High-Resolution X-Ray Spectroscopy

AHEAD meeting February 2022

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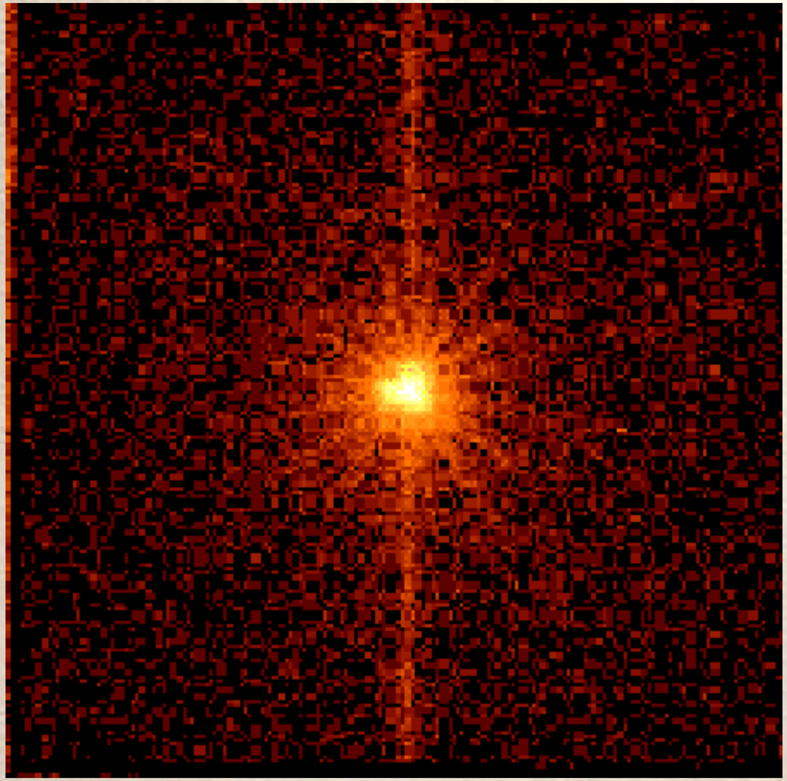
X-Ray Spectroscopy Outline

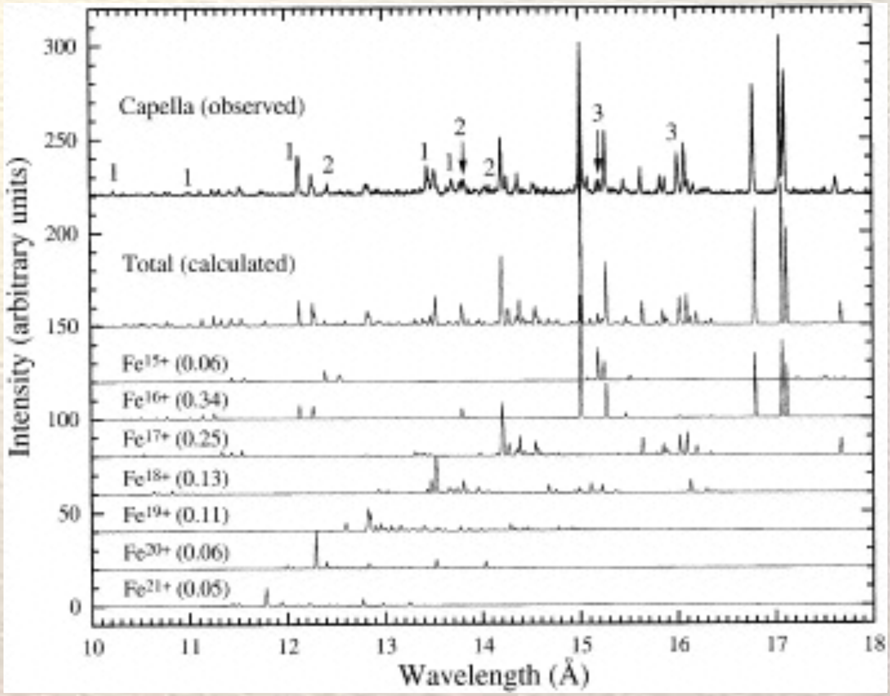
- Introduction - The Power of Spectroscopy
  - Between Gratings, Calorimeters, and Laboratory Astrophysics
- Inner-shell photo-processes
  - Ionization Distributions in AGN Outflows
- Cold gas in hot, shocked plasma
  - Radiative recombination around shocks
- What drives the line emission in X-ray binaries?
  - The need for resolution and timing

~~A Picture is Worth a Thousand Words?~~

A Spectrum is Worth Thousand Pictures



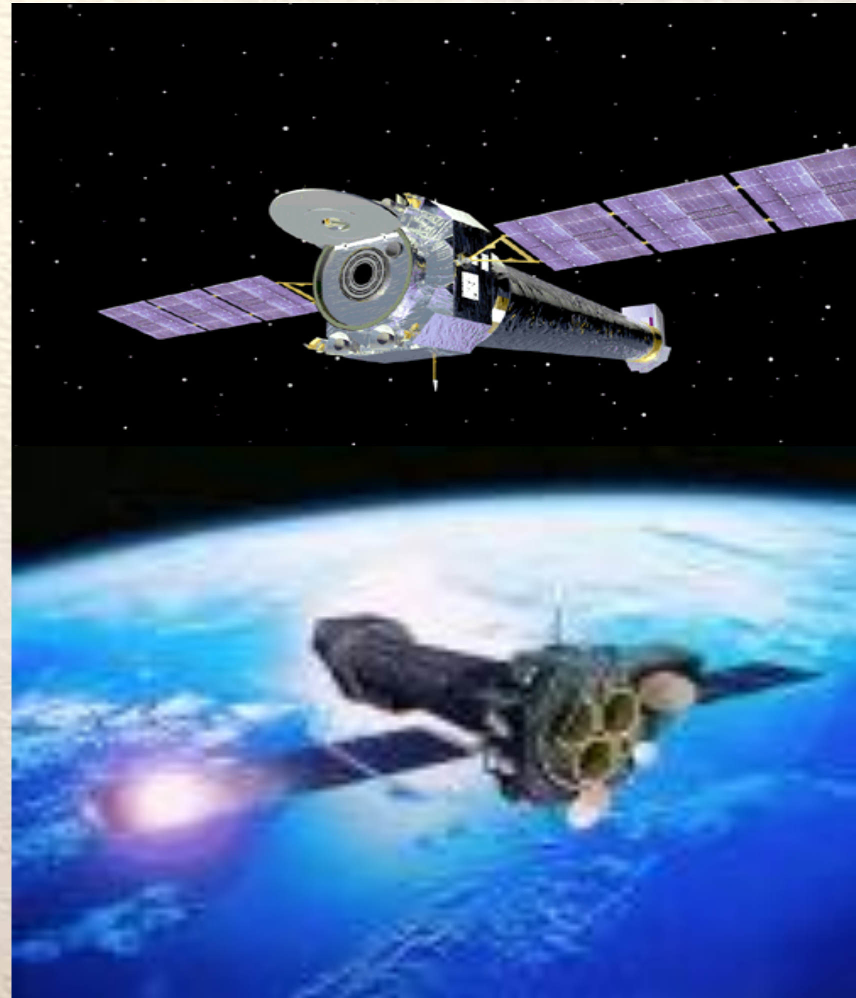
vs.



Spectroscopic Methods
Diagnostics of the Physics

- Continuum vs. Lines
- Emission vs. Absorption
- Line Flux Ratios:
  - Plasma Ionization
  - Temperature
  - Density
  - UV Field (location)
  - Column Density (location)
  - Elemental Abundances
  - Volume, Mass
- Line Shifts:
  - Velocity
  - Gravity
- Line Shapes:
  - Velocity Distribution (e.g., temperature)
  - Pressure
  - EM Fields
  - Relativistic Effects

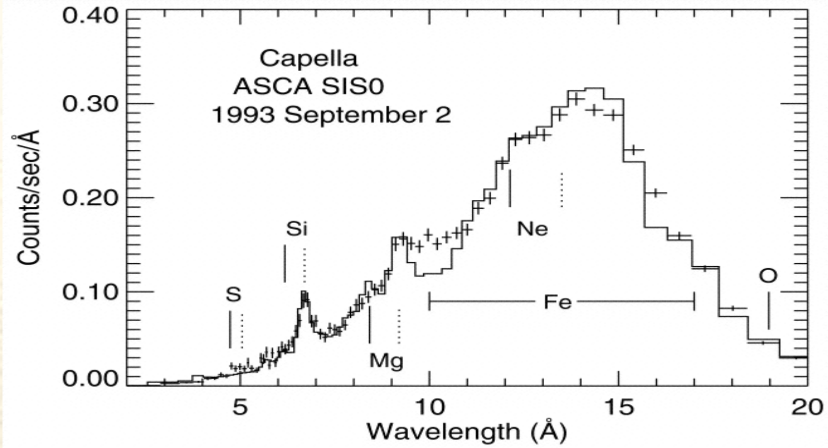
X-Ray Observatories (Work-Horses) Chandra and XMM-Newton



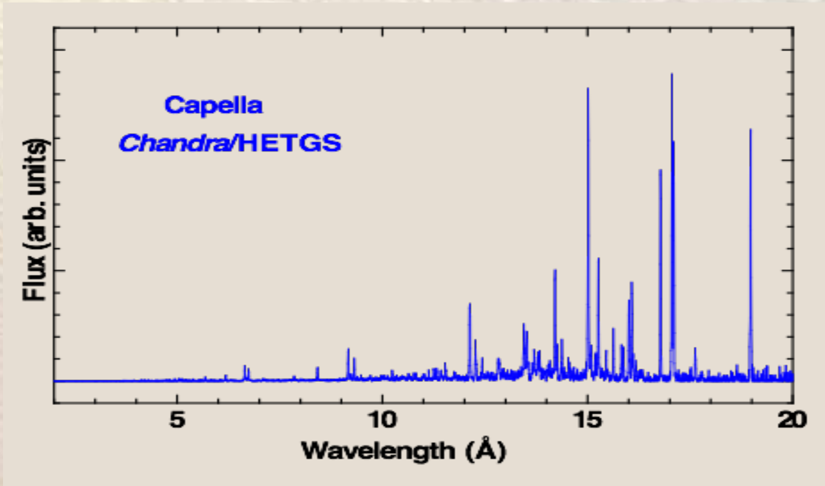
- **The Chandra Observatory (NASA):**
  - superb telescope (0.5")
  - 2 transmission grating spectrometers ($R=\lambda/\Delta\lambda$ up to 1000)
- **XMM-Newton (ESA):**
  - 3 telescopes (eff. area = 4,300 cm^2)
  - 2 reflection grating spectrometers
  - 1 Optical/UV monitor

