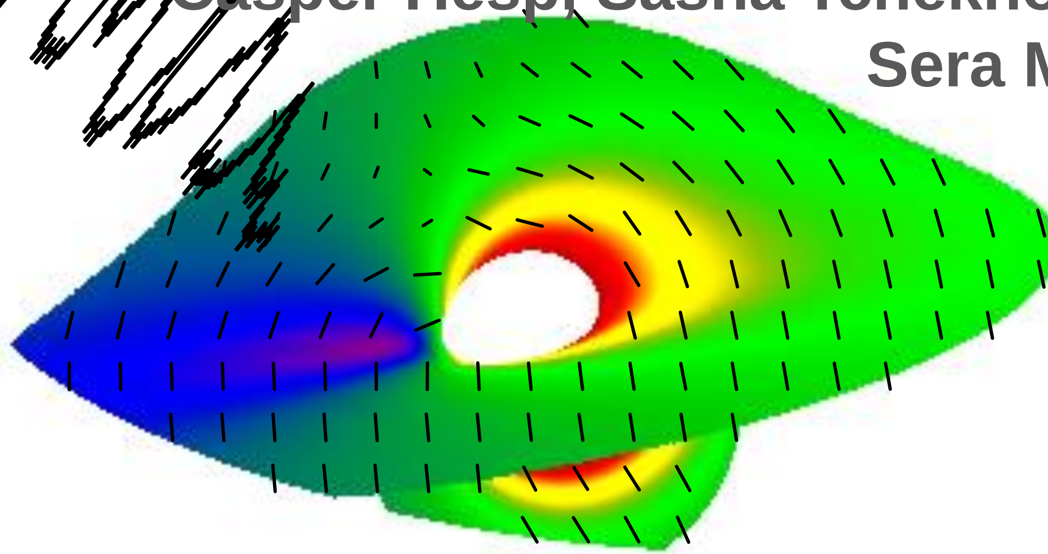
Spectral polarimetry of QPOs

Adam Ingram

Michiel van der Klis, Matt Middleton, Diego Altamirano, Phil Uttley, Chris Done, Tom Maccarone, Juri Poutanen, Henric Krawzynski, Matthew Liska, Casper Hesp, Sasha Tchekhovskoy, Sera Markoff



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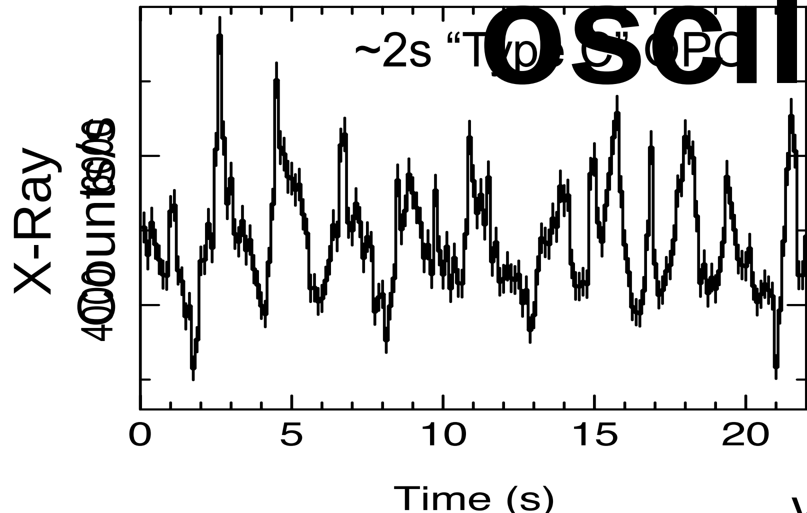
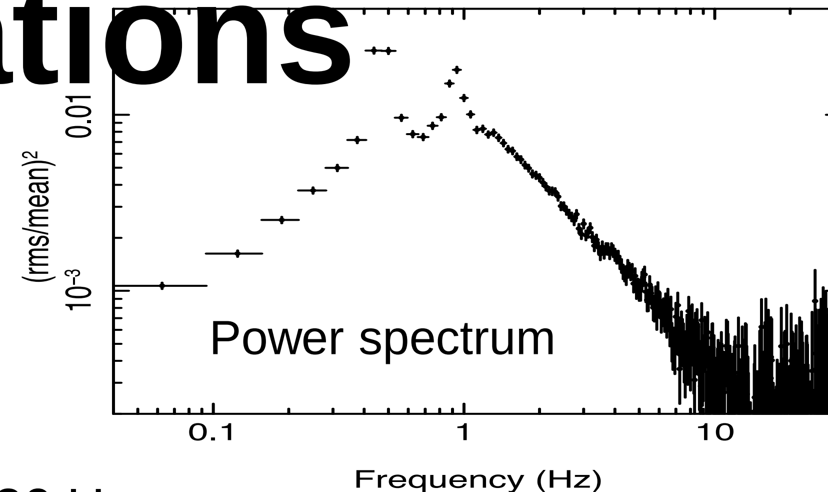
Quasi-periodic oscillations





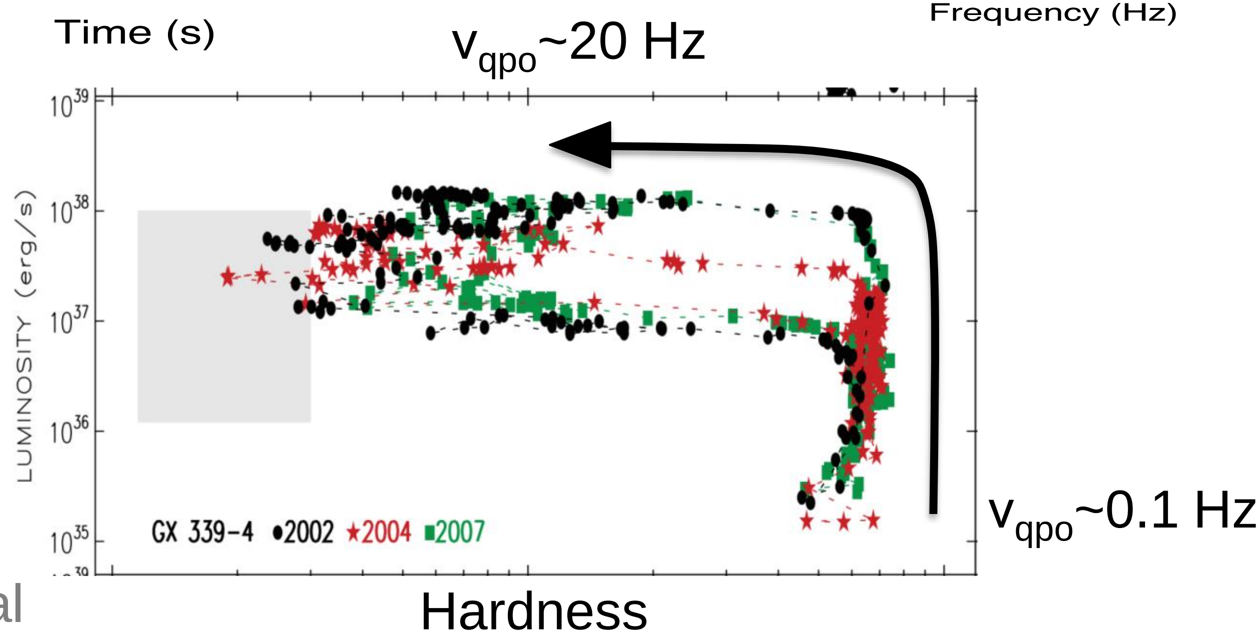
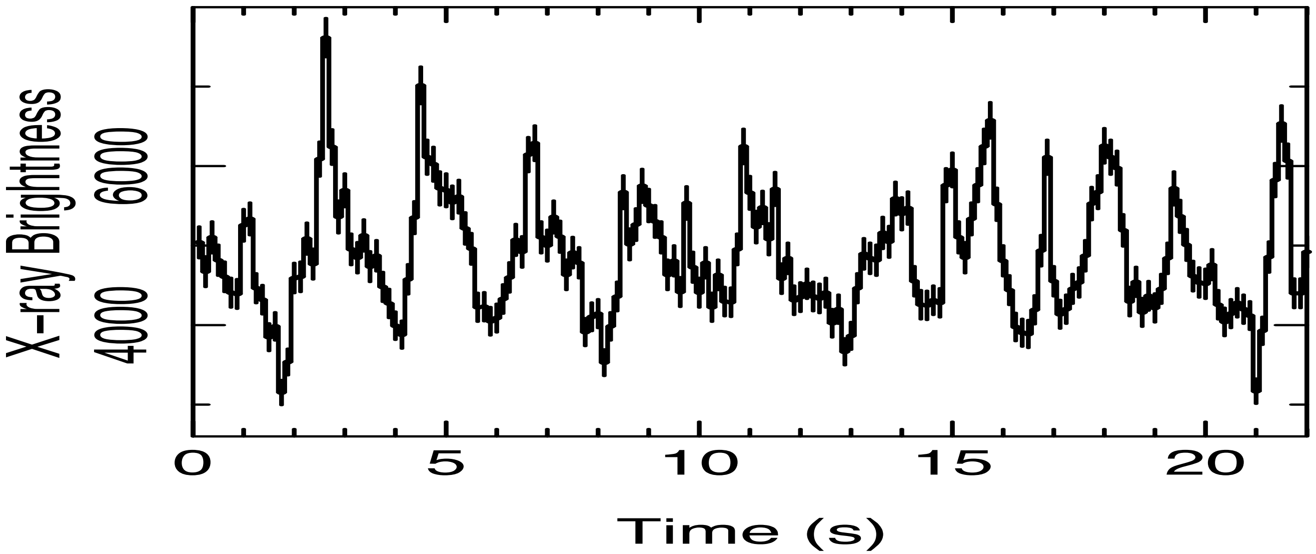
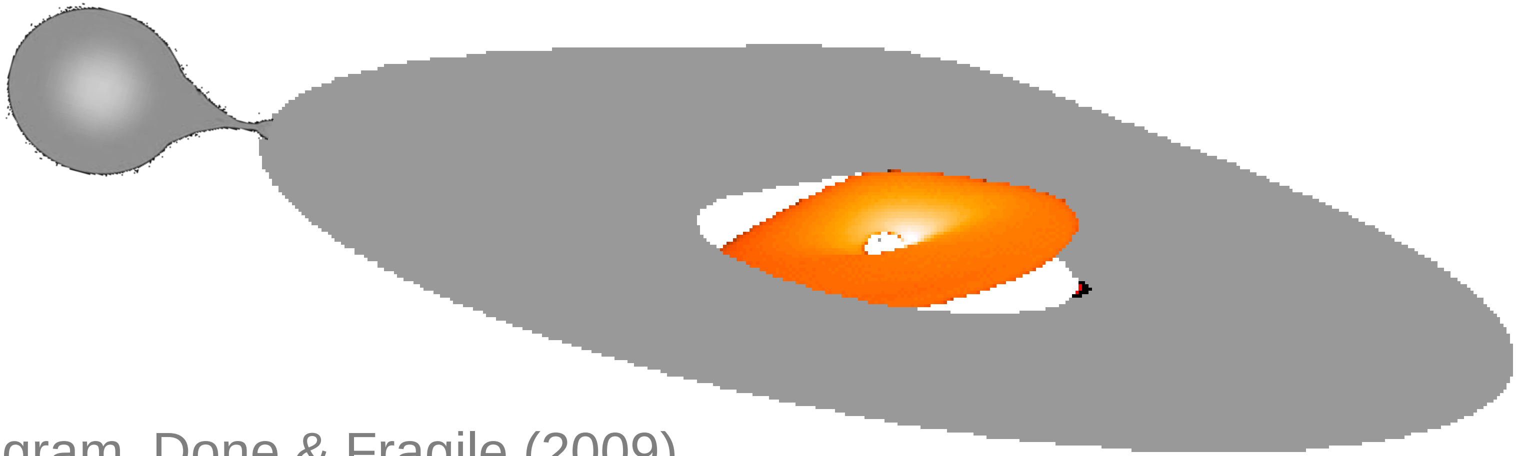


Fig: Muniz-Darias et al 2013

Frame dragging

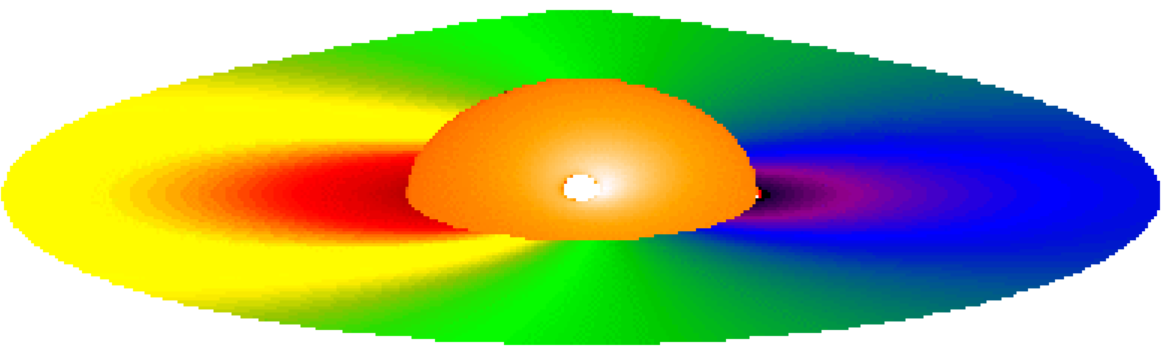


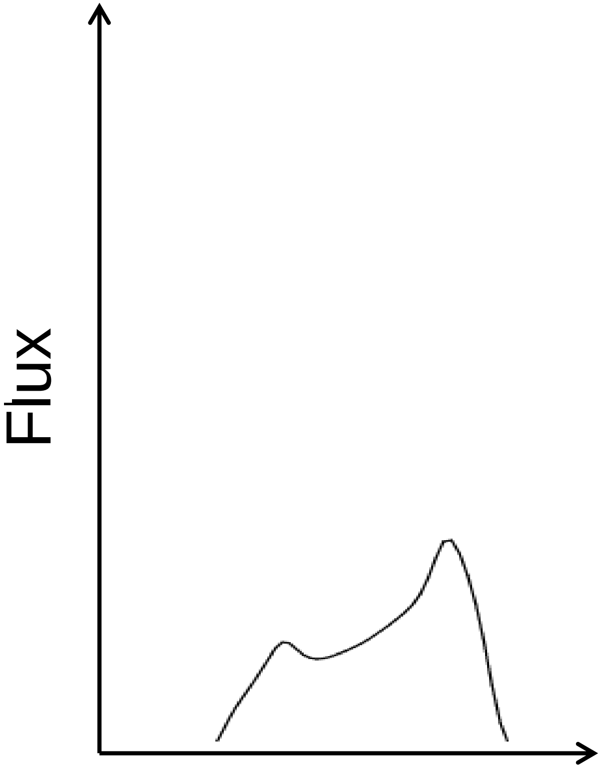


Ingram, Done & Fragile (2009)

Frame dragging

Tell-tale sign of precession: a rocking iron line

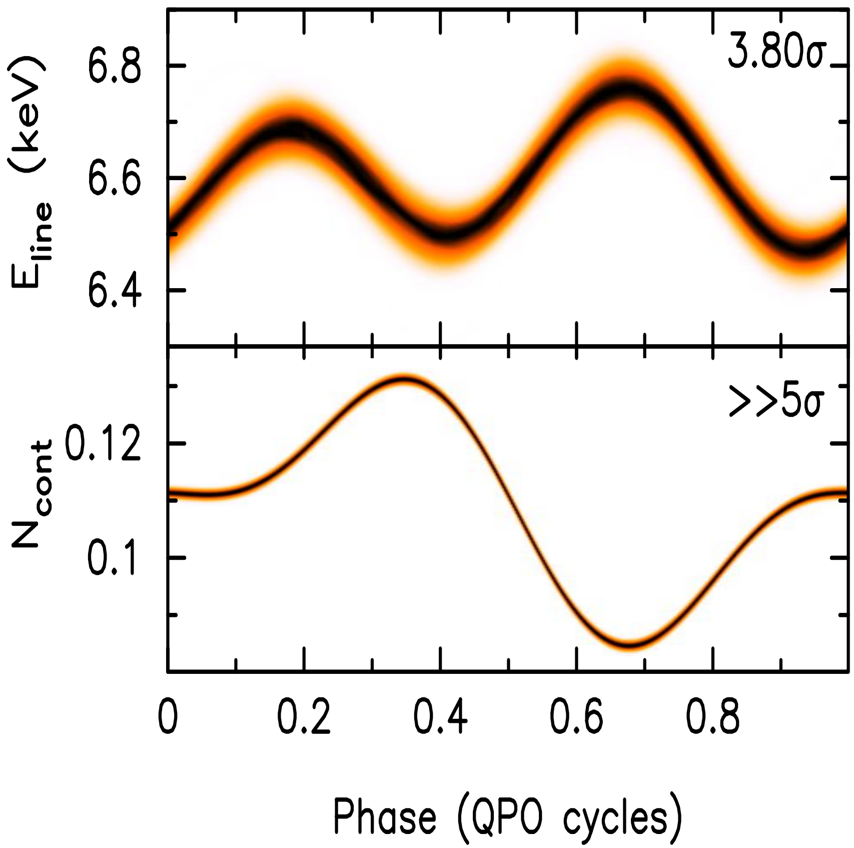


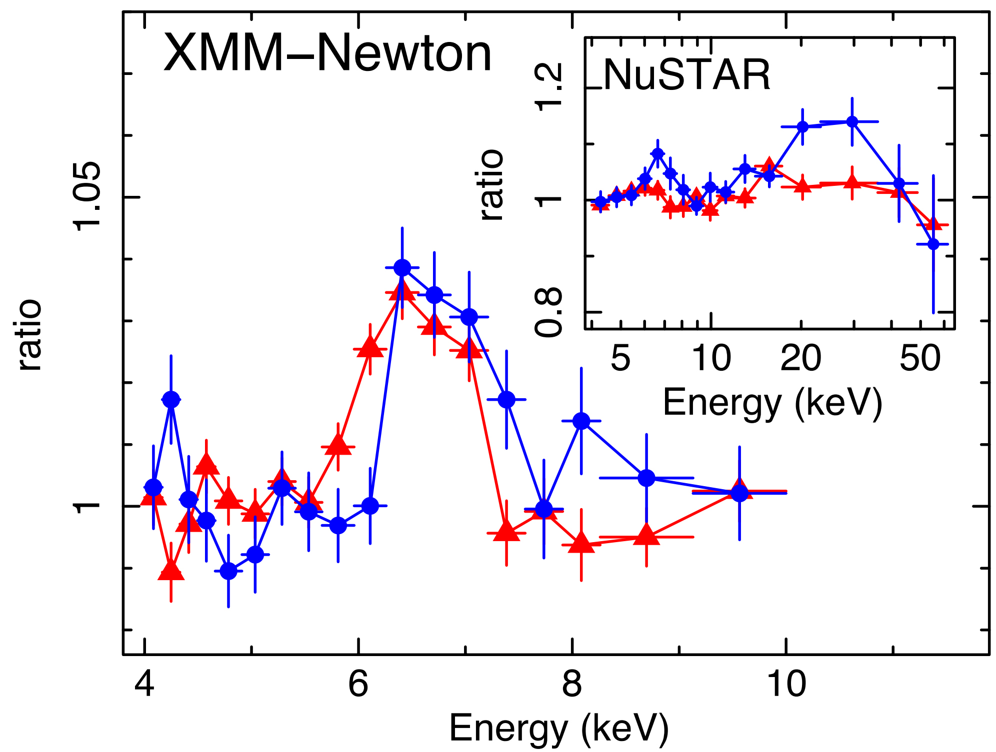


https://www.youtube.com/watch?v=e1QmLg5mGbU

Ingram & Done (2012)

Rocking iron line in H 1743-322



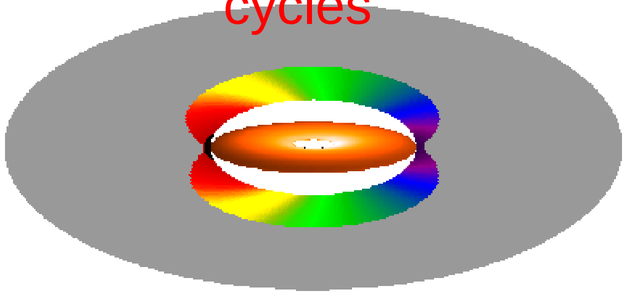


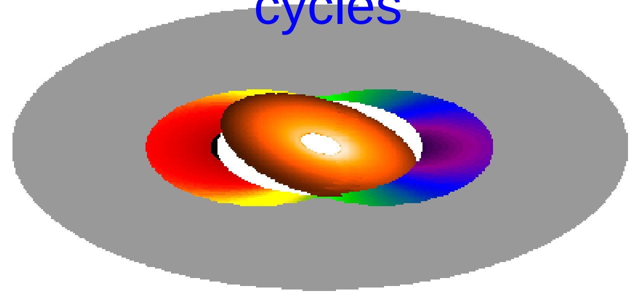
Ingram et al (2016a)

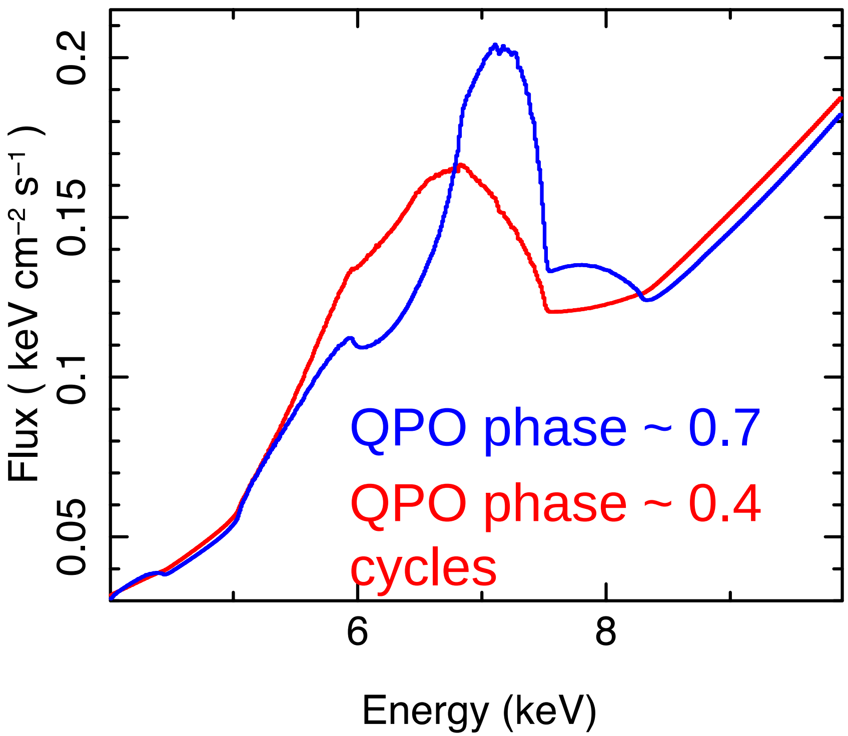
Tomographic modeling

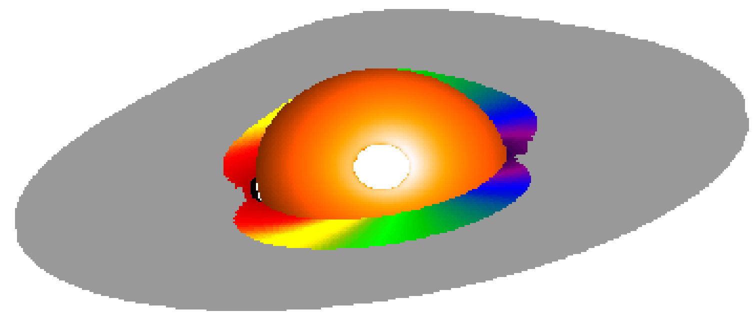
QPO phase ~ 0.4 cycles

QPO phase ~ 0.7 cycles





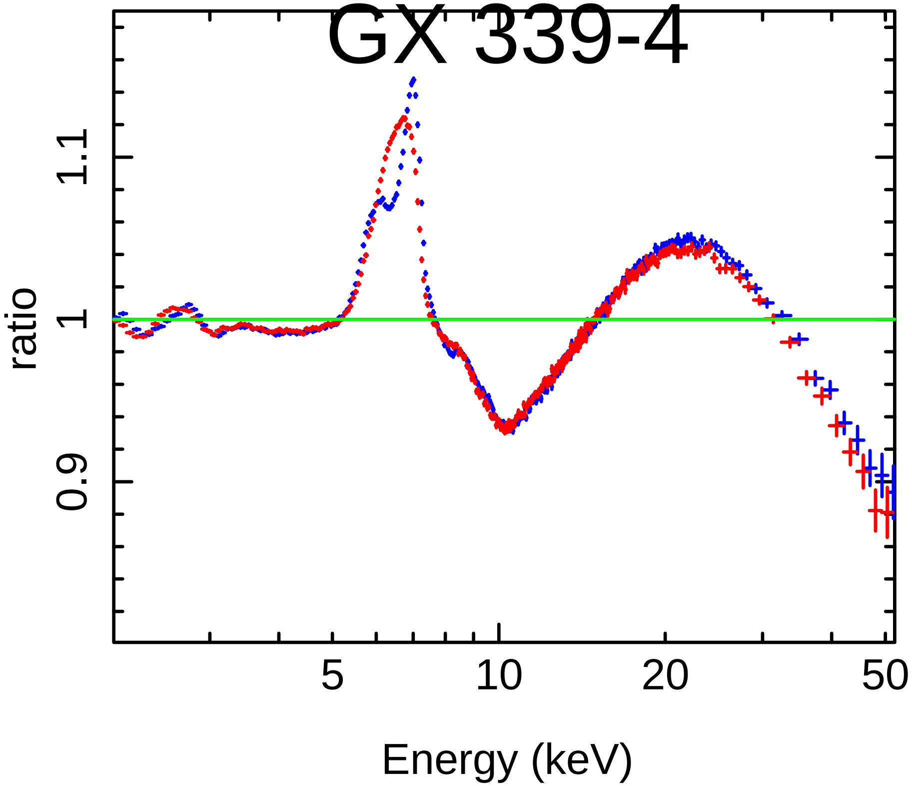




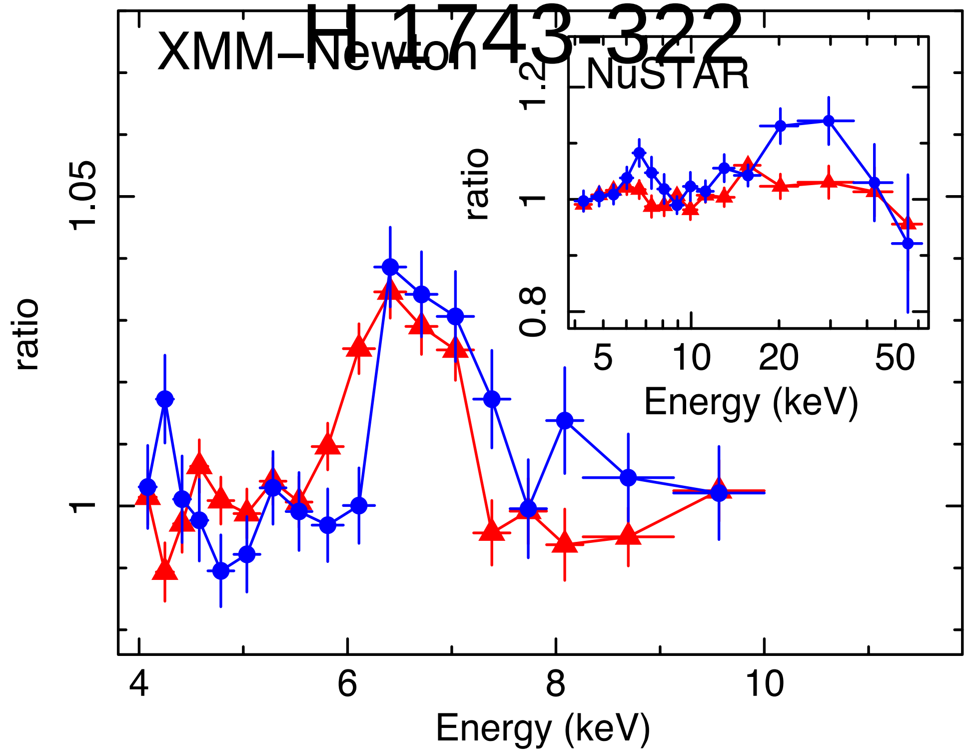
Ingram et al (2016b)

