GRS 1915+105:
An X-ray Spectroscopic Study of Outflows

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Collaborators: Julia C. Lee, Ron Remillard

12 Years of Science with *Chandra*
May 24, 2011

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Big Questions

- What do *Chandra* HETGS observations of GRS 1915+105 tell us about accretion onto compact objects?
- What are the links between accretion, ejection, and radiation processes in X-ray binaries?
- Why and how are outflows, especially disk winds, important?

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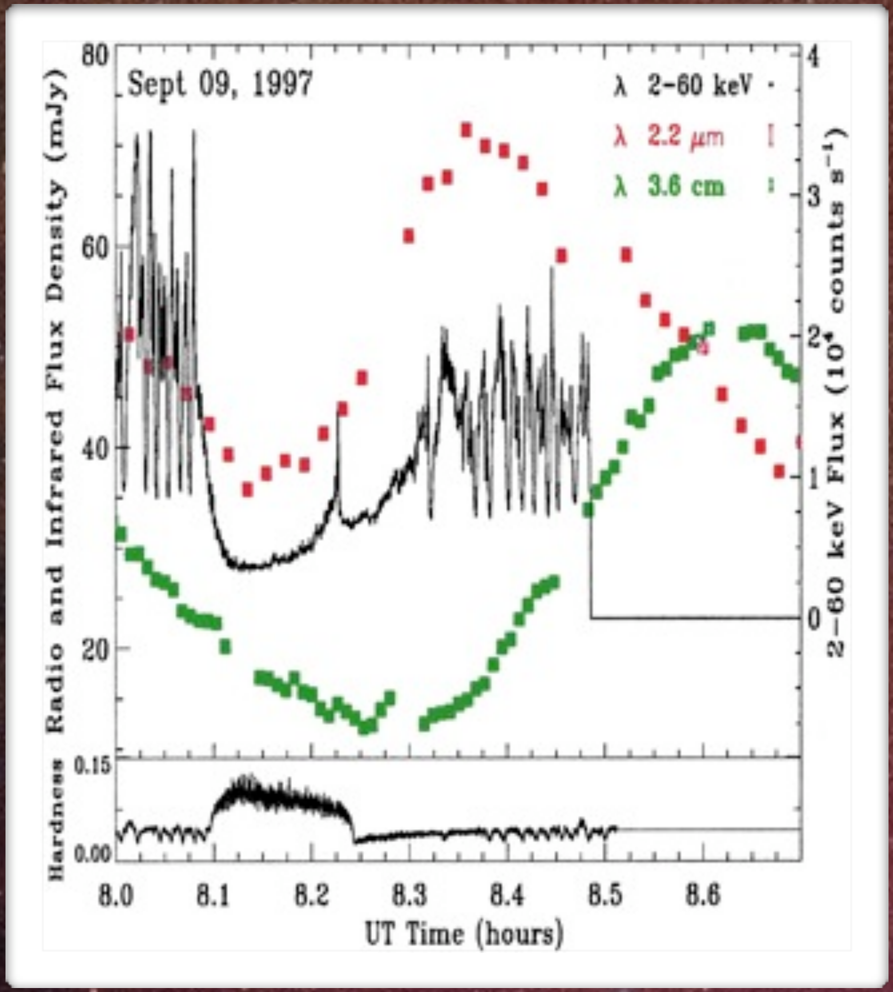
Why GRS 1915+105?

- GRS 1915+105 exhibits strong *spectral* variability: rapidly-changing accretion, ejection, and radiation processes
- Time scales: seconds to decades!



Goal:

- Understand the accretion processes driving this variability. How do these processes drive outflows, link the black hole and its surroundings?
- Need insights into atomic physics: *Chandra* HETGS!

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Chandra Observations

Goal: Study the disk-jet connection at high spectral resolution with the *Chandra* High Energy Transmission Gratings (HETGS)

- 11 public HETGS observations over 10 years
- Use spectral lines to study the long-term influence of accretion processes on the black hole's environment
- Simultaneous *RXTE*
- Measure L_X (3-18 keV)
- PLF = (8.6-18) / (3 - 18)
- PLF = Power Law Fraction: broadband spectrum, physical processes

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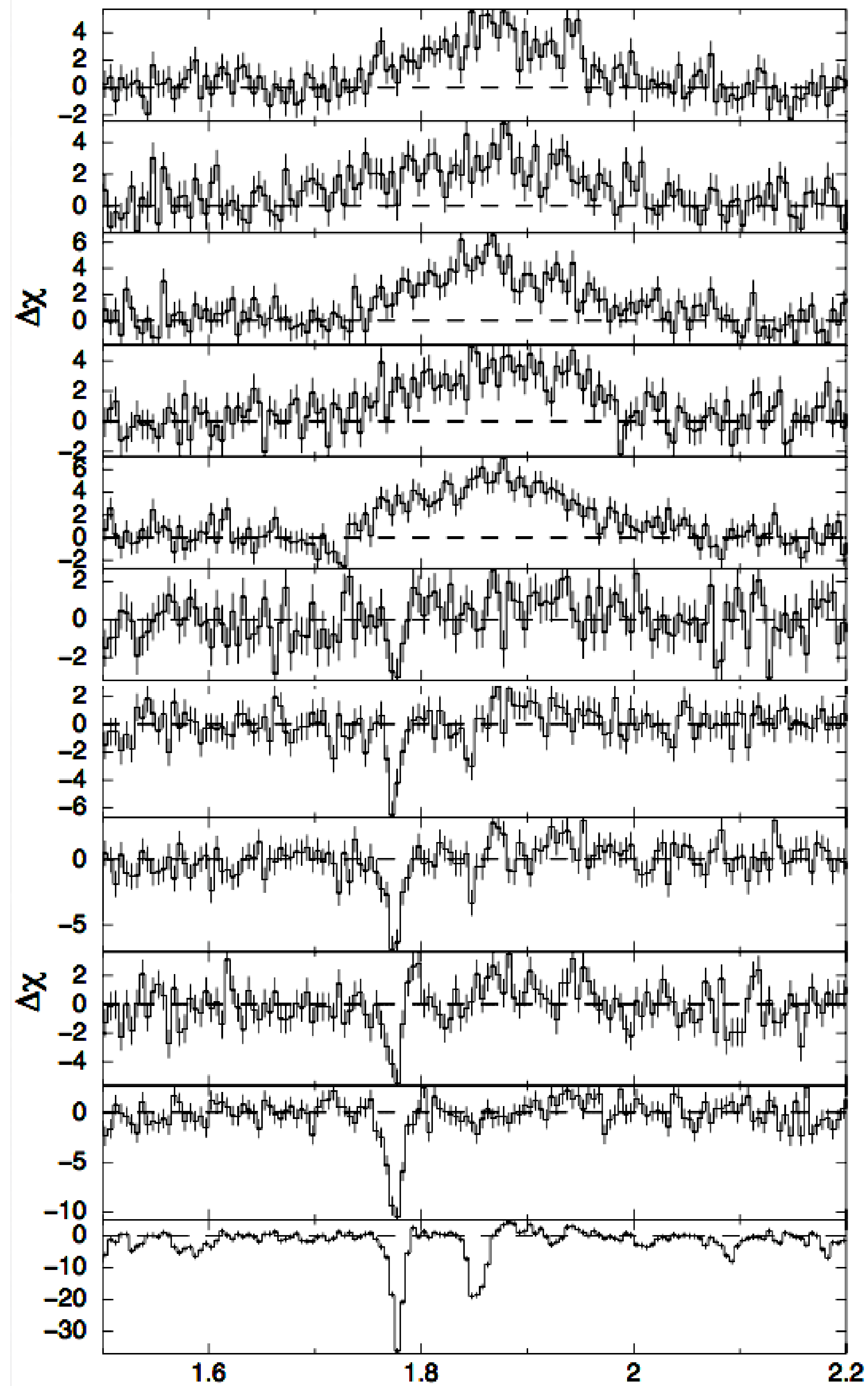
Spectral Lines and Hard Flux

- Iron line spectra on right
- Sometimes broad emission lines, narrow absorption lines
- ***<u>Interpretation</u>***:
- Iron Emission line: accretion disk illuminated by base of the radio jet
- Iron Absorption lines: Fe XXVI, hot (10^6 K) accretion disk wind (1000 km/s blueshift)
- As power law fraction decreases (downwards), we start to see absorption lines instead of emission!
- Links between winds, jets, and broadband spectrum (Comptonization, photoionization)



Neilsen & Lee 2009

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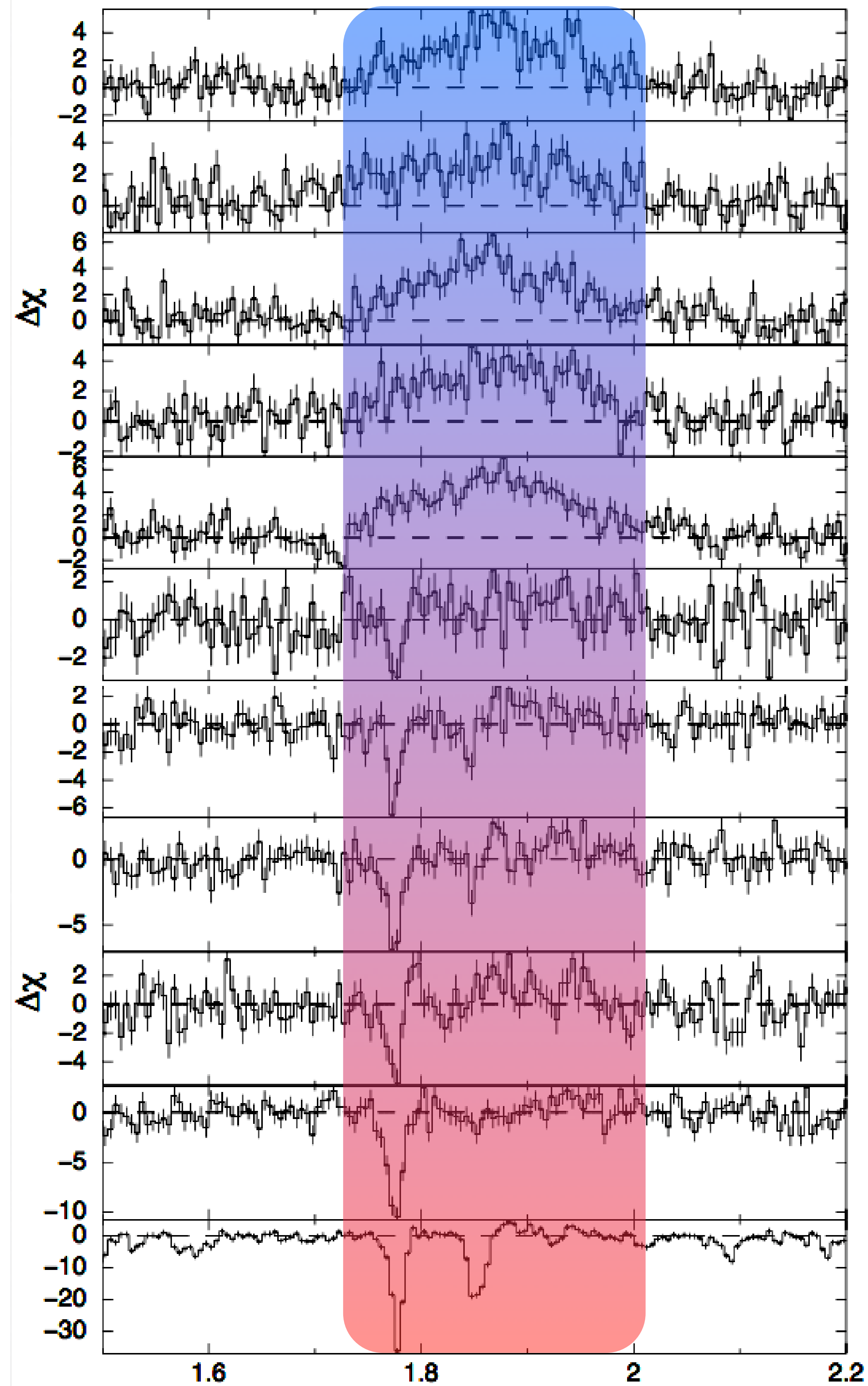
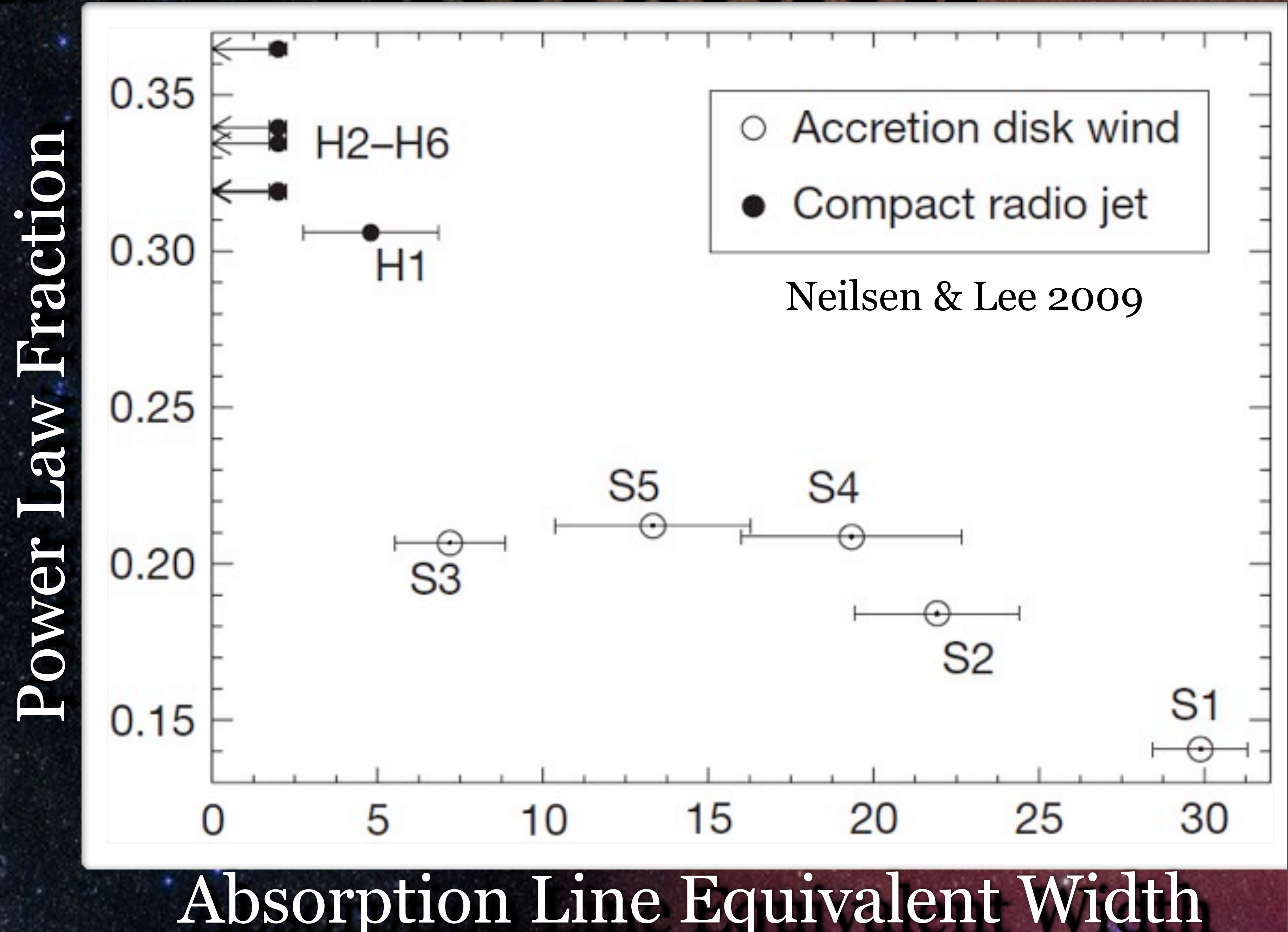


Neilsen & Lee 2009 Wavelength (Å)

Wind-Jet Interaction



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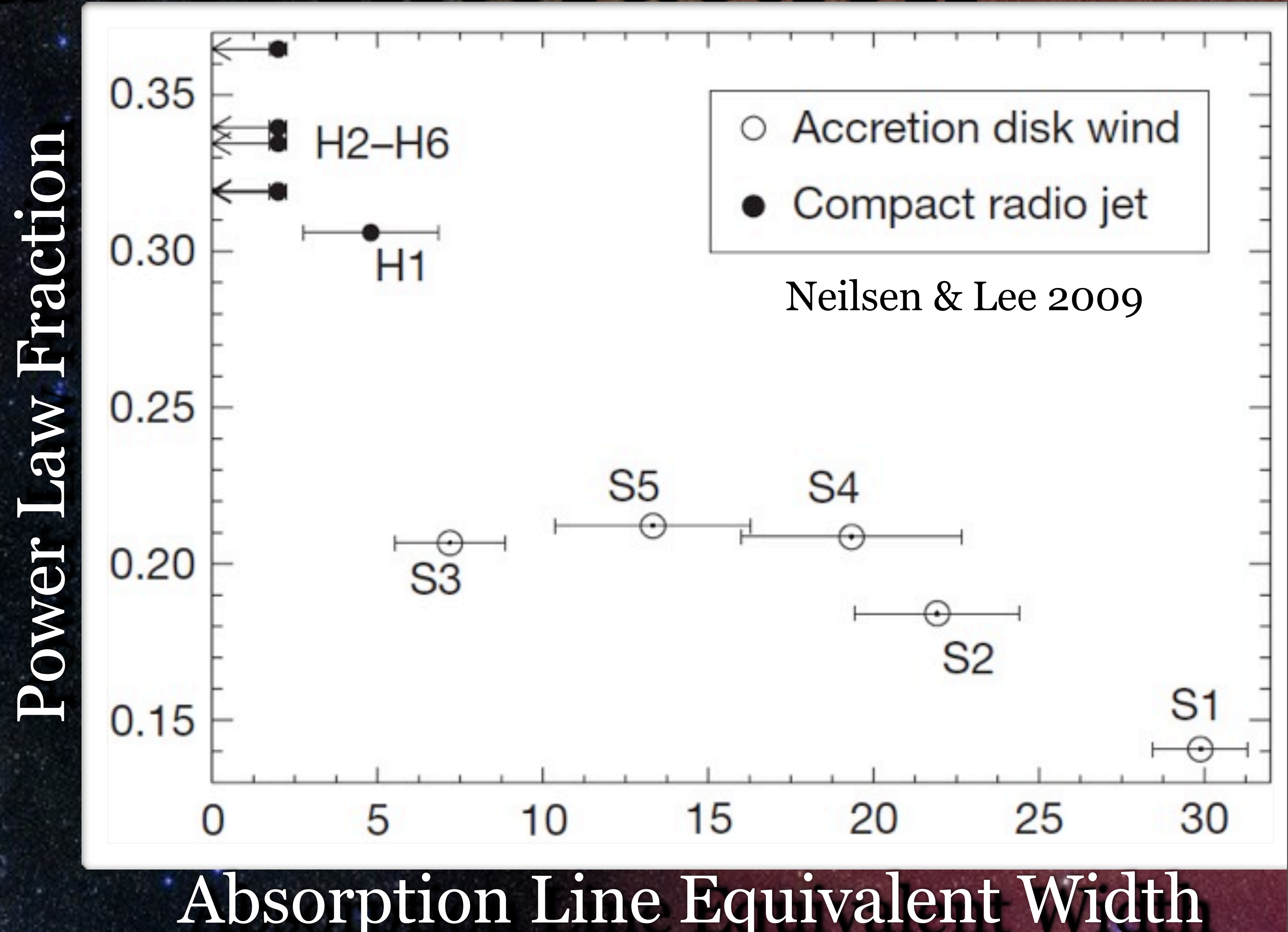
Wind-Jet Interaction

- Jets linked to hard flux
- Disk wind measured in absorption



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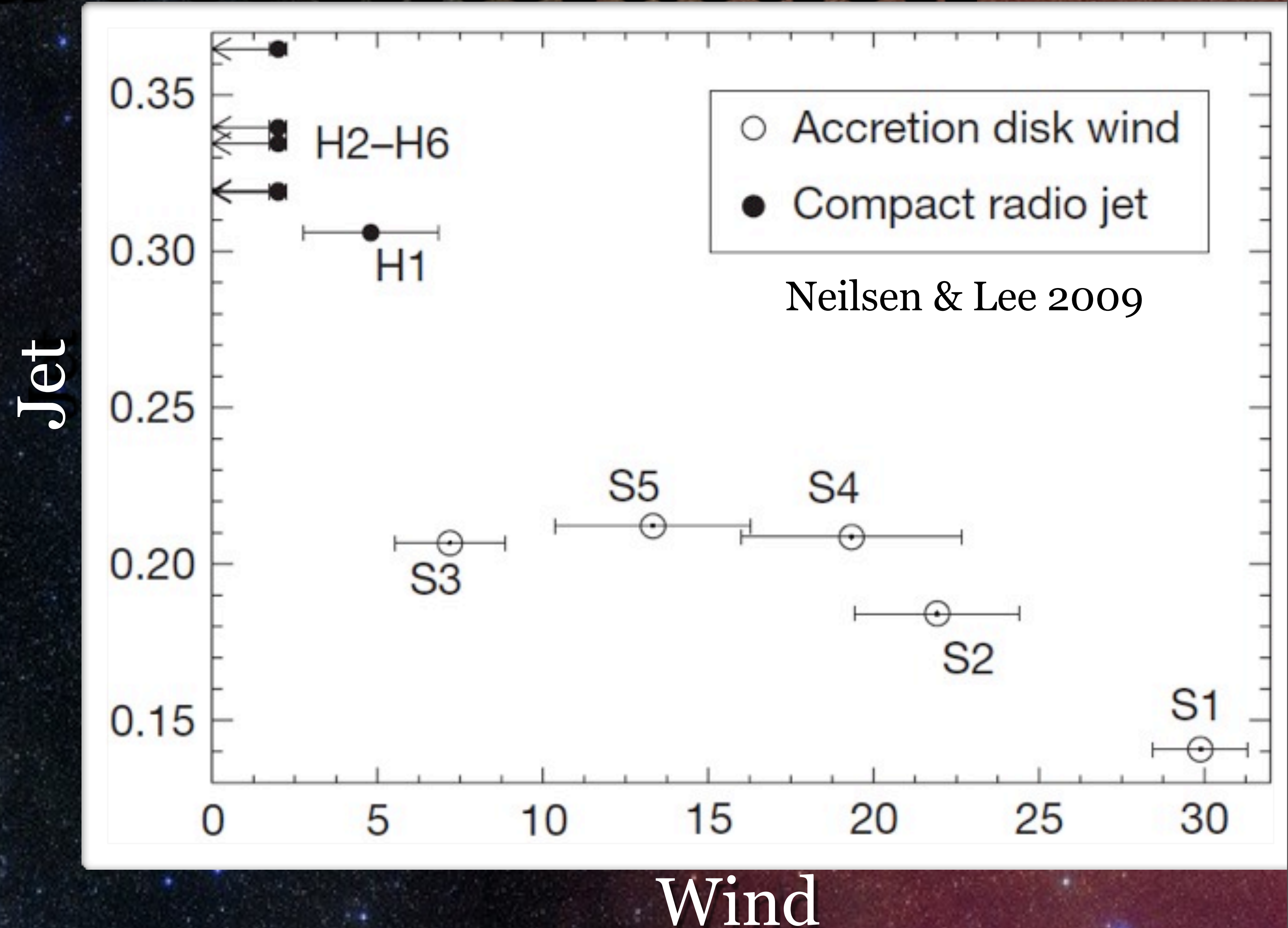

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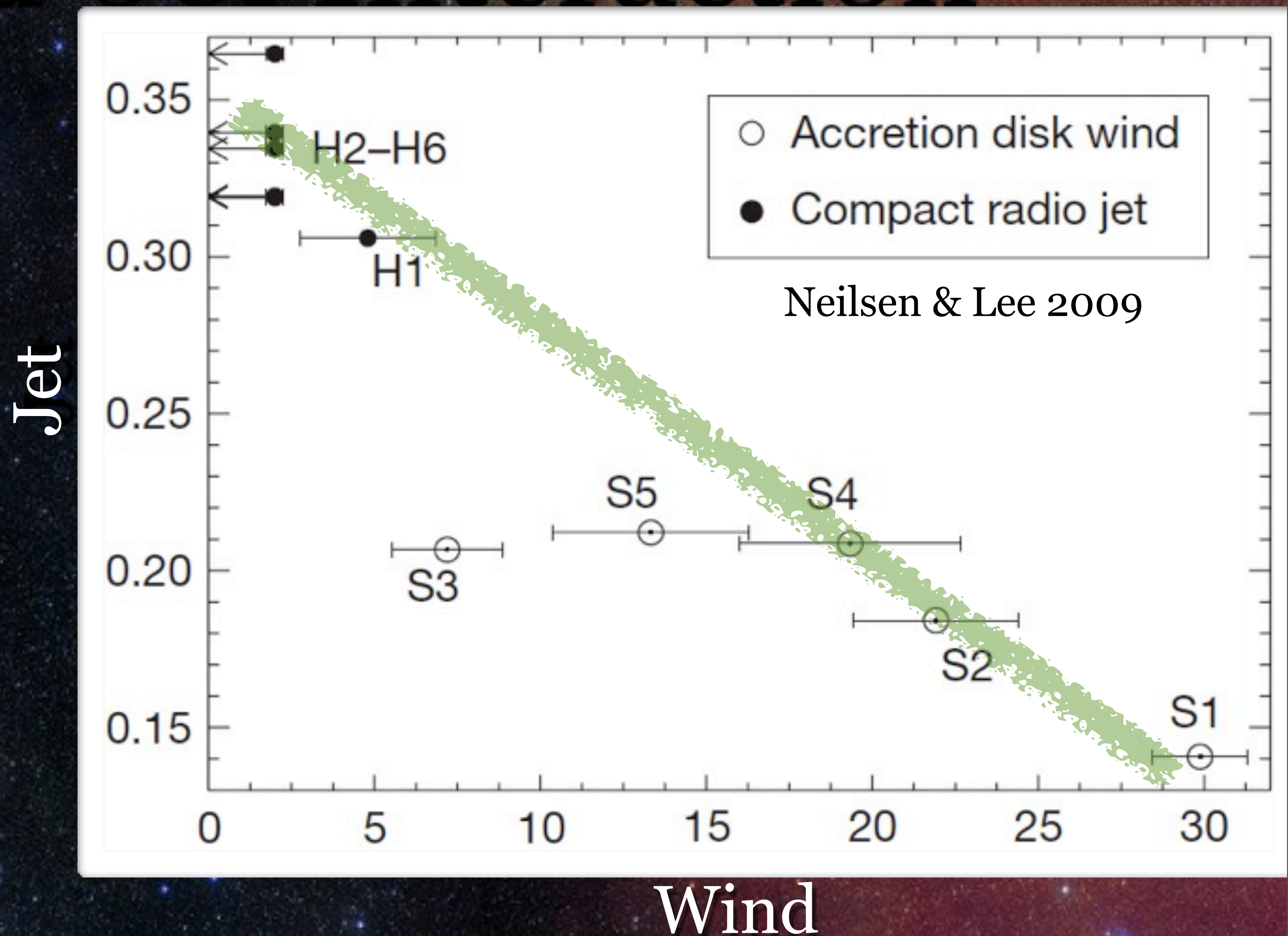

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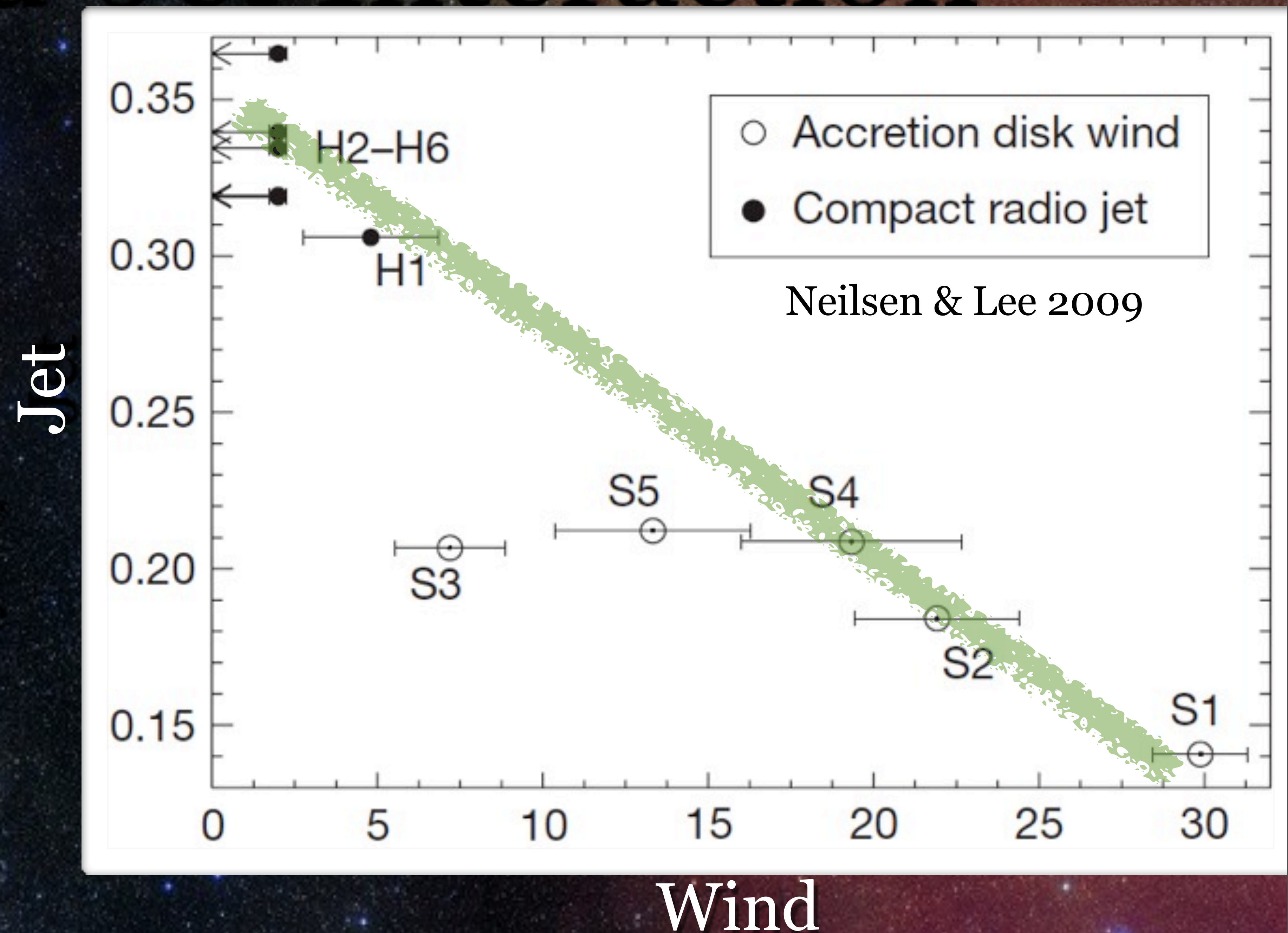

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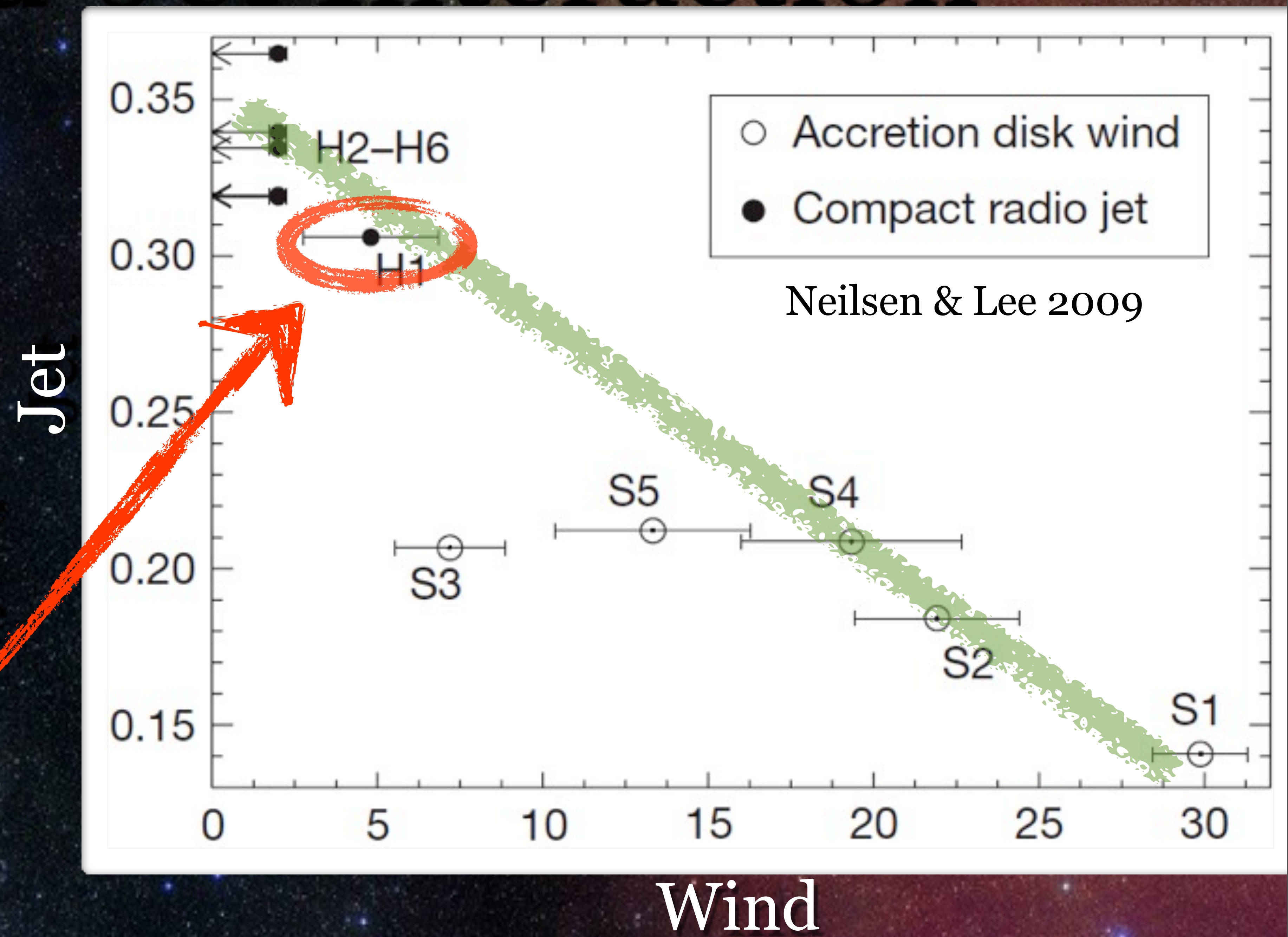

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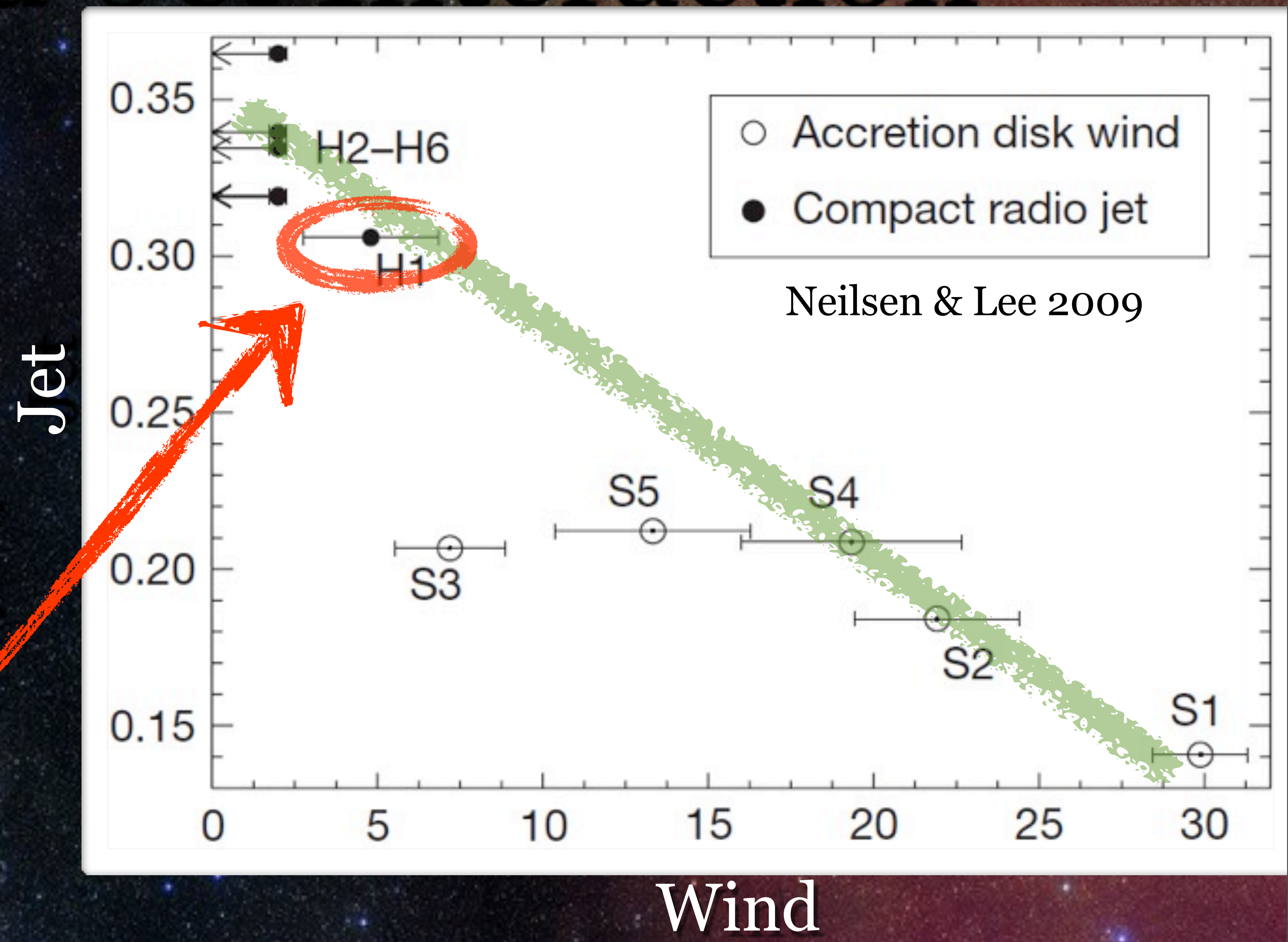

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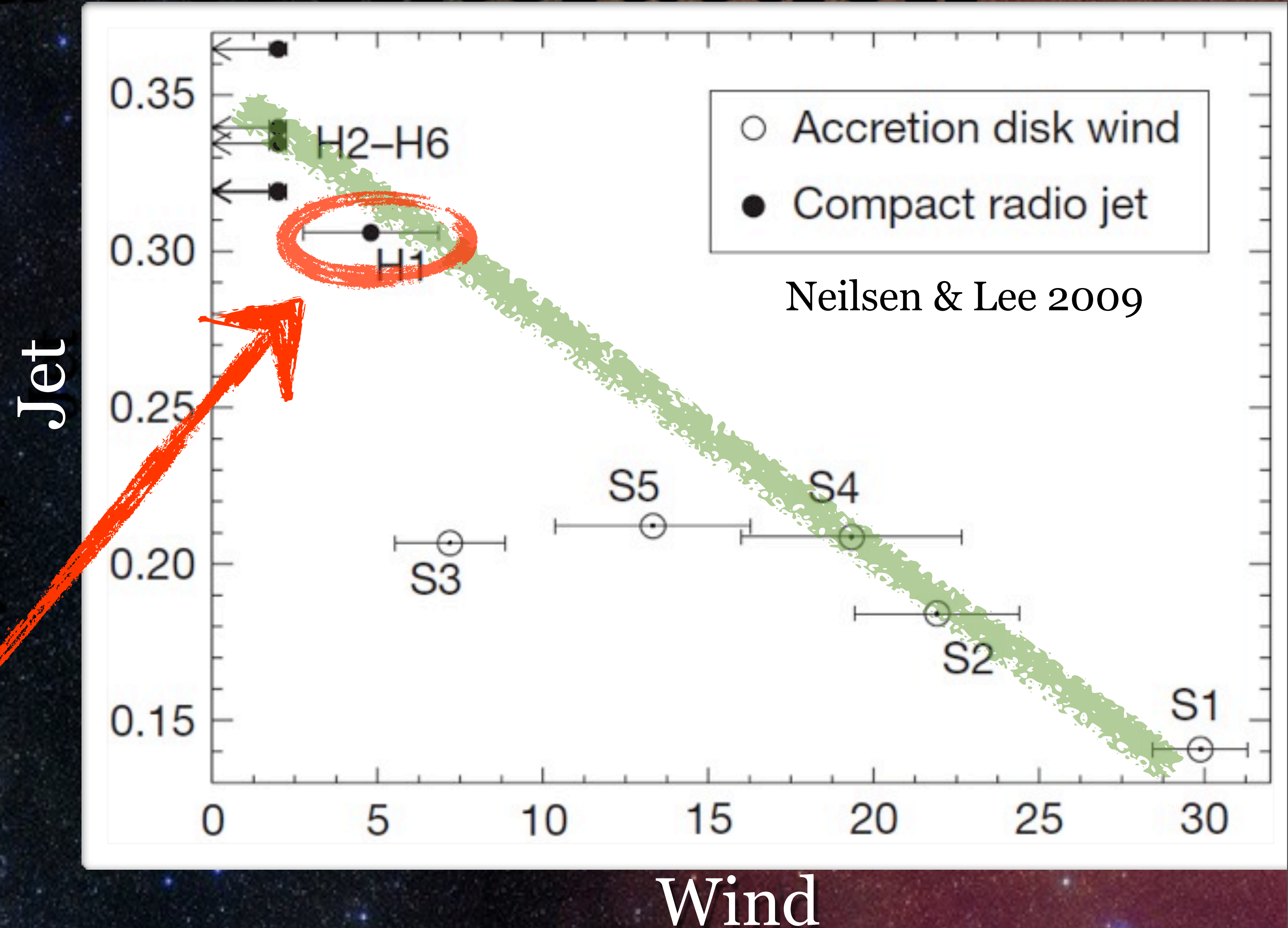

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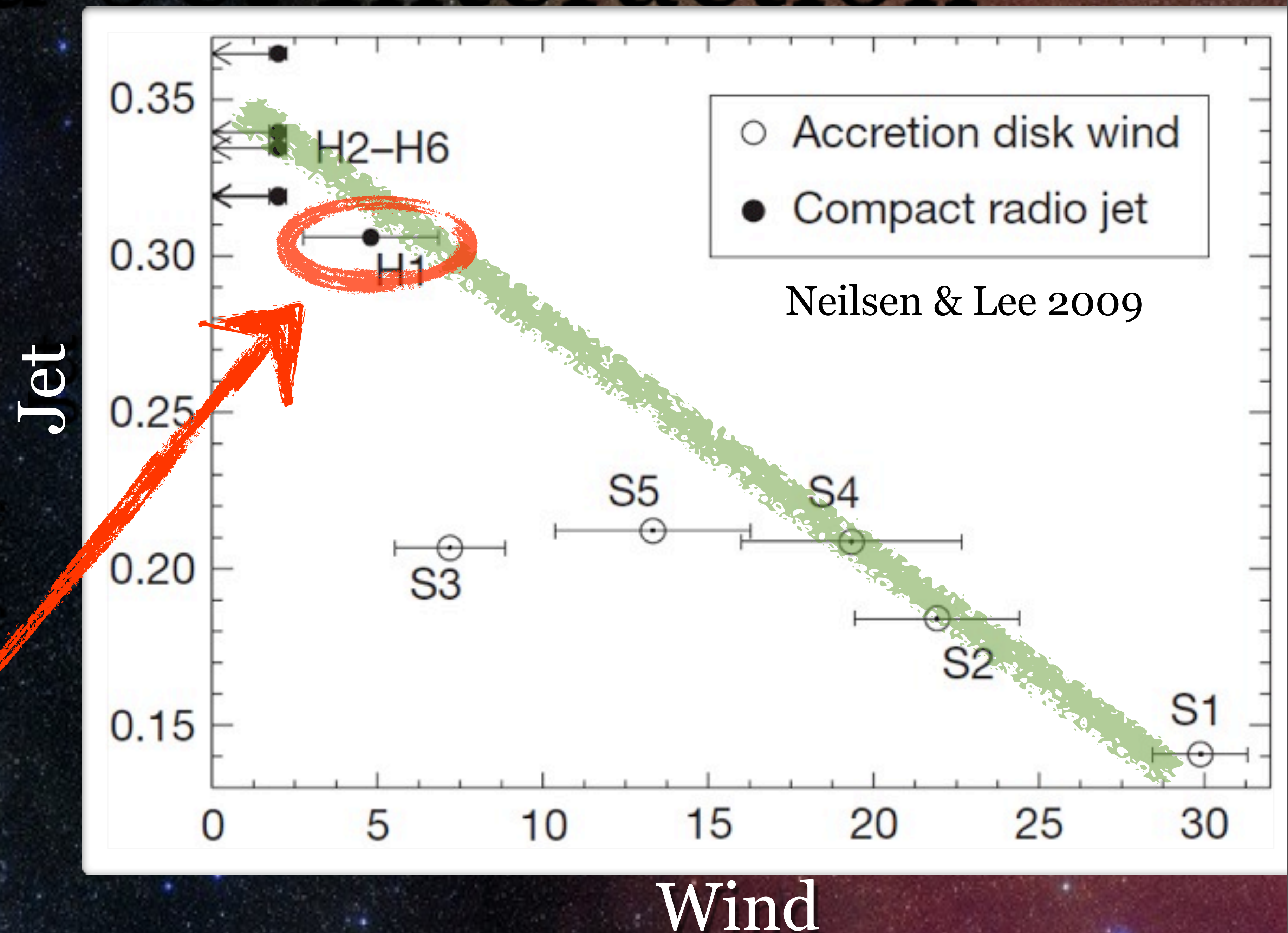

