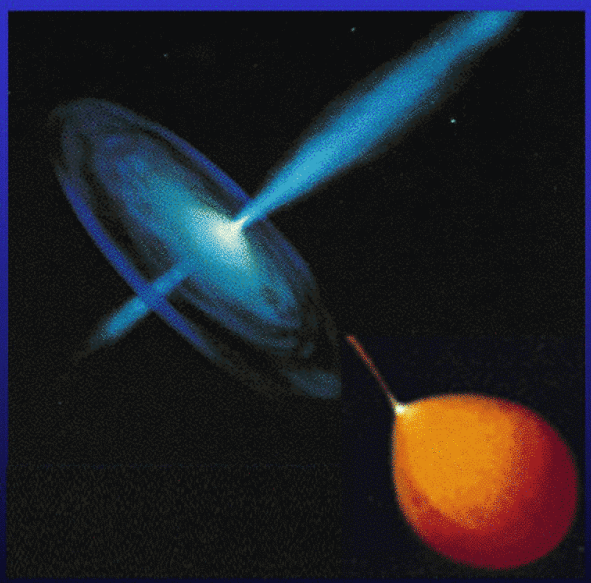
Testing accretion disc theory using X-ray spectra

Chris Done
University of Durham

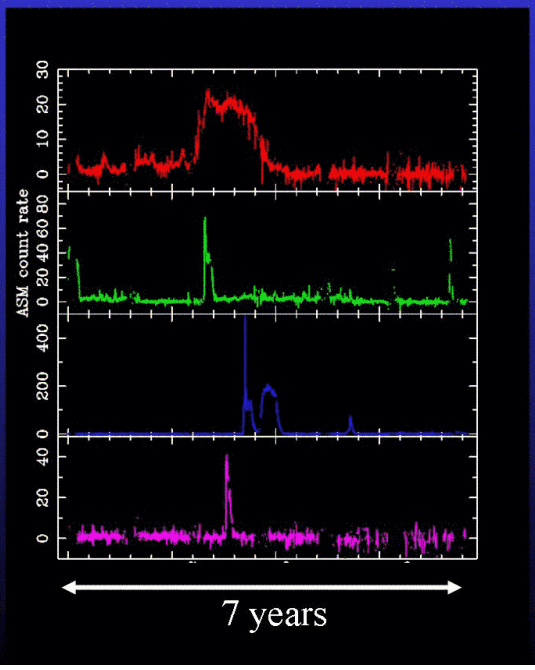
Black holes

- Appearance of BH should depend only on mass and spin (black holes have no hair!)
- Plus mass accretion rate – $L/L_{\rm Edd}$
- 10^4-10^{10} $M_\odot$: Quasars
- 10-1000(?) $M_\odot$: ULX
- 3-20 $M_\odot$: Galactic black holes



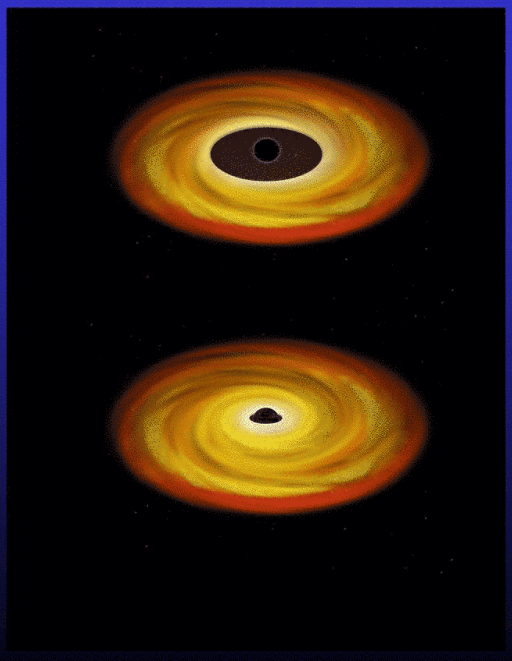
Galactic Binary systems

- Huge amounts of data
- Timescales
  - ms – year (observable!)
  - hours – 10^8 years in quasars
- Observational template of accretion flow as a function of $L/L_{\rm Edd}$ onto ~10 $M_\odot$ BH



