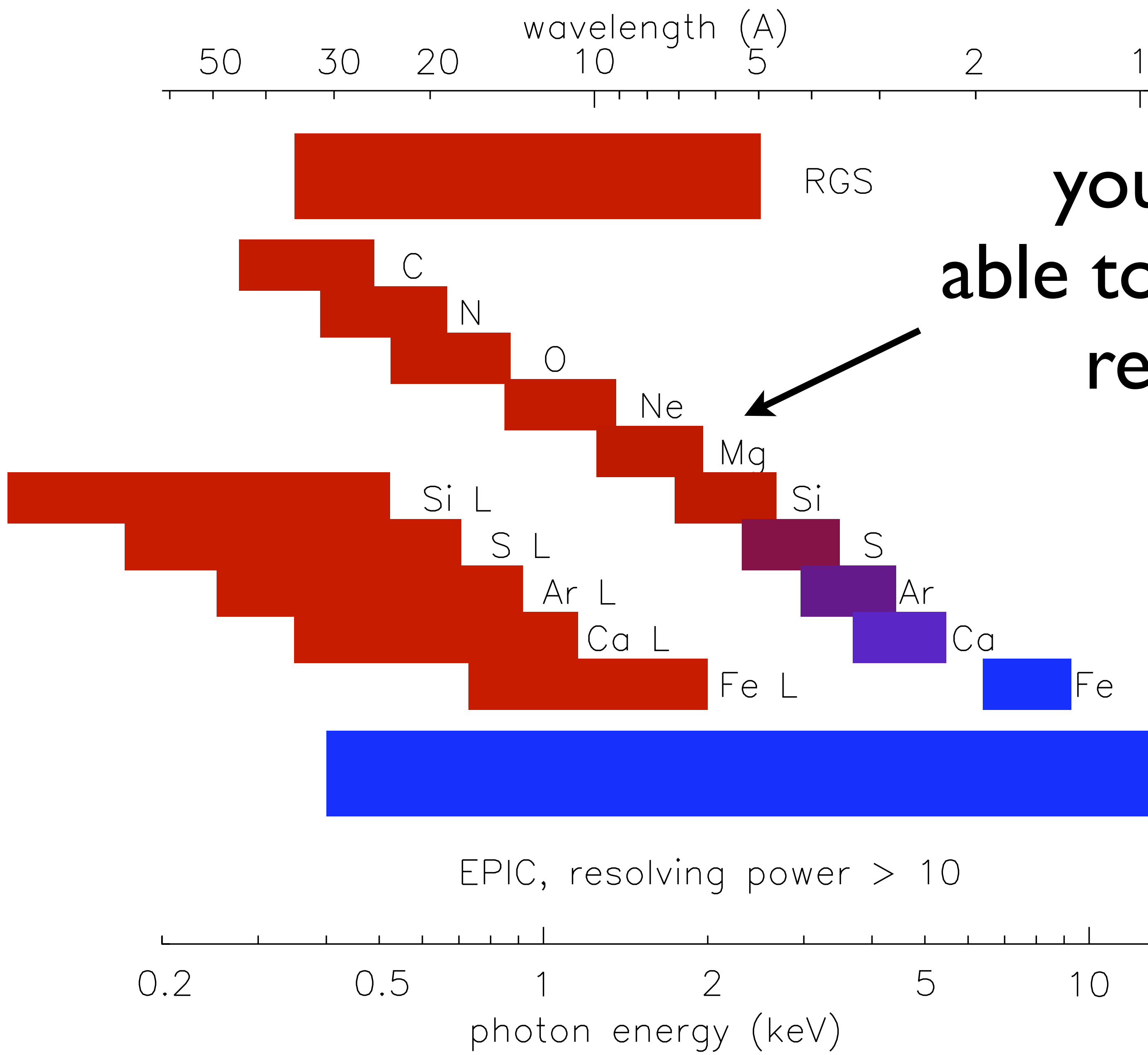
X-ray Spectrometers

CCD's
diffraction grating spectrometers
microcalorimeters

X-ray spectra of the abundant elements



you want to be able to distinguish and resolve these

X-ray spectra, between neutral fluorescent n=2-1, and H-like n=1-∞, estimated from $E = -Z^2 R/n^2$

Never leave home without the Bohr model!

CCD's (and other ionization detectors)

X-ray photon is absorbed;
creates primary photoelectron;
creates secondary electrons:

total amount of charge Q $\propto$ photon energy(*);

statistical fluctuation on Q due to Poisson:

$$\Delta E^2 \propto E \equiv FE \quad (F < 1 \; !?)$$

In practice, for Si: $E/\Delta E = (E/Fw)^{1/2} = 21\ E^{1/2}$ (FWHM)

and charge nicely spatially localized on device

Si: $w = 3.5$ eV
$F = 0.12$

(*) not true for optical CCD's!

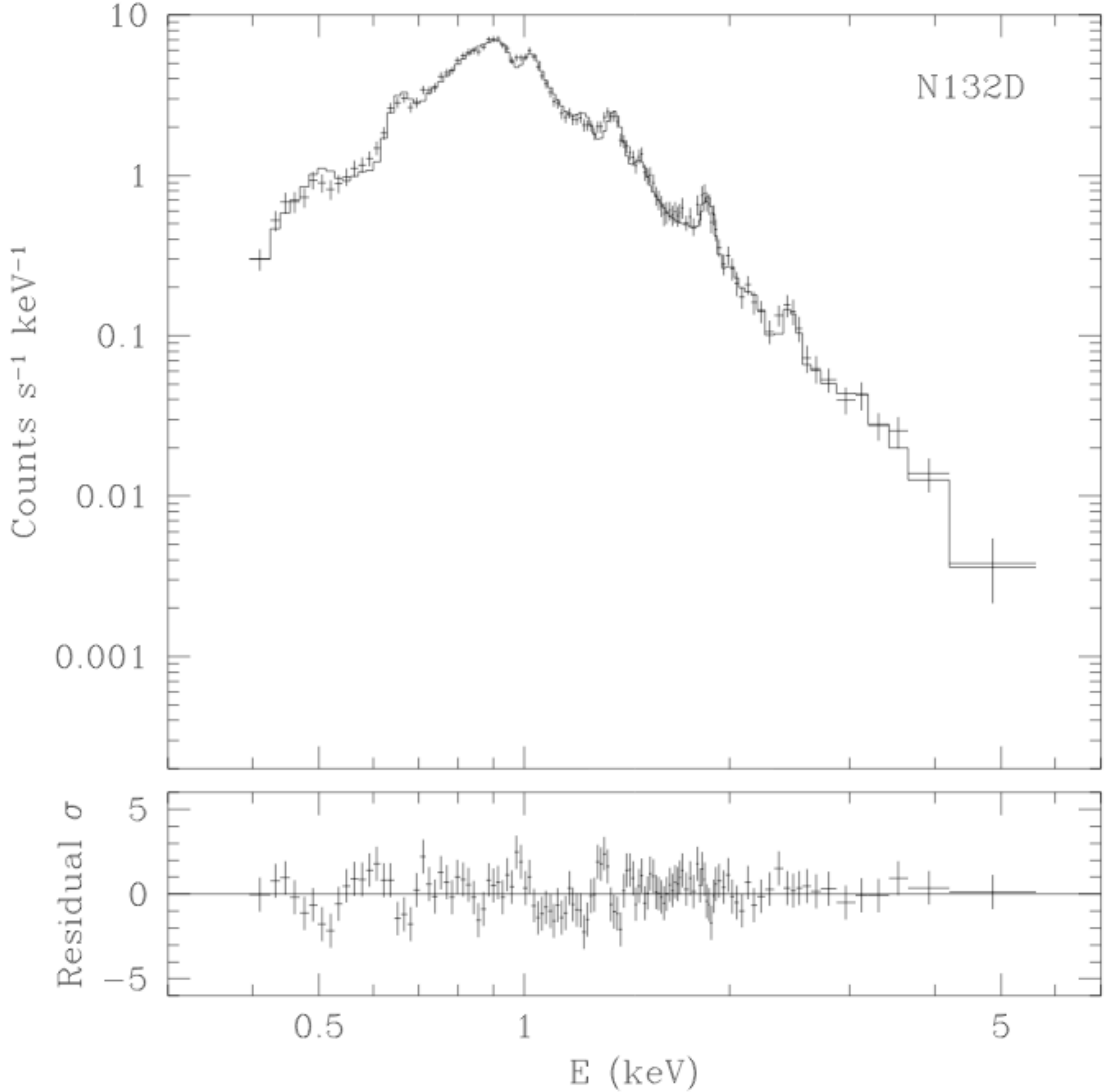
biggest drawbacks:

limits to energy resolution;
classical CCD has slow readout;
which leads to loss of t-information;
and also produces 'pileup' (reduces dynamic range);
also: background relatively high (compared to gas)

CCDs on *ASCA*, *Chandra*, *XMM*, *Suzaku*, Astro-H, ...,
Athena

'imaging semiconductor detectors' likely to
remain 'workhorse' instruments for foreseeable future

N132D in the LMC/ Hughes *et al*. 1998



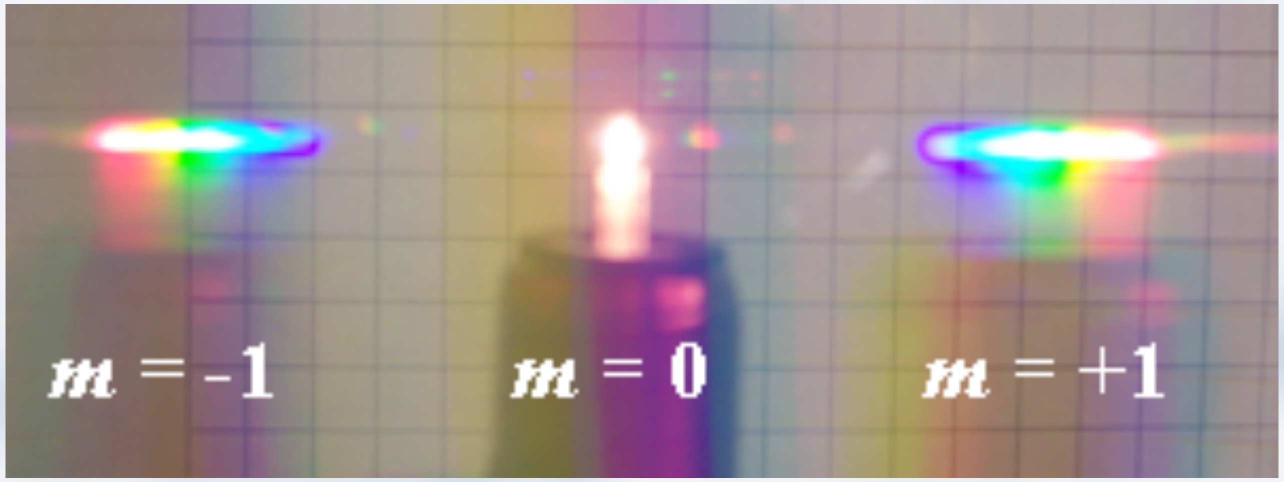
X-ray Diffraction Gratings for Astrophysics

Frits Paerels
Columbia Astrophysics Laboratory
Columbia University, New York

Diffraction Gratings: Plusses and Minuses

+ Simple classical wave optics
+ Relatively simple spectrometers (just imaging)
+ Resolving power only limited by practical considerations
+ highest resolution in soft X-rays; complement ionization detectors, calorimeters

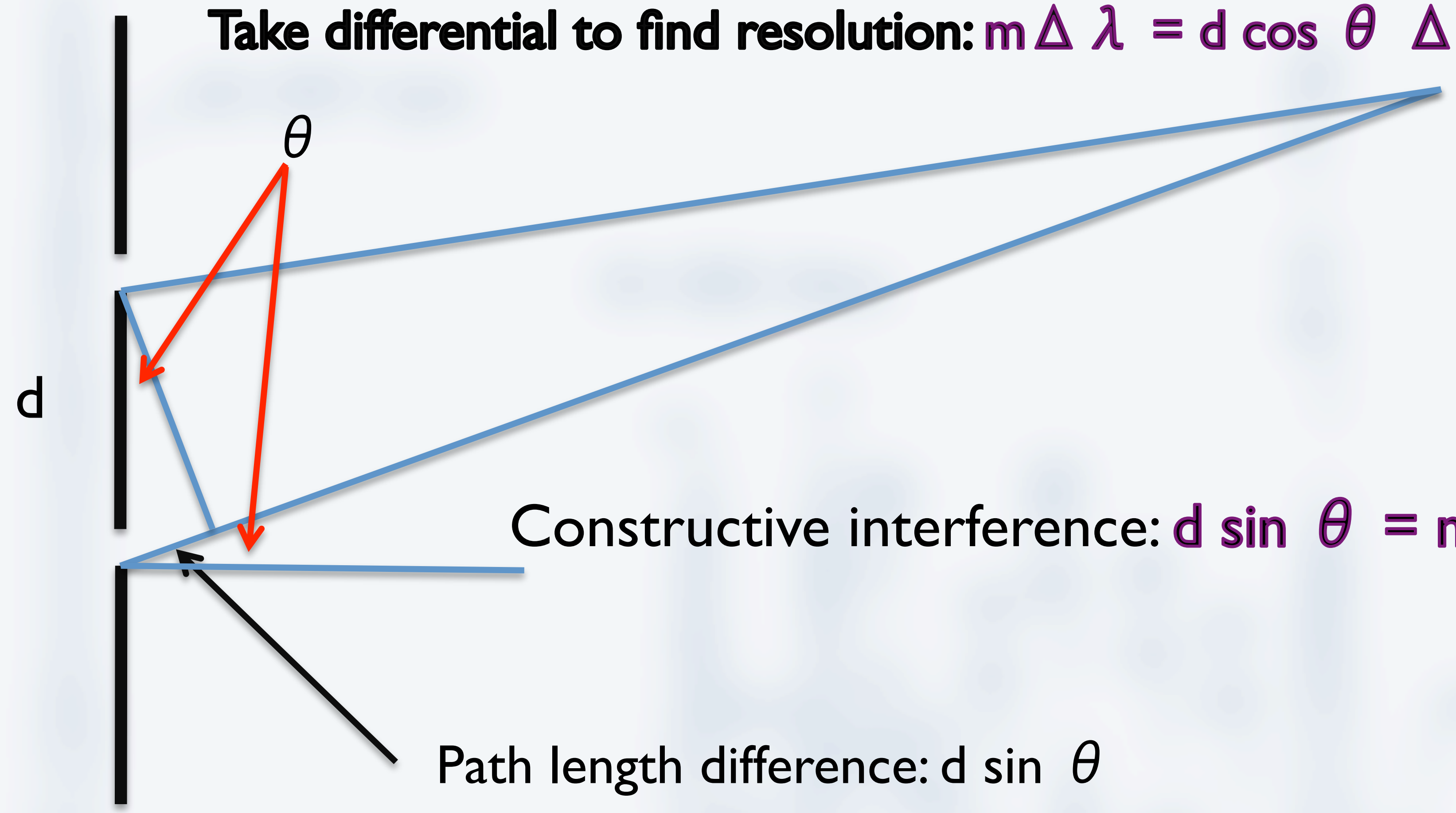
− point sources only
− highest resolution in soft X-rays