Tomography with eXTP

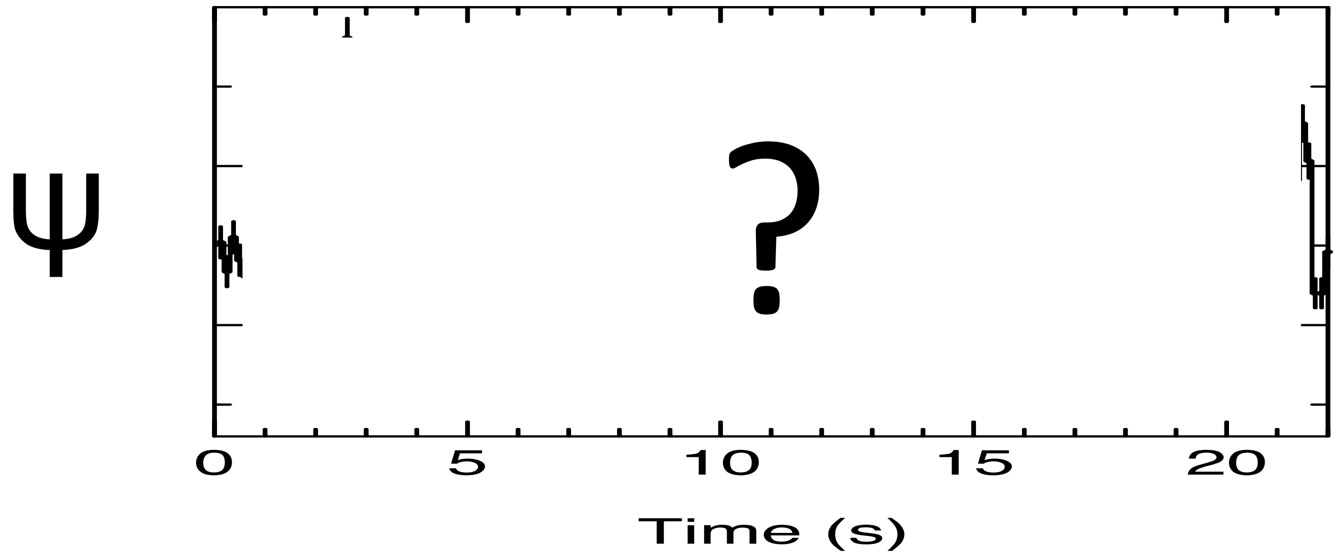
30 ks LAD simulation GX 339-4

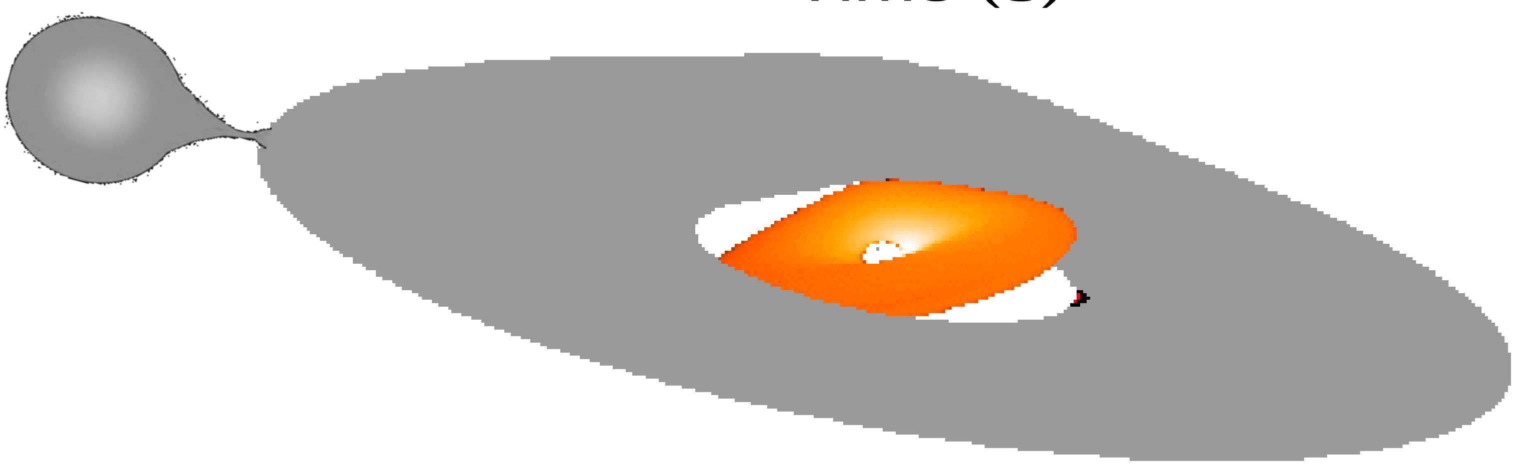


130 ks XMM + 70 ks NuSTAR H 1743-322



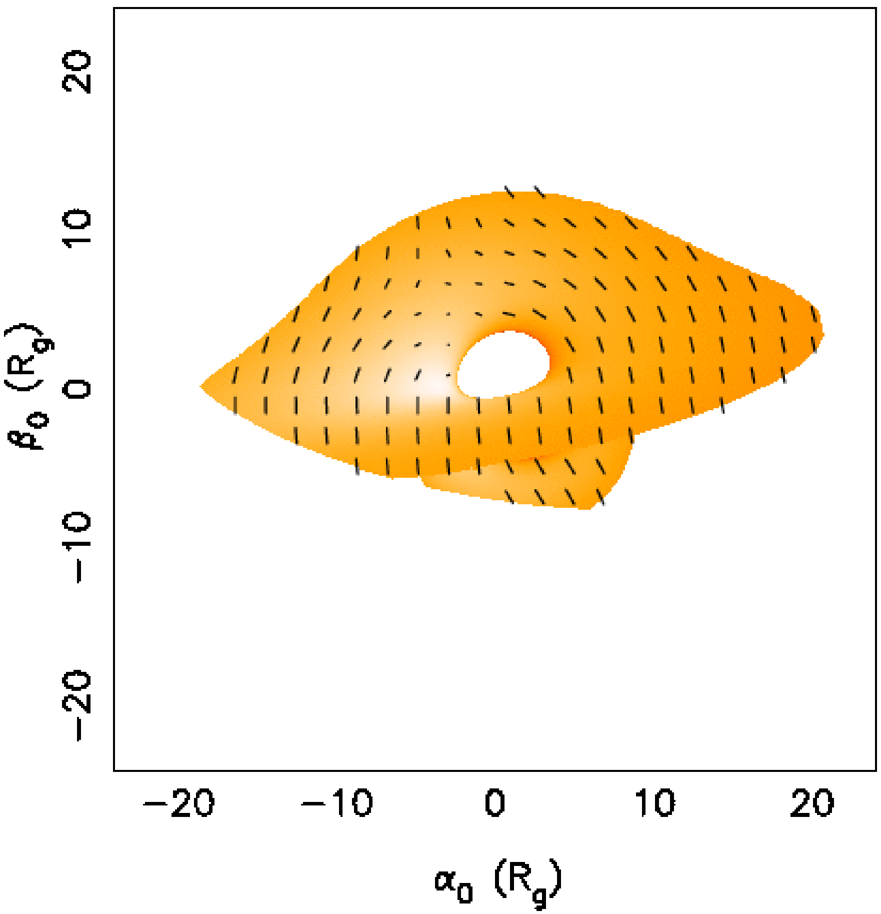
Polarization

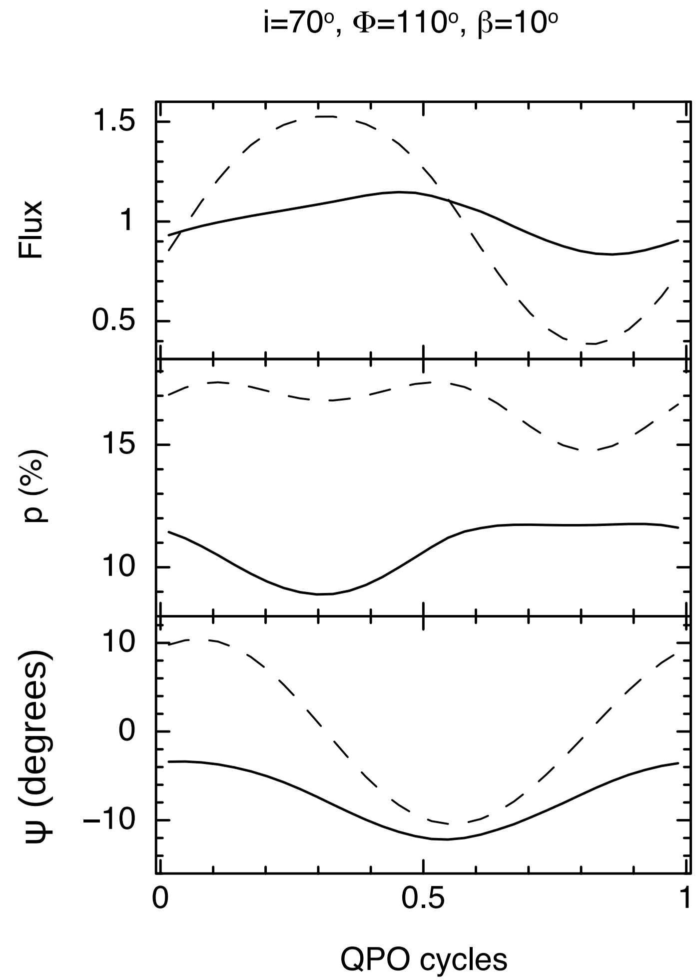




Ingram et al (2015)

Polarization

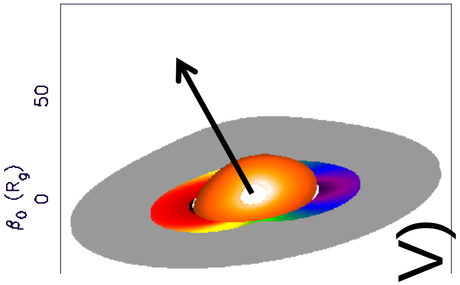




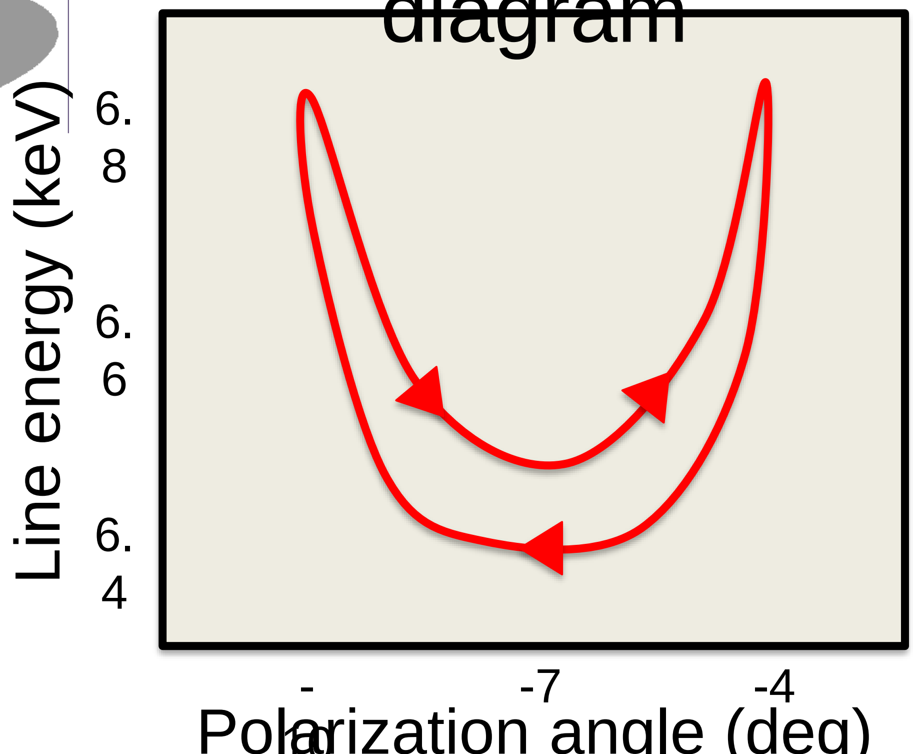
www.youtube.com/watch?v=ieZYYfCapJg&feature=youtu.be

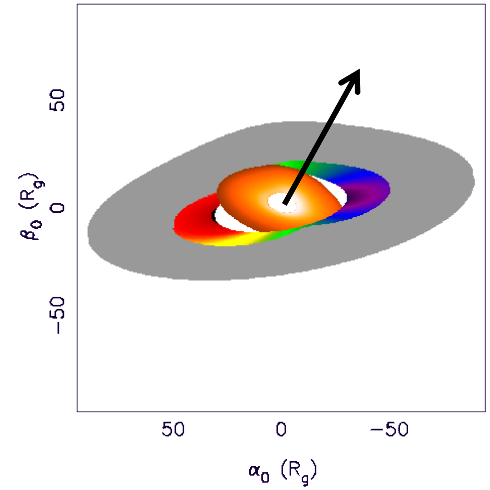
Ingram et al (2015)

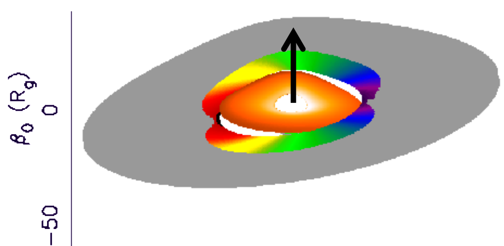
Polarization



The “smile” diagram





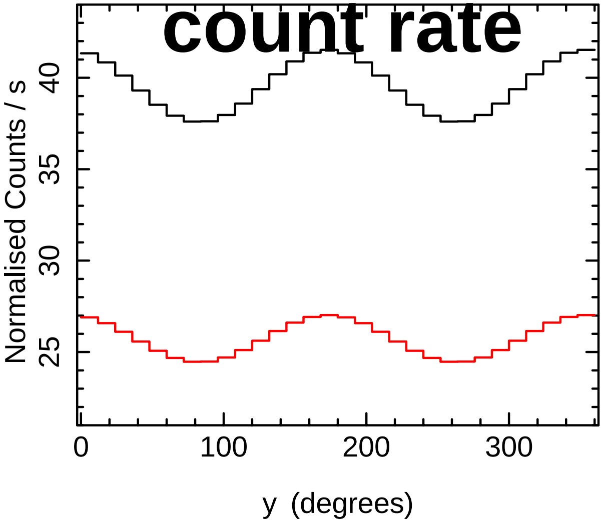


Detection

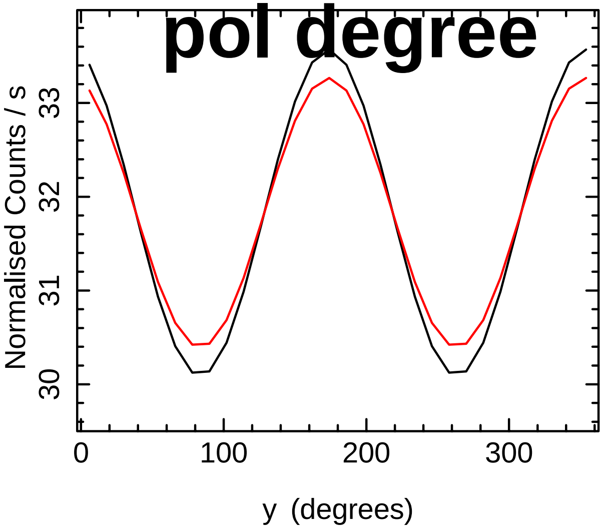
Can't measure p and ψ in arbitrarily small time bins

Can make light curves for different ψ bins

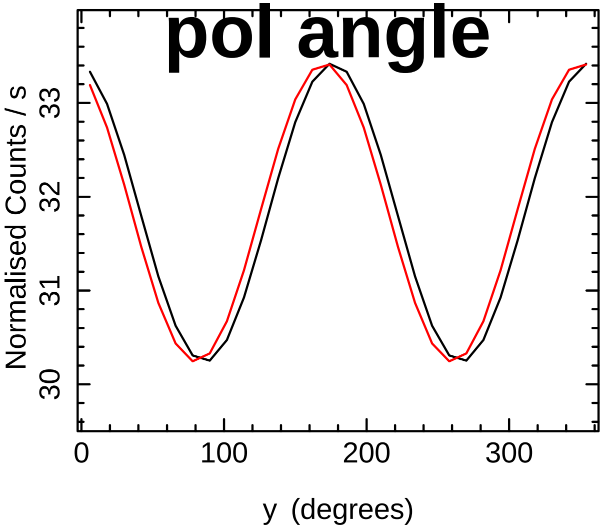
Just variability in count rate



Just variability in pol degree



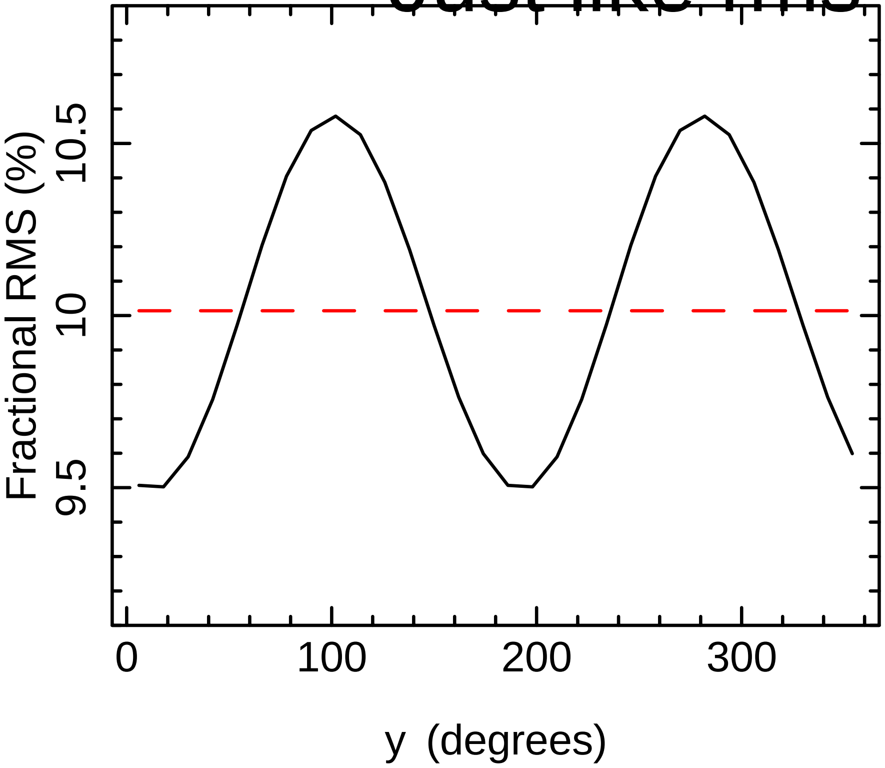
Just variability in pol angle

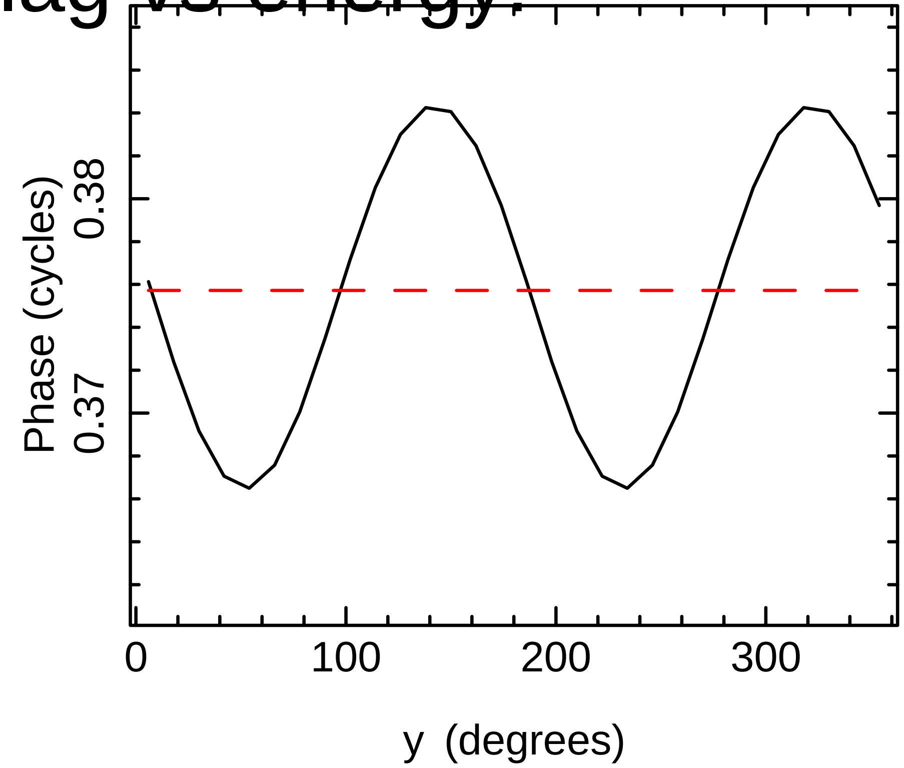


Ingram et al (in prep)

Detection

Calculate fractional rms and phase lag as a function of ψ
Just like rms / lag vs energy!



