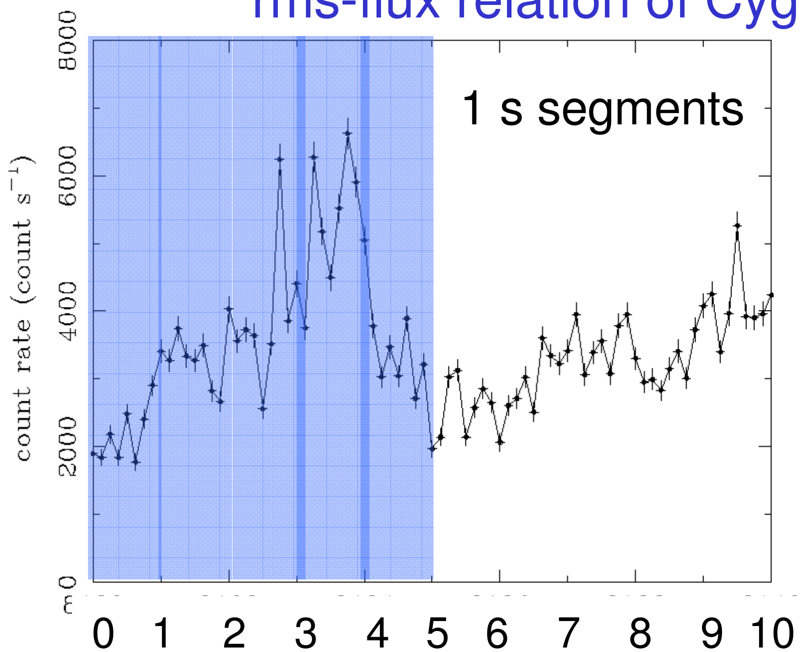
$$X(t) = \Pi\ [1 + A_\iota \sin(\omega_\iota t + \phi_\iota)]$$

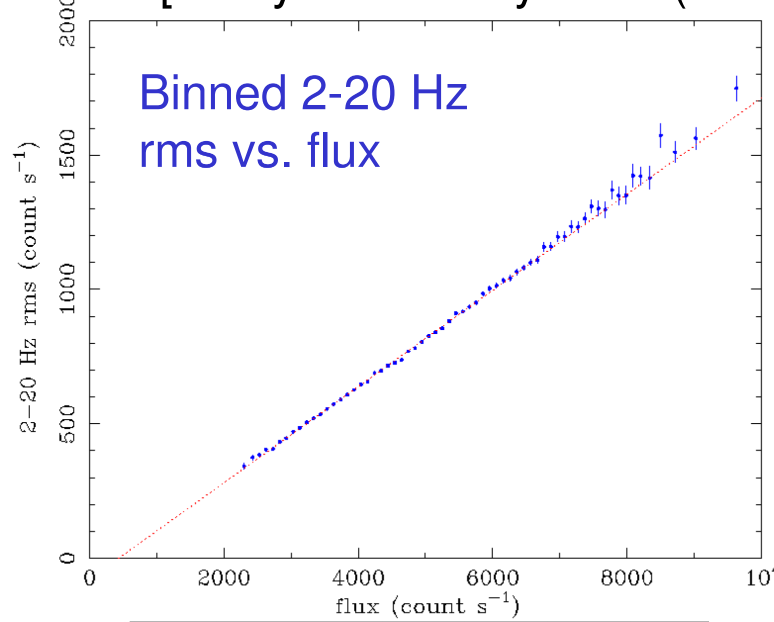
$$X(t) = \exp\ [L(t)]$$

For stationary processes, $L(t)$ has a Gaussian distribution, so $X(t)$ has a *lognormal* distribution….

