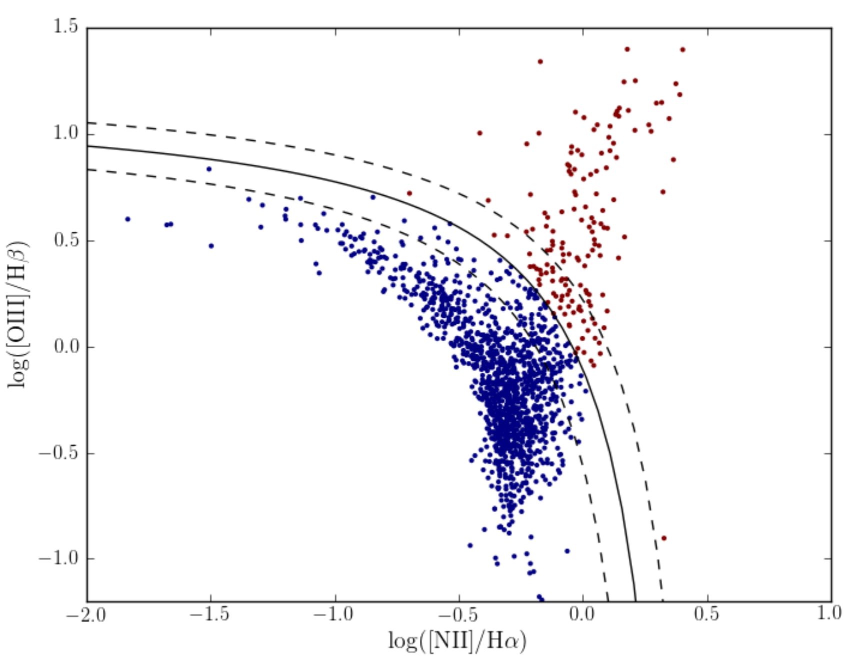
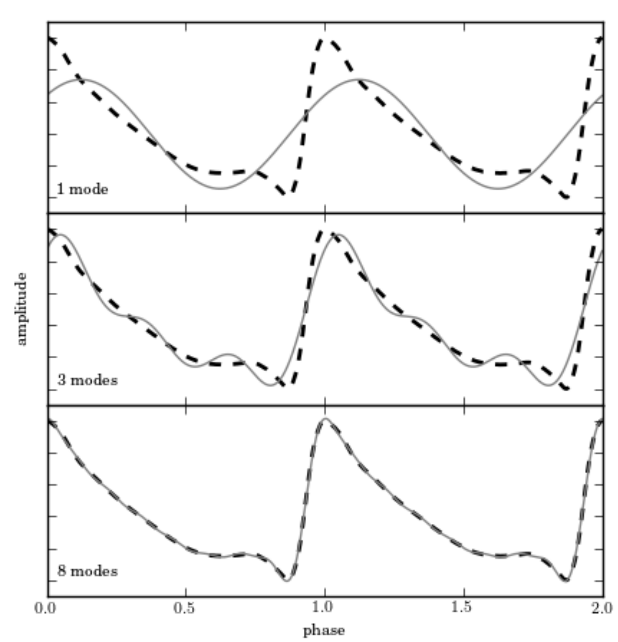
ISYA
INTERNATIONAL SCHOOL FOR YOUNG ASTRONOMERS

Astrostatistics:
Applications in X-Ray and Time-Domain Astronomy

Rafael Martínez-Galarza
Harvard-Smithsonian Center for Astrophysics





About this lecture series:
Astrostatistics with Applications in X-ray and Time-Domain Astronomy

- This is basically a course on astrostats, i.e. how can astronomers profit from statistics to understand the Universe. We will focus on two science cases: X-Ray Astronomy and Time-Domain Astronomy.

- Wait! Does that mean I need to know statistics? - NO. Does it mean I need to know X-ray astronomy? - NO. Does it mean that I need to know Time-Domain - NO.

- We will tackle common problems to all observational (and often theoretical) astronomers: what is a model? What is data? What is uncertainty?

- We will also take a philosophical journey to explore the differences between frequentist and Bayesian statistics and what that means to astronomers.

- Finally, we will also take a quite but practical dip into the Machine Learning world. Enjoy the ride¡

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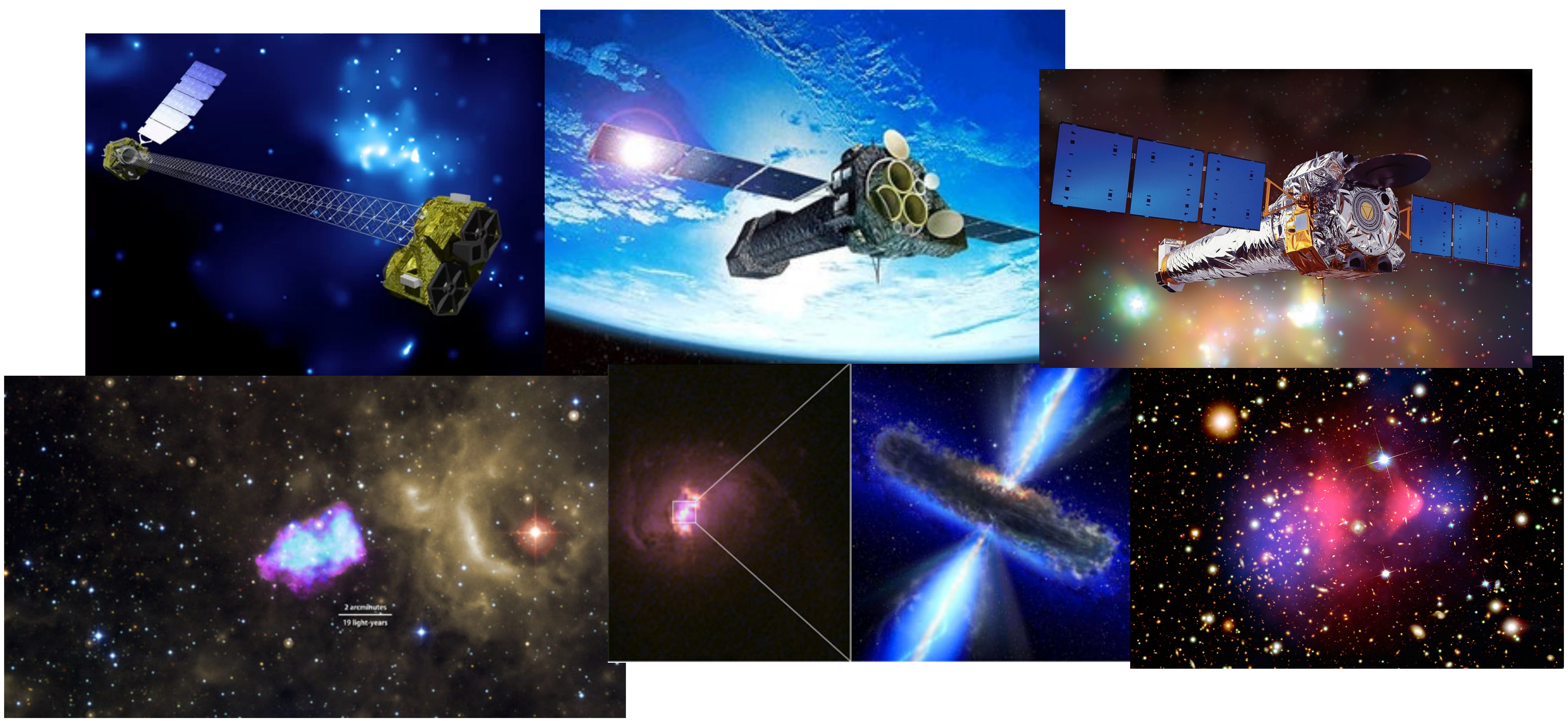
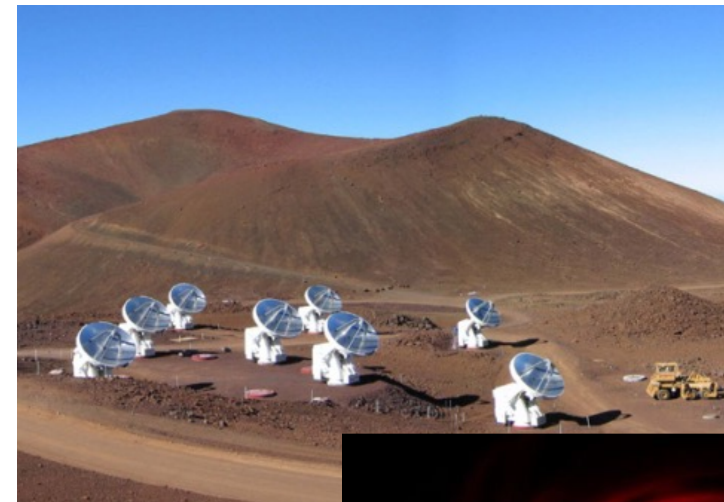
Lecture 1: Introduction to X-ray Astronomy

Rafael Martínez-Galarza, Lorenzo Lovisari
Harvard-Smithsonian Center for Astrophysics

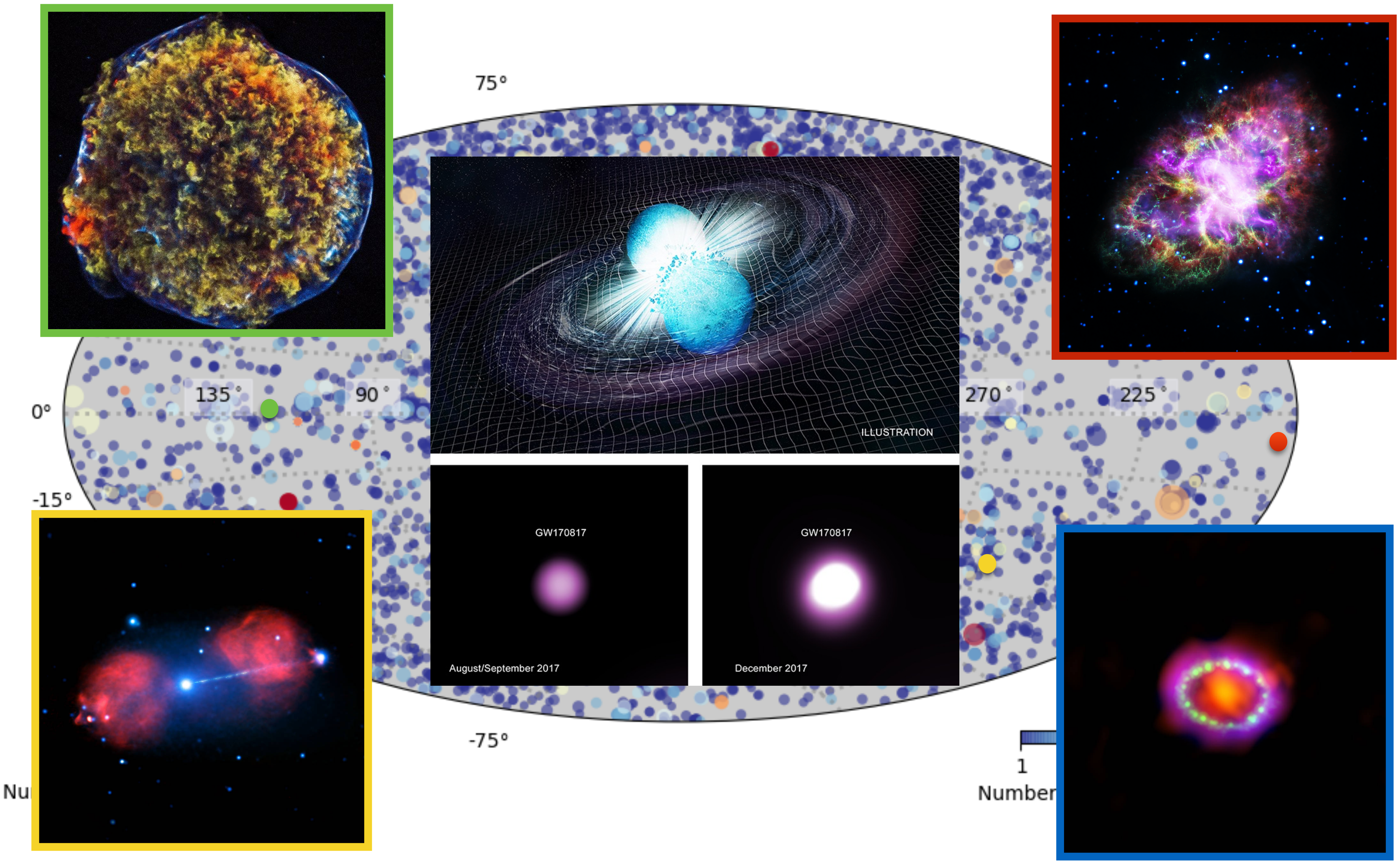


The Harvard-Smithsonian CfA

- Located in Cambridge, MA
- Probably the largest astronomy institute in the world.
- Involved in several large projects such as: Chandra, the Submillimeter Array (SMA), the Event Horizon Telescope (), the Giant Magellan Telescope (GMT).
- After 5 years as a postdoc, I am now the deputy end-to-end scientist for the Chandra Data Center.
- But sometime in the past, just like you guys, I was a student here at ISYA.




