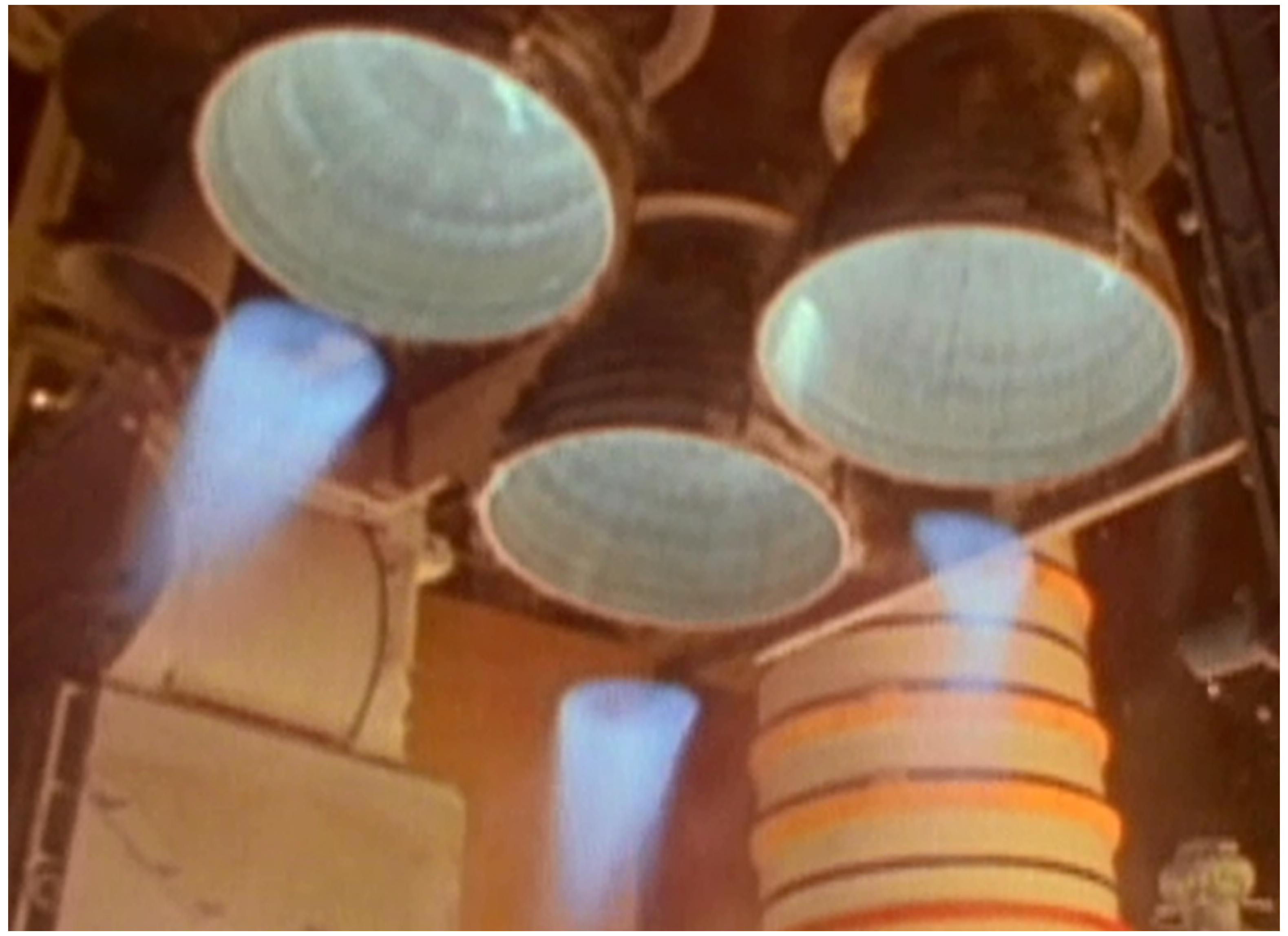
Operating a NASA Great Observatory

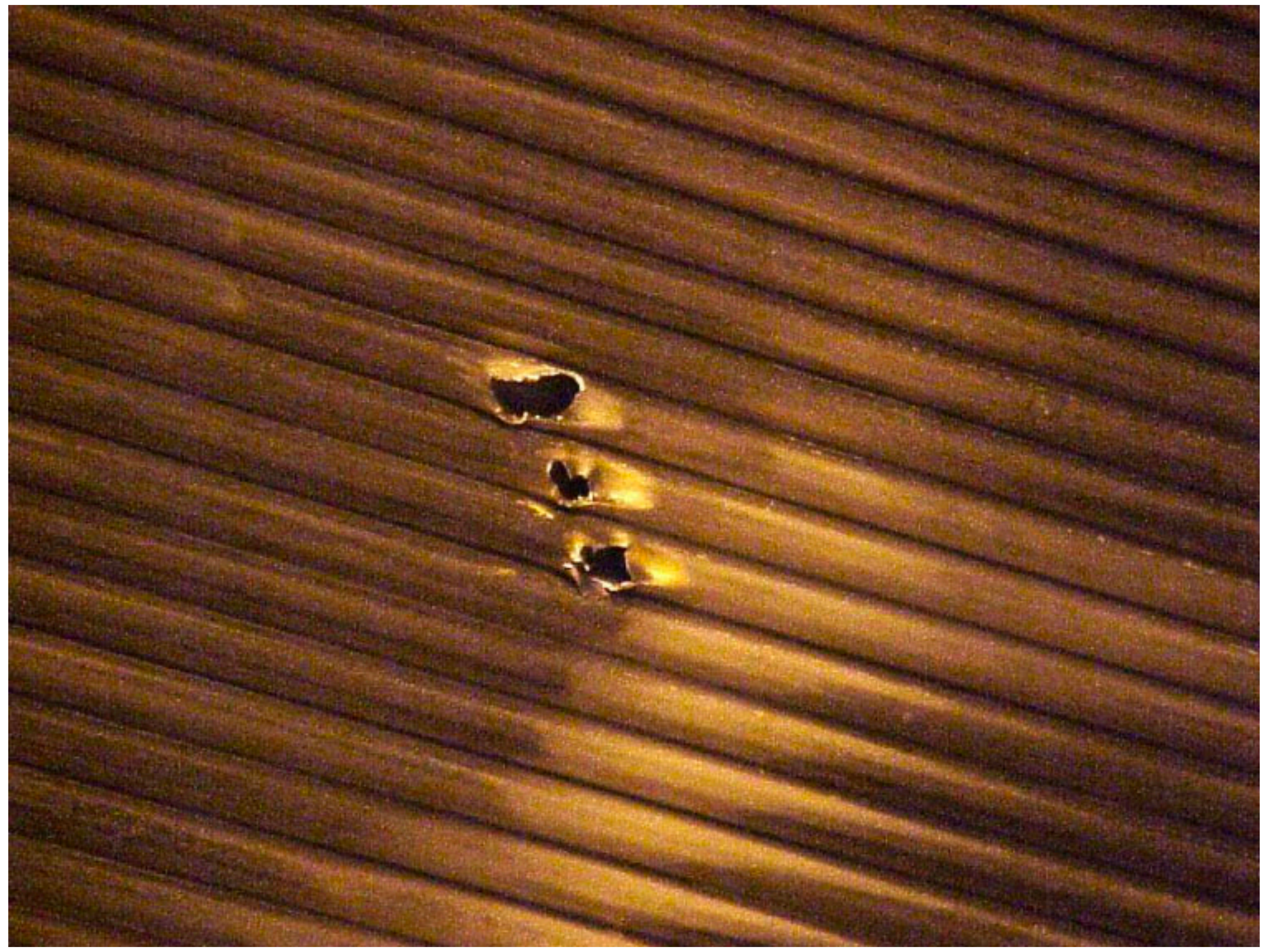
The Chandra X-ray Observatory

Richard Edgar, Smithsonian Astrophysical Observatory (ret). Apr 8, 2021 @ Wind Crest

- Launch narrative, written for the Wind Crest Writers’ group.