Classical Implementation: Transmission and Reflection

Dispersion equation: $d \sin \theta = m\lambda$

Take differential to find resolution: $m\Delta\lambda = d \cos \theta \, \Delta\theta$

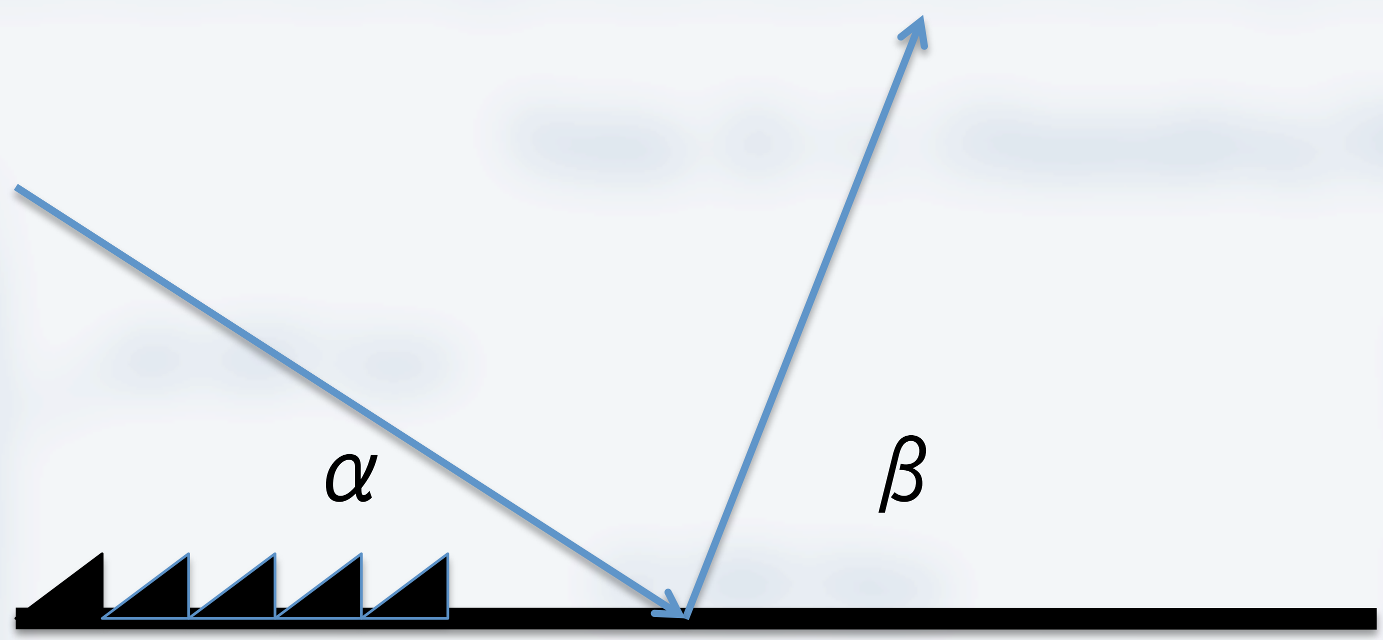


Resolving power: $\lambda/\Delta\lambda = \tan\theta/\Delta\theta \cong \theta/\Delta\theta$ (θ usually small)

Behind focusing mirror of fixed angular resolution: $\Delta\lambda$ fixed;

High resolving power: small $\Delta\theta$ and/or large θ (***requires high line density***)

X-ray reflection gratings have to be grazing incidence



Dispersion equation: $\mathbf{\cos\beta = \cos\alpha + m\lambda/d}$

(*equivalent line density equal to density projected onto incident wavefront*)

Spectral resolution:

$\mathbf{\Delta\lambda = (d/m)\sin\alpha\ \Delta\alpha}$ (telescope blur $\Delta\alpha$: suppressed by large dispersion)

Large dispersion due to small incidence angle; offsets telescope blur;

but have to align gratings to high angular tolerance instead

Diffraction Efficiency: Tune the Band by Blazing

transmission

reflection

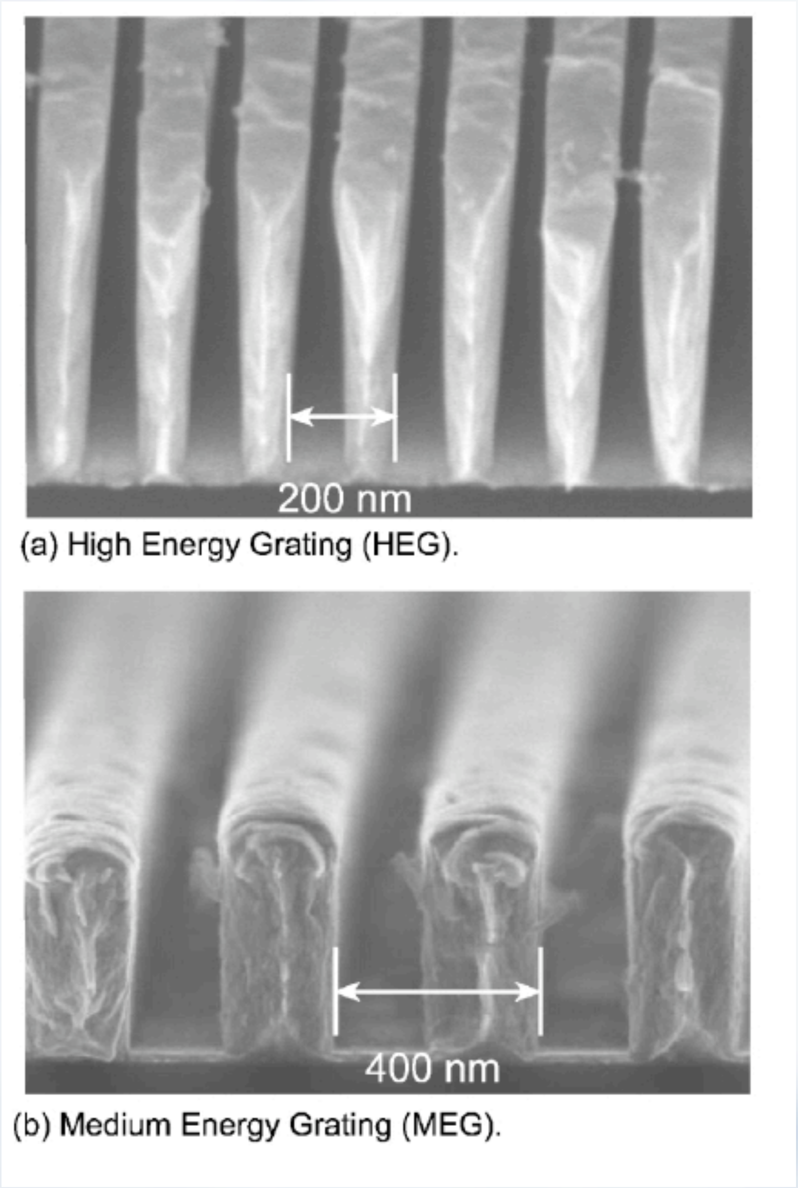
The **grating with the thinner bars**
generally has 'bump' of higher efficiency at shorter wavelengths (due to phase shifted waves passing through the bars)

Simple scalar diffraction calculation usually suffices for efficiency model.

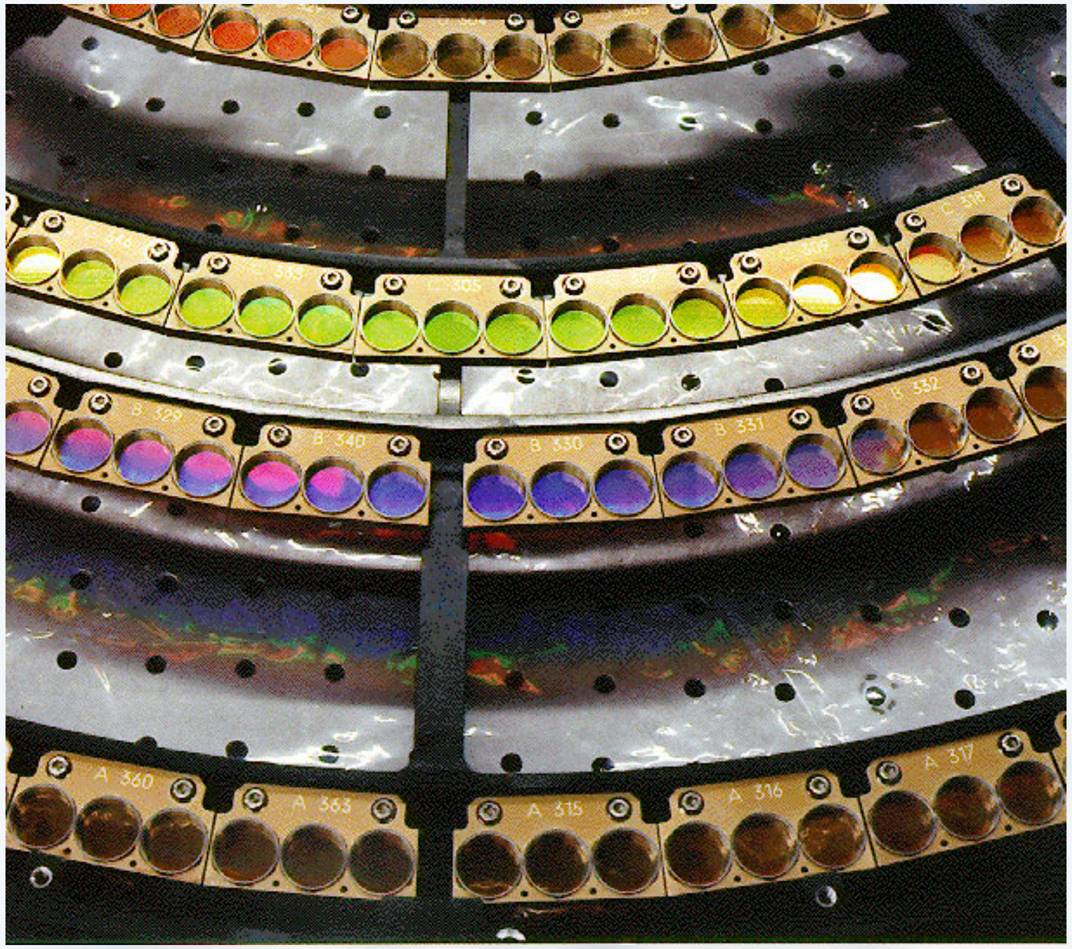
The **lower blaze angle grating** will have highest reflectivity at shorter wavelengths

Reflection gratings: have to calculate reflectivity from solution to Maxwell's Equations, with proper boundary conditions

