Benchmarking atomic physics data for X-ray astrophysics with measurements at the Livermore EBITs

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ESAC seminar

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Lawrence Livermore National Laboratory

NASA

ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Friedrich-Alexander-Universität Erlangen-Nürnberg

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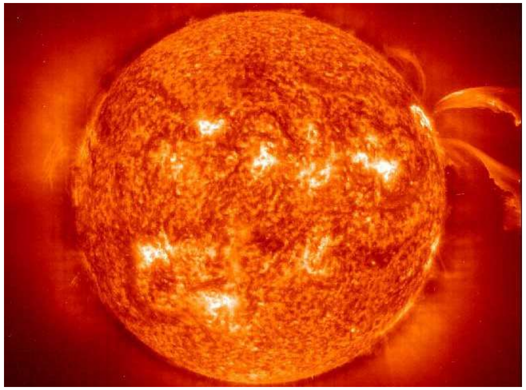
Astrophysics through spectroscopy

Helix nebula

Credit: NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner (STScI), and T.A. Rector (NRAO)

The Sun



Credit: NASA & European Space Agency (ESA)

What can we learn about celestial objects?

composition of stars, clouds; dynamic processes

How do we know?

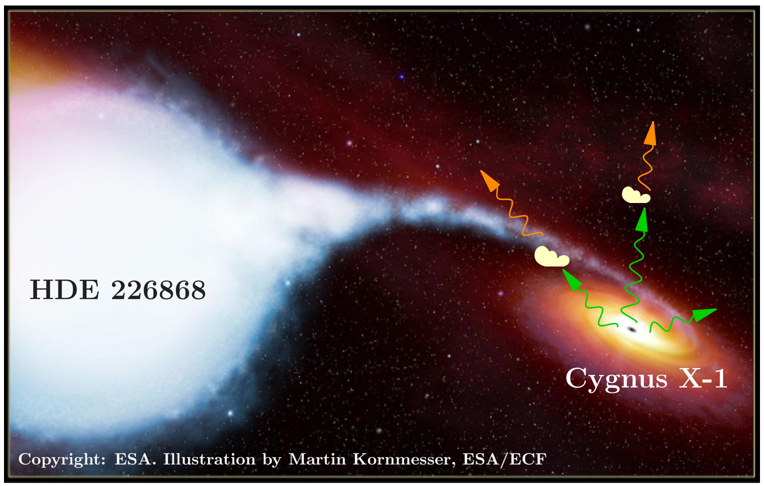
Doppler shifts; temperature / density diagnostics

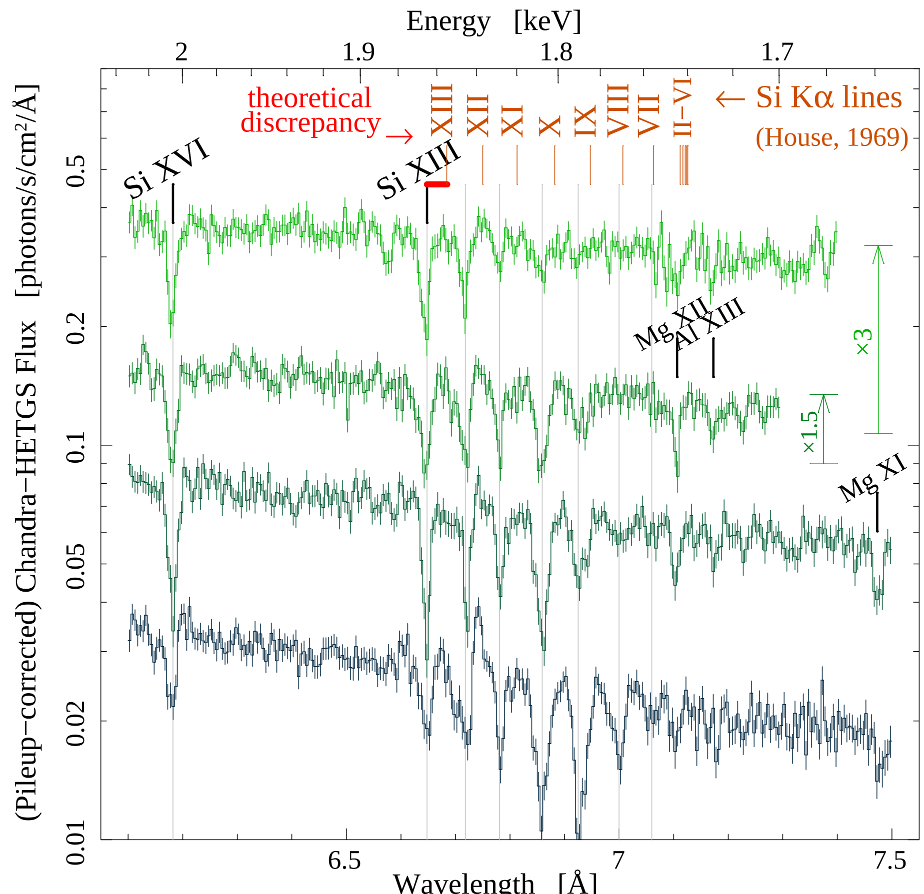
What do we need to know first?

accurate atomic physics references: wavelengths, cross sections, radiation rates, ...

K-shell transitions of low charge states

Example:
Black hole high-mass
X-ray binary Cygnus X-1



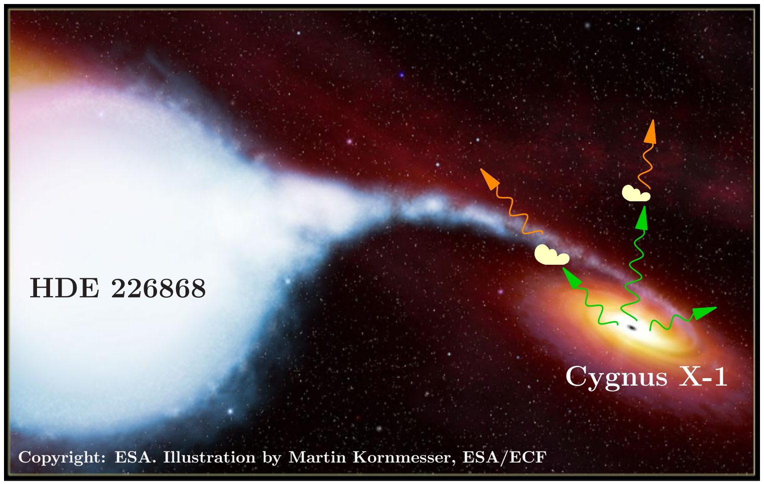


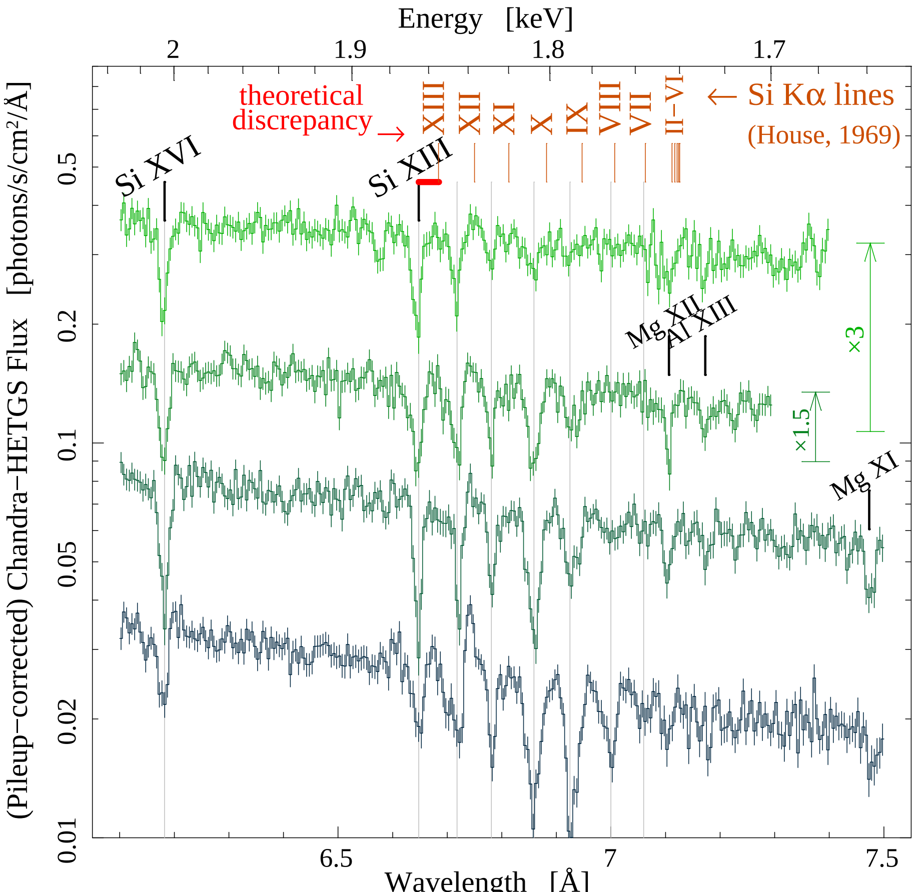
Miskovicova+2010

- 1s – 2p transitions in various ions of Si and S
- similar features in:
  - – a variety of sources: X-ray binaries, solar flares, AGN, . . .
  - – other elements

K-shell transitions of low charge states

Example:
Black hole high-mass
X-ray binary Cygnus X-1





Miskovicova+2010

Problem:

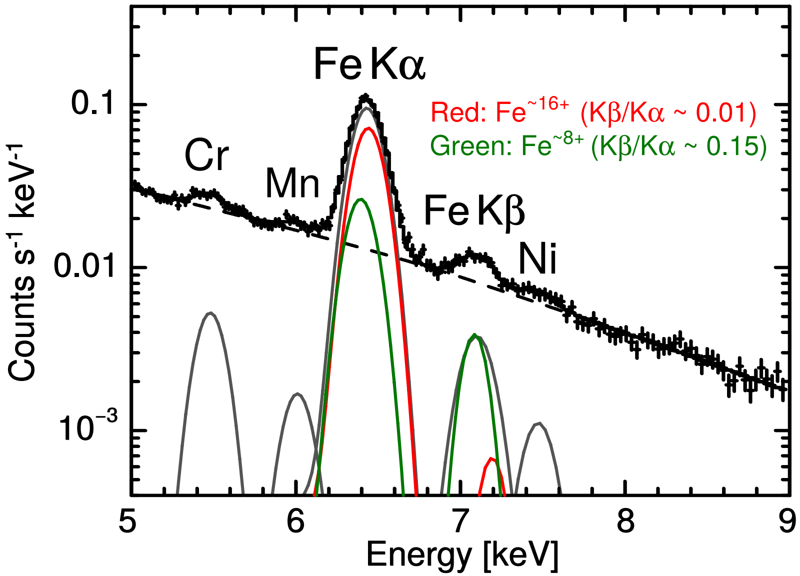
- calculations of transition energies vary $\sim$ 2–5 eV
- uncertainty corresponds to several 100 km s^{-1} in Si

$\Rightarrow$ uncertainties on the order of expected Doppler shifts

The future with Microcalorimeters

Tycho Supernova Remnant

Suzaku-XIS



Yamaguchi et al. (2014)

The future with Microcalorimeters

Tycho Supernova Remnant

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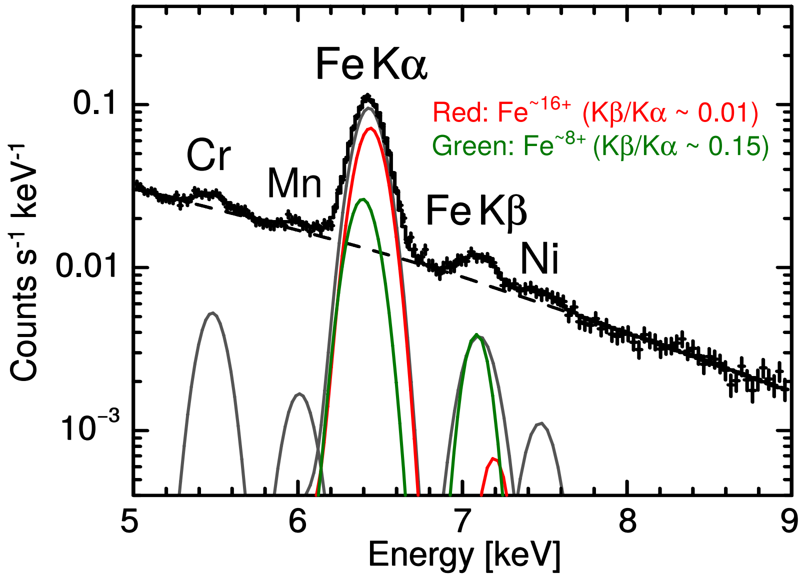
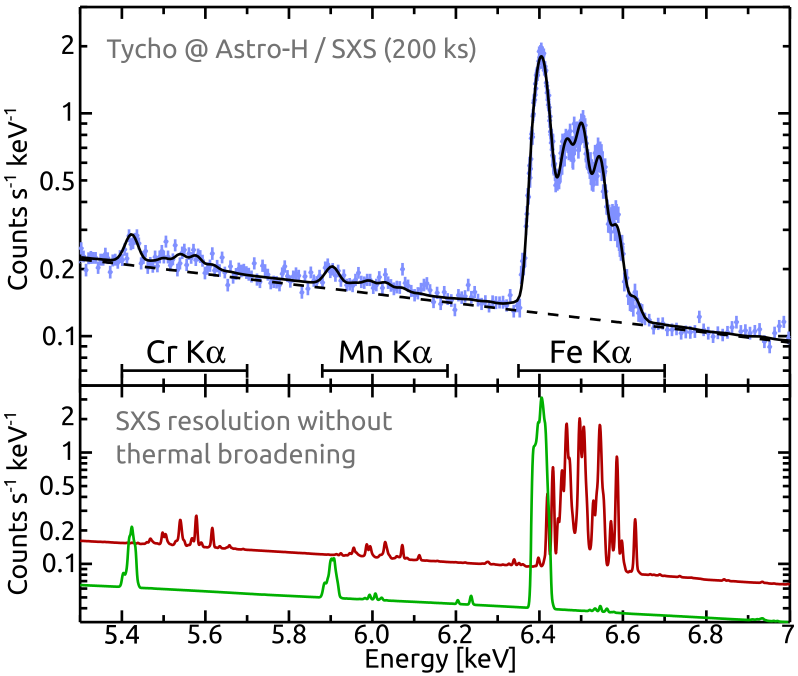


Yamaguchi et al. (2014)

Astro-H-SXS

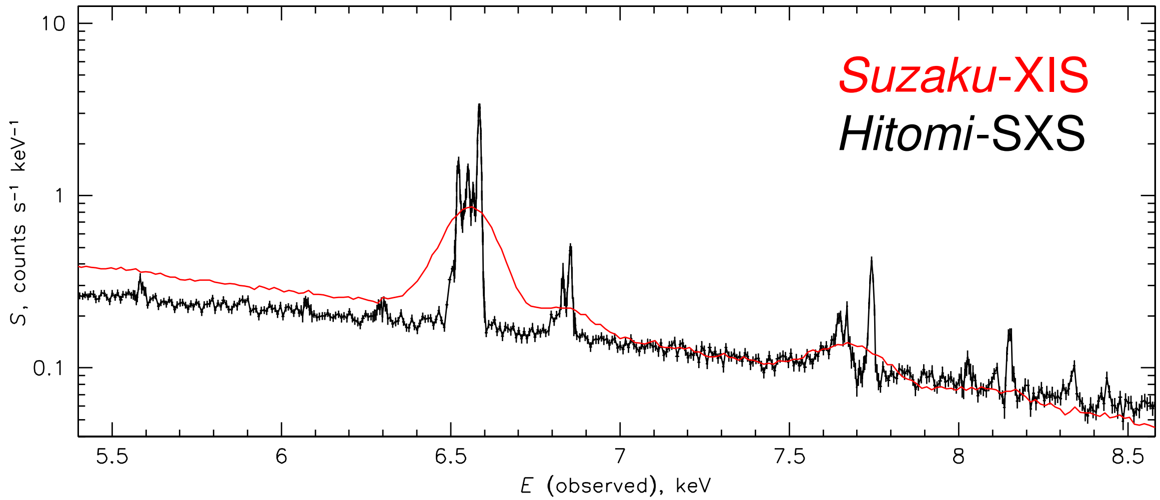


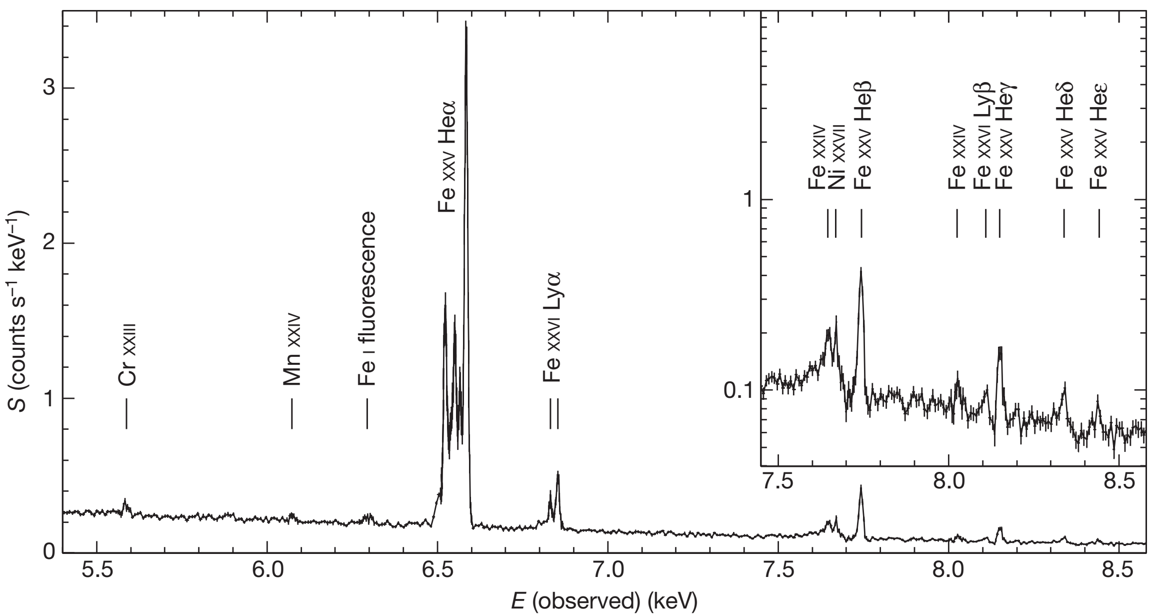
- high-resolution spectroscopy more commonly available – for the first time for extended sources
- improved accuracy on plasma parameters from these spectra