USA





The NASA Great Observatories Program

- In the early 1970s NASA decided to fund a series of “Great Observatories” to do astronomy from space in various wavelength bands.
- Four of these spacecraft were flown:
- The Compton Gamma-Ray Observatory
- The Hubble Space Telescope (ultraviolet, optical, near infrared)
- The Chandra X-ray Observatory
- The Spitzer Space Telescope (far infrared)

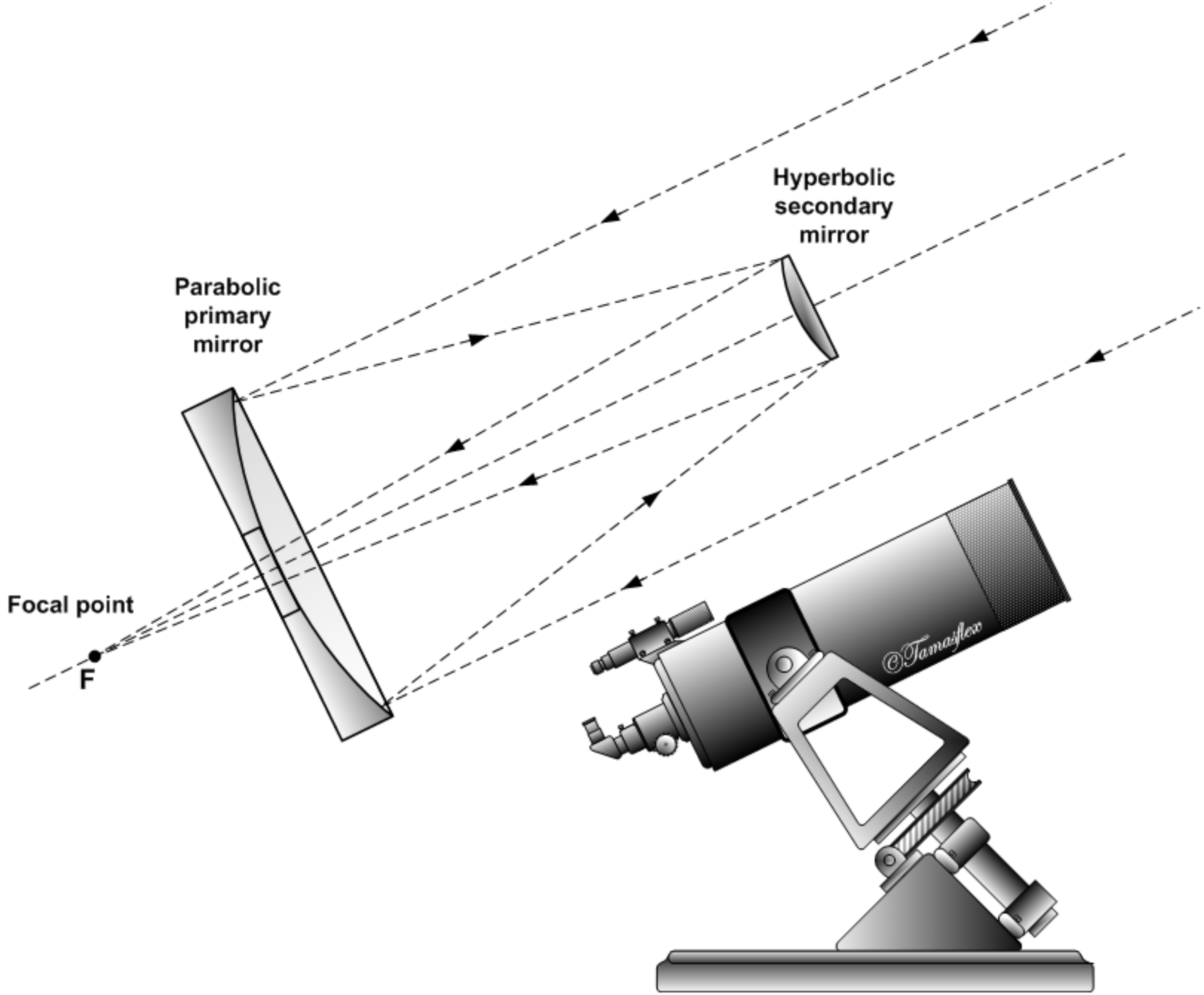

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
100 %
50 %
0 %
Atmospheric opacity
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

Why x-rays?

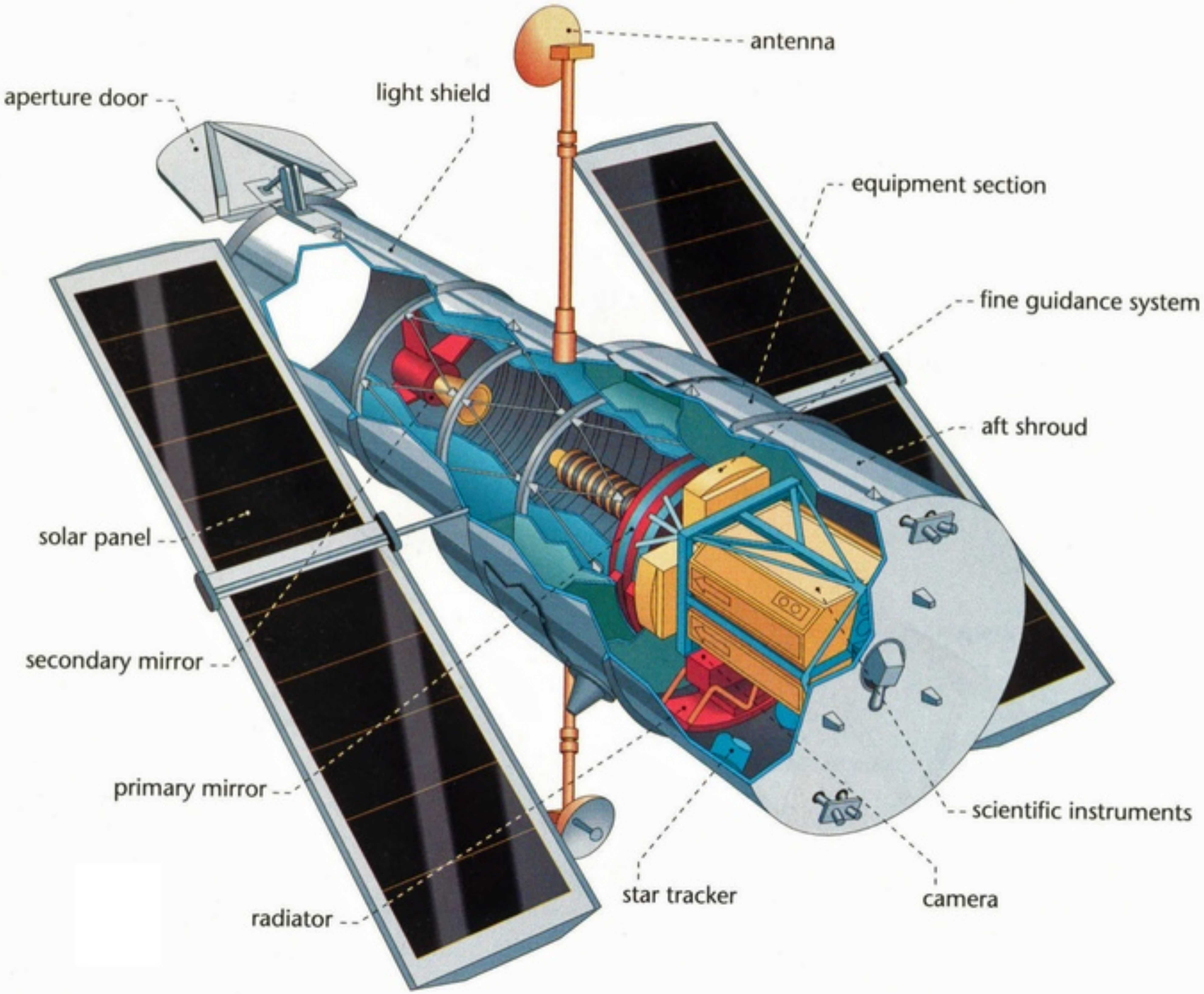
- Short wavelengths (1.2—80 Angstroms, 0.12—8 nm) mean lots of energy per photon, E = hc / wavelength, so ~ 0.15—10 keV per photon.
- At these energies, photons interact with inner-shell electrons in many substances (including the ones in the telescope).
- X-ray photons are emitted by thermal processes in hot gas (T ~ 10^{6-8} K)
- And by non-thermal processes, energetic electrons radiating by various processes (Bremsstrahlung, Synchrotron radiation, Compton scattering, etc.)
- X-rays pass through interstellar clouds more readily than optical light.