The Difference that High Spectral Resolution Makes

- CCD spectrum of Capella with ASCA



- Grating spectrum of Capella with Chandra/HETG



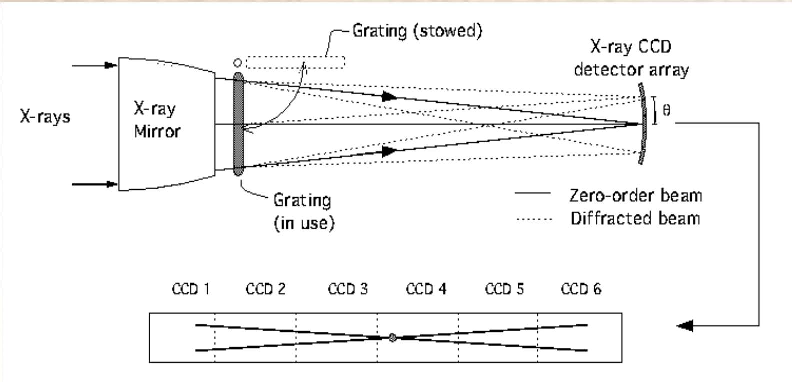
Slitless X-Ray Grating Spectrometers

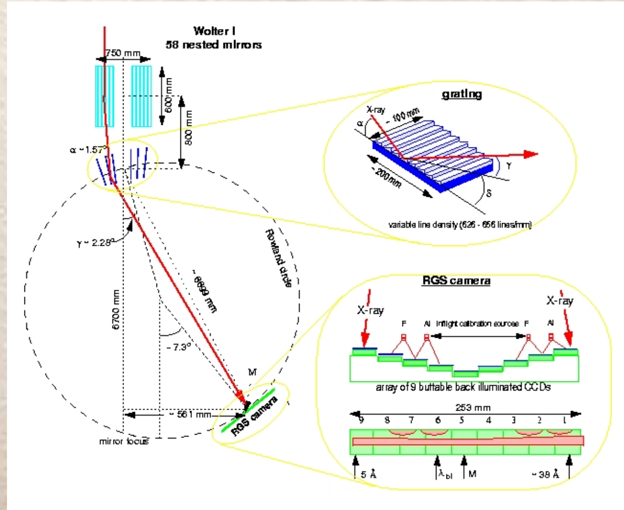
- **Transmission**
- d (Sinβ + Sinα) = **m**λ
- dλ/dβ = d Cosβ ~ d
  dβ/dλ ~ 1/d

- **Reflection**
- d (Cosβ - Cosα) = **m**λ
- dλ/dβ = d Sinβ << d
  dβ/dλ >> 1/d

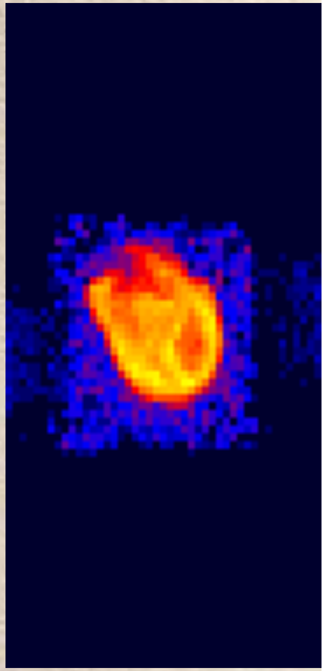
For point source δλ linear in δβ => **Δλ independent of** λ

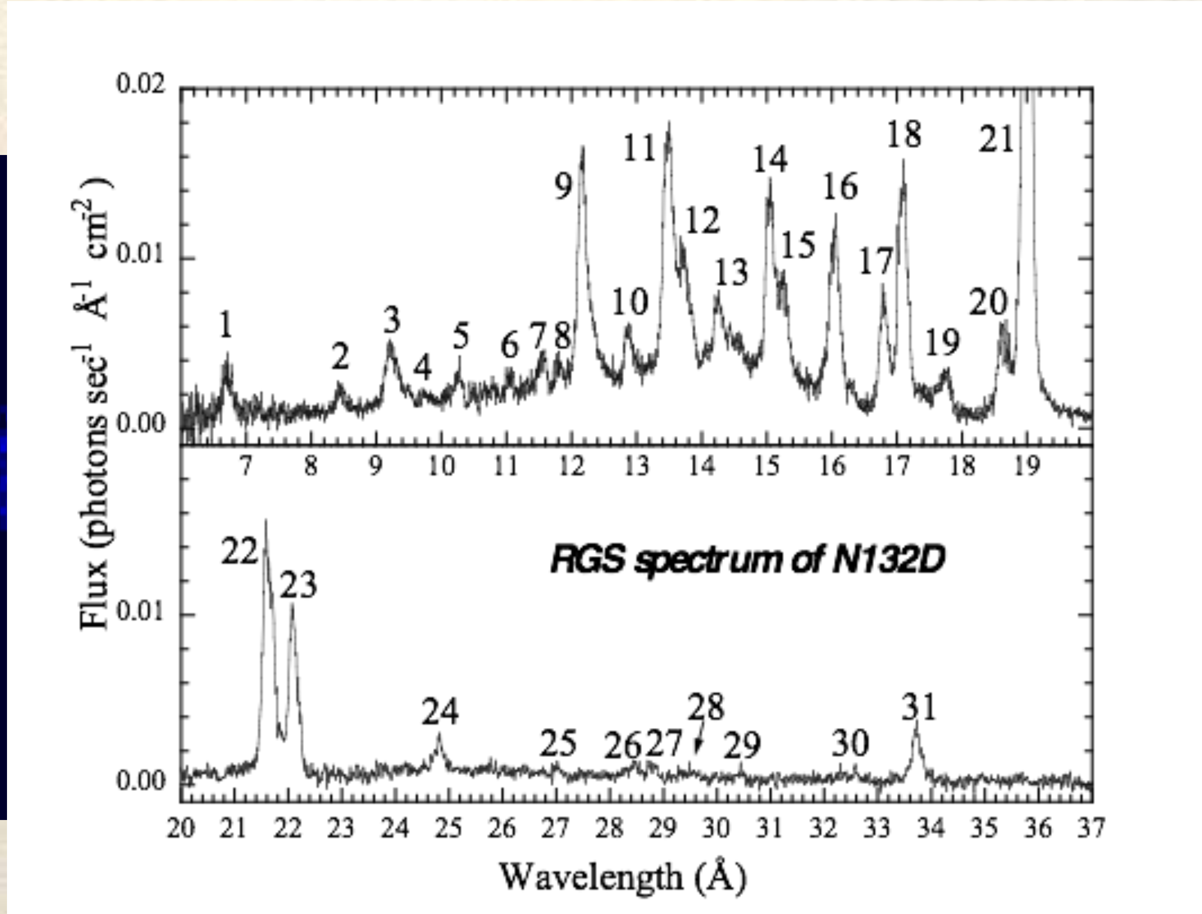
For extended sources reflection much better

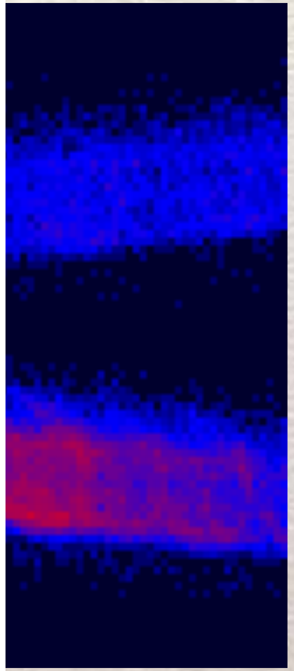




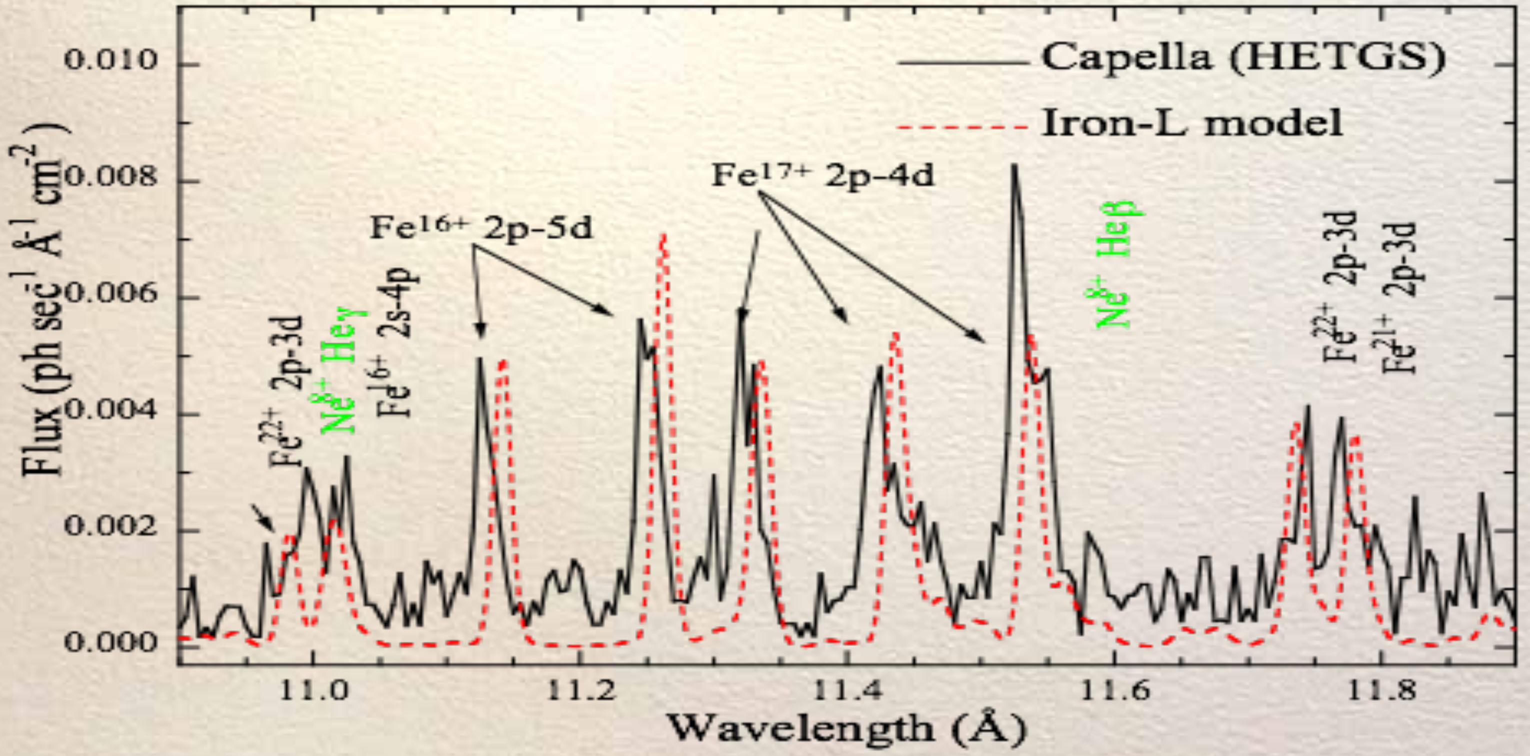
Slitless Spectrometer:
The Challenge of Extended Sources



