New Results on Massive Outflows in Black Hole X-ray Binaries

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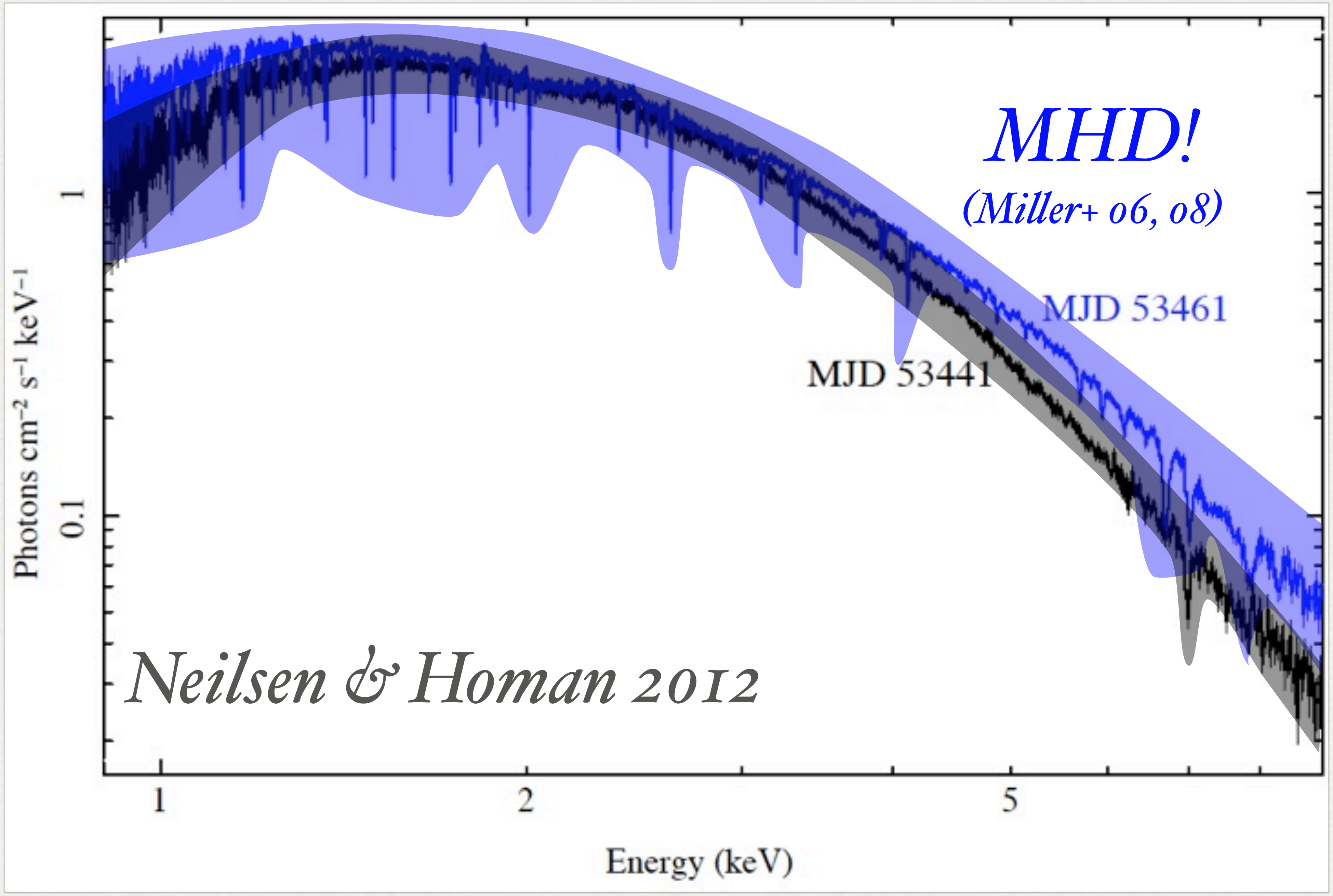
3 October 2012, ESAC

A Puzzle



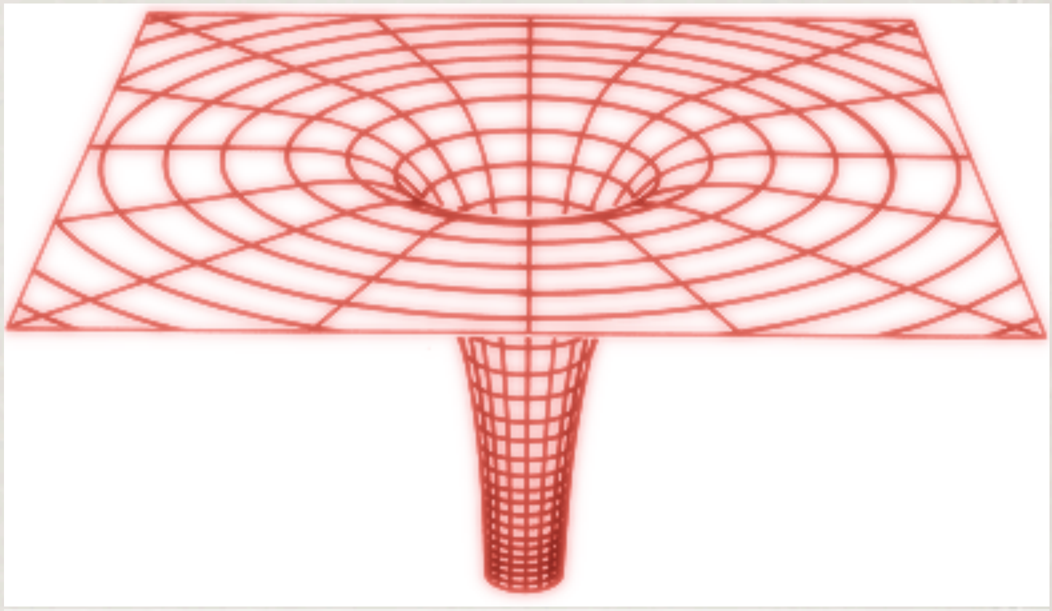
- *Two Chandra HETGS observations of GRO J1655-40, 20 days apart*
- *Obs 1: a single line. Obs 2: a dense forest of lines!*

Big Questions

- *What do high-resolution X-ray spectra tell us about accretion?*
- *What are the links between accretion, ejection, and radiation processes?*
- *Why (and how) are winds and other outflows important?*

Big Answers

VS



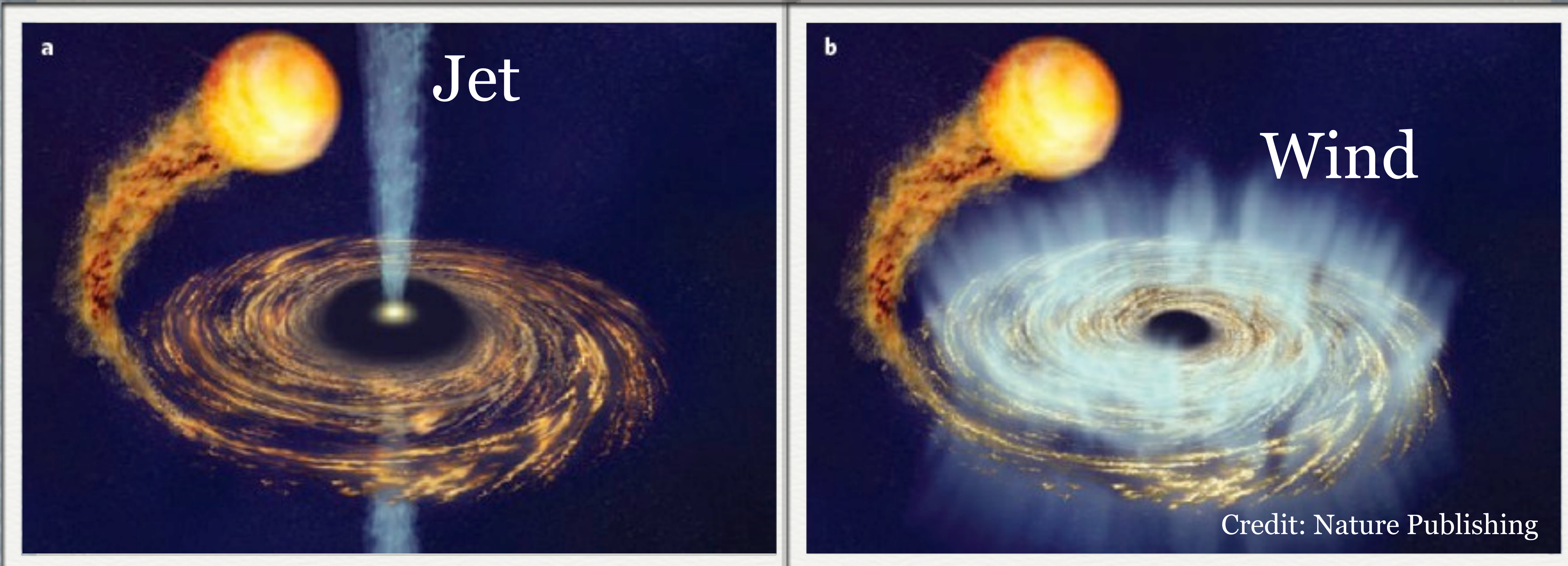
RADIATION

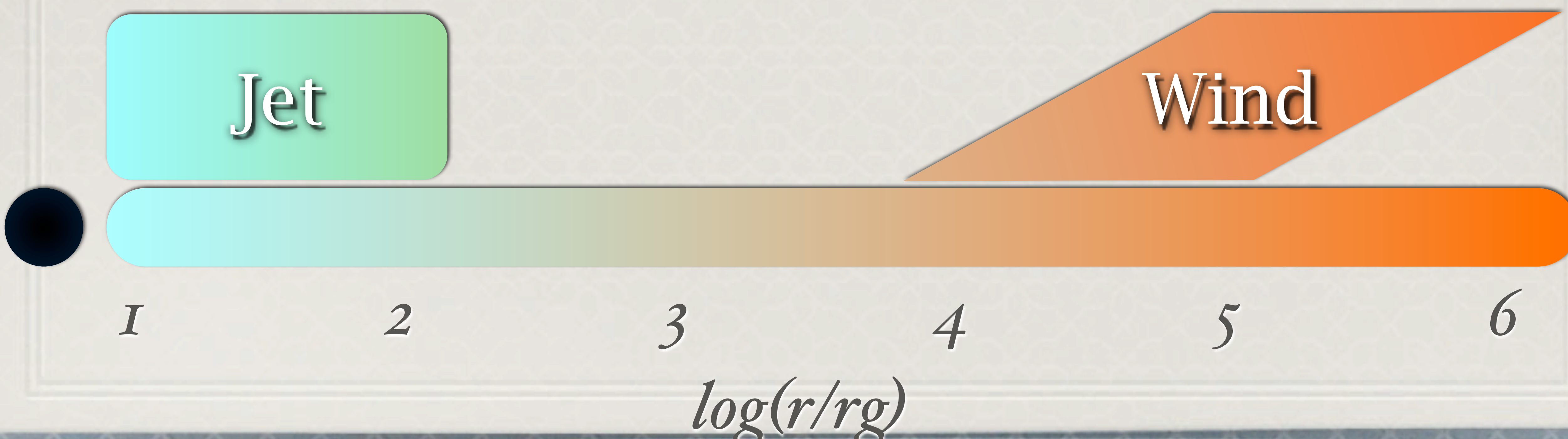
GRAVITY

Outline

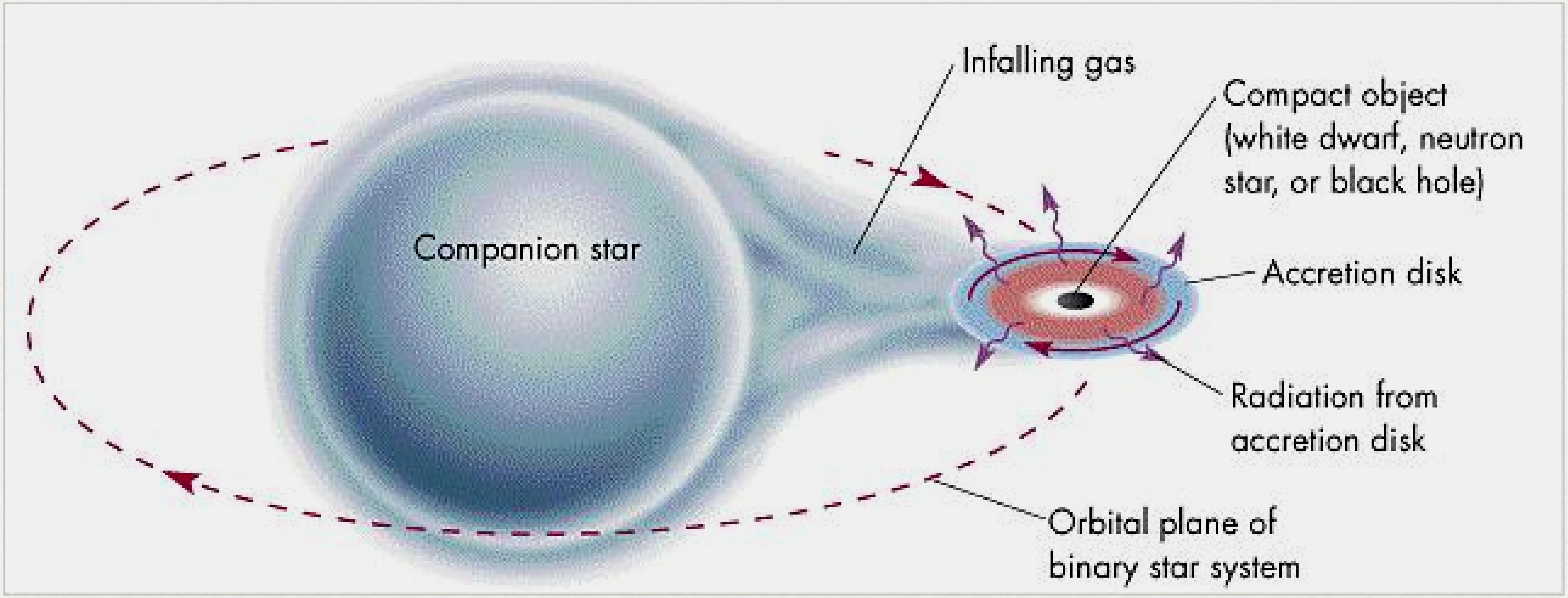
- *Introduction to accretion in X-ray binaries*
- *Crash course in accretion disk winds:*
  - *History and Physics*
- *Accretion disk winds in GRO J1655-40, 4U 1630-47, and GRS 1915+105*
- *Show how we can use high-resolution X-ray spectroscopy to find physical links between key accretion processes*
- *Winds are an important, evolving part of BH accretion flows*

Definitions



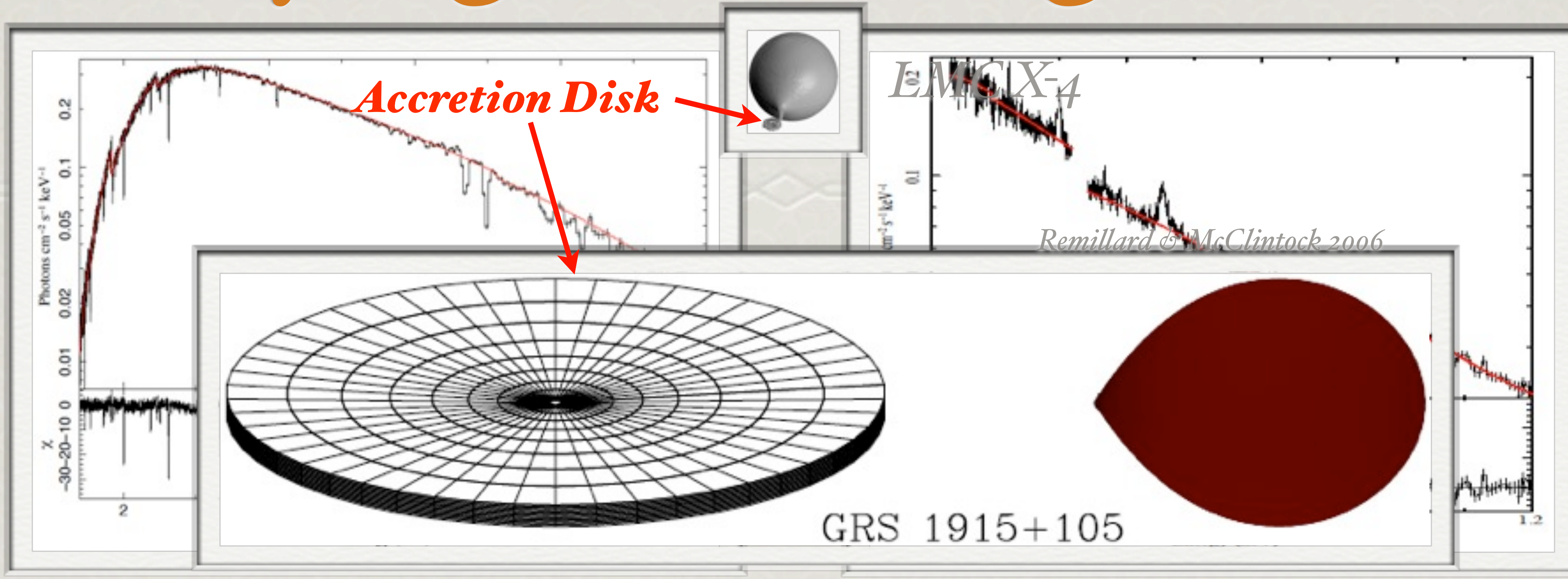


X-ray Binaries



- *Compact object accreting gas, usually in the form of a disk, from a companion star*
- *Accretion converts gravitational potential energy into radiation -> X-rays!*