Telescope design 101

- In the optical, typically telescopes are of the Cassegrain design.
- A large primary mirror is a paraboloid, which would focus to a point.
- Before the light gets there, it hits a hyperboloid, a convex mirror, which diverts it to a second focus, behind the primary mirror.
- This makes for nice compact telescope design, and cameras or spectrographs can be hung off the back end of the telescope.
- The Hubble Space Telescope is of this type.


Hyperbolic
secondary
mirror
Parabolic
primary
mirror
Focal point
F
©Tamaiflex

HUBBLE SPACE TELESCOPE

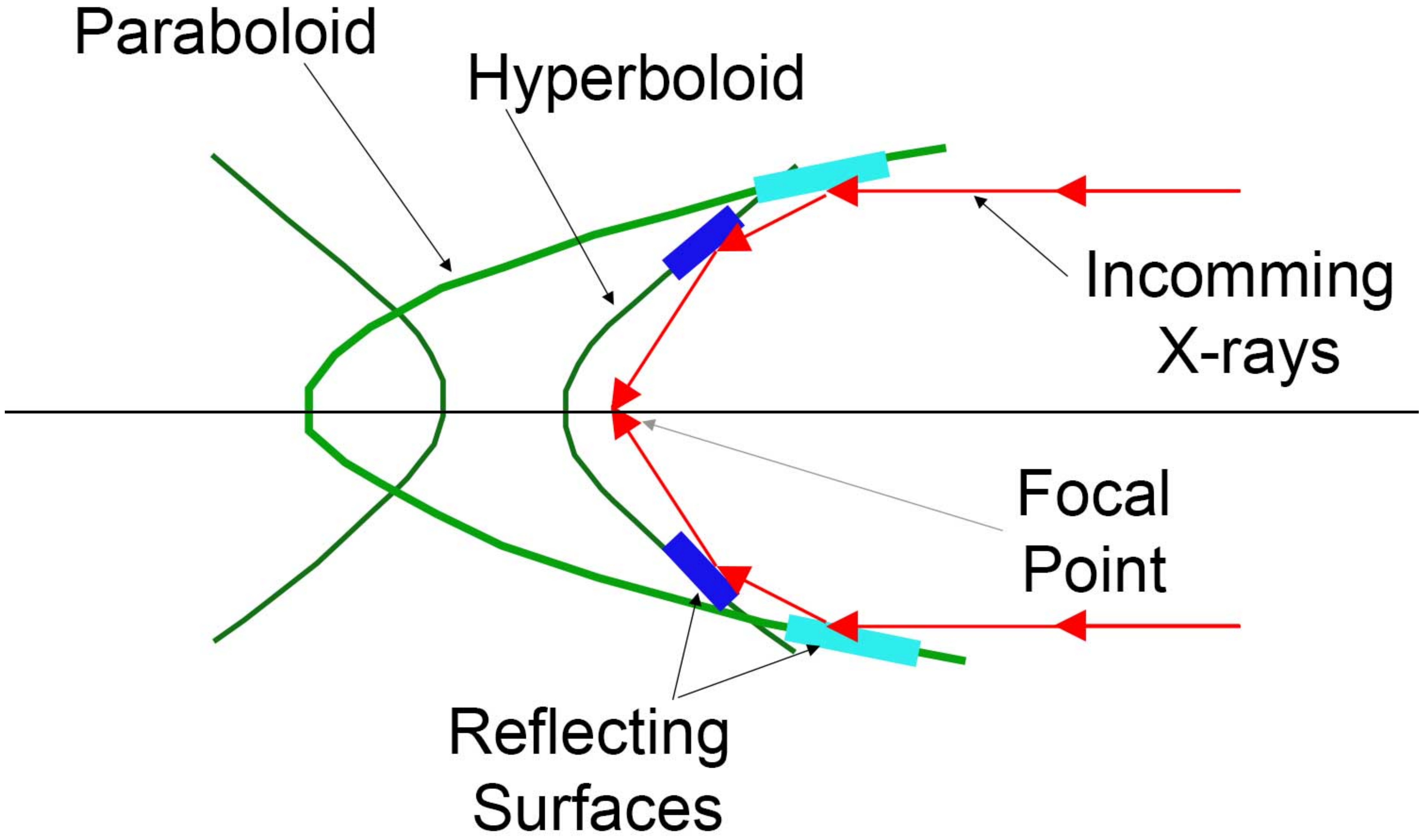


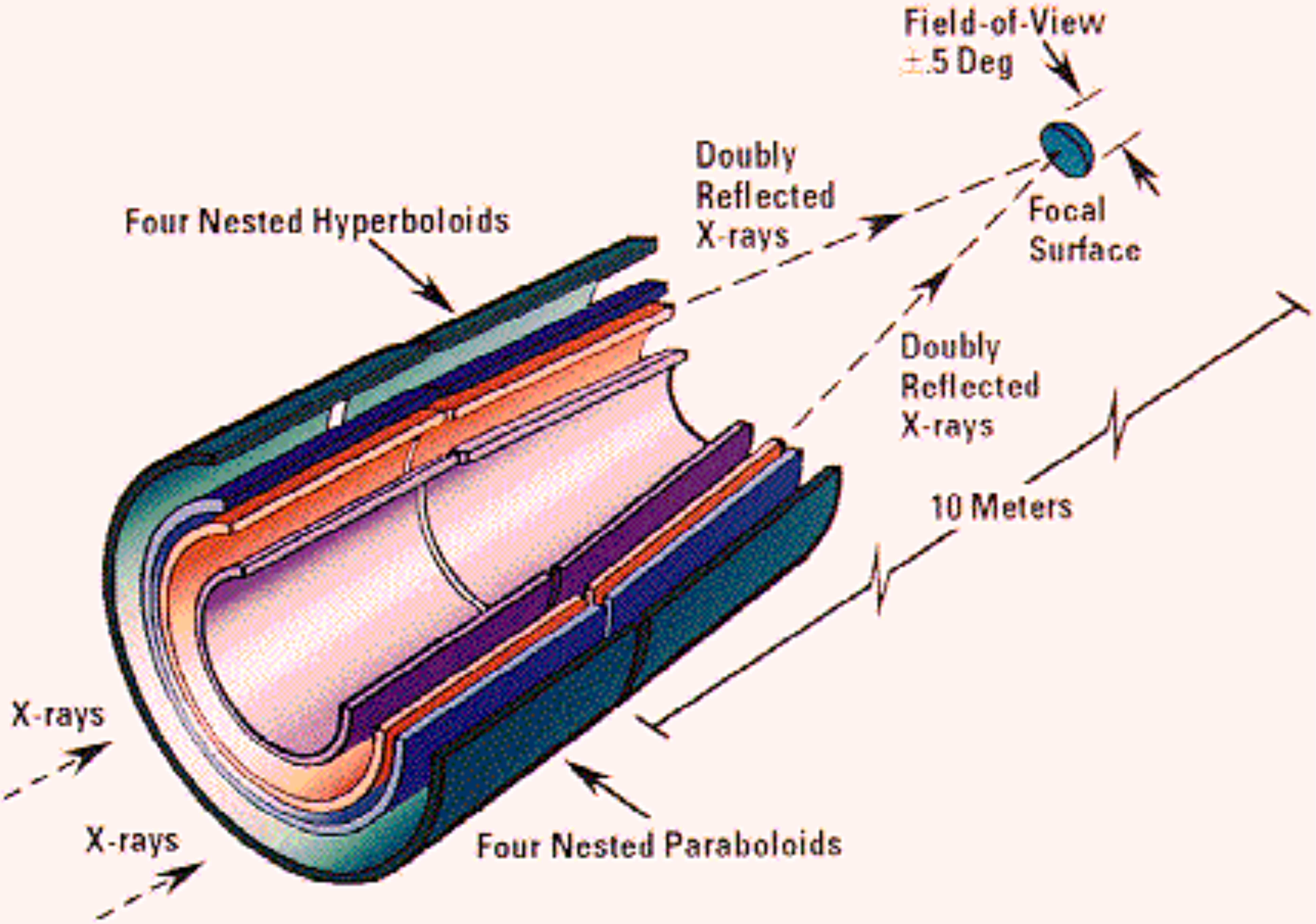
- In x-rays, reflectivity is poor near perpendicular incidence, but reasonable at grazing incidence, where the ray strikes the surface within a few degrees of the tangent plane.

- We like the paraboloid/hyperboloid structure because it makes nice images over a relatively wide field.

