Spectral and timing studies of X-ray binaries

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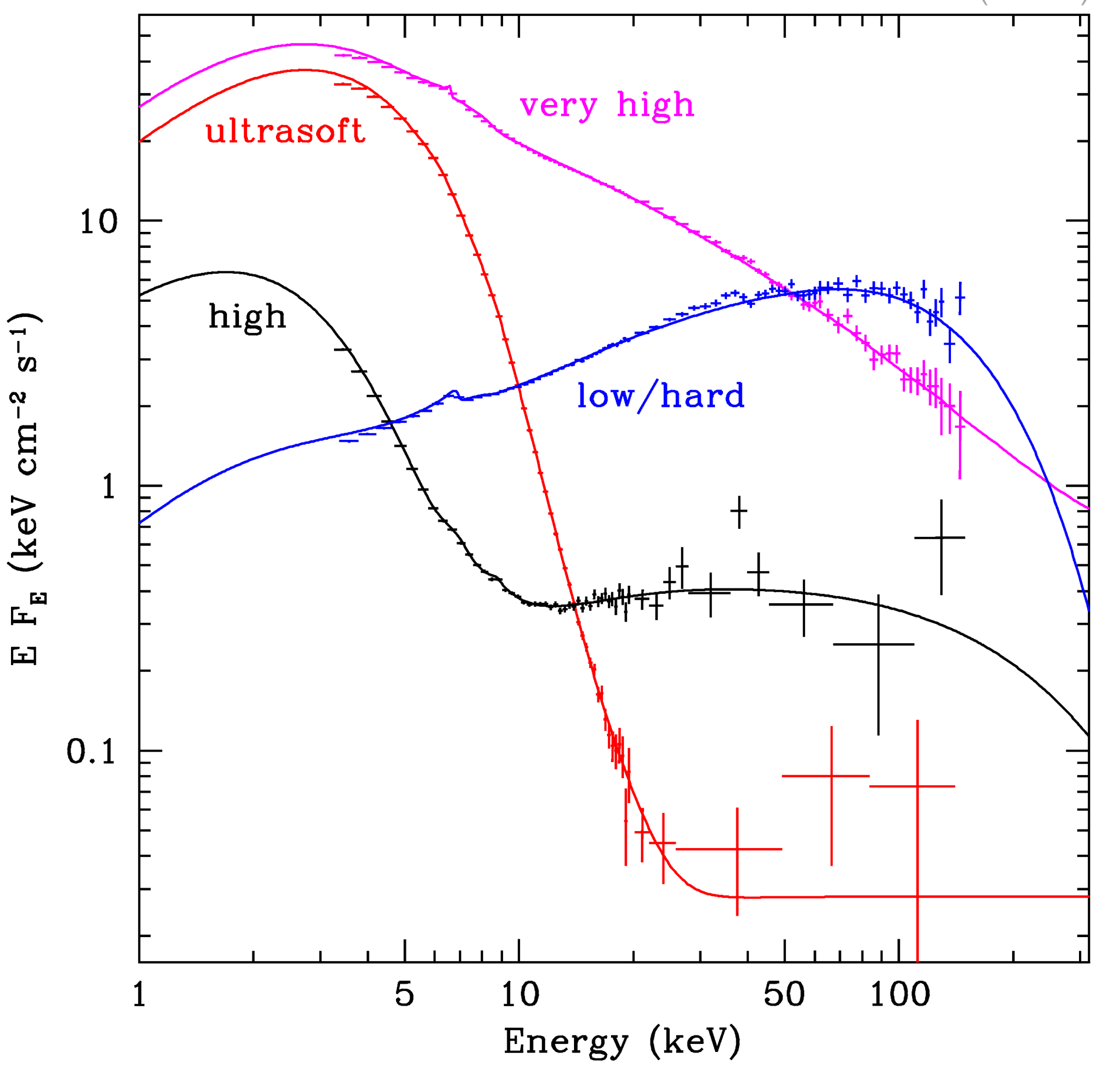
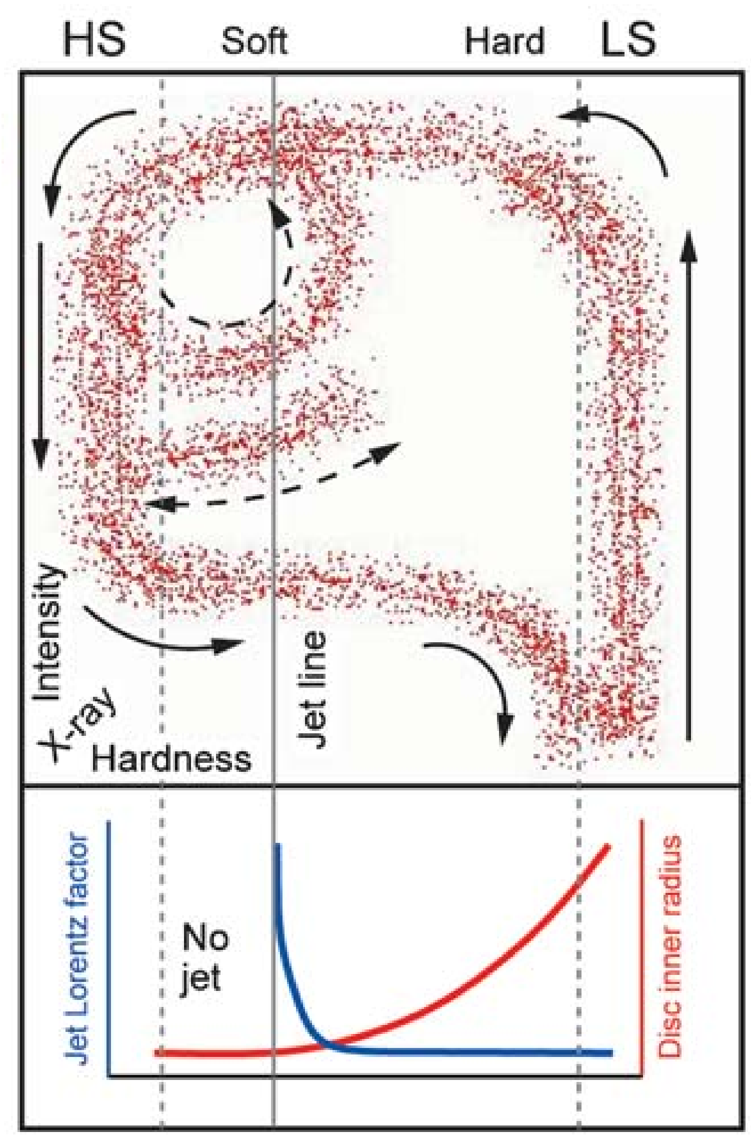
X-ray binaries

- Compact object (NS/BH) accreting from a companion star - I will mainly talk about black hole binaries.
- Two types: low-mass X-ray binary (LMXB) and high-mass X-ray binary (HMXB), depending on companion star
- Strong sources of X-ray emission
- ~190 LMXBs and ~120 HMXBs found
- Only 2 (3) HMXB with black holes known in our Galaxy!

Spectrum comes in many variations!

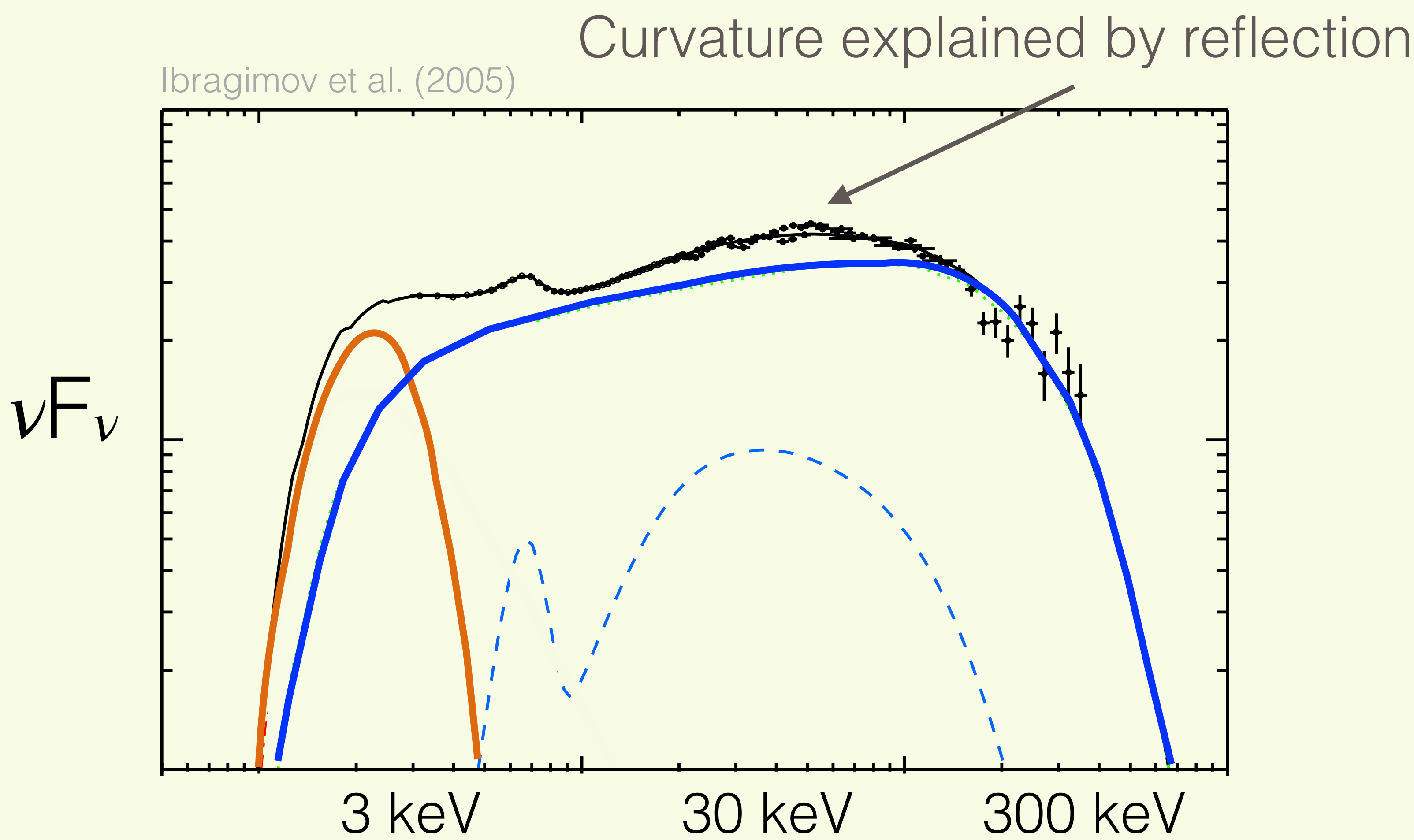
Done et al. (2007)

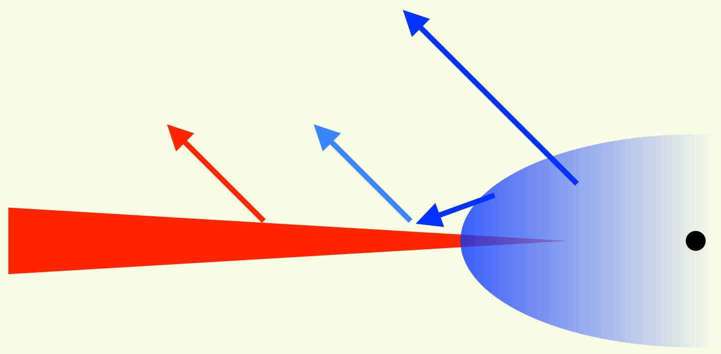




Remillard & McClintock (2006)

Spectral studies have led to a model with several physical components

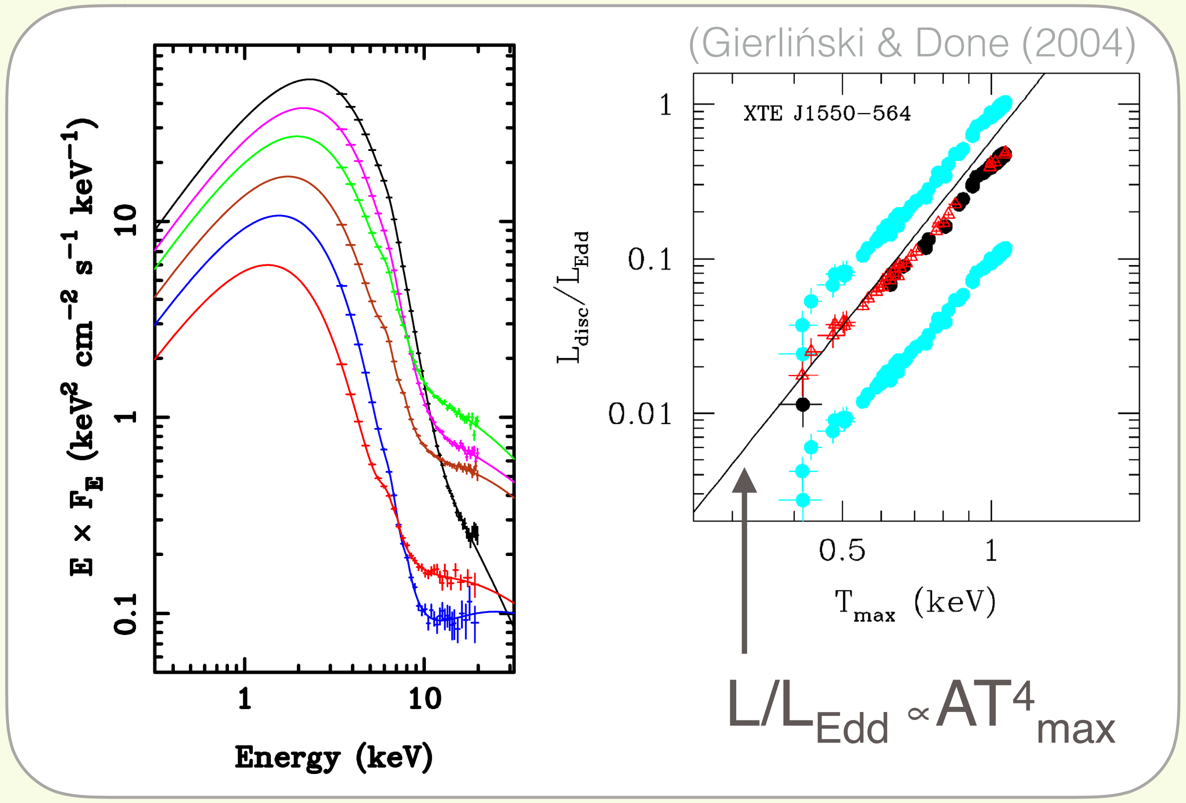




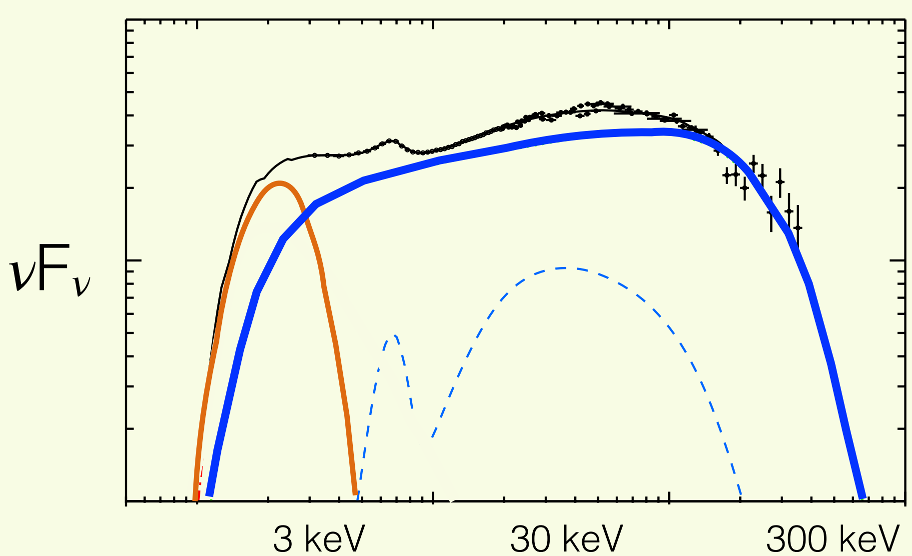
Accretion disc
(<1 keV)

Thermal Comptonisation
(hot, optically thin medium)

Physical information from spectra



Variability of disc-dominated state points to constant size scale: last stable orbit —> BH spin!

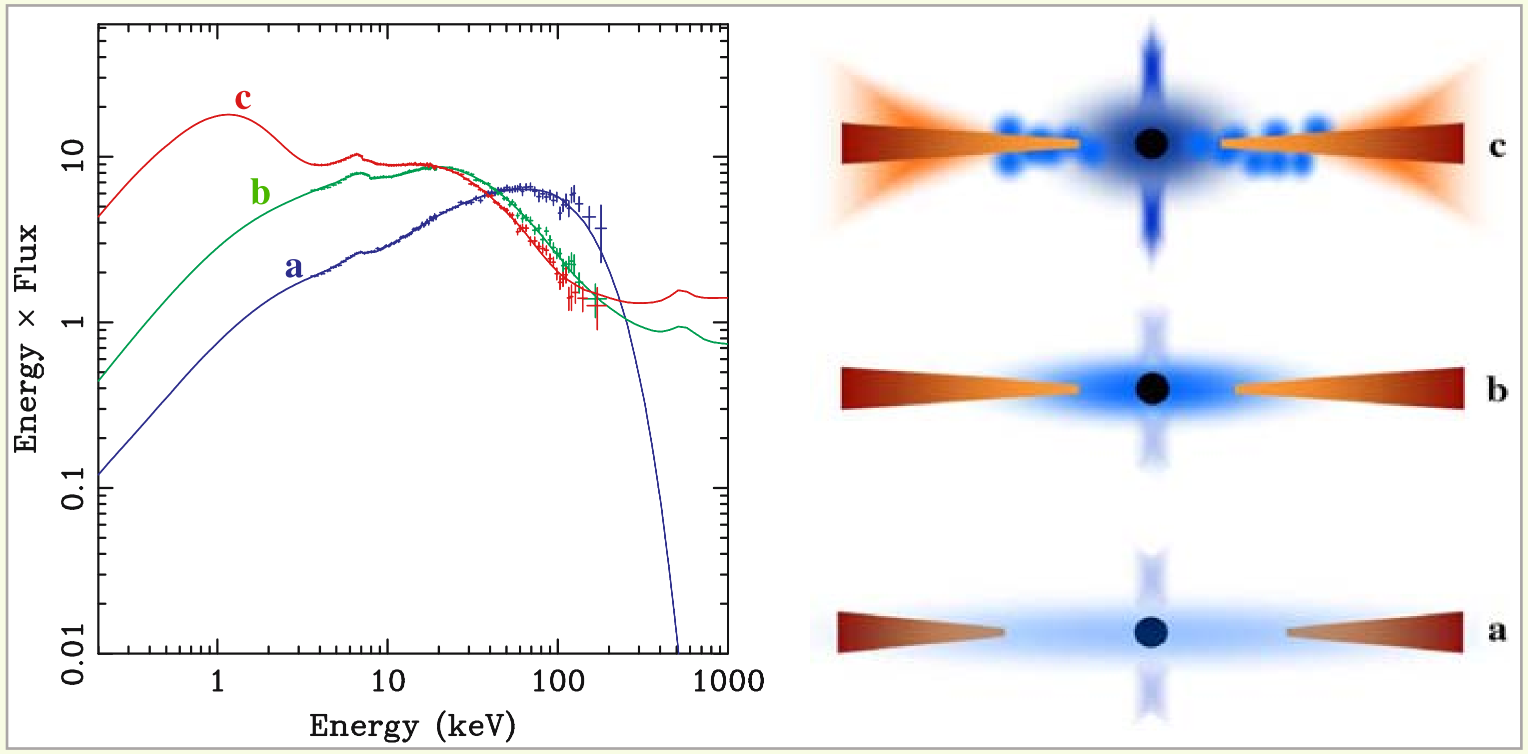


Comptonization gives electron temperature and optical depth

Reflection gives ionisation, covering fraction (though difficult)

This picture has been remarkably successful

Done et al. (2007)



Different geometries can explain large variations in spectra (spectral states)