Unifying Accreting Binaries



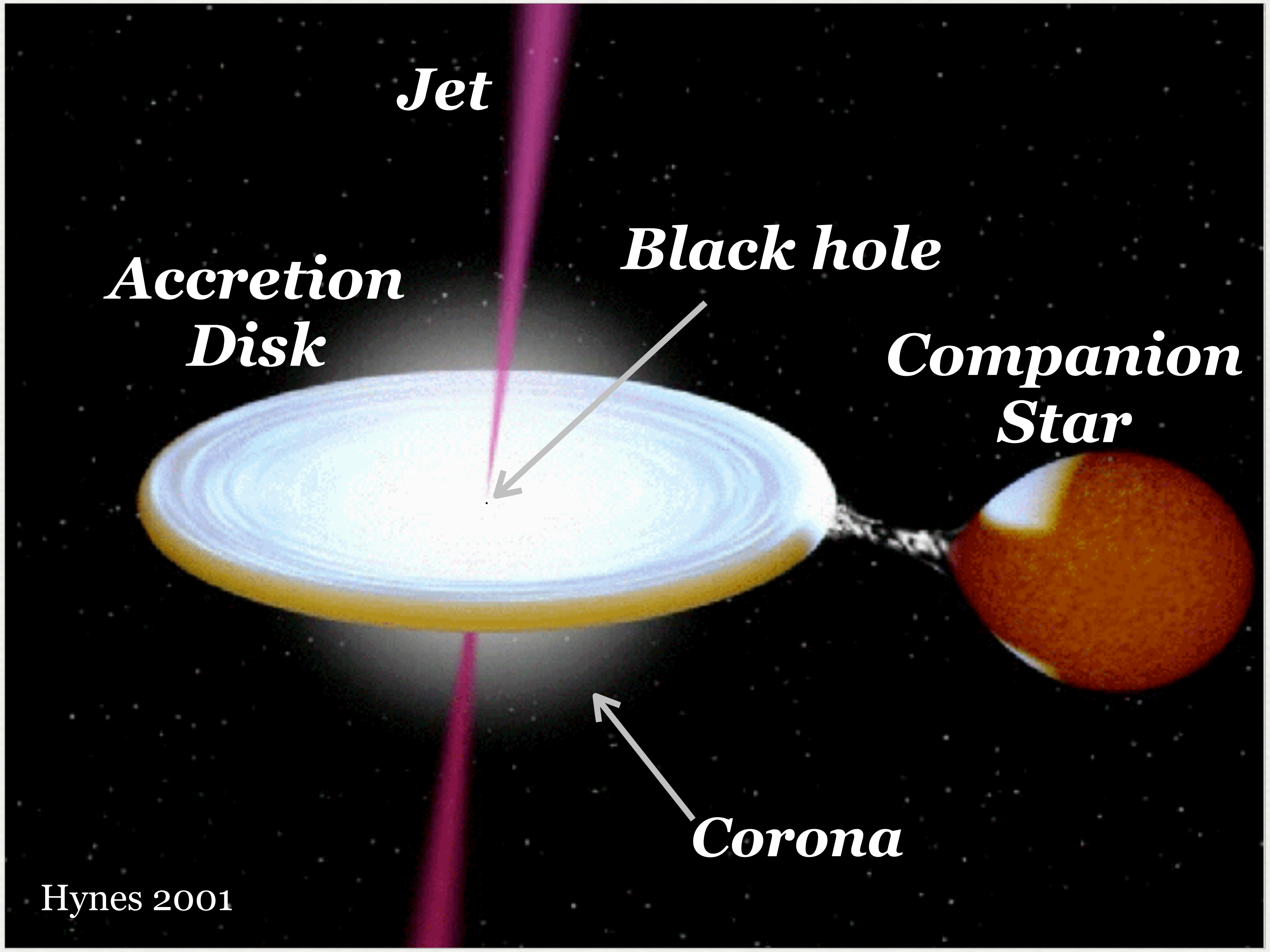
GRS 1915+105

- *Black Hole*
- *Low-Mass Companion*
- *Extreme, fast variability*
- *Absorption Lines*
- *Accretion Disk Wind*

LMC X-4

- *Neutron Star*
- *High-Mass Companion*
- *Slow, periodic variability*
- *Emission Lines*
- *Stellar Wind*

Anatomy of an X-ray Binary

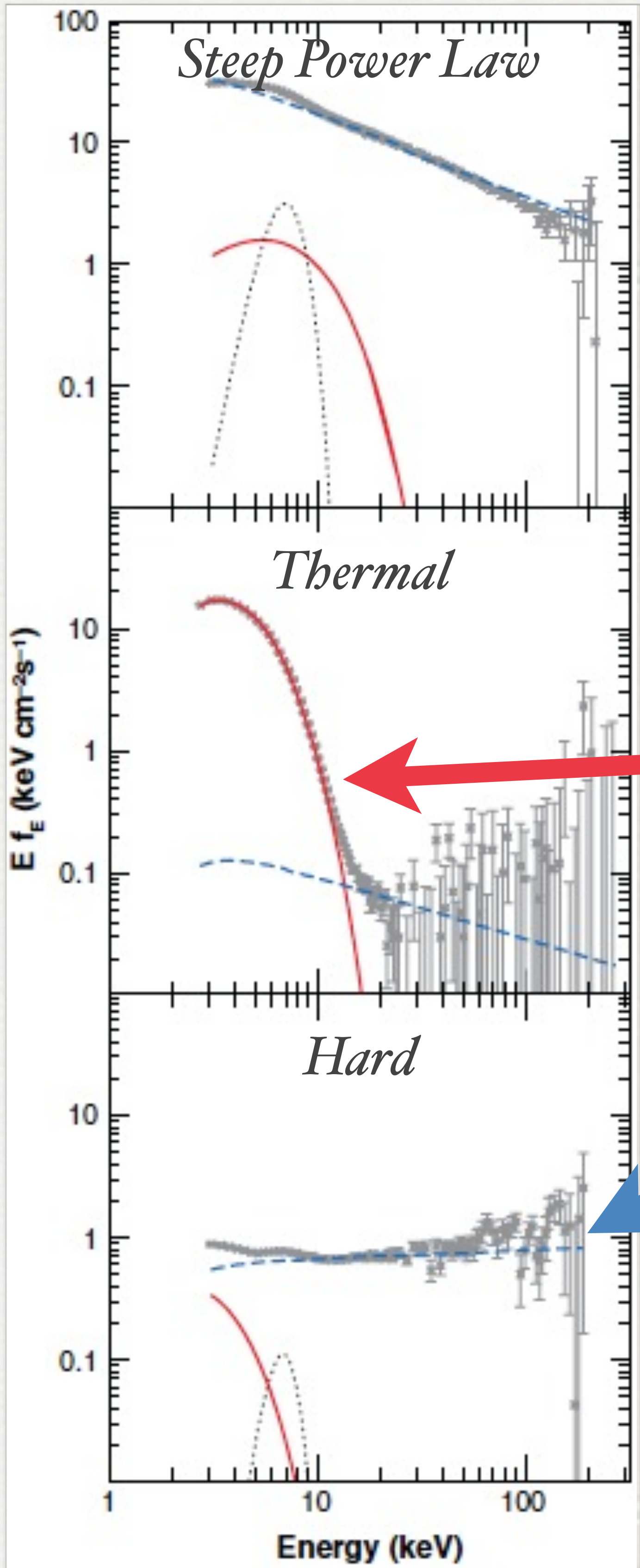


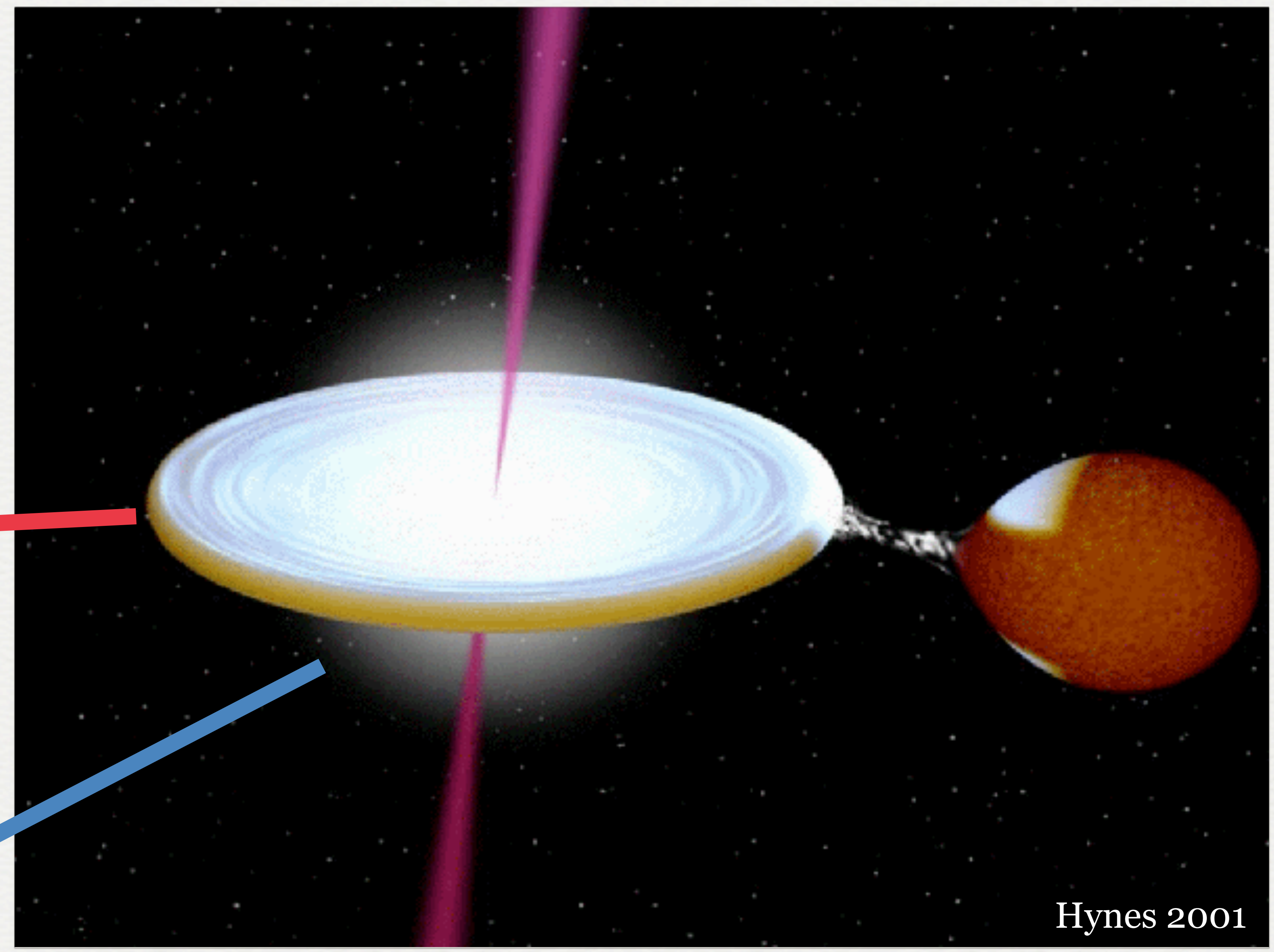
Unifying Accretion Physics

- ***<u>Goal</u>***: *Find relationships between changes in the X-ray luminosity, mass accretion rate, mass ejection rate, environment*
- *How does the accretion flow produce radiation? How does radiation affect the accretion rate?*
  - *Broadband X-ray spectroscopy (see also BH spin; McClintock+ 2006)*
- *How does the X-ray luminosity drive outflows? How do the power, mass of outflows compare to the accretion rate?*
  - *High-resolution X-ray spectroscopy*
- *How do accretion processes influence the environment?*
  - *Combine above with photoionization studies*

