Accretion flows onto black holes

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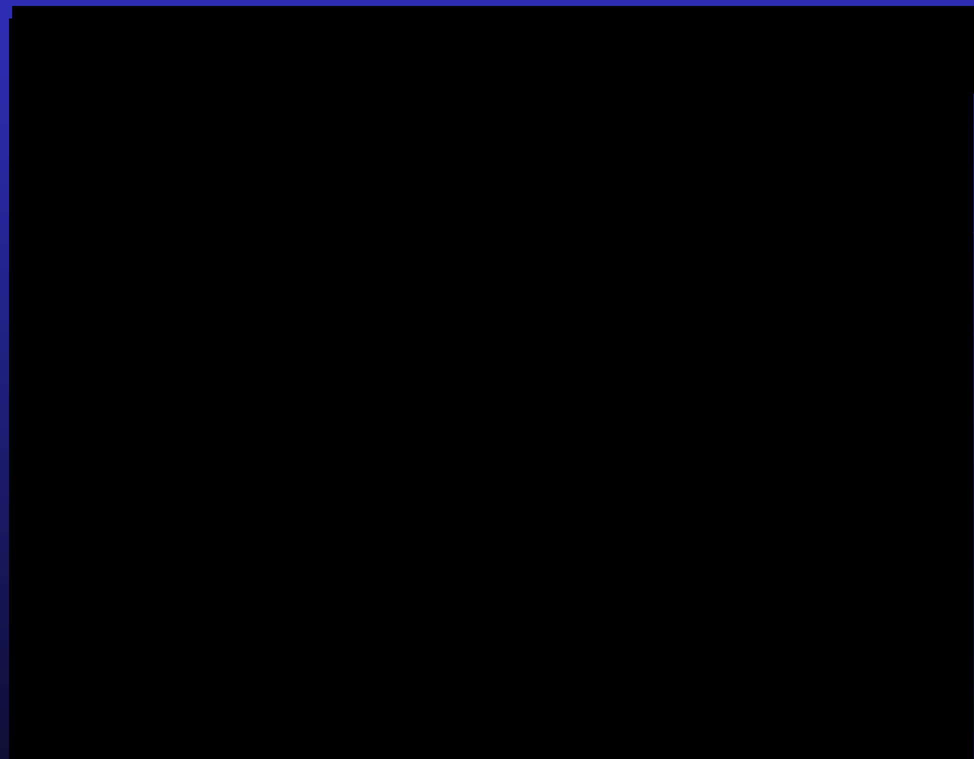
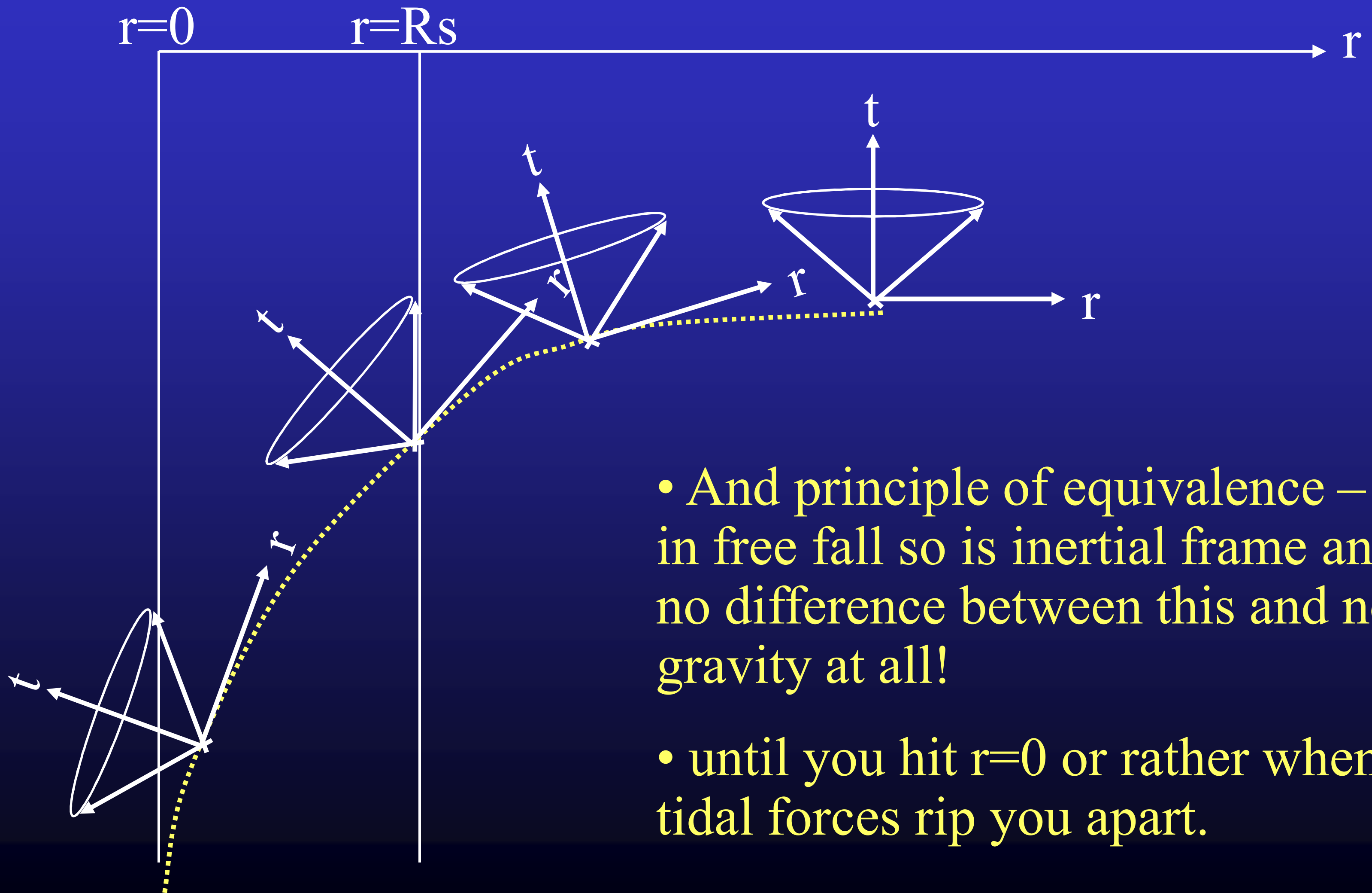
Strong gravity

- Black holes: extreme spacetime curvature
- Test Einsteins GR - event horizon, last stable orbit…..
- The thing about a black hole, its main distinguishing feature is, its black. And the thing about space, your basic space colour is its black. So how are you supposed to see them? (Red Dwarf)



Event horizon

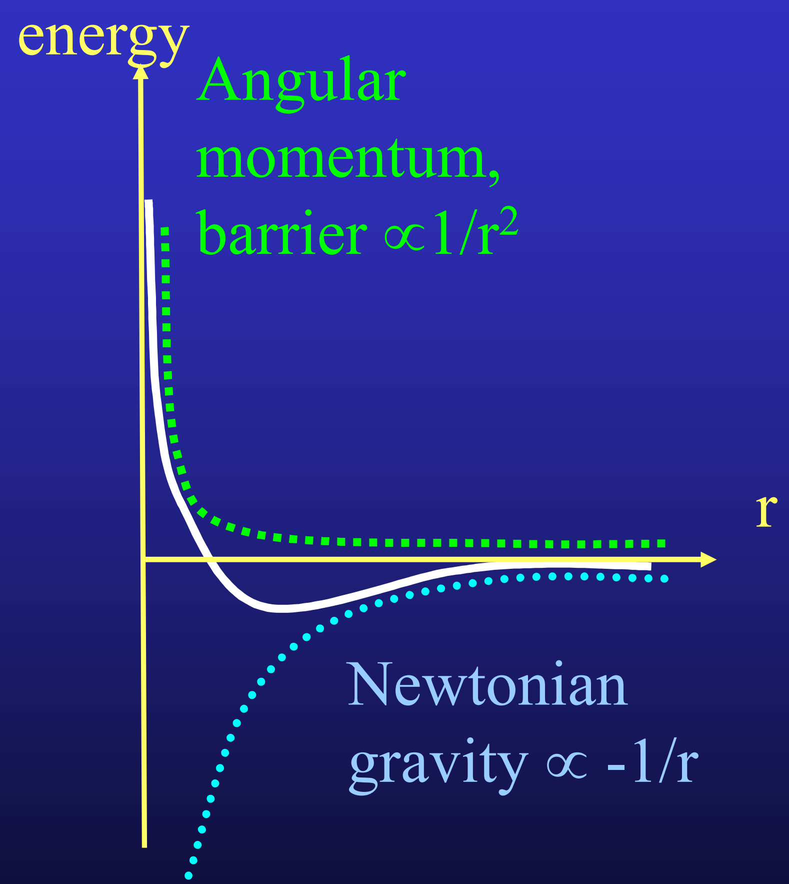
- Spacetime (Riemann) curvature $\rightarrow \infty$ at r=0 and is finite (though large) at $r=R_s=2GM/c^2$



- And principle of equivalence – in free fall so is inertial frame and no difference between this and no gravity at all!
- until you hit r=0 or rather when tidal forces rip you apart.

Orbits at $R>R_s$: Newtonian

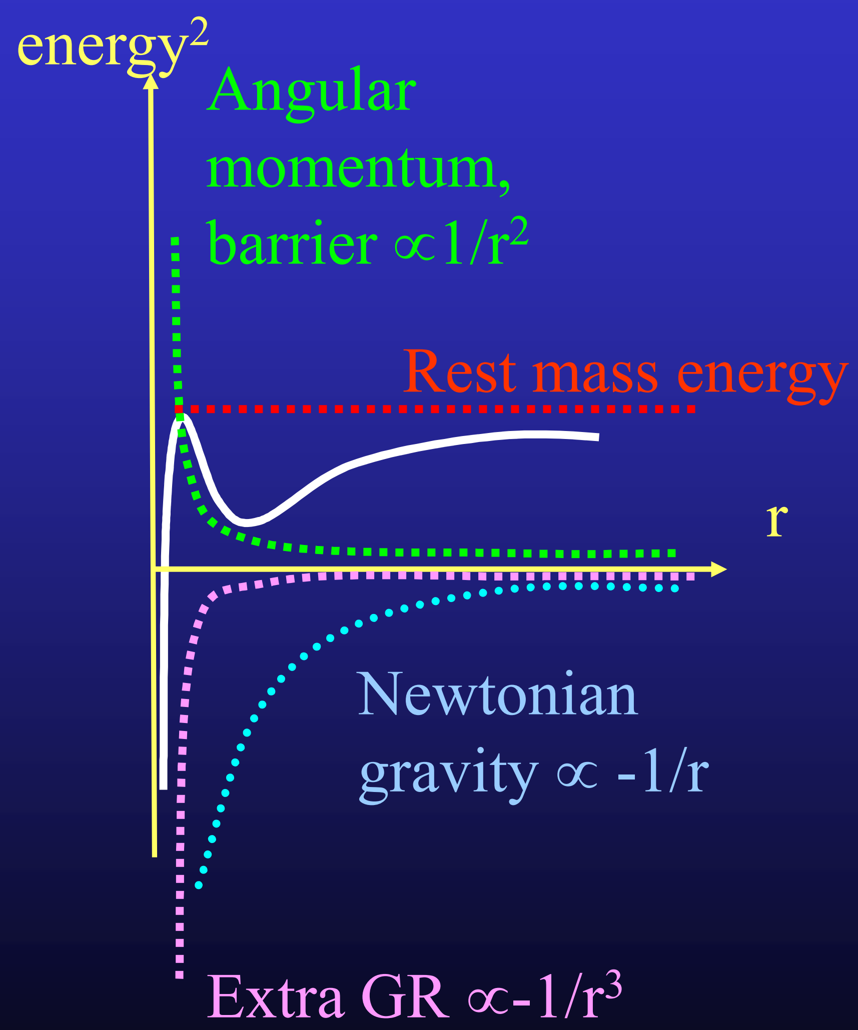
- Newtonian orbits
- Gravity attractive – wants to be closer in.
- but if closer then rotate faster due to angular momentum conservation
- Bigger outward centrifugal force!
- Balance inward gravity with outward angular momentum to get stable orbit
- Can always orbit closer



Orbits at R>Rs: Einstein

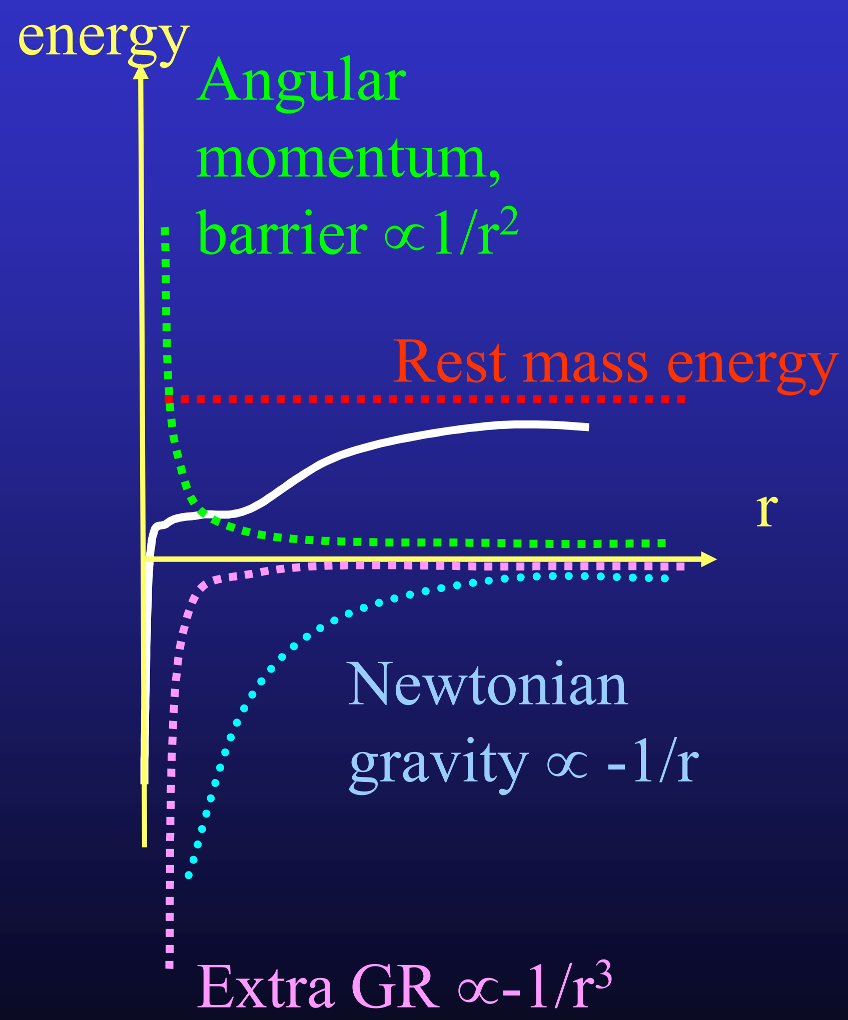
- Extra terms in GR potential
- (Rest mass energy)
- Term which is –ve so adds to gravitational potential

  and makes it **stronger**
- Gravity will always dominate if get to small enough r!



