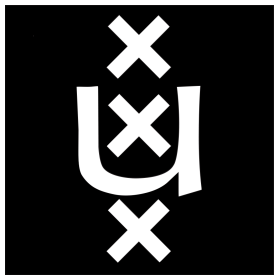
# Comparing origins of low-frequency quasi-periodic oscillations with spectral-timing

Abigail Stevens, Phil Uttley

University of Amsterdam

KITP, DISKS17

# Outline

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- X-ray binaries
- Spectroscopy
- Timing
- Precession model
- Phase-resolved spectroscopy results

# Low-mass X-ray binaries (LMXBs)

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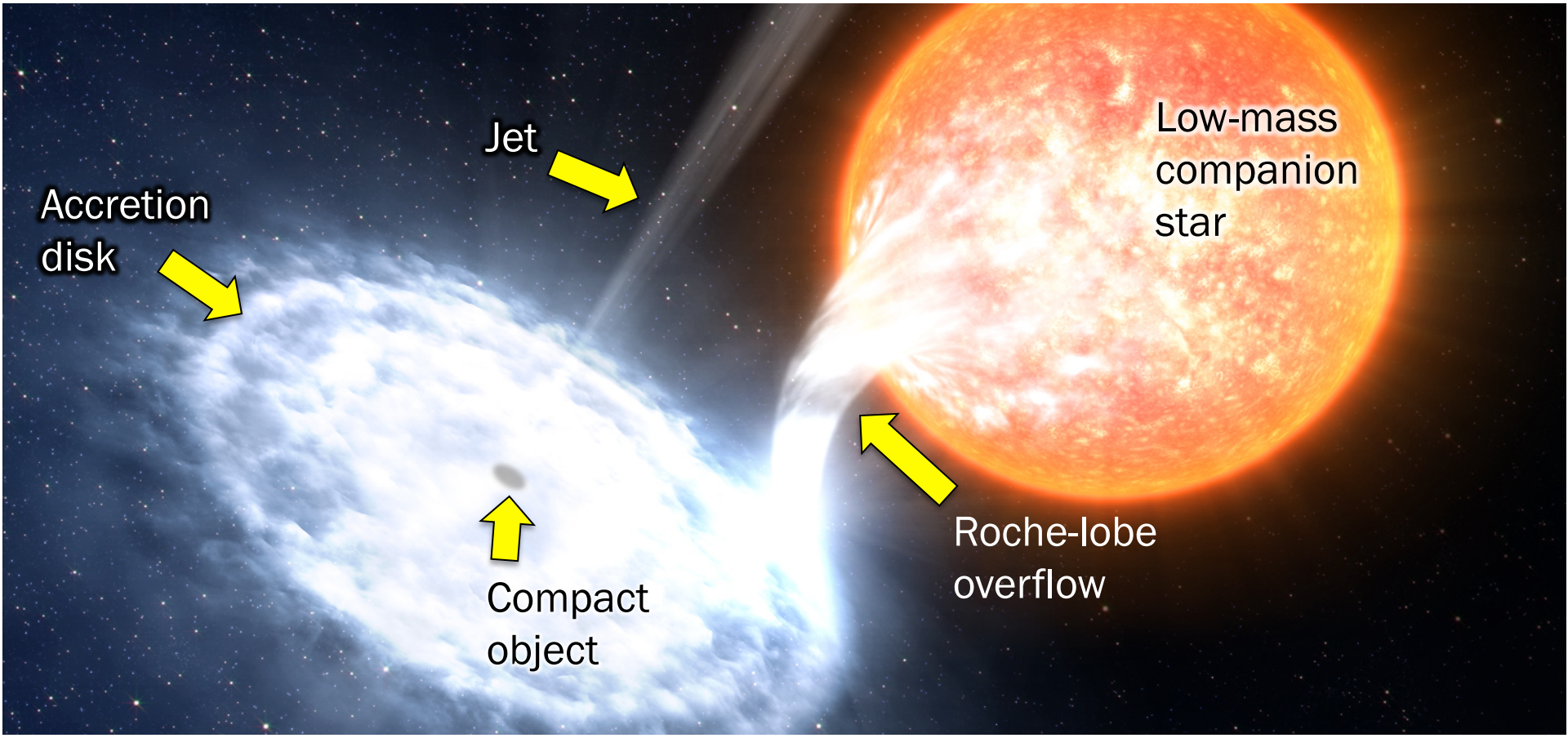


Figure: ESO/L. Calçada

# Low-mass X-ray binaries (LMXBs)

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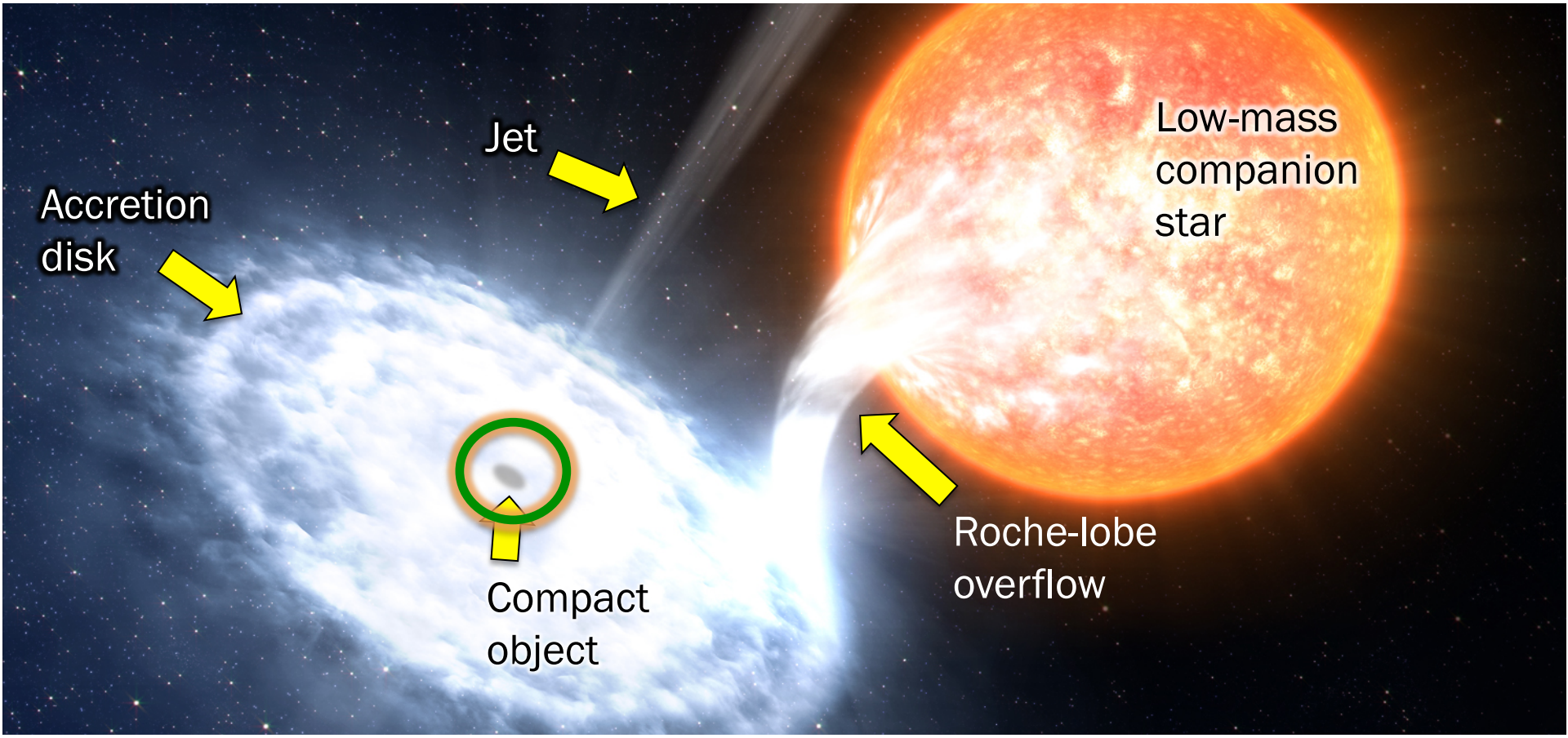


How does matter behave in strong gravitational fields?

Figure: ESO/L. Calçada

# Inner region of an LMXB

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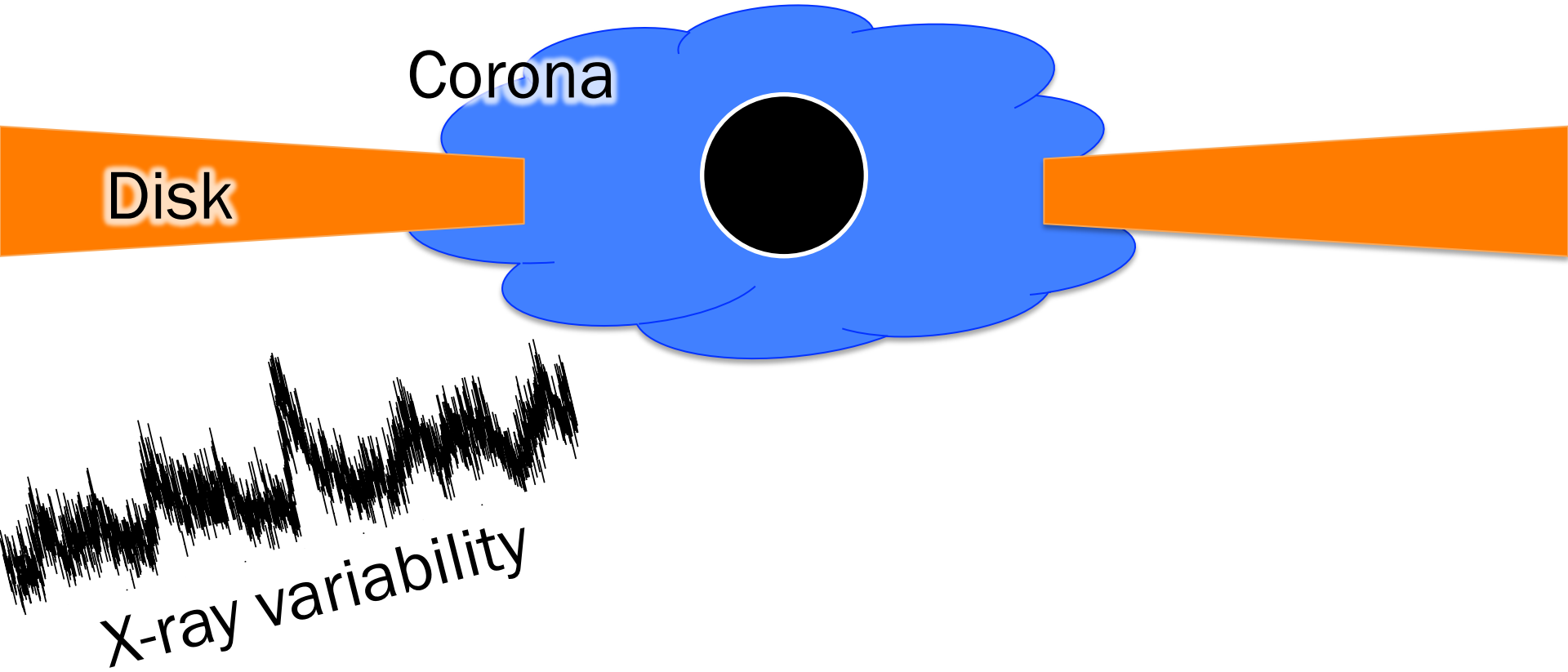

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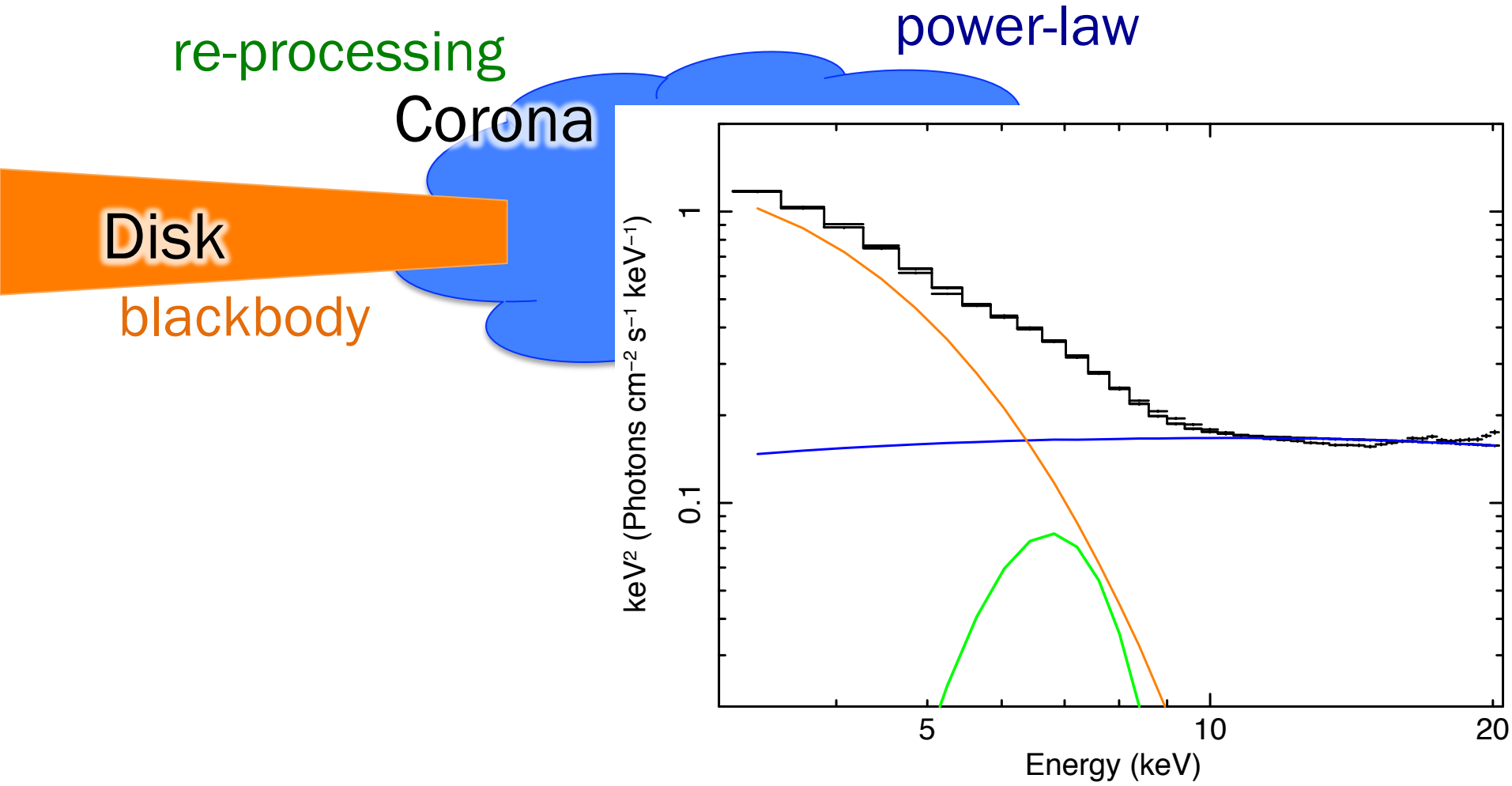