The rms-flux relation

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

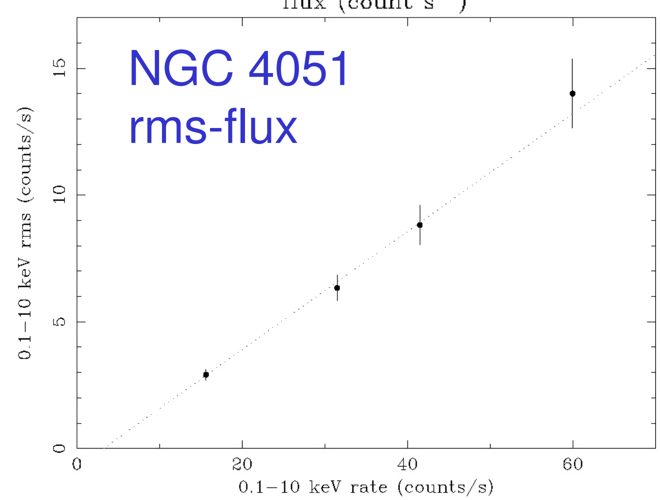




$$rms = \sqrt{ (1/N) \sum_{i=1,N} (flux_i - mean)^2 }$$

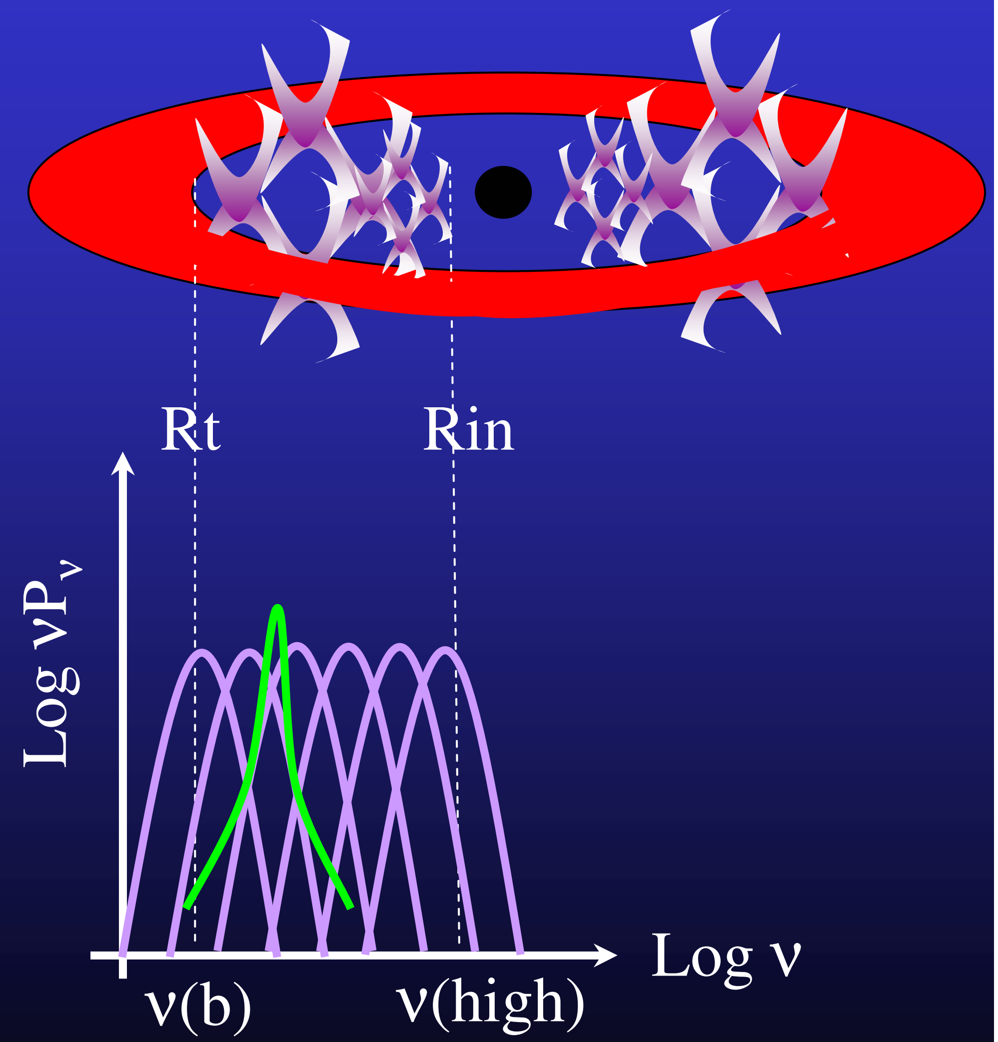
Linear rms-flux relations are also seen in AGN, e.g. NGC 4051

(UM01, McHardy et al. 2004)



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



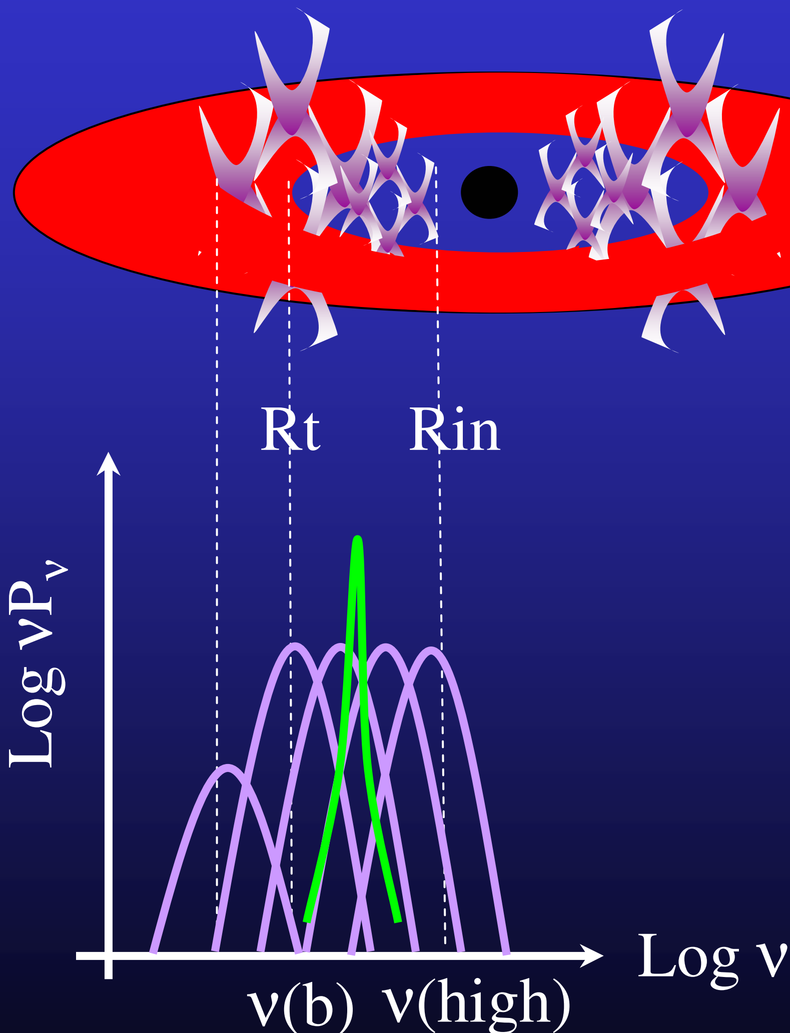
Ingram & Done 2009

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)
- Viscous timescale depends on α as well as H/R…



Ingram & Done 2009

No jet

Decrease fraction of power in nonthermal reconnection above disc

Disc to minimum stable orbit

Decrease inner disc radius, and maybe radial extent of corona giving increasing LF QPO frequency

Jet gets faster, catches up with slower outflow, get flares of radio emission from internal shocks Fender (2004)

