Spectral-timing of low frequency quasi-periodic oscillations

Adam Ingram – Royal Society URF

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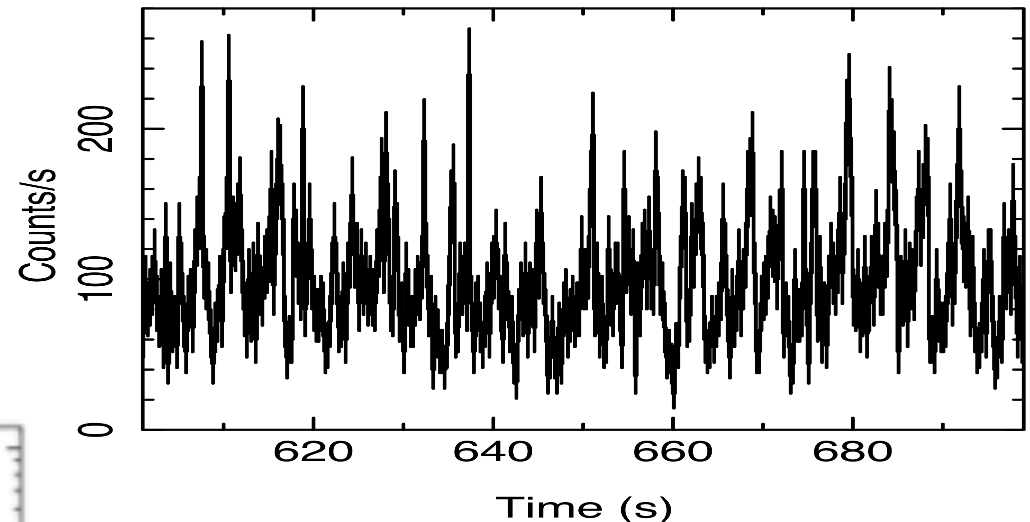
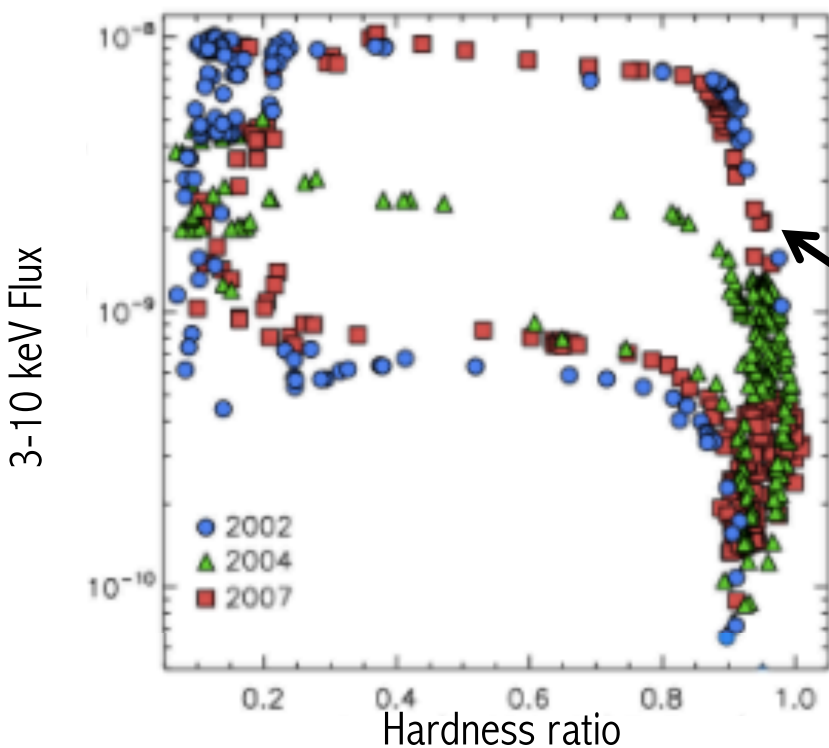
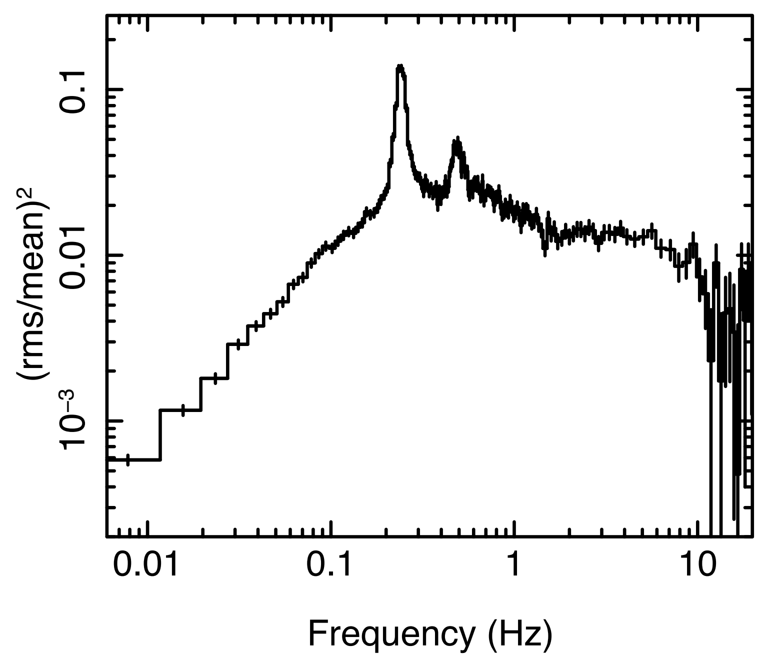
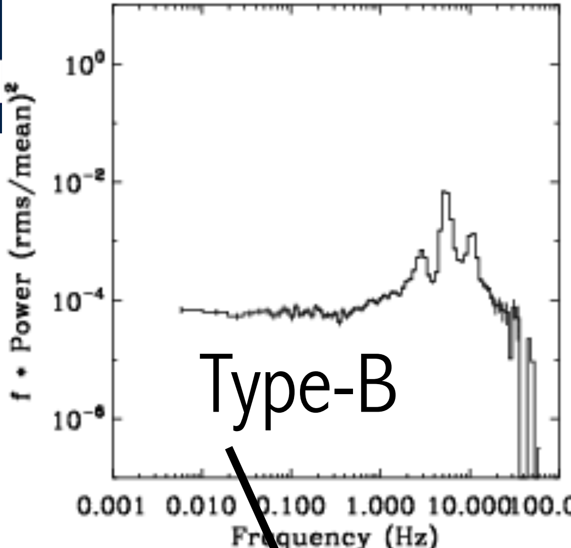
Quasi periodic oscillations

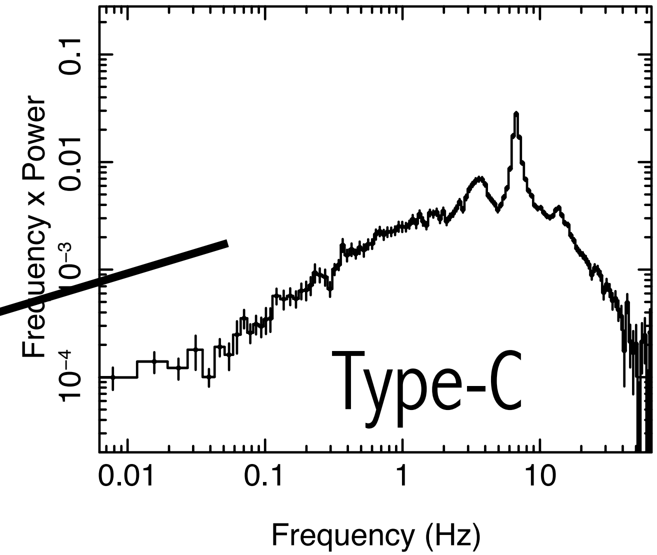


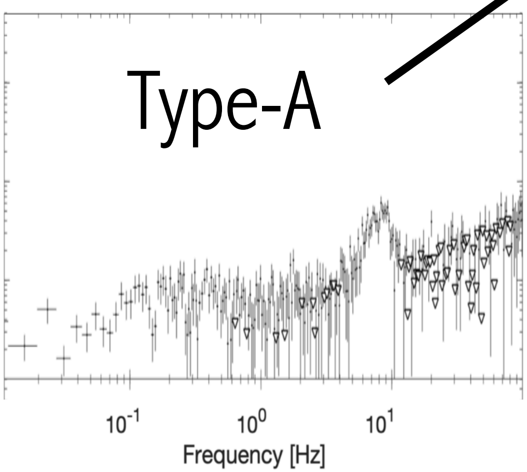


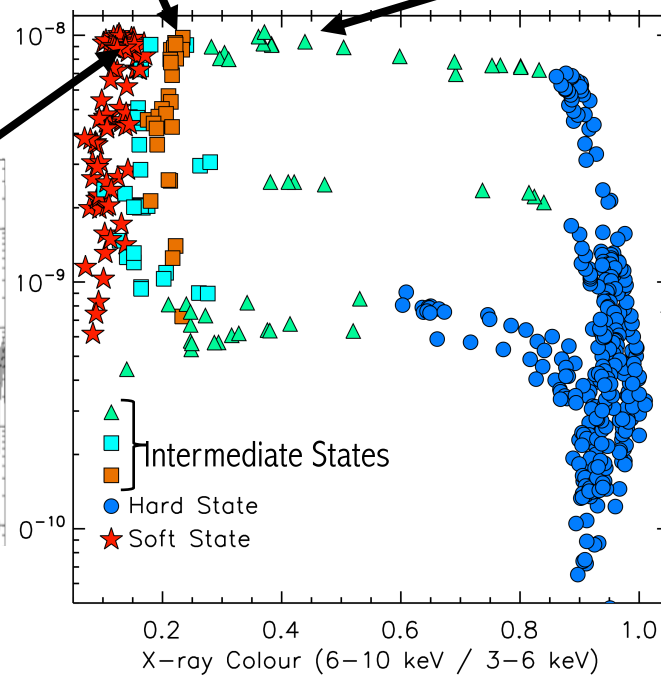


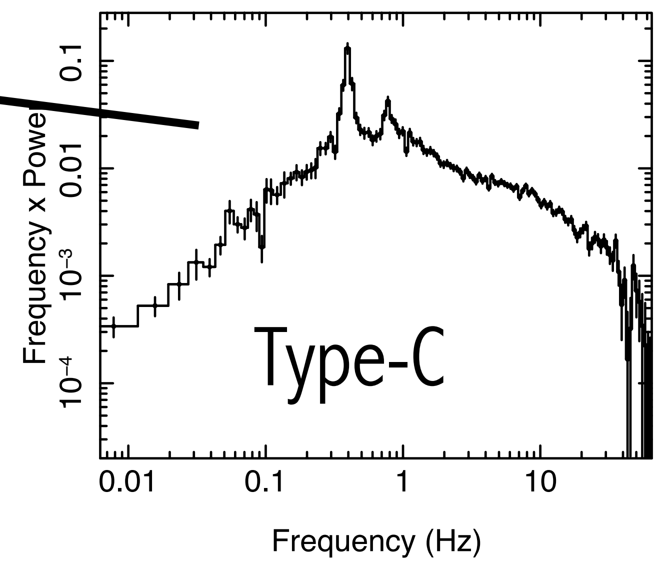
LF QPO Types





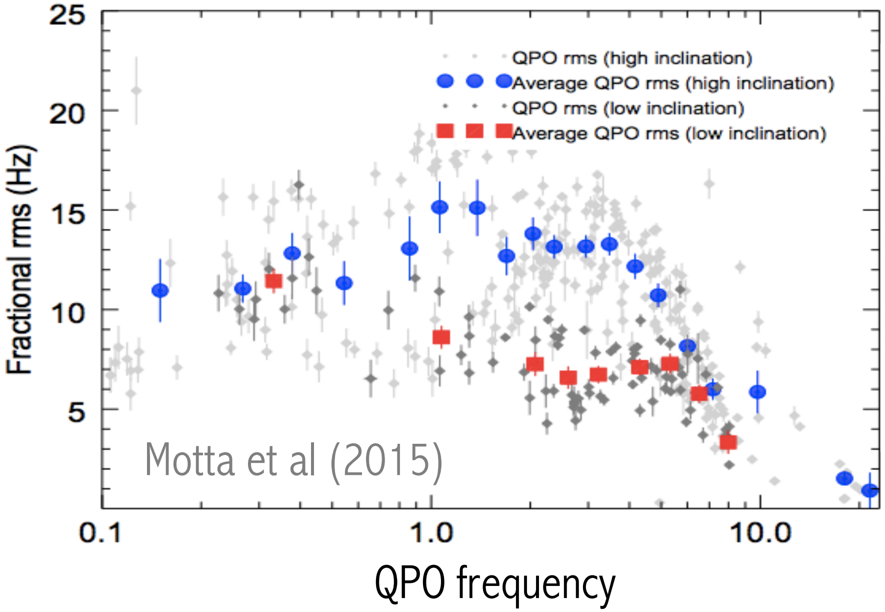


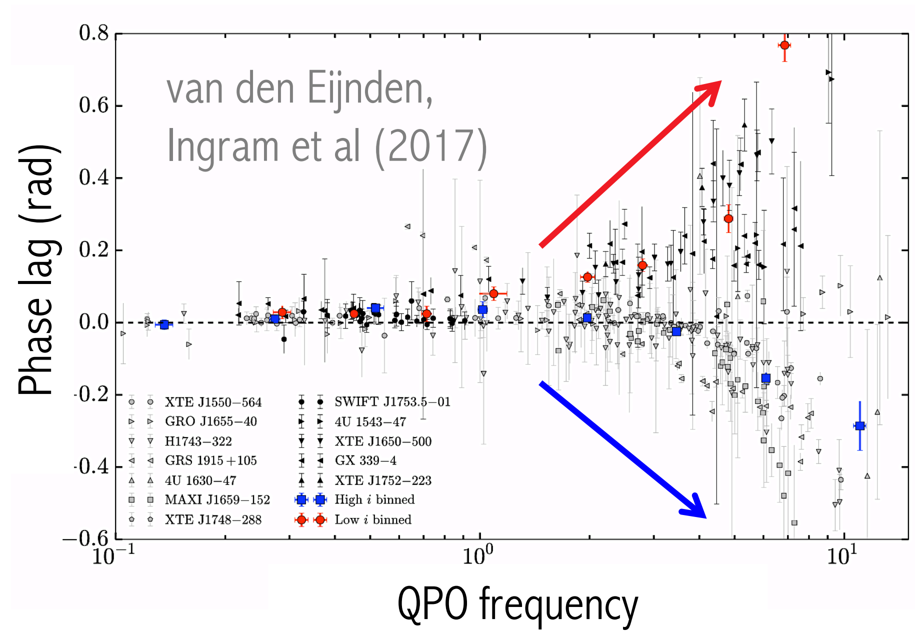


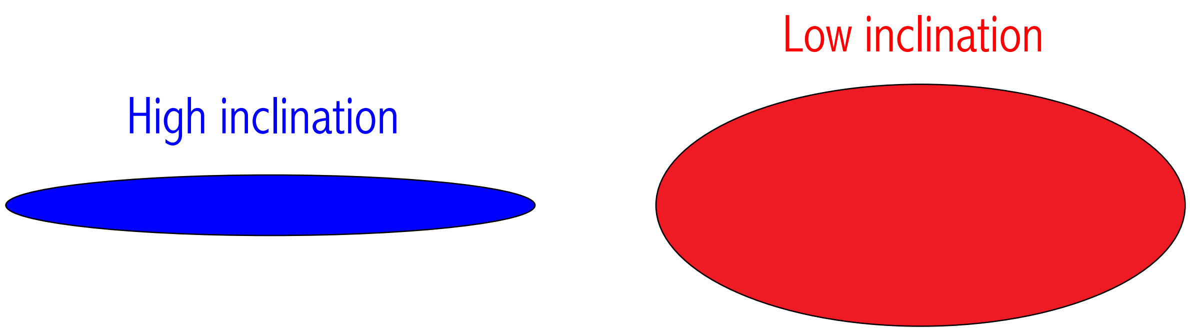


Wijnands et al (1999); Sobszak et al (2000); Casella et al (2005)

Inclination dependence

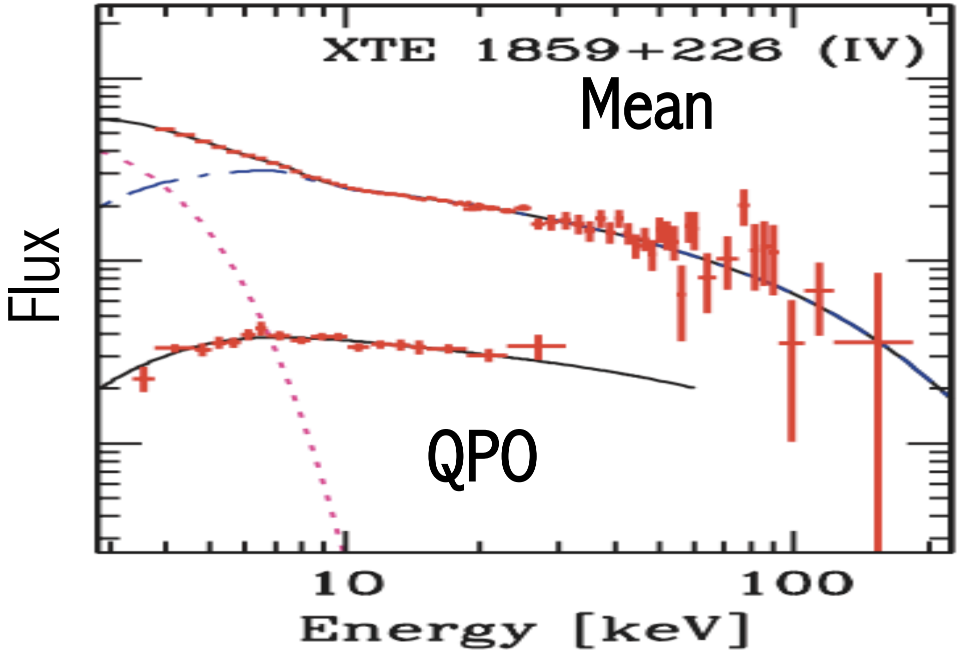






Type-C QPO *amplitude* and *phase lags* depend on inclination ➔ *Geometric!*

Energy spectrum

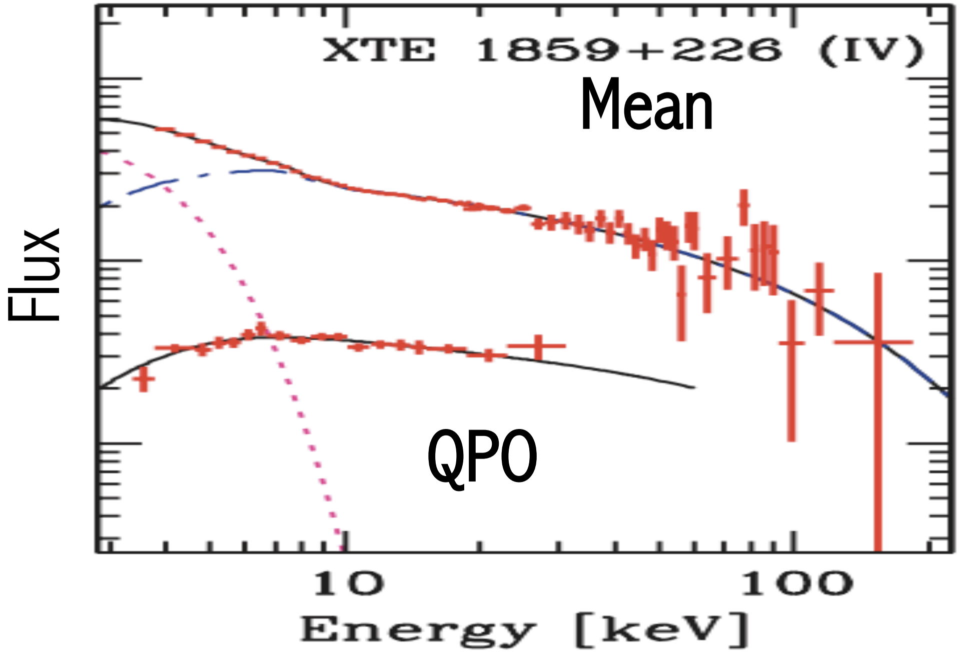


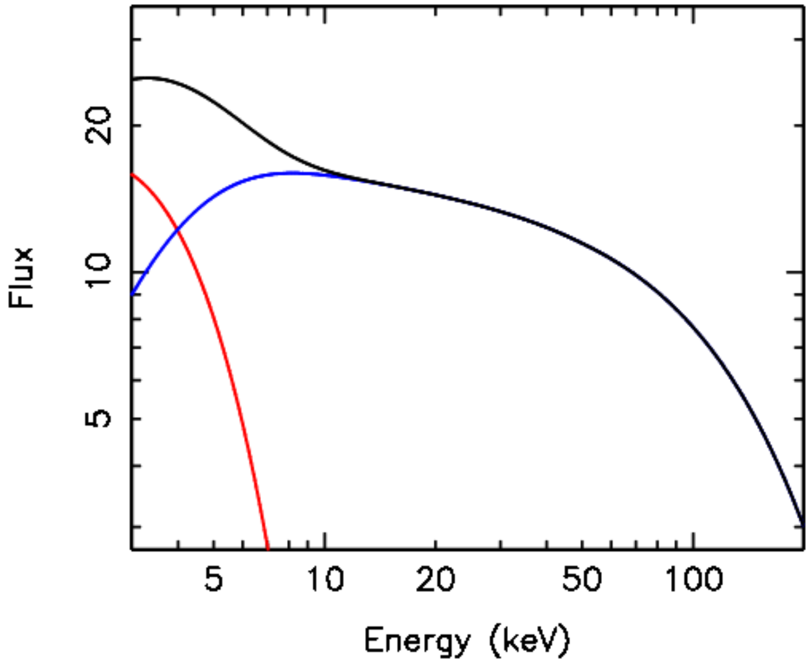
Comptonized emission oscillates more than the disk emission

➔ From corona!