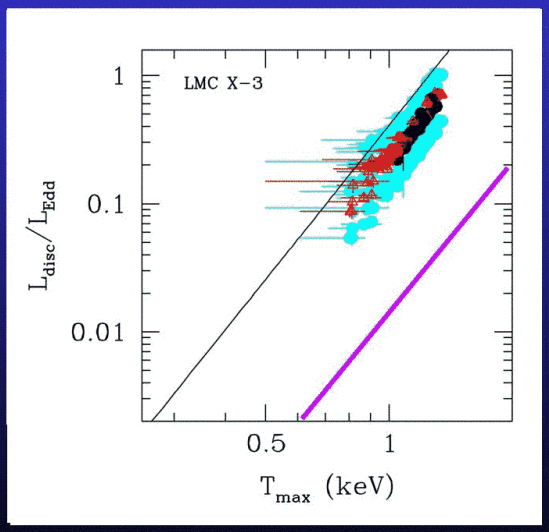
Spectra of accretion flow: disc

- Differential Keplerian rotation
- Viscosity B: gravity → heat
- Thermal emission: $L = A\sigma T^4$
- Temperature increases inwards
- GR last stable orbit gives minimum radius $R_{\rm ms}$ - depends on spin 6 →1 Rg(a = 0 → 1)
- For a=0 and $L \sim L_{\rm Edd}$ $T_{\rm max}$ is
  - 1 keV (10^7 K) for 10 $M_\odot$
  - 10 eV (10^5 K) for 10^8 $M_\odot$



Disc spectra: last stable orbit

- Pick ONLY ones that look like a disc!
- $L/L_{Edd} \propto T^4_{max}$ (Ebisawa et al 1993; Kubota et al 1999; 2001)
- Proportionality constant gives R_{ms} i.e. a as know M
- Consistent with low to moderate spin **not** extreme spin **nor** extreme versions of higher dimensional gravity - braneworlds (Gregory, Whisker, Beckwith & Done 2004)

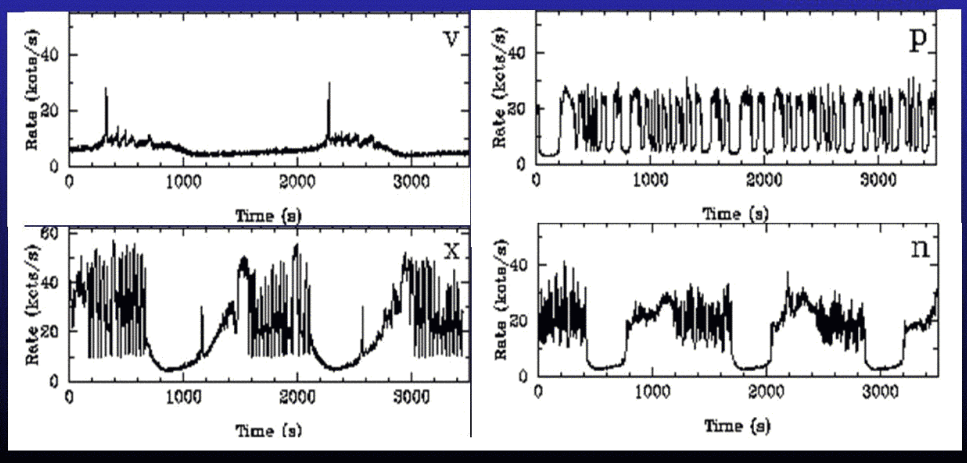


Gierlinski & Done 2003

GRS 1915+105

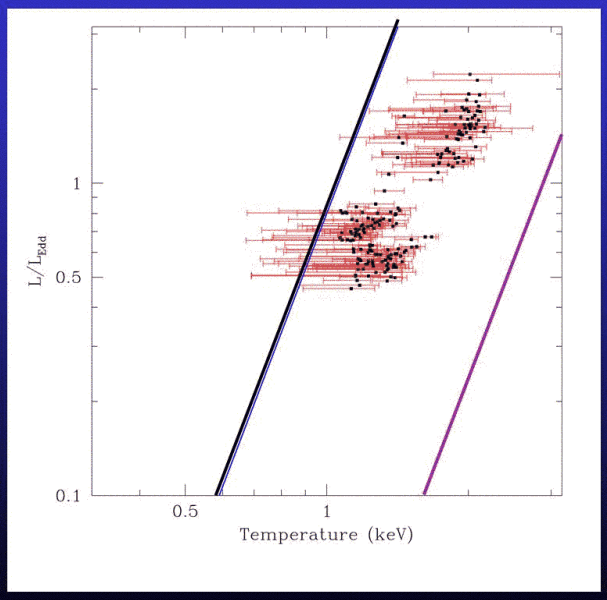
- Microquasar, relativistic jet, UNIQUE limit cycle variability in 50% of data - most likely because it goes to uniquely high L (Done Wardzinski & Gierlinski 2004)