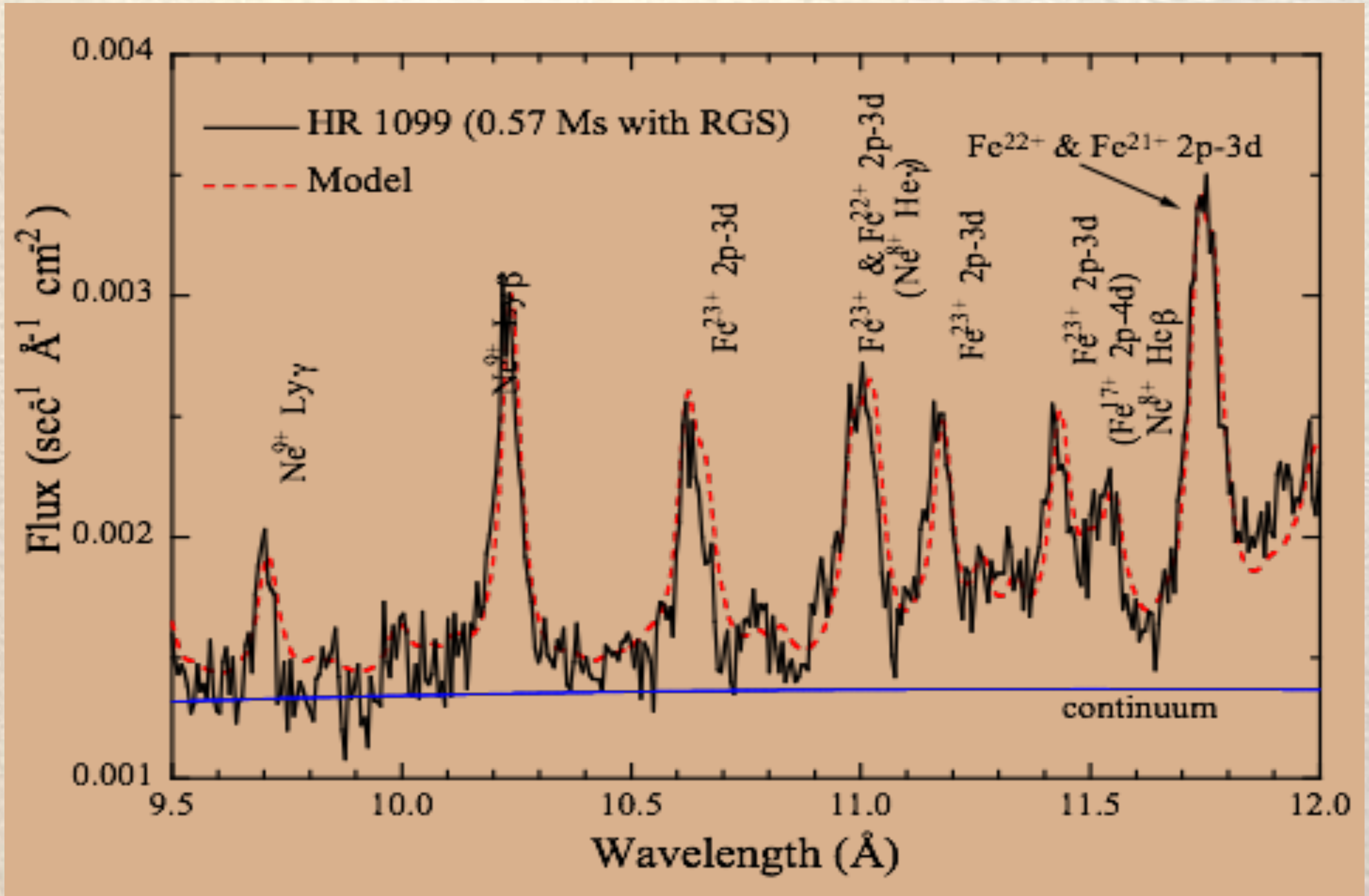




How Good are the Atomic Data?

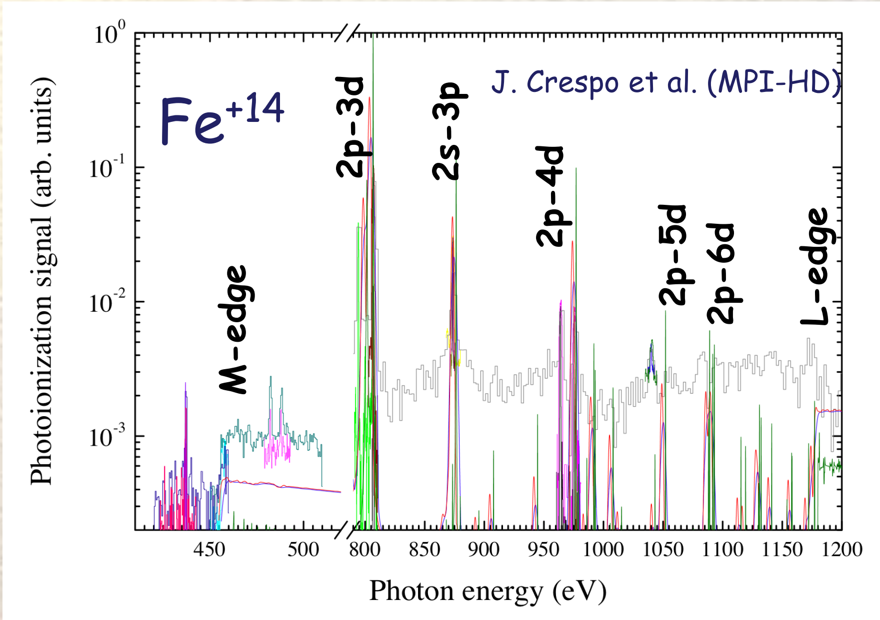


Correcting Computed Wavelengths with Laboratory Atomic Data

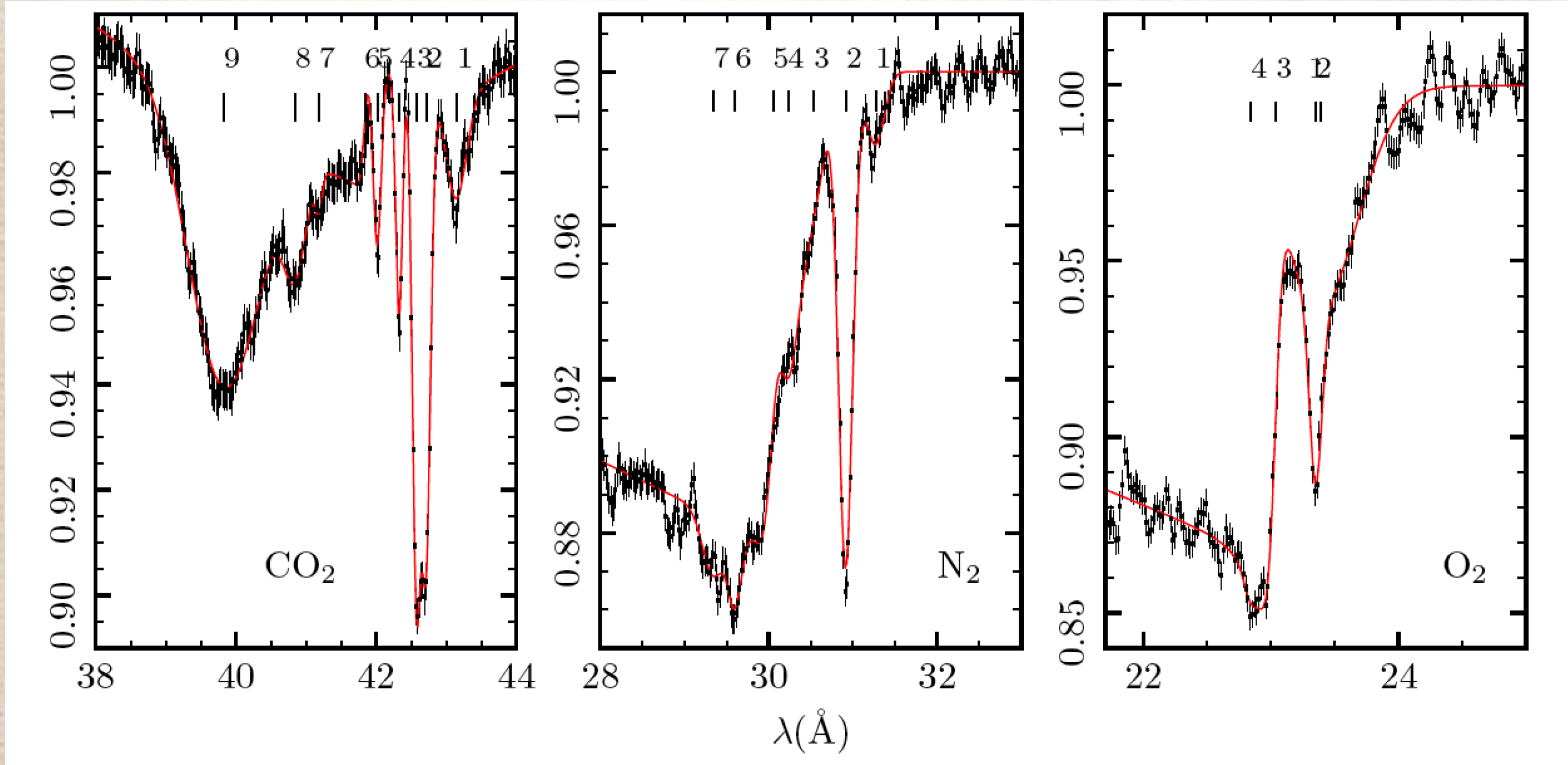


Laboratory Astrophysics with EBIT

- Electron Beam Ion Trap
- Use calorimeter (LLNL)
- Combine with synchrotron Source (MPI-Heidelberg) for photo-processes
- Energy precision as high as $E/\Delta E = 6000$
- Measure photo-ionization by analyzing ions dumped from trap