This picture has been remarkably successful

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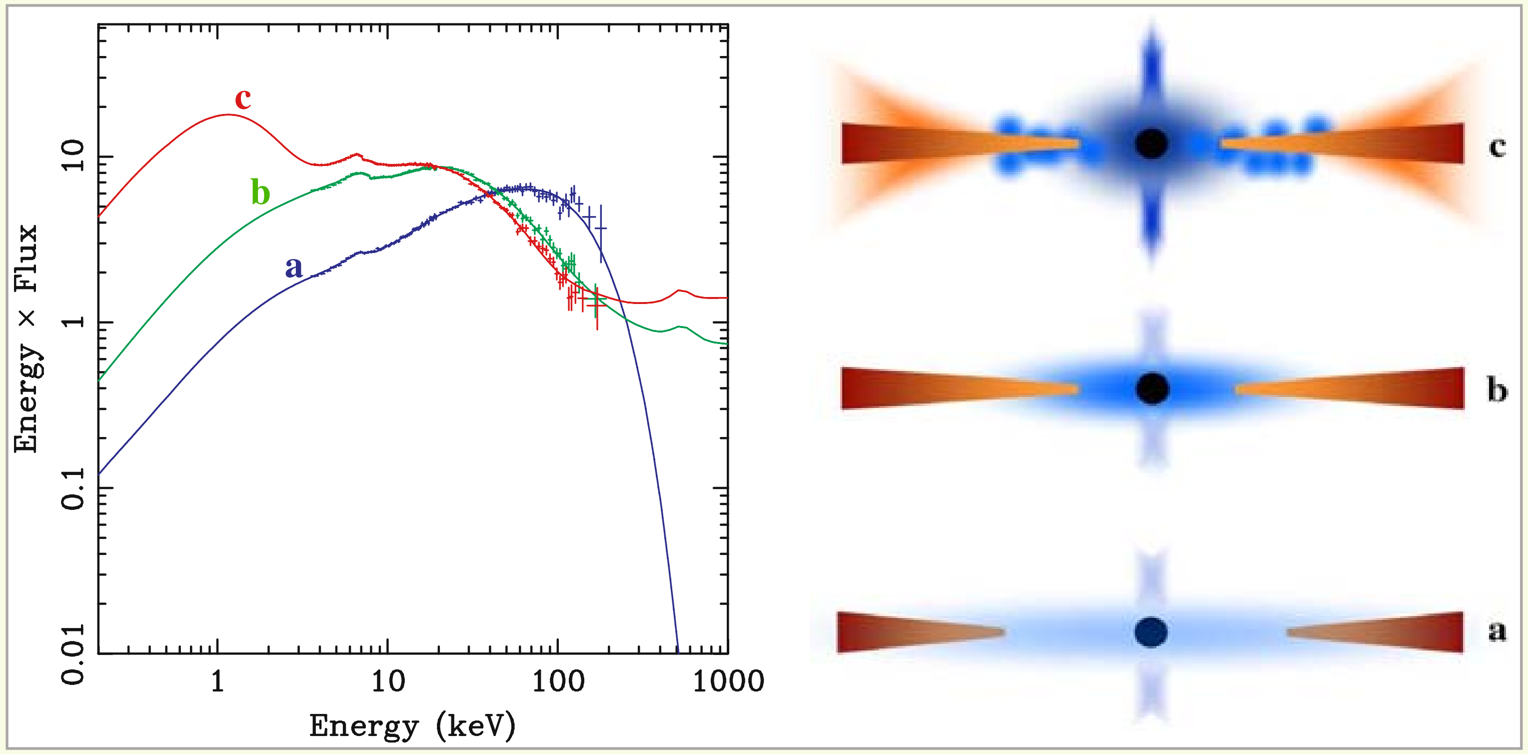
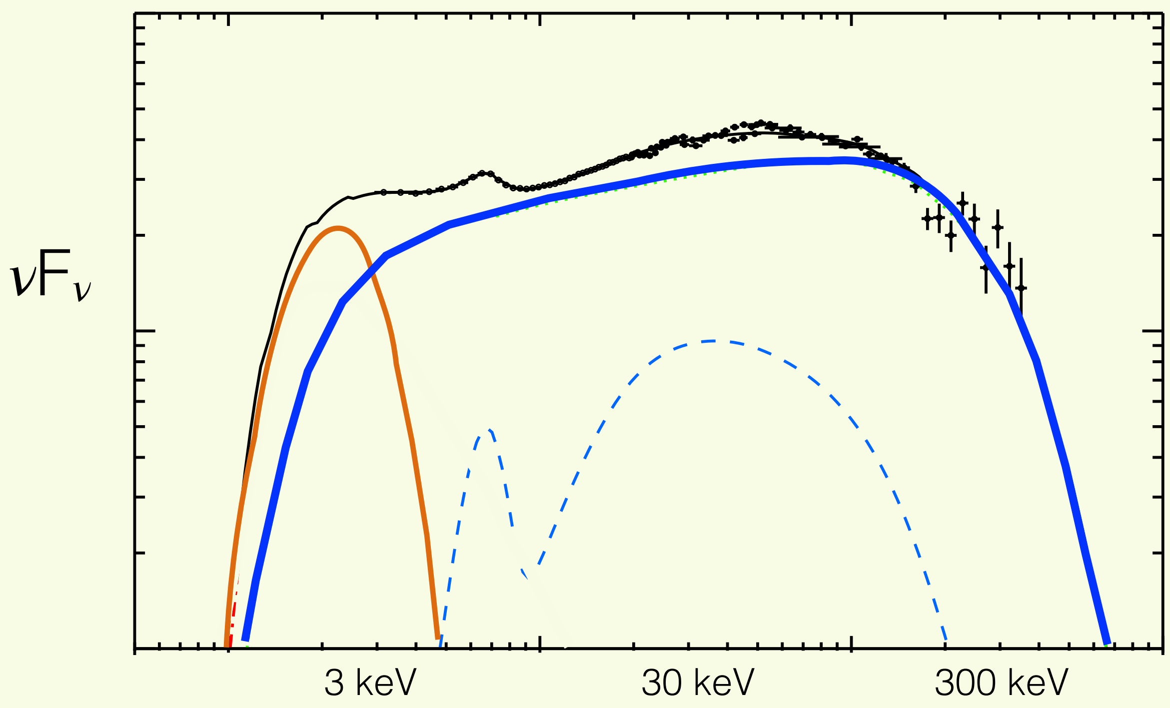


Different geometries can explain large variations in spectra (spectral states)

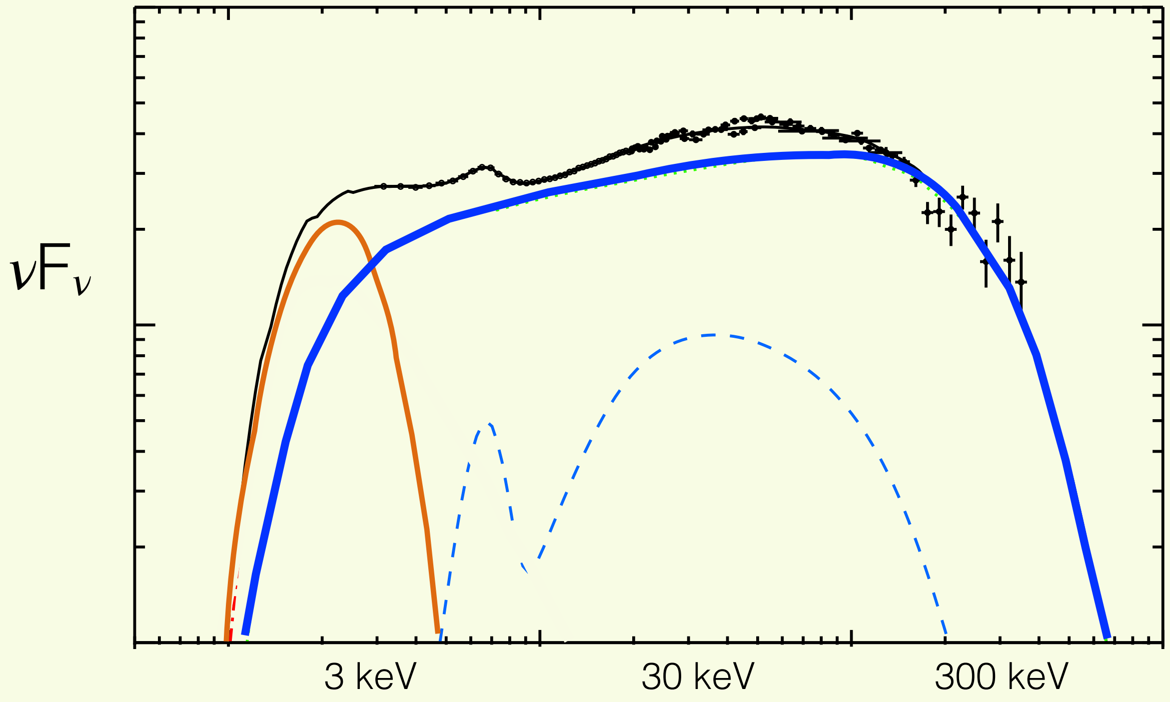
The problem: it doesn't quite match the observations

Disc blackbody often does not quite fit the low-energy part of the spectrum
(e.g.: Ibragimov+ 2005, Makishima+ 2008, Yamada+ 2013, Basak+2017)

Single temperature Compton region cannot explain the energy-dependent time lags (Kotov et al. 2001)

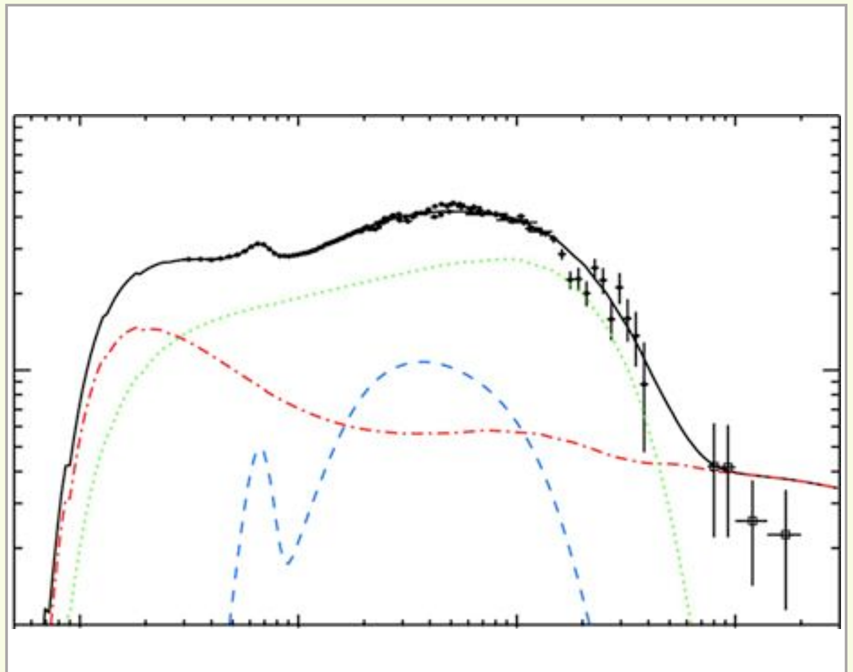


Add extra components?

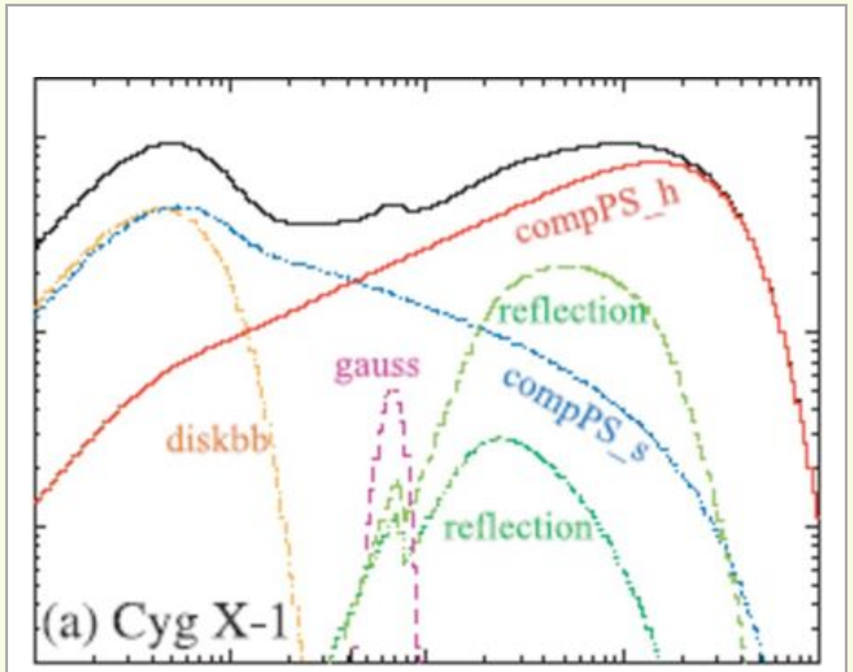


Add extra components?

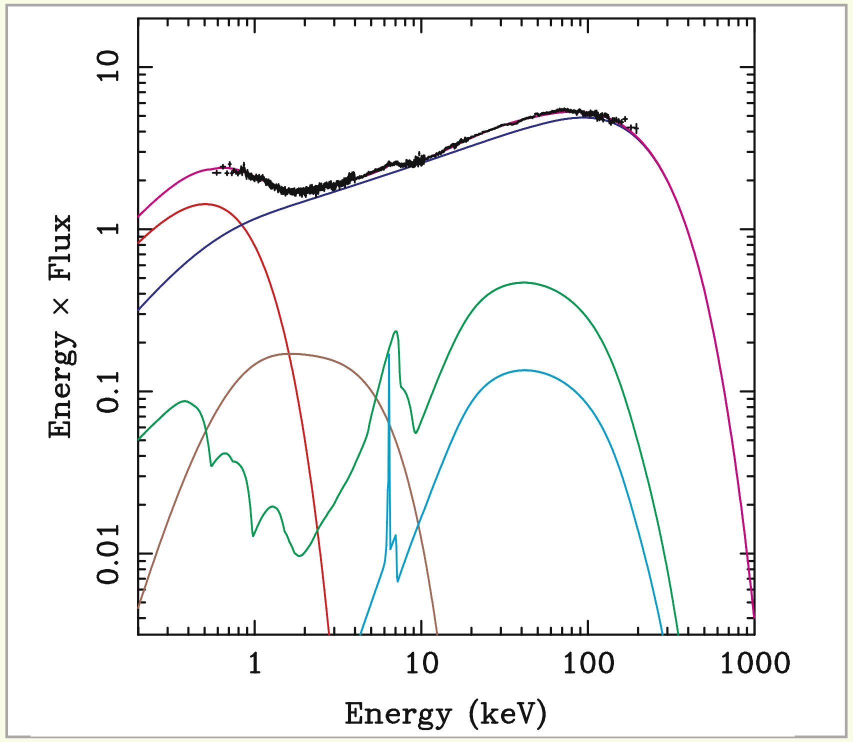
Spectral fitting is degenerate!



Ibragimov et al. (2005)

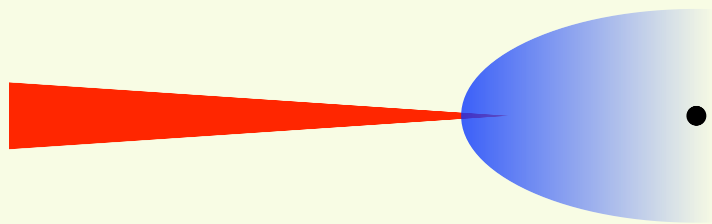


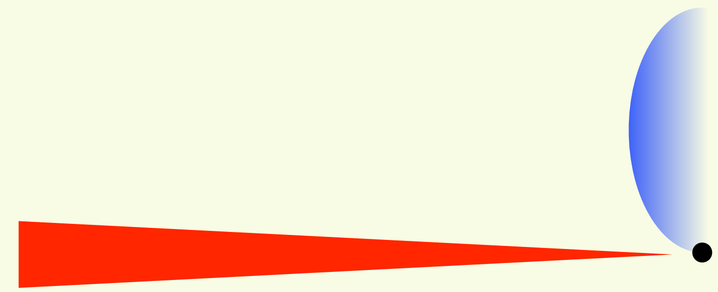
Makishima et al. (2008)

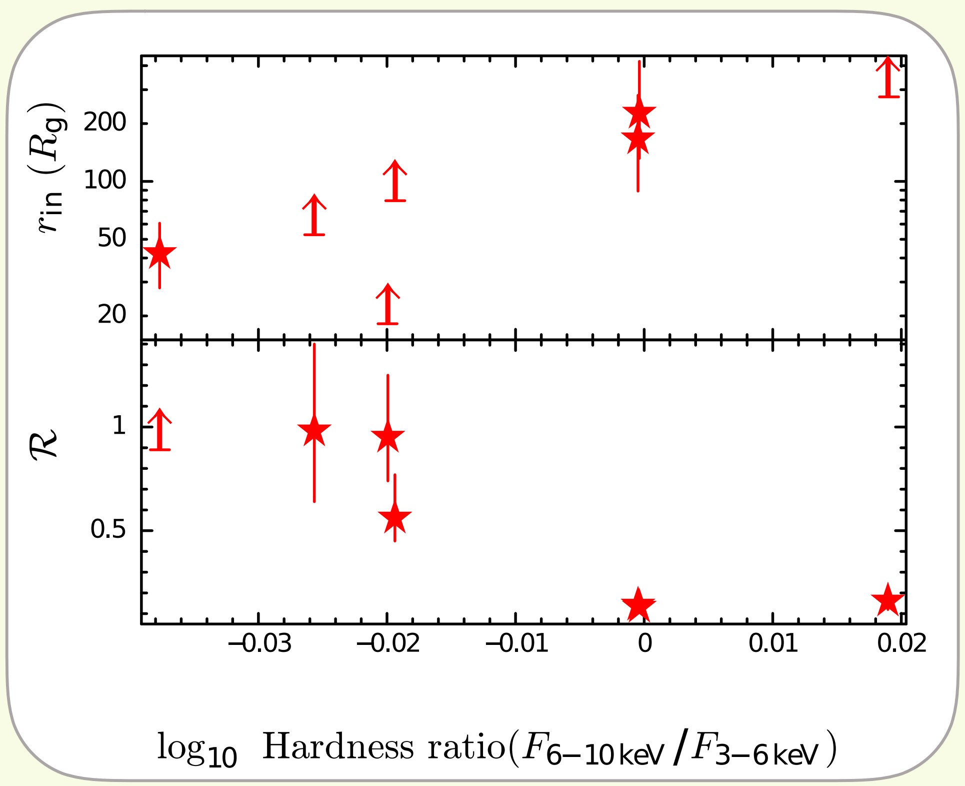


Yamada et al. (2012)

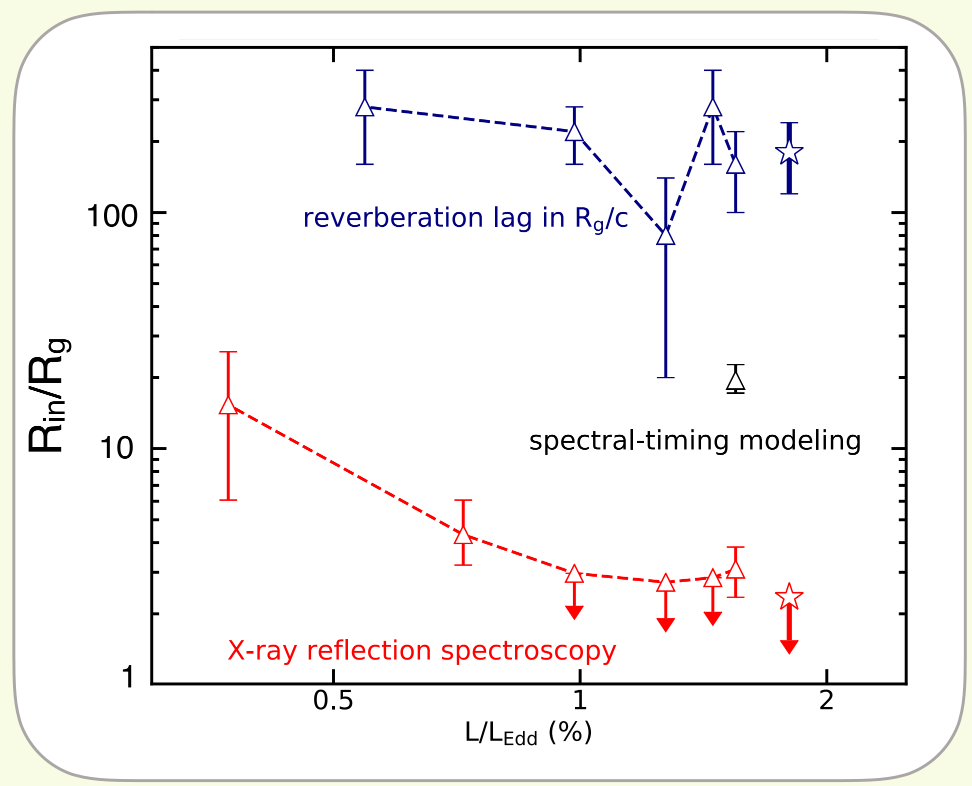
Is the disc truncated in the hard state?







