Proposal Ideas - Due Tuesday 4/30

For next Tuesday's class, be prepared to discuss two proposal ideas. Here I am looking for science topic, which instrument you would use, and any thoughts about sample/targets you have.

Proposals may use:

- one of the imagers on Hubble (ACS or WFC3)
- the Chandra CCD detectors (ACIS)

Proposals may be for new observations or use archival data.

Come talk to me if you need help!

X-ray Astronomy

References

"Measuring the Universe" - G. Reike, Chapt. 10.1-10.4

"Handbook of X-ray Astronomy" - Arnaud, Smith, and Siemiginowska

"Allen's Astrophysical Quantities" - Chapter 15

Chandra X-ray observatory pages - "Field Guide to X-ray Astronomy" as well as cookbooks for X-ray data reduction

Sources of Emission

X-ray emission results from several radiative processes:

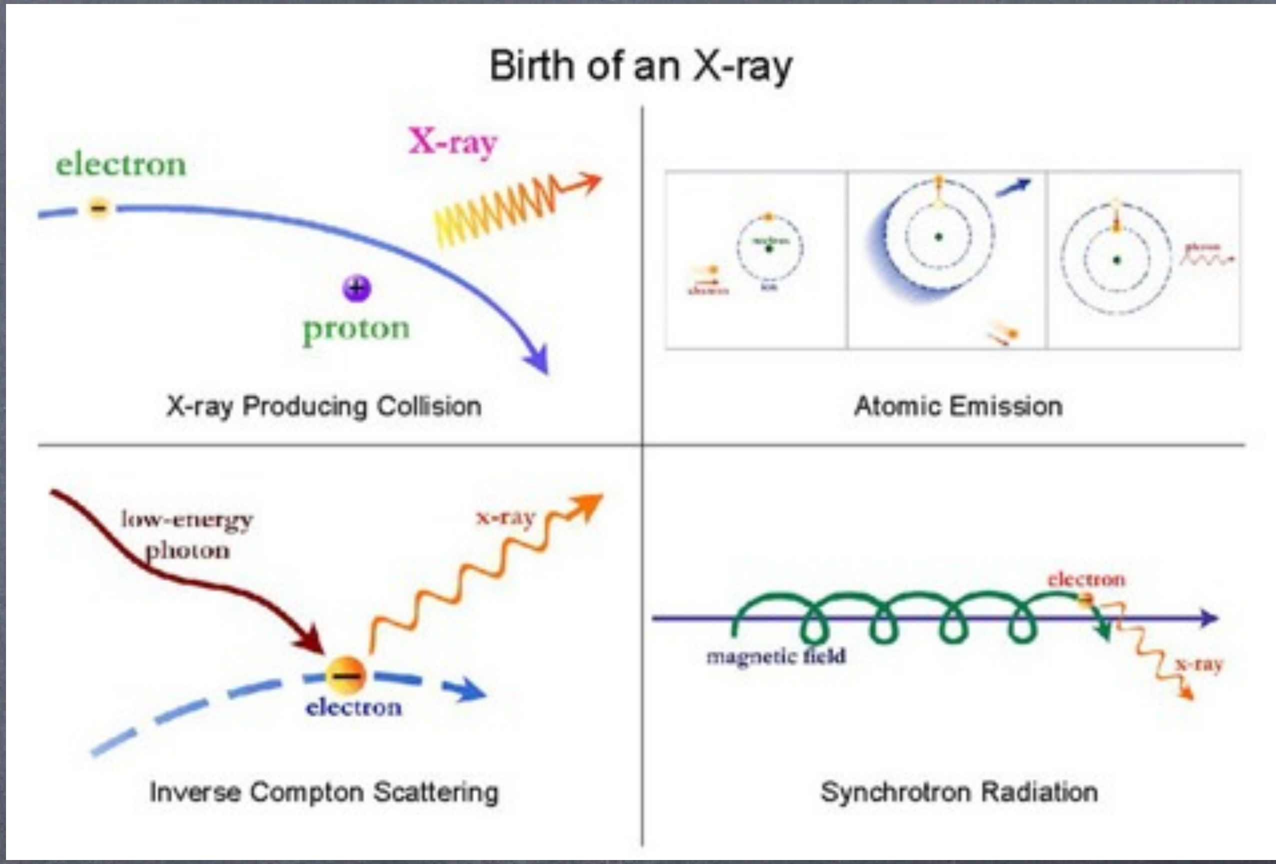
- Thermal bremsstrahlung

- Blackbody radiation

- Synchrotron radiation

- Inverse Compton scattering

- Line emission from several highly ionized elements, notably H-like and He-like O and Fe

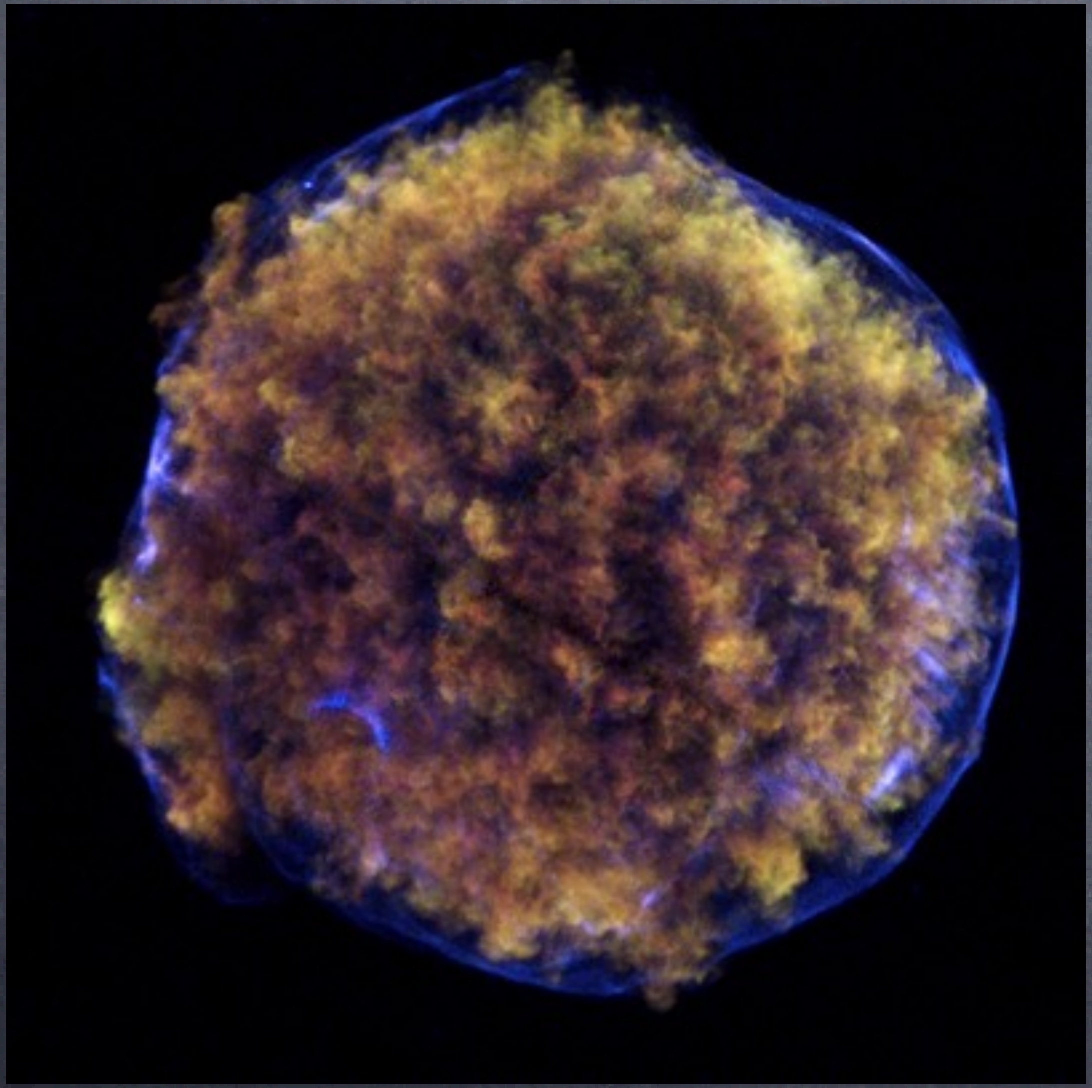


Sources of Emission

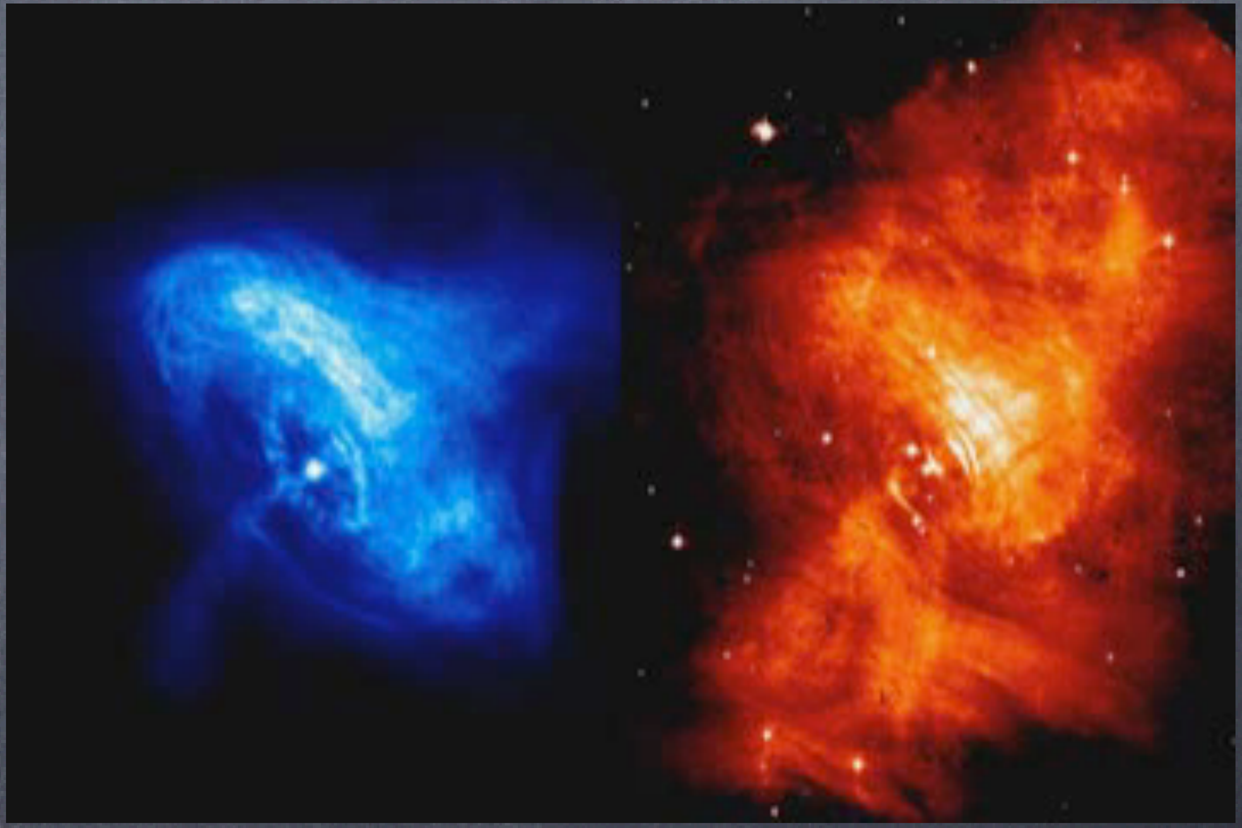
- AGN: hot accretion disk, jets
- Supernova remnants: shocks, line emission, heated gas
- Neutron stars, white dwarfs, and their binaries: accretion, strong magnetic fields
- Clusters of galaxies, galaxies: thermal bremsstrahlung from hot gas at 10^7–10^8 K
- Stars, active stars: hot coronae, shocks from stellar winds from young stars