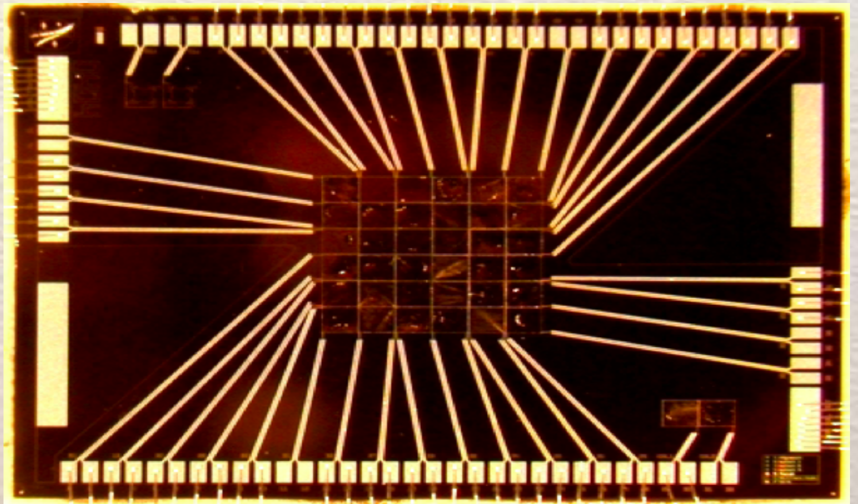
Laboratory Astrophysics
X-Ray Absorption by Molecules



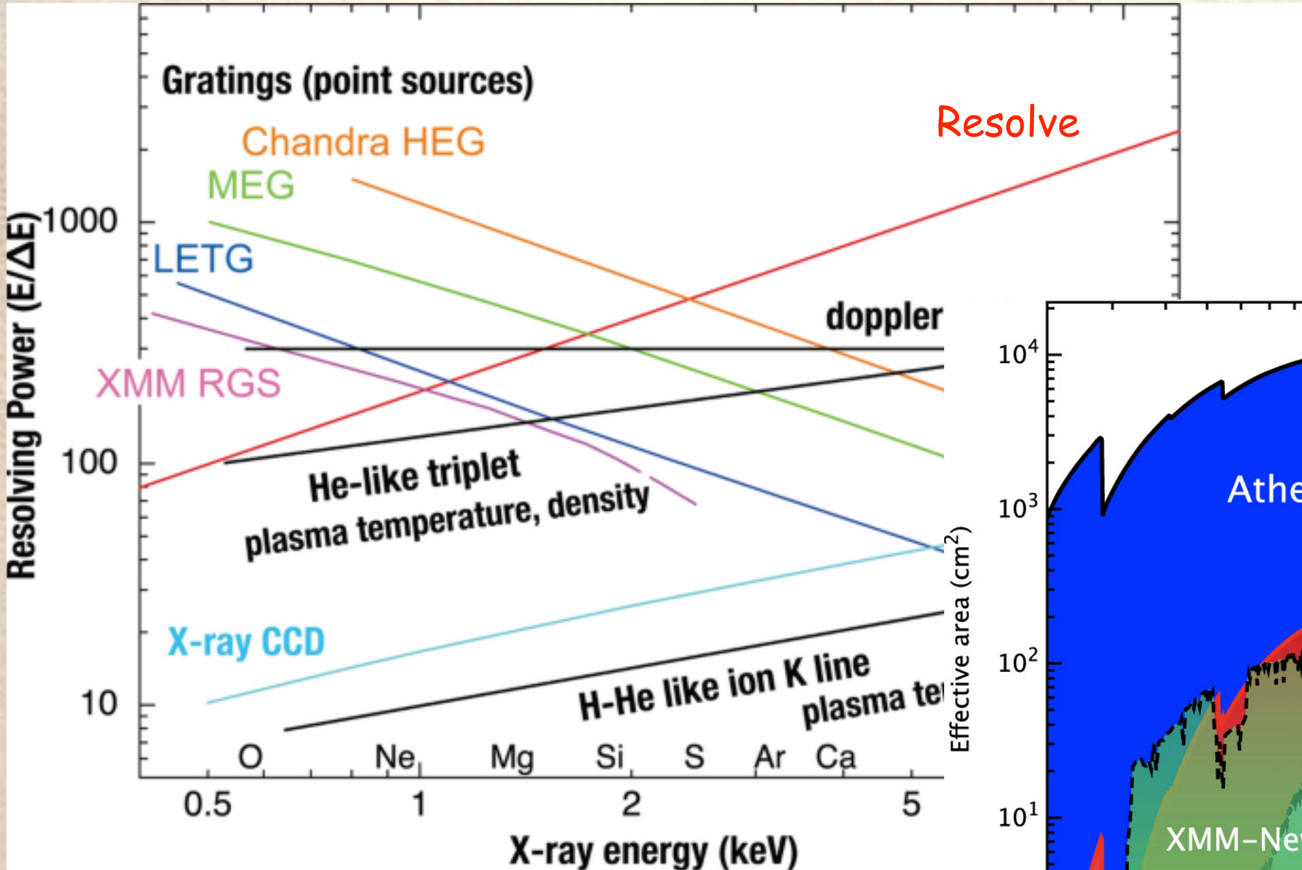
Gissis et al. '21

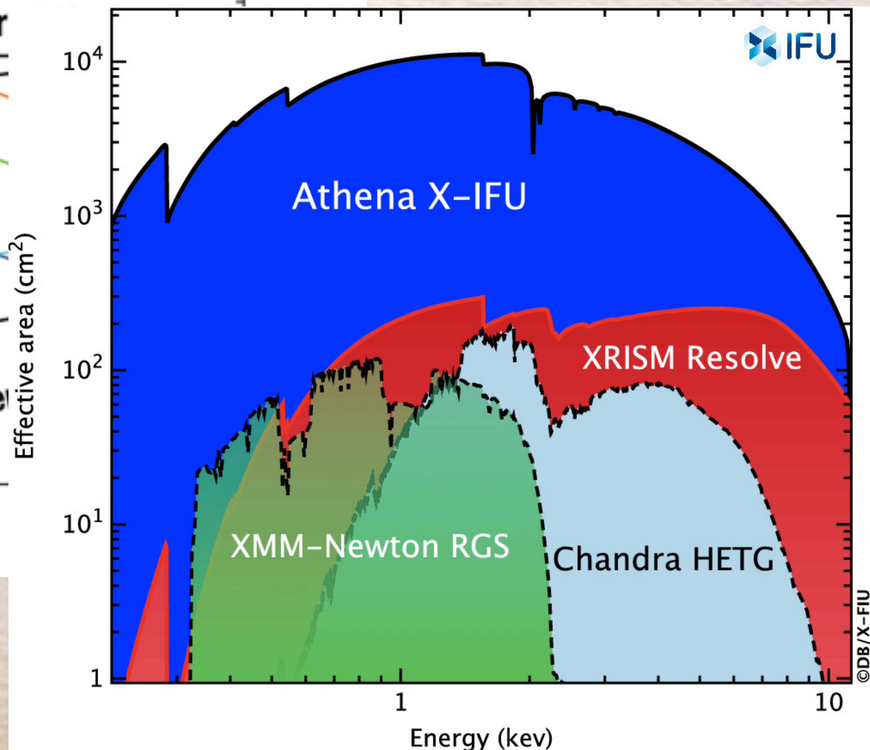
Future Missions: XRISM

- JAXA + NASA collaboration, projected launch Feb. 2023
- Spectroscopy mission with superconducting micro-calorimeter (Resolve) as the main science instrument
- Naturally provides **spatially resolved spectra**
- Fixed ΔE, resolving power increases with E



Calorimeter Superior Resolving Power & High Throughput





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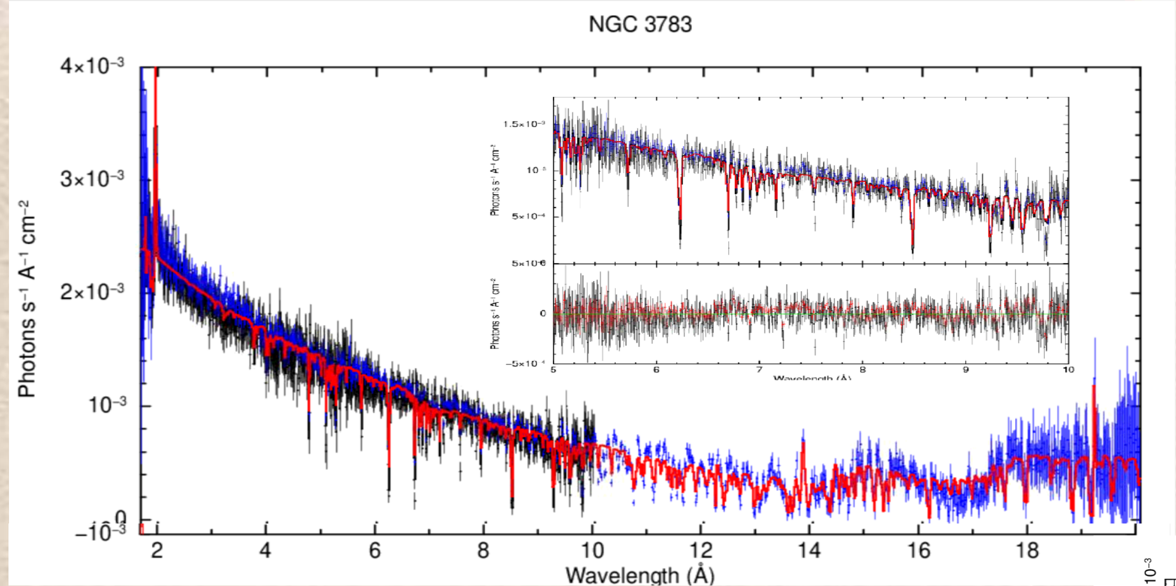
Inner-shell Processes

