# Black Hole Binaries and Active Galactic Nuclei

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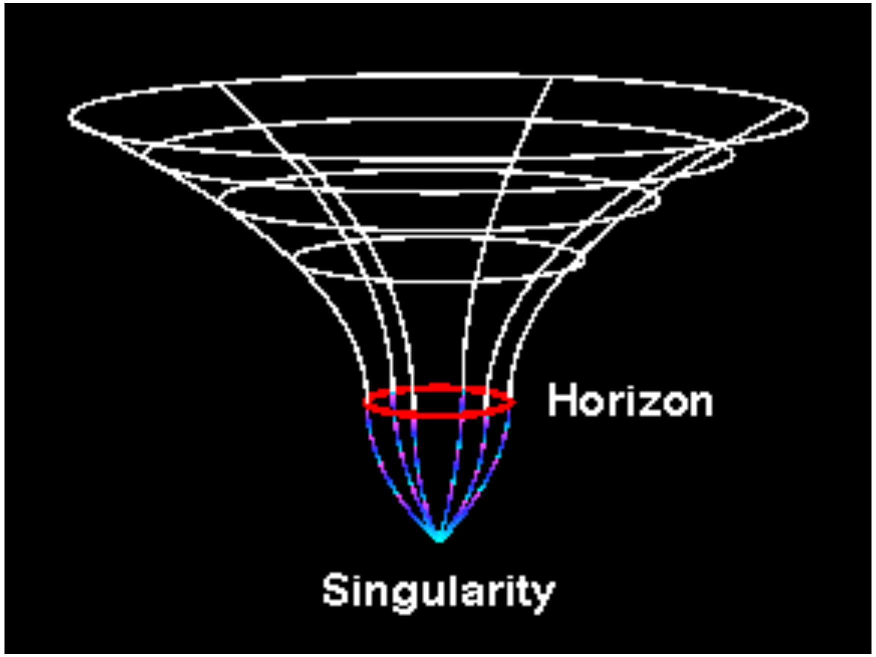
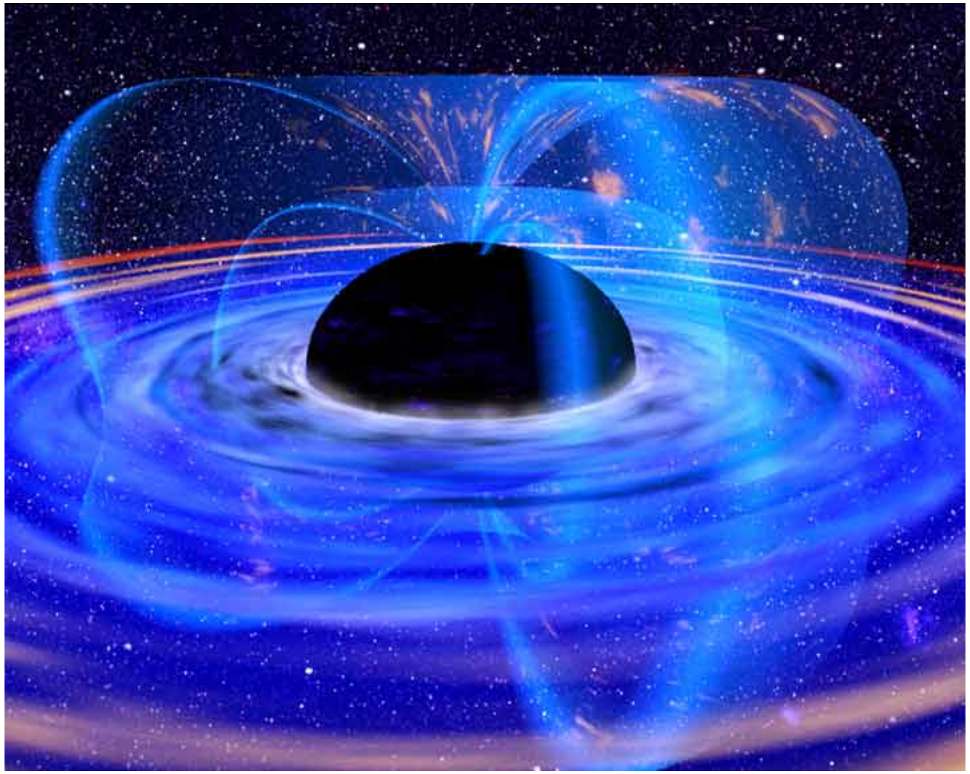
# Black holes

- Black holes – the ultimate triumph of gravity
- Completely determined by mass and spin in Einstein GR
- (any charge is quickly neutralised)
- Space so warped that not even light escapes from below the event horizon
- The thing about black holes, is their black. And the thing about space, your basic space colour is…its black. So how are you meant to see them?



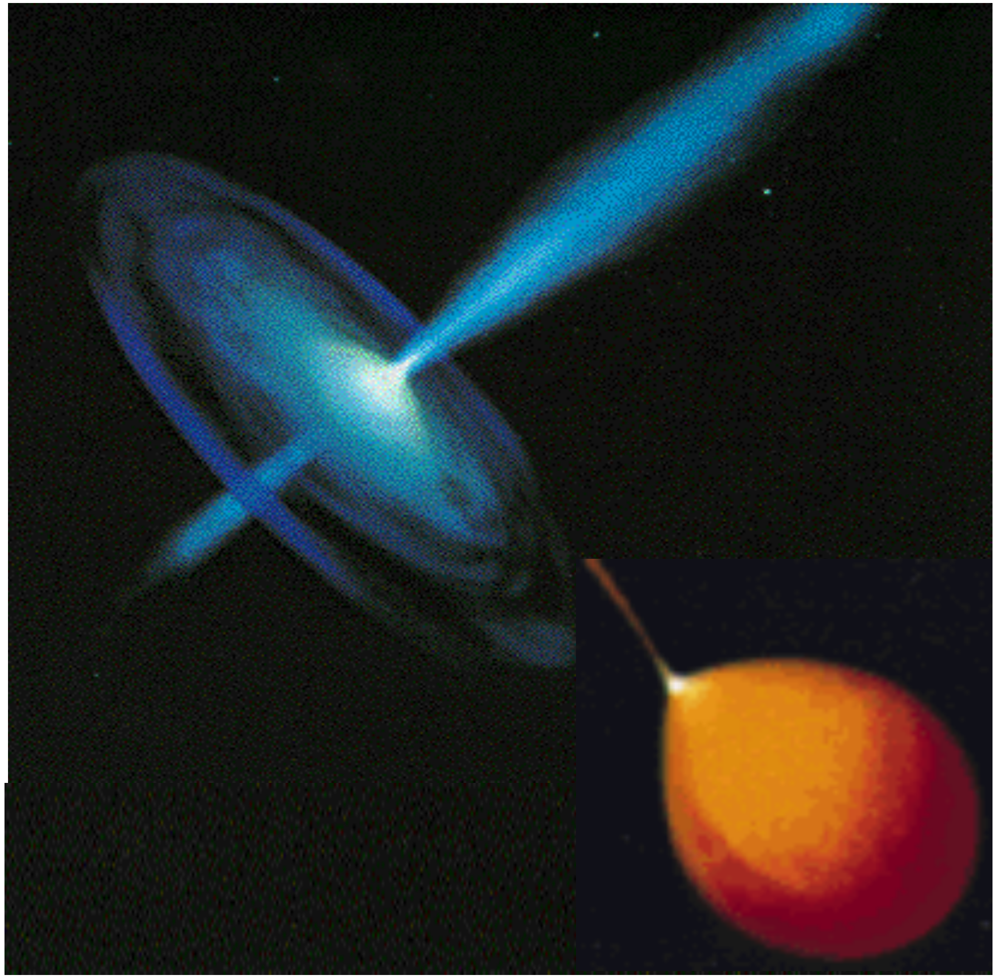
# Accretion

- 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!
- GR predictions - event horizon, last stable orbit (spin), Lense-Thirring precession (spin)



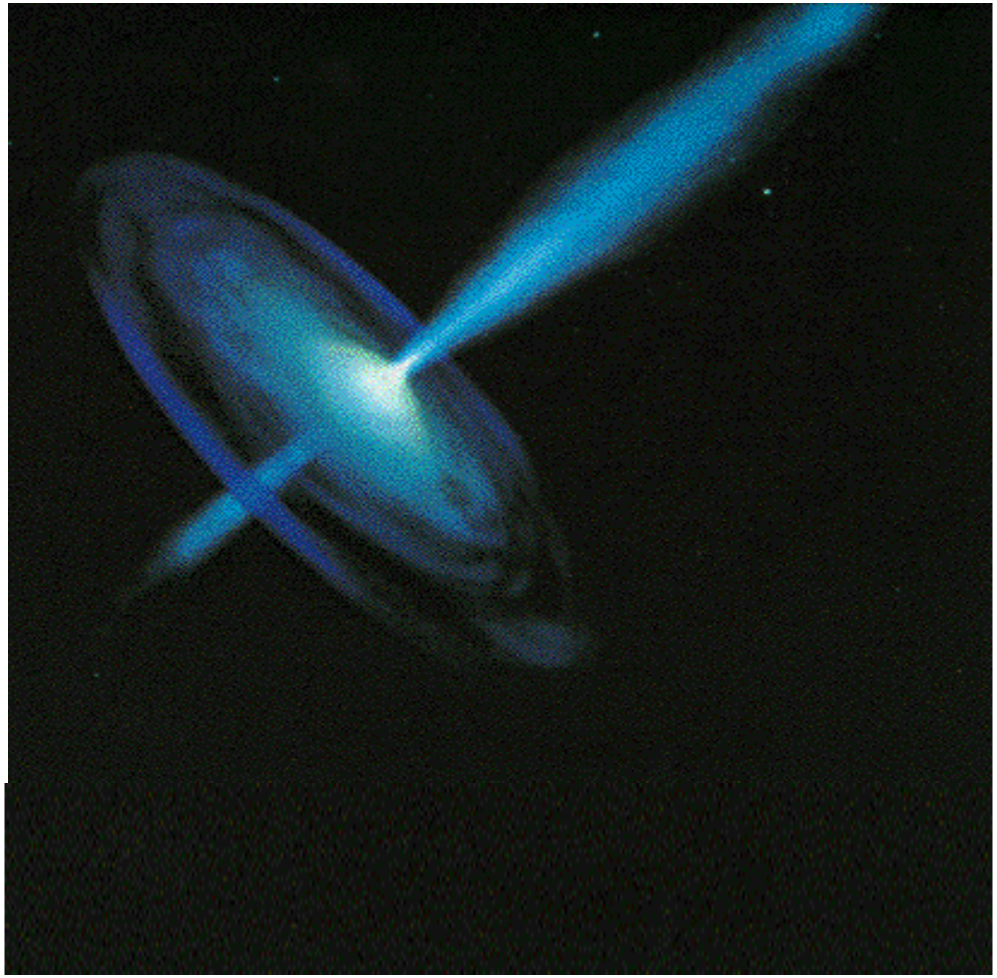
# Black holes

- Black hole binaries – quasars for the impatient!
- Observational template of how accretion flows (spectra and variability) and their associated jet behave
- Build a working physical model of accretion flows



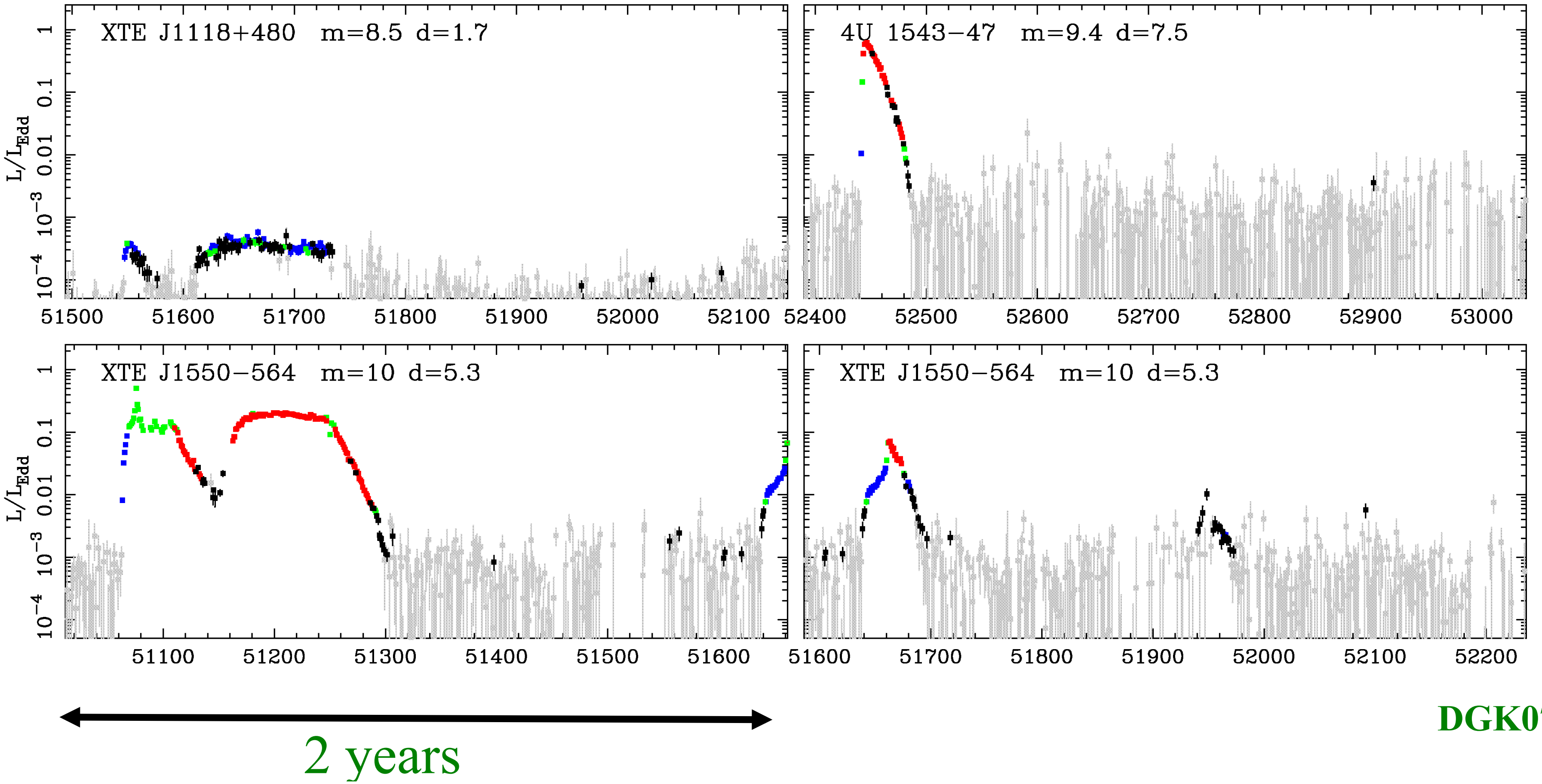
# Black holes

- Scale up to AGN – what works and what doesn't
- Need to understand accretion flow and jet feedback in order to understand galaxy formation
- Does jet depend on spin?



# BHB – Quasars for the impatient

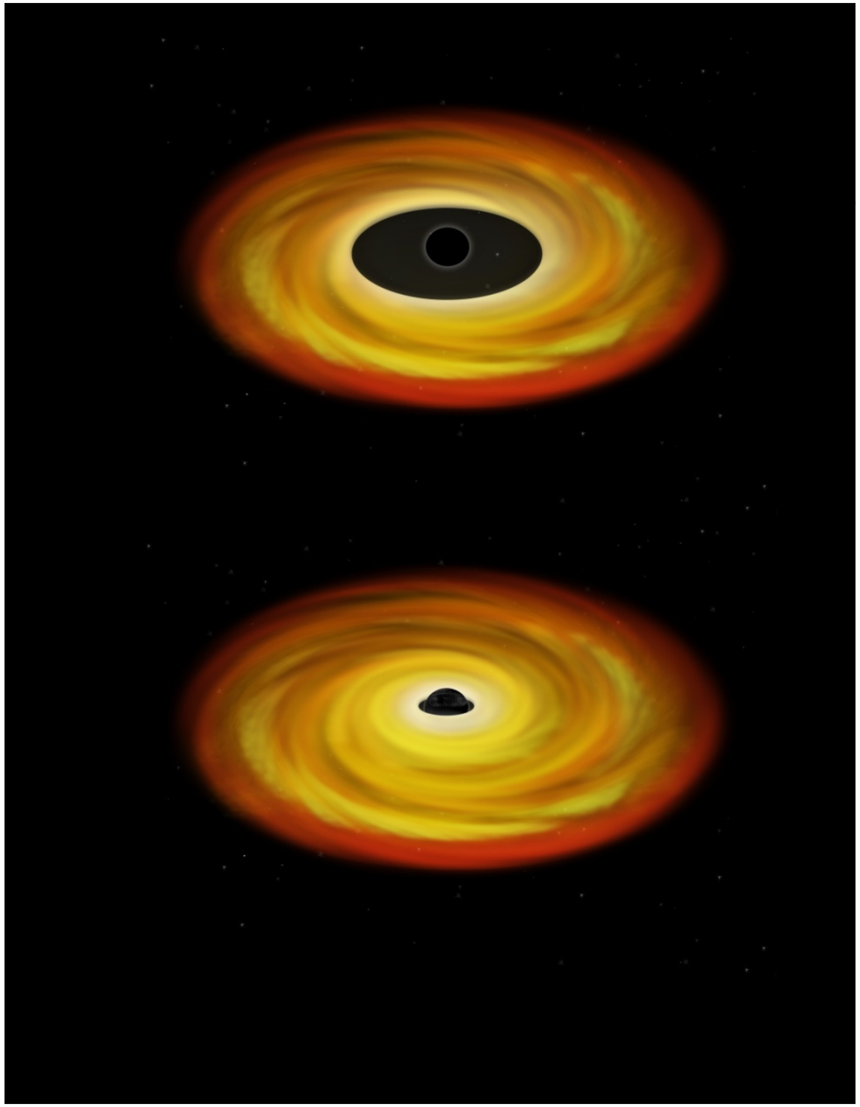
- BRIGHT! Huge amounts of data, long term variability (days –years) in mass accretion rate (due to H ionisation instability in disc)
- Observational template of accretion flow as a function of $L/L_{\mathrm{Edd}}$ onto ~10 $M_\odot$ BH (very homogeneous!)




DGK07

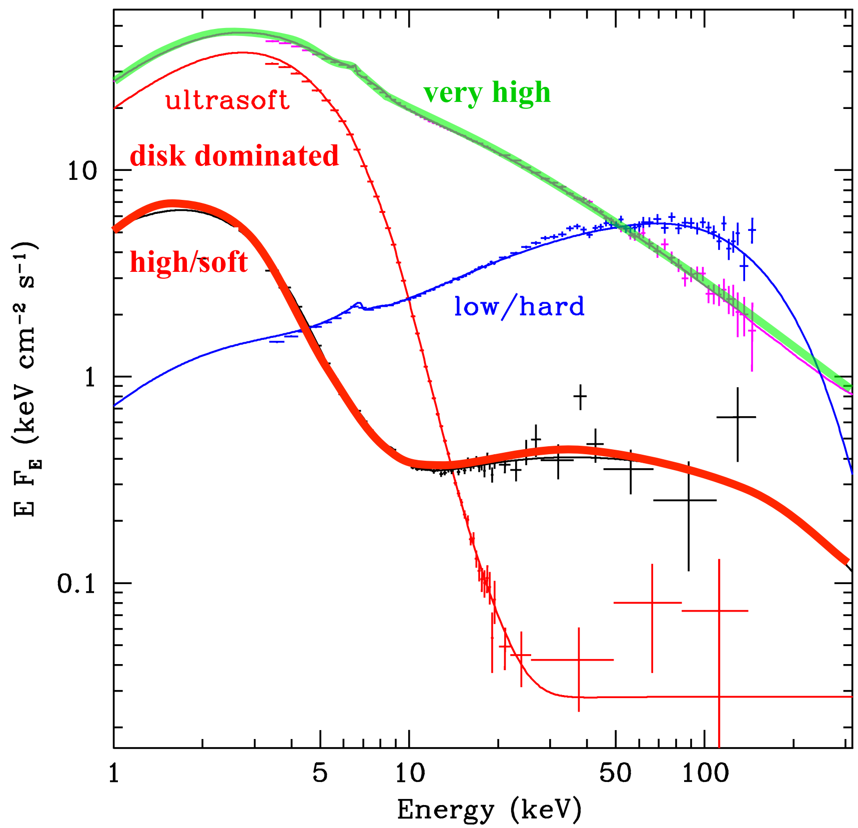
# Spectra of accretion flow: disc

- Differential Keplerian rotation
- Viscosity B: gravity → heat
- Thermal emission: $L = A\sigma T^4$
- Temperature increases inwards until minimum radius $R_{\rm lso}(a_*)$ 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 $10^8$ $M_\odot$
- Maximum spin $T_{\rm max}$ is 3x higher



# Spectral states

- Disc dominated - look like a disc but small tail to high energies
- Very high/intermediate states at least know something about a disc
- Low/hard state look really different, not at all like a disc!
- When not dominated by disc don't get consistent results for radius so can't get spin




Gierlinski & Done 2003

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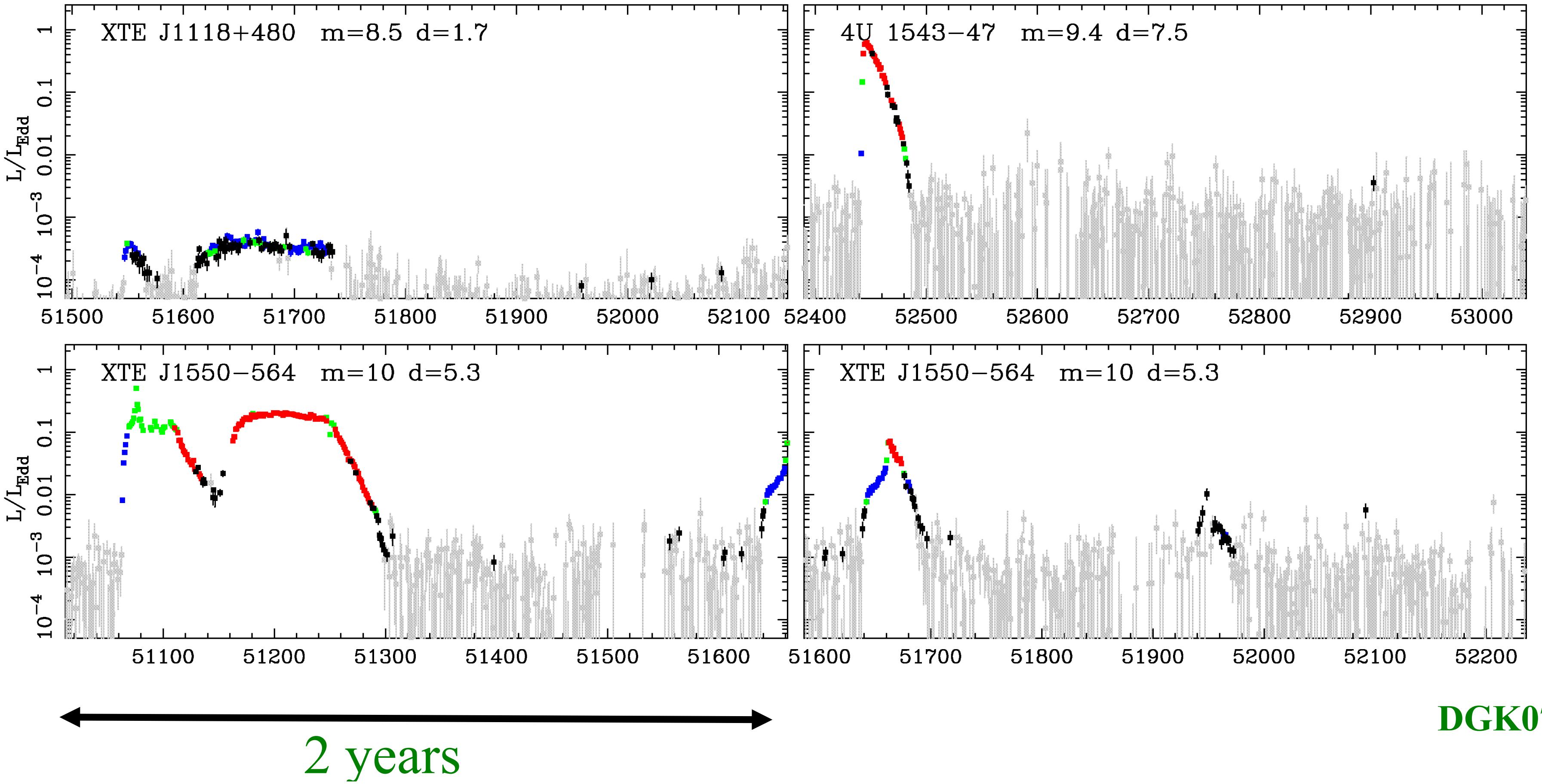


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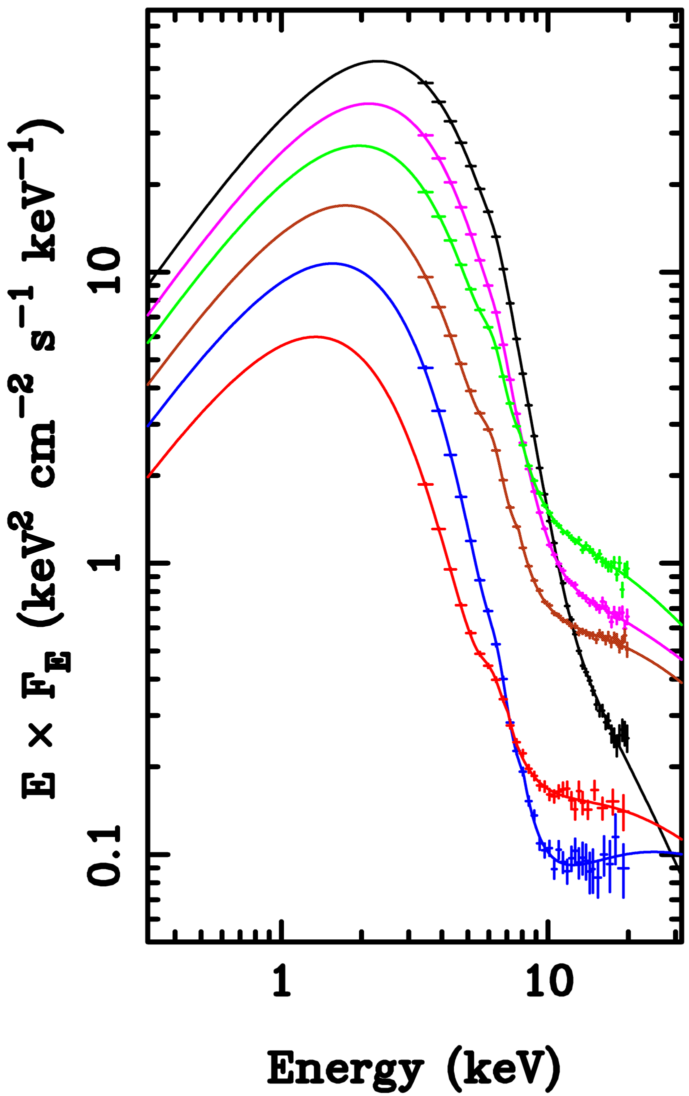
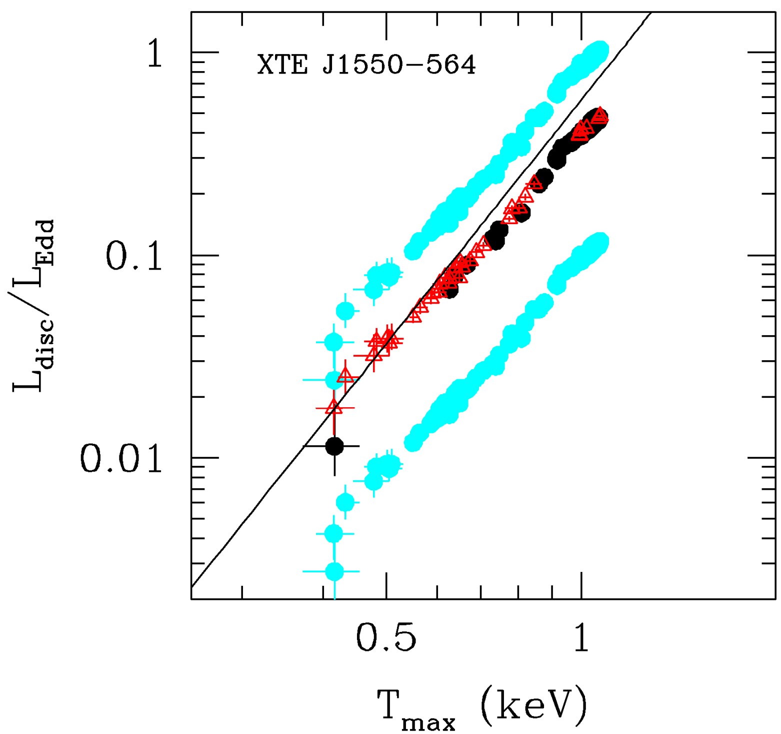
# Variability of disc:long timescale

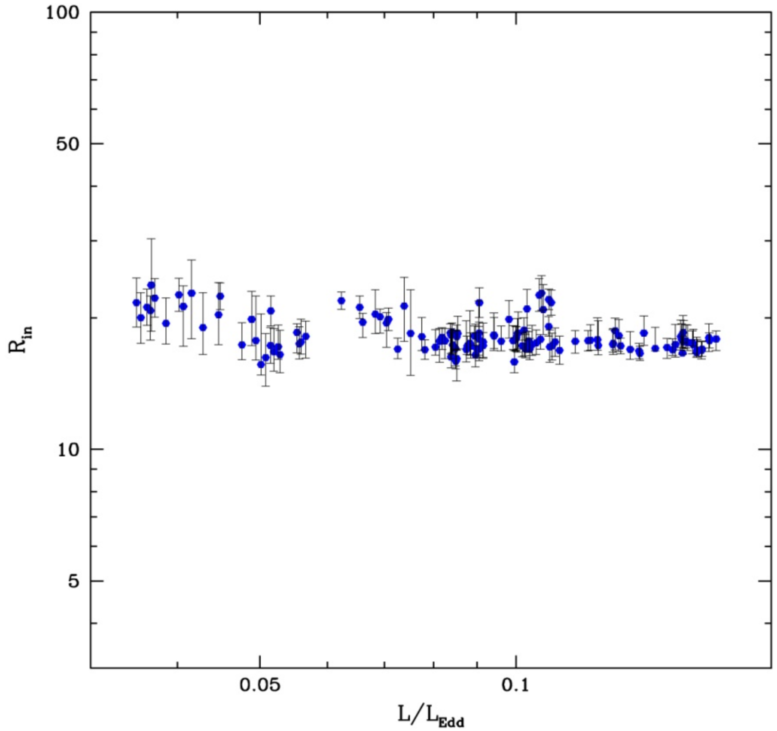



- $L/L_{Edd} \propto AT^4{}_{max}$ (Ebisawa et al 1993; Kubota et al 1999; 2001)
- Constant size scale – last stable orbit!! BH spin

# Disc spectra: last stable orbit

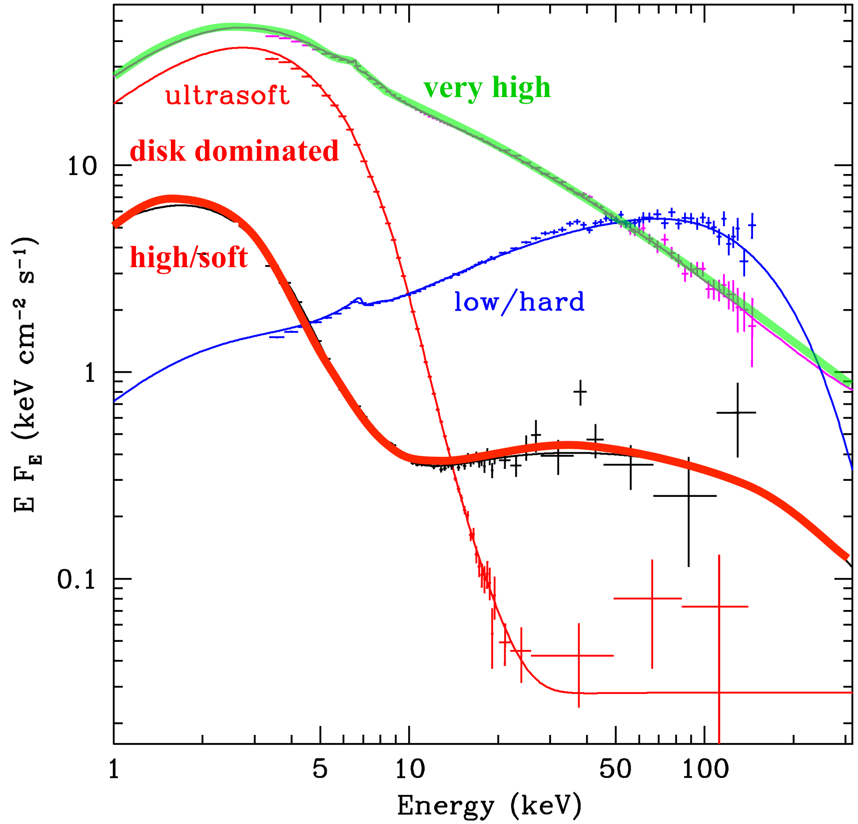
- Bewildering variety
- Pick ONLY ones that look like a disc!
- $L/L_{Edd} \propto T^4_{max}$ (Ebisawa et al 1993; Kubota et al 1999; 2001)
- Constant size scale – last stable orbit!!
- Proportionality constant gives a measure $R_{lso}$ i.e. spin as $L=\sigma R^2 T^4$
- Not quite as simple as this – need to fold in some corrections. But clear evidence for last stable orbit




Kolehmainen & Done 2010

# Spectral states

- Disc dominated look like a disc and vary like a disc
- Very high/intermediate states at least know something about a disc
- Low/hard state look really different, not at all like a disc!

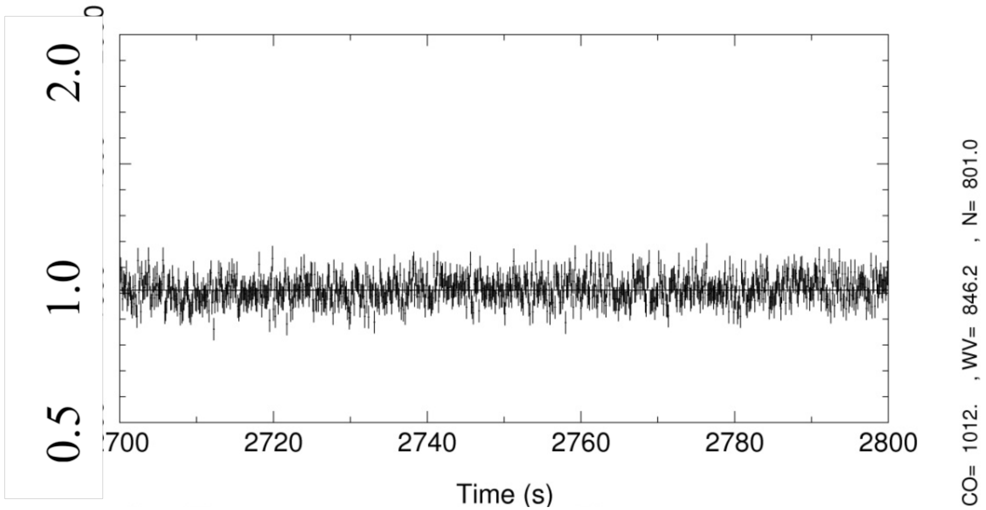


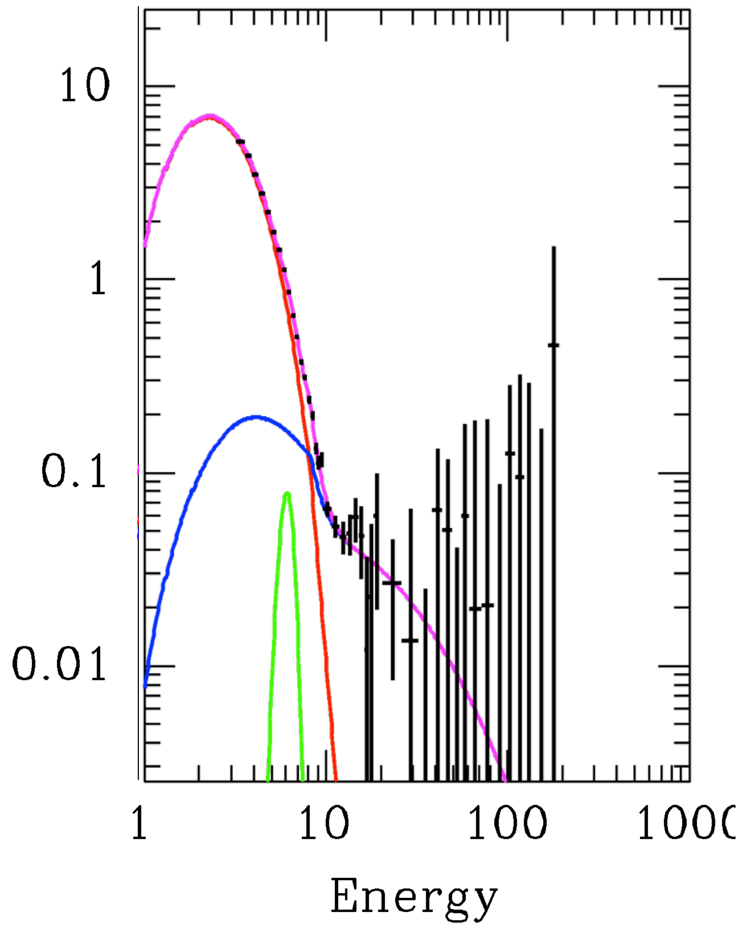

Gierlinski & Done 2003

# Variability of disc:short timescale

- Accretion rate through disc changes on timescales of days
- tvisc= $\alpha^{-1}$ (H/R)$^{-2}$ torb

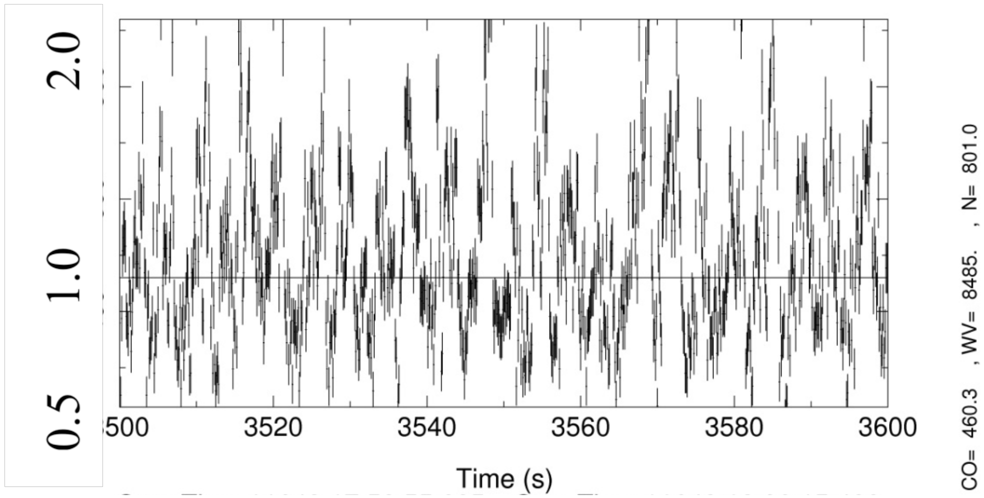
  =5 $\alpha^{-1}$ (H/R)$^{-2}$ (r/6) $^{-3/2}$ ms ~ 500s
- ~ 500s at last stable orbit for 10M
- No rapid variability of disc in disc dominated states!