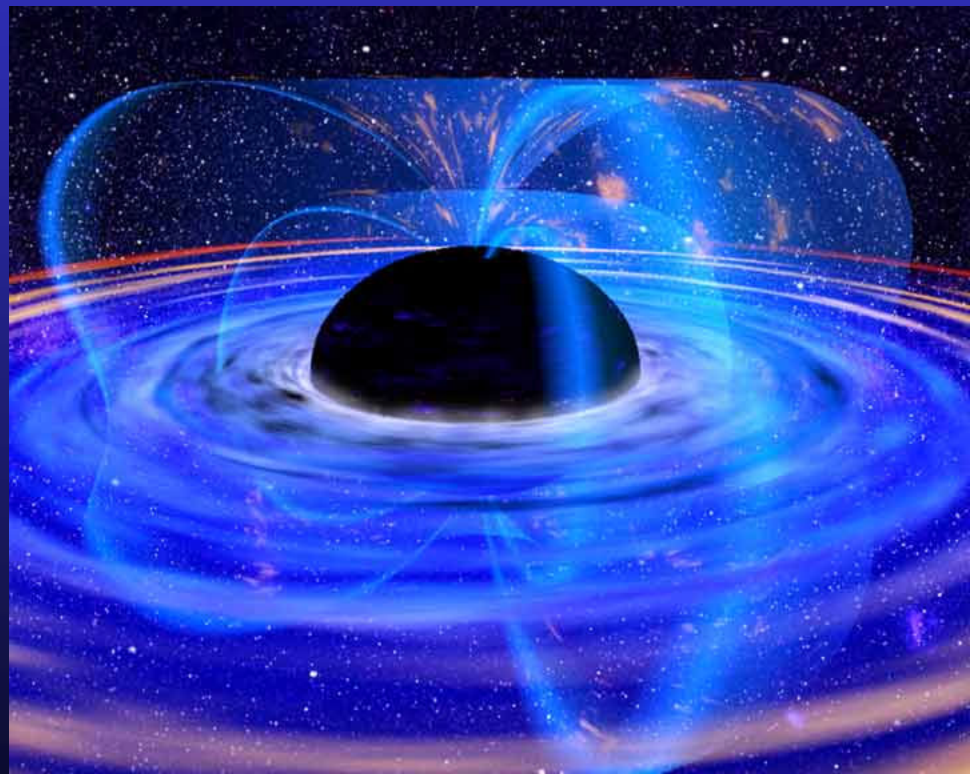
Behaviour of maximum…

- At some point there is a last stable orbit – gravity so strong that no friendly angular momentum barrier to stop you falling down……
- Can't just go round. Like fly-by-wire planes you need engines to keep it stable!
- Origin of 'black holes suck' sci-fi ideas.
- $R_{lso} = 6GM/c^2$ $R_h = 2GM/c^2$
- $R_{lso} = R_h = GM/c^2$ (a=1 spin)



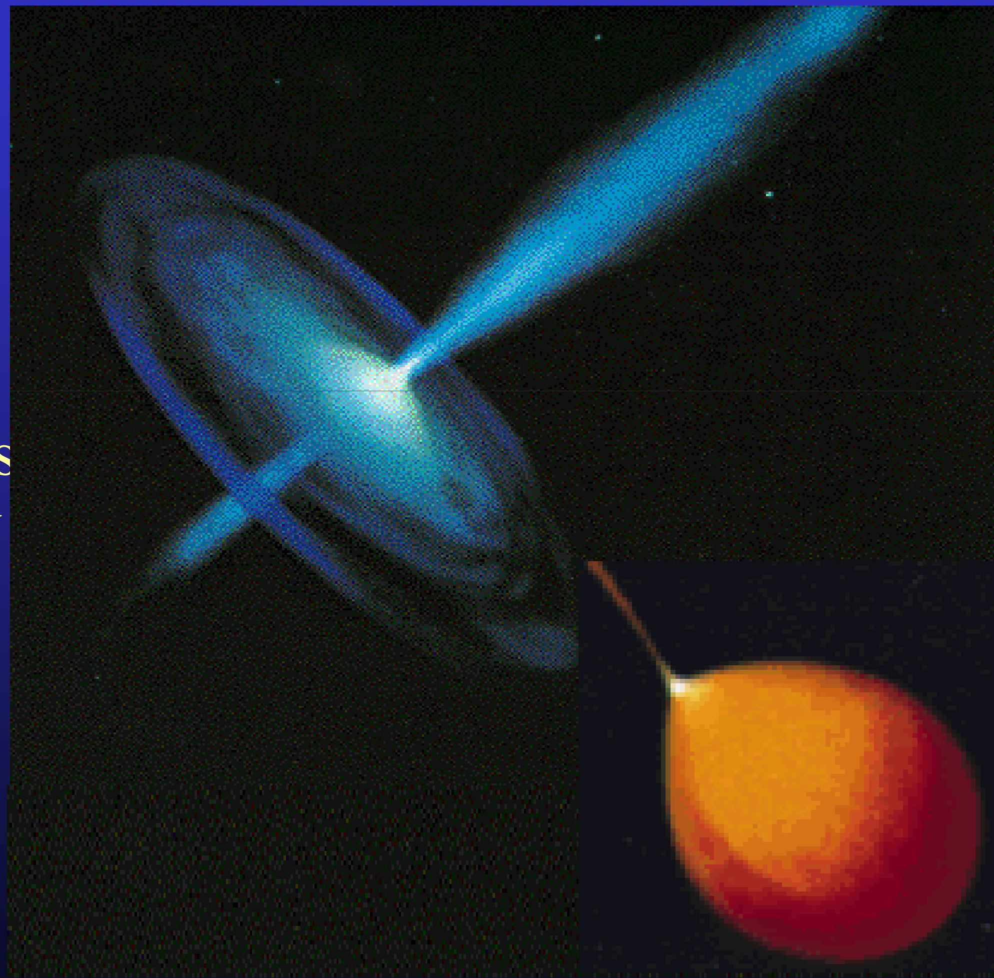
Accretion

- 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!



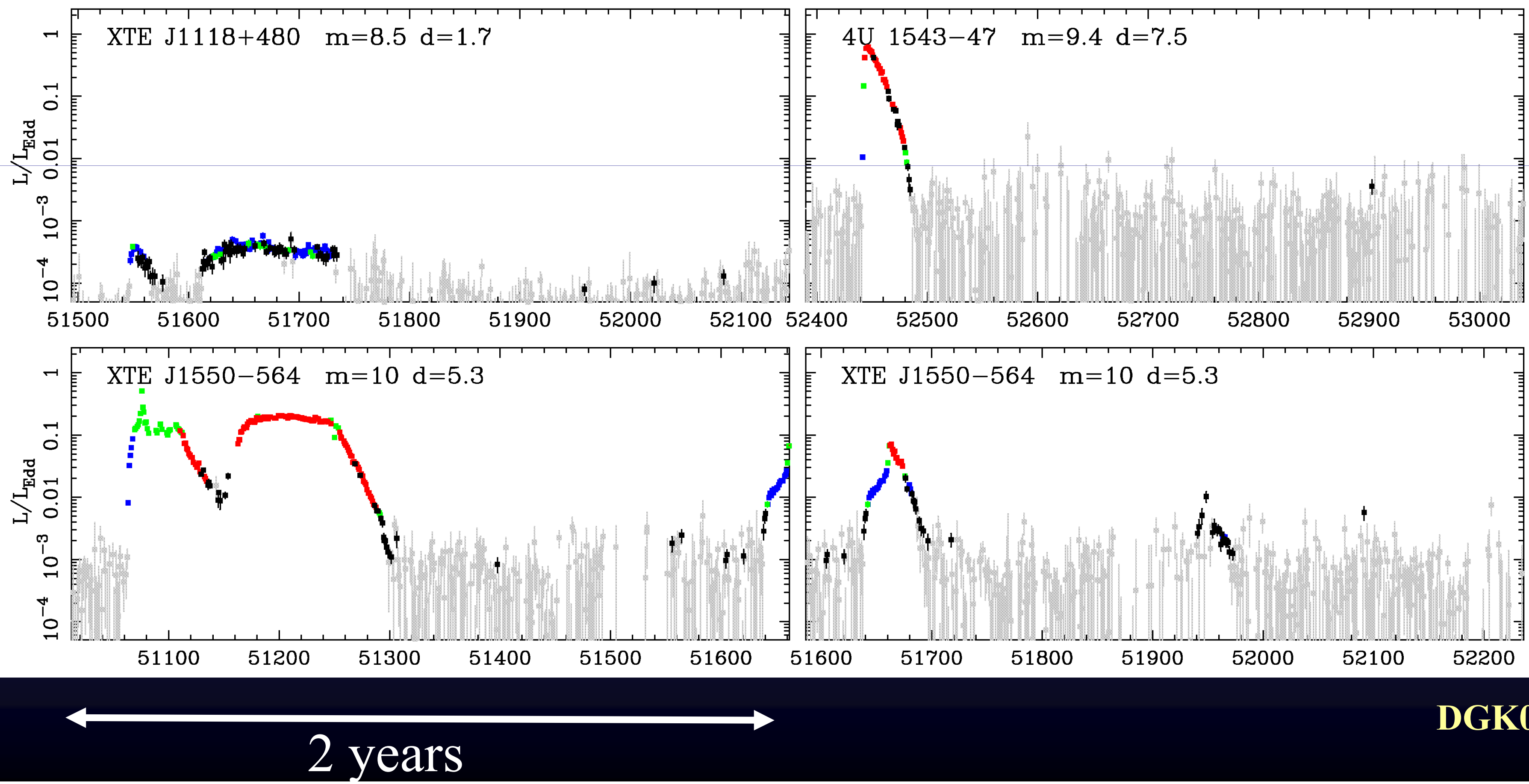
Black holes

- 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

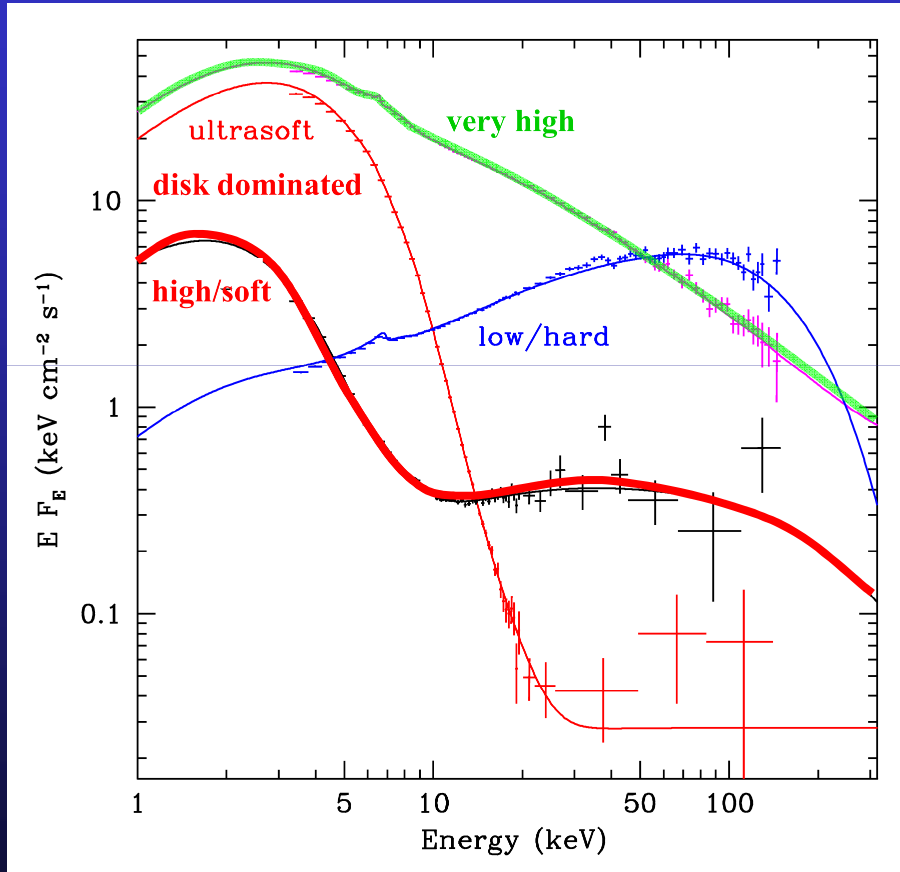
- Huge amounts of data, long term variability (days –years) in mass accretion rate (due to H ionisation instability in disc)
- Observational template of accretion flow as a function of L/L_{Edd} onto ~10 $M_\odot$ BH