Important for Absorption Spectra of AGN and WHIM



Chandra/HETG

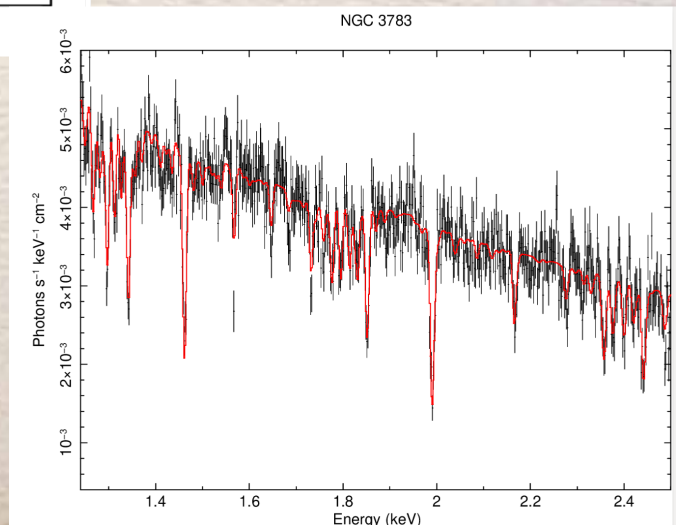
900 ks

Keshet & Behar '22

XRISM/Resolve

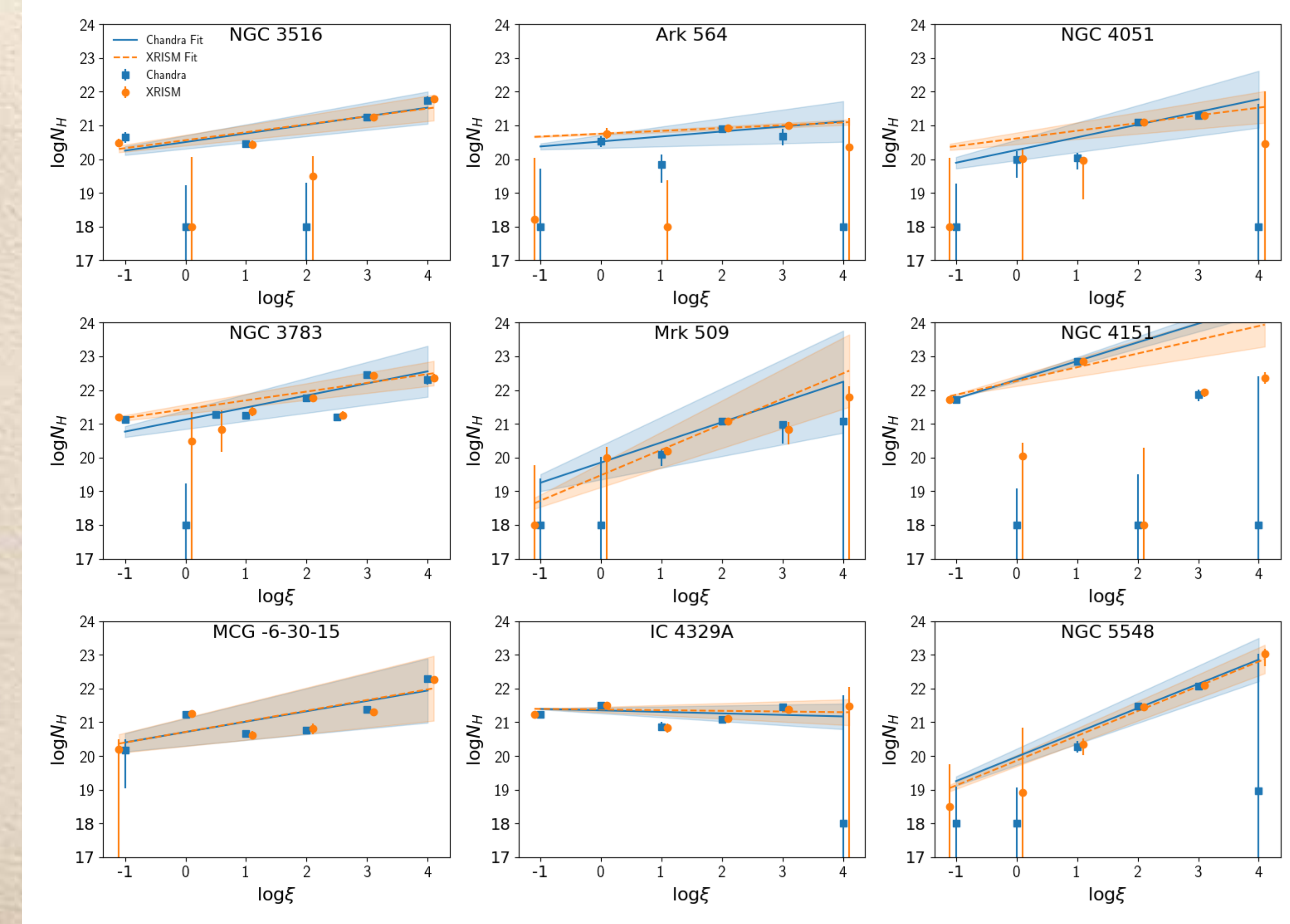
(simulated)

100 ks



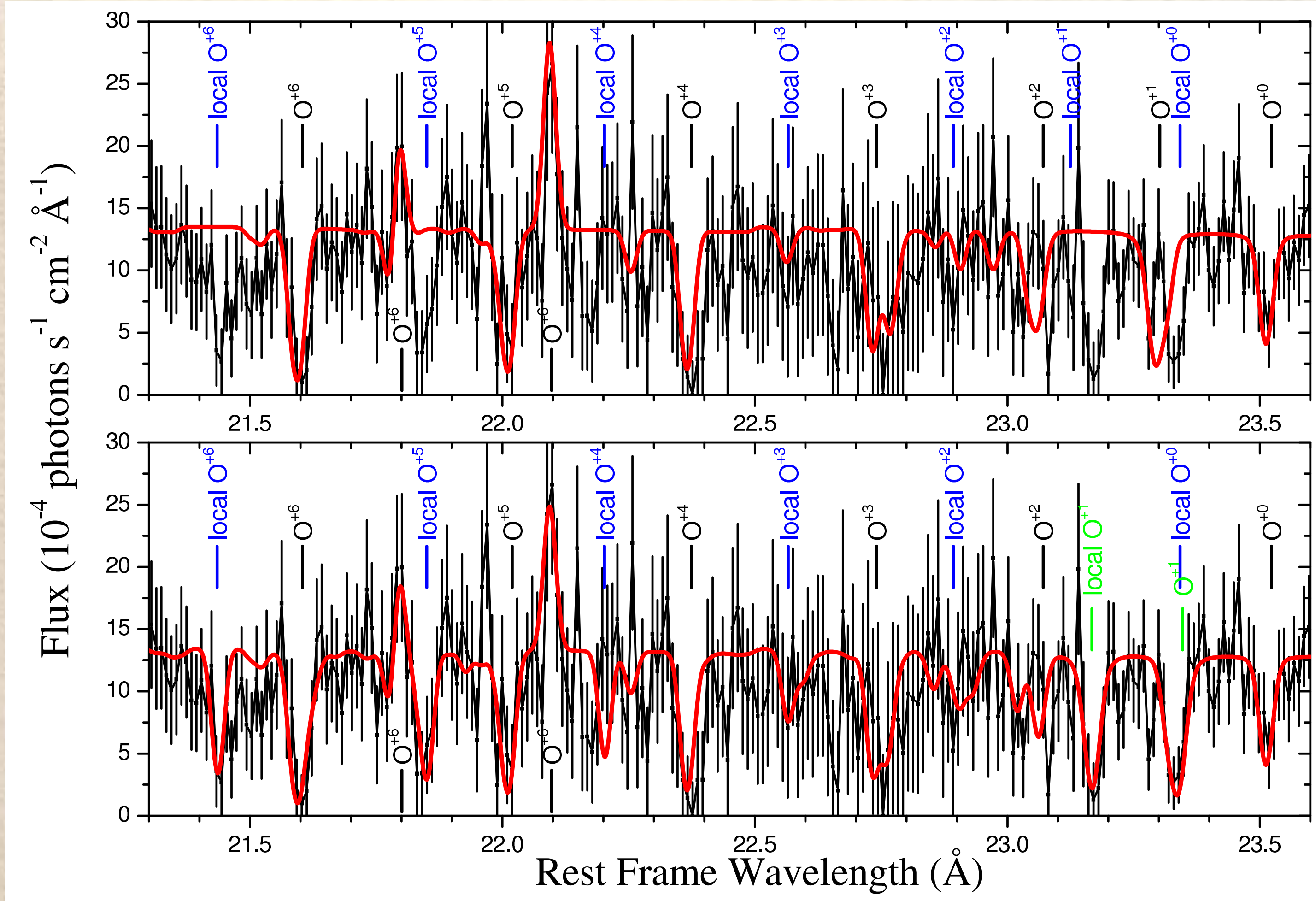
Generic AMD with XSPEC / XSTAR

Recovered with HETG, Simulated with Resolve



Keshet & Behar '22

Laboratory Astrophysics with Chandra/HETG

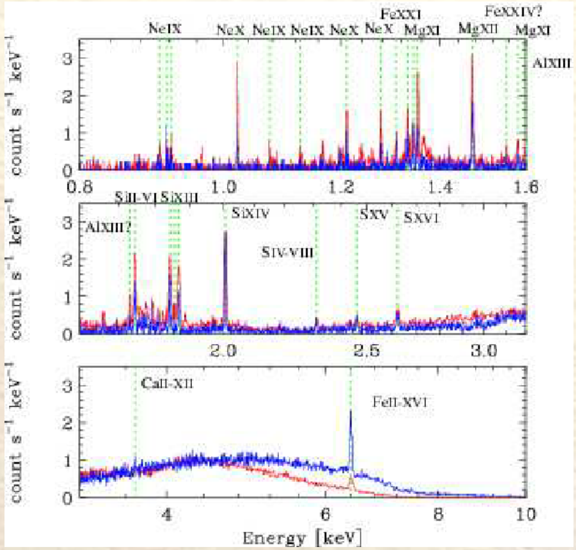


Before corrections

After corrections

Vela X-1 Eclipsing X-Ray Binary

What Drives the Line Emission?