$\Rightarrow$ need reliable reference data

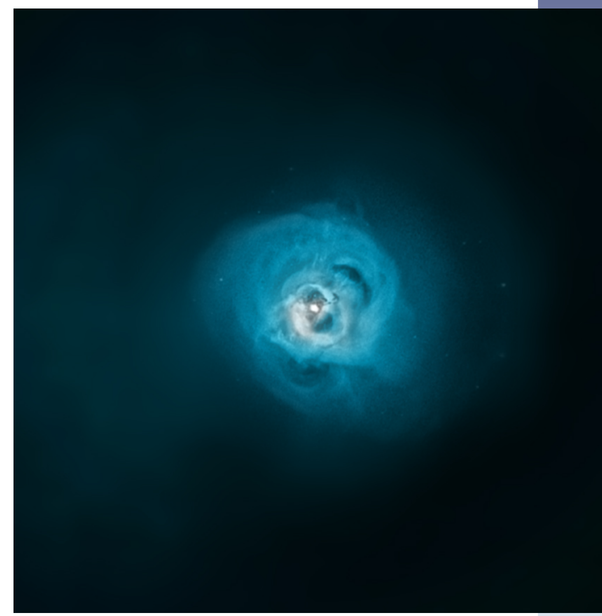
First high-resolution spectra of an extended object

Perseus galaxy cluster with *Hitomi*-SXS





XMM-Newton image of Perseus cluster



`http://chandra.harvard.edu/photo/2014/perseus/perseus_xmm.jpg`

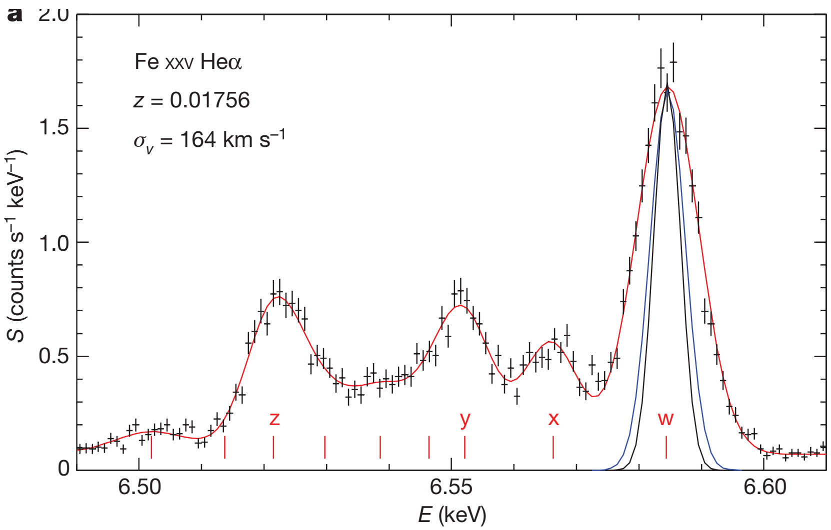
Velocity broadening: $164 \pm 10\,\mathrm{km\,s^{-1}}$

Instrumental resolution: $5 \pm 0.5\,\mathrm{eV}$

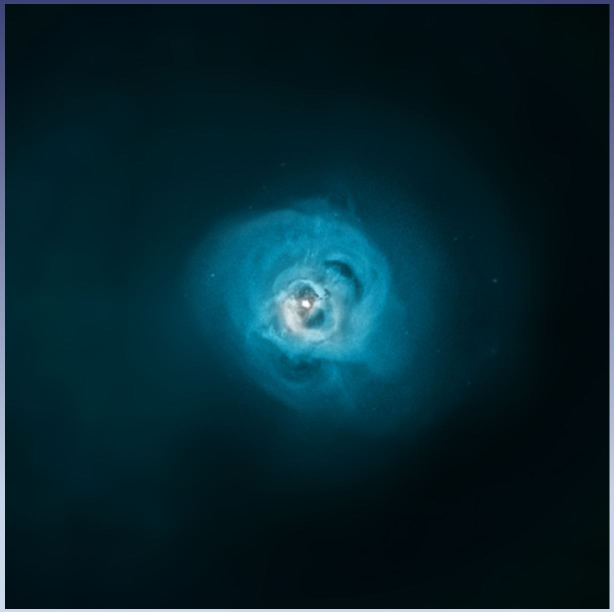
Hitomi Collaboration 2016

Perseus cluster with *Hitomi*-SXS

Fit of individual lines



Hitomi Collaboration 2016



XMM-Newton image of Perseus cluster
`http://chandra.harvard.edu/photo/2014/perseus/perseus_xmm.jpg`

Diagnostics for:

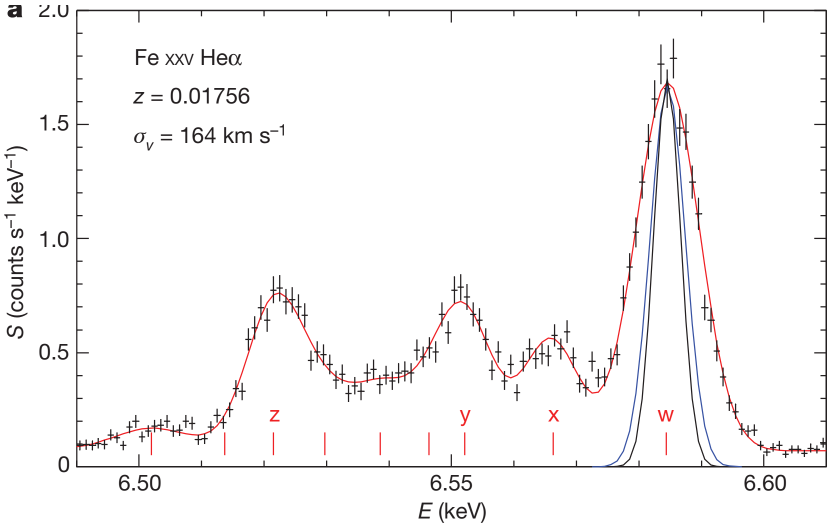
- plasma dynamics
- plasma temperature / density
- resonance scattering
- abundances

Goal for *Athena*:

measure parameters to a few %

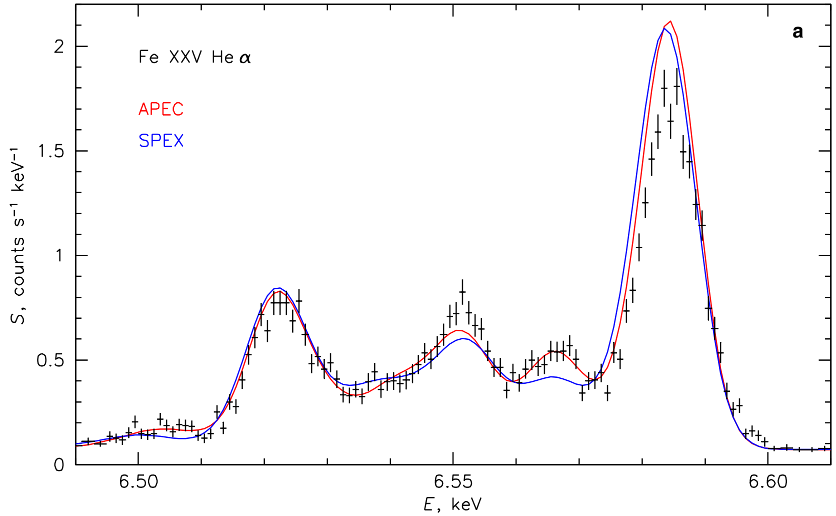
Perseus cluster with *Hitomi*-SXS

Fit of individual lines



Hitomi Collaboration 2016

Fit of plasma physics models

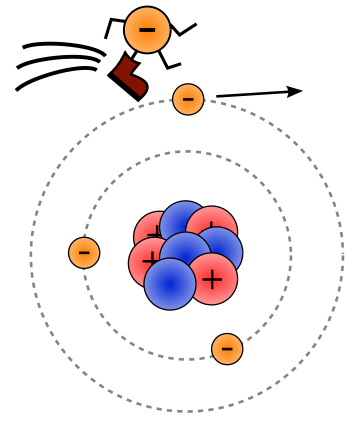


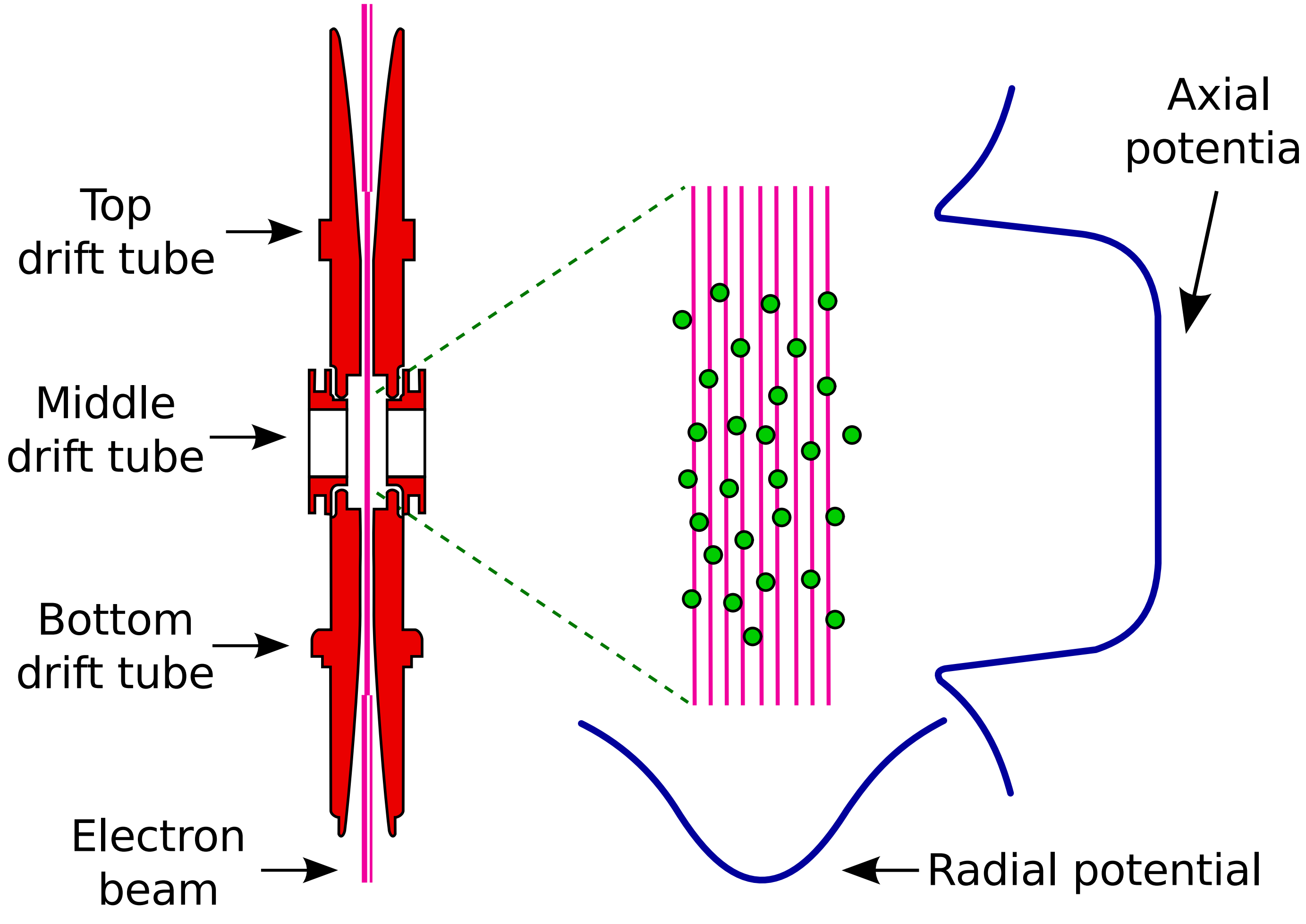
Hitomi Collaboration 2016

- Differences in plasma physics models due to underlying reference data
- missing flux in resonance line due to resonant scattering, which is a diagnostic for ion density

