# X-ray Binaries

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# What is an X-ray binary?

- Binary consisting of non-degenerate star + accreting degenerate star
- Mass transfer fuels accretion, creating X-rays
- Degenerate star is either neutron star or black hole (WD systems = cataclysmic variables)
  - White dwarf+neutron star systems are included

# XRB classification

- Classified according to type of non-degenerate star
  - Early-type star (A or earlier) = ‘high mass X-ray binary’ (HMXB, MXB)
  - Later-type =‘low mass X-ray binary’ (LMXB)
  - Unique, but interesting, source Her X-1 straddles the boundary

# Science questions

- What is the nature of the degenerate object: BH orNS?
  - BH: what is the mass? How does accretion occur? How are jets formed?
  - Ns: what is the equation of state?
- What can we learn about the companion star?
- What is the XRB role in stellar evolution? Can we learn about evolution from XRB statistics or abundances?
- "Physics of extremes"
  - Strong gravity
  - High magnetic field
- XRBs can be a laboratory for study of more distant sources

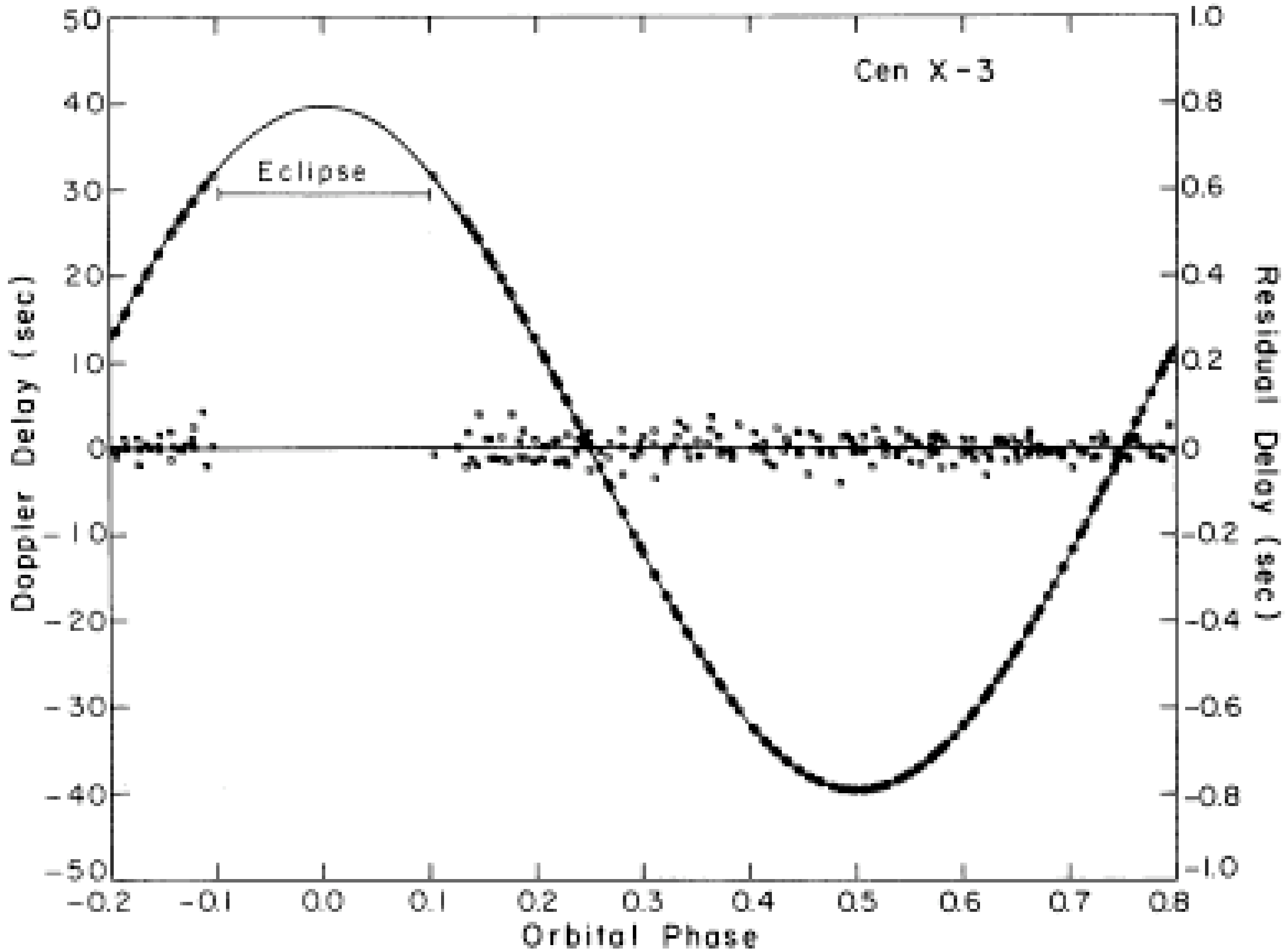
# outline

- Background
- List of subclasses
- Science examples
- What have we learned?

# High-mass X-ray binaries (HMXB)

- Among the first discovered extra-solar sources (eg. Vela X-1, Cyg X-1, Cyg X-3, Her X-1)
- Often contain pulsar
- Often eclipsing
- Pulse timing + stellar radial velocity +eclipses = mass, orbital separation, inclination determination
- Accretion can occur from wind from primary, or from Roche-lobe overflow
- Two different subtypes:
  - Be binaries
  - Supergiant binaries
- Statistics: ~50 known in galaxy
- Young population, lifetime ~$10^5$ yrs: mass transfer is unstable

# Pulse arrival times for Cen X-3




Kelley et al., 1983

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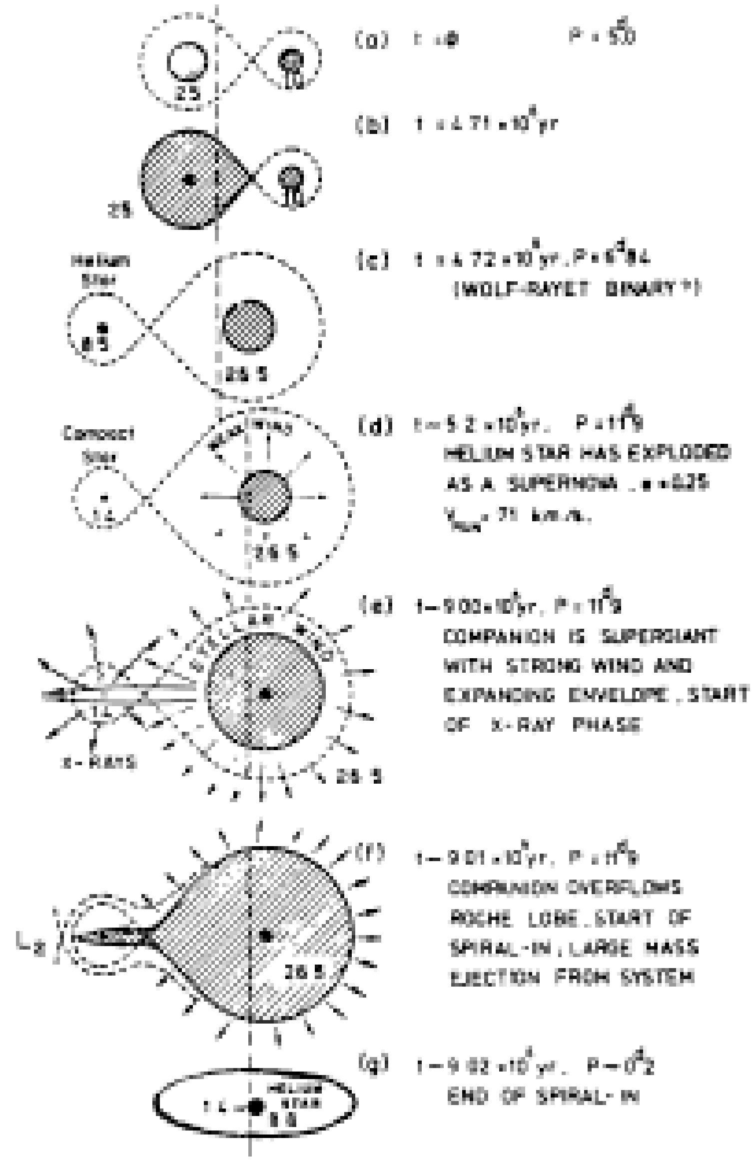
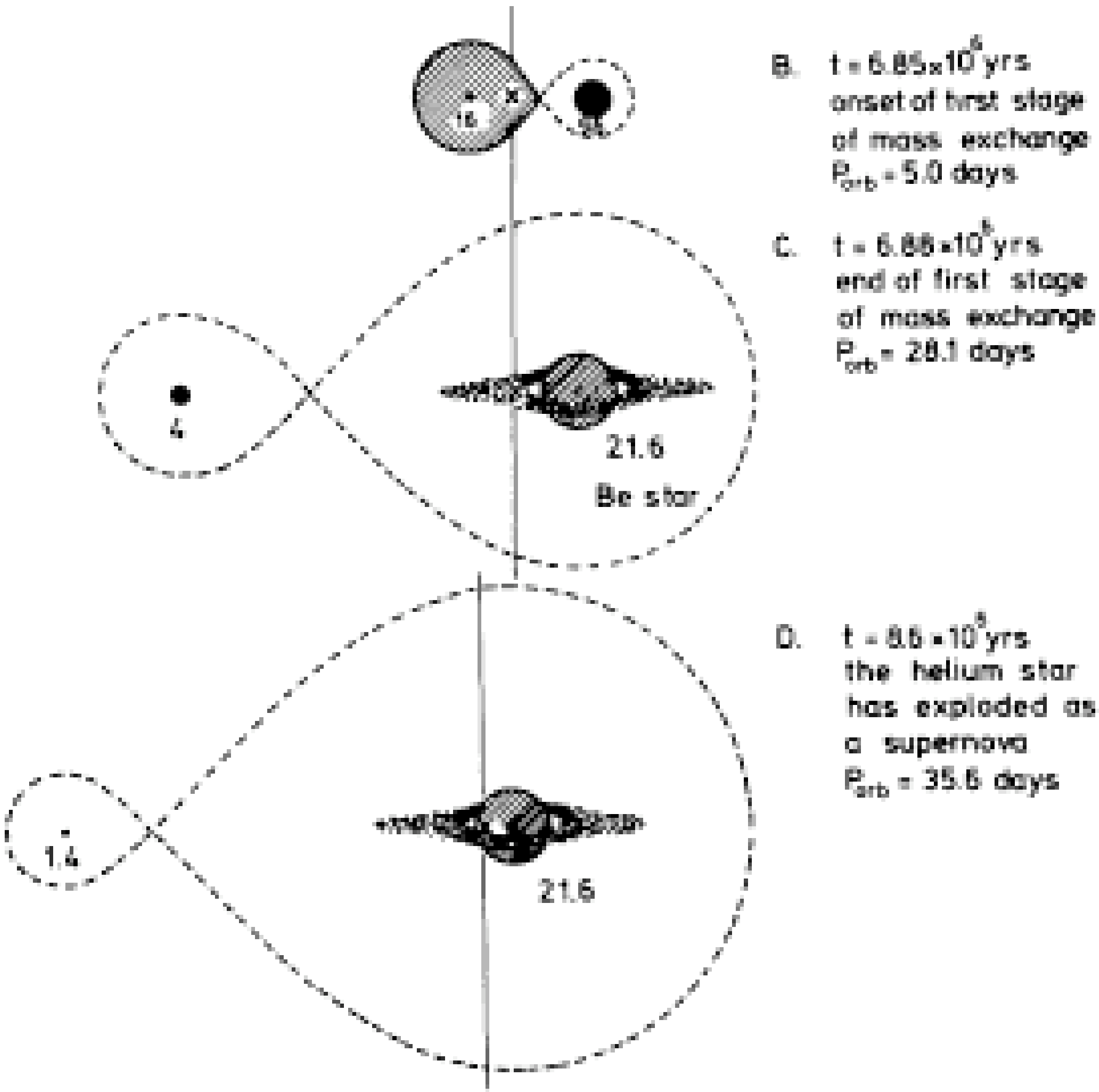
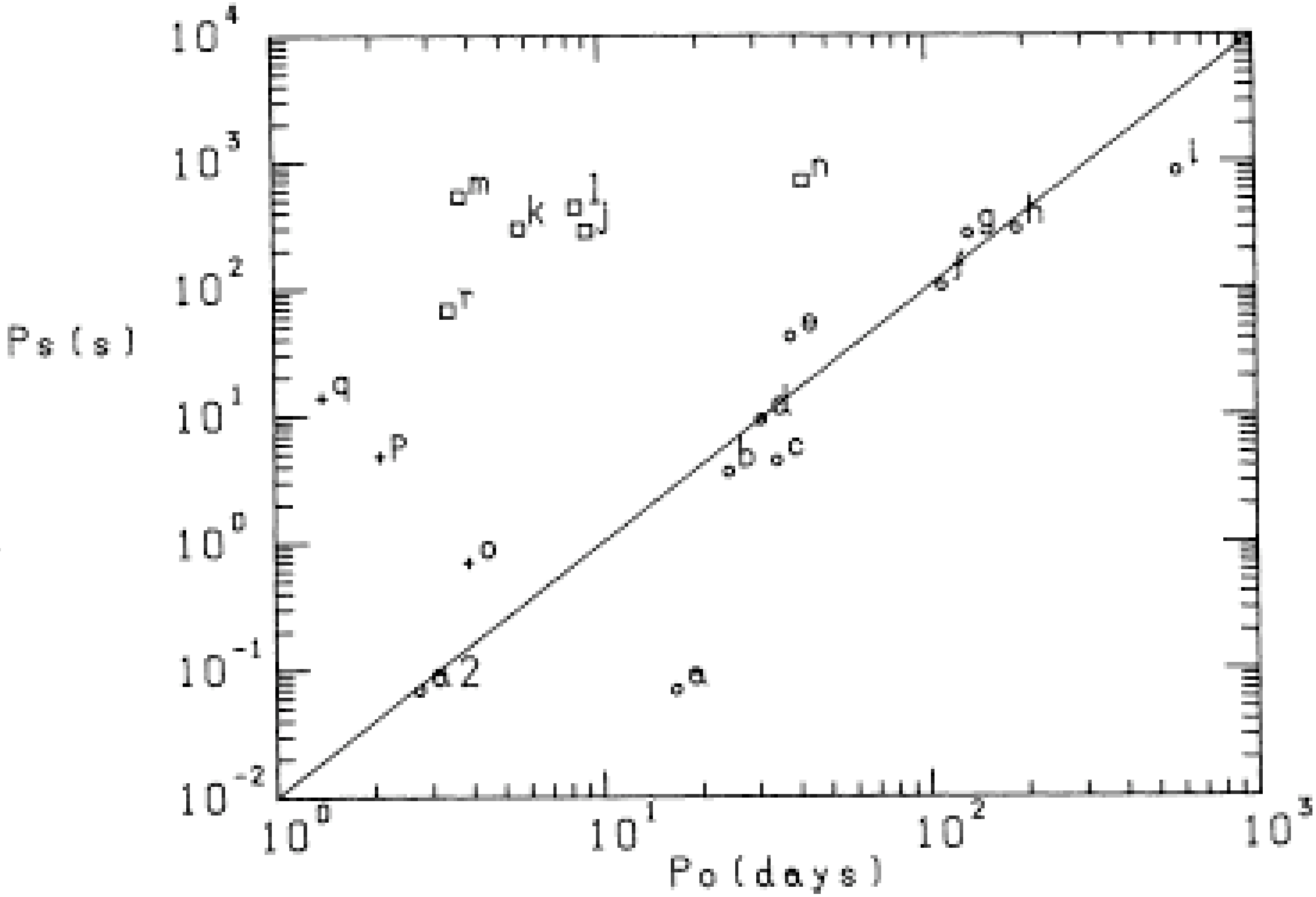



Evolution of a supergiant hmxb

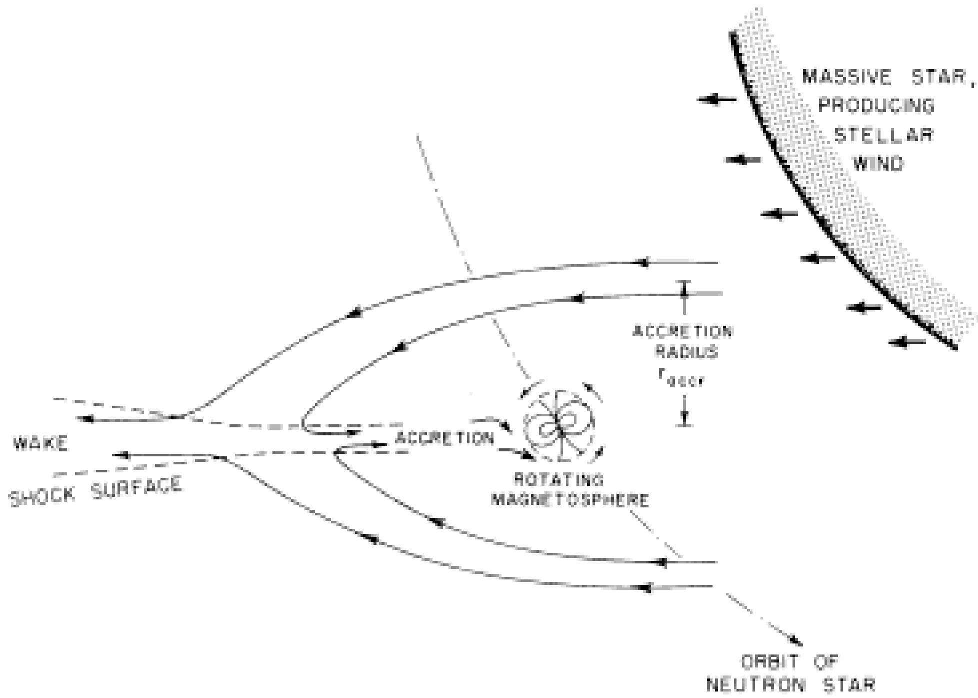



Evoution of Be binary

Be binaries show a strong correlation between X-ray pulse period and orbital period