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

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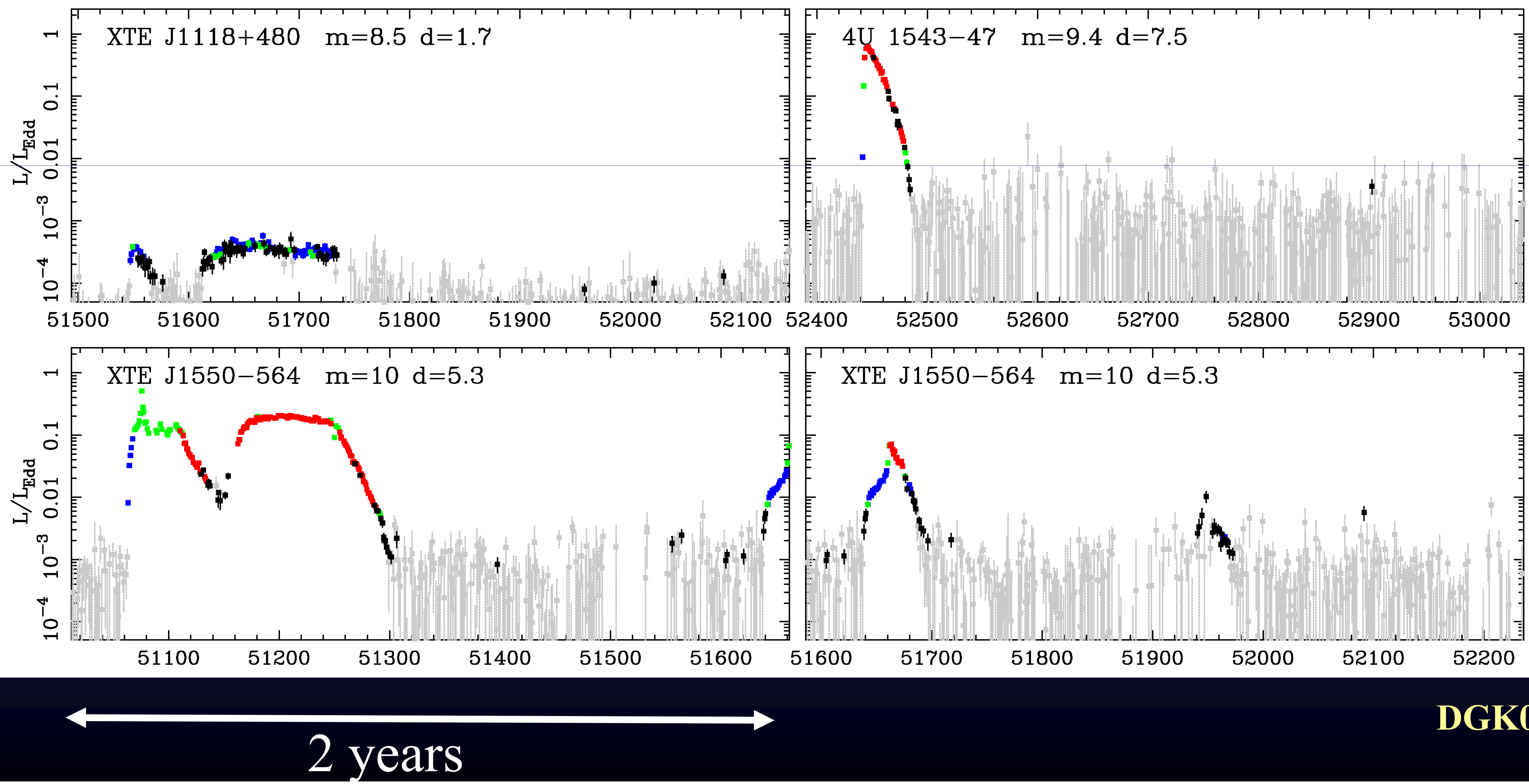
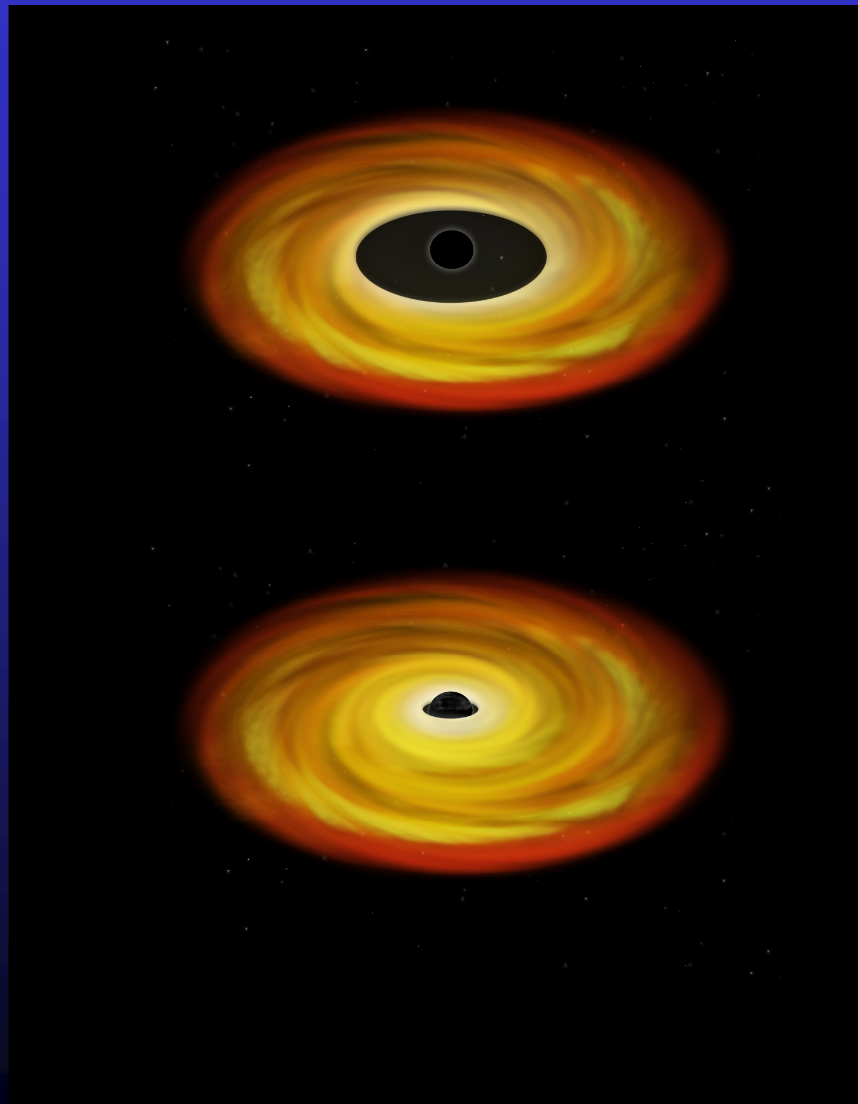


DGK07

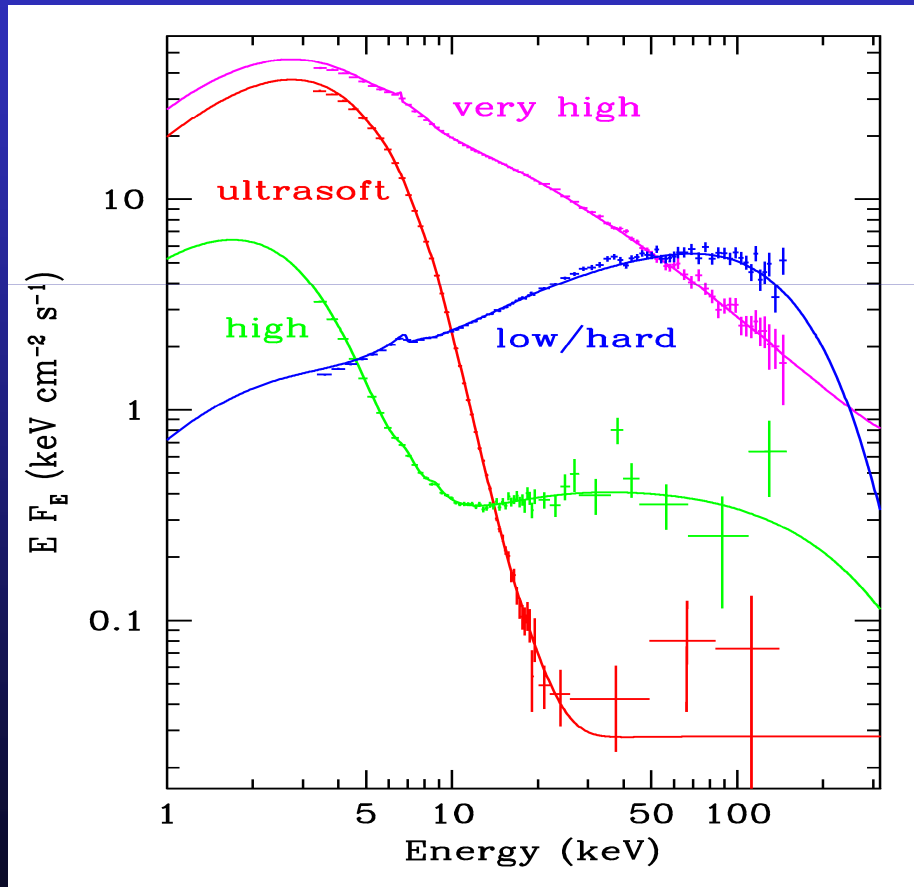
Spectra of accretion flow: disc

- 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



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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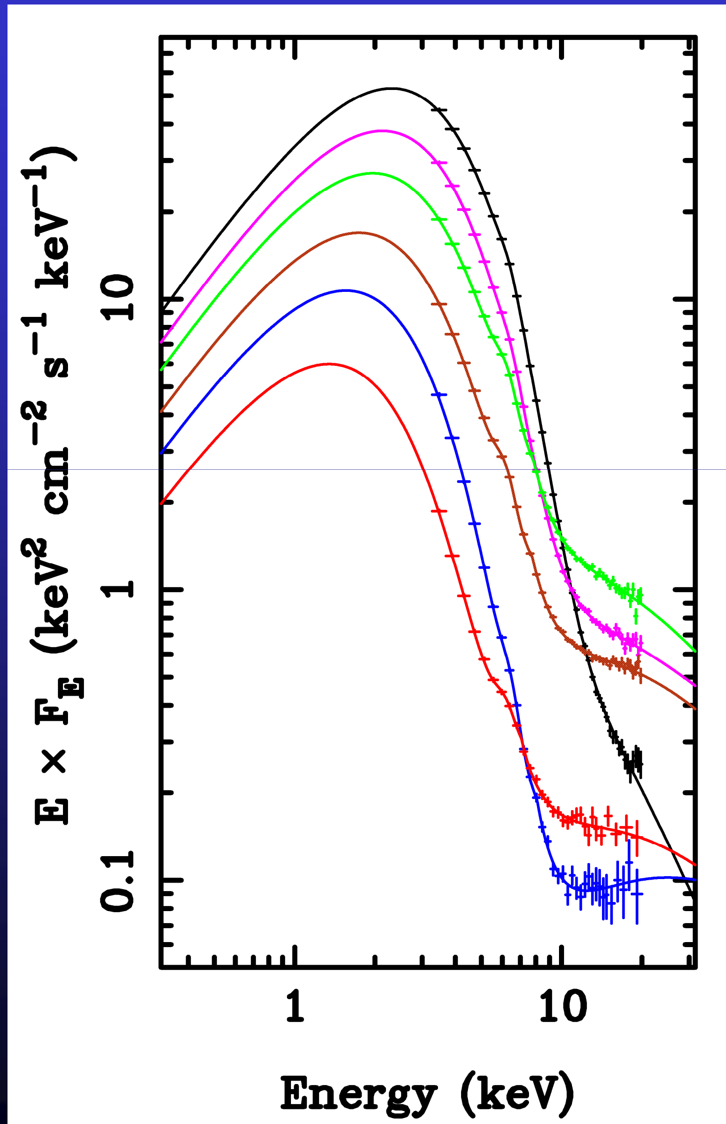

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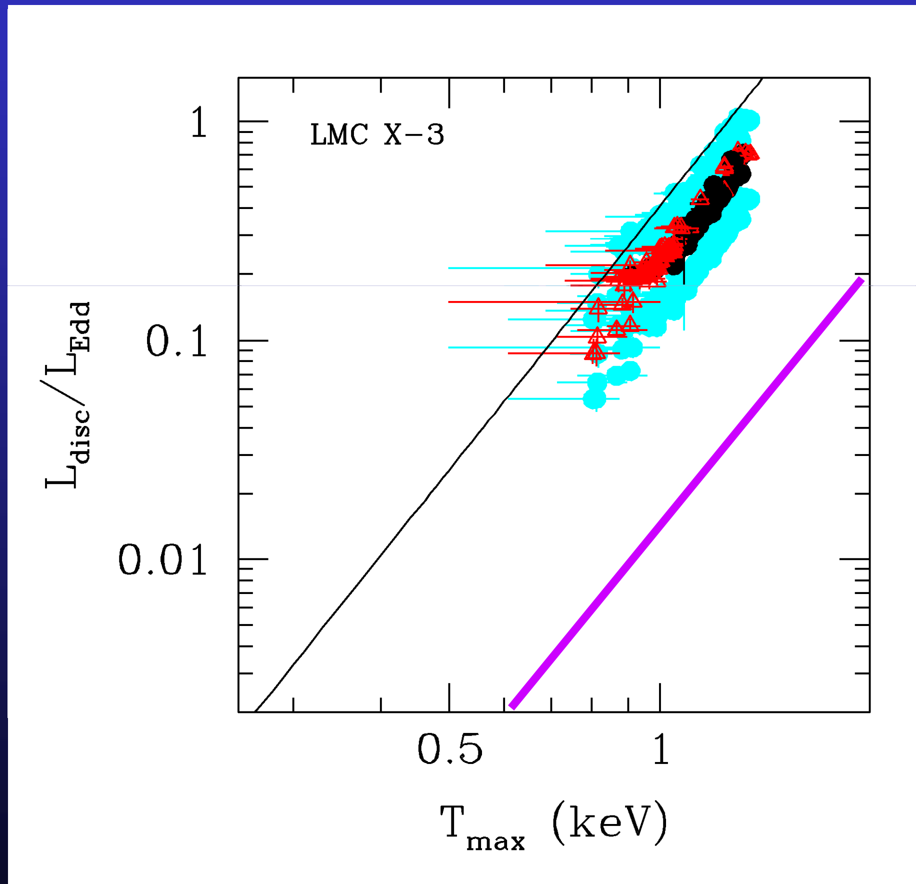
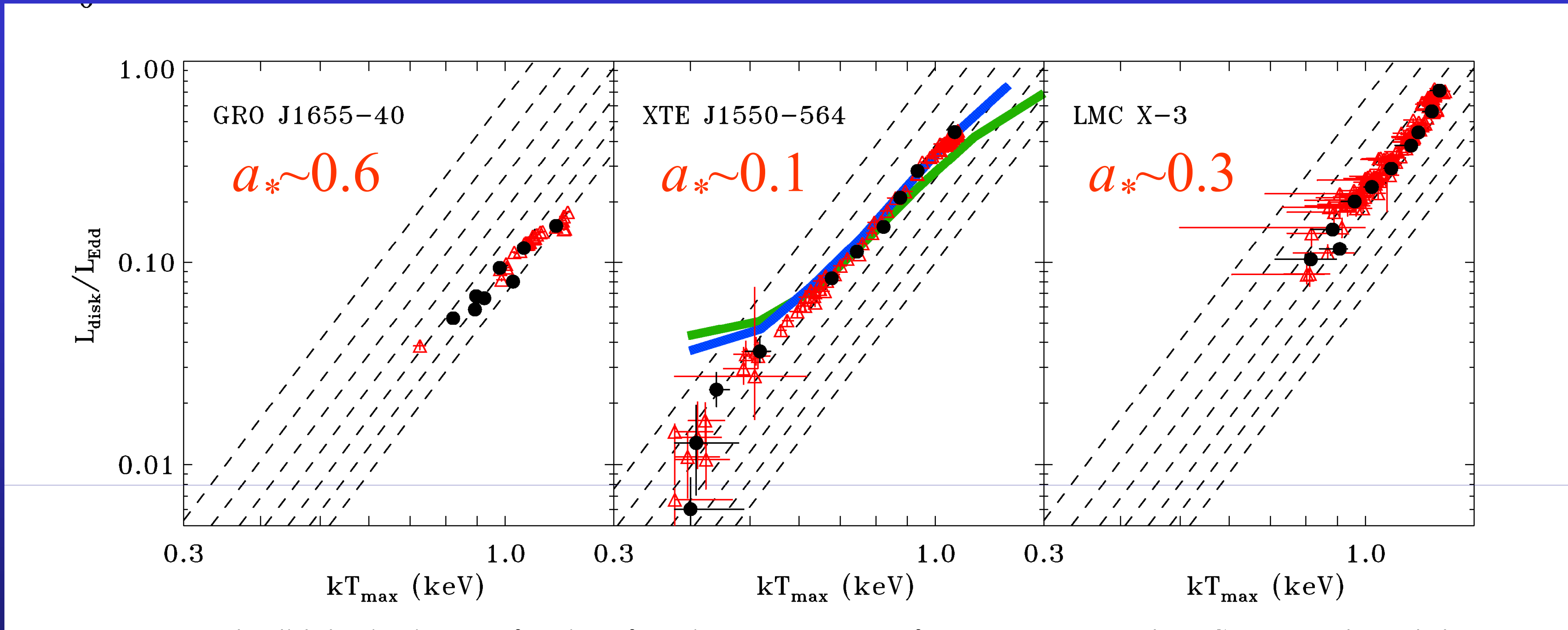