⇒ need good reference collisional excitation cross sections

EBIT operating principle

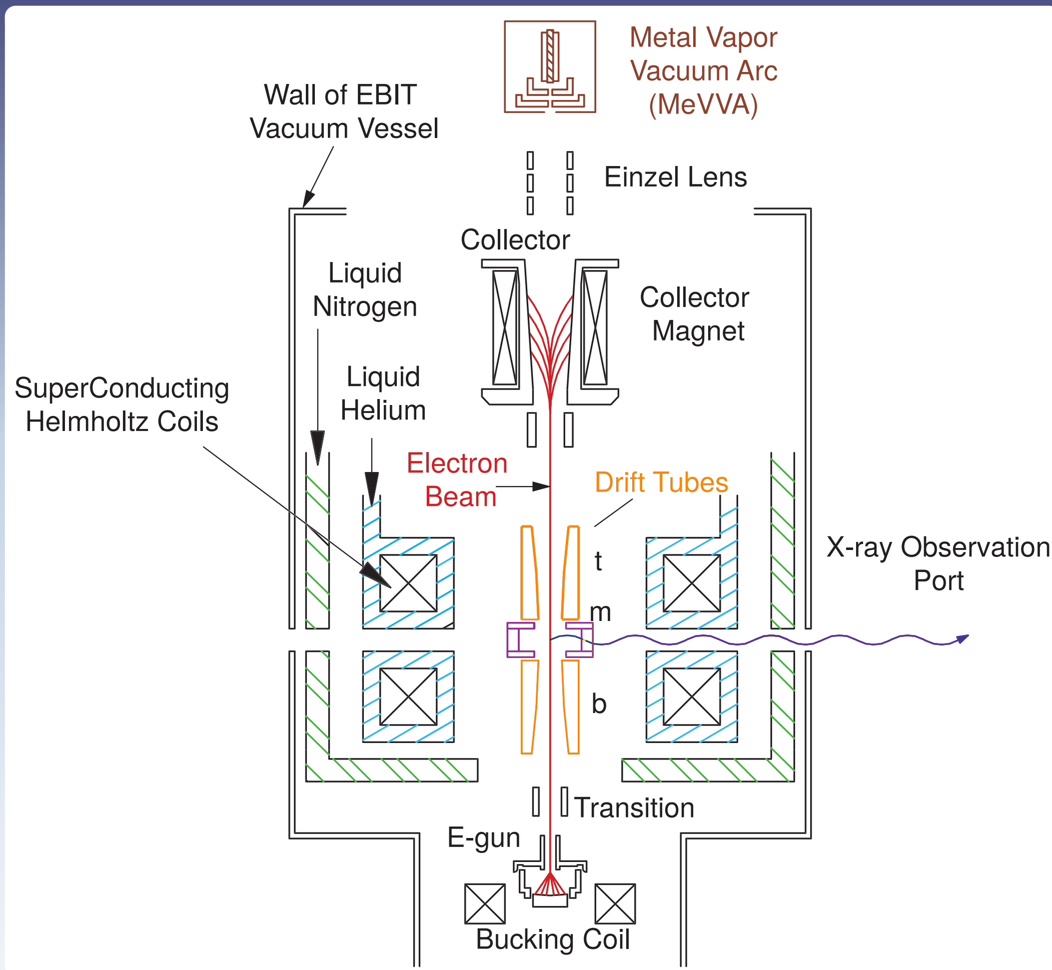


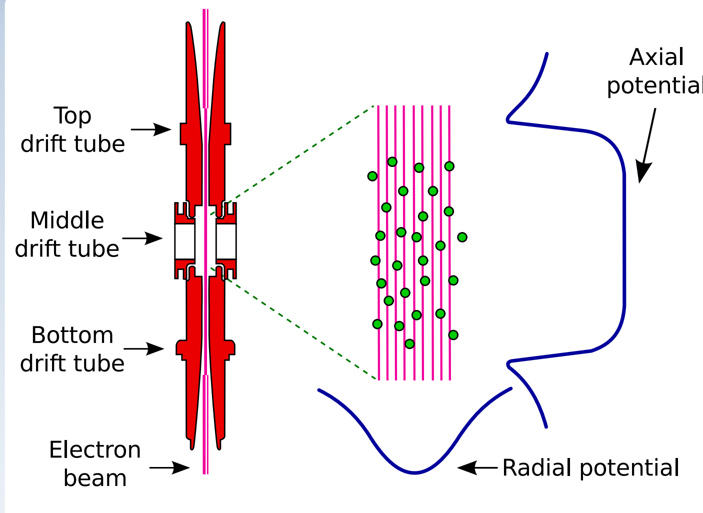


https://ebit.llnl.gov/overviewEBIT.html

ionization and excitation through electron collisions; electrostatic trapping

EBIT setup





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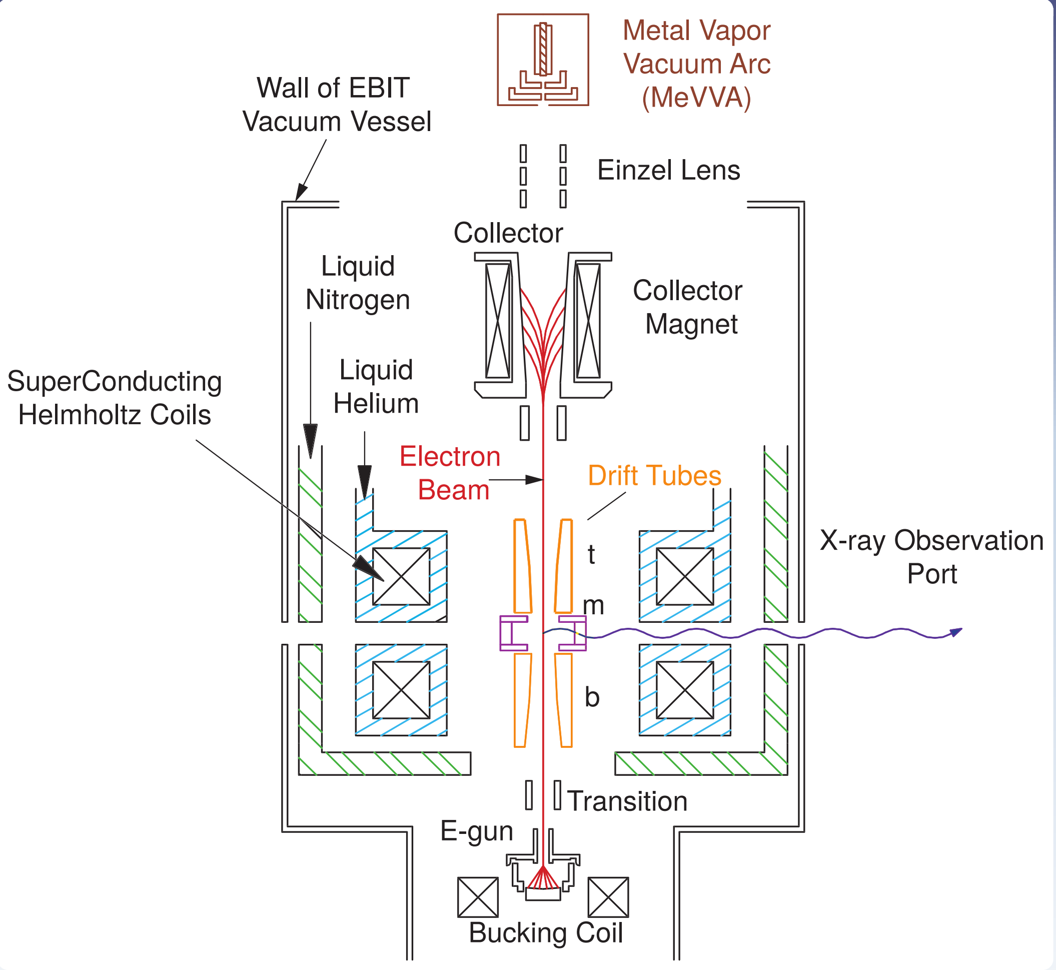
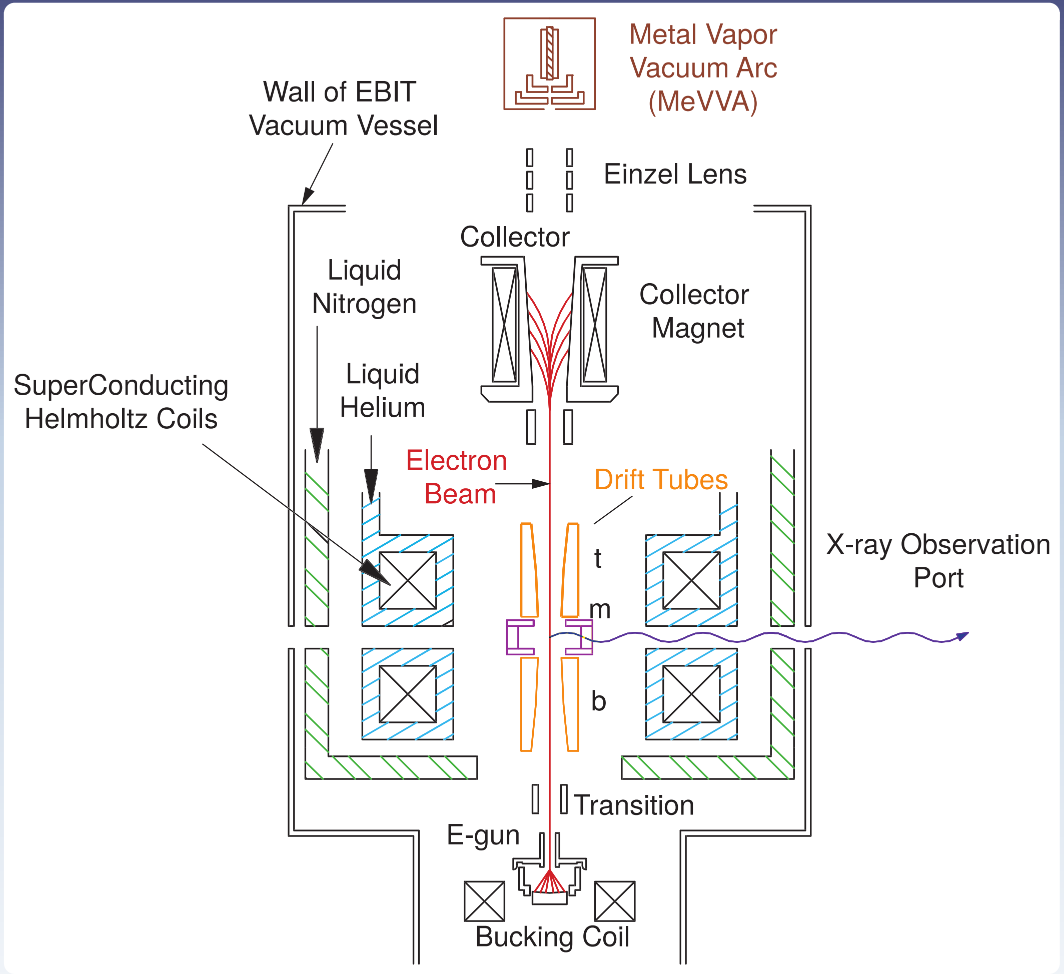
EBIT setup



gun:
electron emissive coating

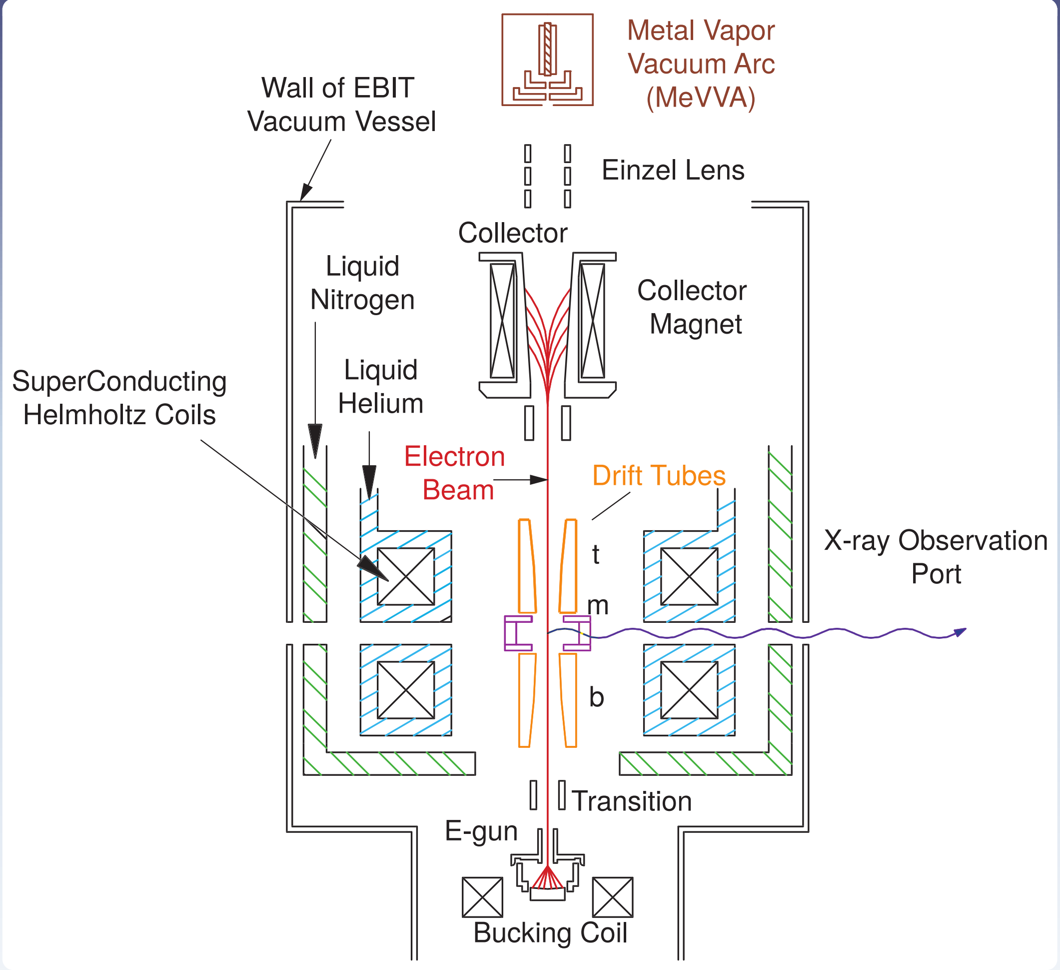
EBIT setup



electrodes:
acceleration and focusing of the beam

gun:
electron emissive coating

EBIT setup

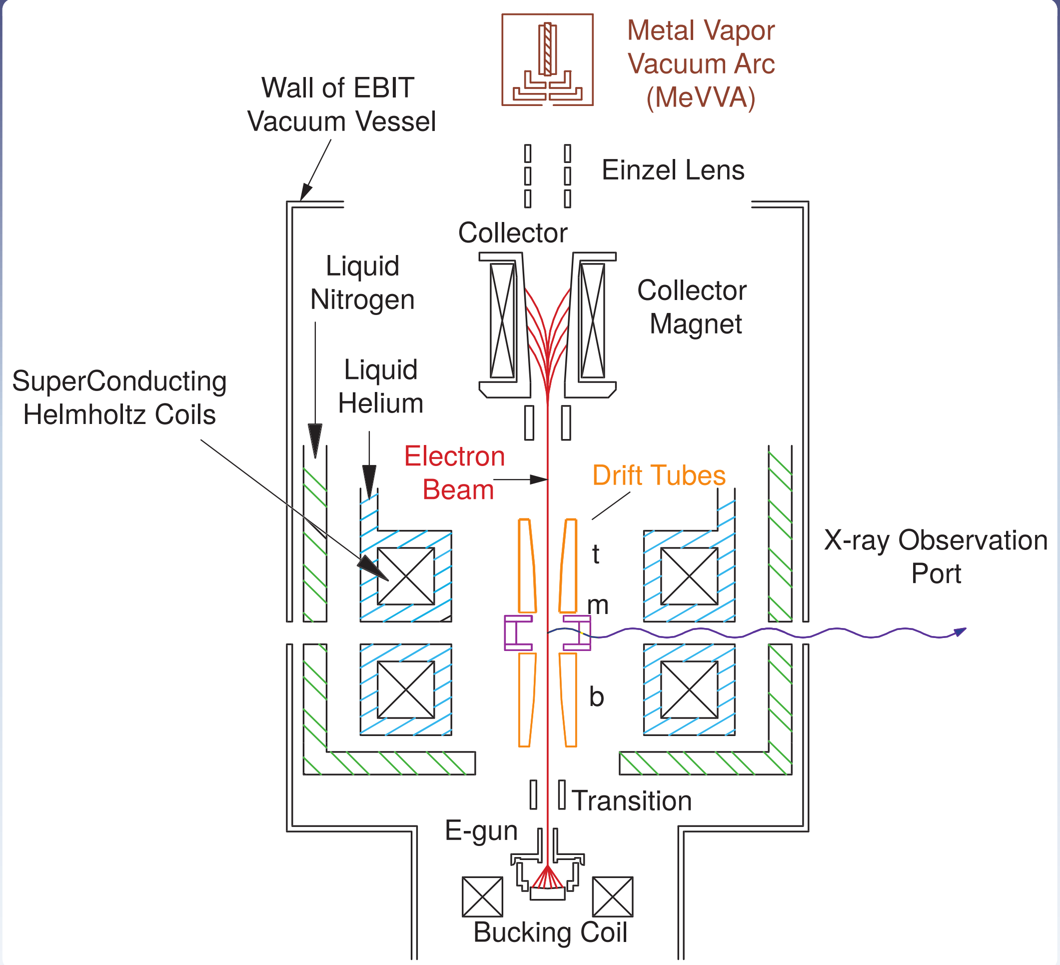


3 T magnetic field:
compression of e-beam

electrodes:
acceleration and
focusing of the beam

gun:
electron emissive
coating

EBIT setup



collector:
defocusing and dumping of e-beam

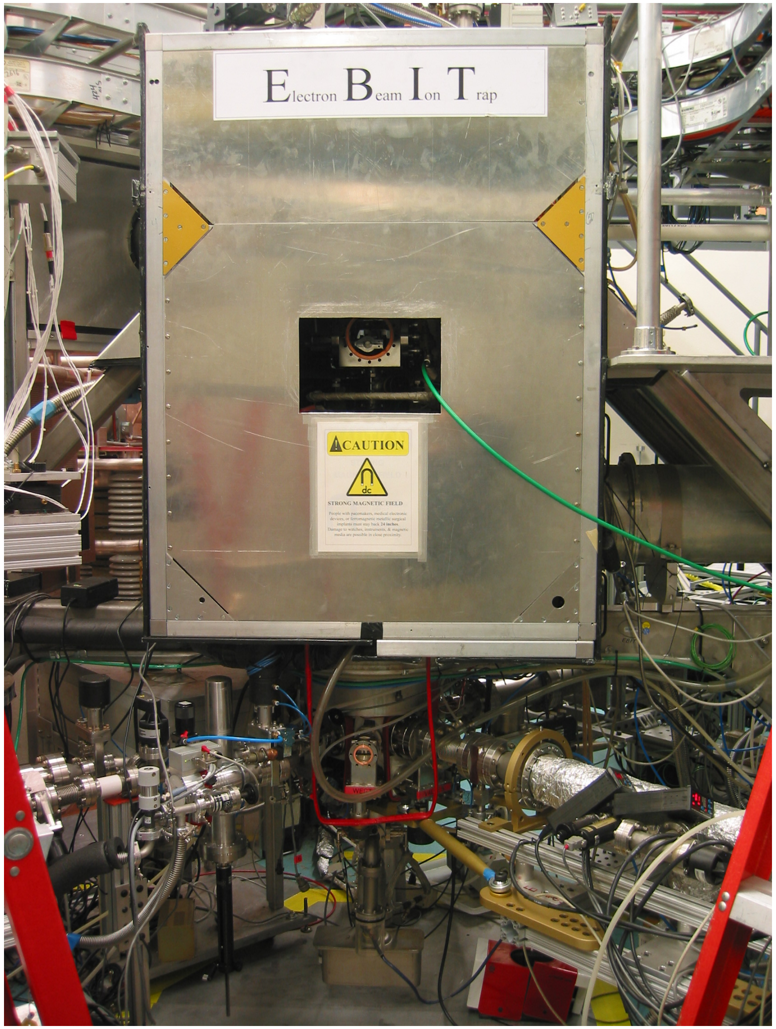
3 T magnetic field:
compression of e-beam

