Quasi-periodic oscillations in black hole X-ray binaries

Adam Ingram

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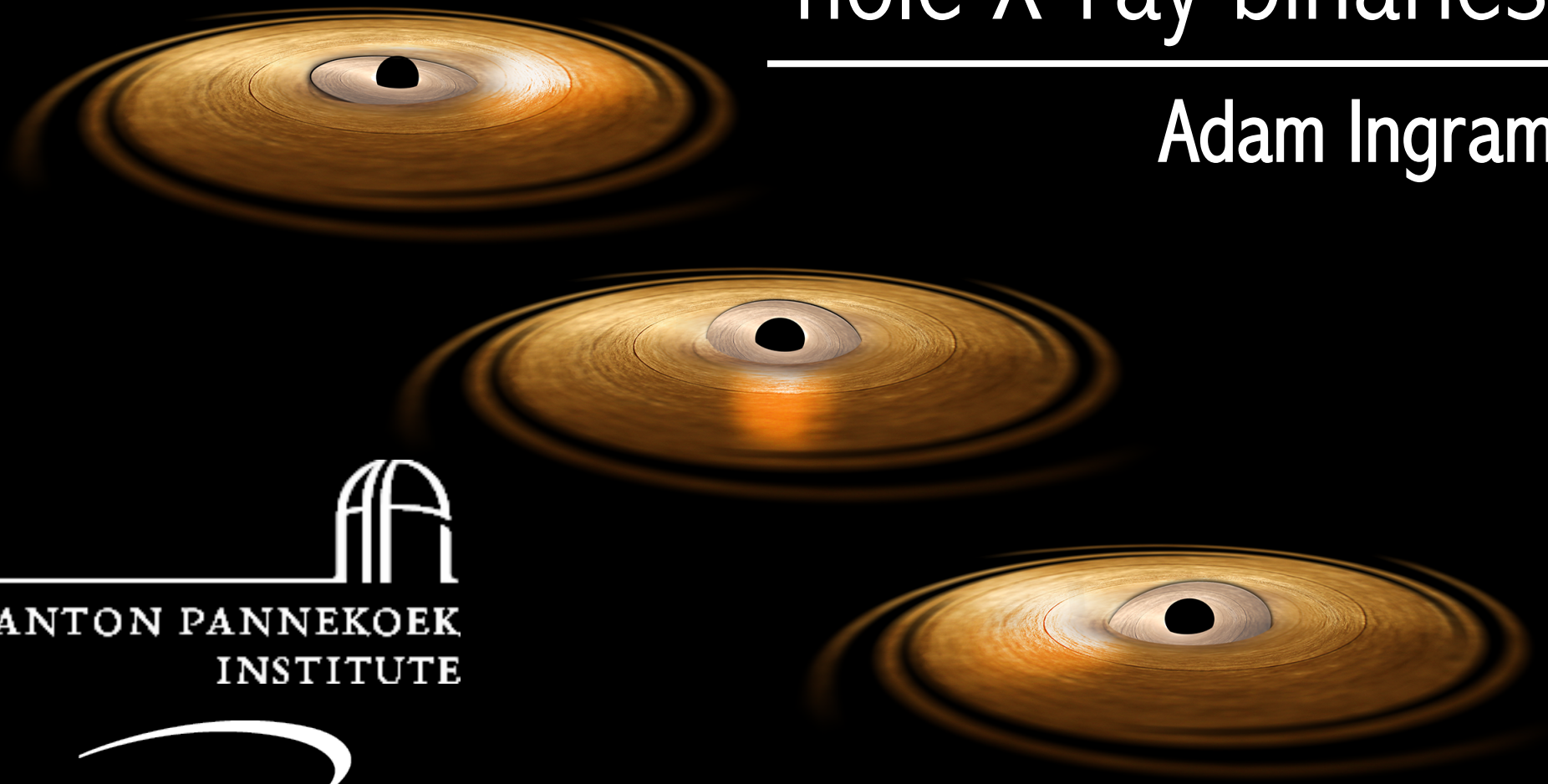
NWO



Shining from the heart of darkness

Kathmandu

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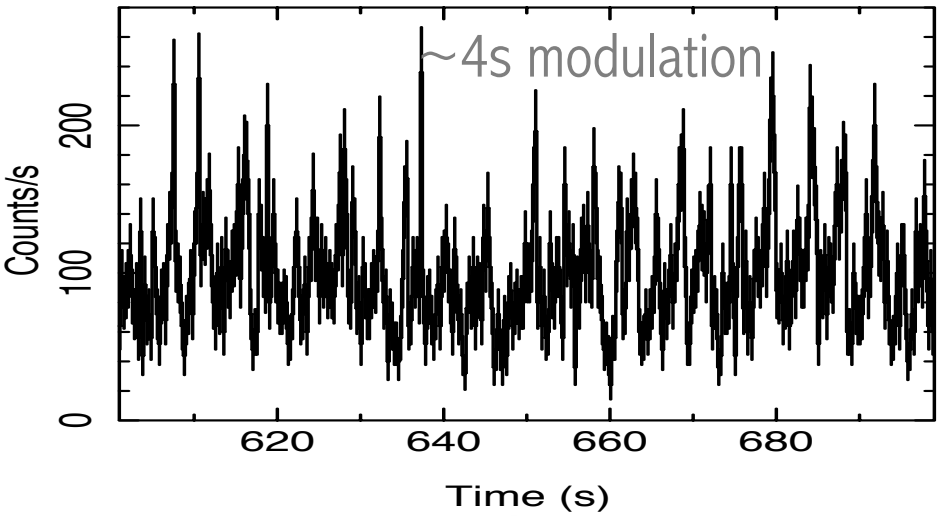
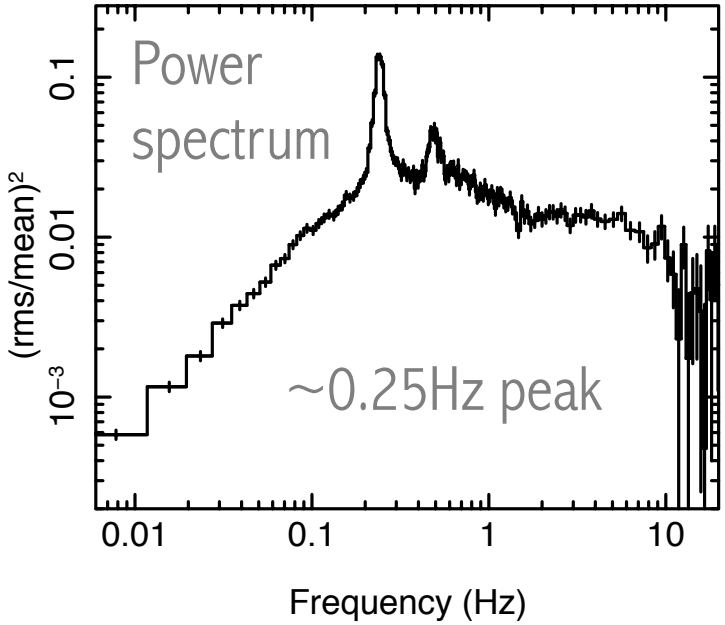
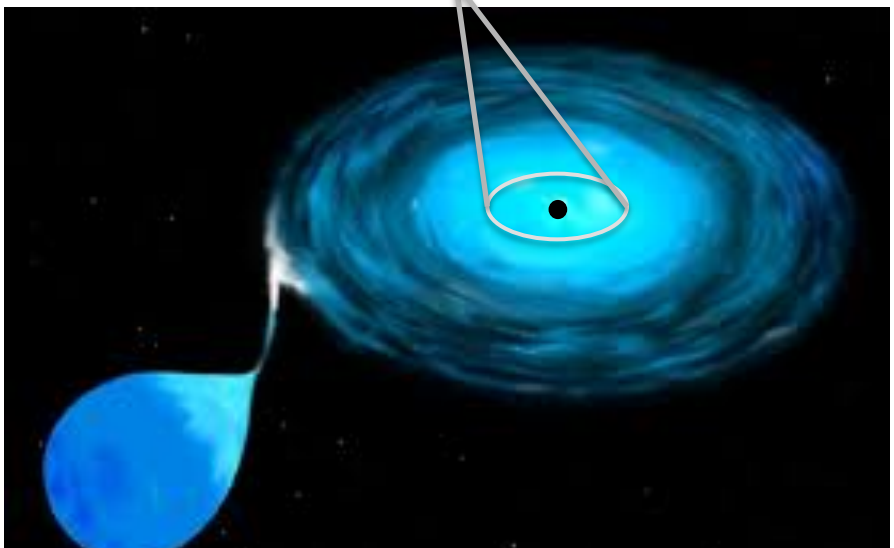
Rapid X-ray variability

- X-ray radiation from black hole vicinity: strong field GR
- Fast variability provides probe of this region
- Best studied in Fourier space