Gierlinski & Done 2003

Disc vertical structure + GR

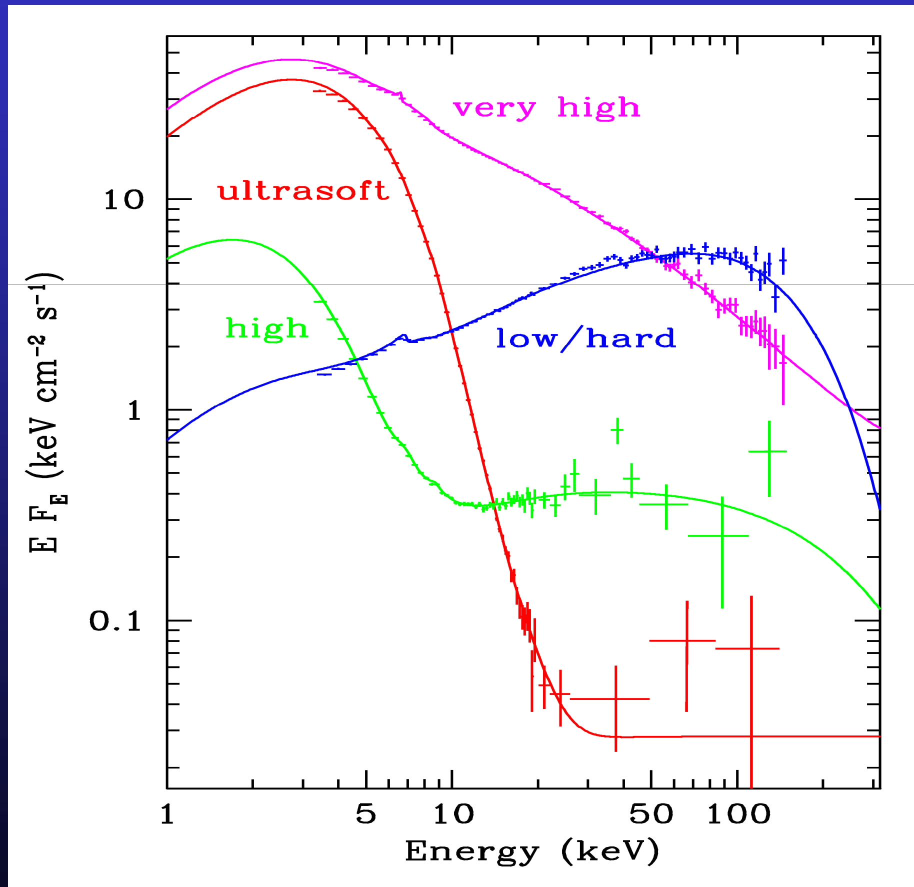


Davies, Done & Blaes 2005

- Spectrum not quite blackbody – calculate disc emission from detailed models of the vertical and radial structure of the disc then propagate out in full GR spacetime
- depends on knowing inclination, distance, mass etc. – inclination not necessarily same as binary!
- Get moderate spin a_* - supernovae collapse (Gammie et al 2006)

But rest are not simple…

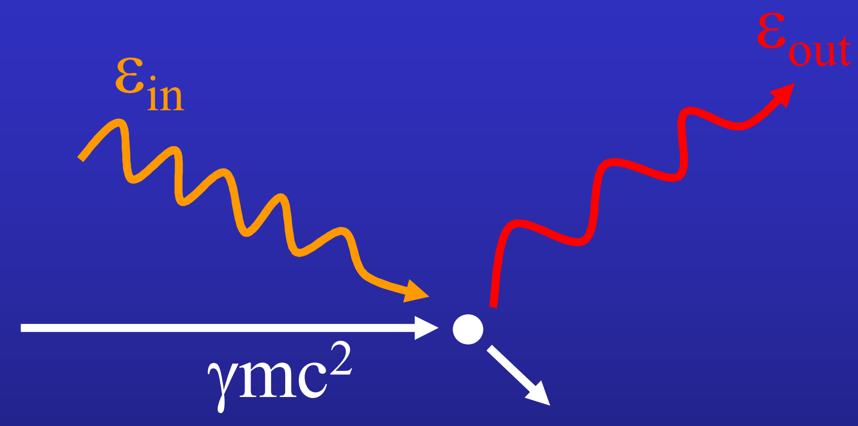
- Bewildering variety of spectra from single object
- Underlying pattern
- High L/L_{Edd}: soft spectrum, peaks at kT_{max} often disc-like, plus tail
- Lower L/L_{Edd}: hard spectrum, peaks at high energies, not like a disc



Gierlinski & Done 2003

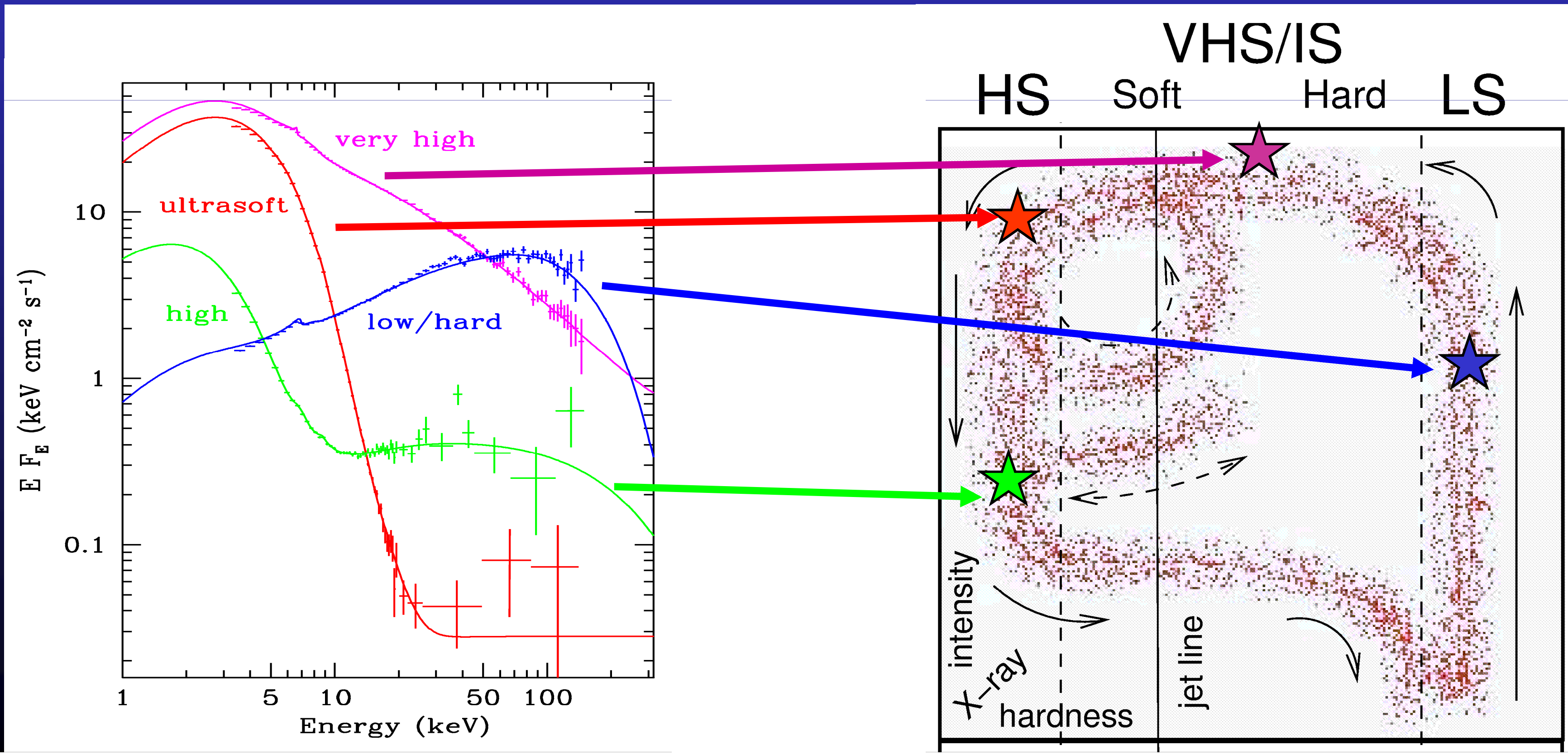
Compton scattering

- Photon-electron collisions – redistribute energy
- If photon has more energy than electron then it loses energy – downscattering
- If photon has less energy than electron then it gains energy – upscattering
- Make a high energy tail by energetic electrons NOT in the disc (or their energy thermalises!) Compton upscatter disc photons



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

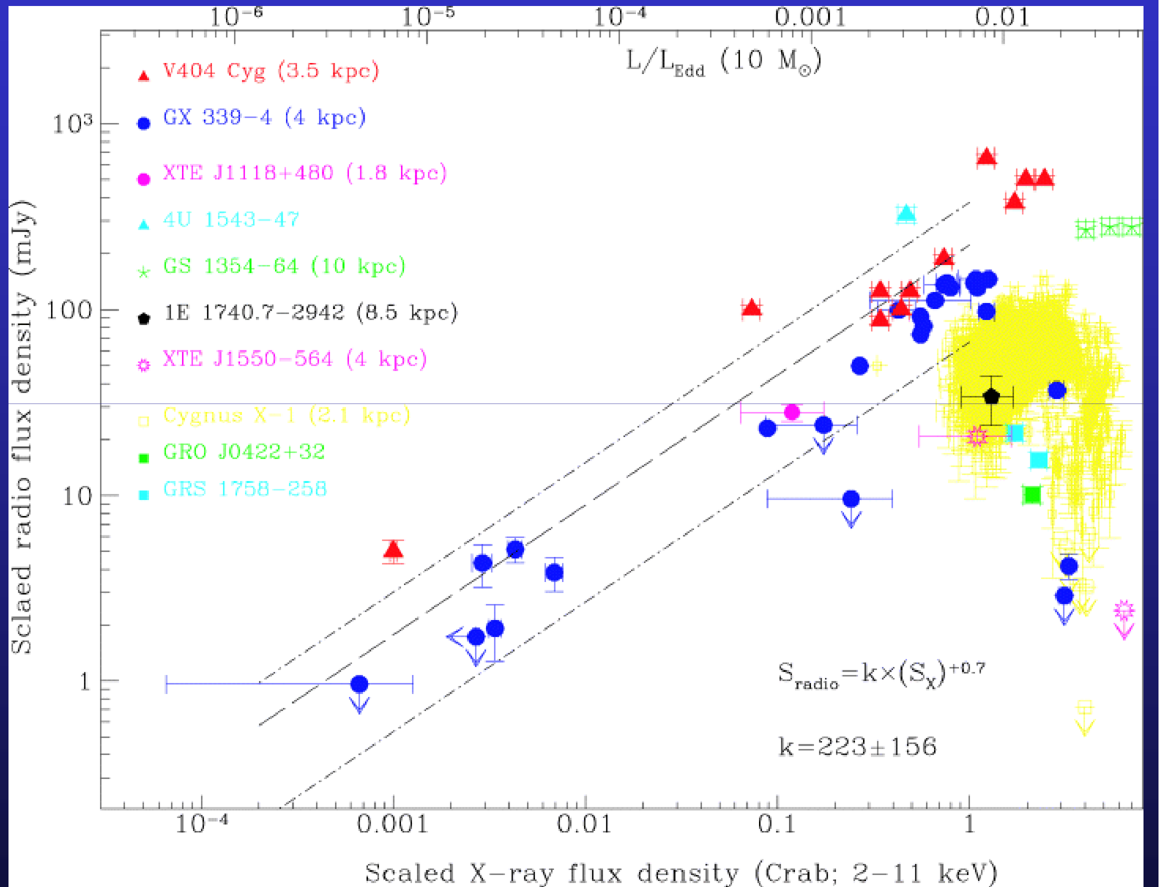


Fender Belloni & Gallo 2004

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)