Tracking Radiation Physics

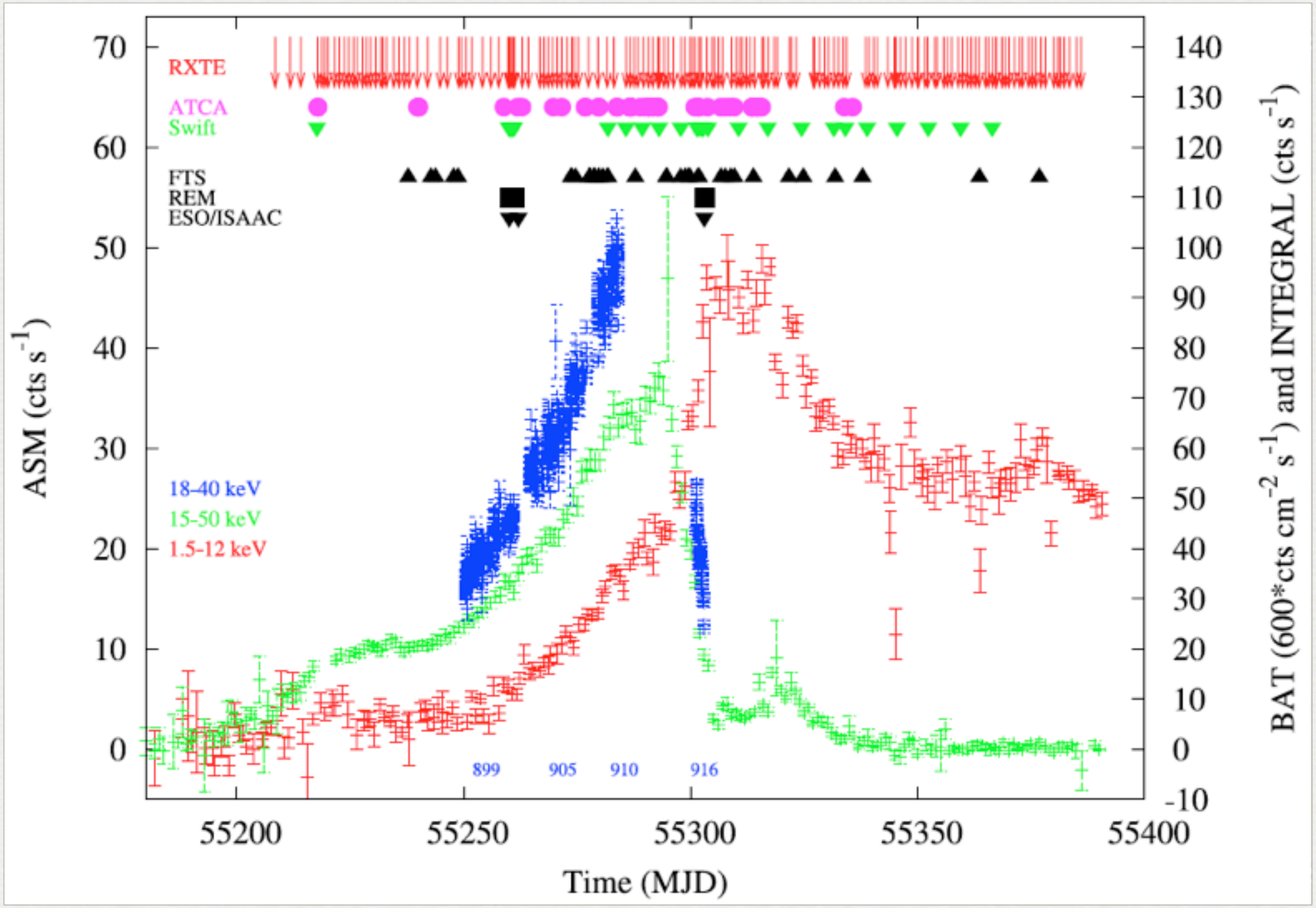
Remillard & McClintock 2006



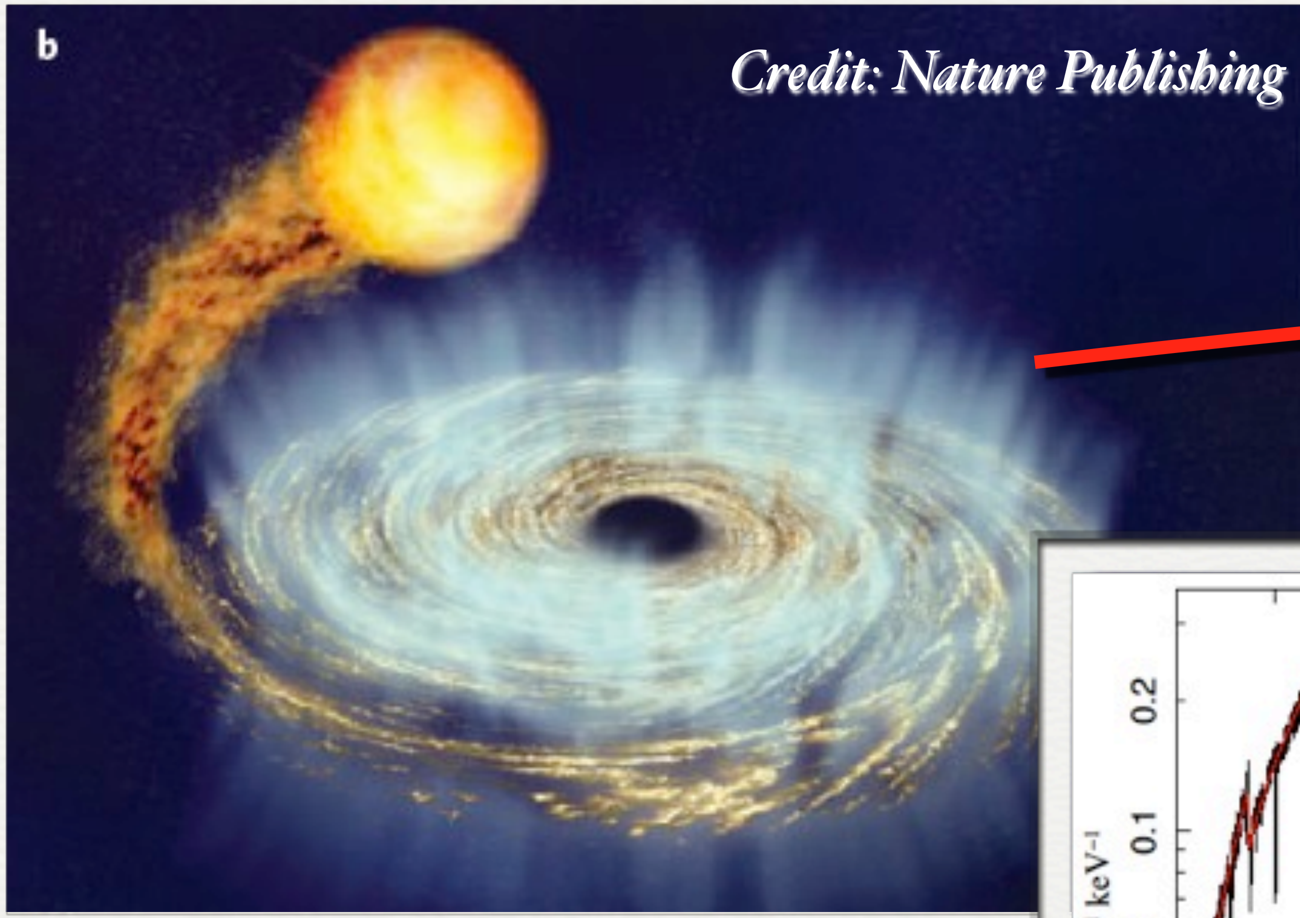


- *Different accretion processes lead to different spectra*

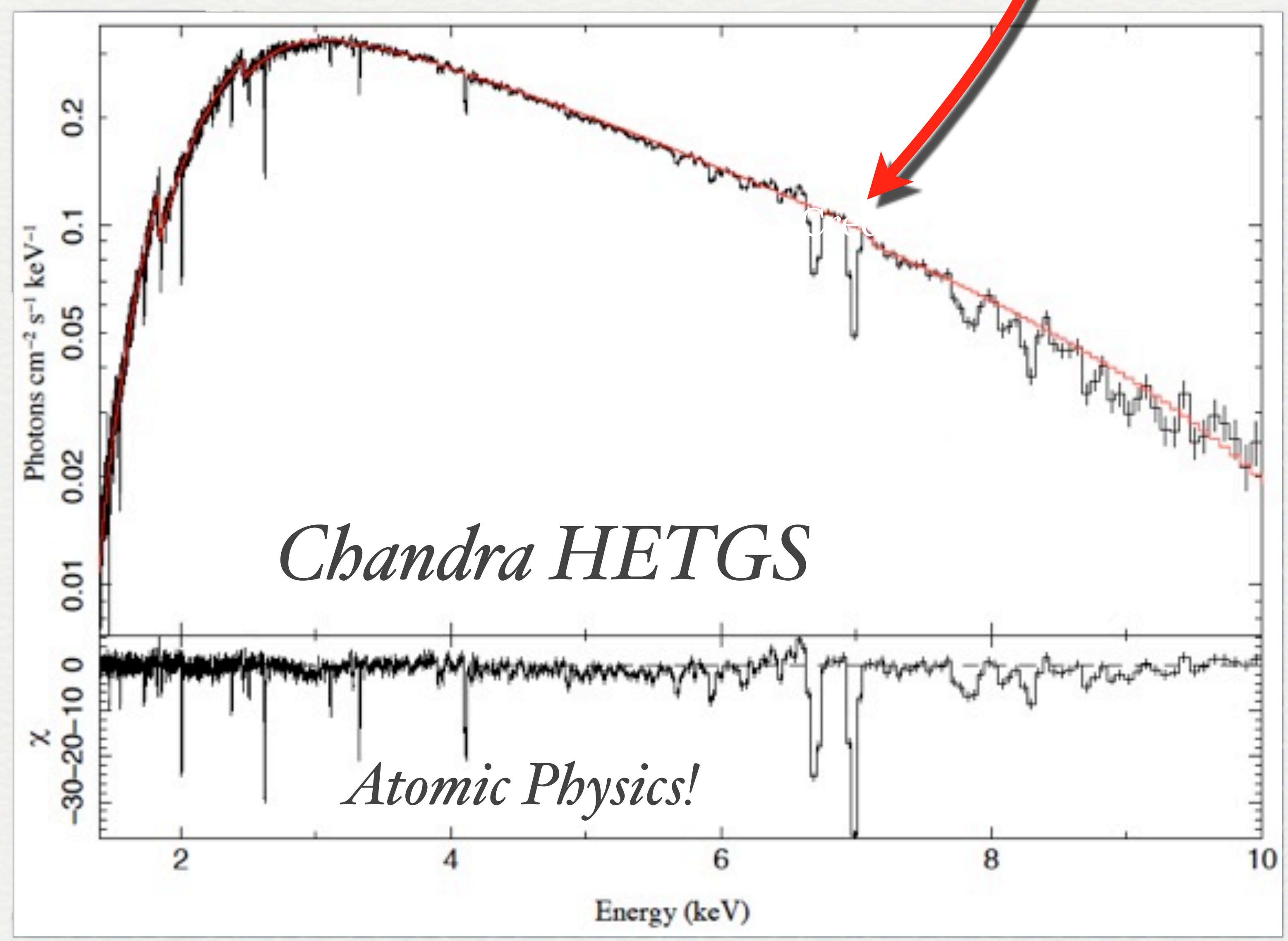
A Brief Note: GX 339-4



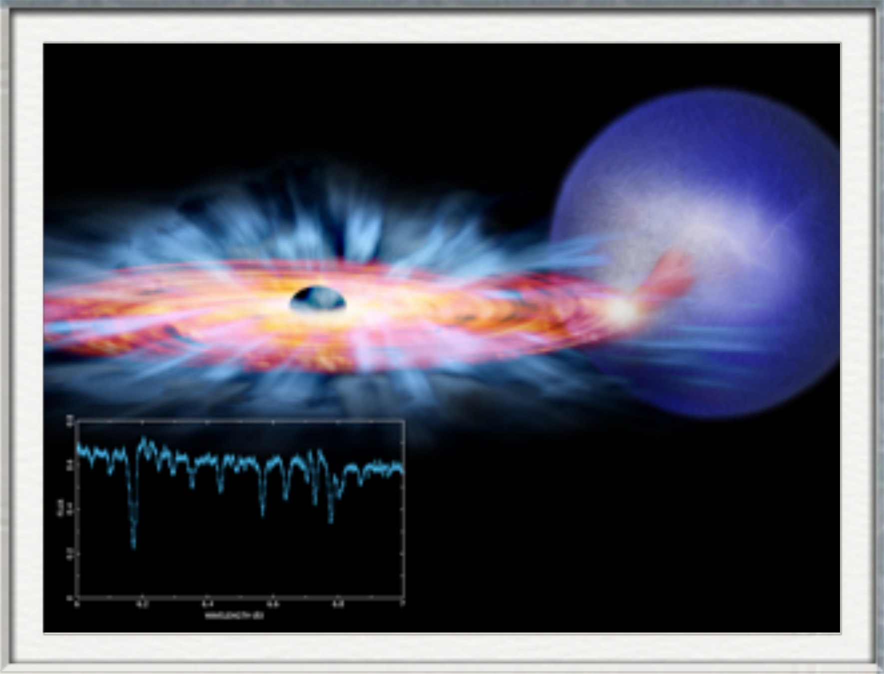
Winds: Radiation Drives Outflows



- *Hot gas flowing off the disk*
- *Typically launched and ionized by intense radiation fields*
- *Visible in high-resolution X-ray spectra from Chandra*



A Little More on Winds

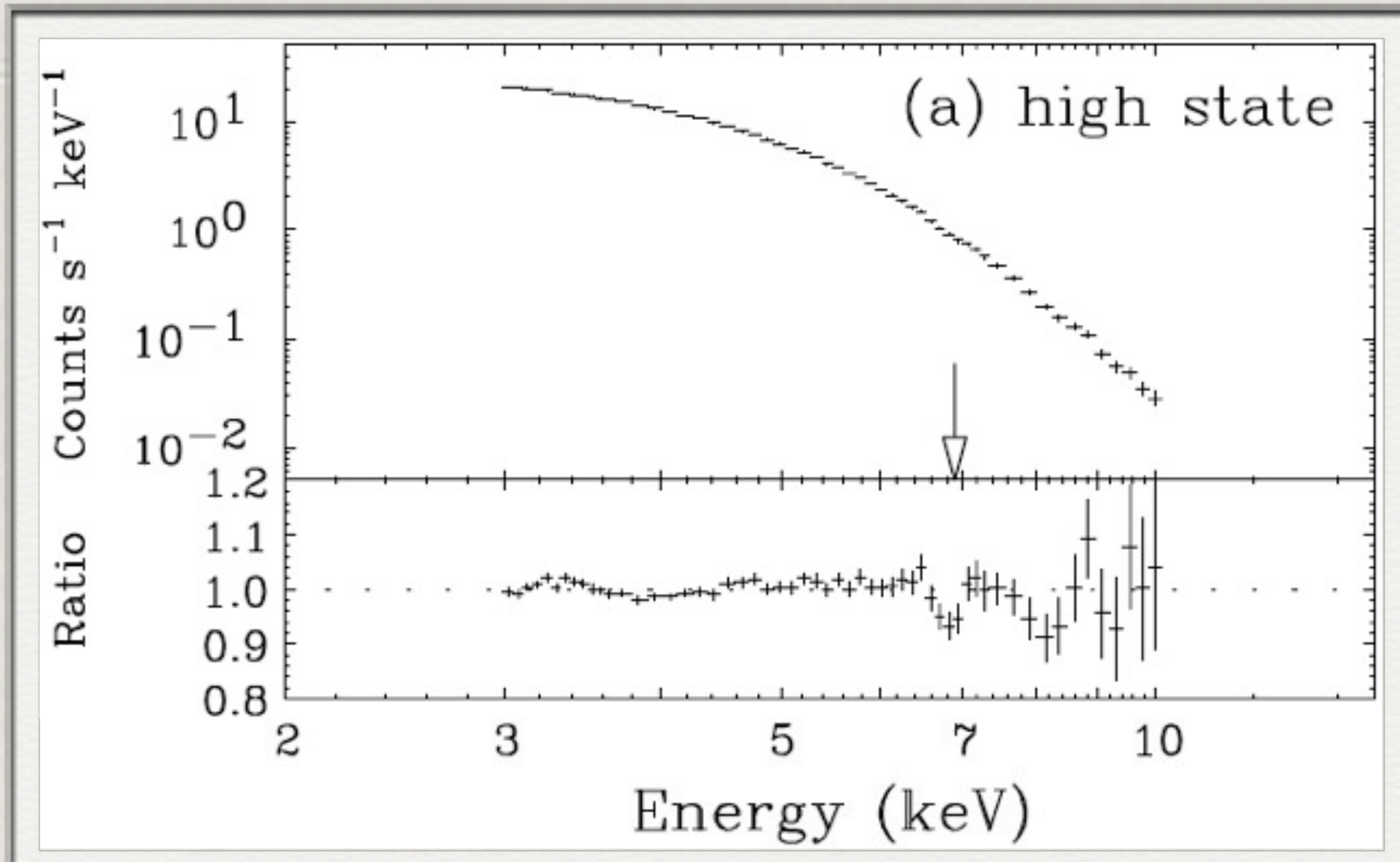


- *What are they?*
  - *Ionized outflow from the accretion disk, driven by radiation, thermal pressure, or magnetic processes*
- *How do we see them?*
  - *Blueshifted ionized absorption lines in X-ray spectra (1000 km/s)*
- *Why are they important?*
  - *Very significant dynamical component: can suppress relativistic jets (Neilsen & Lee 2009)*
  - *Carry most of the infalling matter away from the black hole! (e.g. Neilsen, Remillard, & Lee 2011; Ponti+ 2012; King+ 2012)*

A Brief History of Winds in XRBs

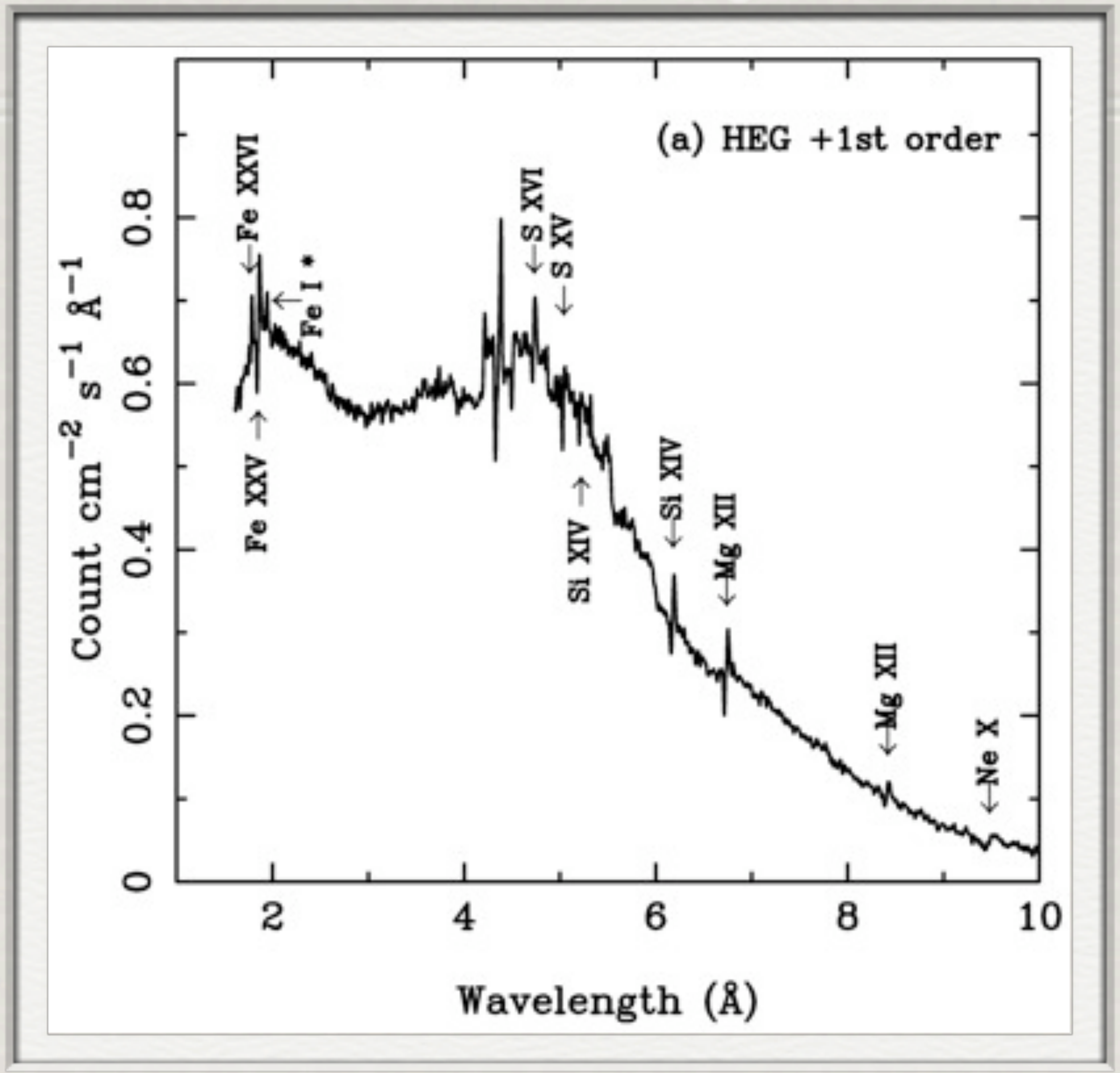
As of 3 October 2009

A Brief History of Winds



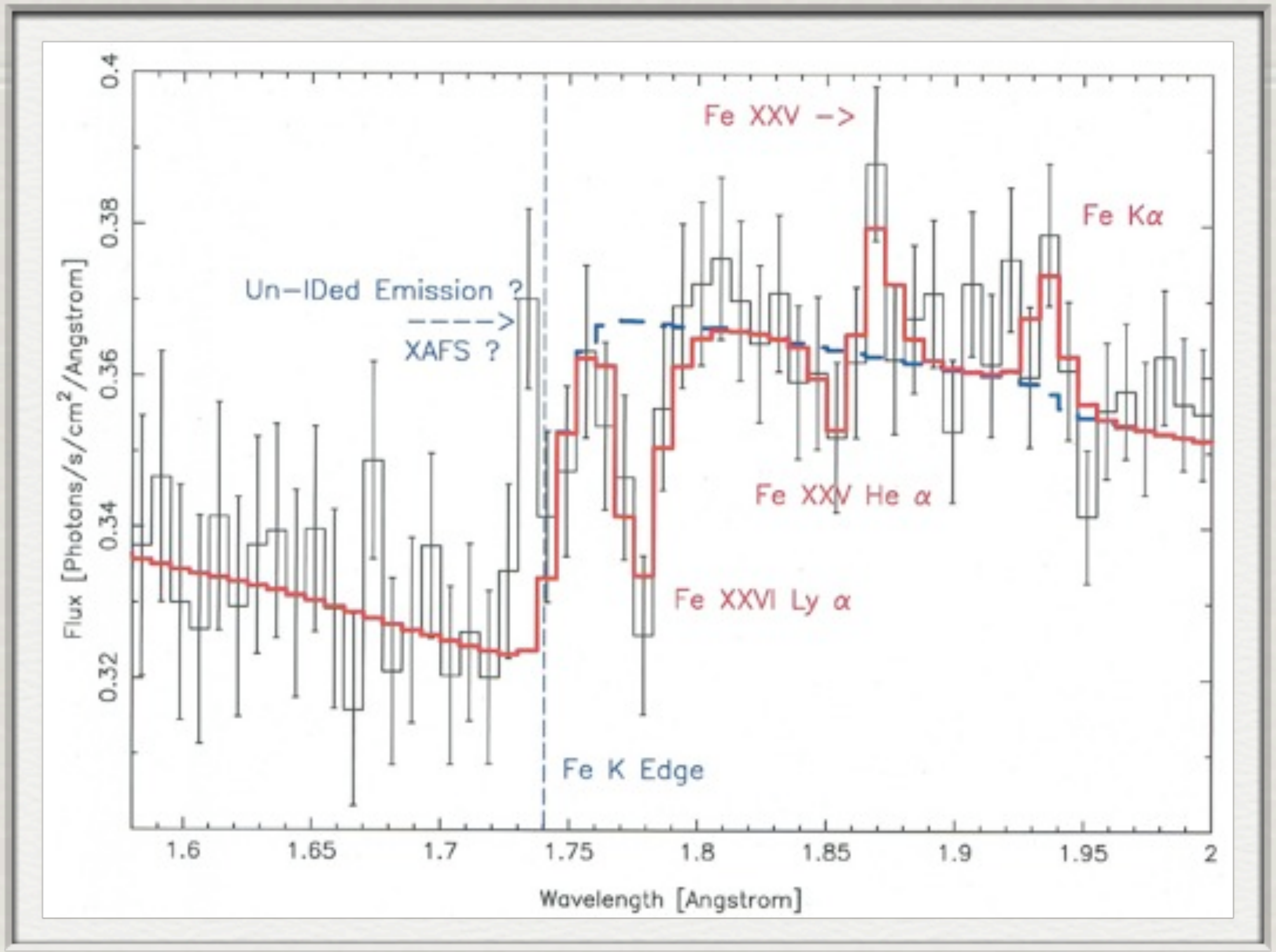
- *ASCA absorbers: Ebisawa 1997, Ueda 1998*
- *Photoionized accretion disk corona:* ***hot gas above the disk?***

A Brief History of Winds



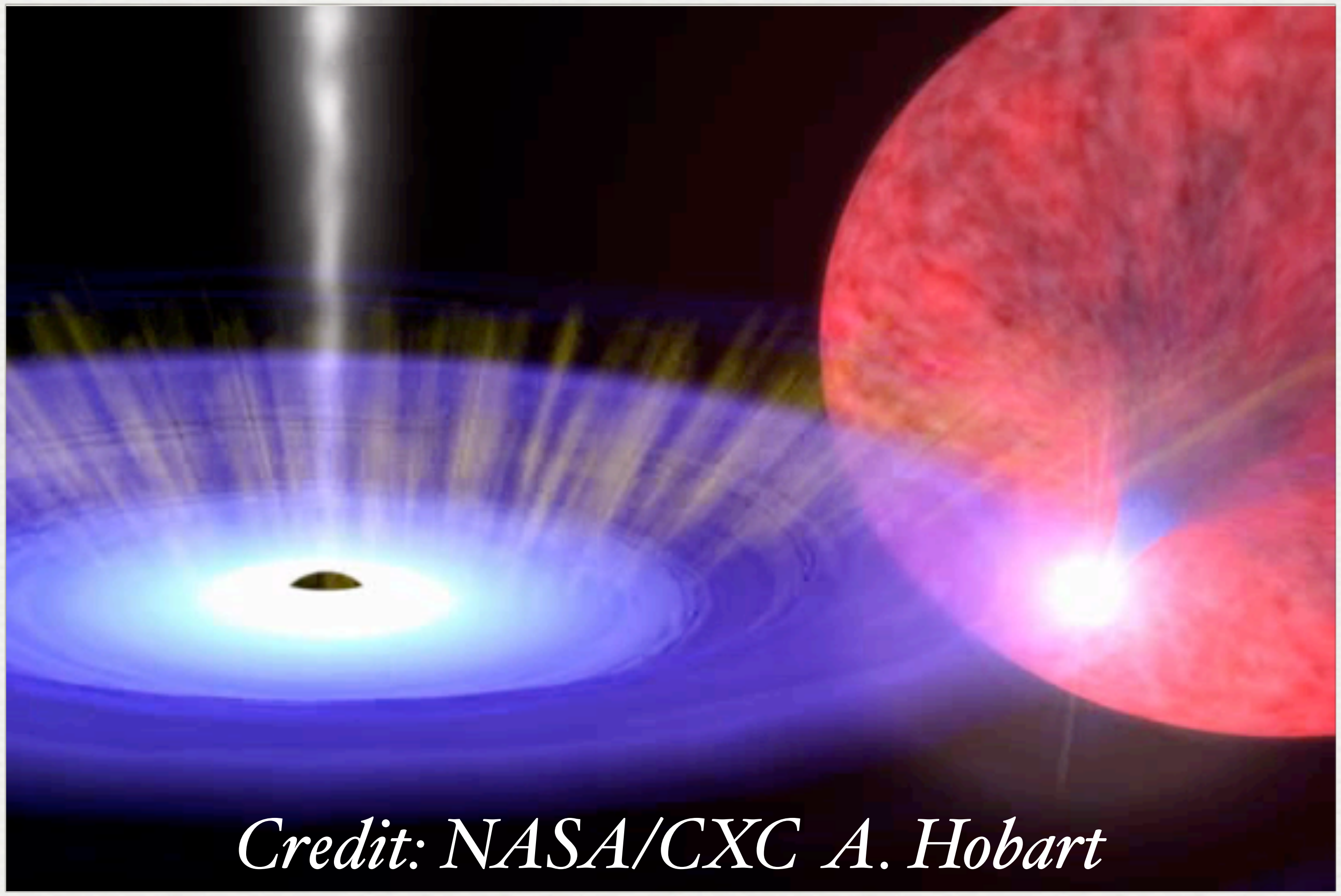
- *Brandt & Schulz (2000): Chandra HETGS, Circinus X-1*
- *First X-ray P-Cygni lines from an XRB:* ***outflowing gas***

