CURRENT and FUTURE X-RAY SPECTROMETERS
Spectroscopy School,
MSSL, March 17-18, 2009

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Overview:

Diffractive vs Non-diffractive Spectrometers

Diffractive Spectrometers: gratings, crystals

Non-diffractive spectrometers: CCD's, calorimeters

Specific instruments: *Chandra*, *XMM-Newton*; *Astro*-H, *IXO*

Diffractive vs Non-diffractive Spectrometers

Non-diffractive spectrometers: convert energy of single photon into
'countable objects' (electrons, broken Cooper pairs, phonons)

Example: Si CCD: ionization energy w, photon energy E,
nr of electrons $N = E/w$
variance on N: $\sigma^2 = FN$; F: Fano factor, < 1 (!!), so

$$\Delta E/E = \Delta N/N = (wF/E)^{1/2}$$ (Si: w = 3.7 eV, F = 0.12)

Resolution ΔE, or resolving power $E/\Delta E$, slow function of E

Other examples: Superconductors (very small w!!), calorimeters

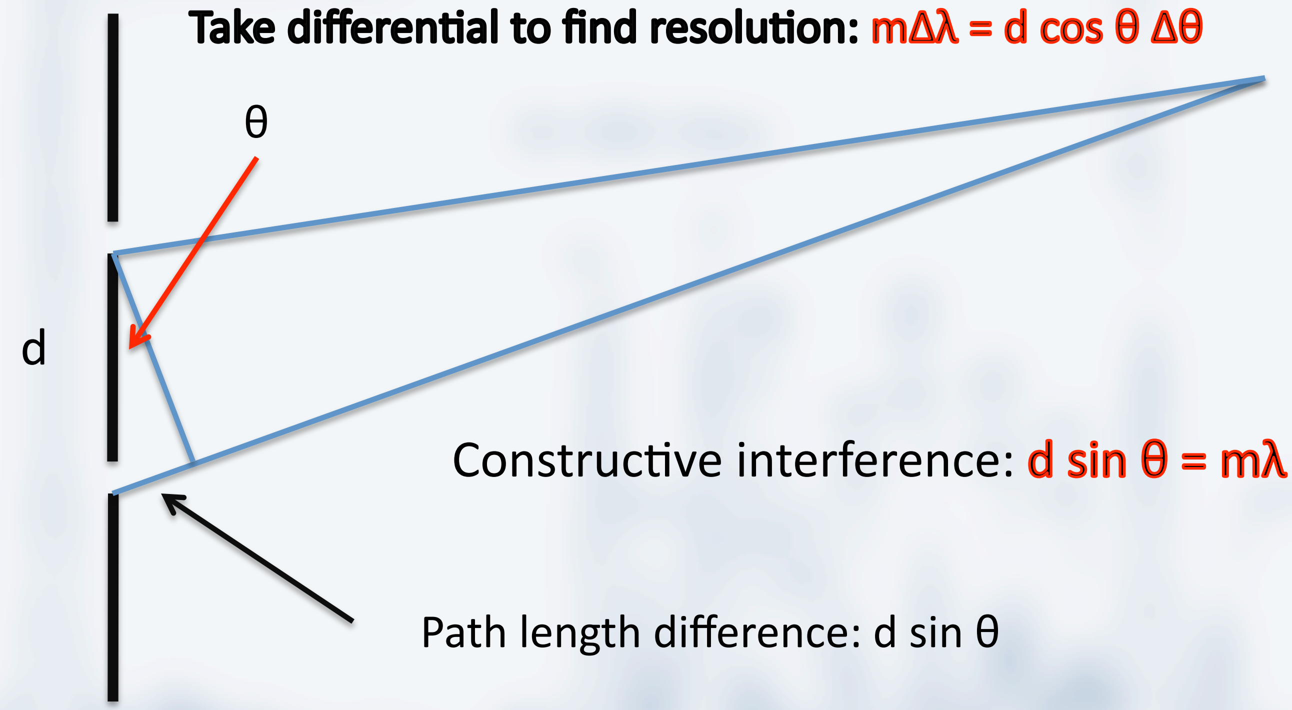
'constant ΔE devices'

Diffractive spectrometers: constructive interference of light along several cleverly chosen paths; no limit to resolution (no 'natural scale', like *w*)

Example: two slits:

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

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



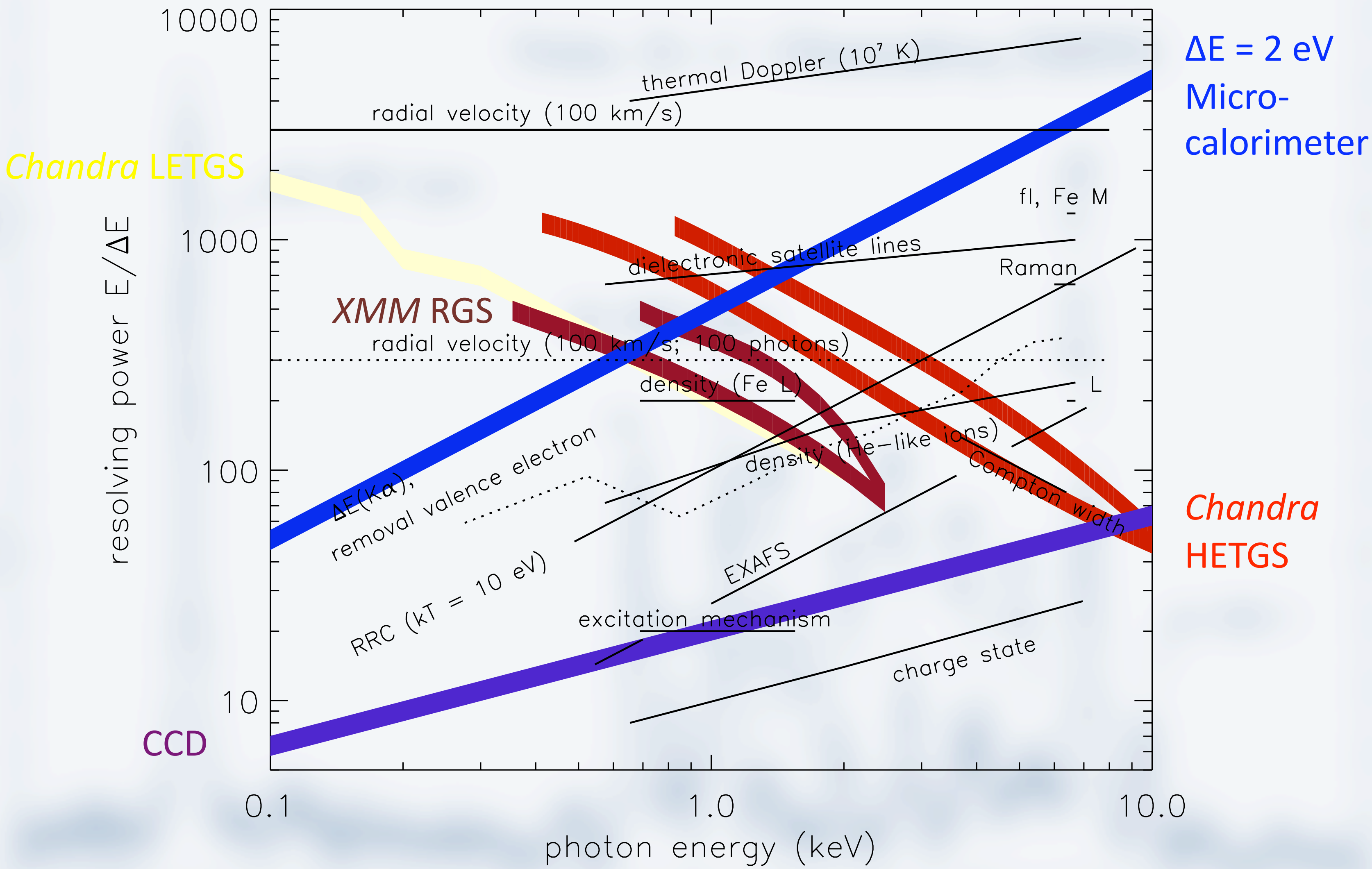
Constructive interference: $d \sin\theta = m\lambda$

Path length difference: $d \sin\theta$

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

'constant Δλ devices'

Resolving Power



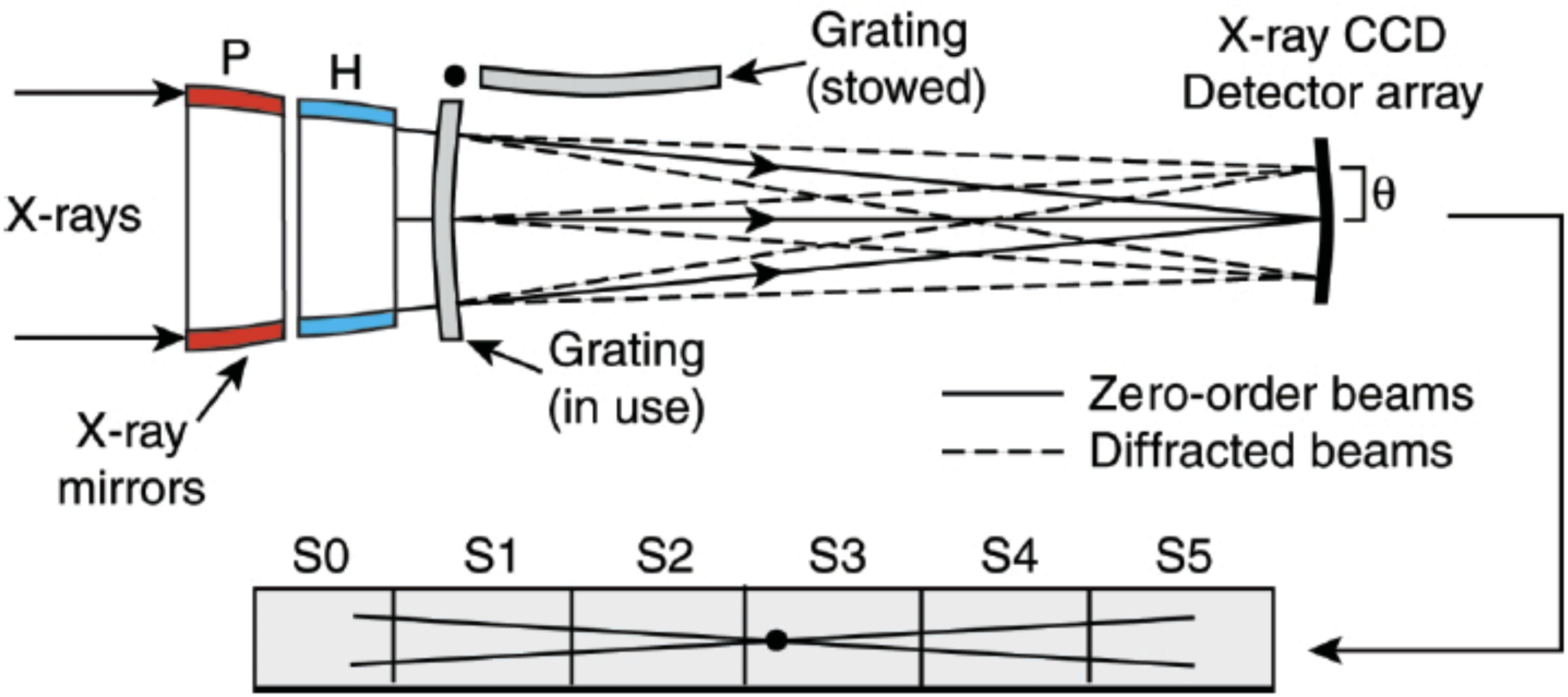
Dispersive spectrometers

Diffraction Grating Spectrometers(*);

- ***Chandra* HETGS and LETGS**
- ***XMM-Newton* RGS**
- ***IXO* XGS**

(*) Only one crystal spectrometer on astrophysics observatory: FPCS on Einstein (1979-1981)

