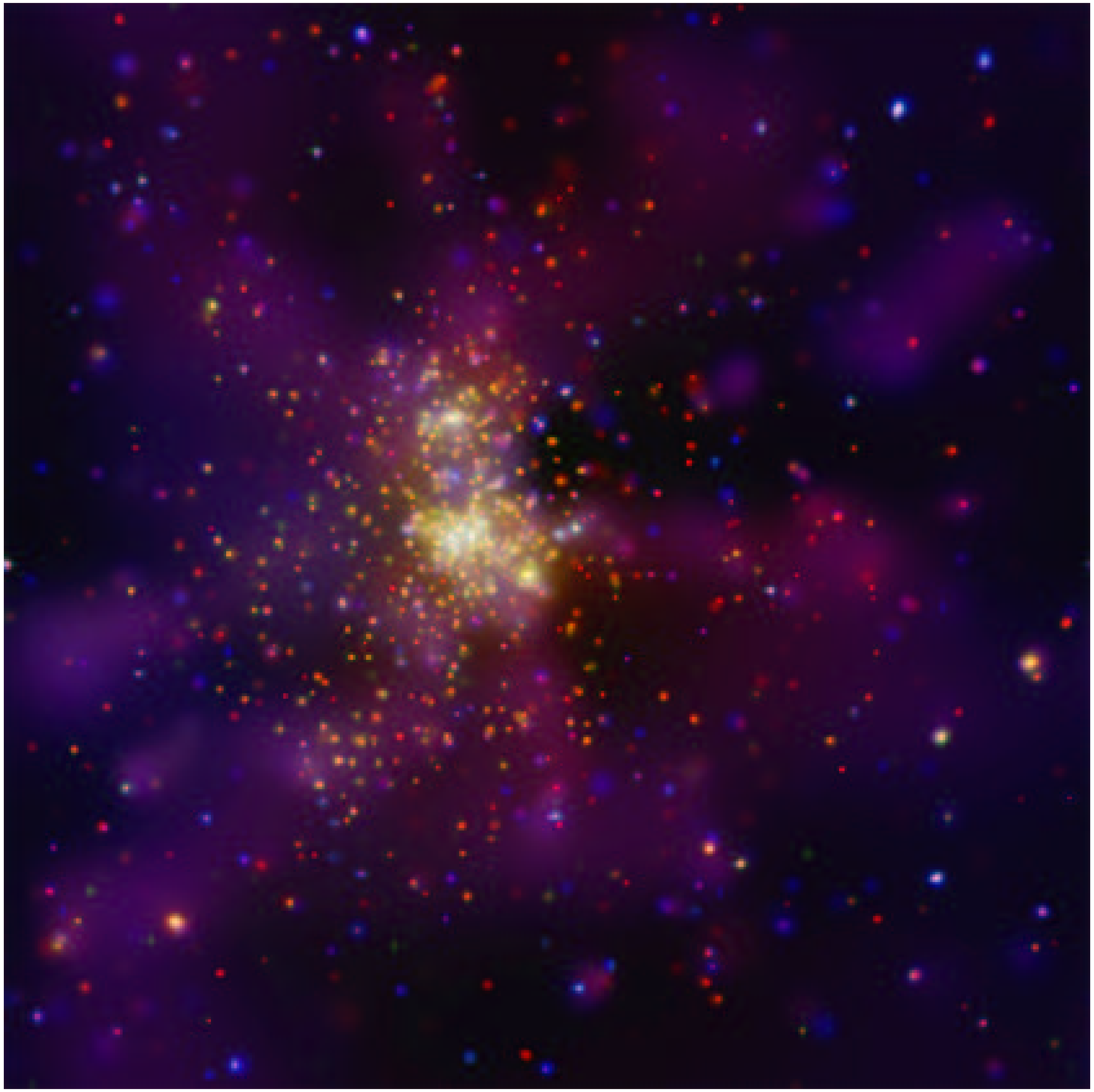
The X-Ray Universe



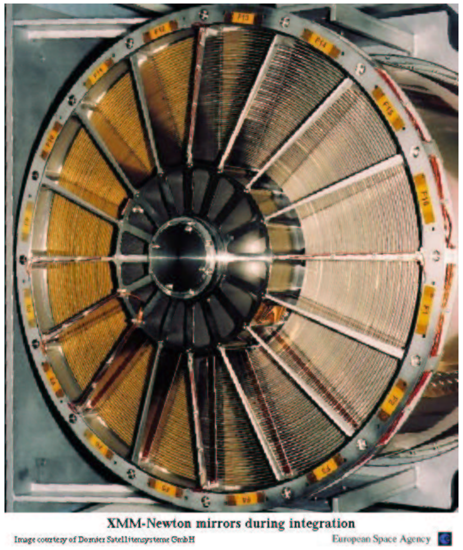
Potsdam University

Dr. Lidia Oskinova
Wintersemester 2008/09

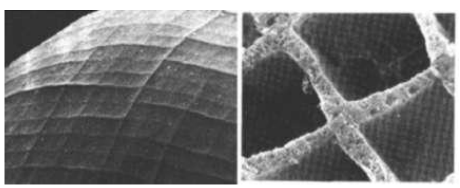
lida@astro.physik.uni-potsdam.de
astro.physik.uni-potsdam.de/~lida/x-ray.html

Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d= 2×10^4 ly

Reminder: X-ray telescopes

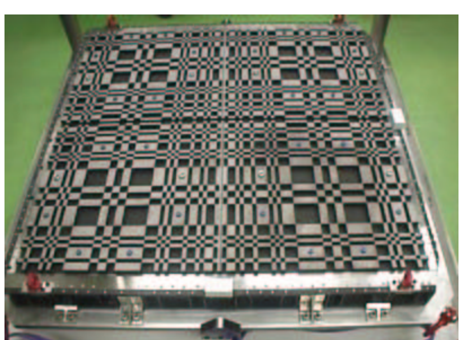


Wolter I mirrors (XMM-Newton, Chandra)



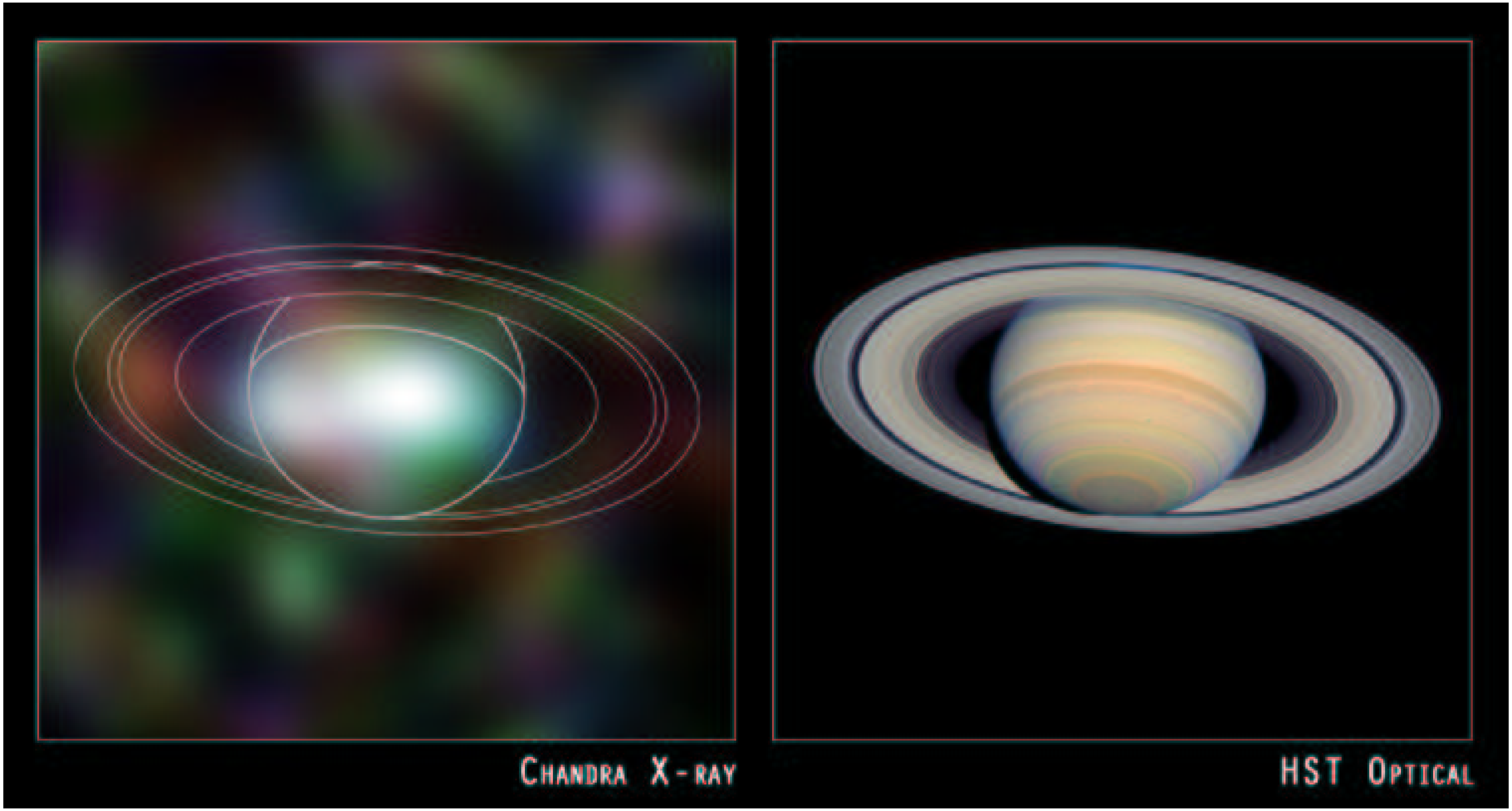
Lobster Eye (LOBSTER-ISS)

Collimators (RXTE)



Coded Mask (Integral)

III. X-ray Detectors



http://chandra.harvard.edu/resources/

III. 1. Introduction

Ideal detector for satellite-borne X-ray astronomy?

- High spatial resolution
- Large useful area
- Excellent temporal resolution
- Good energy resolution
- Broad bandwidth
- Stable on timescales of years
- Very low internal background
- Immune to damage by the in-orbit radiation
- Require no consumables
- Simple and cheap
- Light in weigh
- A minimal power consumption
- No moving parts
- Low data rate

Such a detector does not exist!

from "X-ray Detectors in Astronomy" G.W.Fraser

III. 2. Types of X-ray detectors

We want to detect a weak source against a fairly strong background.

1 ph with E 1..10 keV per 1 cm^2 per s is a strong X-ray source

Integrating detectors (such as film) not much useful

Source detection is done on a photon-by-photon basis.

Non-imaging and imaging detectors

NB Dualism! X-ray quantum is both particle and wave

Ionization detectors: X-ray hits detector and ionizes an atom:

Photo-electric absorption

Resulting free electron will create secondary electrons

Electric field: the electrons can be collected and counted.

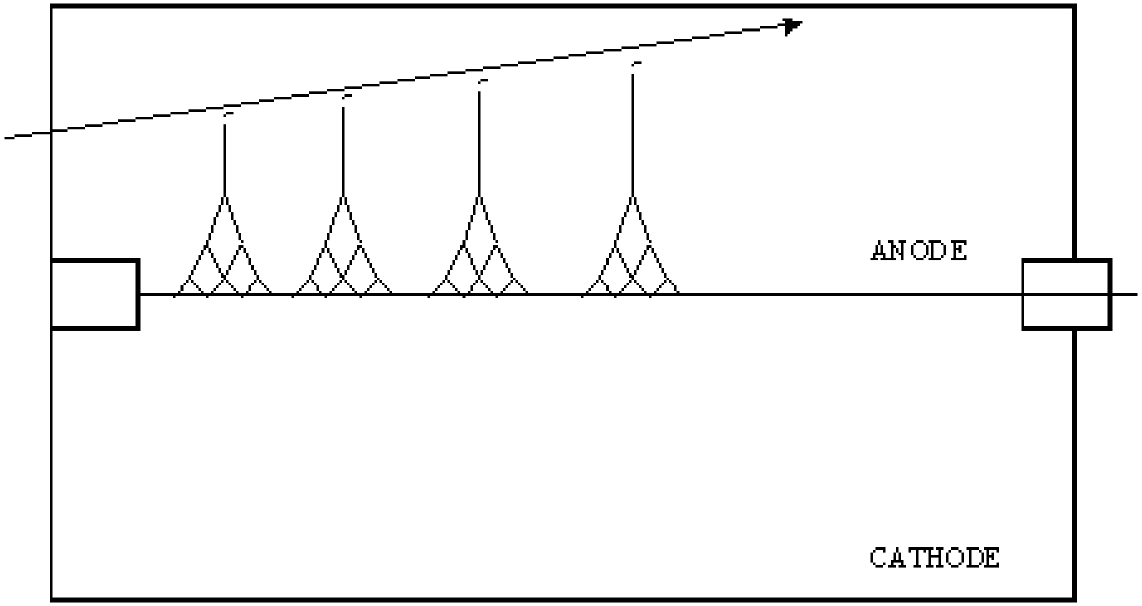
Mesured charge is proportional to the deposited energy

Microcalorimeters: Exited electorns go back to the original energy

Returning to ground state they loose energy to heat

Measured heat is proportional to the deposited energy

III. 3. Proportional counters - Non-imaging



www.orau.org/ptp/

The Size of the Pulse:

1. Operating Voltage.
The higher the operating voltage, the larger each avalanche and the larger the pulse.

2. Energy of X-ray photon.
The greater the energy of photon the larger the number of primary ions the larger the number of avalanches, and the larger the pulse.