HS

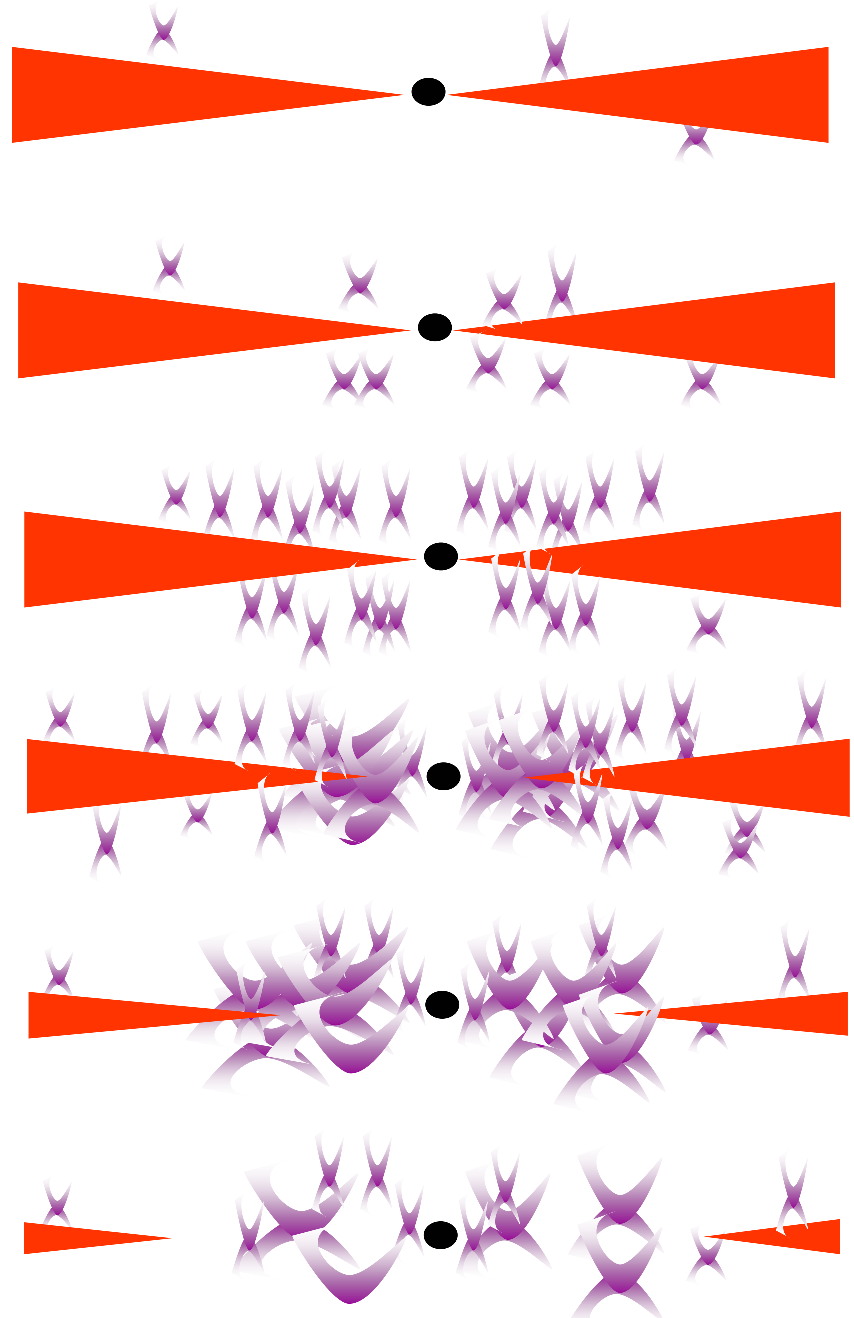
HS

VHS

VHS

LS (bright)

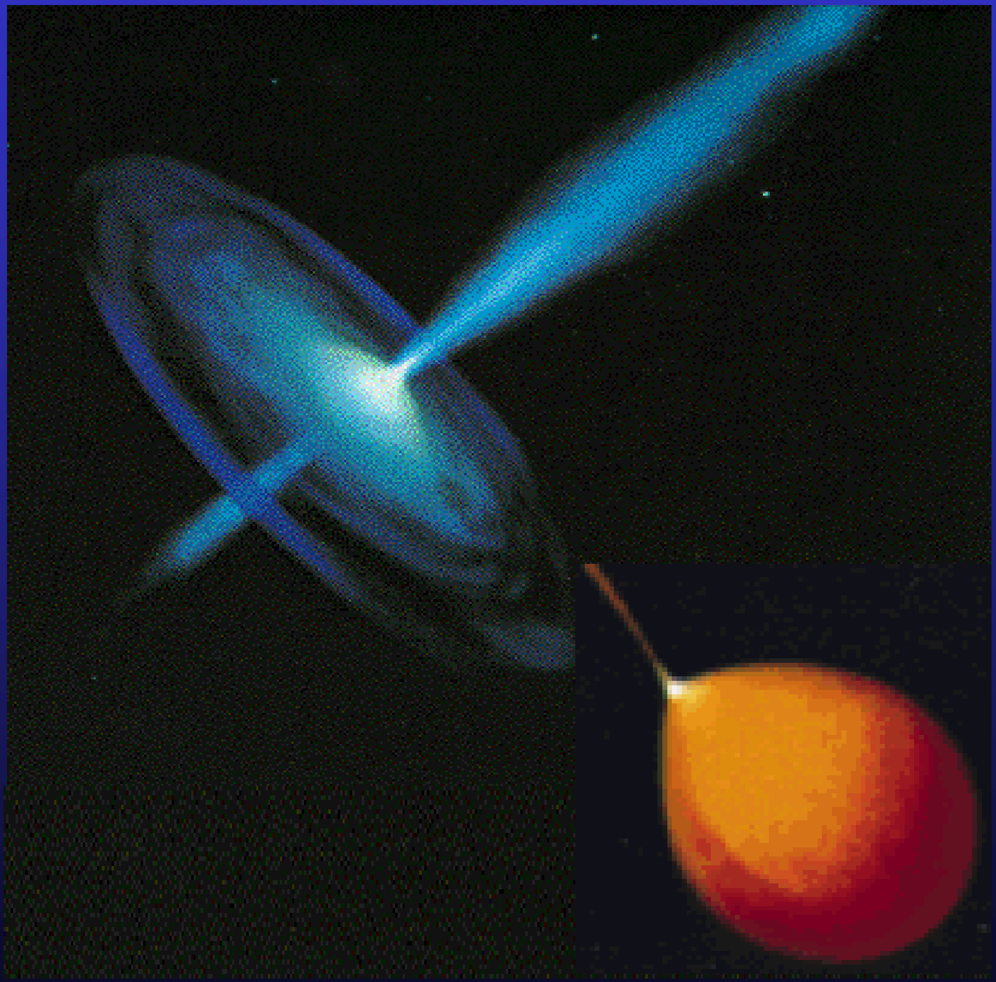
LS (dim)