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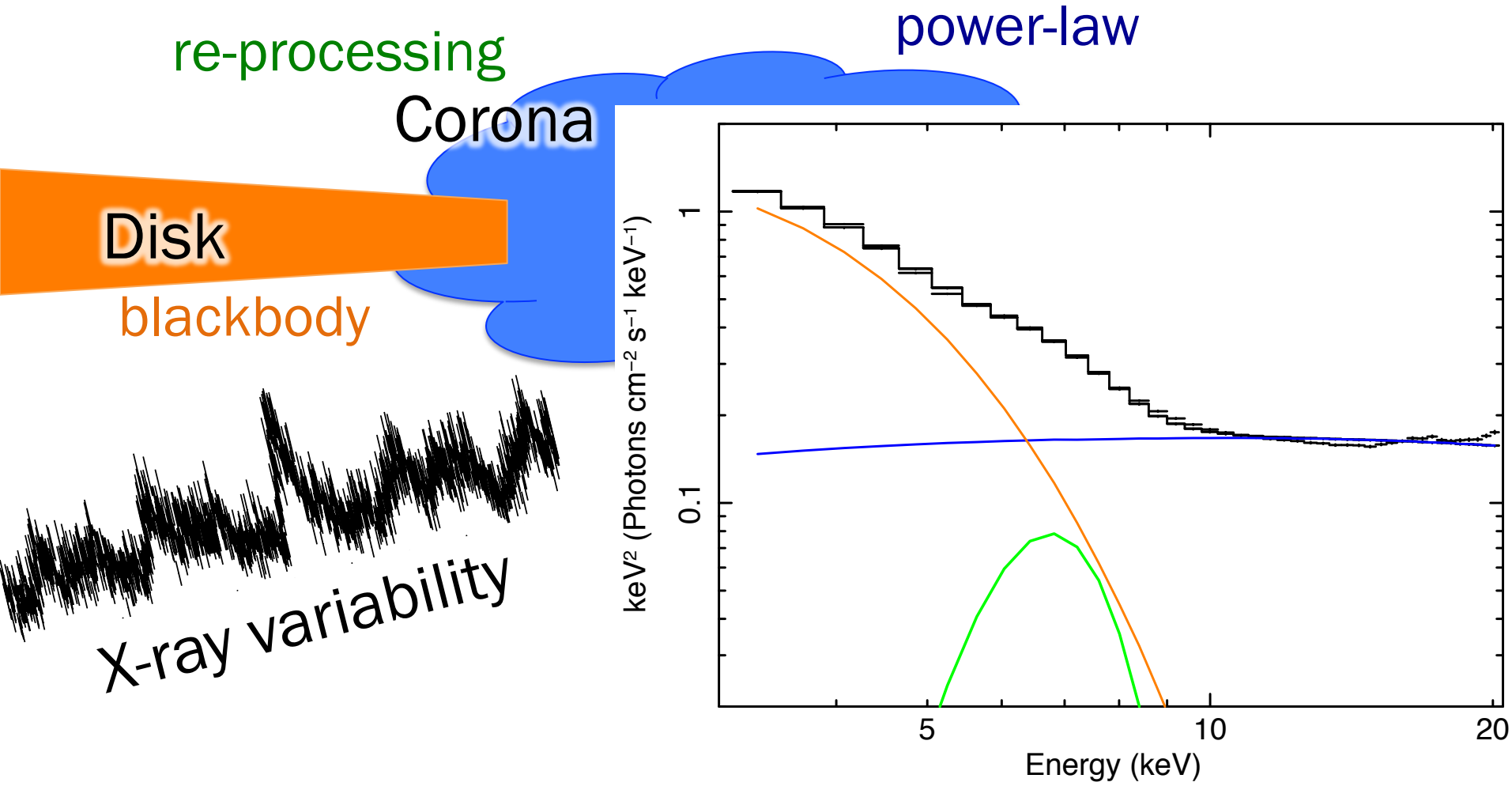

# Spectroscopy

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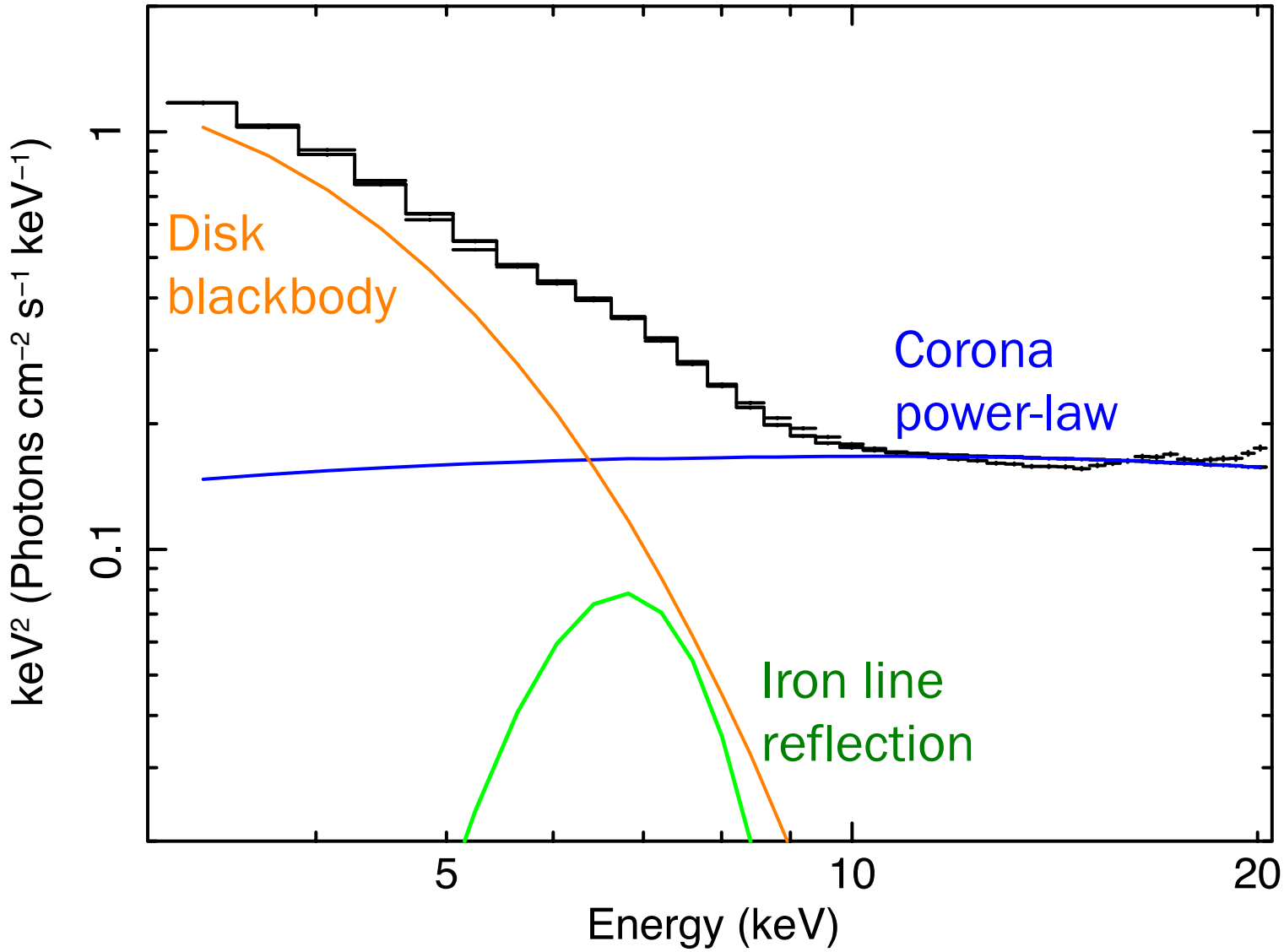

# Spectra in different accretion states

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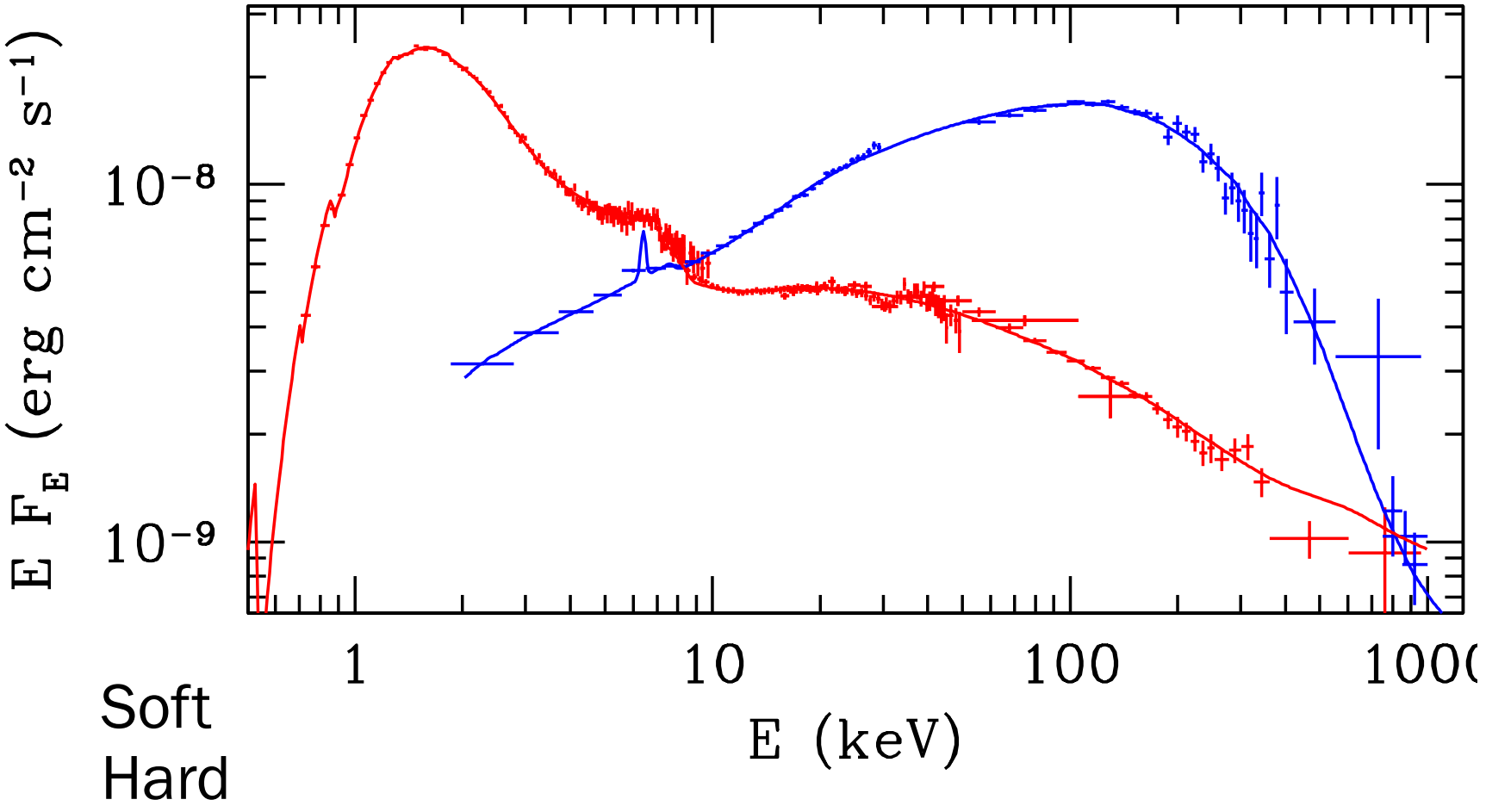


Figure: Done et al 2007

# Black hole spectral states

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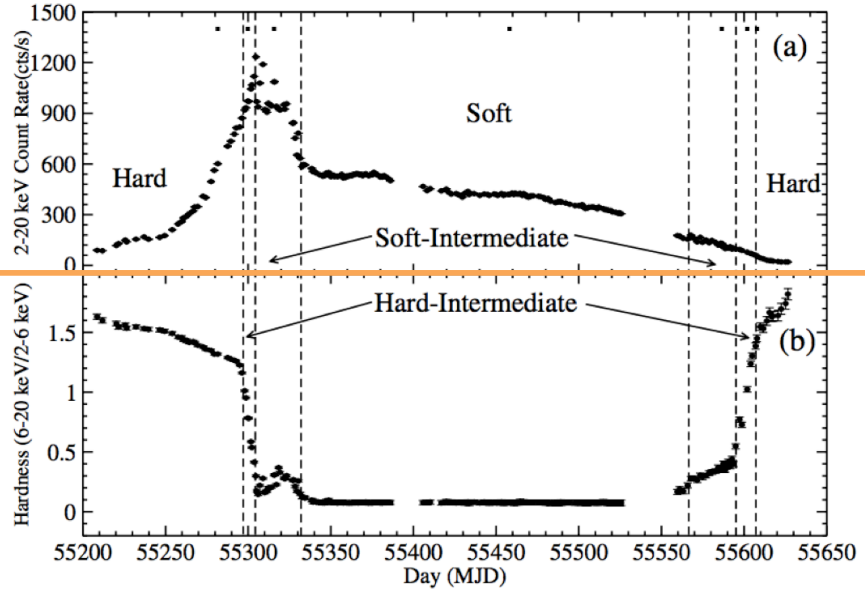
- Many X-ray binaries are transients: outburst!




← Outburst counts light curve

↑ Hardness light curve

Reviews: Nowak 1995; Remillard & McClintock 2006; Done et al 2007

GX 339—4, Nandi et al 2012

# Black hole spectral states

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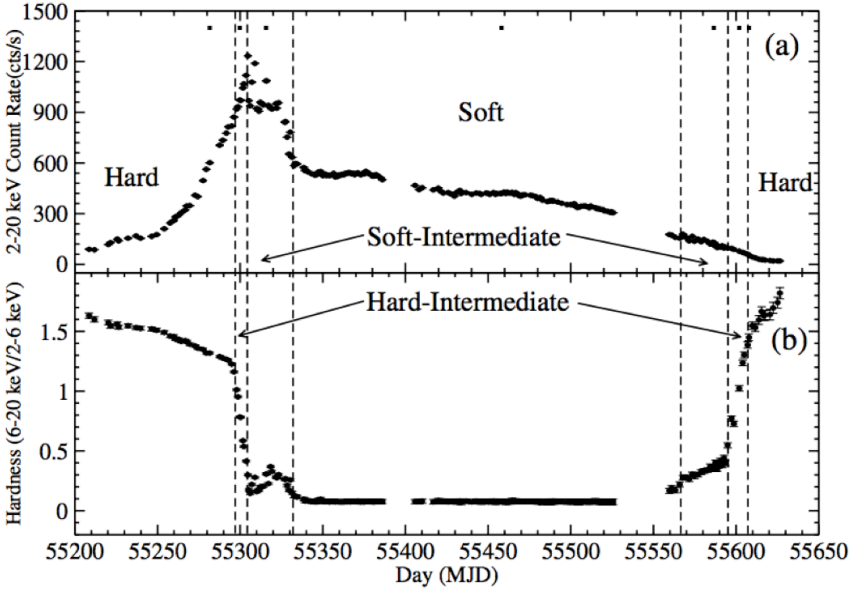
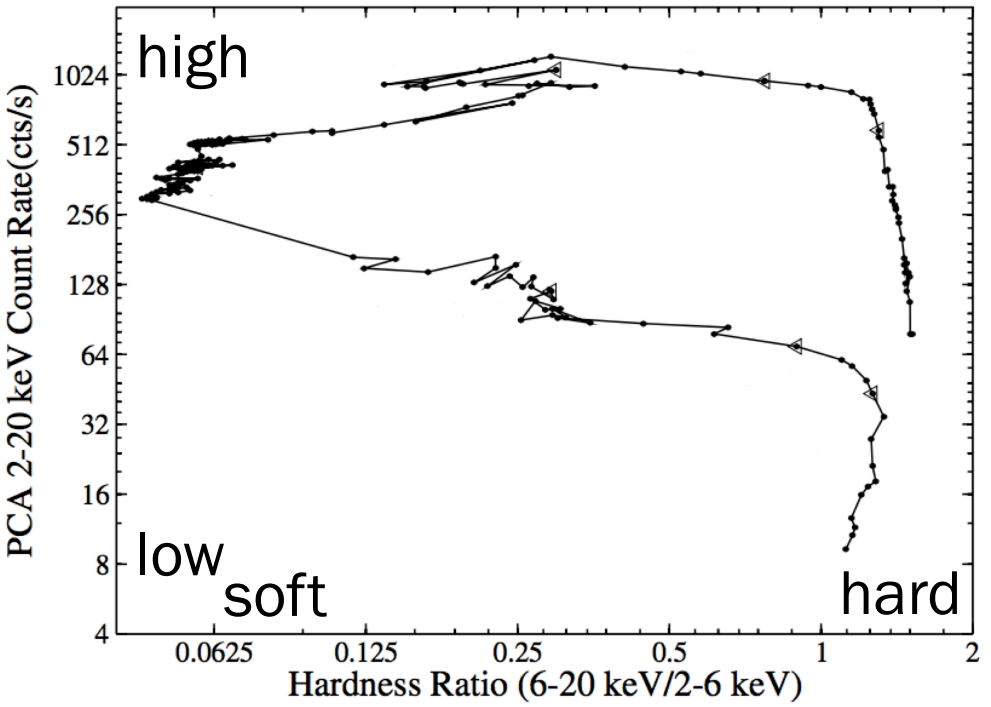



