# The Future of High Resolution Spectroscopy

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# X-ray Spectroscopy is special

*Dense forests of lines from multiple ions*

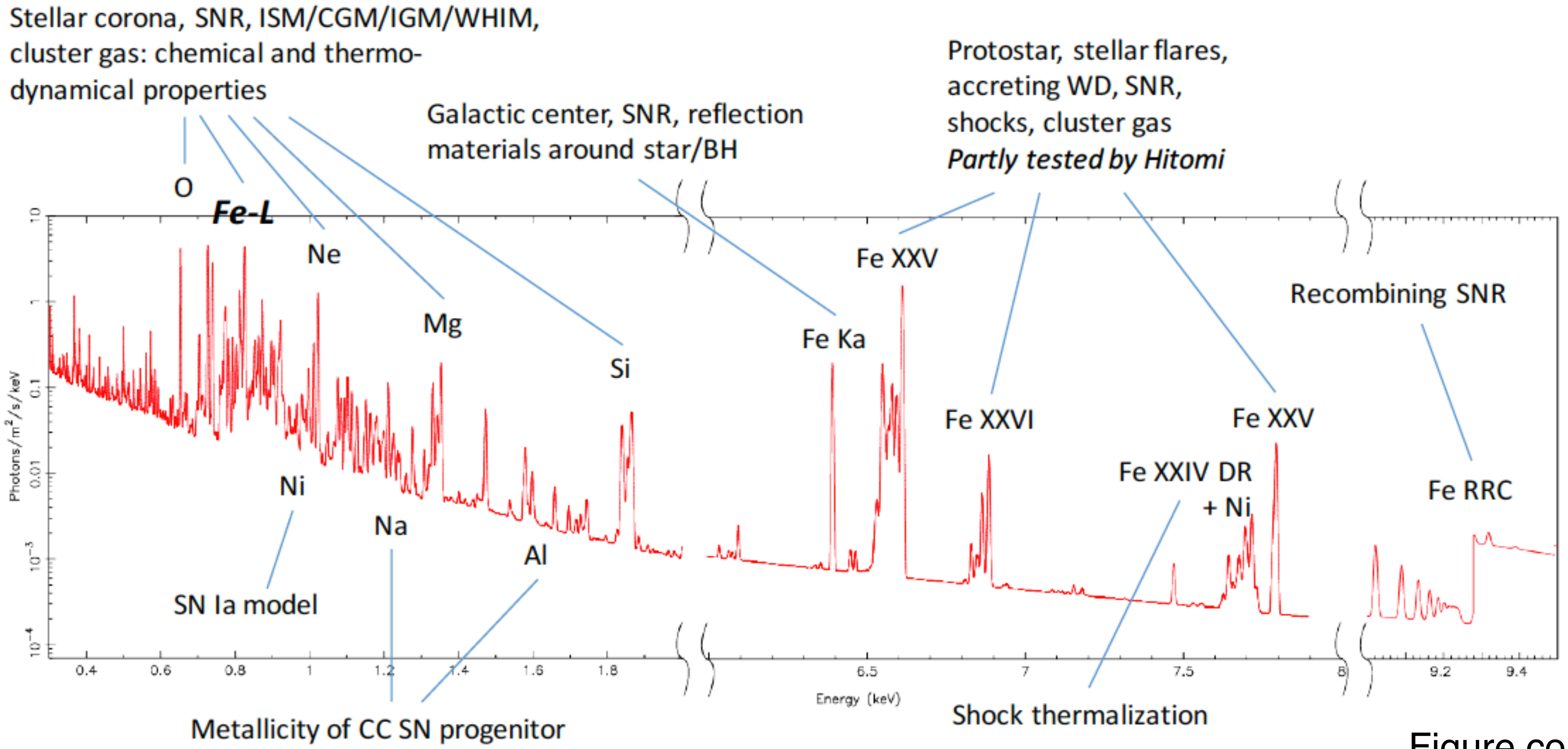


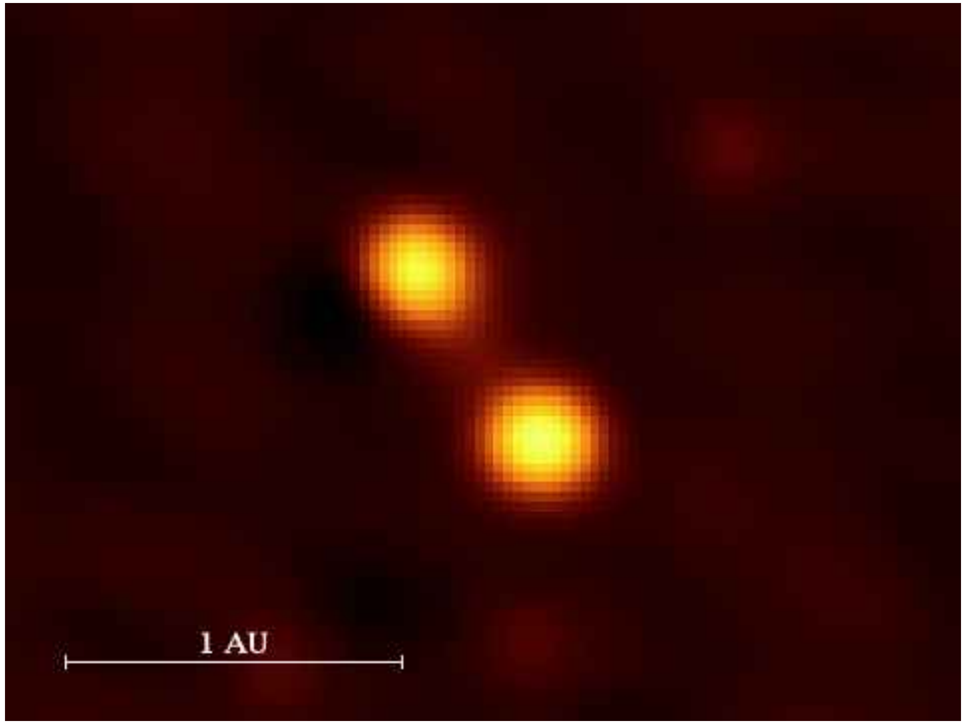

Figure courtesy Liyi Gu

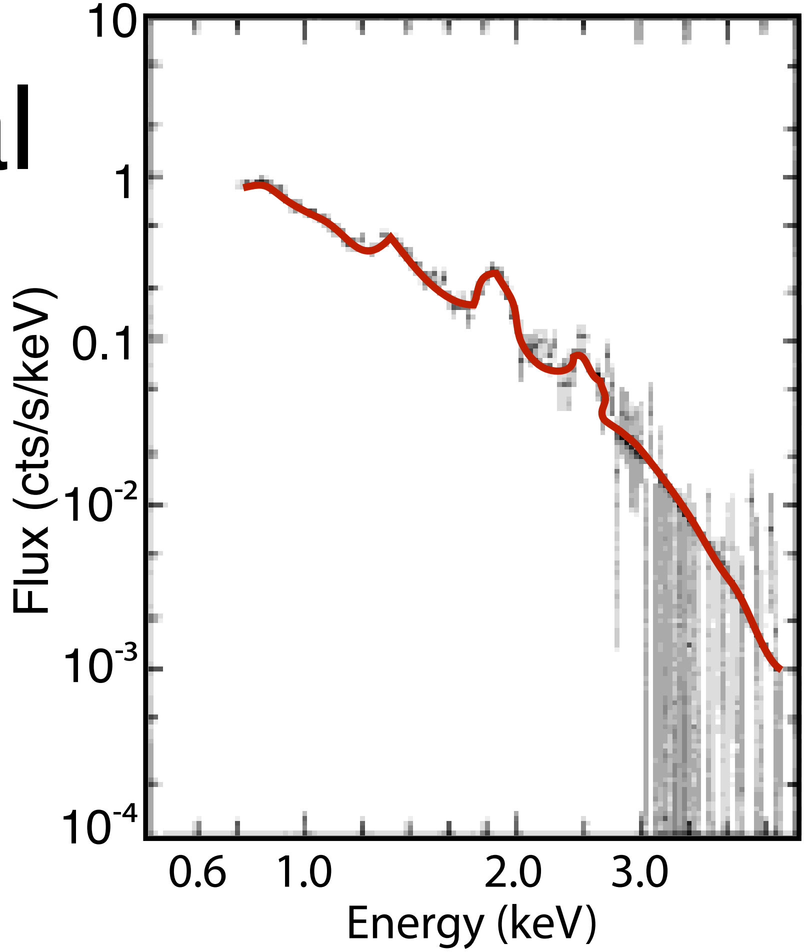
# X-ray Spectroscopy is special

## …and there is much it can reveal.

**Consider Capella:**

G III binary system ~13 pc distant



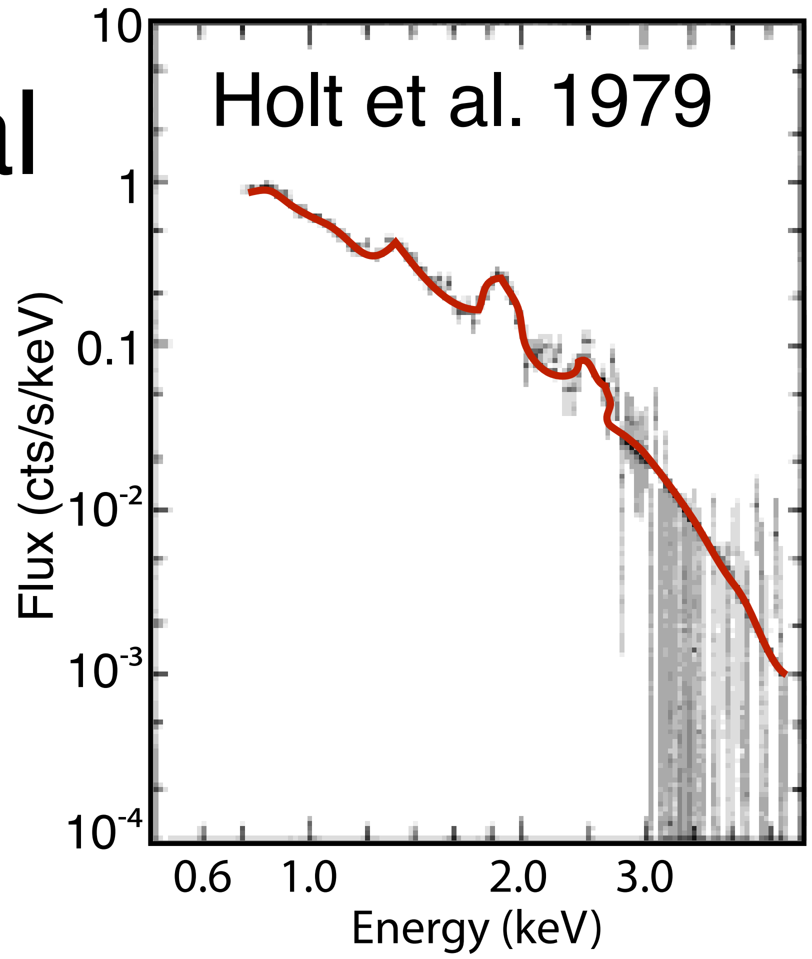

*7 ksec exposure with the Einstein Solid State Spectrometer*

# X-ray Spectroscopy is special

…and there is much it can reveal.

## Conclusions from Holt et al. 1979

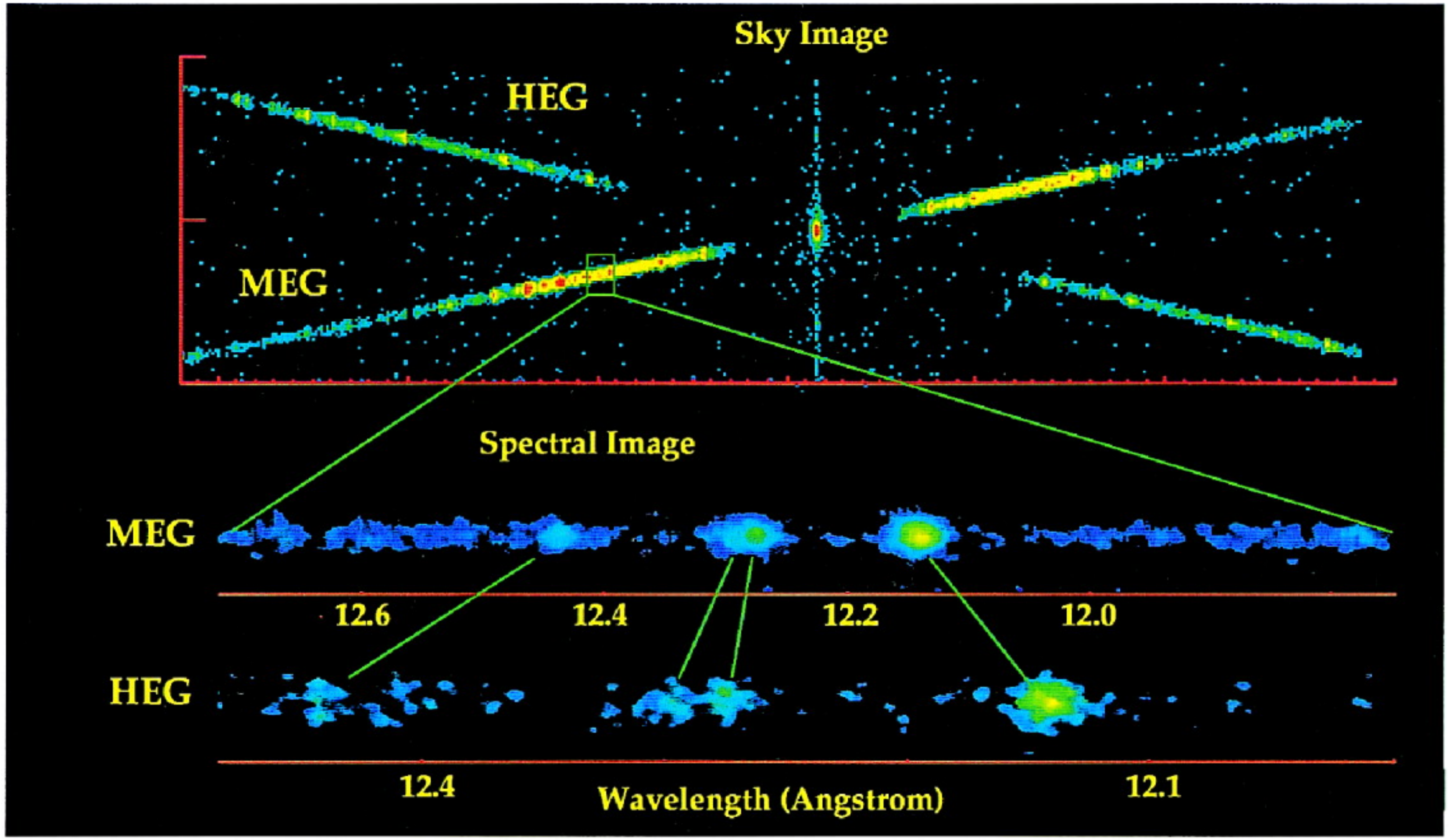
- **Inconsistent** with an isothermal corona; **requires at least two components between 6 – 24 x10$^6$ K** for an adequate fit.
- **Mg, Si, S, and Fe** are **unambiguously** detected