The Chandra Source Catalog

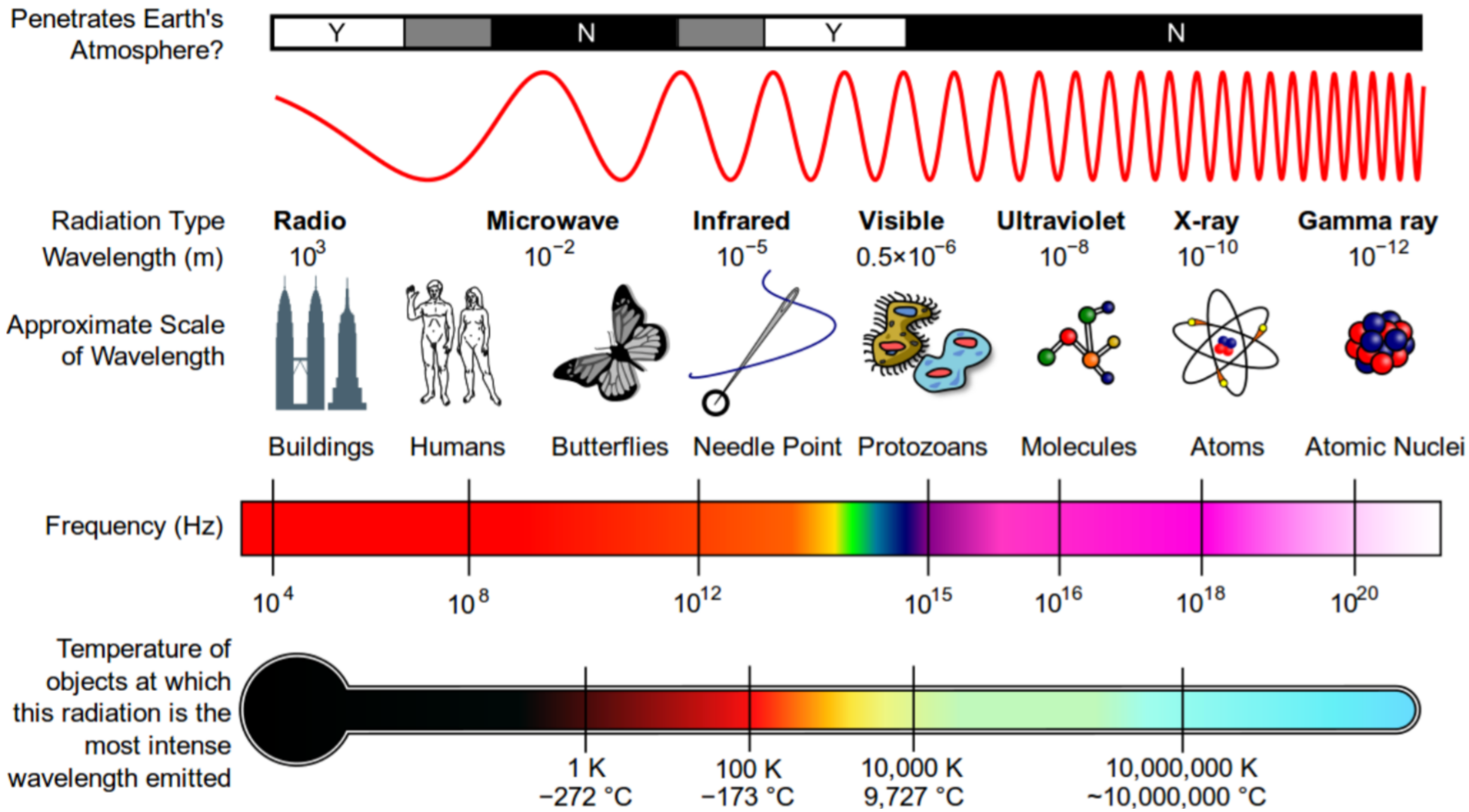


This lecture

- Introduction to X-rays.
- X-ray astronomy: what type of sources and what type of physics?
- Detection of X-rays: reflection, detectors.
- The Chandra X-Ray Observatory and ACIS.
- Getting, displaying and analyzing image data.

What are X-rays?

X-rays are a form of light, but much more energetic than the light detected by our eyes.



	Wavelength (m)	Frequency (Hz)	Energy (J)
Radio	$> 1 \times 10^{-1}$	$< 3 \times 10^{9}$	$< 2 \times 10^{-24}$
Microwave	$1 \times 10^{-3} - 1 \times 10^{-1}$	$3 \times 10^{9} - 3 \times 10^{11}$	$2 \times 10^{-24} - 2 \times 10^{-22}$
Infrared	$7 \times 10^{-7} - 1 \times 10^{-3}$	$3 \times 10^{11} - 4 \times 10^{14}$	$2 \times 10^{-22} - 3 \times 10^{-19}$
Optical	$4 \times 10^{-7} - 7 \times 10^{-7}$	$4 \times 10^{14} - 7.5 \times 10^{14}$	$3 \times 10^{-19} - 5 \times 10^{-19}$
UV	$1 \times 10^{-8} - 4 \times 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{16}$	$5 \times 10^{-19} - 2 \times 10^{-17}$
X-ray	$1 \times 10^{-11} - 1 \times 10^{-8}$	$3 \times 10^{16} - 3 \times 10^{19}$	$2 \times 10^{-17} - 2 \times 10^{-14}$
Gamma-ray	$< 1 \times 10^{-11}$	$> 3 \times 10^{19}$	$> 2 \times 10^{-14}$

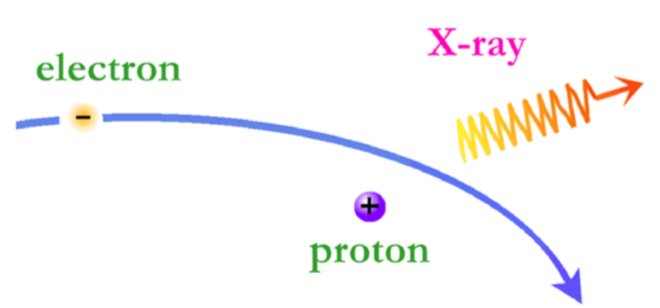
What are X-rays?

X-rays were first observed accidentally in 1895 by Wilhelm Conrad Röntgen. A week later, he took an X-ray photograph of his wife's hand which clearly revealed her wedding ring and her bones. "X" to indicate it was an unknown type of radiation.

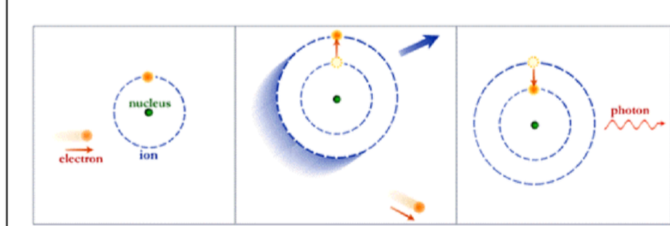
Birth of an X-ray

X-ray emission results from several radiative processes:

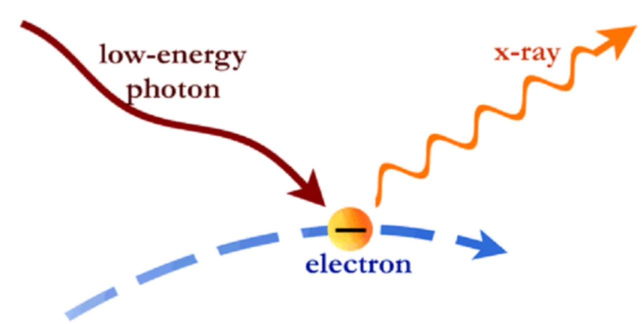
- Thermal bremsstrahlung
- Blackbody radiation
- Synchrotron radiation
- Inverse Compton scattering
- Line emission from ionized elements