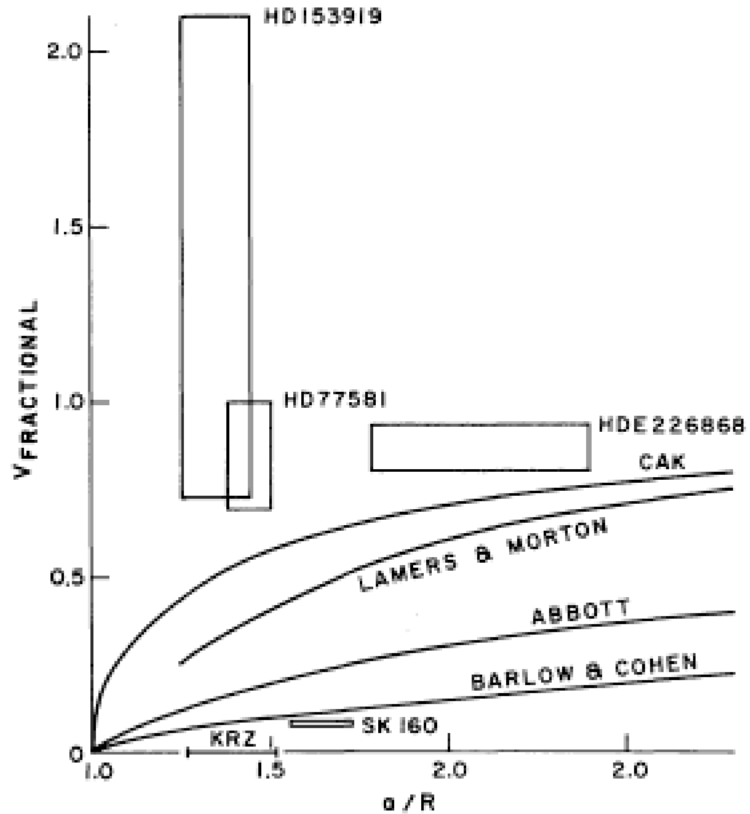

(Corbet 1986)




Theory of wind accretion: (Davidson and Ostriker 1974):

$\rho v_w^2/2 = GM\rho/r$

We can test whether the X-ray source is fueled by wind accretion




Too much

Not enough

(Conti 1976)

Observed X-ray luminosity

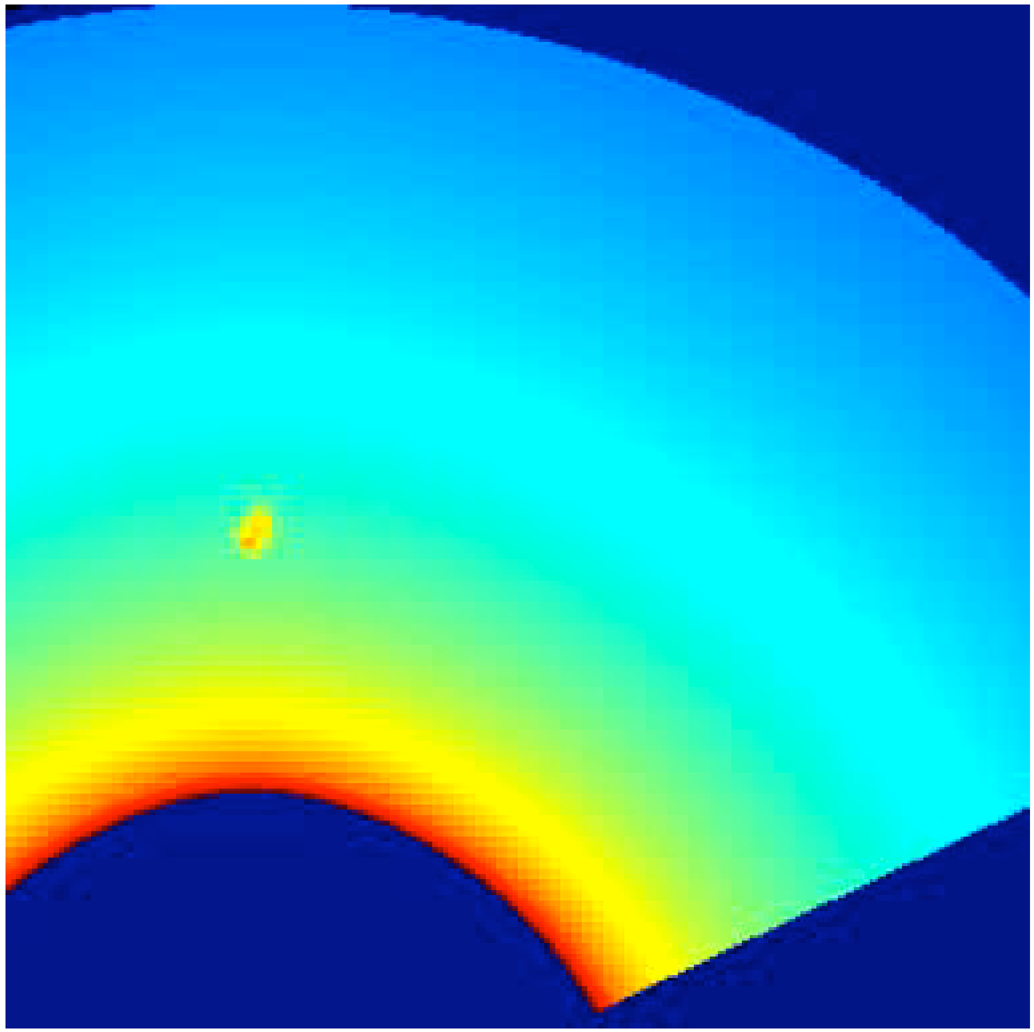
From similar stars

Efficiency Guess: ~0.1

separation

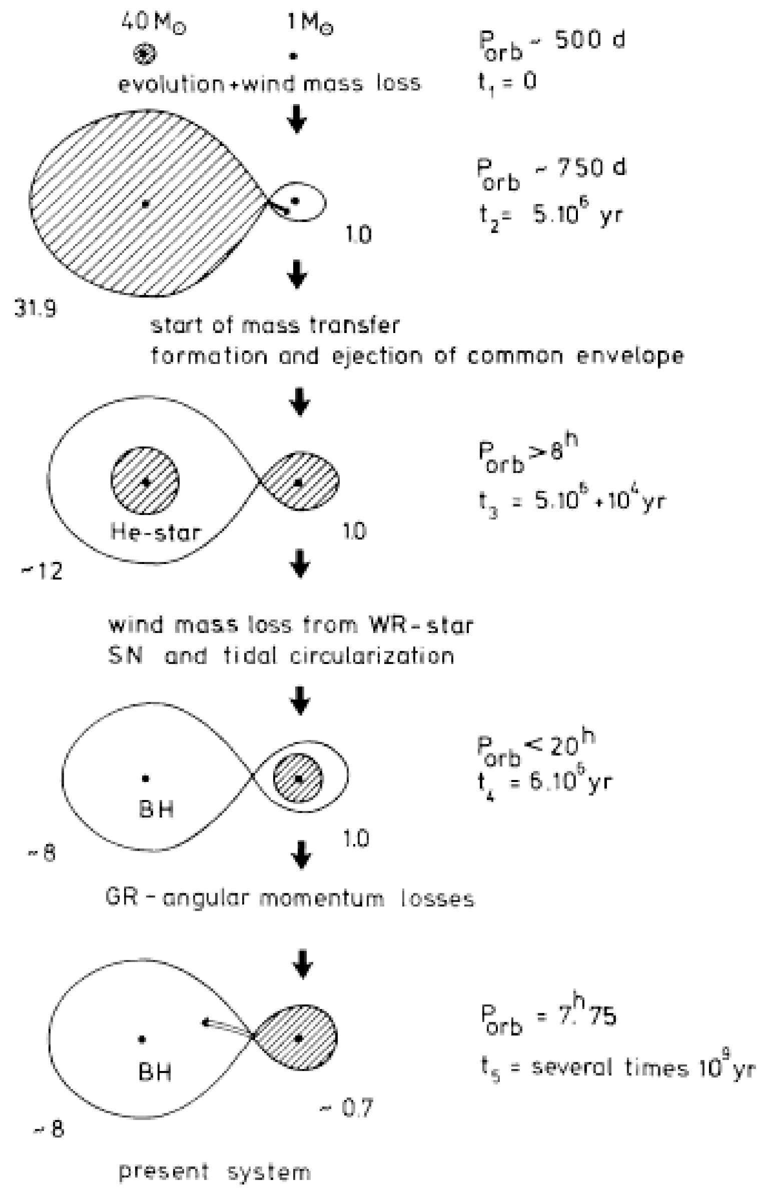
Wind speed

$$L_x \sim \dot{M}_{wind}\, c^2 G^2 M^2 \eta \,/ (a^2\, v_w{}^4)$$

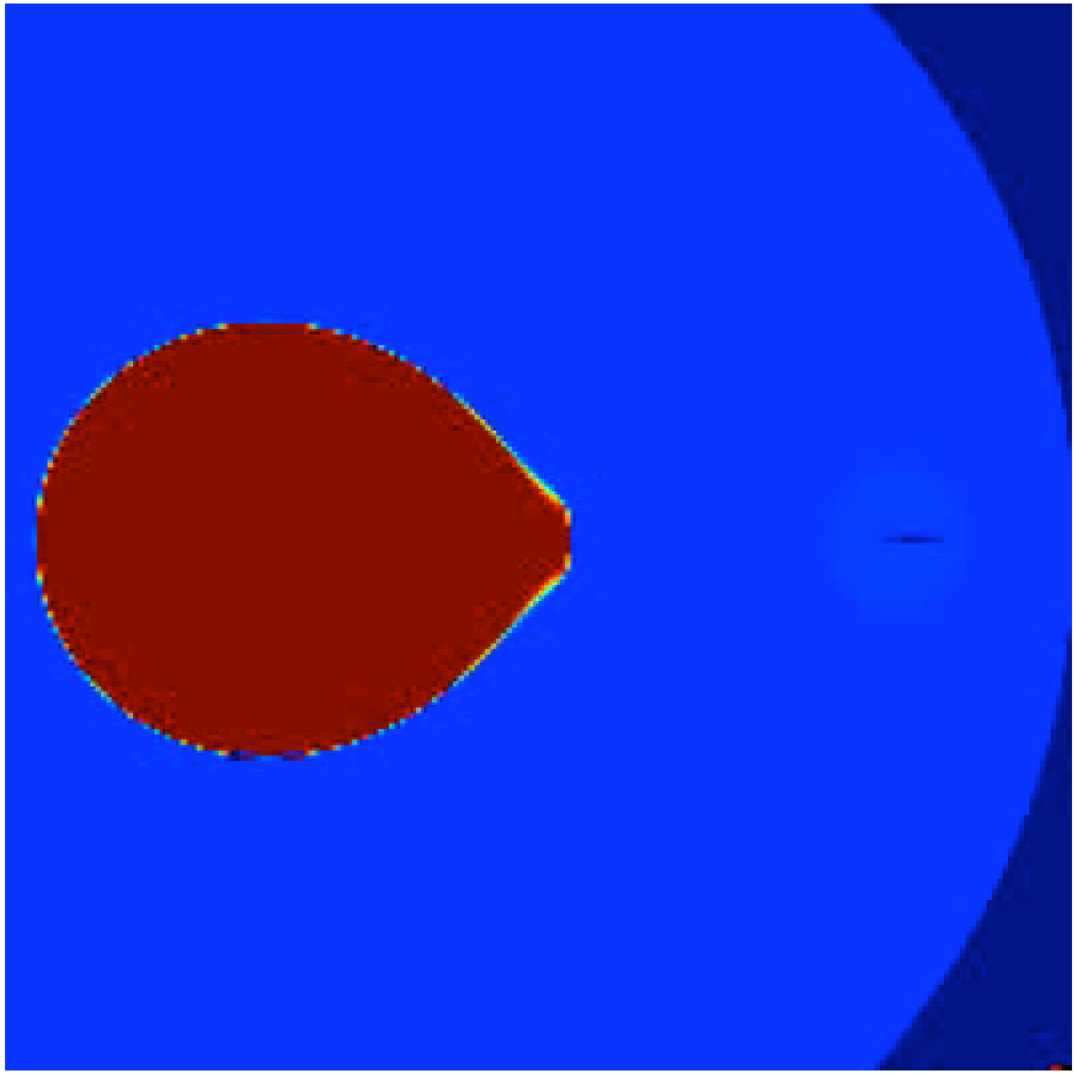


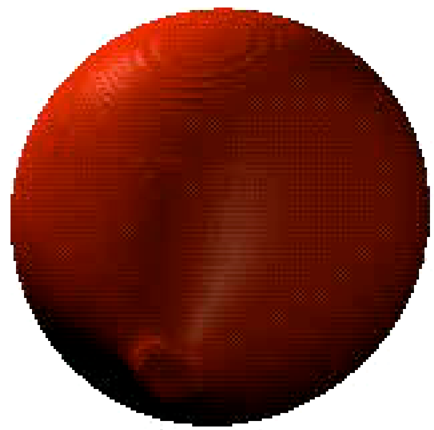
# LMXB

- Many well-known sources (eg. Sco X-1, ‘microquasars’: GRO J1655, 4U1916)
- <10 Hz pulsars are less common
- Eclipses less common
- Orbit determinations more difficult
- Accretion can occur from Roche-lobe overflow
- Many subtypes: Z sources, atoll sources, dippers, adc sources, pulsars, microquasars, black hole transients
- Statistics: ~200 known in galaxy
- bulge population, lifetime ~$10^6$ yrs



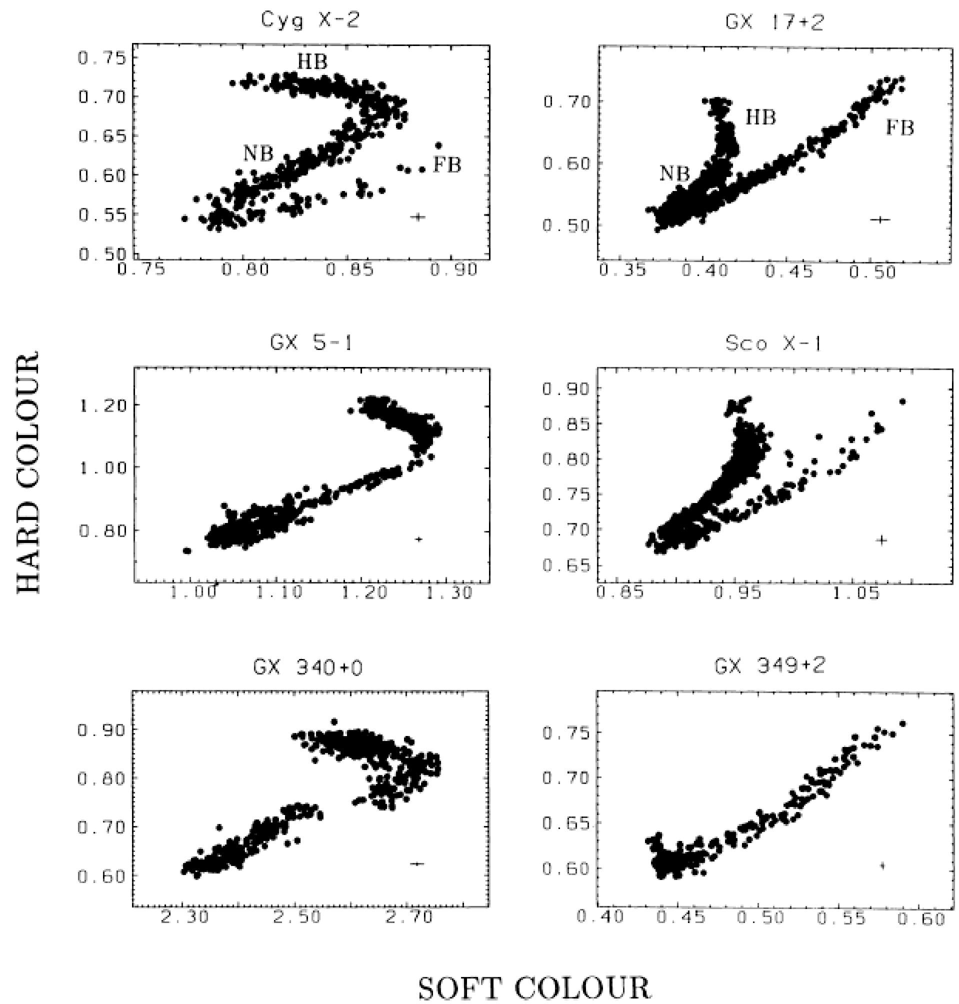

Evolution of a low-mass binary





# Z-sources

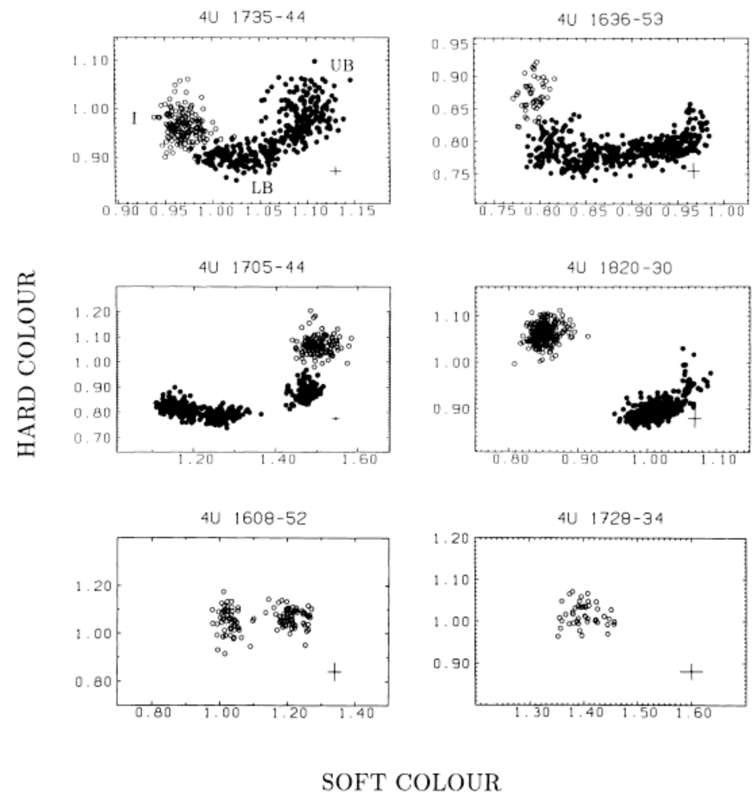
- Among best-known LMXBs: Sco X-1, Cyg X-2,
- Trace out ‘Z’ shape in color-color diagram (Hasinger, 199x; Vander Klis 199x); QPO behavior follows




Hasinger and VanderKlis 1989

# Atoll sources

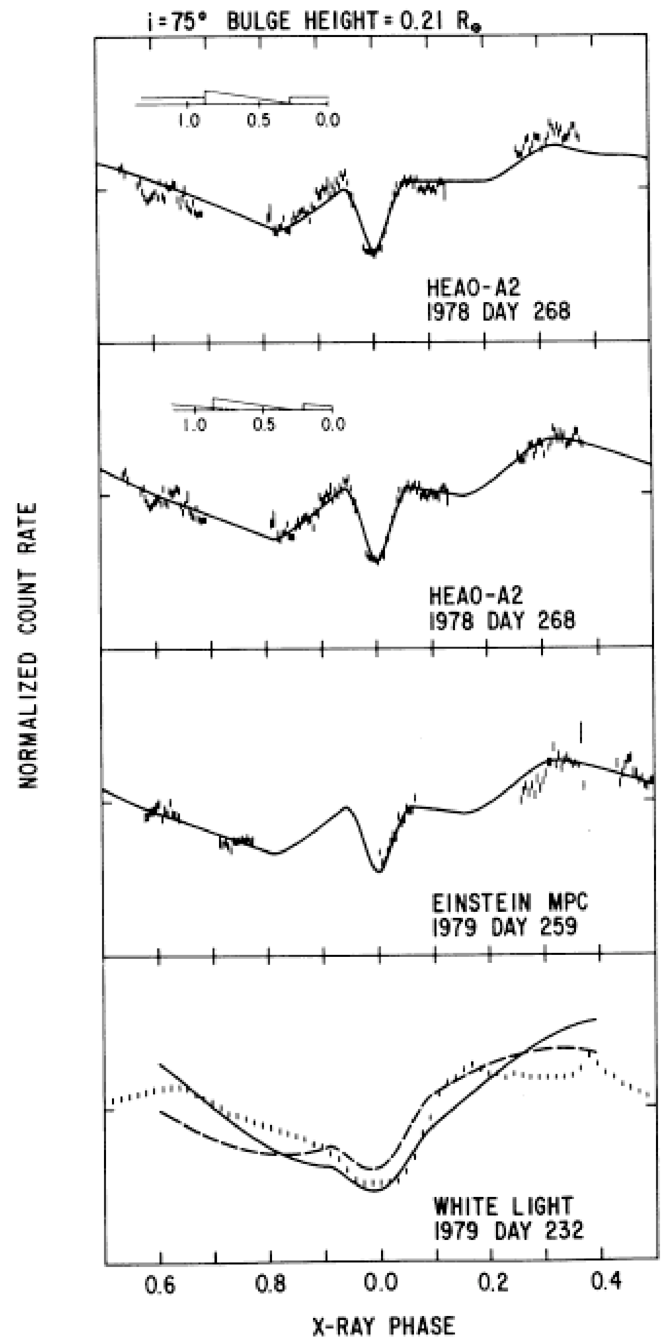
- Trace out ‘island’ or ‘banana’ in color-color diagram
- Truly different from Z-sources?