Basak & Zdziarski (2017)

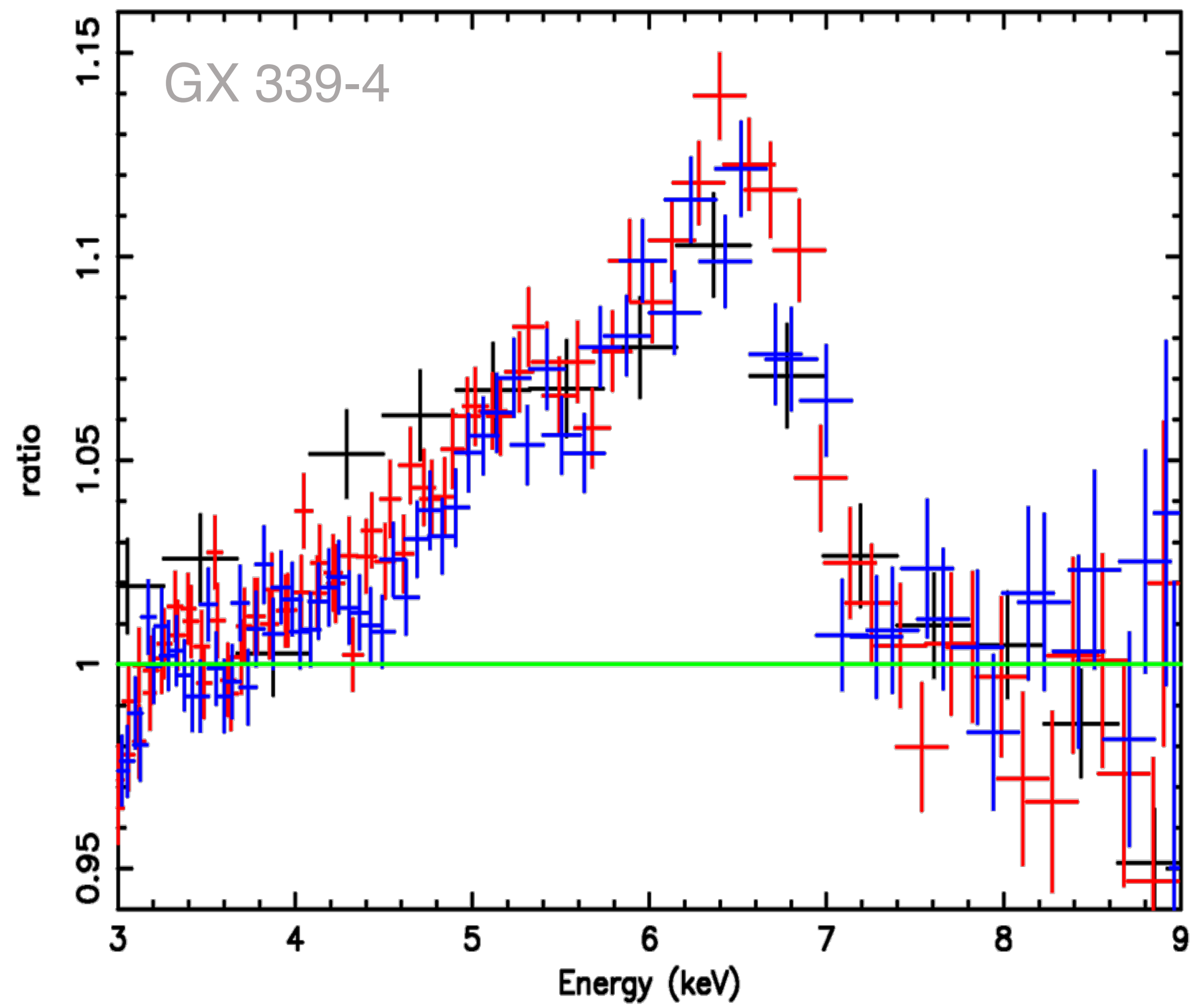


Wang et al. (2020)

Models from broad-band spectral modelling and timing say truncation

Models using reflection and iron-line profiles say close to innermost stable orbit

Profile of the iron line



Initial analysis showed R_{in} ~ a few R_g (Miller et al. 2006)

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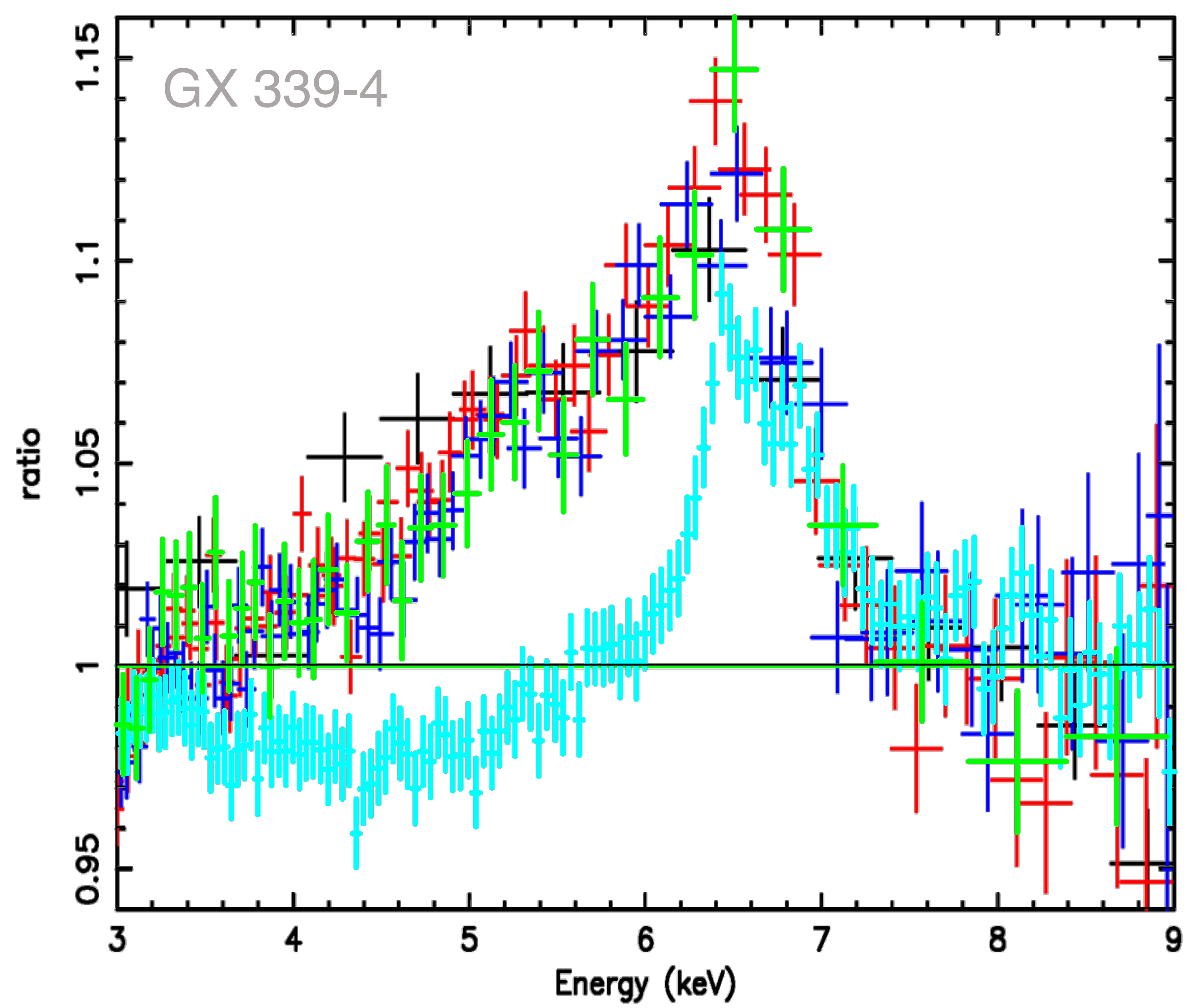

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- reanalysis gave R_{in}>30 R_g
(Done & Díaz Trigo 2009)

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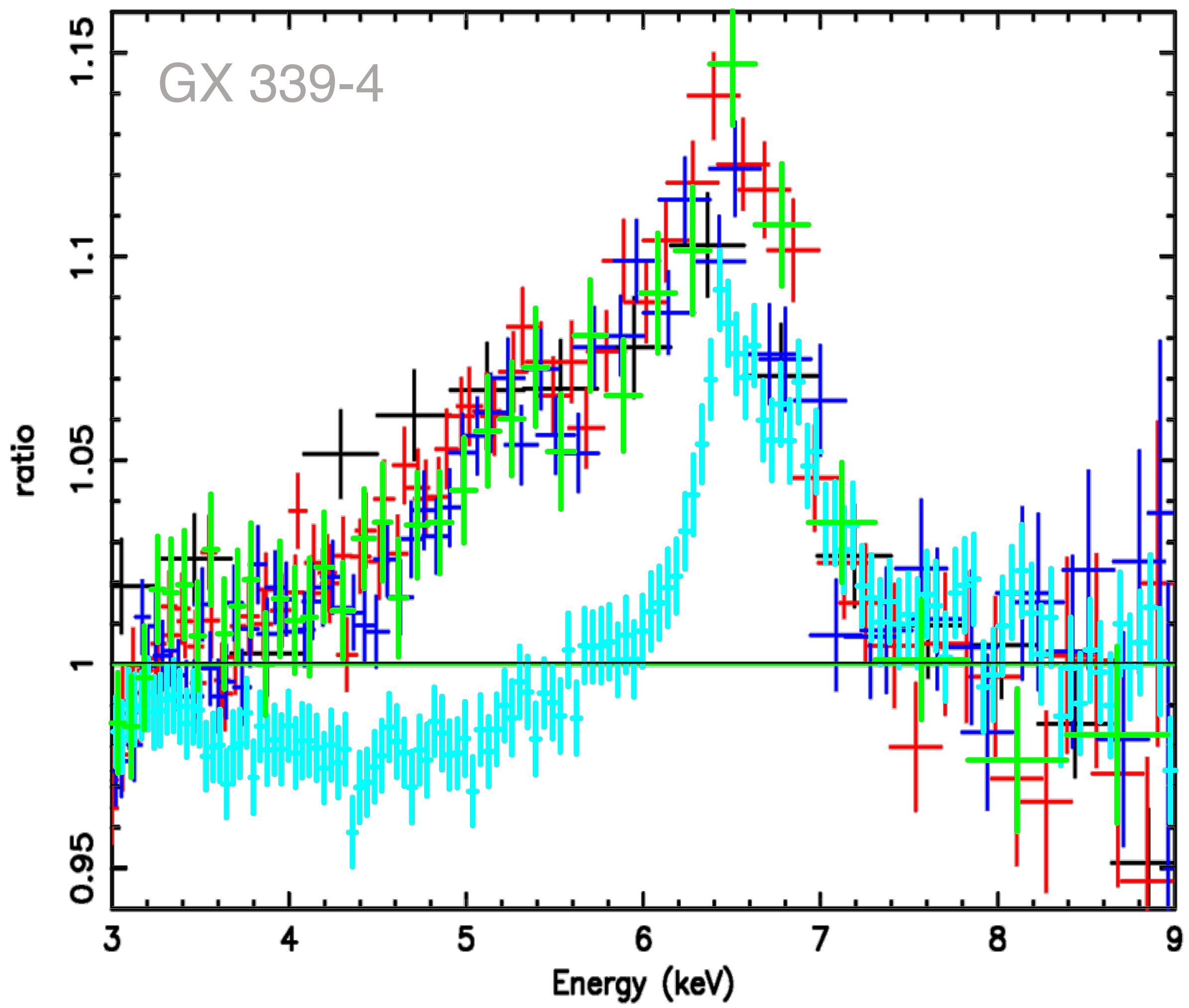

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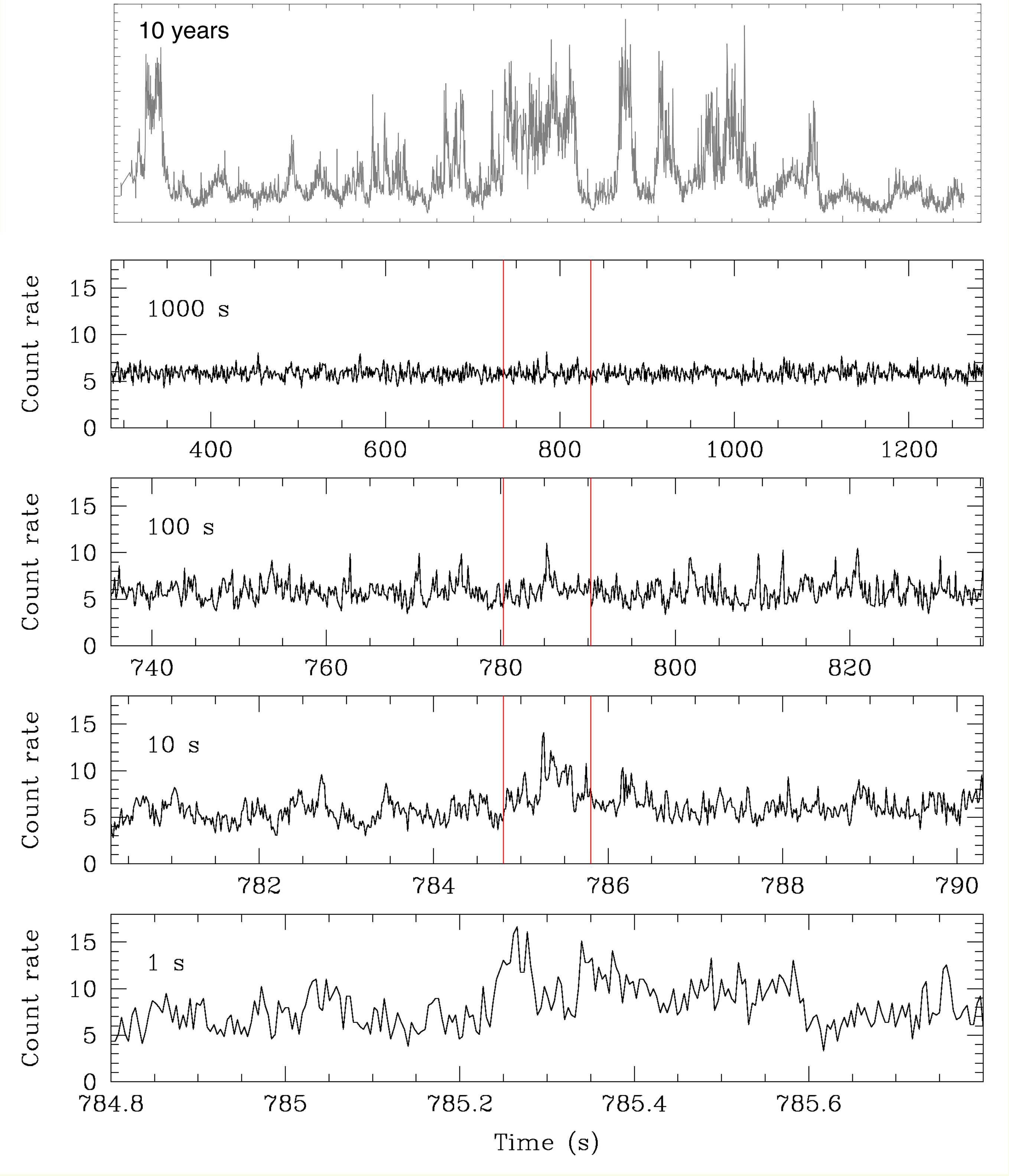
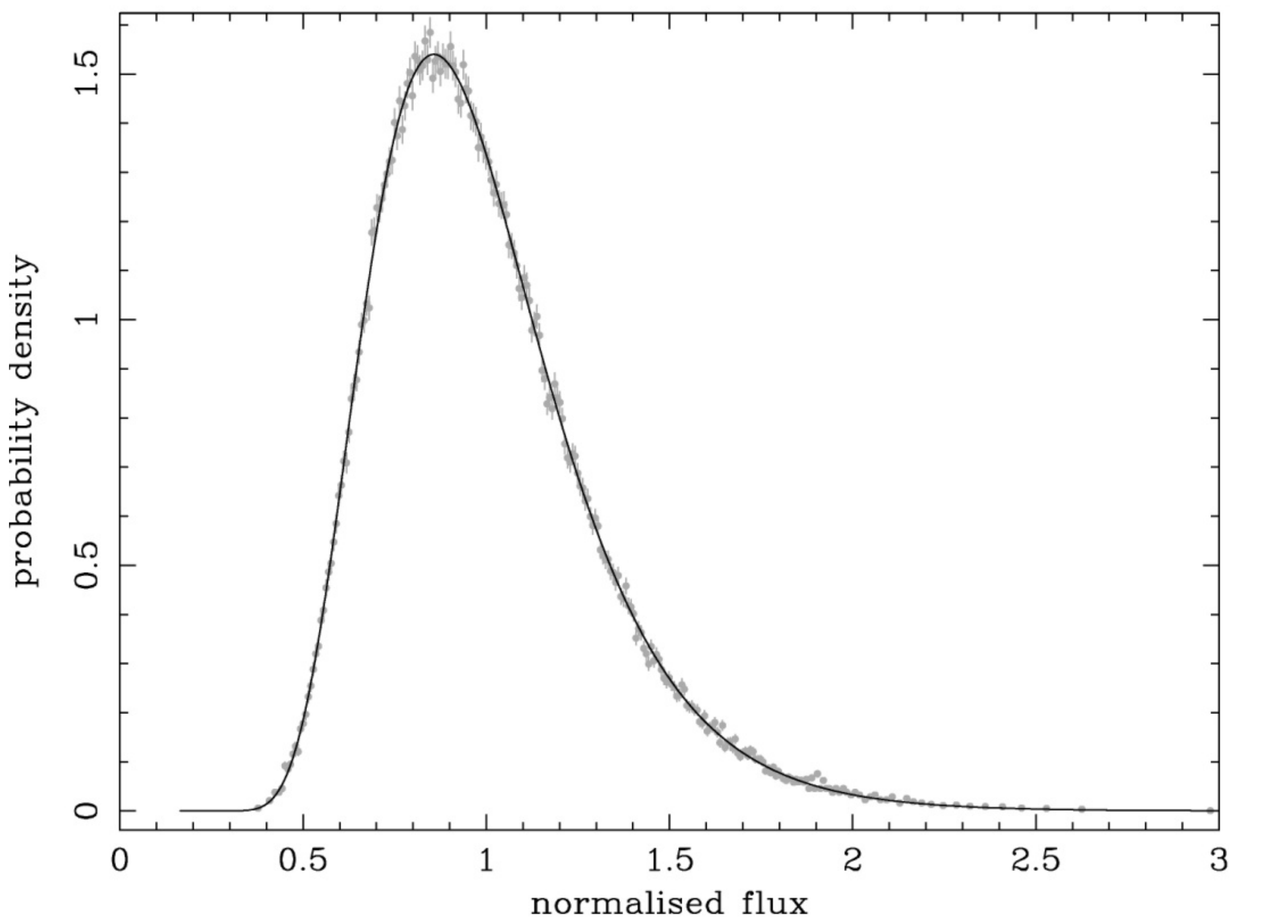
Line shape dependent on broad-band spectral model
- need to understand Comptonization spectrum!

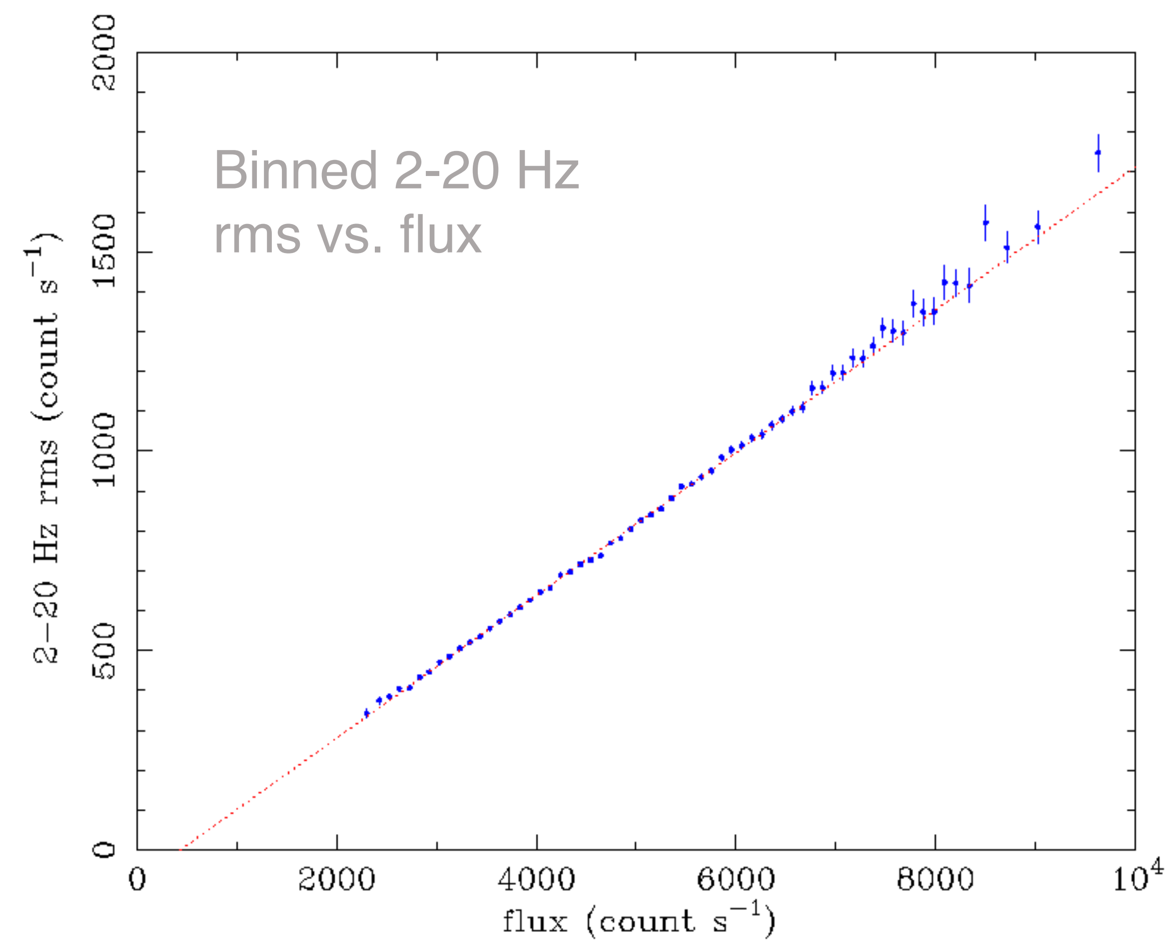
There is variability on all timescales
- from months to milliseconds



(Uttley & McHardy 2001)

$\mathrm{rms} = [(1/N)\ \Sigma_{i=1,N}\ (\mathrm{flux}_i - \mathrm{mean})^2]^{1/2}$