X-ray Producing Collision



Atomic Emission

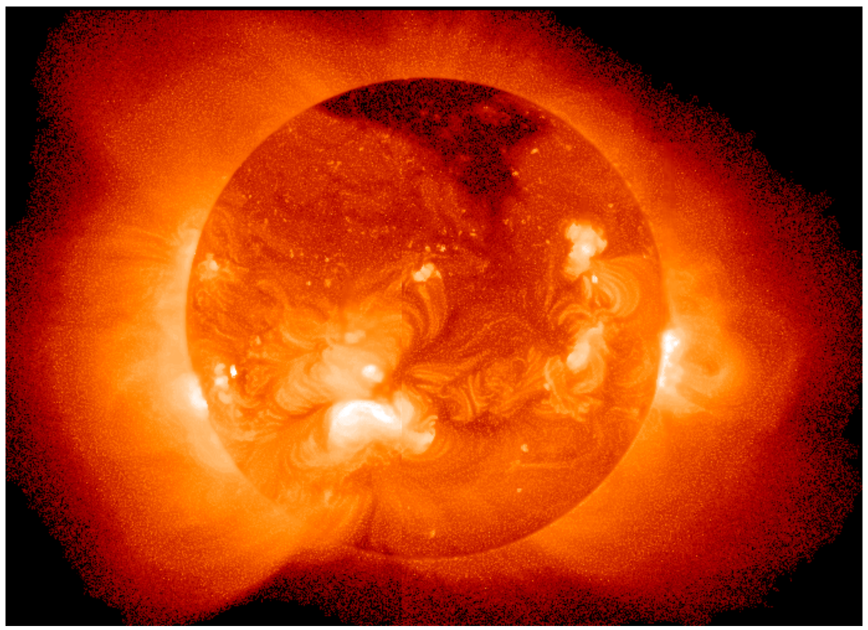


Inverse Compton Scattering

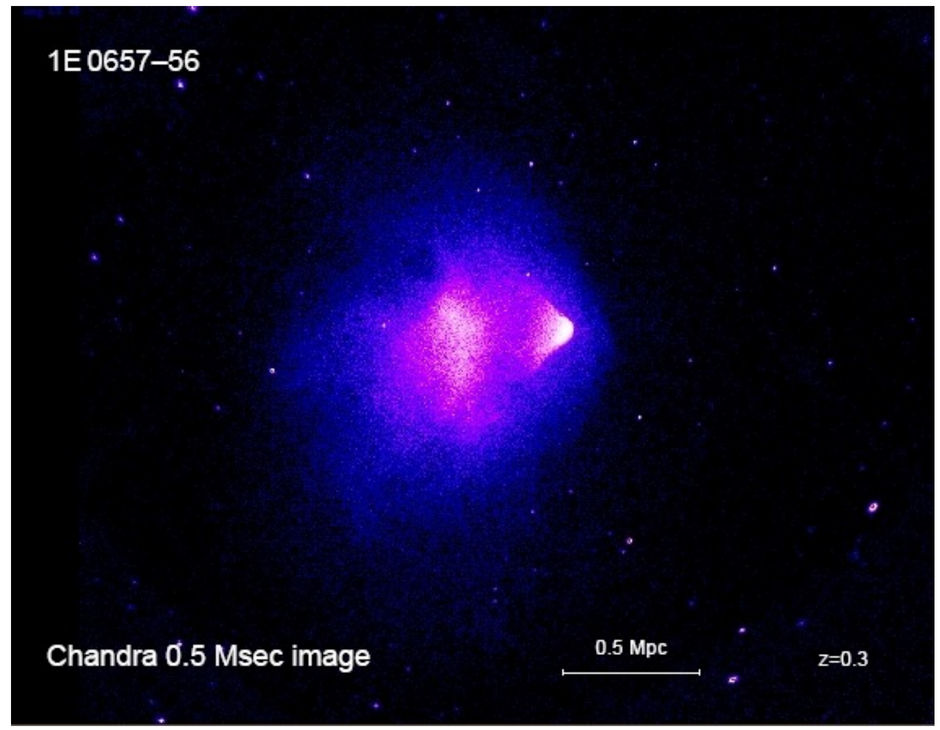
Synchrotron Radiation

Examples of astrophysical X-ray emission

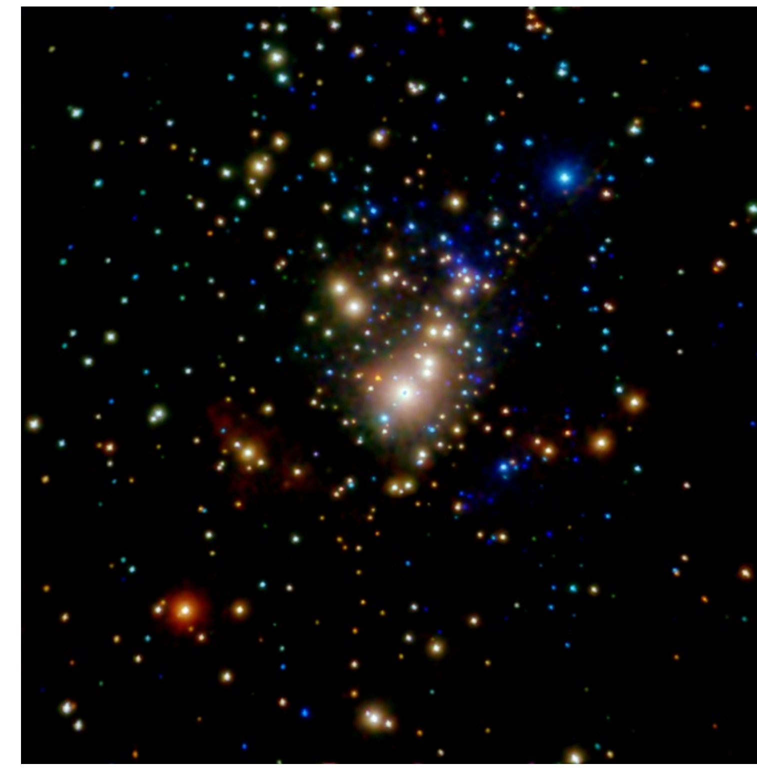
Blackbody - stellar coronae



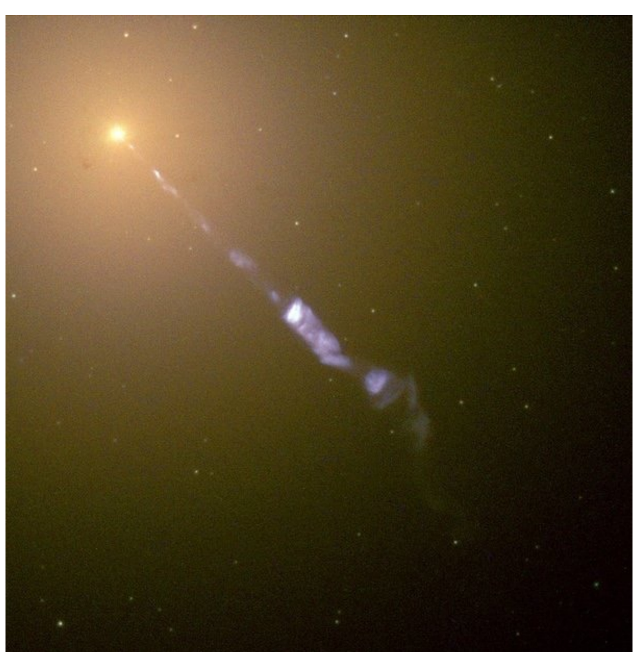
Thermal bremstrahlung - hot gas



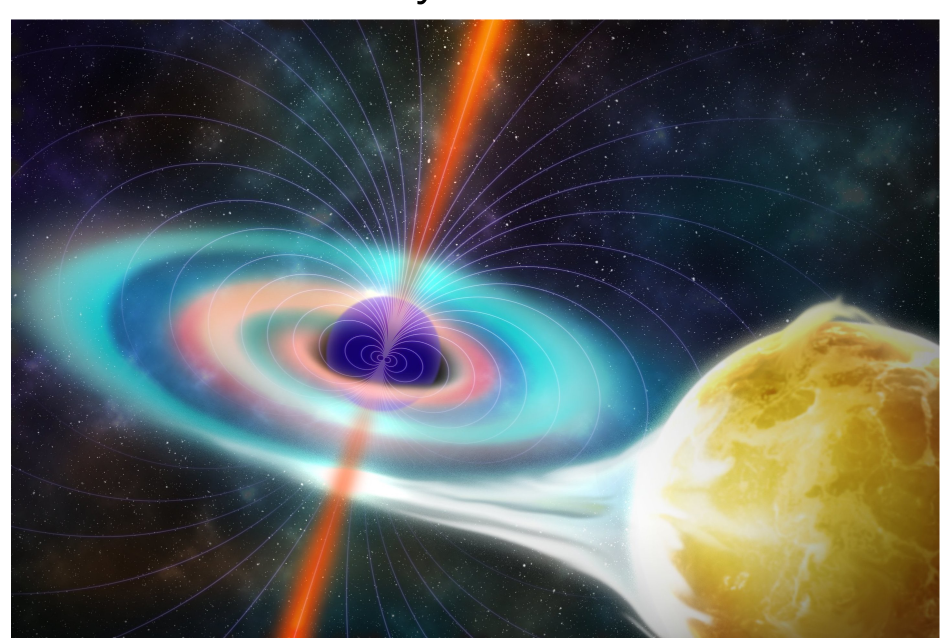
Atomic emission - young stars



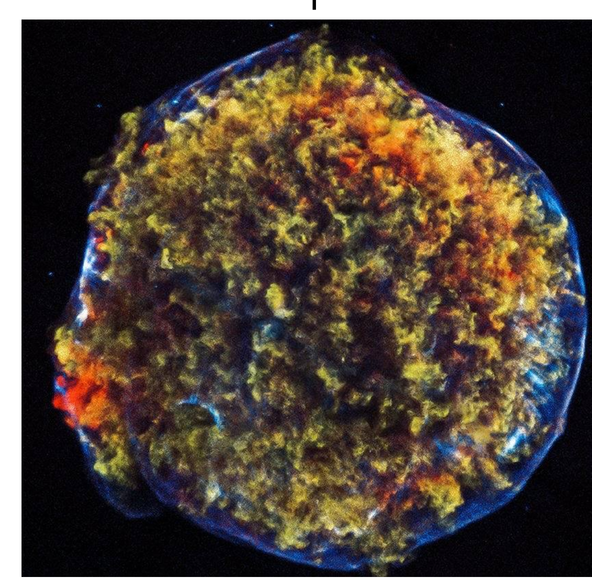
Synchroton - quasars



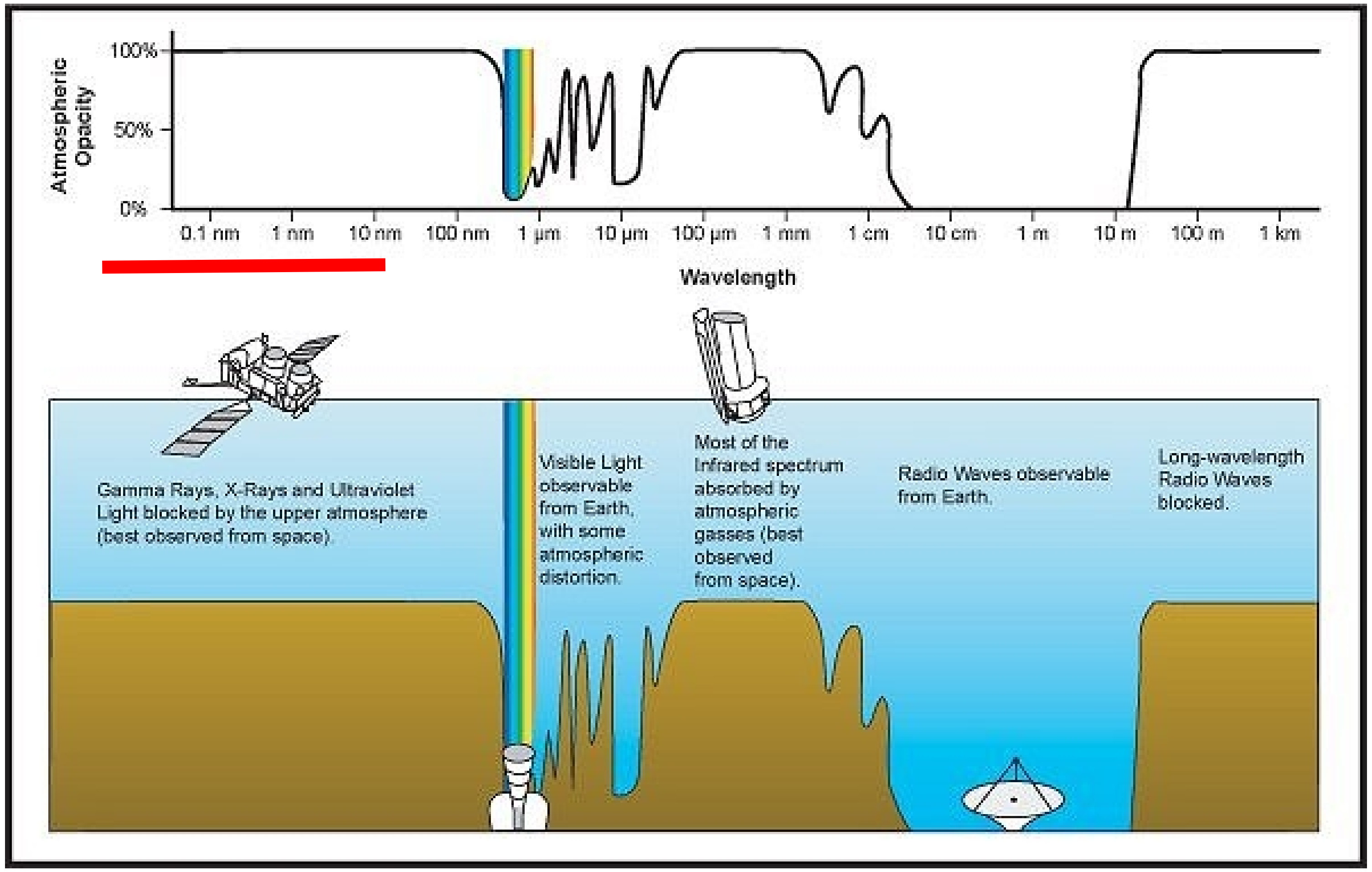
Blackbody - black holes



Inv. Compton - SN



Earth atmosphere



Composition:

- **77% N_2 (molecular nitrogen)**
- **21% O_2 (molecular oxygen)**
- 1% H_2O (Water Vapor)
- 0.93% Argon
- 0.035% CO_2
- Traces of CH4 (methane)
- Inert Gases (Ne, He, Kr, Xe)
- Particulates (e.g. dust, sea salt, etc.)

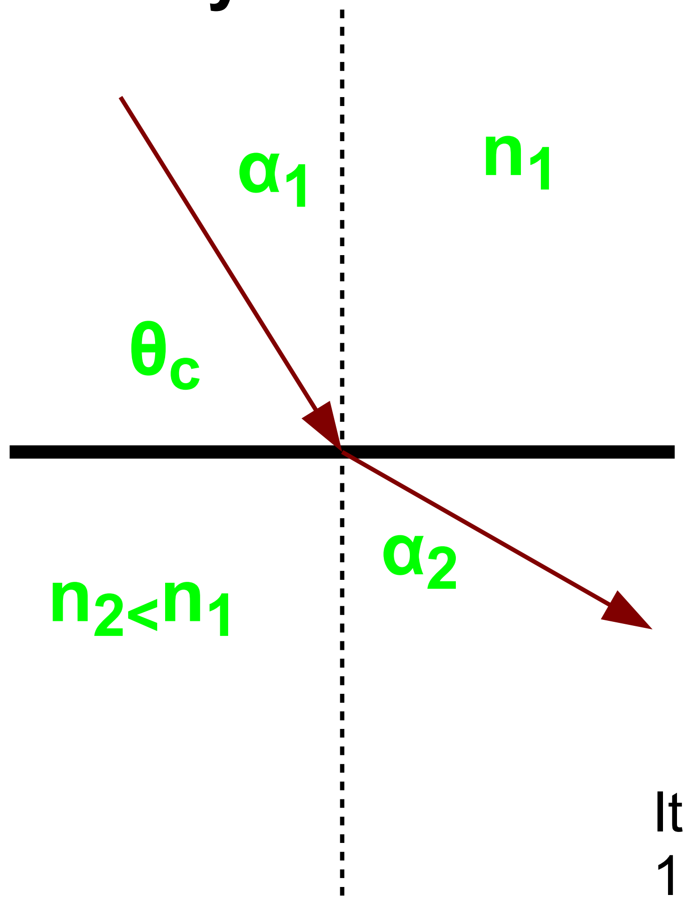
X-rays cannot penetrate the Earth's atmosphere. Thus, observations must be lunched into space: **size**, **weight** and **cost** are always important constraints on the design!!!

Realizing an X-ray telescope involves two key issues:

- **Reflect X-ray photons**
- **Detect them**

X-ray reflection

X-rays do not reflect off mirrors the same way that visible light does.



The interaction of X-rays with matter can be described by the complex index:

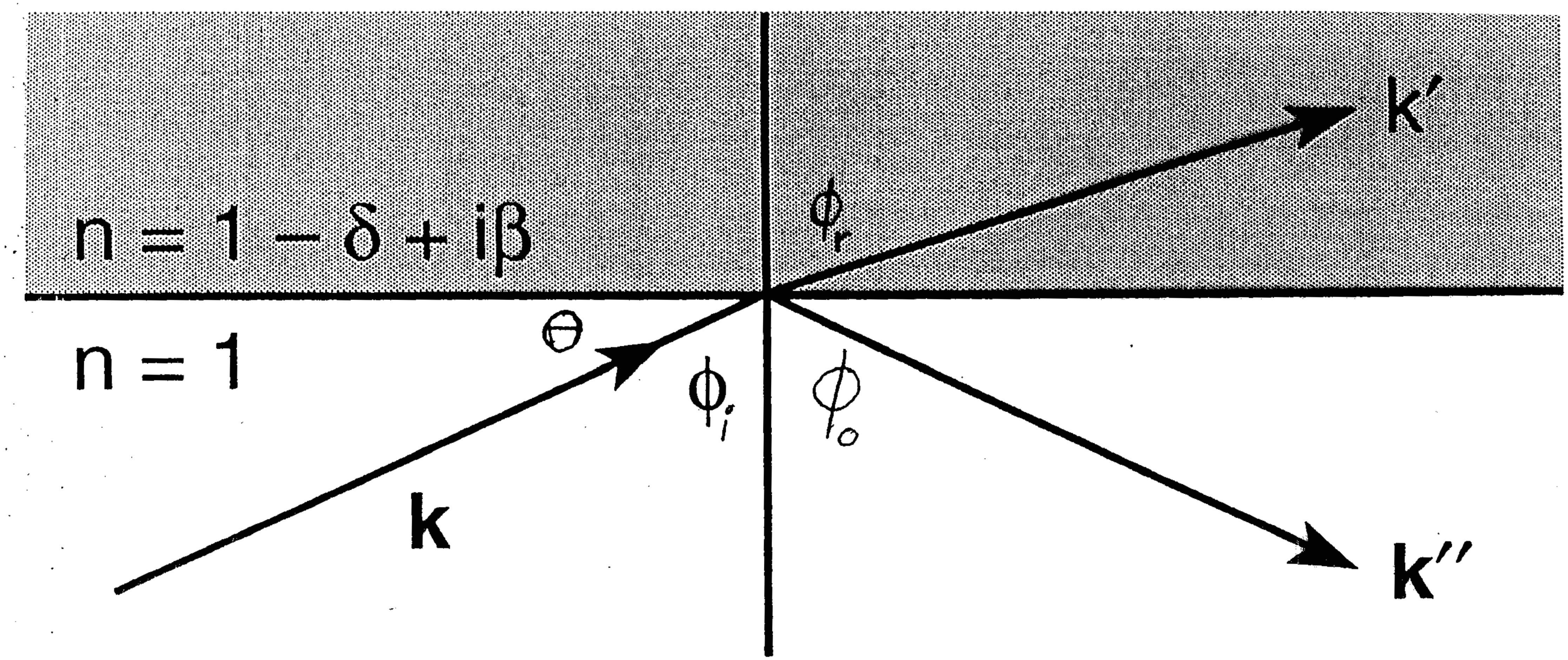
$$n = 1 - \delta + i\beta = \sqrt{\epsilon}$$

$$\delta = \rho \frac{r_e}{2\pi}\lambda^2 \qquad \beta = \frac{k}{2\lambda}$$

It is clear that the real part of the index of refraction n is smaller than 1 (δ is approximately 10^{-5} for solid material at the X-ray wavelength.