Supernovae and Pulsars

Tycho SNR with Chandra

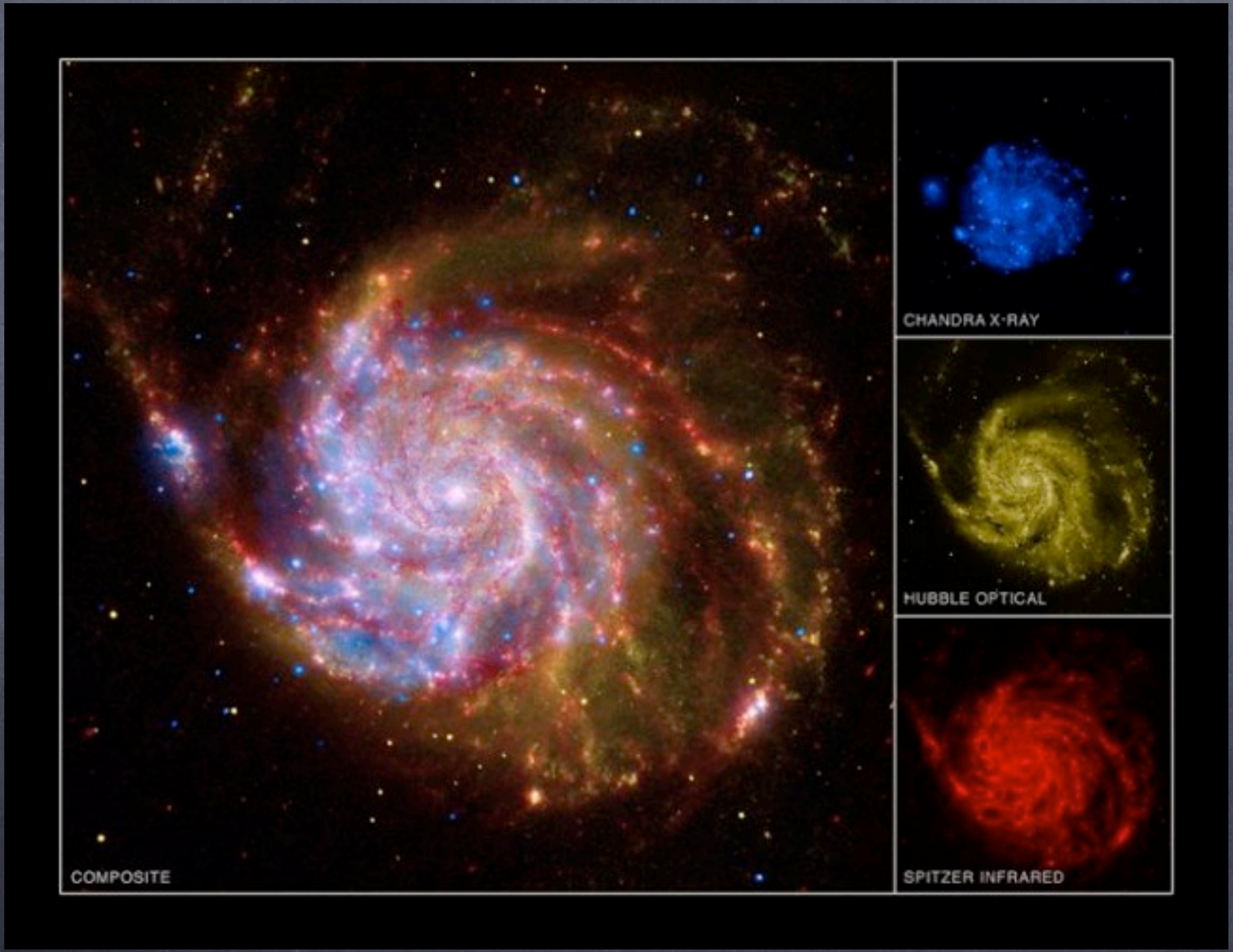


Crab Nebula with Chandra and Hubble



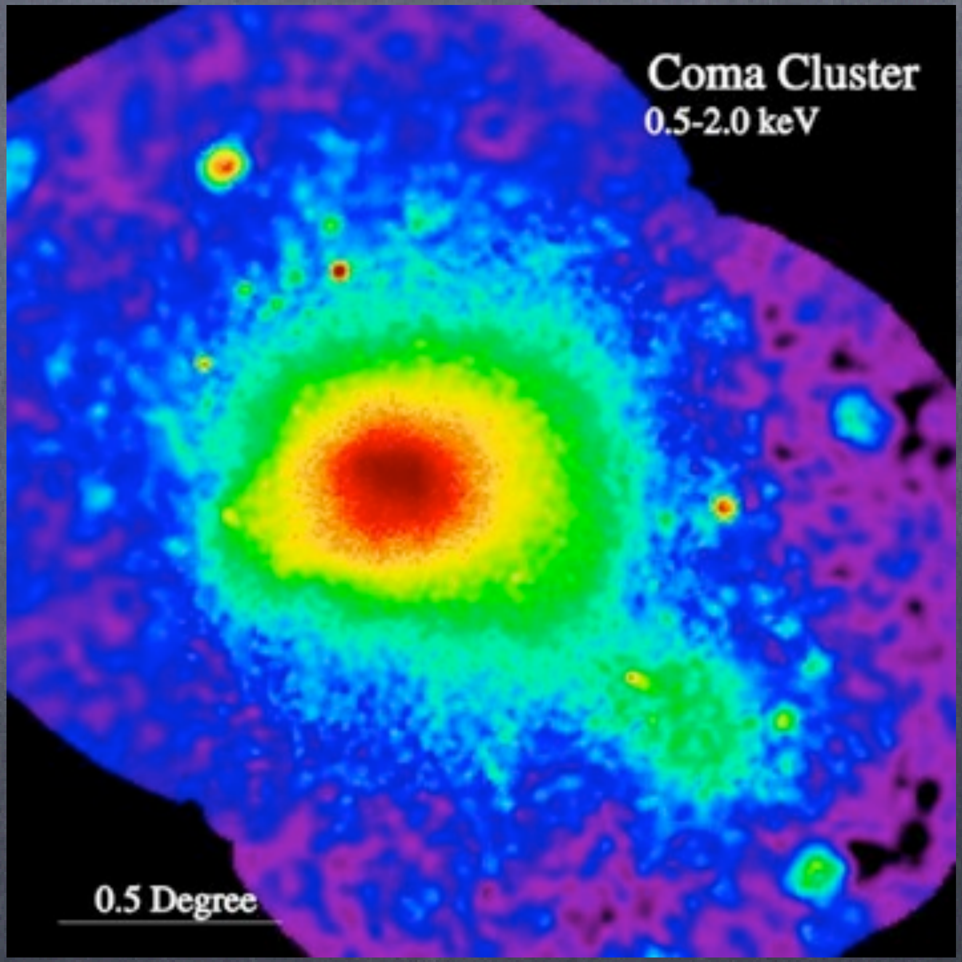
Galaxies

M101 composite from Chandra, Hubble, and Spitzer

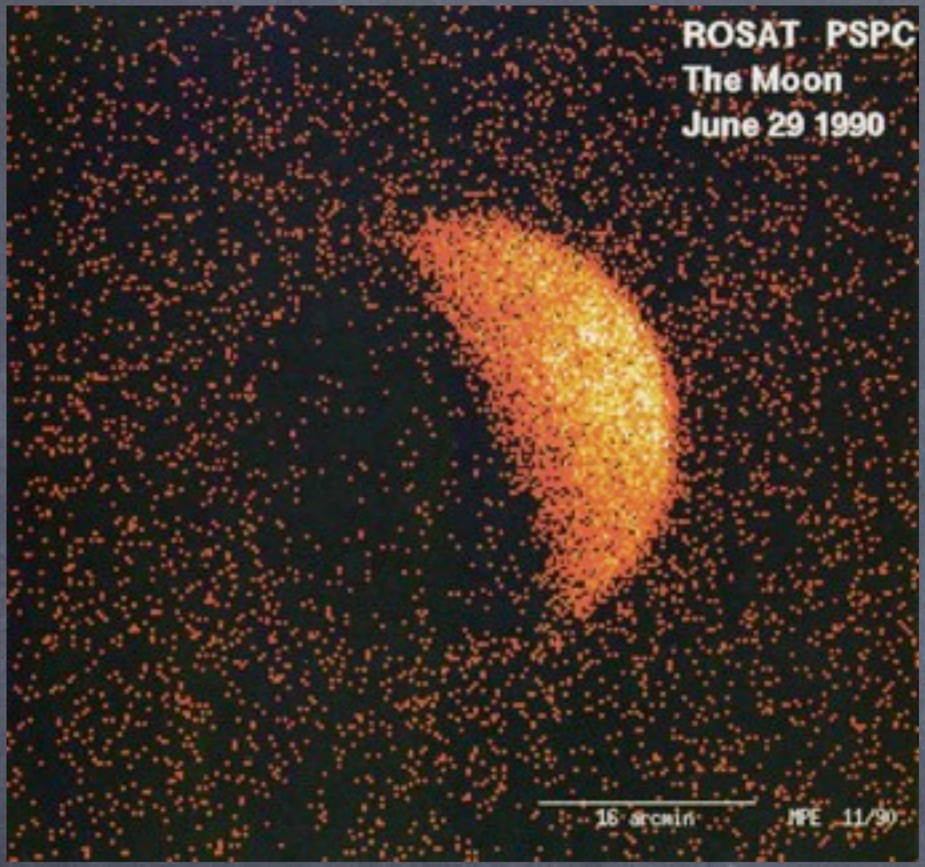


Clusters of Galaxies

Most of the baryons in clusters are in the form of hot plasma at around 10^8 K, which emits in the X-ray through thermal bremsstrahlung.