- The Wolter Type I design allows us to have both grazing incidence optics and two reflective surfaces.

- Note each mirror shell occupies only a small region of the entrance aperture, so typically they’re nested, with all shells coming to a common focus.


Paraboloid
Hyperboloid
Incomming X-rays
Focal Point
Reflecting Surfaces



Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

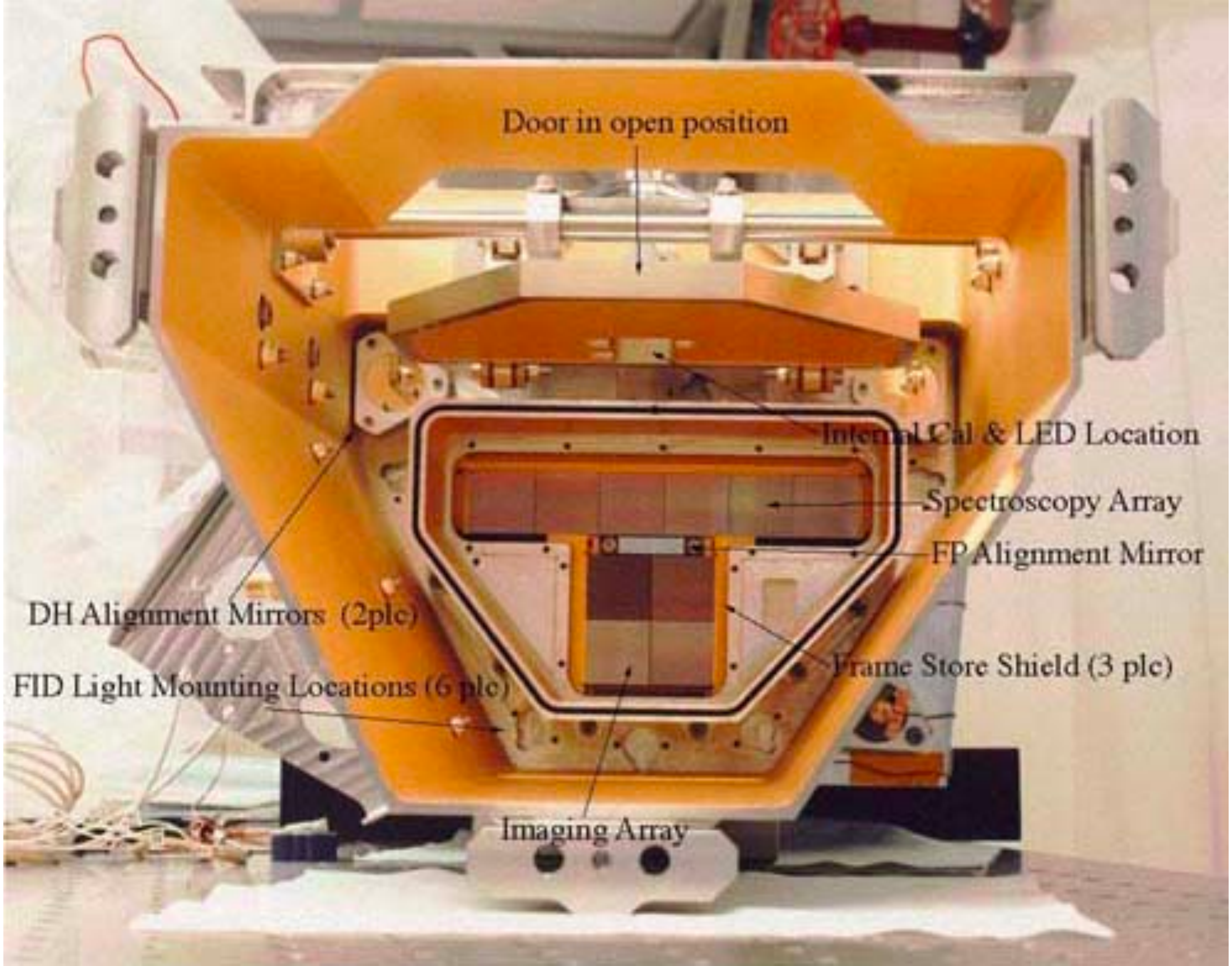
The Chandra X-ray Observatory

- Chandra makes very nice images, with a 0.5 arc second point spread function. This is the best that has been done to date.
- This is comparable to what can be done on a decent night in the optical from the ground (without adaptive optics technology).
- Other operational x-ray telescopes have few arc second to arc minute imaging performance, but other advantages:
  - the ESA X-ray Multiple Mirror (XMM-Newton) has much larger collecting area (catches more x-rays per hour)
  - the NASA Swift mission can slew rapidly to observe transient sources.