Sobolewska & Zycki (2005); (2006)

Energy spectrum





Comptonized emission oscillates more than the disk emission

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Sobolewska & Zycki (2005); (2006)

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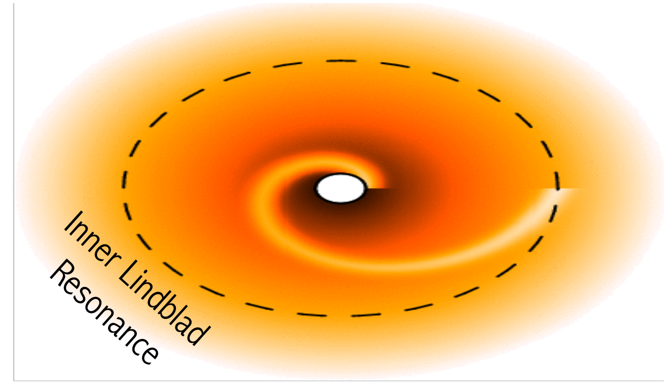
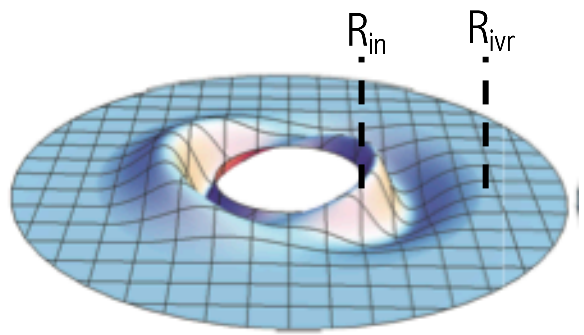
Geometric QPO models

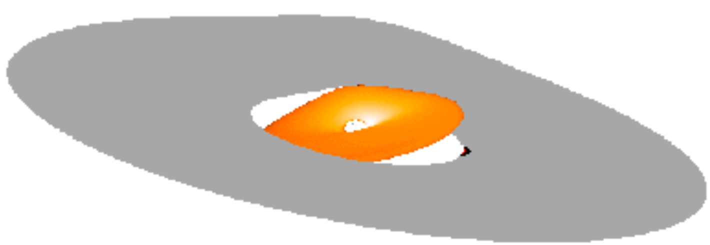
- Accretion Ejection Instability: spiral standing wave from perturbations in poloidal B-field strength (Tagger & Pellat 1999).



- Relativistic precession model: Lense-Thirring (LT) preccesion at a characteristic radius (e.g. truncation radius) (Stella & Vietri 1999).



- Corrugation modes: standing wave between R_{in} and inner vertical resonance (R_{ivr}) at LT frequency of R_{ivr} (Kato & Fuke 1980)

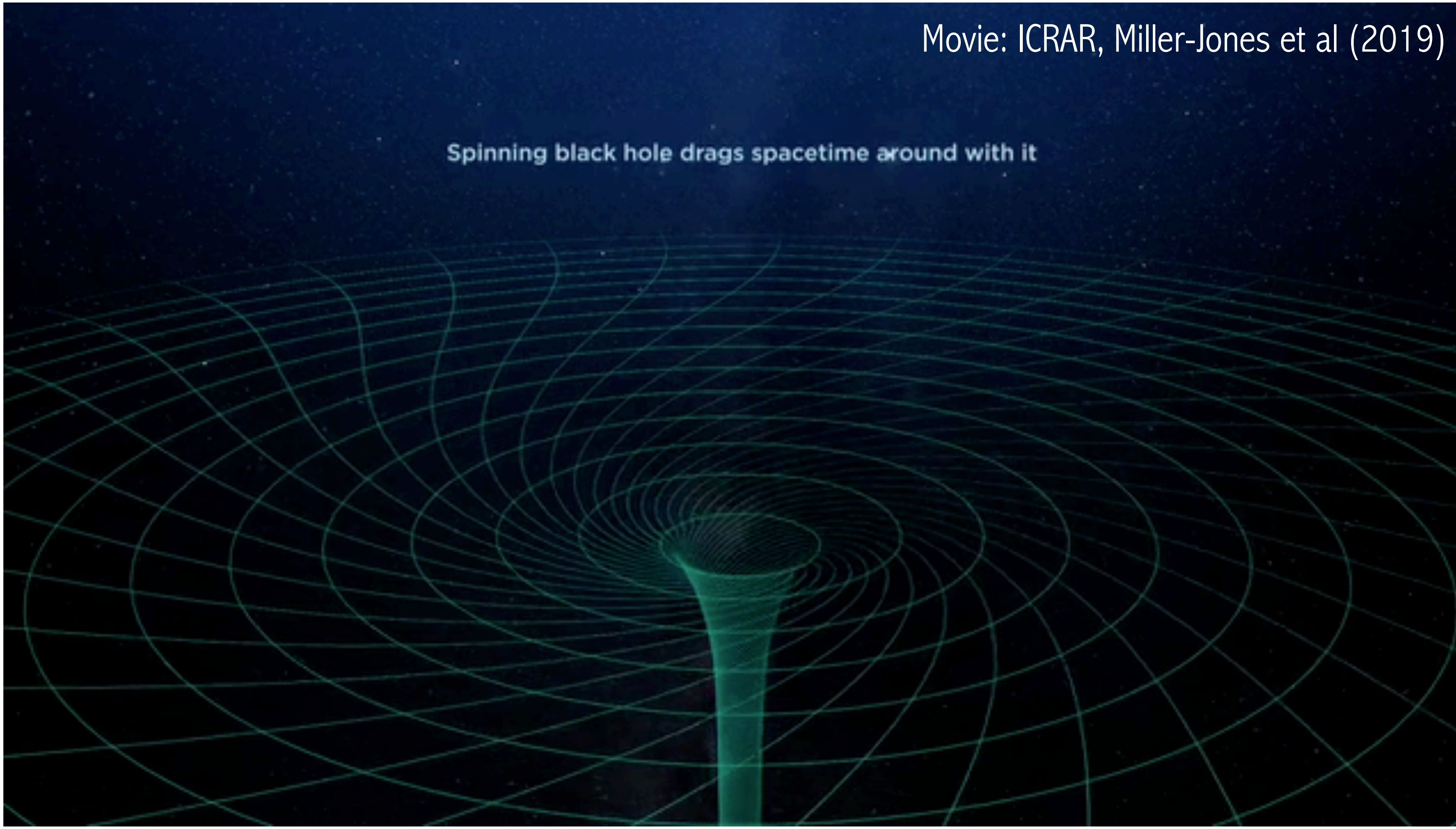


- Precessing corona / jet: LT precessing of corona (Ingram et al (2009)

…*all* models assume QPO frequency changes because of a moving disc inner radius!

Review: Ingram & Motta (2020)

Lense-Thirring precession

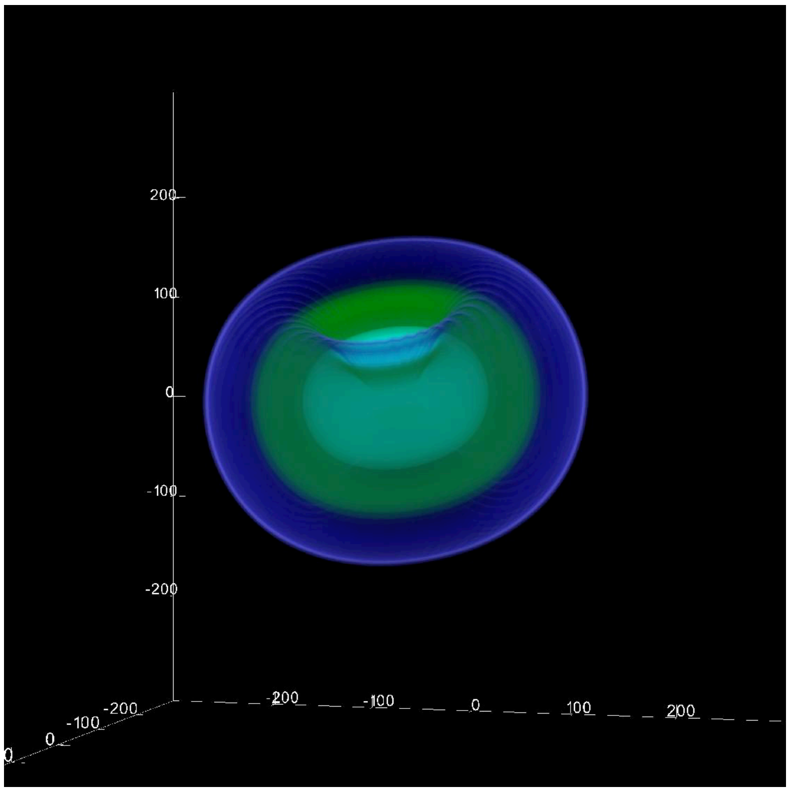


Movie: ICRAR, Miller-Jones et al (2019)

Ingram, Done & Fragile (2009)

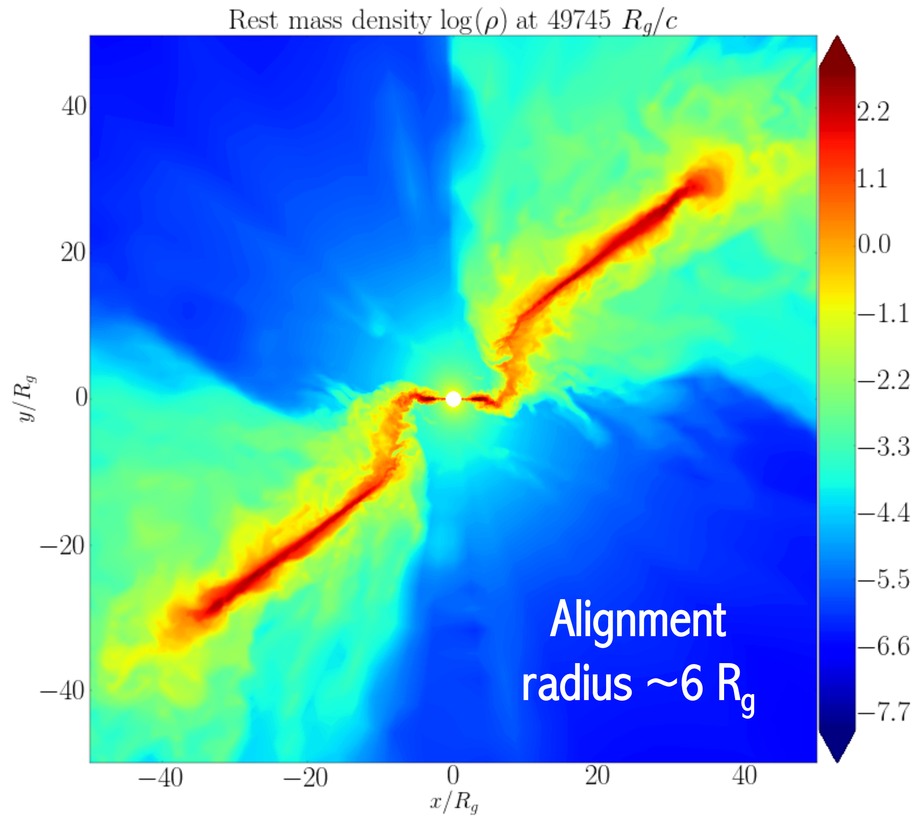
Numerical simulations

Corona – solid body precession
(Fragile et al 2007)



Liska, Hesp, Tchekovskoy, Ingram, van der Klis & Markoff (2018)

Disc – Bardeen-Petterson effect
(Bardeen & Petterson 1975)

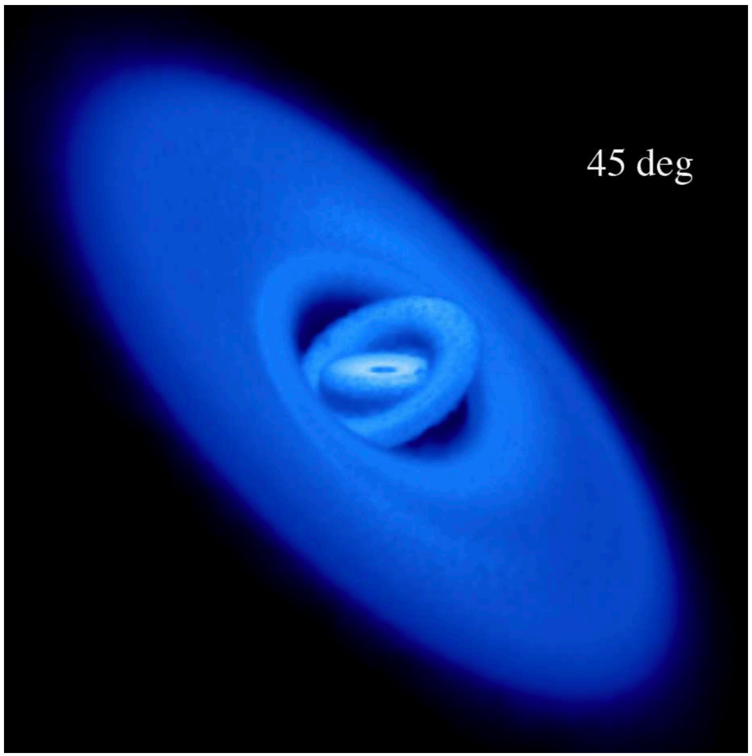


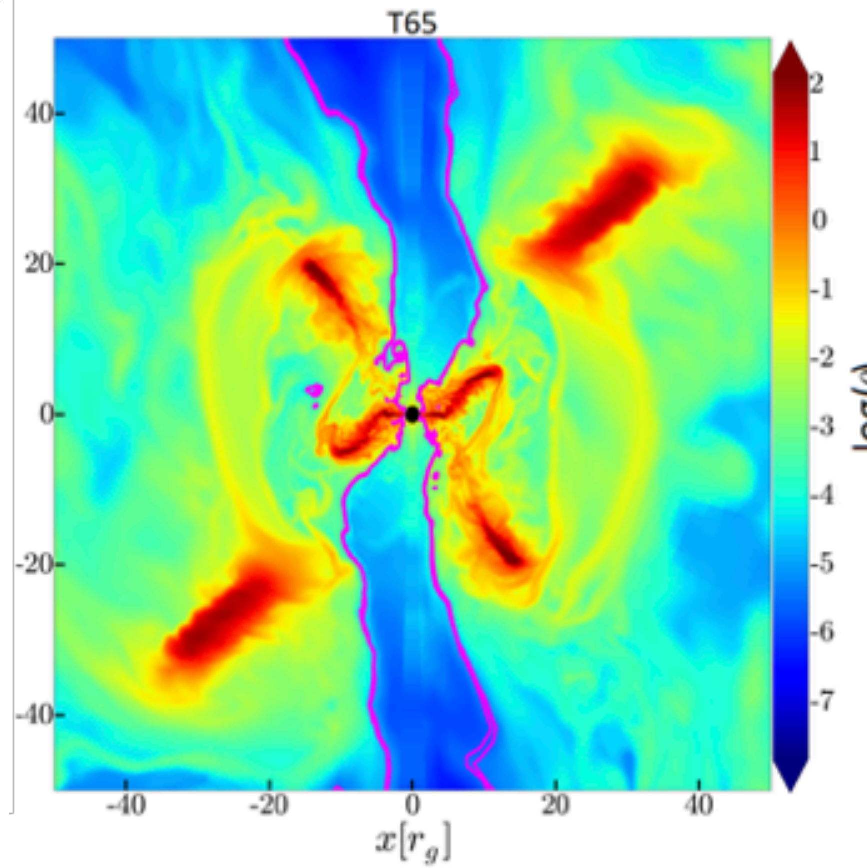
Liska, Tchekovskoy, Ingram & van der Klis (2019)

Numerical simulations

Thinner disk, high tilt – Disk breaking and tearing

(Nixon & King 2012)