The High and Low Energy Transmission Grating Spectrometers on *Chandra*

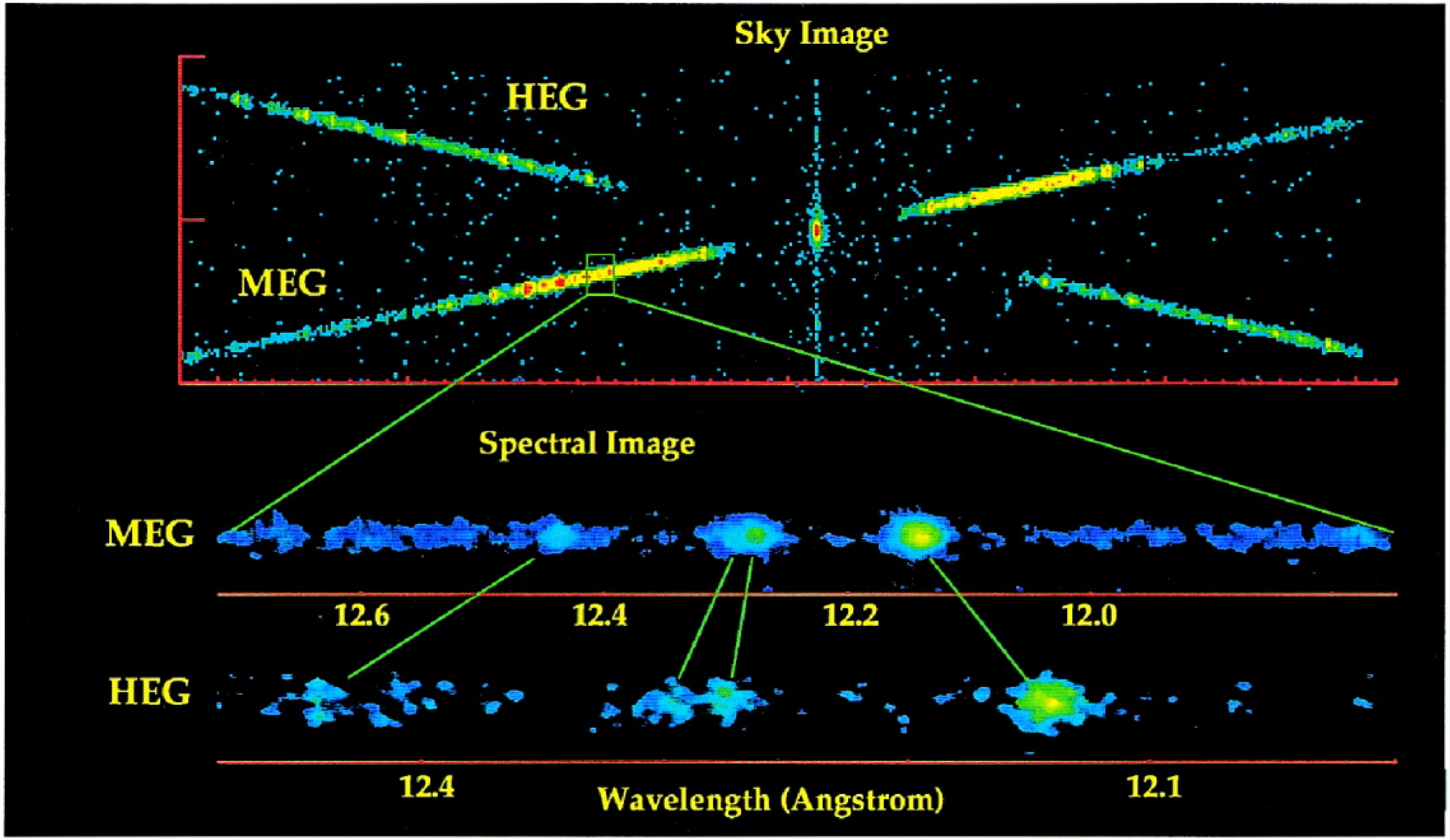


HETGS, MIT



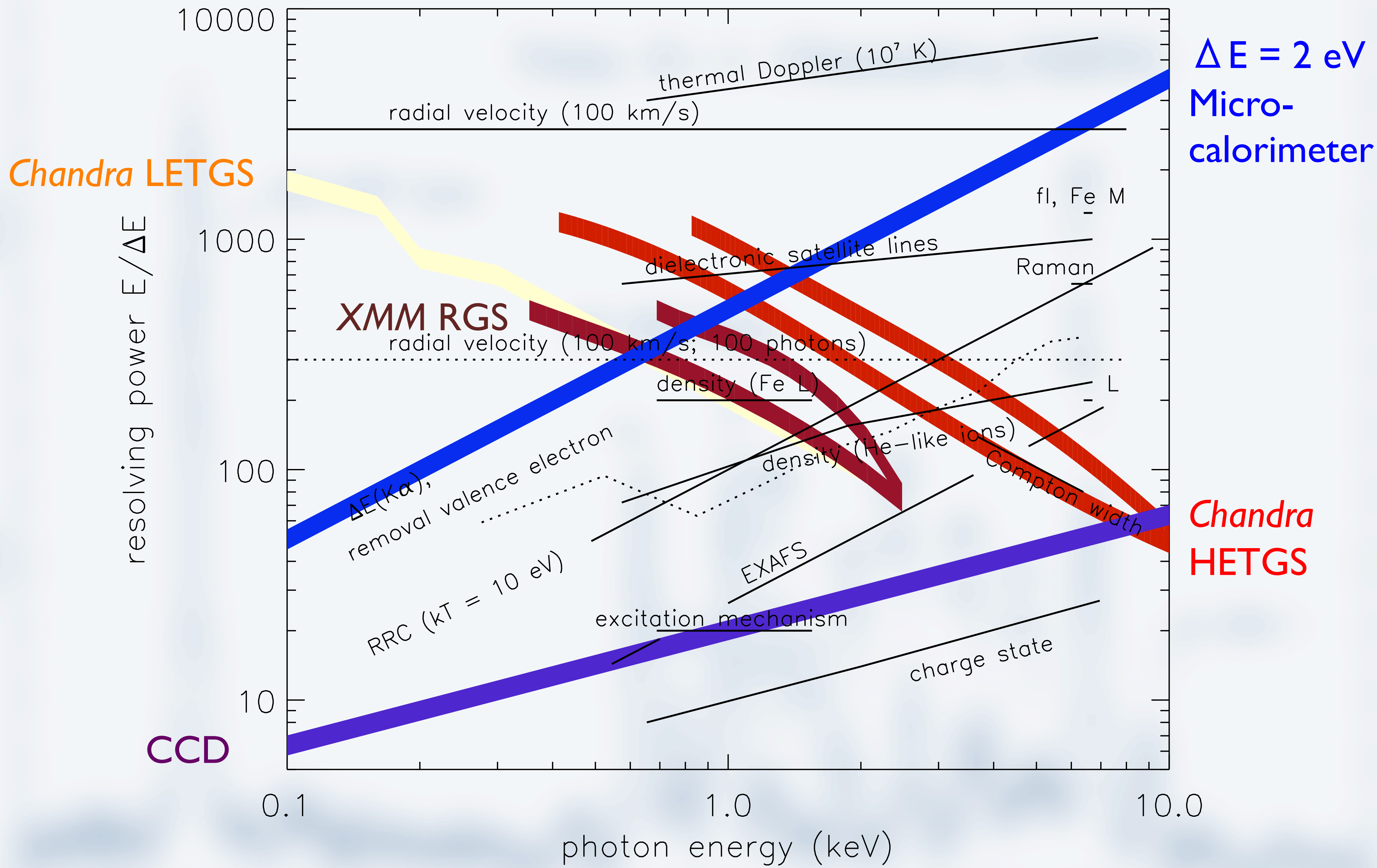
LETGS, SRON+MPE

Example Spectral Image (HETGS, Capella)



And the spectral orders can be separated using photon energy as measured by focal plane CCD detectors (HETGS and LETGS; LETGS also has dedicated MCP out to 180 Å); also suppresses background

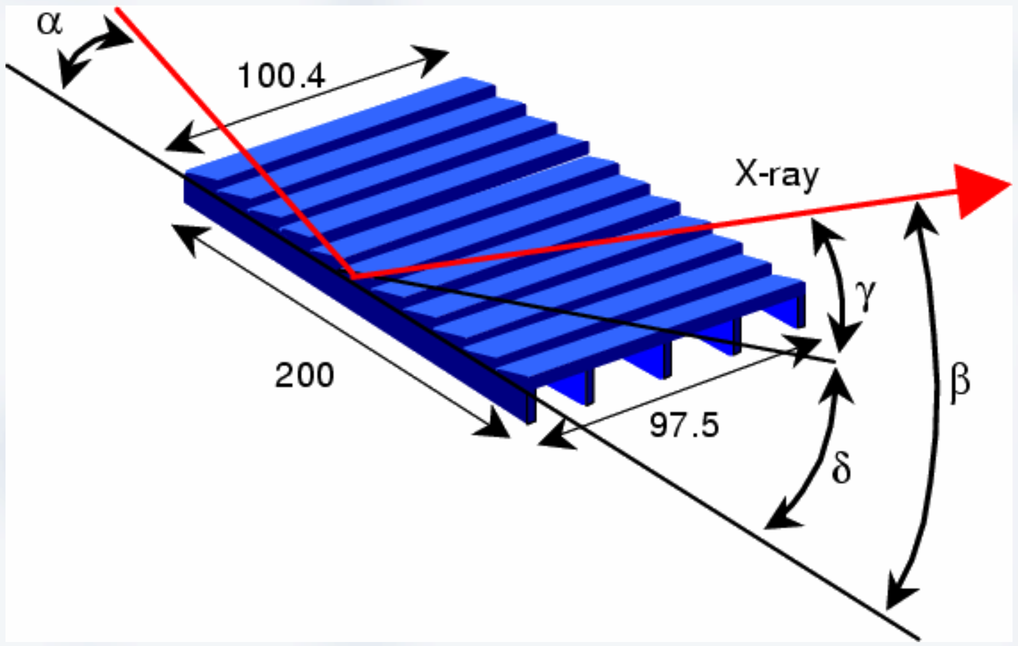
Resolving Power

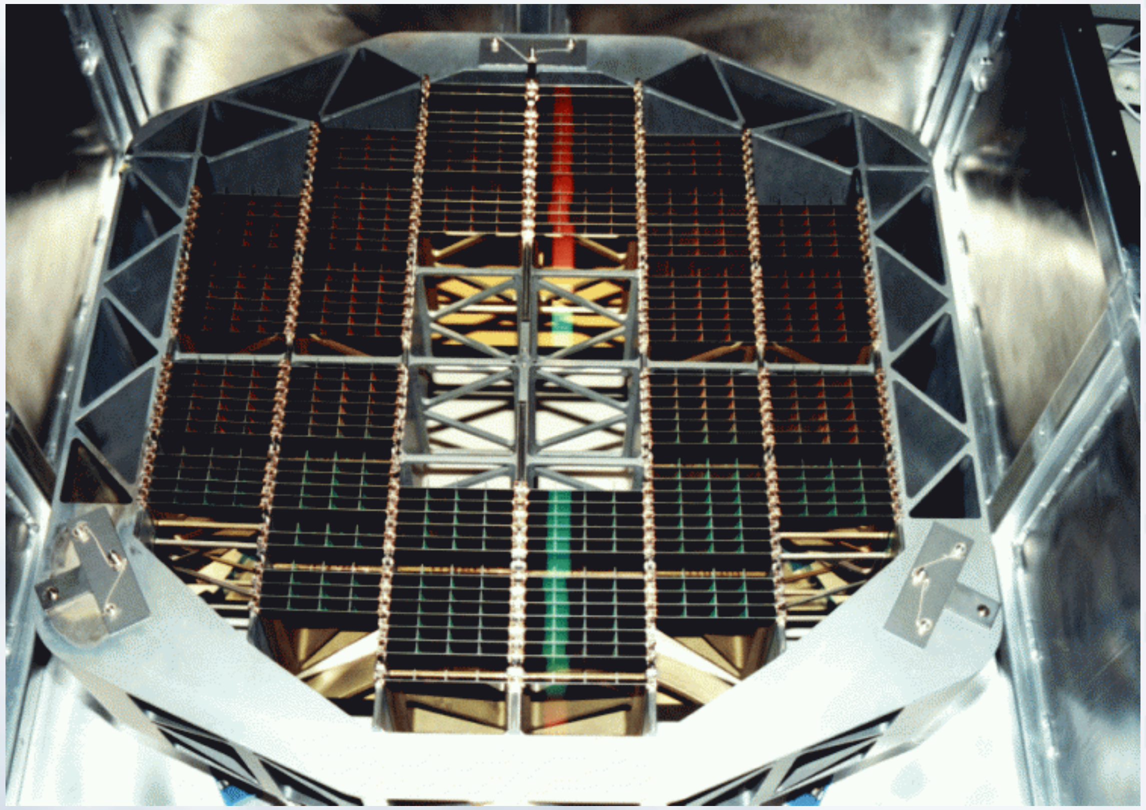


Design goals: at least resolve members of He-like 'triplets'
cover K shells of abundant elements; cover Fe L shell

The Reflection Grating Spectrometer (RGS) on *XMM-Newton*

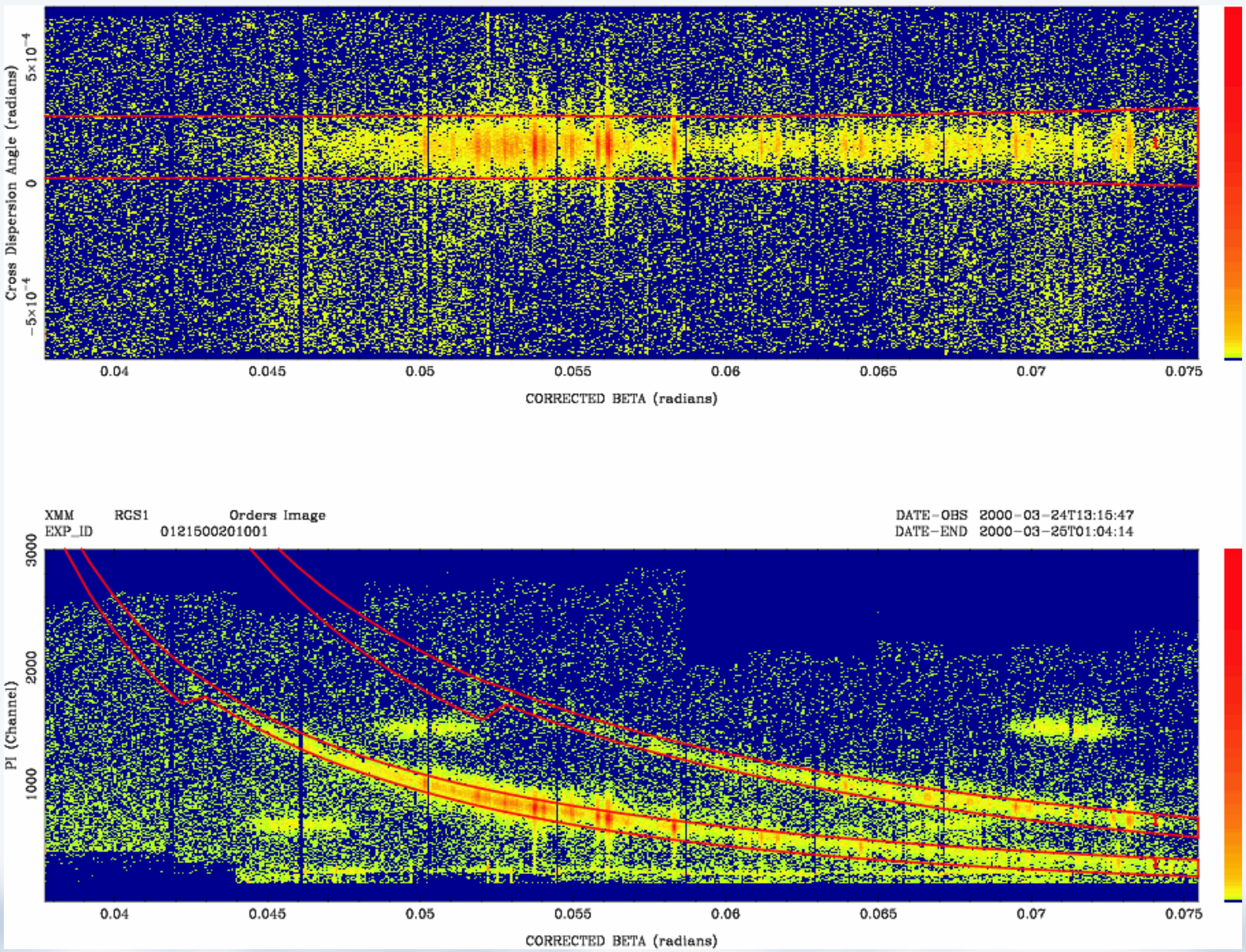
Angular resolution of XMM-Newton optics significantly lower than Chandra:
transmission gratings not a viable option.
Instead, reflection allows very large dispersion angle, producing high resolution.