Belloni et al 2000



Last stable orbit in 1915

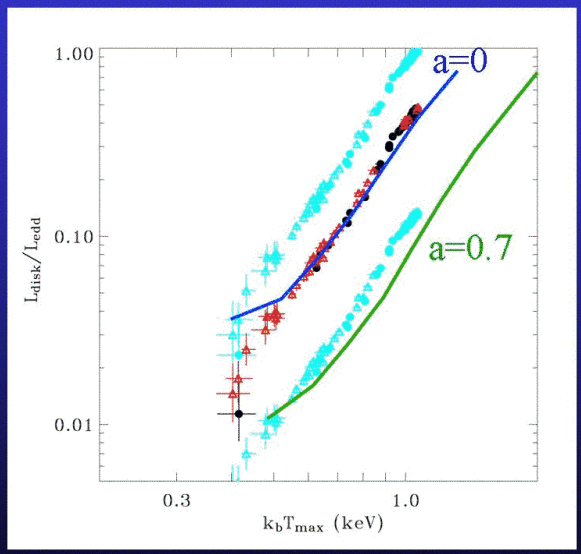
- Fit all 16s spectra! Pick ONLY ones that look like a disc!!!
- Bigger uncertainties as much higher Nh
- Again low-moderate spin.
- Extreme spin is NOT necessary to launch powerful jets.
- Same for other μQSO: eg J1655, J1550 both have strong radio jets and not maximal spin



Middleton, Done & Gierlinski 2005

Theoretical disc spectra

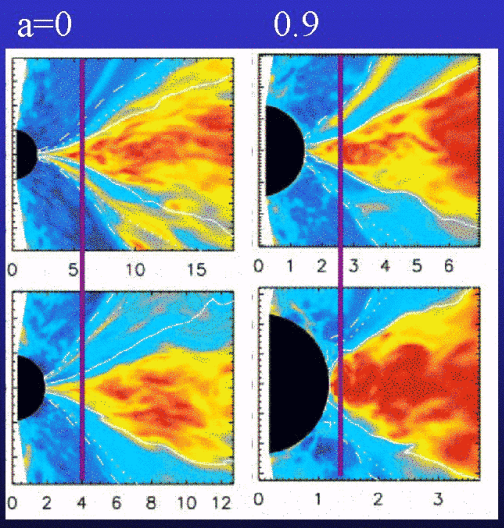
- ONLY works with disc dominated spectra
- Surely even disc spectra aren't this simple!!!!
- Best theoretical models say they can be!
- Fit to XTE J1550 gives a=0.1 (M, D, i: a<0.7)
- Metal opacity (not included in previous work) keeps photosphere close to top of disc so ~ constant colour temperature correction (Davies et al 2005)



Davies, Blaes et al 2005

But no ISO in MRI?

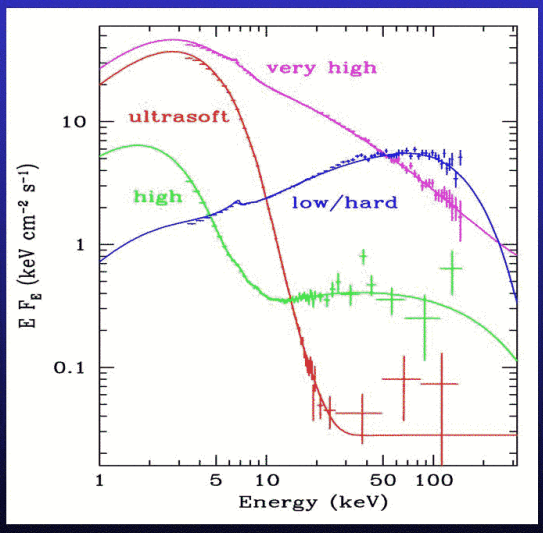
- Accretion flow is not test particle. B field connects material inside plunging region. No ISO (Agol & Krolik 2000)
- But data give clear ISO – maybe this depends on flow? B field height < H. small for thin disc so doesn't connect far into plunging region, large for thick disc so large extent into plunging region (Afshordi & Paczyinski 2003; but see Menou 2003)



