Black holes and Neutron stars accretion flows in strong gravity

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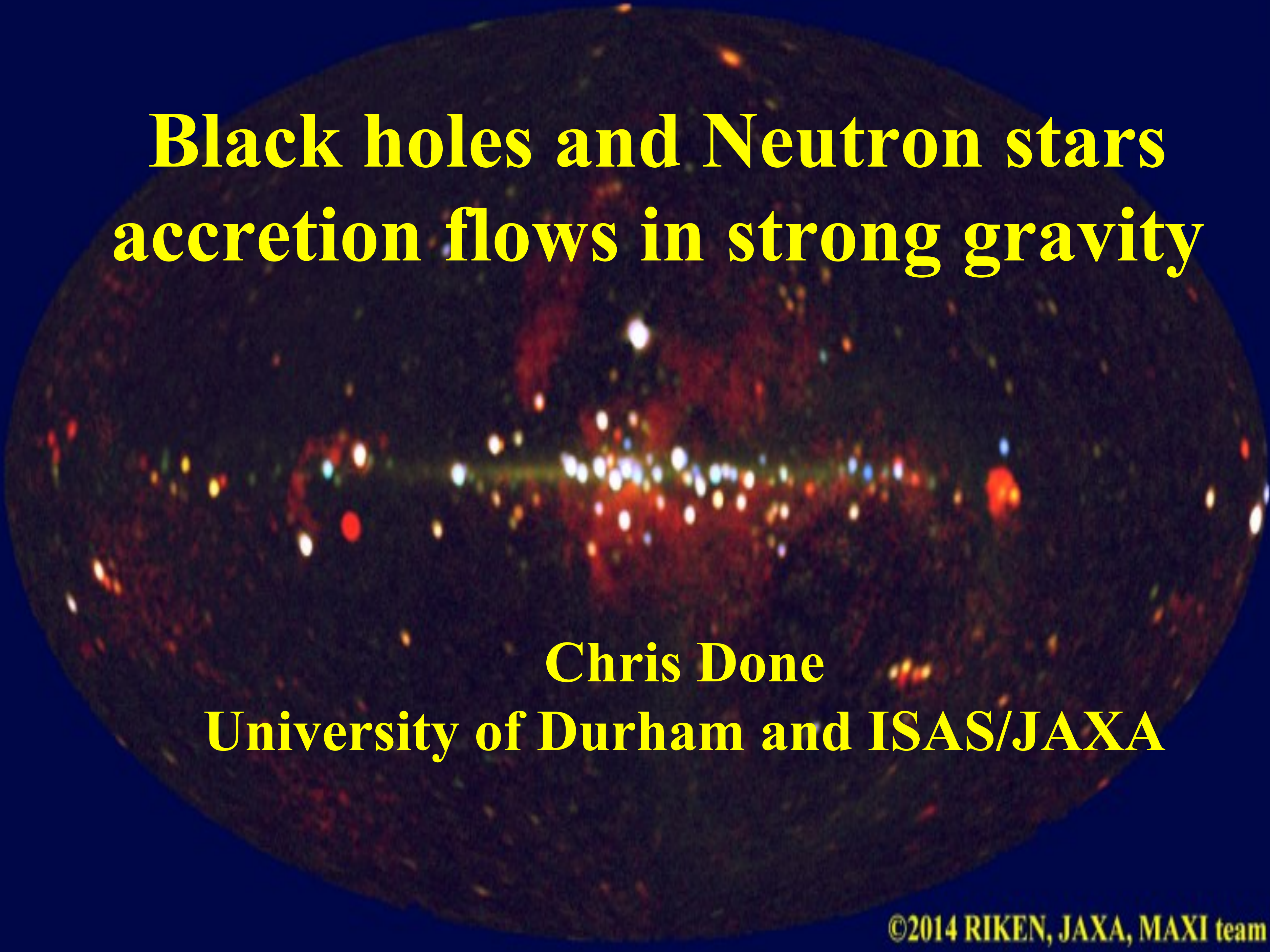
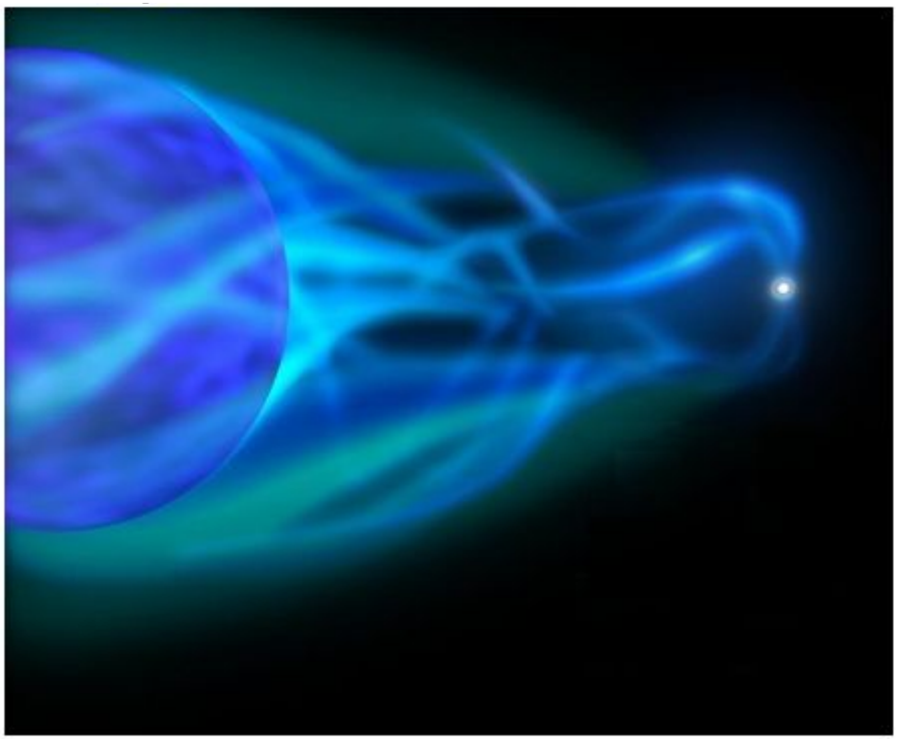
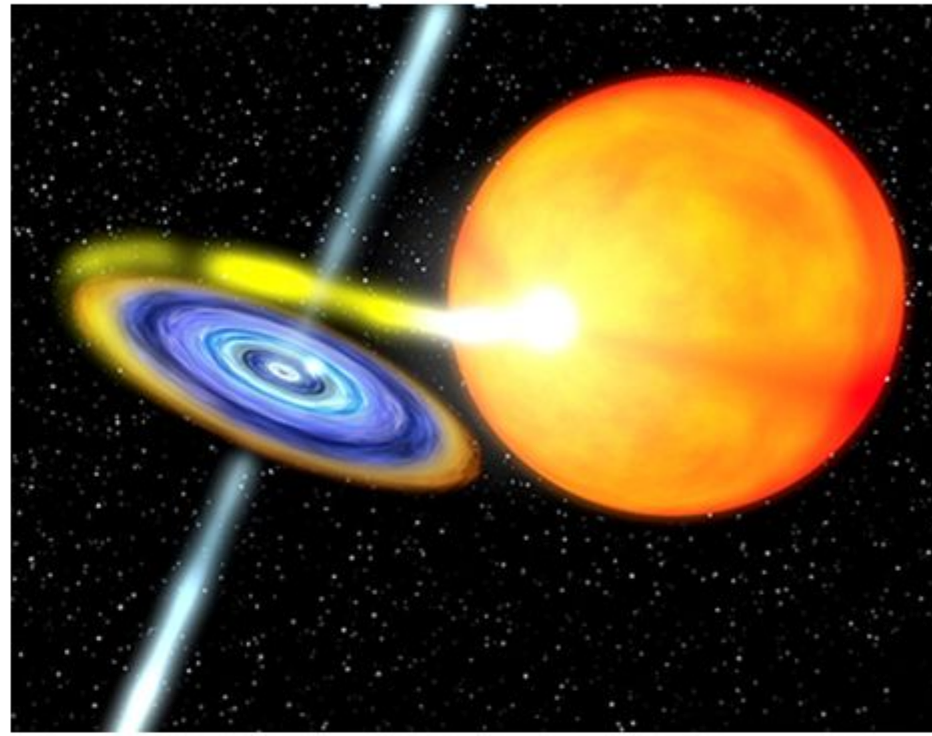


Interacting Binaries - BRIGHT
High mass XRB & low mass XRB



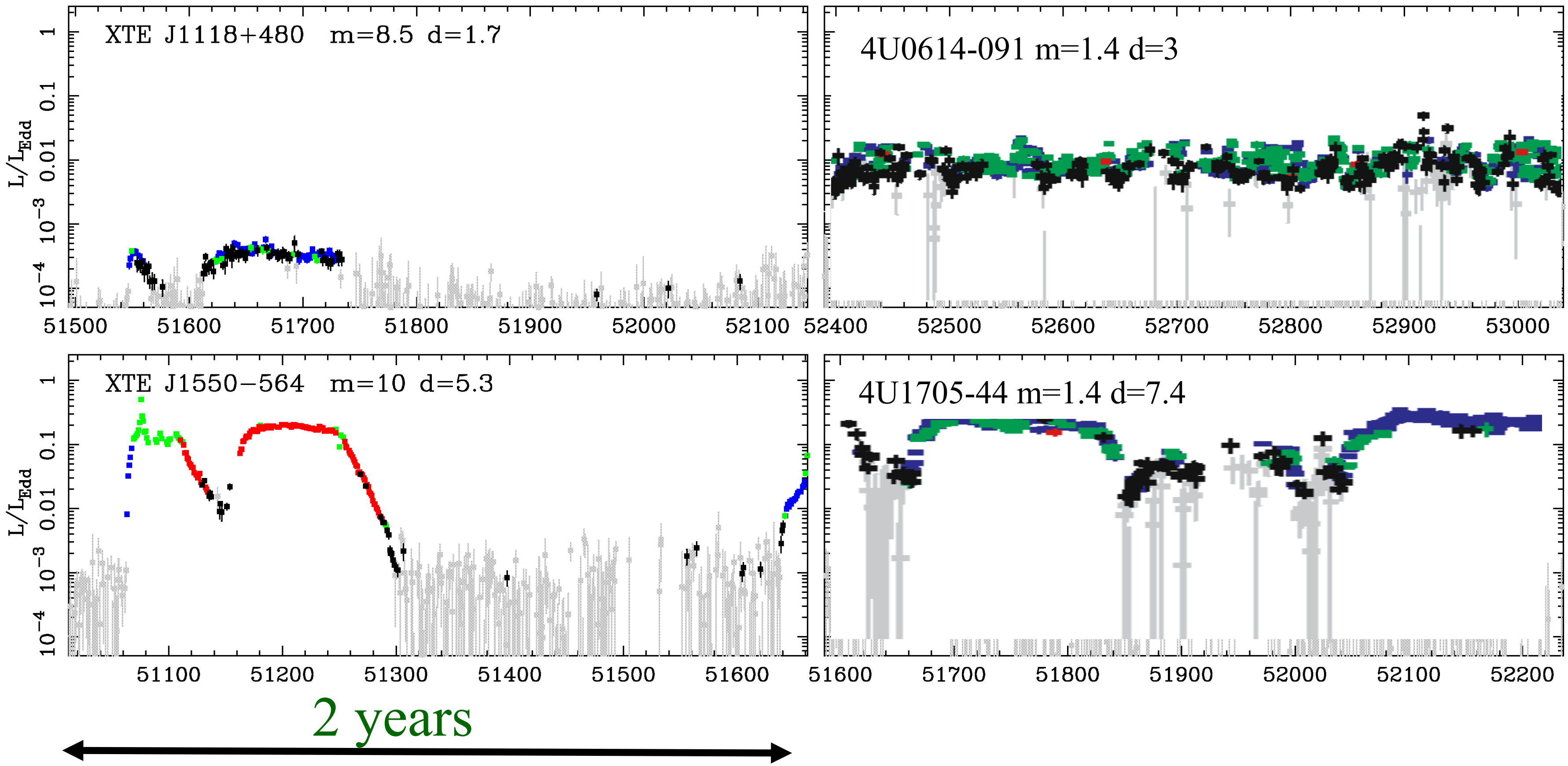


Wind accretion – Messy
High mass companion star

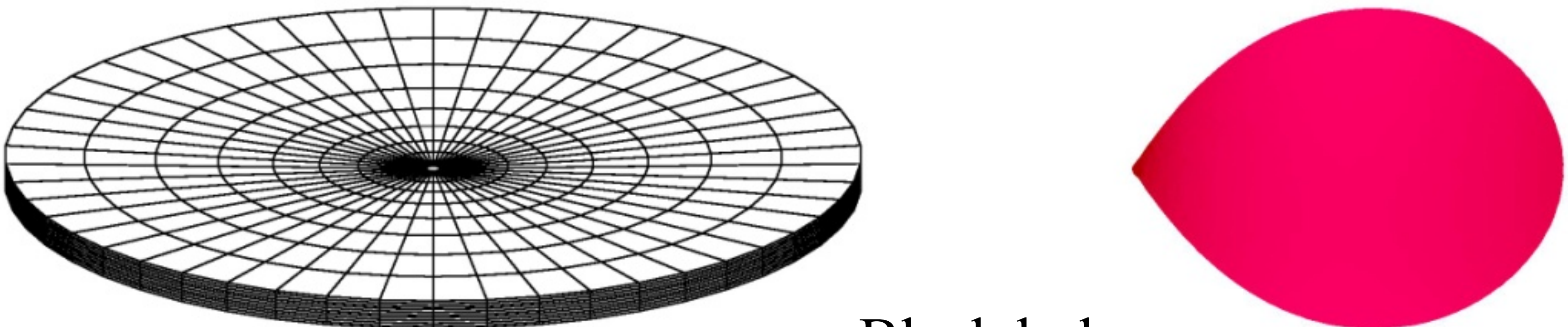
Roche lobe overflow= cleaner
All low mass are Roche lobe, but a few high mass are also

Variable variability!

- Roche lobe accretion onto black hole or low B field NS can vary dramatically, or vary a bit, or be constant!
- Hydrogen ionisation instability (Osaka, Smak, Lasota)



Roche lobe geometry



Black hole

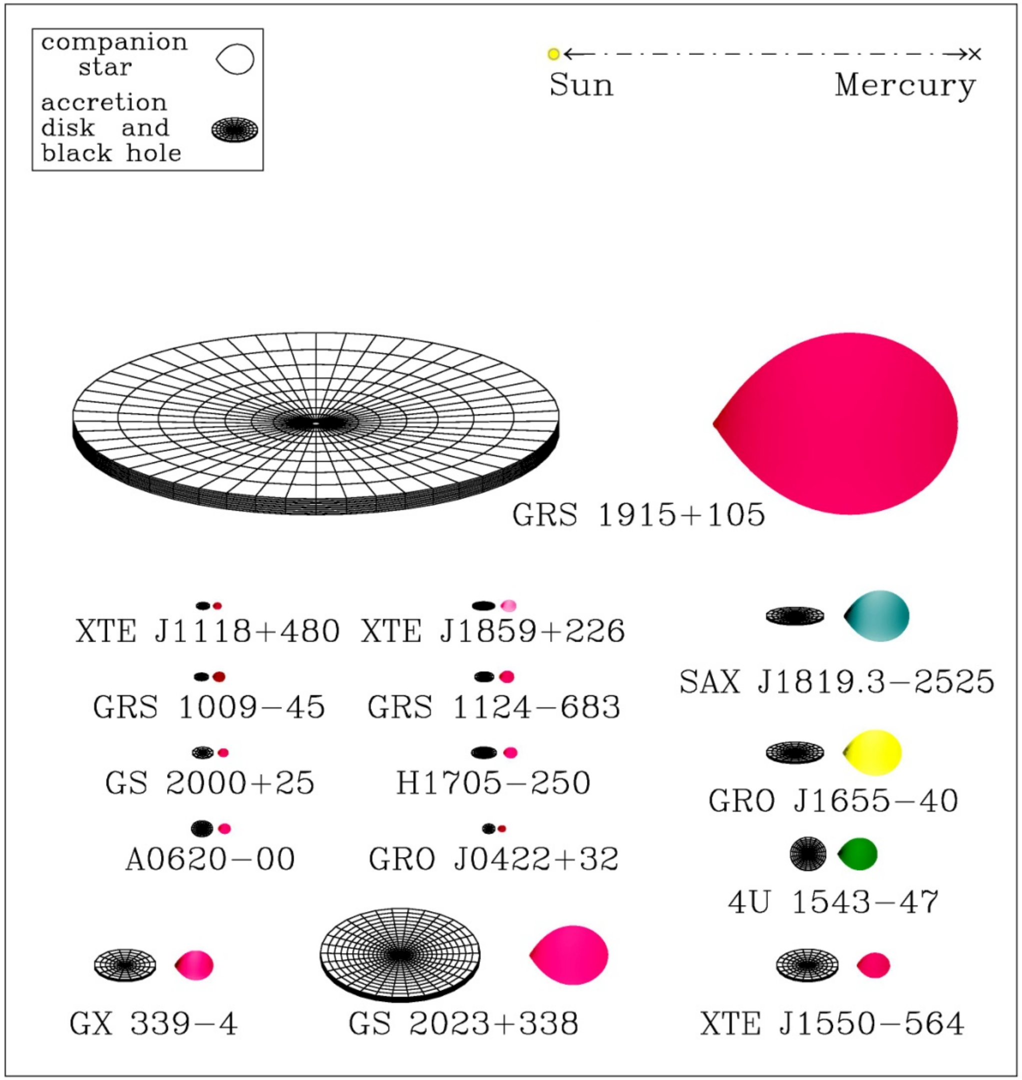
- Neutron star – mass is 1.4 not 10M so binary much smaller for given companion star
- More NS constant, most BHB do transient outbursts

Neutron star

Roche lobe overflow Black holes

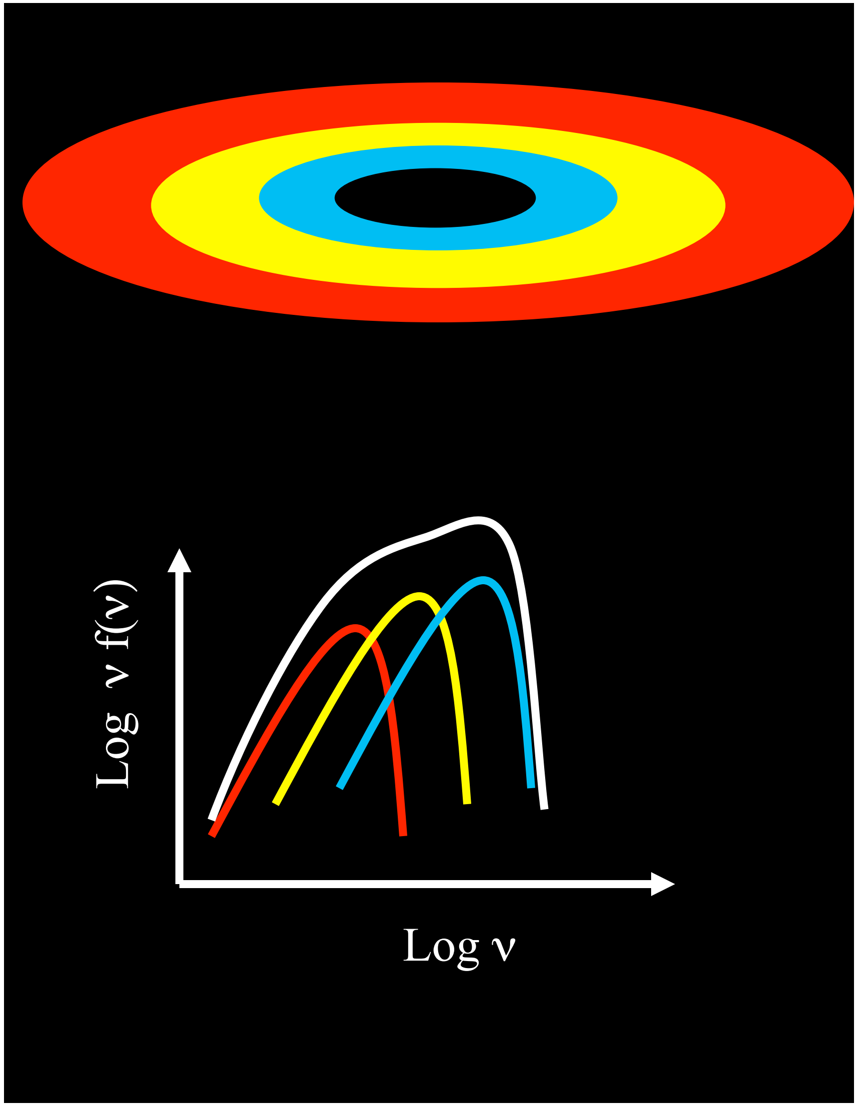
J. Orosz

- Huge range of binary separations even for Roche lobe overflow of low mass (~1 M)
- Evolved stars are big – low surface gravity so fill roche lobe at large distances
- Main sequence stars – similar mass but smaller.