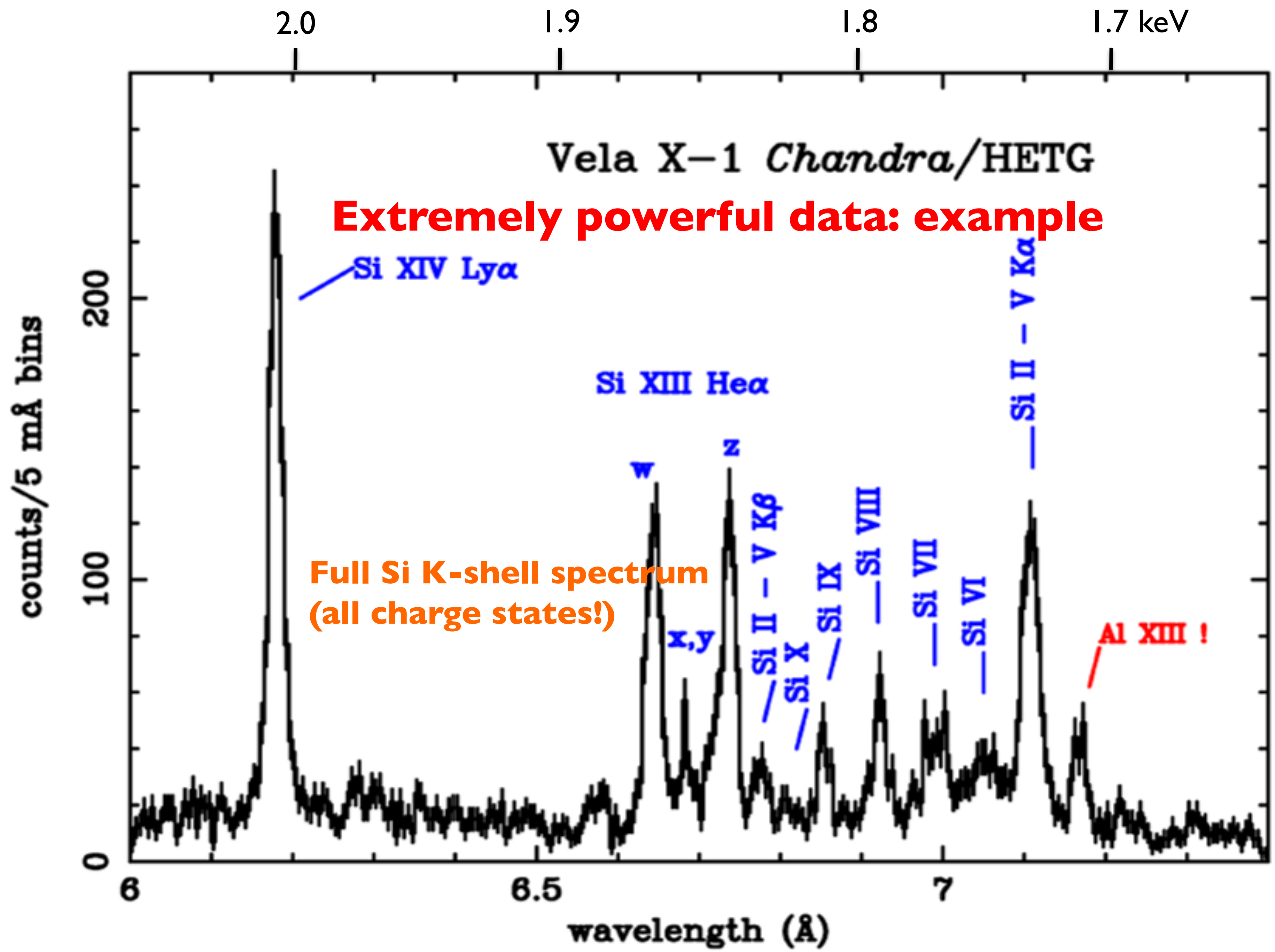


Array of 182 precision-aligned reflection gratings per telescope

Example Spectral Image and Banana Plot (RGS, Capella)

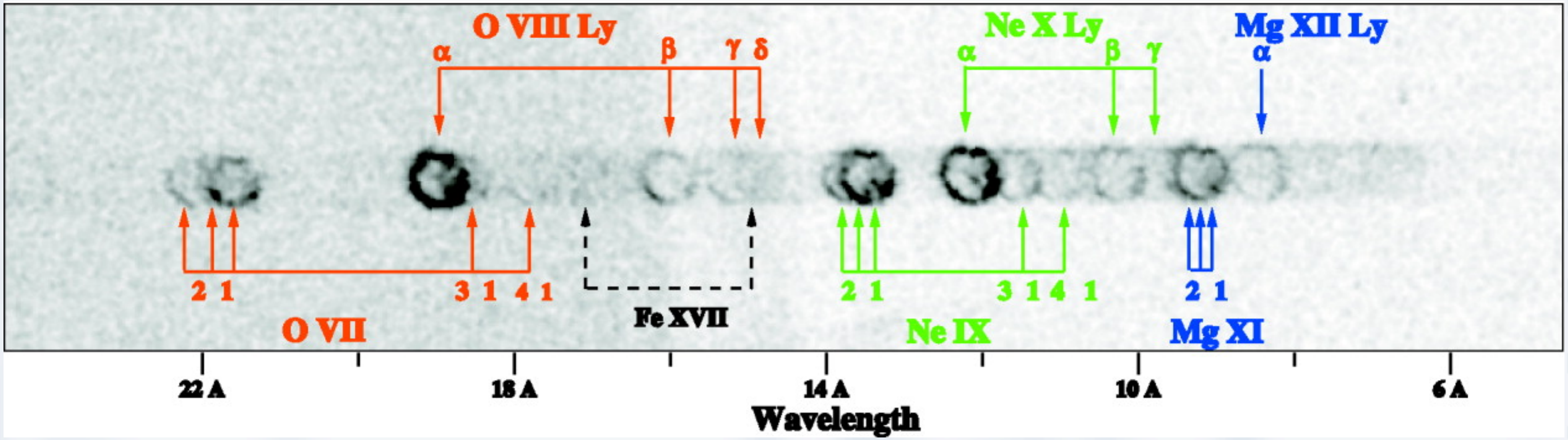


(or to quote Claude Canizares: we're actually checking on the rest mass of the photon…)



Watanabe et al., *ApJ*, **651**, 421 (2006)

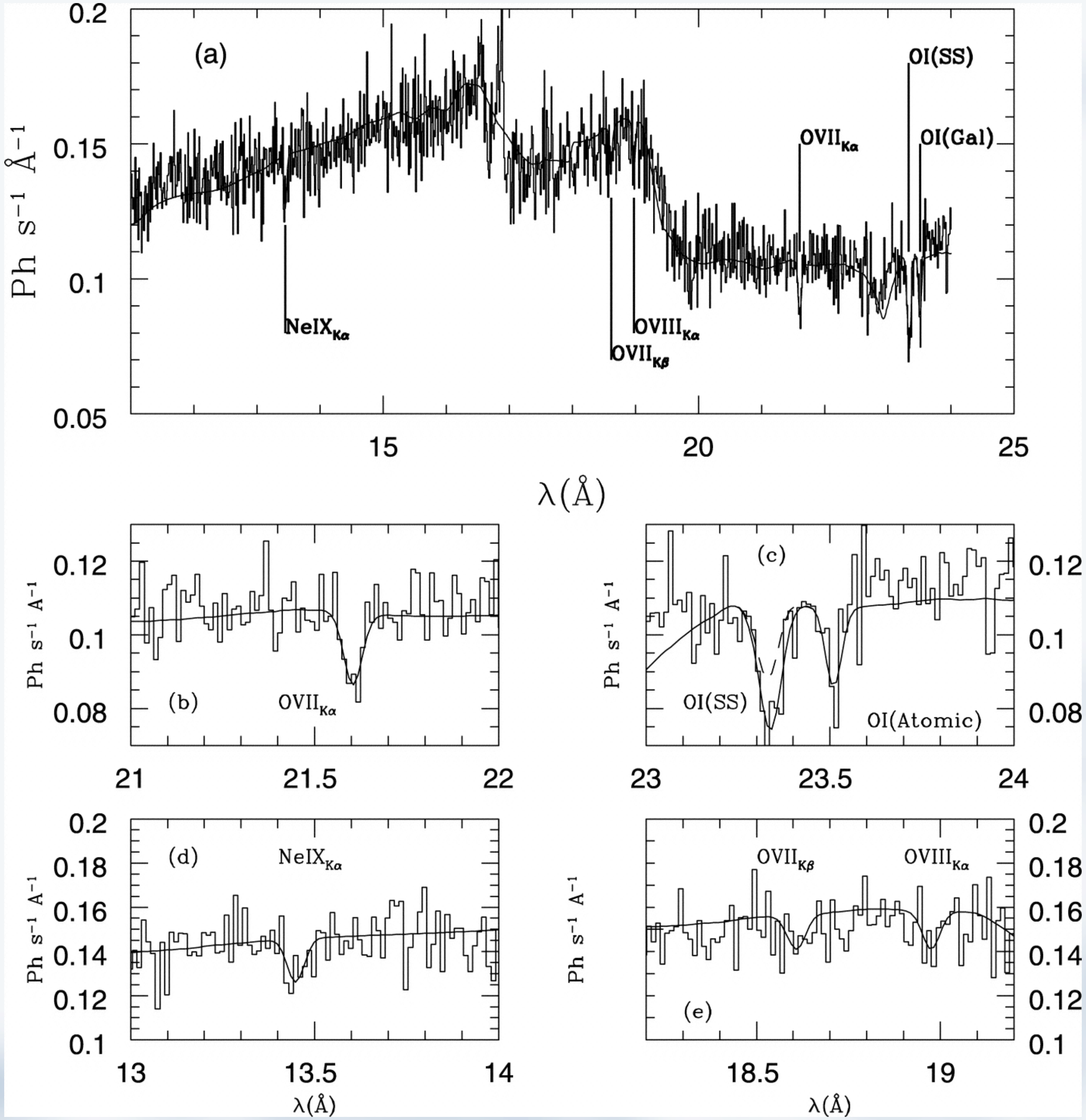
Famous Results: the 'Spectroheliogram' of SNR 1E0102 (*Chandra* HETGS)



Full spatial/velocity structure in multiple ions

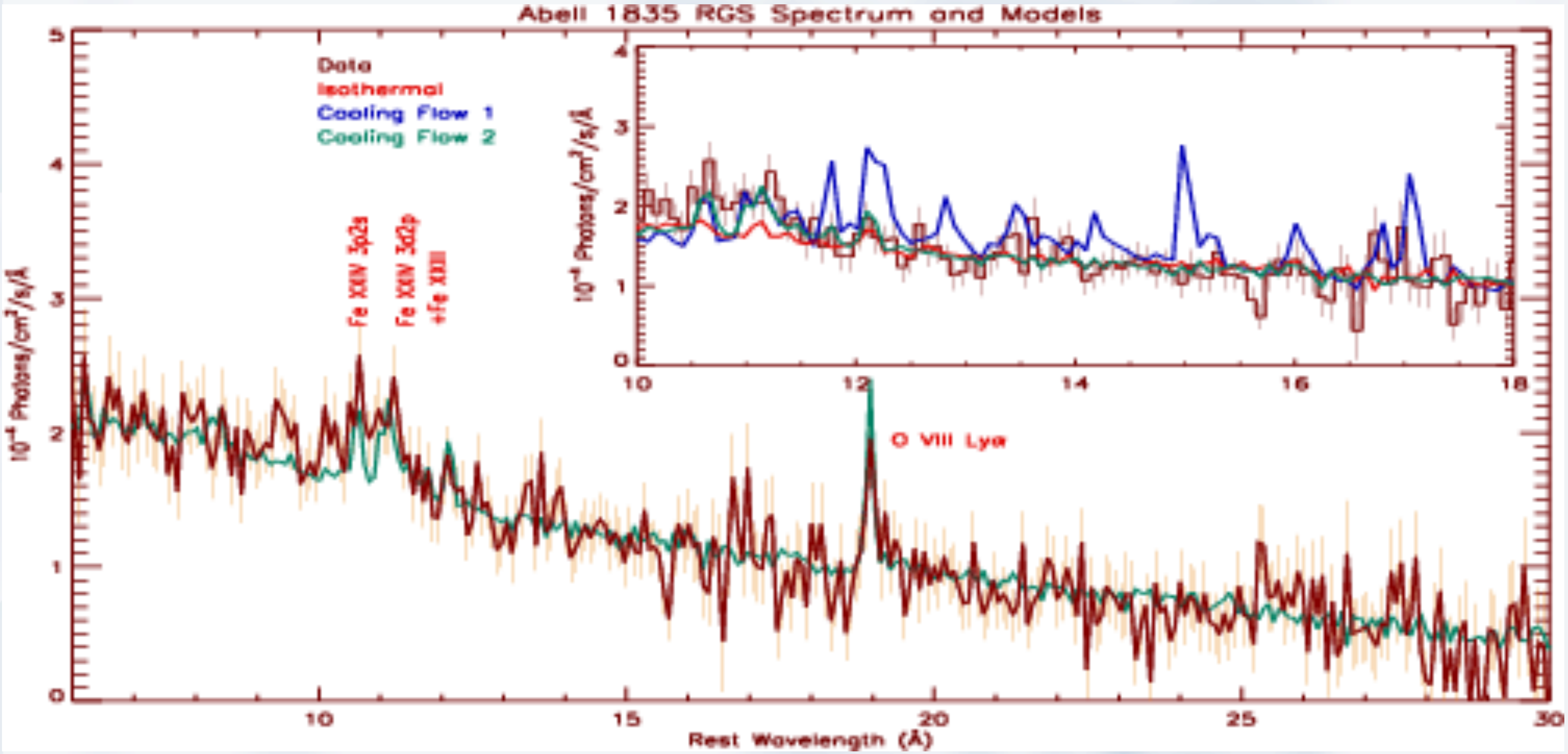
Flanagan et al., 2004, *Astrophys. J.*, **605**, 230

Famous Results: OVII Line Absorption by Extragalactic Hot Gas (*Chandra* LETGS)



PKS2155-304; but now seen in all deep extragalactic continuum spectra
Nicastro et al., 2002, *Astrophys. J.*, **573**, 157

Famous Results: Absence of Fe L emission from Cool Gas in Clusters (*XMM* RGS)



Peterson et al., 2001, *Astron.Astrophys.*, **365**, L104.