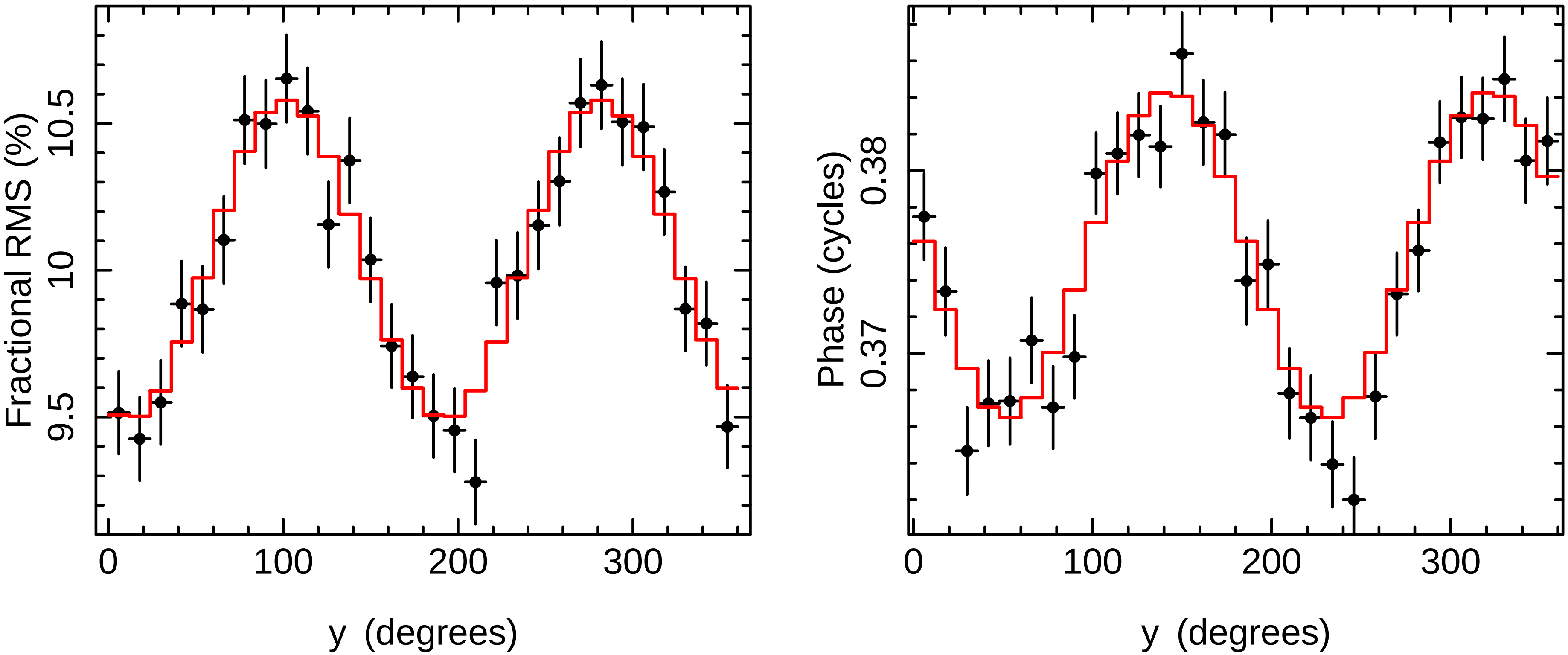


Ingram et al (in prep)

Detection

100 ks exposure of GX 339-4 with eXTP

GPDs: 200 c/s; LAD 38,000 c/s

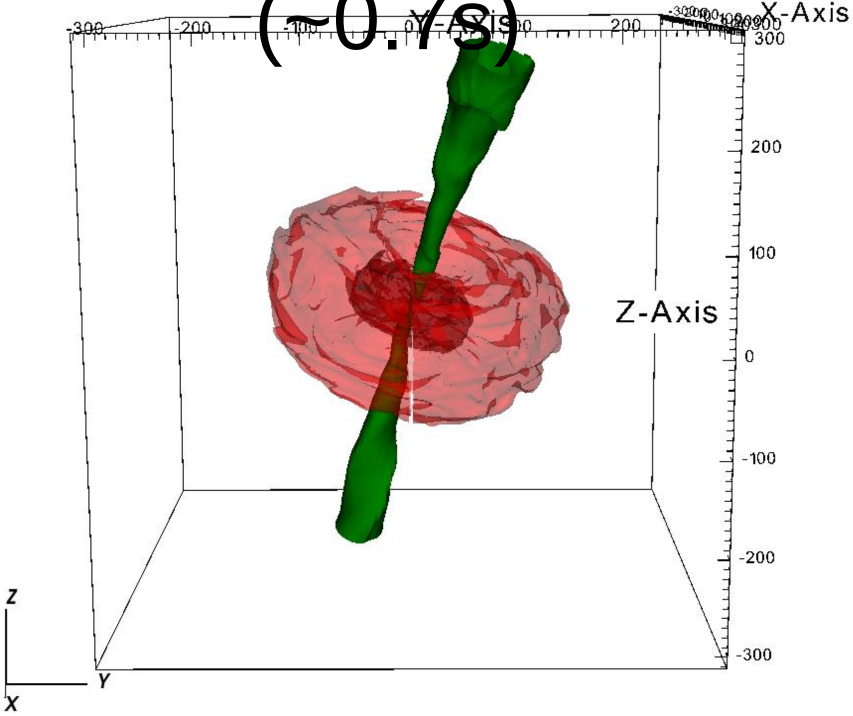


Ingram et al (in prep)

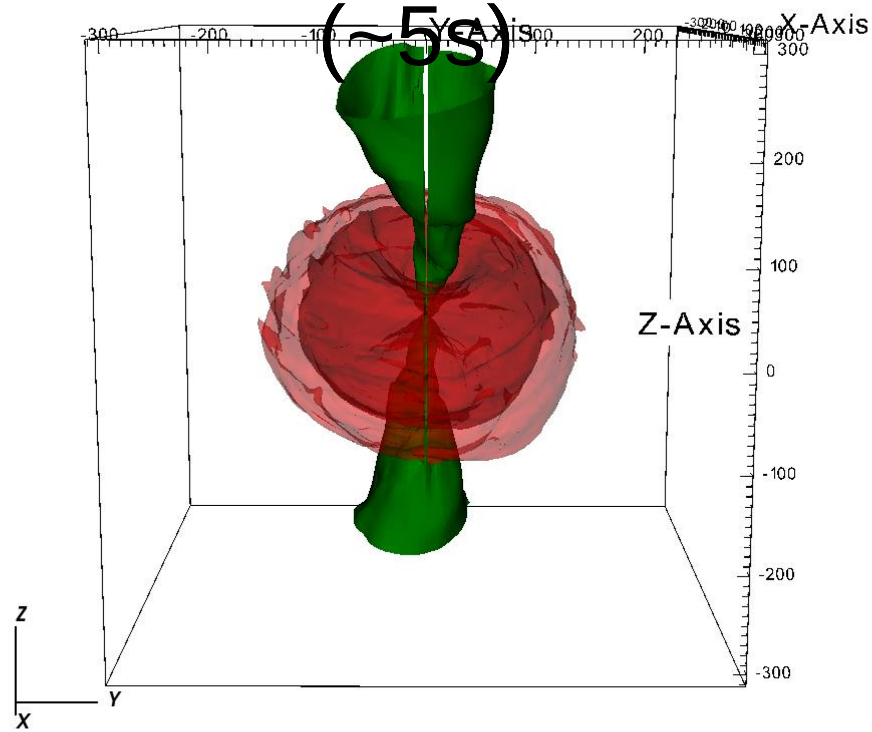
Jet precession

BZ jet that aligns with the accretion flow!

t=14,000 R_g/c (~0.7s)



t=100,000 R_g/c (~5s)



Liska et al (in prep)

Conclusions

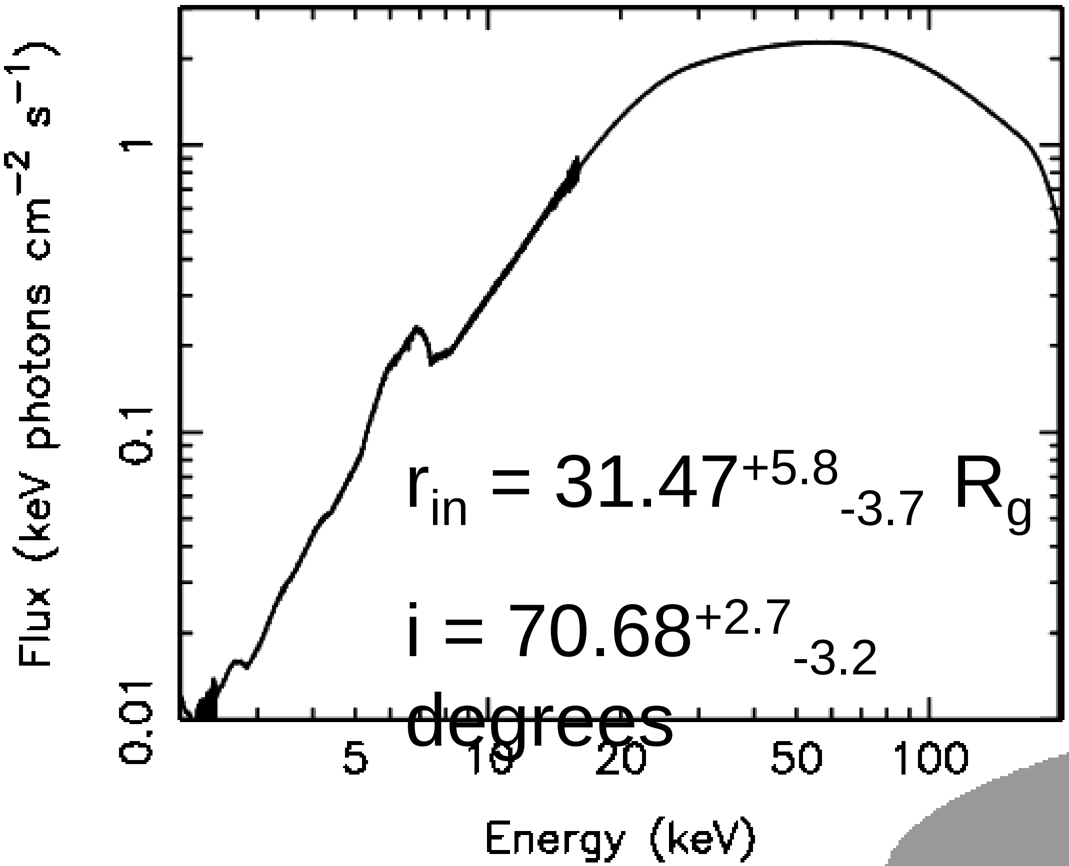
- Rocking iron line in H 1743-322 gives strong evidence for precession
- eXTP will enable detailed tomographic mapping

- QPOs predicted in polarization degree and angle
- p and ψ modulations relate to line centroid modulations

- Developing a method to measure variability in p and ψ
- QPOs in p and ψ should be detectable with eXTP

- Always need lots of counts – long exposures of bright sources
- Using the LAD as a reference band helps!
- IXPE + AstroSat could work, particularly for a precessing

Tomographic modeling

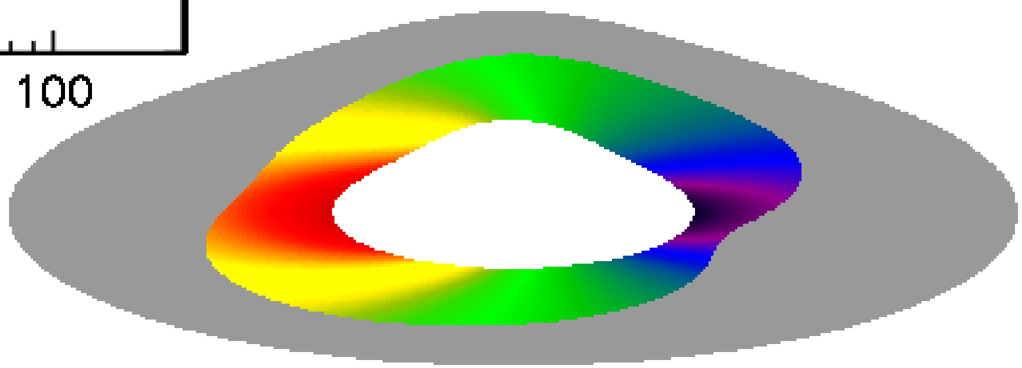


$r_{in} = 31.47^{+5.8}_{-3.7}\ R_g$

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

Parameterize disk illumination:

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

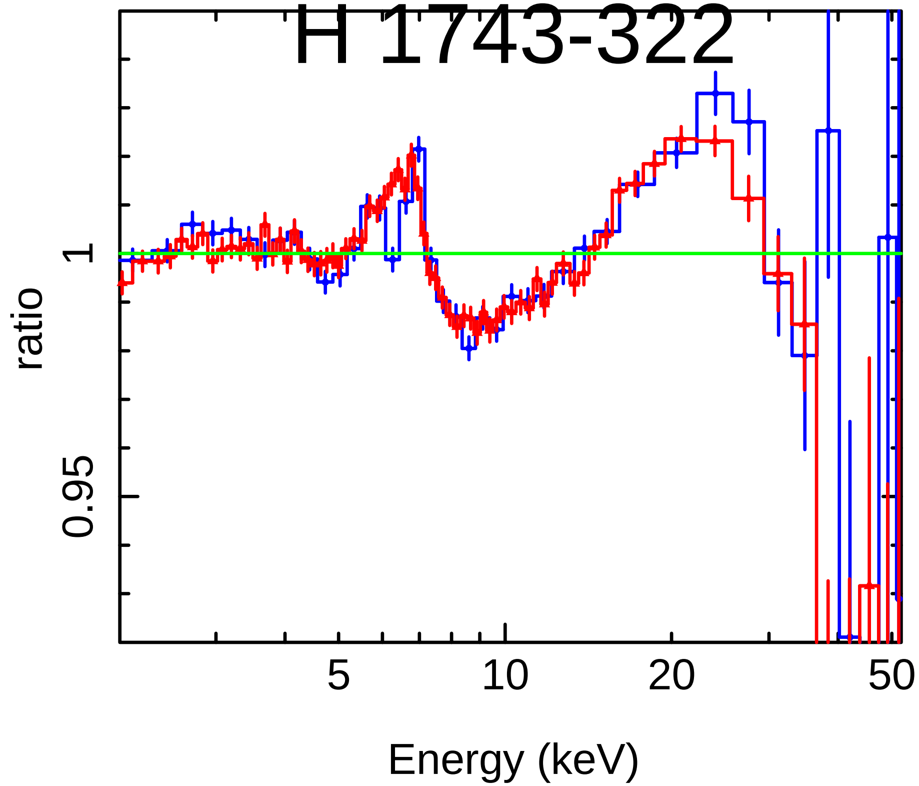


Ingram et al (2016b)

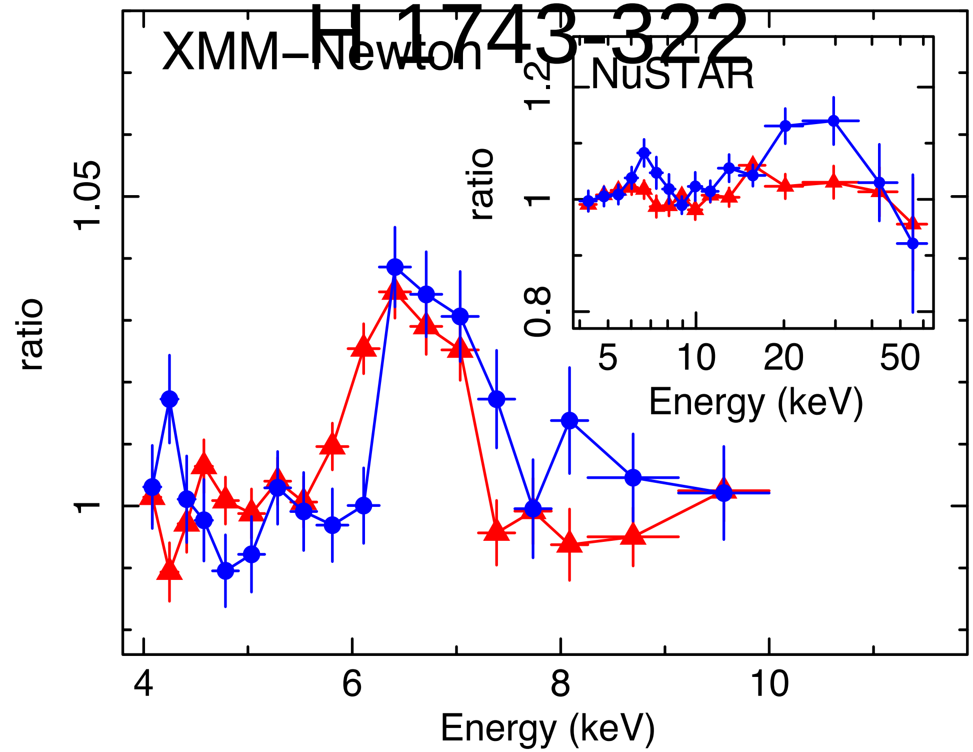
https://figshare.com/articles/Tomographic_modelling_of_H_1743-322/3503933

Tomography with eXTP

30 ks LAD simulation
H 1743-322

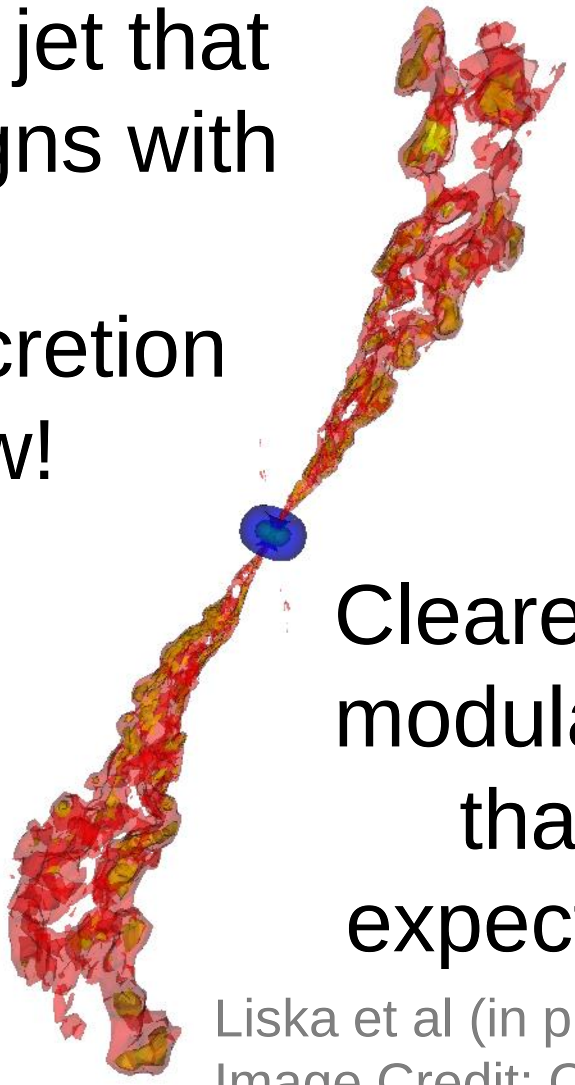


130 ks XMM + 70 ks NuSTAR
H 1743-322



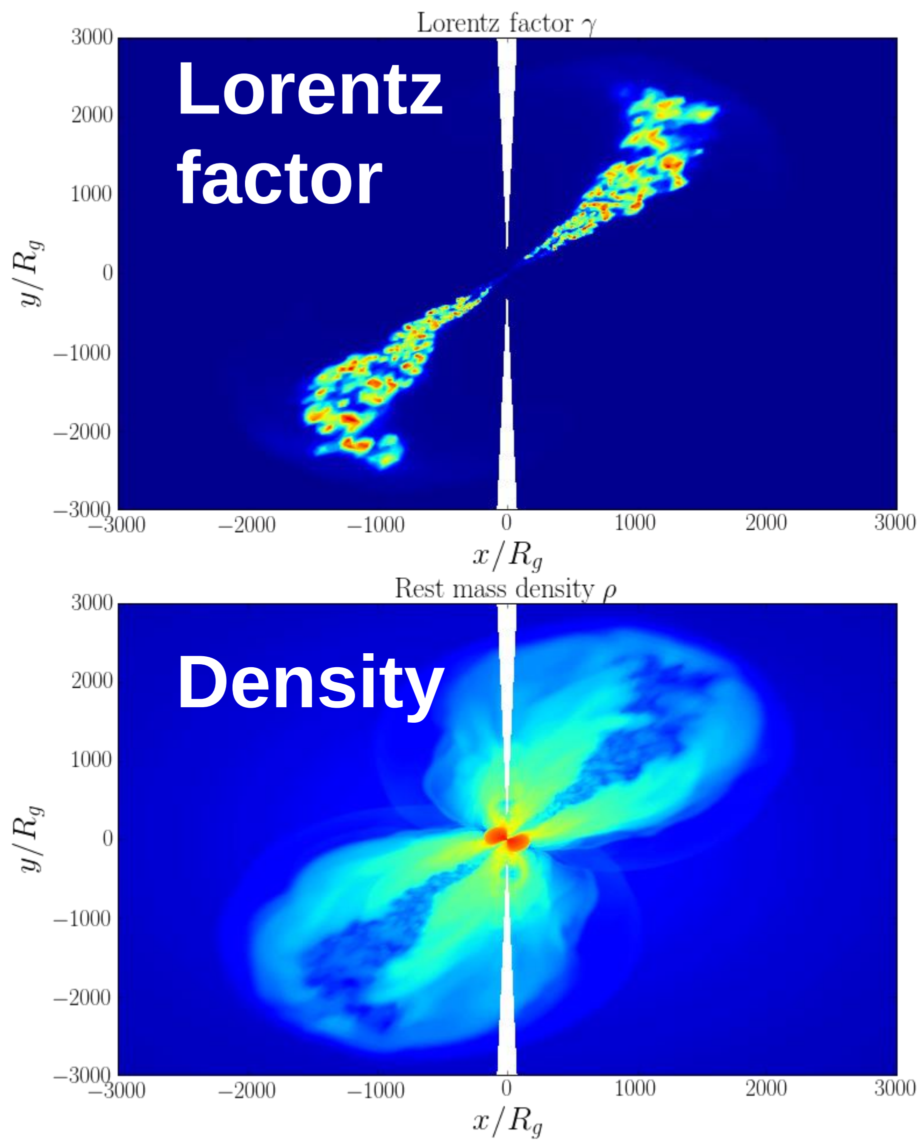
Jet precession

BZ jet that aligns with the accretion flow!

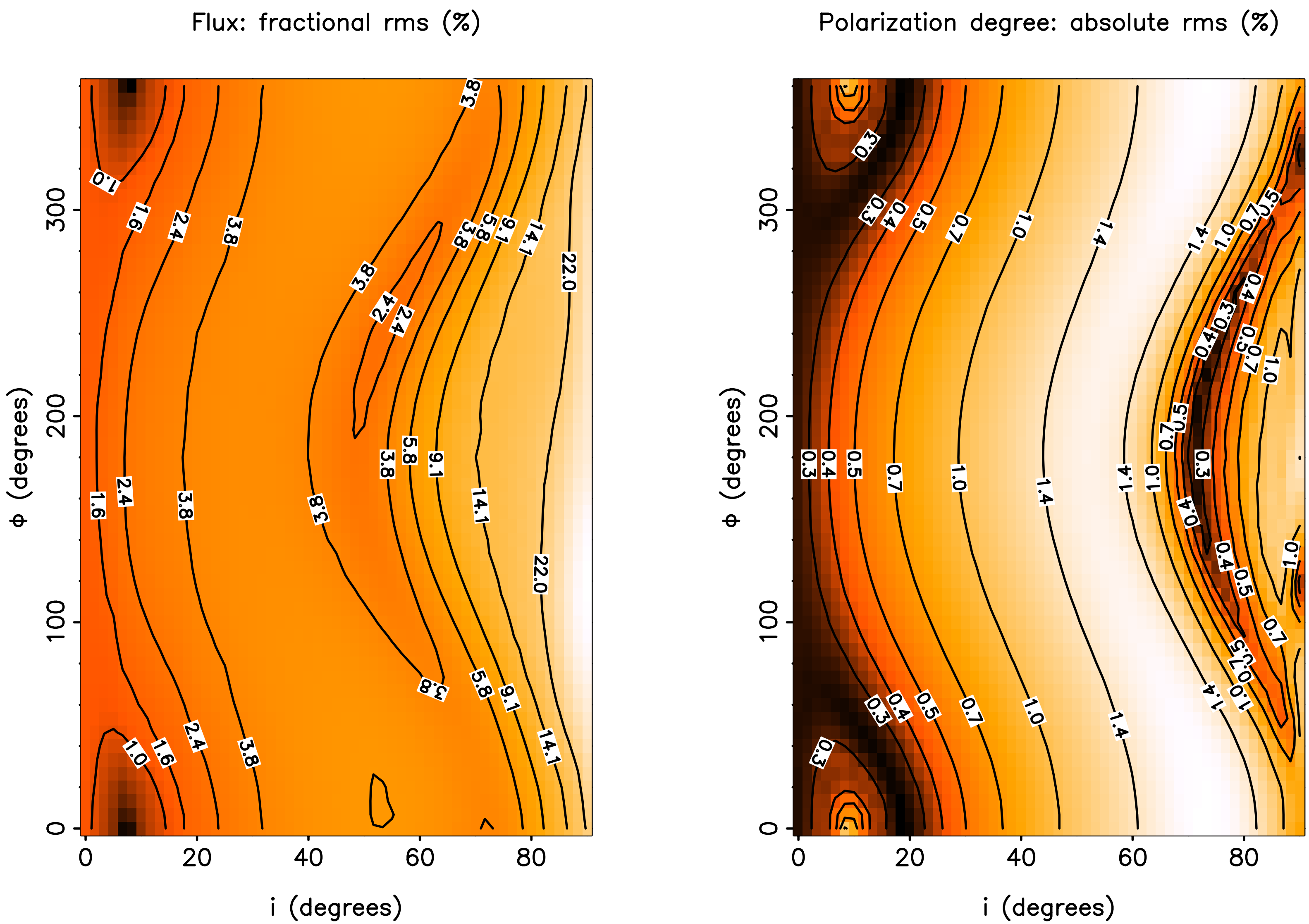


Clearer pol modulation than expected?