Hasinger and VanderKlis 1989

# ADC sources

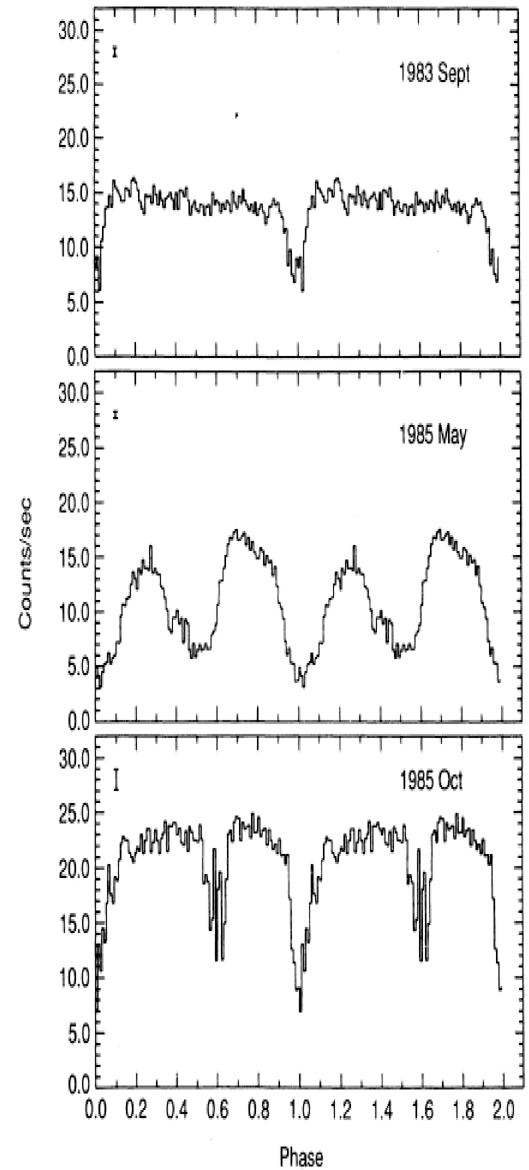
- LMXBs which are viewed at high inclination
- Appearance is dominated by scattered emission from (hot) gas at high lattitudes above the plane of the orbit
- Potential ‘rosetta stone’ for studying accretion disk, heating
- Rare: <5  known




White and Holt 1982

# dippers

- Show ‘dips’ in orbital lightcurve
- Likely Similar to adc sources, but slightly lower inclination
- More numerous than adc sources
- Provides complementary insight into disk above and below the orbital plane

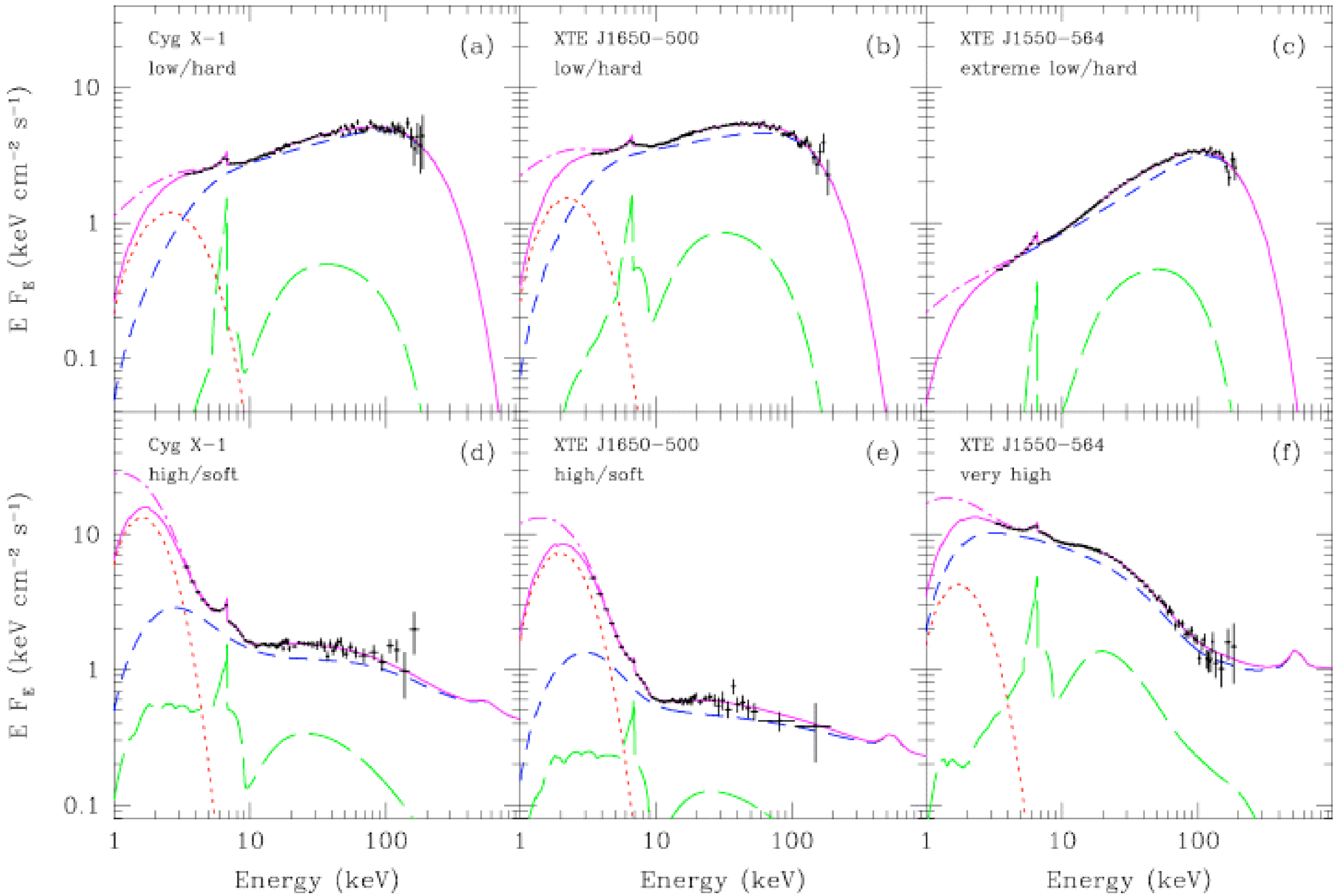



Smale et al. 1988

# ‘Pulsars’

- LMXBs showing pulsations: cluster near ~6 seconds
- + msec burst oscillations observed from some burst sources
- Many spun up neutron stars are expected

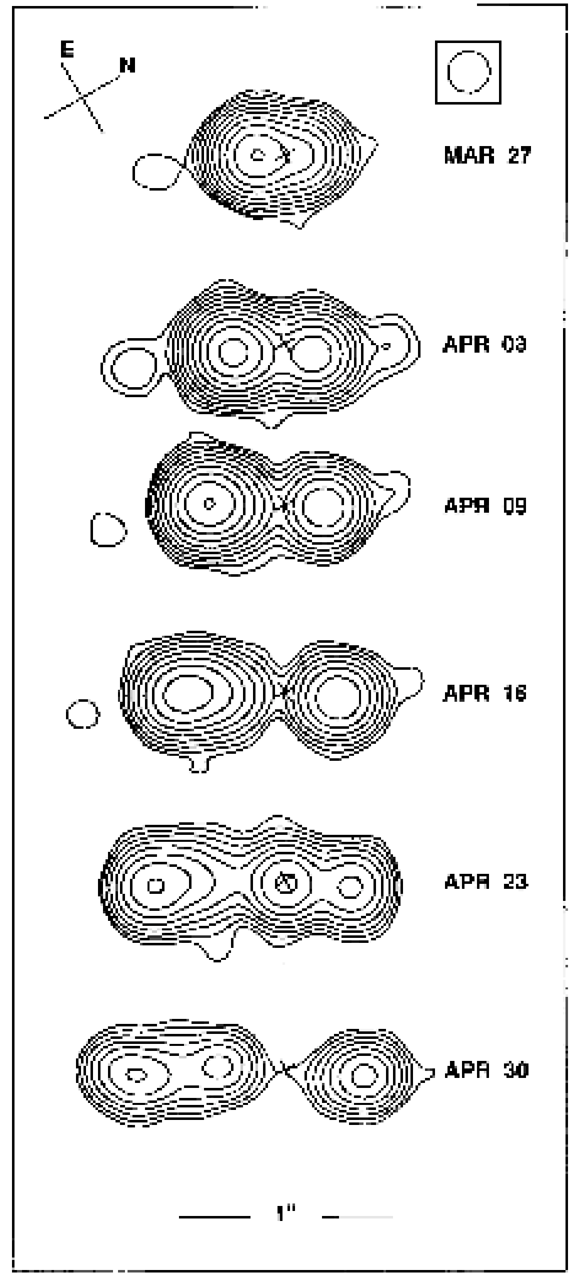
# Microquasars and black hole transients




Gierlinski and Done 2005

# Microquasars and black hole transients

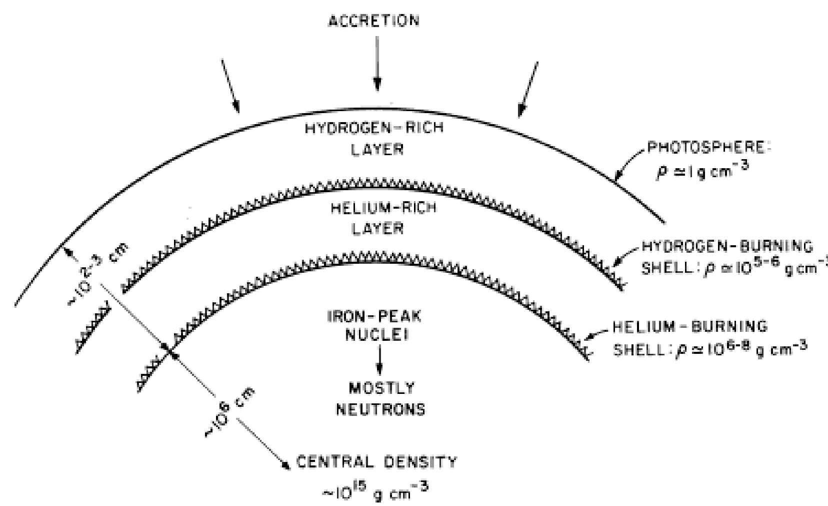
- BHT show outbursts, factor ~$10^8$, on timescale > yrs.
- ~20 black hole candidates known
- Microquasars show jets in the radio and X-ray + superluminal expansion




Mirabel and Rodriguez 1995

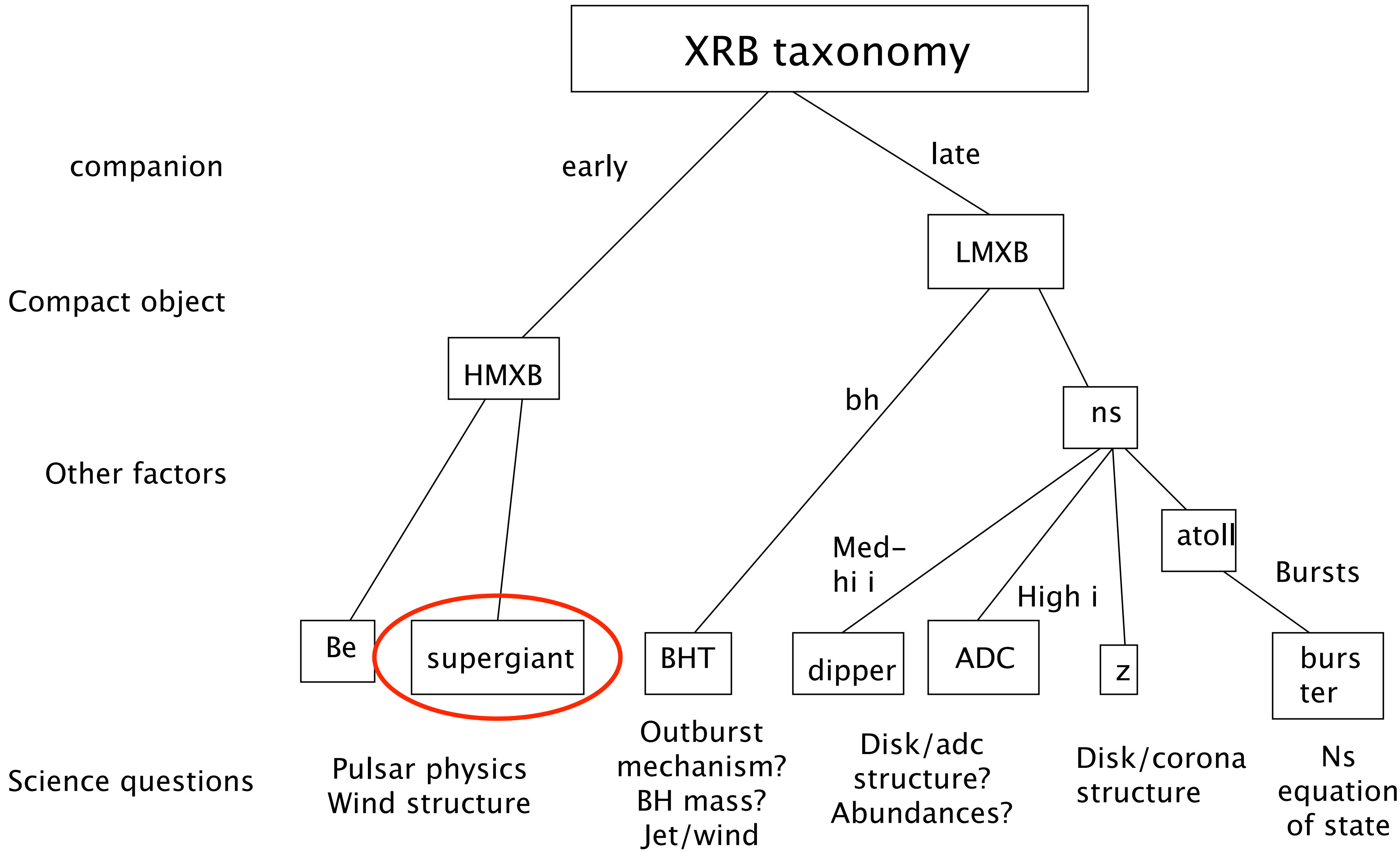
# X-ray burst sources

- Accreted material can burn He explosively on NS surface
- Requires slow rate of accretion --> atoll sources
- ‘relaxation oscillator’: burst fluence, interburst interval anticorrelated



| name | CO | i | # | remarks |
|---|---|---|---|---|
| adc | (ns) | hi | <10 | Sinusoidal lightcurve |
| dipper | (ns) | Med-hi | 10-20 | dips |
| burster | ns | ? | many | X-ray bursts |
| μquasar | bh | Med-hi | <10 | jets |
| BHT | bh | ? | many | outbursts |
| Z-source | (ns) | Low? | <10 | Color-color:Z |
| atoll | (ns) | Low? | many | Color-color:atoll |
| pulsar | ns | ? | <10 | 1s<P<10s |
| msec pulsar | ns | ? | ? | P~.01 s |

