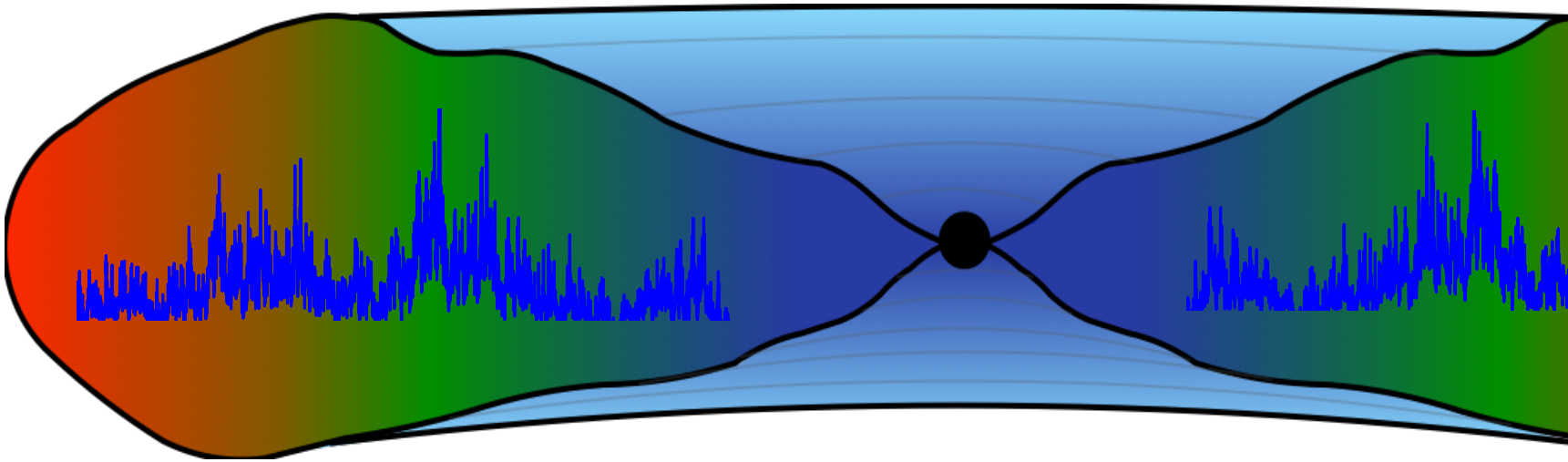
# Review of X-ray variability in black hole binaries

Adam Ingram
Michiel van der Klis, Chris Done



The Extremes of Black Hole Accretion
9th June 2015

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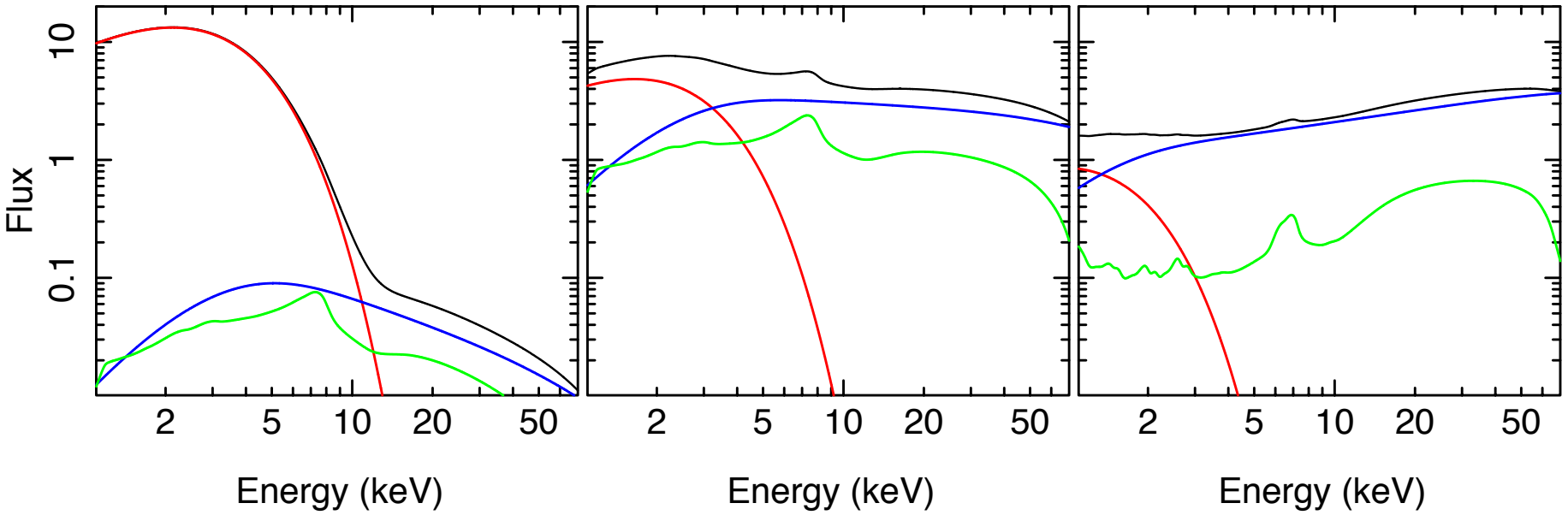
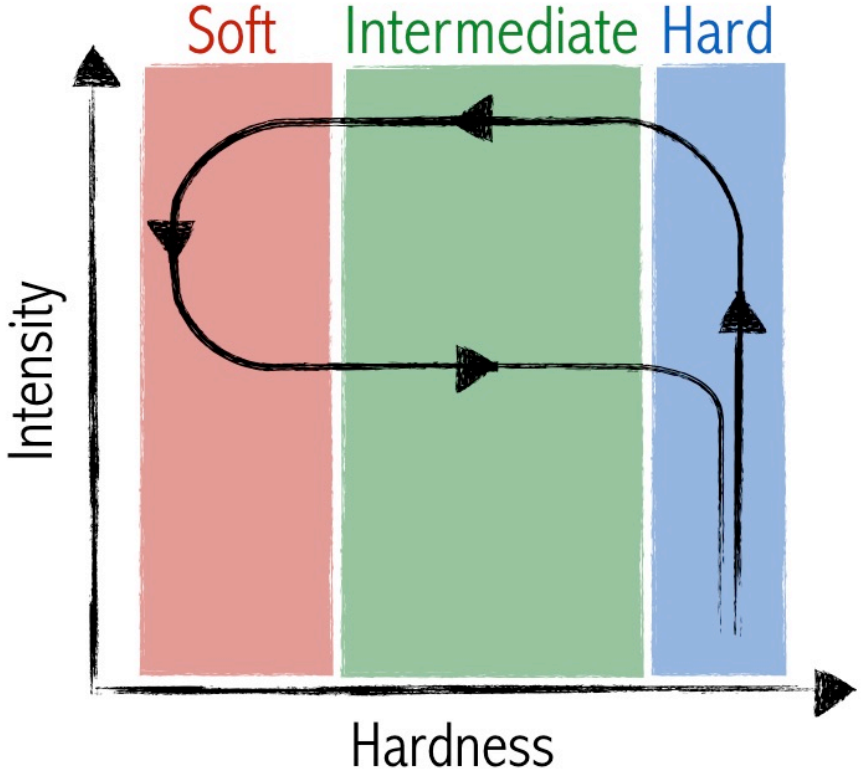
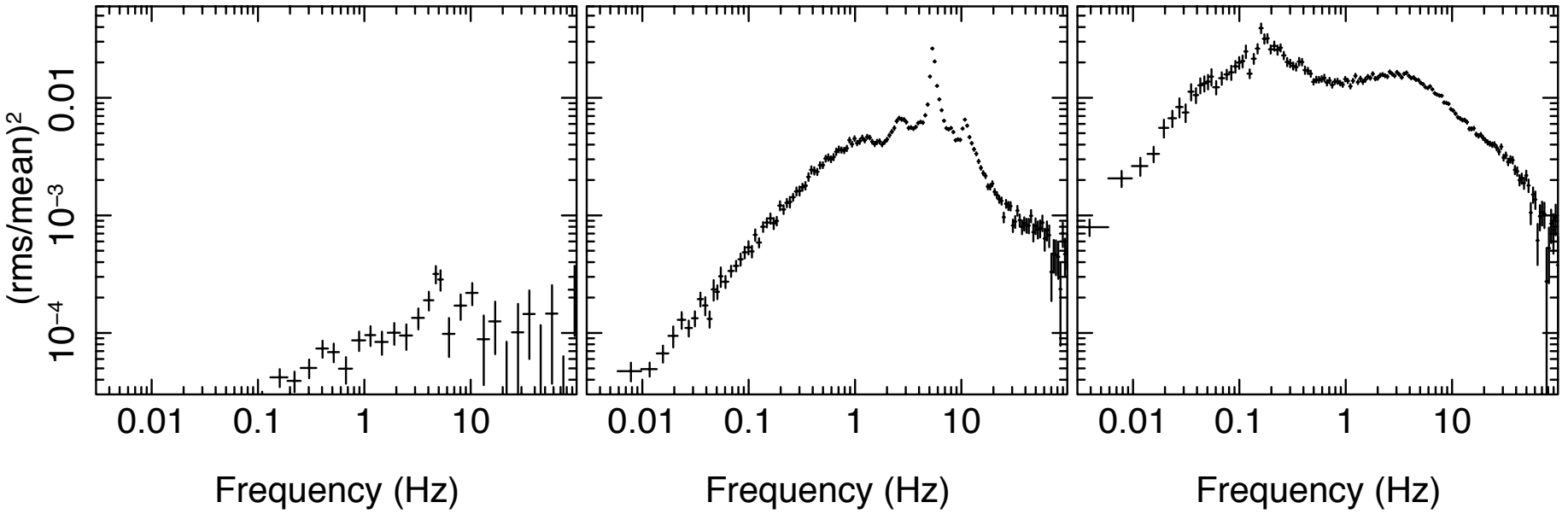
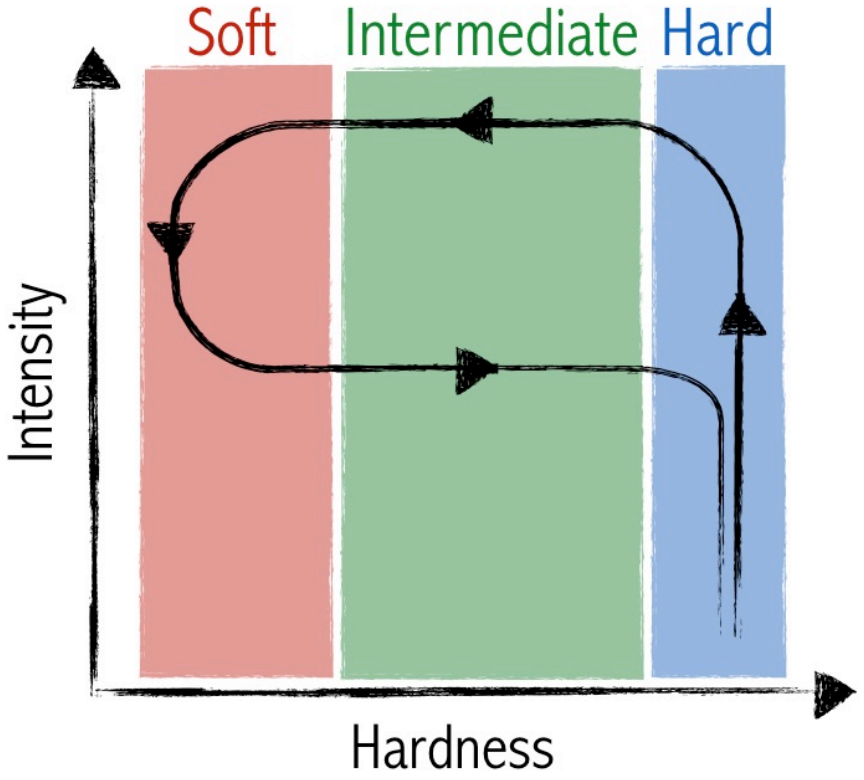

Flux
10
1
0.1
2
5
10
20
50
Energy (keV)
Energy (keV)
Energy (keV)


Soft
Intermediate
Hard
Intensity
Hardness


(rms/mean)$^2$
$10^{-4}$
$10^{-3}$
0.01
0.01
0.1
1
10
Frequency (Hz)
Frequency (Hz)
Frequency (Hz)


Soft
Intermediate
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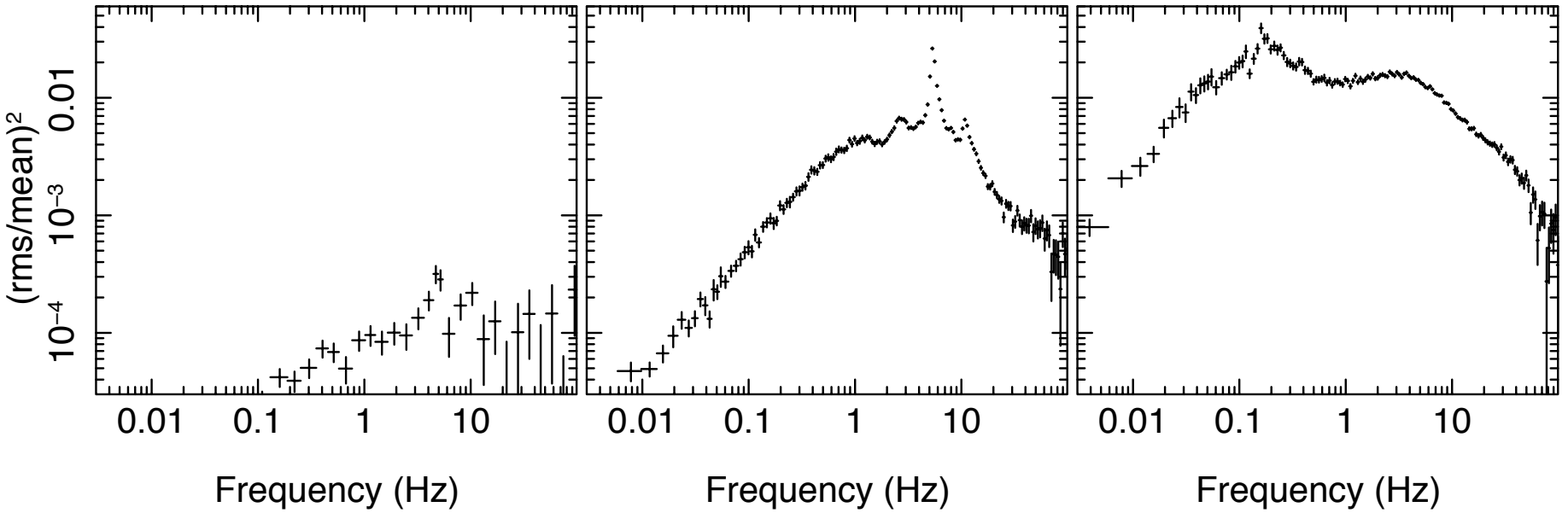
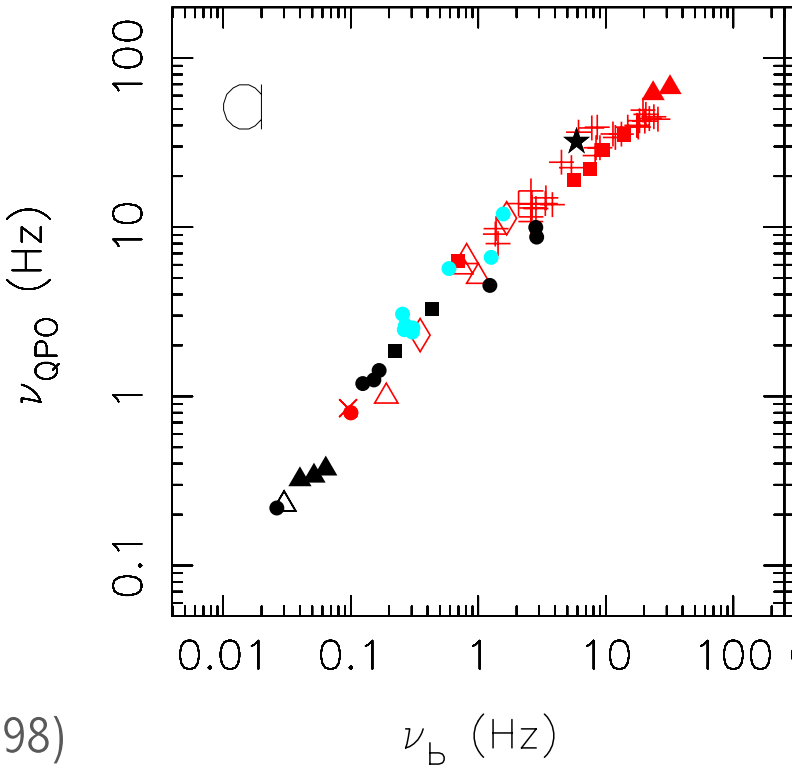
Intensity
Hardness