A Brief History of Winds



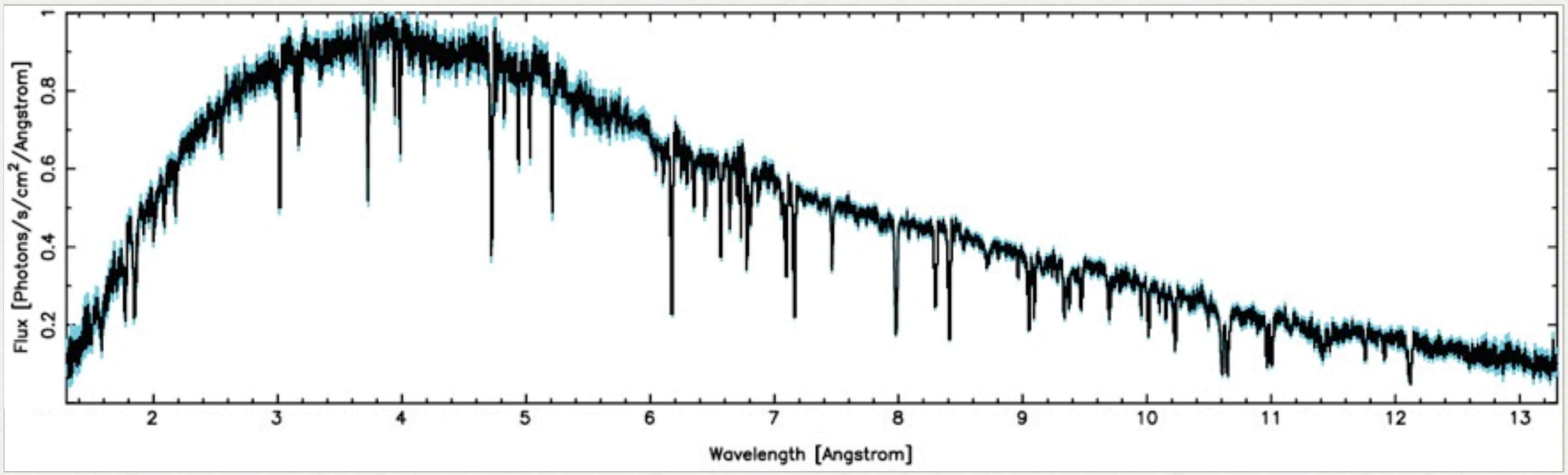
- *Lee et al. (2002): Chandra HETGS, GRS 1915+105*
- *Ionized outflow, $\dot{M}_{out} \approx \dot{M}_{in}$?*

A Brief History of Winds



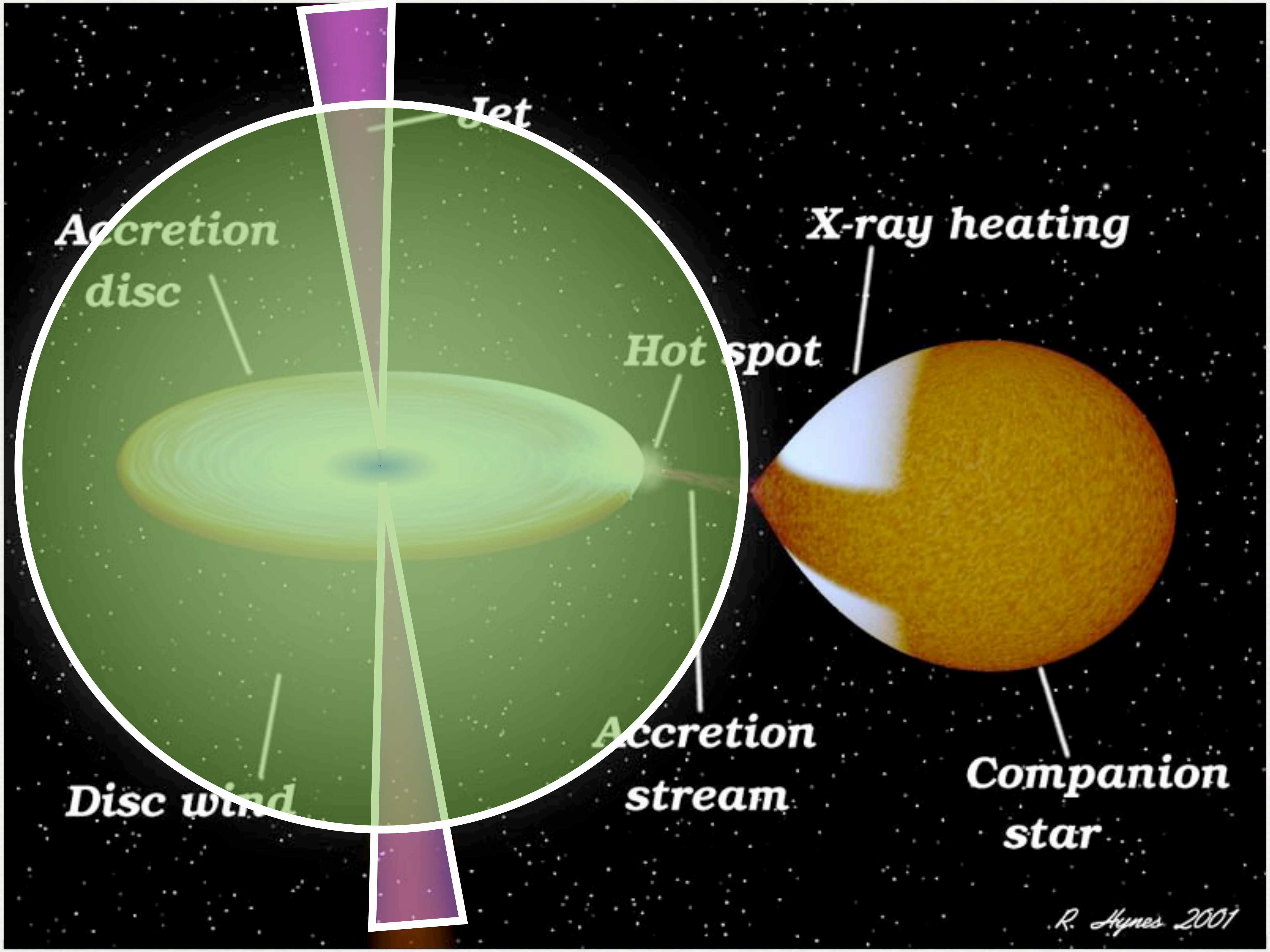
- *Neilsen & Lee (2009): Chandra HETGS, GRS 1915+105*
- *Winds may **quench jets** in GRS 1915 by altering flow of gas*

A Brief History of Winds

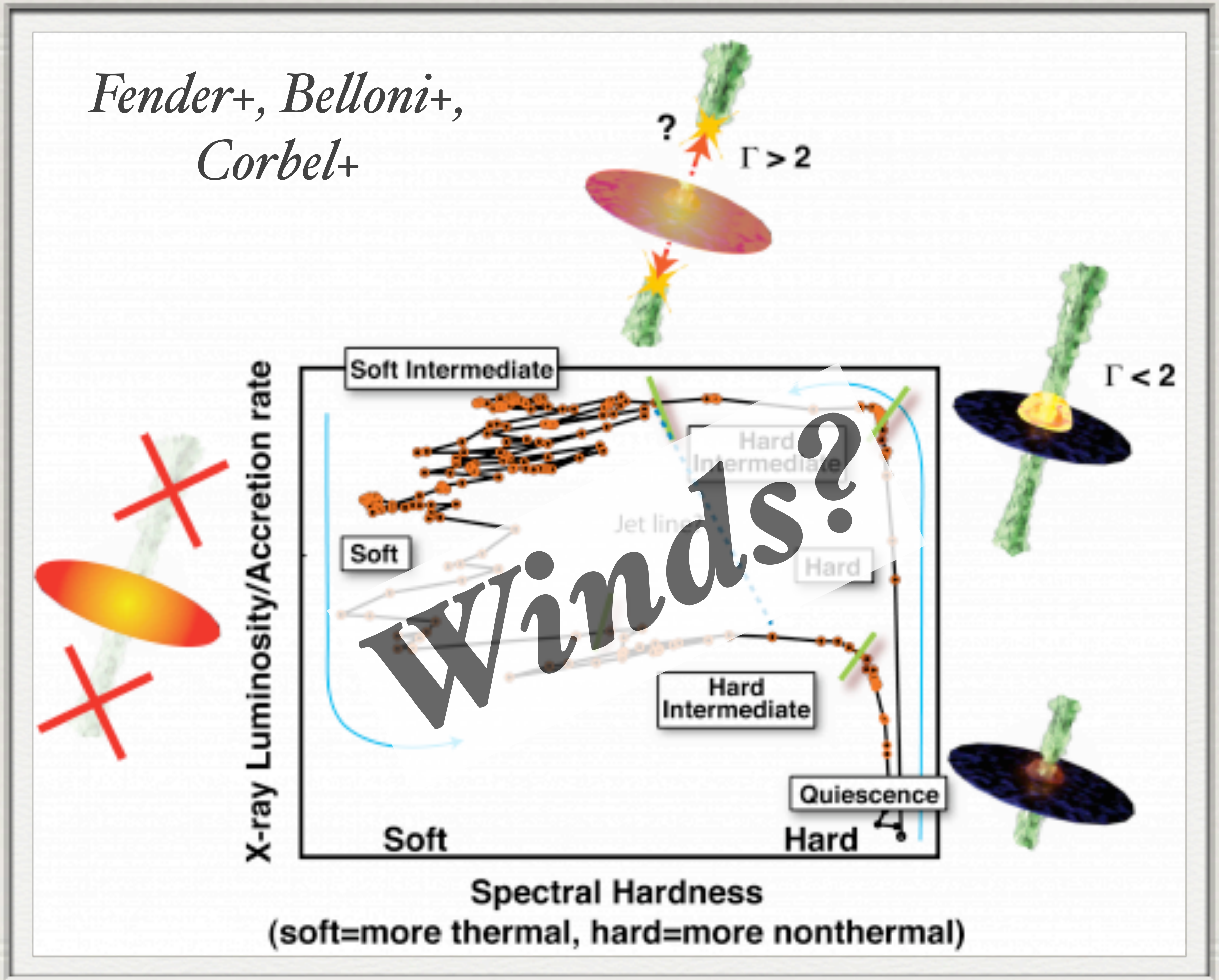


- *Miller et al. (2006, 2008): Chandra HETGS, GRO J1655-40*
- *Only definitive observational evidence for **MHD winds** in XRBs*

Outflows in XRBs



Disk - Jet Connection



Where are the Winds?

- *Three years ago:*
  - *Clear that there might be some links between winds and relativistic jets (see also Miller+ 2008, Lee+ 02)*
  - *The role of winds in black hole outbursts wasn't known, but possibly significant*
- *Particularly important to understand the physics of ionized accretion disk winds and their formation*

The Physics of Disk Winds

As seen by an X-ray observer

How Winds Work

$$\xi = \frac{L_{\mathrm{X}}}{n_{\mathrm{e}} R^2}$$

Ionization Parameter

How Winds Work

- *Three possible origins:*
  - *Radiation pressure (UV line driving)*
  - *Thermal pressure (i.e. irradiation, Compton heating)*
  - *MHD processes*
- *Where is the wind, how ionized is it, and how dense is it?*

- *Wind properties:*
  - *Low-ish ionization < 10^3*
  - *Low-ish density ($<10^{13-14}$), **far from BH** ($>10^{4-5}$ R_g, 10^{11} cm)*
  - *Can be **more dense, closer to BH***

How Thermal Winds Work

- *Broadband continuum: Compton heats electrons in the outer disk*

$$R_{\mathrm{C}} = \frac{9.80 \times 10^{17}}{T_{\mathrm{C}}} \frac{M_{\mathrm{X}}}{M_{\odot}} \ \mathrm{cm}$$

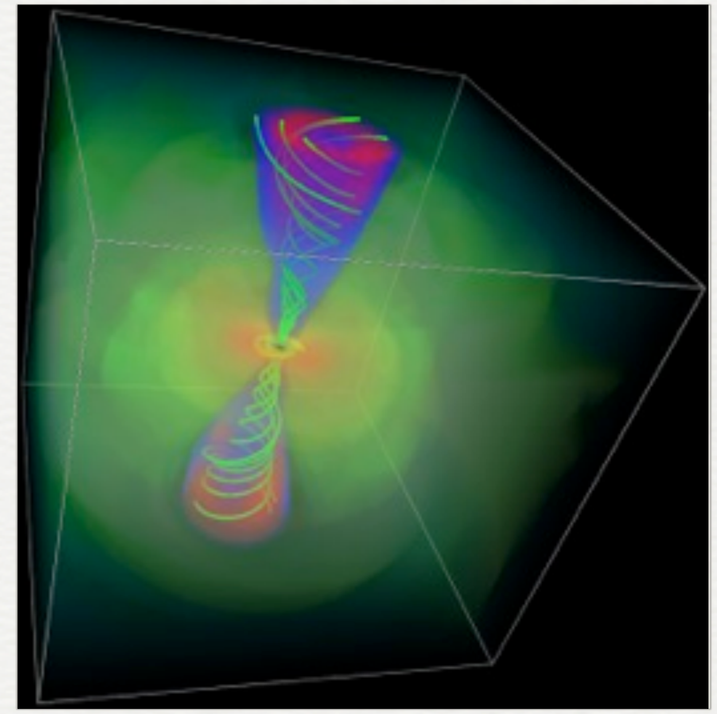
- *Sound speed at the Compton temperature exceeds escape speed*

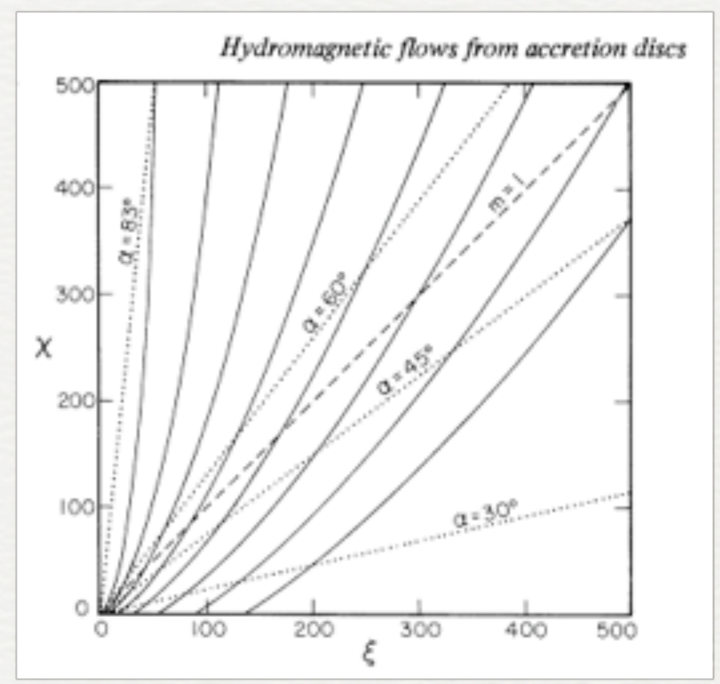
$$T_{\mathrm{C}} = \frac{1}{4k_{\mathrm{B}}} \frac{\int_0^{\infty} h\nu L_{\nu} d\nu}{\int_0^{\infty} L_{\nu} d\nu}$$

- *Expanding wind, expect $v \sim v_{esc}$*

How MHD Winds Work

- *Do appear in simulations (e.g. McKinney)*
- *Driven by magnetocentrifugal effects (B-P '82) or magnetic viscosity; no single theoretical sense*
- *Unclear if winds should escape or not, follow* ***B*** *lines*





Thermal vs MHD Winds

- *Not obvious that these winds should have vastly different lines*
- *Many physical factors influence the observability of absorption lines (along with S/N, of course)*