Spectra of accretion flow: black hole disc

- Energy release by viscosity (MRI dynamo)
- Thermal emission: $L = A\sigma T^4$
- Area constant as radius fixed at ISCO
- $L \propto T^4_{max}$ as mass accretion rate varies Ebisawa et al 1993; Kubota et al 2001; Gierlinski & Done 2004 DGK07



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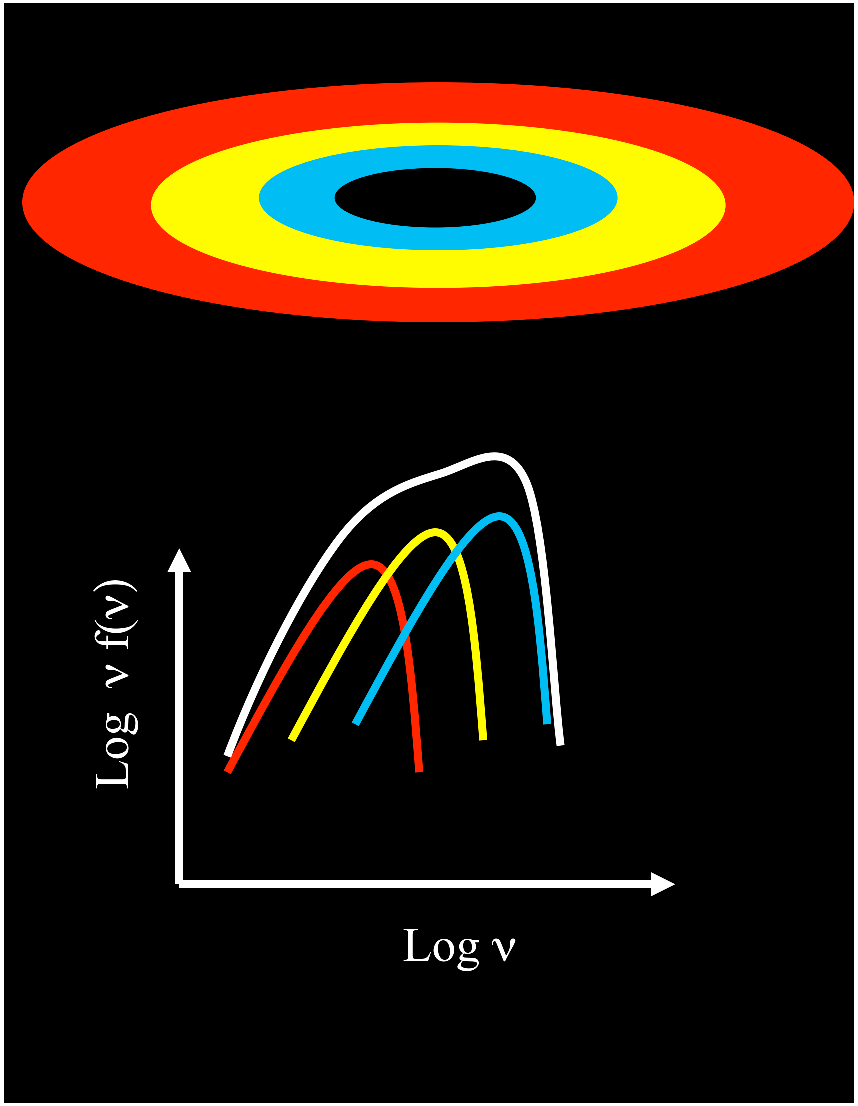
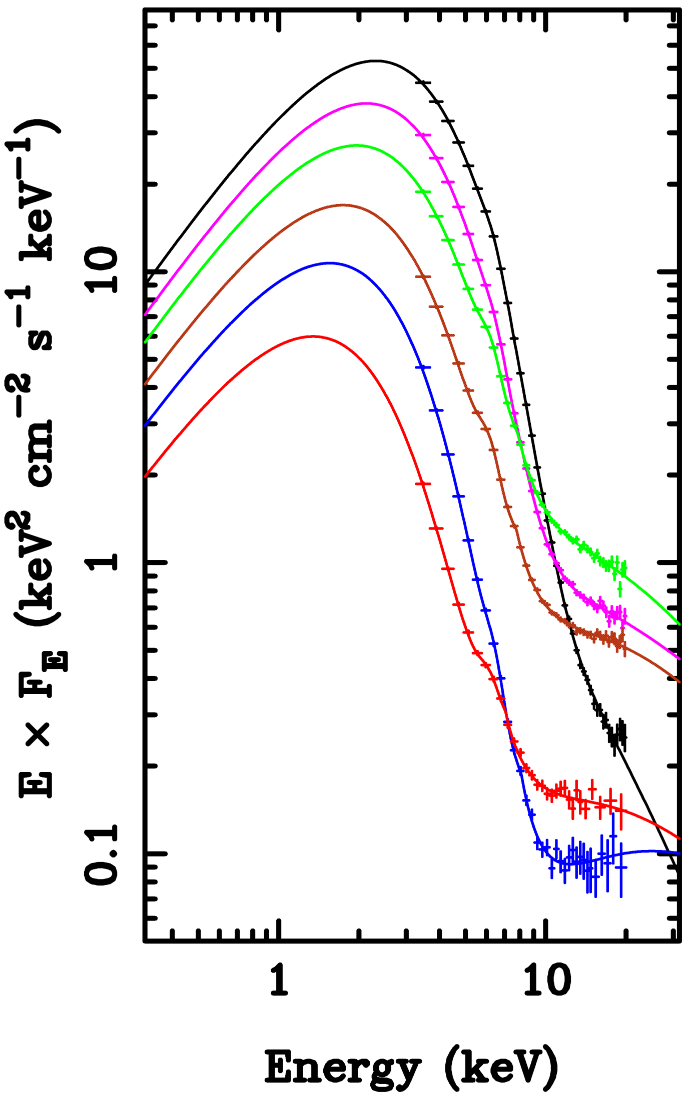
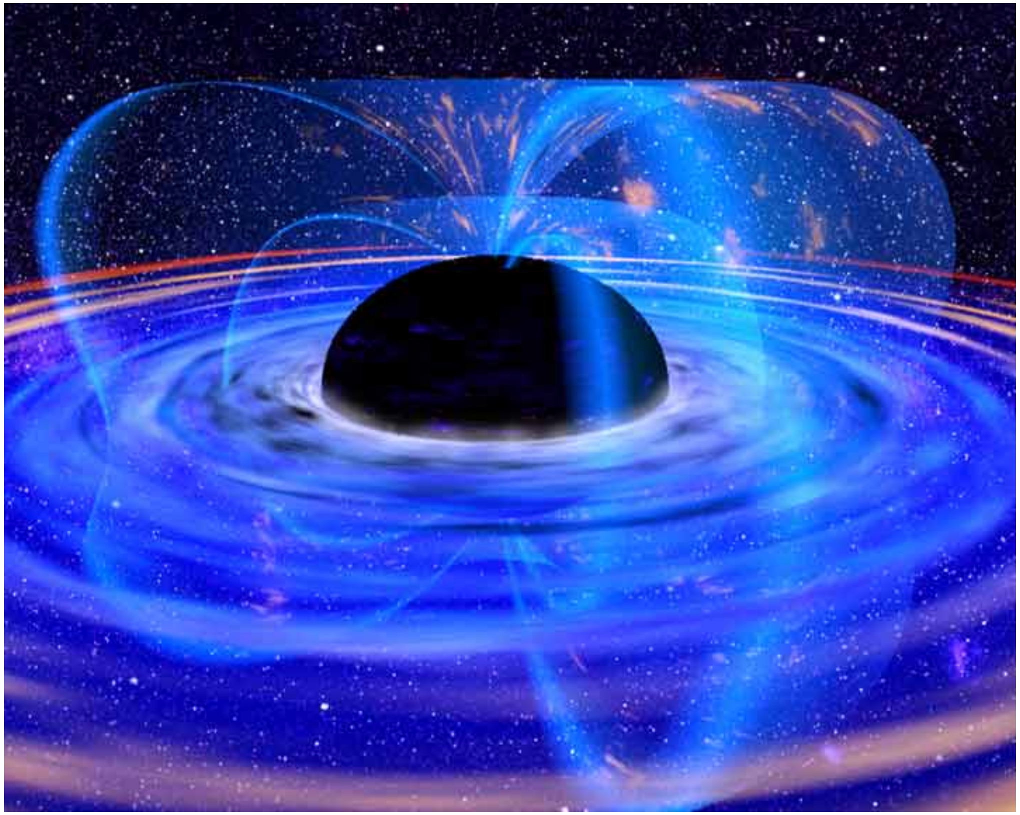


Disc + event horizon

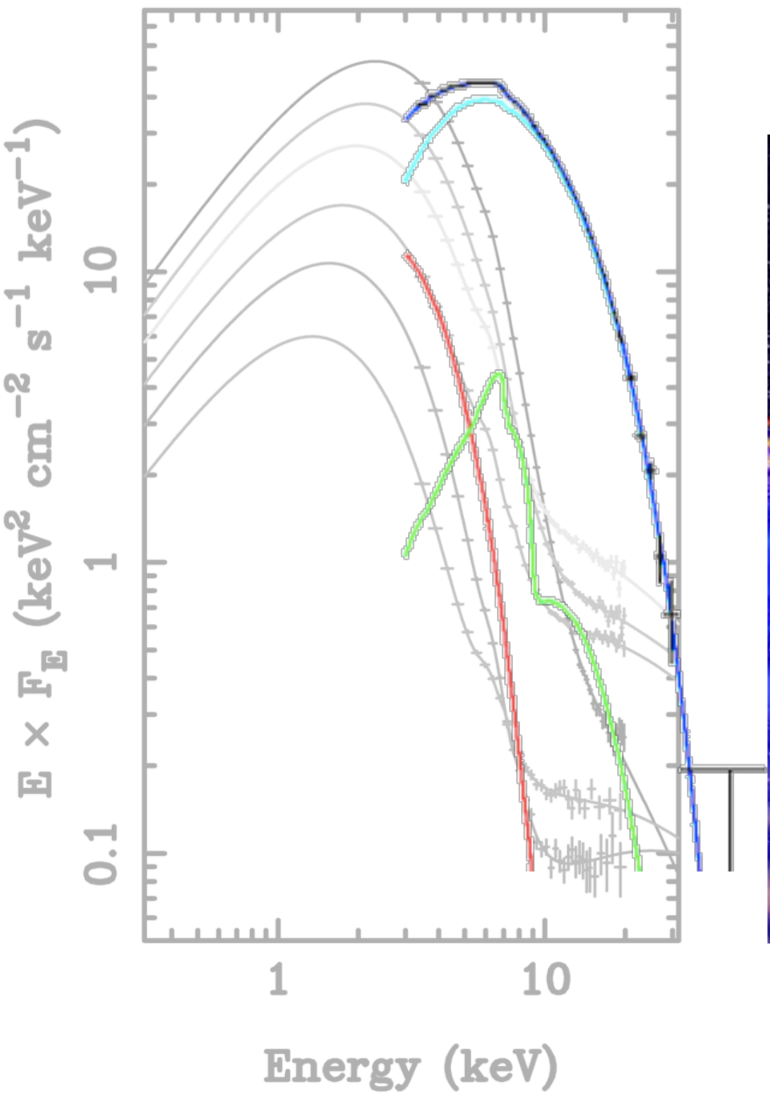


$L \propto T^4_{max}$ and only disc!

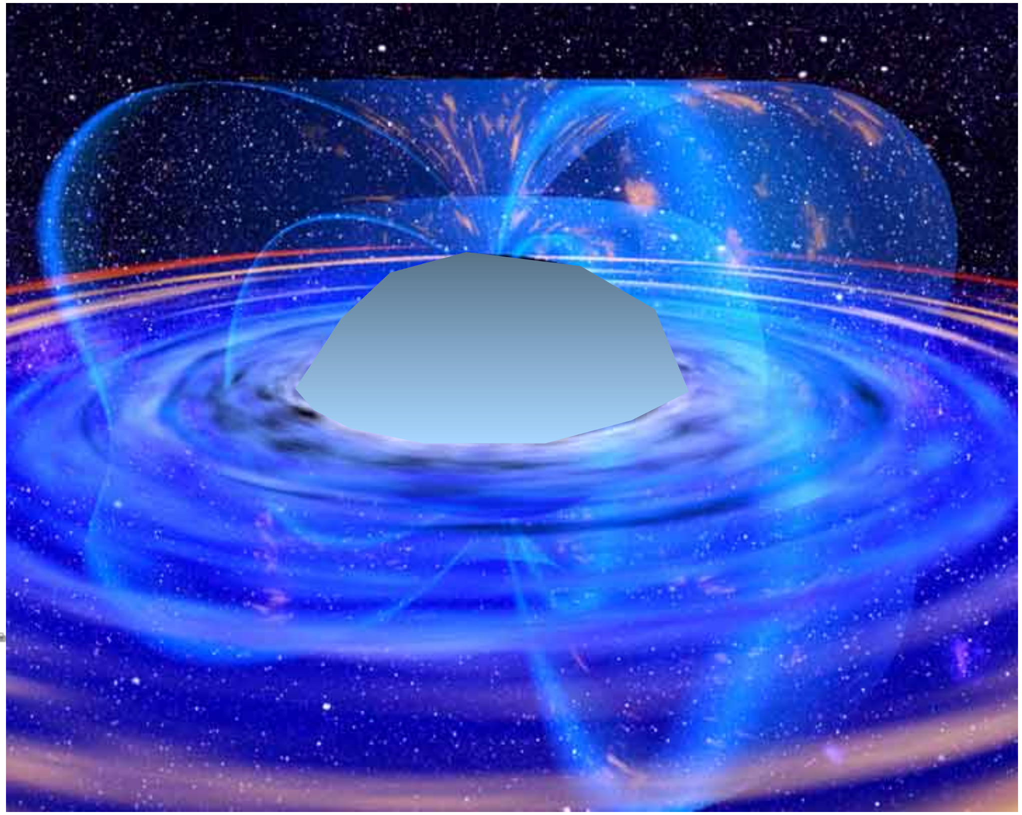


Done & Gierlinski 2003, DGK07

Disk plus surface (NS)



Disc plus BL for NS



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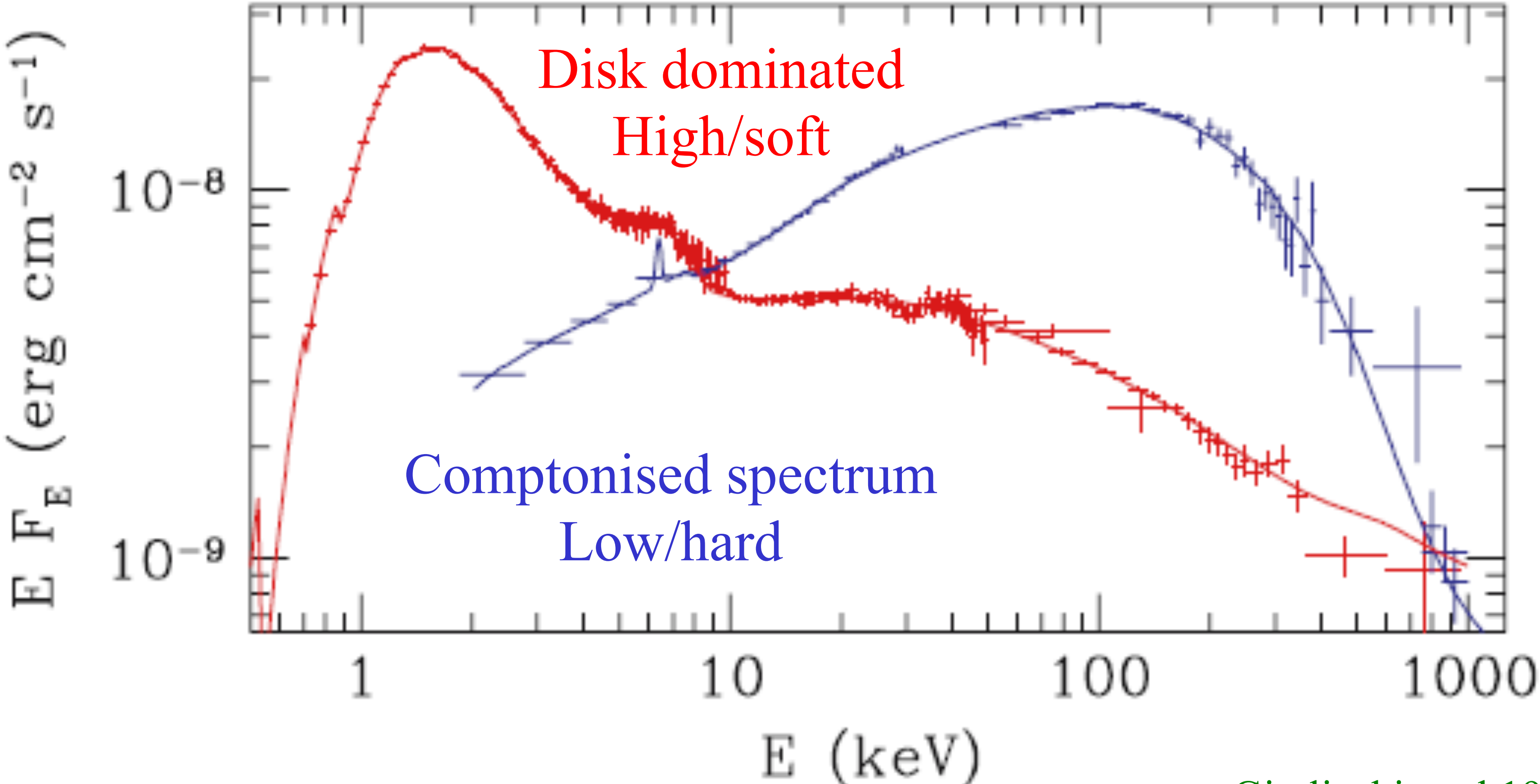
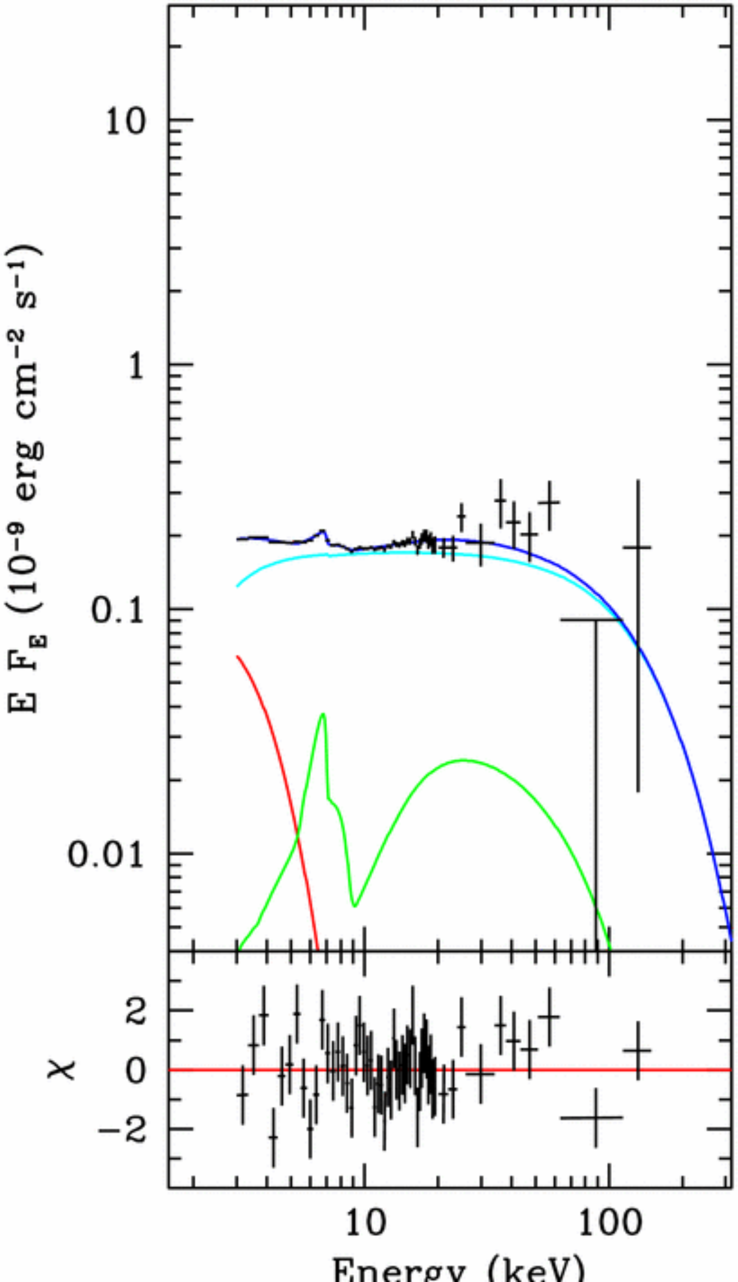
Spectral transitions in BHB



Gierlinski et al 1999

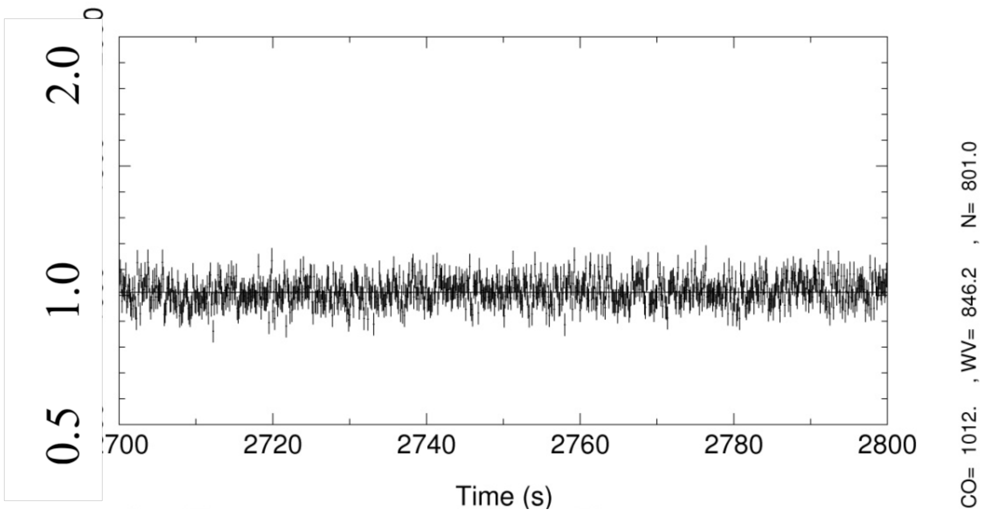
Same behavior in NS systems too

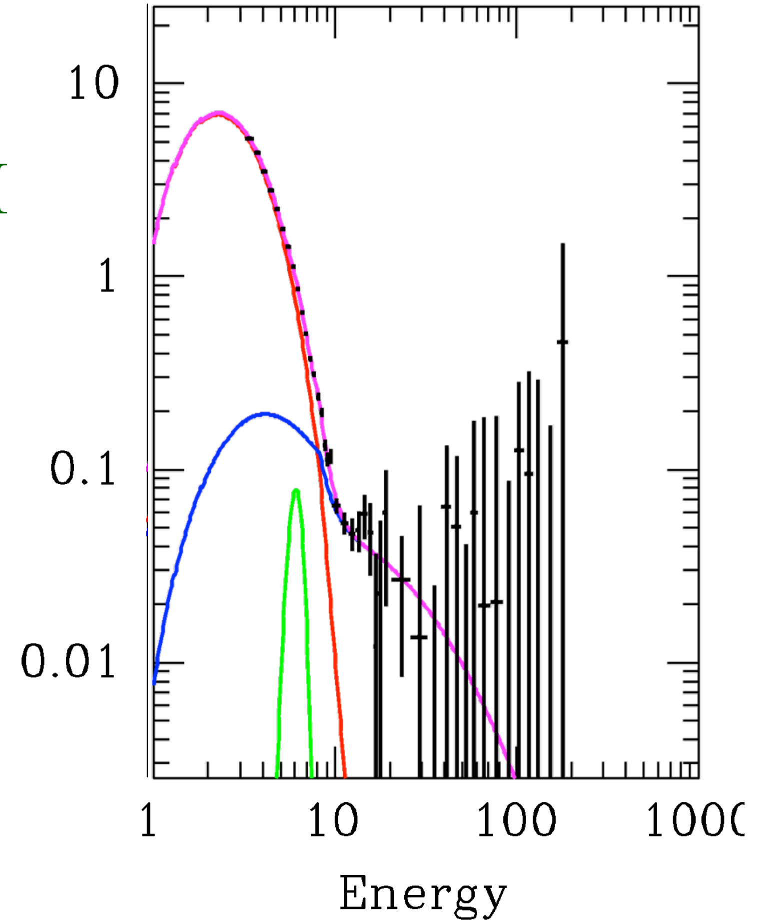
- Switch between compton dominated (island state)
- To disc (and optically thick boundary layer) dominated (banana branch)