Wijnands & van der Klis (1998)

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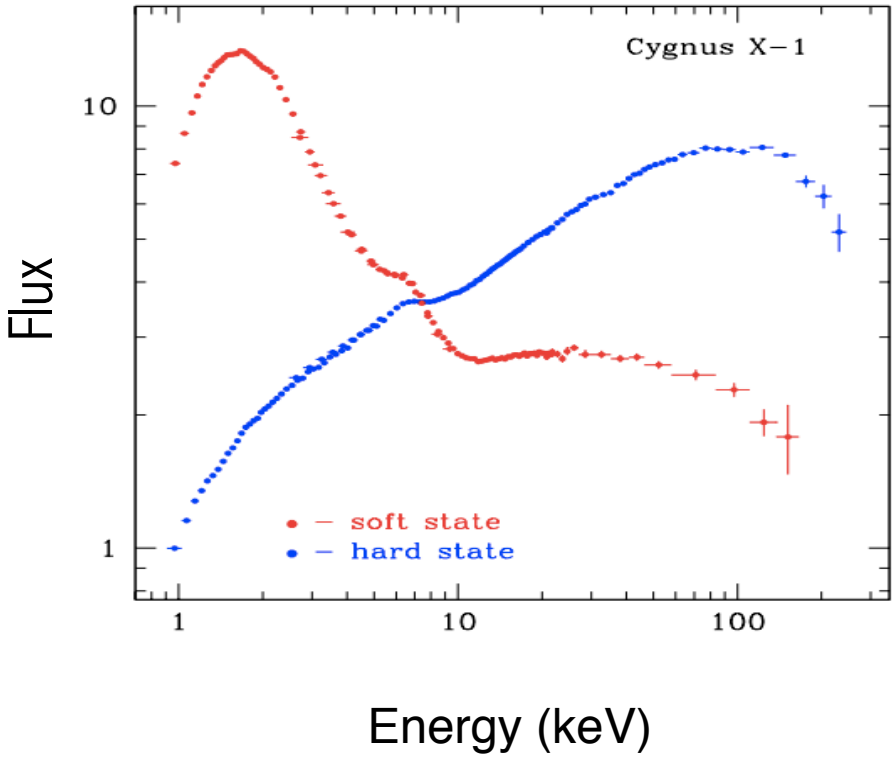
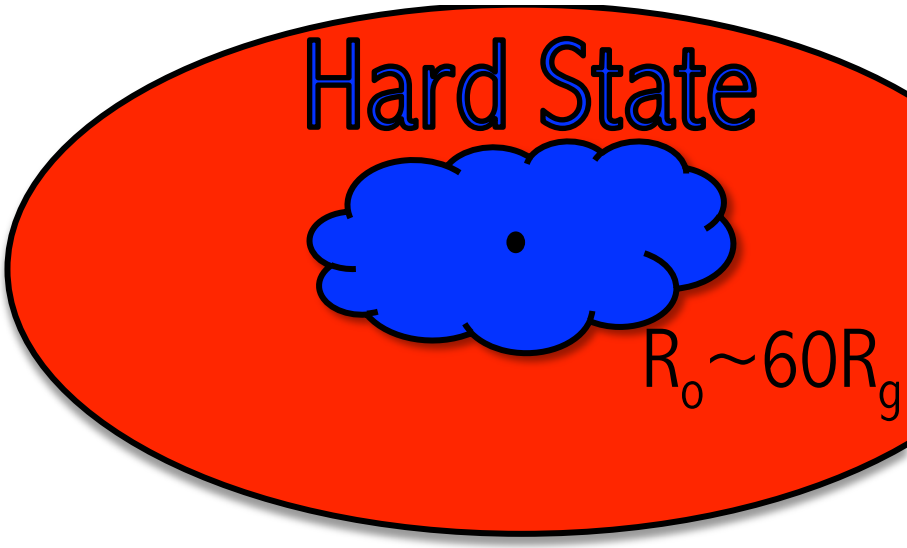
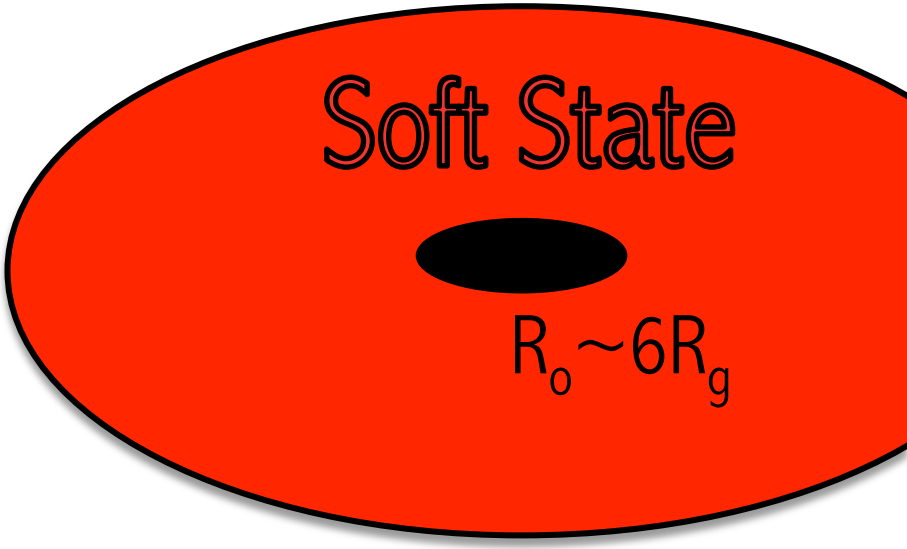
# Truncated disk model

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




Gilfanov (2010)

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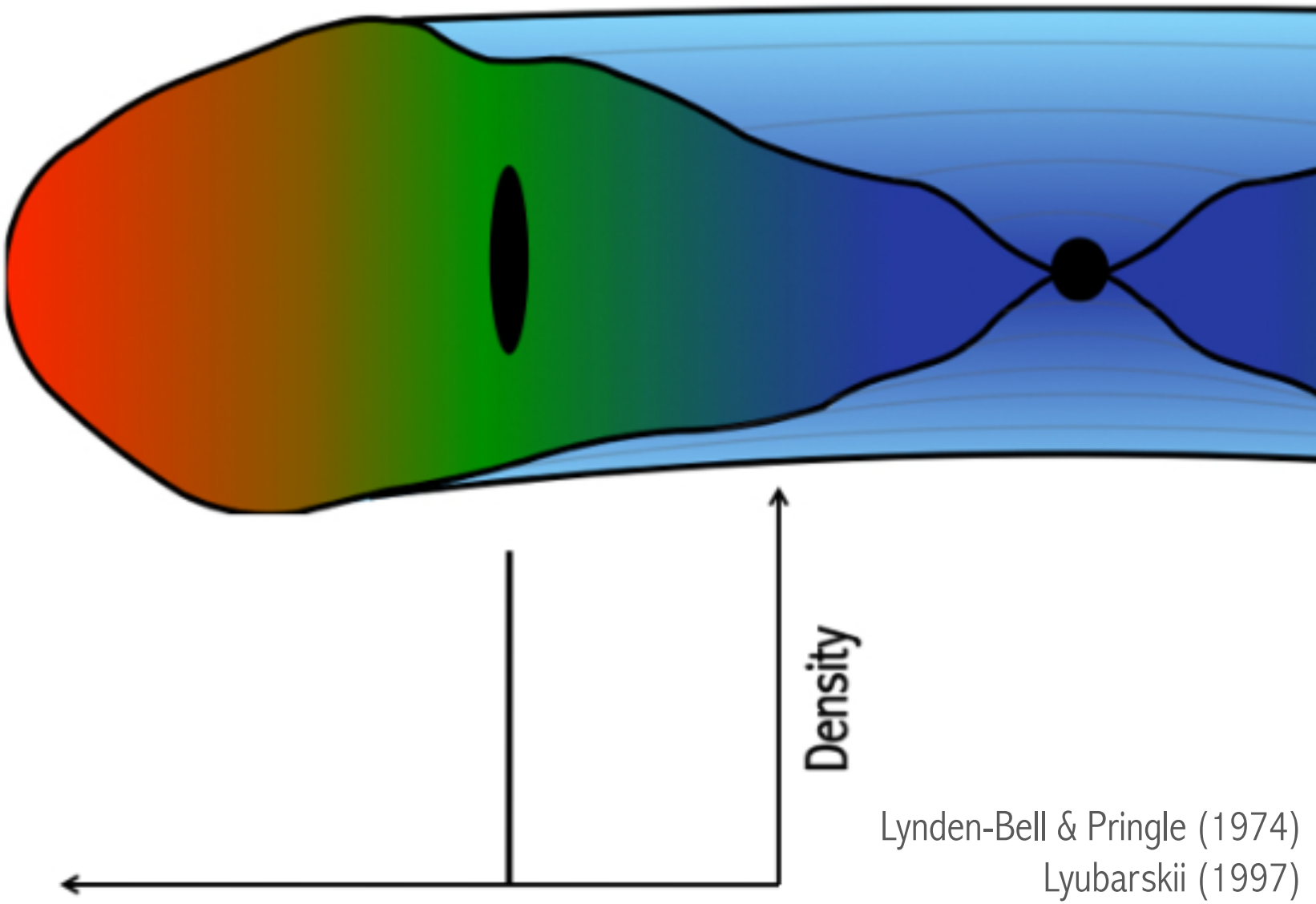
# Diffusion




Lynden-Bell & Pringle (1974)
Lyubarskii (1997)

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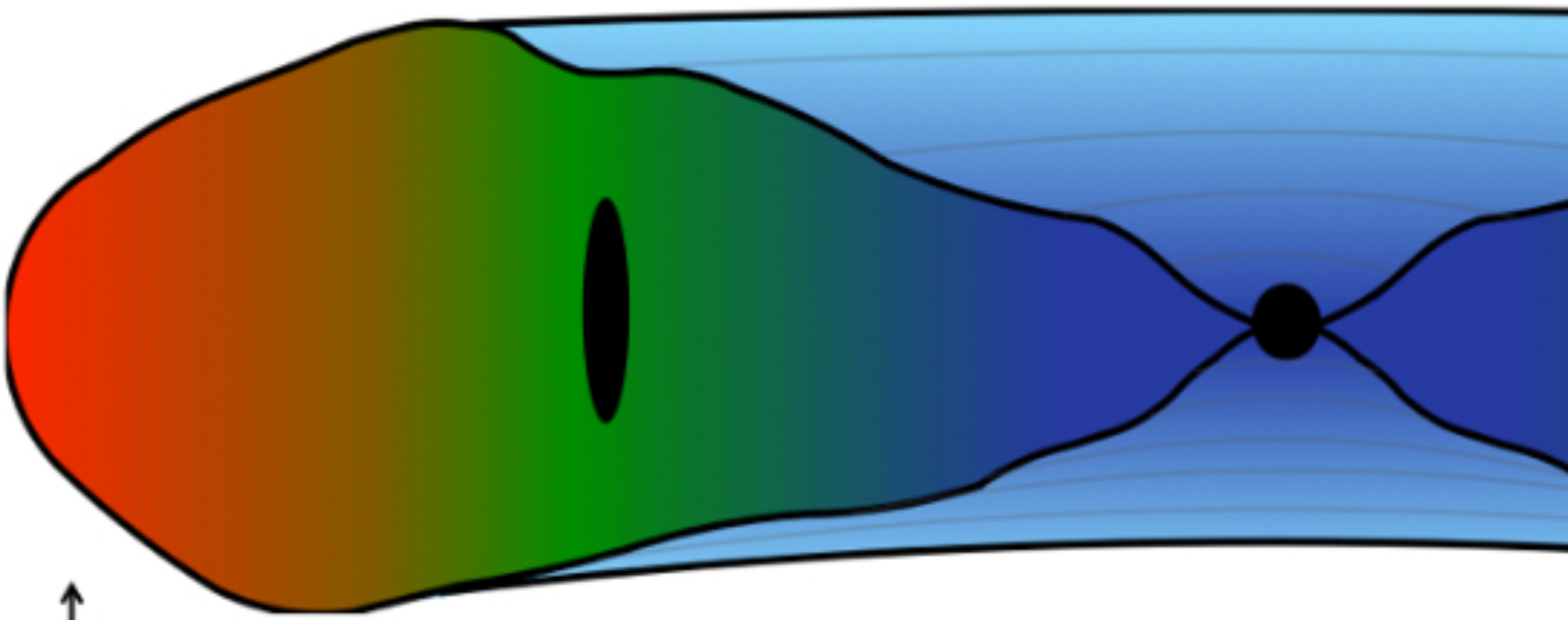
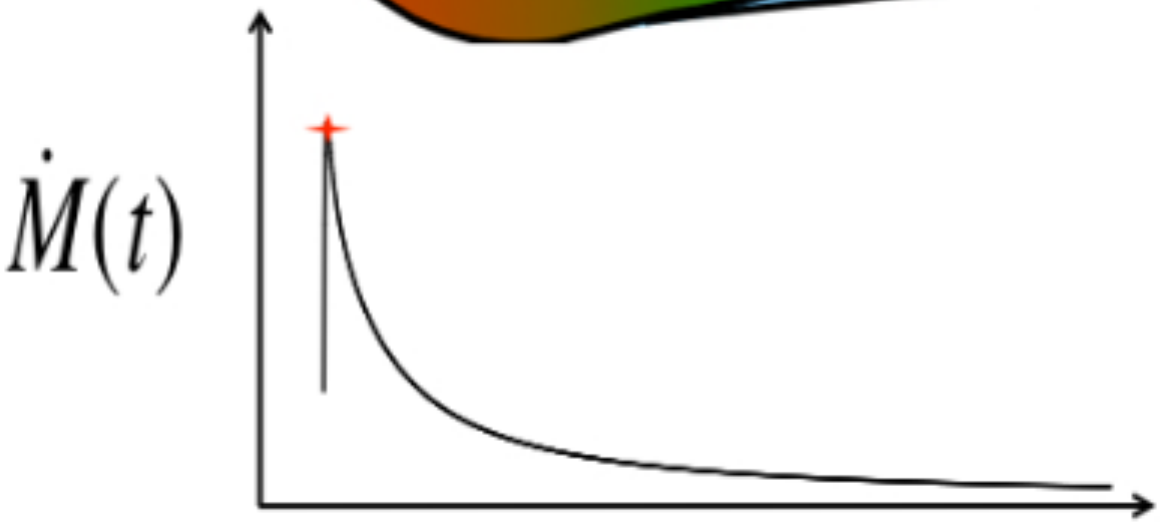
# Diffusion