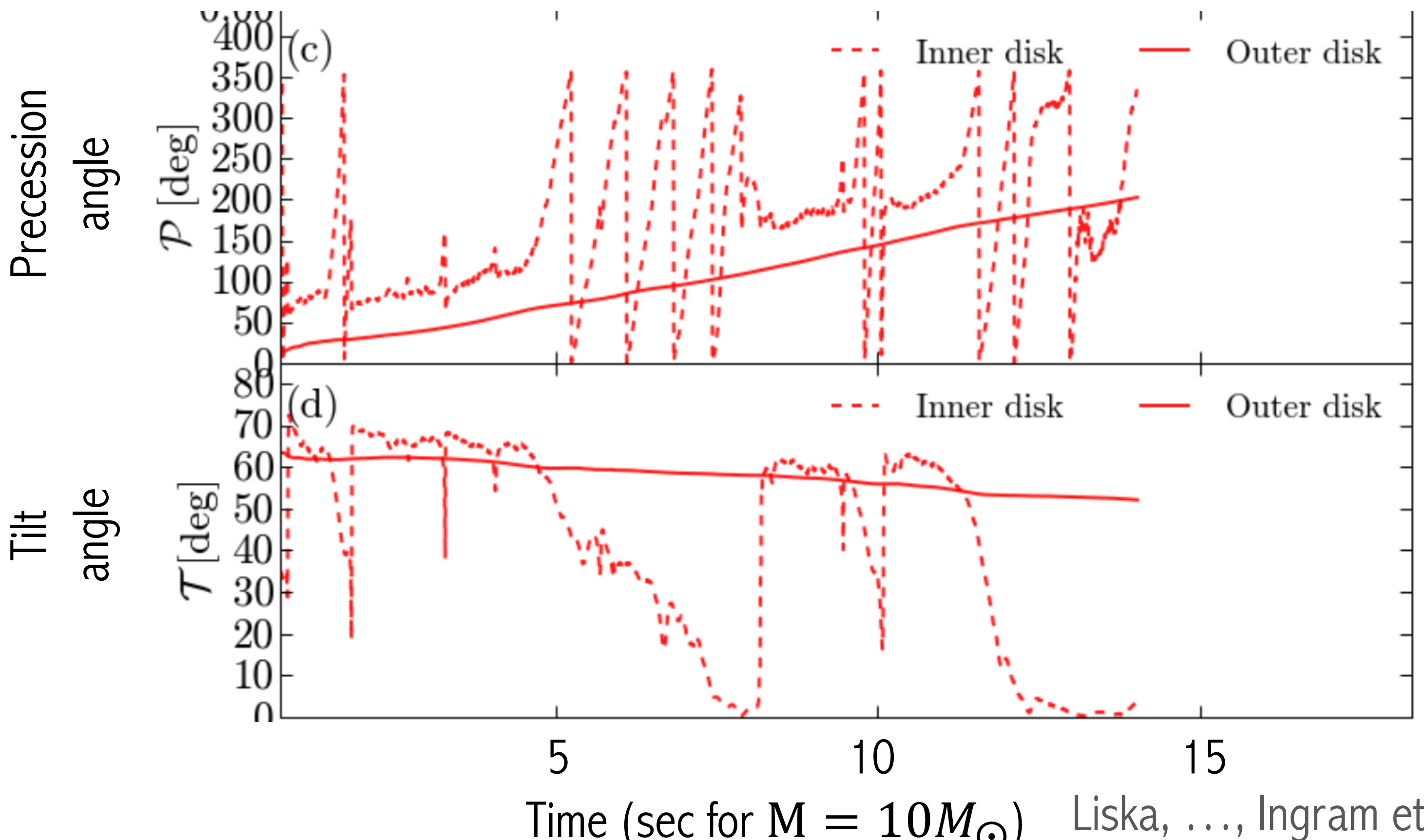
Nealon et al (2016)

Liska, Hesp, Tchekovskoy, Ingram et al (2020)

Numerical simulations

Latest H-AMR run: H/R=0.02 , tilt = 65 degrees, duration 1.4e5 Rg/c

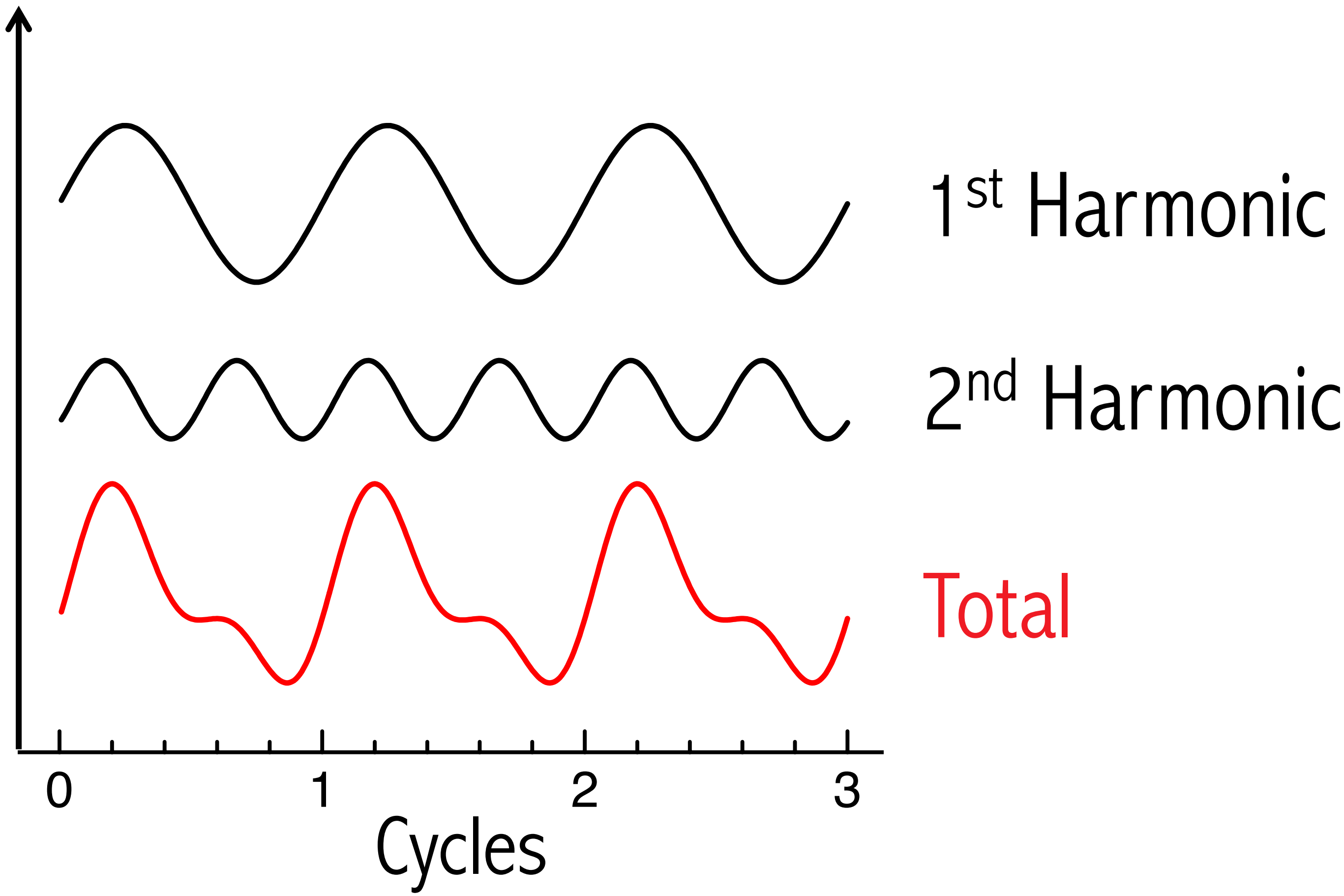
https://drive.google.com/file/d/1lbGBmoLOcHnq3WDwRhQqSLjXpuA8iBTx/view



Liska, …, Ingram et al (submitted),
Liska, …, Ingram et al (in prep)

QPO waveform

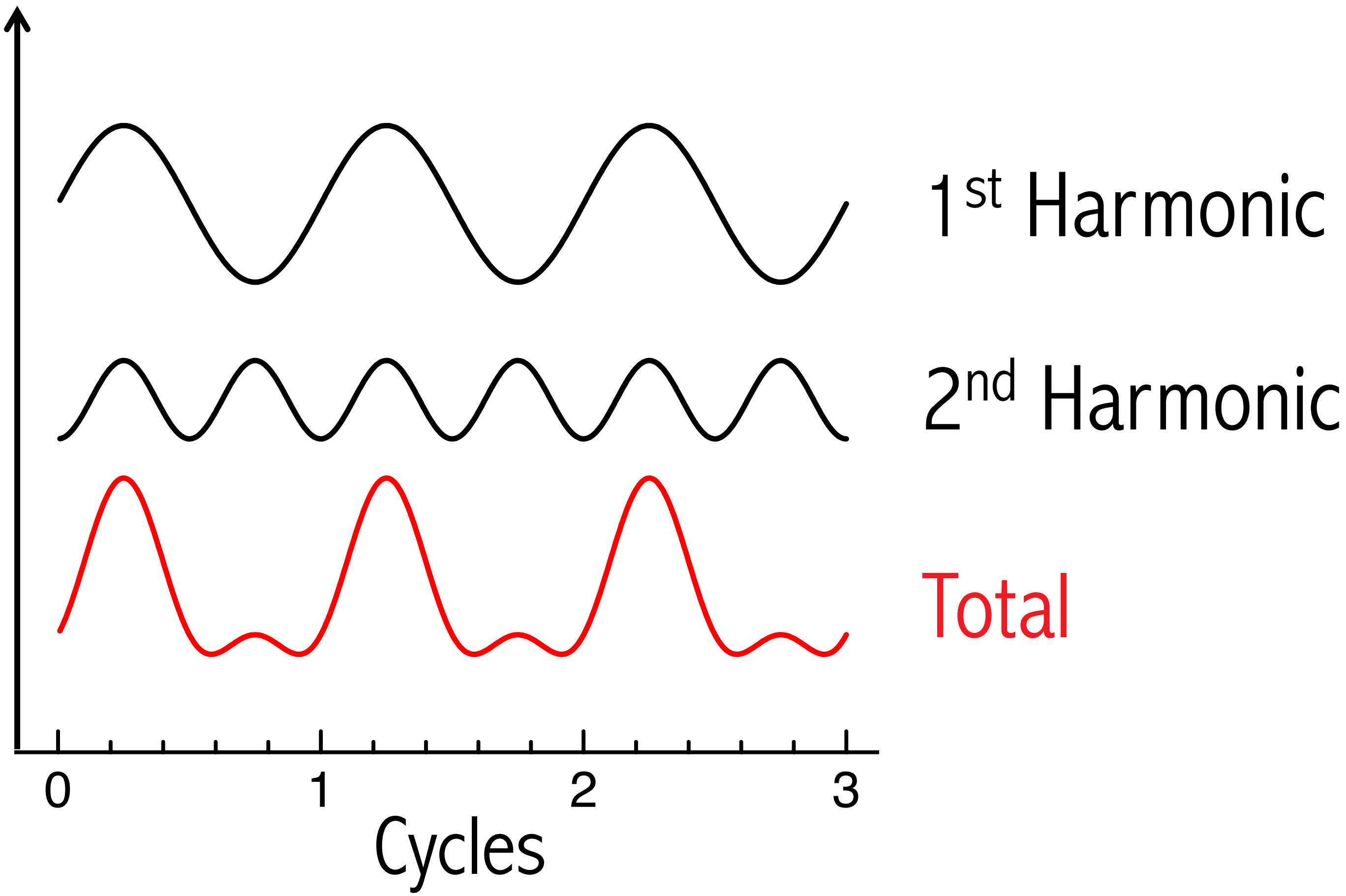
Periodic function: constant phase difference



Ingram & van der Klis (2015)

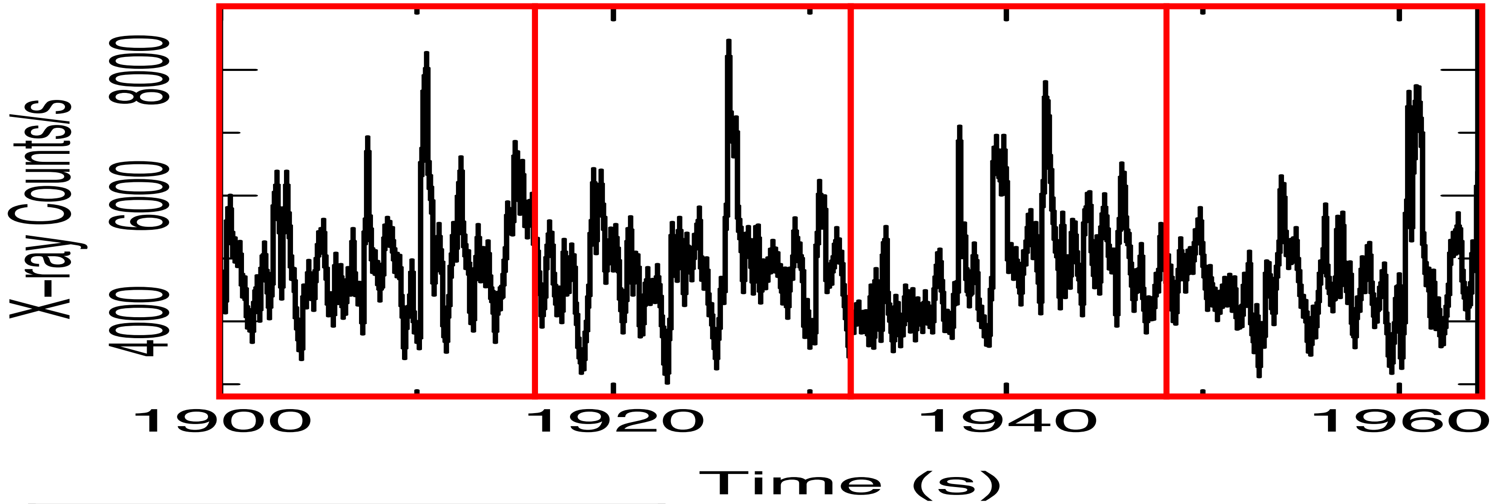
QPO waveform

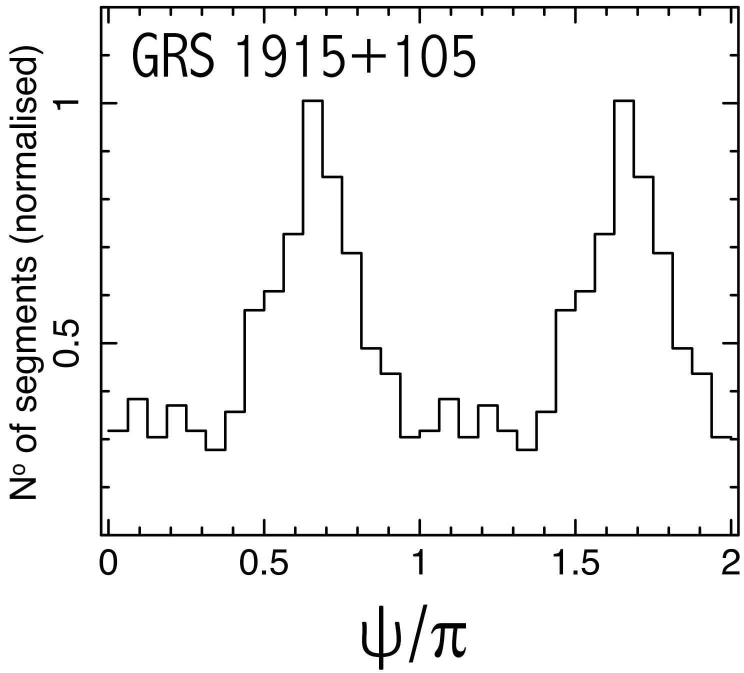
Periodic function: constant phase difference



Ingram & van der Klis (2015)

QPO waveform



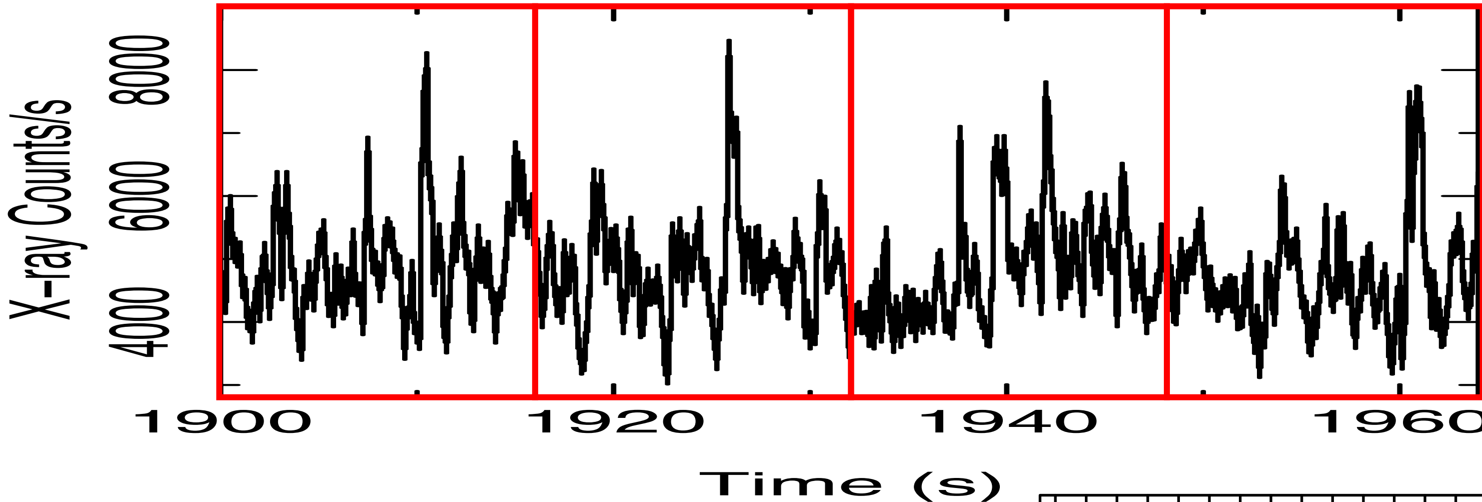


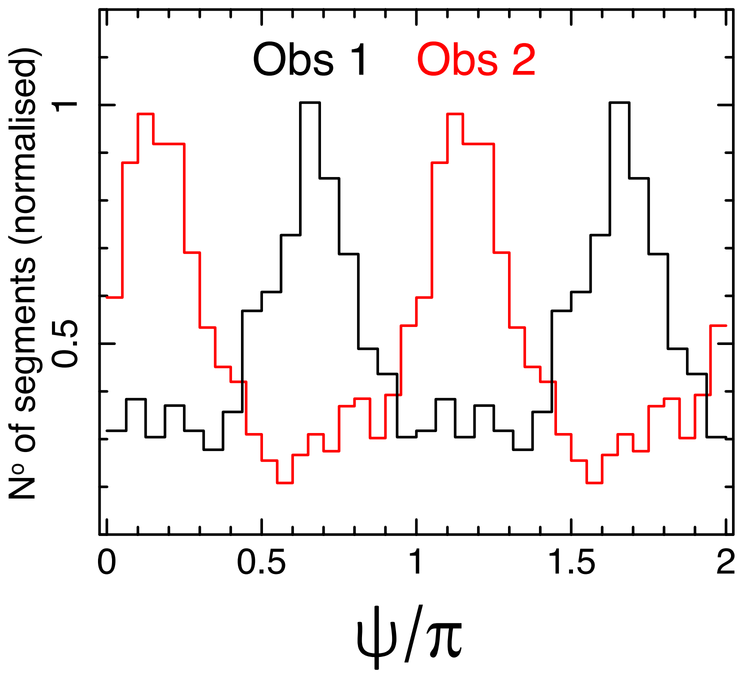
QPO: varying phase difference, ψ.

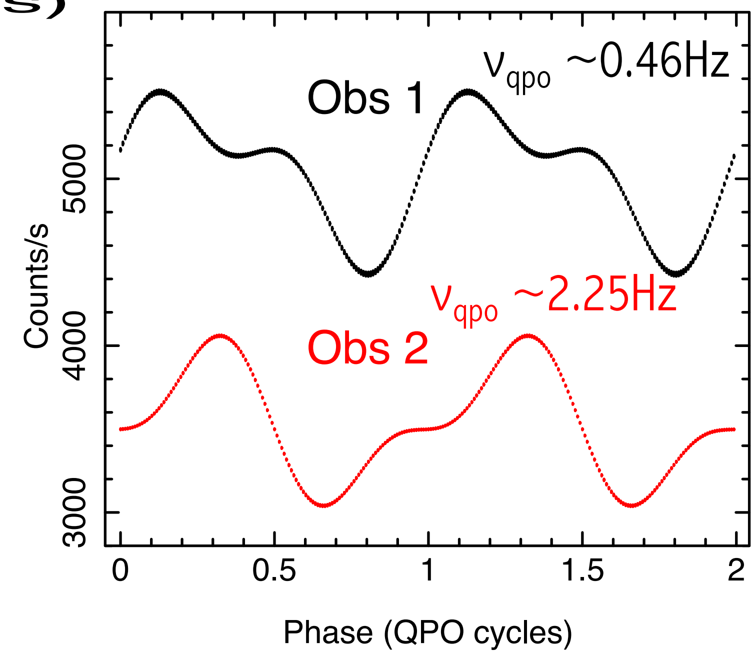
…can measure mean!