*7 ksec exposure with the Einstein Solid State Spectrometer*

# X-ray Spectroscopy is special

…It was twenty years ago today…

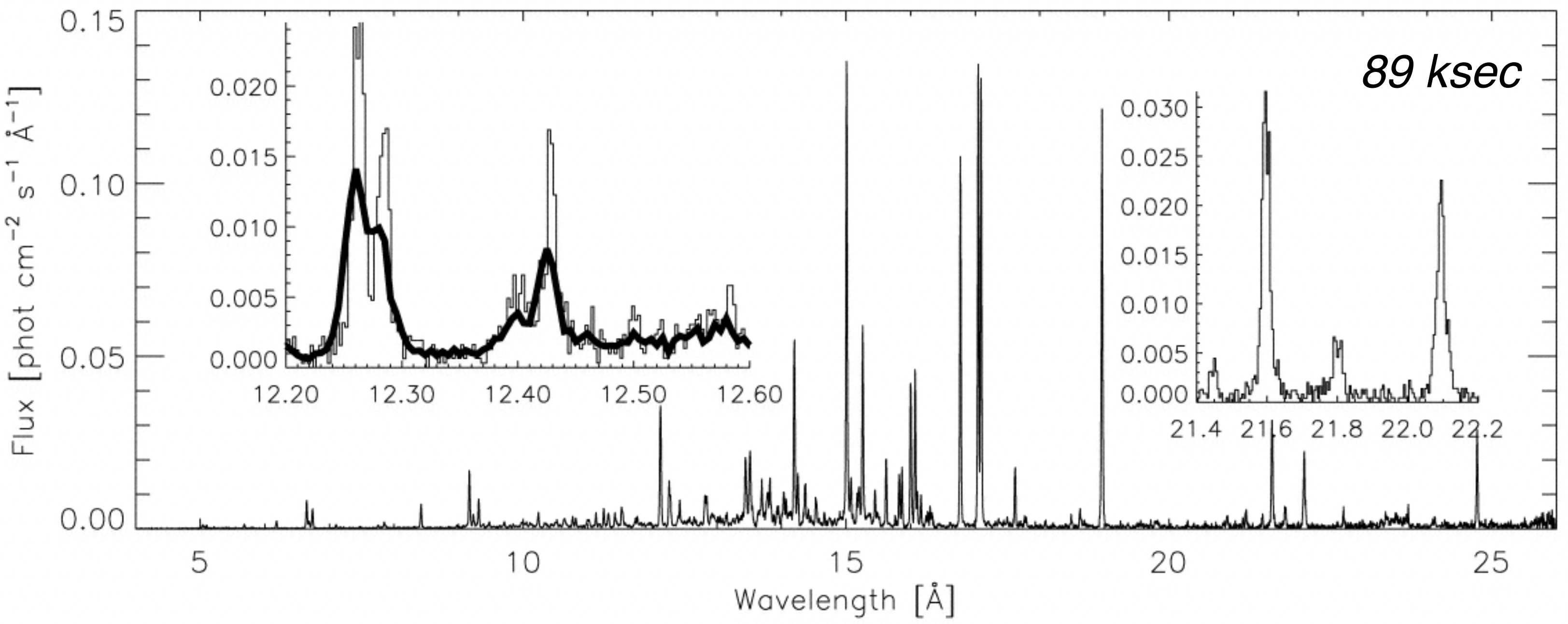



# X-ray Spectroscopy is special

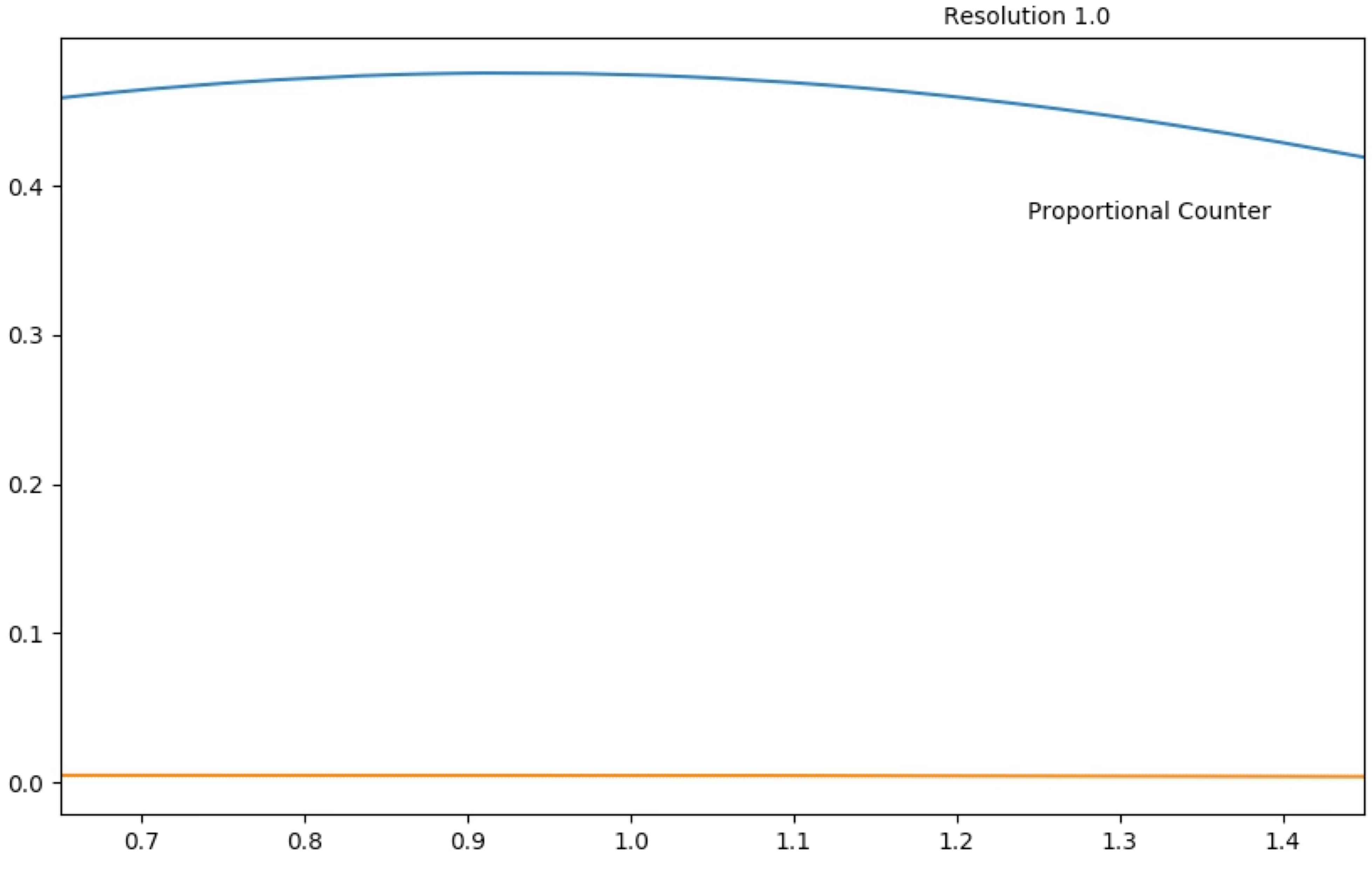
## …It was twenty years ago today…

## **Conclusions from Canizares+2000**

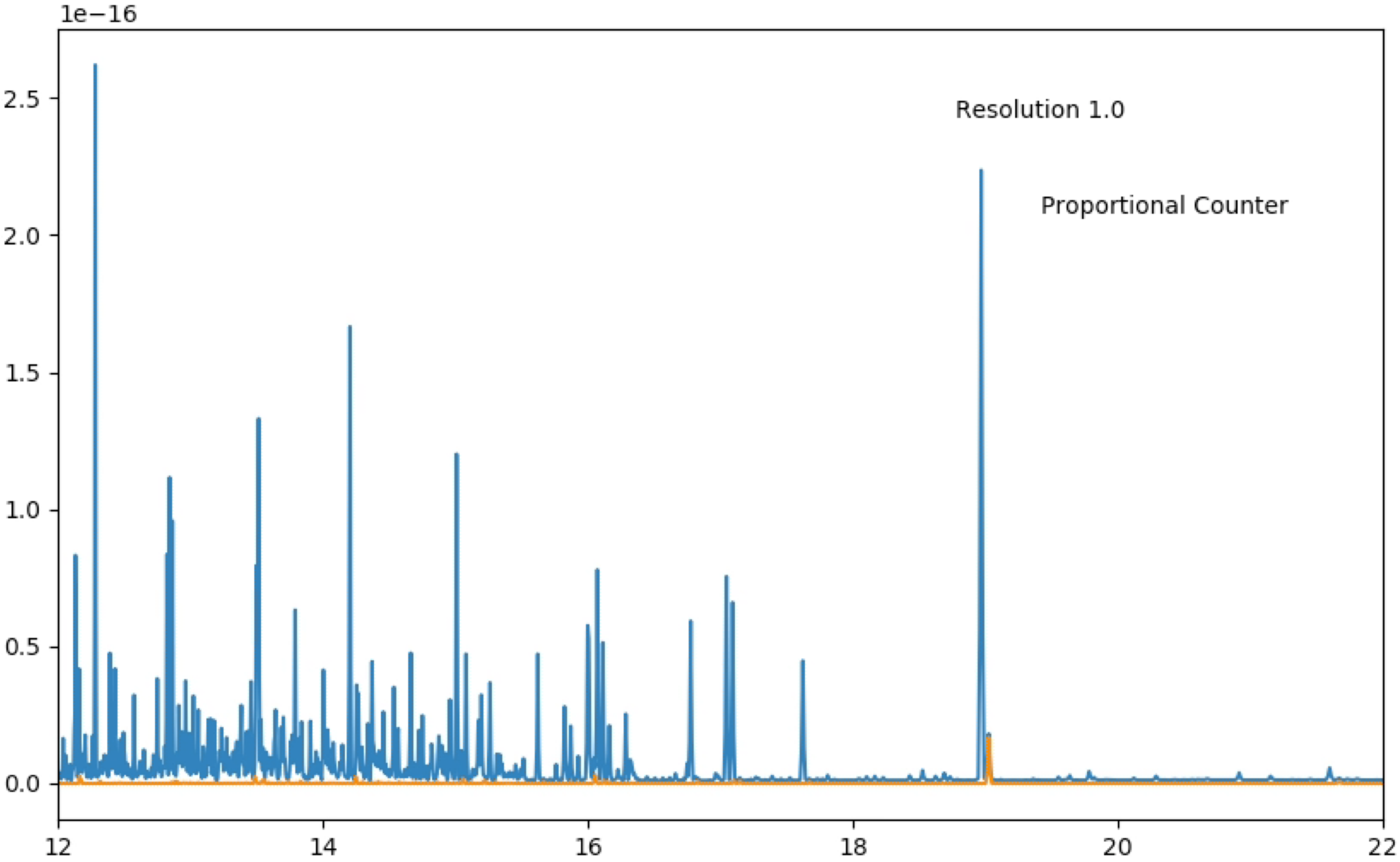
- **Broad temperature range:** 2 – 15 MK
- **Electron density**~$10^{10}$ cm$^{-3}$
- **Coronal loops are significantly smaller than the stellar radius**.