Lynden-Bell & Pringle (1974)
Lyubarskii (1997)

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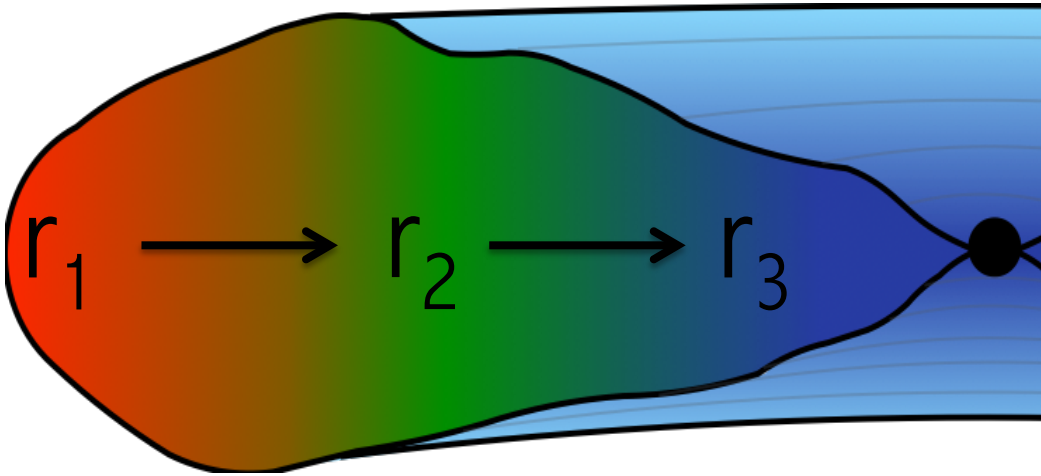
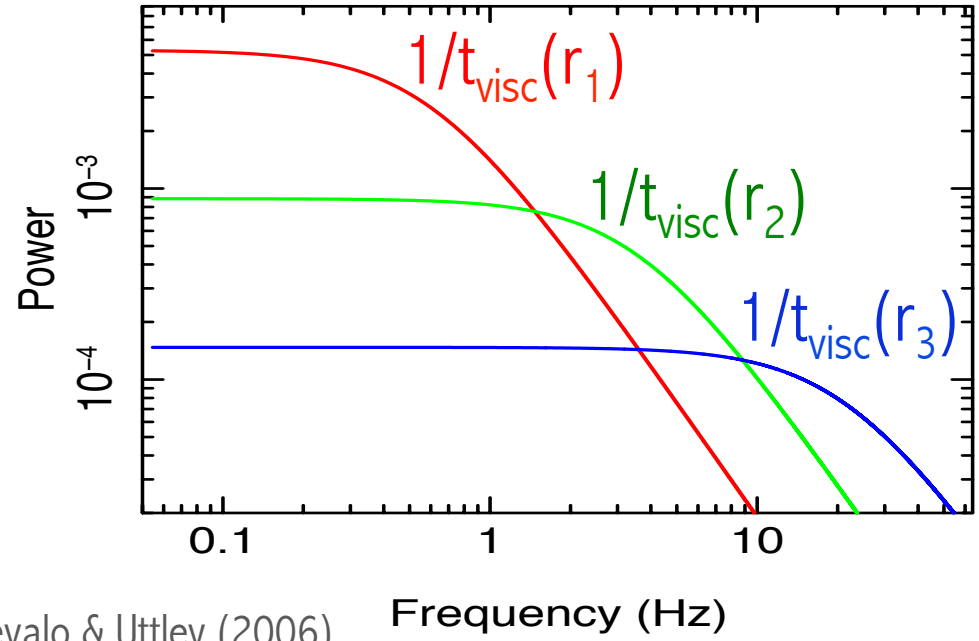
# Propagating fluctuations




Lynden-Bell & Pringle (1974); Lyubarskii (1997); Arevalo & Uttley (2006)

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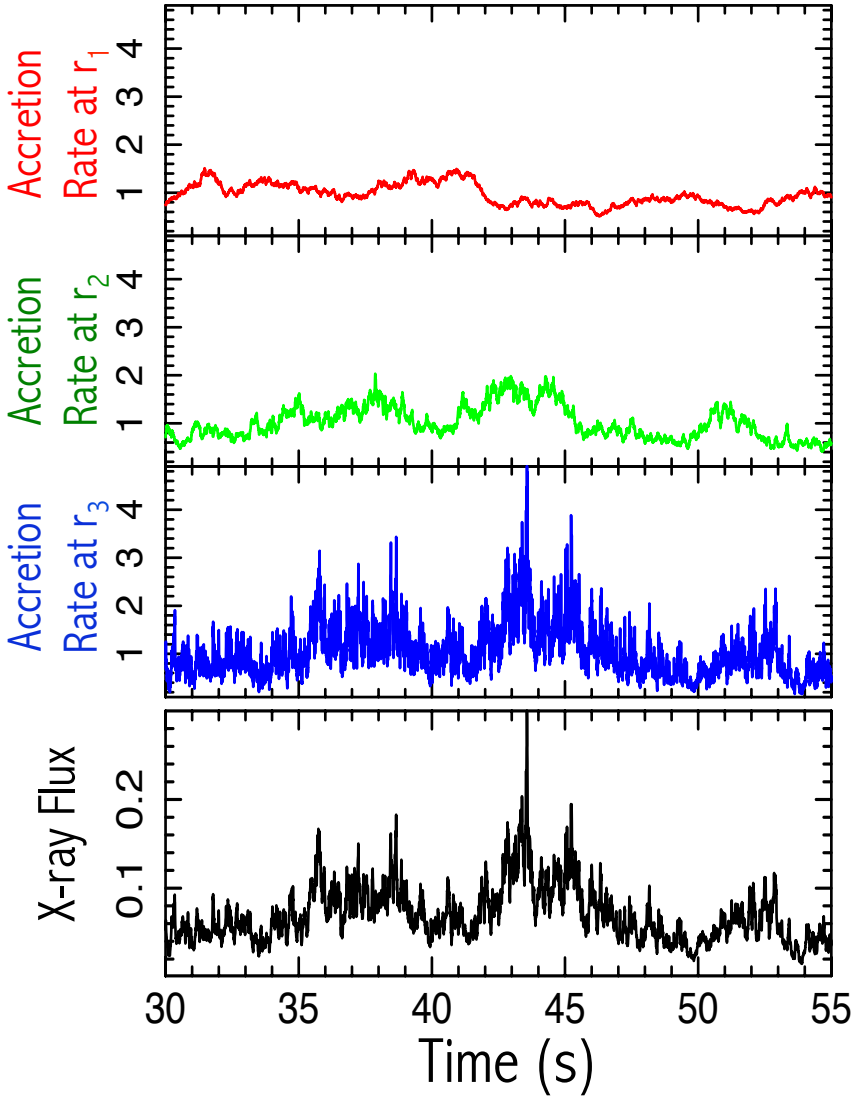
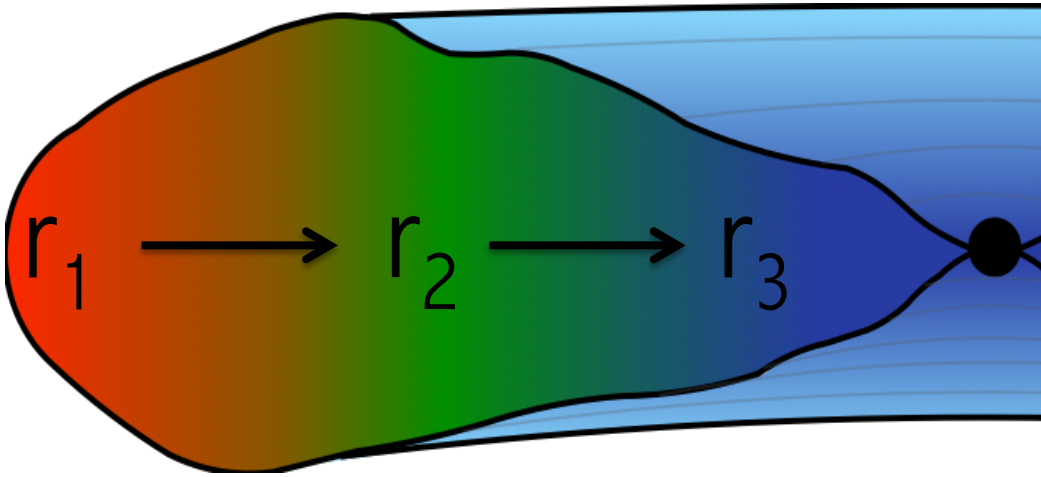
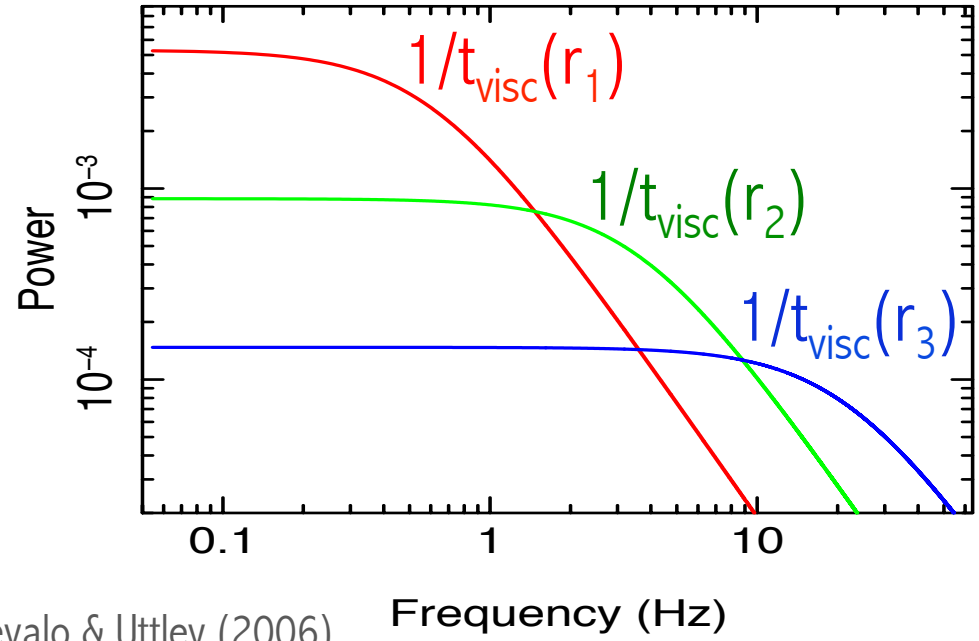
# Propagating fluctuations




Lynden-Bell & Pringle (1974); Lyubarskii (1997); Arevalo & Uttley (2006)

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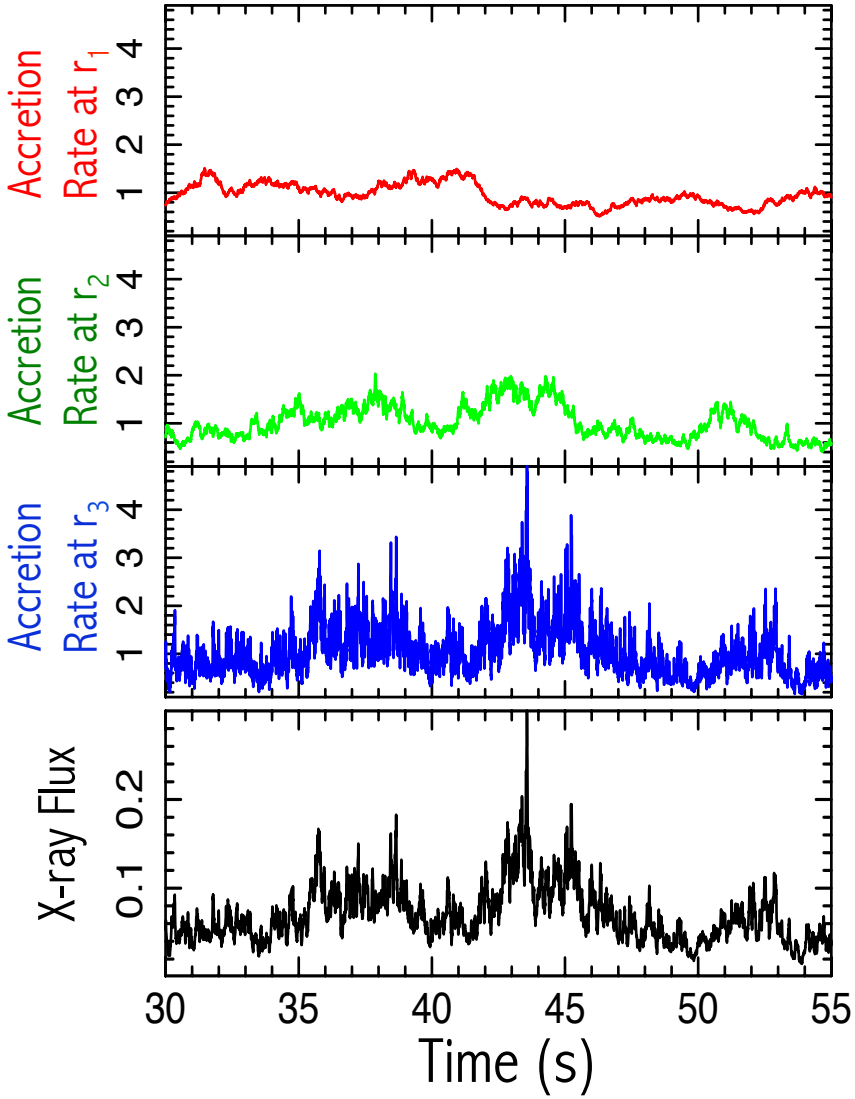
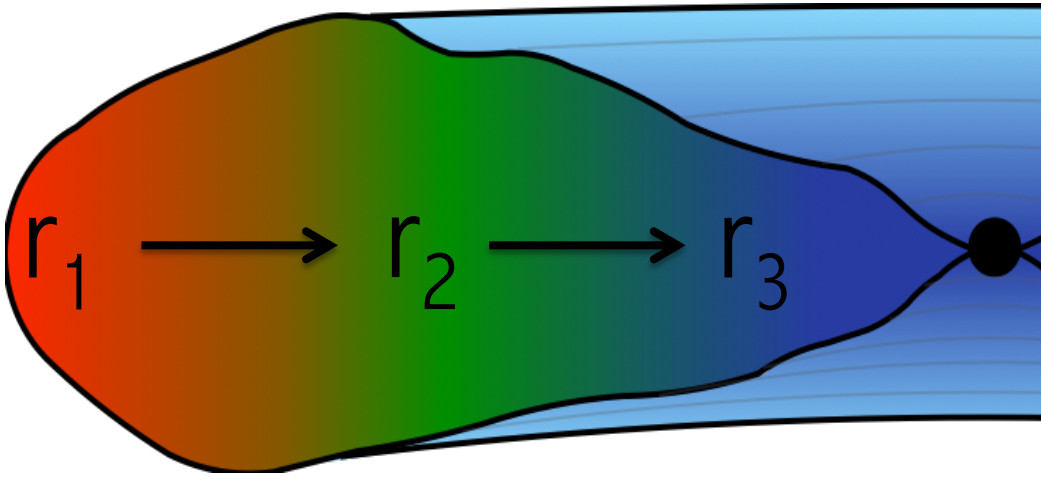
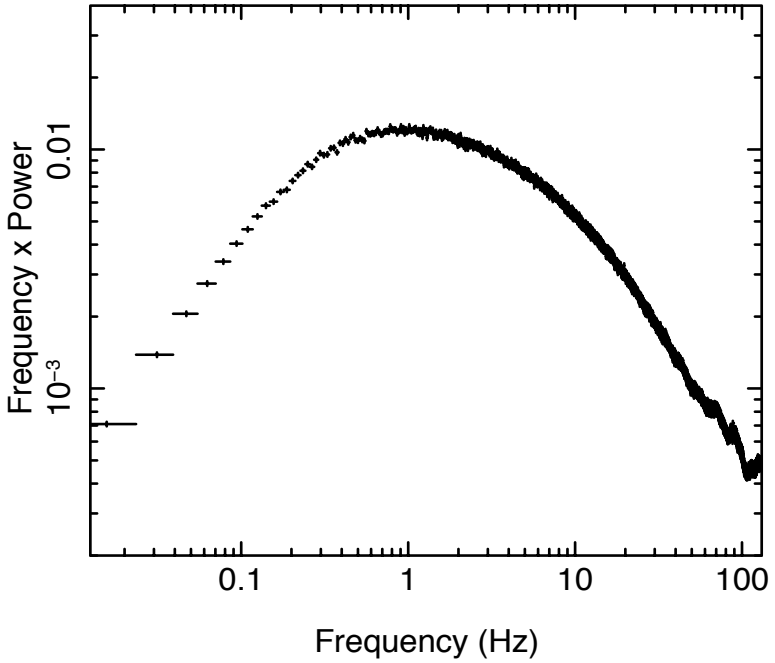
# Propagating fluctuations