Measured voltage:

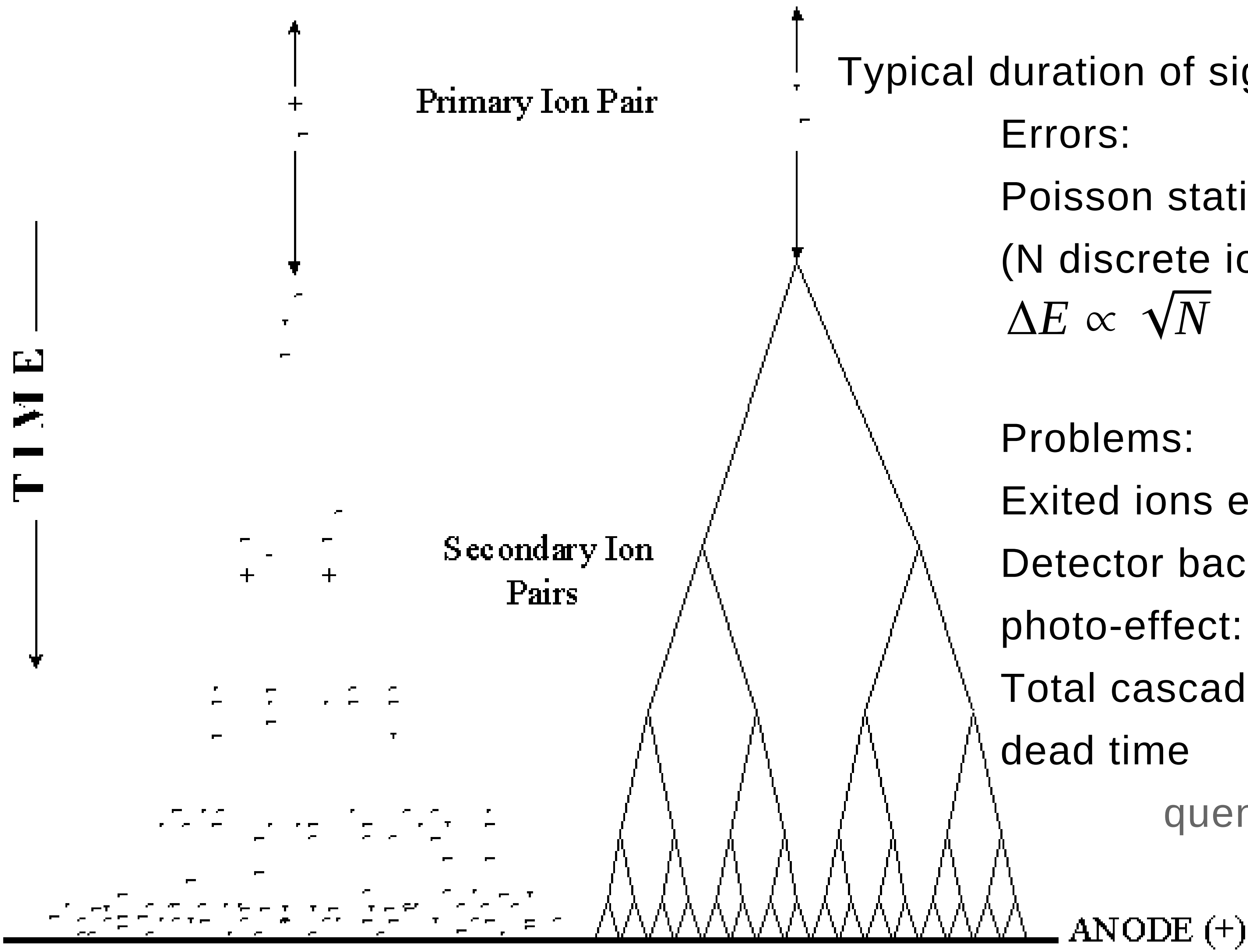
$$\delta U = -\frac{eN}{C} \cdot A$$

A is amplification factor ($10^4 \ldots 10^6$)

A is constant, voltage puls $\propto eN \propto$ energy

Propotional counter.

III. 4. Proportional counters. Avalanche.



Typical duration of signal 100μs

Errors:

Poisson statistics

(N discrete ion pairs)

$\Delta E \propto \sqrt{N}$

Problems:

Exited ions emit UV ph

Detector background:

photo-effect: avalanches

Total cascade takes time:

dead time

quenching

III. 5. Background.

Background results from:

* Particles and Photons
* Particles: cosmic rays, inreplanetary rays, radiation belts around Earth
* radioactivity of detector, trapped electrons, solar activity..
* Cosmic X-ray background, unresolved sources, secondary UV photons
* optical leakage, et cet...

Understanding the background is key to correct intrpreatationofthe data

Non-Imaging Instruments: how to reject background?

Energy Selection:

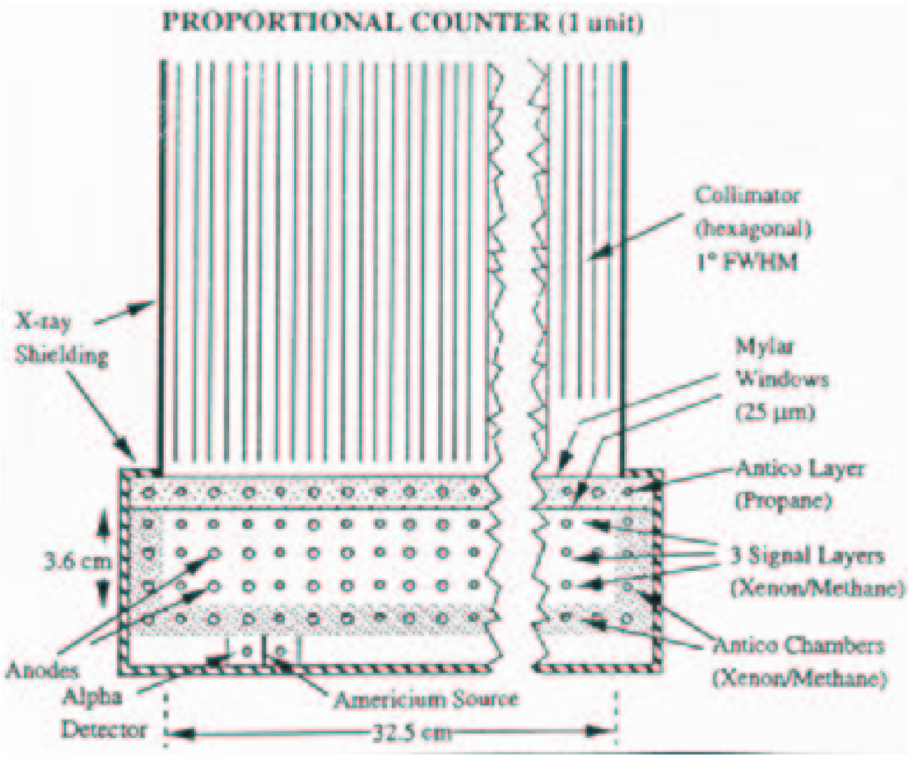
rejecting all events which deposit energies outside the X-ray bandpass

rise-time discrimination

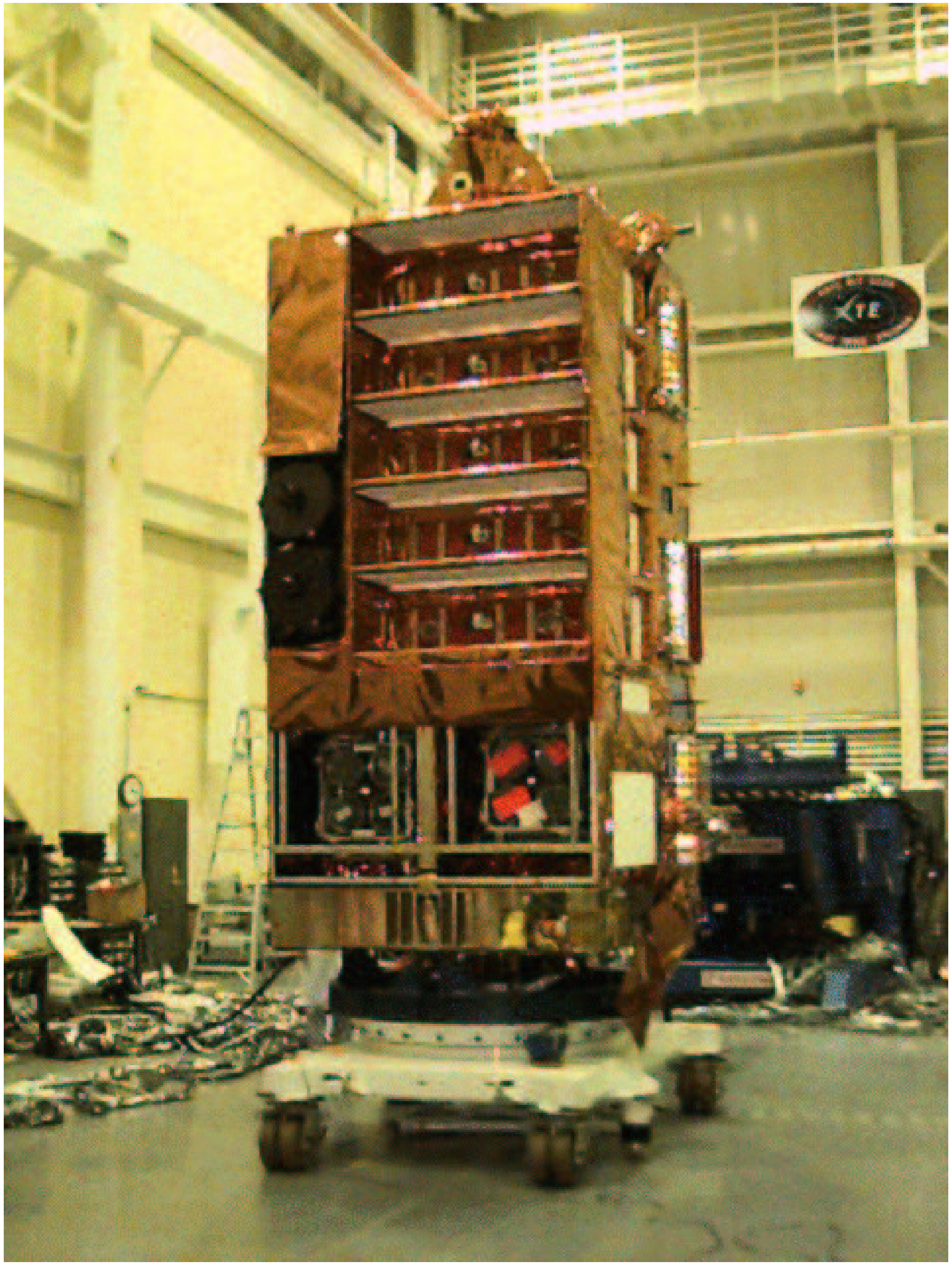
anti-coincidence within a sub-divided gas cell

Reducing backgruond by factor 100!