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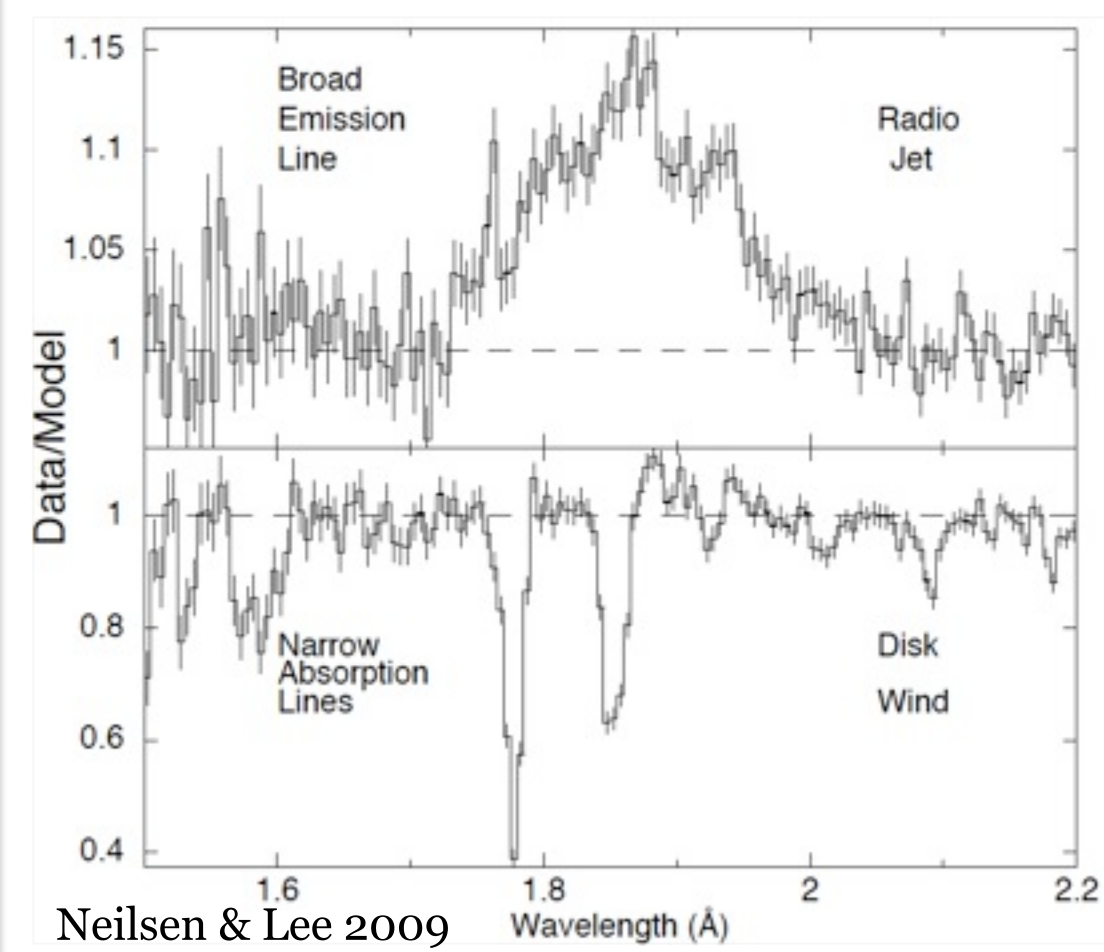
- Interaction between wind and jet mediated by hard X-rays, continuum processes (Lee 02, Miller 04, 06, 08)

Wind-Jet Interaction

- Outflow regulation around this stellar-mass BH over long timescales ($10^{11}\ t_{dyn}$)



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Credit: NASA/CXC/A. Hobart

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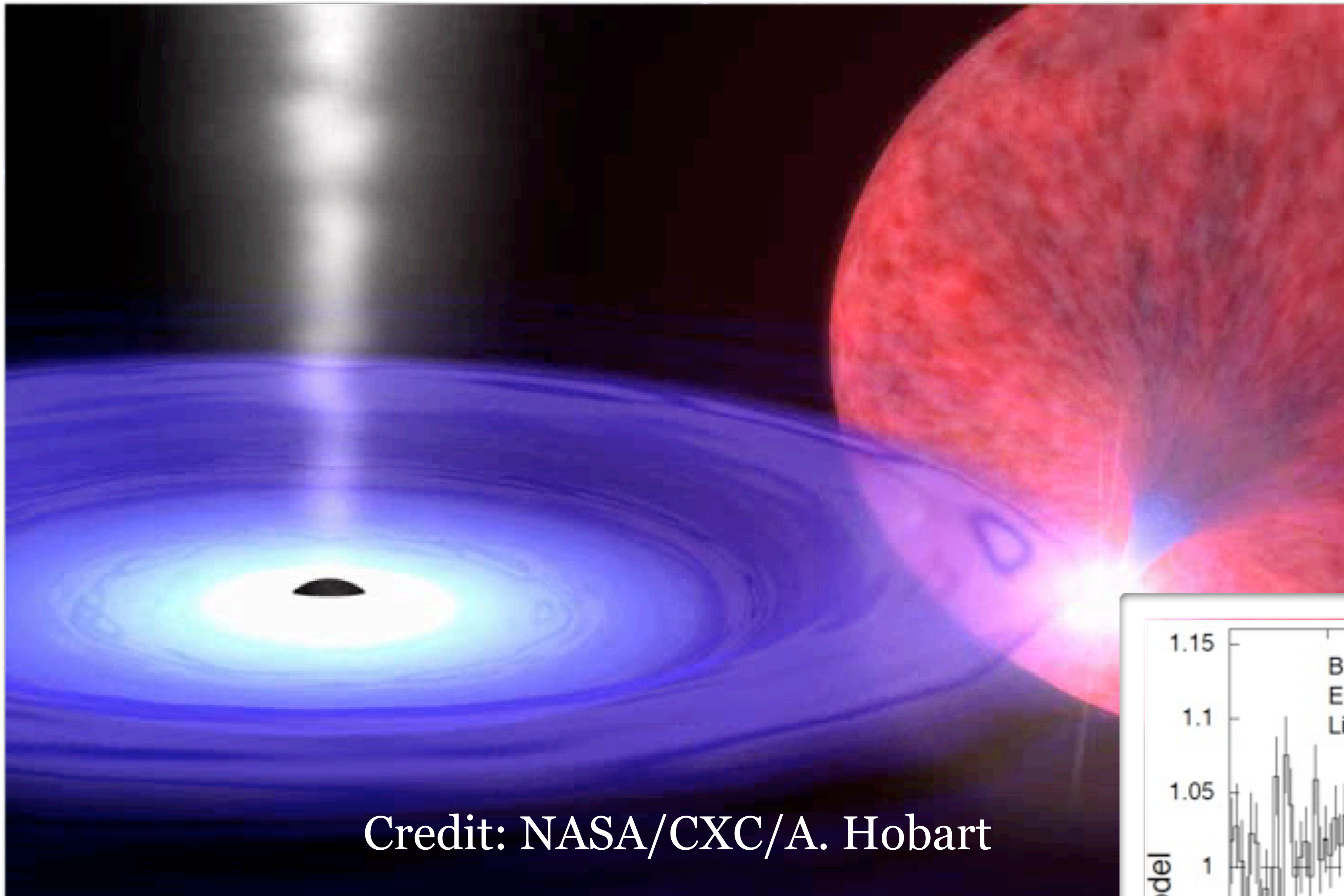

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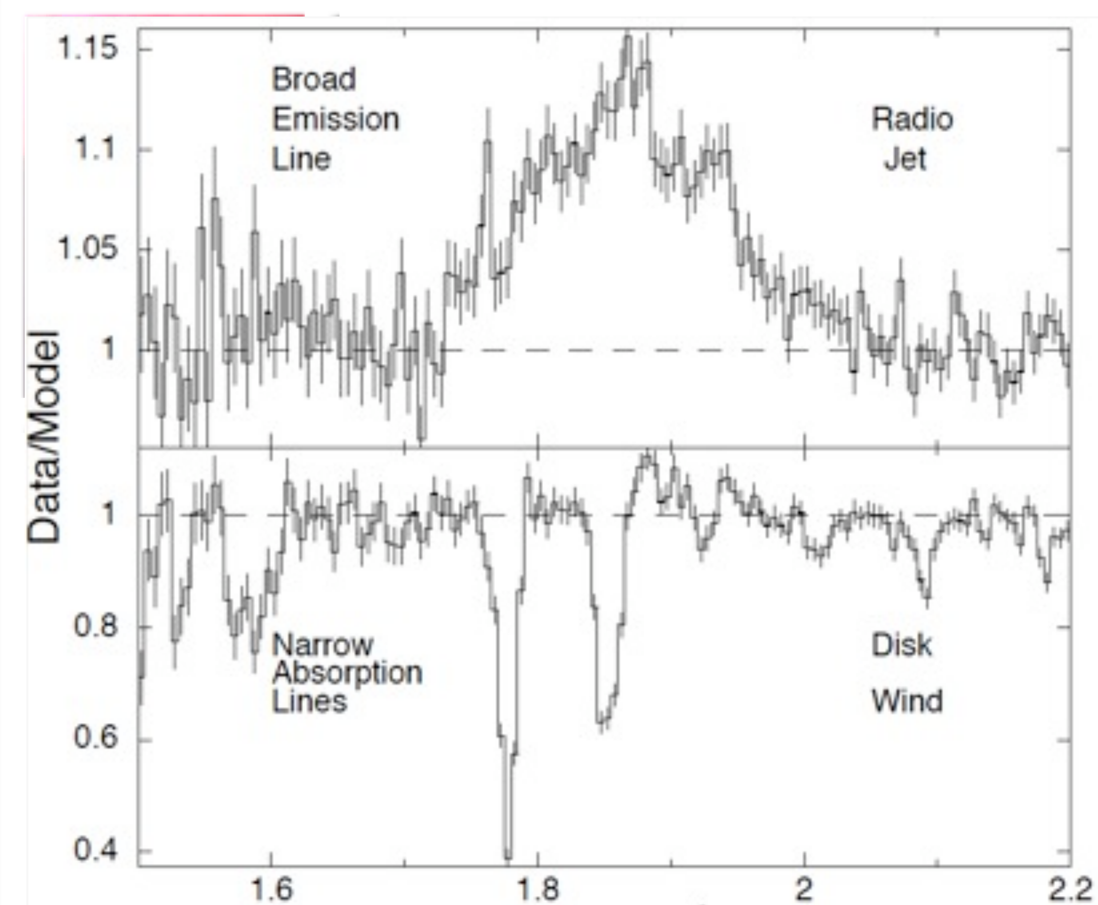

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- By studying the average properties of outflows with 10 years of data:
  - Winds are a ***dynamically-important*** part of the accretion flow: can suppress jets by draining their matter supply!
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  - On what time scales can winds and jets respond to continuum, interact?
  - Need to track accretion, ejection processes on short time scales

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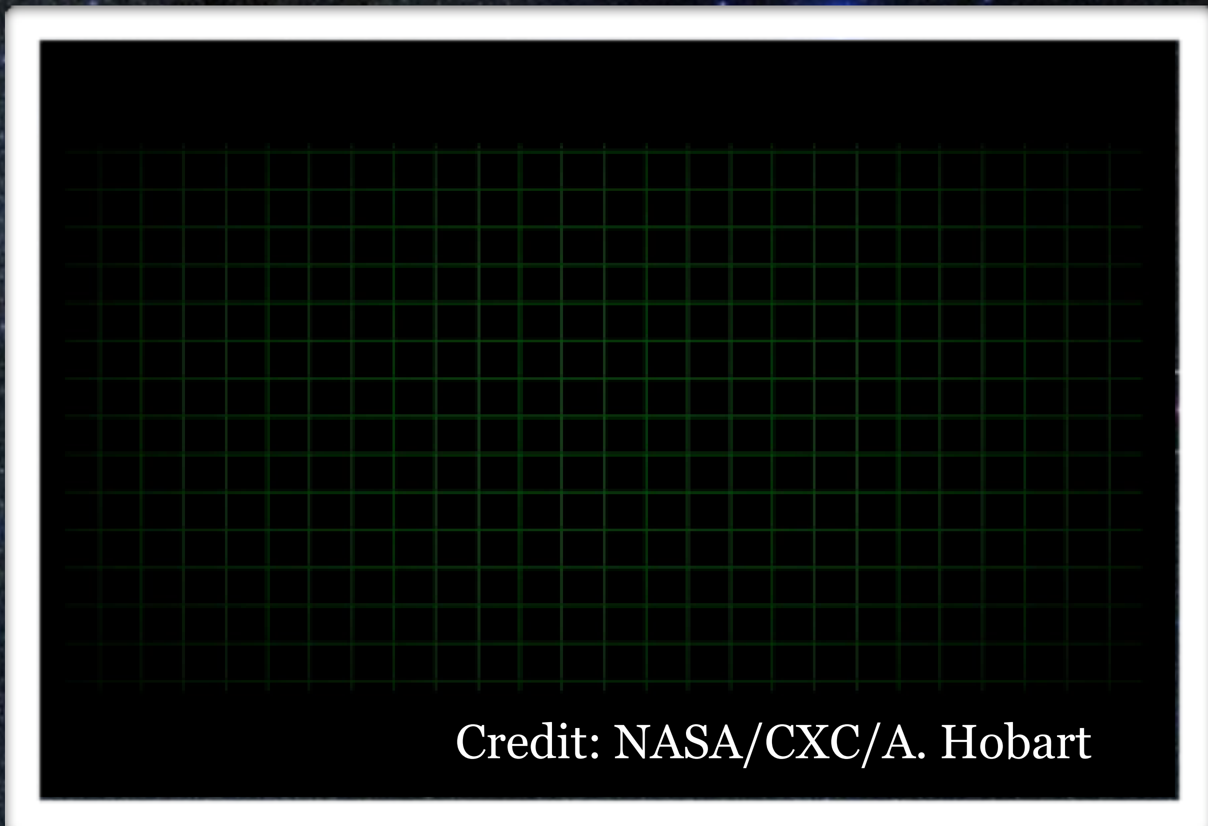
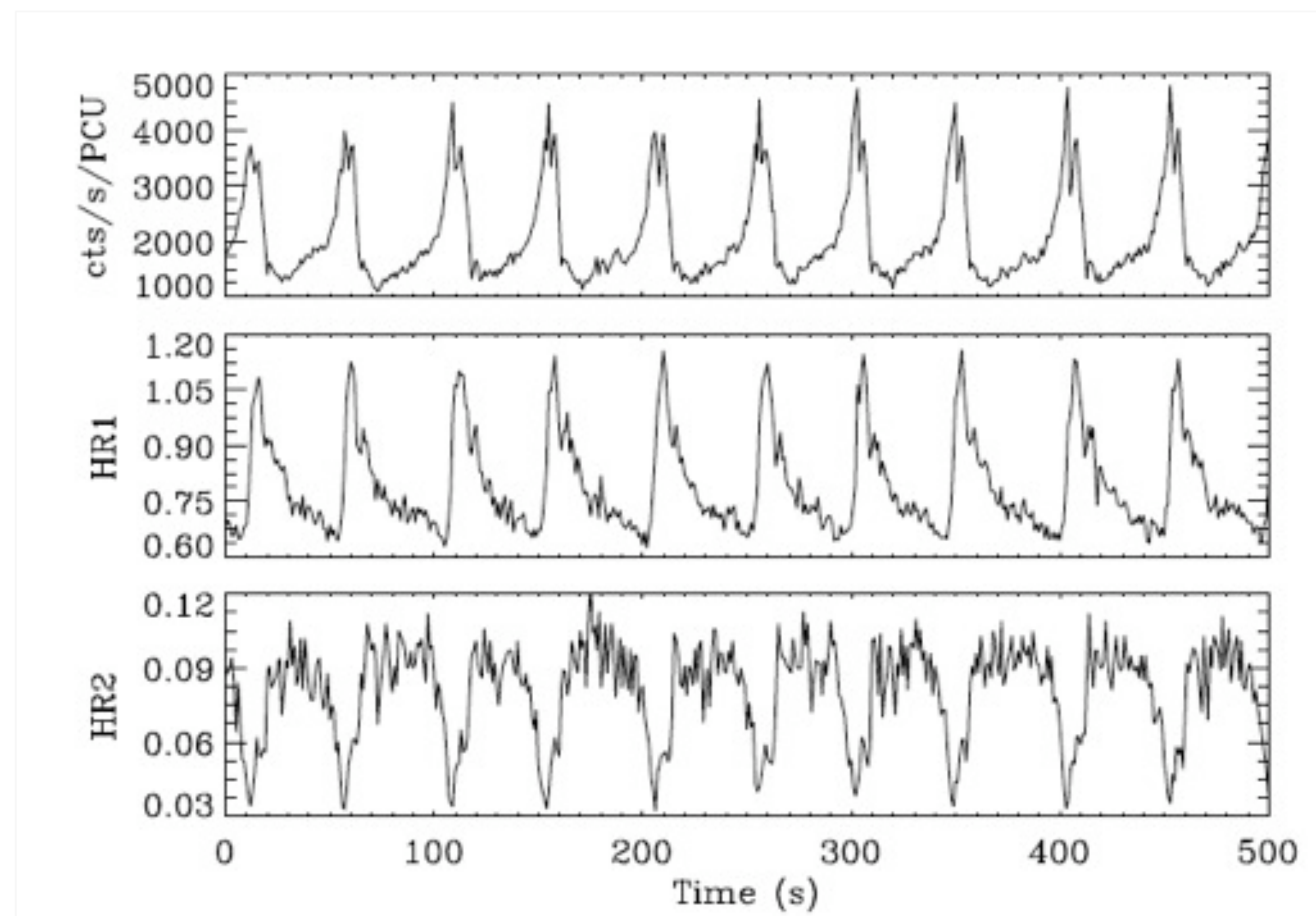
The 'Heartbeat' State



Credit: NASA/CXC/A. Hobart

- Strong 50-second X-ray oscillation
- Where does it come from? How does it affect the BH environment?
- Ideal opportunity to link changes in disk, wind



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- 30 ks Chandra/RXTE obs (1 of the 11)
- What accretion, ejection processes are dominant at each part of the heartbeat?

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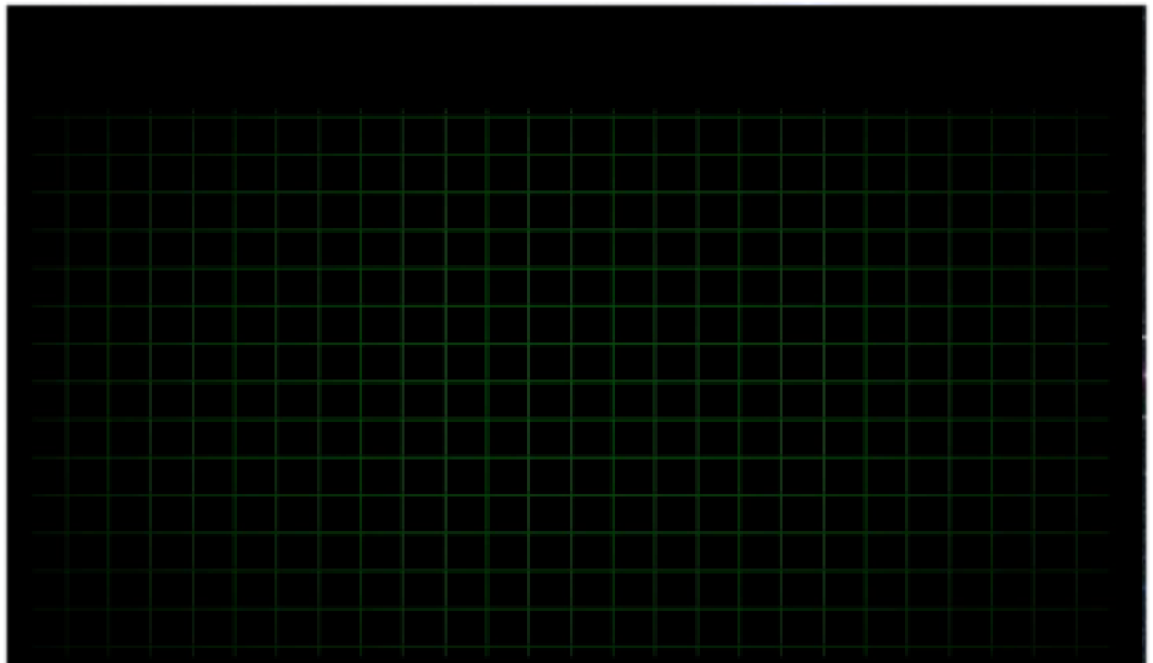

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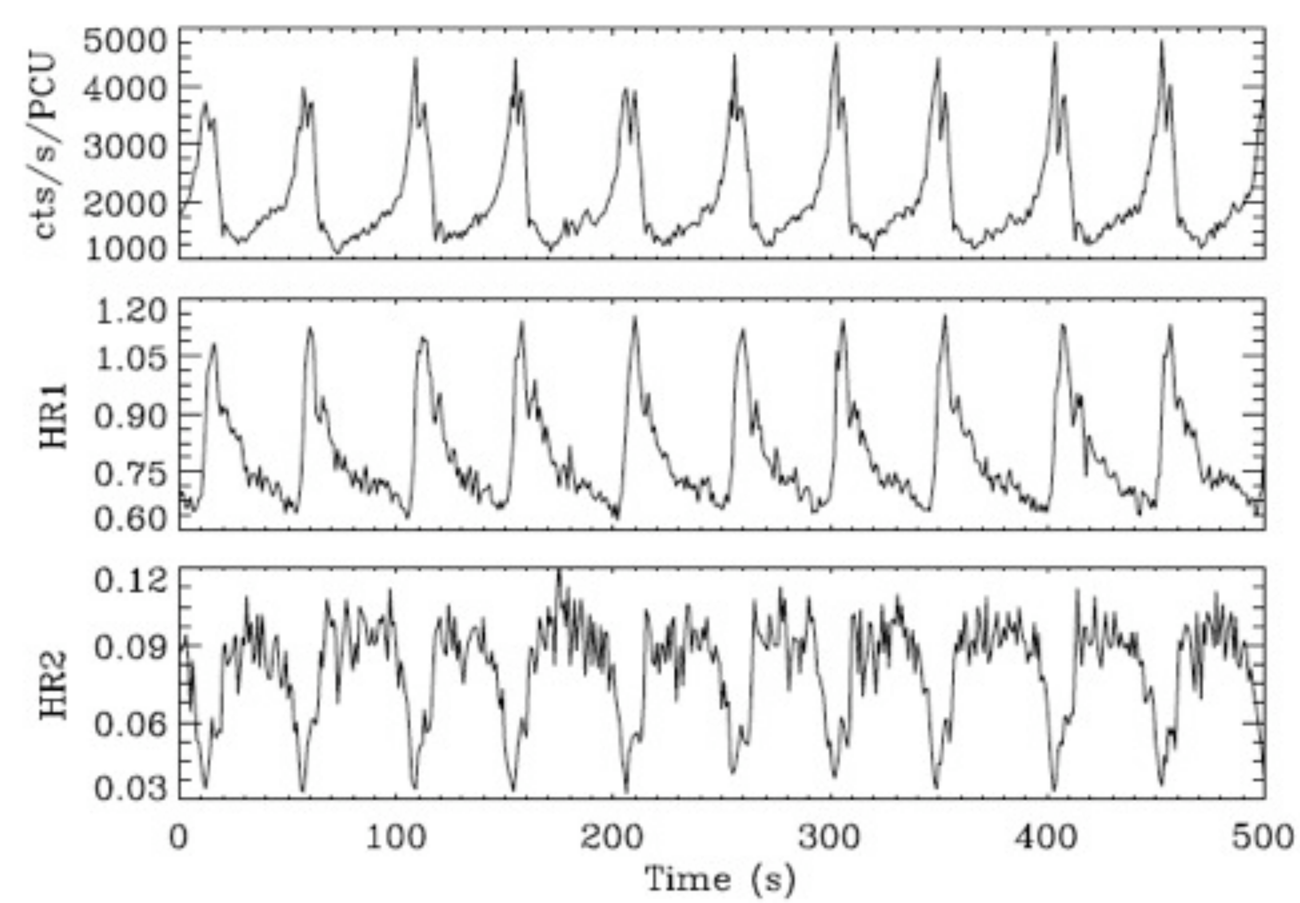

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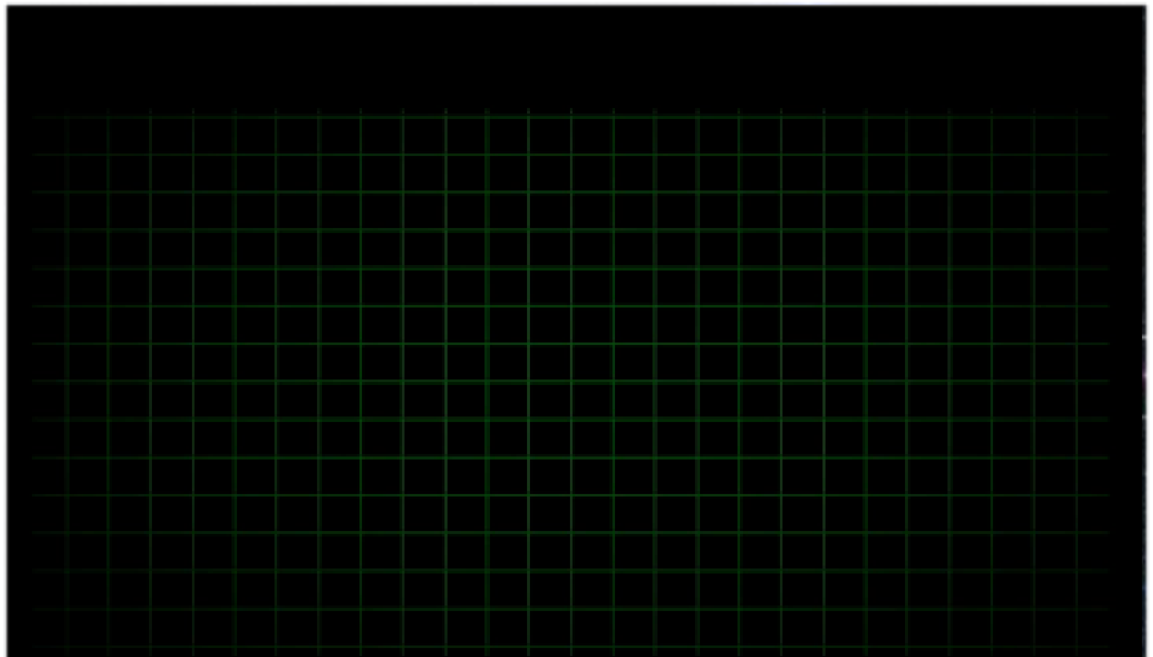

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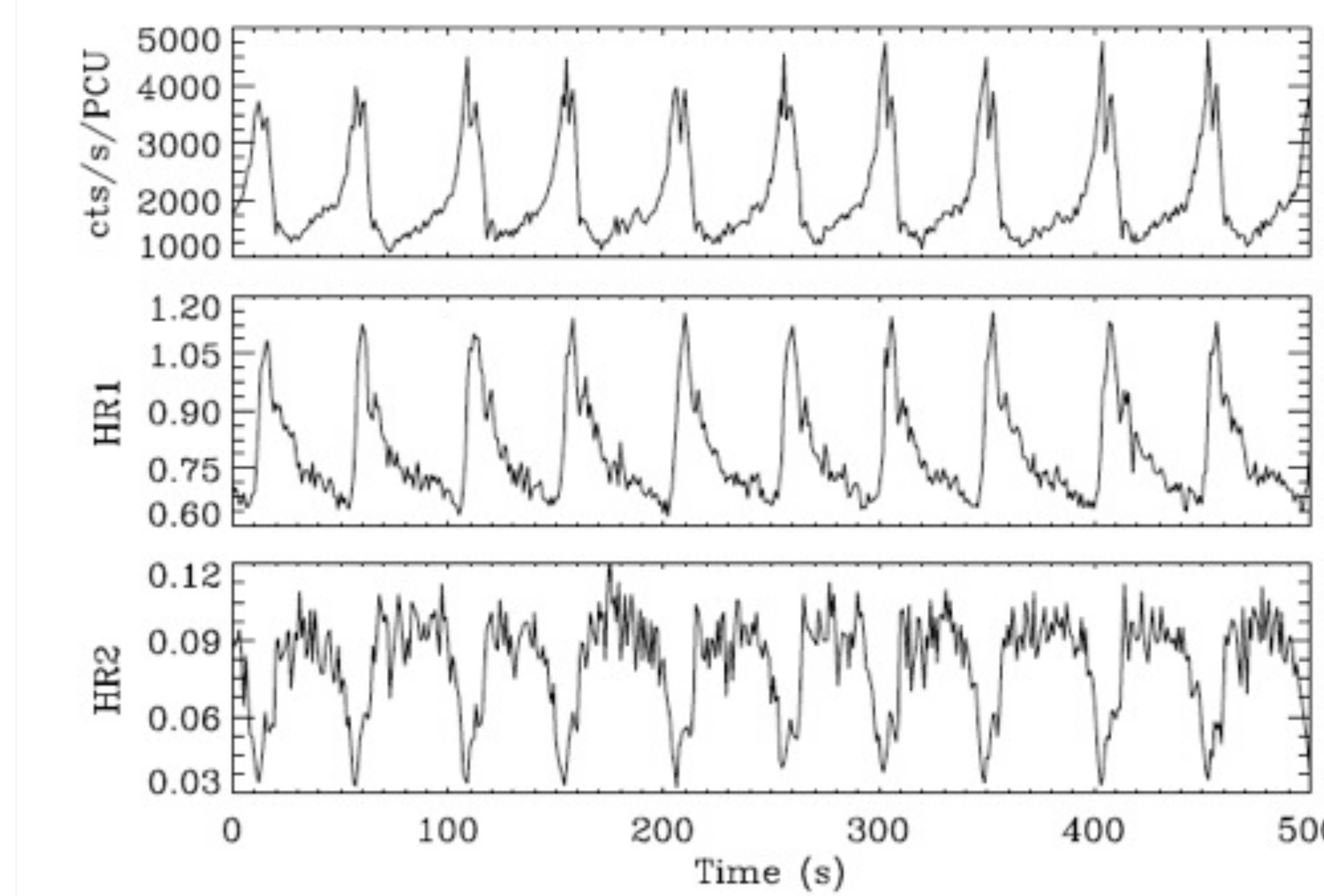
- Stack all the individual cycles (623) together



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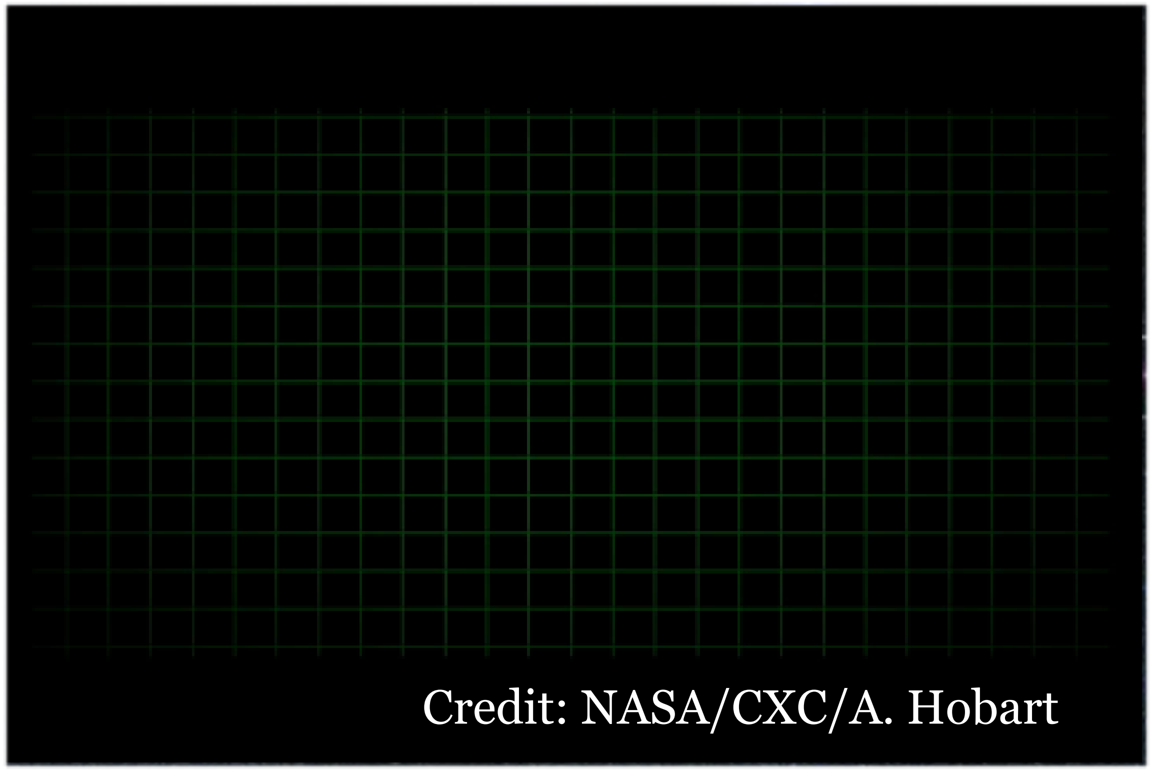

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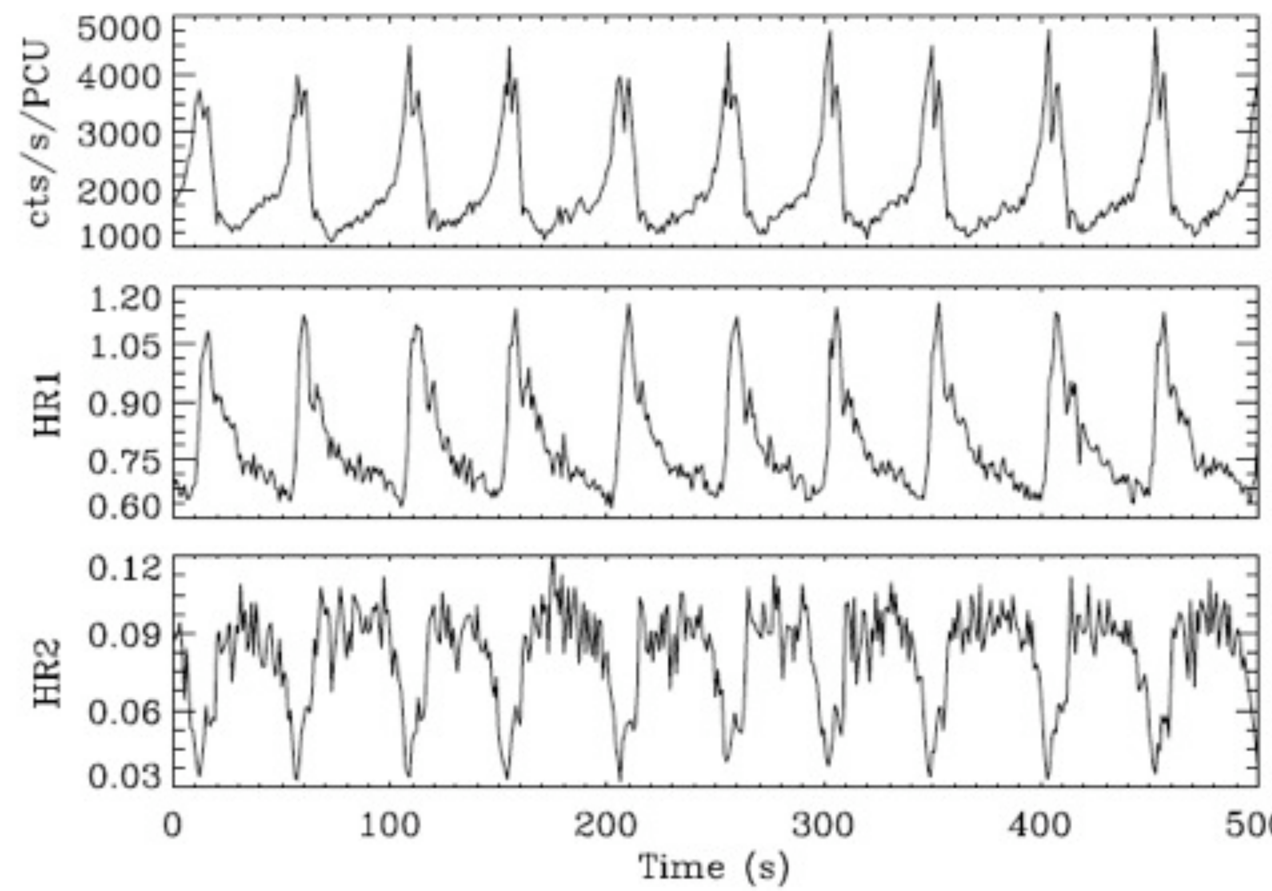

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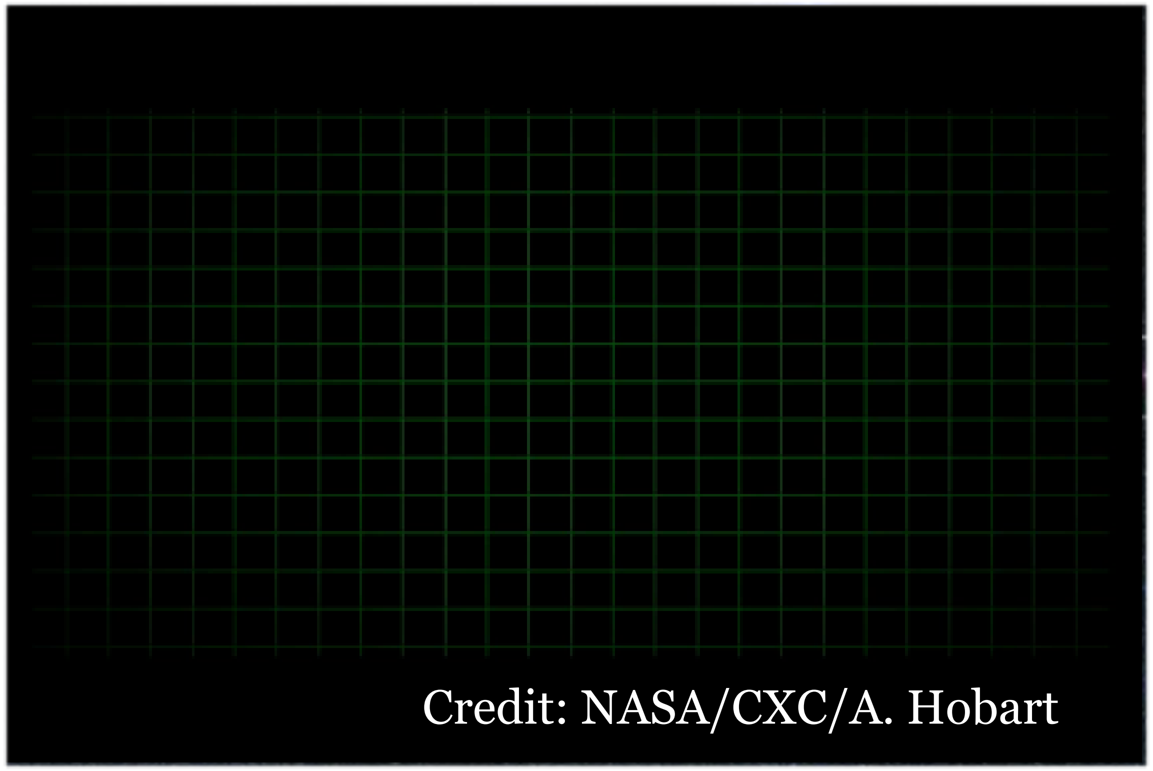

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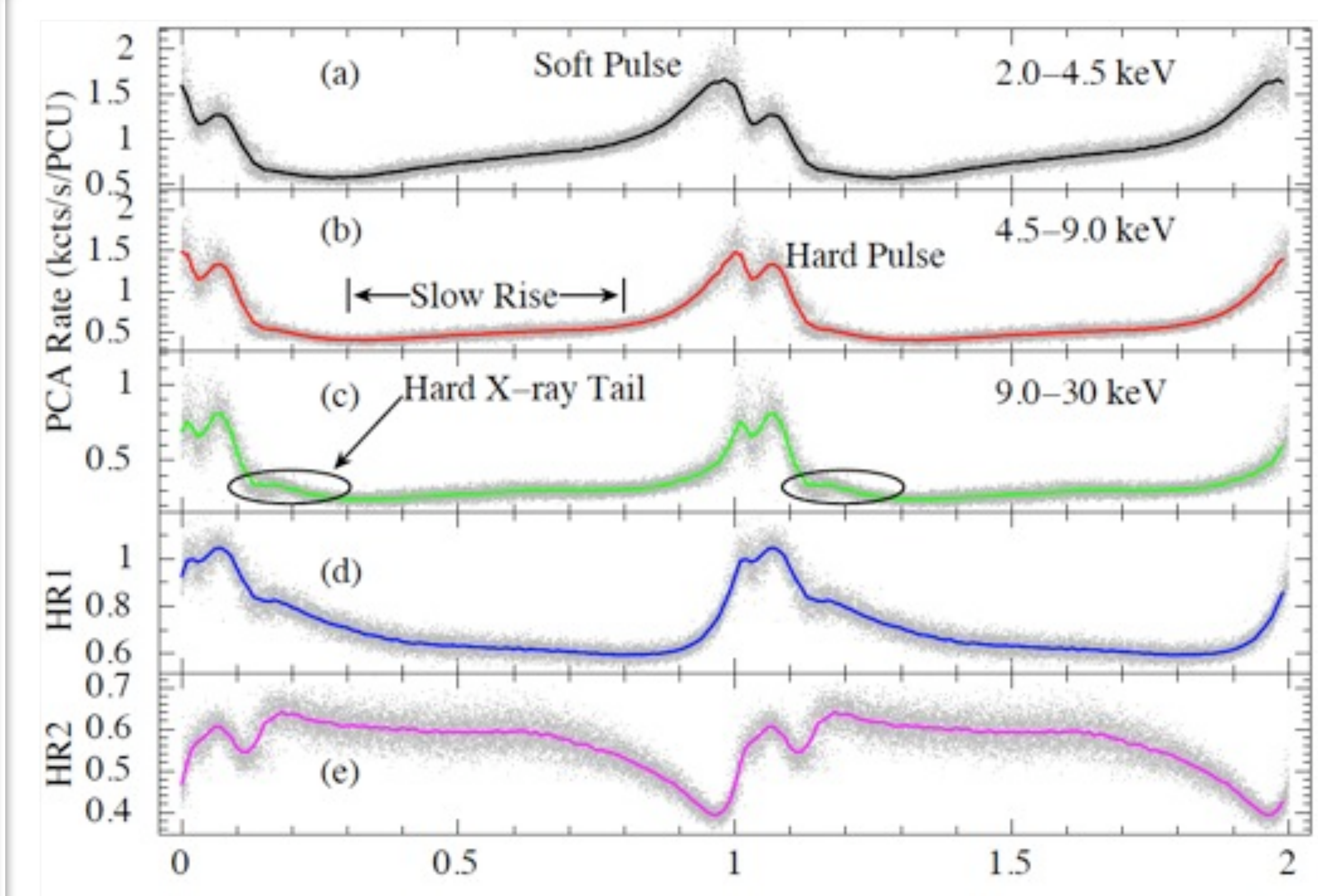

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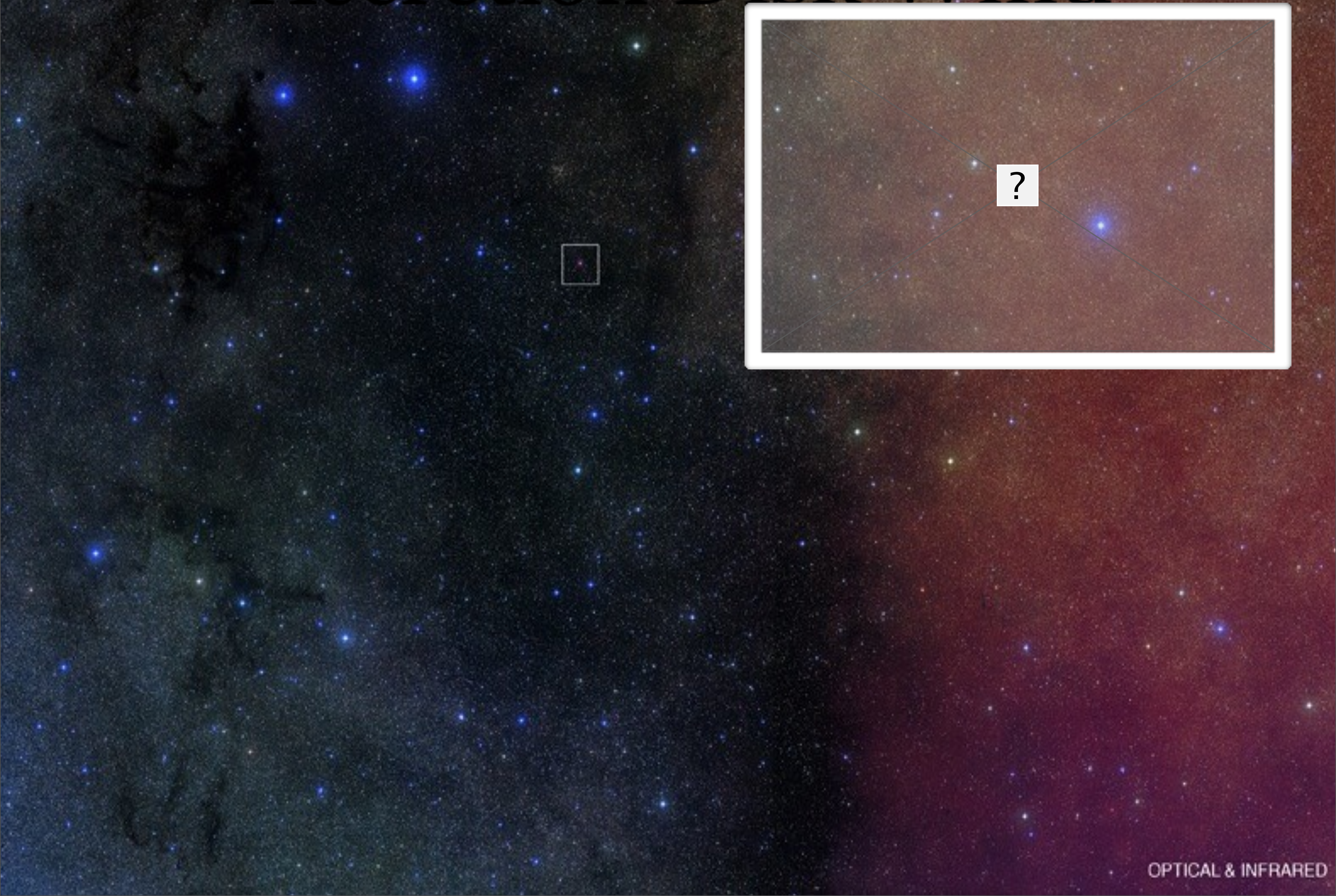
Accretion Disk Wind