The lmxb zoo..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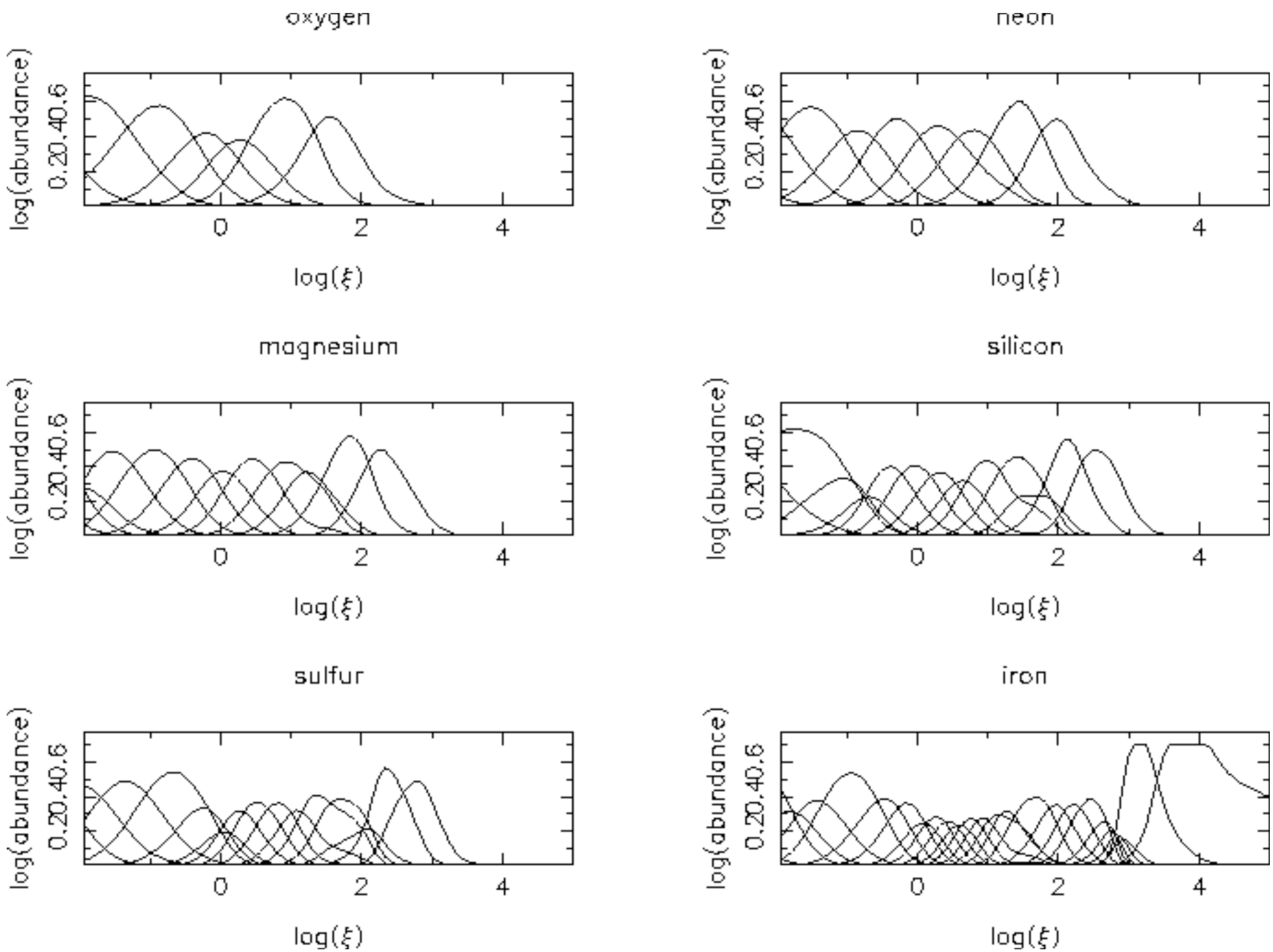
# Ionization and Thermal Balance

- For each ion:
  - Ionization = recombination
  - ~photon flux ~electron density
- For the gas as a whole
  - Heating = cooling
  - ~photon flux ~electron density
- => All results depend on the ratio photon flux/gas density or "ionization parameter"

# Consequences of Photoionization

- Temperature lower for same ionization than coronal, $T \sim 0.1\, Et_h/k$
- Temperature is not a free parameter
- Temperature depends on global shape of spectrum
    - At high ionization parameter, the gas is fully ionized, and the temperature is determined by Compton scattering and inverse $T=\langle E \rangle/4k$
- Ionization balance is more 'democratic'
- Microphysical processes, such as dielectronic recombination, differ
- Observed spectrum differs

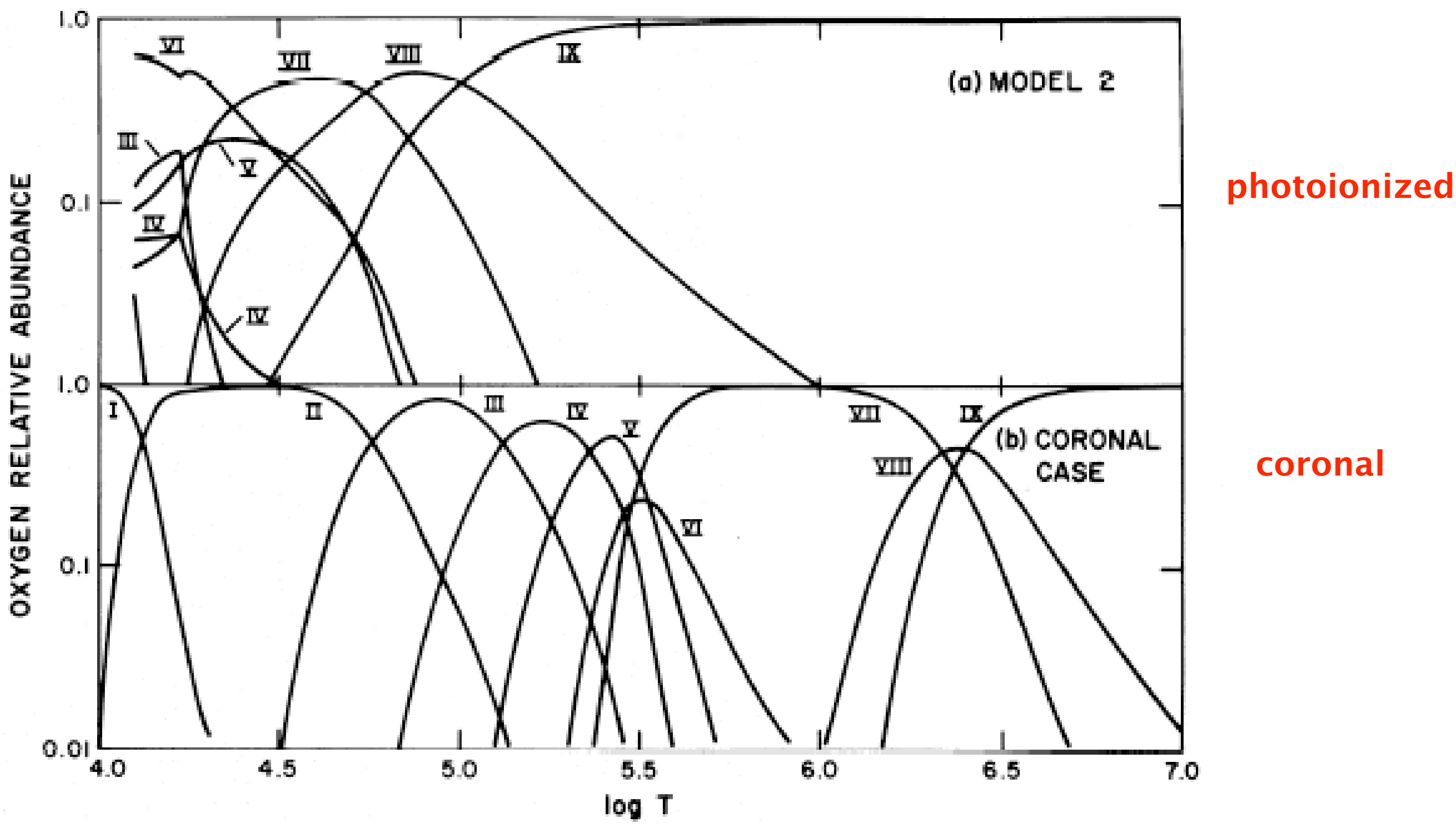
# Ionization fractions of elements in a photoionized gas




$\xi$=X-ray flux/gas density=$4\pi F/n$

Neutral <------------>fully stripped

# Comparison of ionization balance in photoionized and coronal gas

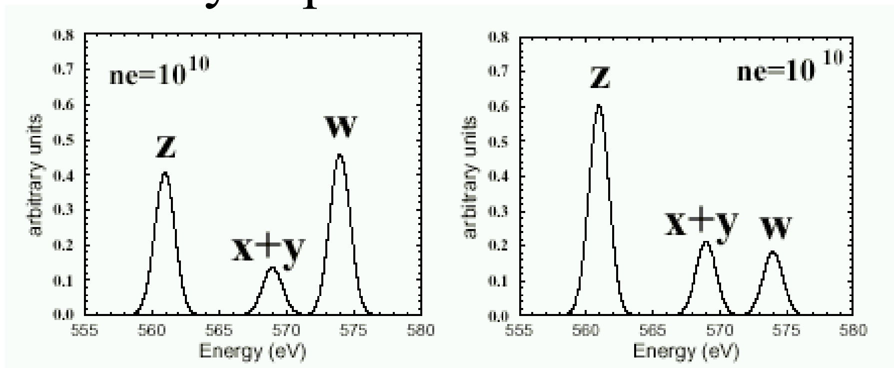


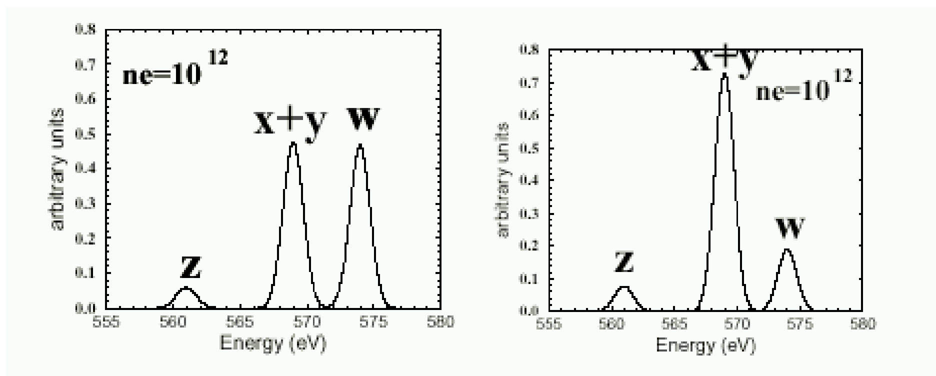

=> Photoionized gas is more ionized at a given temperature, and each ion exists over a broader range of temperatures

# Observed Spectrum: Emission

- In coronal gas, need kTe~ΔE to collisionally excite lines.
- In a photoionized gas there are fewer lines which satisfy this condition.
- Excitation is often by recombination cascade
- Also get recombination continua (RRCs) due to recombination by cold electrons directly to the ground state. The width of these features is directly proportional to temperature
- Due to the democratic ionization balance, it is more likely that diverse ions such as N VII, O VIII, Si XIV can coexist and emit efficiently than it would be in a coronal gas
- Inner shell ionization and fluorescence is also important in gases where the ionization state is low enough to allow ions with filled shells to exist.