Solar System Objects



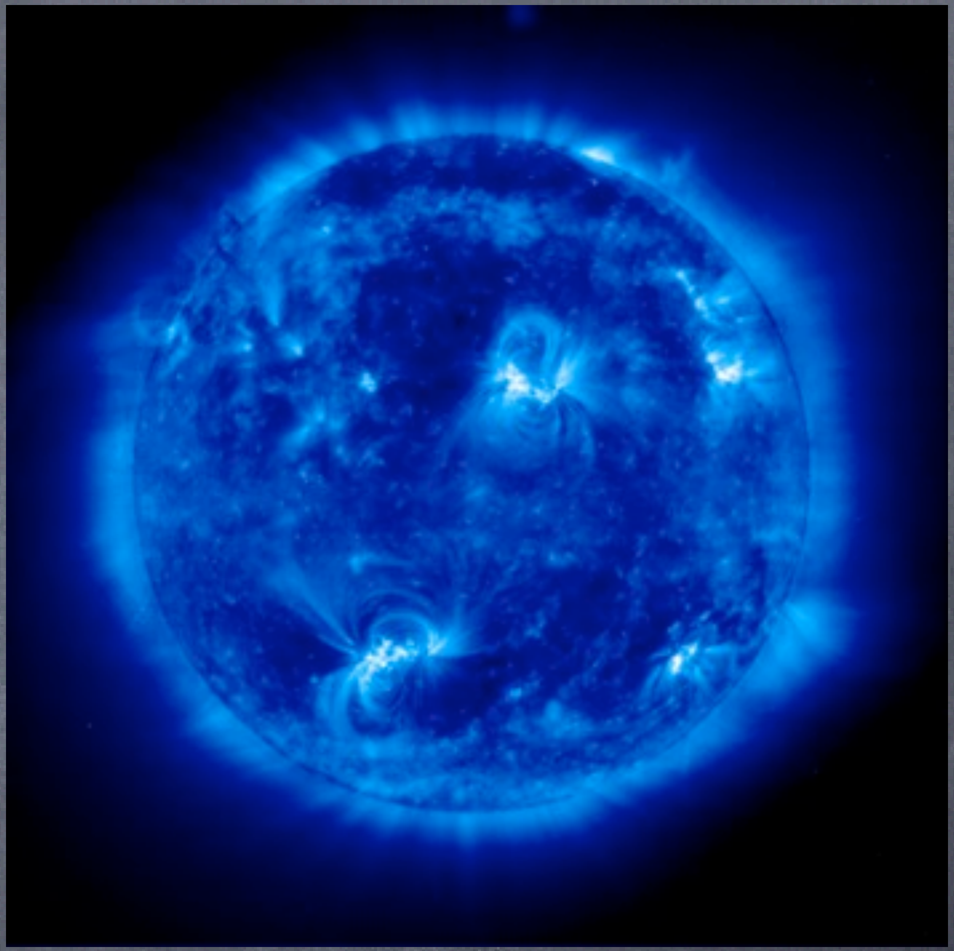


Image credit: GOES satellite

The Sun, Moon, Mars, Venus, Jupiter, and Saturn are all X-ray sources.

Backgrounds and Absorption

The Galaxy: hot gas in the halo, dominates below about 1 keV

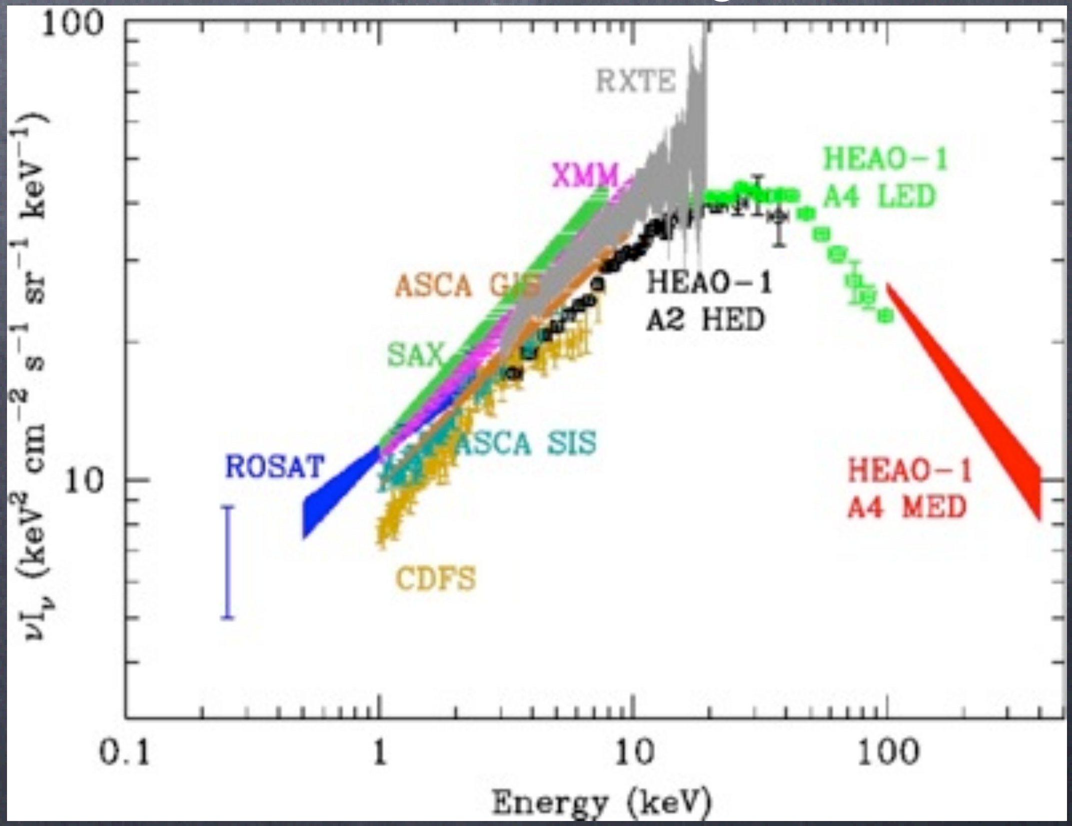
Particle/Instrumental: charged particles interacting with the detector and the material around it, dominates at high energies.

Soft protons: modulated by Earth's magnetic fields, highly variable, dependent of spacecraft position, cause background flares.

Extragalactic background: primarily unresolved AGN, nearly resolved in soft X-ray, but not in hard X-ray where it is likely due to Compton thick AGN

Solar Wind Charge Exchange: ions in the solar wind interact with neutral gas, exchange an electron and emit X-rays

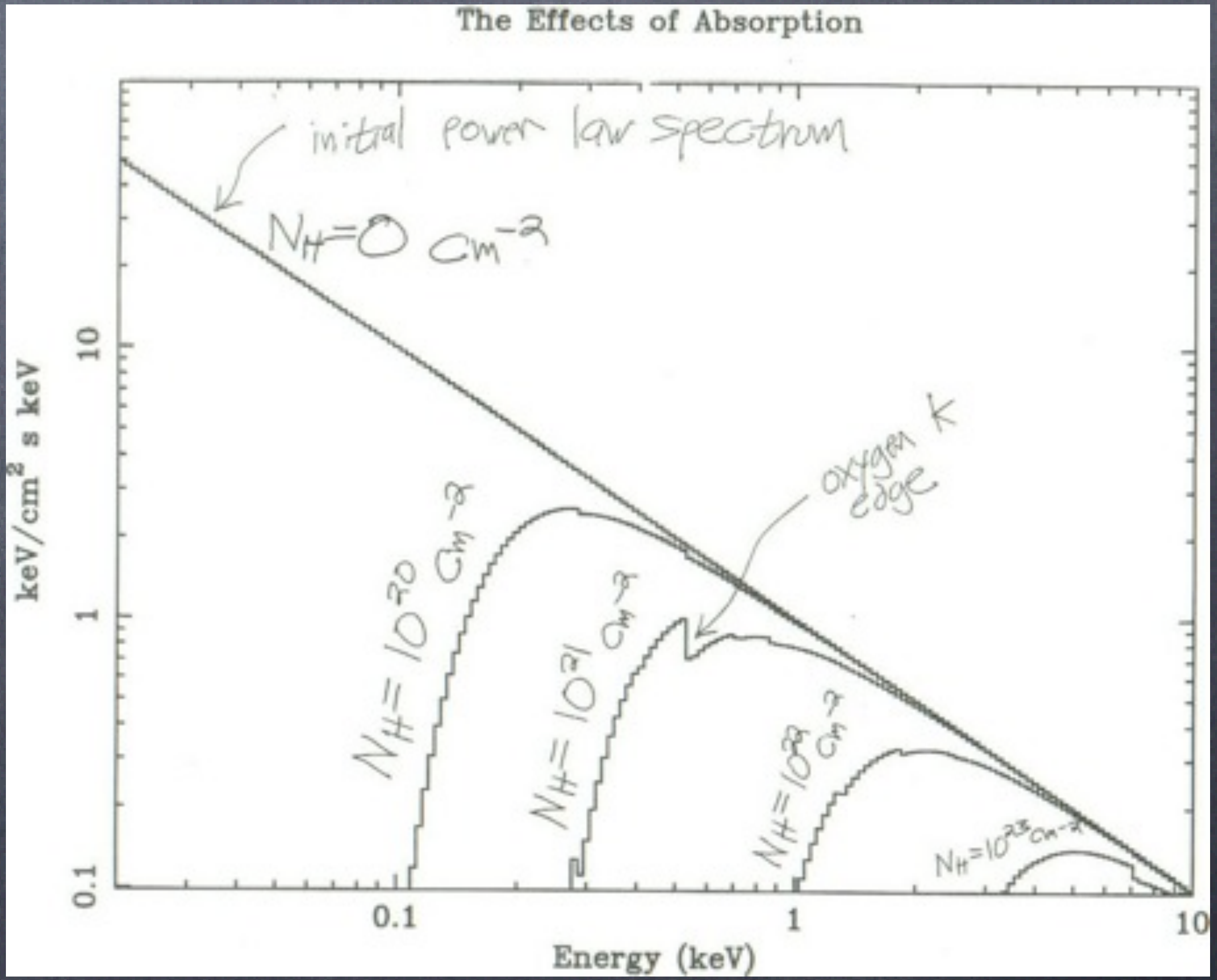
Cosmic X-ray Background



Backgrounds and Absorption

In addition, X-rays can be absorbed by material along the line of sight, typically quoted as the equivalent column density of hydrogen (though typically it is due to heavier elements).