Hirose et al 2004

But rest are not simple…

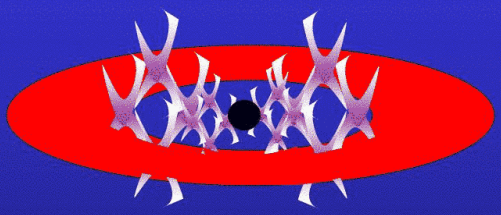
- Bewildering variety of spectra from single object
- Underlying pattern
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail
- Lower L/L_{Edd}: hard spectrum, peaks at high energies, not like a disc

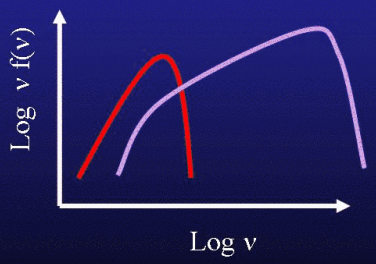


Gierlinski & Done 2003

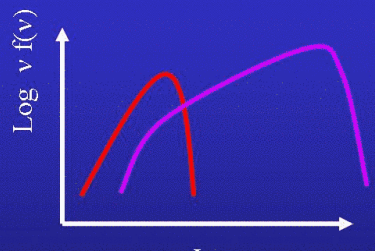
Accretion flows without discs

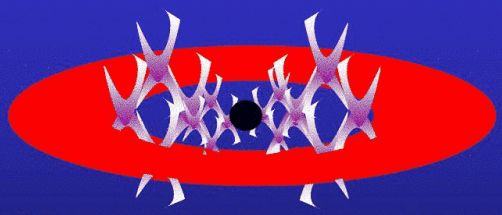
- Disc models assumed thermal plasma – not true at low L/L_{Edd}
- Instead: hot, optically thin, geometrically thick inner flow replacing the inner disc (Shapiro et al. 1976; Narayan & Yi 1995)
- Hot electrons Compton upscatter photons from outer cool disc
- Few seed photons, so spectrum is hard





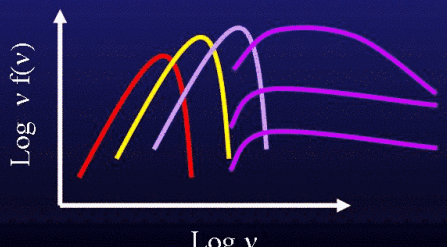
Qualitative and quantitative models: geometry

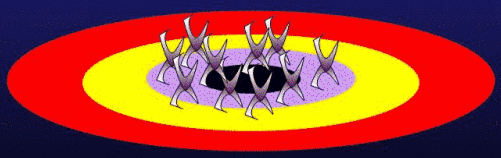




Hard (low L/L_{Edd})

Soft (high L/L_{Edd})