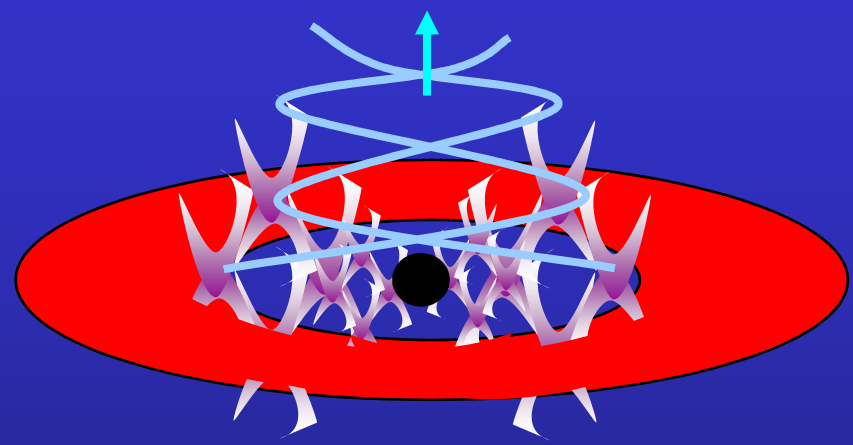
  so jet powered by mass accretion rate ie gravity
- Bright radio flares in rapid low/hard to high/soft associated with outbursts. (Fender et al 2004)

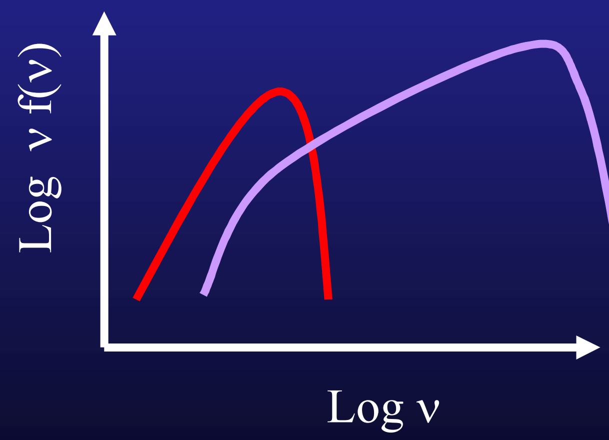


Gallo et al 2003

Accretion flows without discs

- Disc models assumed thermal plasma – not true at low L/L_{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 velocity linked to launch radius

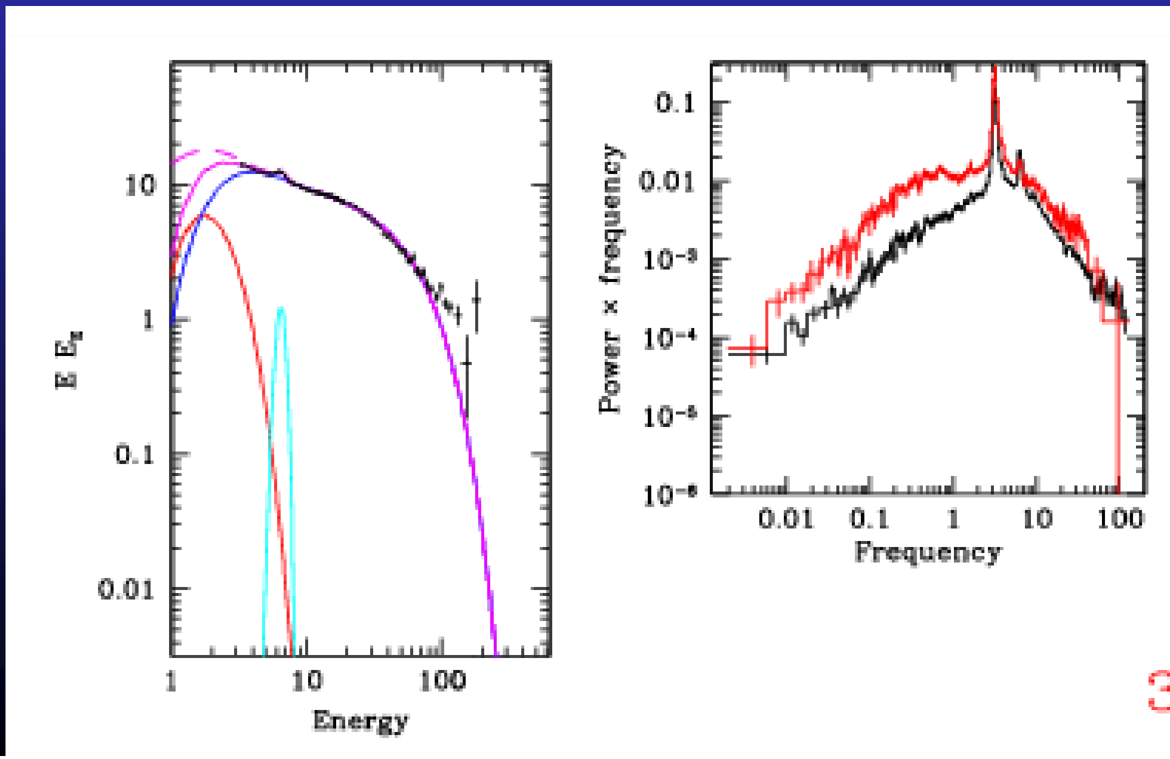


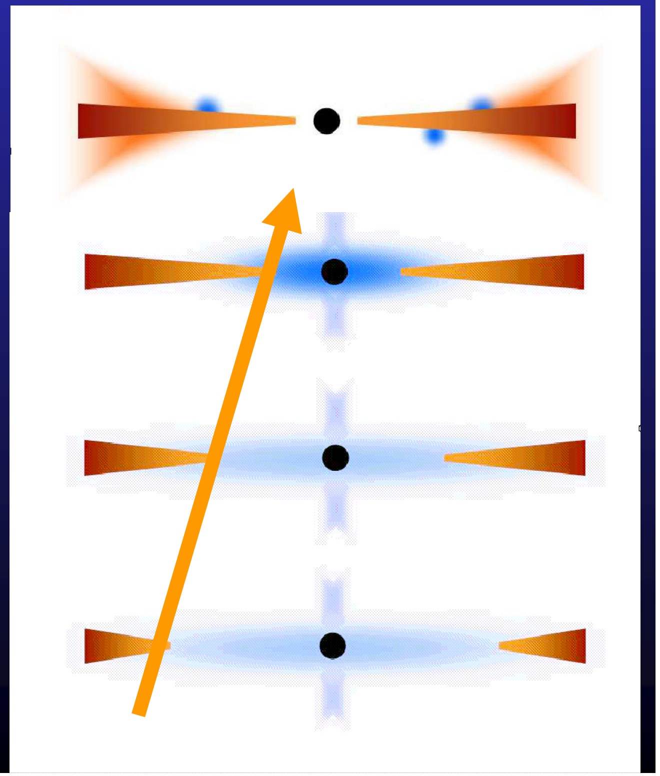


Moving disc – moving QPO

- 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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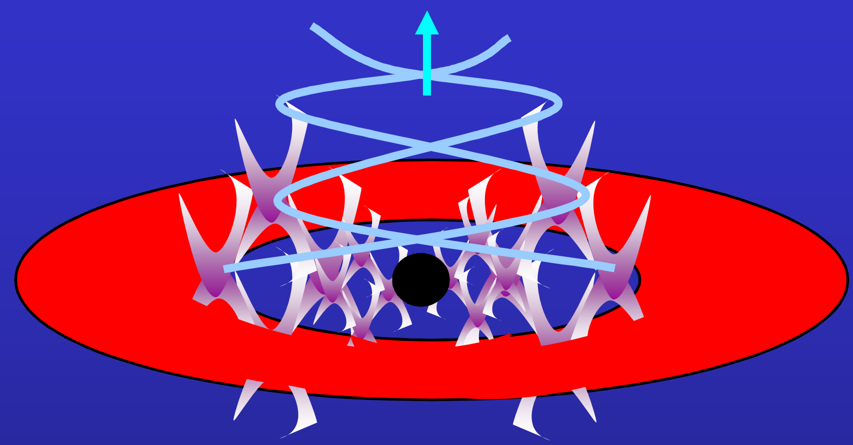

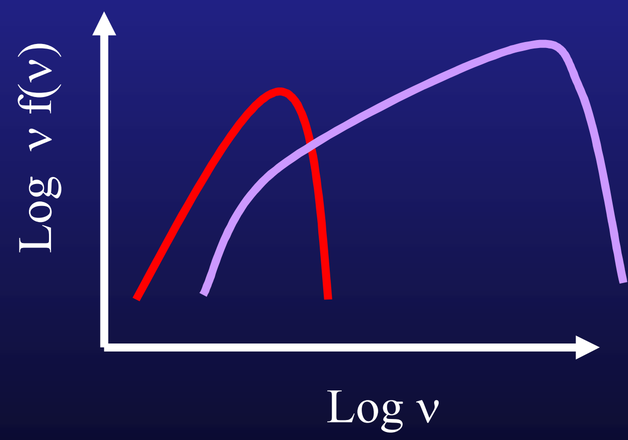

No inner disc

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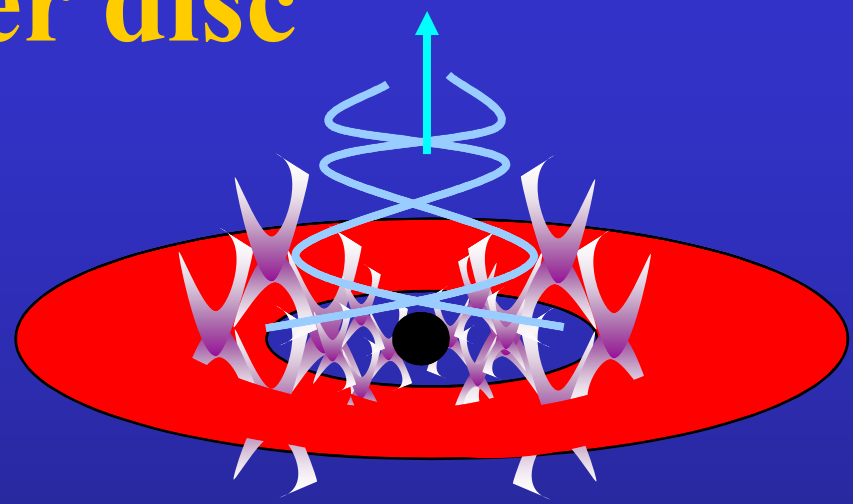

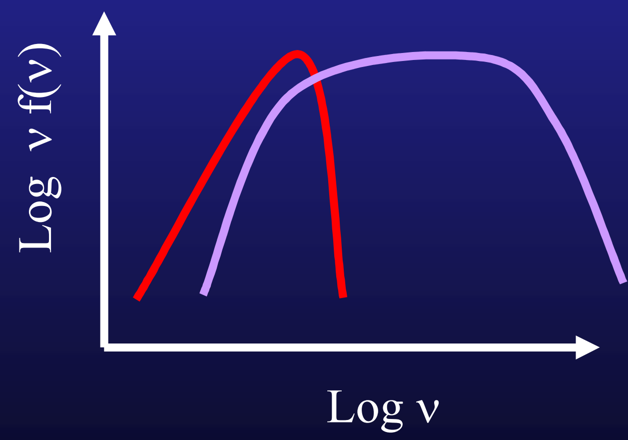

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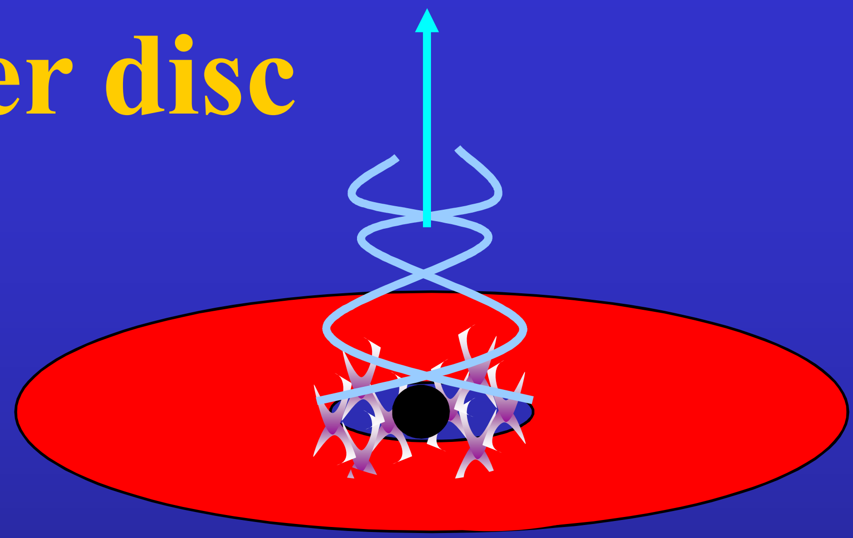

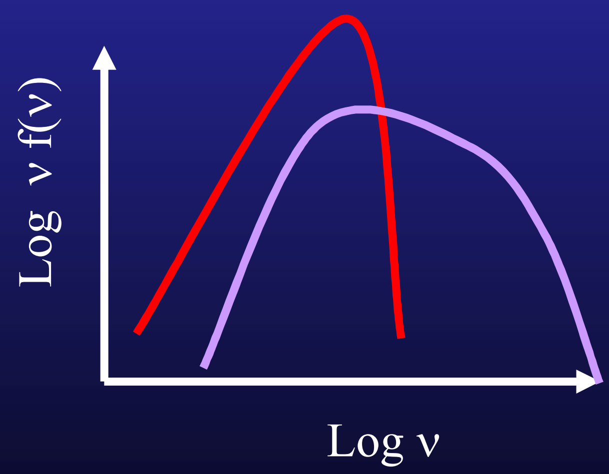

Collapse of hot inner flow

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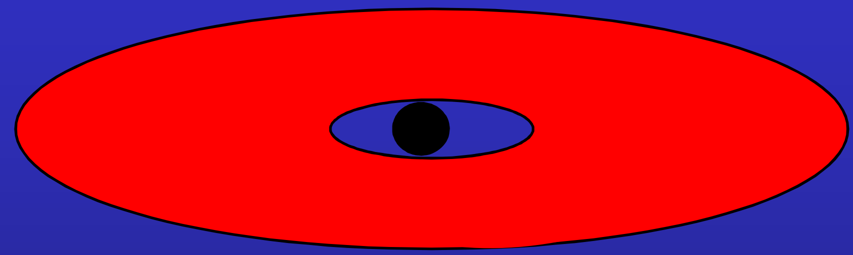
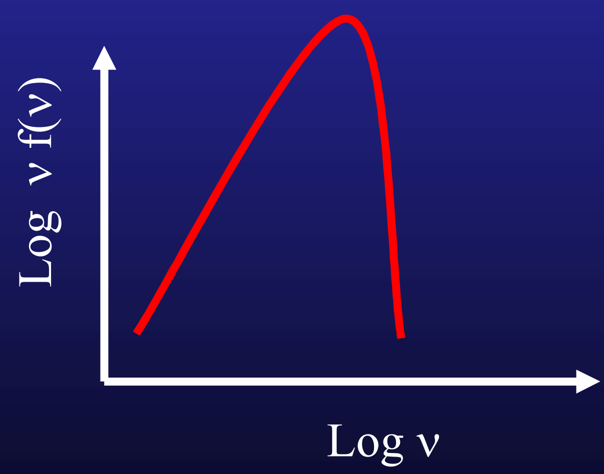
- Few seed photons, so spectrum is hard
- Jet from large scale height flow velocity linked to launch radius collapse of flow=collapse of jet