Particularly a problem when looking though the Galactic plane or at obscured objects (like some AGN)



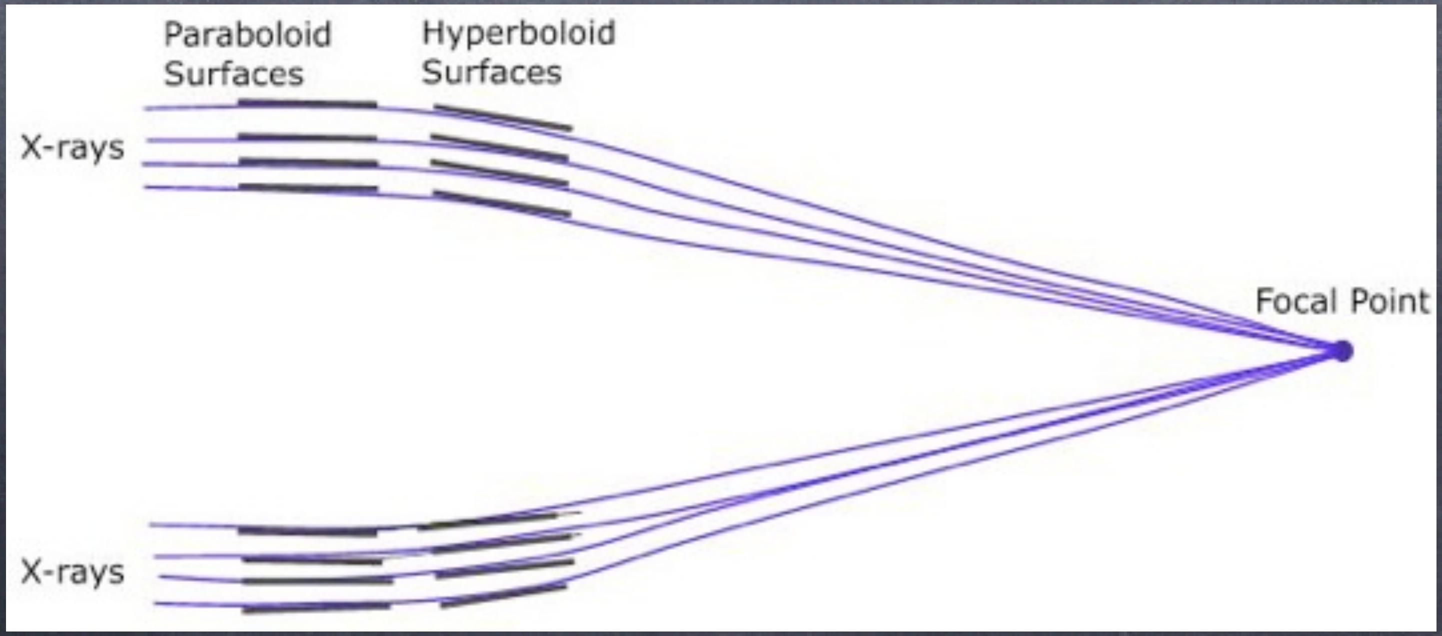
from Neil Brandt's lecture notes

X-ray Mirrors

Focusing X-rays is hard! X-rays are typically absorbed rather than reflected by mirrors. However, for very small incident angles and appropriate mirror coatings, X-rays can be reflected.

X-ray optics employ a "grazing" angle of incidence. A combination of two reflecting surfaces, typically paraboloid followed by hyperboloid, are used to focus without coma.

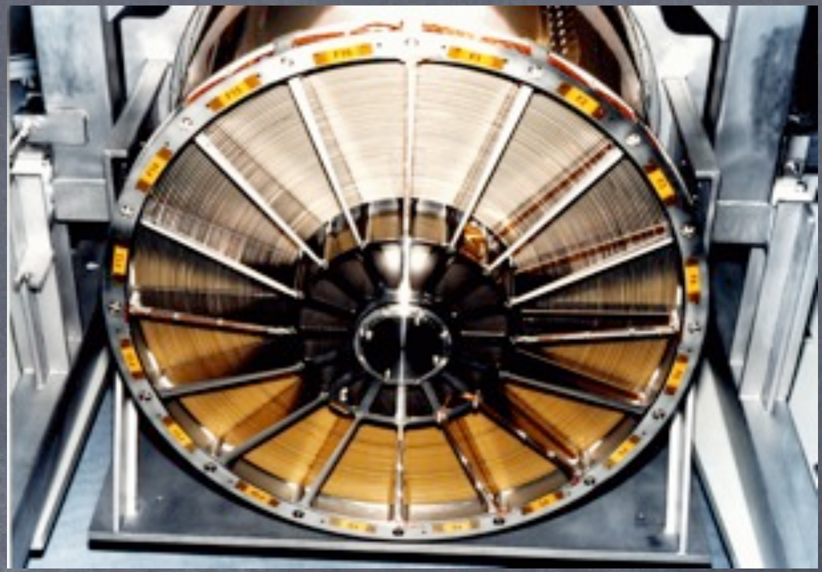
Wolter Type 1

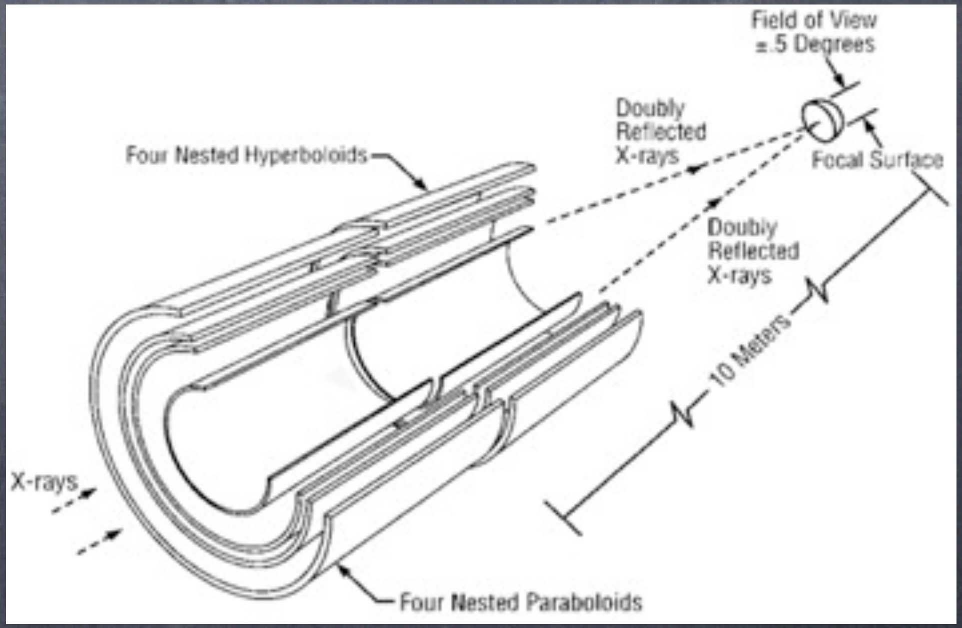


X-ray Mirrors

- Grazing angle requires long focal length (something like 10-m)
- Critical angle for reflection $\theta_c \propto \sqrt{Z}/E$ where Z is atomic number of the material.
  - current telescopes use gold or iridium coating and grazing angles of 0.5-1 deg for energy range 0.1-10 keV
- A set of several nested mirror shells is used to increase the effective area
- Angular resolution limited by irregularities in the mirror which cause scattering

XMM mirrors





X-ray Detectors

X-ray detectors primarily use CCDs combined with an optical blocking filter to limit contamination from other wavelengths.

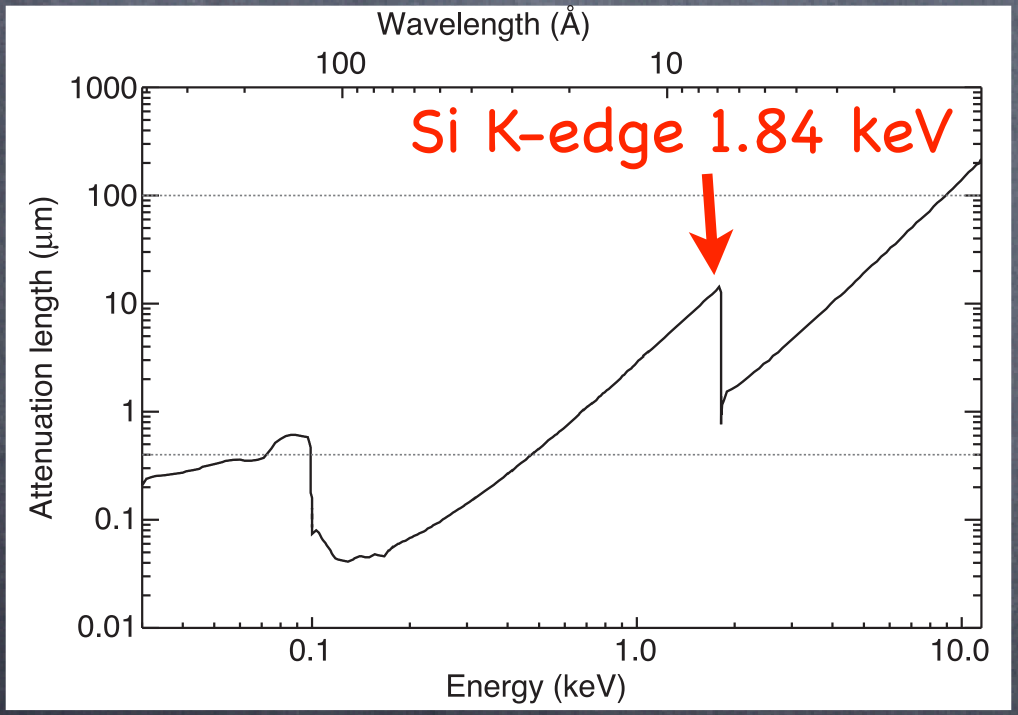
In X-ray, CCDs measure individual photons.
How do they measure photon energy?

Answer: An individual X-ray photon liberates multiple electrons in Si through Compton scattering. The number of electrons scales with photon energy.

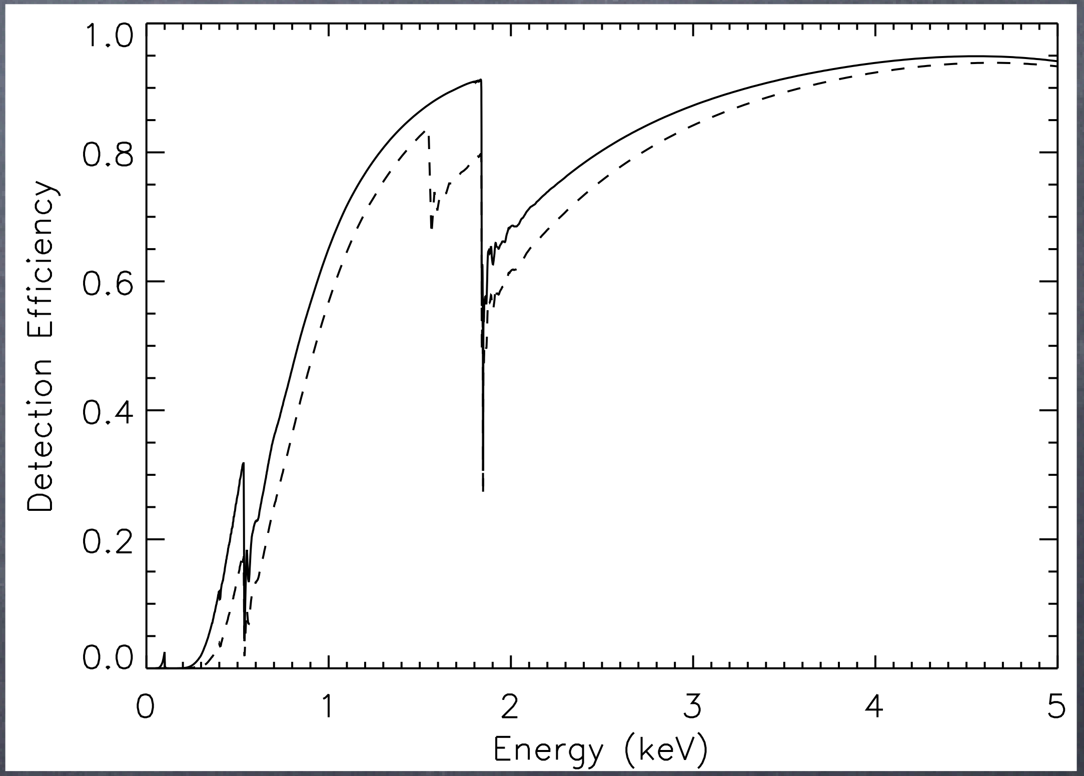
X-ray Detectors

X-ray detectors primarily use CCDs combined with an optical blocking filter to limit contamination from other wavelengths.