Liska et al (in prep)
Image Credit: Casper Hesp

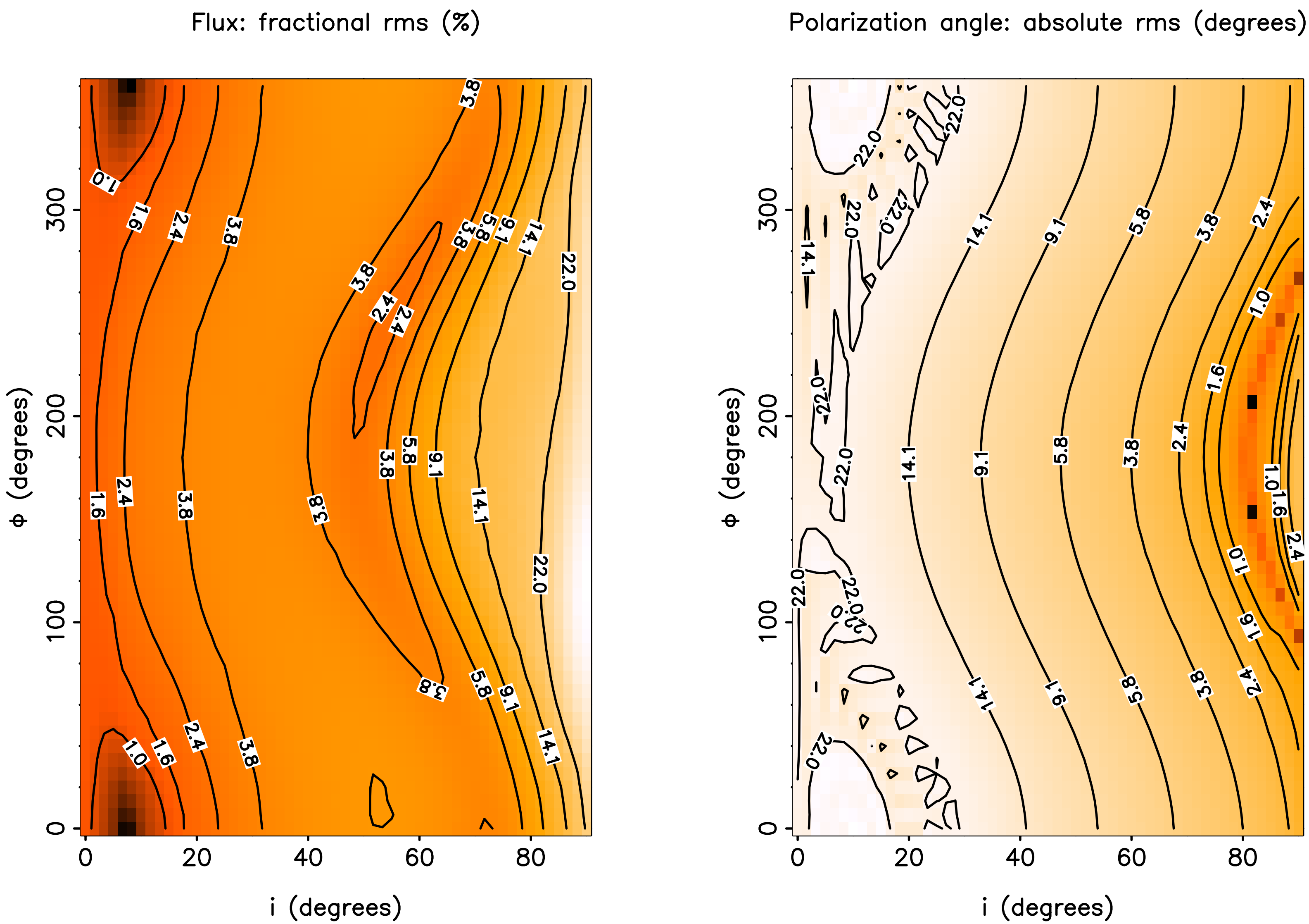


Results



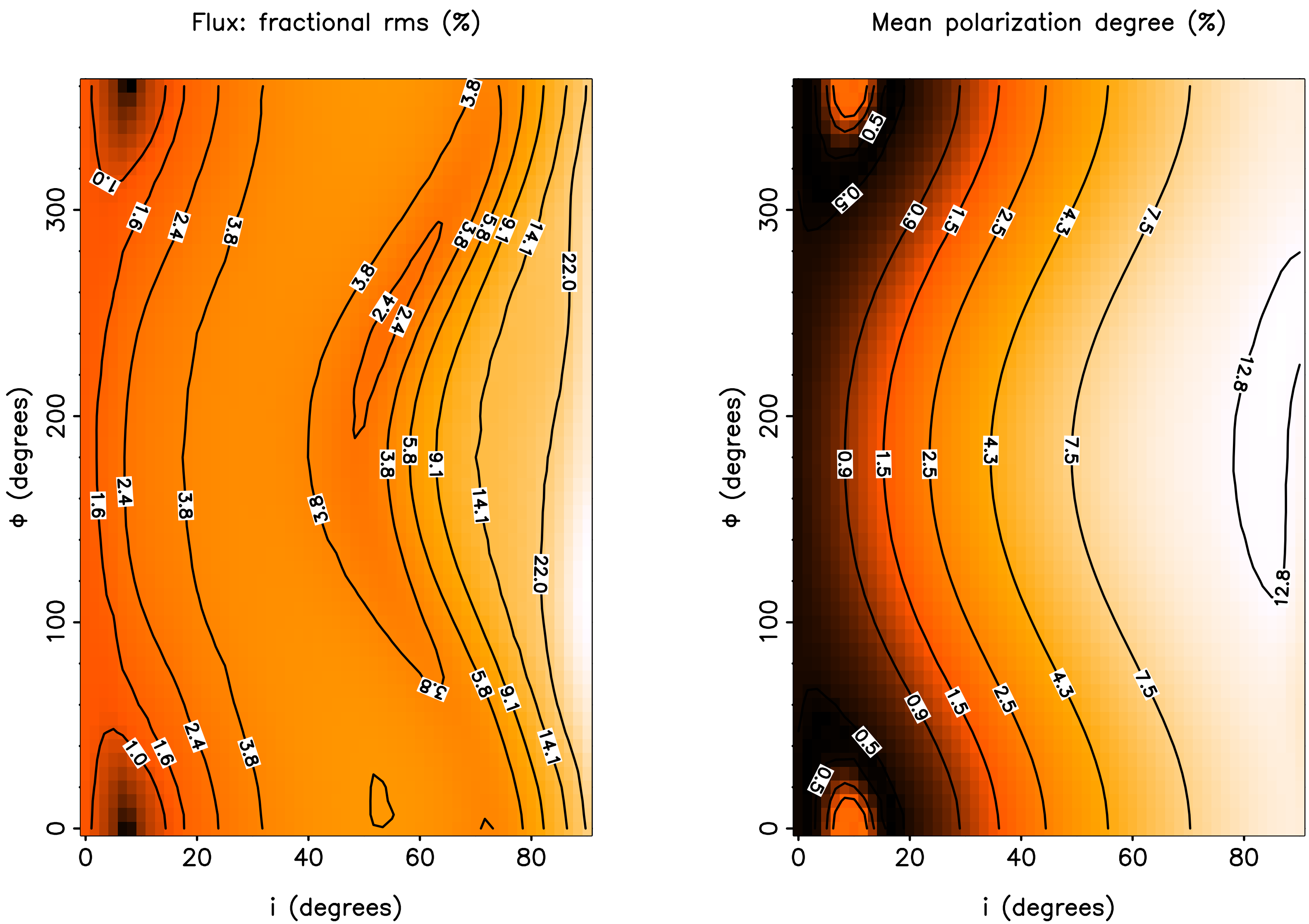
Ingram et al (2015)

Results



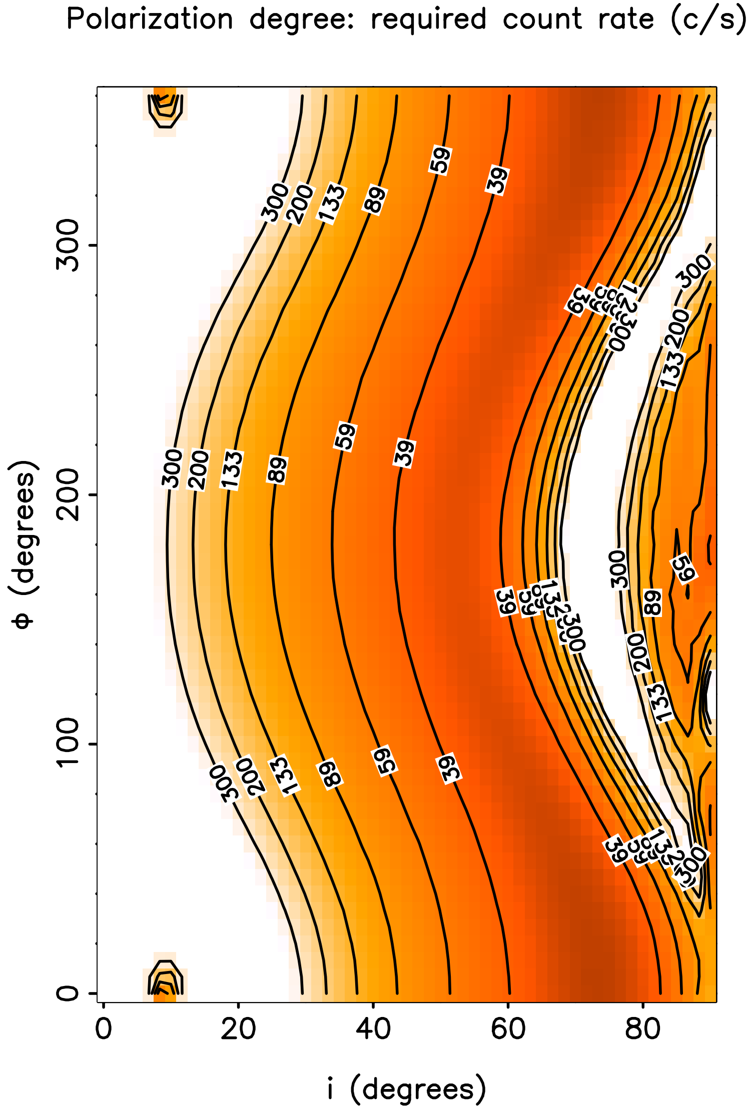
Ingram et al (2015)

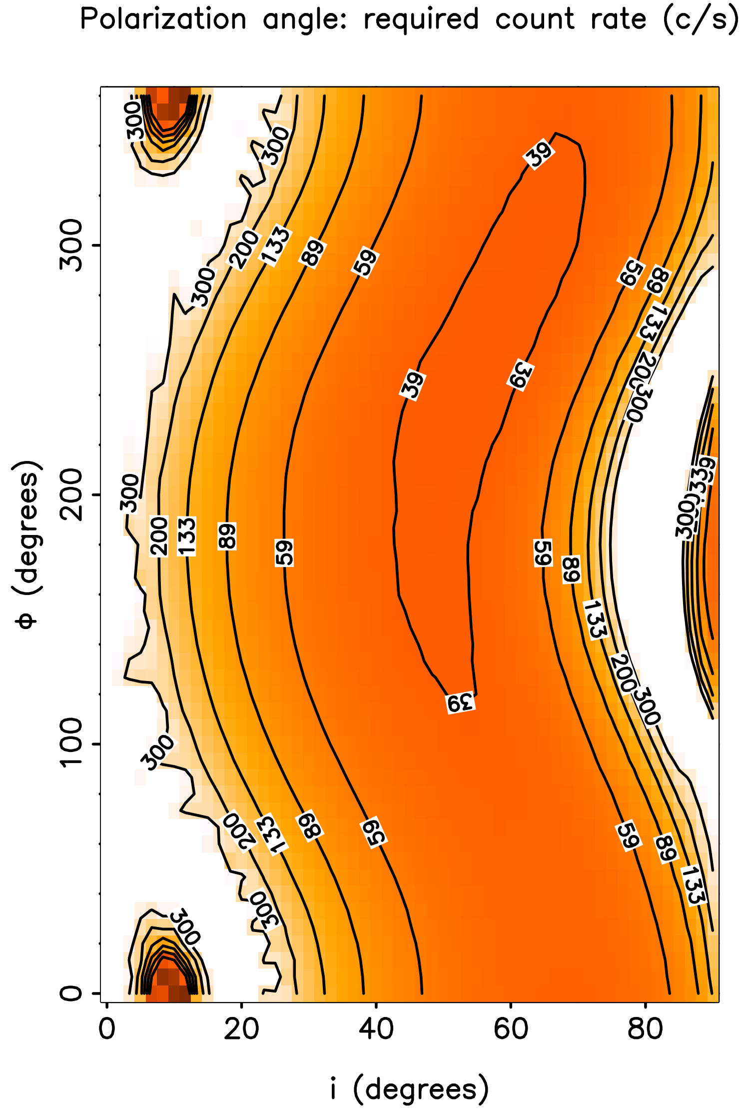
Results



Ingram et al (2015)

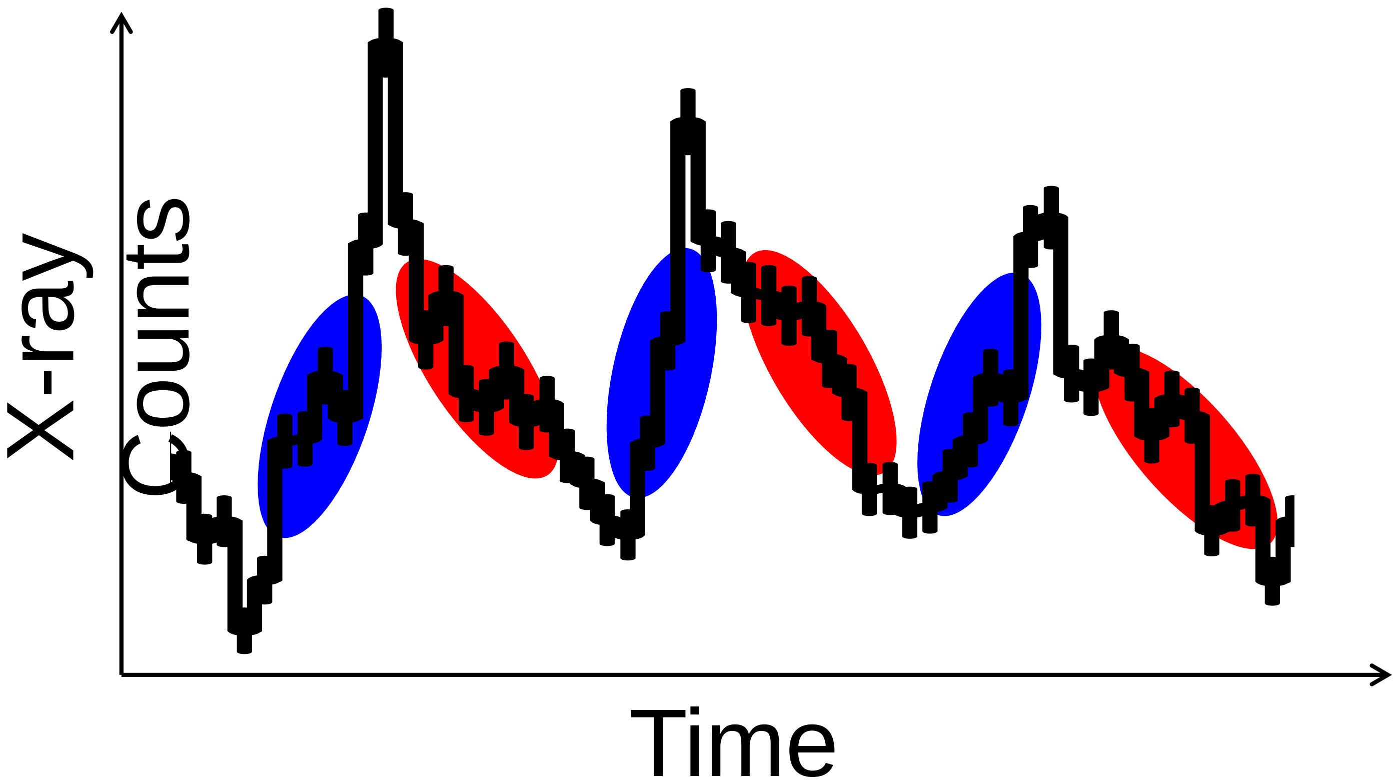
Results





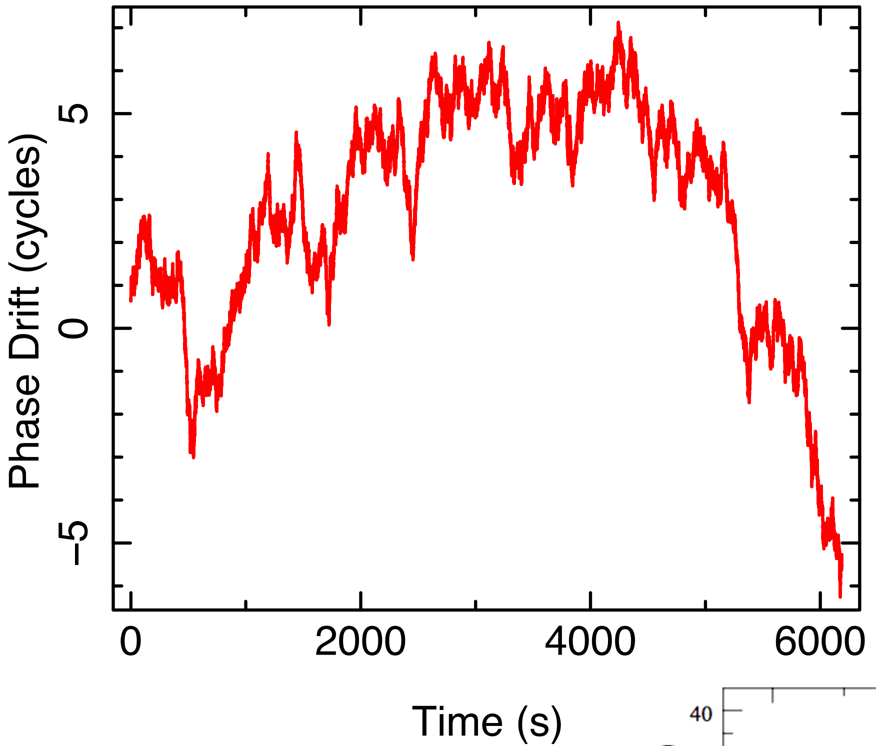
Ingram et al (2015)

Phase folding



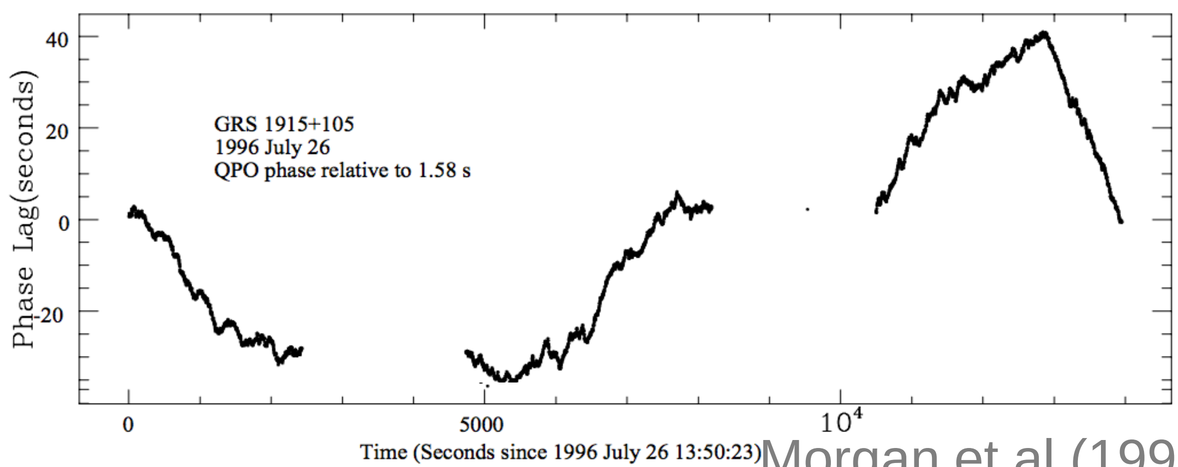
p_0 & ψ_0 p_0 & ψ_0

Simulation



Simulate sinusoidal QPO with a random walk phase drift

GRS 1915+105

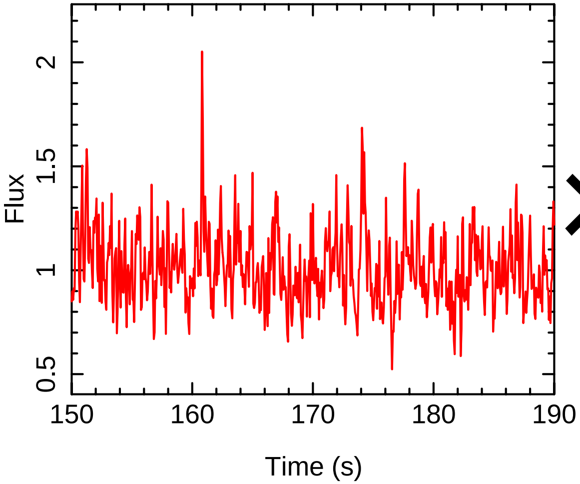


Ingram et al (in prep)

Morgan et al (1997)

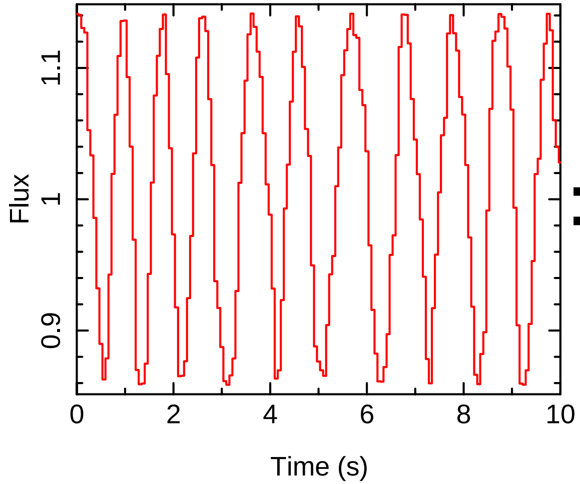
Simulation

“Exponentiated” broad band noise



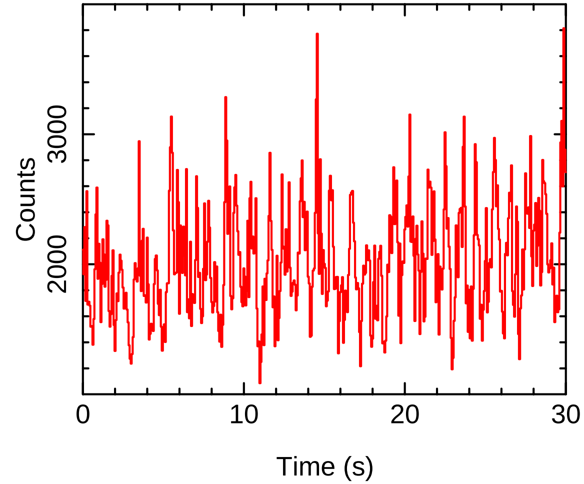
×

“Random walk” QPO



=

Synthetic LAD light curve

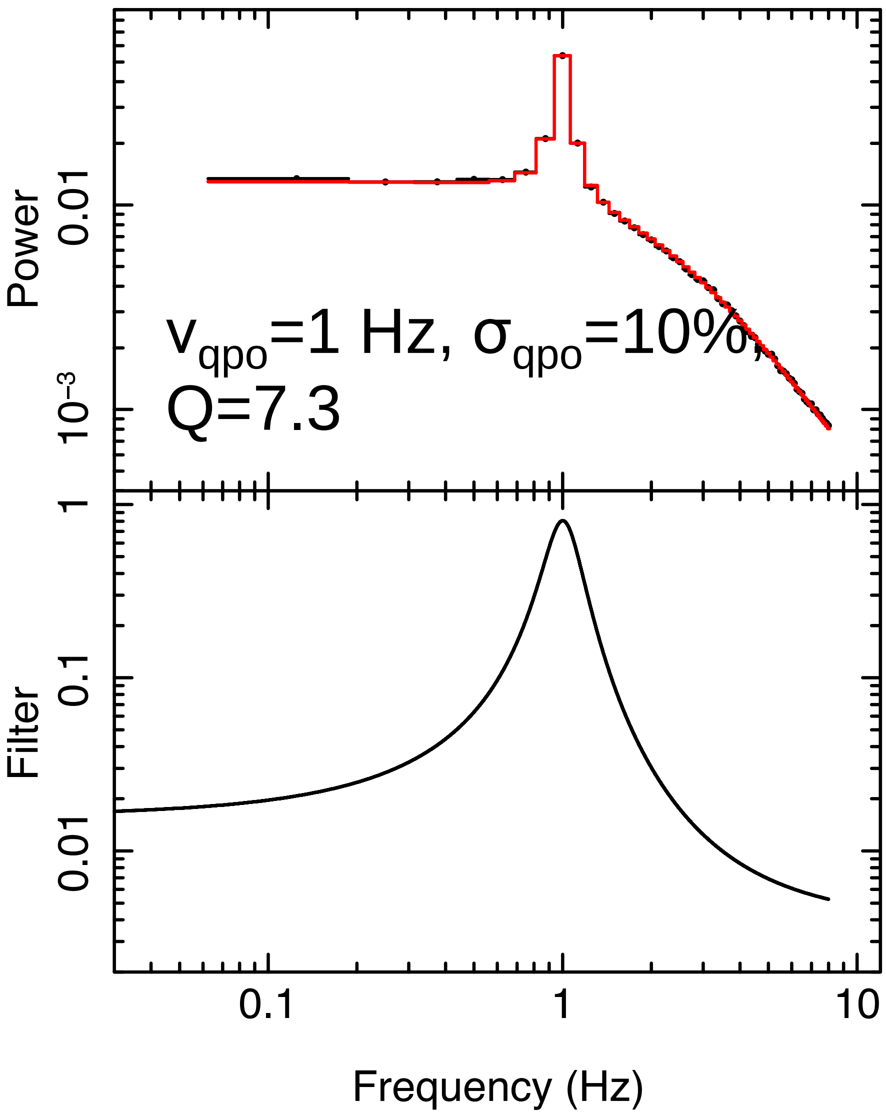


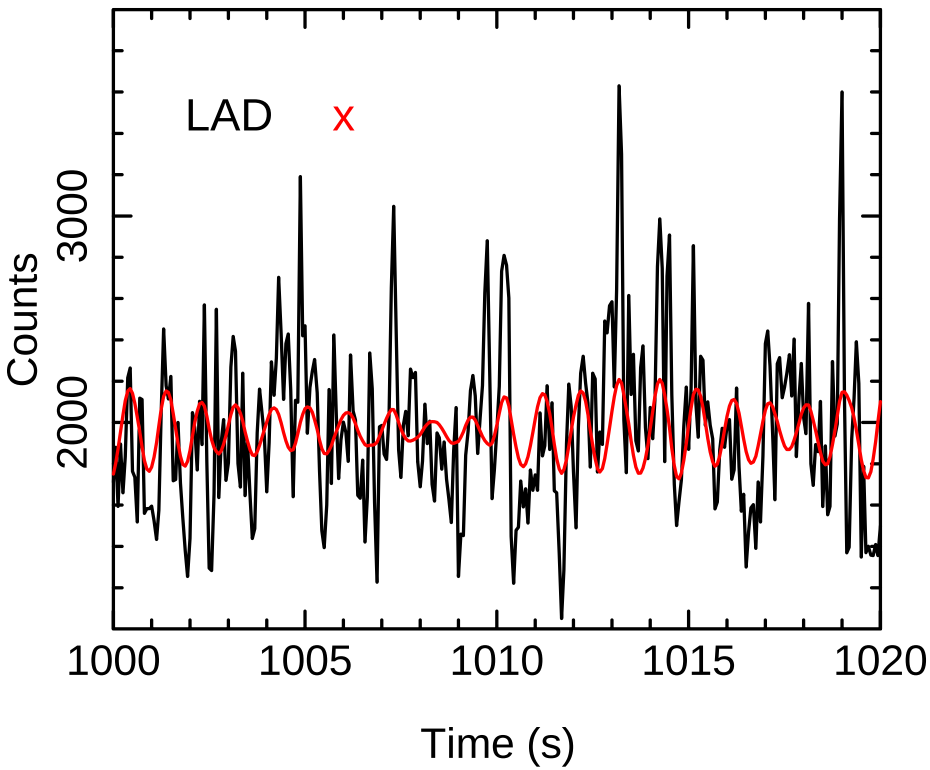
$$f(\psi,t|\psi_0,p_0) = (2\pi)^{-1} \{ 1 + p_0(t)\, \mu \cos[2(\psi-\psi_0(t))] \}$$

