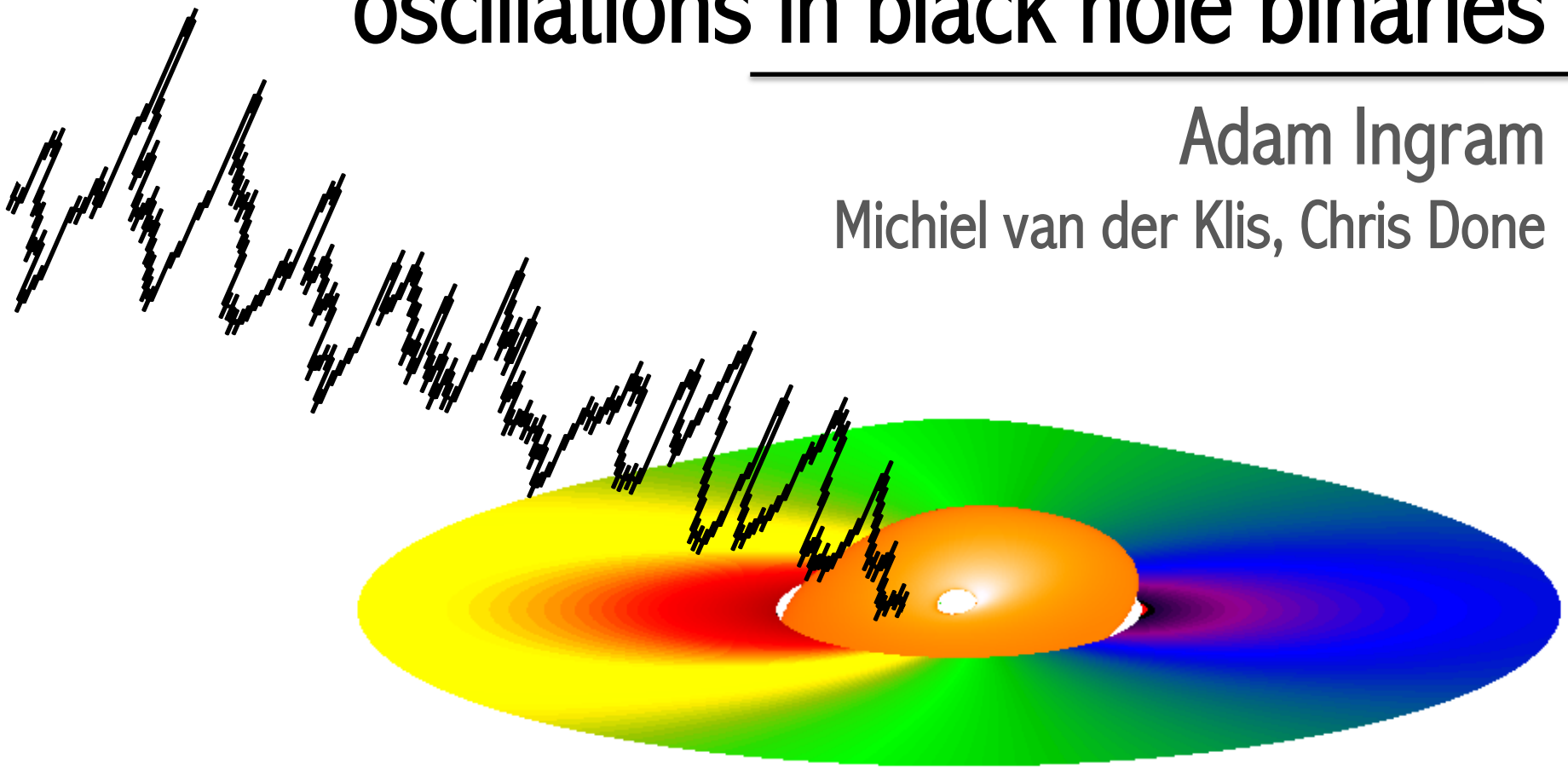
The geometric origin of quasi-periodic oscillations in black hole binaries

Adam Ingram
Michiel van der Klis, Chris Done



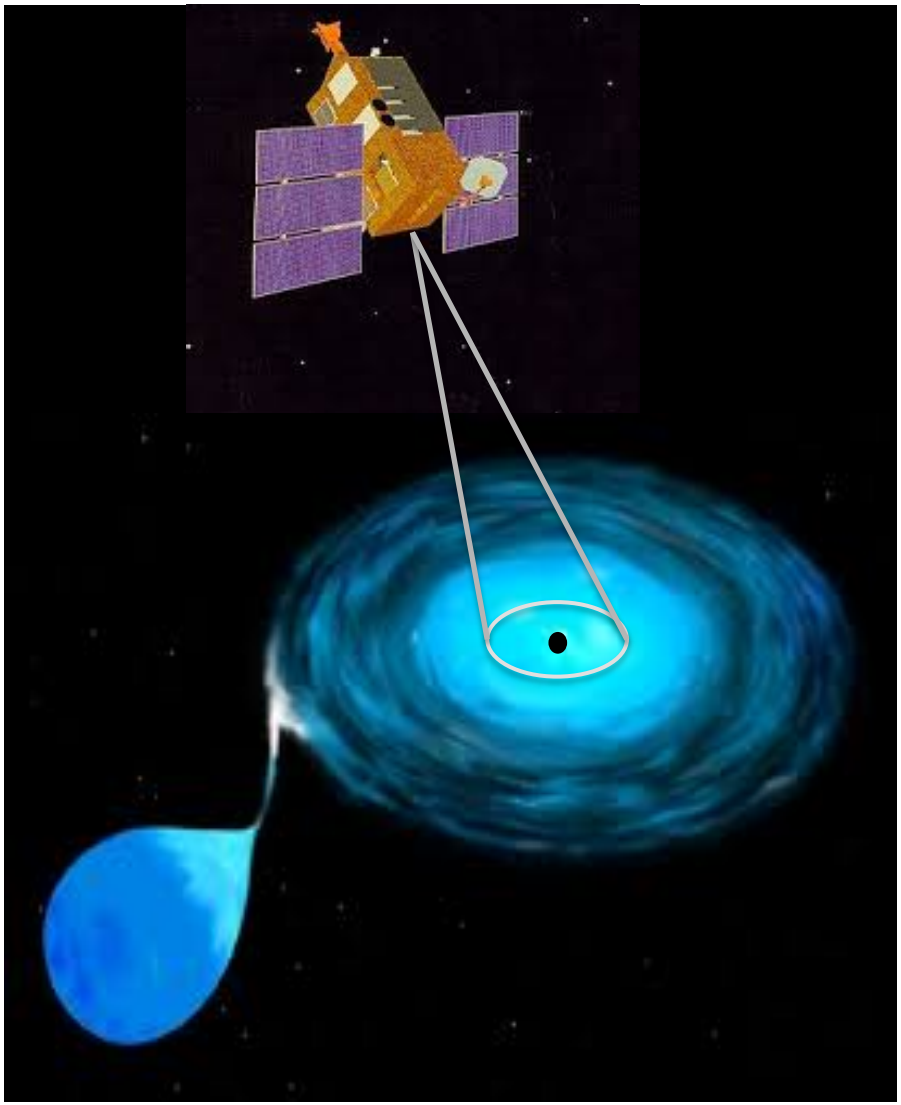
X-ray Universe 2014
Dublin - 17th June

ASTRONOMICAL INSTITUTE
ANTON PANNEKOEK

UNIVERSITY OF AMSTERDAM

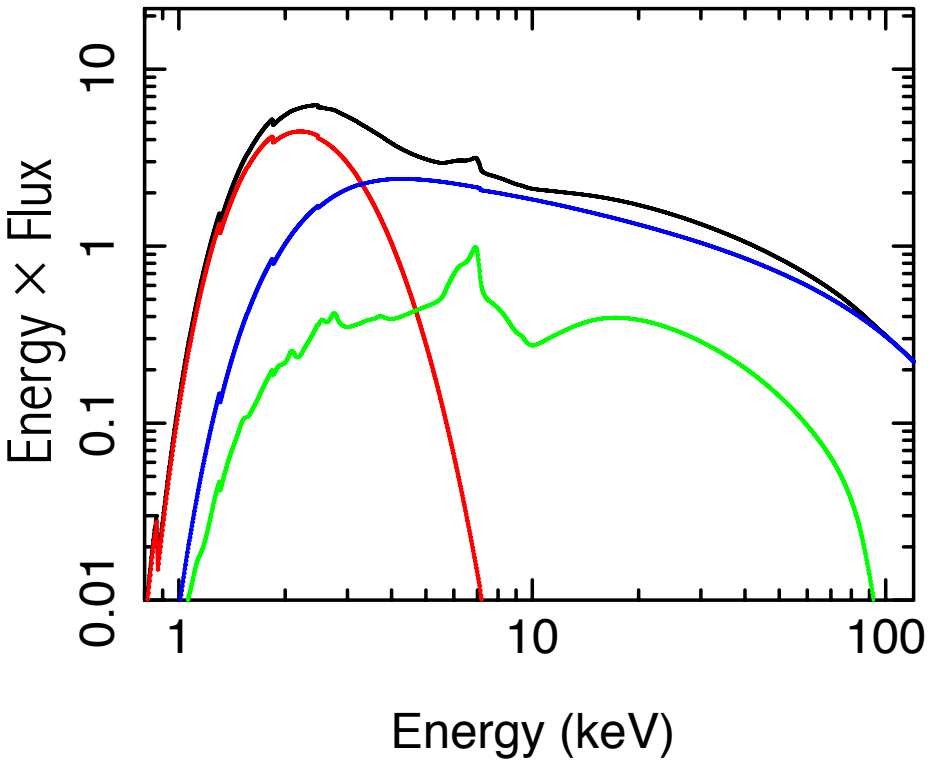
Black Hole Binaries

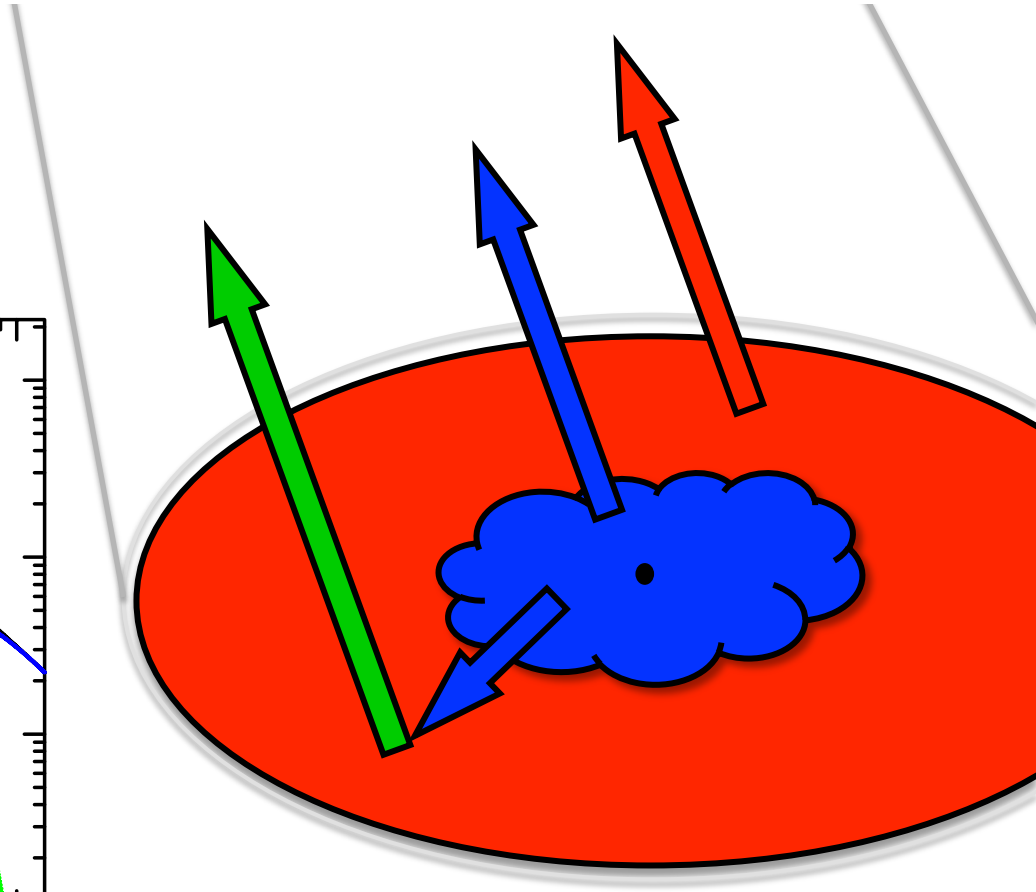
- Unique laboratories for relativity
- Too small to directly image
- Must infer geometry from spectral & timing properties



Truncated Disk Model

Multi-coloured blackbody,
Comptonisation and
Reflection

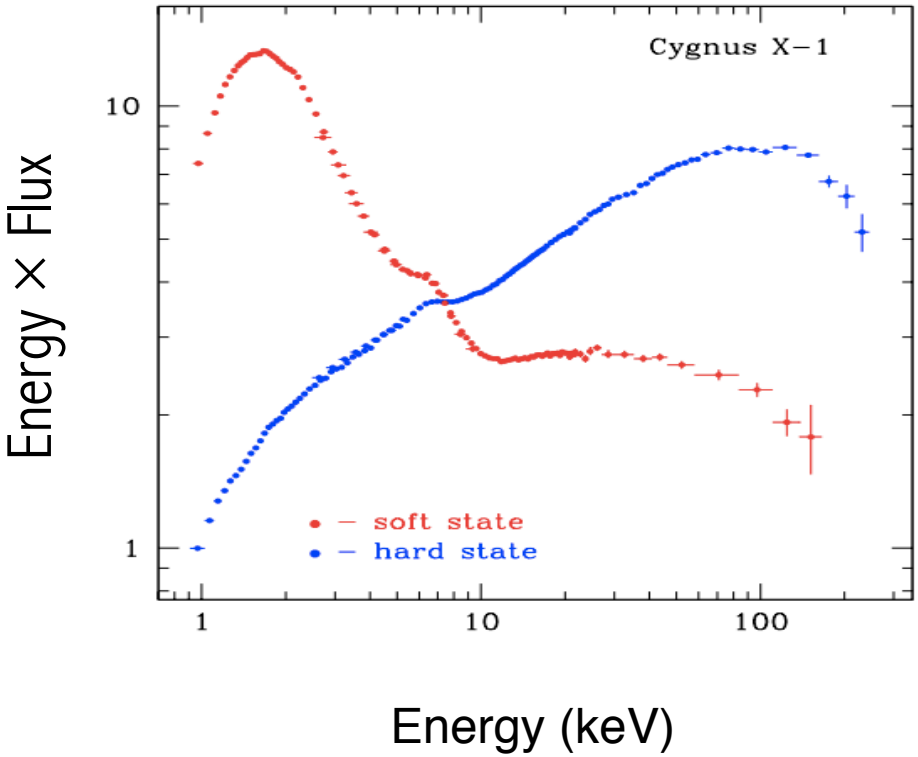




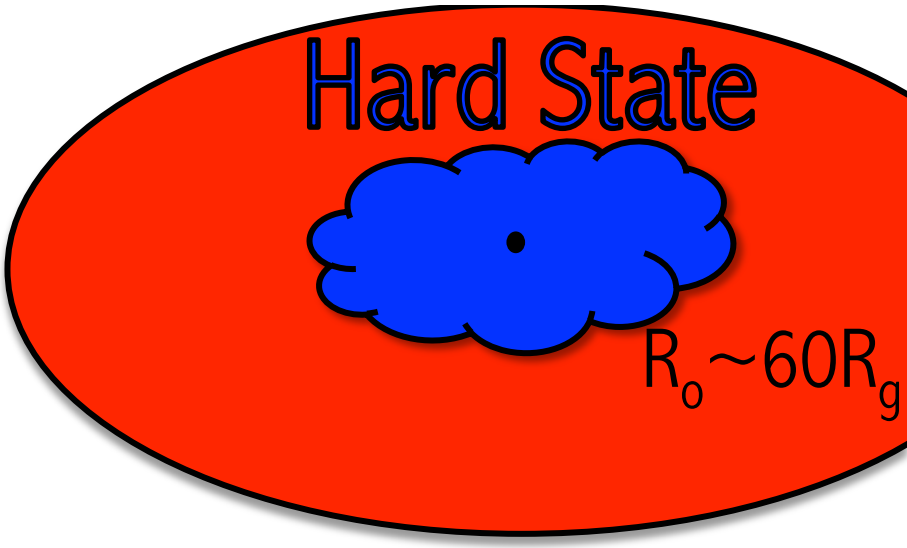
e.g. Done, Gierlinski & Kubota (2007)

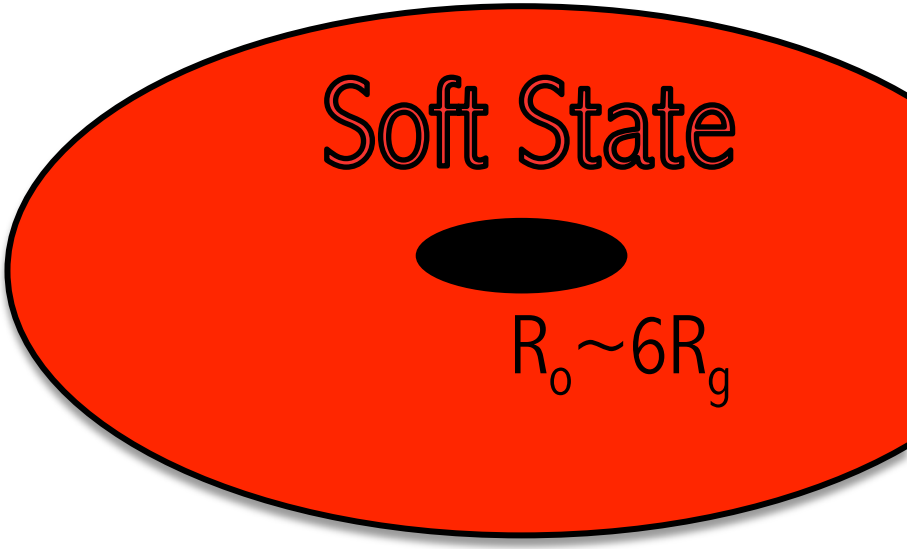
Truncated Disk Model

State changes from moving truncation radius ($R_g = GM/c^2$)