Use active region with depth 0.4-100 µm to detect photons between a few hundred eV and 10 keV.



"Handbook of X-ray Astronomy"



QE is combination of absorption efficiency and losses from optical blocking filter

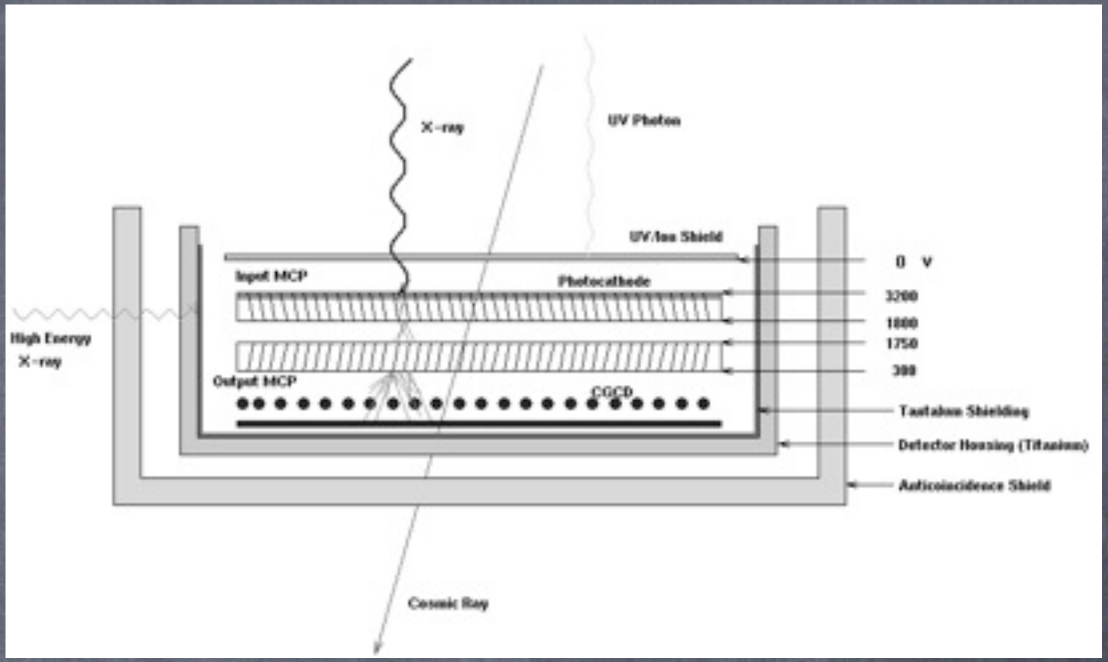
X-ray Detectors

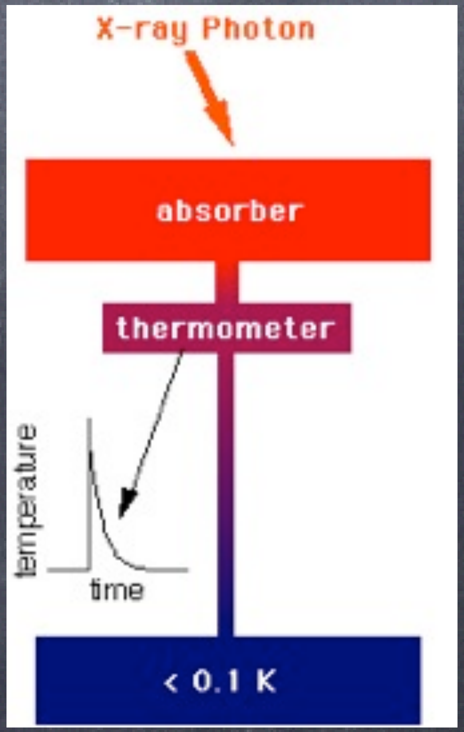
Other detector types include:

- Microchannel plates: also used in UV, and for X-ray include UV shield. High spatial resolution and good QE for low energy X-rays, but bad spectral resolution

- Microcalorimeters: measure change in temperature of a material like silicon when it absorbs an X-ray. Good for high-resolution spectroscopy. Must be very cold (similar to far-IR) to detect the mK changes in temperature.

Chandra HRC MCP detector





Some Terms

Effective Area: measure of sensitivity. Effective telescope area after reduction for detector QE, reflectivity and vignetting

CTI: CTE

Pile-up: two or more photons detected in a single pixel before readout. Appear as a single event with the wrong energy

Pulse Height: integrated charge per pixel, proportional to energy

PSF: point spread function, shape of the image of a point source

Vignetting: decrease in telescope effective area for off-axis sources due to shading by nested mirrors. Depends on energy.

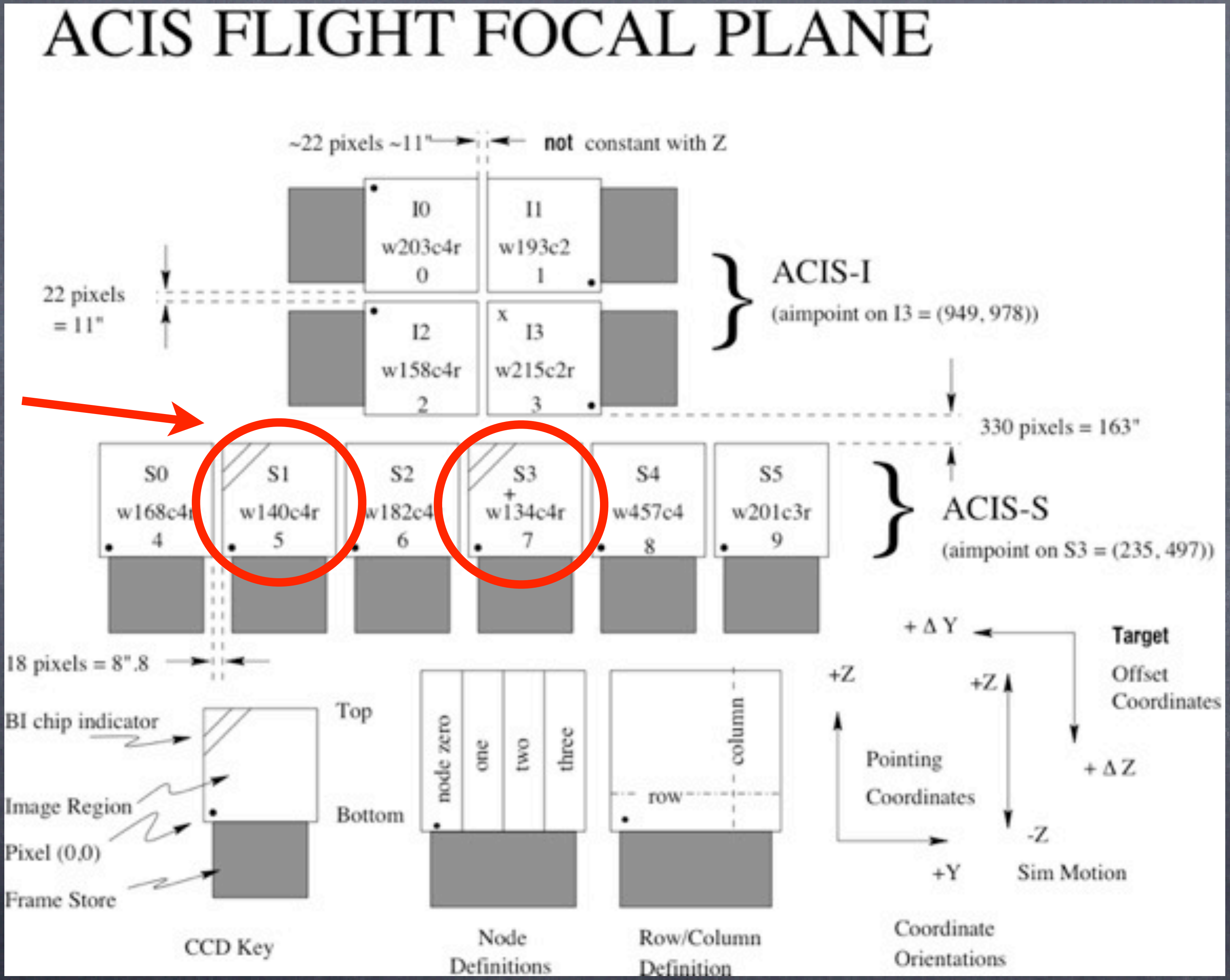
X-ray Units: energy in eV, keV and flux in ergs/cm^2/s

Chandra X-ray Observatory

- Launched in the shuttle in 1999
- 4 nested mirror shells, Iridium coated, sensitive from roughly 0.1-10 keV
- 0.5" on-axis resolution, unequaled by current or planned X-ray telescopes
- Two detectors and two grating spectrometers:
  Advanced CCD Imaging Spectrometer (ACIS): two CCD arrays
  High Resolution Camera (HRC): two microchannel plate detectors
  HETG: resolving power (E/ΔE) up to 1000 in 0.4-10.0 keV band, used with ACIS-S
  LETG: 0.08-7 keV, used with HRC-S