Variability of disc: short timescale

- Timescale to change mass accretion rate through disc
- tvisc= α^{-1} $(H/R)^{-2}$ torb
  $=5\ \alpha^{-1}\ (H/R)^{-2}\ (r/6)^{-3/2}$ ms
- ~ 500s at last stable orbit for 10M
- No rapid variability of disc

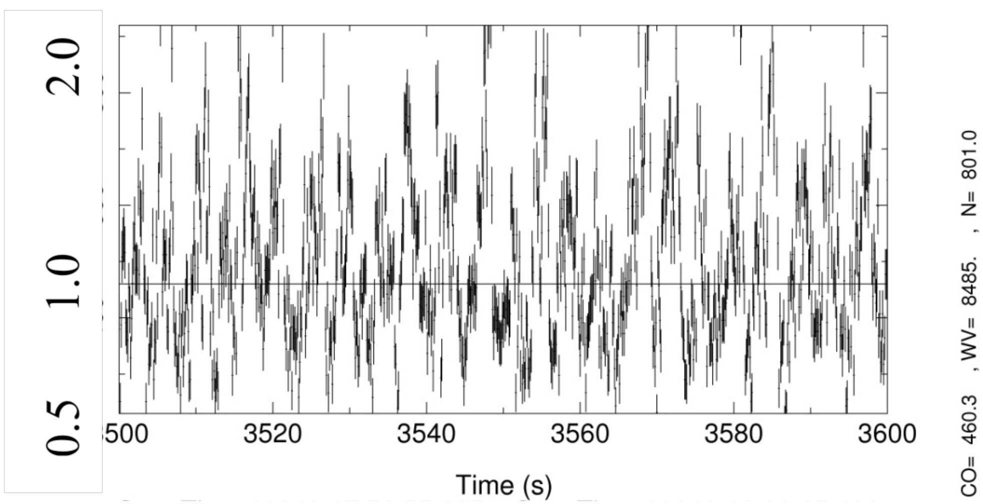


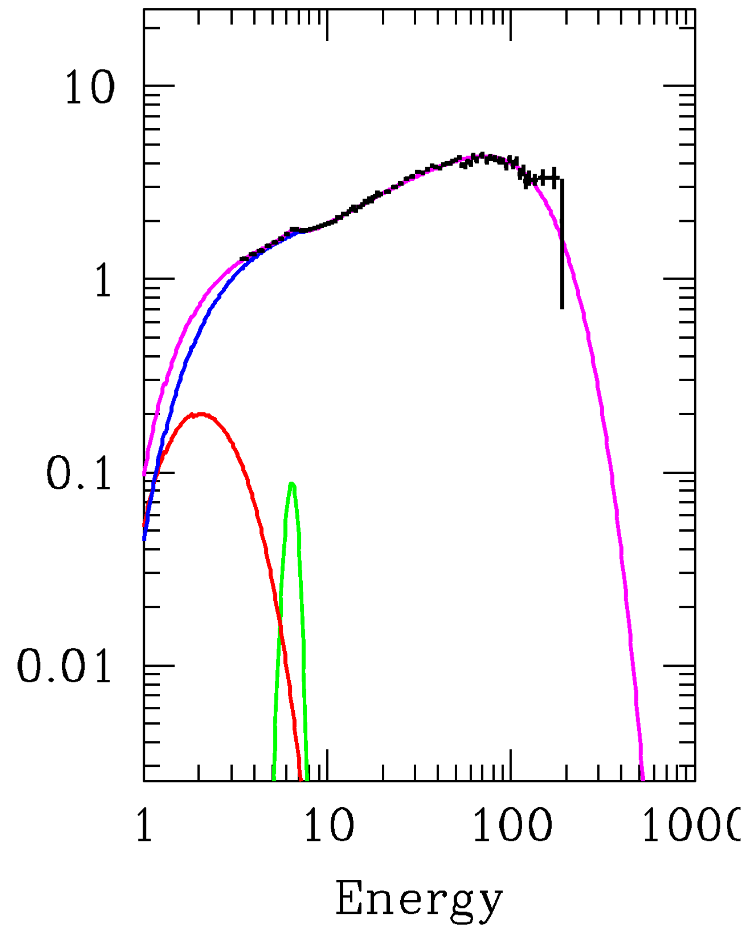


Low/hard state variability

- Low/Hard state variability down to few 10s of ms
- tvisc= α^{-1} $(H/R)^{-2}$ tdyn = 5 α^{-1} $(H/R)^{-2}$ $(r/6)^{-3/2}$ ms
- IF viscous timescale then

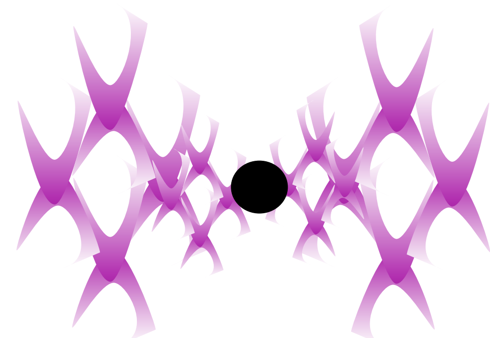
  H/R~1

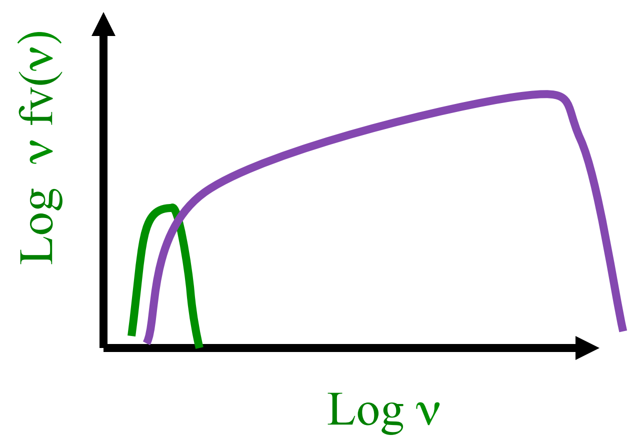




Accretion flows without discs

- Low L/Ledd: another stable solution of accretion flow
- Hot, optically thin, geometrically thick inner flow replacing the inner disc (Shapiro et al. 1976; Narayan & Yi 1995- ADAF)

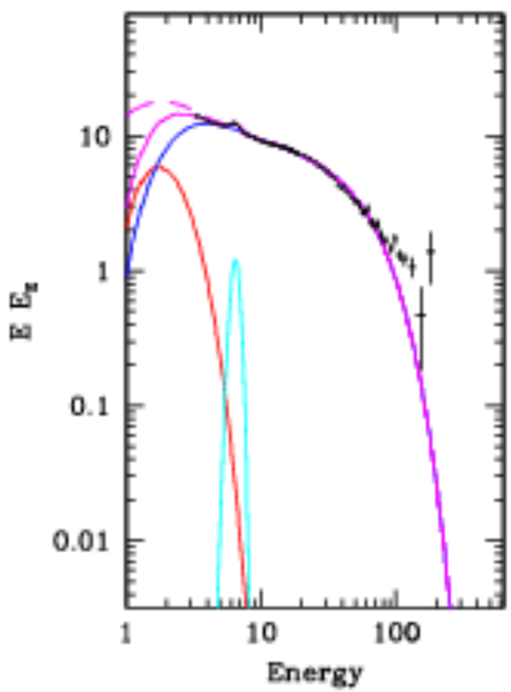


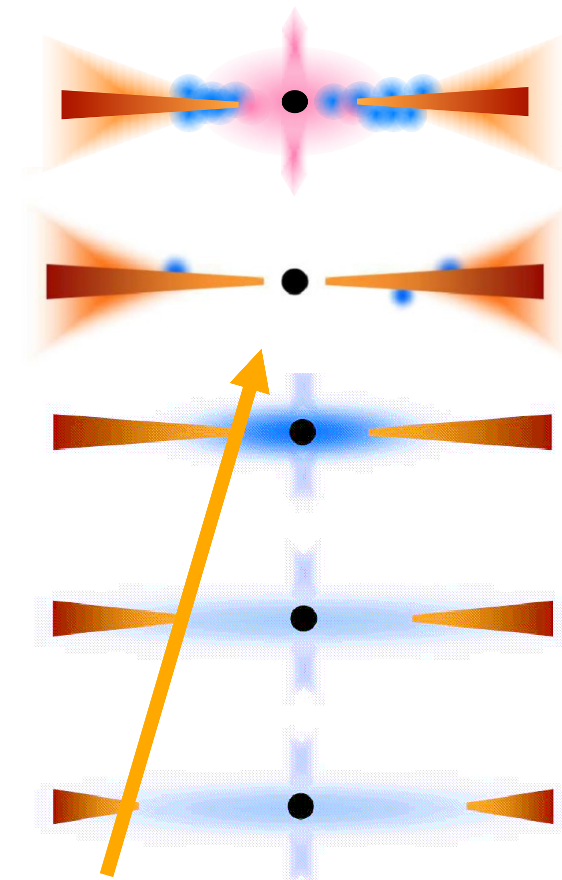


Moving disc – moving QPO

- Energy spectra need disc to move from 50-6ish Rg as make transition

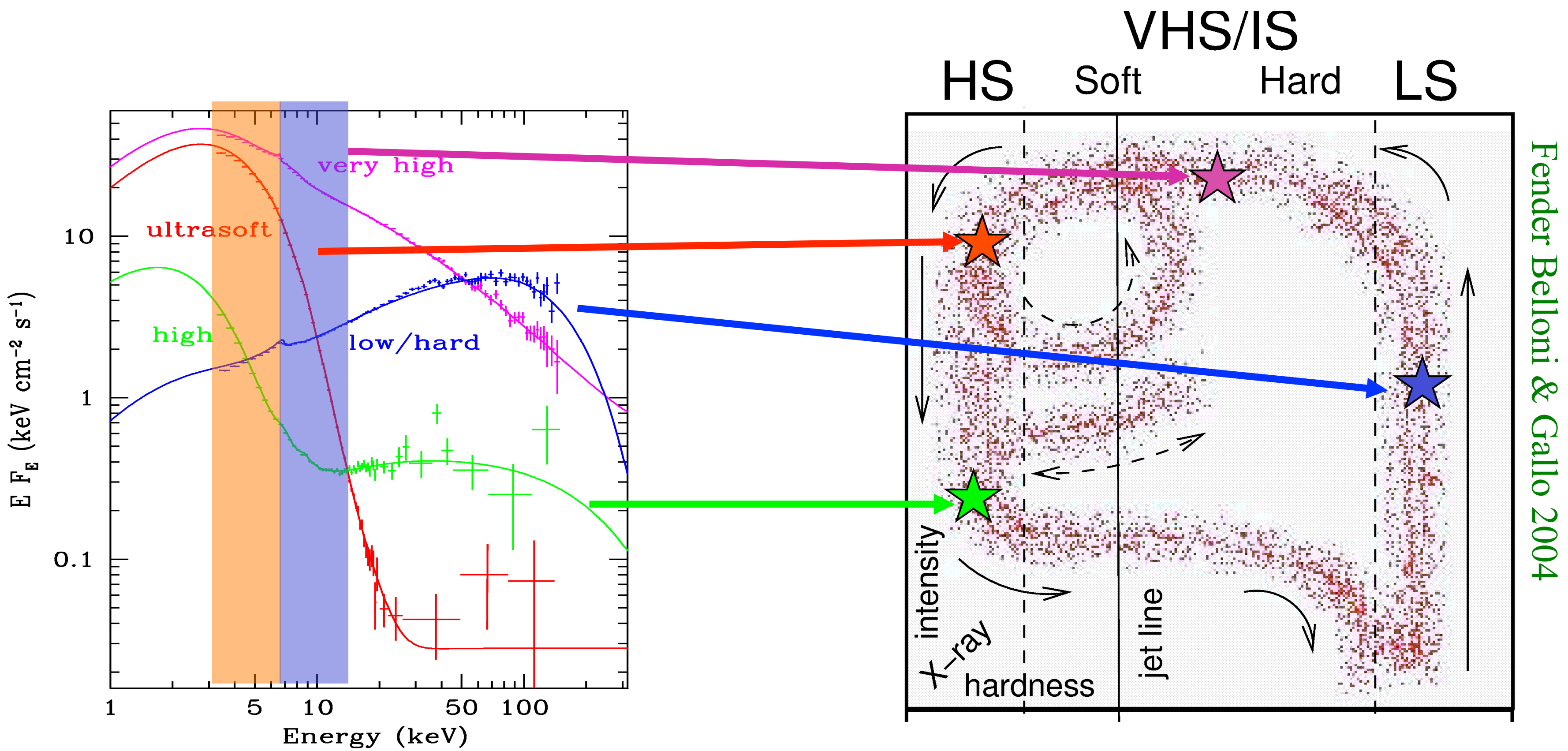
DGK07





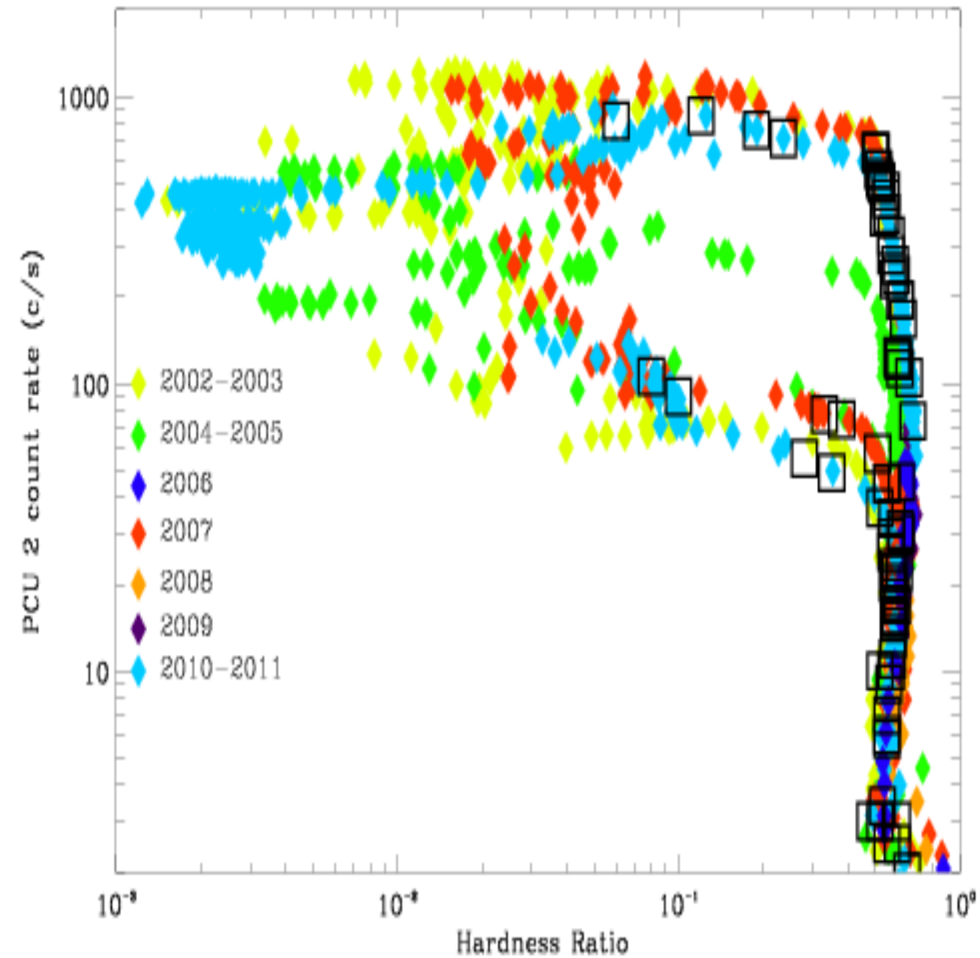
Hardness – intensity diagram

- But not at fixed luminosity like the models say!
- Outburst starts hard, source stays hard as source brightens
- Makes transition to disc dominated via come complex spectra
- Then returns to hard state at lower luminosity



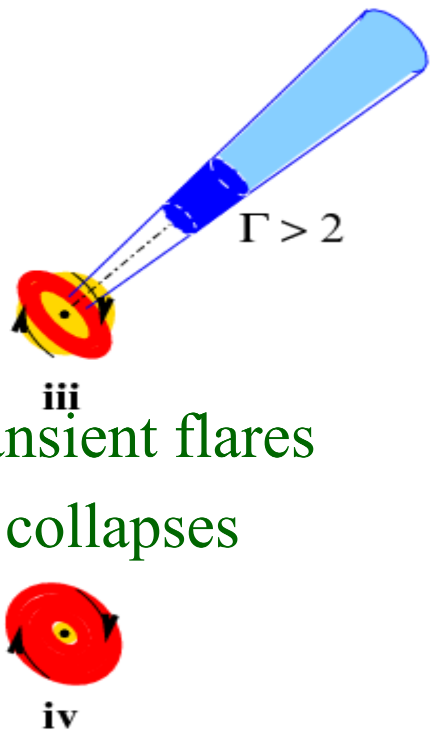
Hysteresis

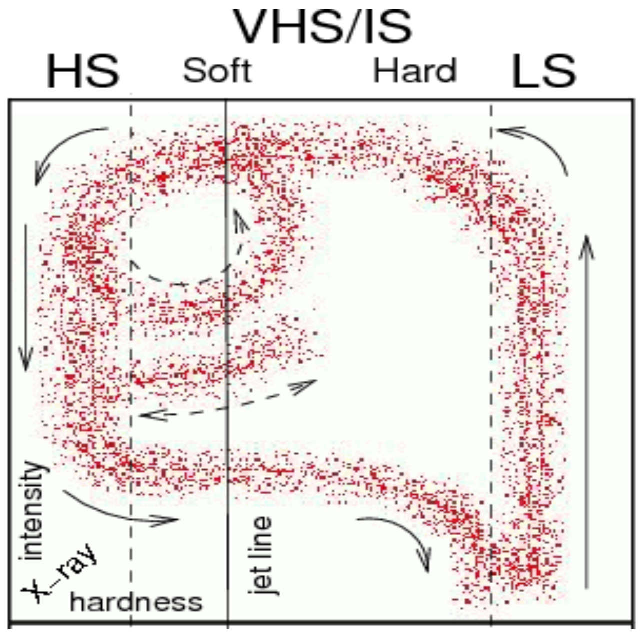
- Luminosity of transition on fast rise higher not fixed either!
- Accretion flow out of steady state on fast rise? Smith et al 2002; Gladstone et al 2007
- Magnetic field can't be expelled from collapse in hot flow? MRI simulations Machida et al 2006

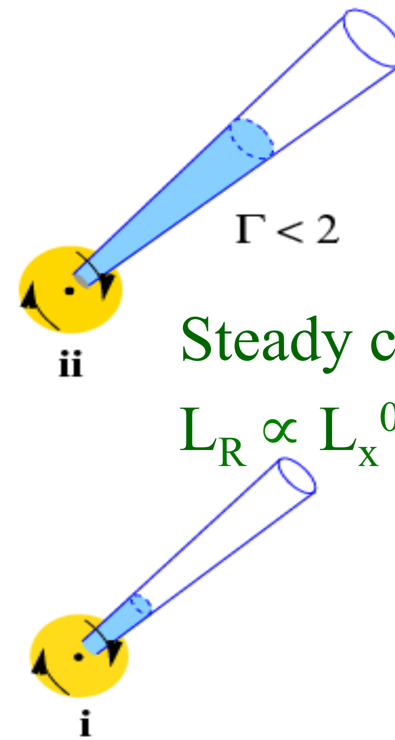


GX339-4 Corbel et al 2013

Jet evolution in BHB outburst







Transient flares

Jet collapses

Steady compact

$L_R \propto L_x^{0.7}$

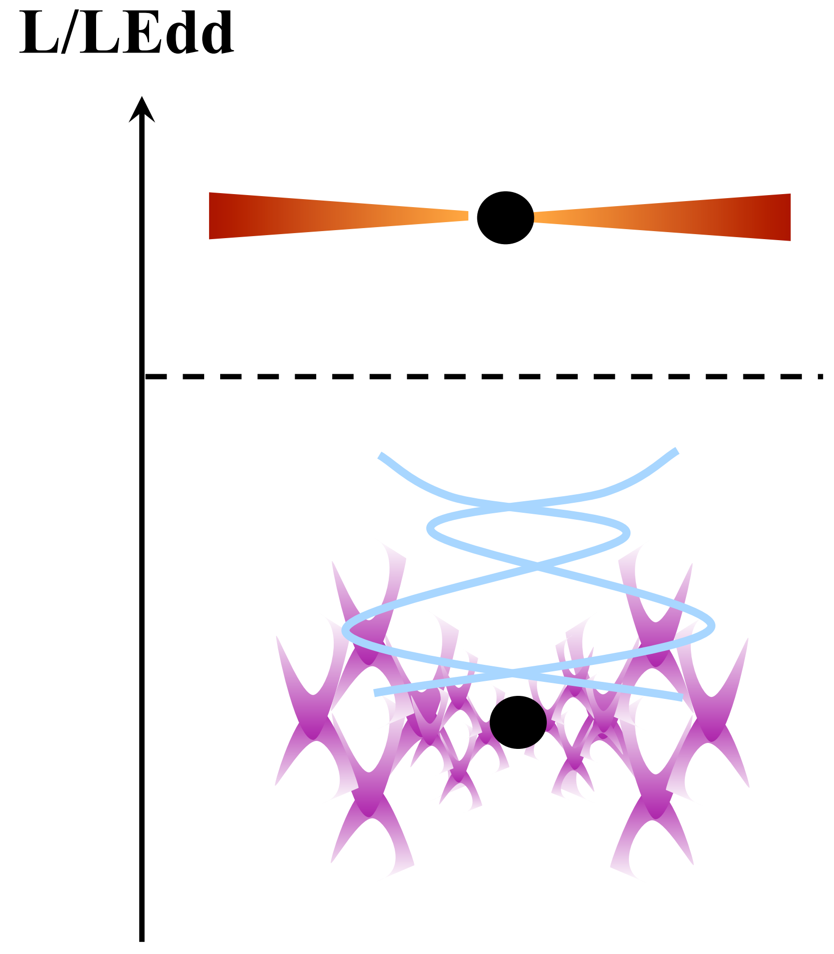
Fender Belloni Gallo 2003

Chaty et al 2003

Corbel, Russell….