Done Gierlinski & Kubota 2007

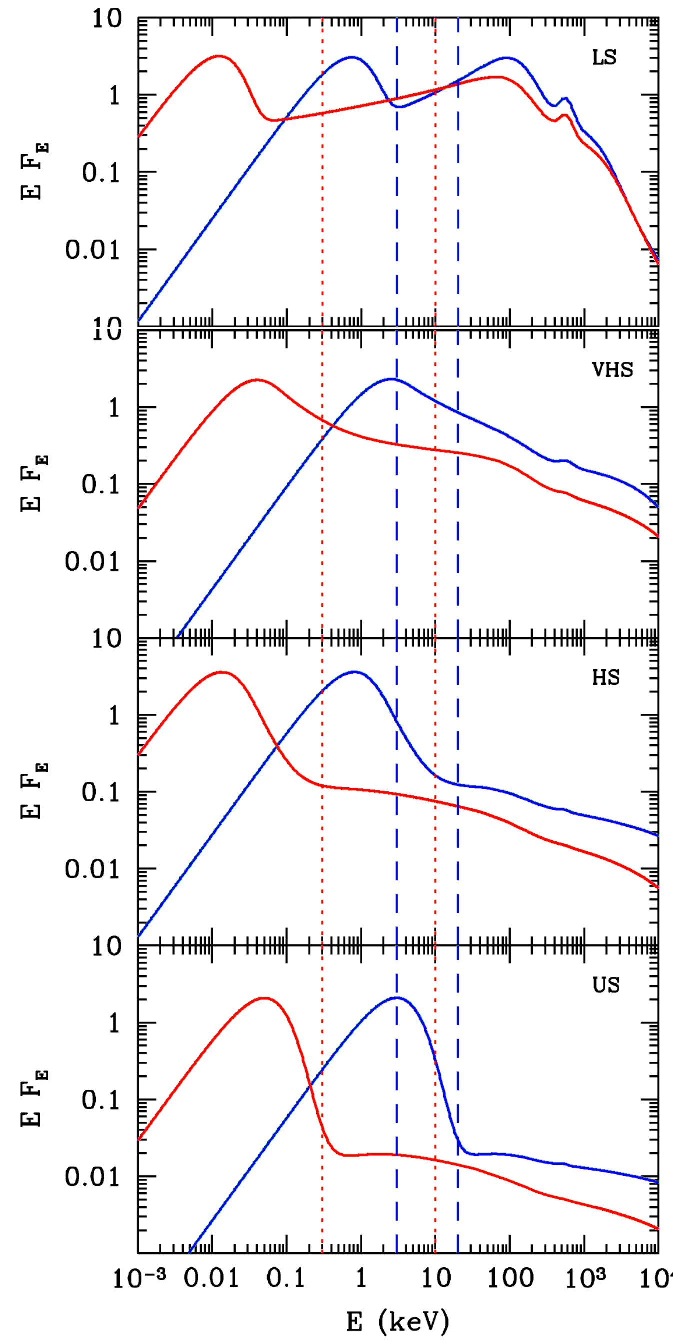
Scale up to AGN

- AGN – much more massive so disc in UV



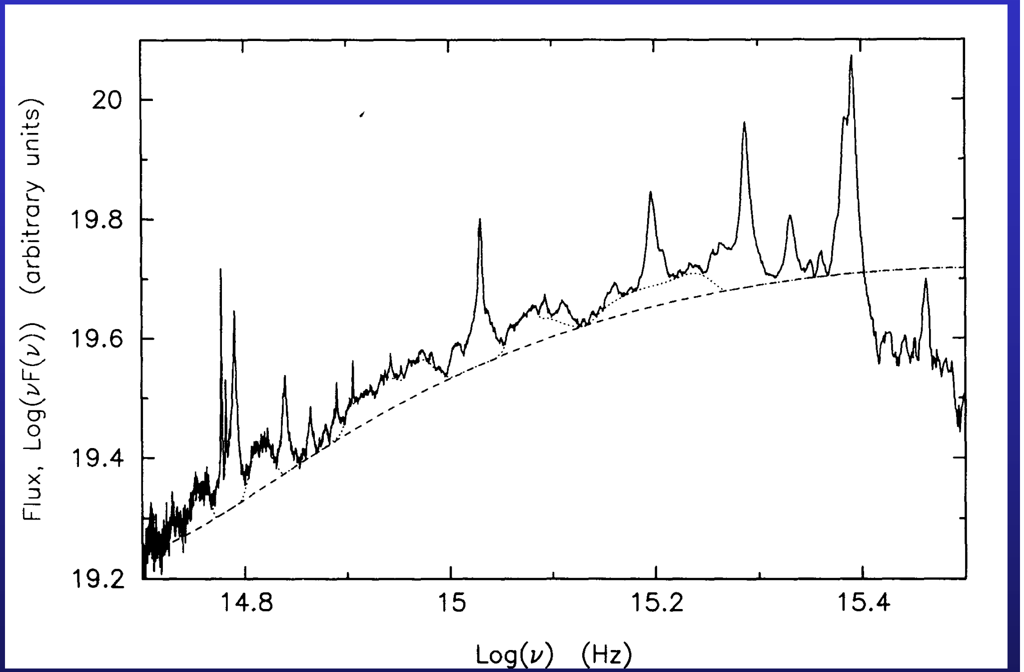
AGN spectral states

- Stretched out by lower disc temperature so not so obvious as in BHB
- BUT range in Lx/Lbol
- High mass accretion rates (high L/LEdd) have lower Lx/Lbol as dominated by UV disc
- Lower mass accretion rates (low L/LEdd) dominated by hard X-rays from hot flow