Propfluc: Ingram & Done (2011, 2012)

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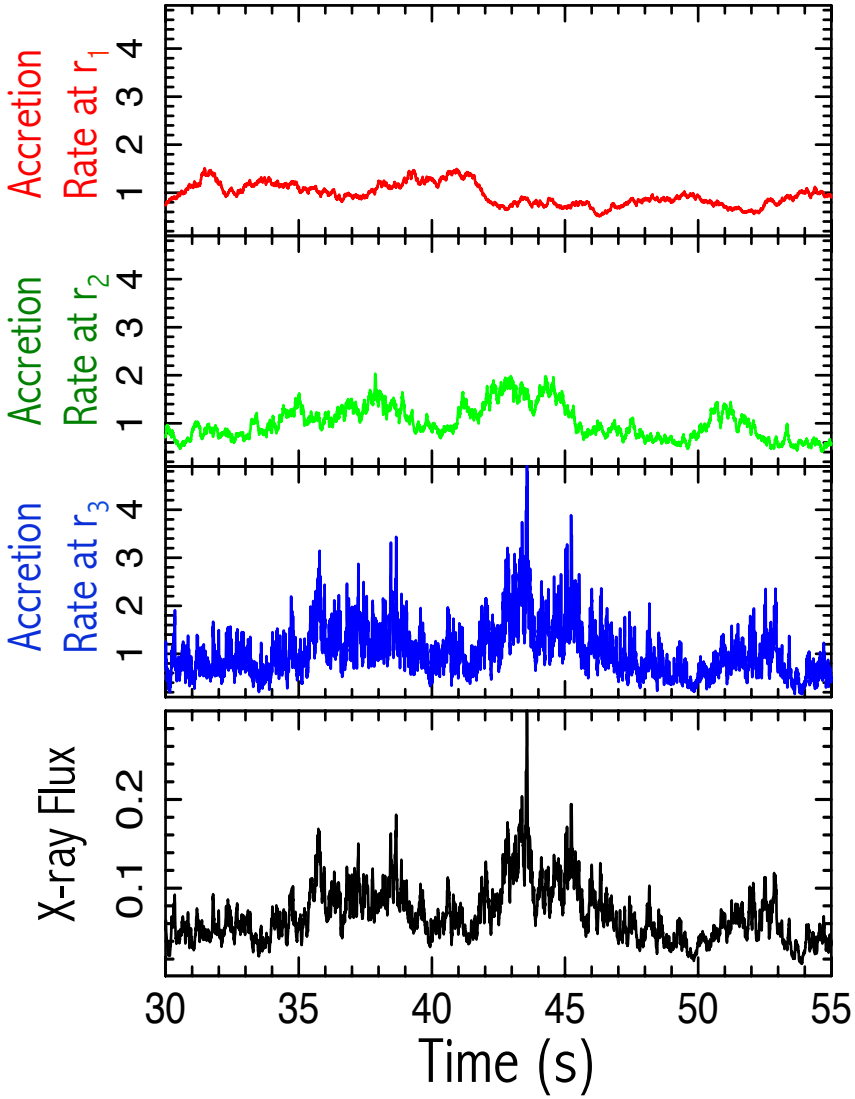
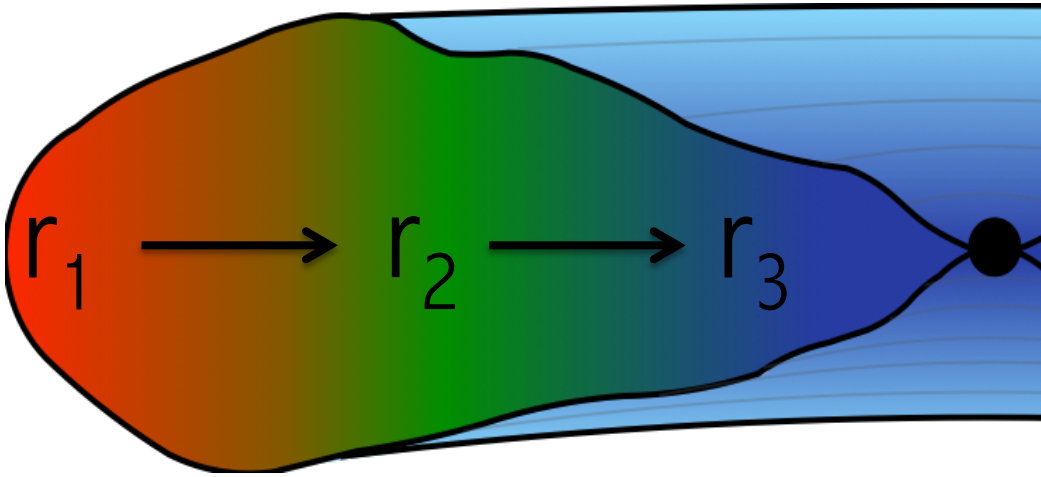
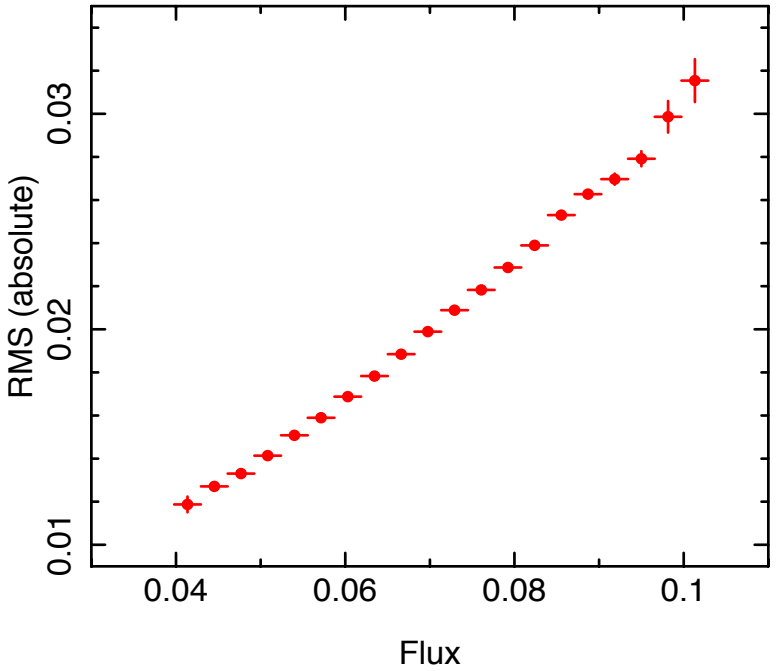
# Propagating fluctuations

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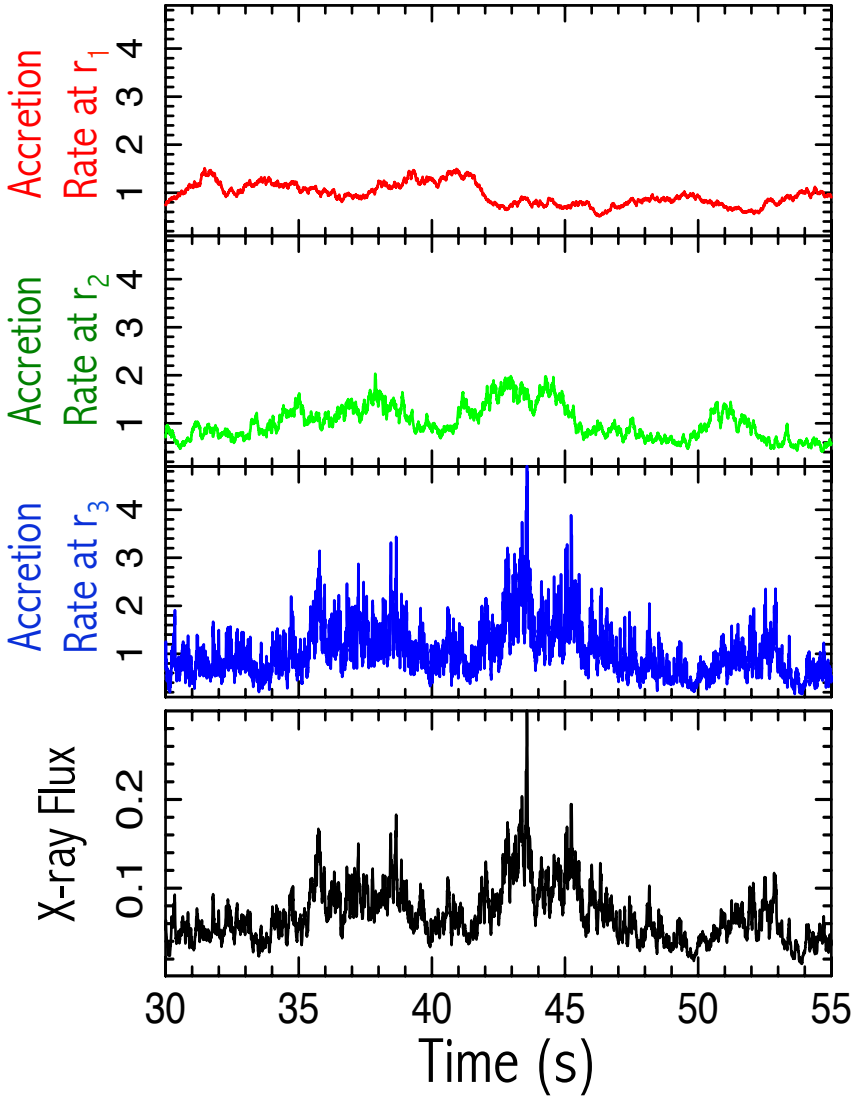
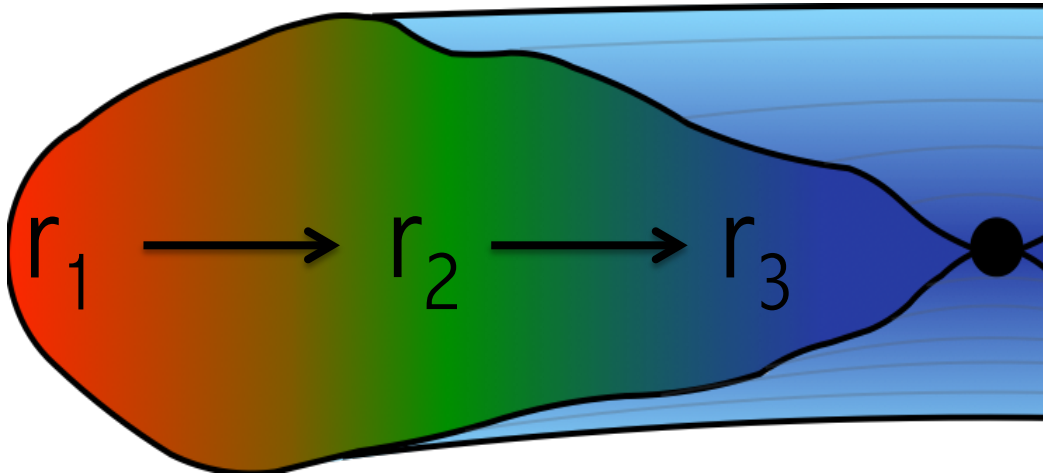
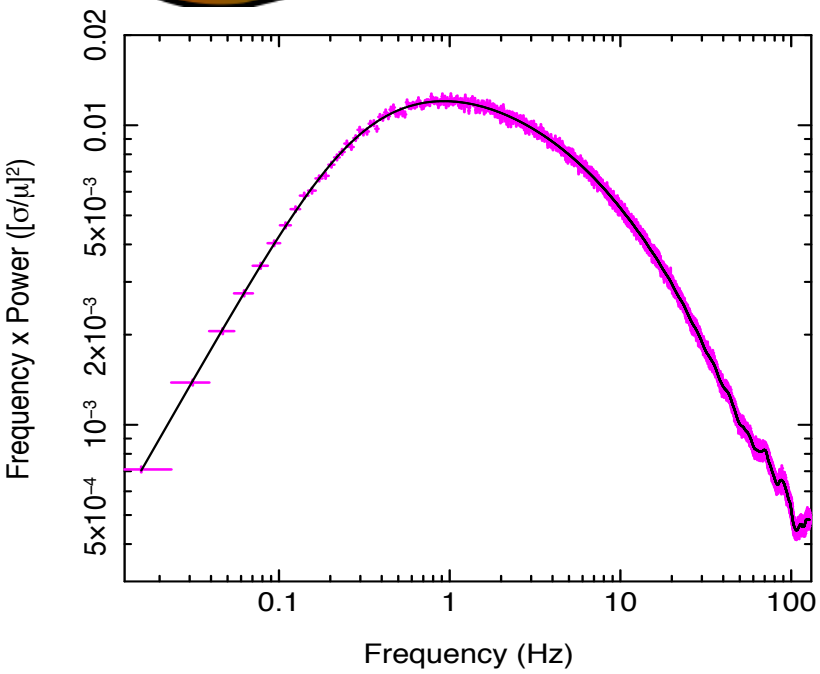
# Propagating fluctuations