III. 6. The Rossi X-ray Timing Explorer Mission (1995-present)



http://heasarc.gsfc.nasa.gov/docs/xte/xtegof.html



NASA, 2 to 250 keV

Proportional Counter Array

High-energy X-ray timing experiment

All Sky Monitor

µsec resolution, it is all about timing

Blach Holes, pulsars, etc...

III. 7. CCD: Charge Coupled Devices - Imaging

* An array of linked ("coupled") capacitors

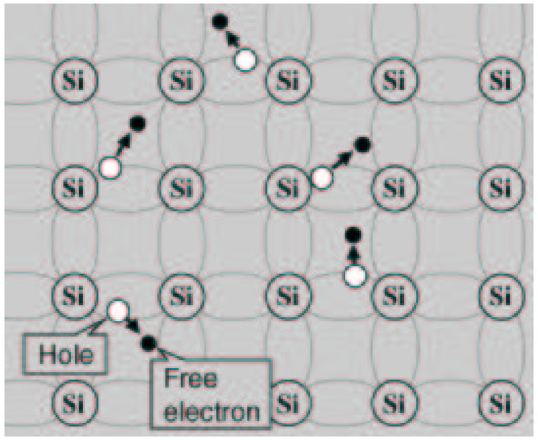
* Photons interact in a semiconductor substrate
and are converted into electrons

* An applied electric field collects
and stores the electrons in pixels

* Pixels are "coupled" and can transfer their stored charge
to neighboring pixels

* Stored charge is transferred to a output amplifier and read out

III. 8. Reminder: What is Semiconductor?



A silicon crystal is different from an insulator

- T>0: finite probability that an electron in the lattice
- is knocked loose from its position
- behind is an electron deficiency called a "hole"
- voltage: both the electron and the hole contribute to small cu

The Doping of Semiconductors

The addition of a small percentage of foreign atoms in the regular crystal lattice of silicon or germanium changes their electrical properties producing n-type and p-type semiconductors.

see http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

-Atoms with 5 valence electrons produce n-type semiconductors by contributing extra electrons.

-Atoms with 3 valence electrons produce p-type semiconductors by producing a "hole" or electron deficiency.

III. 9. Photoelectric Absorption

Photoelectric interaction of X-ray with Si atoms generates electron-hole pairs.

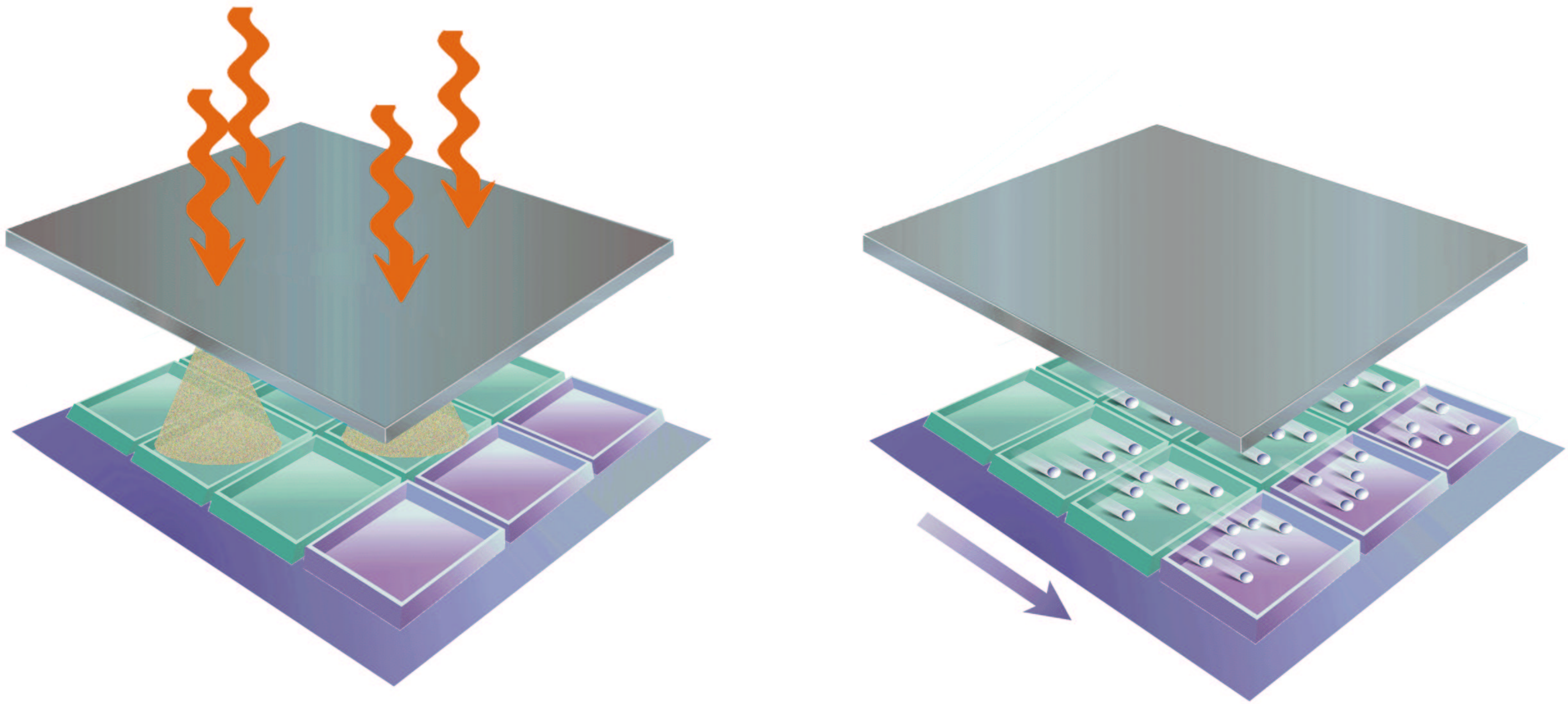
On average: $Ne = E_X/w$, Ne = number of electrons, E_X = energy of X-ray photon
W ~ 3.7 eV/e- (temperature dependent)

X-ray creates a charge cloud which can diffuse and/or move under influence of an electric field

A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD

- X-ray CCDs operated in photon-counting mode
- Spectroscopy requires 1 photon interaction per pixel per frametime
- Minimum frametime limited by readout rate
- Tradeoff between increasing readout rate and noise

III. 10. Schematic illustration of Chandra CCD

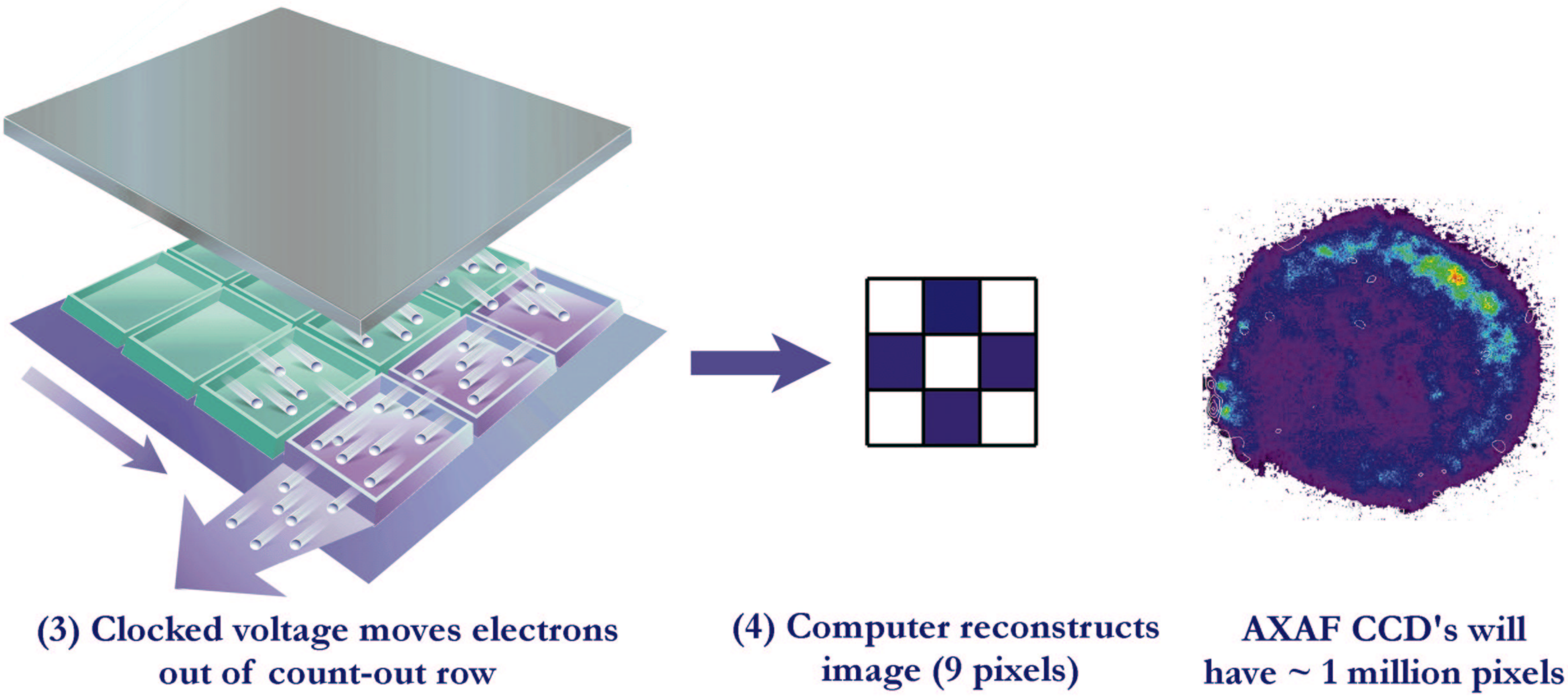


(1) Incident x-ray produces shower of electrons in selected pixels

(2) Voltage moves electrons to the right to "count-out" row

http://chandra.harvard.edu/resources/illustrations/instrumentsSchema.html

III. 11. Schematic illustration of Chandra CCD



http://chandra.harvard.edu/resources/illustrations/instrumentsSchema.html

III. 12. Front illuminated CCD structure

See figure in the leaflet.

X-rays incident from the top must pass through a number of "dead" layers which make up the "**gate"** structure.

After they enter the photosensitive volume of the device.

The gate structure is to allow charge collected in the device to be moved from the vicinity of the photon interaction site to an output amplifier.

see figure "the CCD charge transfer".

Aplifier converts the charge to a measurable electrical signal.

III. 13. Back illuminated CCD structure

Many astrophysically interesting problems require good low-energy (< 1 keV) efficiency (pulsars, ISM, SNR, et cet....)

Soft X-rays are lost to absorption in gate structures and filters

Solutions:

Thinned gates, open gates (XMM EPIC-MOS, Swift)

Back-illumination (Chandra ACIS, XMM EPIC-PN, Suzaku XIS)

See figure in the leaflet.

Back-illuminated CCDs differ from the front-illuminated devices:

1) They are much thinner. 2) X-rays do not pass through the gates.