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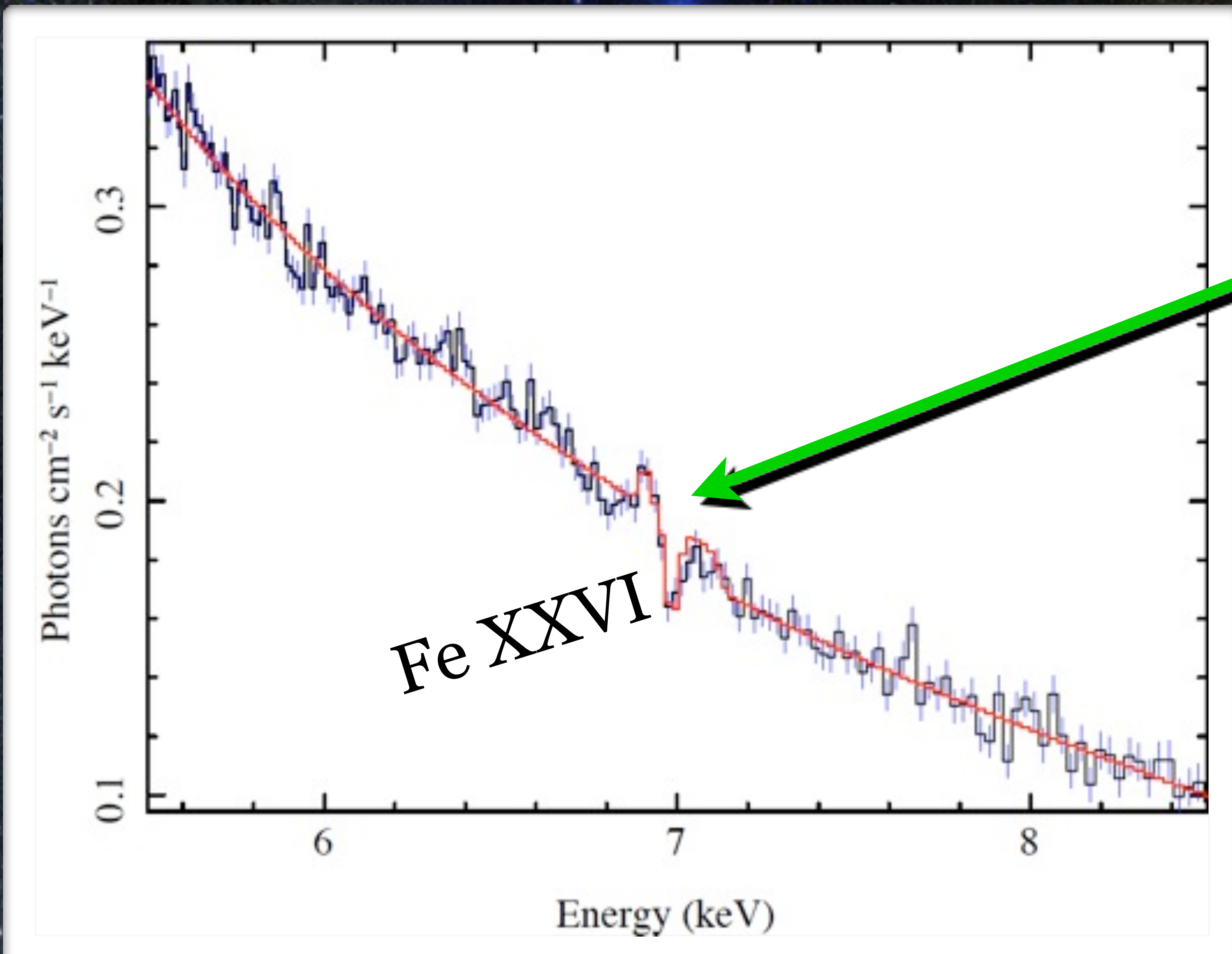

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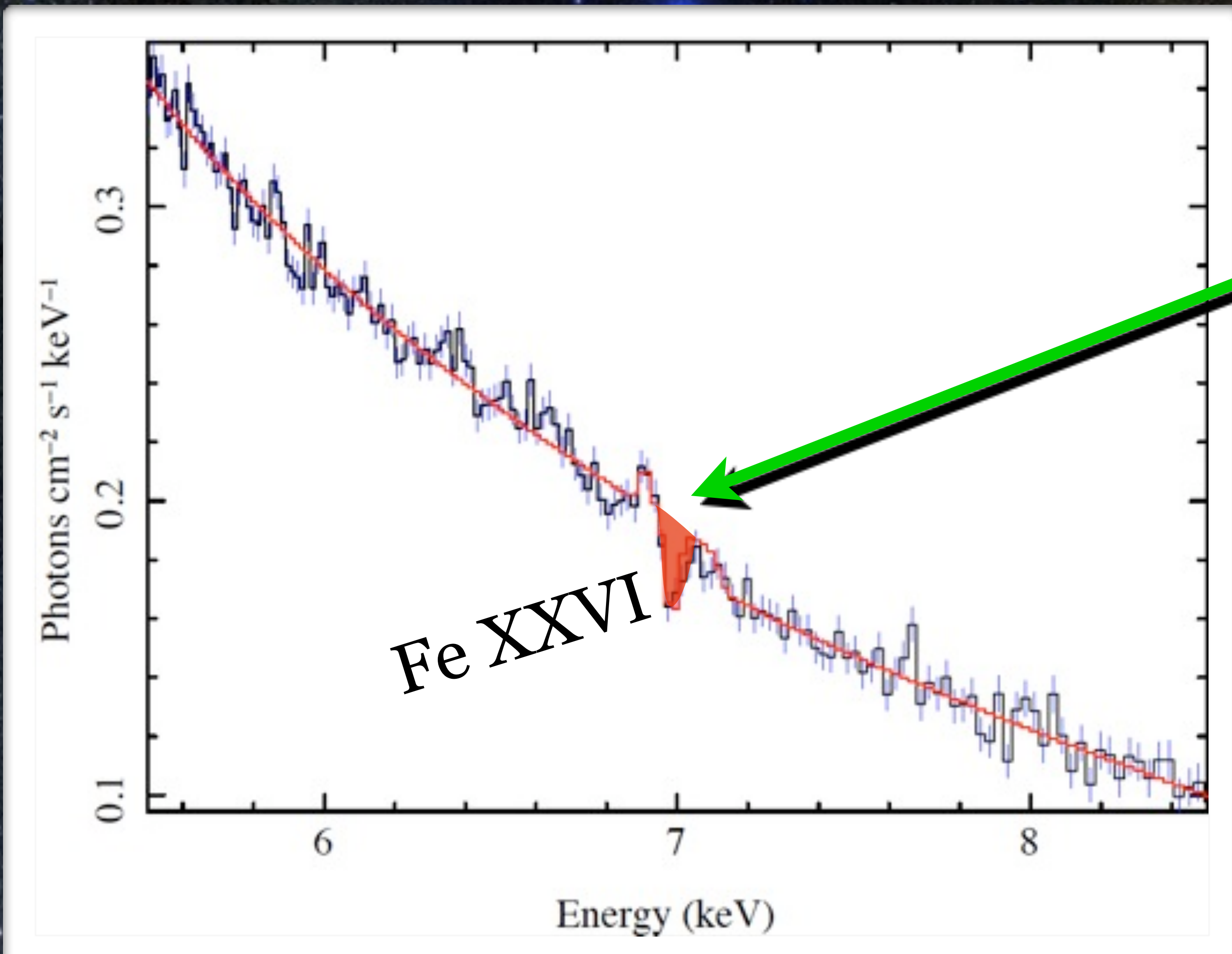

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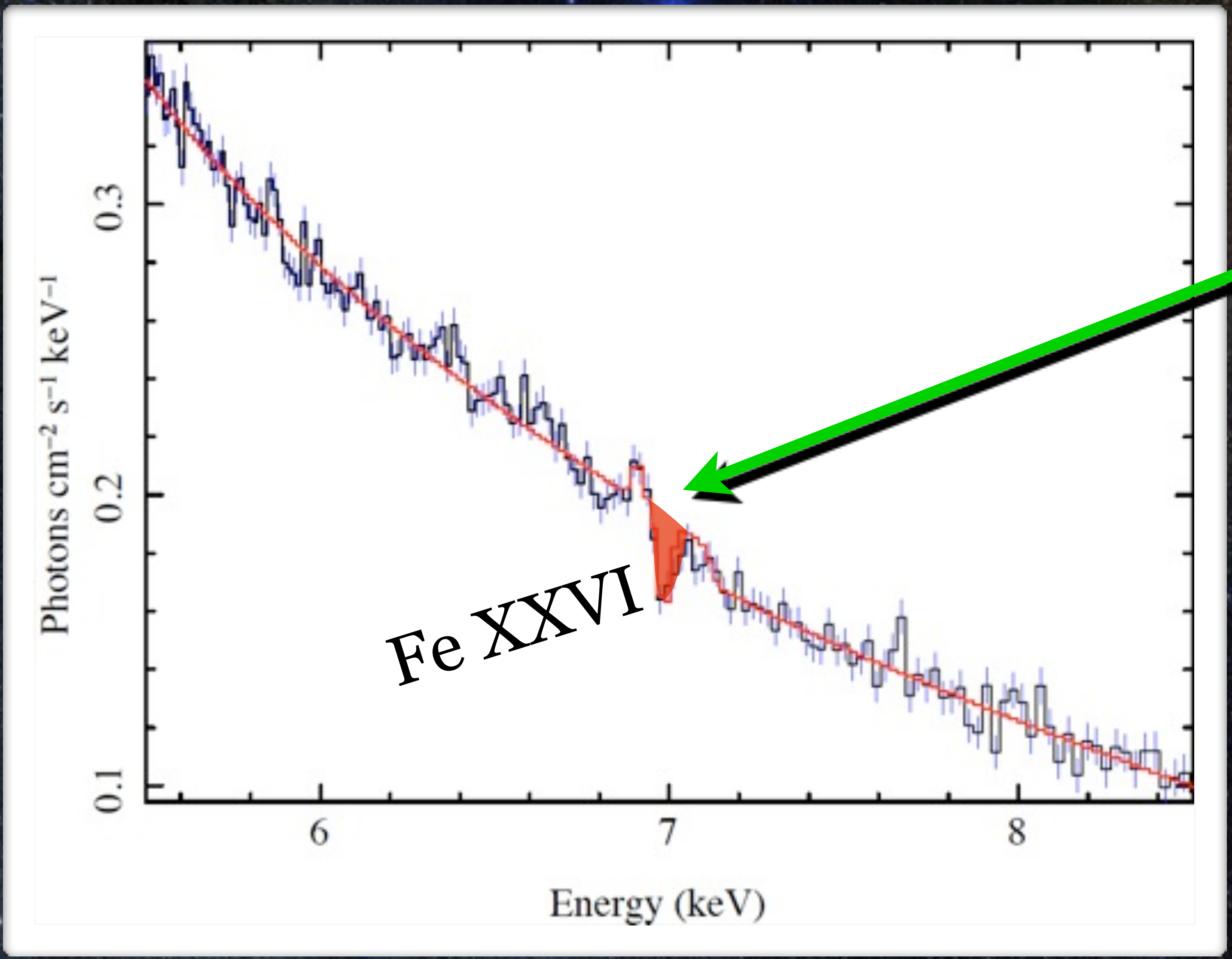

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- Complemented by simultaneous *RXTE* broadband spectroscopy

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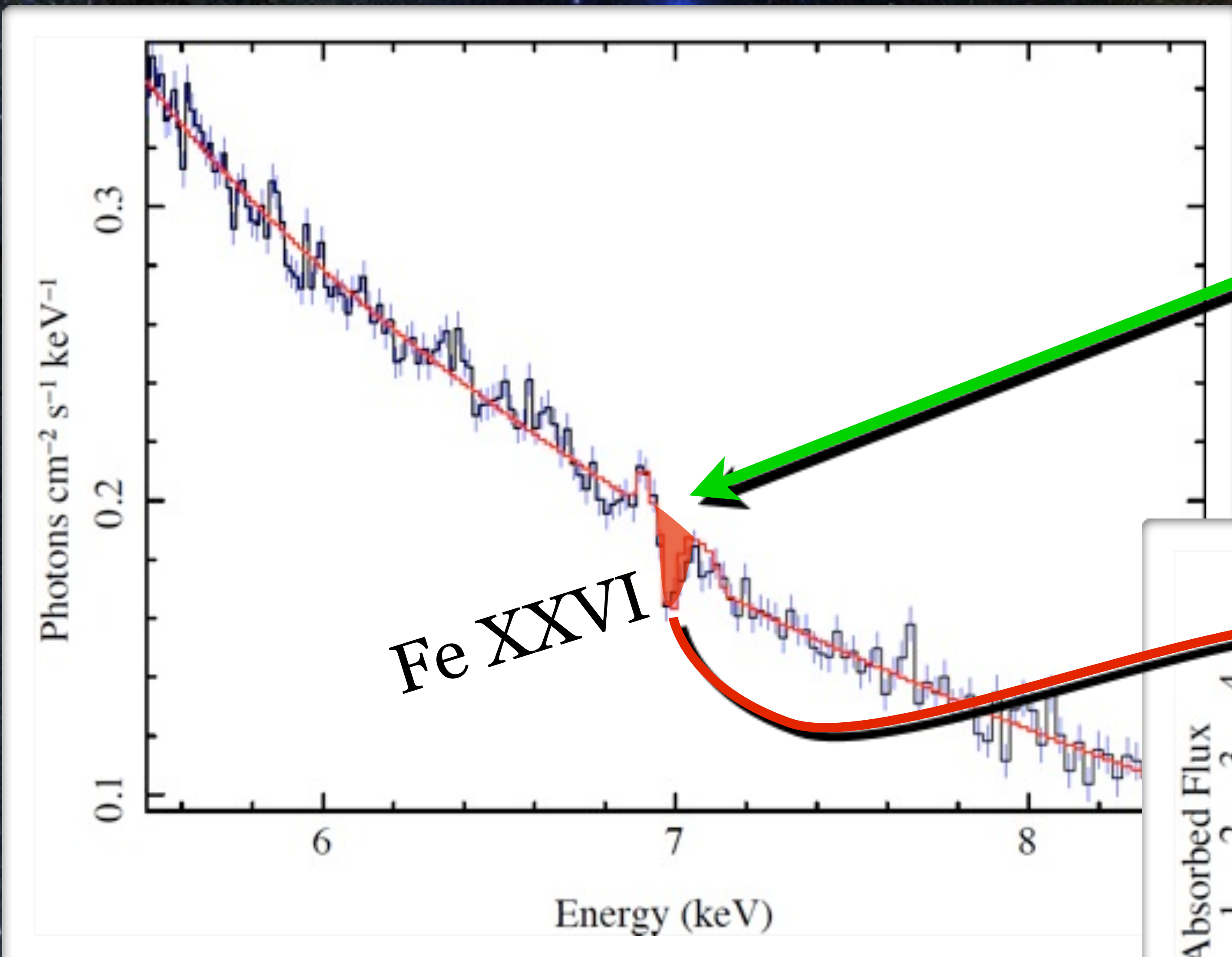

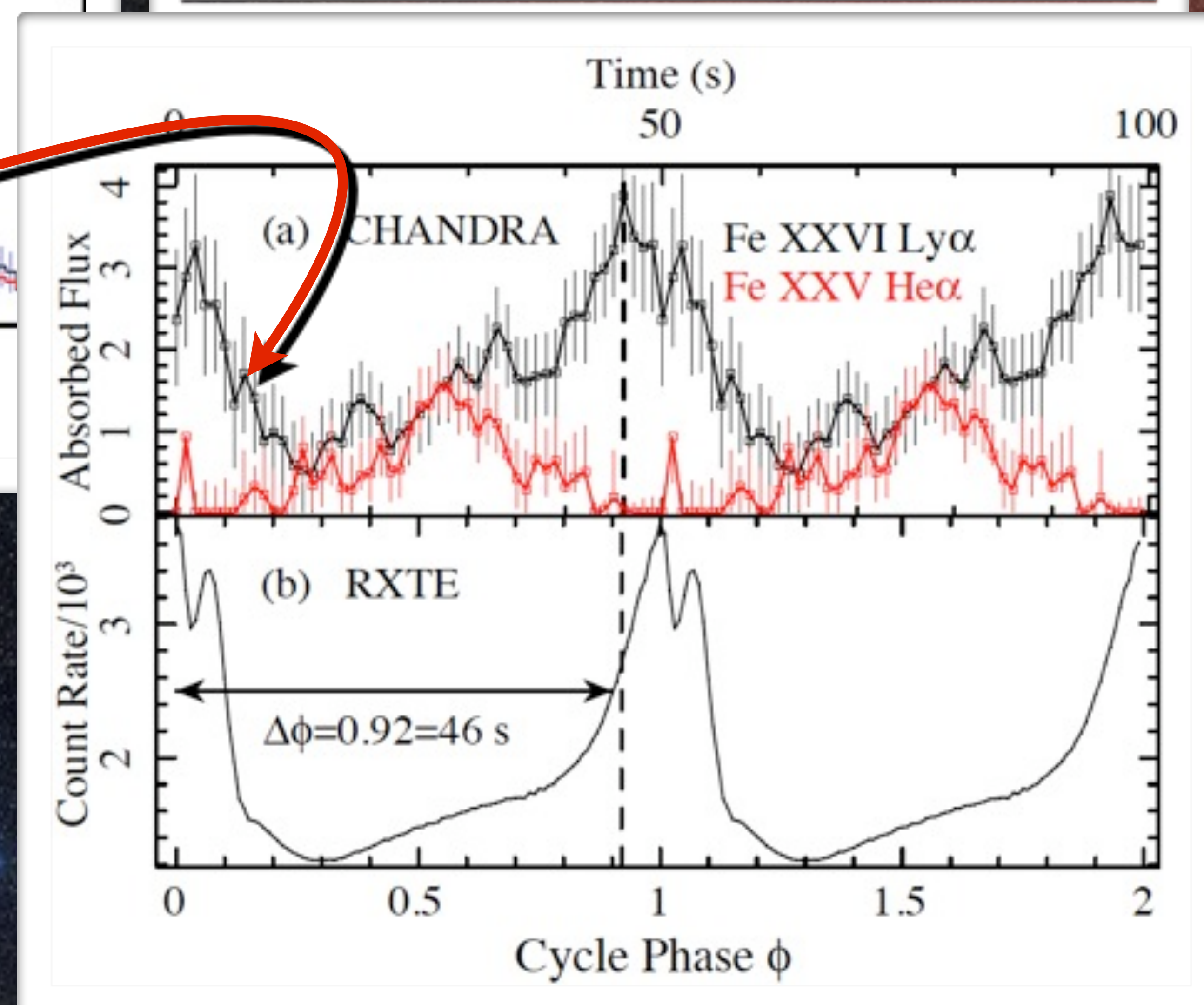

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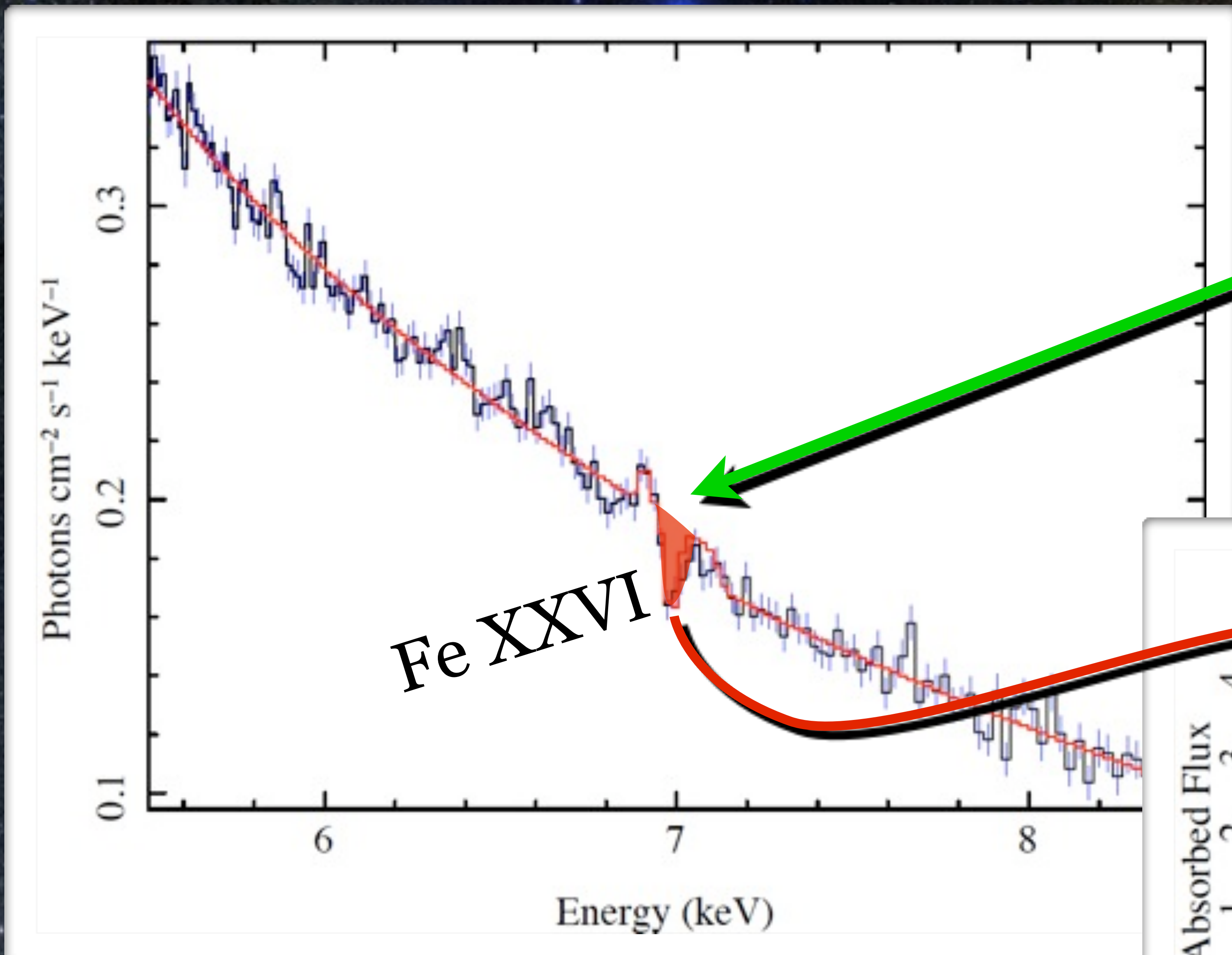

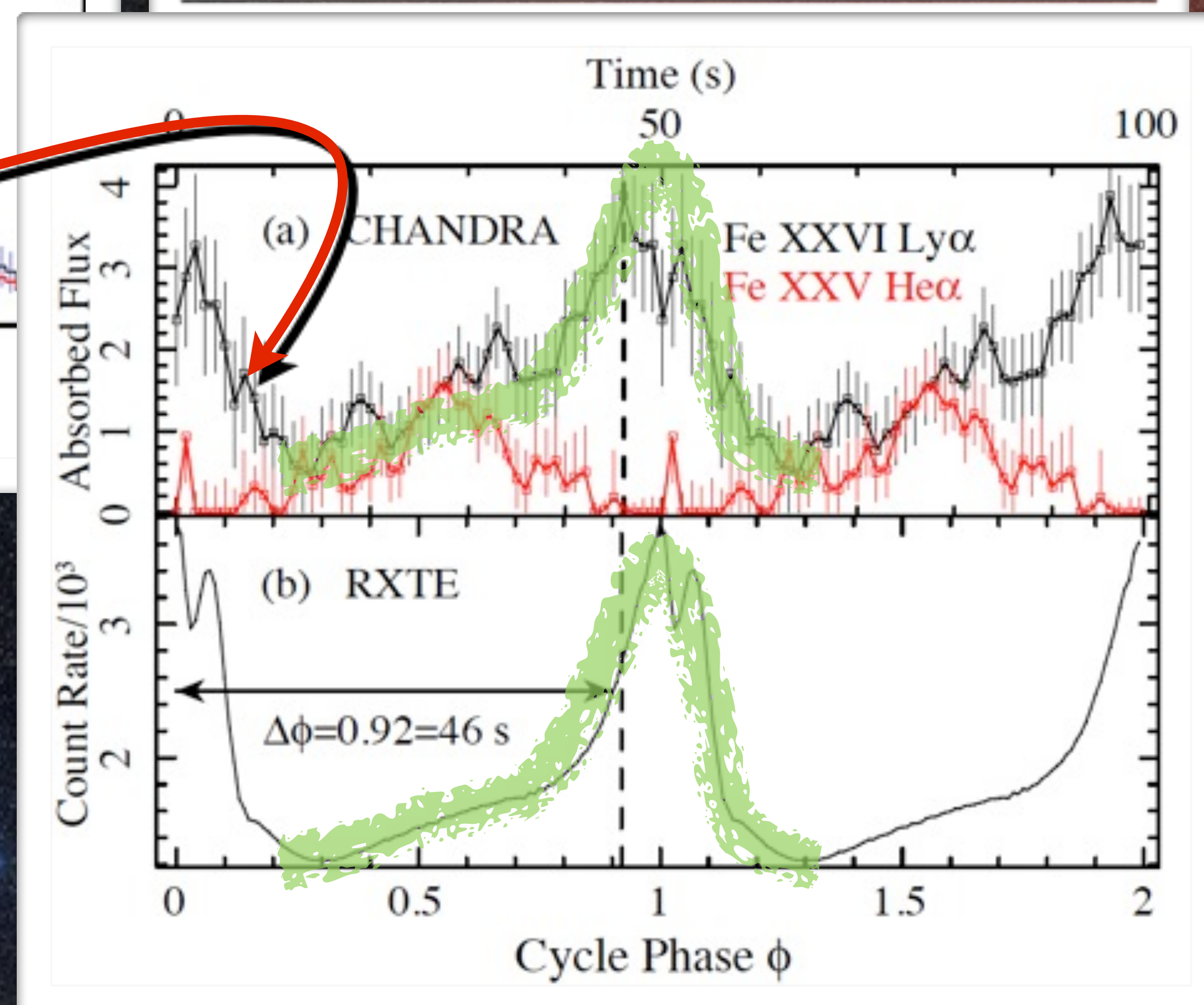

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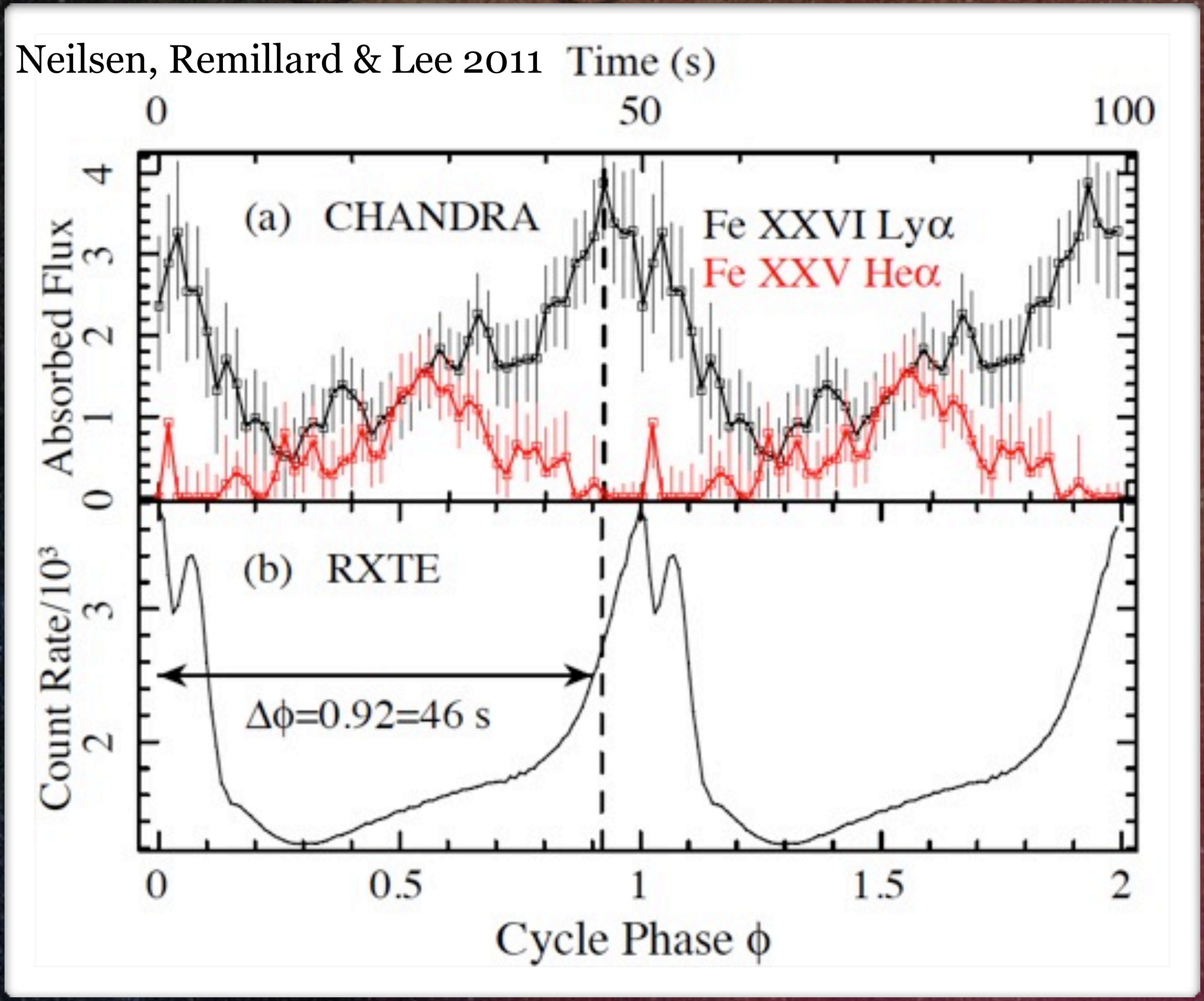

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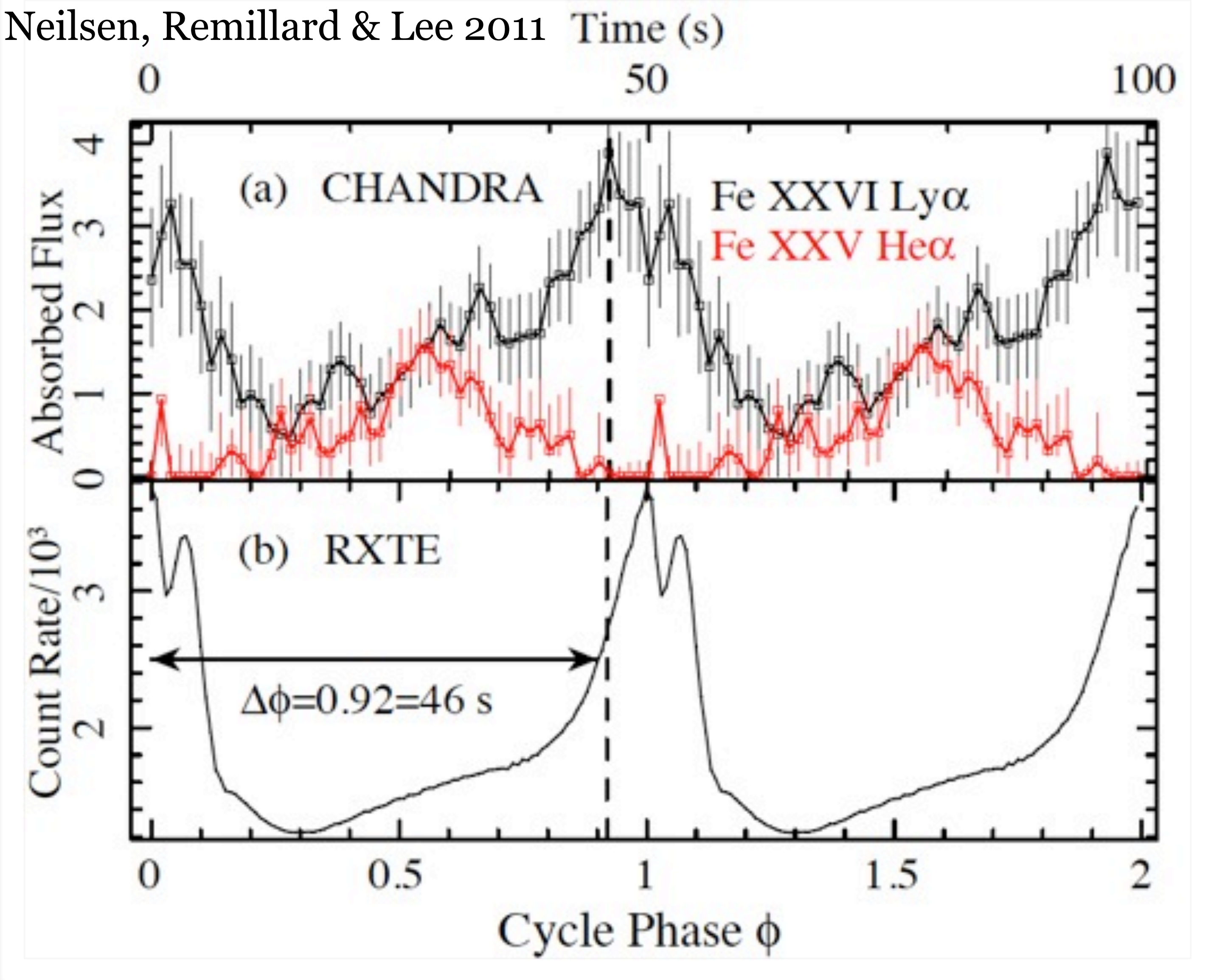

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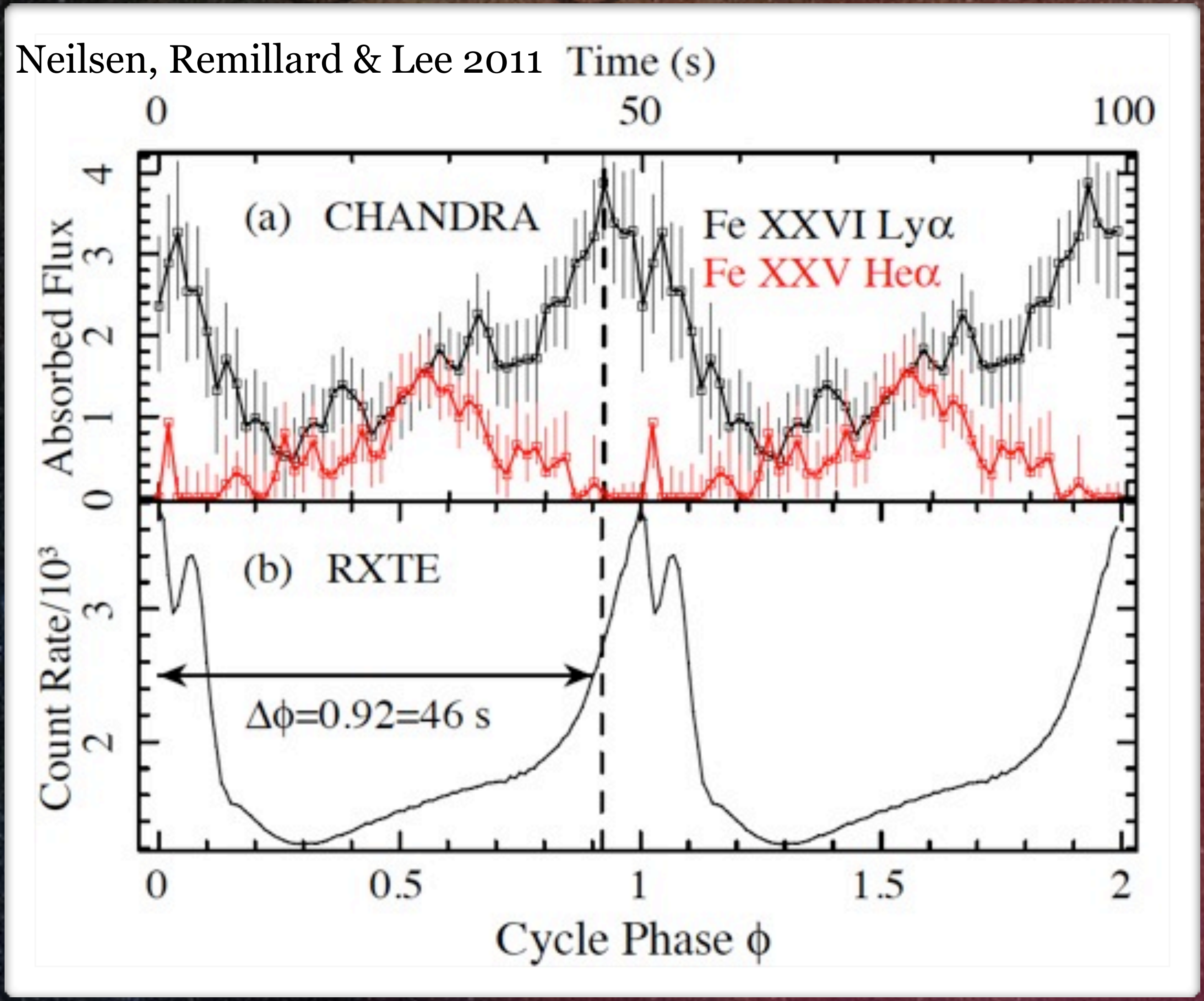

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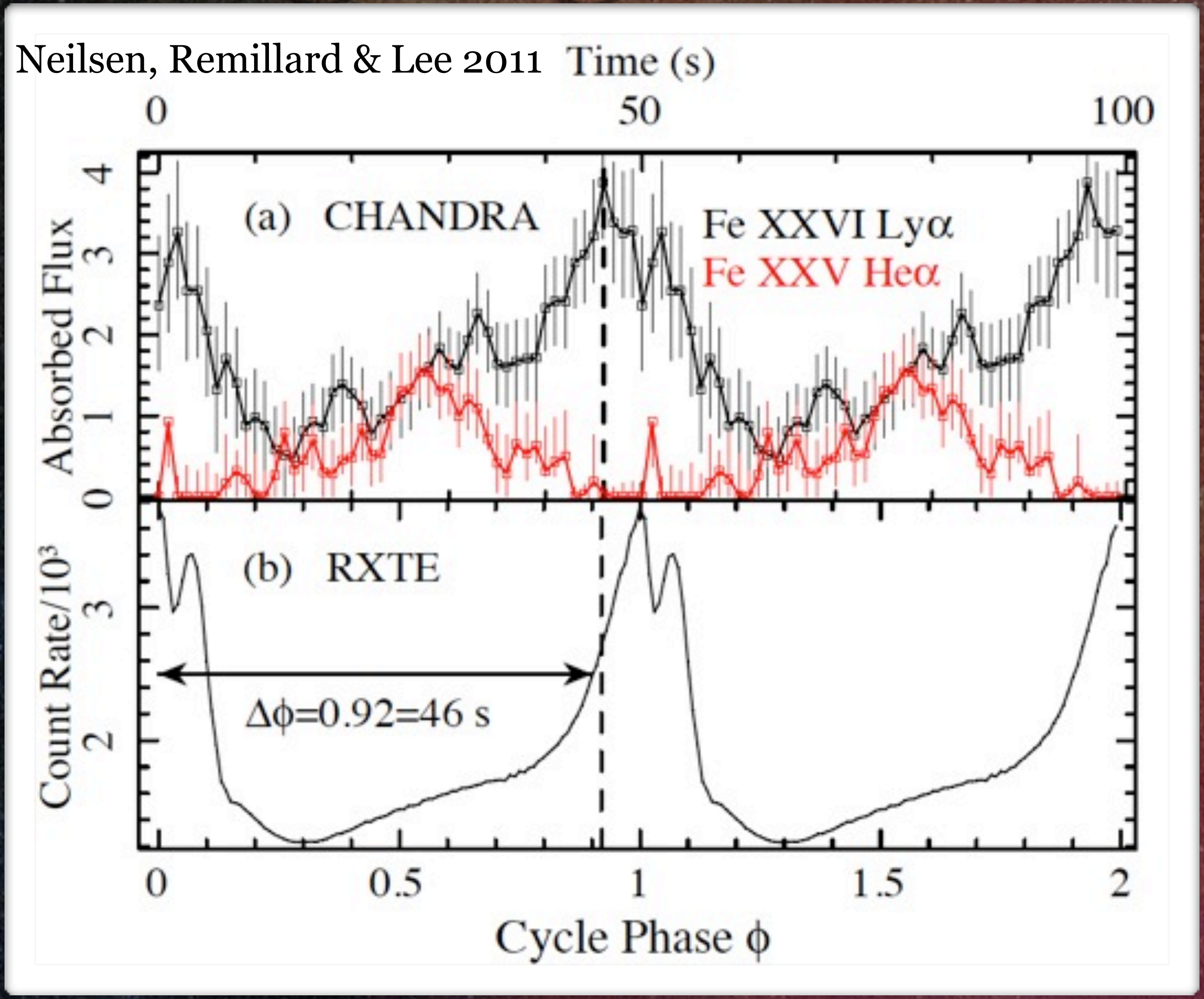

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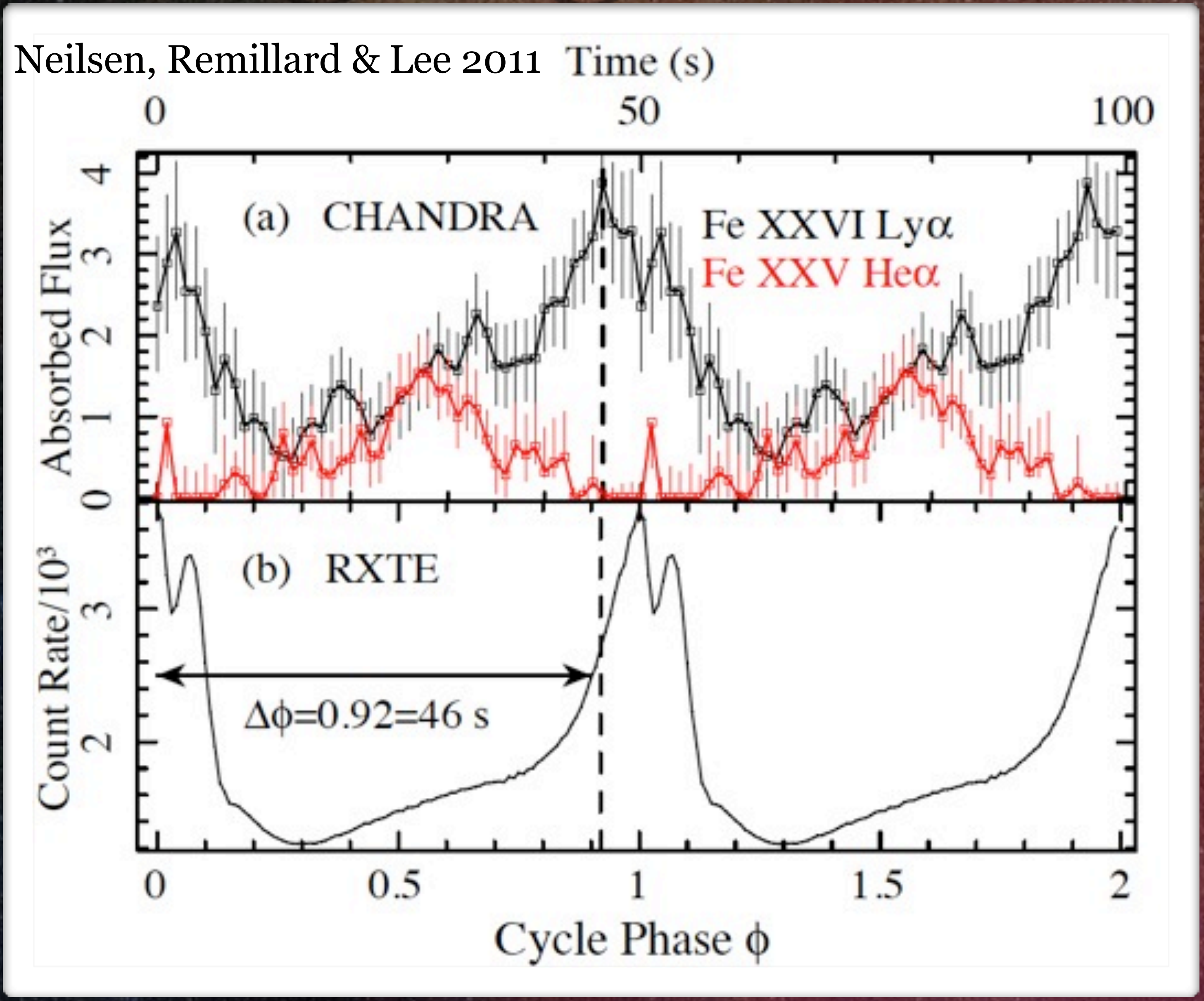

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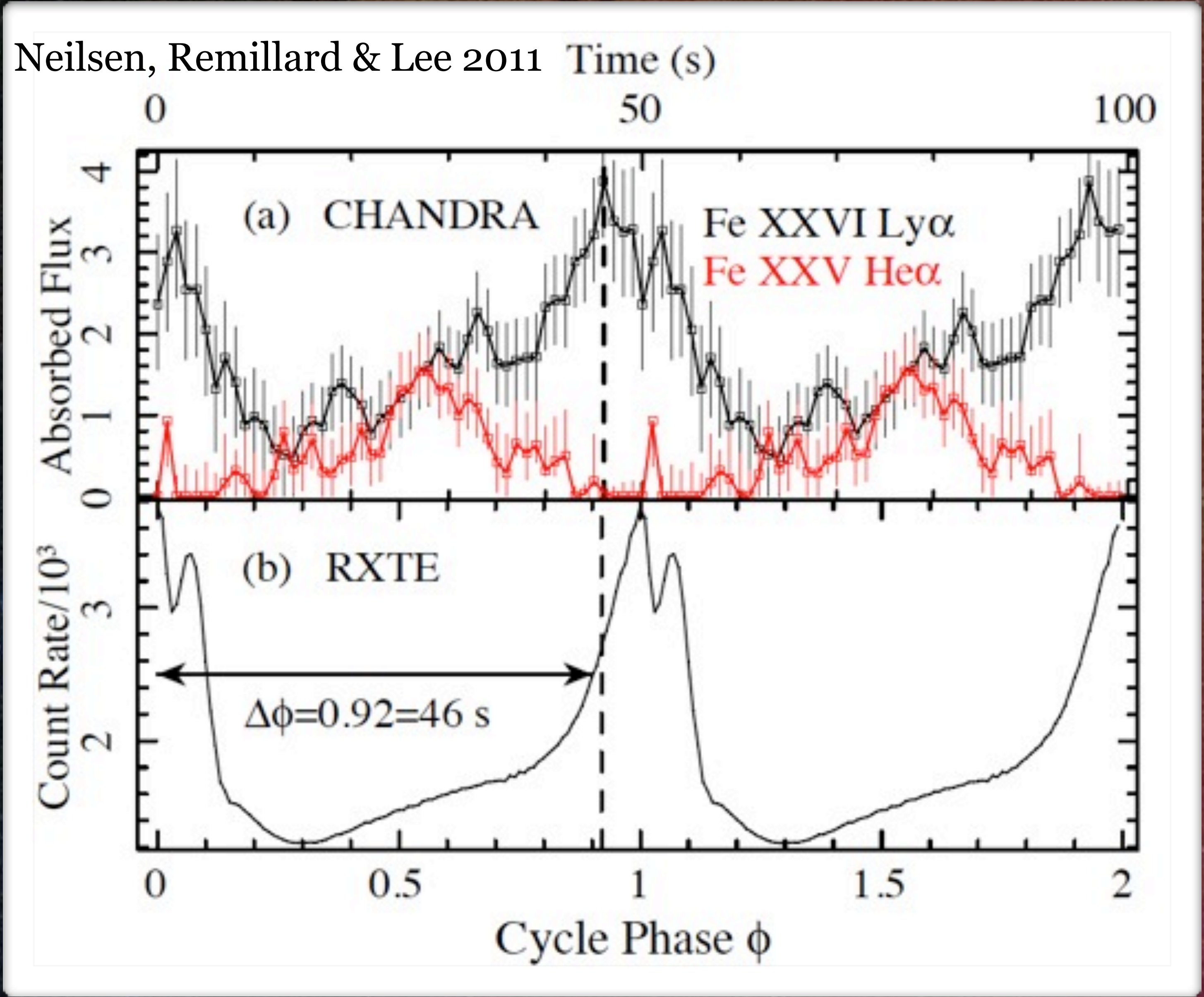