"High-Resolution X-Ray Spectra of Capella: Initial Results from the Chandra HETGS"



Resolution 1.0
Proportional Counter
0.0
0.1
0.2
0.3
0.4
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4

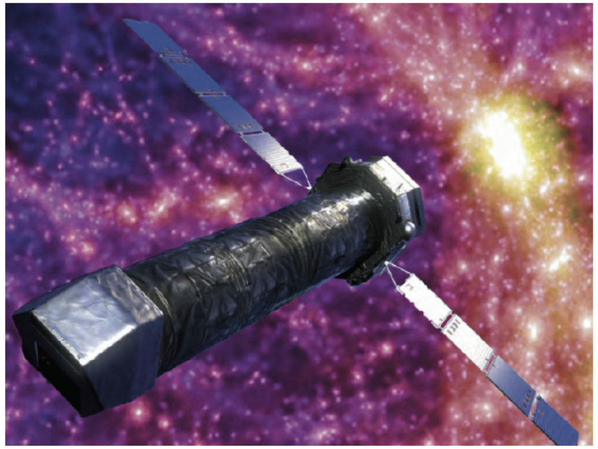


1e−16
2.5
2.0
1.5
1.0
0.5
0.0
12
14
16
18
20
22
Resolution 1.0
Proportional Counter


DUH

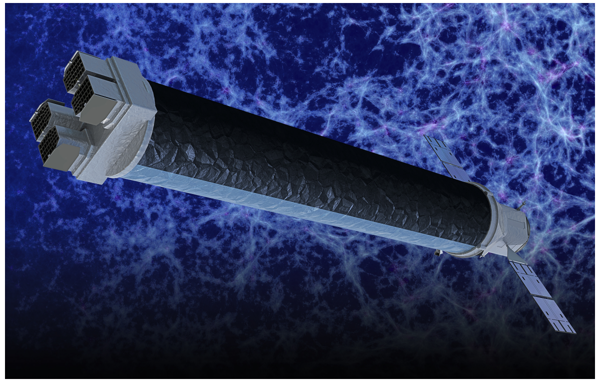
# The Future of X-ray Spectroscopy: Planned and Proposed Missions

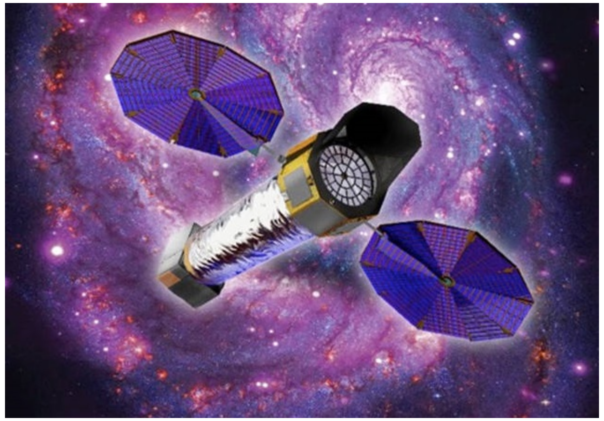
XRISM (2022)
7 eV uCal
~1 arcmin resolution



Athena (early 2030s)
2.5 eV uCal
~5 arcsec resolution

Arcus
$\lambda/\Delta\lambda$ = 2500 grating
Point sources

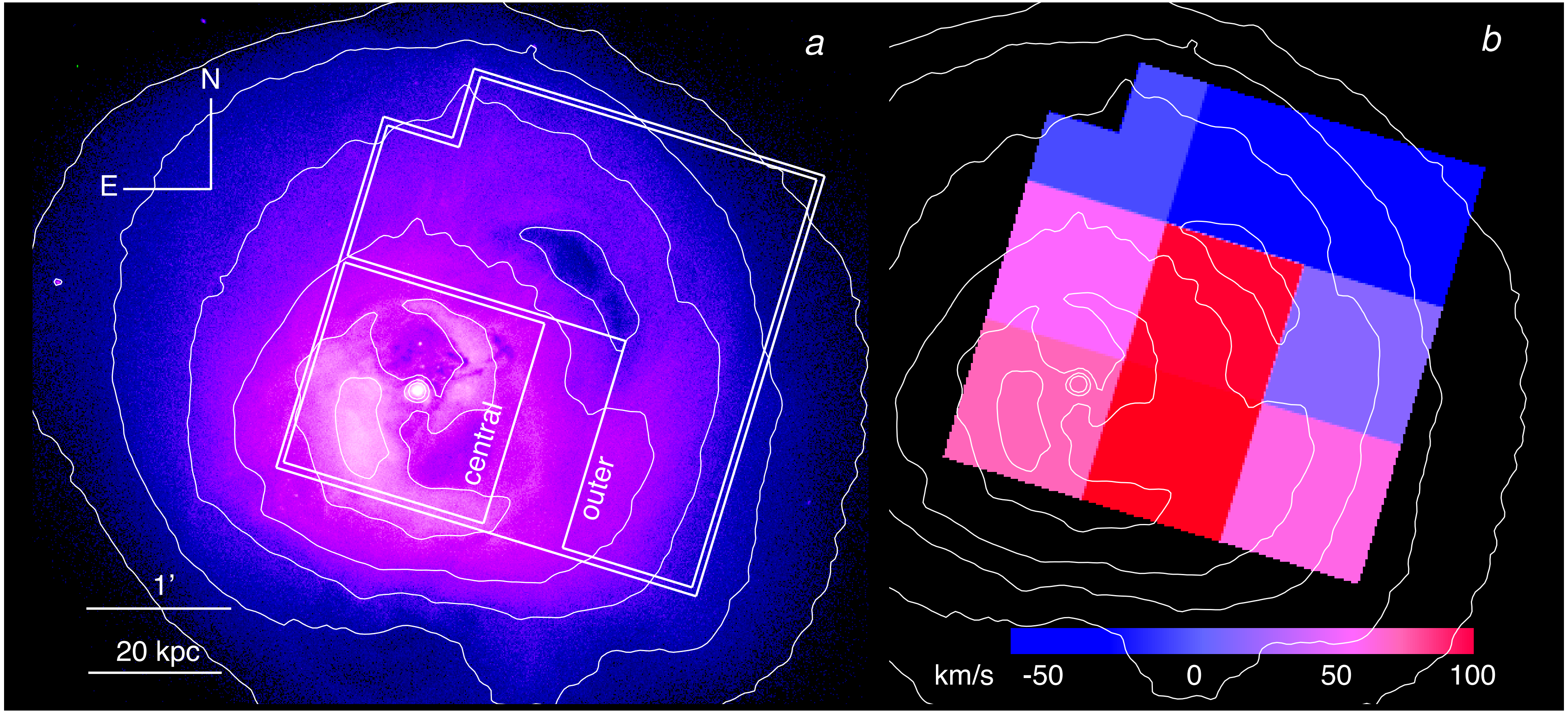




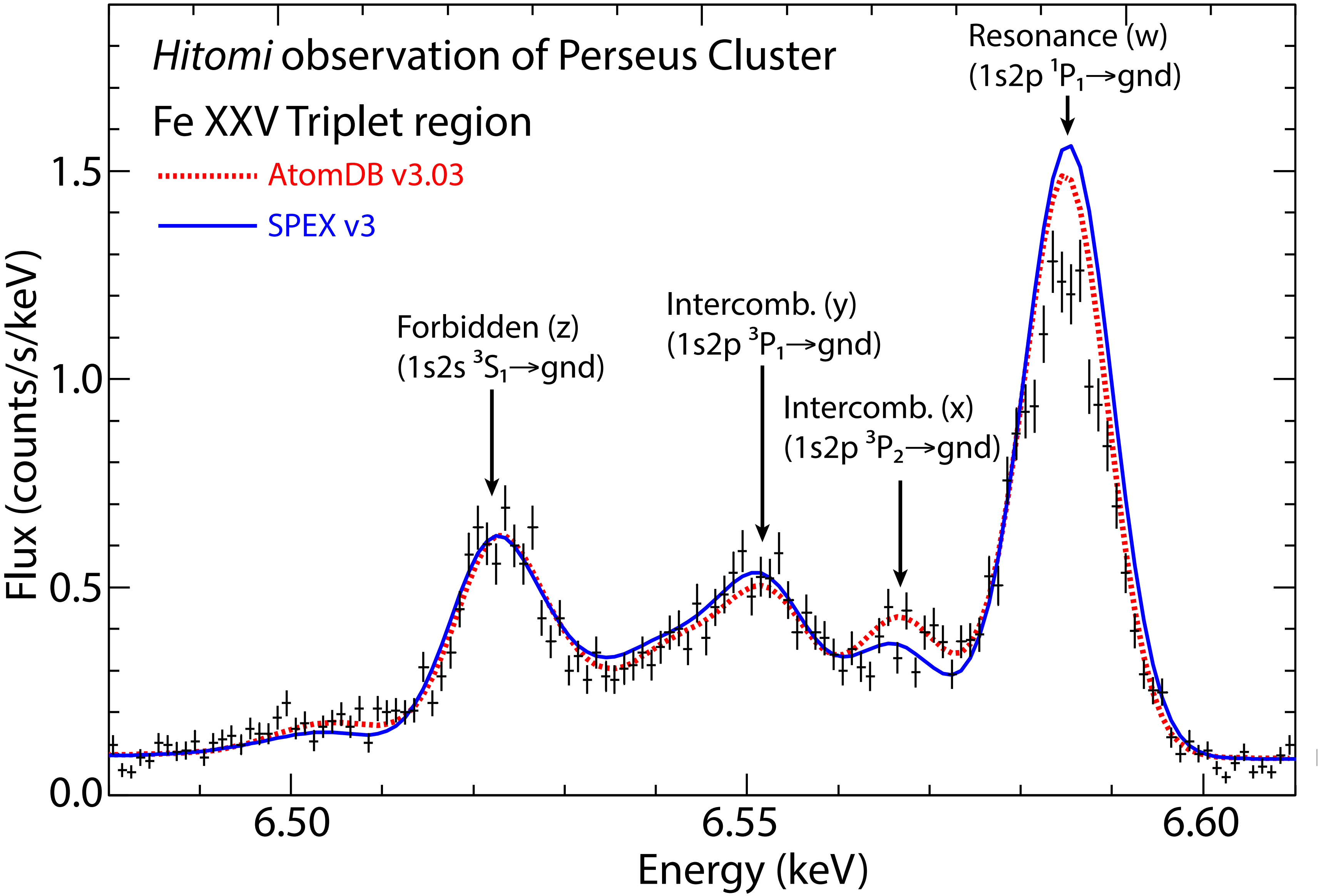
Lynx
3 & 0.3 eV uCal
$\lambda/\Delta\lambda$ > 5000 grating
<1 arcsec resolution

# Hitomi Observations of Perseus

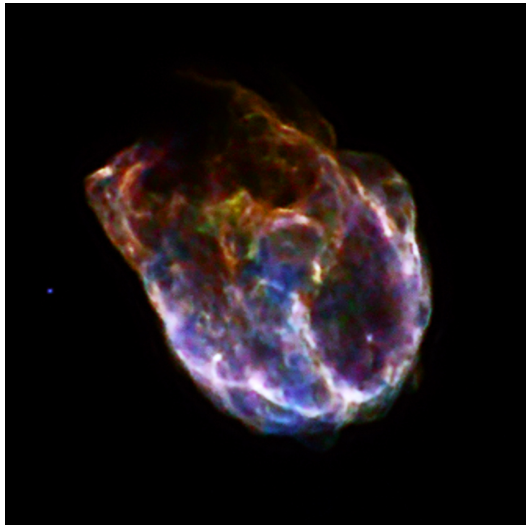
Assuming the measured velocity dispersion is due to turbulence, the energy fraction in turbulence is about 4% and would offset radiative cooling.



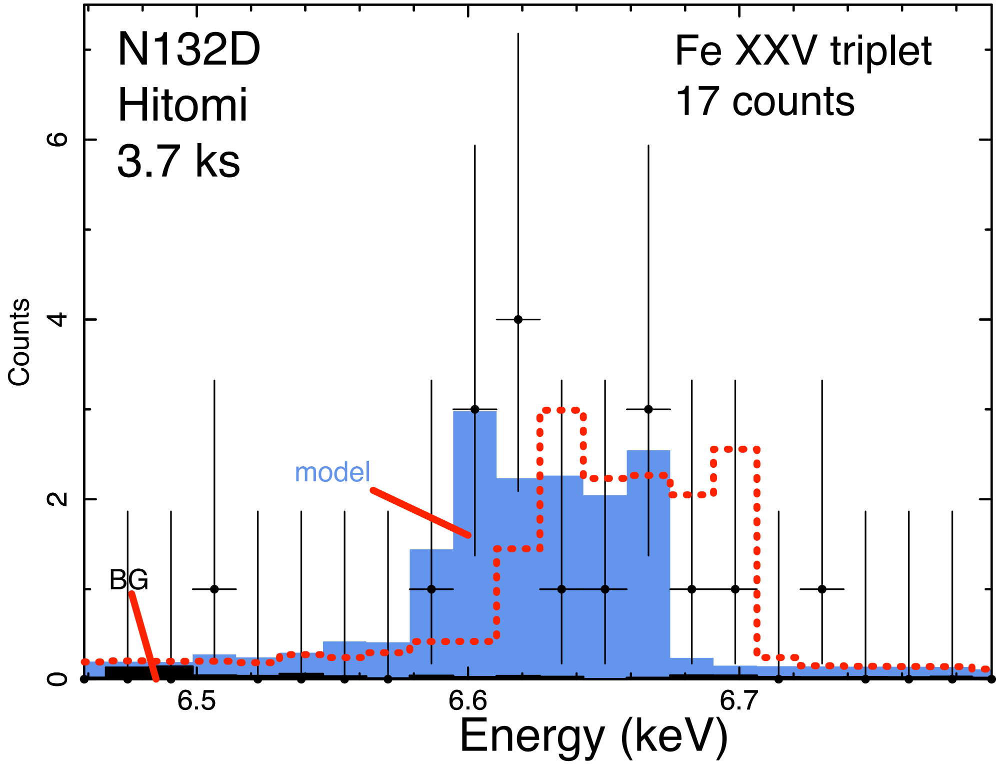
# Hitomi Observations of Perseus



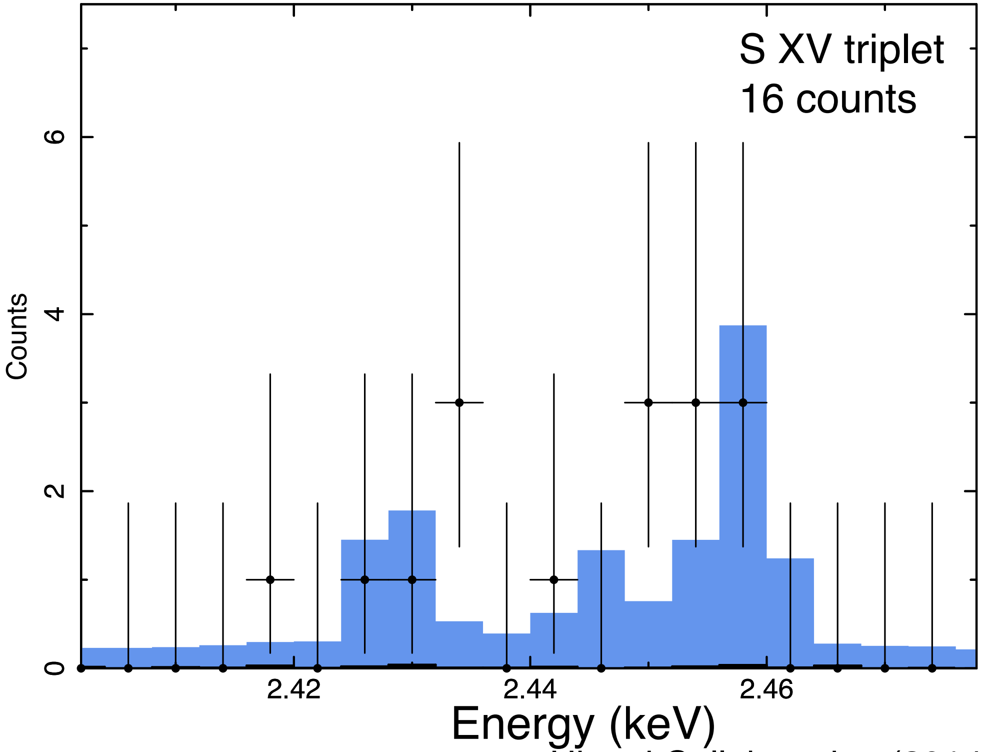
# SNR N132D with Hitomi



The Fe emission is redshifted and likely from ejecta, while the S lines are probably swept-up ISM in the shell.