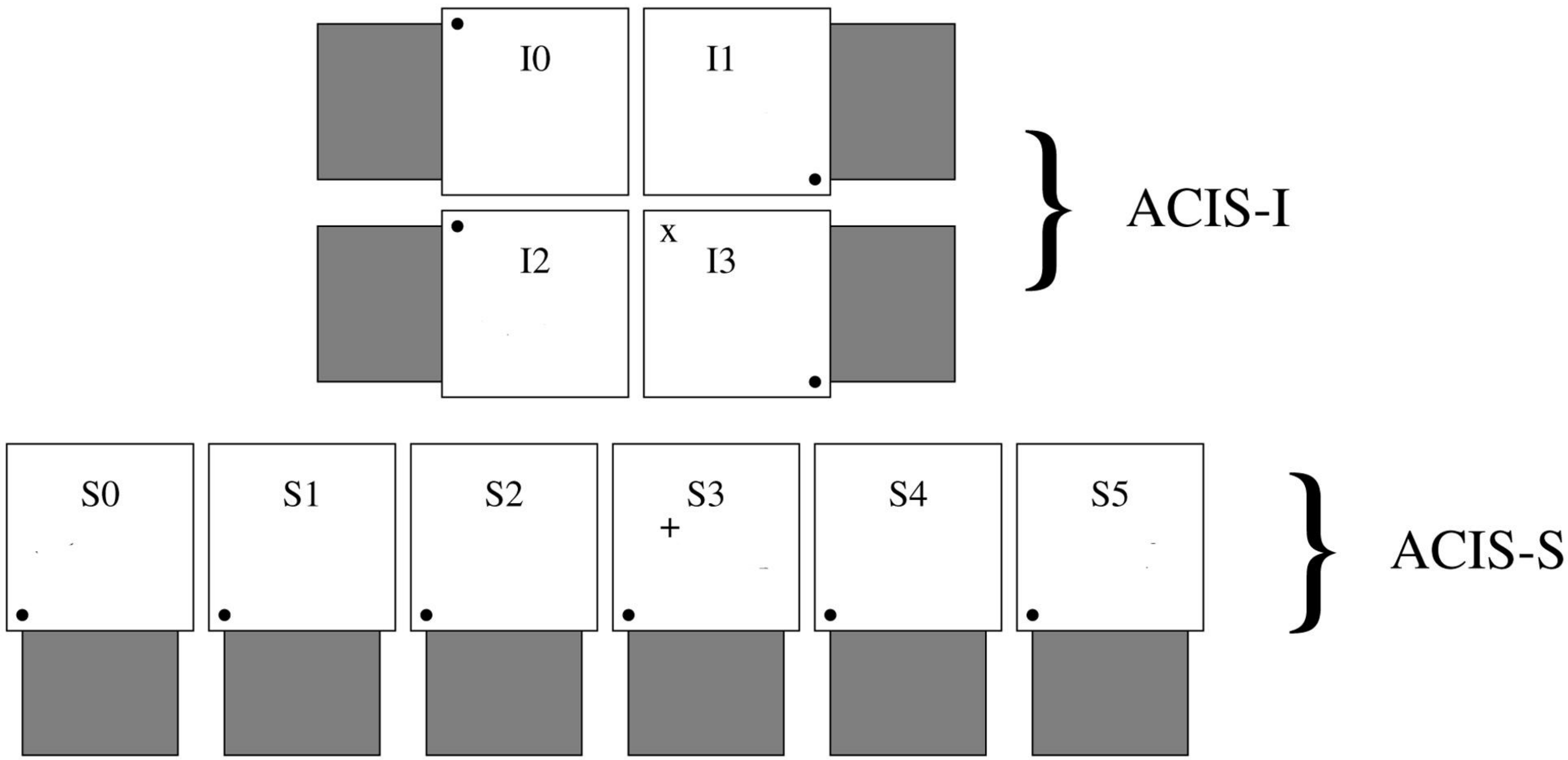
Thin deadlayers -- higher low-energy quantum efficiency

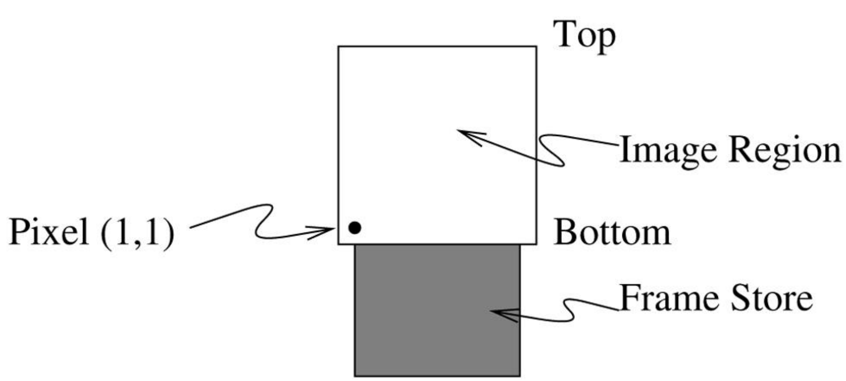
Thin active regions - low high-energy quantum efficiency

But! Increased noise, charge transfer iefficiency, higher FWHM

III. 14. Chandra ACIS: Advanced CCD Imaging Spectrometer

ACIS FLIGHT FOCAL PLANE





10 chips, 8 FI, 2 BI

Each CCD 1024 x 1024 pixels

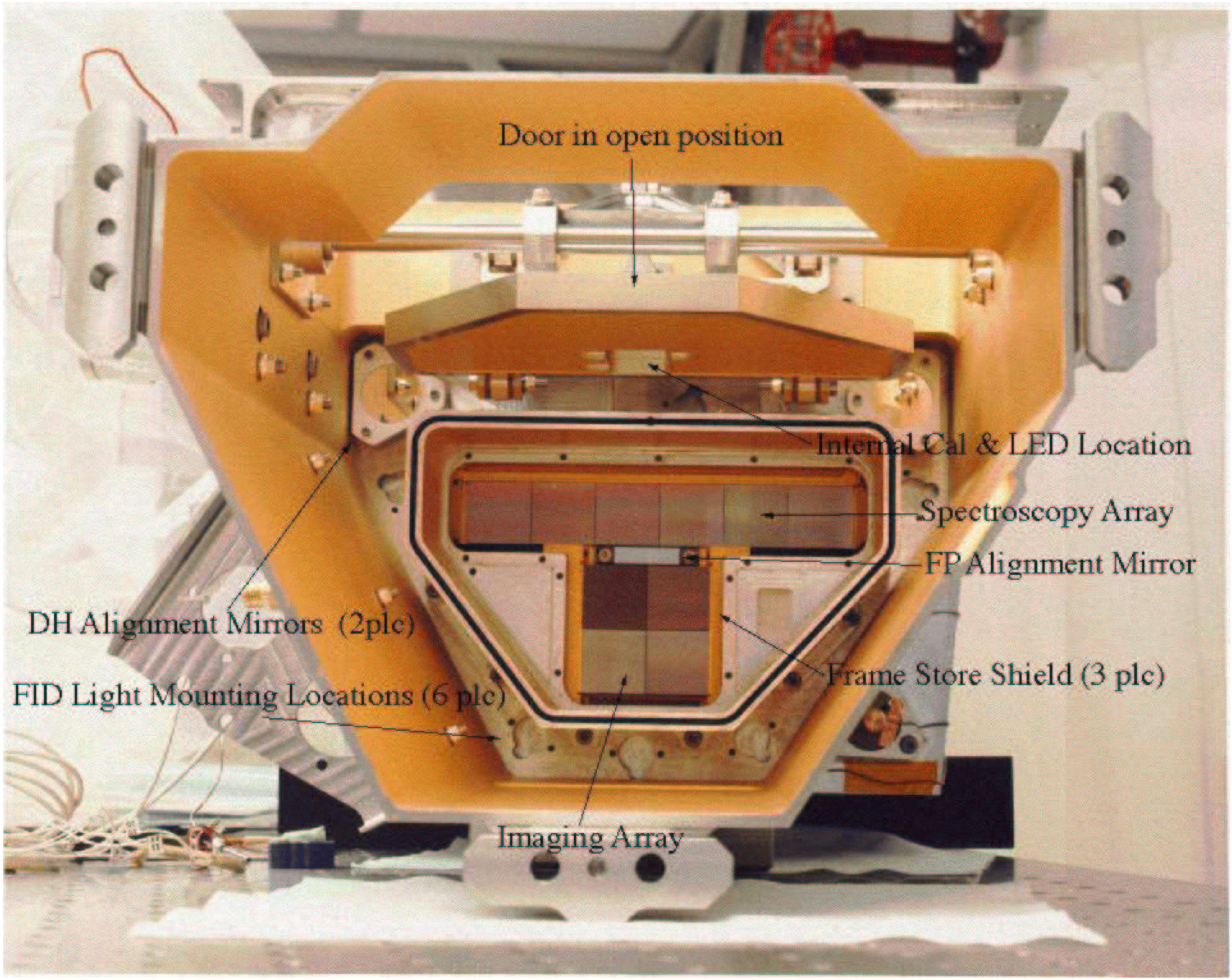
Pixel size 24 micron (0.5 arcsec)