Hardness light curve

Outburst counts light curve




Hardness-Intensity diagram

Reviews: Nowak 1995; Remillard & McClintock 2006; Done et al 2007

GX 339—4, Nandi et al 2012

# Timing

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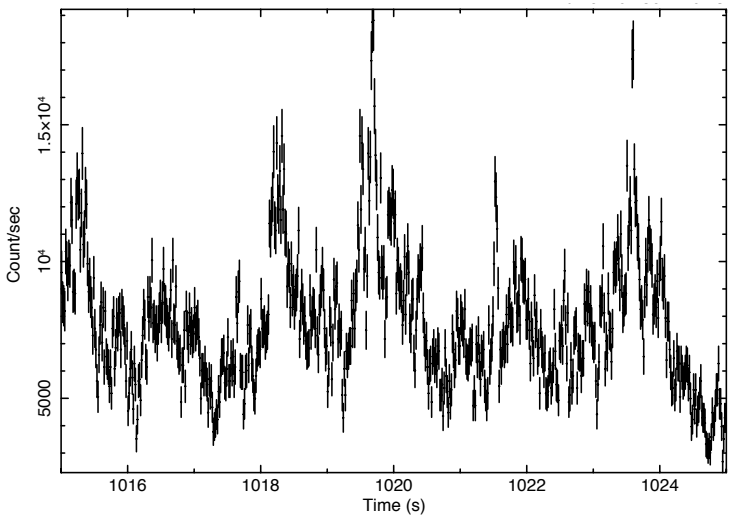
Study light curves in the frequency domain

Time domain

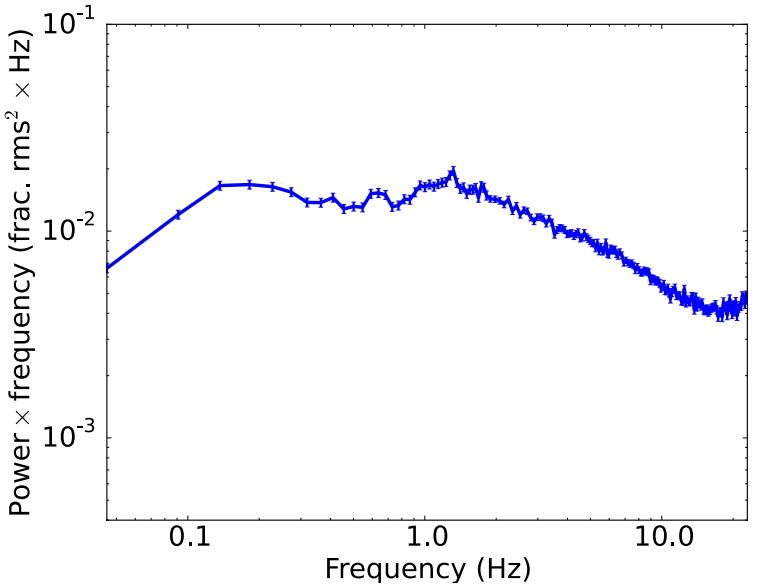
Light curve




FOURIER TRANSFORM

Frequency/Fourier domain

Power density spectrum



# X-ray variability: Hard to see by eye

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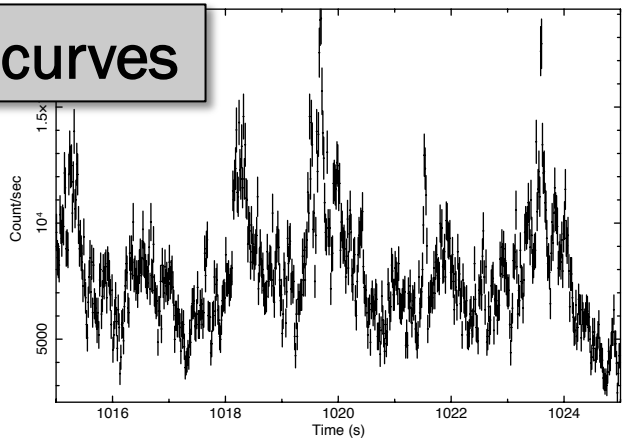
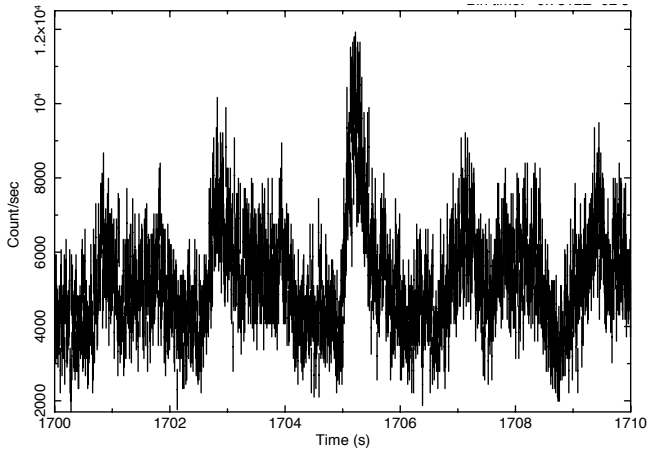
Light curves



# X-ray variability: Hard to see by eye

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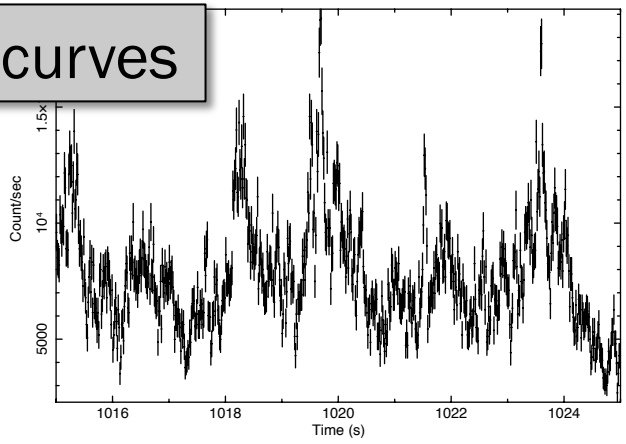
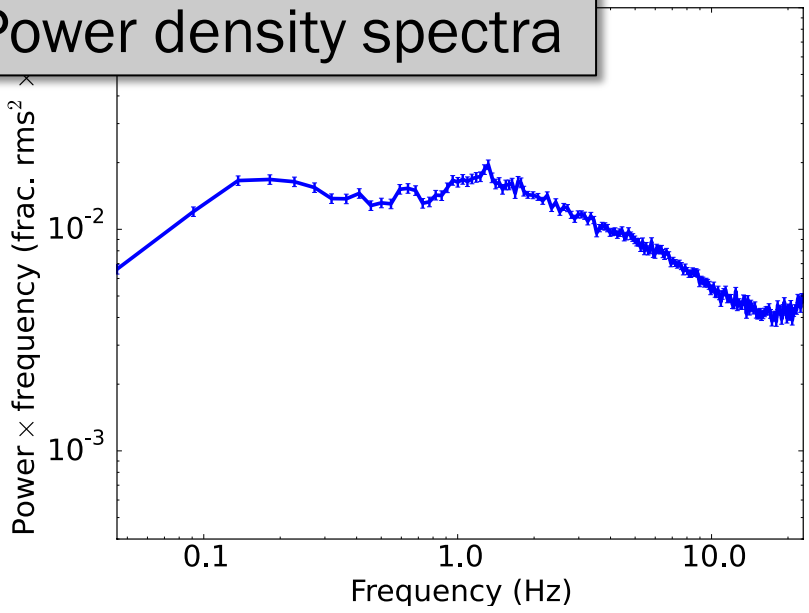
## Noise: Cygnus X-1

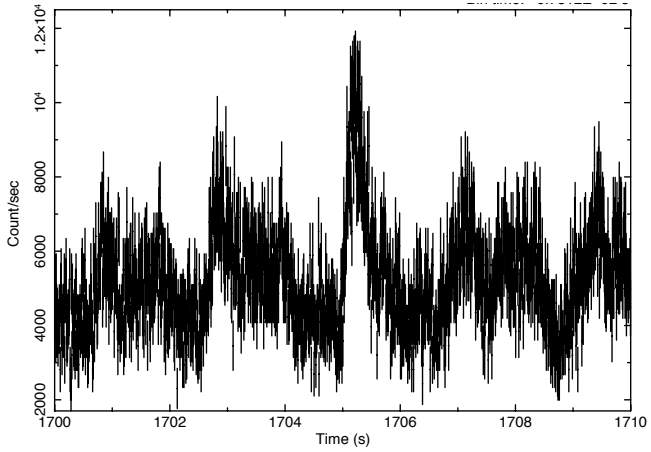
### Light curves

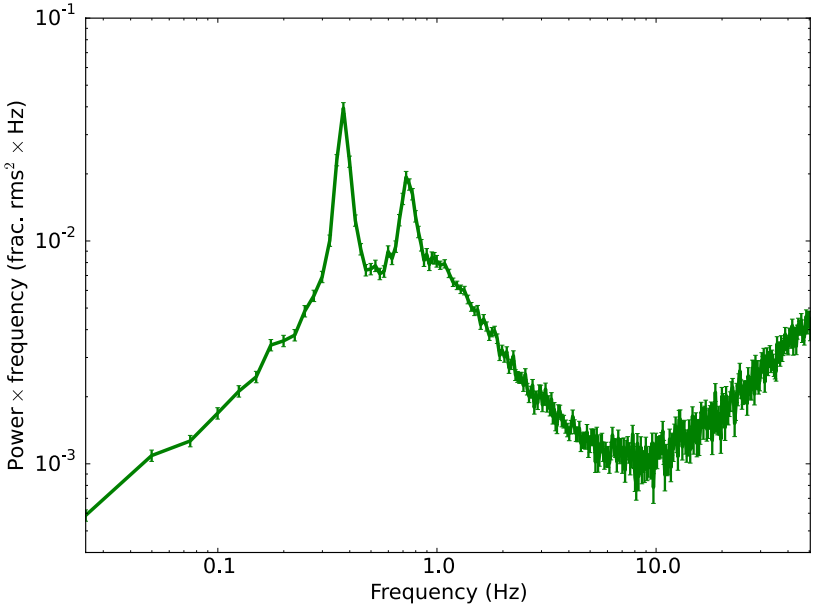



### Power density spectra




## Signal: GRS 1915



# Quasi-periodic oscillations (QPOs)

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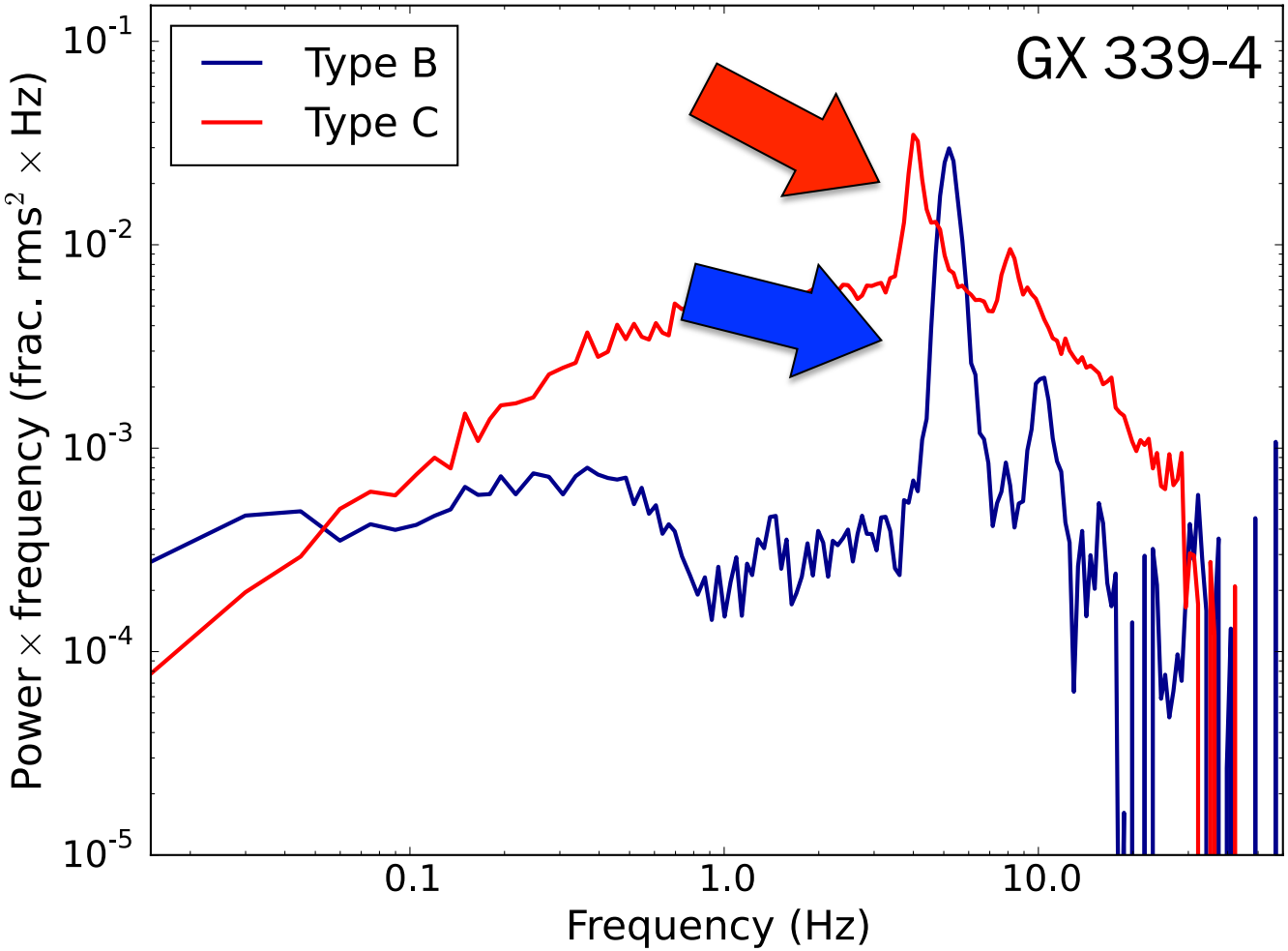
Power spectra show amount of variability in a light curve at different frequencies



# Flashback: BH spectral states

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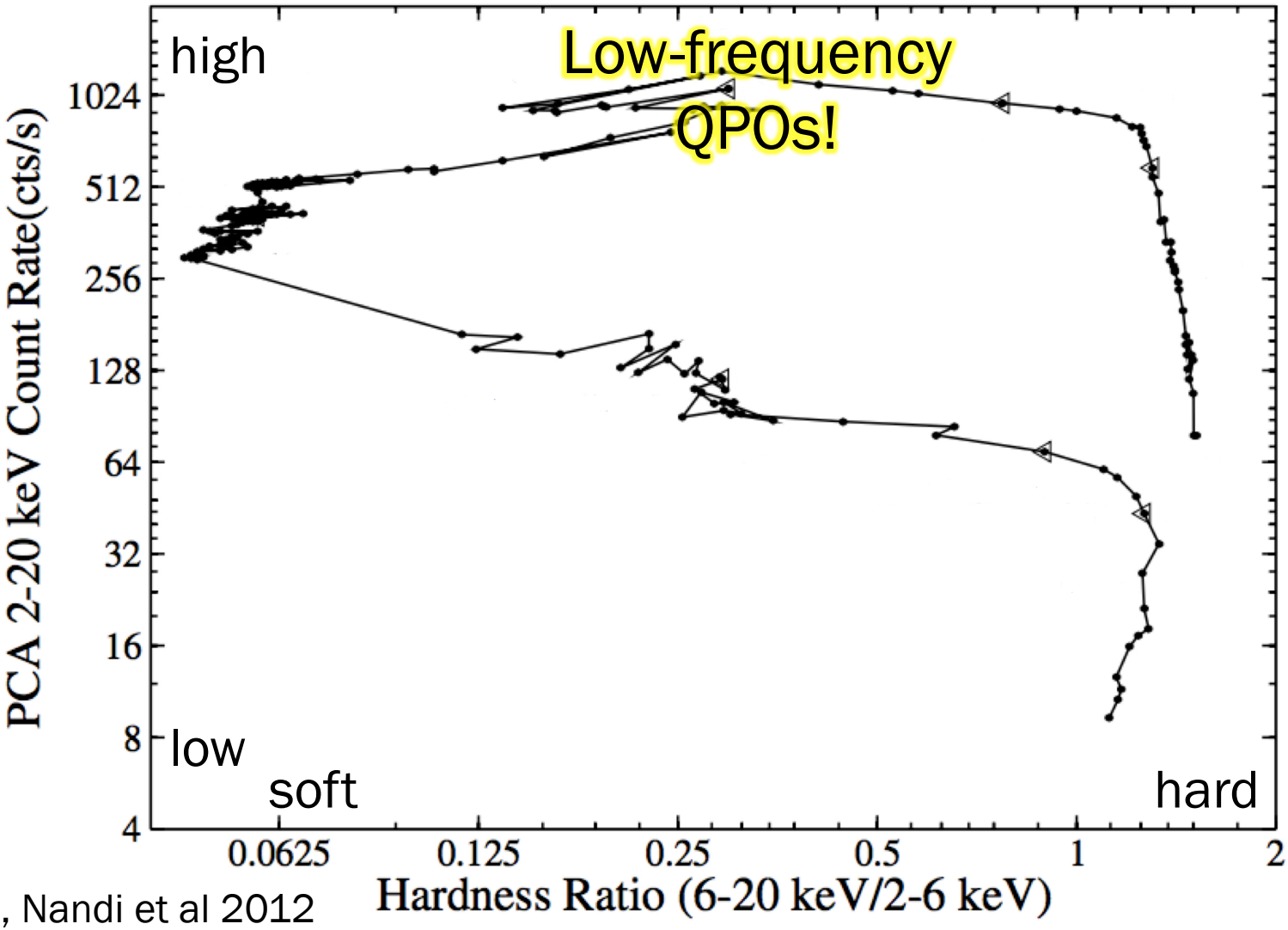
Hardness-Intensity diagram