How Winds Work

$$\xi = \frac{\boxed{L_X}}{\boxed{n_e}\boxed{R^2}}$$

$$N_H = \boxed{n}\boxed{\Delta R}$$

$$\frac{W_\lambda}{\lambda} = \frac{\pi e^2}{m_e c^2}\boxed{N_i}\lambda f_{ji}$$

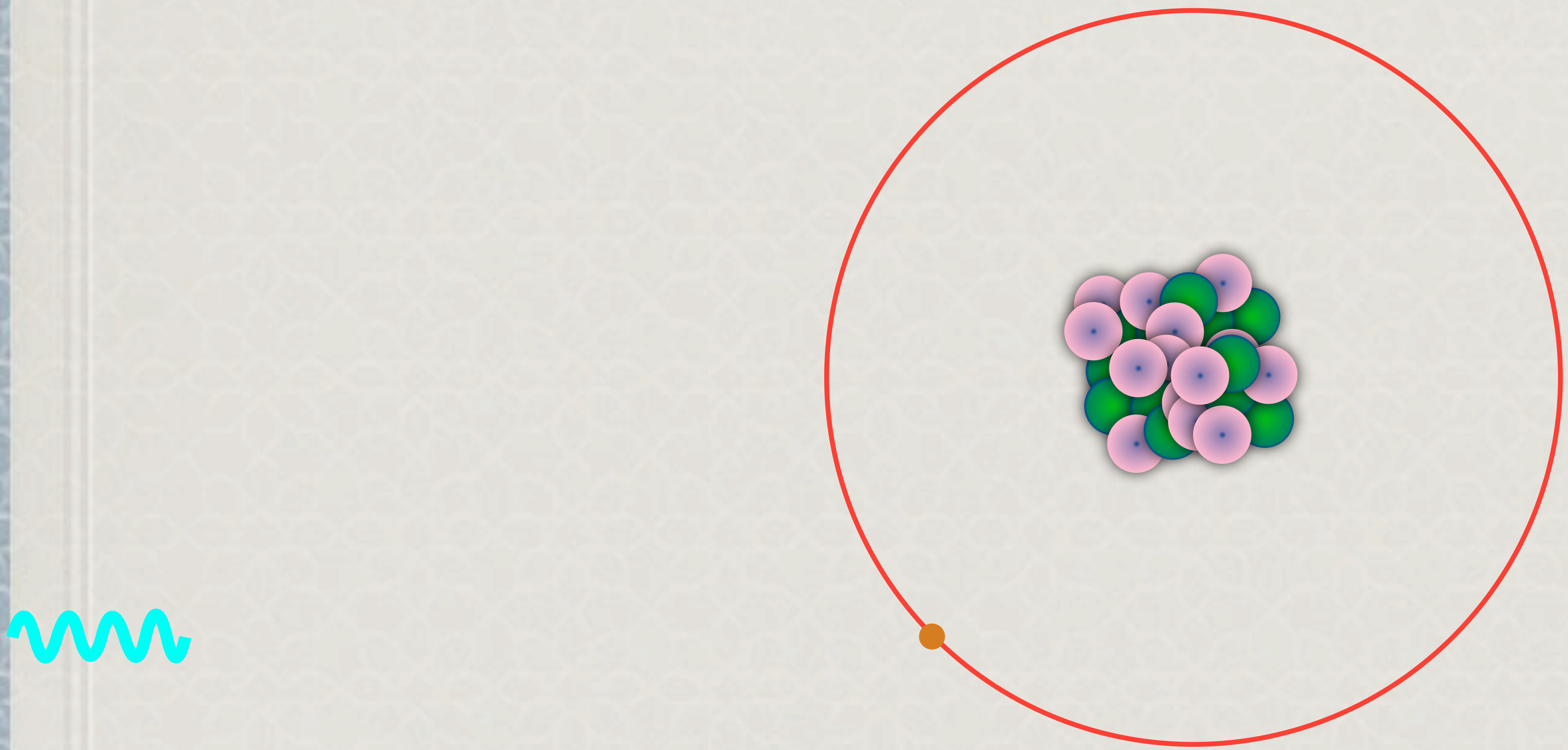
- ***Luminosity***: more photons per electron means hotter, more ionized wind
- ***Broadband spectrum***: a harder spectrum means hotter, more ionized wind; sets which ions visible at a fixed ξ
- ***Distance***: larger distance between X-ray source and absorber means fewer photons per electron
- ***Density***: decreases ionization at fixed luminosity, distance, also sets visible ions
- ***Extent/Column Density***: at fixed ionization, more gas in the line of sight means stronger lines
- ***Curve of Growth***: equivalent widths increase with ionic columns; ionization, abundance

How Winds Work

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

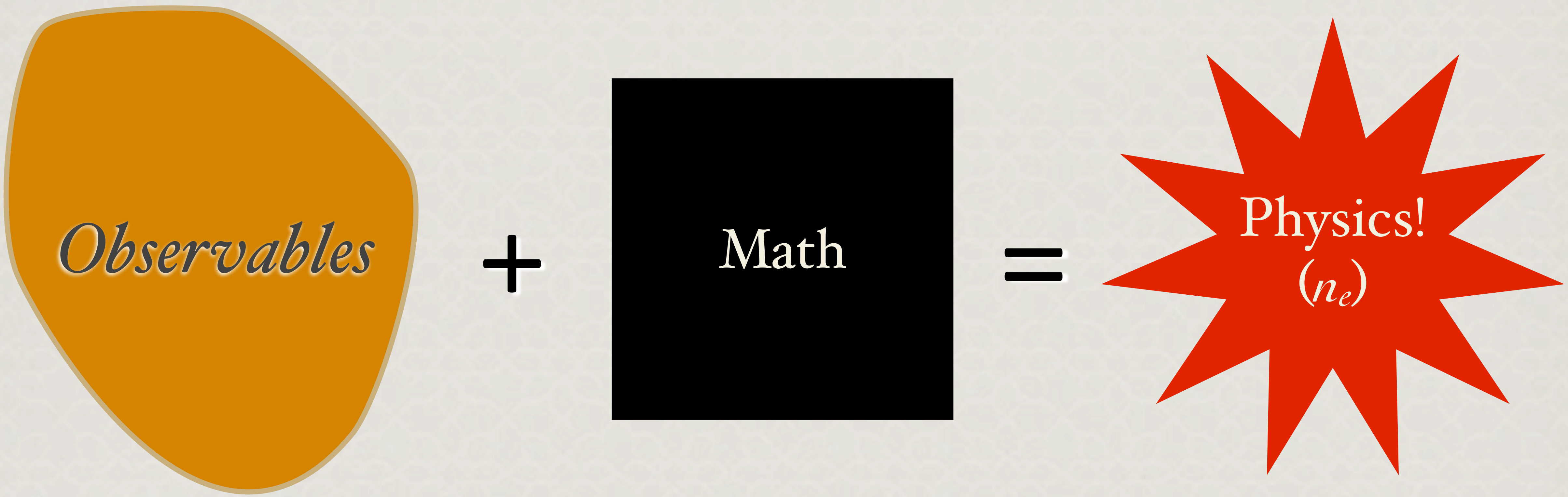
Ionization Balance

Photoionization



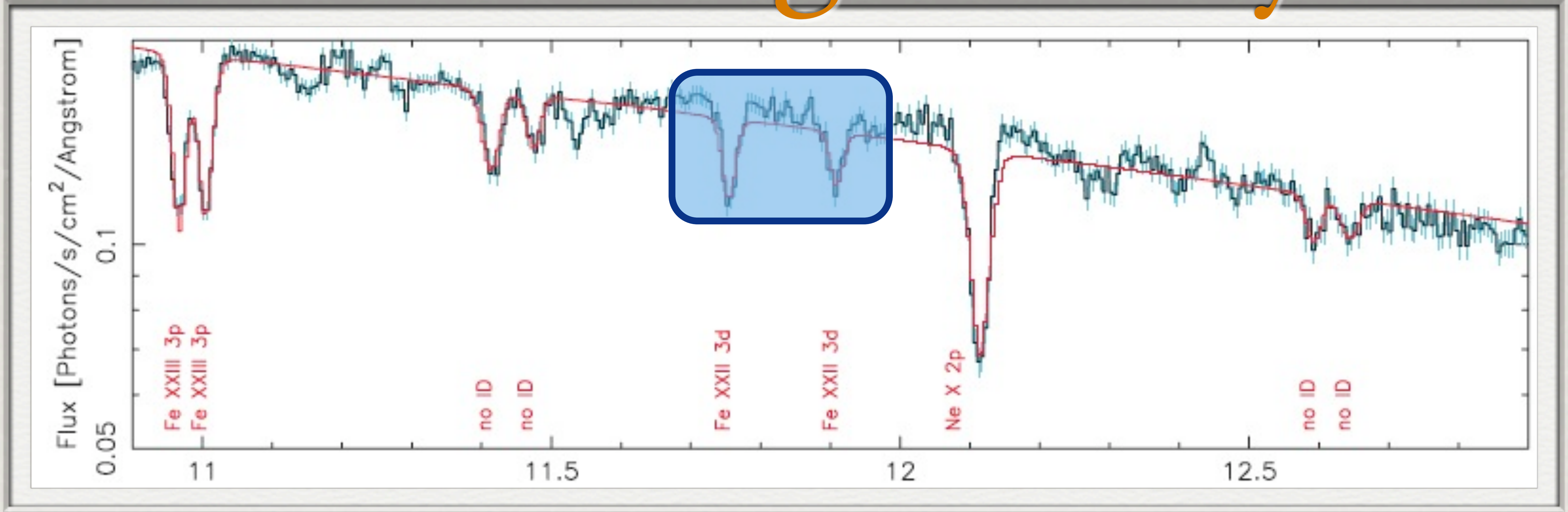
- *Coupling between X-ray emission and plasma conditions: photoionization*
- *Sensitive to gas density and temperature*

Why are we doing this again?



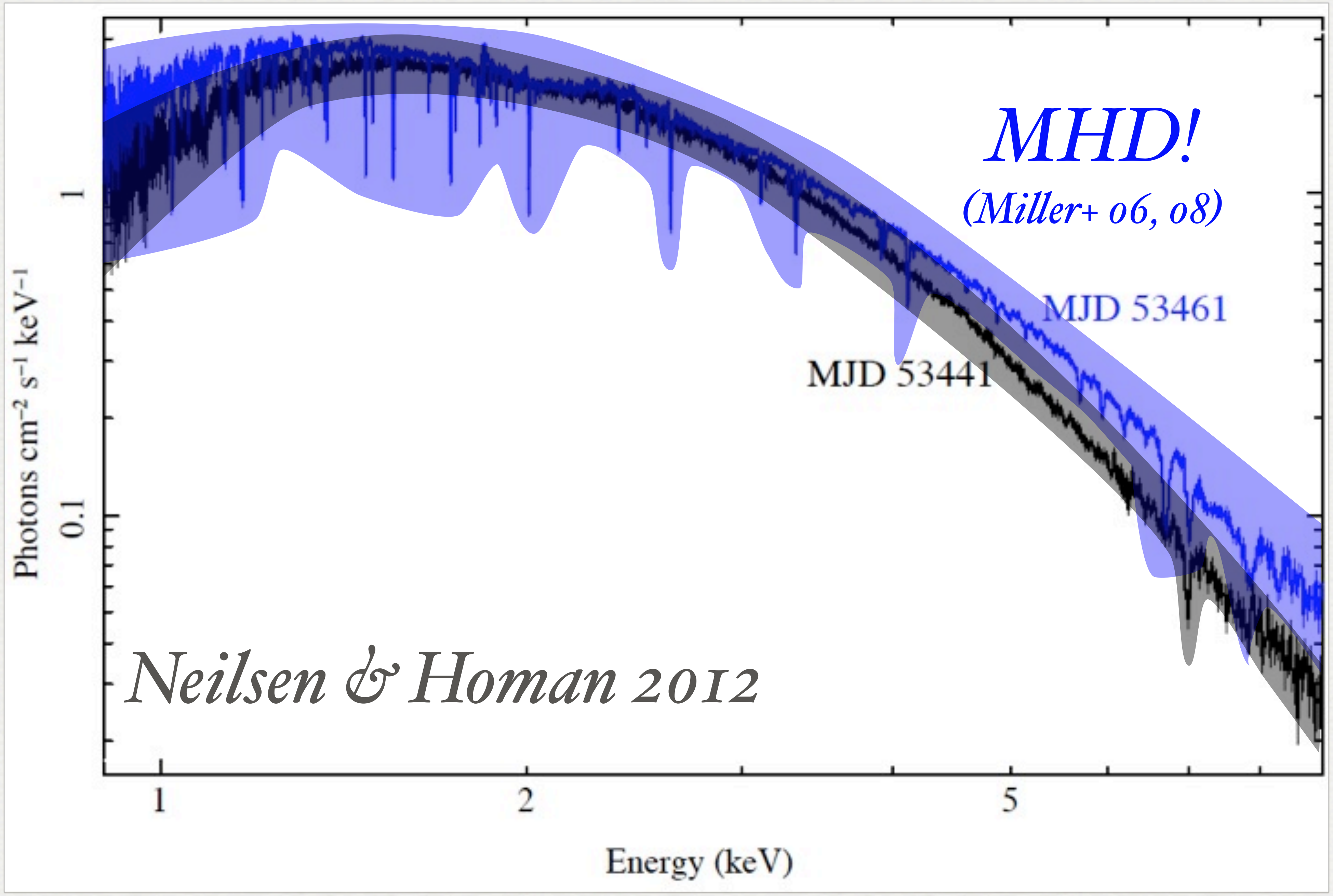
- *Intricate connections between the local radiation field, the properties of the gas, wind physics, and the observed lines*

Measuring Density



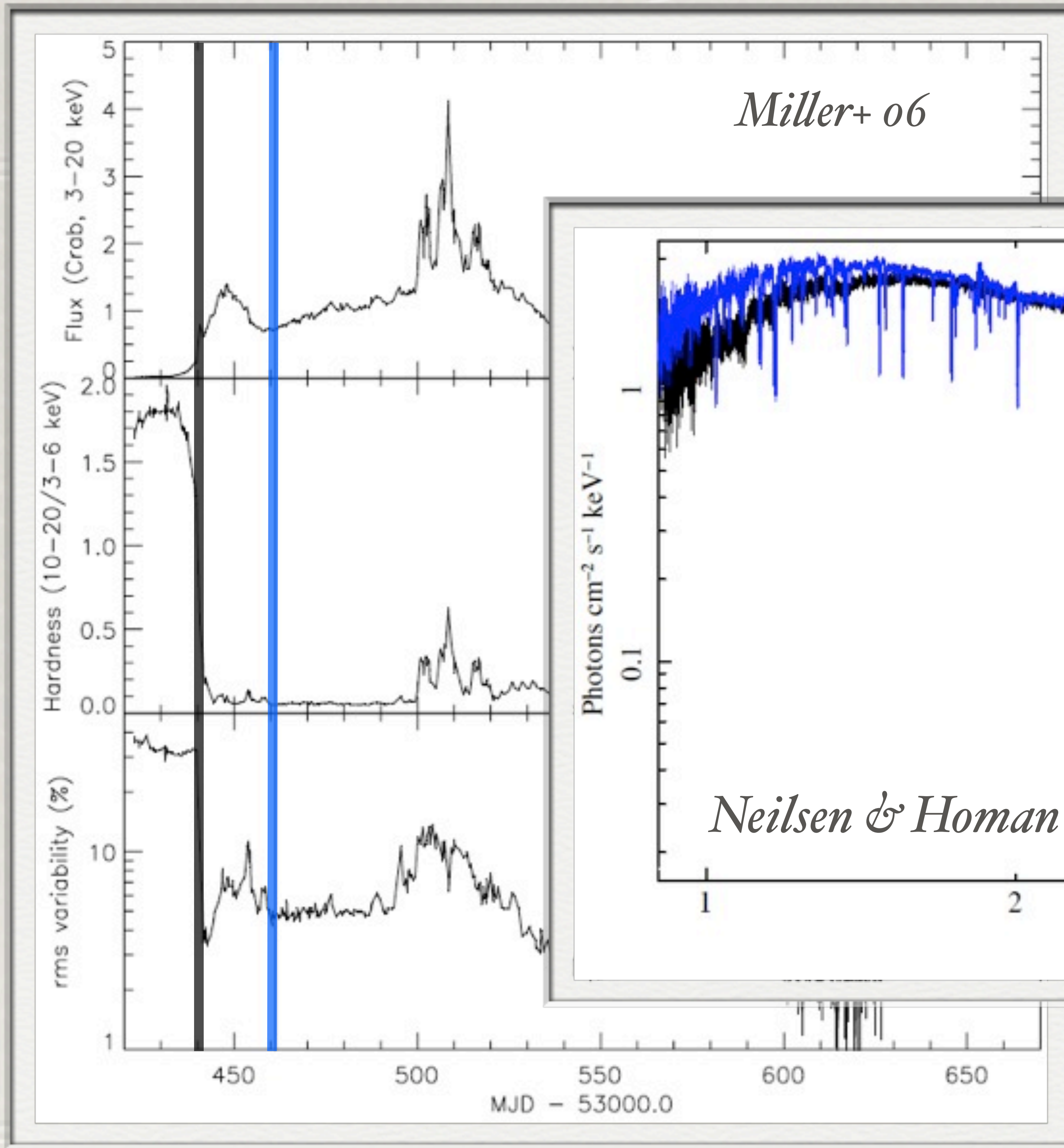
- *Very hard to constrain, best done with density-sensitive atomic lines, e.g. Fe XXIII*
- *(Above) 2005 GRO J1655-40: Miller+ (2006a, 2008), density $n \gtrsim 10^{14}$ cm^{-3} (compared to a nominal 10^{12} cm^{-3}).*
- *Rules out Compton heating and radiation pressure as dominant, leaving MHD! **Only** direct evidence for MHD winds in XRBs*

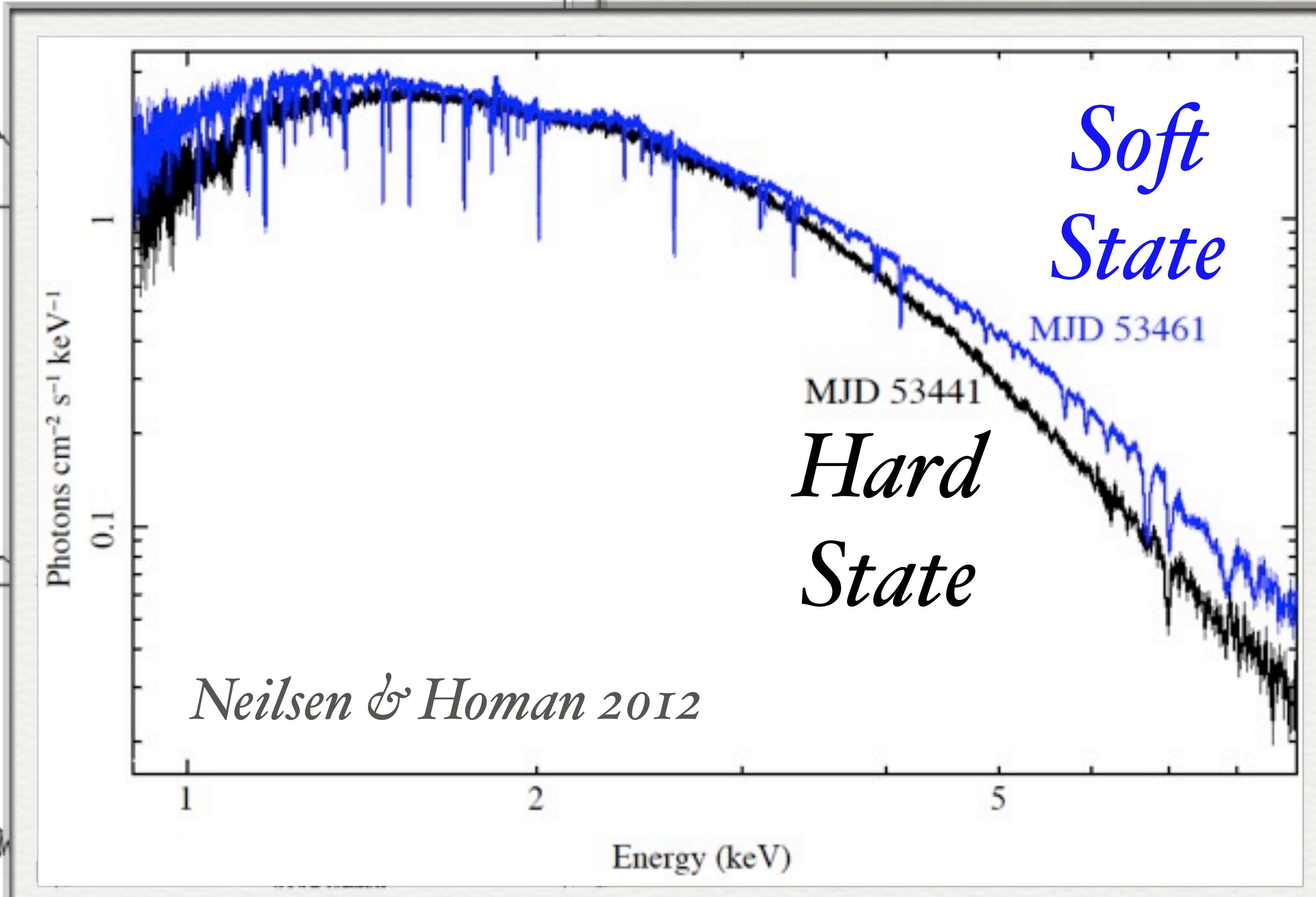
Back to Our Puzzle



- *Two Chandra HETGS observations of GRO J1655-40, 20 days apart*
- *Obs 1: a single line. Obs 2: a dense forest of lines!*

