Laboratory atomic reference data for Cyg X-1 and beyond

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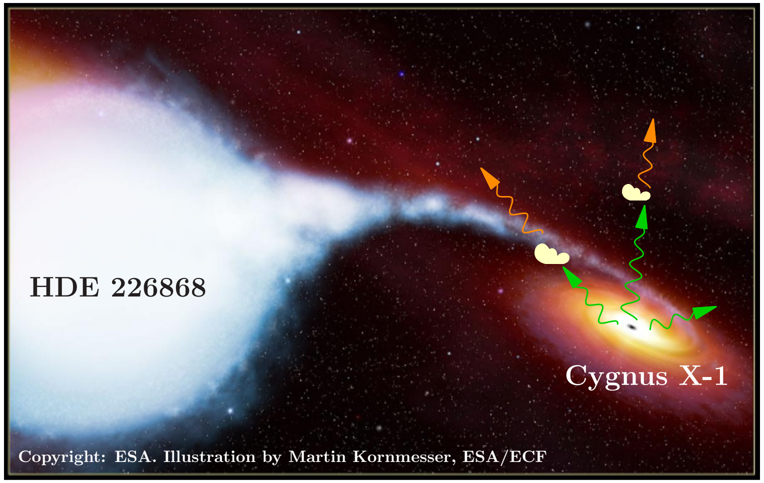
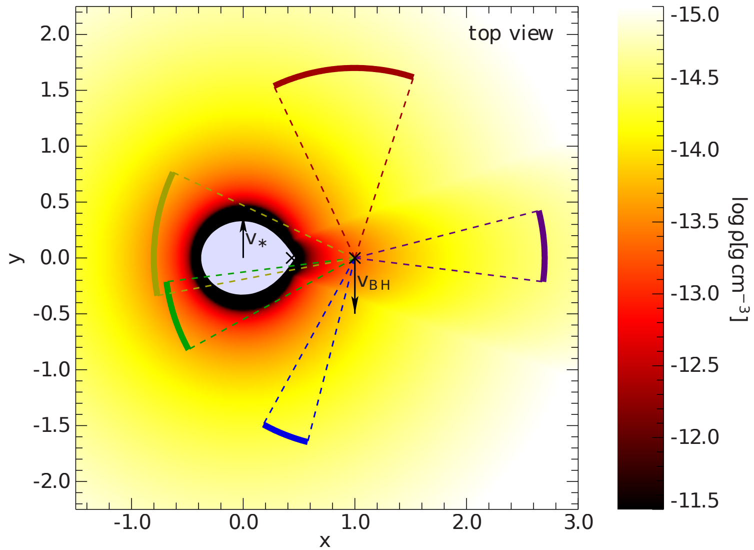
The high mass X-ray binary Cygnus X-1

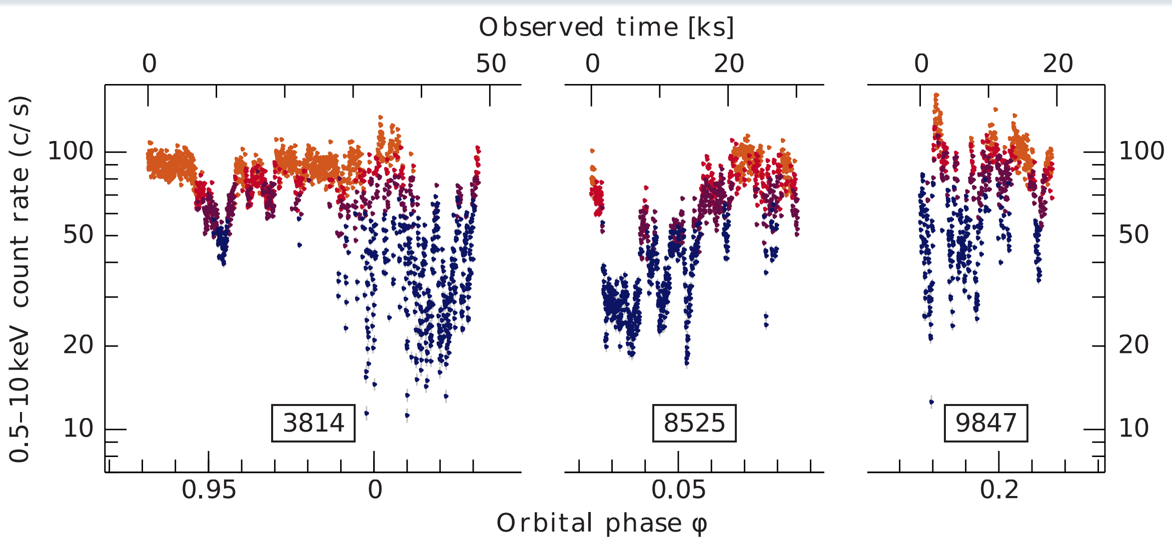
Black hole powered by accretion of focused wind