GX 339-4, Nandi et al 2012

# BH QPOs and spectral states

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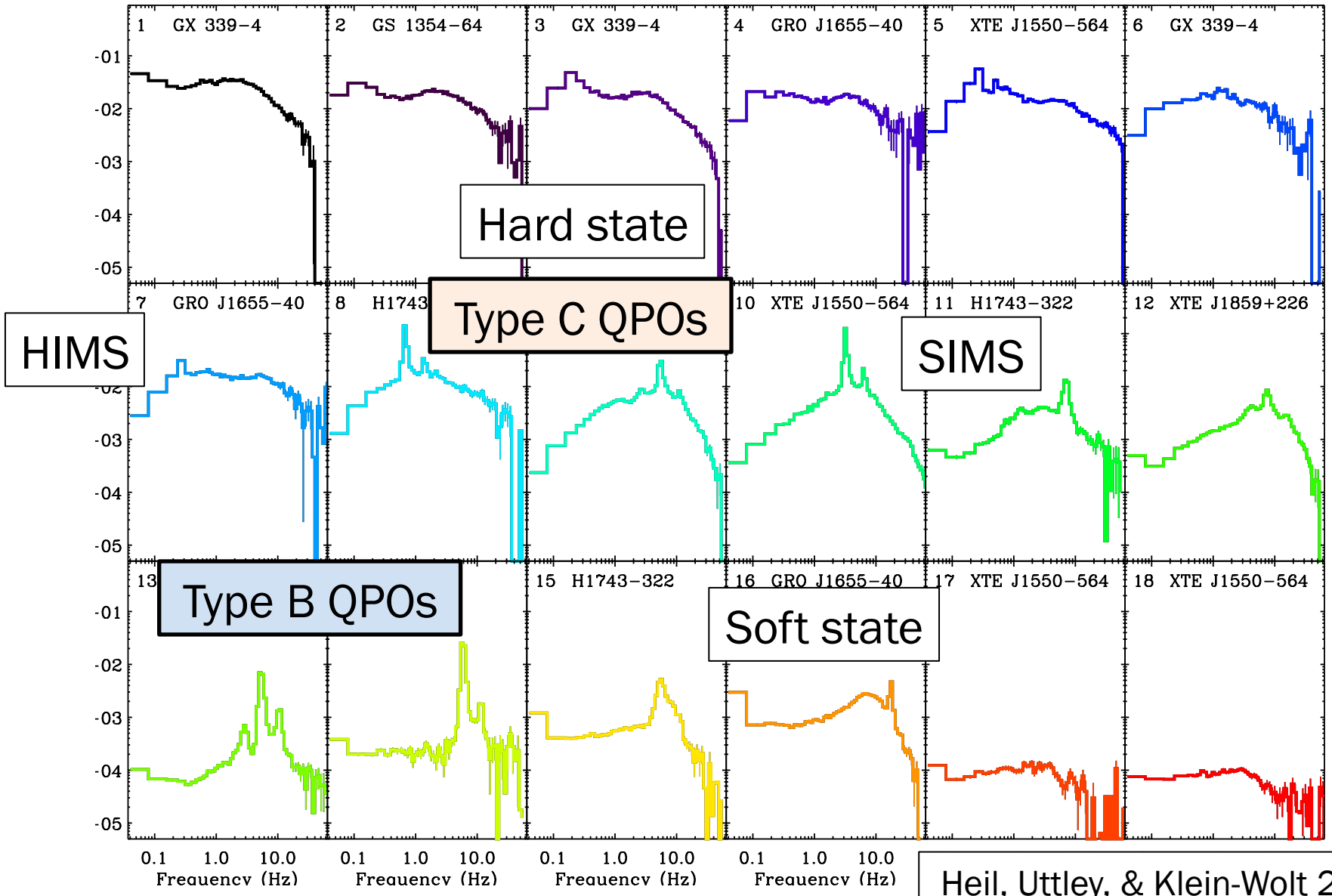


Heil, Uttley, & Klein-Wolt 2015a

# Binary inclination dependence

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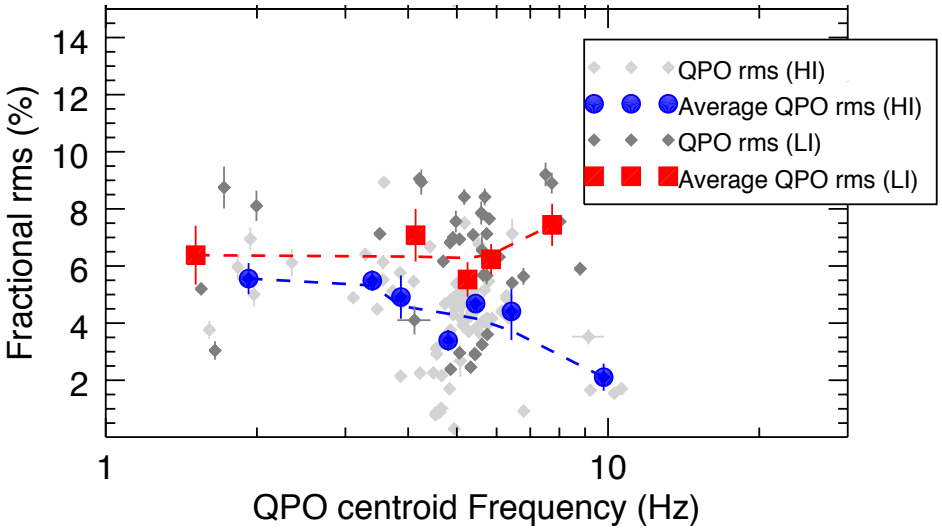
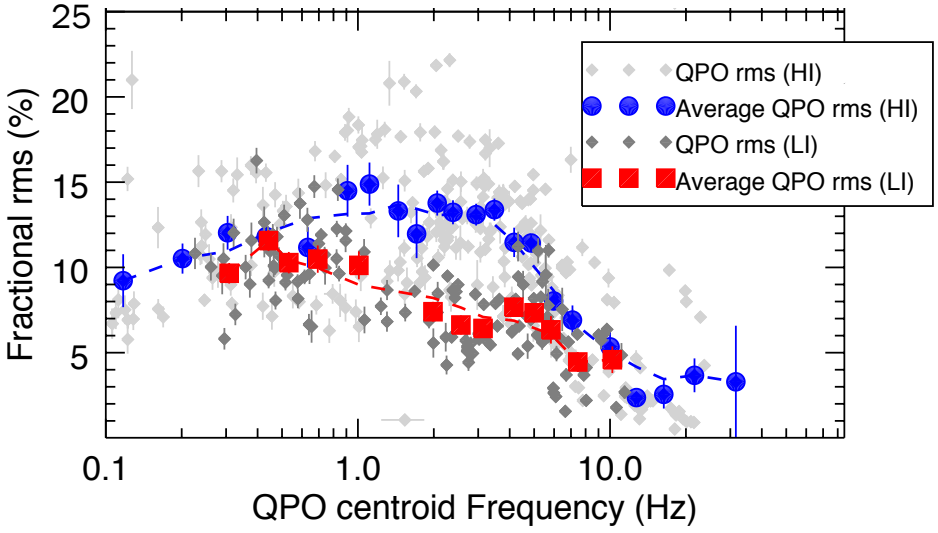
Type B's:
stronger face-on




Type C's:
stronger edge-on




(binary system inclination)

Schnittman, Homan & Miller 2006; Motta et al 2015 (images); Heil et al 2015b

# Inner region of an LMXB

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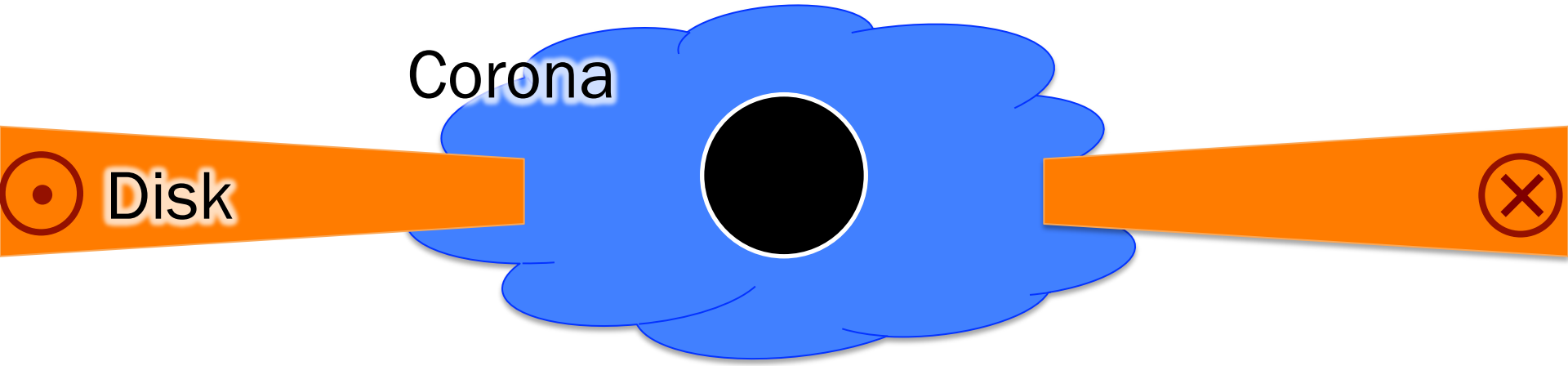

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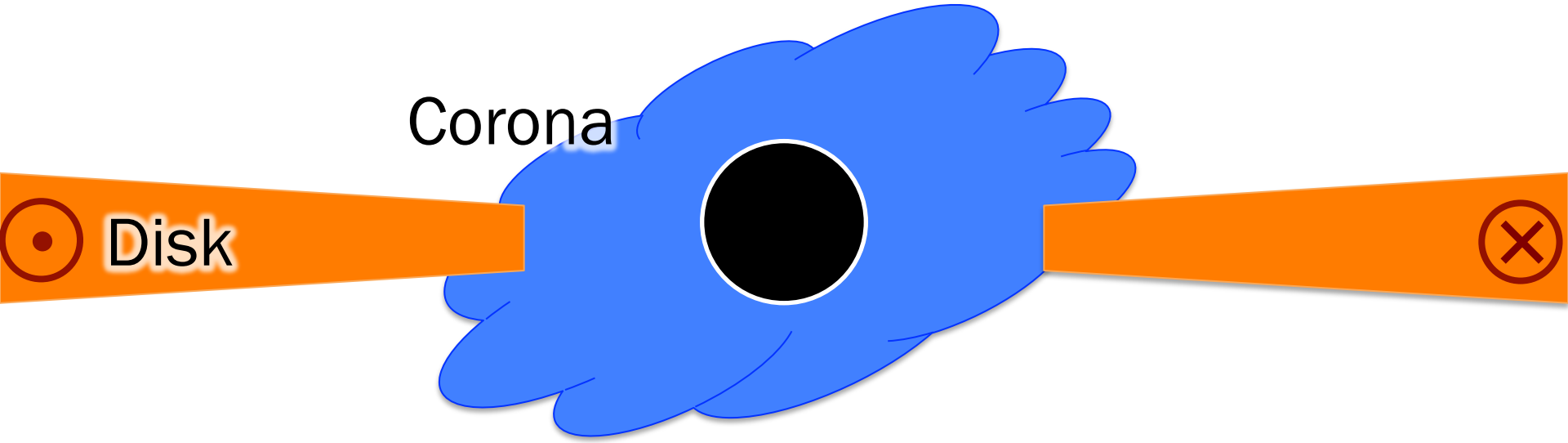


Lense-Thirring precession

Stella & Vietri 1998; Fragile & Anninos 2005; Schnittman, Homan & Miller 2006; Ingram, Done & Fragile 2009; Ingram & van der Klis 2015; Fragile et al. 2016; Ingram et al. 2016a,b

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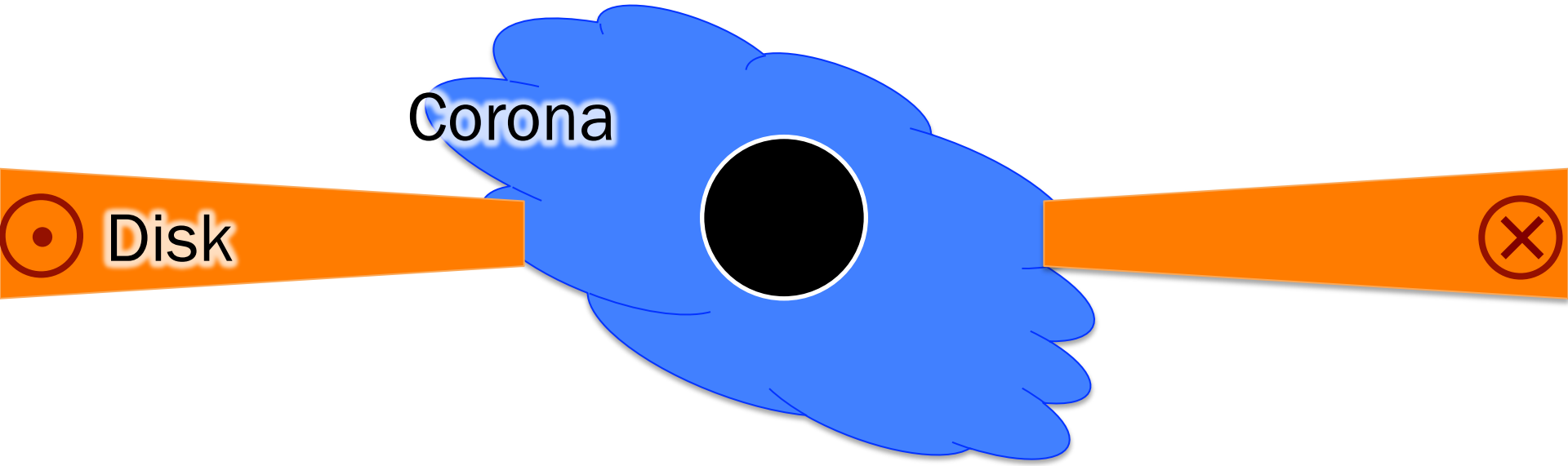


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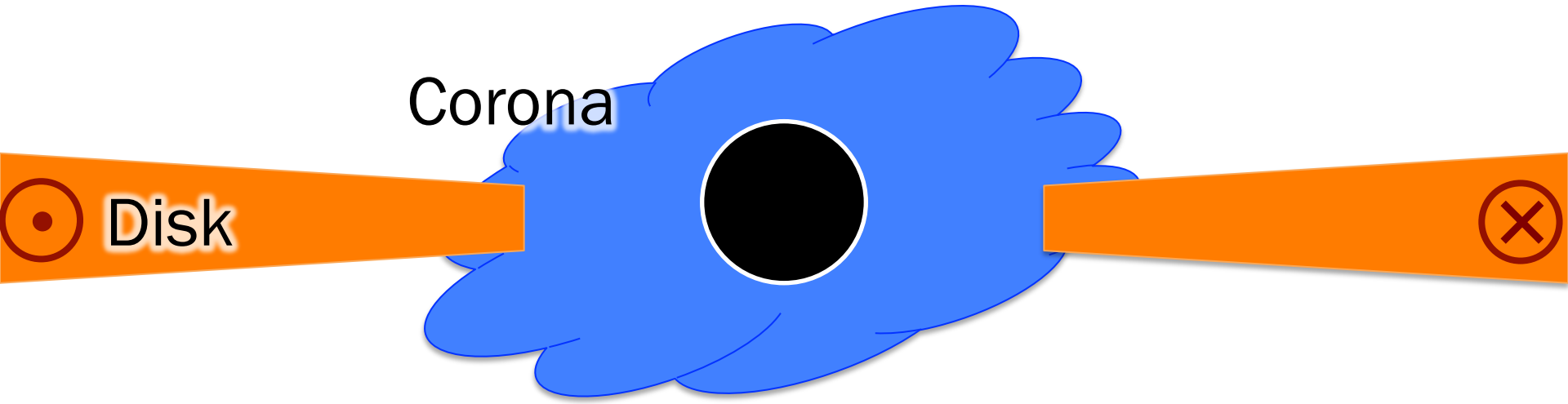