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

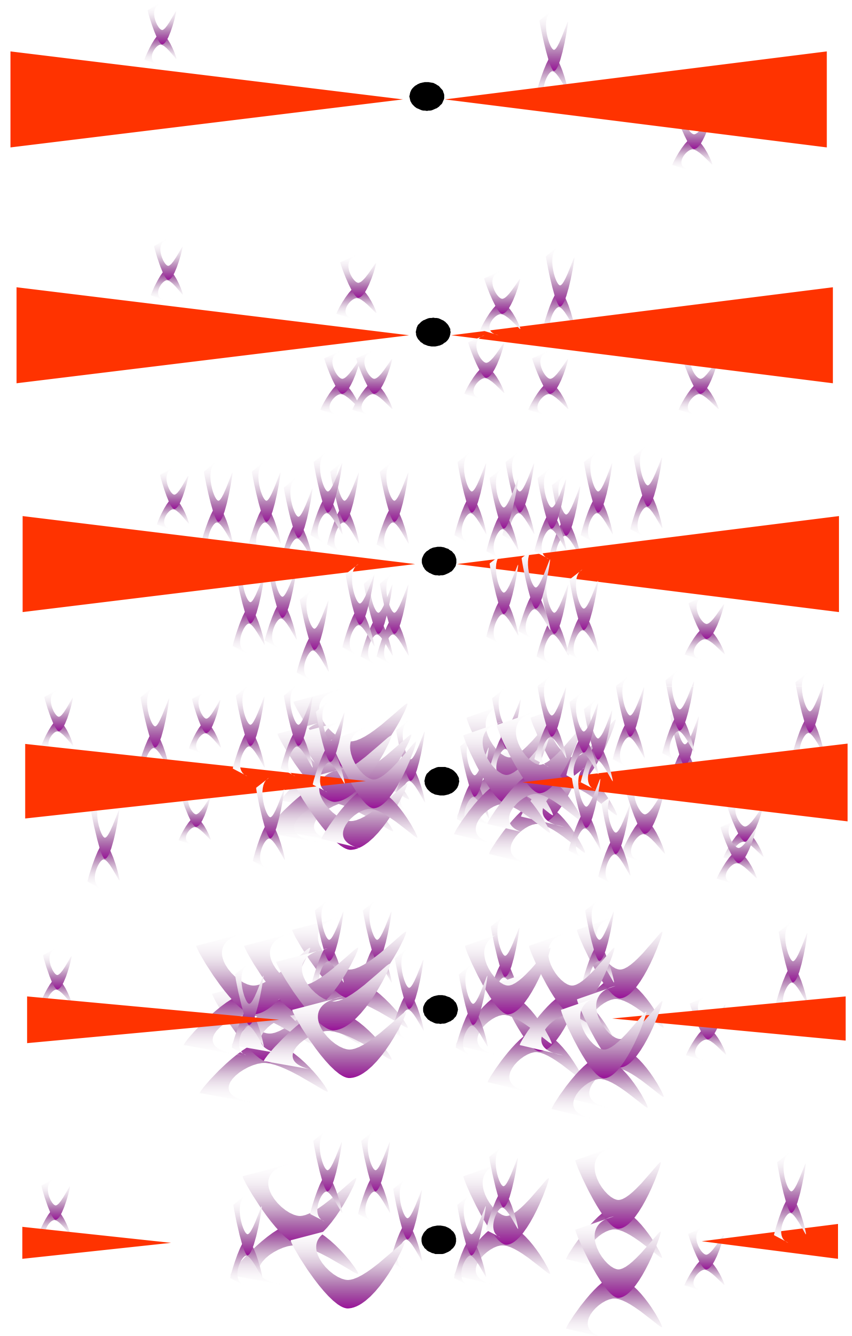
HS

VHS

VHS

LS (bright)

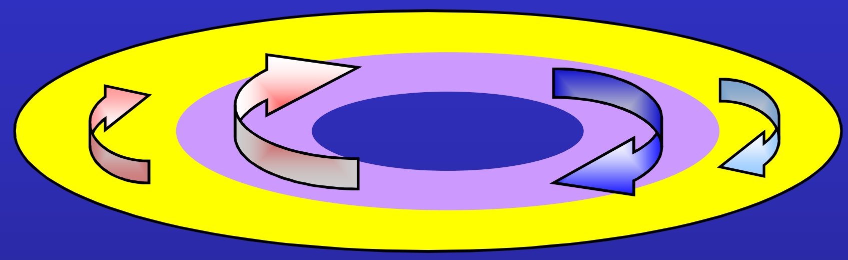
LS (dim)

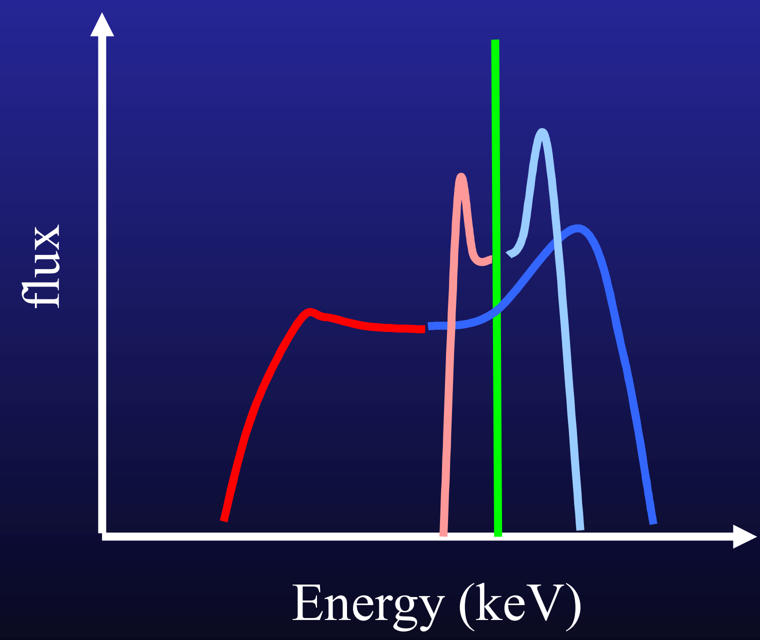


Done Gierlinski & Kubota 2007

Relativistic smearing: spin

- Relativistic effects (special and general) affect all emission
- Emission from side of disc coming towards us:
  - Doppler blueshifted
  - Beamed from length contraction
  - Time dilation as fast moving (SR)
  - Gravitational redshift (GR)
- Fe Kα line from irradiated disc should be broad and skewed, and shape depends on R_{in} (and spin)

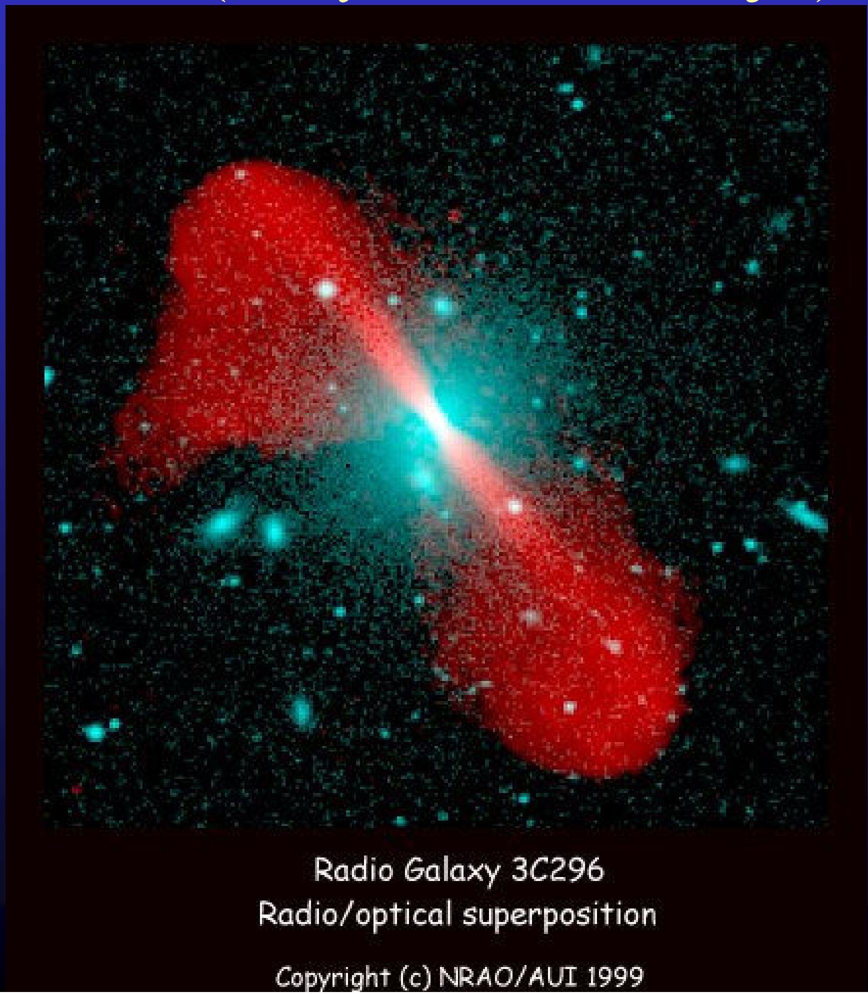


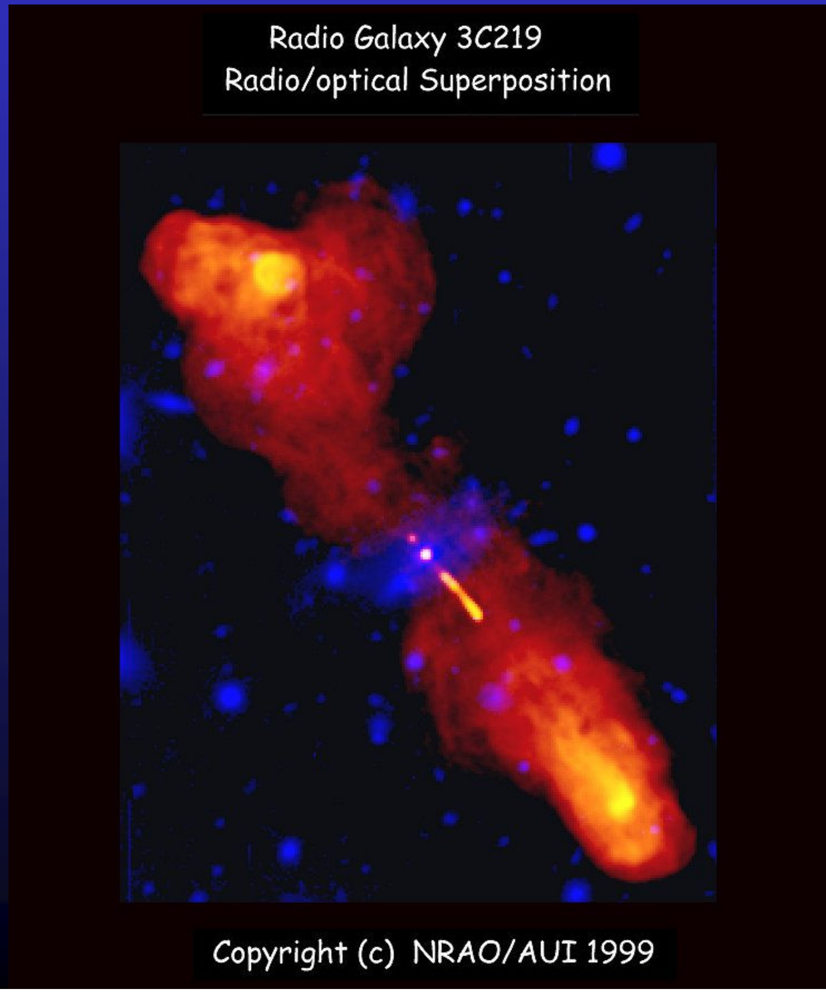


Fabian et al. 1989

AGN/QSO Zoo!!! Radio loud

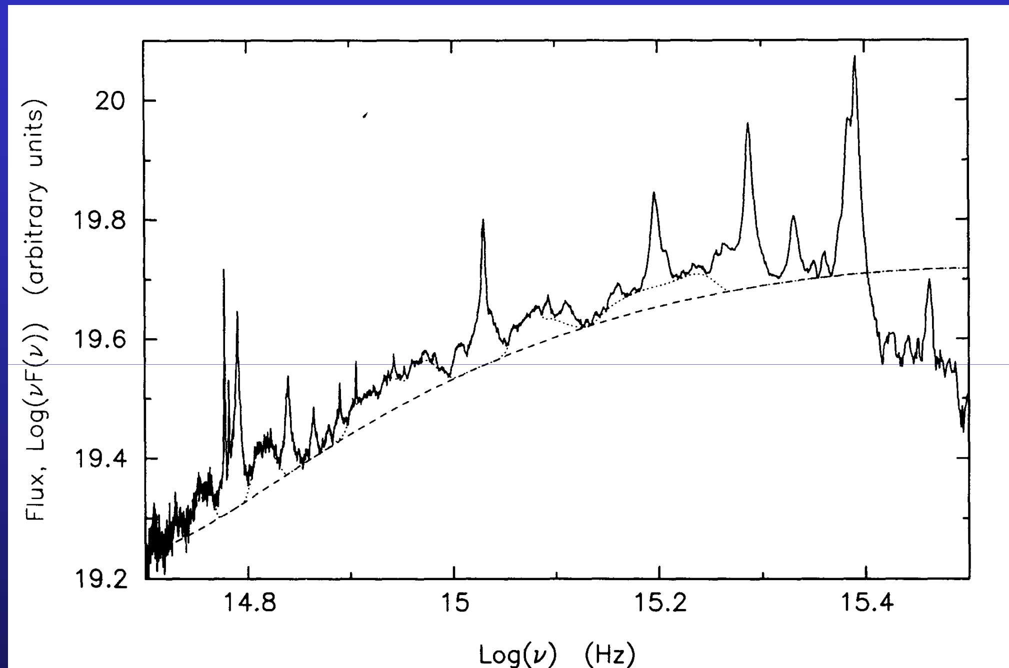
- Some have enormous, powerful jets on Mpc scales
- How QSO first found. But now most known to be radio quiet
- FRI (fuzzy lobes, 2 sided jet) FRII (bright hot spot, 1sided jet)