Modeled wind density

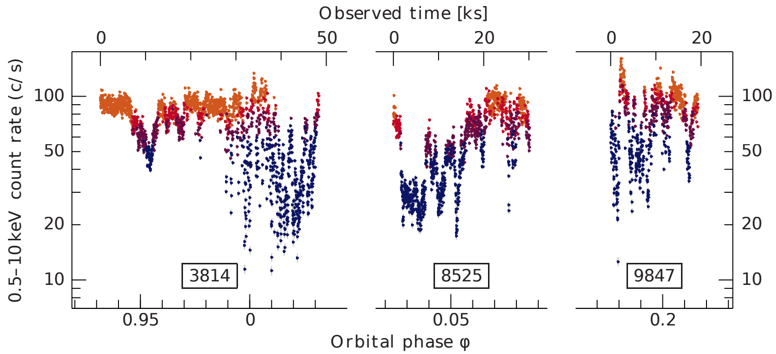


Dipping in *Chandra*-HETG lightcurves



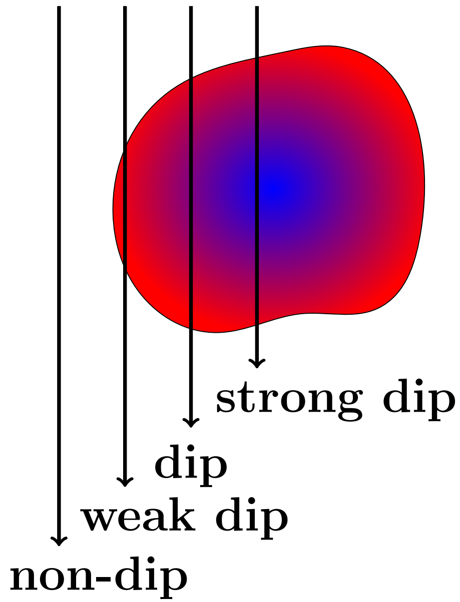
X-raying the clumpy wind

Dipping in the lightcurves



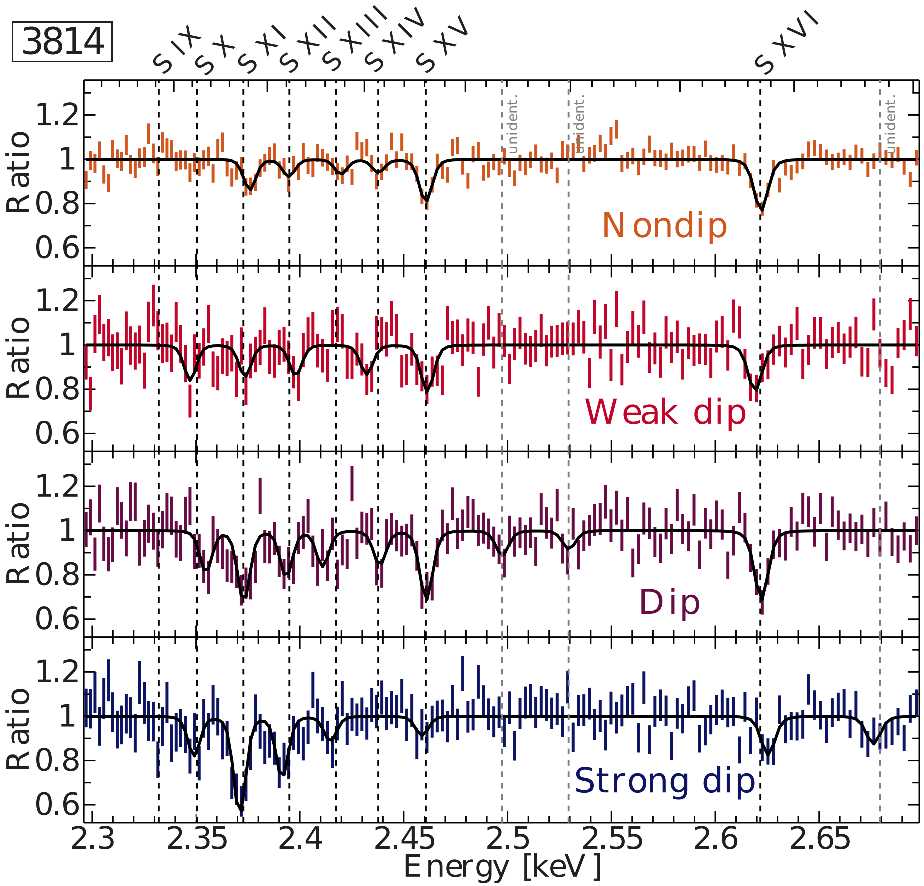
Dipping stages

clump passing line of sight:



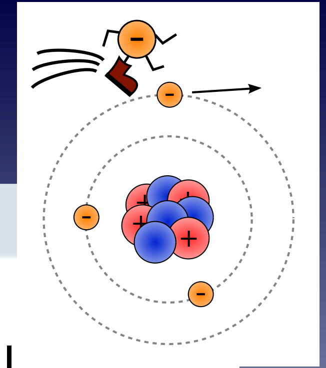
Dipping in the spectra

Chandra-HETG spectra, normalized to continuum model

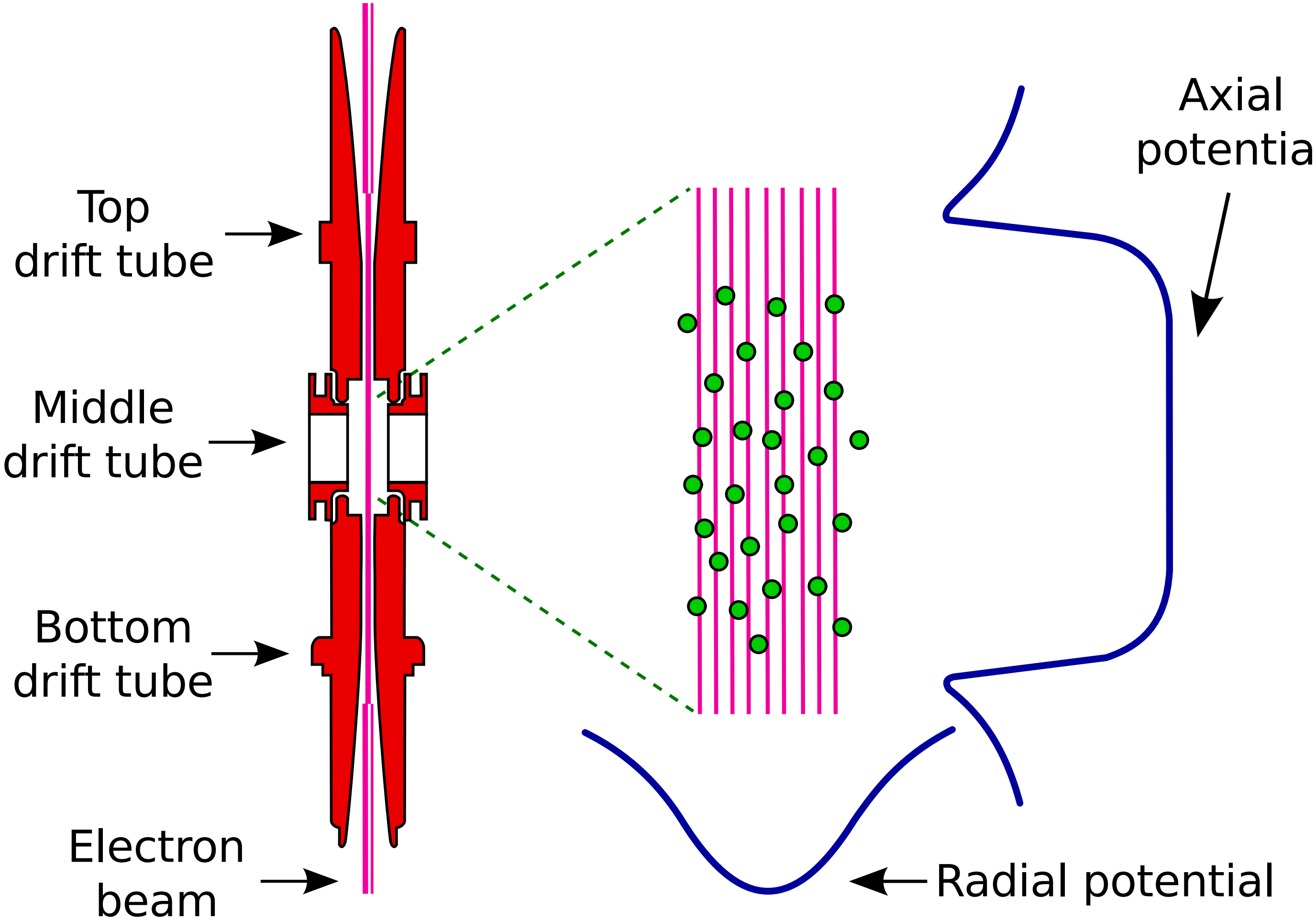


low charge states of S and Si

Measure K-shell emission with EBIT . . .