Chandra - ACIS

Backside

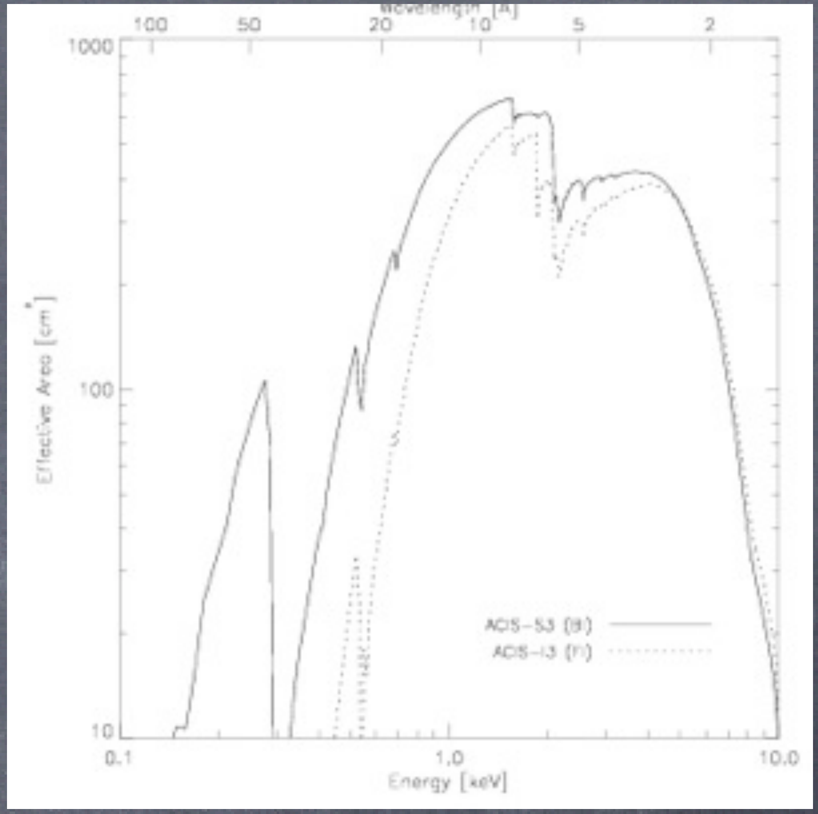


Two CCD arrays named ACIS-I and ACIS-S

Each CCD is 8.3′ across

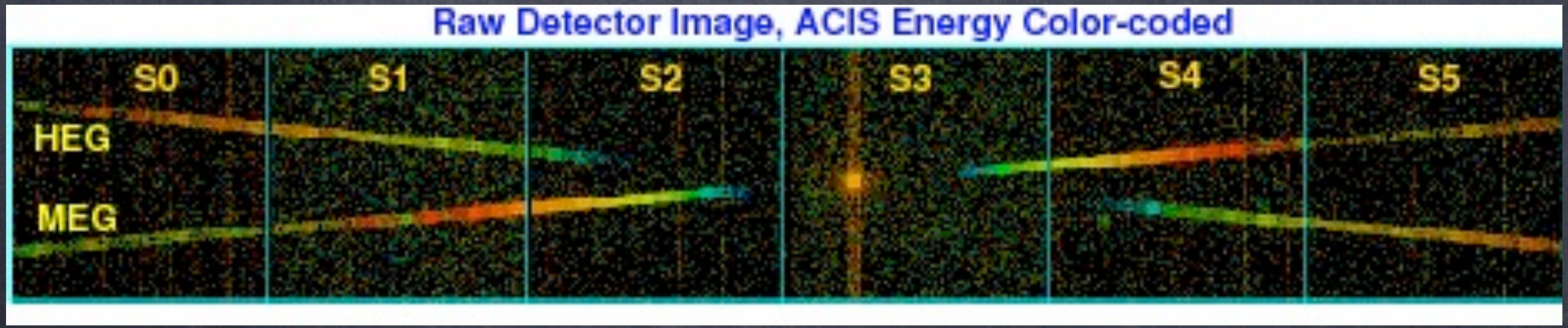
Chandra - ACIS

ACIS-I offers a larger FOV. The FI chips suffered radiation damage early in the mission during passage through the radiation belts increasing the CTI and decreasing the energy resolution (though software corrections exist).



ACIS-S3 offers higher effective area, particularly at low energy, but the BI chips have higher backgrounds.

ACIS-S can be used in conjunction with the high energy transmission grating (HETG)



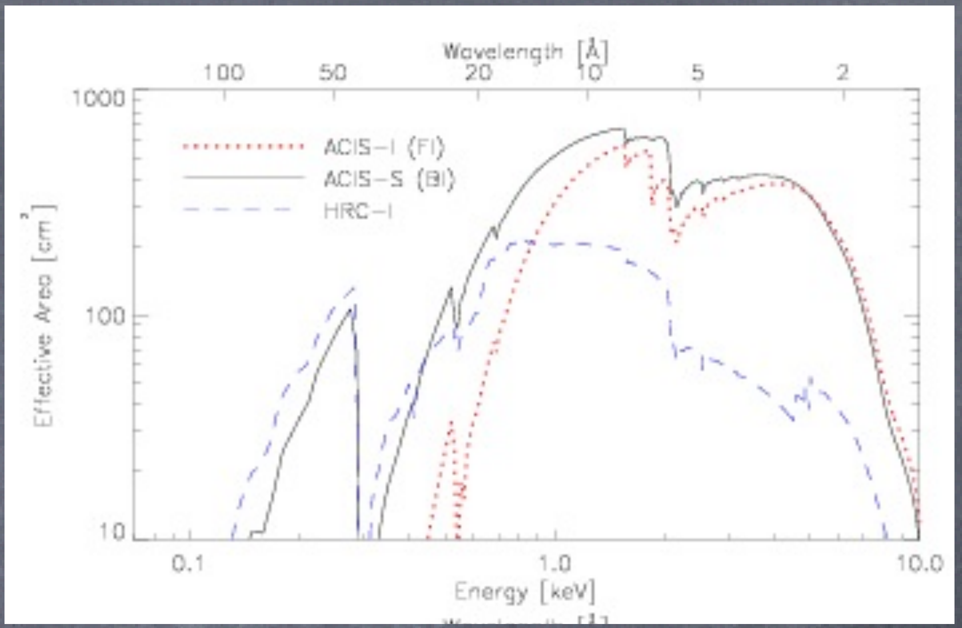
Chandra - HRC

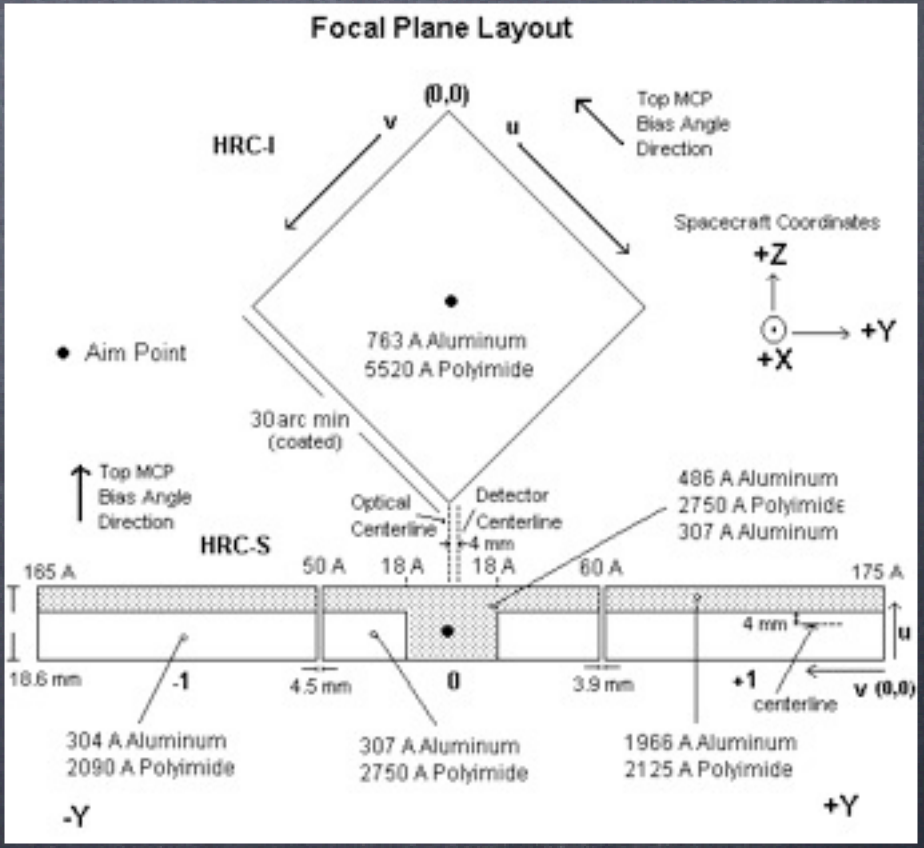
The HRC can give the highest spatial resolution and fast timing

Energy range: 0.08-10 keV
resolution: 0.4"
time resolution: 16 μs

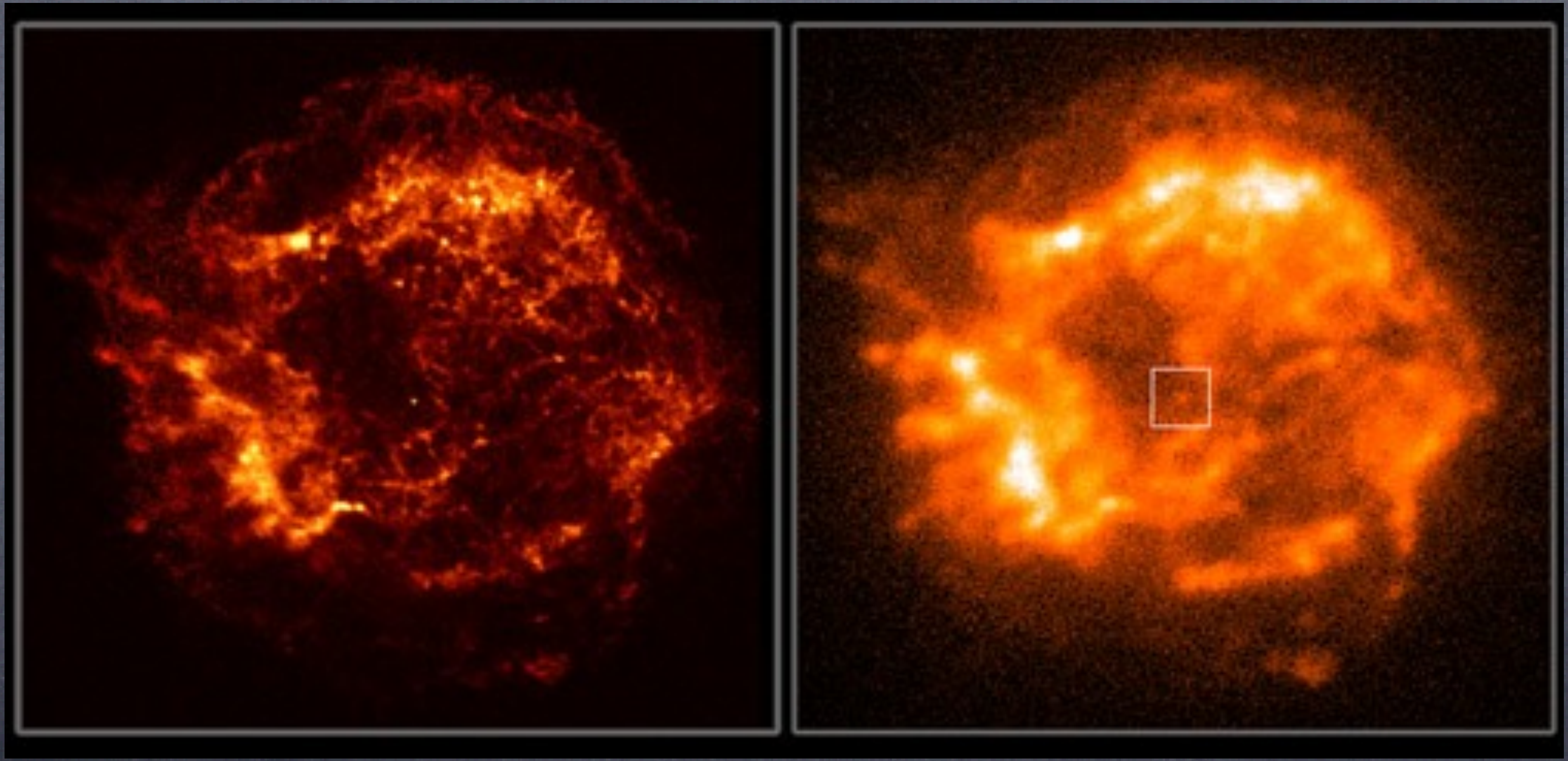
HRC-I FOV 30', HRC-S 6'x99'

HRC-S is used in conjunction with the low energy transmission grating





Chandra First Light Image of Cassiopia A



XMM-Newton

- Launched in December 1999
- 58 nested mirror shells, gold coated, 0.15-12 keV
- 6″ on-axis resolution
- Higher effective area than Chandra and larger FOV (30′)
- Three major instruments:

European Photon Imaging Camera (EPIC): 3 CCD arrays operated simultaneously, PN more sensitive, MOS higher resolution

Reflection Grating Spectrometer (RGS): high resolution spectroscopy in the 0.3-2.5 keV range