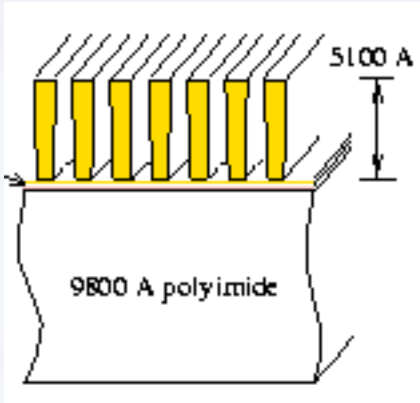
1. *Chandra* HETGS

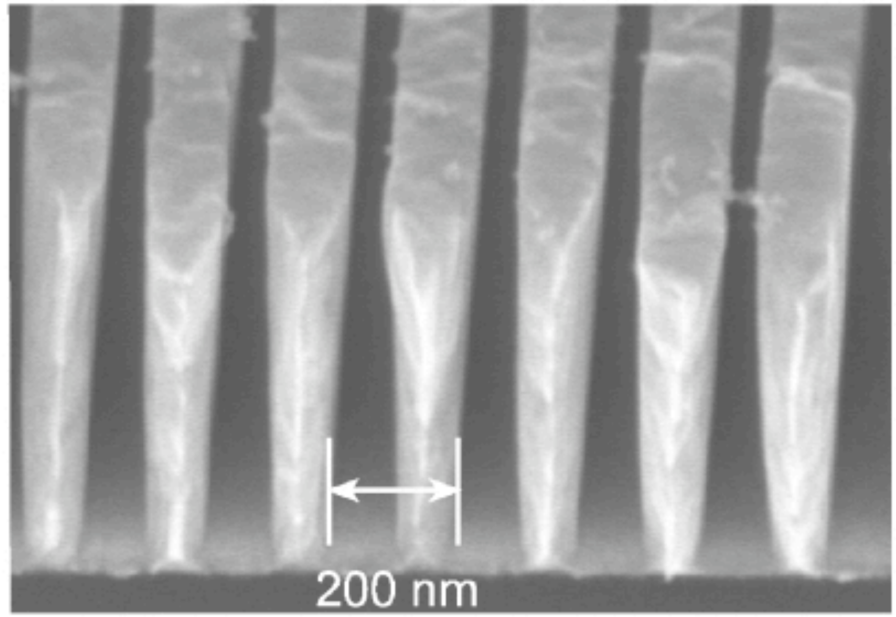


Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)

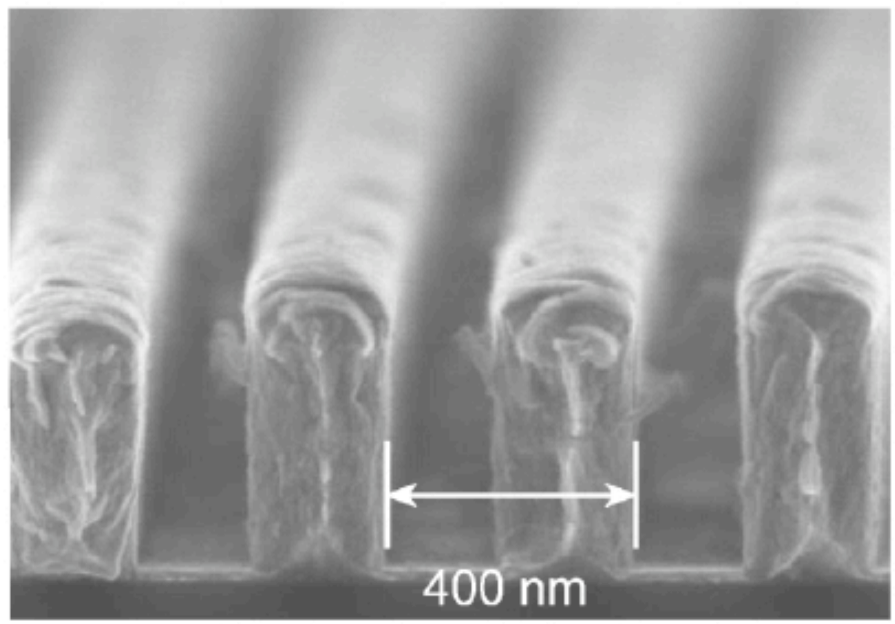
Dispersion equation: $\sin\theta = m\lambda/d$ (θ: dispersion angle, d: grating period, m: spectral order

Spectral resolution: $\Delta\lambda = (d/m)\cos\theta\,\Delta\theta \cong (d/m)\Delta\theta$: dominated by telescope image ($\Delta\theta$)



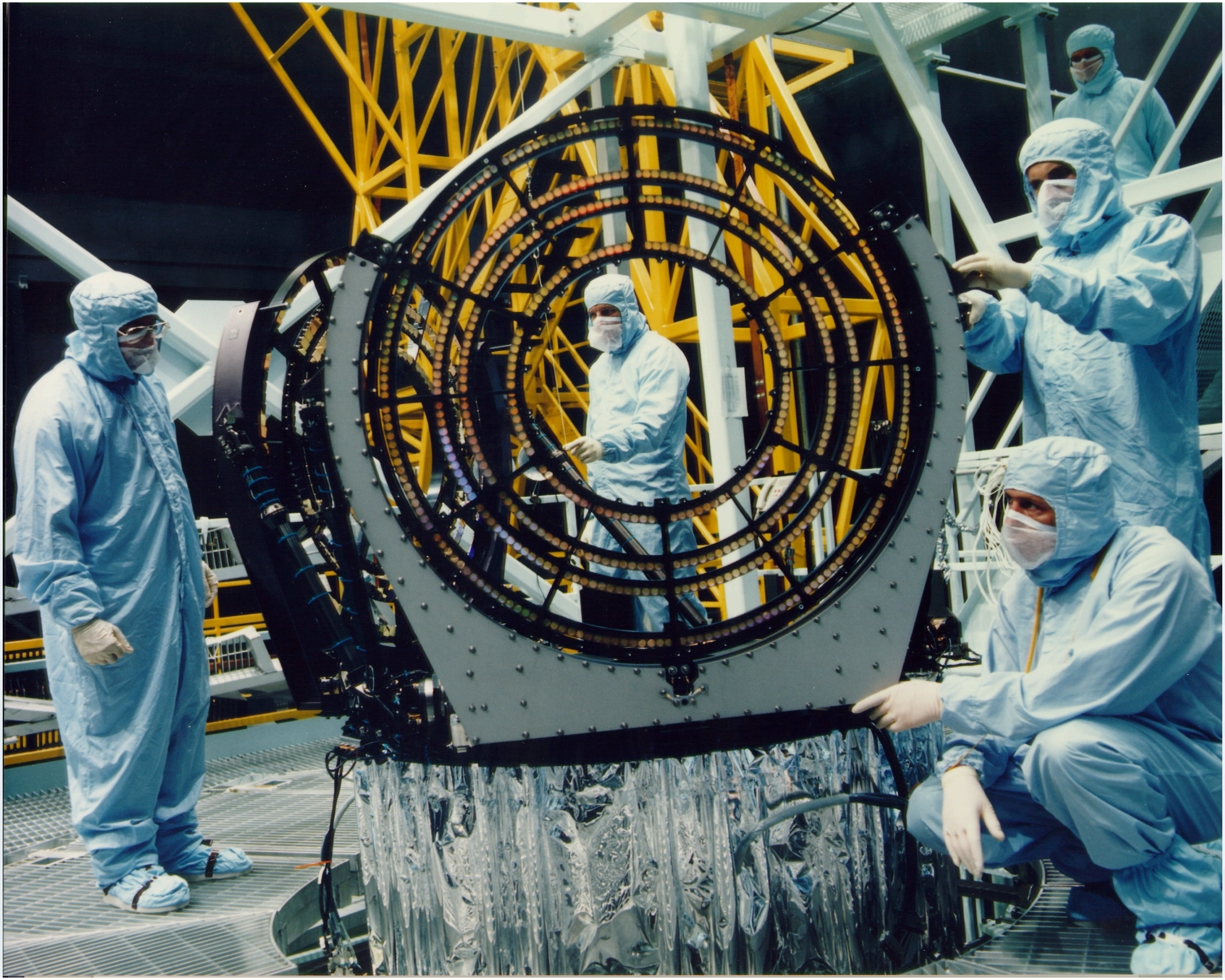


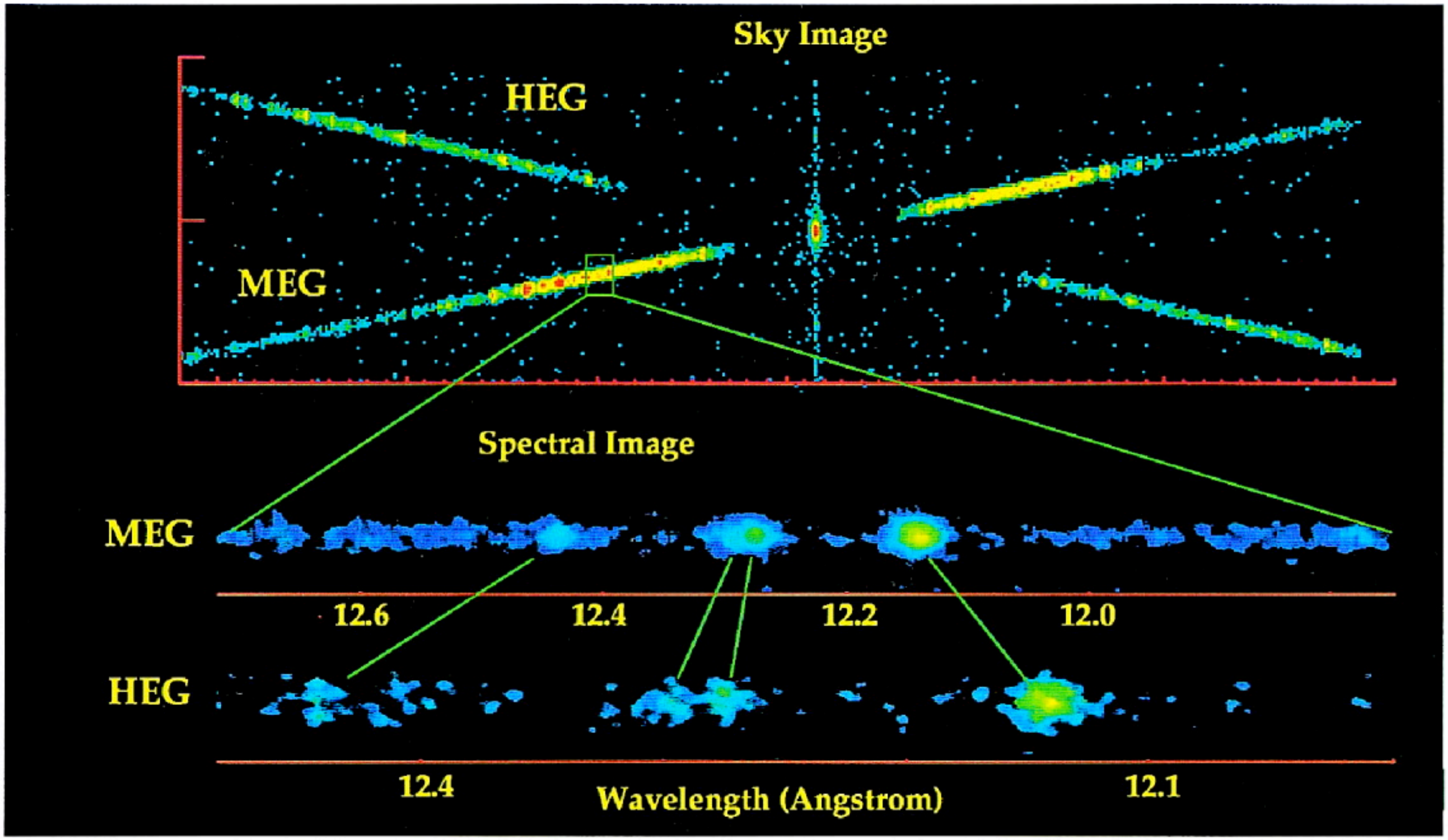
(a) High Energy Grating (HEG).