Ingram & van der Klis (2015)

QPO waveform

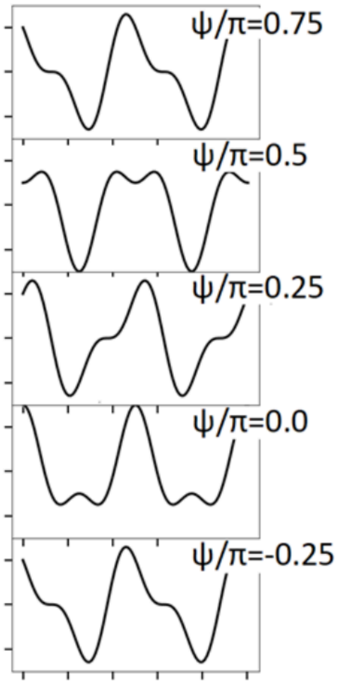


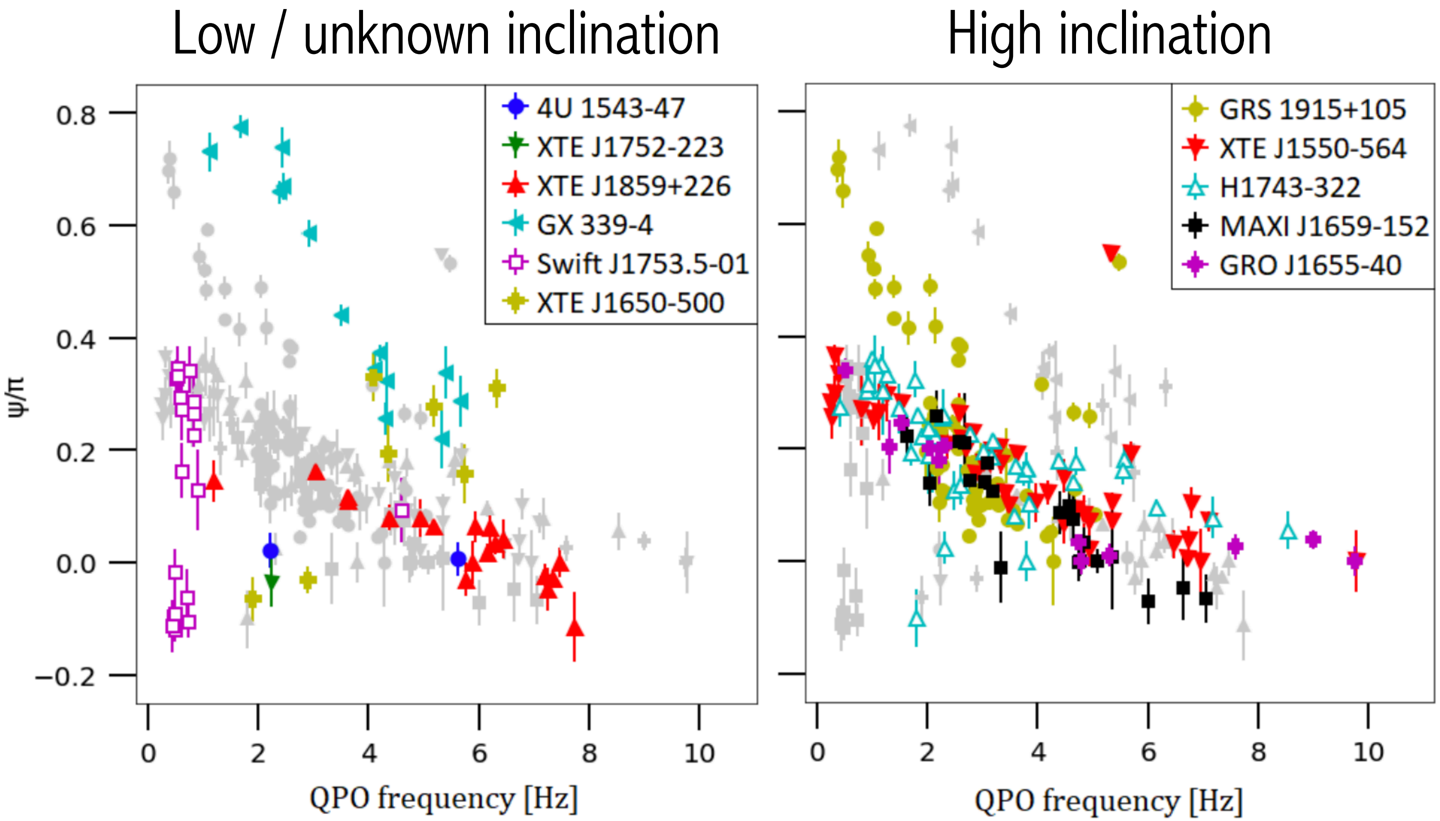




QPO waveform

Type C:



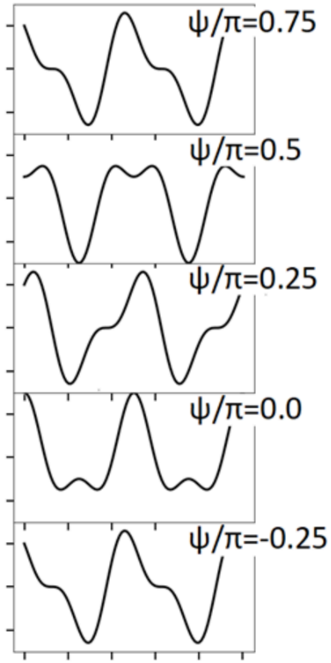


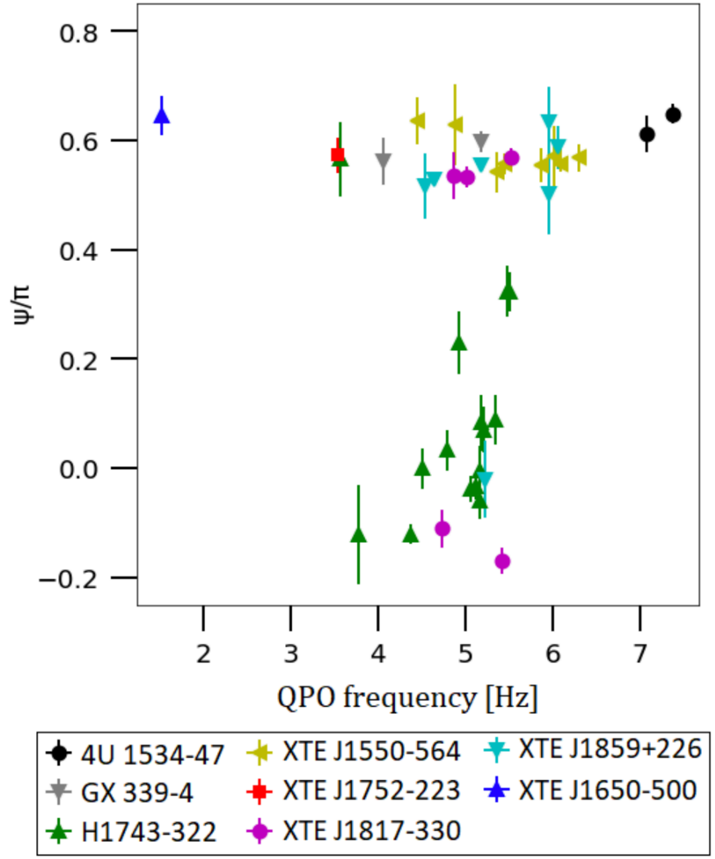
- High inclination "better behaved" than low inclination?
- XTE J1859+226 QPOs behave like high inclination source
- High inc: Doppler effects dominate over seed photon variations?

De Ruiter, van den Eijnden, Ingram & Uttley (2019)

QPO waveform

Type B:



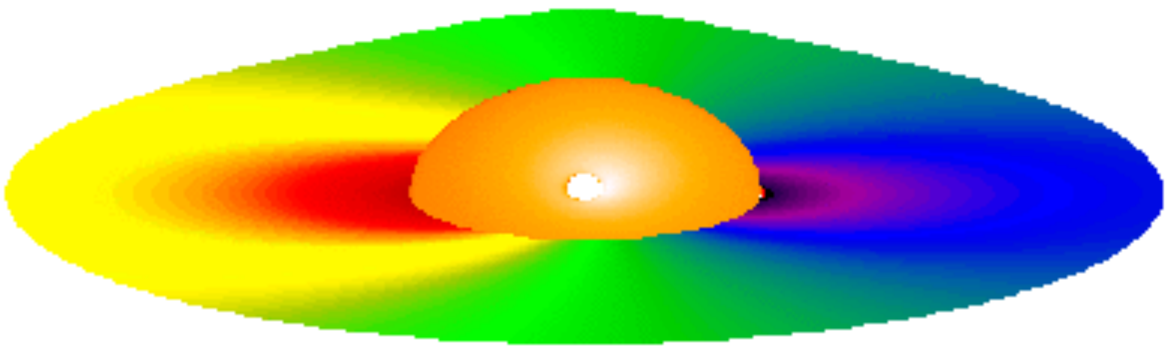


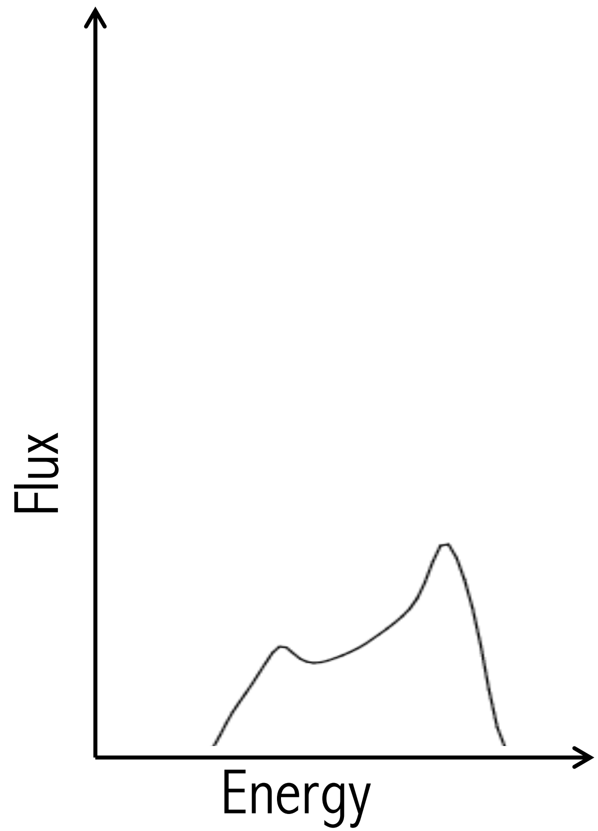
- Looked like all have the same phase difference!
- …but H 1743-322 and XTE J1817-330 spoiled this!
- Very simple precessing jet model gives ψ≃π/2

De Ruiter, van den Eijnden, Ingram & Uttley (2019)

Phase-resolved spectroscopy

Tell-tale sign of precession: a rocking iron line

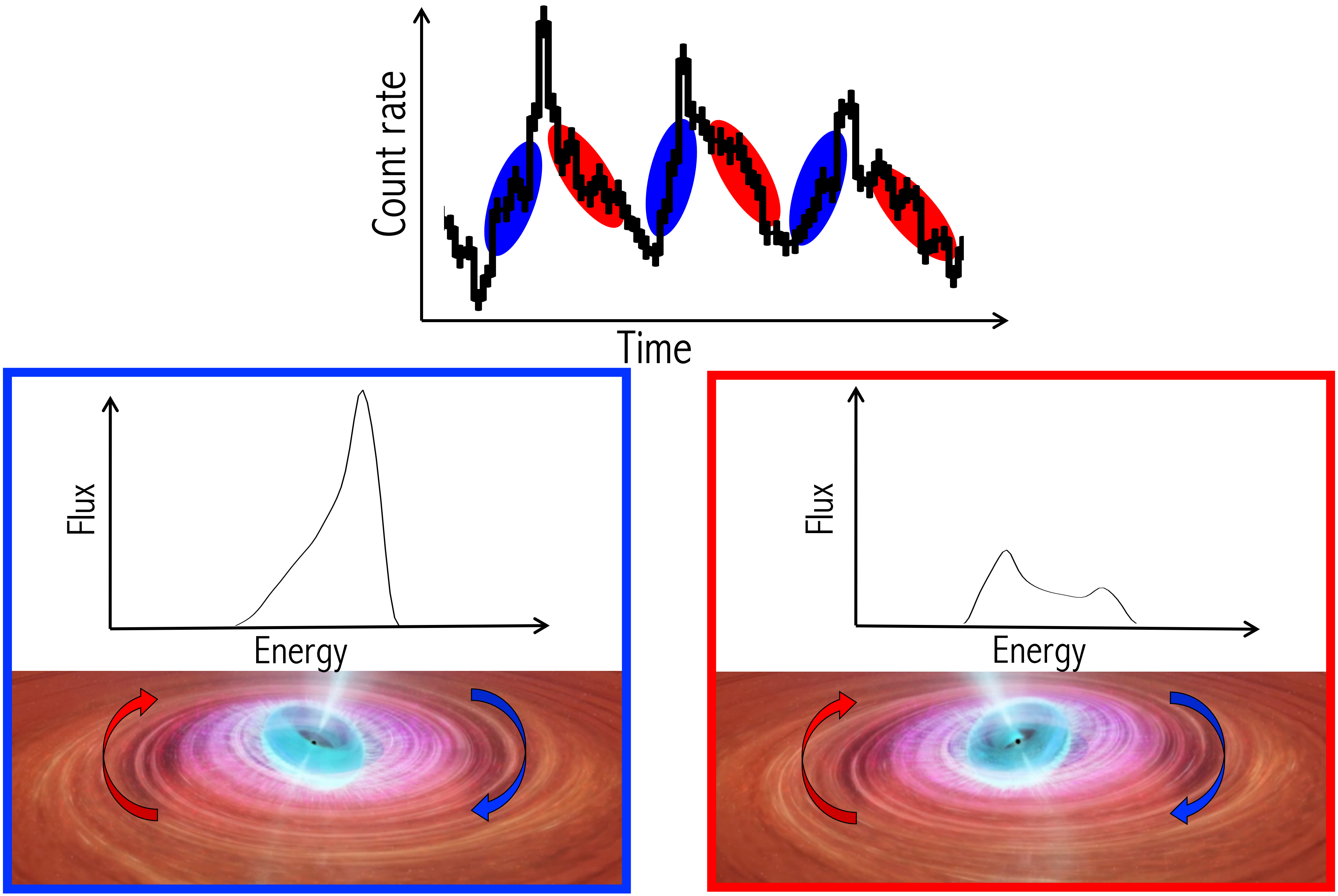




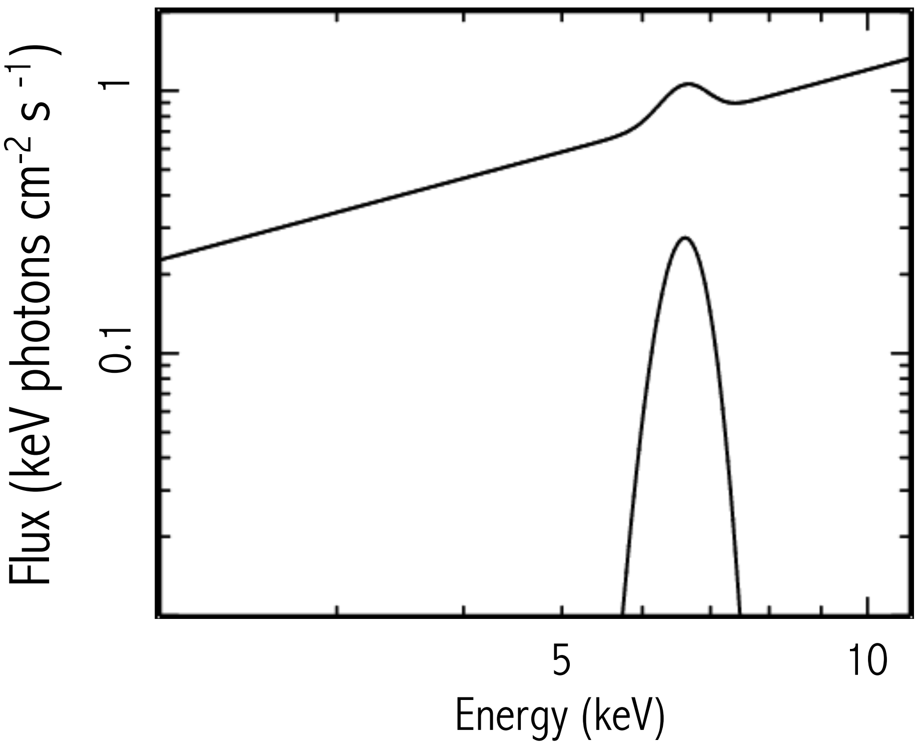
https://www.youtube.com/watch?v=e1QmLg5mGbU

Ingram & Done (2012); Schnittman et al (2006)

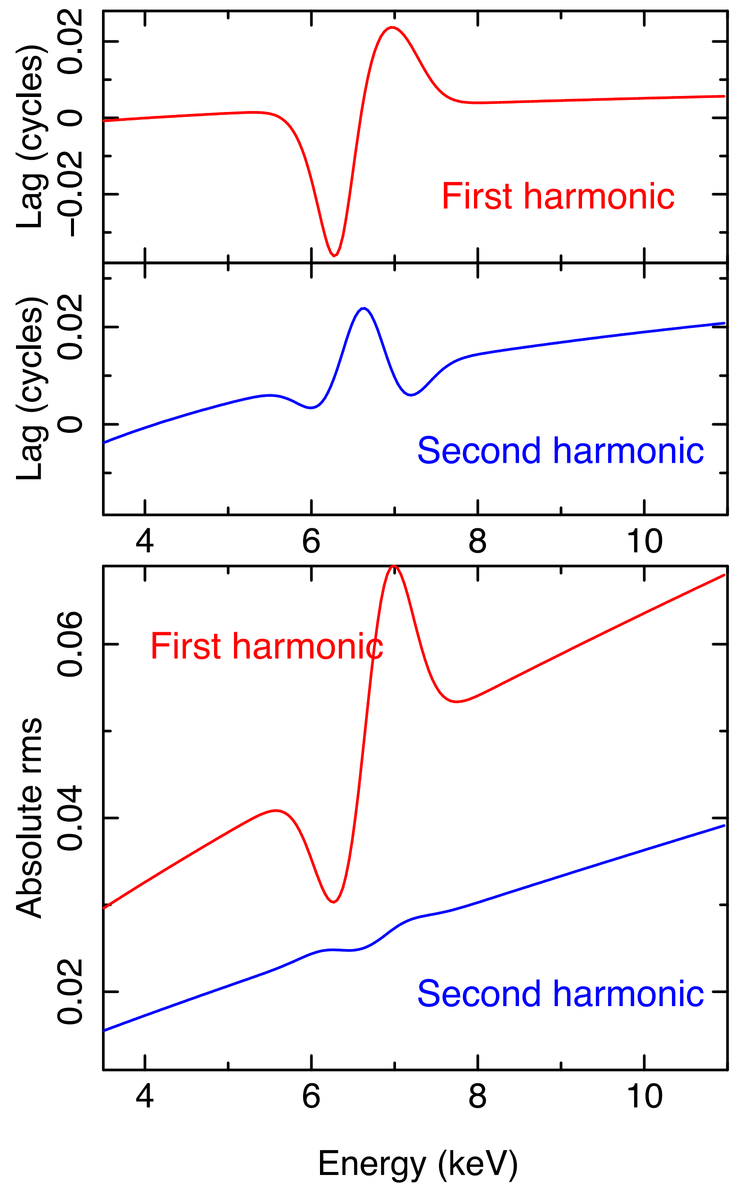
Phase-resolved spectroscopy



Phase-resolved spectroscopy



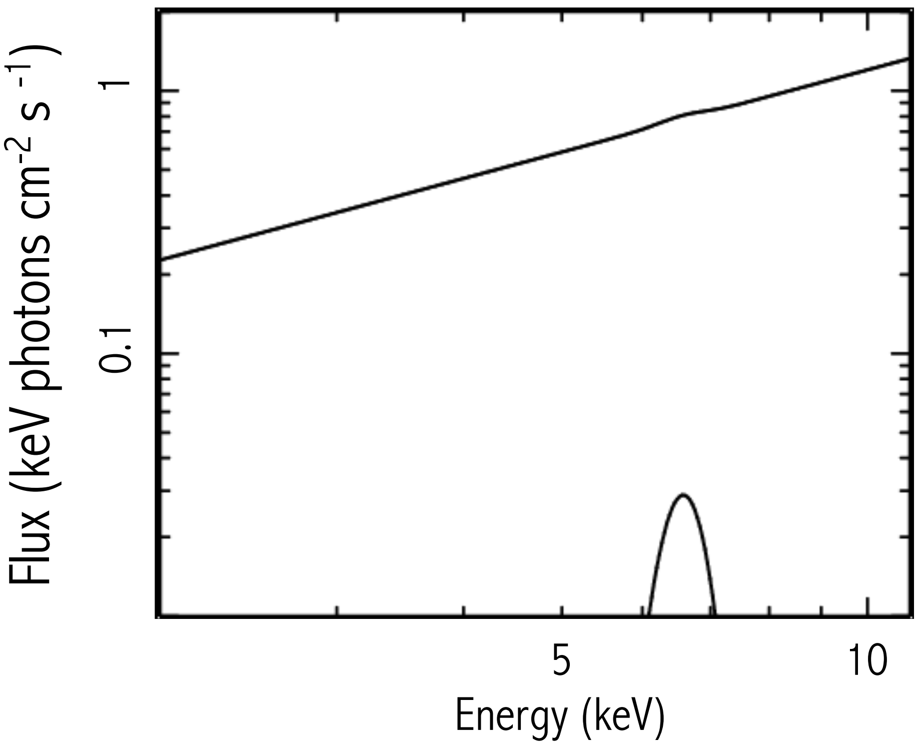
Rocking iron line creates "wiggles" in the rms-energy and lag-energy spectrum

