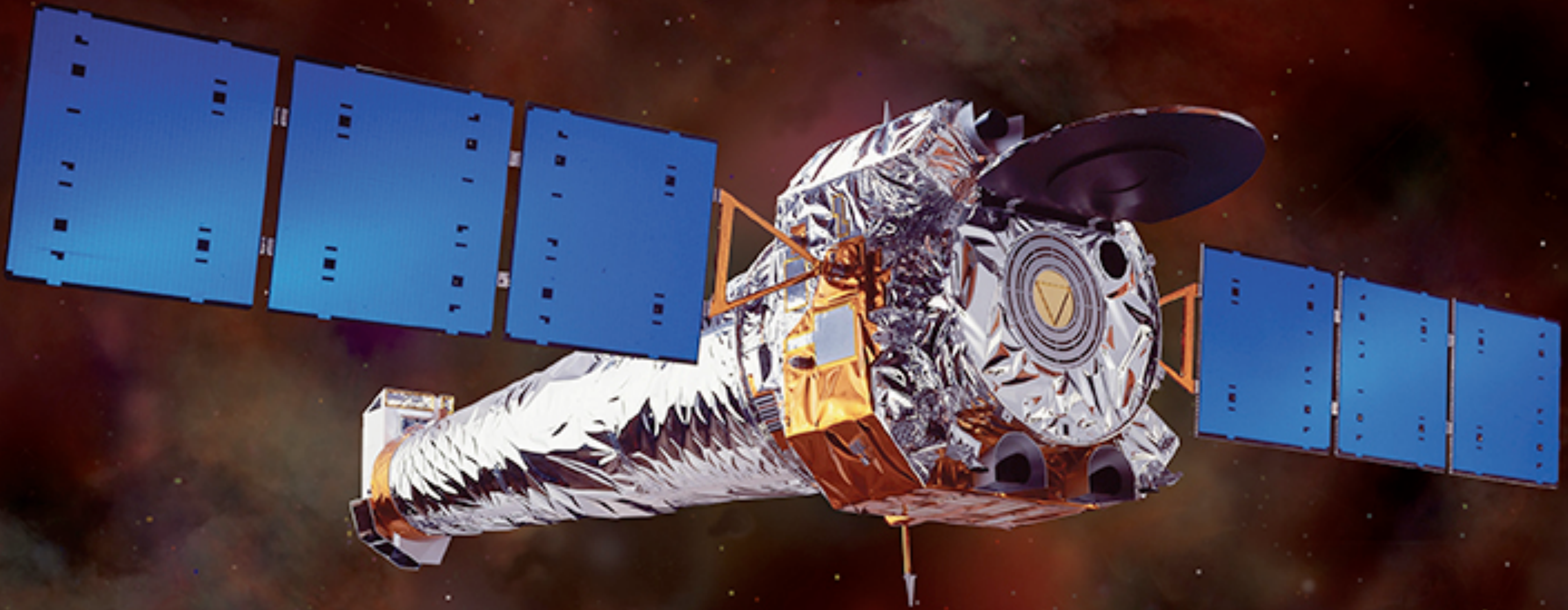
The Chandra X-ray Observatory

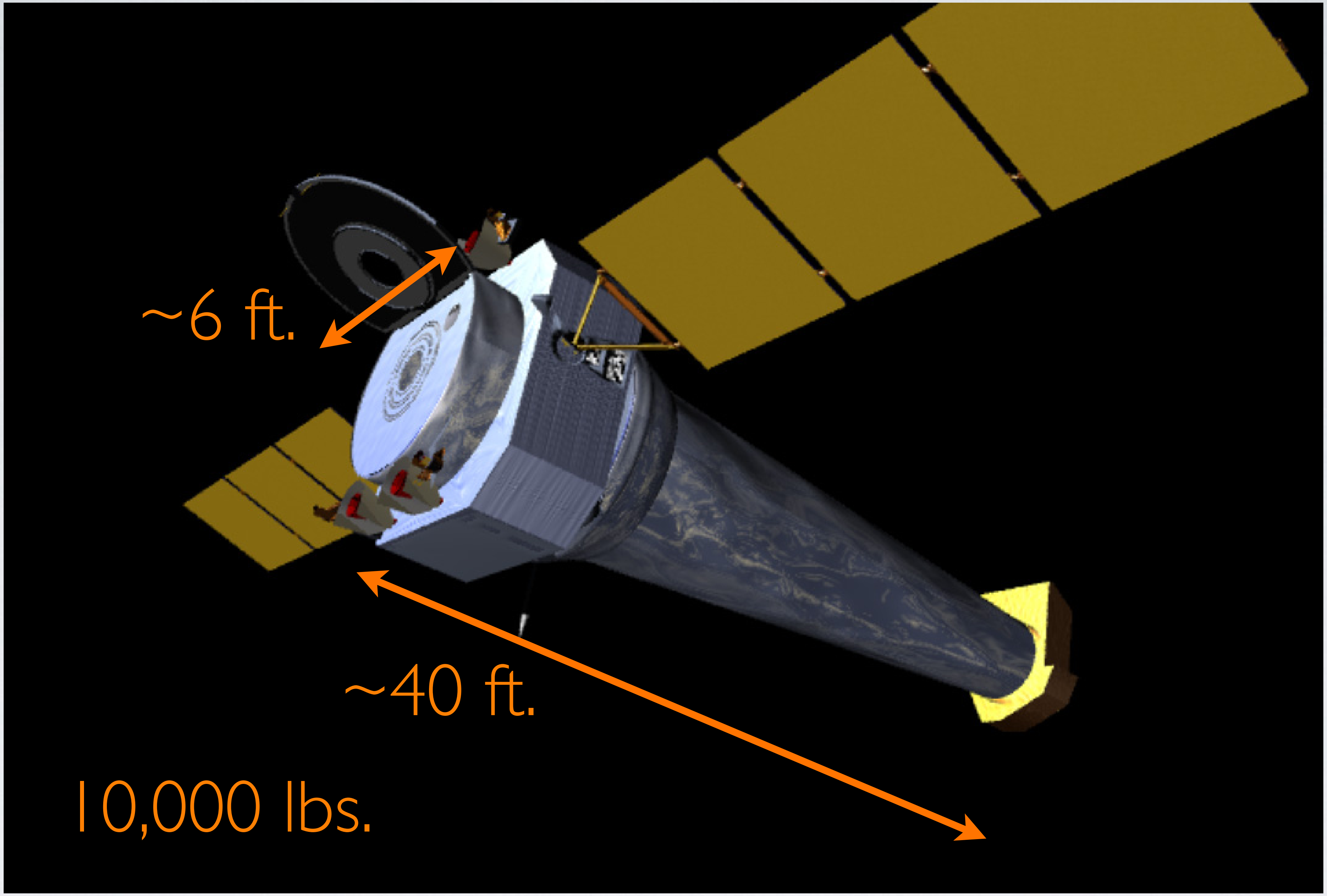


Instruments and Operations

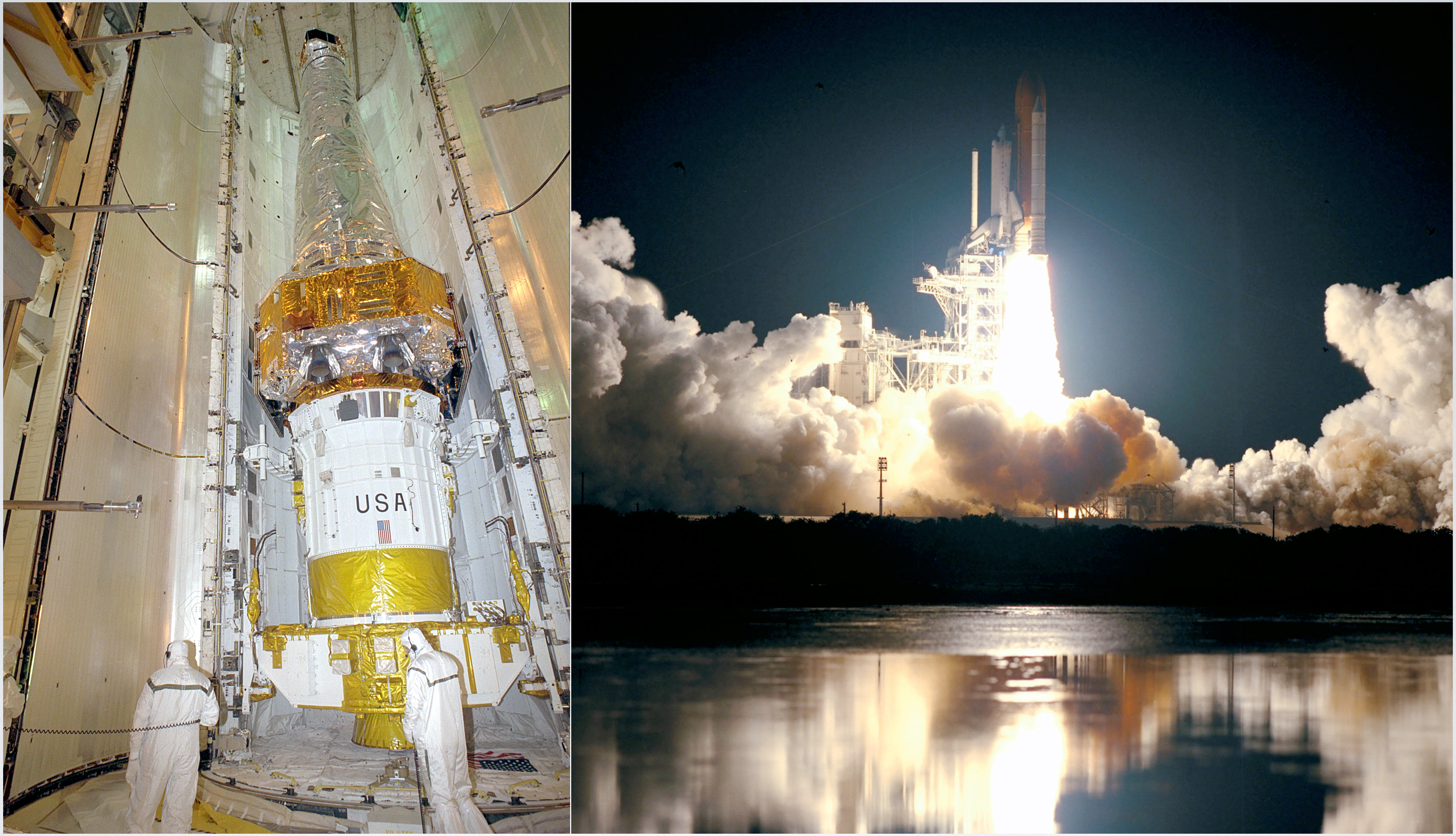
Dr. Michael Nowak
Chandra X-ray Science Center

UNIQUE CHANDRA ATTRIBUTES:

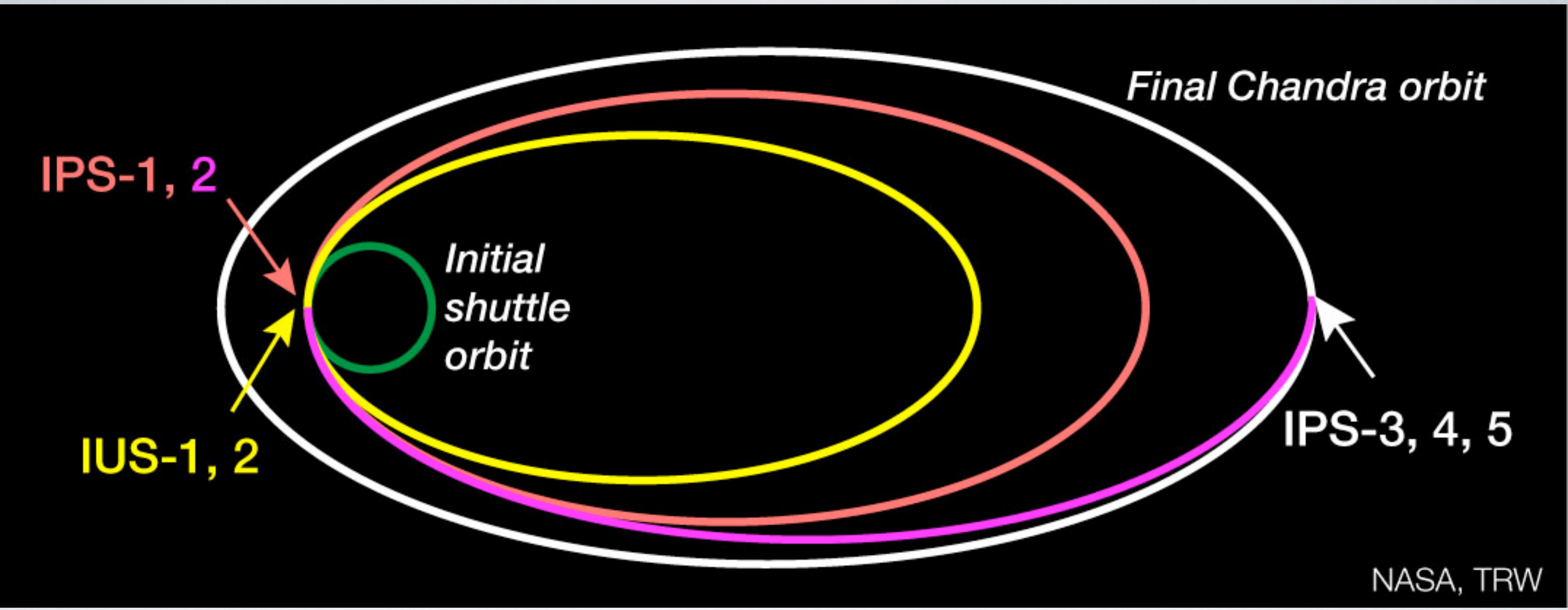
- Best Spatial Resolution of Any X-ray Satellite
  - ~1" (Hubble ~0.1", next best X-ray satellite, XMM-Newton ~10", ROSAT ~5")
  - This is coupled with good energy range & resolution – we view 300 eV – 9 keV, E/**Δ**E ~5 – 40
- Best Energy Resolution (Gratings) of Any X-ray Satellite
  - E/**Δ**E ~1400 – 200 (Radio & Hubble ~20,000, next best X-ray satellite, XMM-Newton ~ 500 – 40)
- Largest Dynamic Flux Range of Any Satellite Ever Flown: 11 Orders of Magntiude; 10^{-18} – 10^{-7} erg cm^{-2} s^{-1}



LARGEST SATELLITE LAUNCHED BY SPACE SHUTTLE: JULY 23, 1999 – 2030 (?)