(resolved spectroscopy of moderately extended sources still possible with RGS)

Future: the International X-ray Observatory

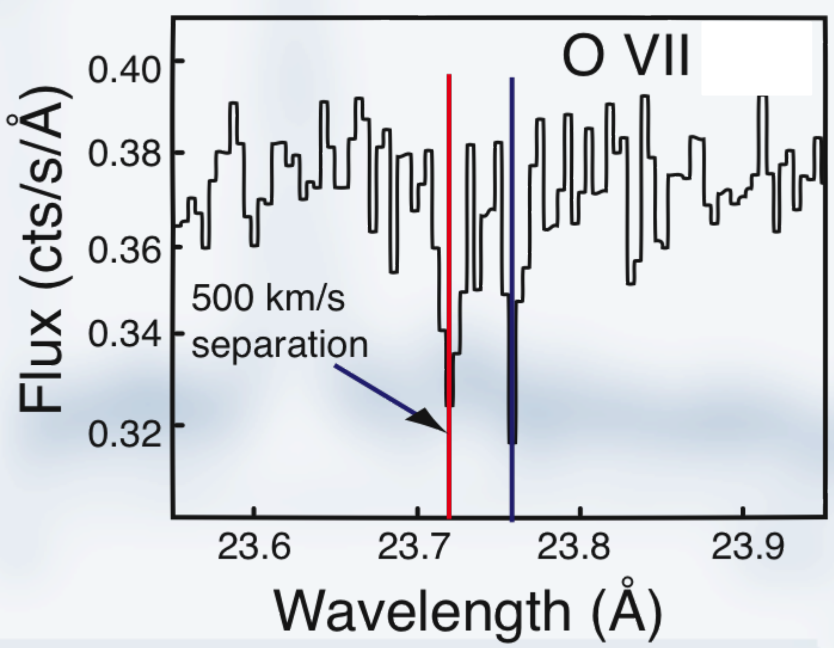
Requirement:

Spectroscopic Resolving Power > 3000 implies grating
0.3 – 1 keV; >1000 cm^2 effective area

Example of Driving Science:

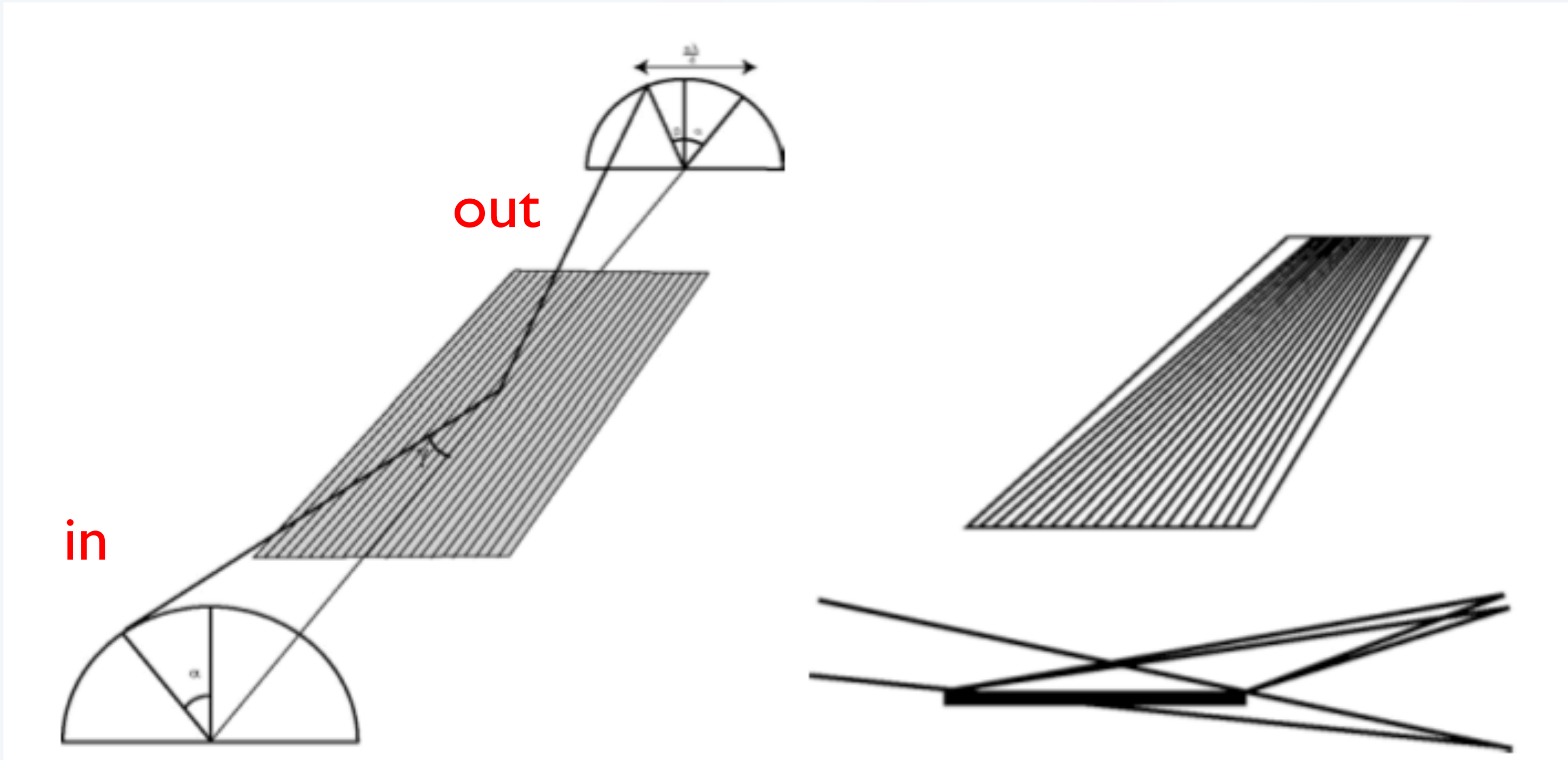
desire to detect sample intergalactic metal absorption lines

1. Twist on reflection: off-plane mount
2. Twist on transmission: the CAT grating



Example IXO XGS intergalactic absorption lines

Option 1: Off-plane Reflection Gratings



Incoming ray not perpendicular to grooves:

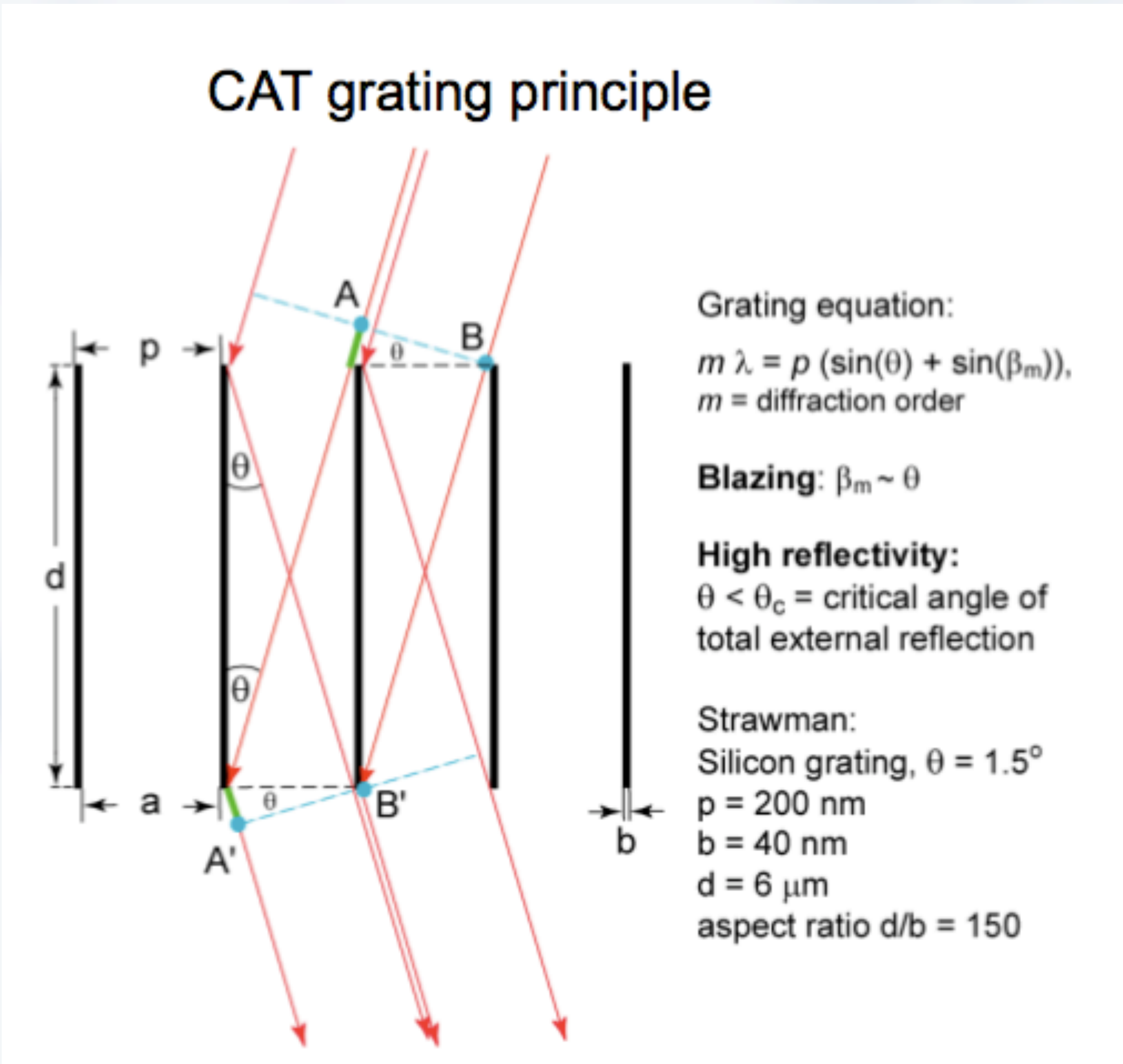
\+ allows in principle for **both** large dispersion angle **and** high reflectivity (not true for in-plane mount, as in XMM RGS)

− need high groove density, in potentially challenging radial pattern

Design calls for array of radial groove gratings, operated in overlapping high spectral orders in order to ensure R > 3000 over wide band

Originally proposed by Webster Cash

Option 2: Critical Angle Transmission (CAT) Gratings



X-rays reflect off sides of bars:

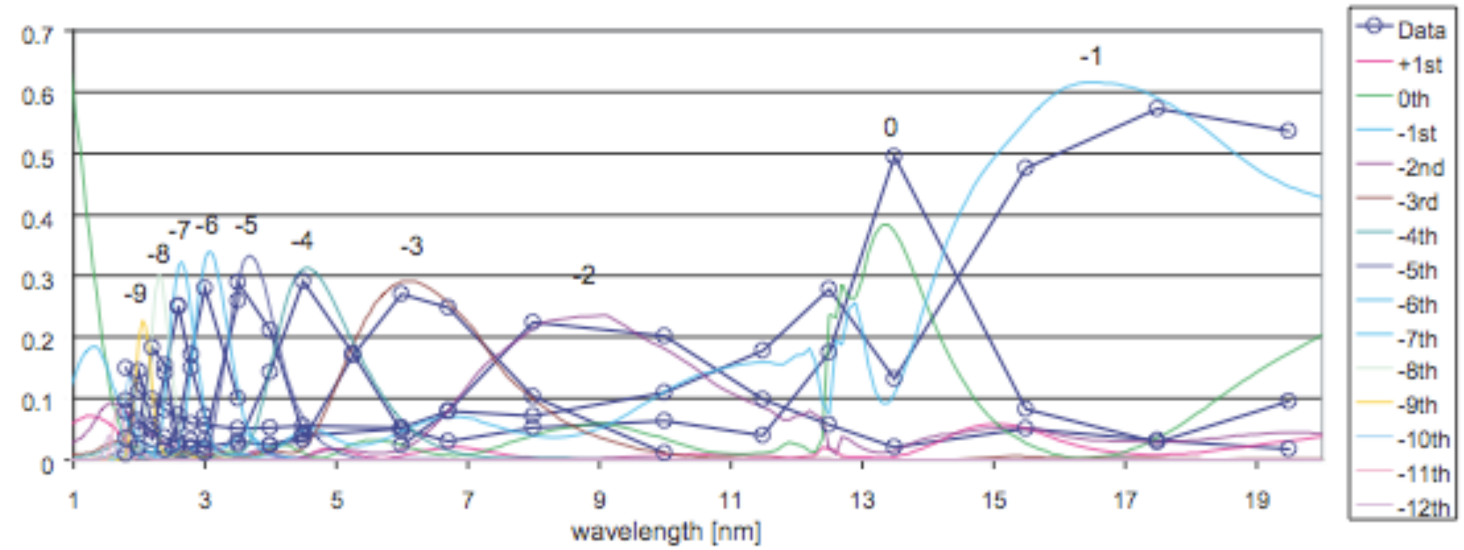
Dispersion equation behaves as
transmission grating
Efficiency behaves as
reflection grating

Low mass and obscuration

Invented by Ralf Heilmann (MIT)