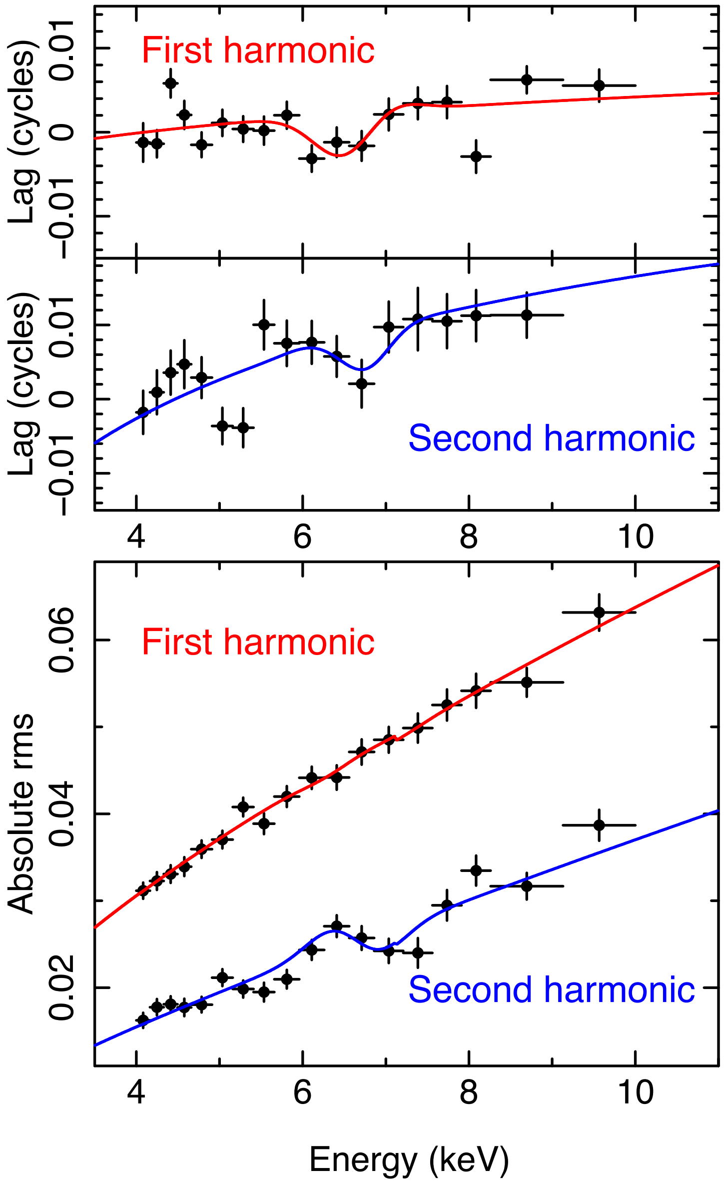


Ingram & van der Klis (2015); Ingram et al (2016)

Rocking iron line in H 1743-322

200ks XMM-Newton + 70ks NuSTAR

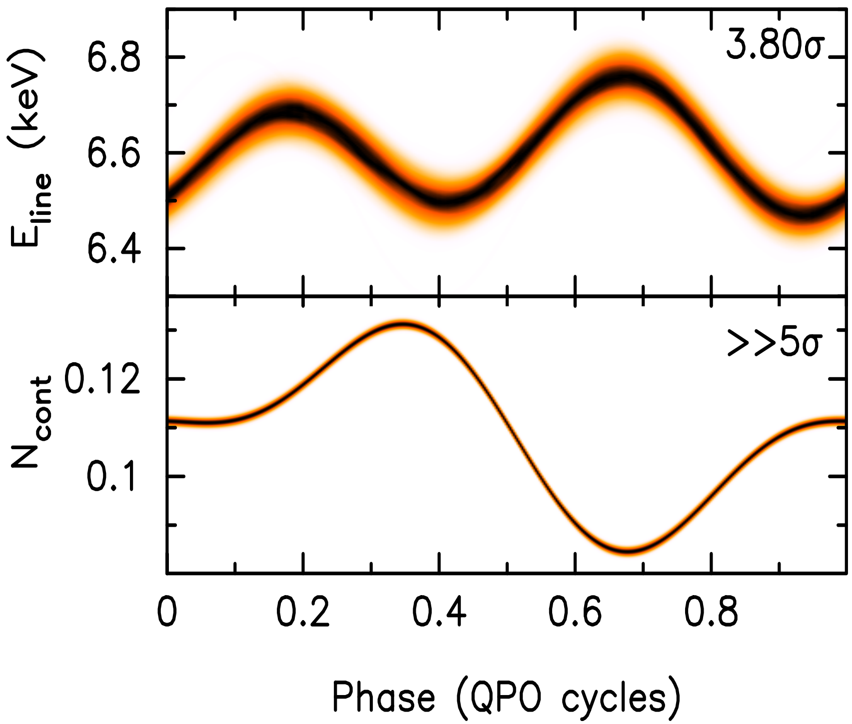


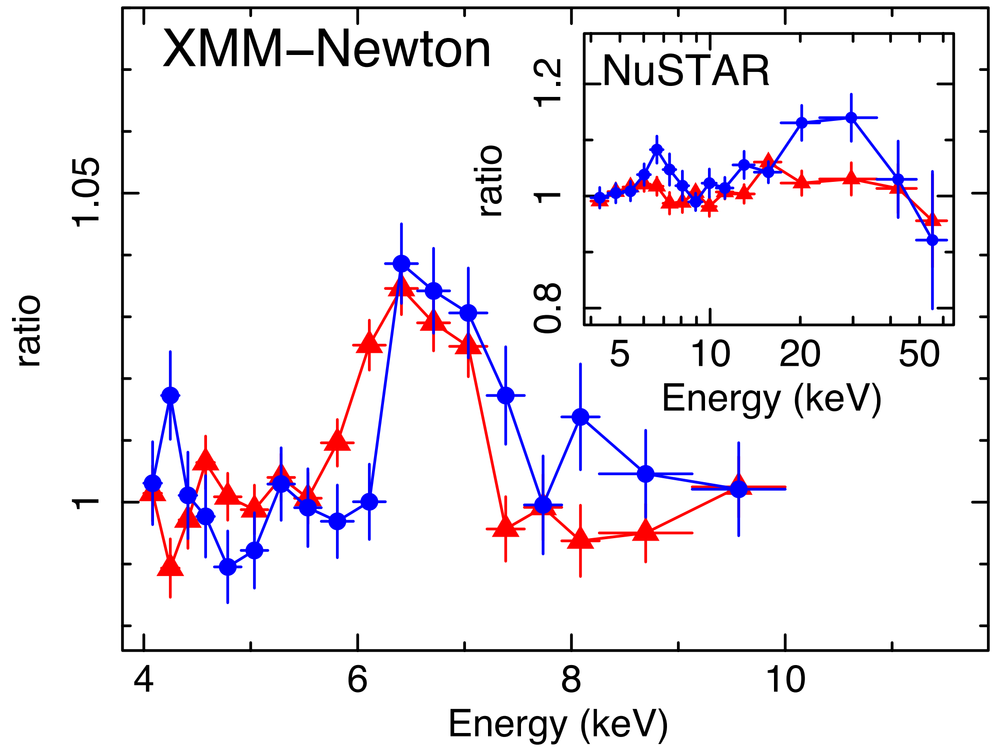


Only ~65ks of XMM data shown for clarity

Ingram et al (2016)

Rocking iron line in H 1743-322

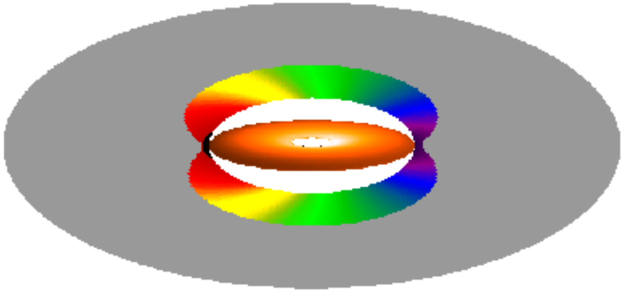




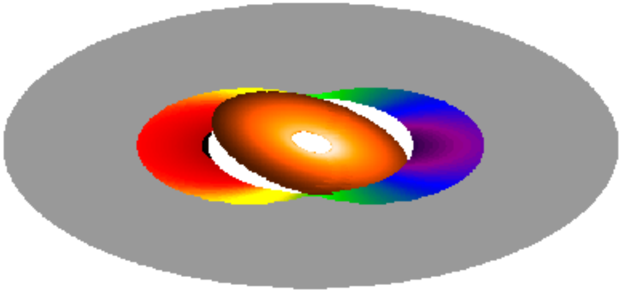
Ingram et al (2016)

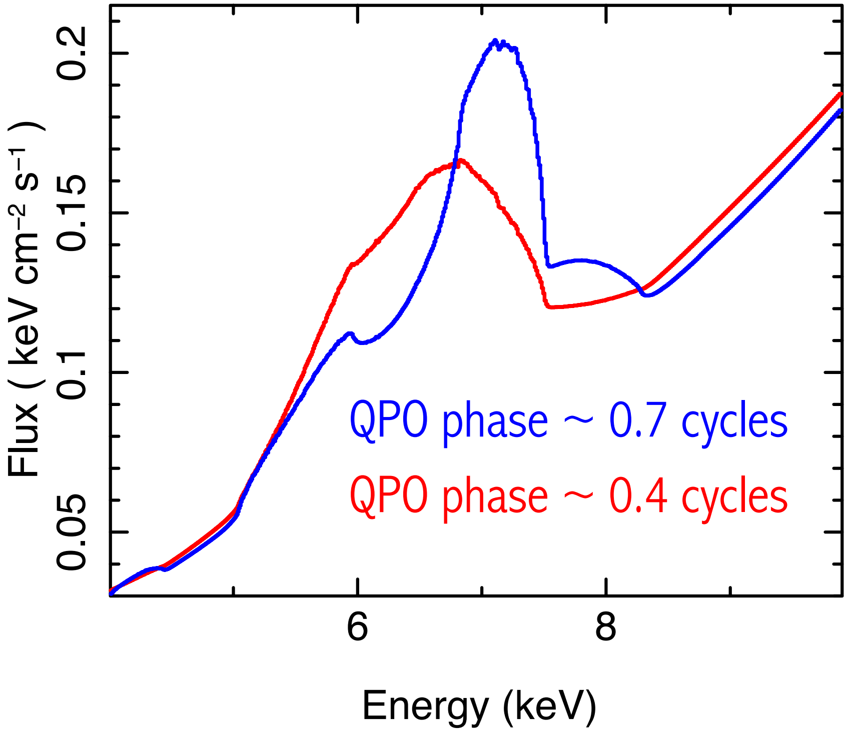
Interpretation

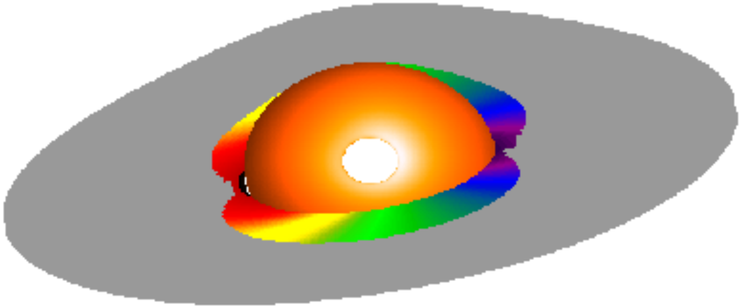
QPO phase ~ 0.4 cycles



QPO phase ~ 0.7 cycles







Ingram et al (2017)

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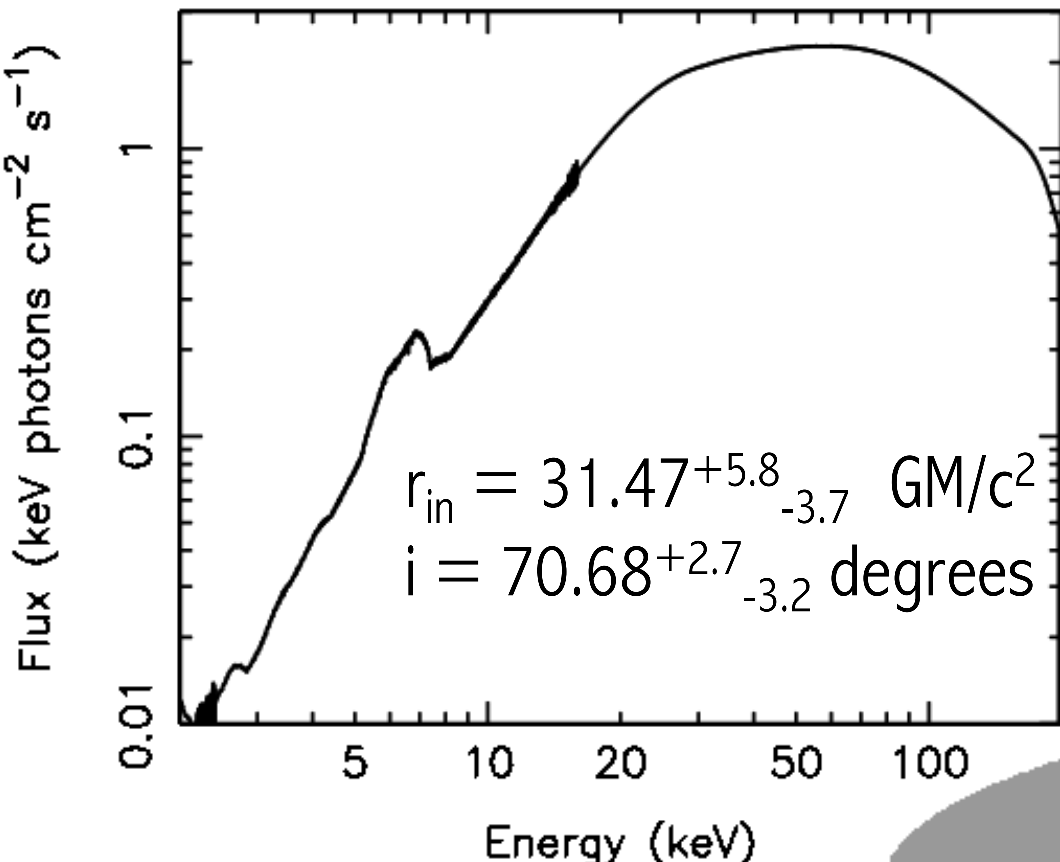
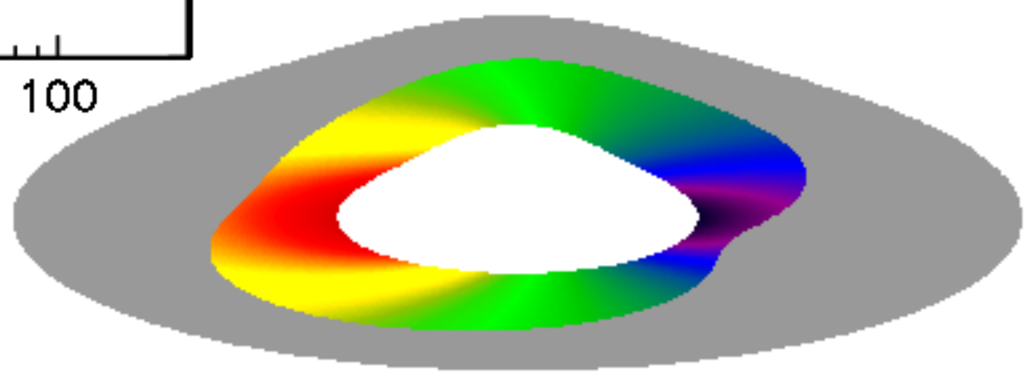
Tomographic modeling



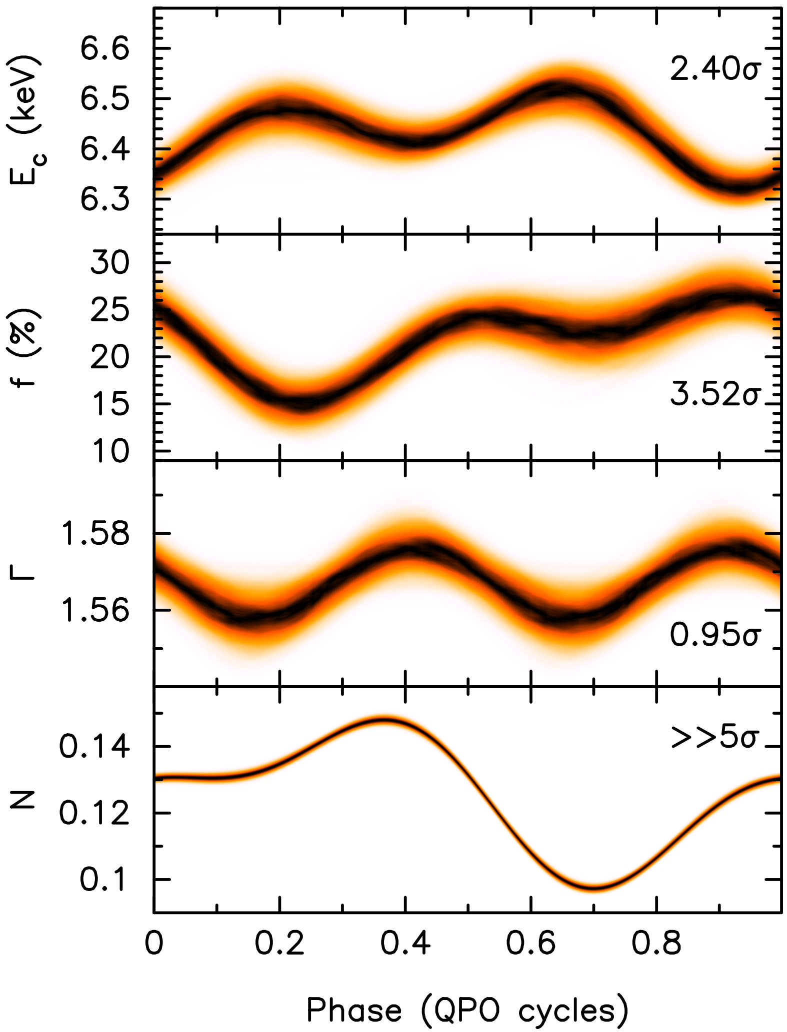
Parameterize disk illumination:

$$I_{E_e}(r,\phi,\gamma) \propto$$
$$r^{-q} \quad \Big\{1 + A_1 \cos^2 [(\gamma - \phi + \phi_1)/2]$$
$$+ \quad A_2 \cos^2 [\gamma - \phi + \phi_2] \Big\} I_{E_e},$$



https://figshare.com/articles/Tomographic_modelling_of_H_1743-322/3503933 Ingram et al (2017)