Propfluc: Ingram & van der Klis (2013)

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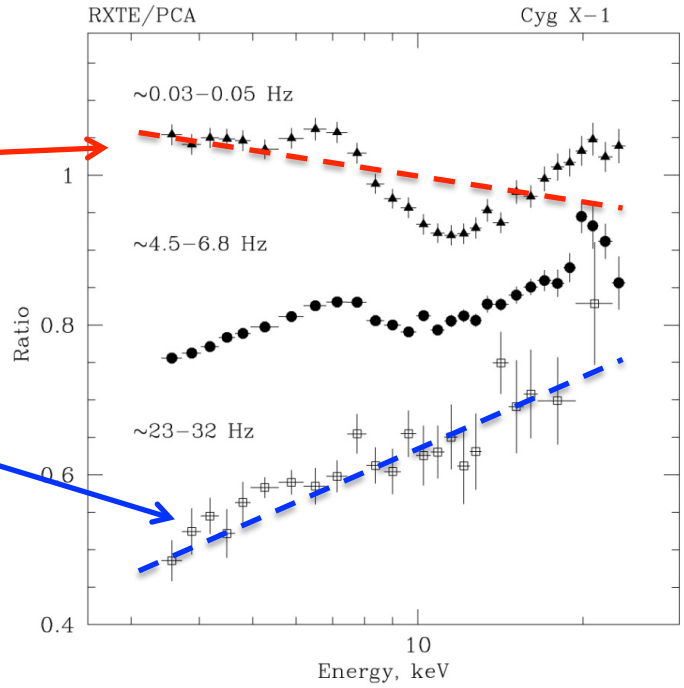
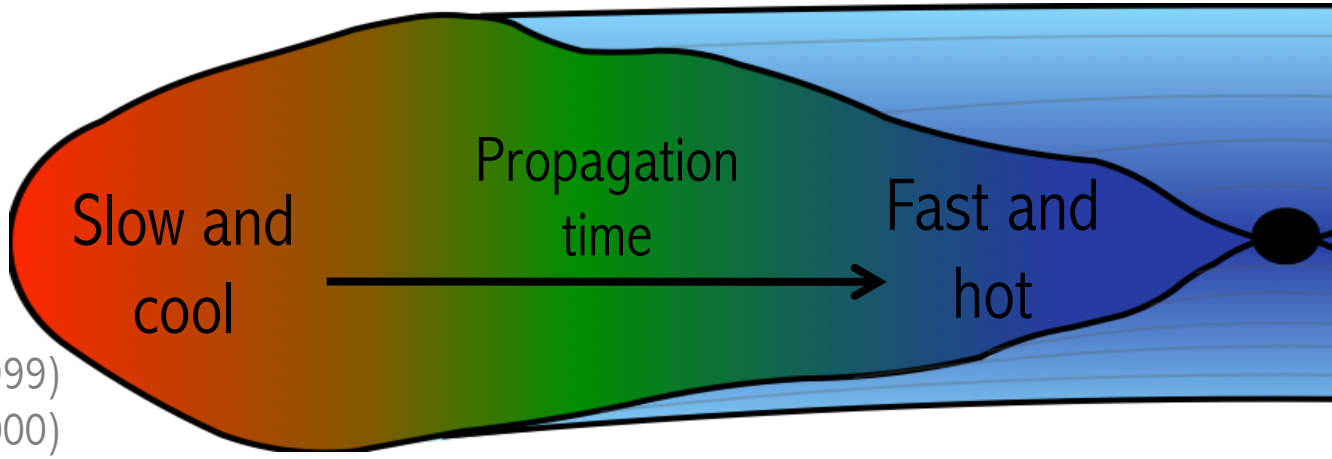
# Freq-resolved spectra

**Slow** variability has a **softer** spectrum than fast variability




Revnivtsev, Gilfanov & Churazov (1999)
Gilfanov, Revnivtsev & Churazov (2000)

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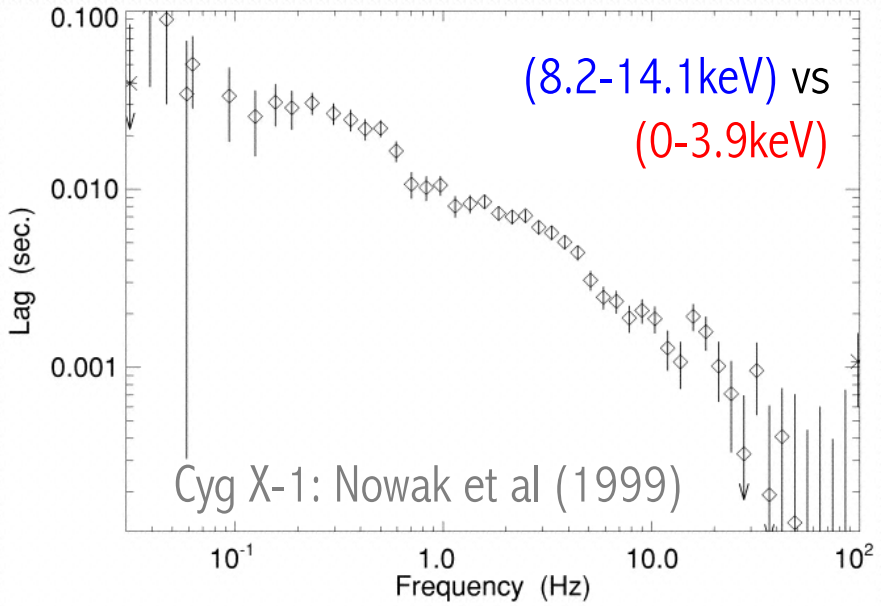
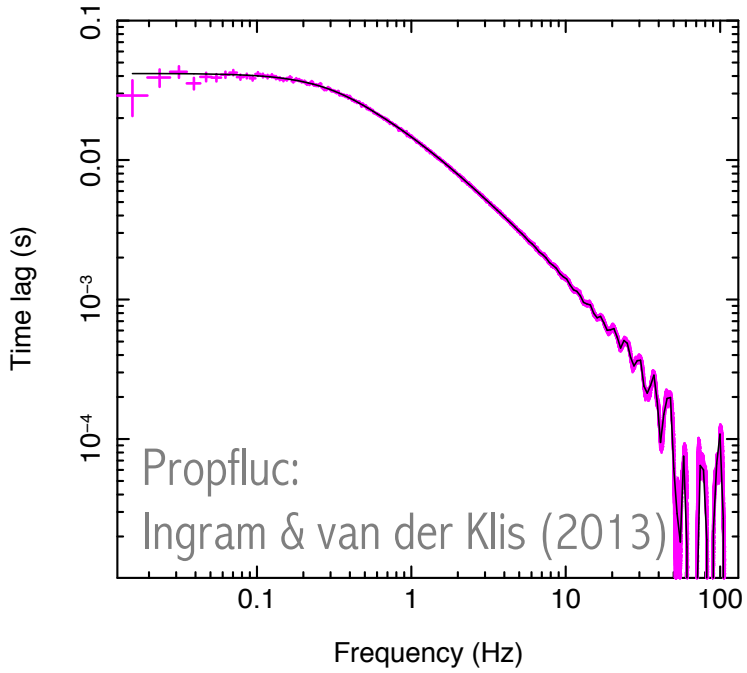
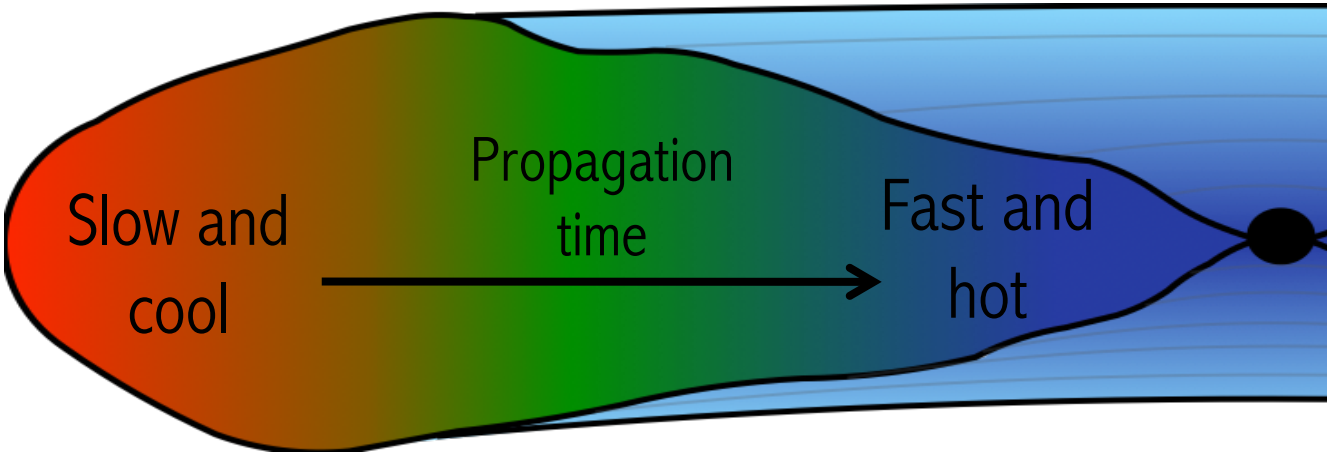
# Time lags

## Hard photons lag soft




Kotov et al (2001);
Arevalo & Uttley (2006)

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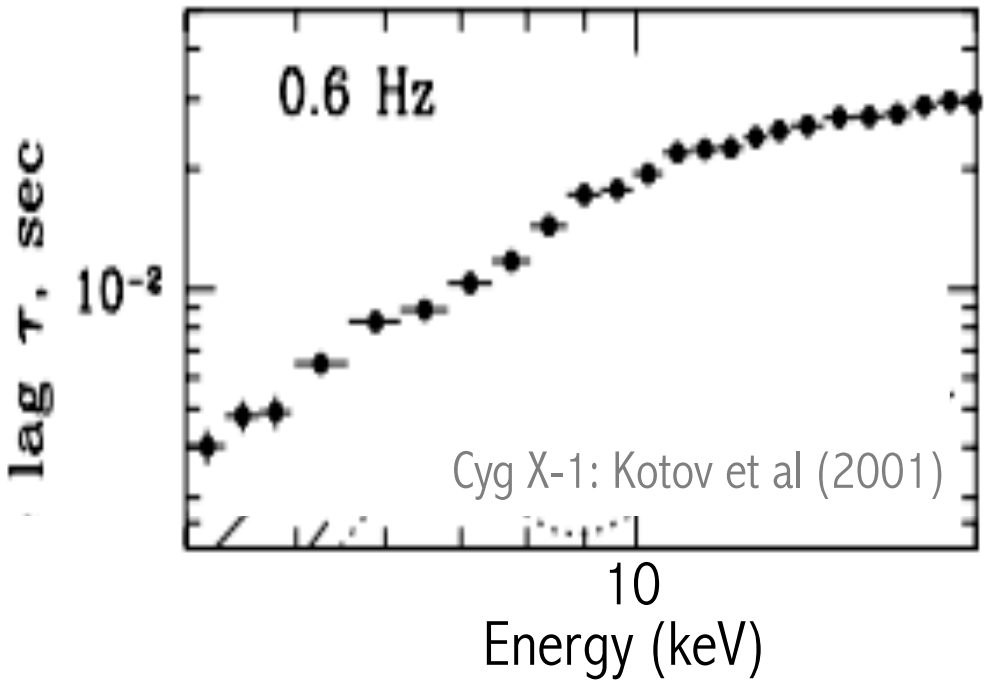
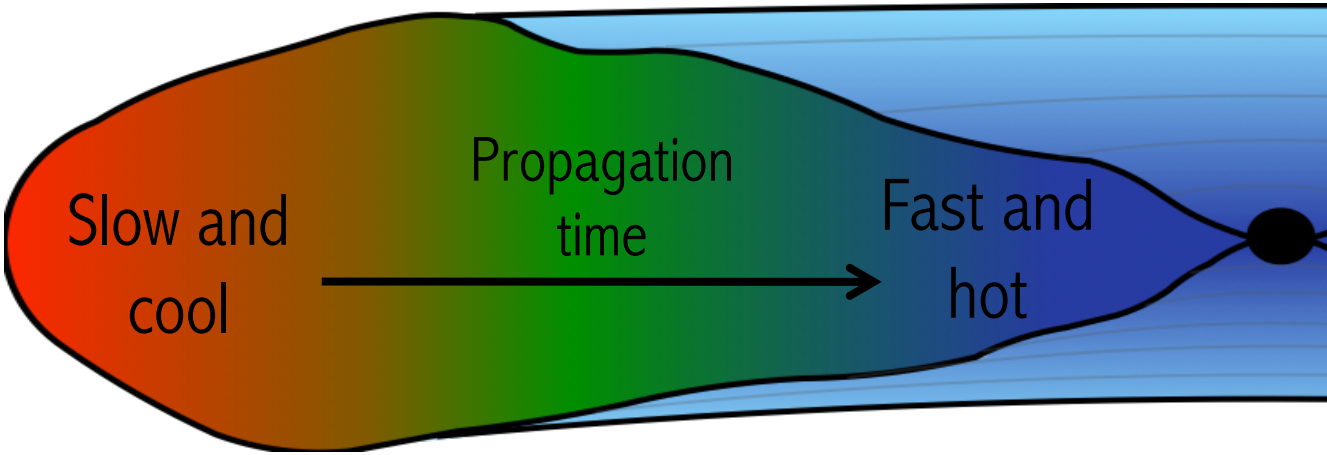
# Time lags

Hard photons lag soft

Harder photons: greater lag




Kotov et al (2001);
Arevalo & Uttley (2006)