For the GPD, generate 100 light curves, each for a different ψ bin

32.768ks exposure, dt=1/16 s, no background

Phase folding

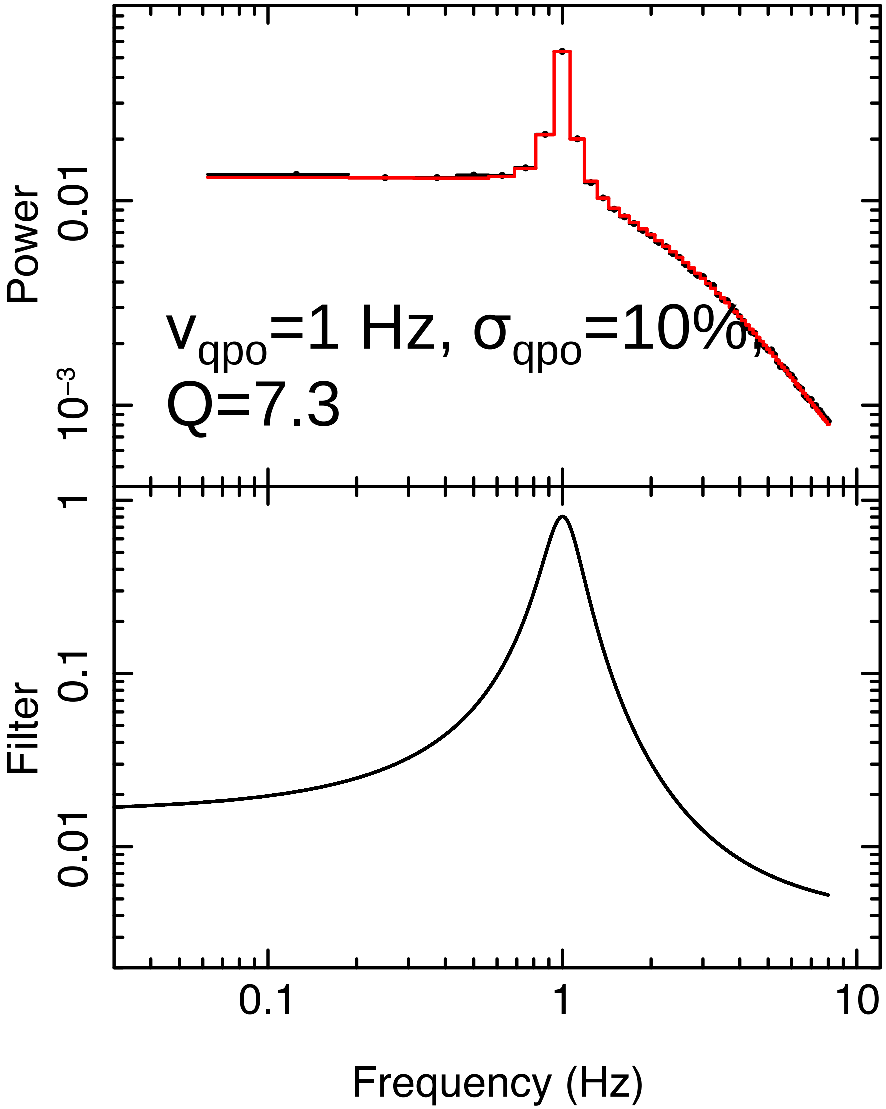


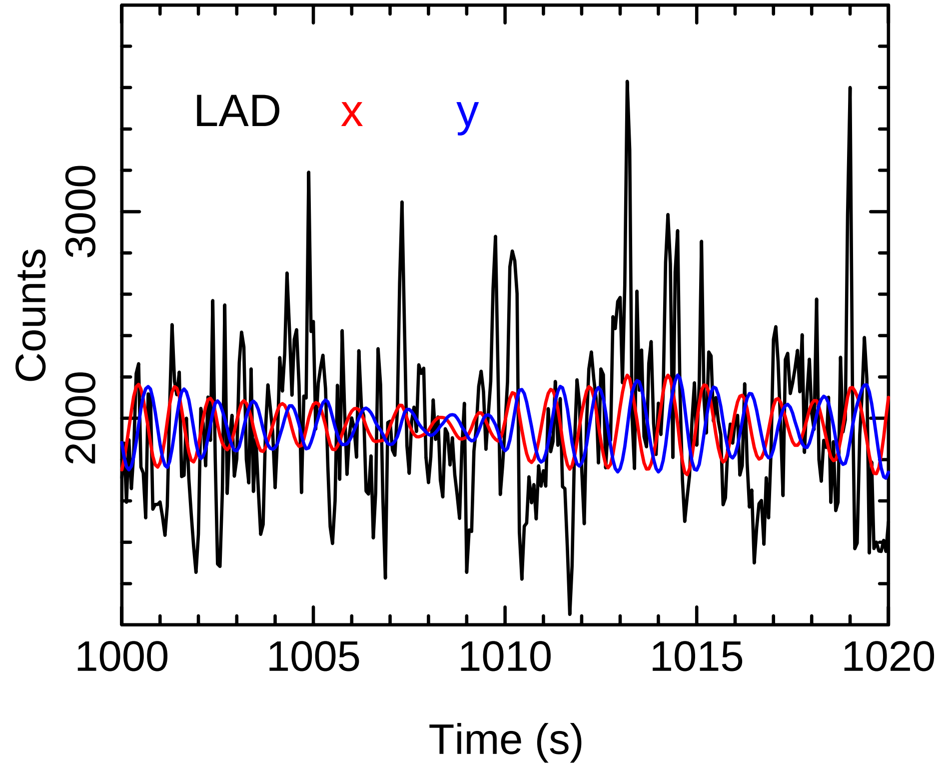


- $x(t)$ = optimally filtered light curve

van den Eijnden, Ingram & Uttley (in prep)

Phase folding

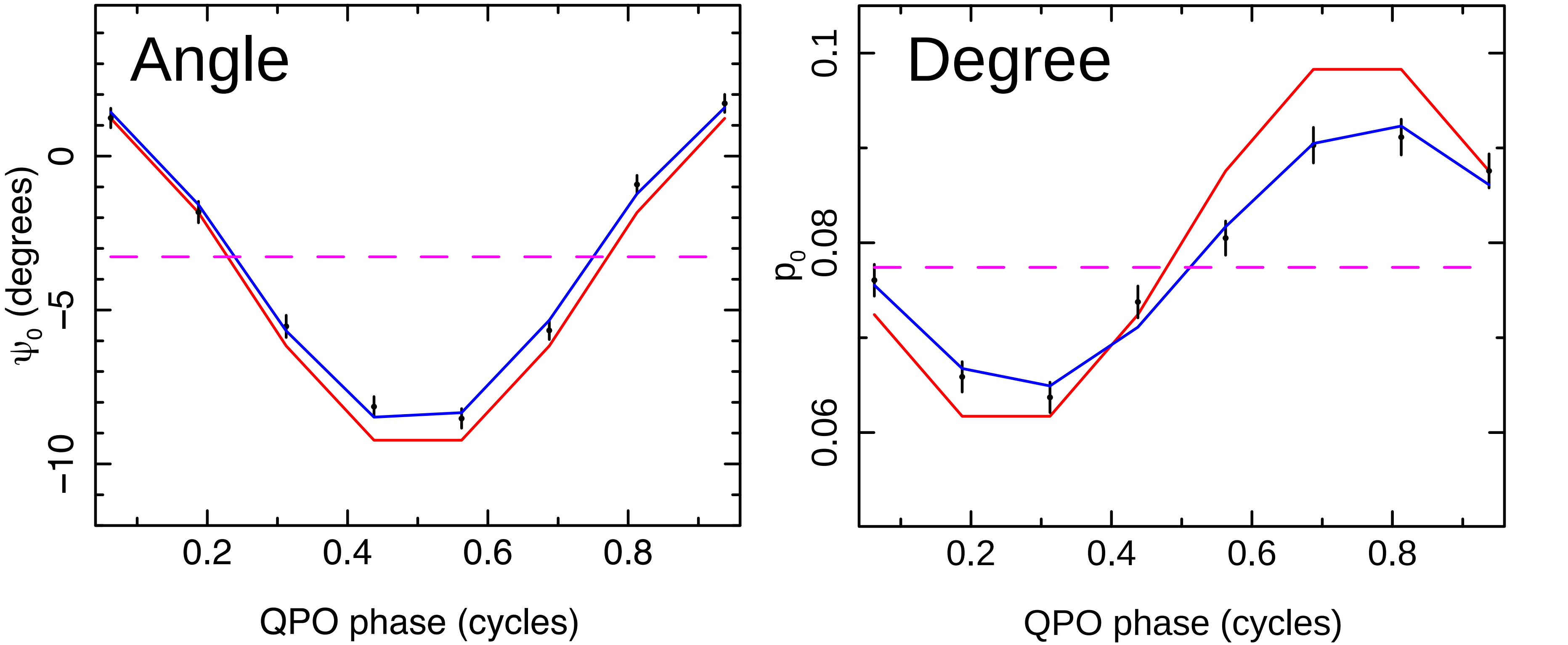




Huang et al (1998); Huang & Wu (2008)

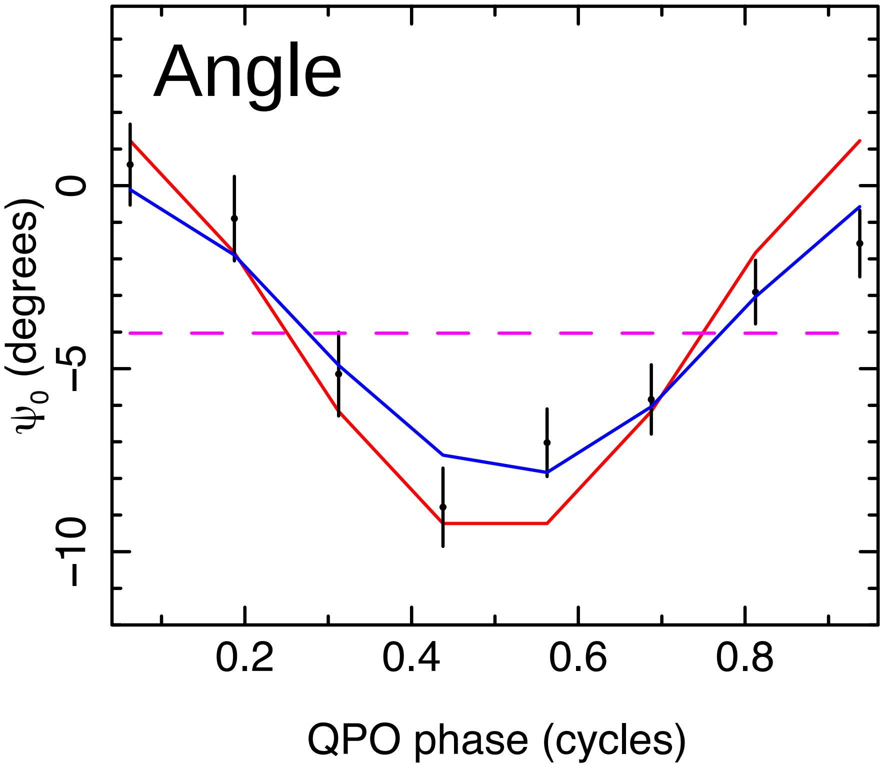
- x(t) = optimally filtered light curve
- y(t) = Hilbert transform of x(t)

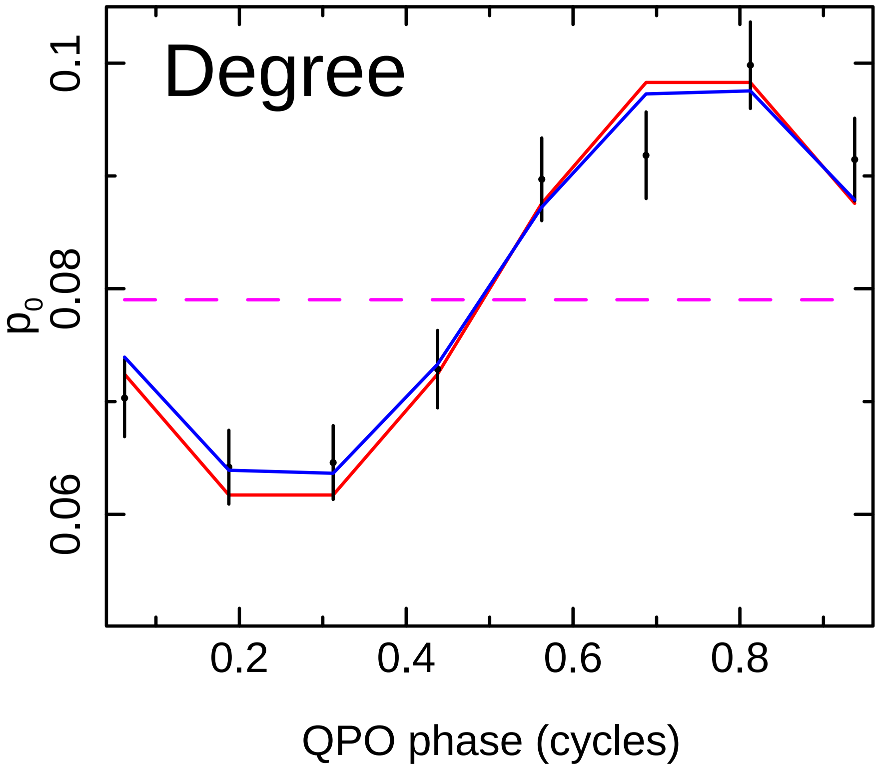
Phase folding



- 32.768ks exposure
- $<p_0>=8\%$, $\sigma_{p_0}=1.4\%$, $<\psi_0>=-4$ degrees, $\sigma_{\psi_0}=4$ degrees
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with $\Gamma=2$ and $N_h=1\times10^{22}cm^{-2}$
- 40 LAD modules, 2 GPD units

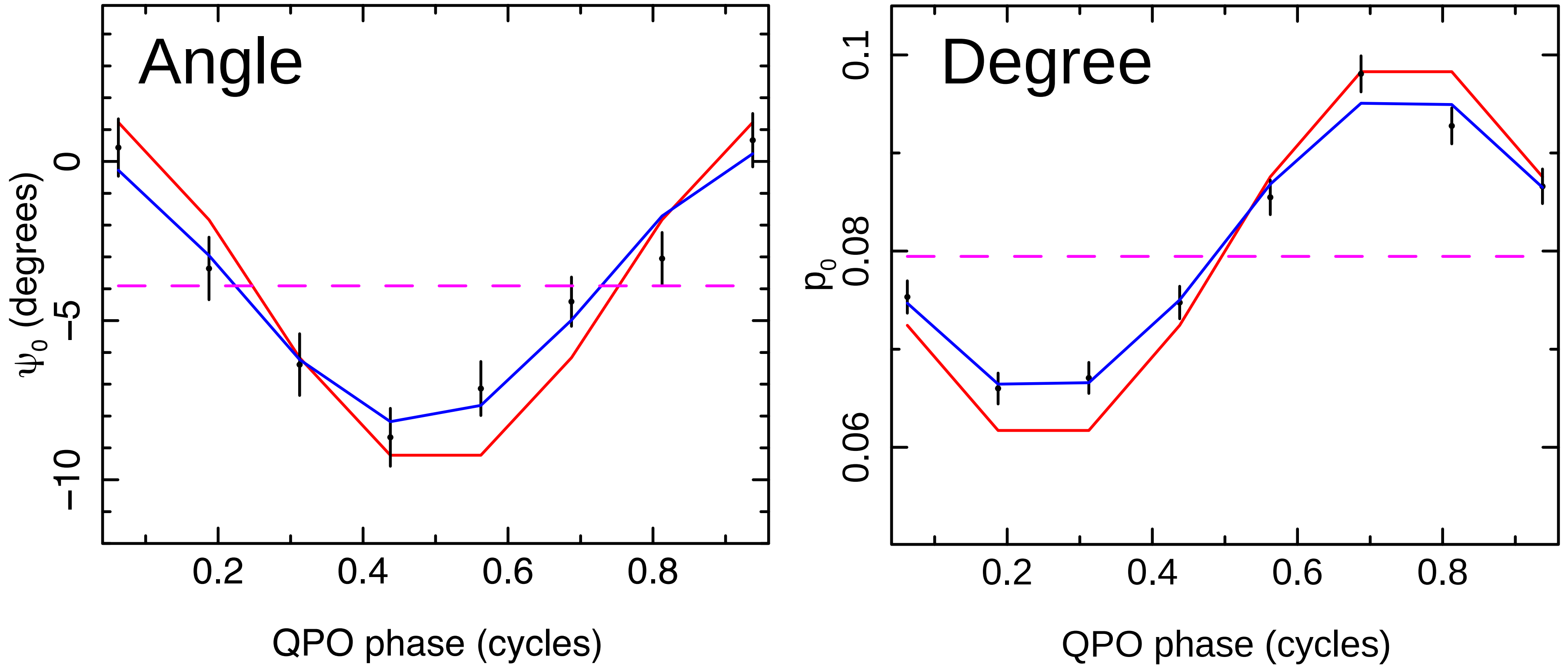
Phase folding





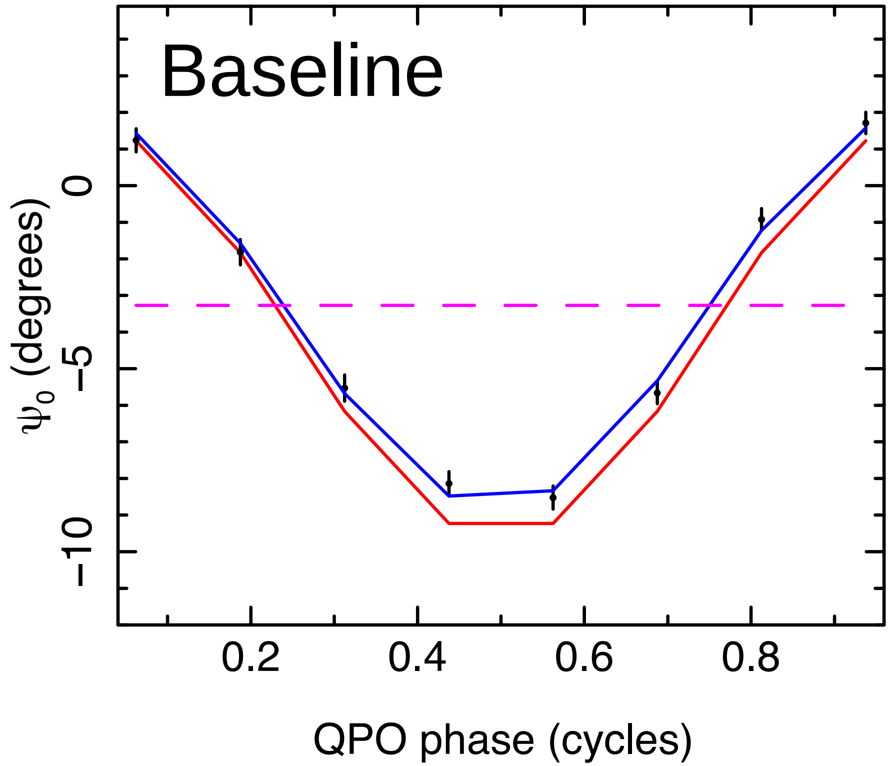
- 32.768ks exposure
- $<p_0>=8\%$, $\sigma_{p_0}=1.4\%$, $<\psi_0>=-4$ degrees, $\sigma_{\psi_0}=4$ degrees
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with $\Gamma=2$ and $N_h=1\times10^{22}cm^{-2}$
- **20 LAD modules**, 2 GPD units

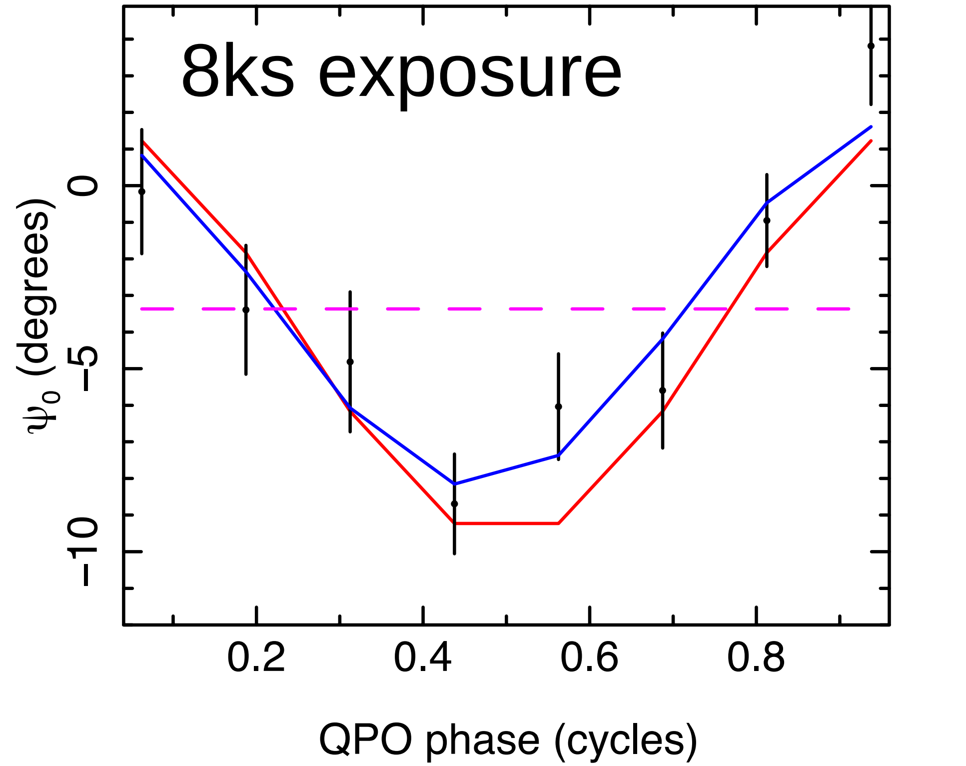
Phase folding



- 32.768ks exposure
- $<p_0>$=8%, σ_{p_0}=1.4%, $<\psi_0>$=-4 degrees, σ_{ψ_0}=4 degrees
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with Γ=2 and $N_h=1\times10^{22}cm^{-2}$
- **20 LAD modules, 3 GPD units**

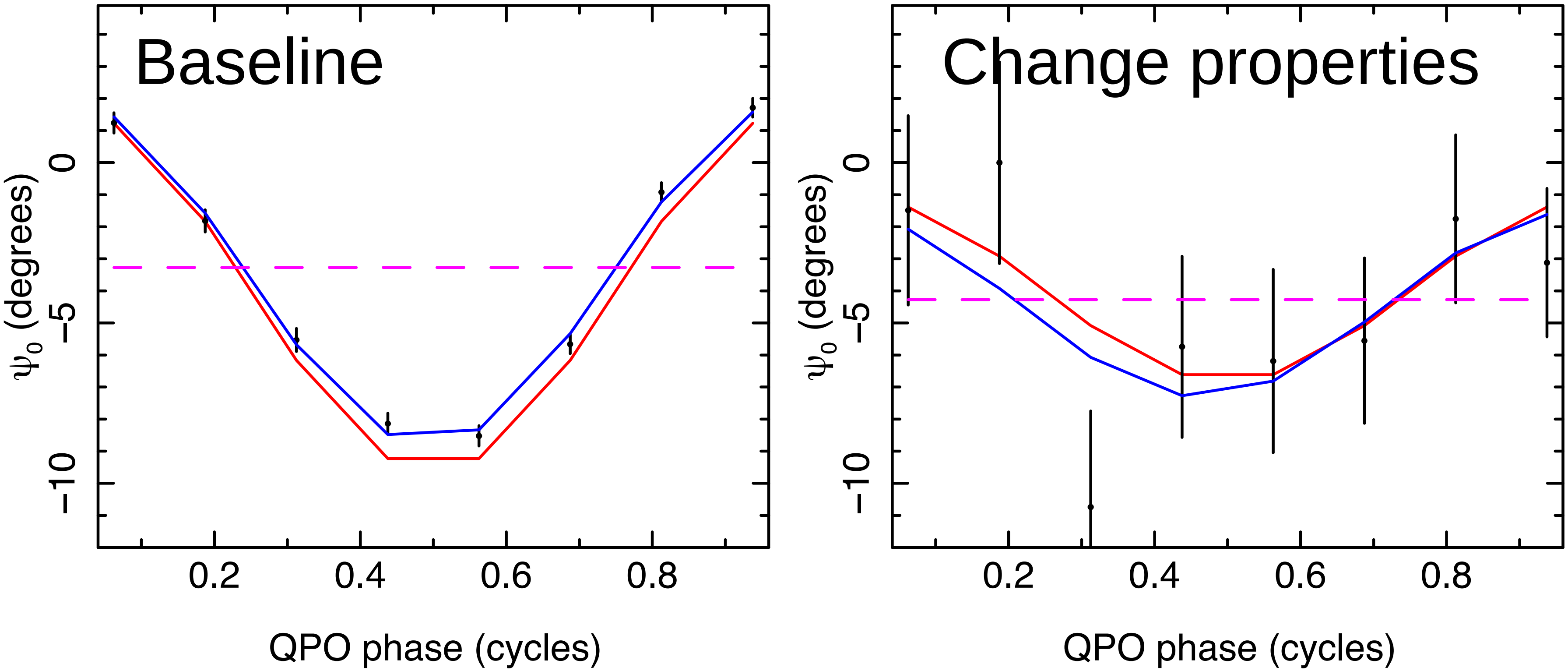
Phase folding





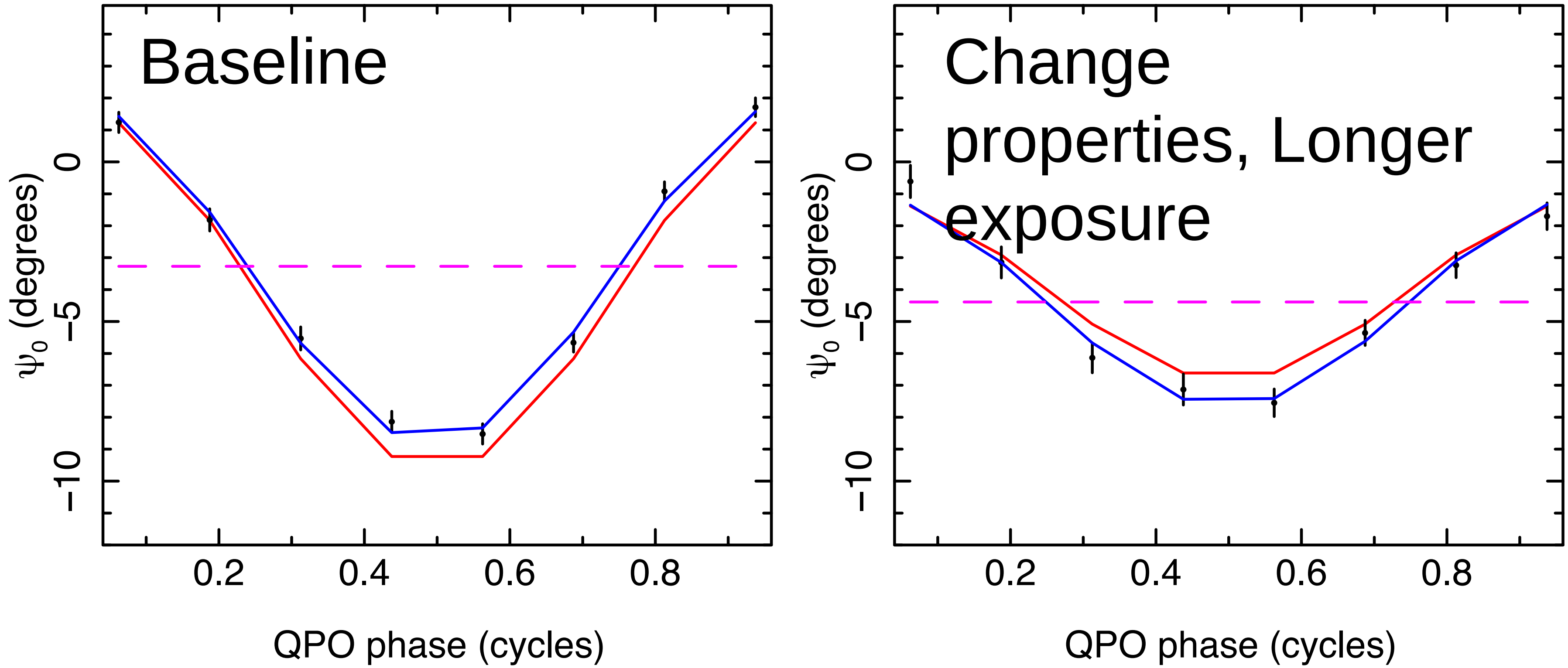
- **8ks exposure**
- $<p_0>$=8%, σ_{p_0}=1.4%, $<\psi_0>$=-4 degrees, σ_{ψ_0}=4 degrees
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with Γ=2 and $N_h=1\times10^{22}cm^{-2}$
- 40 LAD modules, 2 GPD units