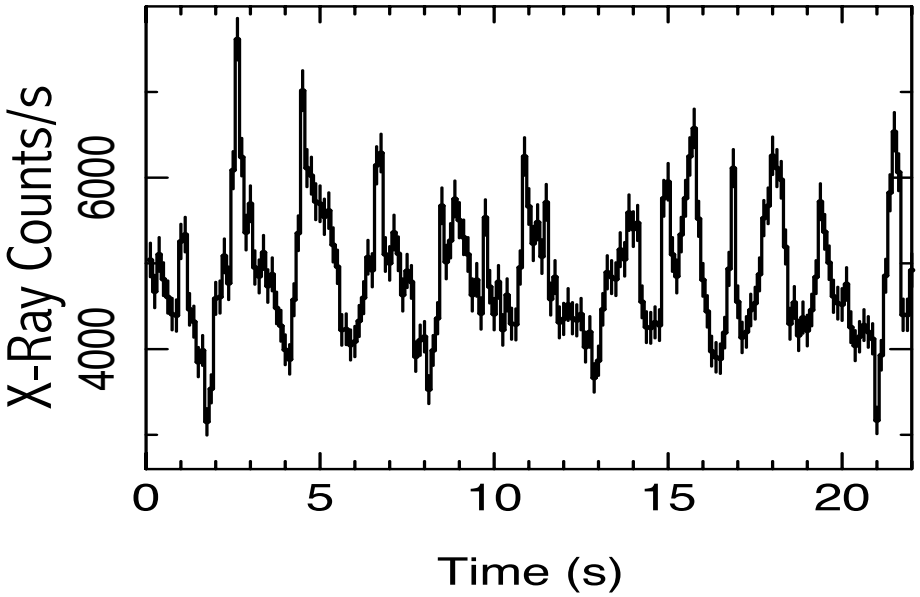


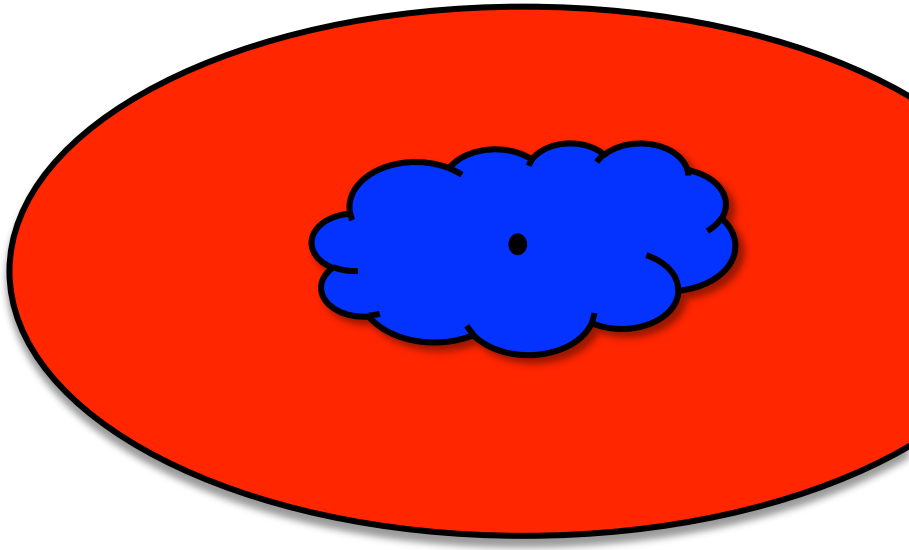
Gilfanov (2010)

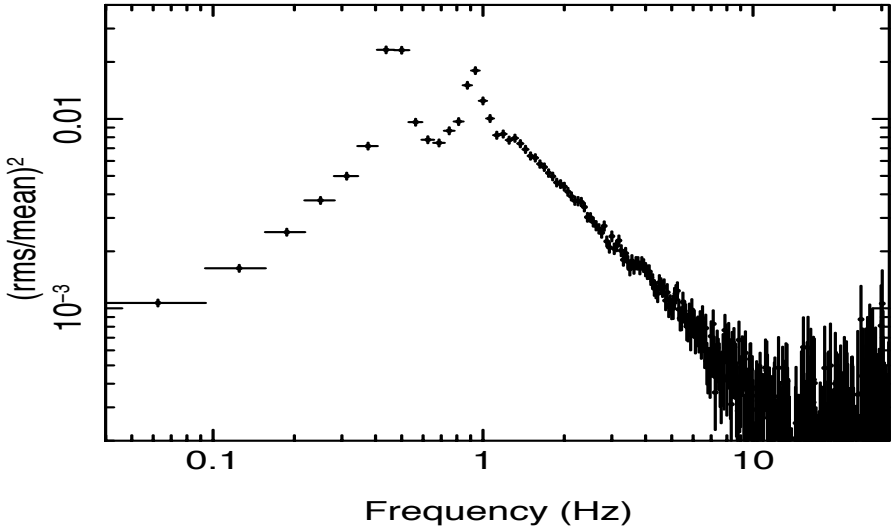




Quasi-periodic oscillations



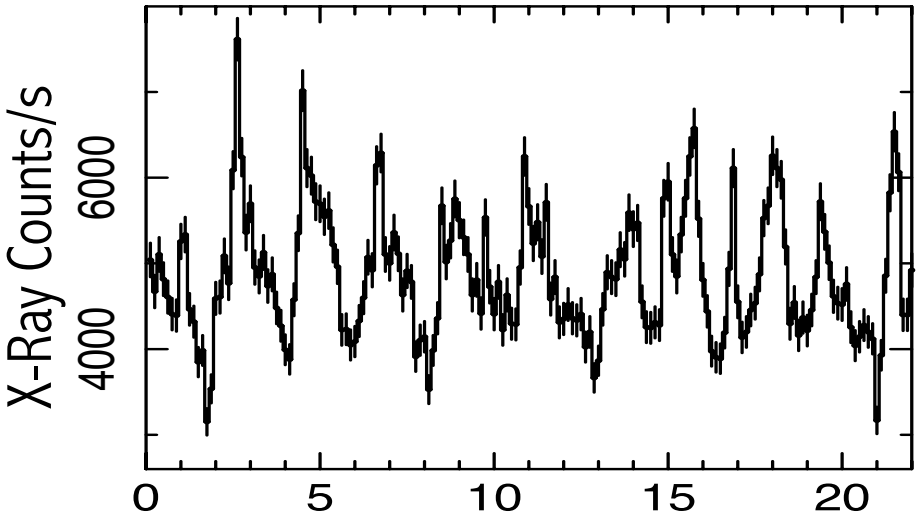


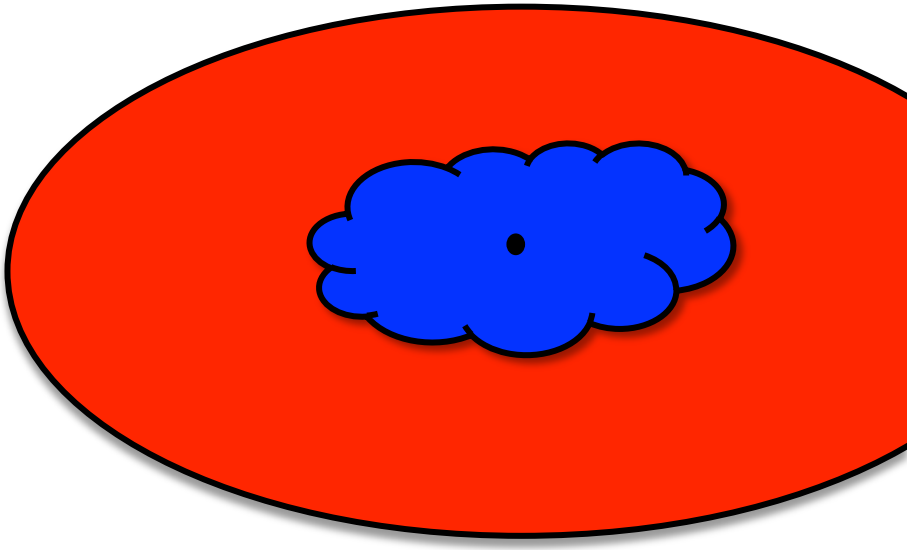


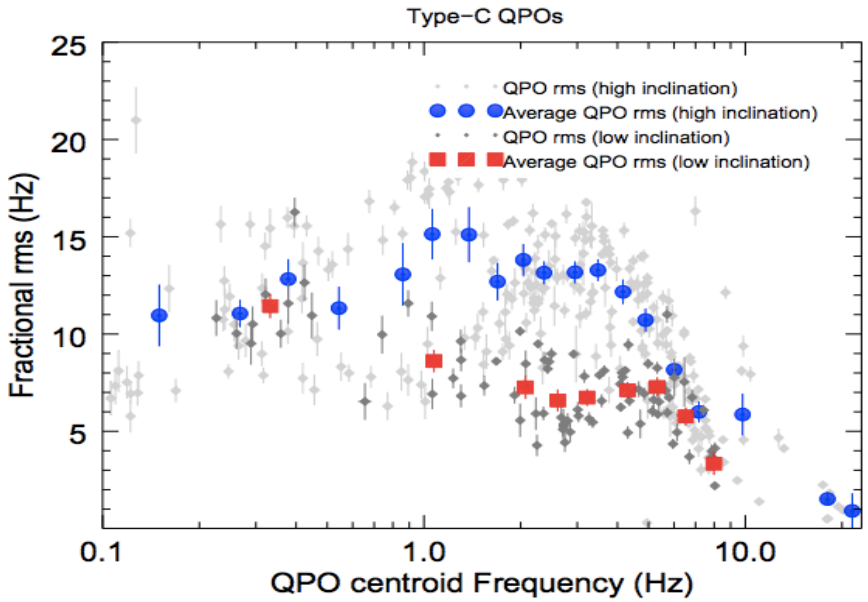
$\nu_{qpo} \sim 0.1 - 10$ Hz

as $R_o \sim 60 - 6\ R_g$

Quasi-periodic oscillations







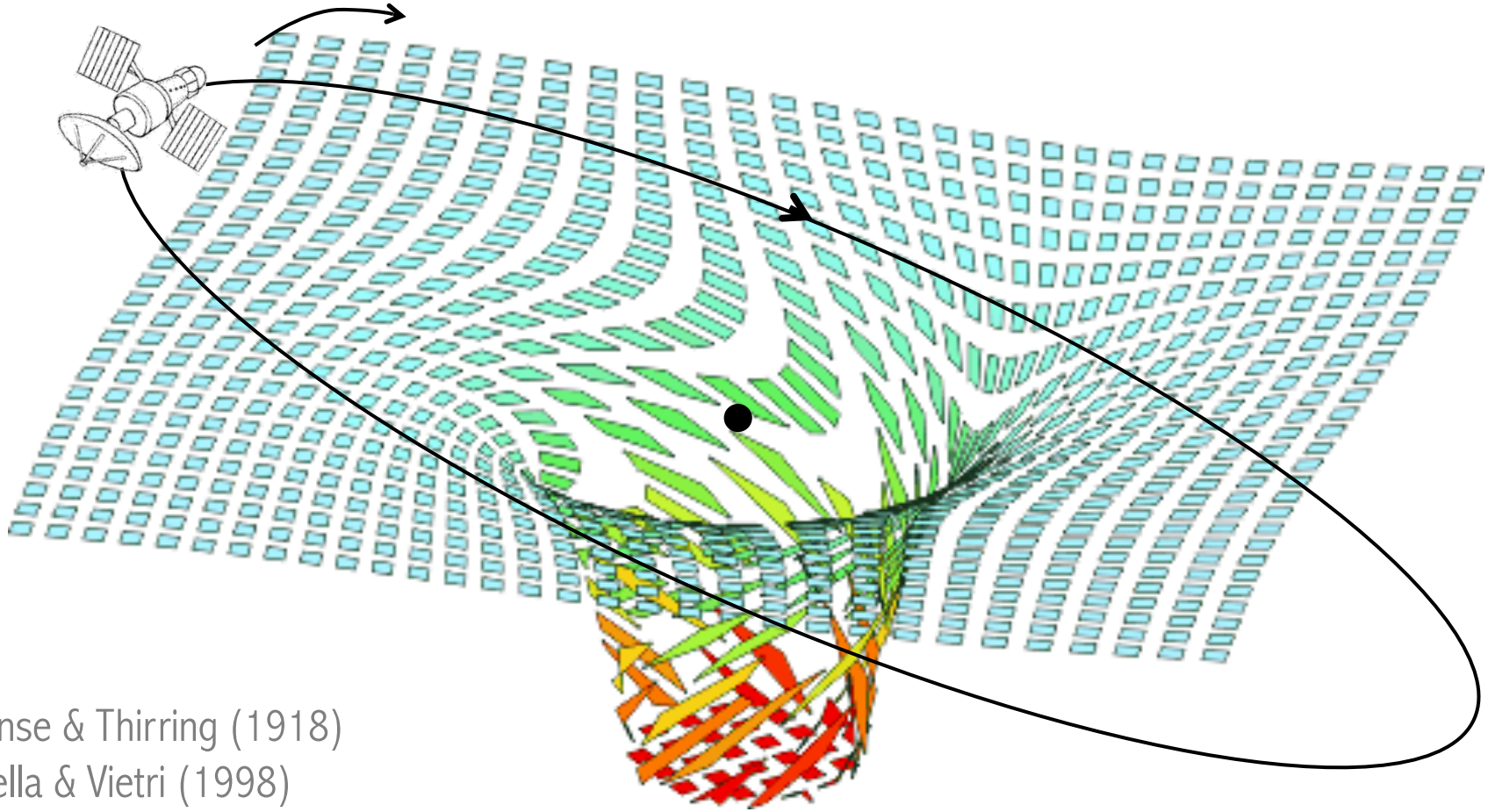
Higher inclination objects have stronger QPOs

Motta et al (2014); Heil, Uttley & Klein-Wolt (2014)

Frame dragging

A spinning black hole **distorts** space and time

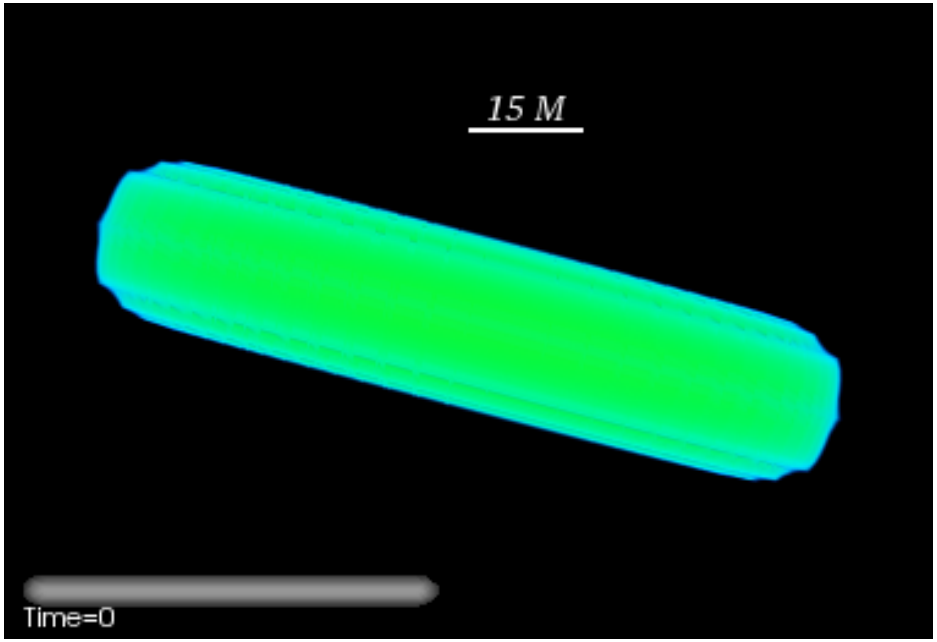
The satellite's motion is **influenced** by the spin of the black hole



Lense & Thirring (1918)
Stella & Vietri (1998)

Frame dragging

FLOW



Solid body precession at average LT frequency

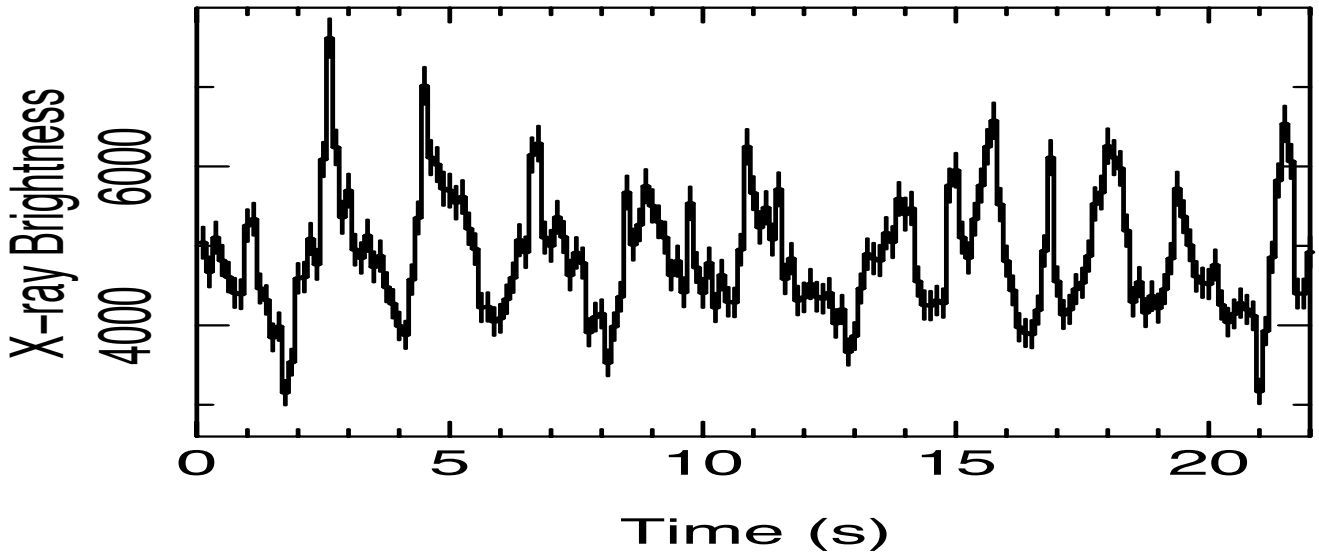
Fragile et al (2007)