Array size 17 x 17 arcmin

Nominal frame time 3.2s

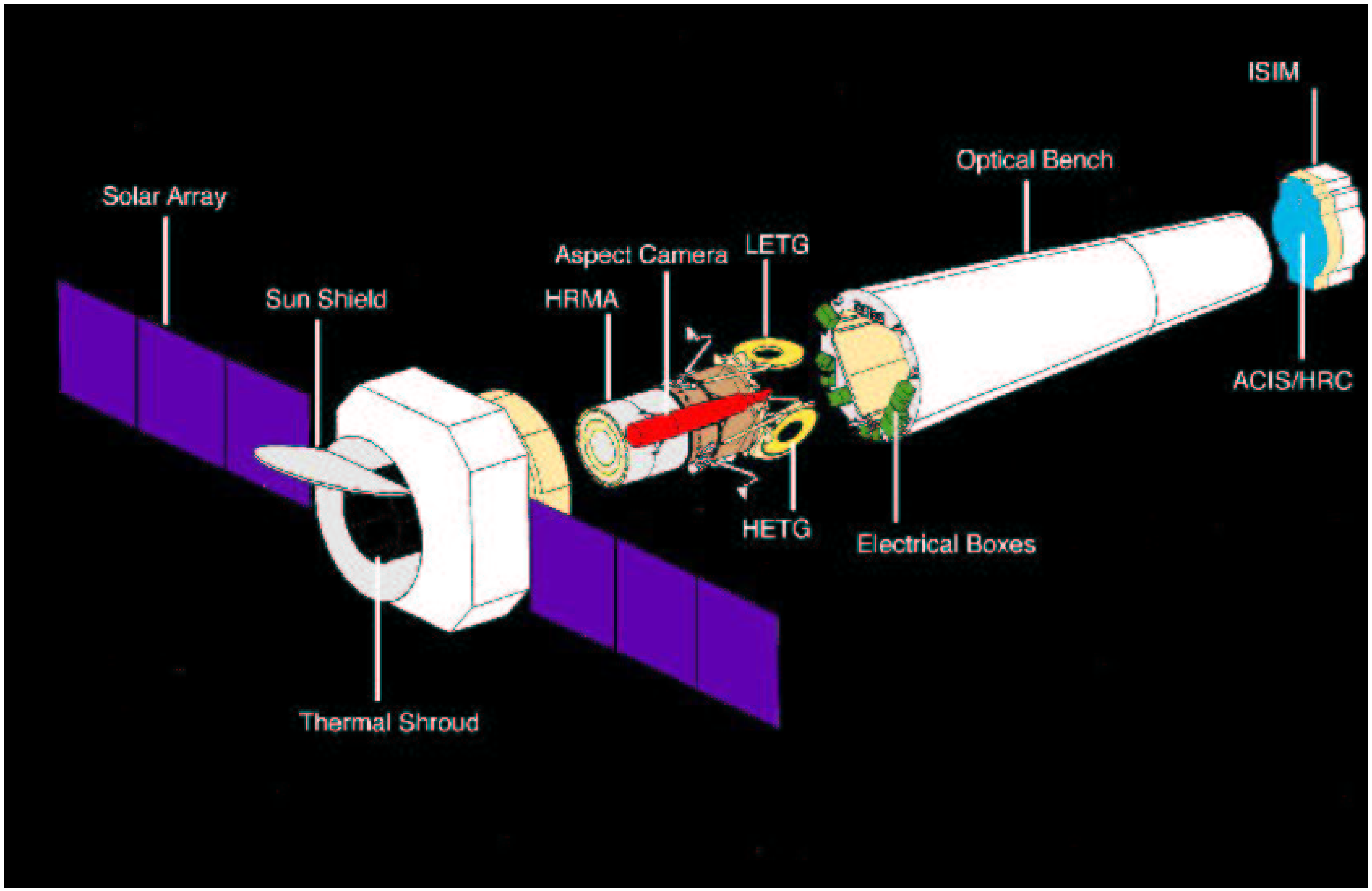
http://asc.harvard.edu/proposer/POG/

III. 15. View of ACIS as seen by HRMA



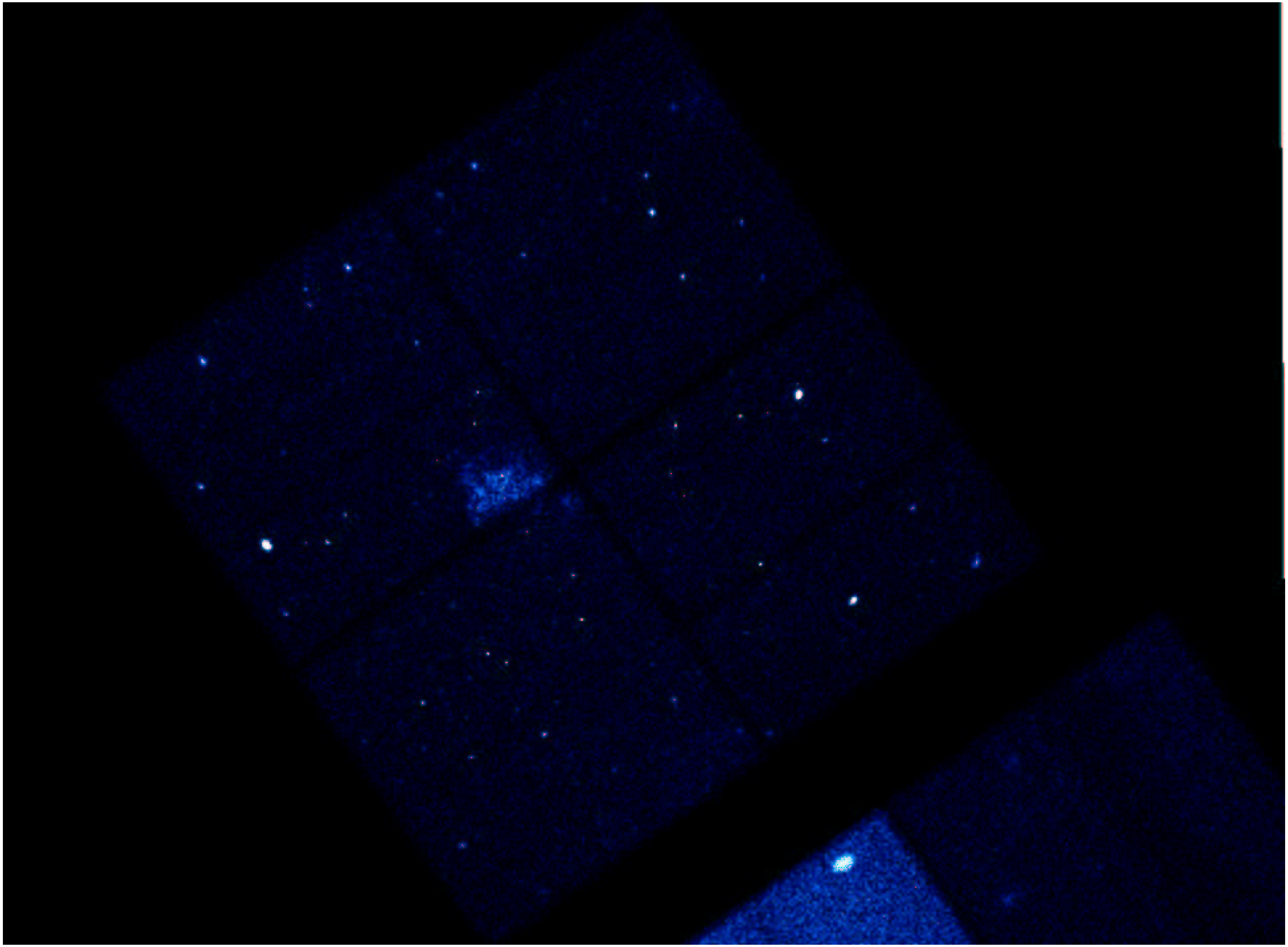
http://chandra.harvard.edu/resources/illustrations/ACIS.html

III. 16. Chandra Spacecraft

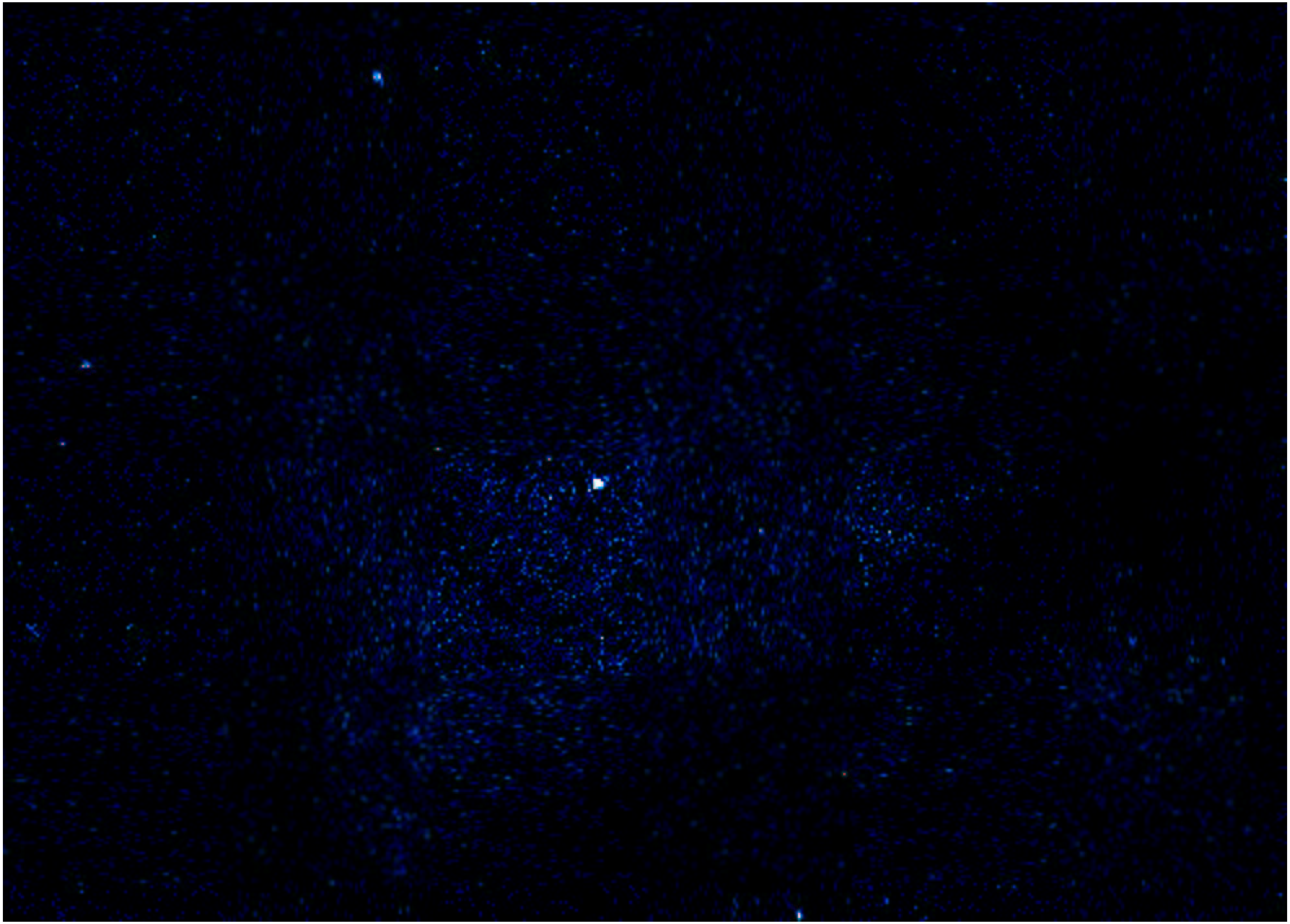


http://chandra.harvard.edu/resources

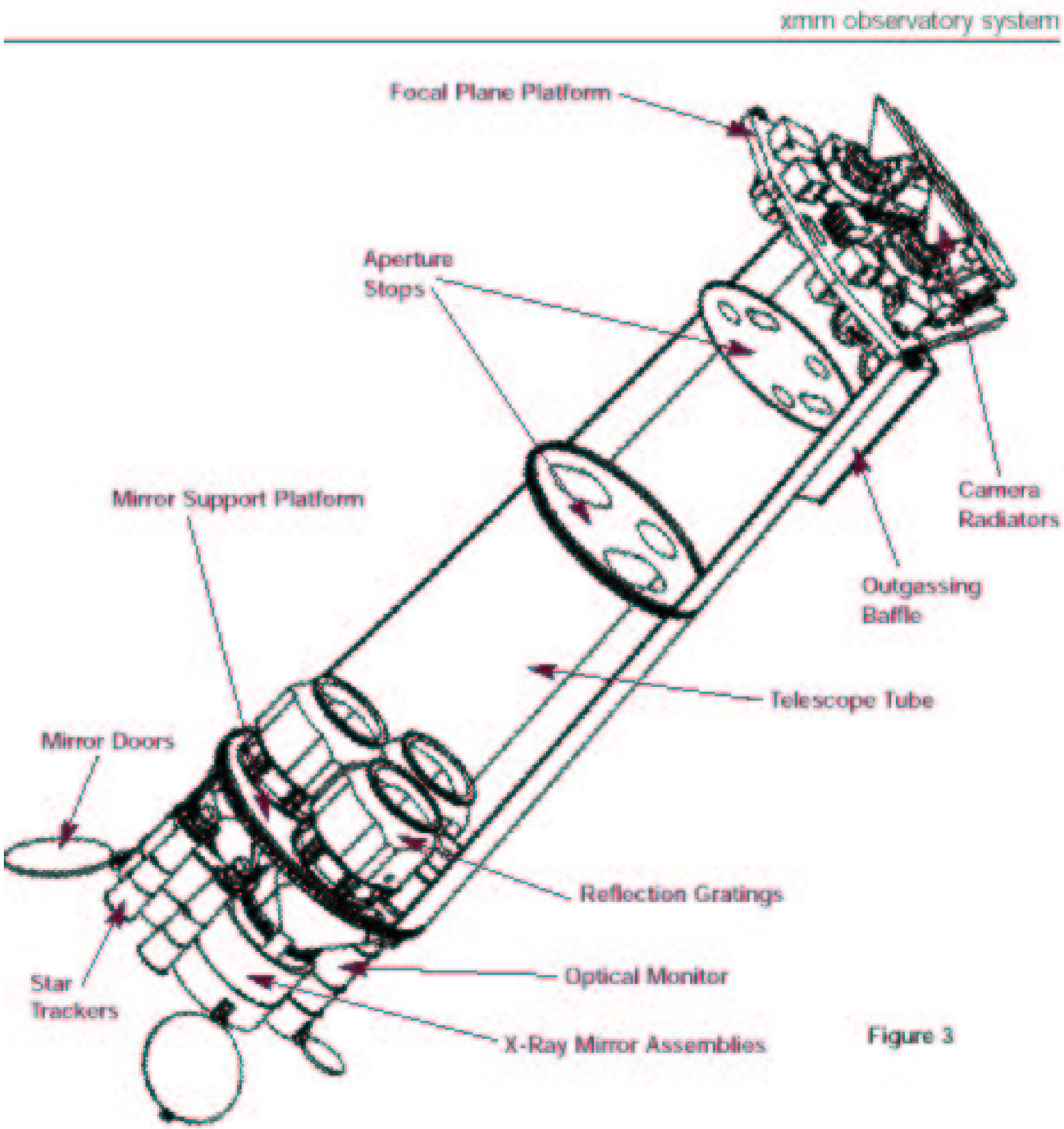
III. 16. ACIS image of NGC346 in the SMC