Phase folding



- 32.768ks exposure
- **$<p_0>$=4%, σ_{p_0}=0.7%, $<\psi_0>$=-2 degrees, σ_{ψ_0}=4 degrees**
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with Γ=2 and $N_h=1\times10^{22}cm^{-2}$
- 40 LAD modules, 2 GPD units

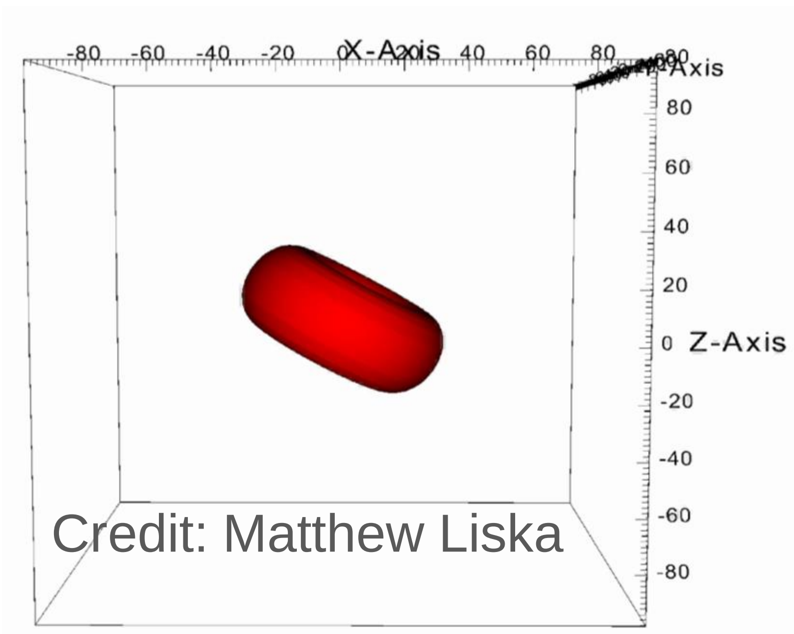
Phase folding



- **65.536ks exposure**
- **$\langle p_0 \rangle$=4%, σ_{p_0}=0.7%, $\langle \psi_0 \rangle$=-2 degrees, σ_{ψ_0}=4 degrees**
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with Γ=2 and $N_h = 1 \times 10^{22} cm^{-2}$
- 40 LAD modules, 2 GPD units

Frame dragging

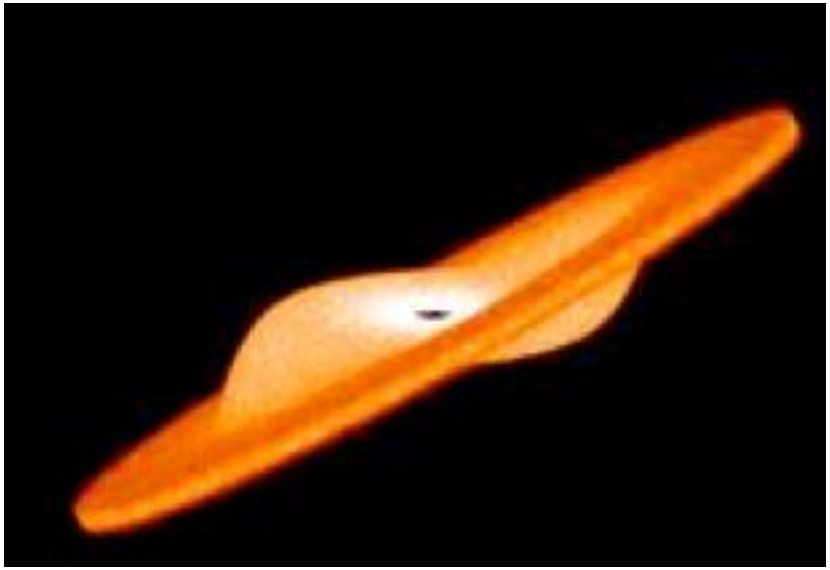
H/R > α



Solid body precession at average LT frequency

Fragile et al (2007); Liska et al in prep

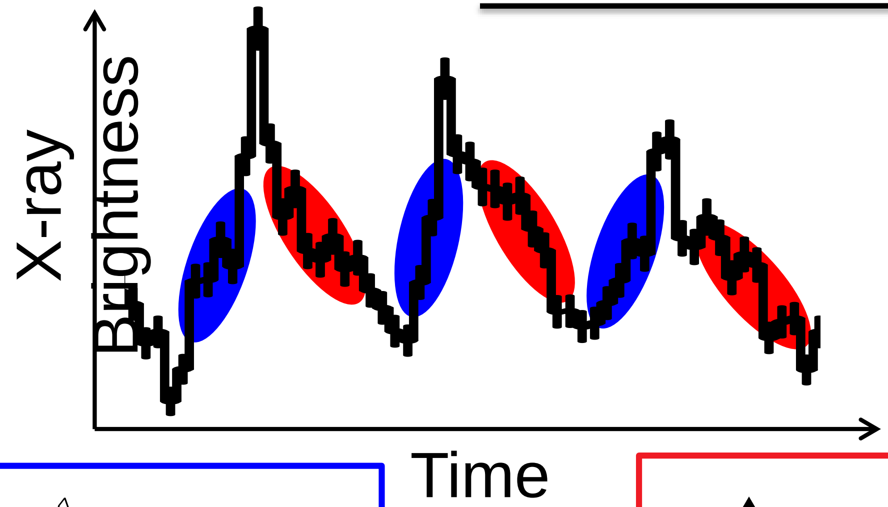
H/R < α

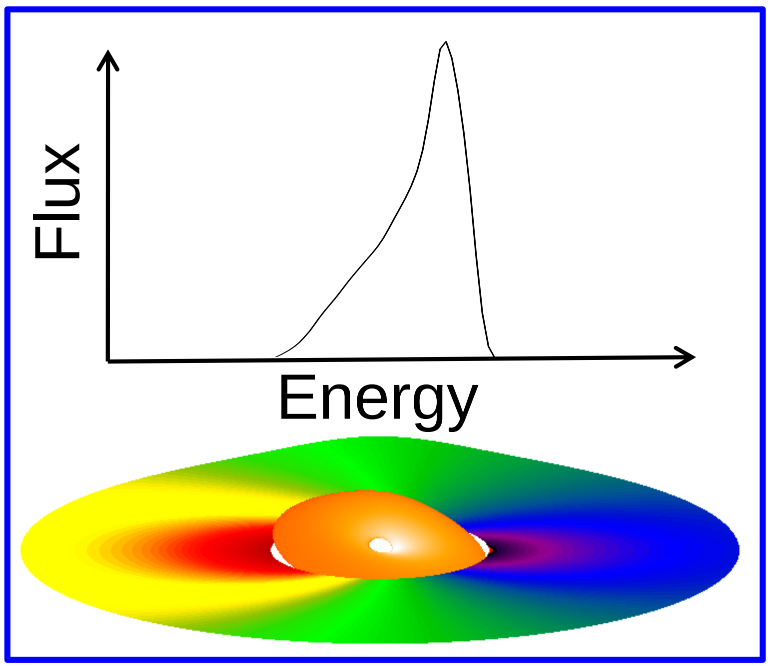


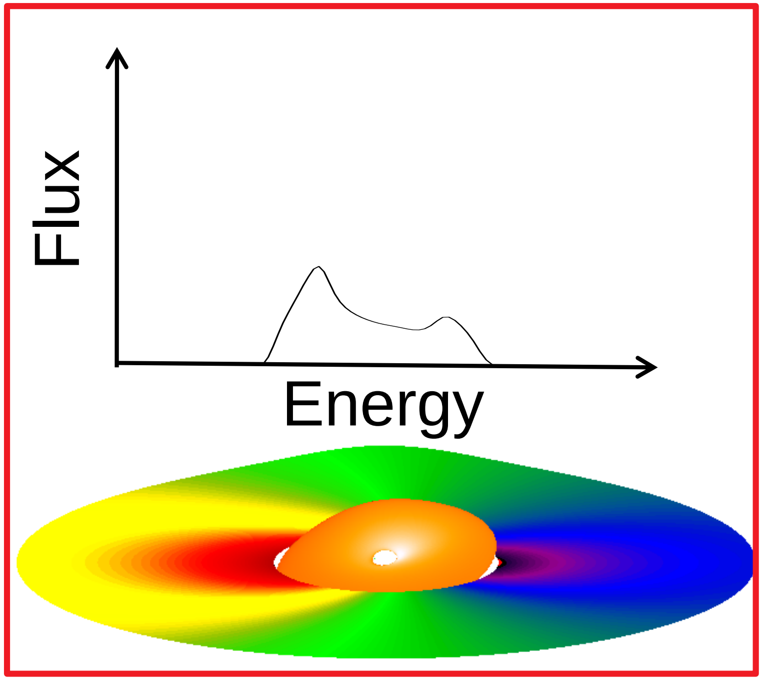
Viscosity aligns inner regions with the BH and outer regions with the binary partner

Bardeen & Petterson (1975)

Phase Resolving





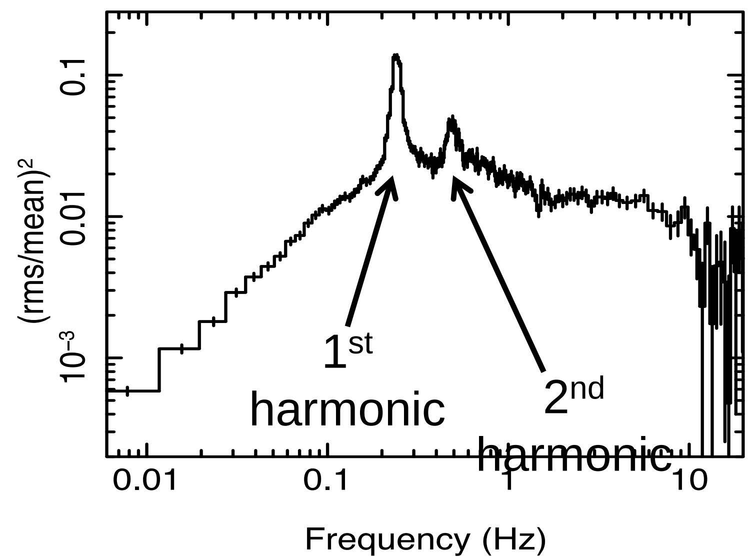


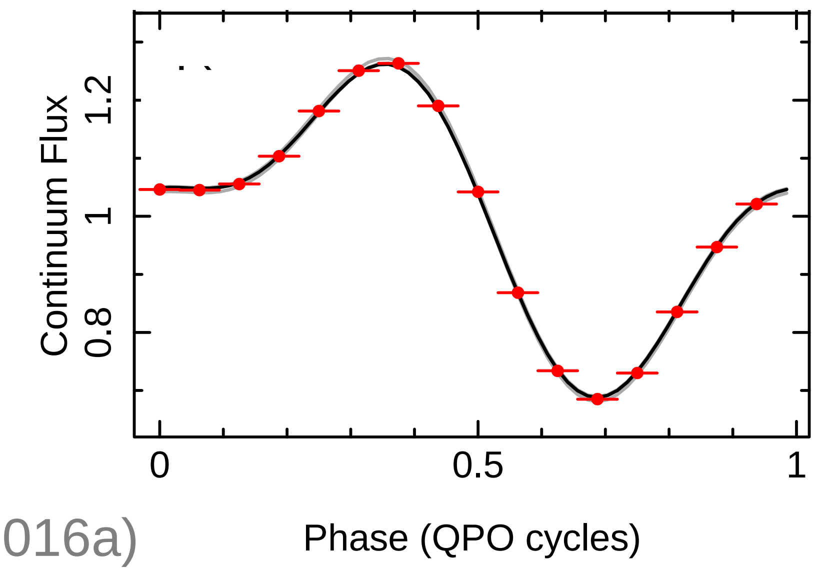
Phase Resolving

Observed H 1743-322: ~260 ks XMM; ~70 ks NuSTAR

Reconstruct QPO waveform in each energy band from:

1. Amplitude of first and second harmonics (power spectrum)
2. Phase difference between the two harmonics (Ingram & van der Klis 2015)
3. Phase difference between energy bands (cross-

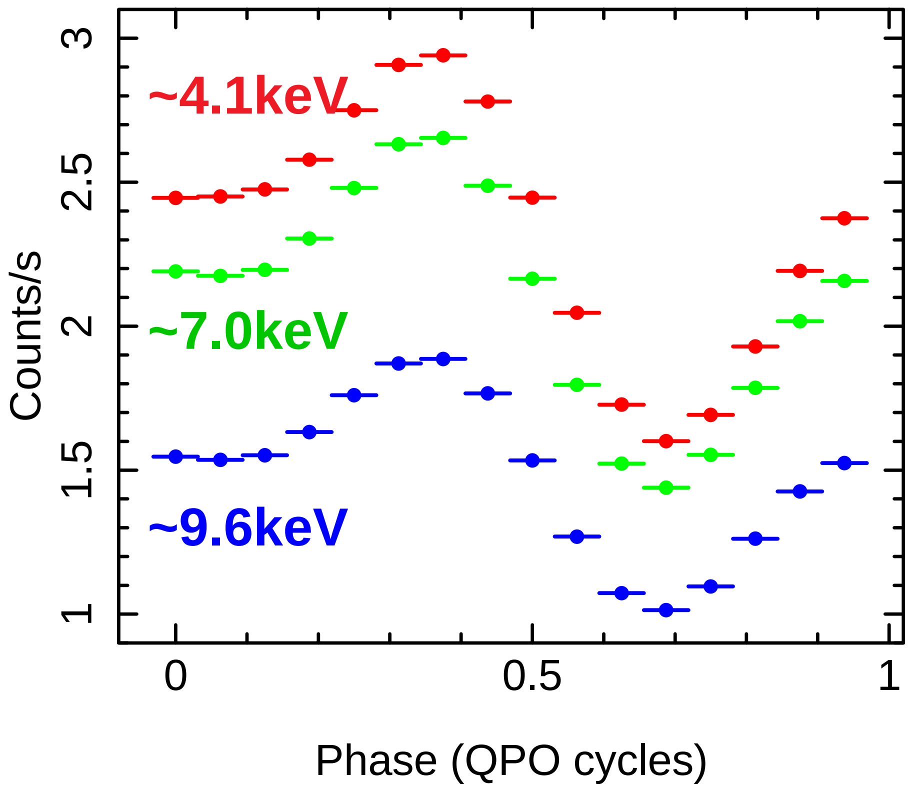




Ingram & van der Klis (2015); Ingram et al (2016a)

Phase Resolving

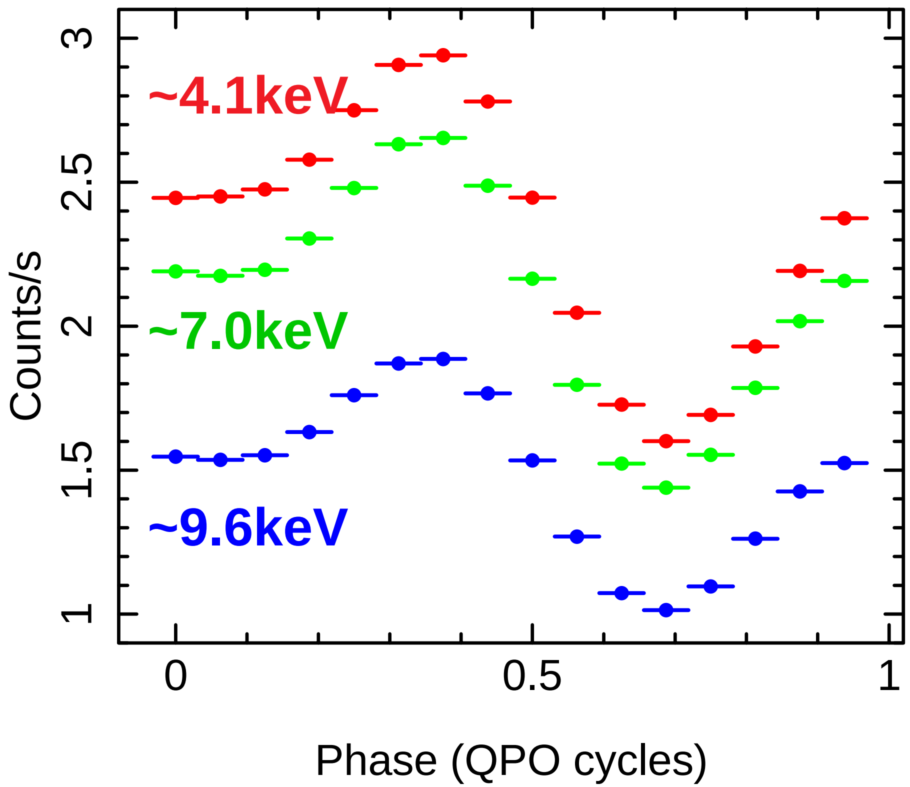
Reconstructing a waveform in each energy band gives phase-resolved spectra!

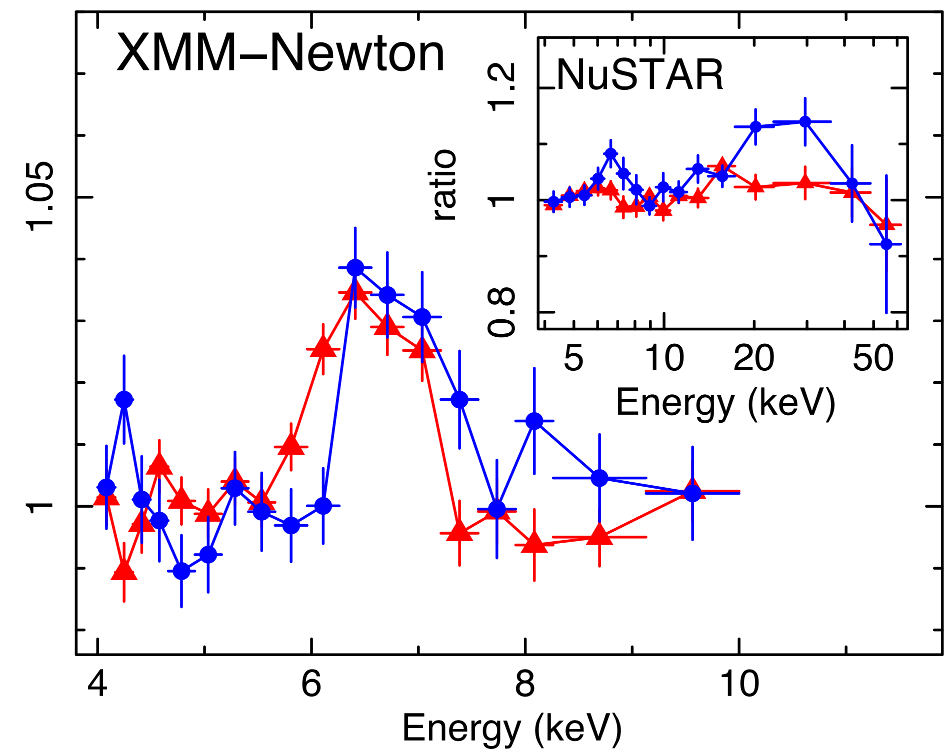


Ingram et al (2016a)

Phase Resolving

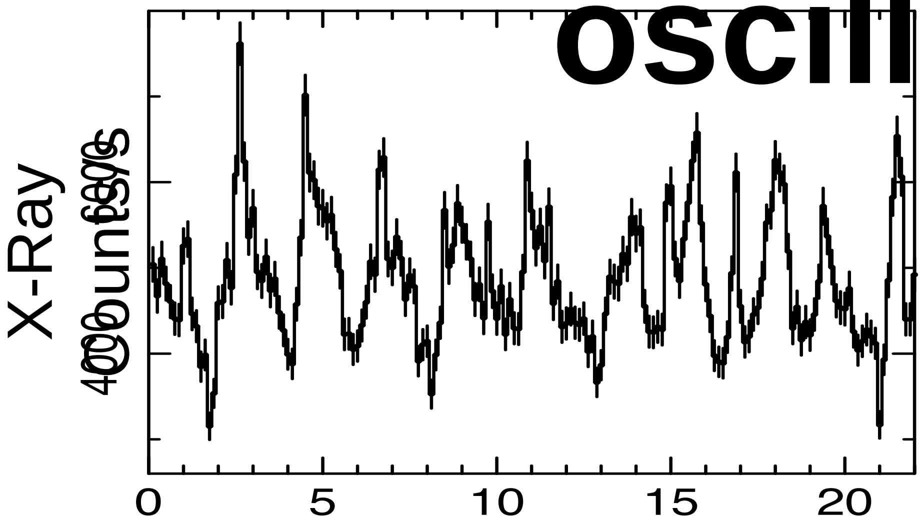
Reconstructing a waveform in each energy band gives phase-resolved spectra!

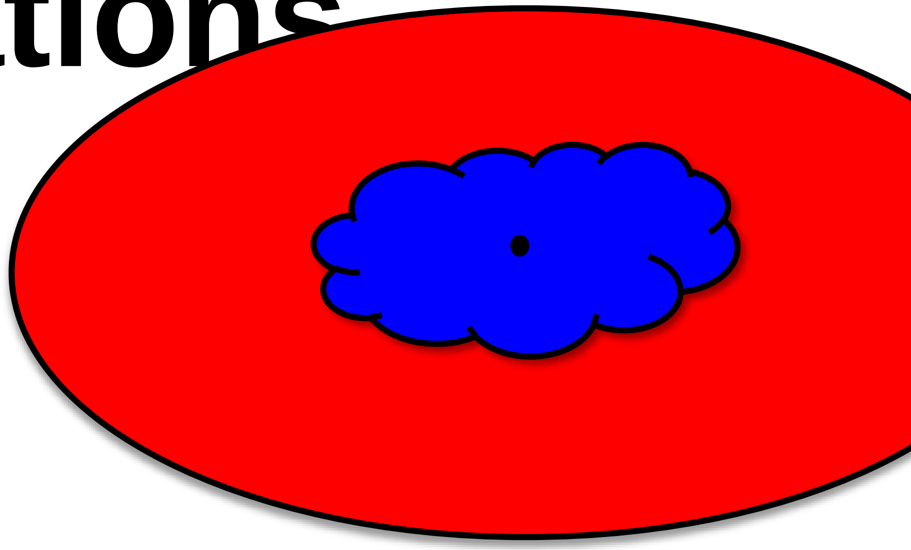


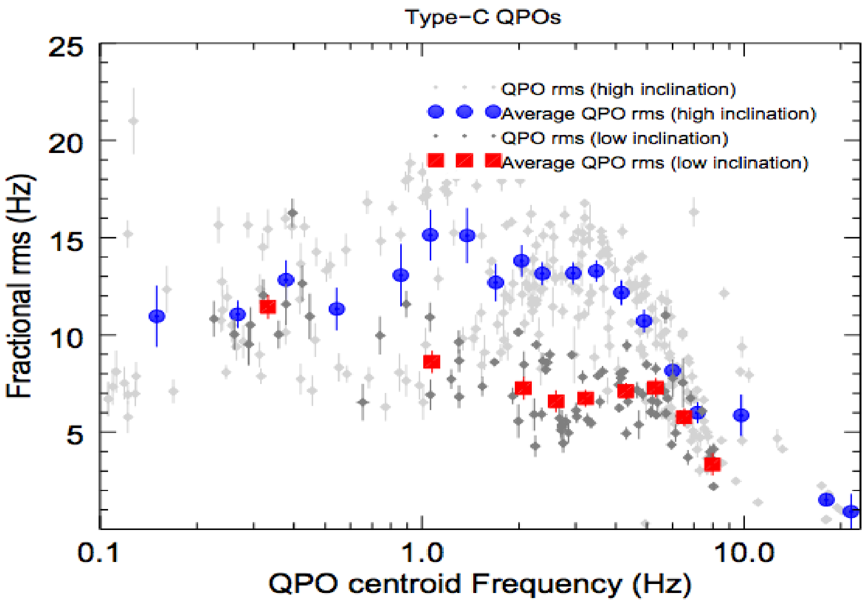


Ingram et al (2016a)