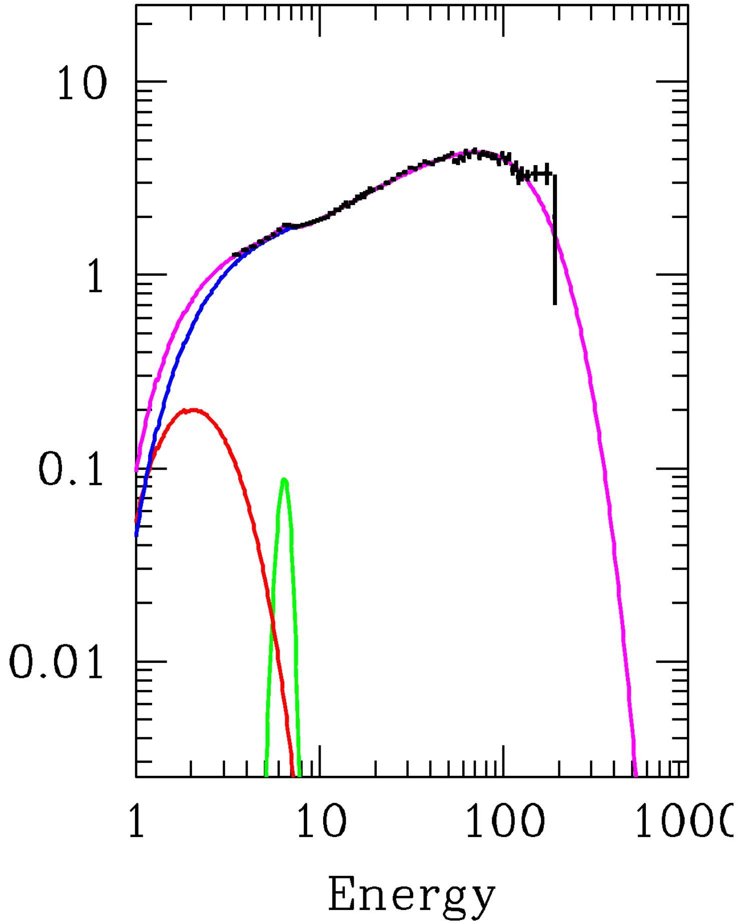


# Low/hard state variability

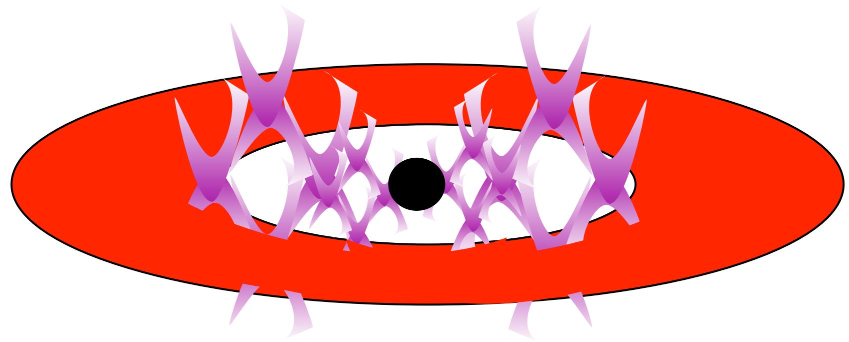
- Hard X-rays show much more dramatic change on short timescales down to few 10s of ms
- tvisc= $\alpha^{-1}$ $(H/R)^{-2}$ tdyn = 5 $\alpha^{-1}$ $(H/R)^{-2}$ $(r/6)^{-3/2}$ ms
- IF viscous timescale then H/R~1

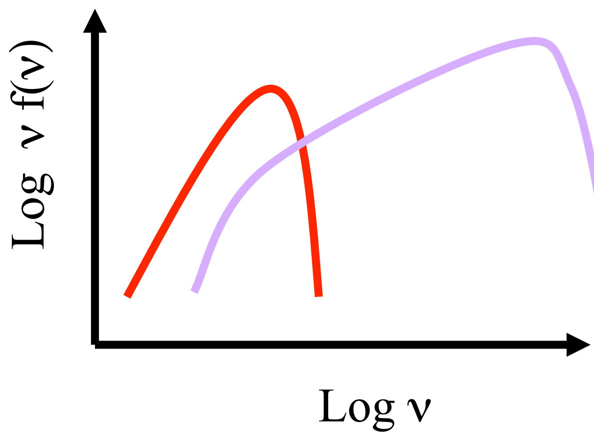


# Accretion flows without discs

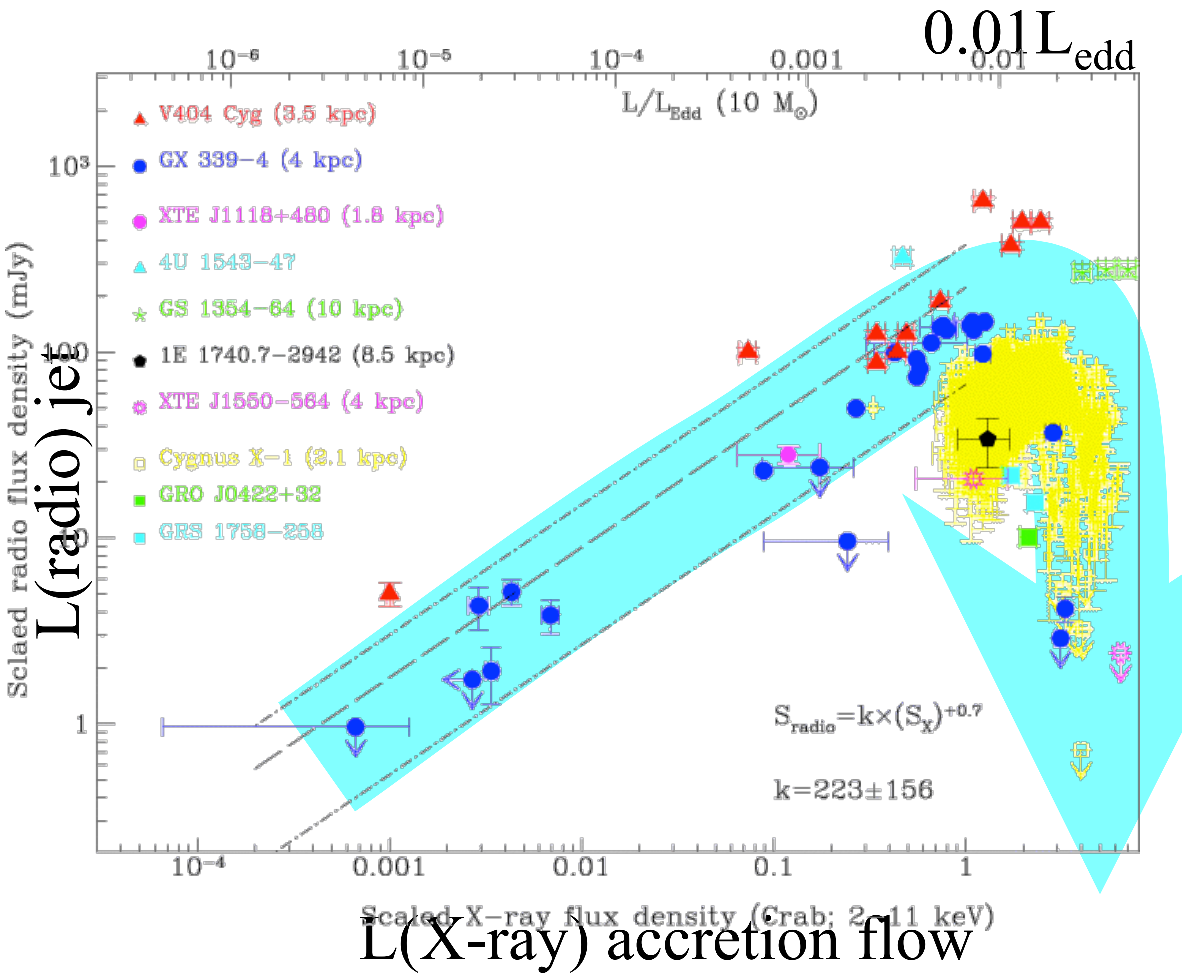
- Disc models assumed thermal plasma – not true at low $L/L_{Edd}$
- Instead: hot, optically thin, geometrically thick inner flow replacing the inner disc (Shapiro et al. 1976; Narayan & Yi 1995)
- Hot electrons Compton upscatter photons from outer cool disc
- Few seed photons, so spectrum is hard





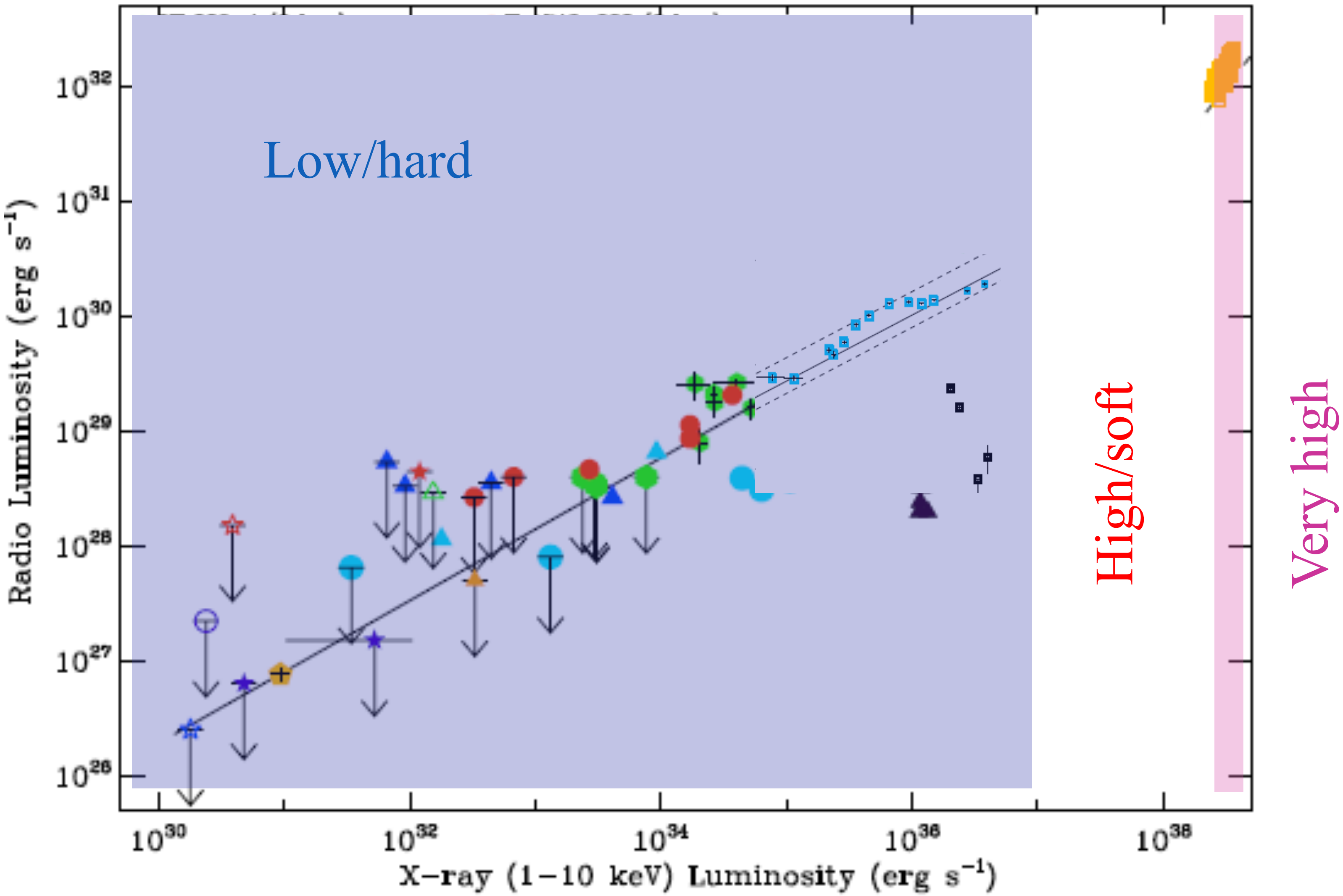
# And the radio jet… link to spin?

- 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 2005)



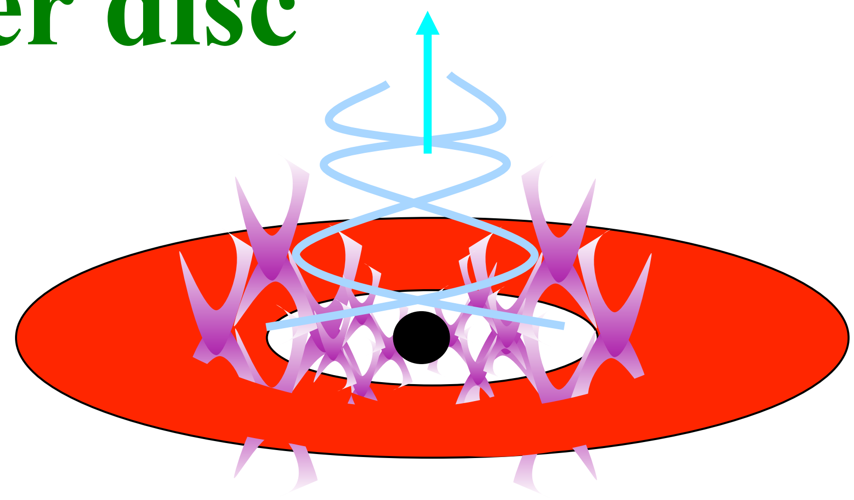

Gallo et al 2003 Corbel et al 2013

# Accretion flows – Jet




Corbel et al 2012

# No inner disc



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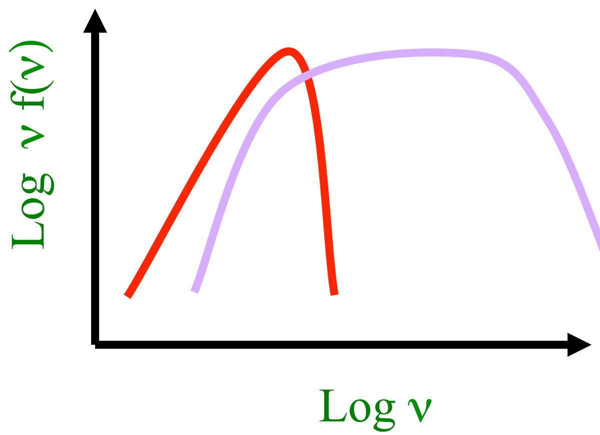
- Jet from large scale height flow



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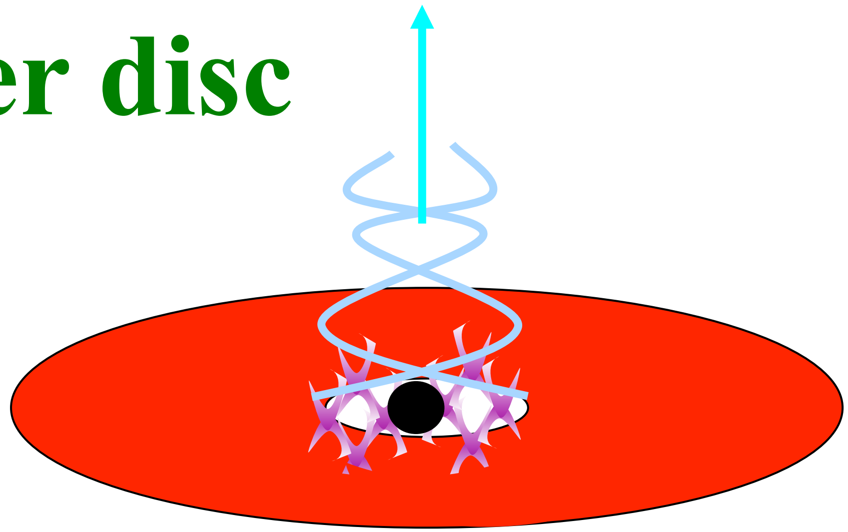

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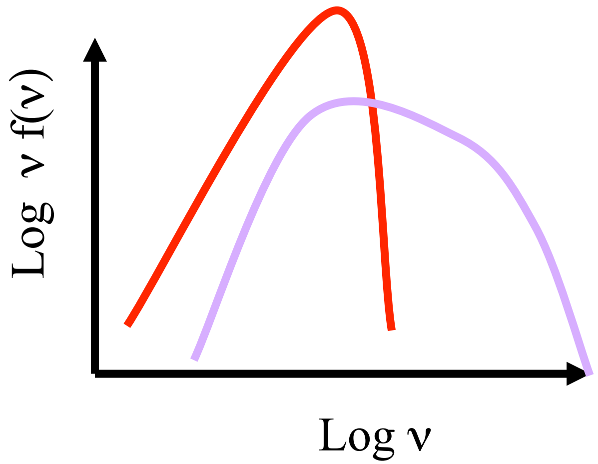

# Collapse of hot inner flow

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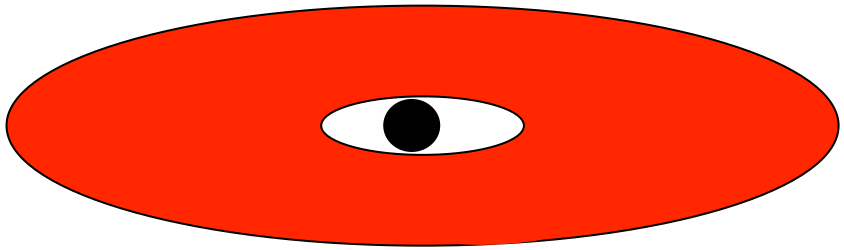
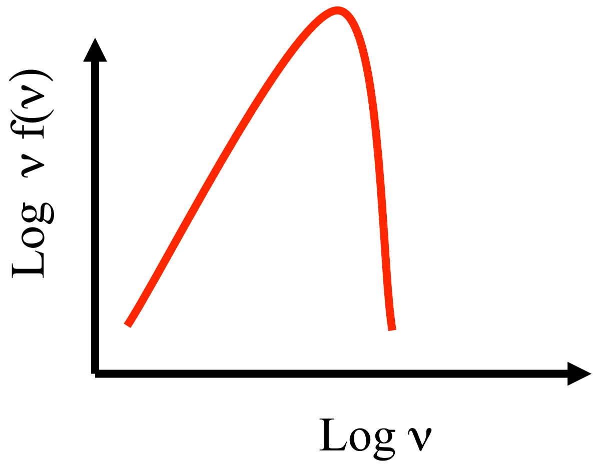
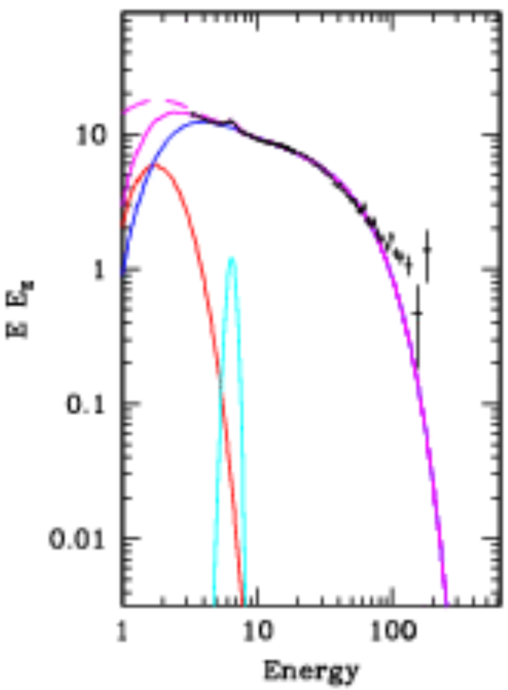
- Hot electrons Compton upscatter photons from outer cool disc
- Few seed photons, so spectrum is hard
- Jet from large scale height flow collapse of flow=collapse of jet





# Moving disc – moving QPO

- 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

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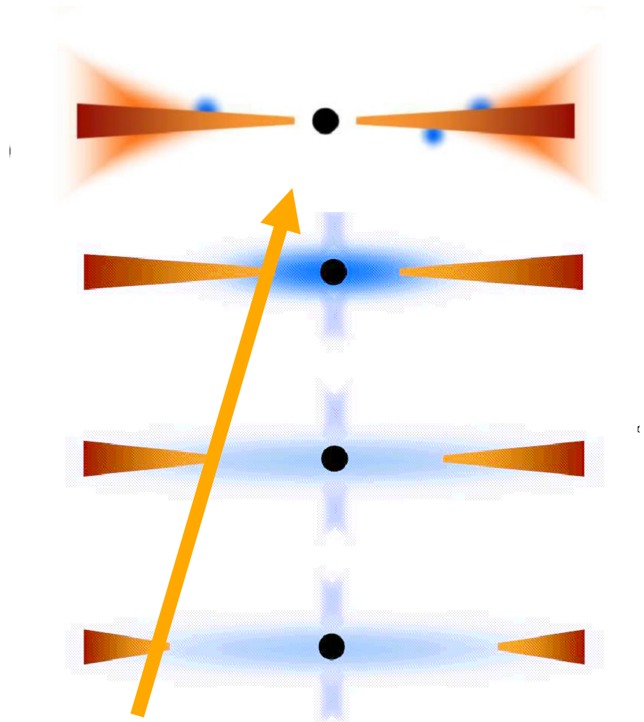

# Low/hard state variability

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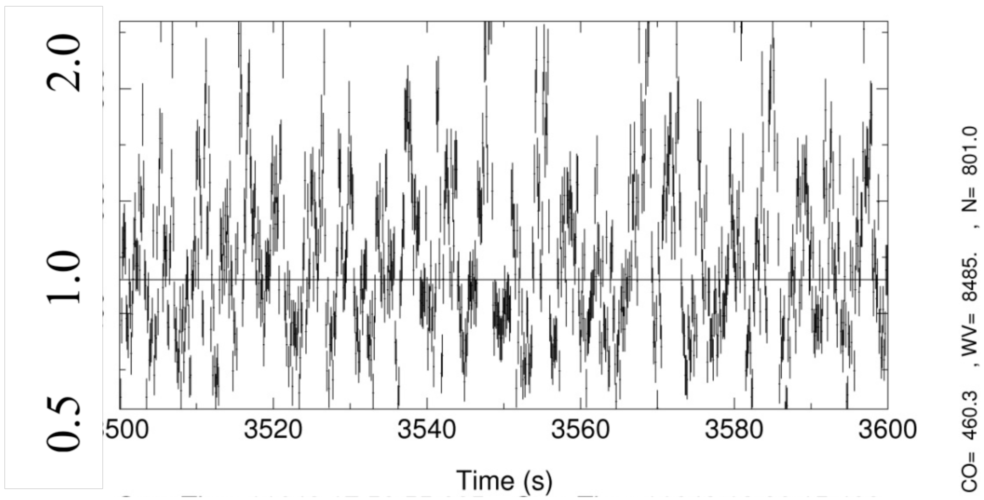
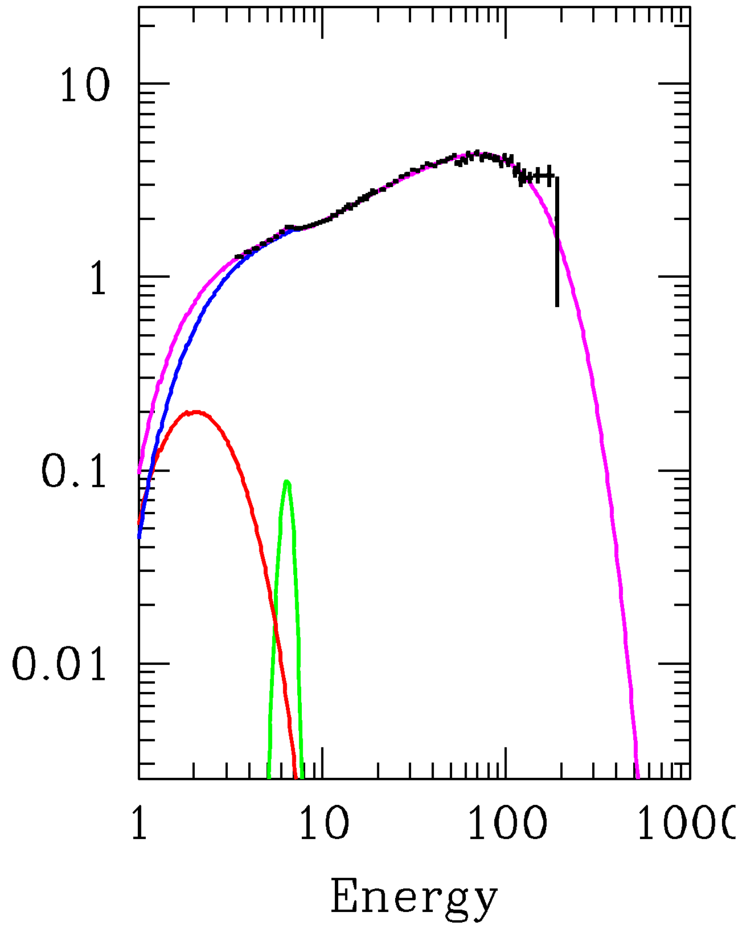
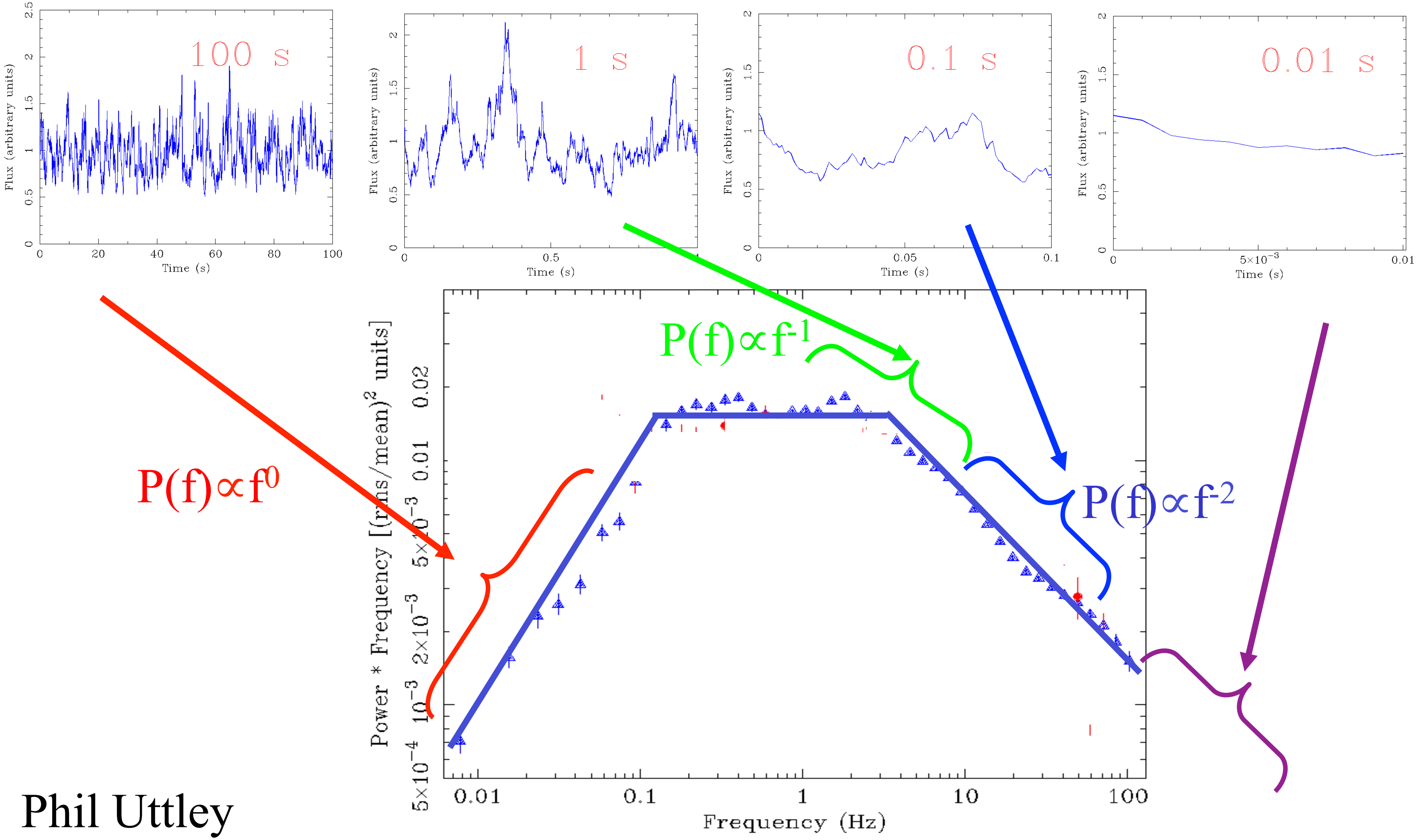
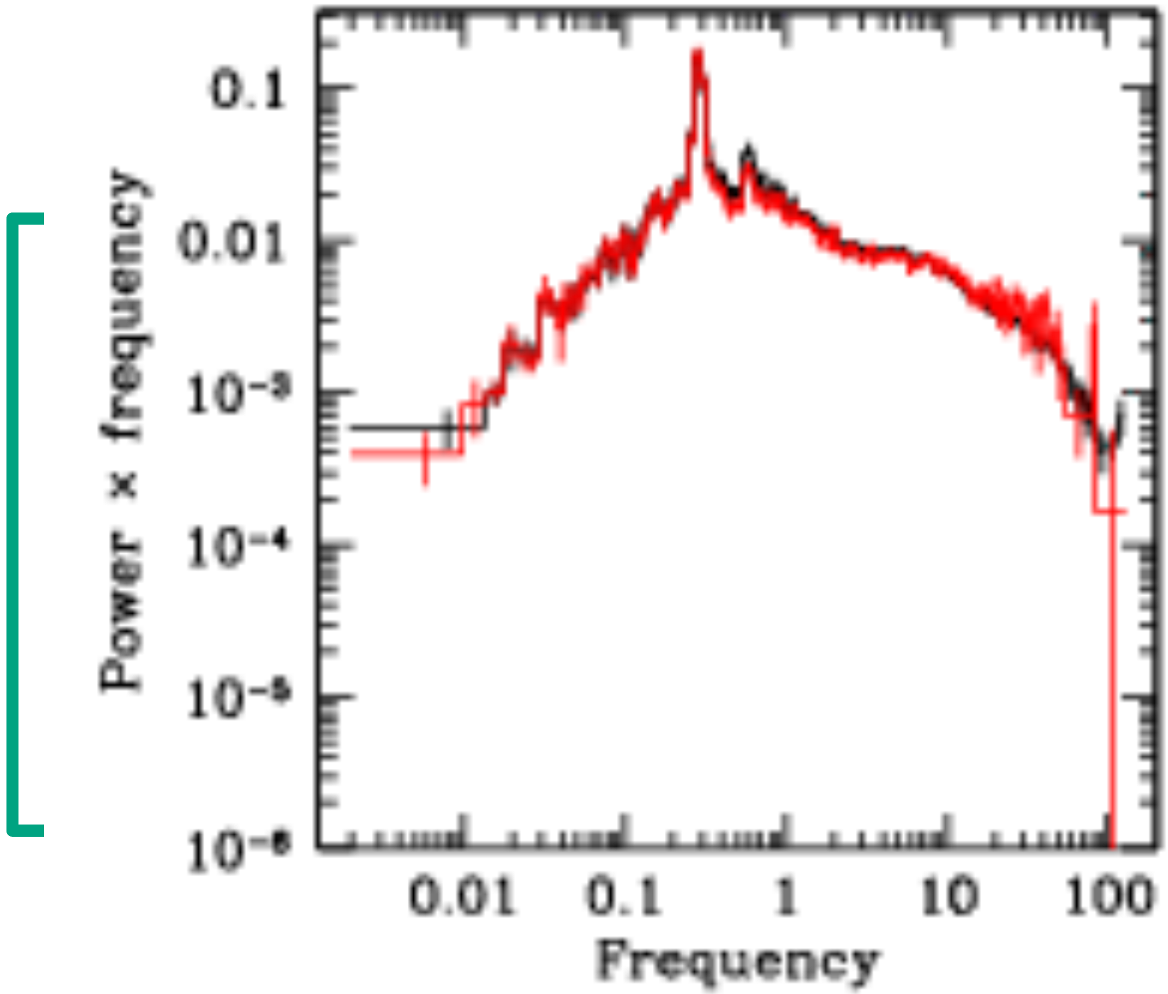


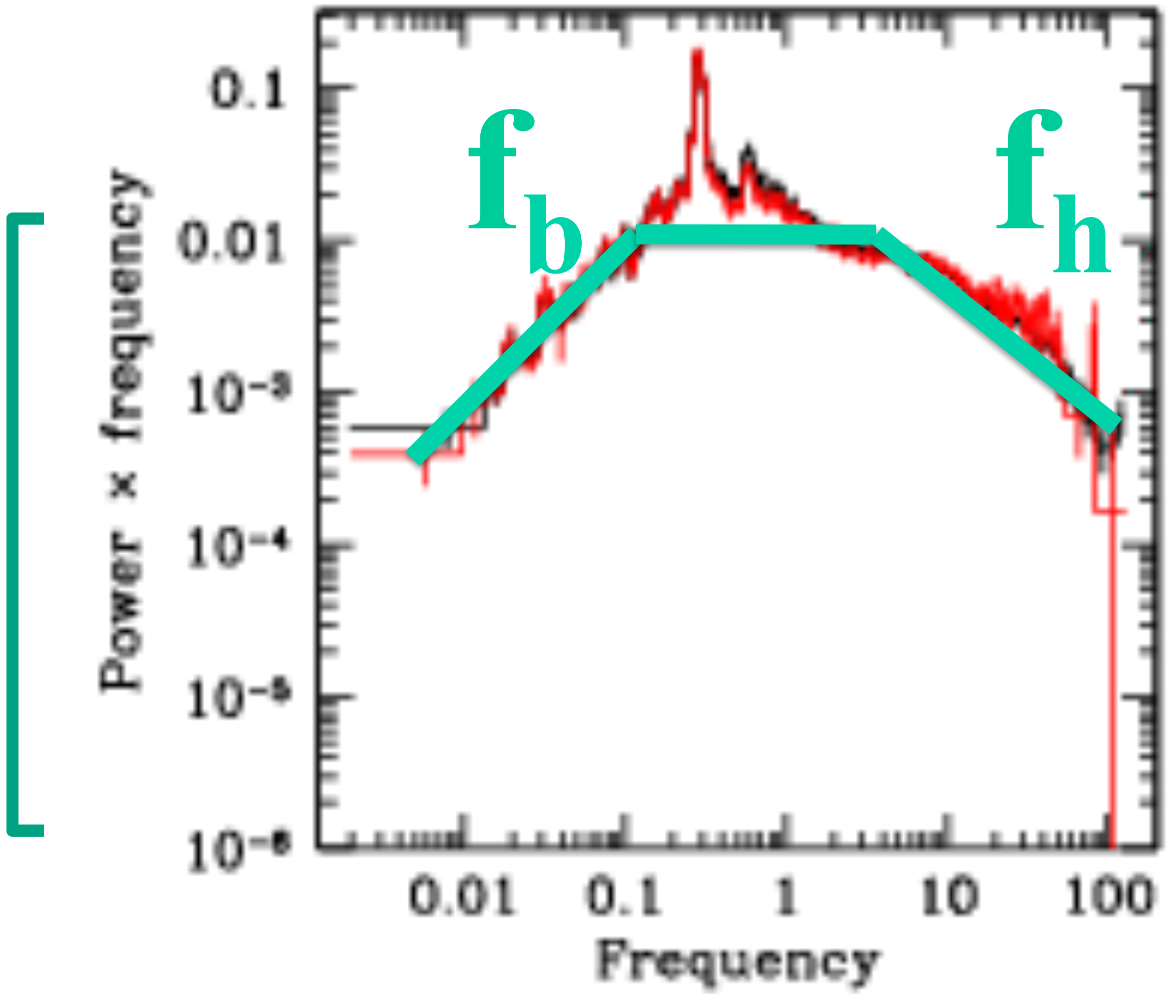
# Quantifying variability: the power spectral density (PSD) of Cyg X-1



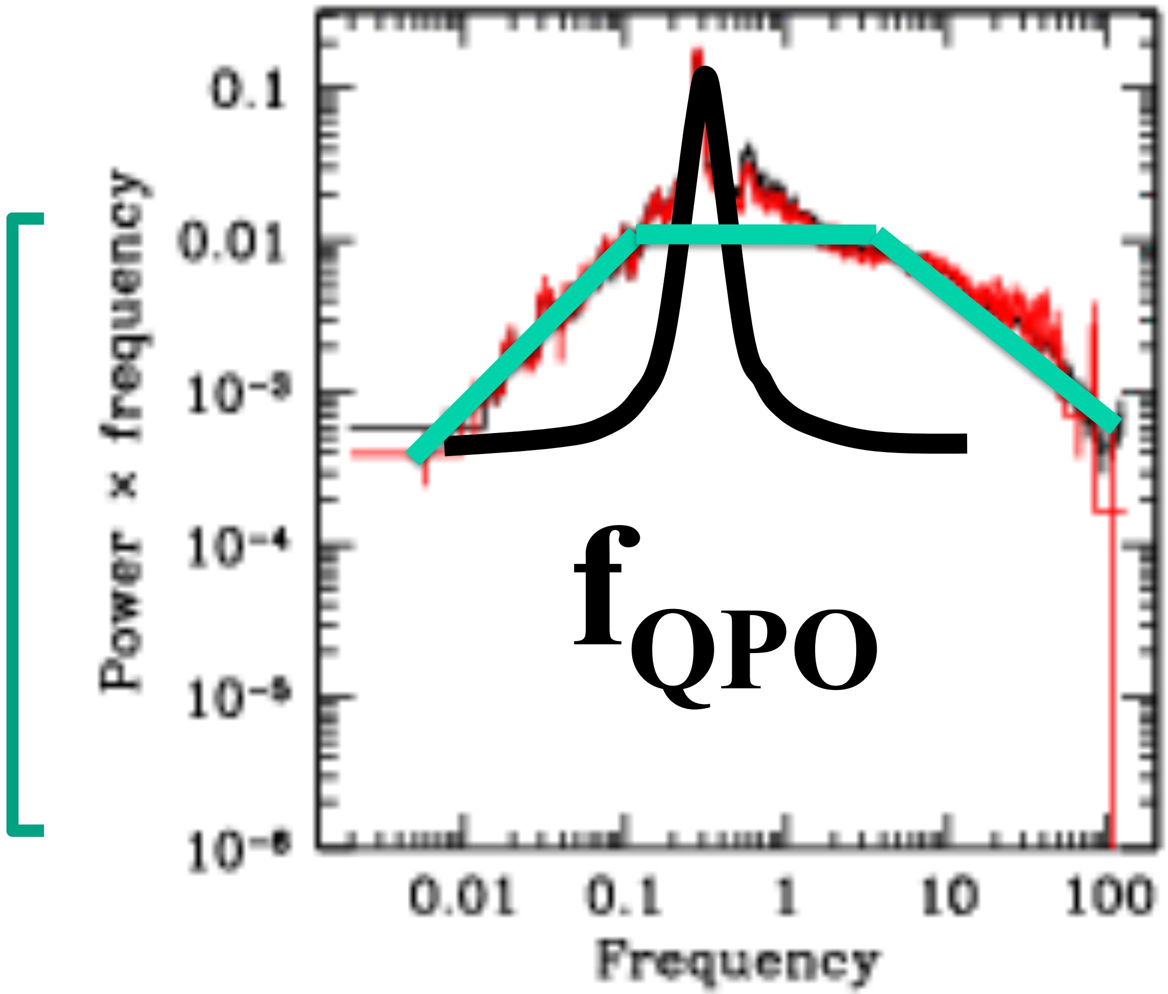

Phil Uttley



0.1
0.01
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
Power × frequency
0.01
0.1
1
10
100
Frequency



0.1
0.01
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.01
0.1
1
10
100
Frequency
Power × frequency
$f_b$
$f_h$



Power × frequency
0.1
0.01
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.01
0.1
1
10
100
Frequency
$f_{QPO}$

# 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

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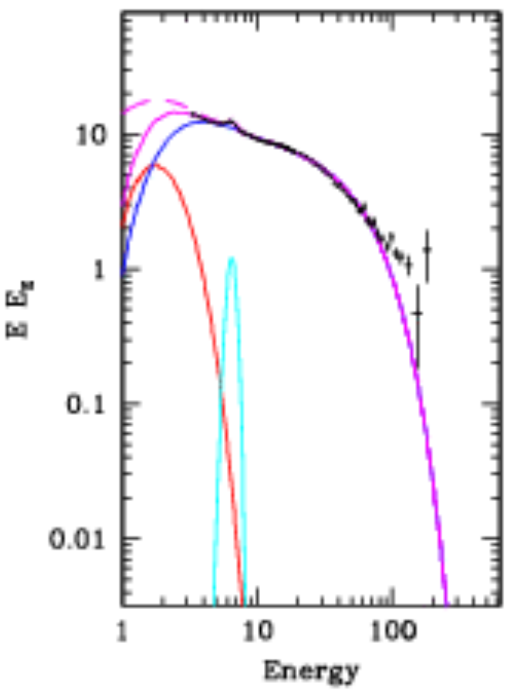
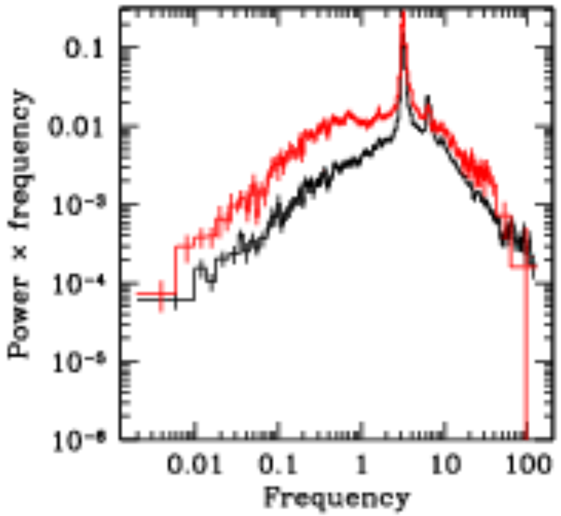
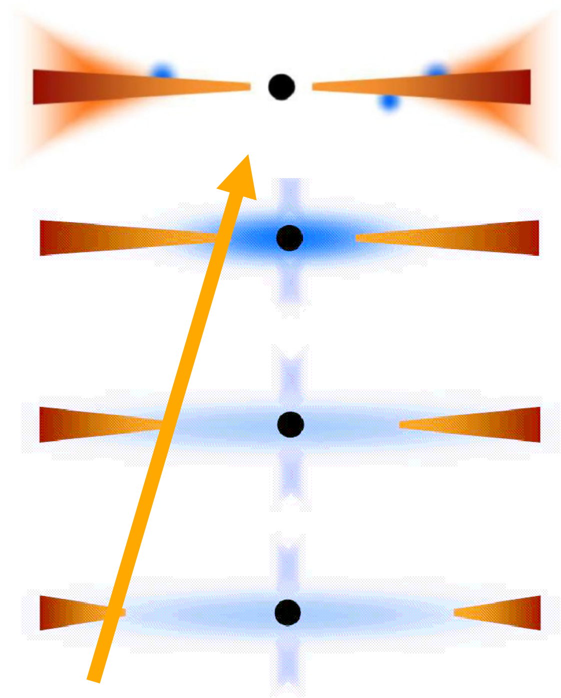
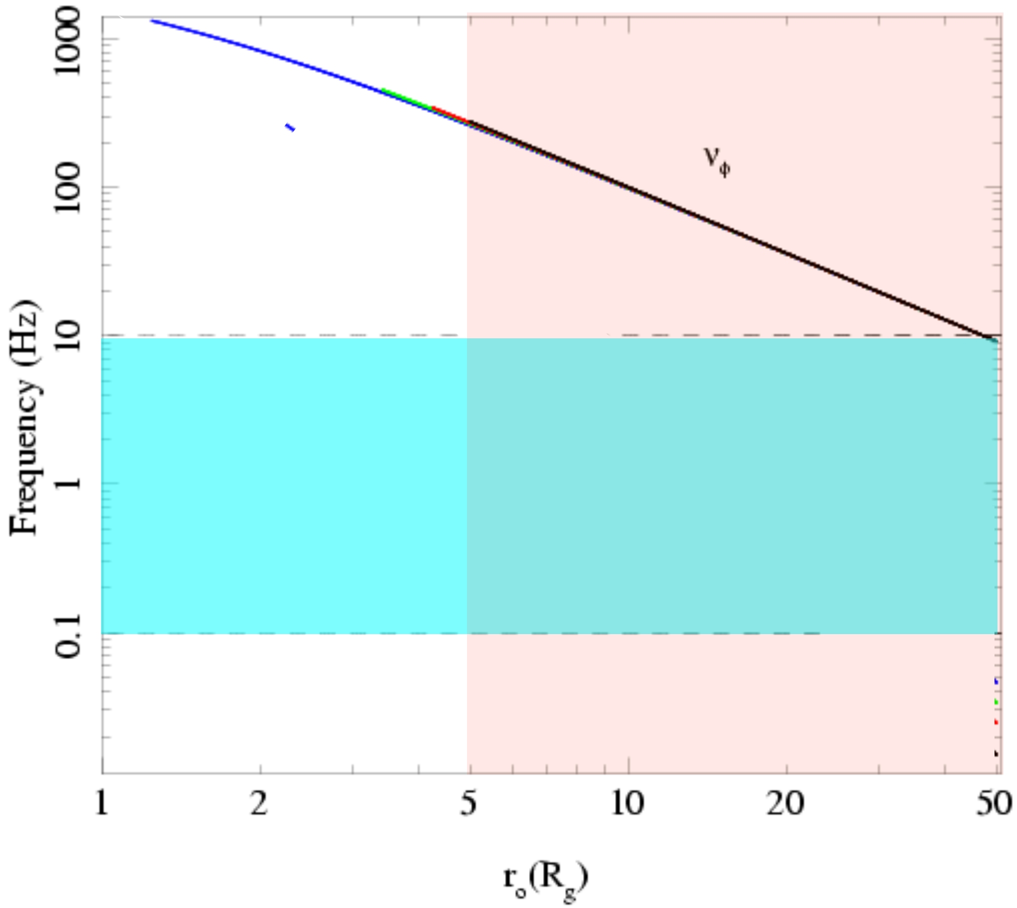


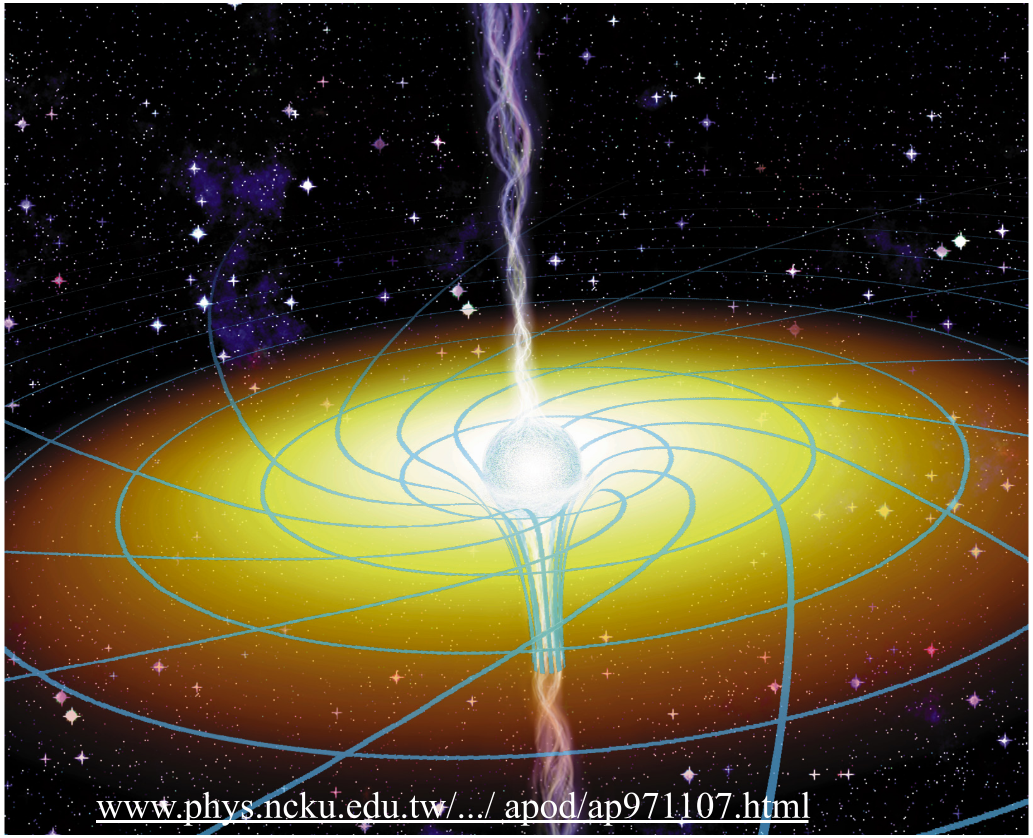
# Low frequency QPO

- 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 ν(φ) as too fast!