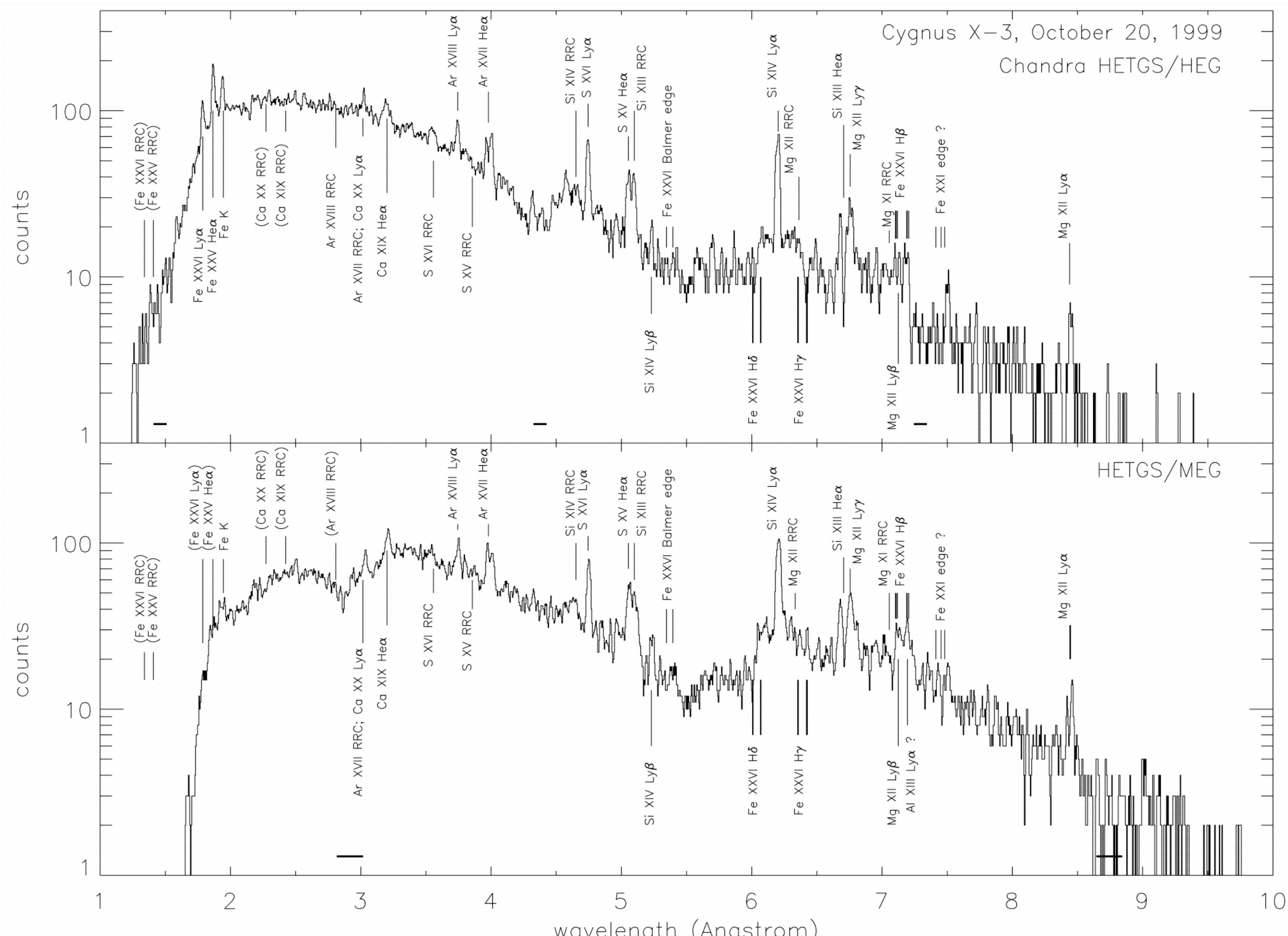
# Density dependence of He-like lines



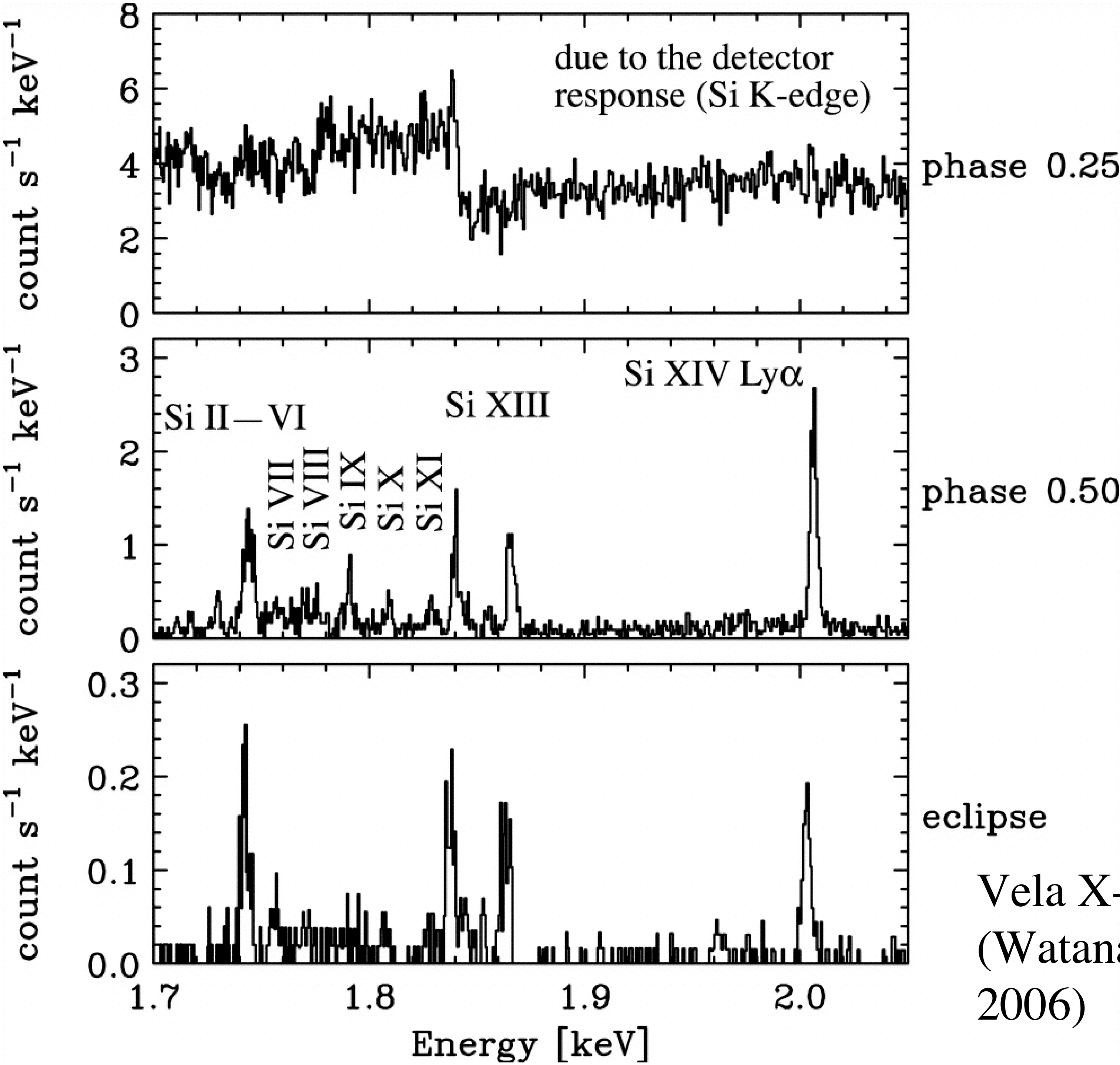




Coronal photoionized

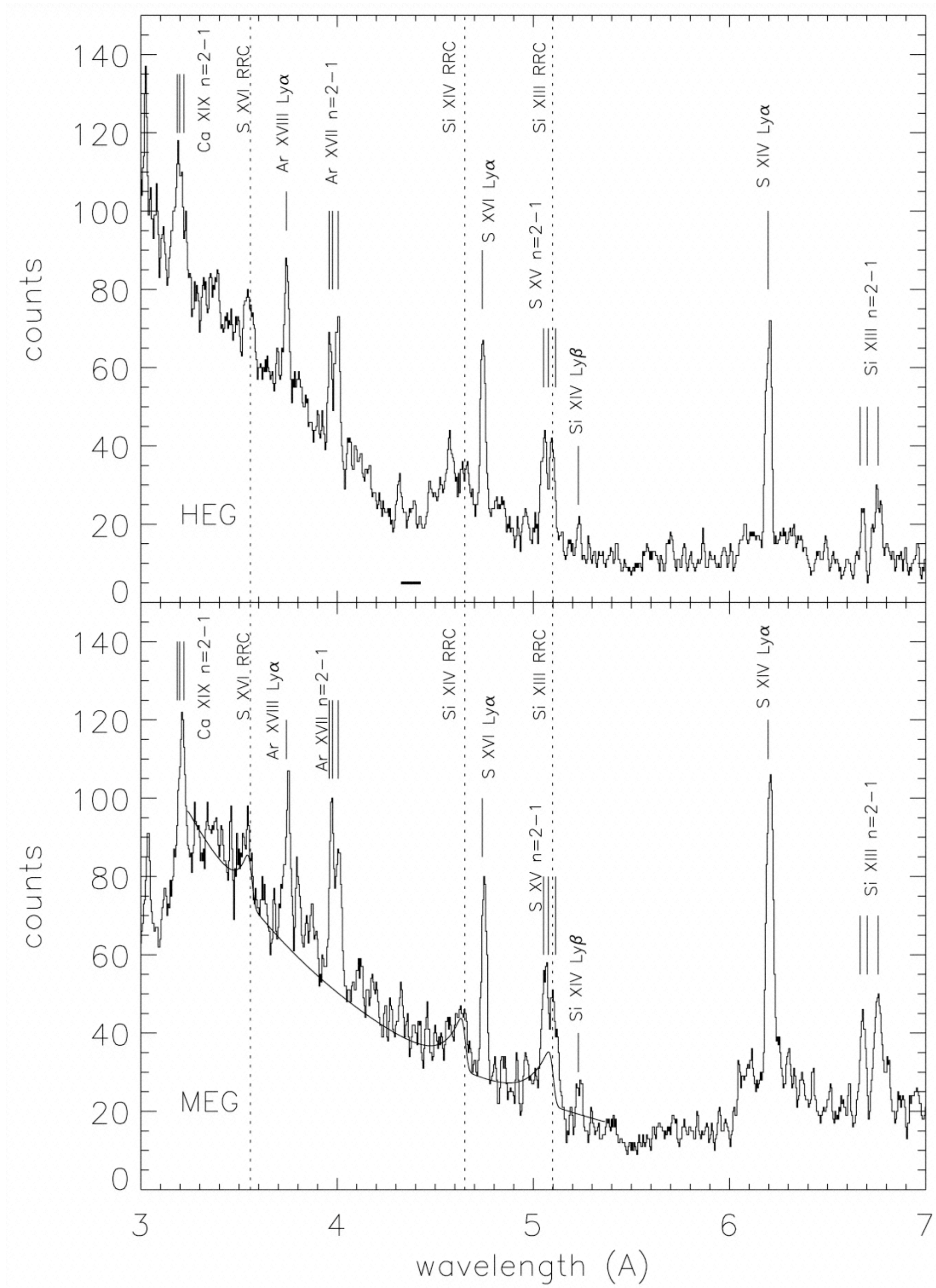
(Porquet and Dubau 1998)




Cyg X-3 Chandra HETG (Paerels et al. 2000)




Vela X-1
(Watanabe et al.
2006)

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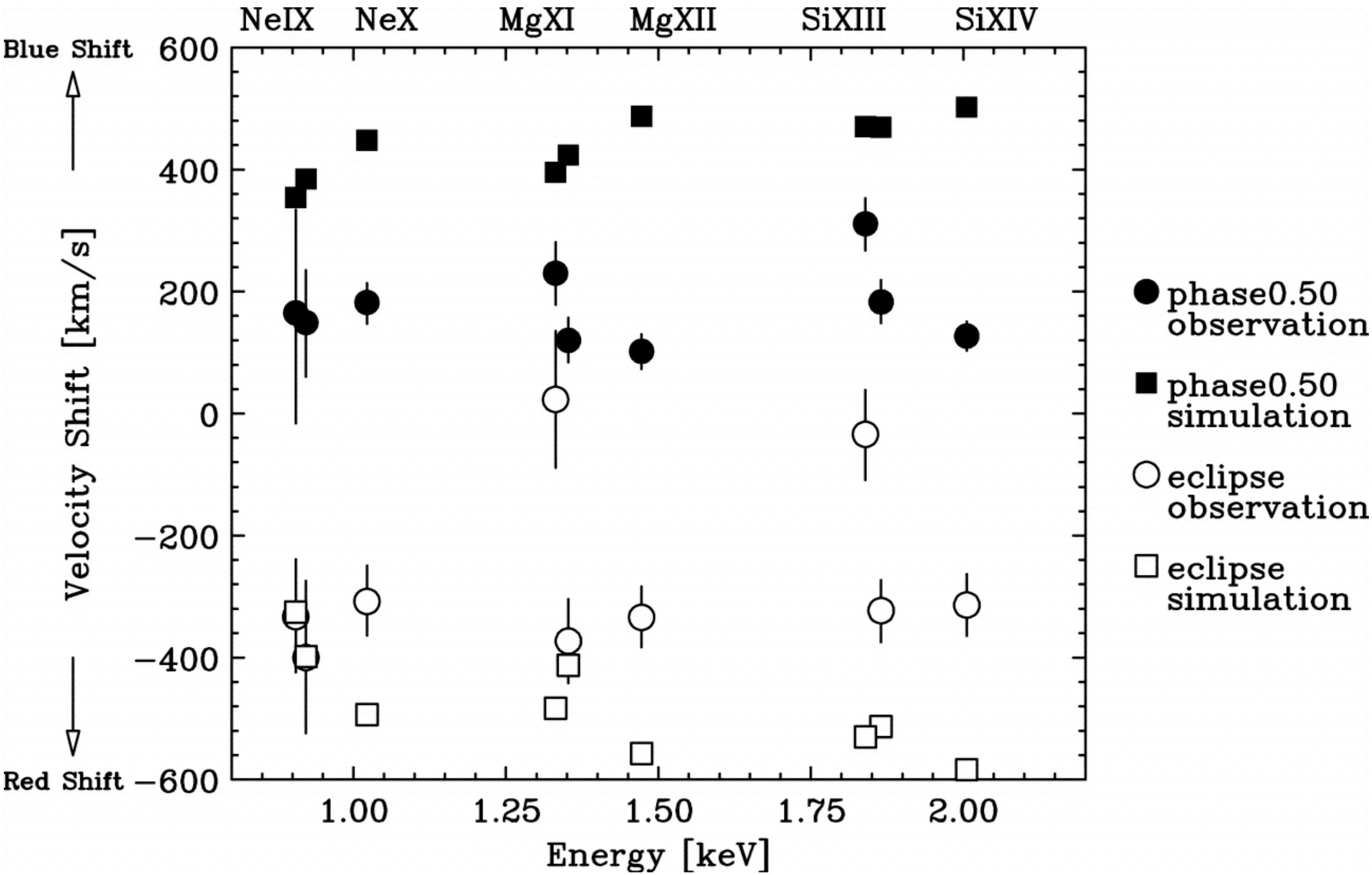
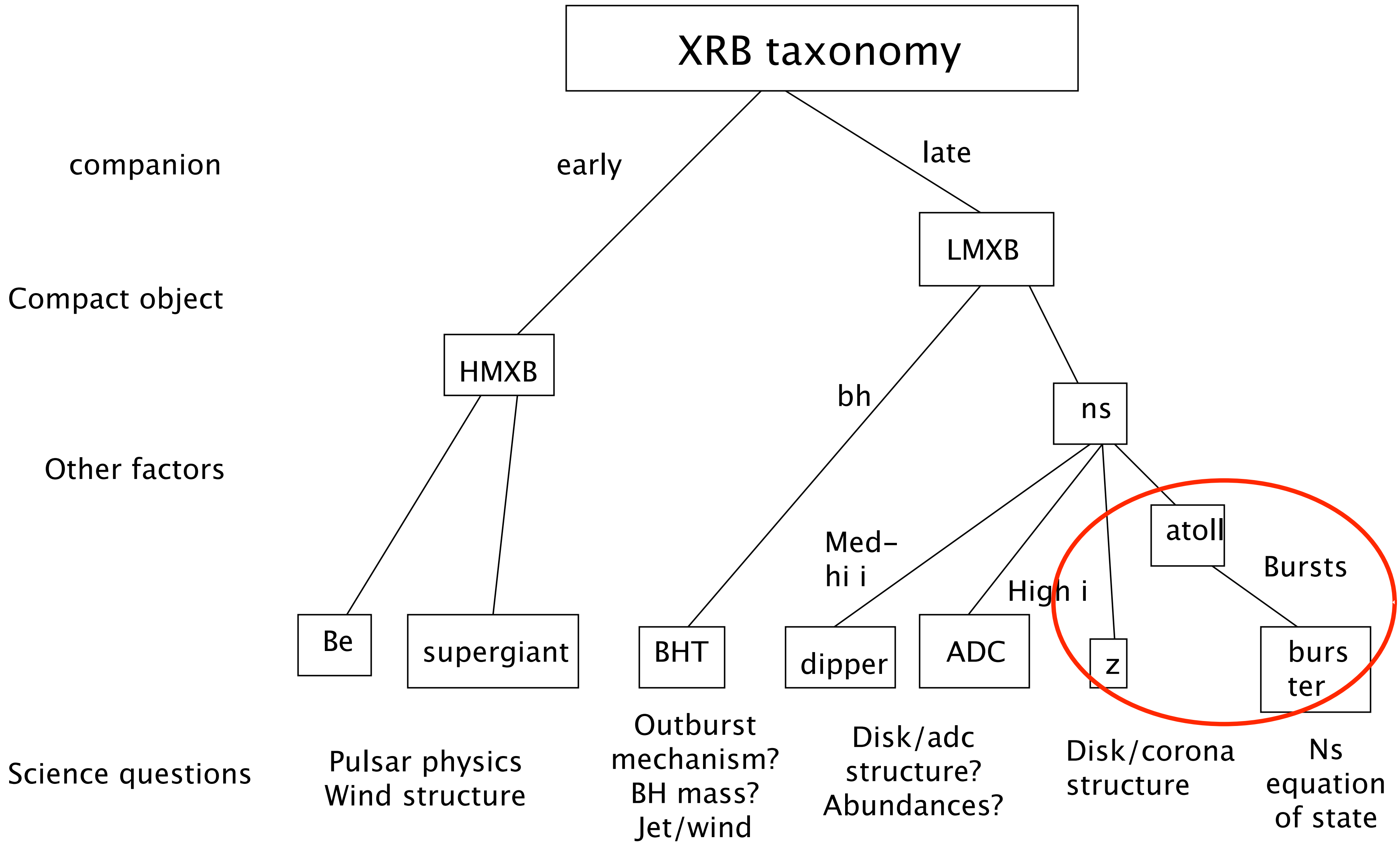



Vela X-1: line offsets (Watanabe et al. 2006)

# X-ray spectra of HMXBs

- Clearly show evidence of photoionization:
  - RRCs
  - Inner shell lines
  - He-like triplet
- RRC detection allows temperature determination: ~1-2 eV
- He-like triplet shows evidence for resonance scattering
- Velocity offsets of lines vs. orbital phase
- Inner shell lines of Si, S allow X-ray probe of low ionization material
- Interpretation is complicated, requires detailed modeling of gas dynamics and ionization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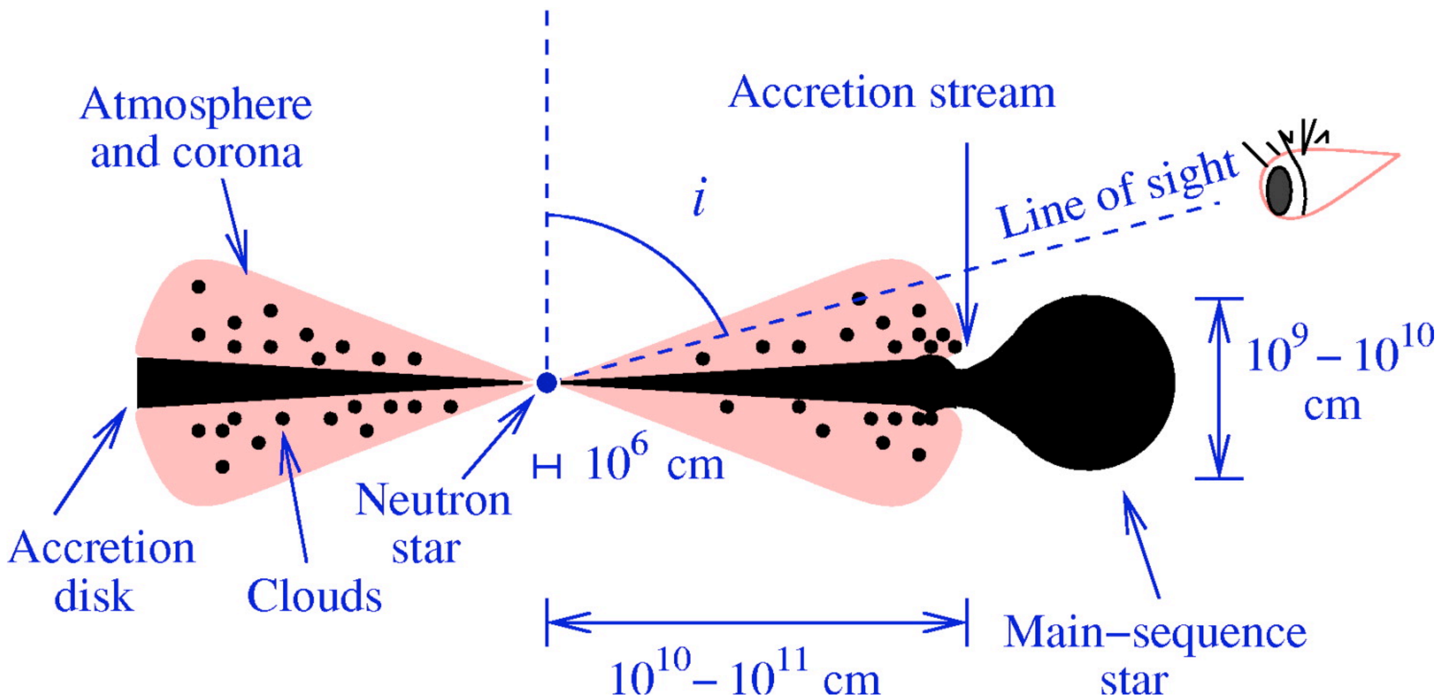
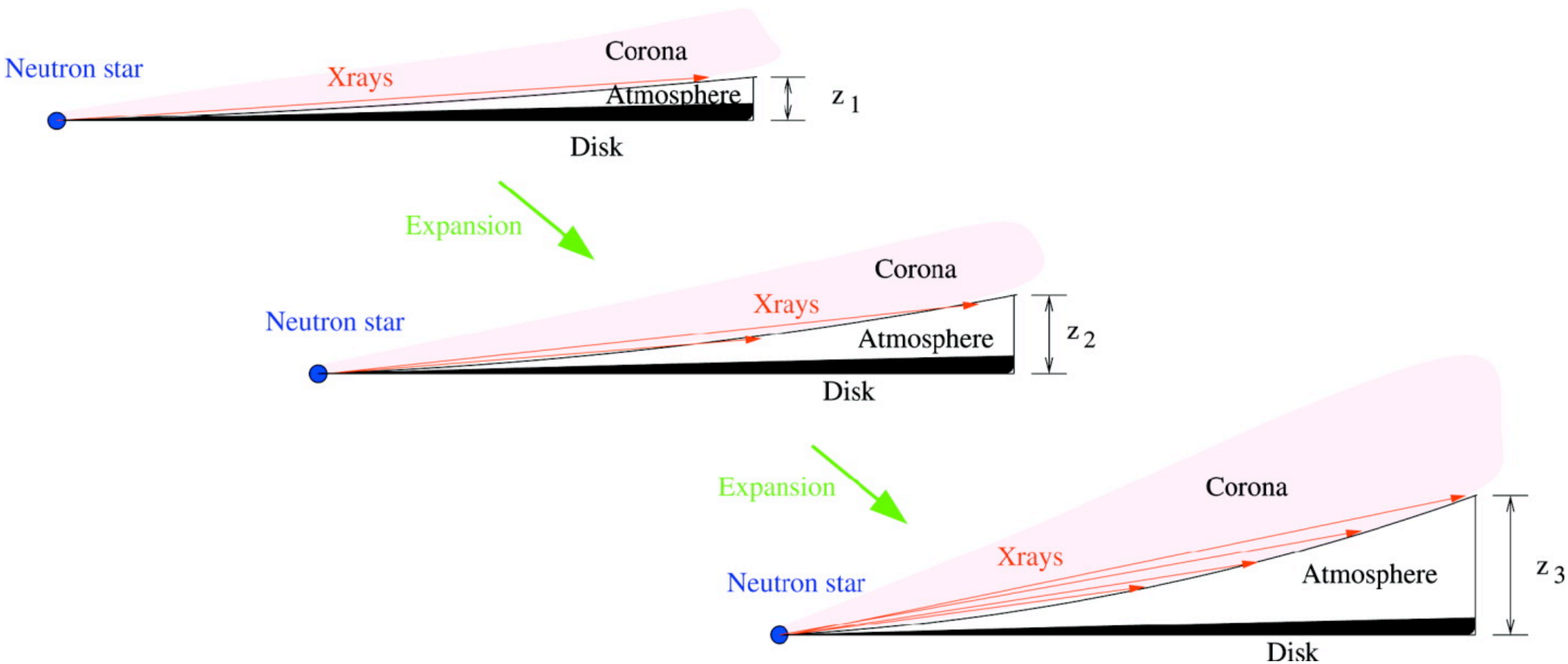
# Geometry of heated accretion disk + coronal in LMXB