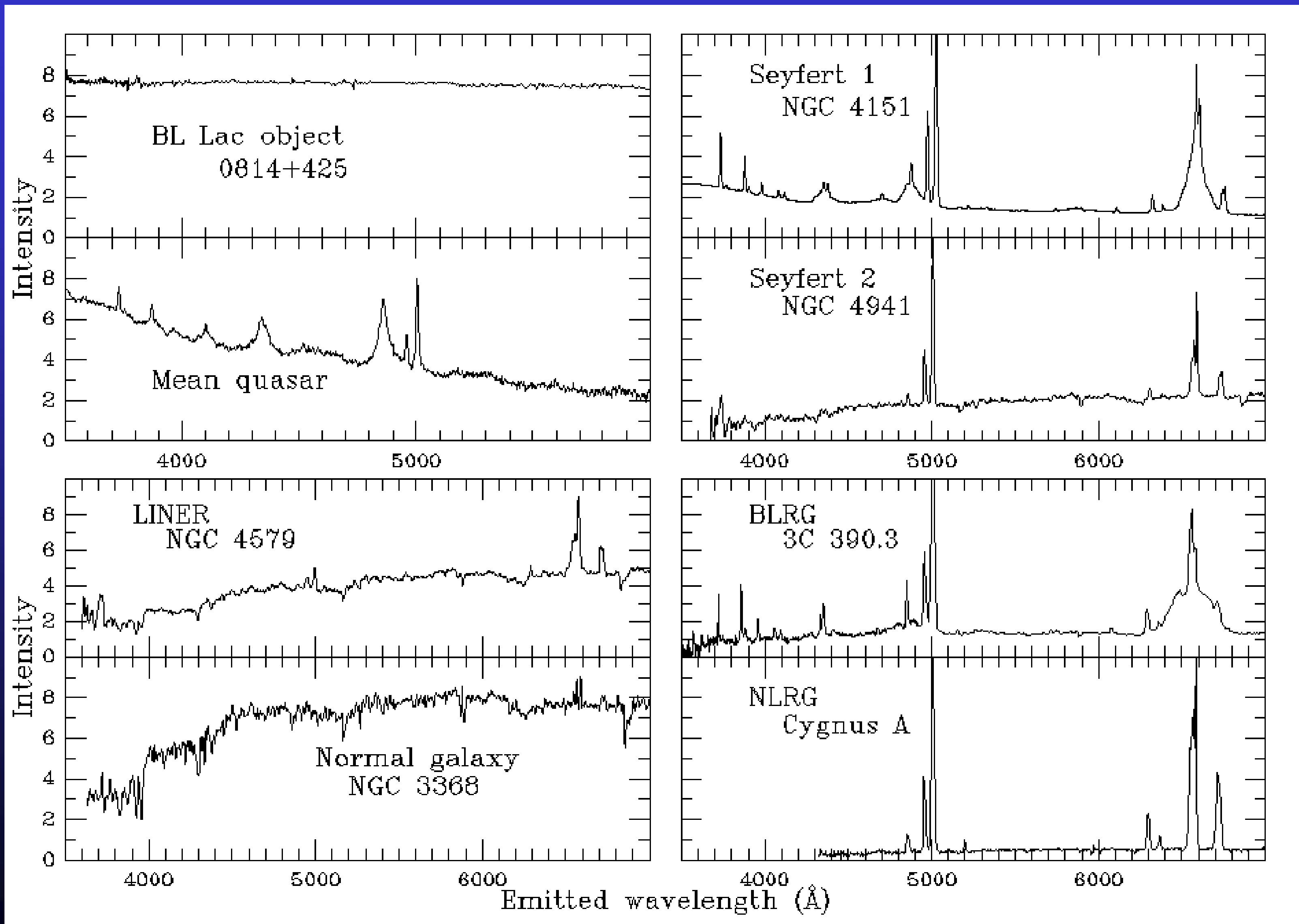
UV disc seen in Quasars!

- Bright, blue/UV continuum from accretion disc.
- Gas close to nucleus irradiated and photo-ionised – lines!
- Broad permitted lines ~ 5000 km/s (BLR)
- Narrow forbidden lines ~ 200 km/s (NLR)
- Forbidden lines suppressed if collisions so NLR is less dense than BLR