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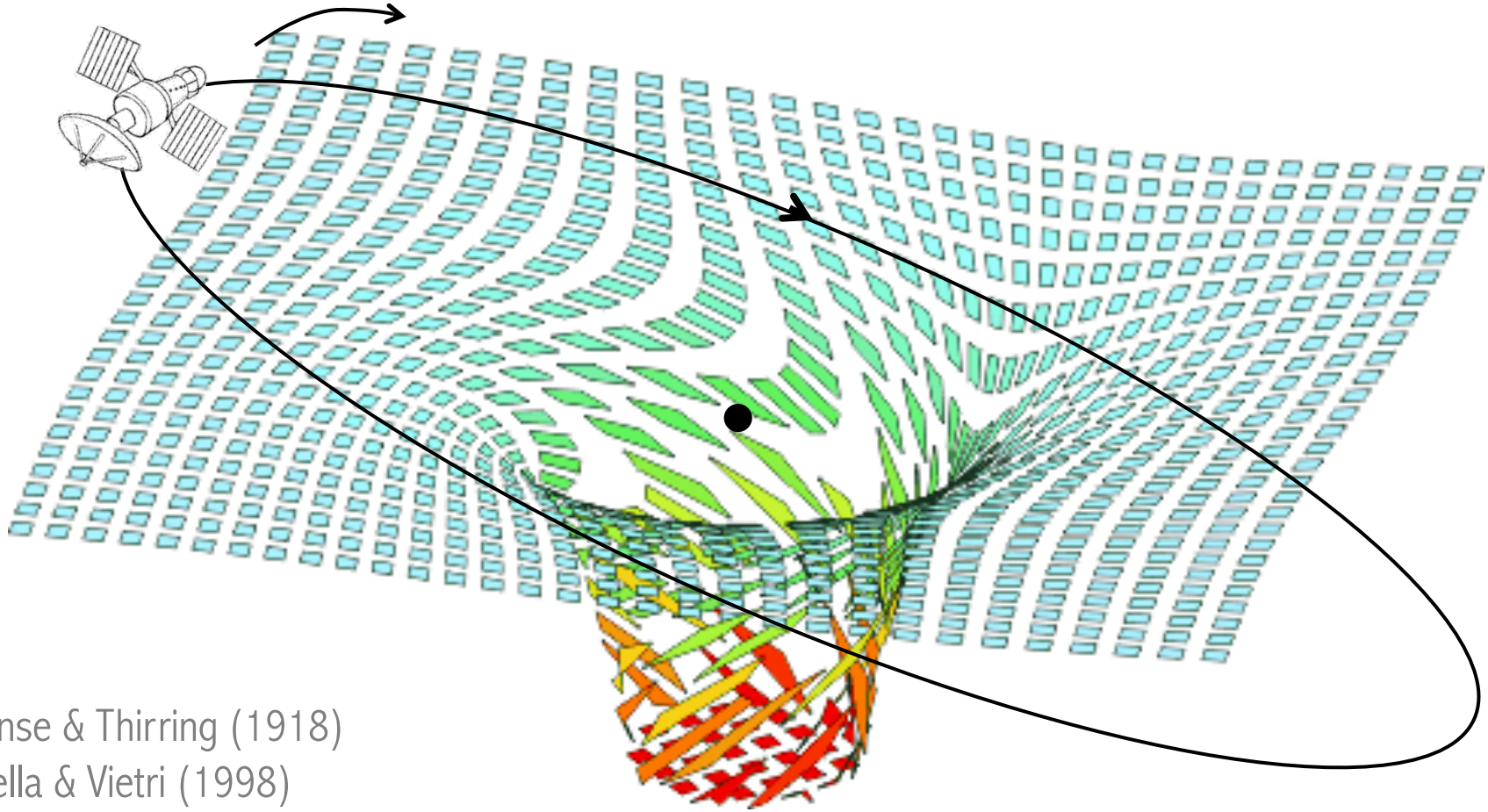
# QPO: Frame dragging

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)

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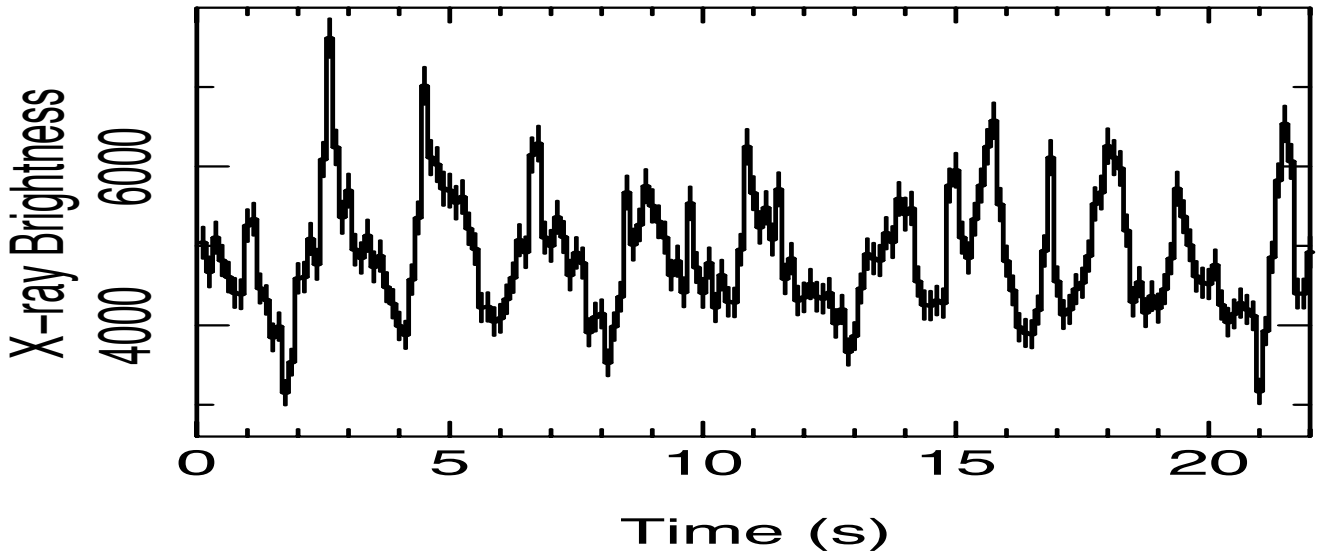
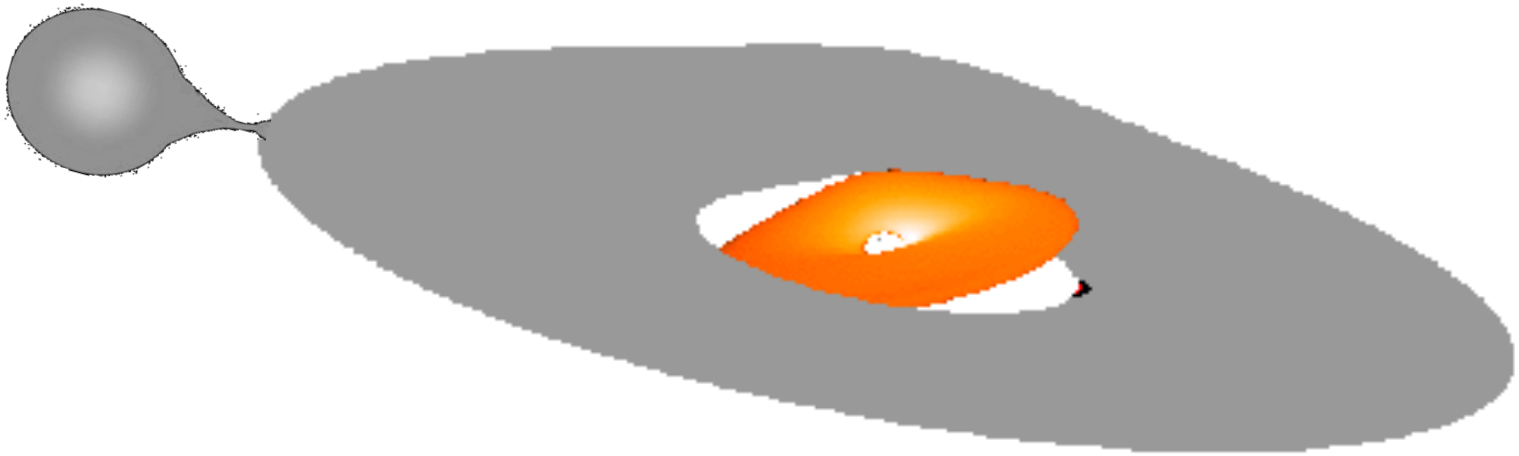
# QPO: Frame dragging



Ingram, Done & Fragile (2009)

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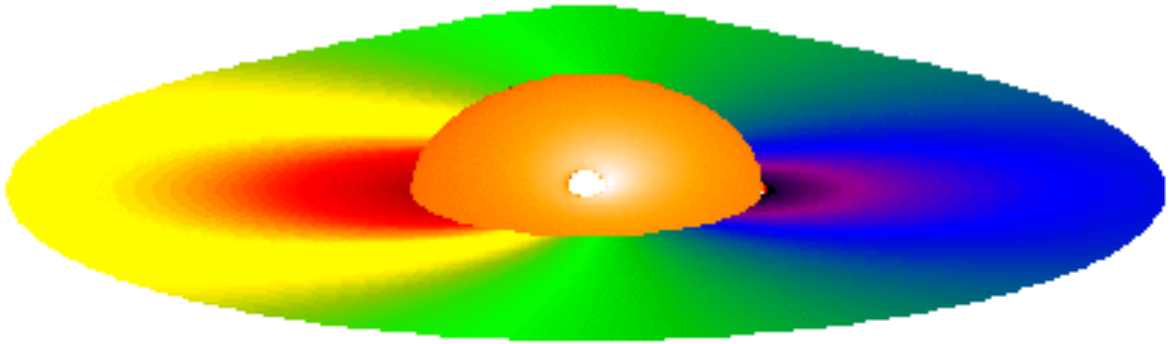
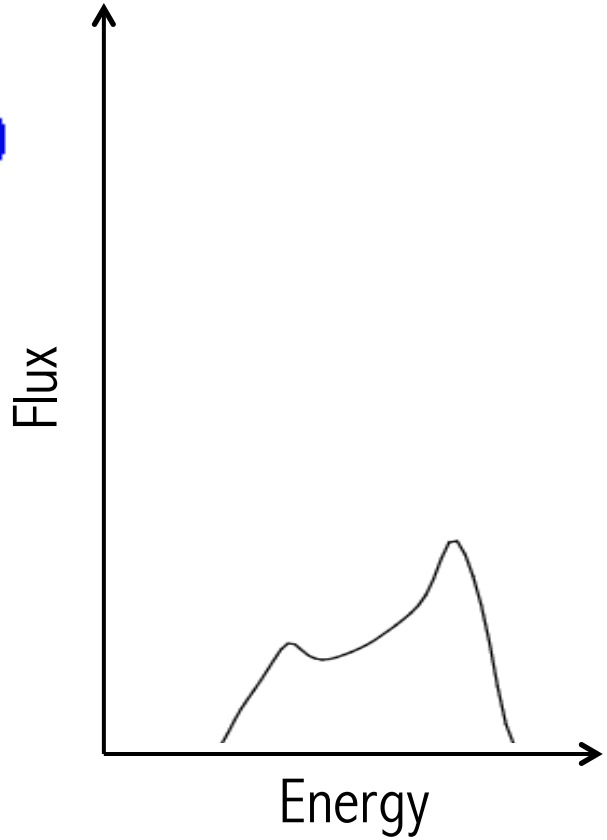
# QPO: Frame dragging

Tell-tale sign of precession: a rocking iron line






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

Ingram & Done (2012)

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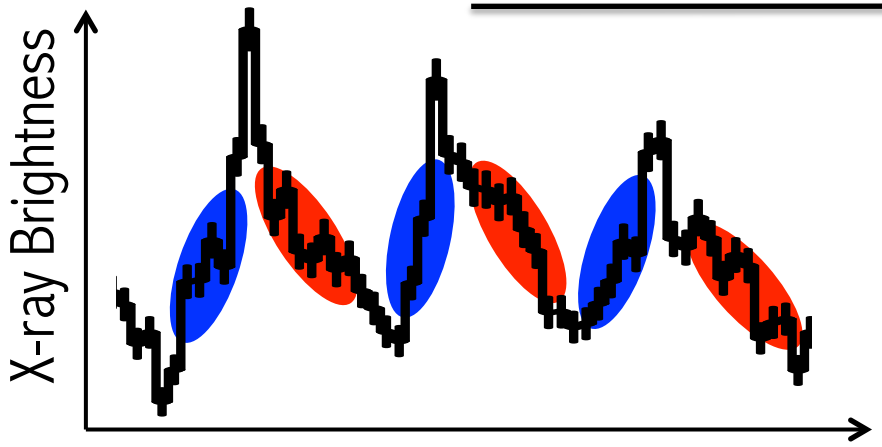
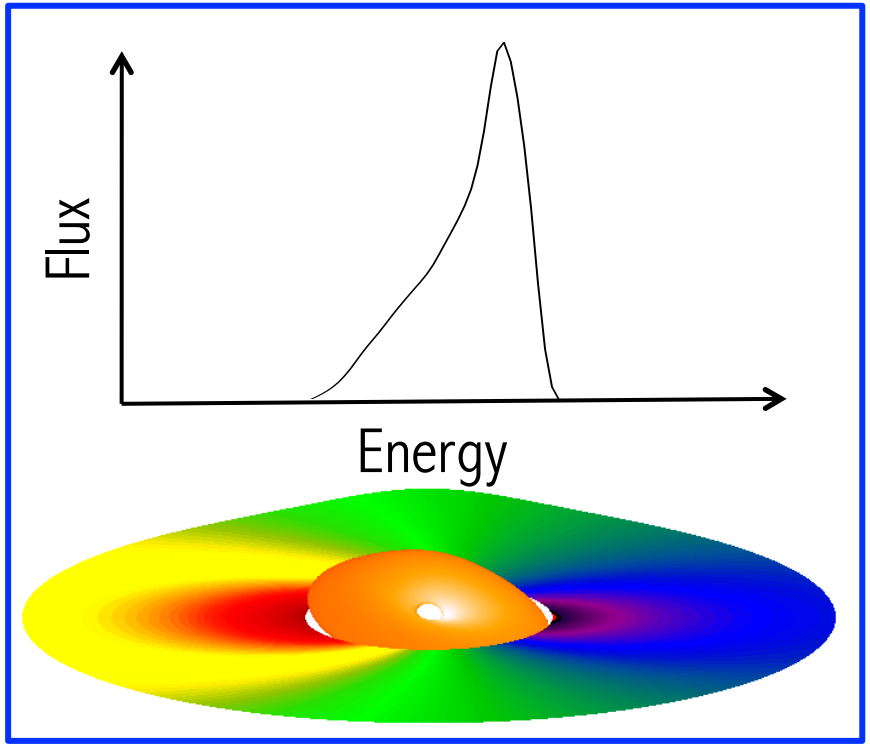
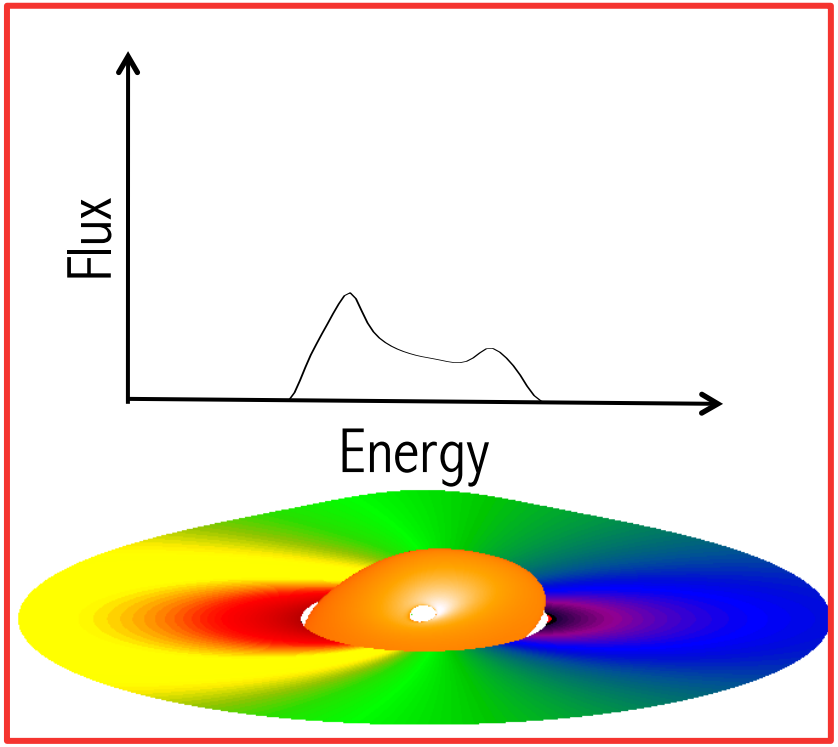
# Phase Resolving