Hitomi Collaboration (2014)

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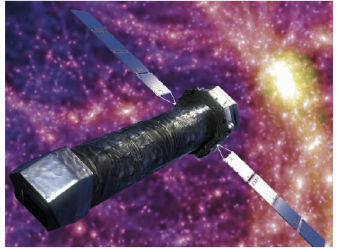
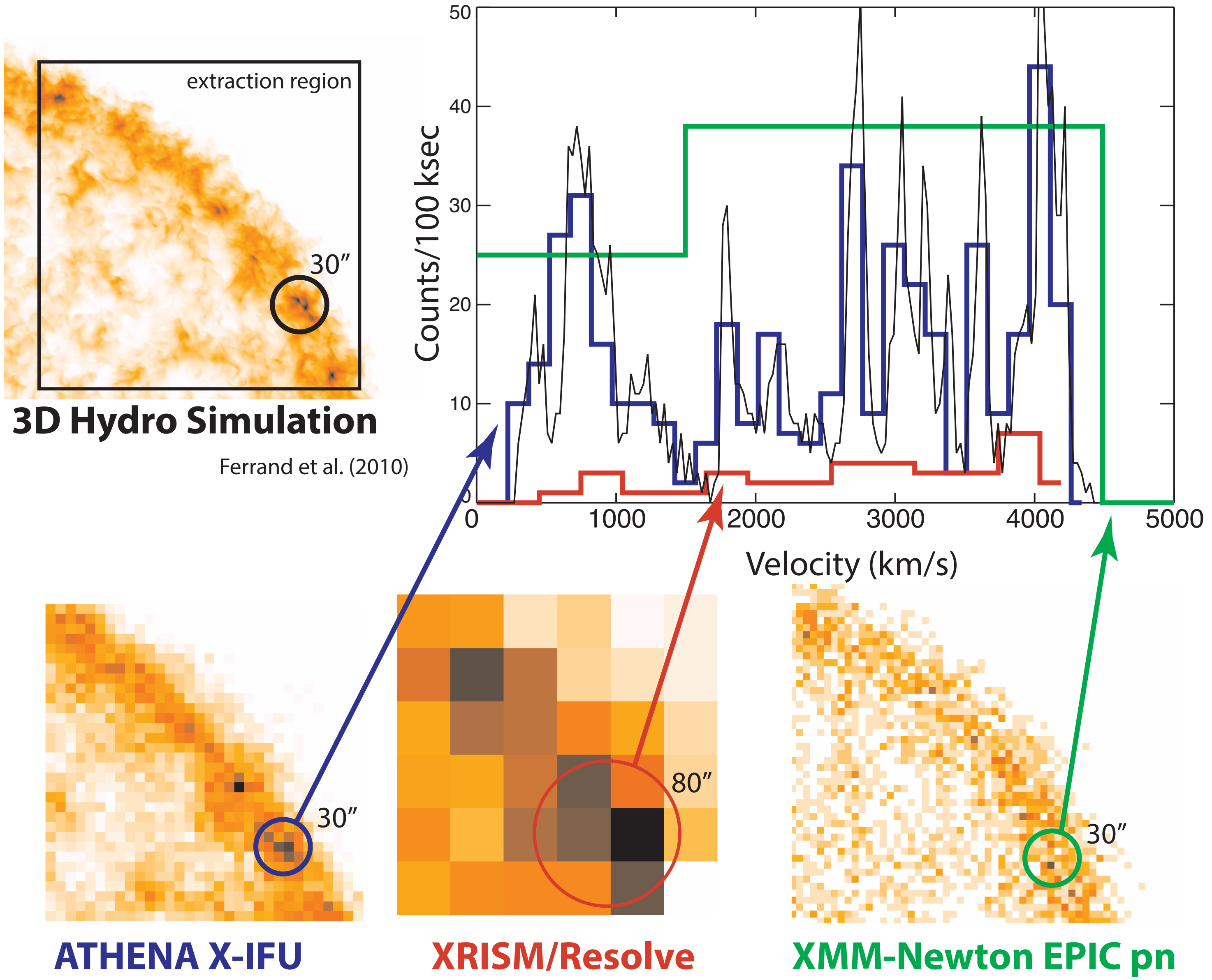
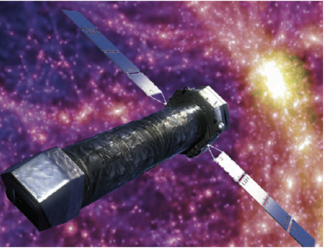


# Tycho's SNR with Athena & XRISM

XRISM will measure velocities on large scales, but Athena will image bulk velocities and broadening on an element-by-element and ion-by-ion basis, showing how SNR shocks disperse newly-formed material and energy into the ISM.

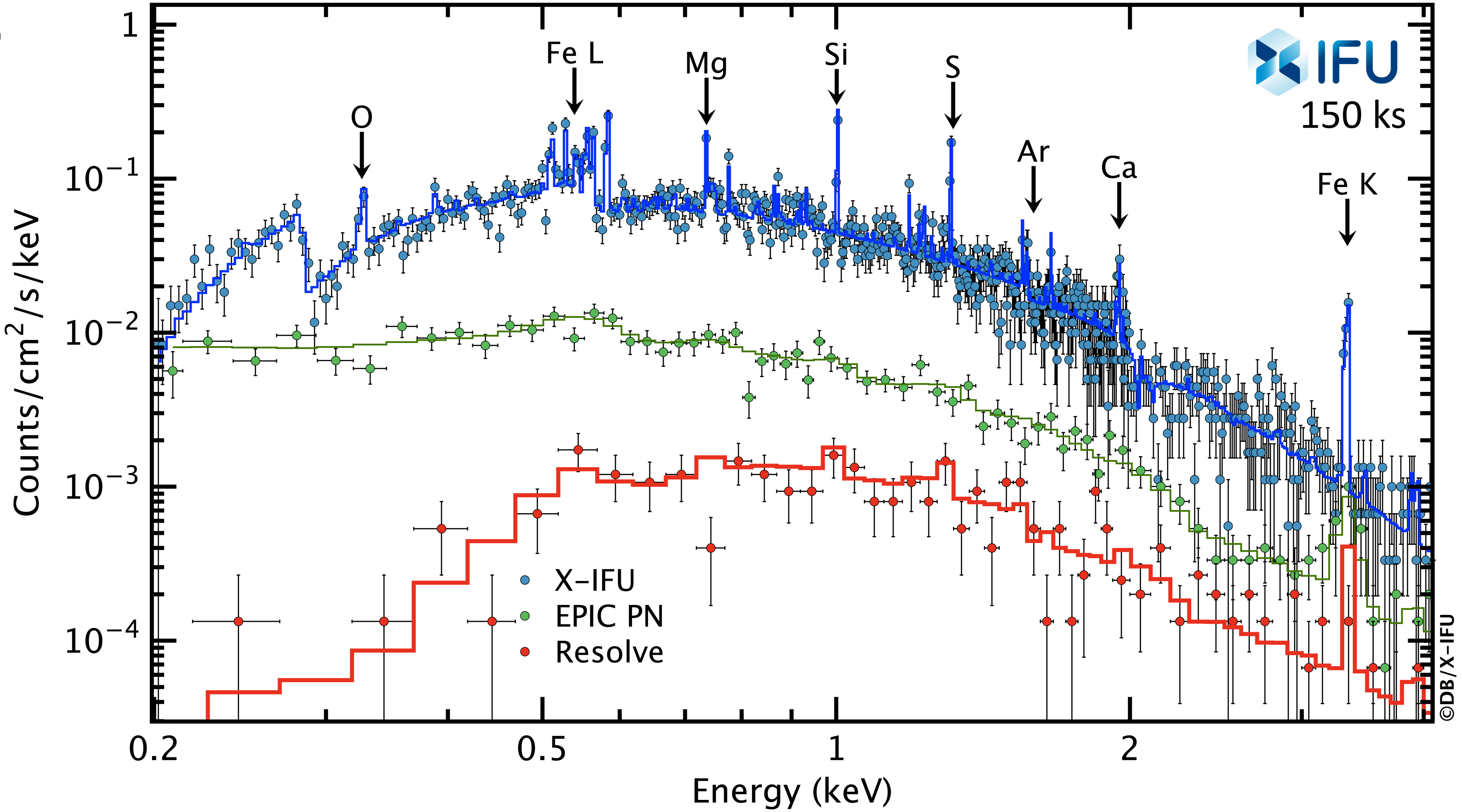


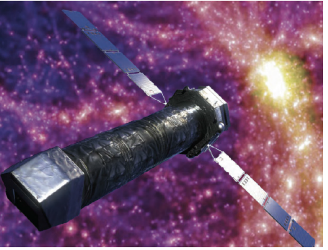


# Galaxy clusters at z=1

A $z$ = 1 galaxy cluster with $kT$ = 3 keV and $L_X$ = $10^{44}$ erg $s^{-1}$

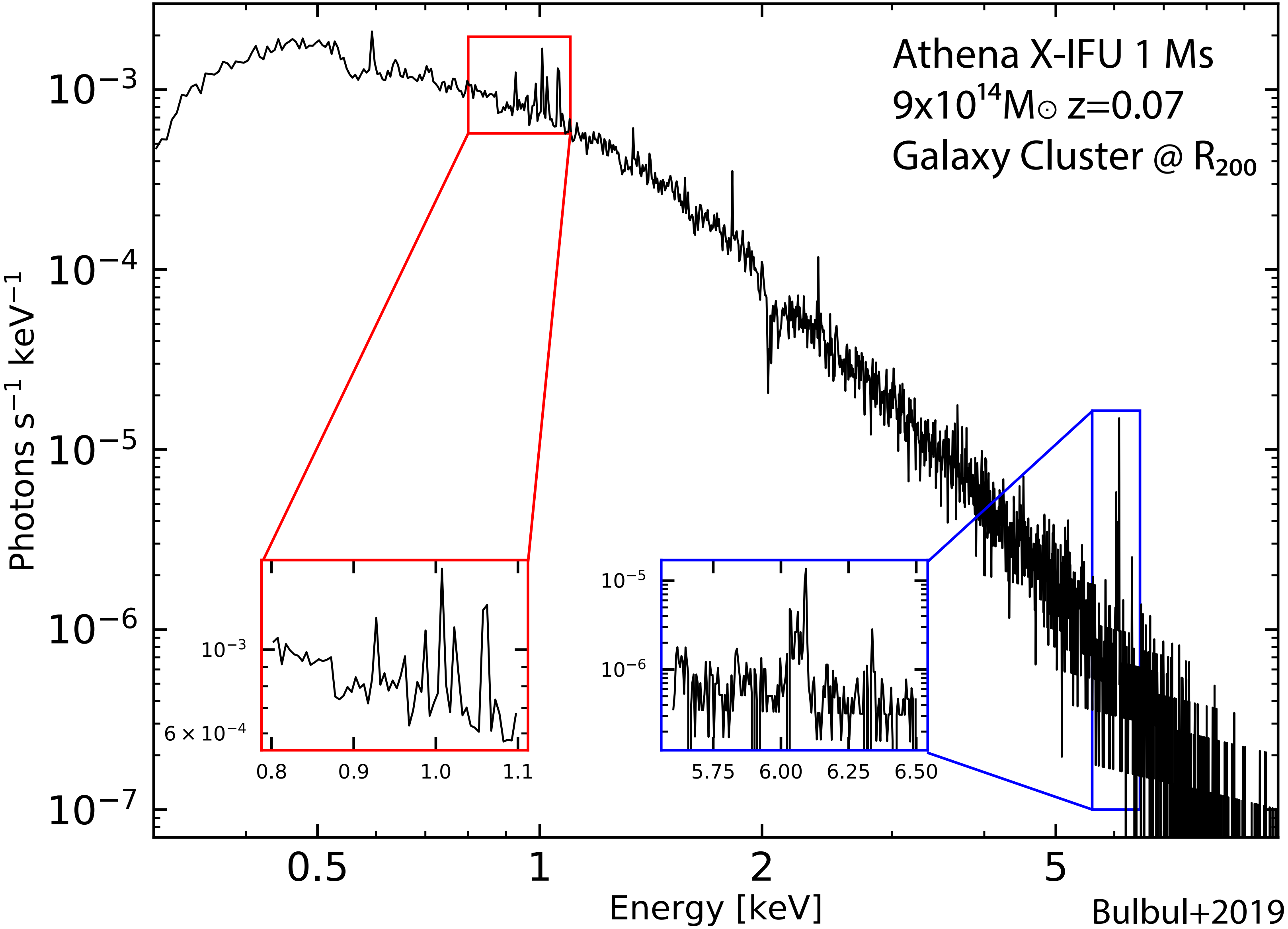
Emission lines from elements which are key to understand chemical evolution can be clearly seen.