Ingram, Done & Fragile 2009

# Frame dragging

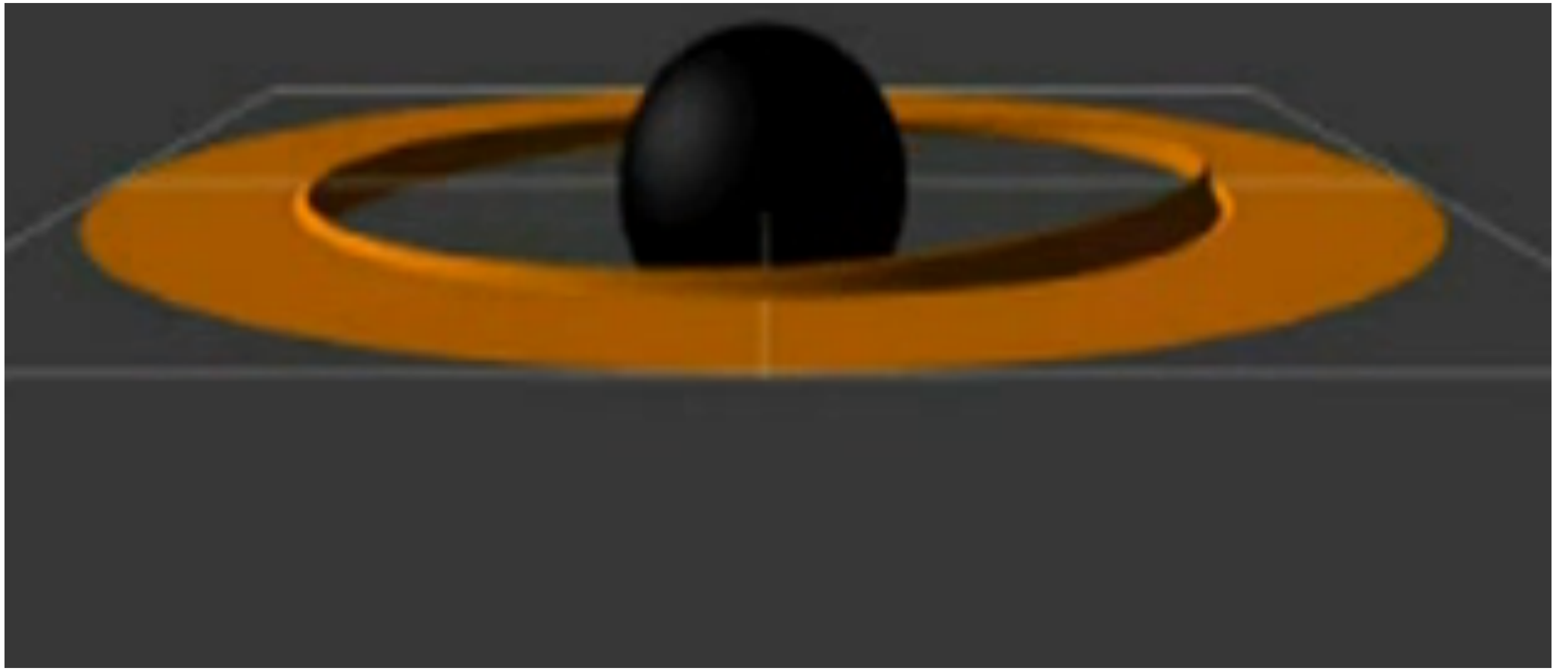



- Spacetime rotating
- Asymmetric potential
- Orbits get dragged around
- So any orbit which crosses the equatorial plane will precess
- Lense-Thirring precession

# Low frequency QPO

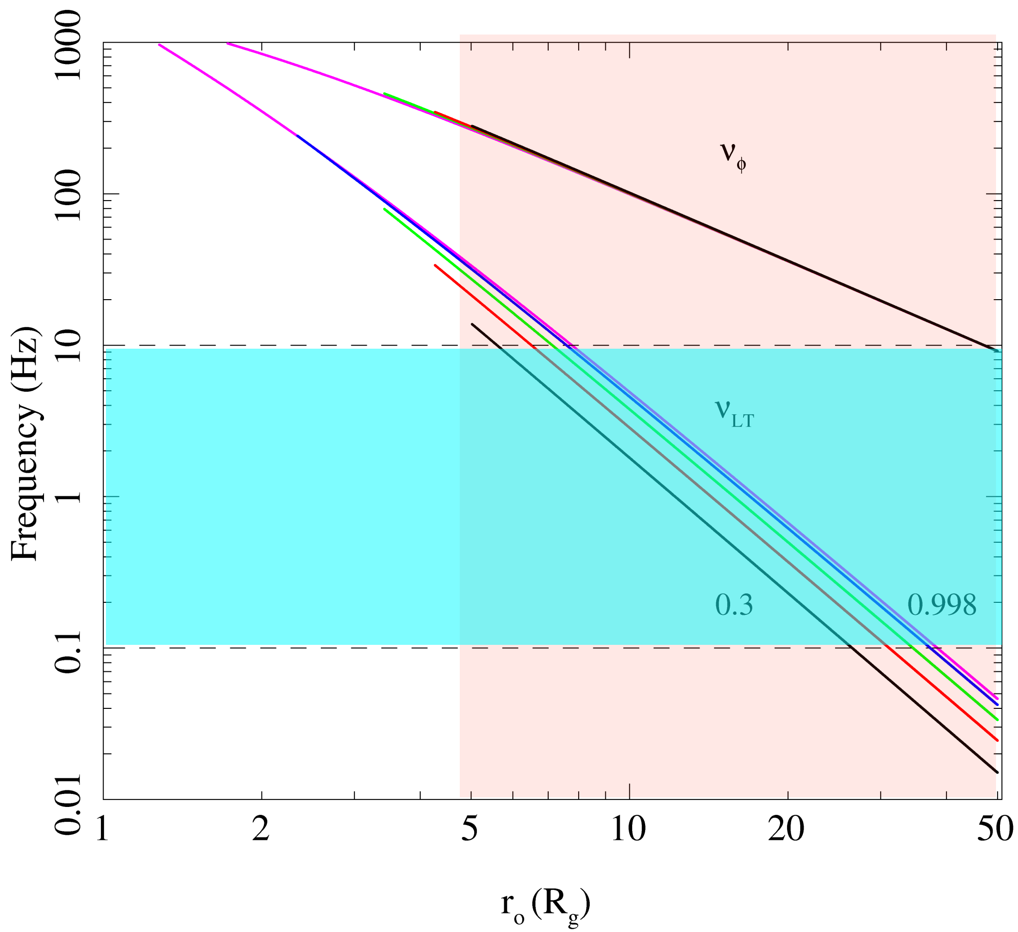
- Stella & Vietri 1998 – GR potential not spherically symmetric so vertically offset circular orbit has $\nu(\theta) \neq \nu(\varphi)$
- Lense-Thirring precession $\nu_{LT} = \nu(\theta) - \nu(\varphi)$

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

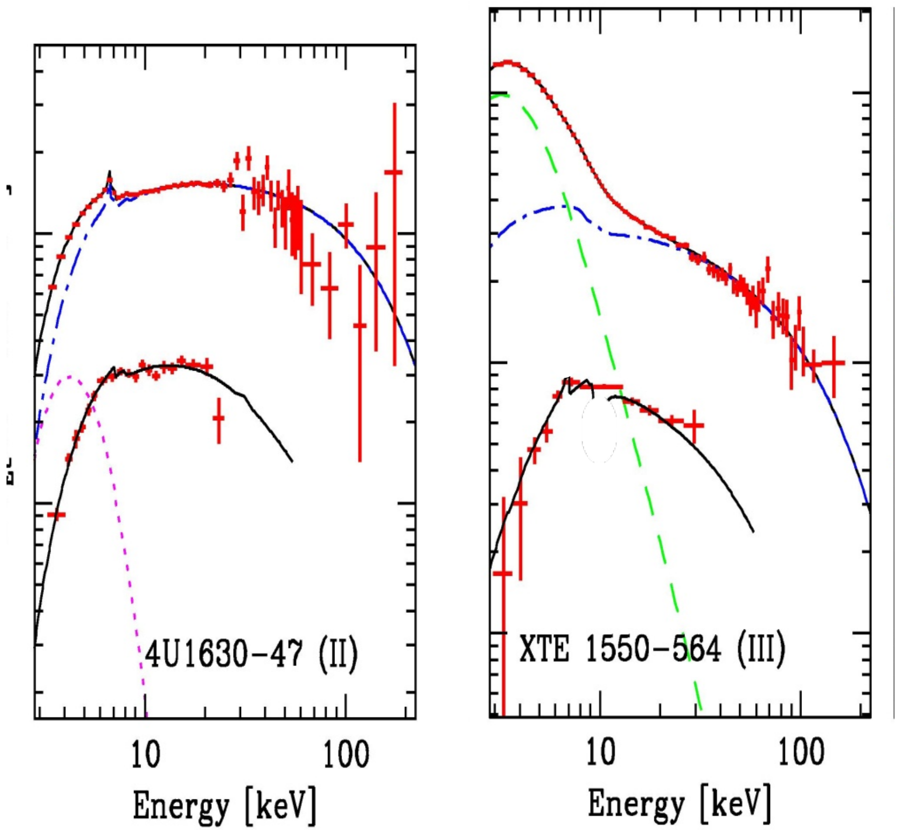


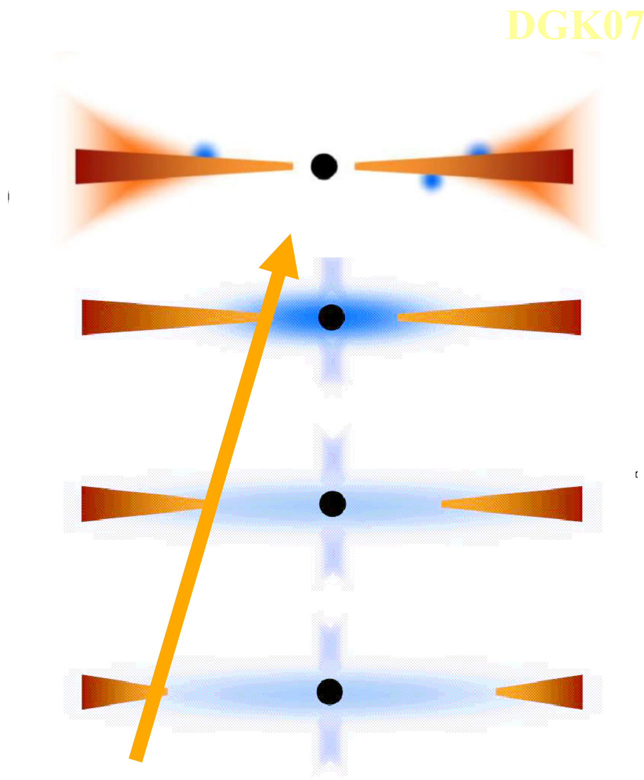

Ingram, Done & Fragile 2009

# How does it modulate?

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

Zycki & Sobolewska 2005; 2006



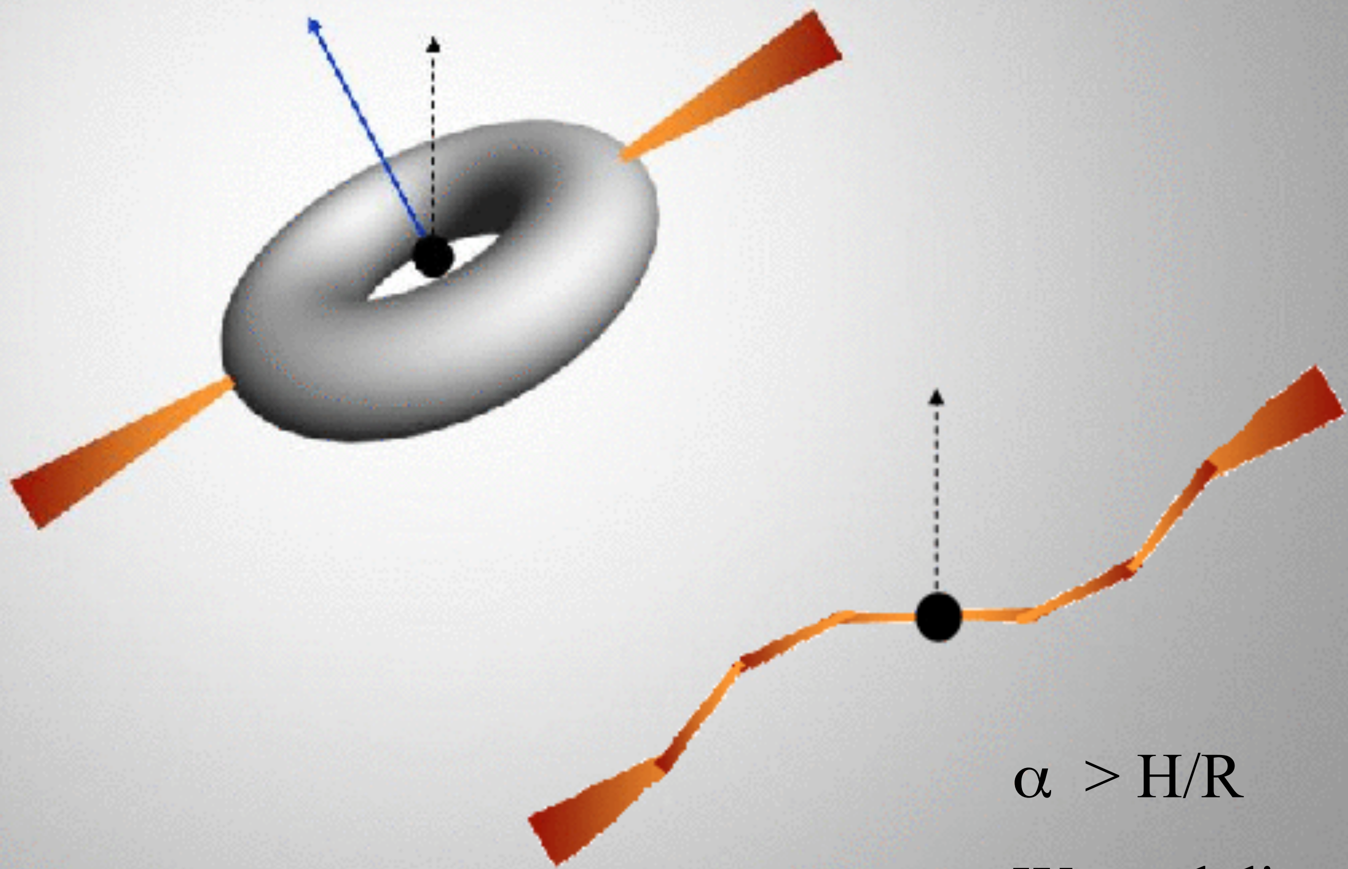




Ingram, Done & Fragile 2009

# Solid body precession of the flow

$\alpha < H/R$

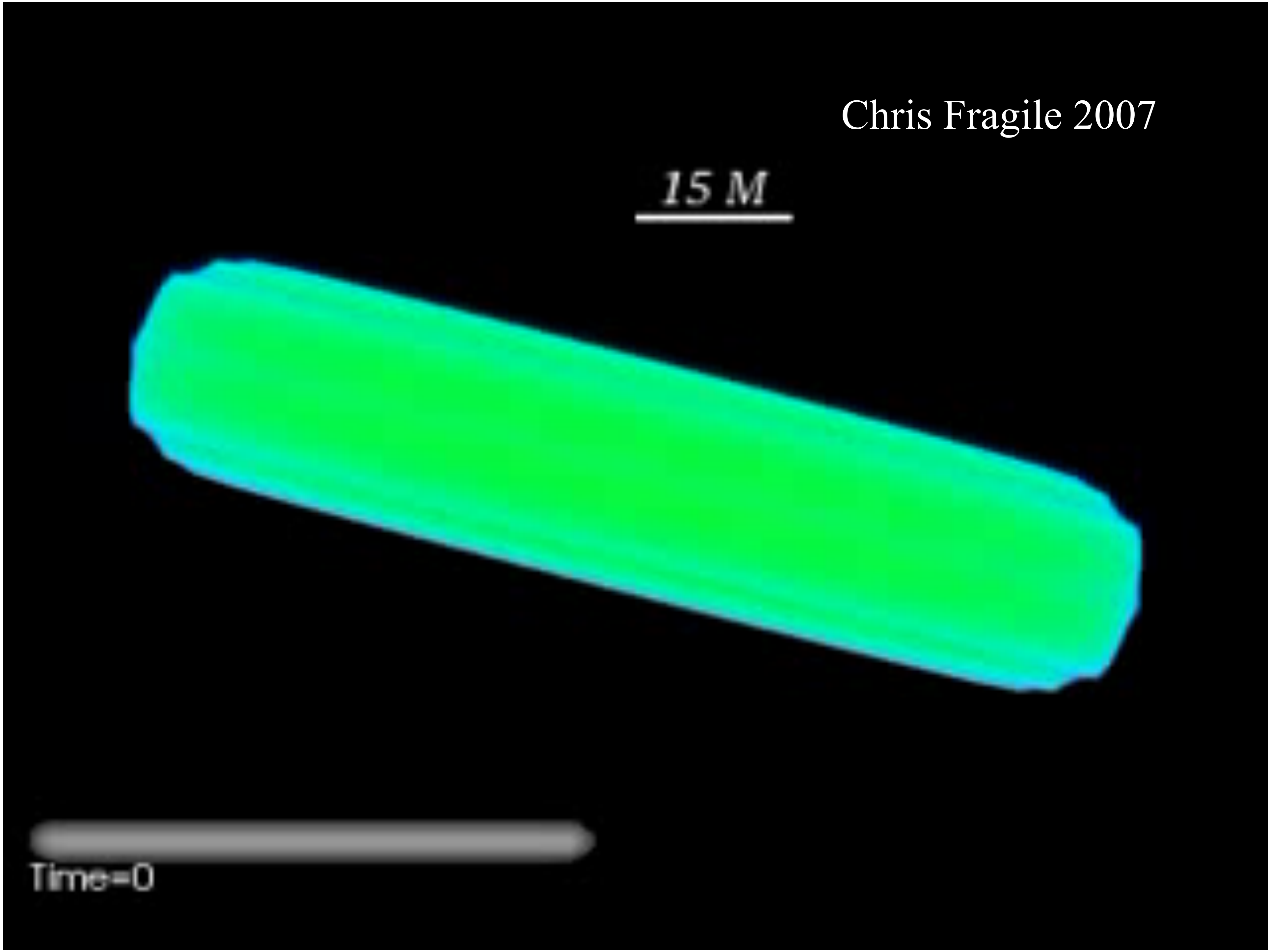
precession



$\alpha > H/R$

Warped disc

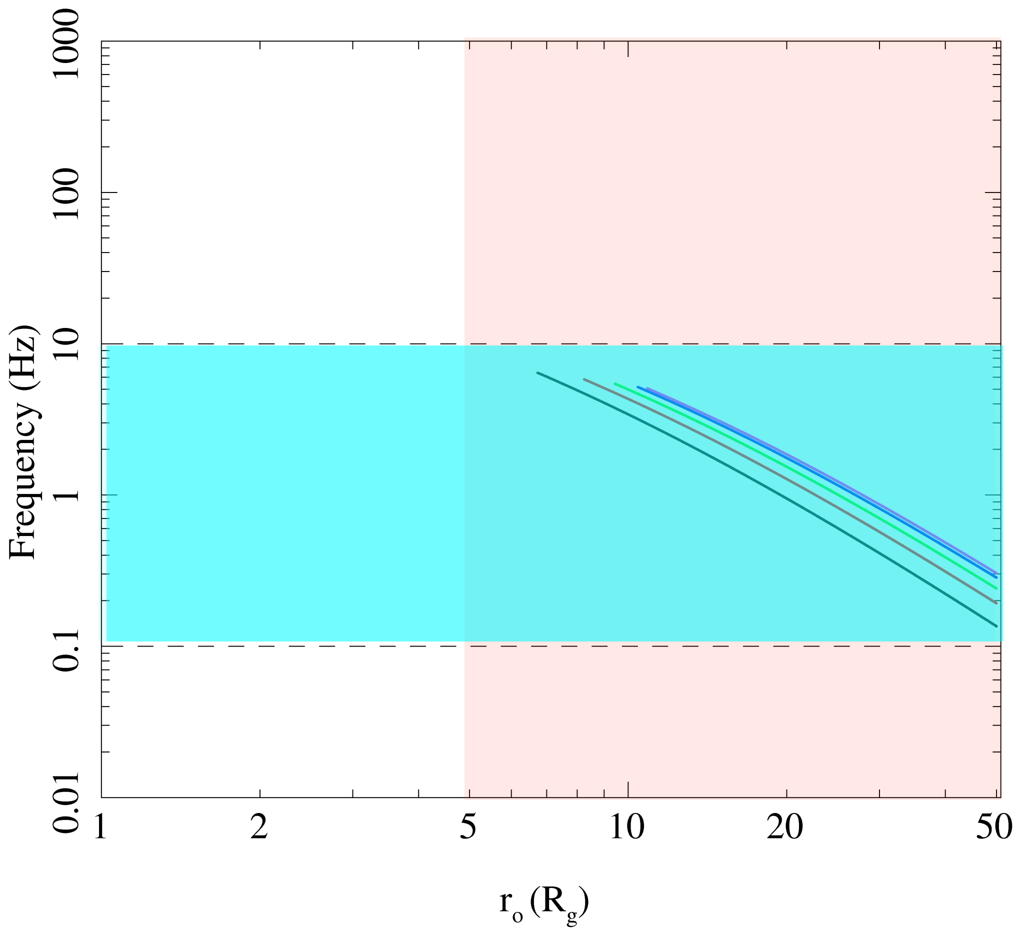
*Ingram, Done & Fragile 2009*


Chris Fragile 2007
15 M
Time=0

# LT precession of hot flow?

- QPO frequency given by weighted average of LT precession frequency over all radii in hot flow
- Gets the frequencies correct!!
- Modulates Compton region so gets spectrum

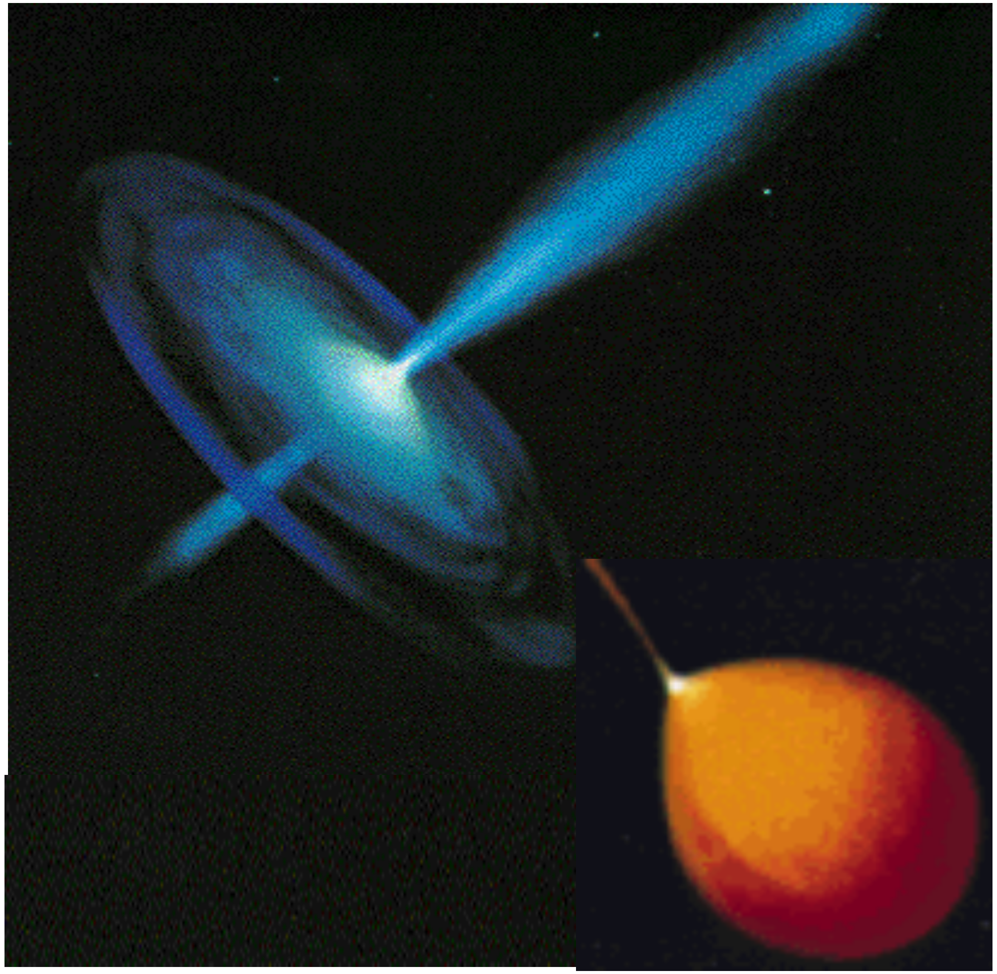
- Truncates at ~ bending wave radius




Ingram, Done & Fragile 2009

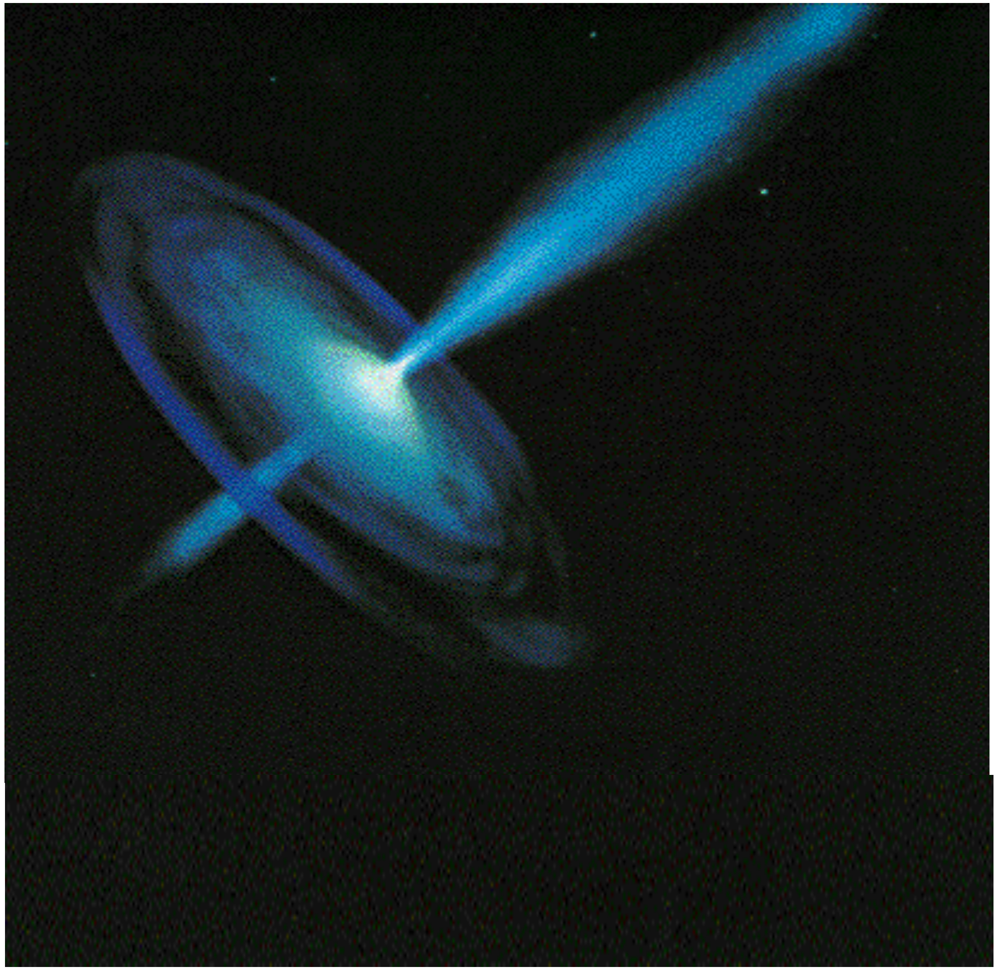
# Black holes

- Black hole binaries –
- Observational template of how accretion flows (spectra and variability) and their associated jet behave
- Build a working physical model of accretion flows
- GR tests – last stable orbit, Lense-Thirring precession (also compare to disc accreting NS to get evidence for event horizon!)



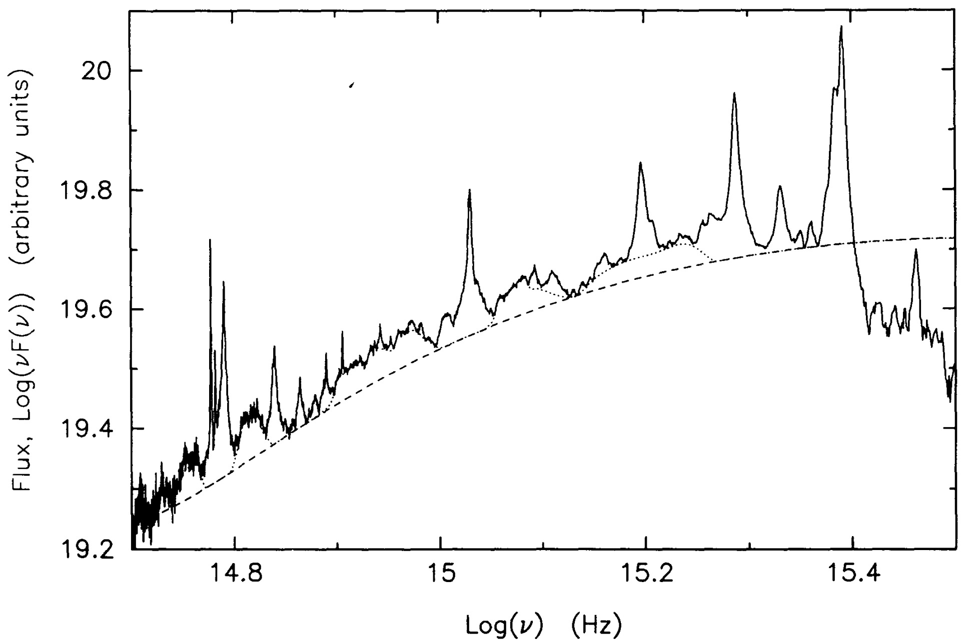
# Black holes

- Scale up to AGN
- Bigger mass! $L = AT^4$ -L goes with M but A goes with $R^2$ so $M^2$ so area wins and disc temp lower!
- Larger RANGE in mass – all BHB within factor 2 of 10M whereas AGN from $10^5$-$10^{10}$M disc in UV



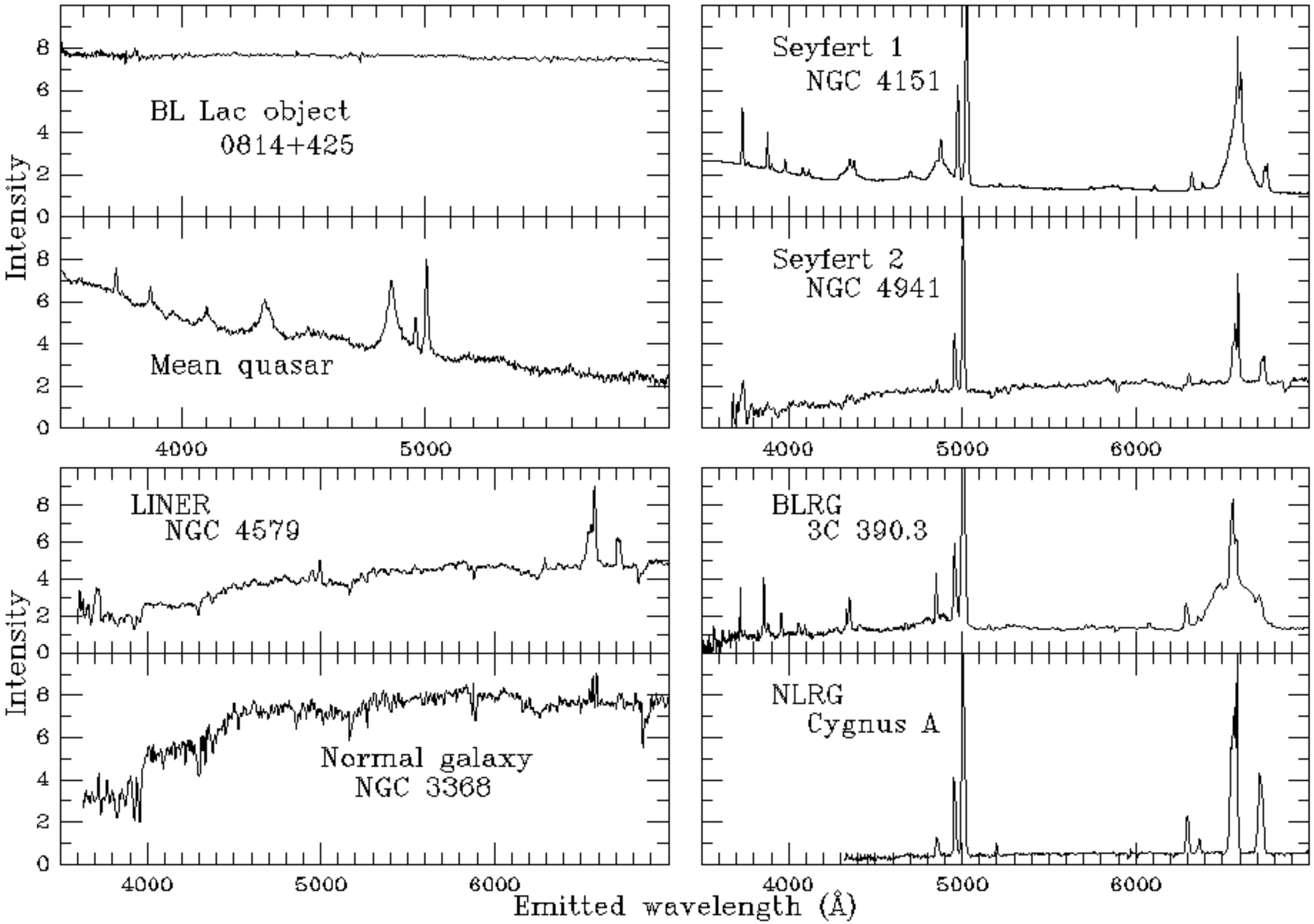
# UV disc seen in Quasars!

- Bright, blue/UV continuum from 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



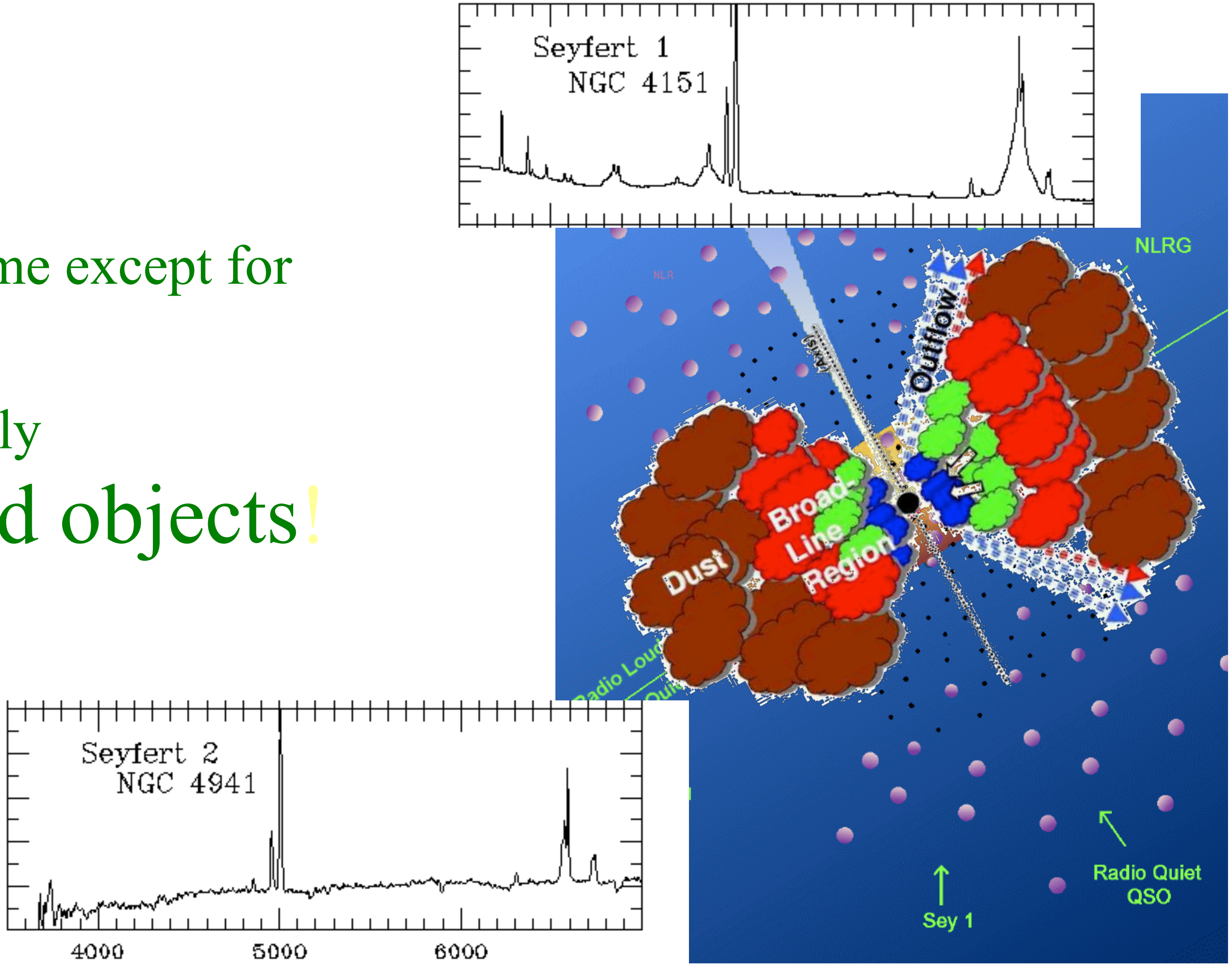

Francis et al 1991

# AGN/QSO Zoo!!! Optical



# Seyfert 1 – Seyfert 2

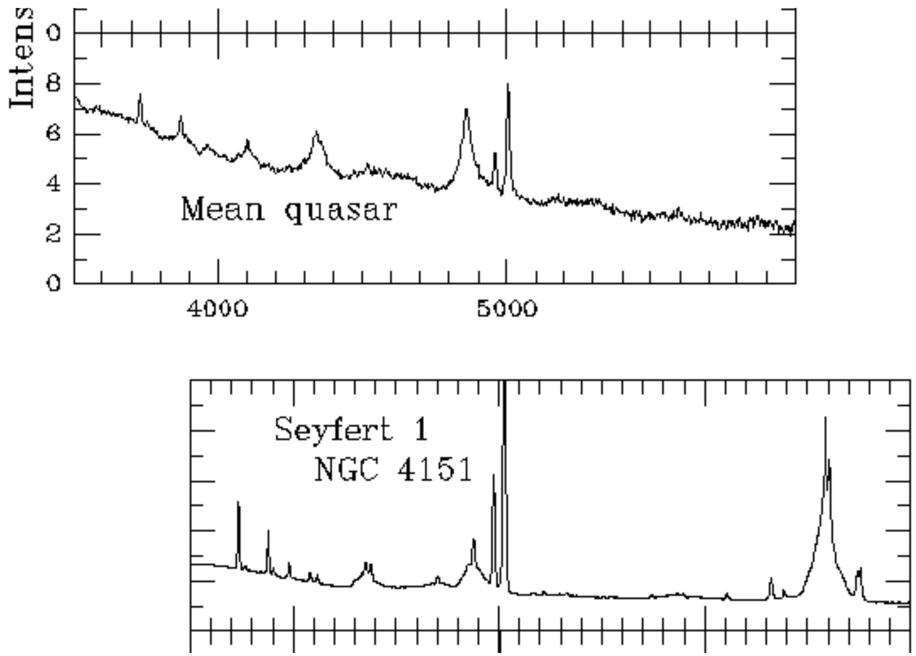
- Intrinsically same except for obscuration ?
- So now take only unobscured objects!