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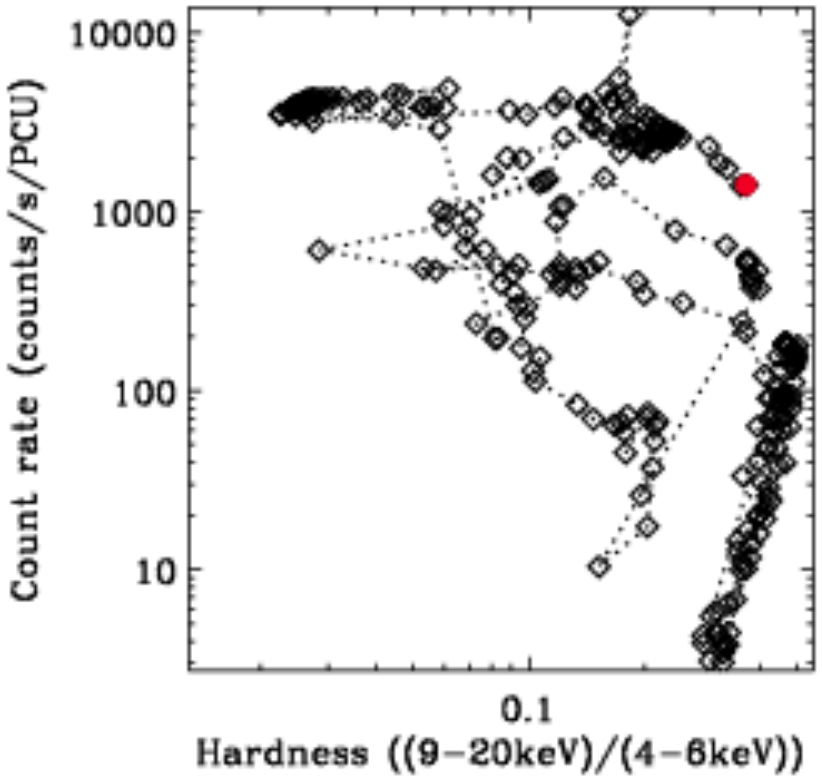
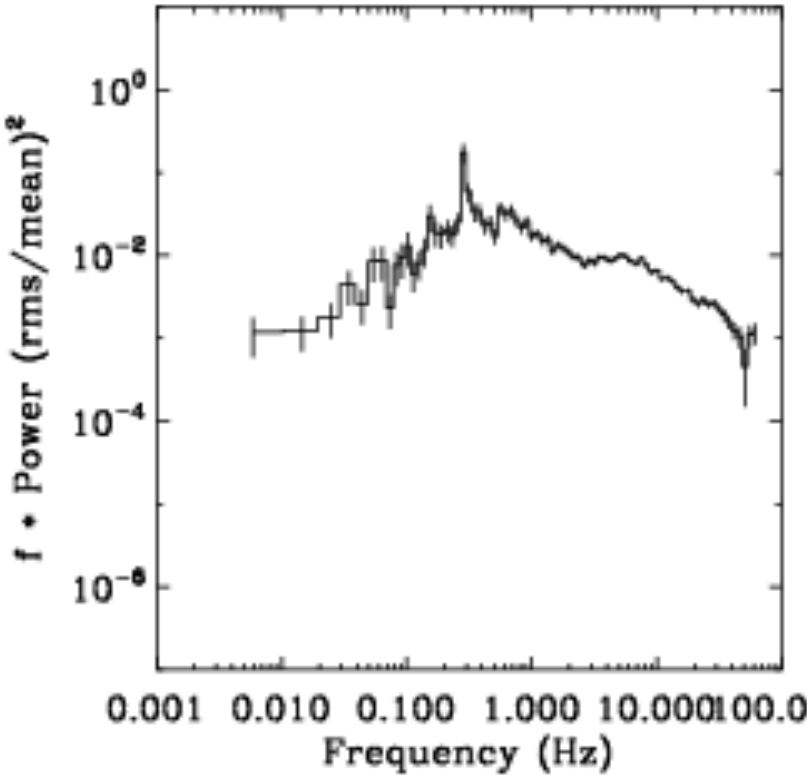
Low frequency QPOs

Hardness Intensity Diagram



Power spectrum



e.g. Belloni (2010)

Credit: Lucy Heil

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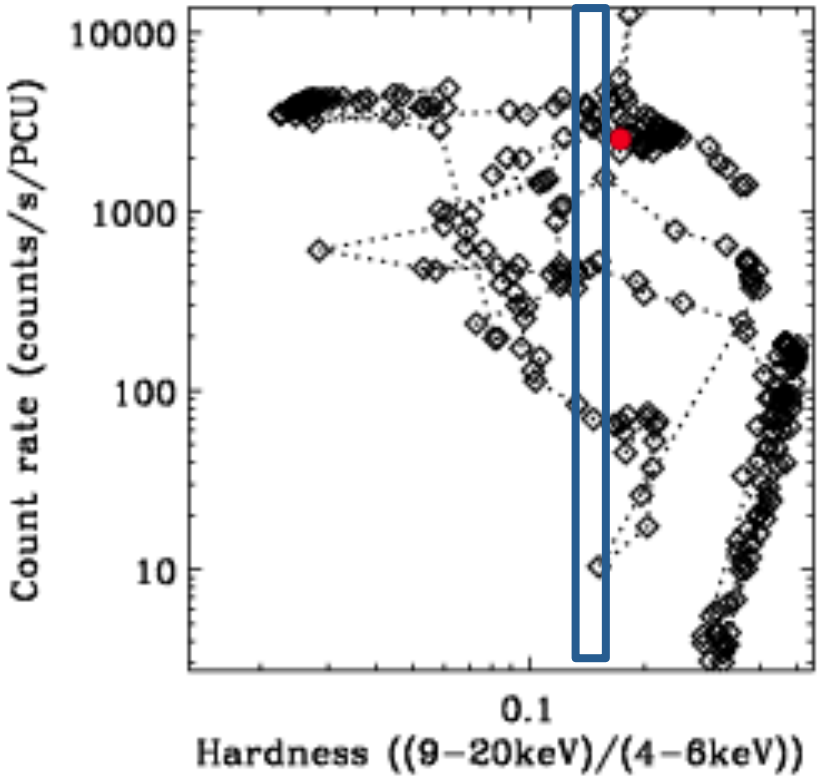
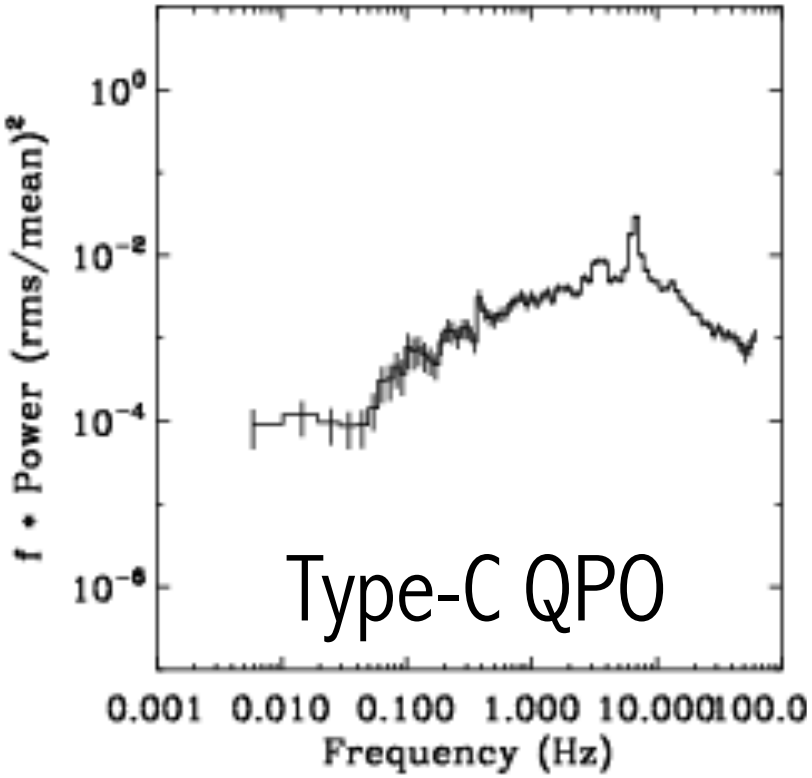
Low frequency QPOs

Hardness Intensity Diagram



Power spectrum



Credit: Lucy Heil

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Low frequency QPOs

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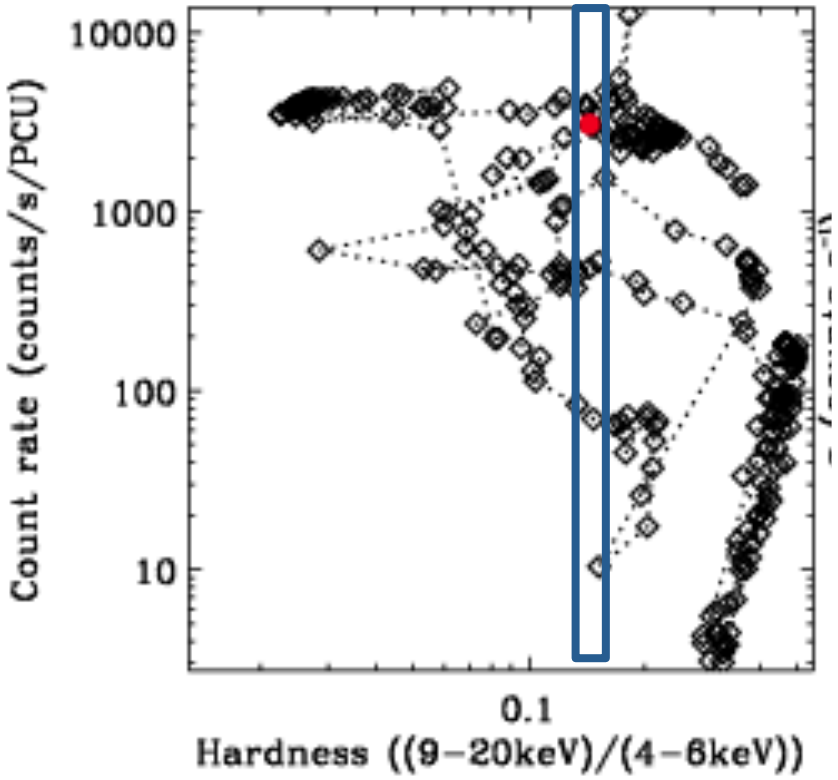
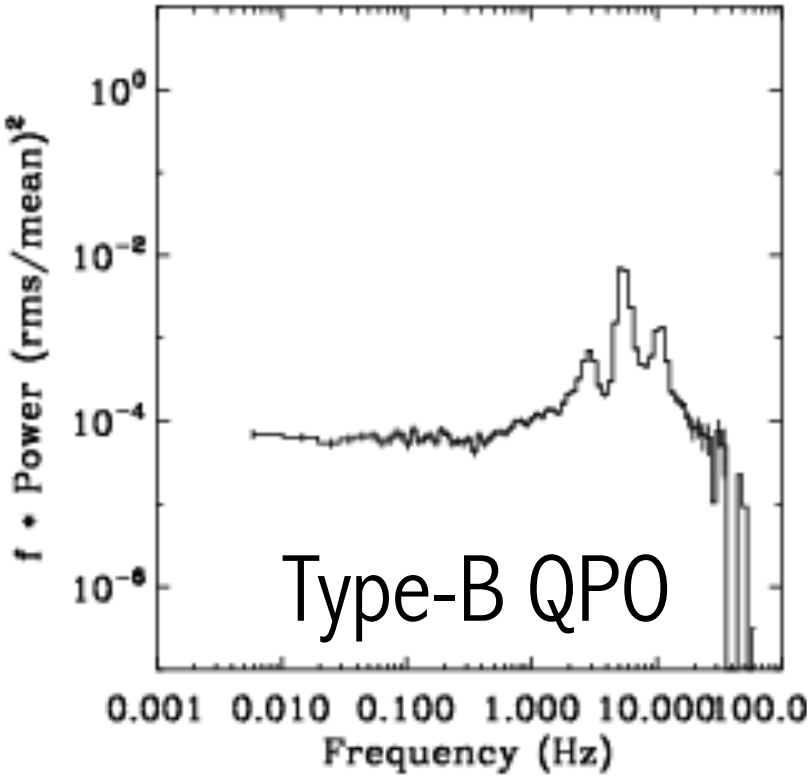