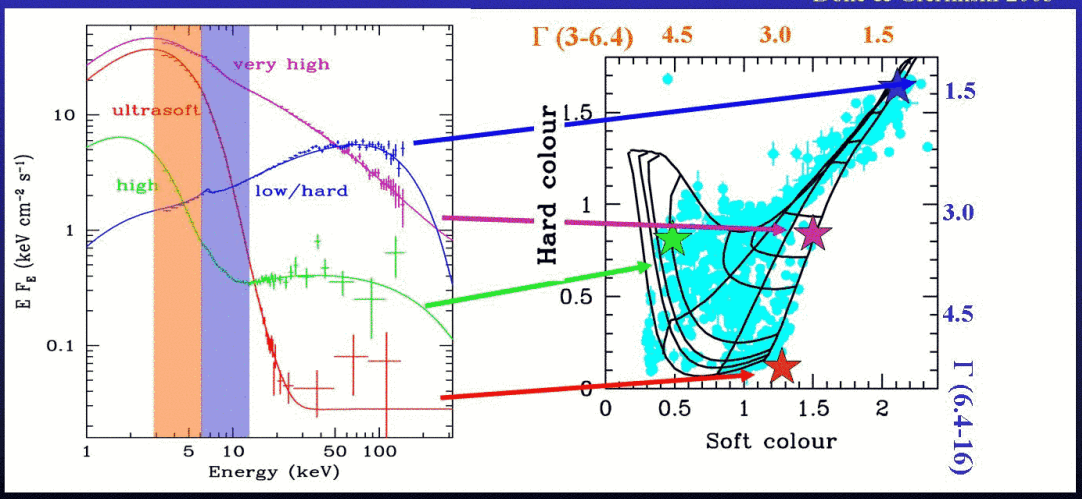


Done & Gierliński 2004

Observed GBH spectra

- RXTE archive of many GBH
- Same spectral evolution $10^{-3} < L/L_{Edd} < 1$
- Truncated disc $\rightarrow R_{ms}$ qualitative and quantitative

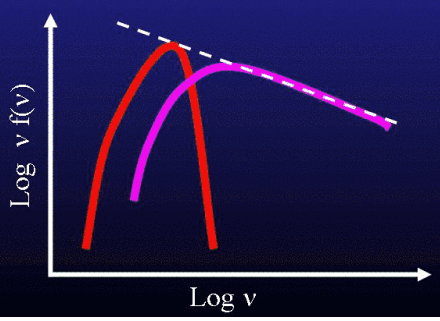
Done & Gierliński 2003

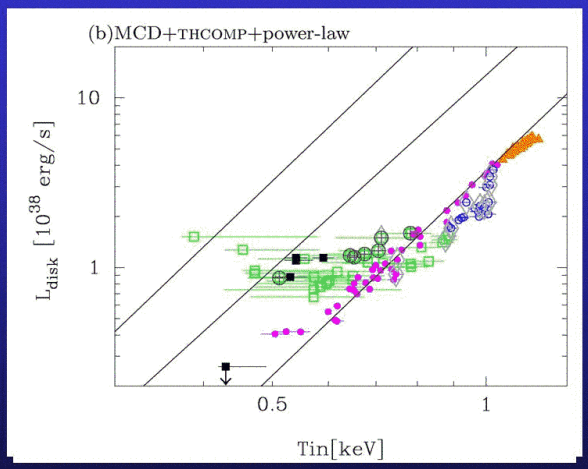


Very High State: Spectrum

Kubota & Done 2004

- Disc AND tail have roughly equal power. BE CAREFUL!!!
- Now depends on models - Comptonized spectrum is NOT a power law close to seed photons!



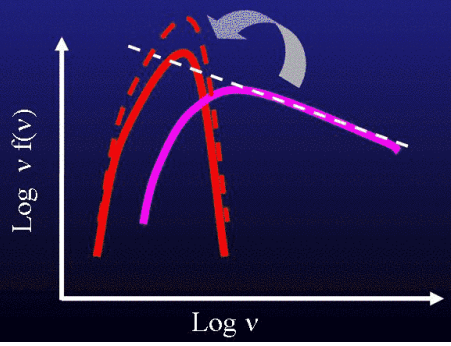


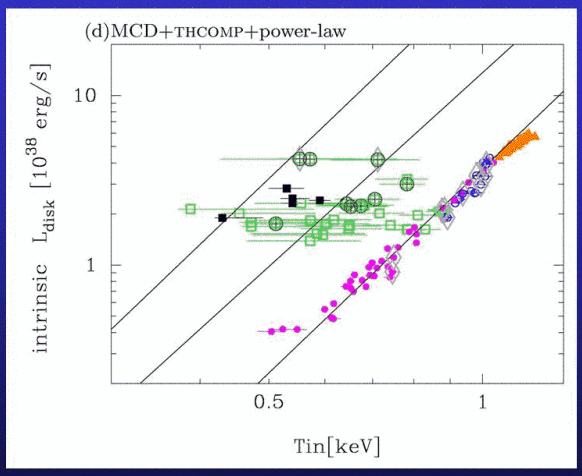
- Disc dominated (low L / high L)
- Very high state (comp < disc)
- Very high state (comp > disc)

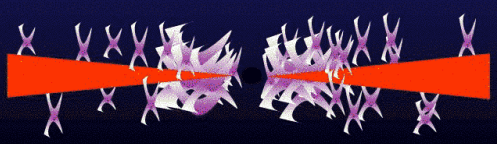
Very High State: photons

Kubota & Done 2004

- But Comptonised photons come from the disc – optically thick so suppresses apparent disc emission
- Correct for this