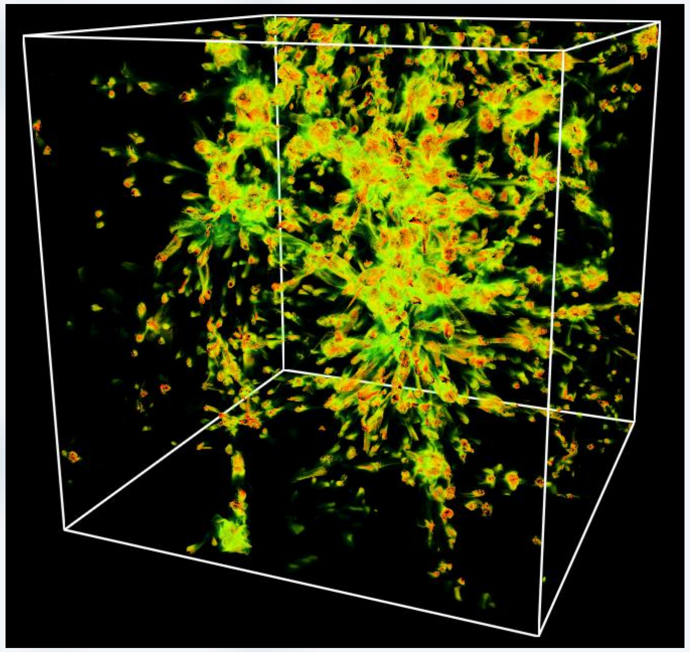
CAT grating efficiency

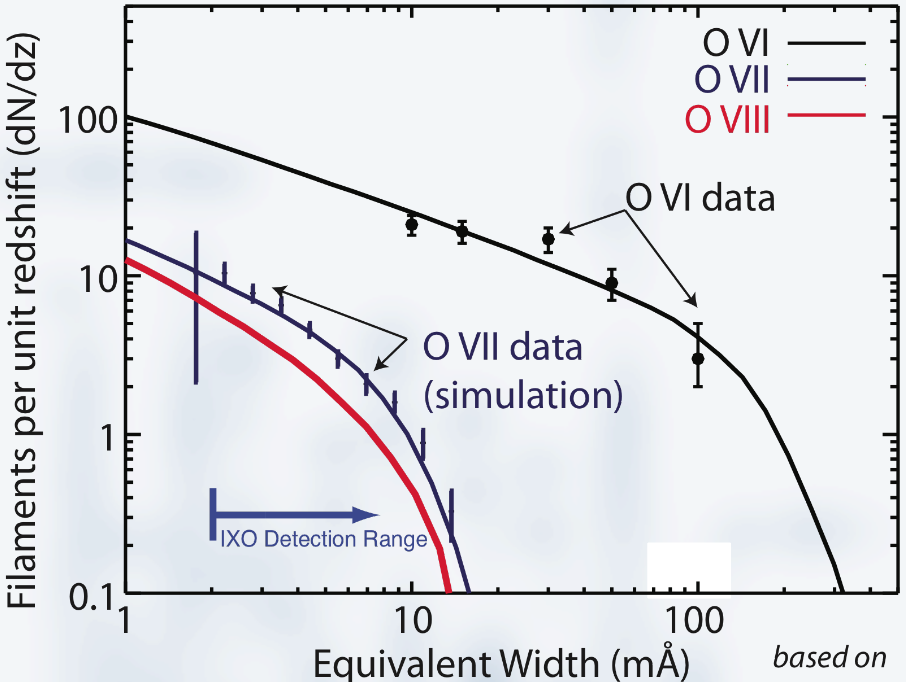
Measurements in very good agreement with theory



Design calls for multiple overlapping high orders, to maintain R > 3000 over wide band

IXO X-ray Grating Spectrometer (XGS) – Example of Transformational Science





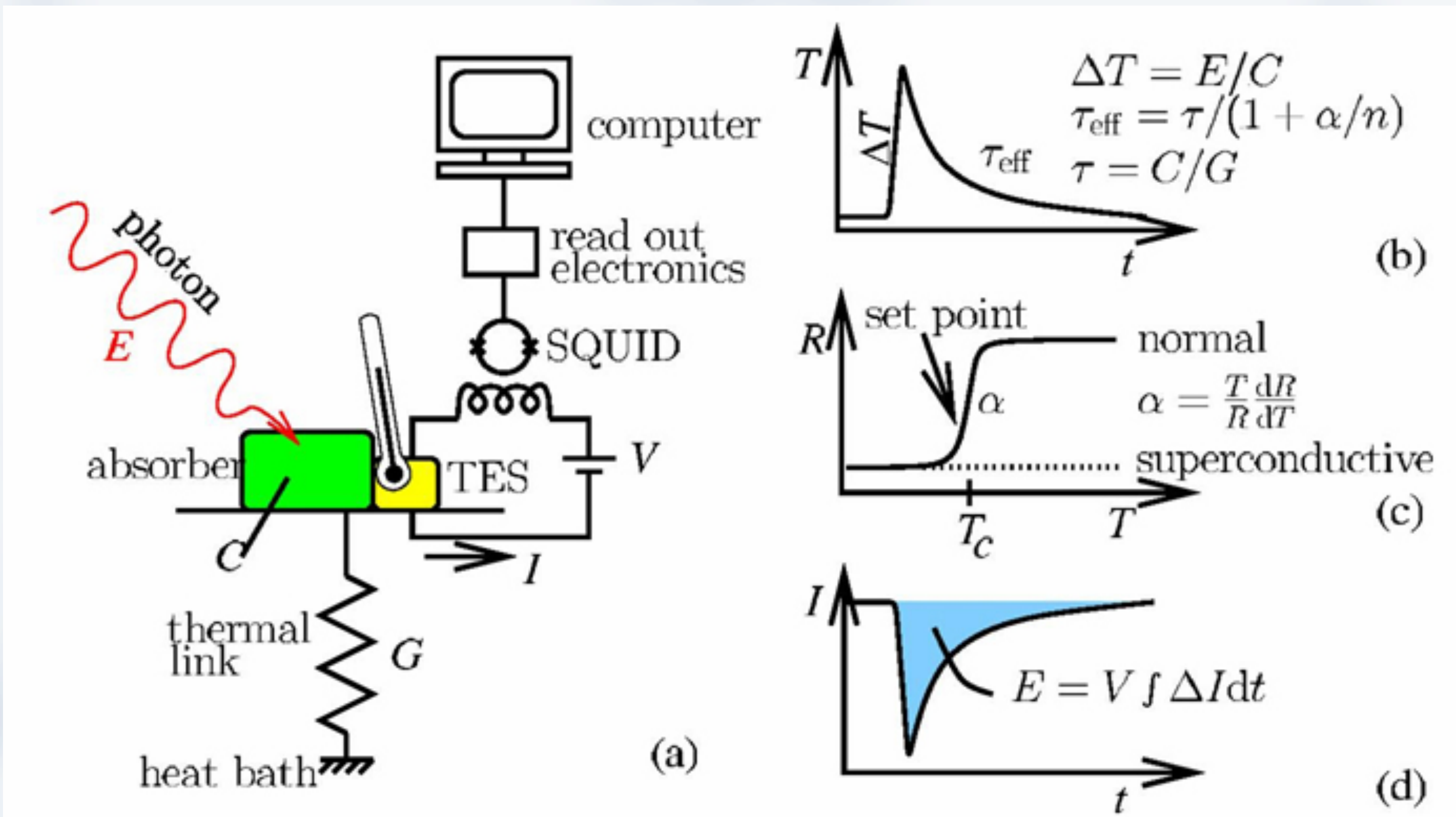
based on Cen & Fang (2006)

MIDEX? X-ray Surveyor?

microcalorimeters

(a.k.a. single photon calorimeter, X-ray quantum calorimeter, Transition Edge Sensor (TES) microcalorimeter(*))

Directly measure heat deposited by single X-ray photon



(*) refers to clever, sensitive thermometer principle; not to principles of the μ Cal)

Principle of a microcalorimeter

Temperature jump: $\Delta T = E/c_V$

c_V: heat capacity, E photon energy; make c_V small: big ΔT for given E

Classically: $c_V = 3Nk$, *independent of T* (equipartition theorem)
(N: number of atoms, k Boltzmann's constant)

Example: 1 mm^3 of Si: $N = 5 \times 10^{19}$ atoms; $c_V = 2 \times 10^4$ erg/K

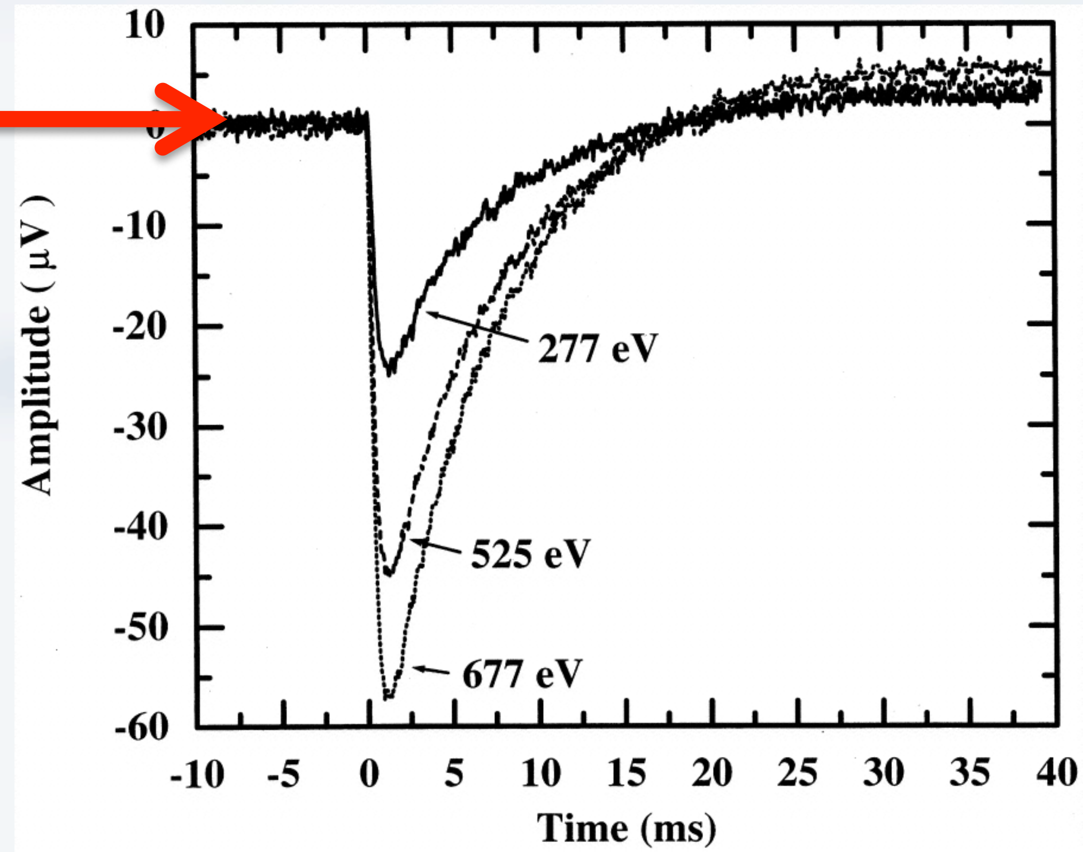
$E = 1$ keV $= 1.6 \times 10^{-9}$ erg: $\Delta T = 8 \times 10^{-14}$ K !!

So what is so great about microcalorimeters?

theoretical energy resolution/simple calculation

in simple calculation, $<\Delta E^2>$ refers to *this* noise level

Proportional to temperature



XQC rocket experiment; McCammon et al. (2002)

Energy resolution set by spontaneous temperature fluctuations;

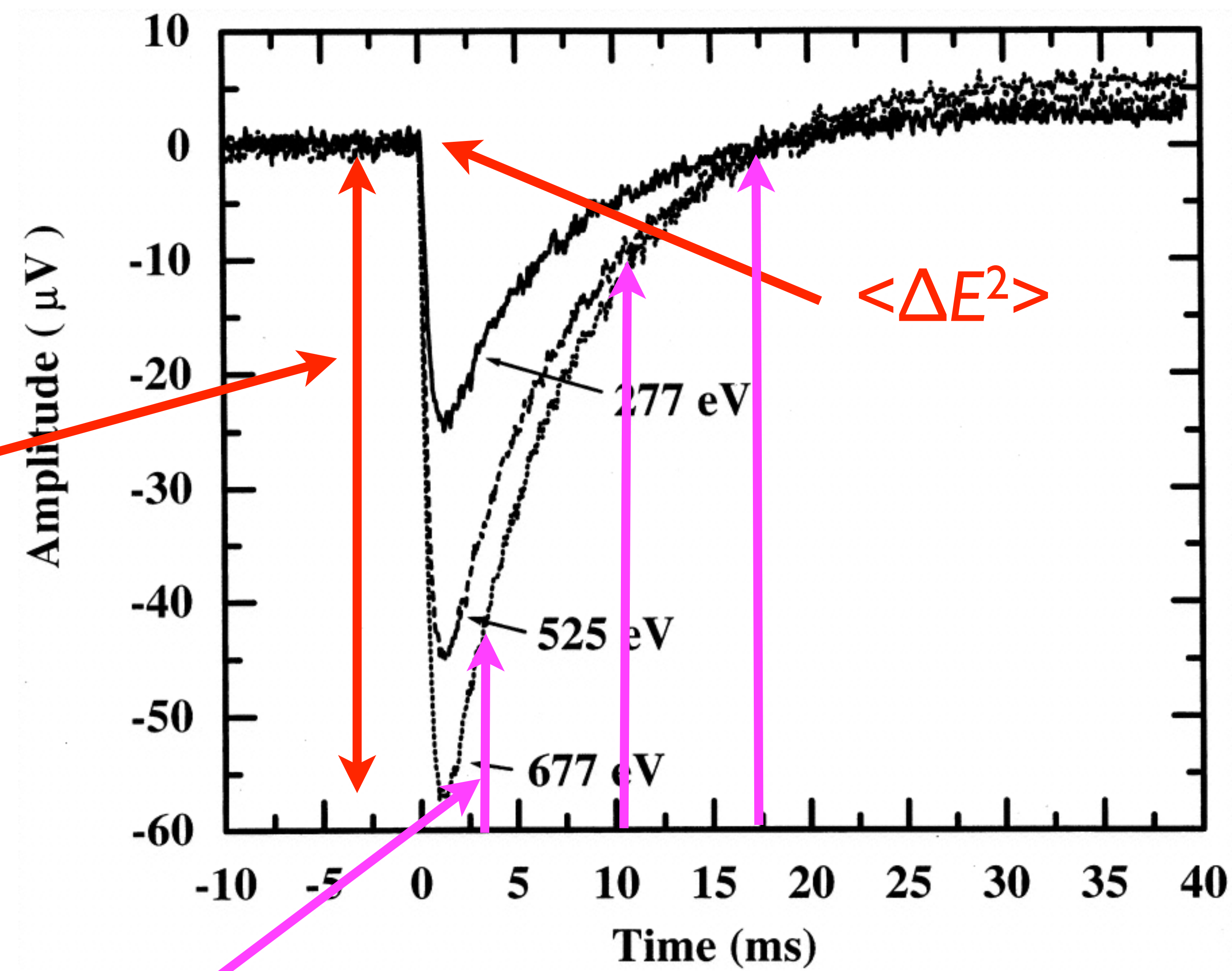
From thermodynamics, straightforward:

$< \Delta E^2 > = c_V \, kT^2$; $T \sim 0.1$ K: $\Delta E_{rms} \sim$ few eV!

theoretical energy resolution/sophisticated calculation

$<\Delta E^2>$ we just calculated corresponds to taking only *one* sample for computing E (the height of the peak)