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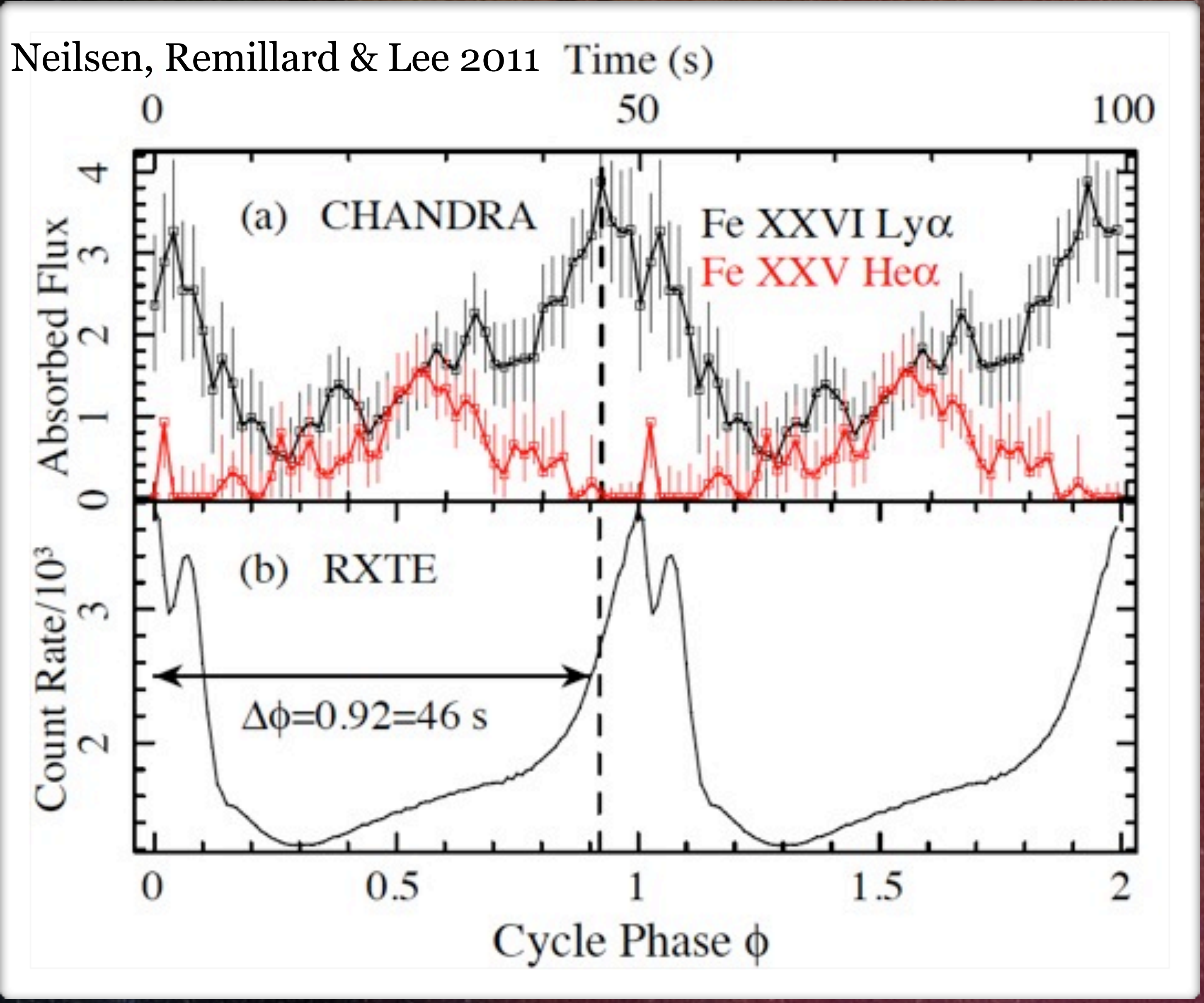

- For this type of wind, we estimate $Mdot_{wind} \lesssim 25\ Mdot_{BH}$

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Influence of a Massive Wind

- Shields et al. (1986) studied theoretical implications of very massive winds
- These winds drive an instability that can drain mass from the disk on long timescales
- For GRS 1915+105, the characteristic timescale could be as short as 2 weeks
- Shields instability could be responsible not only for turning off jets, but also for causing state transitions

Recap

- Our study of the global properties of the wind and the jet in GRS 1915+105 showed that disk winds may be able suppress jets on long time scales

Credit: NASA/CXC/A. Hobart

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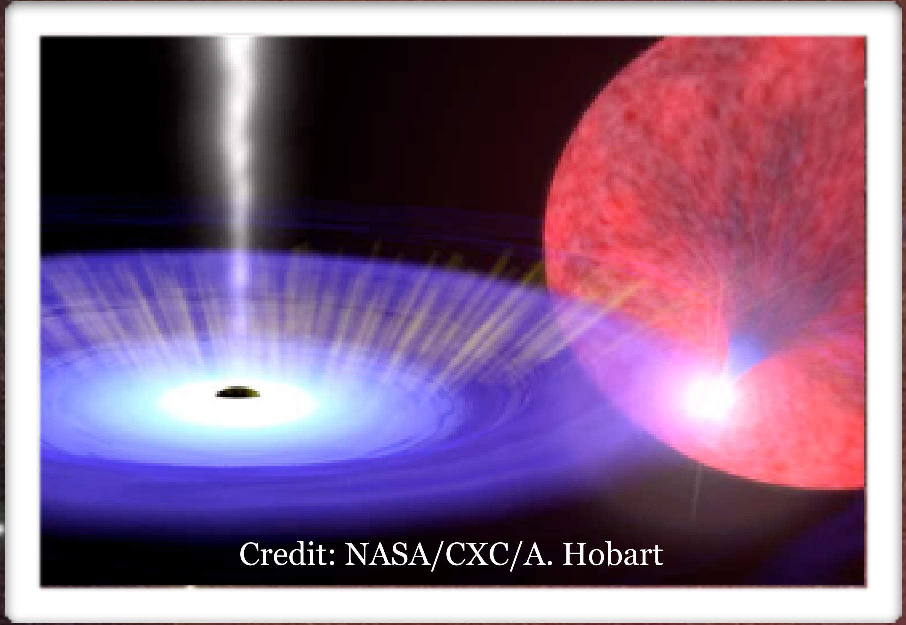

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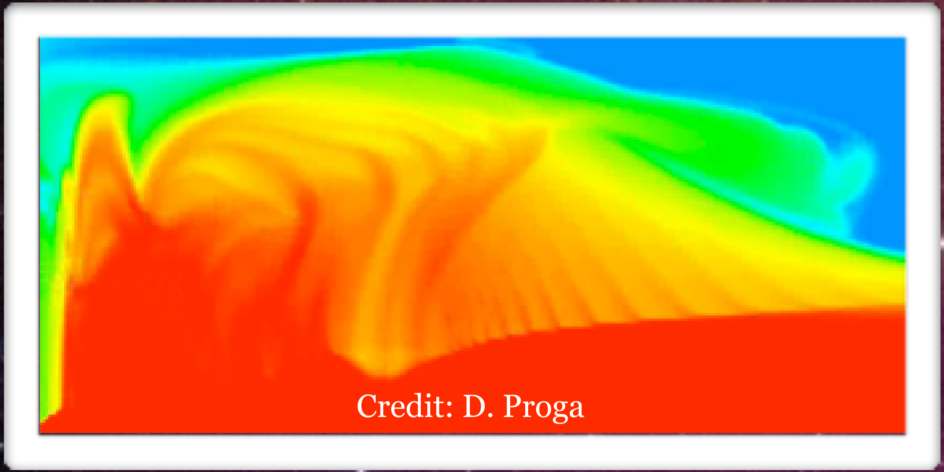

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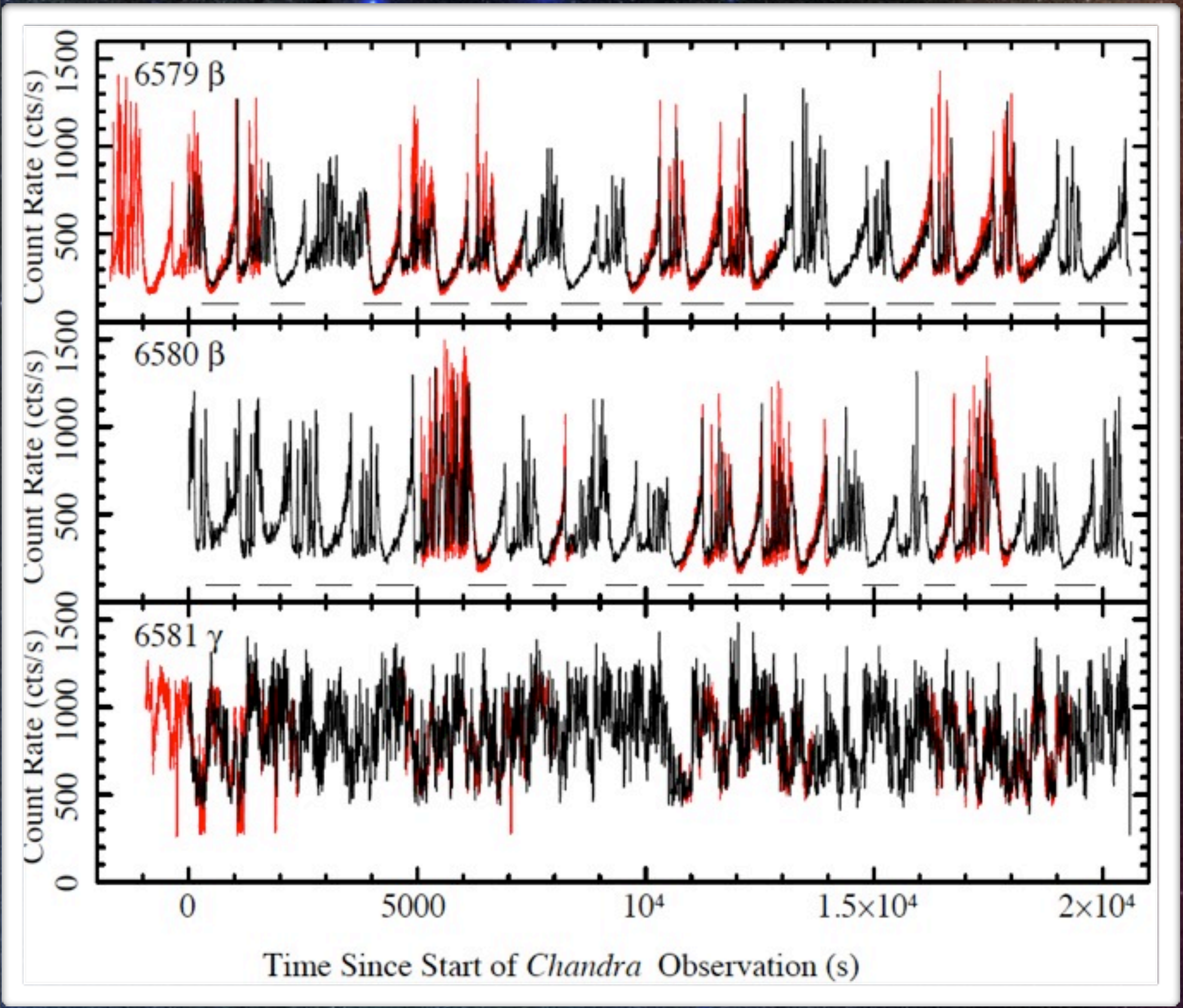
Other Variability



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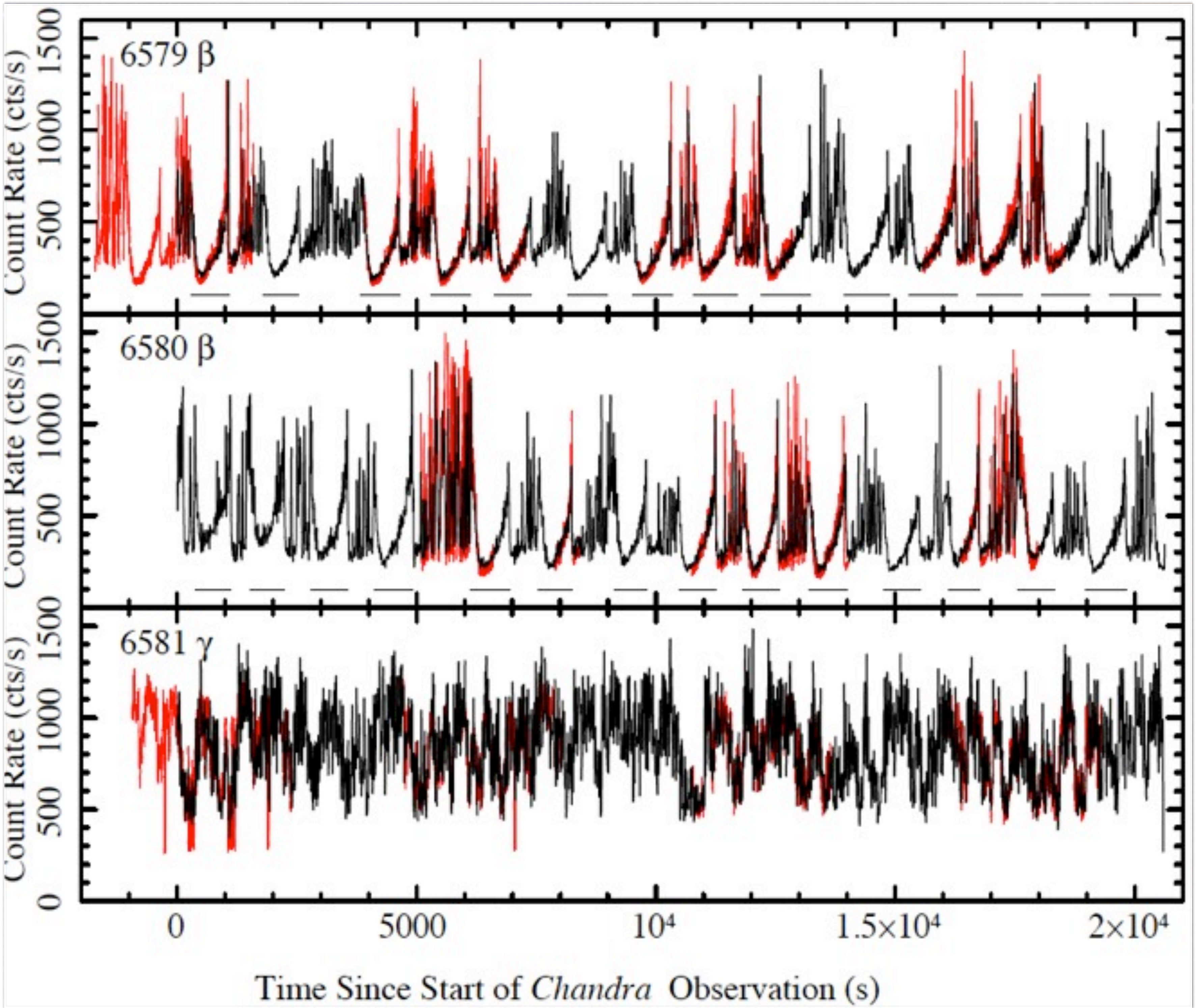

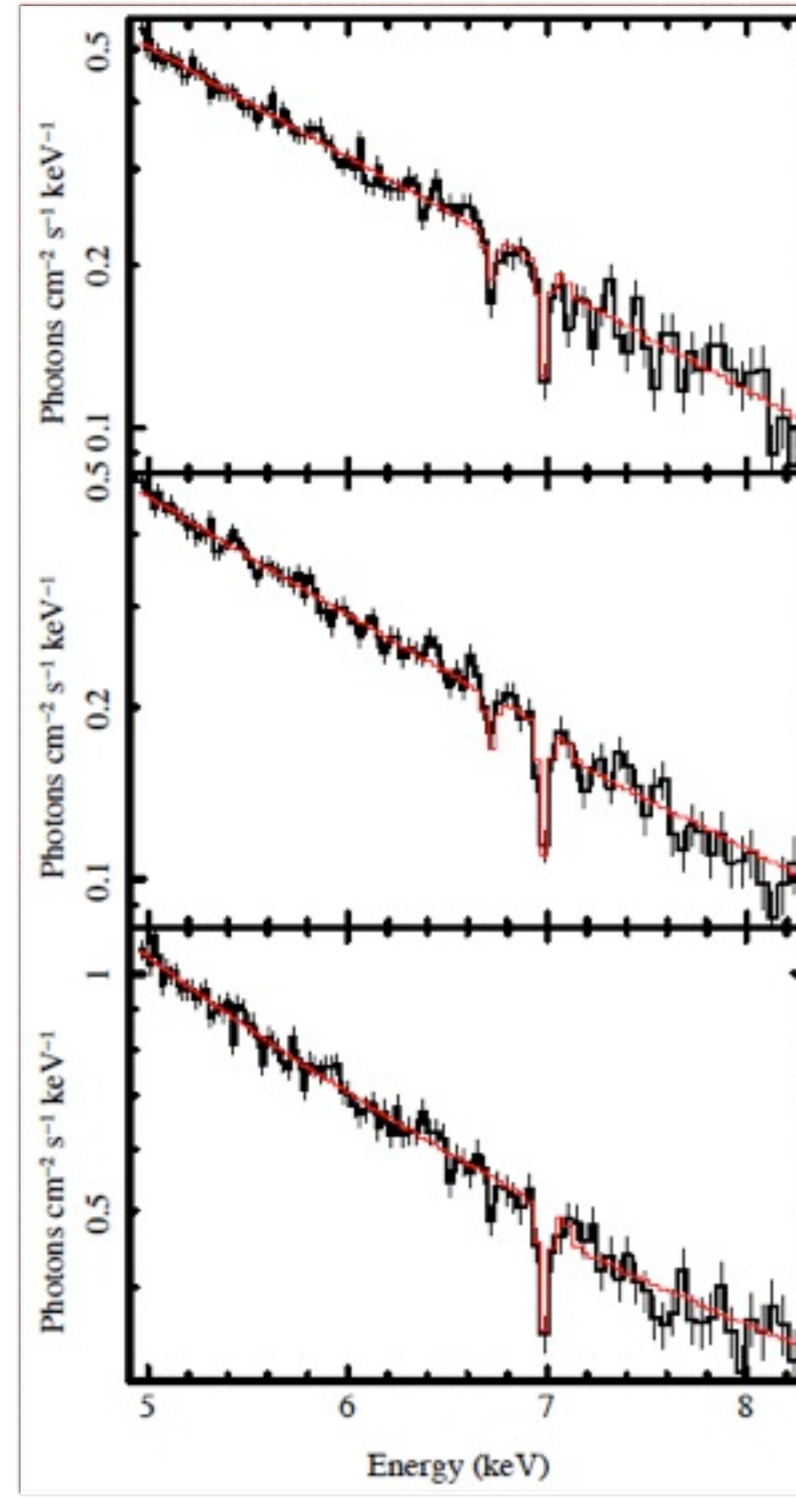

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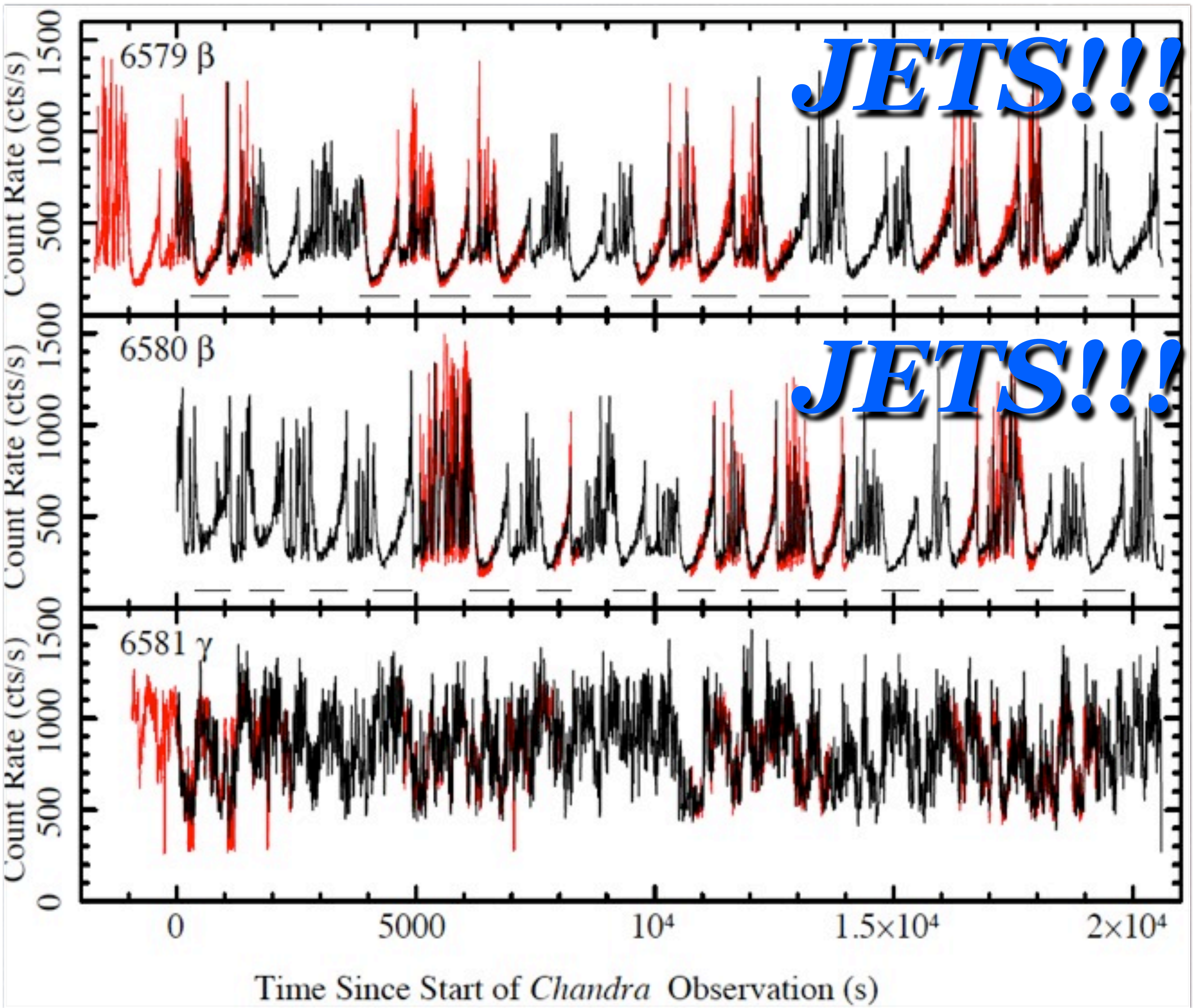
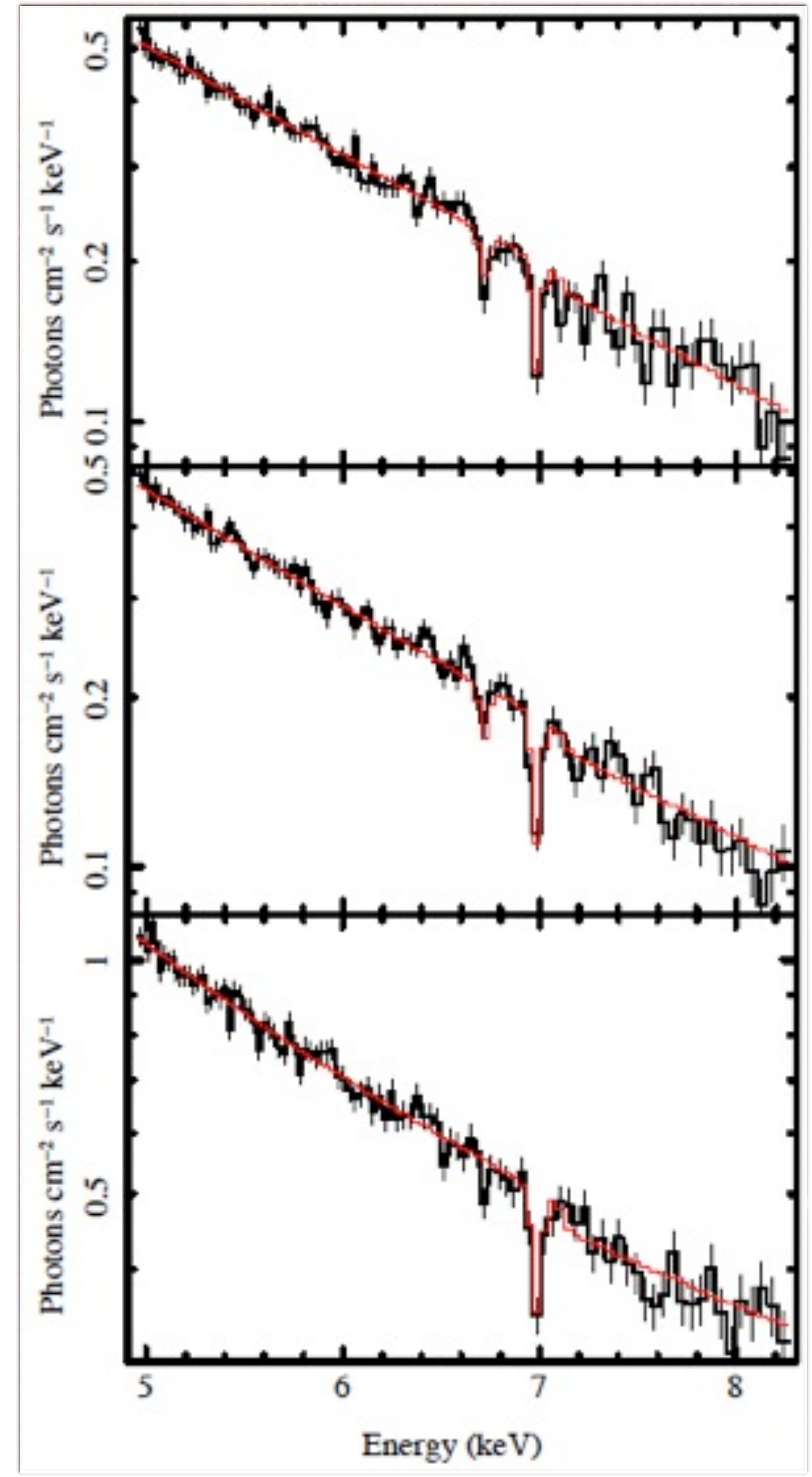


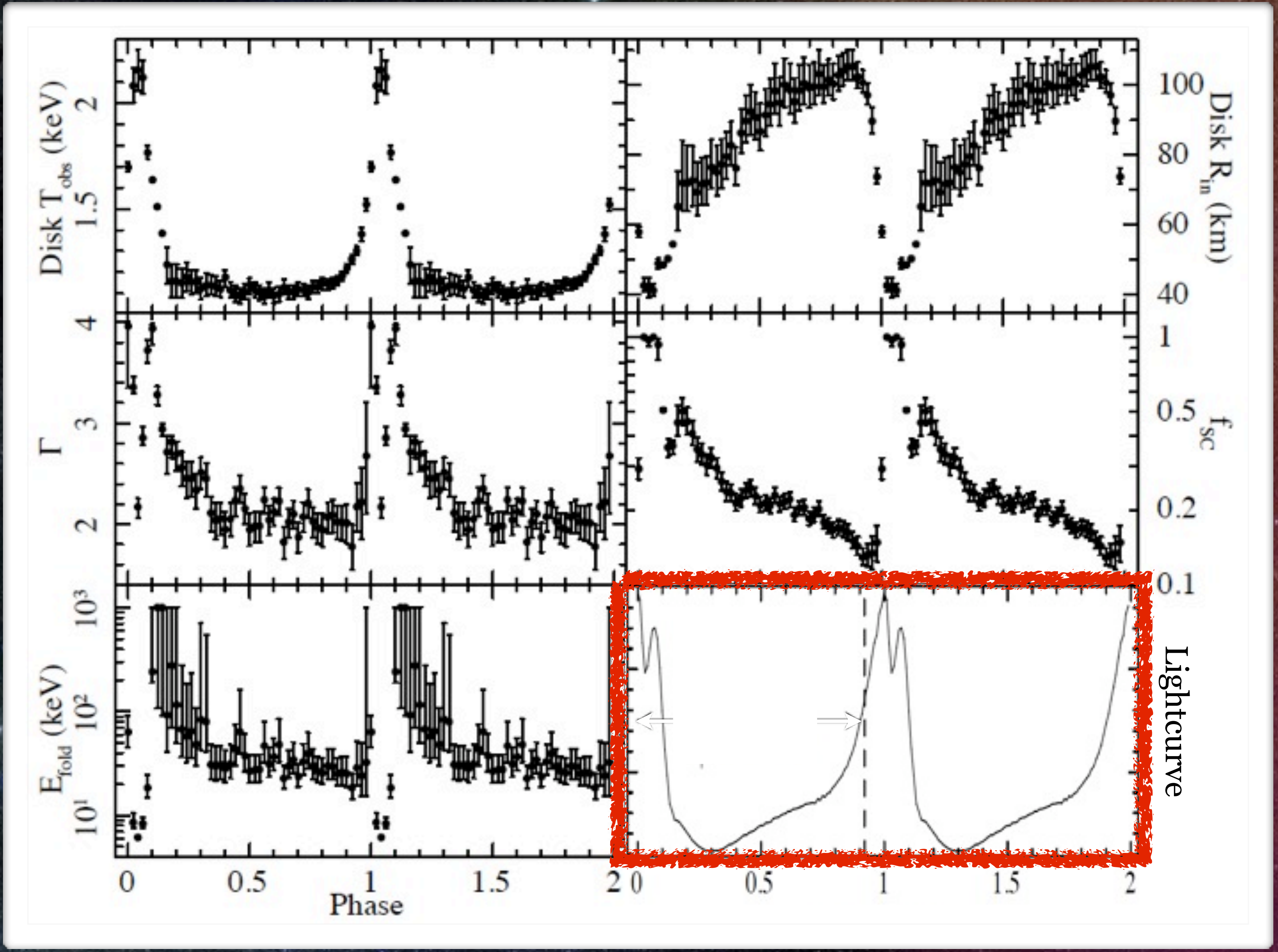


Conclusion

- Can do really amazing physics with spectral variability at high resolution with the *Chandra* HETGS:
  - Atomic Physics, Doppler shifts: What are we seeing, where is it, where is it going, and why?
  - Photoionization: Origin, evolution, and influence of winds (from disks or stars)
  - Variability: Accretion instabilities and disk dynamics
    - Oscillations, Quasi-regular cycles, Irregular variability
  - ***Links between radiation, accretion processes, and outflows***

OPTICAL & INFRARED

The Heartbeat State



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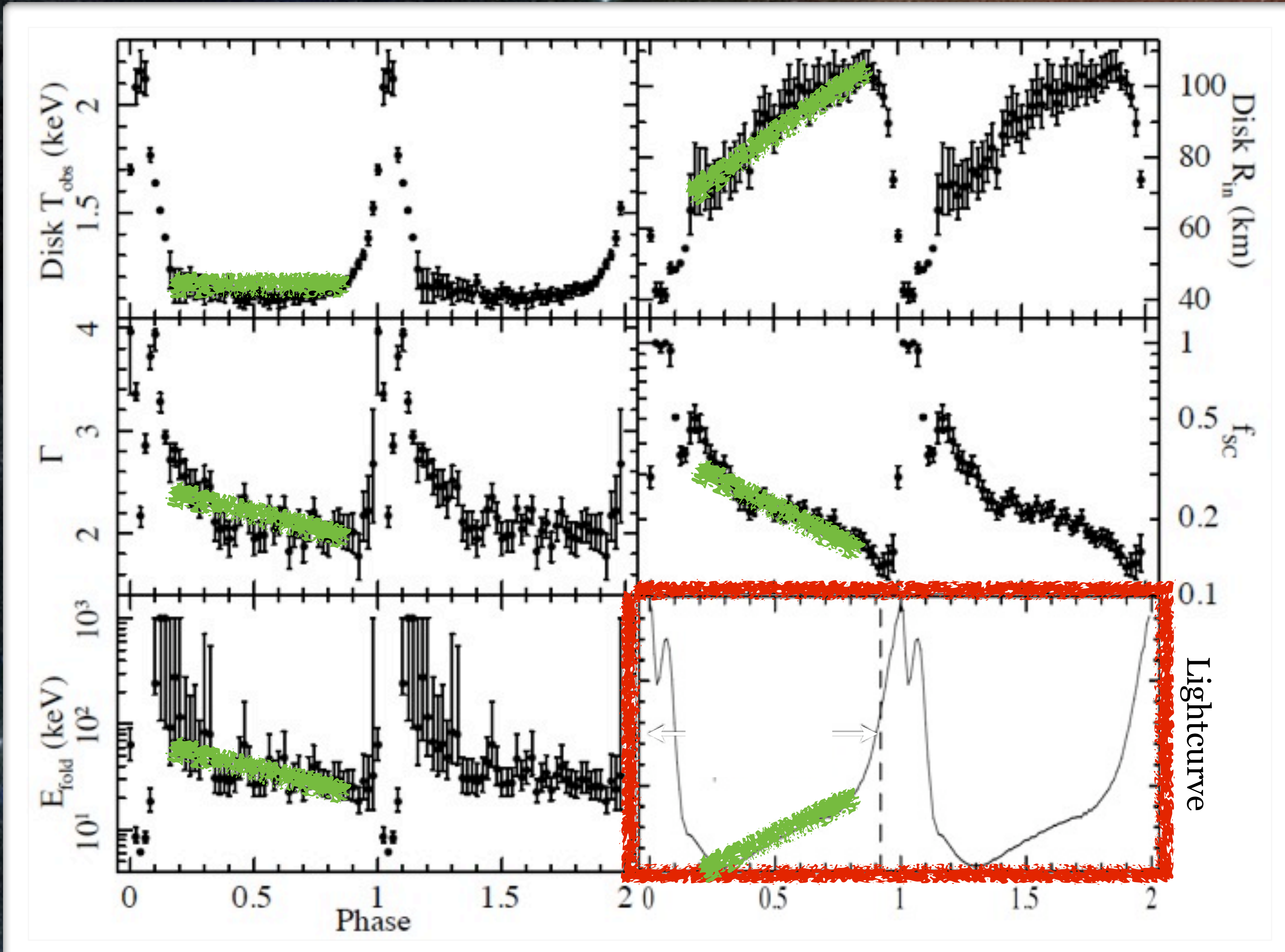

- Smooth changes in the disk, corona, X-rays

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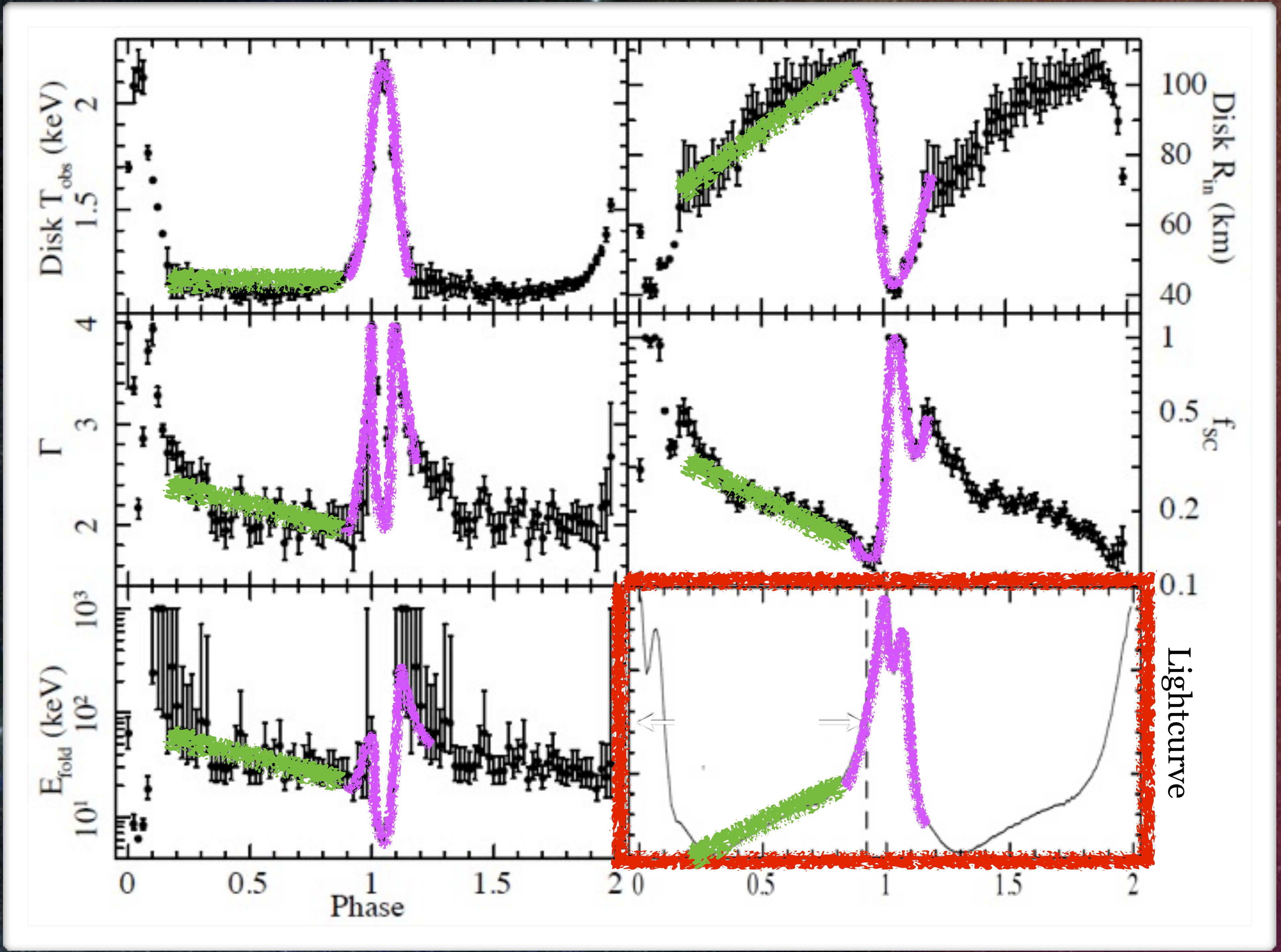

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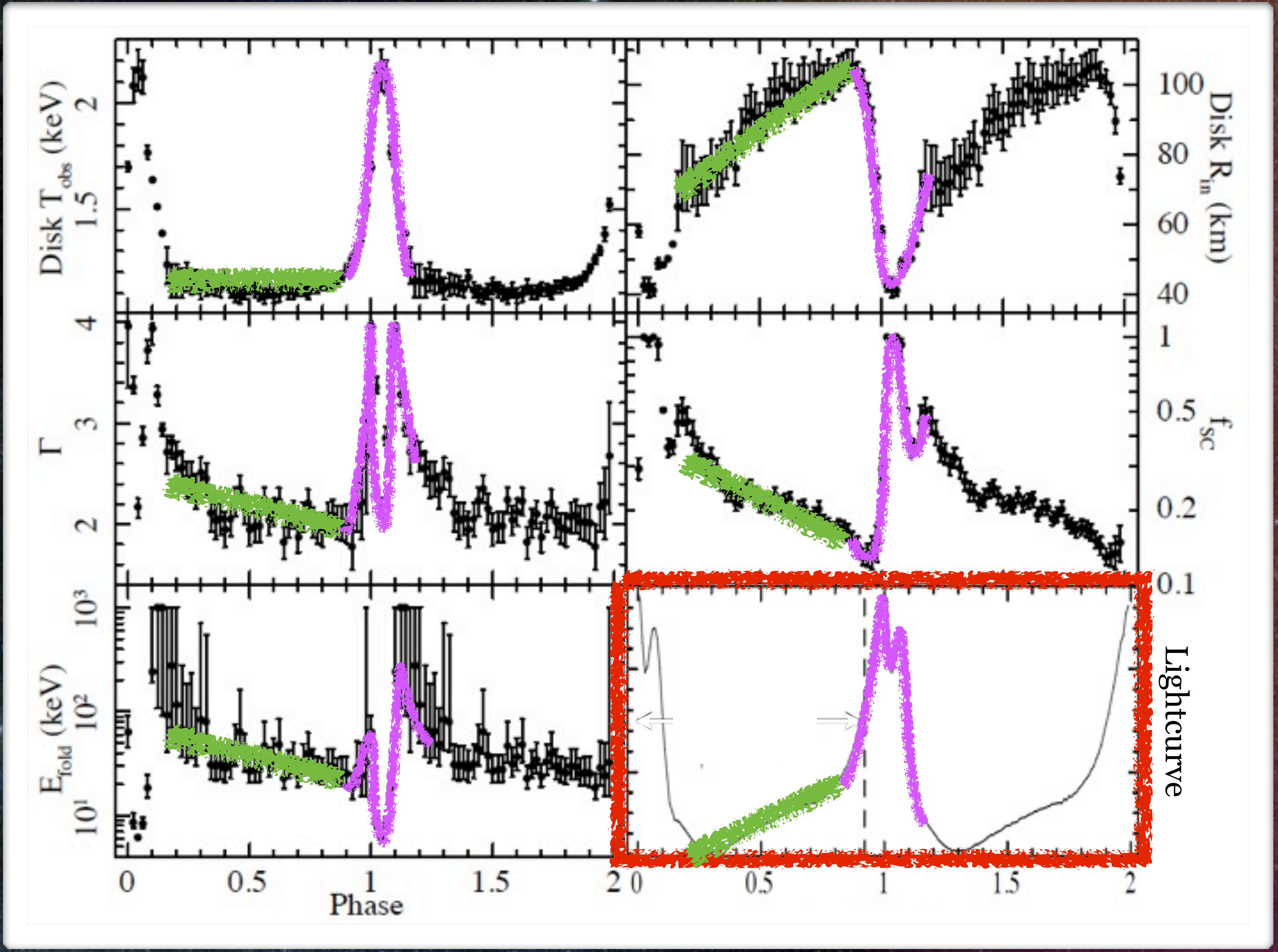


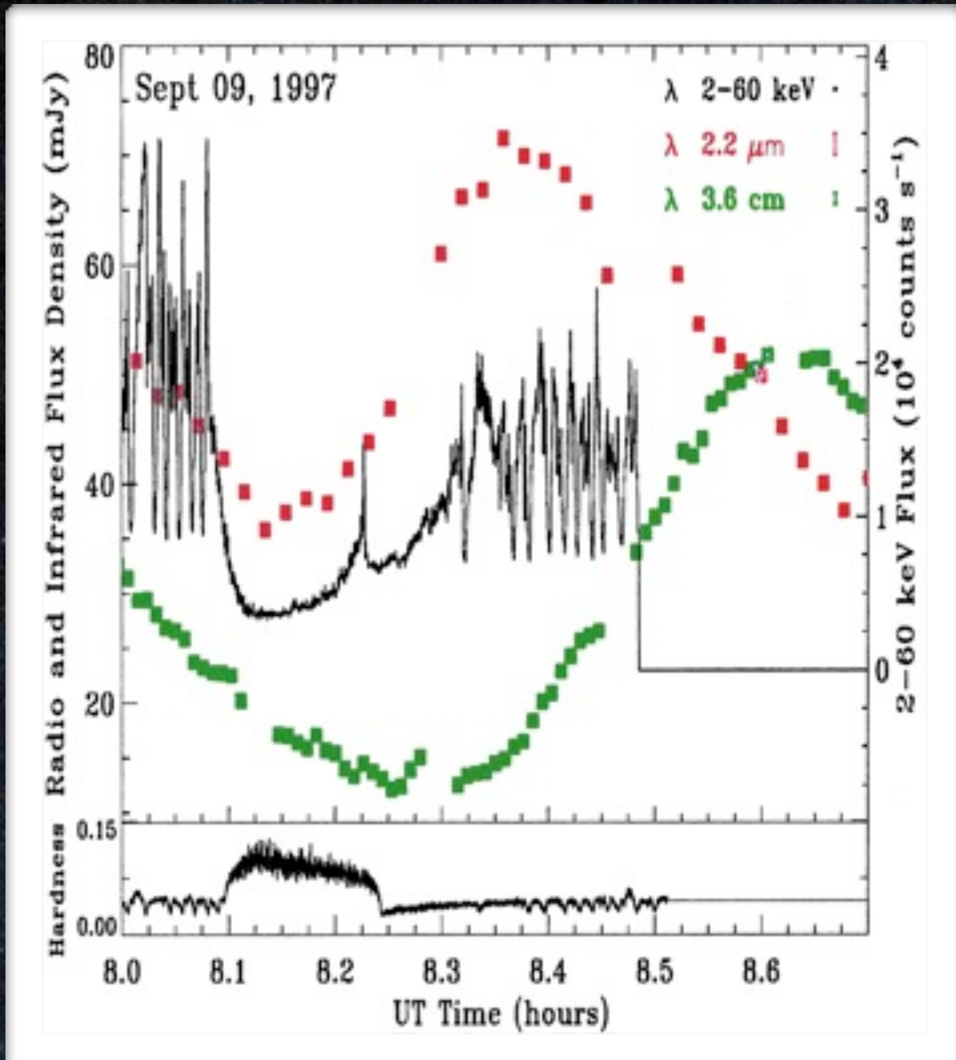
- Smooth changes in the disk, corona, X-rays
- Sudden, catastrophic variability

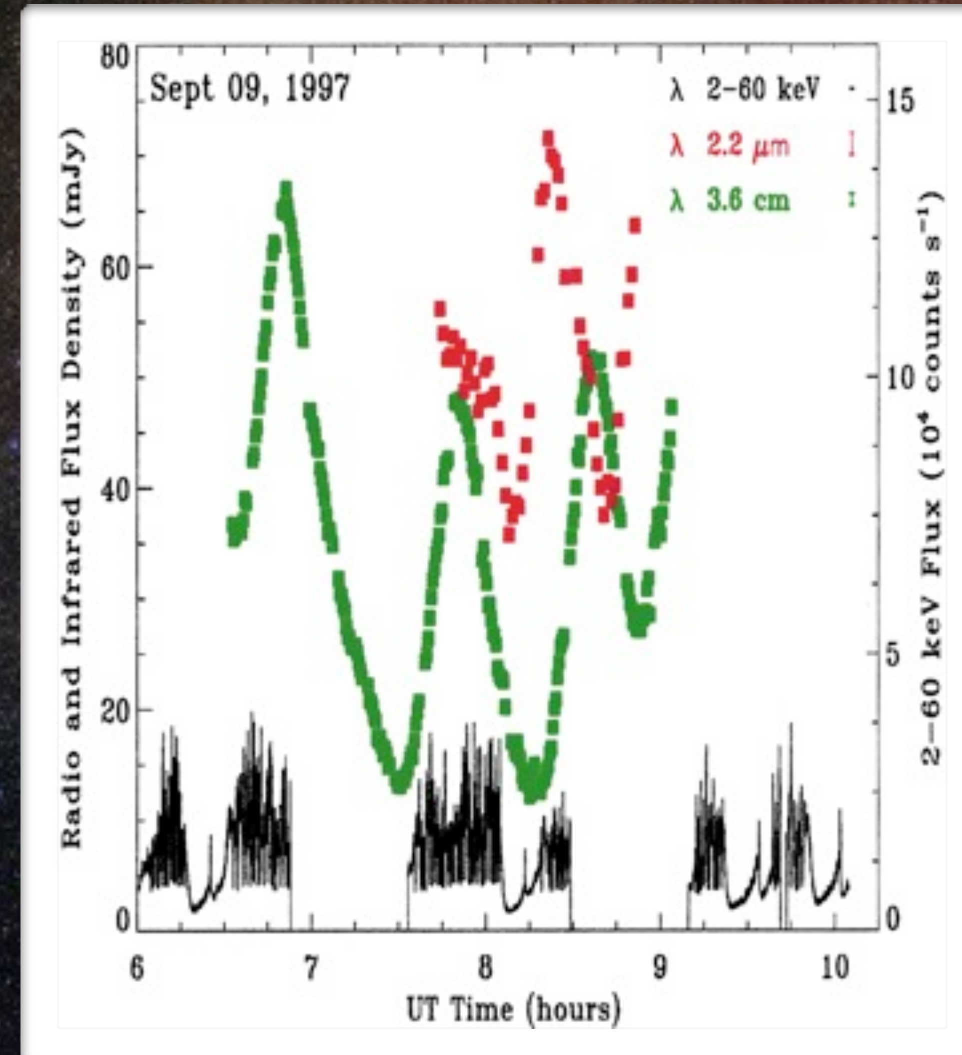
Why GRS 1915+105?