electrodes:
acceleration and focusing of the beam

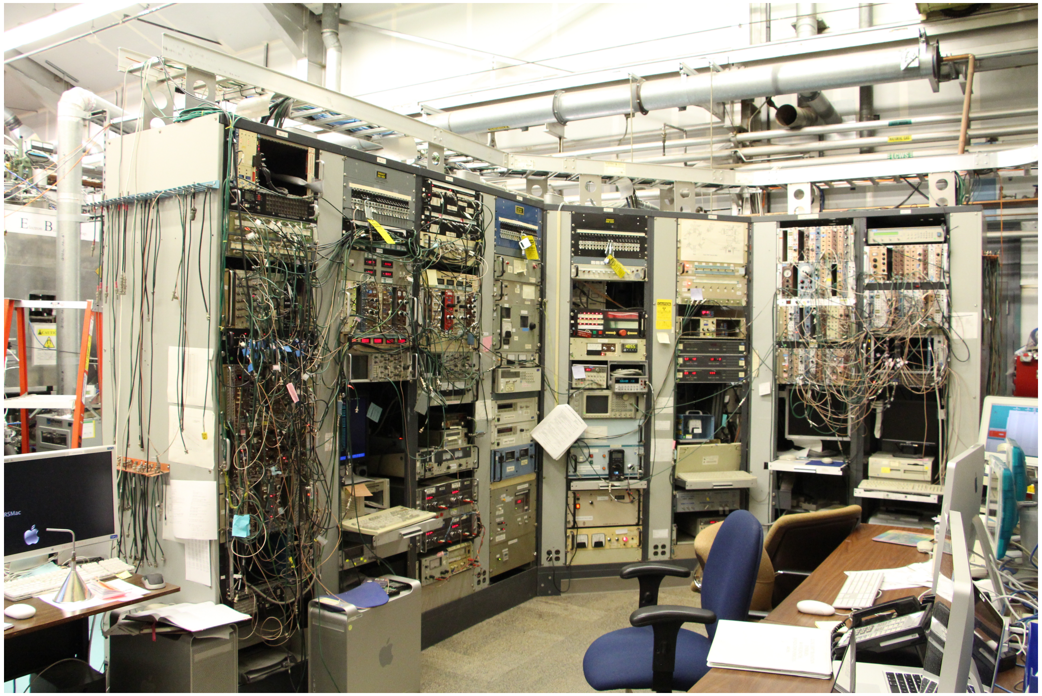
gun:
electron emissive coating

EBIT-I

EBIT-I

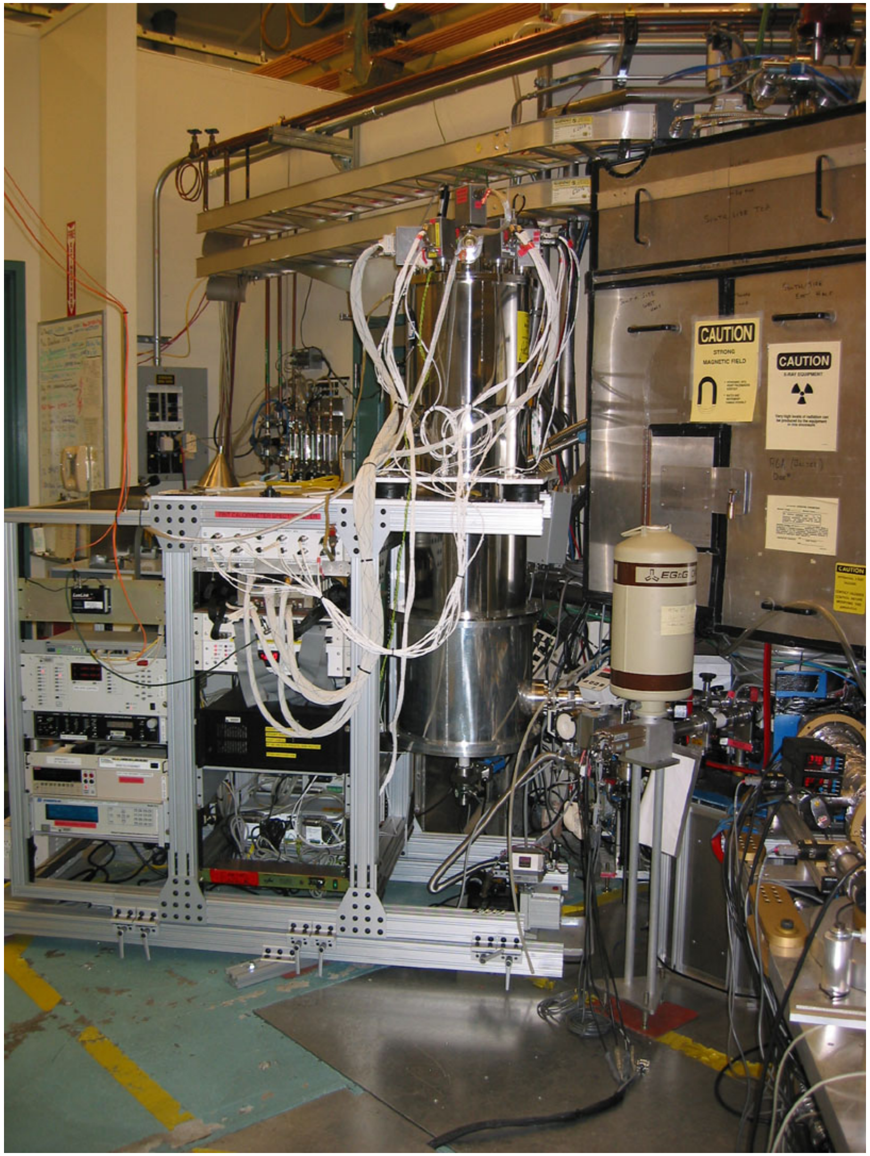


control room

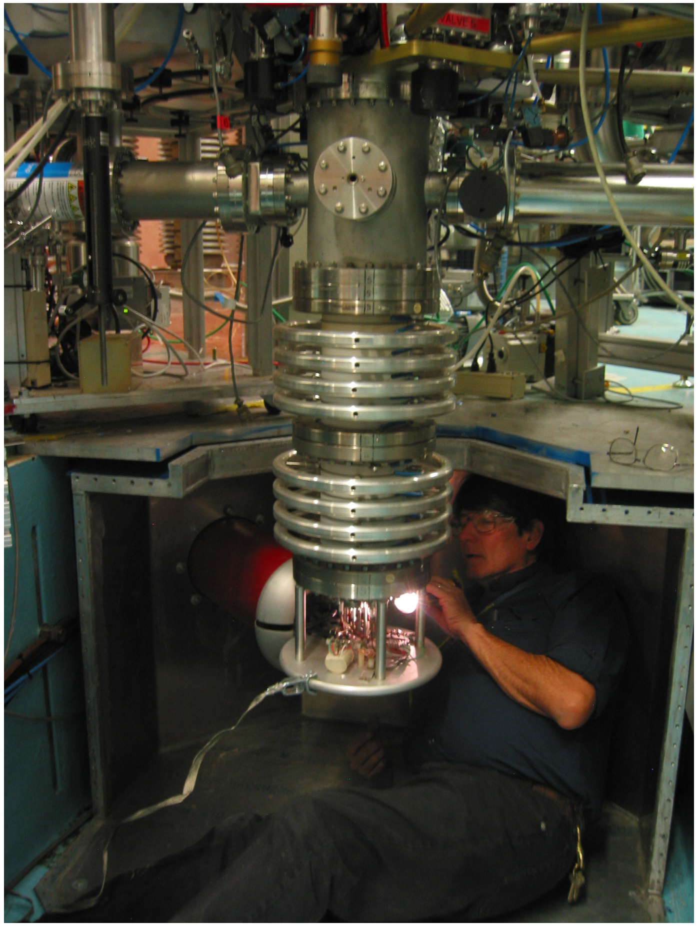


SuperEBIT

SuperEBIT



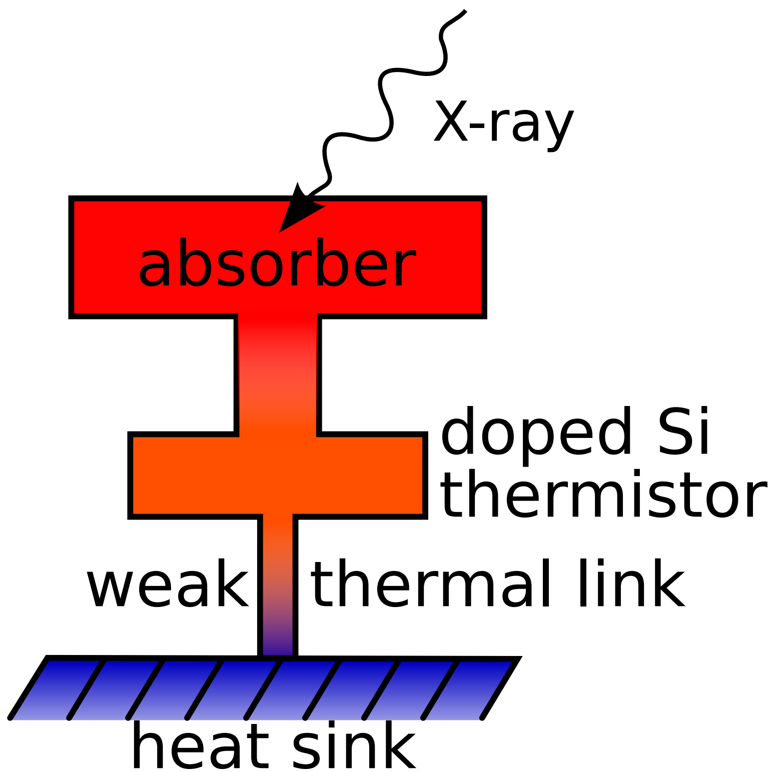
electron-gun assembly



high energy variant, SuperEBIT, can produce bare Uranium (U^{92+})

EBIT calorimeter spectrometer

Micro-calorimeter

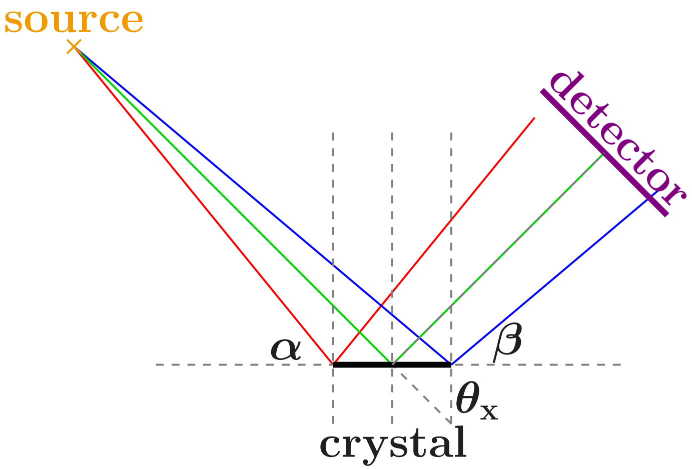


- non-diffractive
- operated at $T < 0.1\,\mathrm{K}$ (heat sink)
- absorbed photon causes rise in temperature $\Delta T \sim E_{\mathrm{photon}}$ (few mK!)
- 16 mid-energy pixels: 0.1–10 keV, $\sim$ 5 eV resolution
- 10 high-energy pixels: 0.5–>100 keV, $\sim$ 30 eV resolution

similar to *Hitomi* SXS, *Athena* X-IFU

High-resolution crystal spectrometer

Diffractive

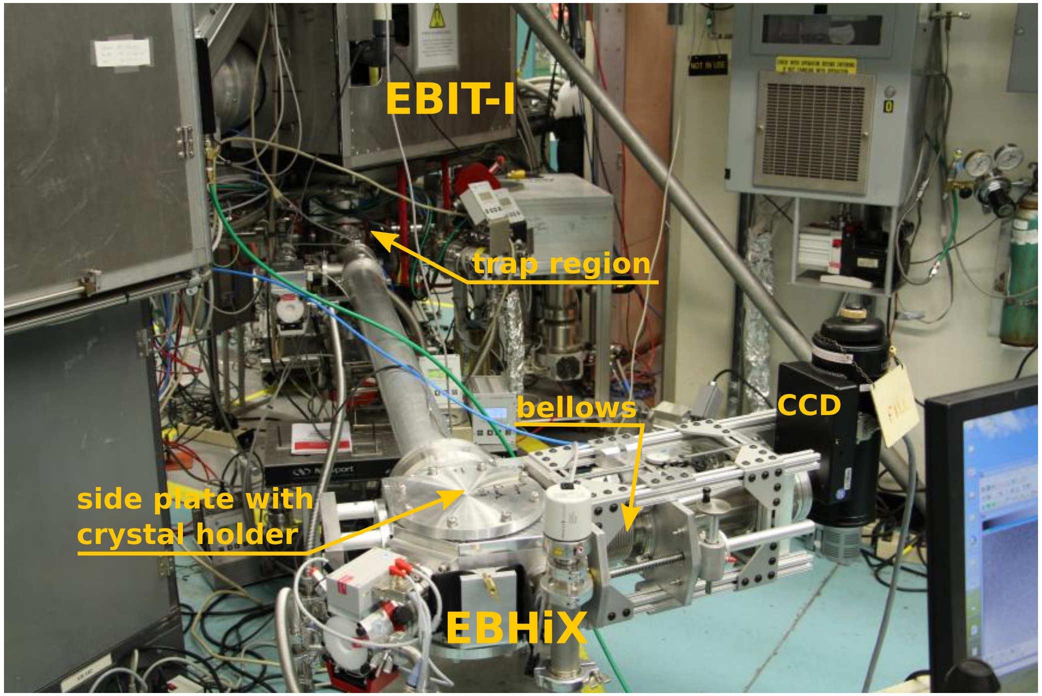


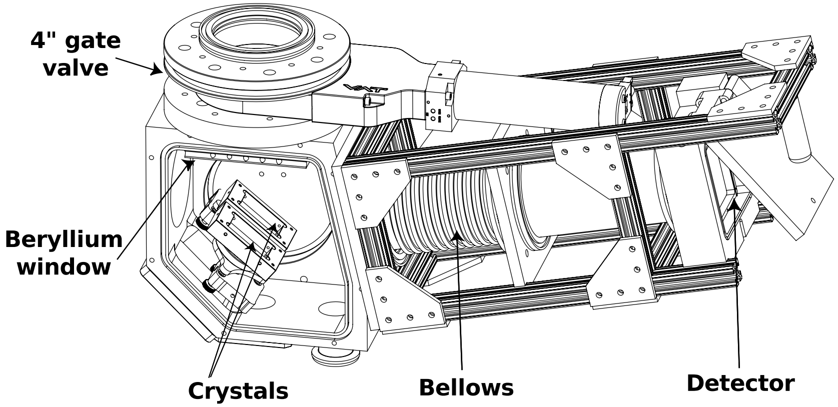
Spherically bent crystal:

⇒ focusing

⇒ imaging

EBHiX crystal spectrometer

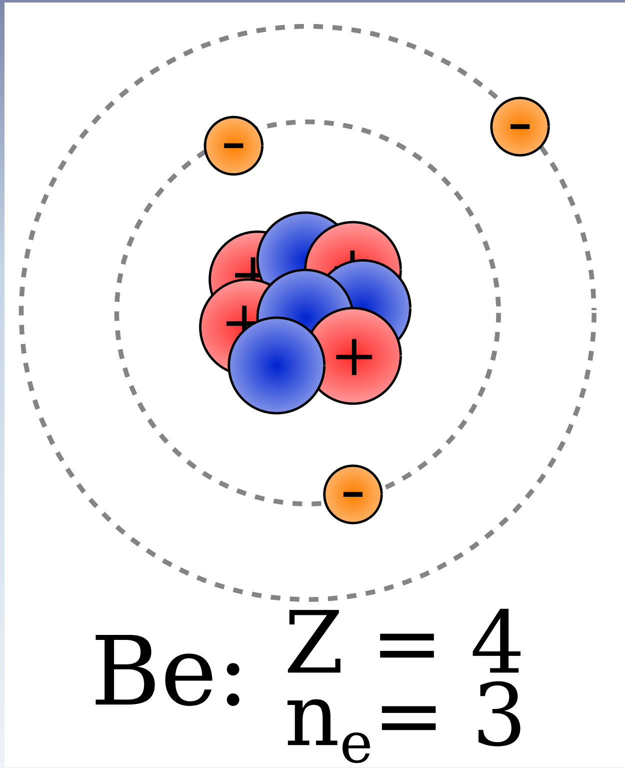




Beiersdorfer+2016

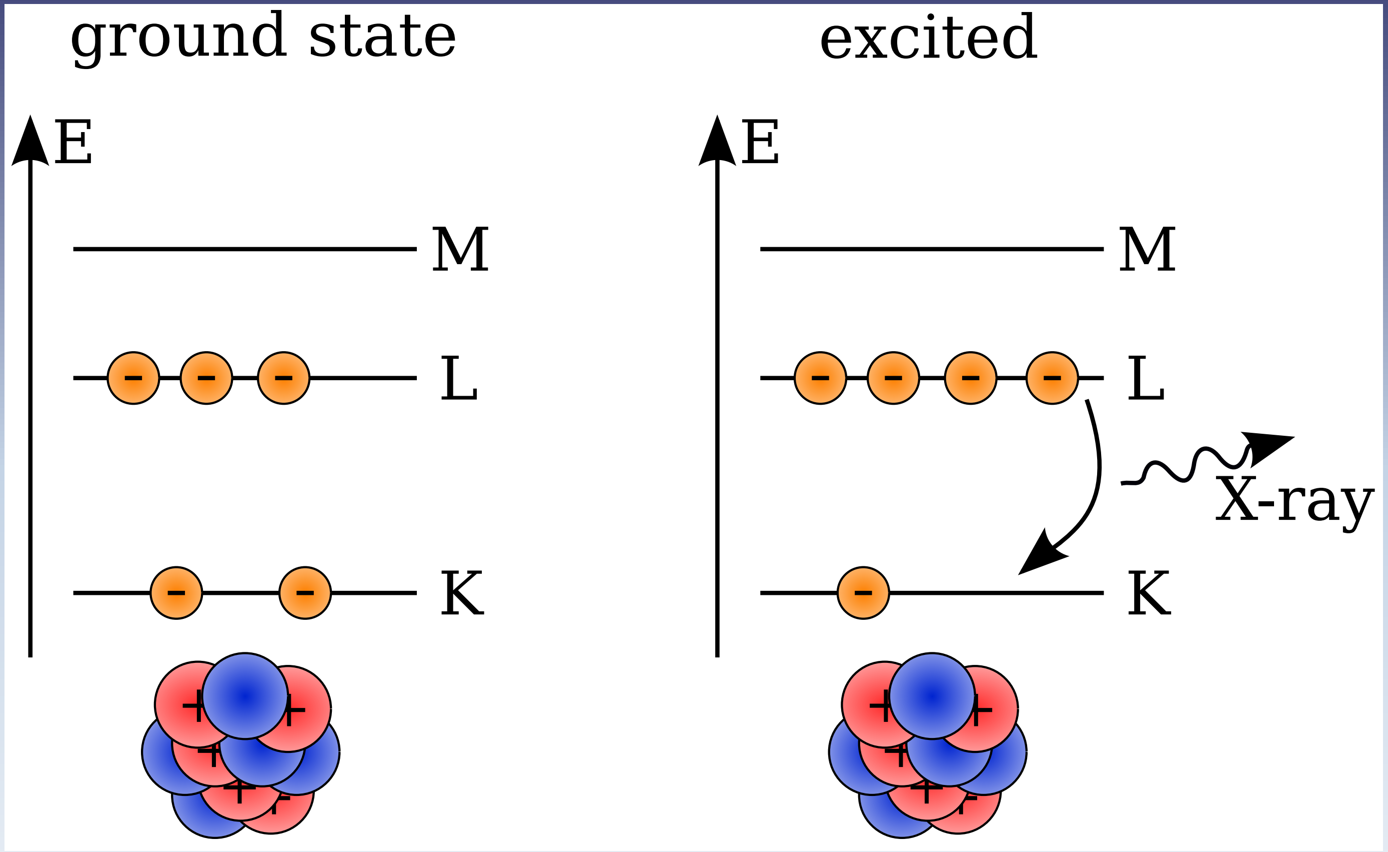
Nomenclature

Since we talk a lot about different charge states:
a quick reminder of the notation generally used



- chemistry: Be^{1+}
  (count missing e^{-})
- astrophysics: Be II
  (start counting at neutral)
- atomic physics: Li-like Be
  (denote iso-electronic sequence)

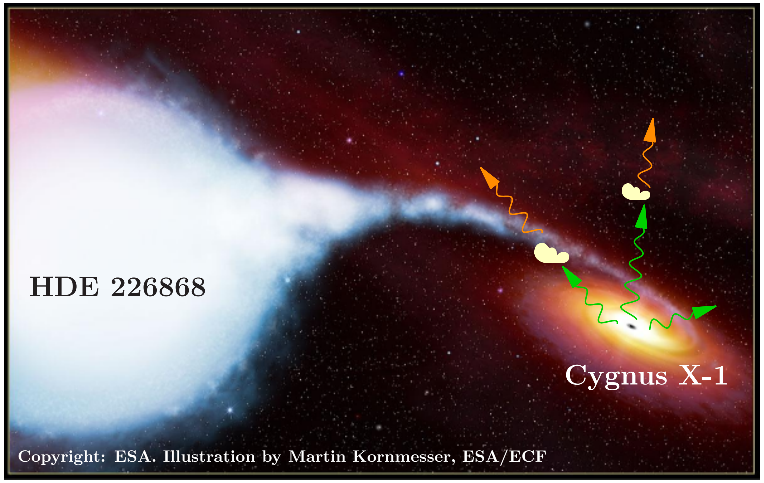
K-shell transitions

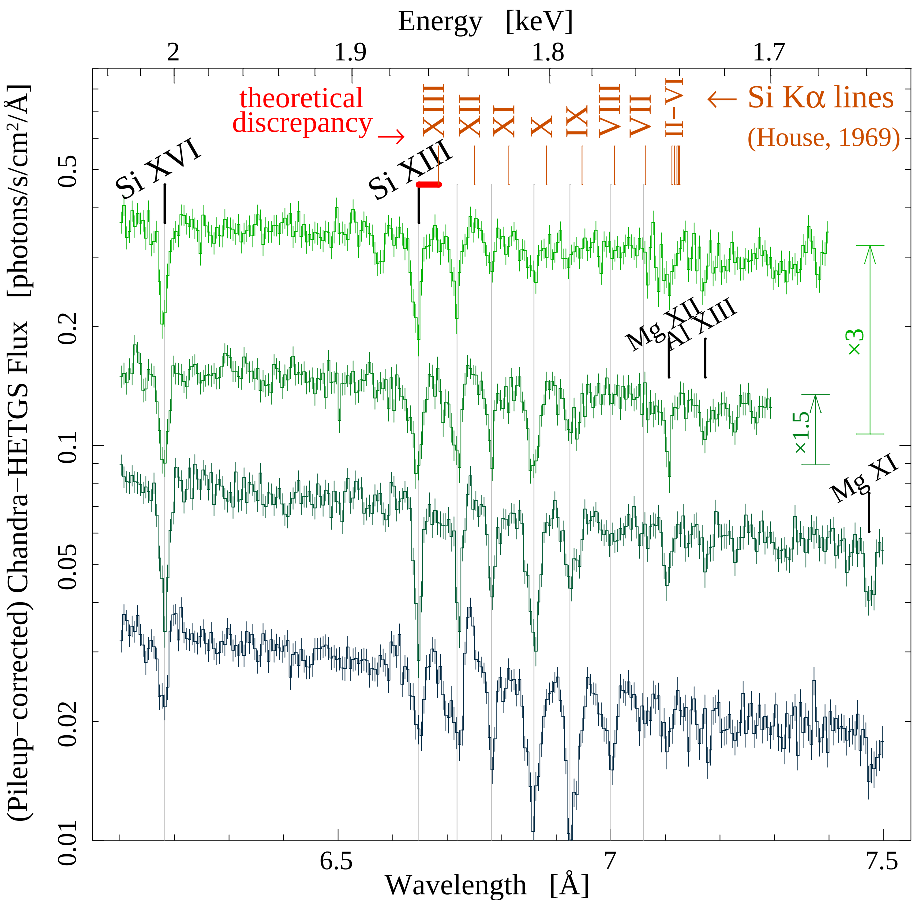


$\Rightarrow \widehat{=}$ Lyman series for lower charge states

Project 1: transition energy measurements

Example:
Black hole high-mass
X-ray binary Cygnus X-1



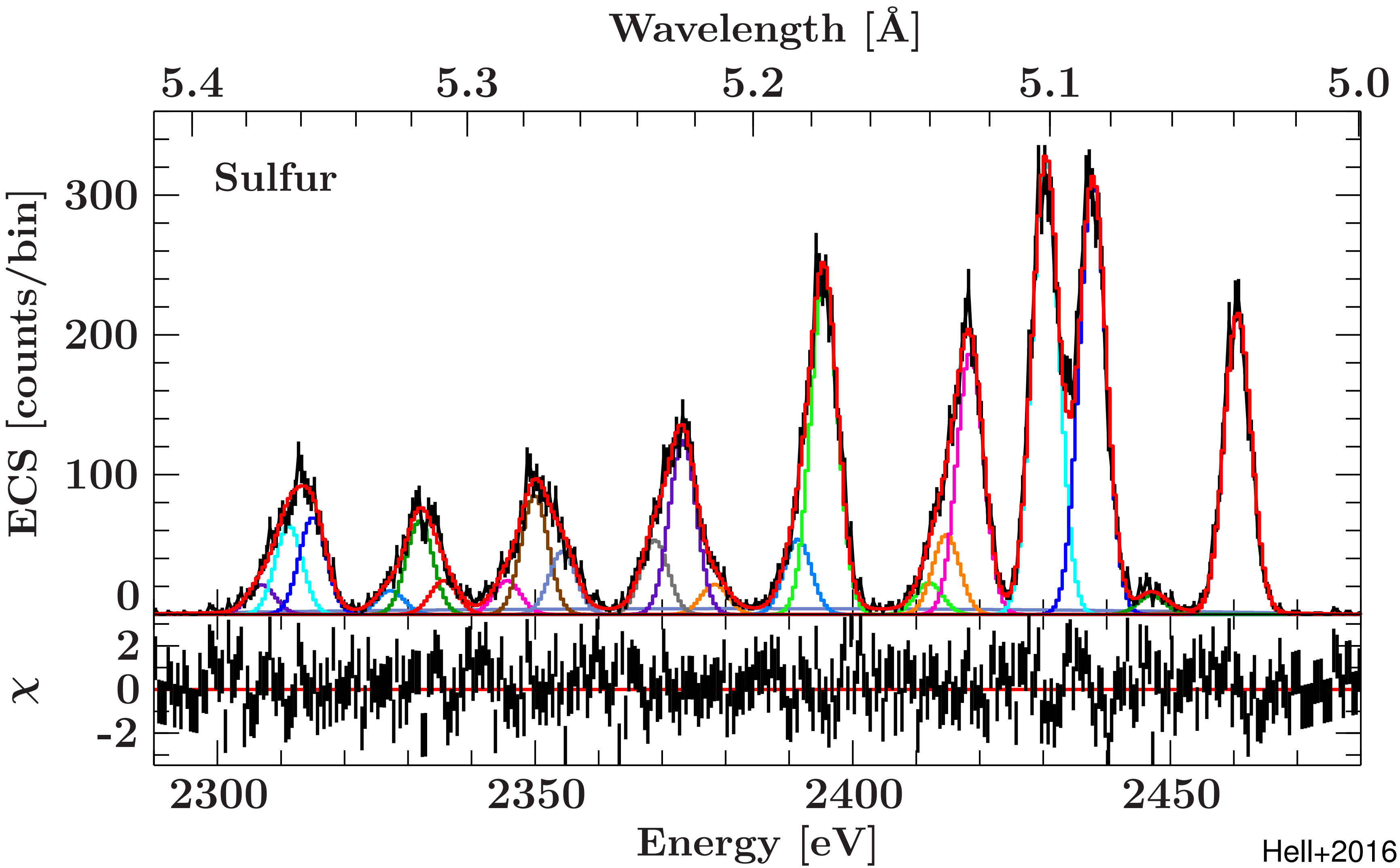


Problem:

- calculations of transition energies vary $\sim$ 2–5 eV
- uncertainty corresponds to several 100 km s^{-1} in Si

$\Rightarrow$ uncertainties on the order of expected Doppler shifts

Measurement at EBIT with ECS calorimeter



Hell+2016

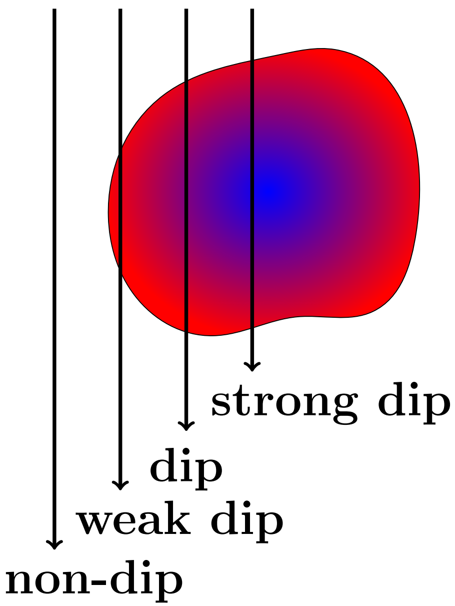
Uncertainties: $< 0.5\,\mathrm{eV}$ (strong lines) – $< 1\,\mathrm{eV}$ (weak lines)

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

X-raying the clumpy wind of Cyg X-1

Dipping stages

clump passing line of sight:



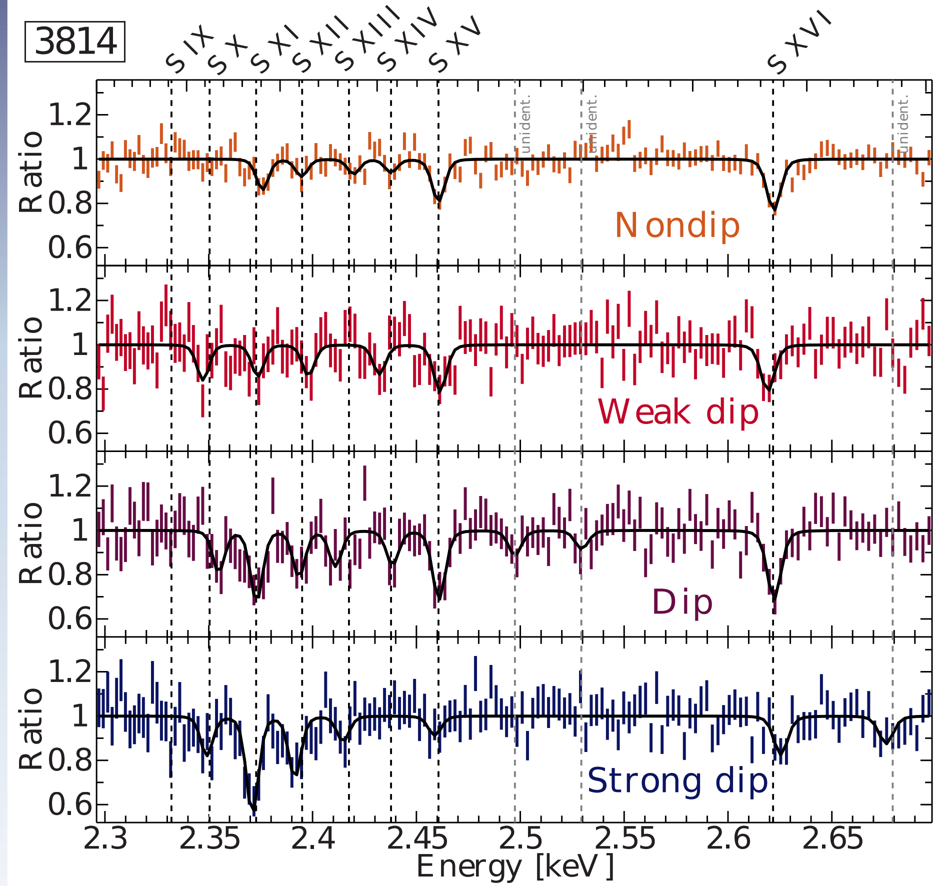
Hirsch, Hell, et al. (in prep)

Results:

same Doppler shifts in all ionization and absorption stages (within single observation)

Dipping in the spectra

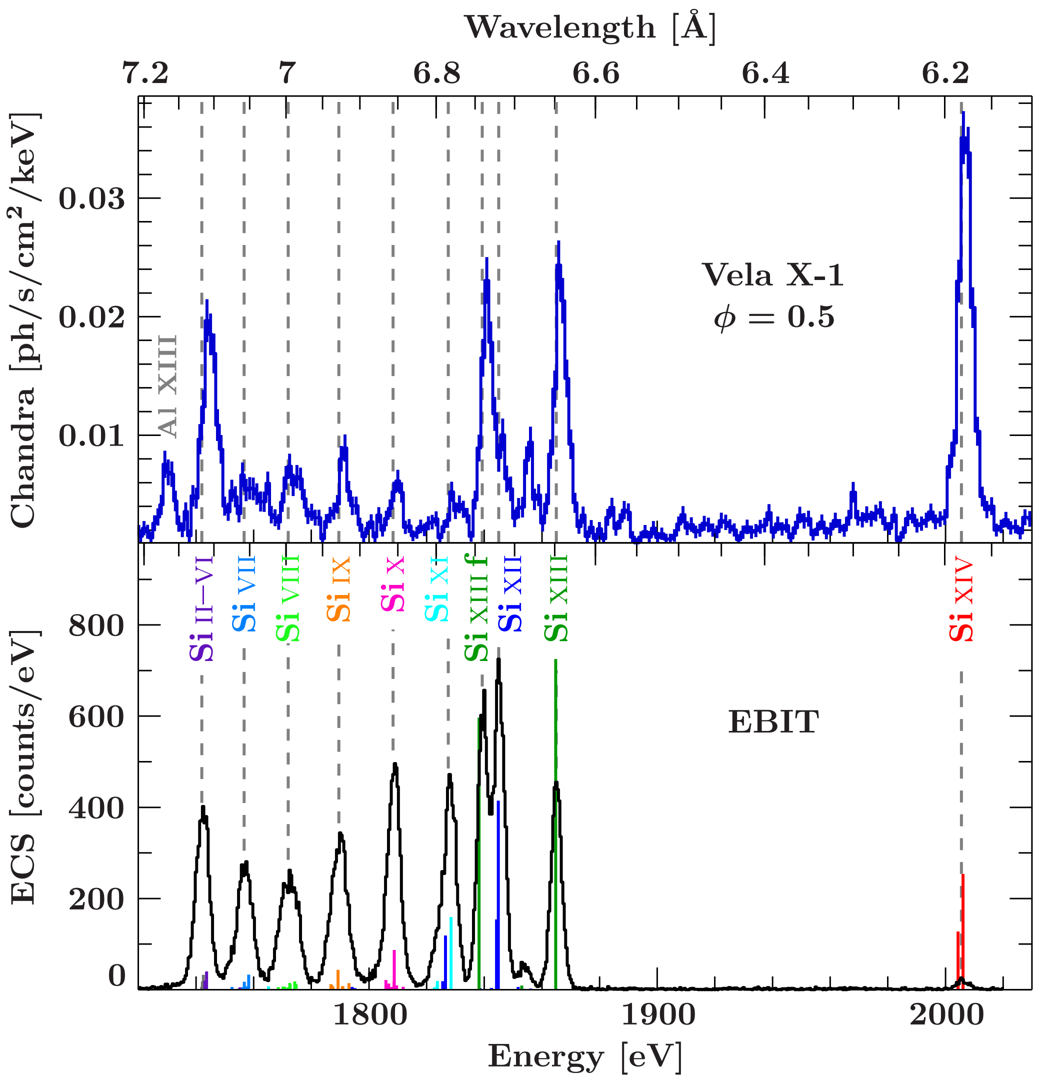
Chandra-HETG spectra, normalized to continuum model



low charge states of S and Si

More sources

Vela X-1



K-shell transitions of low charge states:

Seen in:

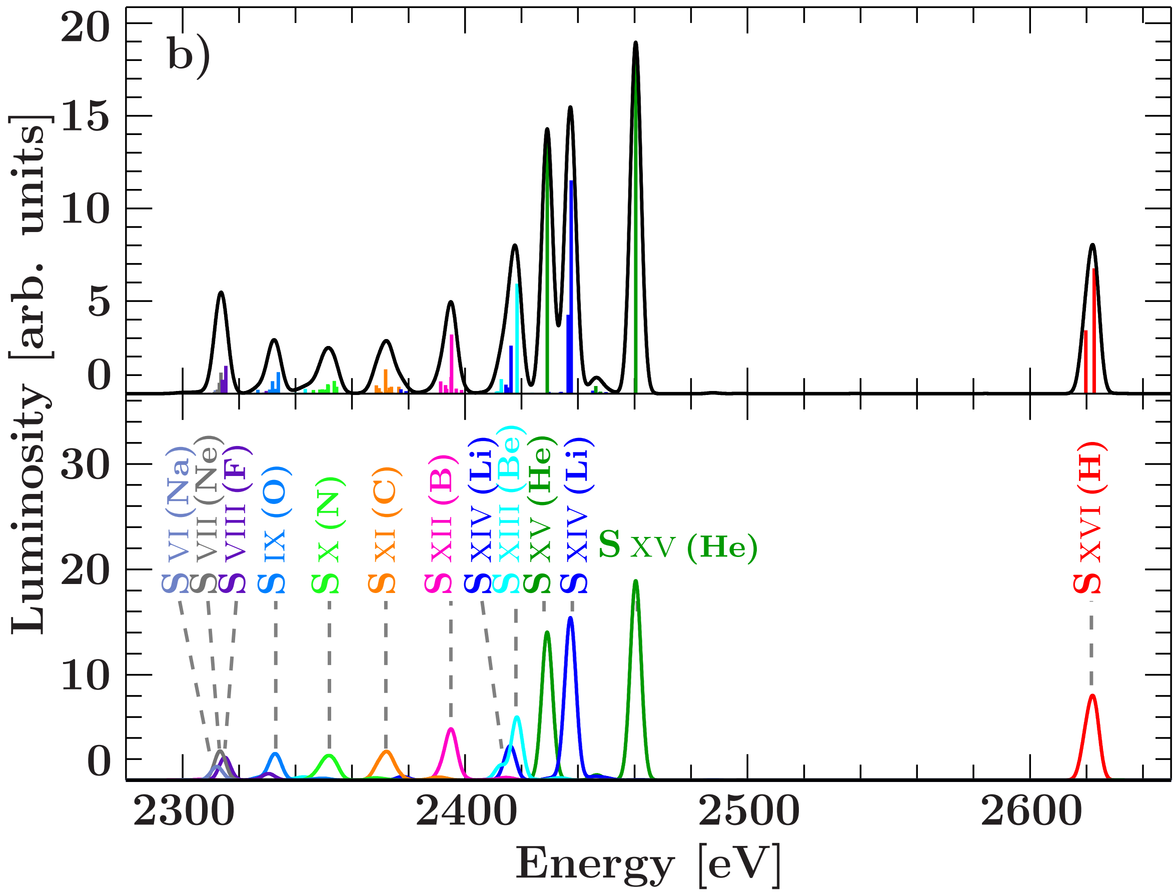
- high-mass X-ray binaries
- solar flares
- active galactic nuclei

Expected in:

- supernova remnants
- other (less abundant) elements

Theoretical Predictions

Flexible Atomic code (FAC): fully relativistic, jj-coupling

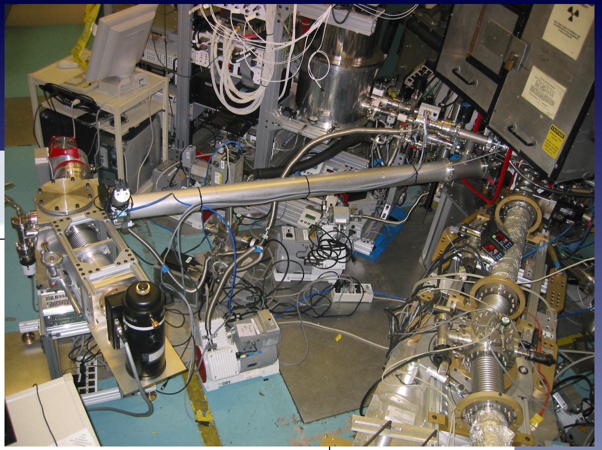


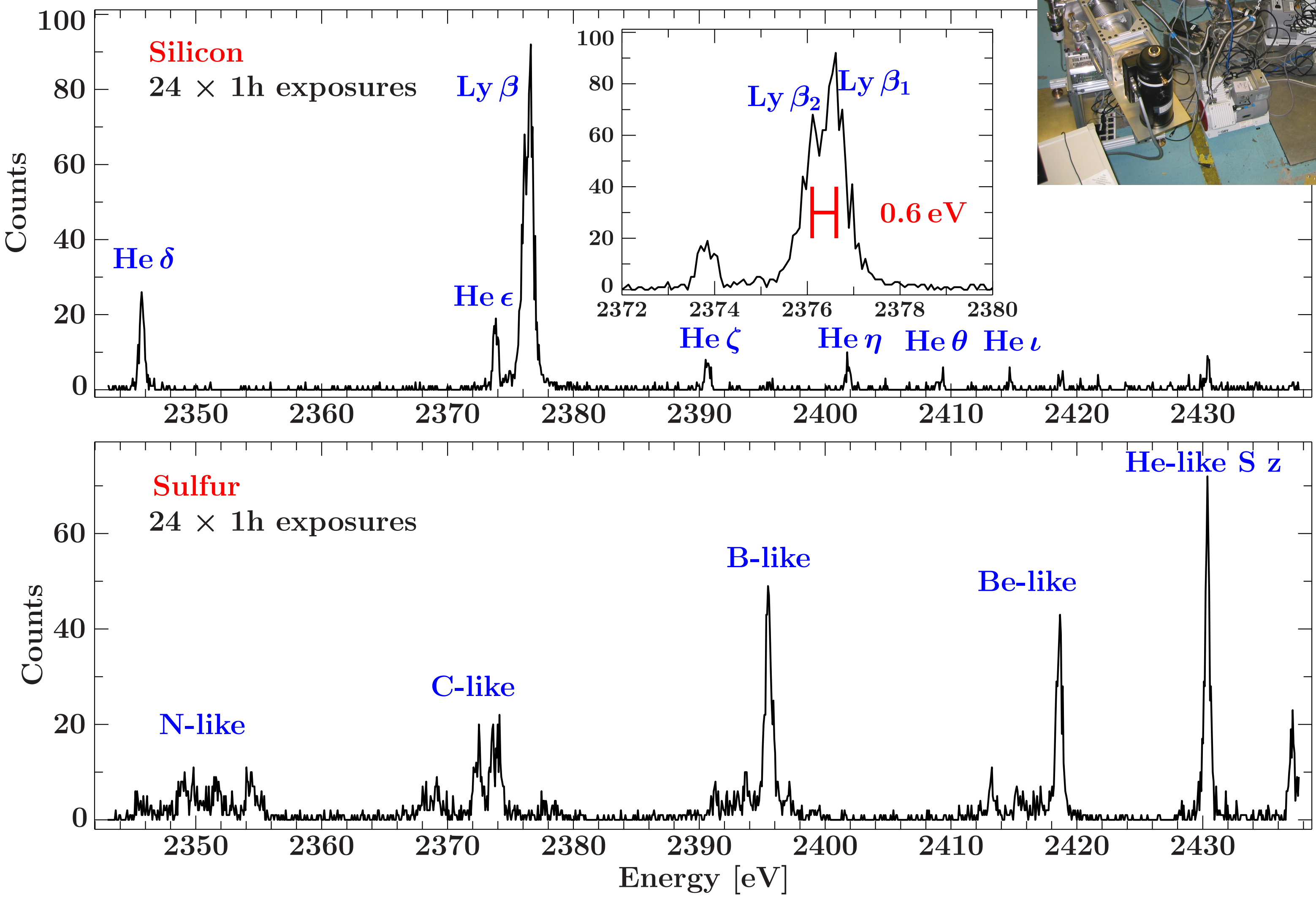
Calculation accuracy (based on EBIT measurement:

transition energies good to ~ 1 eV

Confirmation of ECS results

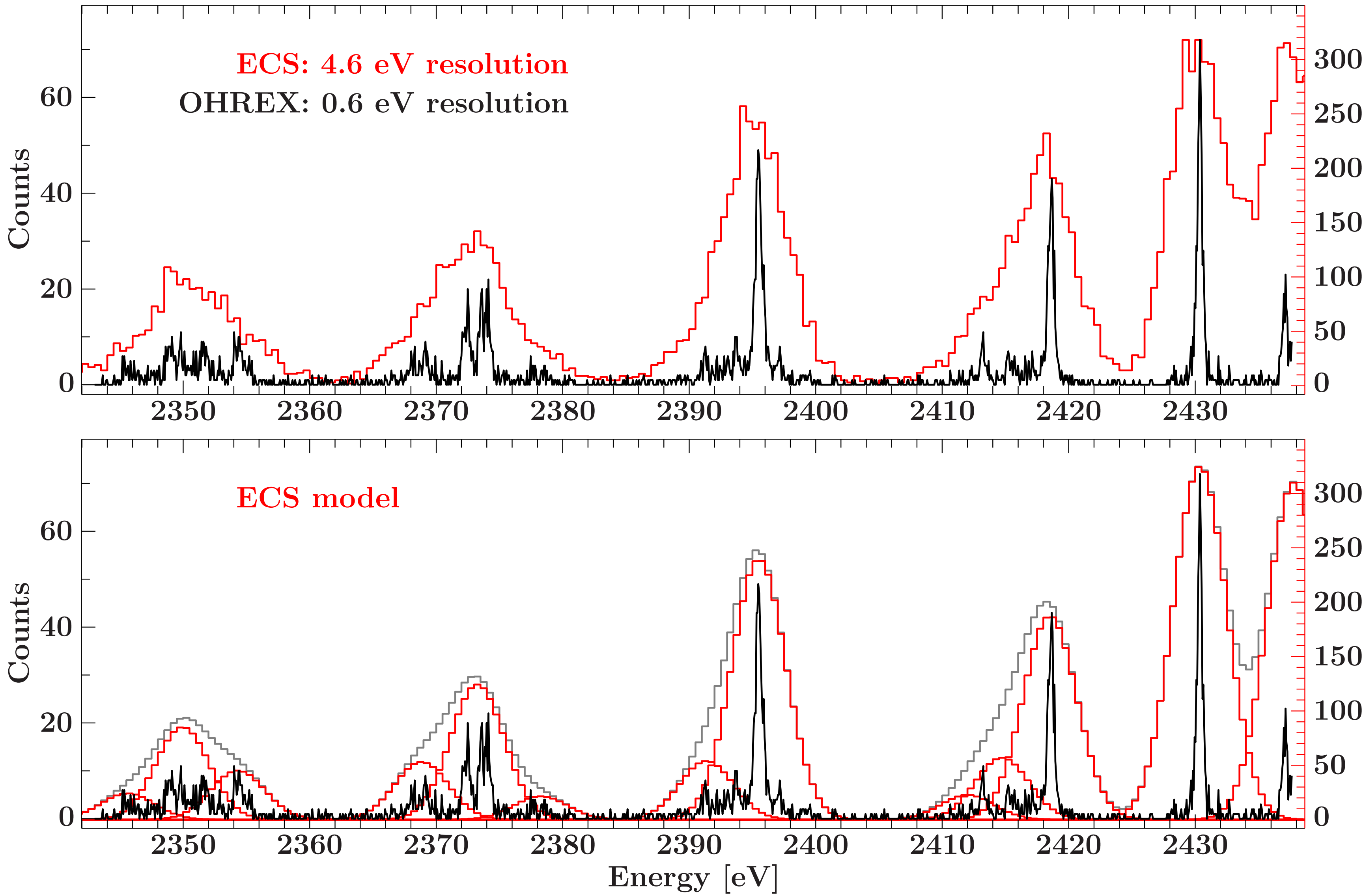
High-resolution crystal spectrometer:





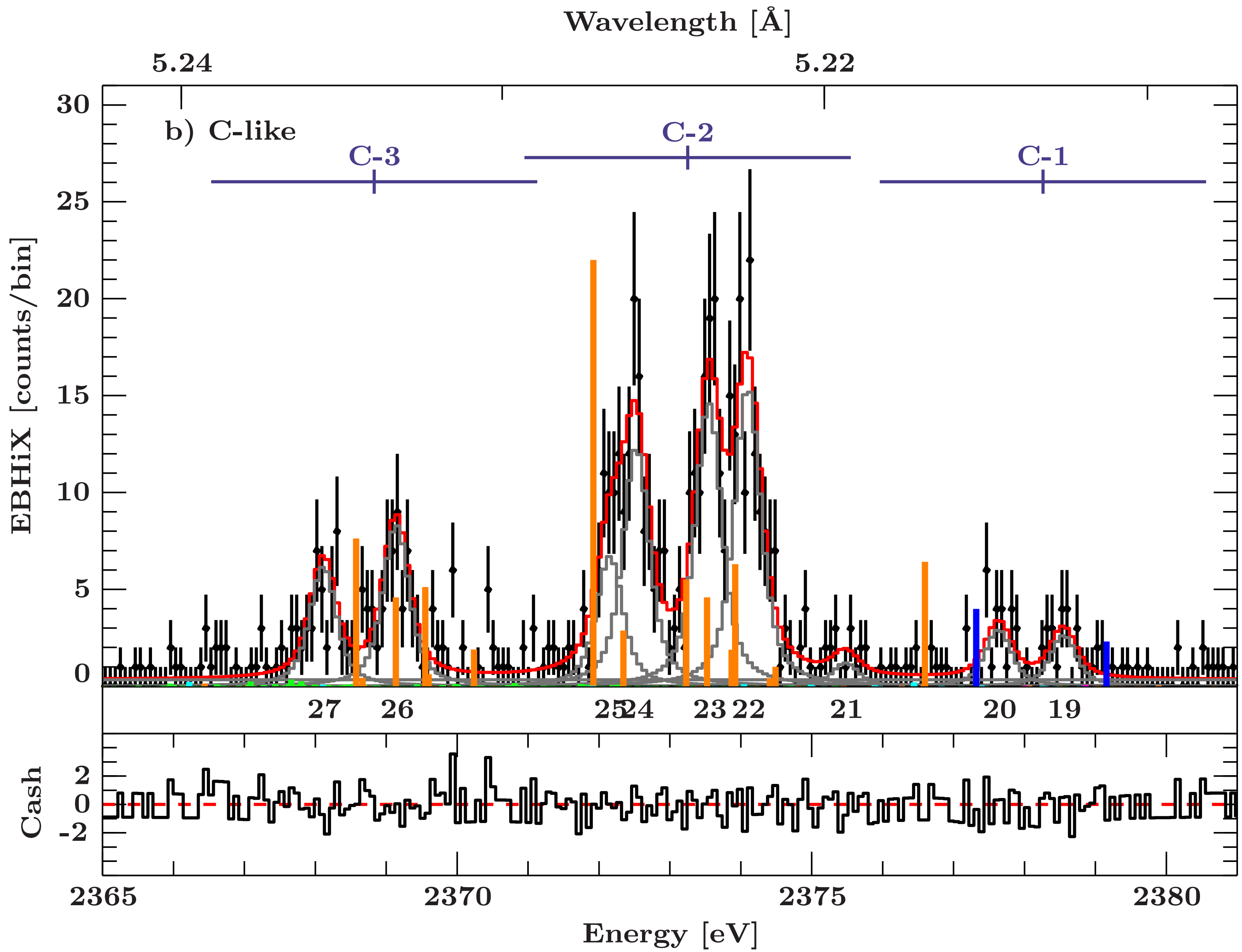
disadvantages: very slow; limited bandwidth

ECS vs crystal spectrometer

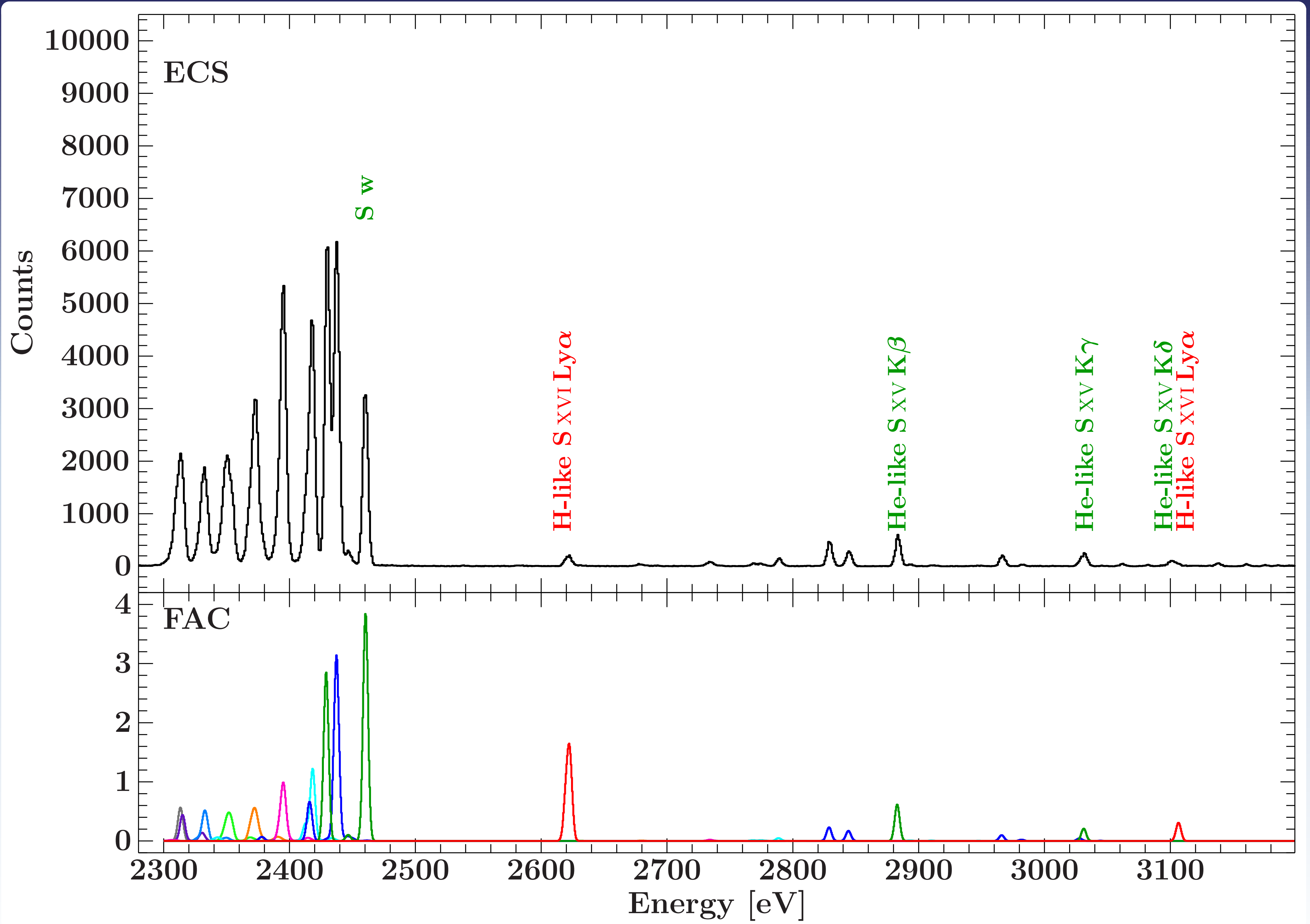


modeling of lower res. ECS data reproduces strong features

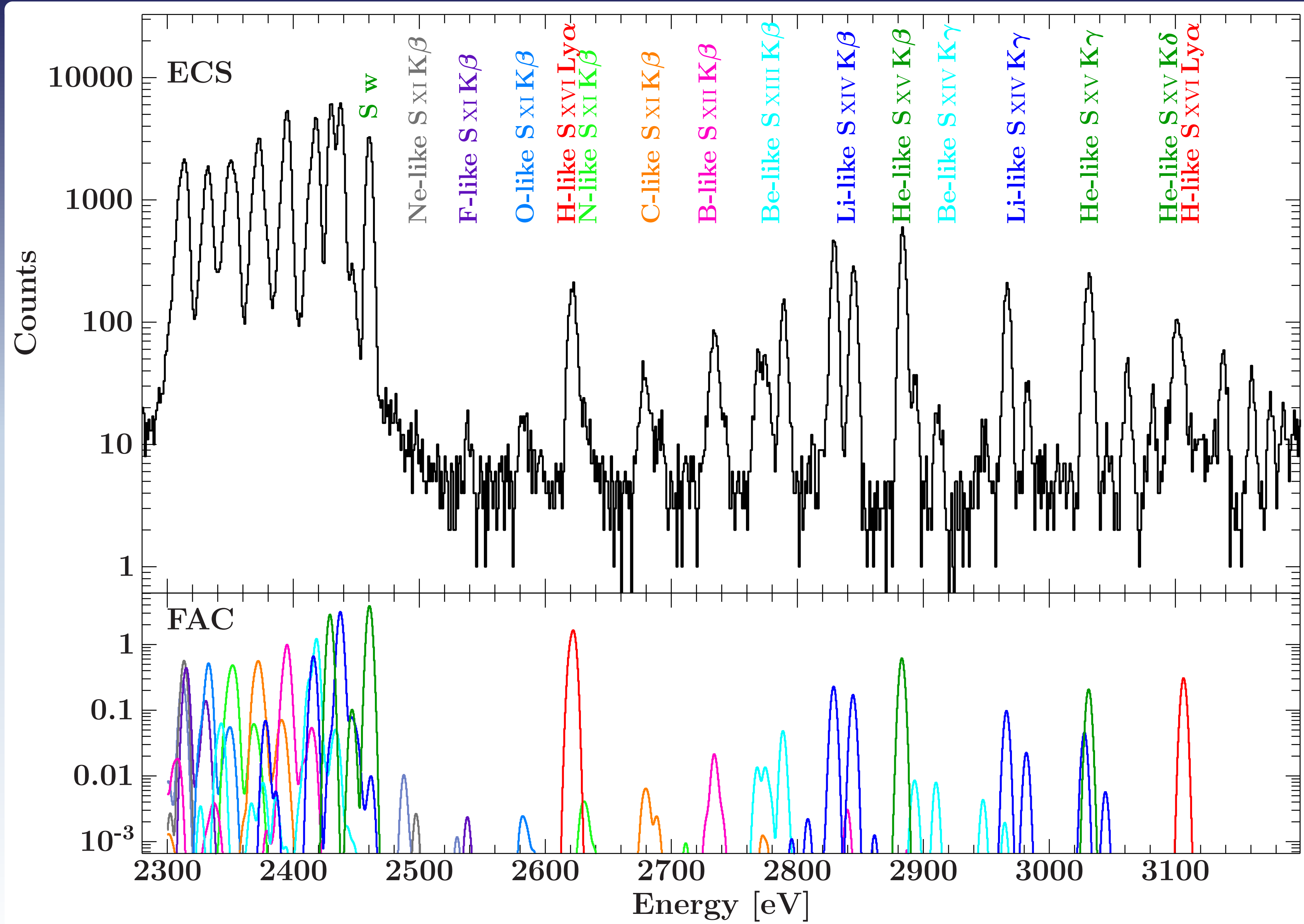
Crystal spectrometer fit: $< 0.2\,\mathrm{eV}$ accuracy



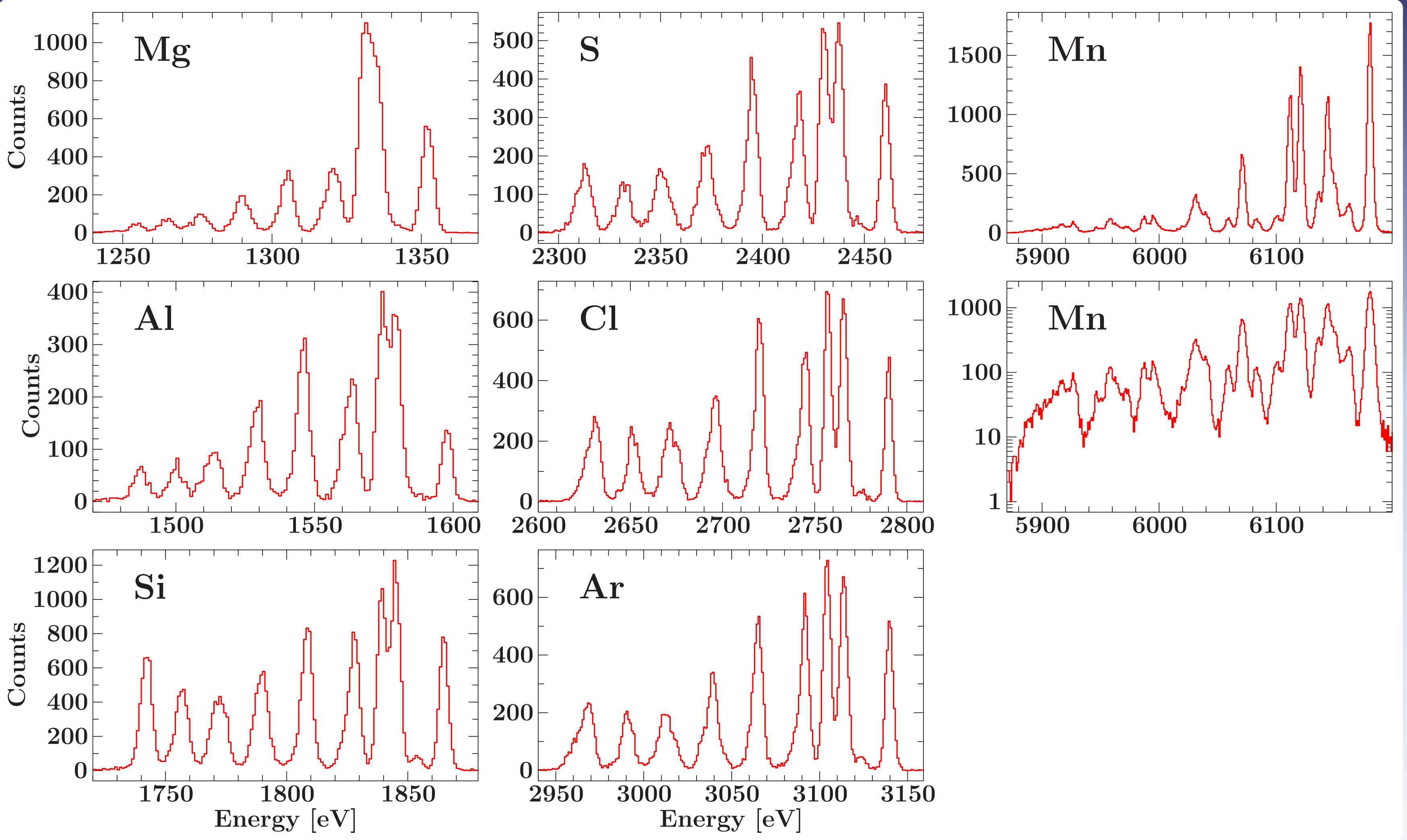
Sulfur Kβ of L-shell ions with the ECS calorimeter