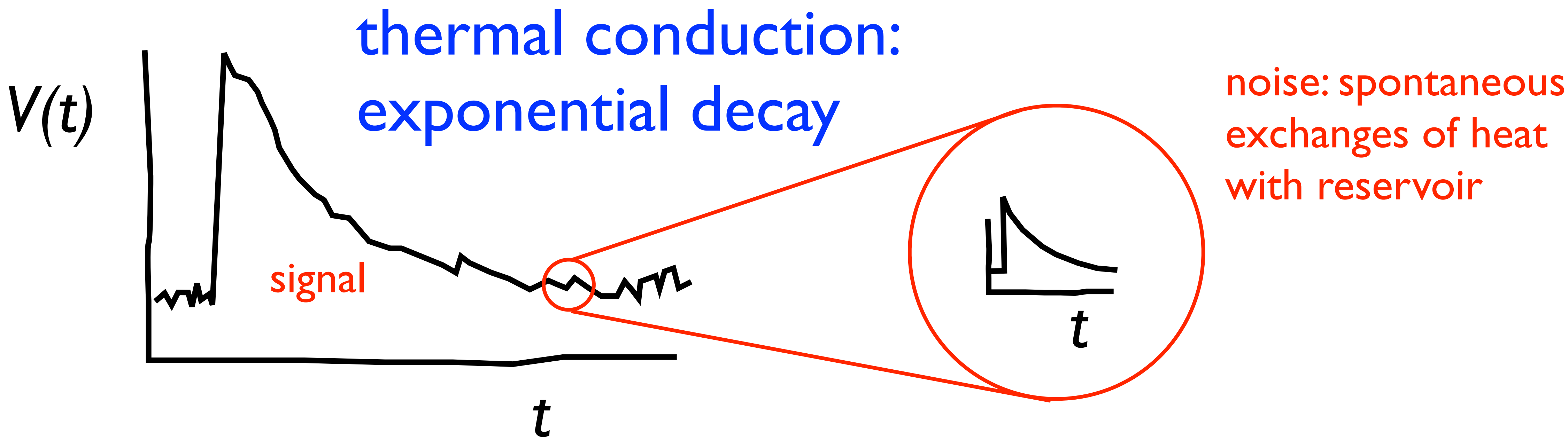
$\Delta V \rightarrow \Delta T \rightarrow E_{photon}$

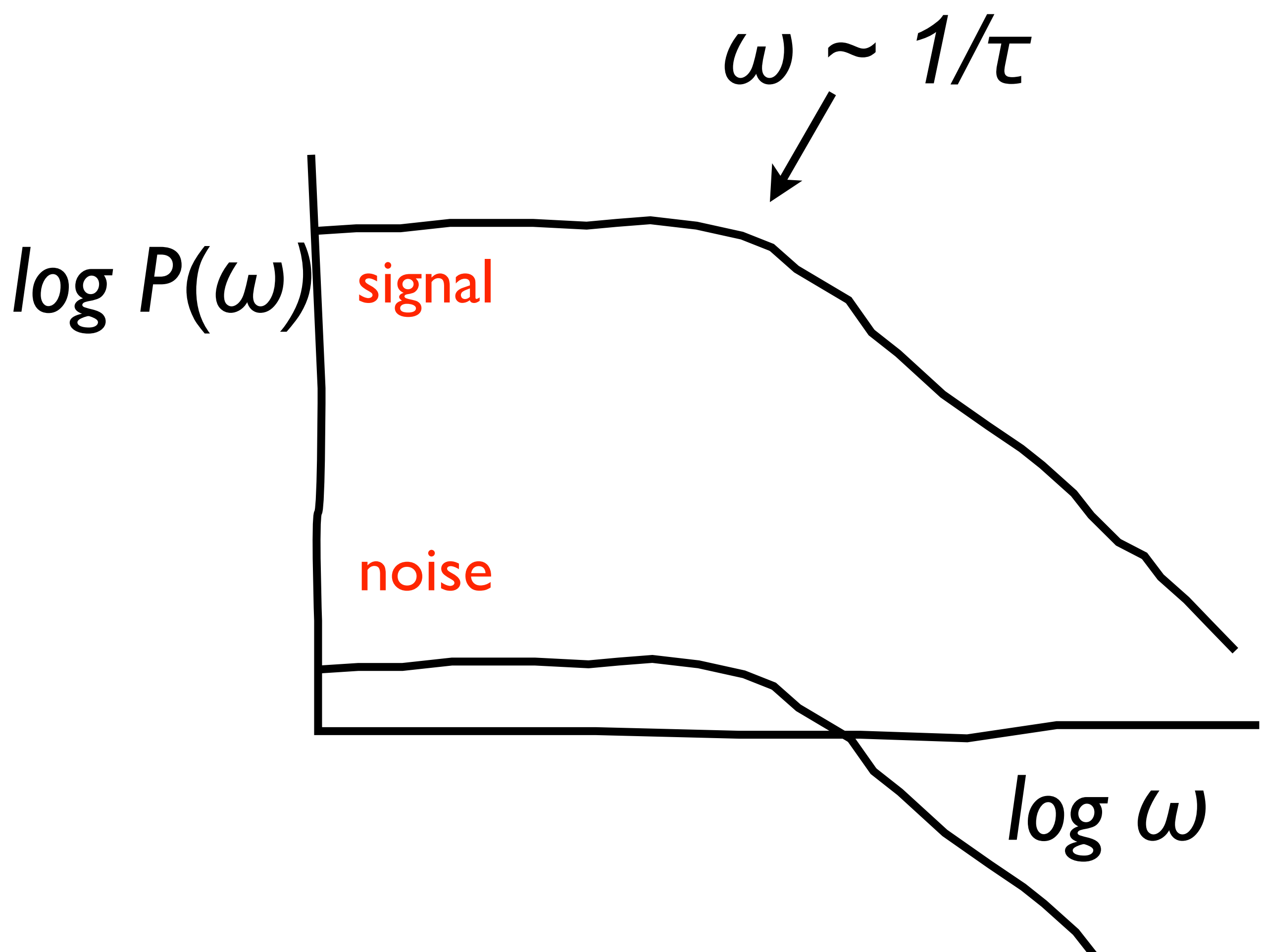


but the shape of $V(t)$ is known (thermal conduction to the reservoir), so you can take *many more independent readings,* only limited by how fast the thermometer(*) and the electronics are!

(*) hence Transition Edge Sensors (TES)

another way of looking at this: the power spectrum of the signal





in the absence of any other source of noise

$$\text{signal/noise} = \int_0^\infty (\text{signal}(\omega)/\text{noise}(\omega))\, d\omega$$

$$= E \,/\, (\langle E \rangle^2)^{1/2} \qquad \text{infinite!}$$

but in practice: $\omega/2\pi \lesssim 1000$ Hz

Kilbourne *et al.* 2007

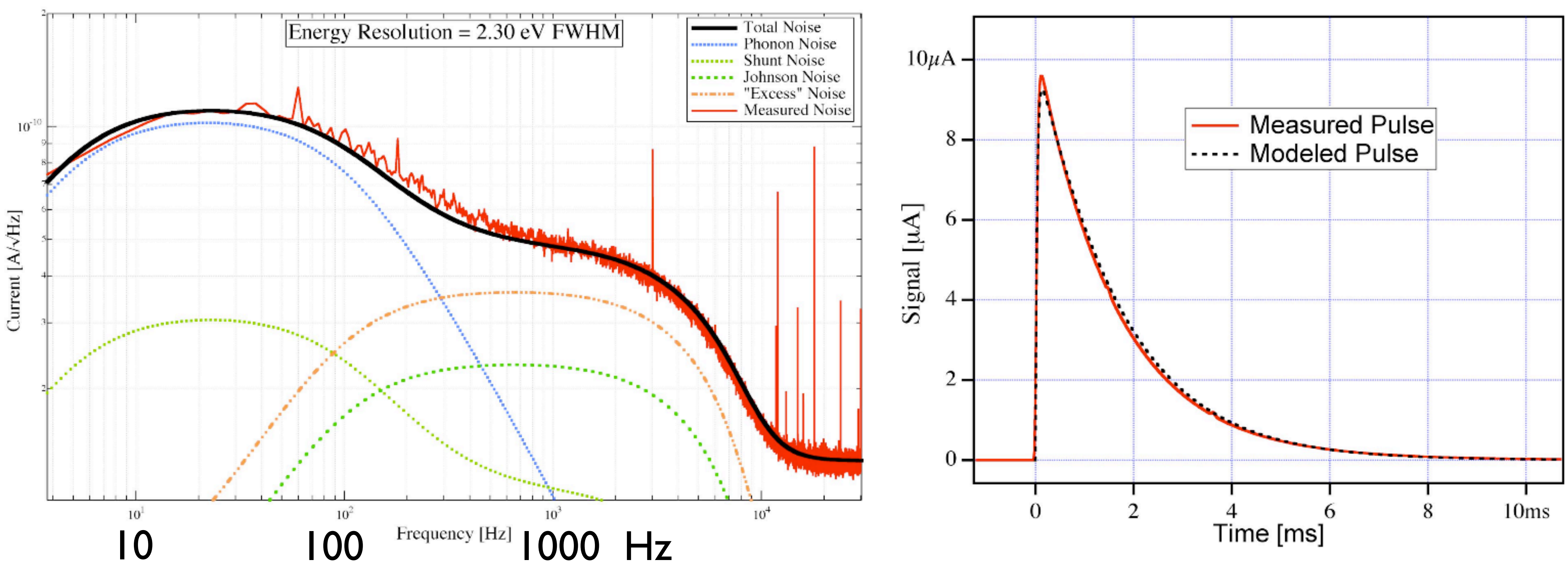
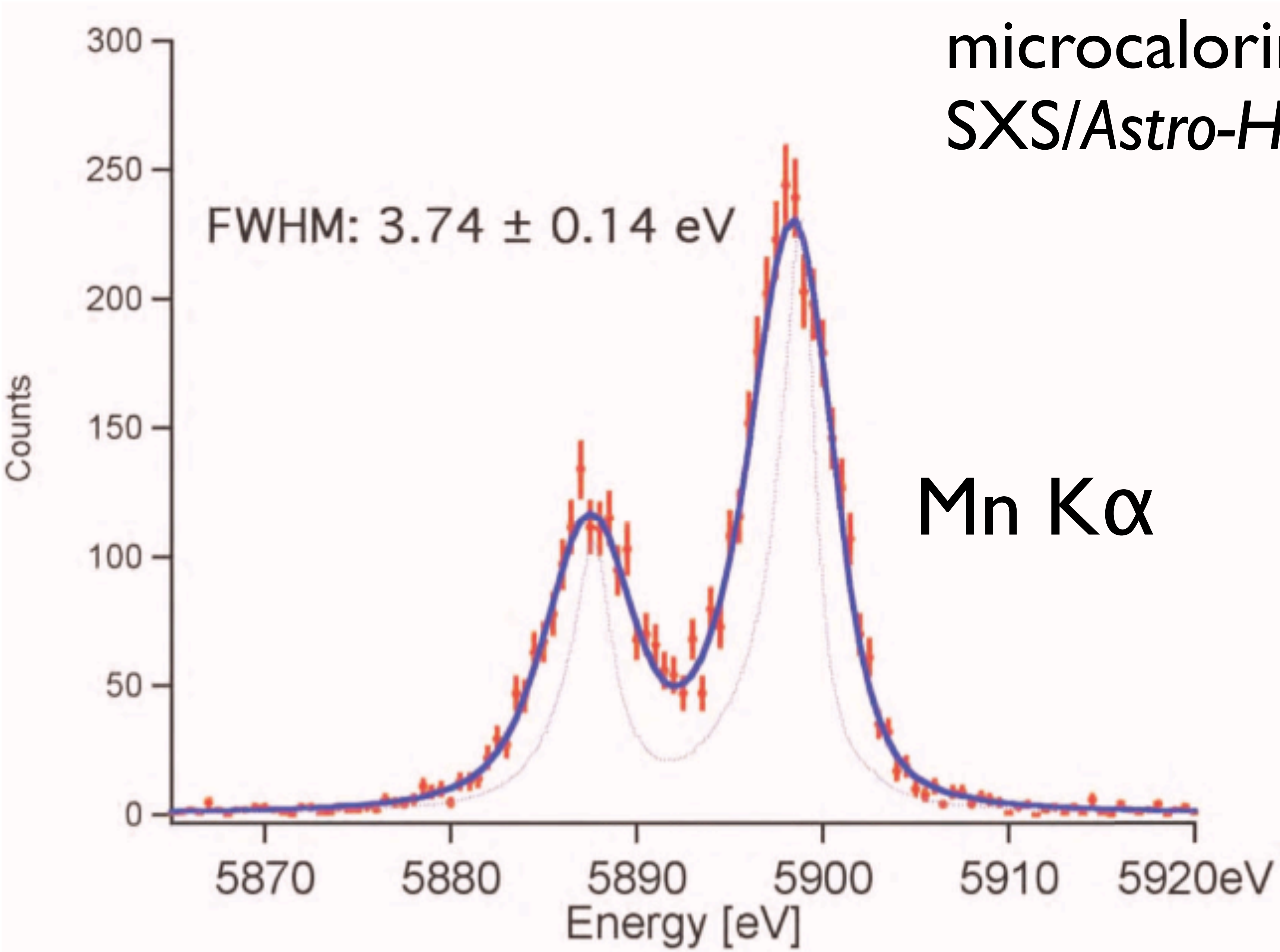


Figure 3. (left) The measured noise of a TES pixel with a gold absorber at its optimal operating point and the best fit using parameters from fitting a simple calorimeter model to complex impedance data. The main noise components that contribute to the total noise are also shown. (right) Measured pulse from a 6 keV x-ray compared with a simulated pulse using the best fit detector parameters.