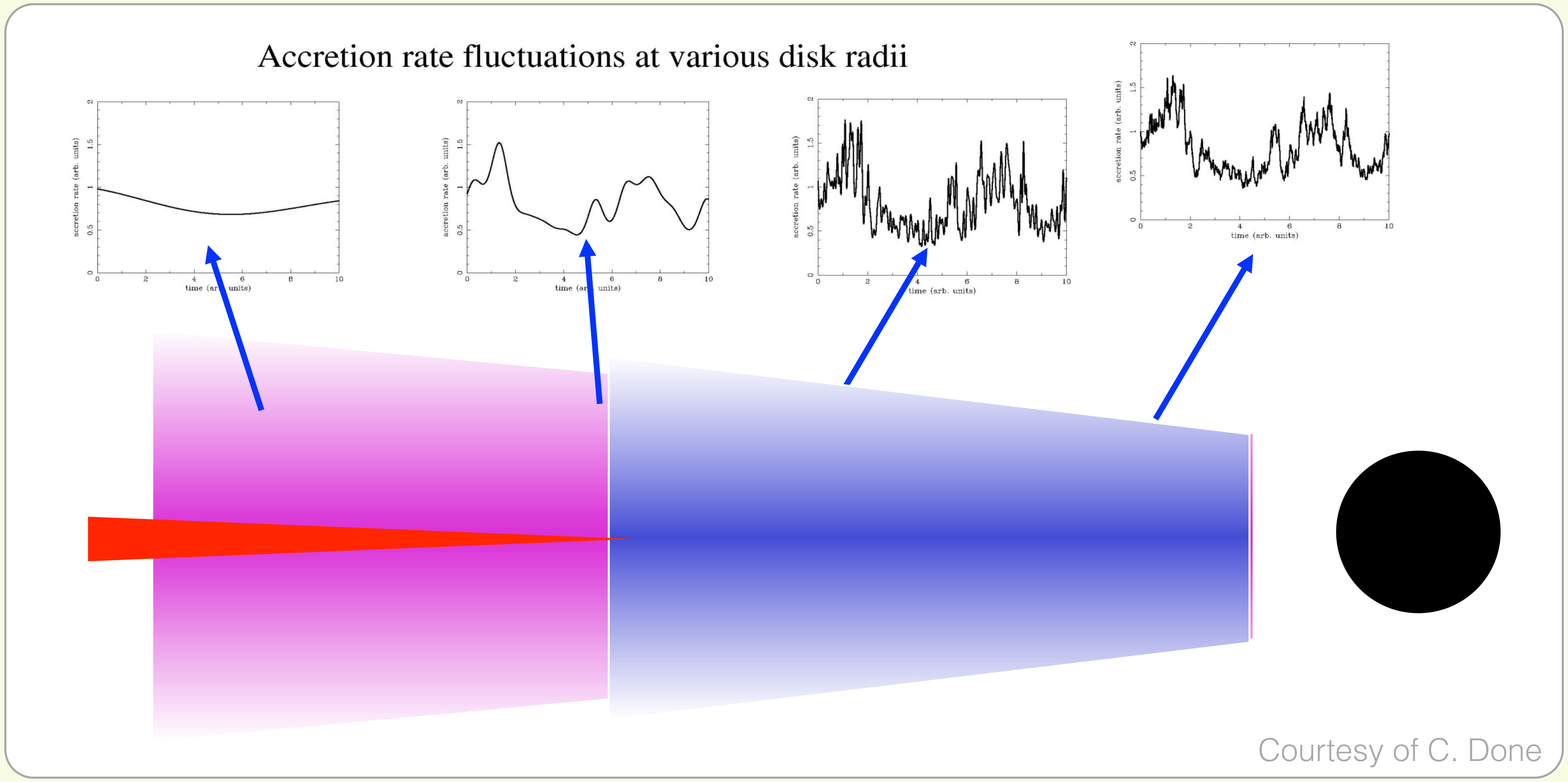


Flux distribution is lognormal

Linear rms-flux relation

Cannot get this from shot-noise or additive process (sum of independent regions)

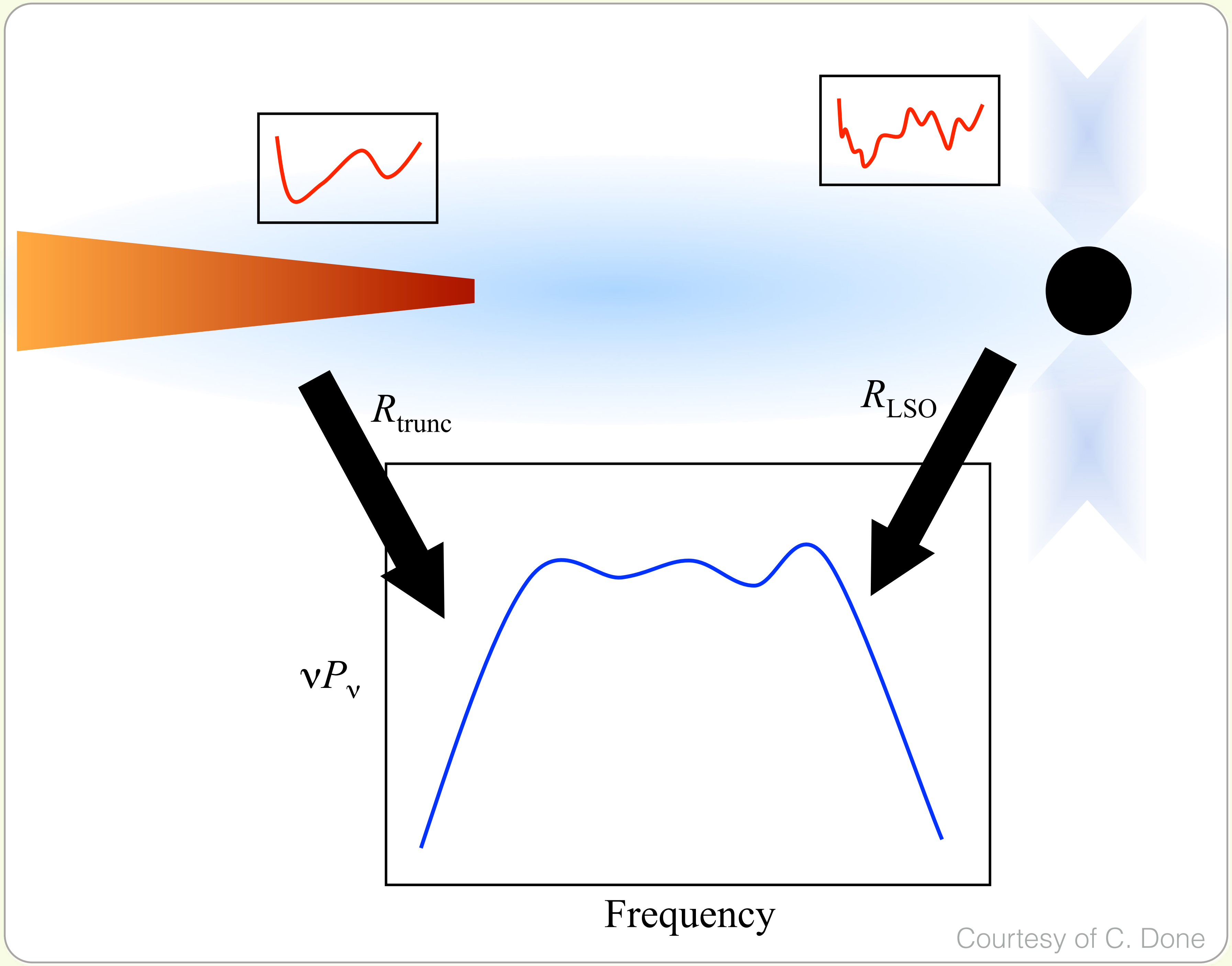
Broadband variability from propagating fluctuations



Fluctuations start at large radii - soft and slow propagate down to smaller radii, where faster variability arises in the hard emission (Lyubarskii 1997, Kotov et al. 2001, Arévalo & Uttley 2006)

Allows us to couple temporal and spectral information!

Origin of broad band variability



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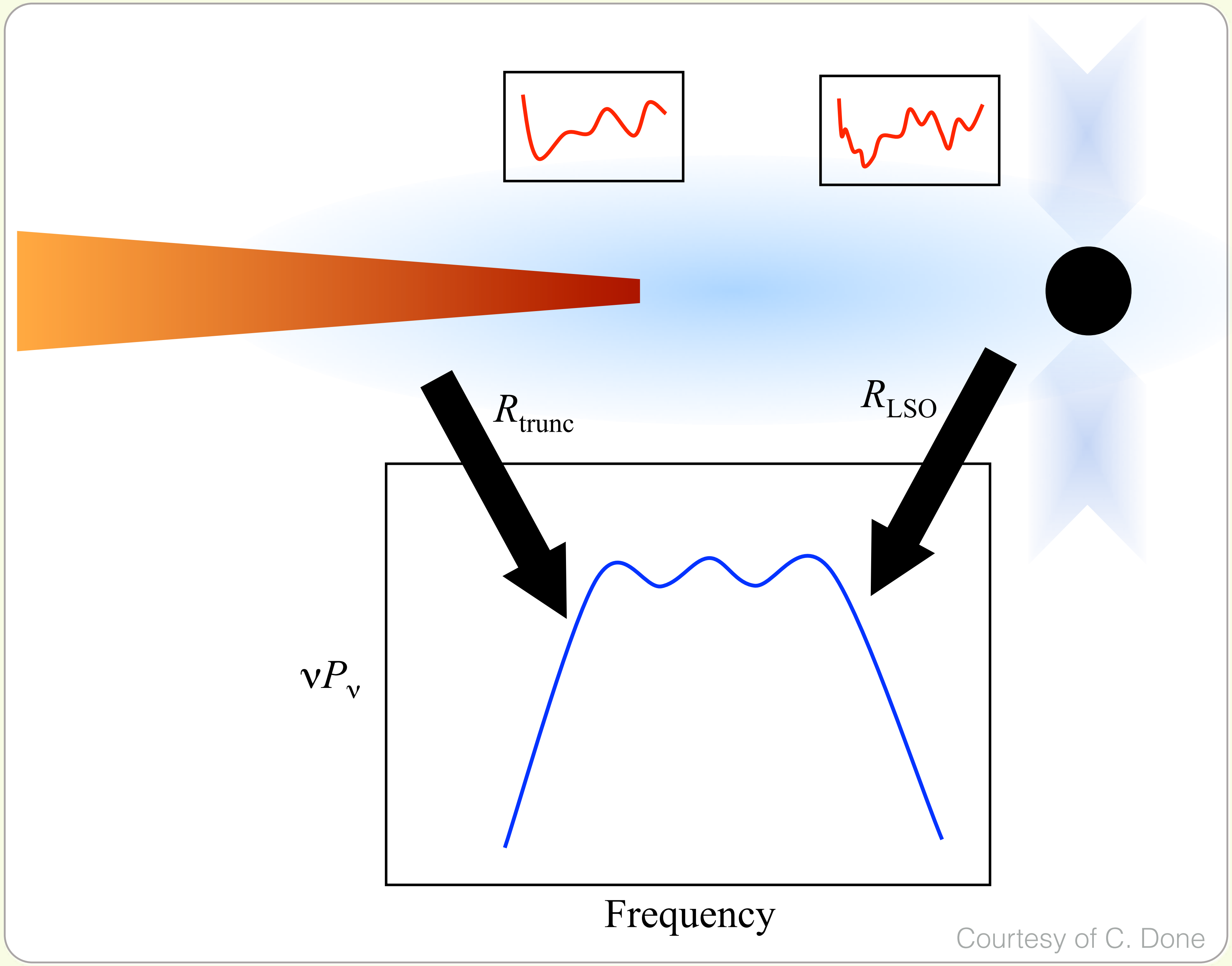

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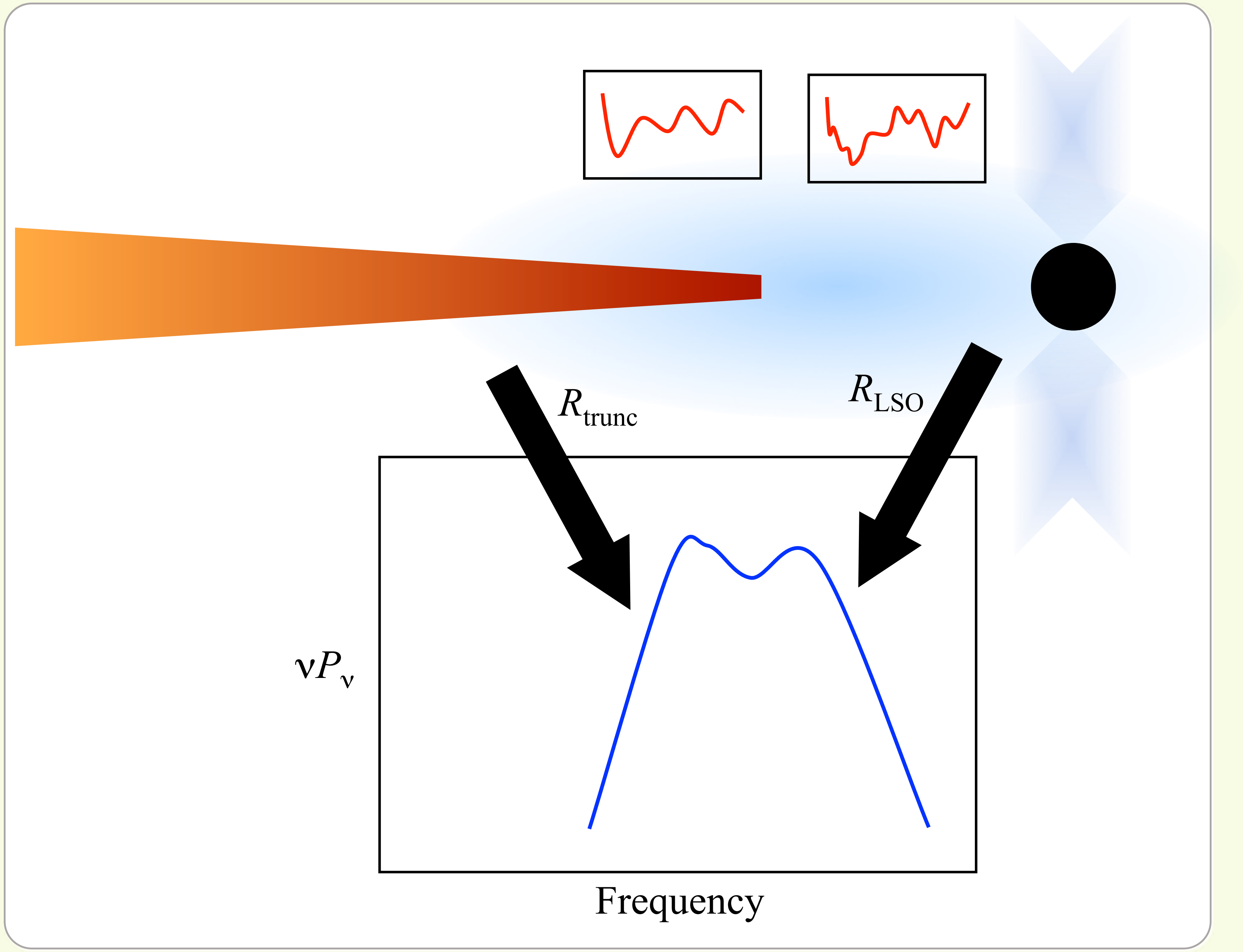

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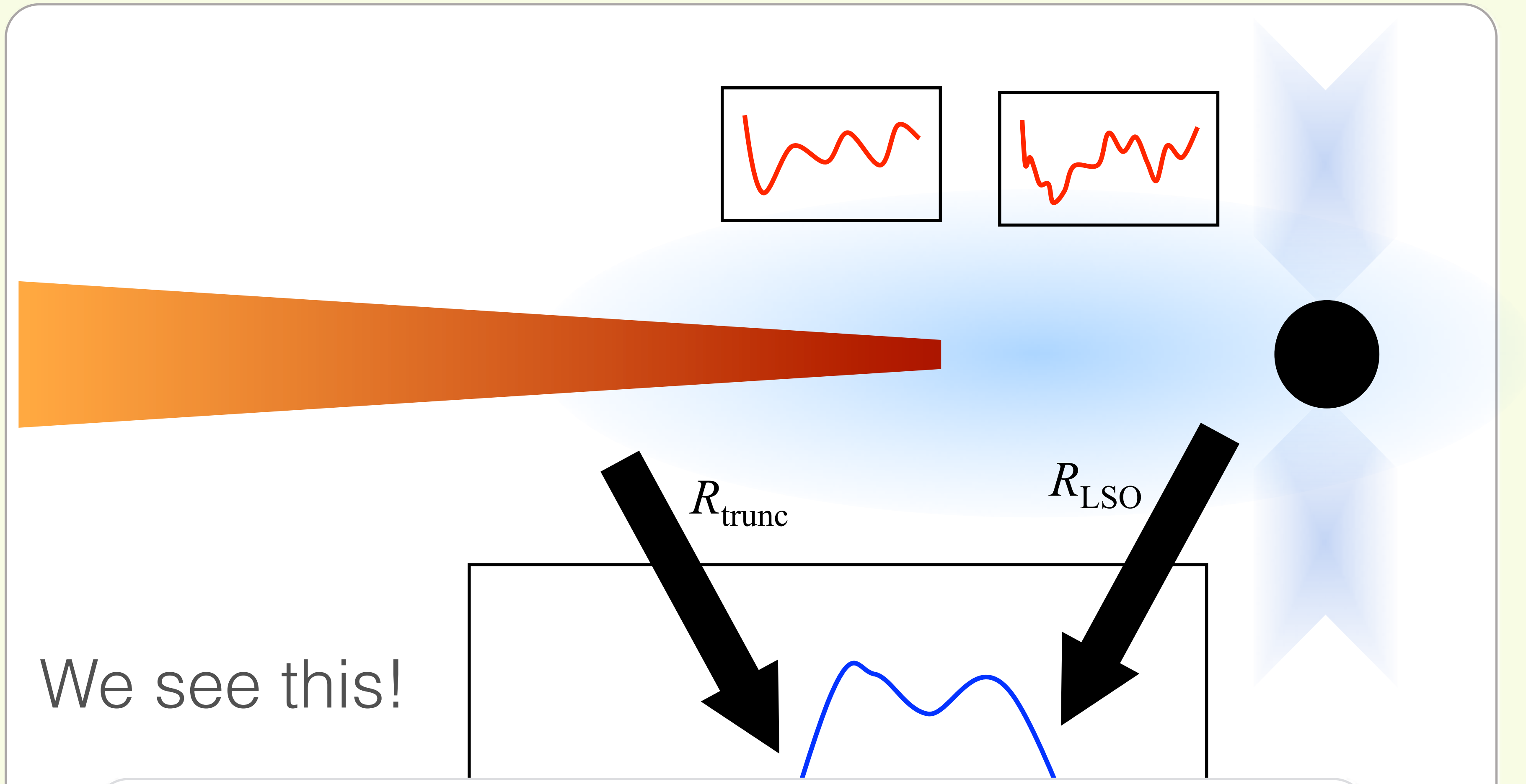
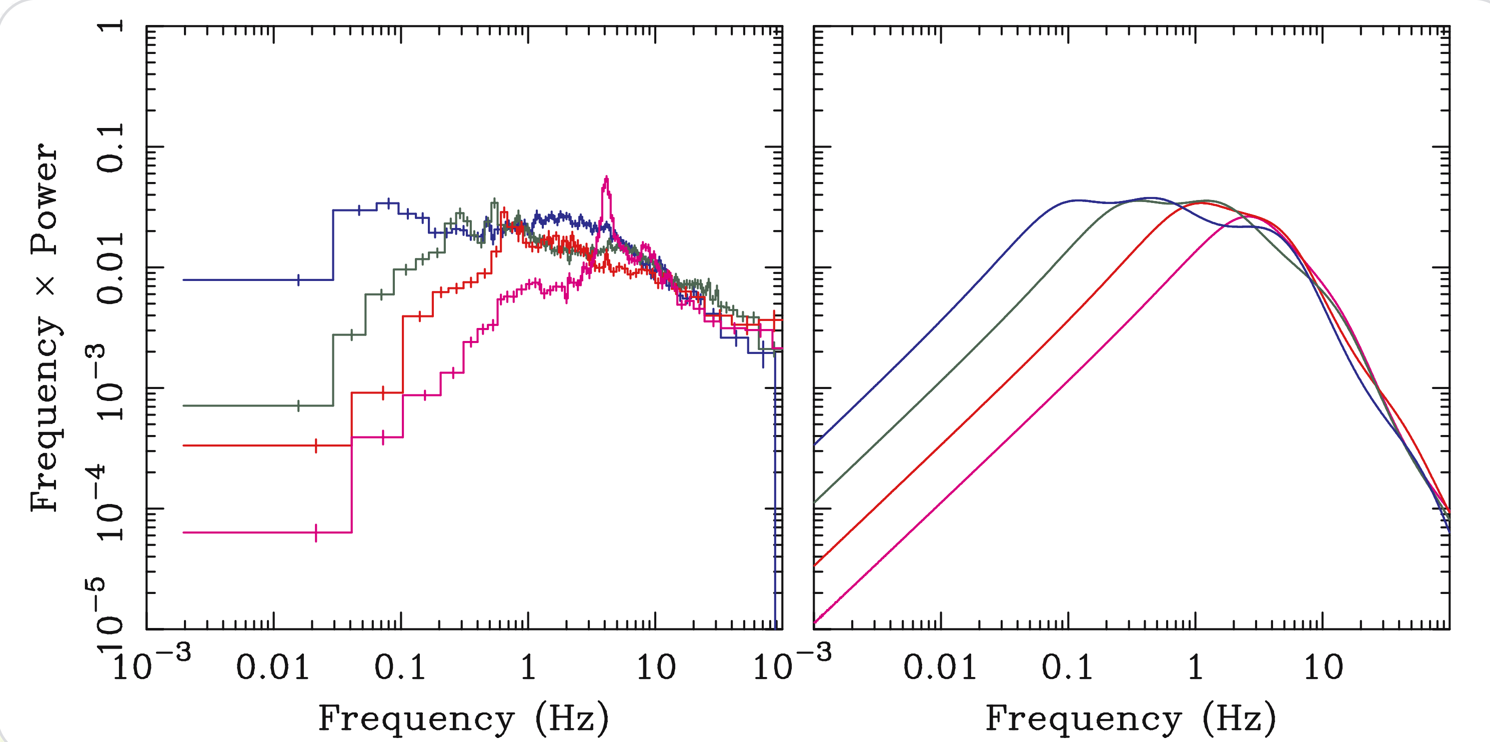
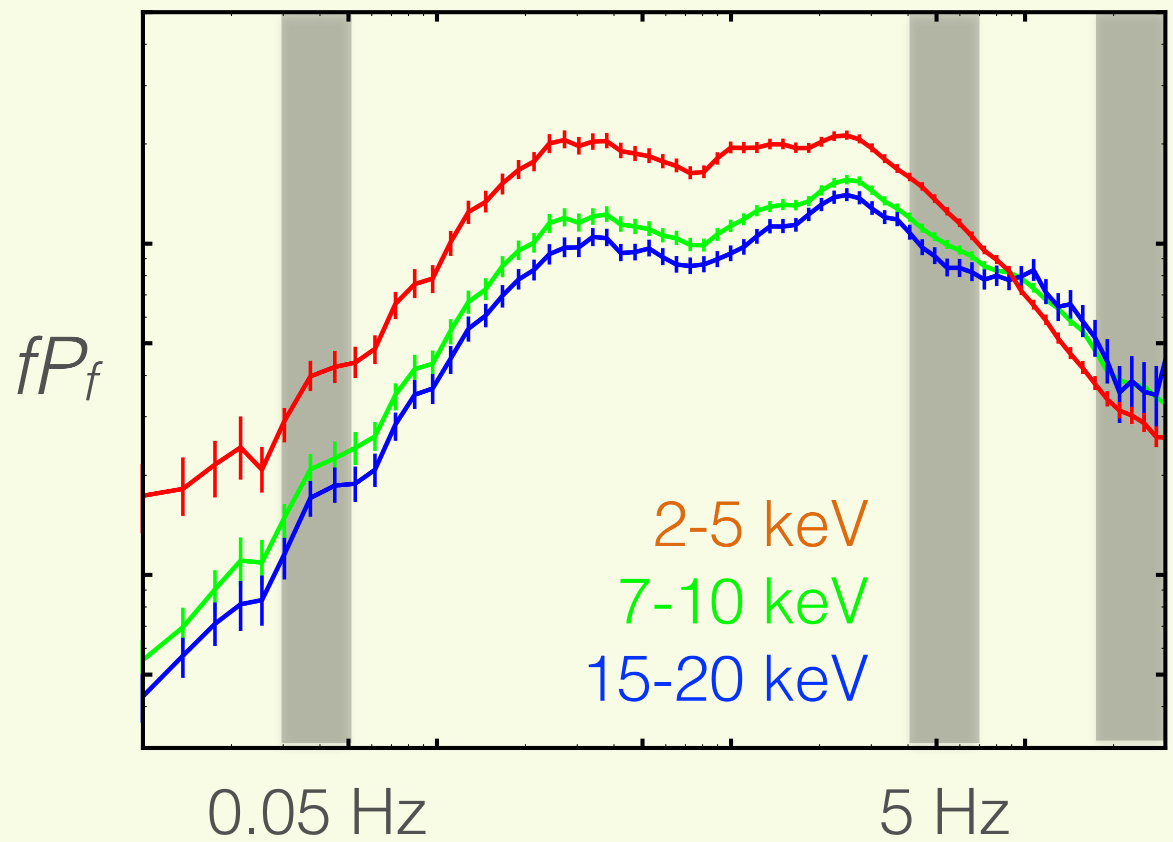