# Seyfert 1 - Quasars

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

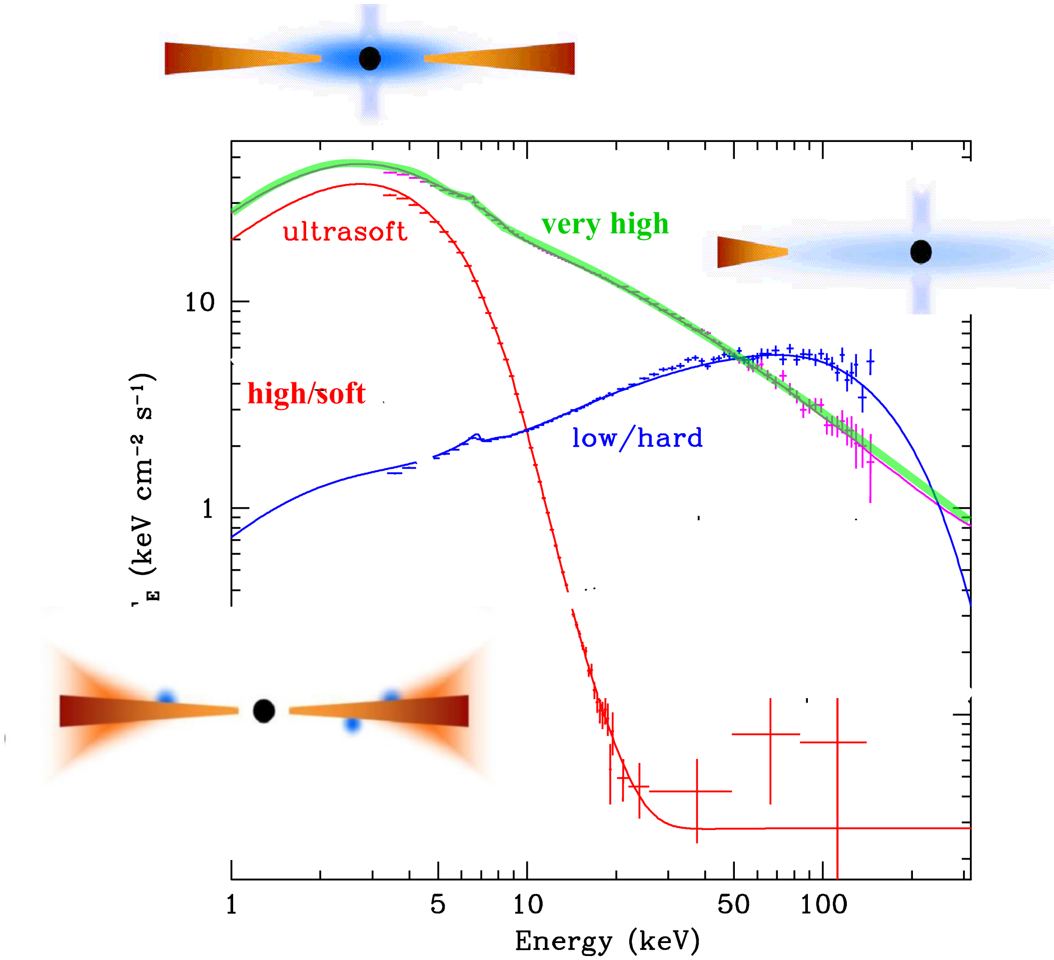
Increasing L




Increasing M

# Spectral states - BHB

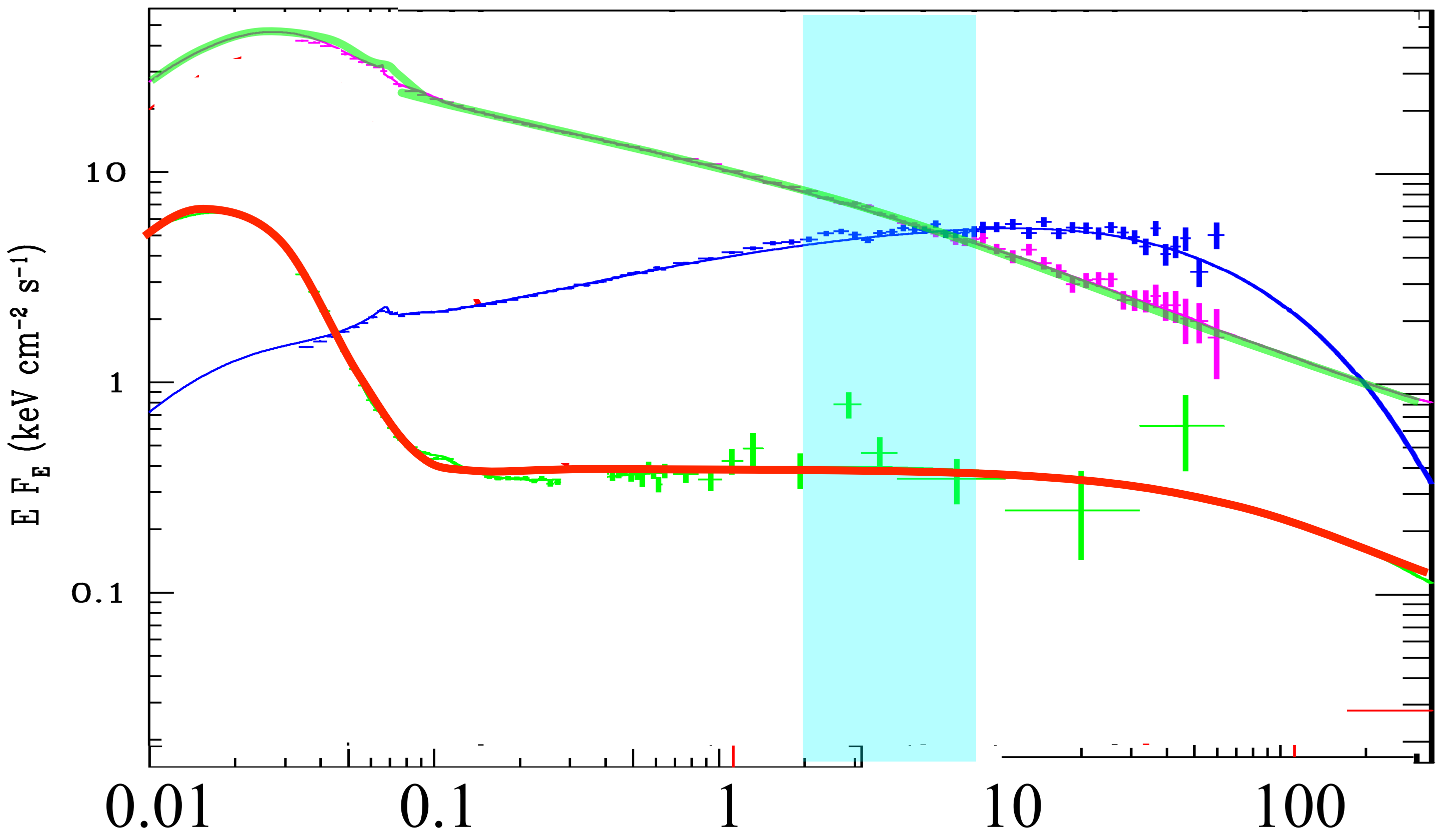
- Dramatic changes in continuum – single object, different days
- Underlying pattern in all systems
- High $L/L_{Edd}$: soft spectrum, peaks at $kT_{max}$ often disc-like, plus tail
- Lower $L/L_{Edd}$: hard spectrum, peaks at high energies, not like a disc (McClintock & Remillard 2006)




Gierlinski & Done 2003

# ‘Spectral states in AGN’

Disc BELOW X-ray bandpass. Only see tail

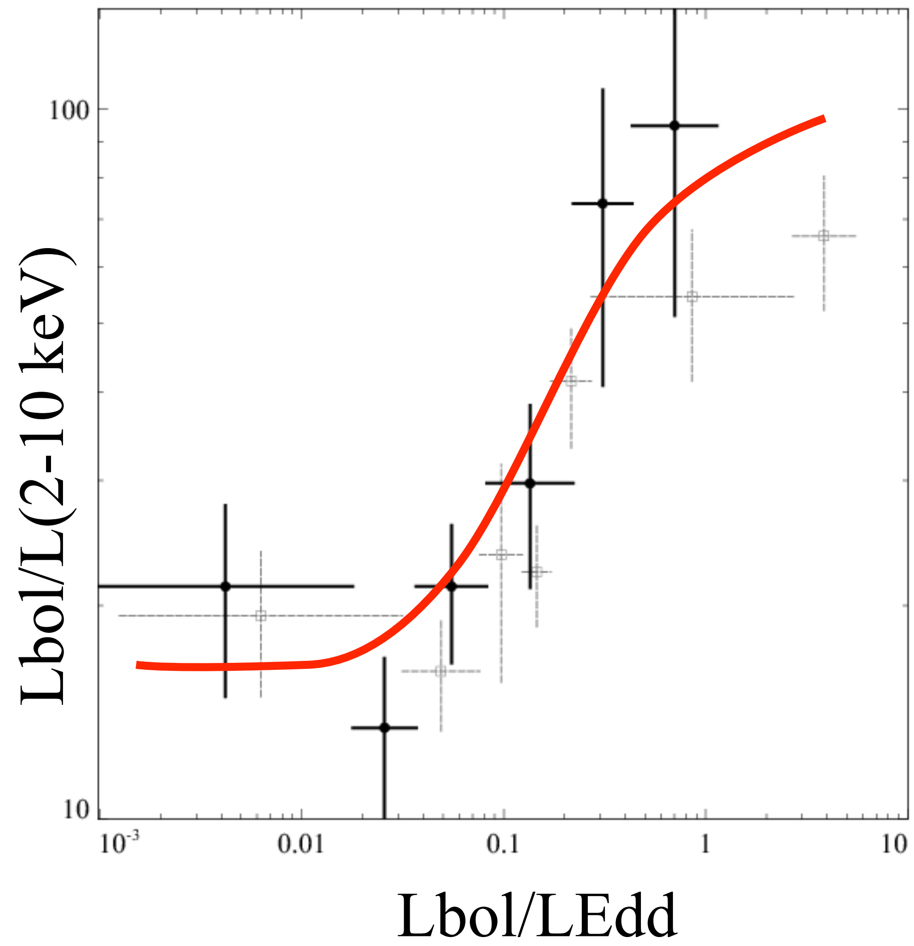



Any evidence for this? L(2-10 keV) / Lbol bigger at low L/LEdd

# AGN spectral states

Vasuvaden & Fabian 2008

- Big change in ratio of Lbol/L(2-10 keV) with Eddington ratio L/LEdd
- Looks good!!



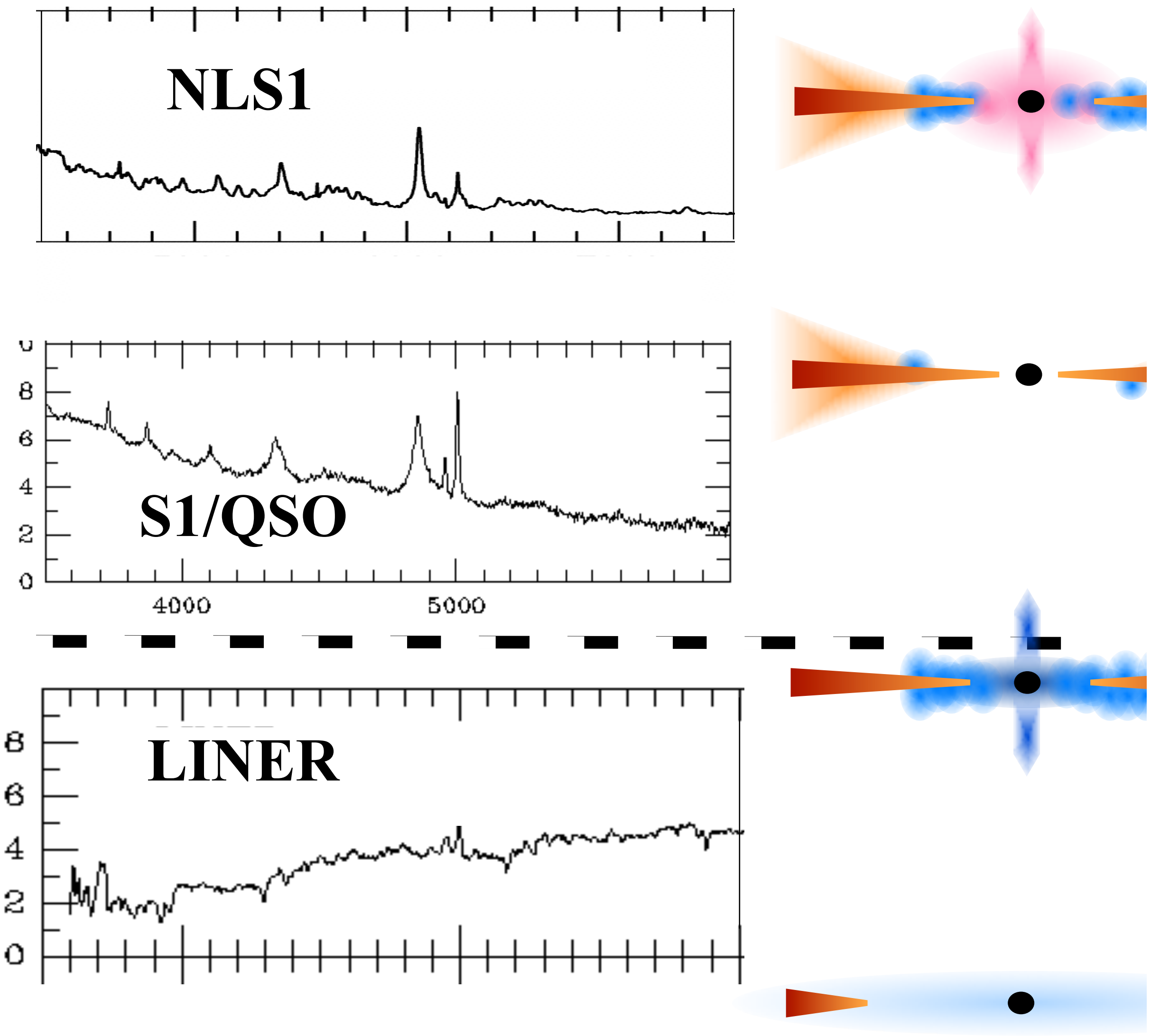
# LINERS-S1-NLS1 ?

Similar mass.
Different $L/L_{Edd}$
Different ionisation

Increasing $L/L_{Edd}$

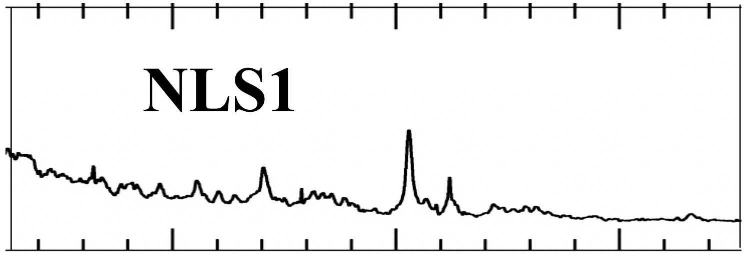
disc

Hot inner flow, no UV bright disc – true type 2 Seyferts

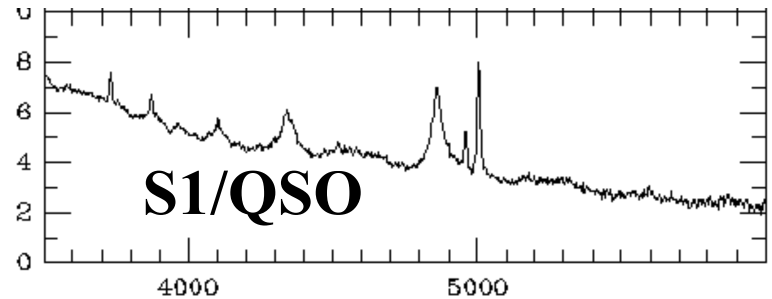


# LINERS-S1-NLS1 - radio???

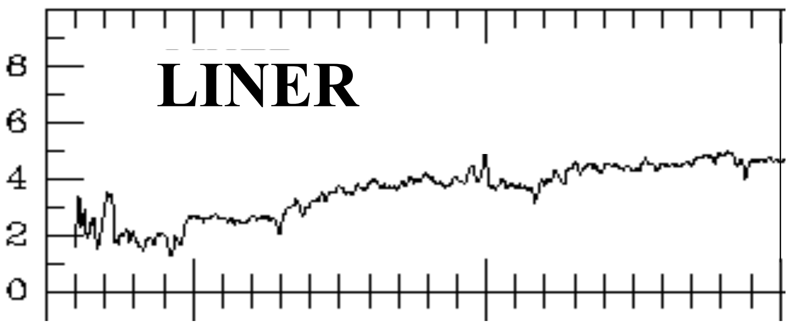
Similar mass.
Different $L/L_{Edd}$
Different ionisation




Increasing $L/L_{Edd}$




disc

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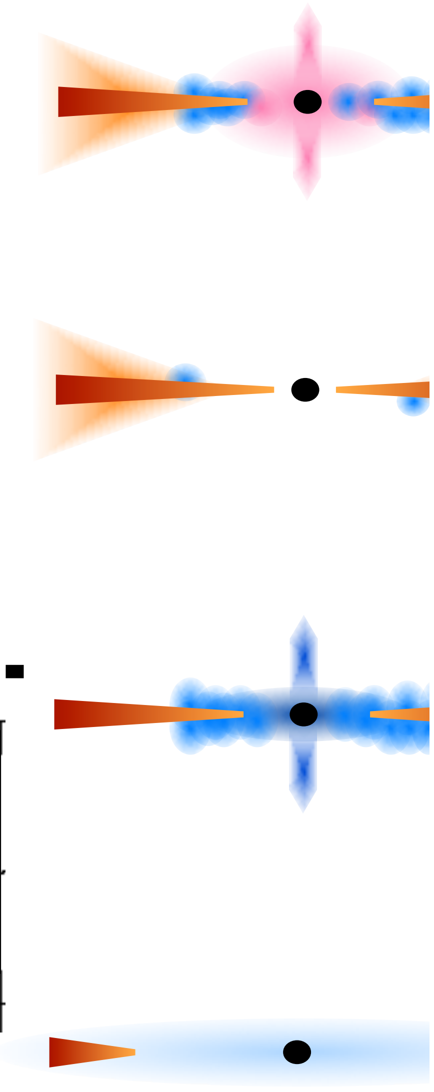
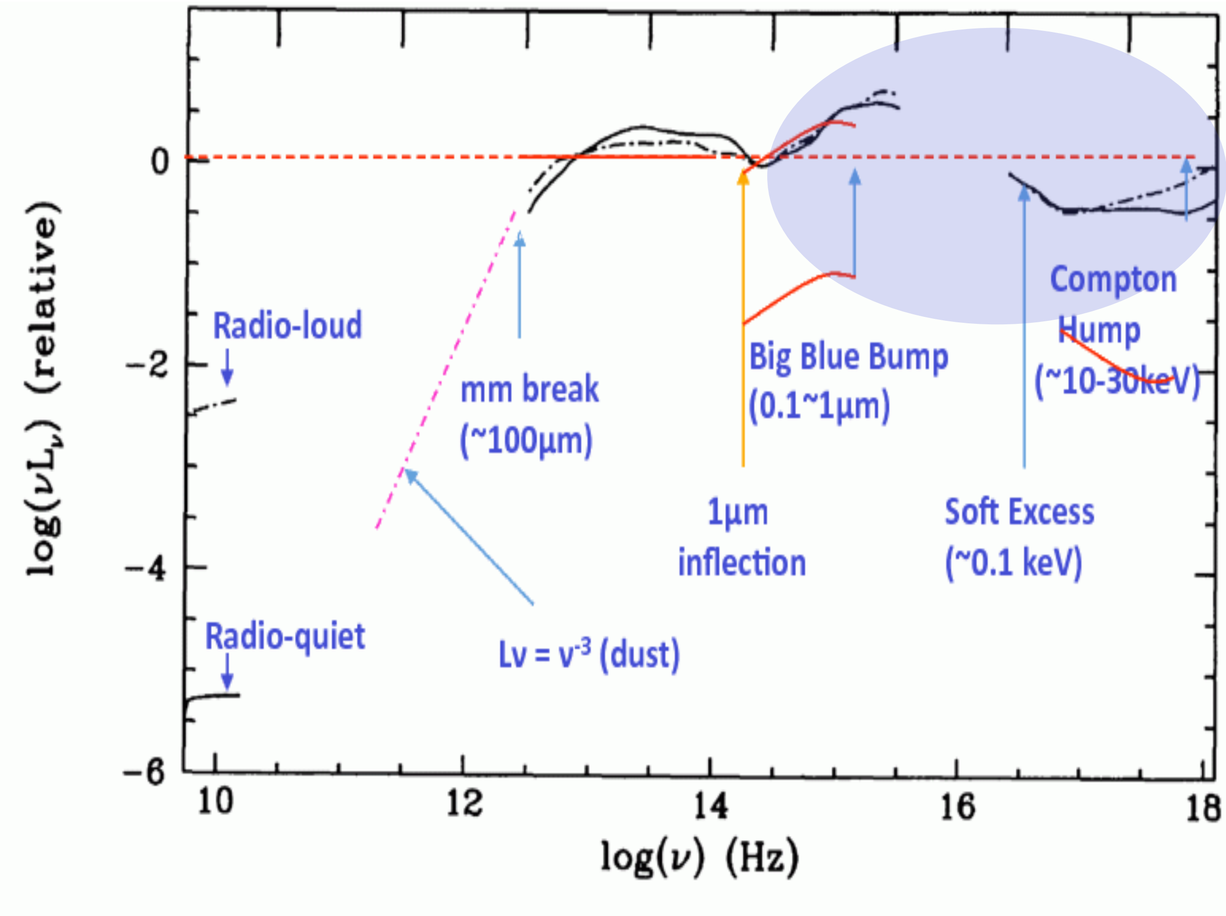


# What do AGN look like?

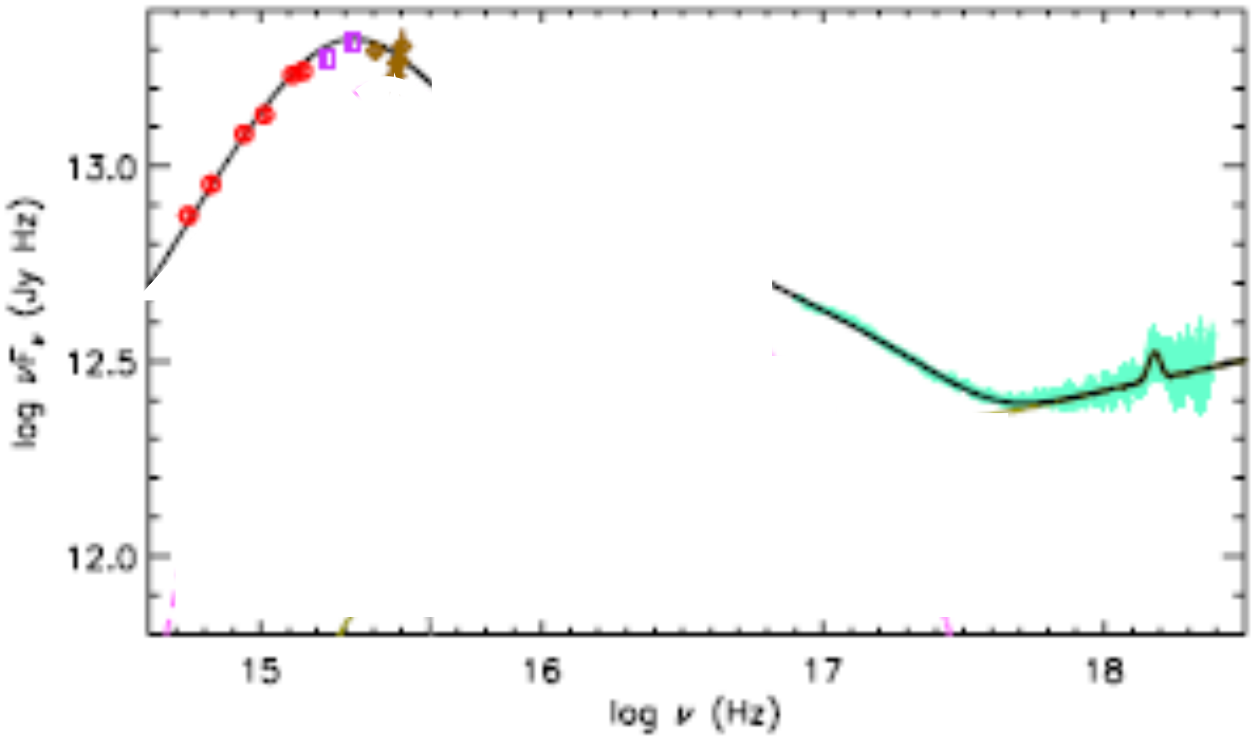
- Mass not well known 10 years ago…
- Big! So disc peak somewhere in unobservable UV/ EUV !!
- Spectra generally no dominated by the disc – hard tail often carries a large fraction of Lbol and puzzling soft excess also can carry large fraction of Lbol

Richards et al 2006, Elvis et al 2004



# Classic QSO?

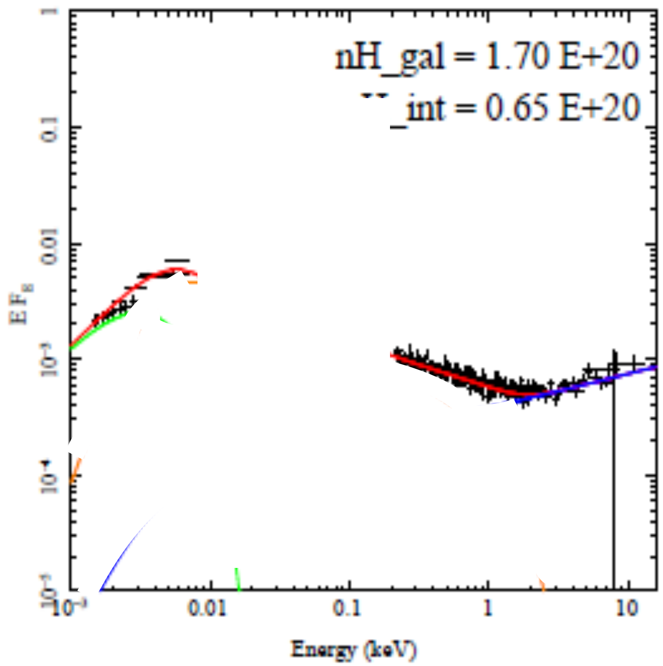
- Mkn 509 XMM-Newton OM + FUSE +EPIC
- $10^8$M L/LEdd~0.1
- Not low/hard as no jet and too bright! AGN are (should be!) high soft state. But disc turnover far too soon. Plus strange soft X-ray excess….What is this????

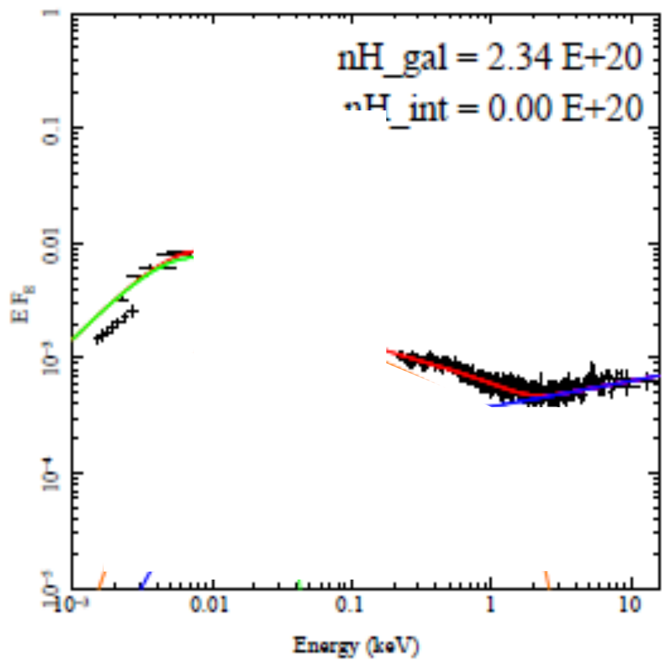



Medhipour et al 2011

# So what do AGN look like?

- 51 objects with SDSS-2XMM with high s/n and low absorption
- High M, low L/LEdd, disc far from SX




Jin et al 2011

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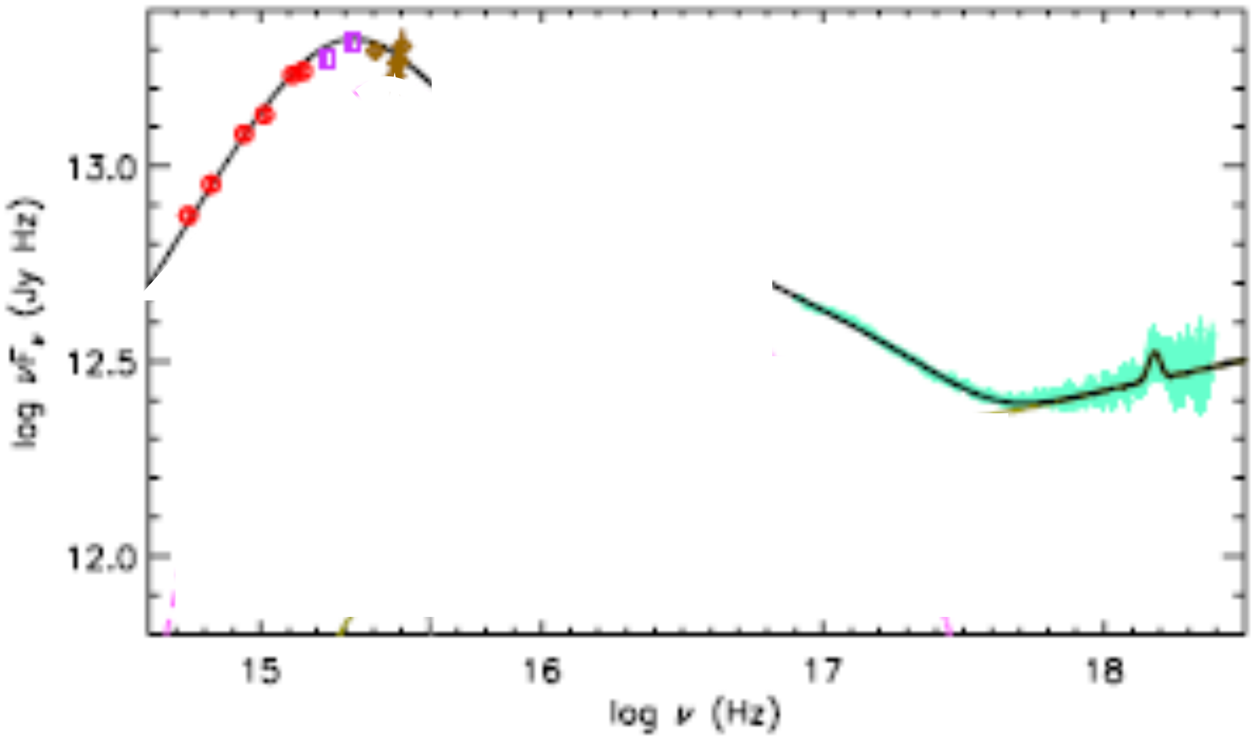


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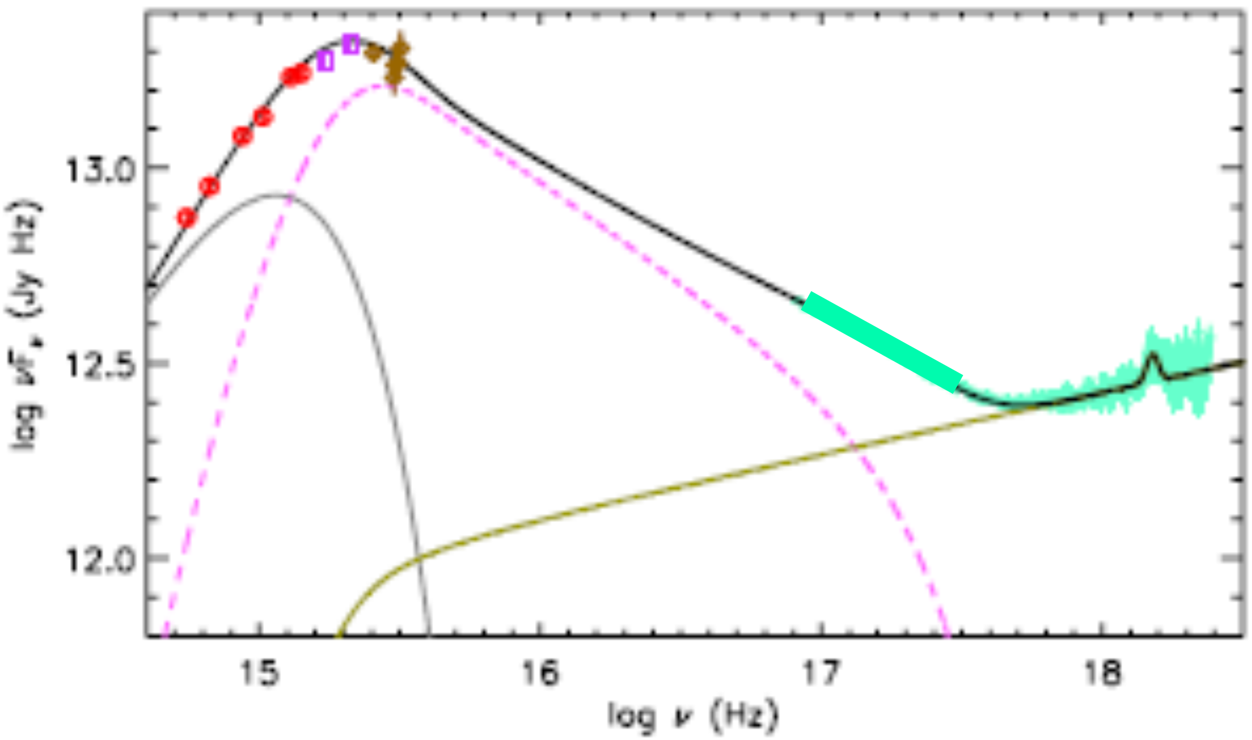


Medhipour et al 2011

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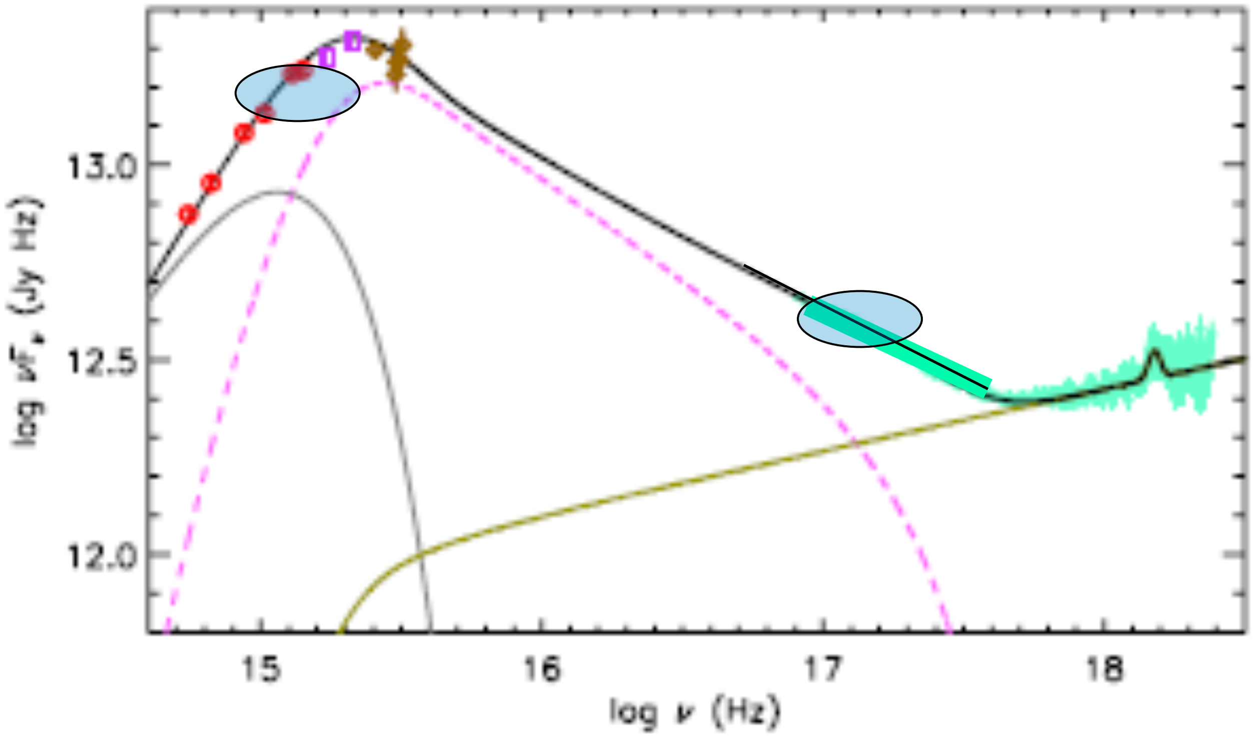
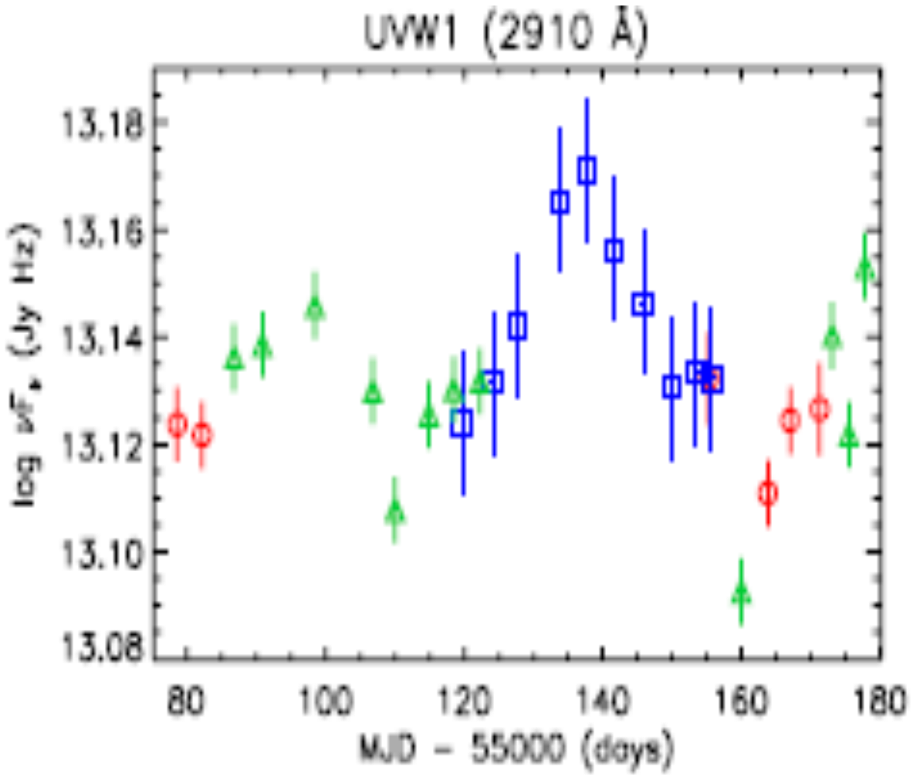
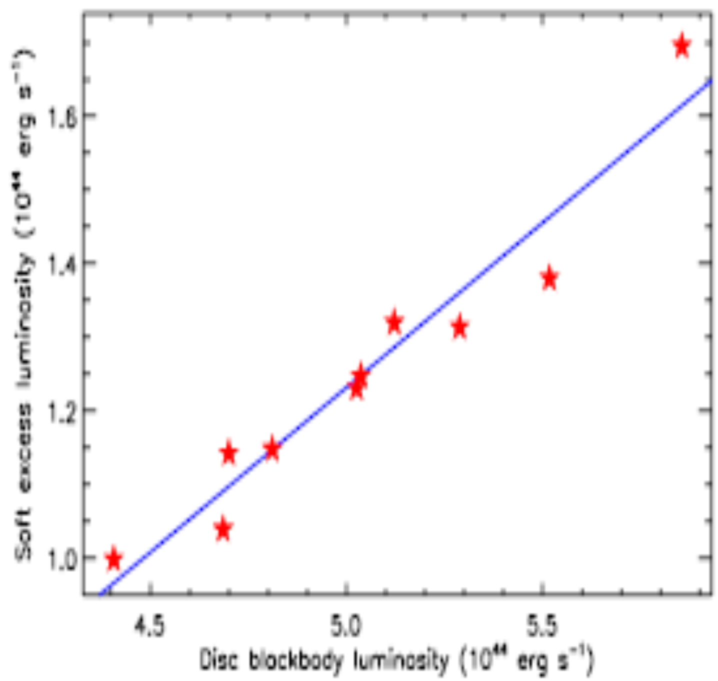



Medhipour et al 2011

# Variability on ~month

- Mkn 509 XMM-Newton OM + FUSE +EPIC
- Soft excess correlates with UV NOT X-ray on long timescales

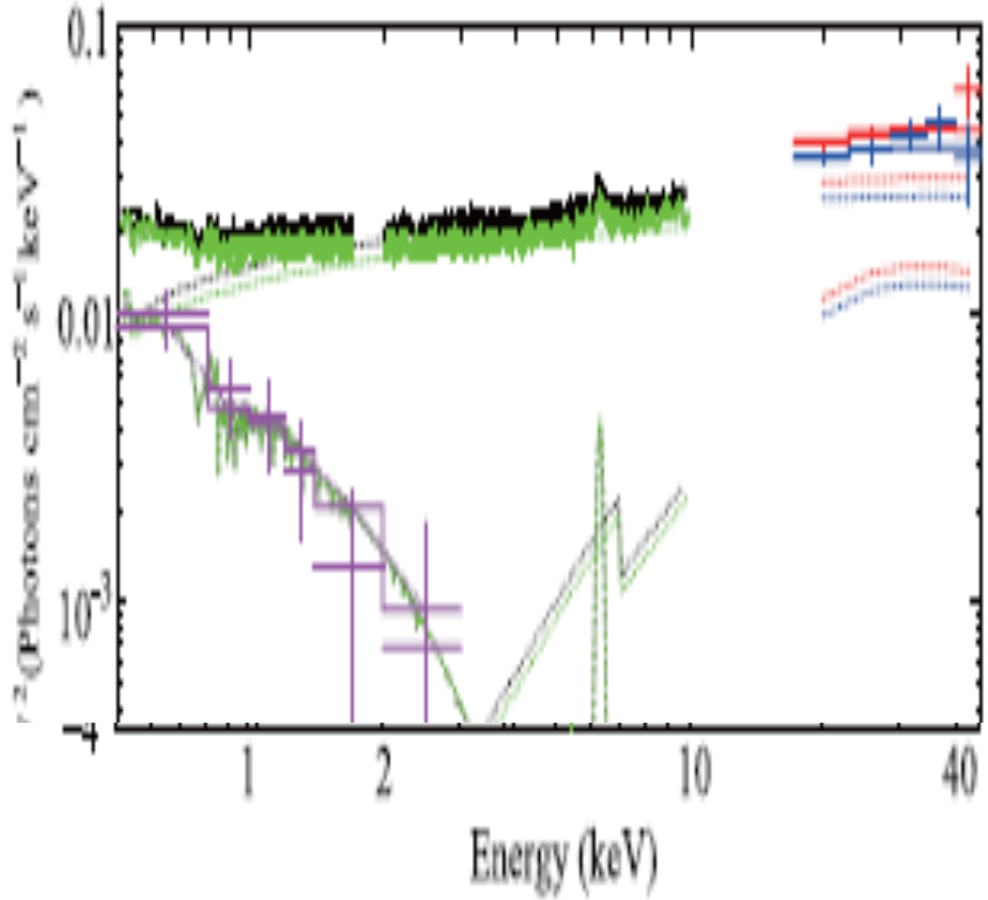



Medhipour et al 2011

# Variability on < day

- Short timescale. Soft excess does NOT vary, hard power law does
- It's a separate component!!!! Noda et al 2011; 2012