Sulfur Kβ of L-shell ions with the ECS calorimeter

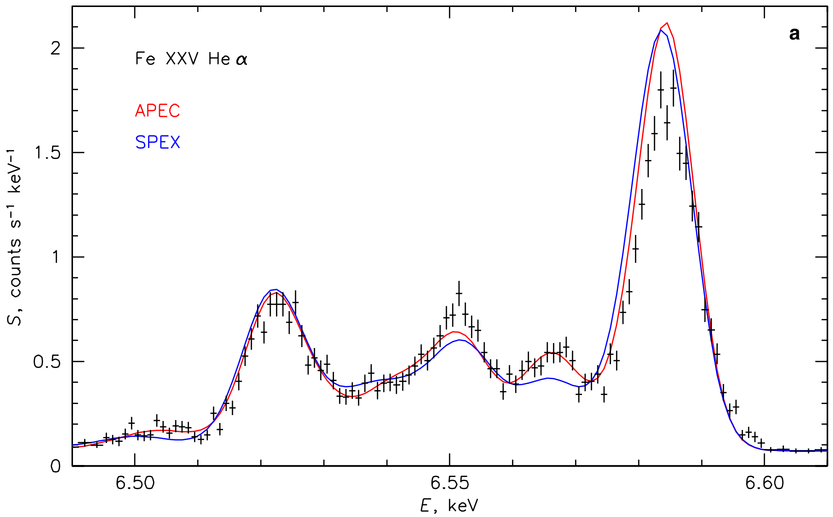


ECS measurements across the periodic table

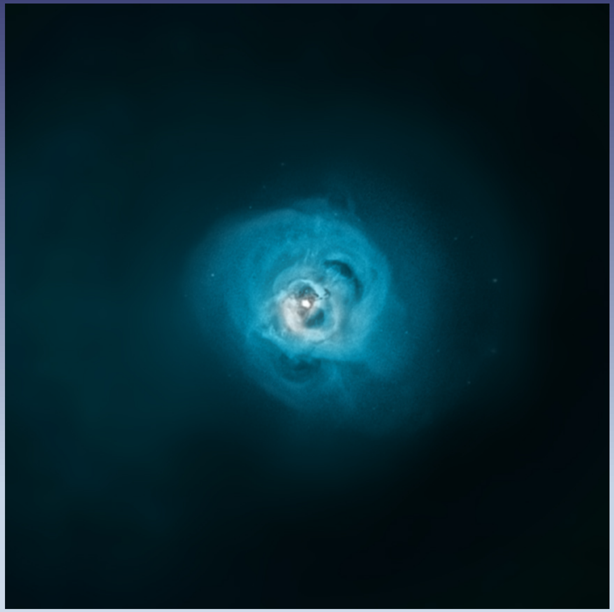


Project 2: collisional excitation cross sections: Perseus cluster with *Hitomi*

Fit of plasma physics models



Hitomi Collaboration 2016



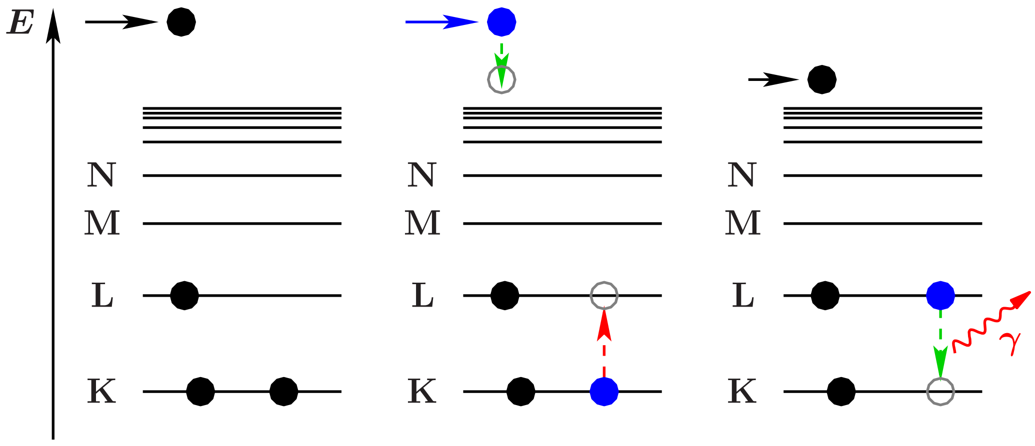
XMM-Newton image of Perseus cluster
http://chandra.harvard.edu/photo/2014/perseus/perseus_xmm.jpg

- Differences in plasma physics models due to underlying reference data
- missing flux in resonance line due to resonant scattering, which is a diagnostic for ion density

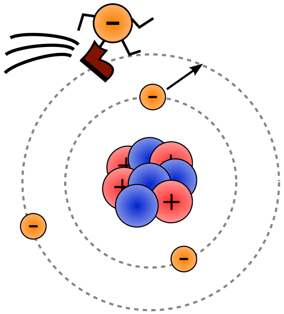
⇒ need good reference collisional excitation cross sections

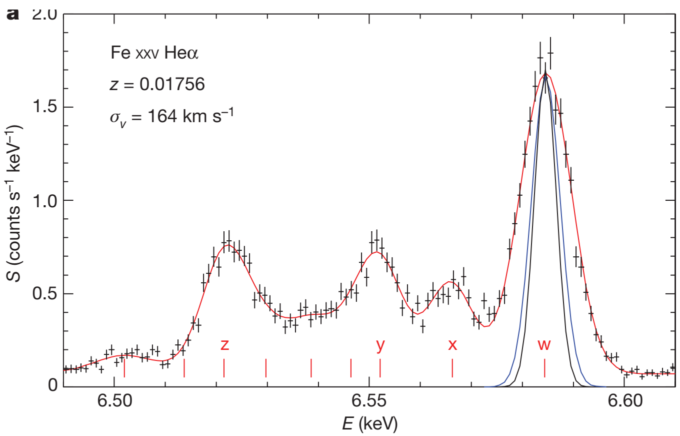
Absolute emission cross sections of Fe K

Direct excitation



collisional excitation
$E_\gamma = E_{KL} < E_{kin}$





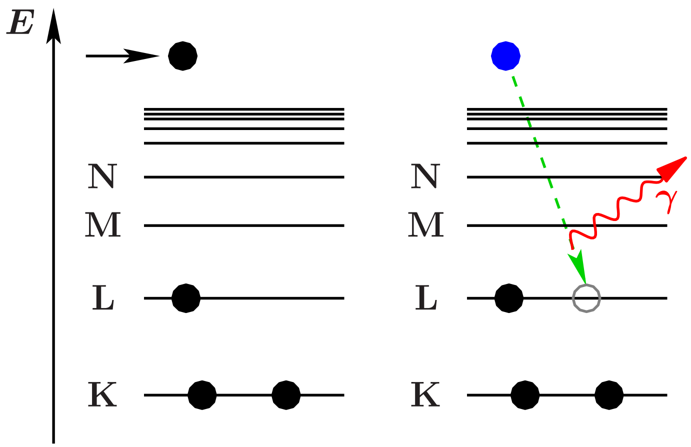
Hitomi Collaboration 2016

Flux

$$I_{DE} = n_e n_i < v_e \sigma_{DE} >$$

Radiative Recombination for normalization

Radiative recombination



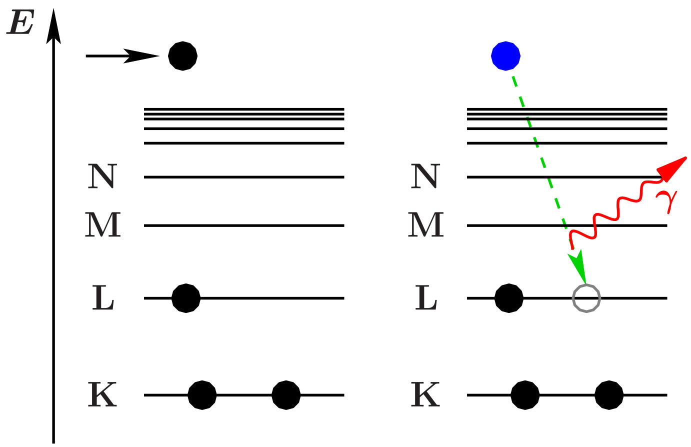
radiative recombination

$E_\gamma = E_{\text{ion. pot}} + E_{\text{kin}}$

Cross section calculations good to 3%

Radiative Recombination for normalization

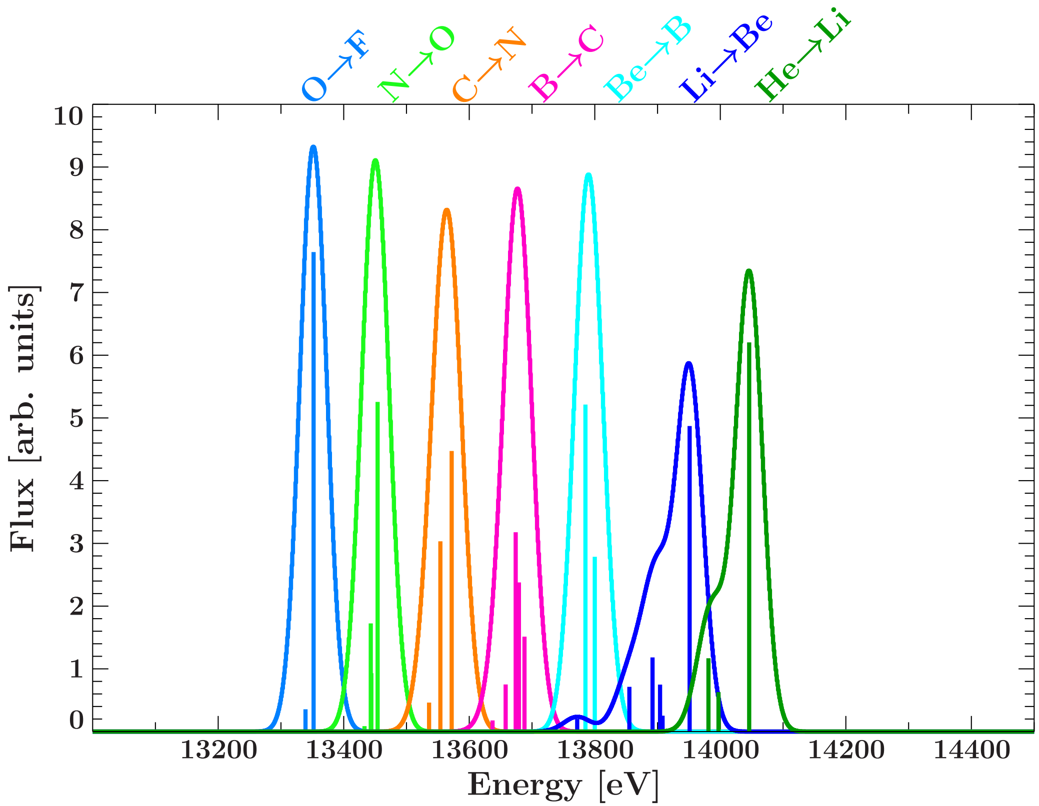
Radiative recombination



radiative recombination

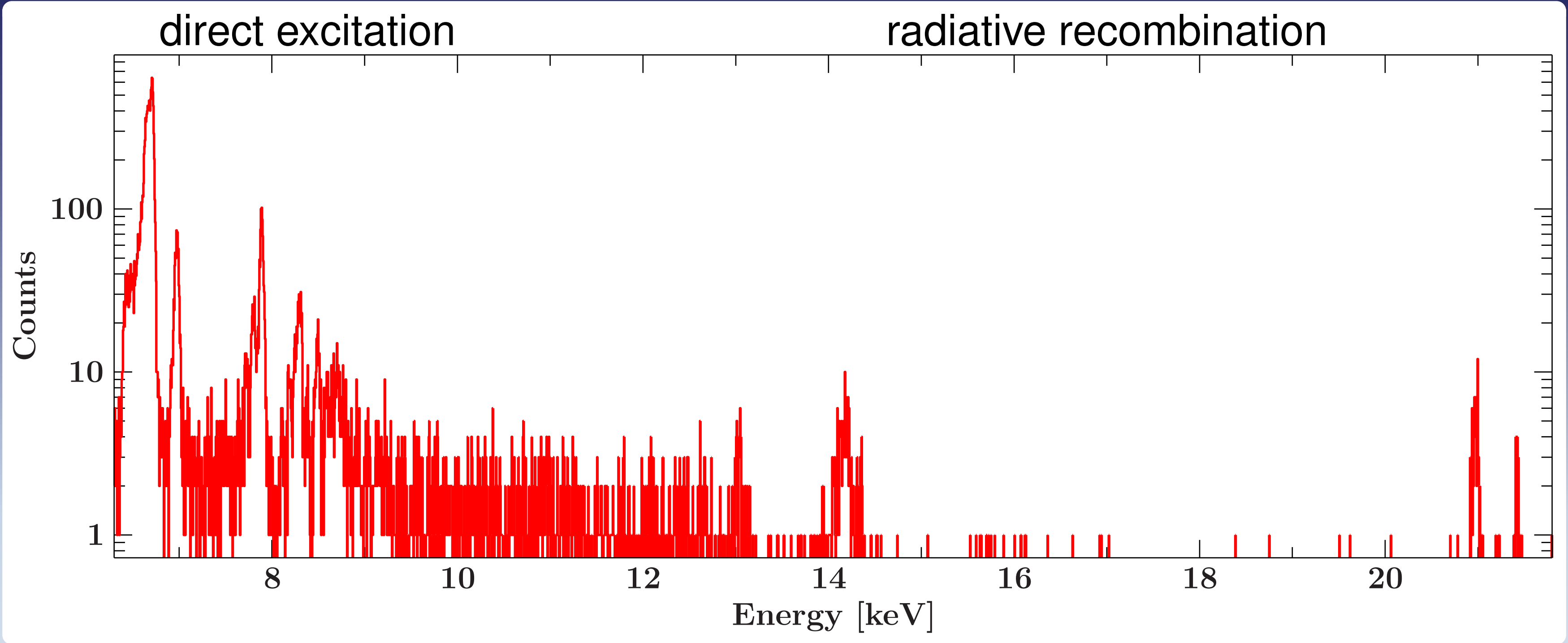
$E_\gamma = E_{\text{ion. pot}} + E_{\text{kin}}$

RR fine structure



Cross section calculations good to 3%

Instrumental requirements



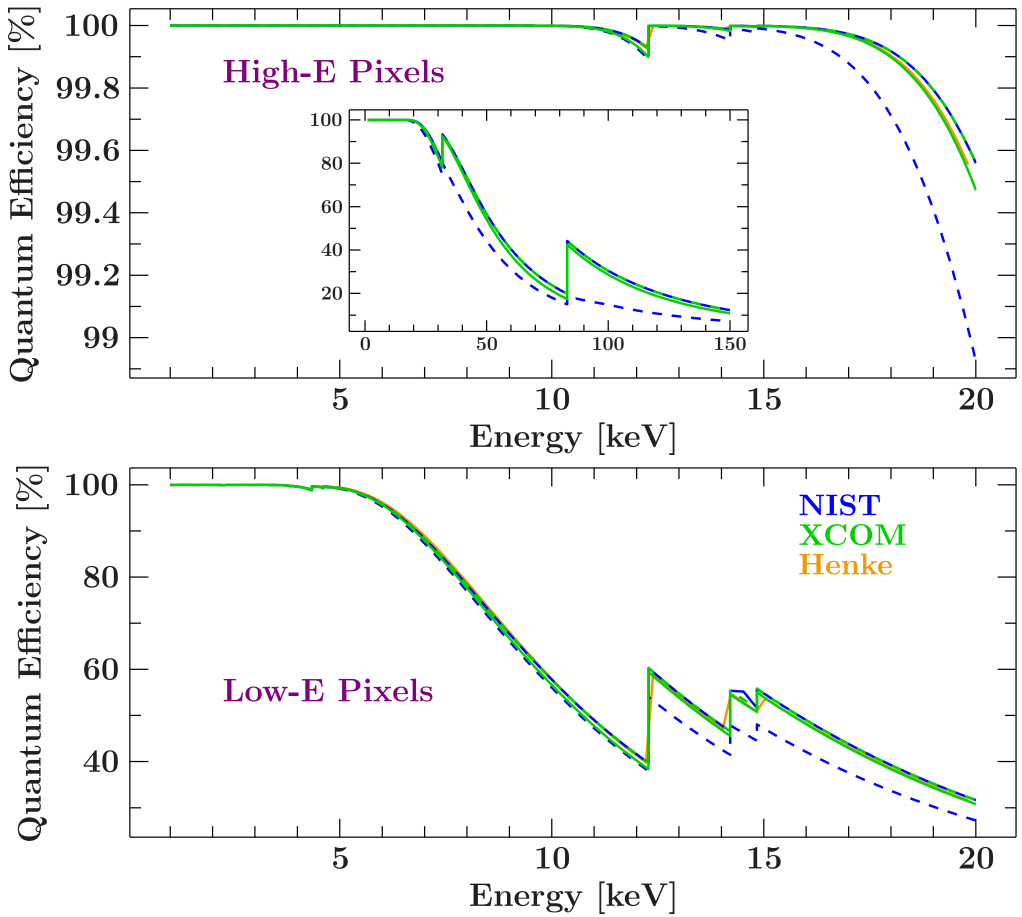
- high spectral resolution in mid-energy band: DE spectrum
- high spectral resolution in high-energy band RR into $n = 2$
- broad energy band: eliminate geometry effects
- high quantum efficiency: $\sigma_{\rm RR} \sim 10^{-3}\sigma_{\rm DE}$

$\Rightarrow$ current generation X-ray microcalorimeters fullfill (almost) all requirements (Porter et al. 2008)

More about the ECS

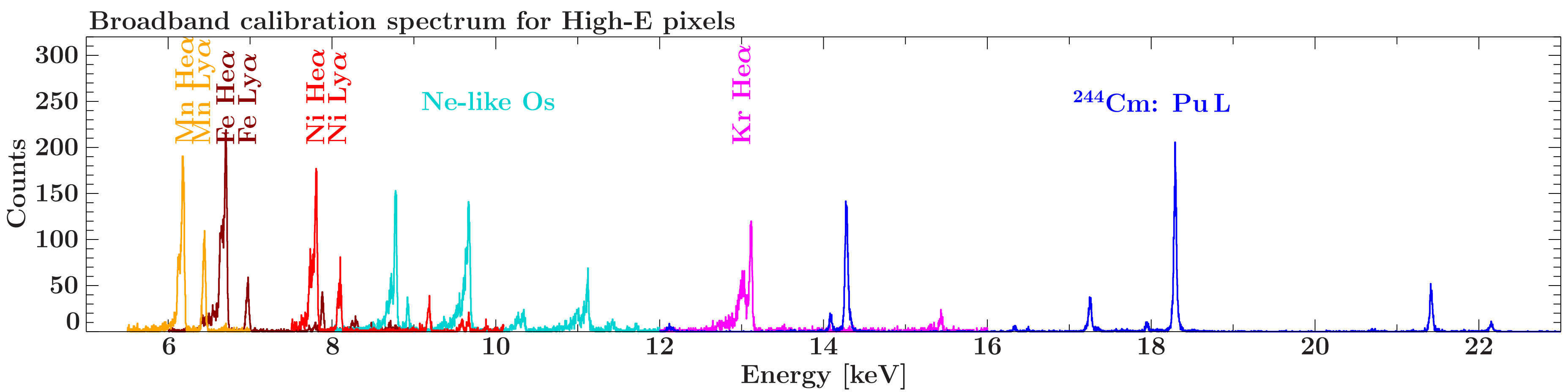
- two subarrays for broadband energy coverage
- 14 low energy pixels:
  8 μm thick
  625 $\times$ 625 $\mu\mathrm{m}^2$ area
  $\sim$ 5.75 eV resolution 60 mK
  0.2 to 10 keV
- 10 high energy pixels:
  114 μm thick
  625 $\times$ 500 $\mu\mathrm{m}^2$ area
  $\sim$ 35 eV resolution 60 mK
  0.5 to $>$ 100 keV
- high quantum efficiency over wide energy band
- both subarrays housed together in a single instrument $\Rightarrow$ simple geometry