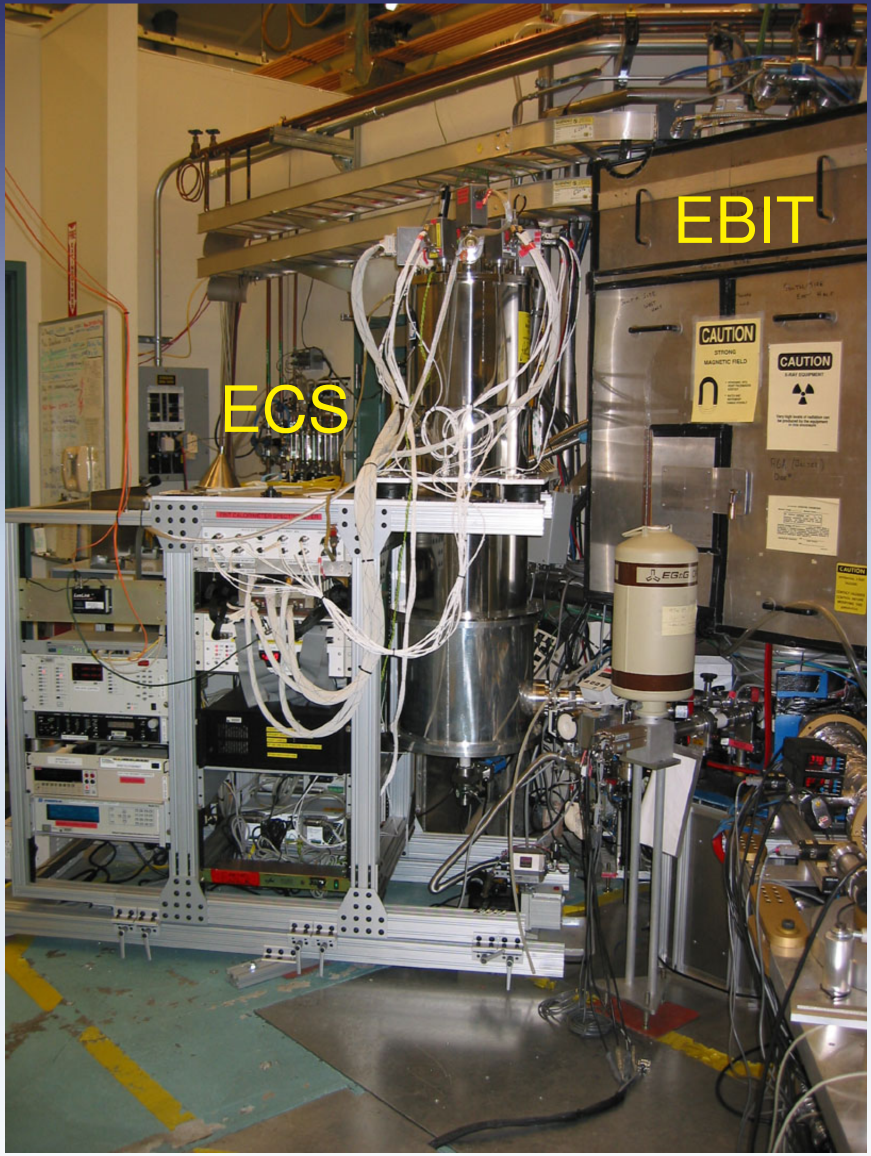


Electron Beam Ion Trap (EBIT-I)

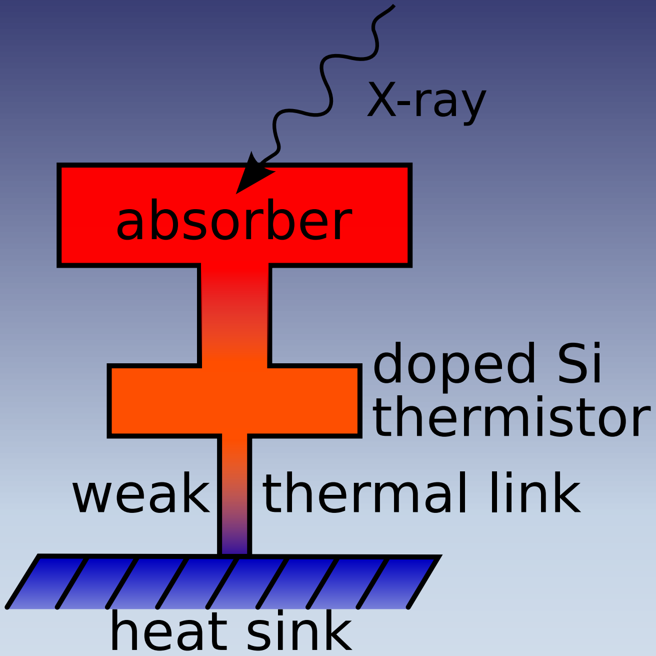


https://ebit.llnl.gov/overviewEBIT.html

... and the EBIT Calorimeter Spectrometer (ECS)



https://ebit.llnl.gov/EBITPhotoGallery.html



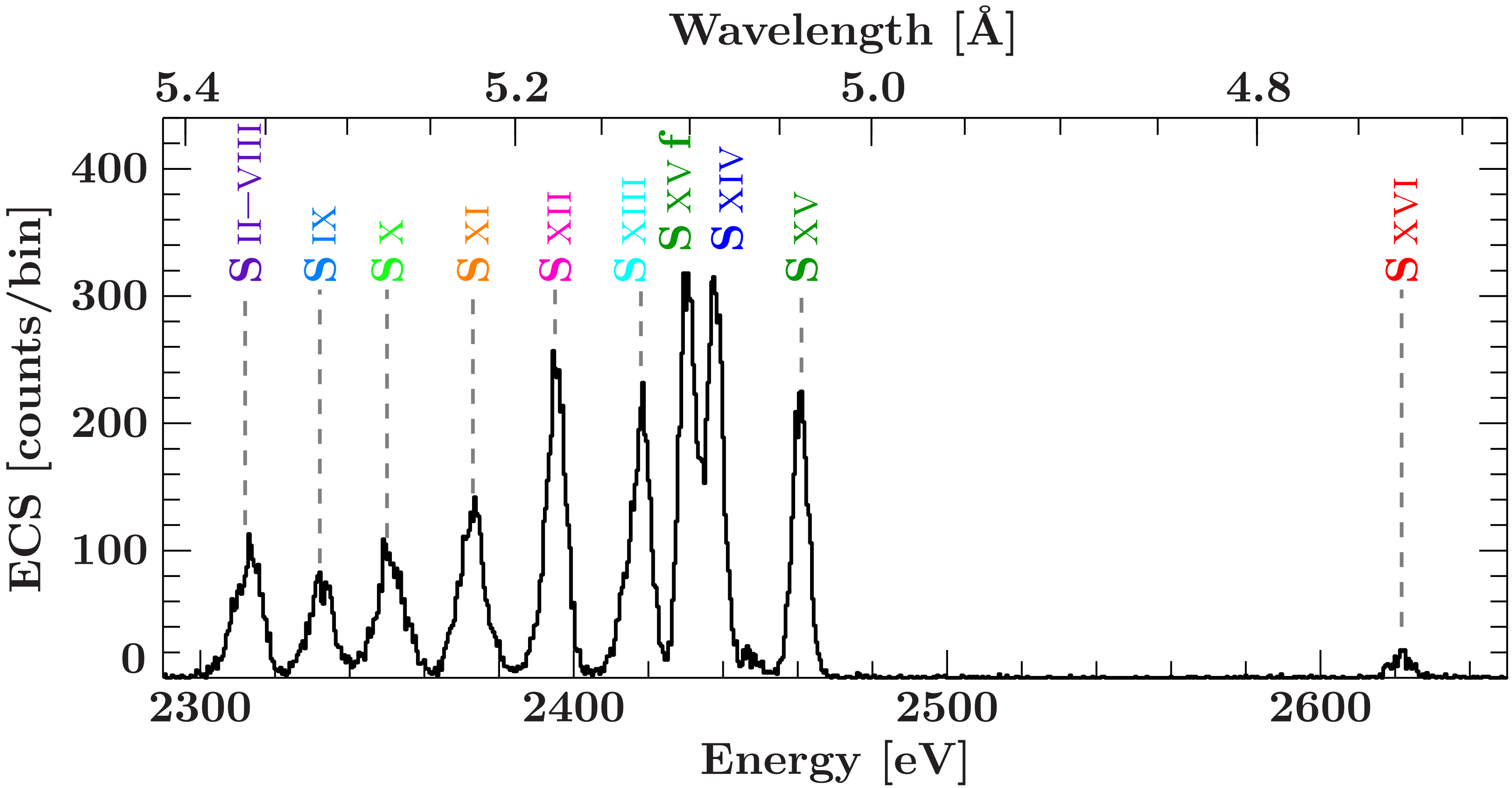
- operated at 50 mK
- 32 pixels (HgTe absorbers):
- 18 mid energy: 0.1-10 keV
  625 x 625 μm^2, 8 μm thick
- 14 high energy: 0.5-100 keV
  625 x 500 μm^2, 100 μm thick

Example: K-shell emission in Sulfur

Energy calibration:

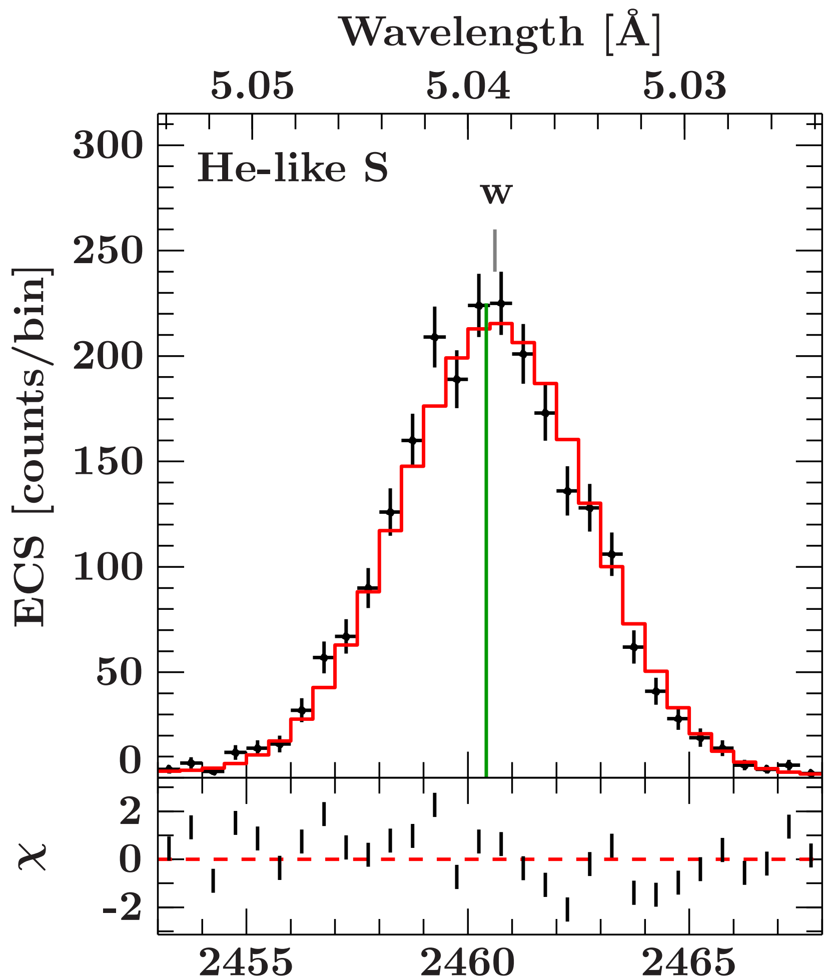
- calibrate pixels individually
- reference lines: Rydberg series of He-like and H-like ions

Spectrum: add calibrated pixels



Spectral resolution

assumption: resolution constant over observed energy range
$\Rightarrow$ determine through unblended line



He-like line w:

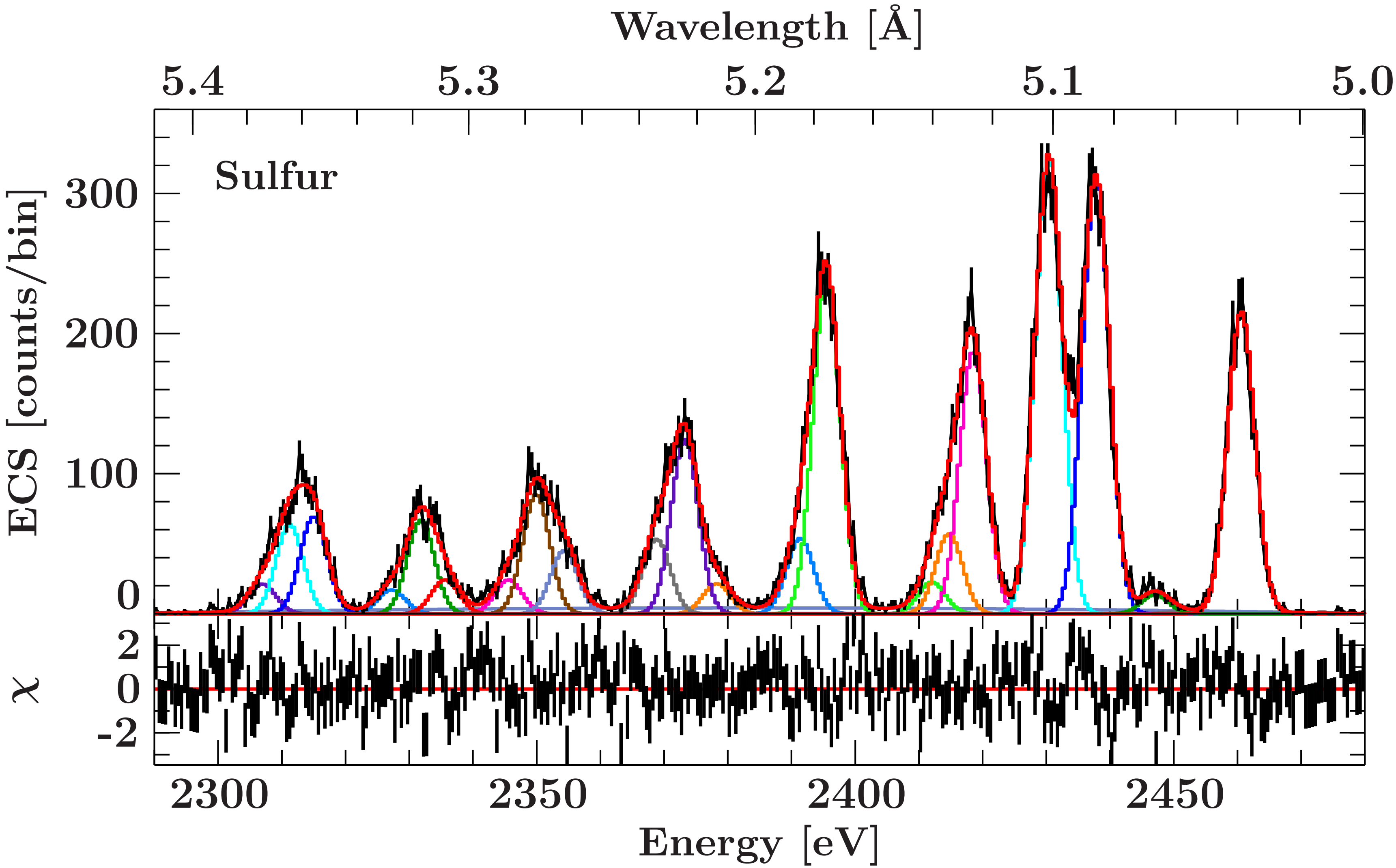
FWHM = 4.6 ± 0.1 eV

measured line center:
2460.61 ± 0.02 eV

reference line (Drake'88):
2460.626 eV

estimated systematic uncertainty from calibration:
0.1-0.2 eV

Resulting line distribution



Uncertainties: $< 0.5\,\mathrm{eV}$ (strong lines) – $< 1\,\mathrm{eV}$ (weak lines)