We see this!

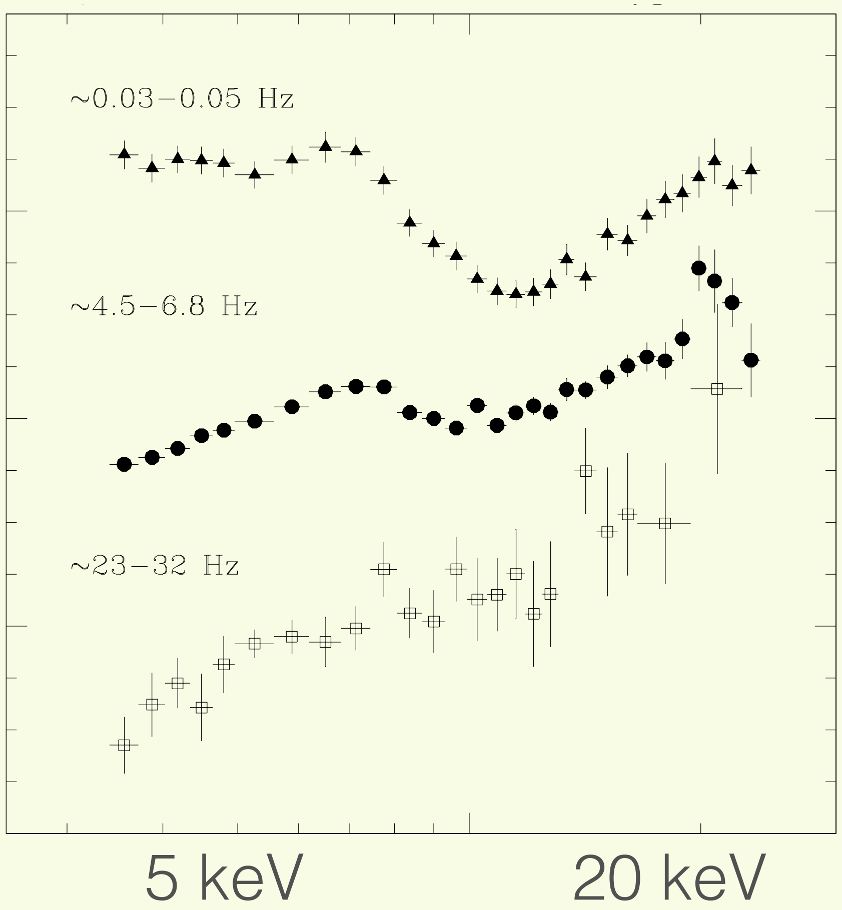


Done et al. (2007)

Frequency-resolved spectroscopy supports stratified flow



Revnivtsev et al. (1999)



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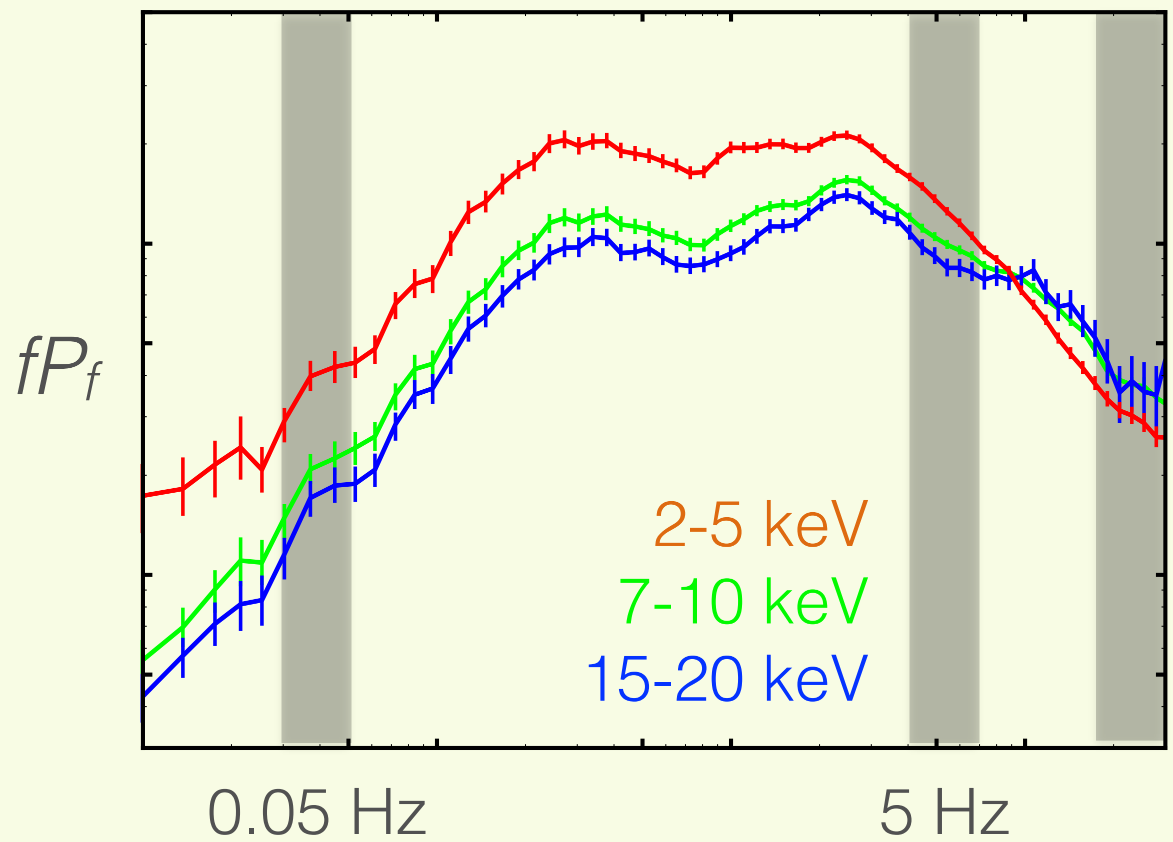
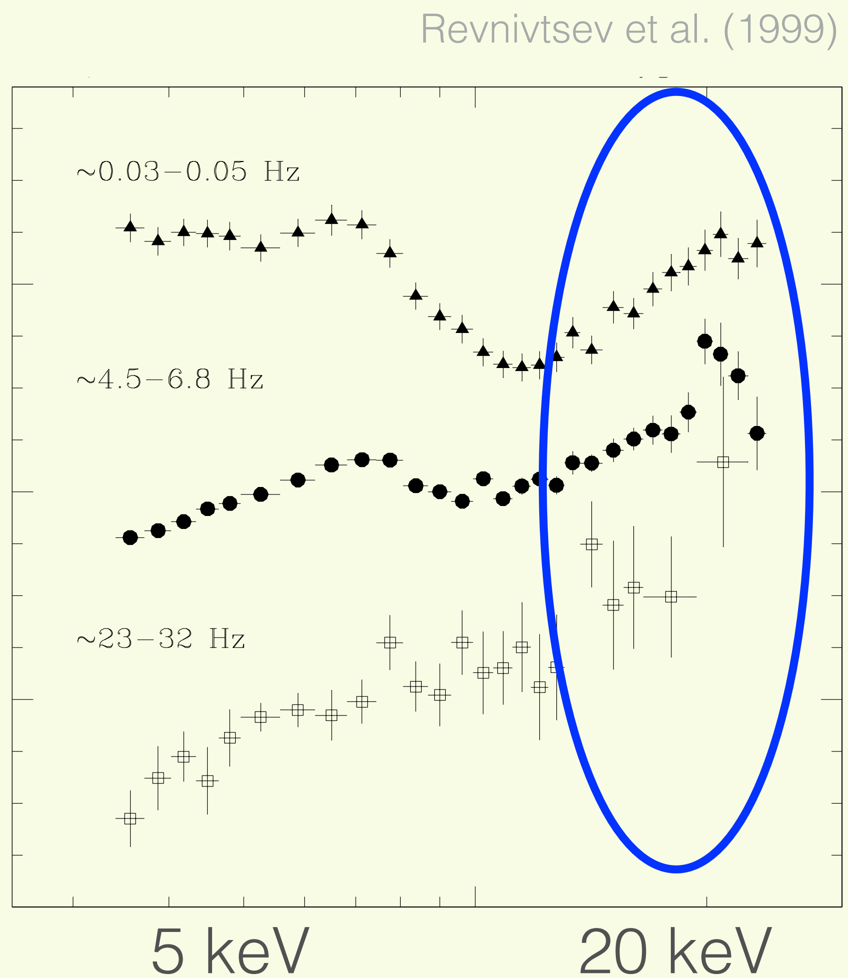
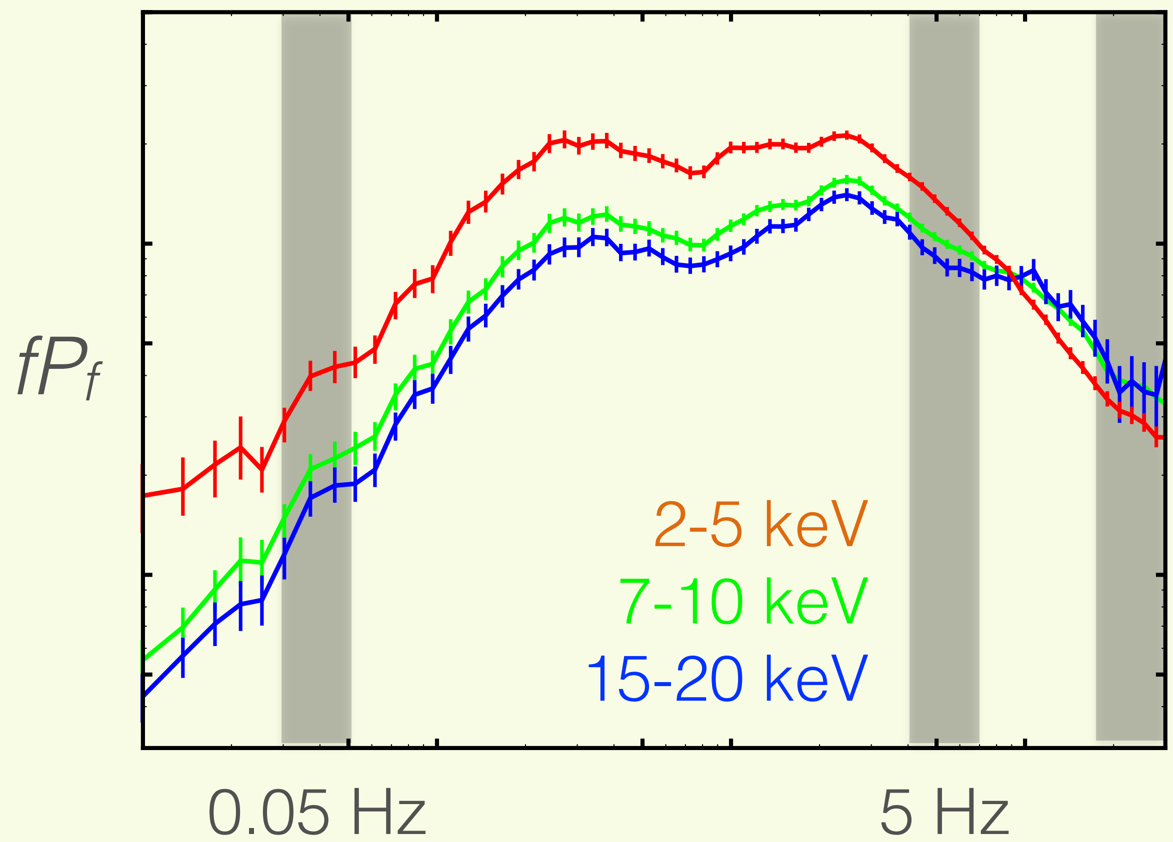
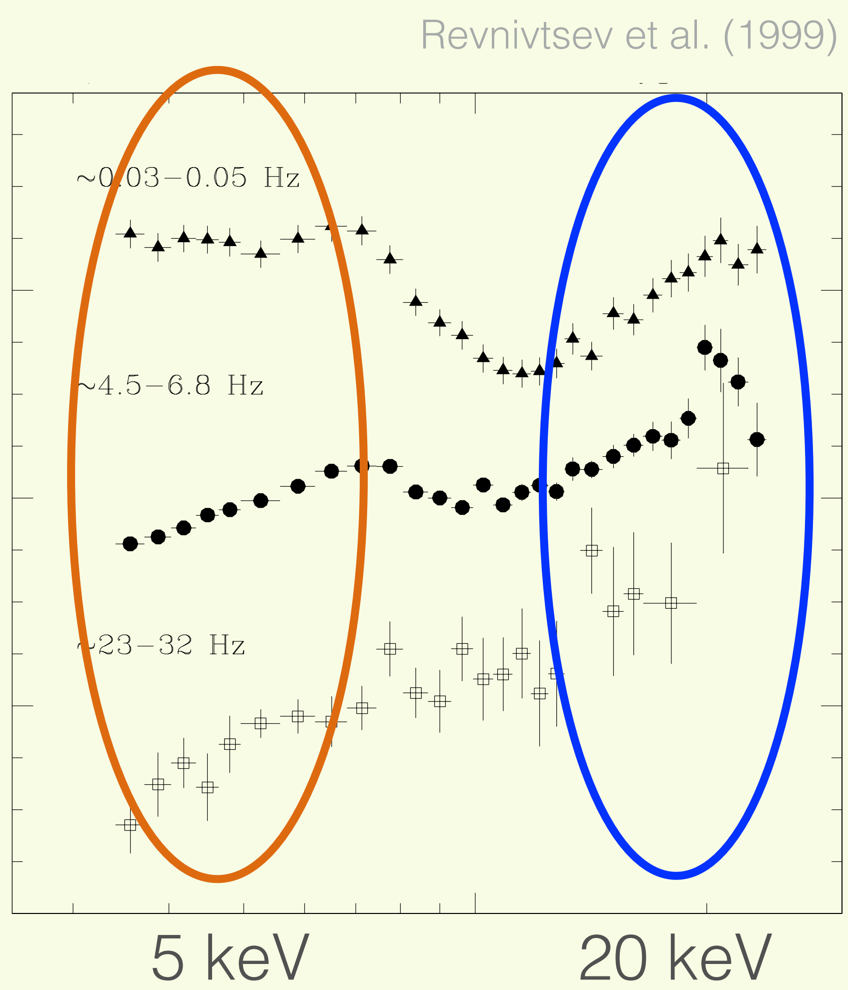