III. 17. Zoom on NGC346

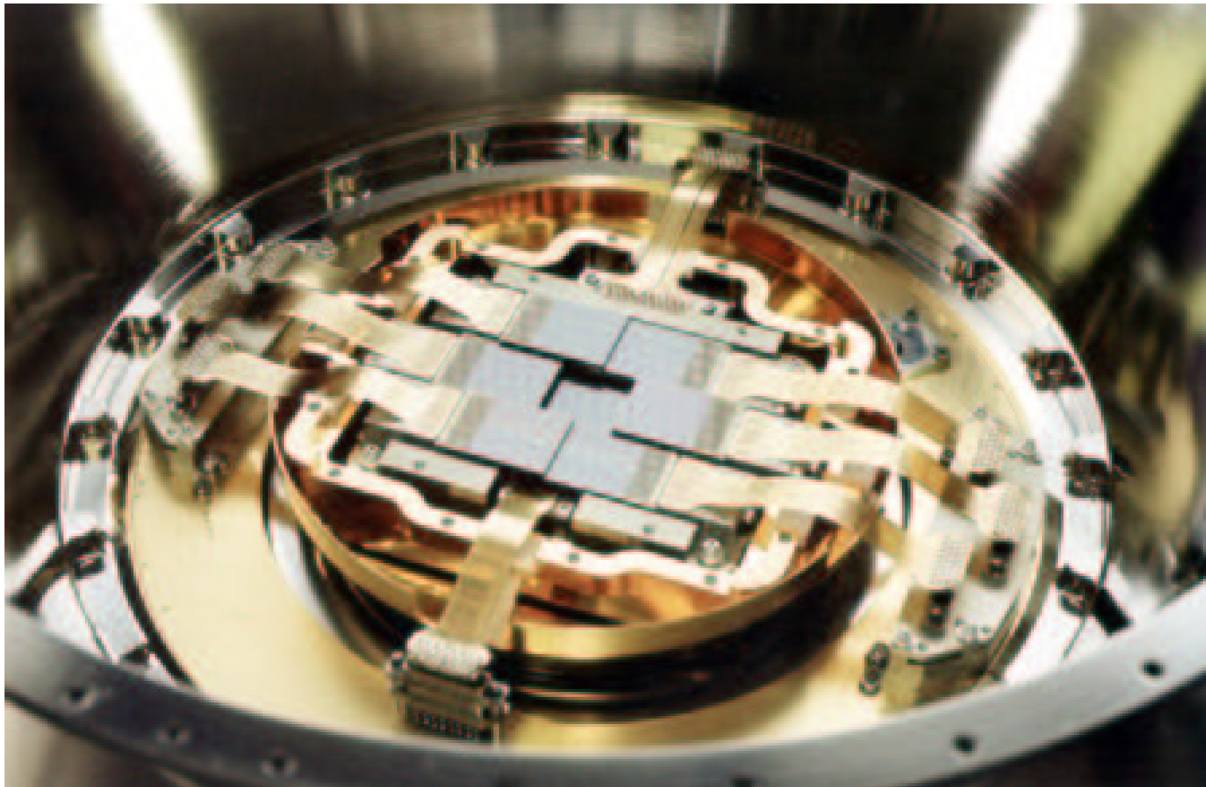


III. 18. XMM-Newton has three telescopes and 3 detectors



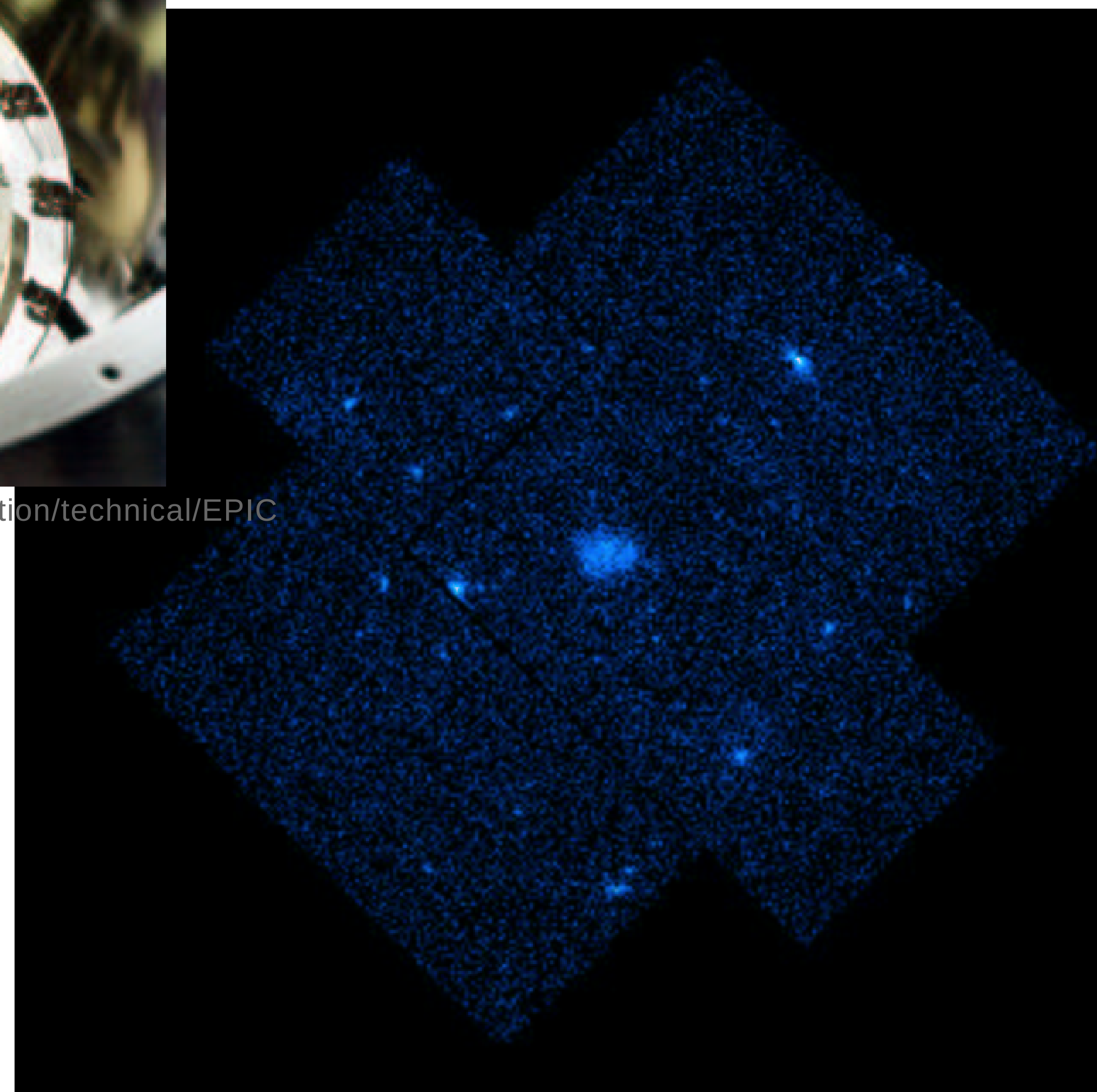
http://xmm.esac.esa.int/external/xmm_user_support/documentation/technical/Spacecraft/i