Noda et al 2011

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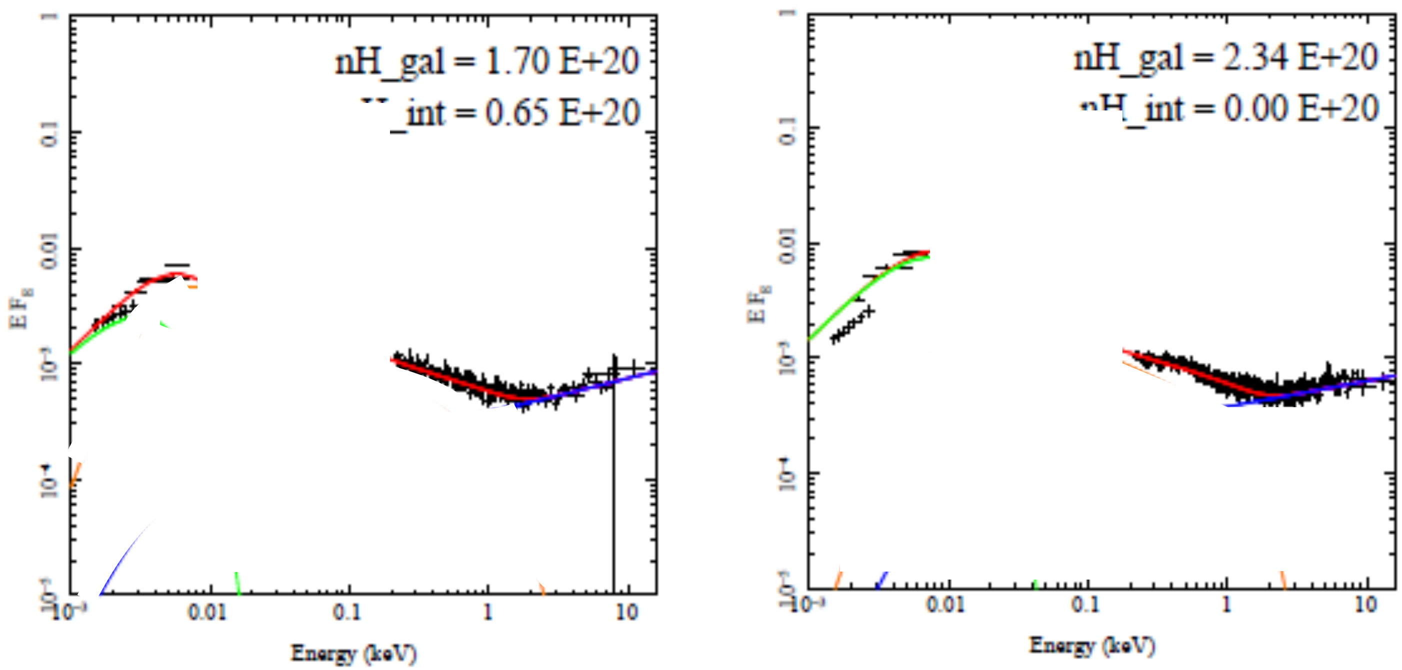
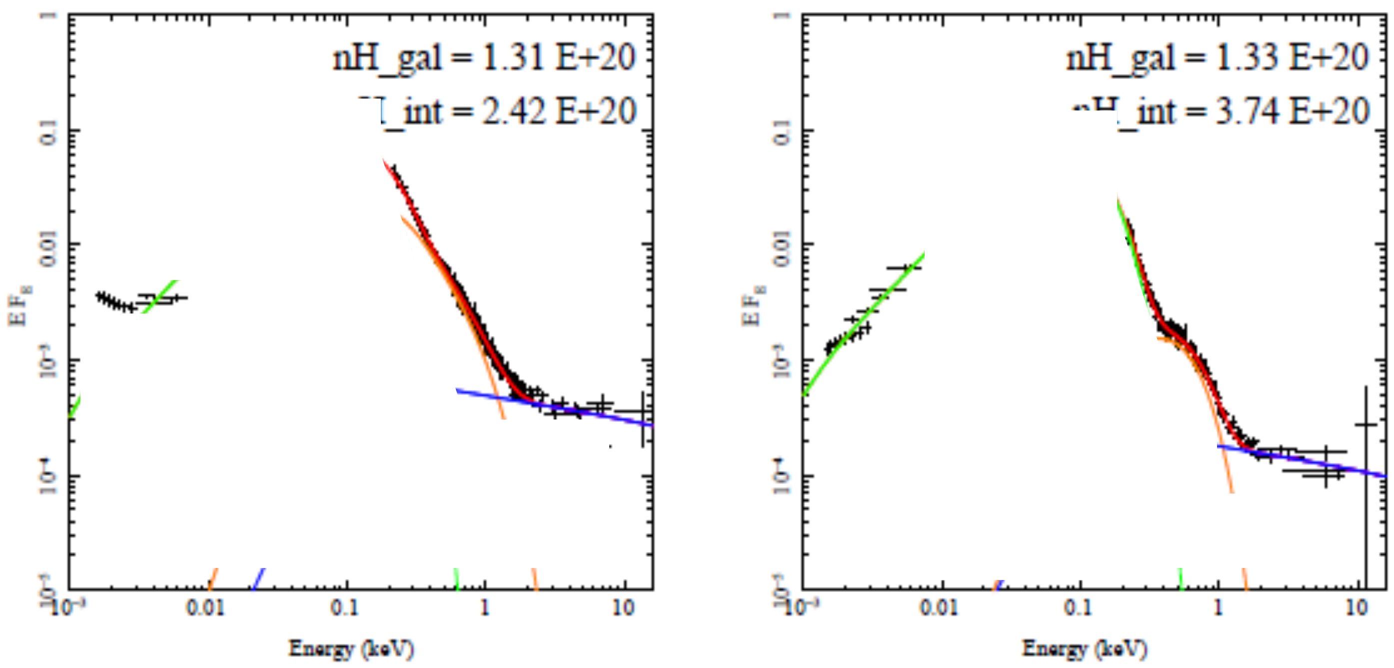



Jin et al 2011

# So what do AGN look like?

- 51 objects with SDSS-2XMM with HIGH S/N AND LOW NH
- Low M, high L/LEdd disc makes most of Soft Xrays

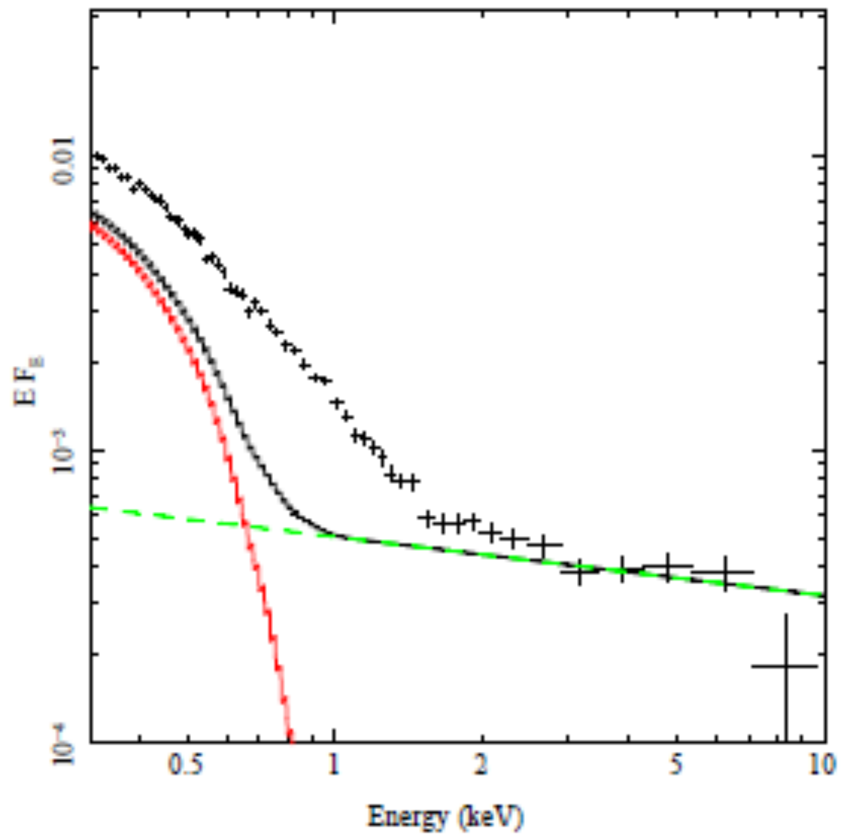



Jin et al 2011

# Disc spectra from $10^6$ M L/$L_{Edd}$ ~1

Done, Davis, Jin, Blaes Ward 2011

- Enormous soft excess in REJ1034
- But actually a lot of it should be the bare disc!
- Plus a little bit of soft comptonisation !
- Again variability says it's a separate component to the power law (Middleton et al 2010)
- More like disc dominated black holes



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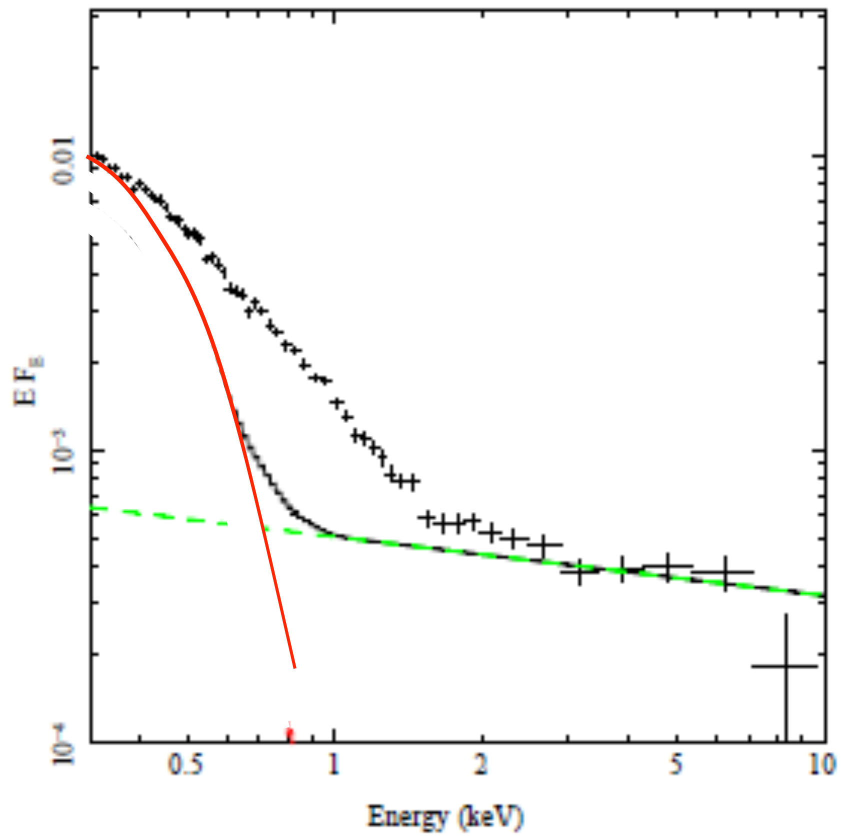
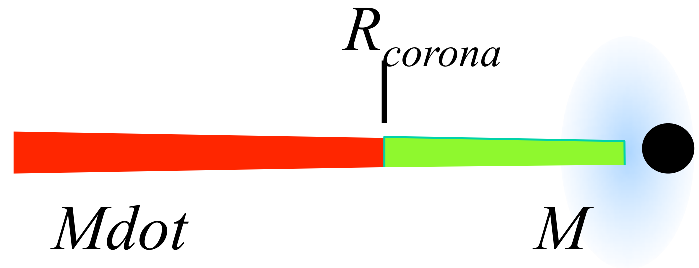
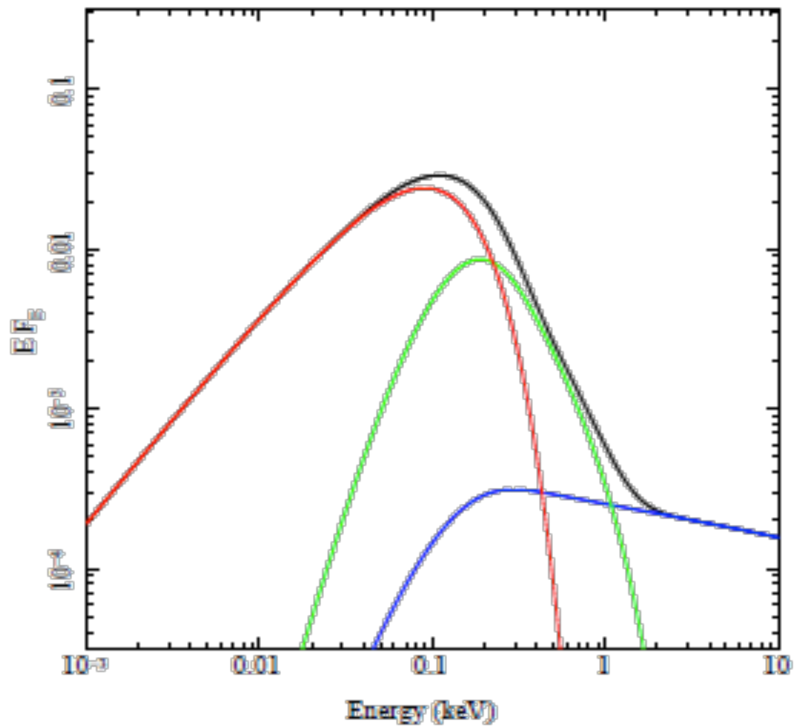


# Models conserving energy!!

- Lopt $\propto$M Mdot
- Know M from optical and Hβ
- Measure Mdot from L opt. Lbol = η Mdot $c^2$
- Schwarzchild a=0 η=0.0572
- If powered by accretion of material through the outer disc then this also makes soft excess and power law tail
- Thermal down to $R_{corona}$ with colour temp correction
- Comptonised/power law after this – XSPEC optxagn Done et al 2011 cf dkbbfth Done & Kubota 2006




Done et al 2011

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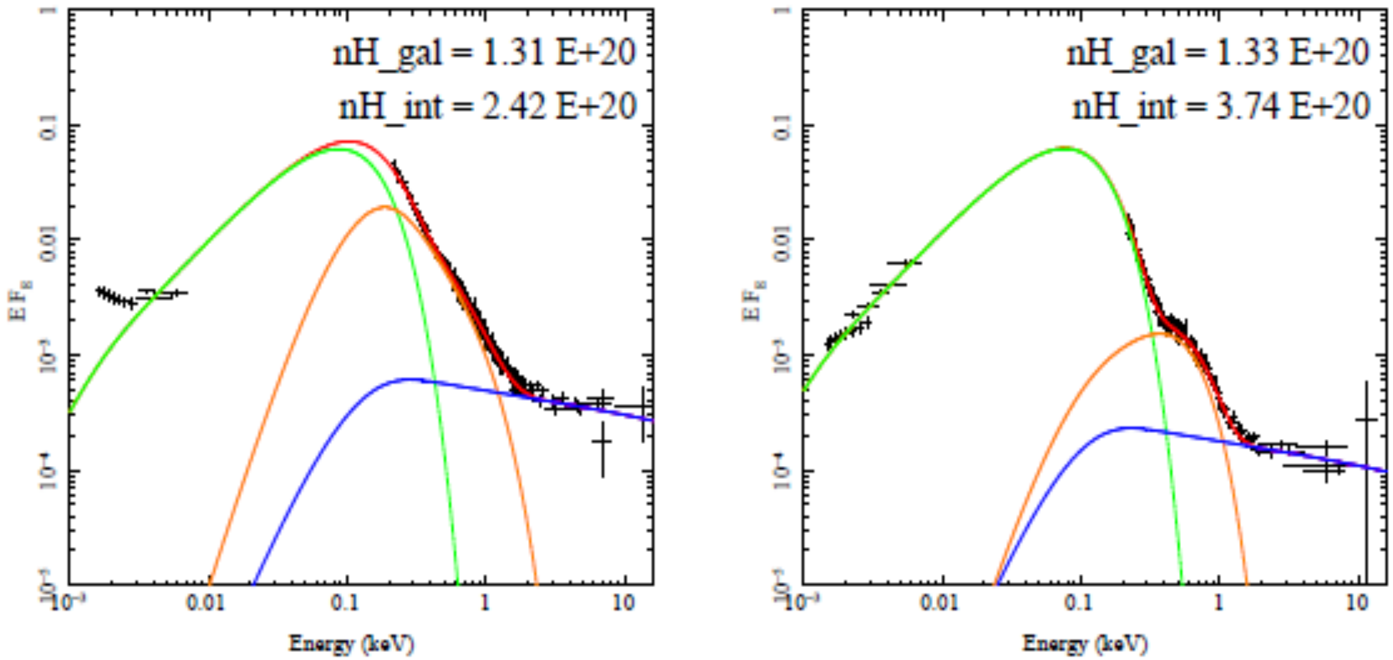


Jin et al 2011

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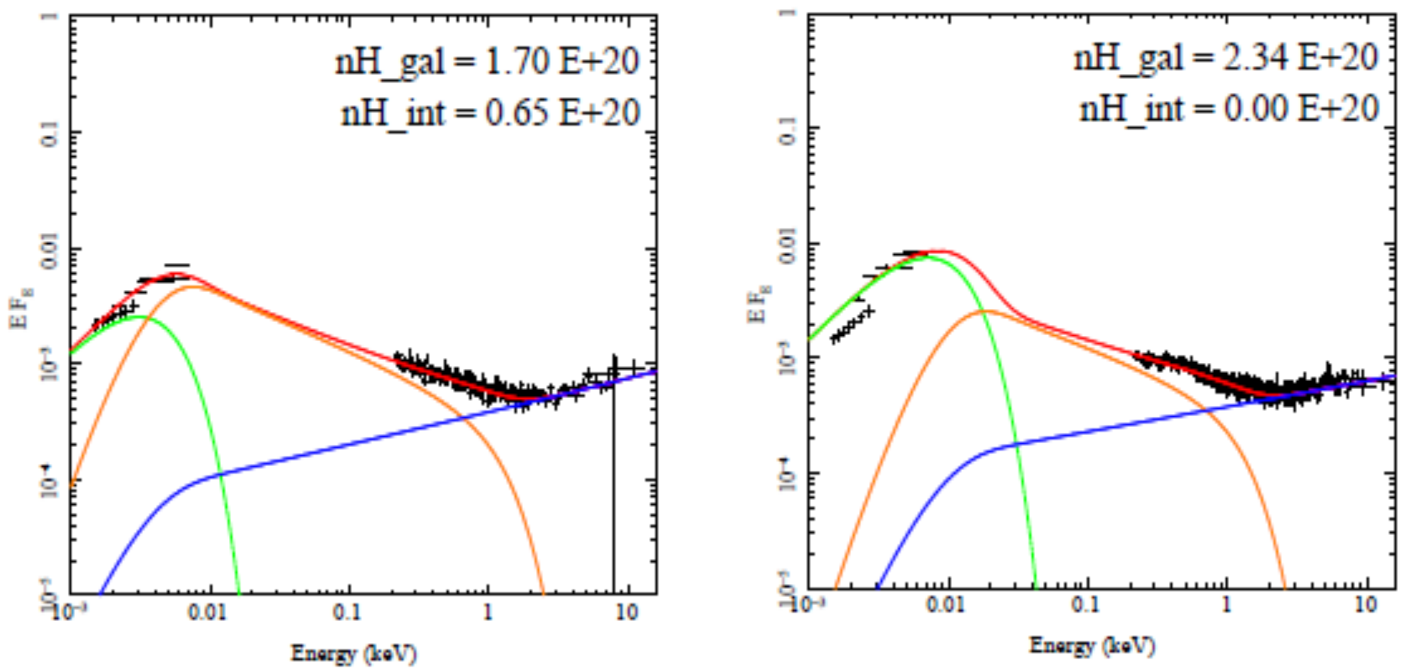
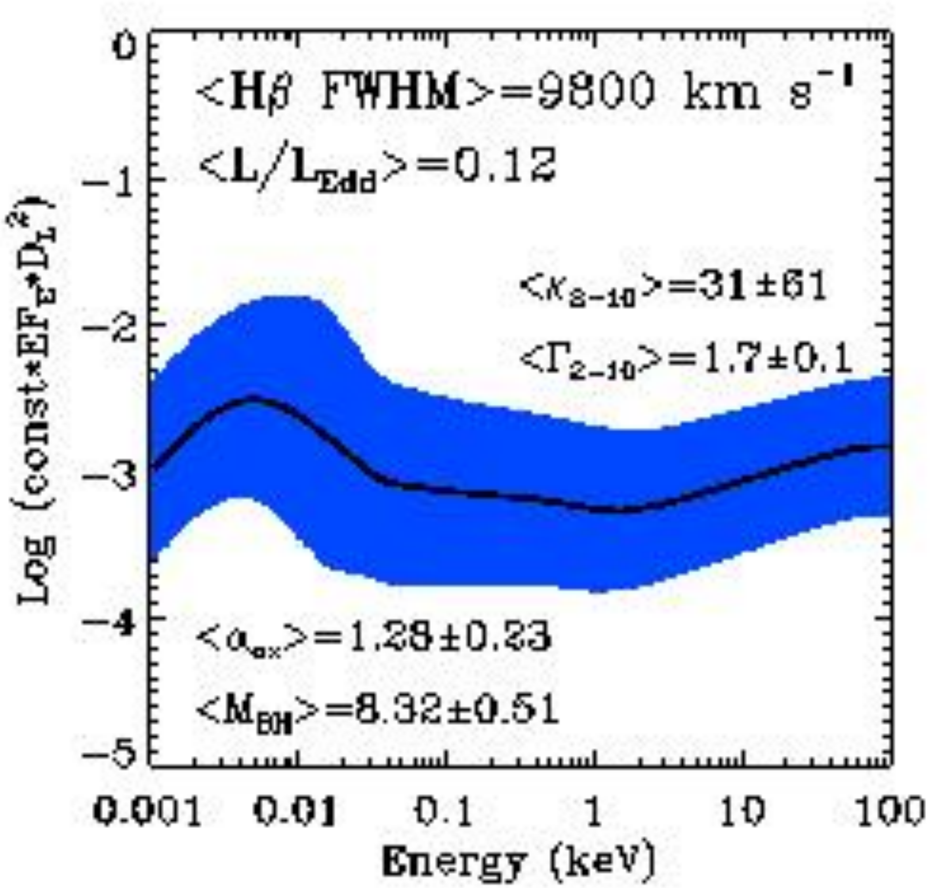


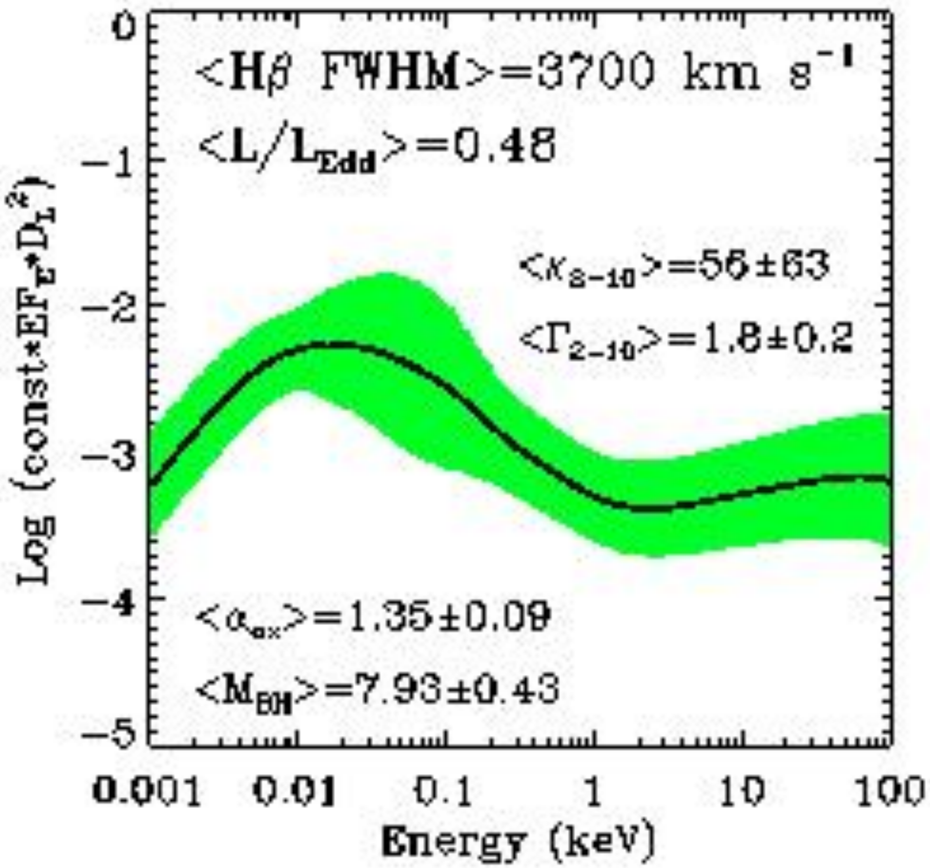

Jin et al 2011

# AGN spectral states




Jine, Ward, Done Gelbord 2011

# AGN spectral states




Jine, Ward, Done Gelbord 2011

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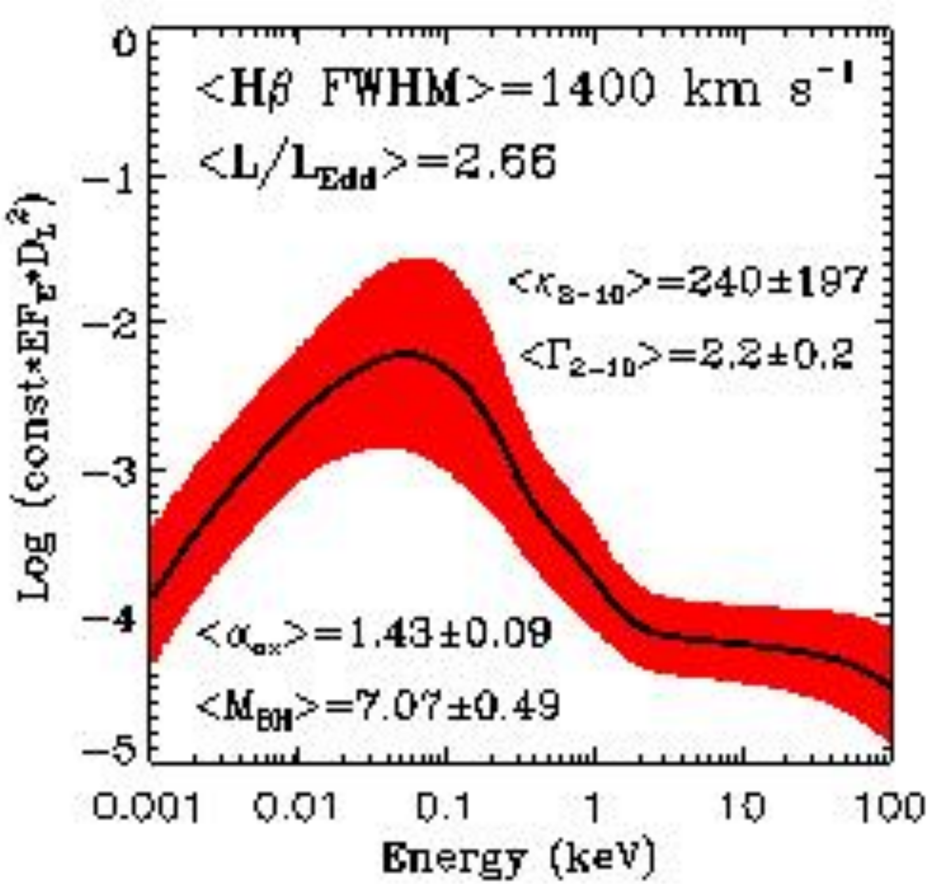
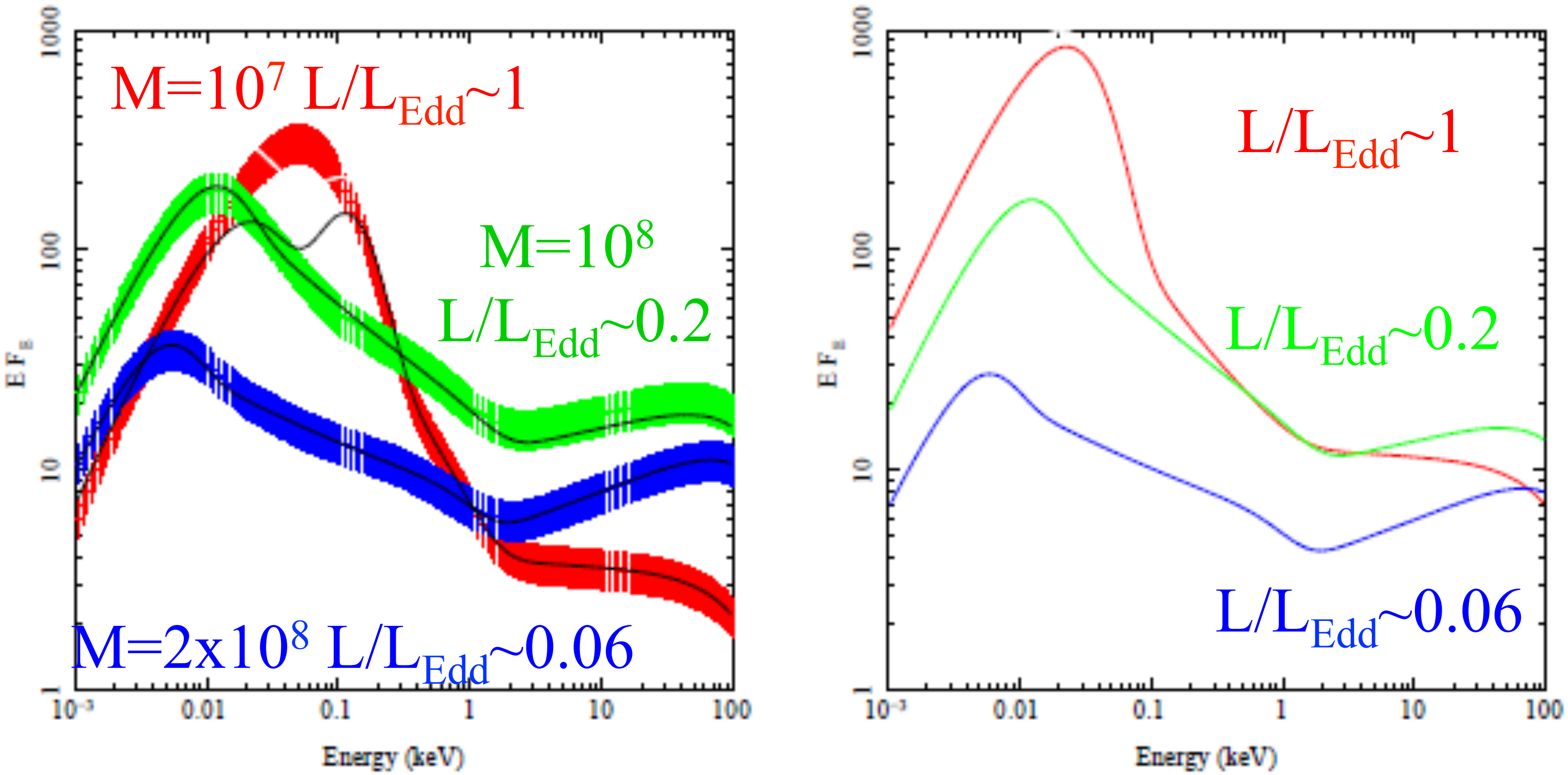



Jine, Ward, Done Gelbord 2011

# INTRINSIC changes in SED

- Co-add models in 3 bins of $L/L_{Edd}$
- Correlates with M due to galaxy formation. high mass objects have low $L/L_{Edd}$ in local Universe – downsizing
- Physical model so shift to same mass $M=10^8$ to compare with BHB




Done et al 2011

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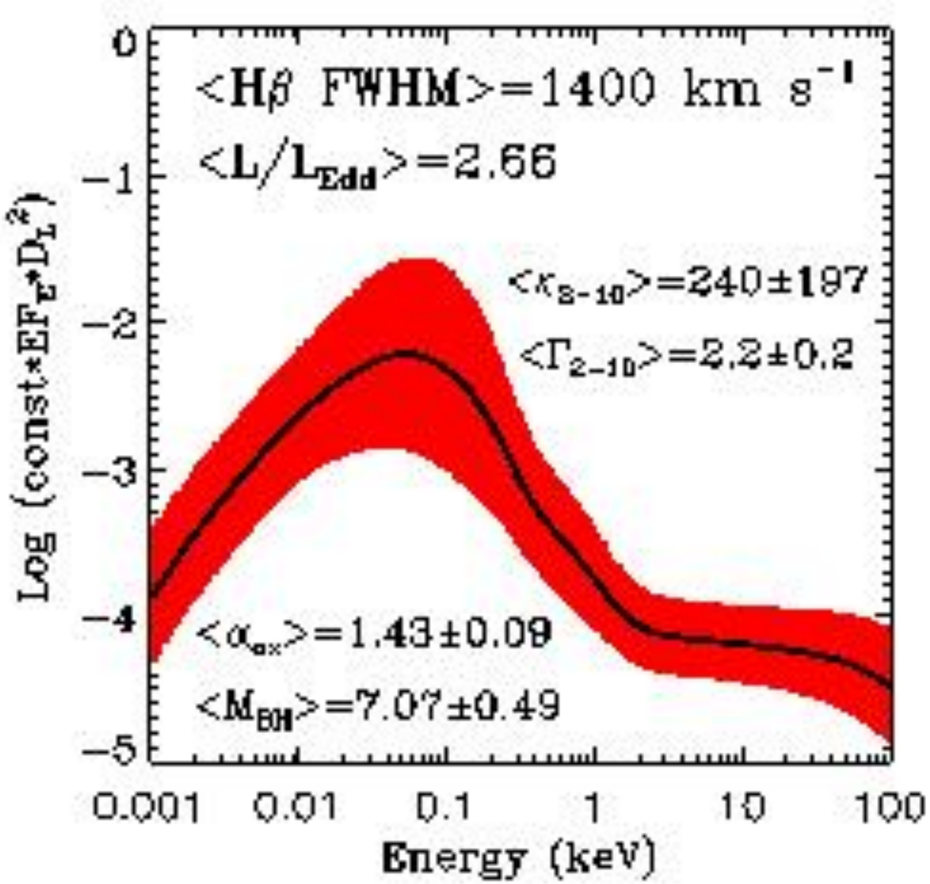


Jine, Ward, Done Gelbord 2011

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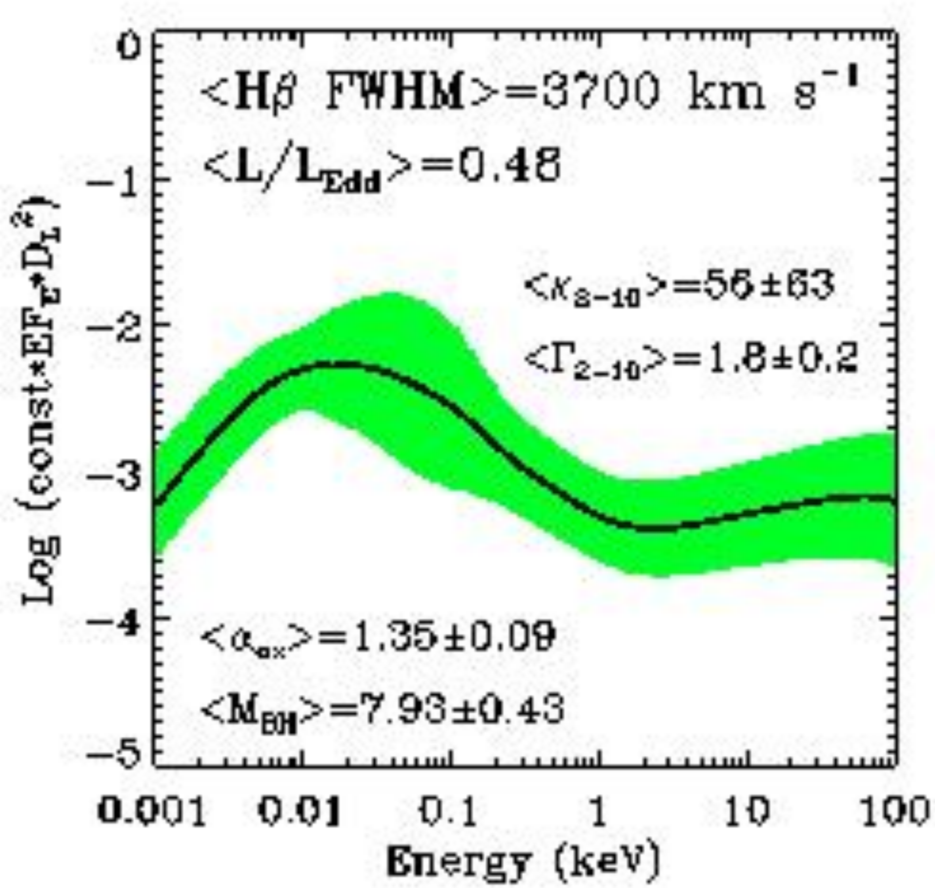


Jine, Ward, Done Gelbord 2011

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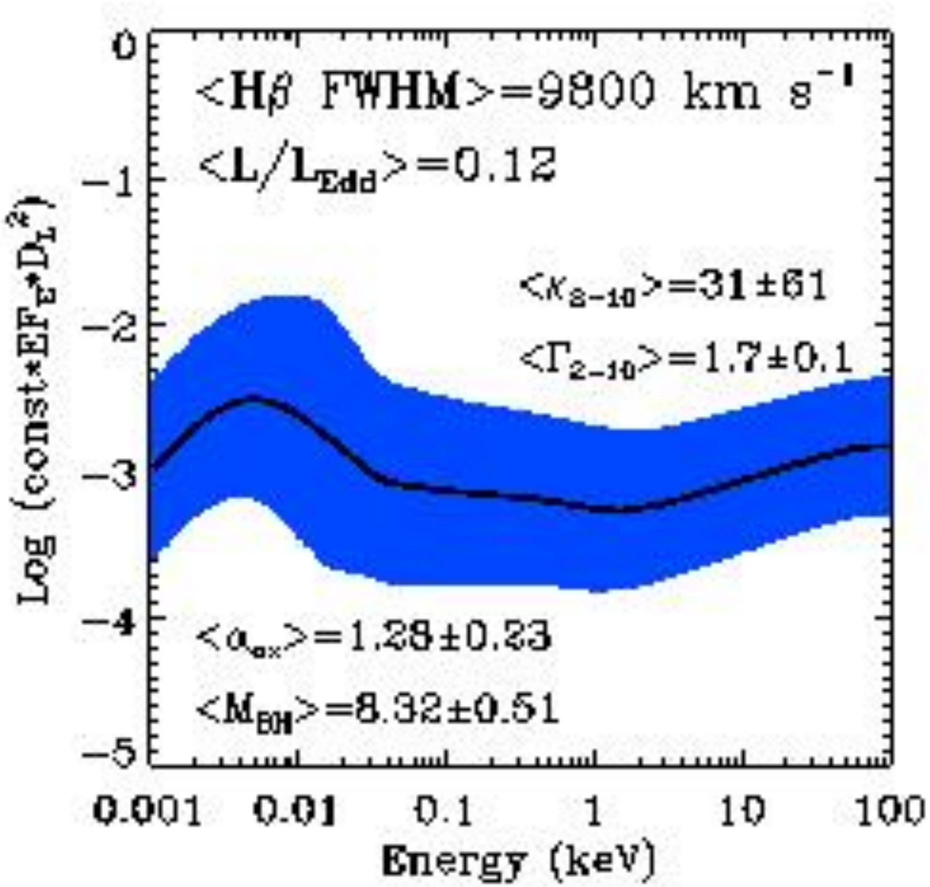


Jine, Ward, Done Gelbord 2011

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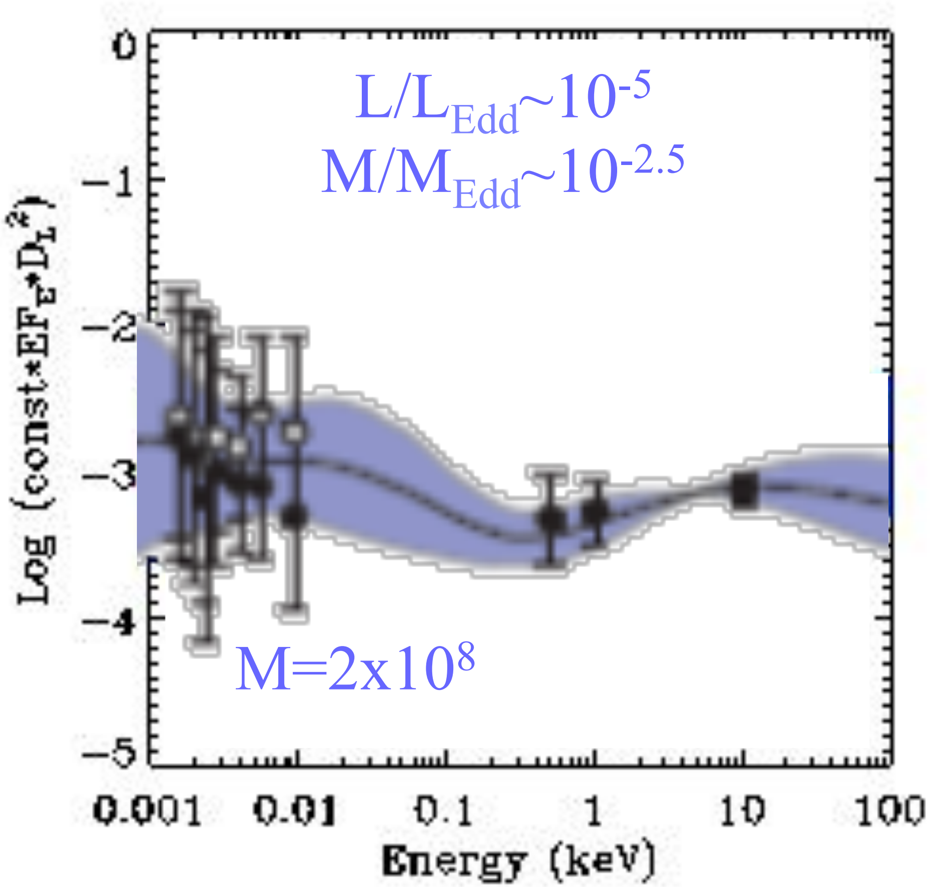