Total reflection occurs when α_2=90°, i.e. for: $\sin\alpha_{1,c} = n \Longleftrightarrow \cos\theta_c = n$

Since $\delta \ll 1$, Taylor$(\cos x \sim 1 - x^2/2)$ → $\theta_c = \sqrt{2\delta} = 5.6' \left(\frac{\rho}{1\ g\ cm^{-3}}\right)^{1/2} \frac{\lambda}{1\mathring{A}}$



We have Snell's law for refraction, $\sin \phi_r = \sin \phi_i / n$ or $\cos \theta_r = \cos \theta_i / n$

ϕ is the standard angle of incidence from the surface normal,

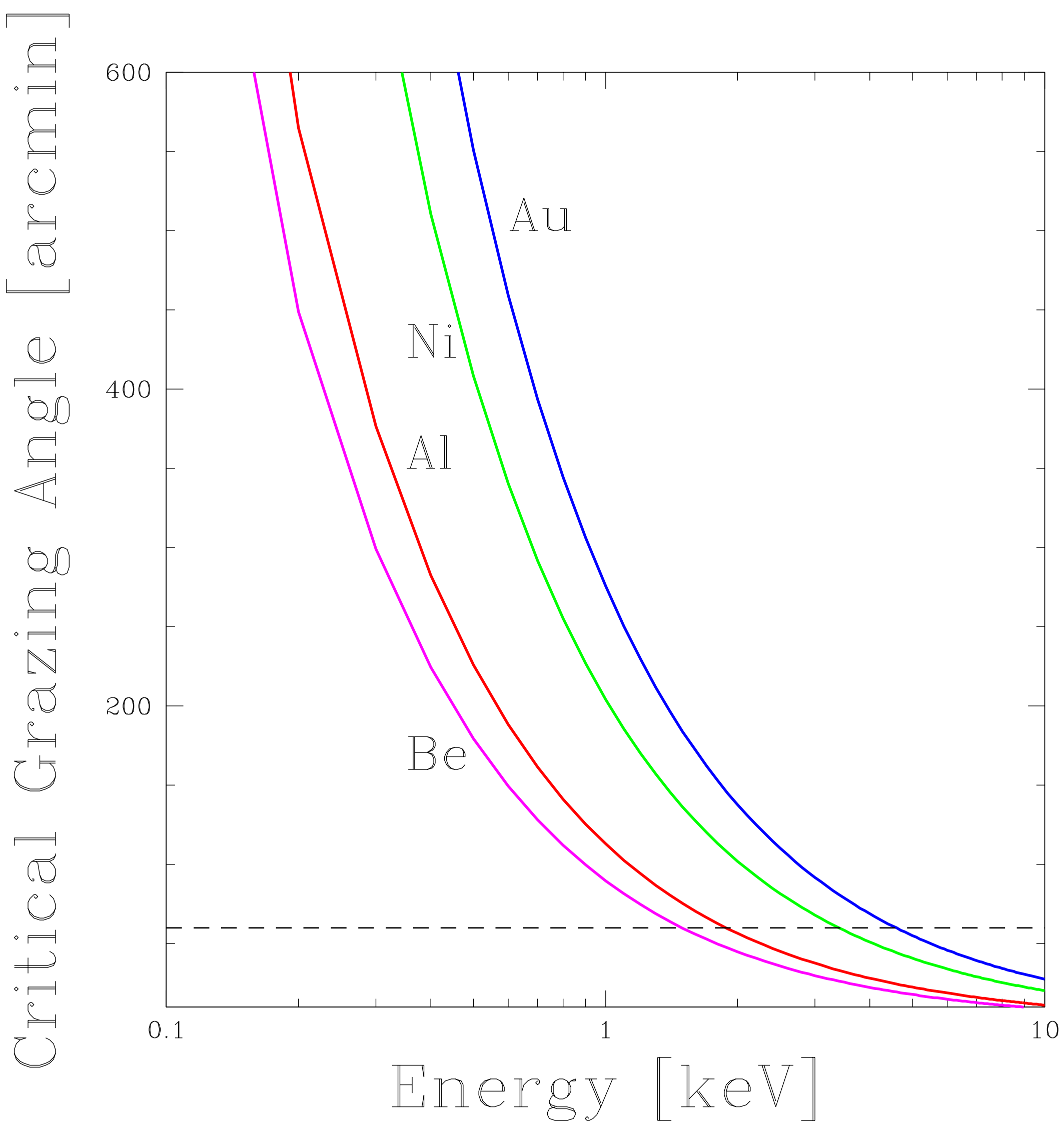
θ is the grazing angle from the surface.

The complex index of refraction is $n = 1 - \delta + i\beta$.

We have used the subscripts *i* for the incident photon, *o* for the reflected or outgoing photon, and *r* for the refracted photon.

Figure from Atwood, D. 1999, "Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications, (http://www.coe.berkeley.edu/AST/sxreuv)

Critical Grazing Angle



Total external reflection works for $\theta_i \leq \theta_c$

since $\cos\theta_c/n = \cos\theta_r = 1$.

The limiting condition is $\cos\theta_c = n$.

$\cos\theta_c \approx 1 - \theta_c^2/2 = 1 - \delta$, $\therefore\ \theta_c = \sqrt{(2\delta)}$.

Away from absorption edges, $\delta = r_0\lambda^2 N_e/(2\pi)$. $\therefore\ \theta_c \propto \sqrt{(Z)}/E$

- **The critical angle decreases inversely proportional to the energy.**
- **Higher Z materials reflect higher energies, for fixed grazing angles.**
- **Higher Z materials have a larger critical angle at any energy.**

X-ray reflection

$$\theta_c = \sqrt{2\delta} = 5.6' \left(\frac{\rho}{1\ g\ cm^{-3}} \right)^{1/2} \frac{\lambda}{1\mathring{A}}$$

High density materials are desireable for reflecting surface since they have a larger critical angle at any energy and will reflect at higher energies at any fixed grazing angle.

Typical parameters for selected elements

	Z	ρ g cm^{-3}	nZ e$^-$ Å^{-3}
C	6	2.26	0.680
Si	14	2.33	0.699
Ag	47	10.50	2.755
W	74	19.30	4.678
Au	79	19.32	4.666

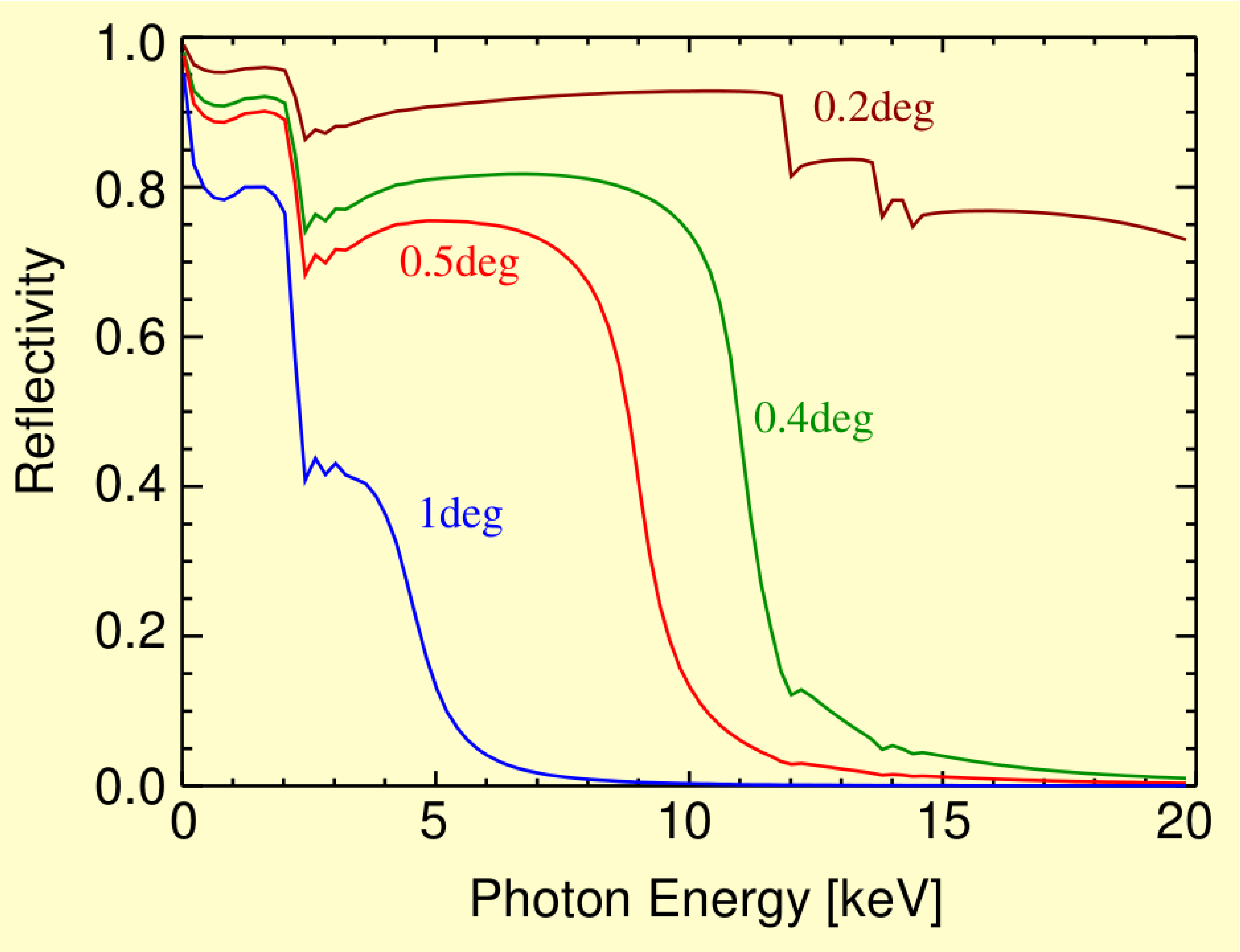
After Als-Nielsen & McMorrow (2004, Tab. 3.1)

Currently X-ray telescopes have energy range between 0.1 and 10 keV and grazing angles between 0.5 and 1 degree.

Problem

The relation above is not really true just above the atomic edges where the absorption coefficient increases and reflectivity decreases . The values in this case are verified experimentally during the calibration studies

Reflectivity for gold



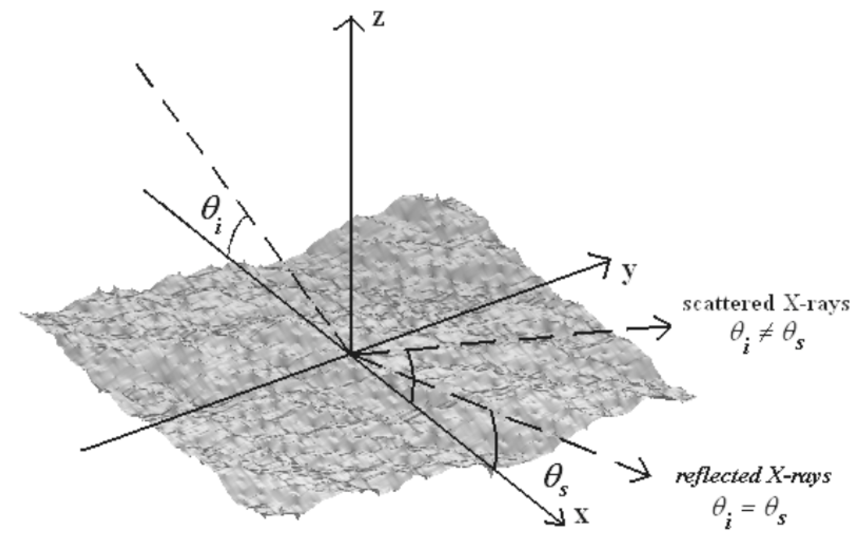
Total reflection works only in the soft X-rays and with very small grazing angles

X-ray reflection in practice

Problem: Surfaces are not infinitely smooth

Effect: X-rays will be scattered

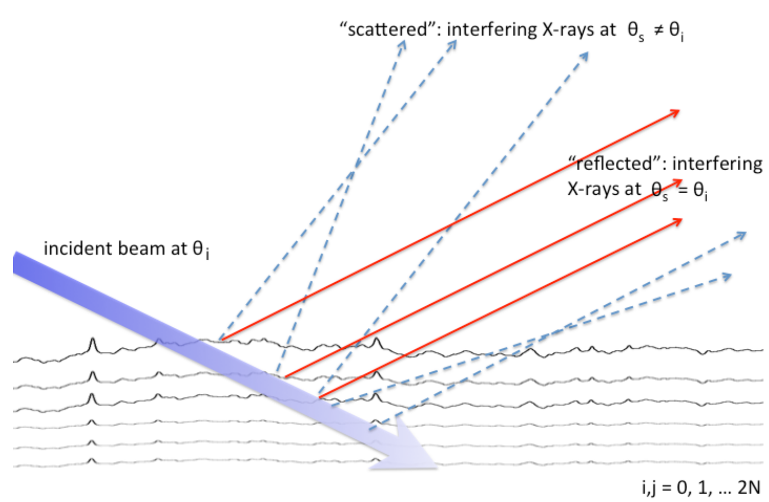
Solution: Statistical description



Problem: impact of surface scattering upon reflectivity

Effect: reflectivity enhanced due to (constructive) interference from different layers

Solution: this has been exploited to construct multi-layer mirrors for high E



Problem: assumption of the ideal density of the material

Effect: different densities give different grazing angles

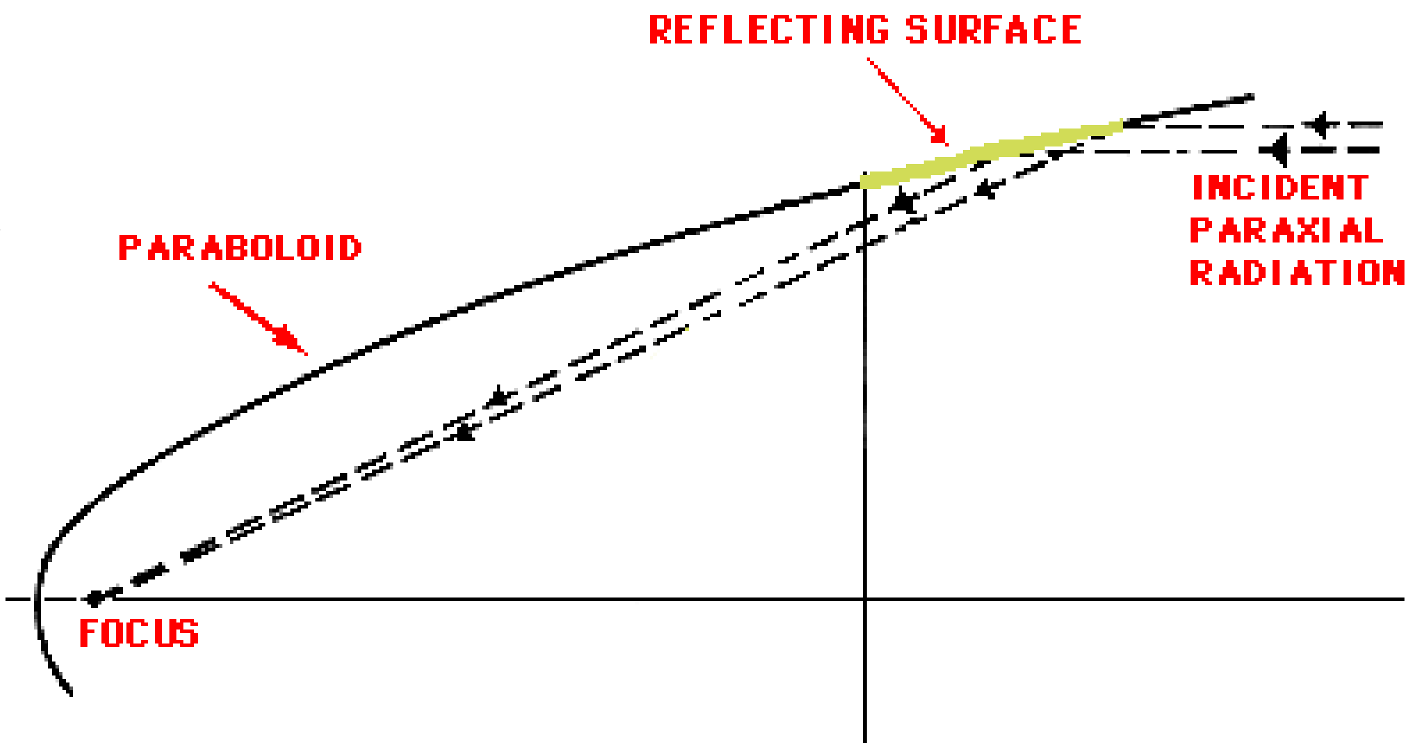
Solution: sputtering results in a higher density than evaporative heating and deposition