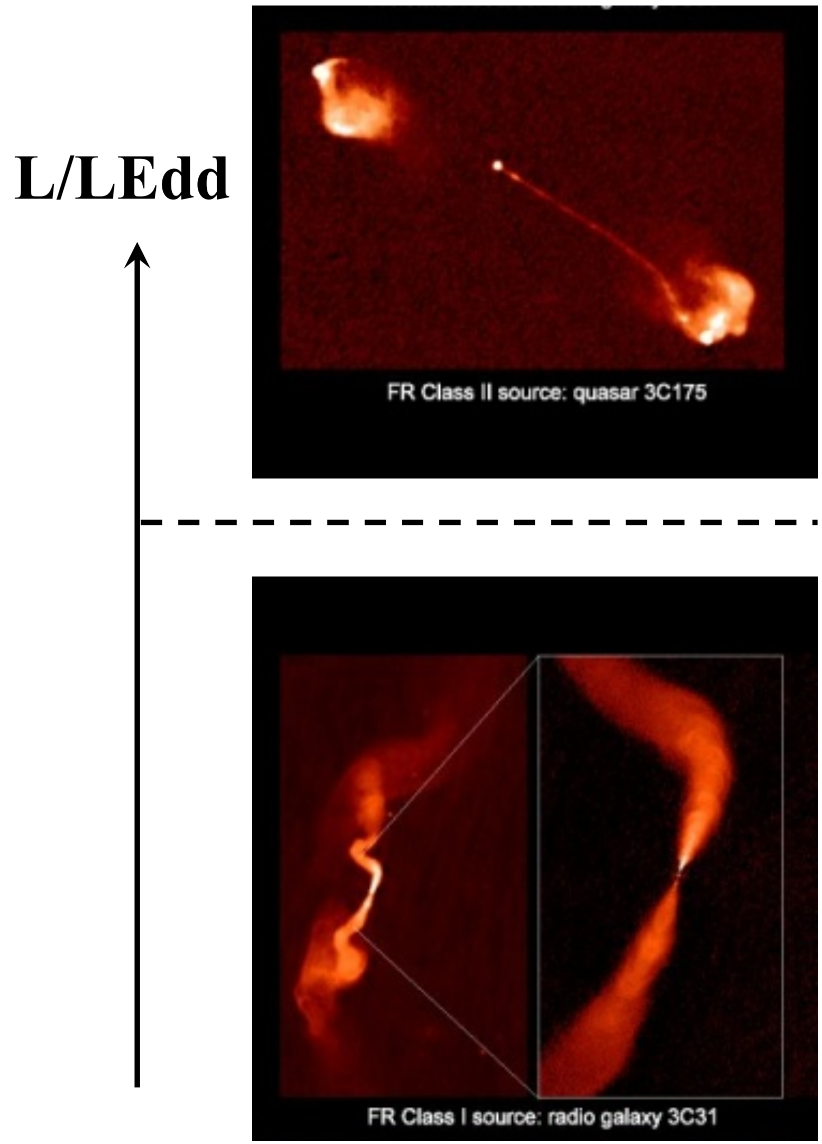
Jet evolution in BHB outburst

- Compton dominated state - steady, compact jet, bulk outflow $\Gamma \sim 1.5$-2: $L_R \propto L_x^{0.7}$
- Radio collapses at transition to disc state – jet requires large scale height flow to have large scale height B field



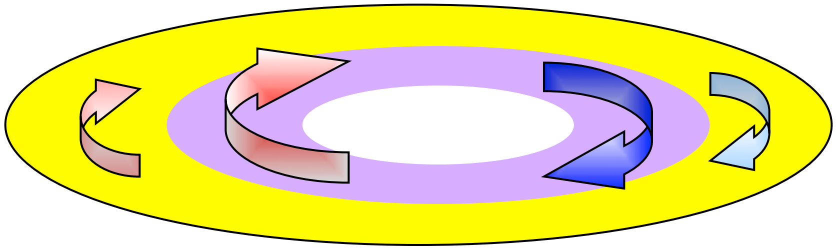
Origin of Highly relativisitic Jets

- radio loud AGN have $\Gamma=15$ at all mass accretion rates
- Bl Lacs/FRI have low mass accretion rate (ADAF)
- FSRQ/FRII have discs so additional seed photons
- Black hole spin? Done & Jin 2016
- But iron line profiles….

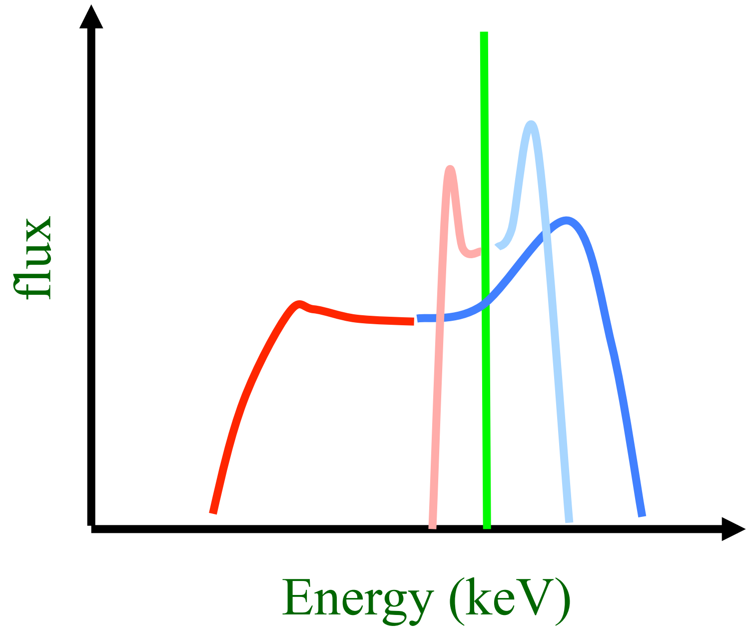


Iron line profile

Fabian et al. 1989



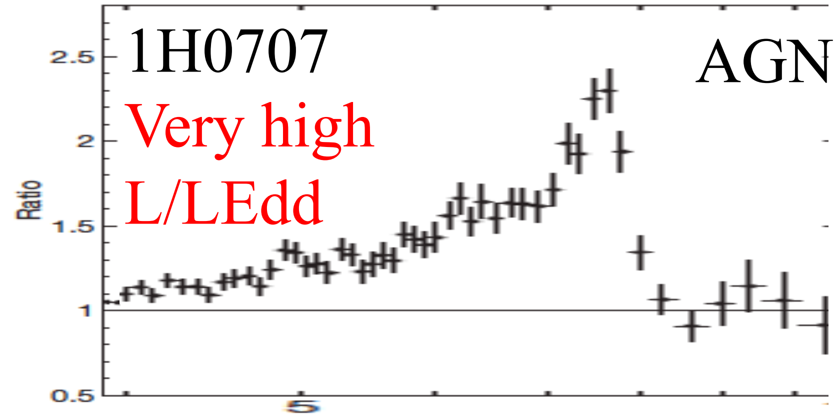
- Emission from the side of the disc coming towards us is blueshifted and boosted by Doppler effects, while opposite side is redshifted and suppressed.
- Also time dilation and gravitational redshift



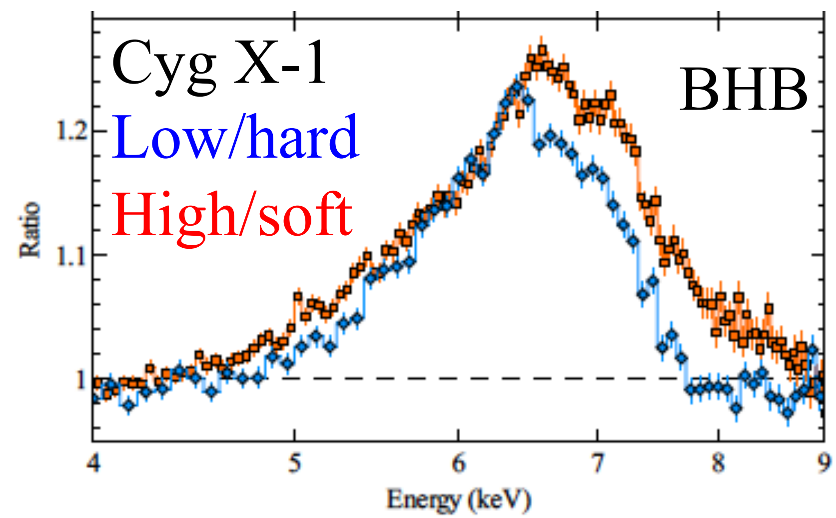
Origin of Highly relativistic Jets

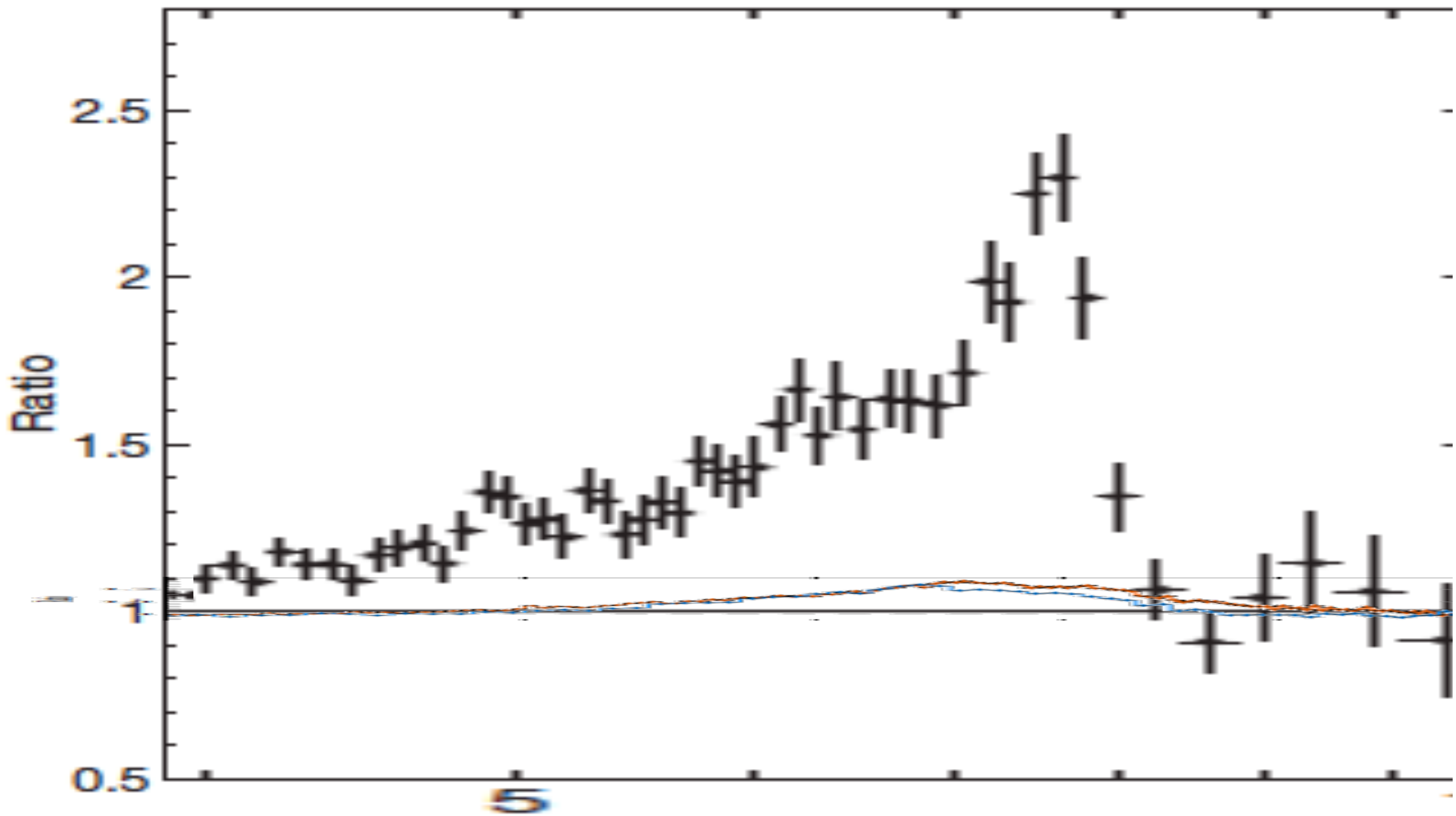
- Radio quiet AGN do not have Γ=15 jets!
- But some do have very high spin from iron lines (but see Hagino et al 2016; Done & Jin 2016)
- BHB do not have Γ=15 jets but do have very high spin from iron lines Done & Jin 2016
- And some low/hard state BHB also have disc down to isco of high spin….

Fabian et al 2009



Parker et al 2015

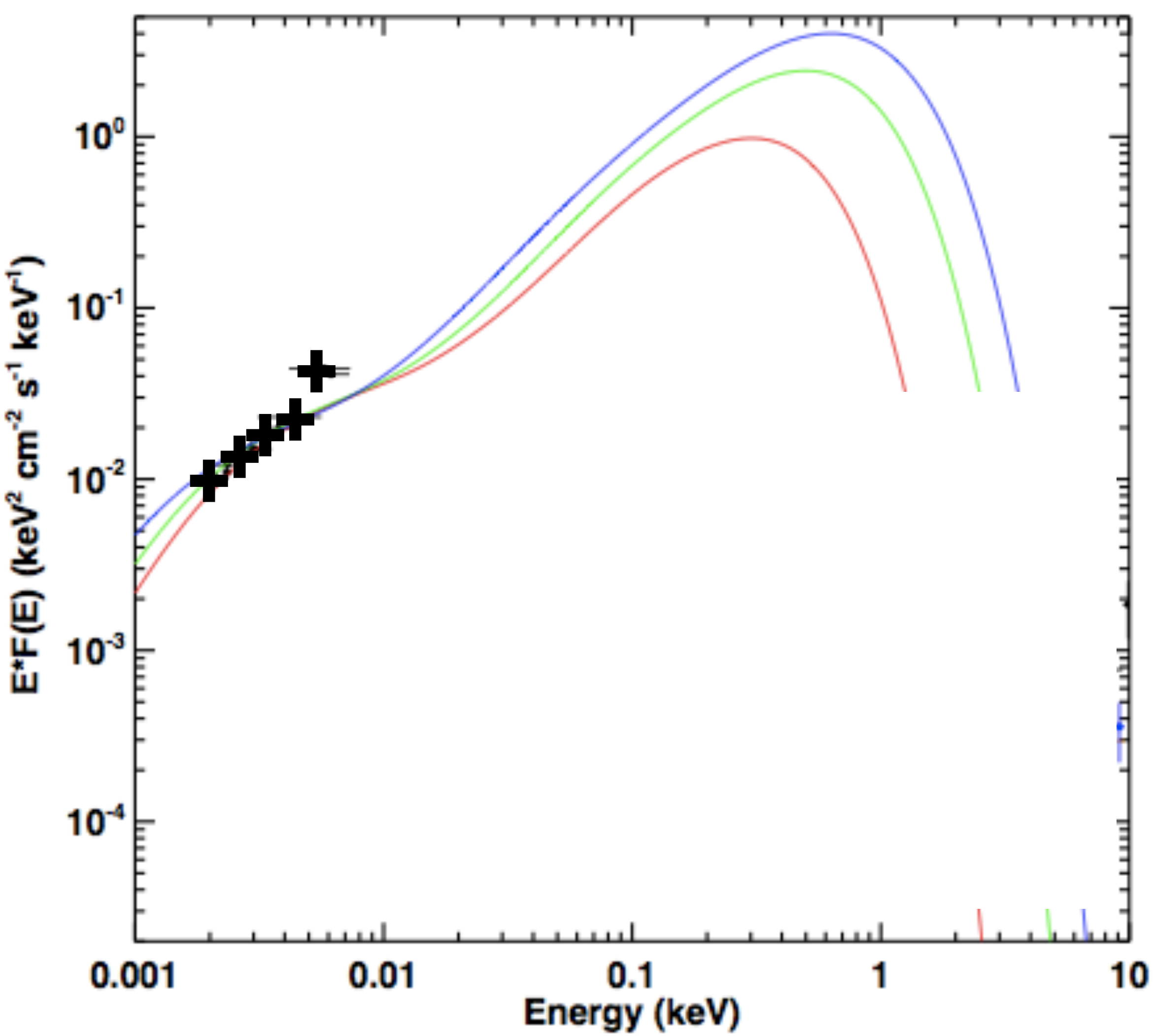




Ratio
2.5
2
1.5
1
0.5
5

Do we have a clean view - Winds

- 1H0707
- 2e6M a=0, 0.9, 0.998
- L/Ledd = 20, 63 150 (30 degrees)
- L/Ledd = 44, 123 270 (60 degrees)
- Done & Jin 2016
- Clean disc??



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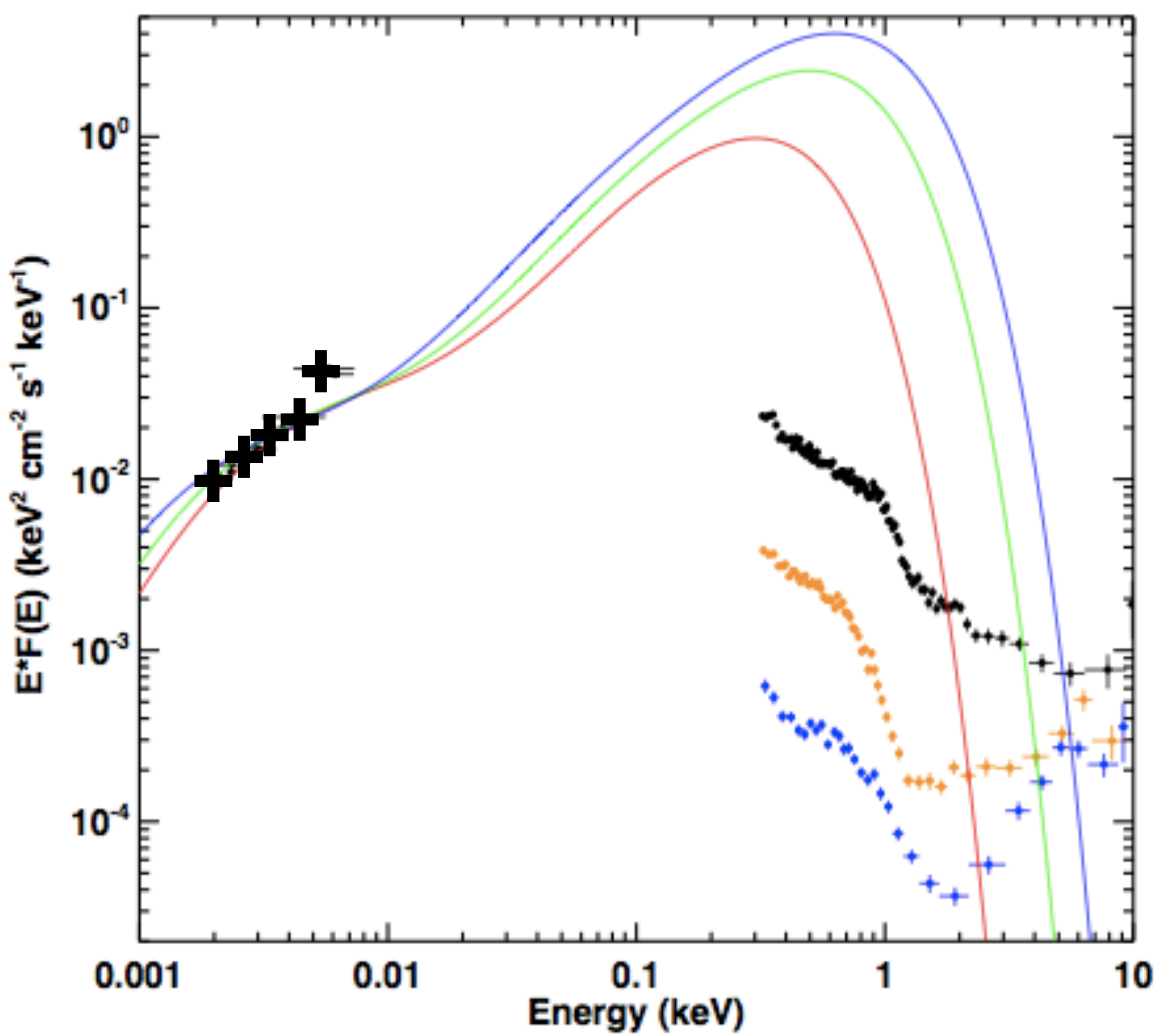
- SUPEREDDINGTON
- Strong winds???