$\lesssim 100\,\mathrm{km\,s^{-1}}$

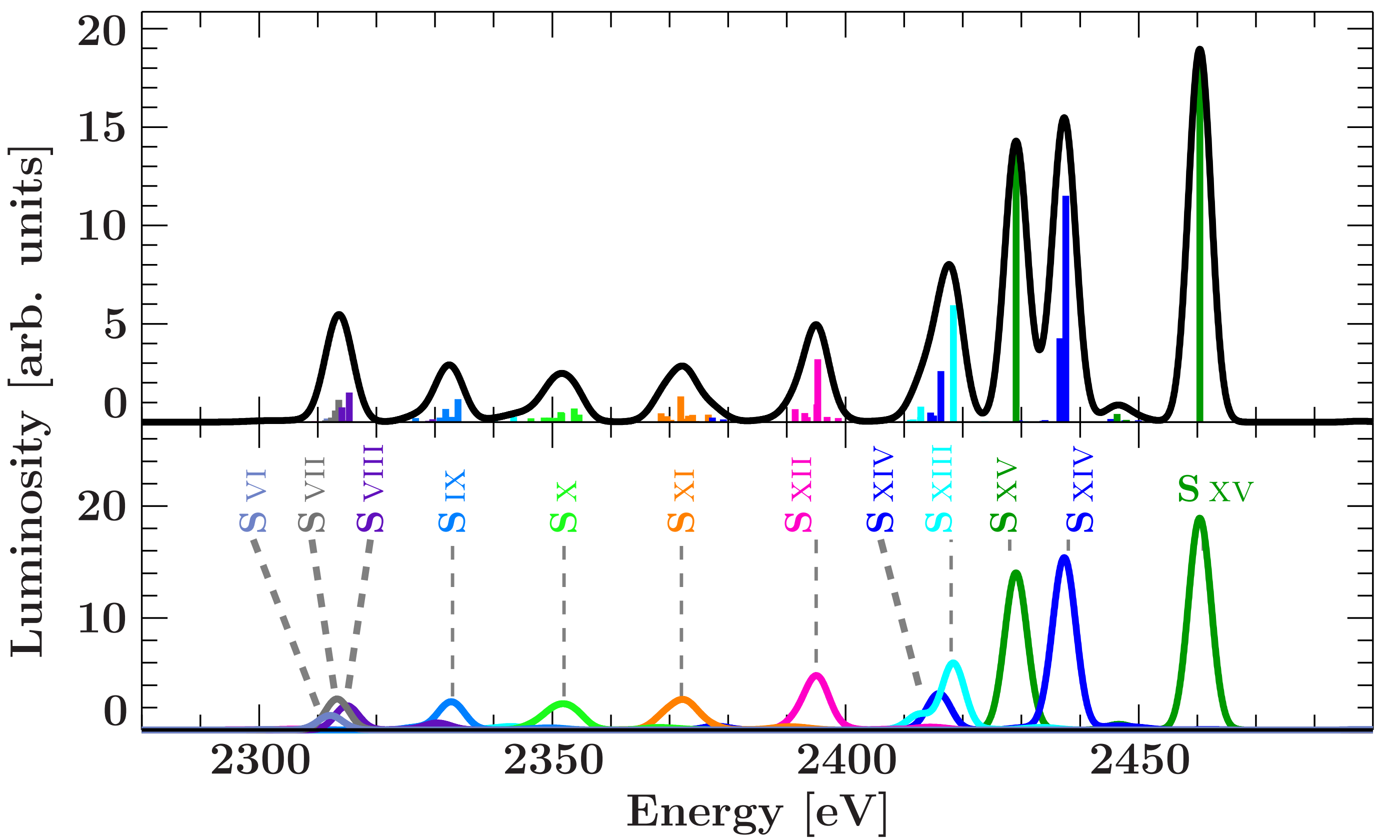
Theoretical Predictions for line identification

simulate spectra: Flexible Atomic Code (FAC; Gu 2004)

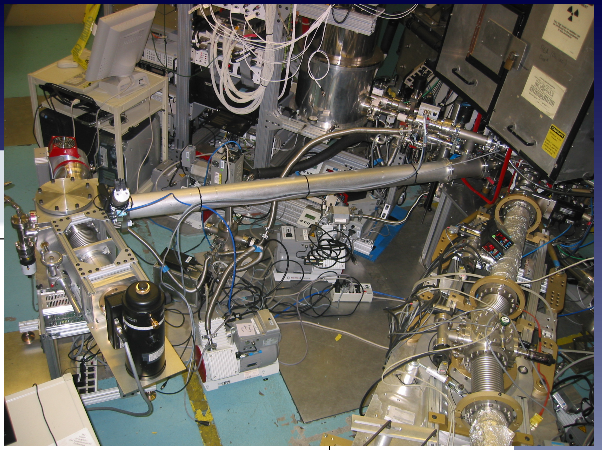
fully relativistic ansatz: $H = \sum_i H_\mathrm{D}(i) + \sum_{i<j} \frac{1}{r_{ij}}$

based on jj-coupling: $j_i = l_i + s_i \;\rightarrow\; J = \sum j_i$

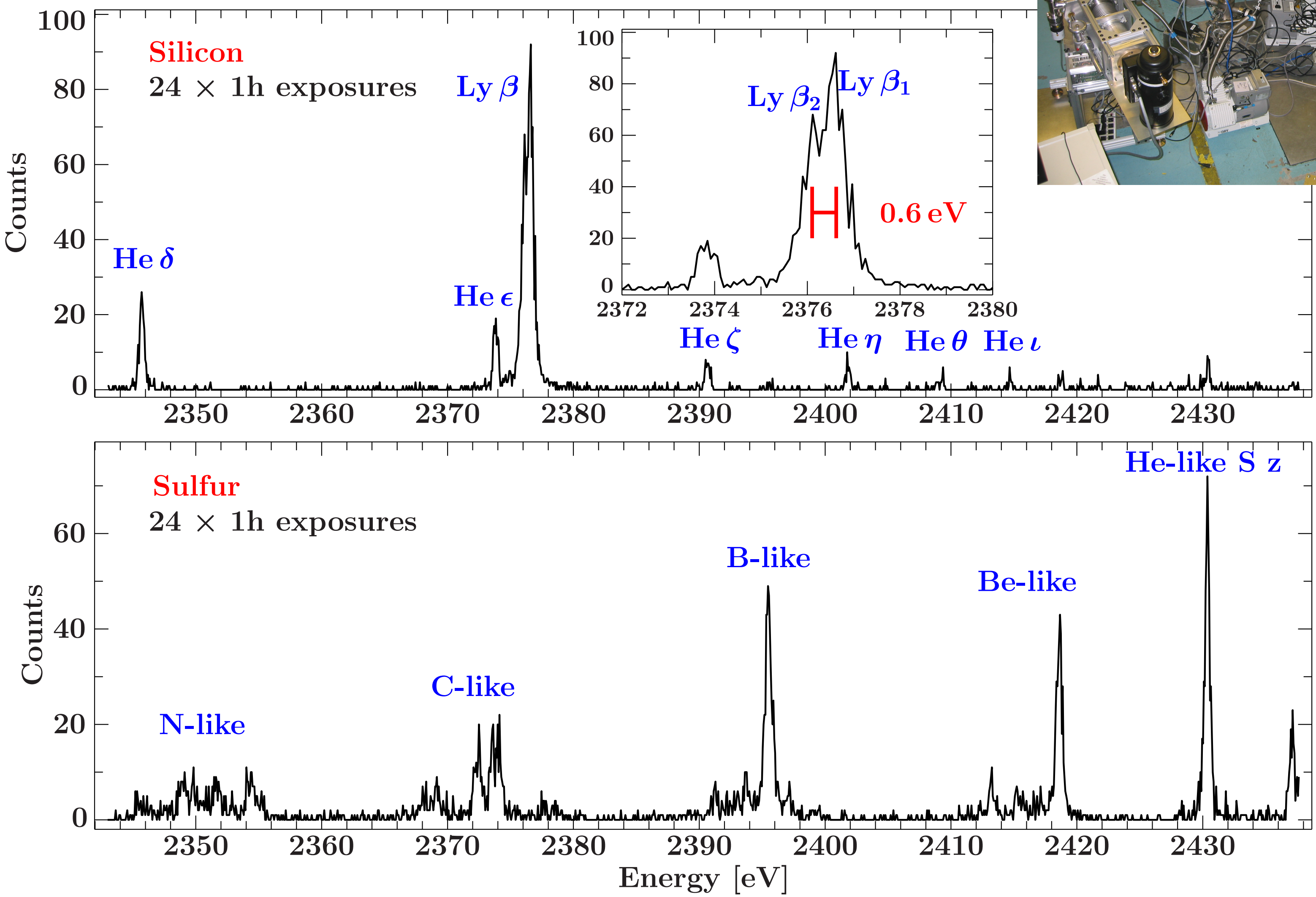
solve rate equations: $n_i \sum_{j\neq i} P_{ij} = \sum_{j\neq i} n_j P_{ji} \rightarrow 4\pi I_\nu = n_\mathrm{u} A_\mathrm{ul} \nu_\mathrm{ul}$