<u>Why not make a mirror out of pure gold?</u>

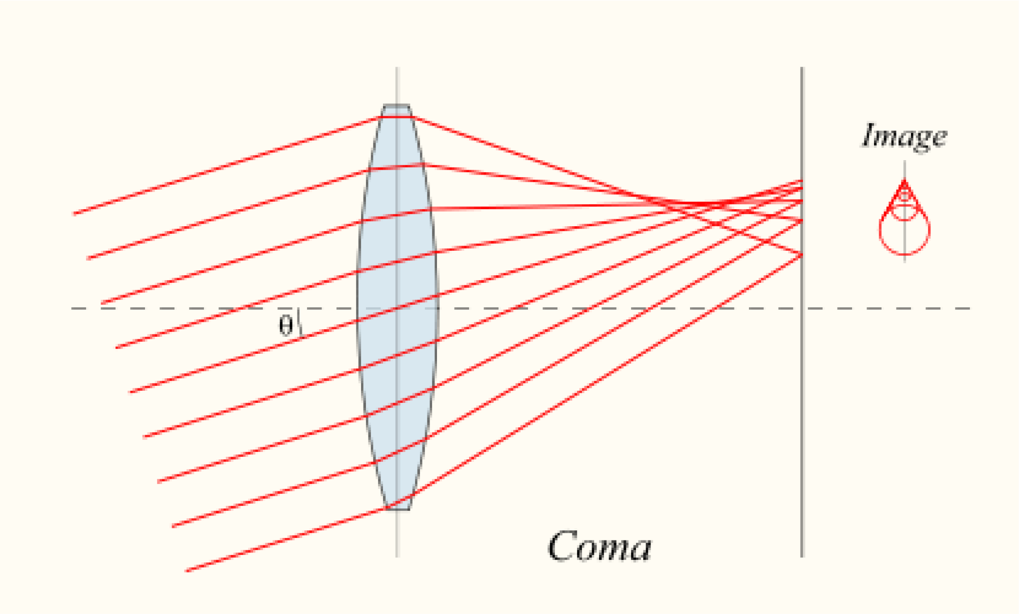
- obviously it would be too expansive
- it has an high coefficient of thermal expansion
- high weight to be launched into space

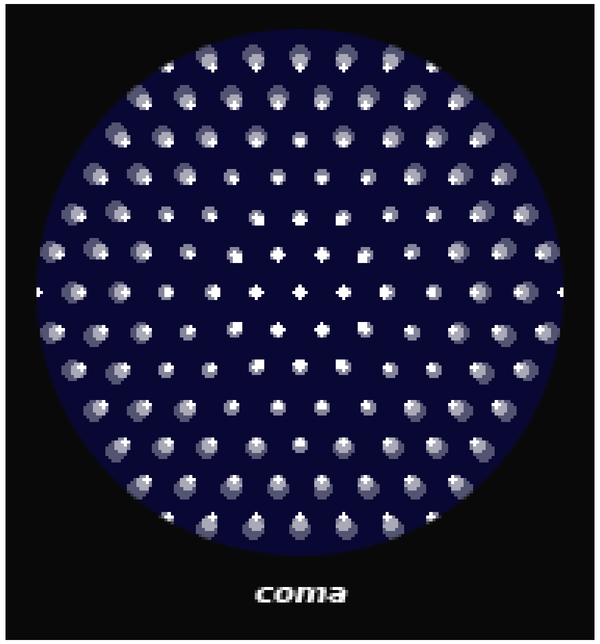
X-ray mirrors: Parabolas

A Paraboloid produces a perfect focus for on-axis rays no matter where they strike the mirror. However, this is only true if the rays are parallel to the axis of the parabola.



If the incoming rays strike the mirror at an angle this results in an image that is not in the center of the field.
Off-axis it gives a coma blur size proportional to the distance off-axis.



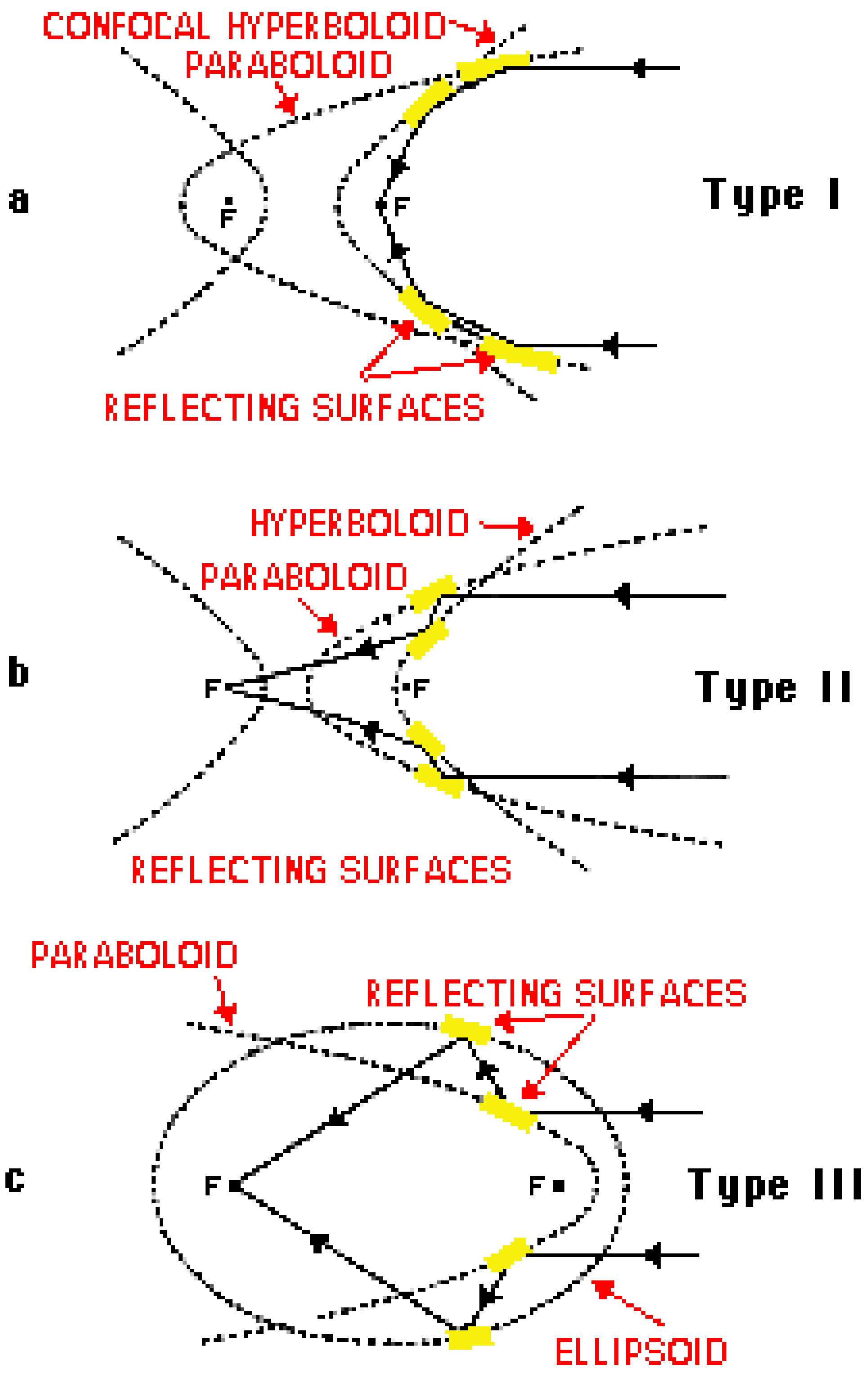


X-ray mirrors: Wolter configurations

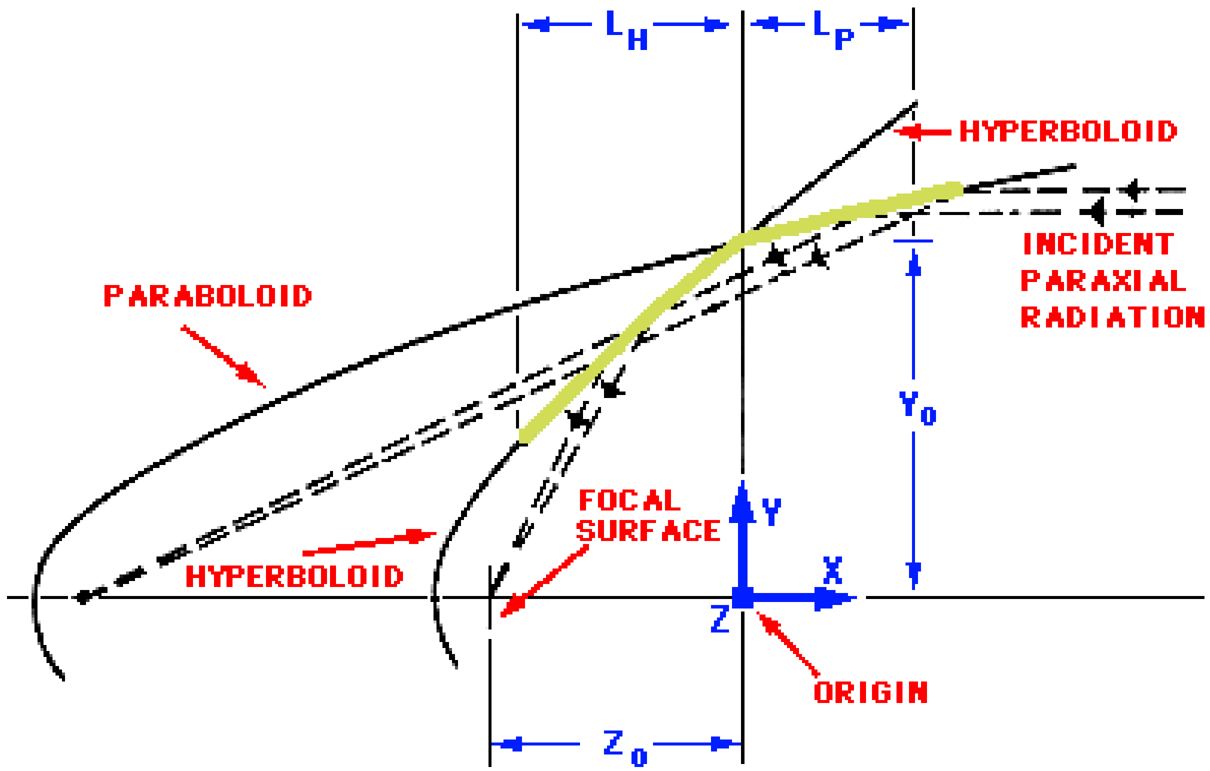
The main difference between the three systems is the ratio of focal length to total system length.

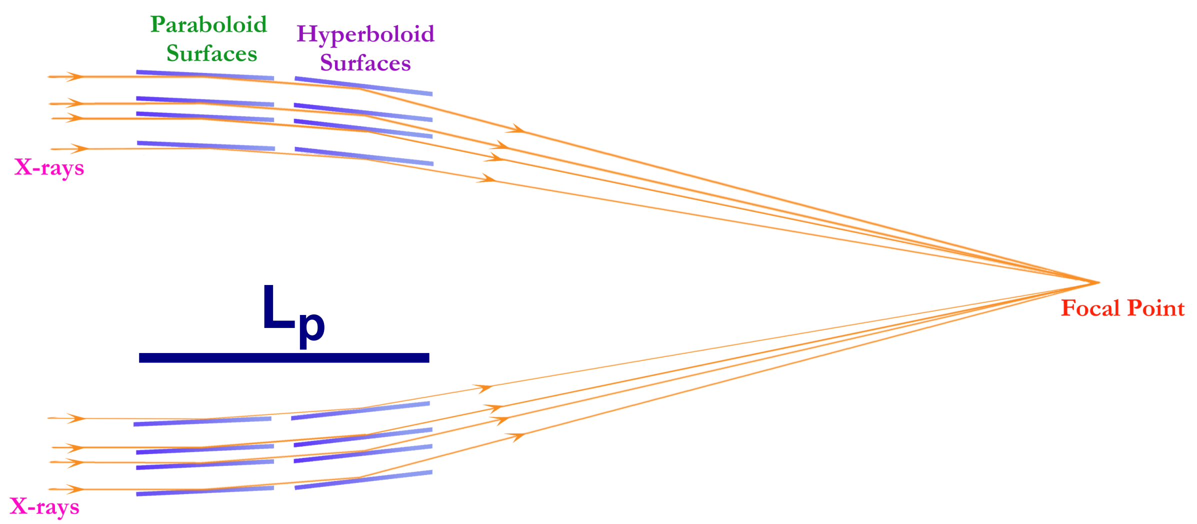
The most used in the X-ray astronomy is the type I because it give the shortest Focal length to aperture ratio. This is a very important parameter because we need to maximize the collecting area to detect weak fluxes, but we are limited by the severe restrictions on diameter (and length) imposed by available space vehicles.

Type I also allows to nest many shells to increase the collecting area.



X-ray mirrors: Wolter 1





Focal length $F = R/4\alpha$

Collecting area $A = 2\pi R L_p \alpha$

X-ray detectors

What would be the ideal detector for satellite-borne X-ray astronomy?

It would possess high spatial resolution with a large useful area, excellent temporal resolution with the ability to handle large count rates, good energy resolution with unit quantum efficiency over a large bandwidth. Its output would be stable on timescales of years and its internal background of spurious signals would be negligibly low. It would be immune to damage by the in-orbit radiation environment and would require no consumables. It would be simple, rugged, and cheap to construct, light in weight and have a minimal power consumption. It would have no moving parts and a low output data rate.

Such a detector does not exist.

- taken from X-ray Detectors in Astronomy by G. W. Fraser.

X-ray detectors

The radiation can be detected through:

- Imaging detectors: detector with a spatial resolution (e.g. CCD, PSPC)
- Non-imaging detectors: detectors capable of detecting photons from a source, but without any (or low) spatial resolution (e.g proportional counters; scintillators)

Who?

When?

Where?

Information

- Energy
- Arrival time
- Number of detections
- Position (possibly 2D)
- Polarization

What?

How?

Characteristics

- They should be able to discriminate between other types of ionizing radiations
- They should be robust, able to function in the vacuum

X-ray detectors (properties)

Spatial resolution

The ability of a detection system to record details of the objects under study. In imaging it is usually defined in terms of how close two features can be within an image and still be recorded as distinct. In many practical situations the Point Spread Function is a good definition of resolution.

Energy resolution

For detector designed to measure the energy of the incident radiation this is the most important factor. This is the ability of the detector to distinguish two close line energies.