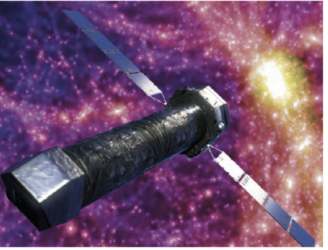


# Galaxy cluster outskirts

With 1.4m$^2$ of effective area at 1 keV, Athena can measure not only abundances but also turbulence & bulk flows at the edges of a galaxy cluster – where all the action is.



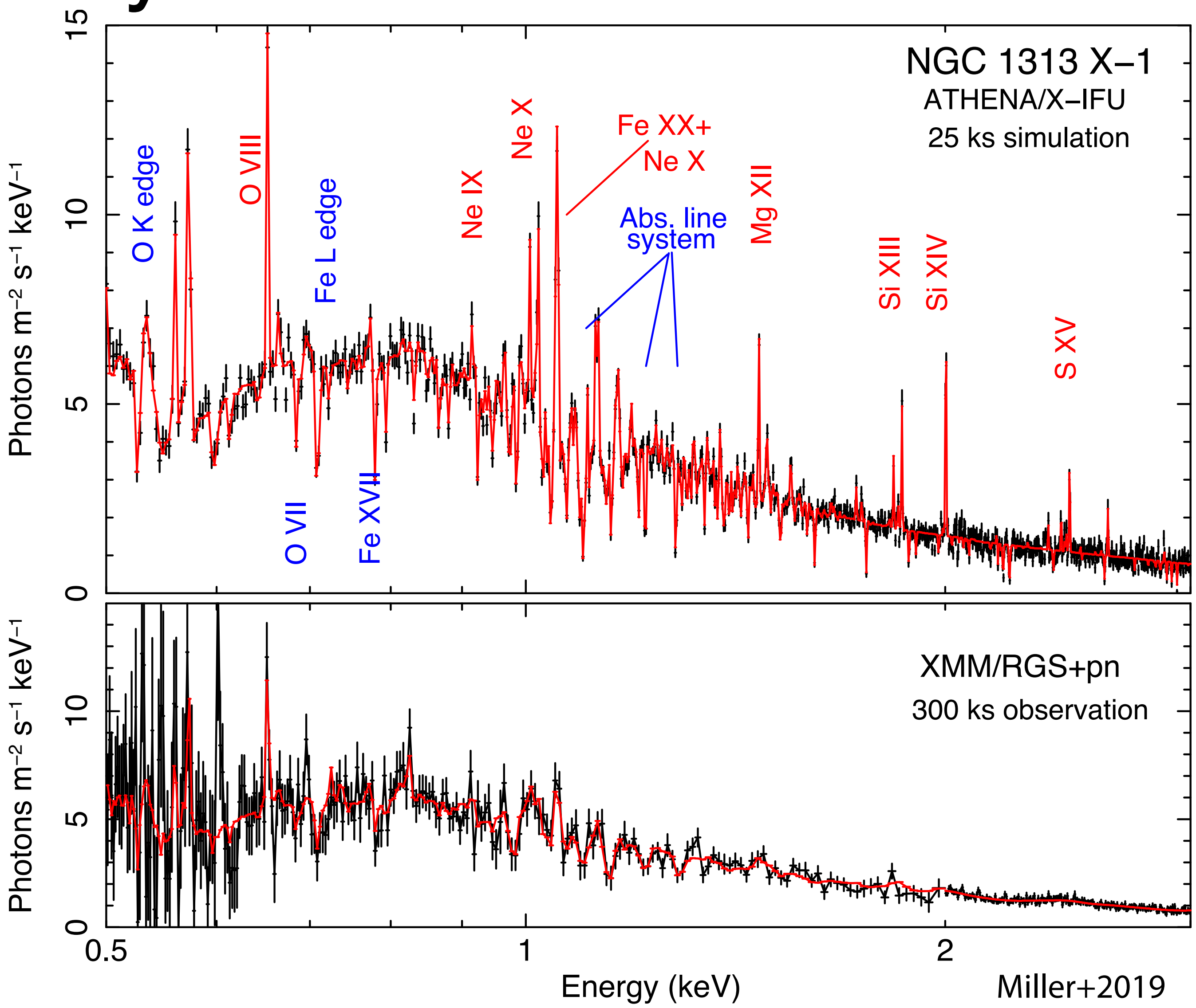

Bulbul+2019

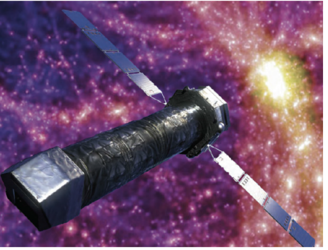


# Ultra-luminous X-ray Sources

Extremely deep XMM-Newton/ RGS spectra suggest a combination of emission and absorption lines consistent with a v = 0.2c outflow.

Athena/XIFU spectra will reveal fast outflows characteristic of super-Eddington accretion, and examine the variability of such flows

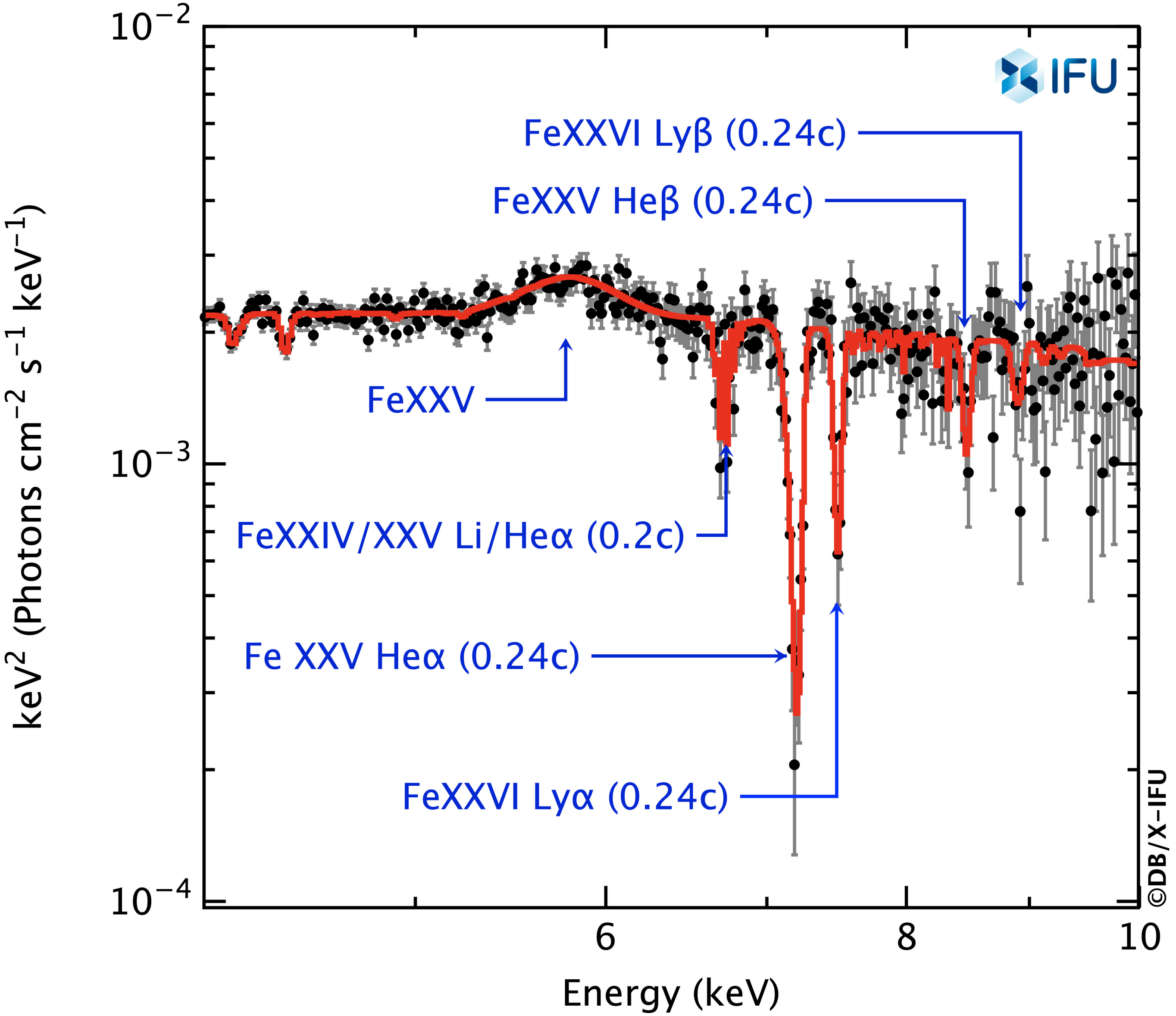


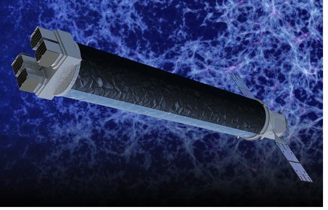


# Ultra-fast outflows with Athena's X-IFU…

100 ks X-IFU spectrum of PDS456 ($z=0.184$) with two wind components. The $-0.2c$ component has a column of $\sim 2\text{x}10^{22}$ cm$^{-2}$ and ionization of log $\xi=3.1$; the other has a column density of $\sim 1.5\text{x}10^{23}$ cm$^{-2}$, log $\xi=3.6$ and $v_{out}= -0.24c$.

UFOs are hard to see now; high-resolution sensitive spectroscopy will make this easy.





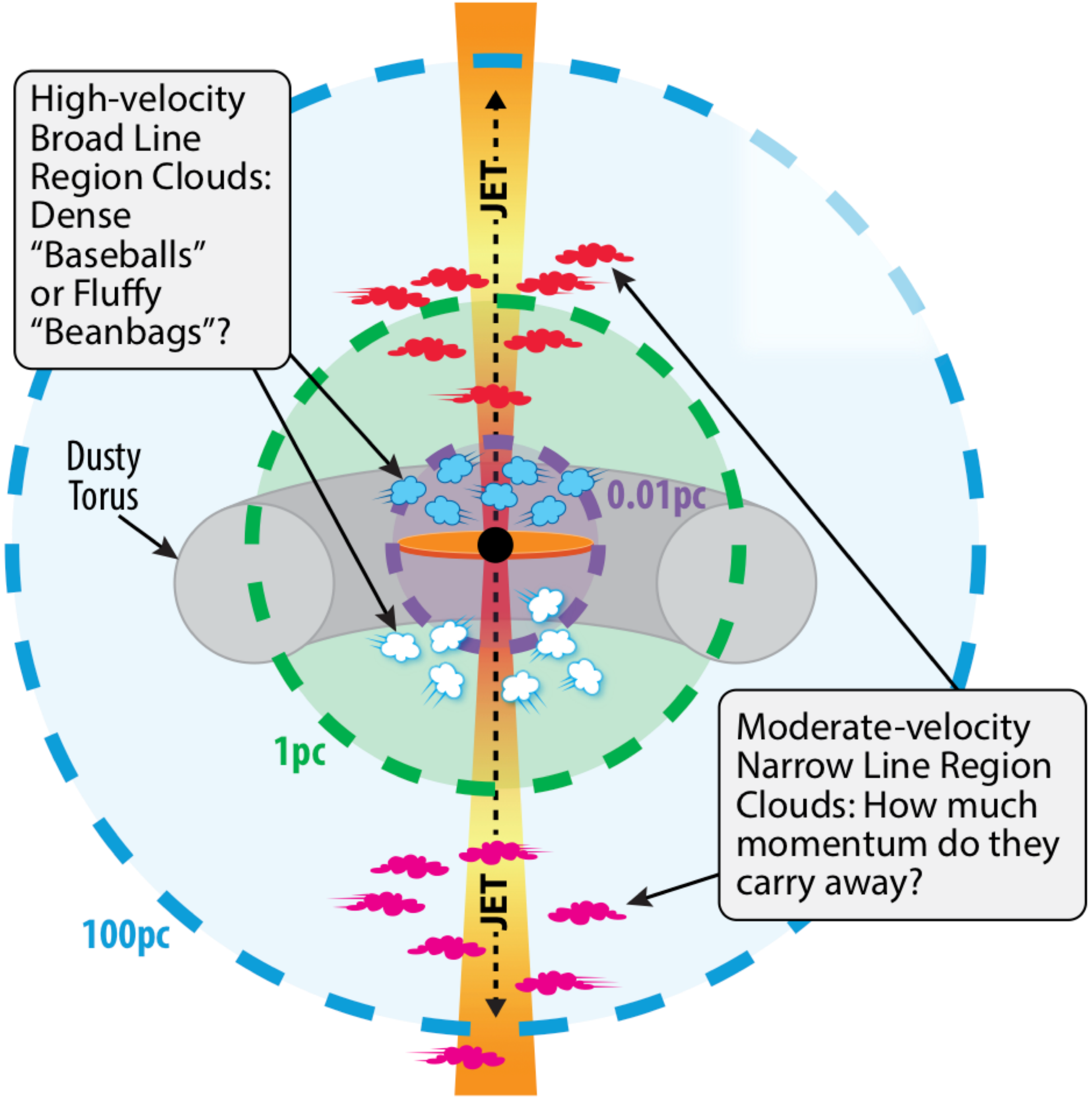
# …And Warm Absorbers with Arcus's Gratings

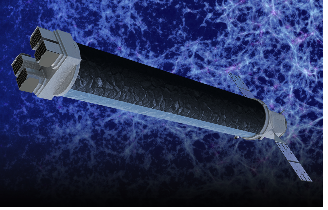
- Arcus measures wind momentum by tracking the response time of the wind properties to changes in the continuum on timescales from 10 ks to 10 Ms.