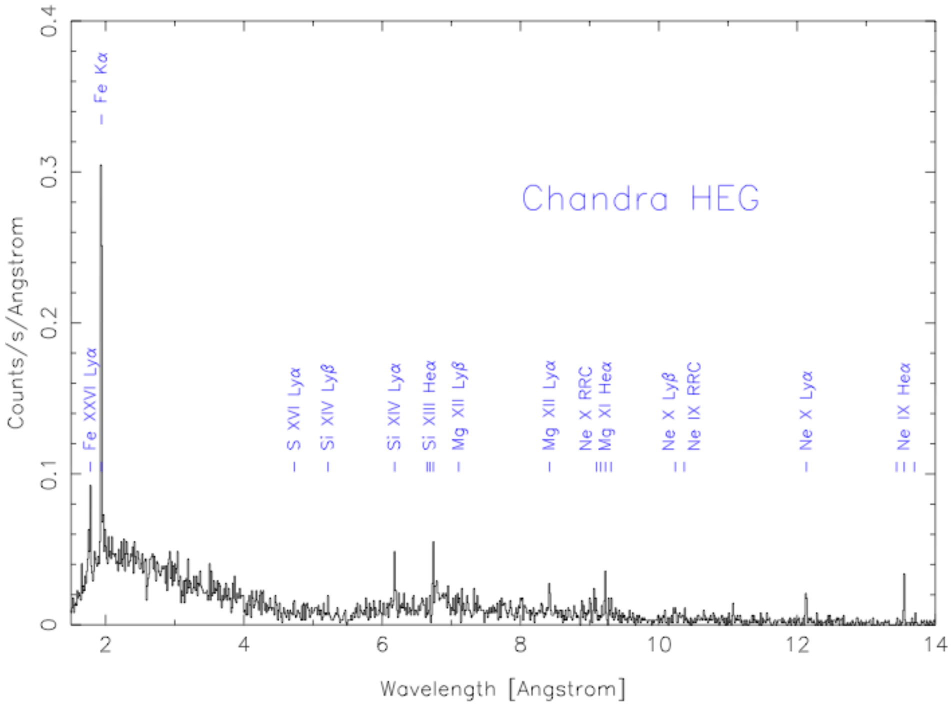

Jimenez-Garate et al. 2002

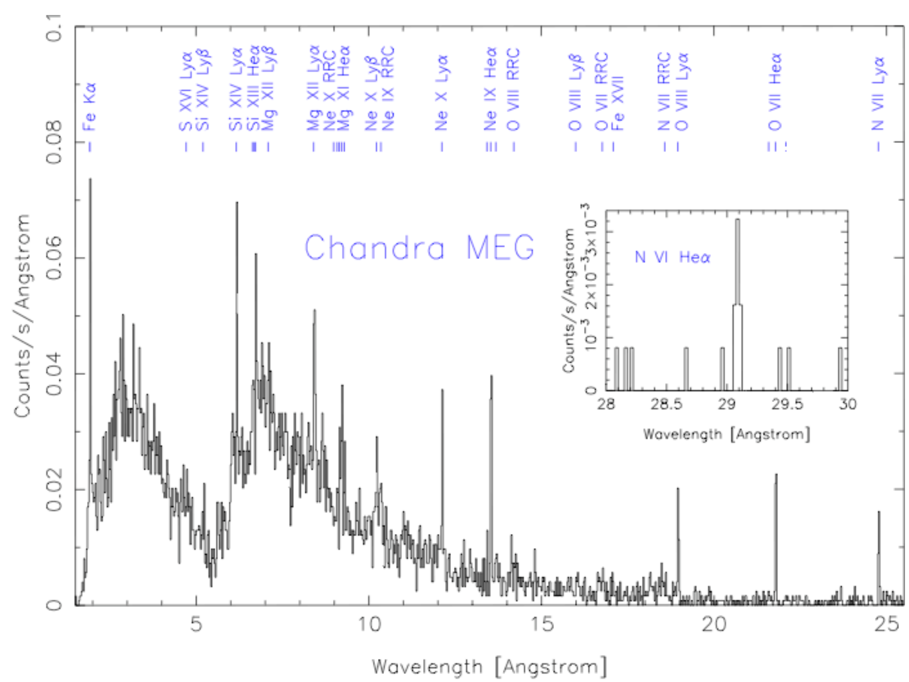
# Effect of X-rays on atmosphere structure




Jimenez-Garate et al. 2002

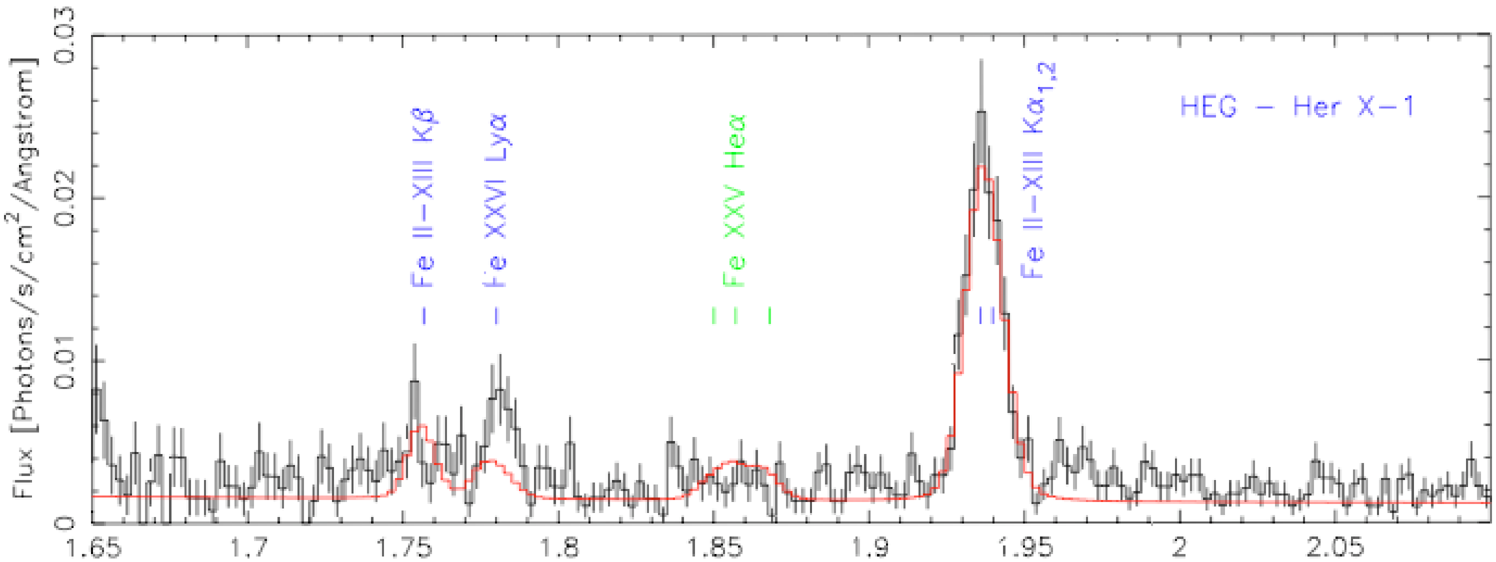
# Chandra Spectrum of Her X-1



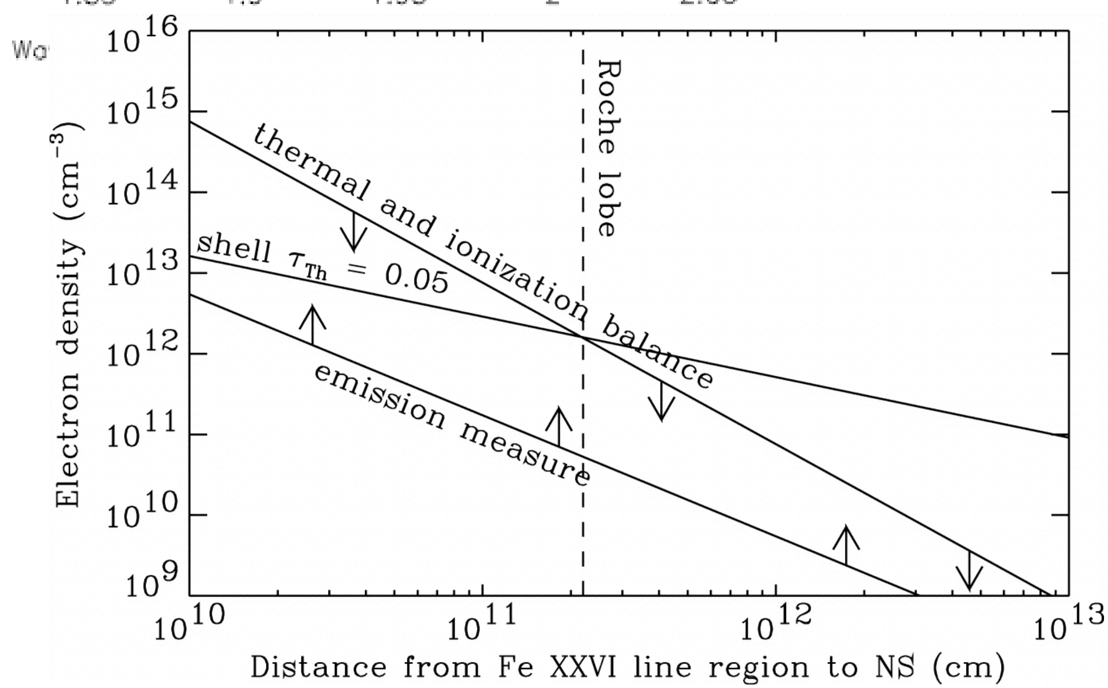

(Jimenez et al. 2005)

# Chandra Spectrum of Her X-1 in the iron line region

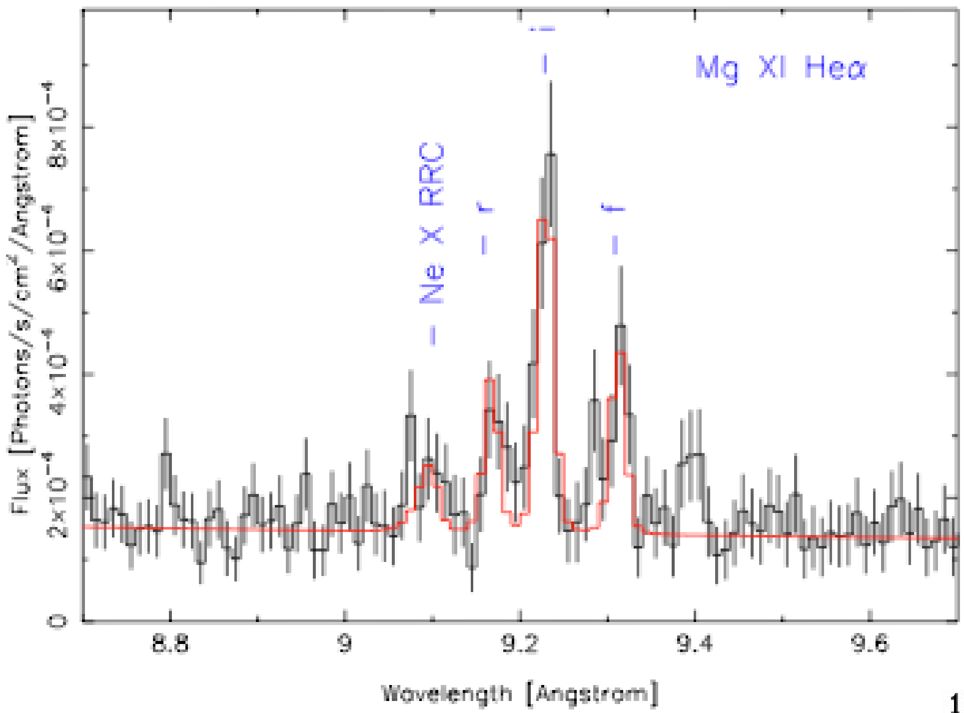



From H/He-like ratio
+ models ionization
balance
==> can set limits on
location of Fe
emitting gas

(Jimenez et al. 2005)



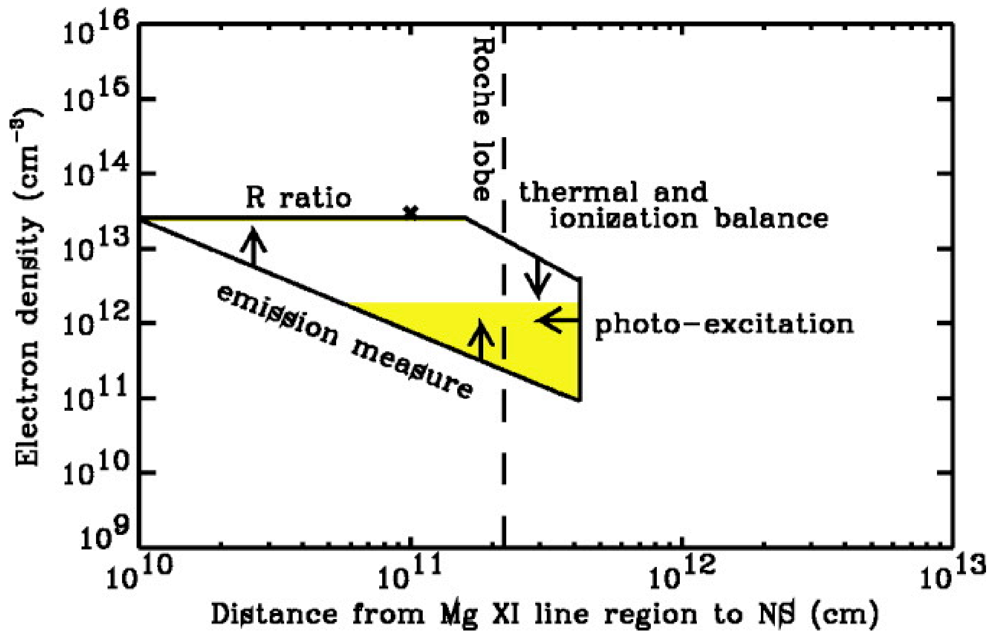
# Spectrum of Her X-1: Mg XI line



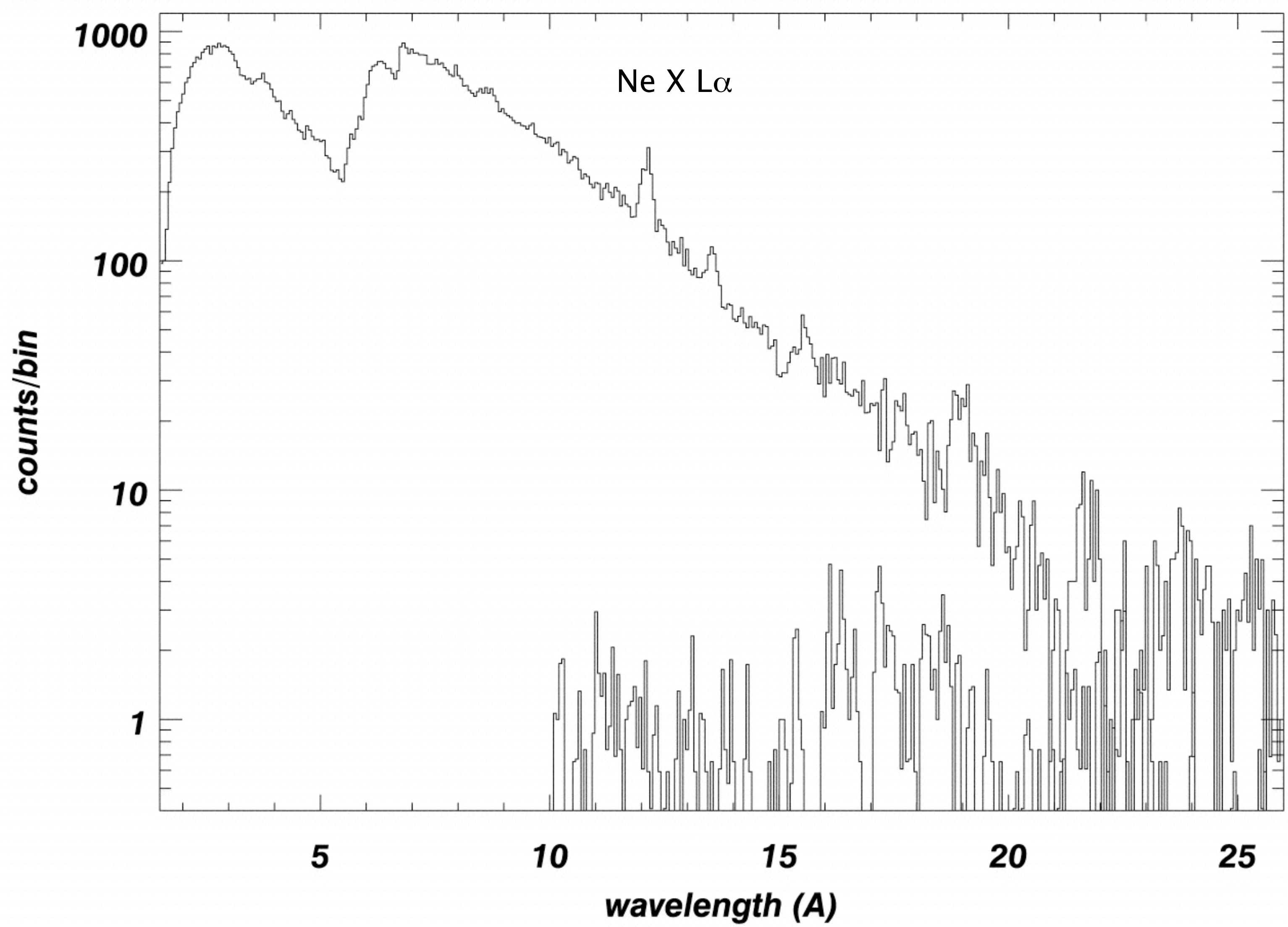

♣R ratio < 1 => upper limit on density

♣Photoexcitation => lower limit on EUV flux, distance

(Jimenez et al. 2005)