Confirmation of ECS results

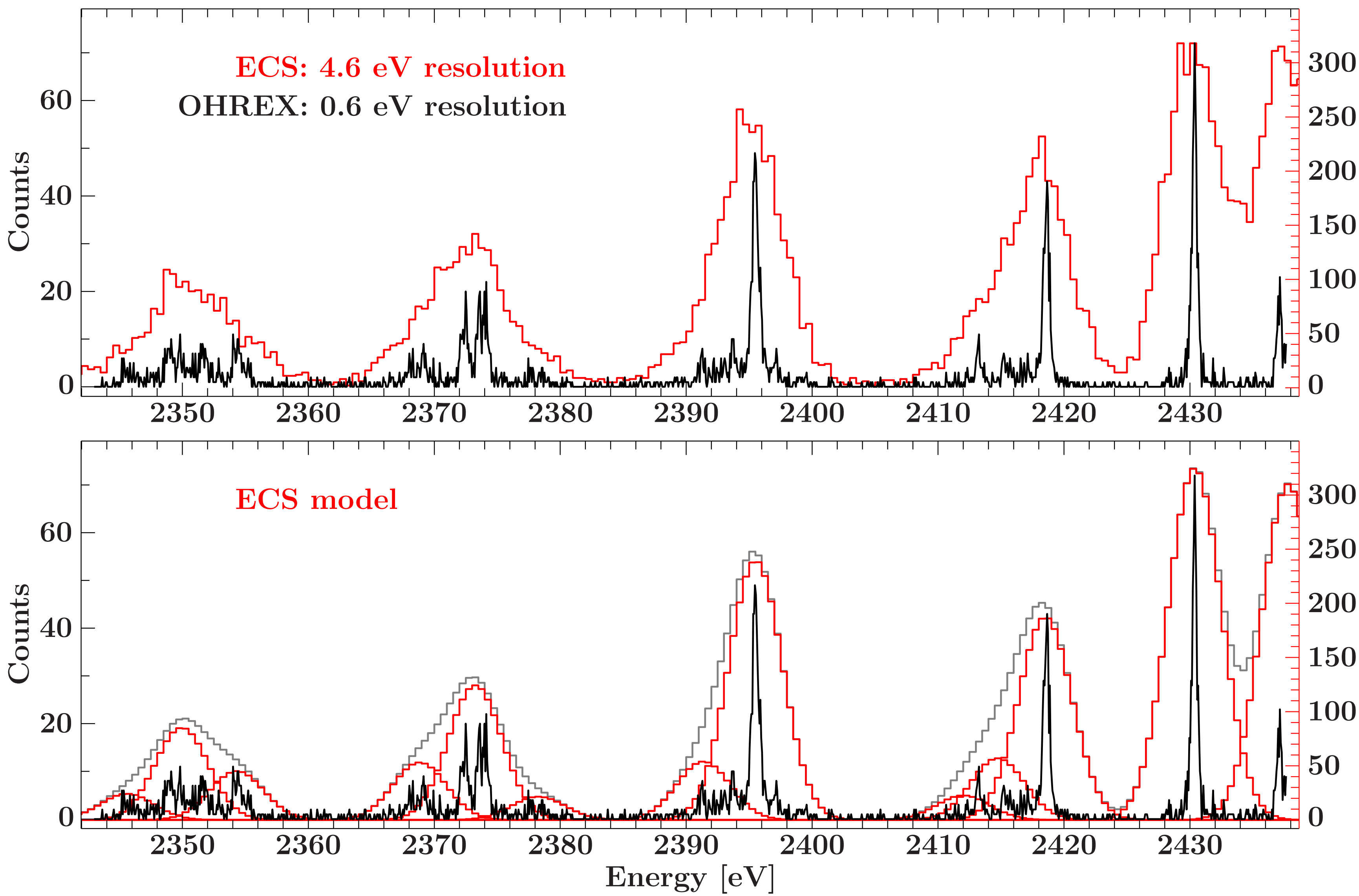


High-resolution crystal spectrometer:



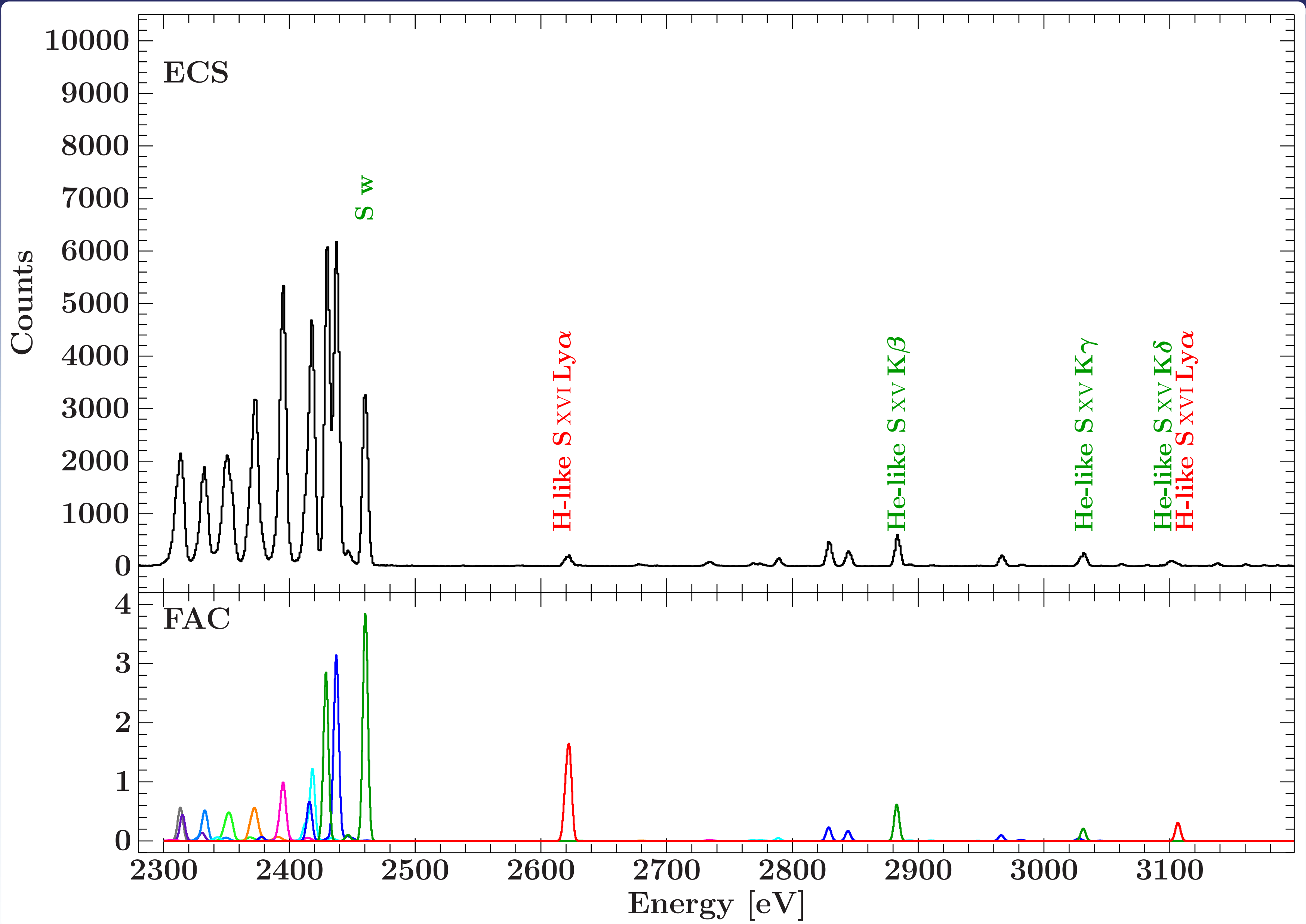
disadvantages: very slow; limited bandwidth