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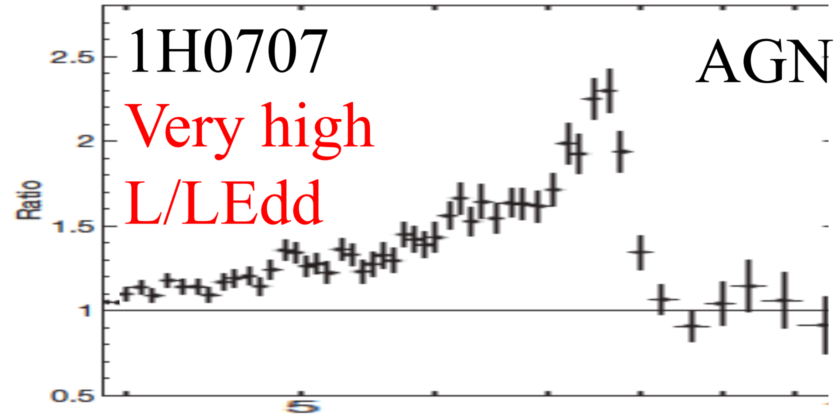

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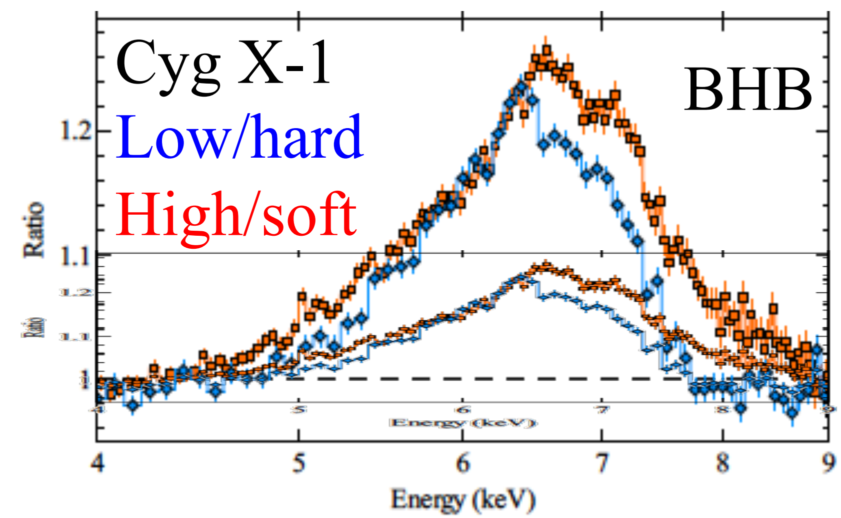
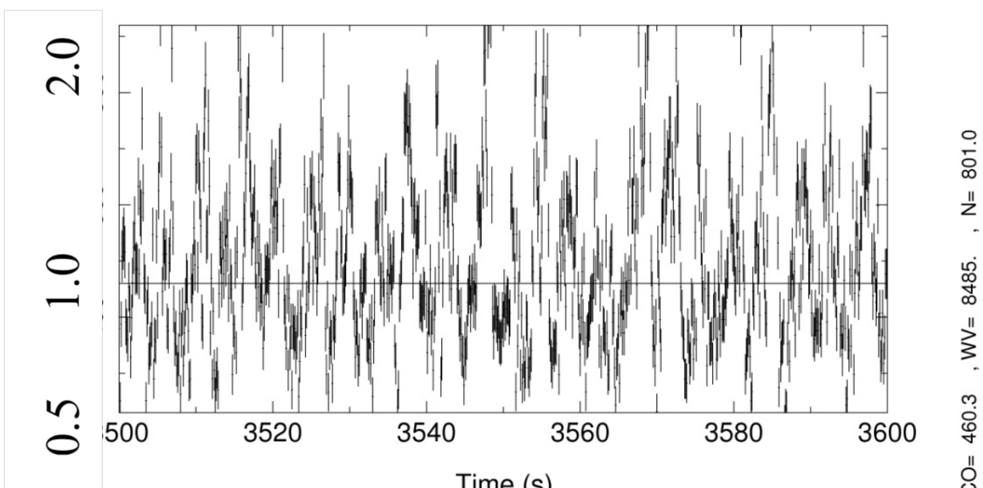
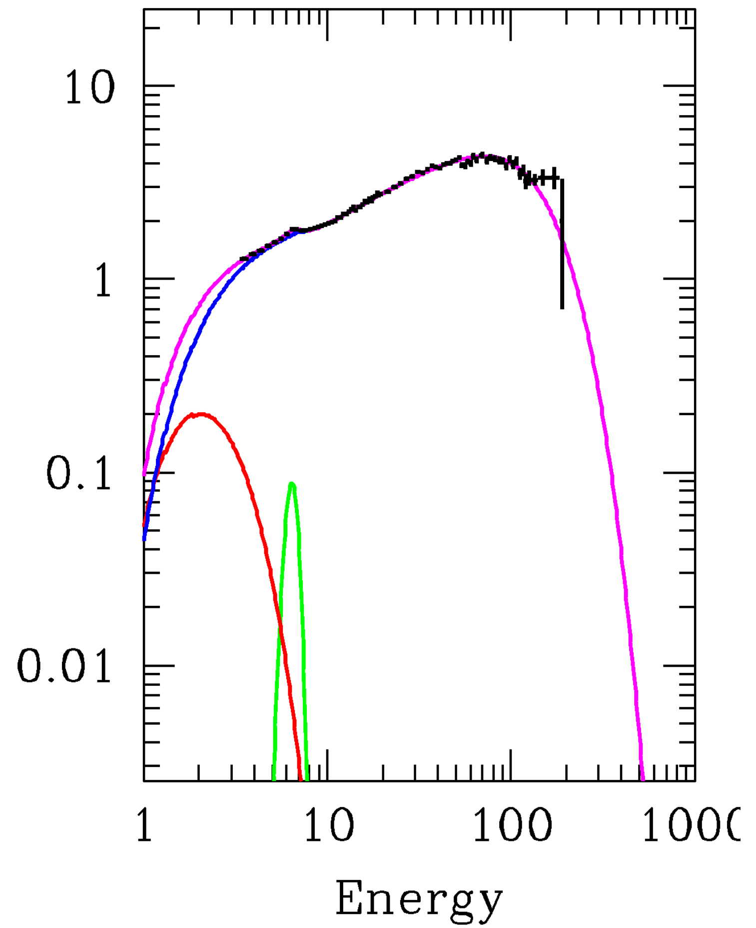


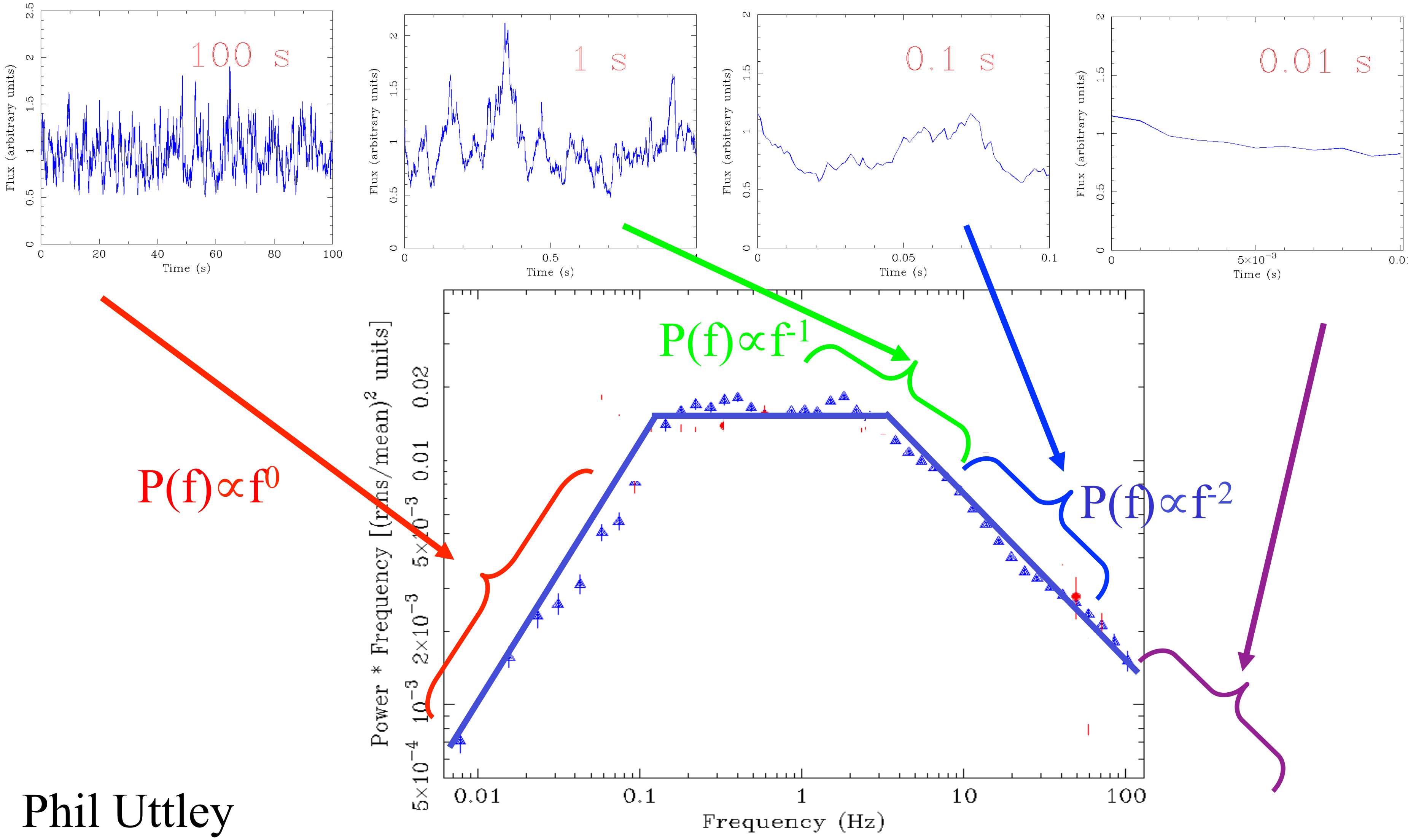
Low/hard state variability- QPO

- So either iron line in low/hard state or truncated disc is wrong!
- How else to figure out nature of low/hard state flow?
- Fast variability!



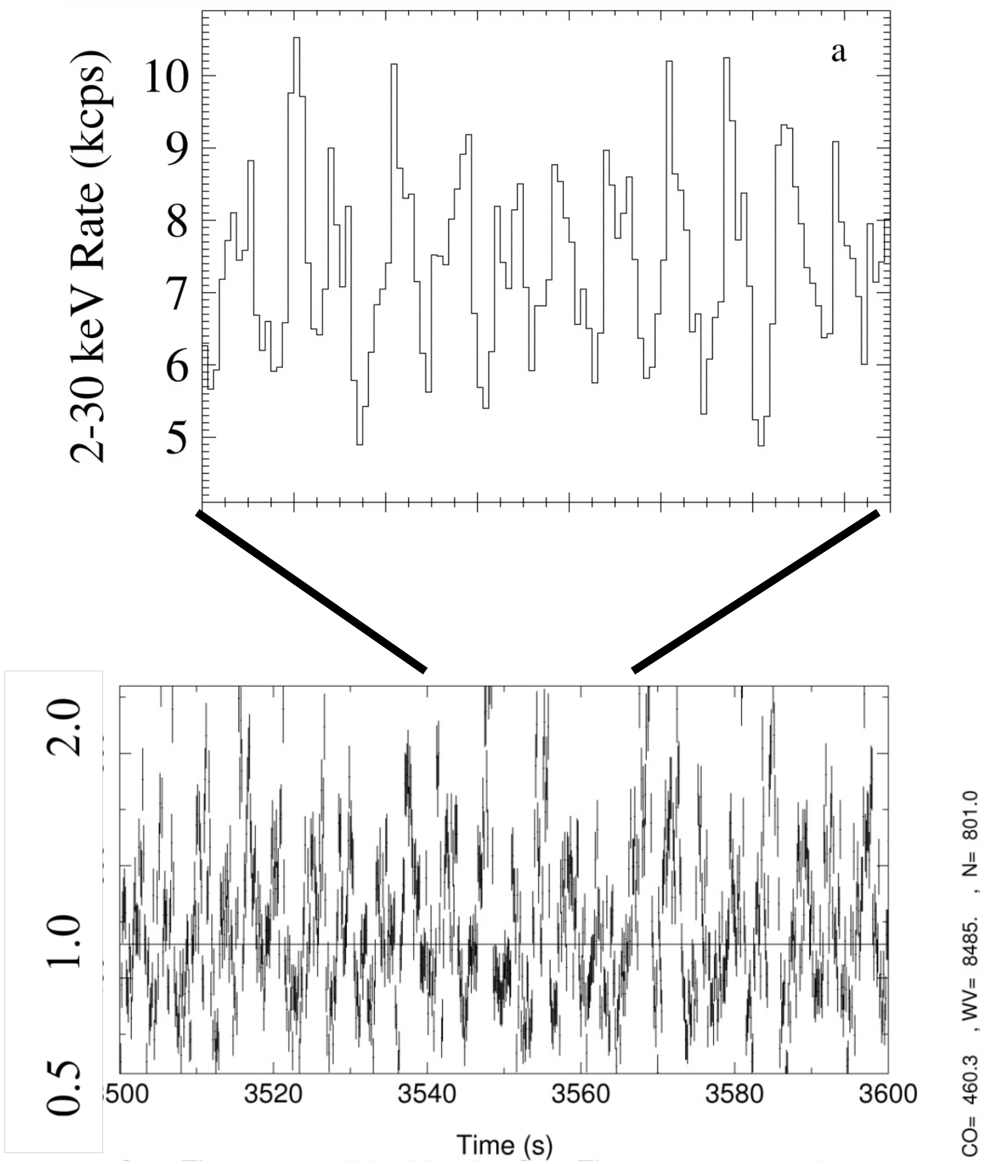


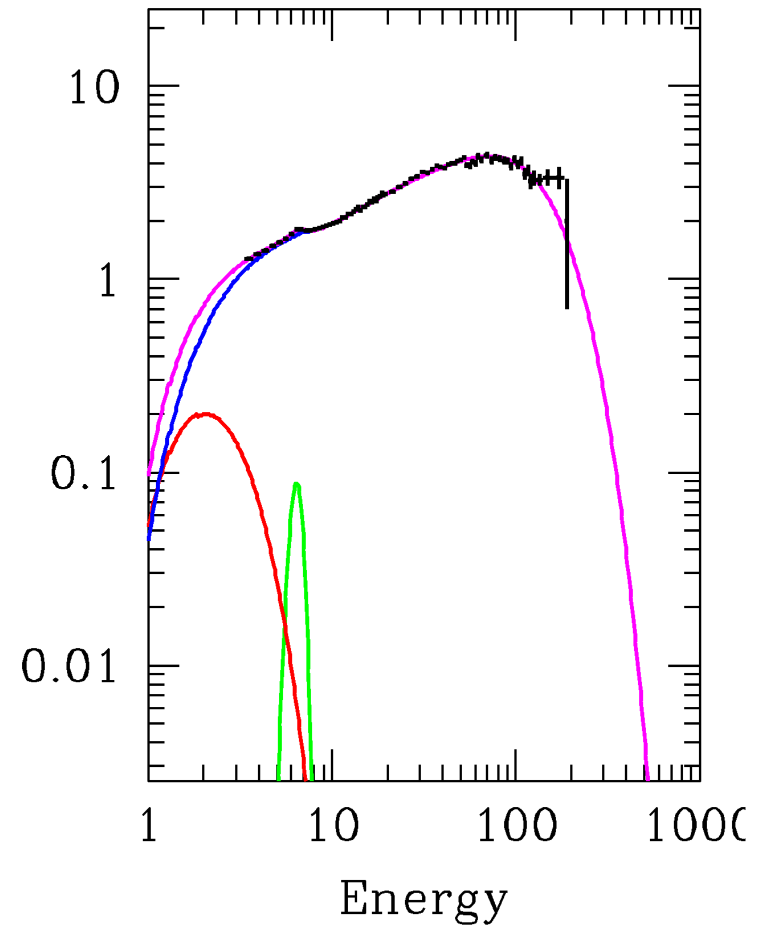
Quantifying variability: the power spectral density (PSD) of Cyg X-1

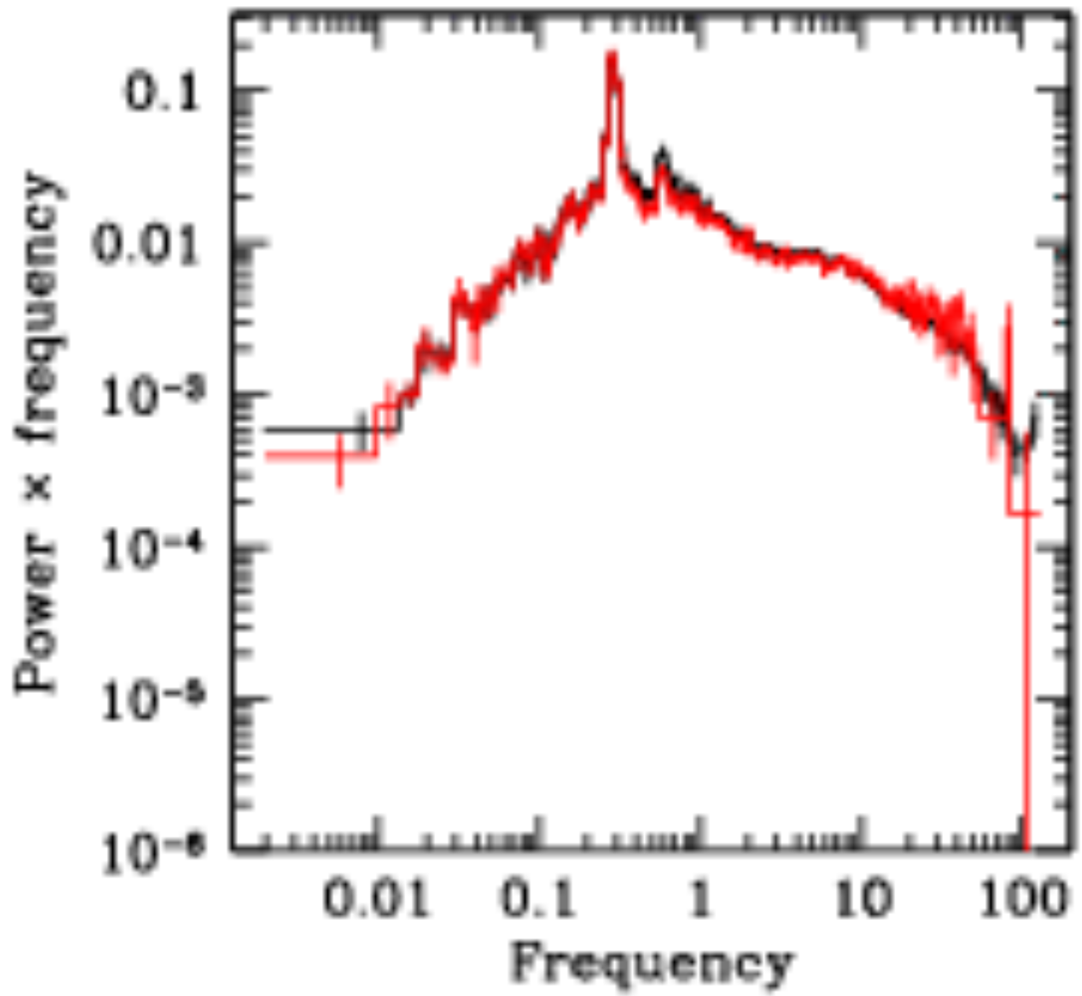


Phil Uttley

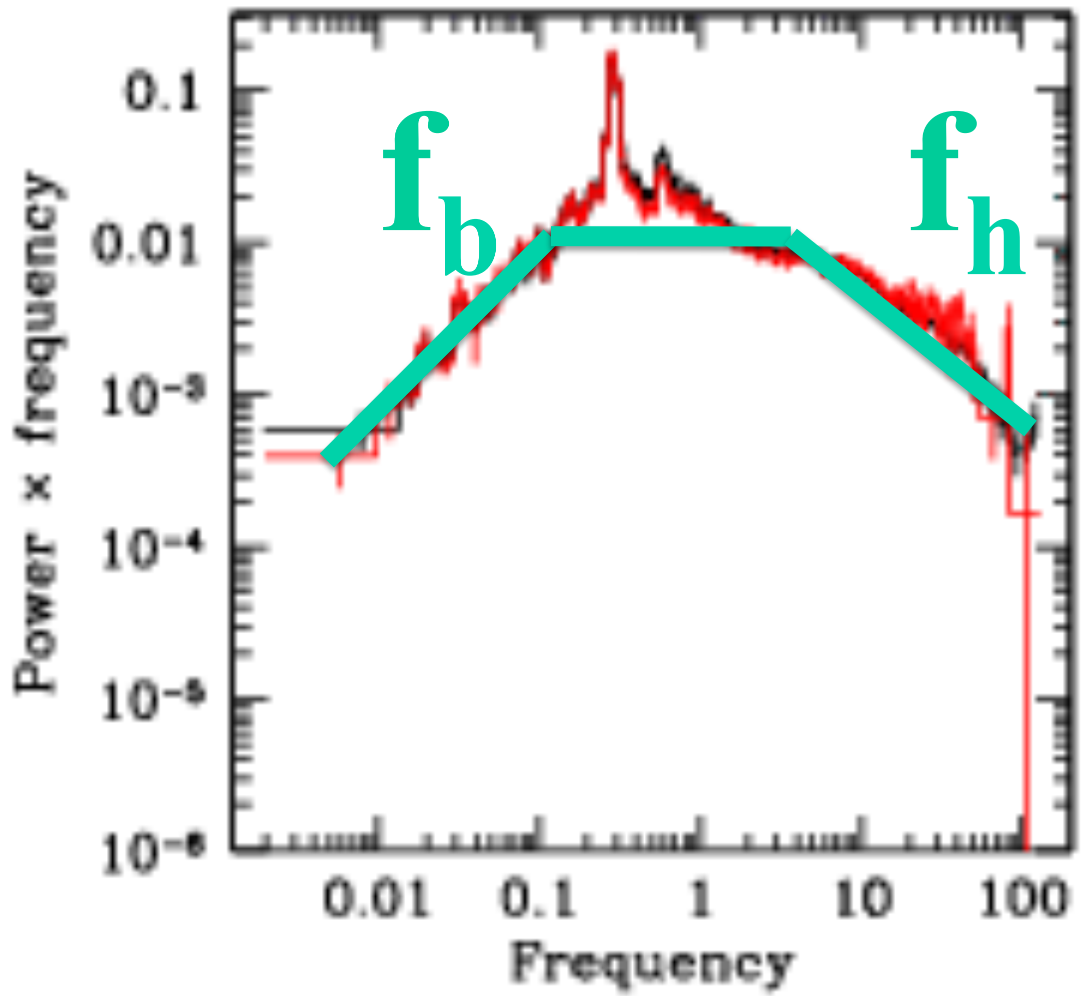
Low/hard state variability- QPO



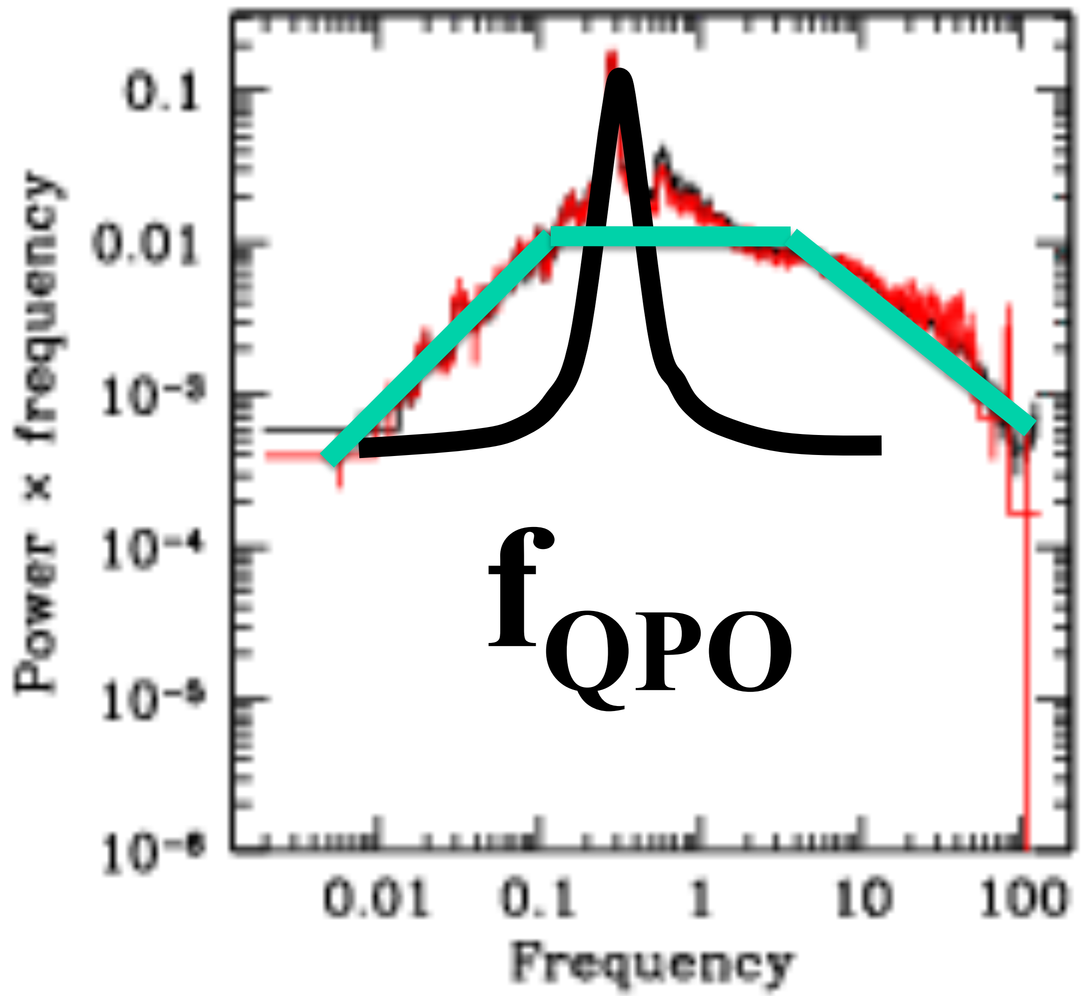




Power × frequency
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.01
0.1
1
10
100
Frequency