Tomographic modeling



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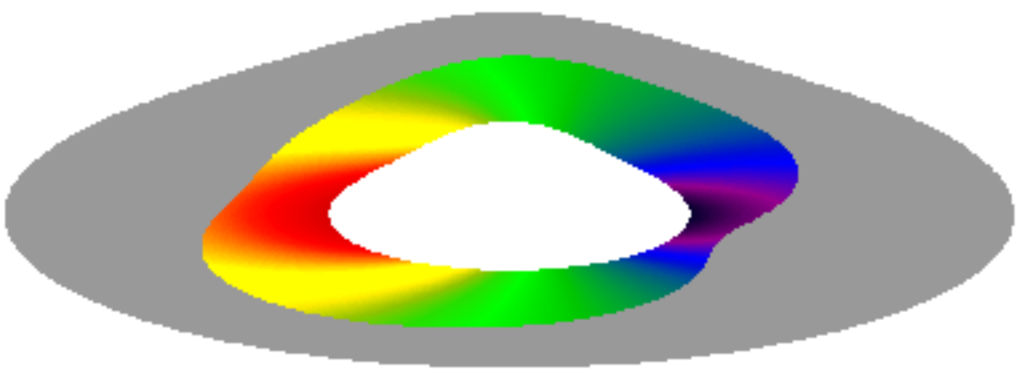
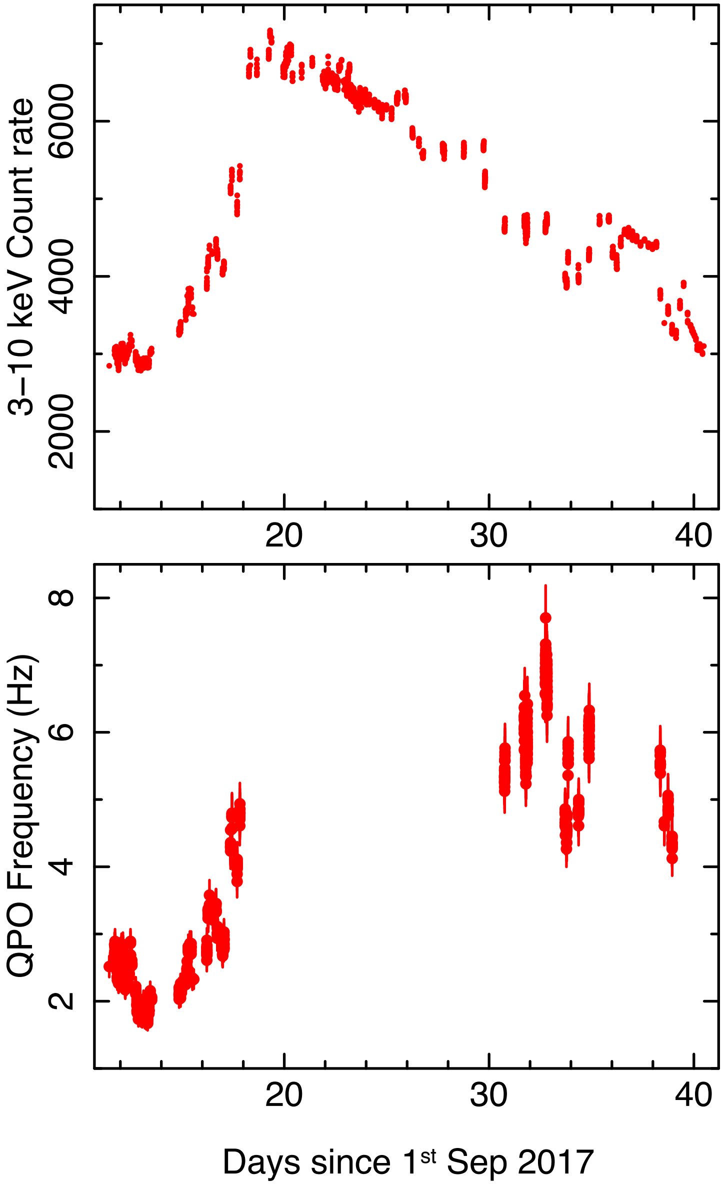


Ingram et al (2017)

$A_1 = A_2 = 0$ ruled out with 2.4σ confidence

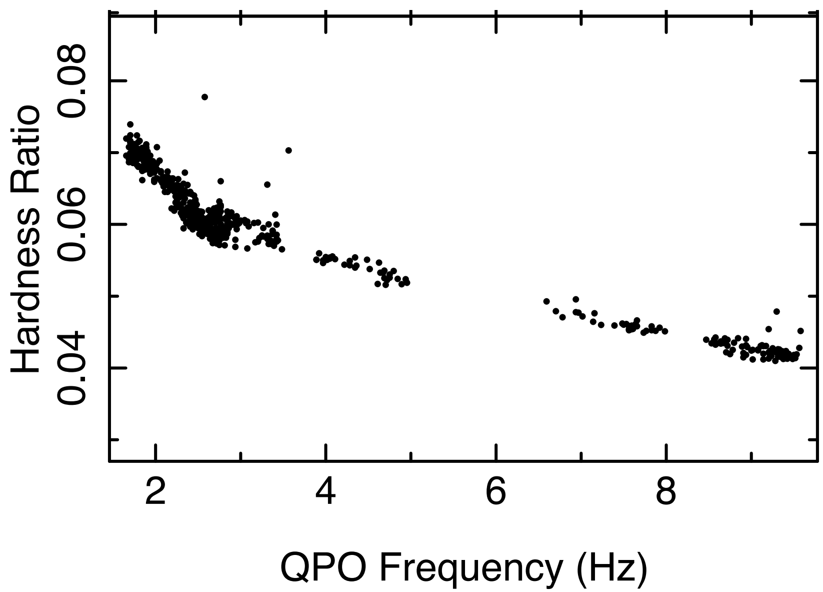
MAXI J1535-571

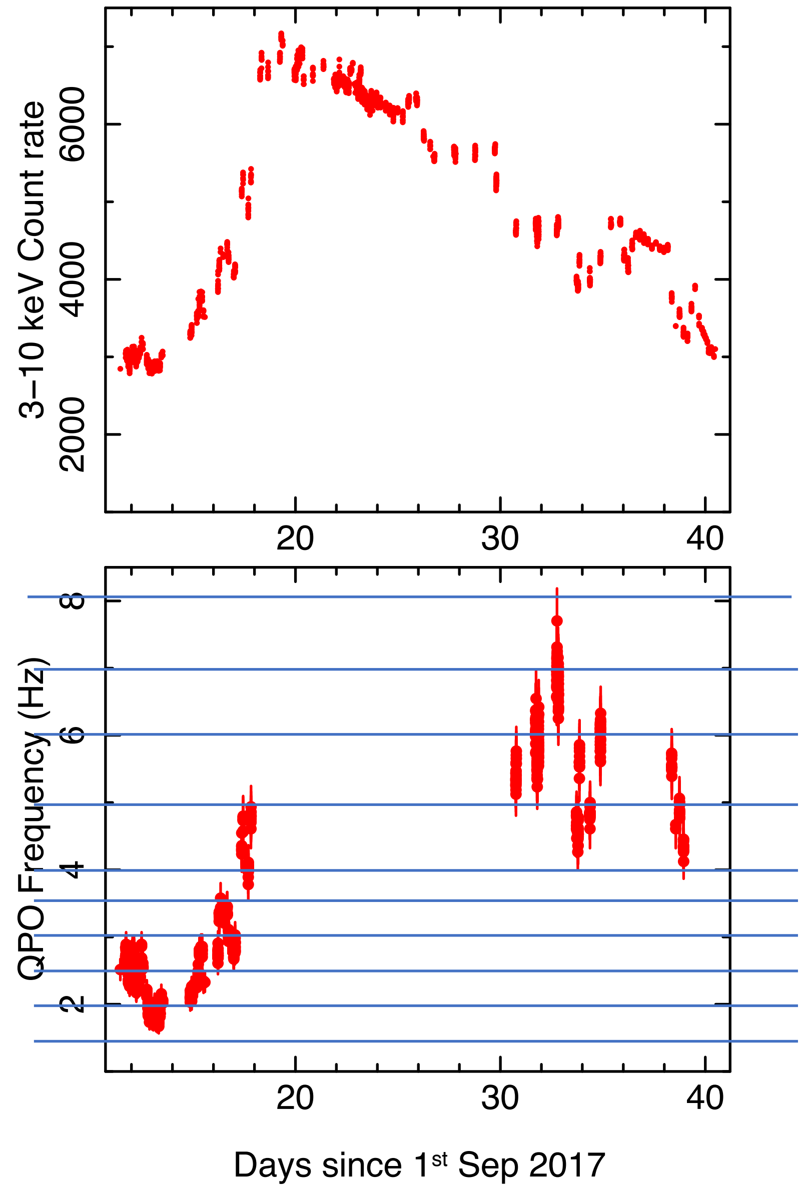
- Super-bright *NICER* discovery
- Very bright and beautiful QPOs – perfect for tomography
- Lots of data!



MAXI J1535-571

- Spectral shape correlates nicely with QPO frequency
- So create bins of QPO frequency and stack cross-spectra on those bins

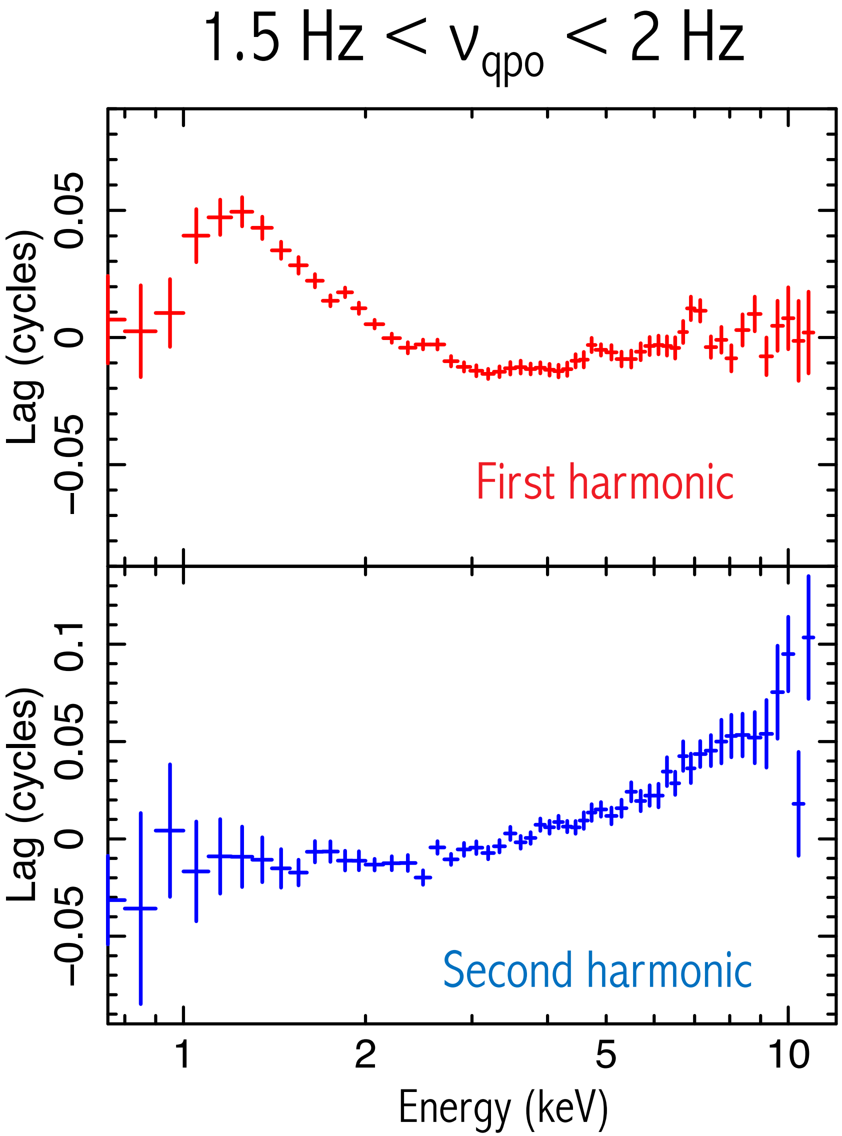




Uttley et al (in prep); Ingram et al (in prep)

MAXI J1535-571

- Can see the iron line feature very clearly!
- Big thermal feature (~1-2 keV)
- Iron line time lag ~10✕ line feature in MAXI J1820 – this is *not* reverberation



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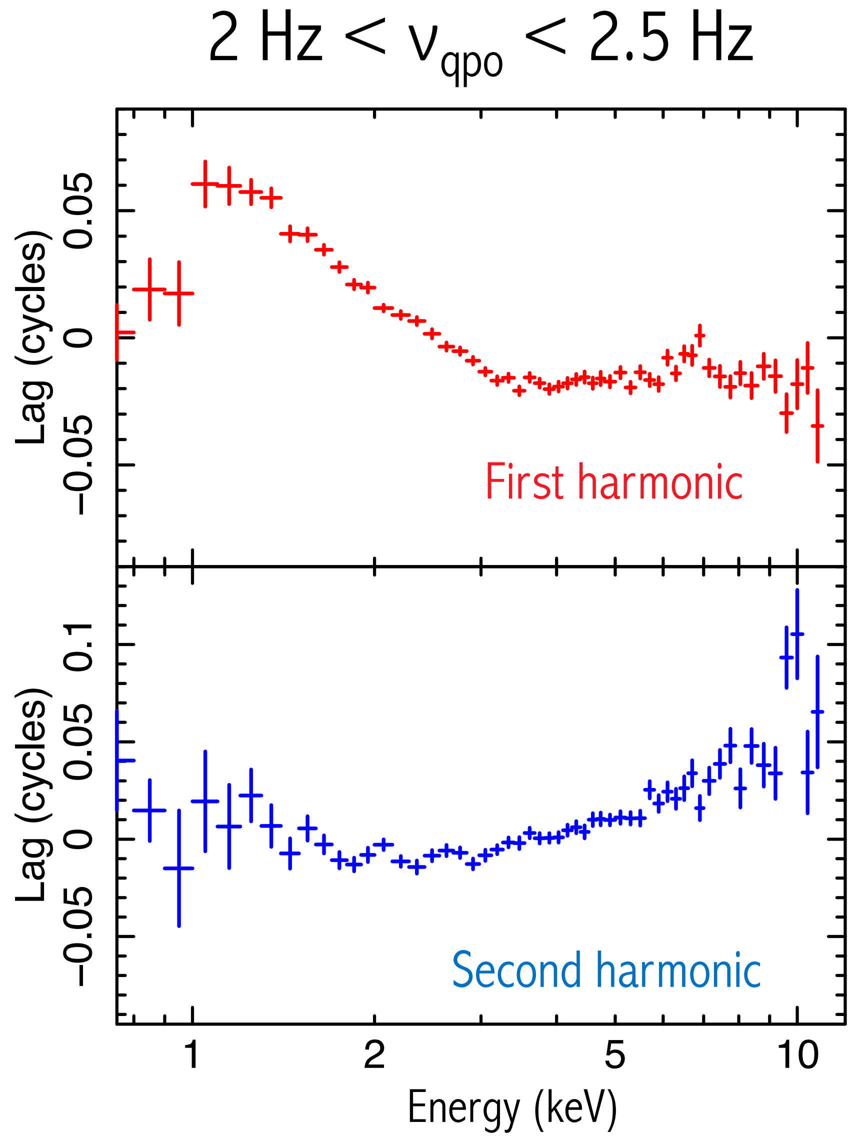

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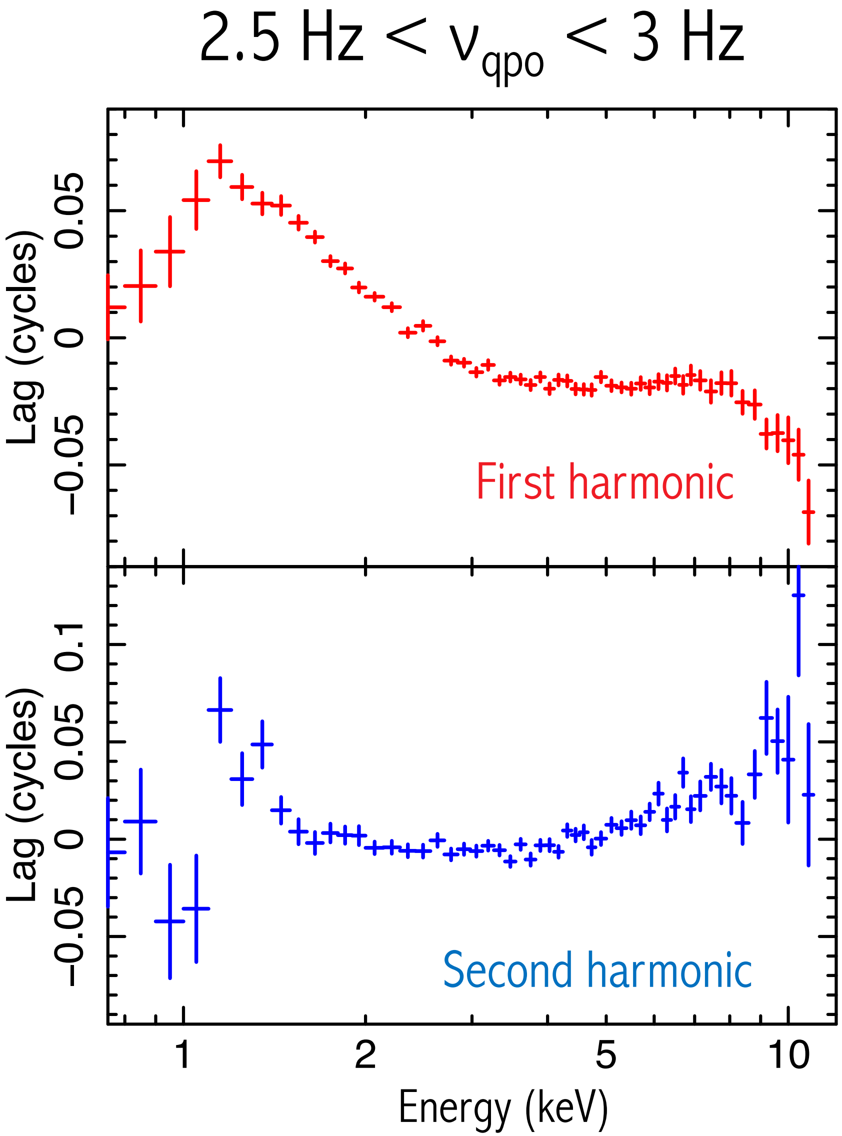