High energies vary at all frequencies and dominate at high freq

Frequency-resolved spectroscopy supports stratified flow



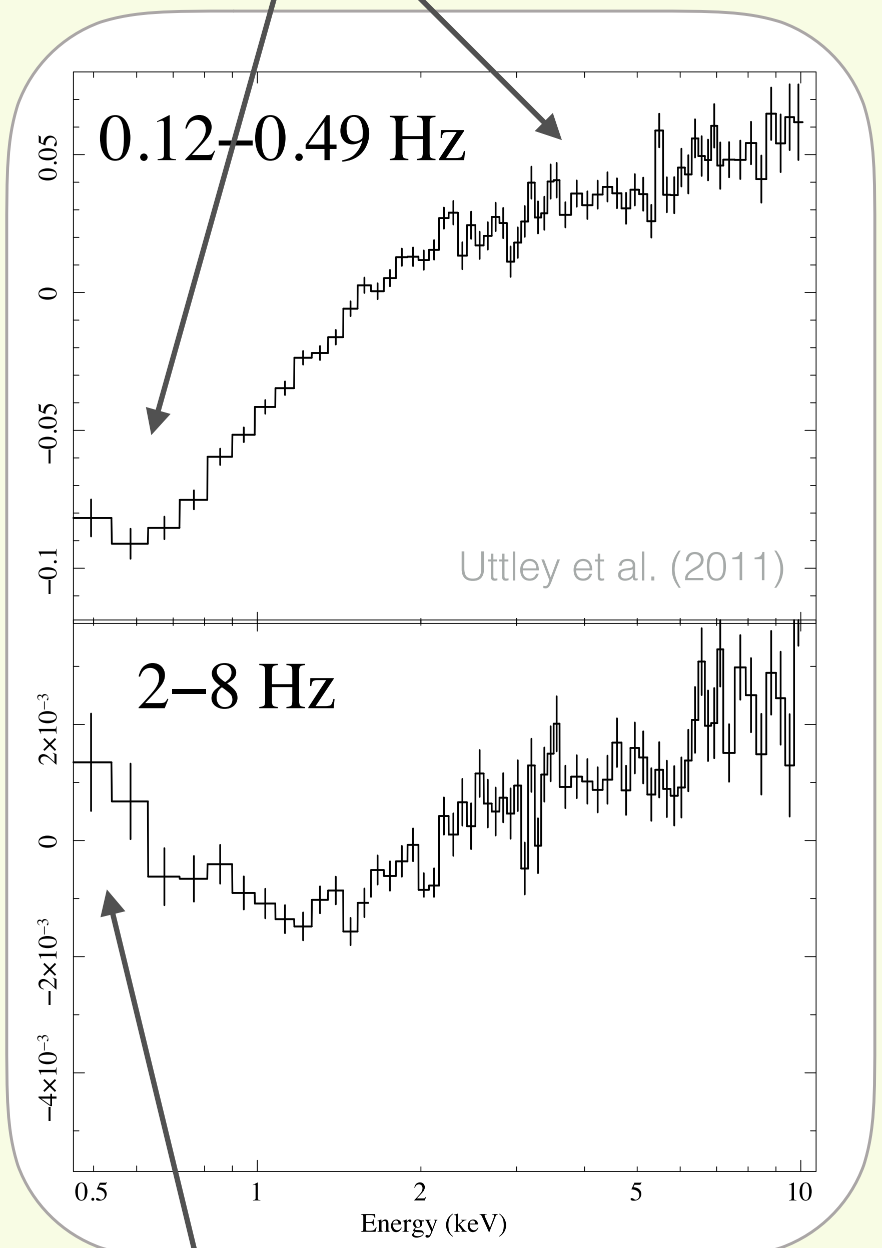


Low energies show strong variability at low frequencies

High energies vary at all frequencies and dominate at high freq

Time lags

Soft lead hard

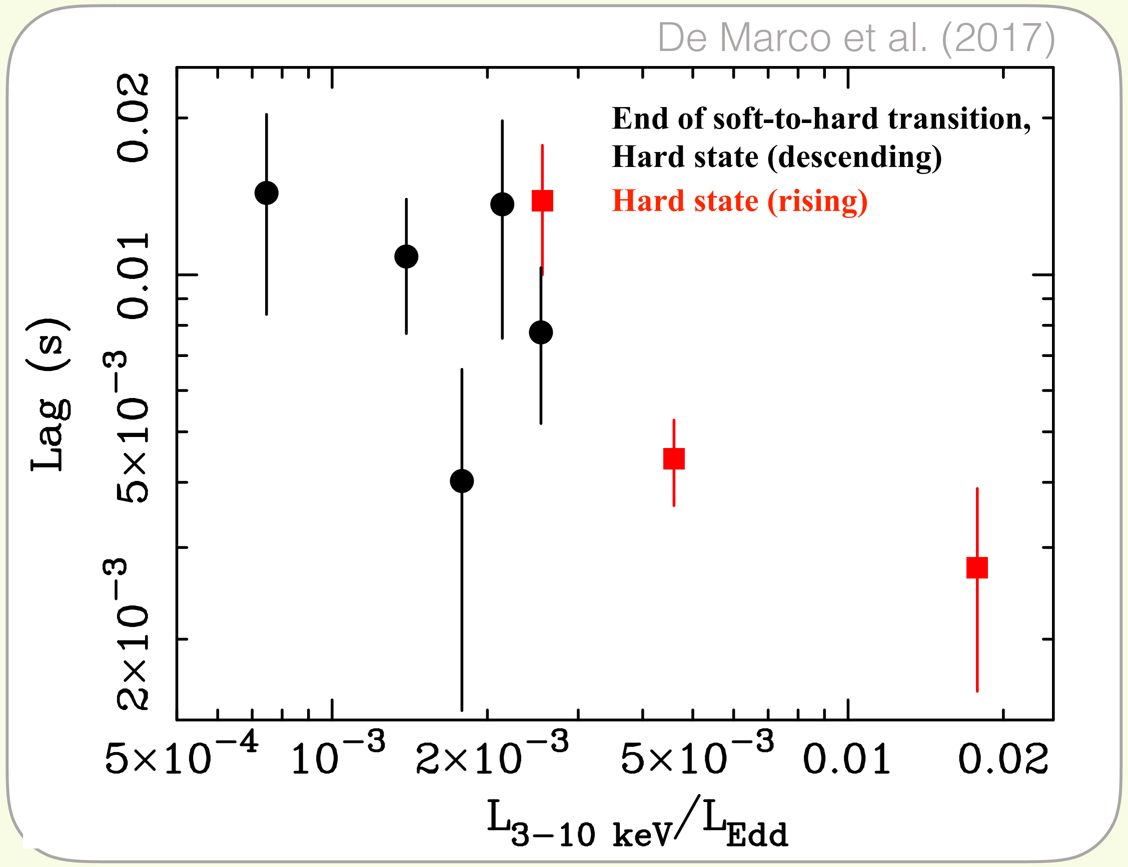


Soft lag hard

Hard lag too long for Comptonization: slow variability arises in the disc, and propagates inwards

Short soft lag consistent with reprocessing of hard emission striking disc

Reverberation studies - disc truncation?

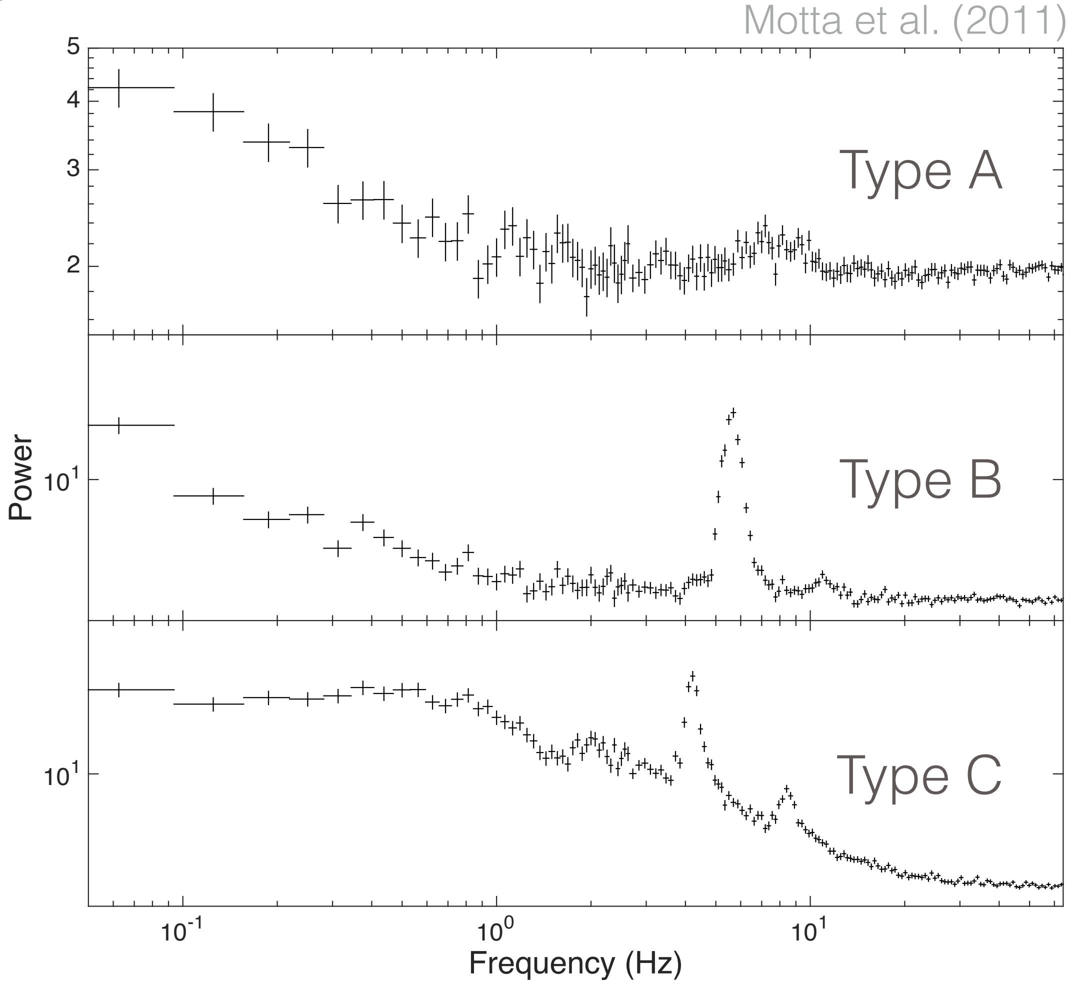


Difficult to study reverberation in XRBs
- only a few sources

Soft lags decrease with luminosity - disc moving closer?

Quasi-periodic oscillations

Different types in different states



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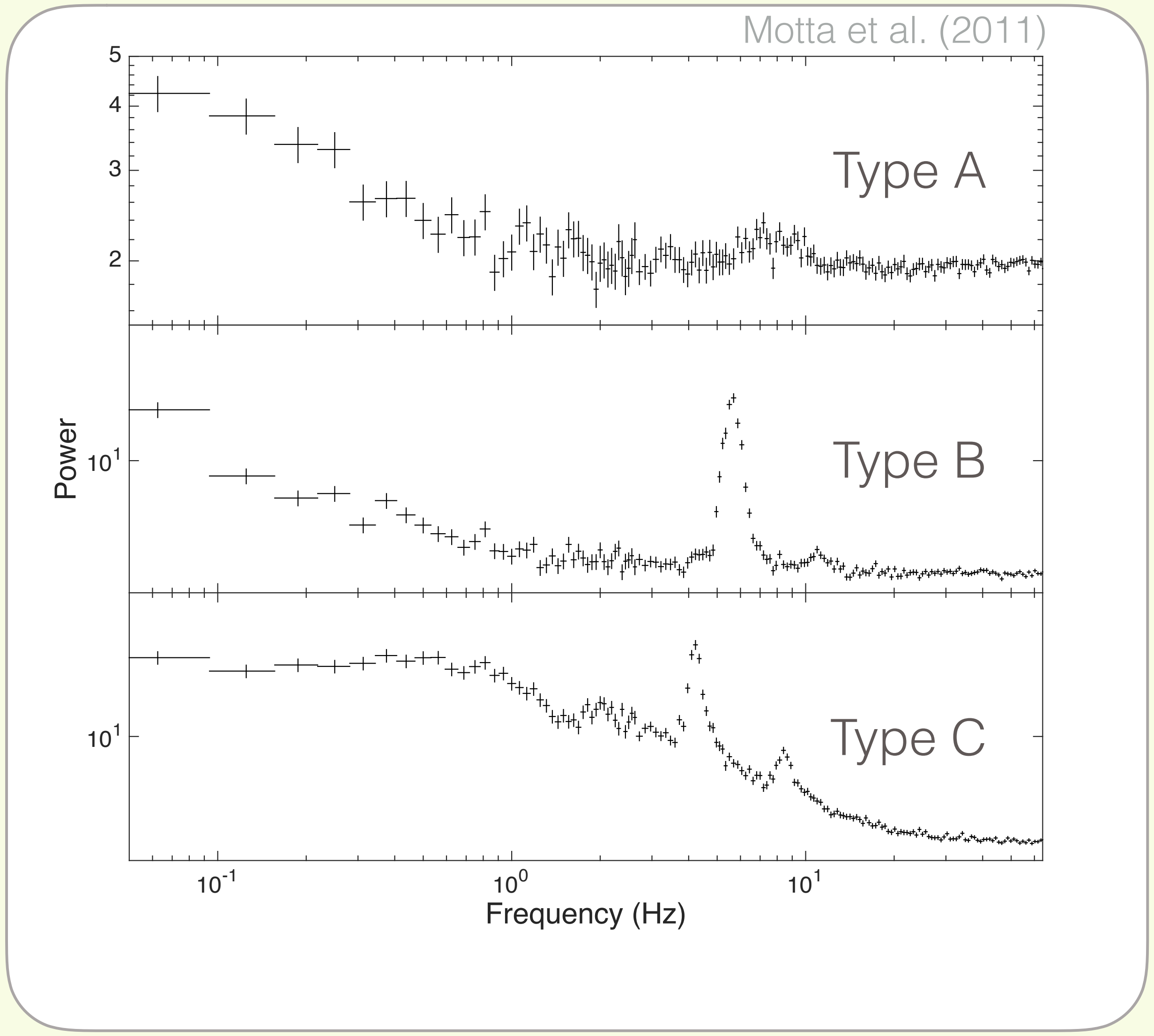
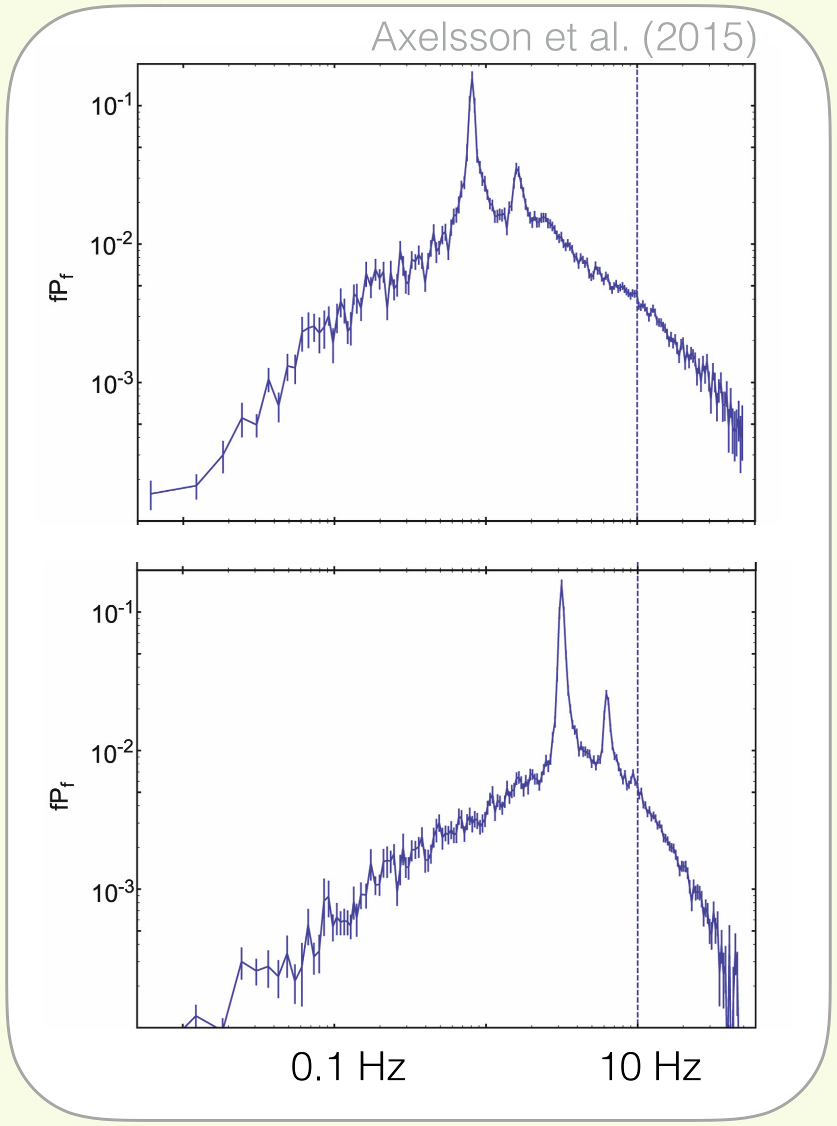


Move with power spectrum



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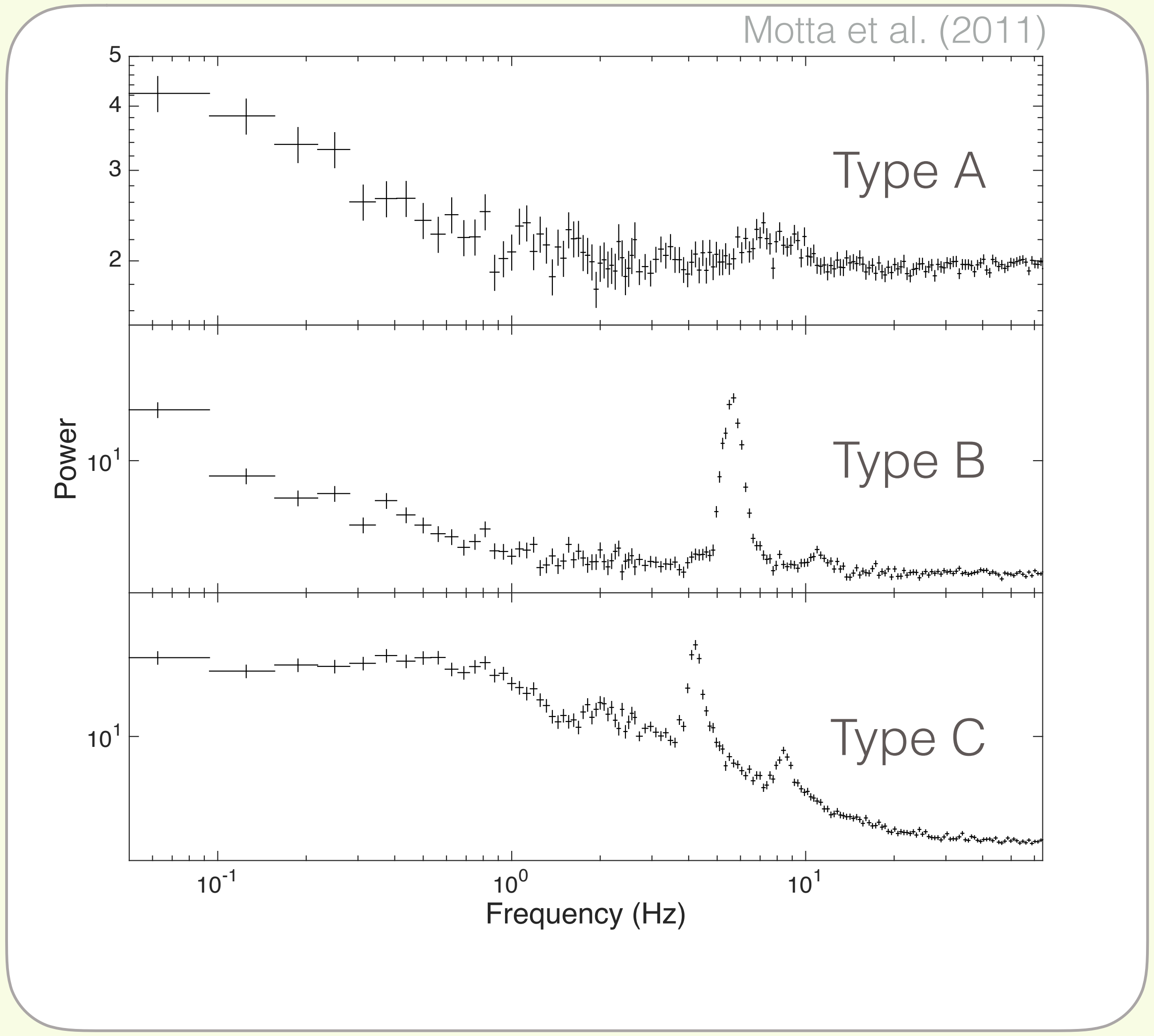

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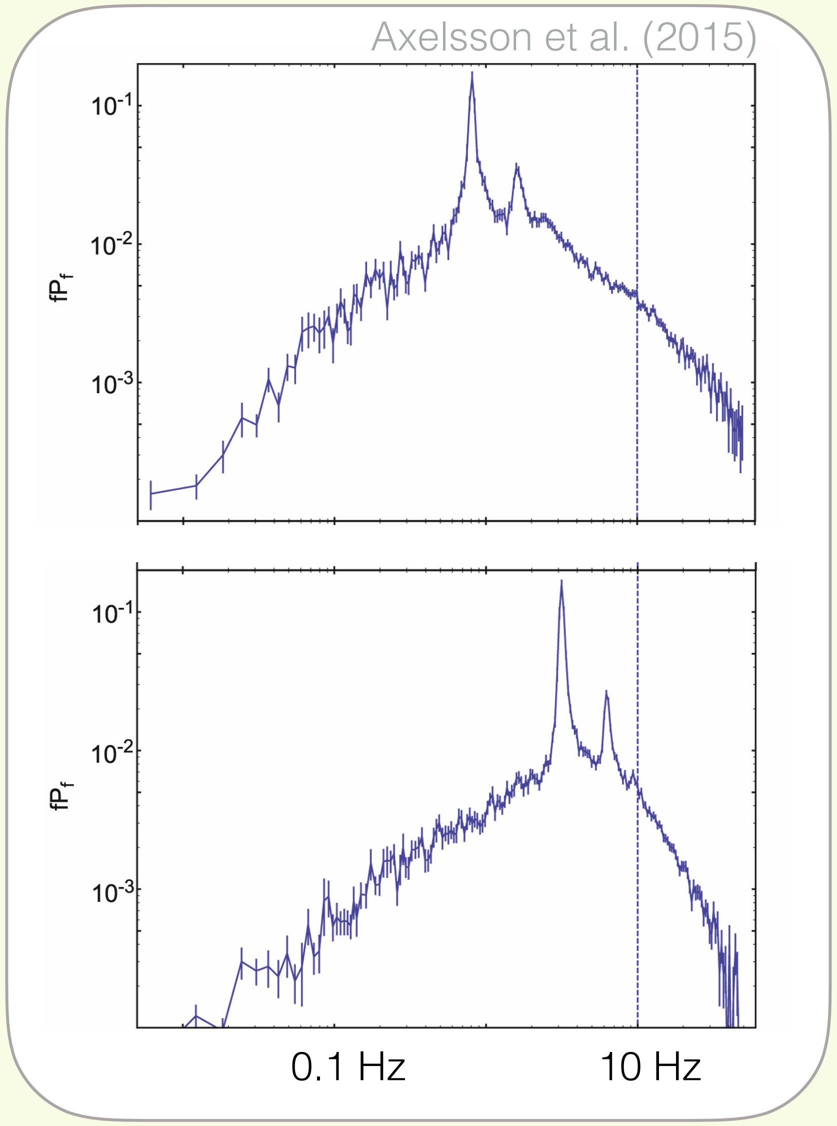
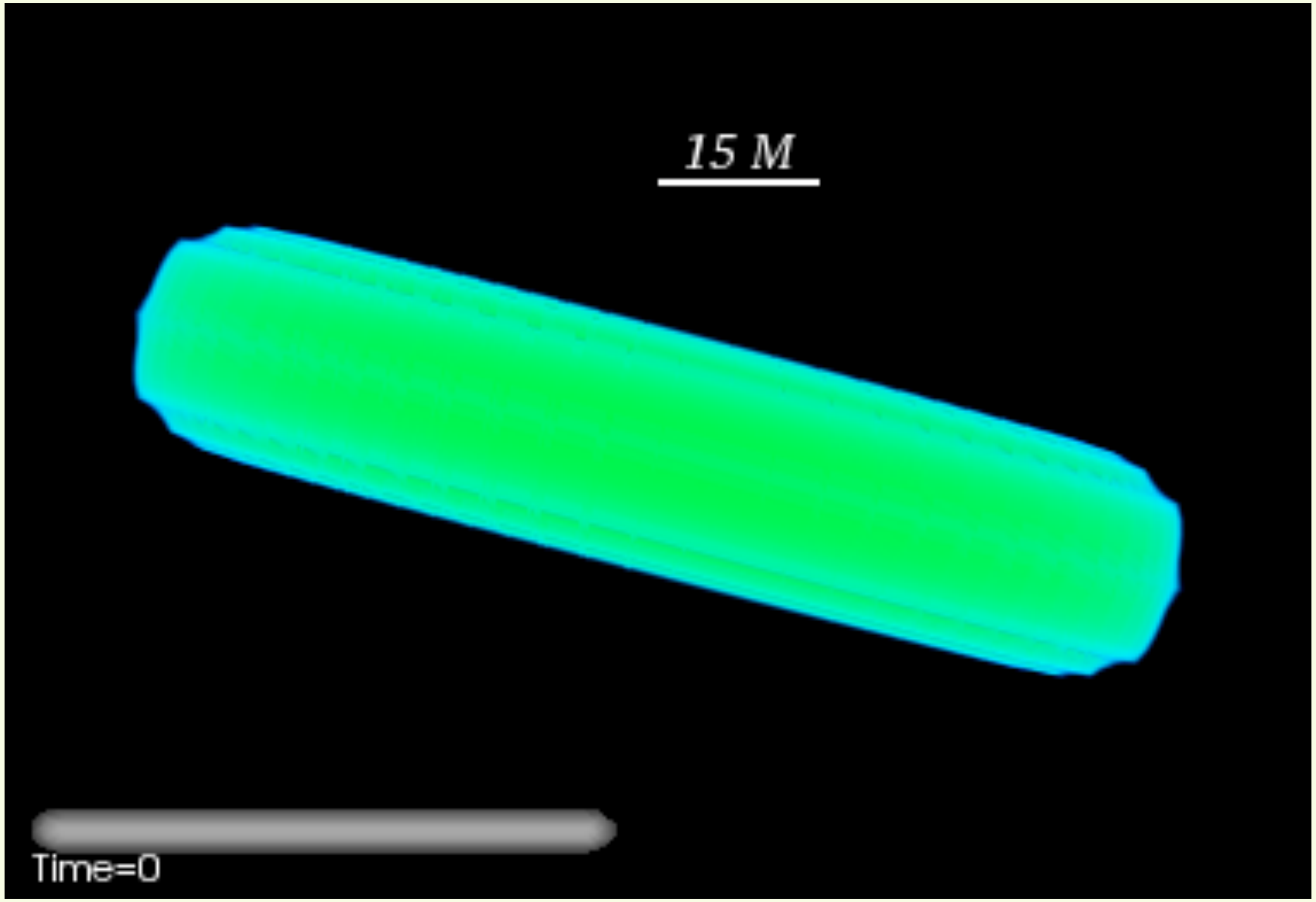


What is the physical mechanism behind?