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

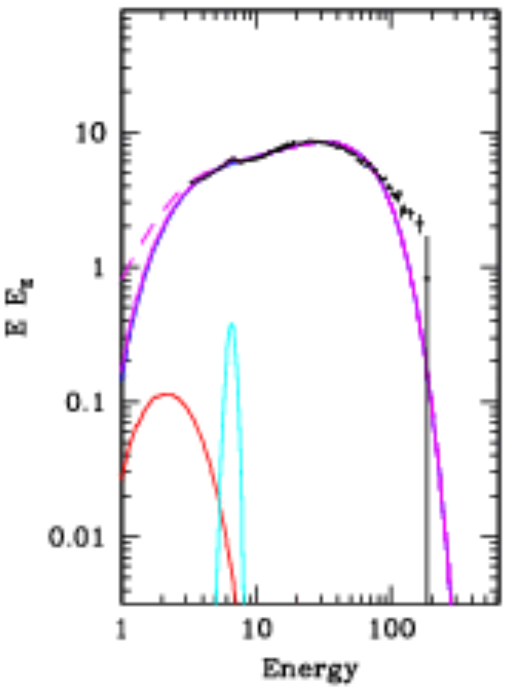


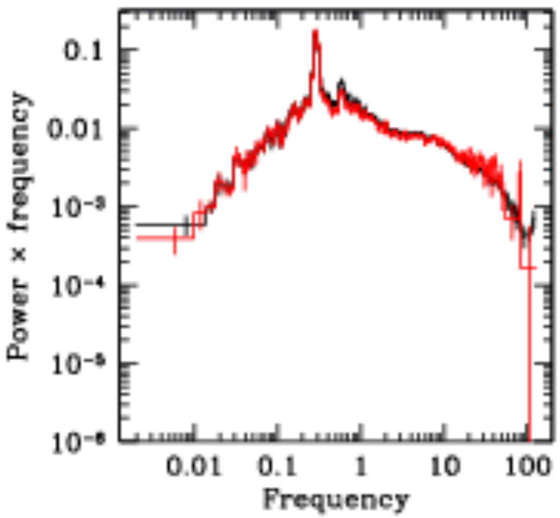
Power × frequency
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.01
0.1
1
10
100
Frequency
f_{QPO}

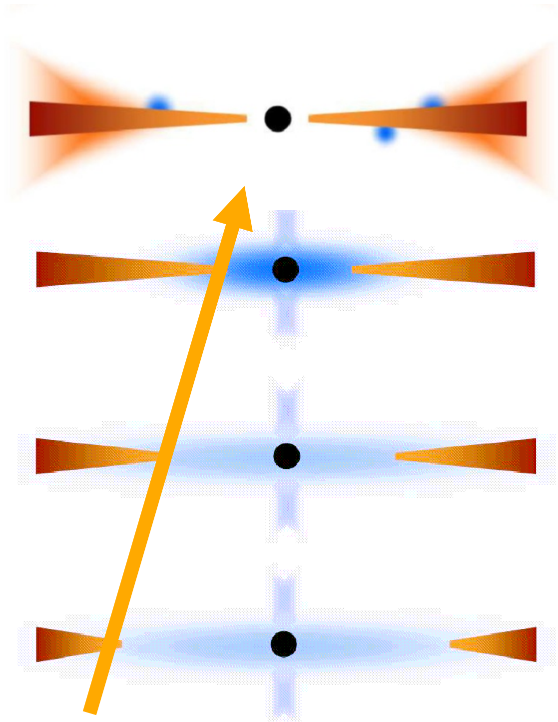
Moving disc – moving QPO

- 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

DGK07







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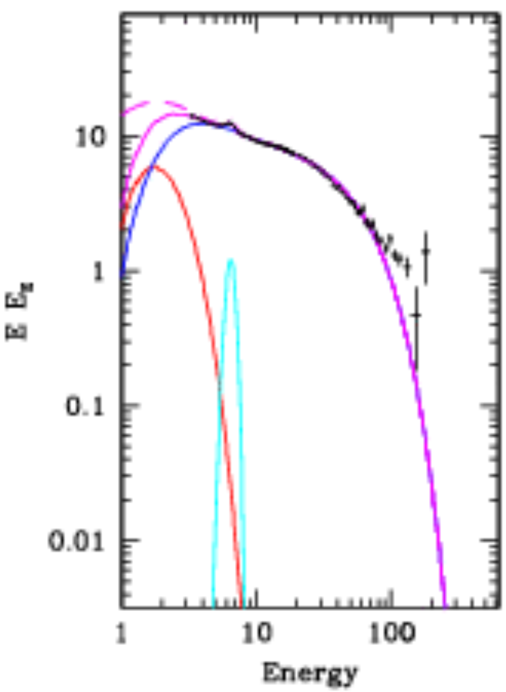
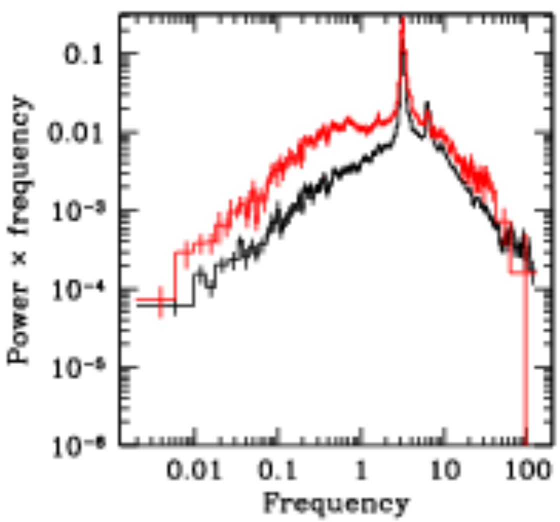
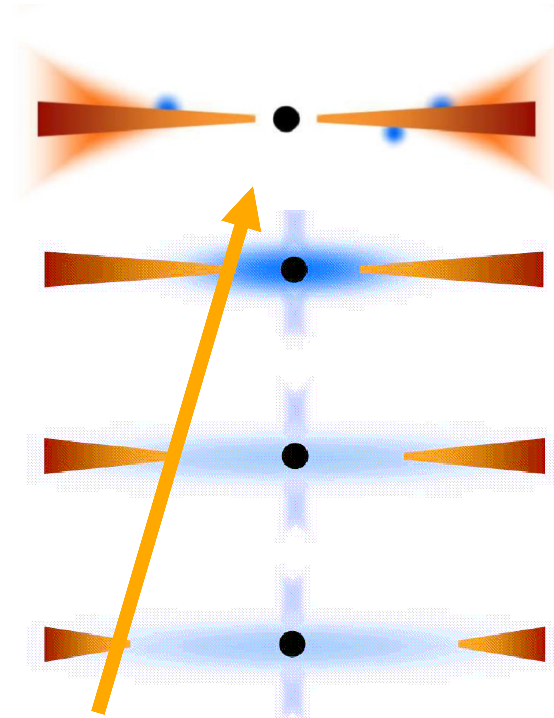
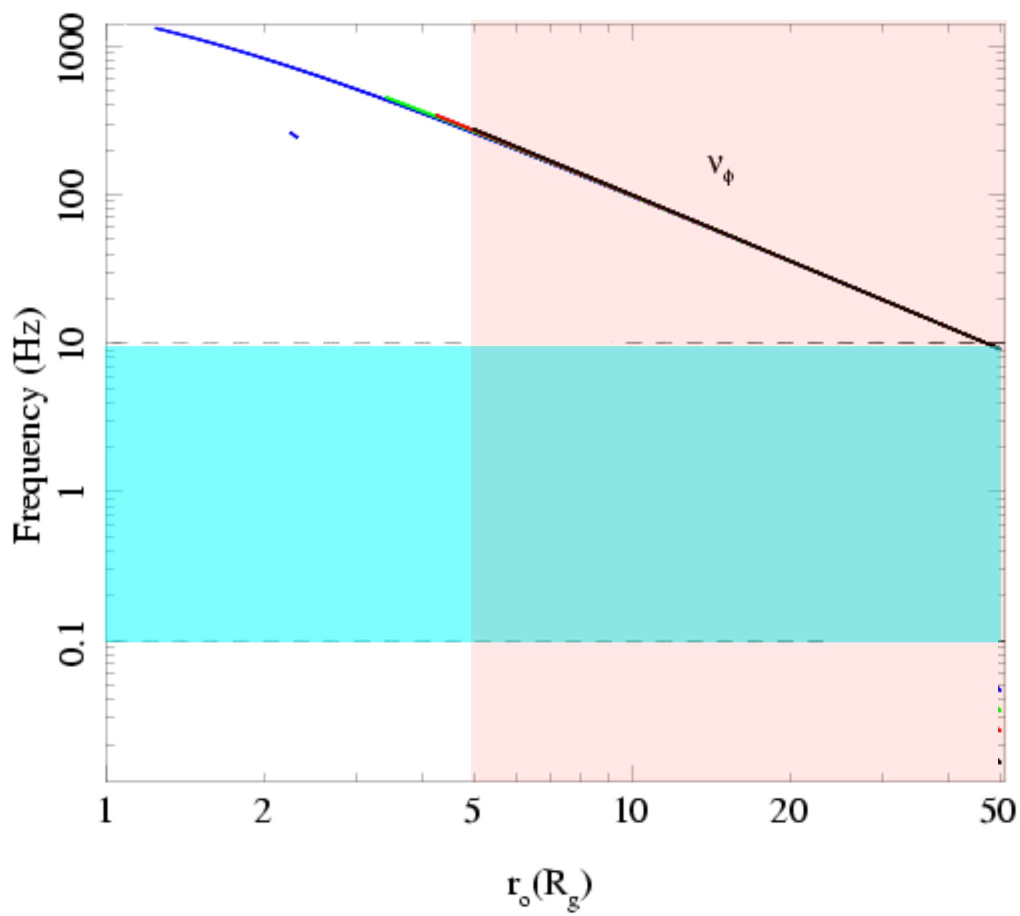






Low frequency QPO

- 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 $\nu(\varphi)$ as too fast!



Ingram, Done & Fragile 2009

Low frequency QPO

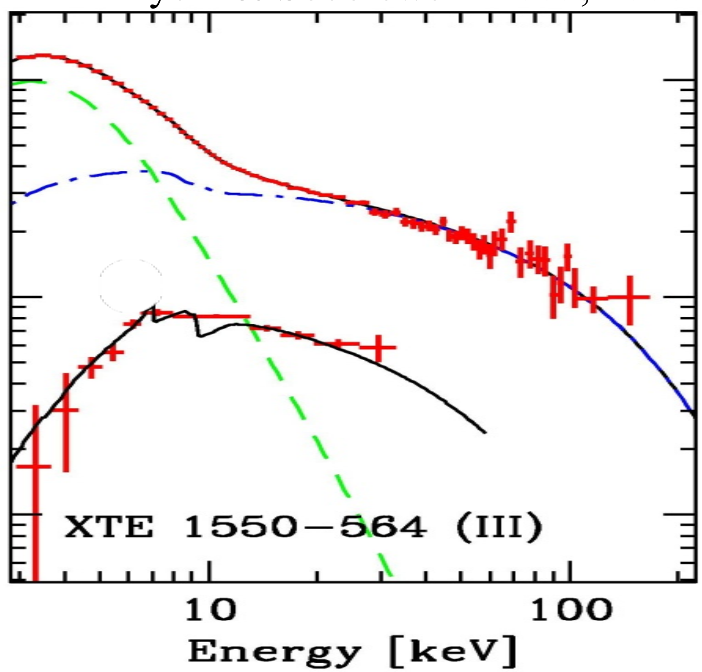
- Stella & Vietri 1998 – GR potential not spherically symmetric so vertically offset circular orbit has $\nu(\theta) \neq \nu(\varphi)$
- Lense-Thirring precession $\nu_{LT} = \nu(\theta) - \nu(\varphi)$

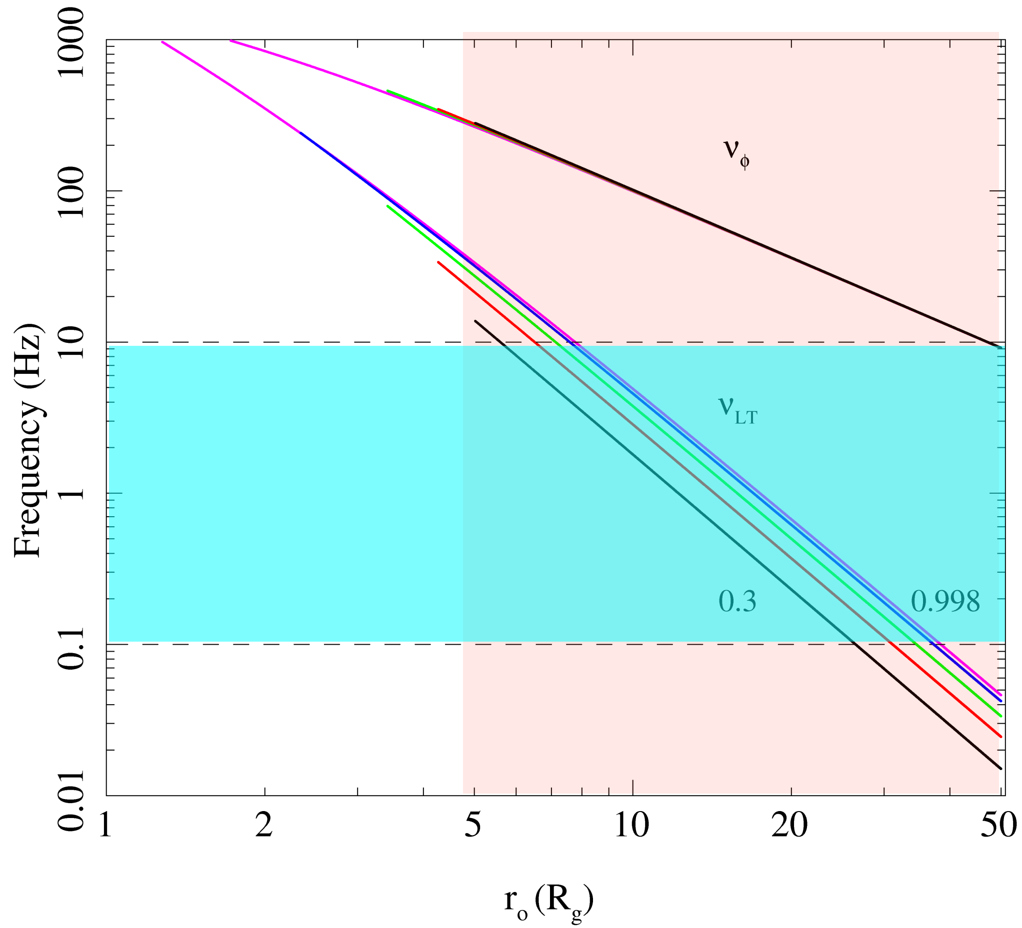
Lamb & Markovic

Does it work ?

- Not really
- Edge of disc would have blackbody spectrum. QPO has spectrum of hot inner flow!