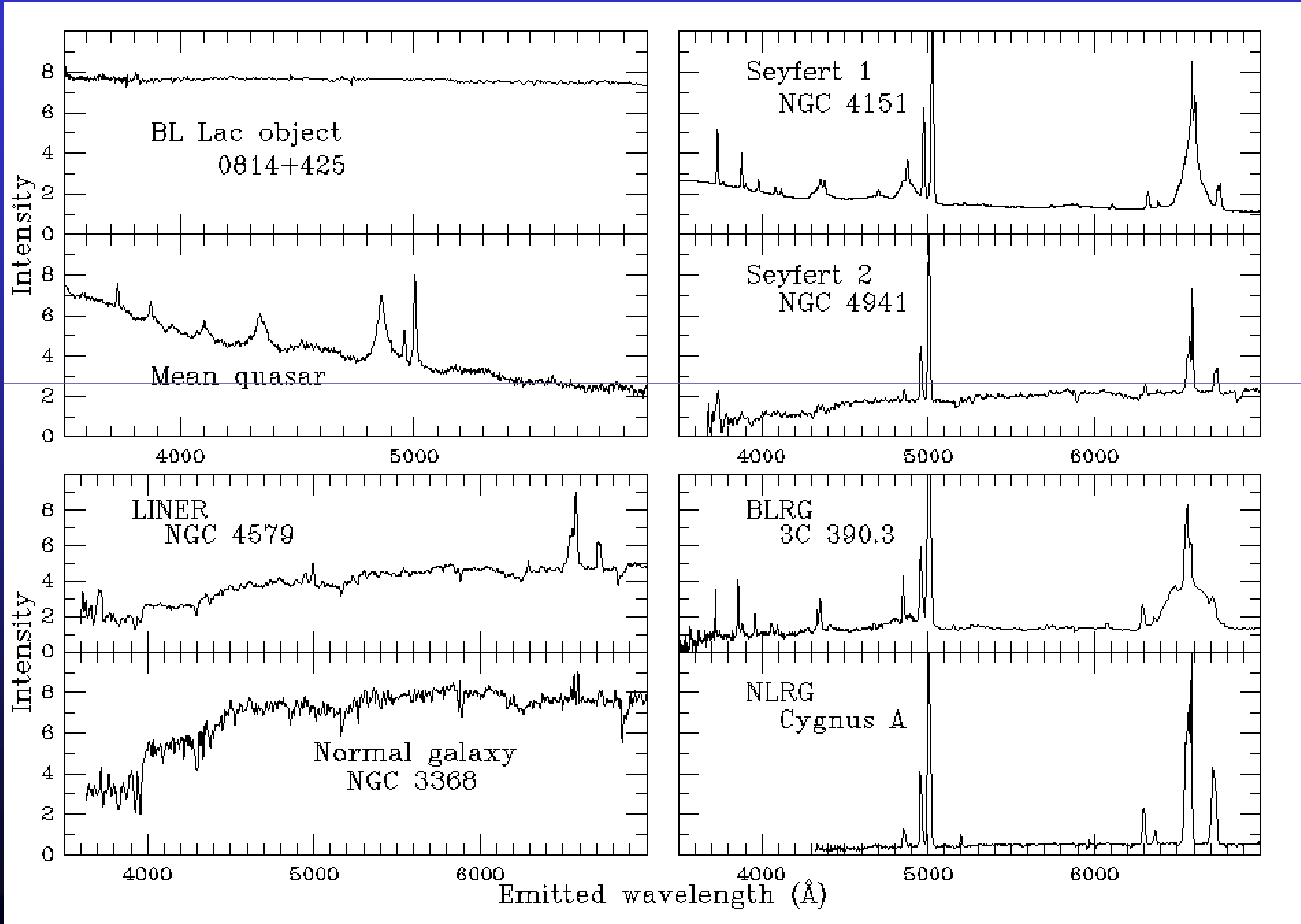
AGN/QSO Zoo!!! Optical

- Bright, blue 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
- Lines give diagnositic of unobservable EUV disc continuum



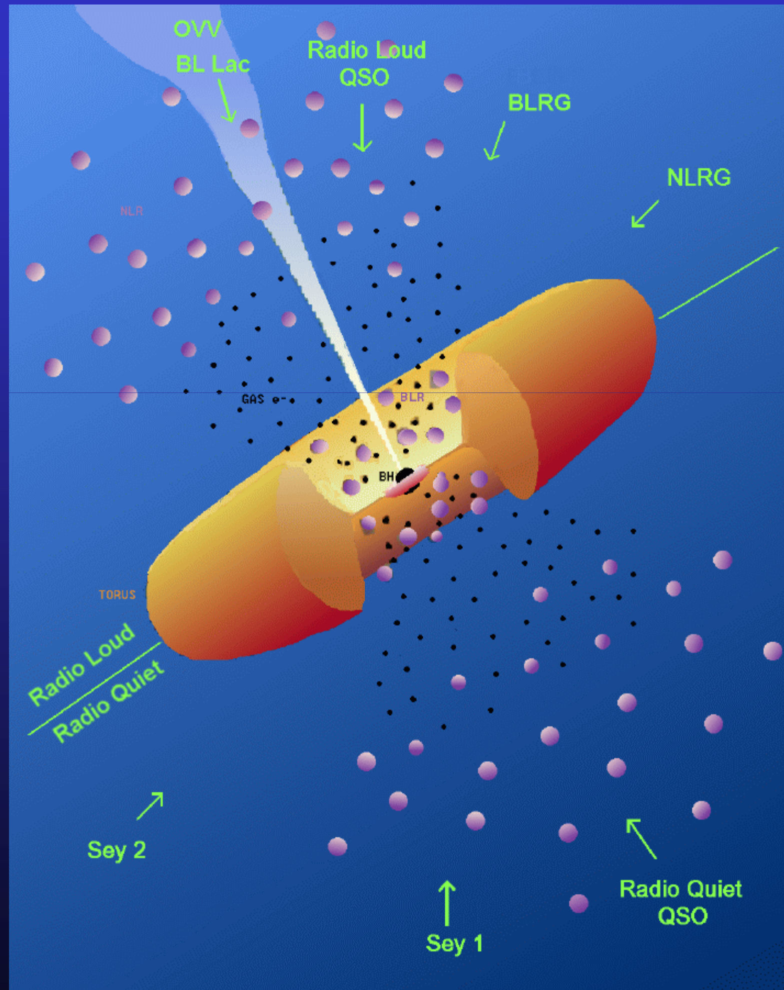
Francis et al 1991

AGN/QSO Zoo!!! Optical



AGN/QSO unification

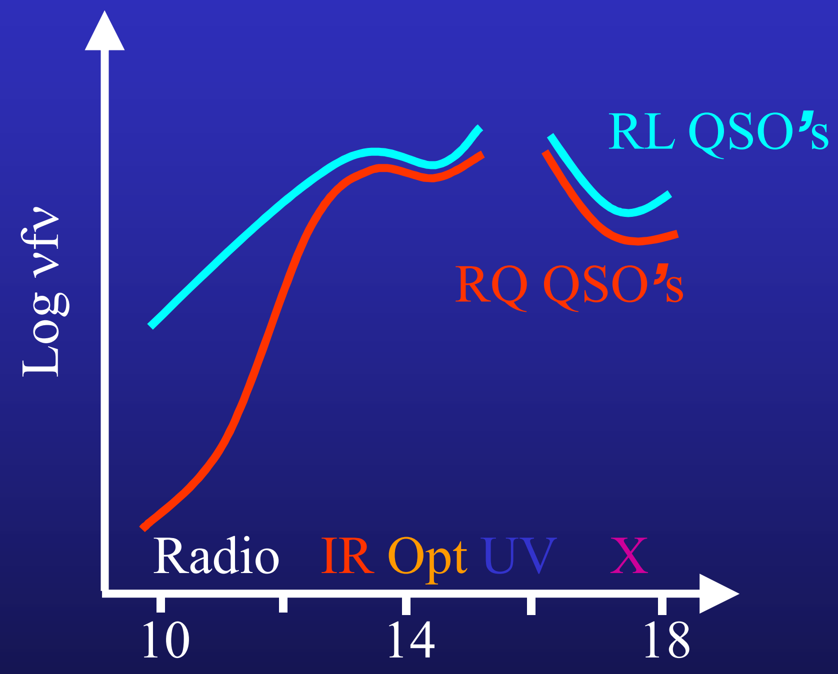
- Bigger range in mass 10^5-10^9
- L varies without much else changing if same L/L_{Edd} with different BH mass: Sey/QSO
- Cold absorption from torus along equatorial plane
- BLR and disc within torus so obscured if line of sight intersects torus. See only NLR
- But can see BLR in polarised (scattered!) light
- Unification of narrow and broad line Sey1/Sey 2 via inclination