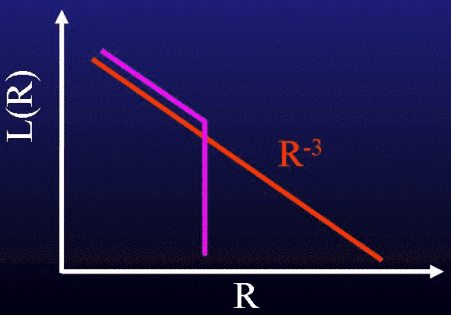


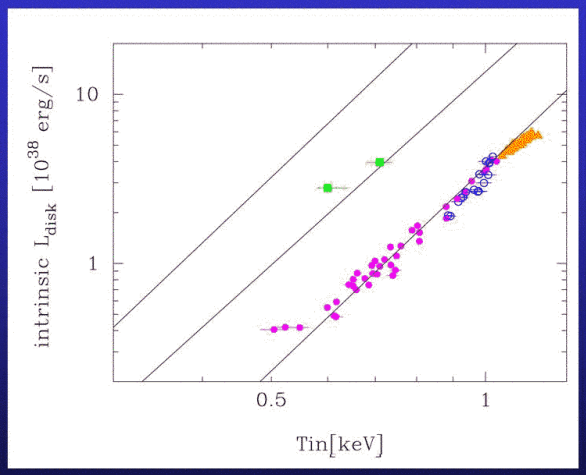


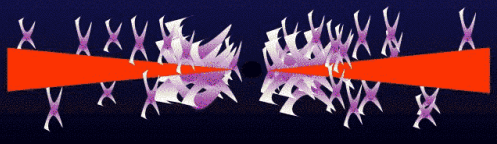
Very High State: energy

Kubota & Done 2004

- But ENERGY of corona came from disc as well. Lower T under corona but more importantly lower L enhancing outer disc



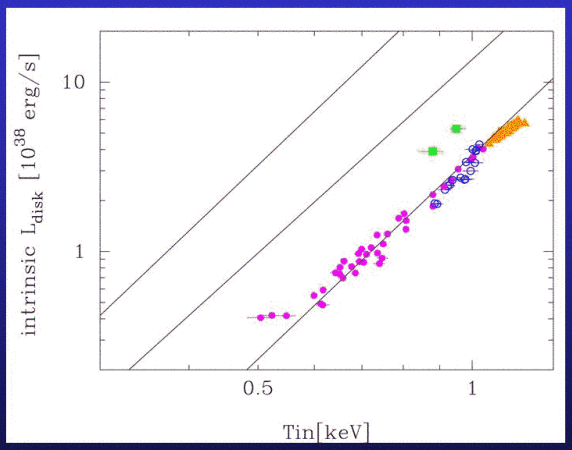


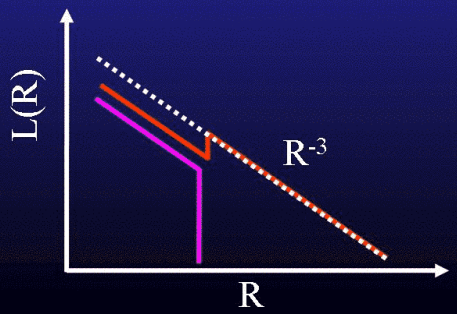


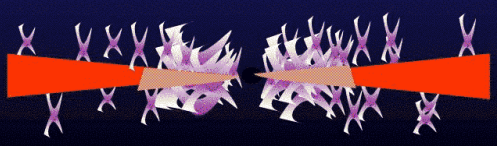
Very High State: energy

Done & Kubota 2005

- But ENERGY of corona came from disc as well. Lower T under corona but more importantly lower L enhancing outer disc (Svensson & Zdziarski 1994)