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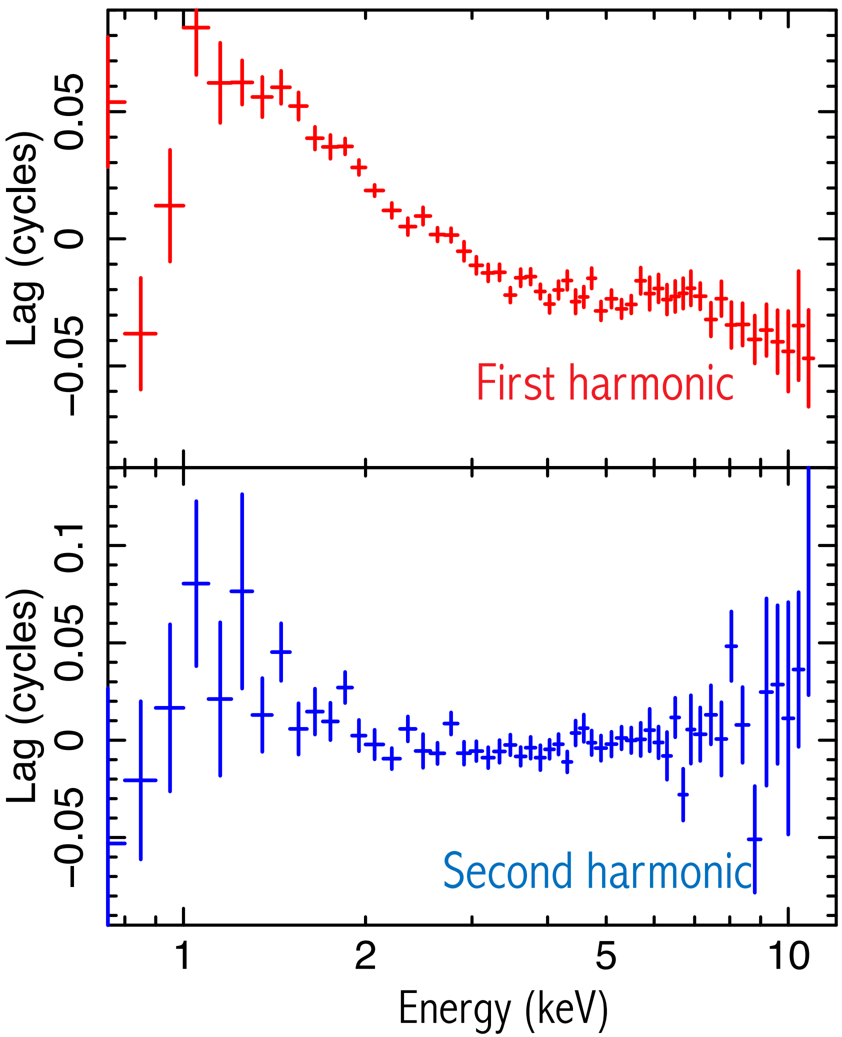
$3 \text{ Hz} < \nu_{qpo} < 3.5 \text{ Hz}$



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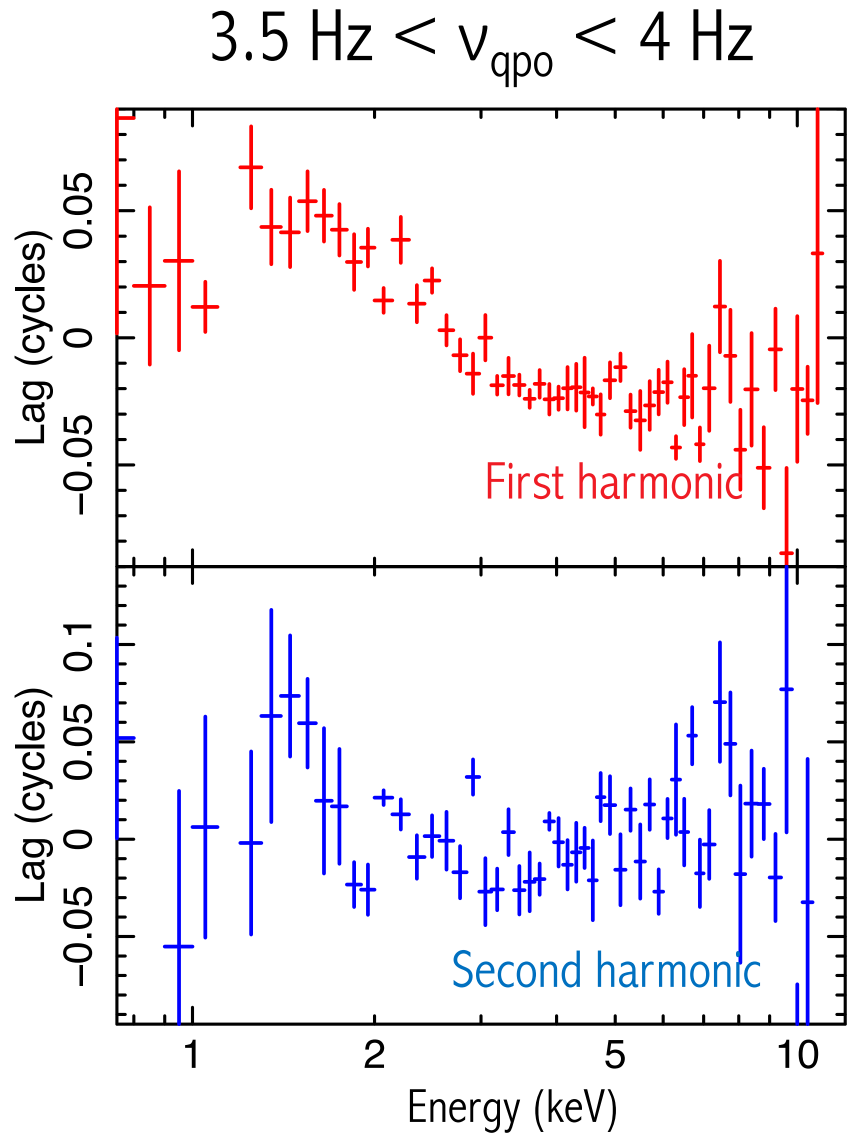

Uttley et al (in prep); Ingram et al (in prep)

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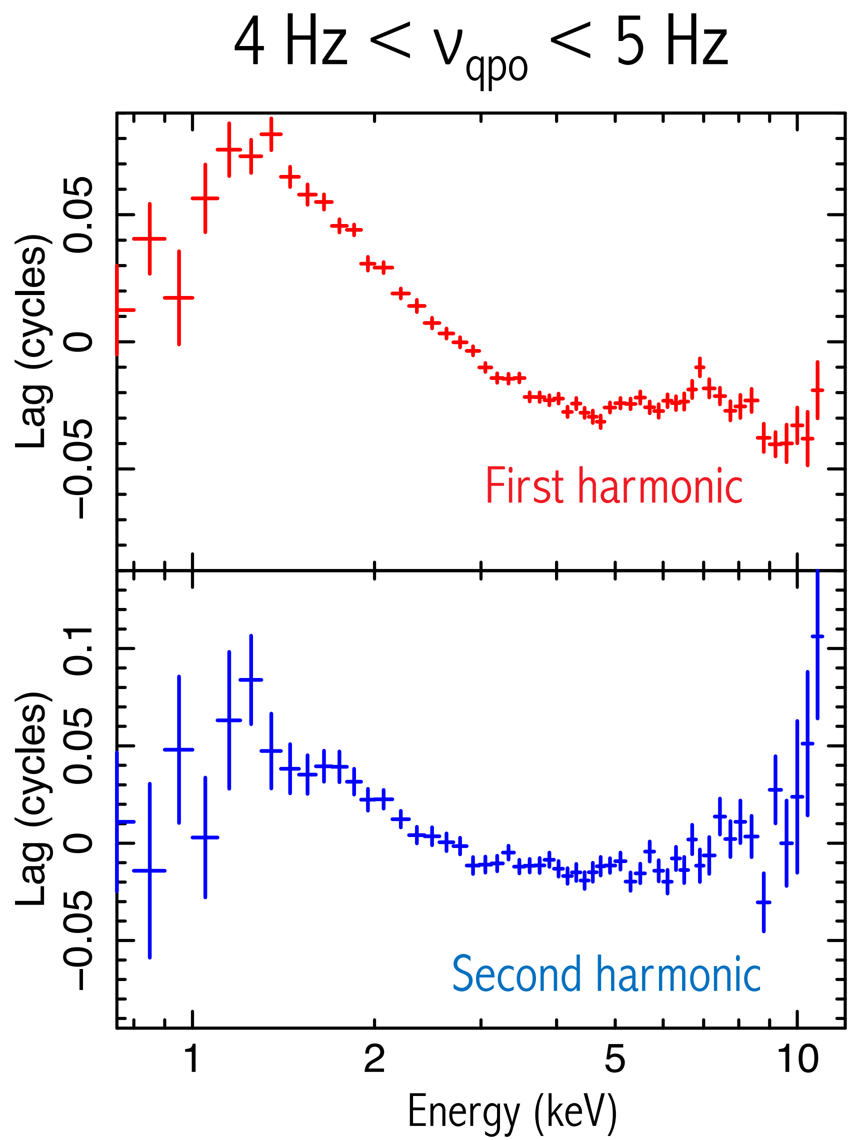

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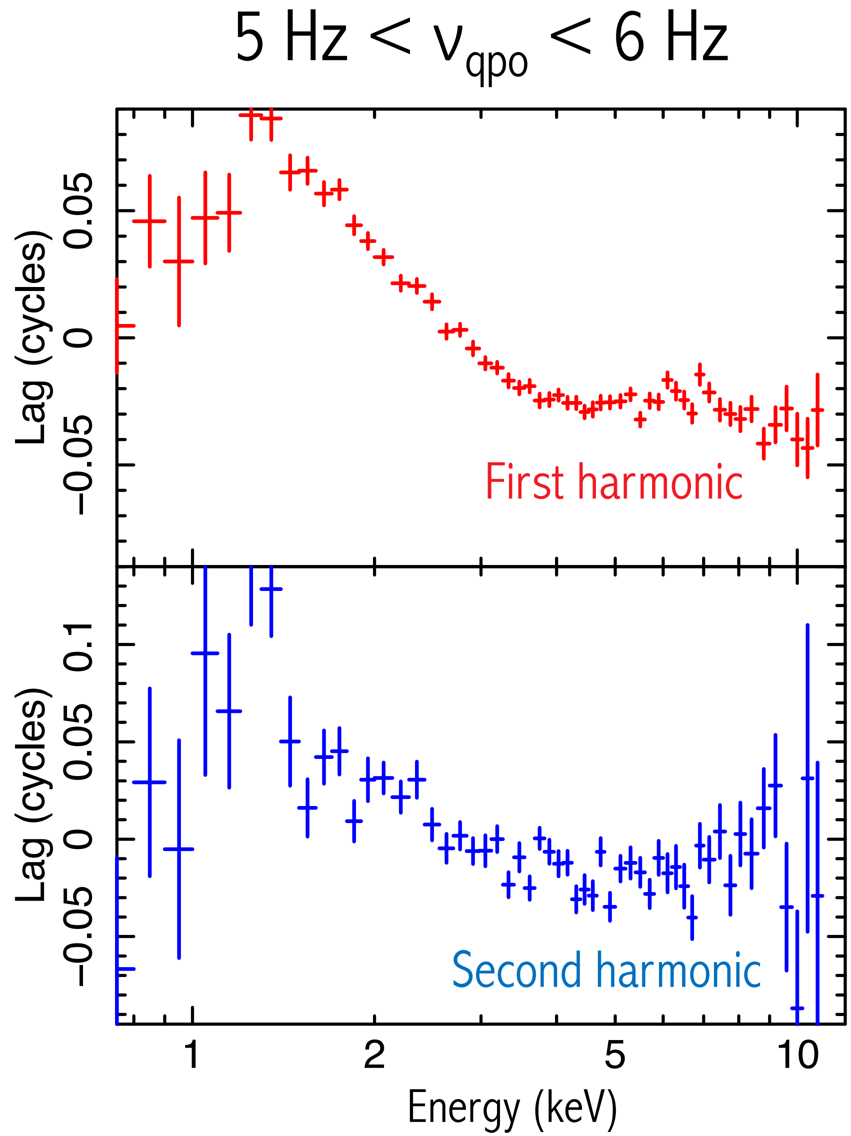

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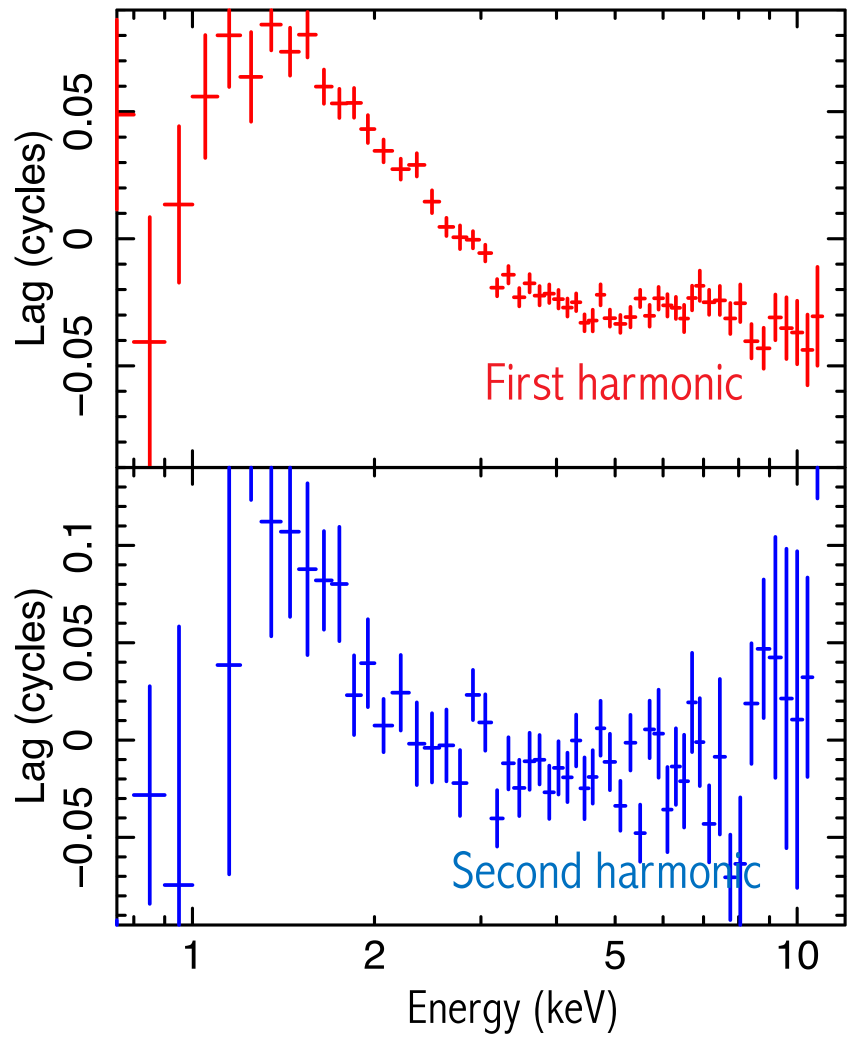
$6\ \mathrm{Hz} < \nu_{qpo} < 7\ \mathrm{Hz}$



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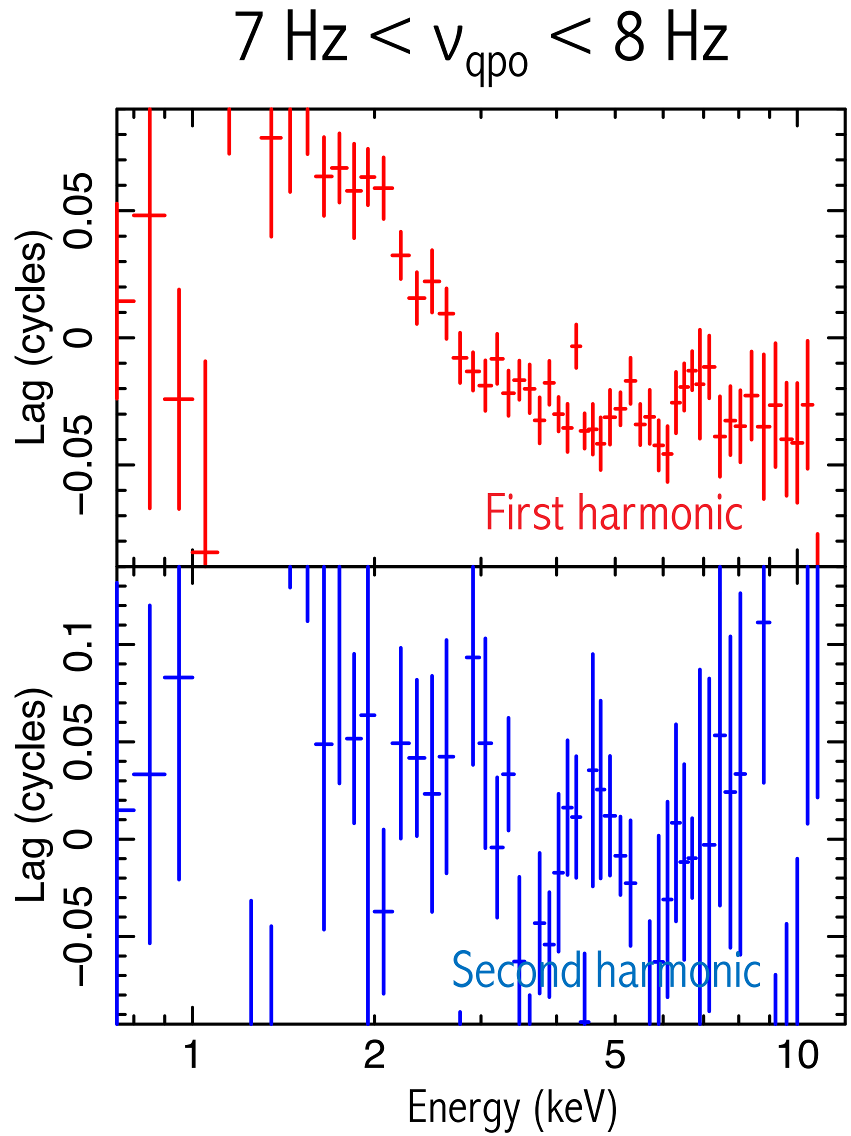
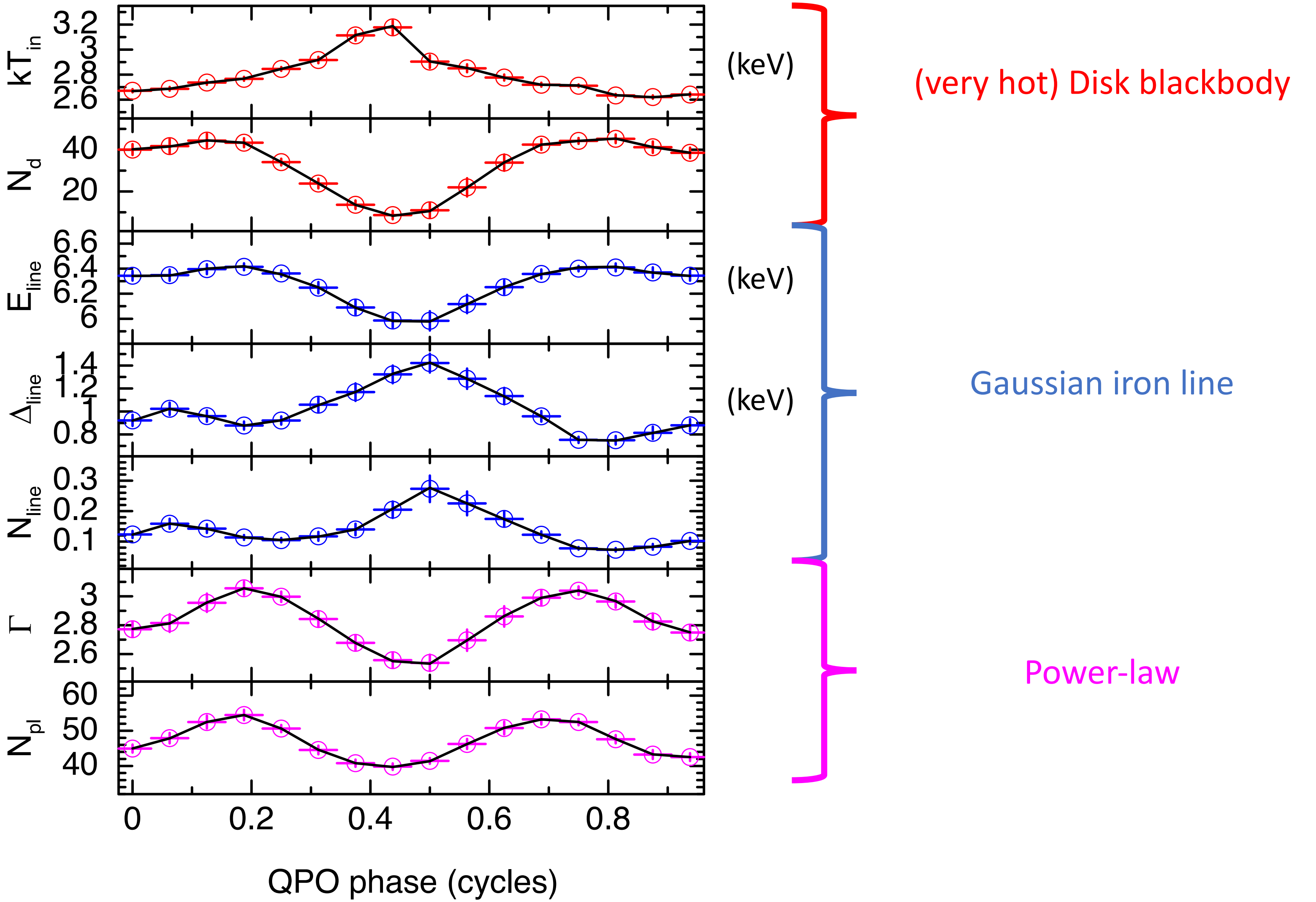