- GRS 1915+105 exhibits strong *spectral* variability: rapidly-changing accretion, ejection, and radiation processes
- Time scales: seconds to decades!

OPTICAL & INFRARED

Why GRS 1915+105?





- Multiwavelength studies clearly indicate a relationship between the jet (radio/infrared) and the accretion disk (X-ray) (Mirabel et al. 1998)
- ***14*** classes of variability represent "limit cycles" of accretion and ejection

OPTICAL & INFRARED

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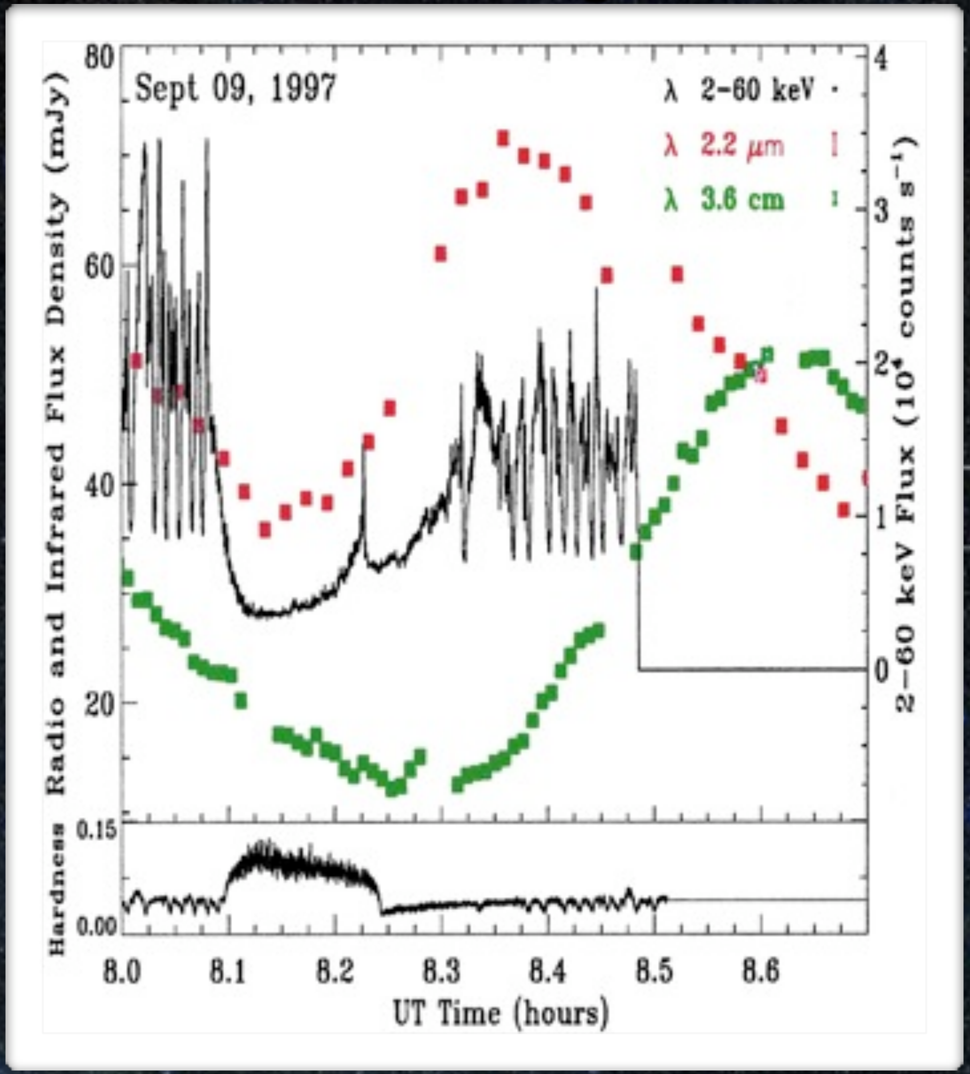

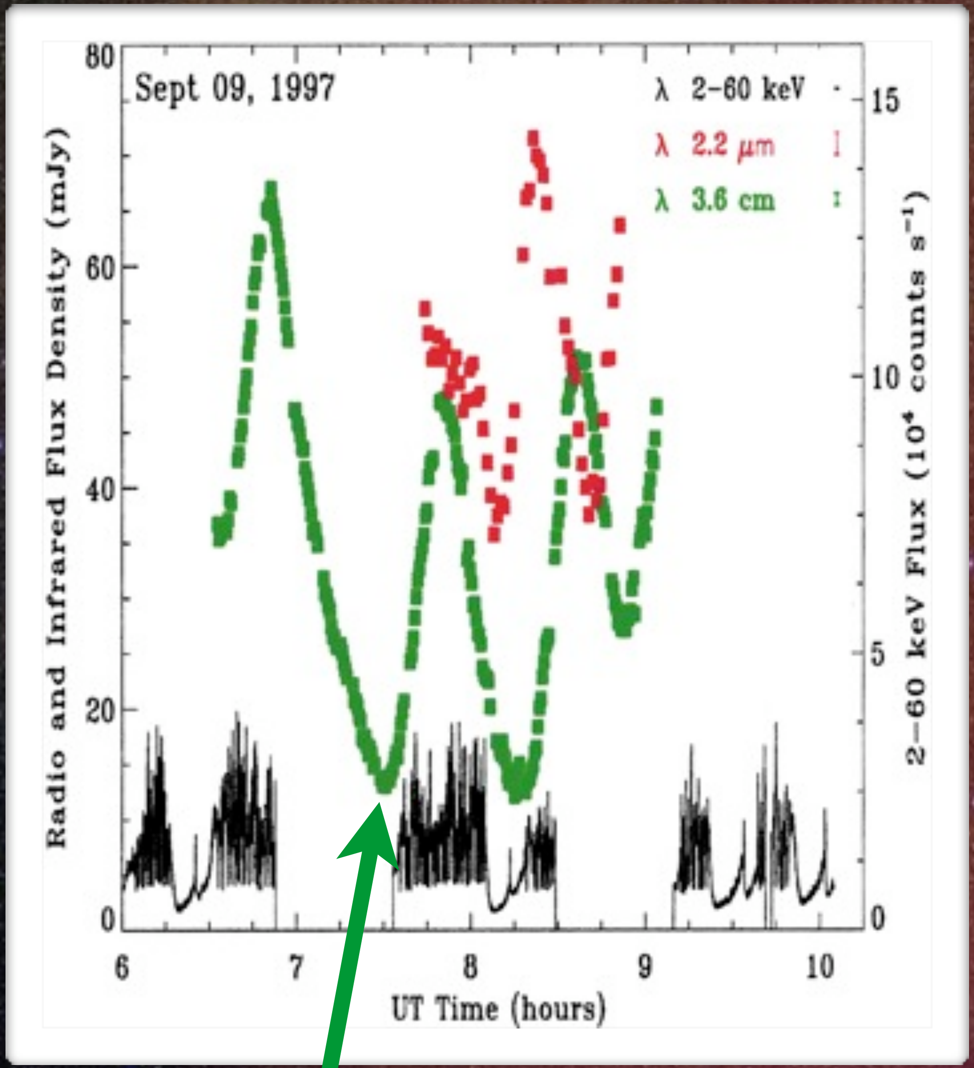

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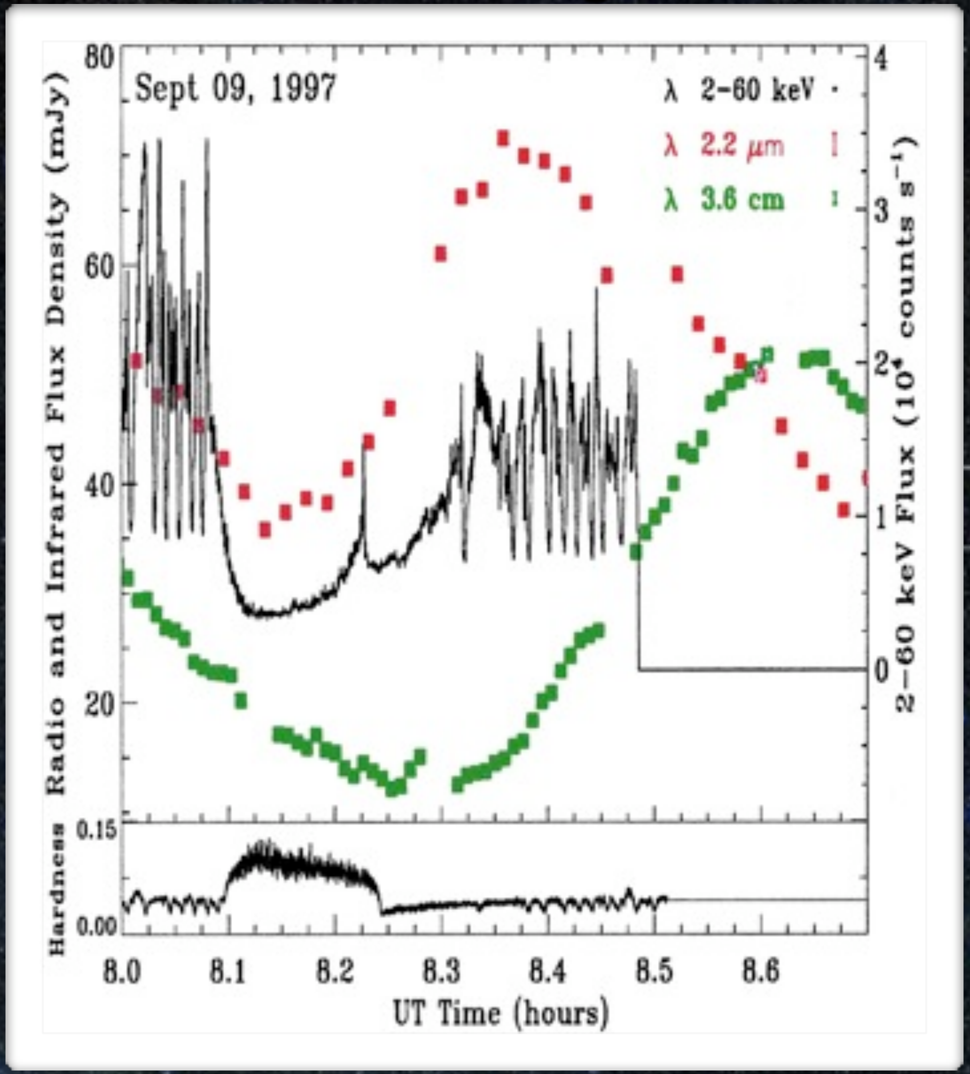

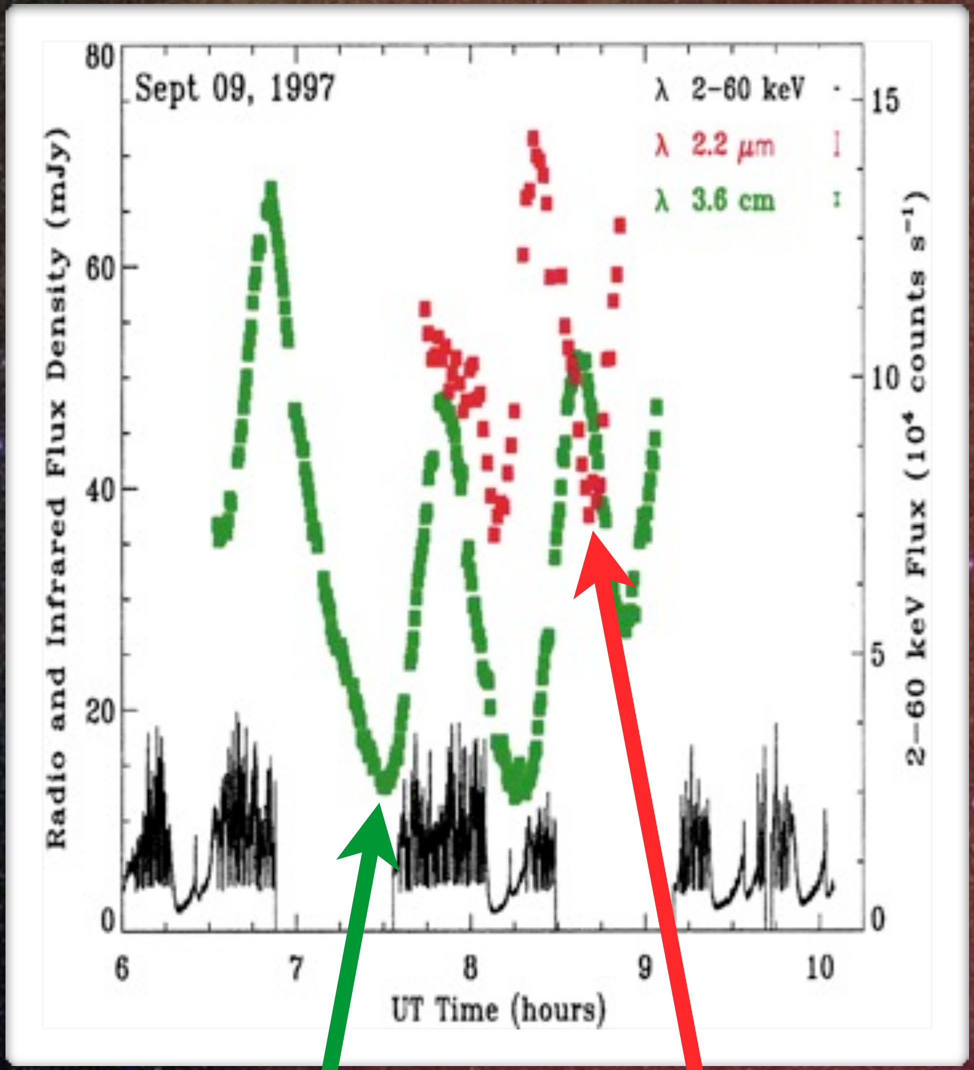

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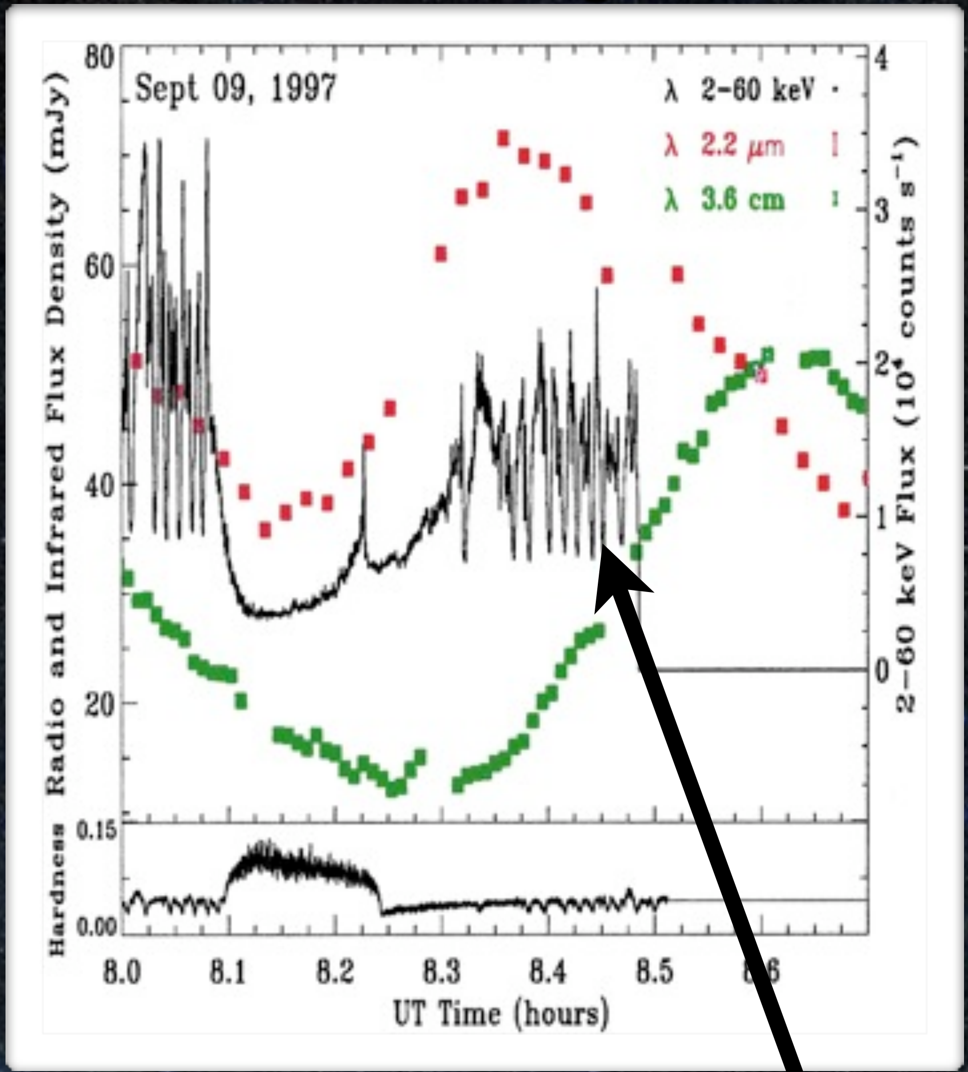

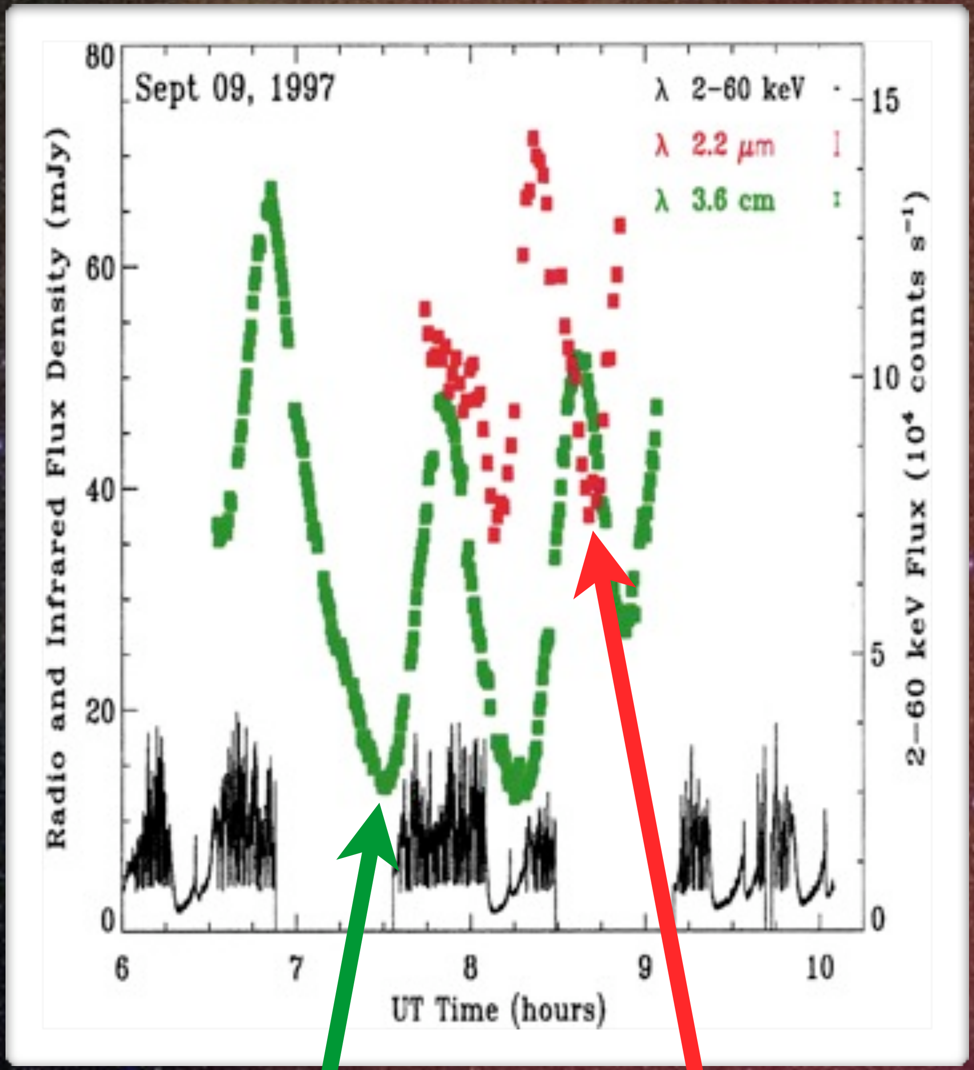

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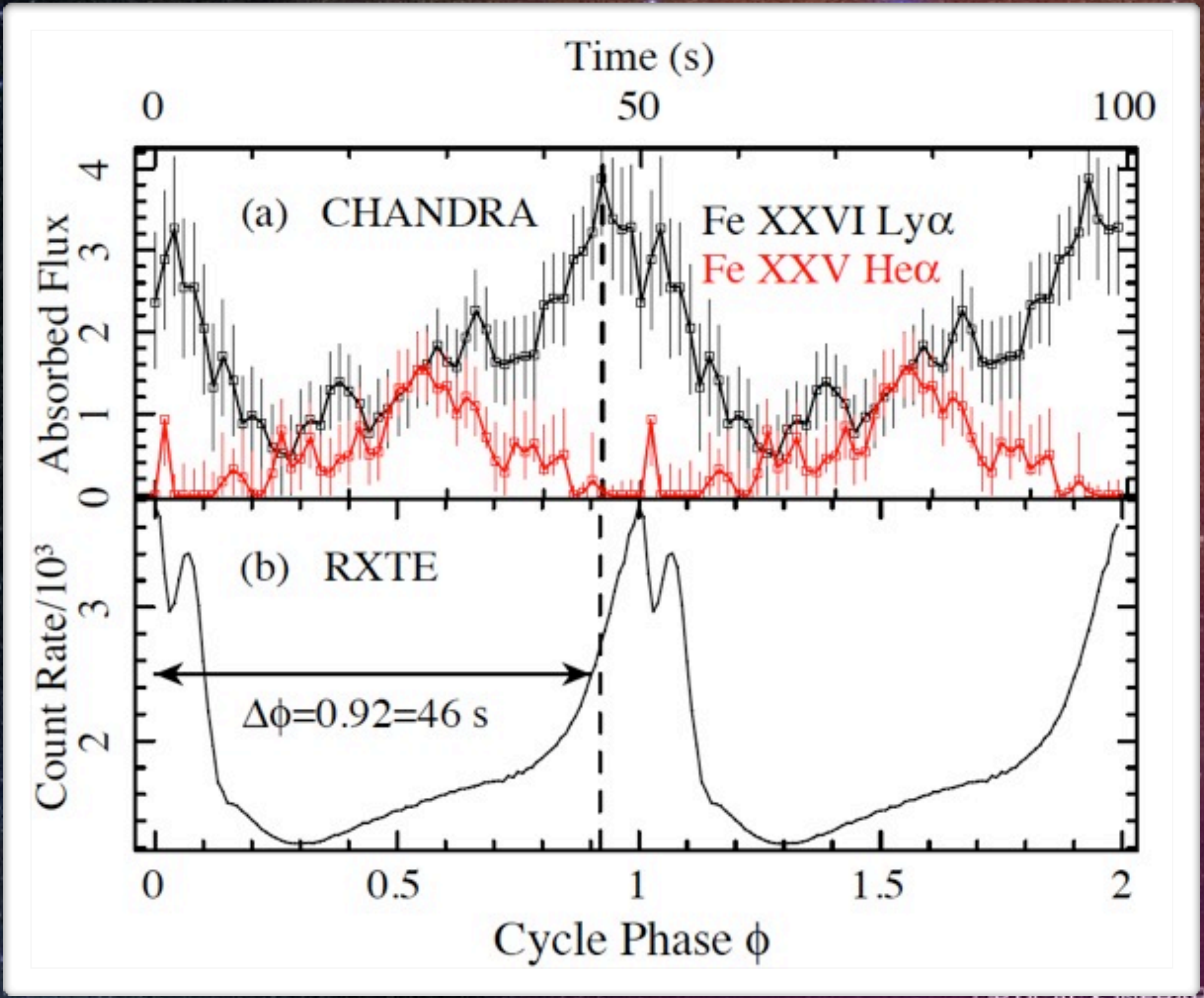
OPTICAL & INFRARED

Disk Wind Variability

- Highly ionized ABSORPTION: only Fe XXV, Fe XXVI
- Blueshifted by ~1000 km/s (same as we found in 10 yrs of data)

- Extremely variable
- Modulated like light-curve
- Wind changes in t≲5 seconds!!
- Unprecedented fast wind variability, on timescales shorter than dynamical, viscous, and sound crossing times



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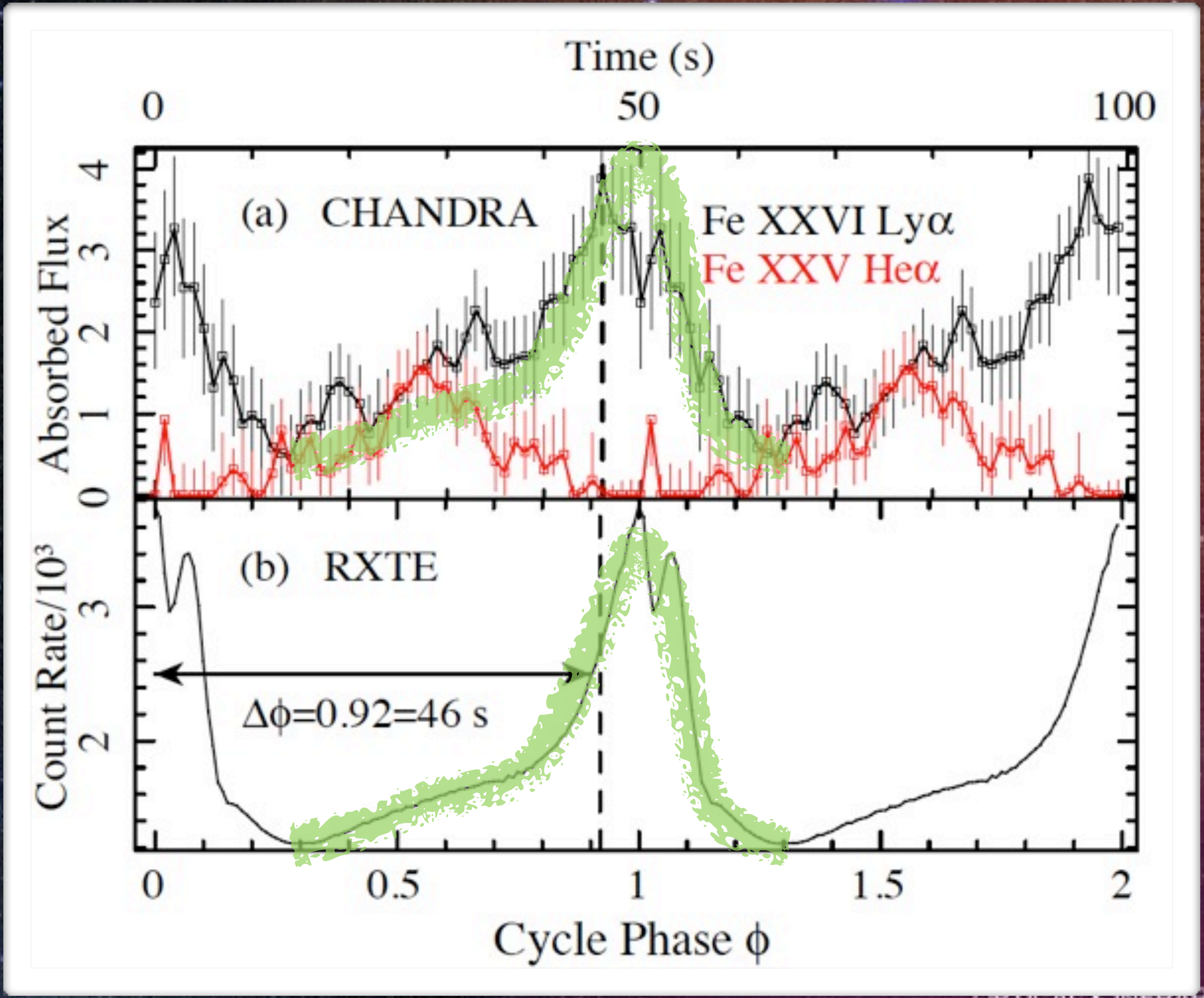

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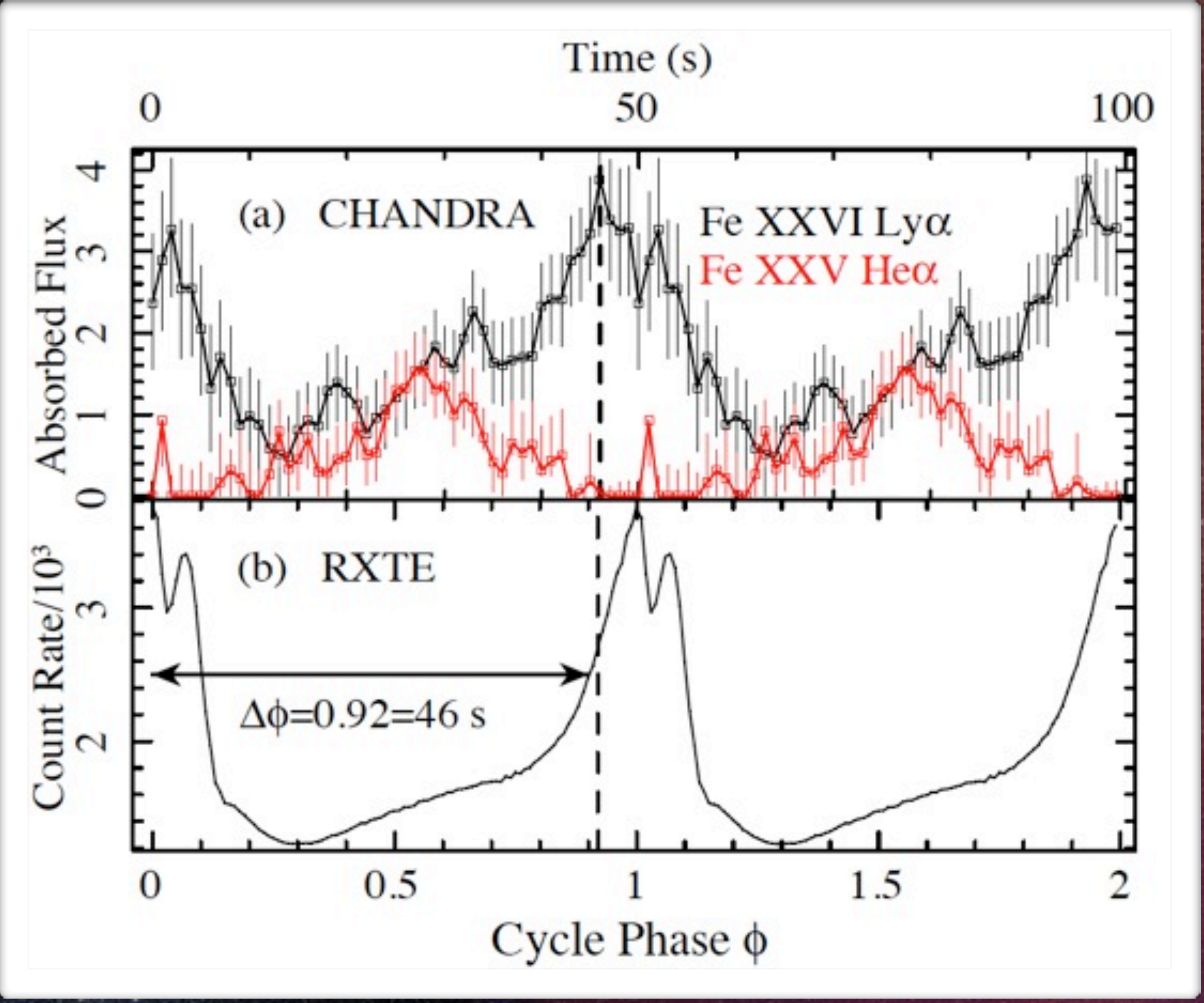
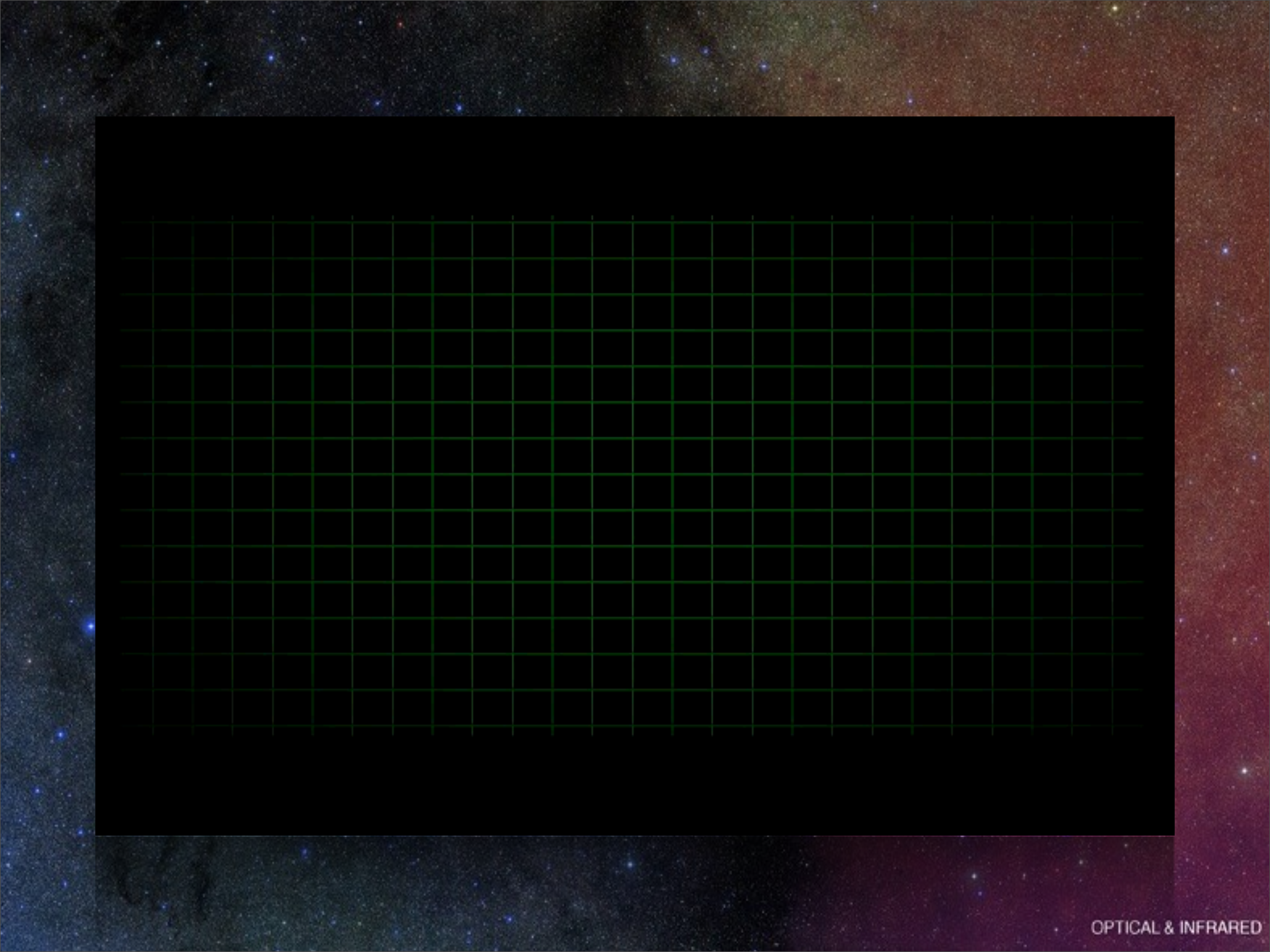


- For this type of wind, we estimate $\dot{M}_{wind} \lesssim 25\ \dot{M}_{BH}$

OPTICAL & INFRARED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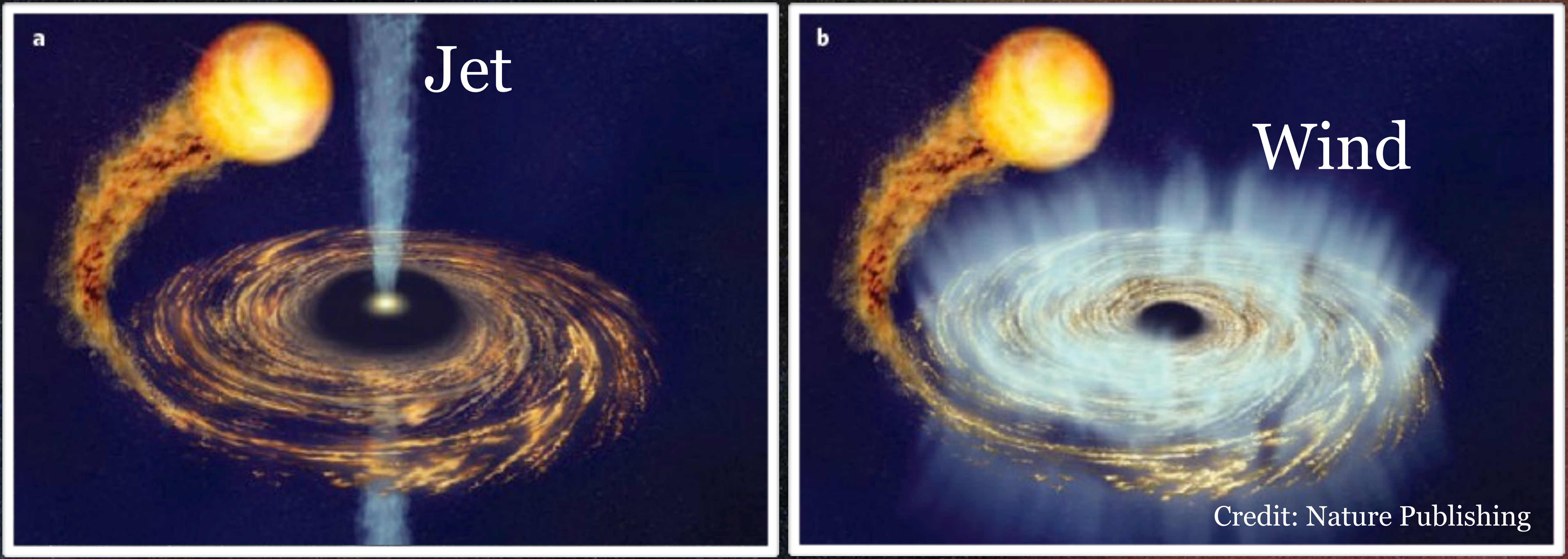
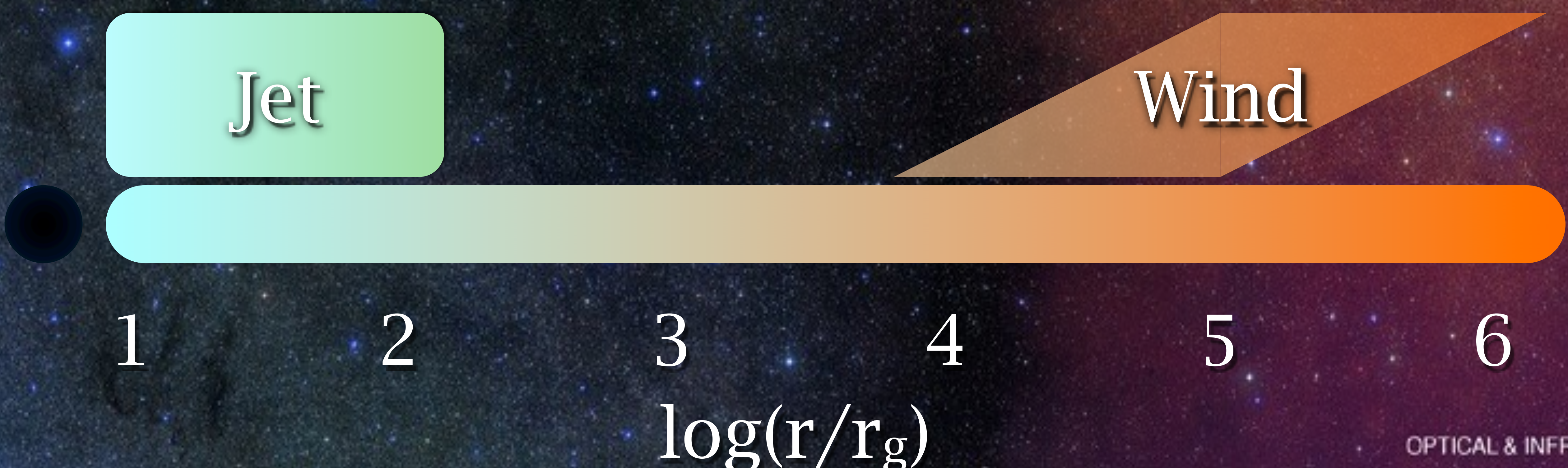
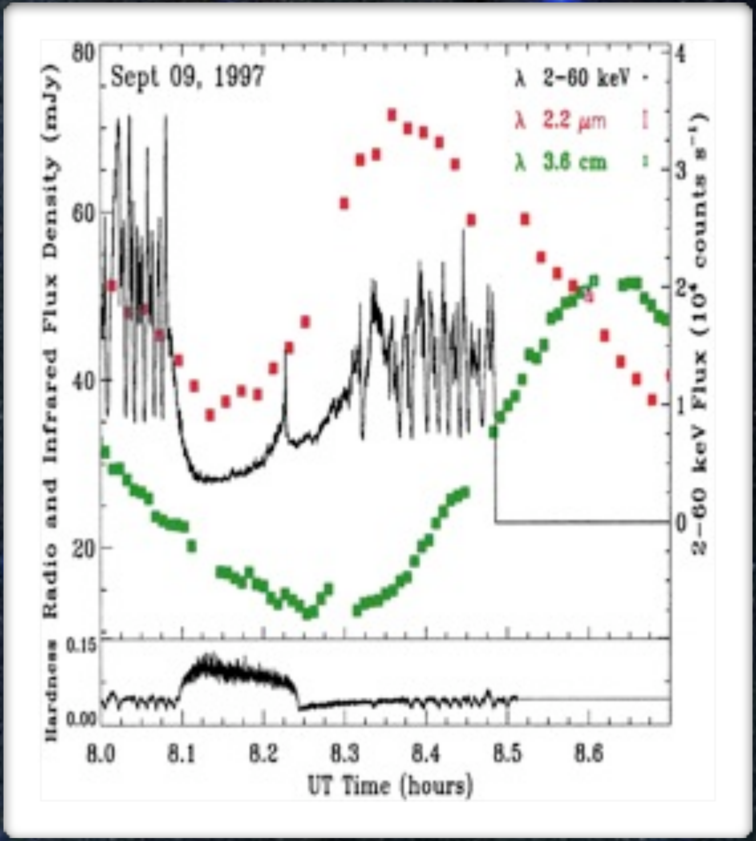
Outflows and Definitions

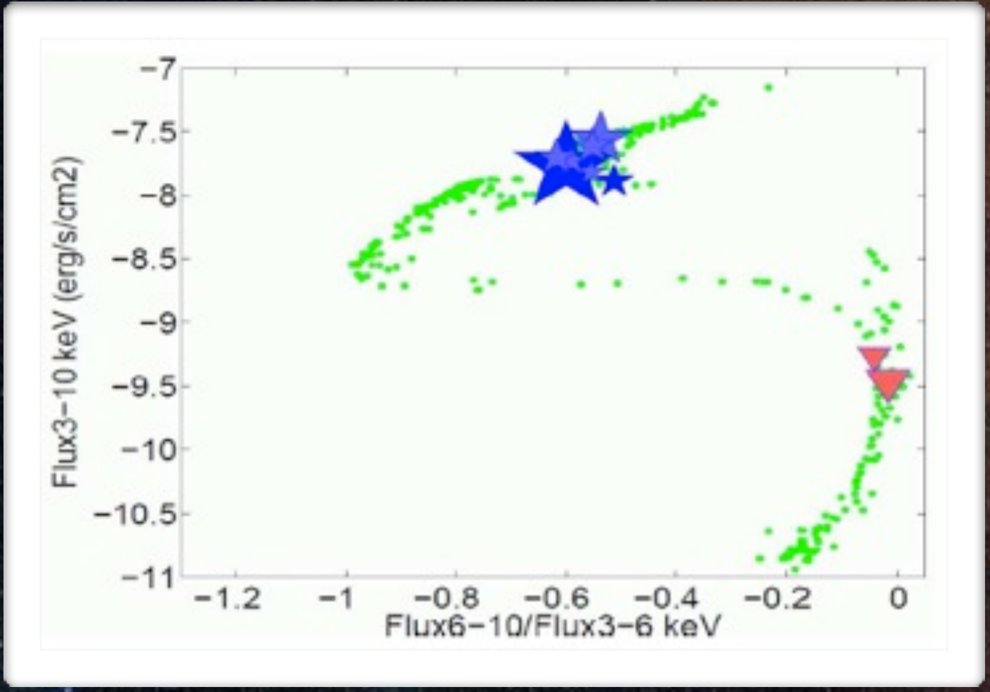




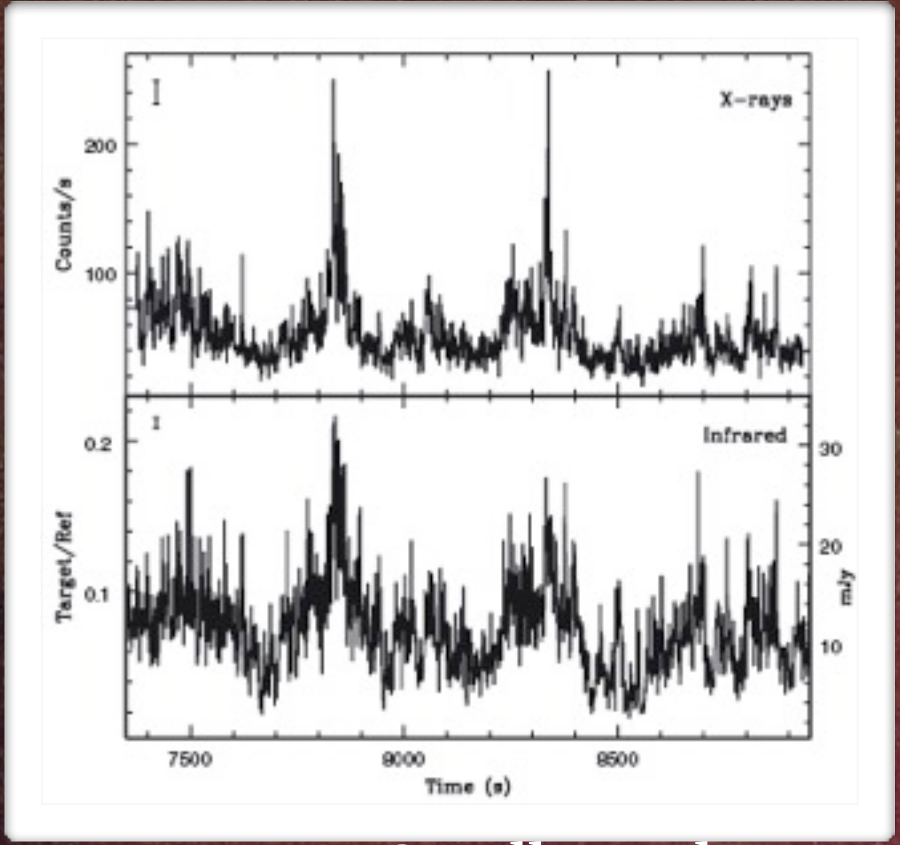
Future Directions: Multi-Outflow Variability Studies



Mirabel et al 98



Ponti et al 2011



Casella et al 2010

- New radio, IR capabilities are beginning to allow jet monitoring on <1s timescales
- Simultaneous monitoring of all major accretion/ejection processes every second!