Simulations by

Mauche et al. 2007

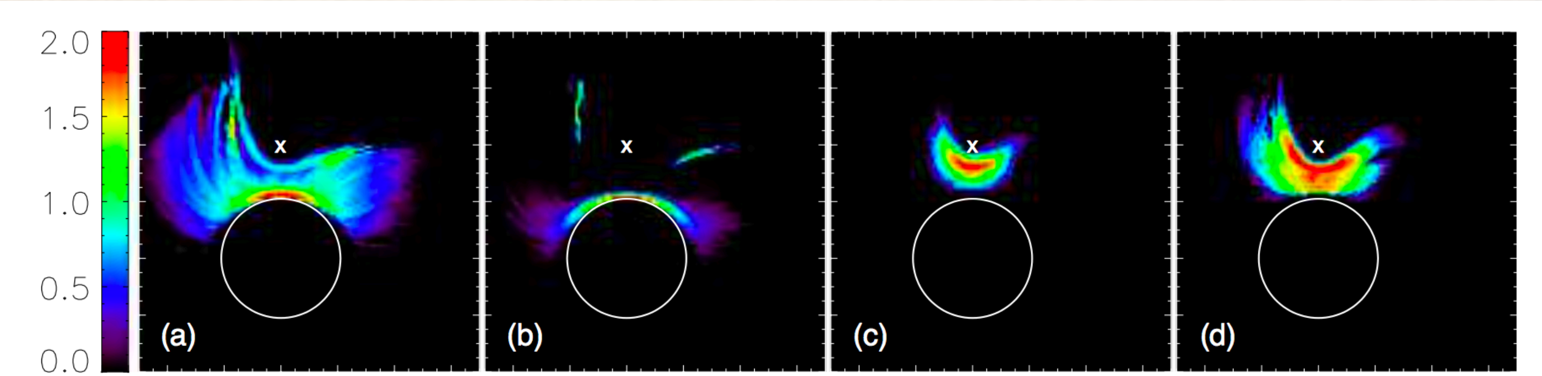
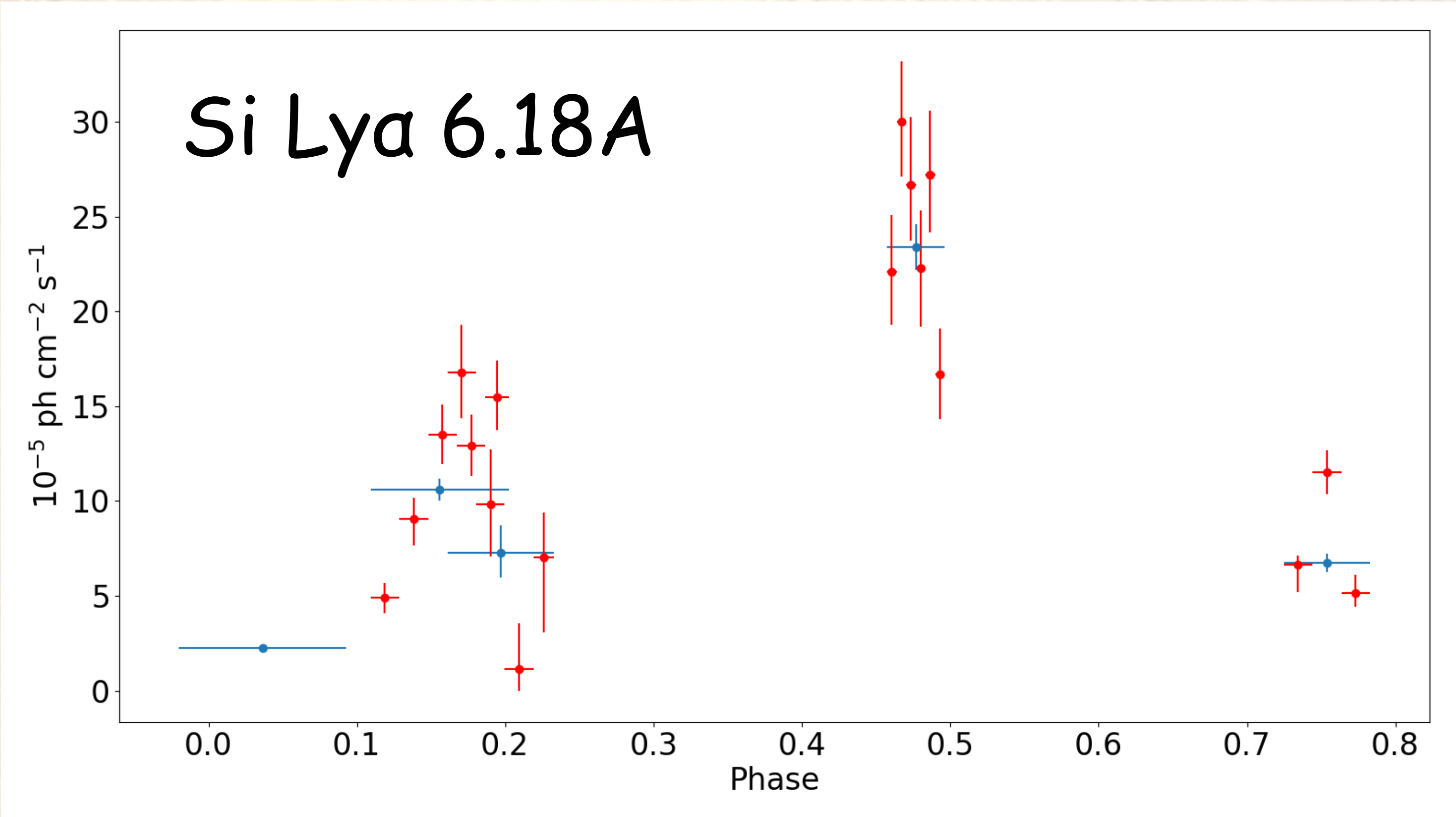


Fig. 2. Color-coded maps of the log of the X-ray emissivity of (a) Si XIV Lyα, (b) Si XIII Heα, (c) Fe XXVI Lyα, and (d) Fe XXV Heα. In each case, two orders of magnitude are plotted.

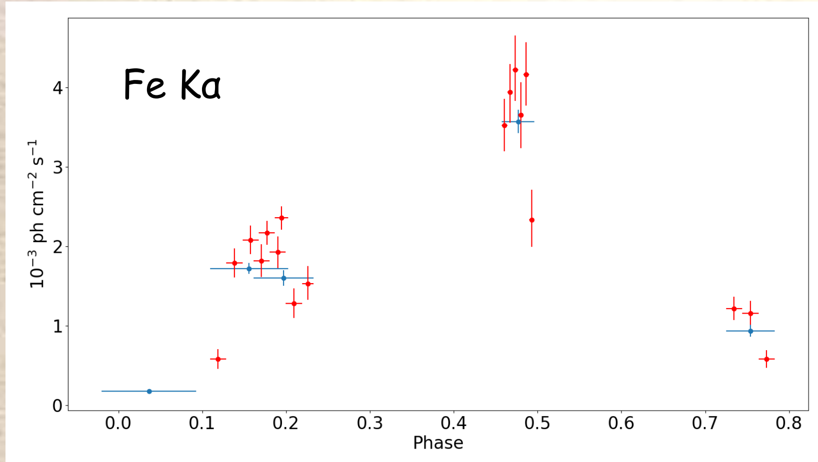
What Drives Line Emission in Vela X-1?

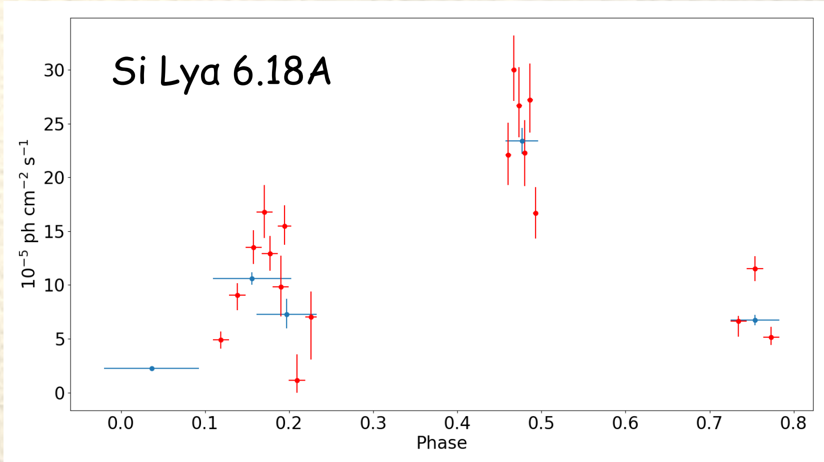


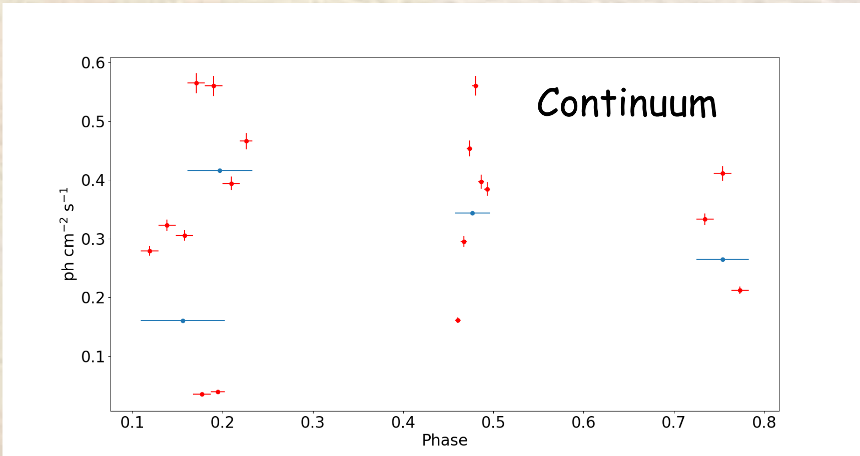
Answer depends on the time resolution

What Drives Line Emission in Vela X-1?

The Continuum?