Lense-Thirring precession?

Simulations show that misaligned flow can precess



Fragile et al. (2007)

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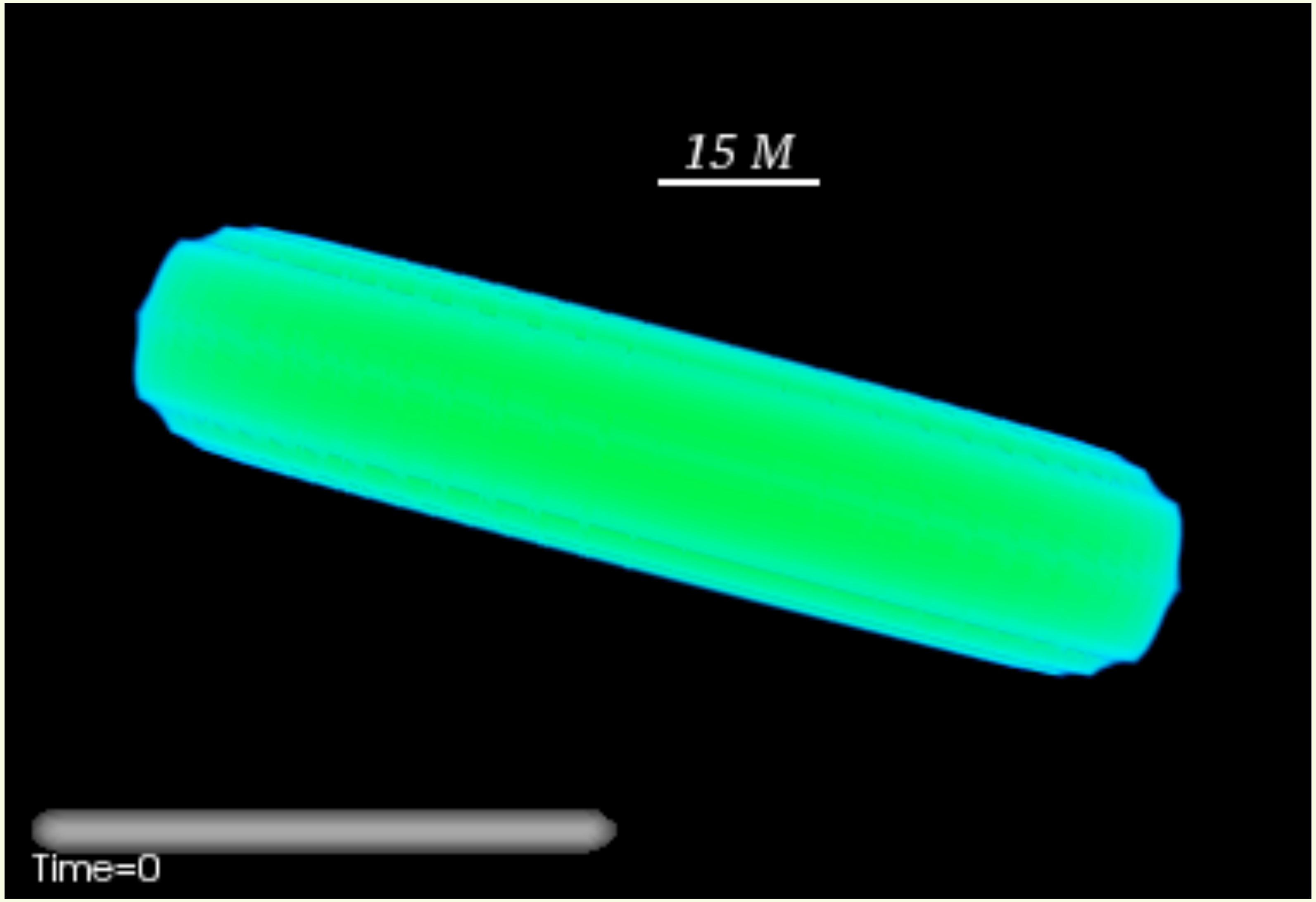
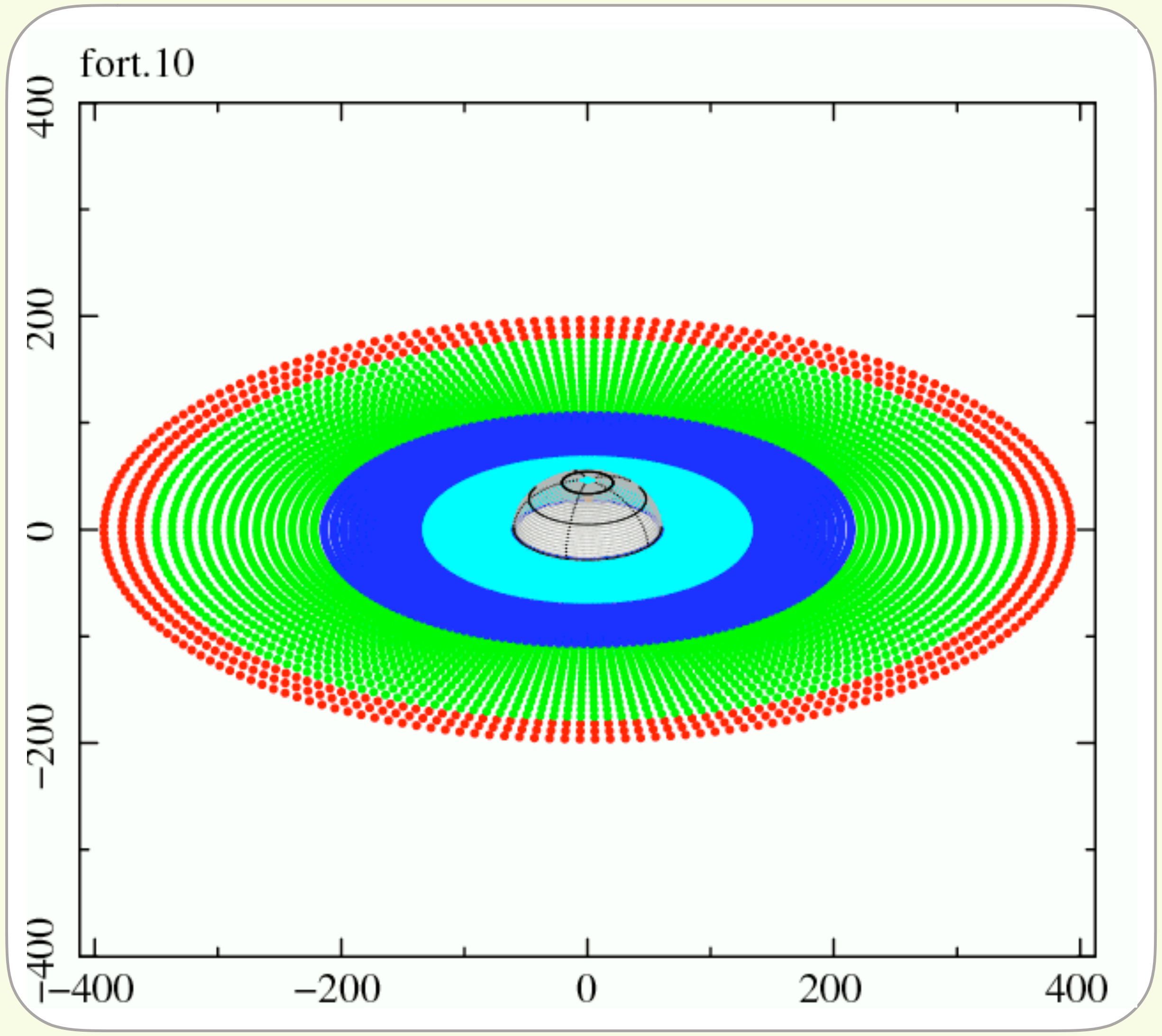


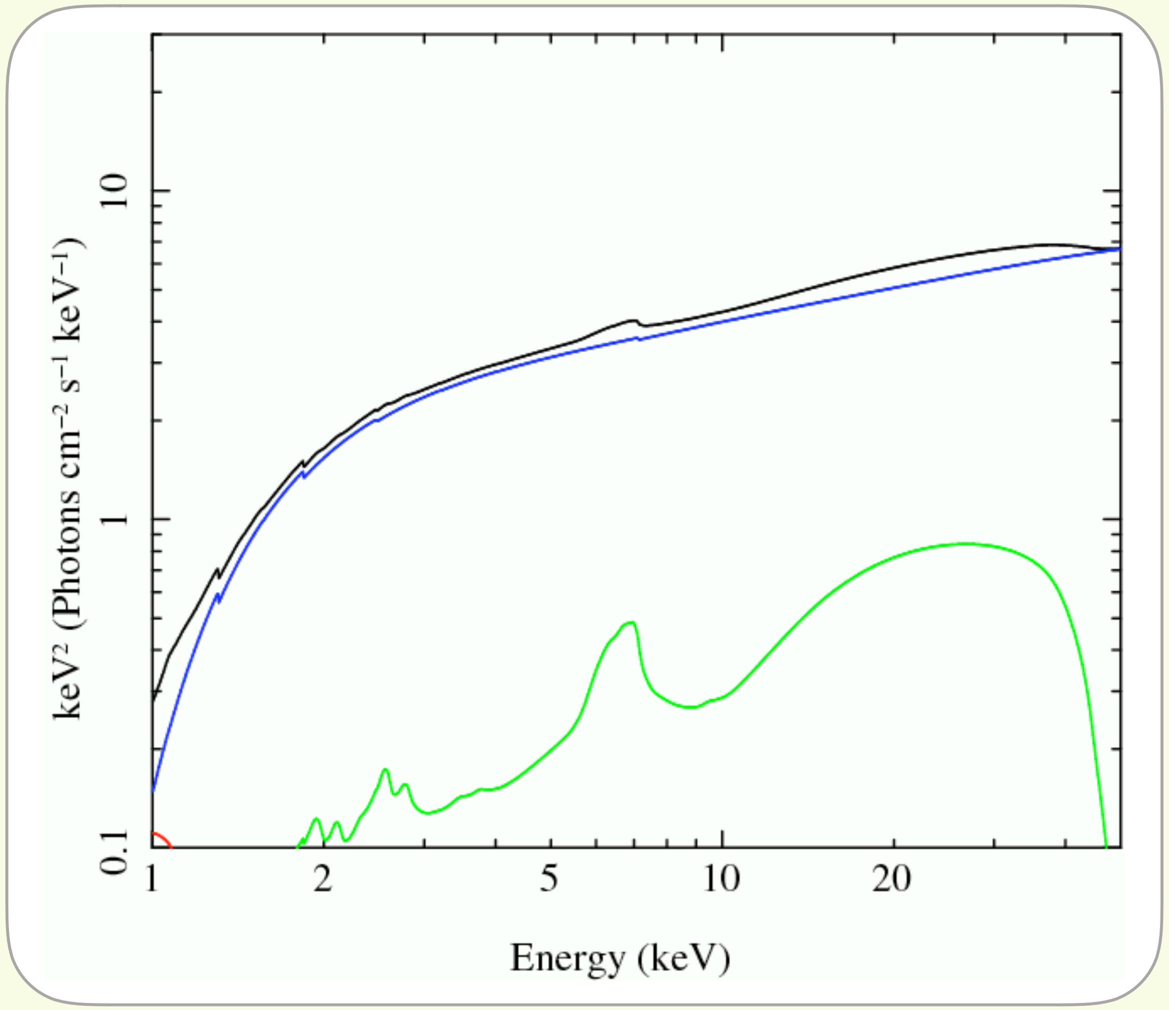
Fragile et al. (2007)

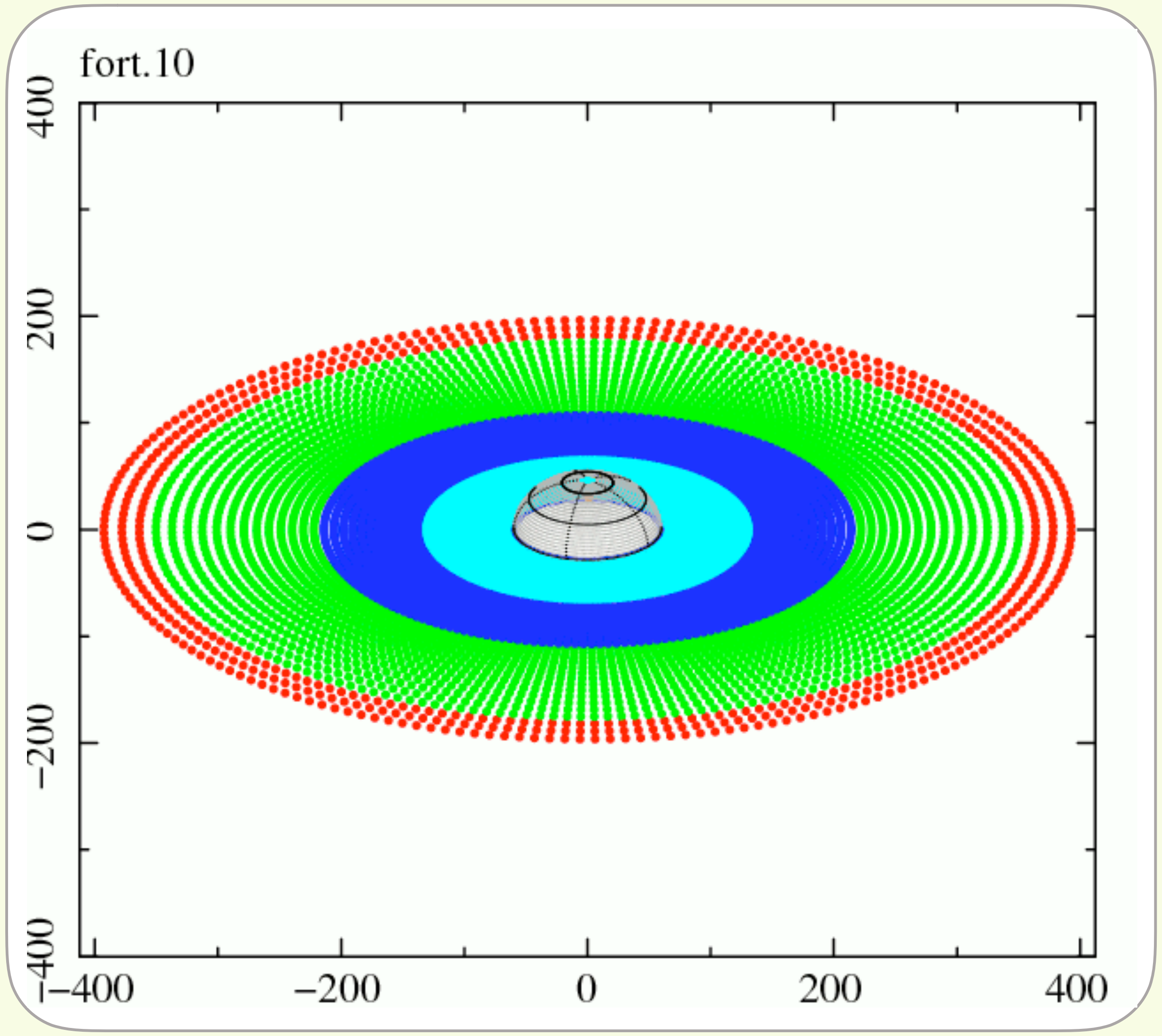
Animations from A. Ingram



Variable illumination
of the disc...

...gives varying spectral
components.