Power spectrum



Credit: Lucy Heil

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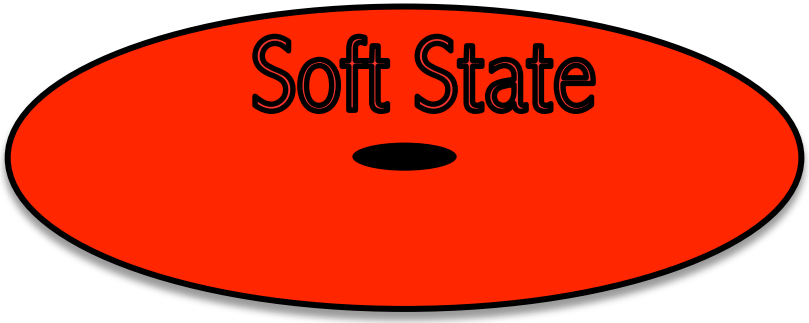
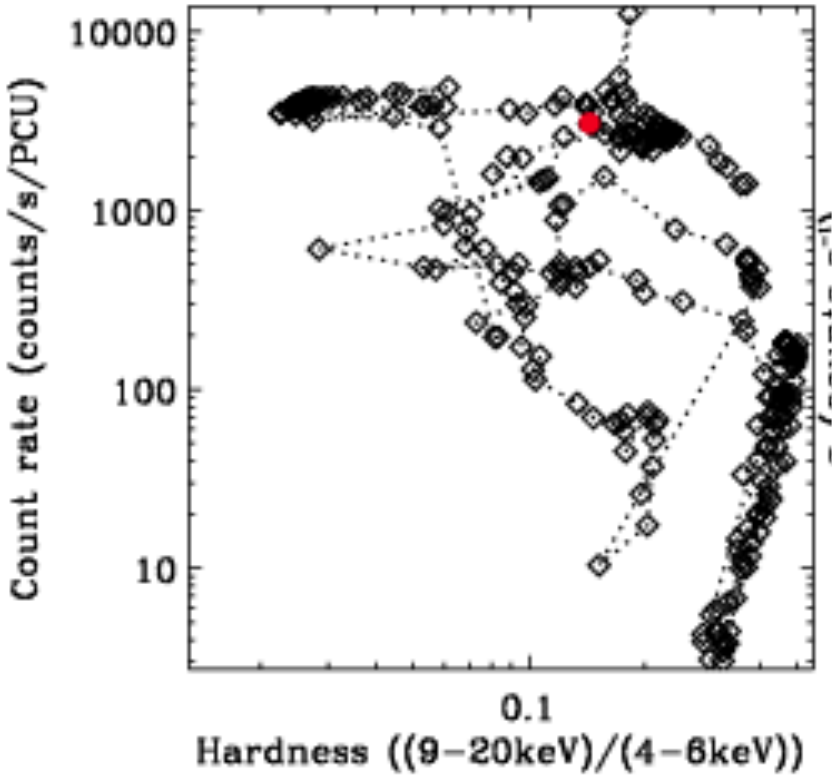
Truncated Disk Model





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

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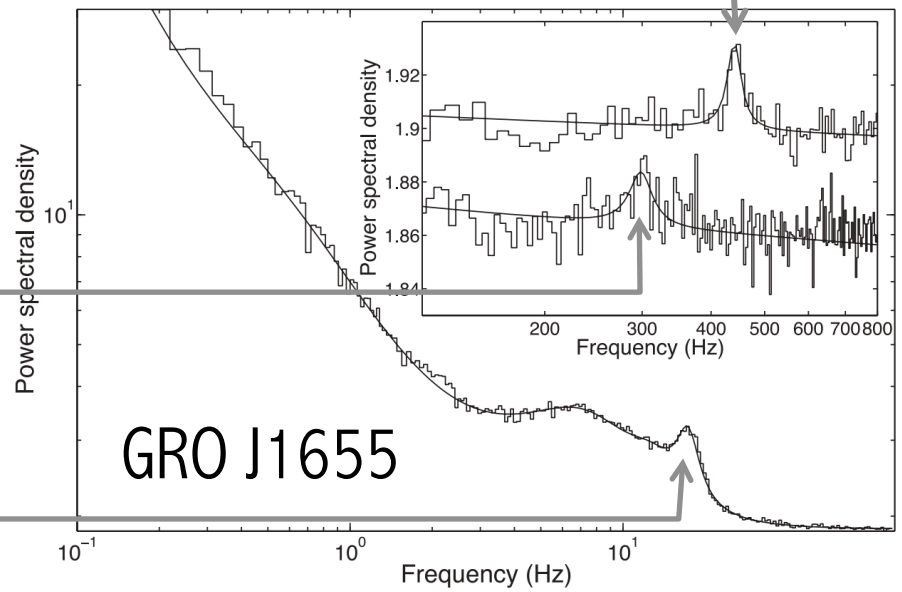
High frequency QPOs

Upper HF QPO

Lower HF QPO

LF QPO



HF QPO frequency range in BHs: >~100 Hz

Very rare, very noisy data.

Motta et al (2014)

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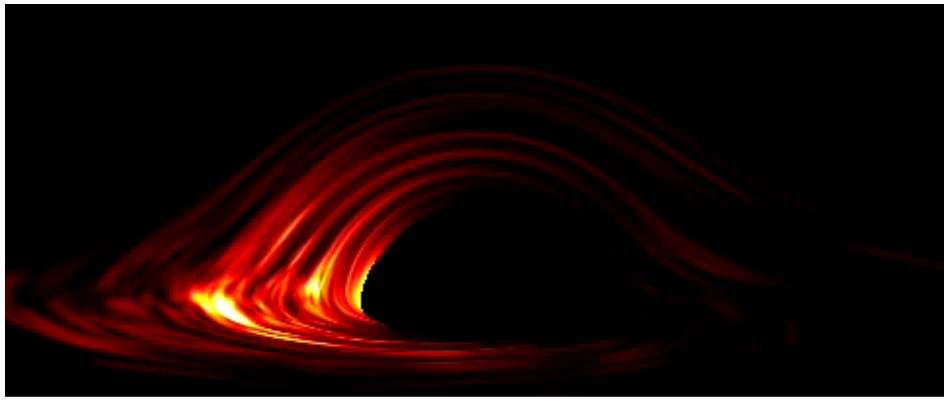
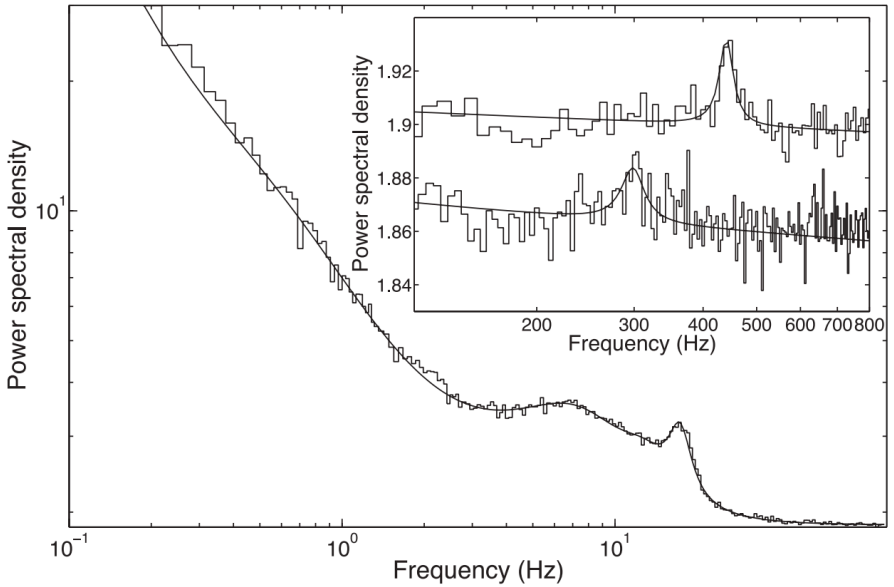
High frequency QPOs



Credit: Phil Armitage & Chris Reynolds
http://jila.colorado.edu/~pja/black_hole.html



HF QPO frequency range in BHs: >~100 Hz

Very rare, very noisy data.

But ~rotational frequency of inner accretion flow!