III. 19. Two MOS cameras: Front illuminated.



http://xmm.esac.esa.int/external/xmm_user_support/documentation/technical/EPIC

NGC 346 in the SMC

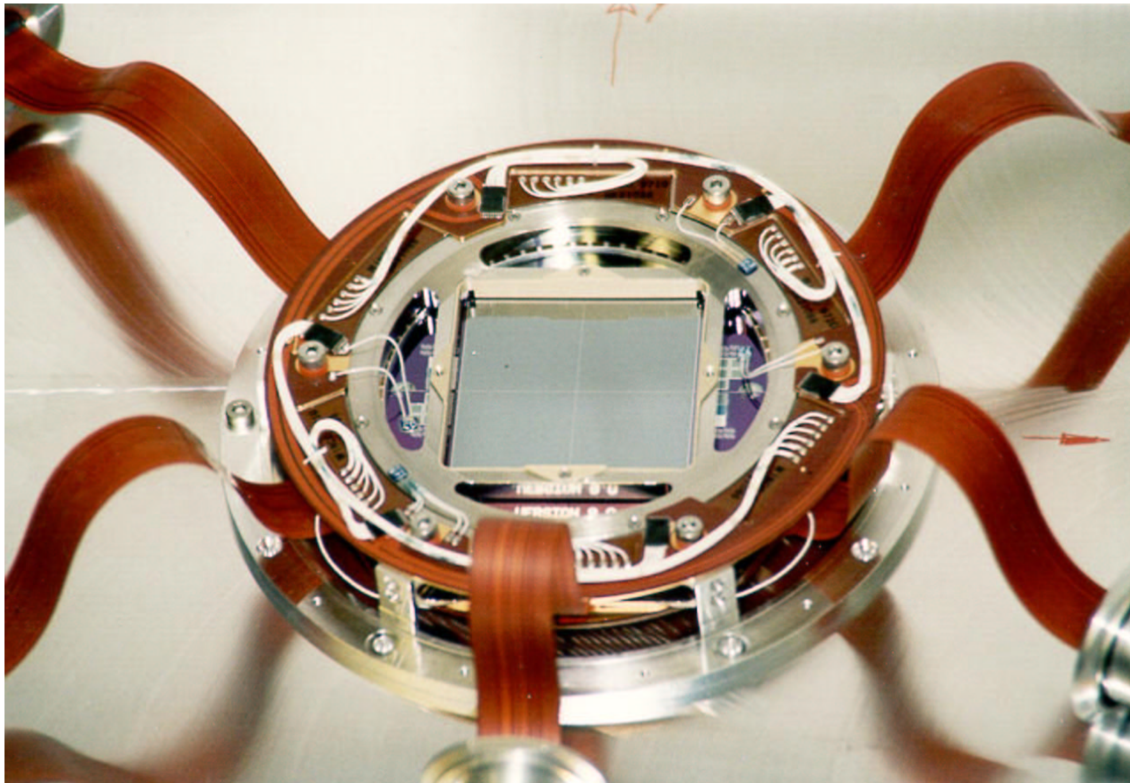


Two identical cameras

7 chips each

30 armin diameter

III. 20. XMM-Newton PN camera: back illuminated

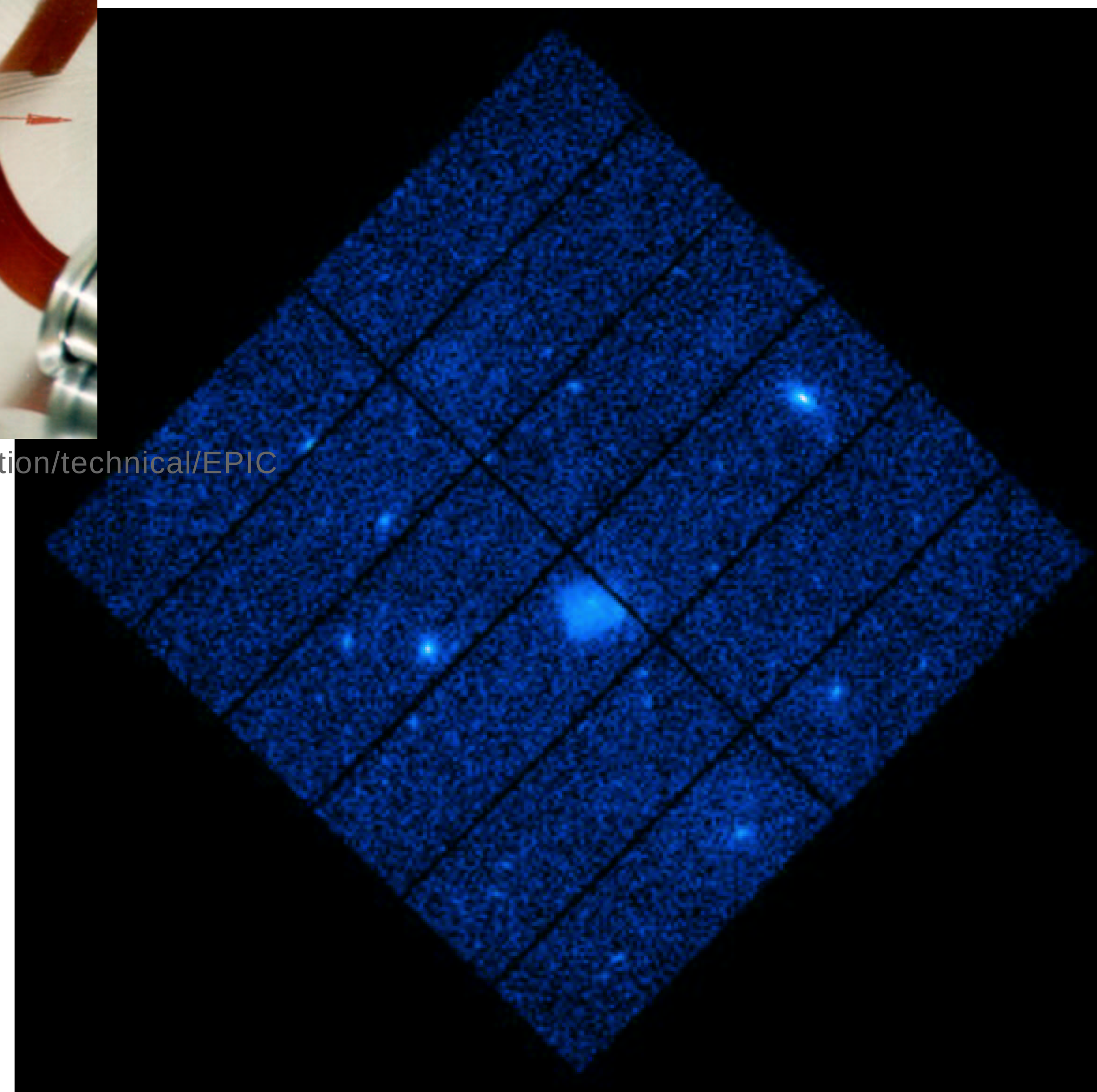


http://xmm.esac.esa.int/external/xmm_user_support/documentation/technical/EPIC

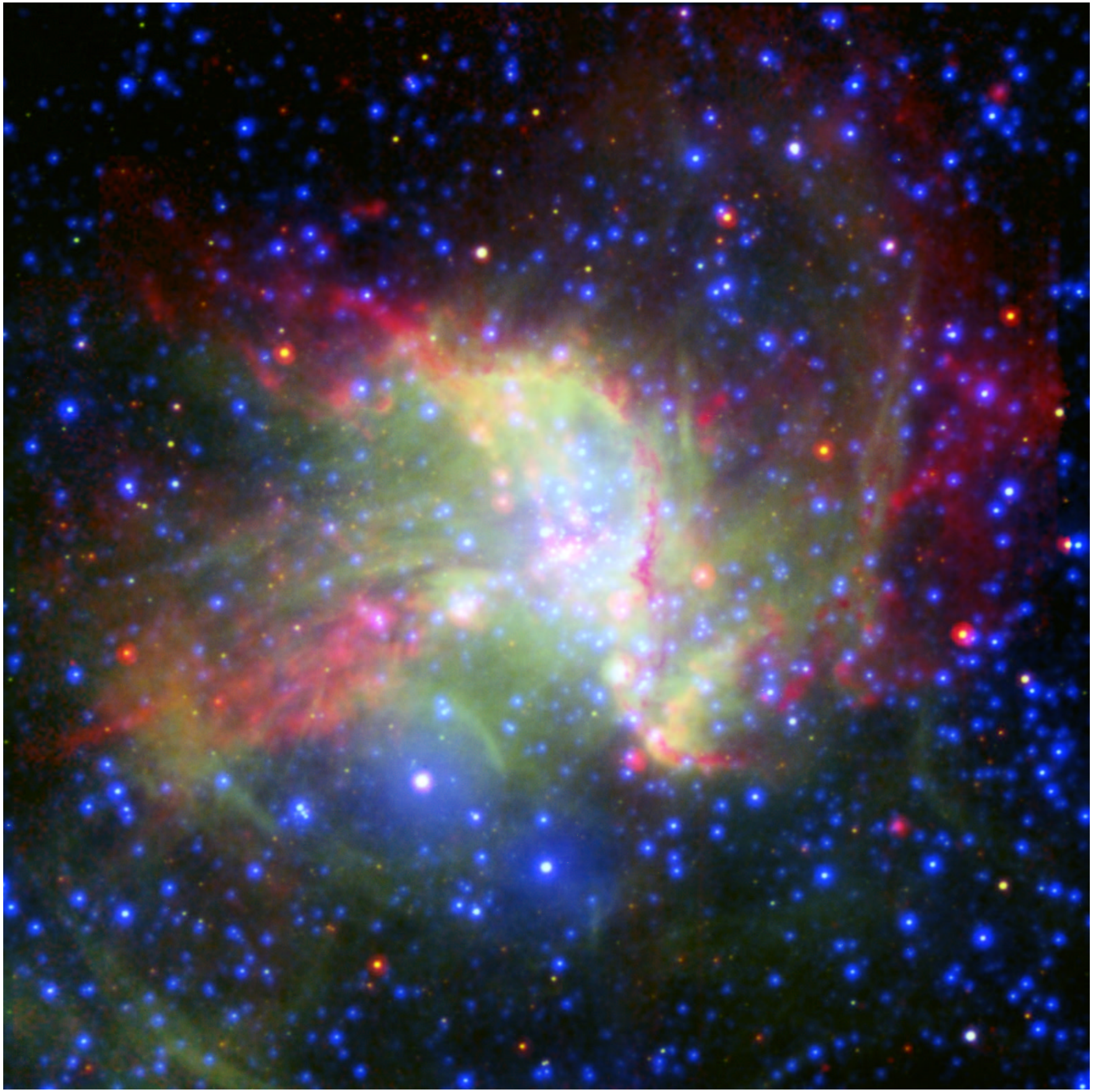
12 chips each

30 armin diameter

NGC 346 in the SMC



III. 21. NGC346: X-ray + optic + IR



III. 22. CCD X-ray spectroscopy

- Photoelectric interaction of a single X-ray photon with a Si atom produces free electrons:

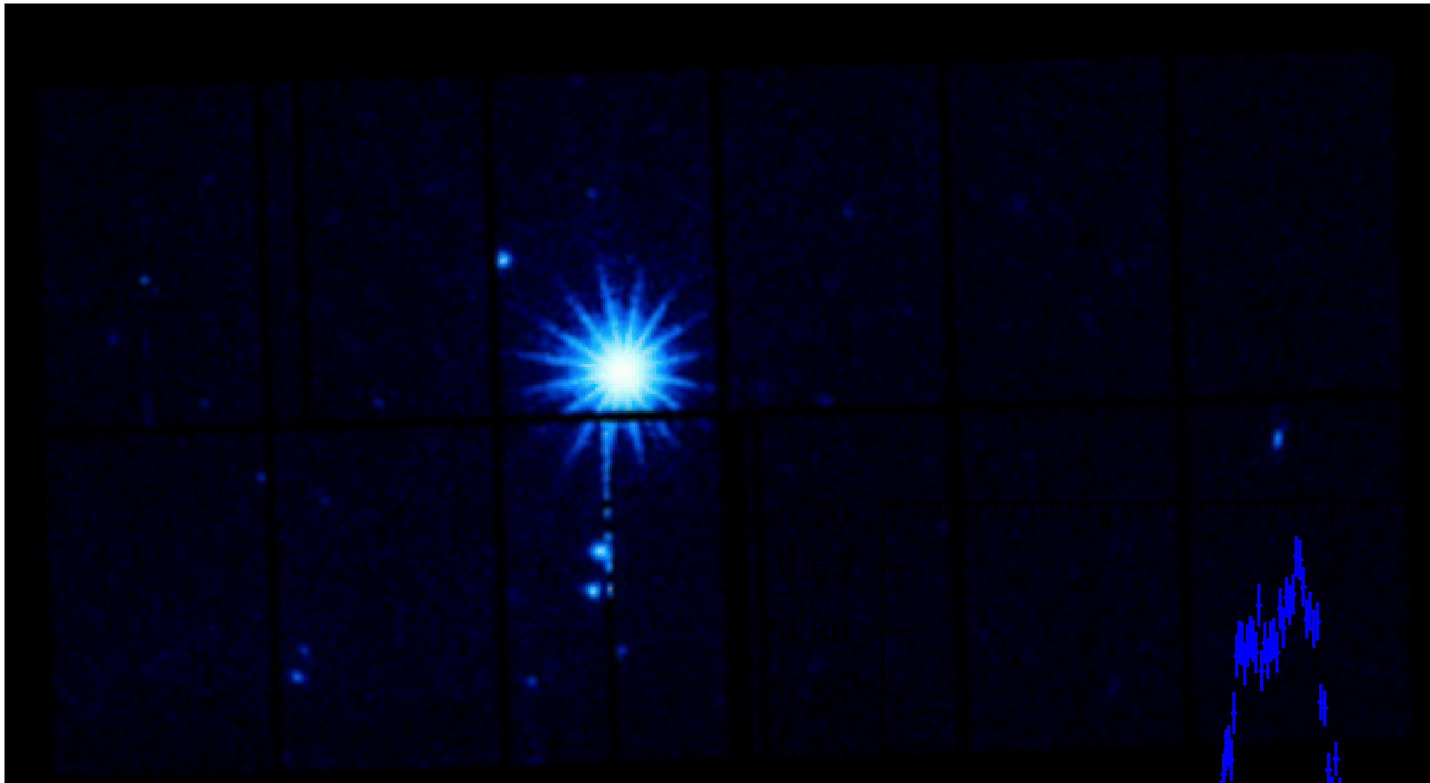
  $N_e = E_X / W$, where W=3.7eV

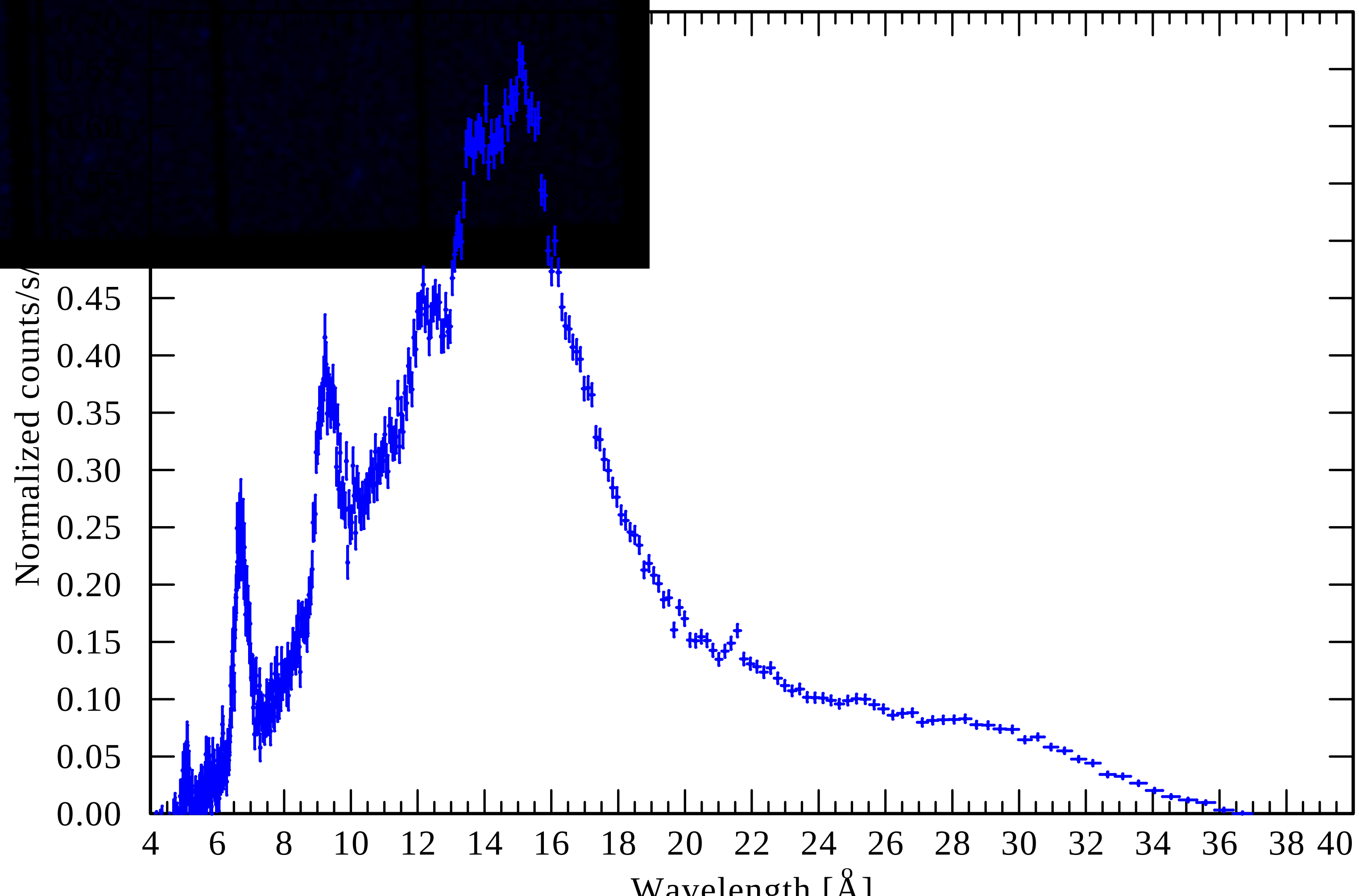
- Spectral resolution depends on CCD readout noise and physics of secondary ionization:

  At 1 keV ACIS-I: 50eV; MOS: 70eV, PN 80eV

- CCD characteristics that maximize spectral resolution:
  - * Good charge collection and transfer efficiencies
  - * Low readout and dark-current noise (low ccd temperature)
  - * High readout rate (requires tradeoff vs. noise)

III. 23. XMM-Newton PN image of O type star ζ Puppis

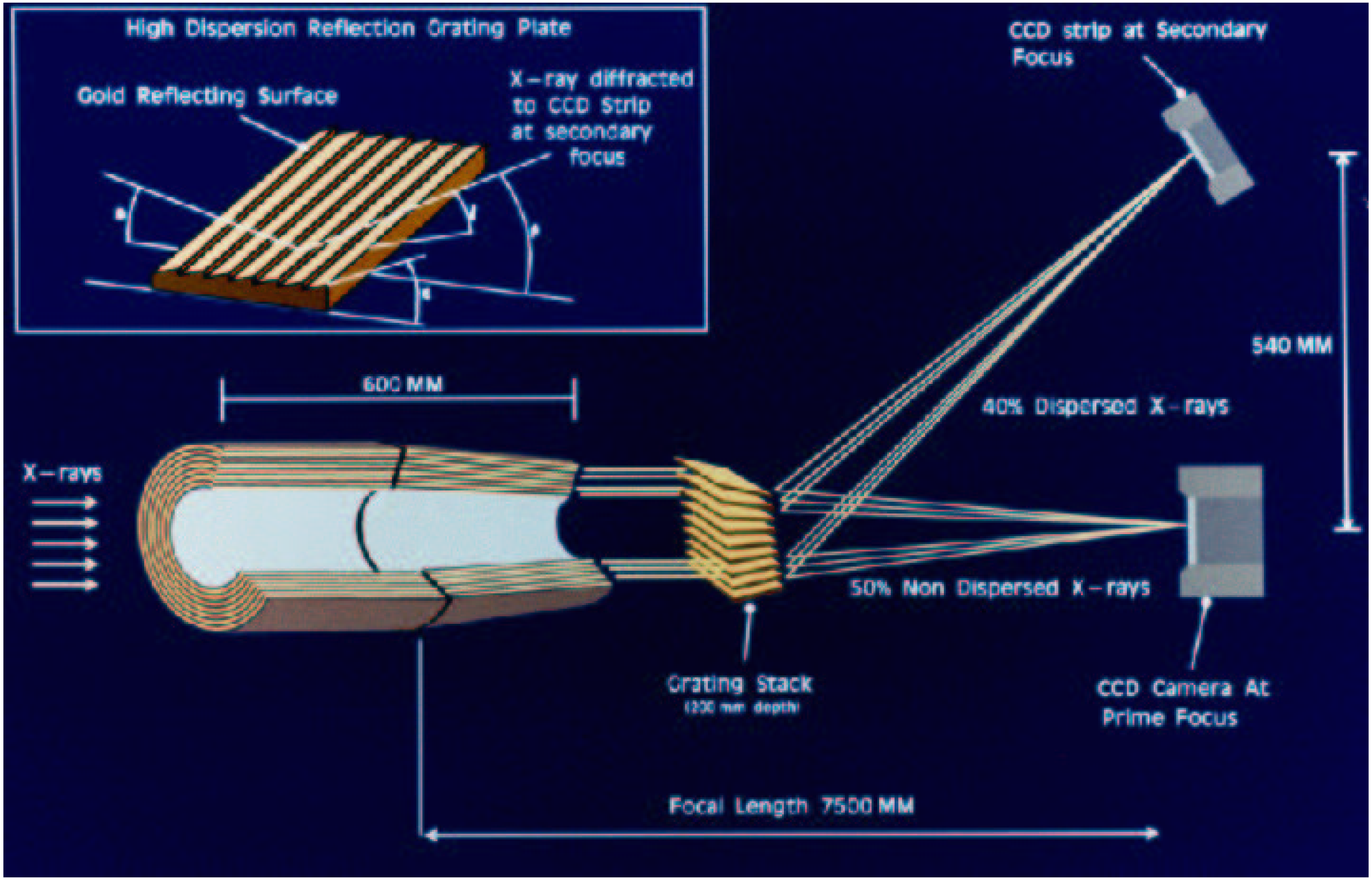




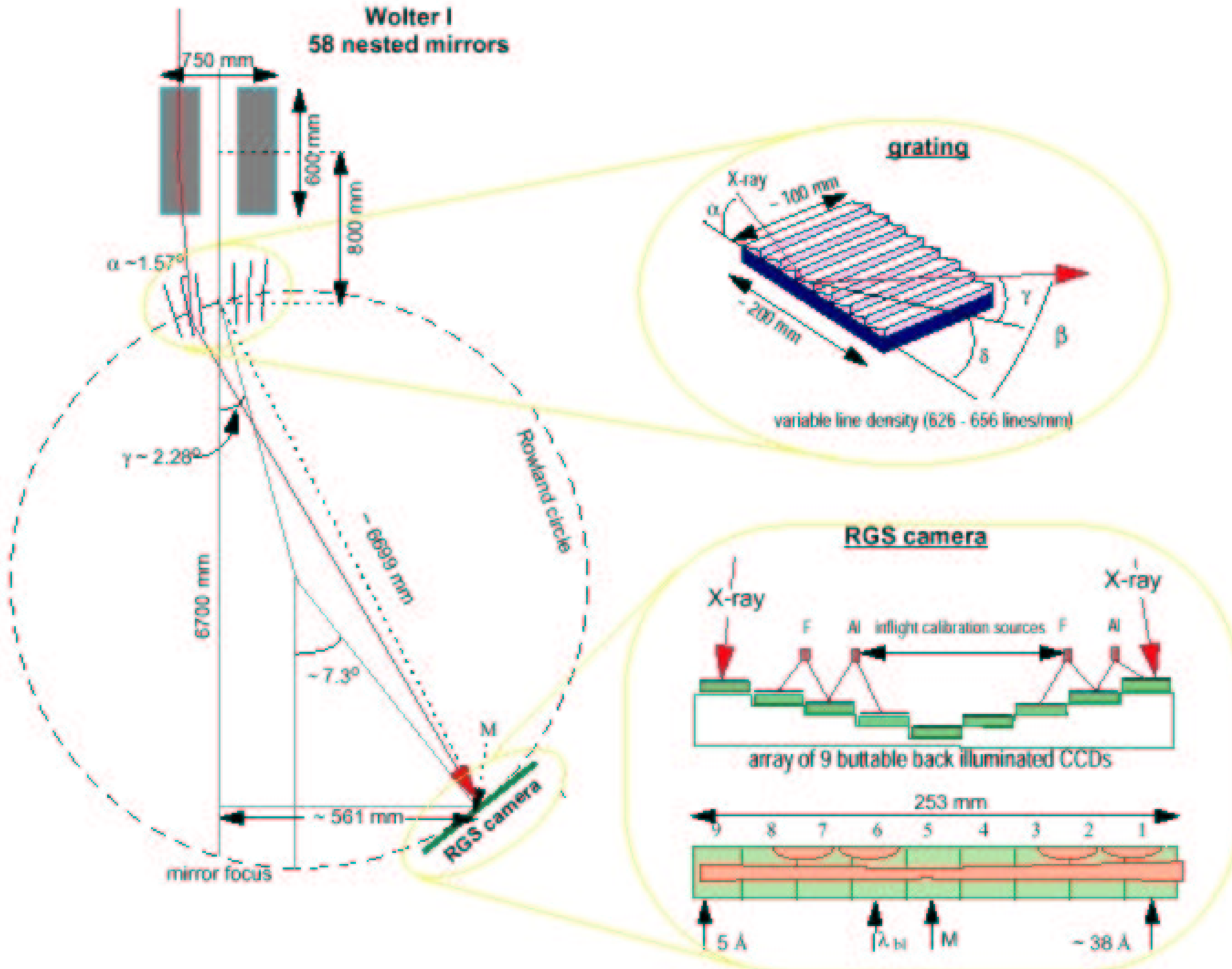
Very few lines resolved

No line structure

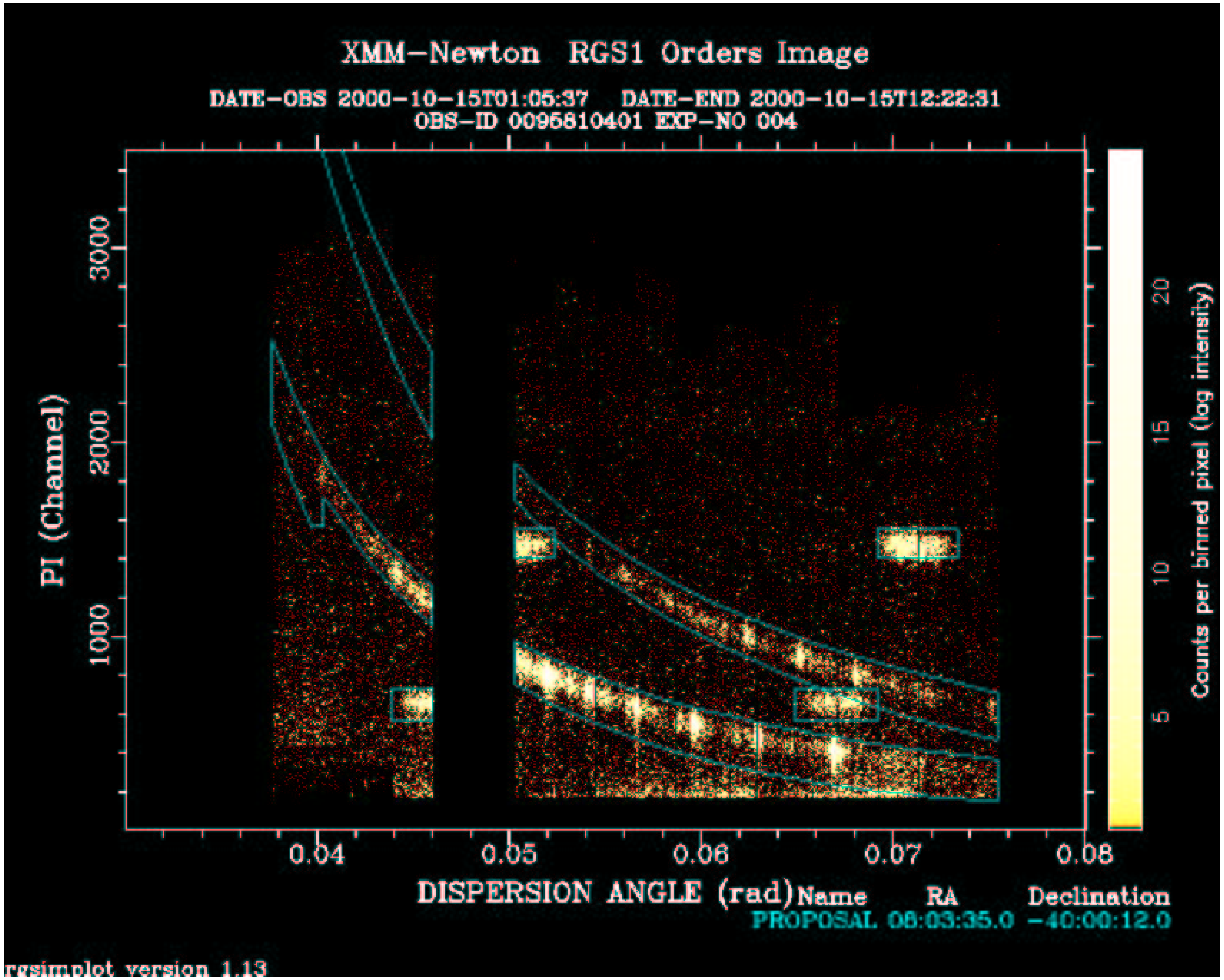
III. 24. Two XMM-Newton telescopes have grating assemblies



III. 25. The Reflection Grating Spectrometer (RGS) onboard XMM-Newton



III. 26. Image in RGS camera of O star ζ Puppis



X-ray grating works identical to optical grating both follow the grating equaiton

$$\sin\beta = m\lambda/p$$

λ is wavelength, β is dispersion angle, m is order 1, 2, 3 etc

p is the spatial period if the grating, RGS $\Delta\lambda$=0.05Å

III. 27. Science spectra of O stars