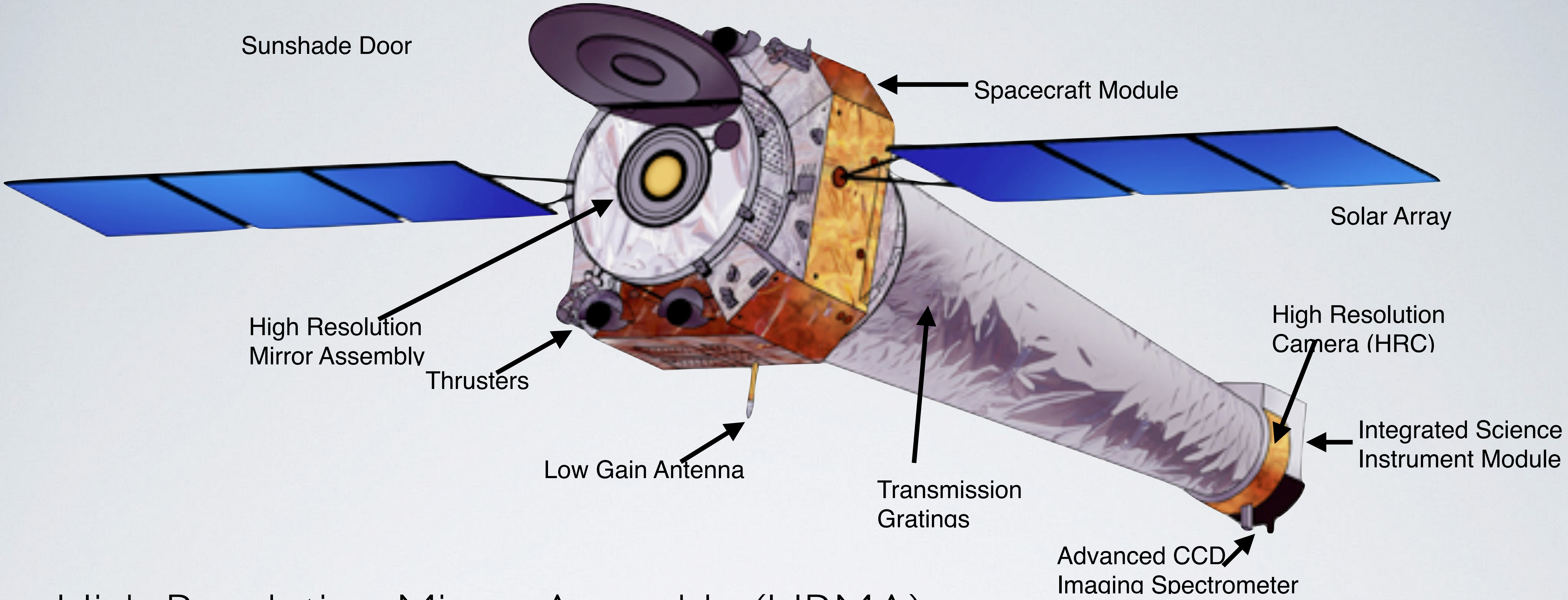
BOOSTED INTO ELLIPTICAL ORBIT: 229 KSEC=63.5 HOURS



CONTINUOUS OBSERVATIONS AS LONG AS 170 KSEC

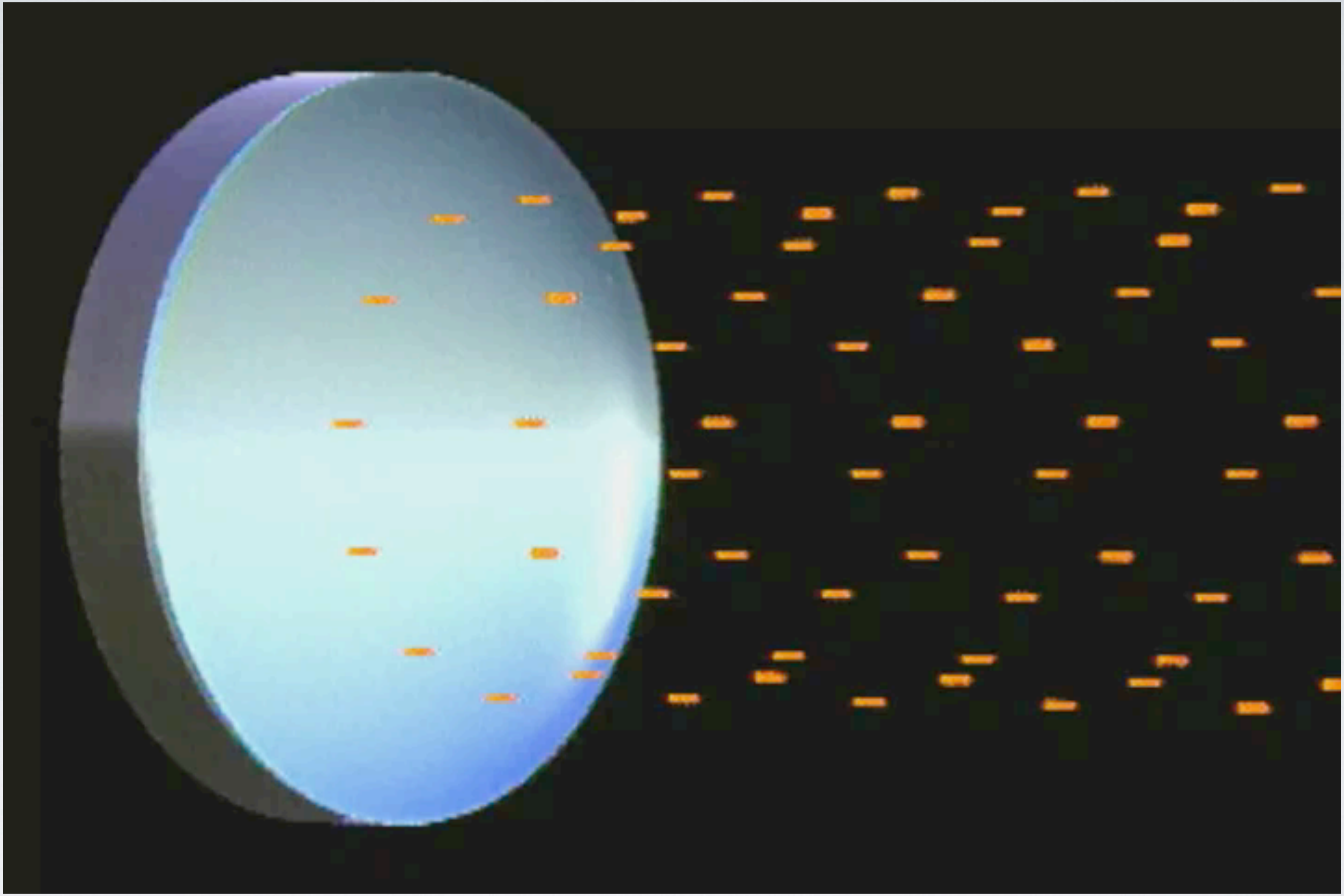
IN PRACTICE, USUALLY SHORTER

($\lesssim$20 KSEC, EASY TO DO)

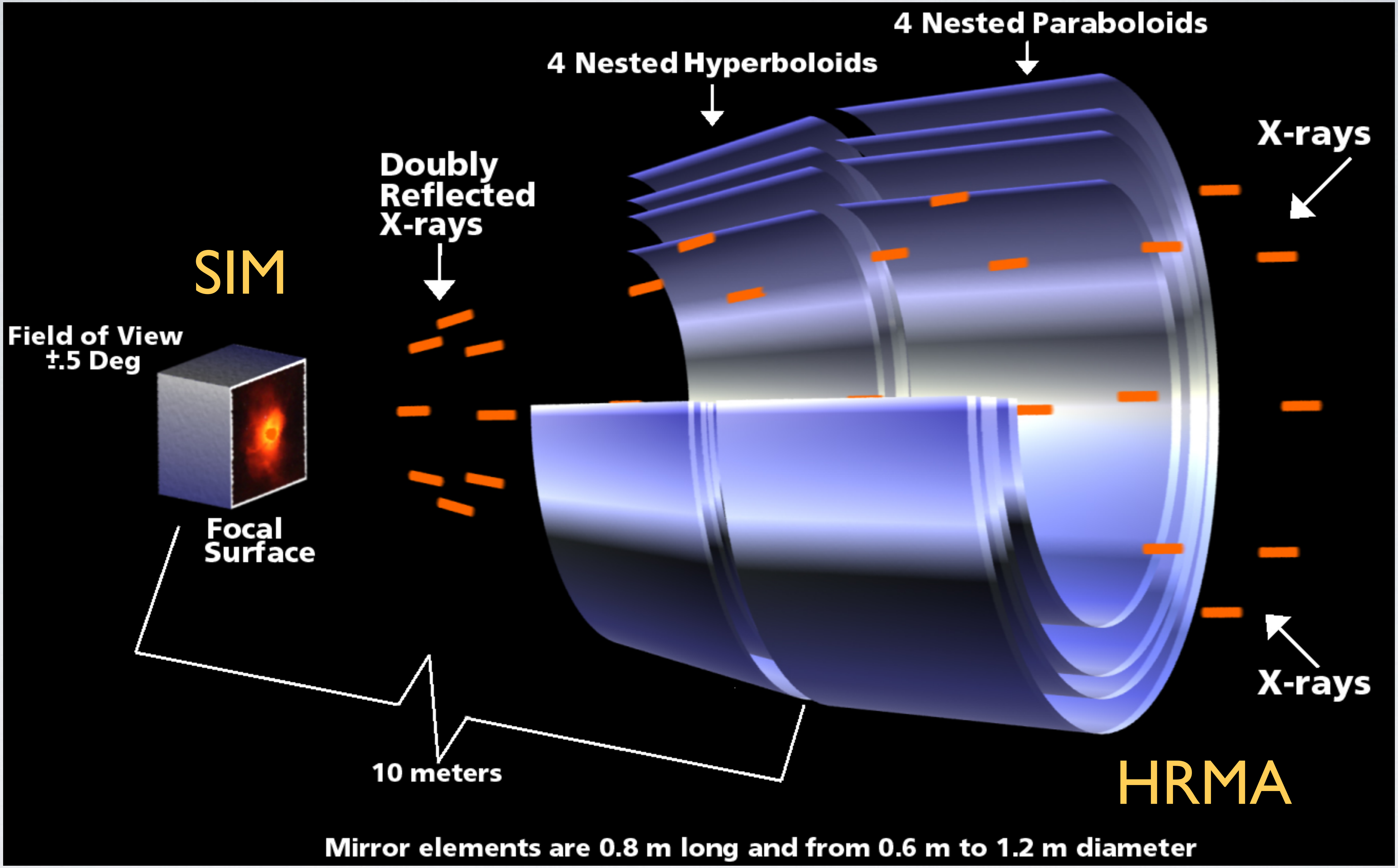


- High Resolution Mirror Assembly (HRMA)
- Scientific Instrument Module (SIM)
  - Advanced CCD Imaging Spectrometer (ACIS)
  - High Resolution Camera (HRC)
- Transmission Gratings: HETG and LETG

- ACIS-S, ACIS-I Imaging
- HETG/ACIS-S, LETG/ACIS-S
- HRC-I/-S Imaging & Timing
- LETG/HRC-S



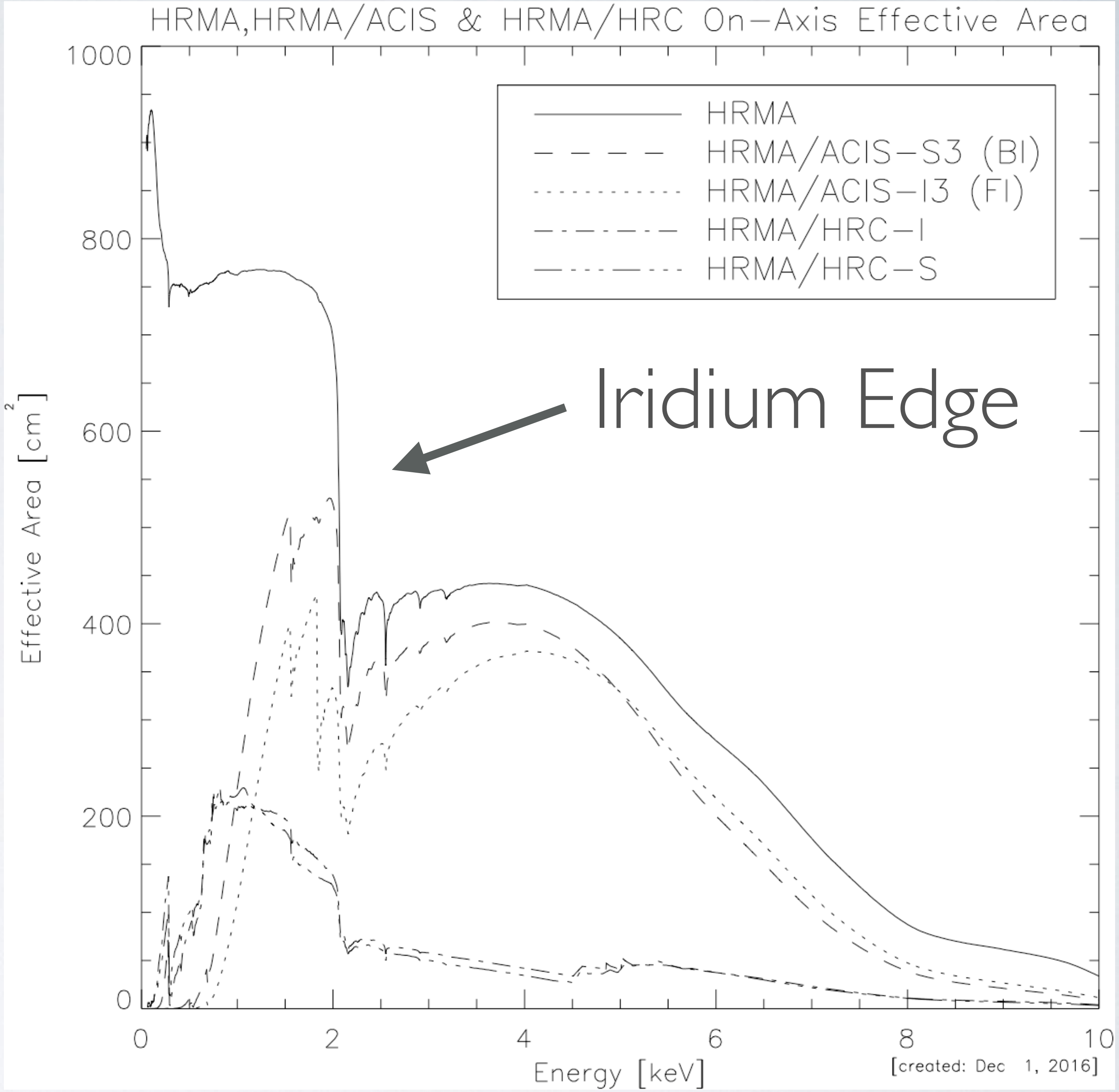
CHANDRA MIRRORS



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

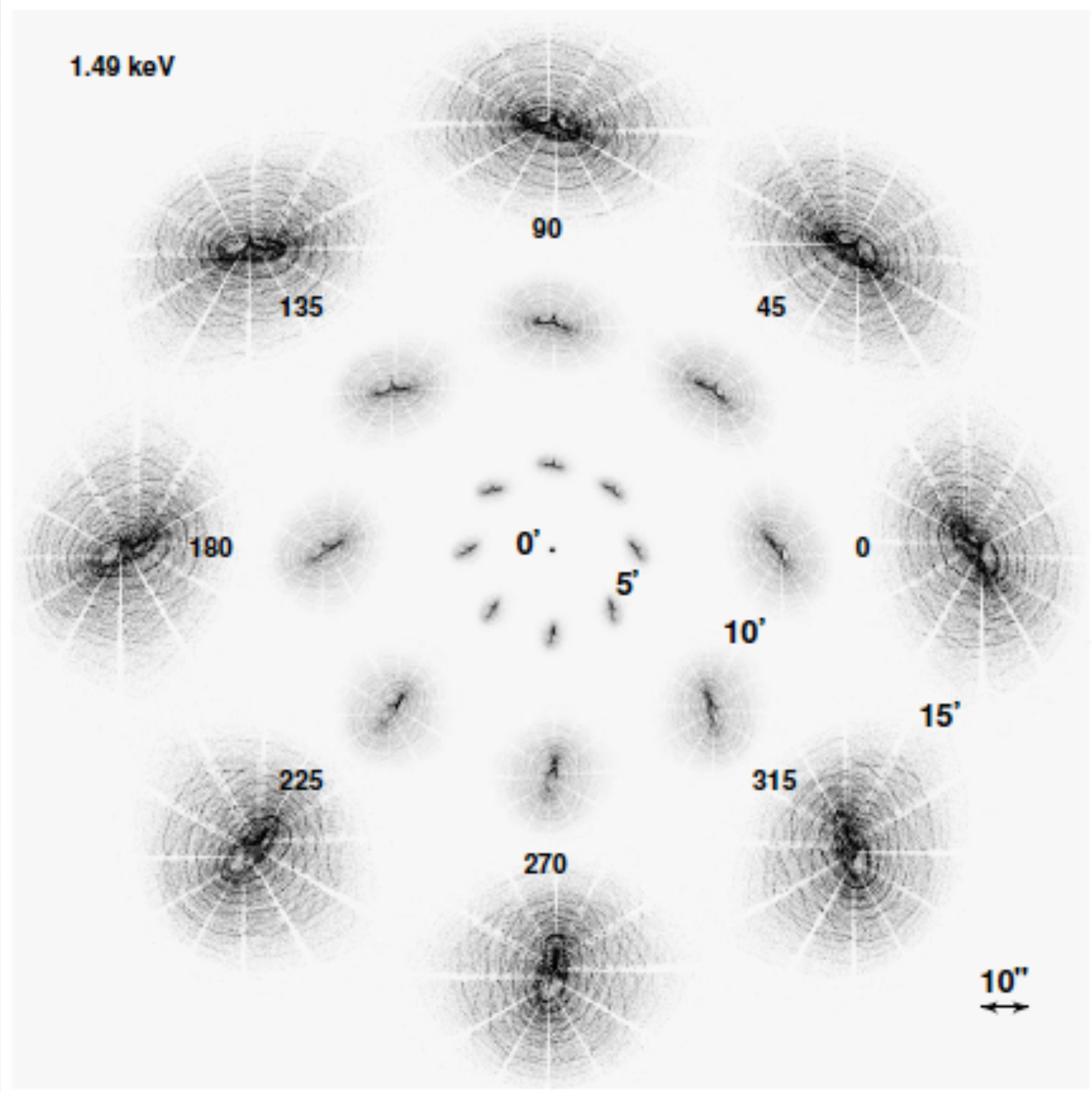
WOLTER TYPE I – SHORTENS FOCAL LENGTH

- Low Angle for Full Reflection
- Small Effective Area
  - Nested Mirrors
- Reflectivity exhibits atomic edge features of mirror materials
- Point Spread Function has strong dependence on angle & energy