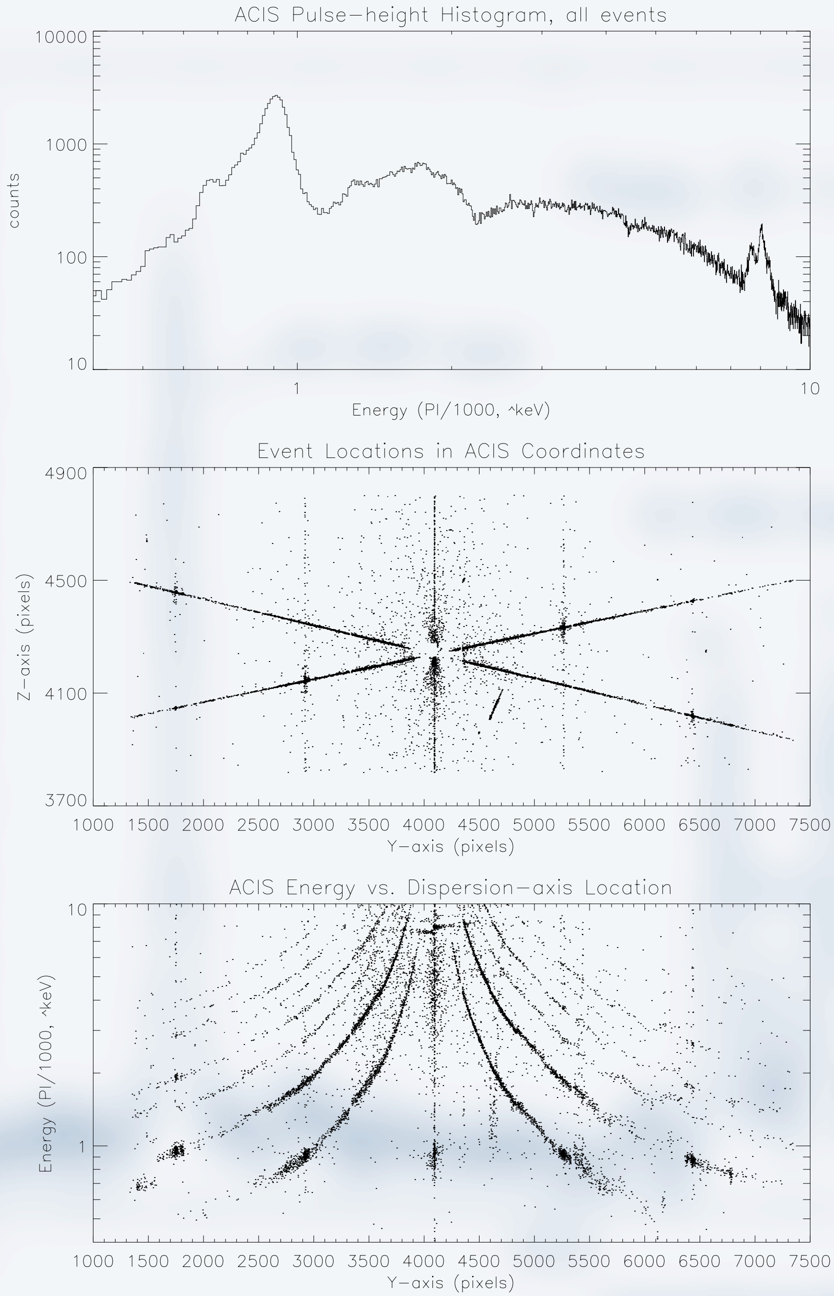
(b) Medium Energy Grating (MEG).

Chandra HETGS diffraction grating assembly




Sky Image
HEG
MEG
Spectral Image
MEG
12.6
12.4
12.2
12.0
HEG
12.4
12.1
Wavelength (Angstrom)

Chandra HETGS



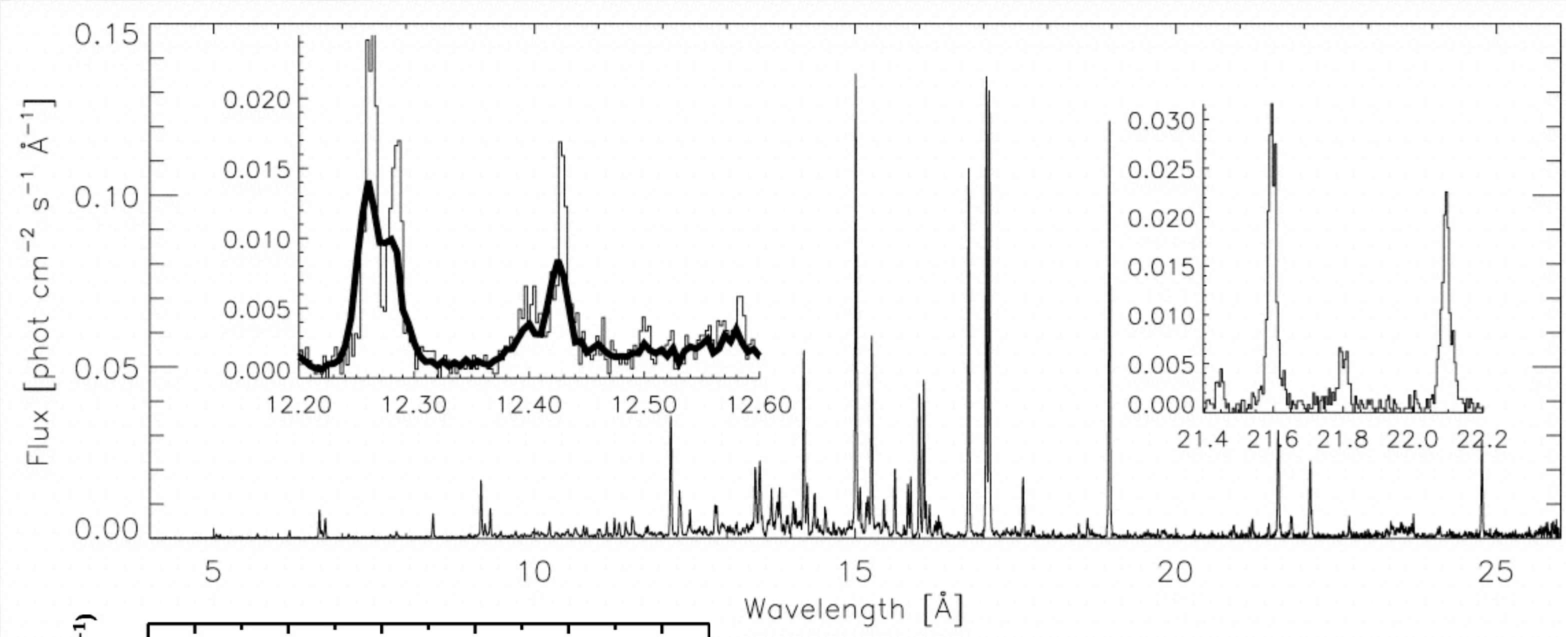
spectrum

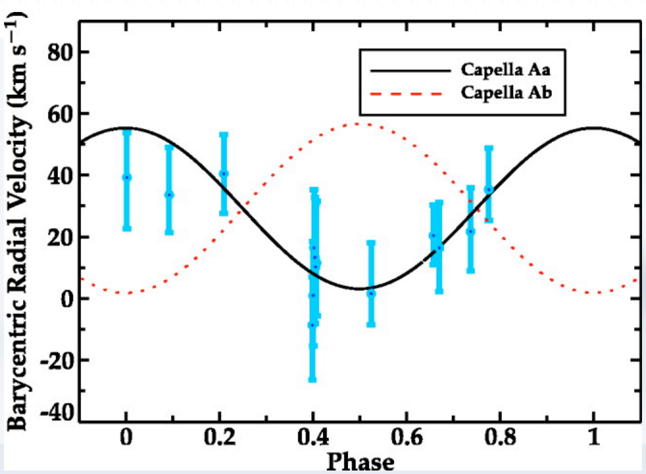
Focal plane image

CCD/dispersion diagram ('banana')
NB: CCD energy resolution sufficient to separate spectral orders (m = ±1,±2, …)

HETGS Spectral Resolution: 0.0125/0.025 Å; approximately constant

Example: radial velocities in Capella (G8 III + G1 III; approx 2.5 M_O each)



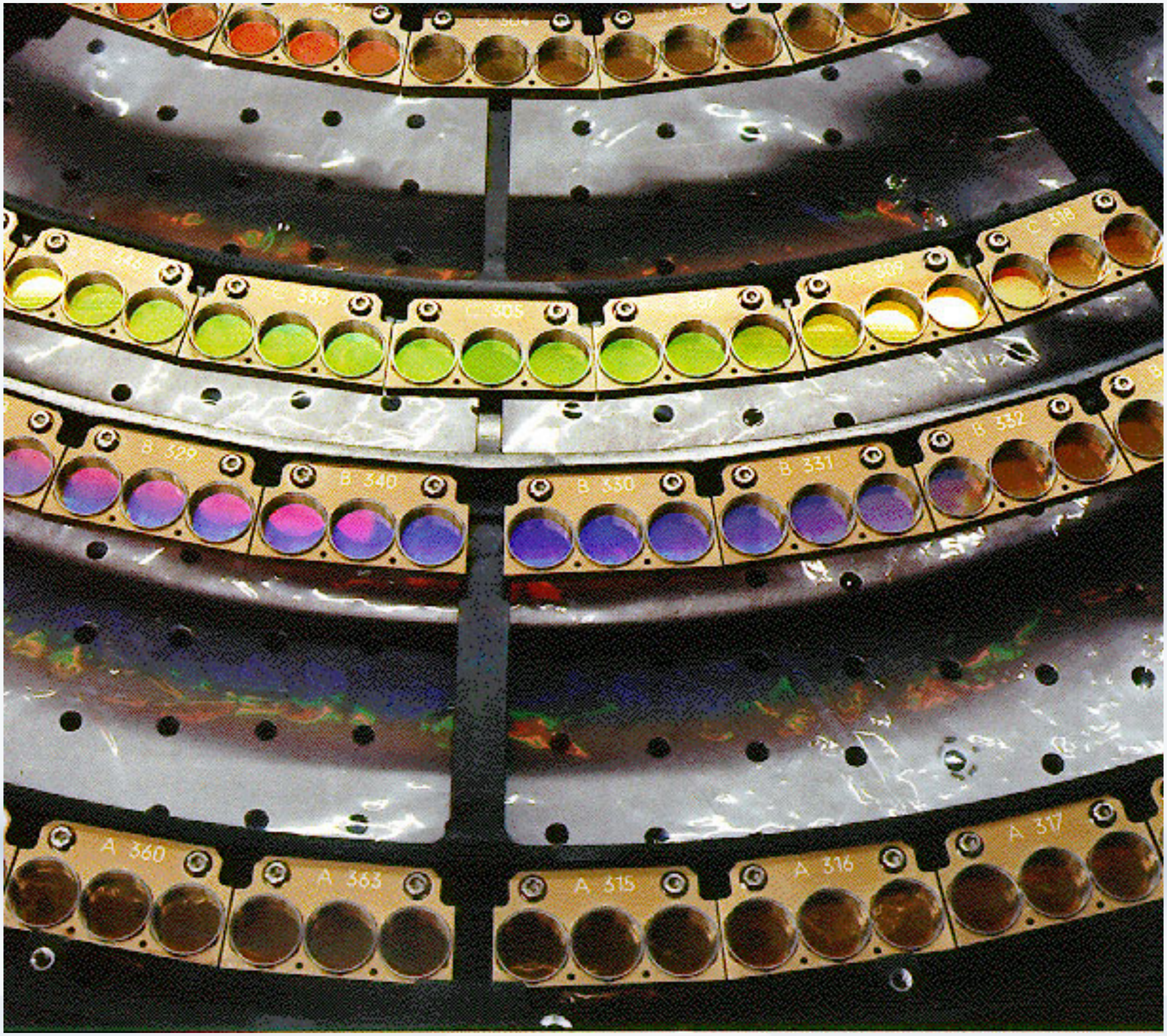


Very accurate wavelength scale:
Δv/c ~ 1/10,000 !