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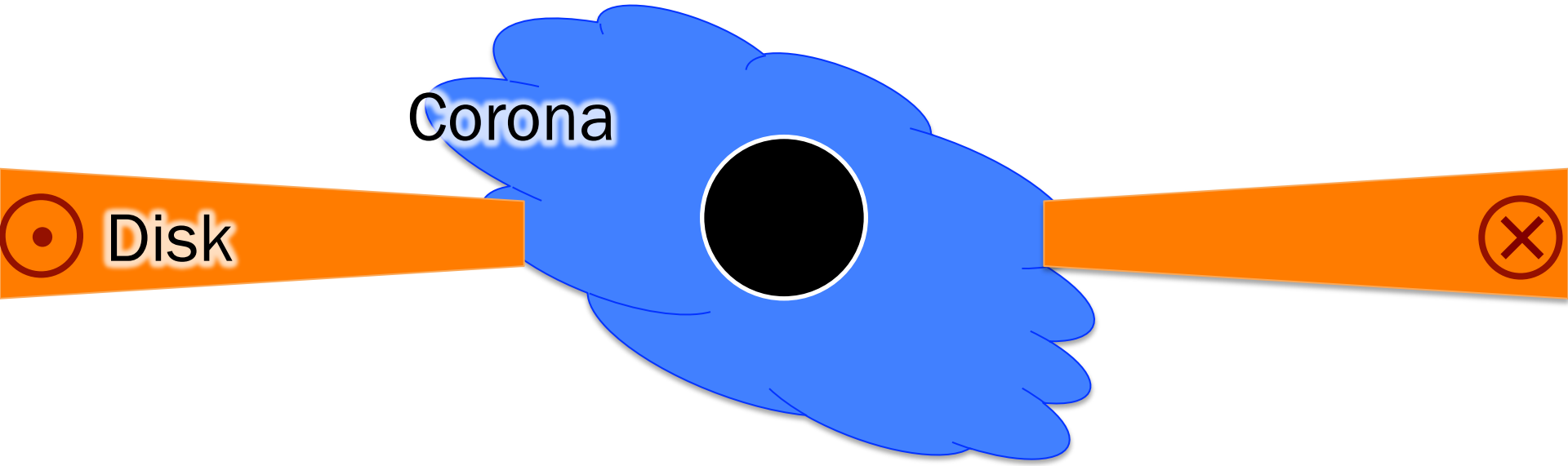


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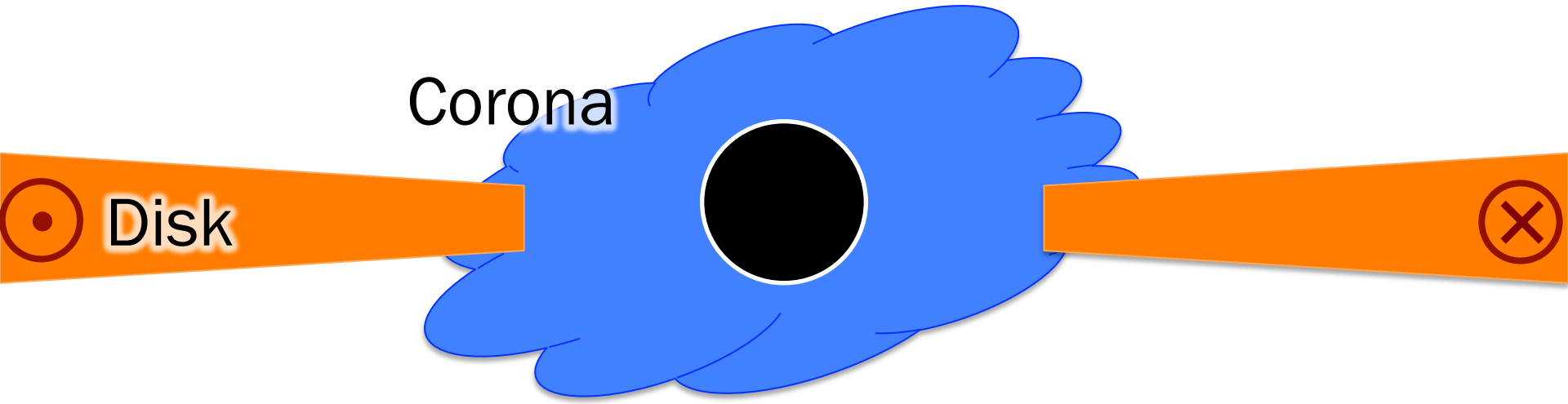


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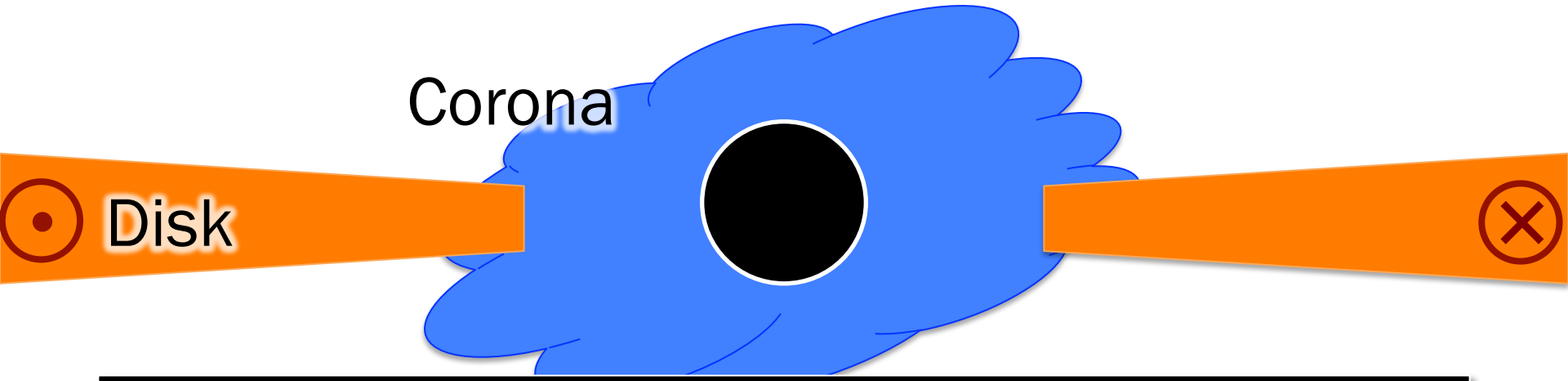


Want to study energy spectra on sub-QPO timescale

- Determine LF QPO emission mechanism
- Different mechanism for Type B vs Type C?

Stella & Vietri 1998; Fragile & Anninos 2005; Schnittman, Homan & Miller 2006; Ingram, Done & Fragile 2009; Ingram & van der Klis 2015; Fragile et al. 2016; Ingram et al. 2016a,b

# Phase-resolved spectroscopy

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- New technique allows us to effectively do phase-resolved spectroscopy of QPOs
- Details in paper -- arXiv: 1605.01753

# Phase-resolved spectroscopy

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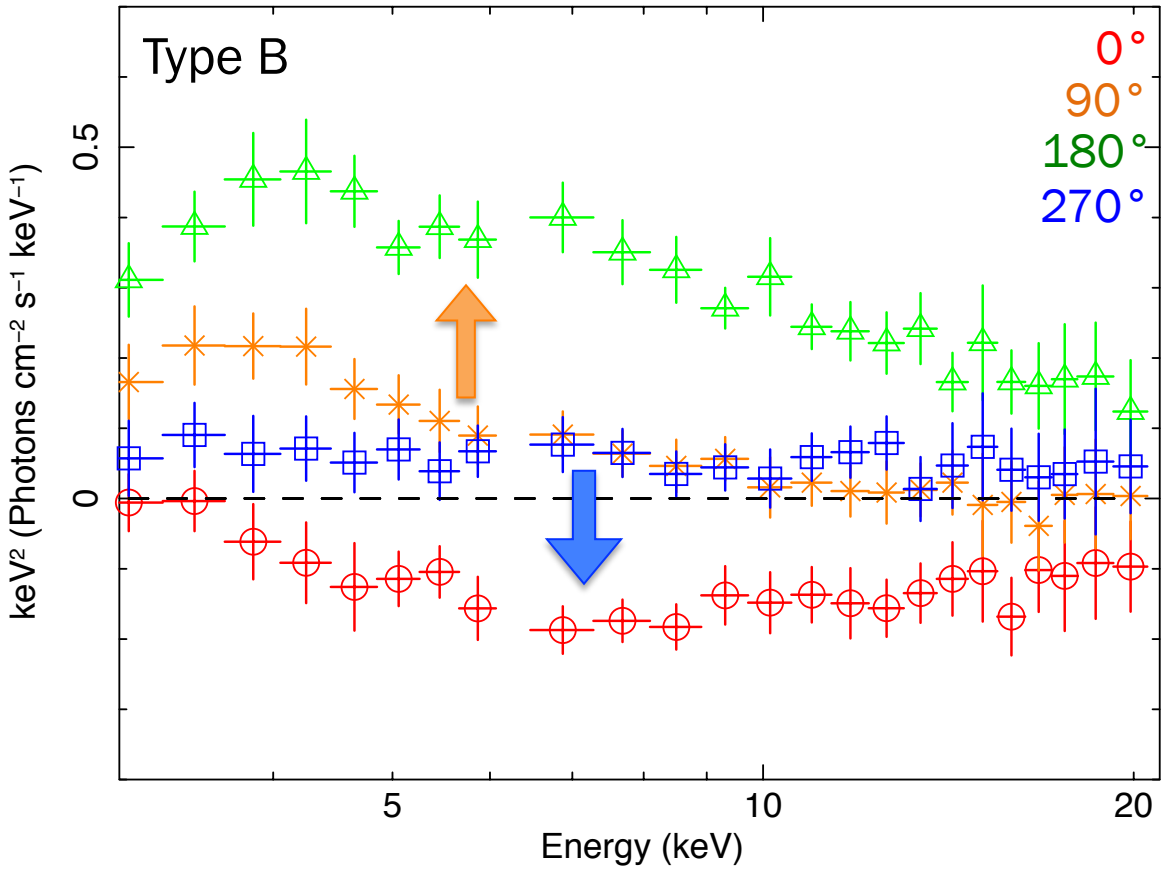
- Deviations from mean energy spectrum
- Spectral shape varying with QPO phase!



# Type B QPO spectral variations

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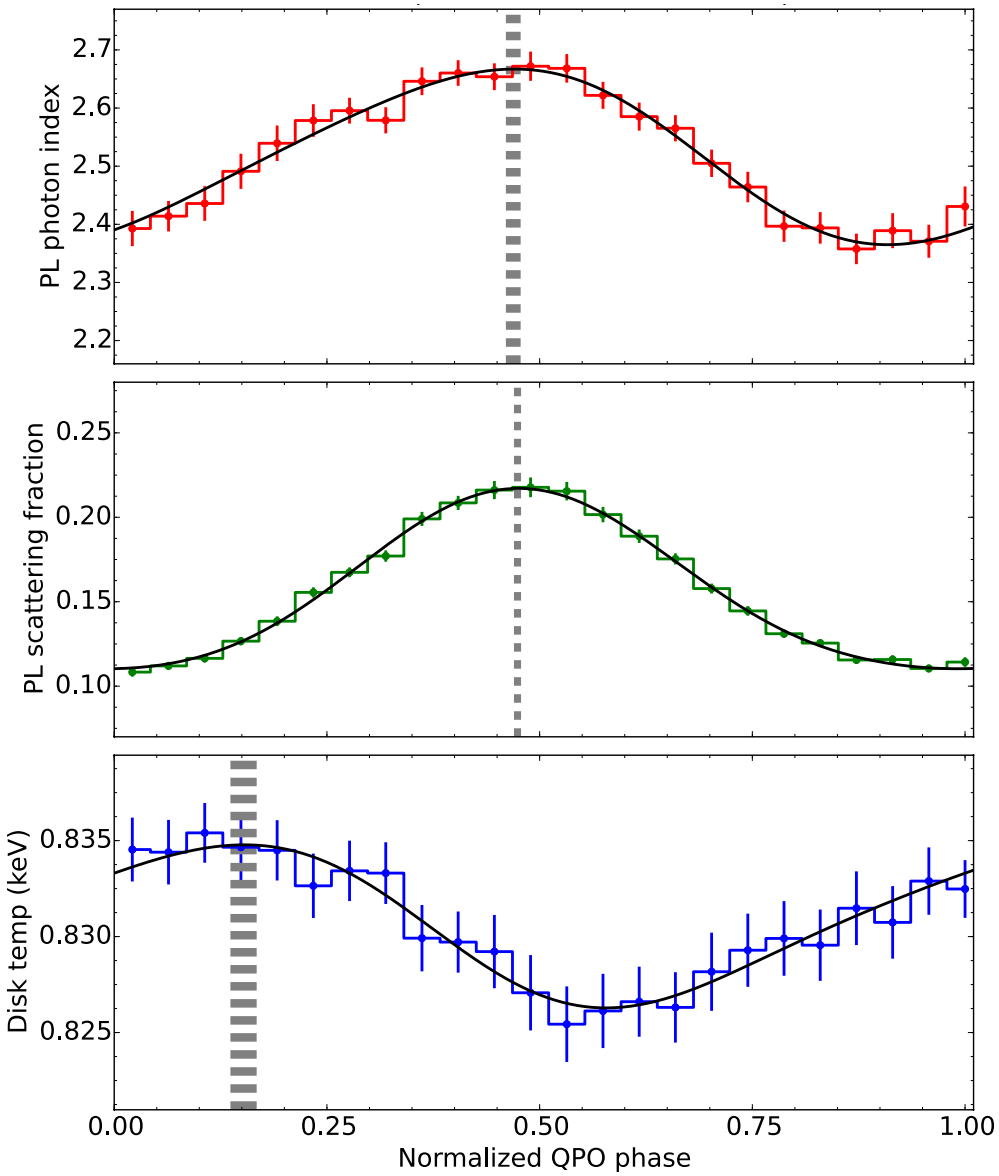
- Blackbody variation leads the power-law variation by ~0.3 (110°)
- Power-law: 25% rms variation
- Blackbody: 1.4% rms variation