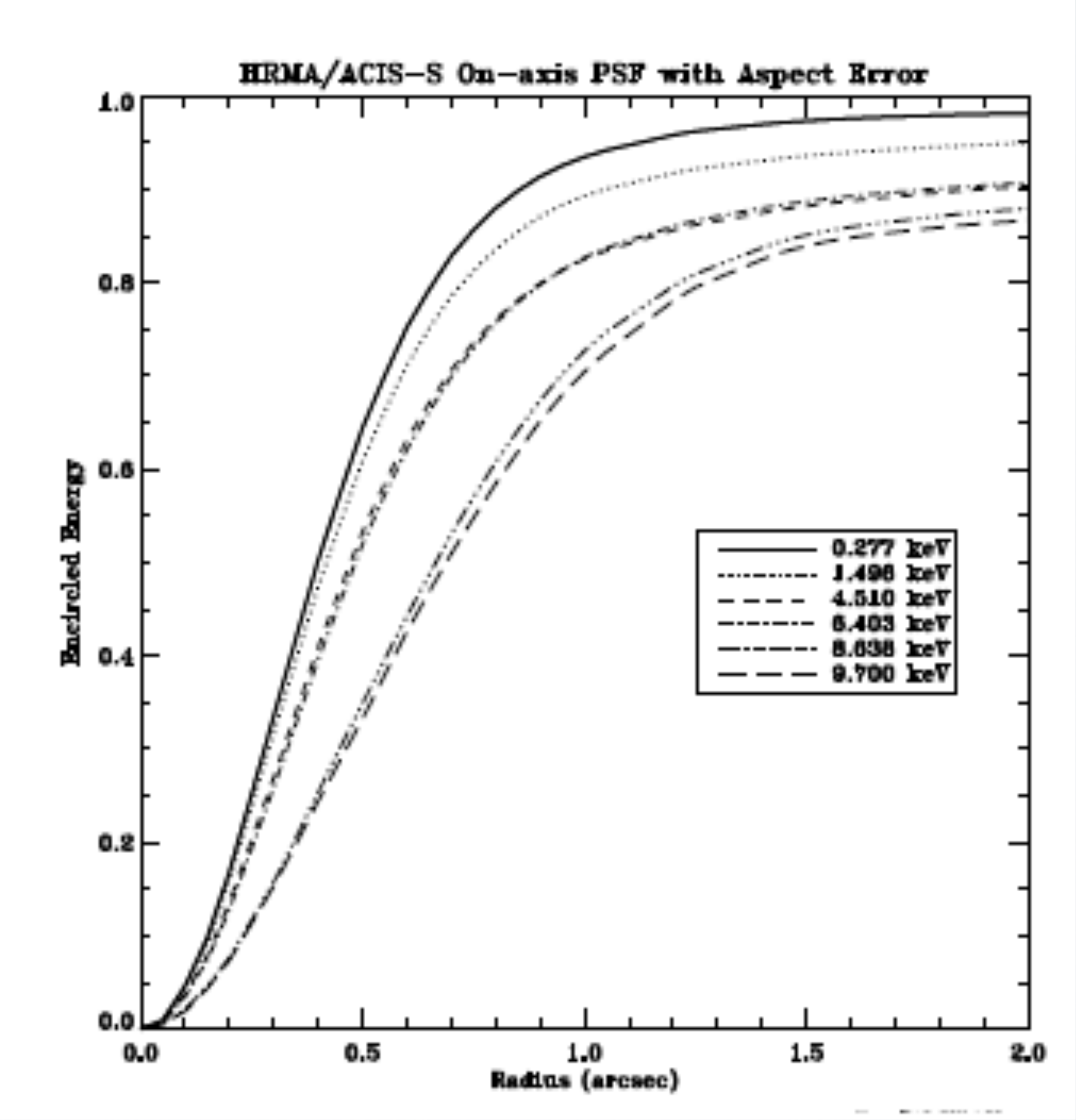


Iridium Edge

HRMA Effective Area vs. Energy (with & without instruments)

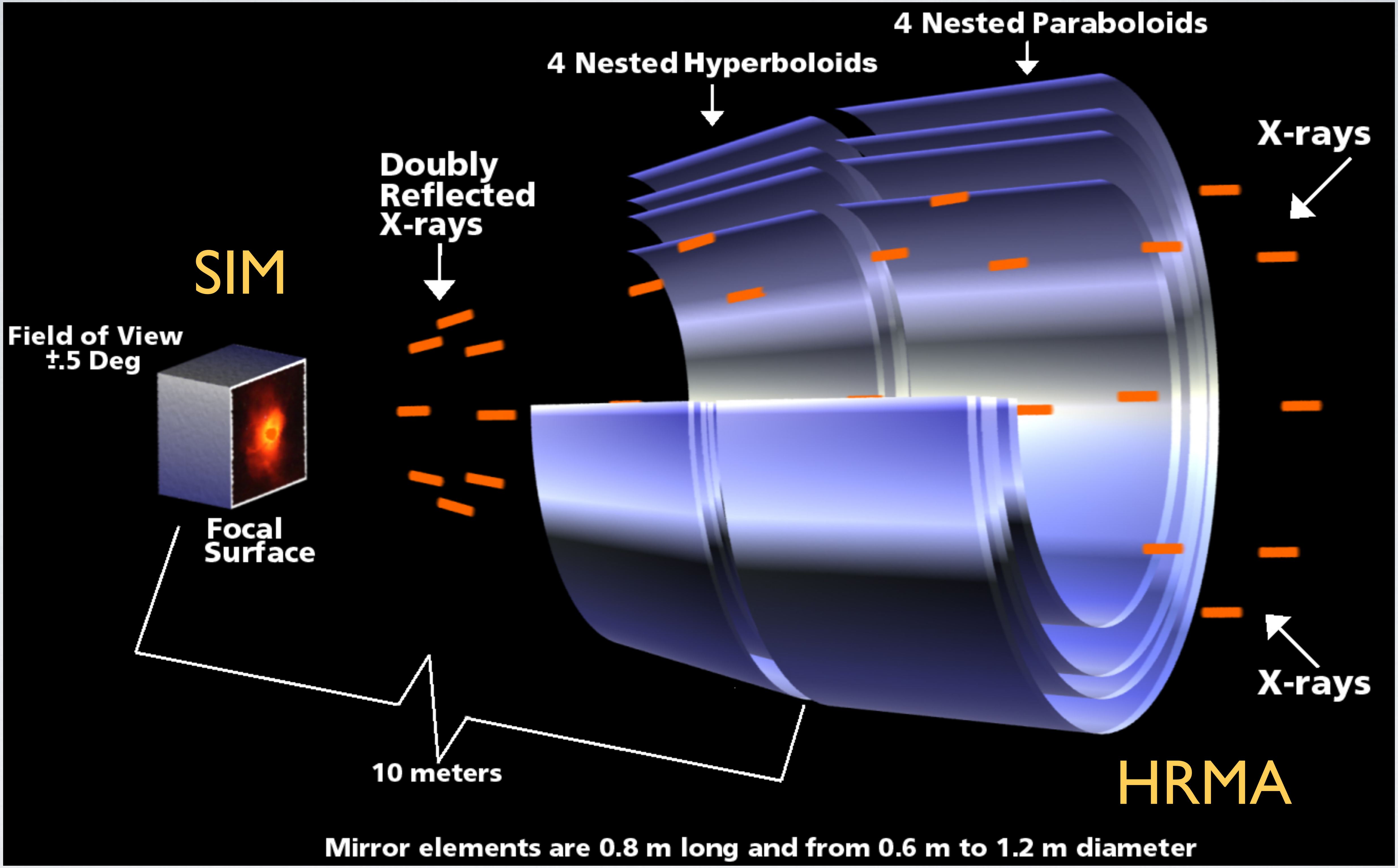


Chandra Point Spread Function



Chandra Encircled Energy Fraction

Chandra Spectrum Changes Depends Upon Detector Location and Width of Extraction Region!



MULTIPLE COORDINATE SYSTEMS (DETECTOR ← ASPECT → SKY)

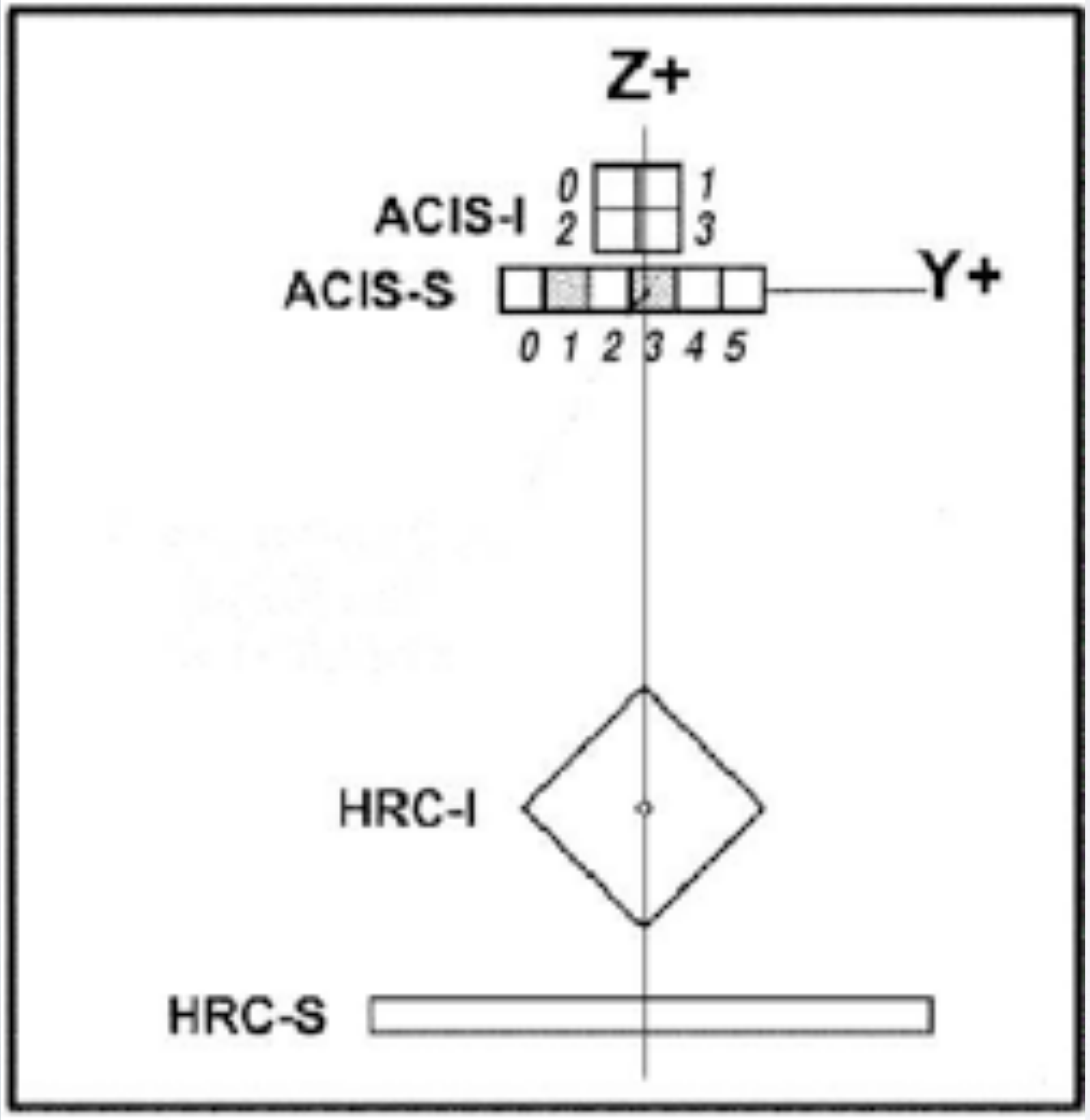
MIRROR GEOMETRY & STABILITY

- HRMA has been stable relative to SIM (i.e., stable optical axis and focus). SIM can be moved relative to optical axis (Y, Z) and focus (X);
- Star tracker relative to HRMA changes with time: aimpoint drift.
- We *reconstruct* our positions (detectors & spacecraft) very accurately, (≲0.6”) but *during* the observation, we can be off by up to ≈10”.
- We intentionally dither our spacecraft ±8”, in two directions, so as to smooth out detector issues, and fill in the gaps between CCDs.

COORDINATE SYSTEMS

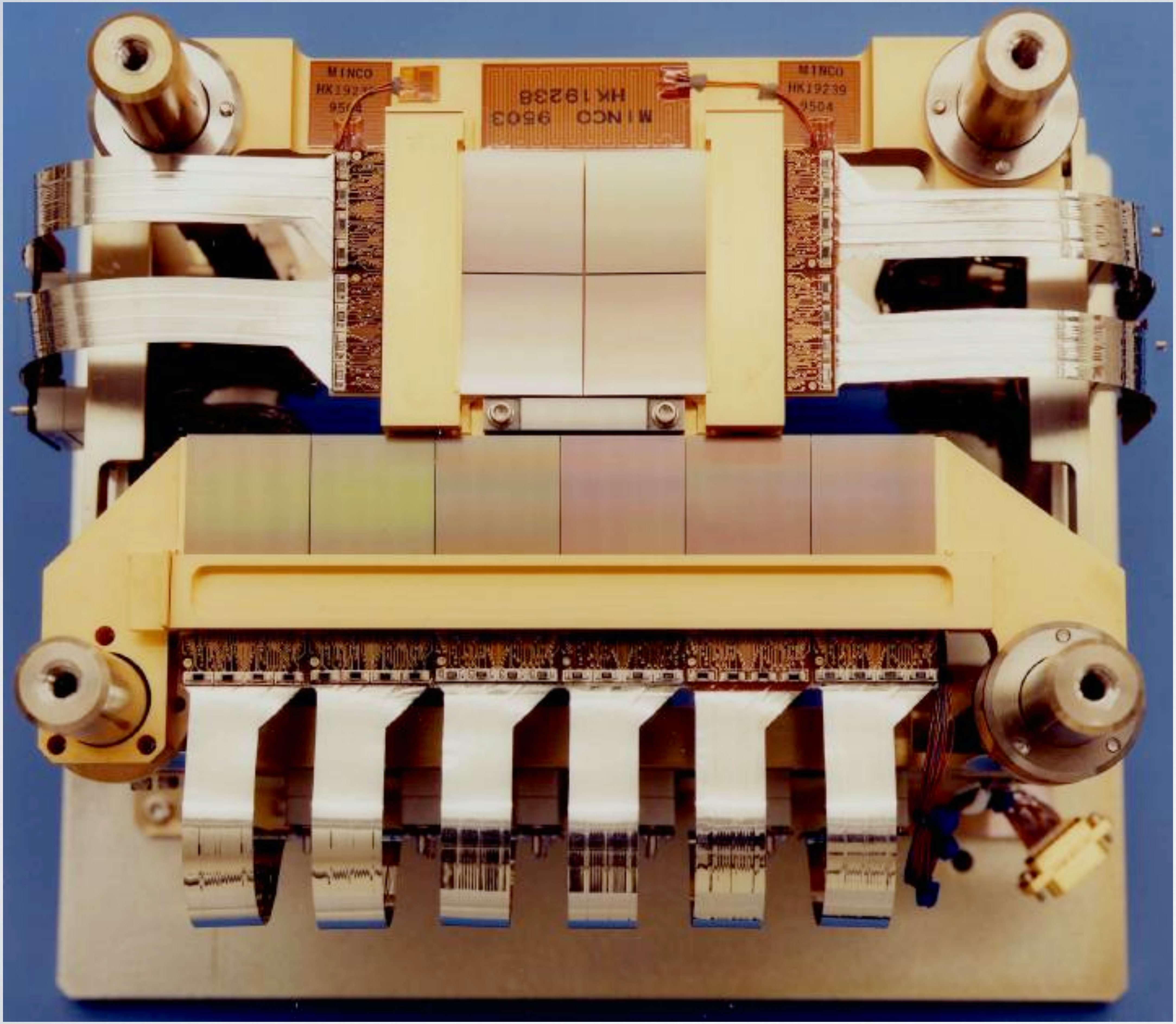
- Two Classes: Sky (e.g., X, Y) & Detectors (e.g., CHIPX, CHIPY)
- Special detector coordinates are used for gratings observations.
- The relationship between Sky, Mirrors, & Detectors is called the **aspect solution**.