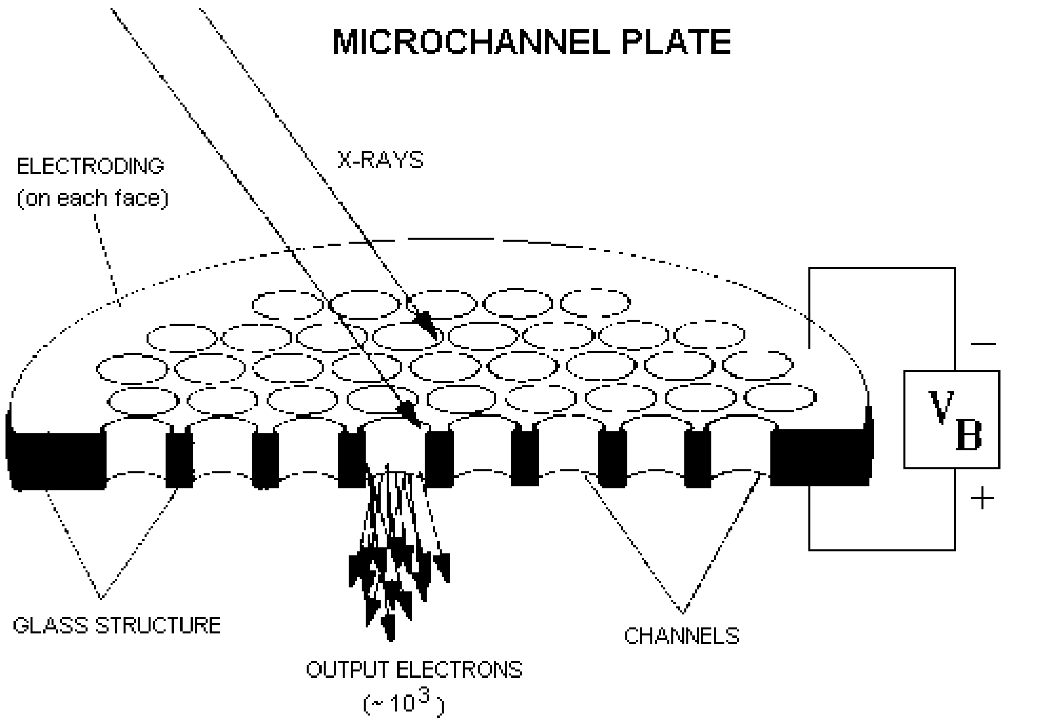
Time resolution

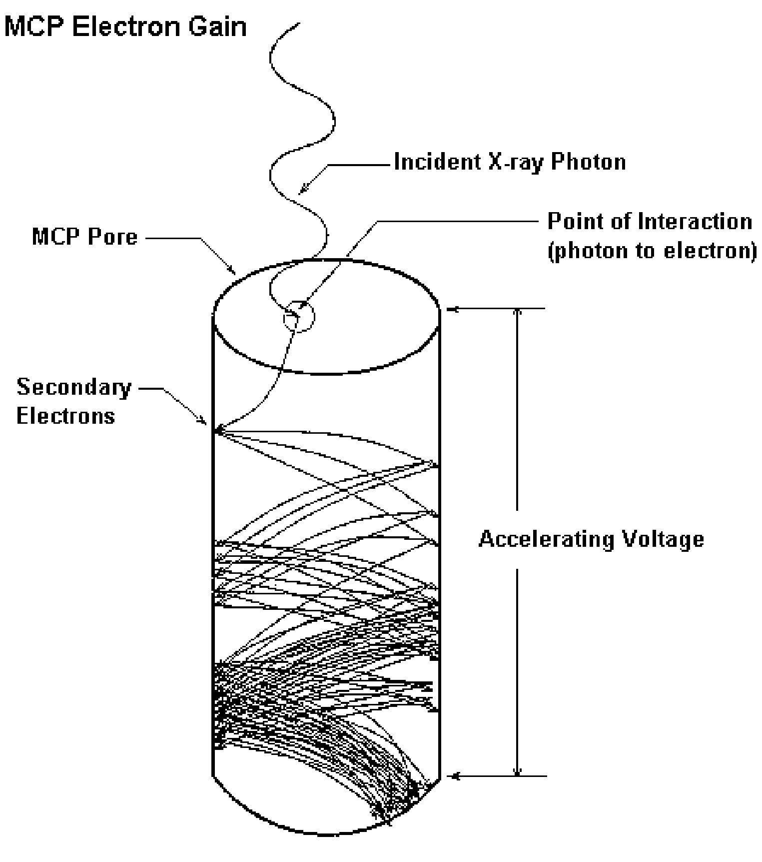
The time needed by a detector to form the signal after the arrival of the radiation. For good timing, it is important for the signal to be quickly formed otherwise a second event cannot be accepted.

Microchannel plates

High spatial resolution
No energy resolution

- Grid of many parallel micro-channels
- An X-ray photon interacting in a channel produces a charge pulse (10^3-10^4 e^-)
- Since the individual tubes confine the pulse, the spatial pattern of electron pulses at the rear of the plate preserve the pattern (image) of X-rays incident on the front surface.
- Walls are coated with a material of high photoelectric yield (e.g. nickel)
- At E>5 keV, X-rays can penetrate the channel walls to release photoelectrons in neighboring channels. This degrades resolution. At E>10 keV the photons penetrate deeper into the material and will hardly release photons.
- No detector noise





Microchannel plates

event

arrival time

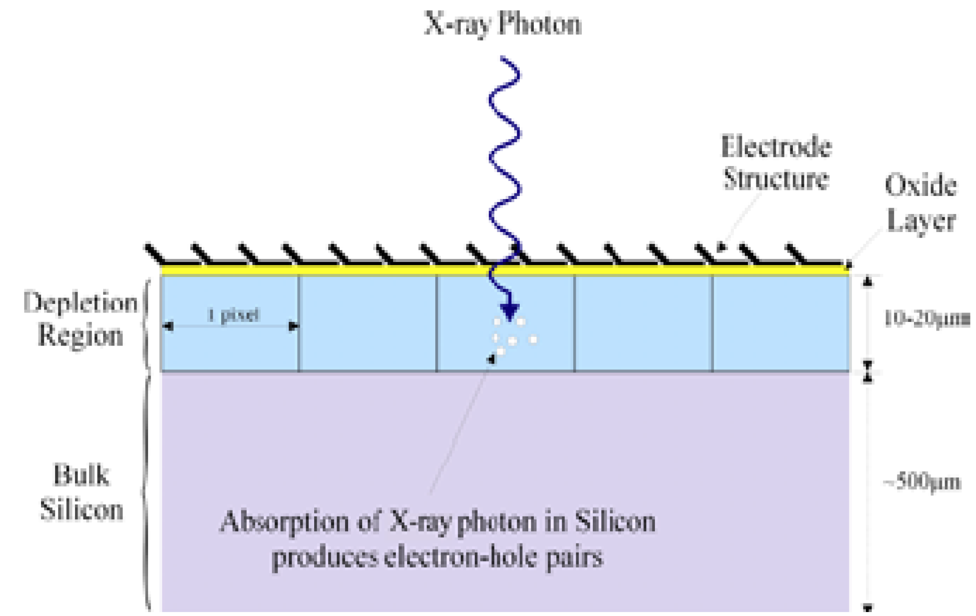
position

# row	TIME	RAWX	RAWY
#	s	pixel	pixel
1	0.	309	300
2	0.	969	737
3	0.032	694	308
4	0.032	386	179
5	0.032	444	547
6	0.032	64	299
7	0.032	811	204
8	0.064	281	276
9	0.064	783	439
10	0.064	897	397
11	0.064	516	284
12	0.064	431	707
13	0.064	764	587
14	0.096	409	369
15	0.096	505	825
16	0.096	539	570

CCDs

How does a CCD work?

- Generate photoelectrons
- Collect electrons
- Transfer the collected charges
- Read the charges



Optical

light generate a single electron-hole pair

UV

CCDs become very inefficient, primarily because of the electrodes in use which are opaque to radiation

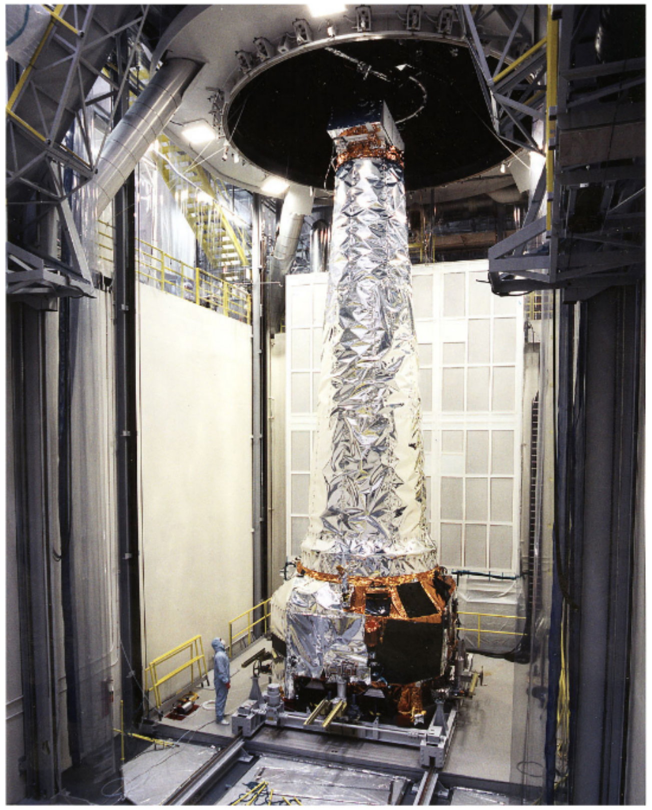
X-rays

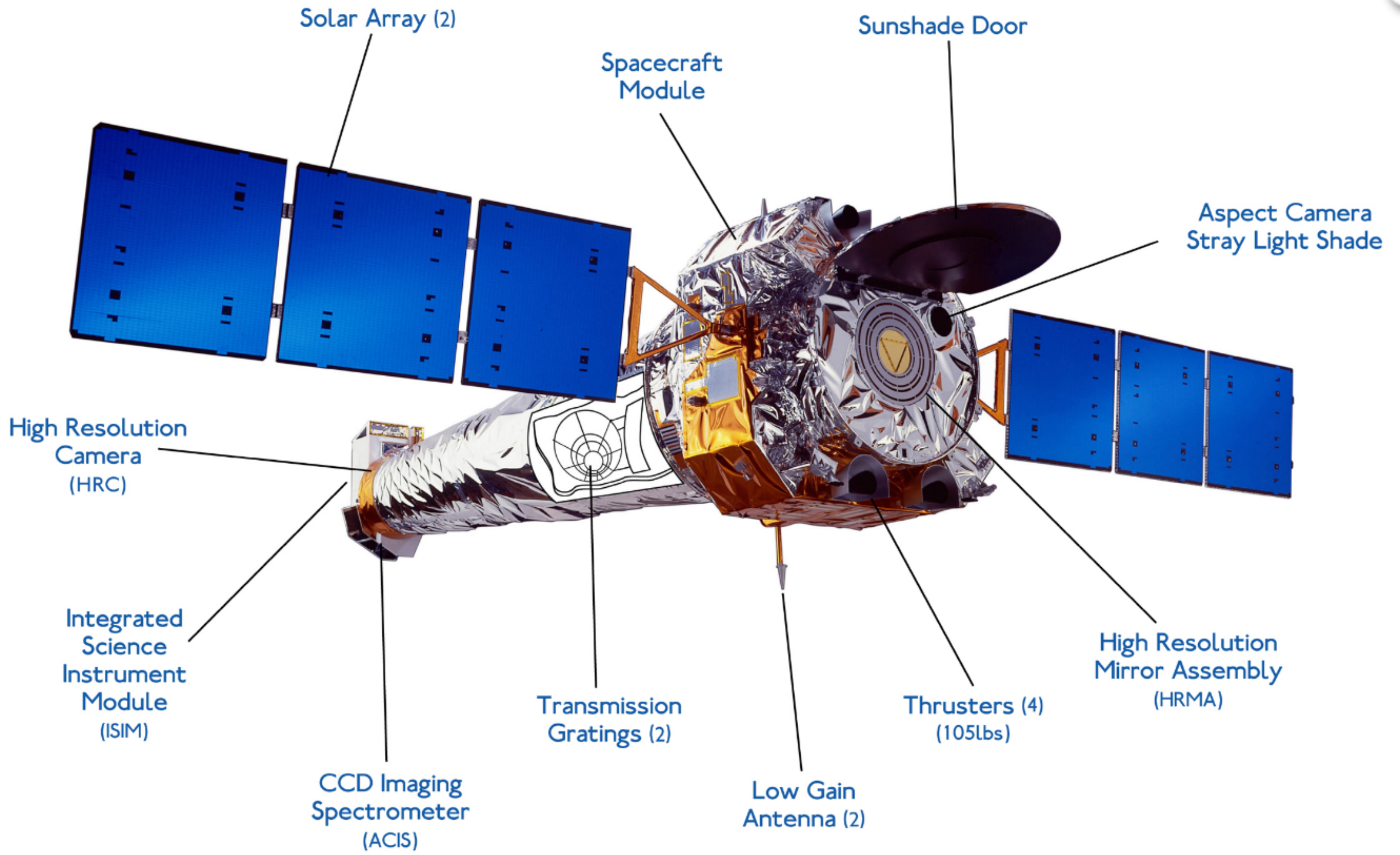
at soft X-ray wavelengths they become efficient again producing many electron-hole pairs per incident photon

X-ray CCDs usually operate in photon-counting mode where the **position and energy of every X-ray photon** can be determine individually.

In optical every photon produces too little signal to be independently sensed and longer frame times are used to accumulate many photons.