ACIS, the prime camera

Advanced CCD Imaging Spectrometer

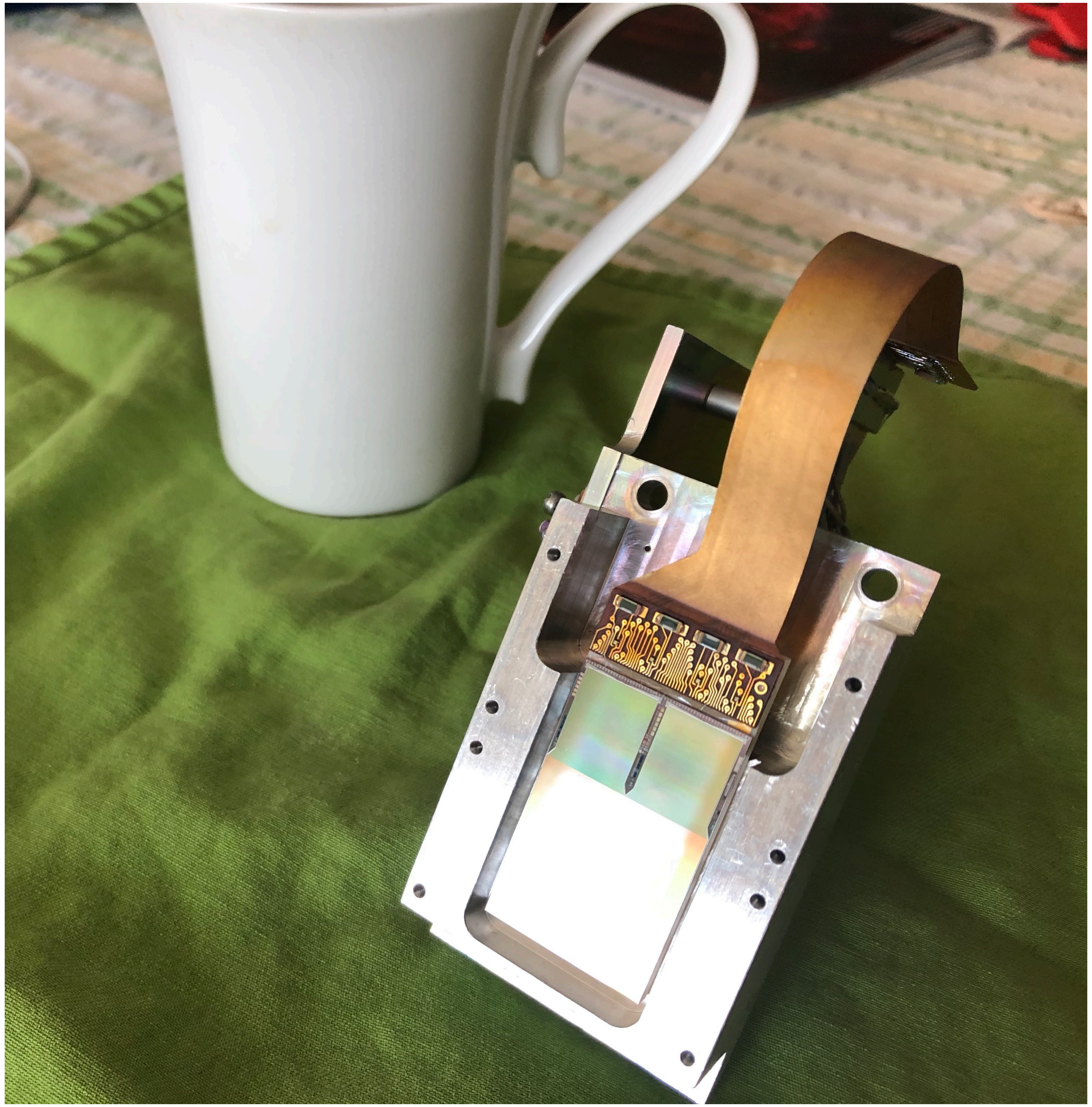
- The prime camera is a CCD camera much like an optical digital camera
- For optical astronomy, the CCD is exposed typically for hours, and read out all at once. Charge collected is related to the number of photons in each pixel.
- In x-rays, we read the CCD out very often (typ. 3.2 sec) hoping that only one photon will hit each 3x3 pixel area. The charge collected is related to the energy of the original x-ray photon.
- CCDs must be kept cold (-120 C = -184 F) and are subject to damage from radiation (solar coronal mass ejections).



Door in open position
Internal Cal & LED Location
Spectroscopy Array
FP Alignment Mirror
DH Alignment Mirrors (2plc)
Frame Store Shield (3 plc)
FID Light Mounting Locations (6 plc)
Imaging Array

Flight-like CCD

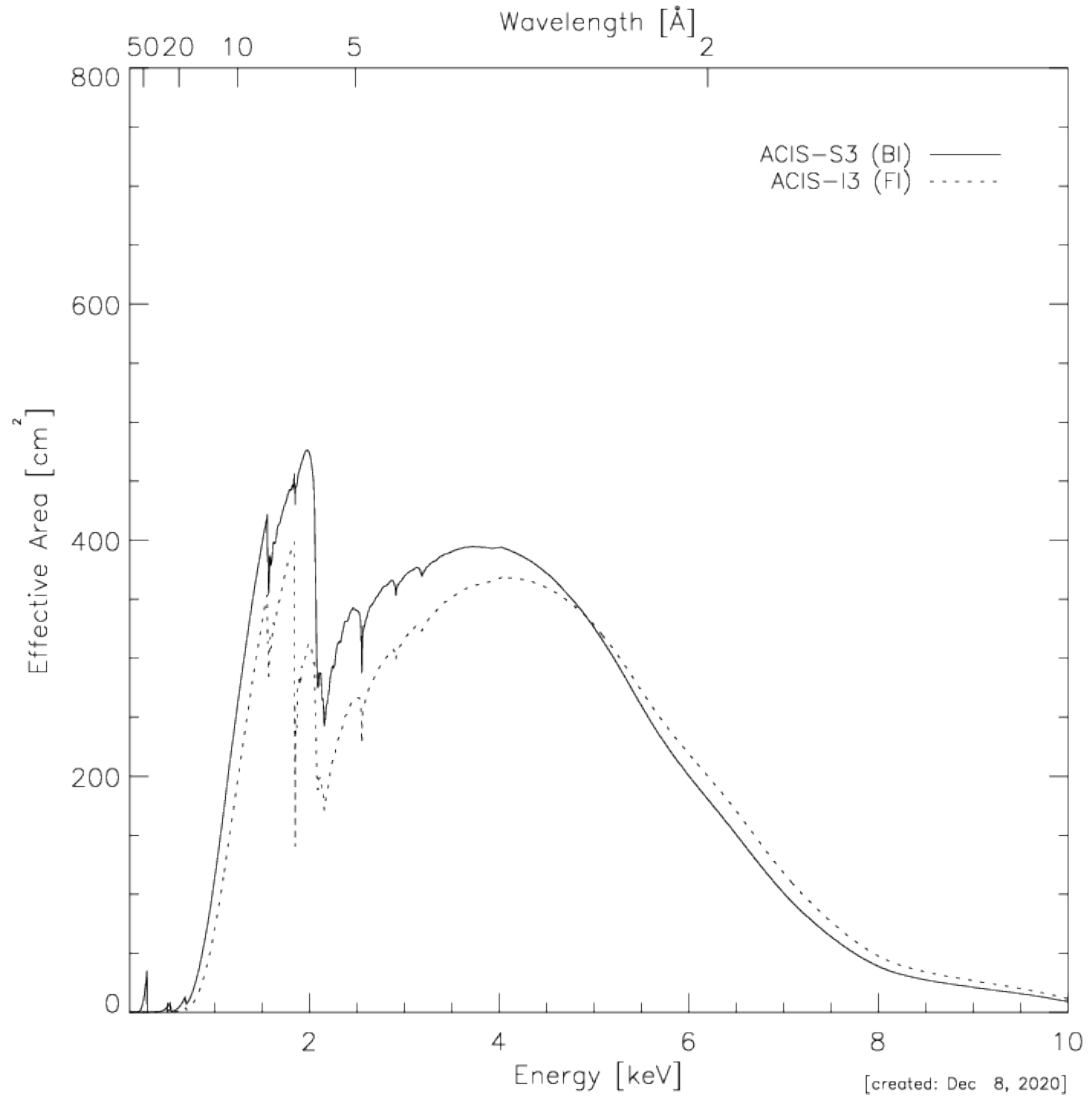
- This CCD came from the flight batch, but flunked testing.
- It was a retirement gift from the MIT instrument team.
- The imaging section (the shiny bit) is about an inch square.
- Those in the room may examine the actual device.