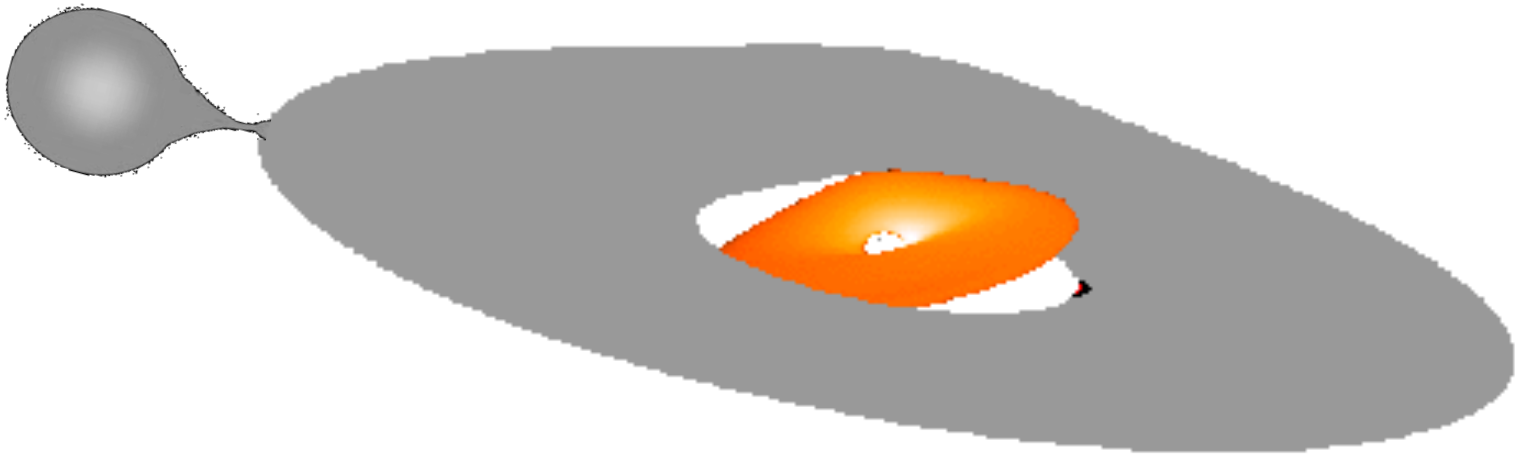
DISK

Viscosity aligns inner regions with the BH and outer regions with the binary partner

Bardeen & Petterson (1975)

Frame dragging

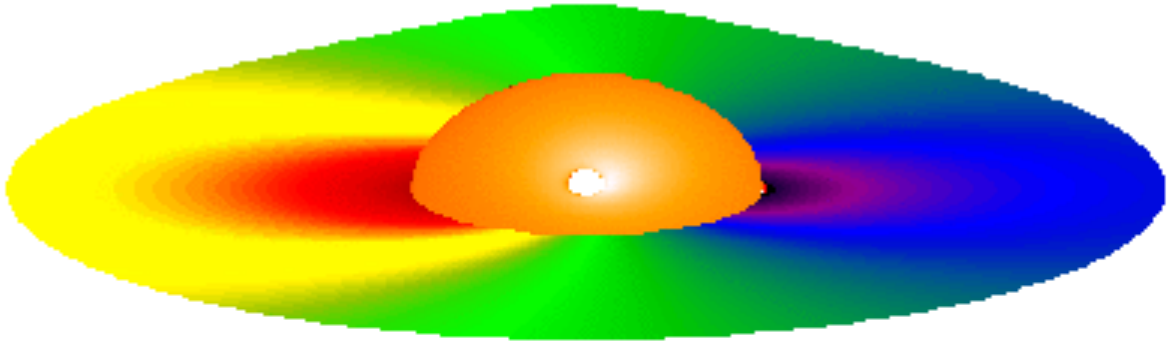


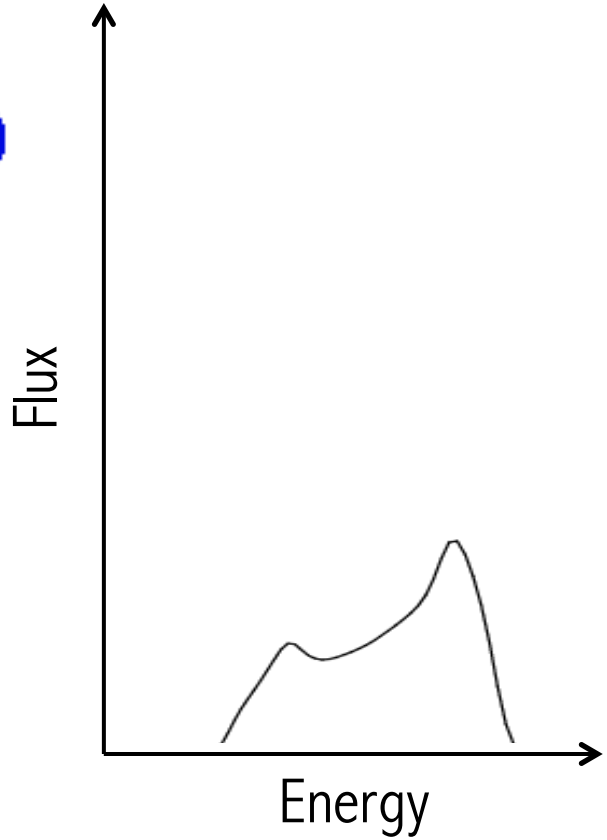


Ingram, Done & Fragile (2009)

Frame dragging

Tell-tale sign of relativistic precession: a rocking iron line

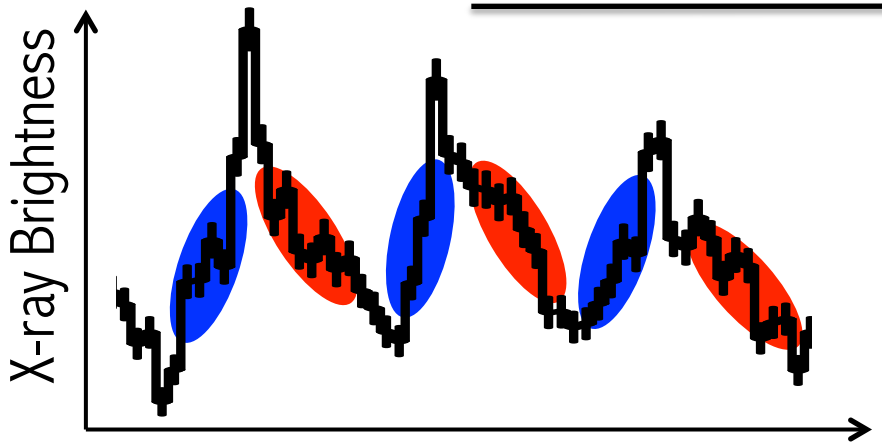


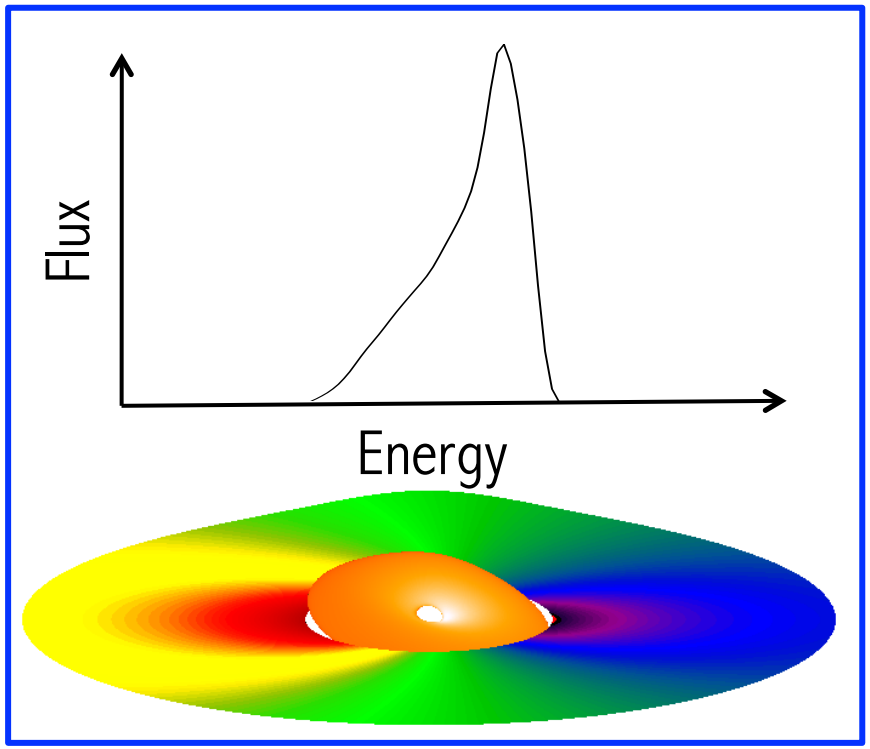


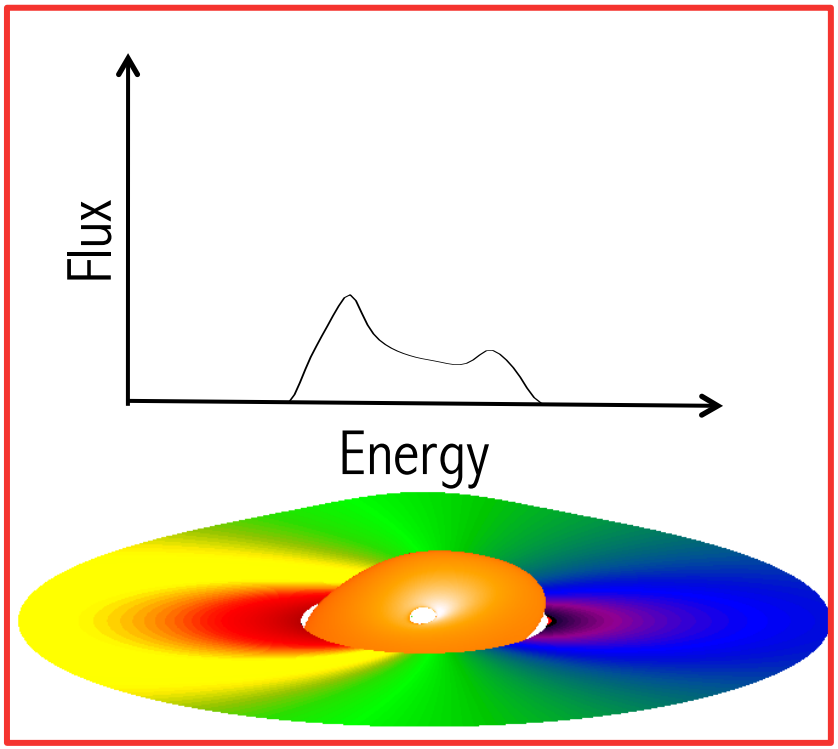
https://www.youtube.com/watch?v=e1QmLg5mGbU

Ingram & Done (2012)