The G8 III primary turns out to be the dominant source of X-ray emission

Ishibashi et al., 2006, *ApJ*, **644**, L117

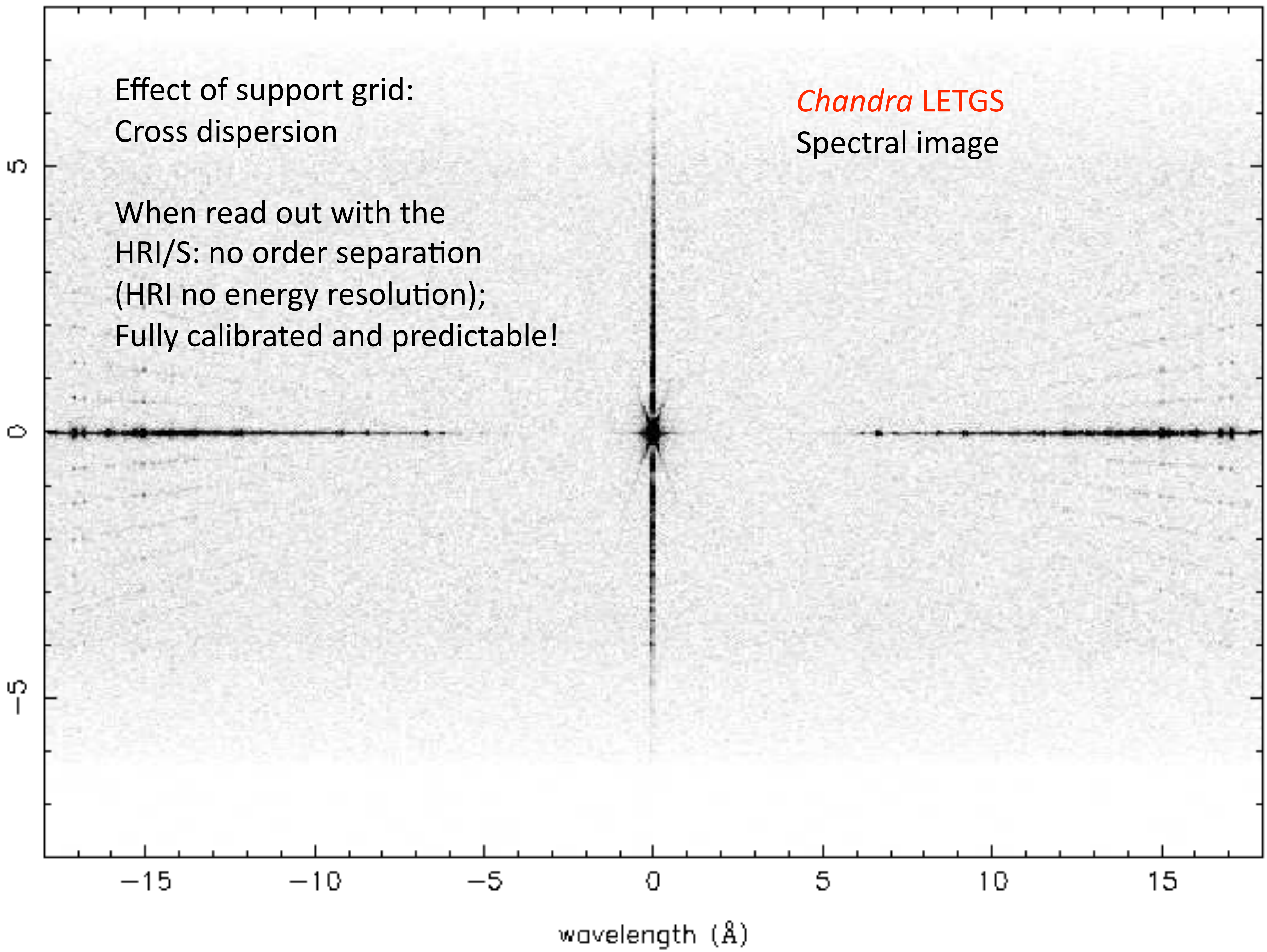
2. *Chandra* LETGS



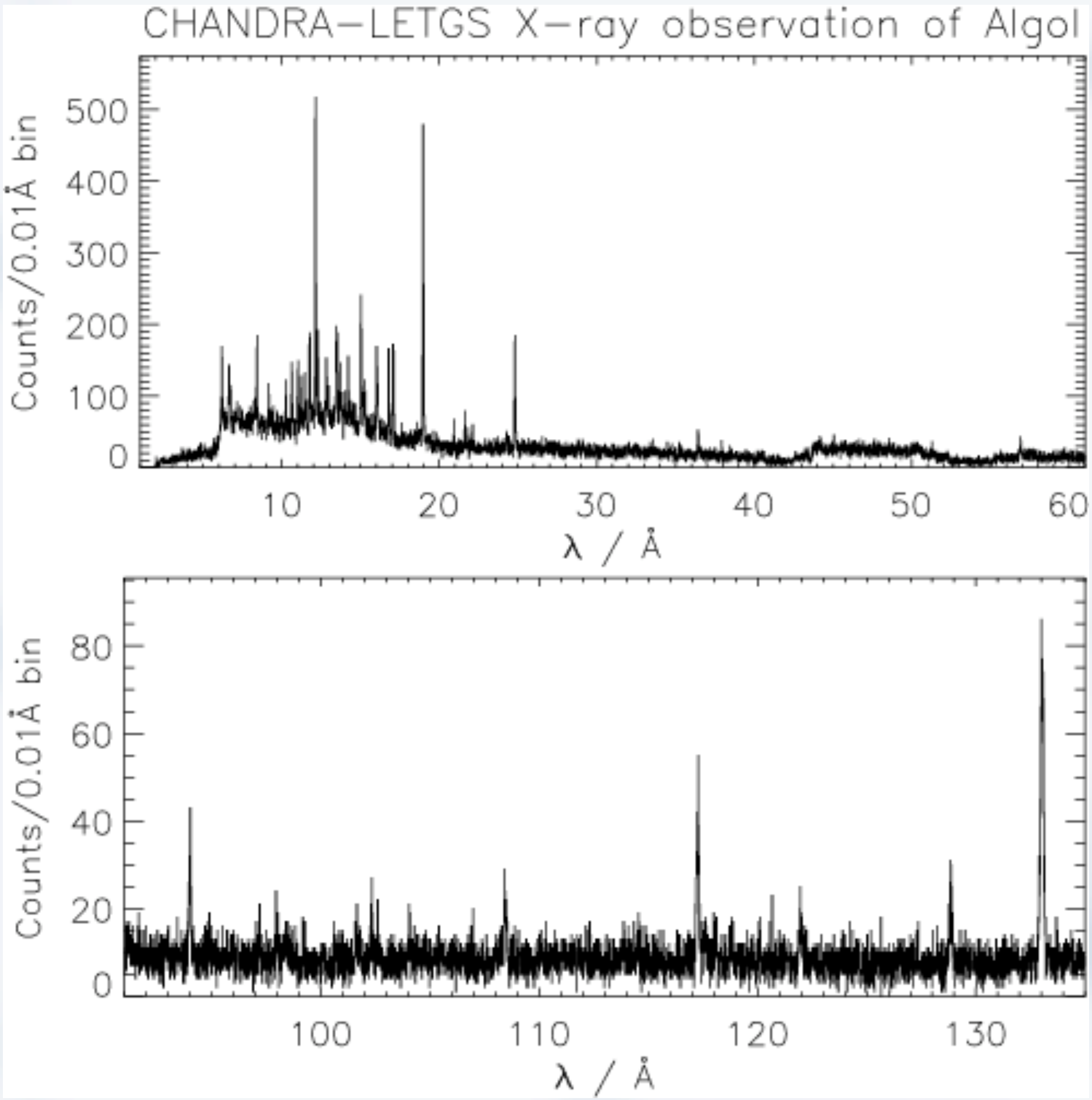
Effect of support grid:
Cross dispersion

When read out with the HRI/S: no order separation (HRI no energy resolution);
Fully calibrated and predictable!

Chandra LETGS
Spectral image



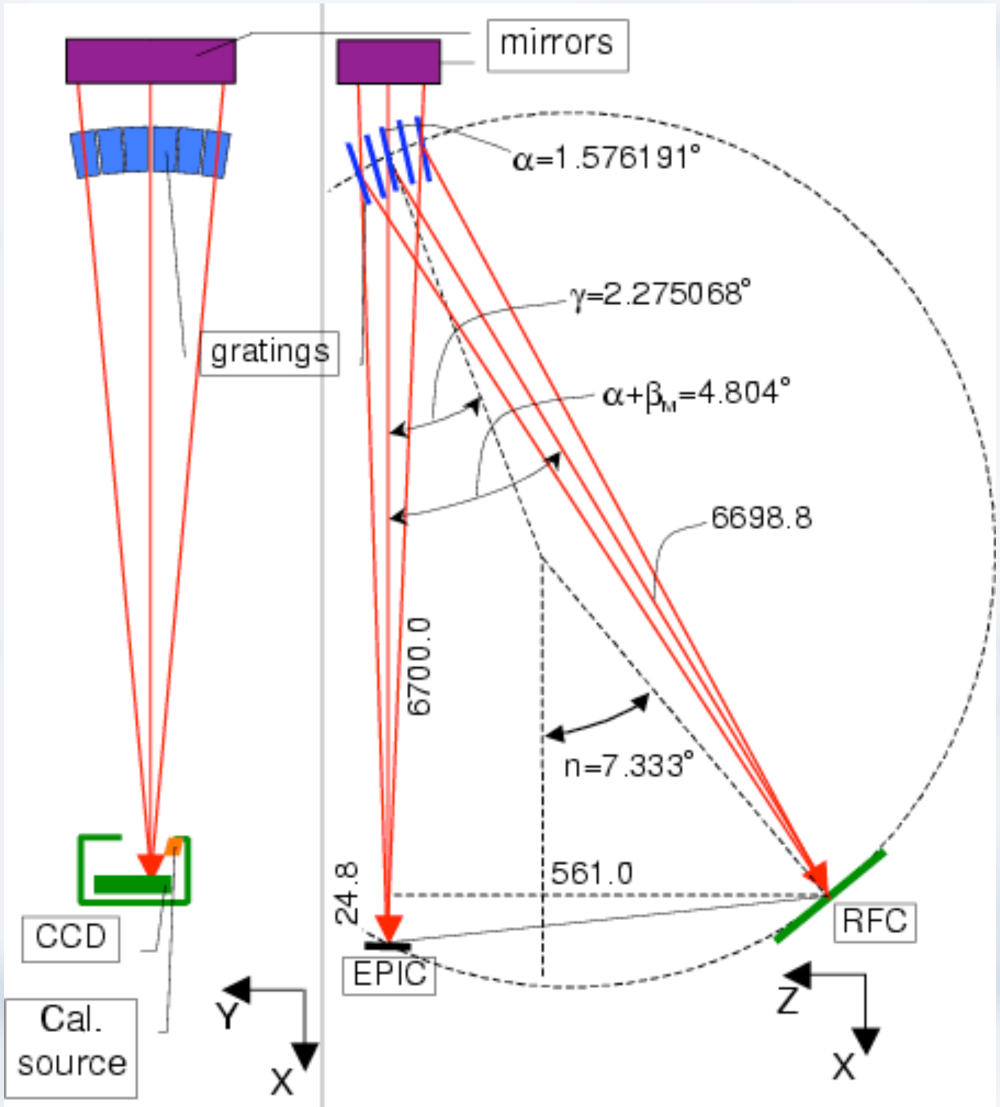
Spectral resolution: ~0.05 Å; low dispersion: goes out to 170 Å, $\mathcal{R}$ ~ 3000!



note the long wavelengths

Ness et al., 2002, *Astron. Astrophys.*, **387**, 1032

3. *XMM-Newton* Reflection Grating Spectrometer (RGS)