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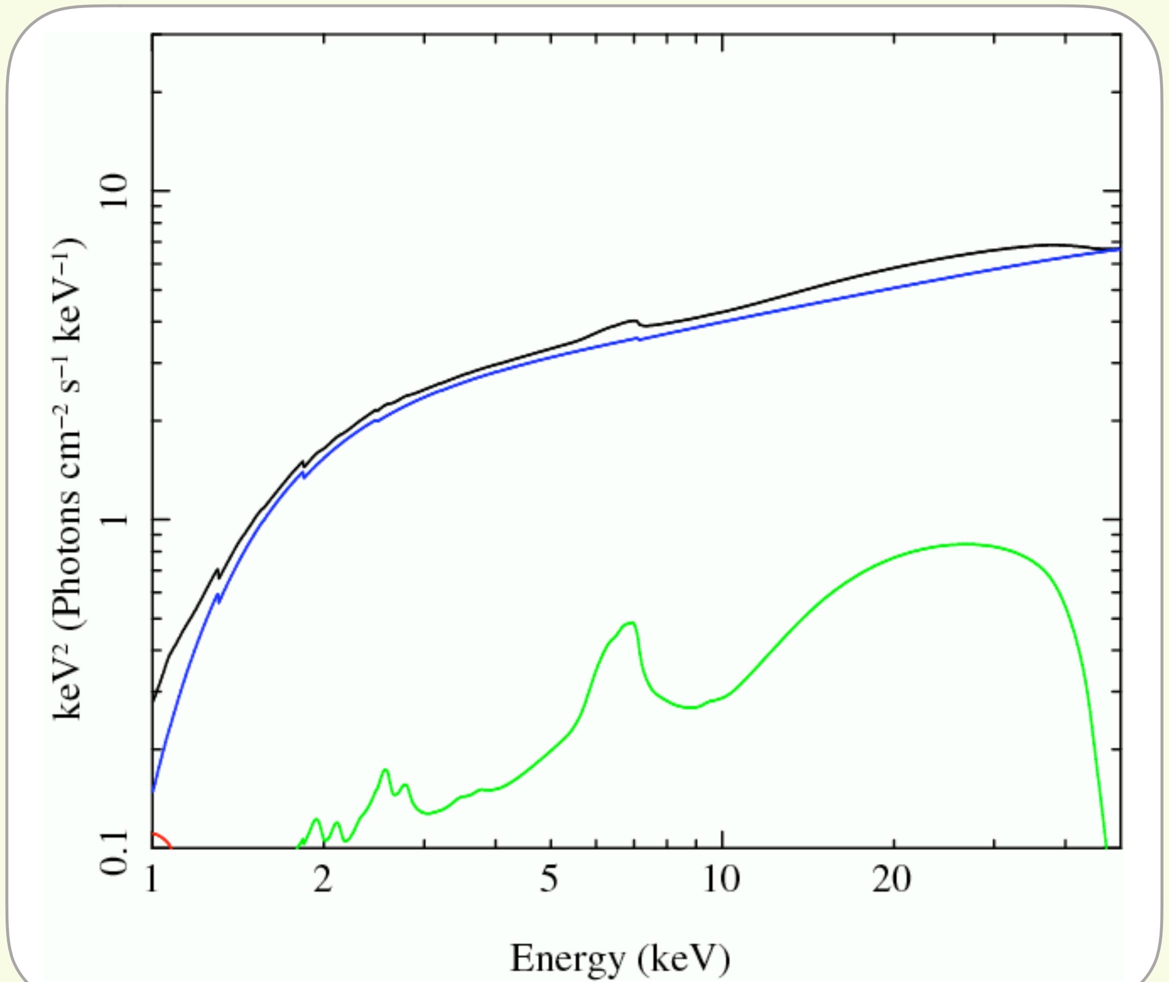
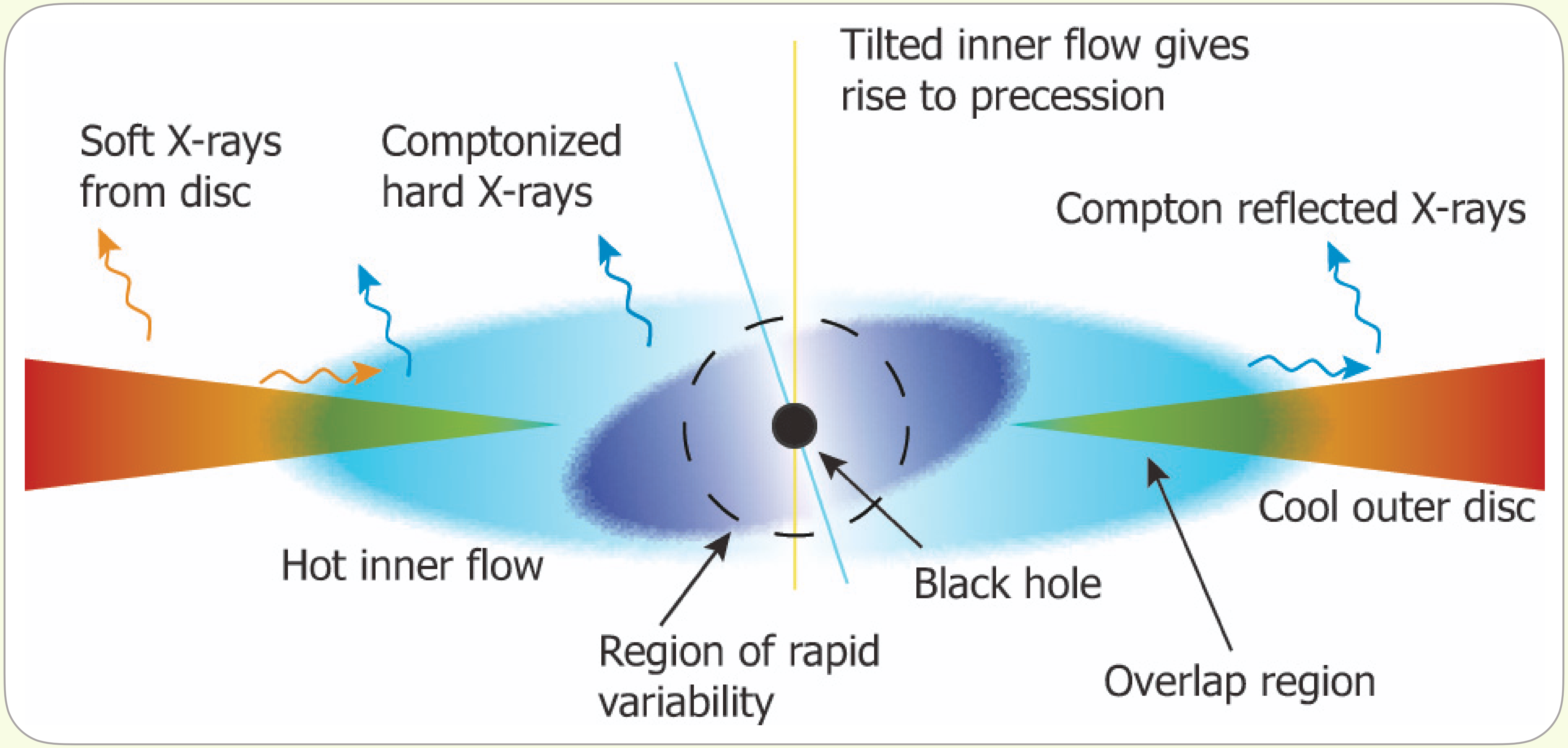
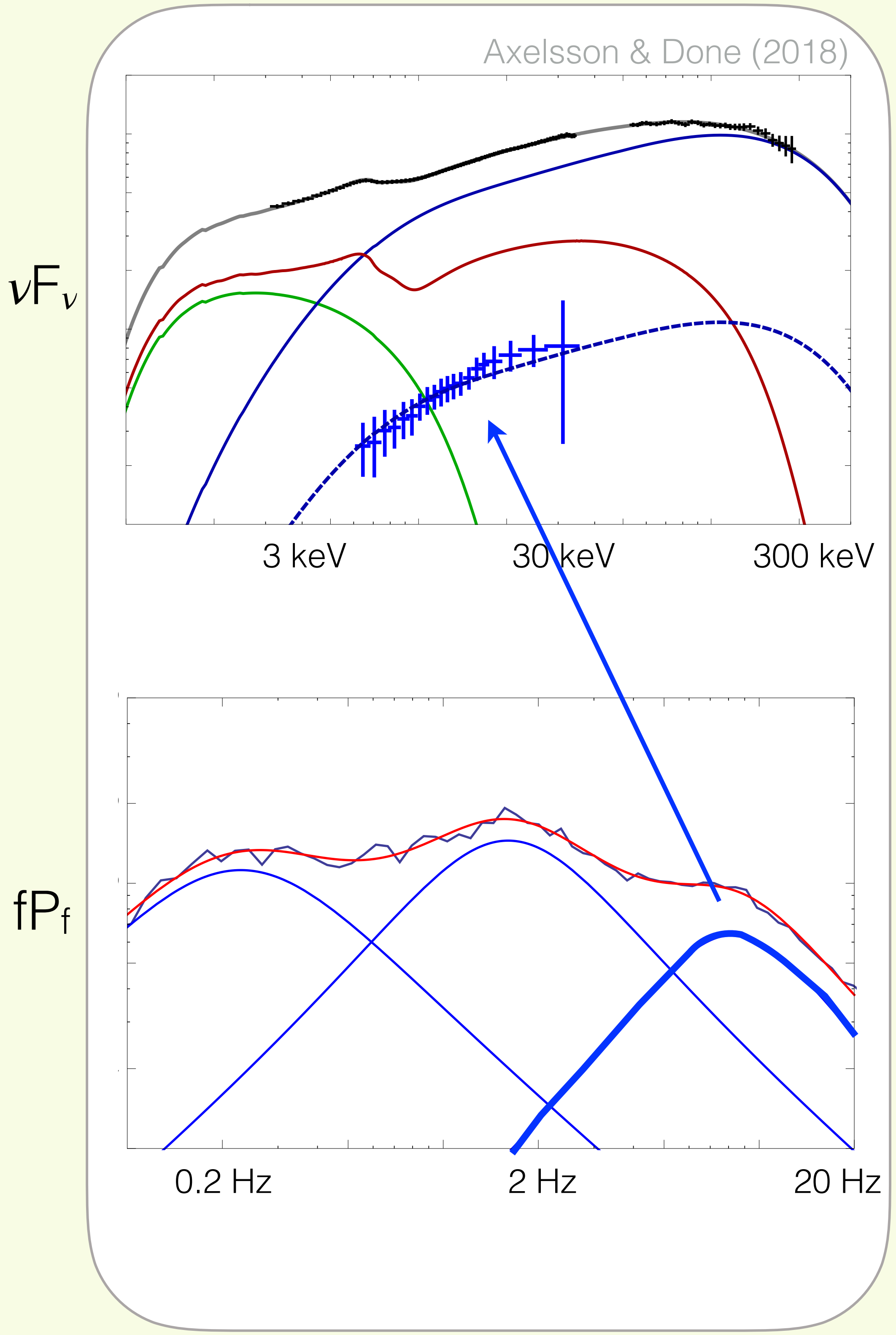


Combining the information



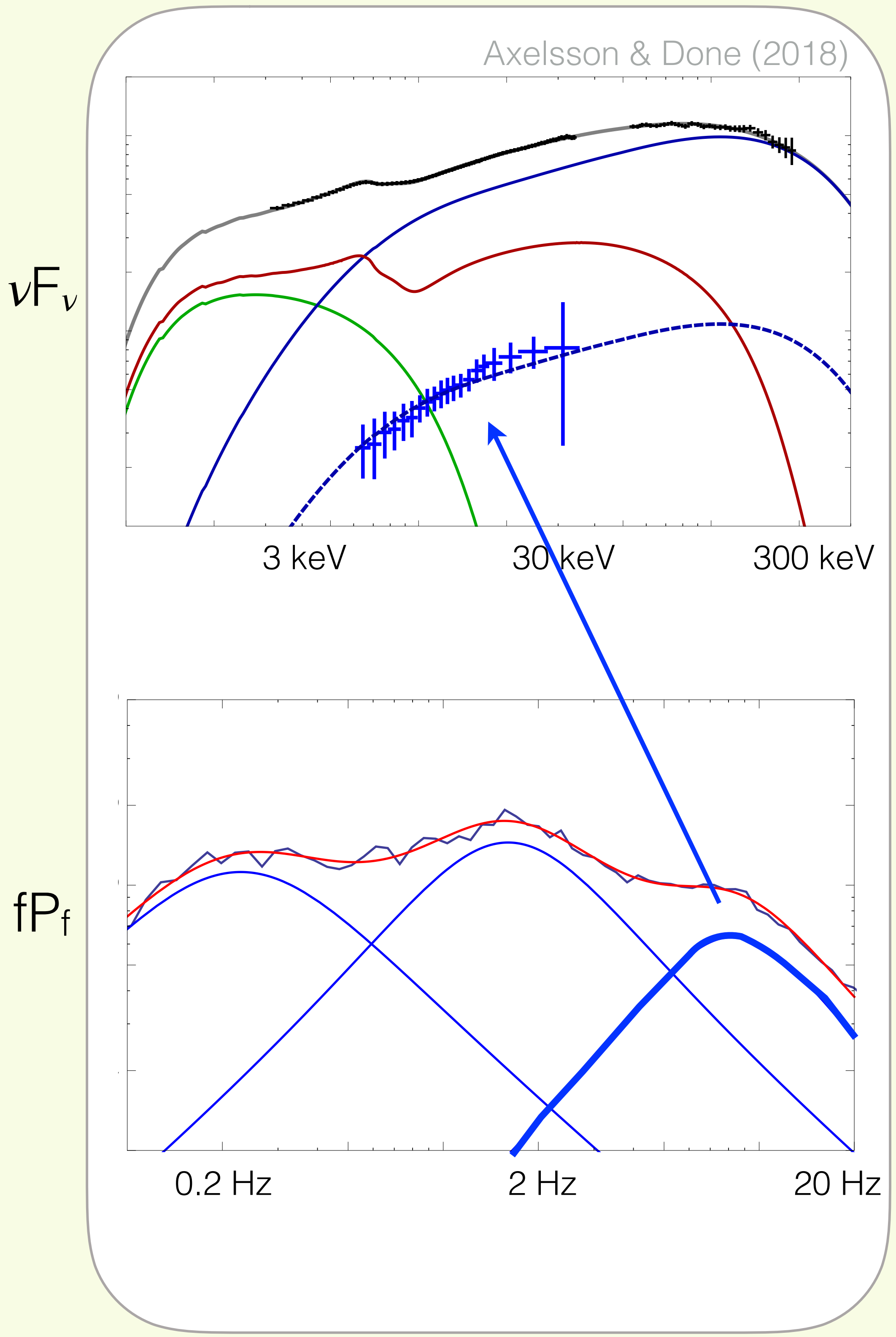
Complex hot inner flow - multiple Comptonisation regions?

Variability can constrain Comptonisation



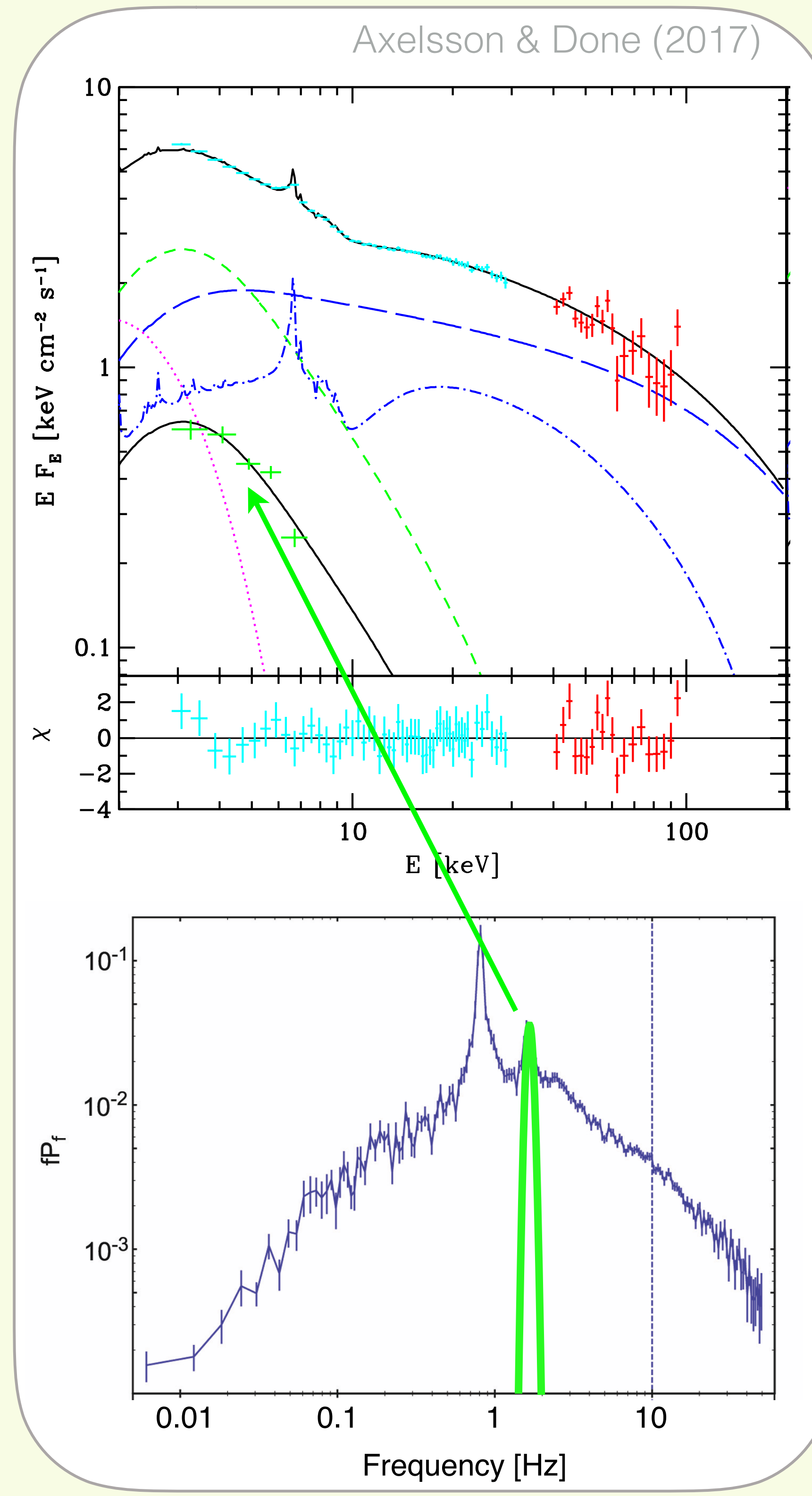
Hard compton component in Cyg X-1

Variability can constrain Comptonisation



Hard compton component in Cyg X-1

Soft compton component in GX 339-4



Probably not that simple…

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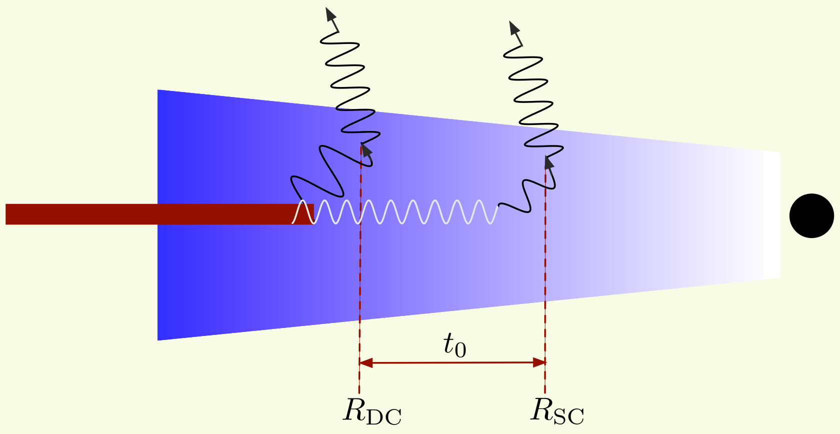
- Different sources of seed photons (synchrotron, disc)



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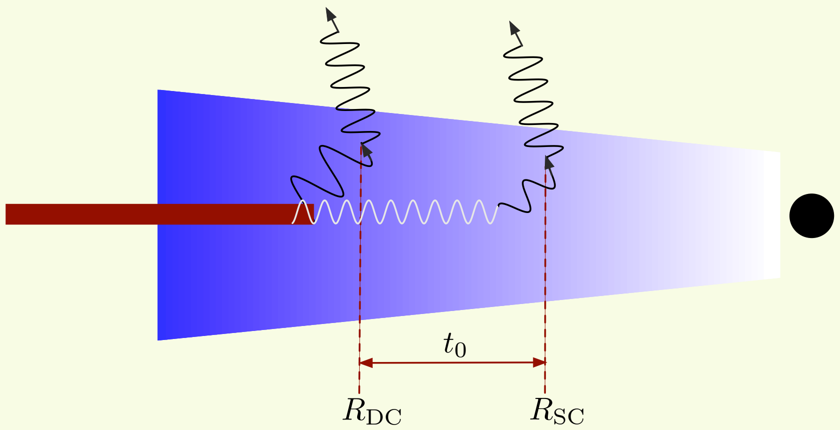
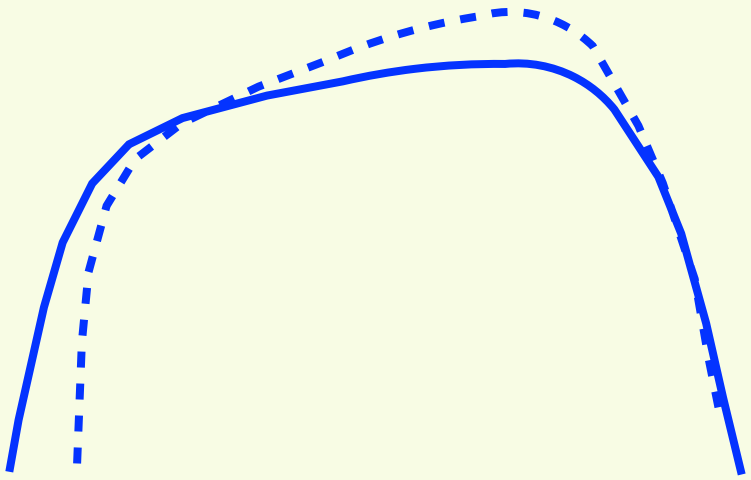


- Spectral pivoting



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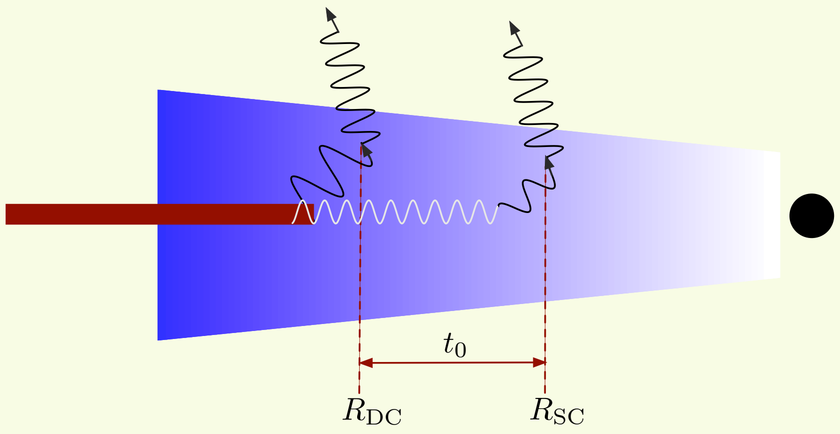

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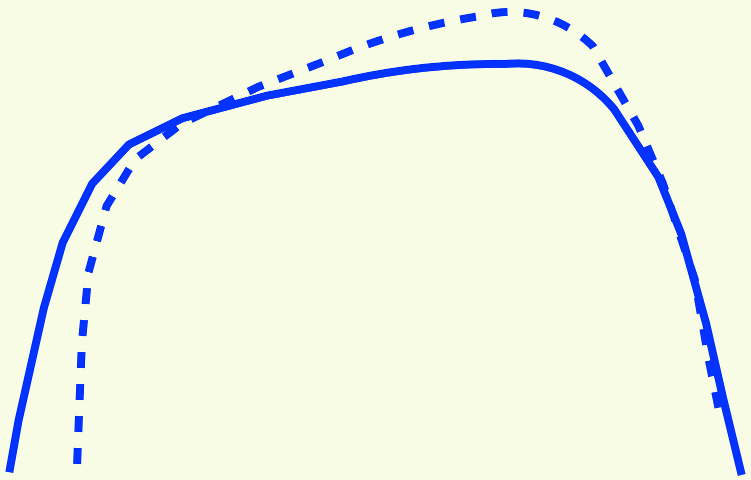

- Interplay of variability from several components (Veledina 2018)

(Some) things I didn’t mention

- Multi-wavelength studies
- Jets!
- What about the other QPO types?
- Neutron star systems - effects of a surface!
- Similarities/differences with AGN

Lots of interesting results in the other talks!

Summary

- X-ray binaries are excellent sources to study extreme physics: high gravity, strong radiation
- Spectra and timing require a stratified flow
- Their spectra are more complex than we like to think
- Combined spectral-temporal studies are necessary to understand accretion physics
- Many questions remain to be answered!