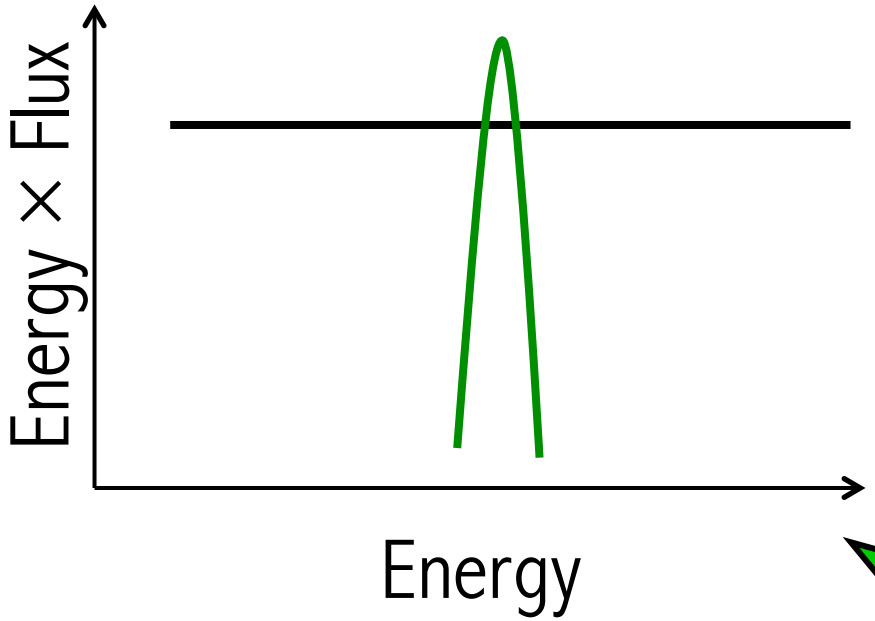
Phase Resolving

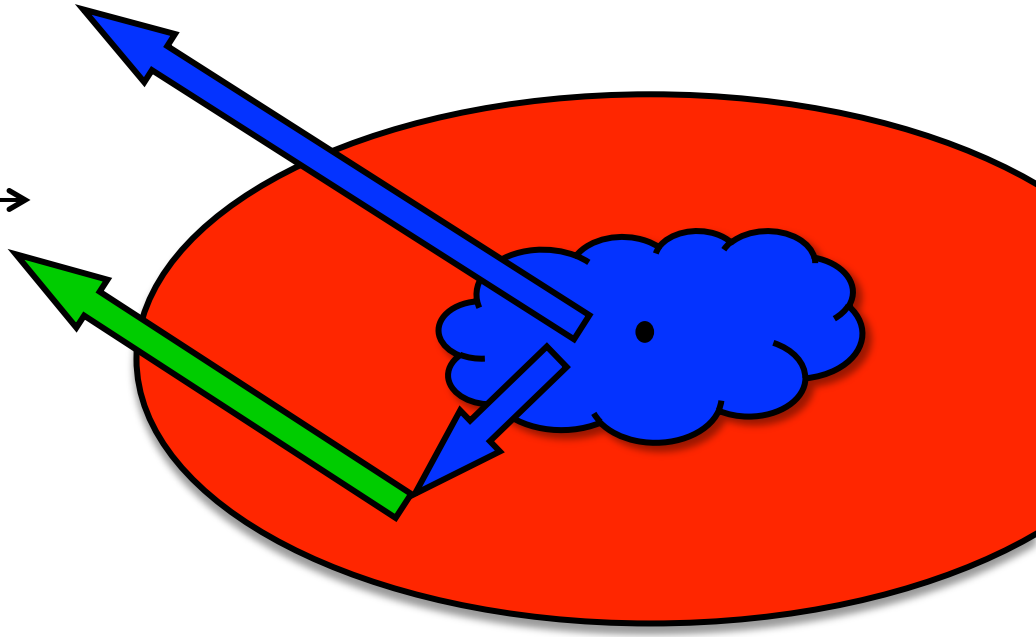






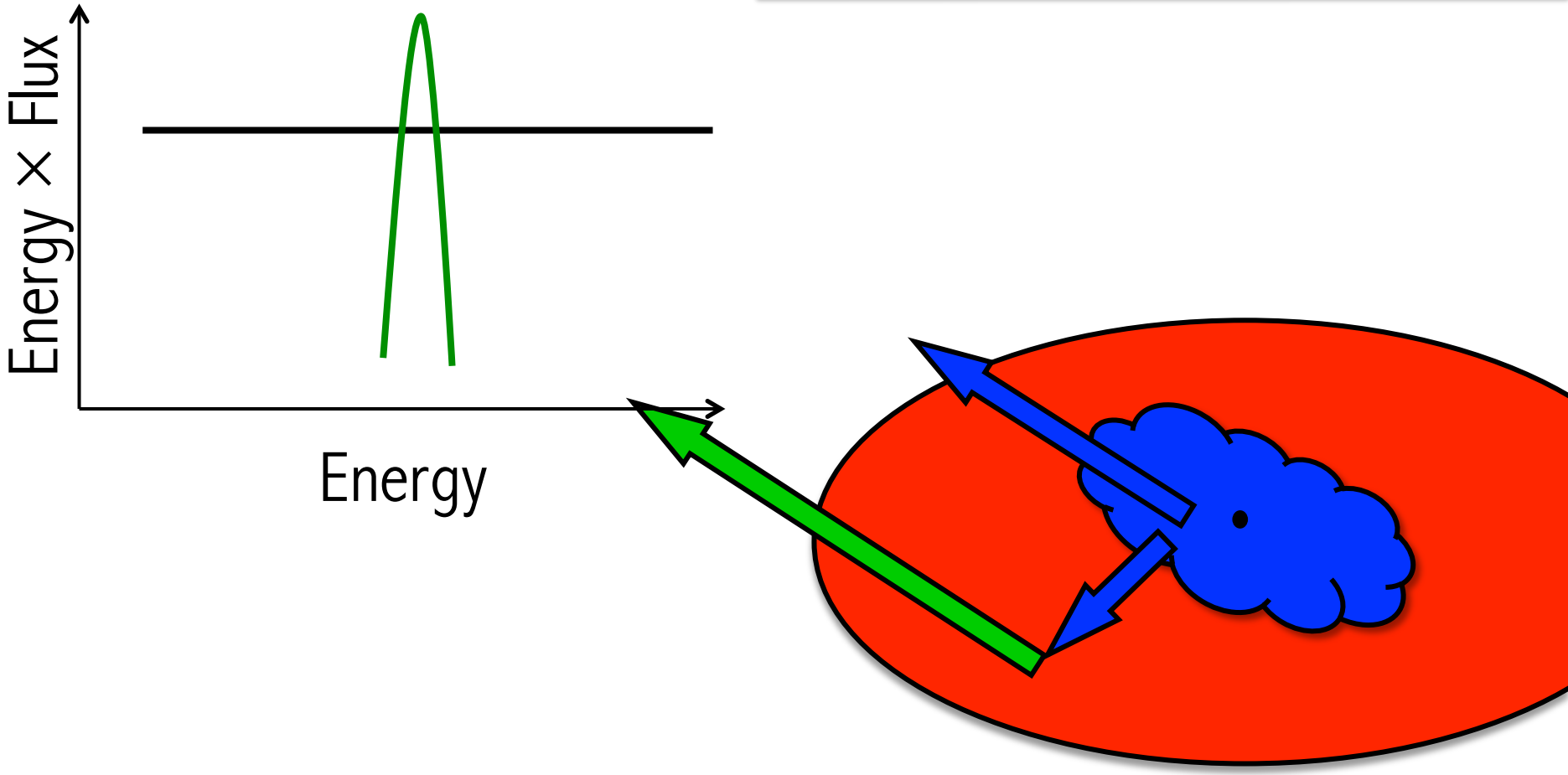
Phase Resolving





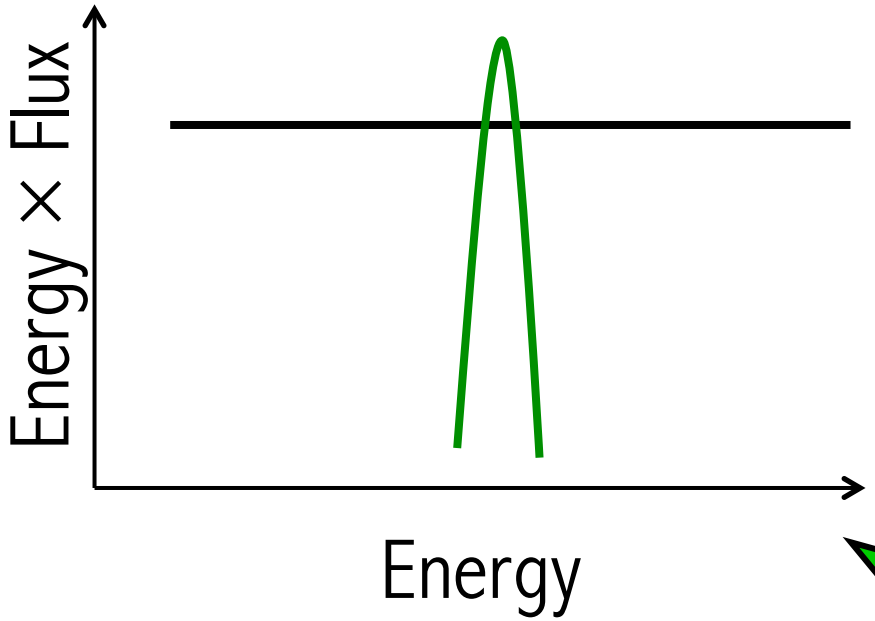
Geometric origin ➔ Line EW varies

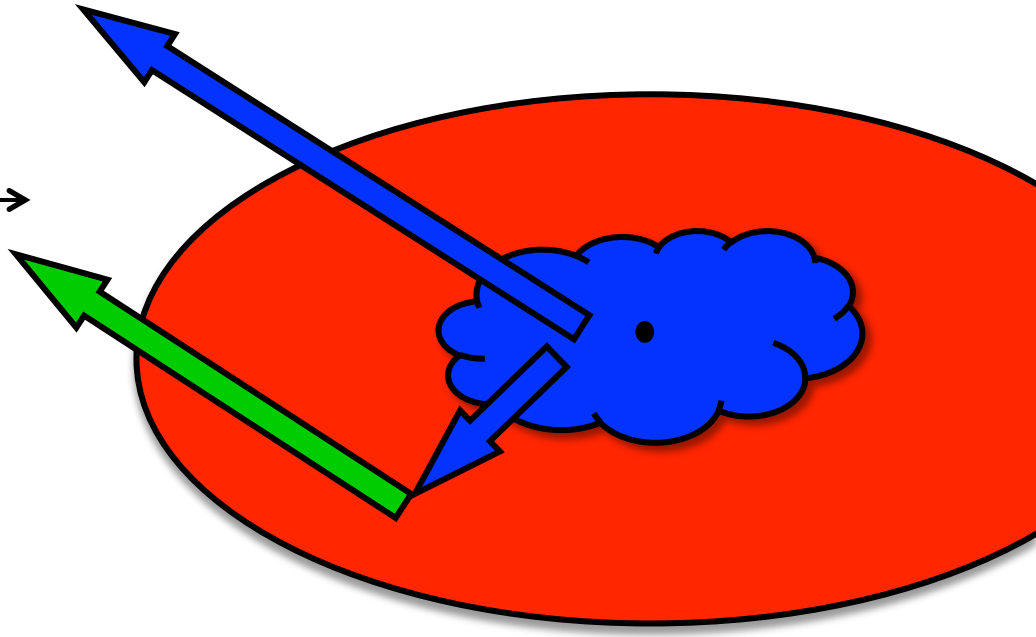
Phase Resolving



Geometric origin ➔ Line EW varies

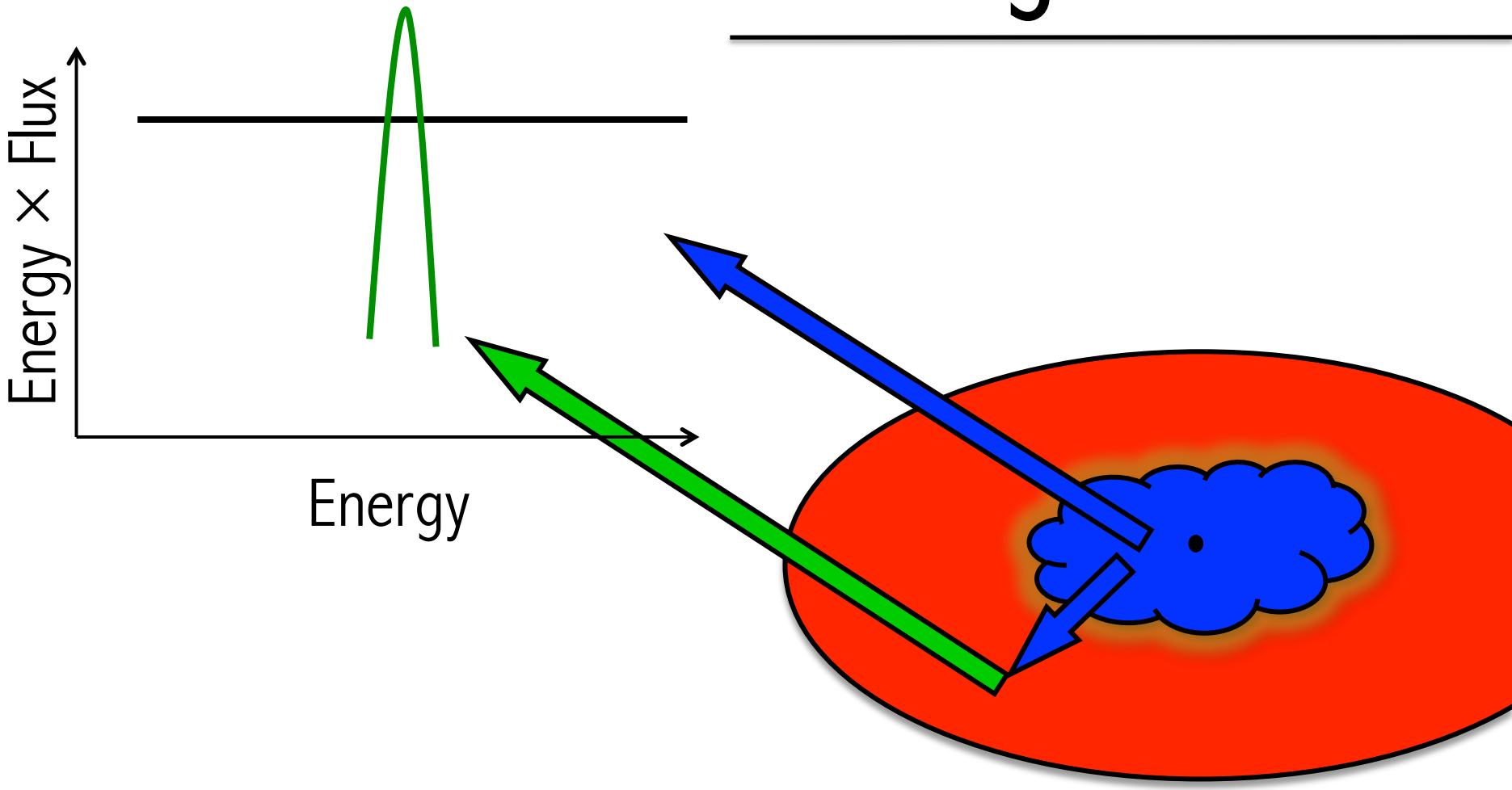
Phase Resolving





Non-geometric origin ➔ Line EW **in phase** with continuum

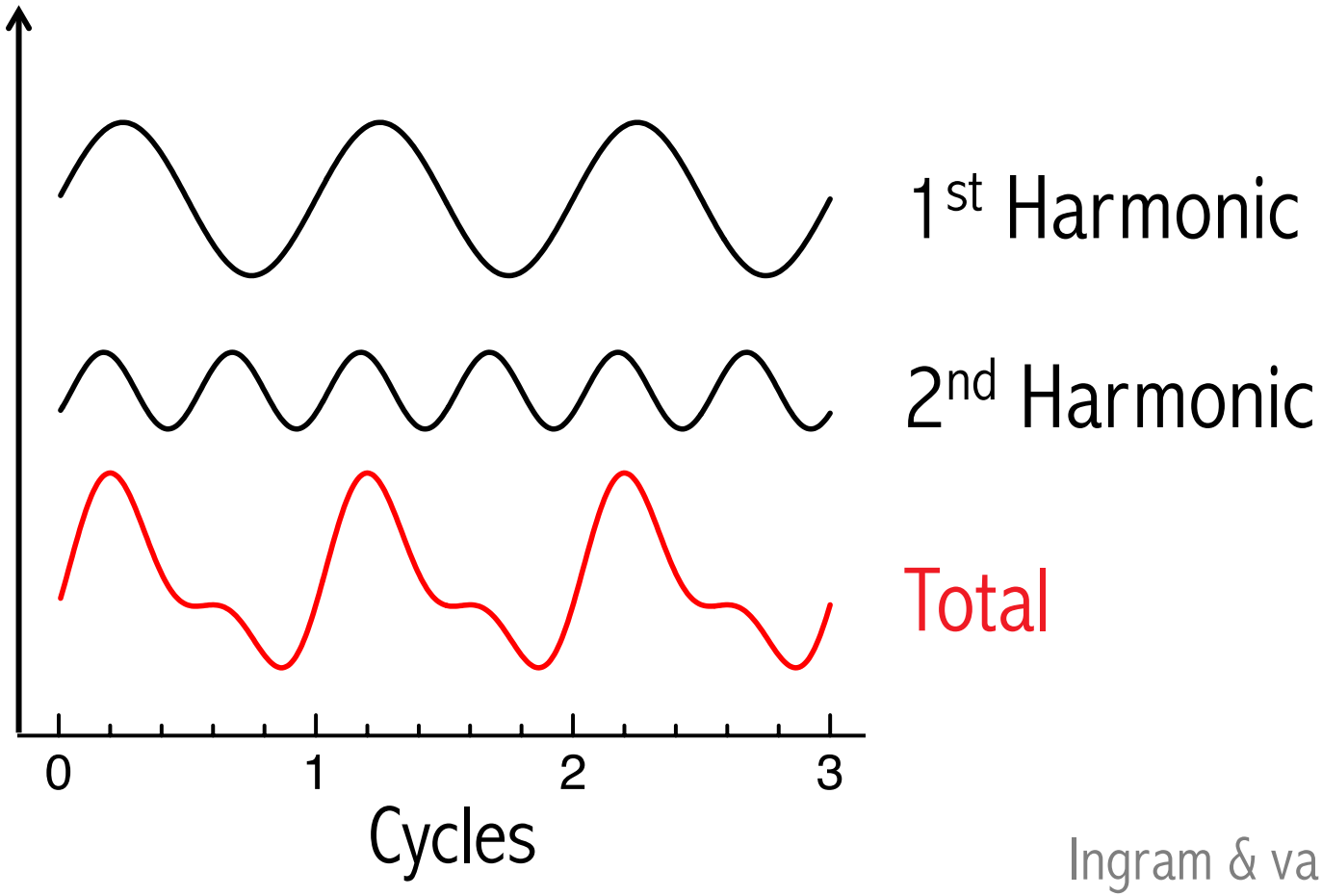
Phase Resolving



Non-geometric origin ➔ Line EW **in phase** with continuum

QPO waveform

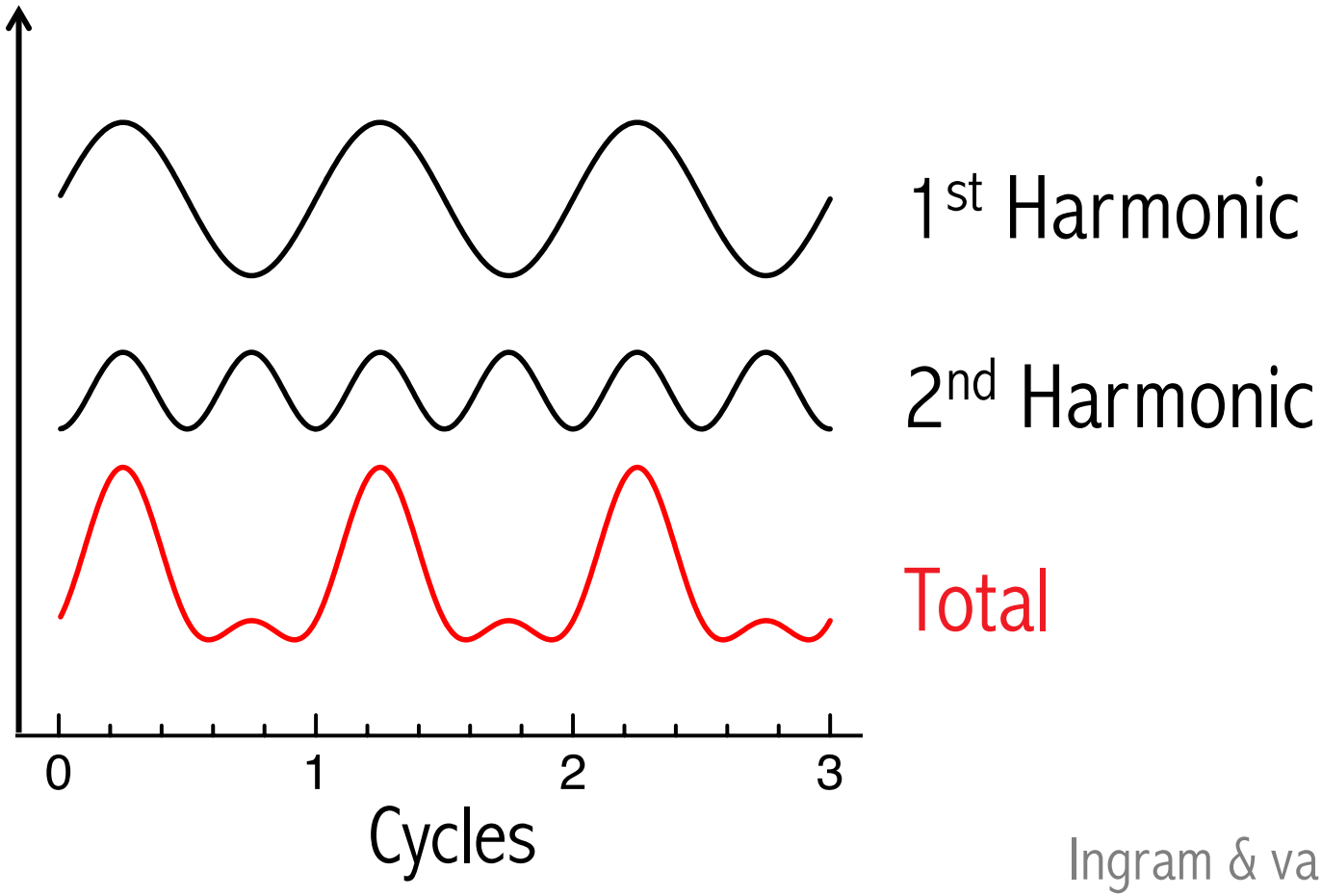
Periodic function: constant phase difference



Ingram & van der Klis (in prep)

QPO waveform

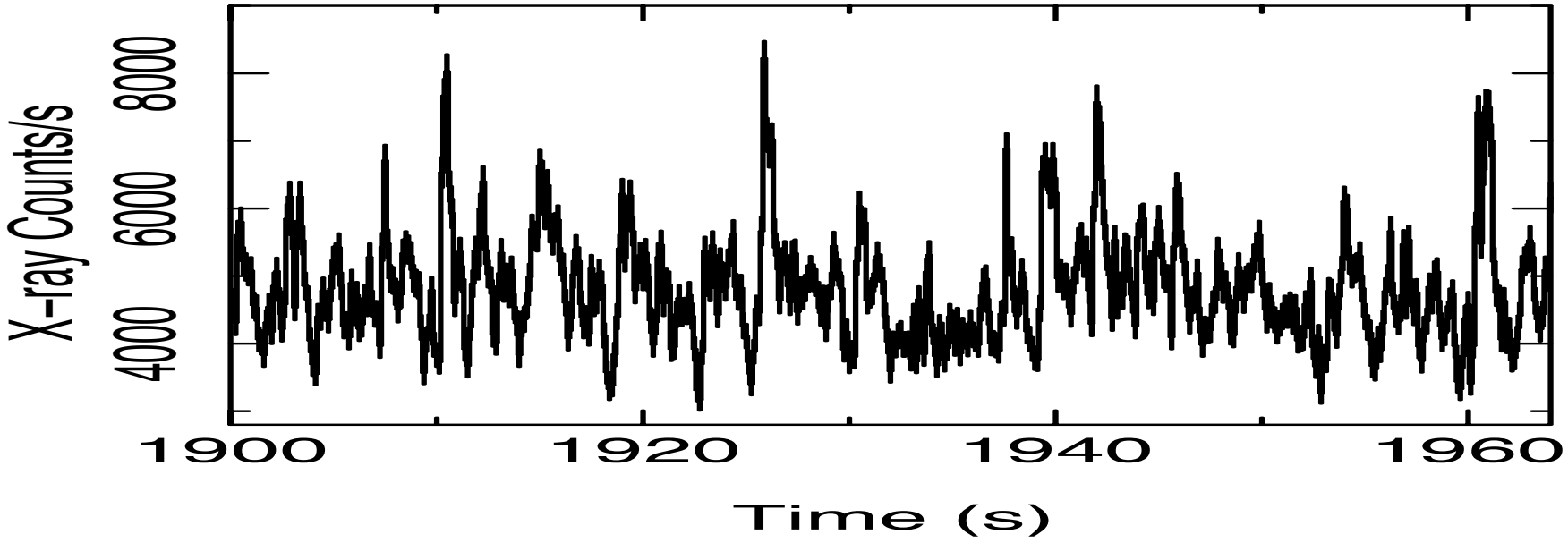
Periodic function: constant phase difference



Ingram & van der Klis (in prep)

QPO waveform

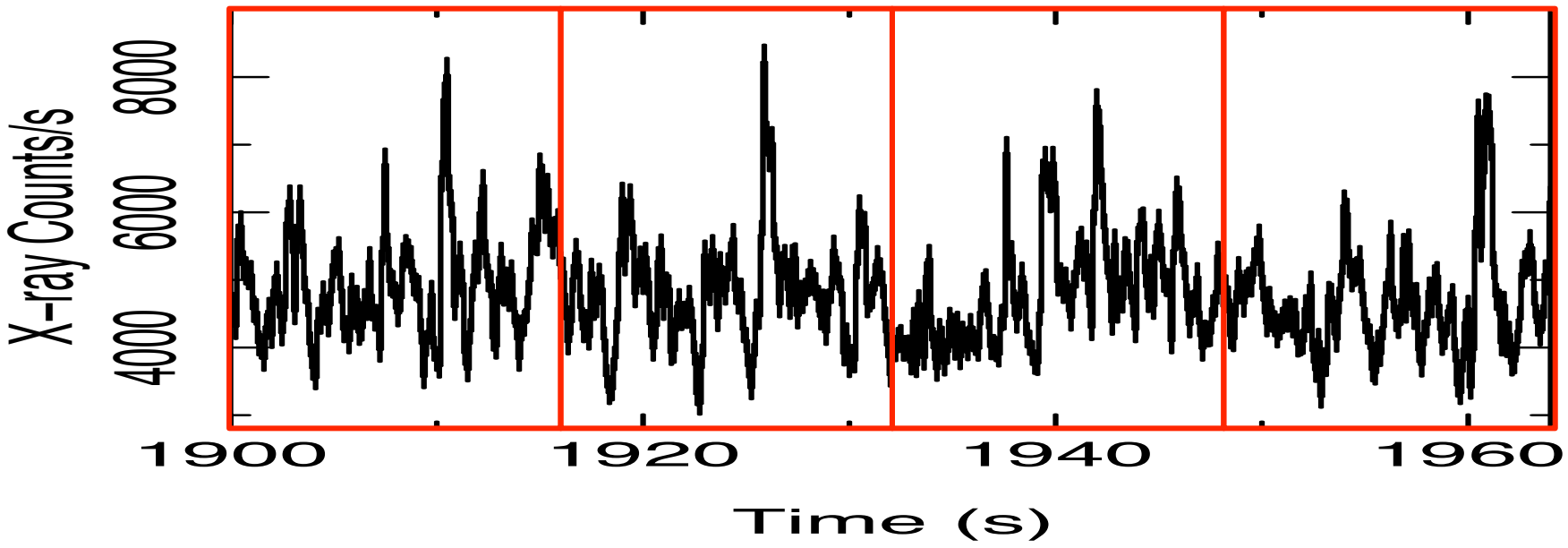
Quasi-periodic function: changing phase difference



…but does the phase difference vary randomly or around a well defined mean?