SCIENTIFIC INSTRUMENT MODULE (SIM)



Advanced CCD for Imaging Spectroscopy

High Resolution Camera



ACIS-I
16'x16'

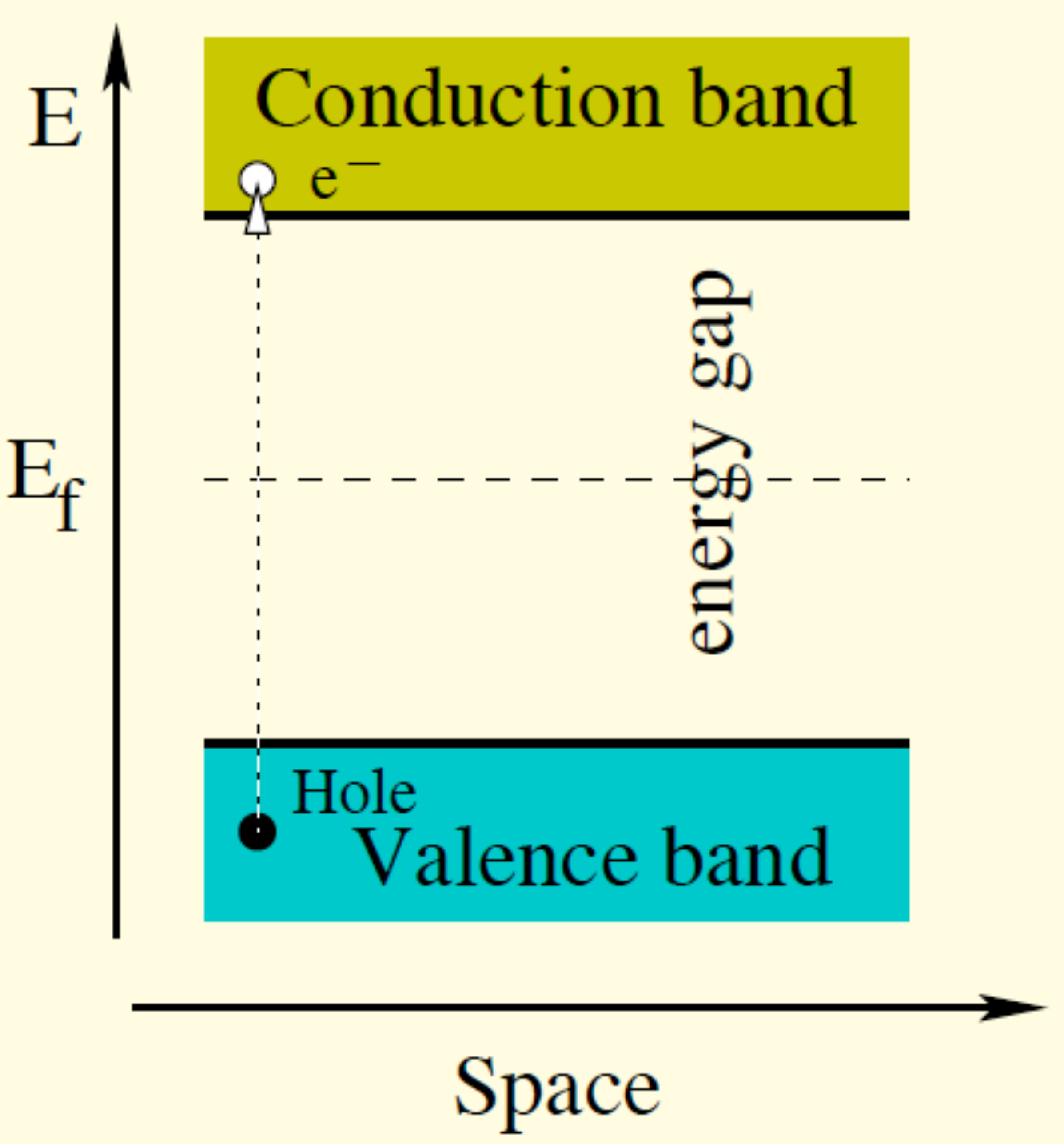
ACIS-S
40'x8'

CCD DETECTORS

- Semi-conductor: absorption of a photon moves electrons across the energy gap between valence and conduction bands

- Number of electrons liberated go as: $N \sim h\nu/E_{gap}$

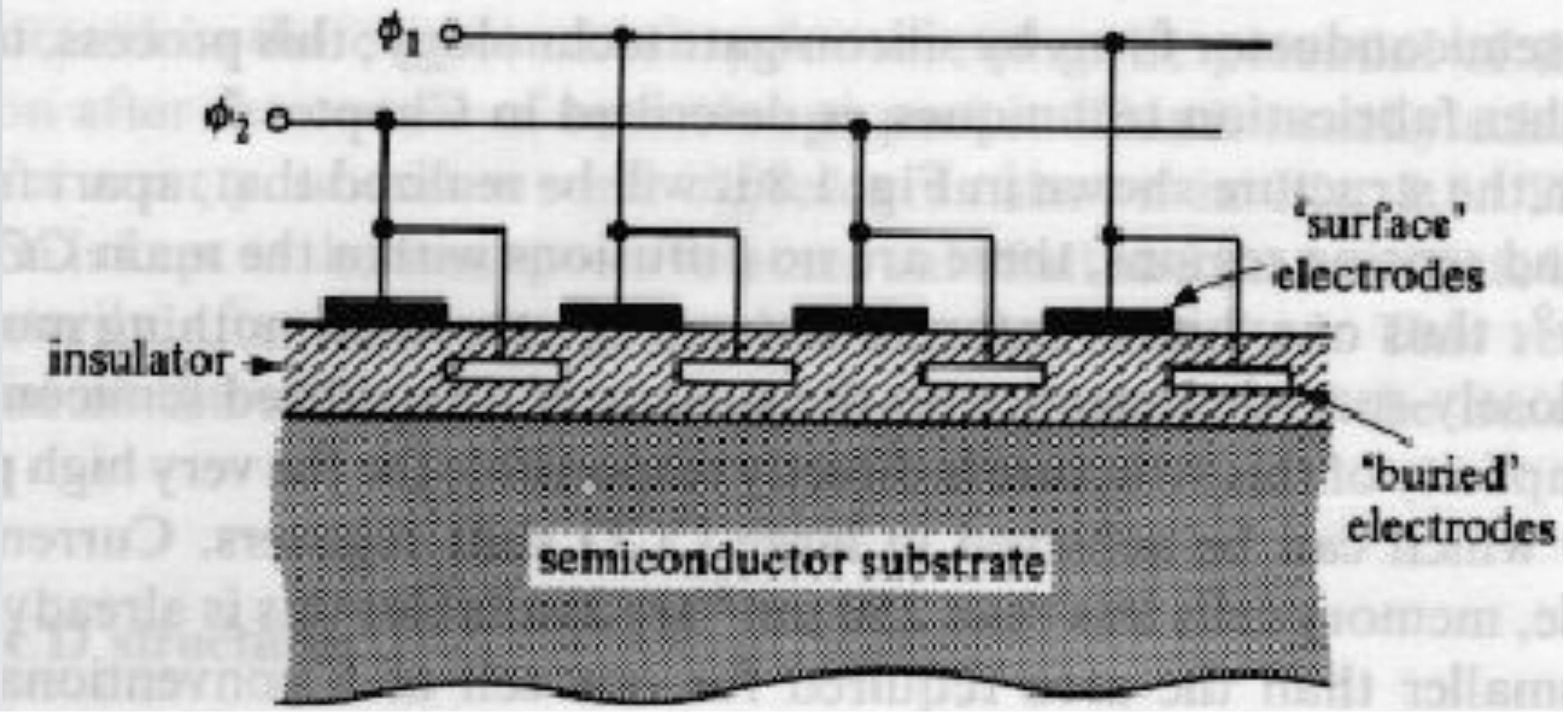
- $E_{gap} \sim 1$ eV, so $N \sim 1000$ at 1 keV. Resolution: $\alpha \sqrt{N} \alpha \sqrt{E}$

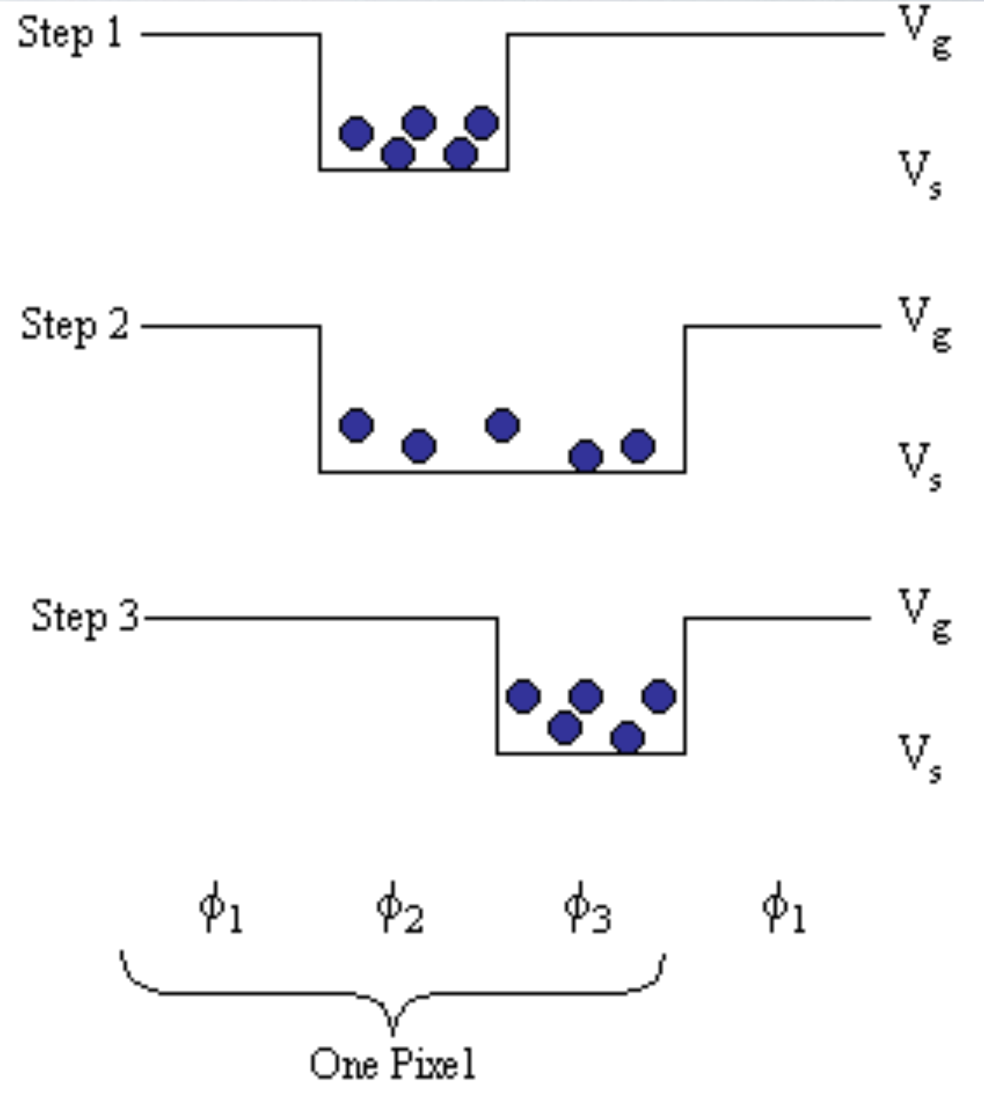


- CCD pixels are defined by physical structure and electrodes with applied alternating currents ("gate structure")

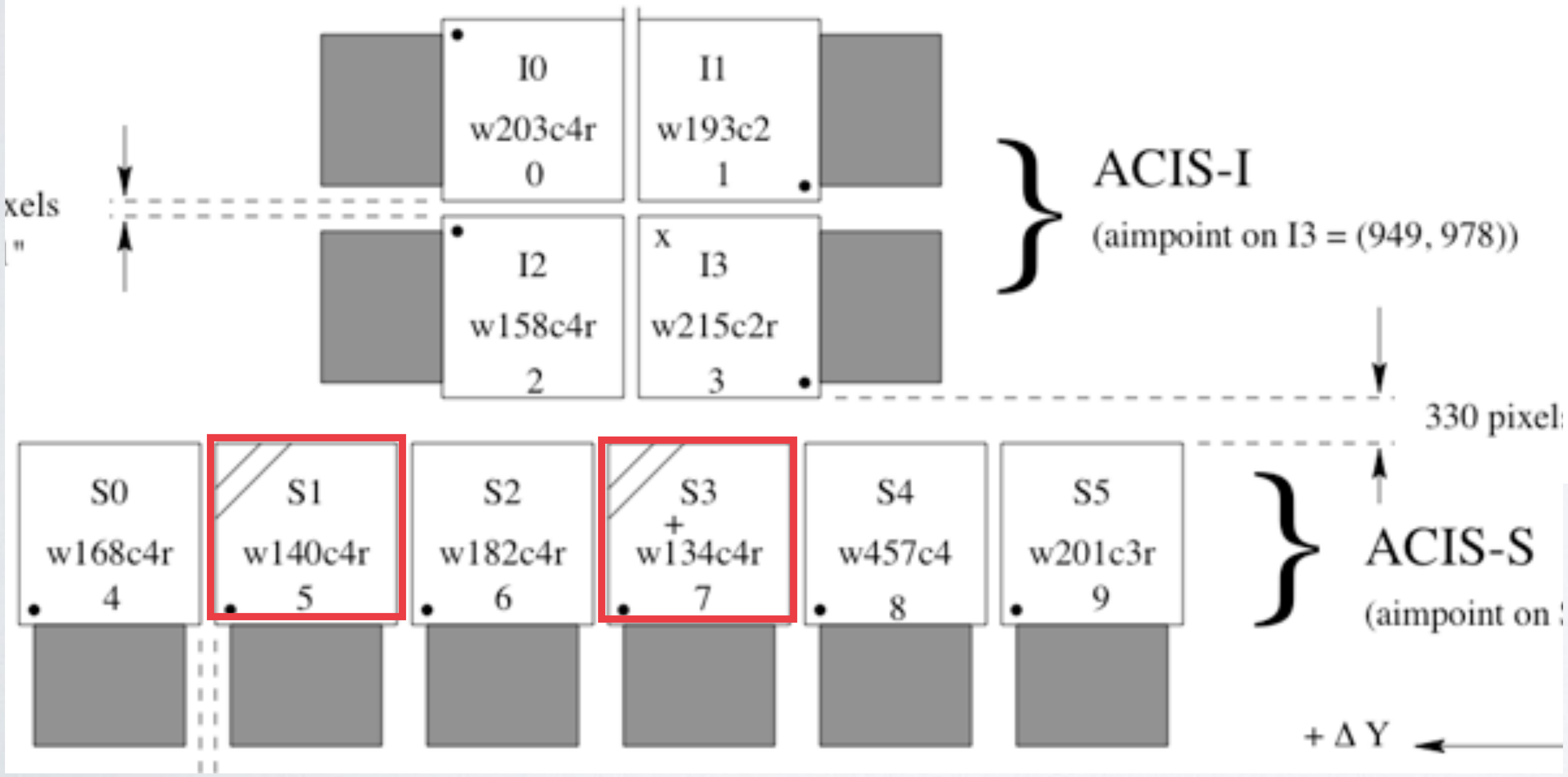
- Applied voltage moves charge across pixels to readout

CCD DETECTORS





After every 3 steps, charge packet moves closer to the output by 1/3 of a pixel.