Nemmen et al 2012

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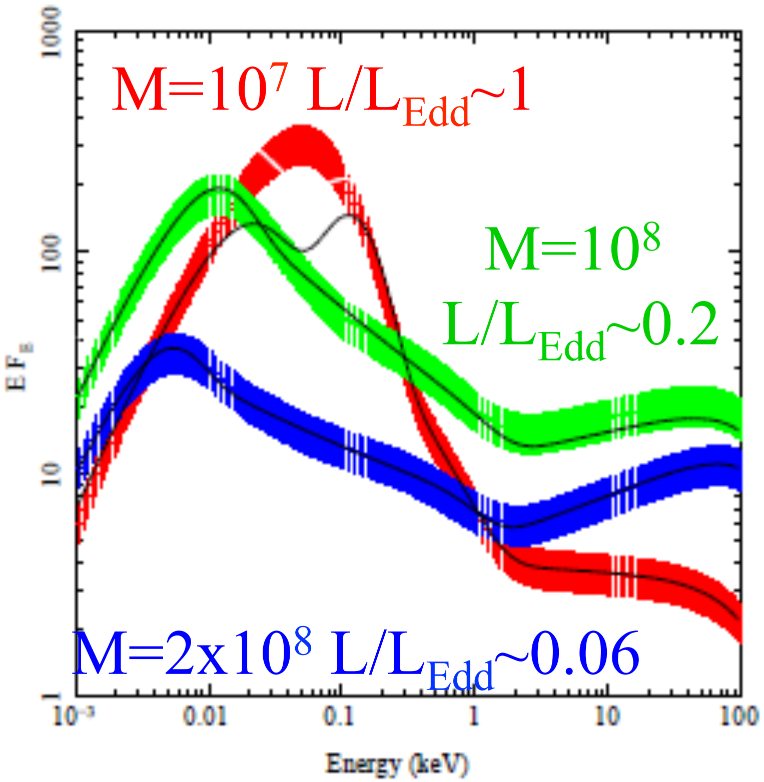
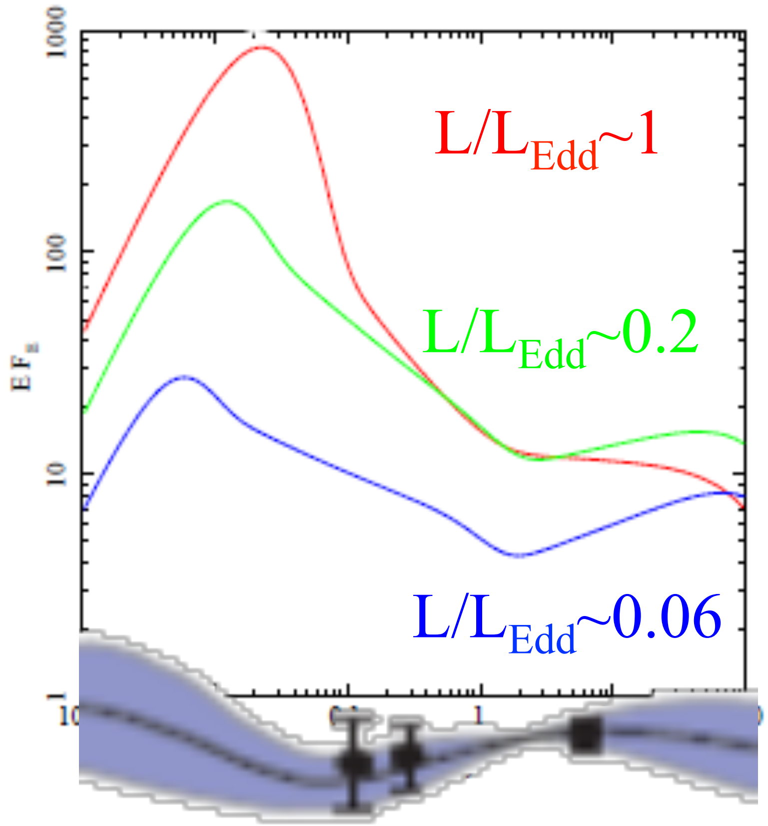
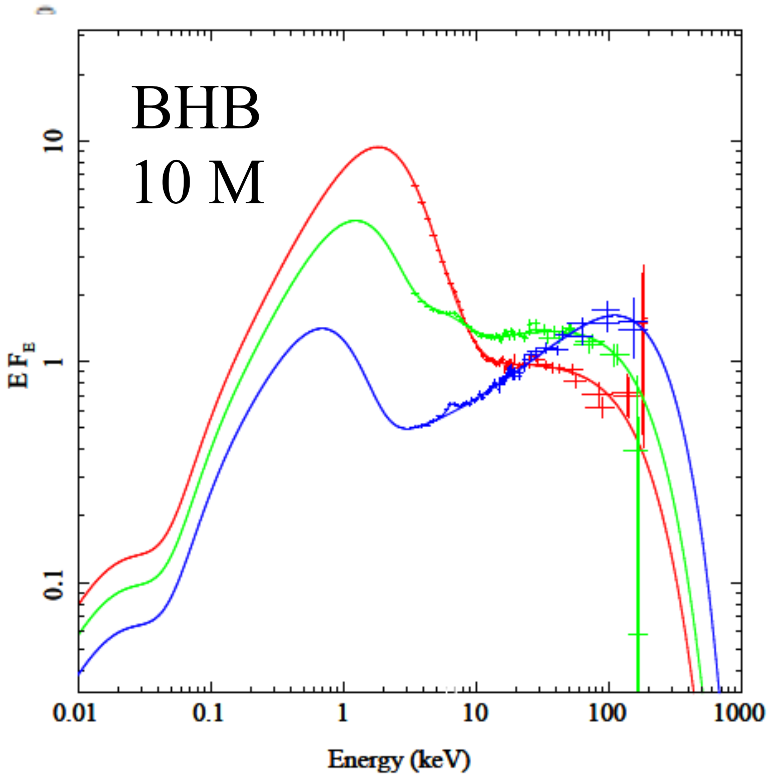


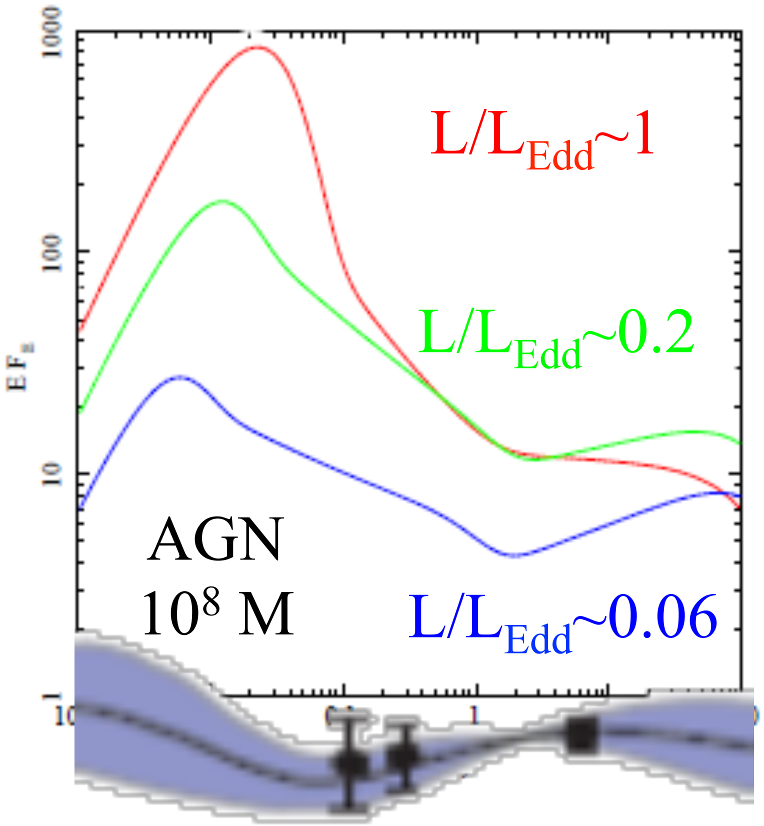




Done et al 2012

# Low/hard to high/soft ?

- Looks good to zeroth order… but….
- Transition at L/LEdd=0.02 in steady state accretion - 0.2 in AGN
- LINERS are low/hard state (strong radio)
- Green/blue are classic QSO – not low/hard state – what are they?




Done et al 2012

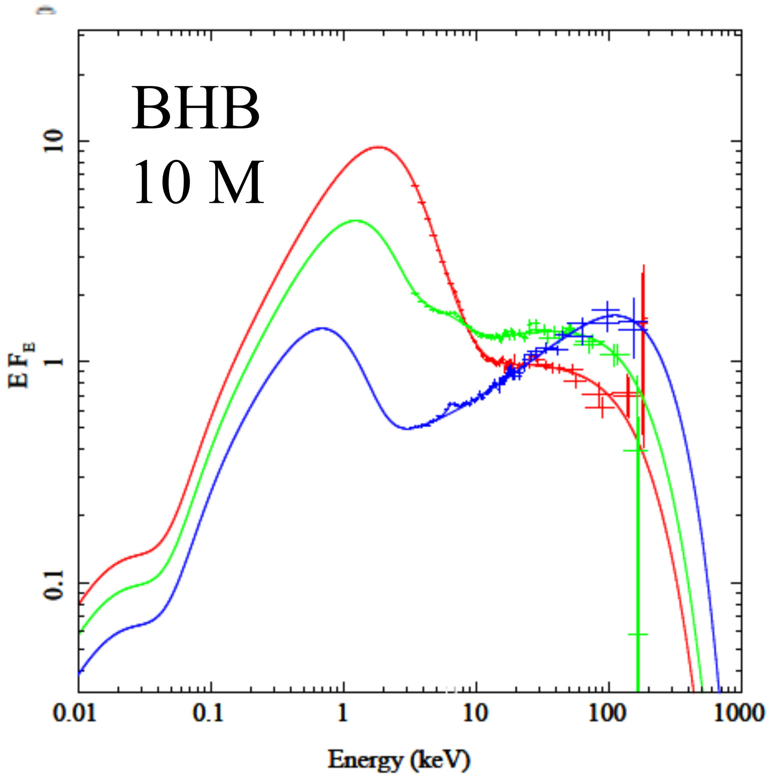
# Scale up to AGN

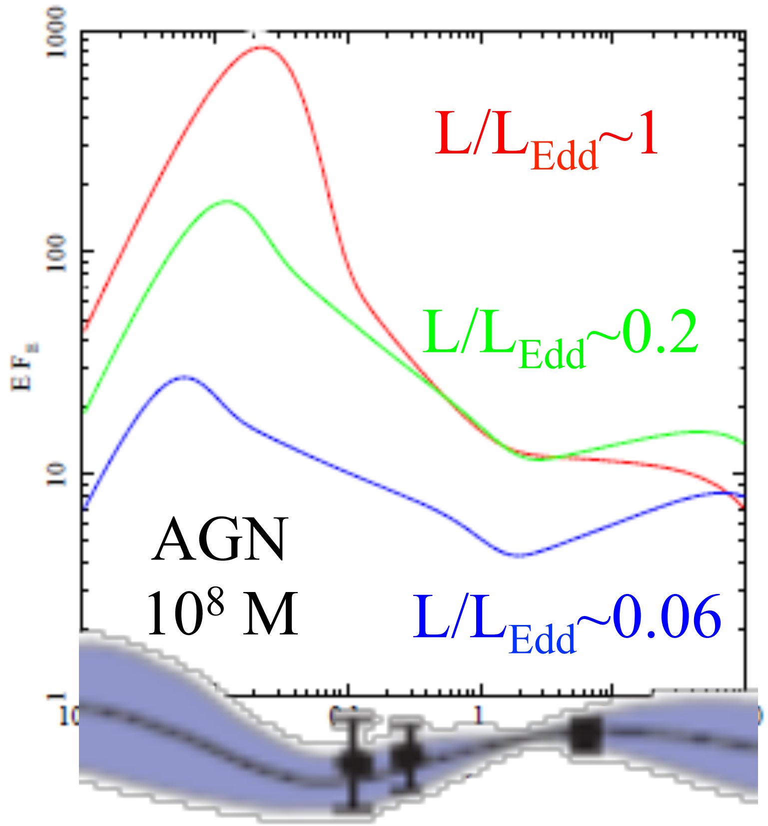
- UV line driven discwind (origin of BLR/torus?) - BAL QSOs
- Can this change the disc structure in AGN from BHB? Mass loss rate can be large so disc no longer constant mass accretion rate at all radii. Lose mass predominantly from UV emitting zone
- Throws material above disc so maybe more mass in corona

Proga et al

# Low/hard to high/soft ?

- LINERS are low/hard state (strong radio)
- Green/blue are classic QSO – not low/hard state – winds?
- NLS1 – look disc dominated!!

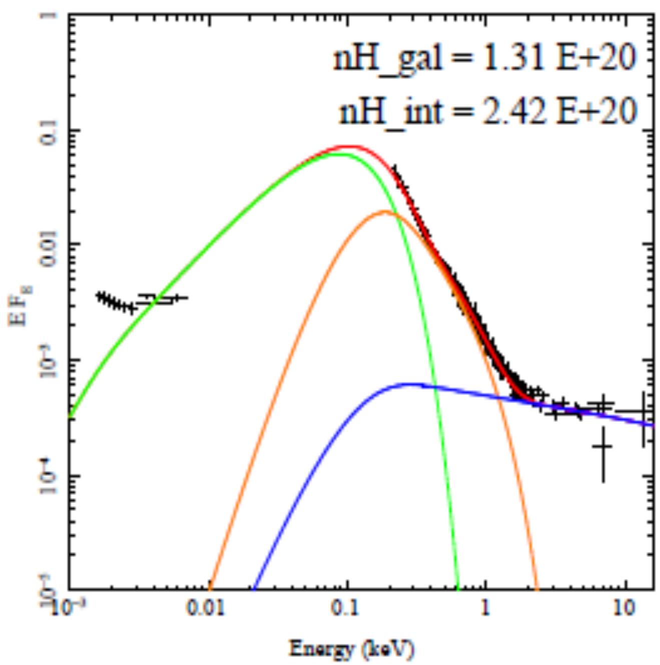


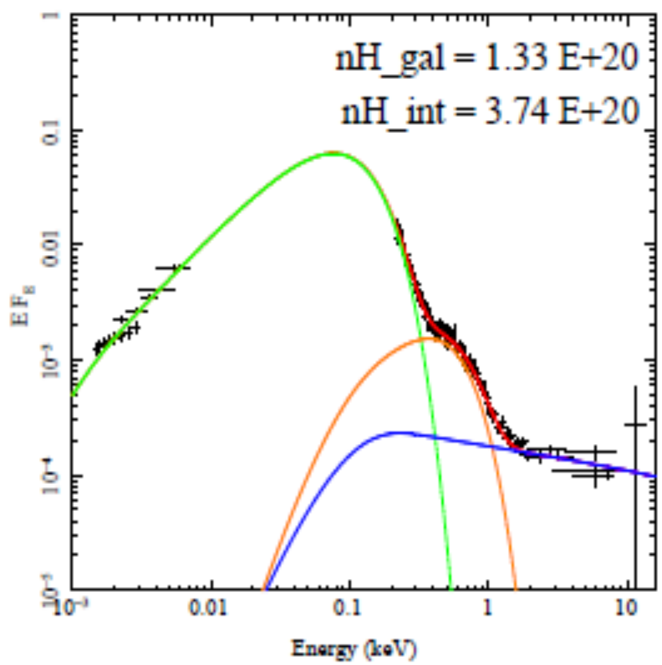




Done et al 2012

# NLS1 as disc dominated ?

- Surprising as might expect stronger winds at Eddington – but maybe higher temperature (from lower mass) supresses wind

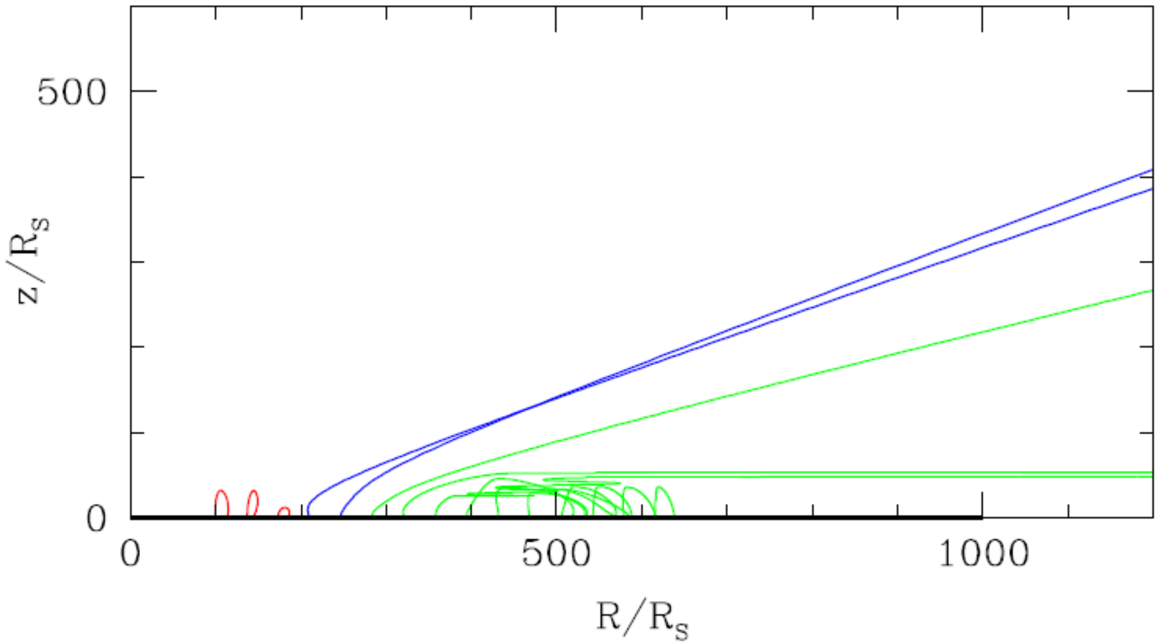



Jin et al 2011

# Scale up to AGN

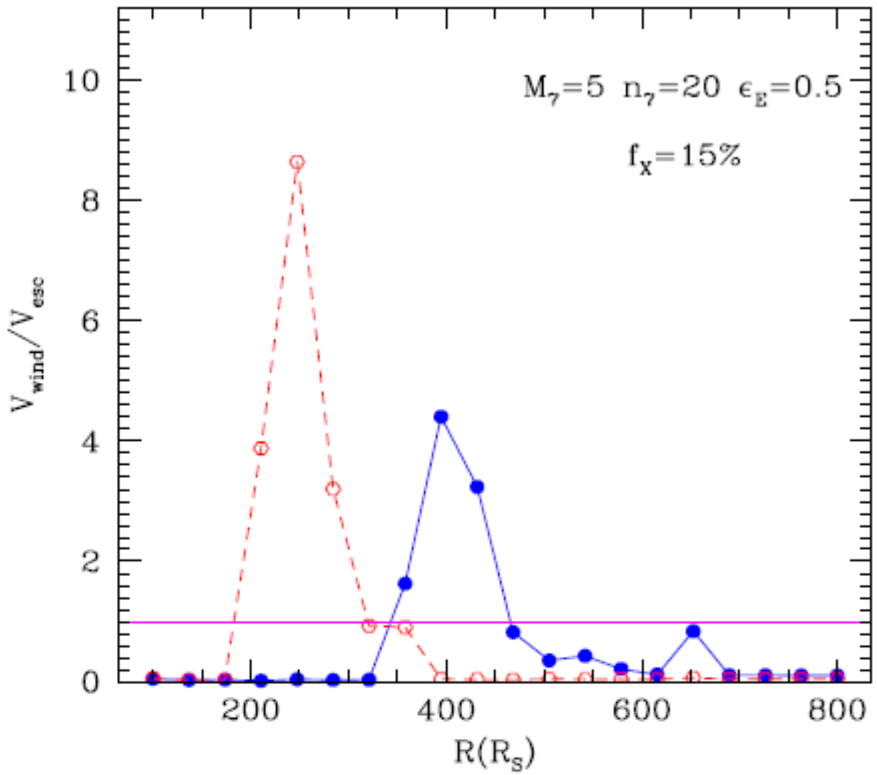
- UV line driven discwind as function of BH mass and L/LEdd
- UV line driven wind – rises and is overionised by central source and falls back down (shocks produce soft X-ray excess?)
- shields UV line driven discwind further out so its not overionised and keeps on acceleration and can escape
- Then run out of UV photons for driving as disc temperature too low




Risaliti & Elvis 2010

# Scale up to AGN

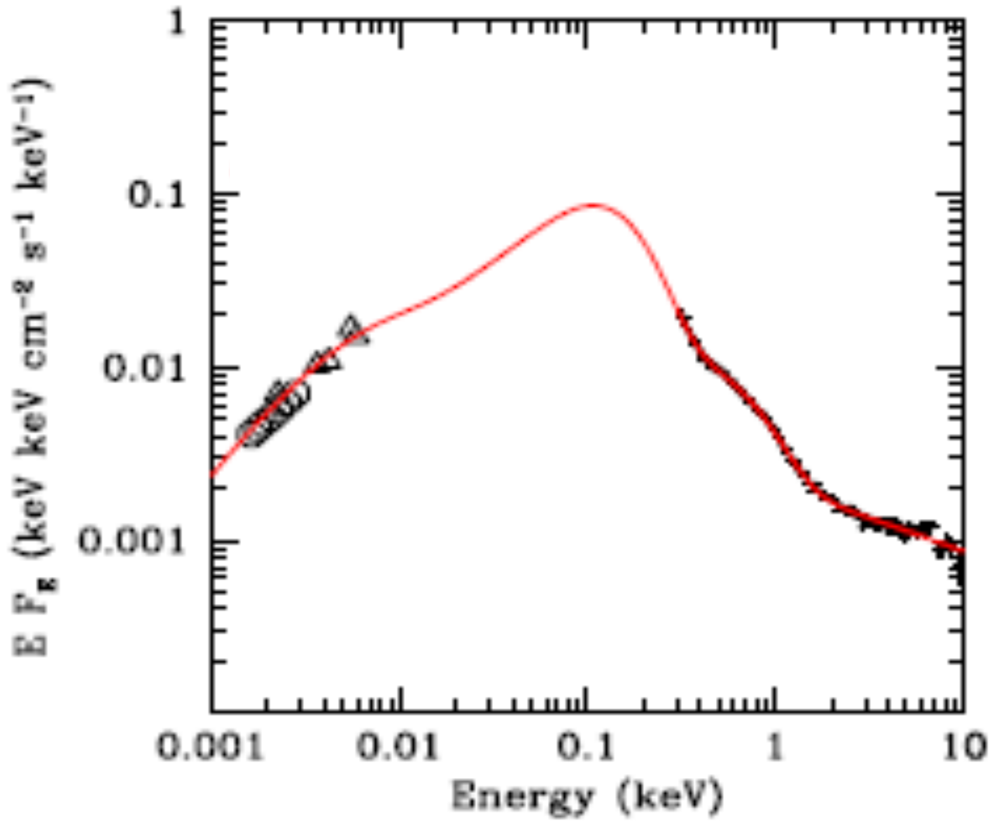
- UV comes from further out for lower mass for same L/LEdd as disc is hotter
- If BLR is wind from disc then wind is further away – narrower lines…
- Is the BLR a UV line driven disc wind ? Chiang & Murray 1997, Elvis 2000; Risaliti & Elvis 2010




Risaliti & Elvis 2010

# Black Hole spin!

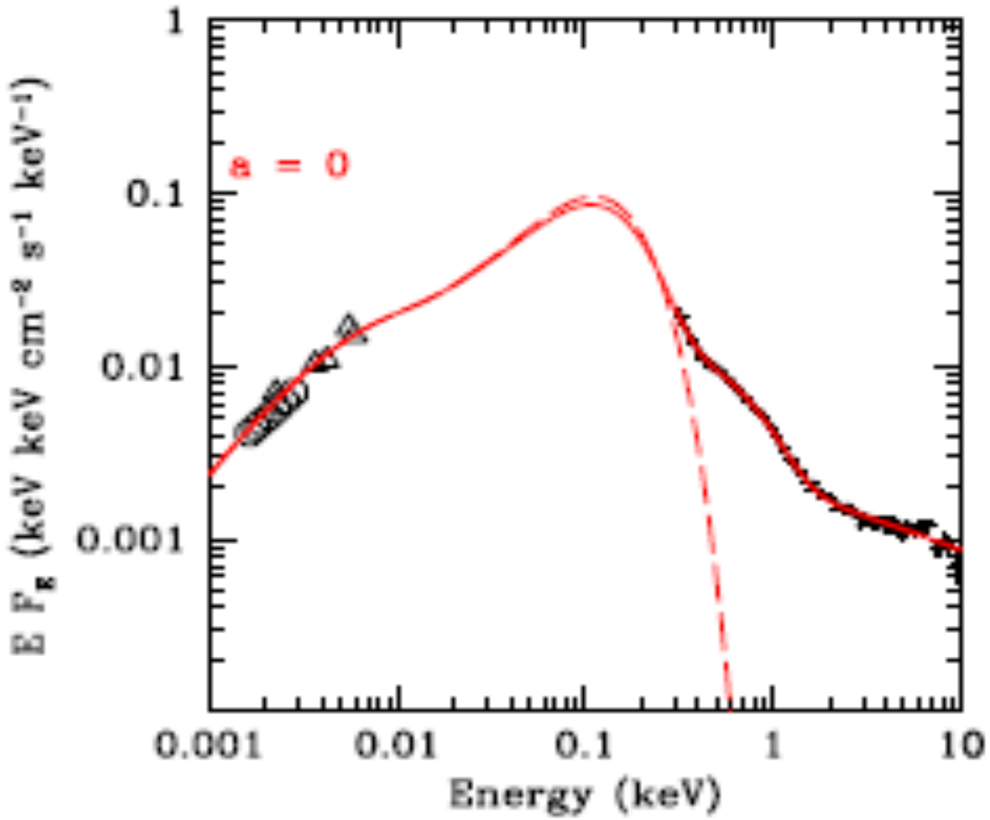
- PG1244
- M from Hb
  $0.8 - 8.0\times10^6$M
- Correct for $P_{rad}$
  $2.5\times10^7$M
- M from Lx variability compared to reverberation mapped sample
  $0.2 - 2.0\times10^7$M
- Best fit $0.8L_{edd}$
  $1.7\times10^7$M




Done,, Jin, Middleton Ward 2012

# Black Hole spin!

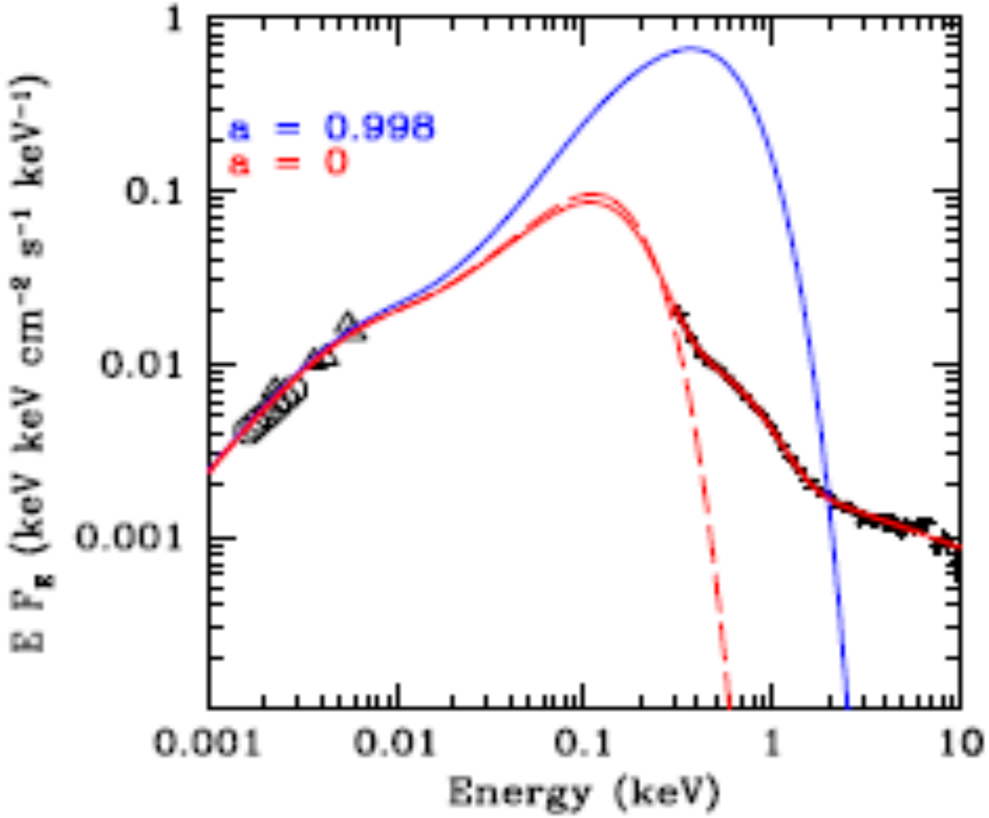
- PG1244
- Pure disc at this mass and mass accretion rate - a=0
- Already goes VERY close to soft X-rays – constrains SPIN




Done,, Jin, Middleton Ward 2012

# Black Hole spin!

- To put maximum spinn need lower disc T ie higher M lower mass accretion rate
- Need M>$10^8$M
- Withing mass limits get a<0.6



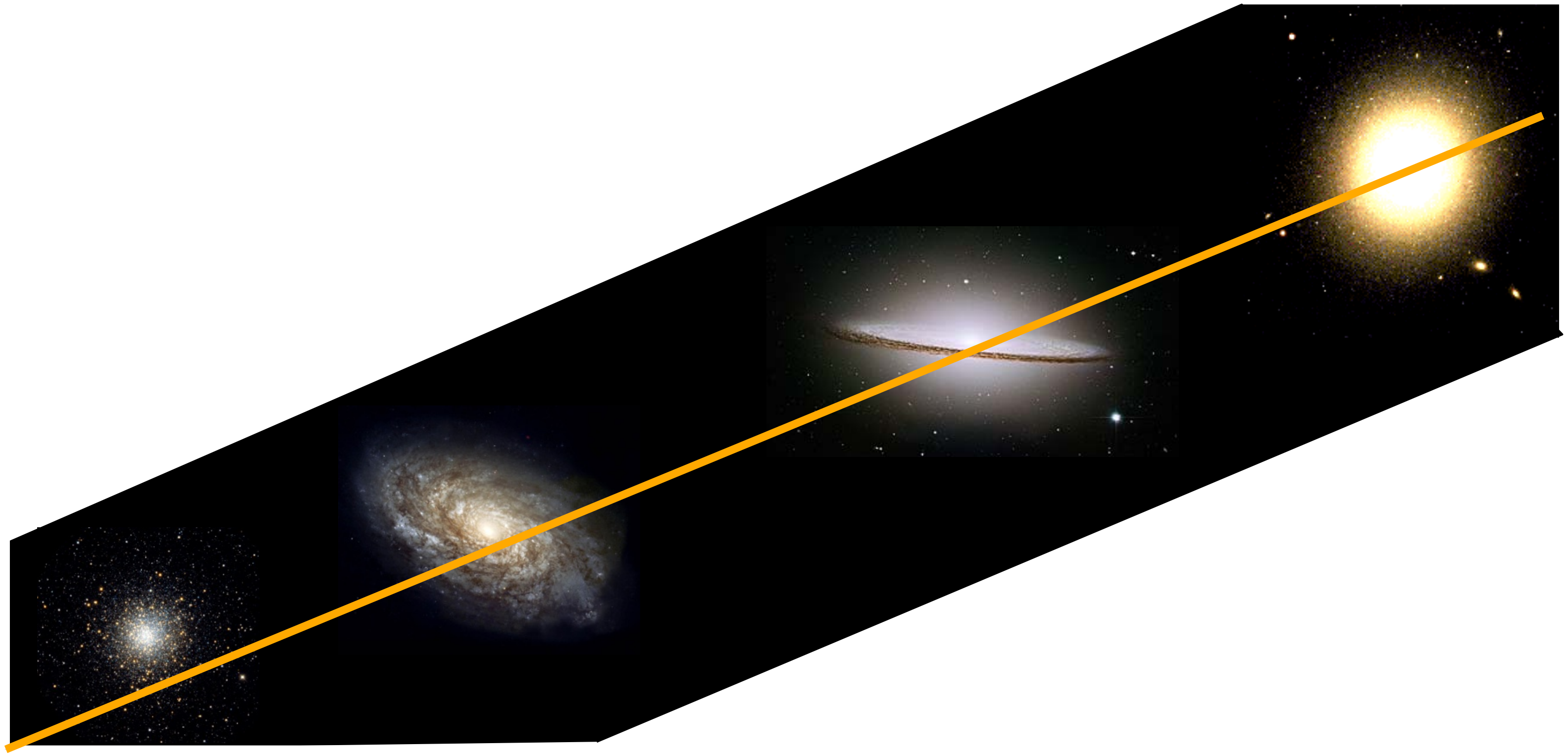

Done,, Jin, Middleton Ward 2012

# Conclusions: BHB-AGN

- Use BHB to understand (characterize) accretion
- See disc down to last stable orbit at high L/Ledd !!
- Disc progressively recedes below L/Ledd<0.01
- moving radius, moving QPO Lense-Thirring precession?
- Scale to AGN: different BHB spectral states mean different ionising spectra so different optical line ratios
- Unabsorbed LINERS-S1-NLS1 increasing $L/L_{Edd}$ and decreasing M (downsizing) so L often SAME!
- DON'T assume Lopt/Lbol or Lx/Lbol constant or L
- LINERS – low/hard state
- NLS1 – disc dominated with SMALL SX – can get spin!
- S1/QSO don't look like any BHB state – wind??

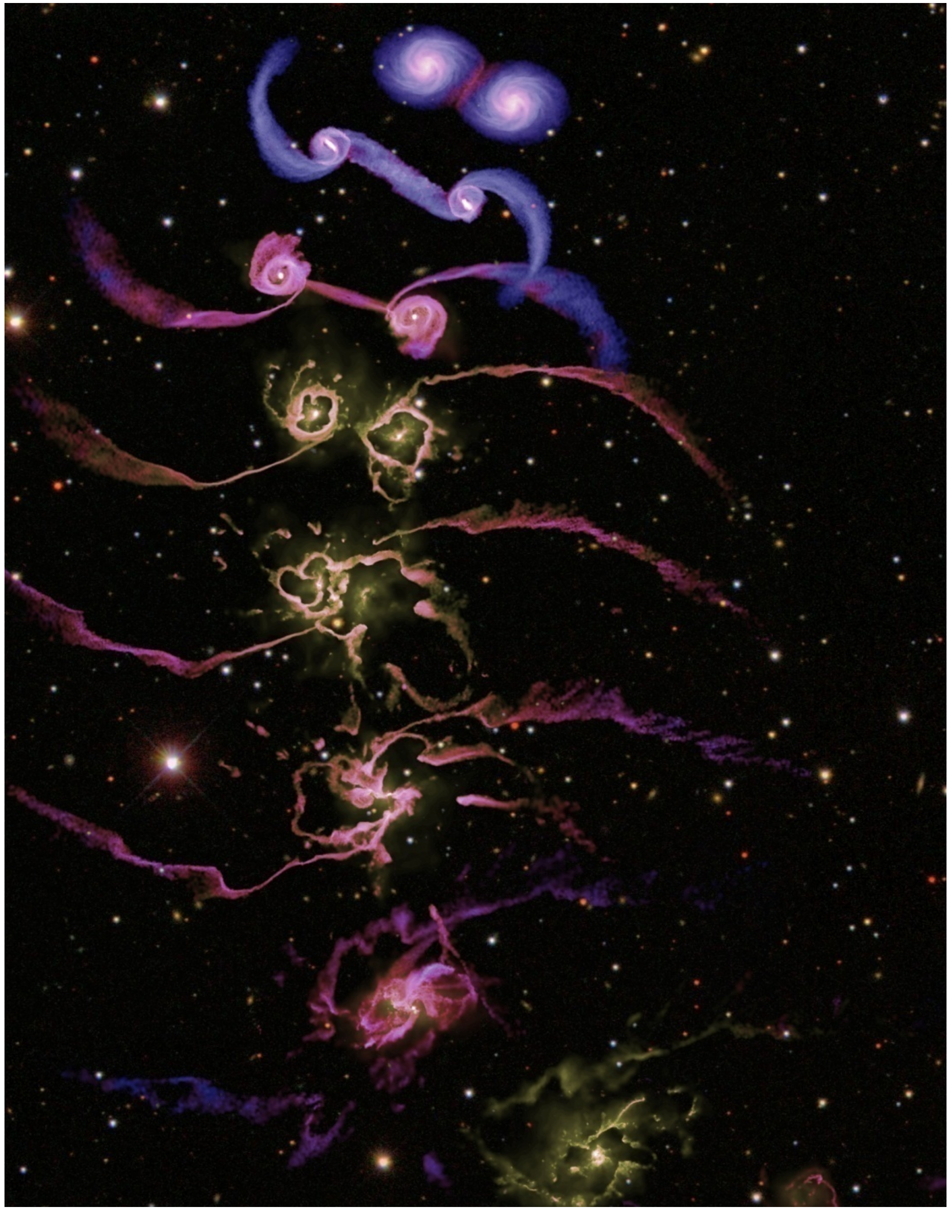
# Mass of AGN??

- 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
- $10^{5-10}$M



# Black holes in AGN grow by accretion

- Gas supply to nucleus
  - Galaxy disc instabilities
  - Major mergers
  - Minor mergers
  - Cooling flow of hot gas from halo
- Regulated by feedback
  - Supernovae
  - Kinetic energy from jet
  - Momentum from wind and/or radiation
- Need to understand accretion to understand feedback

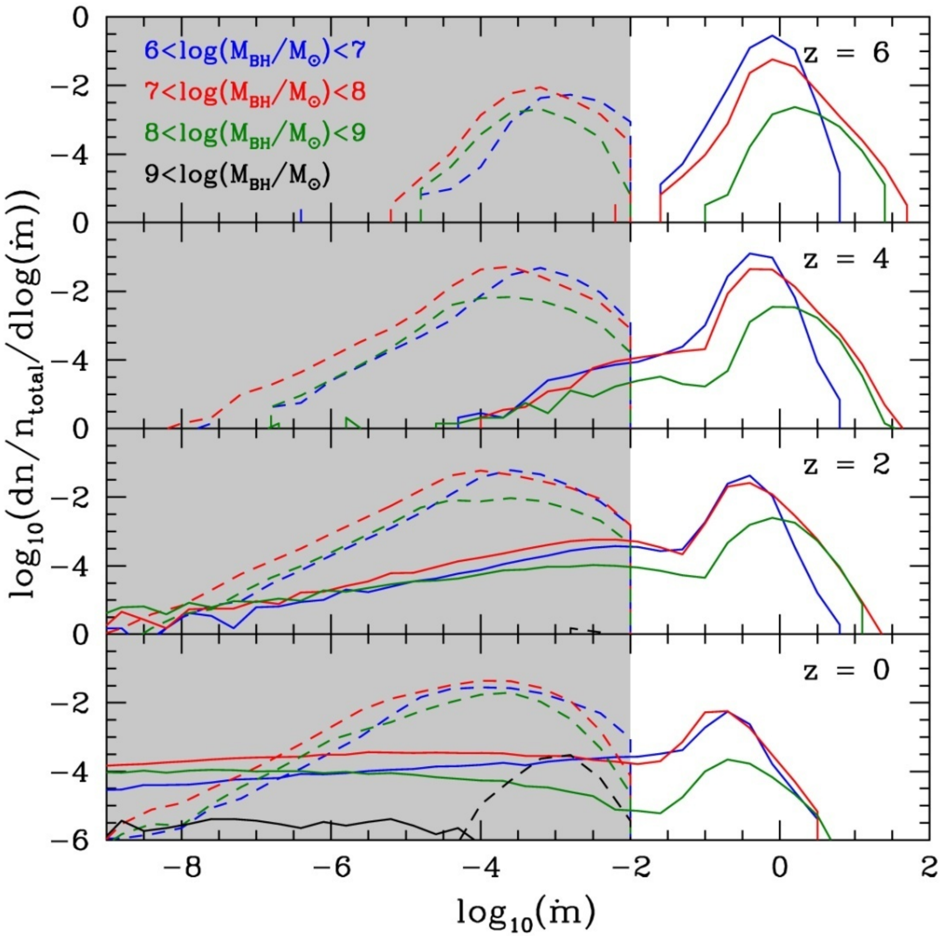


Di Matteo et al 2005

# Black hole mass accretion rate

Fanidakis et al 2010

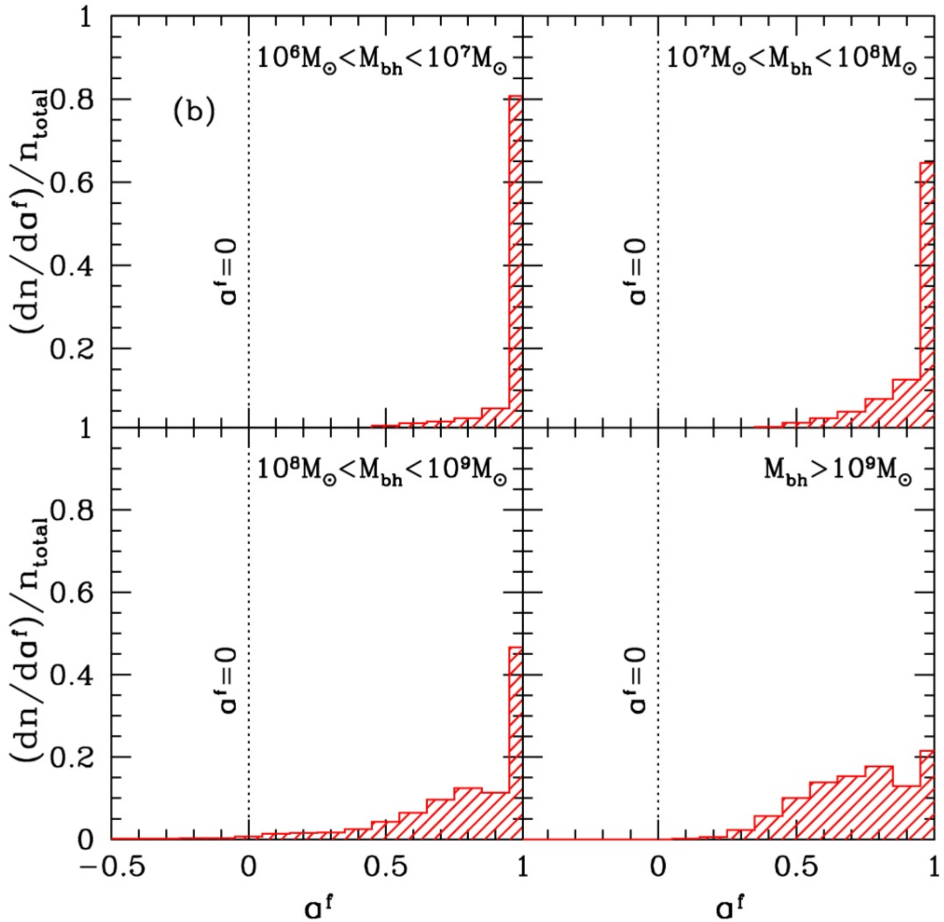
- Now need a prescription to link M and L/Ledd to the jet kinetic power
- And another prescrition to link jet power to radio power (also depends on M and L/Ledd)
- Does it also depend on spin??