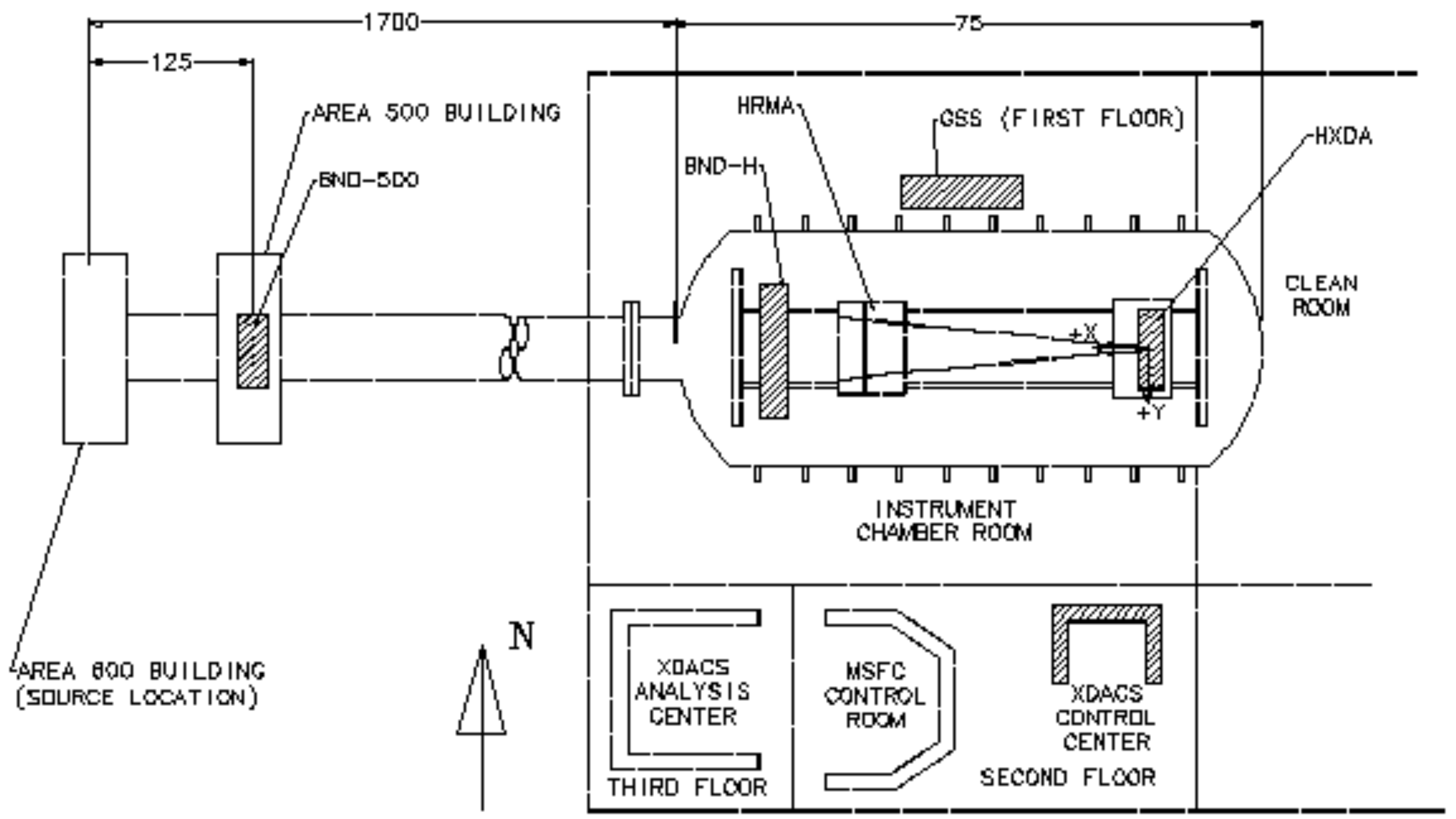



USA

Calibration

- We attempted to calibrate the absolute sensitivity of Chandra to an accuracy of 1%. I believe we achieved about 3%. This is a remarkable accomplishment.
- The mirror assembly and flight cameras were calibrated on the ground at the X-ray Calibration Facility at Marshall Space Flight Center in Huntsville, AL in 1996-97.
- Real x-rays were produced 600 m away and focused by the telescope on an assortment of instruments. Fluxes were measured outside the telescope.
- The calibration validated a sophisticated ray-trace model


Wavelength [Å]
50 20 10 5 2
800
600
400
200
0
Effective Area [cm^2]
ACIS−S3 (BI)
ACIS−I3 (FI)
2 4 6 8 10
Energy [keV]
[created: Dec 8, 2020]


1700
75
125
AREA 500 BUILDING
HRMA
GSS (FIRST FLOOR)
HXDA
BND-H
BND-500
CLEAN ROOM
+X
+Y
INSTRUMENT CHAMBER ROOM
AREA 600 BUILDING (SOURCE LOCATION)
N
XDACS ANALYSIS CENTER
THIRD FLOOR
MSFC CONTROL ROOM
XDACS CONTROL CENTER
SECOND FLOOR

Life Cycle of a Chandra Observation

Using Cassiopeia A as an example.

- Scientist has idea. “Hey, we know this supernova remnant emits x-rays, let’s get a really high resolution image. Also it’s young, maybe we can watch it expanding by coming back in 10 years.”

- They write a proposal. Typically Chandra time is oversubscribed by a factor of about seven, so use your 4—6 pages wisely.

- Proposals are gathered by the Chandra X-ray Center, in Cambridge, MA.

- They are assessed for feasibility, safety, etc. by the staff. Cas A is bright, so we looked at how the ACIS camera was to be operated.

- The proposals are peer-reviewed. About 200 x-ray astronomers are gathered in the Boston airport hotel and spend a week picking the best proposals. Roughly one in seven are selected.
- Scientists are notified of results.
- Observing parameters are extracted from the proposal database and massaged into the Observation Catalog. Setup is verified by the observers.
- Mission Planning picks proposals (far from sun, good thermal properties, any time constraints) and makes a Short Term Schedule, which is then reviewed by all subsystems, including the camera science team.
- The weekly command load is uplinked to Chandra via the Deep Space Network (DSN).

- At the scheduled time, the telescope points at the target coordinates and starts the camera running.

- The CCD (charge-coupled device) at the focal point reads out every 3.2 seconds, and the electronics digitize the image, locate the “events” and pack them into the telemetry buffer.