Quasi-periodic oscillations





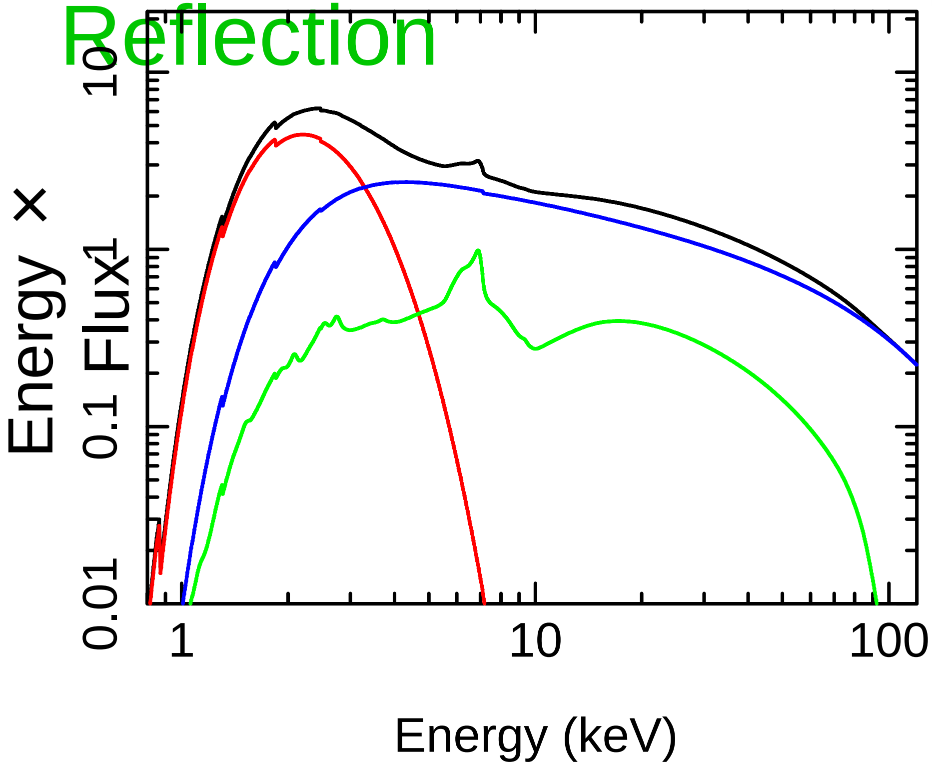


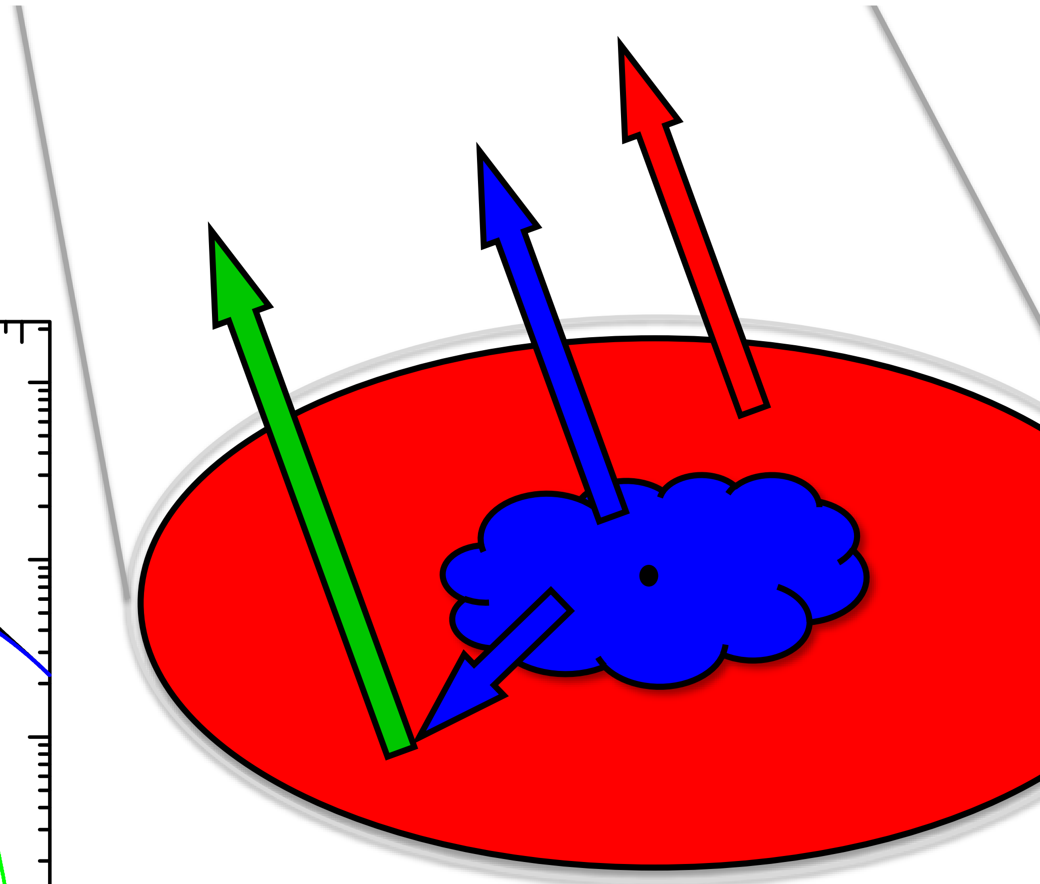
Higher inclination objects have stronger QPOs

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

Truncated Disk Model

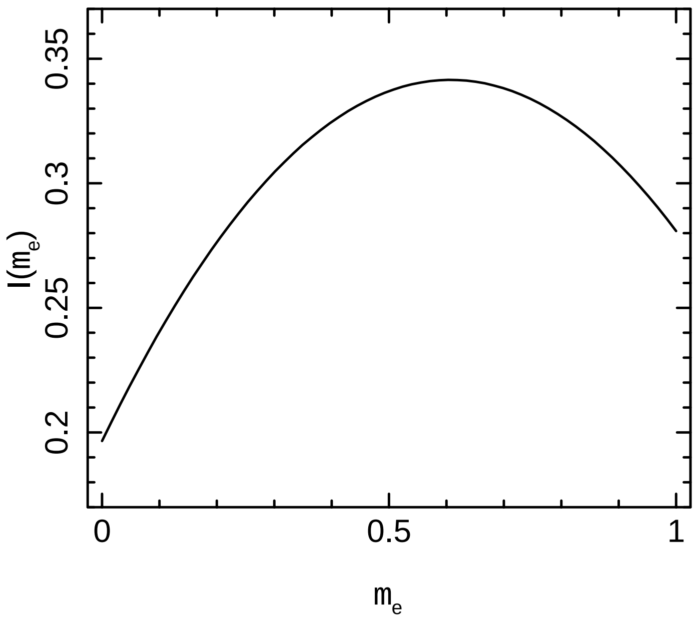
Multi-coloured blackbody, Comptonisation and Reflection

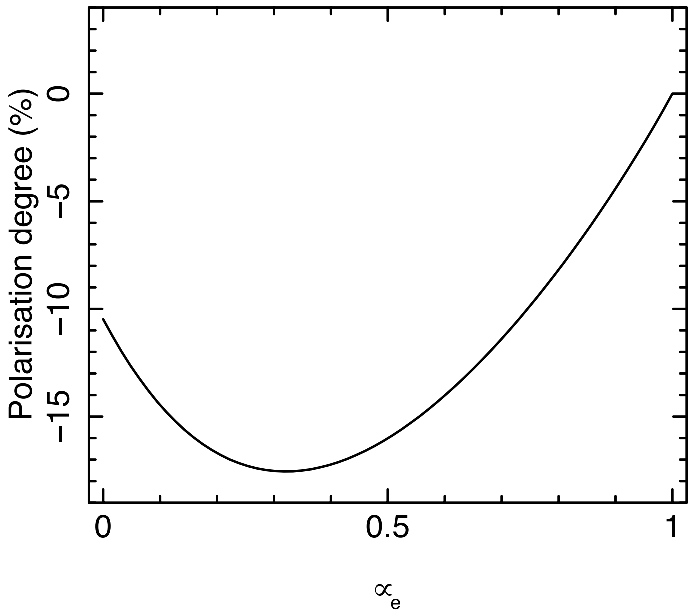




e.g. Done, Gierlinski & Kubota

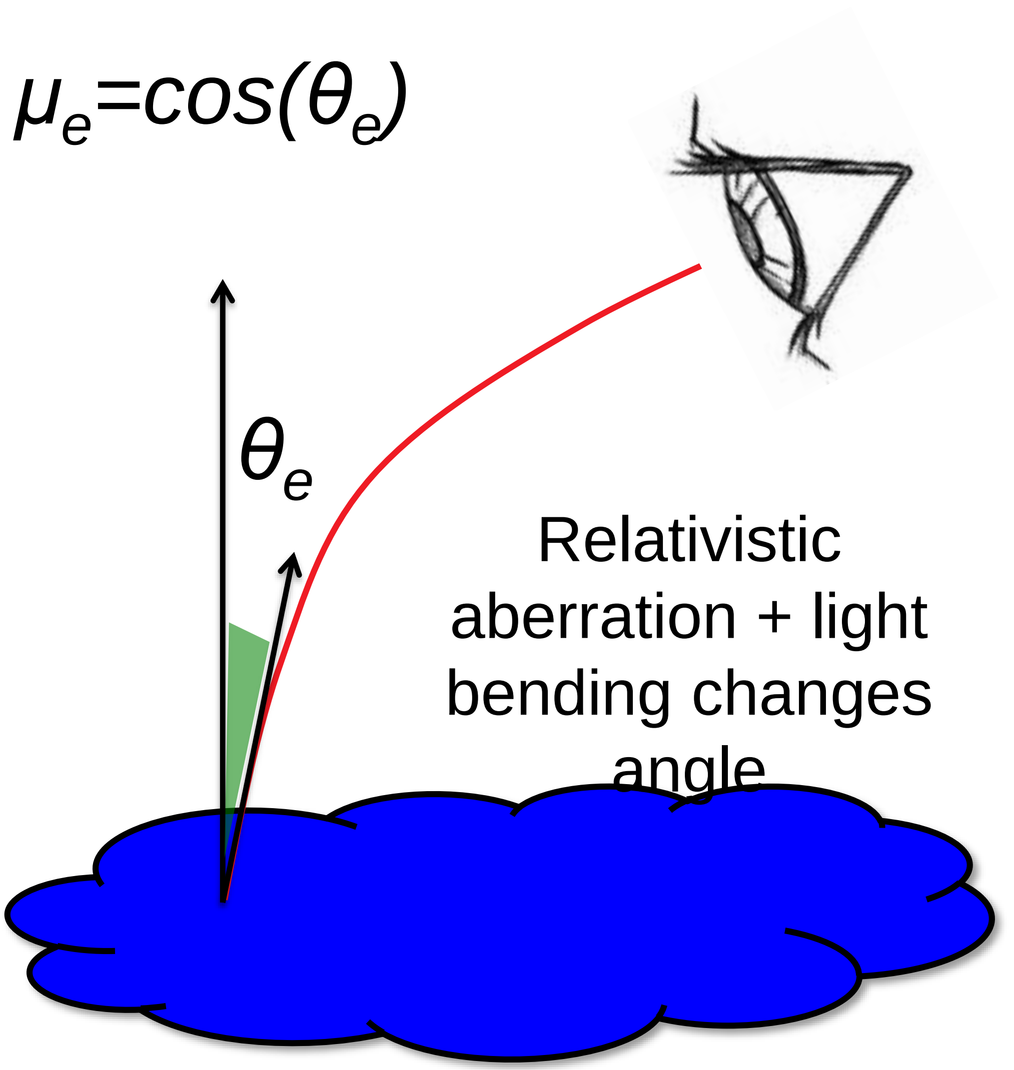
Setup



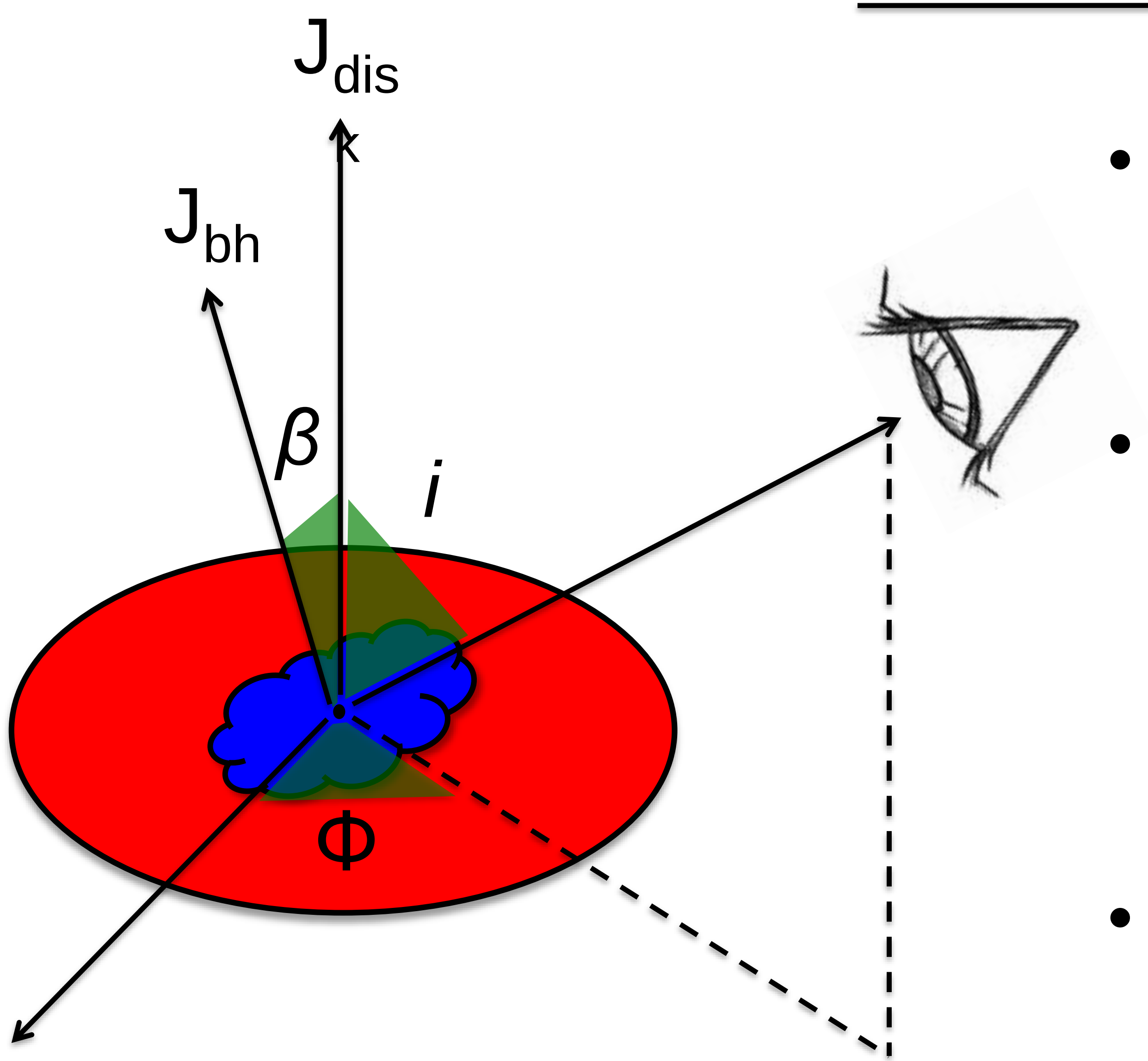


Sunyaev & Titarchuk (1985)

$\mu_e = cos(\theta_e)$



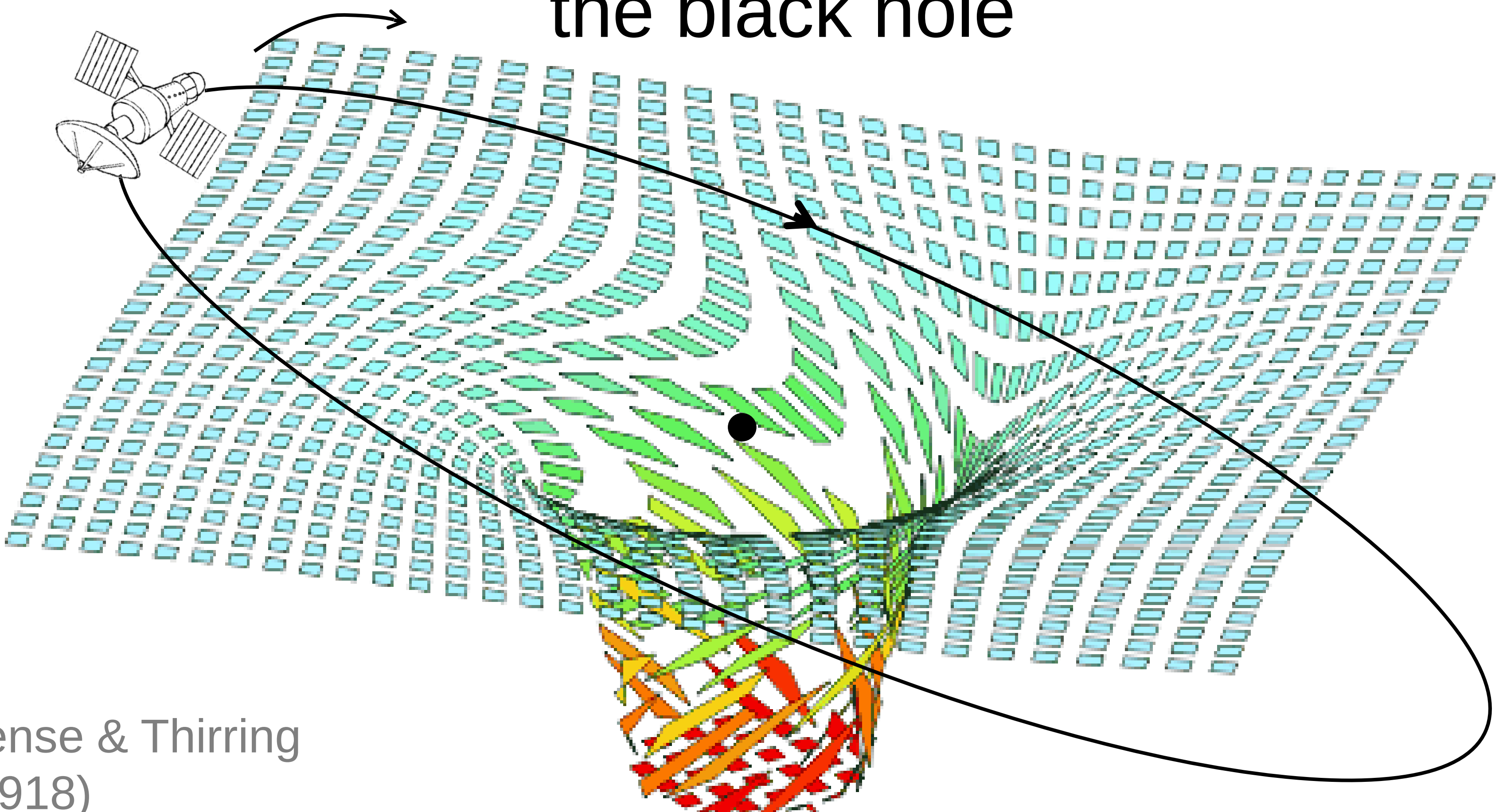
Setup



- BH and disk misaligned
- Flow precesses around BH spin axis
- Viewer position defined by 2

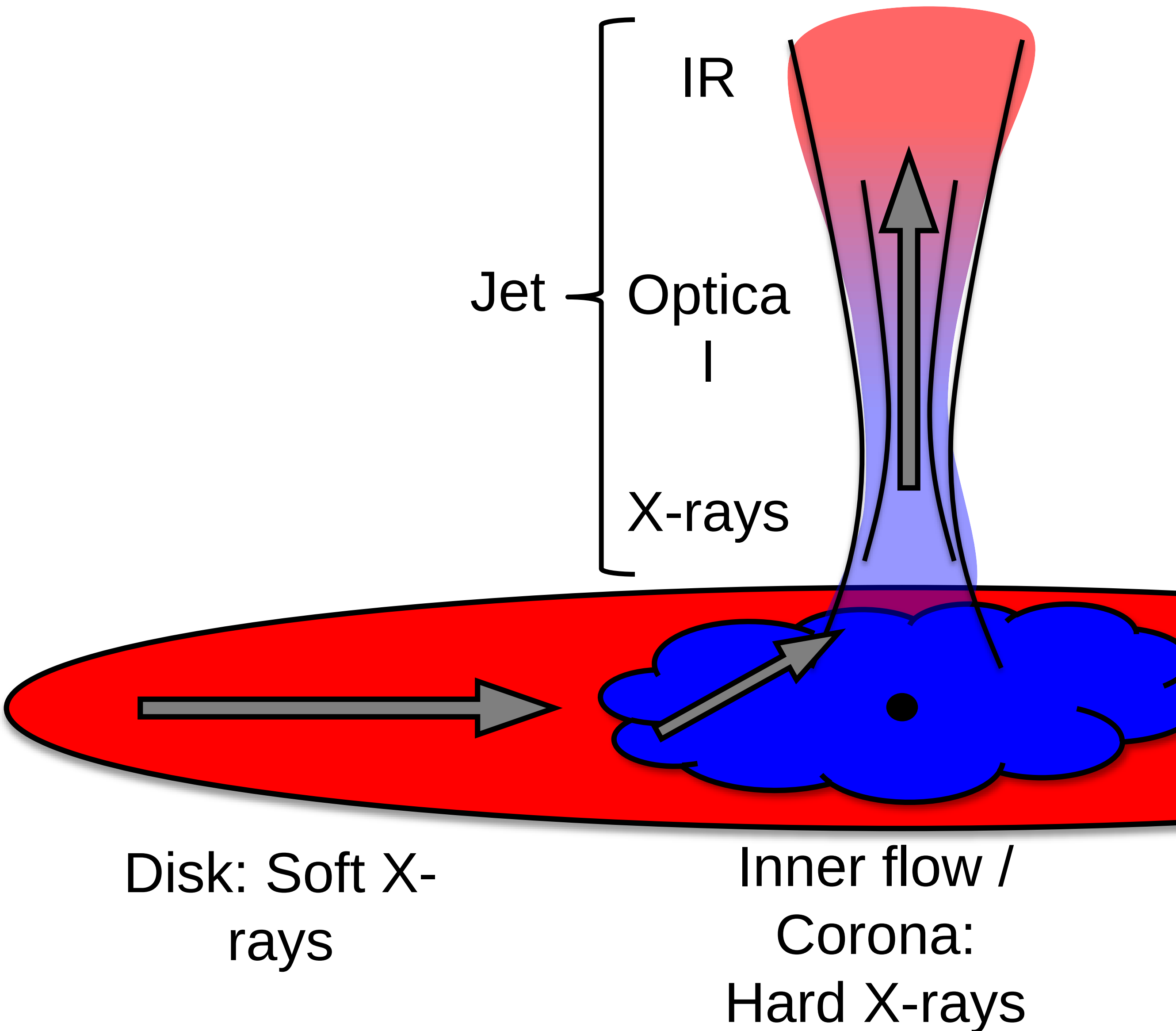
Frame dragging

A spinning black hole **distorts** space and time
The satellite's motion is **influenced** by the spin of the black hole



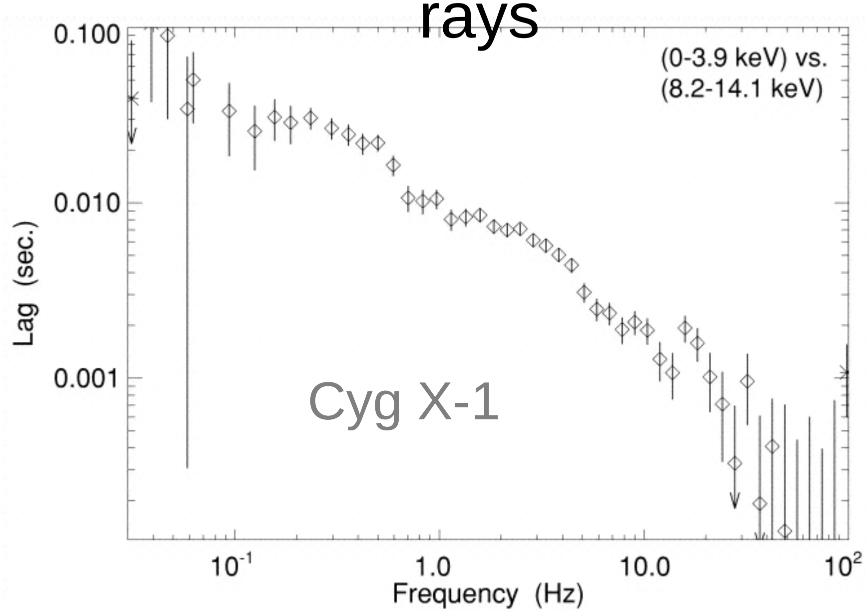
Lense & Thirring (1918)
Stella & Vietri ([illegible])

Broad band noise: propagating fluctuations

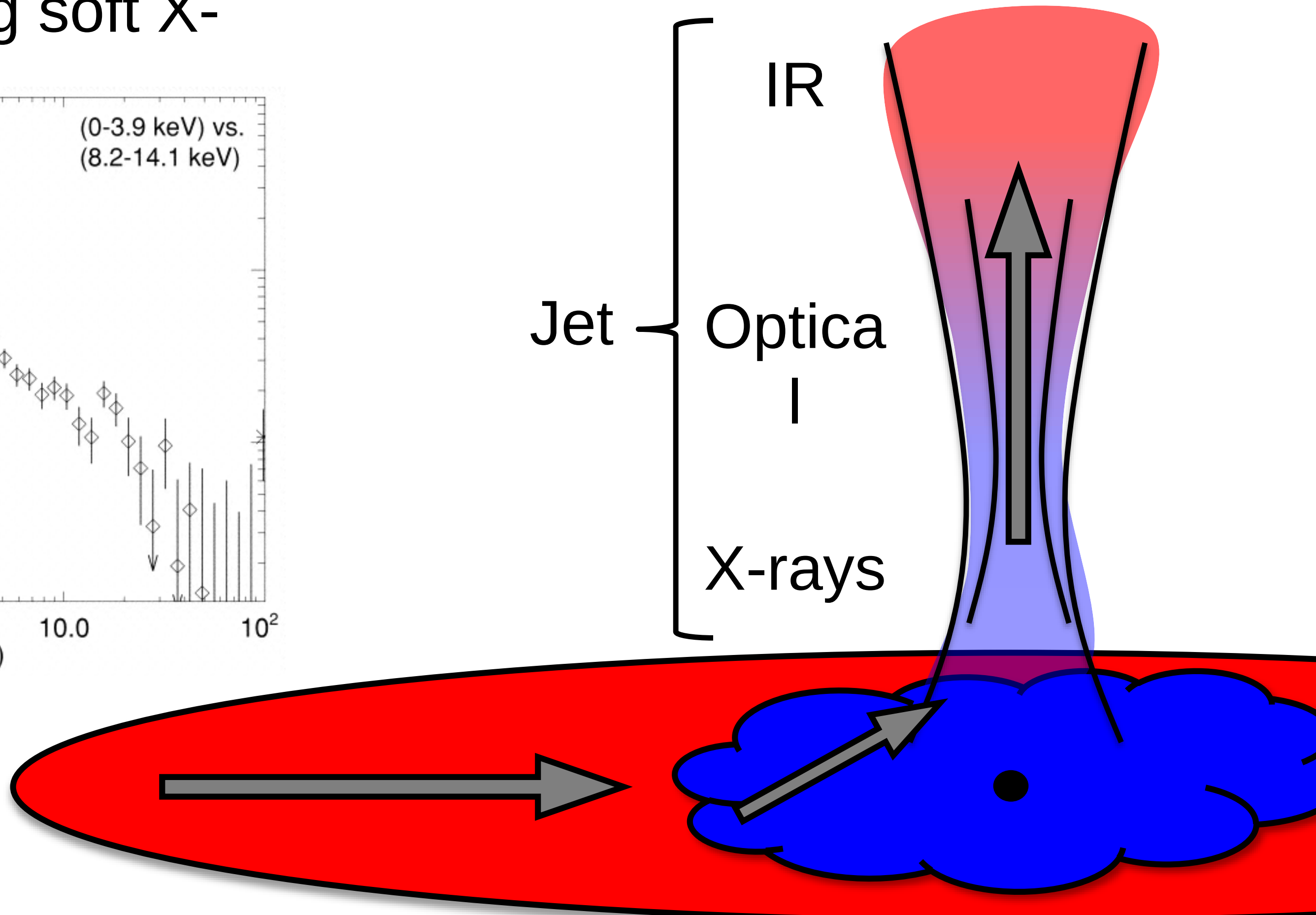


Broad band noise: propagating fluctuations

Hard X-rays lag soft X-rays



Nowak et al (1999)