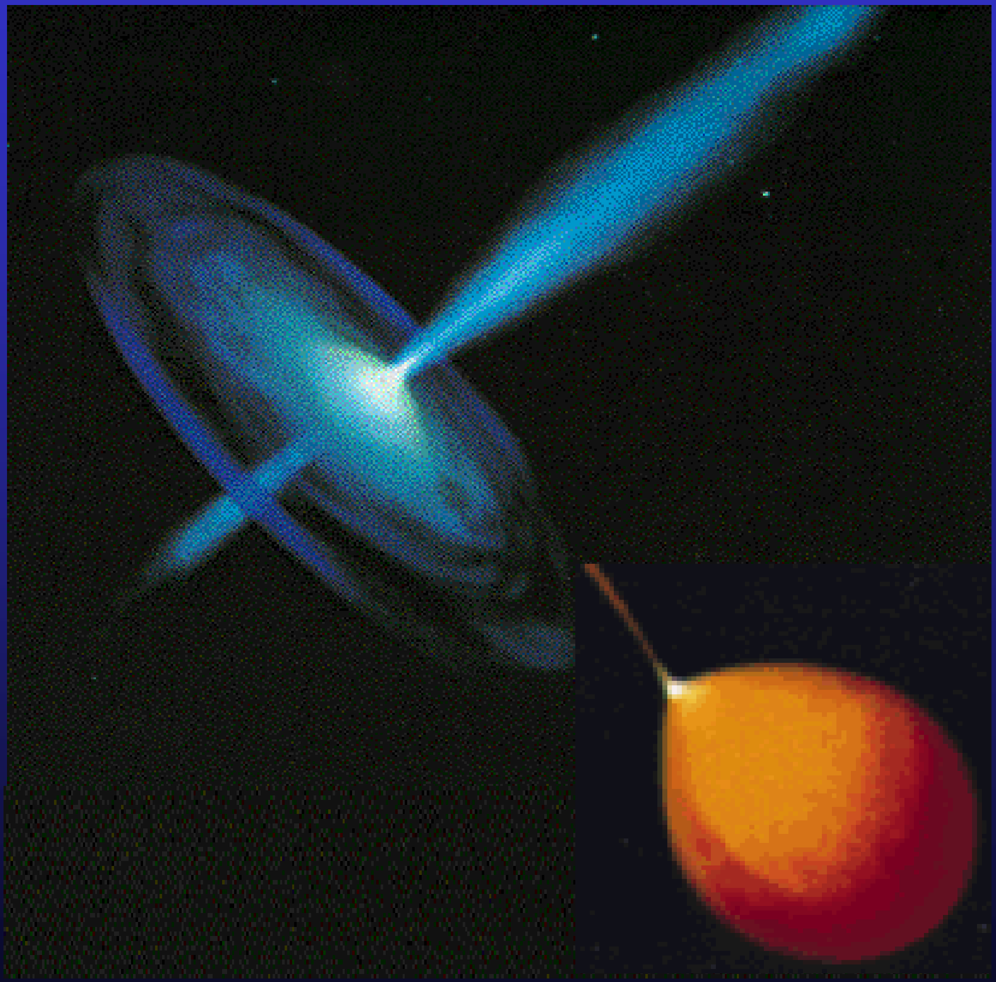
Francis et al 1991

AGN/QSO Zoo!!! Optical



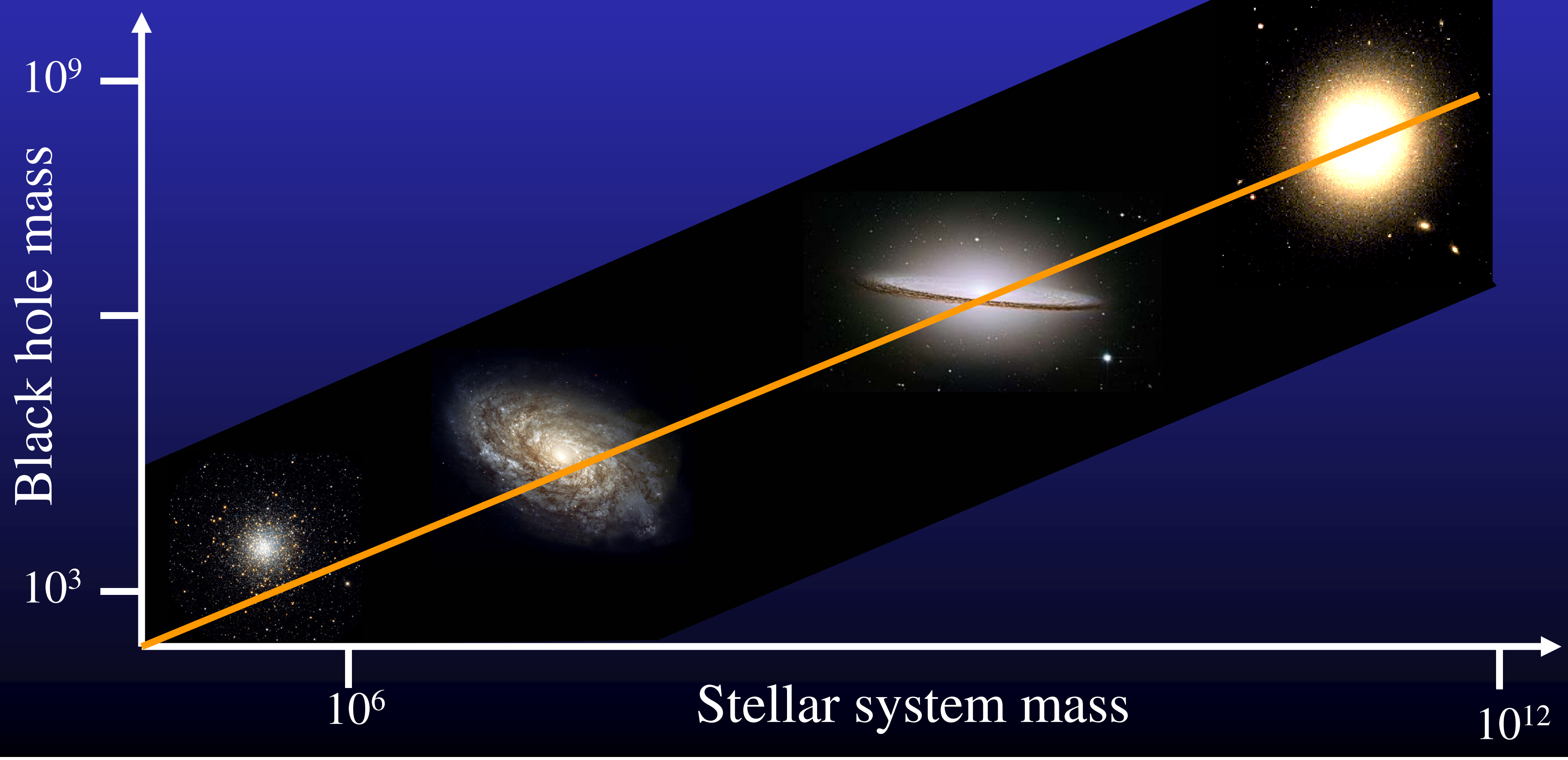
Scale up to AGN

- Wider range in mass and spin – all BHB born in similar way but AGN built by accretion
- Fuelling mechanism change:
- BHB companion star
- maximum mass accretion rate set by size of binary
- $10^{-6} < L/L_{Edd} < 0.5$
- Only very few have higher L/L_{Edd} (GRS1915+105)
- Different fuelling of AGN means not limited in same way – can reach $L/L_{Edd} \geq 1$?



Mass of AGN??

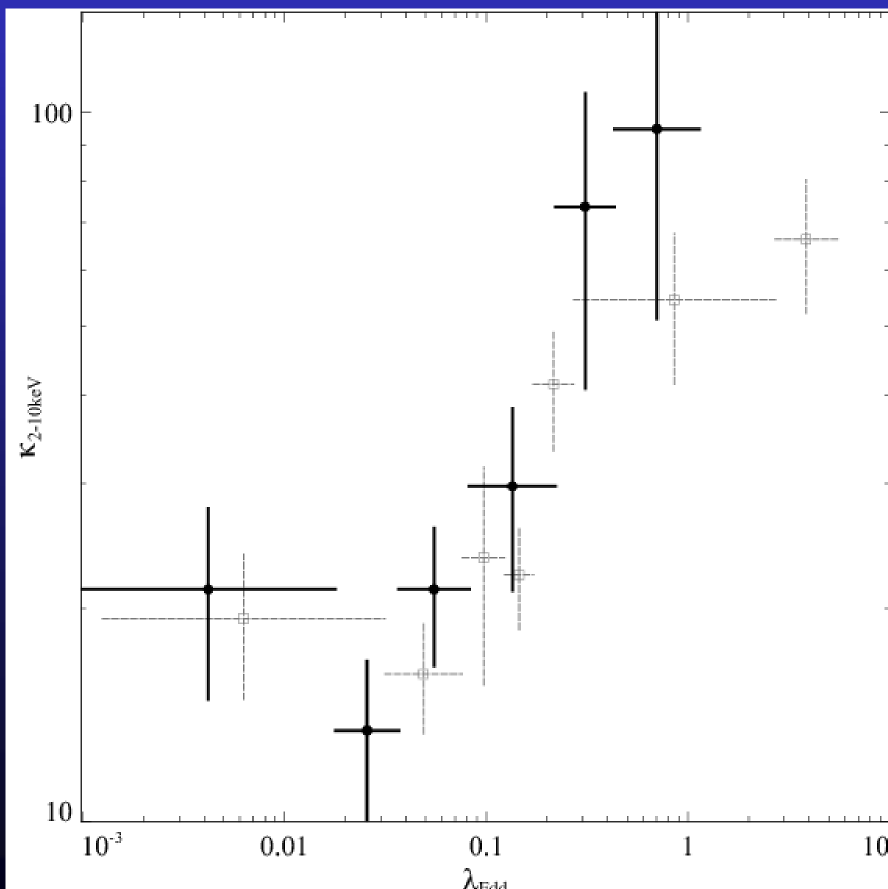
- Magorrian-Gebhardt relation gives BH mass!! Big black holes live in host galaxies with big bulges! Either measured by bulge luminosity or bulge mass (stellar velocity dispersion) or BLR