Quantum efficiency

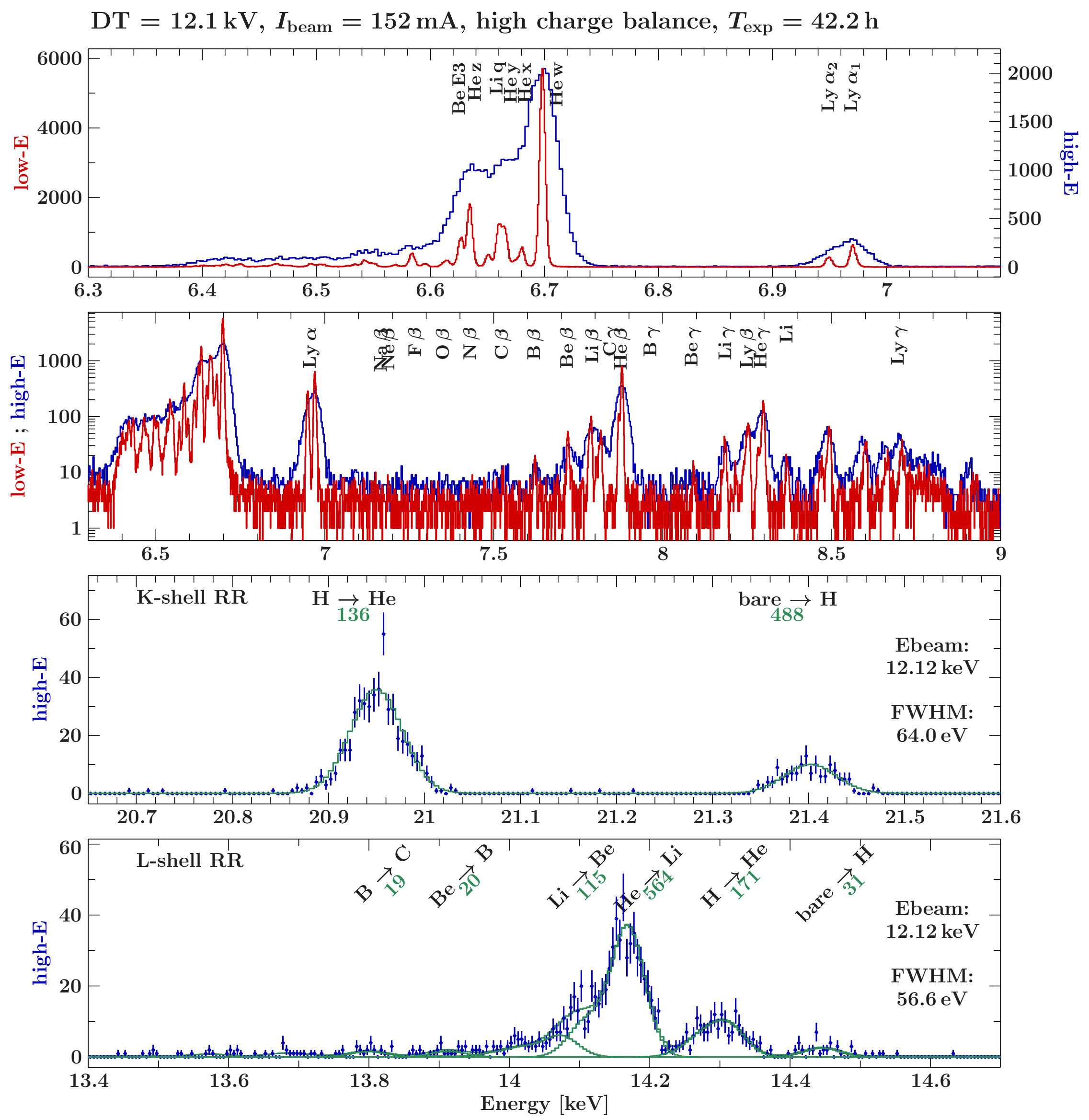


More about the ECS

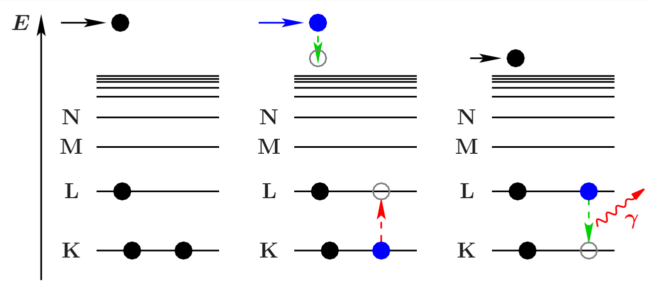
Broadband calibration spectrum for high-E pixels



Fe K spectrum at 12 keV beam energy



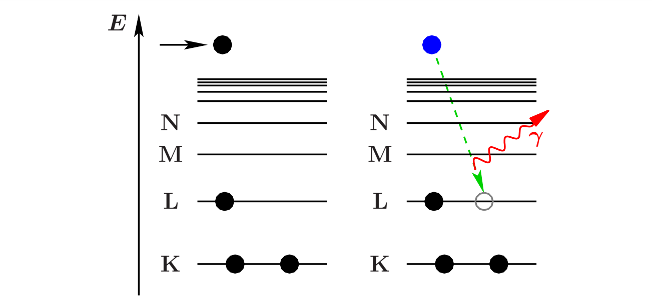
Direct Excitation (DE)



collisional excitation

$E_\gamma = E_{\text{KL}} < E_{\text{kin}}$

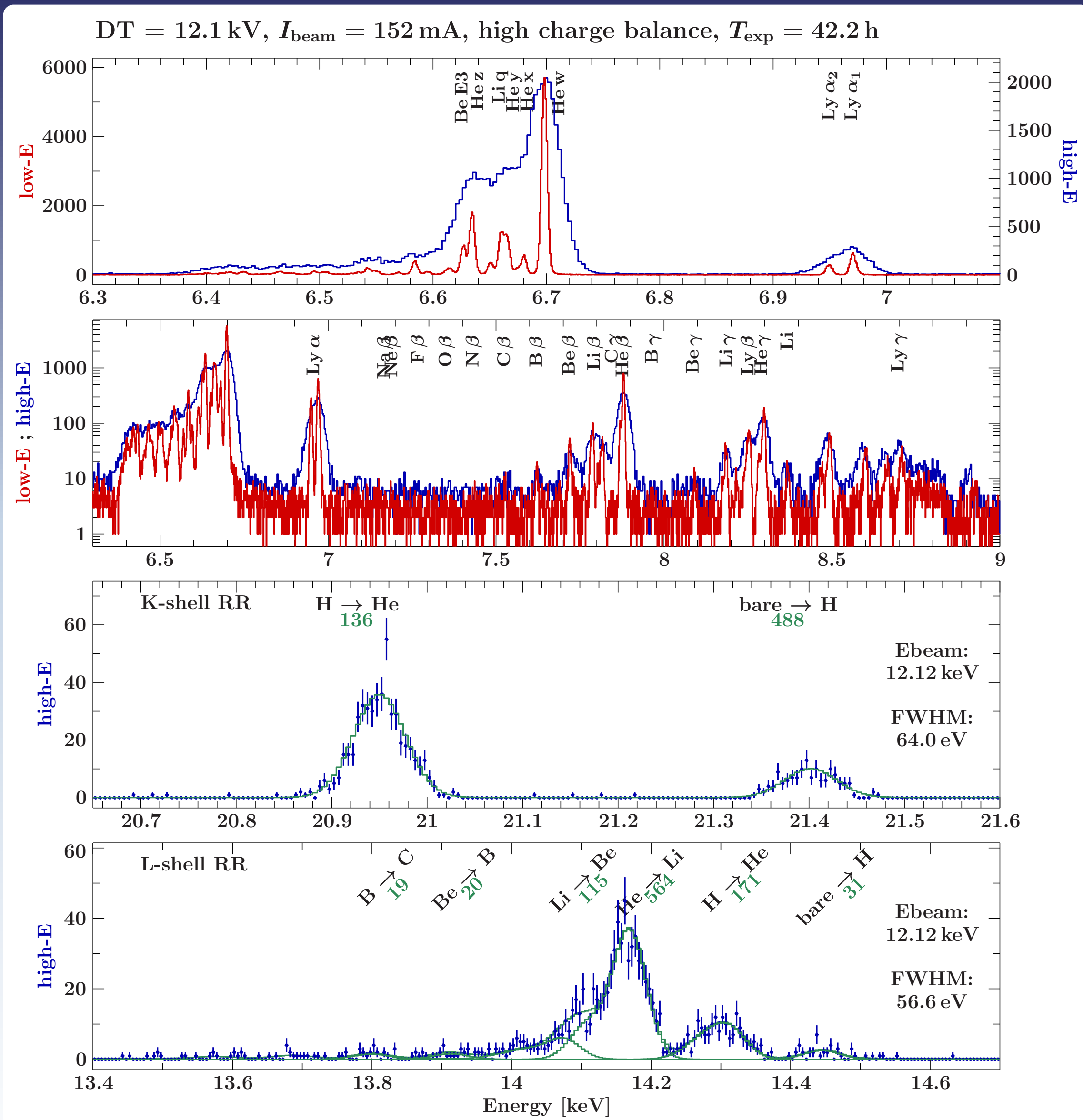
Radiative Recombination (RR)



radiative recombination

$E_\gamma = E_{\text{ion. pot}} + E_{\text{kin}}$

Fe K spectrum at 12 keV beam energy



Direct Excitation (DE)

$$I_{\mathrm{DE}} = n_e n_i < v_e \sigma_{\mathrm{DE}} >$$

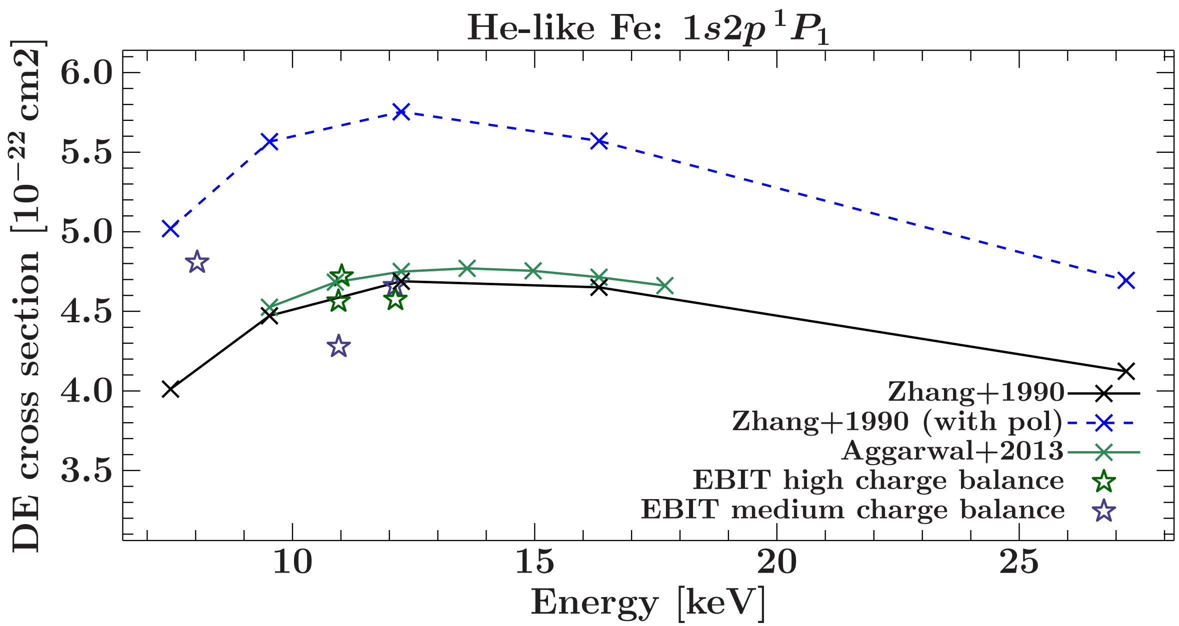
Radiative Recombination (RR)

$$I_{\mathrm{RR}} = n_e n_i < v_e \sigma_{\mathrm{RR}} >$$

$$\sigma_{\mathrm{DE}} = \frac{I_{\mathrm{DE}}}{I_{\mathrm{RR}}} \sigma_{\mathrm{RR}}$$

Absolute collisional excitation cross sections

Results for He-like Fe w:



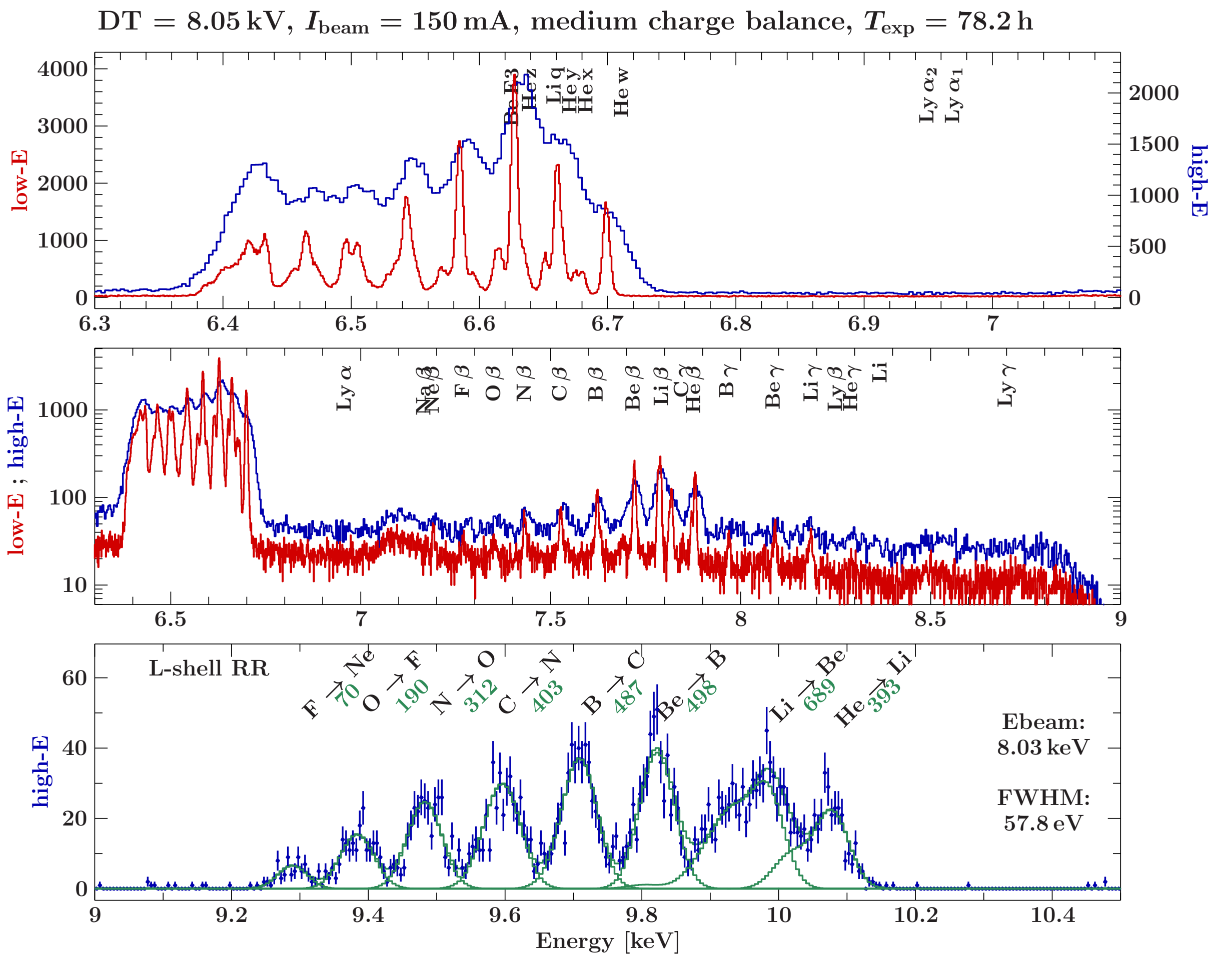
black/green: theoretical absolute cross sections
blue: theoretical cross sections adjusted for polarization

Measured cross sections with EBIT and calorimeter:

accuracy better than ∼10%

More cross sections

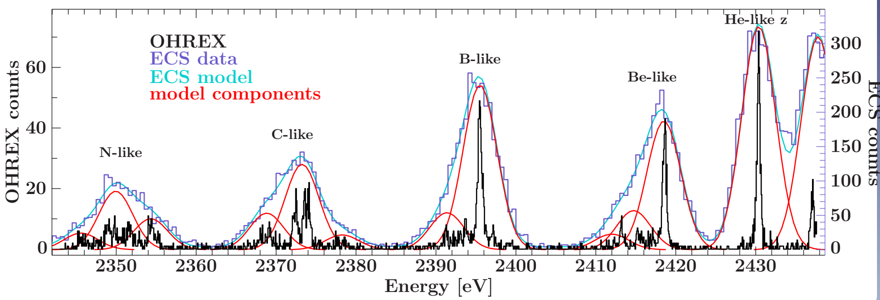
Lower charge states



RR into $n = 2$ resolved for the first time at high electron impact energies

Summary

Transition Energies



Measurement accuracy:

- better than 0.5–1 eV with ECS microcalorimeter

→ better than 100 km s^{-1}

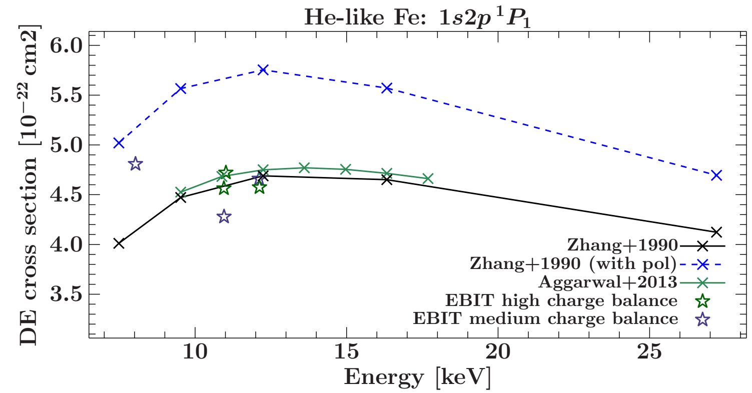
⇒ within calibration uncertainty of *Chandra* HETG

- better than 0.2 eV with crystal spectrometer

→ better than 30 km s^{-1}

⇒ within requirements for *Athena* X-IFU

Excitation cross sections



Measurement accuracy:

- better than ∼10%

⇒ fulfilling requirements identified by community (e.g., NASA LAW)

- dominant contributions to uncertainty addressable

⇒ on track for *Athena* X-IFU to measure plasma parameters within few %