OPTICAL & INFRARED

Does This Actually Work?

$i=66^\circ$

$\log(\theta)$

- s

Proga et al 2011

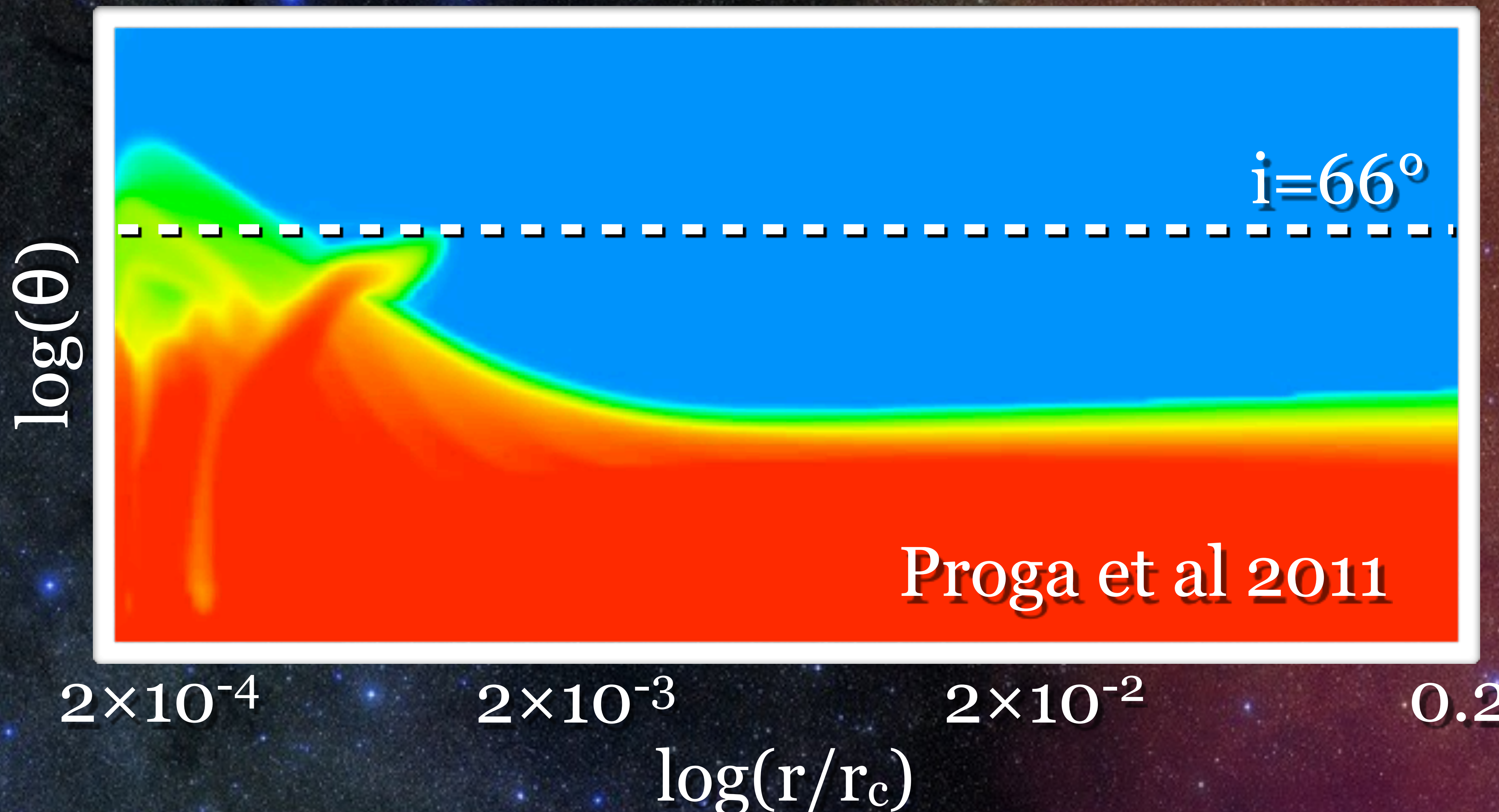
2×10^{-4} 2×10^{-3} 2×10^{-2} 0.2

$\log(r/r_c)$

- Hydrodynamic simulations with strong luminosity variations based on heartbeat state

OPTICAL & INFRARED

Does This Actually Work?



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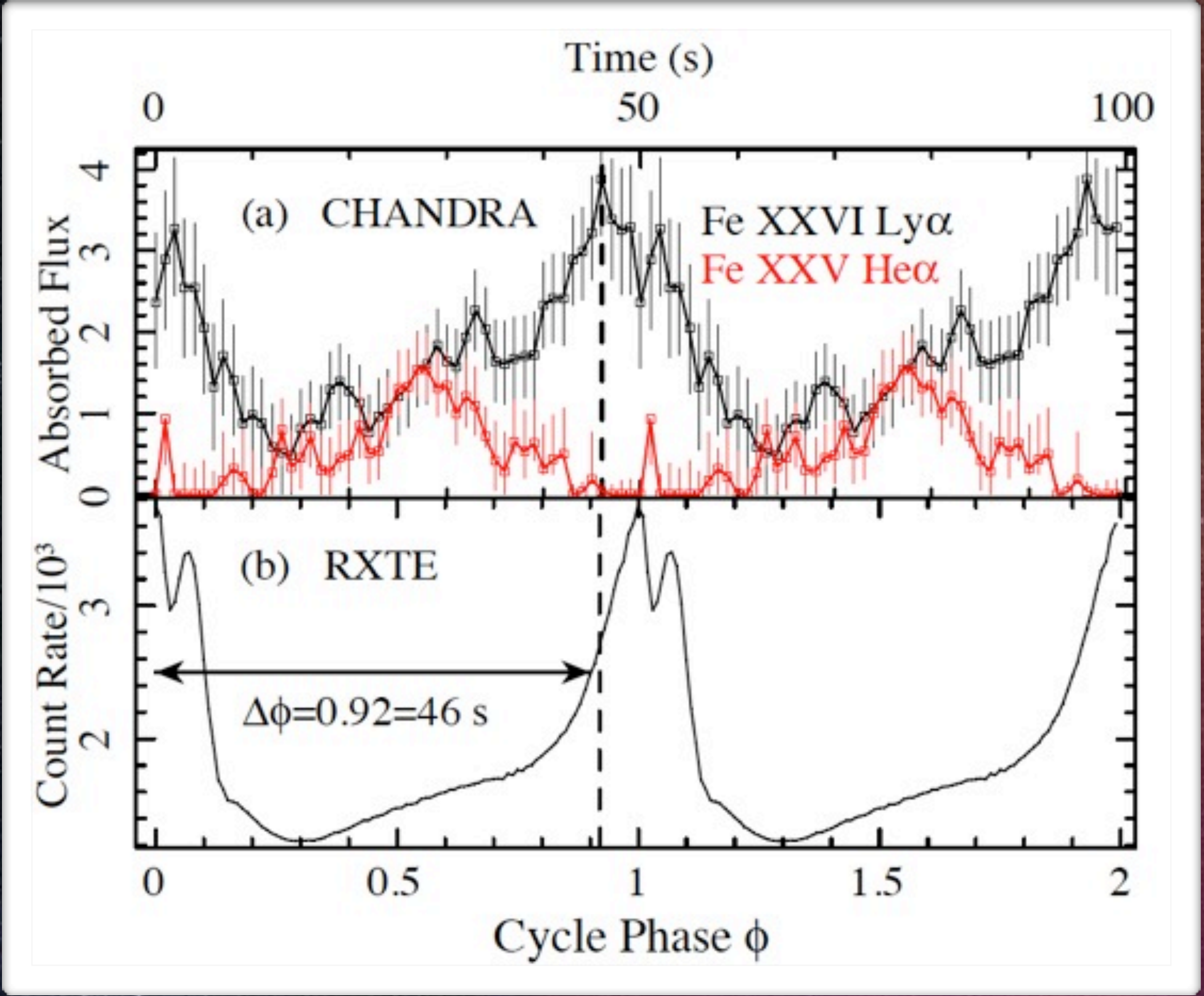

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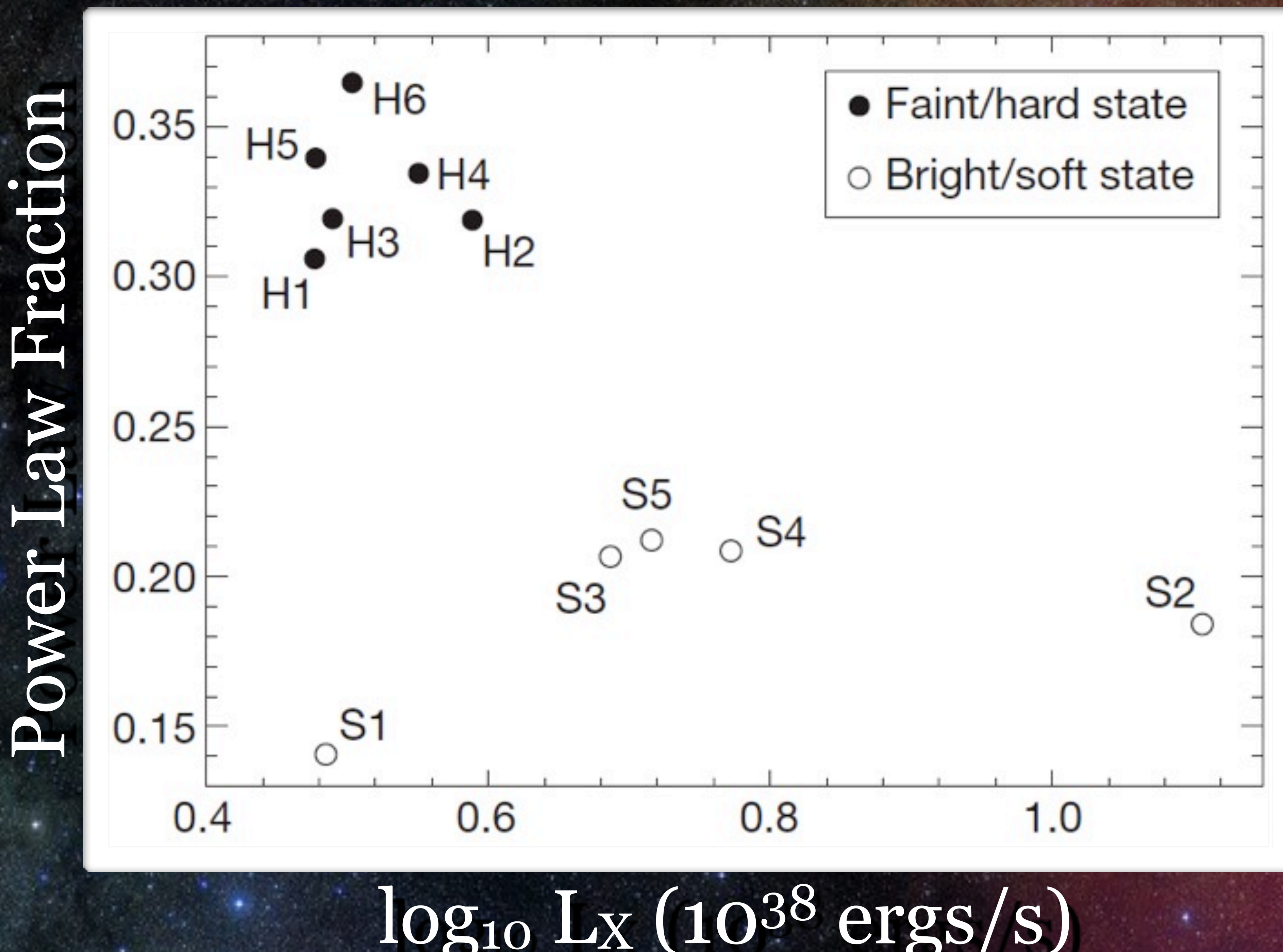
11 Observations



- Power law fraction vs X-ray luminosity
- Interestingly, spectral lines vary with power law fraction

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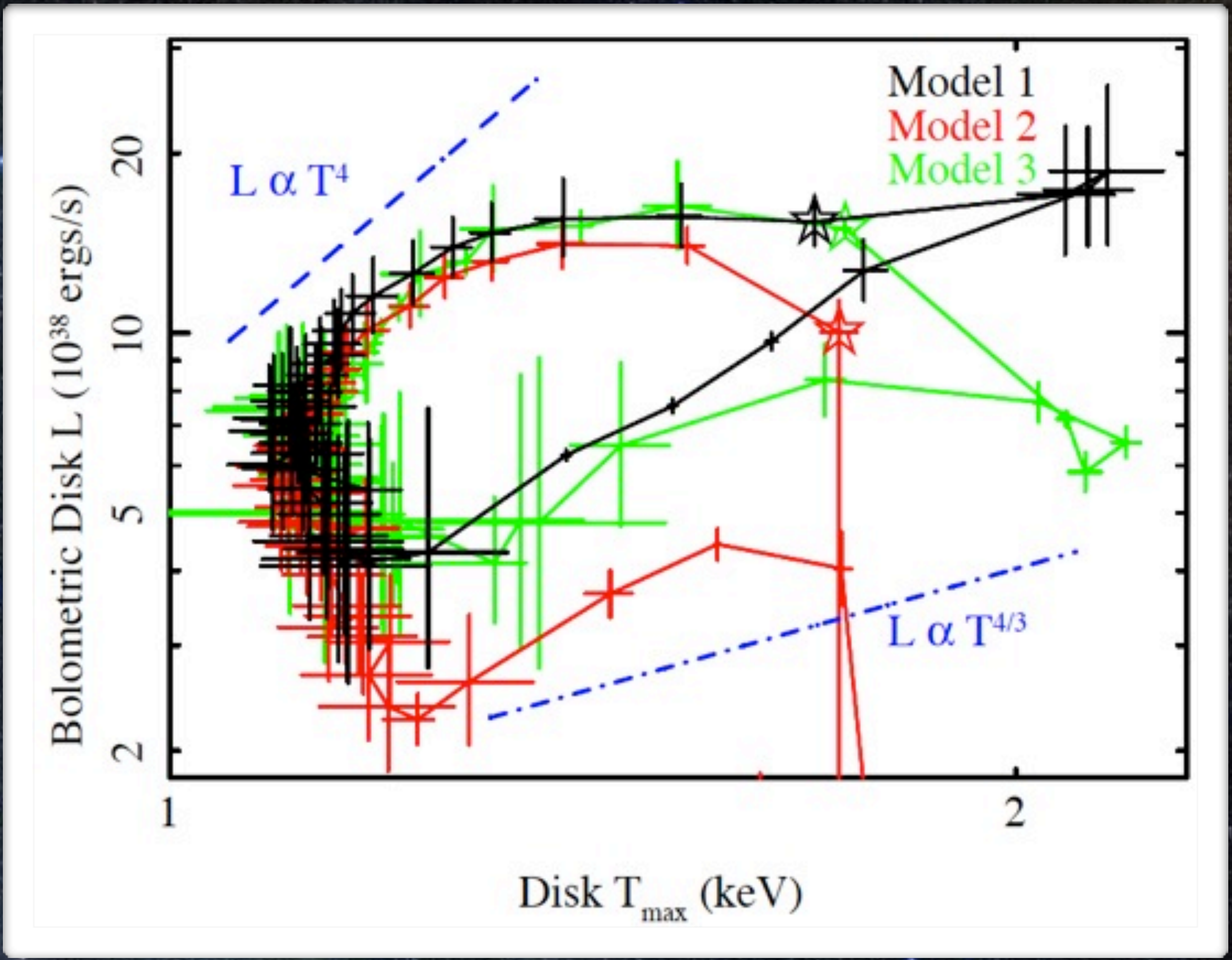
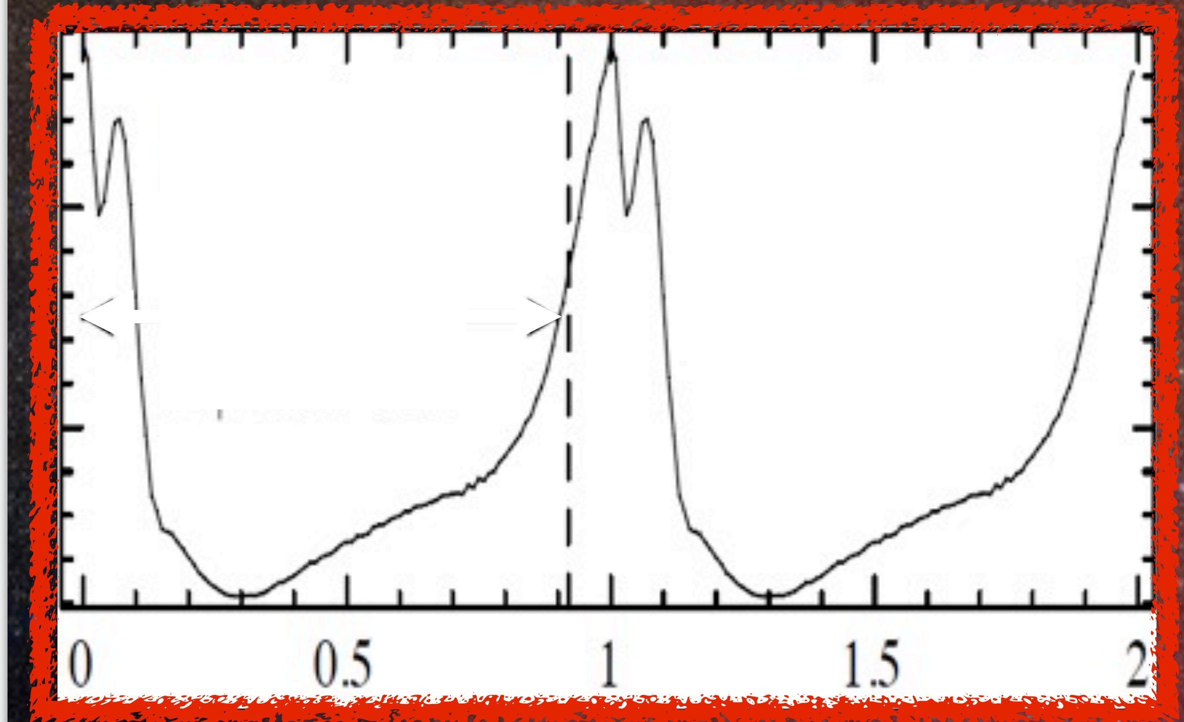
Tracking the Accretion Flow





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- Rising luminosity at constant temperature
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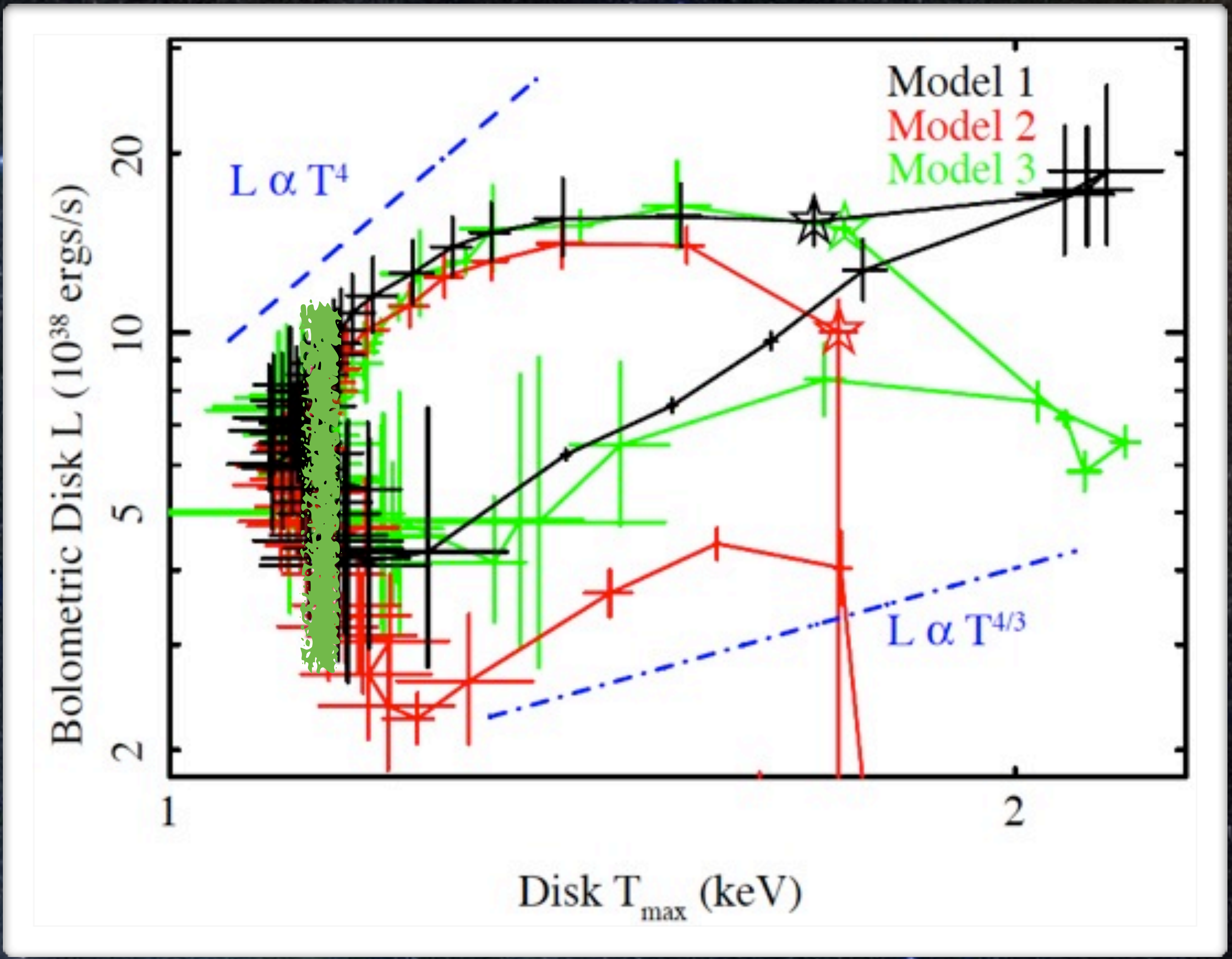

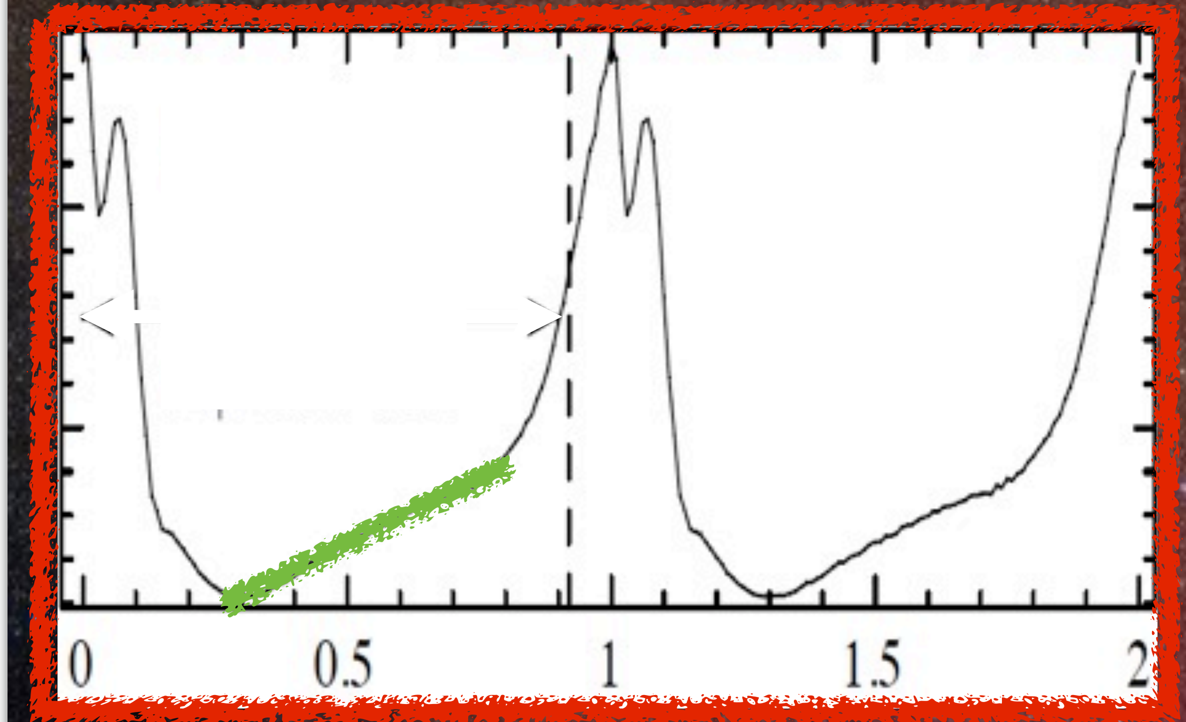

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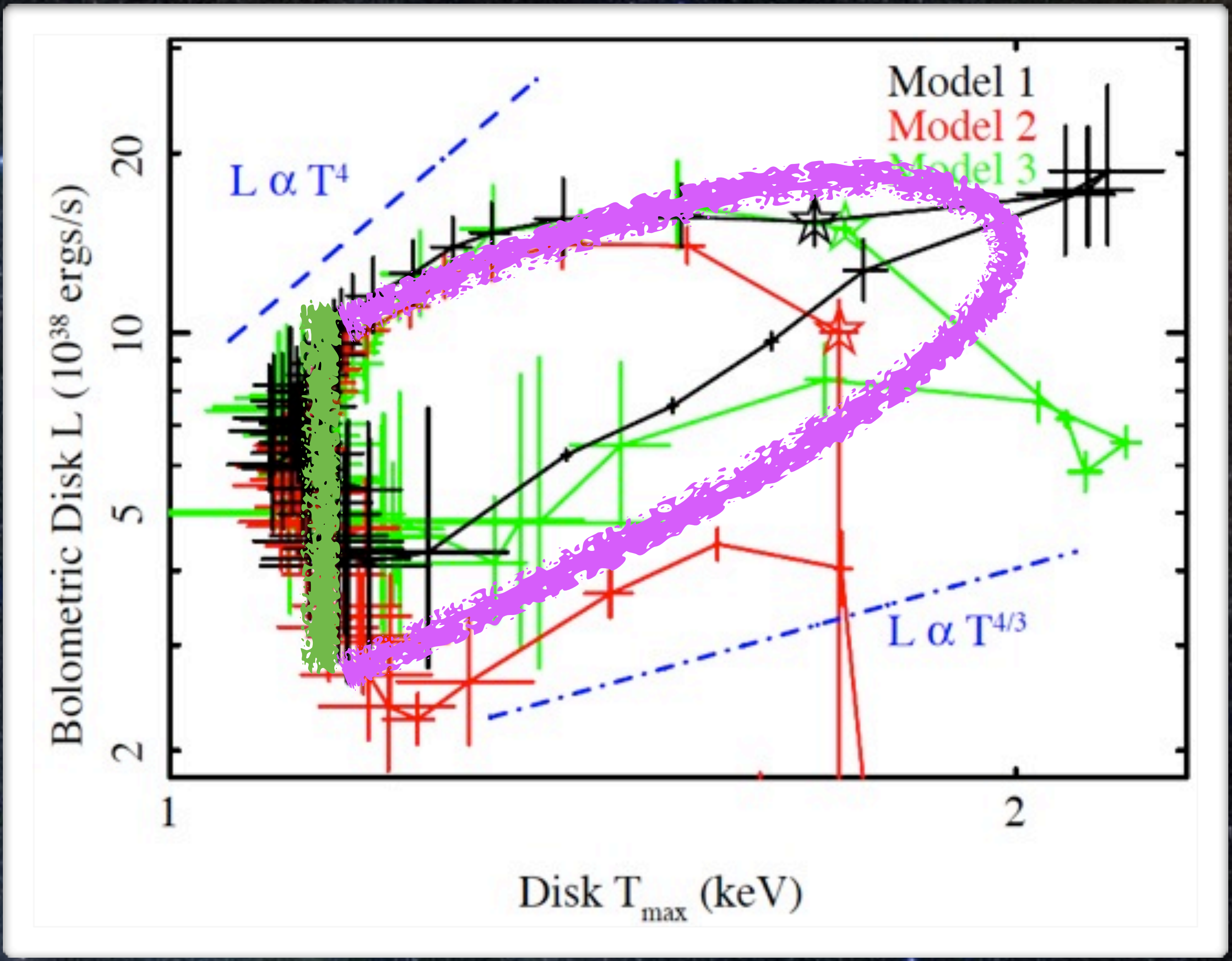

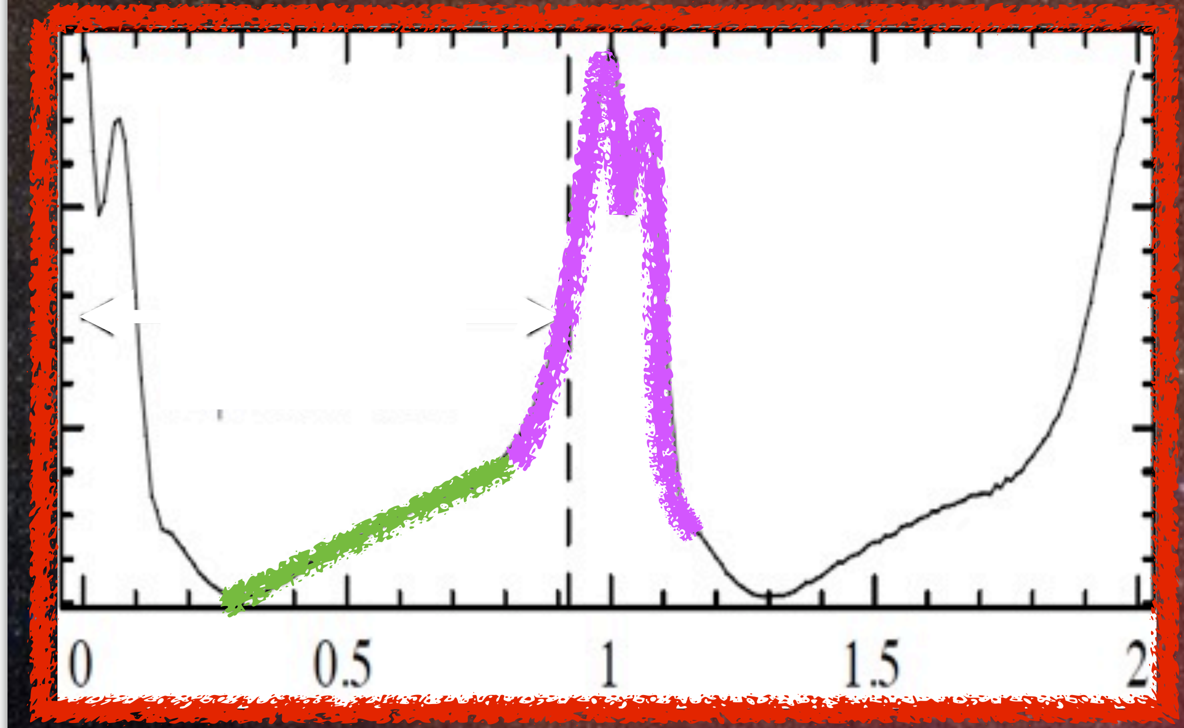

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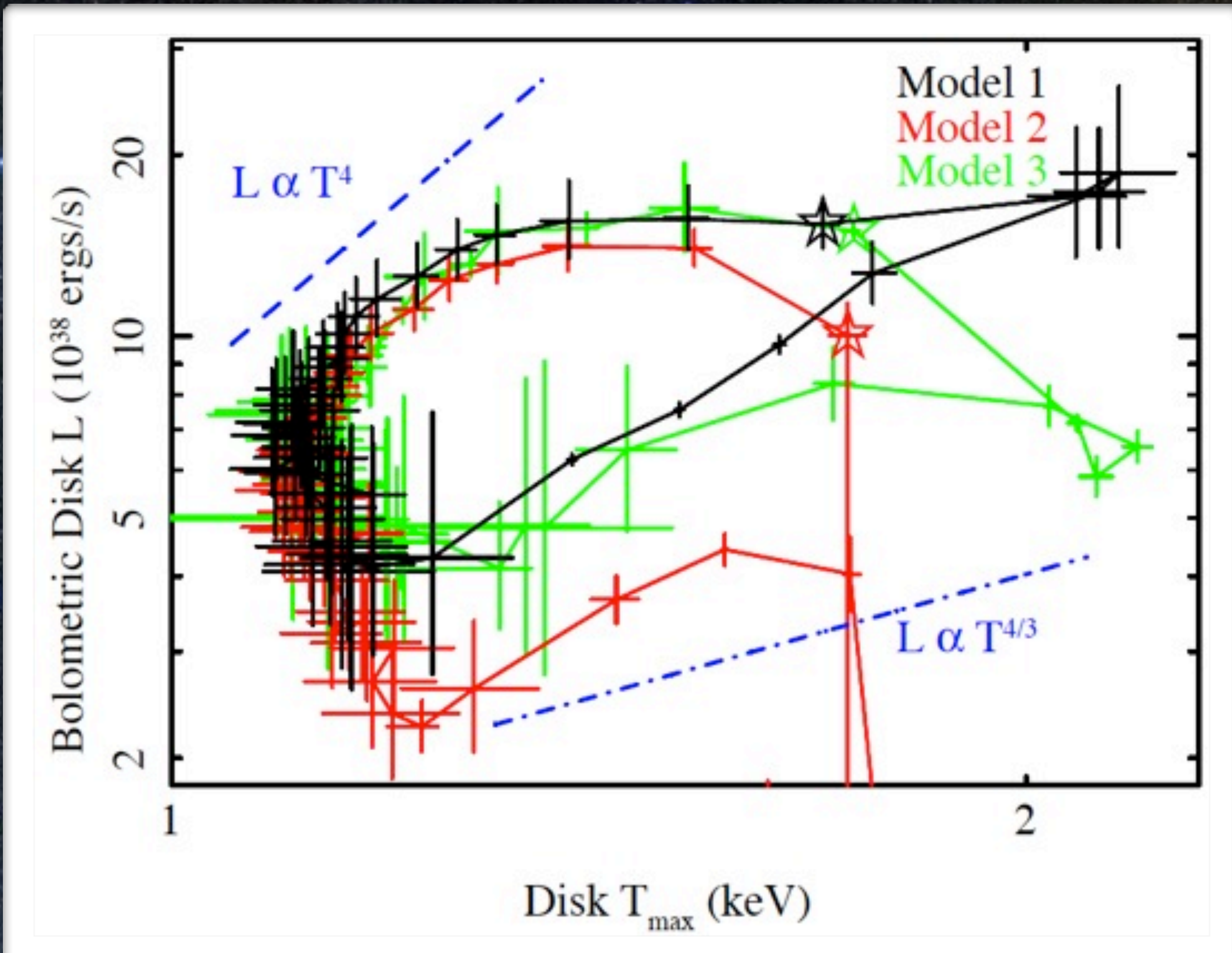

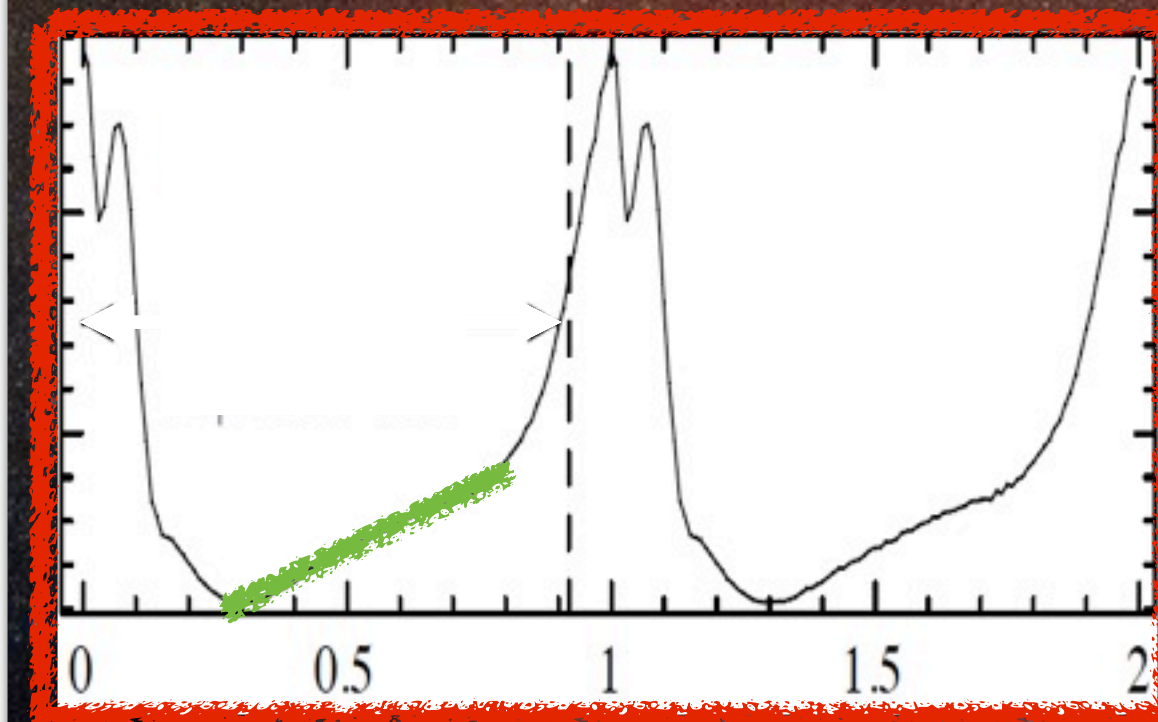

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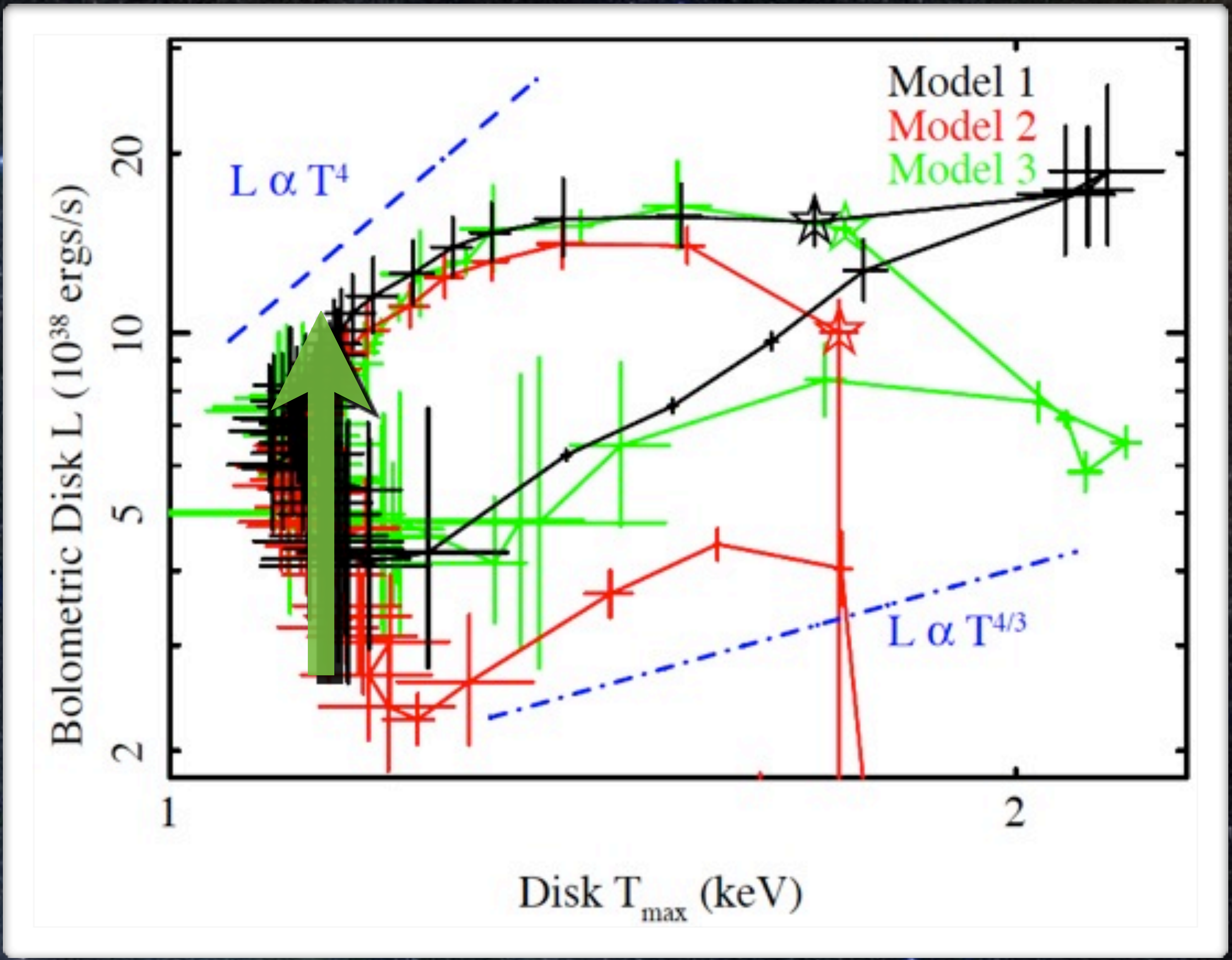

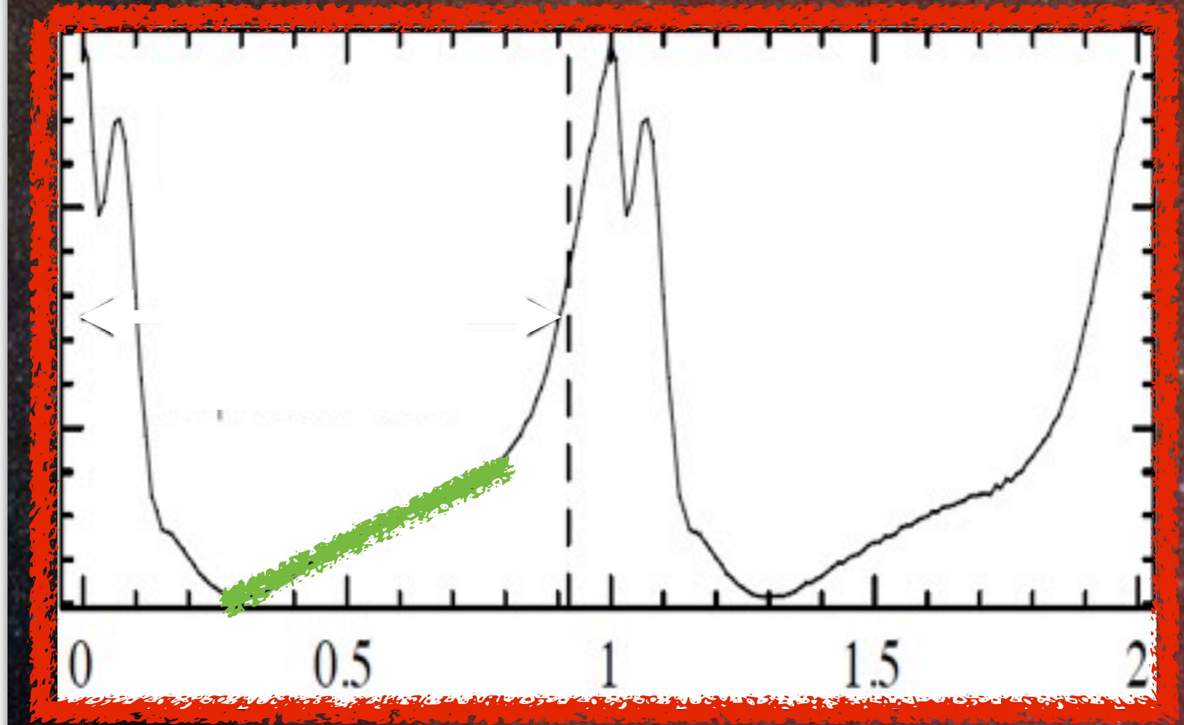

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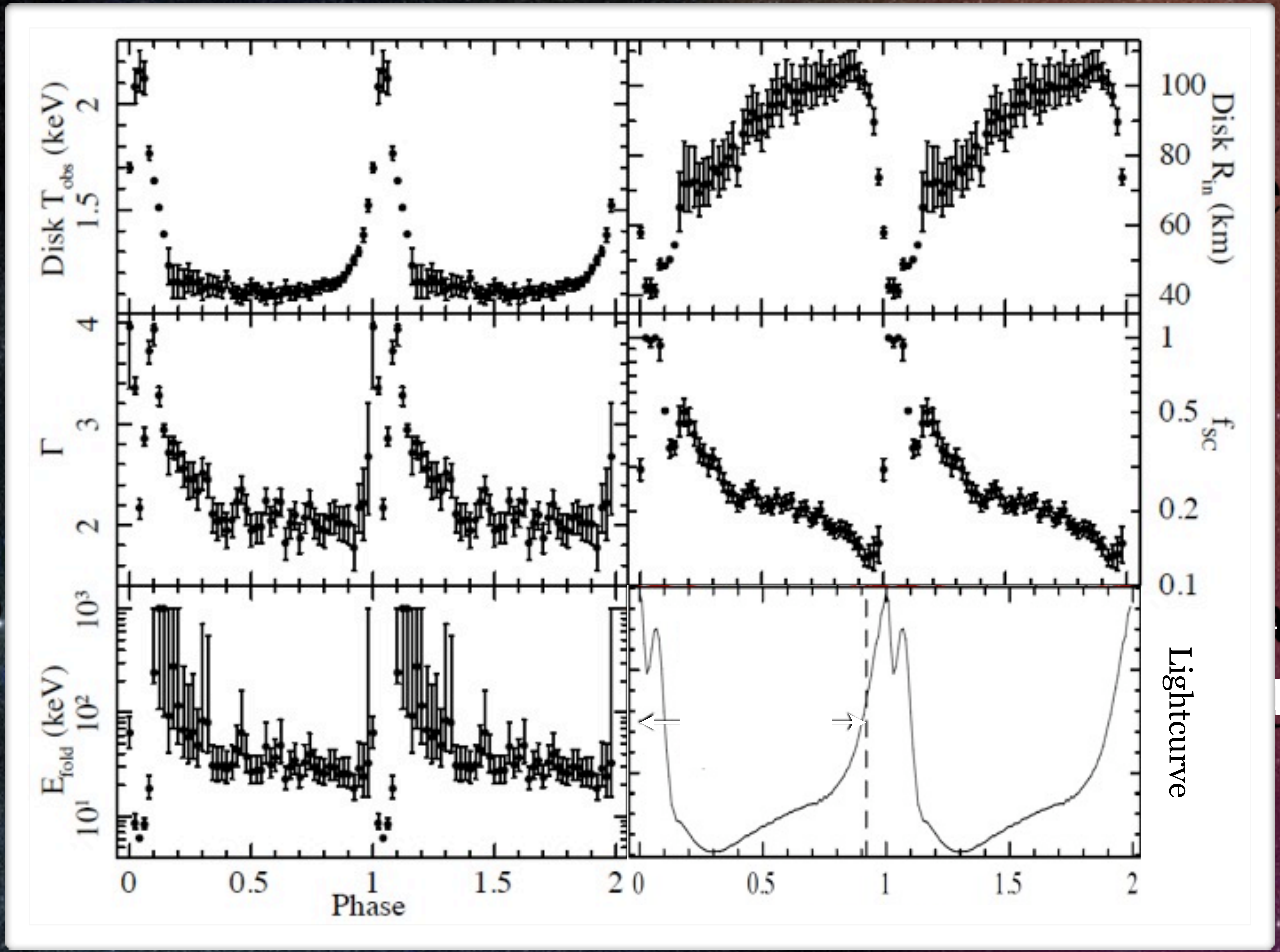
Local Eddington Limit?