ECS vs crystal spectrometer

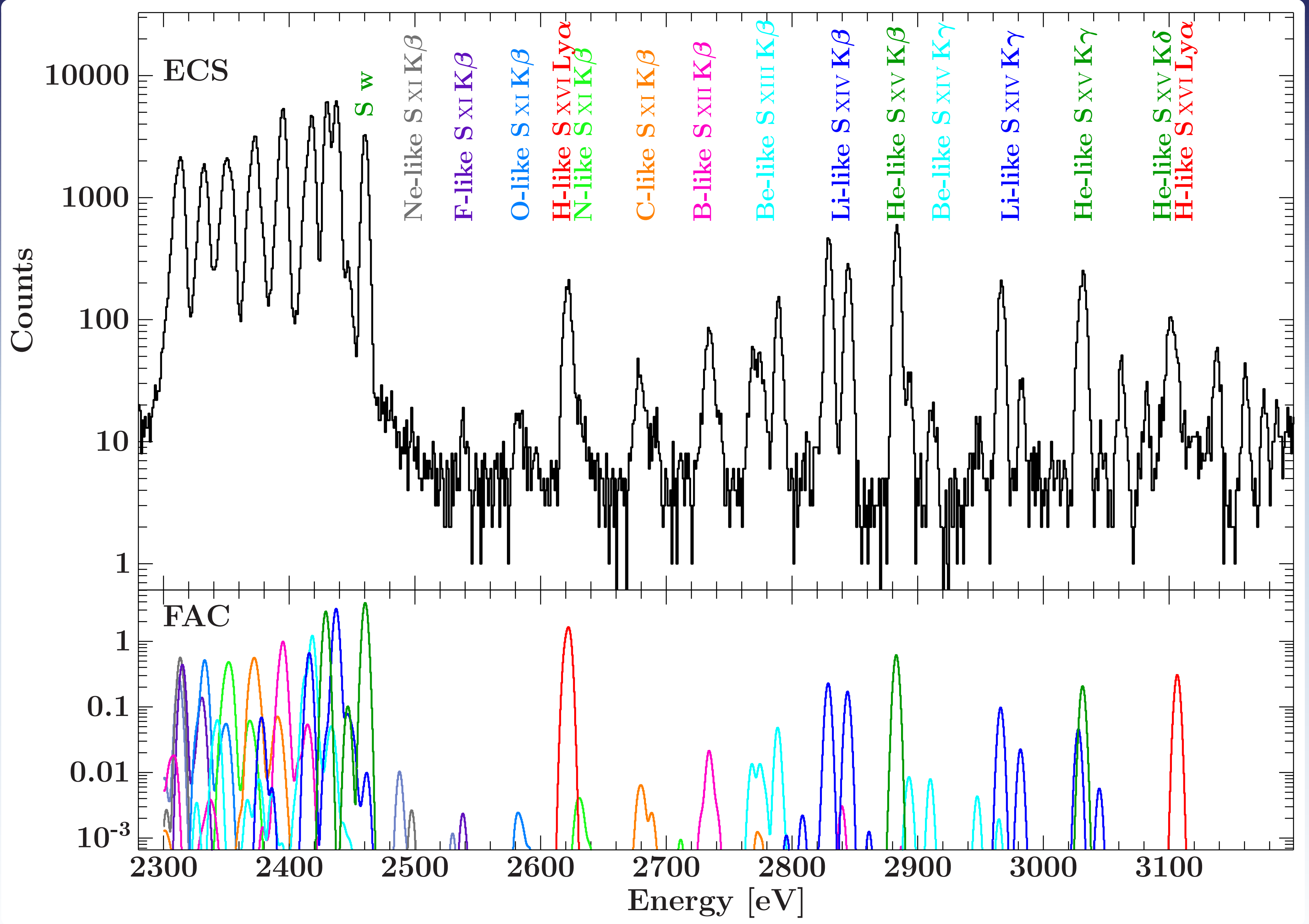


modeling of lower res. ECS data reproduces strong features

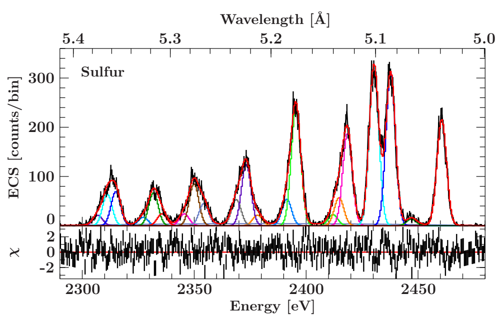
Sulfur Kβ of L-shell ions with the ECS



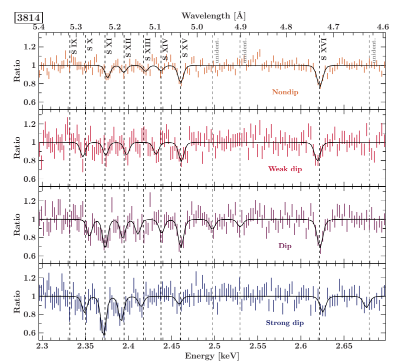
Sulfur Kβ of L-shell ions with the ECS



Back to Cyg X-1: Doppler Shifts



+

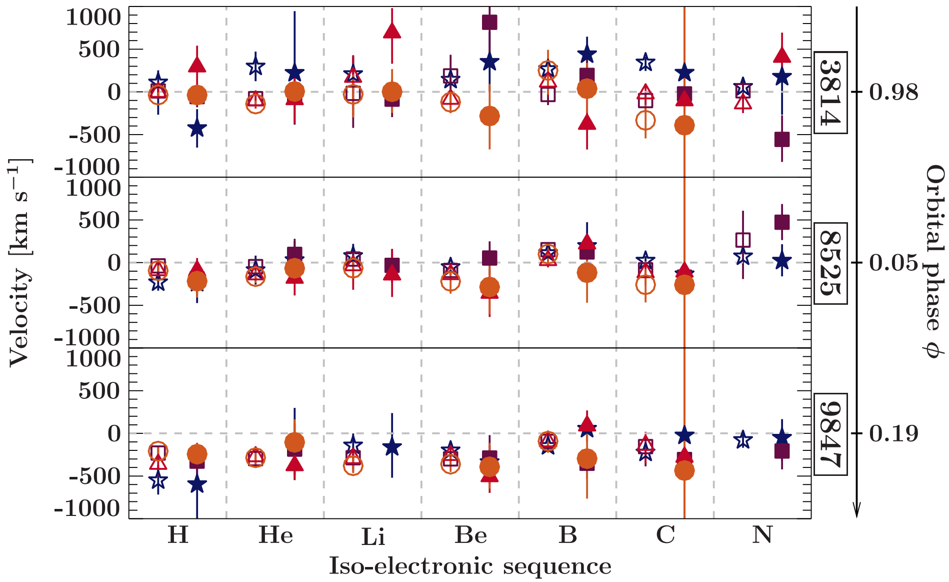


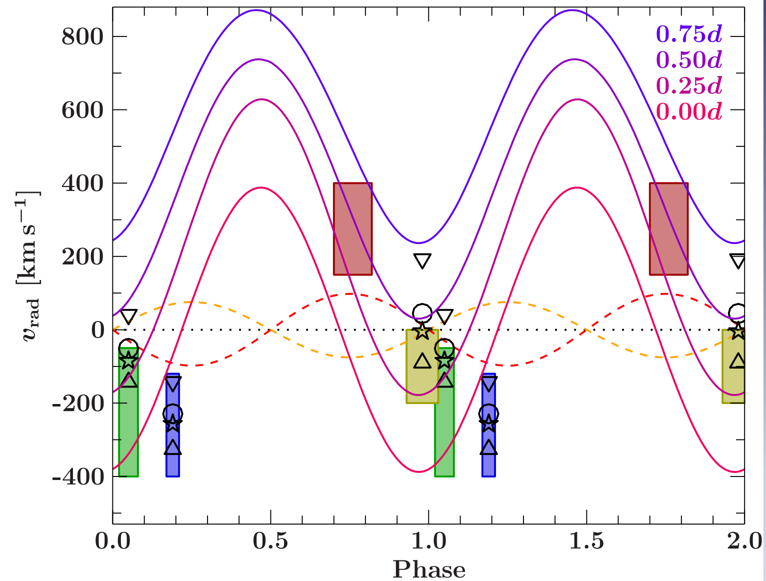
→

$$\frac{v}{c} \sim \frac{\Delta E}{E_{\mathrm{obs}}}$$

Back to Cyg X-1: Doppler Shifts

Doppler shifts by ion and orbital phase





● non-dip; ▲ weak dip; ■ dip; ★ strong dip
full: S; empty: Si

Keplerian velocities of star and BH
purple: projected wind velocity
d: binary distance
boxes: non-dip all lines
symbols: Si/S (mean / median / quartiles)