CCD_ID = 0–9; Chips I0-I4, S0–S5

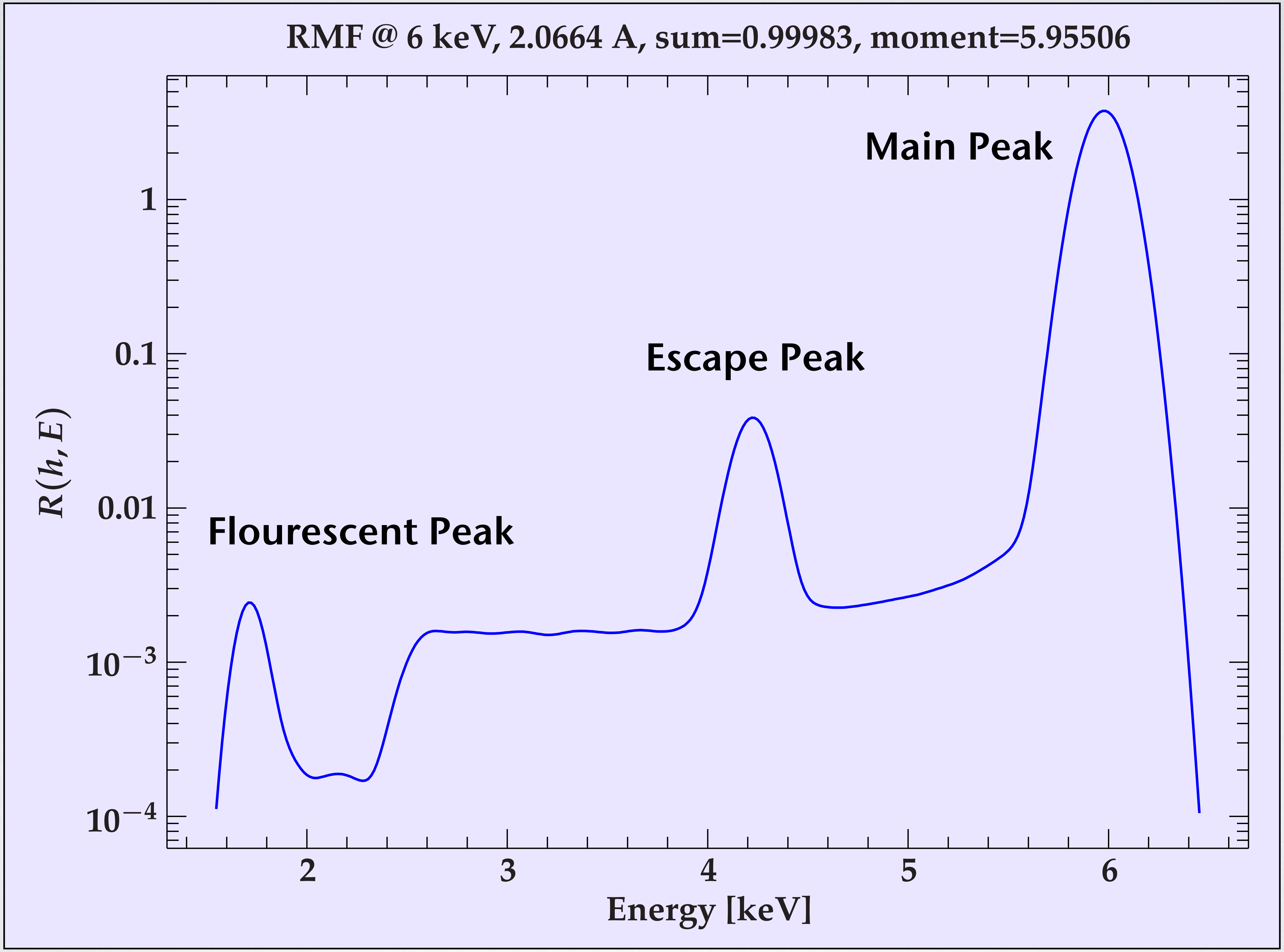
CCD DETECTORS

- Number of readouts could be: one (a row at a time), one per column, or one per pixel. Chandra = row at a time
- Charge is quickly transferred to “readout frame” (41.04 msec), where it is readout one row at a time (2.85 msec/row; 3.2 sec total) (Total: 3.24104 sec)
- Can decrease “Frame Time” by only reading out part of chip
- Can sacrifice one spatial simension and read rows in “Continuous Clocking” (CC-) mode. 2.85 msec per row.
    - In practice, CC-mode is (mostly) only used with gratings.

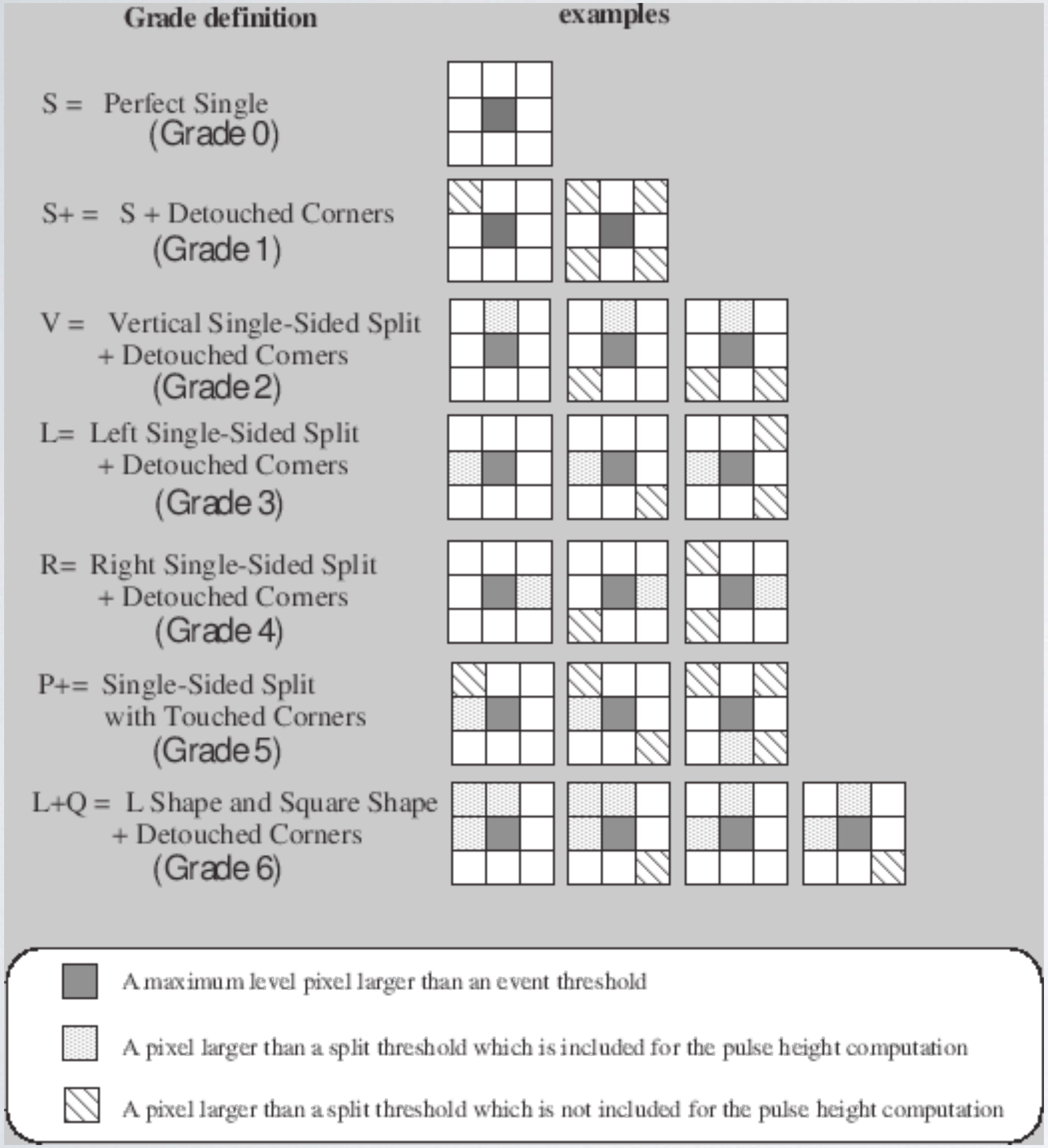
CCD DETECTORS

- Photons can interact with the detector material!
- If E > Silicon K-edge energy (1.84 keV), K-shell (n=1) electron can be liberated and reabsorbed
  - L⇒ K fluorescent line (1.74 keV)
  - Free-bound & higher n-shell cascade transitions, with summed energy = $E - E_{\text{fluorescent}}$ = Escape Peak
- Aside from resolution width, signatures can appear near fluorescent and "escape peak" energies!

CCD DETECTORS



CCD DETECTORS



■ A maximum level pixel larger than an event threshold

▒ A pixel larger than a split threshold which is included for the pulse height computation

▨ A pixel larger than a split threshold which is not included for the pulse height computation

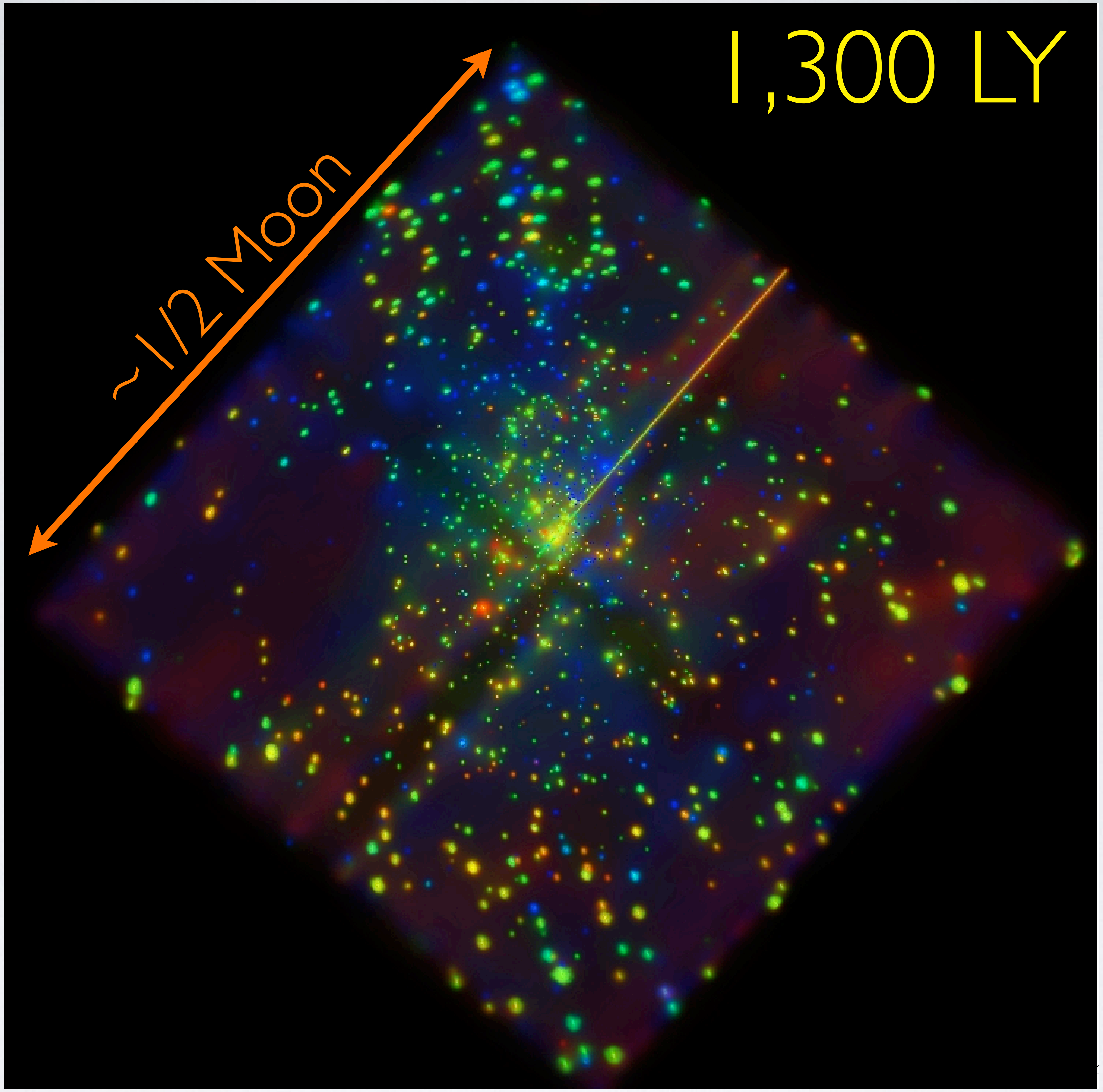
- Charge is typically deposited in more than one pixel.
- Chandra: 3x3 pixel regions ⇒ Grades.
- Bad grades more likely to be background (cosmic rays)

CCD DETECTORS

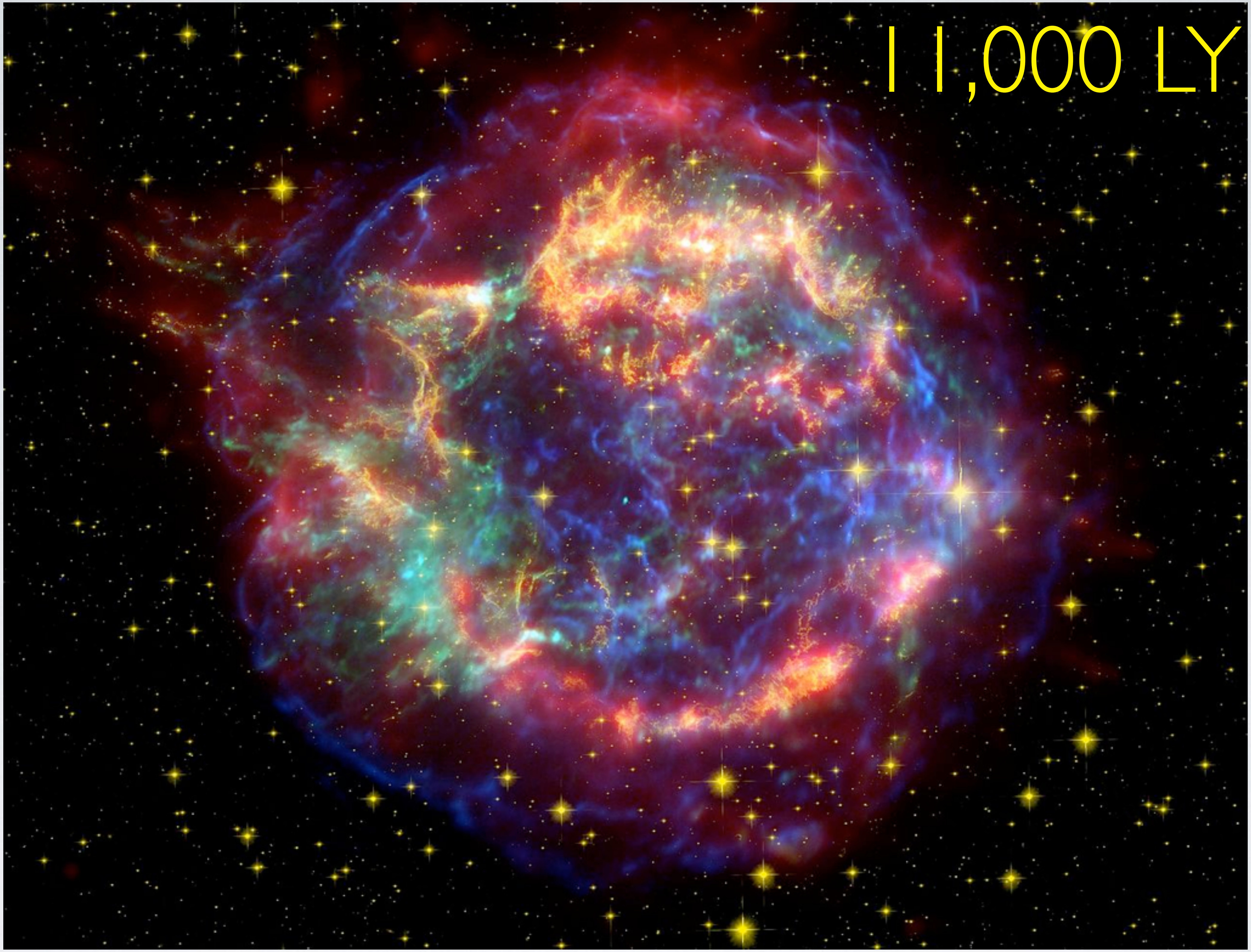
- One or more photons landing in the same region in the same frame = pileup.
- Piled photons are either read as a "bad grade", or as an event with the summed energy!
- Pileup can be avoided by limiting the exposure:
  - Filters, i.e., inserting gratings
  - Reading only a fraction of the CCD imaging area to reduce readout times
  - "continuous readout" modes which sacrifice one spatial dimension of information

CCD DETECTORS

- CCD “gate structure” can be placed either facing the X-ray source (“front side illuminated” – more silicon), or away from the source (“backside illuminated” – less silicon).
  - ACIS-S has two “backside illuminated” CCDs: S1, **S3**
- Backside illuminated is more sensitive to low energy photons, but has higher noise
- CCD pixels can be damaged, leading to “charge transfer inefficiency” (CTI). Charge is left behind as it is moved, leading to decreased spectral resolution in the detector
- Chandra has CTI damage, but we have tools to help correct it.