Zycki & Sobolewska 2005; 2006



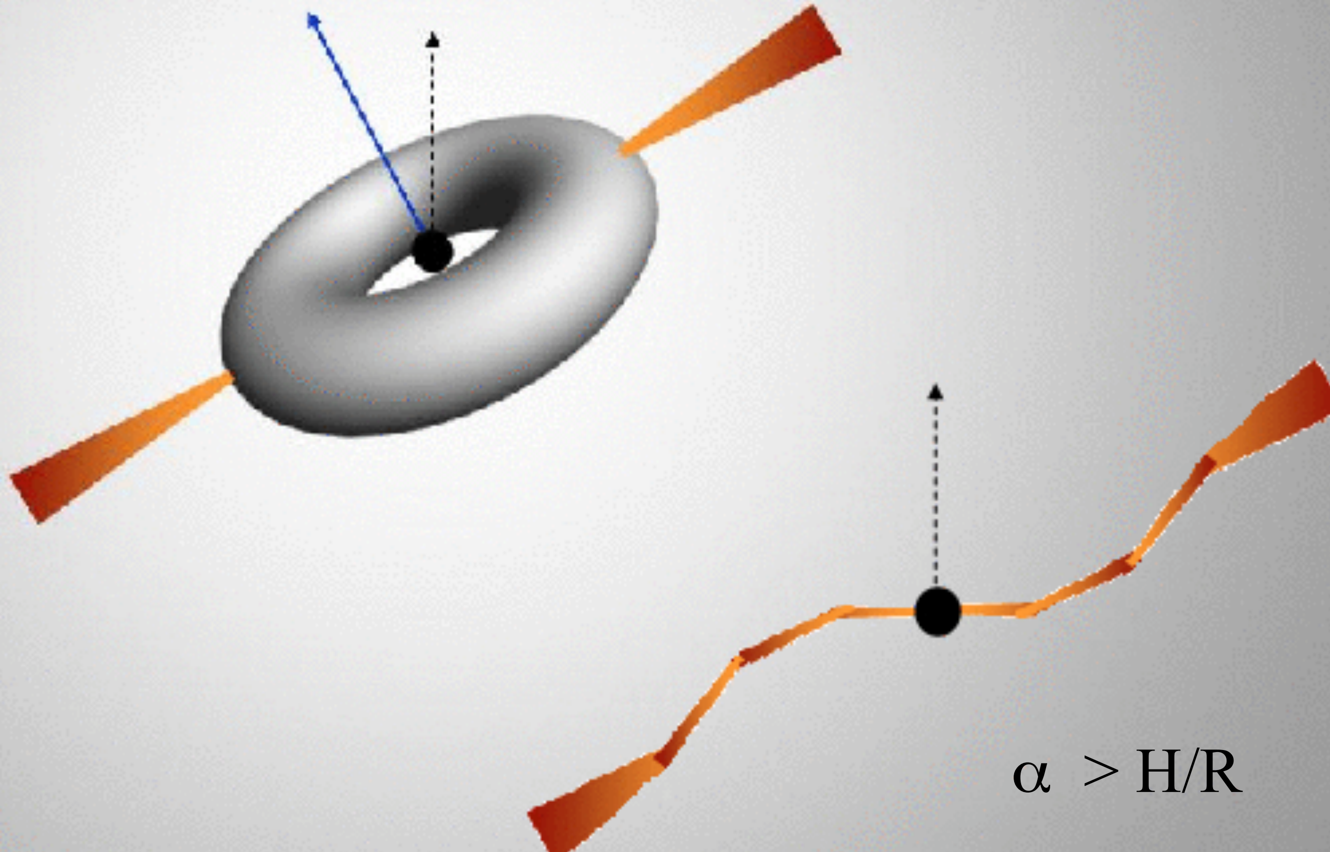


Ingram, Done & Fragile 2009

Solid body precession of the flow

$\alpha < H/R$

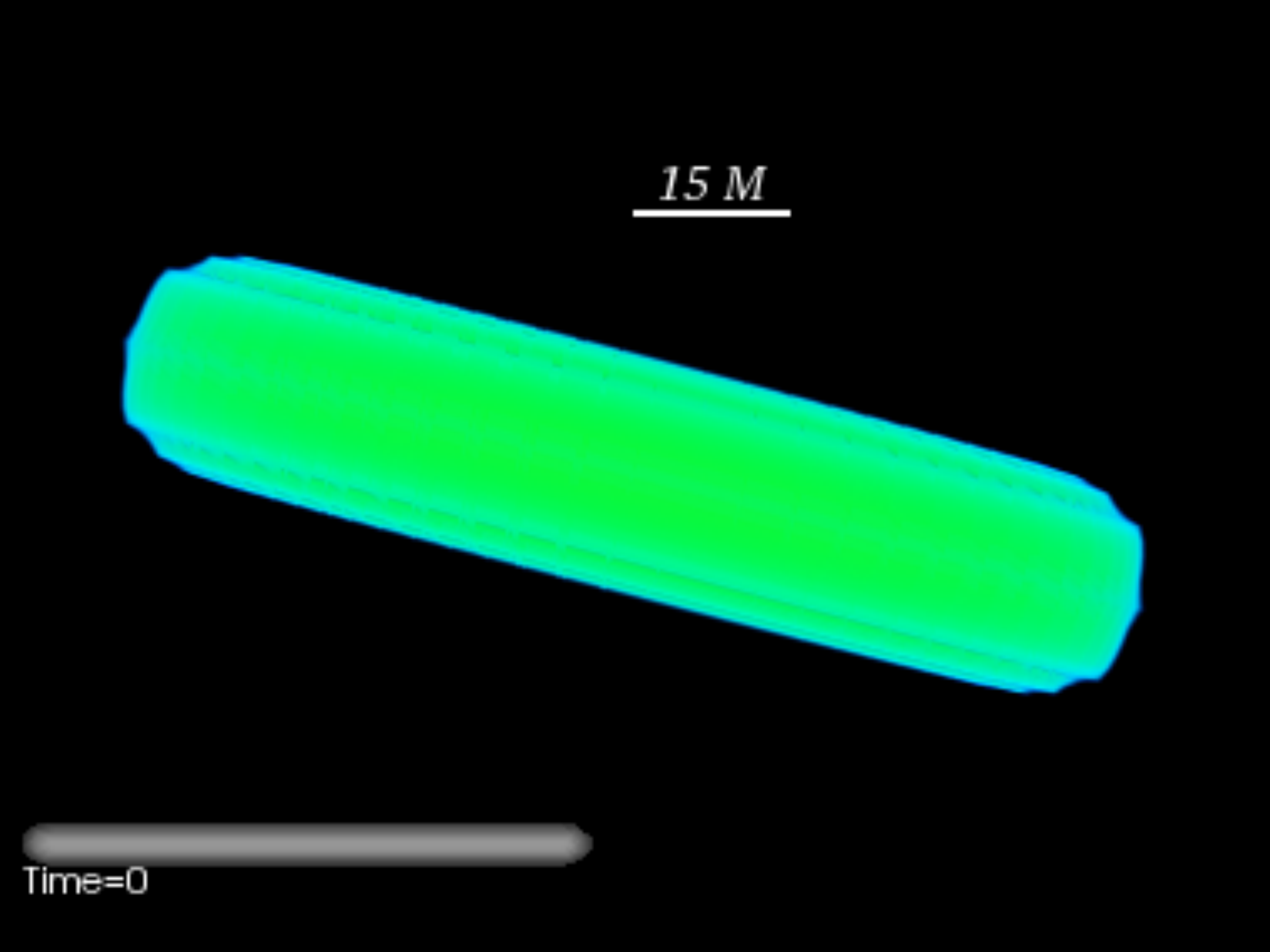
precession



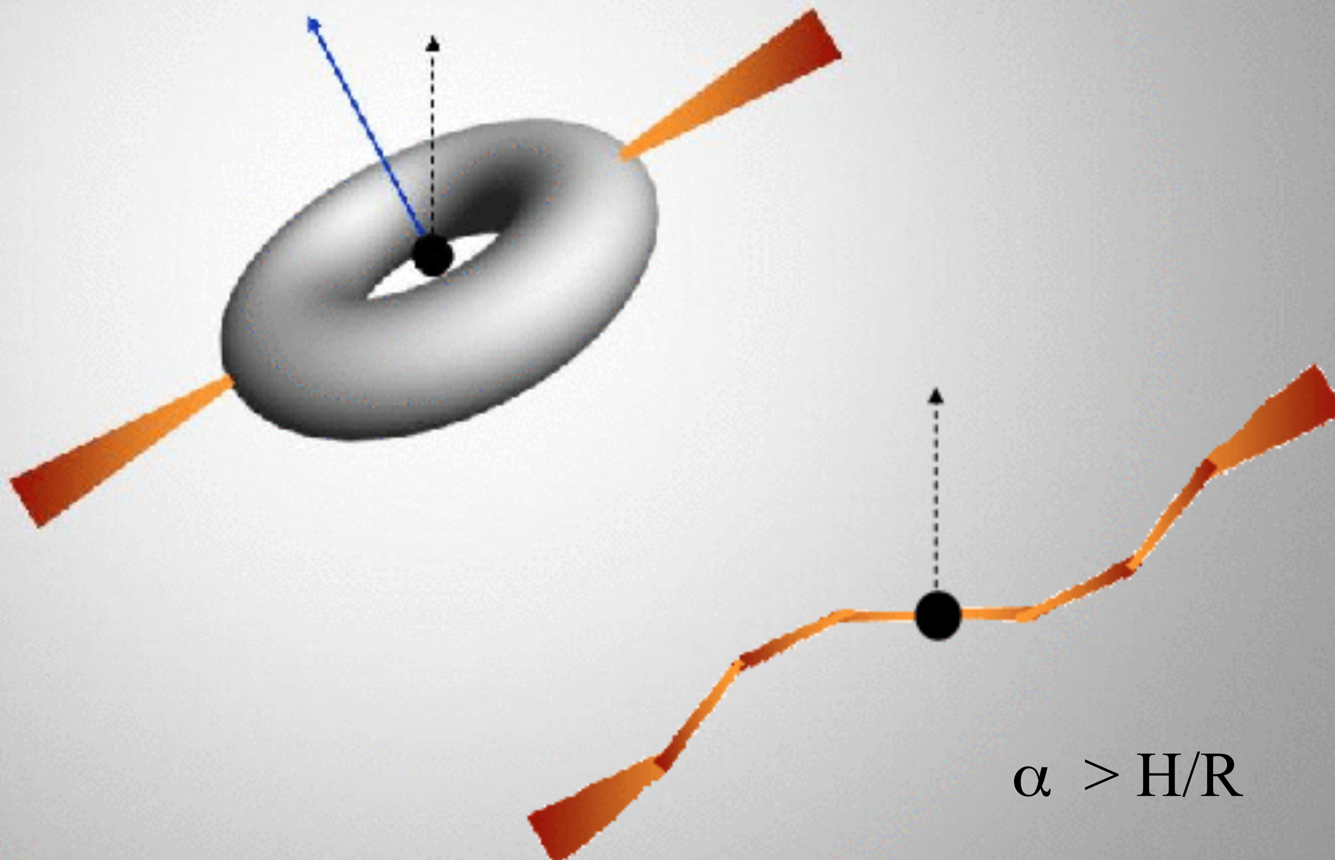
$\alpha > H/R$

Warped disc

Ingram, Done & Fragile 2009


15 M
Time=0

Solid body precession of the flow

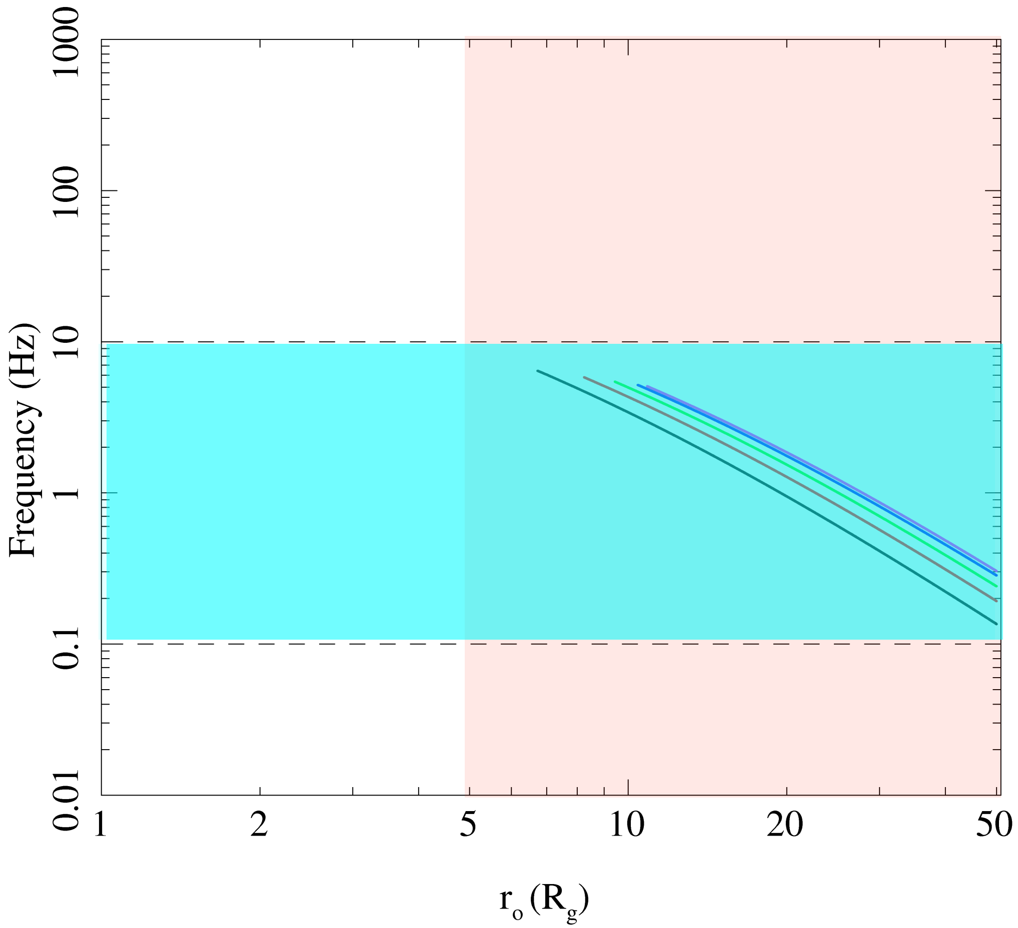


Ingram, Done & Fragile 2009

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

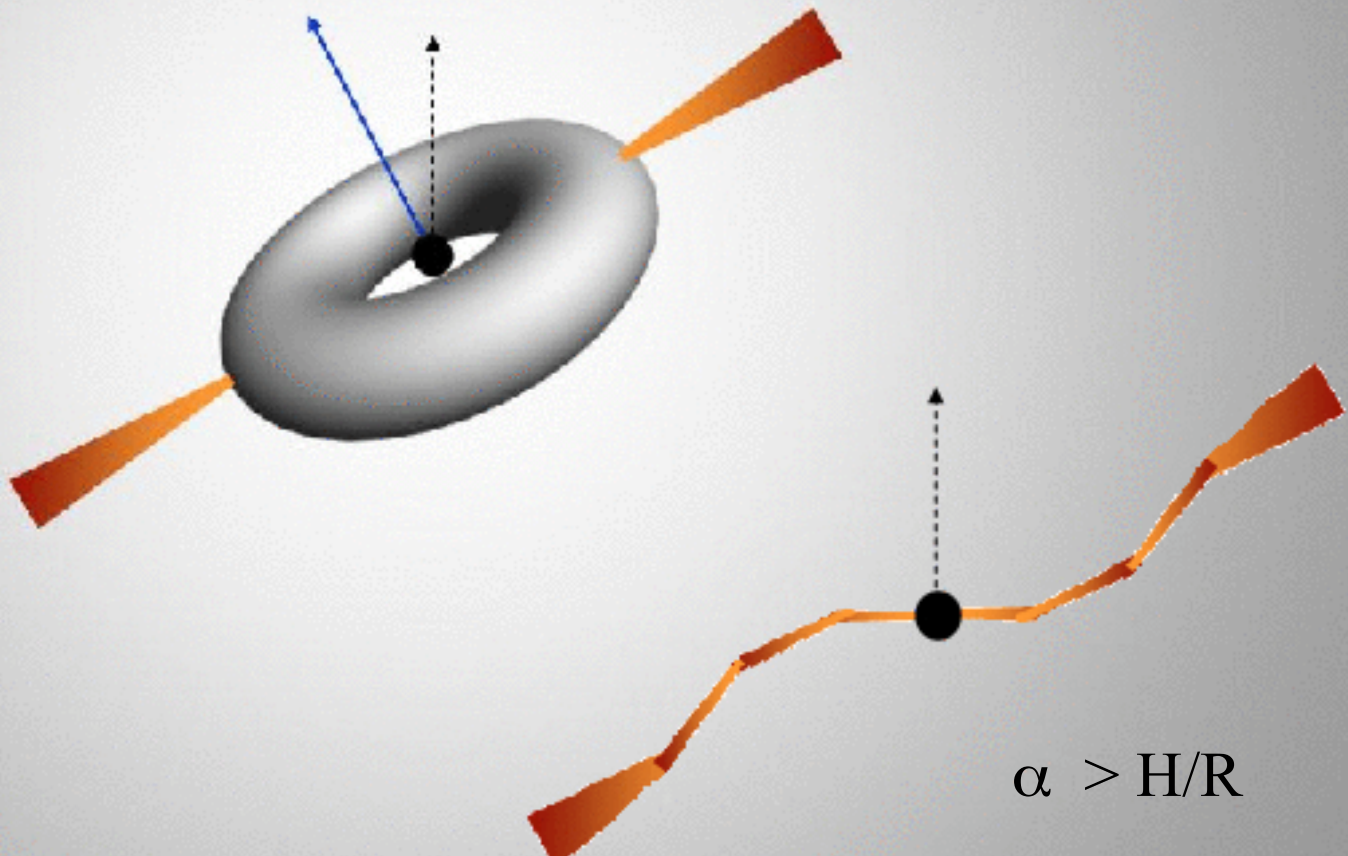


Ingram, Done & Fragile 2009

Solid body precession of the flow

α < H/R

precession



α > H/R

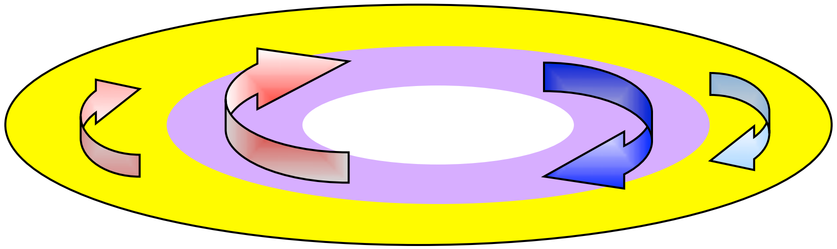
Warped disc

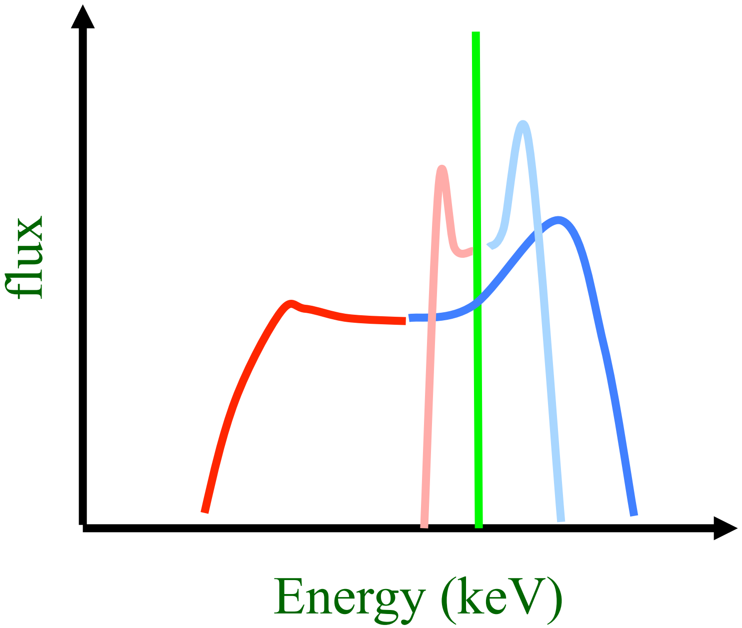
Ingram, Done & Fragile 2009

Relativistic effects

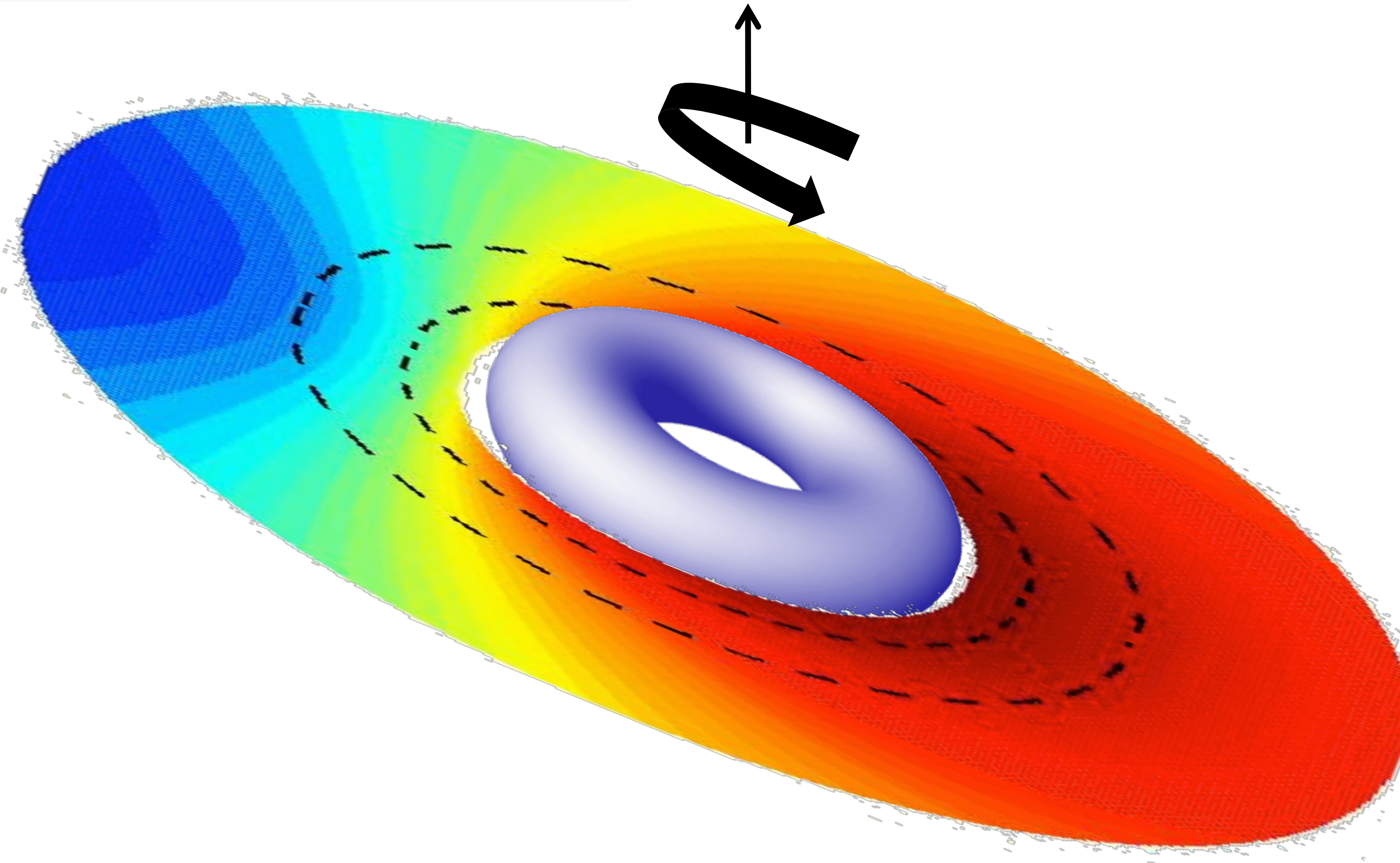
Fabian et al. 1989

- Emission from the side of the disc coming towards us is blueshifted and boosted by Doppler effects, while opposite side is redshifted and suppressed.
- Also time dilation and gravitational redshift

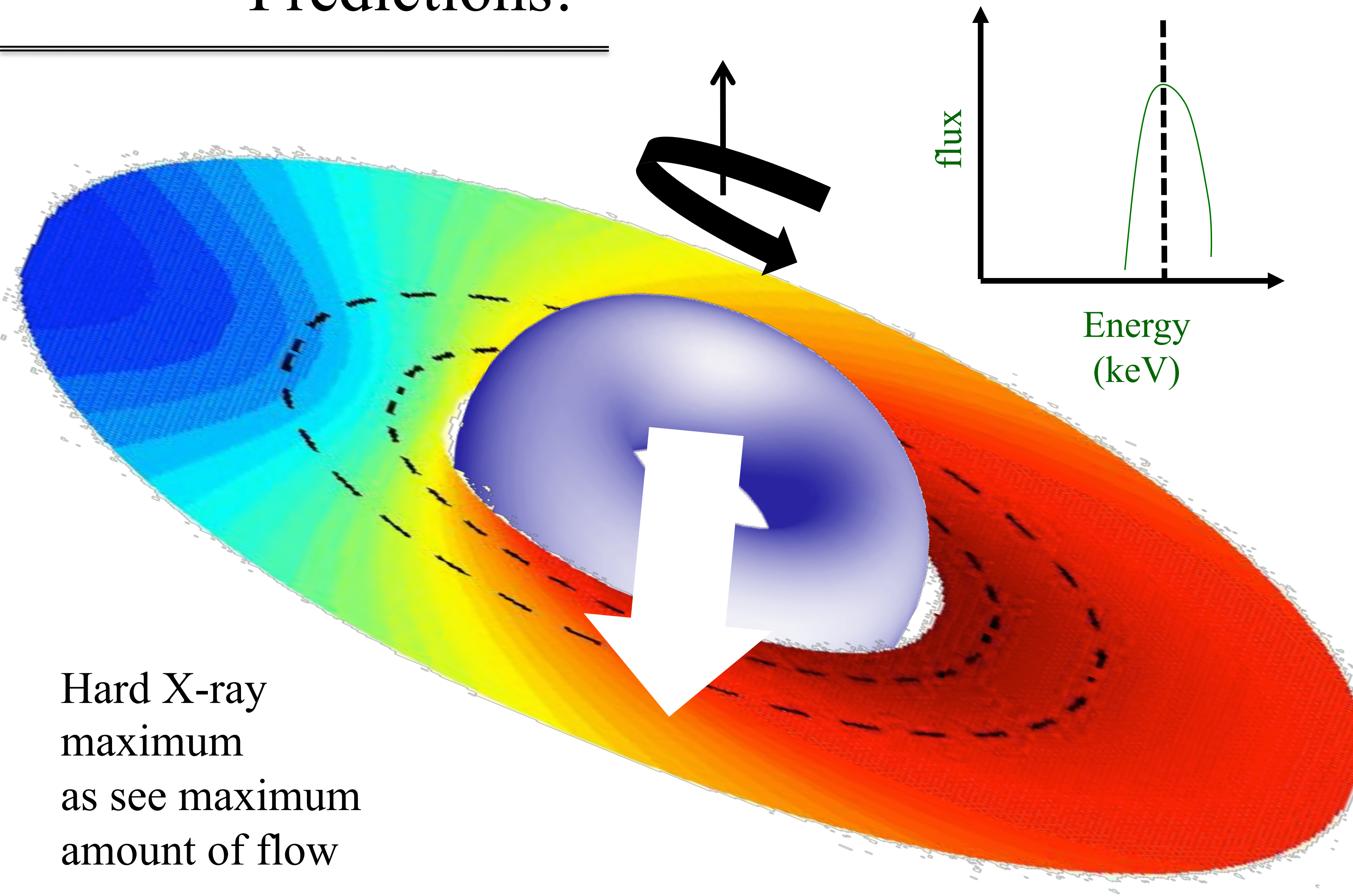




Predictions!

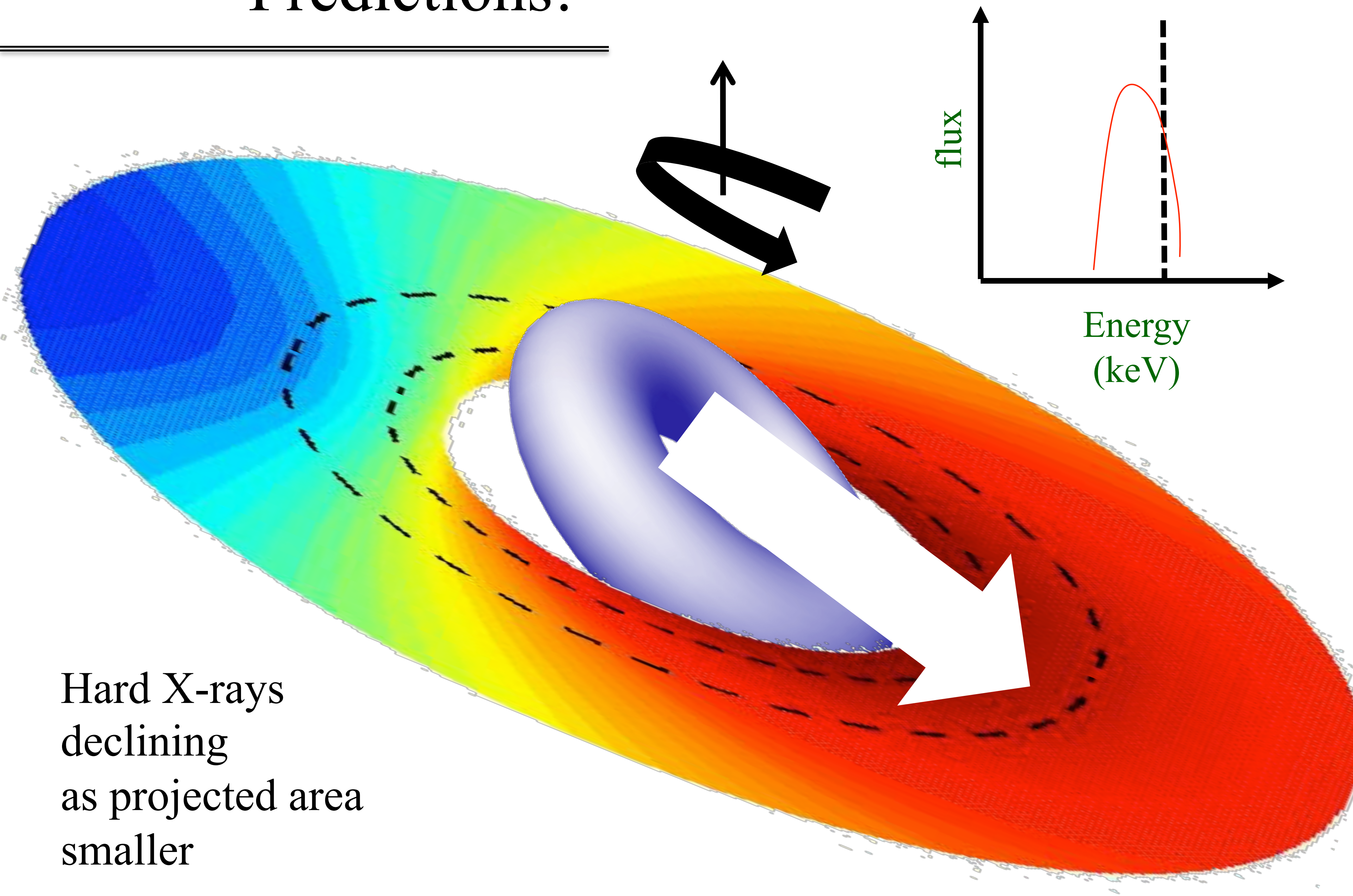


Predictions!