QPO waveform

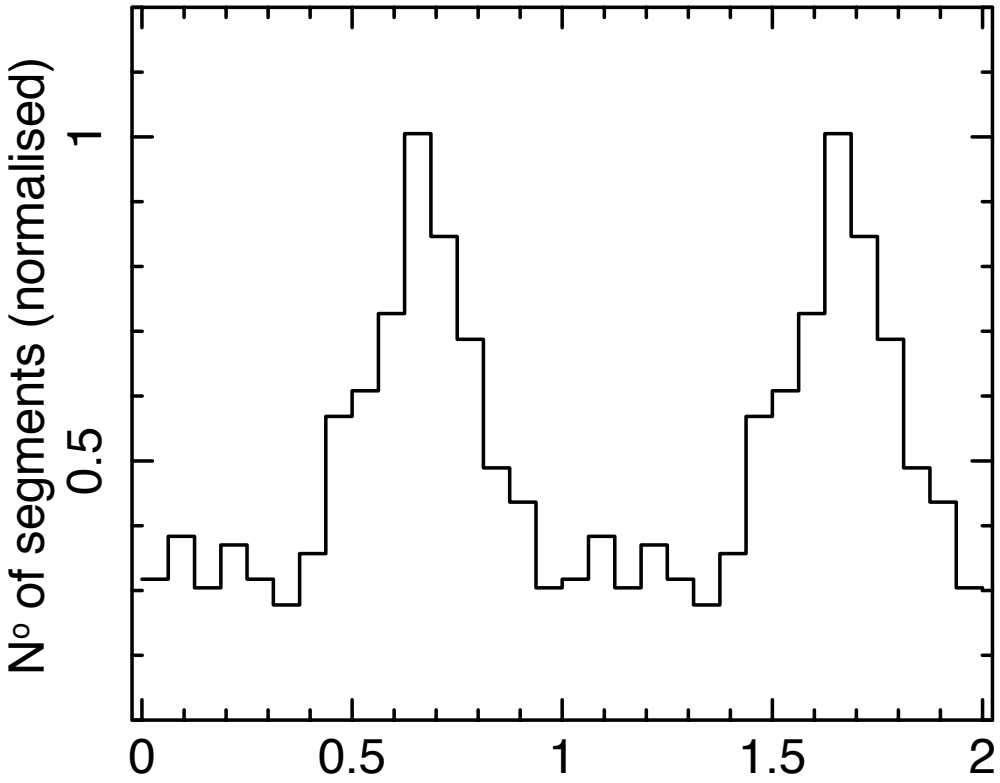
Quasi-periodic function: changing phase difference



Split long light curve into many segments and measure the phase difference Ψ for each segment

QPO waveform

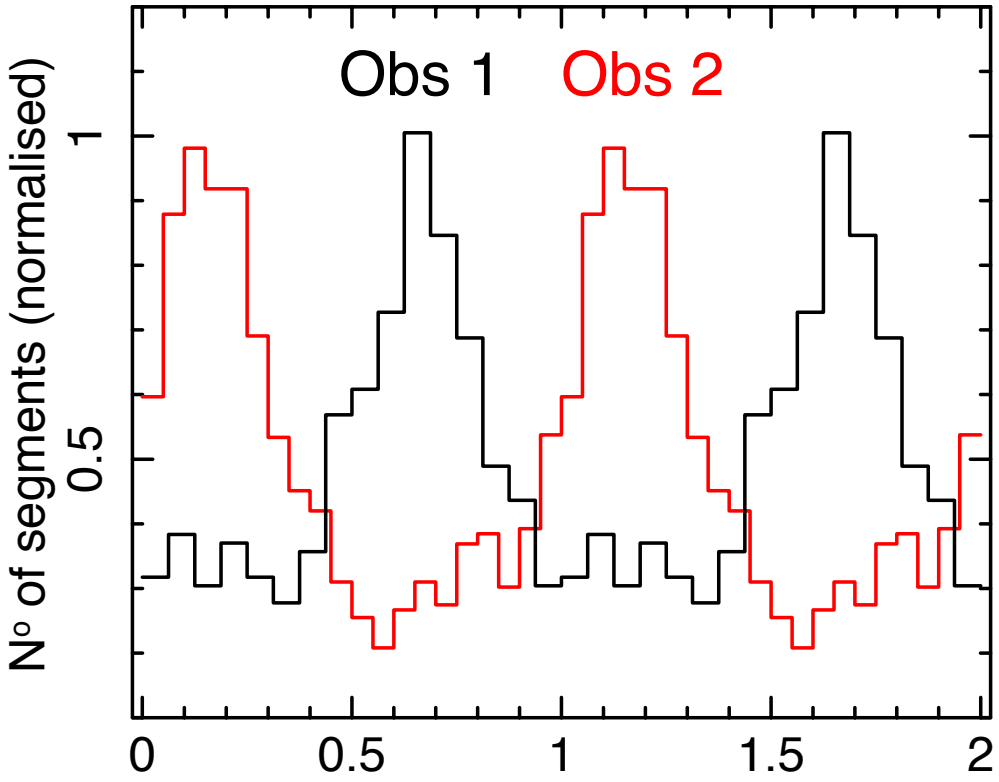
Phase difference varies around a mean: there is an underlying waveform



Ingram & van der Klis (in prep)

QPO waveform

Phase difference varies around a mean: there is an underlying waveform



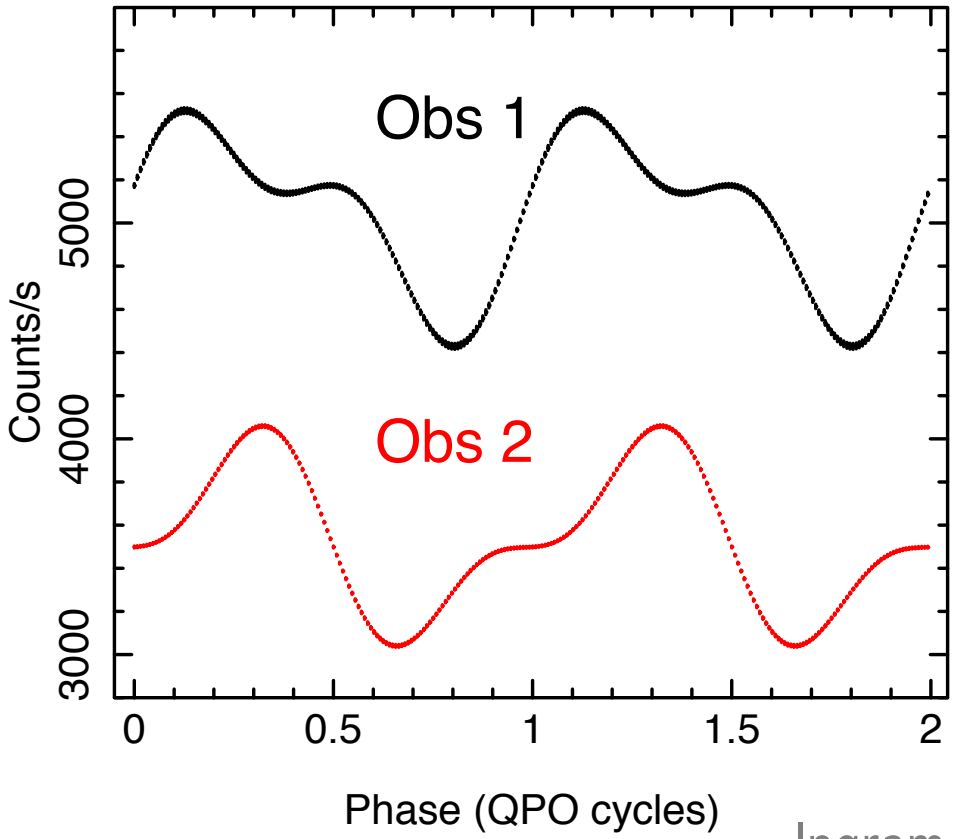
Obs 1:
ν_{qpo} ~0.46Hz

Obs 2:
ν_{qpo} ~2.25Hz

Ingram & van der Klis (in prep)

QPO waveform

Phase difference varies around a mean: there is an underlying waveform



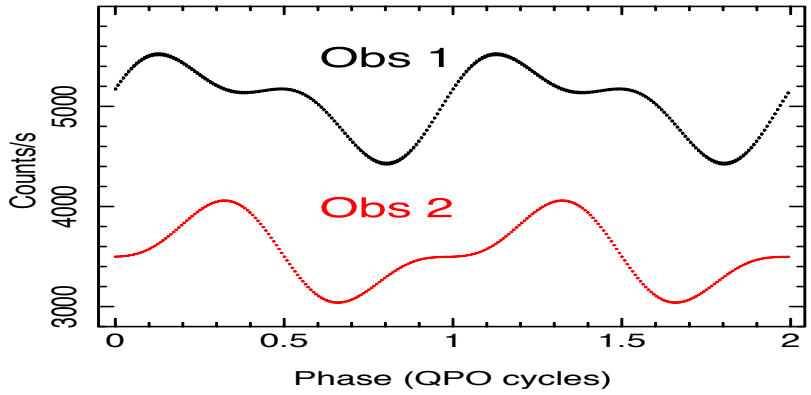
Obs 1:
ν_{qpo} ~0.46Hz

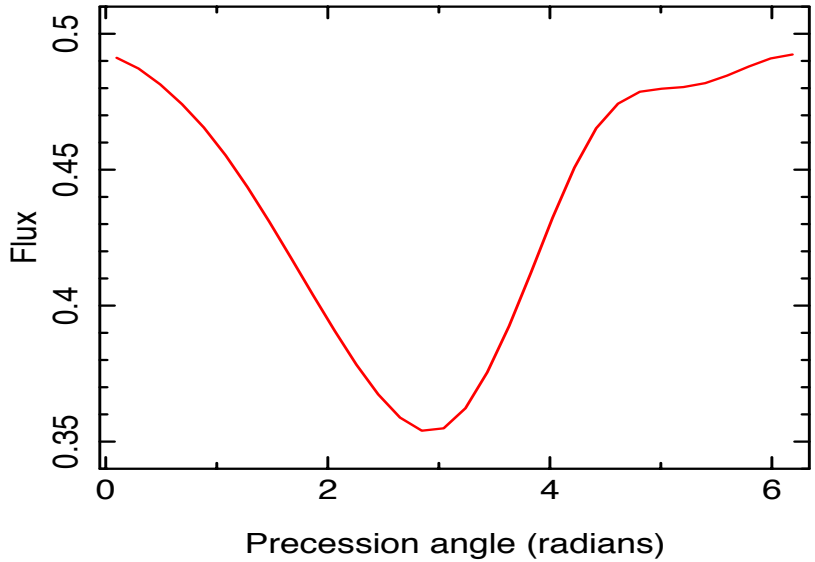
Obs 2:
ν_{qpo} ~2.25Hz

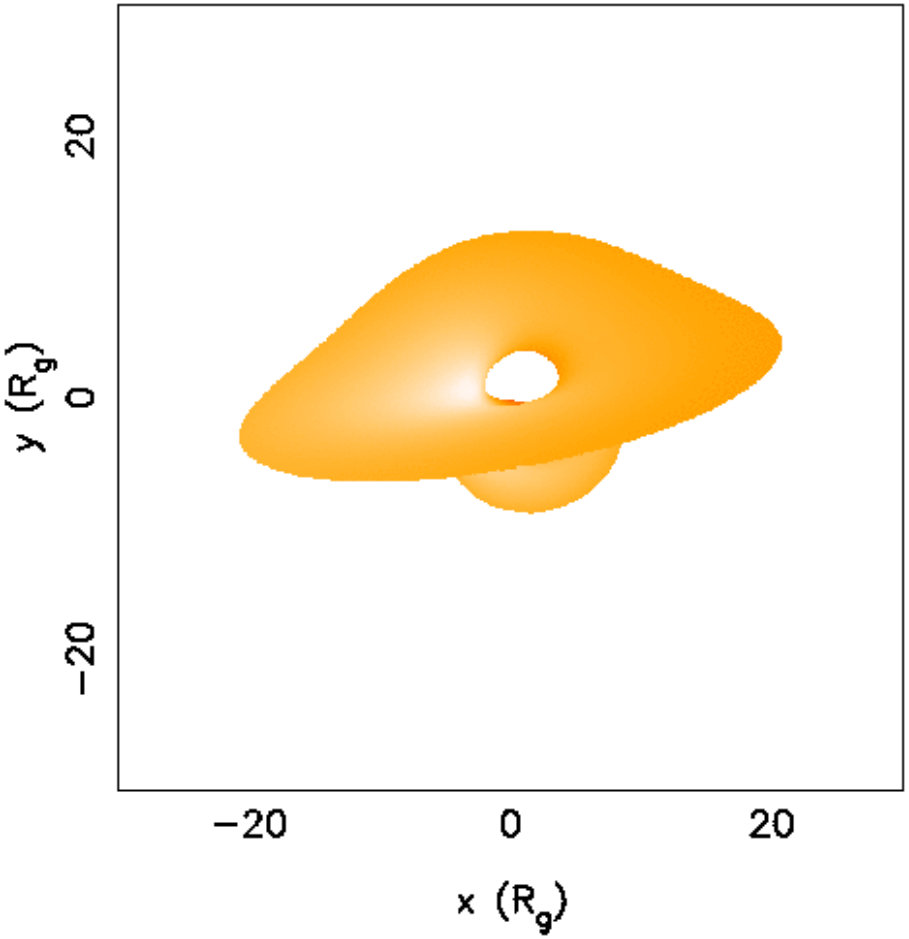
Ingram & van der Klis (in prep)

QPO waveform

Enables waveform fitting of QPO models

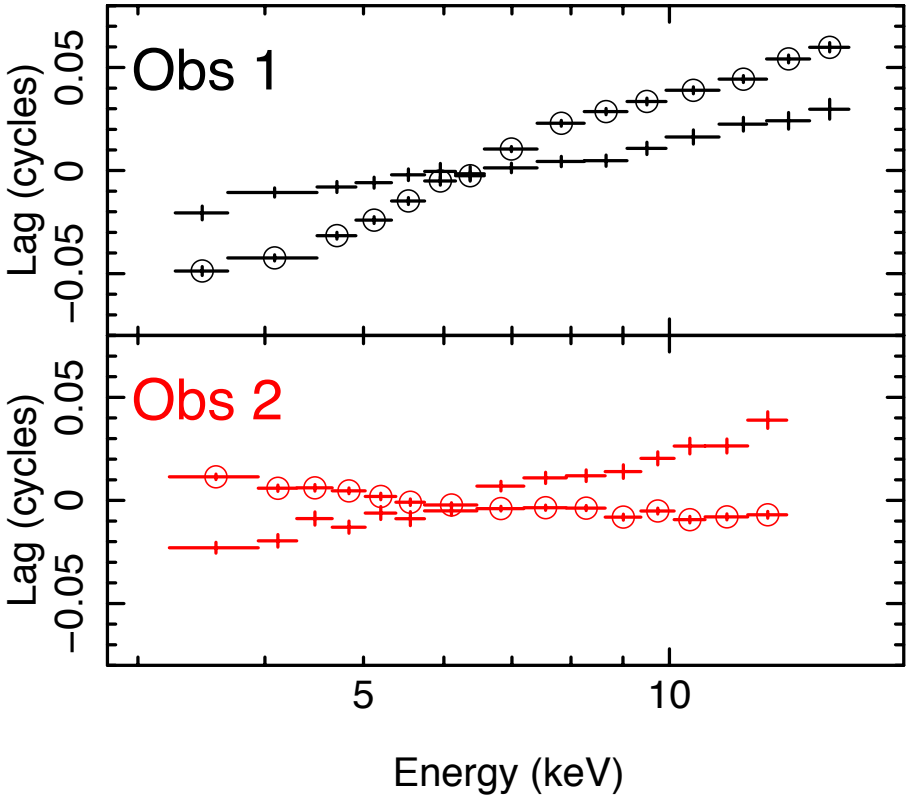


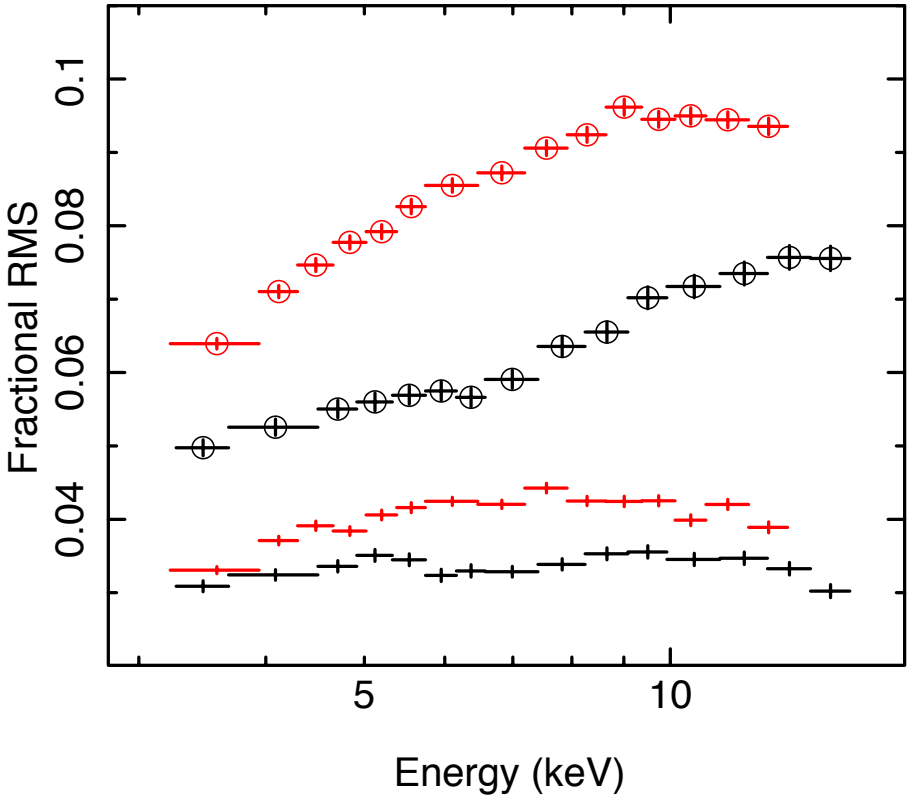




Phase resolving

Can now reconstruct waveform in each energy band using phase lag with the full band