- Local Eddington effects arise because radiation pressure, gravity have different radial dependence

- Allows radiation pressure to disrupt a thin disk inside a critical radius (Fukue 2004; Lin 2009)

OPTICAL & INFRARED

Local Eddington Limit?



OPTICAL & INFRARED

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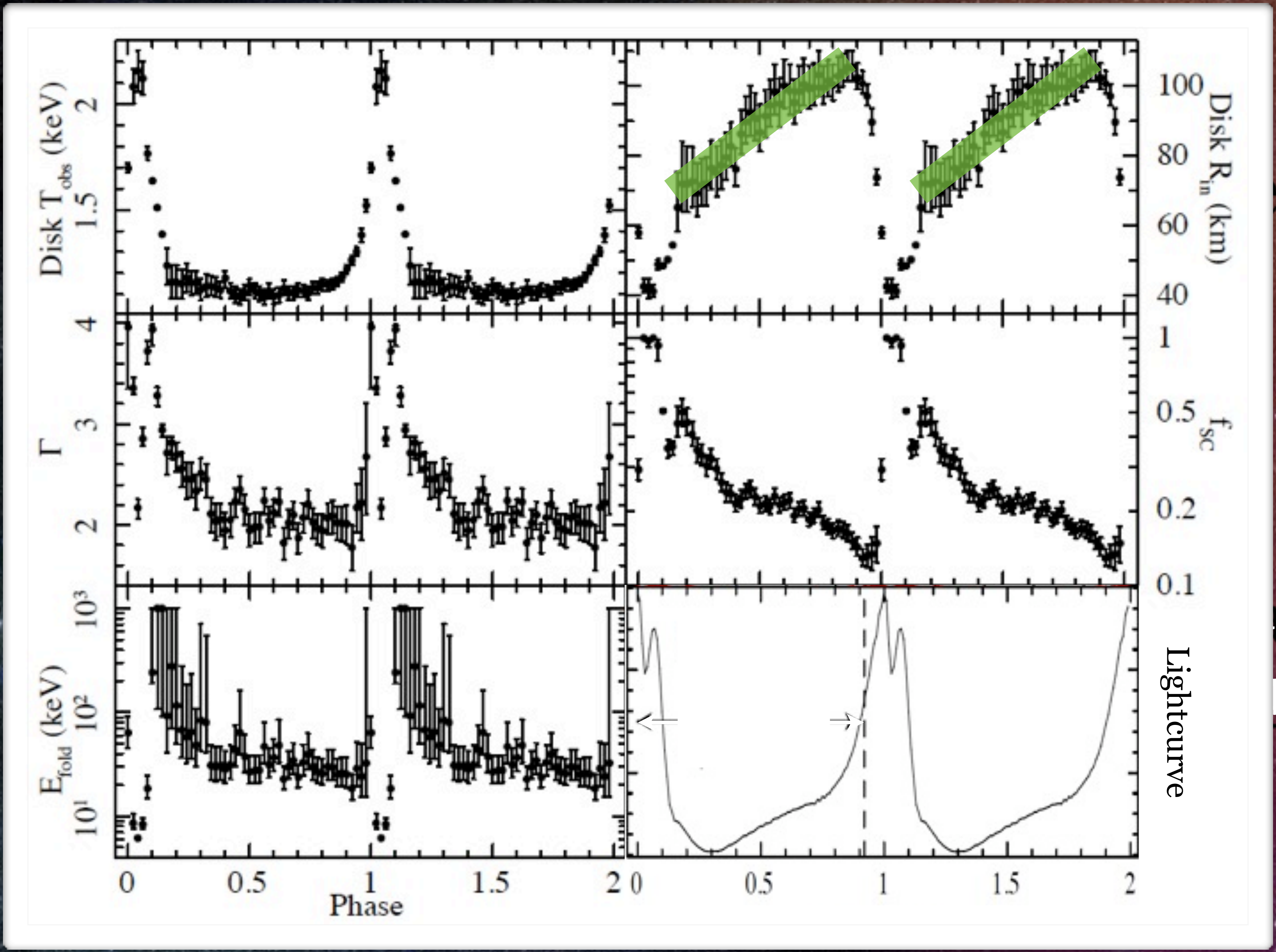

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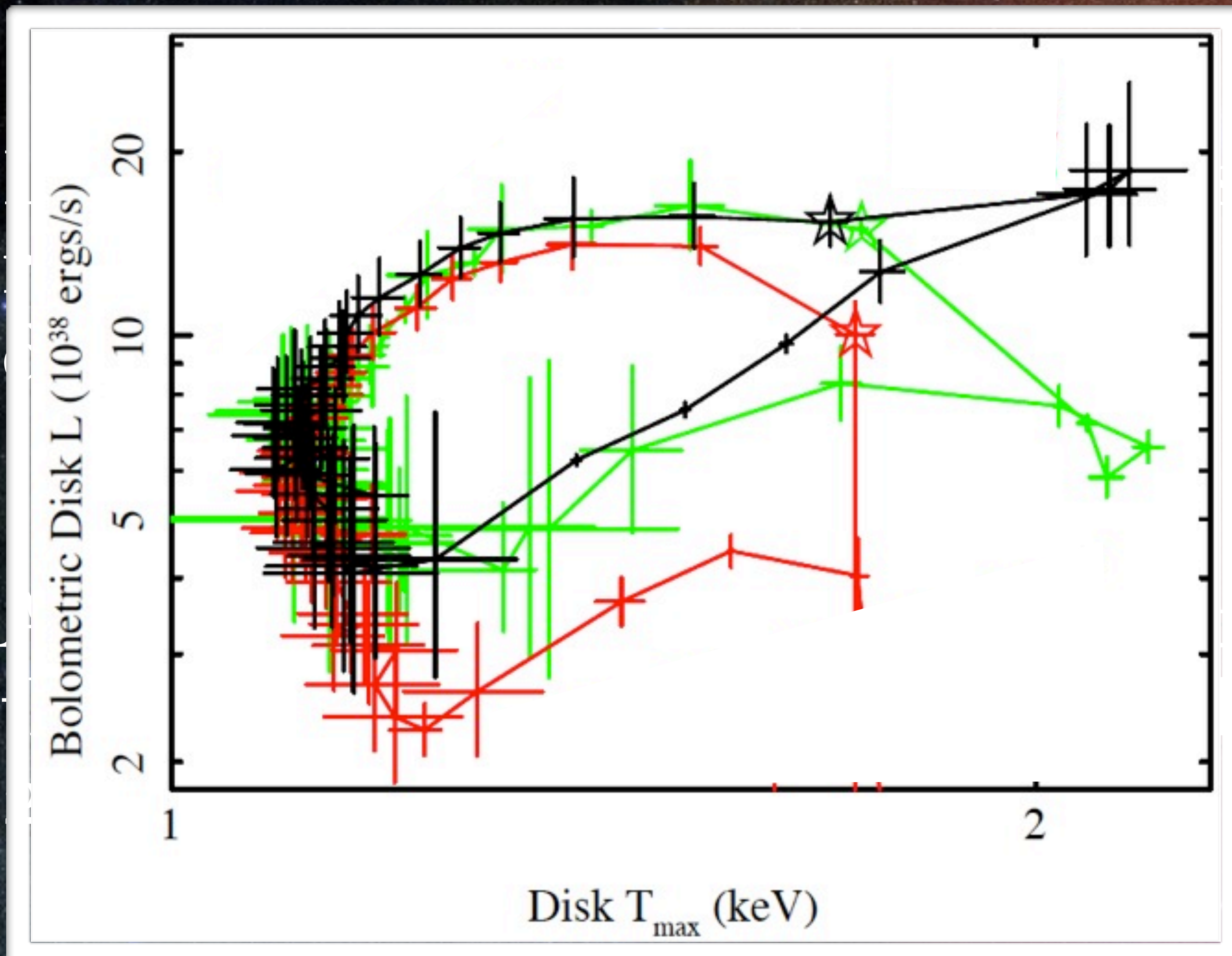

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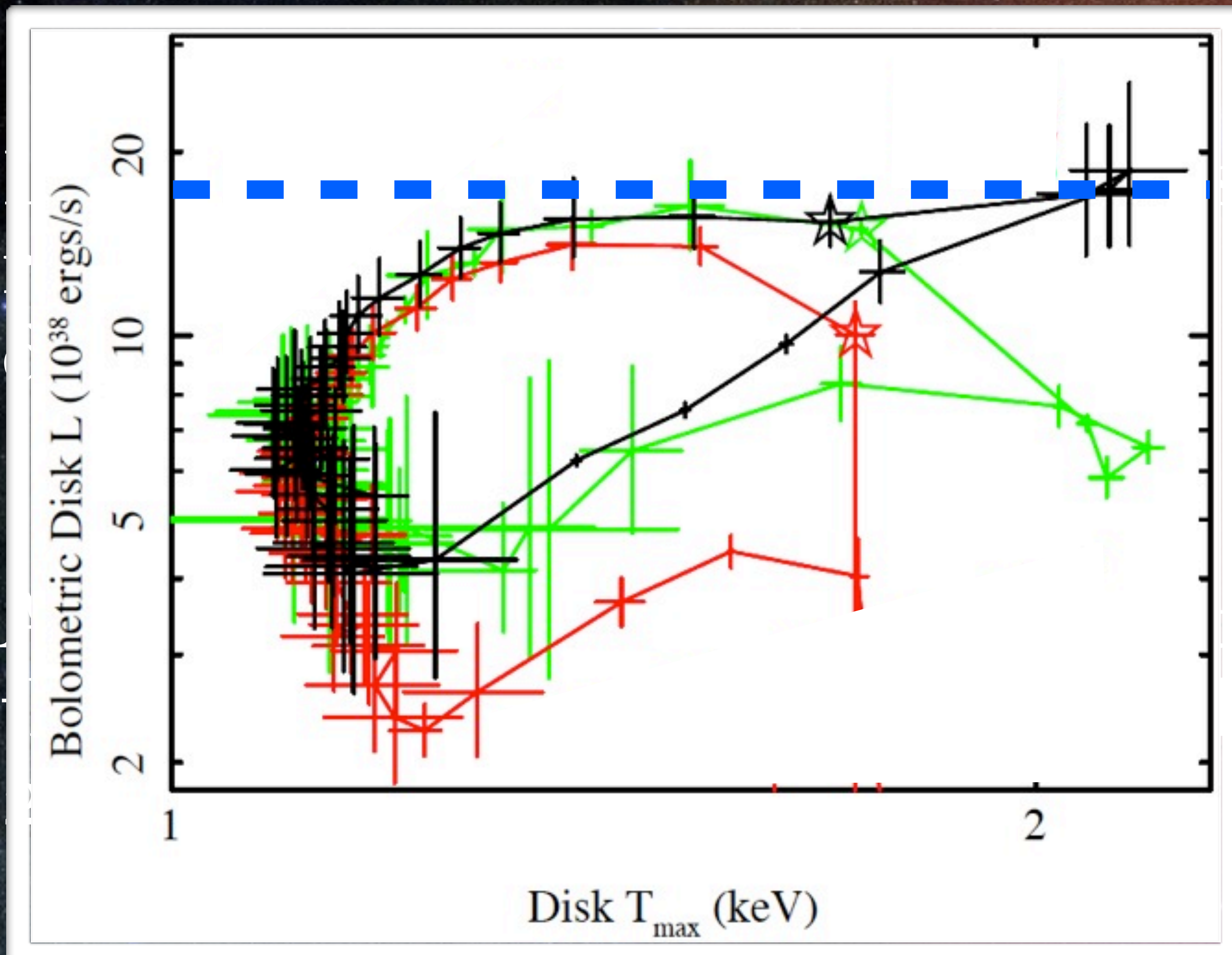

Effects of Global Eddington Limit?

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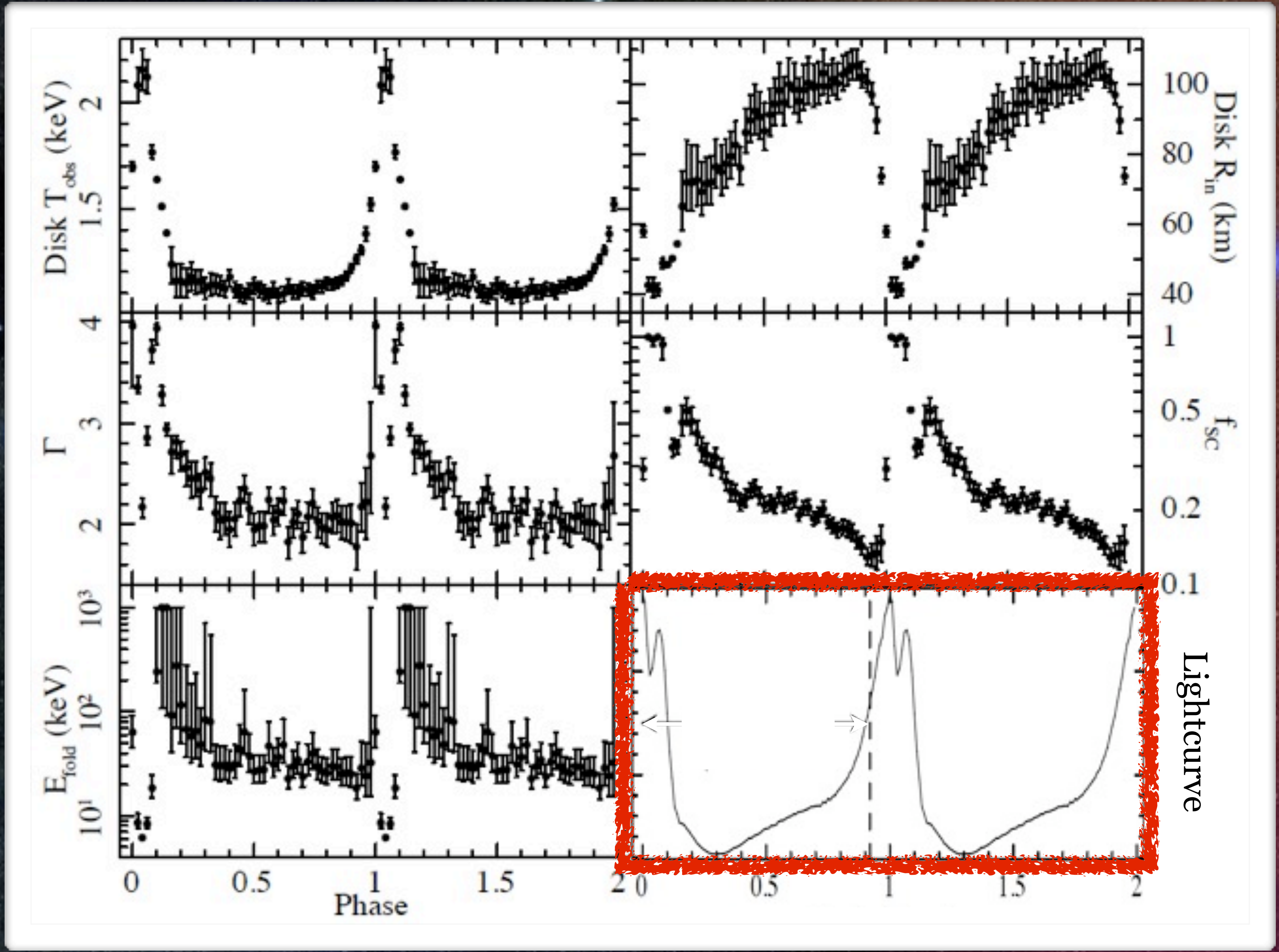

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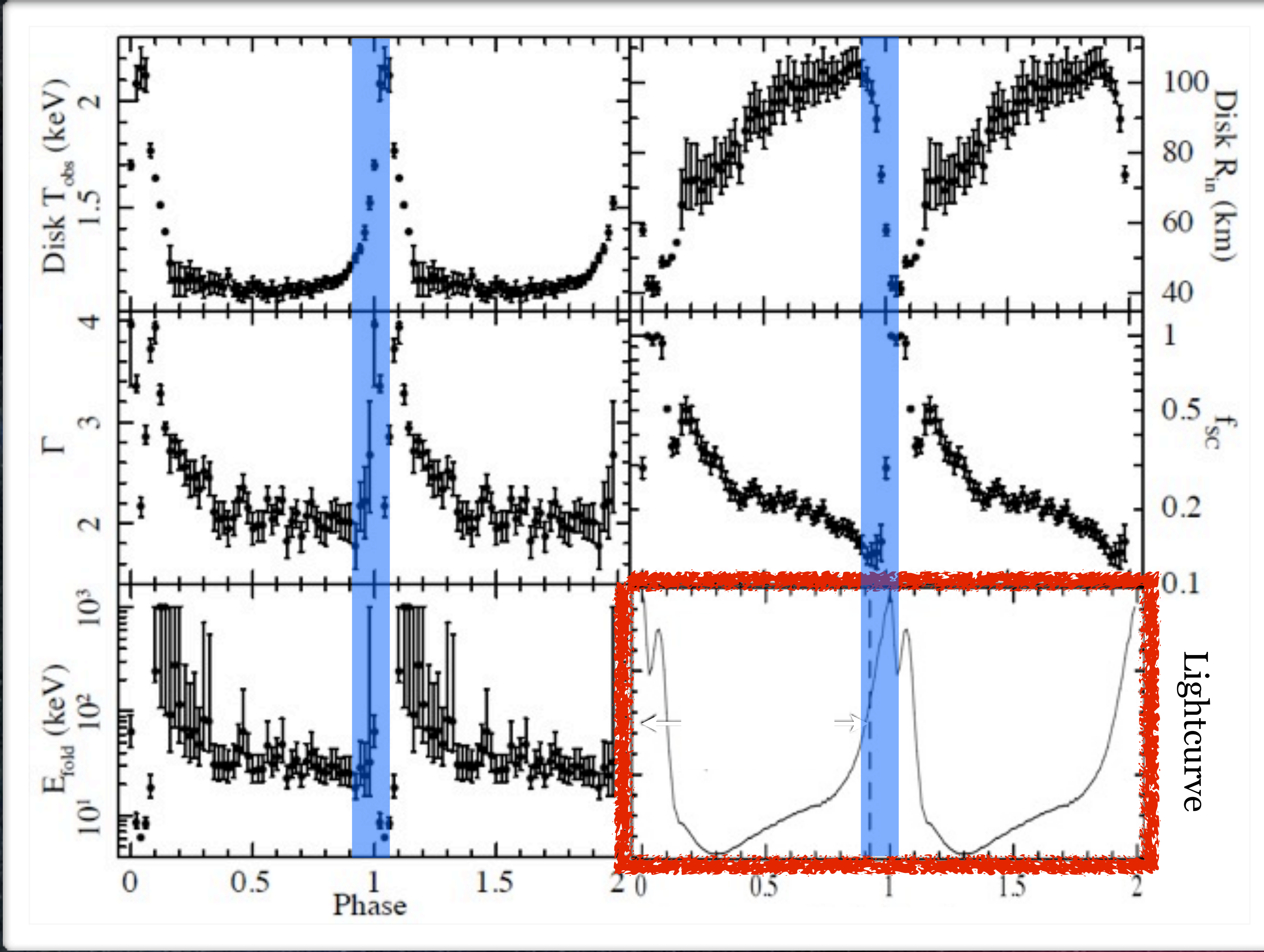

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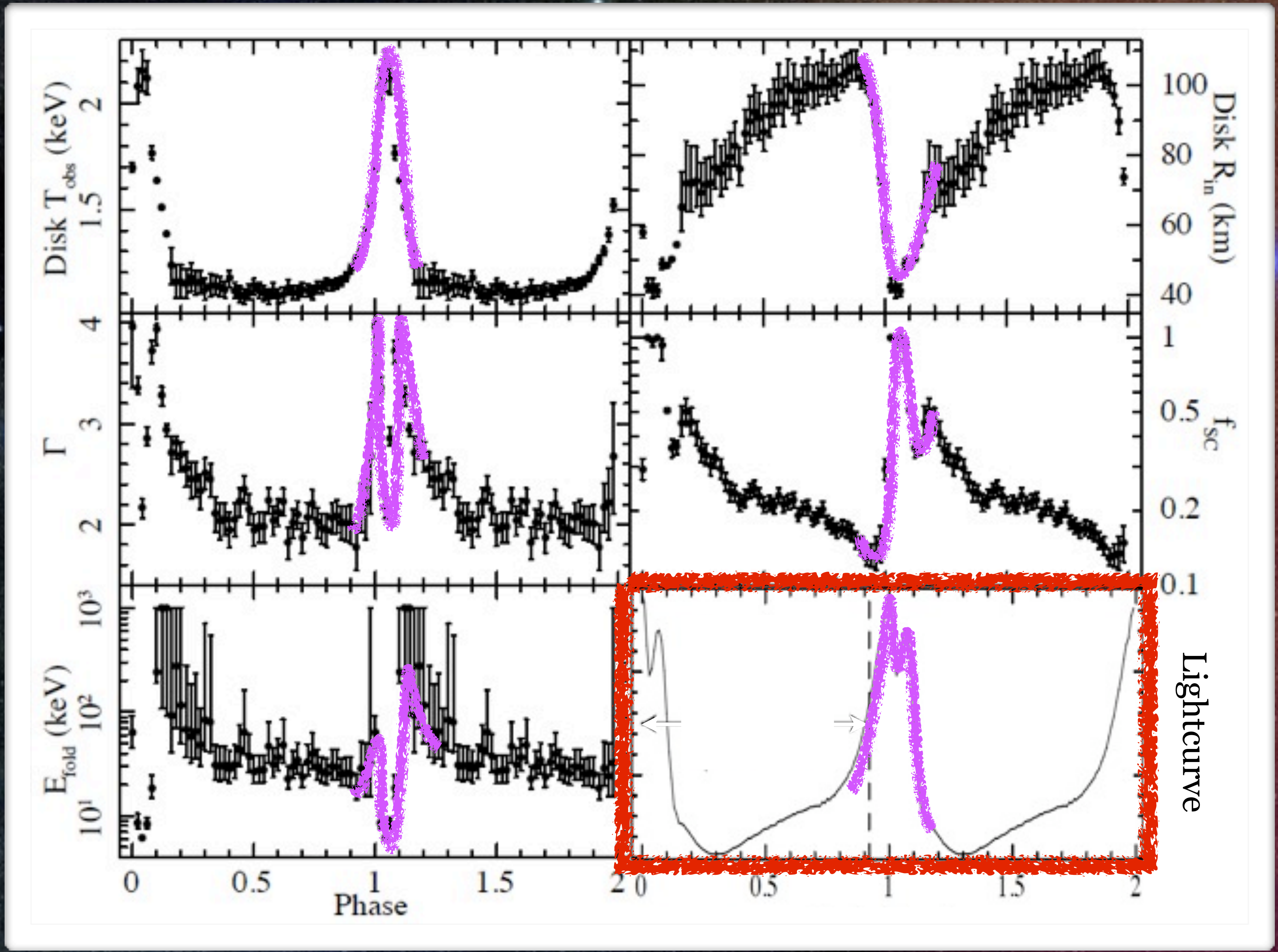

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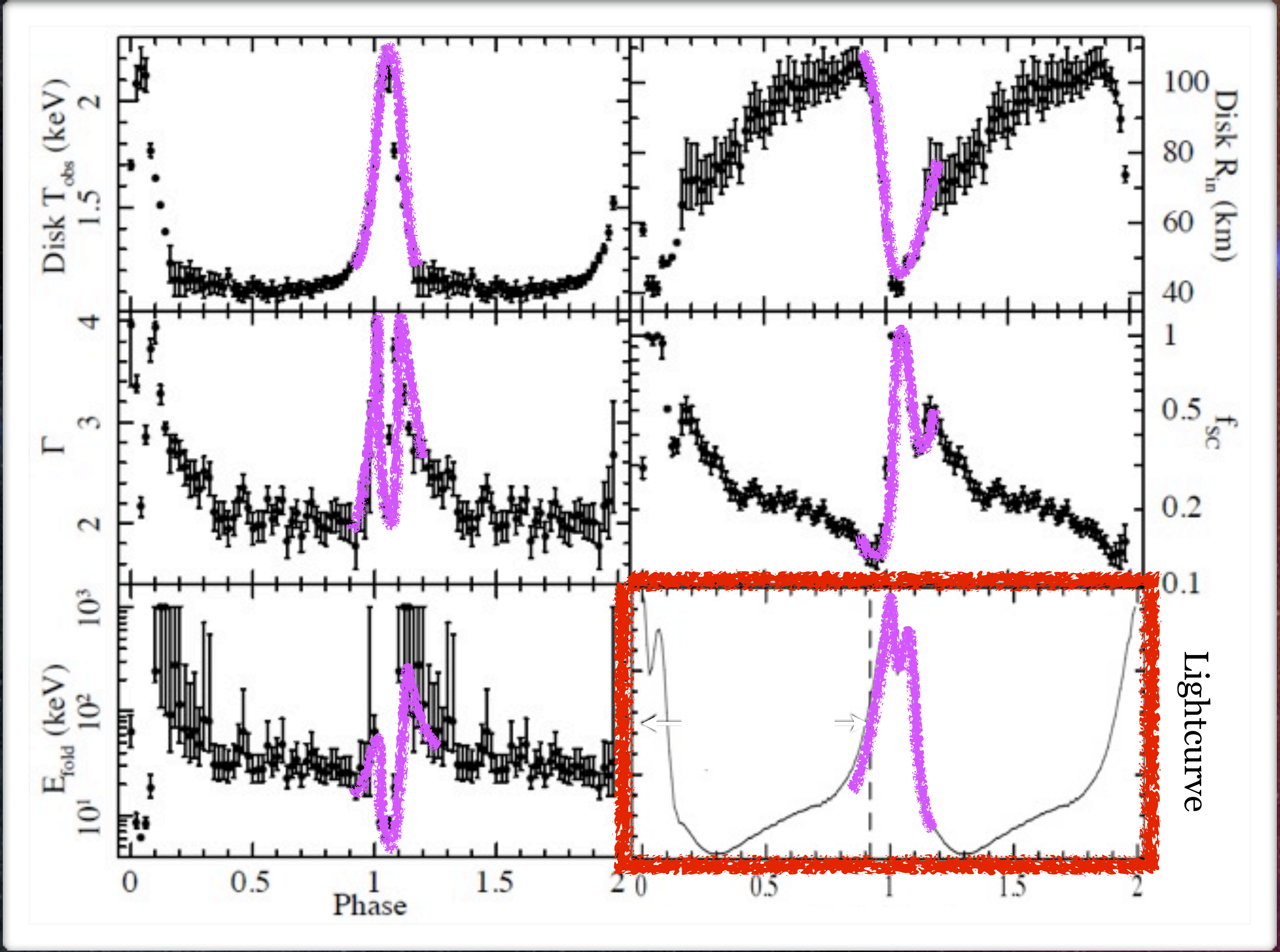

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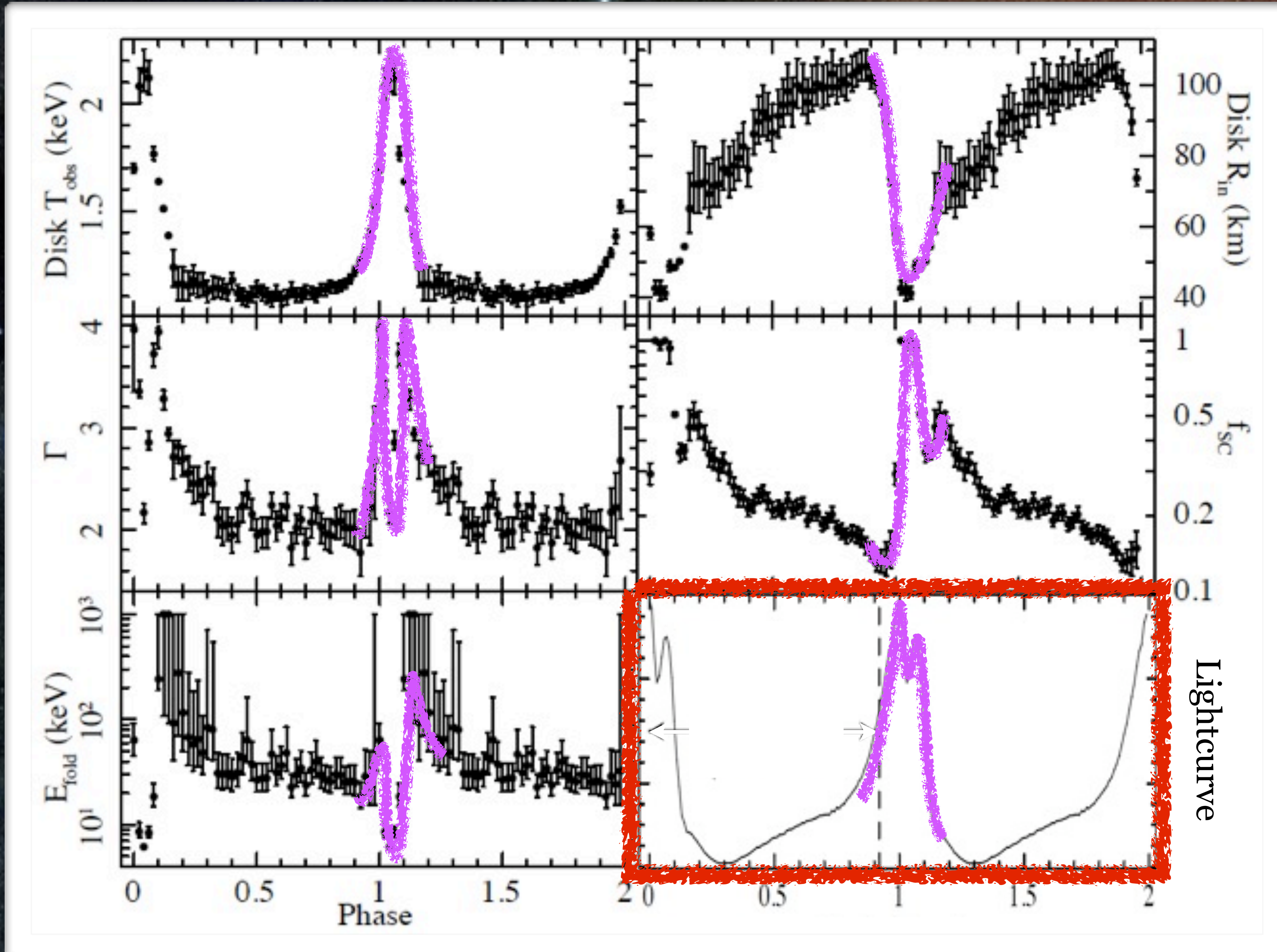

- Just after $L \sim L_{Edd}$, sudden changes in the corona: temperature drops, becomes Compton thick
- Sudden appearance of new electrons = plasma ejection?

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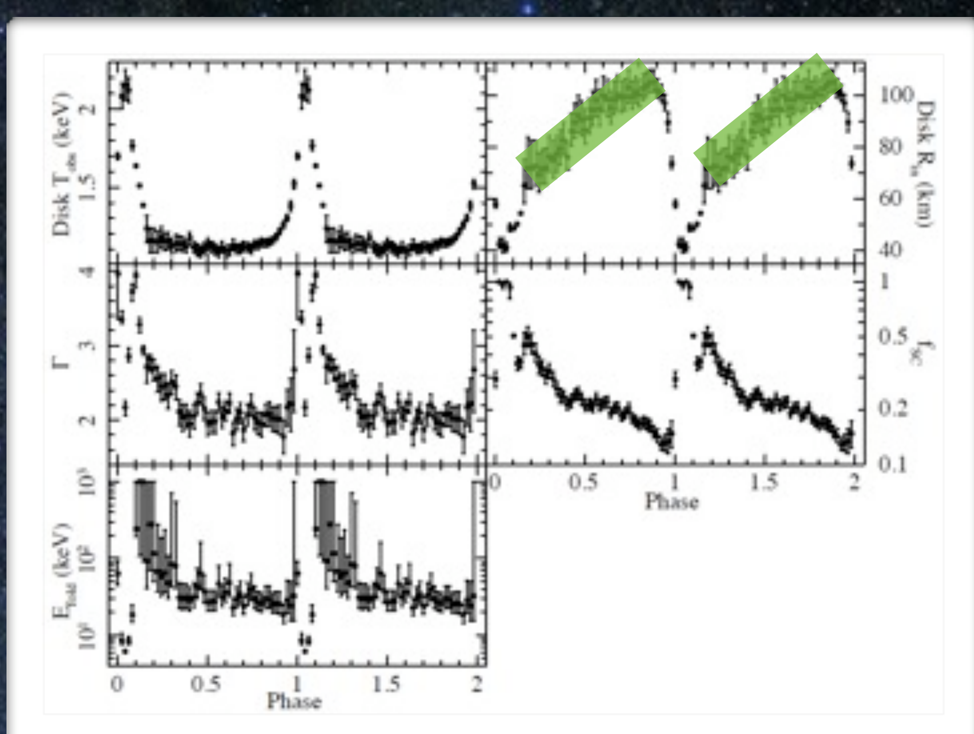
Heartbeats: Radiation vs Gravity

- Radiation pressure pushes the inner edge of the disk away from the black hole



Credit: NASA/CXC/M. Weiss

- Eventually overwhelmed by the waves of matter falling in

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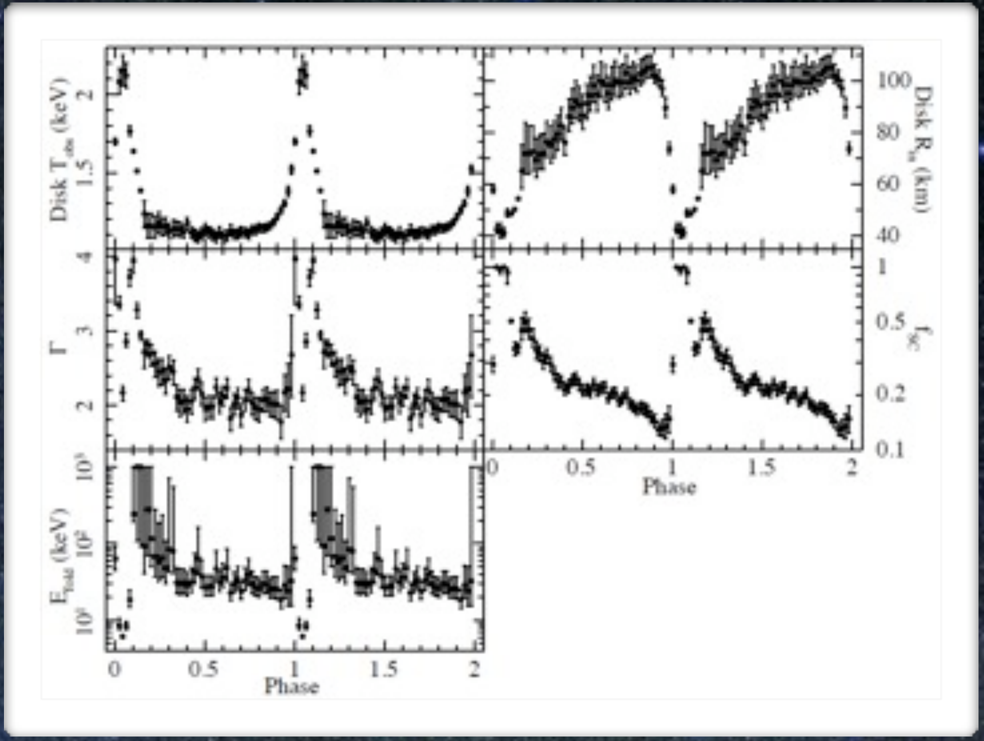

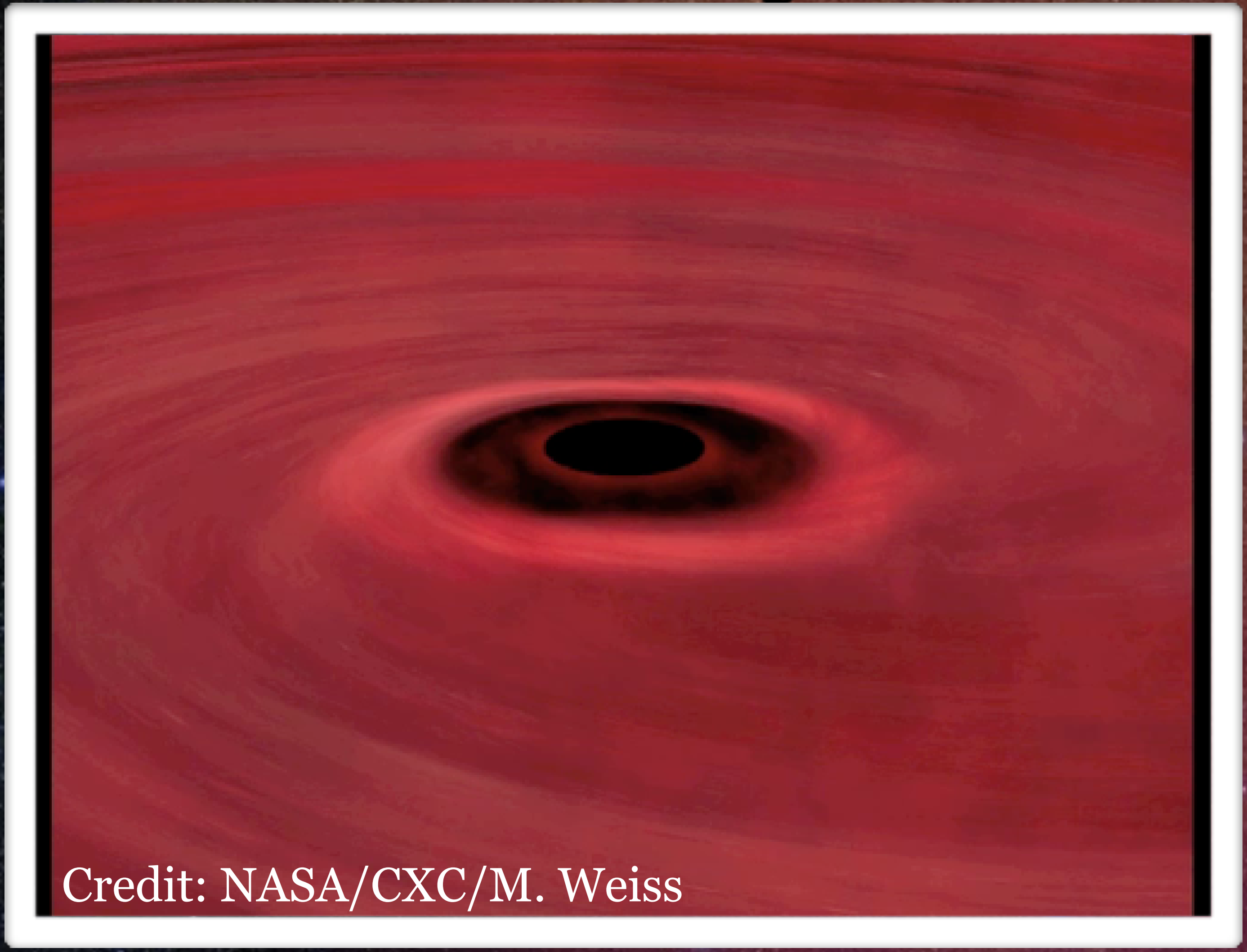

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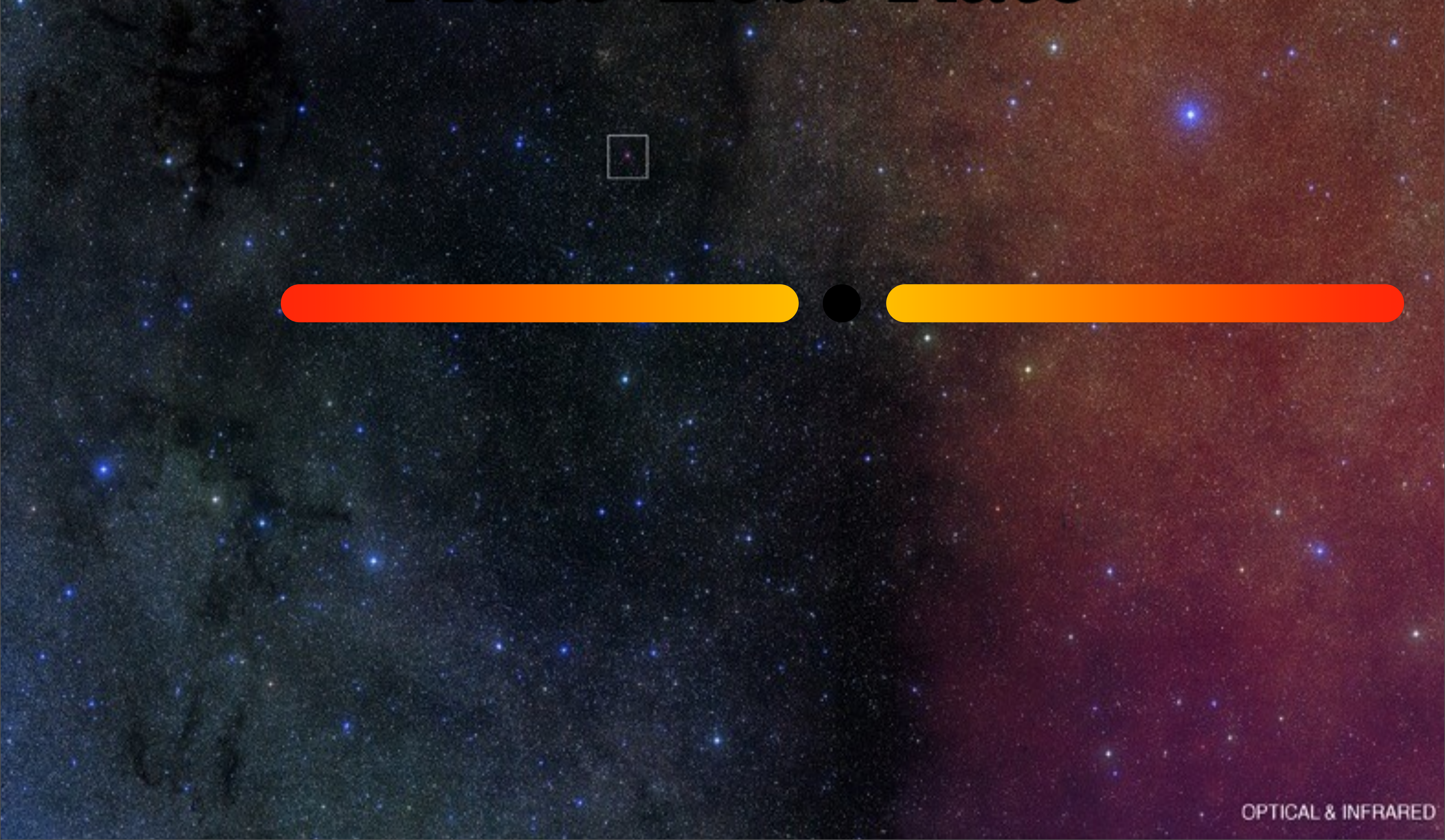
Estimating the Wind Mass-Loss Rate



Estimating the Wind Mass-Loss Rate

- Mass loss rate in the wind is proportional to:

OPTICAL & INFRARED

Estimating the Wind Mass-Loss Rate

- Mass loss rate in the wind is proportional to:
- Wind speed

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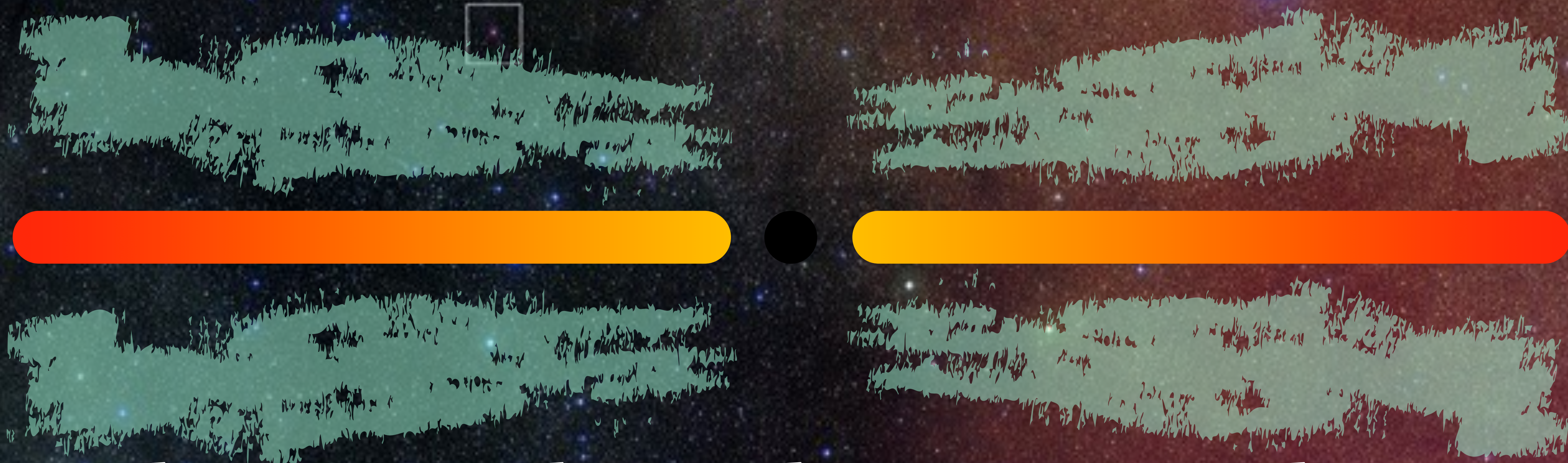
Estimating the Wind Mass-Loss Rate



- Mass loss rate in the wind is proportional to:
- Wind speed
- Column density

Estimating the Wind Mass-Loss Rate

- Mass loss rate in the wind is proportional to:
- Wind speed
- Column density
- Radial extend of the wind