2005 Outburst





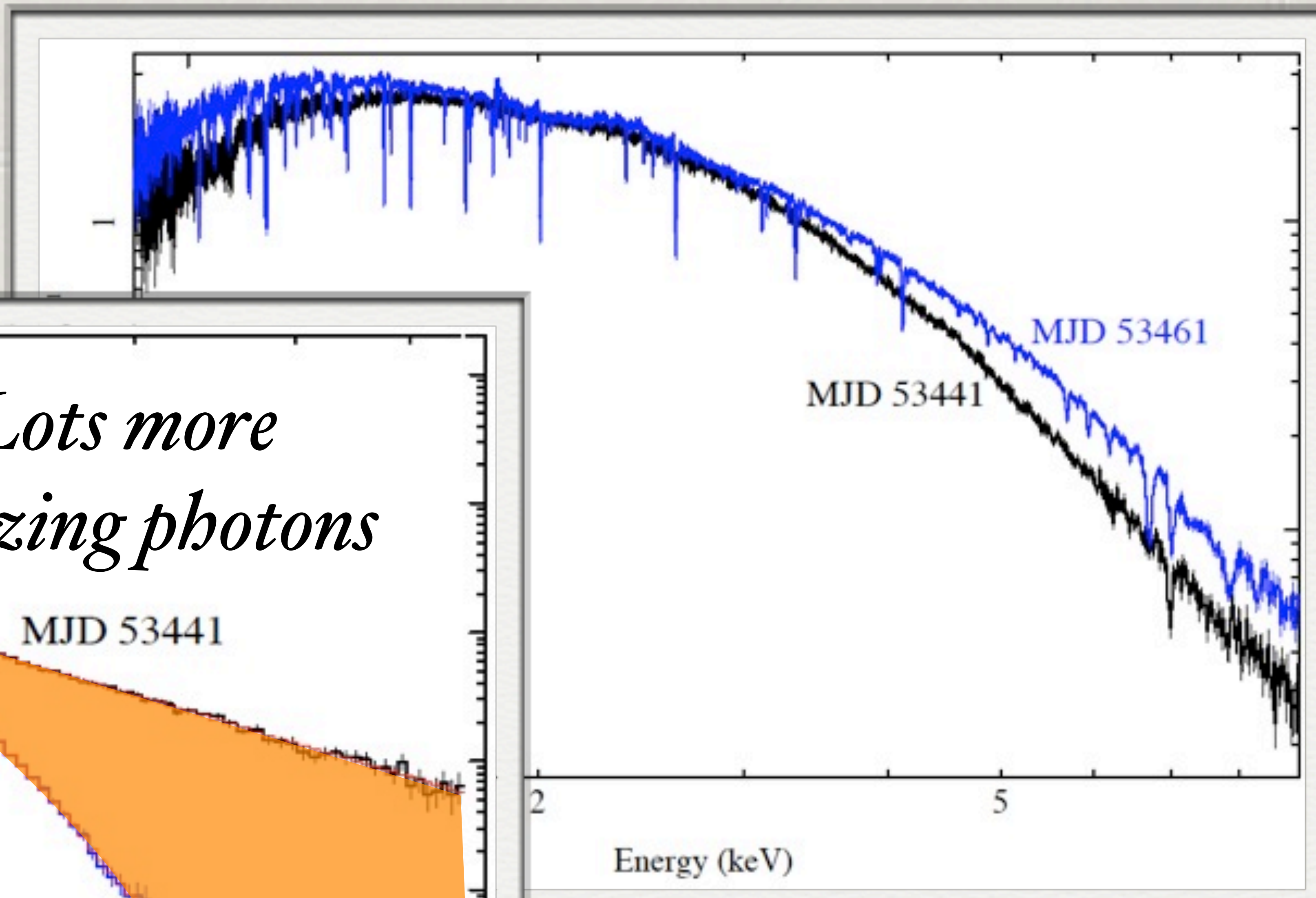
Where Did the Lines Go?

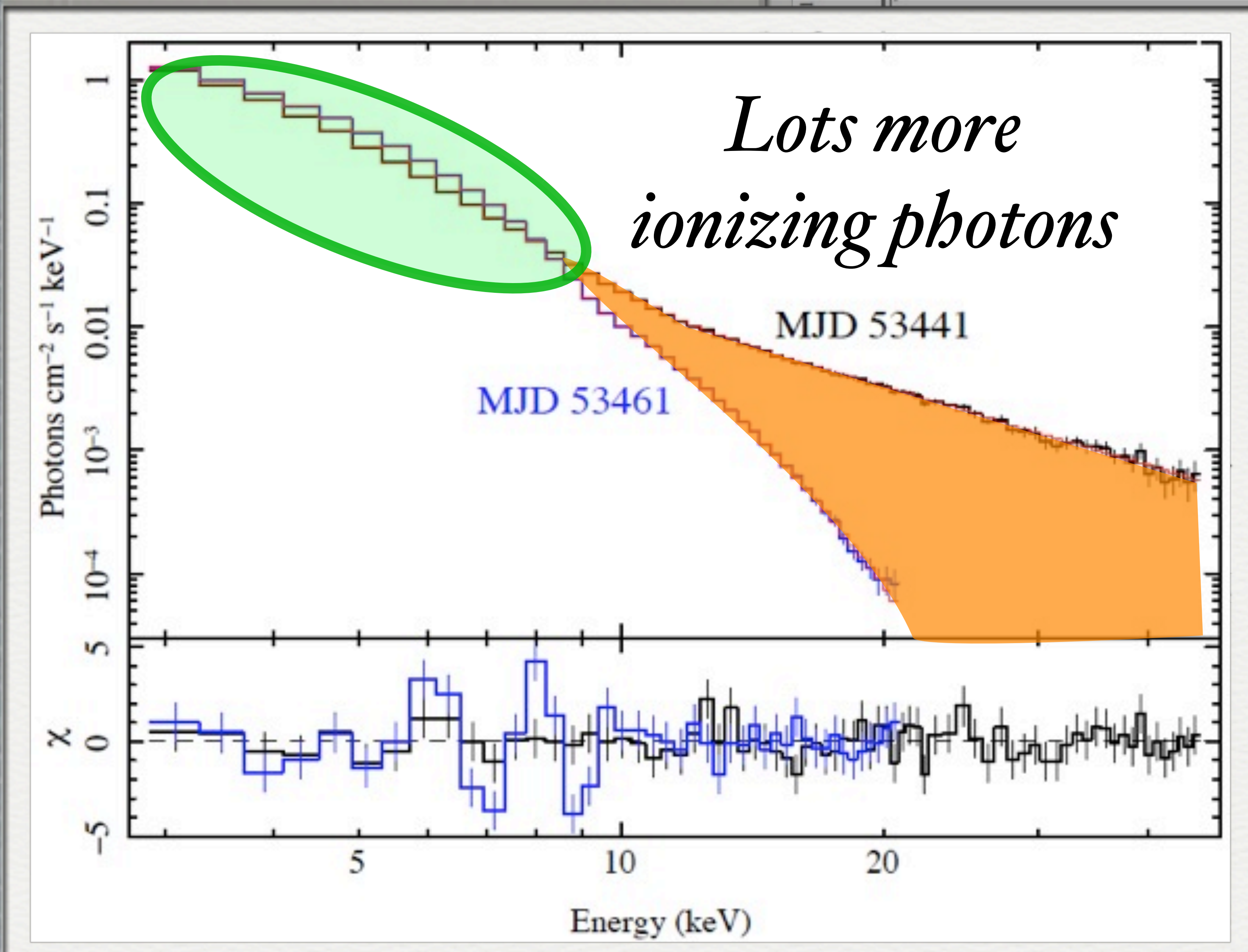
- *Why did the first Chandra observation show only one line, when >100 lines were visible 20 days later?*
    - *Hard state vs soft state: ionization important? Wind present but "fried" by a harder ionizing spectrum?*
    - *Wind really evolving throughout the outburst?*
- *Details in Neilsen & Homan 2012, ApJ, 750, 27*

Can changes in the ionizing spectrum alone explain the differences in the lines?

If the wind were the same in both observations, would the lines be the same?

Testing Ionization: Round 1





- *Ions with Z≲25 have small cross-sections above 10 keV. So most ions see the same ionizing light!*
- *If the wind were the same, the lines would be the same!!!*

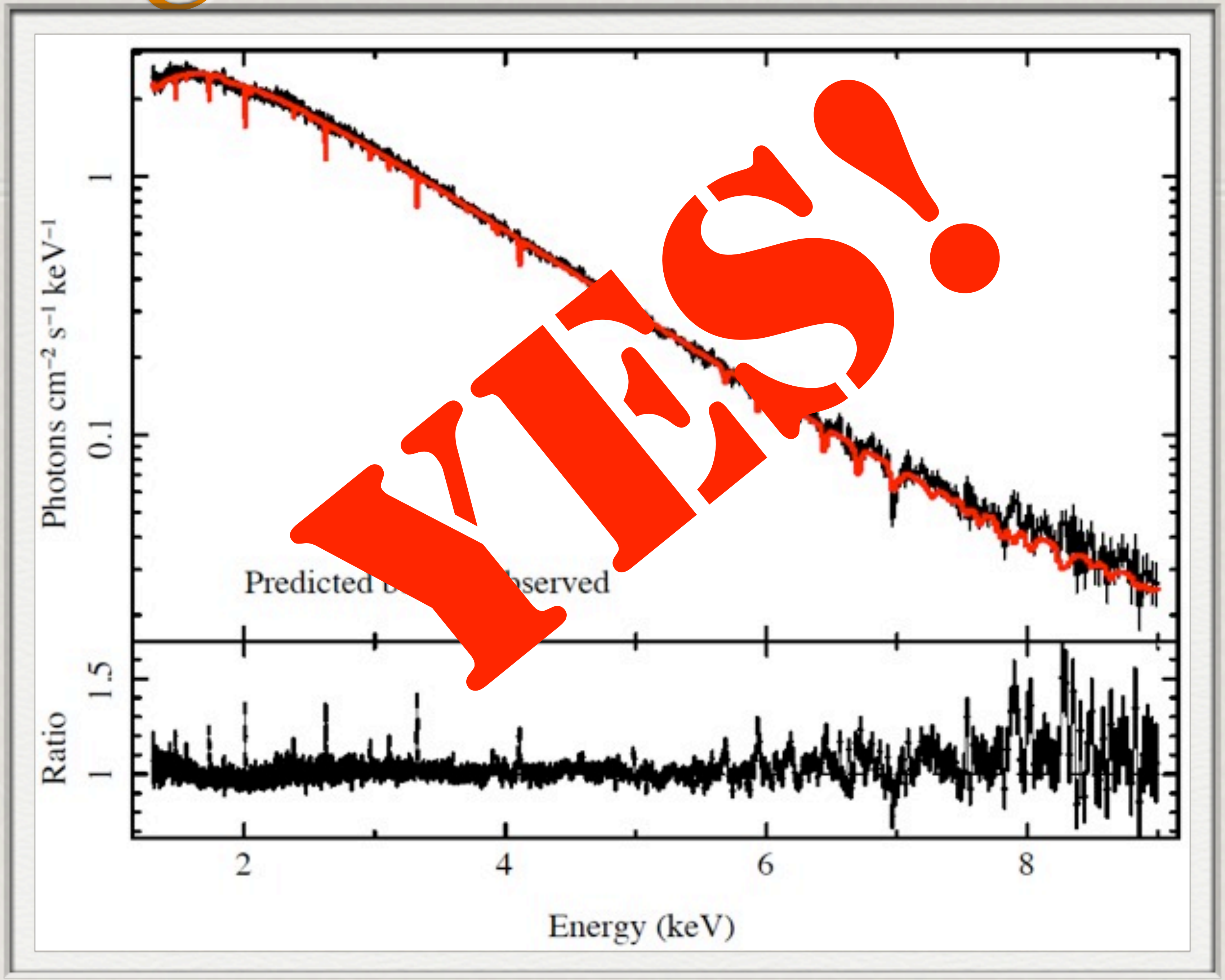
Testing Ionization: Round 2

Obs 1

Obs 2

- *A quantitative version of test 1 with XSTAR:*
- *If the absorber is physically the same but ionized by a different (harder) continuum, does that explain the different lines?*
- *Use previous results for wind properties (Kallman+ 09)*

Testing Ionization: Round 2

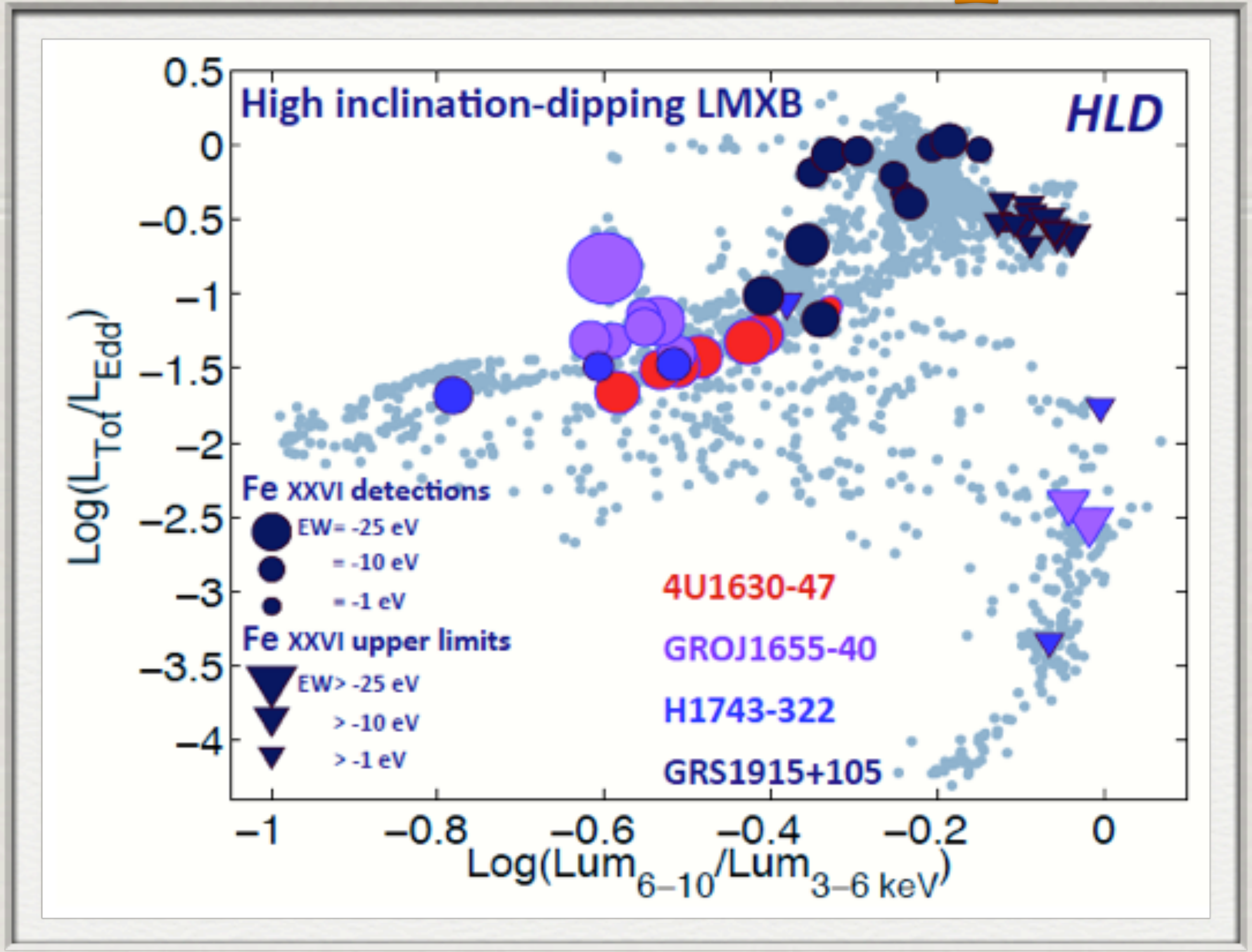


- *Built photoionization models based on obs. 2 (Miller+ 06,08; Kallman+ 09)*
- *Would we have seen all the lines if the same wind were there during obs 1?*

Ionization Explains it All?