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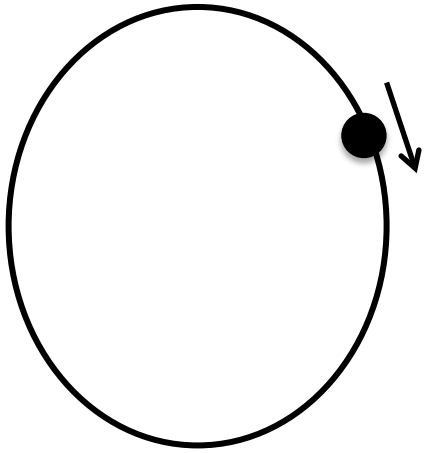
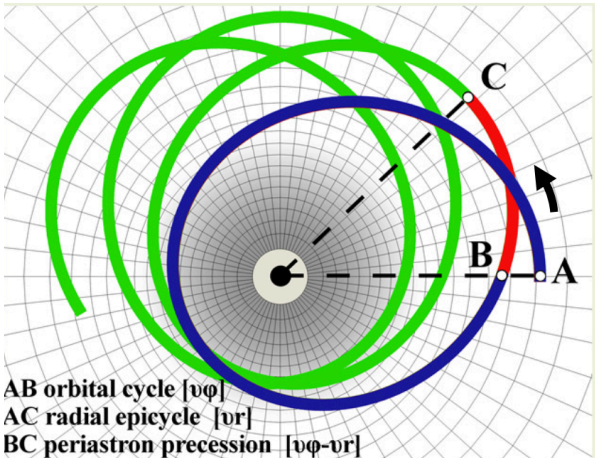
Relativistic precession model

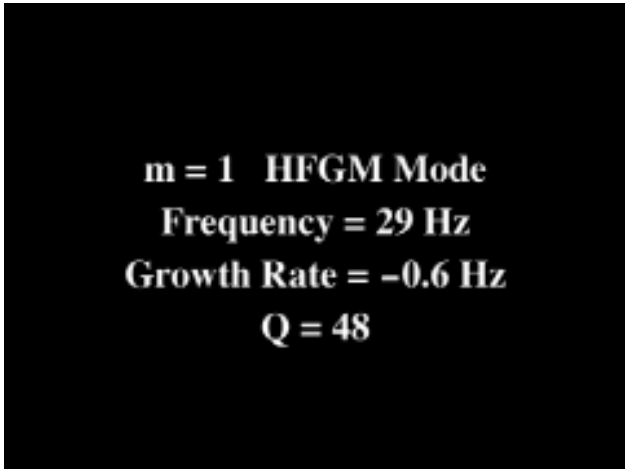
Upper HF QPO



Lower HF QPO



Type C QPO



Orbital motion

Periastron precession

Lense-Thirring precession

Motta et al (2014)

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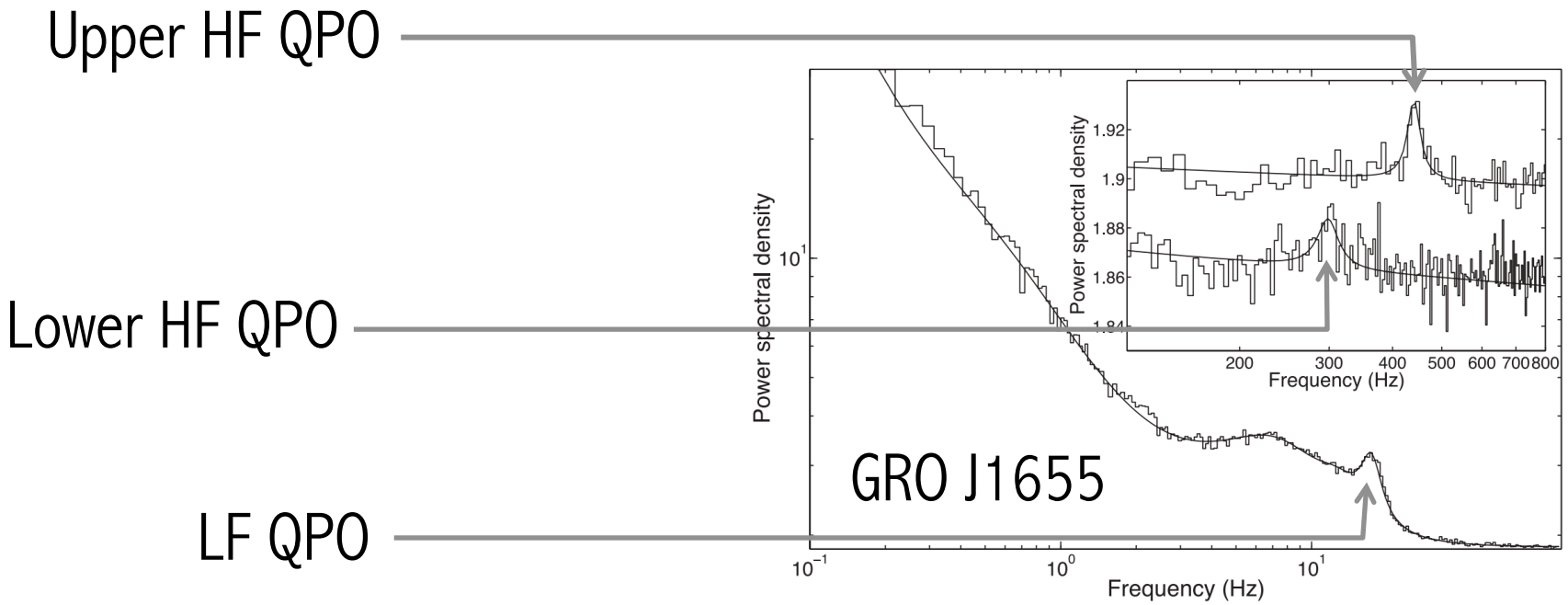
Relativistic precession model



Motta et al (2014):

- All 3 frequencies depend on BH mass and spin
- Therefore if you see all 3 QPOs, can solve for BH mass and spin!
- In the 1 instance: $M = 5.31 \pm 0.07\ M_{\odot}$ agrees with optical mass!

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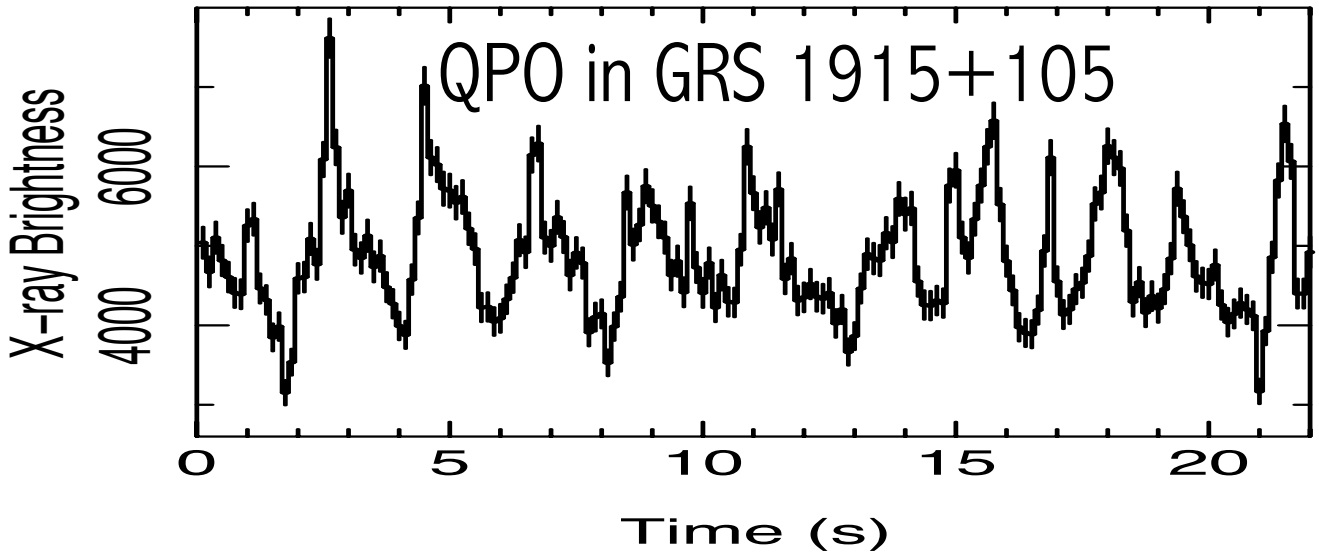
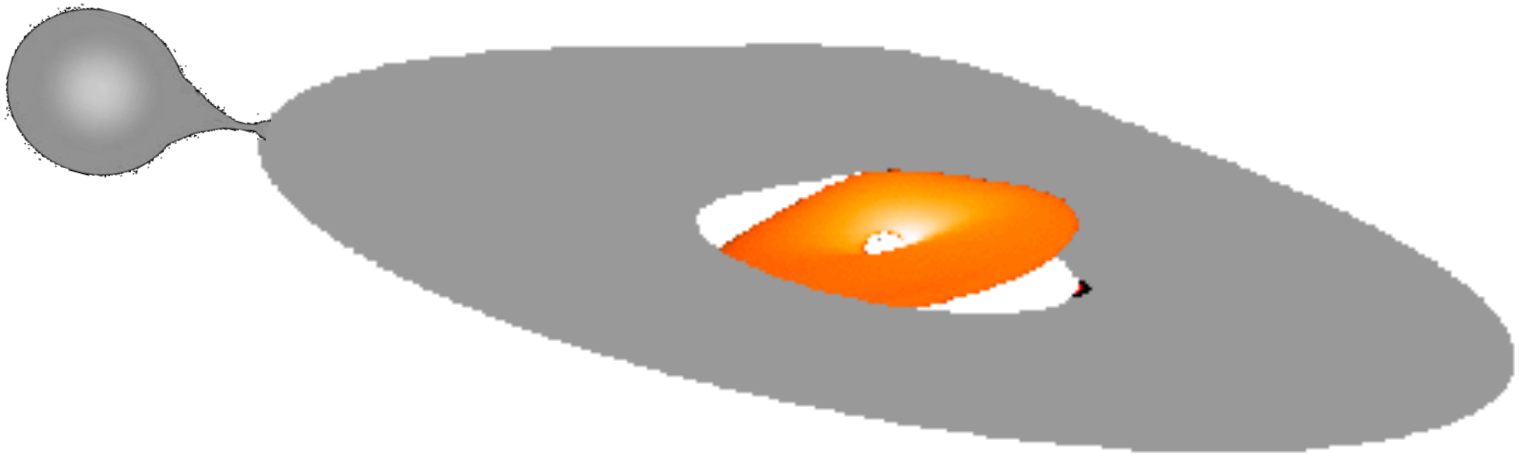
Precessing flow





Ingram, Done & Fragile (2009)