Chandra HETGS: Disk Wind

Phase-Folded PCA Lightcurve

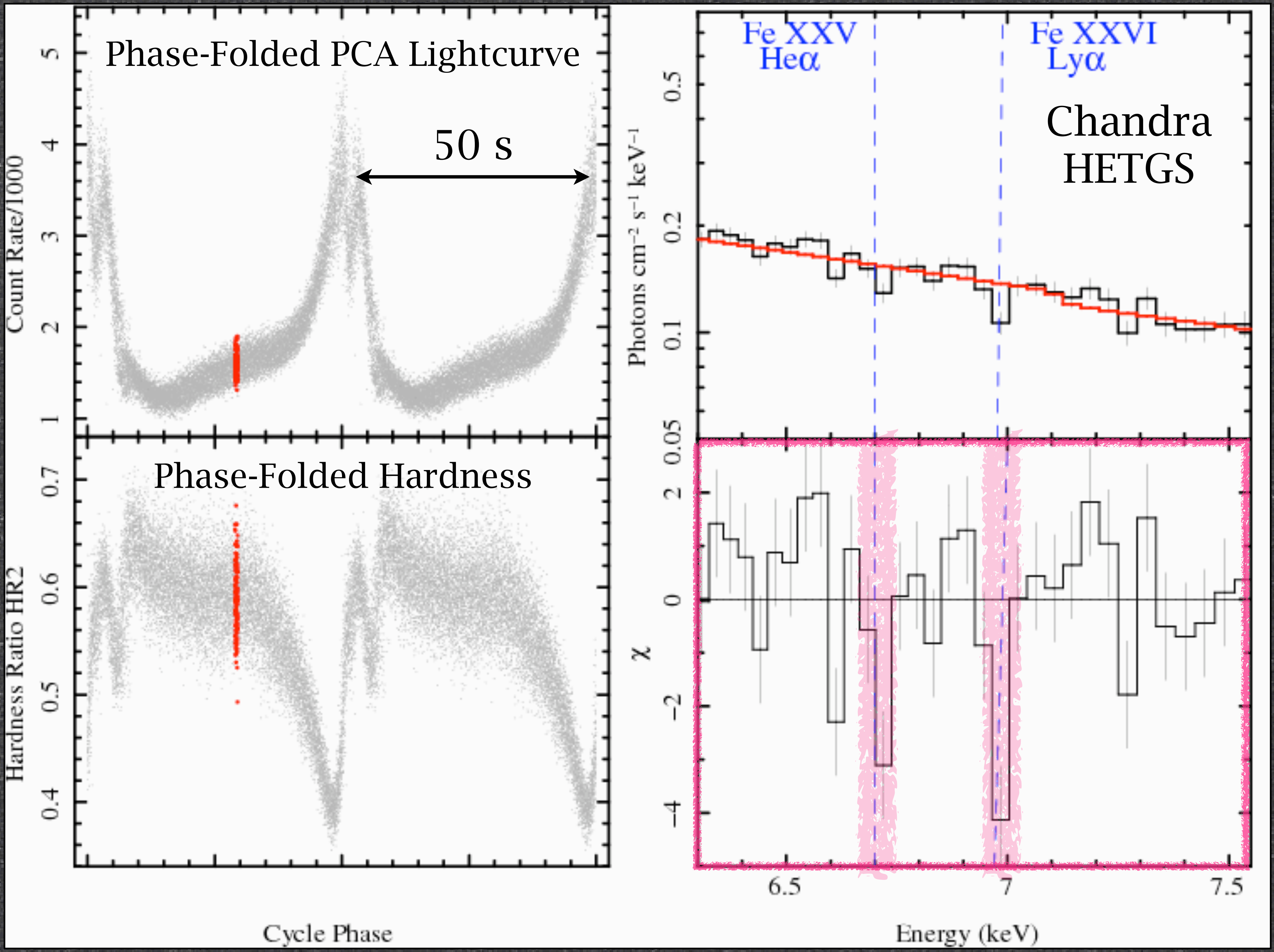
50 s

Chandra HETGS

Phase-Folded Hardness

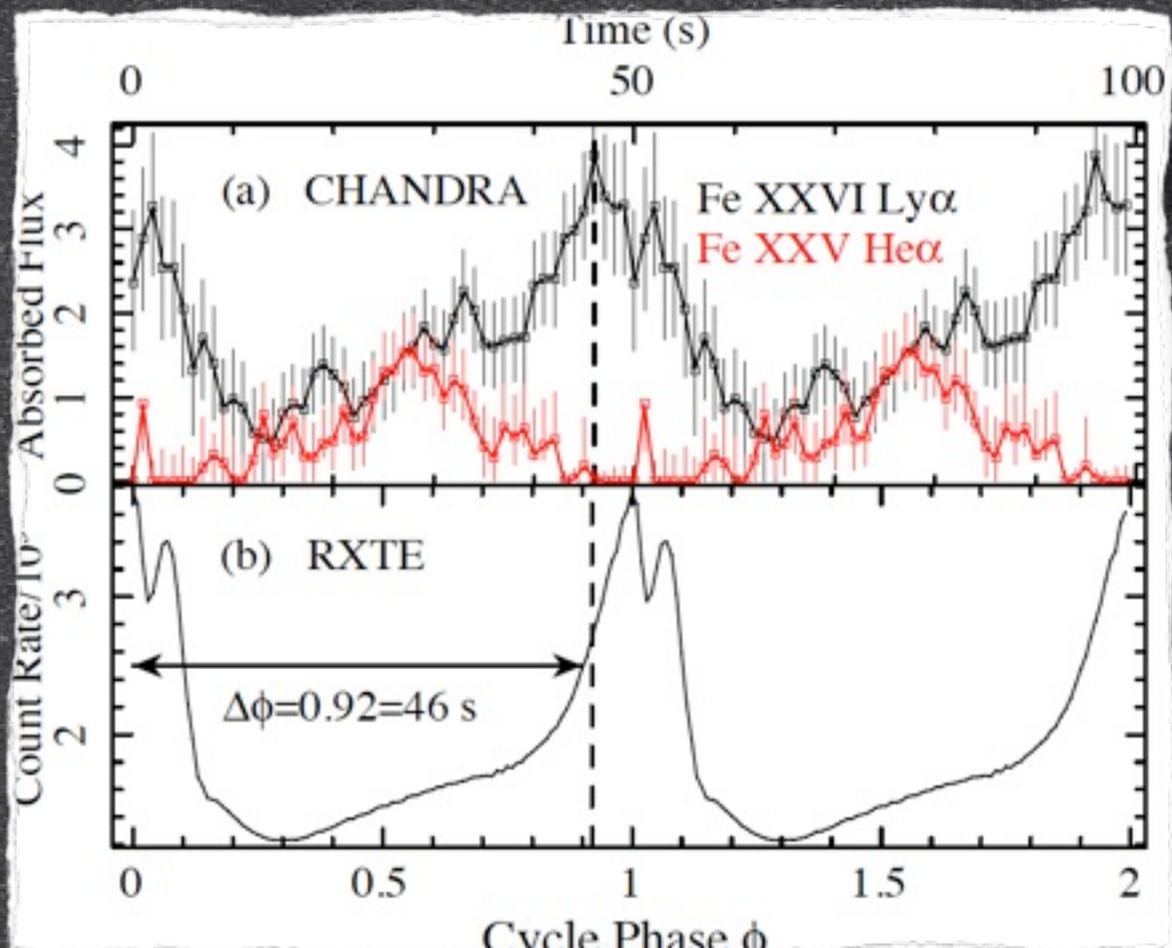
- 273 individual oscillations, PHASE-FOLDED and stacked

Chandra HETGS: Disk

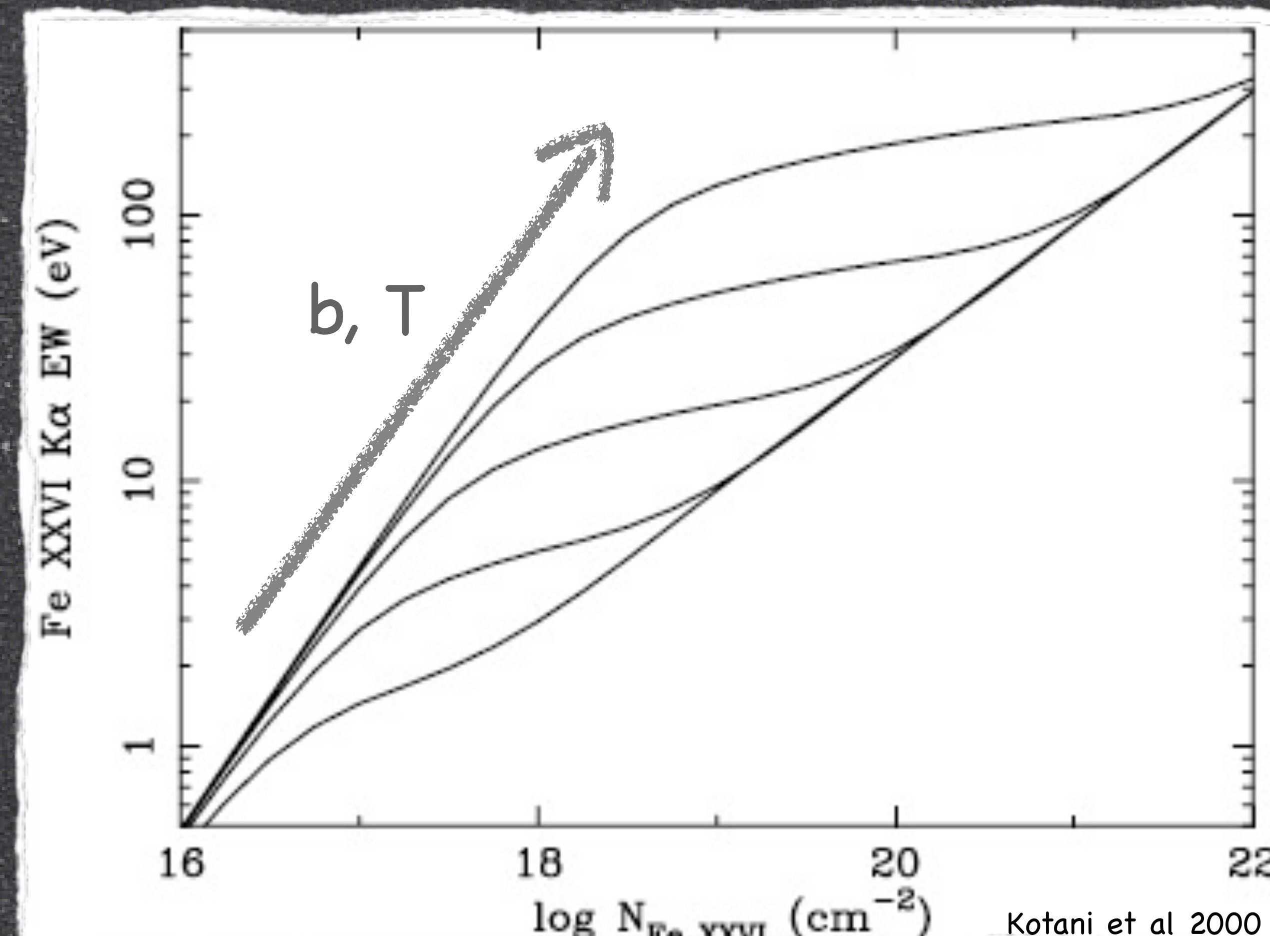


- 273 individual oscillations, PHASE-FOLDED and stacked

Fun With Atomic Physics



Line Fluxes, Eq. Widths



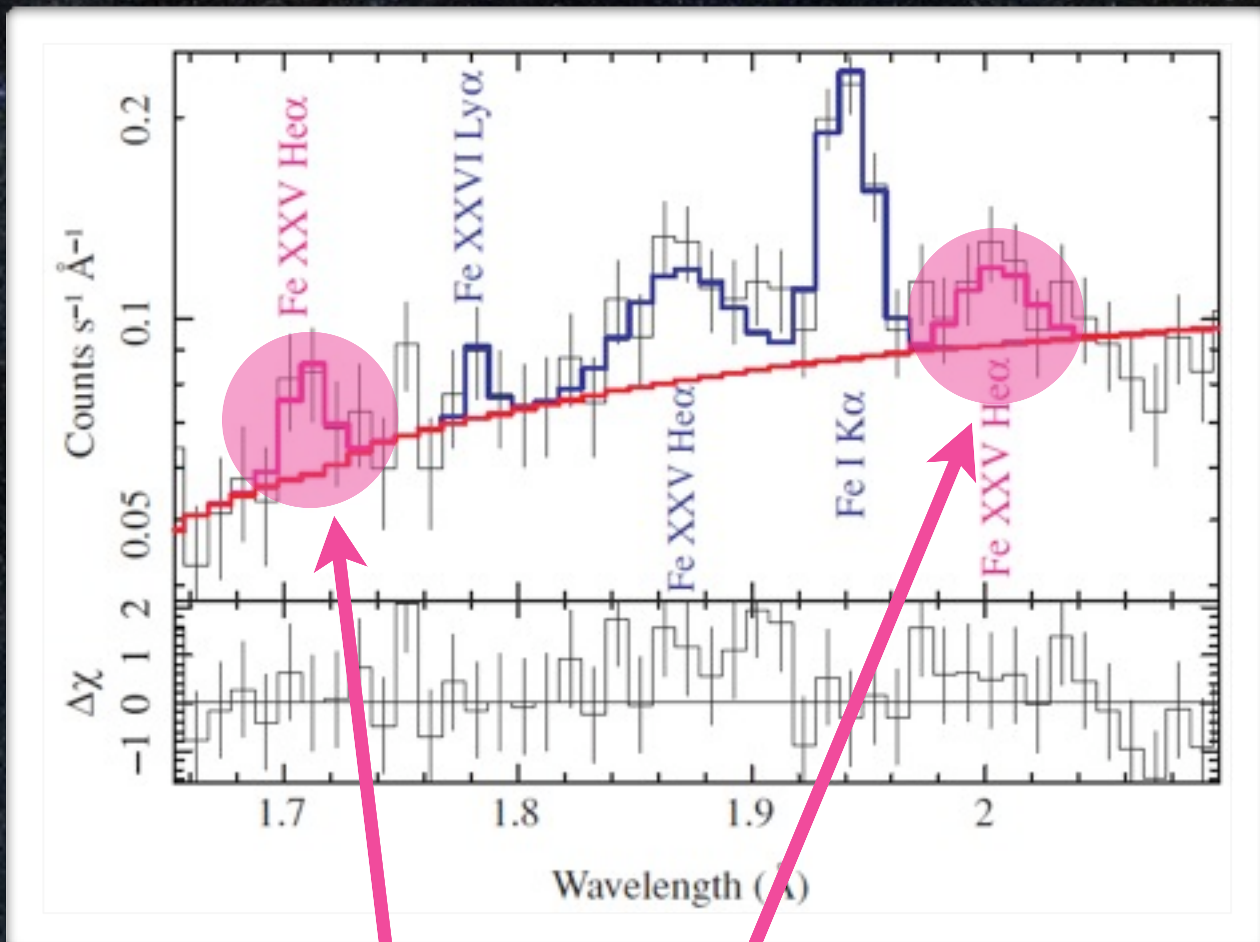
Curve of Growth

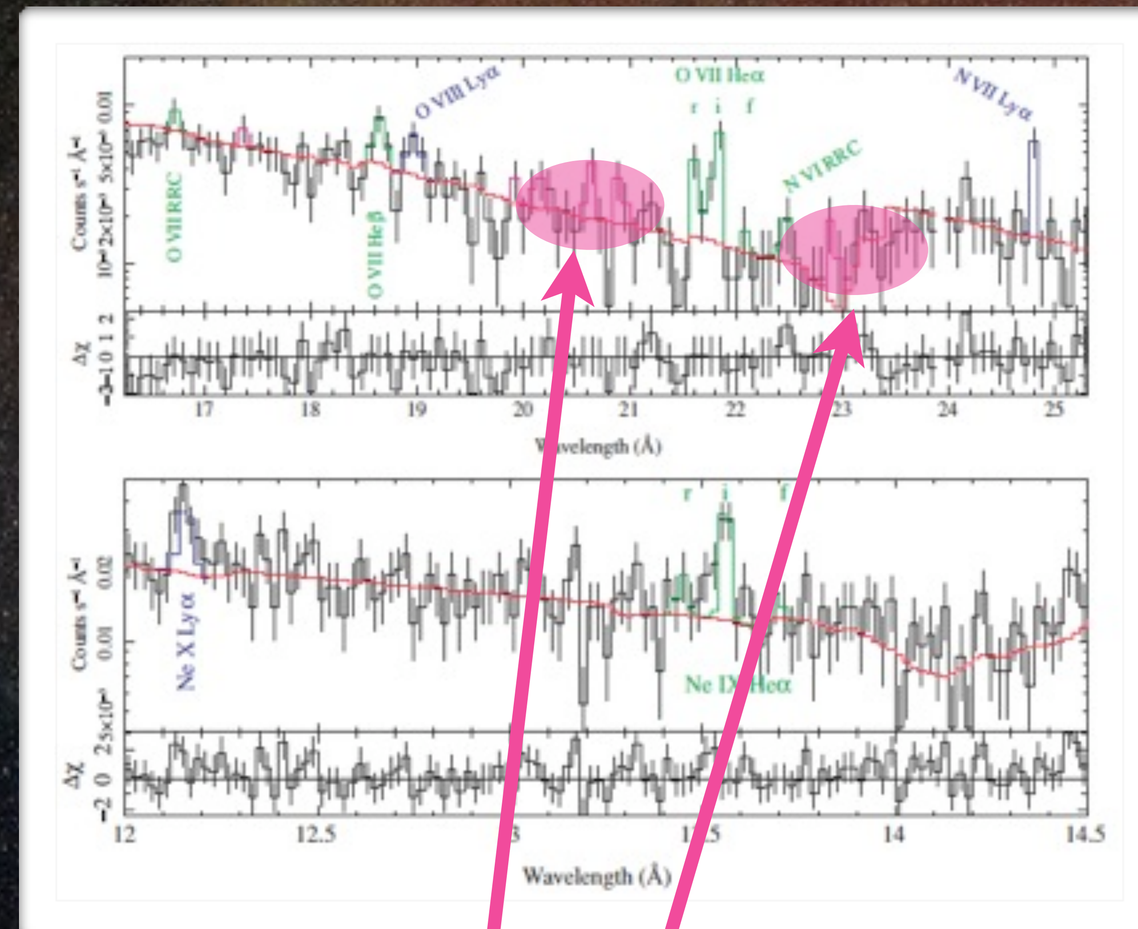
$$\frac{1}{4\pi R^2}\, n_i \int_{\chi_i}^{\infty} \varepsilon^{-1}\sigma_i(\varepsilon) L_\varepsilon d\varepsilon = \alpha_{i+1} n_e n_{i+1}$$

Ionization Balance

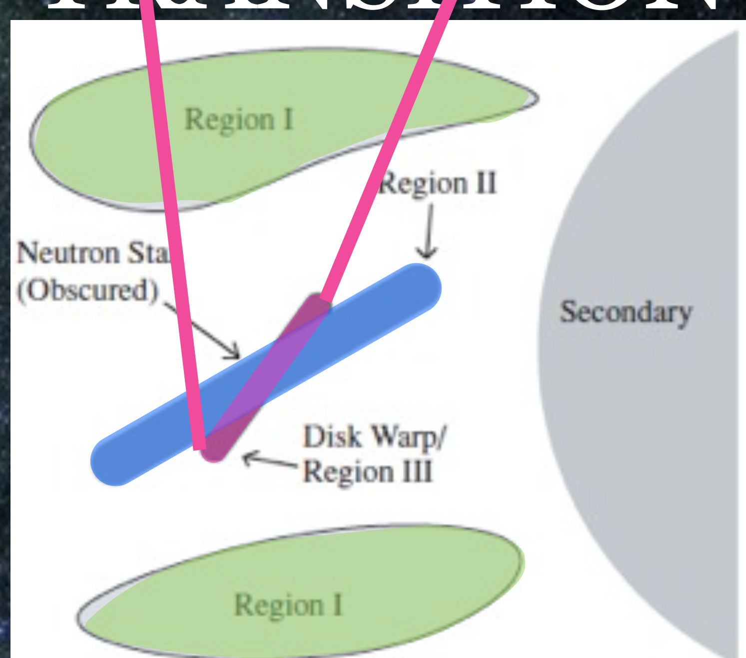
Use data, atomic physics -> solve for density, ionization!

Evidence for Disk Precession

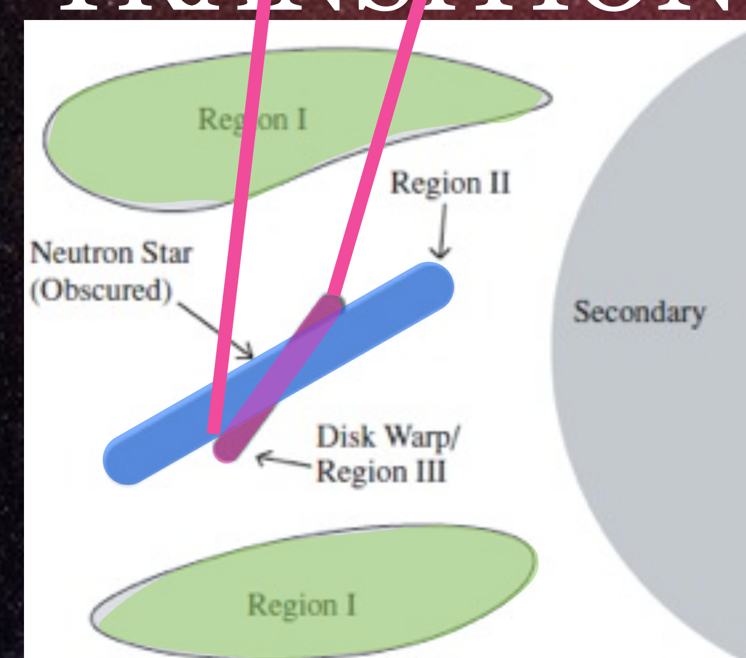




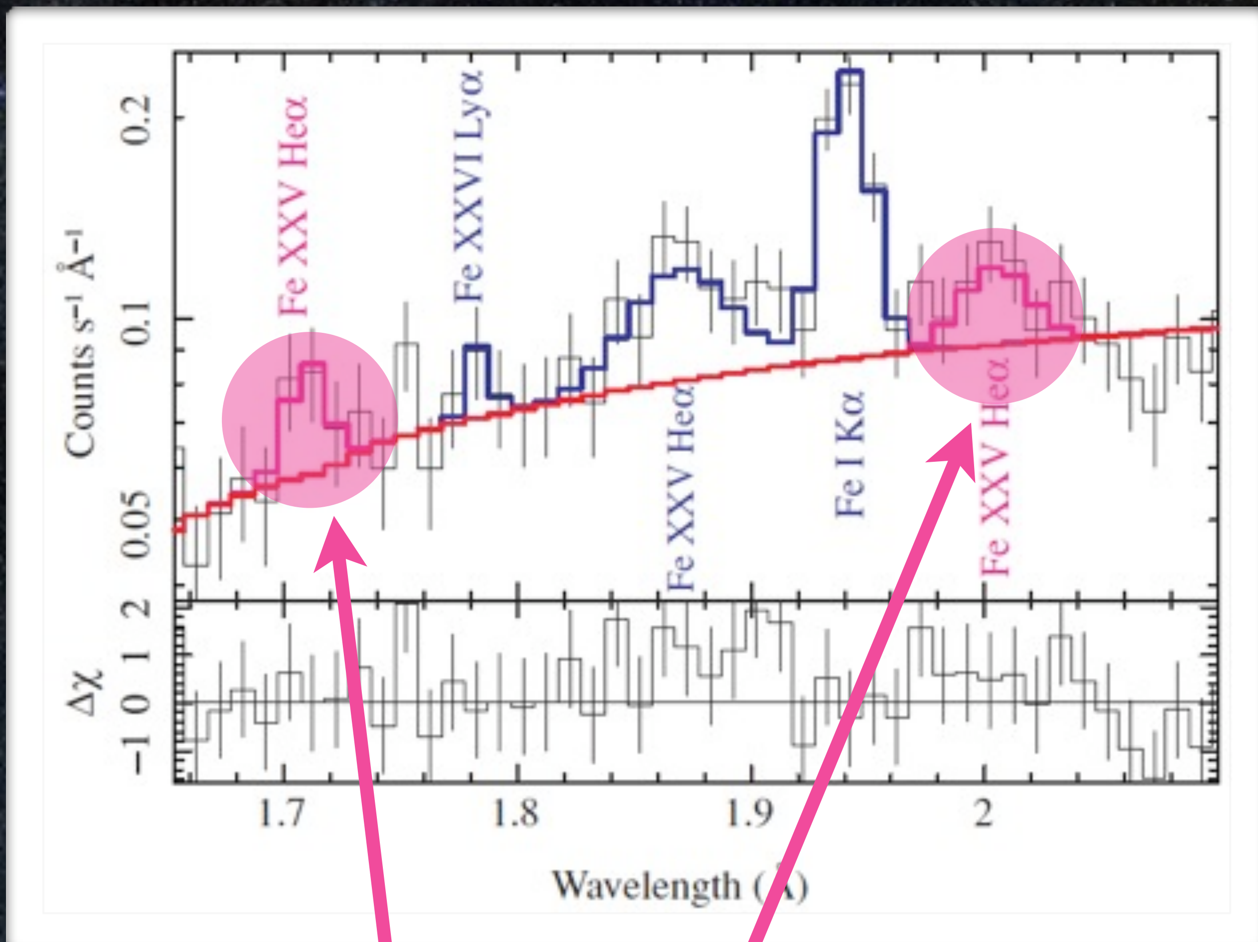
TRANSITION

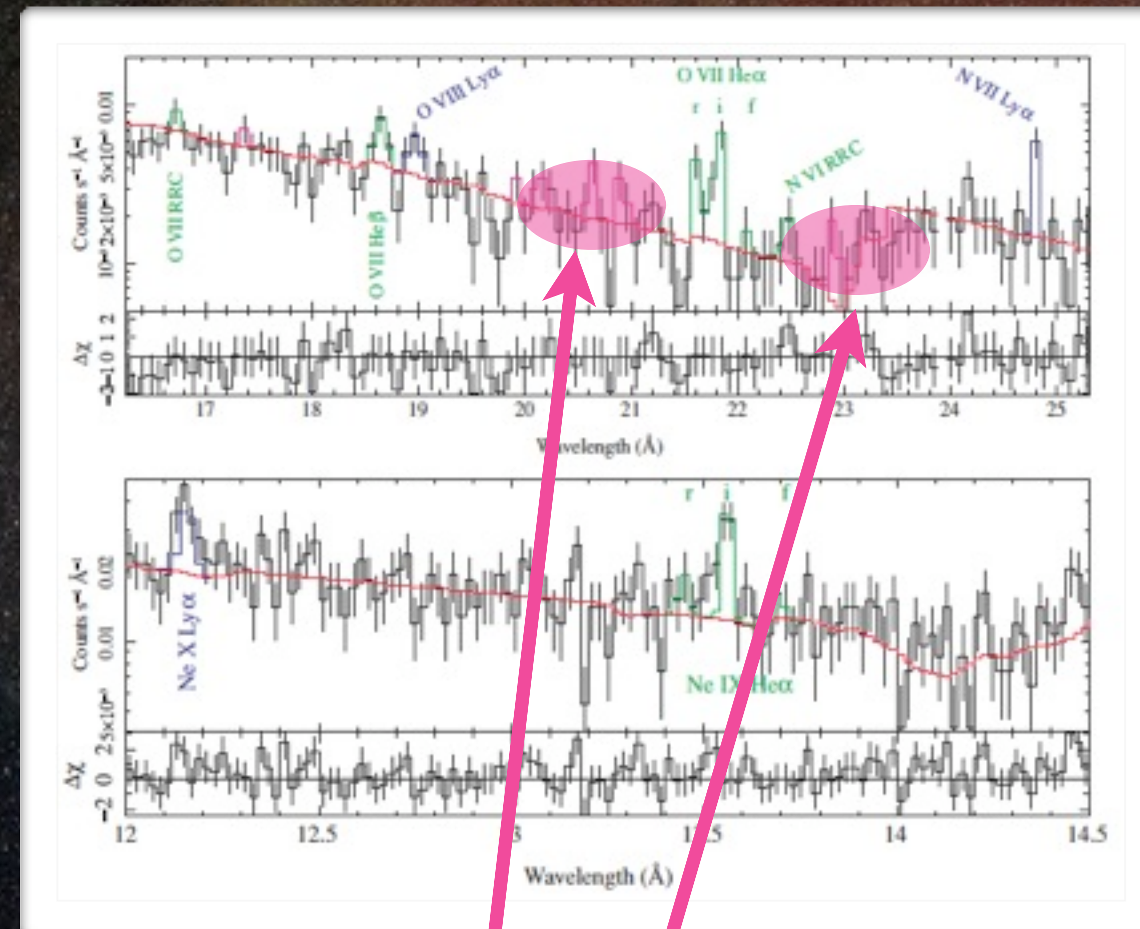


TRANSITION



Evidence for Disk Precession





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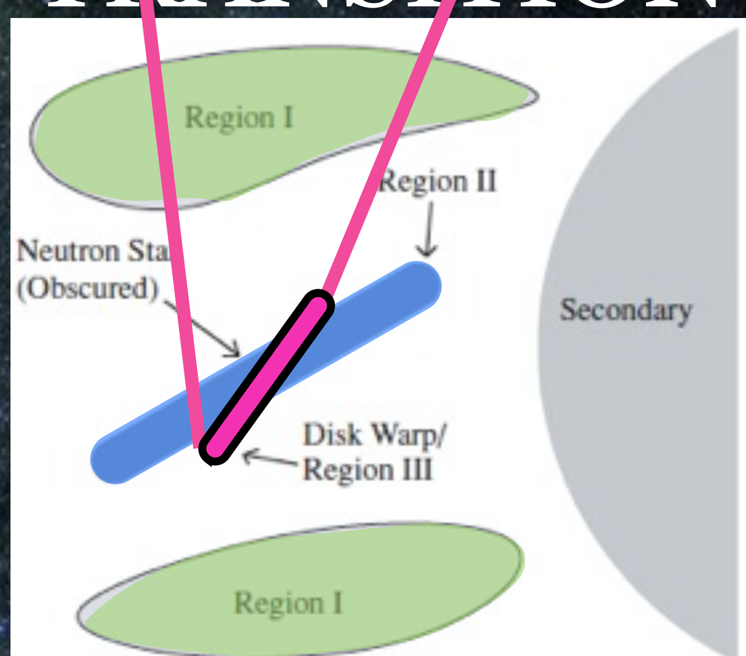

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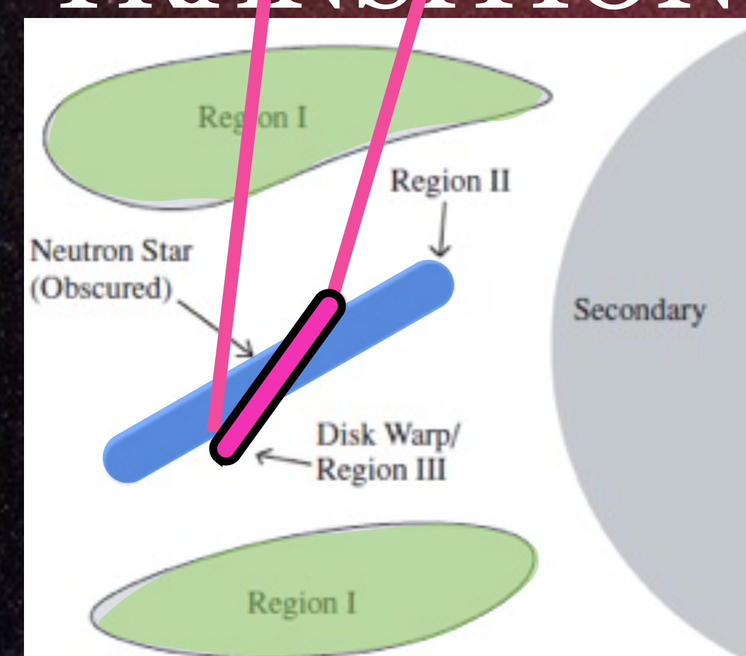
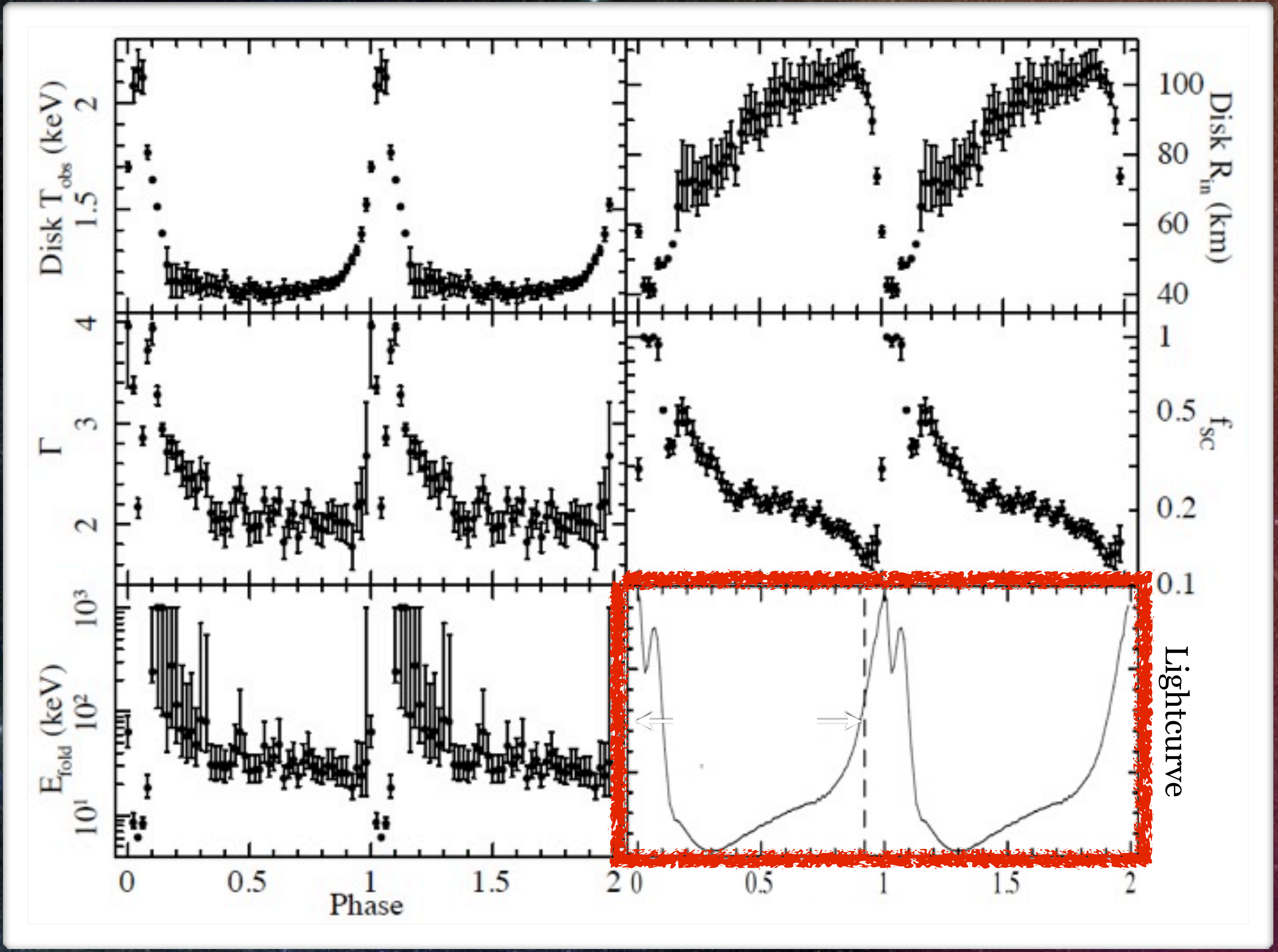
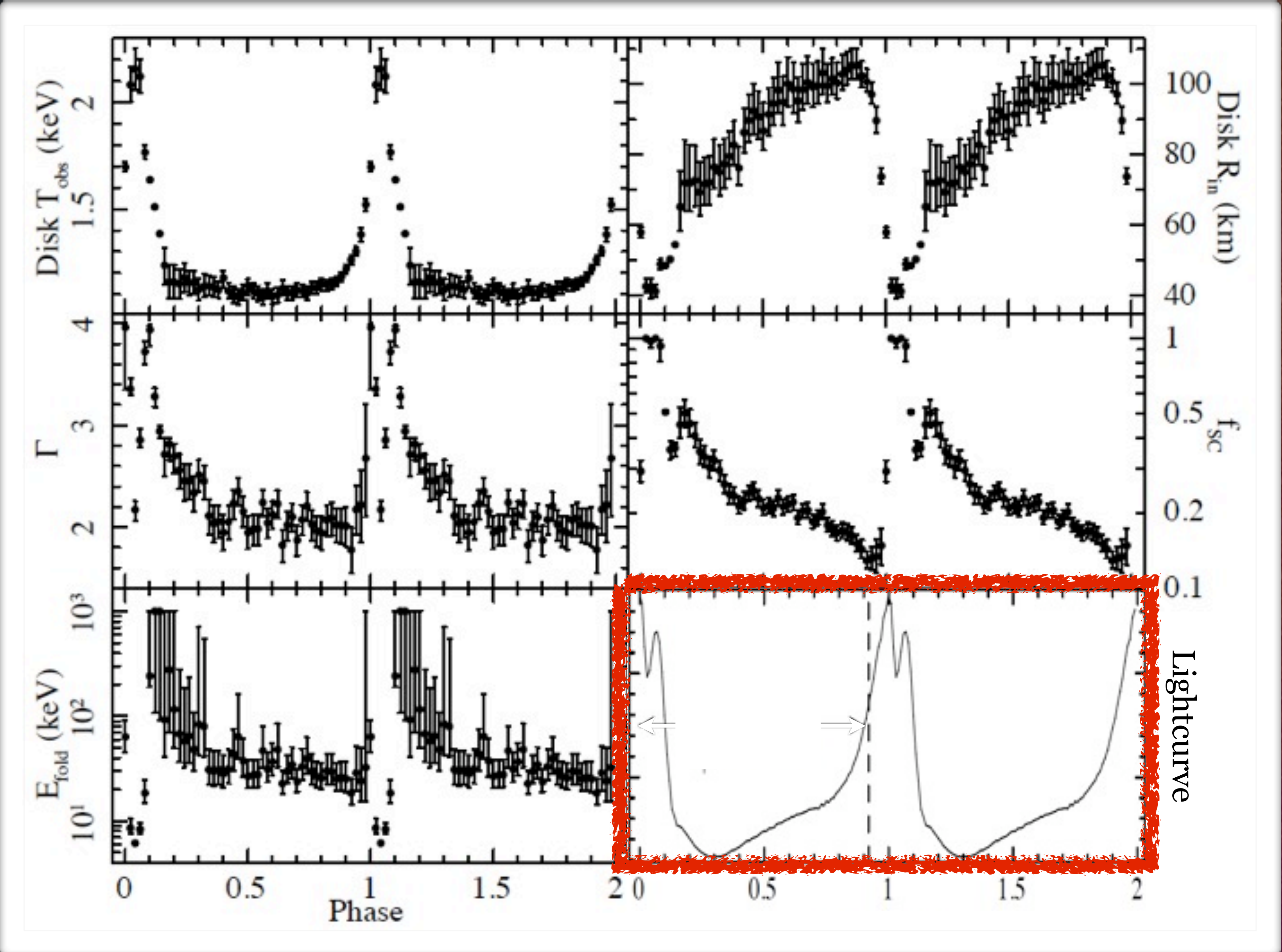


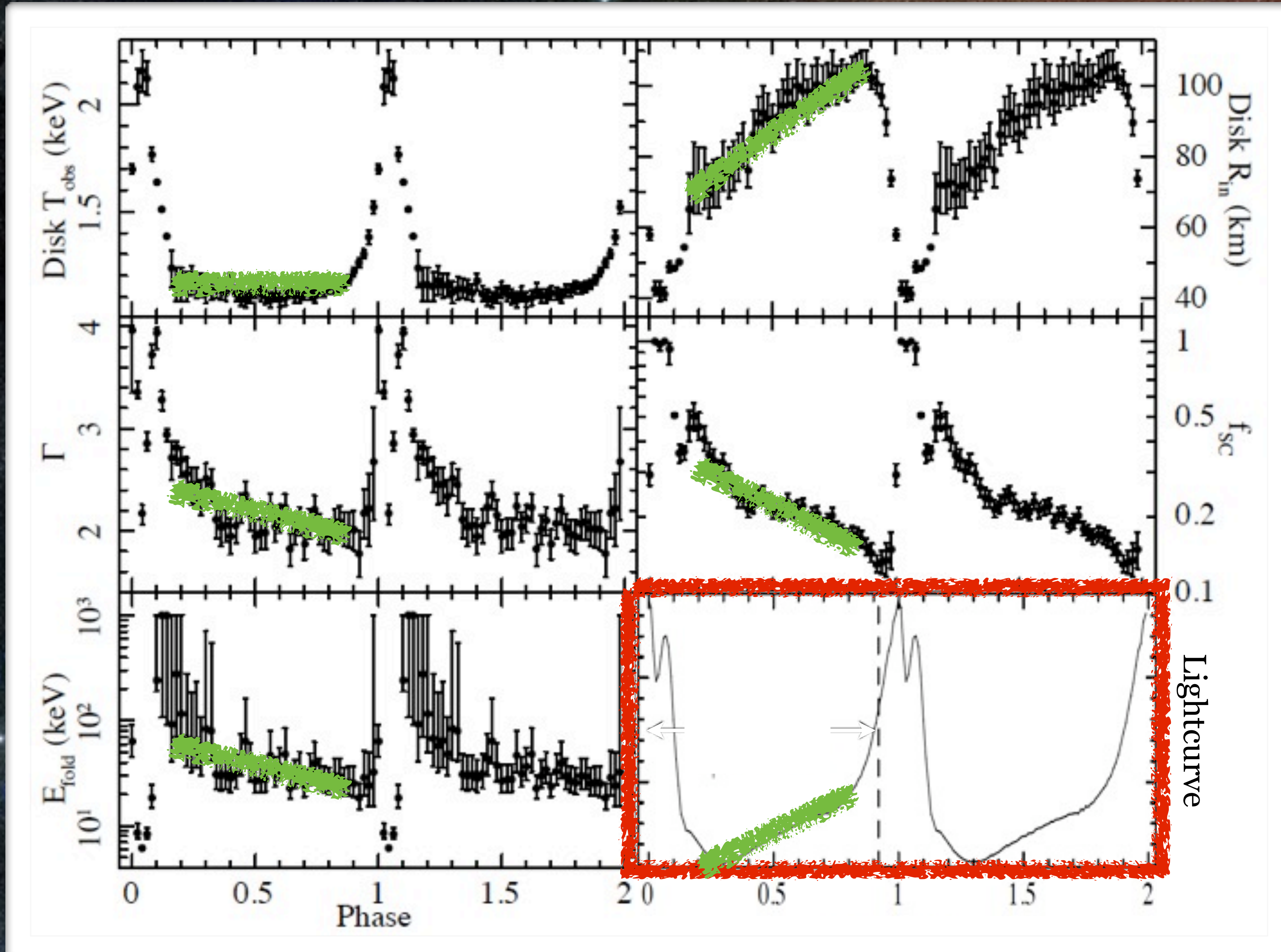
The Heartbeat State



The Heartbeat State

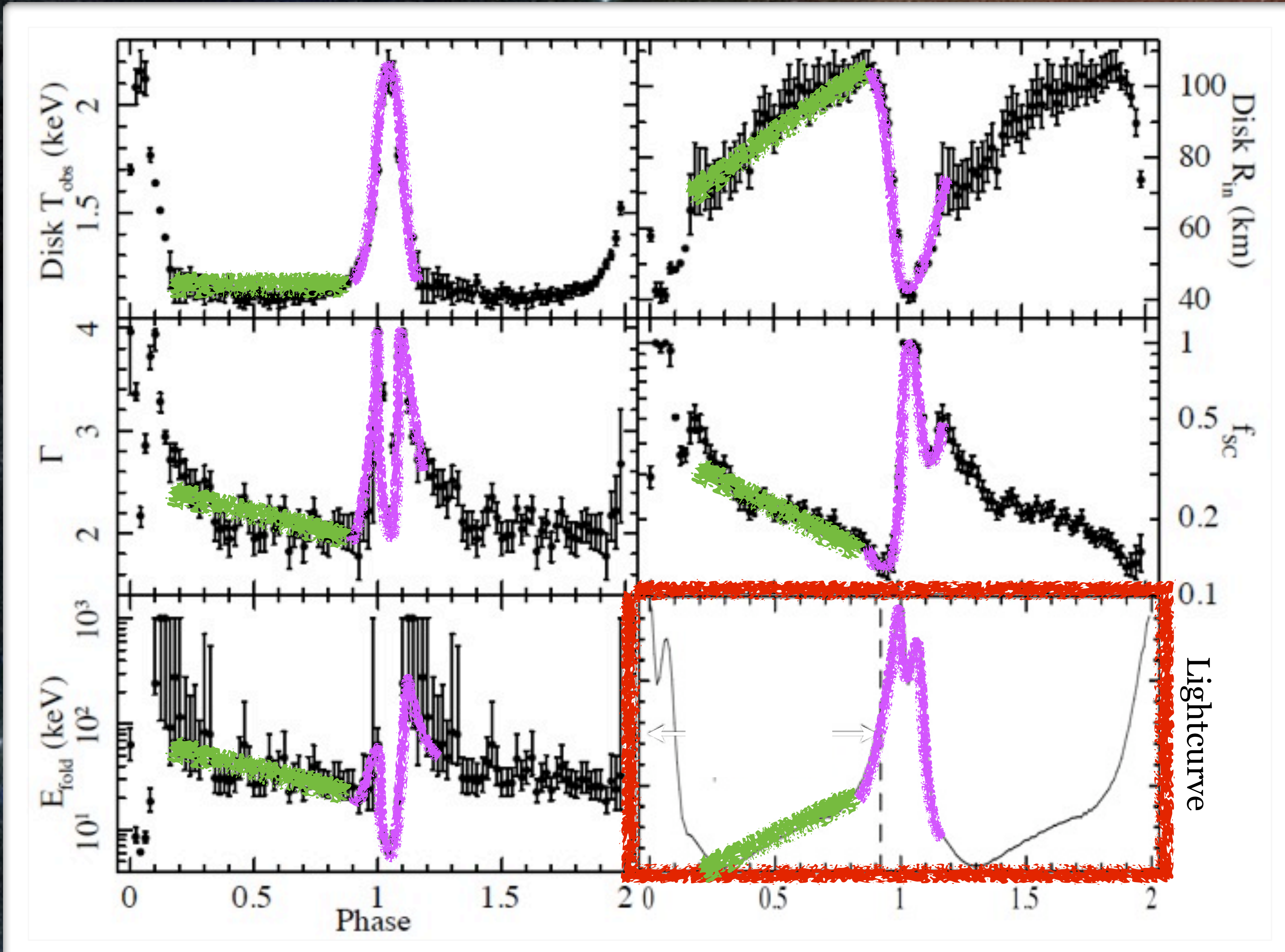


The Heartbeat State



- Smooth changes in the disk, corona, X-rays

The Heartbeat State



- Smooth changes in the disk, corona, X-rays
- Sudden, catastrophic variability