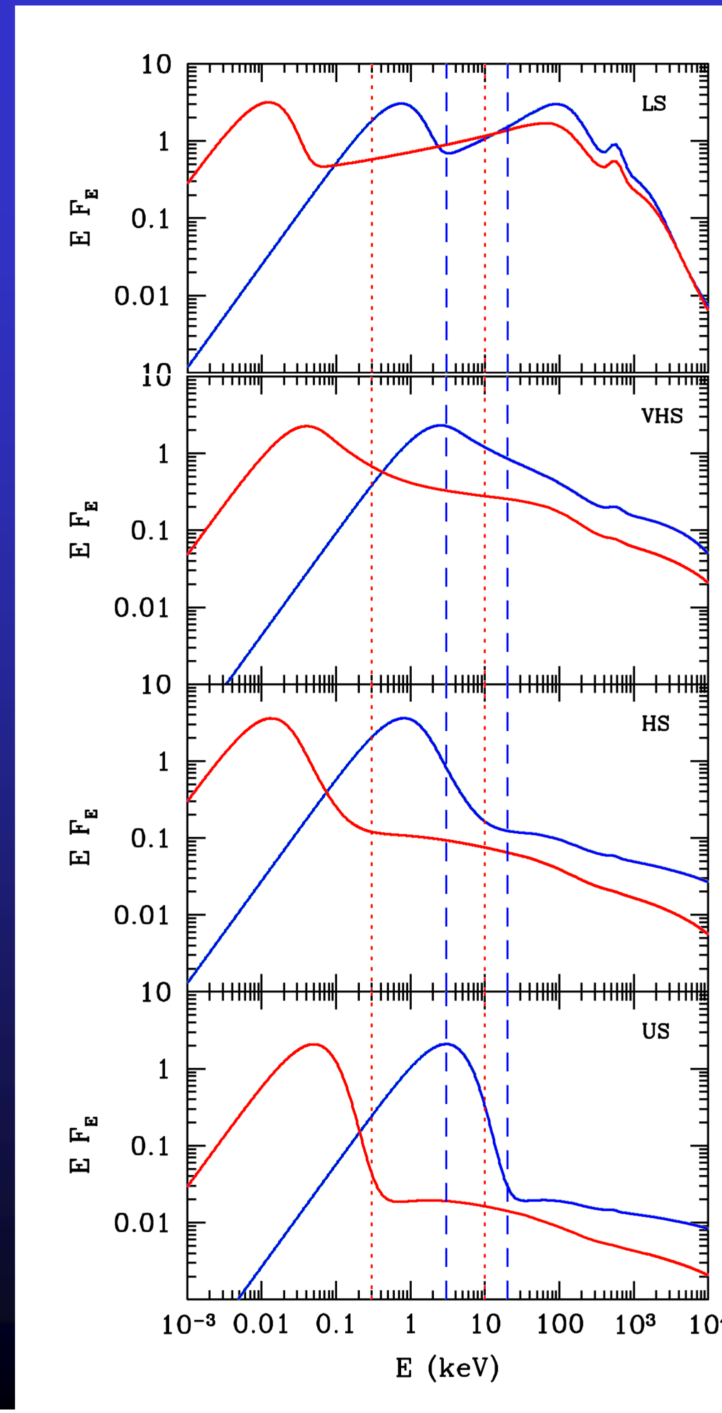


AGN spectral states

- High mass accretion rates (high L/LEdd) have lower Lx/Lbol ie higher Lbol/Lx!