- *Definitely not!*
- *If the wind were the same, the lines would still be there*
- *The wind must have evolved significantly during the outburst! (See also Blum et al. 2010, Ponti et al. 2012)*
- *From hard to soft state, density increased by 25x-300x!*

Winds are Ubiquitous

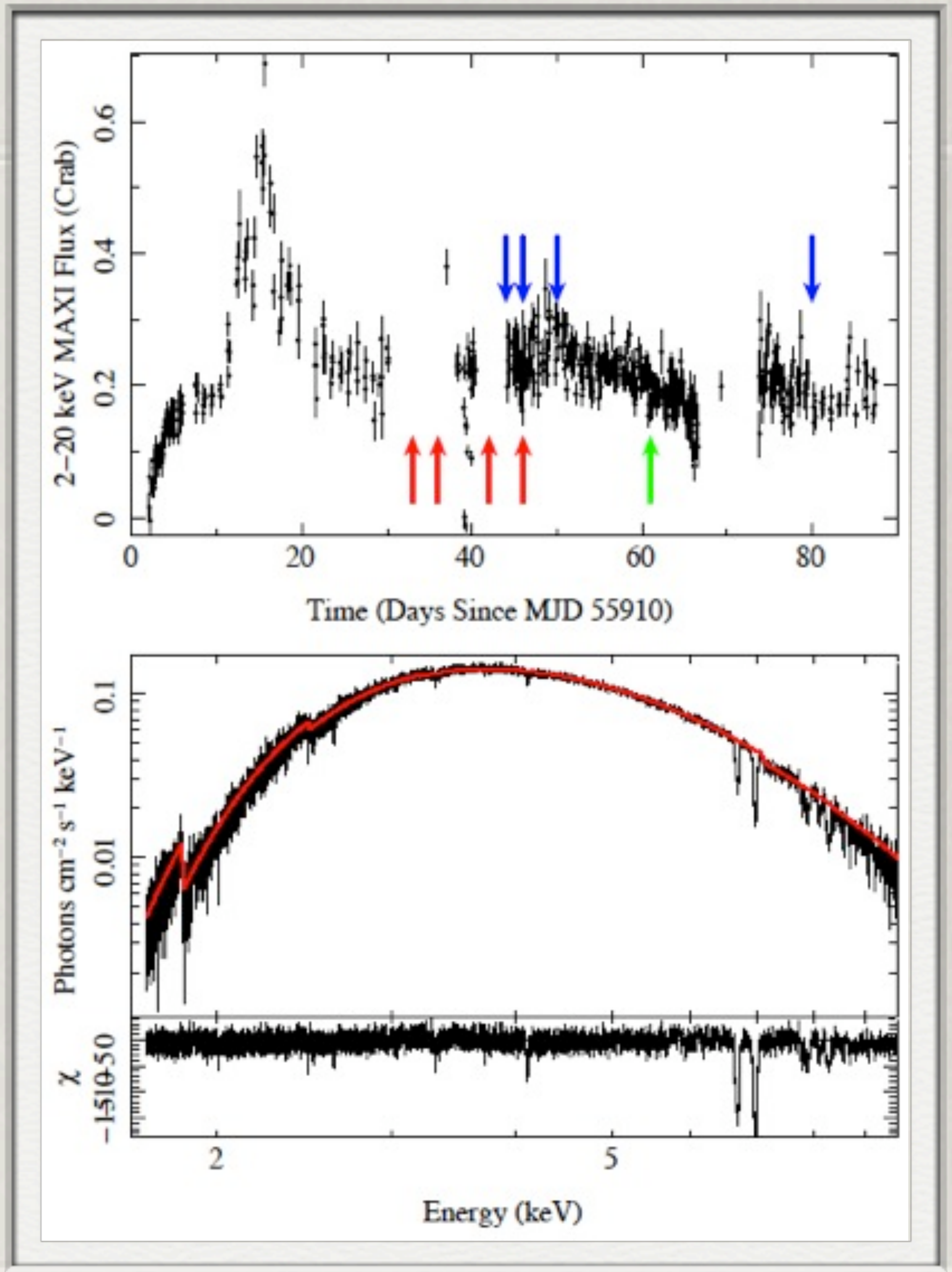


Ponti+ 2012

- *Winds dominate the "state transition" phase of the outburst, where the accretion flow changes and steady jets disappear*
- *Analysis suggests that in general, winds evolve during outburst!*

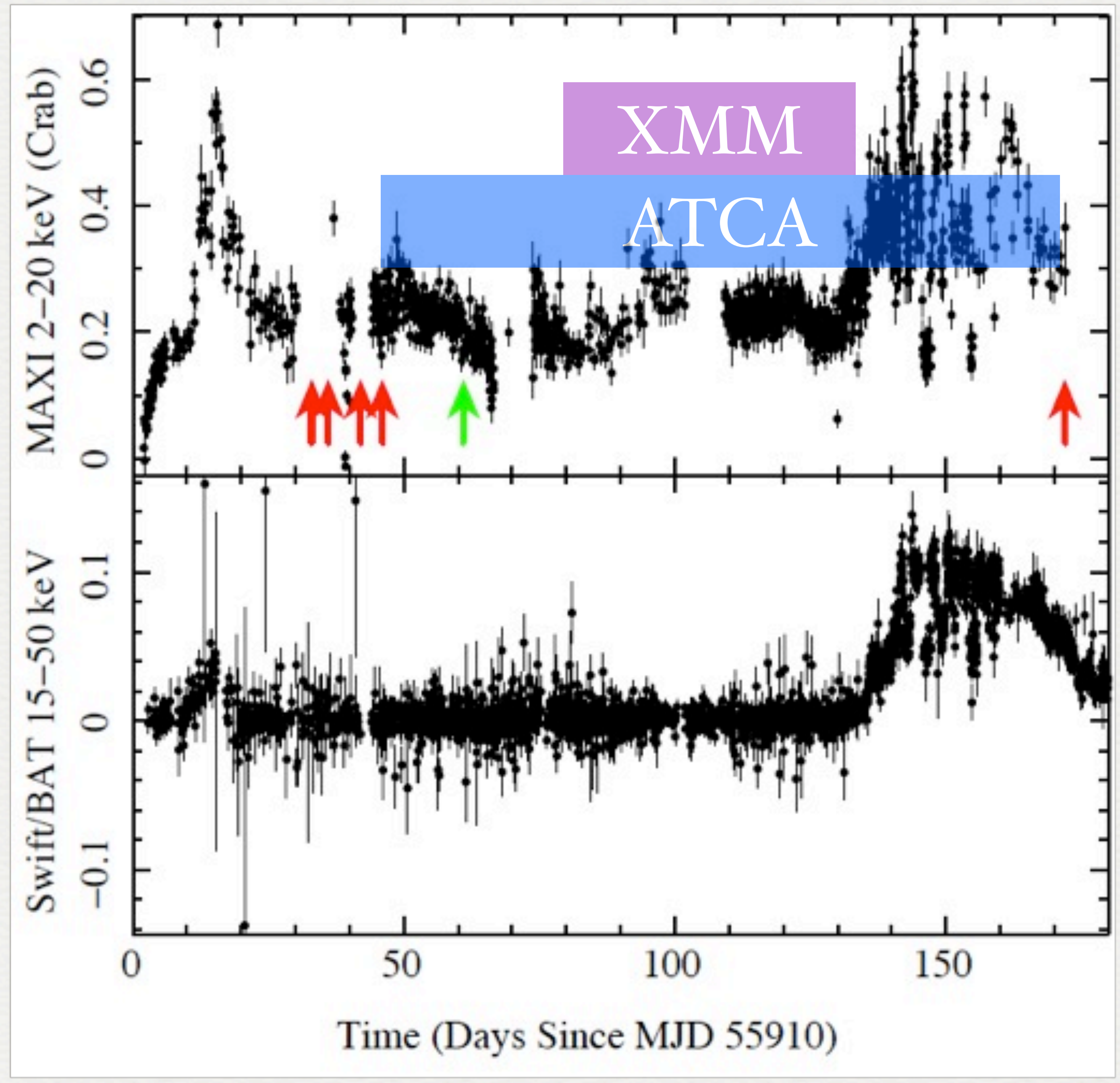
Coincidence? I Think Not!

- *Target of Opportunity observations of 4U 1630-47*
- *Based on Ponti 2012, designed to catch a disk wind*
- *Very successful!!!*
- *Winds reliably appear during this state transition*



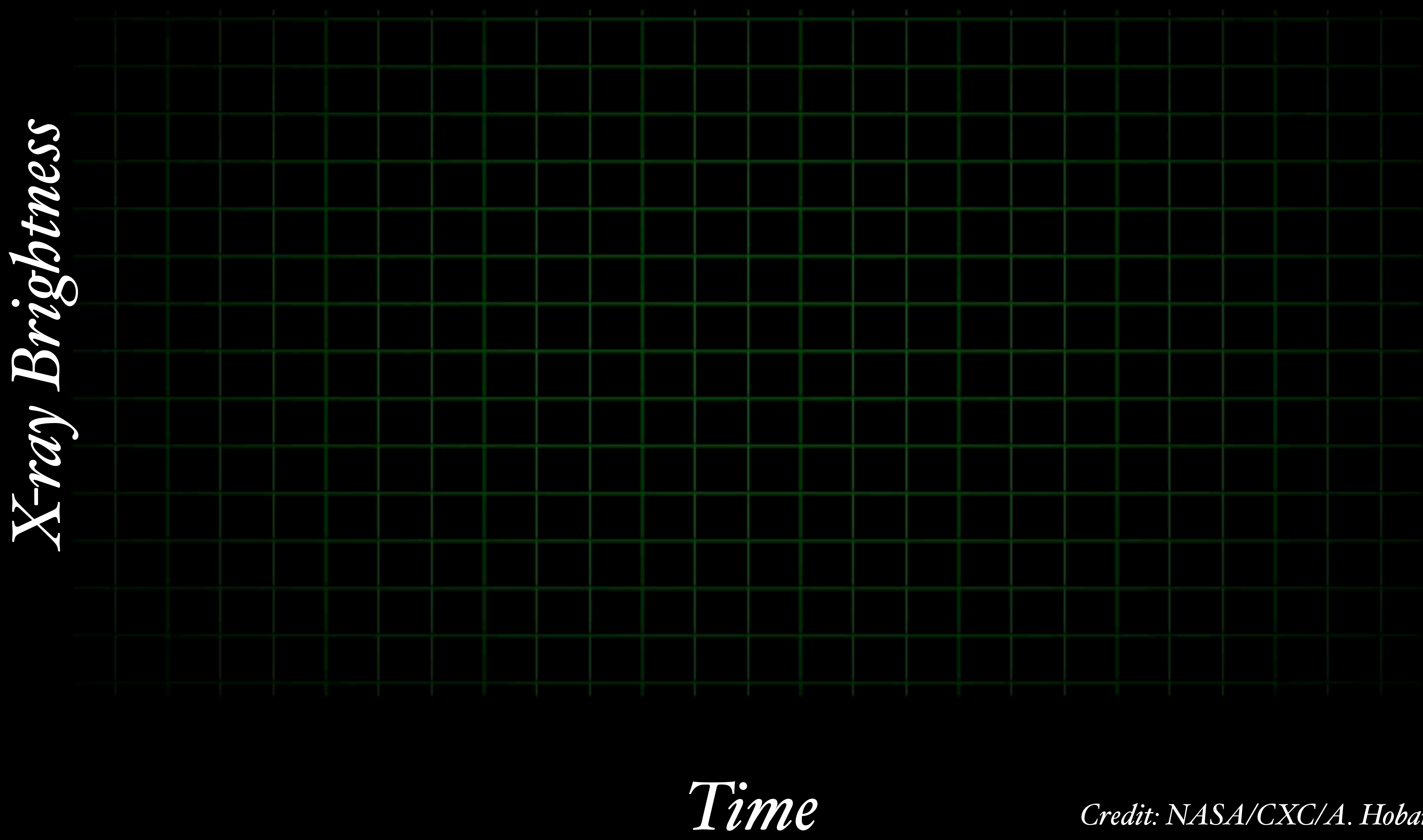
Continued Monitoring

- *Lots of multiwavelength data*
- *Chandra, Suzaku, XMM, ATCA*
- *Neilsen, Ponti, Coriat, Fender, Miller-Jones, Diaz Trigo*



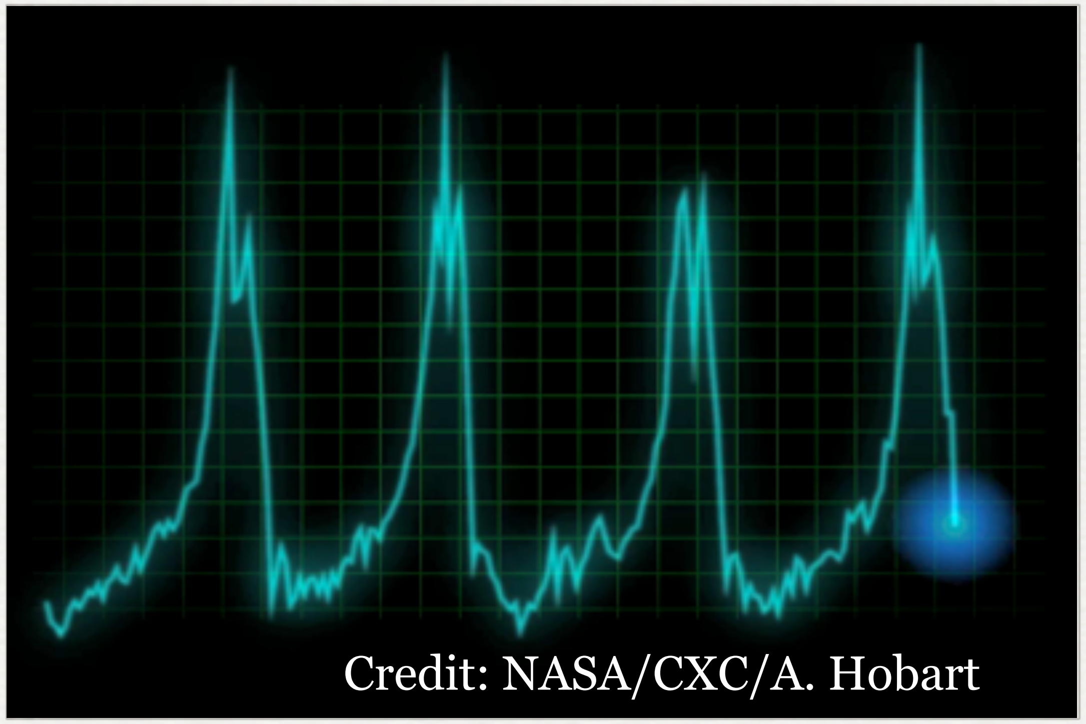
Implications

Winds are preferentially launched at a certain phase of BH outbursts... so what?