The Chandra Space Observatory





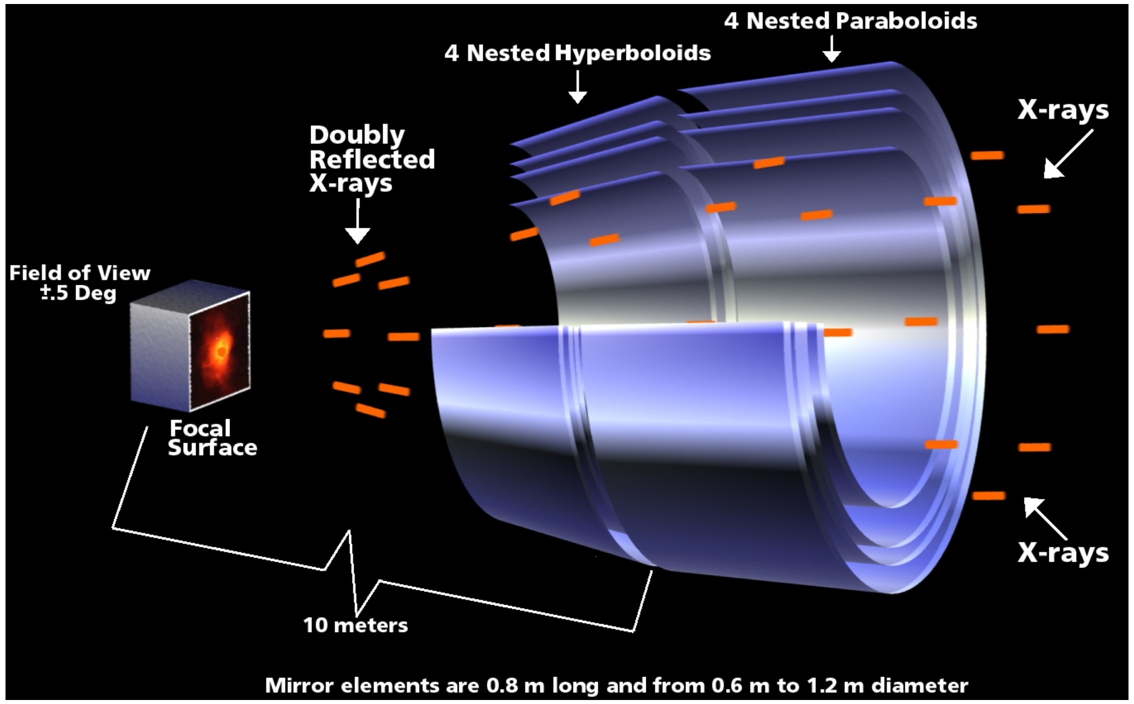
Chandra

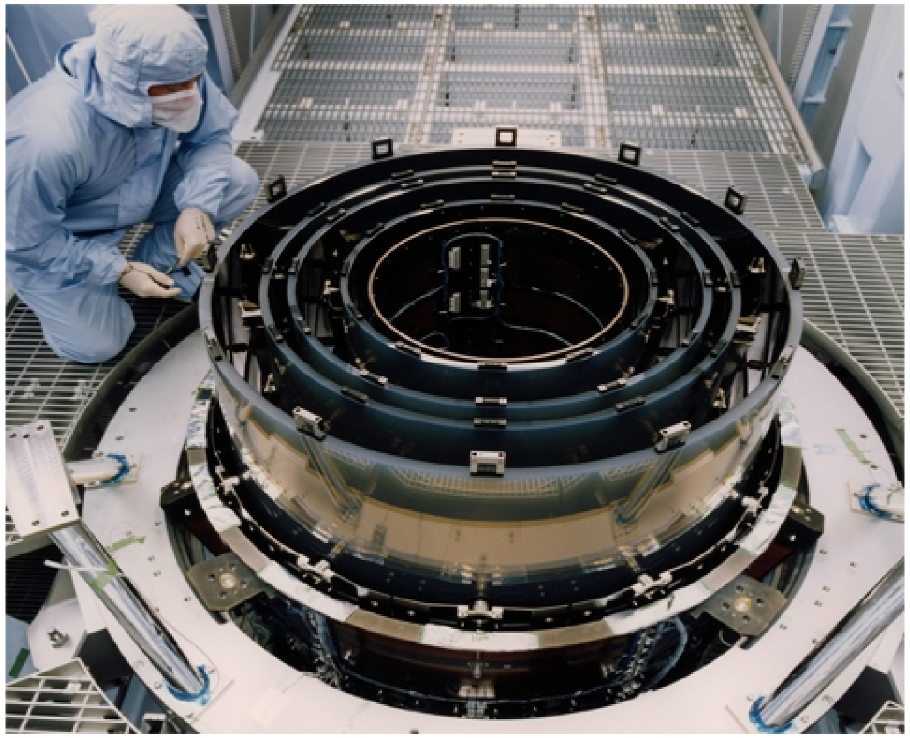
- Launched in 1999

- Single X-ray telescope with 4 nested Wolter mirrors

- Orbits Earth every 64 hours, ranging as far as 140,000 km - about 1/3 the way to the moon (HEO)

- Chandra's resolving power is 10x than any previous X-ray telescope



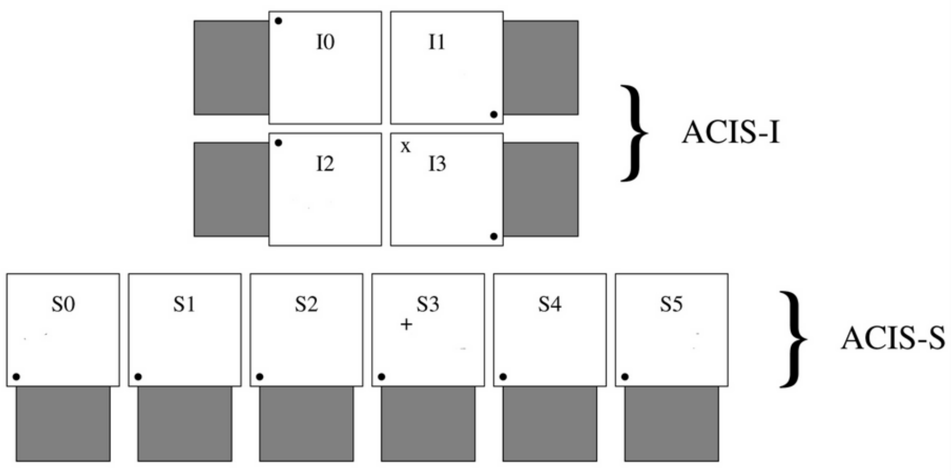


Science instruments

- 2 imaging cameras:
  - ACIS (CCD)
  - HRC (microchannel plates)
- 2 insertable transmission gratings

Chandra (instruments)

ACIS-I 4 chips array (4 CCDs FI)
ACIS-S 6 chips array (4 FI & 2 BI)



HRC-I & **HRC-S**

HRC offers the highest spatial resolution

Under certain circumstances, the HRC-S detector also offers a time resolution

HRC-S to serve as readout for the LETG

HETG+ACIS-S=HETGS high resolution spectroscopy (E/ΔE≤1000 in the 0.4-10 keV band)

HETG
- **HEG** (intercepts X-rays from only the two inner mirror shells)
- **MEG** (intercepts X-rays from only the two outer mirror shells)

LETG+HRC-S=HRCS the highest spectral resolution at low (0.08-0.2 keV) E

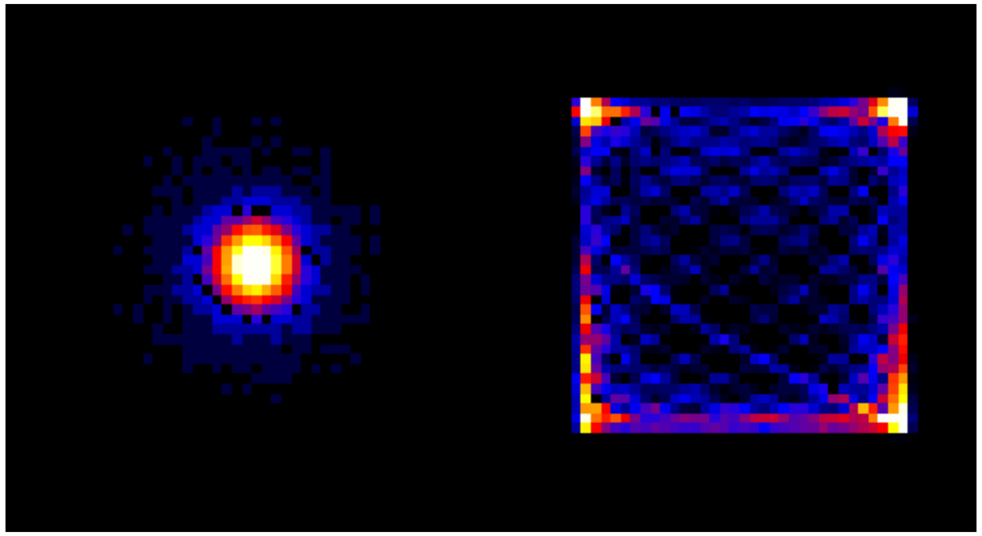
LETG single grating (intercept and disperse the flux from all the mirror shells)

A Chandra ACIS dataset: evt2 file

An event file is a list of events (photons hitting the detector that are detected). An event file is *not* an image (but can easily be turned into one).

The calibration is performed by transforming detector coordinates of the events into sky coordinates by applying an aspect solution, that accounts for telescope motion

The time of each event recorded using a correlation between telemetry and an absolute reference



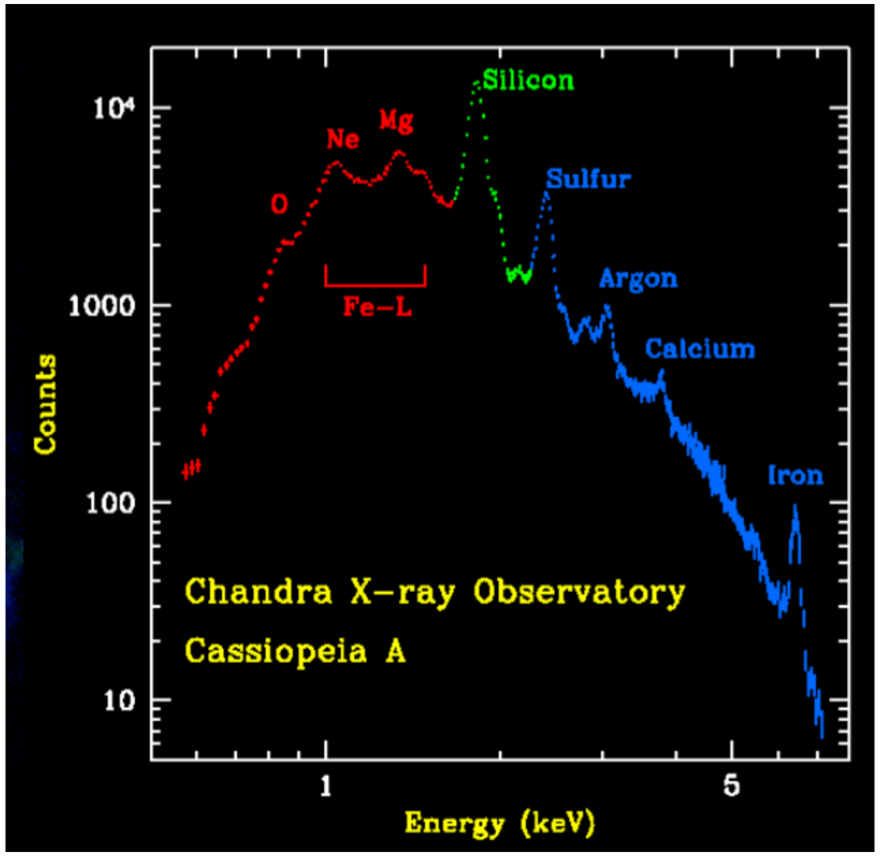
How a point source might look on the detector

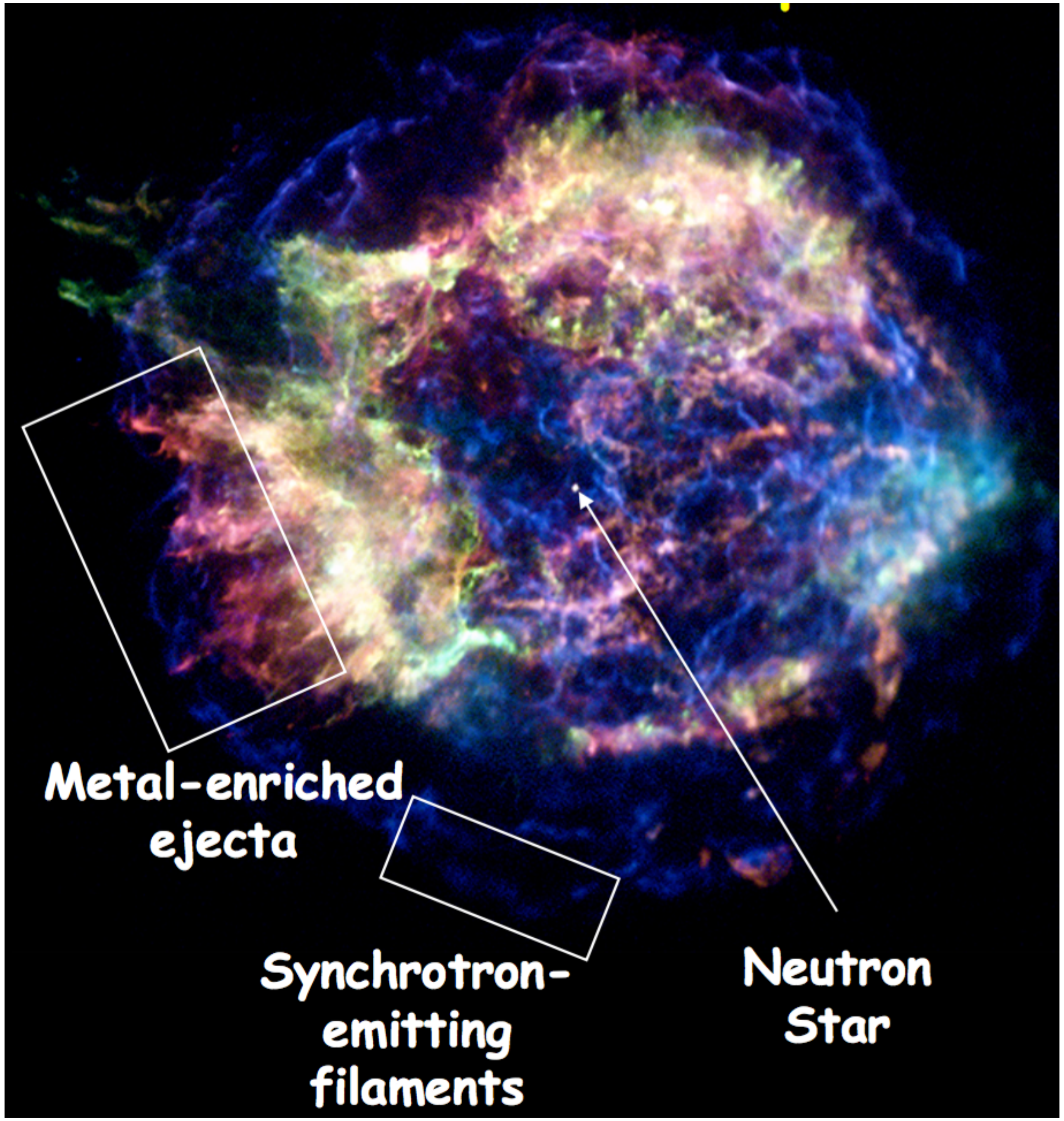
Chandra-ACIS
Some extension columns

Column Name	Description
TIME	S/C TT corresponding to mid-exposure
CCD_ID	ccd reporting event
NODE_ID	ccd serial readout amplifier node
EXPNO	exposure number of ccd frame reporting event
CHIPX	X position of center pixel of event
CHIPY	Y position of center pixel of event
TDETX	X position of event in tiled detector coordinates
TDETY	Y position of event in tiled detector coordinates
DETX	X position of event in ACIS detector coordinates
DETY	Y position of event in ACIS detector coordinates
X	X position of event in sky coordinates
Y	Y position of event in sky coordinates
ENERGY	nominal energy of event