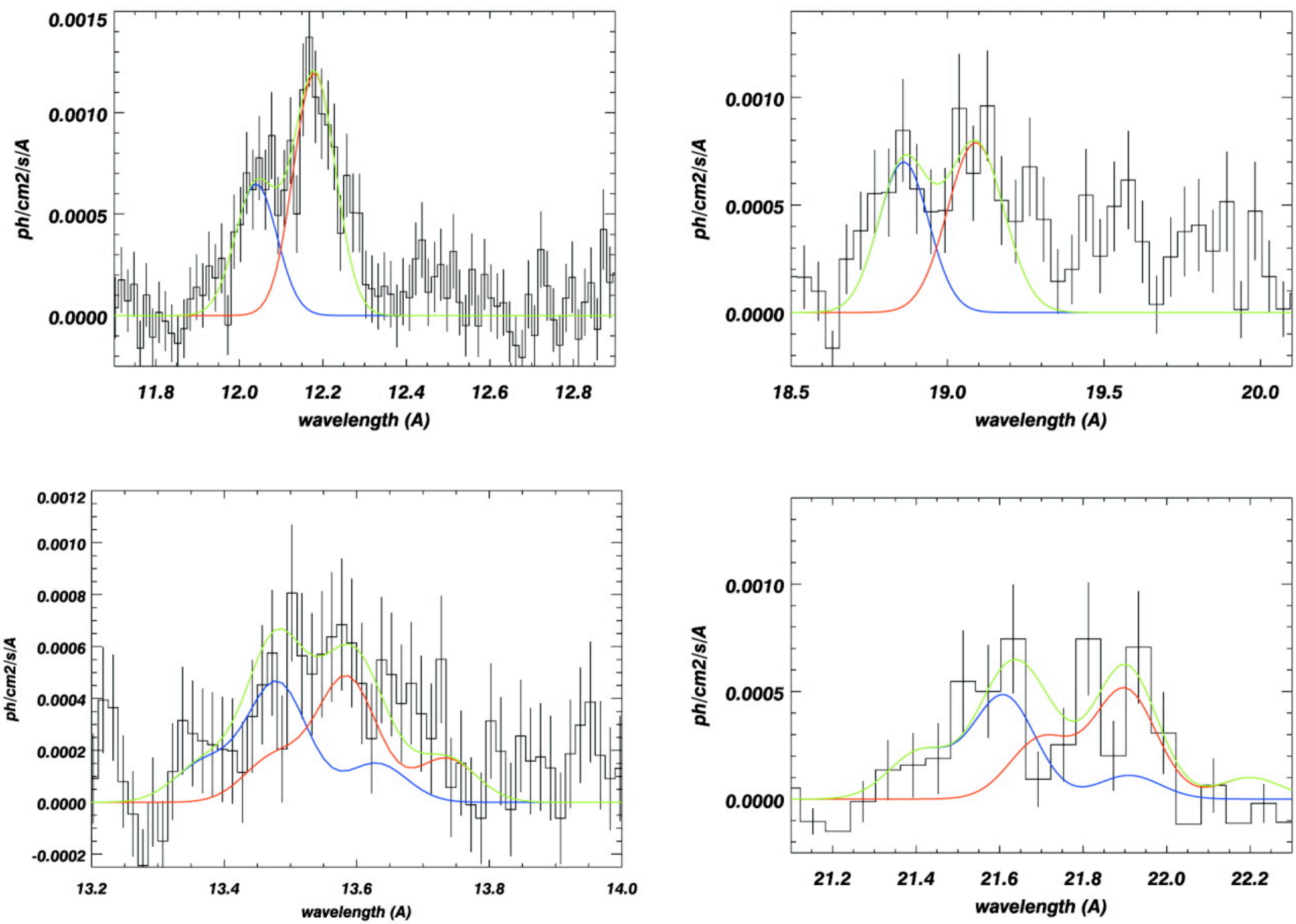


# Chandra spctrum of 4U1626-67 (6 sec pulsar)



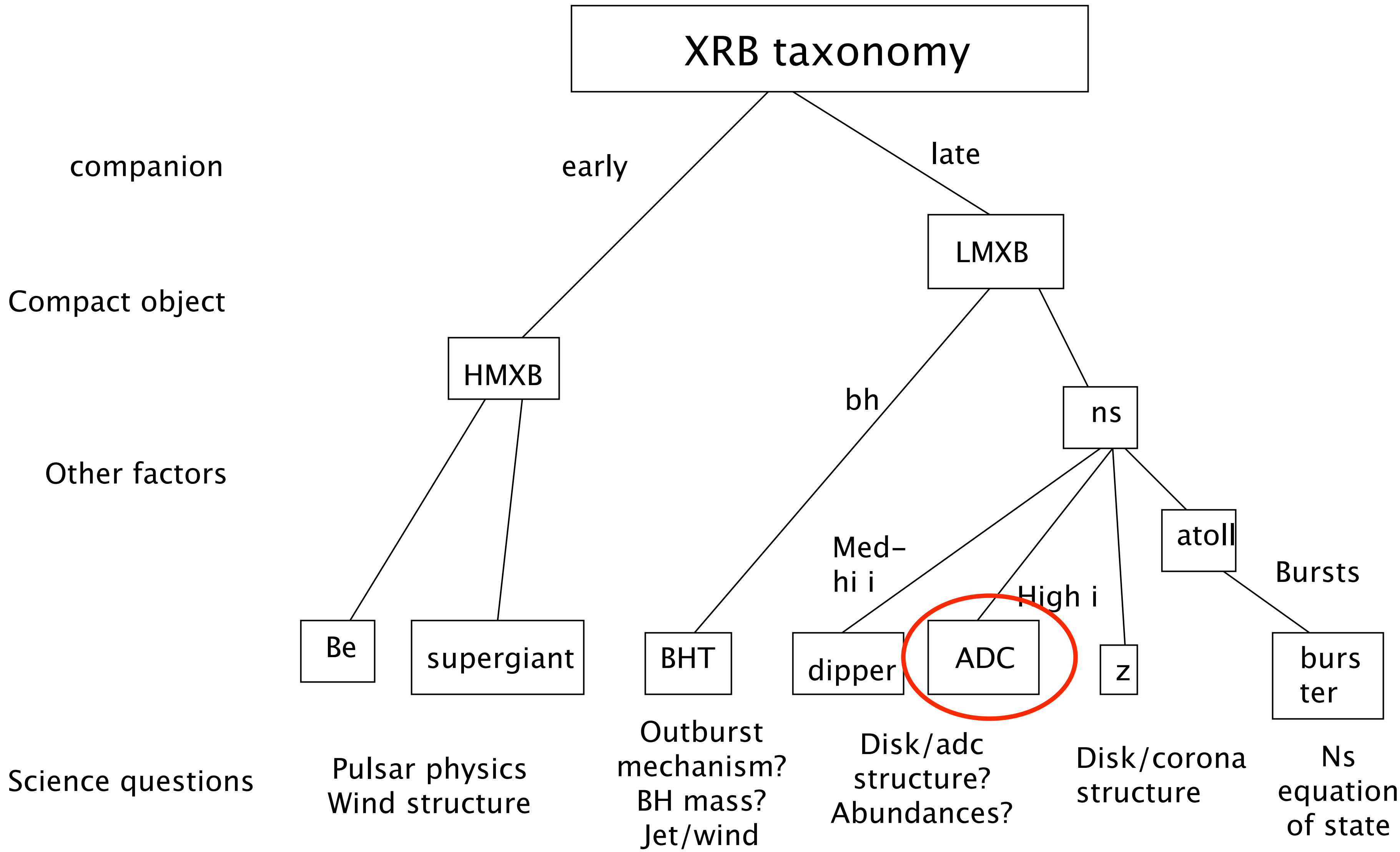

(Schulz et al. 2002)

# detail of 4U1626-67 spectrum,




=> Lines show double peaks, characteristic of accretion disk

(Schulz et al. 2002)



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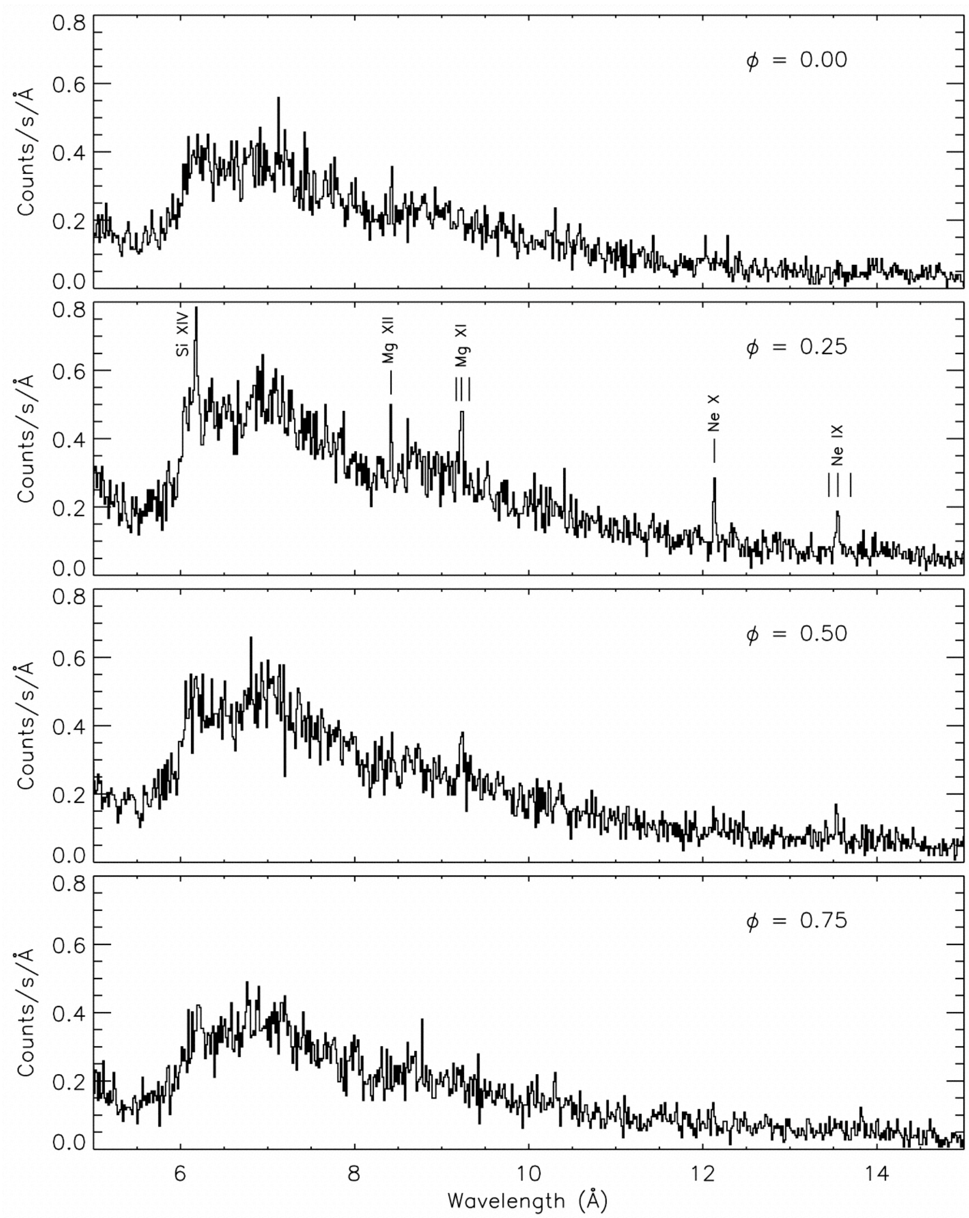
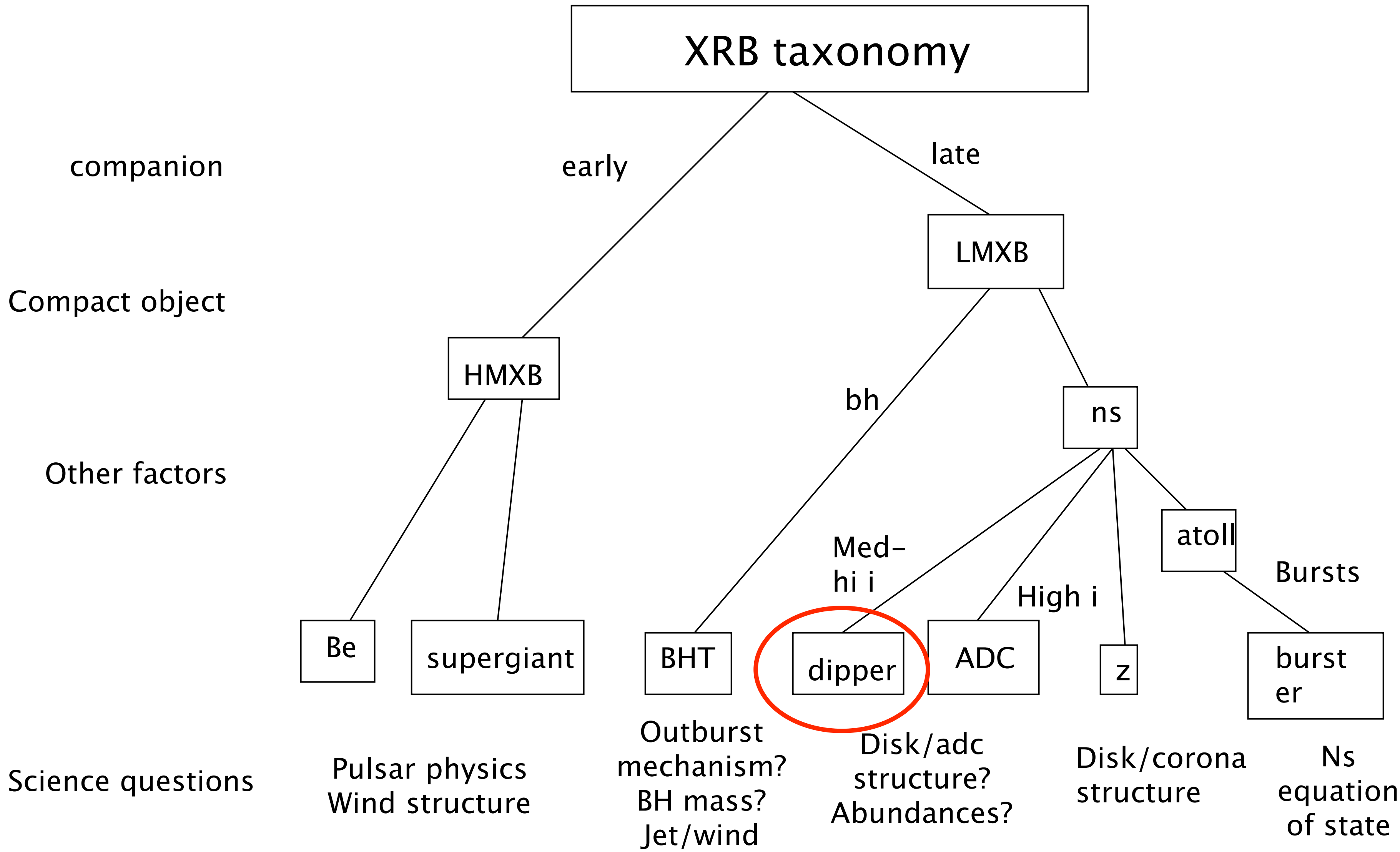
# Chandra HETG spectrum of ADC source 4U1822-37




Emission lines are strongest at phase 0.25
=> Bulge on disk edge

(Cottam et al., 2001)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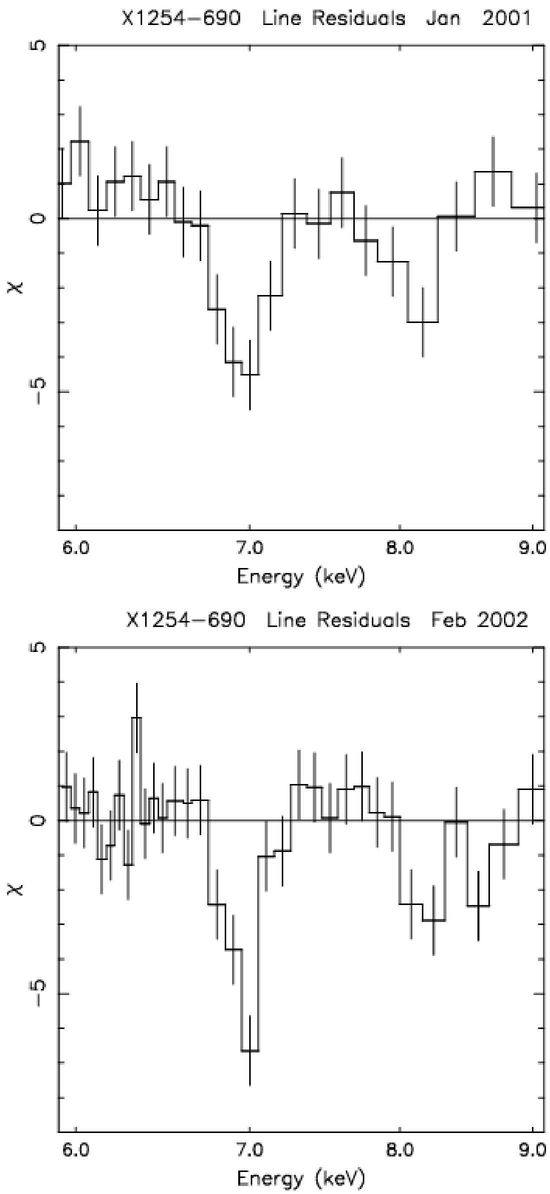
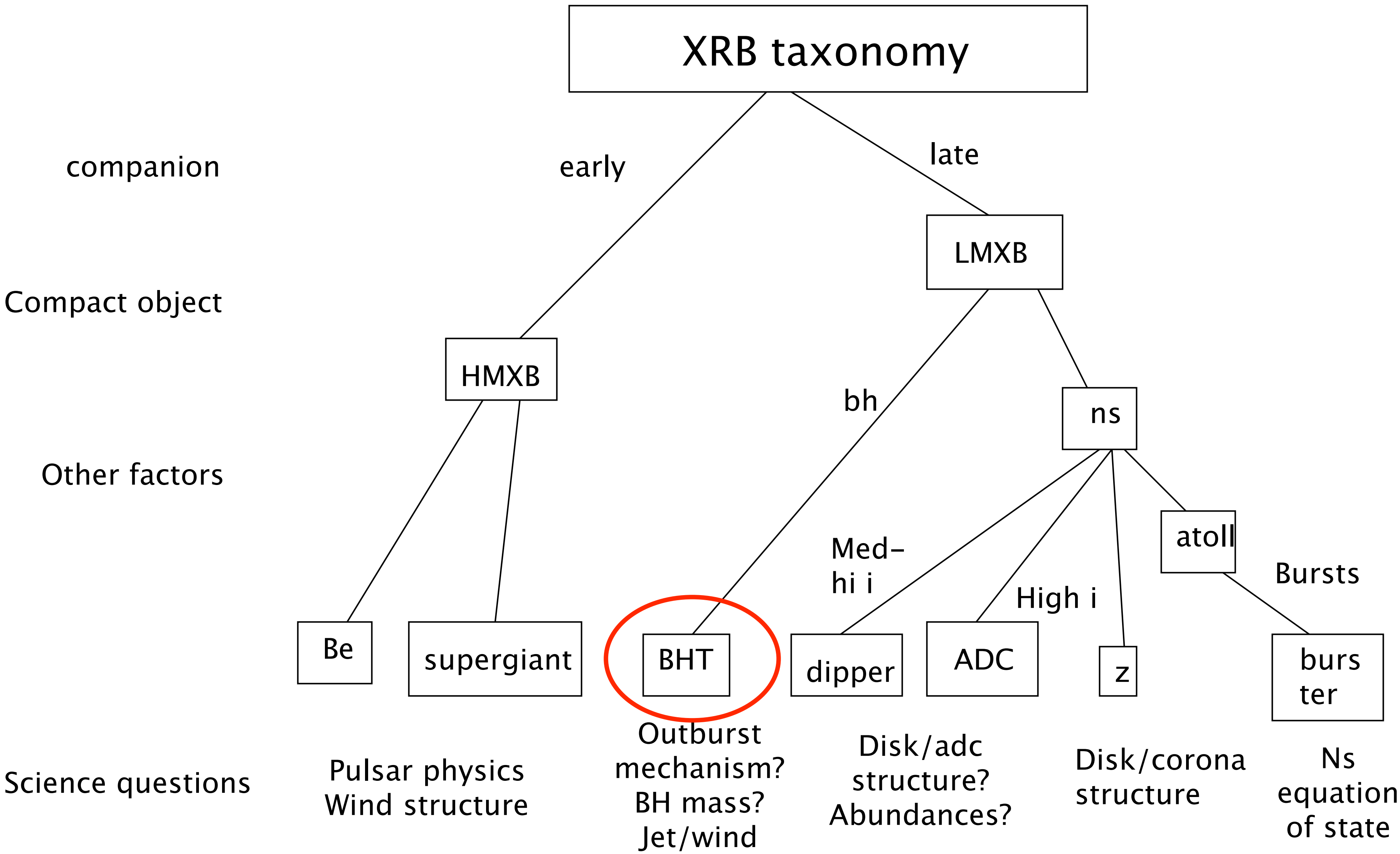
# Dipper iron line spectrum