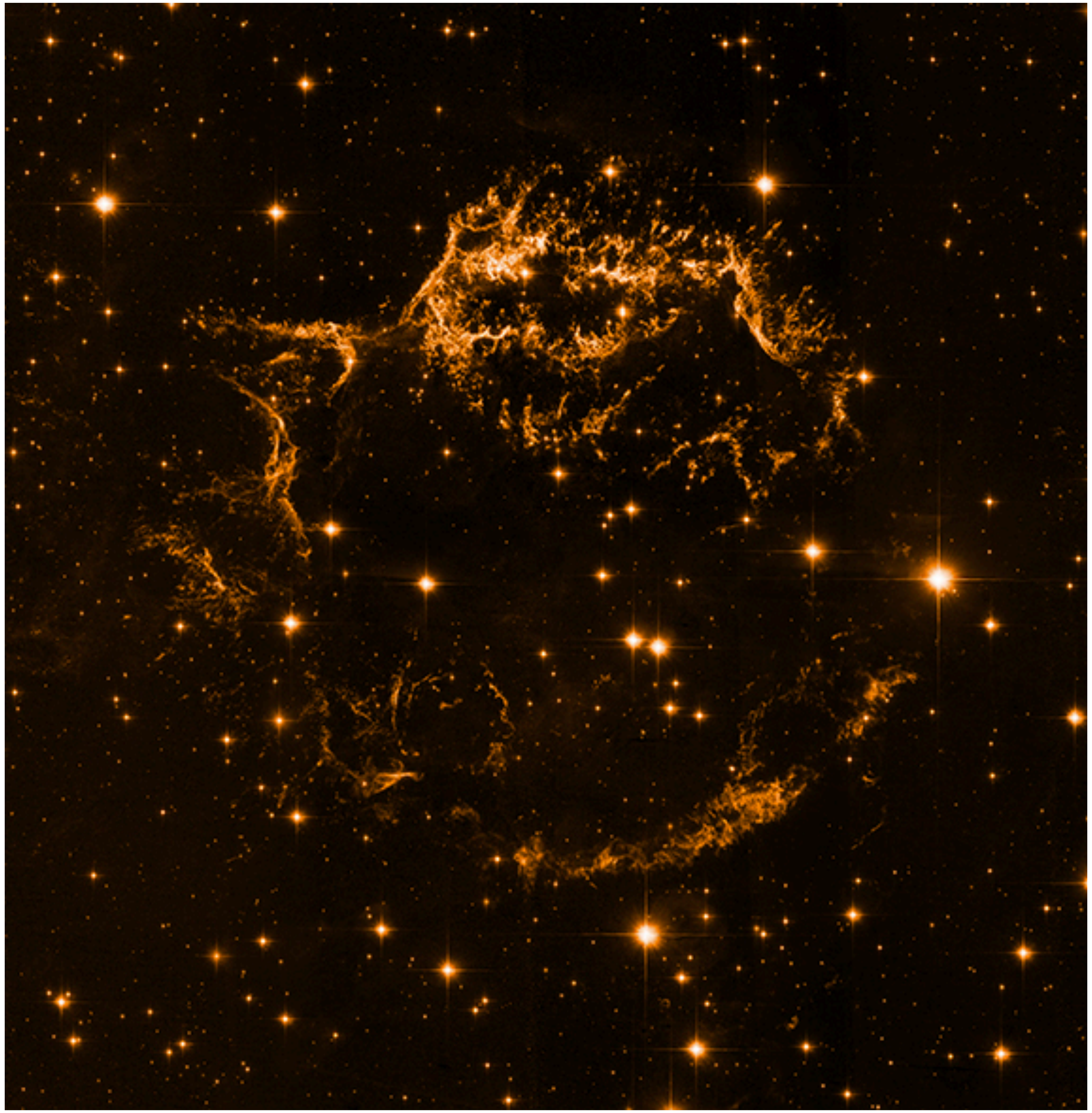
- At a subsequent DSN contact, the on-board solid-state recorder is played back, the data are sliced and diced and archived, and sent to the observer.

- The basic data product is an “event list” with coordinates, total charge in the event, arrival time, etc. for each event.

- These can be used to make spectra (histogram vs. energy) or images (2D histogram vs. sky coordinates).