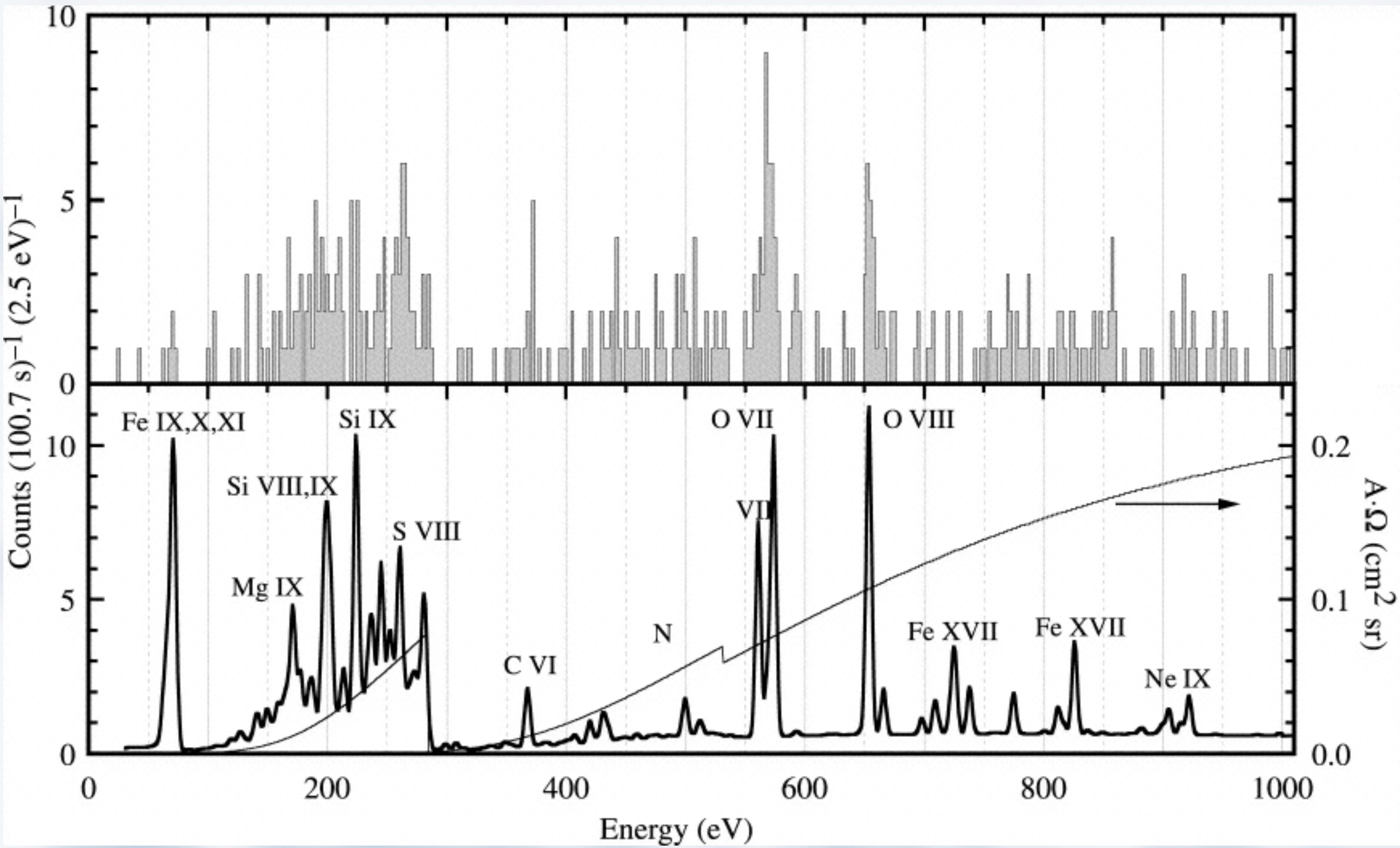
microcalorimeters for
SXS/*Astro-H*



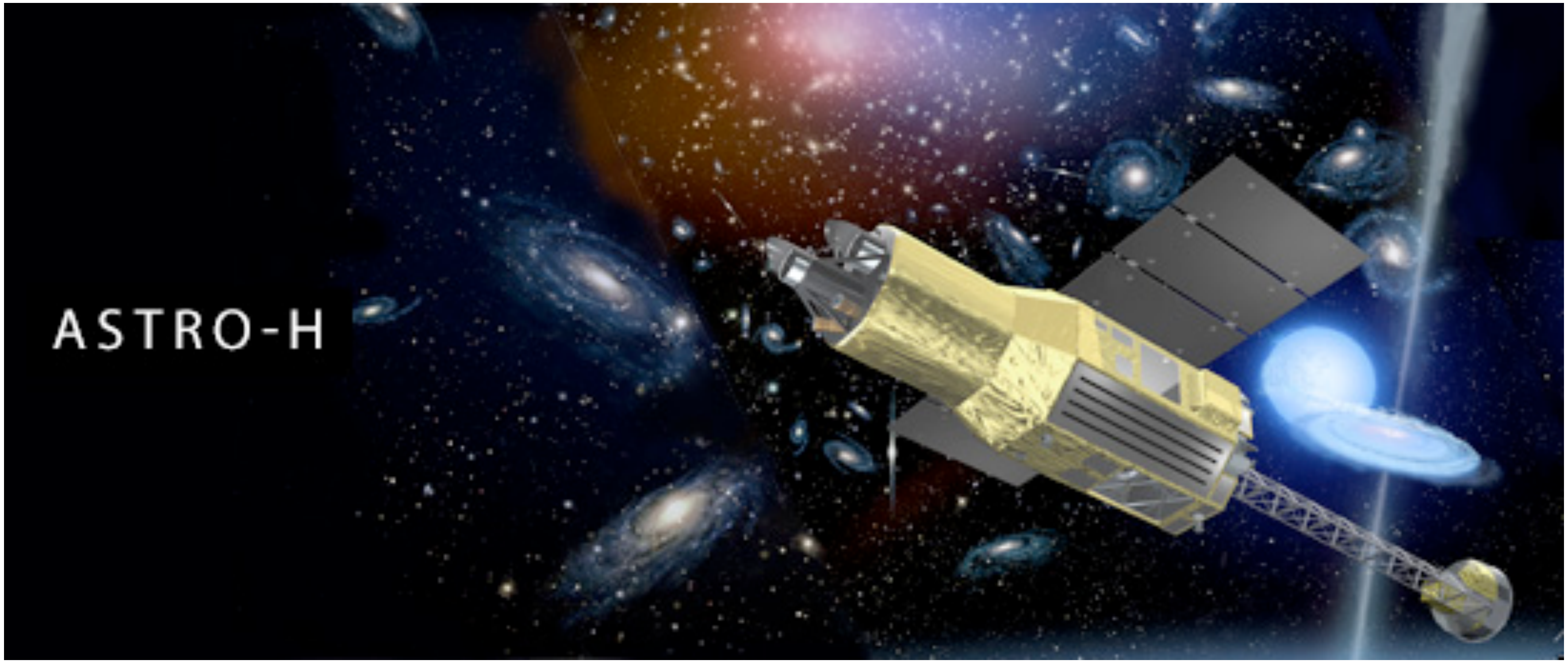
Mn Kα

Mitsuda *et al.* 2010

First astrophysical microcalorimeter spectrum:
Diffuse soft X-ray emission from the sky (π steradians)

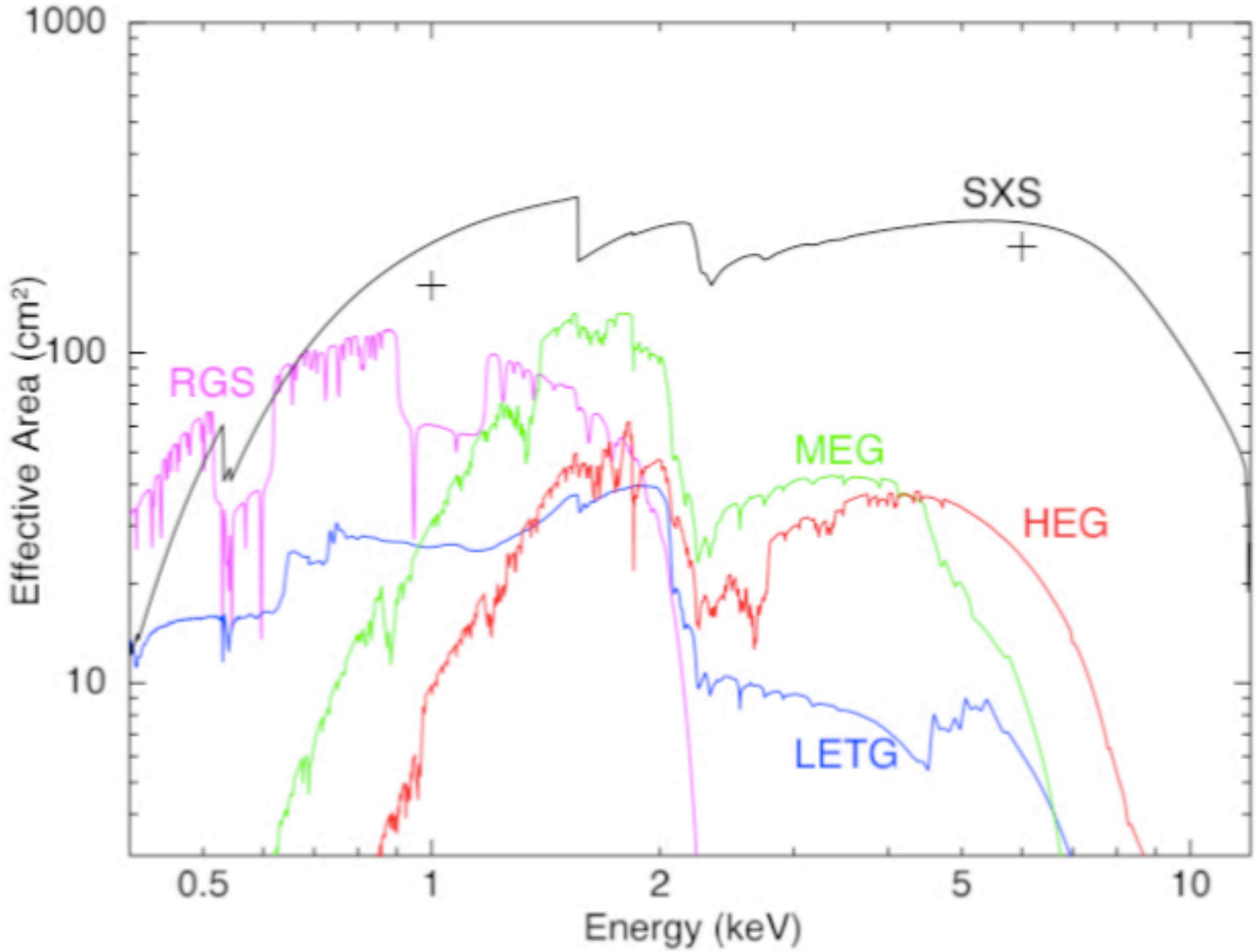


X-ray Quantum Calorimeter rocket experiment; McCammon et al. 2002



Astro-H: JAXA(ISAS)/NASA/ESA/.....
launch: end of Japanese fiscal 2015

http://astro-h.isas.jaxa.jp/doc/ahqr.pdf



Astro-H Soft X-ray Spectrometer: 6x6 TES array;
ΔE = (5) 7 (10) eV

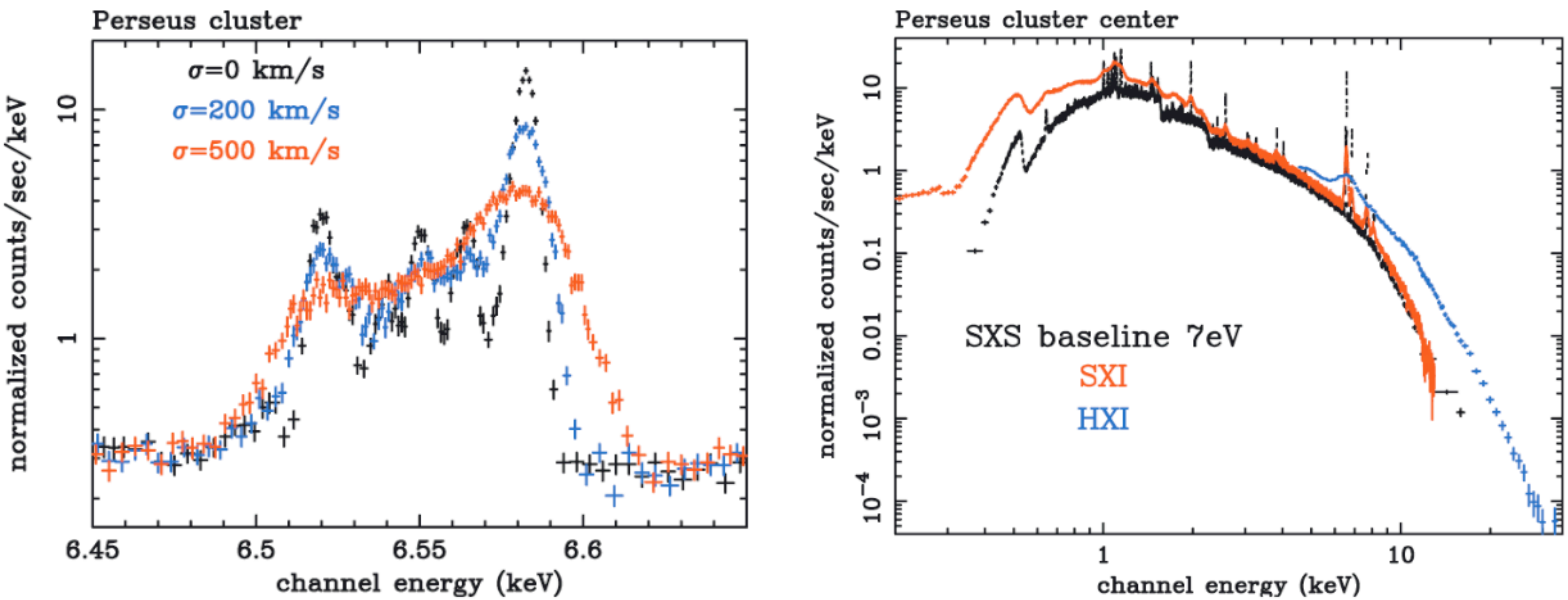


Figure 13. Simulated spectra for 100 ks ASTRO-H observations of Perseus Cluster. **(left)** SXS spectra around the iron K line complex. Line profiles assuming $\sigma = 0$, 200 and 500 km s^{-1} turbulence. **(right)** SXS (black), SXI (red), and HXI (blue) spectra for hot plasma with a mixture of three different temperatures of 0.6, 2.6 and 6.1 keV $(r < 2')$.[6]

Takahashi *et multi al.*, 2014

Biggest challenges for the future with μCal:

small fields of view

complexity of spatial⊗spectral

nonlinearity of detectors at 'high' count rates

(decrease in energy resolution,
loss of light in funny nonlinear way, ...)