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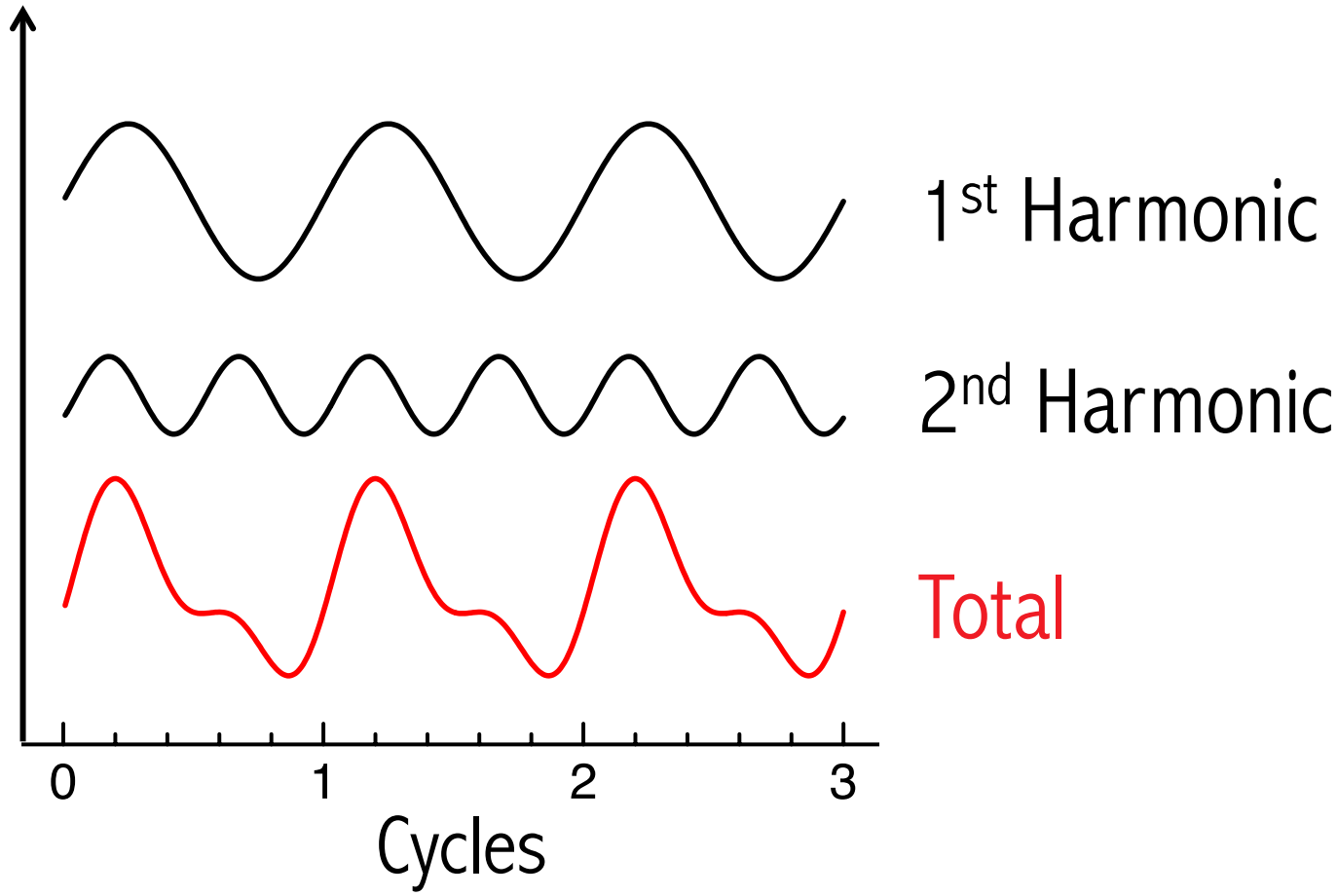
# QPO waveform

Periodic function: constant phase difference



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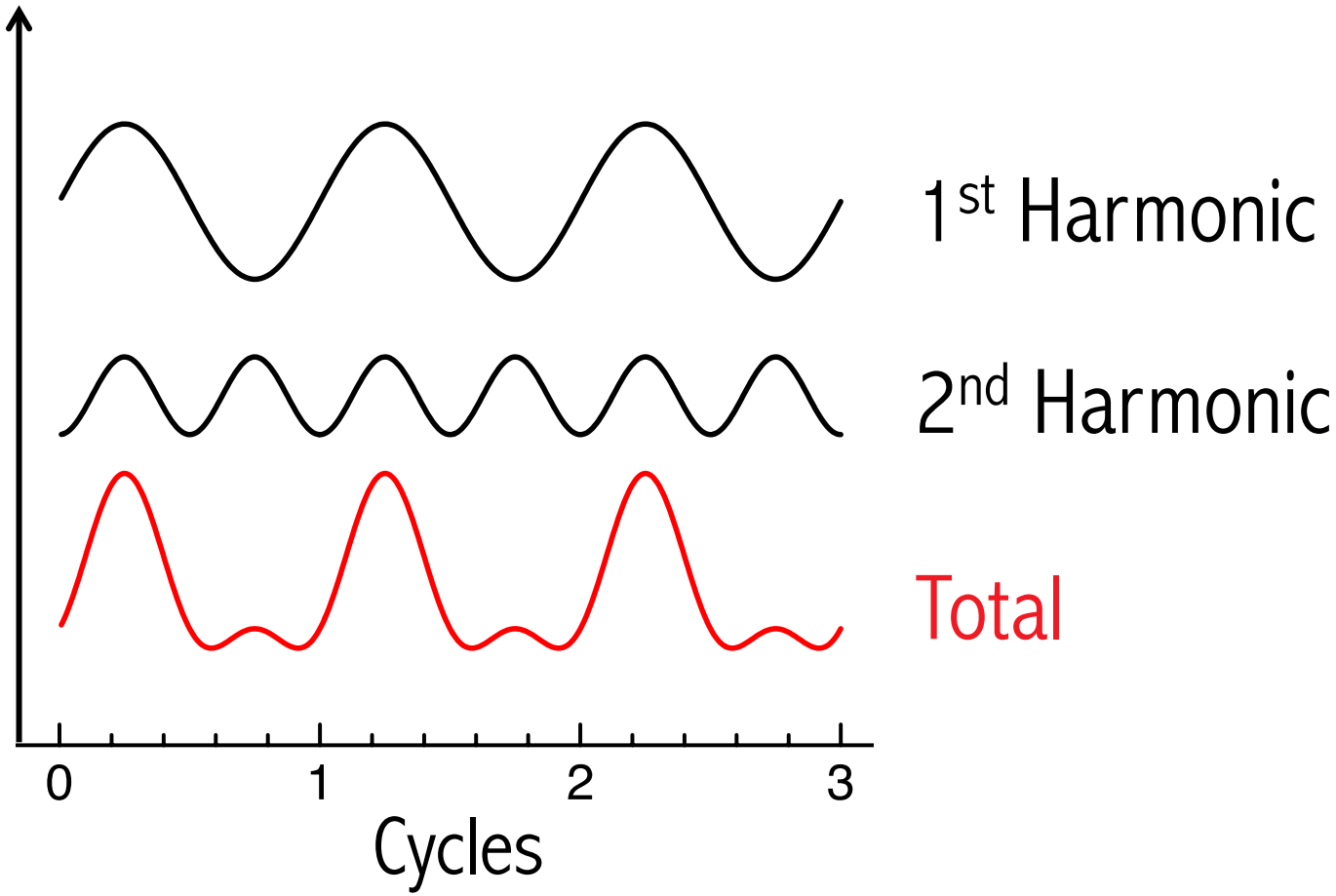
# QPO waveform

Periodic function: constant phase difference



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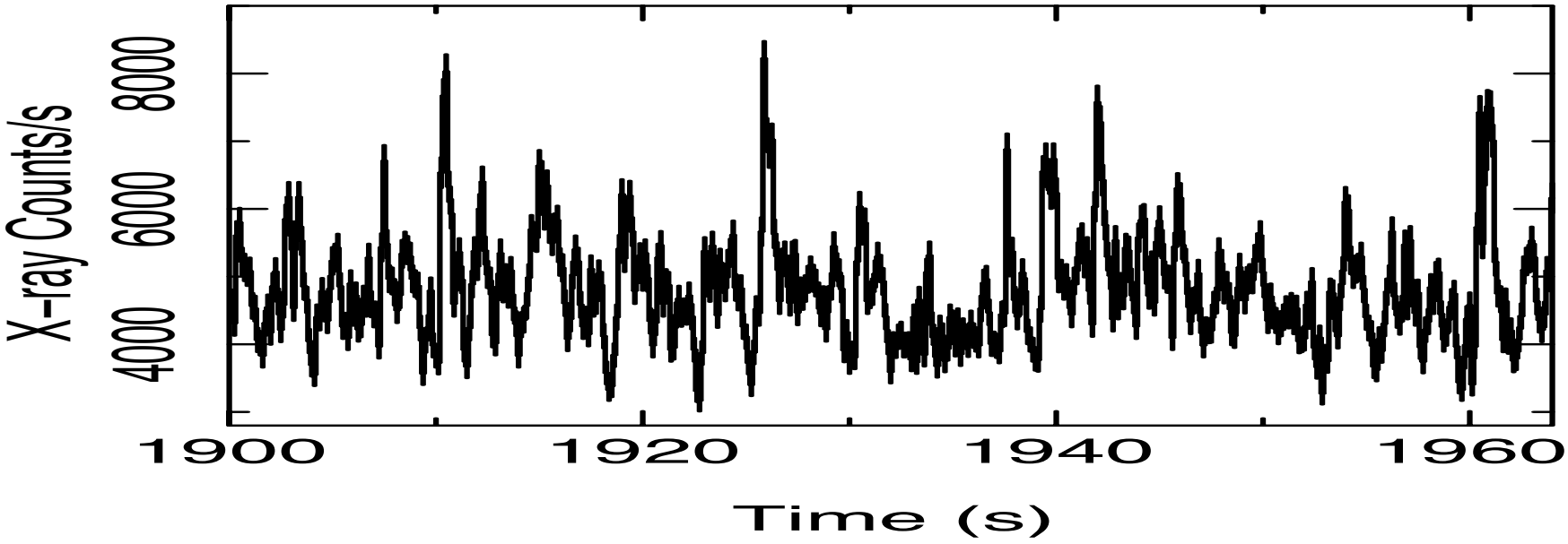
# QPO waveform

Quasi-periodic function: changing phase difference




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

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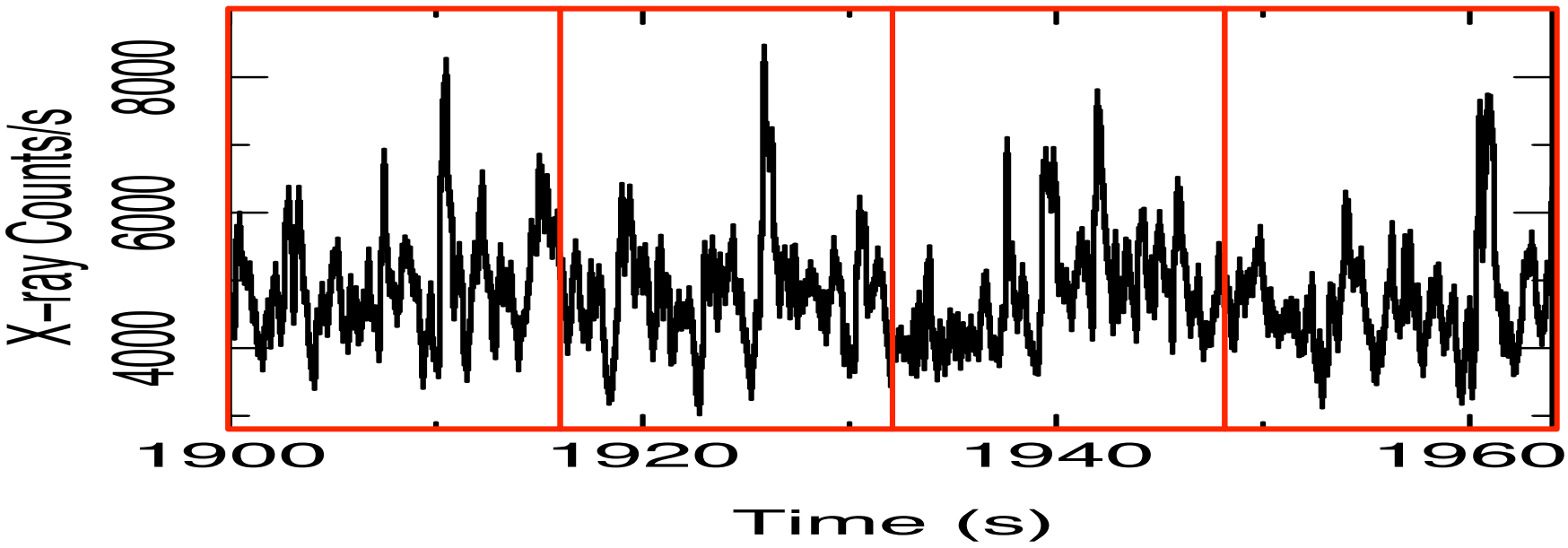
# QPO waveform

Quasi-periodic function: changing phase difference




Split long light curve into many segments and measure the phase difference $\Psi$ for each segment

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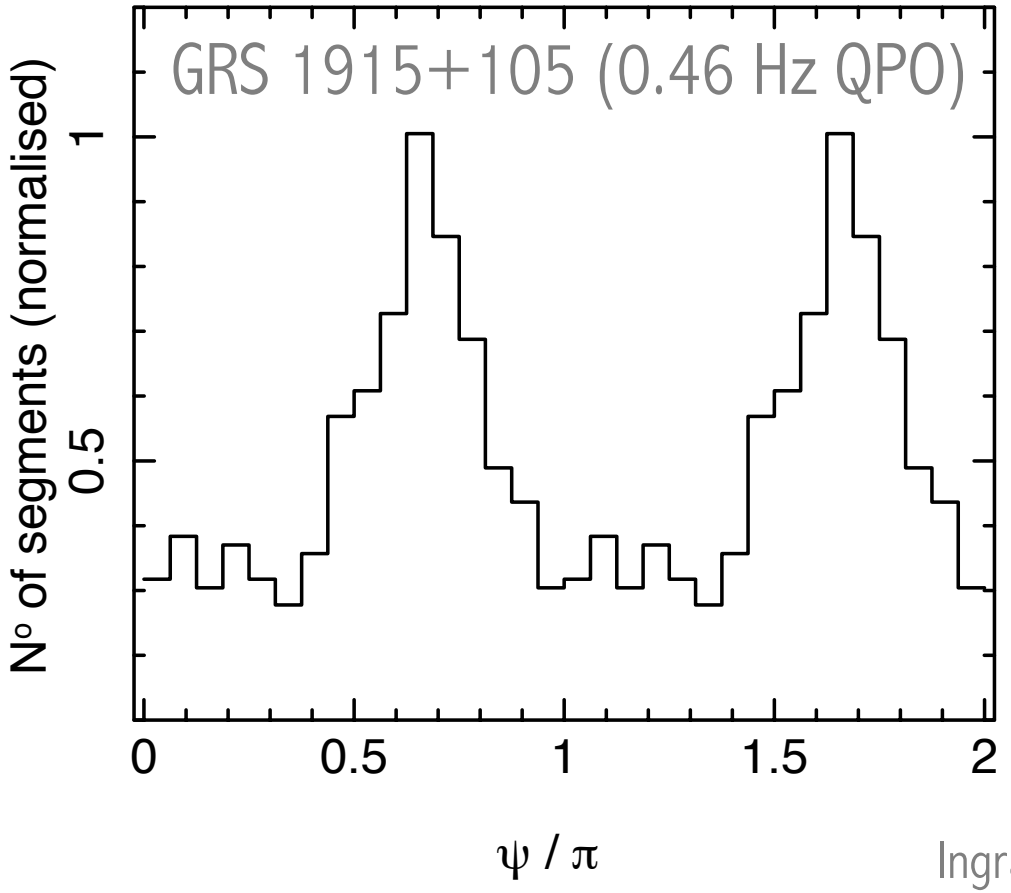
# QPO waveform