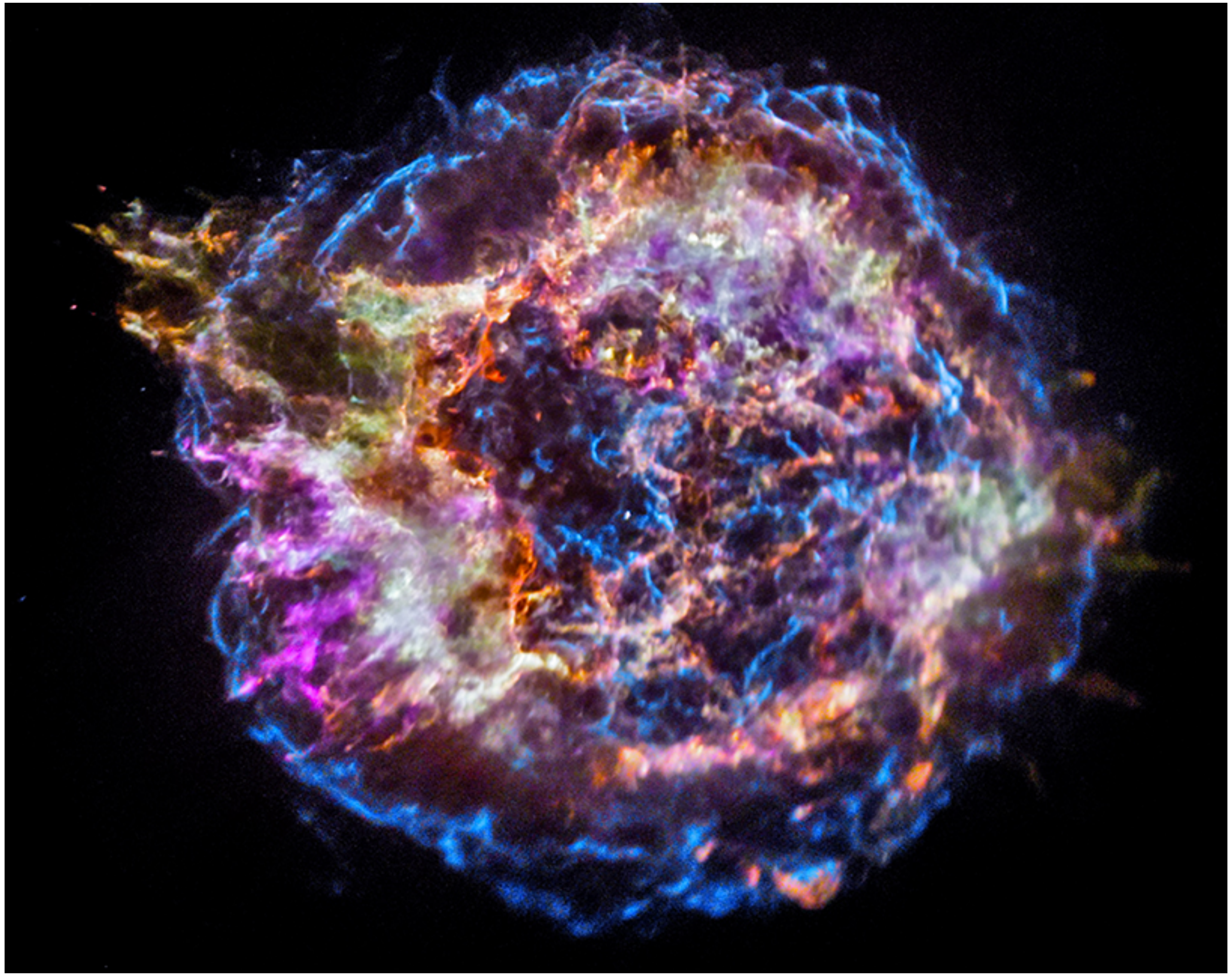
Cas A

the optical image



Cas A

The Chandra X-ray Image

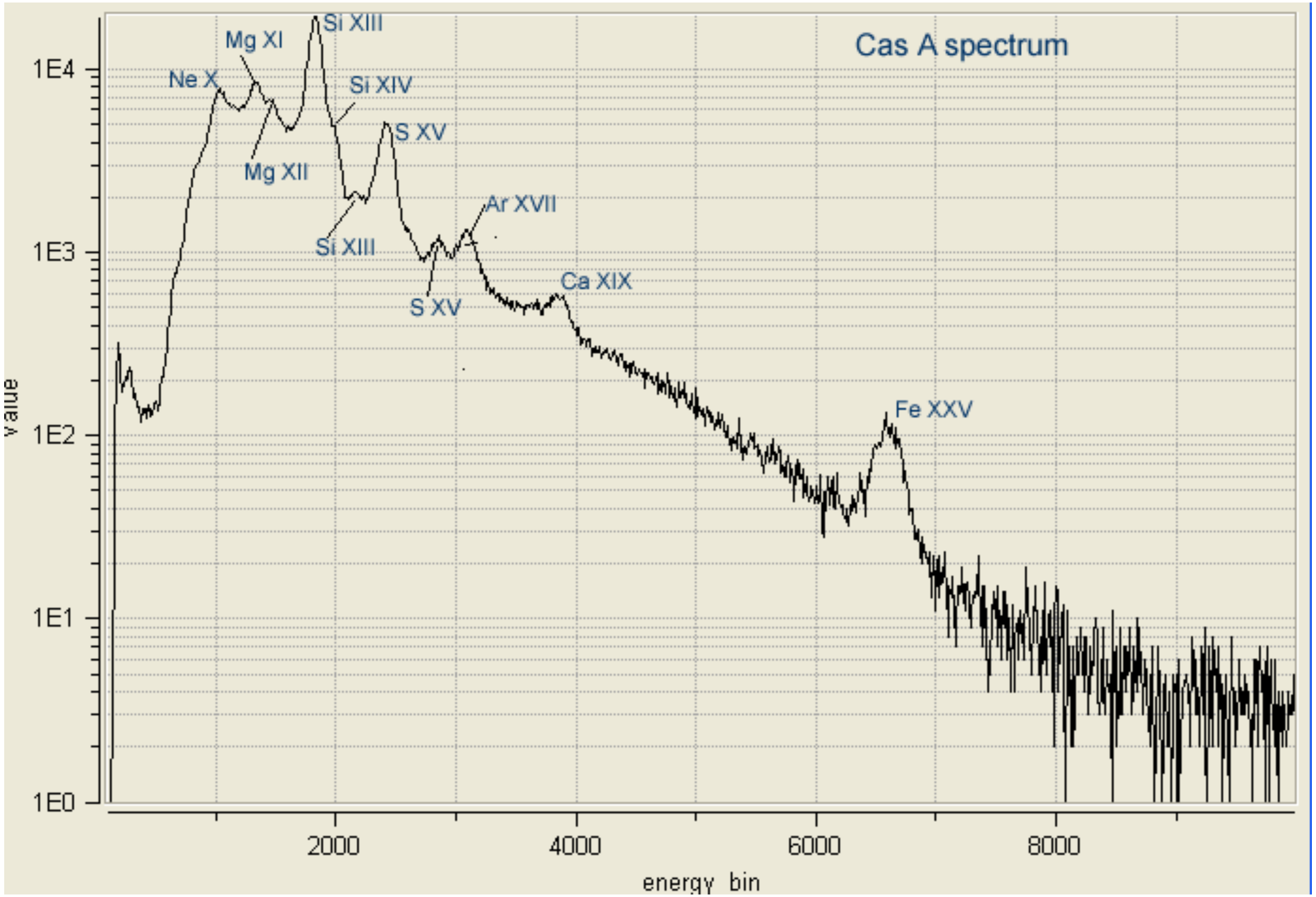


Cas A

- Note the wealth of fine detail.
- The colors represent what element from the supernova ejecta we’re seeing
- This is done by selecting energy ranges from the spectrum (histogram of number of events vs. photon energy), and making separate images in each spectral line.

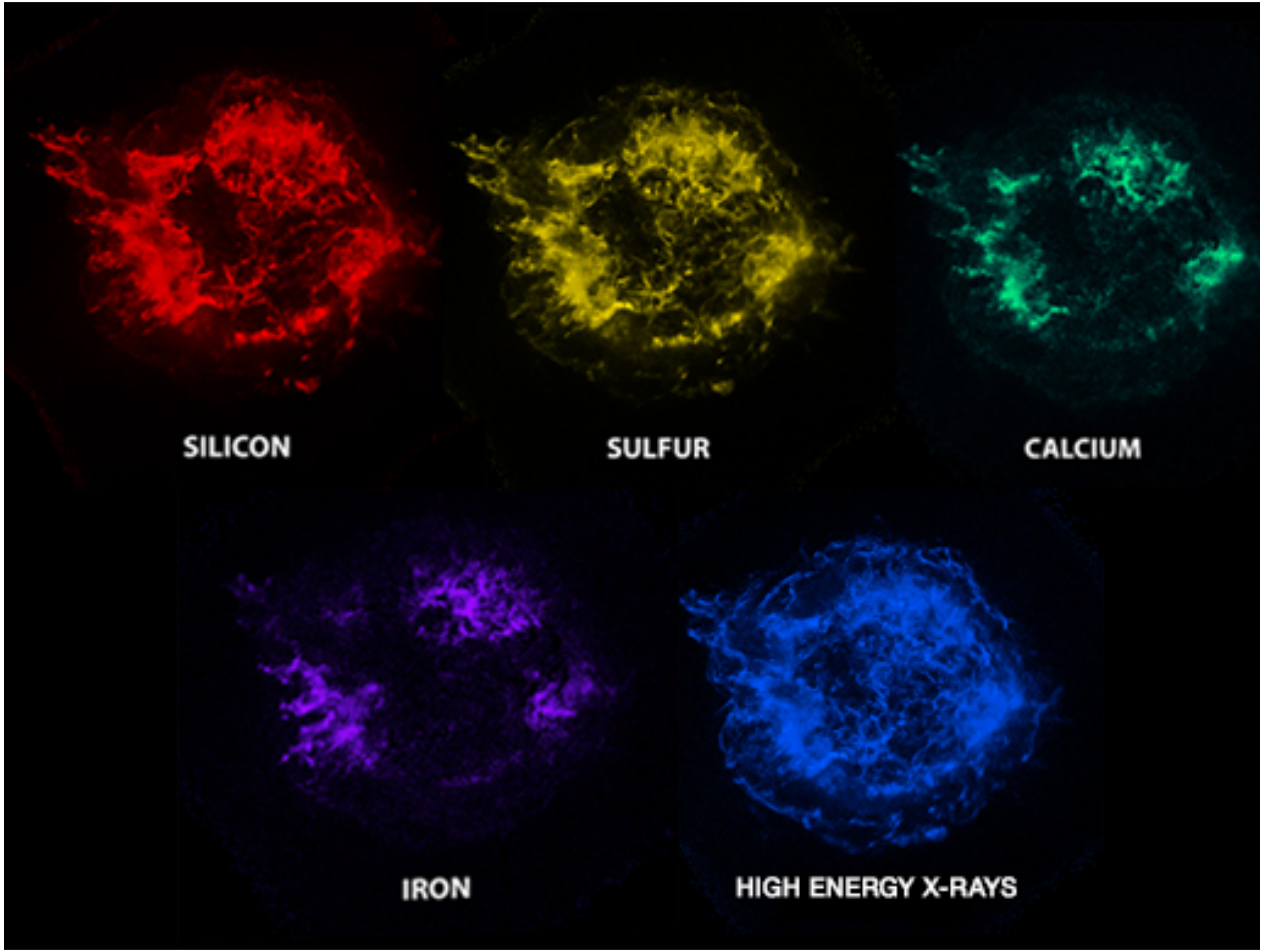
Cas A

The x-ray spectrum



Cas A

one element at a time



Operations

- The ACIS operations group consists of five scientists. Each is on call one week in four or five, and responsible for the instrument, planning future week's camera operations, monitoring real-time communications passes, and everything else.

- The following is a day-in-the-life narrative I wrote up for the Wind Crest Writers' Group. In the six years I worked operations, we had perhaps two dozen anomalies of various kinds.