# Type B QPO interpretation

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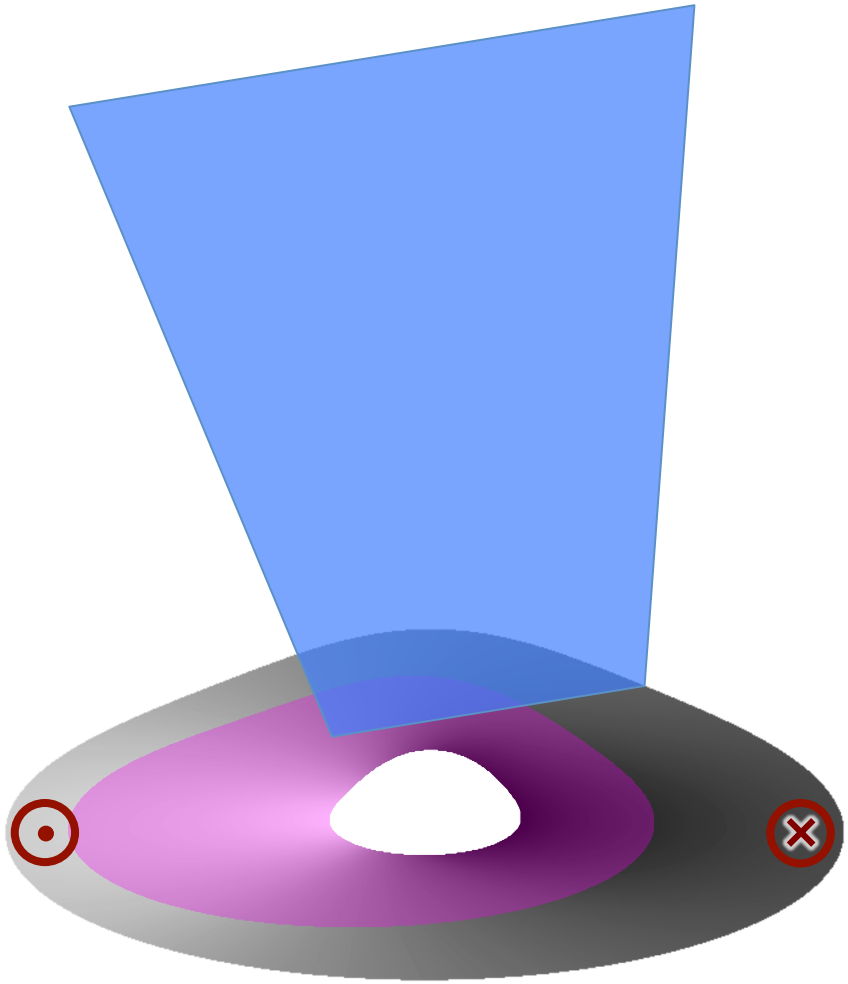
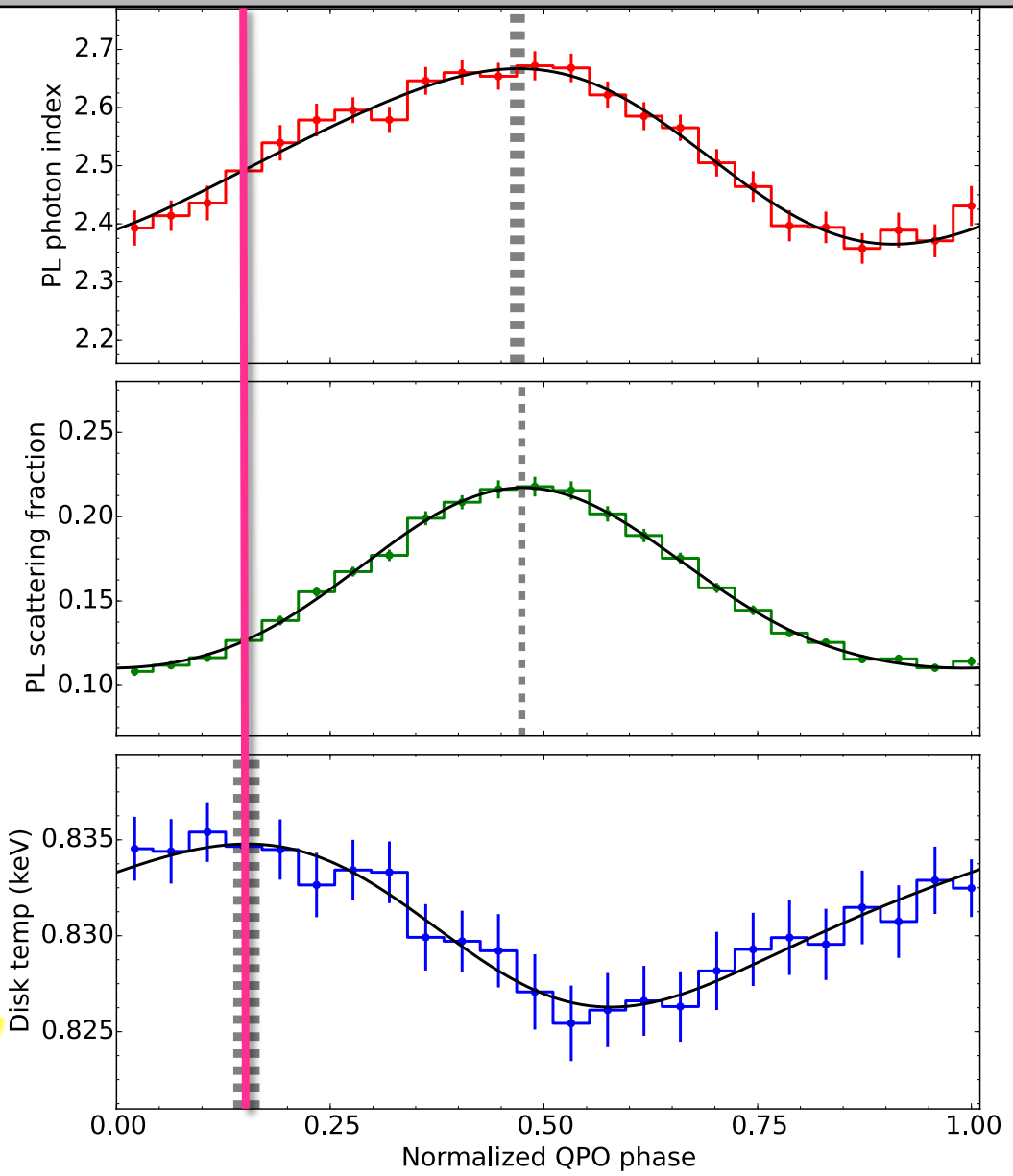


Large scale height, weakly modulated illumination



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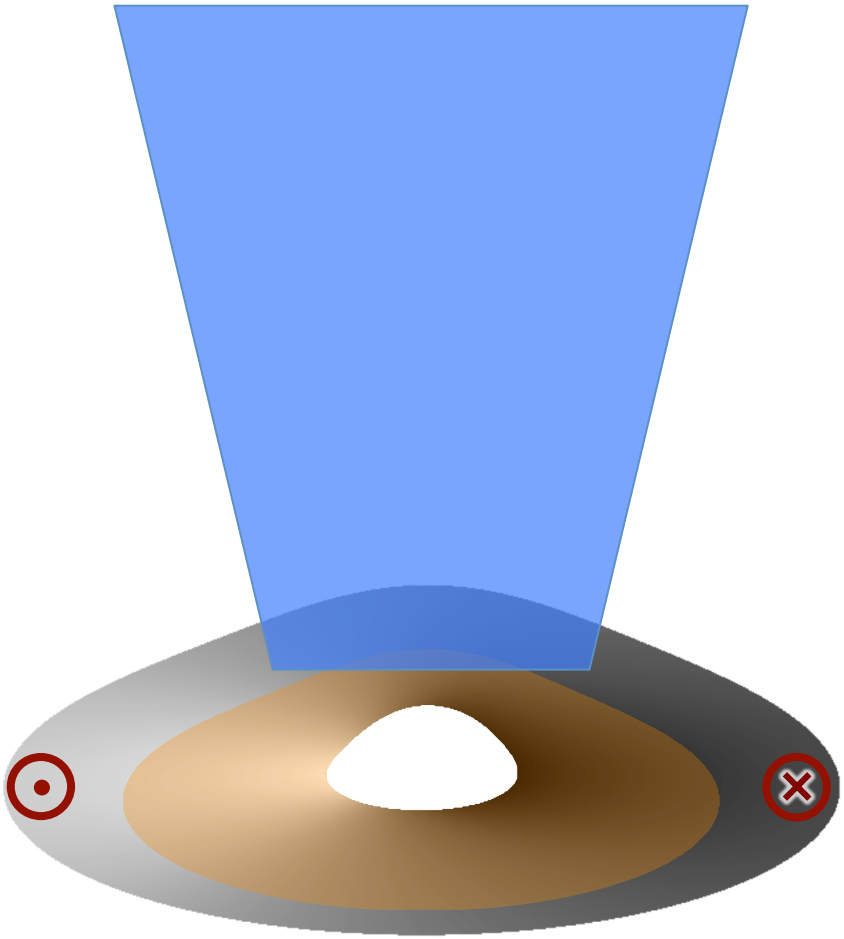

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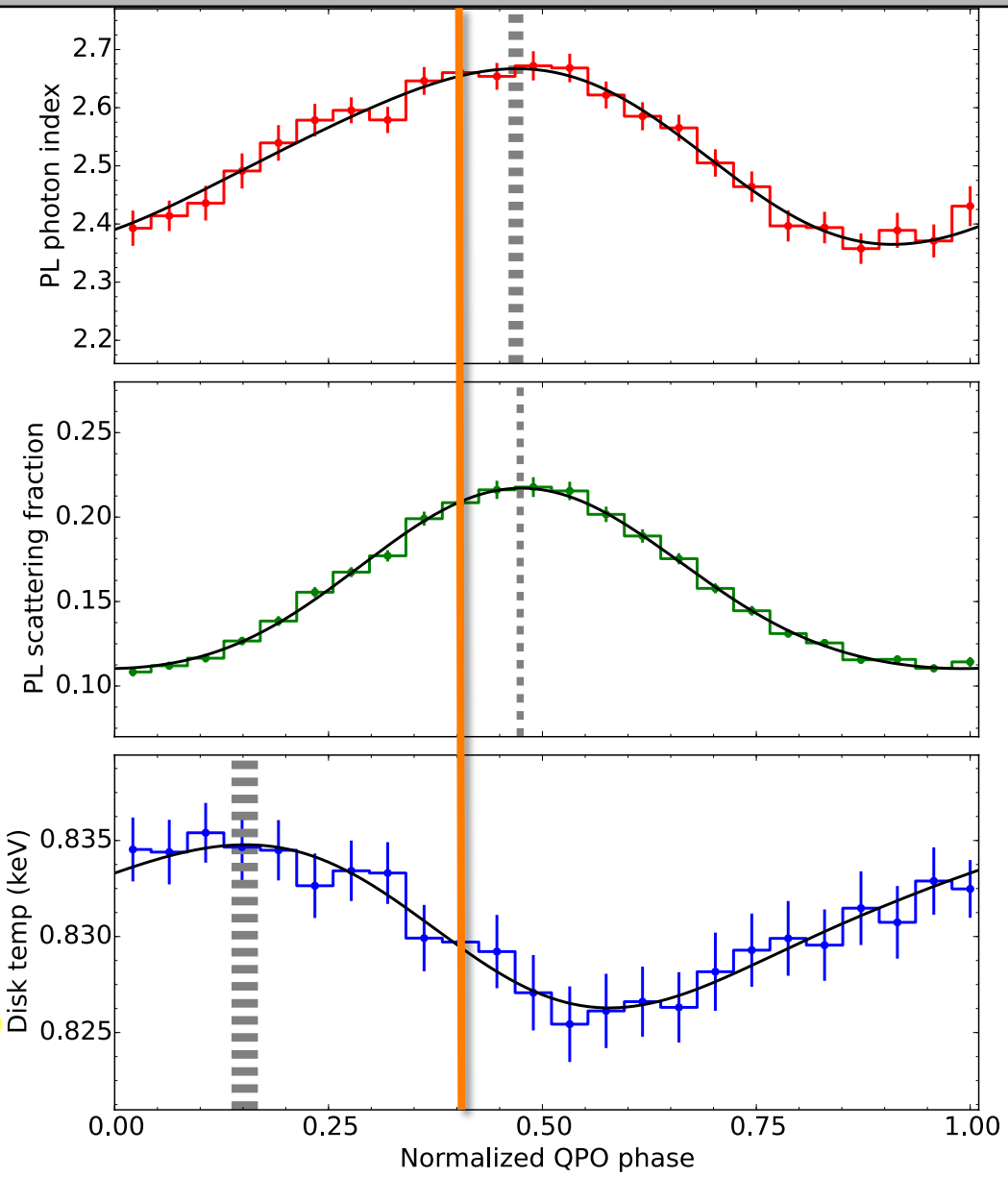

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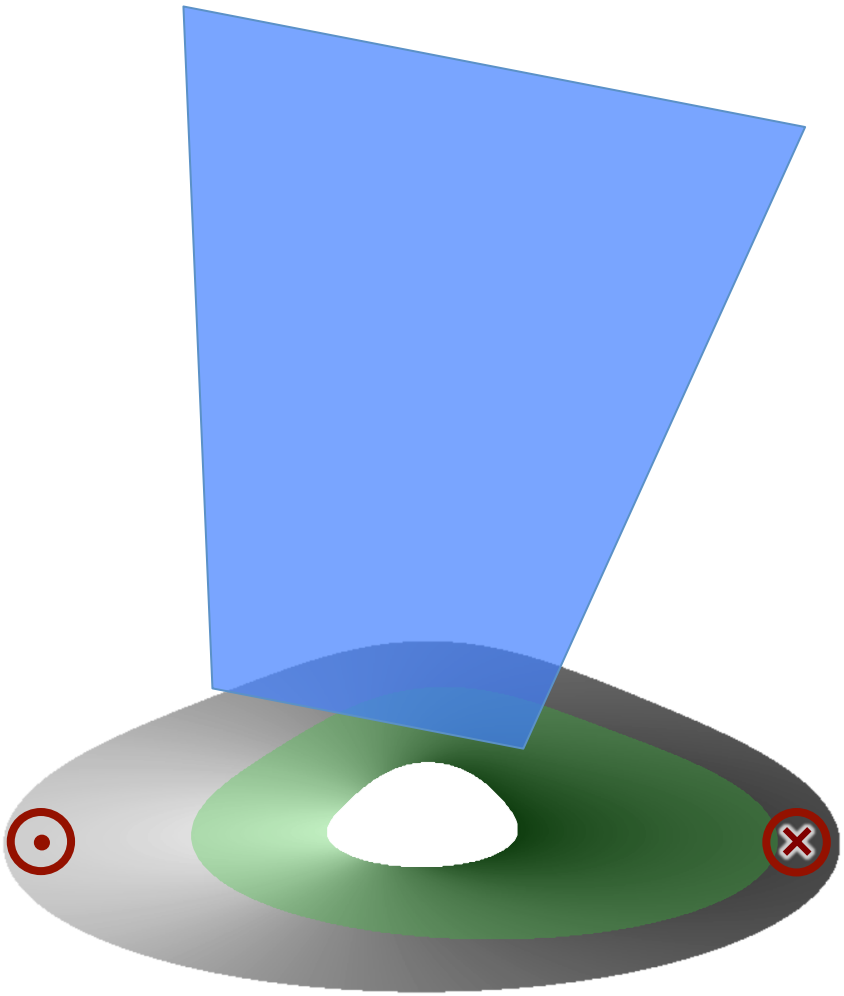

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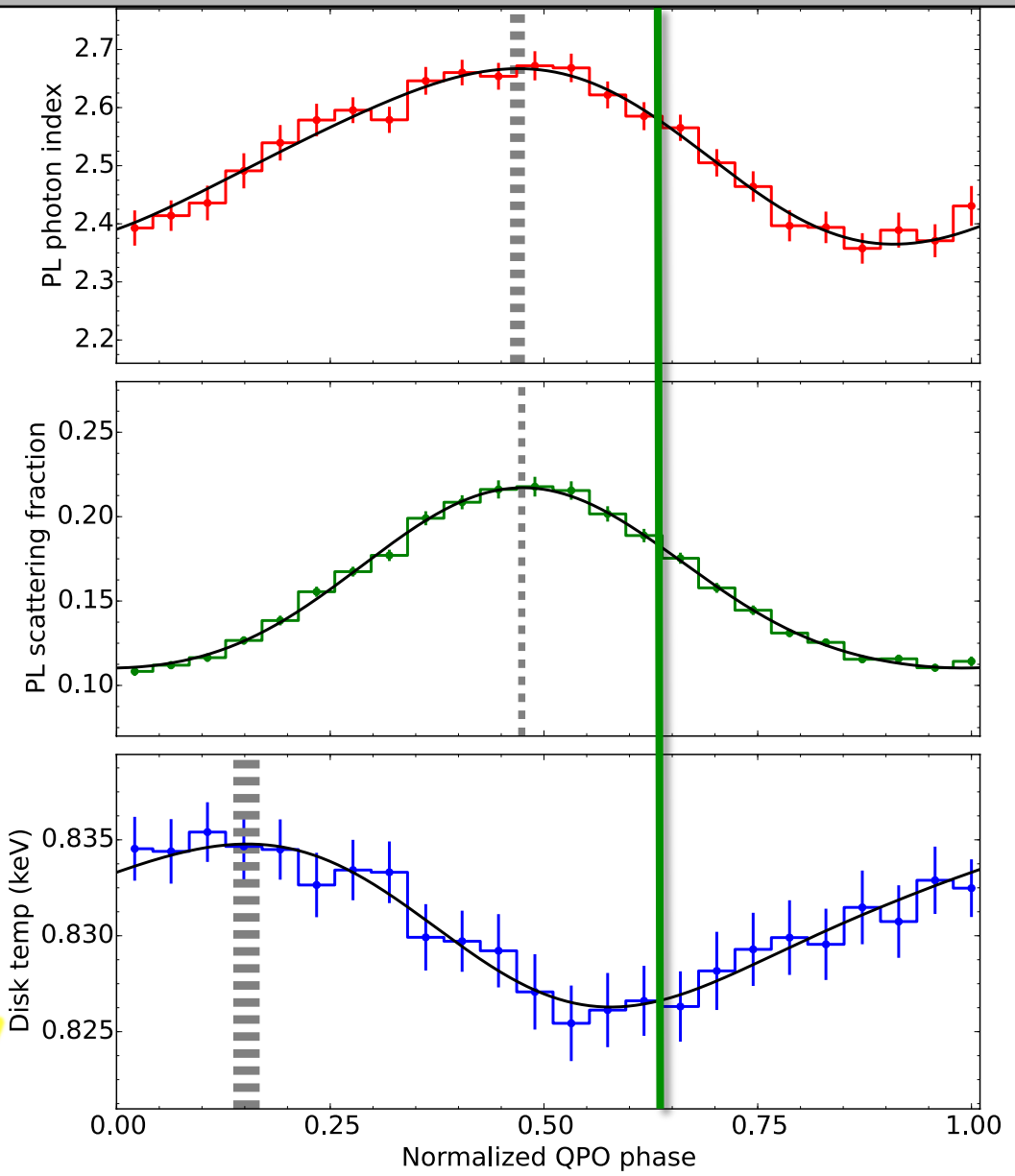