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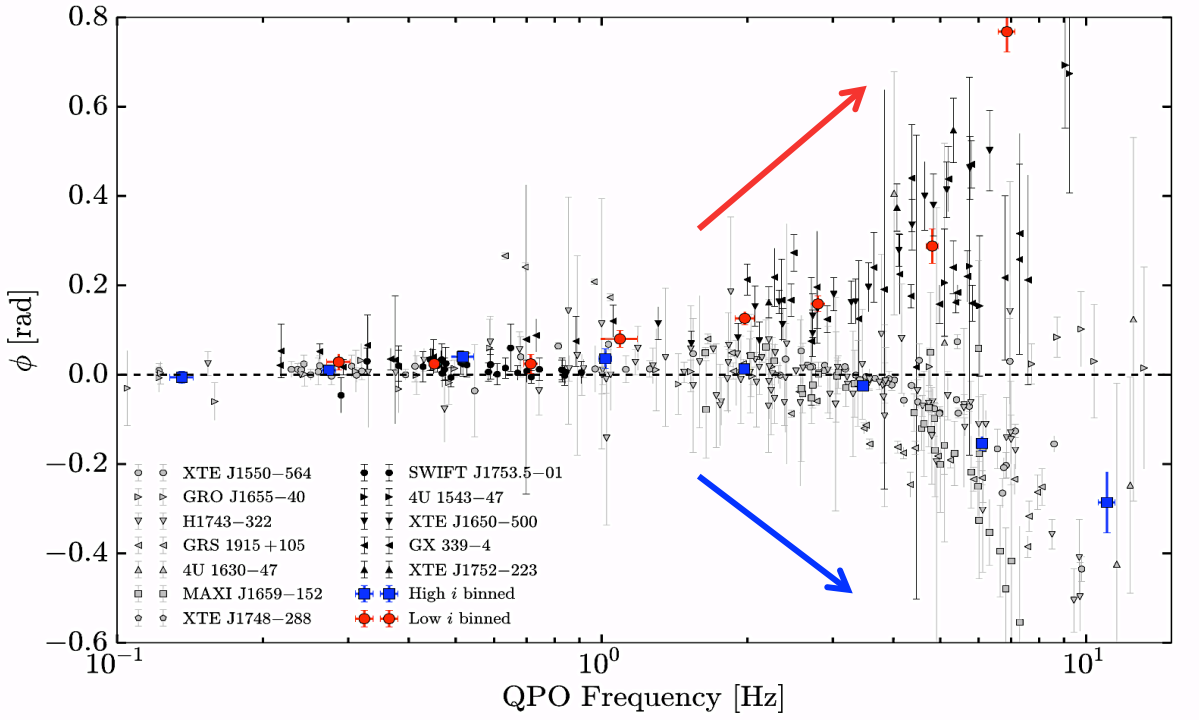
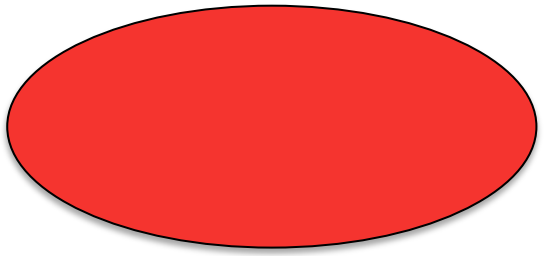
Inclination effects

1) QPO amplitude higher for higher inclination sources

(Schnittman et al 2006; Heil et al 2015, Motta et al 2015)



Low inclination



High inclination

2) QPO phase lags depend on inclination (van den Eijnden, Ingram et al 2016)

➔ Geometric!

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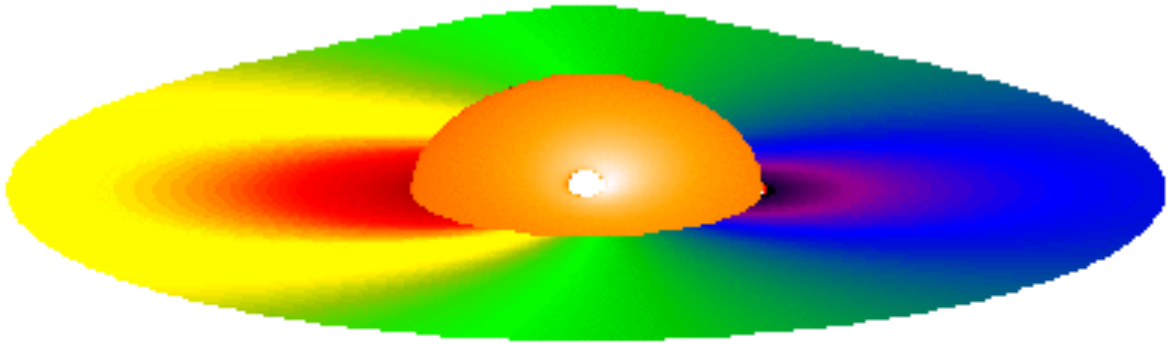
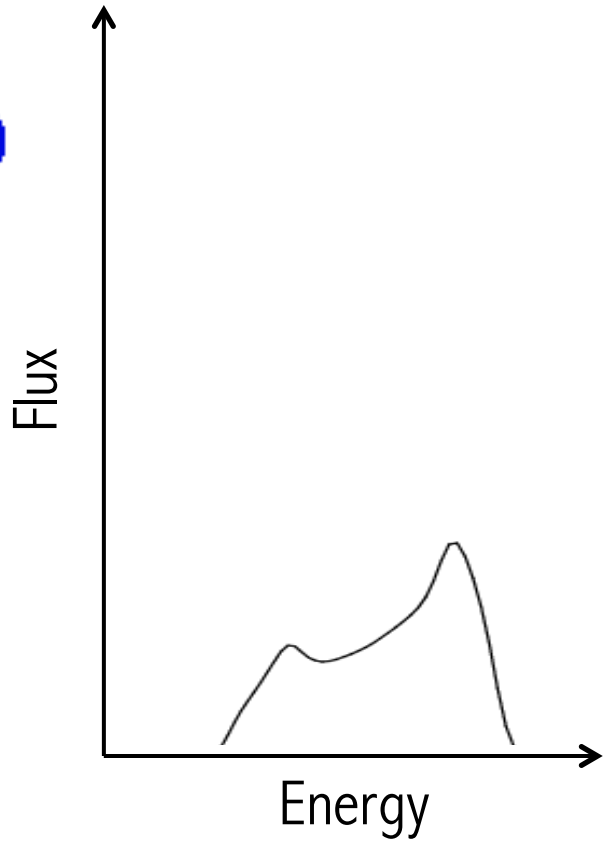
Precessing flow

Tell-tale sign of precession: a rocking iron line





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

Ingram & Done (2012)

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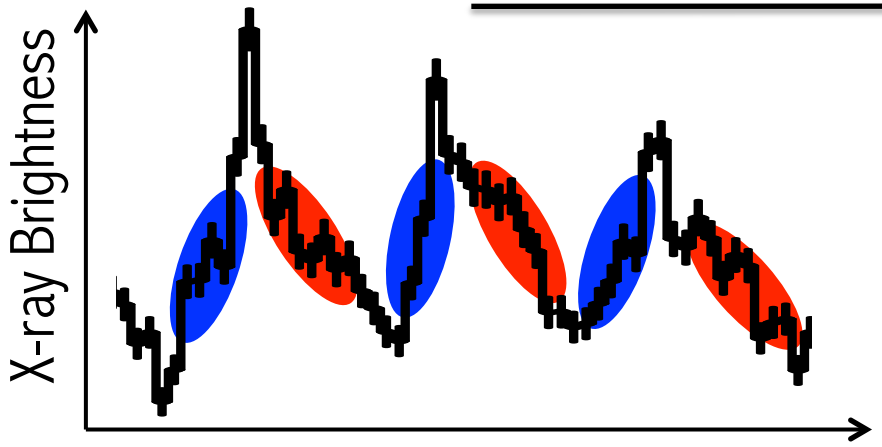
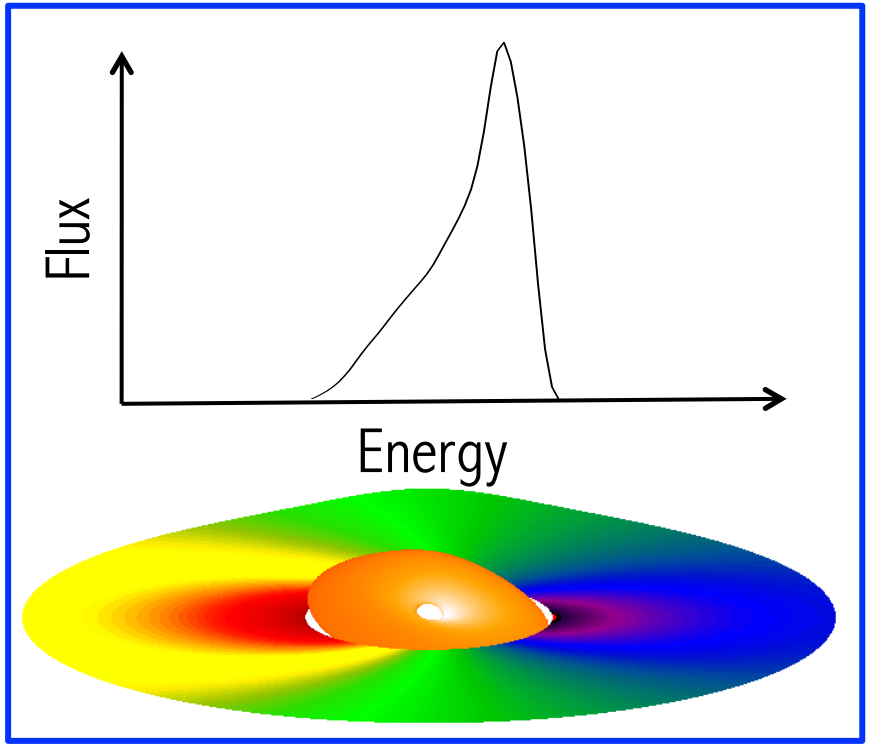
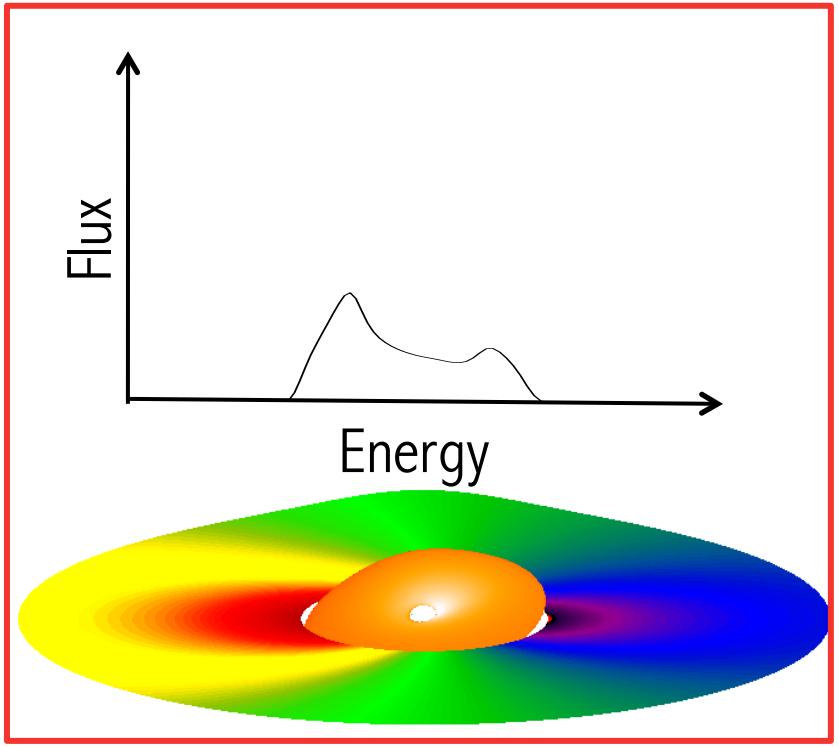
Phase Resolving