Optical Monitor (OM): UV/optical telescope

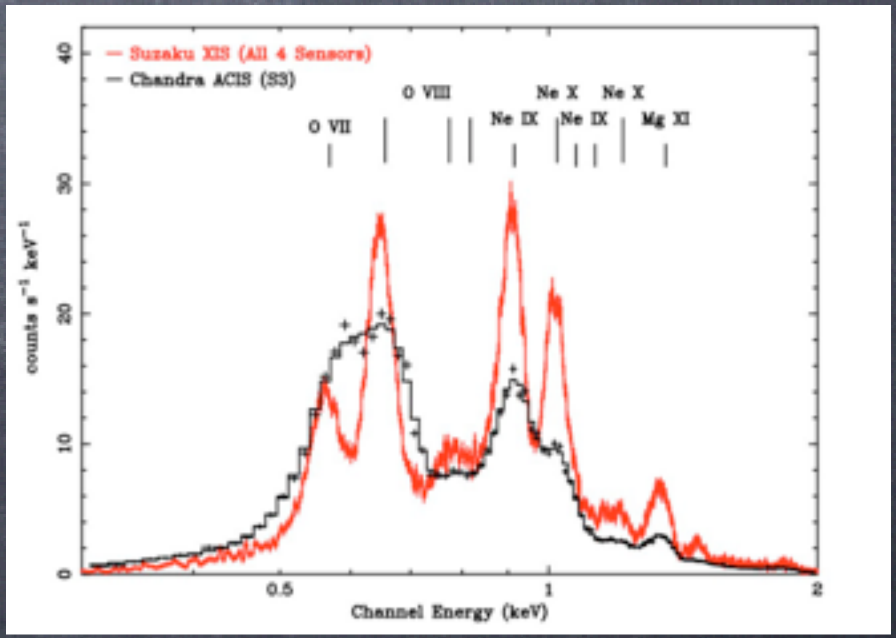
Suzaku

- Launched in 2005
- 4x175 nested mirror shells, gold coated, shorter 4.75m focal length, 0.2-600 keV
- 2′ HPD on-axis resolution
- Instruments:
  XRS: calorimeter that failed due to coolant loss just after launch
  XIS: 4x CCD arrays (3FI, 1BI), 18′ FOV
  HXD: hard X-ray detector, 10-600 keV

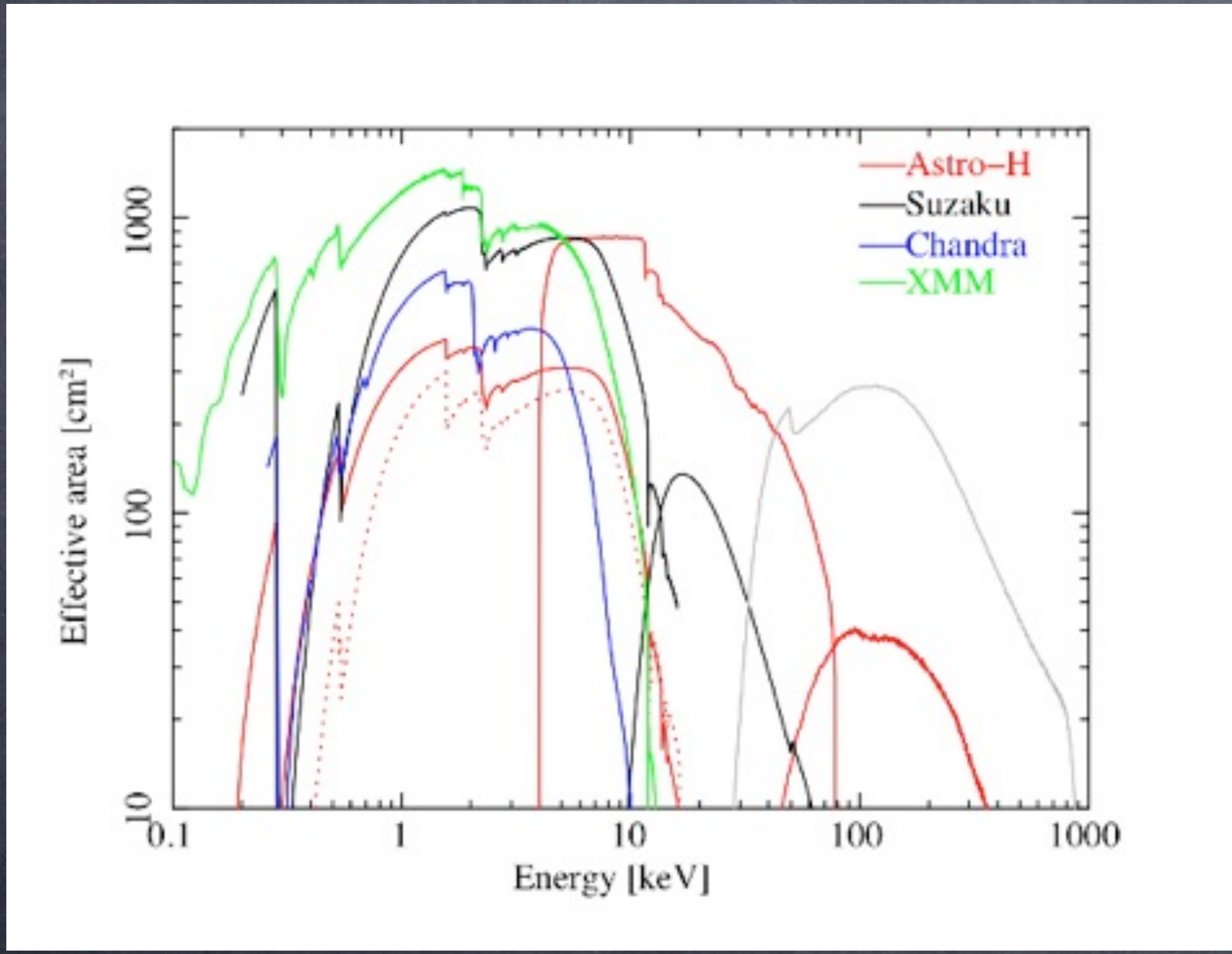
Despite problems Suzaku does have advantages:
- low background orbit
- high EA near Fe K lines at 6.4 keV
- good low-energy spectral resolution
- simultaneous soft and hard X-ray coverage

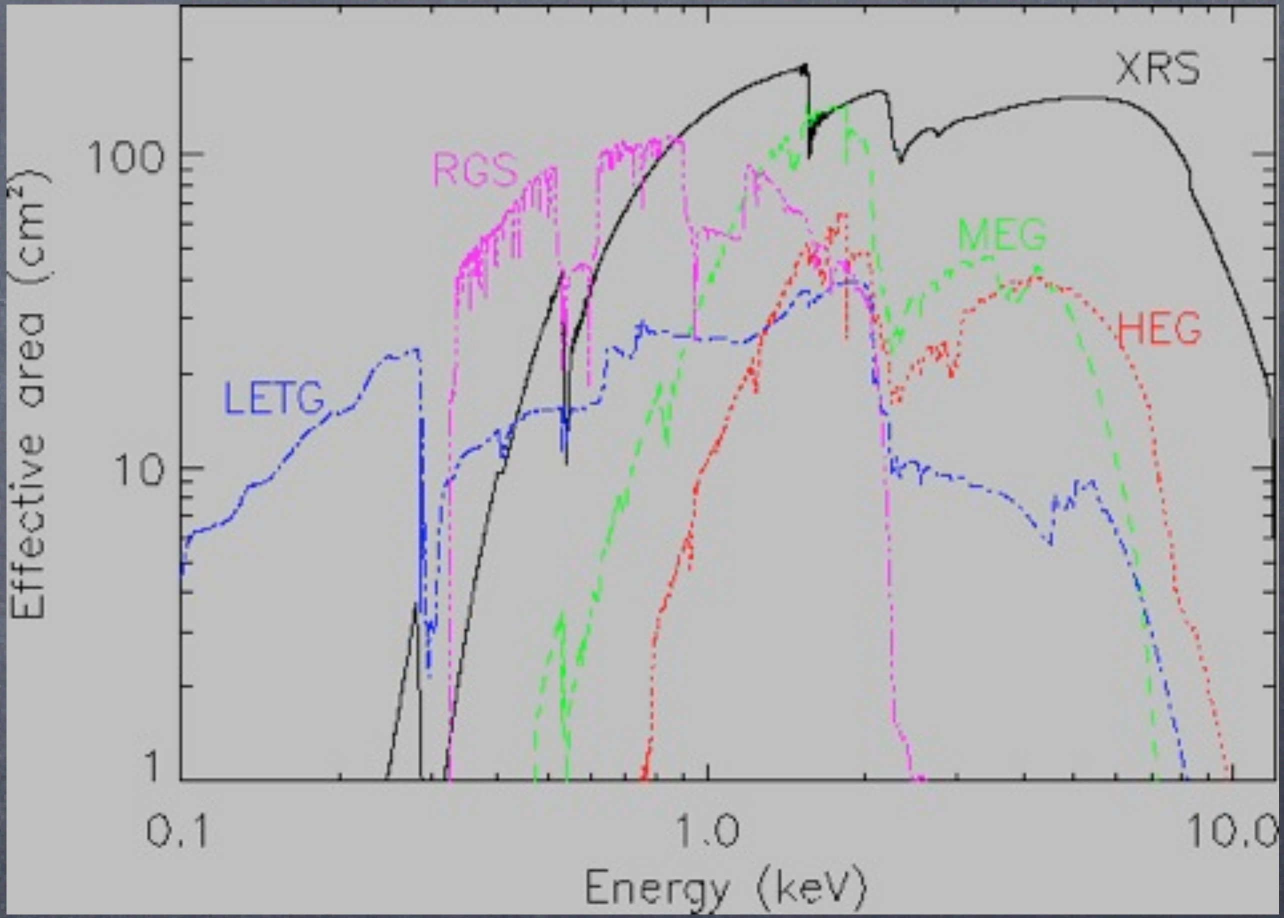
Suzaku=ASTRO-E2

ASTRO-E



Telescope Comparisons





Telescope Comparisons

Comparison of Various X-ray Observatories

Observatory	XMM			Chandra					Suzaku		Constellation X	
Detector	EPIC MOS	EPIC PN	RGS	ACIS back	ACIS front	HRC	HETG	LETG	XRS	XIS	Calori-meter	Grating
Energy Range (keV)	0.2-12	0.2-12	0.4-2.5	0.1-10	0.4-10	0.1-10	0.6-10	0.1-6	0.3-12	0.2-12	0.2-10	0.2-2
Effective Area (cm^2)												
@0.25 keV	133	460	-	30	-	150	-	25	-	-	3081	1235
@0.4 keV	360	771	44	120	35	50	-	12	-	-	864	2000
@0.6 keV	591	1061	94	345	70	65	-	25			5127	3720
@1.0 keV	922	1227	185	615	385	215	10	55	100	1600	11274	5327
@1.5 keV	1180	1304	160	500	525	162	45	105			13362	4100
@2.5 keV	696	779	-	320	320	65	20	50			7765	-
@6.0 keV	768	851	-	205	235	45	25	20	150	1000	6600	-
@8.0 keV	390	557	-	45	60	10	7	4			4277	-
@12.0 keV	19	56	-	-	-	-	-	-			638	-
Energy Resolution (eV)												
@0.25 keV	35	35	-	130	37	-	-	0.4	-	-	2	0.25
@0.4 keV	45	45	0.5	120	42	-	-	0.8	6.5	30	2	0.65
@1.0 keV	55	55	2.9	100	56	-	1.0	5.4	6.5	50	2	4.1
@2.5 keV	85	85	17	120	82	-	5.2	34	6.5	80	2	-
@6.0 keV	130	130	-	170	130	-	29	-	6.5	120	2	-
@8.0 keV	150	150	-	190	150	-	50	-	6.5	140	2	-
Angular Resolution (FWHM)	~6"	~6"	-	1"	1"	<0.5"	-	-	limited	<1.5'	6"	-
Field of View	30'	30'	-	17'x17'	17'x17'	31'x31'	-	-	3'x3'	19'x19'	2.5'	-