- Breaks degeneracy between the density of the outflowing wind and its launching radius:

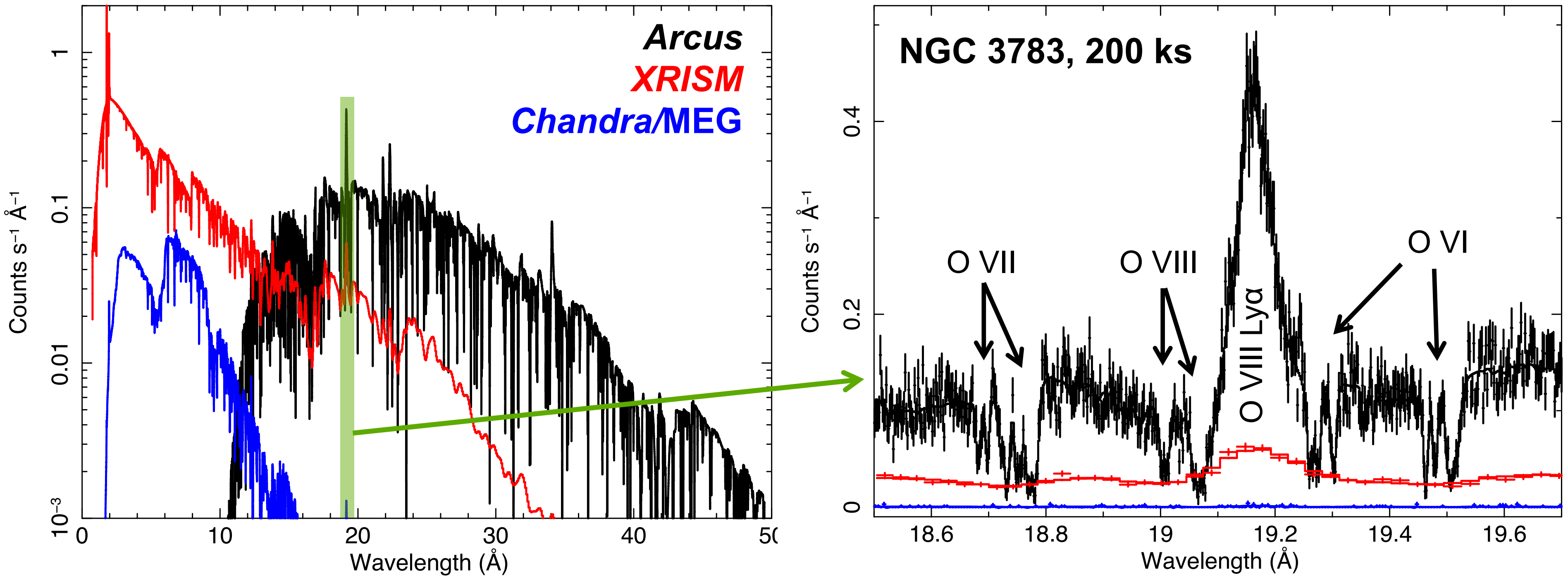
$$\textit{Gas ionization} \propto \frac{L}{nr^2}$$

- Important implications for the role of AGN feedback in shaping host galaxies: kinetic power goes as $v^3 N_H r$

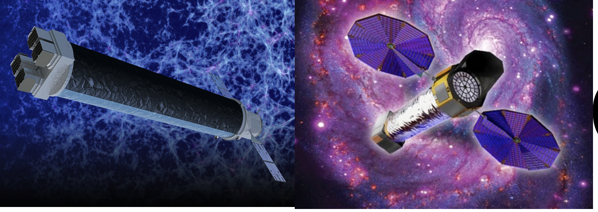




# …And Warm Absorbers with Arcus's Gratings

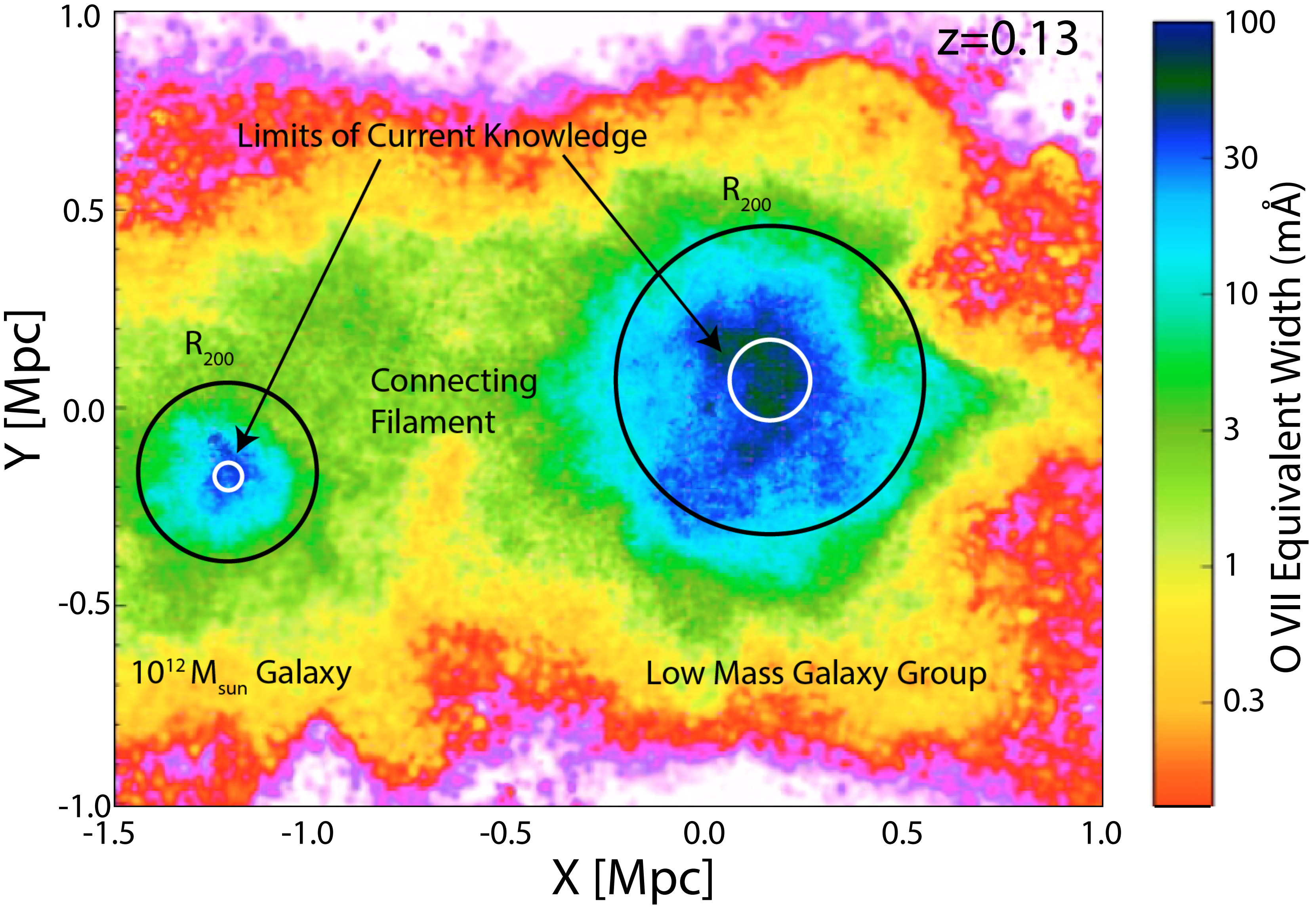



Arcus is superior to current gratings, both in spectral resolution and effective area, providing an order-of-magnitude improvement in sensitivity across the 10-50 Å bandpass.



# Characterizing the Hot Halos Around Galaxies

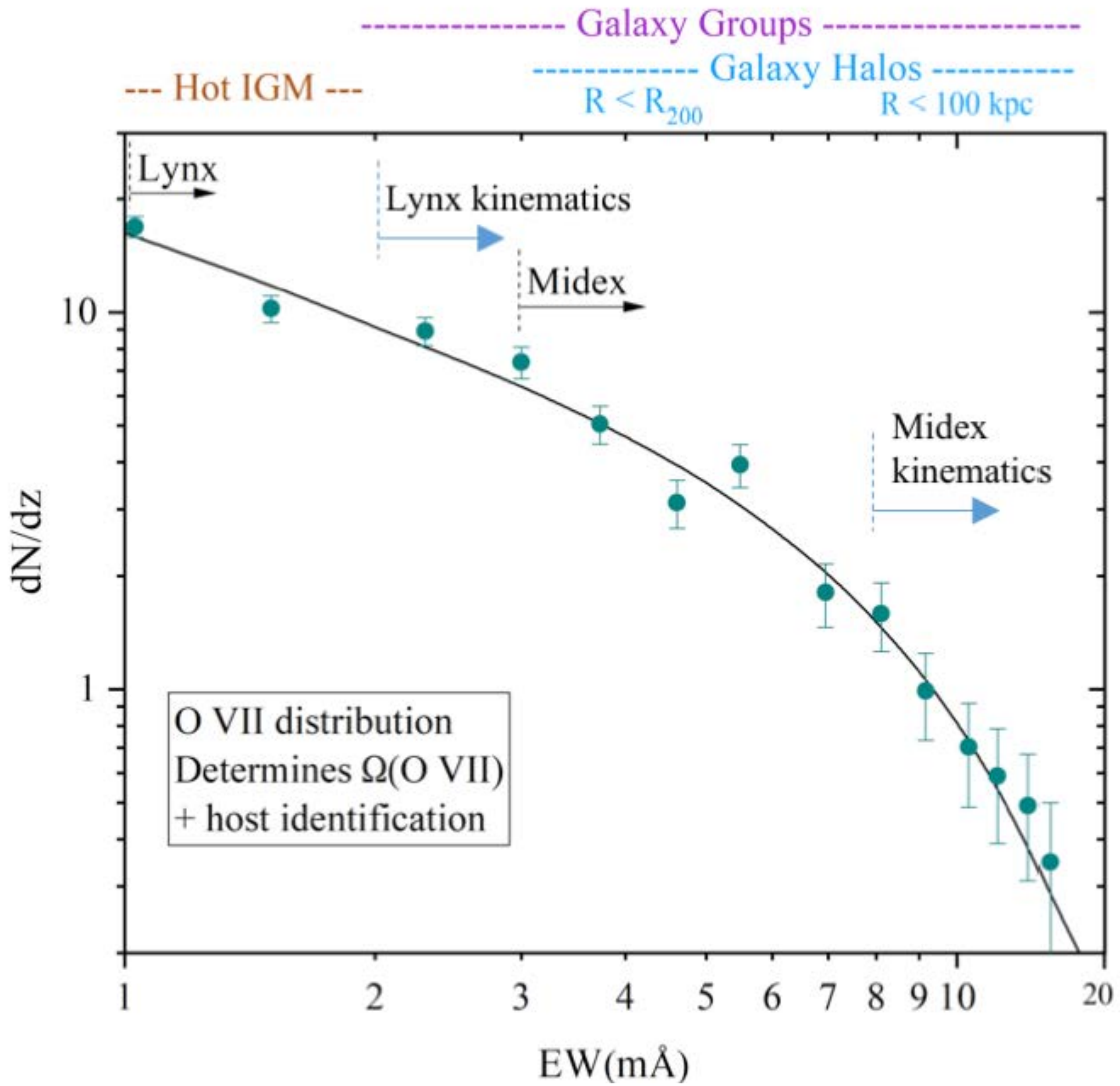
"A statistical sample of robust O VII and O VIII absorption detections requires a future spectroscopic X-ray satellite… Probes of ~$10^6$ K gas will be most sensitive to dense gas either within or at the outskirts of galactic halos… [and] solve the great mystery of why an increasing number of galaxies at low redshifts are red and dead, with no recent star formation." (McQuinn 2016)