Uttley et al (in prep); Ingram et al (in prep)

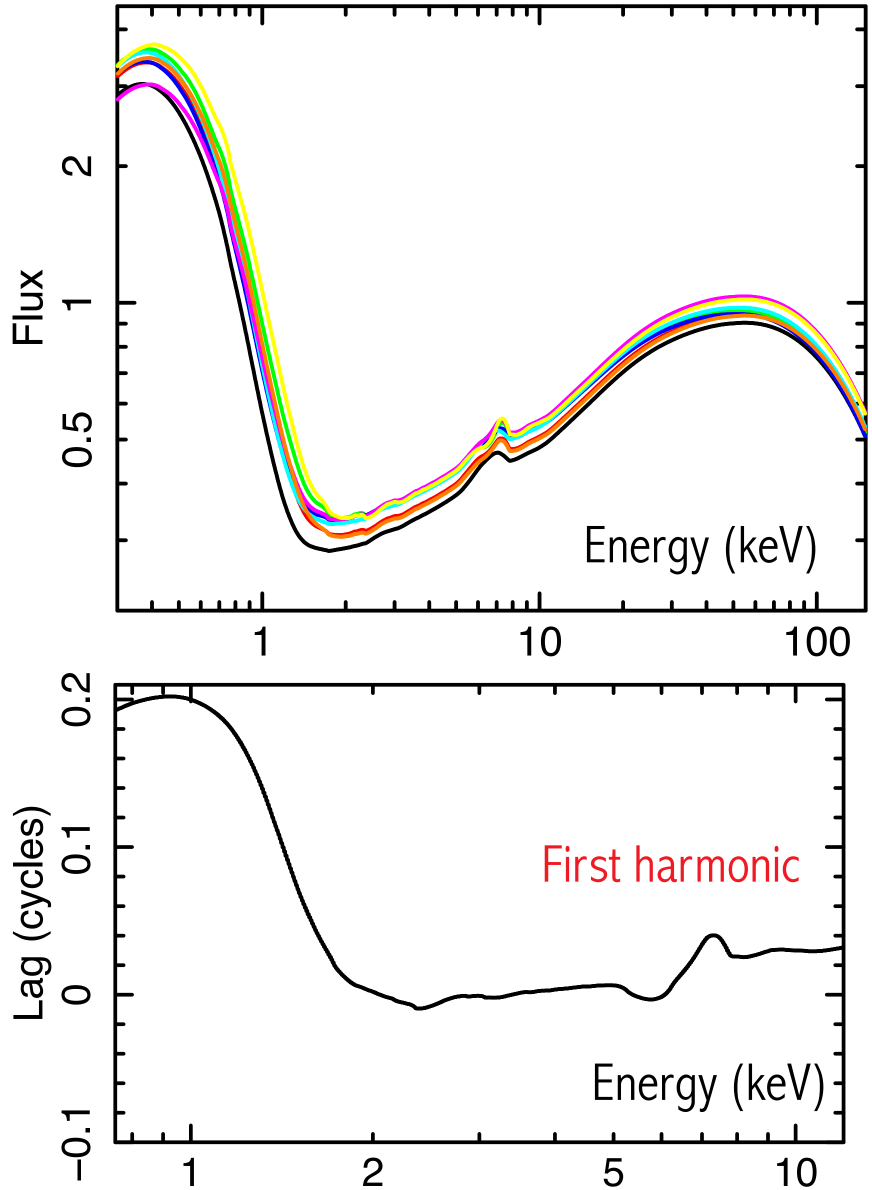
1.5 Hz < ν_{qpo} < 2 Hz



Thermal reprocessing

- Some fraction of irradiating flux thermalizes:
  $F_{th} = \sigma T_{irr}^4 \approx f F_{irr}$
- Use low density XILLVER grid ($n_e = 10^{15}\mathrm{cm}^{-3}$)
- Blackbody temperature of a disc patch:
  $T^4(r,\phi,\gamma) = T_{irr}^4(r,\phi,\gamma-\Delta\gamma) + T_{visc}^4(r)$
- i.e. thermalization timescale:
  $t_{th} = \Delta\gamma/(2\pi\nu_{qpo})$
- Model parameters are $T_{irr,max}(\gamma)$ and $T_{visc,max}(\gamma)$

- Could get big thermal component using high n_e grid, BUT: no intrinsic disc flux, no thermal lag, and model wouldn't be as fast!



Ingram et al (in prep)

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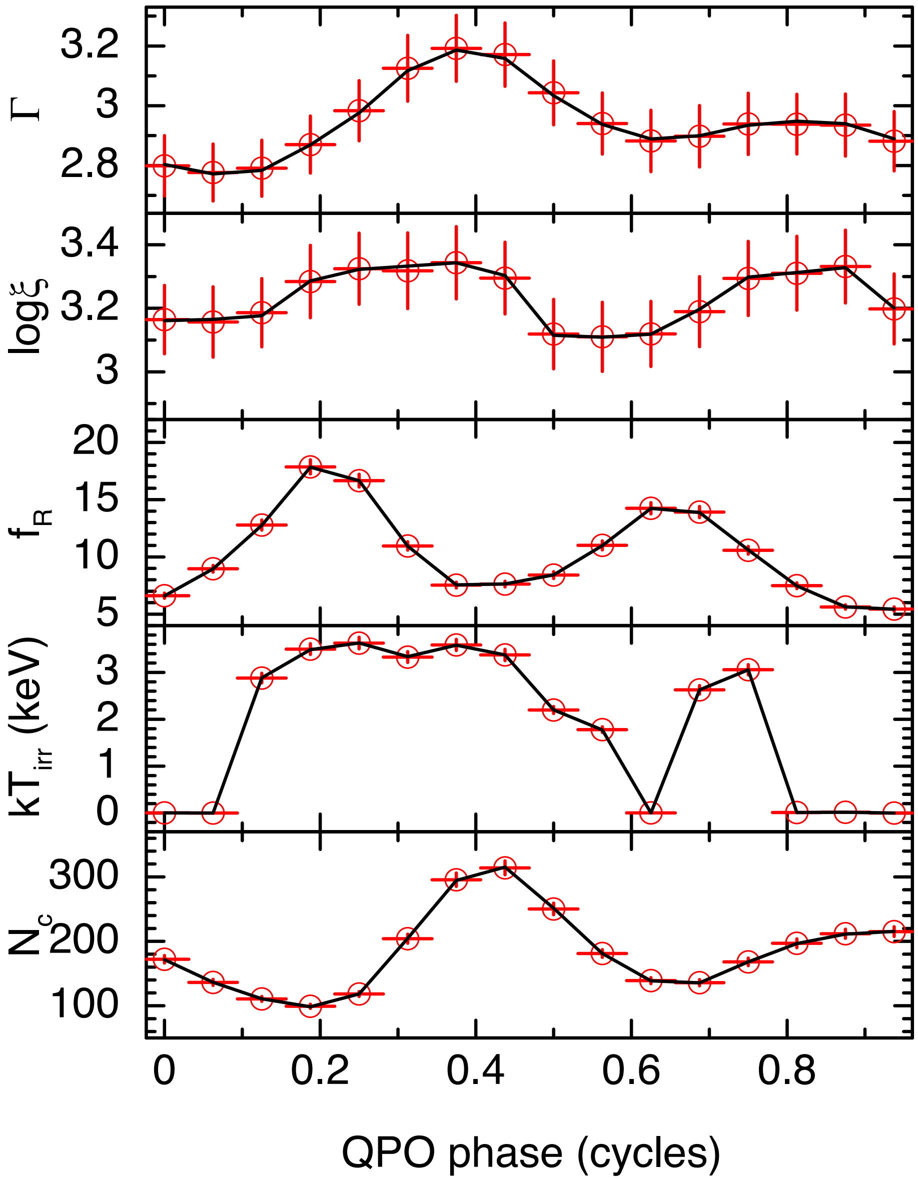


$$A_1 = 0.95^{+0.06}_{-0.17};$$
$$A_2 = 0.27^{+0.05}_{-0.04};$$
$$\Delta\gamma = 0.02^{+0.05}_{-0.38} \text{ cycles } (\sim 10 \text{ ms})$$

← Ionisation

← Reflection fraction (~reflected flux / continuum flux - excuse the arbitrary units)

← Disk heating temperature (i.e. peak irradiating flux ∝ kT_{irr}^4)

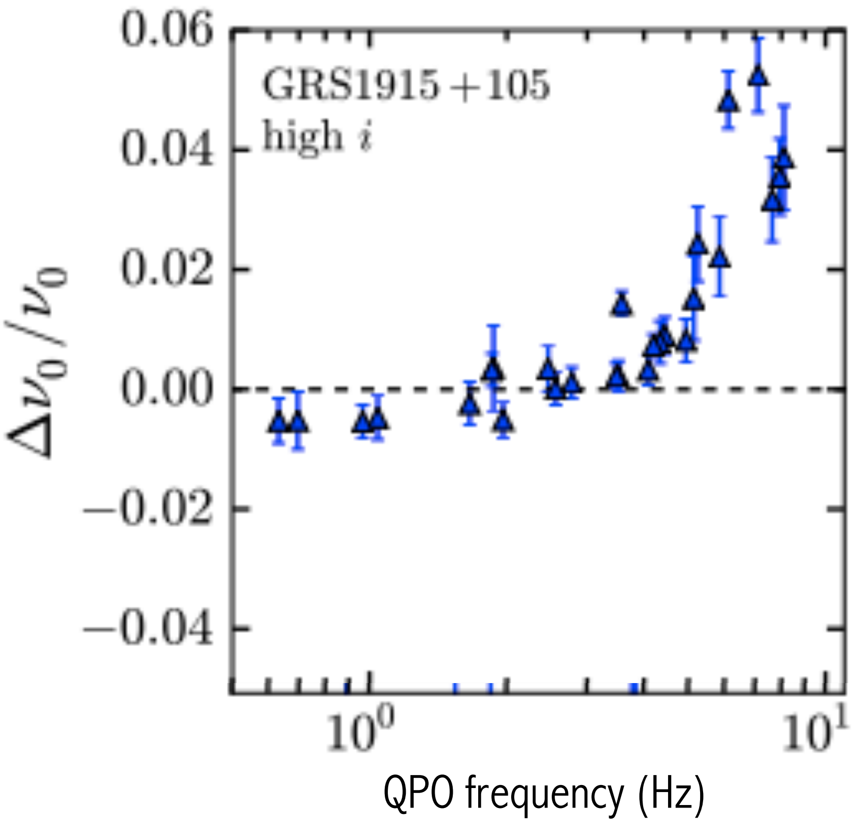
← Bolometric continuum flux

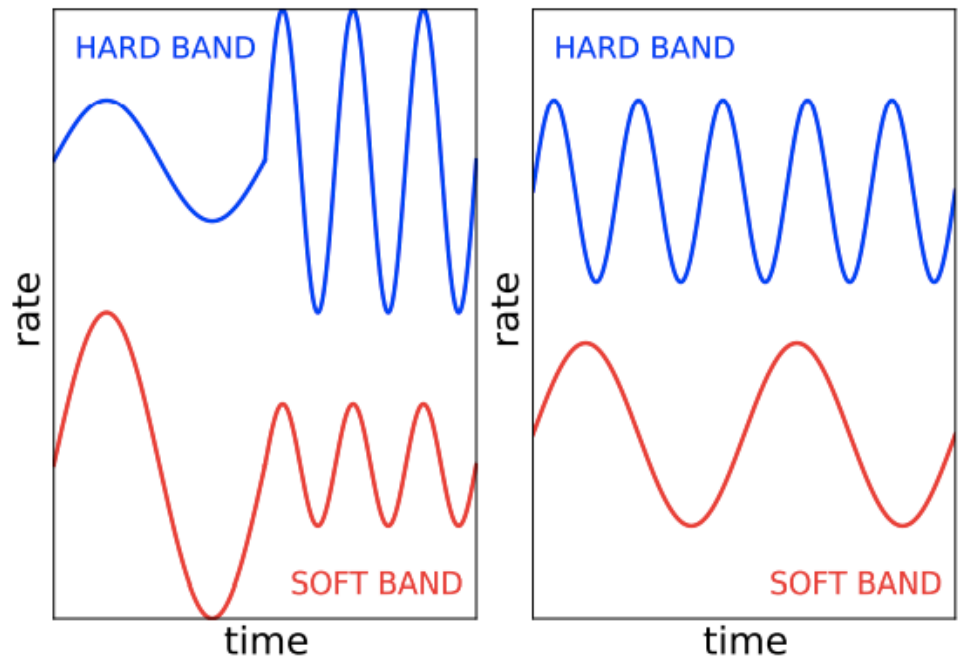
$$r_{in} < 2\,R_g$$

…what is precessing?

Differential precession?

In some sources, QPO frequency depends on energy
($\Delta\nu$=hard X-rays frequency - soft X-rays frequency)





van den Eijnden, Ingram & Uttley (2016)

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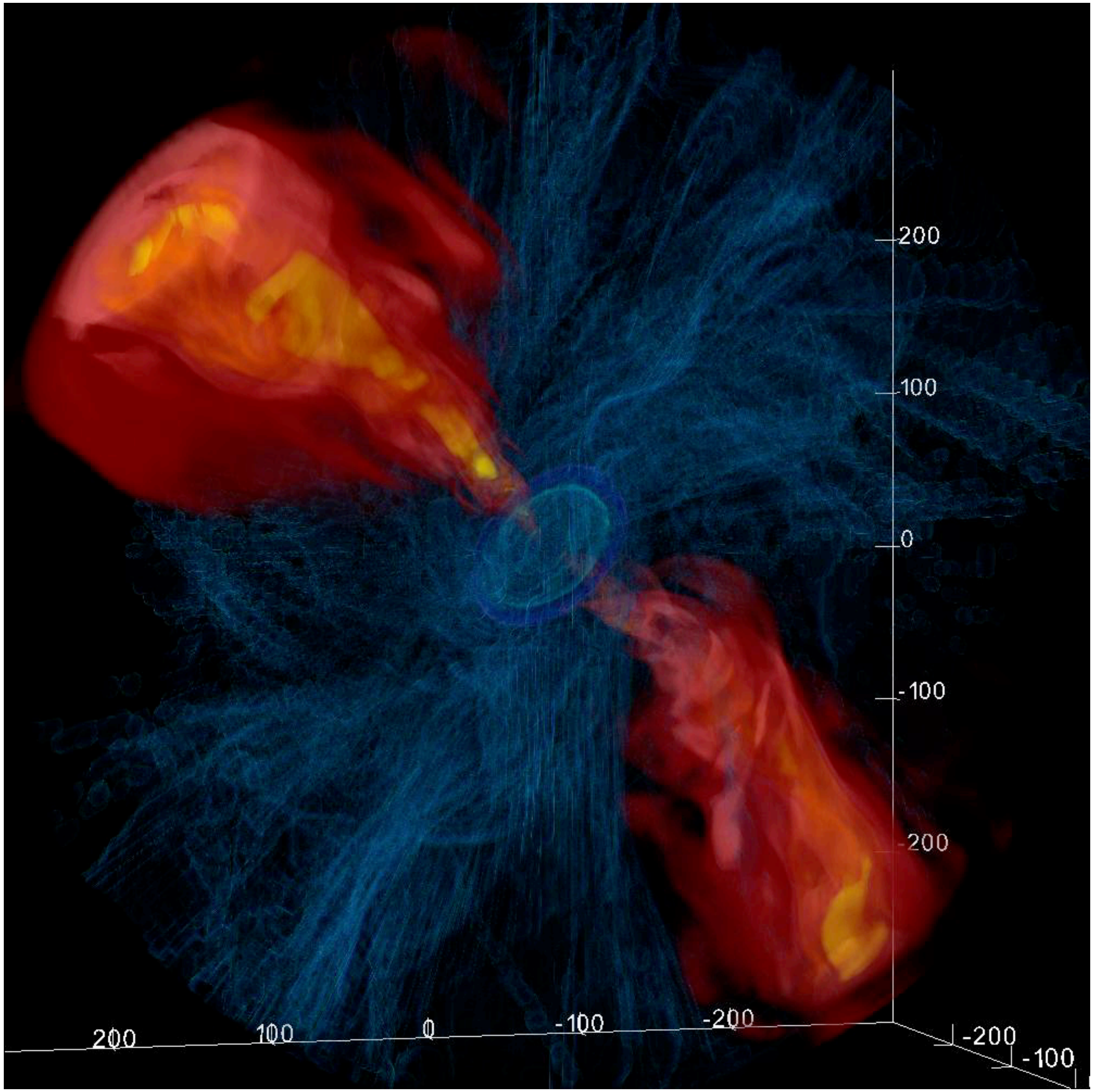
Differential precession?

H/R = 0.1 run:

jet lags corona, which lags disc!



Liska, Hesp, Tchekovskoy, Ingram et al (submitted)

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Conclusions

- Inclination dependencies: Type C QPOs are geometric effect
- All QPO models in the literature assume frequency changes driven by moving radius
- GRMHD: GR can cause jets and thick discs to precess, and tear very thin discs
- QPO waveform evolves smoothly with centroid frequency, hints of an inclination dependence
- Iron line centroid energy modulation + reflection fraction modulation => QPOs driven by precession
- Even stronger evidence in MAXI J1535-571, broad iron line requires small disc inner radius: what is precessing, or what is the spectral model missing?
- Need some differential precession to explain energy dependence of QPO frequency (even more spectacular in HXMT data)