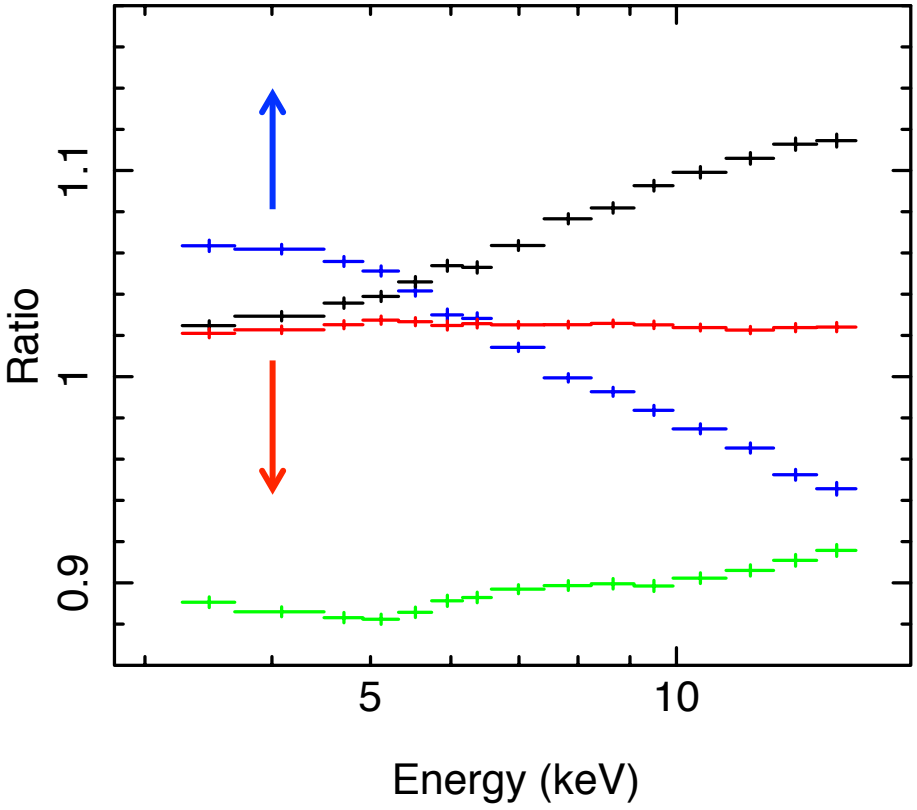


Ingram & van der Klis (in prep)

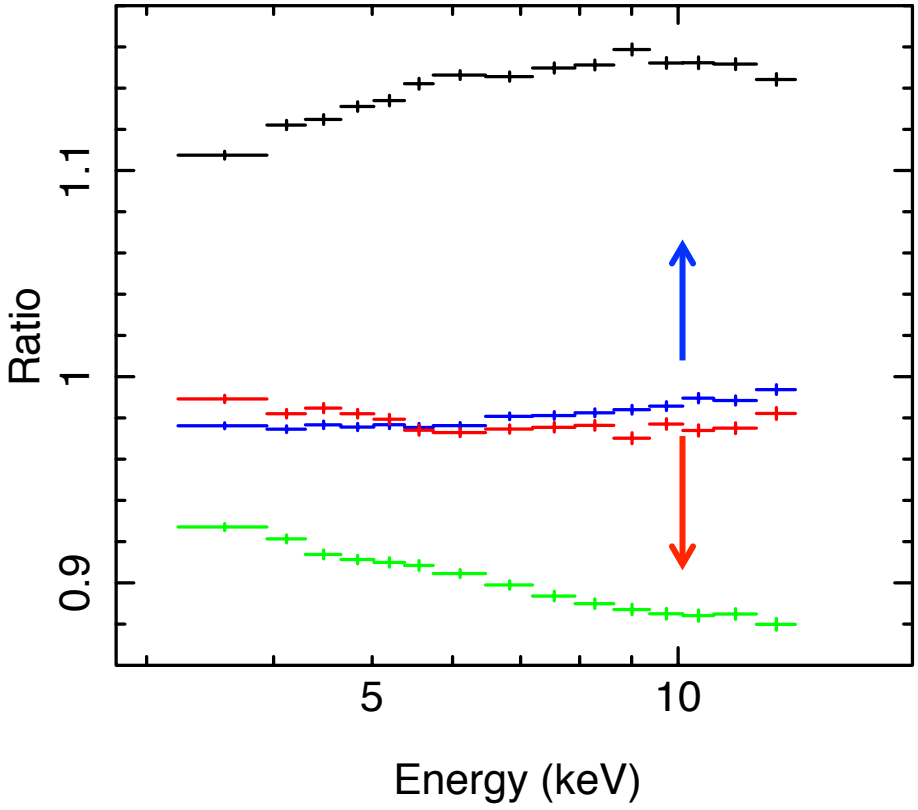
Phase resolving

Spectra for 4 snapshots of phase

Obs 1

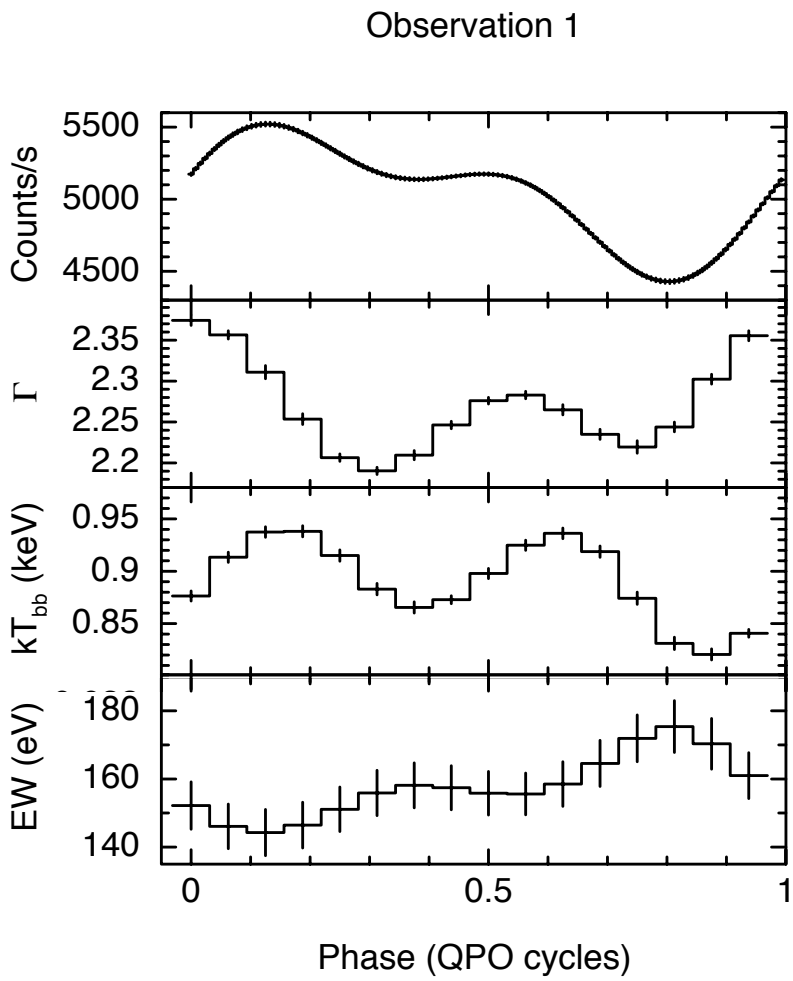


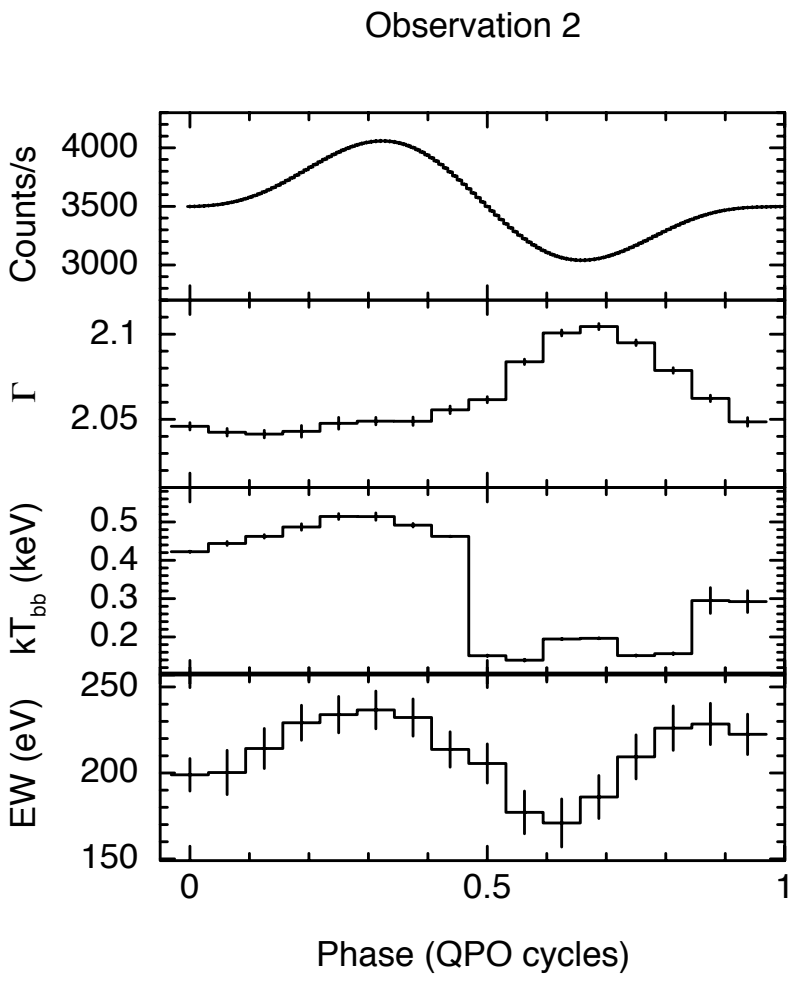
Obs 2



Ingram & van der Klis (in prep)

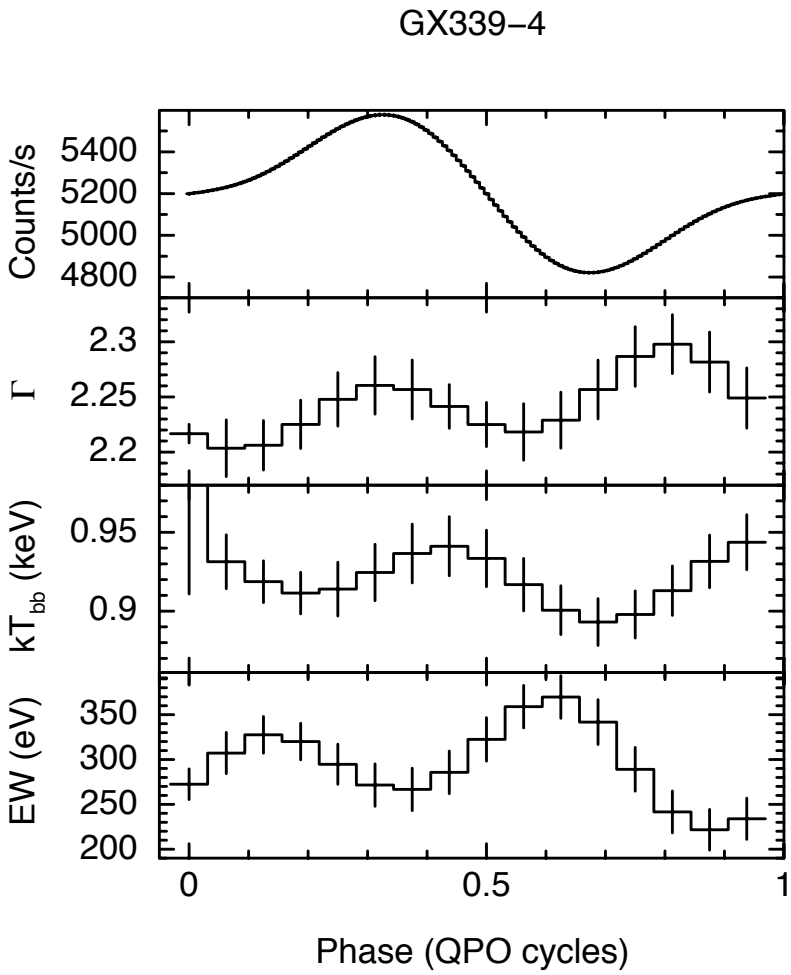
Phase resolving

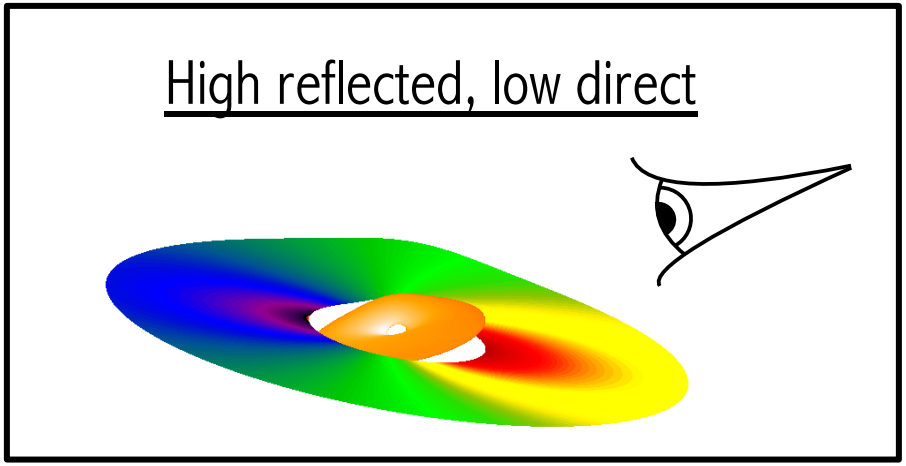


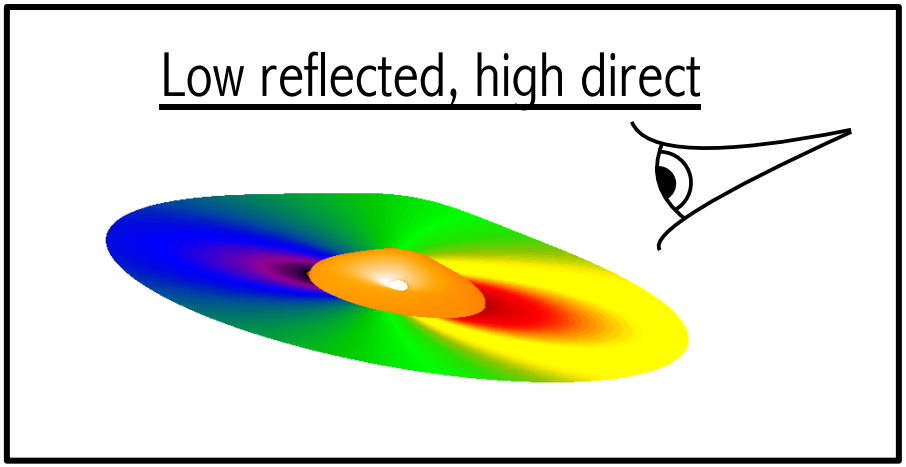


Ingram & van der Klis (in prep)

Phase resolving

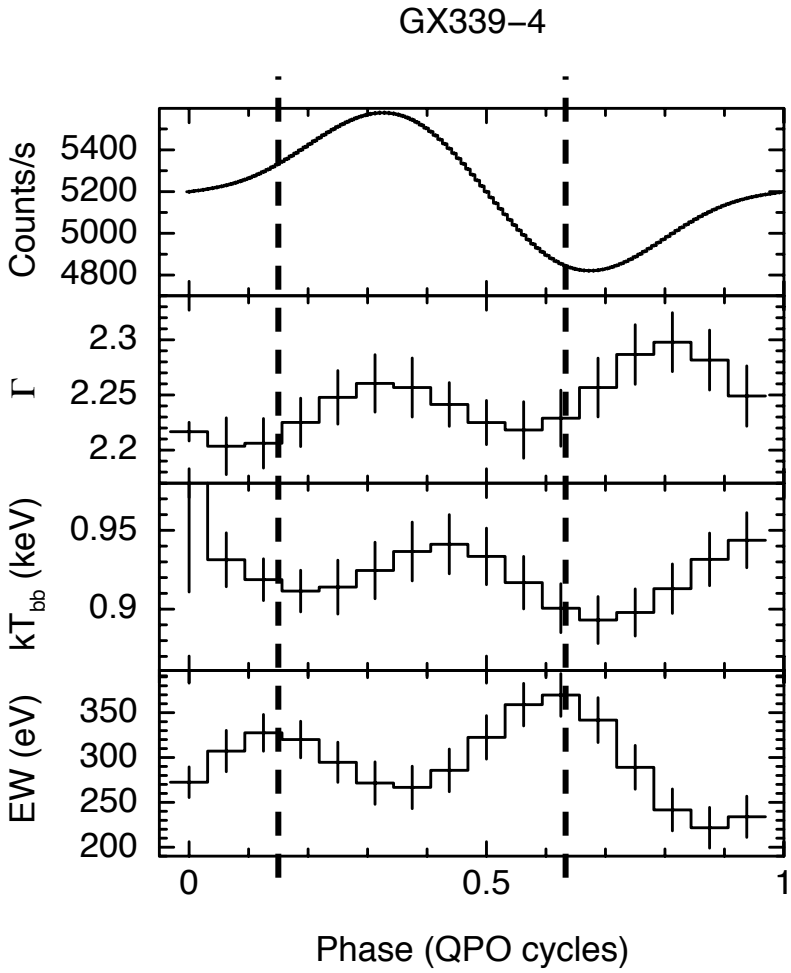


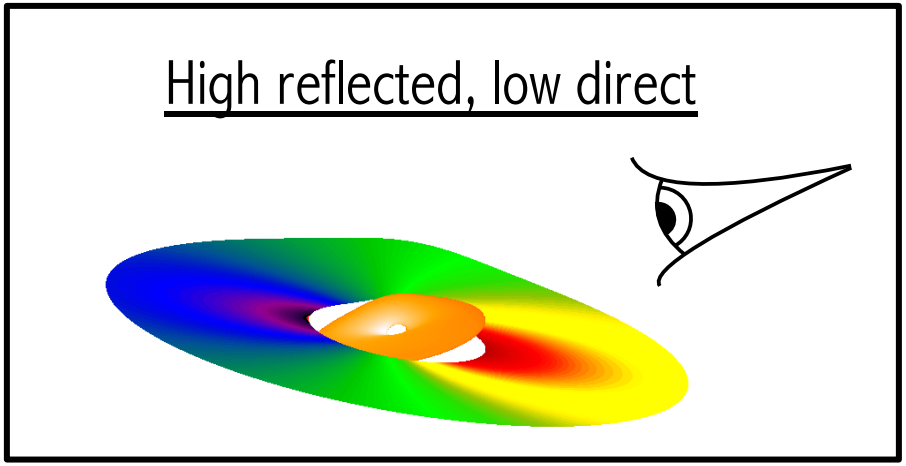


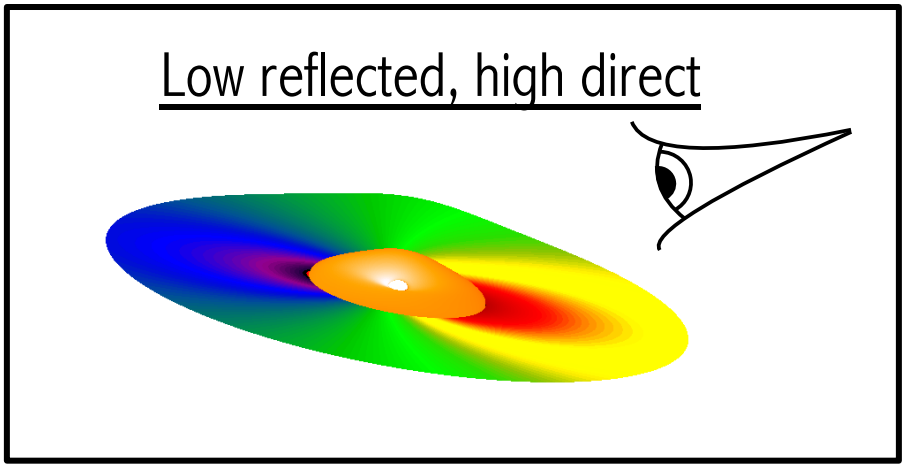


Ingram, van der Klis & Done (in prep)