# Characterizing the Hot Halos Around Galaxies

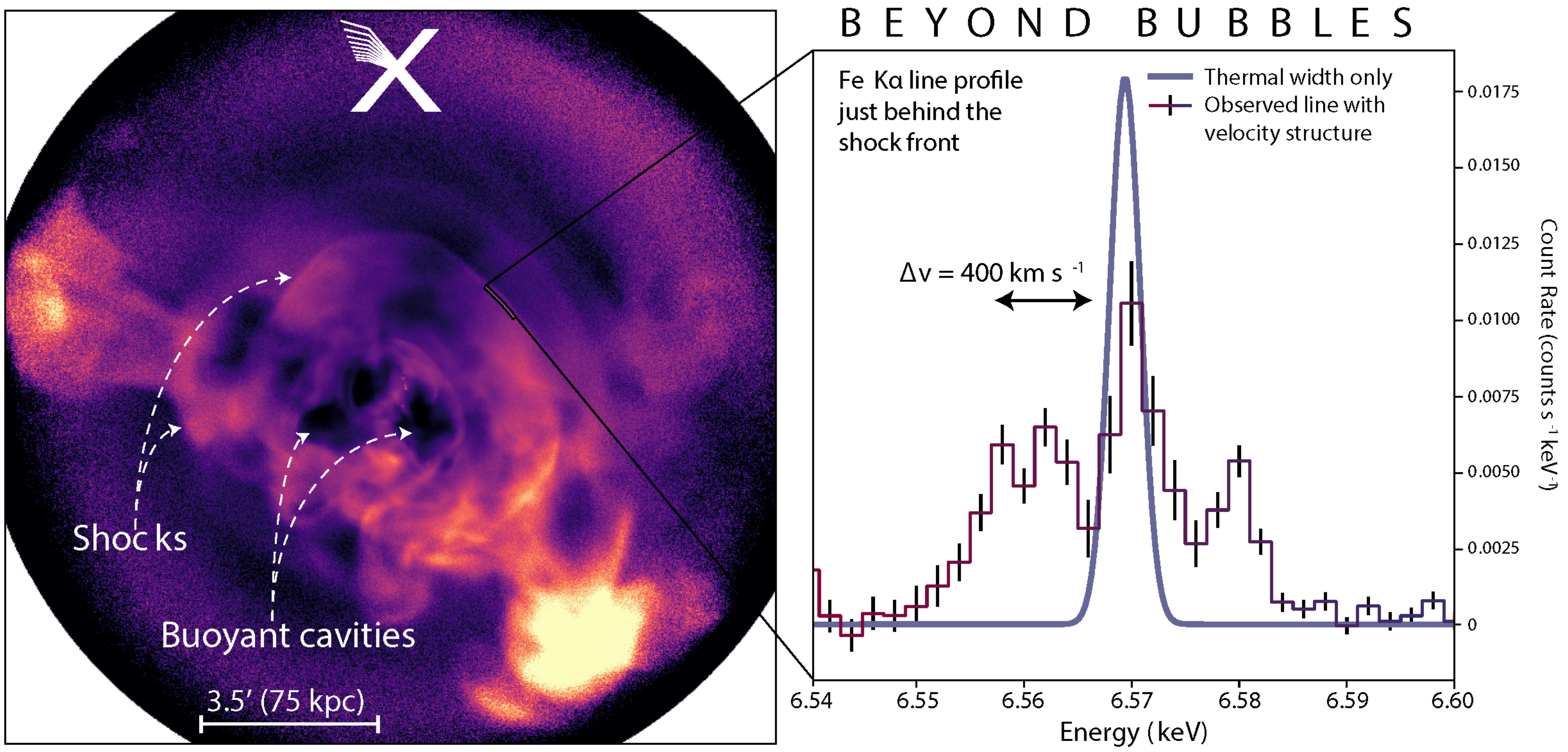
Arcus will survey pencil beams through the hot halos of galaxies, and will measure the kinematics of our own hot halo.

Lynx will be able to measure X-rays both in absorption and emission, detecting ultra-diffuse gas in the hot IGM and measuring motions in the halos of galaxy groups



# Characterizing the Hot Halos Around Galaxies

With ~arcsec imaging resolution and 3 eV resolution, Lynx will measure gas motions in cluster shocks and cavities, revealing just how energy from the central SMBH is dissipated

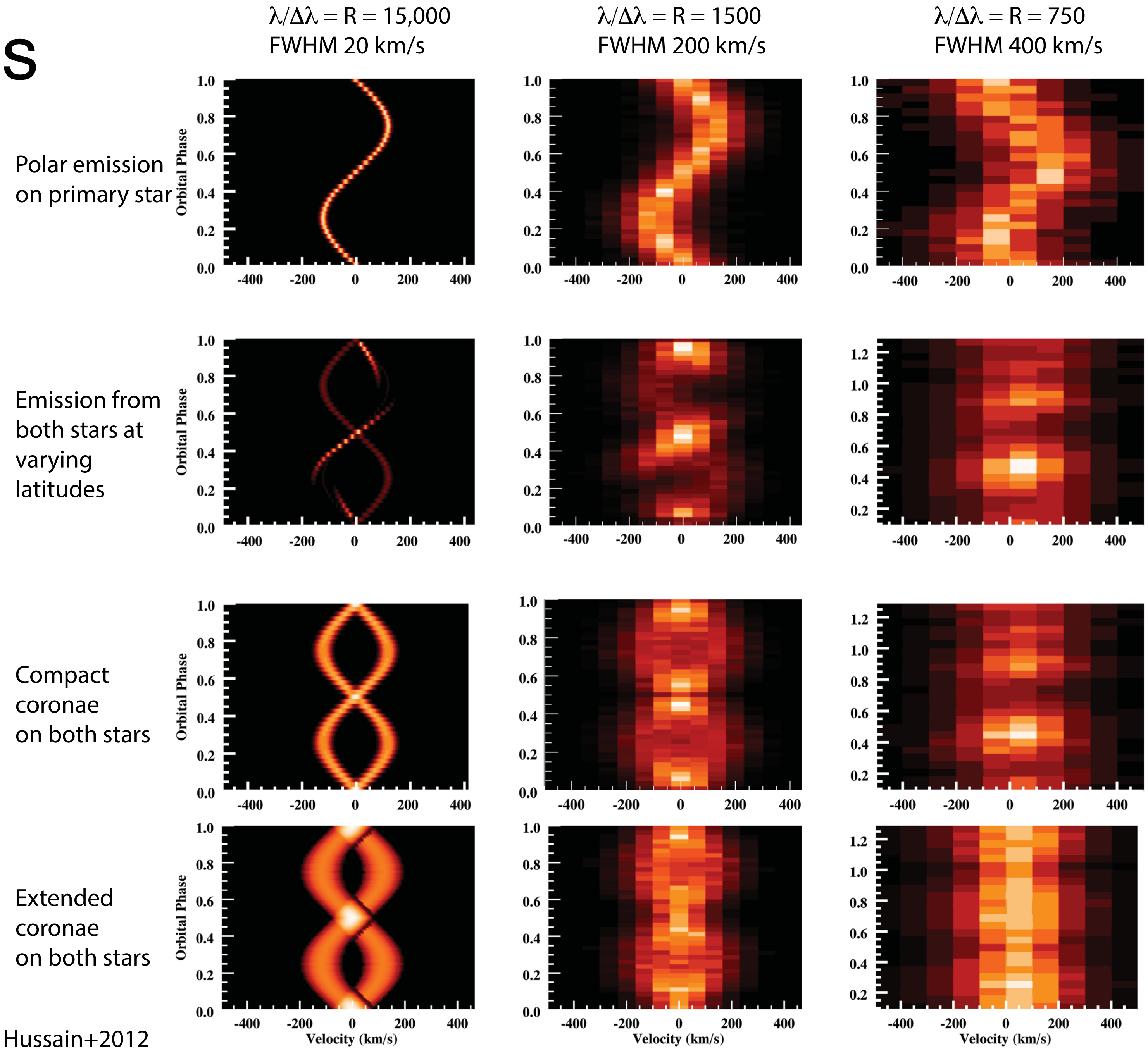



750 ksec LXM exposure of a Perseus-like cluster

Fe-line profile extracted from the LXM data cube

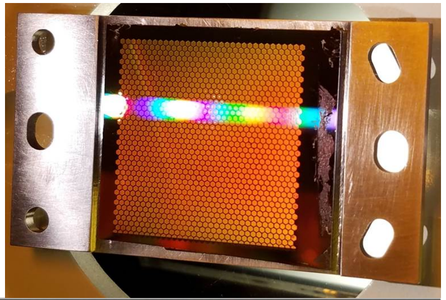
# Stellar physics

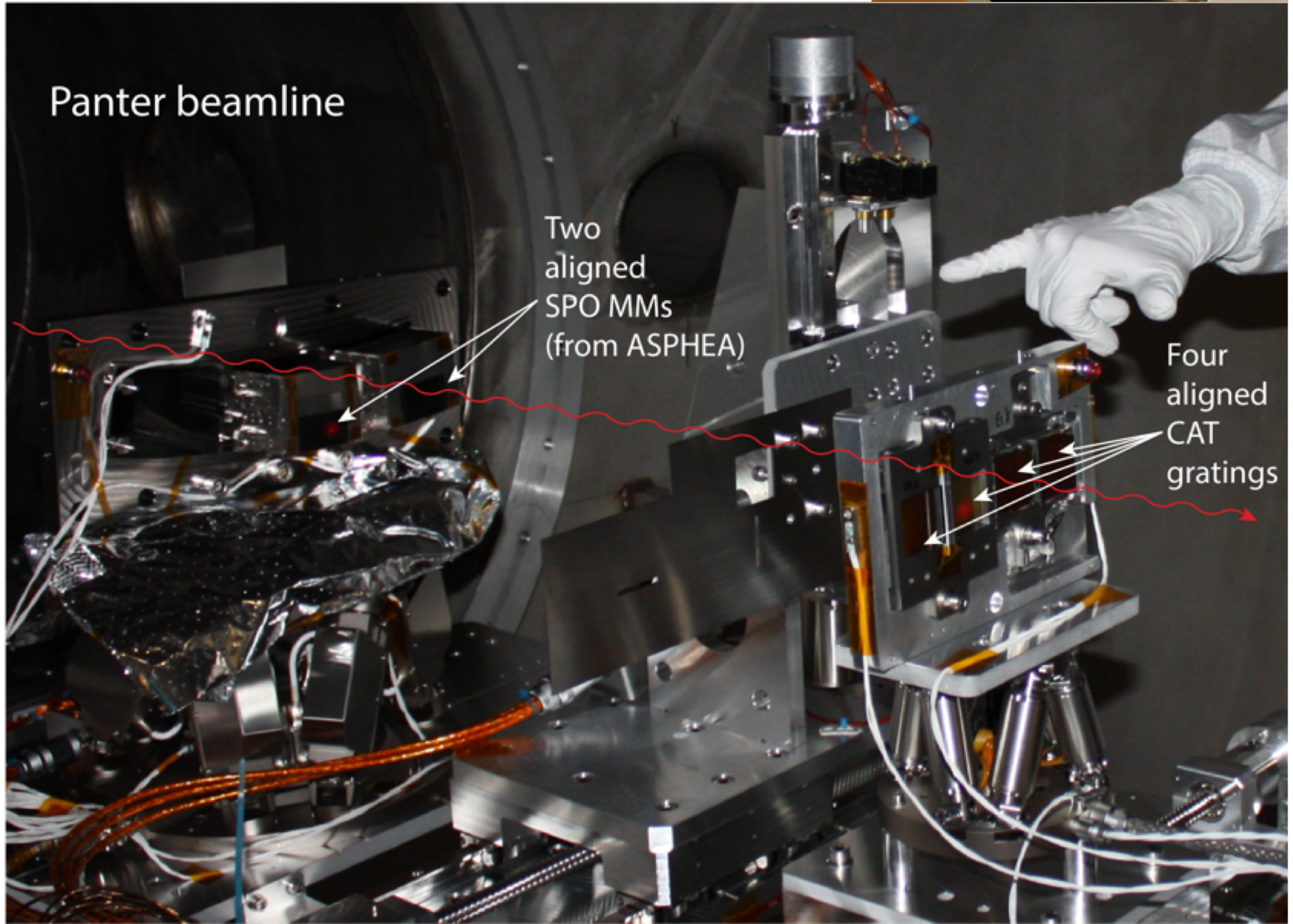
Sufficient X-ray spectral resolution applied to binary stars can not only reveal features due to magnetic fields (stars are not always magnetic dipoles!), it can even determine the size of the corona of each star.