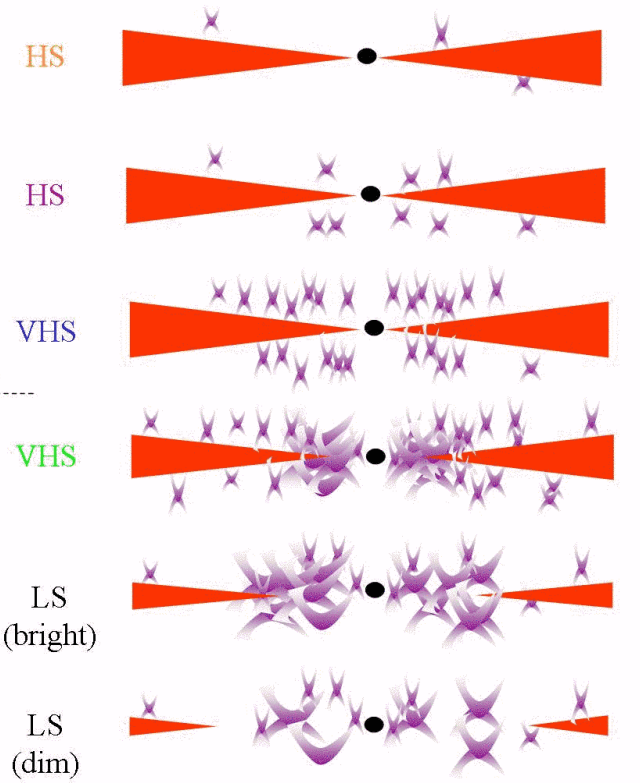


Decrease fraction of power in nonthermal reconnection above disc

Disc to minimum stable orbit

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

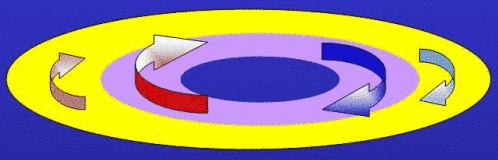
Jet gets faster, catches up with slower outflow, get flares of radio emission from internal shocks Fender (2004)

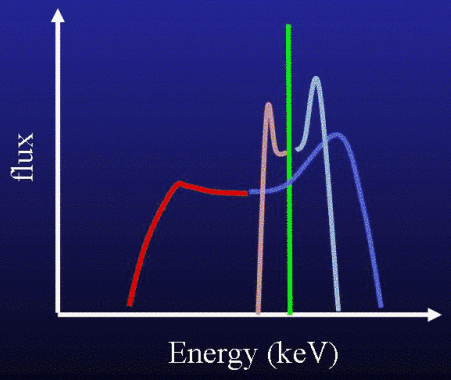


Kubota & Done 2004

Relativistic effects

- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Hard to easily spot on continuum components
- Fe Kα line from irradiated disc – broad and skewed! (Fabian et al 1989)
- Broadening gives an independent measure of Rin – so spin if ISO (Laor 1991)
- Models predict increasing width as go from low/hard to high/soft states