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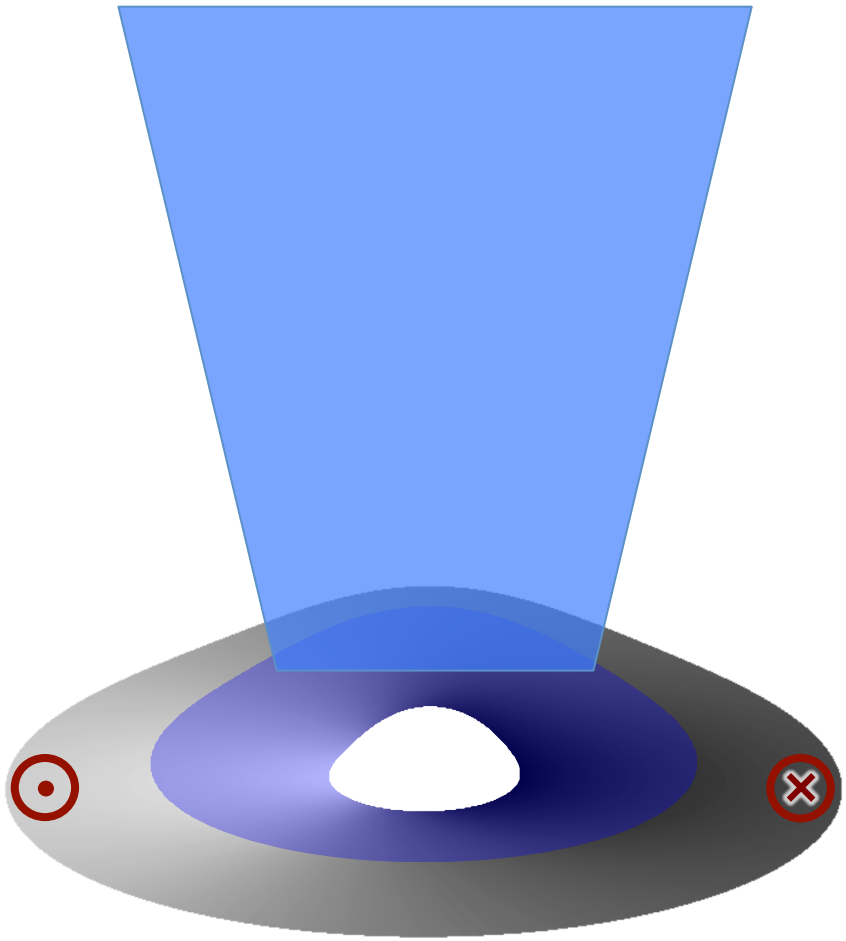

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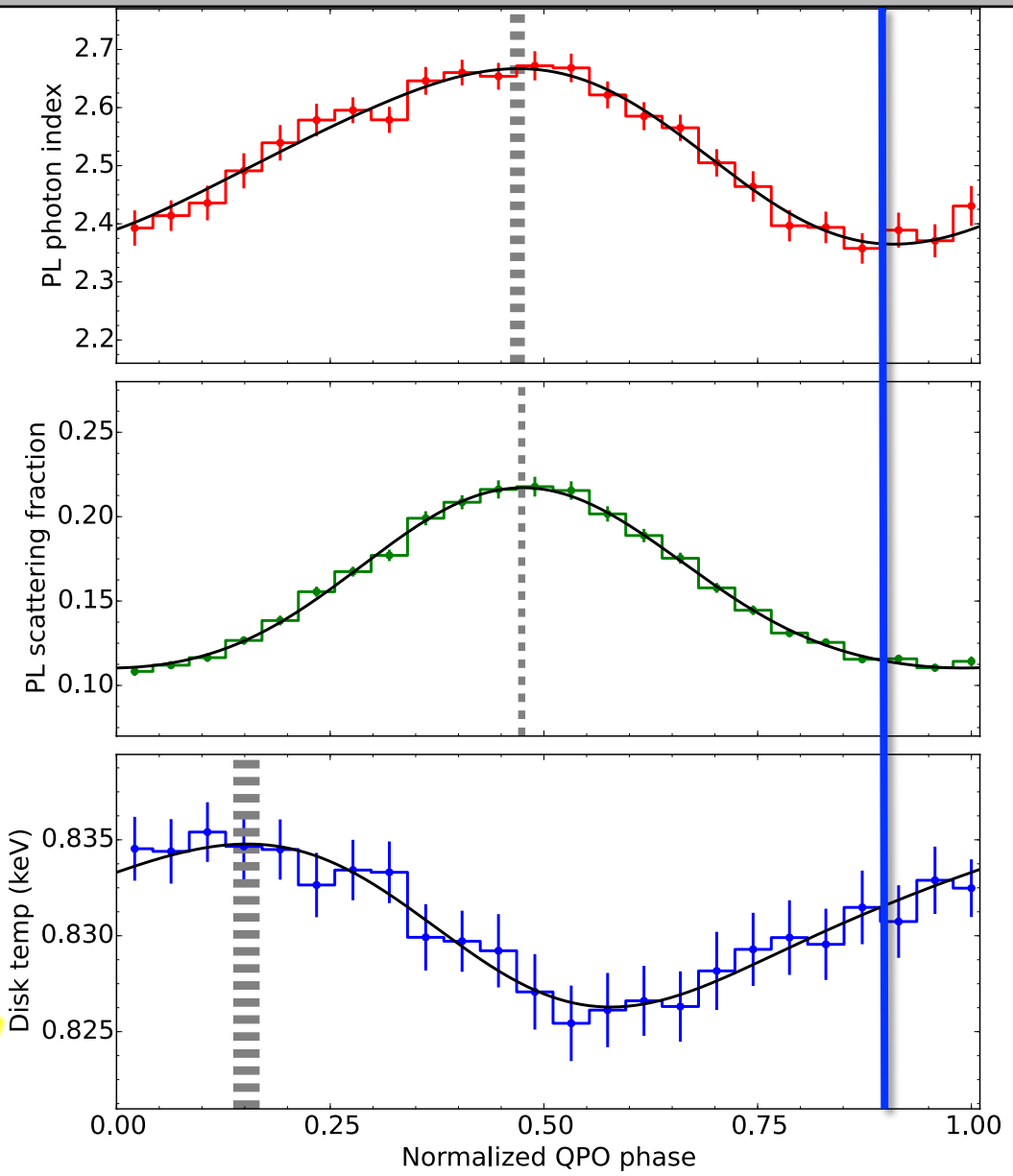

# Ruling out other Type B models

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- Intrinsic PL variations reflected in disk?
  - Phase lag in wrong direction
- Intrinsic disk variations upscattered by PL?
  - Phase lag (60ms) implies massive distance (1000's rg) for light travel time
- Propagating fluctuations from disk to PL?
  - Tiny disk variation couldn't give such a large PL variation

# Type C QPO spectral variations

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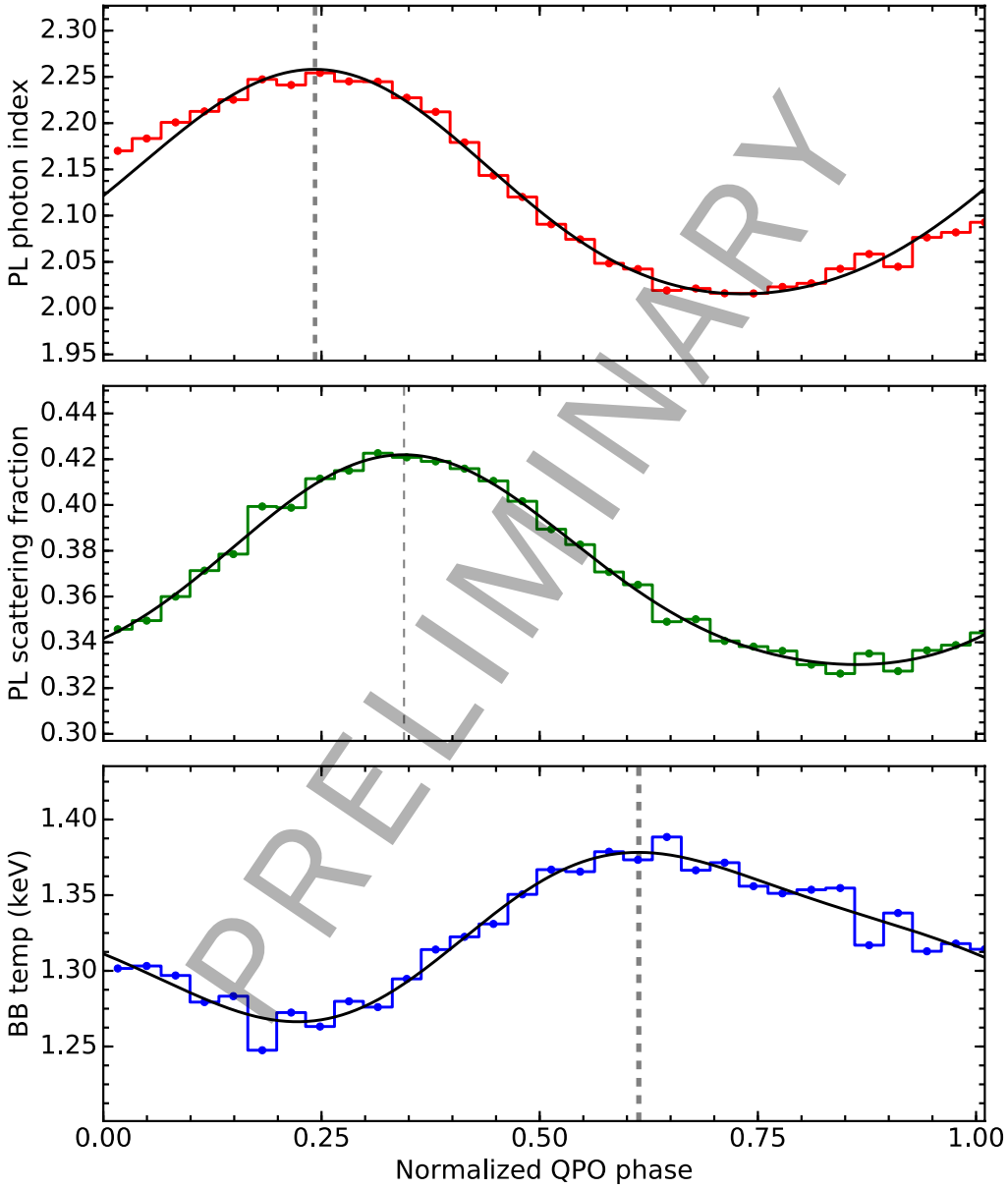
- Different parameter phase relationship
- Power-law: smaller variation (compared to Type B)
- Blackbody: larger variation



# Type C QPO interpretation

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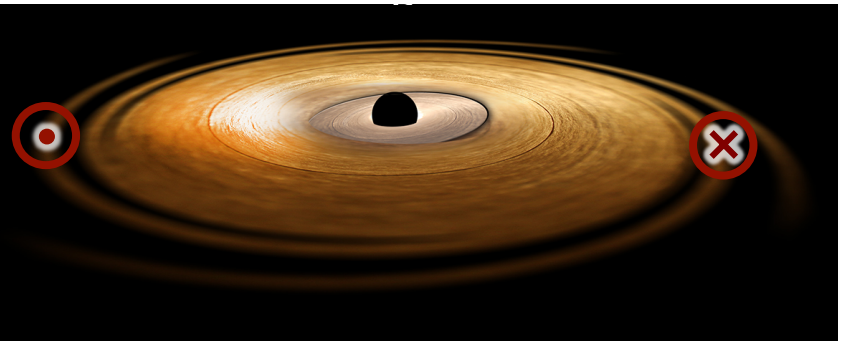
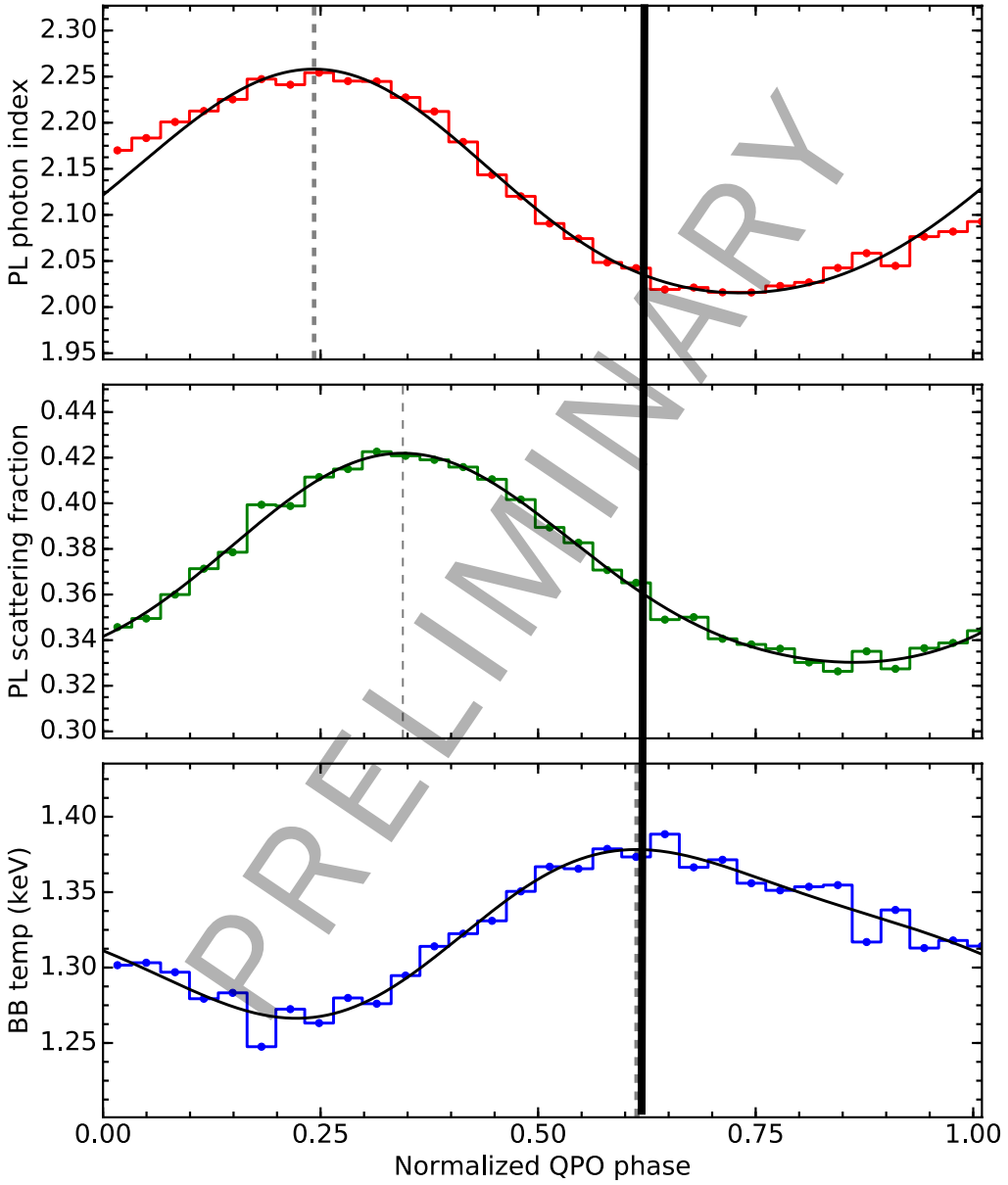