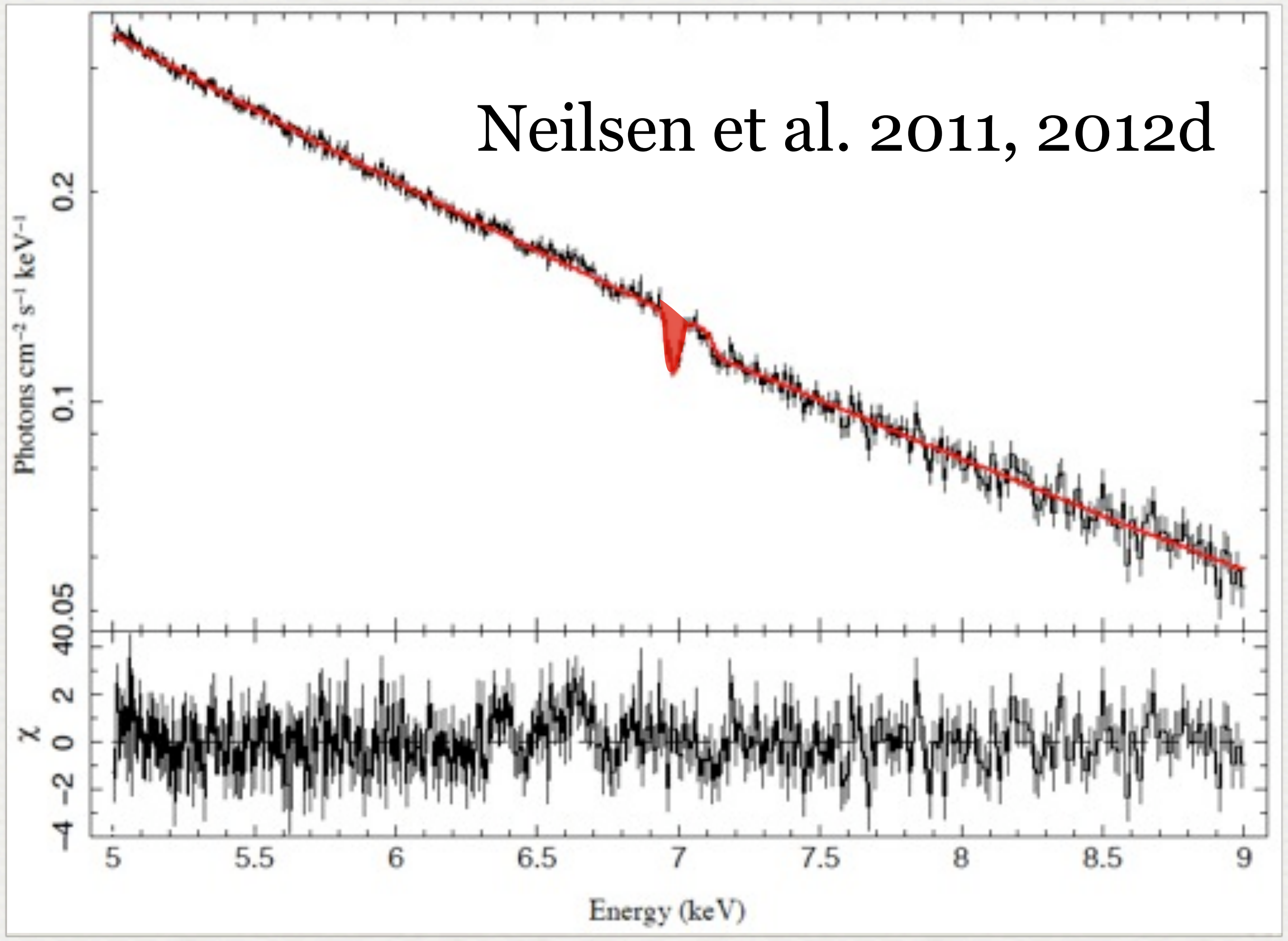


Credit: NASA/CXC/A. Hobart

The 'Heartbeat' State of GRS 1915+105

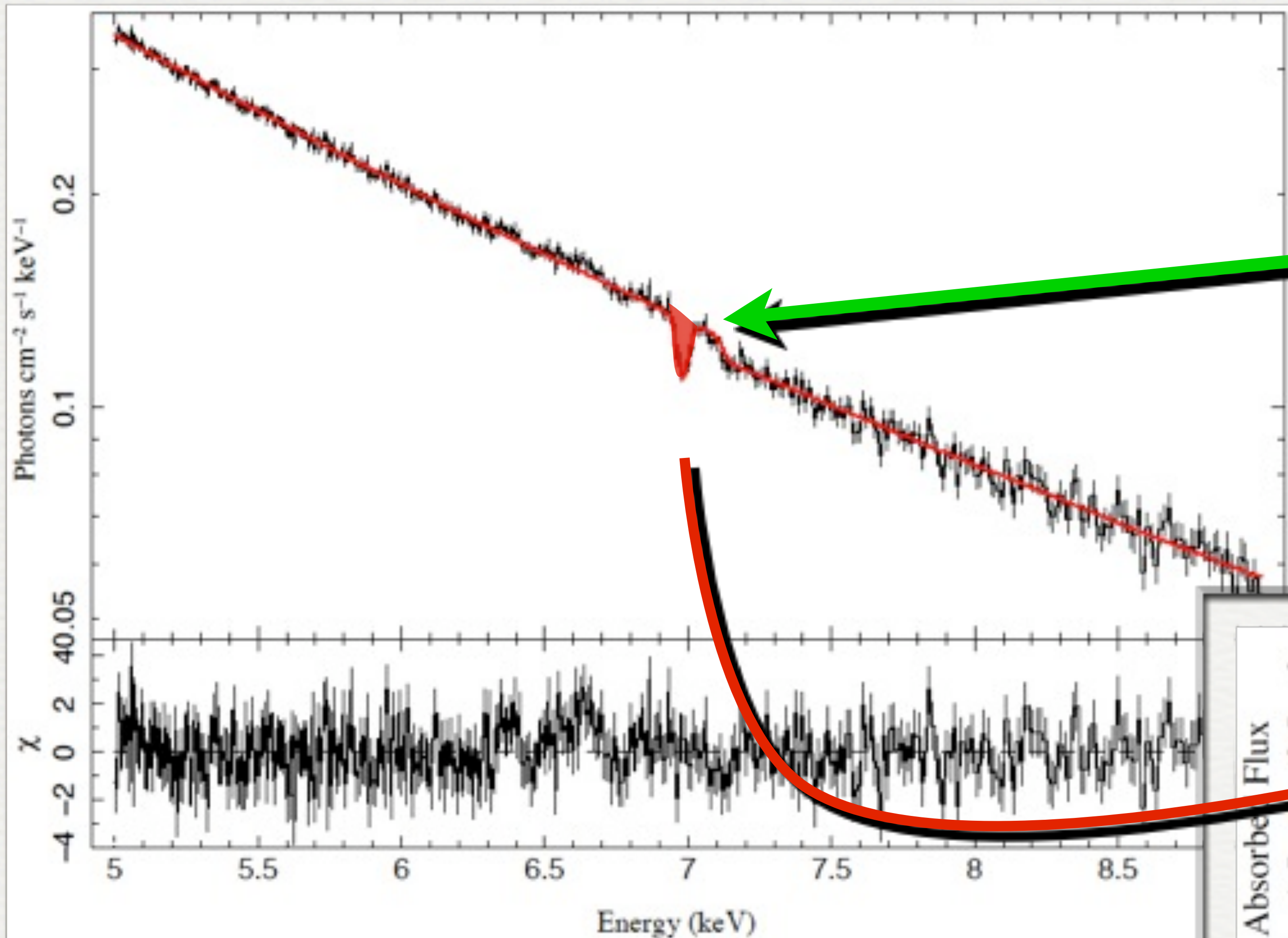


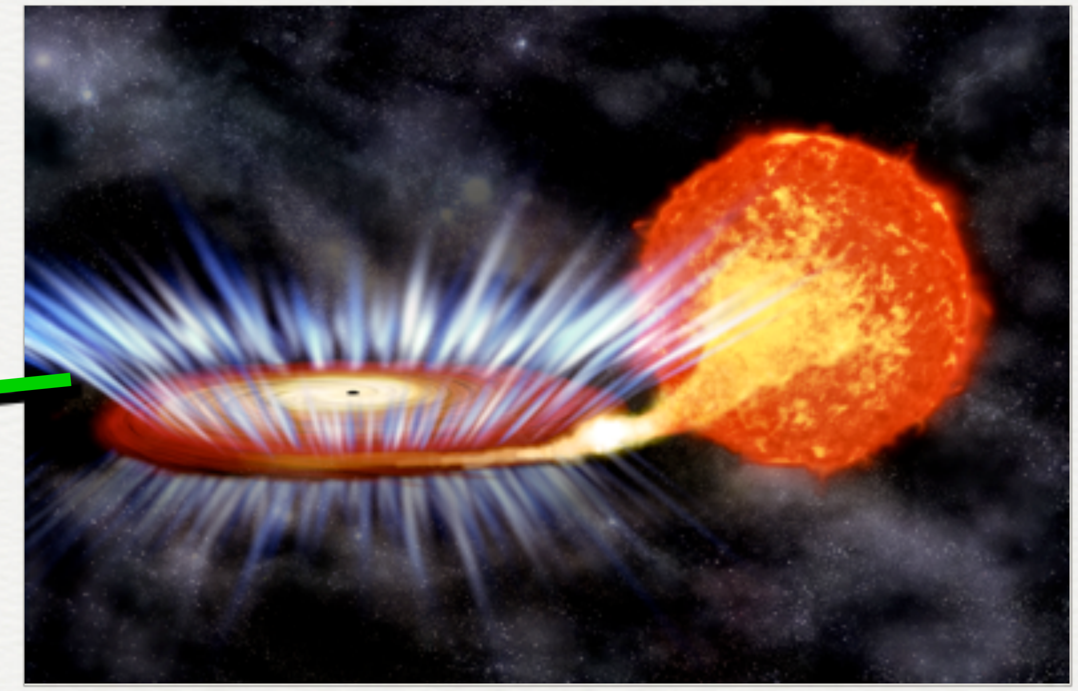
- *Strong, strange 50-second pulse observed by RXTE*

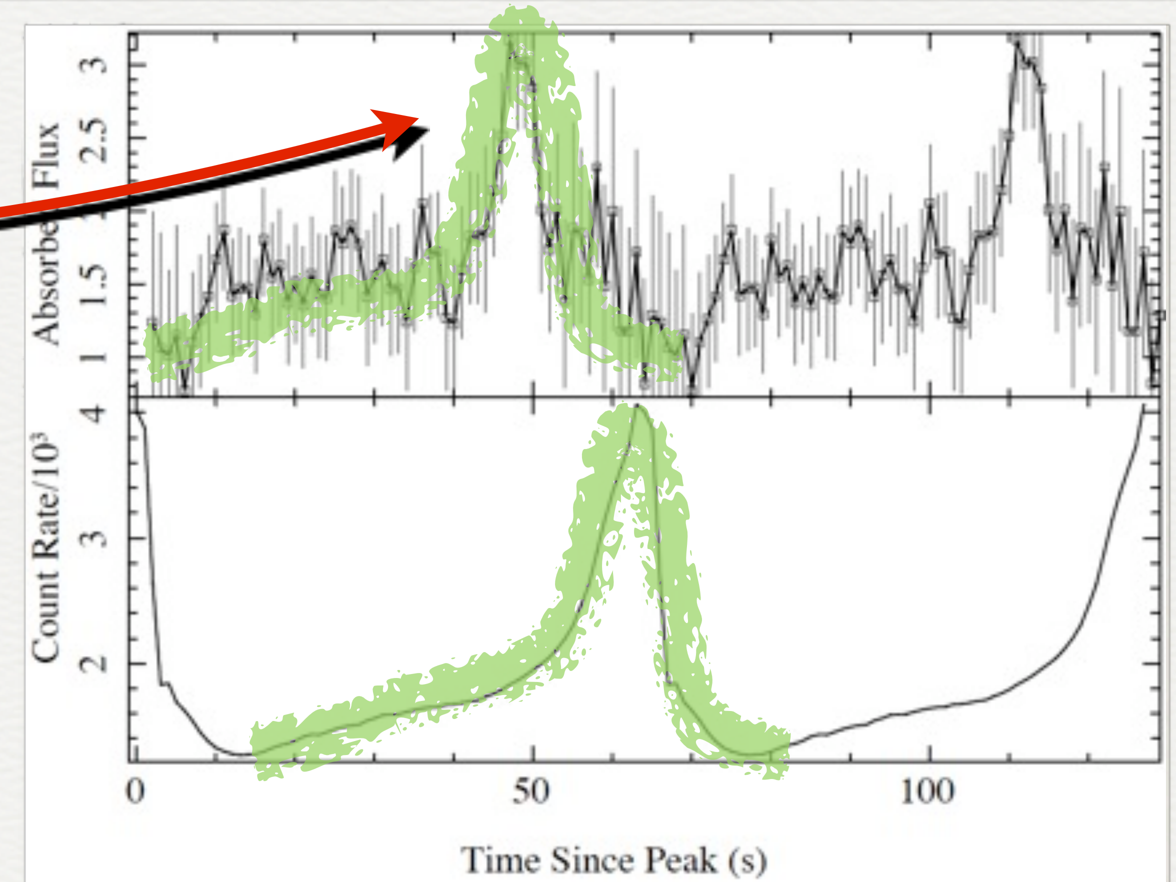


- *Chandra observations of this 'heartbeat' reveal a disk wind!*

Accretion Disk Wind





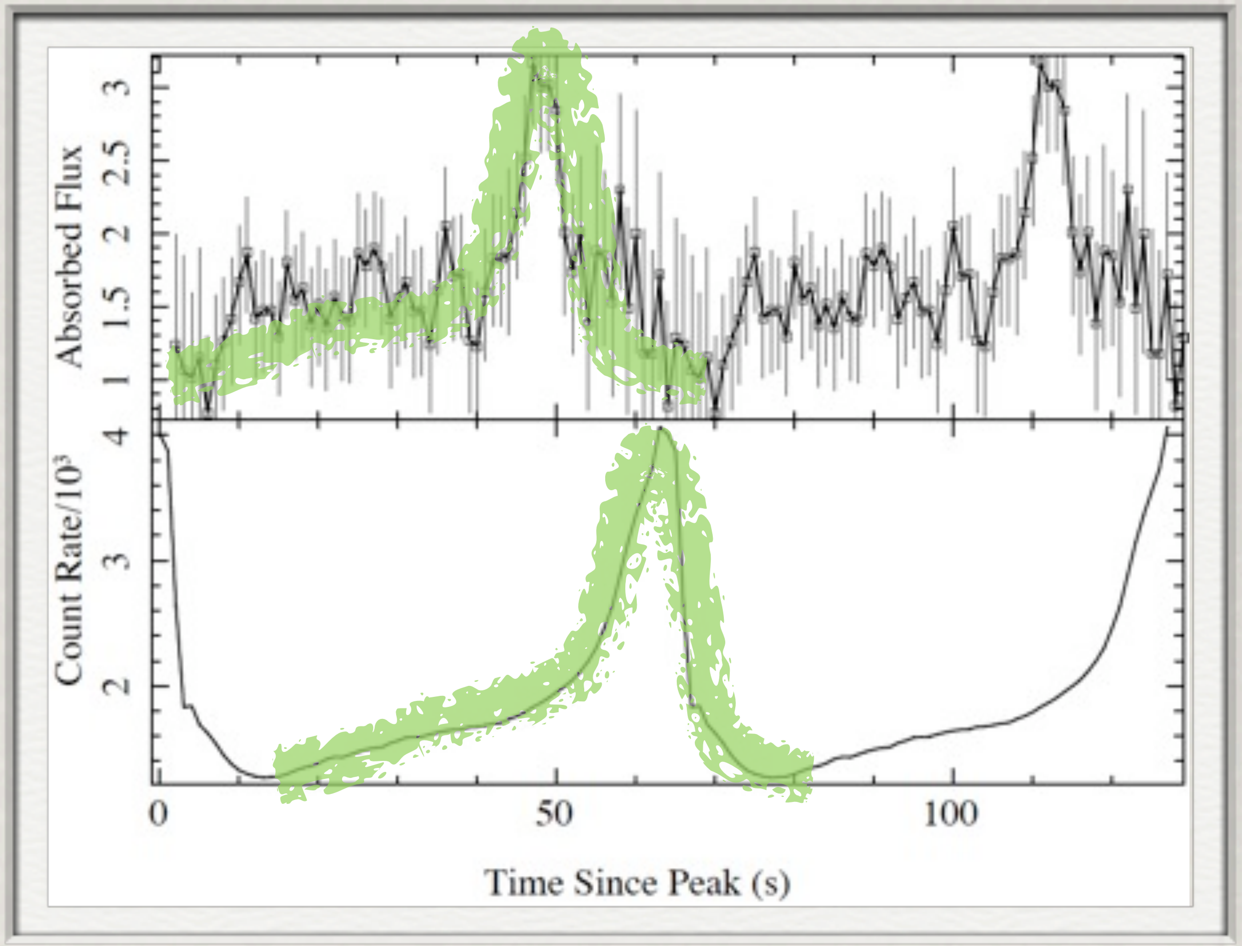


- *Measure wind at each part of the 'heartbeat'*

The Amazing Massive Wind

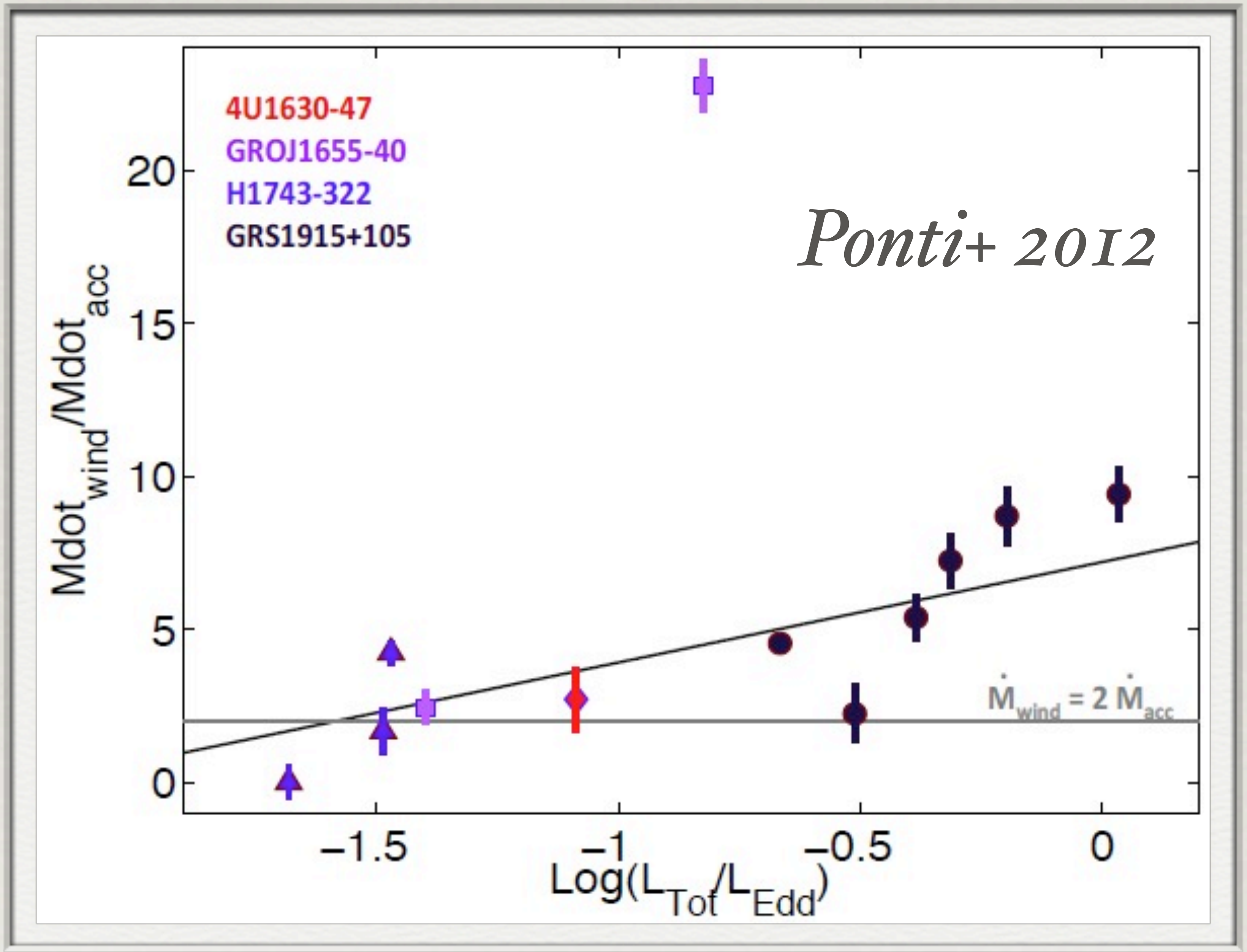
- *Each heartbeat blasts more gas off the disk*
- *R~10^{11} cm, but variable on time scales of 5 seconds*
- *Arguments from geometry, variability, line properties imply $\dot{M}_{out} \approx 25 \dot{M}_{BH}$ (Neilsen, Remillard, & Lee 2011)*
- *Has a huge effect on the disk*

Neilsen et al. 2011, 2012d

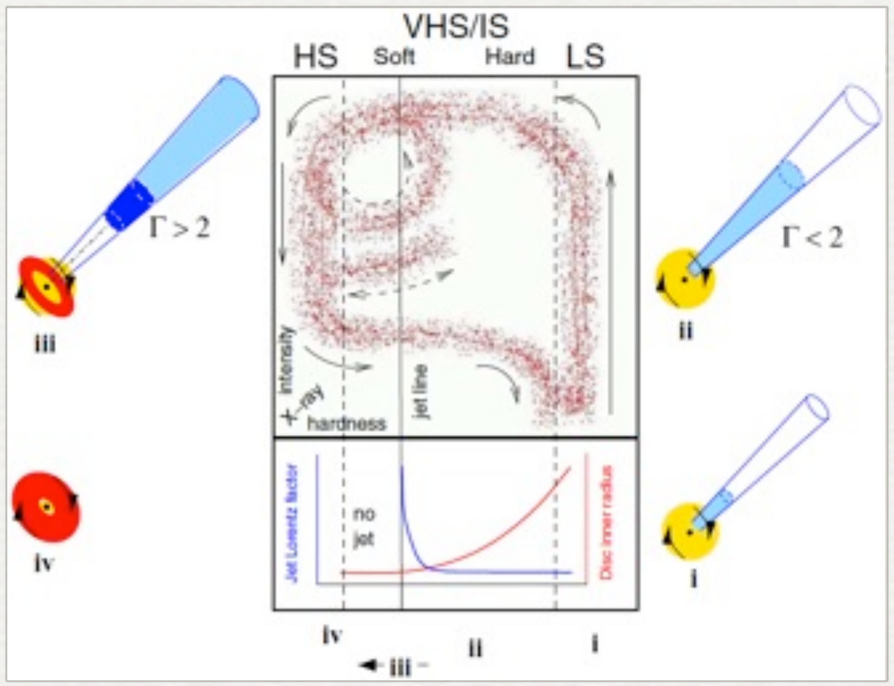


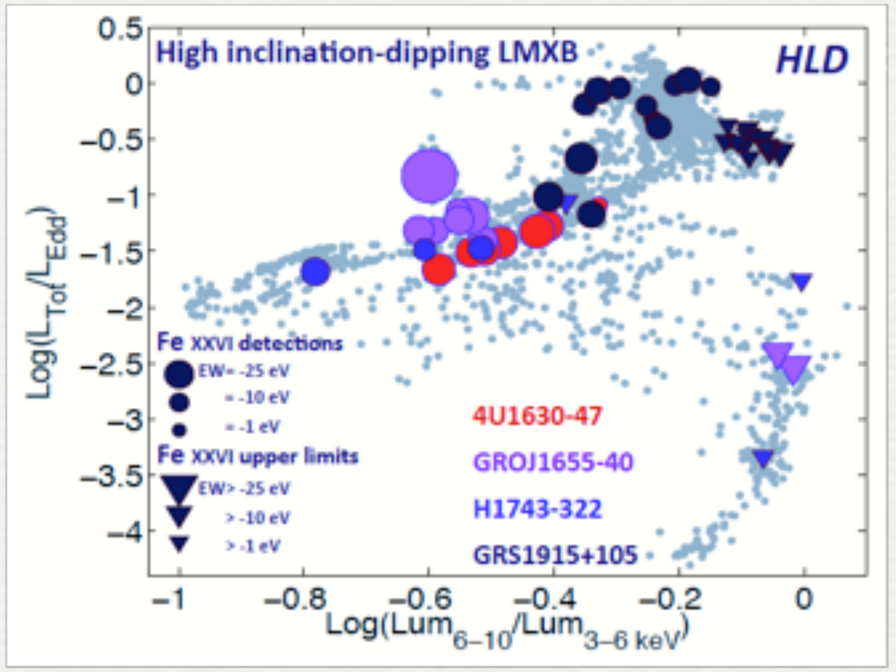
- *Other XRBS too! Ponti et al (2012)*

Massive Winds!



Implications





- *No coincidence that winds appear when they do*
- *Luminosity rises, illuminates disk, drives gas away*
- *Changes BH mass, energy budget*
- *State transition, jet turns off*

Summary

- *In GRO J1655-40, accretion disk winds evolve significantly during outburst (Neilsen & Homan 2012)*
- *This evolution is* ***universal!*** *(Archival studies: Ponti+ 2012; 4U 1630-47: Neilsen+ 2012e, in prep)*
- *Significant because:*
    - *Winds may* ***dominate*** *the mass budget (e.g. Neilsen+ 2011)*
    - *Winds are* ***not a part of the conventional understanding*** *of BH outbursts*
- *Would be great to see winds in theory/phenomenology of state transitions*

Future Work

- *Are winds actually driven by irradiation of the outer disk or magnetic fields?*
    - *Keep looking for connections between radiation and outflows*
- *Do winds suppress/quench relativistic jets or do they appear <u>after</u> the jets are gone?*
    - *Can we see this in action?*
- *Is there evidence of the same processes in AGN?*
    - *Partial, but hard to scale outflow microphysics across mass scale*