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




Ingram & van der Klis (2015)

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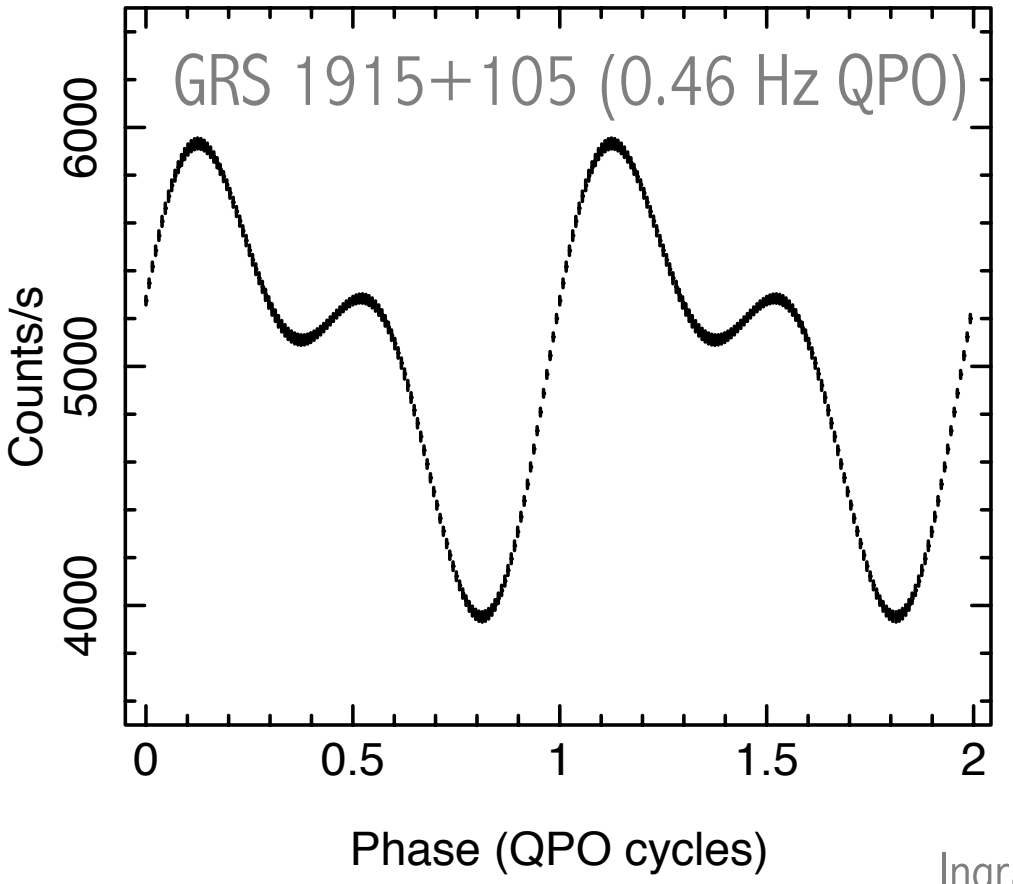
# QPO waveform

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




Ingram & van der Klis (2015)

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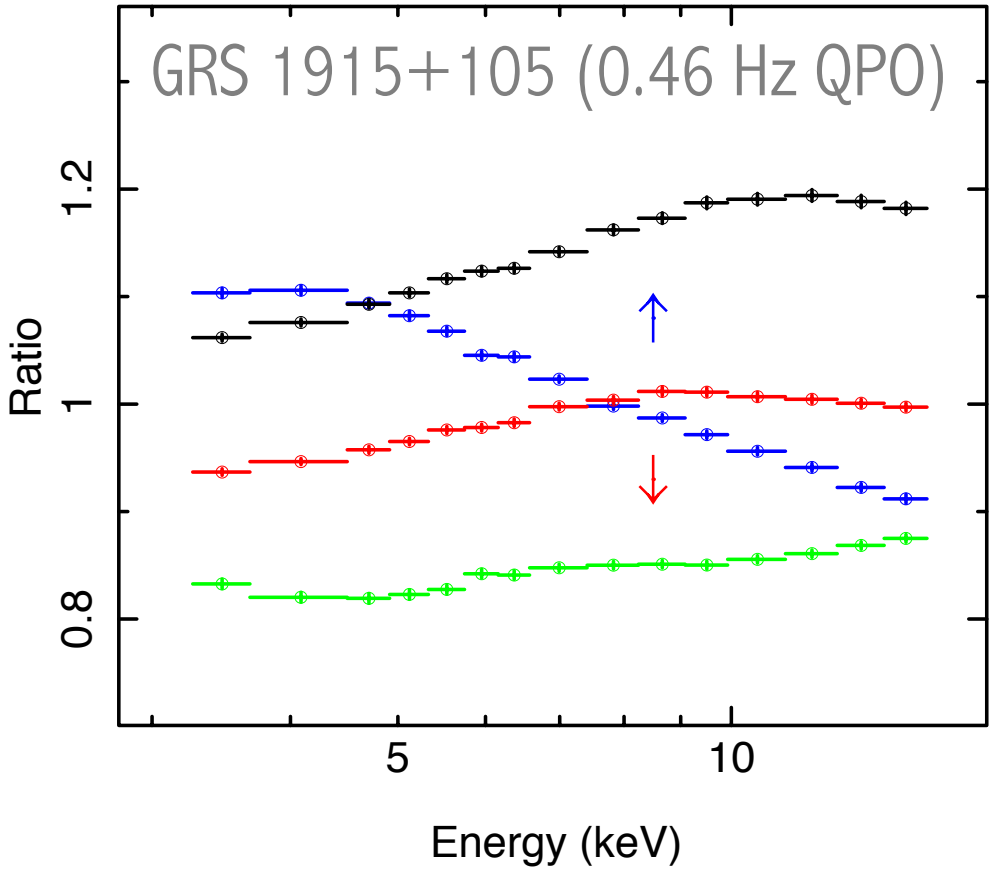
# Phase resolving

## Spectra for 4 snapshots of phase




Ingram & van der Klis (2015)

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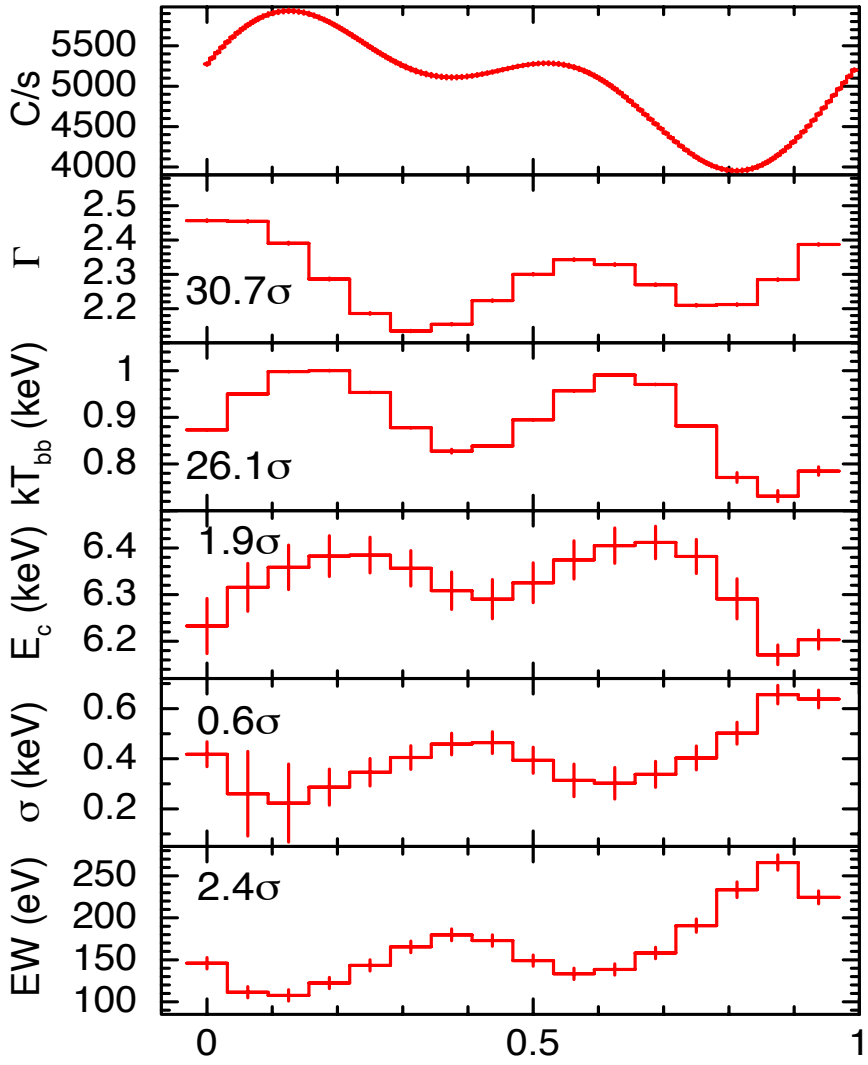
# Spectral modeling




Ingram & van der Klis (2015)

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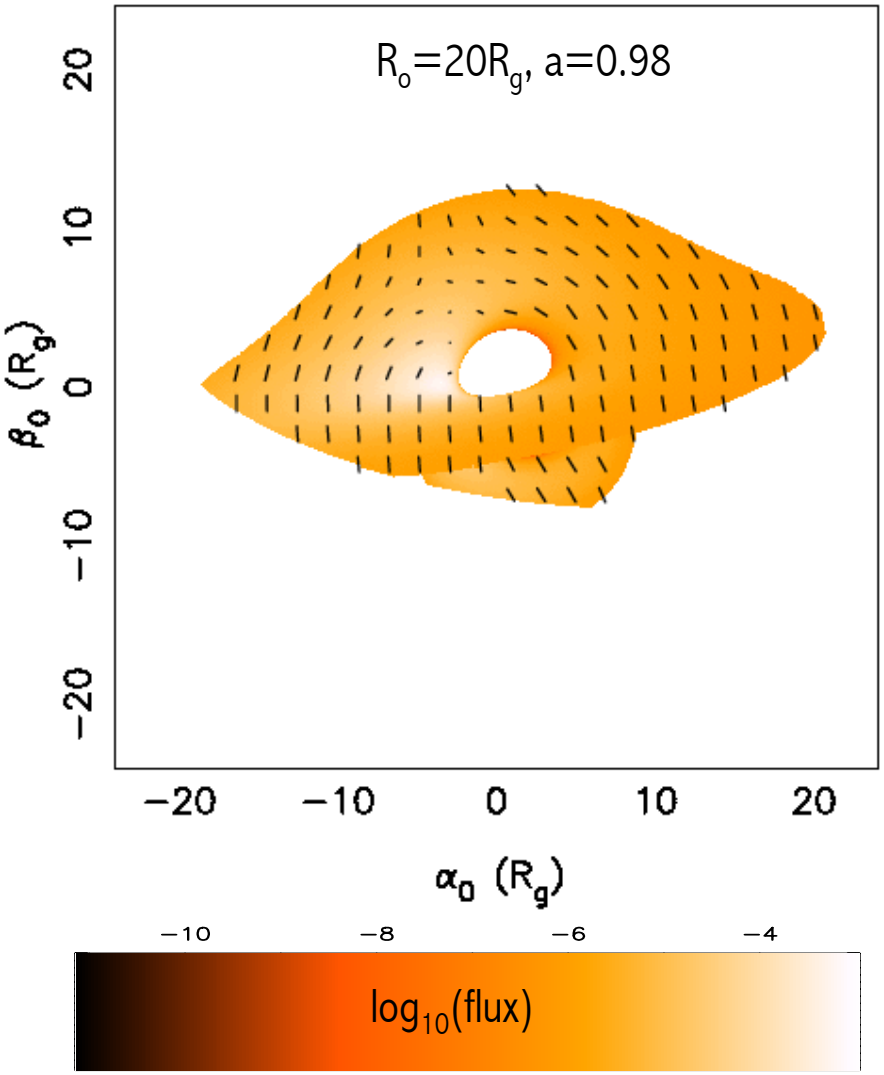
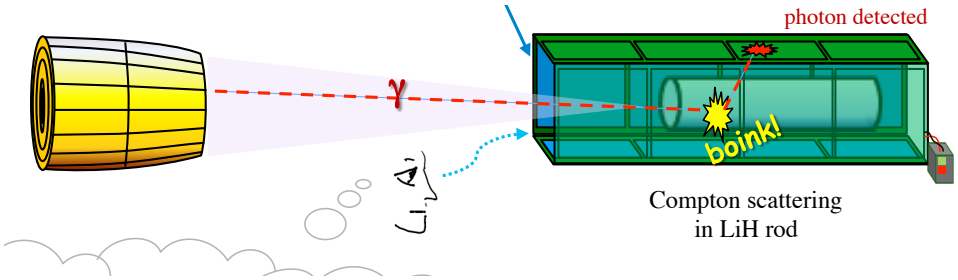
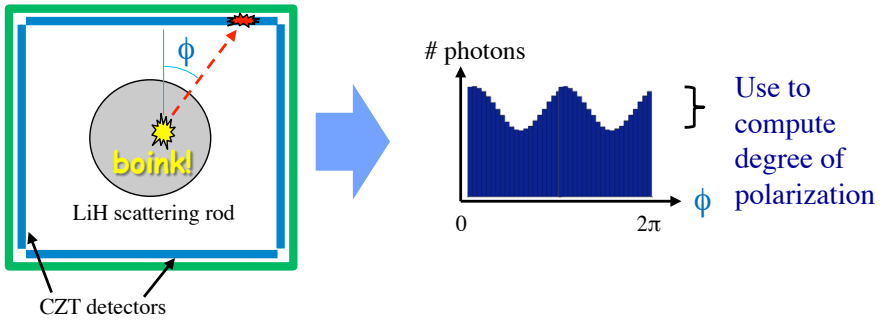
# Polarization




PolSTAR




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

Ingram et al (2015)

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# Conclusions

- Propagating fluctuations model consistent with power spectrum, linear rms-flux relation, time-lags, frequency-resolved spectra…
- Can now do propfluc analytically, so fitting lots of data is feasible (see Stefano Rapisarda's talk)
- If the QPO is due to precession, the iron line shape should change with QPO phase
- QPO phase-resolved spectroscopy is now possible (see Abi Stevens' talk)
- Need to look at more observations