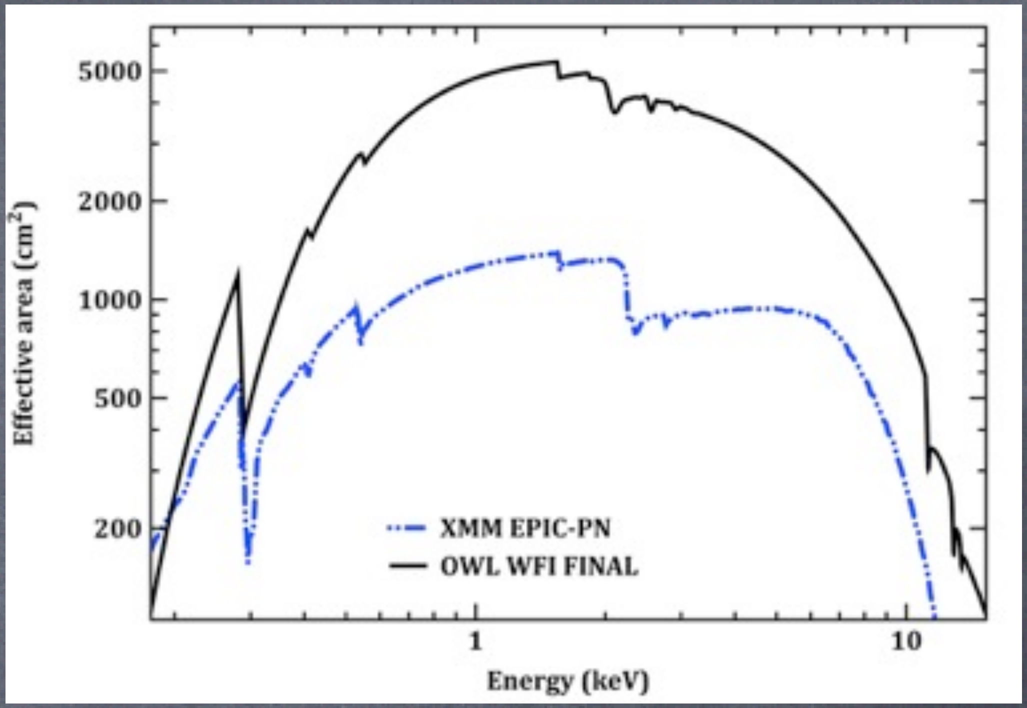
from HEASARC

Major Scientific Results

- Resolved the soft X-ray background
- AGN growth to z~2
- Strongest constraints on cosmology with clusters of galaxies
- X-ray emission from Sag A*
- AGN feedback in clusters and galaxies, tracing cool cores
- Resolving features of SNR (shock waves, central compact object) and studying their chemical composition
- Bullet cluster limits on dark matter self-interaction
- Ultra-luminous X-ray sources, possibly IMBHs

Future X-ray Telescopes

ATHENA:
(formerly known as IXO and Con-X)
launch ???, orbit at L2
Wide-Field Imager: 24′ FOV, 0.1-15 keV
  5-10″ resolution, factor of 5 in
  effective area over XMM
X-ray Microcalorimeter Spectrometer:
  3 eV spectral resolution



ASTRO-H:
launch in 2014, will carry a high spectral resolution microcalorimeter with 7 eV resolution as well as imaging hard and soft X-ray detectors. Third time is the charm!

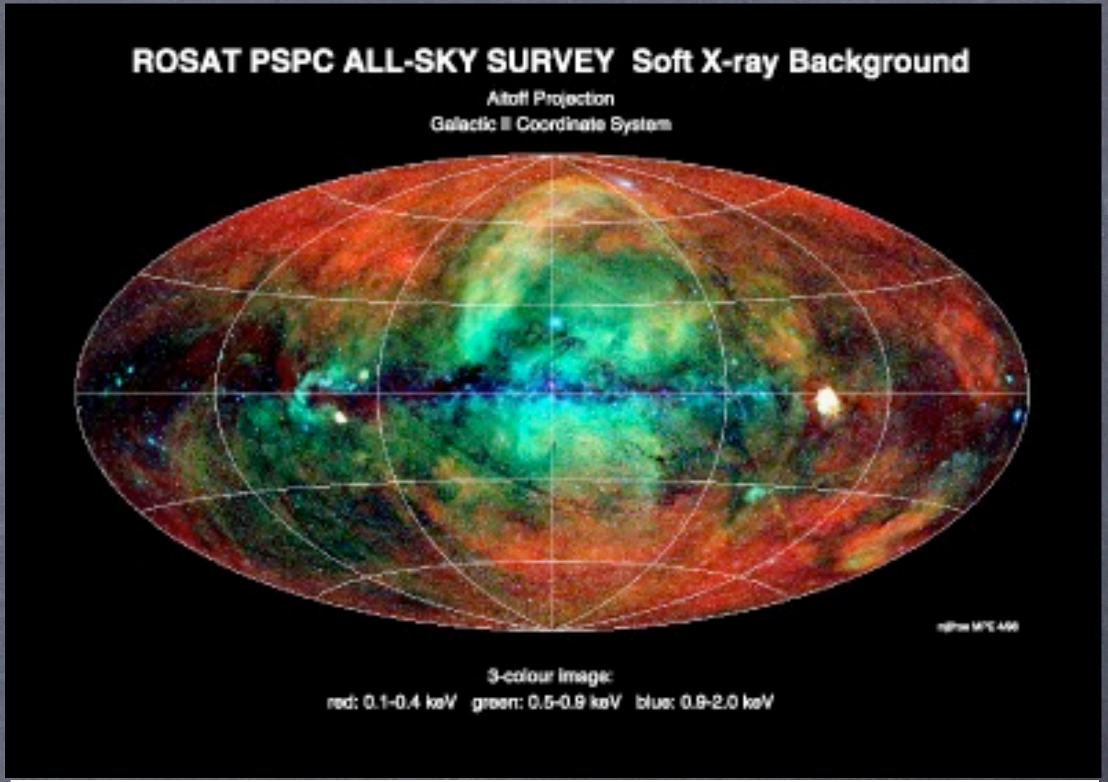
ROSAT All-Sky Survey

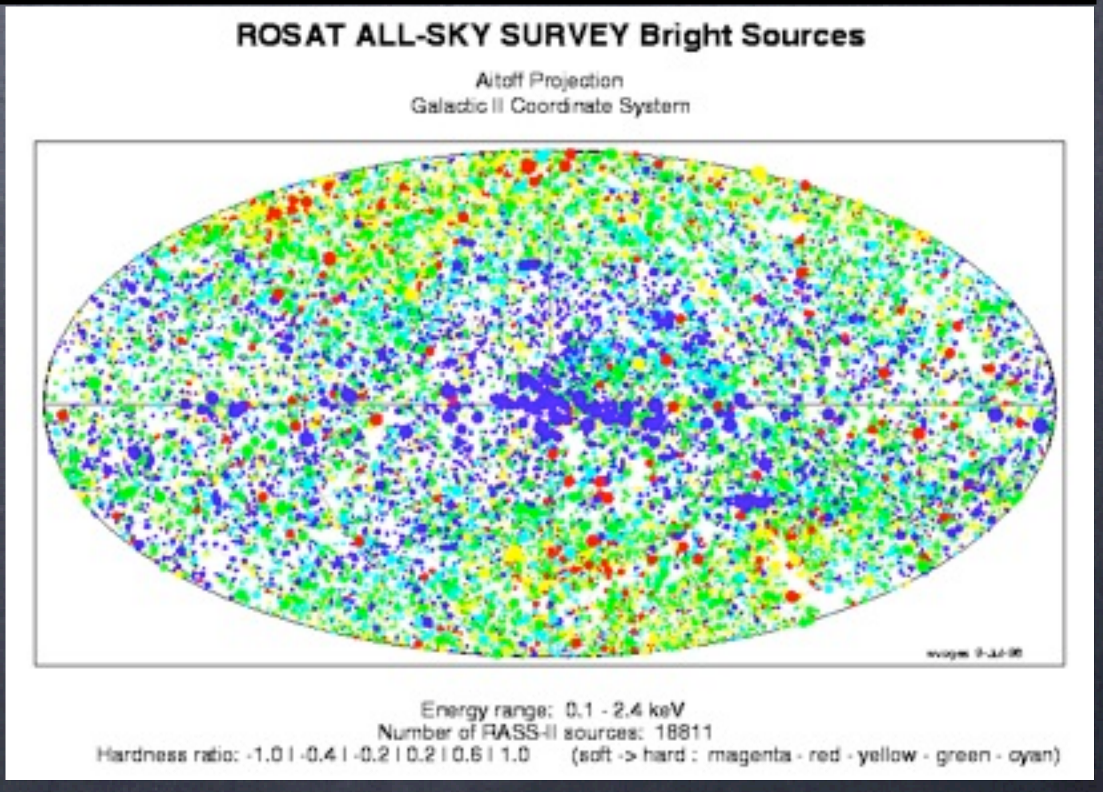
ROSAT was a soft X-ray telescope running from 1990-1999.

ROSAT performed both pointed observations as well as an all-sky survey in scanning mode.

RASS:

- soft X-ray 0.1-2.4 keV
- exposure times between 400s (near the ecliptic equator) and 40,000s (near the ecliptic poles)
- data products include X-ray background maps, bright and faint source catalogs





eROSITA

German-Russian collaboration to perform an all-sky X-ray survey much deeper than ROSAT over broader energy band and with better resolution.

- launch 2014
- 0.5-10 keV
- 15″ (on-axis) - 30″ (full survey) resolution

Summary of Rosita Surveys (after 4 yrs)		
Survey	All-Sky Survey	Deep Survey
Solid Angle (deg2)	42000 (20.000 extragal)	200
Exposure time (average)	2-3 ks	20-30 ks
0.5-2 keV S_{min} AGN	$\sim 10^{-14}$	$\sim 4 \times 10^{-15}$
2-10 keV S_{min} AGN	$\sim 10^{-13}$	$\sim 3 \times 10^{-14}$
0.5-5 keV S_{min} Clusters	$\sim 3 \times 10^{-14}$	$\sim 8 \times 10^{-15}$
Expected # of AGN (0.5-2 keV)	1.76×10^{6}	60000
Expected # of AGN (2-10 keV)	130000	15000
Expected # of Clusters (0.5-2 keV)	72000	6500