# Black hole mass and spin

- Prolonged accretion?
- Typical mass available in each accretion episode is > $M_{BH}$ so spin BH up to maximal a ~ 1
- BH – BH mergers spin DOWN the most massive BH to 0.7

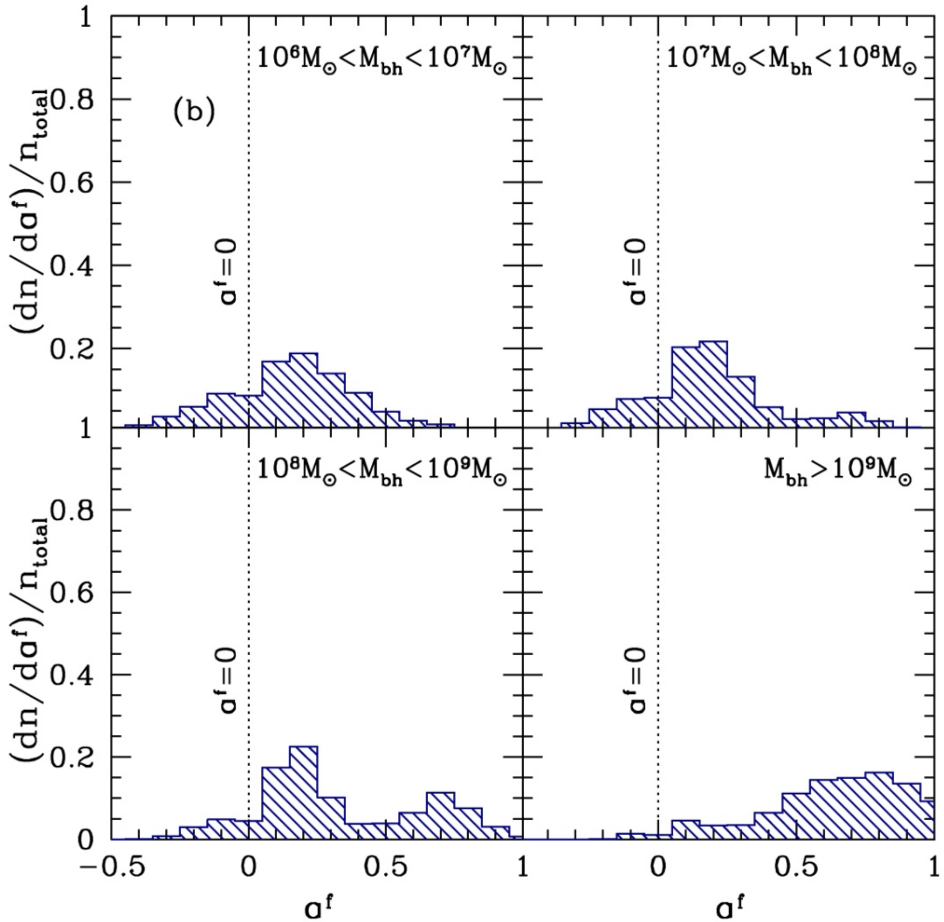
Fanidakis et al 2010



# Black hole mass and spin

Fanidakis et al 2010

- Chaotic accretion?
- Mass of thin disc limited by self gravity to ~ (H/R) $M_{BH}$ (King et al 2008)
- Each accretion episode splits up into multiple events with randomised direction
- Low spin except for most massive BH where mergers spin UP

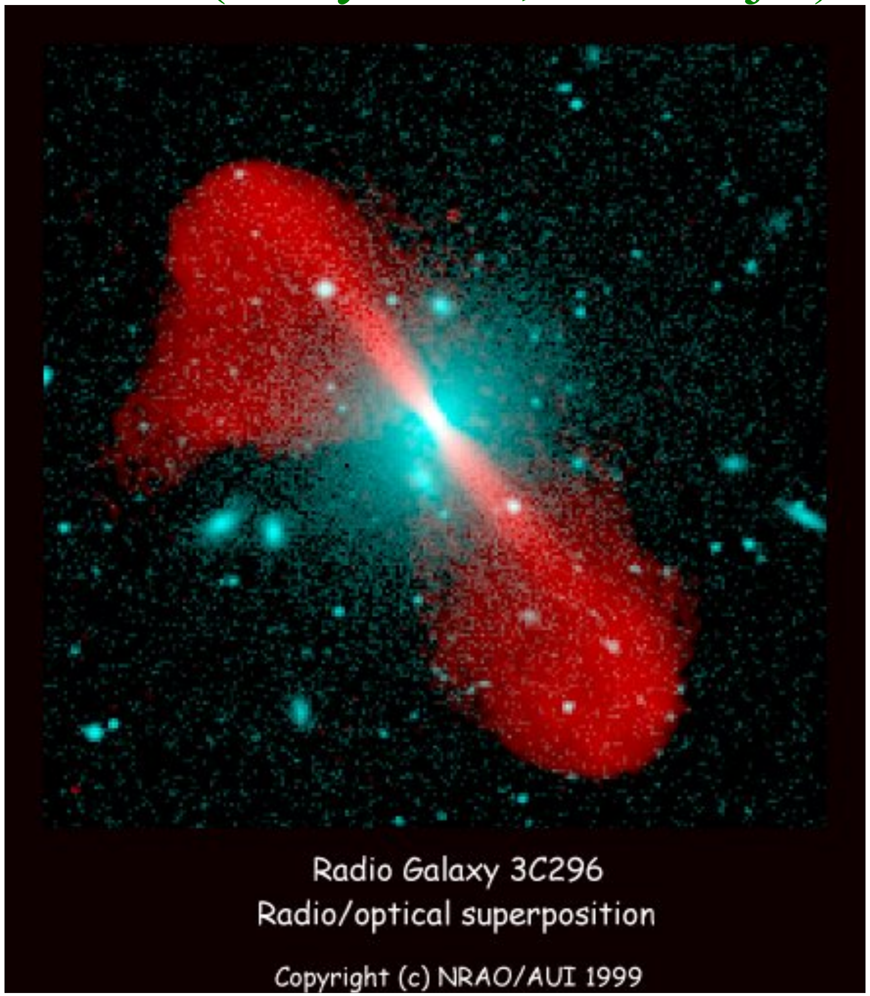


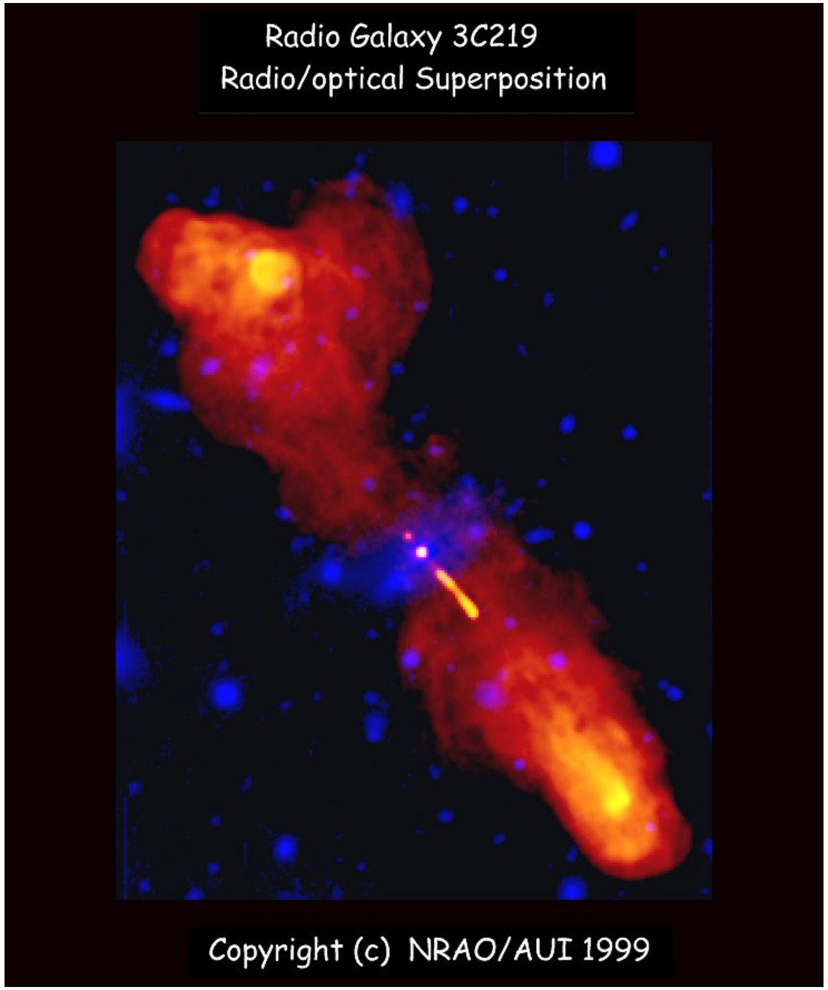
# Conclusions: BHB-AGN

- BHB - disc down to last stable orbit at high L/Ledd !!
- Test of GR in strong field limit
- Disc progressively recedes below L/Ledd~0.01
- Moving disc explains moving characteristic frequencies in power spectrum – QPO as Lense-Thirring precession ?
- AGN

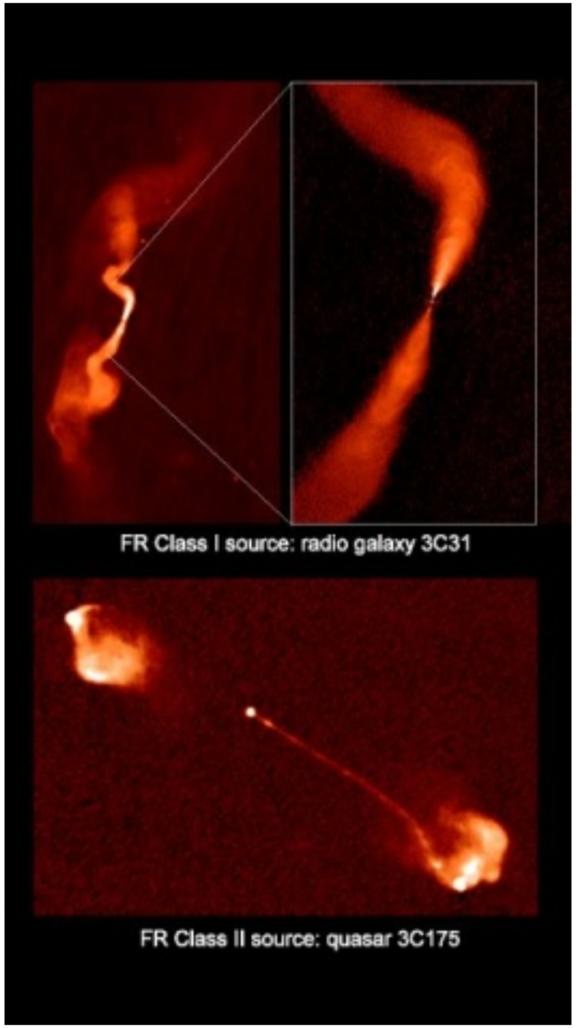
# AGN/QSO Zoo!!! Radio loud

- 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)

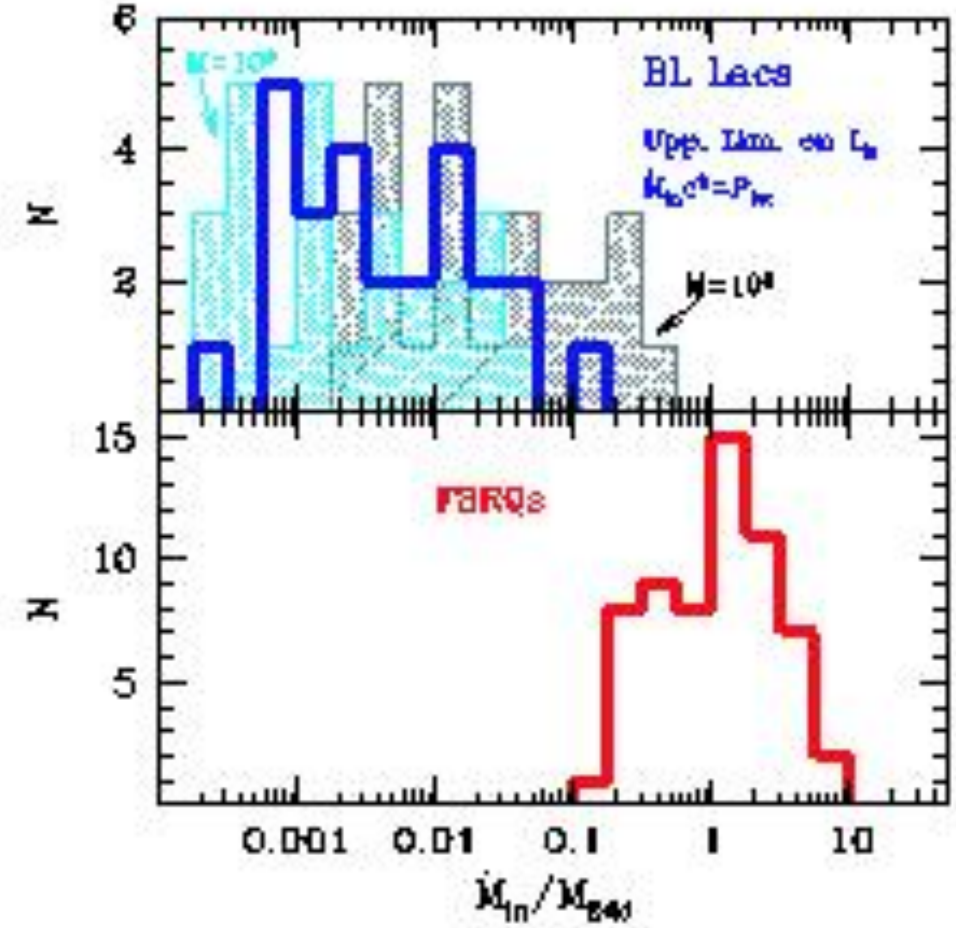


# FRI is top of ADAF branch


FR Class I source: radio galaxy 3C31

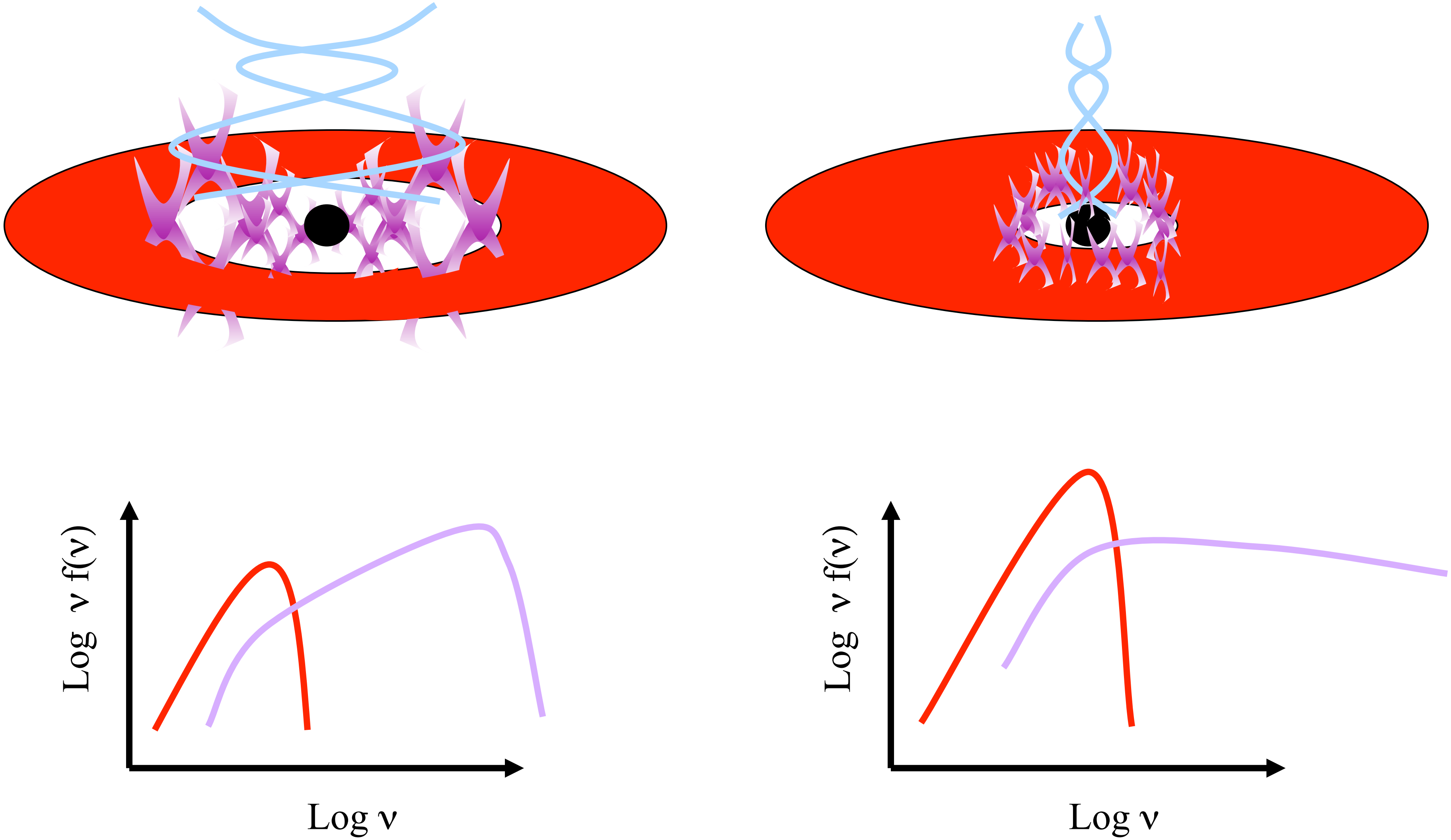
FR Class II source: quasar 3C175




Ghisellini et al 2010

L/Ledd < 0.01 ADAF FRI,
weak disk, low excitation
Broader, slower

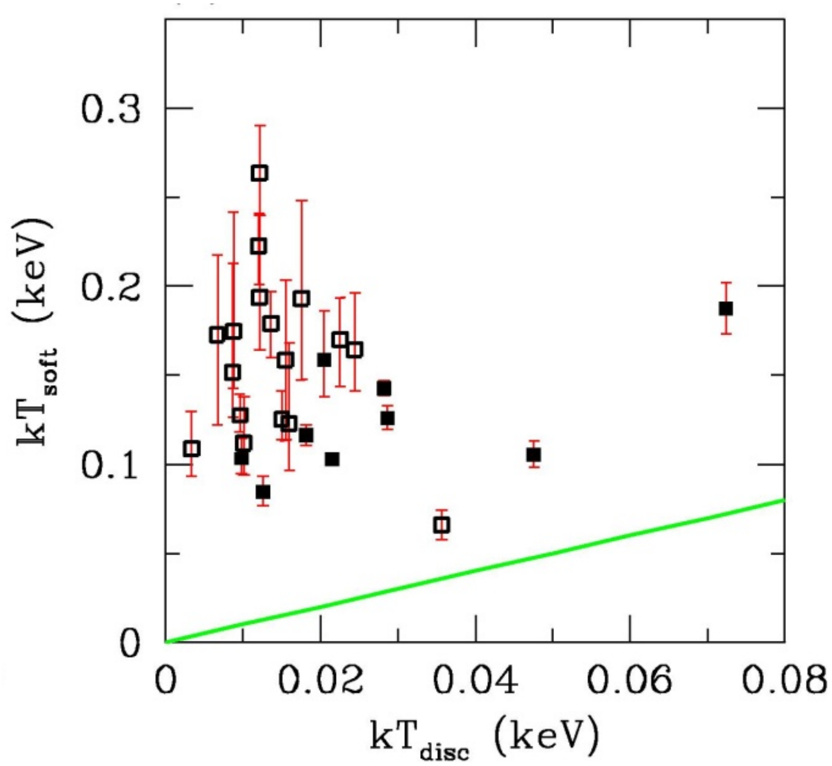
L/Ledd~1 Disc+tail FRII
strong disk, high excitation
Faster, narrower (Krause et al 2011)



# An additional component

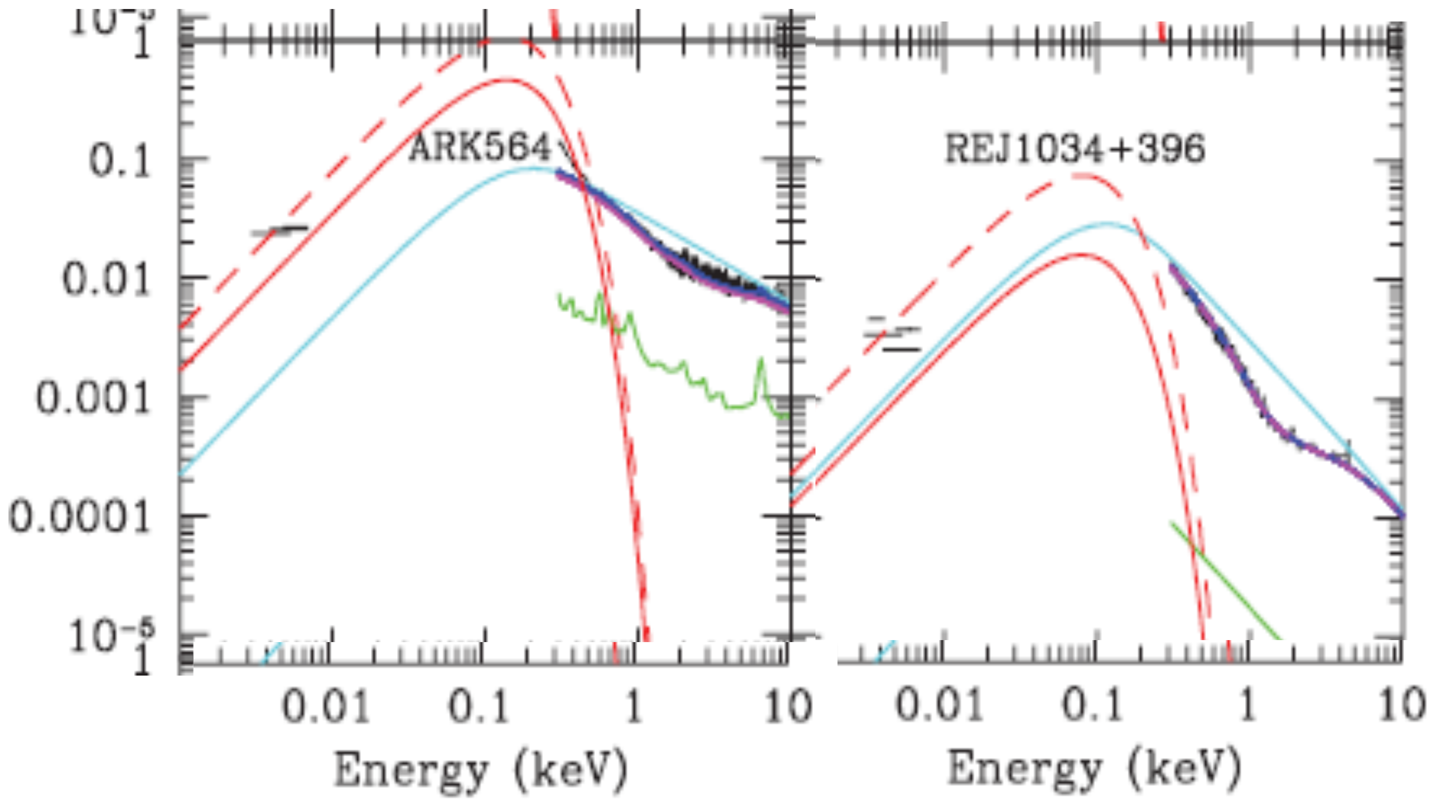
- ALL PG QSO need soft excess! This is very gradual and smooth, not steep, though strength varies
- Generally too hot to be the disc – we know mass and L/LEdd from optical and Hβ

Gierlinski & Done 2004



# But some discs do get close…

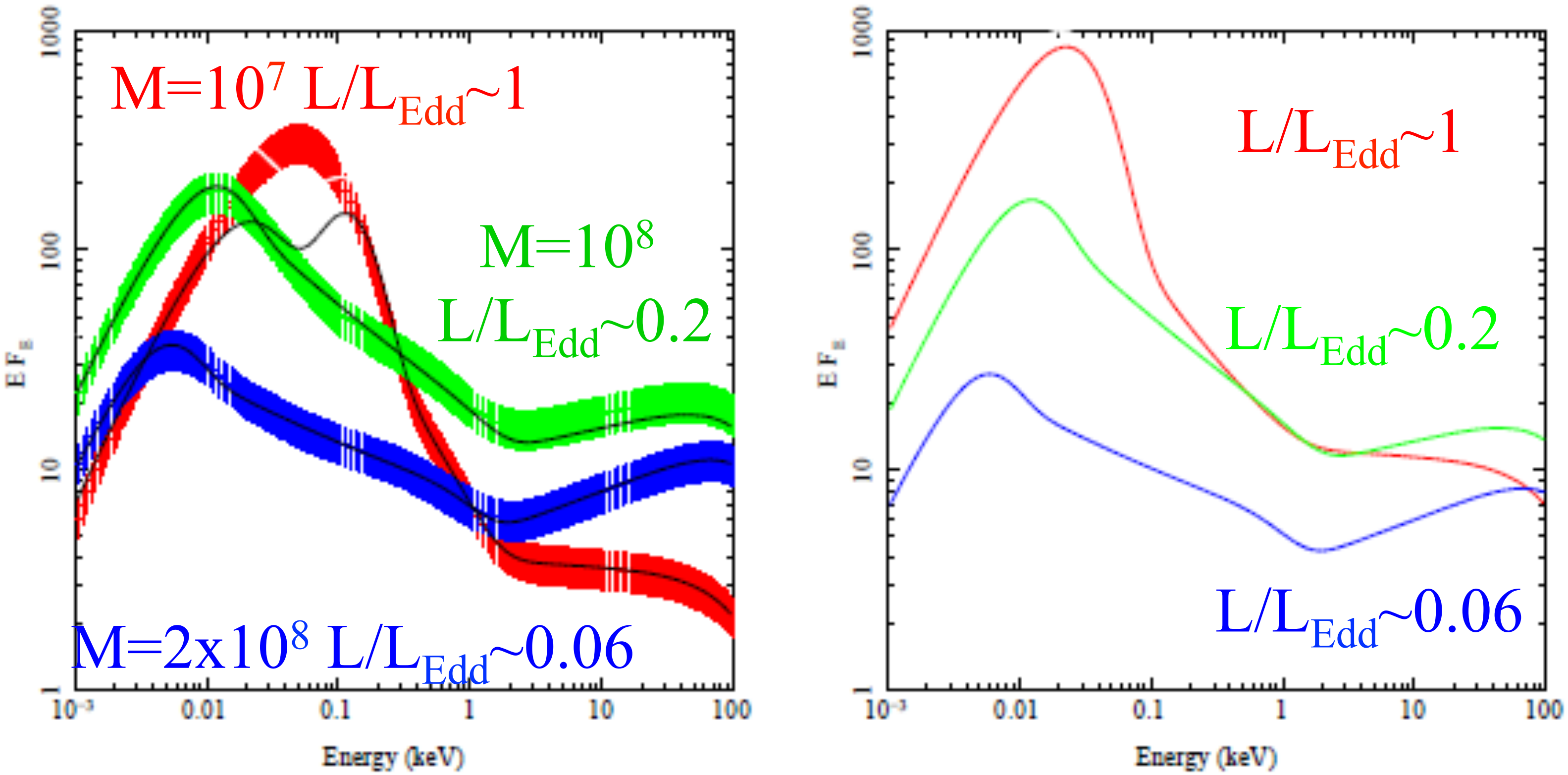
- Low mass, high $L/L_{Edd}$ – NLS1 !!
- Typically the objects with the biggest SX if just fit X-ray ….




Middleton et al 2007

# So what do AGN look like?

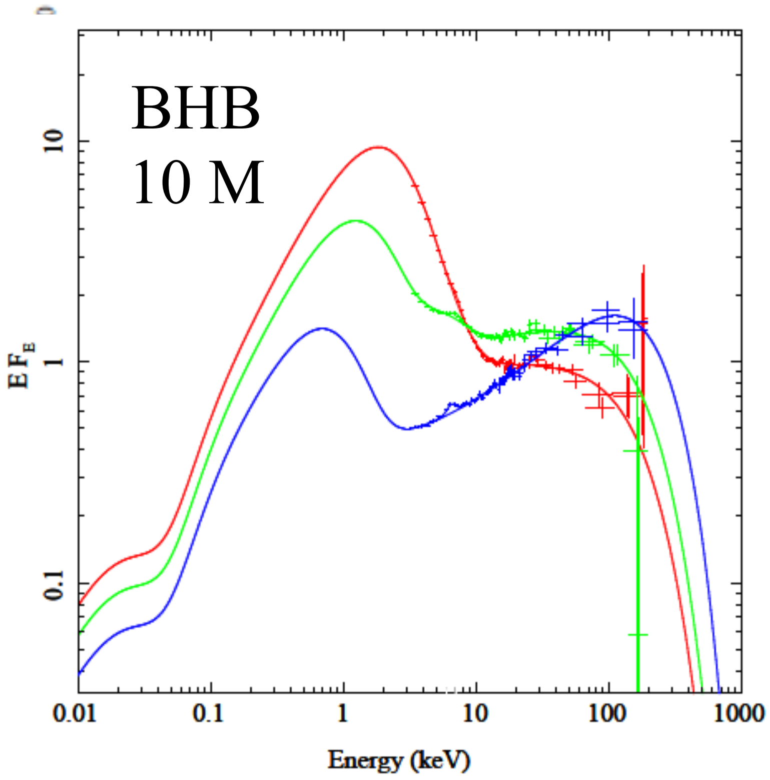
- Co-add models in 3 bins of $L/L_{Edd}$
- Correlates with M due to galaxy formation. high mass objects have low $L/L_{Edd}$ in local Universe – downsizing
- Physical model so shift to same mass $M=10^8$ to compare with BHB

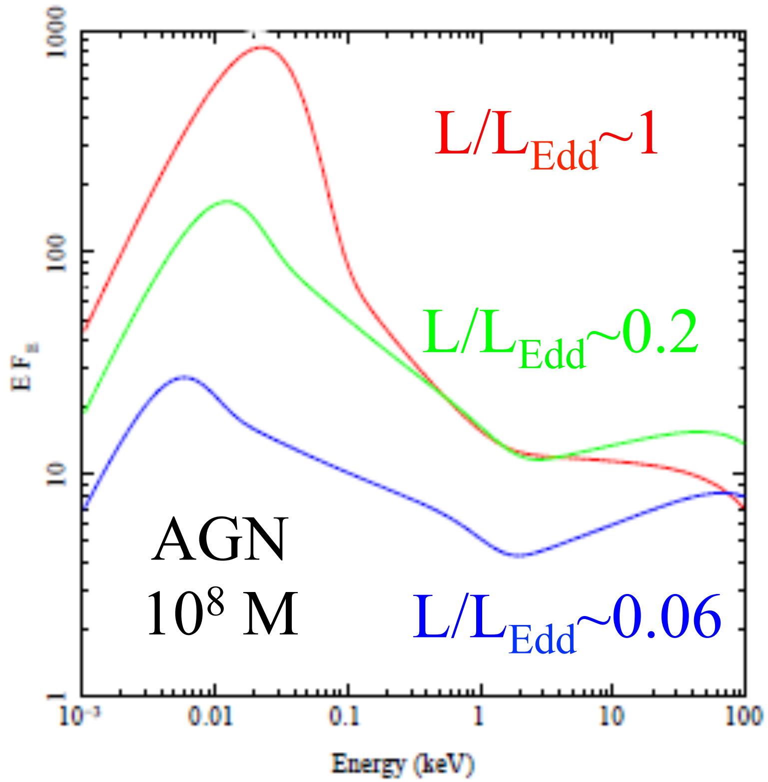



Done et al 2011

# Low/hard to high/soft ?

- Looks good to zeroth order… but….
- Transition at L/LEdd=0.02 in steady state accretion - 0.2 in AGN
- Green/blue are classic QSO NOT LINERS – not low/hard state as no jet! Disc shape very strange, soft X-ray excess….

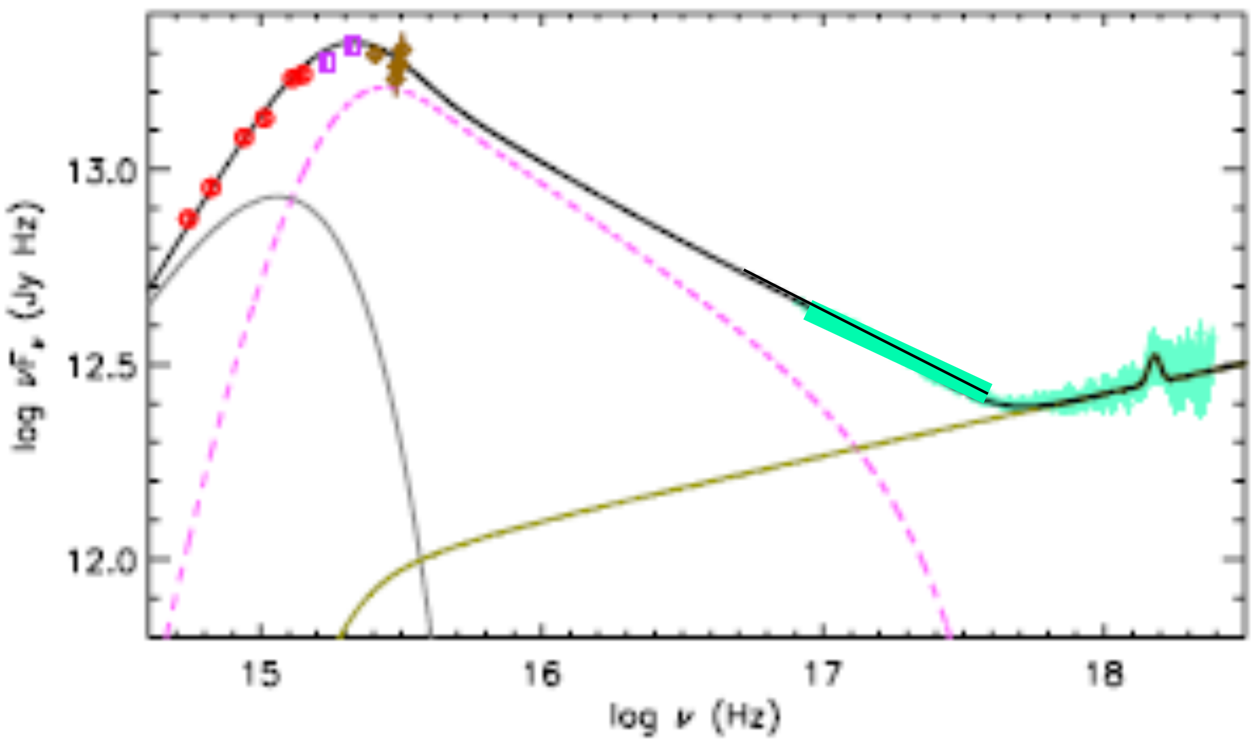



Done et al 2011

# Classic QSO?

- It's the classic QSO shape which is strange. Not low/hard as no jet, and strange soft excess…. WHICH IS REAL
- Mkn 509 (Suzaku SX constant, PL varies Noda et al 2011) !
- Different disc structure due to wind mass loss ???????




Medhipour et al 2011

# Classic QSO?

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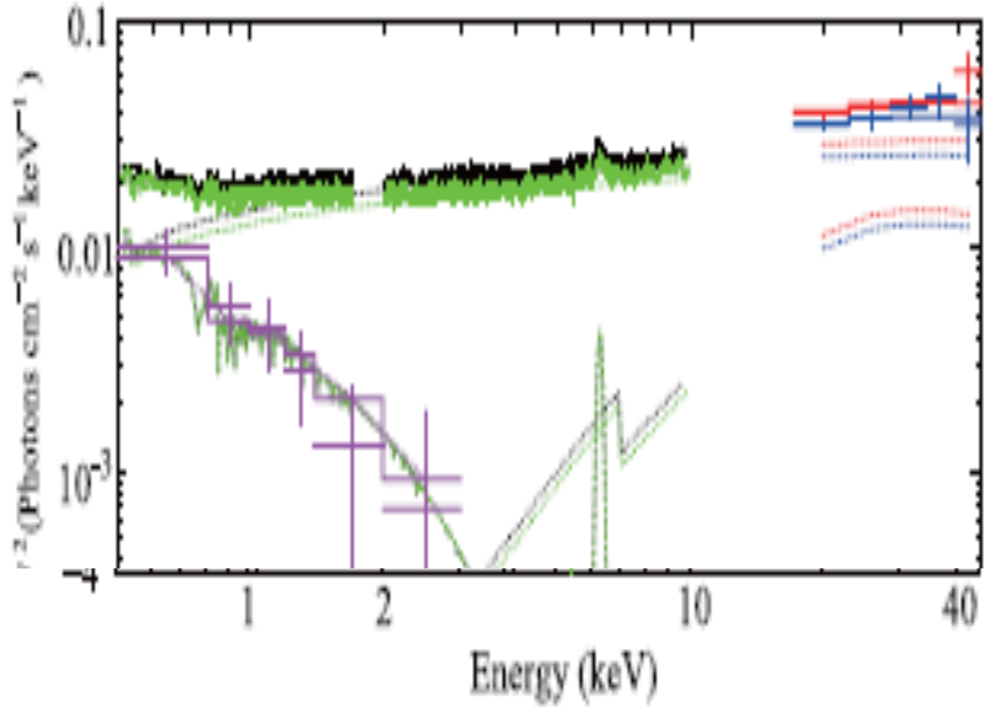
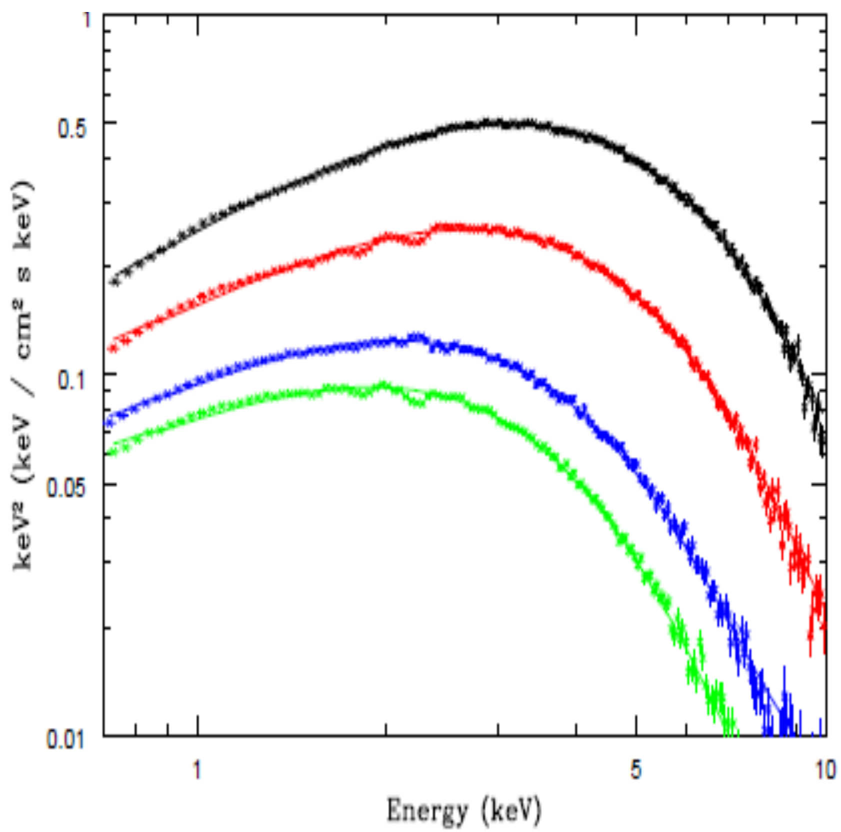



Noda et al 2011

# And at lower energies…

- RXTE misses peak of disc..
- XMM-Newton can see it directly still get good fits to constant radius disc models, though some residuals at the 5% level even with BHSPEC.
- Best disc models are not quite up to describing real data at the <5% level
- And still a few dirty things in the calibration