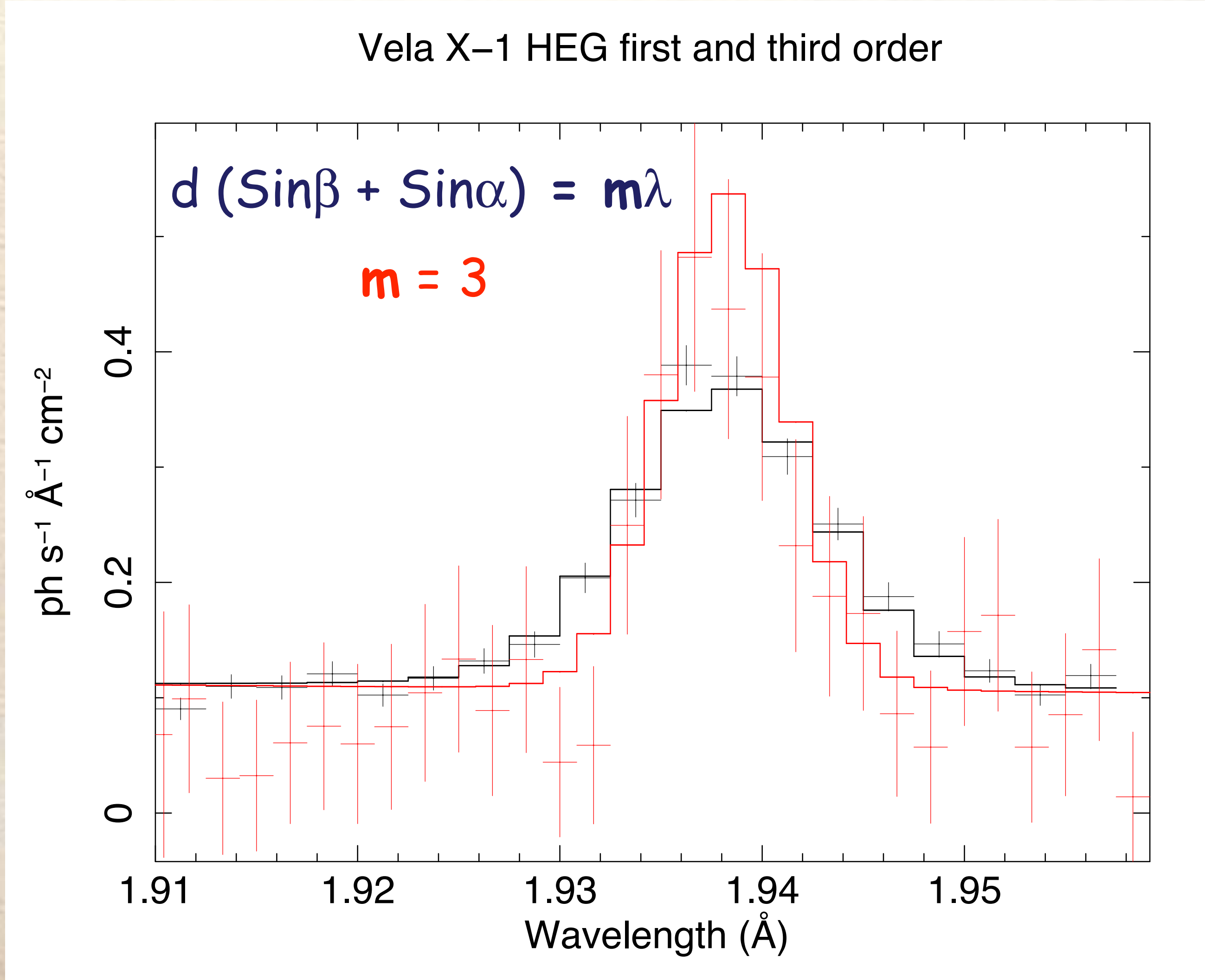




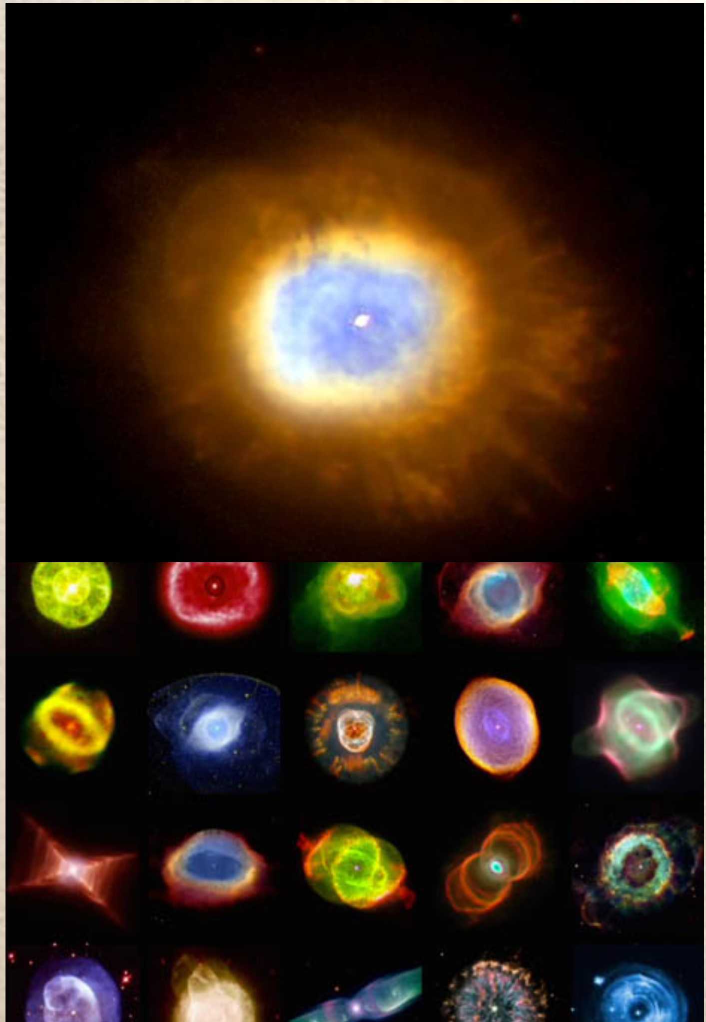
Rahin+

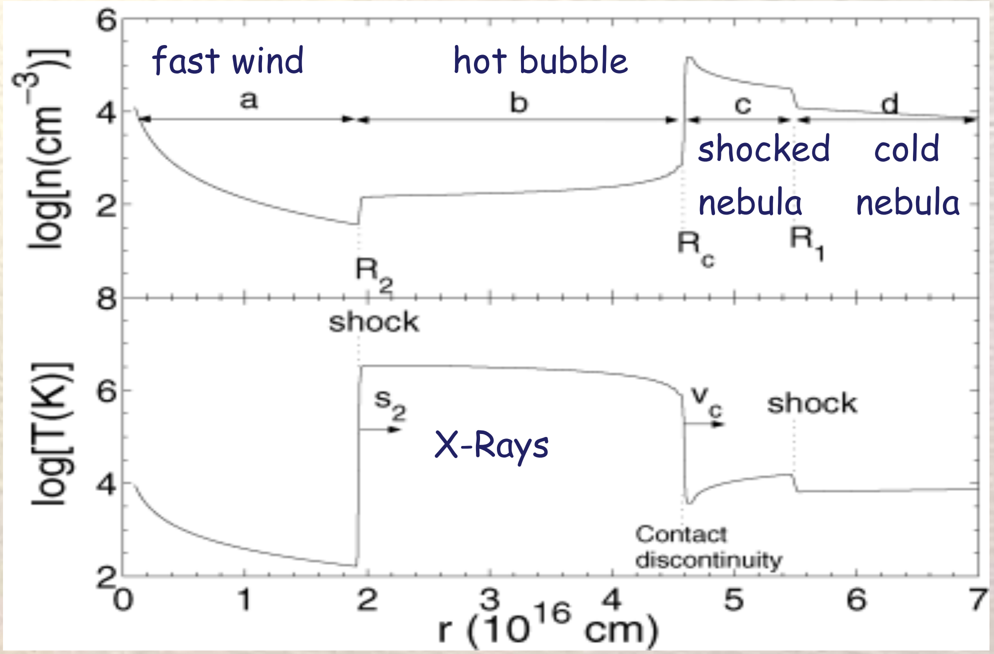
in prep.

Bright Sources (X-Ray Binaries) Allow the use of High Diffraction Order



Collisionless Shocks





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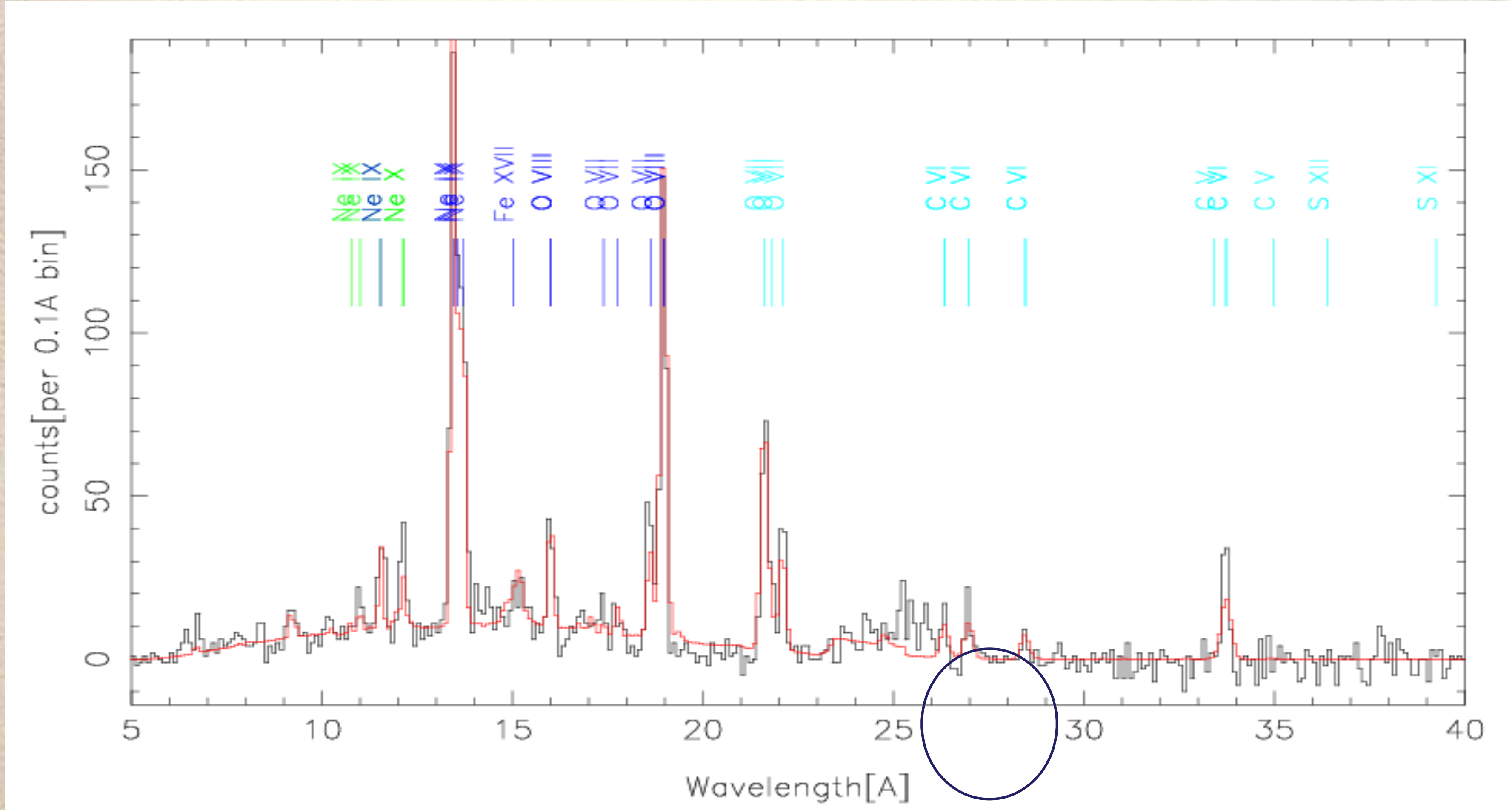
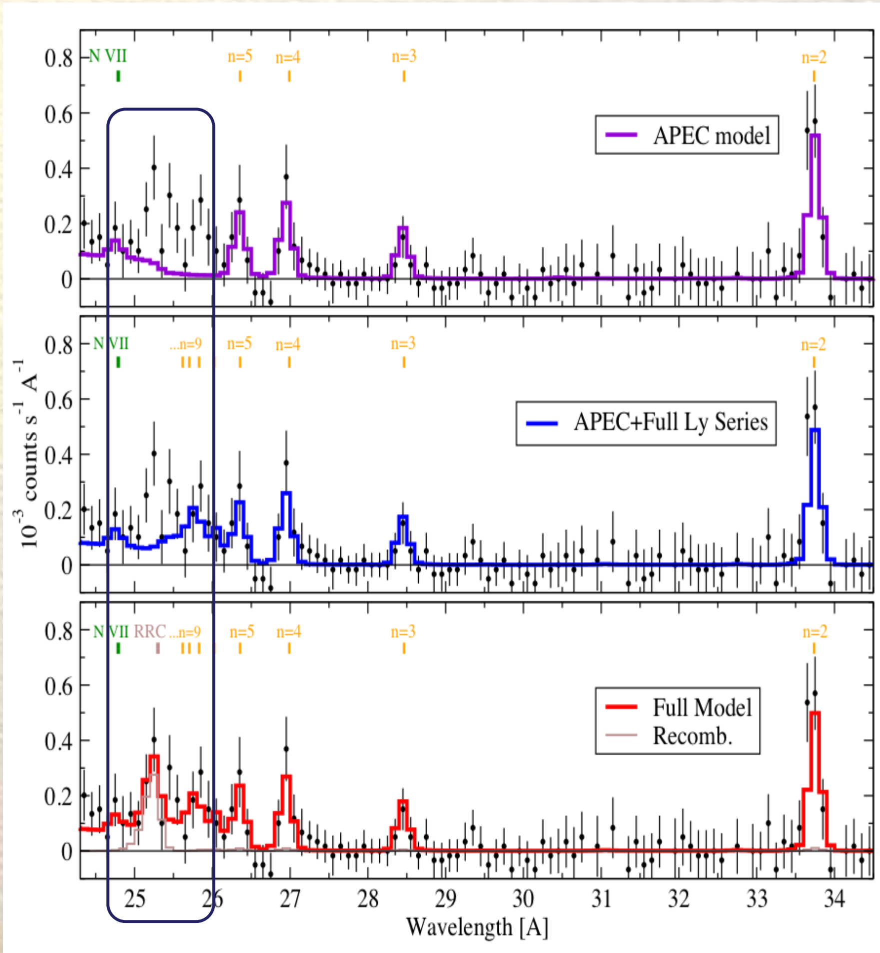
Grating Spectrum of Hot Bubble