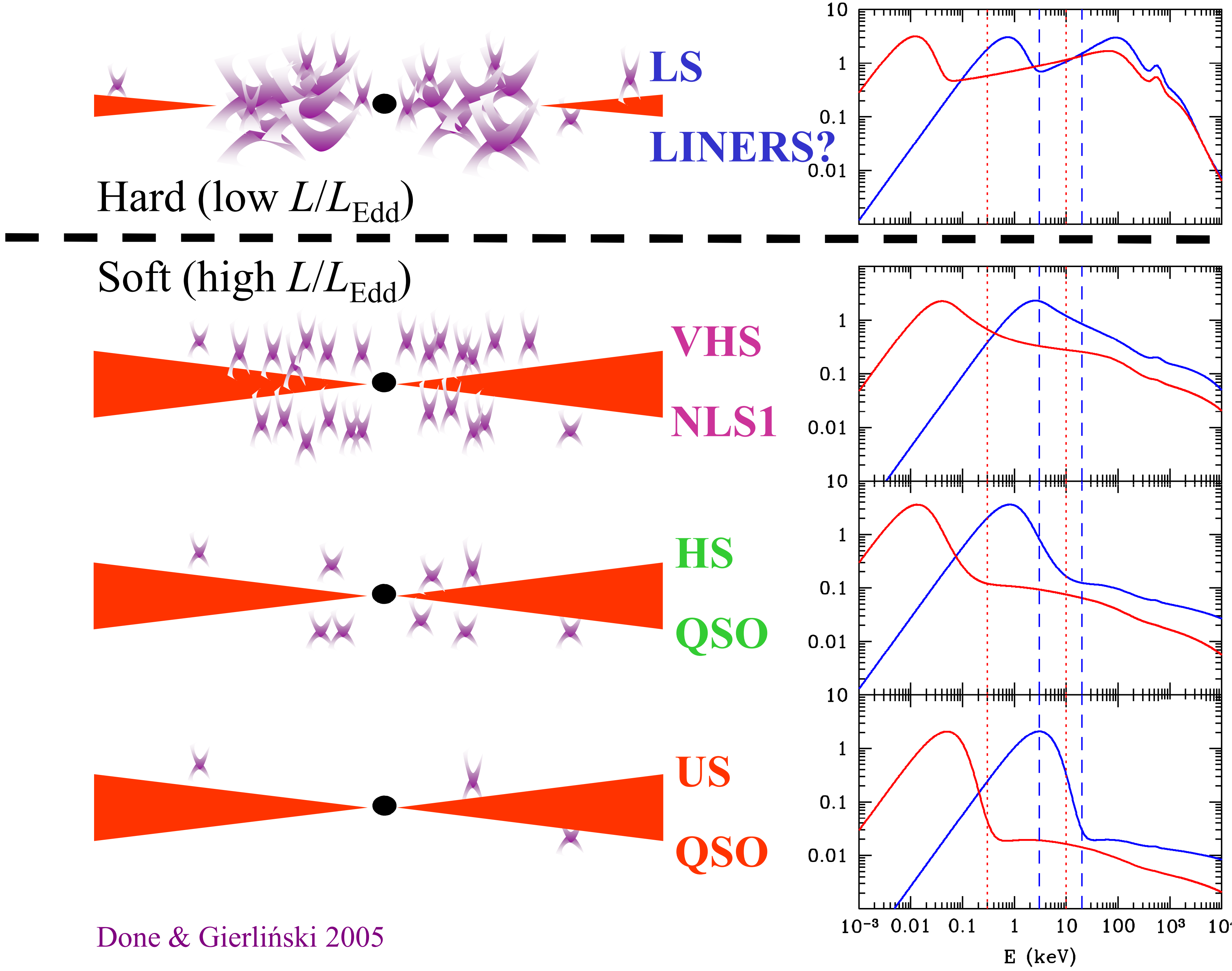


Urry & Padovani 1995

AGN/QSO unification

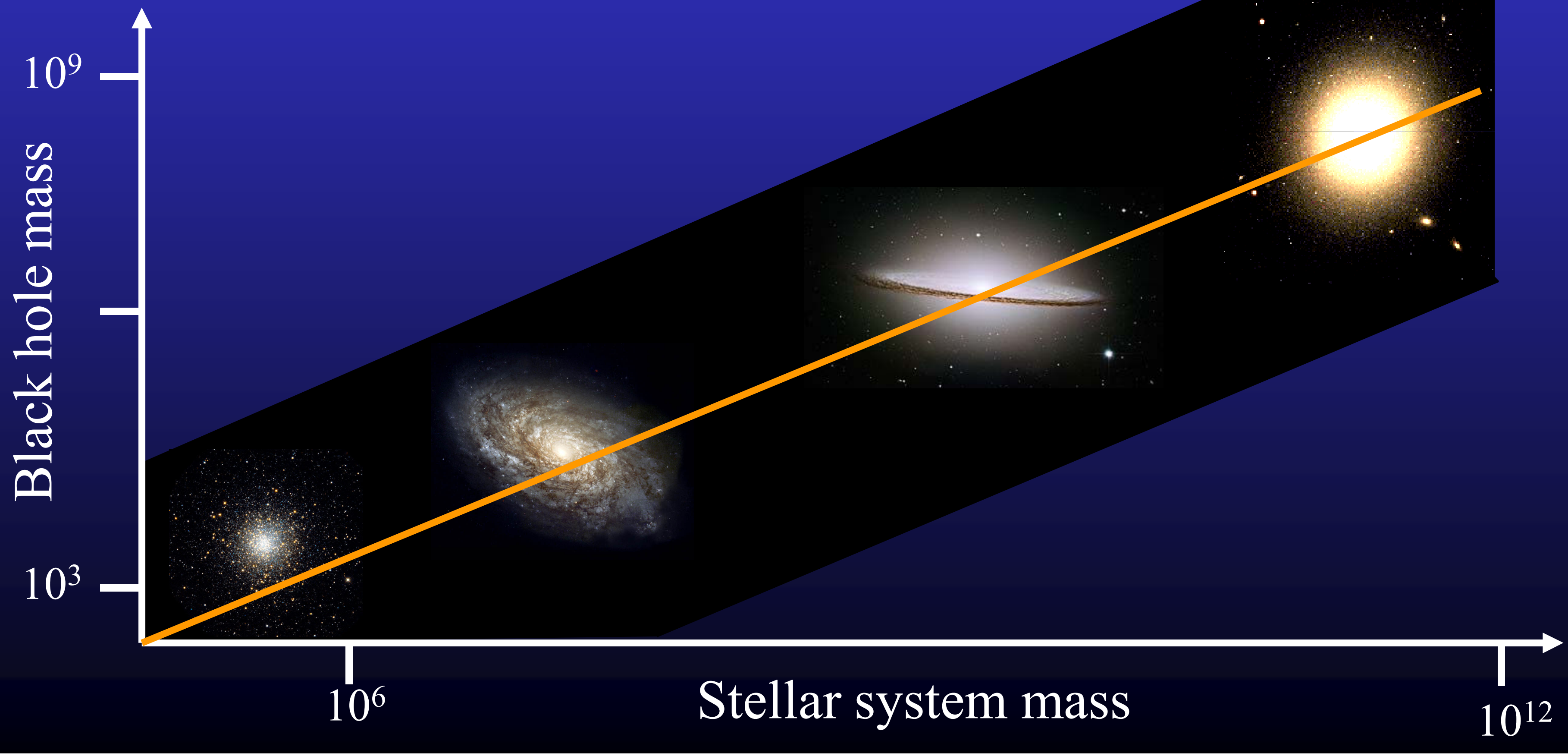
- IR bump is also evidence for dusty torus reradiating UV disc flux – also see AGN coexisting with starburst so some IR from that too
- BUT BHB not all the same underneath: spectral states with L/L_{Edd}
- Do AGN show the same states?
- What controls radio loud/quiet jet? Is this just L/L_{Edd} as in BHB?

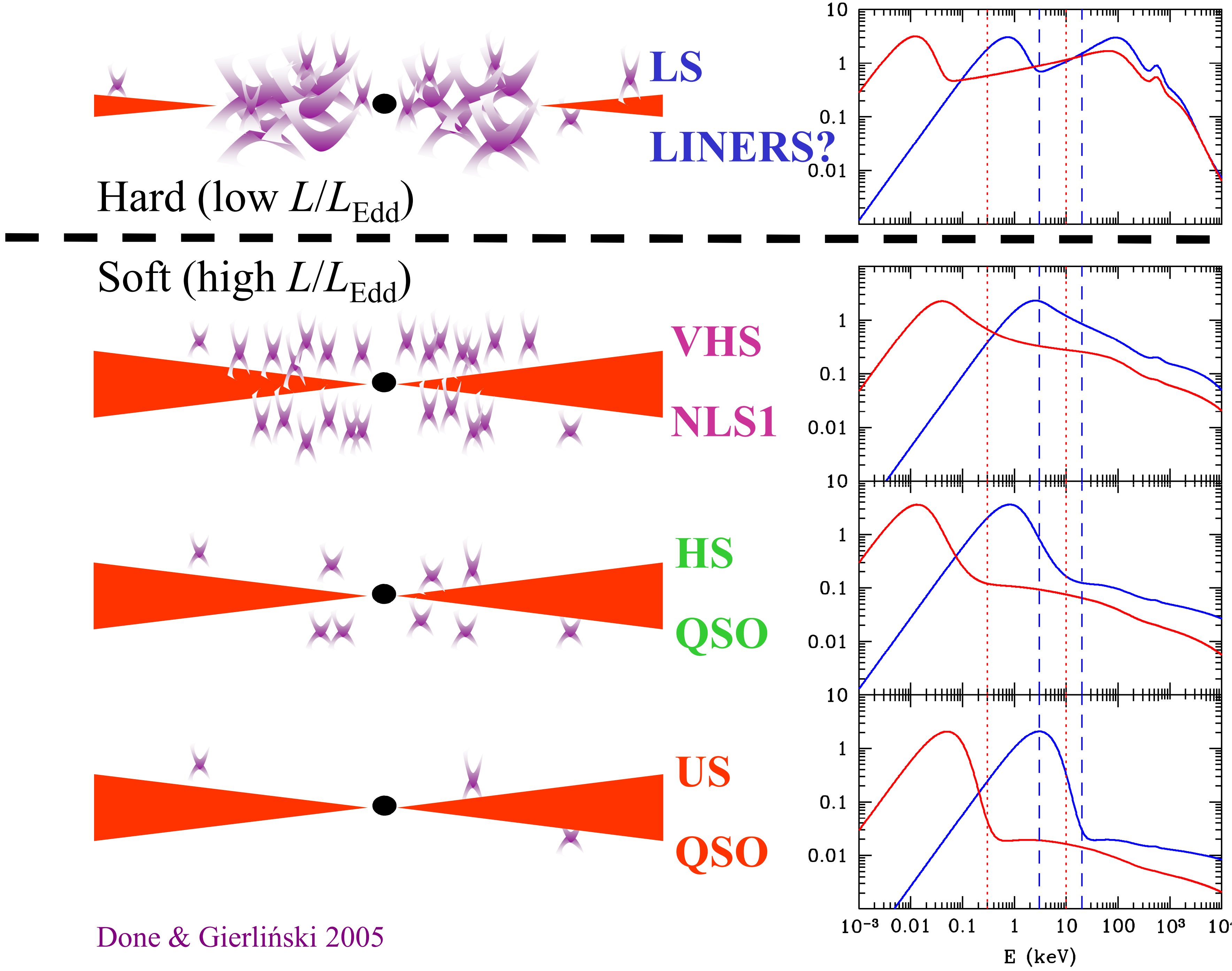



LS
LINERS?
Hard (low L/L_{Edd})
Soft (high L/L_{Edd})
VHS
NLS1
HS
QSO
US
QSO
Done & Gierliński 2005
E (keV)

Easier way to get mass

- 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)

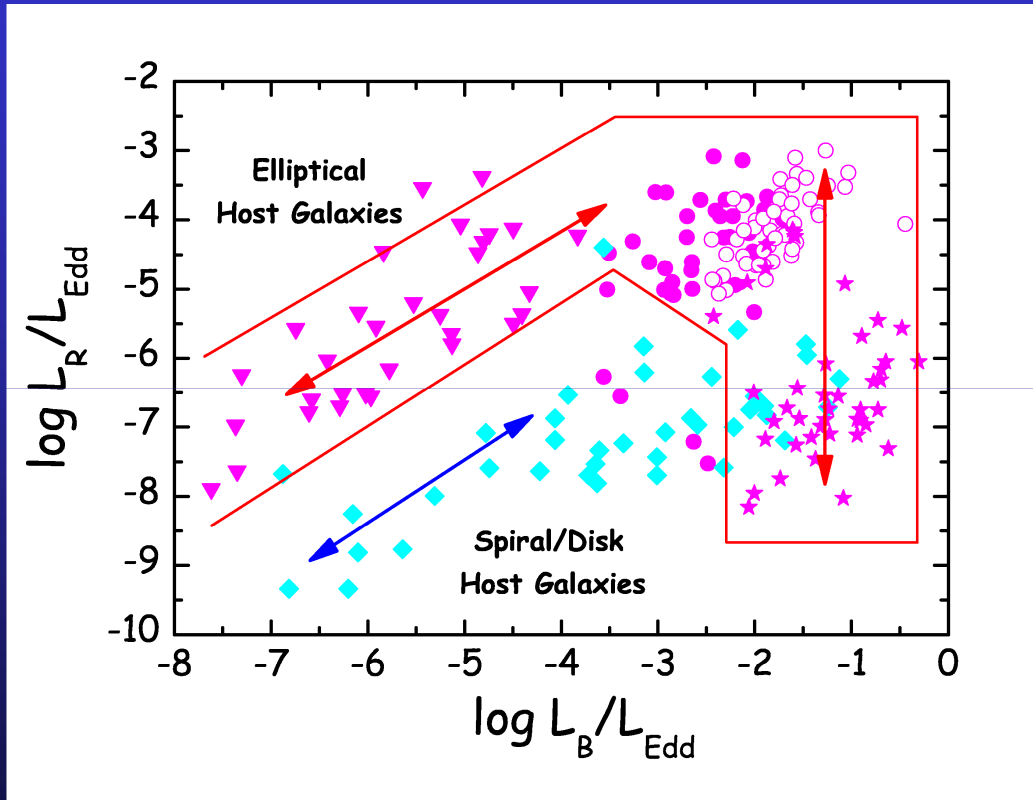




LS
LINERS?
Hard (low L/L_{Edd})
Soft (high L/L_{Edd})
VHS
NLS1
HS
QSO
US
QSO
Done & Gierliński 2005
10
1
0.1
0.01
10^{-3} 0.01 0.1 1 10 100 10^{3}
E (keV)

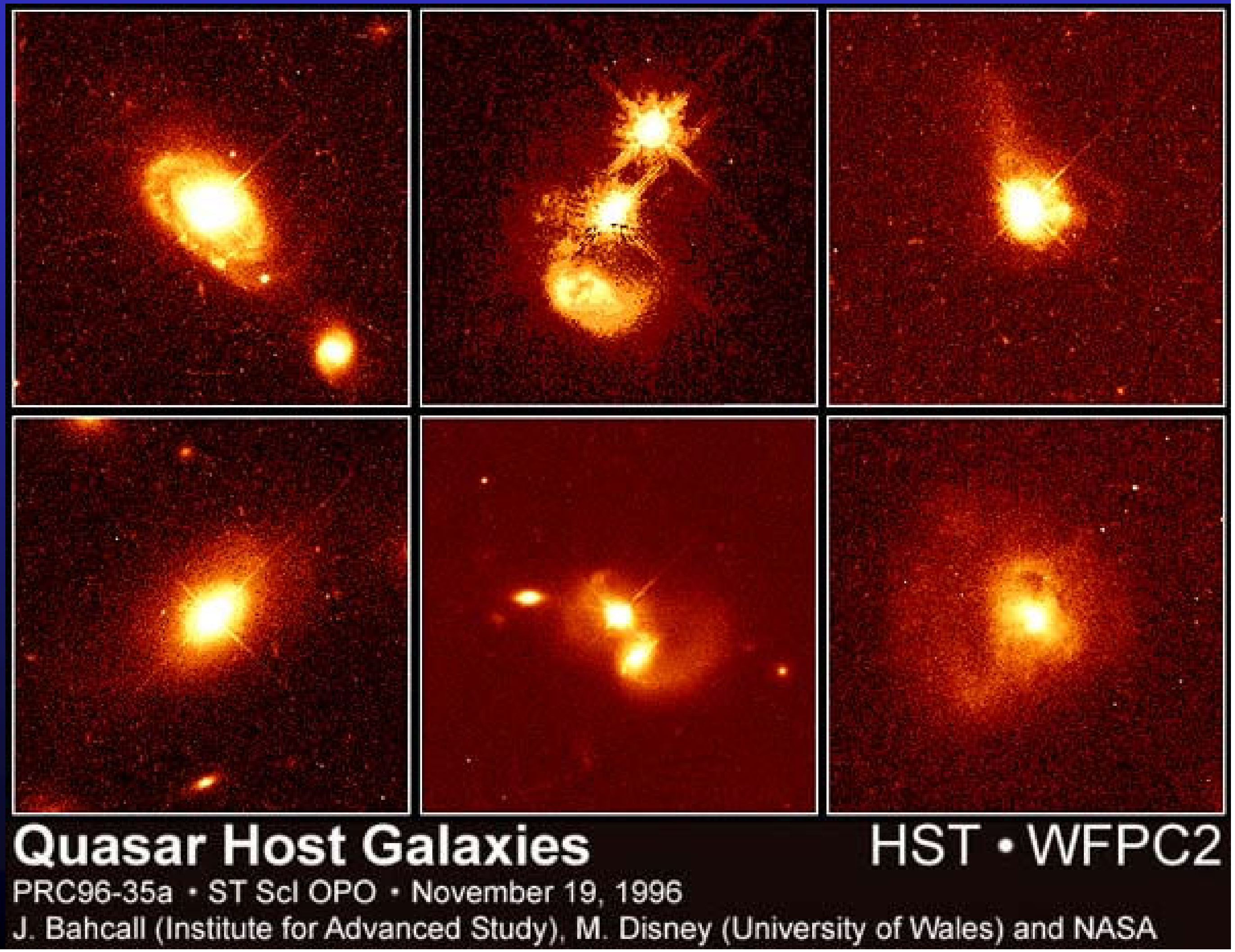
AGN - *spin*

- Origin of jet – L/L_{Edd} ?
- But standard QSO's can be radio loud OR radio quiet at high L/L_{Edd}
- Environment difference? Radio loud in ellipticals so can have high spin from accretion spinup in major mergers
- Low spin in spirals from random orientation small accretion events (Sikora Stawarz & Lasota 2007)



AGN/QSO Zoo!!! Host galaxy

- Link to galaxy formation – ellipticals/bulge from major mergers so accretion spins up BH to maximal – more powerful jet
- Spirals from random small satellite galaxy accretion – low spin (Volonteri et al 2007)



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
- Corrections to GR from proper gravity must be smallish
- Accretion flow NOT always simple disc – X-ray tail!
- Mass ~10 M_{sun}. Accretion flow + jet change with L/L_{Edd}
- Apply to AGN – mass has bigger spread ($10^{5\text{-}9}$ M_{sun})
- More complex environment – torus/dust obscuration – inclination!
- Spectrum and jet change with L/L_{Edd} but jet probably depends on spin as well. Feedback from this controls galaxy formation
- PHYSICS ↔ ASTROPHYSICS ↔ ASTRONOMY