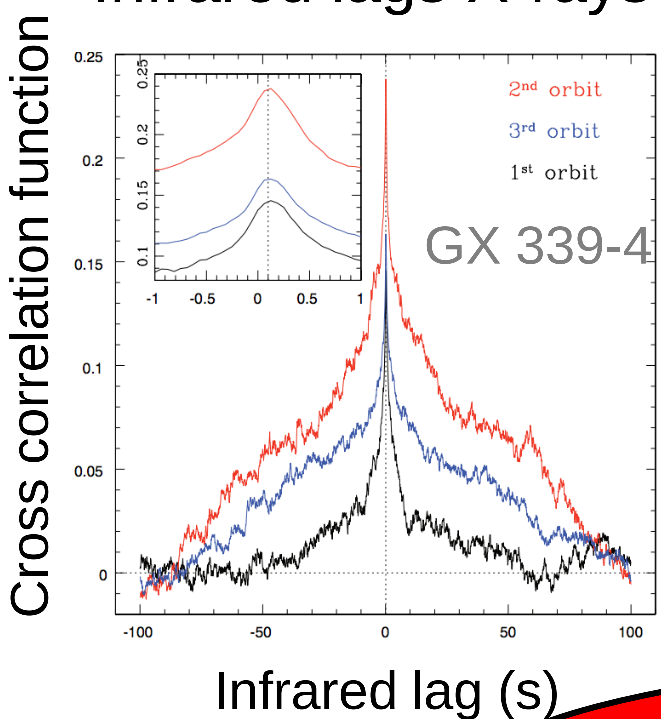


Disk: Soft X-rays

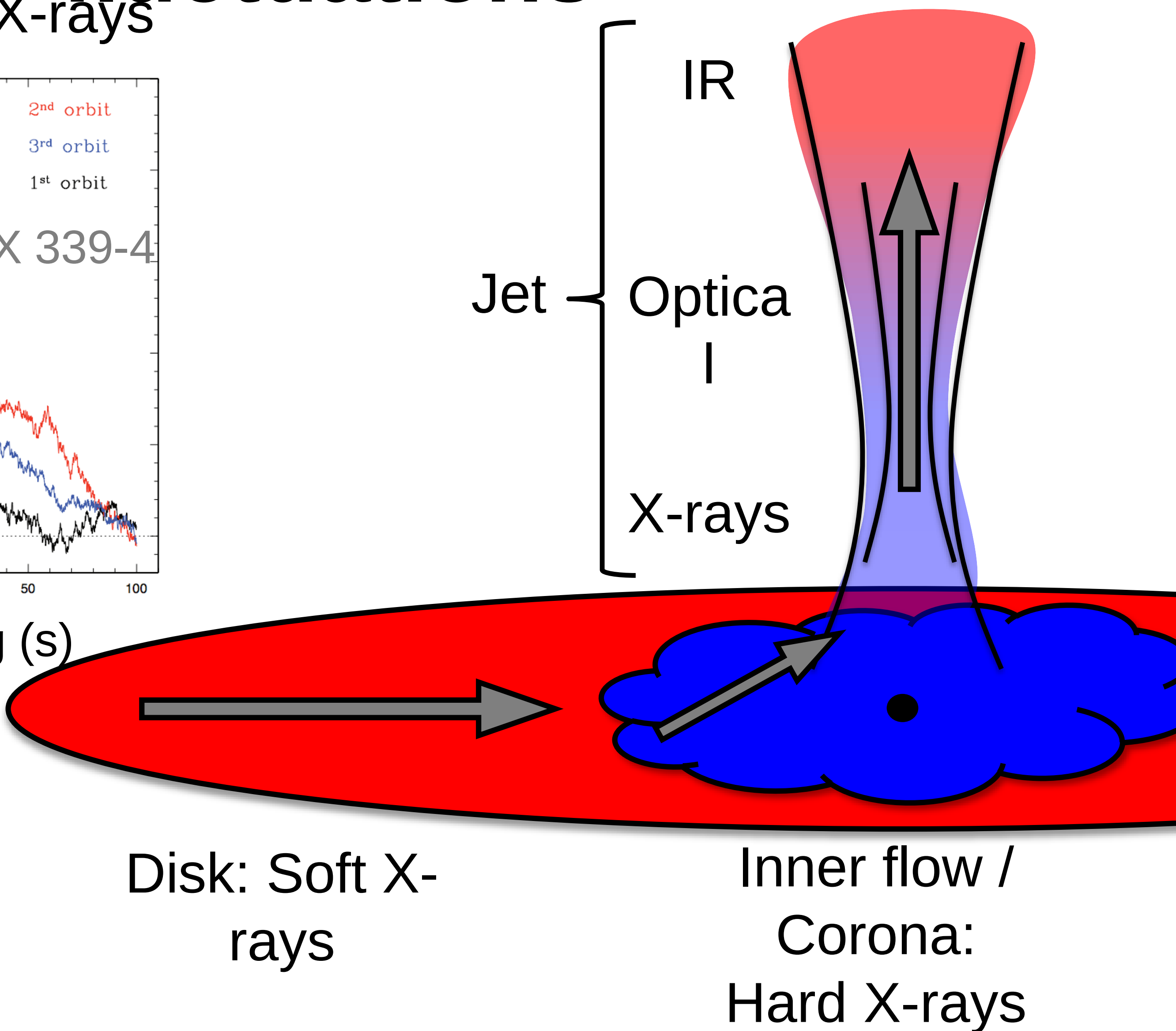
Inner flow / Corona: Hard X-rays

Broad band noise: propagating fluctuations

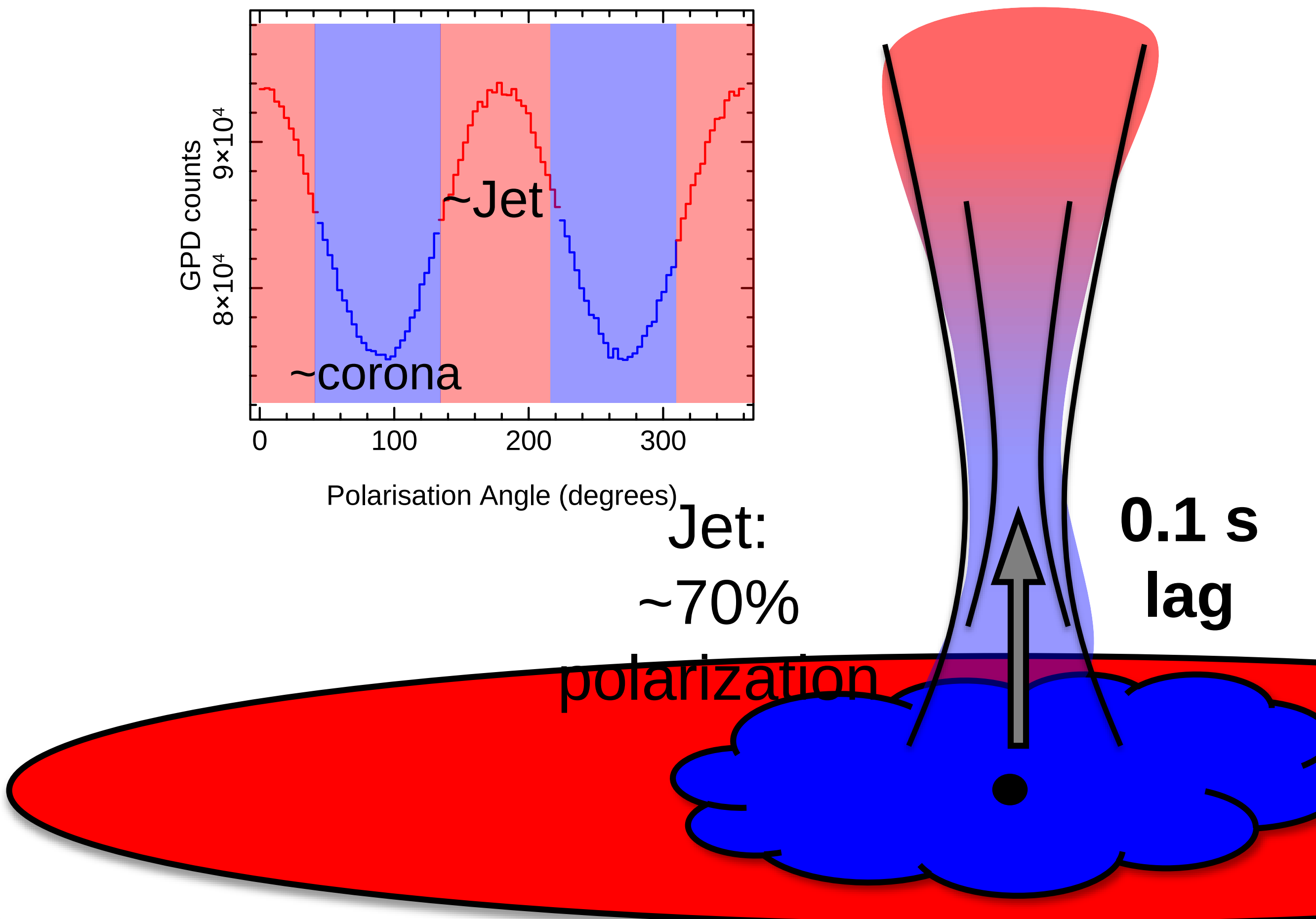
Infrared lags X-rays



Casella et al (2010)



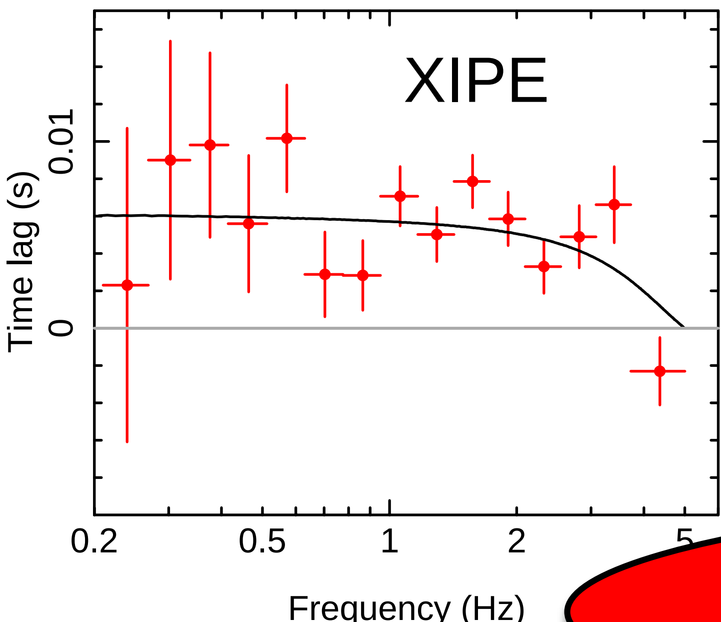
Broad band noise: propagating fluctuations

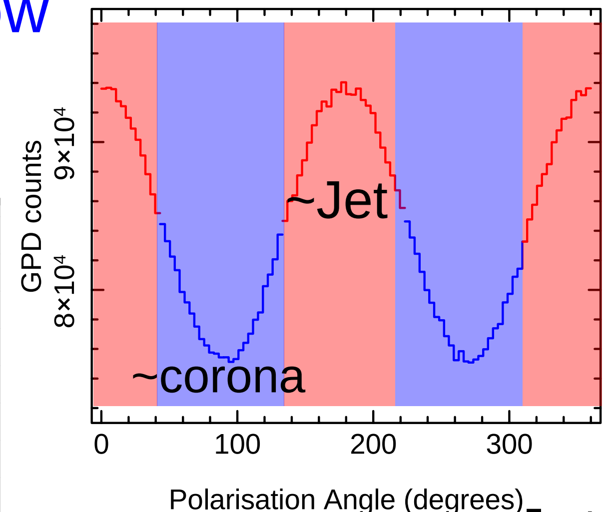


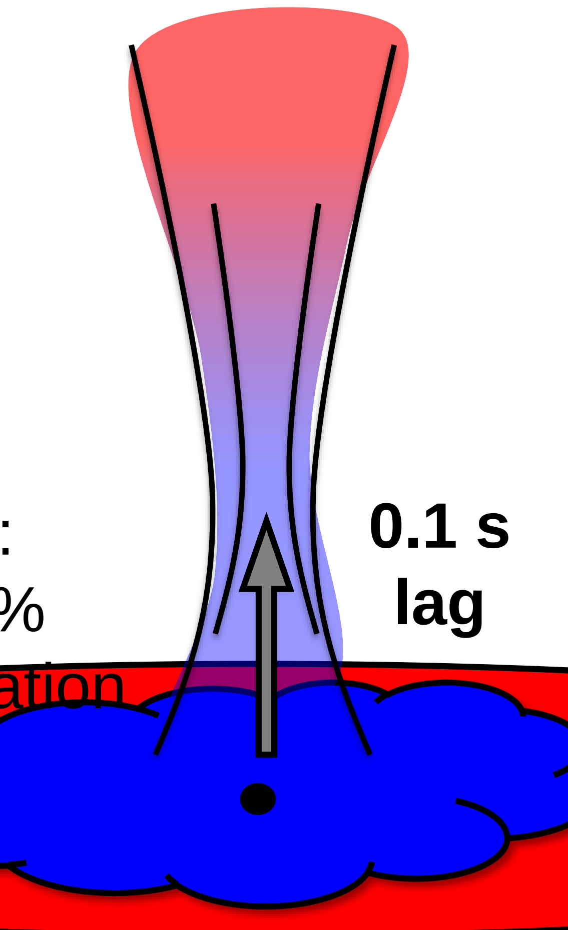
- 200 ks exposure
- Bright source (~GRS 1915+105)

Broad band noise: propagating fluctuations

High polarization lags low polarization?



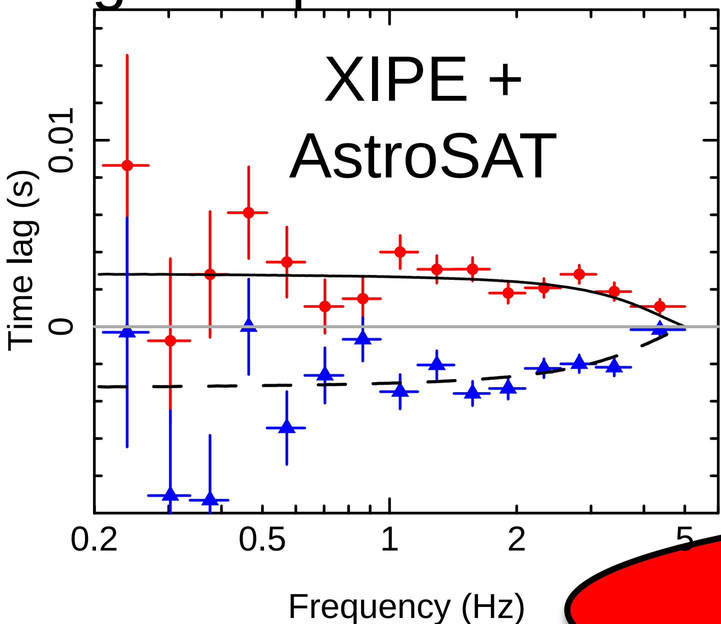


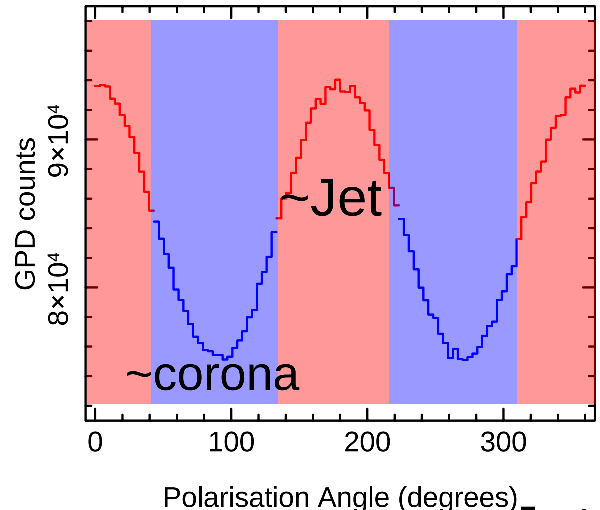


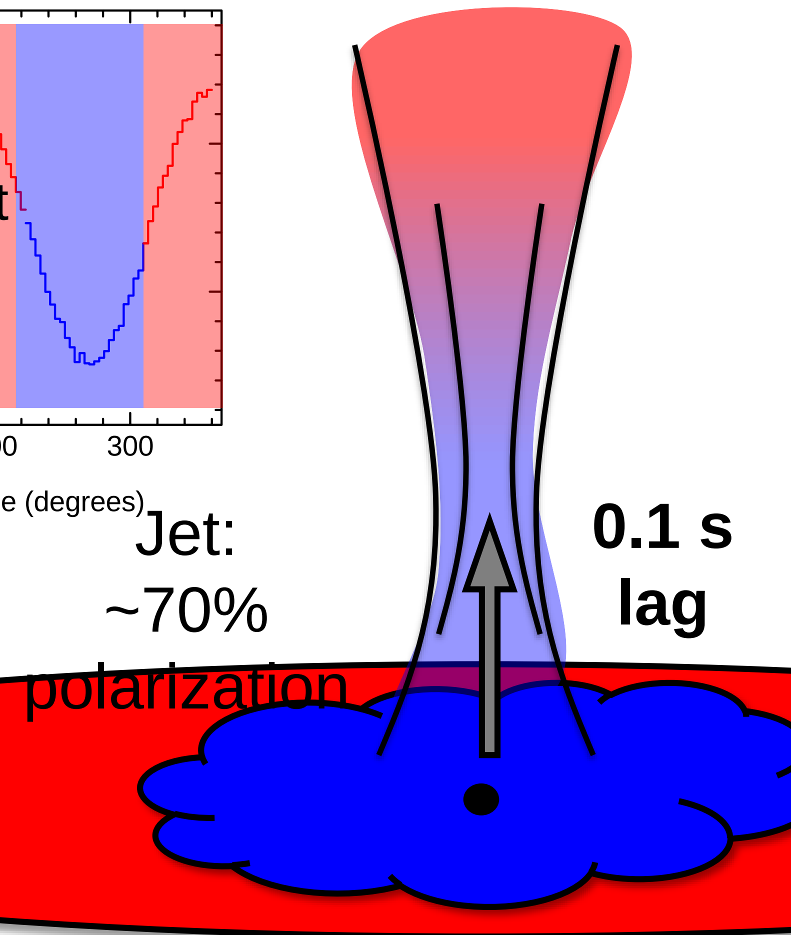
- 200 ks exposure
- Bright source (~GRS 1915+105)

Broad band noise: propagating fluctuations

High polarization lags reference band, which lags low polarization?







Inner flow / corona: ~10 % polarization

- 200 ks exposure
- Bright source (~GRS 1915+105)

Detection

$I(t)$ = GPD count rate
$Q(t) = I(t)\, p(t) \cos[\, 2\psi(t)\,]$
$U(t) = I(t)\, p(t) \sin[\, 2\psi(t)\,]$
$R(t)$ = LAD count rate

The problem:

- Want to measure $p(\nu)$ & $\psi(\nu)$
- But can't measure $p(t)$ and $\psi(t)$ for arbitrarily small time bins due to Poisson statistics
- Can measure $Q(t)$ & $U(t)$
- Can measure $Q(\nu)R^*(\nu)$ & $U(\nu)R^*(\nu)$

Ingram & Maccarone (in prep)

Detection

I(t) = GPD count rate
$Q(t) = I(t)\, p(t) \cos[\, 2\psi(t)\,]$
$U(t) = I(t)\, p(t) \sin[\, 2\psi(t)\,]$
R(t) = LAD count rate

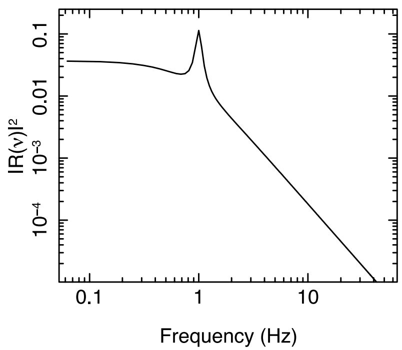
The solution:

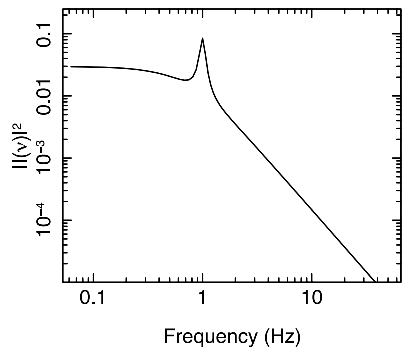
- Define phenomenological model for $p(\nu)$ & $\psi(\nu)$
- For a given set of model parameters, calculate model $Q(\nu)R^*(\nu)$ & $U(\nu)R^*(\nu)$
- Fit to measured $Q(\nu)R^*(\nu)$ & $U(\nu)R^*(\nu)$

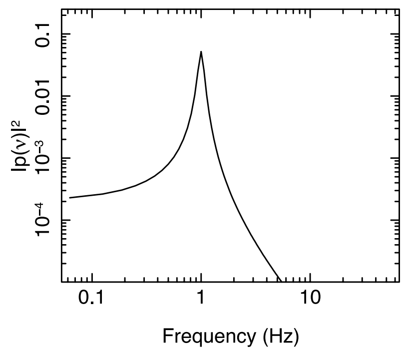
Ingram & Maccarone (in prep)

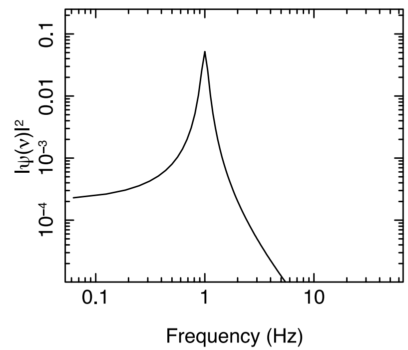
Detection

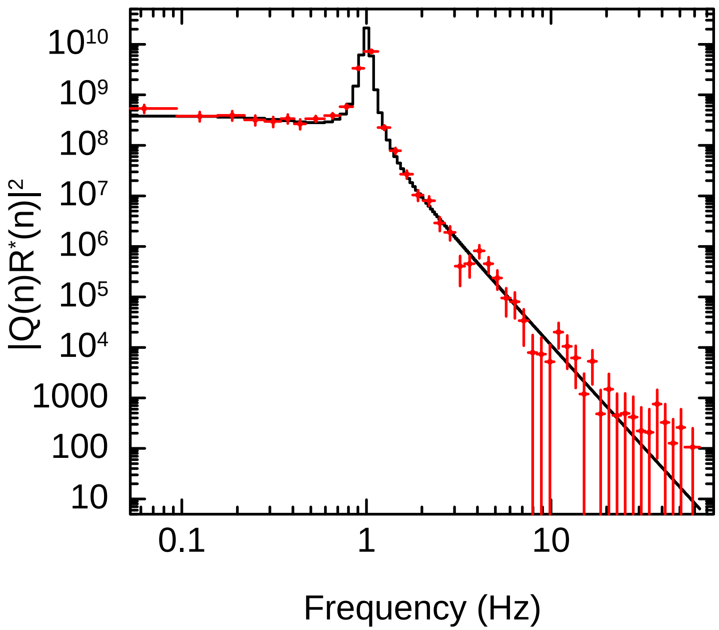
LAD	GPD	Pol degree	Pol angle

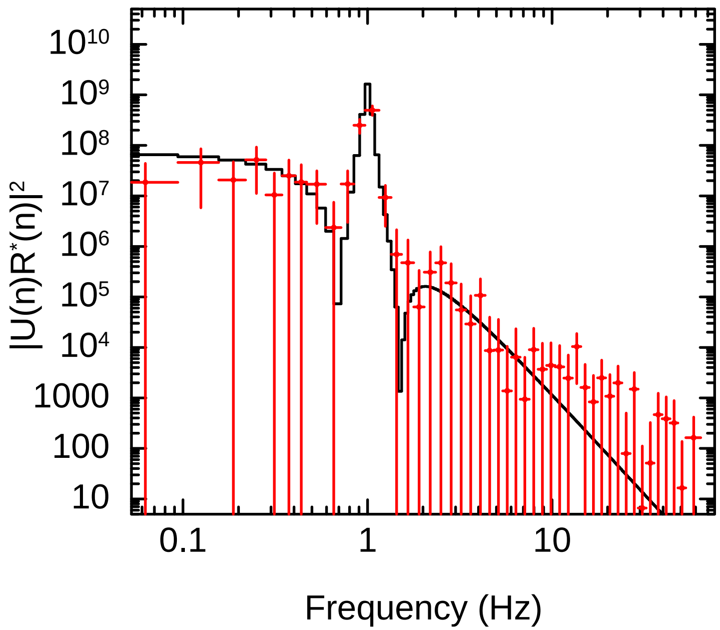






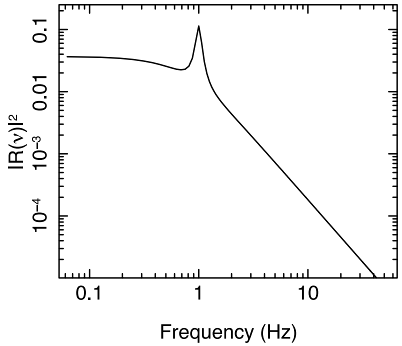




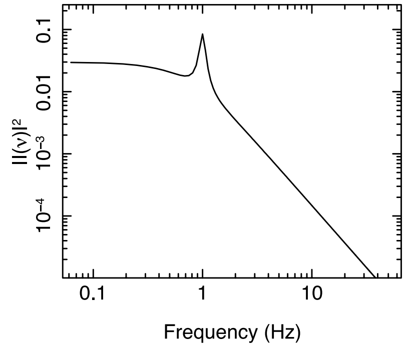


Detection

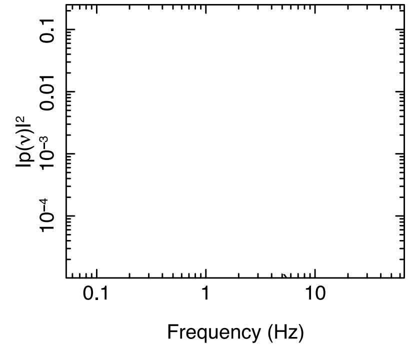
LAD



GPD



Pol degree



Pol angle