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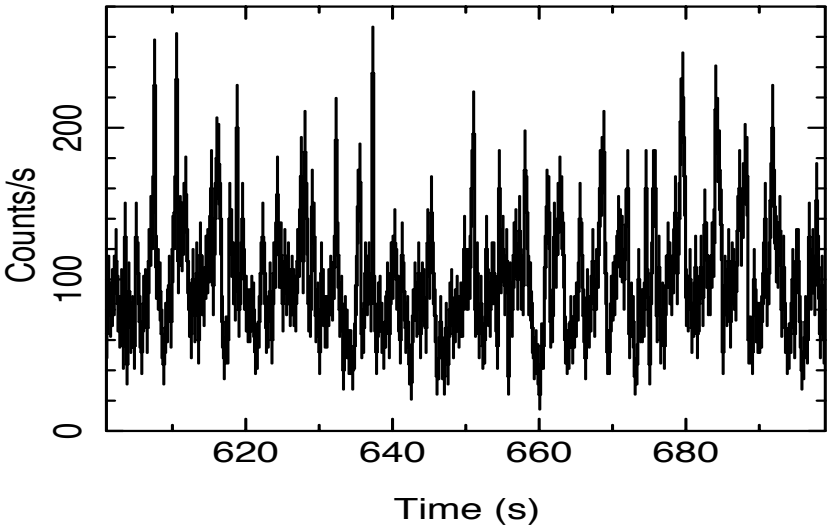
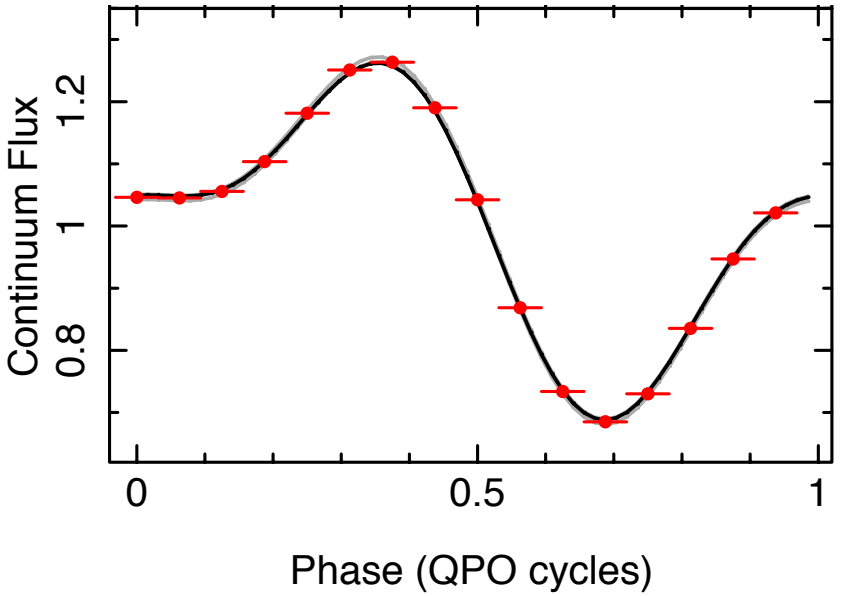
Phase Resolving

Reconstruct QPO waveform in each energy band from:

1. Amplitude of fundamental (power spectrum)
2. Amplitude of overtone (power spectrum)
3. Phase difference between fundamental and overtone (Ingram & van der Klis 2015)





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

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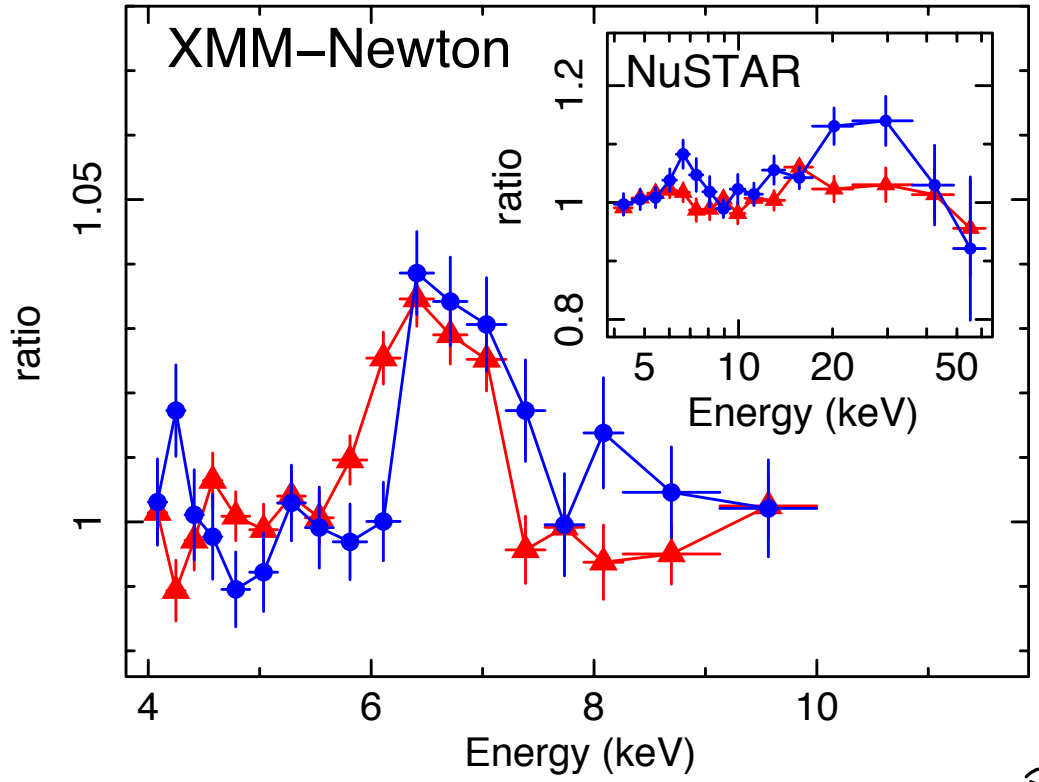
Rocking iron line!

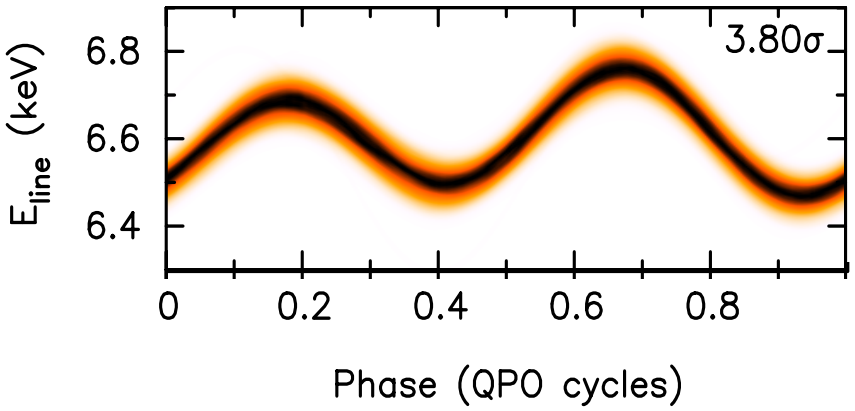


H 1743-322 Observation

~260 ks XMM-Newton

~70 ks NuSTAR

QPO: ~0.21 – 0.25 Hz



Ingram et al (2016a)