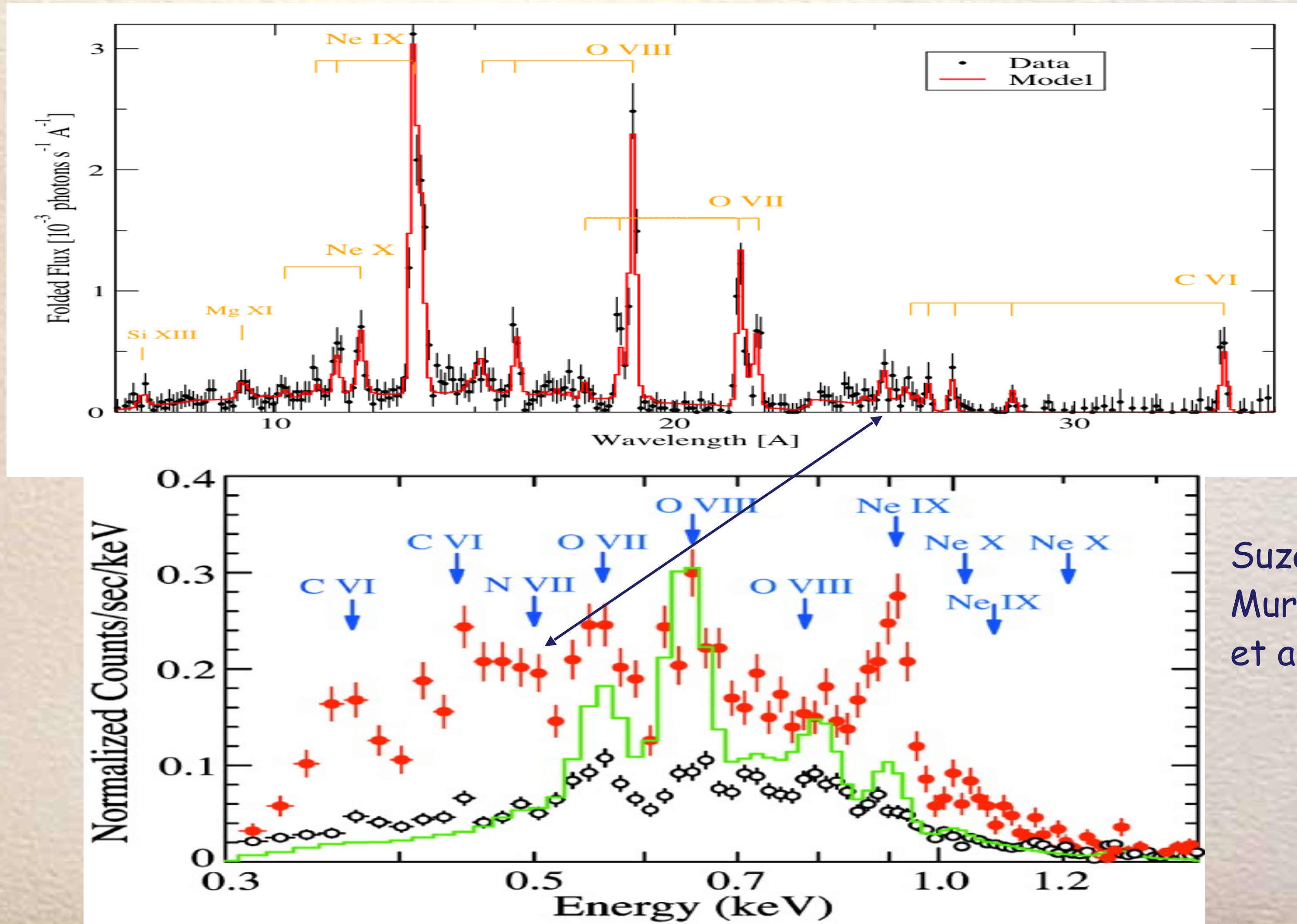


Narrow C^{+6} RRC
Radiative Recombination Continuum

- Recombination of hot ions (~100 eV) with cold electrons (~ 1 eV)
- RRC width => $kT_e = 1.7 \pm 1.3$ eV
- Intermediate temperatures 1 eV < kT < 100 eV can not be significant
- Origin?



Importance of High Spectral Resolution



Suzaku, Murashima et al. 2006

RRCs in Supernova Remnants w/ Suzaku

Best Evidence for Contact Discon. in an Astrophysical Shock?

or Different Interpretation? Stay tuned for XRISM

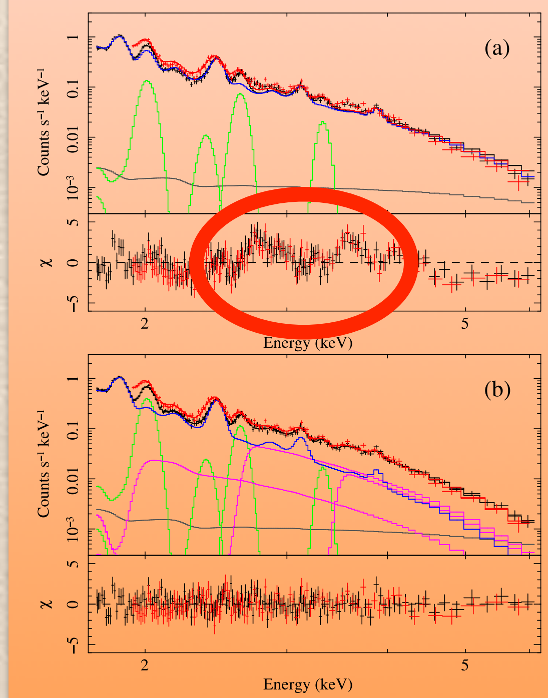


FIG. 3.— (a) XIS spectrum in the 1.75–6.0 keV band. Black and red represent FI and BI, respectively. Individual components of the best-fit model for the FI data are shown with solid colored lines: blue, green, and gray are the VAPEC, Gaussians (Si-Lyα, Si-Lyβ, S-Lyα, and Ar-Lyα), and CXB, respectively. The lower panel shows the residual from the best-fit model. Two hump-like features are clearly found around the energies of ~2.7 keV and ~3.5 keV. (b) Same spectrum as (a), but for a fit with RRC components of H-like Mg, Si, and S (magenta lines). The residuals seen in (a) are disappeared.

Yamaguchi+'09

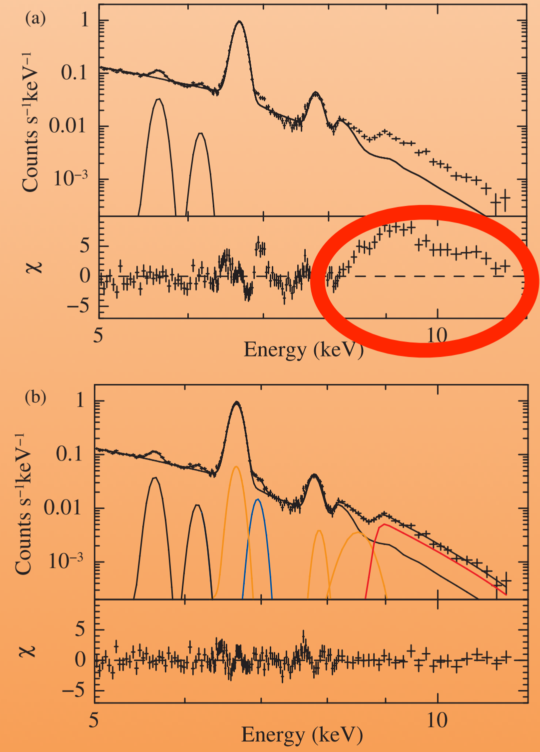


Figure 3. (a) XIS spectrum in the 5–12 keV band. The best-fit VAPEC mode and additional Kα lines of Cr and Mn with Gaussian functions are shown b solid lines. The lower panel shows the residual from the best-fit model. (t Same spectrum as (a), but with the radiative recombination continuum (red recombination lines (orange), and a Lyα line (blue) of Fe.

Ozawa+'09

Take Home Messages

- Atomic Spectroscopy is the most reliable tool for detailed physical diagnostics
- Atomic databases and codes are up to date for the majority of data needs
- Upcoming calorimeter instruments on board **XRISM** and later **Athena** will improve our measurements in both spectral and time domain

THANK YOU
FOR YOUR ATTENTION