♣Essentially every dipper shows evidence for highly ionized iron obsorption
♣Discovered with XMM CCD detectors
♣Absorption is in addition to gas resposible for dips
♣It is likely that we are seeing the accretion disk corona in absorption
♣In one case, possible indication of outflow

Boirin and Parmar 2002)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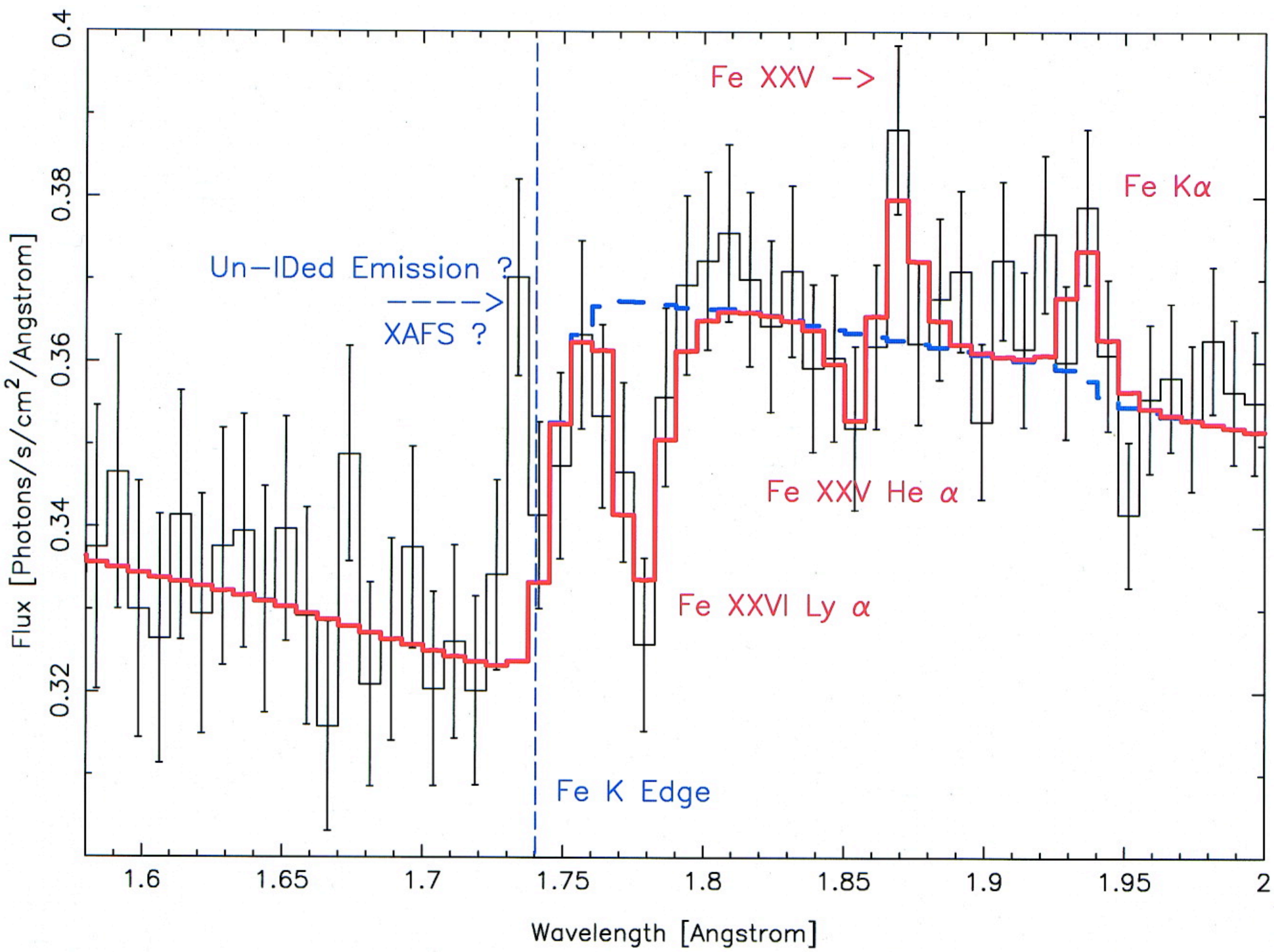
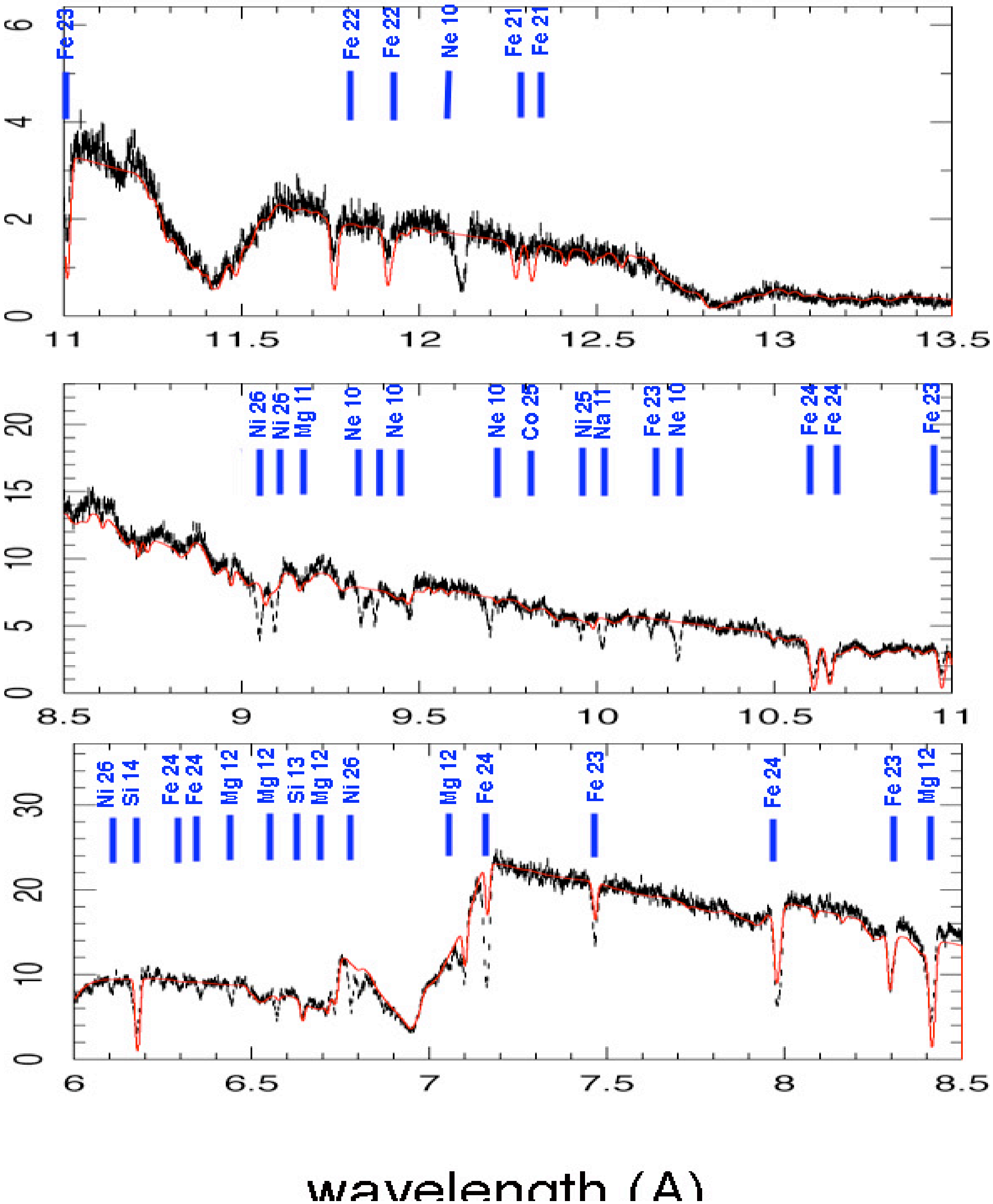
# Iron line spectrum from GRS 1915+105




(Lee et al. 2002)

- ♣Many black hole transients show absorption by highly ionized iron during outblurst
- ♣Lines are blueshifted, indicating outflows with v~500-1000 km/s
- ♣Such outflows are similar to those observed in AGN
- ♣It's likely that most of the outflow is fully stripped
- ♣Mass fluxes are difficult to estimate



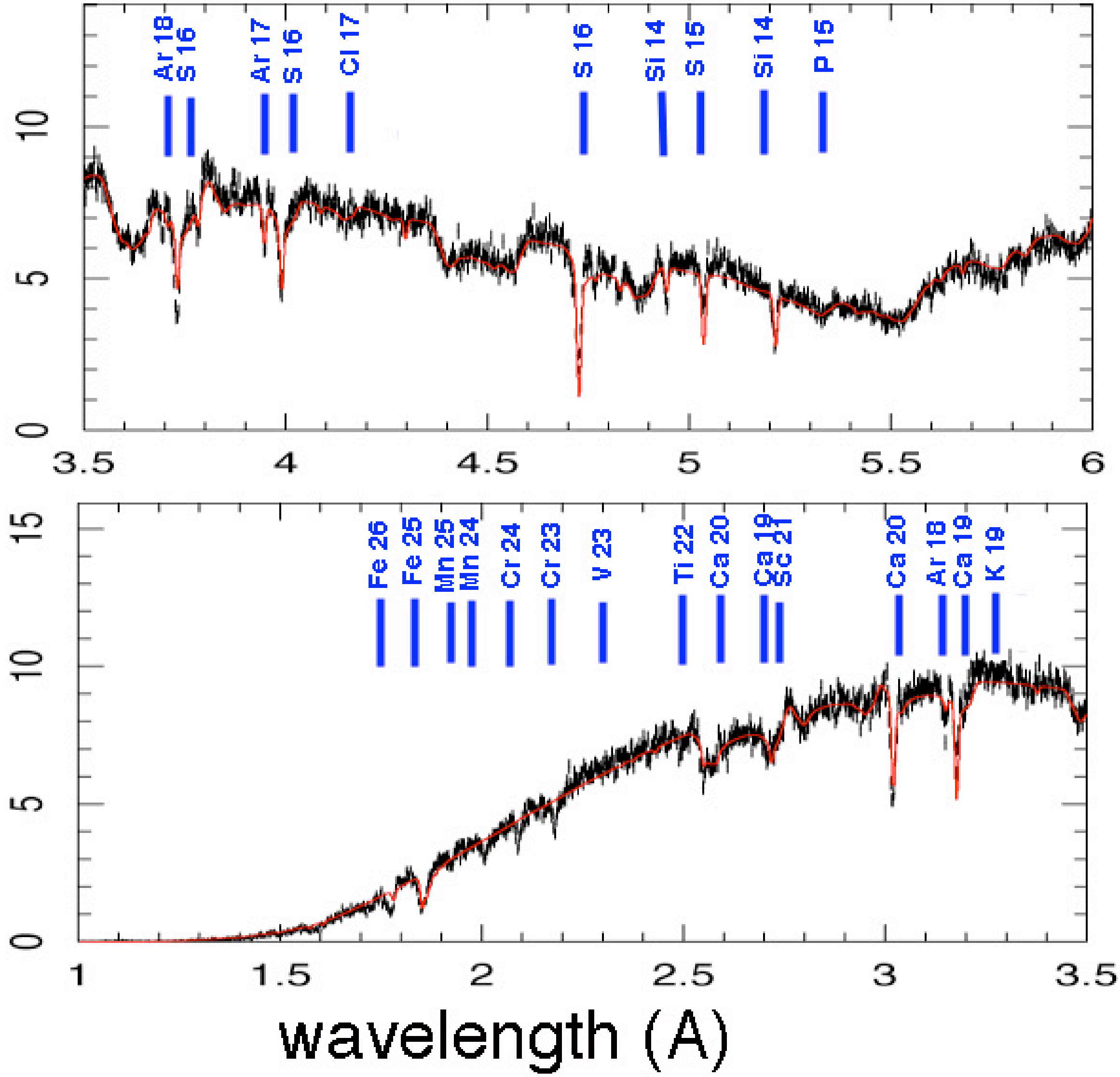

♣spectrum of GRO J1655-304 obtained during outburst

♣It shows absorption lines from H- and He-like species of every element between Ne and Ni

♣This is the first time many of these elements have been detected in X-ray astronomy

♣Presents interesting questions about the evolutionary origins of the companion star

♣Lines of Fe XXII allow density determination => test of dynamics

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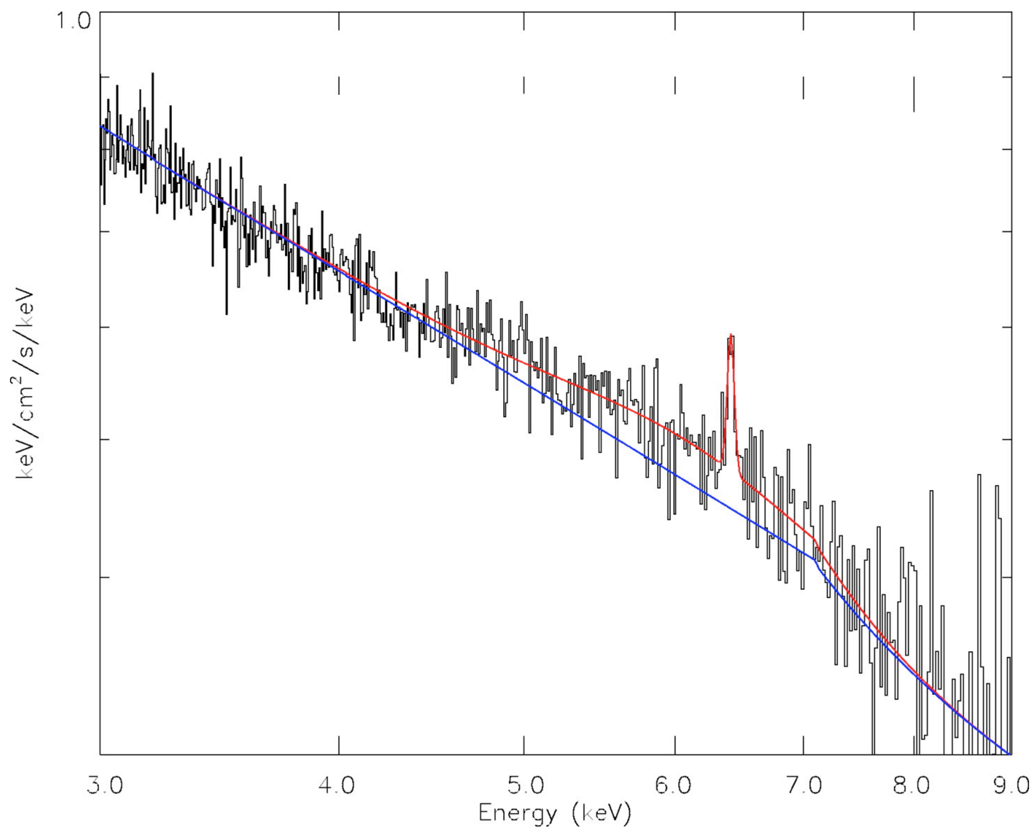
# Iron K line from Cyg X-1

- Iron K lines are diagnostic of reprocessing in very optically thick material, eg. The accretion disk
- Relativistically broadened iron K lines are found in some AGN
- The galactic black hole candidate Cyg X-1 shows a line with is composite: it has both broad and narrow components, but only in low/hard states




Miller et al., 2003

# summary

- X-ray binaries exhibit a wide range of behaviors, but much of the interesting physics/astrophysics is common to all
- Understanding of accretion disks, accretion flows, X-ray induced winds, compact obect evolution are all in a primitive state.
- Spectra provide new insights: importance of outflows, broad and narrow iron lines, importance of X-ray heating of accretion disks

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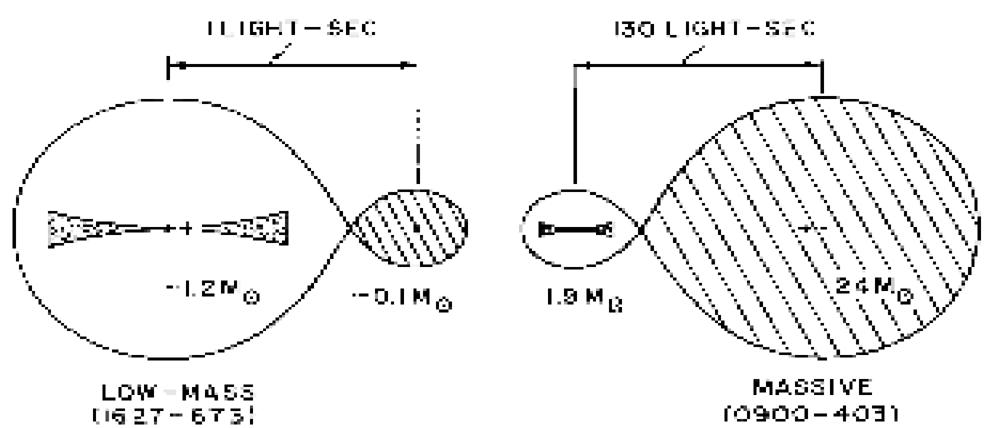

1 LIGHT-SEC
~1.2 $M_\odot$
~0.1 $M_\odot$
LOW-MASS
(1627-673)
130 LIGHT-SEC
1.9 $M_\odot$
24 $M_\odot$
MASSIVE
(0900-403)