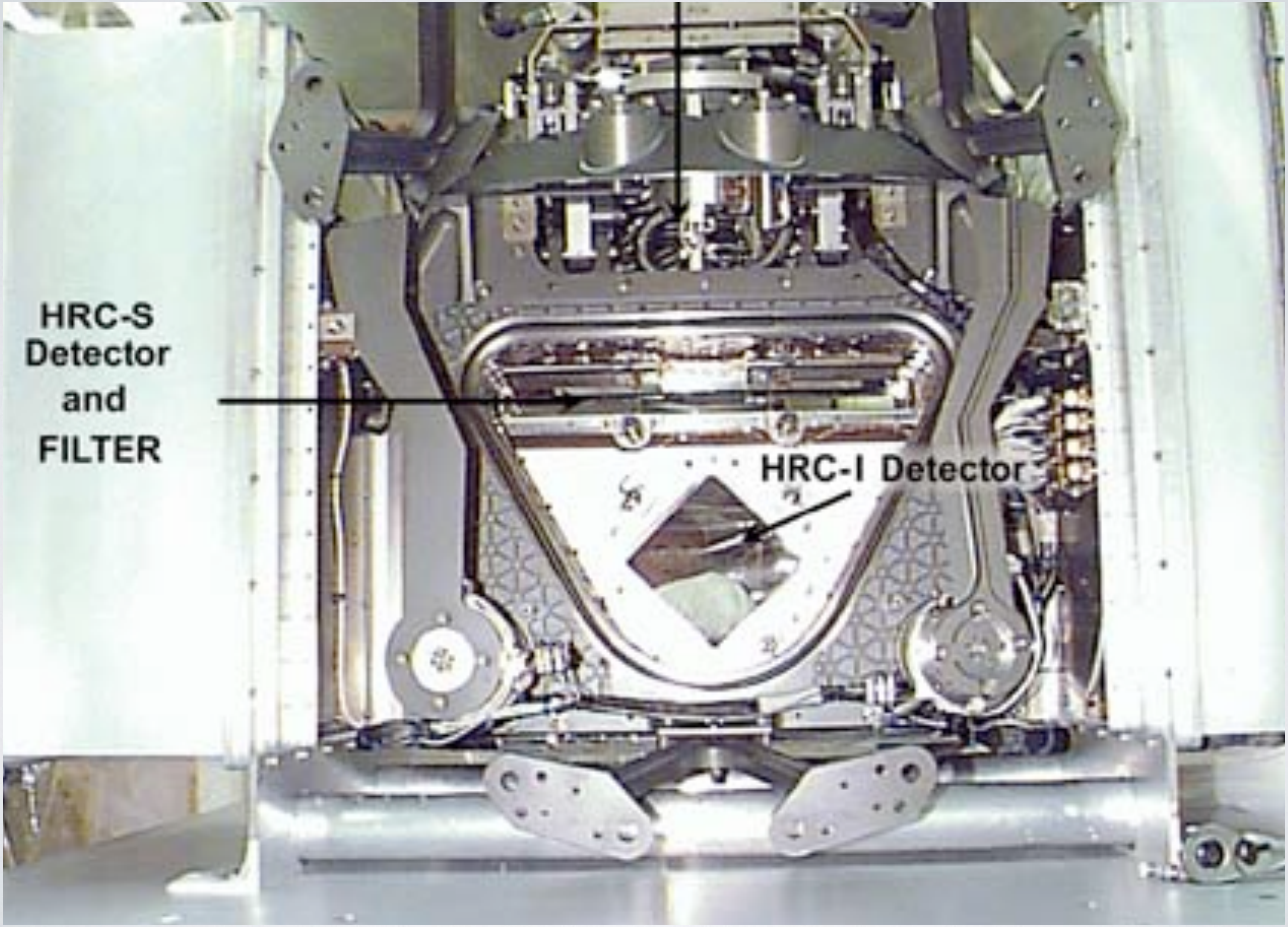


ORION STAR CLUSTER



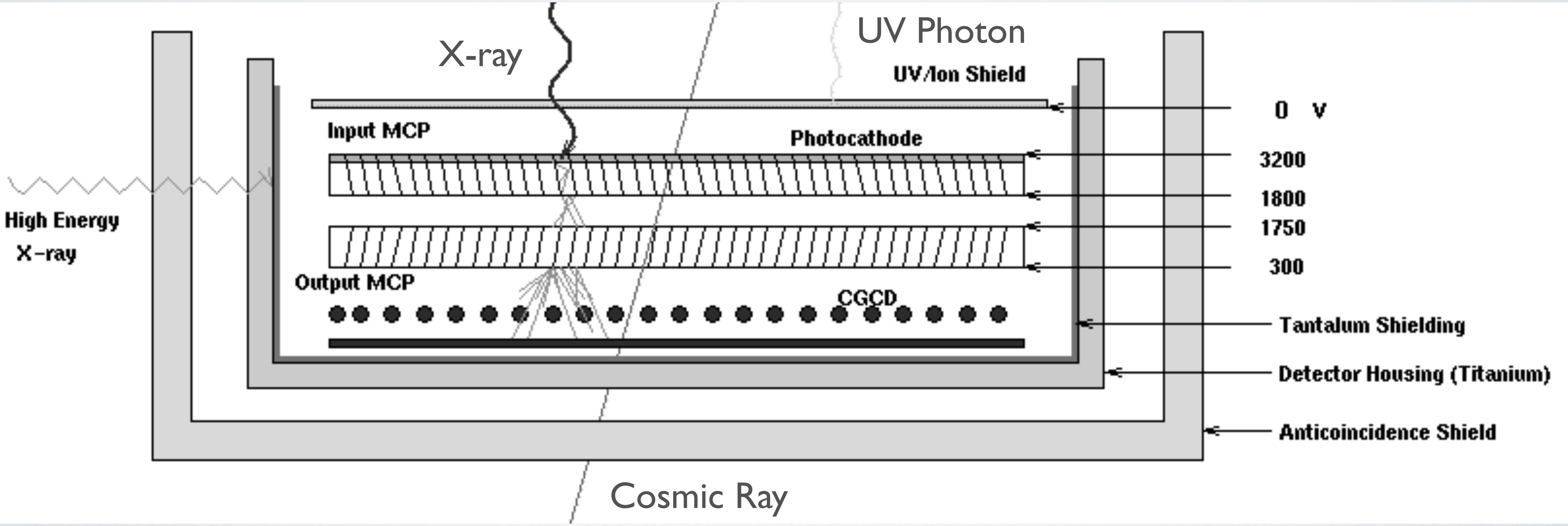
CASSEOPEIA A SUPERNOVA REMNANT

HRC-I: 30’x30’



MICRO-CHANNEL PLATE

- X-rays interact with CsI coated, narrow & canted tubes, to produce photoelectrons that are then detected.
- Lower energy range than even ACIS-S, but essentially no energy resolution. (But also no pileup!)



HRC

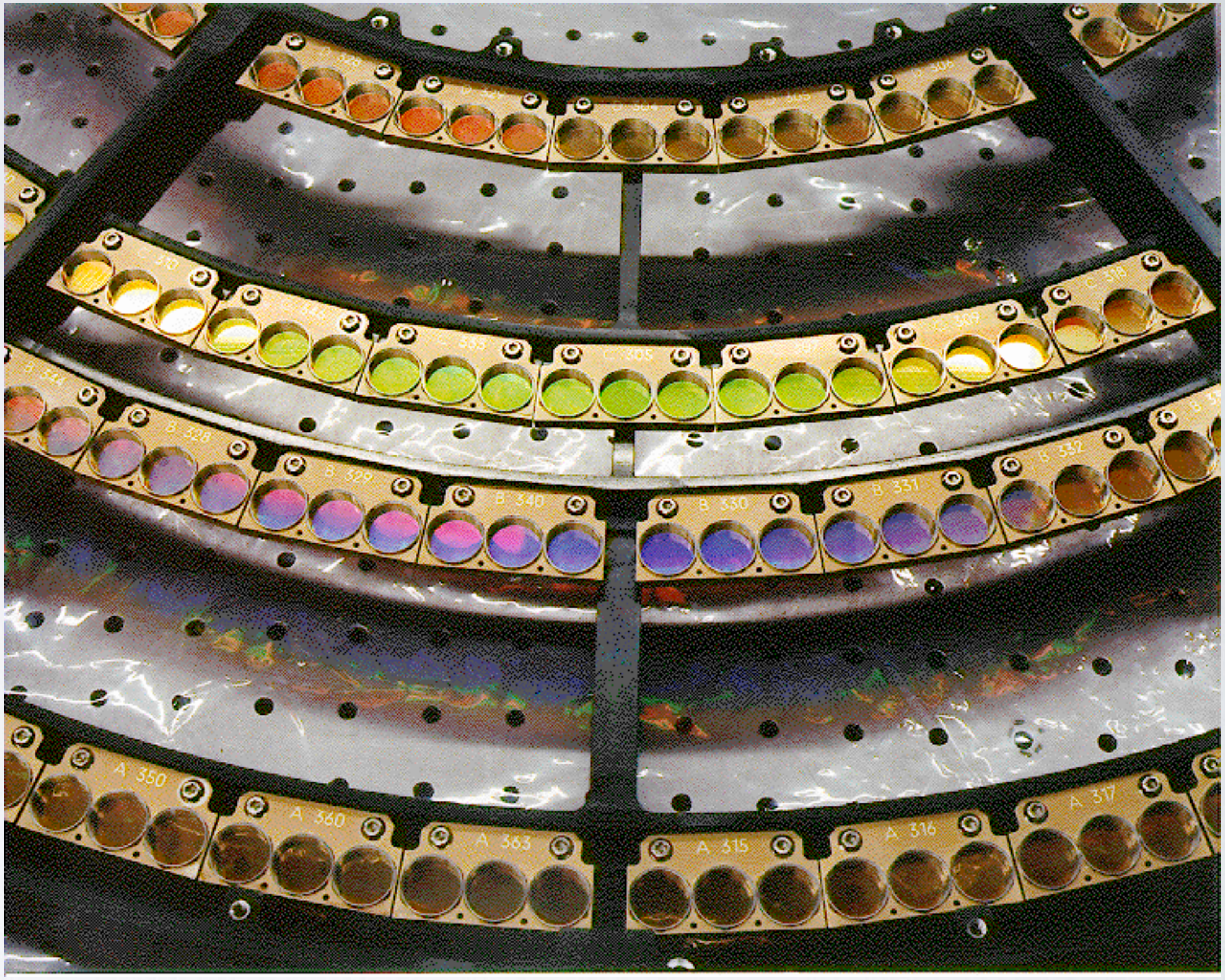
- Best Timing on Chandra – 16 microseconds in principle, but wiring error leads to time tag being for next event (⇒ msec timing)
  - Most likely coming from background event (rates ≈180 cps).
  - Recoverable if no events are lost. HRC-S timing mode uses only 6’x30’ detector region to limit background rate
- HRC is typically used in very crowded fields where best position is necessary, and/or when timing information is necessary
  - E.g., localize an accreting, X-ray msec pulsar