ACIS: Working with X-ray images

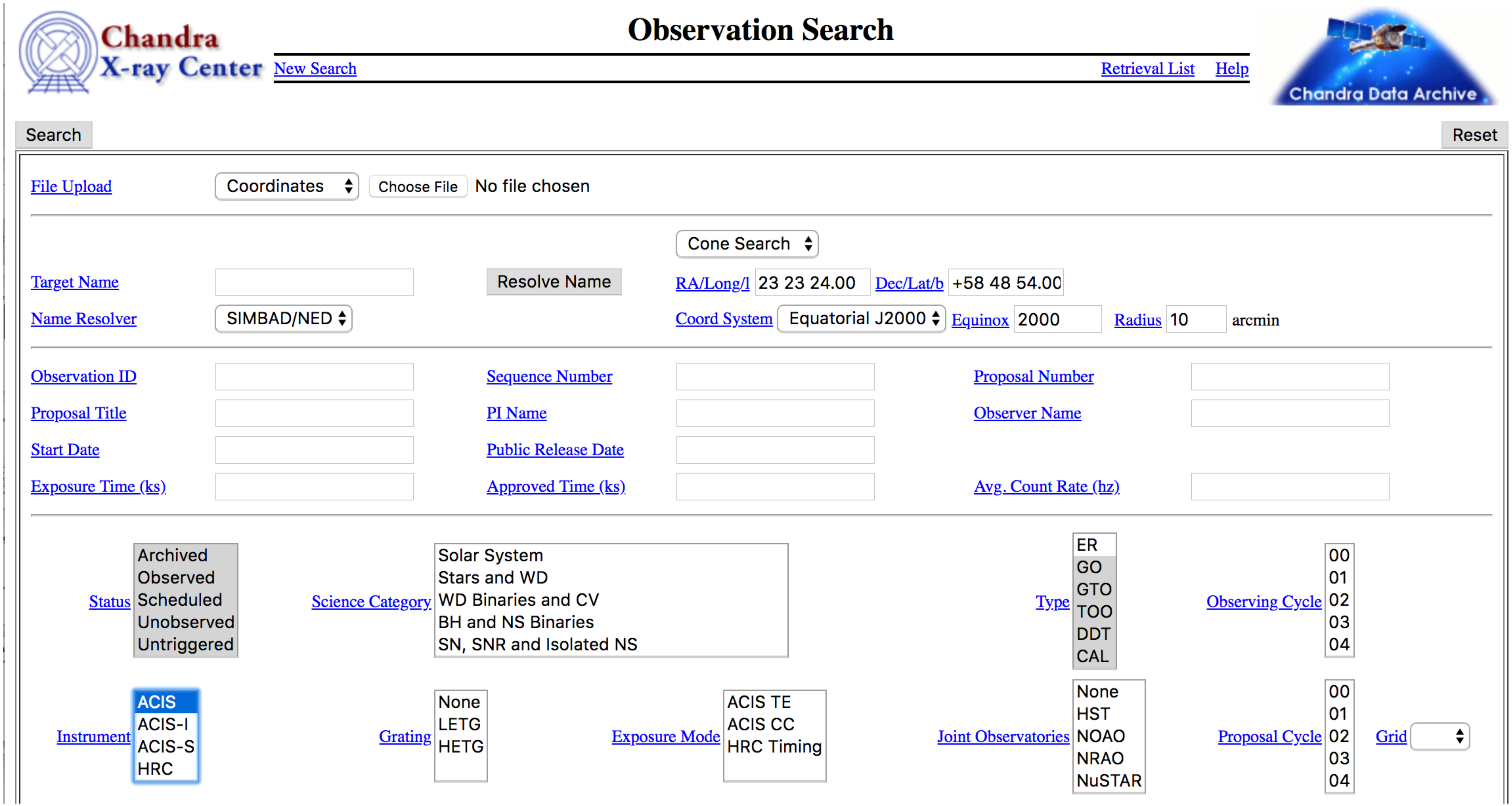
- ACIS has different bands, that depend on the energy of the incoming photons:
    - broad band (b): 0.5-7.0 keV (2.73 keV)
    - ultrasoft band (u): 0.2-0.5 keV (0.4 keV)
    - soft band (s): 0.5-1.2 keV (0.92 keV)
    - medium band (m): 1.2-2.0 keV (1.56 keV)
    - hard band (h): 2.0-7.0 keV (3.8 keV)





This is a Chandra image of Cassiopea A, a supernova remnant located at about 3.4 kpc from us.

Retrieving data from the Chandra Archive

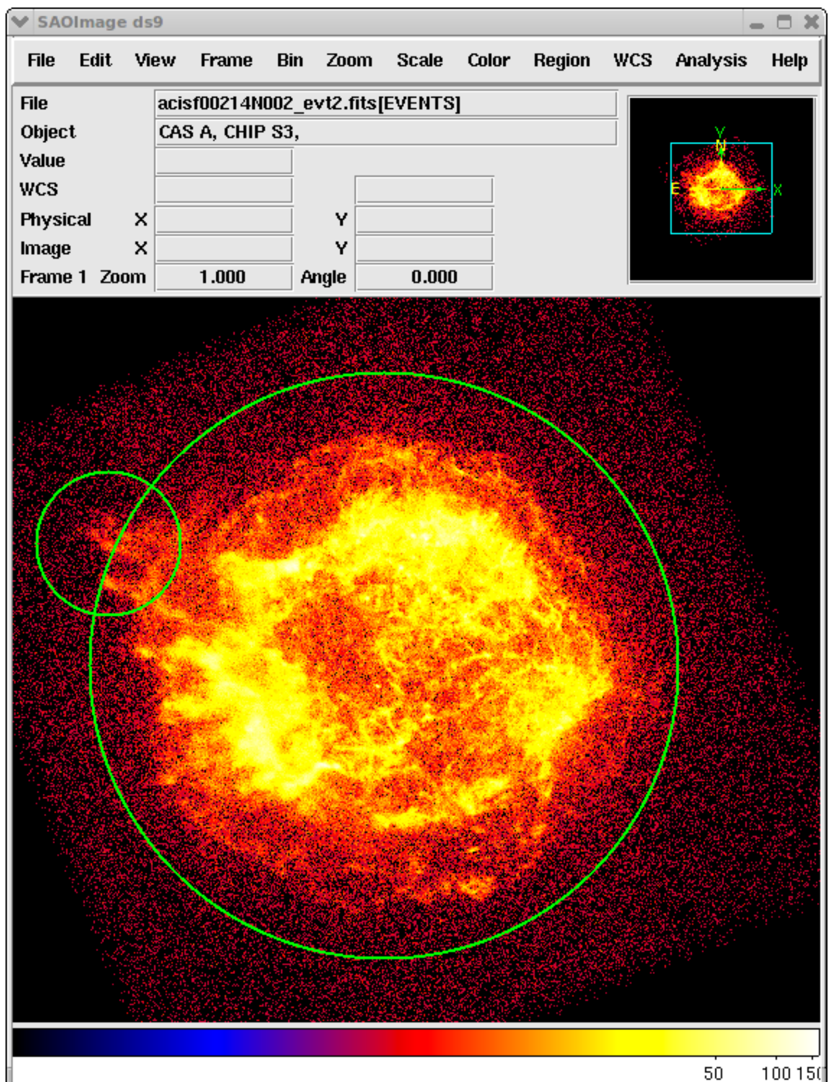


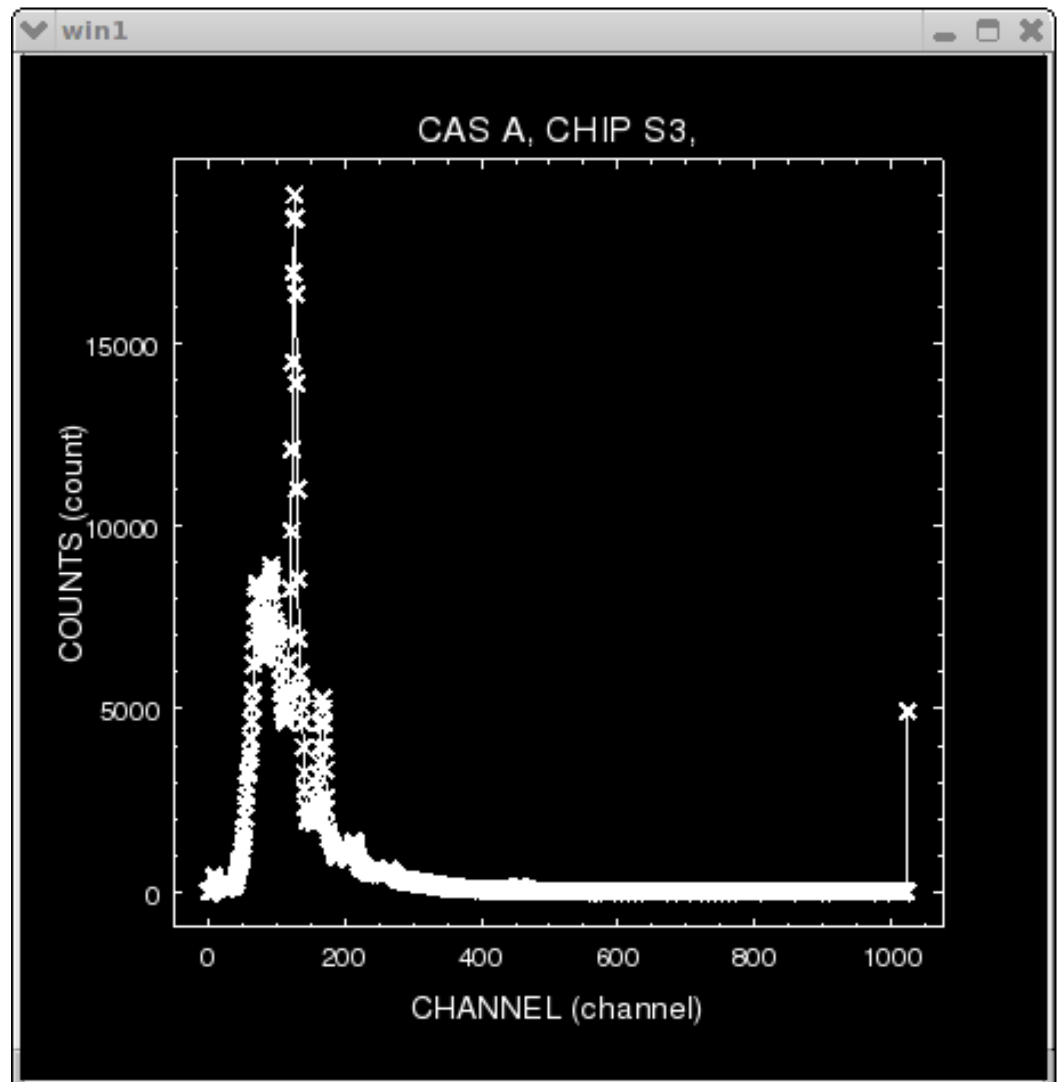
The typical data product is an event file with a list of photon detections.

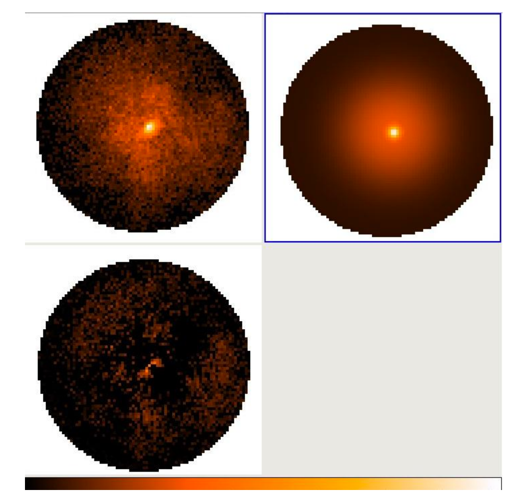
Chandra Interactive Analysis of Observations

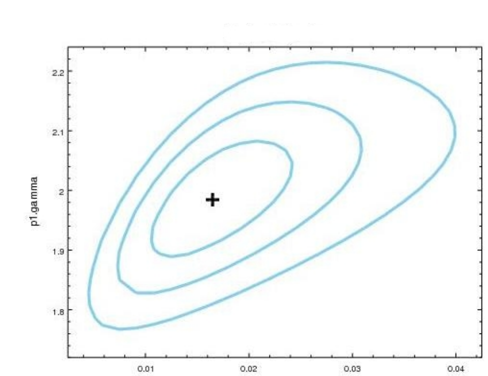
*from "s'sciavo", "I am your servant" in Venetian dialect**

CIAO is the software package developed by the Chandra X-Ray Center for analysing data from the Chandra X-ray Telescope. It can also be used with data from other Astronomical observatories, whether ground or space based.









We will now learn how to:

- Download Chandra data using CIAO.
  - ciao> download_chandra_obsid 115
- Exploring and filtering evt2 files.
  - ciao> dmlist acisf12020_repro_evt2.fits"[EVENTS][energy<14941.08593750][cols energy]" data | head
  - Making images at different energy bands and combine them to create RGB images.
  - ciao> dmcopy "acisf12020_repro_evt2.fits[energy=1650:2250]" casA_medium.fits

Exercise

- 1. Go to the catalog of SNRs and find your favorite supernova remnant (https://hea-www.harvard.edu/ChandraSNR/gallery_gal.html). Record its distance from us.

- Go to Chandra Chaser (http://cda.harvard.edu/chaser/) and find ACIS obsIDs for that source. Pick one with an exposure between 20ks and 50ks.

- Start CIAO and download your chosen obsID

- Create three images from the evt2 file: one for each energy and s,m, and h, and create a three color image of the remnant in DS9.

- What is the physical radius of this SNR?

- What regions of the supernova are brighter in each different band?