Phase resolving





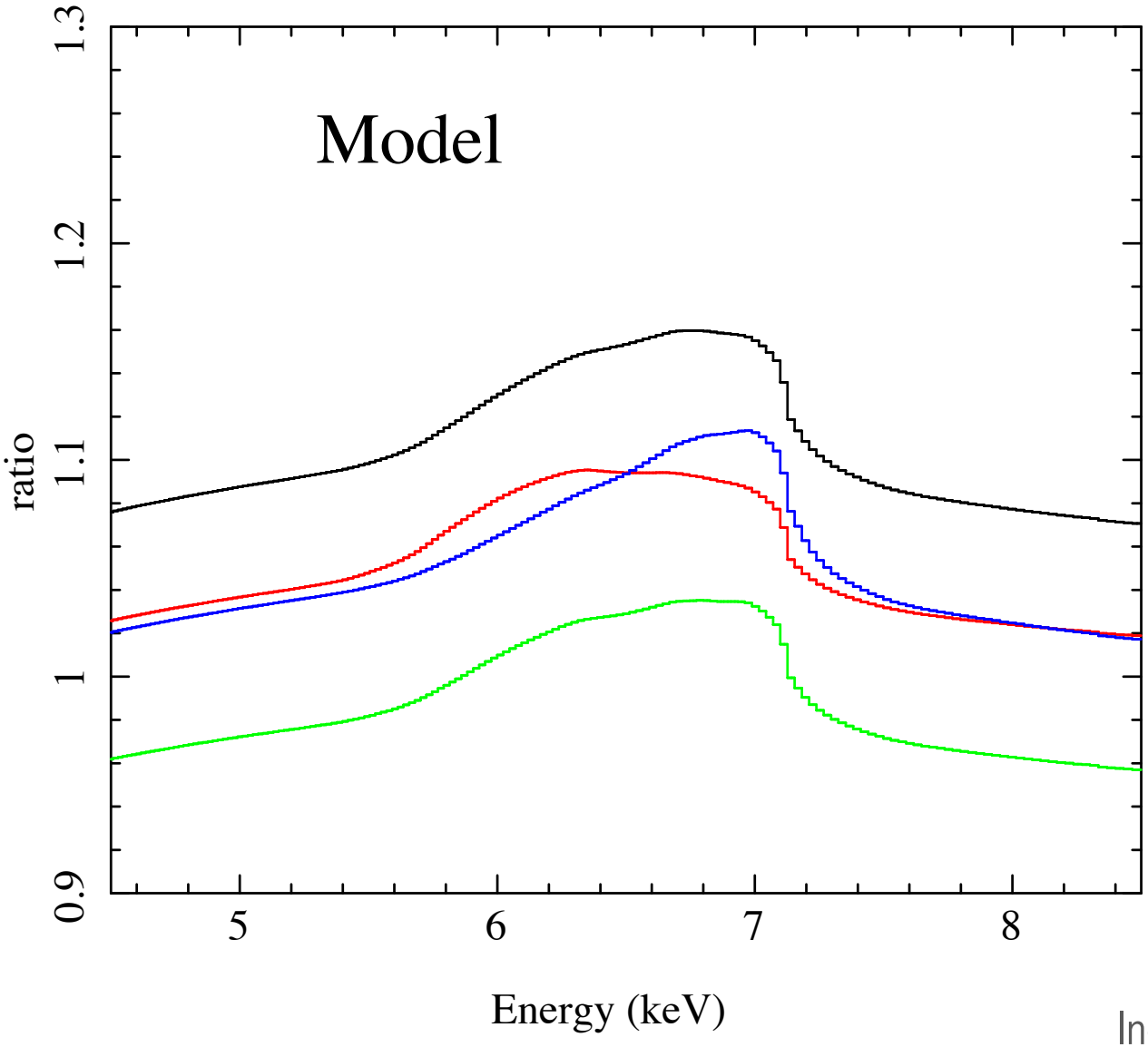


Ingram, van der Klis & Done (in prep)

Conclusions

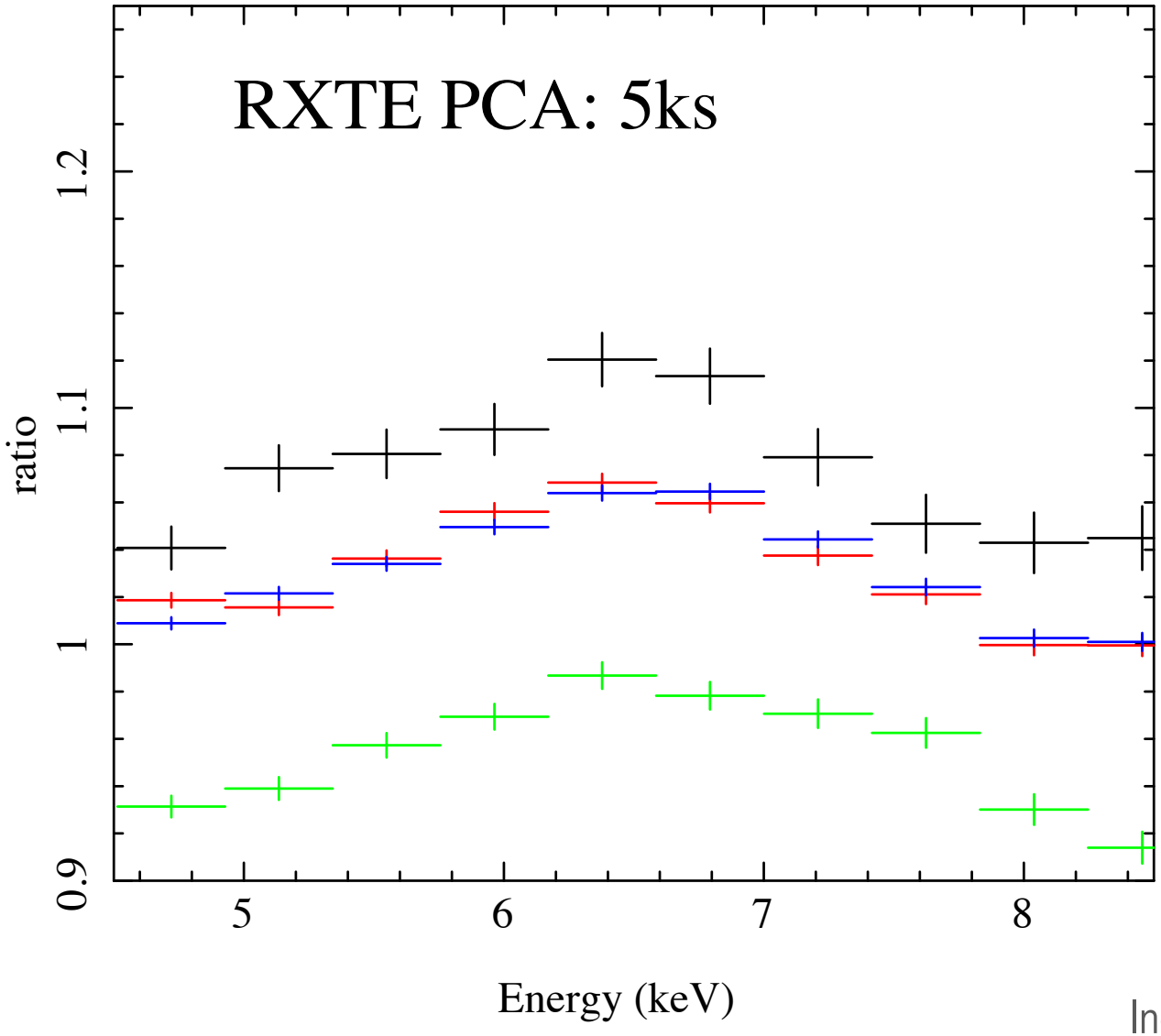
- The QPO does have an underlying waveform
- Waveform fitting will provide a diagnostic tool
- Modulations seen in spectral parameters: photon index, disk temperature & Fe line equivalent width
- Variation in Fe line equivalent width is strong evidence for geometric QPO origin
- Need better data to see a rocking iron line shape