VELA X-1

6200 LY

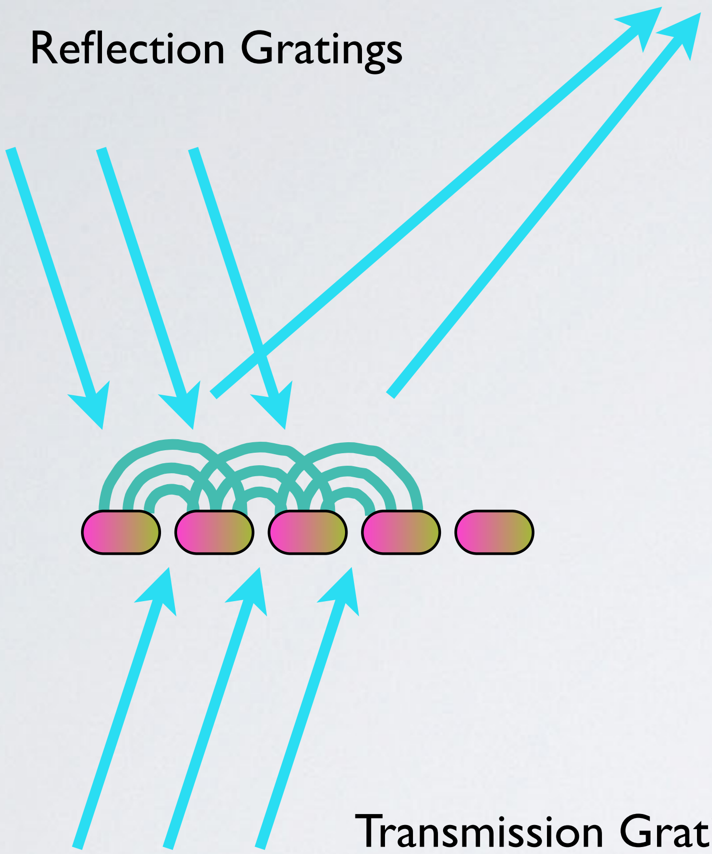
TRANSMISSION GRATINGS

High Energy
Transmission Gratings



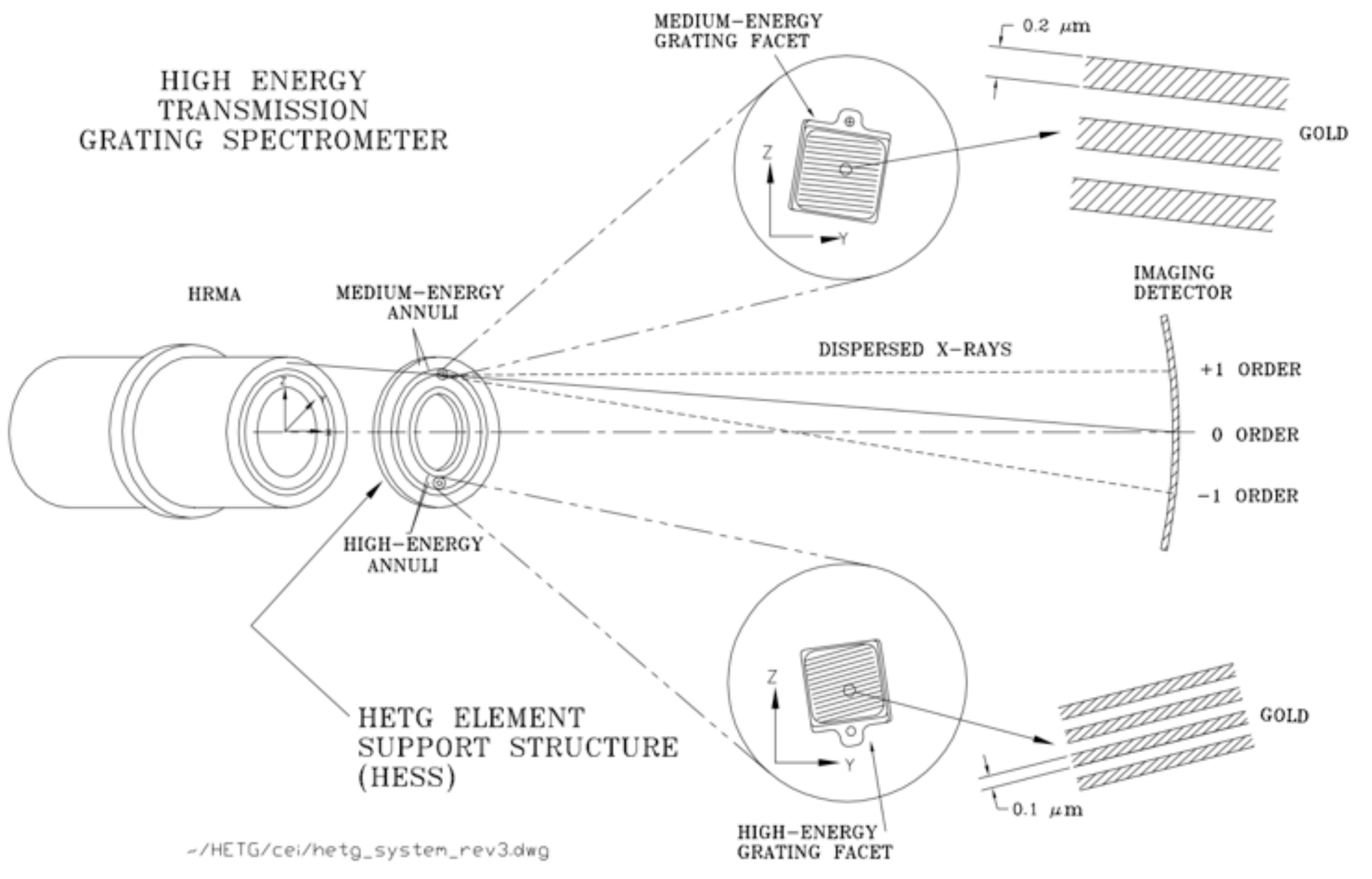
Low Energy
Transmission Gratings

GRATINGS



Reflection Gratings

Transmission Gratings

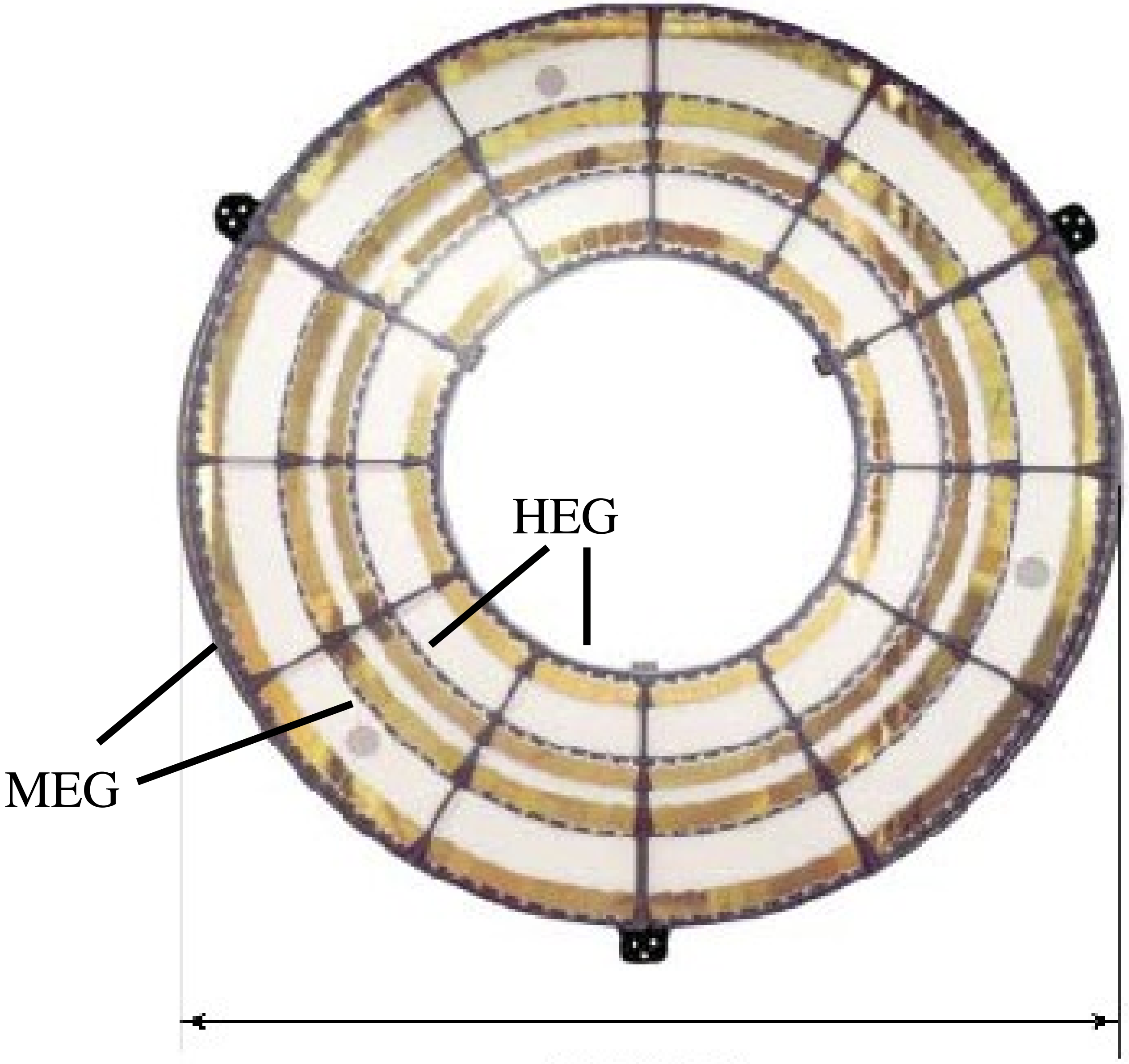


Gratings Equation:

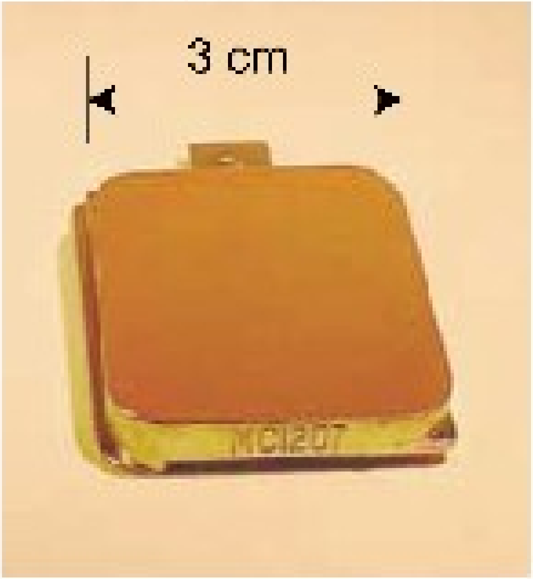
$$\boxed{m\lambda = m\frac{hc}{E} = p\sin \approx p\beta}$$

CHANDRA-HETG

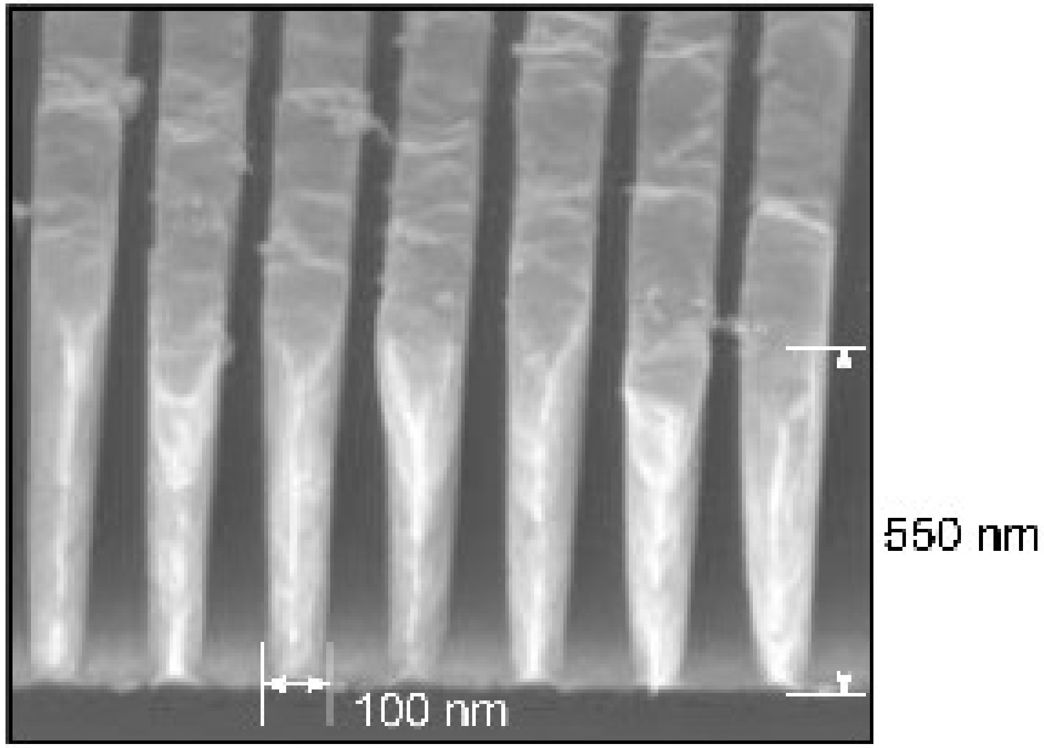
HETGS instrument.



Invar grating frame.



Scanning electron micrograph of gold grating.



1/1000 of a Human Hair

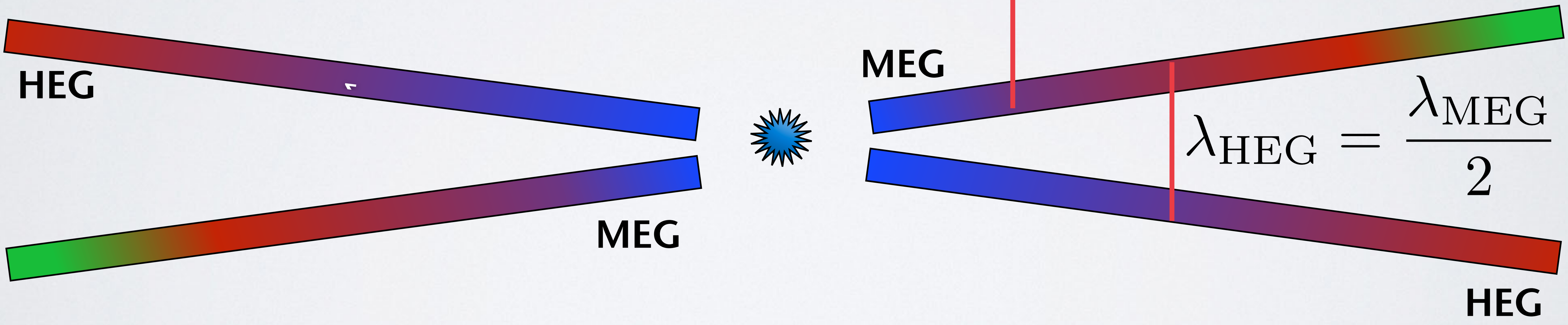
$$m\lambda = m\frac{hc}{E} = p\sin \approx p\beta$$

LETG

$$\lambda,\ \frac{\lambda}{2},\ \frac{\lambda}{3},\ldots$$

$$E, 2E,\ 3E,\ldots$$

HETG



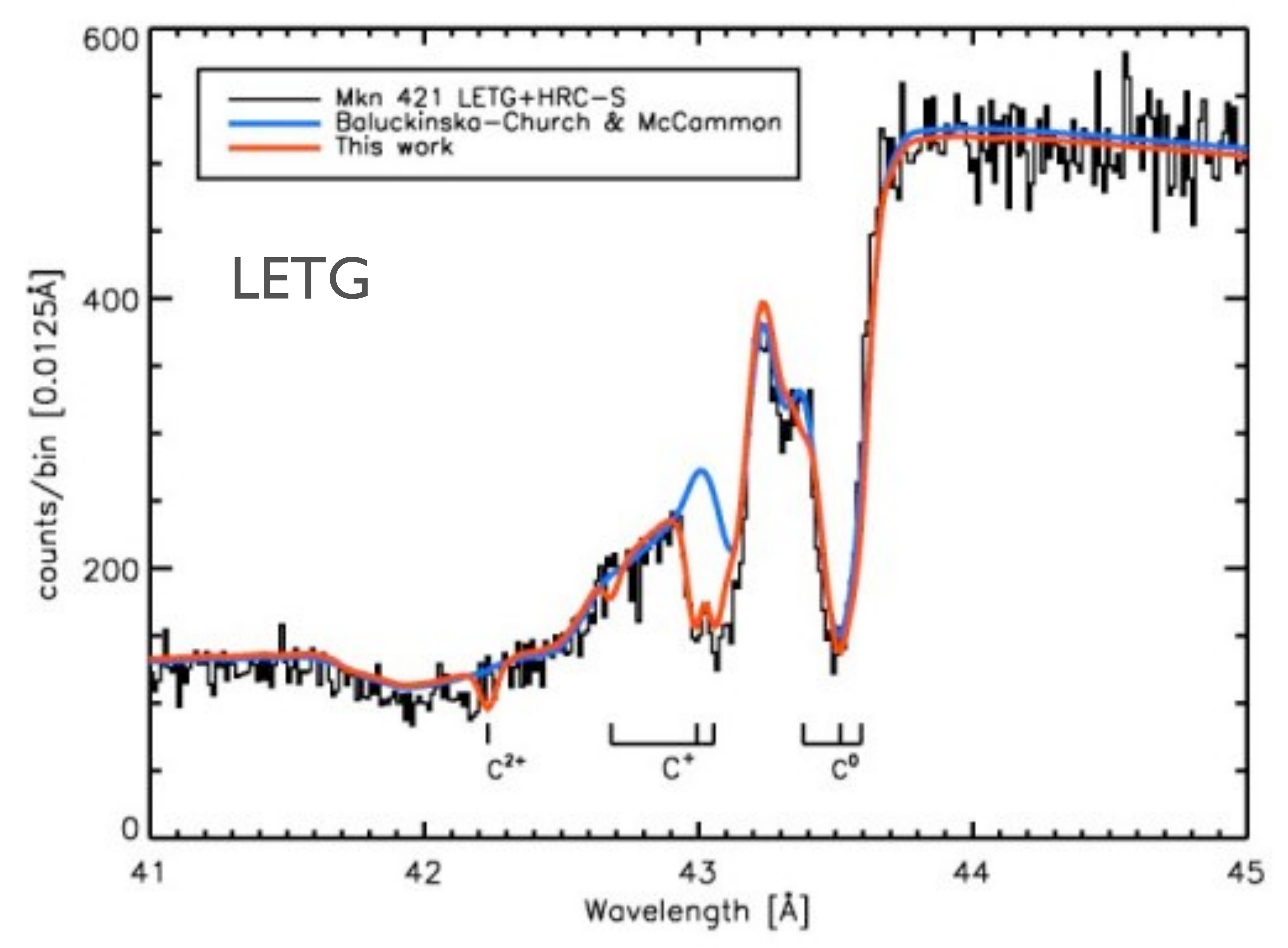
$$\lambda_{\text{HEG}} = \frac{\lambda_{\text{MEG}}}{2}$$