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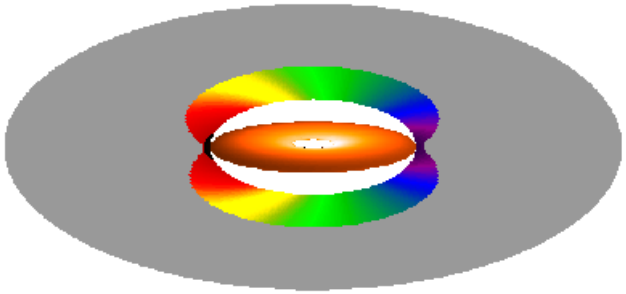
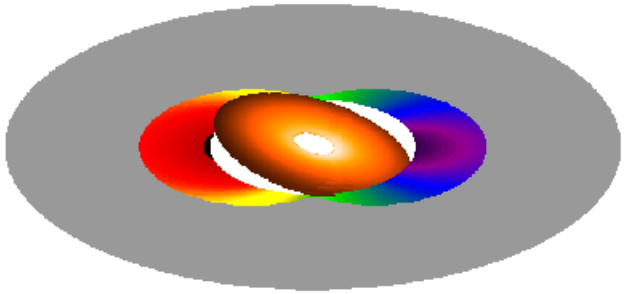
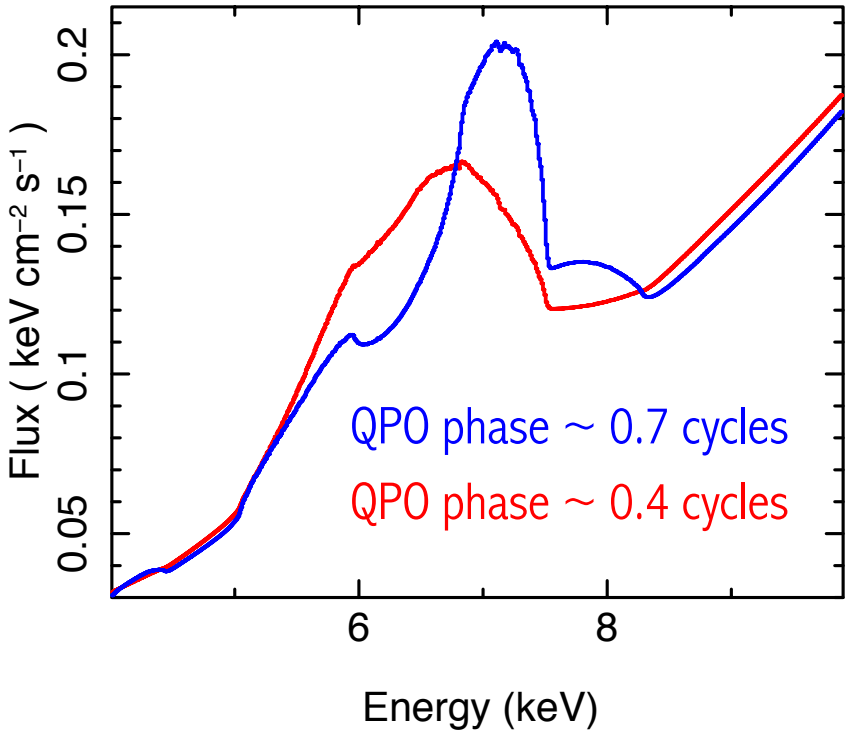
Rocking iron line!

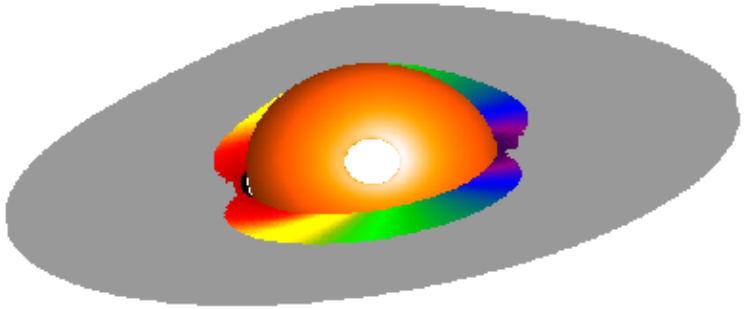
QPO phase ~ 0.4 cycles

QPO phase ~ 0.7 cycles









Ingram et al (2016b)

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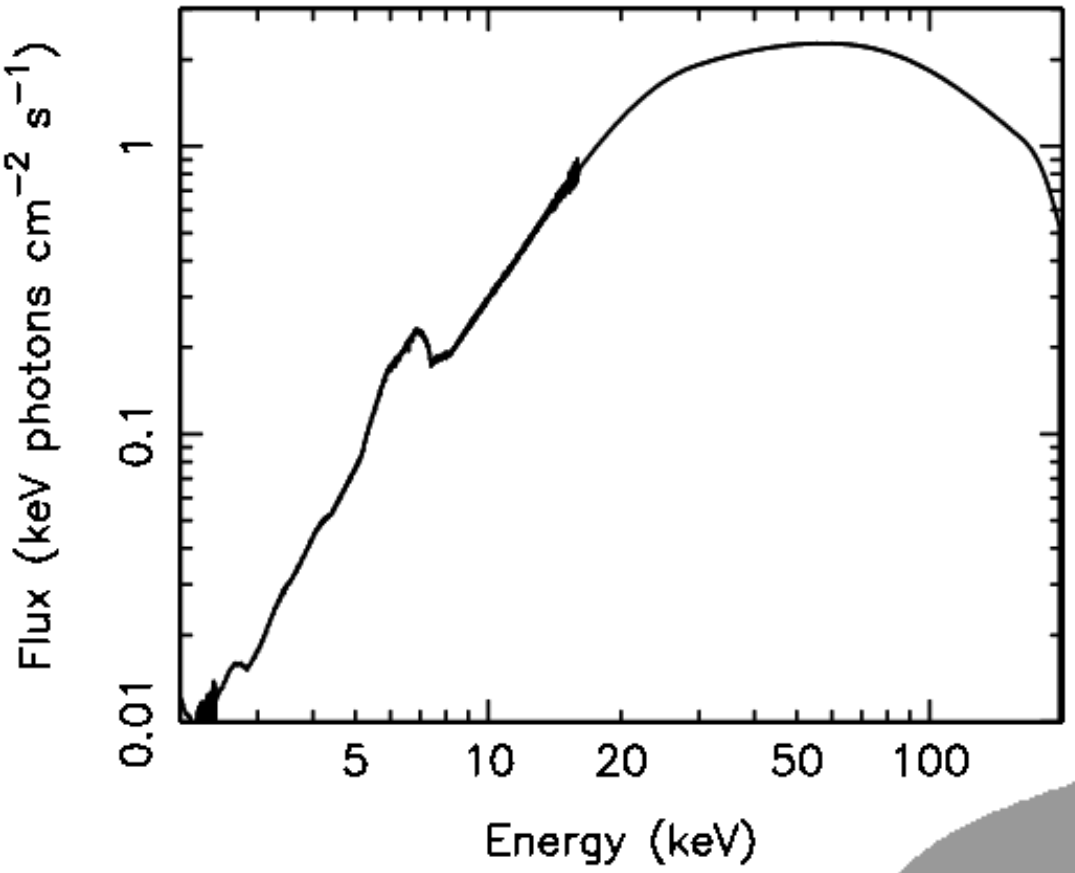
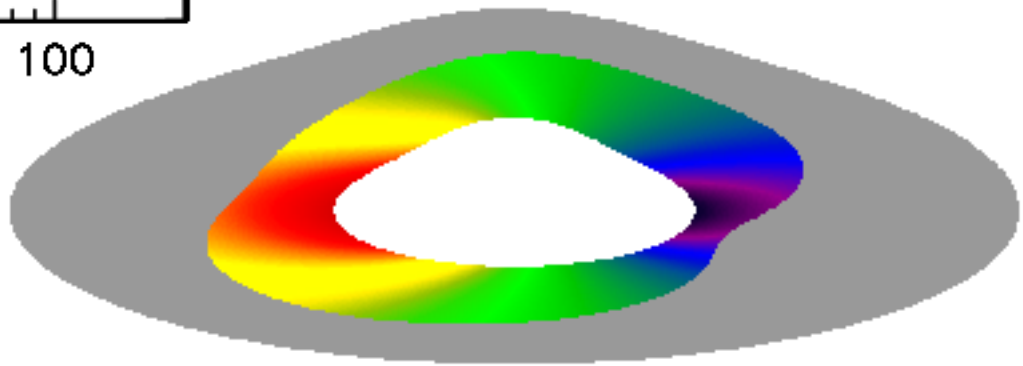
Tomographic mapping



Parameterize disk illumination:

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



$r_{in} = 31.47^{+5.8}_{-3.7}\ R_g$

$i = 70.68^{+2.7}_{-3.2}$ degrees

Ingram et al (2016b)

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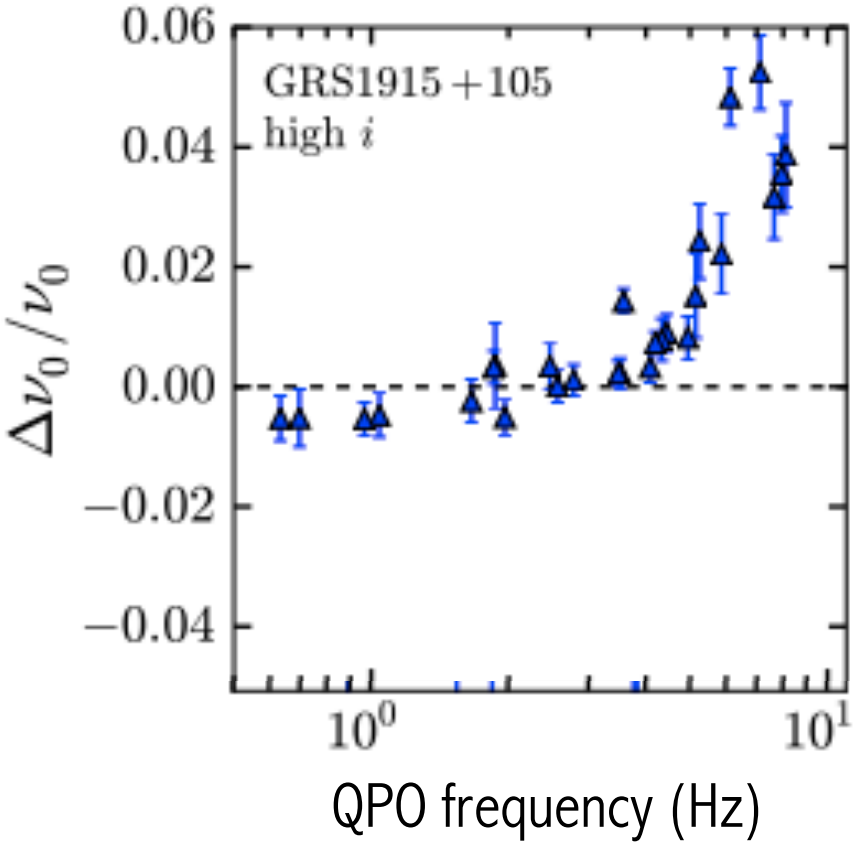
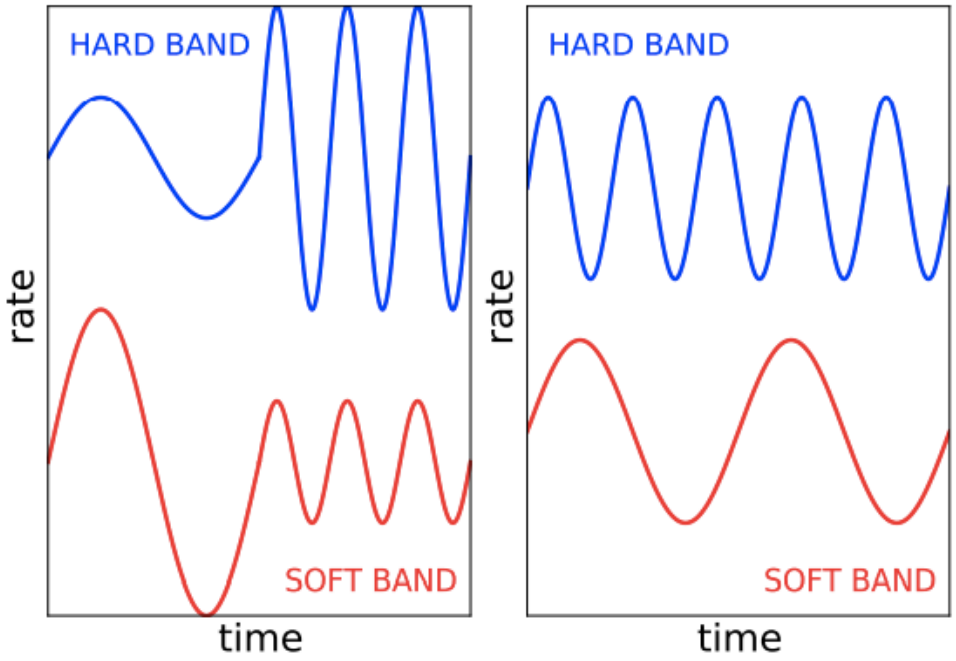
Differential precession?