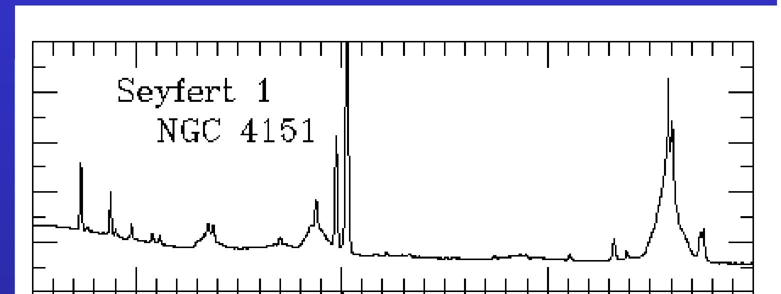
Vasuvaden & Fabian 2008

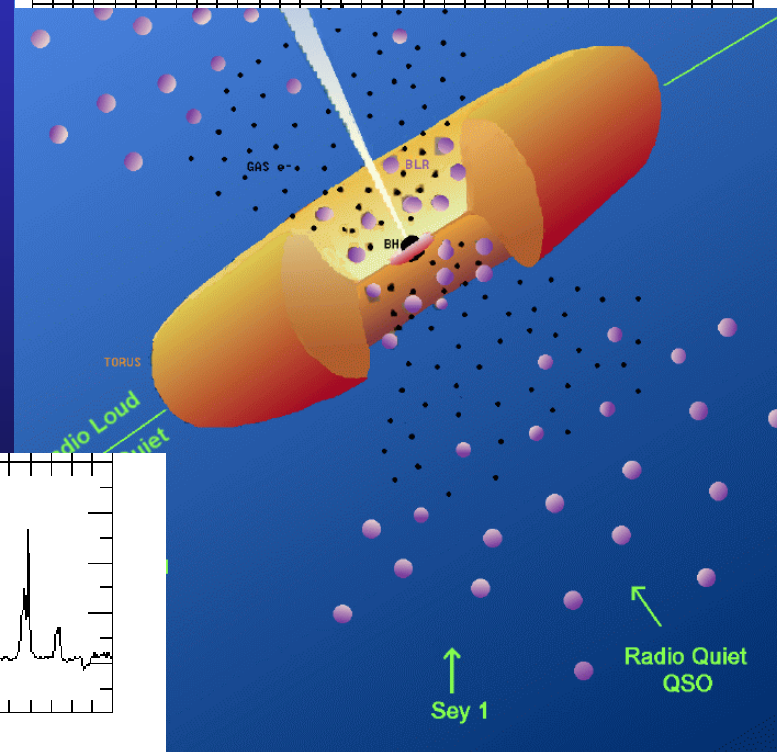


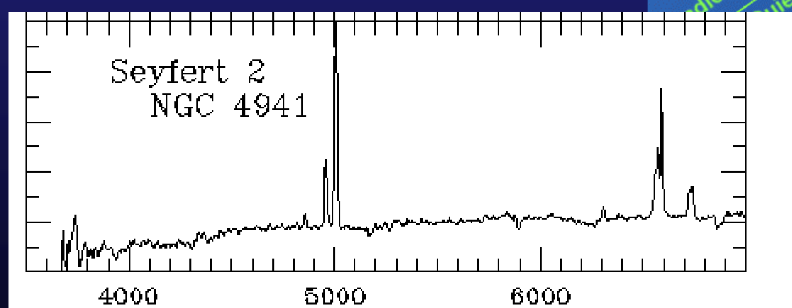


Seyfert 1 – Seyfert 2

- Intrinsically same except for obscuration ?
- But differences in HIGH energy spectra (20-200 keV). S1's softer than S2's – but also have higher $\langle L/L_{Edd}\rangle$ than S2 sample so same correlation as in BHB - softer when higher L/L_{Edd} in LHS (Middleton, Done & Schurch 2008; Winter et al 2009)



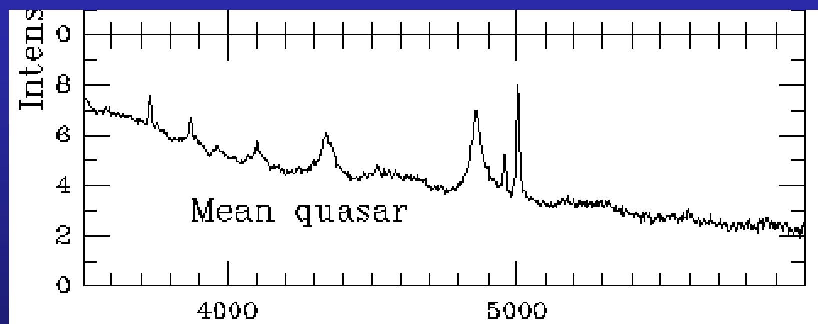


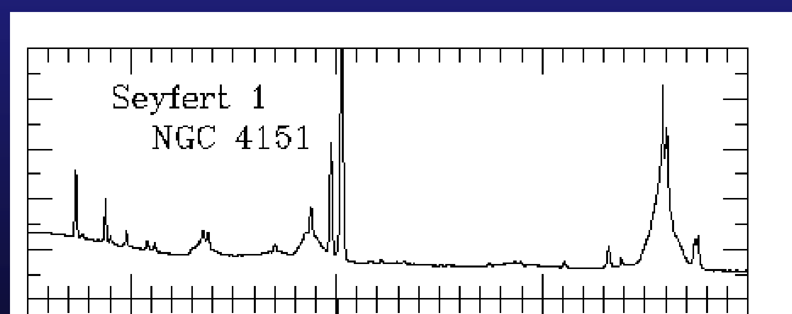


Seyfert 1 - Quasars

Similar spectra and line ratios,
strong UV flux to excite lines,
probably similar $L/L_{Edd} \sim 0.1\text{-}0.3$

Increasing L





Increasing M

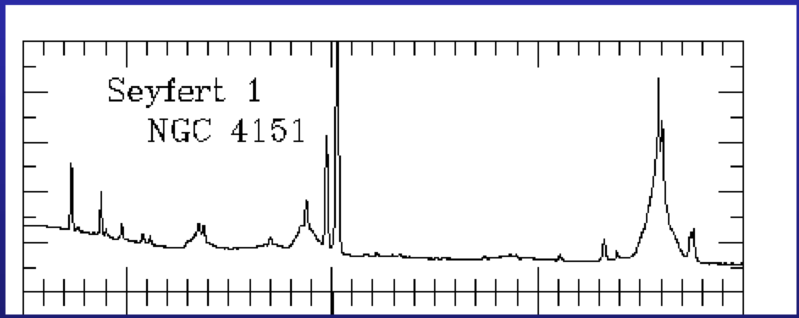
Seyferts - LINERS

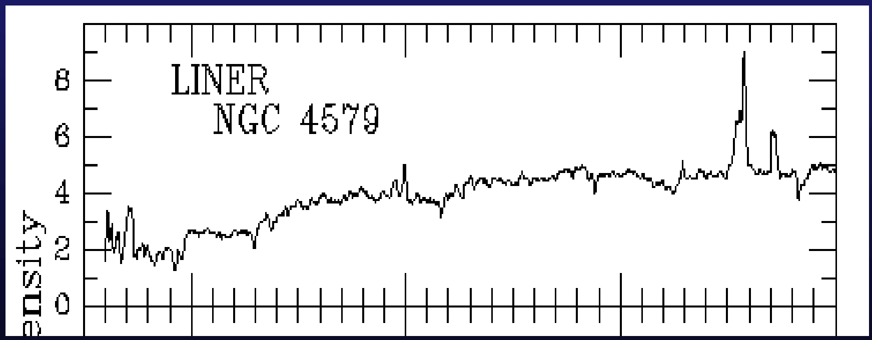
Very different spectra,
Similar mass.

Increasing
L/L_{Edd}

disc

Hot inner
flow, no UV
bright disc





Conclusions

- Test GR - X-rays from accreting black holes produced in regions of strong gravity
- 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!
- Mass ~10 M_{sun}. Spectra, variability and jet change with L/L_{Edd}
- Apply to AGN – seems to scale pretty well with mas
- Mass has much bigger spread (10^{5-9} M_{sun})
- More complex environment – torus/dust obscuration – inclination!
- Spectrum and jet change with L/L_{Edd} but jet may depend on spin as well. Feedback from this controls galaxy formation