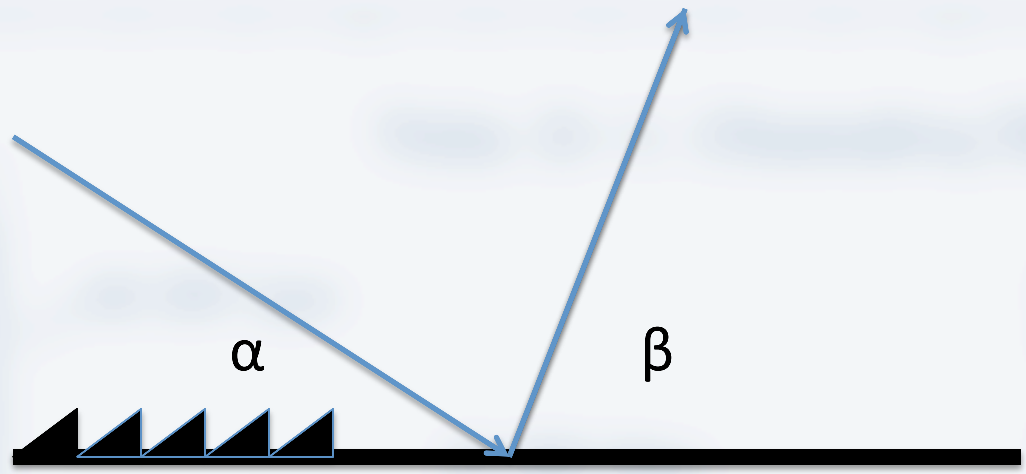


Compared to *Chandra*:
lower resolution,
much bigger effective area;

Compensate by designing **much larger dispersion angles**

Den Herder et al., 2001, *Astron. Astrophys.*, **365**, L7

Basics of grazing incidence X-ray reflection gratings



Dispersion equation: $\cos\beta = \cos\alpha + m\lambda/d$ (as if dispersion by grating with equivalent line density equal to density projected onto incident wavefront)

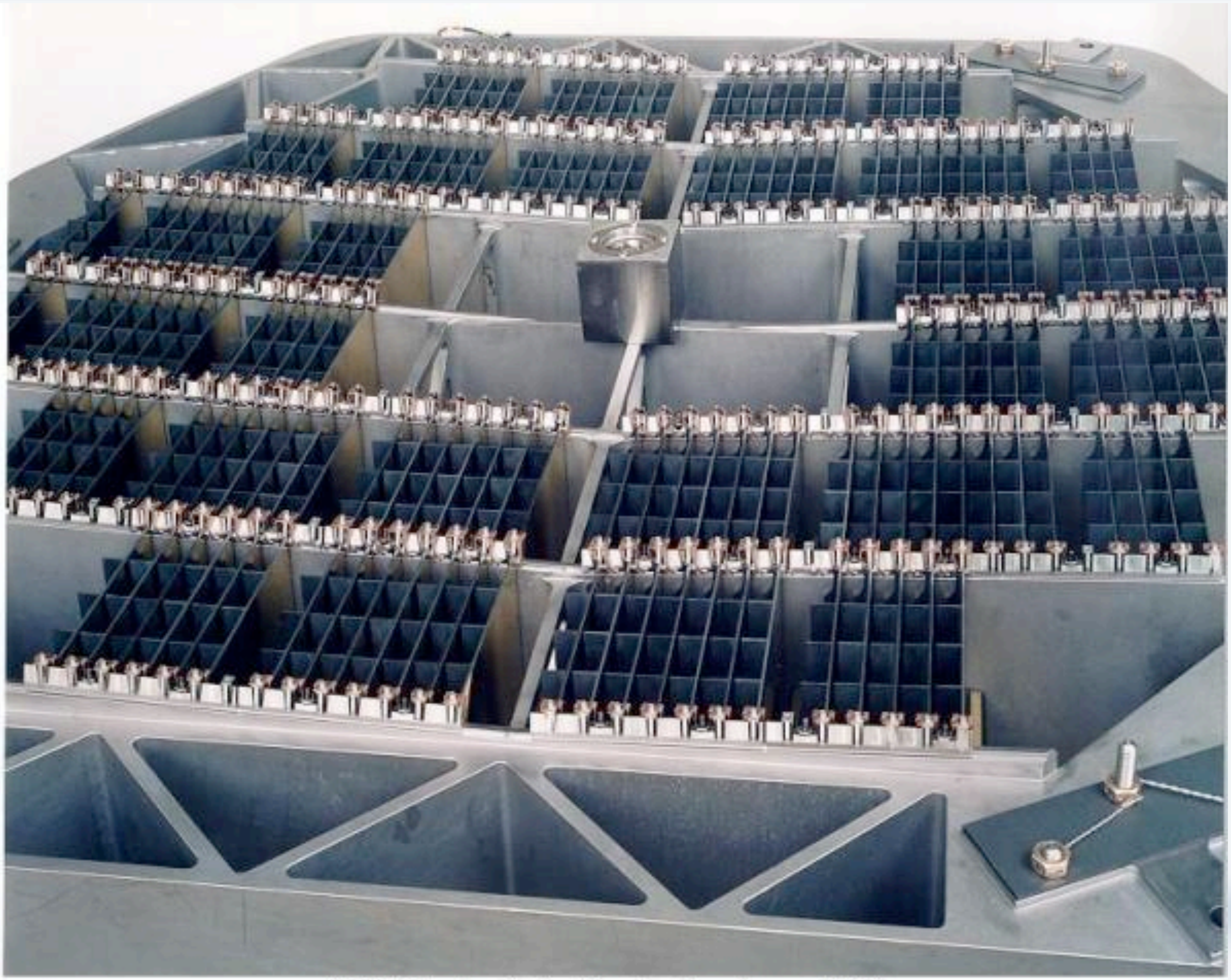
Spectral resolution:

- telescope blur $\Delta\alpha$: $\Delta\lambda = (d/m)\sin\alpha\,\Delta\alpha$ (suppressed by large dispersion)
- grating alignment: $\Delta\lambda = (d/m)(\sin\alpha + \sin\beta)\,\Delta\alpha$
- and a few other terms

RGS: $\alpha = 1.58$ deg, $\beta = 2.97$ deg at 15 Å; $d = 1.546$ micron (!)

Large dispersion due to small incidence angle; offsets telescope blur

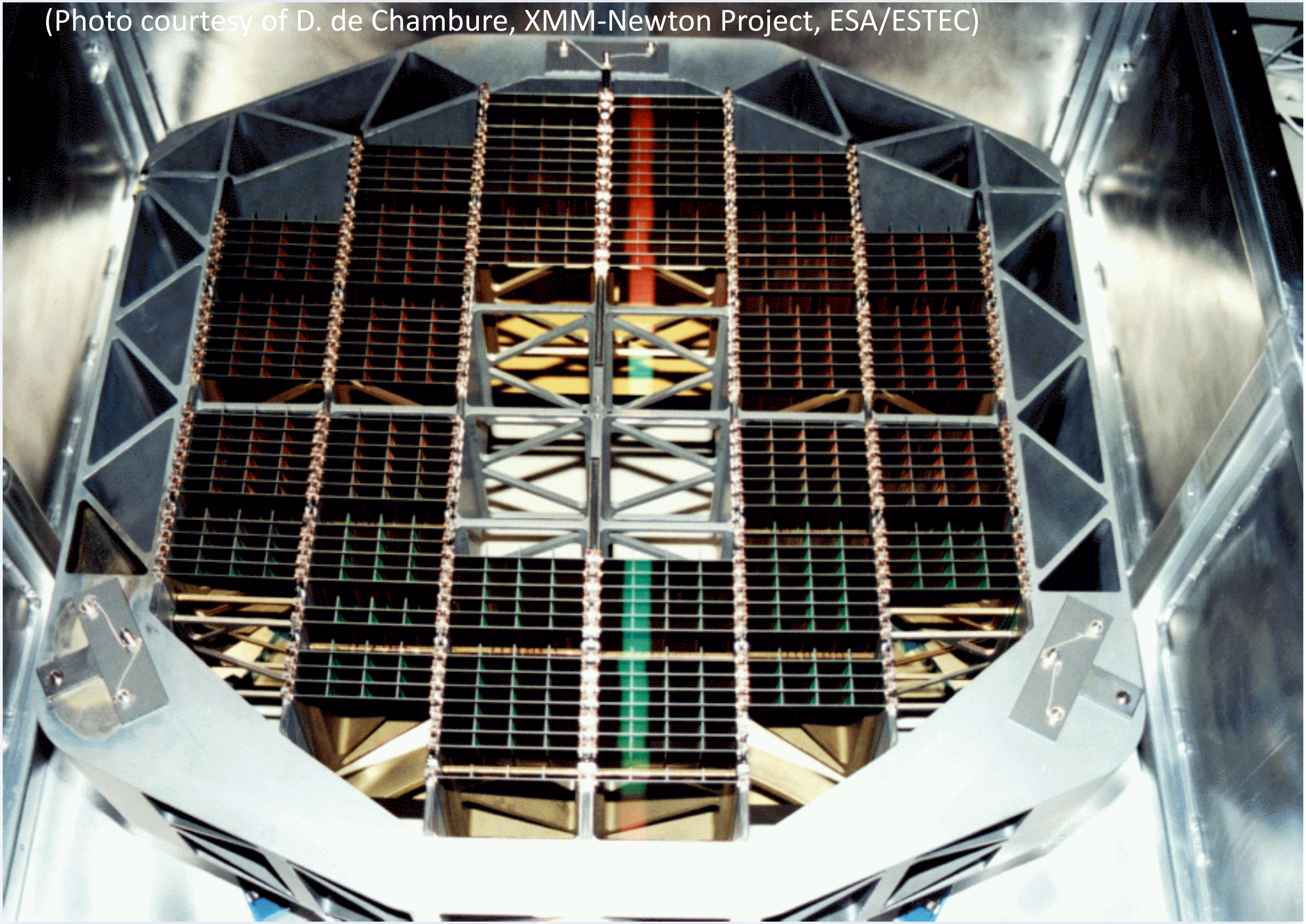
Grating reflectivity of order 0.3 !



XMM-Newton Reflection Grating Array (RGA)

Image courtesy of Columbia University

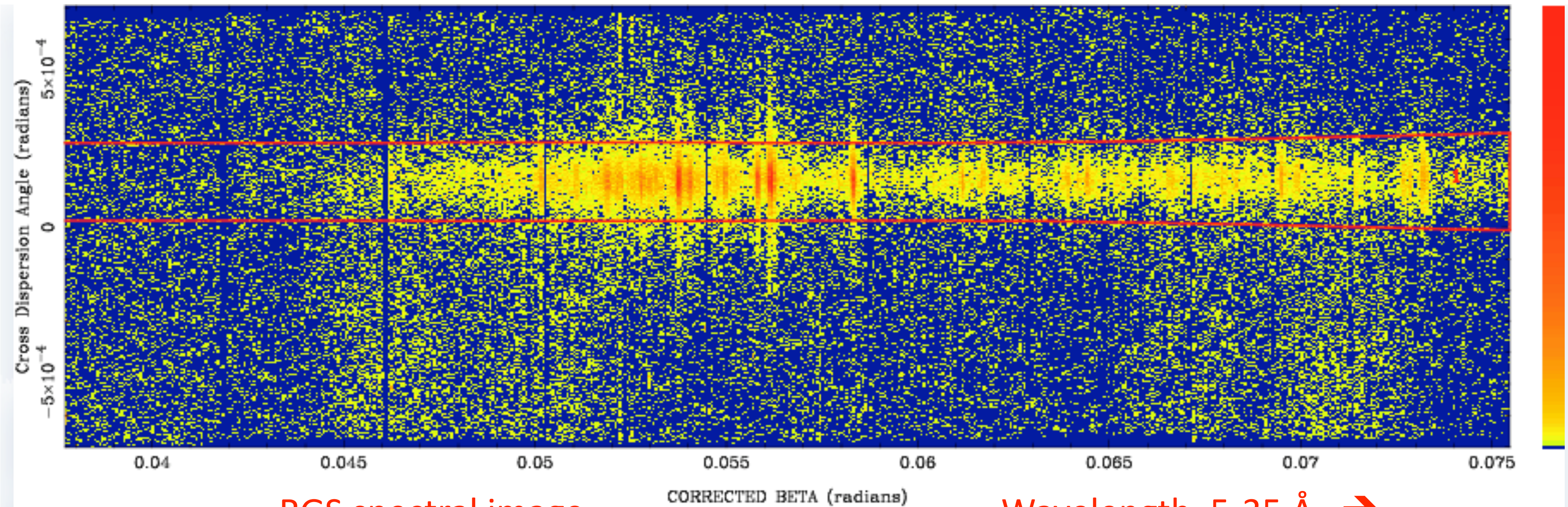
European Space Agency


(Photo courtesy of D. de Chambure, XMM-Newton Project, ESA/ESTEC)