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





van den Eijnden, Ingram & Uttley (2016a)

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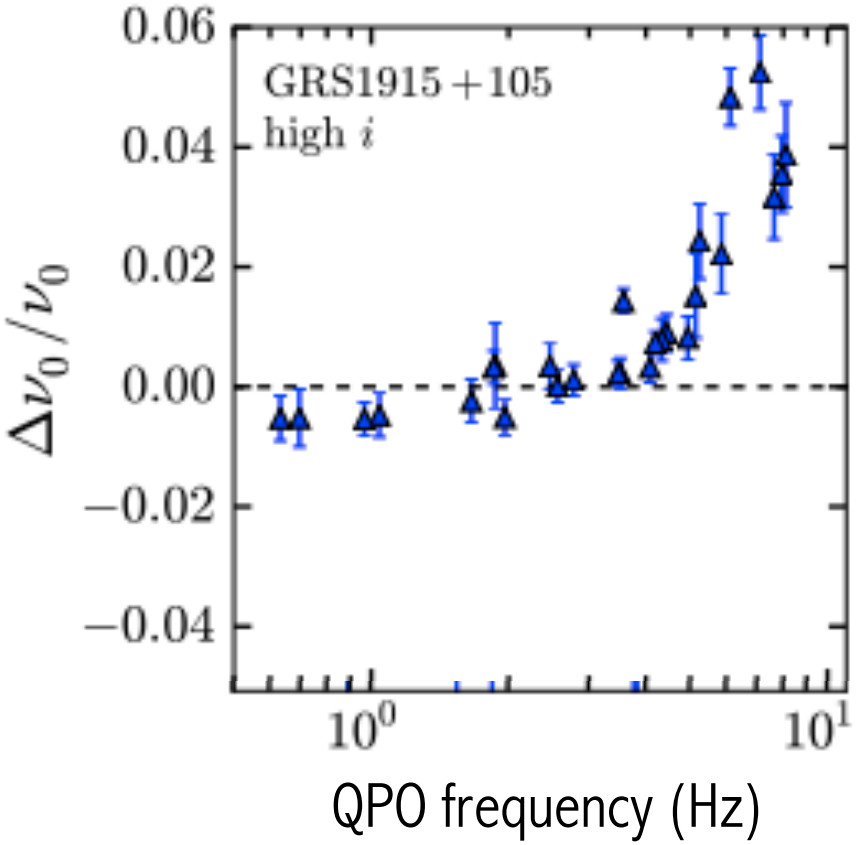

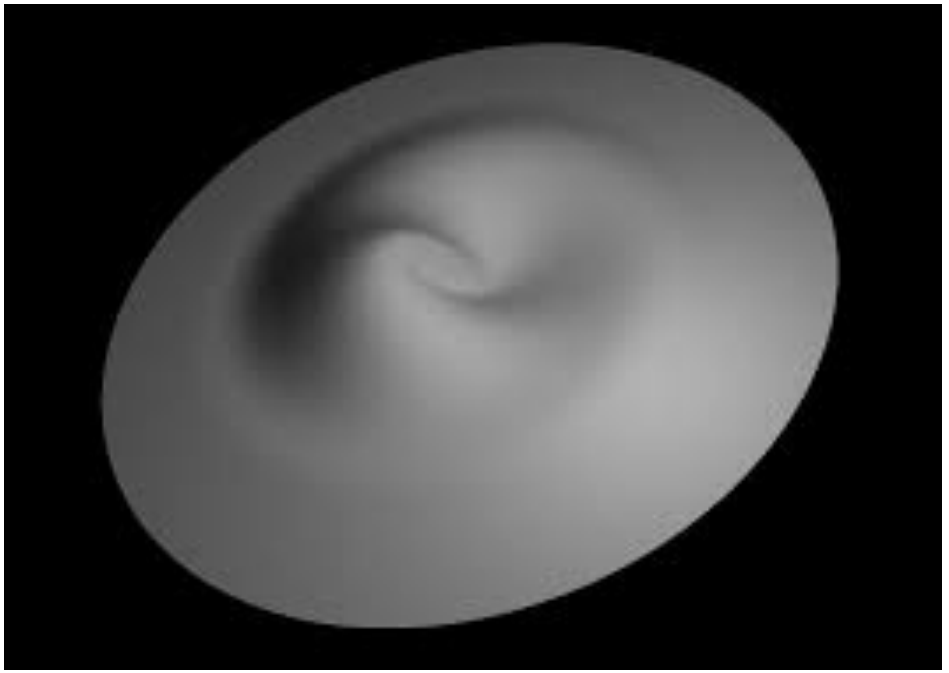

van den Eijnden, Ingram & Uttley (2016a)

Image from Martin et al (2008)

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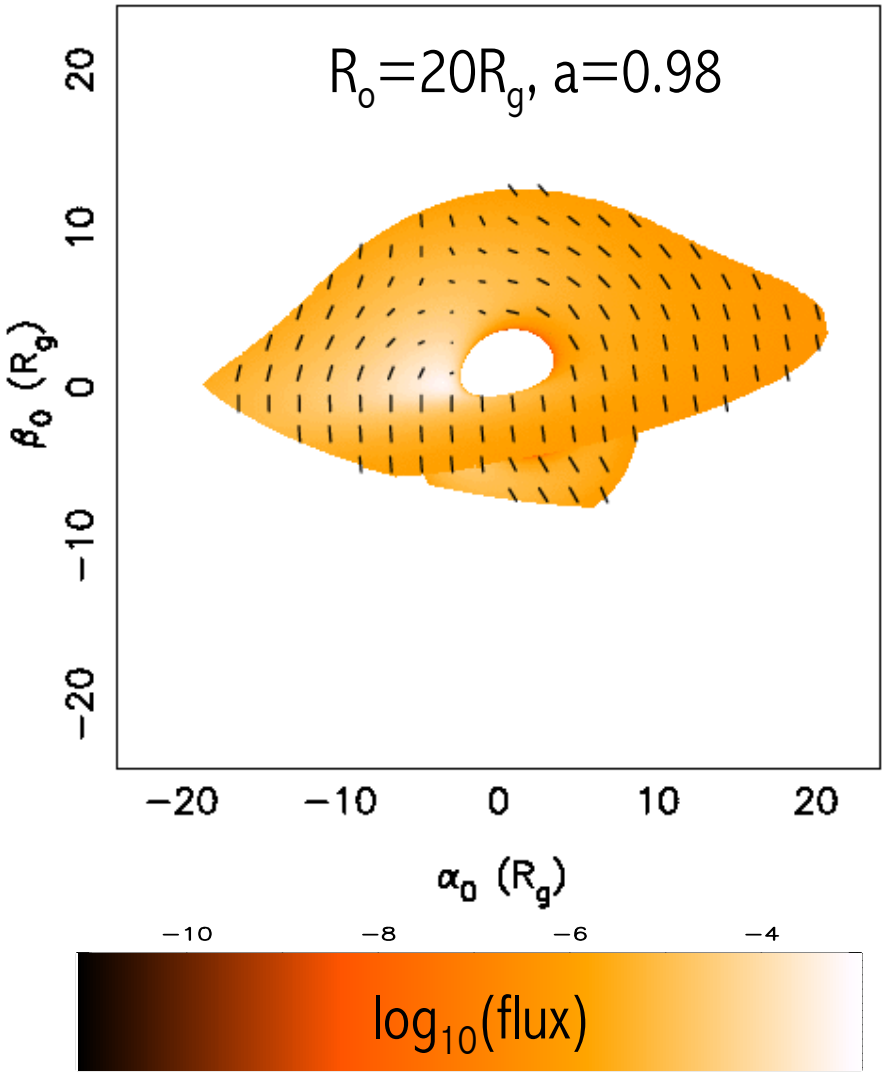
The future: Polarization



- Swings in polarization angle should correlate with line energy shifts
- Polarization modulation should be detectable with next generation X-ray polarimeters: eXTP, XIPE etc

www.youtube.com/watch?v=ieZYYfCapJg&feature=youtu.be

Ingram et al (2015)

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Conclusions

- See a variety of QPOs: LF (~0.1-30 Hz) & HF (>~100Hz)
- Relativistic precession model works but: not much data, it's just a toy model, less successful for neutron stars
- The centroid energy of the iron line in H 1743-322 is modulated on the QPO frequency => LT precession!
- Precession of inner flow, jet etc?
- First instance of tomographic mapping
- Differential precession?
- Also see QPOs in UV/optical/ IR – precessing jet?
- X-ray polarimetry will open a new window on this