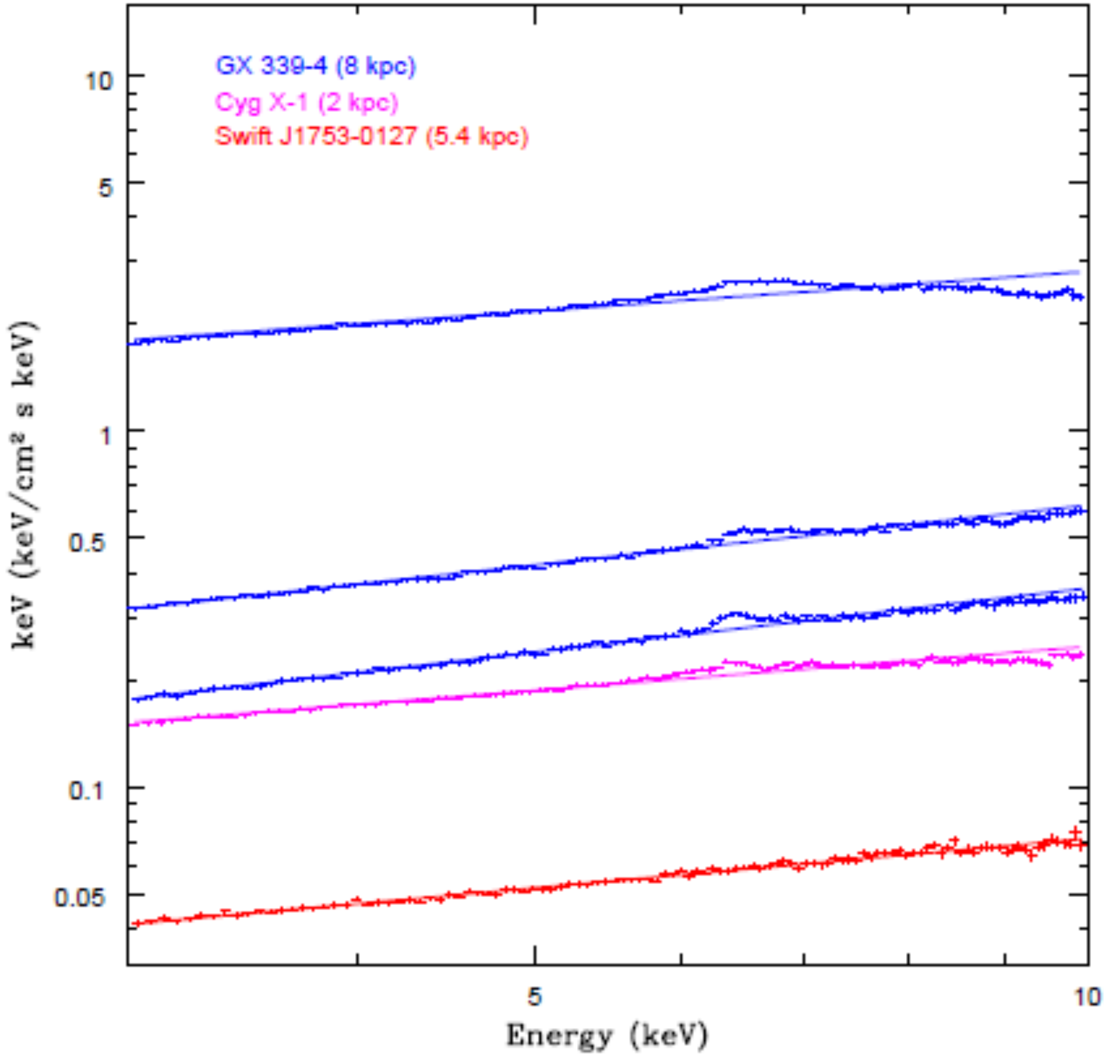
Kolehmainen et al 2012



# Moving disc

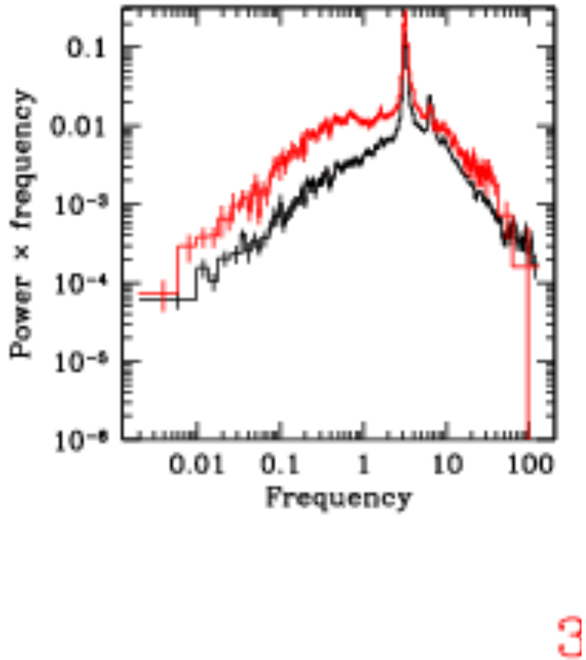
Kolehmainen Done & Diaz Trigo 2012

- Iron line should be very small and narrow for low L/LEdd
- Gets bigger and broader as disc moves in
- XMM-Newton timing mode - Kolehmainen Done & Diaz Trigo 2011 cf Tomsick et al 2010

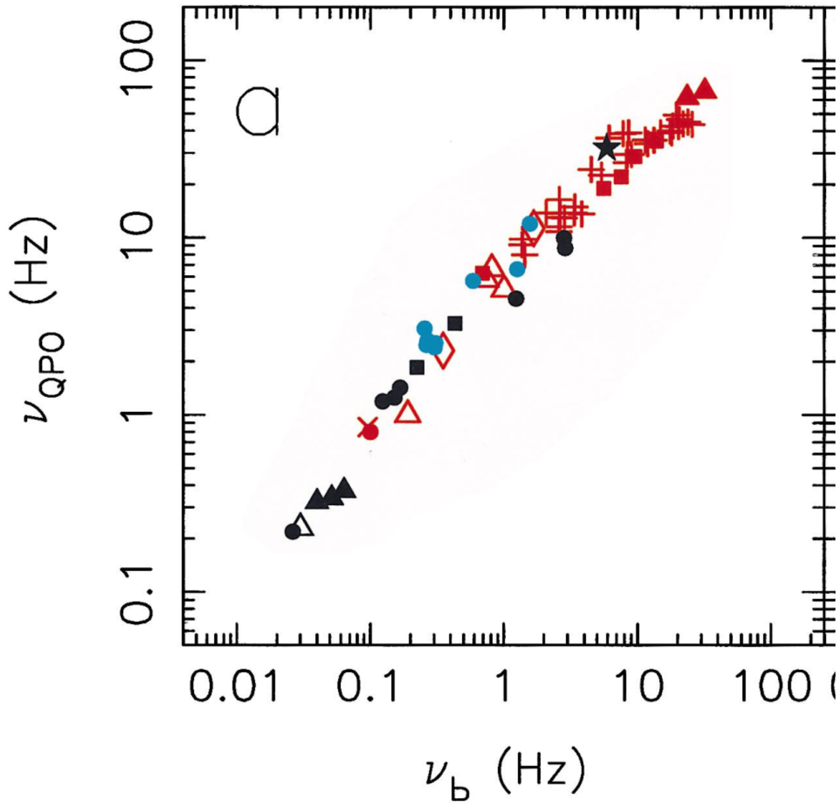


# QPO and broadband noise

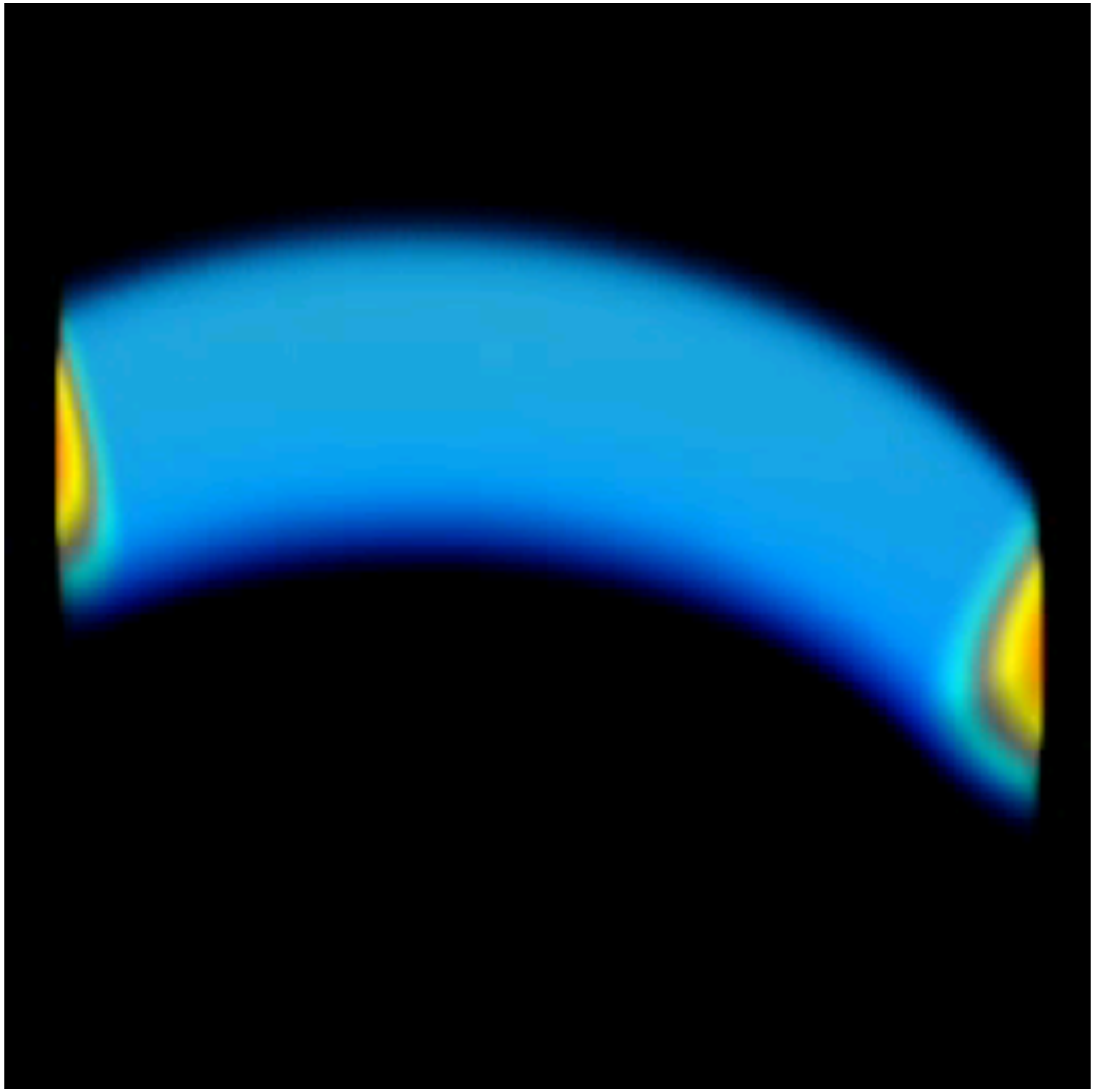
- Low frequency QPO moves with low frequency break



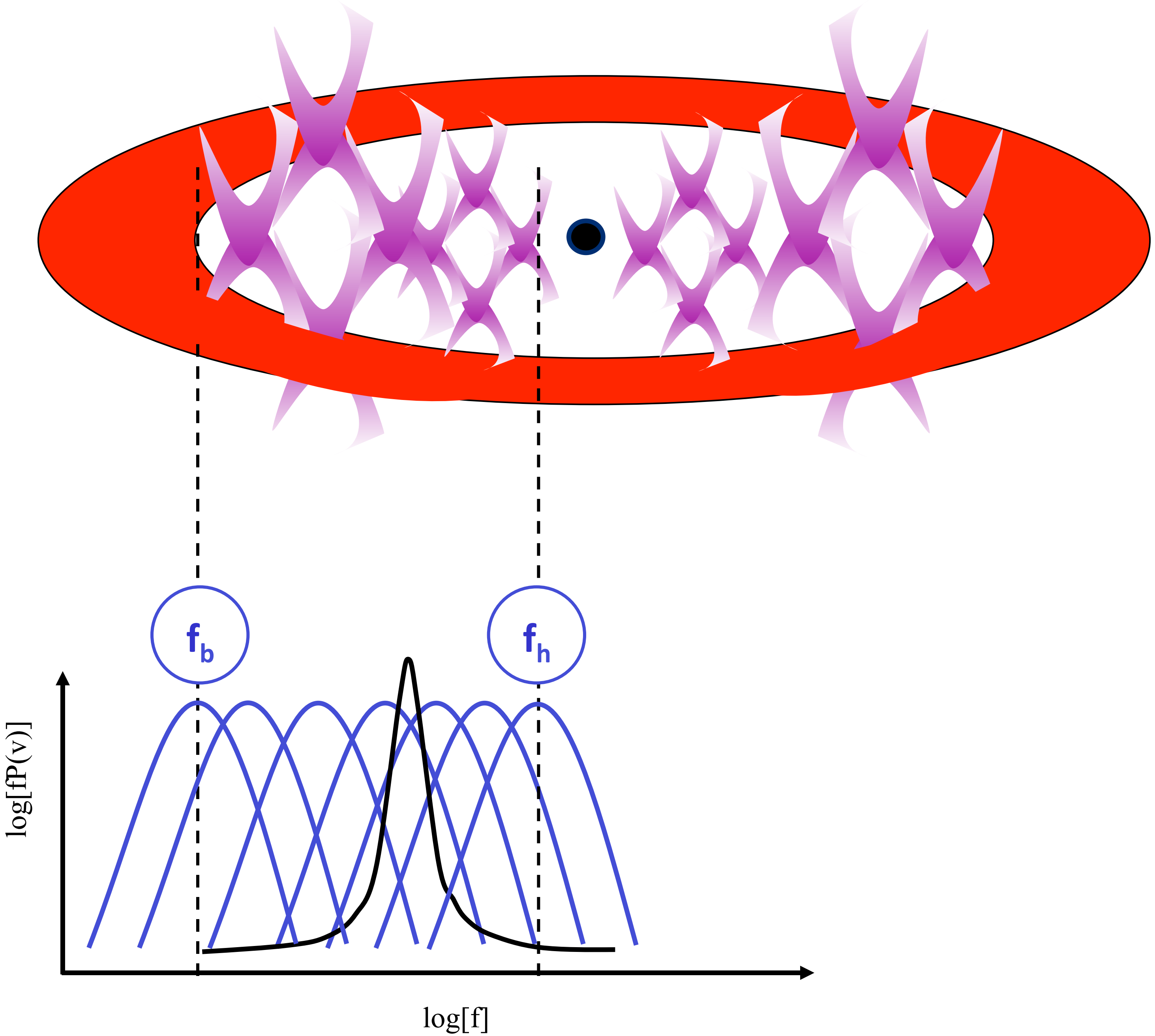

Wijnands & van der Klis 1989



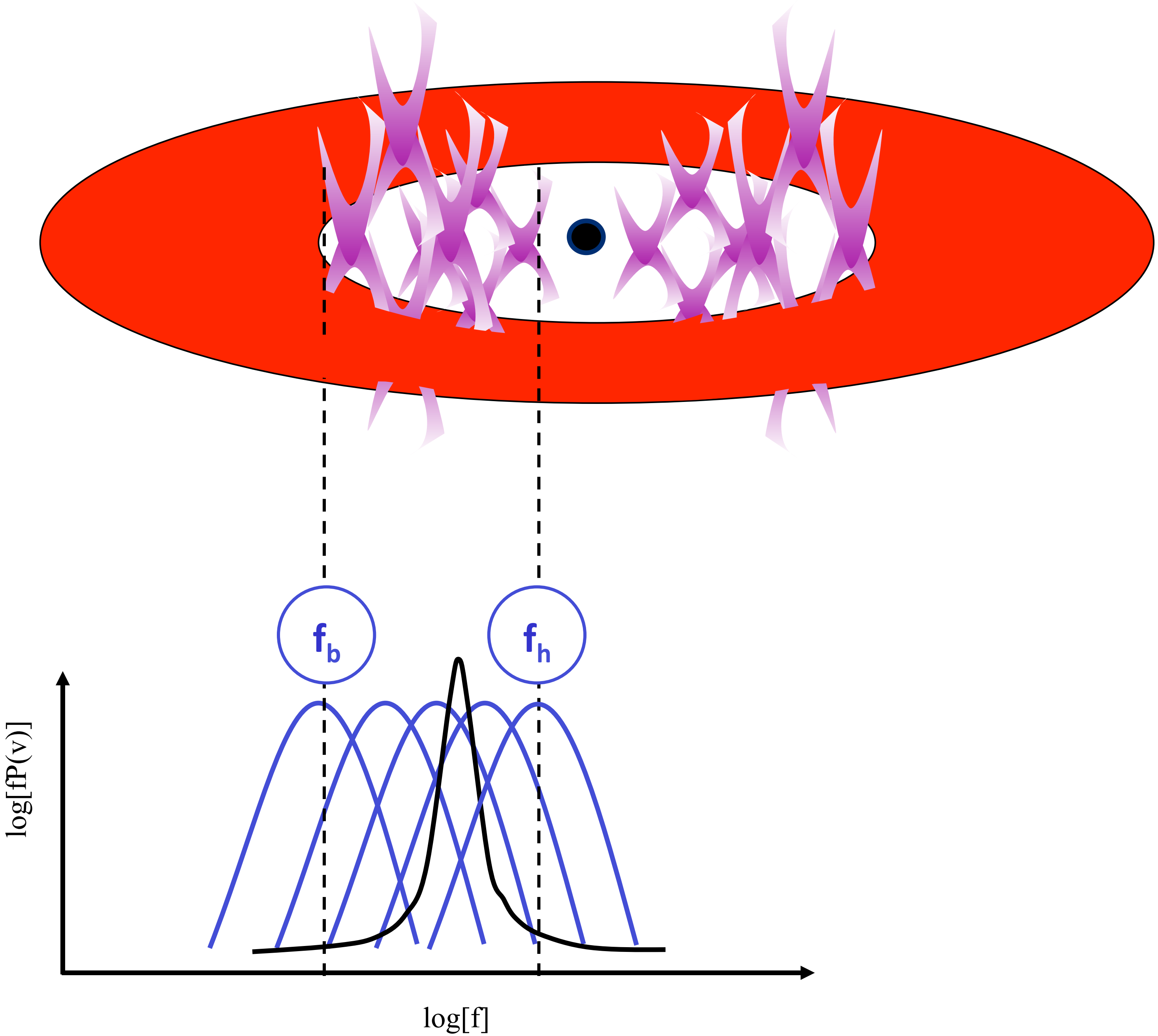
# Origin of variability: MRI



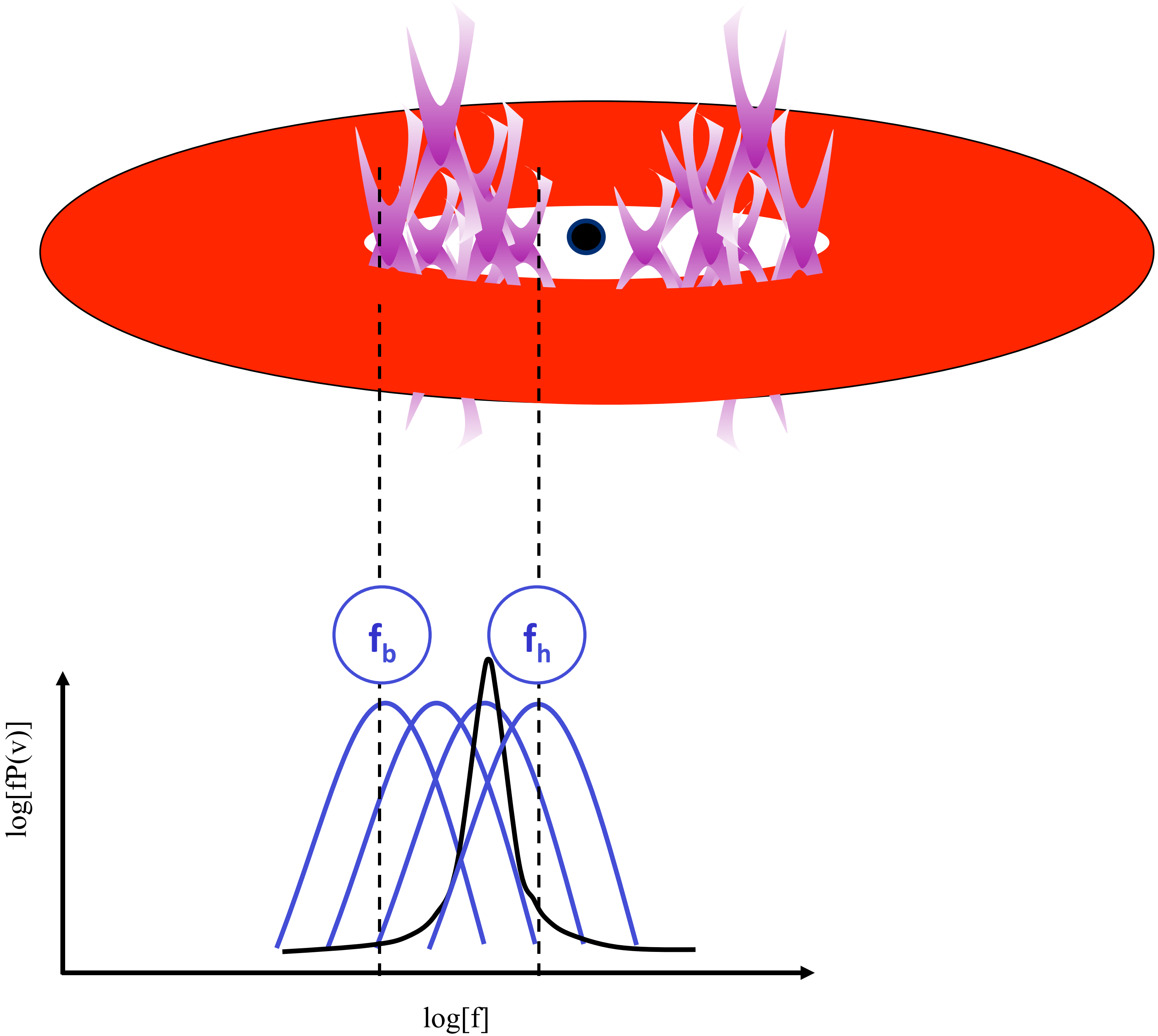
Krolik, de Villiers, Hawley



$f_b$
$f_h$
log[fP(ν)]
log[f]

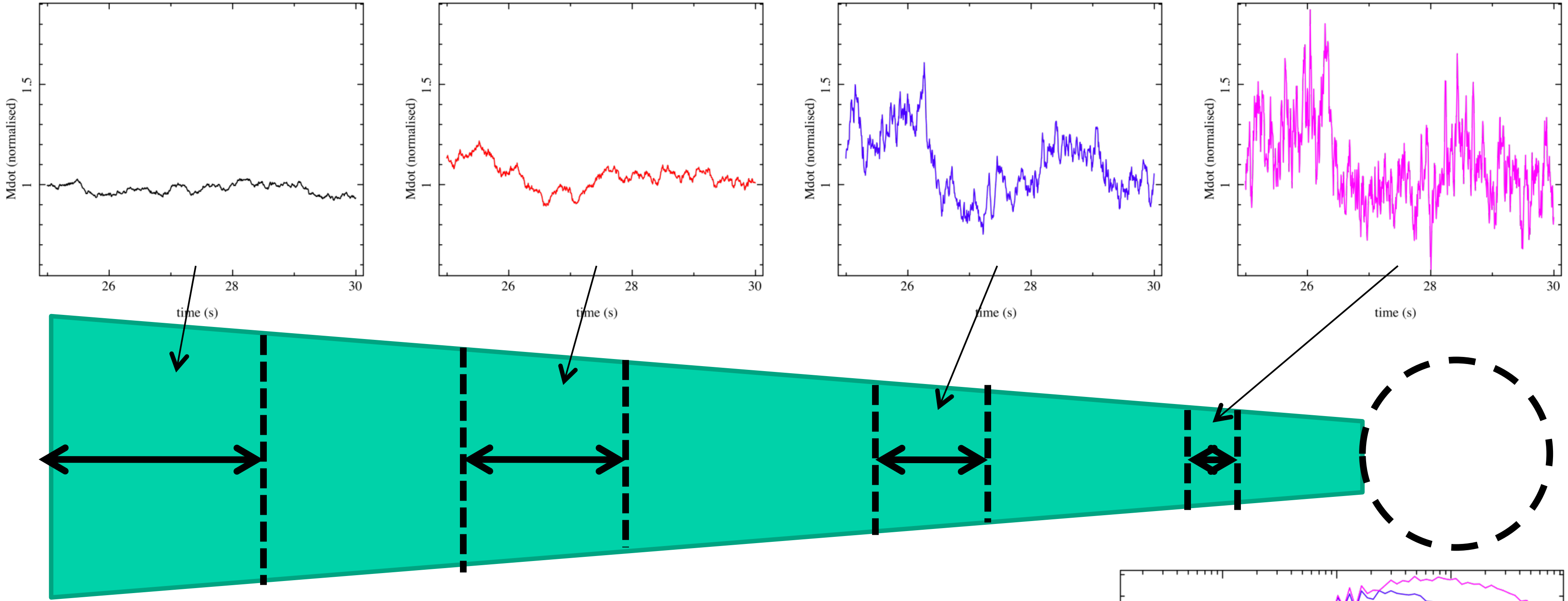


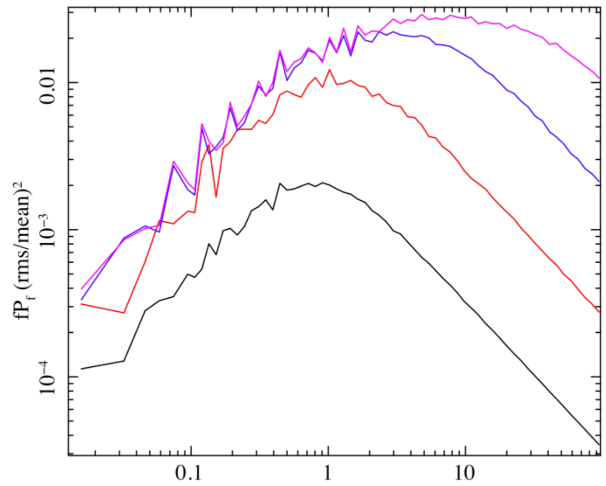
$f_b$
$f_h$
log[fP(v)]
log[f]



$f_b$
$f_h$
log[fP(ν)]
log[f]

# Propagating fluctuations



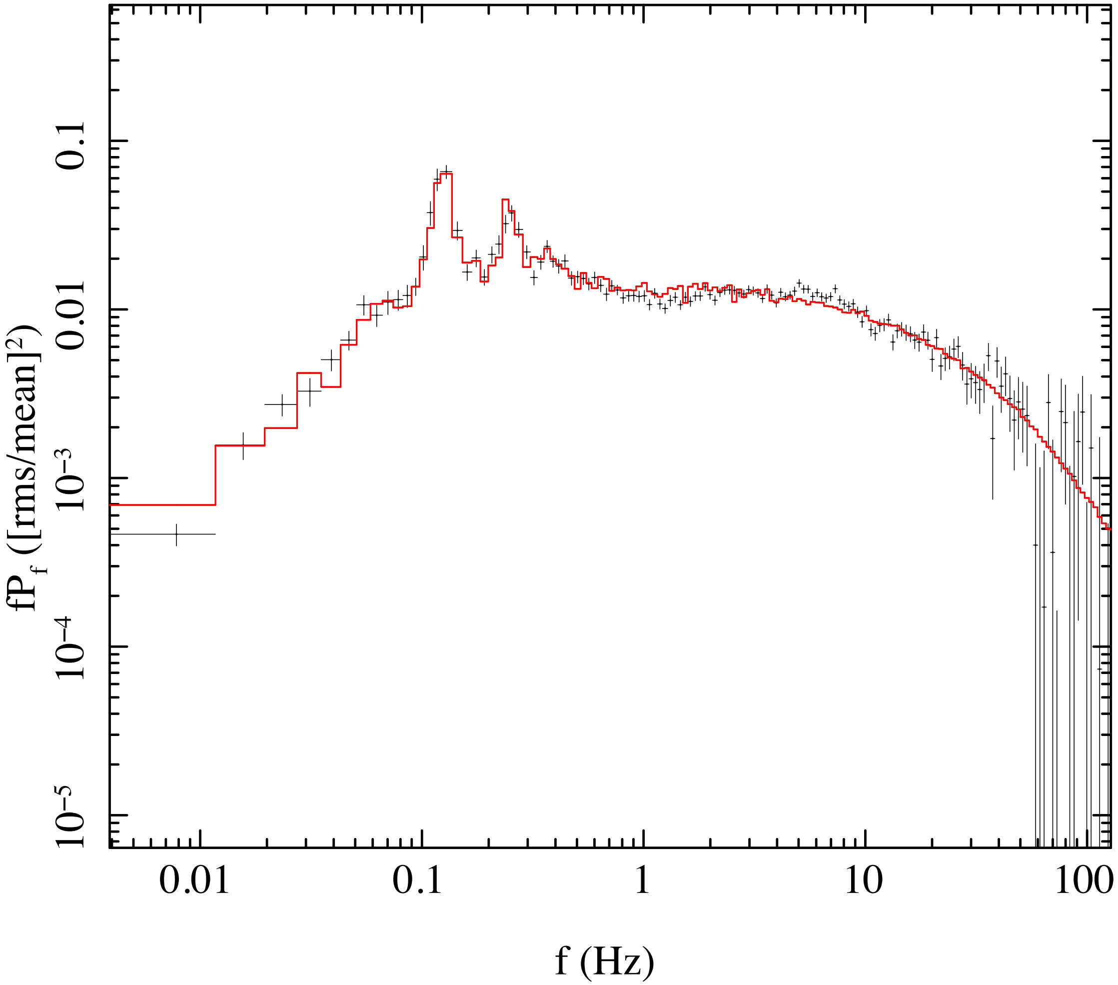




**This gives the noise spectrum EMMITED at each annulus**

Lyubarskii 1997; Arevalo & Uttley 2006, Kotov et al 2001

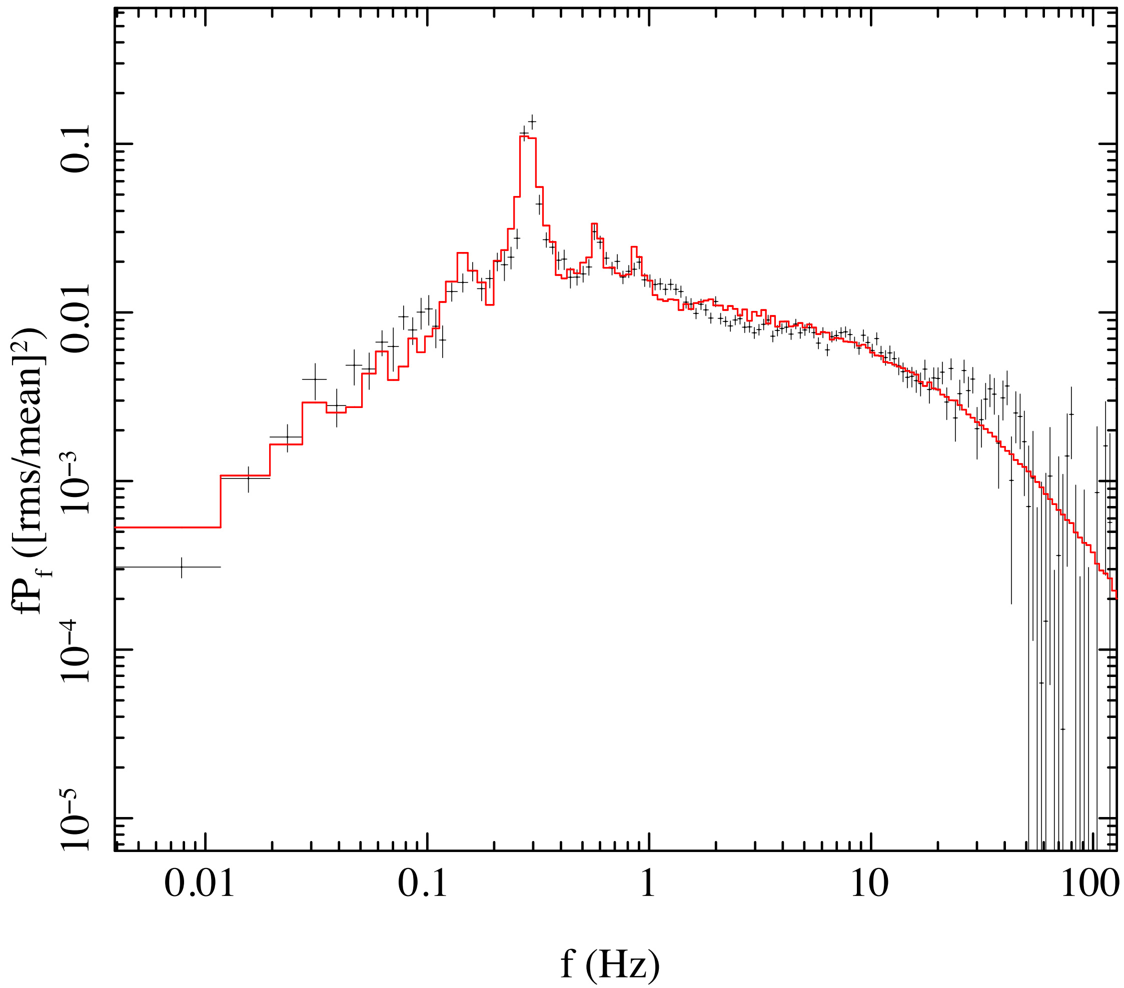
# Fitting to XTE J1550-564

## $r_o$=68.0



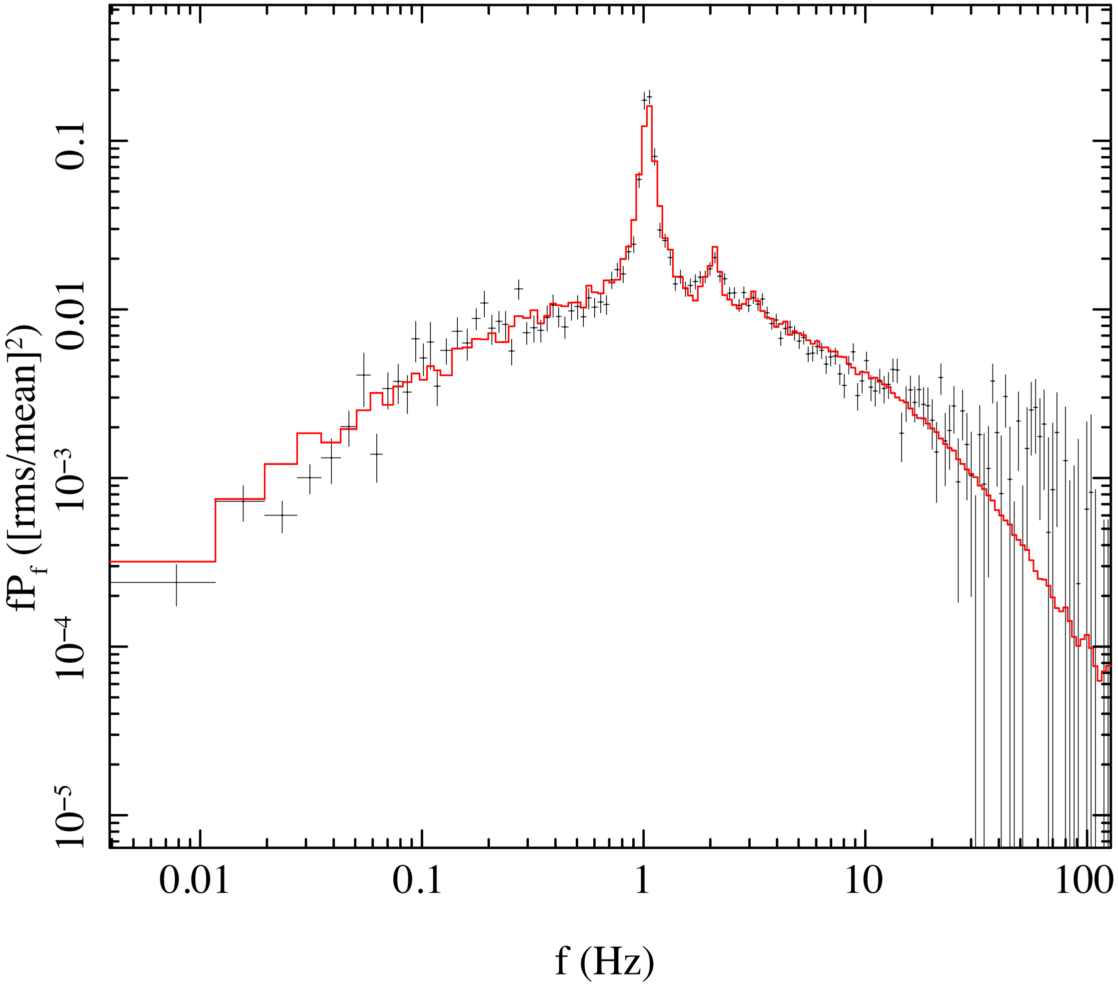
# Fitting to XTE J1550-564

## $r_o$=45.7



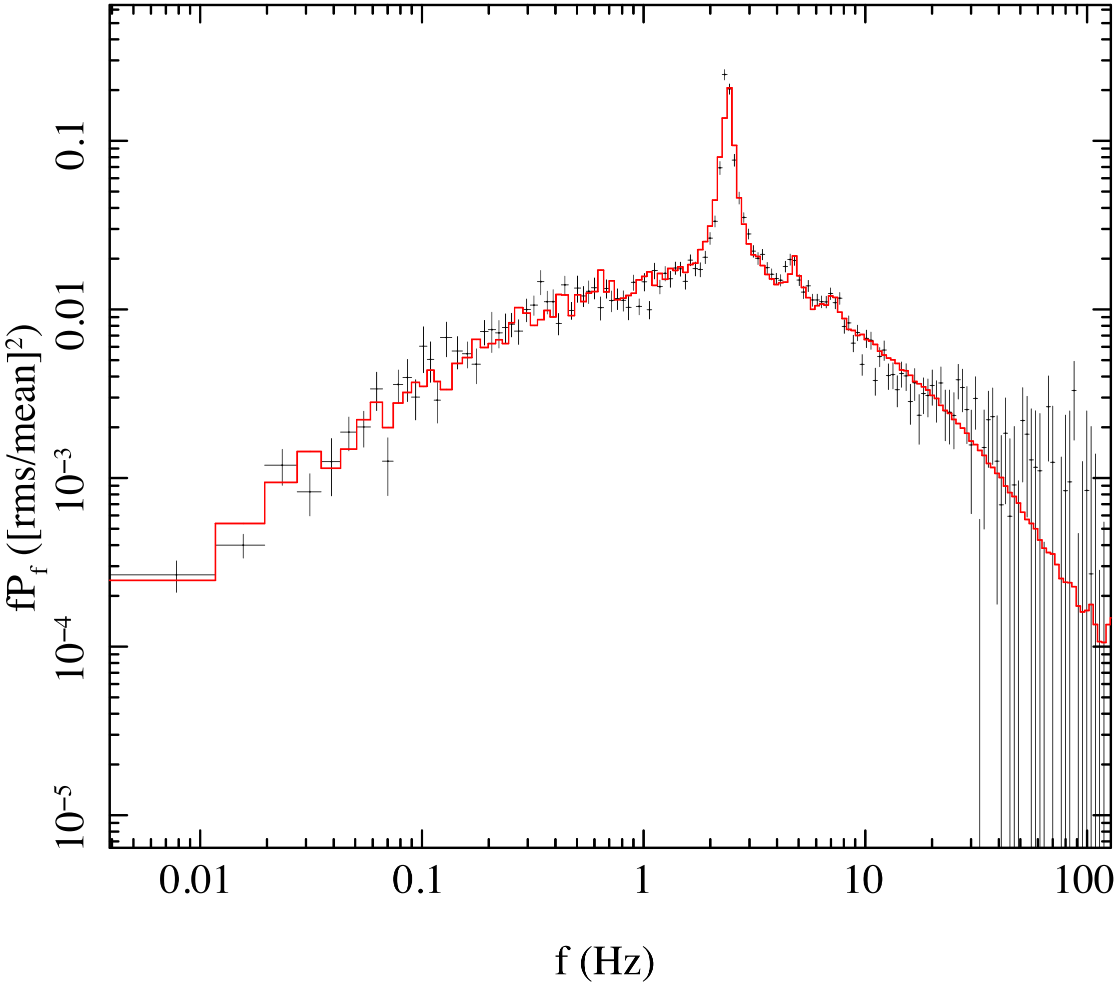
# Fitting to XTE J1550-564

## $r_o$=25.0



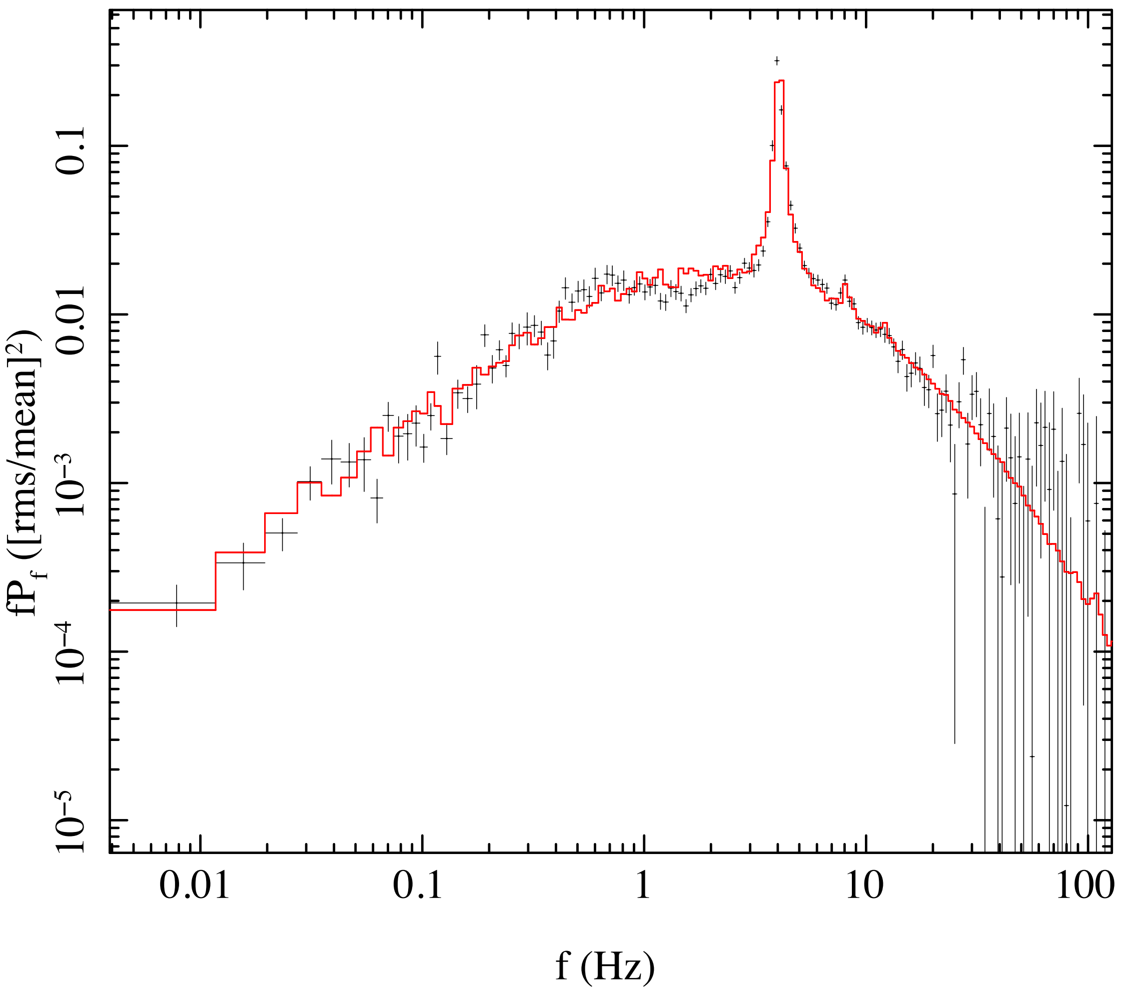
# Fitting to XTE J1550-564

## $r_o$=16.3



# Fitting to XTE J1550-564

## $r_o$=12.8




Ingram & Done 2011