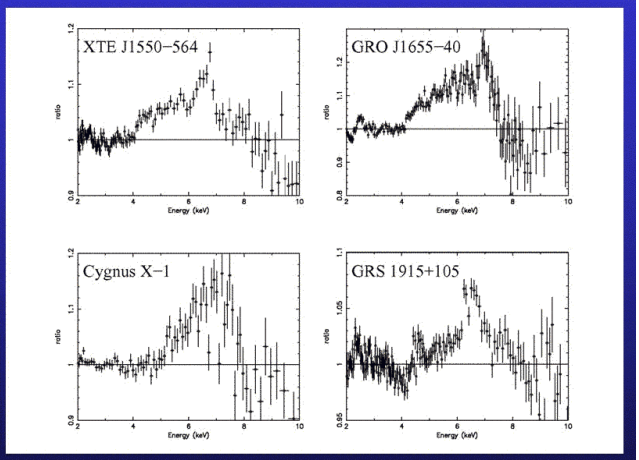


Fabian et al. 1989

Problems: extreme Fe lines

Miller et al 2004

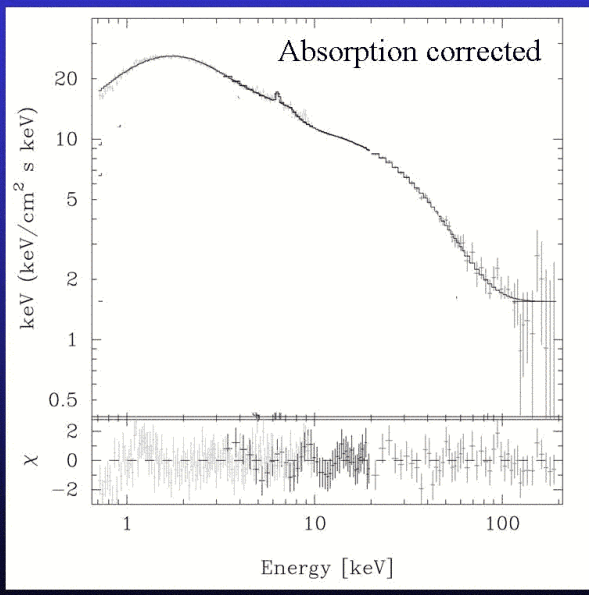
- Broad iron lines are common in GBH. Some indications of increasing width with spectral softness
- But some are *extremely* broad, indicating high spin (if disc to ISO) and extreme emissivity – tapping spin energy of black hole? (Miller et al 2002; 2003; 2004; Minuitti et al 2004)



- BUT these are the same objects for which a<~0.7 from disc spectra
- Mainly in VHS and softest low/hard states (intermediate states) flow extends below ISO?

Extreme line in VHS of J1550?

- VHS has optically thick material covering inner disc – not possible to see reflected spectrum/line from inner disc
- J1550-564: VHS ASCA data – some evidence for extreme spin and emissivity (Miller et al 2004)
- Simultaneous XTE-OSSE with ASCA shows clearly that cannot see disc – no clear disc component so corona must be optically thick with large covering fraction

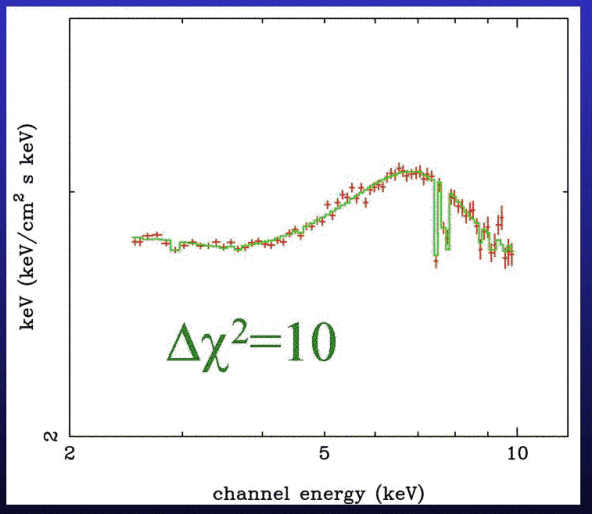


Done & Kubota 2005

Extreme line in IS of J1650

- QPO and broadband data say that disc not down to ISO
- MECS pexriv+narrow line. Best fit is extreme spin (Rin=2) and emissivity (Miniutti et al 2004)
- But ionised reflection – line is intrinsically comptonised (Ross, Fabian & Young 1999)
- Same extreme line with proper ionised reflection but MUCH less significant
- Absorption lines – outflow. Rin~15 with normal emissivity. Diskwind?

Done et al 2005



Conclusions

- Fabulous time - enough data to build and test accretion models !
- Last stable orbit (ONLY simple disc spectra) $L \propto T^4_{max}$
- Test GR - Corrections to GR from proper gravity must be smallish
- ISO not predicted in MRI – thin disc simulations
- Accretion flow NOT always simple disc – X-ray tail!
- Jet related to strong tail NOT to extreme spin!!
- Strong tail at high L/L_{Edd} (very high state) – sucking energy from disc so lower T_{max} than expect from L.
- Consistent picture from broadband spectral evolution, QPO's, jets for truncated disc, with moving Rin to ISO as LS-IS-VHS-HS
- Lines are generally broad, and should be broader in softer states
- Conflict in some spectra for some objects with extreme spin, extreme emissivity broad lines – maybe complex absorption?

Wish list

1. Radiative MHD – just MRI or is there more physics?
   - Geometrically thin disc – ISO?
   - Hot inner flow properties?
   - Transition between disc and hot flow/corona?
   - Jet launching from hot flow/corona from low spin?
   - QPO models!
2. Microphysics of B reconnection – particle acc? 2T?
3. Better s/n high spectral resolution data
   - Extreme broad line or absorption ?
4. Better models of GBH discwinds?
5. Systematic line studies throughout outbursts
6. Better distances, masses and inclinations