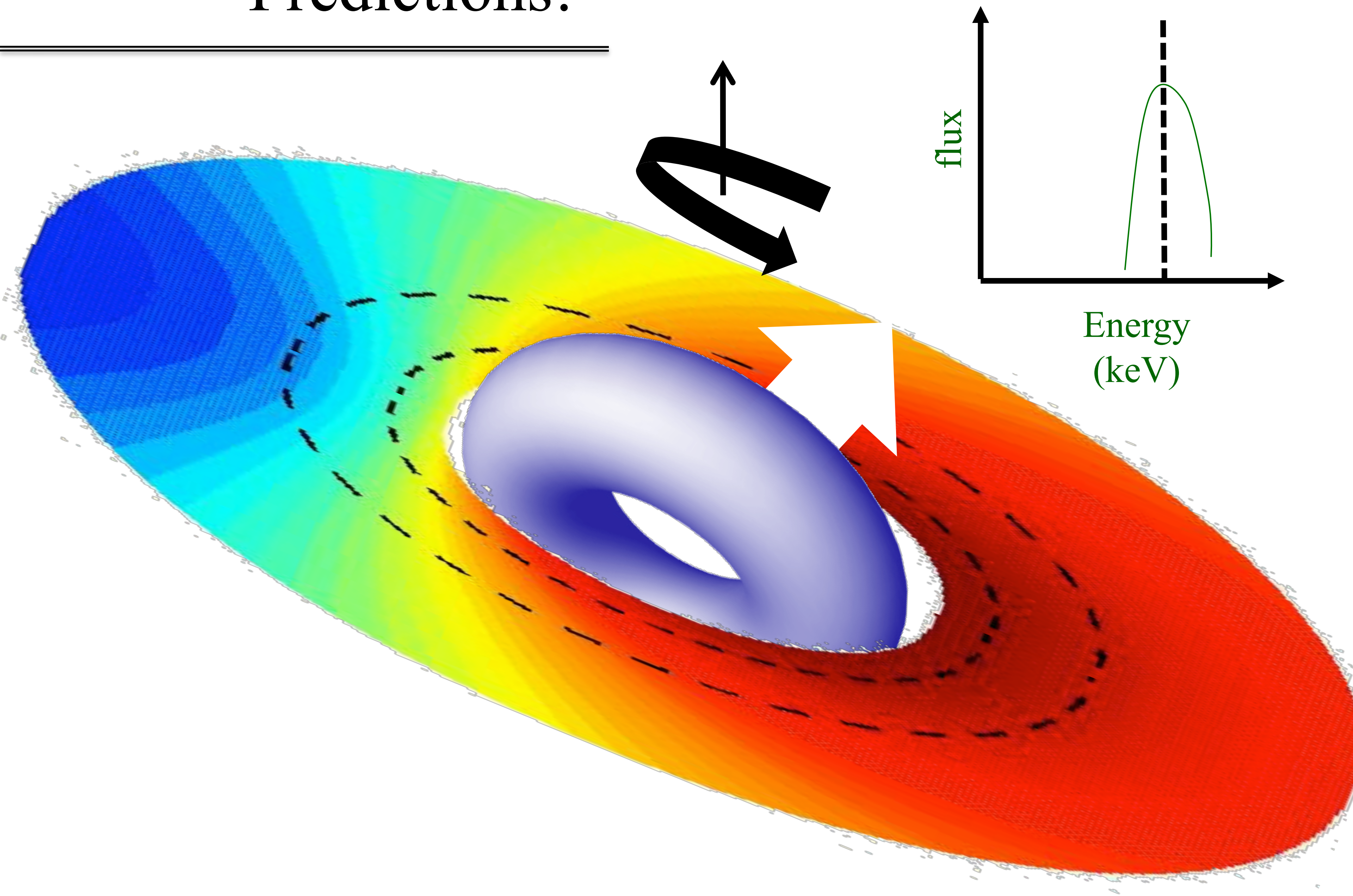
Hard X-ray
maximum
as see maximum
amount of flow

Predictions!

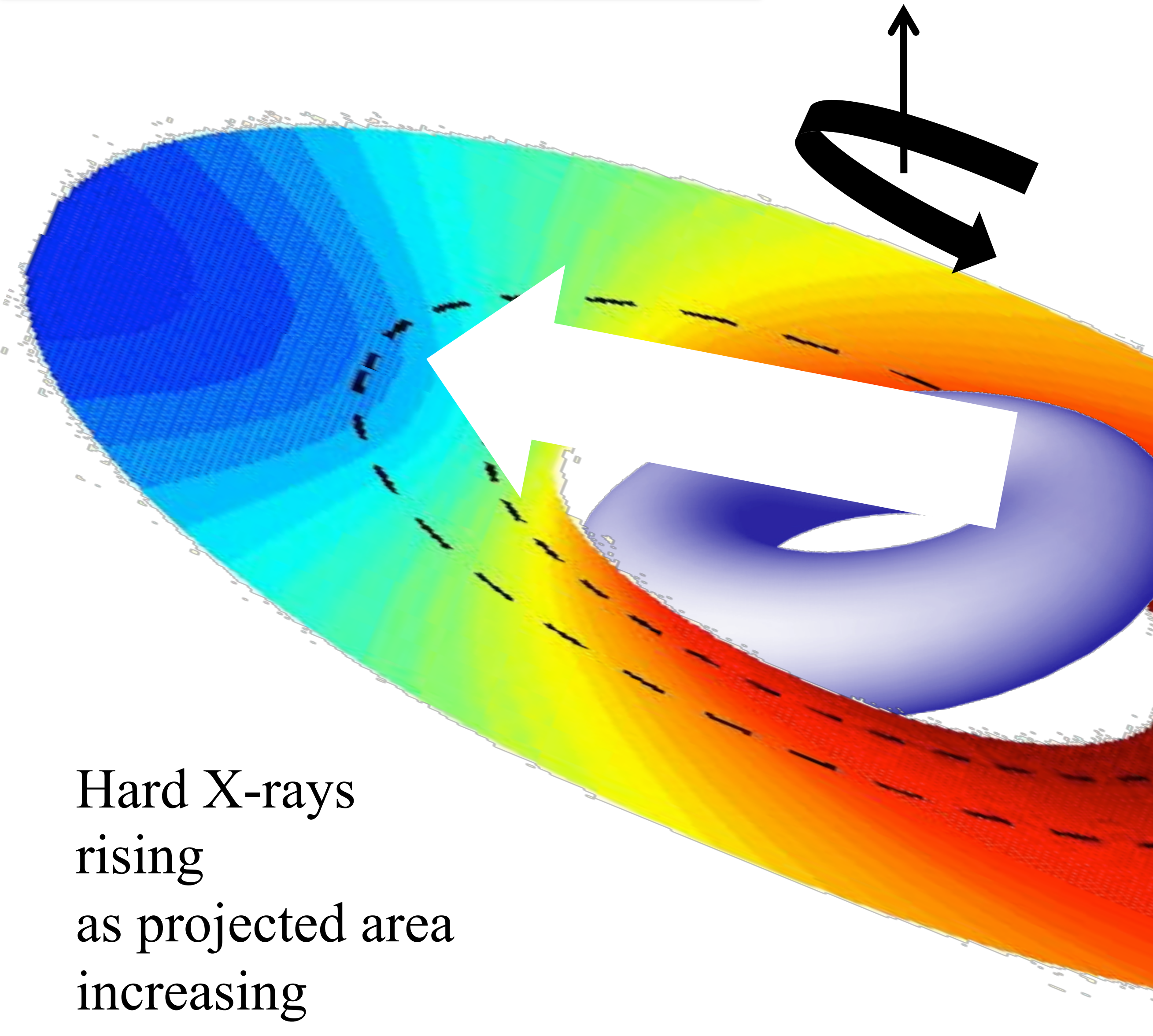


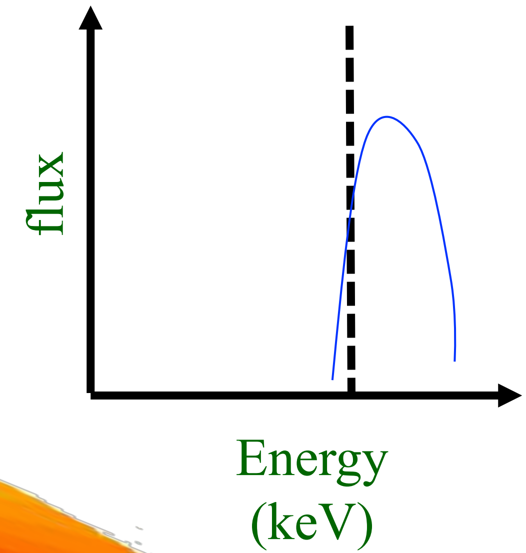
Hard X-rays
declining
as projected area
smaller

Predictions!



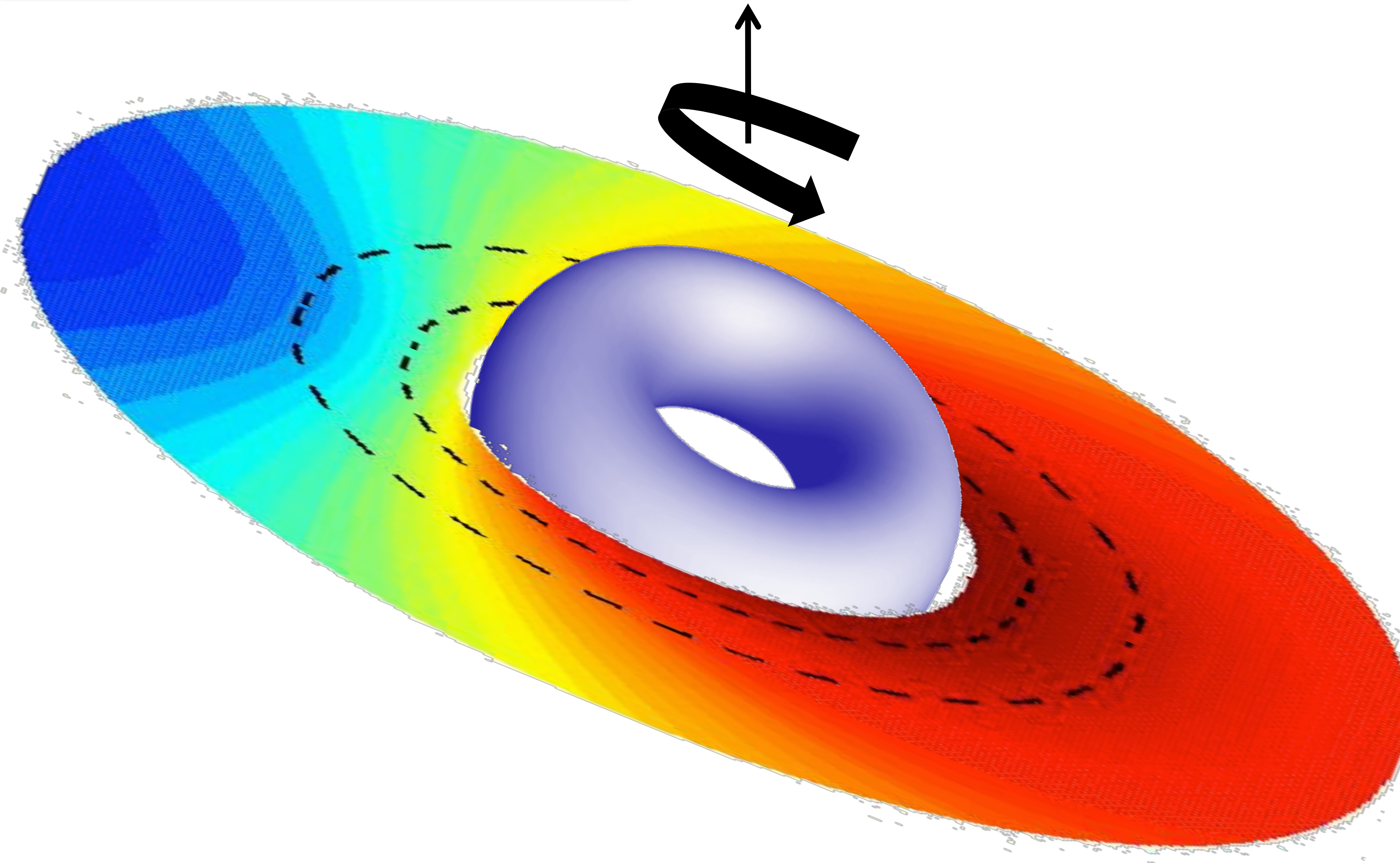
Predictions!





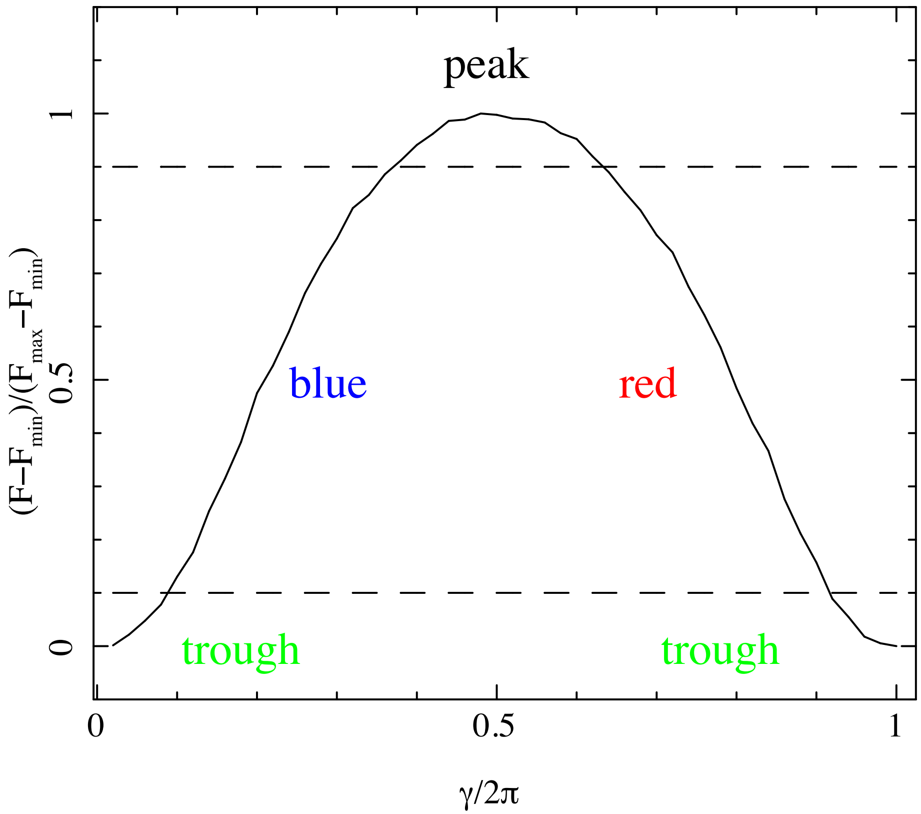
Hard X-rays
rising
as projected area
increasing

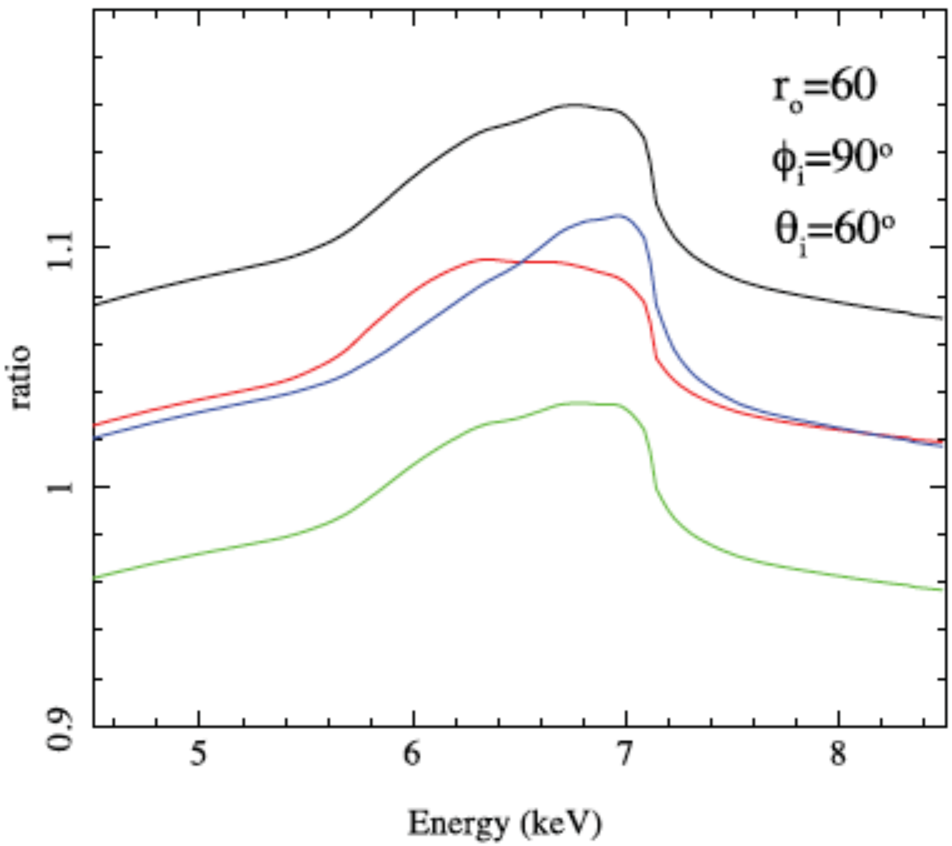
Predictions!



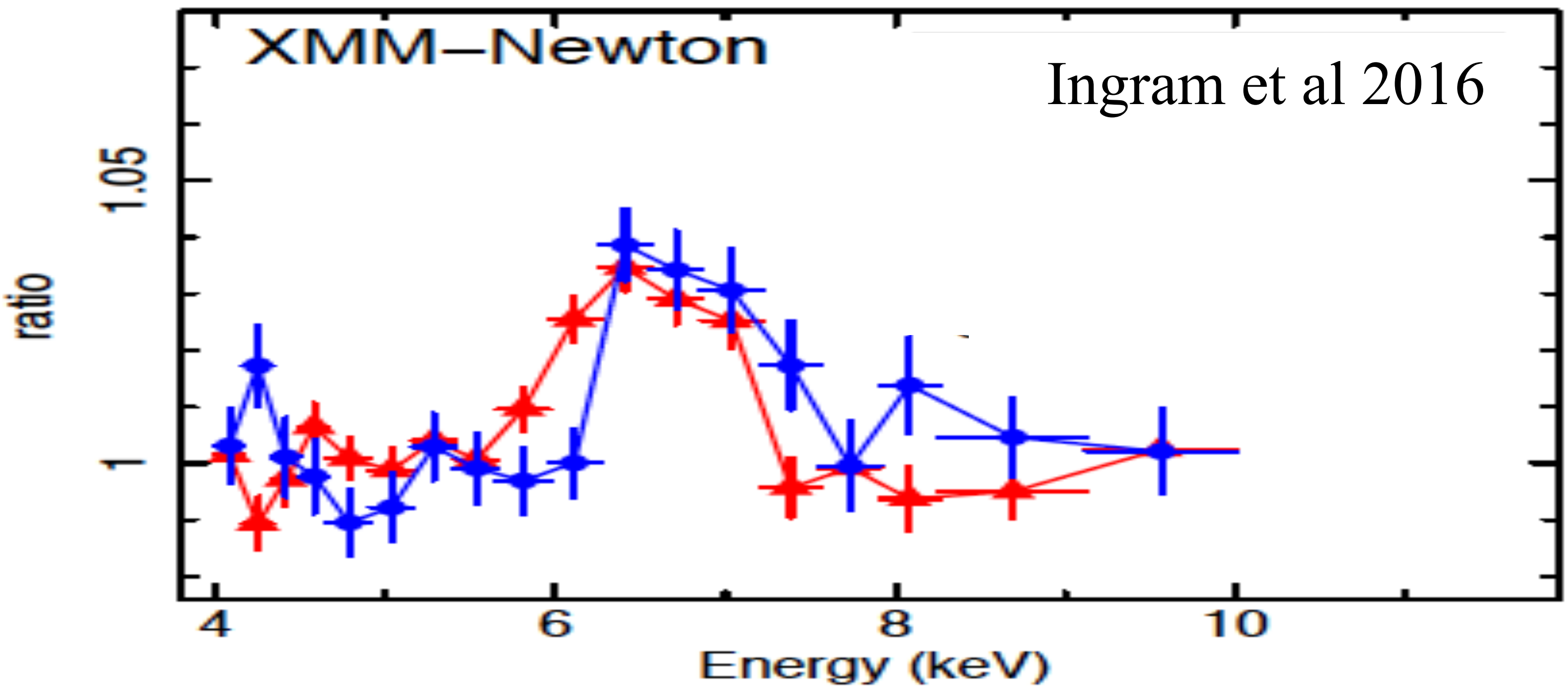
Lense-Thirring origin of QPO

Correlation of QPO lightcurve with line shift
Filter and then select rising/falling phase of QPO
Ingram & Done 2012





Lense-Thirring origin of QPO!!



- Line energy rocks on QPO phase as predicted! 3.7σ
- First detection of LT in strong field limit
- Origin of QPO!
- REQUIRES a truncated disc (can't do vertical precession if there is a disc in the midplane

Conclusions

- Not only can we understand BHB and NS….
- High L/Ledd disk=ISCO and event horizon in BHB
- Disc down to NS surface in NS
- low L/Ledd: hot flow/truncated disc (+jet $\Gamma \sim 1.5$)
- QPO - Lense-Thirring precession!
- Iron line energy shifts with QPO phase as predicted!
- First detection of LT in strong field limit!!
- It means there is something wrong with broad Fe lines
- …we can also understand highly relativistic jets
  - High spin BZ (spin powered) jets give $\Gamma=15$ at all mass and L
  - Low spin accretion powered jets give $\Gamma \sim 1.5$ at all mass and L
- Opens the way to quantitative models of AGN feedback