Testing precession



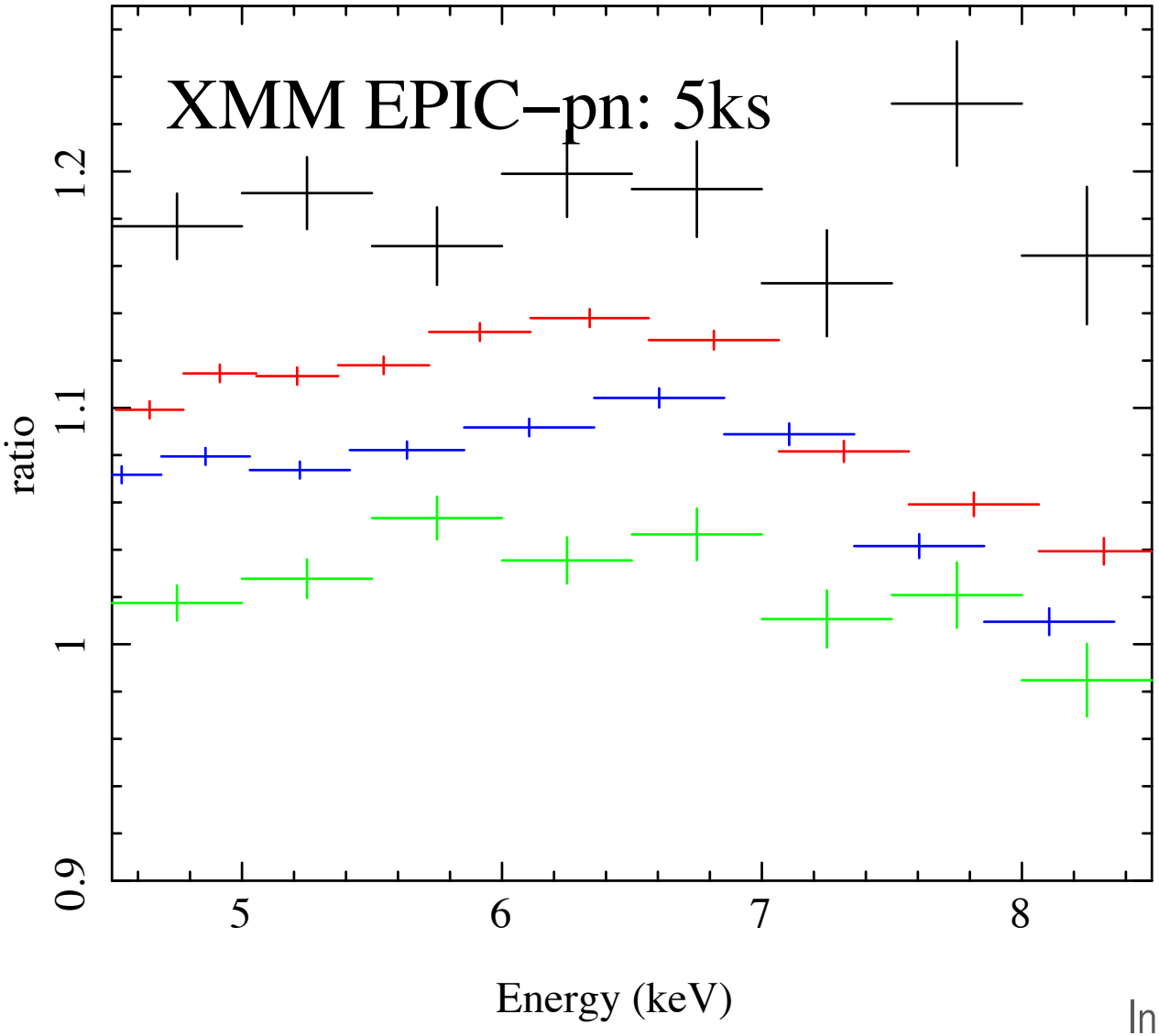
Ingram & Done 2012b

Testing precession



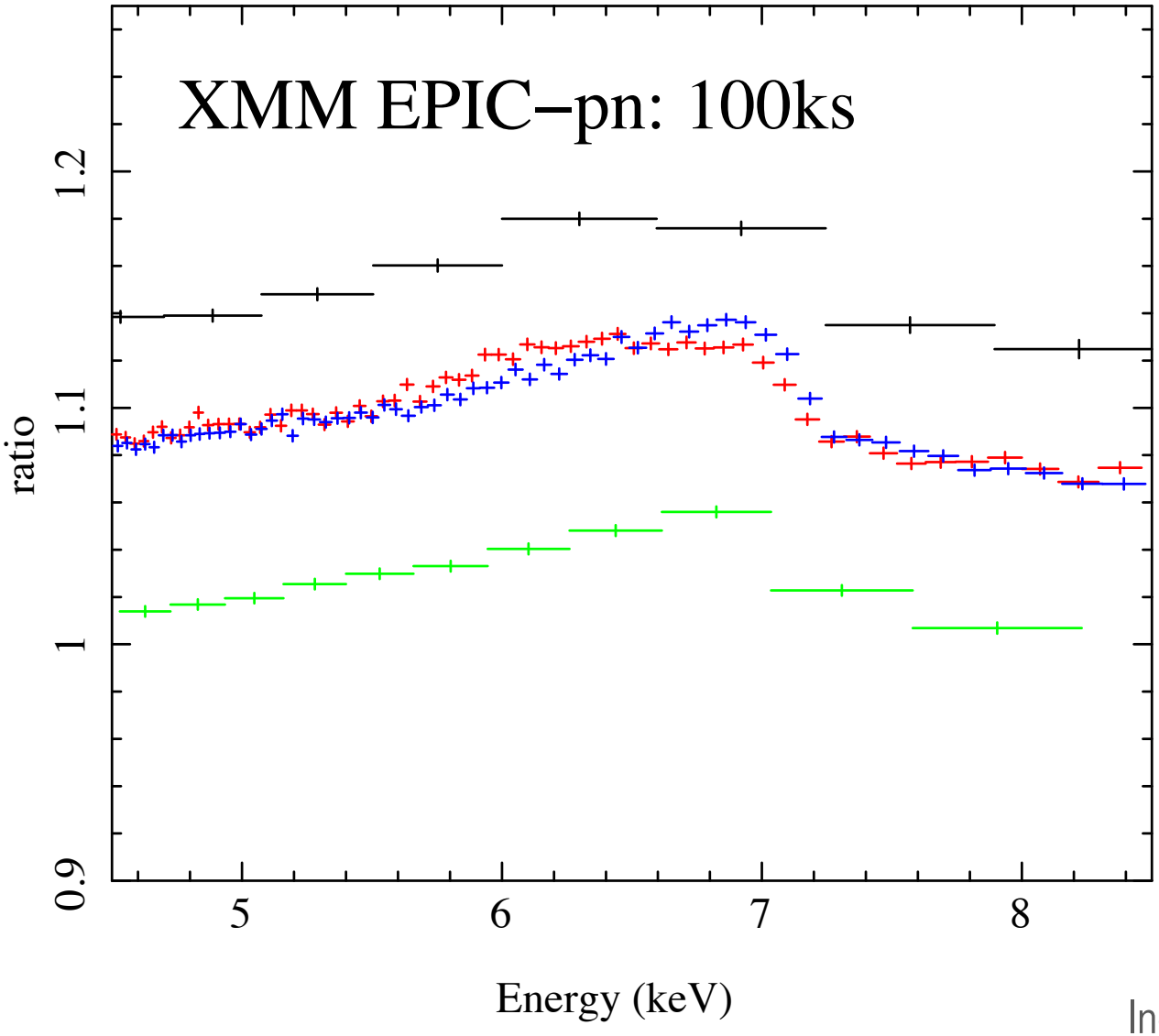
Ingram & Done 2012b

Testing precession



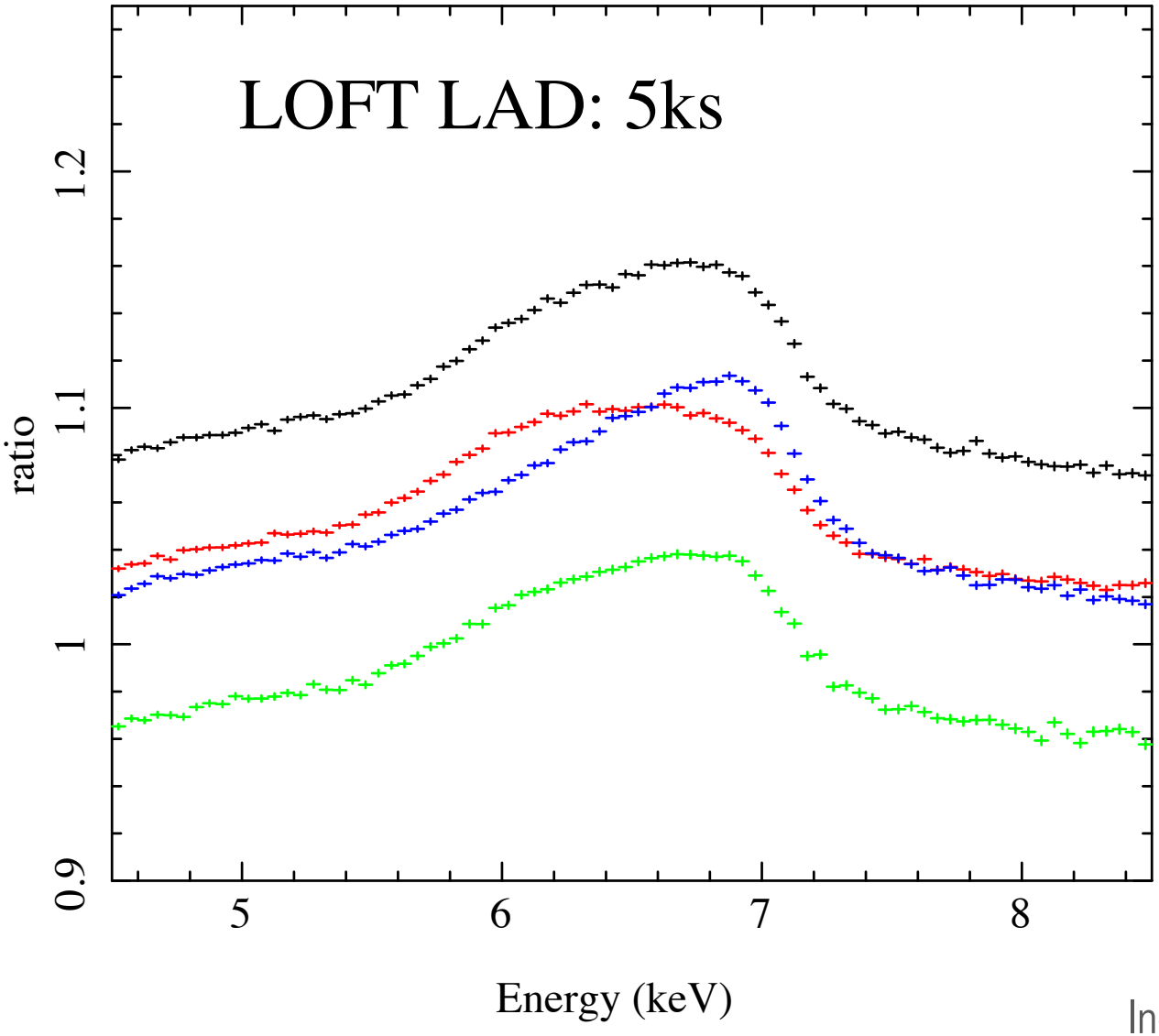
Ingram & Done 2012b

Testing precession



Ingram & Done 2012b

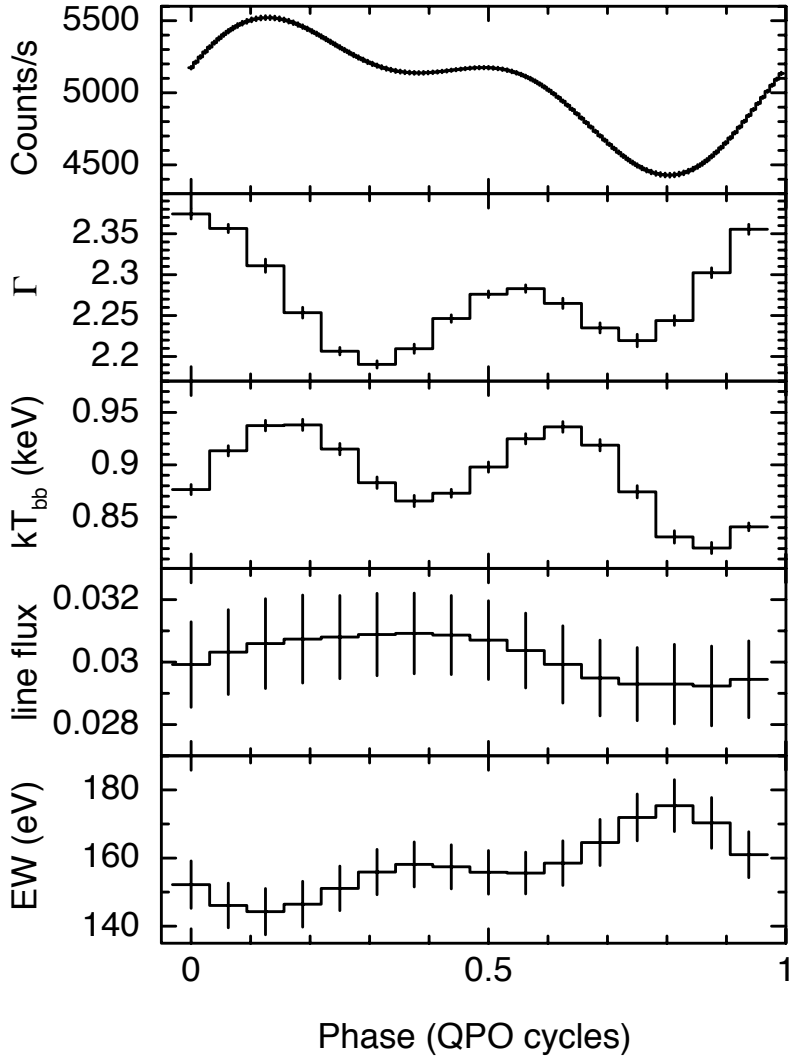
Testing precession



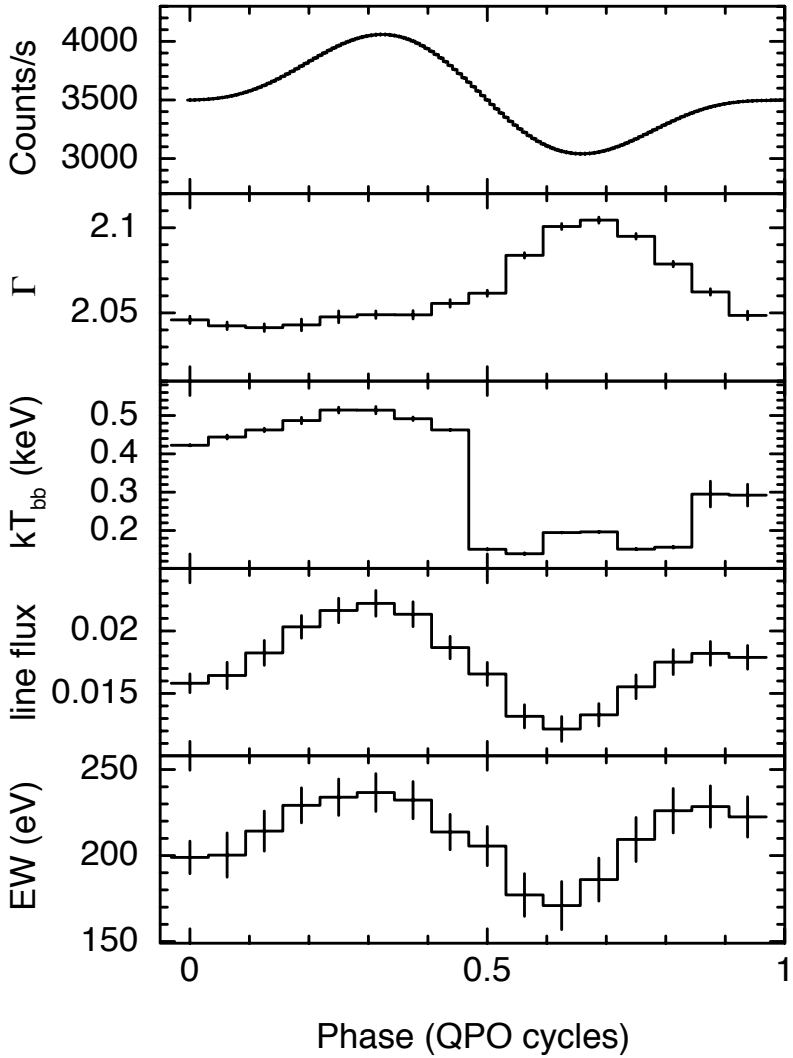
Ingram & Done 2012b

Phase resolving

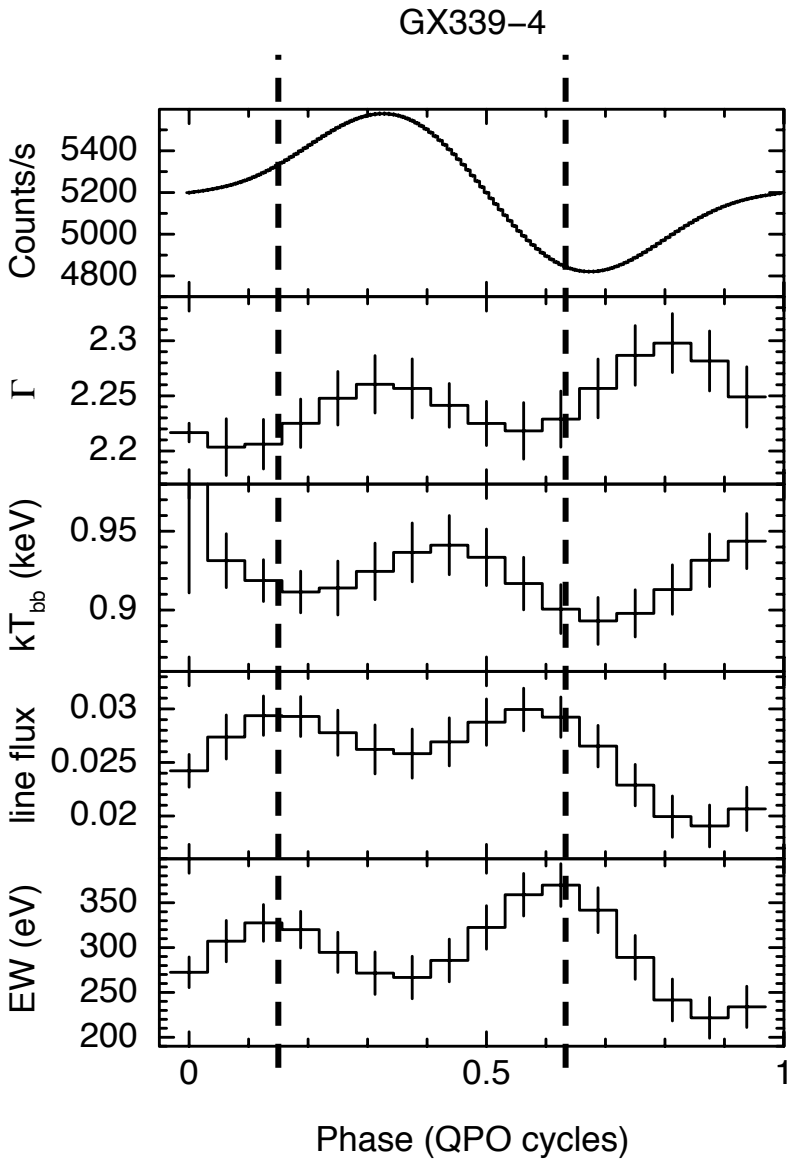
Observation 1

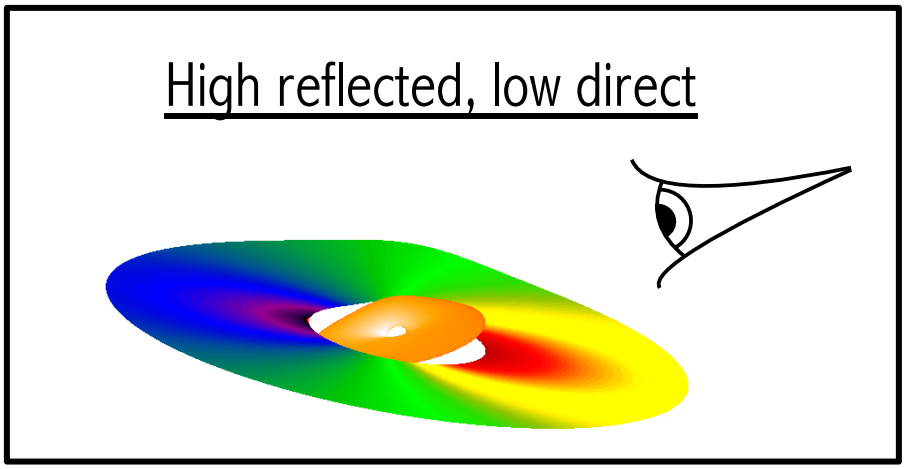


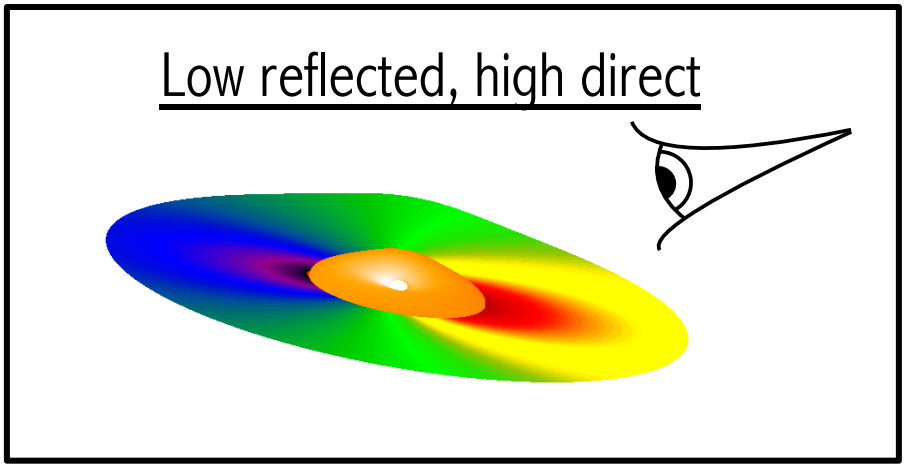
Observation 2



Phase resolving

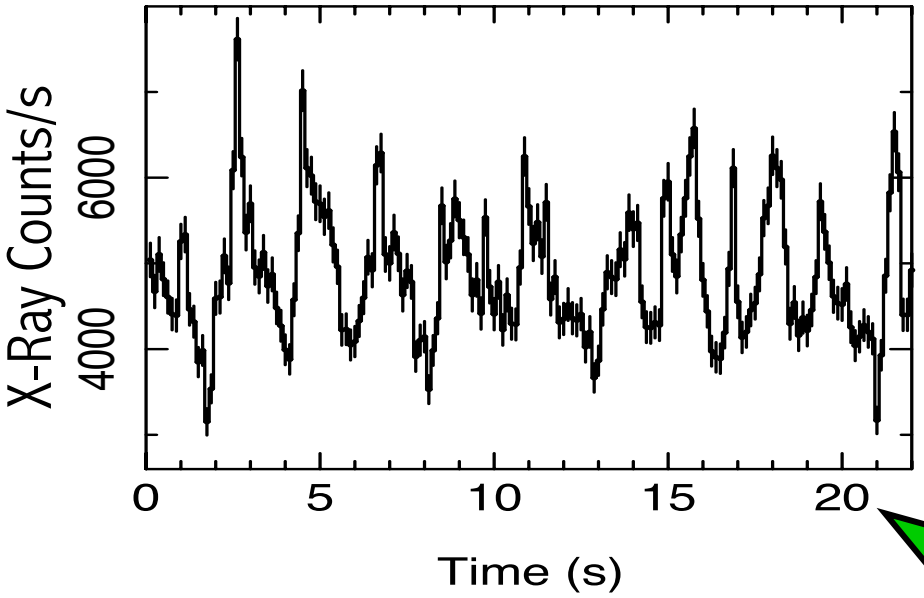


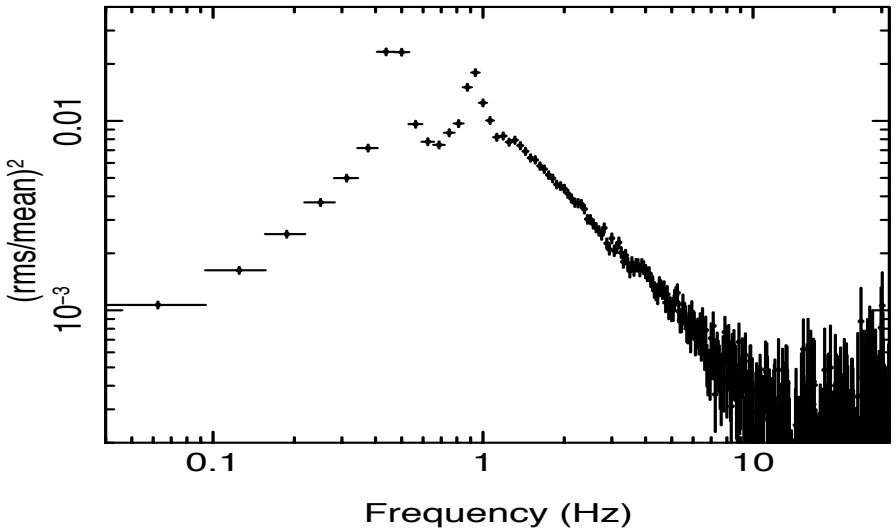


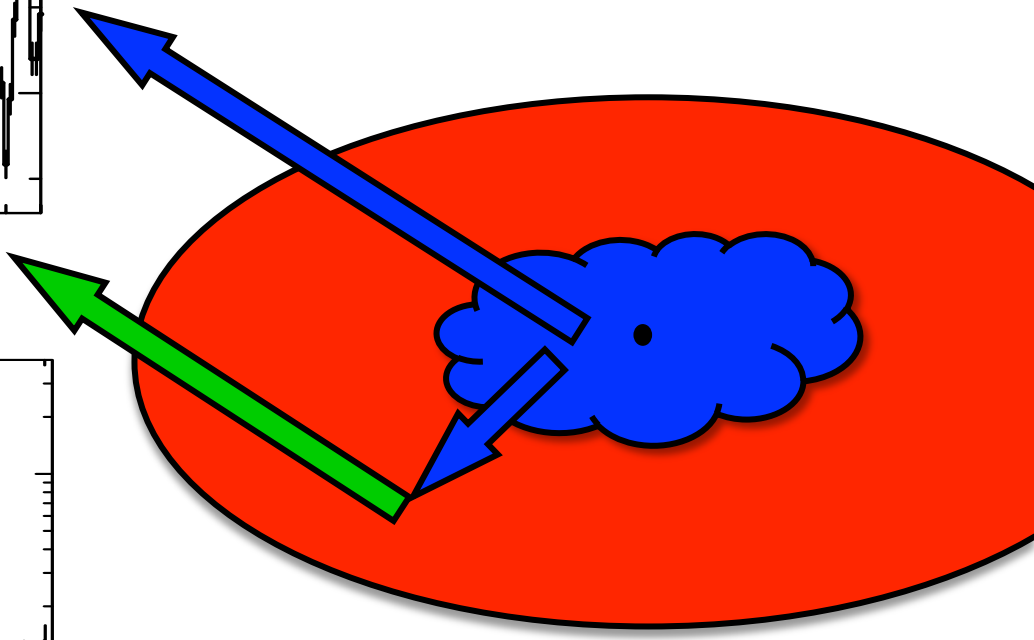


Ingram, van der Klis & Done (in prep)

Quasi-periodic oscillations







QPO from inner regions