XMM-Newton preparation

Image courtesy of D. Parker

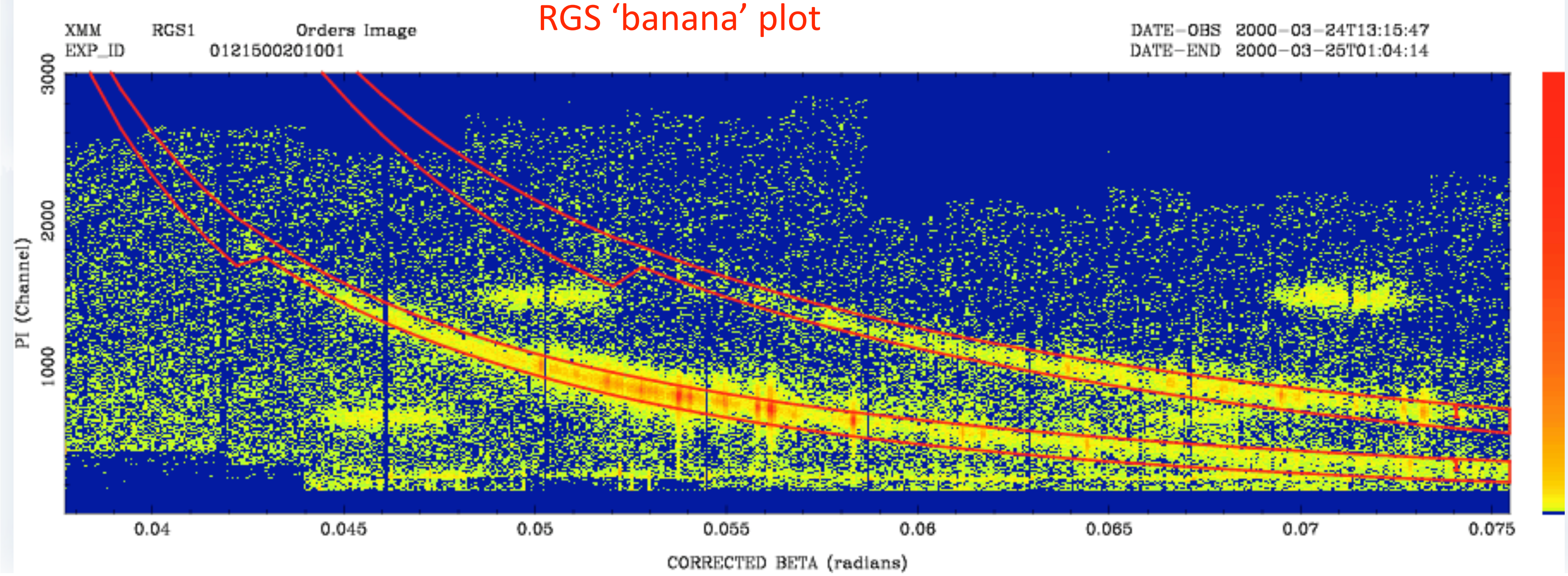
European Space Agency



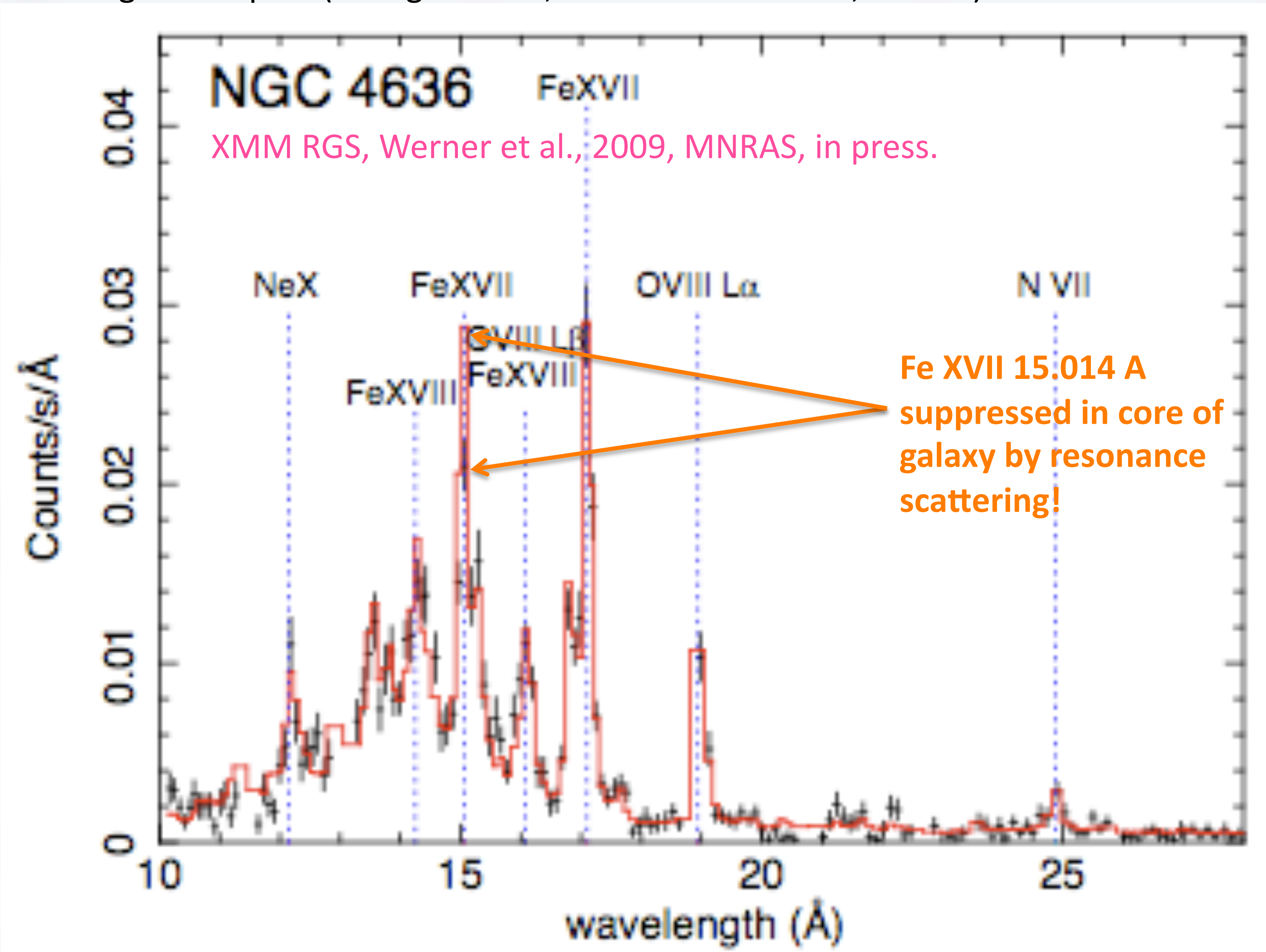
RGS spectral image

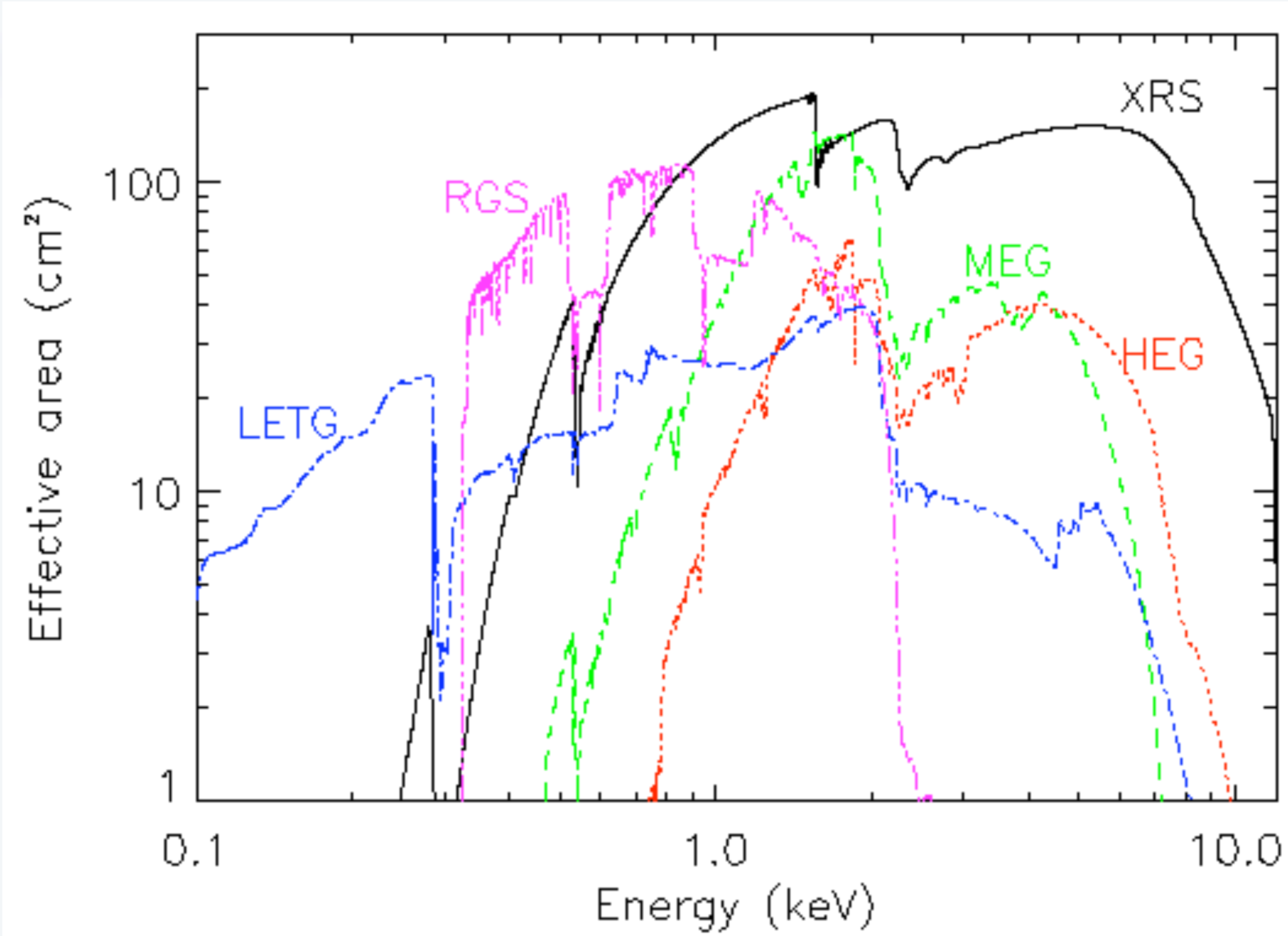
Wavelength, 5-35 Å →

RGS 'banana' plot



Source of finite extent: large dispersion of RGS still produces useable spectrum as long as compact (in angular size; Δα < 1 arcmin or so; no slit!)





Effective area = geometric aperture x mirror throughput x grating efficiency x detector quantum efficiency x 'other factors(...)'

Current Diffraction Grating Spectrometers: Quirks; Calibration

- not all properties completely encoded in matrix to required accuracy!
  EXERCISE PROPER CAUTION! Just because something doesn't fit, that does not mean it's something astrophysical!

- wavelength scale: HETGS: about 1 in 10,000 accurate, averaged over entire band
  LETGS: similar
  RGS: $\Delta\lambda \sim 8$ mÅ, or about 1 in 2,000 (average); improvement by factor 2 under way

- instrumental profile shape ('LSF'): RGS profile depends noticeably on wavelength (mainly due to rapidly varying contribution from scattering by micro-roughness). Also careful with estimating line fluxes, absorption line equivalent widths: non-negligible fraction of power in wings outside two times the resolution: use matrix (not just by eye, or DIY Gauss!)