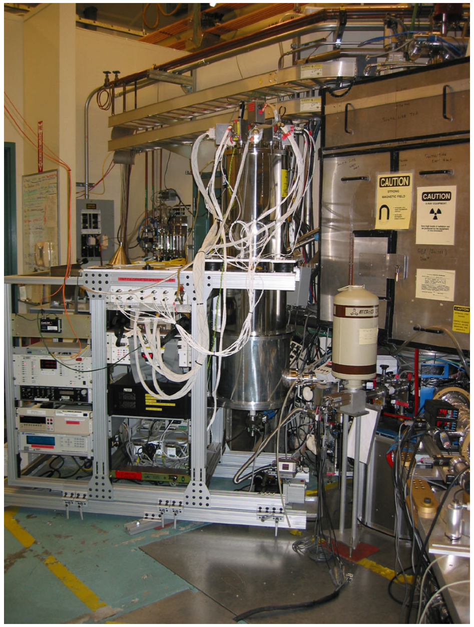
⇒ Doppler shifts consistent between dip stages

⇒ Doppler shifts consistent between ions

⇒ material close to black hole

Summary

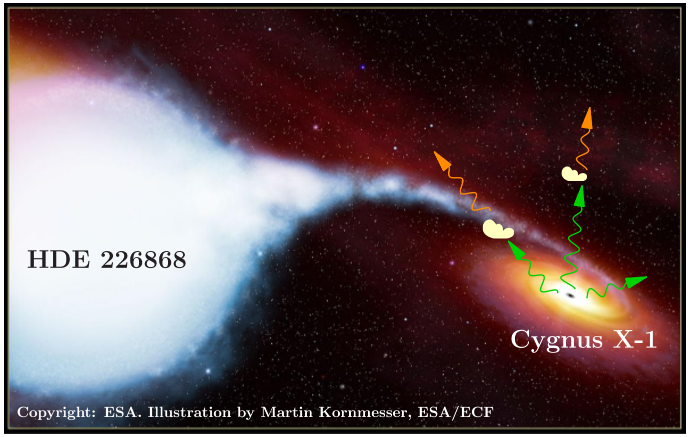
Lab: ECS @ EBIT



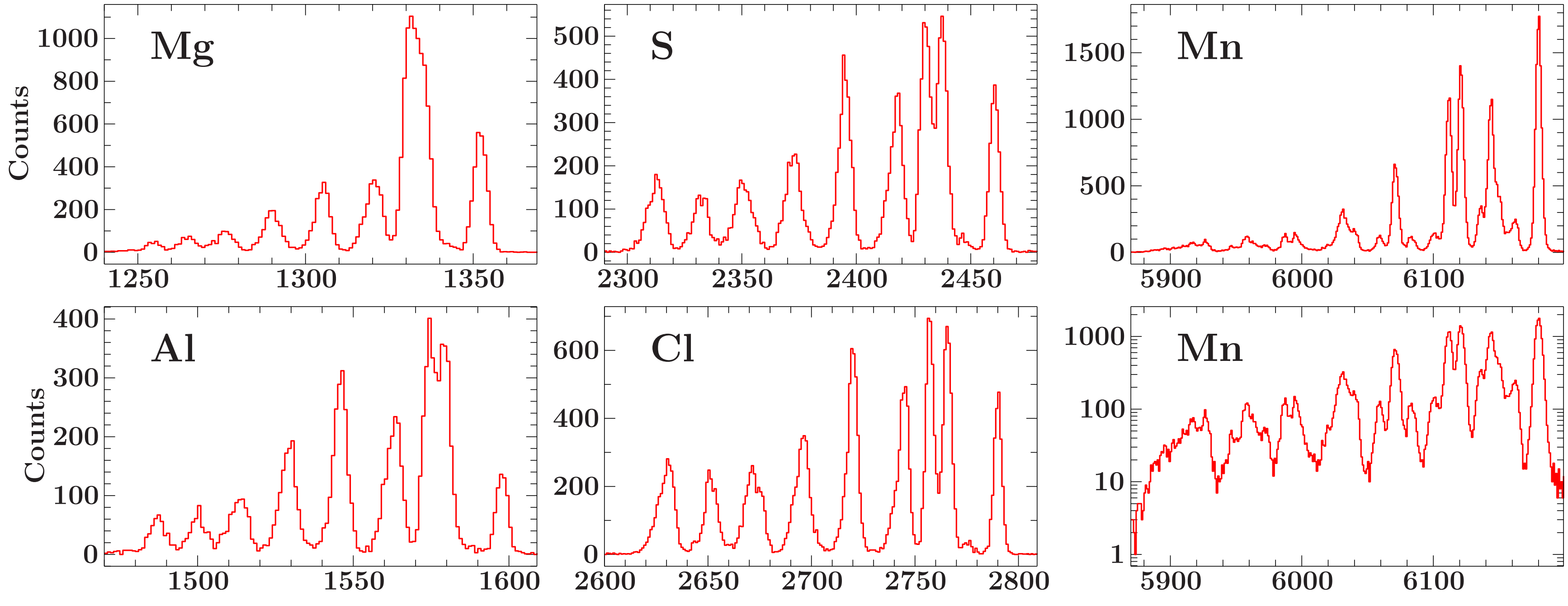
- measurements of transition energies: Si and S
- with calorimeter (ECS): resolution of 4.6 eV, comparable to *Astro-H* SXS
- uncertainties $\lesssim 100\,\mathrm{km\,s^{-1}}$, slightly better than with satellites
- high-res crystal data confirm lower-res ECS results

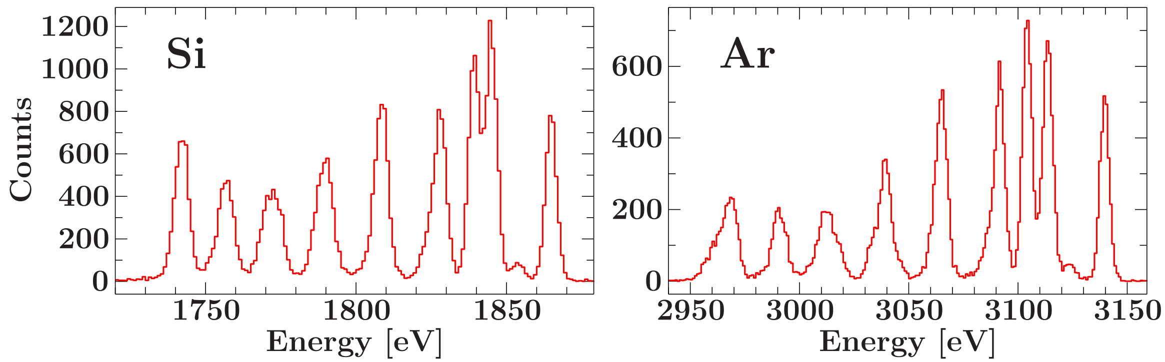
Astro: *Chandra*/HETG @ Cyg X-1

- Doppler shifts consistent between ions and dipping stages
- clumps show ionization structure
- observed material close to BH



ECS measurements across the periodic table





- more elements
- cover range Mg – Ni