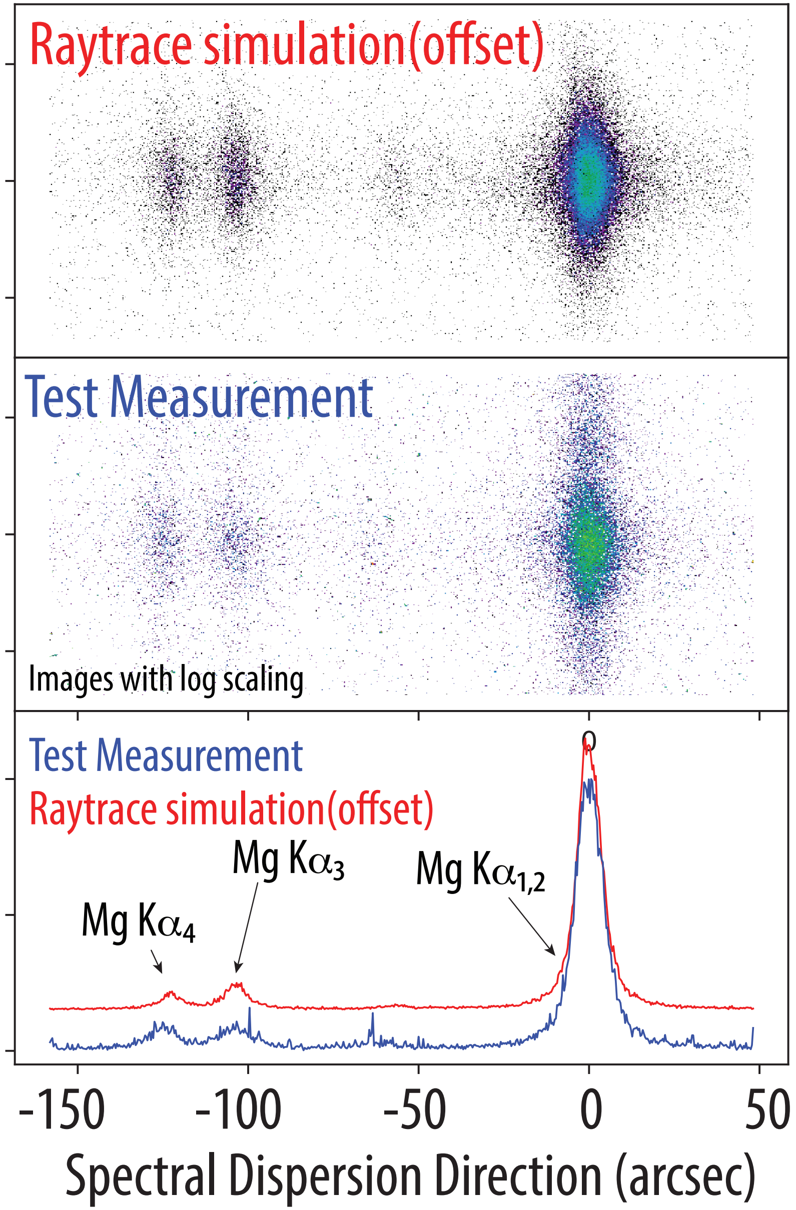



Hussain+2012

# Critical-Angle Transmission Gratings



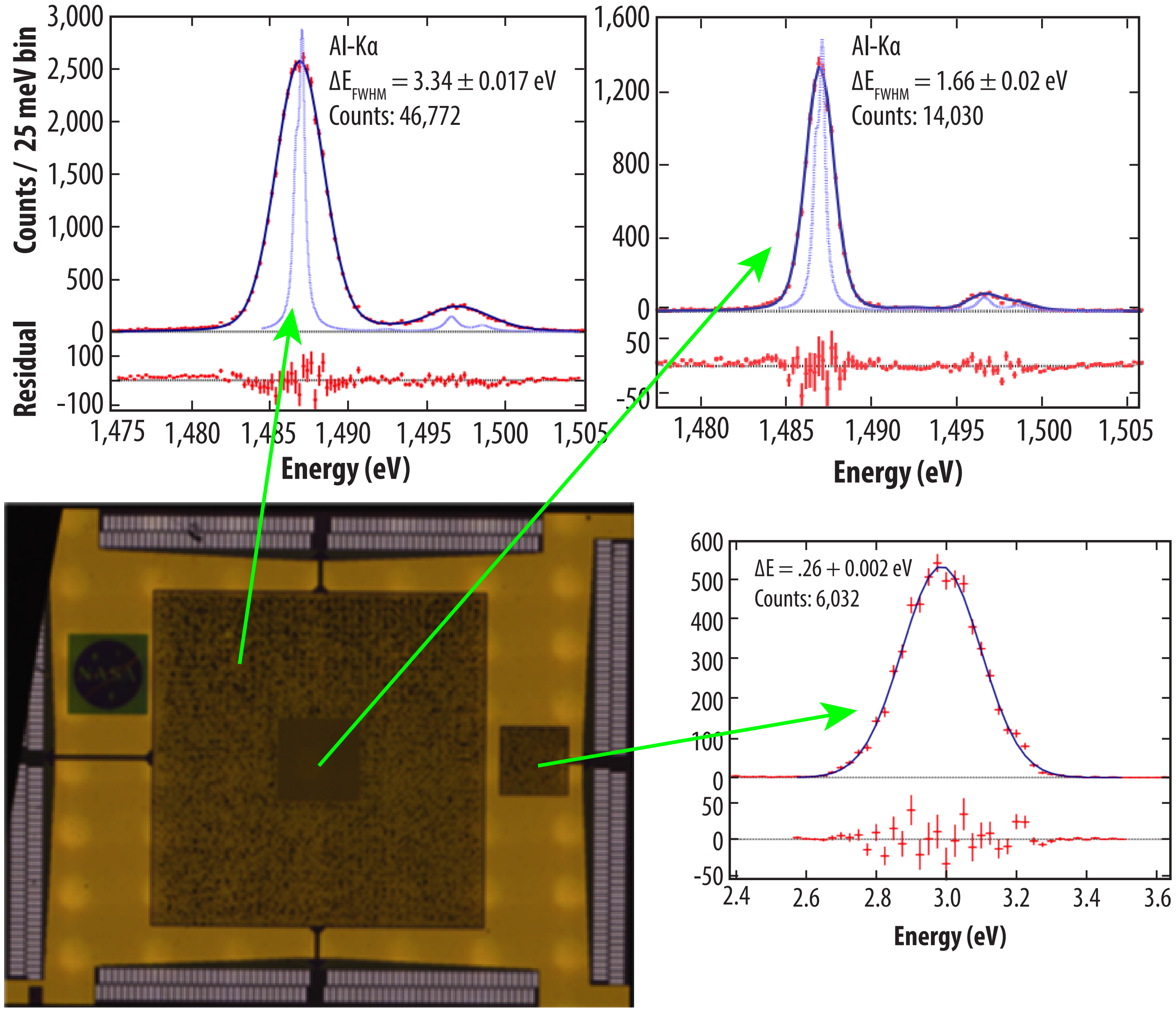


# Microcalorimeter Arrays

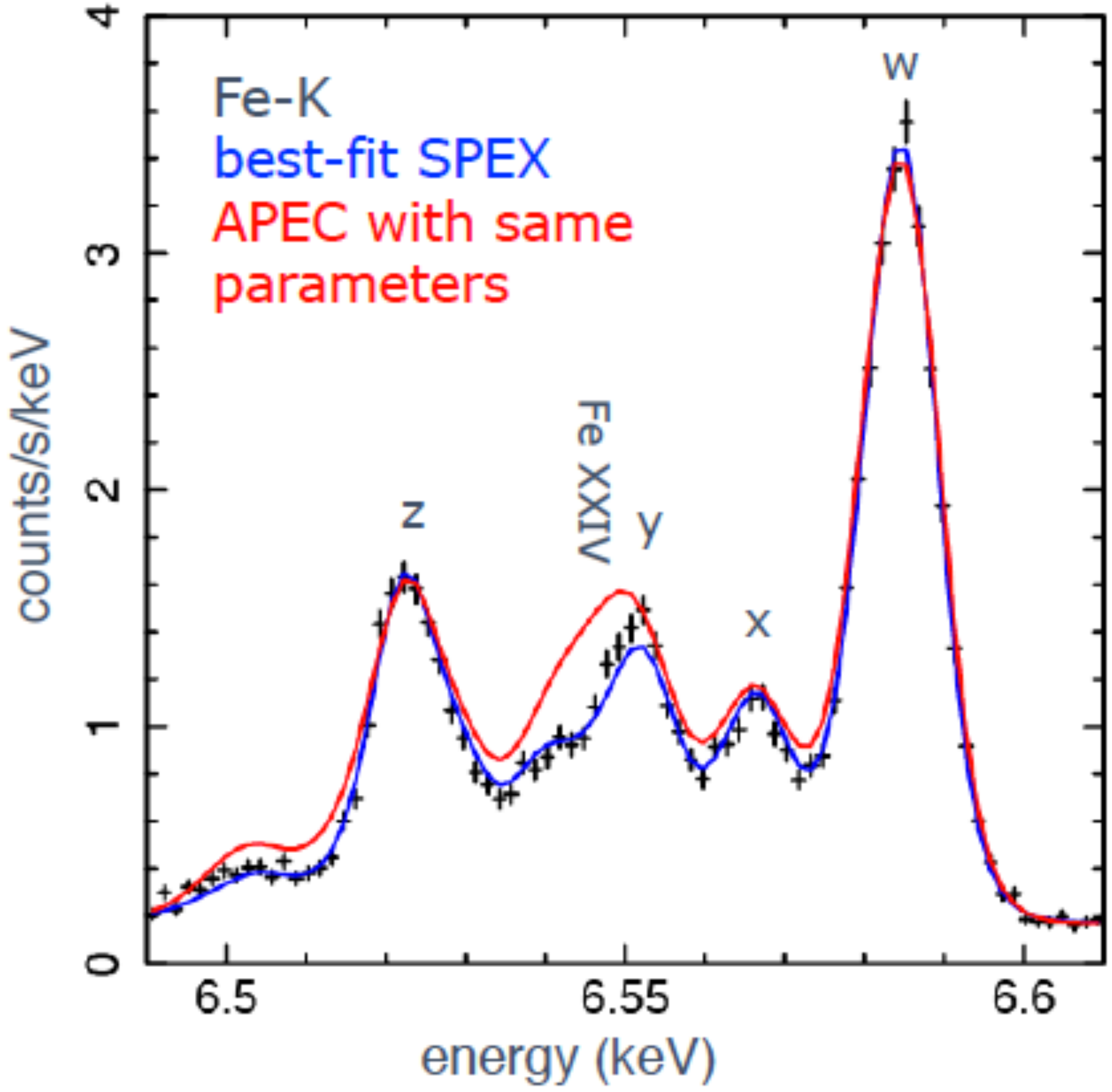
Hitomi/Resolve, Athena/X-IFU, and the Lynx/LXM all use microcalorimeters to measure X-ray energies non-dispersively.

The most challenging technology is, unsurprisingly, in Lynx and yet is well on its way to a full demonstration



# Plasma Spectral codes

- 20+ years ago we transitioned from “**Raymond-Smith**” and “**Mekal**” to **AtomDB** and **SPEX** to get ready for Chandra and XMM-Newton.
- Today, excitation rate calculations can differ by up to 70% at 4 keV
- Fe XXIV inner-shell radiative/Auger rates and branching ratios differ by up to 50%
- ➤ Iron abundance results differ by 16%



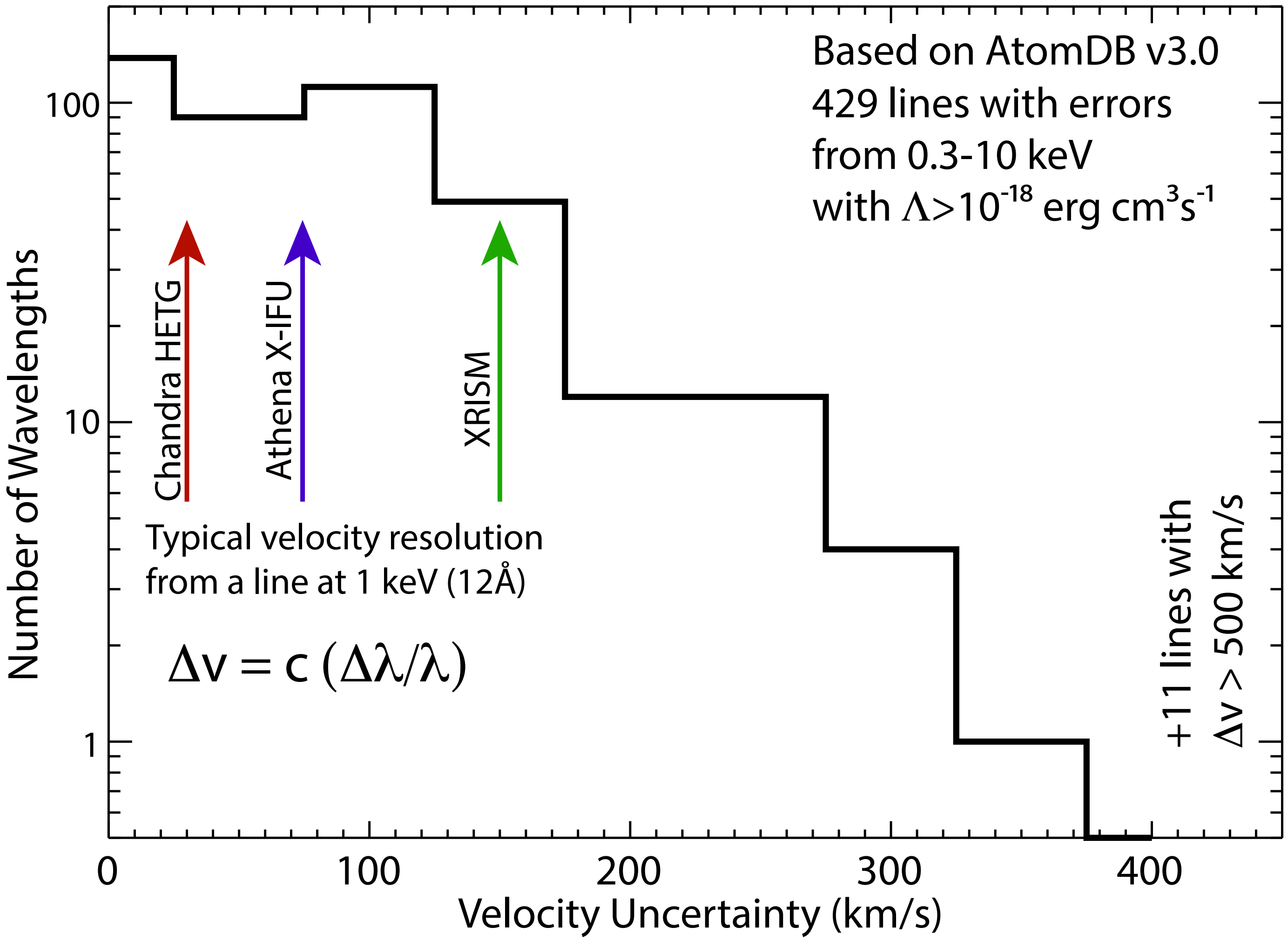
# Plasma Spectral codes

| Effect | Flux | Temperature | Abundances | Turbulence | Column density |
|---|---|---|---|---|---|
| Plasma code | - | - | 15% | 10% | 40% |
| Ionisation balance | 3% | - | - | - | - |
| T-structure | 3% | 3% | 10% | - | 30% |
| Resonance scattering | - | - | 10% | 10% | - |
| Effective area | 5% | 3% | - | - | - |
| Energy scale | - | - | 15% | 10% | - |

Hitomi Collaboration 2014

The effect of systematics on results; note that uncertainty in the plasma code is amongst the largest terms.

# Plasma Spectral codes




Substantial work remains to be done even in measuring wavelengths

# Conclusions

- 20 years ago, Chandra & XMM-Newton opened up the X-ray world, especially via CCD-resolution imaging spectroscopy, and the results have been transformative.
- The next 20 years will see high-resolution imaging spectroscopy with microcalorimeters, as well as sensitive grating spectroscopy. Features just at the edge of detectability will become summer projects for undergrads.
- The technology is ready and while we have work to do on modeling (and analysis!) codes, it's going to be an exciting time!