Small scale height, strongly modulated illumination

Image: ESA/NASA/A. Ingram



# Type C QPO interpretation

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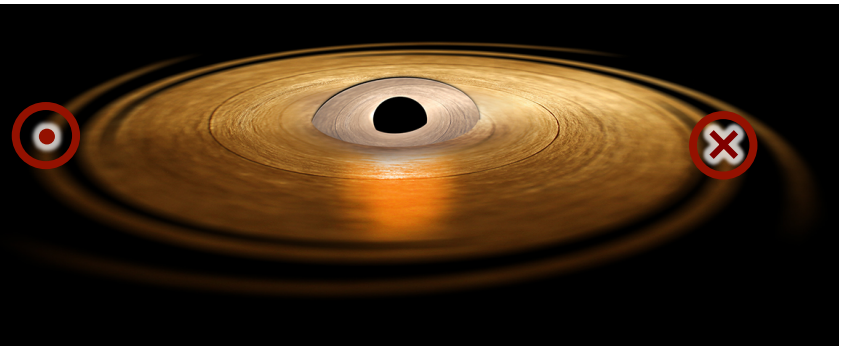

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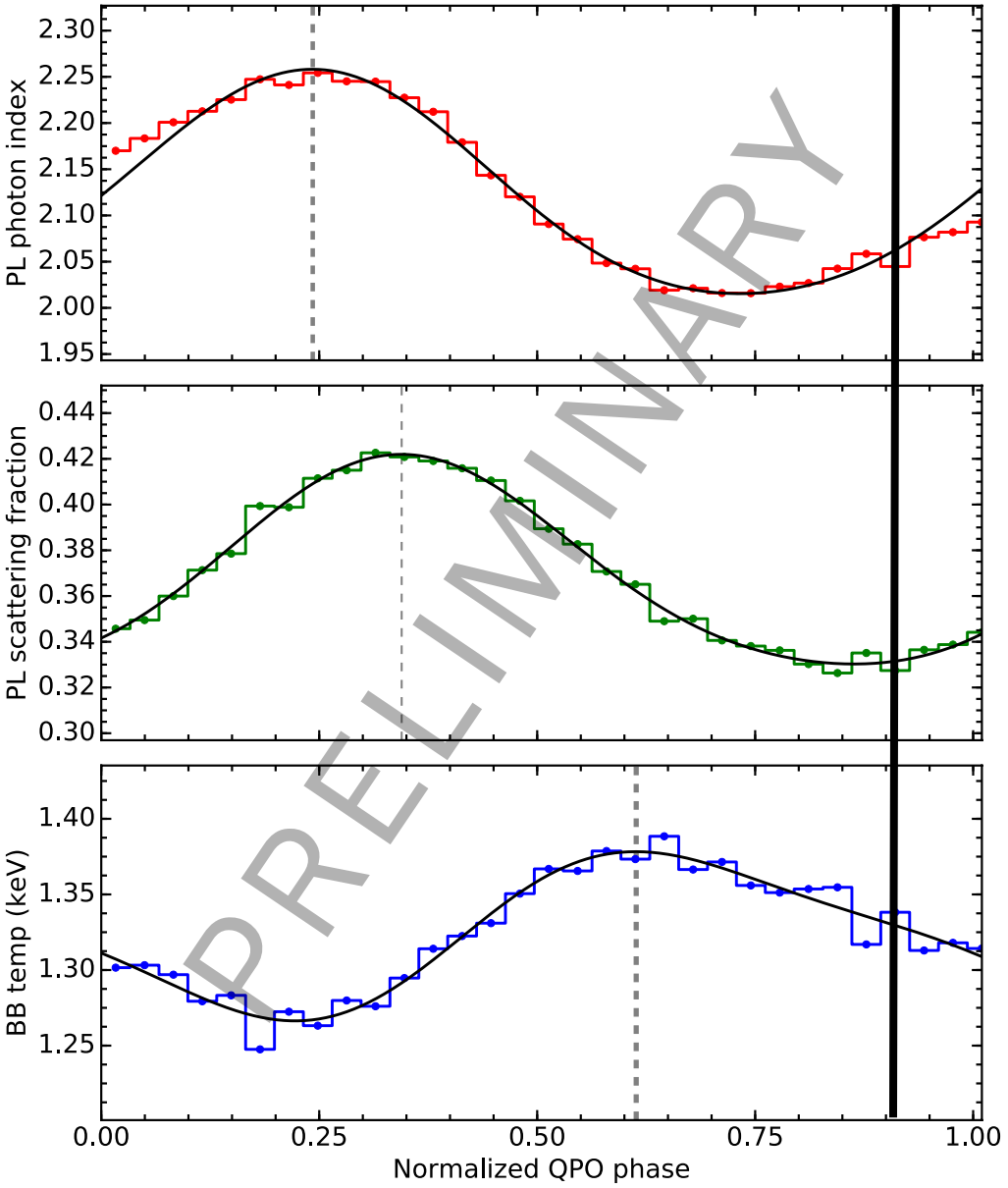

# Type C QPO interpretation

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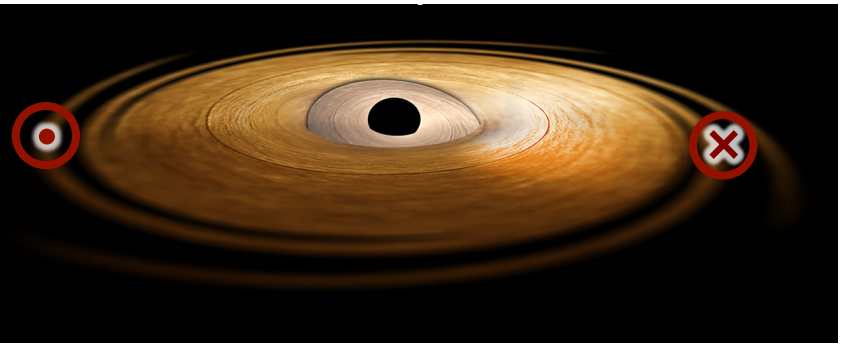

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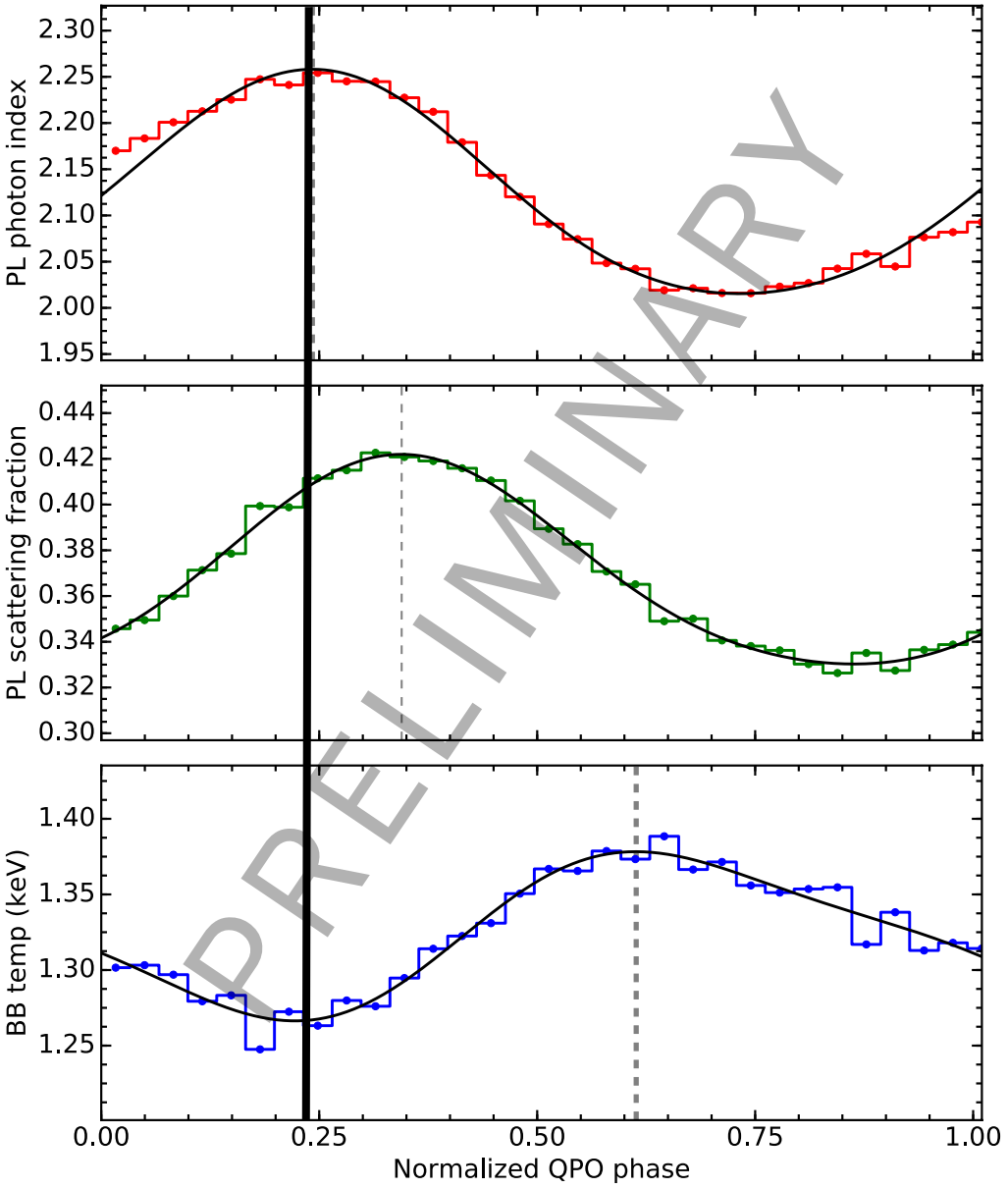

# XMM and NuSTAR: H 1743

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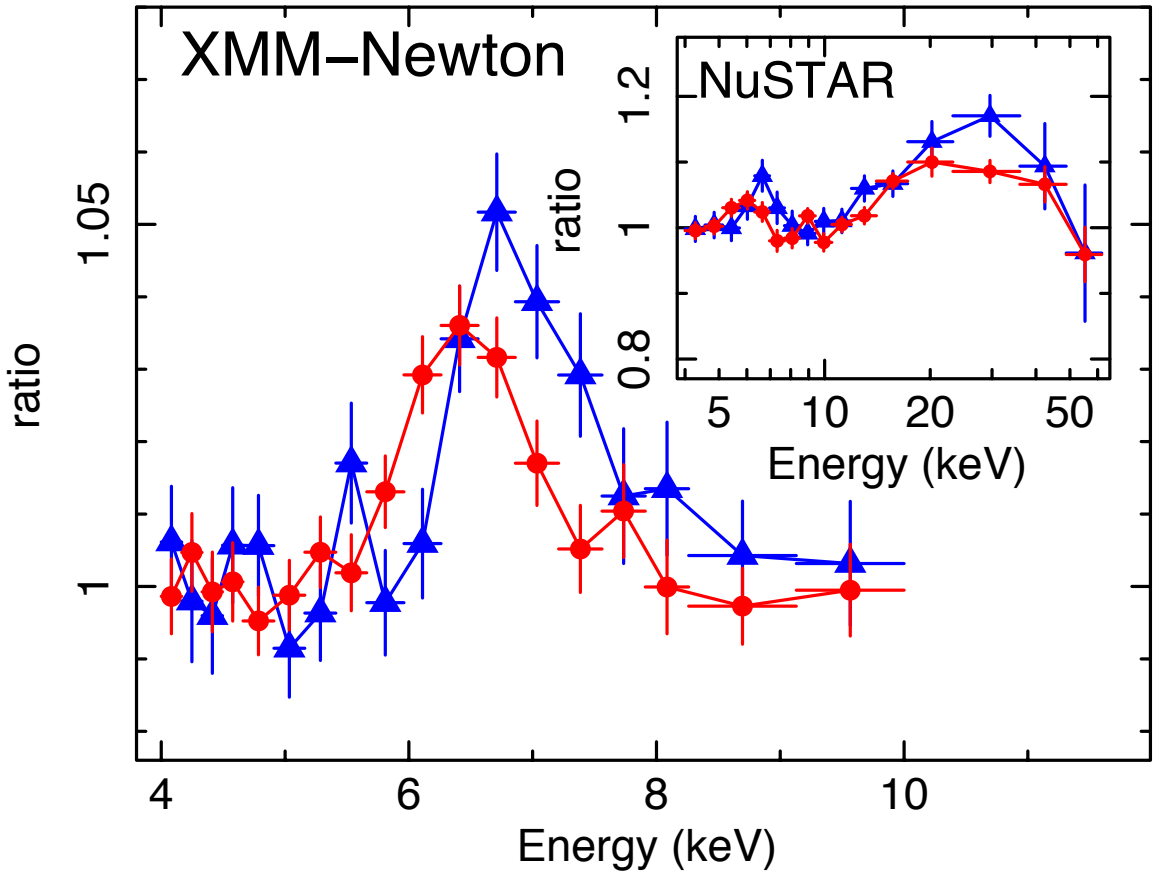
- CCD energy resolution: see iron line wiggling
- Method: Ingram and van der Klis 2015

- Red is phase=0.5, blue is phase=0.75




Ingram et al. 2016a

# Future directions

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- More kinds of variability!
  - Low-frequency QPOs in neutron stars
  - High-frequency QPOs in black holes
  - Kilohertz QPOs in neutron stars
- More data!
  - RXTE archives
  - XMM-Newton, NuSTAR
  - AstroSat
  - NICER (launch ~April 2017)
  - eXTP (by 2025)

# Summary

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- X-ray binaries are one of the best tools to study matter in strong gravitational fields
- Phase-resolved spectroscopy of QPOs can help break degeneracies between physical models
- Type B QPO in GX 339—4:
  - Jet-like precessing region
  - arXiv: 1605.01753
- Type C QPO in GX 339—4:
  - Disk-like precessing region
  - Paper in prep.

GitHub: abigailStev
Email: A.L.Stevens@uva.nl
Twitter: @abigailStev


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# Astrosat

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- Launched in Sept 2015
- 3 Large area photon counters
  - Timing down to ~10 μs
  - Energy range: 3—80 keV
  - Larger effective area than RXTE above 15 keV
- Soft X-ray telescope
  - X-ray CCD detector
  - Energy range: 0.3—8 keV

# NICER

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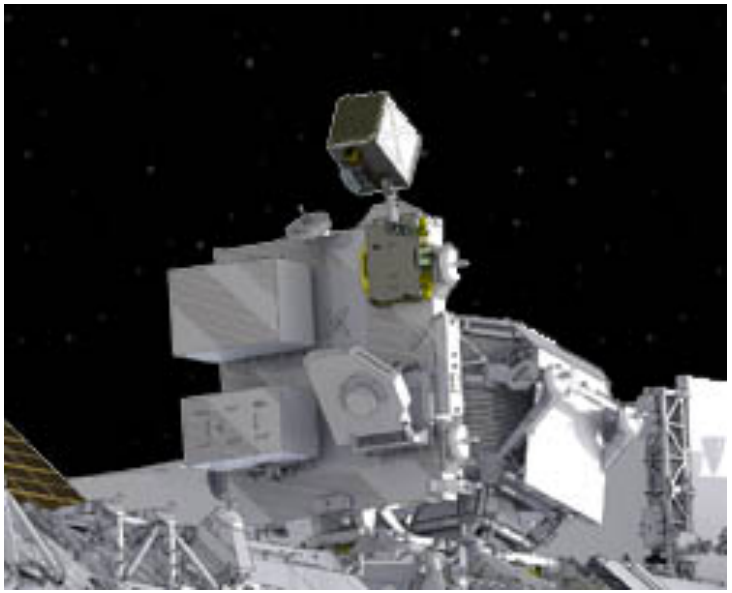
- Neutron star Interior Composition ExploreR
- Launch: ~April 2017
- All-in-one: better timing than RXTE, energy resolution of XMM!
- Attached to space station



NASA

- Timing down to 85 ns
- Energy range: 0.2—12 keV