Greater Distance = Higher Resolution

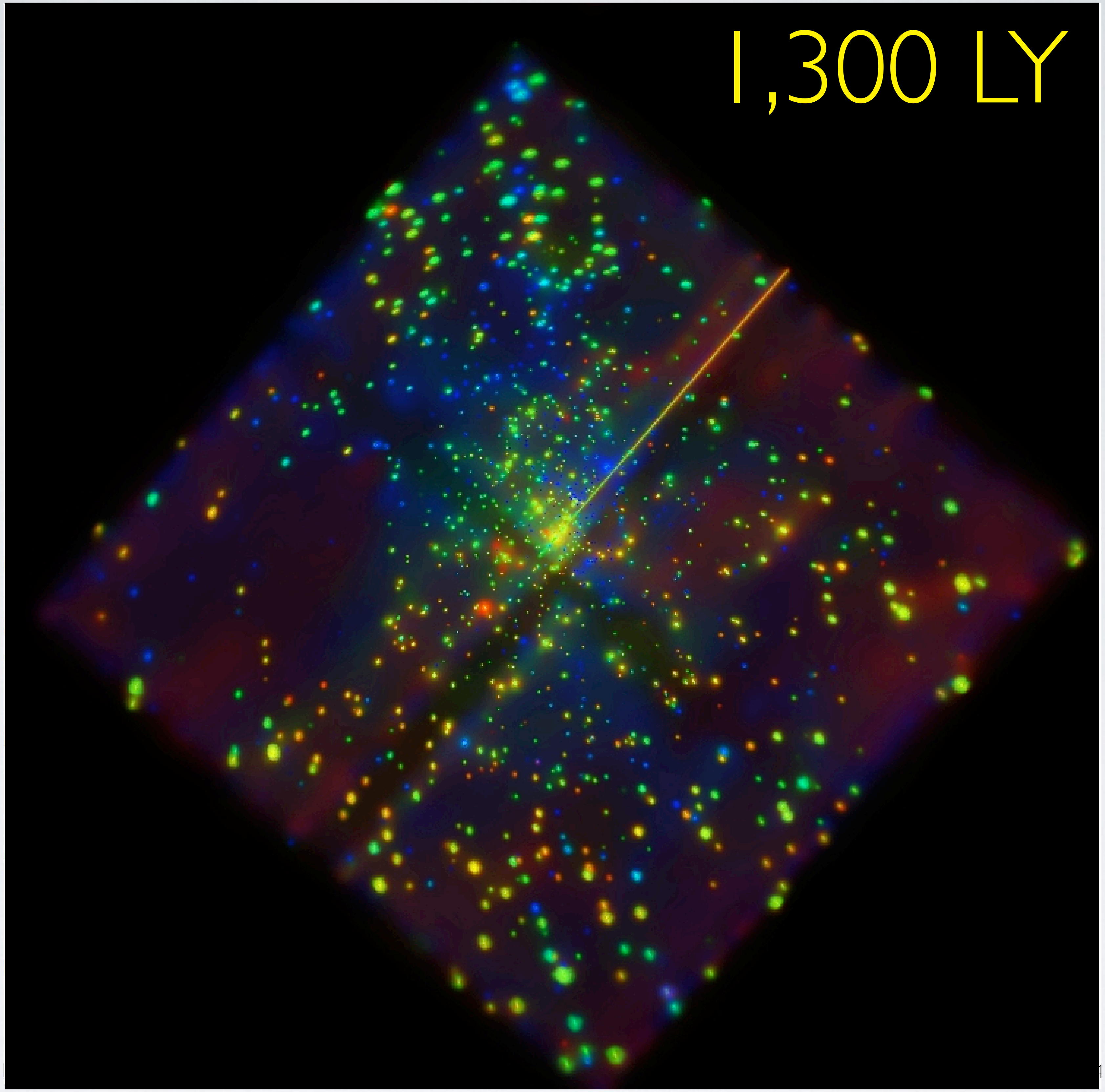
Resolution Limited by CCDs & Gratings Accuracy

TRANSMISSION GRATINGS

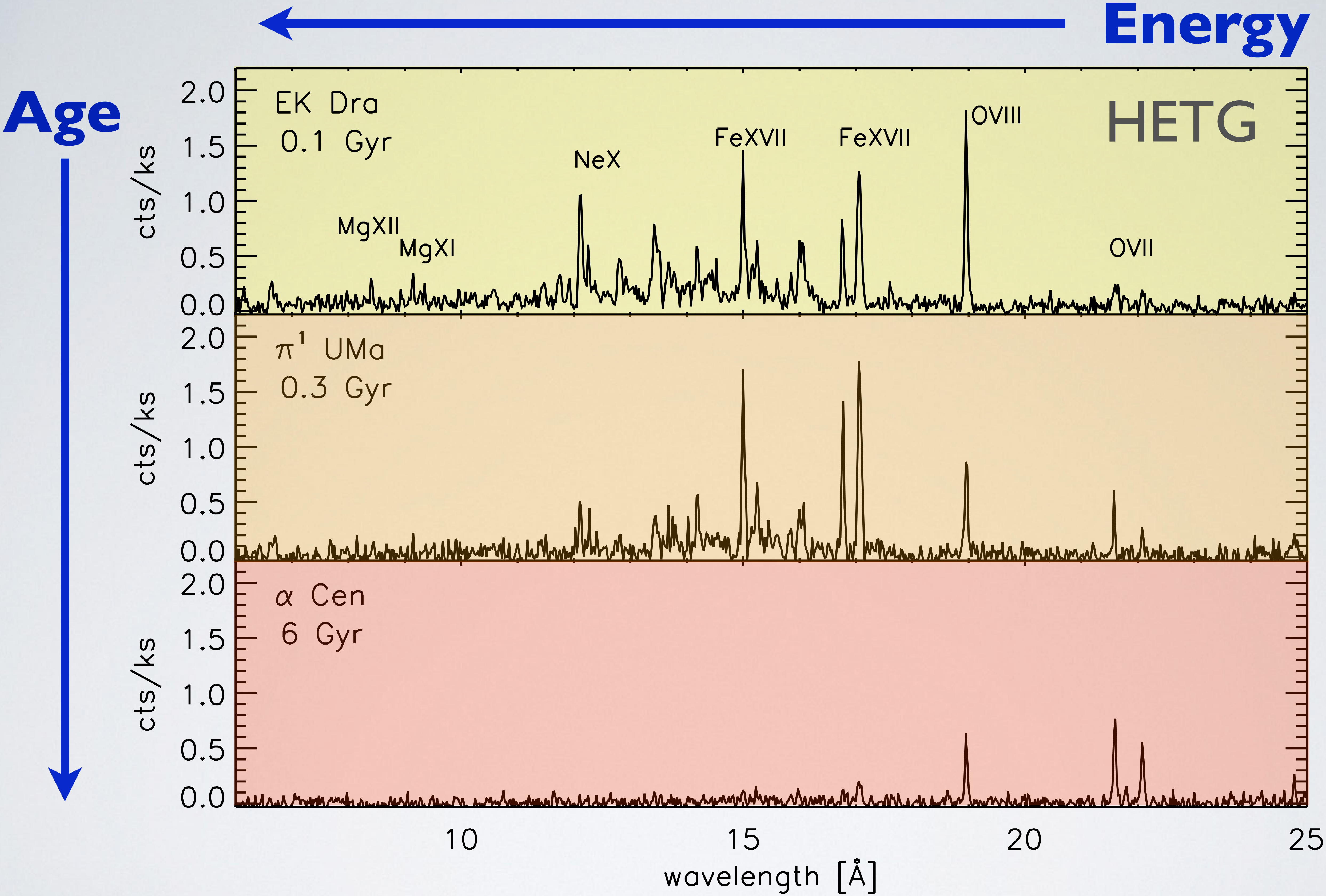
- HETG & LETG can be used with any combination of ACIS-S/-I and HRC-S/-I (-S array geometries optimized for specific gratings)
  - Almost all are: HETG/ACIS-S, LETG/HRC-S, or LETG/ACIS-S
- ACIS-S has CCD energy resolution, HRC-S no energy resolution
  - Can separate orders on ACIS-S, cannot with HRC-S
- Highest resolution is ACIS-S/HETG (with HEG), longest wavelength/lowest energy is HRC-S/LETG
- Gratings lowers the effective area; however, brightest objects observed by Chandra are all CC-mode, HETG/ACIS-S.



MKN 421, ISM CARBON EDGE



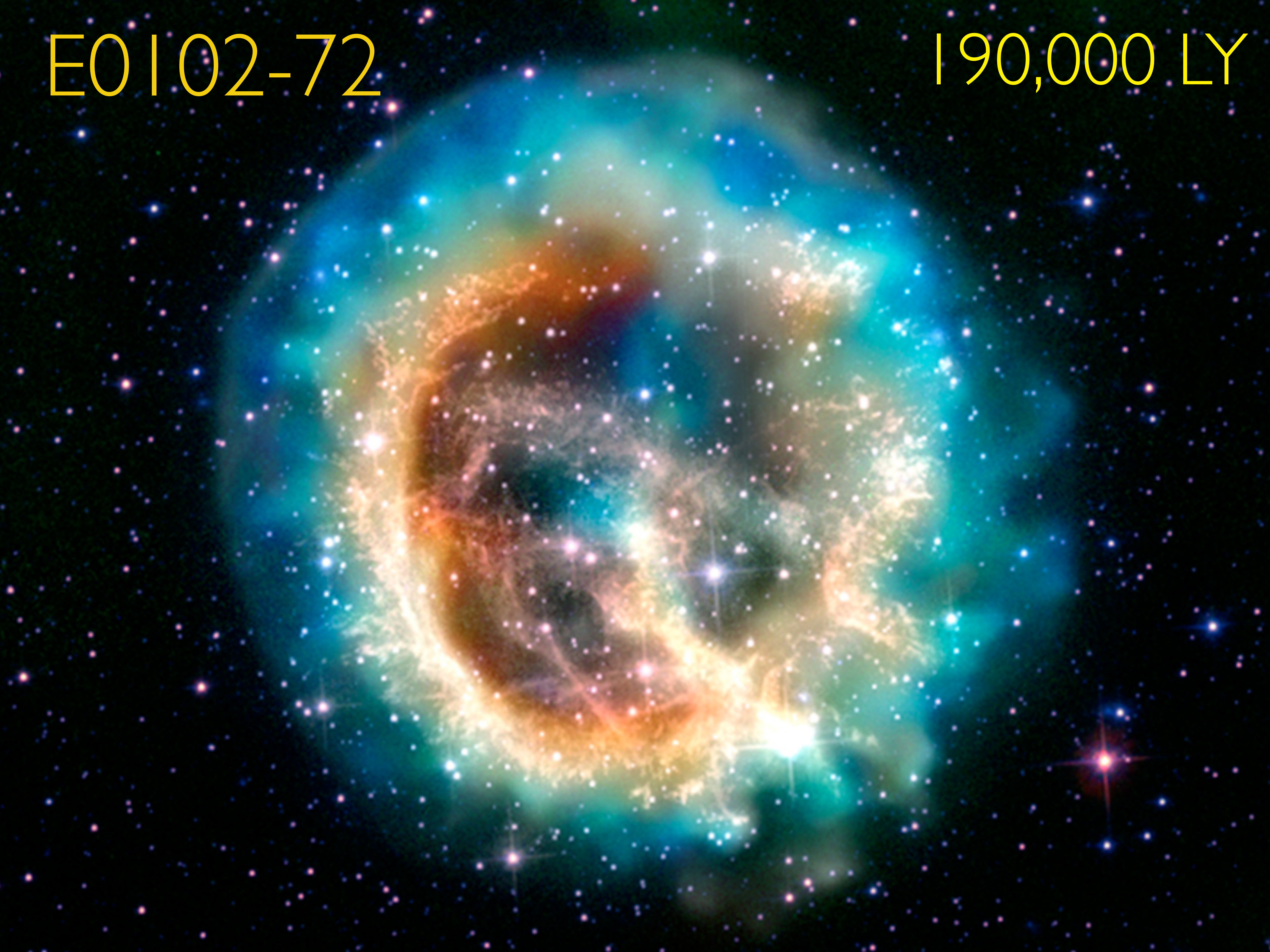
ORION STAR CLUSTER



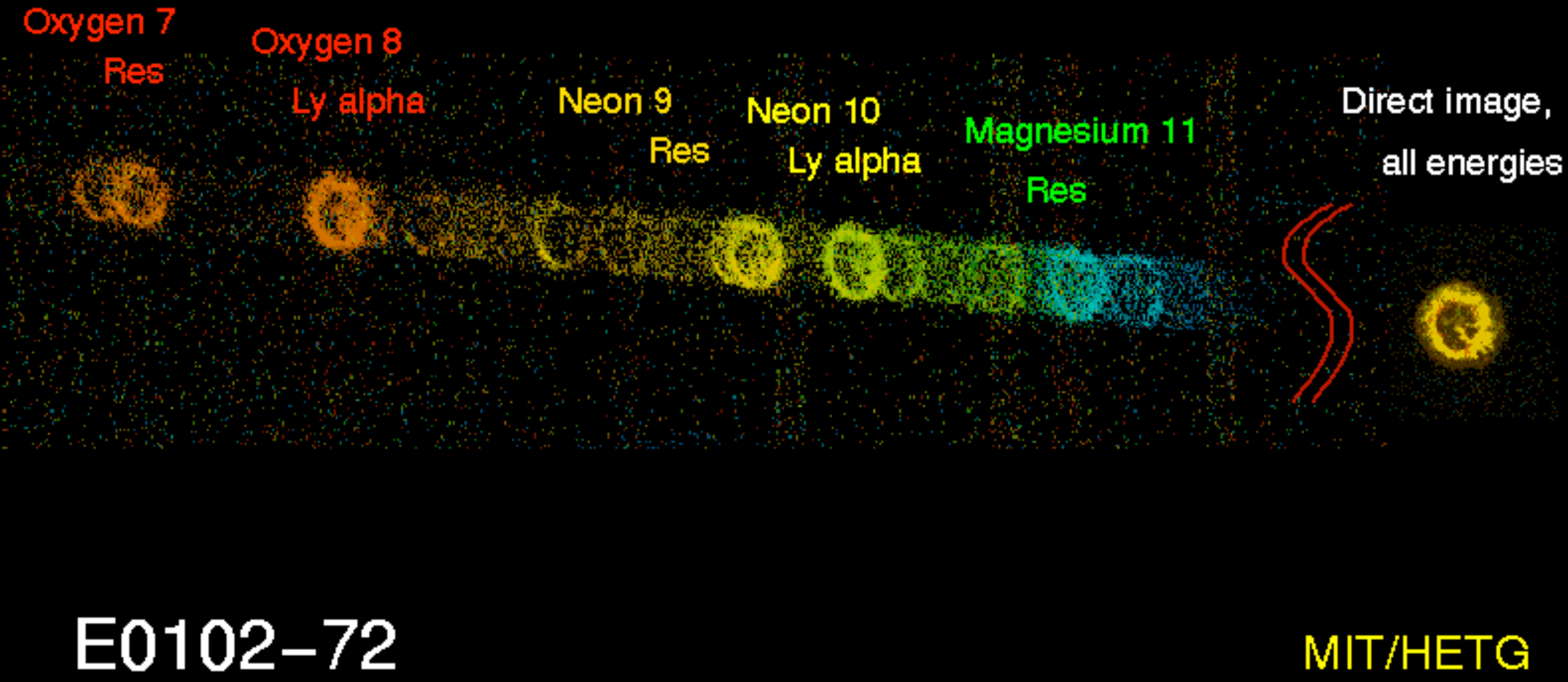
A "HISTORY" OF OUR SUN

E0102-72

190,000 LY



E0102-72


Oxygen 7
Res
Oxygen 8
Ly alpha
Neon 9
Res
Neon 10
Ly alpha
Magnesium 11
Res
Direct image,
all energies
E0102−72
MIT/HETG

YEARLY OBSERVATION CYCLE:

- Guest Observer (GO) Program: ~17 Msec
  - Propose ~March, Reviewed ~June, starts ~October–January
- Guaranteed Time Observations (GTO): ~2 Msec
  - Instrument teams, without duplicating GO
- Calibration: ~1 Msec
- Director’s Discretionary Time (DDT): ~700 ksec
  - (Typically) Unanticipated events & unique opportunities.

OBSERVATIONAL CONSTRAINTS:

- How long per orbit is the object visible?
- Where is it relative to the sun (& moon)?
- Thermal constraints (alternate between "hot" & "cold"):
  - We want to keep the CCDs operating at -120° C (CTI increases with temperature)
  - We want to keep fuel lines from freezing.
  - Schedule 1 week at a time; thermal balance affects whole week
- Observations can run from 1 ksec to 170 ksec. The latter is more difficult in these later years of the mission.

TYPES OF OBSERVATIONS WE DO

- ACIS-I Imaging: ~40%, ACIS-S Imaging: ~40%, HETG/ACIS-S Spectra: ~18%, (HRC-S or ACIS-S)/LETG:~2%
- Science Topics:
  - Stars ~13%
  - Black Hole/Neutron Star Binaries ~9%
  - Galaxies, X-ray Populations, Surveys, & Diffuse Emission ~7%
  - Active Galactic Nuclei & Quasars ~23%
  - Clusters of Galaxies ~32%

LOTS MORE LEFT TO DO,
SO COME JOIN US!