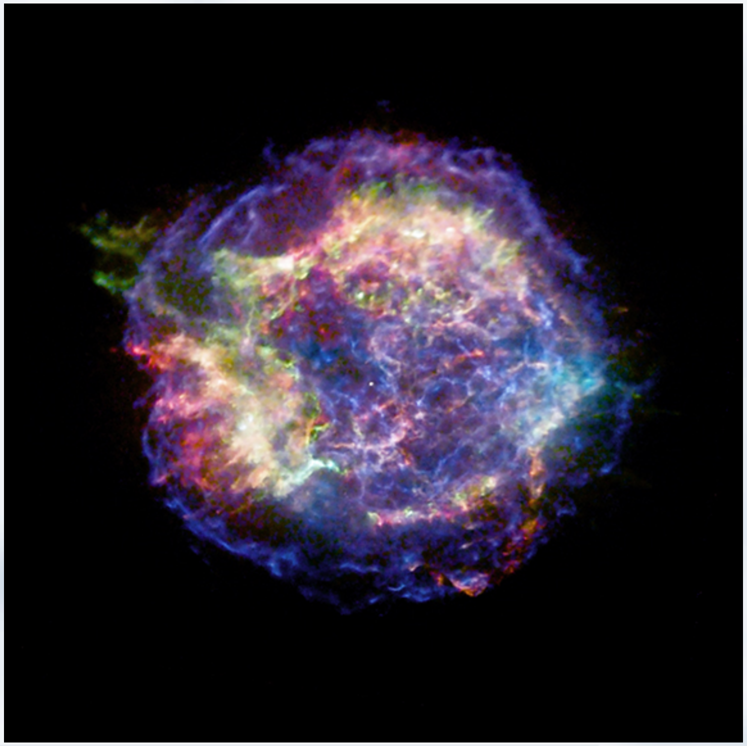
- always watch out for detector features (dead spots, cool spots, hot spots, …)

- effective area: absolute flux measurement probably reliable to level of remaining cross-calibration discrepancies: of order, or smaller than 10%

Non-dispersive spectrometers

1. CCD Spectrometers
   (*Chandra* ACIS, *XMM-Newton* EPIC, *Suzaku* XIS)

Resolving power limited; see above
Obvious advantage: high efficiency, spatial resolution (imaging)



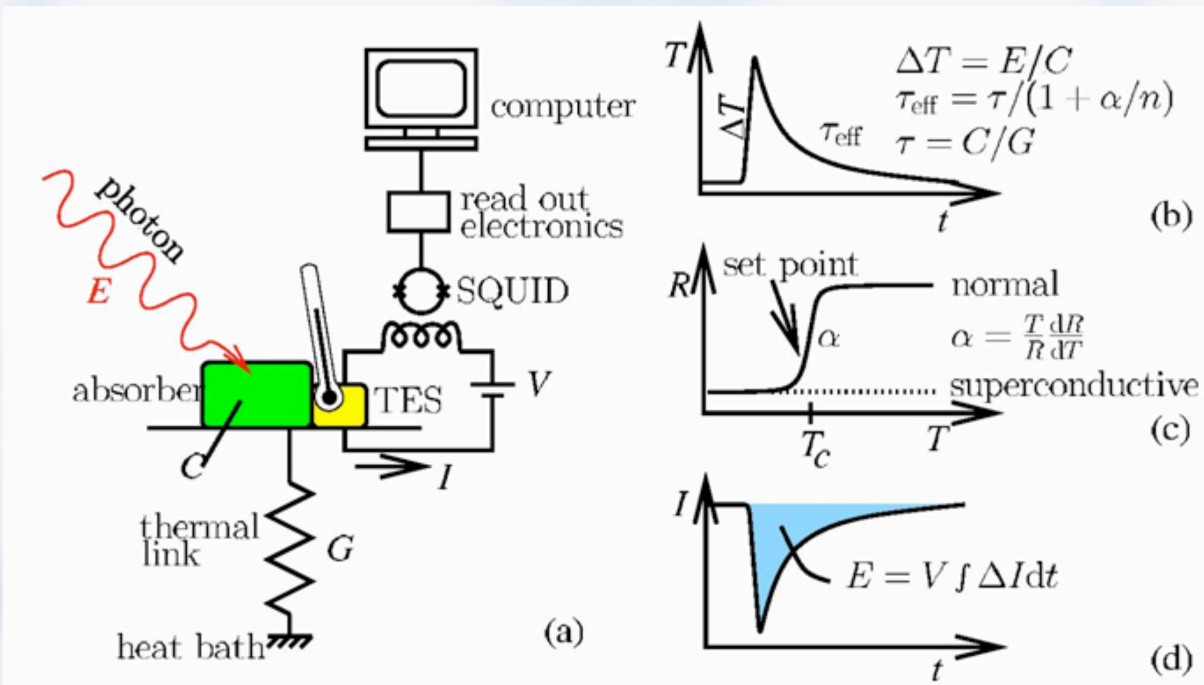
Credit: NASA/CXC/SAO/D.Patnaude et al.

Supernova remnant Cas A,
Chandra ACIS-I

2. Microcalorimeter Spectrometers

(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 µCal)

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?

Quantum mechanics:

At low T, harmonic oscillators go into ground state; c_V collapses!

Debye's famous calculation:

$$c_V = \frac{12\pi^4}{5} kNr \left(\frac{T}{\Theta}\right)^3$$

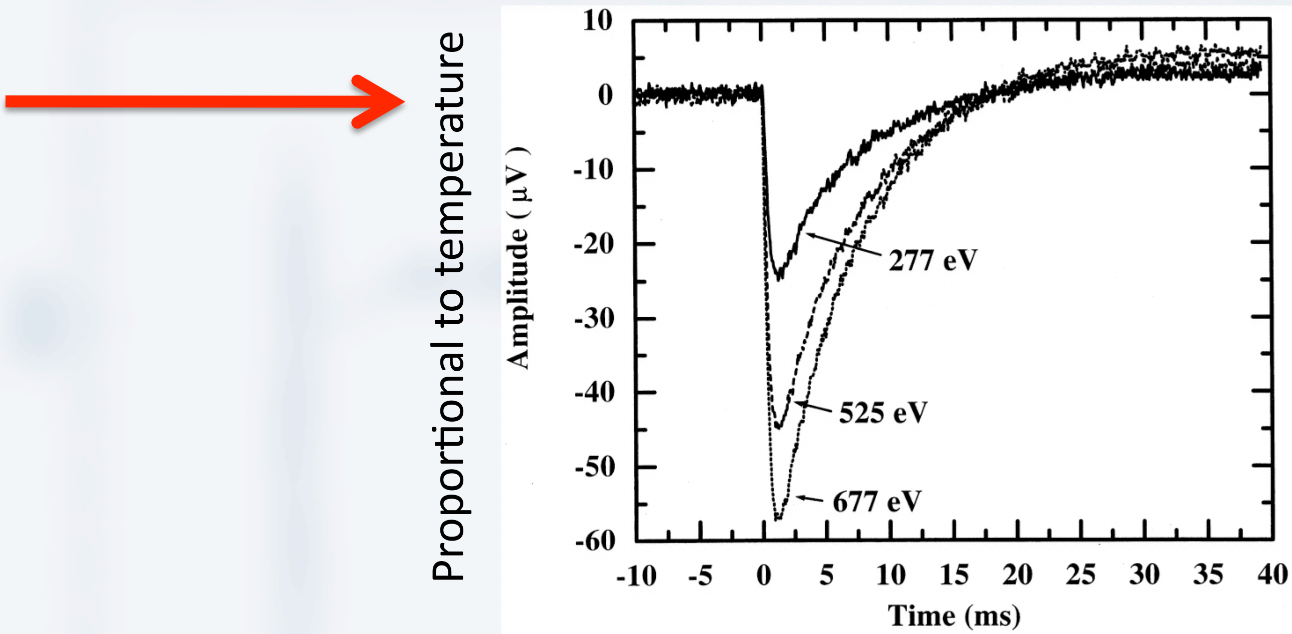
And Θ is the Debye temperature;

kΘ ~ ħω of the highest-frequency vibration in the crystal.

For Si, Θ = 640 K, so for low T (T = 0.1 K) ,

c_V is ~ $(0.1/640)^3 = 3 \times 10^8$ times smaller than classical value!

(e.g. Kittel: Thermal Physics; Peierls: the Quantum Theory of Solids)



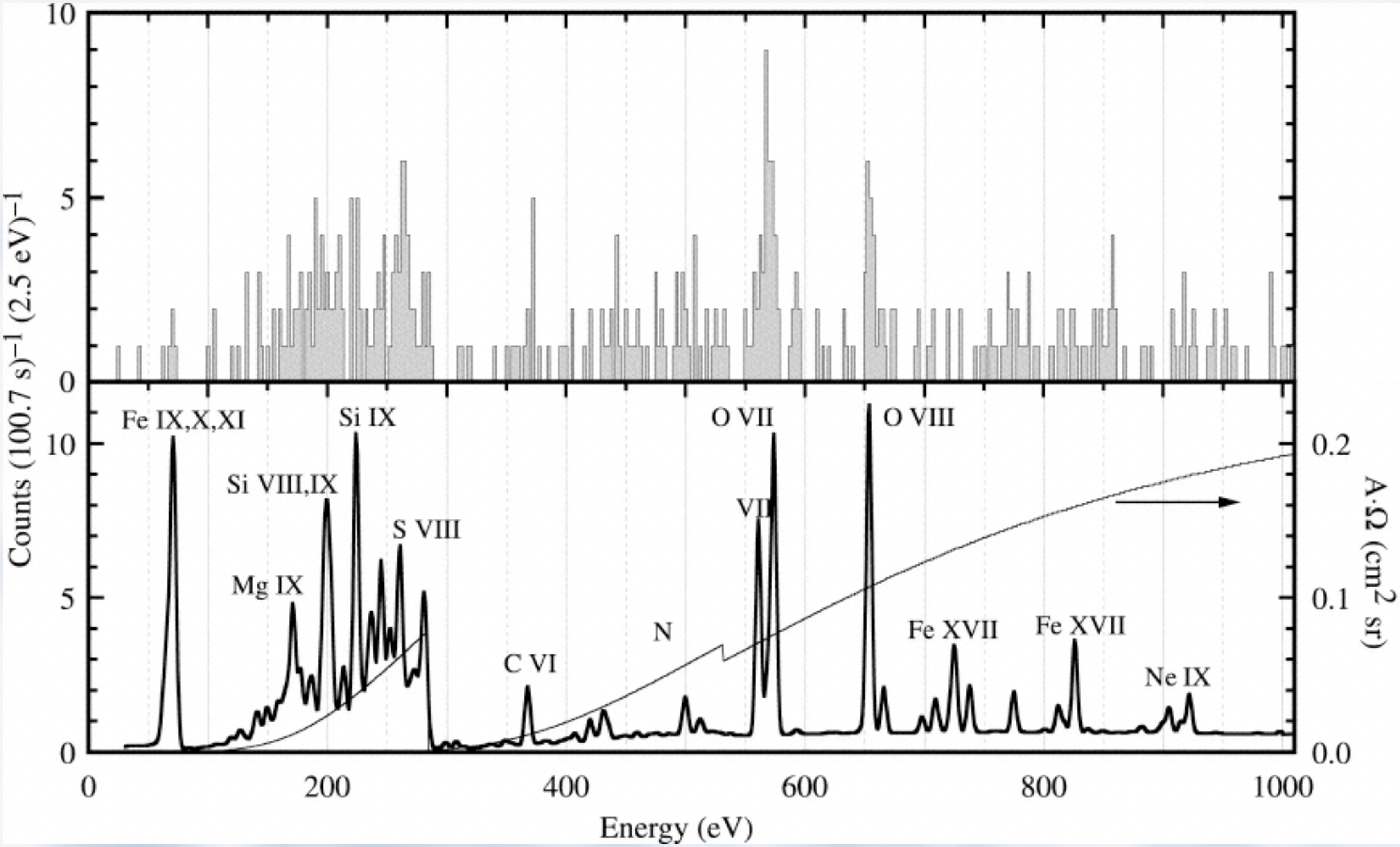
XQC rocket experiment; McCammon et al. (2002)

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!

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

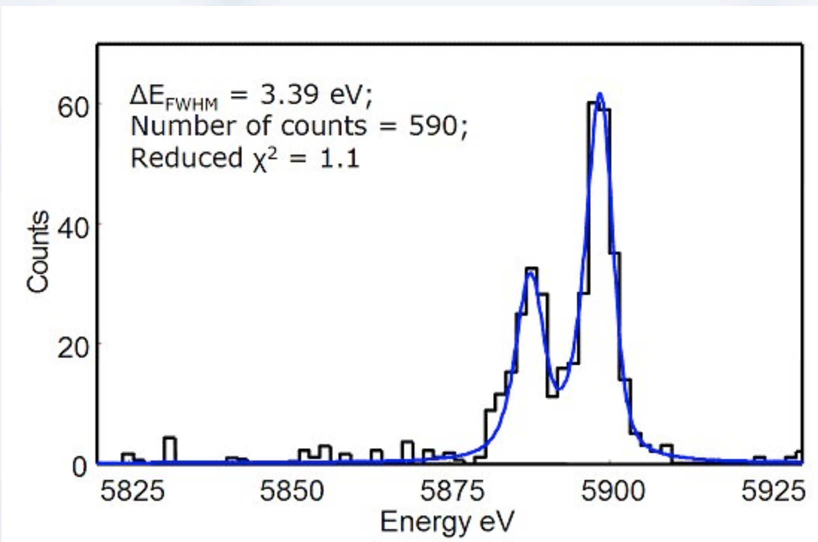


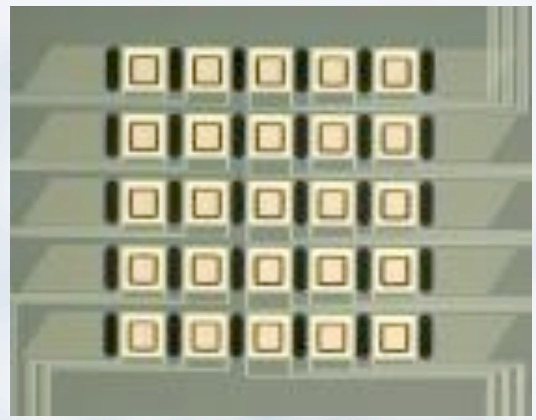
X-ray Quantum Calorimeter rocket experiment; McCammon et al. 2002

So: what is so great about microcalorimeters?

'no limit' to energy resolution (gets better with lower T, N; *higher signal sampling rate*; also practical improvements: TES sensors)

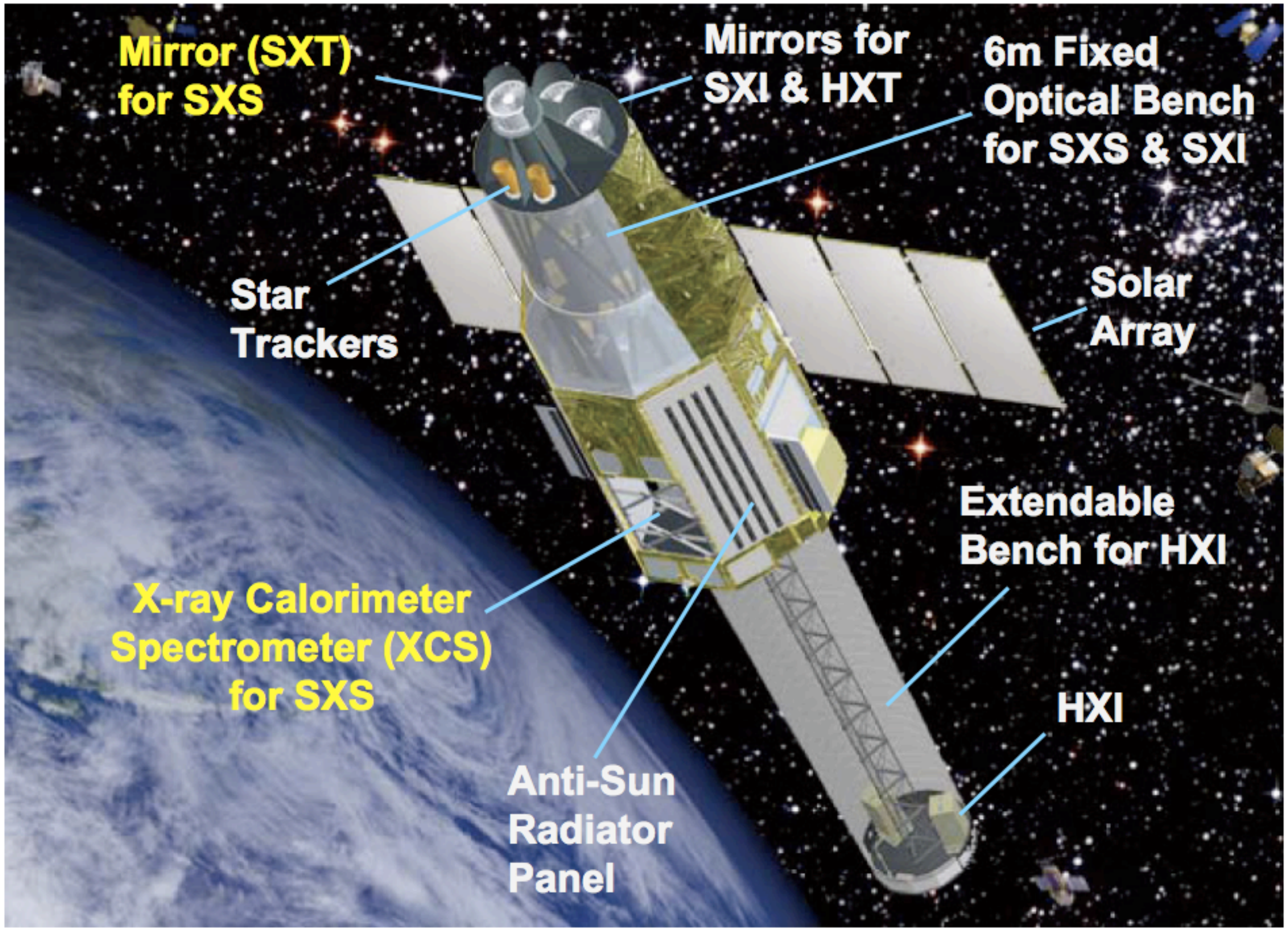
Can make imaging arrays! (not trivial, because not based on charge collection, but current modulation)





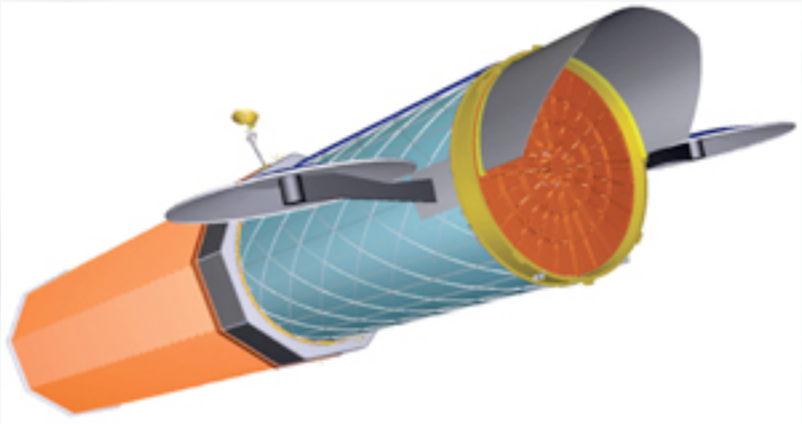
But remember, **even at ΔE = 2 eV, resolving power < current grating spectrometers, E < 1 keV!**

2013: Astro-H/完成予想図-4 (US/Japan/ESA)



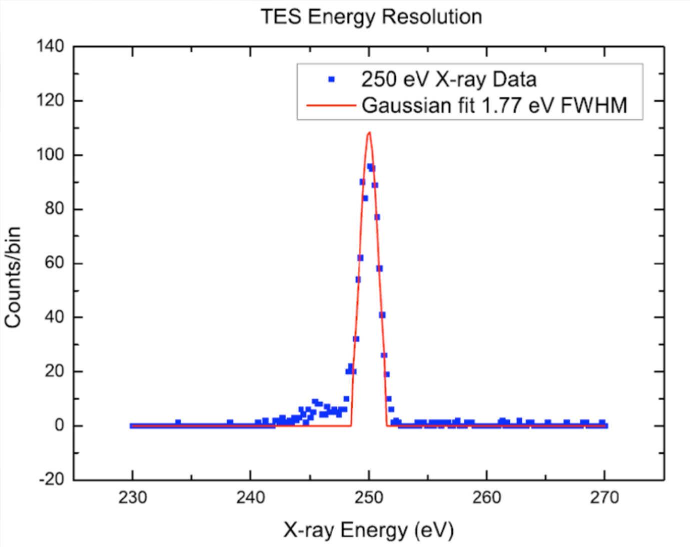
XCS/X-ray Calorimeter Spectrometer: ΔE = 7 eV, 0.5-10 keV

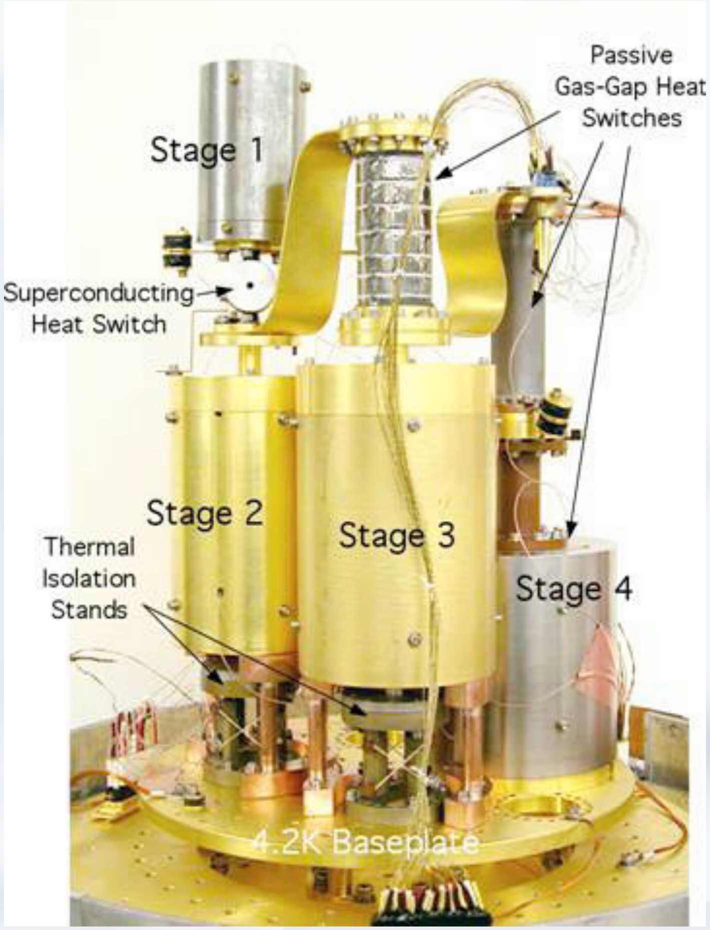
International X-ray Observatory (IXO)



F = 20 m; A = 3 m^2 @ 1 keV

Microcalorimeters, CCDs, gratings, polarimeter, ultrafast photometer





Resources:

- *Chandra* HETGS: Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)
  Nice entry into detailed understanding of HETGS, with discussion of manufacturing and scientific results; follow references.
- *XMM-Newton* RGS: den Herder et al., 2001, *Astron. Astrophys.*, **365**, L7
  Early instrument paper; good description of the instrument, with references

F. Paerels: *Future X-ray Spectroscopy Missions*, in *X-ray Spectroscopy in Astrophysics*, Lecture Notes in Physics, **520**, p.347 (Springer, 1999) (**accessible through ADS**)

- recent results: see lecture 1