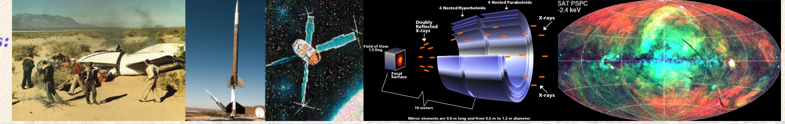


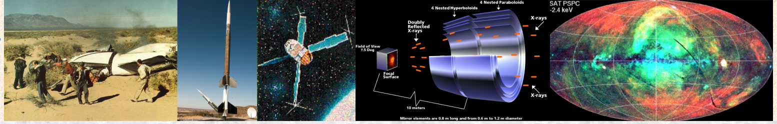
From the 1960s to the current and future generation of X-ray observatories:

successive X-ray instruments and some crucial discoveries

René W. Goosmann

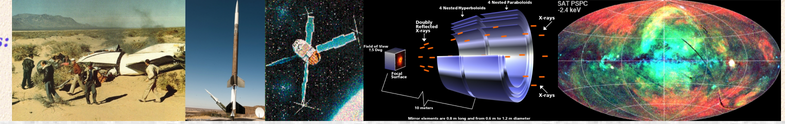
Observatoire astronomique de Strasbourg

Programme national hautes énergies



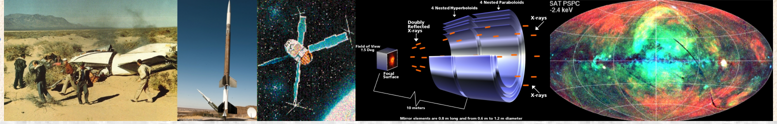
Outline

- **X-rays in astronomy and how they are produced**
- The beginnings of X-ray astronomy: rocket experiments
- Space-born X-ray observatories
- Towards the future

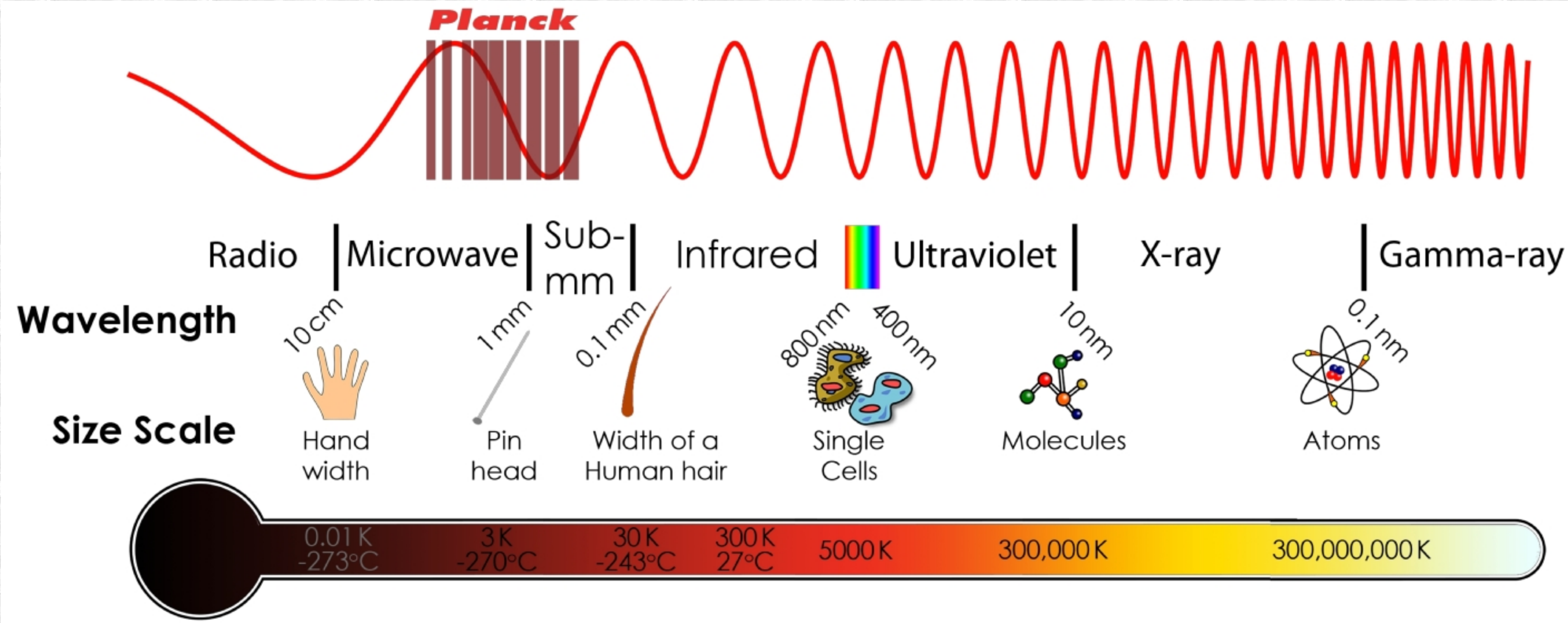


121 years ago: discovery of X-rays

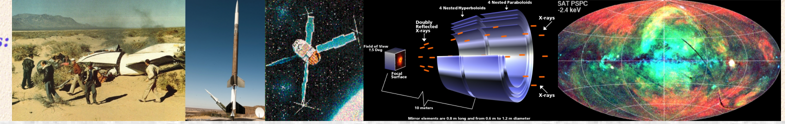
- 1895: Discovery of "X-Strahlen" ("X-rays", named "Röntgen radiation" in several languages).
- Awarded the first Nobel Price ever in 1901 *"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him."*



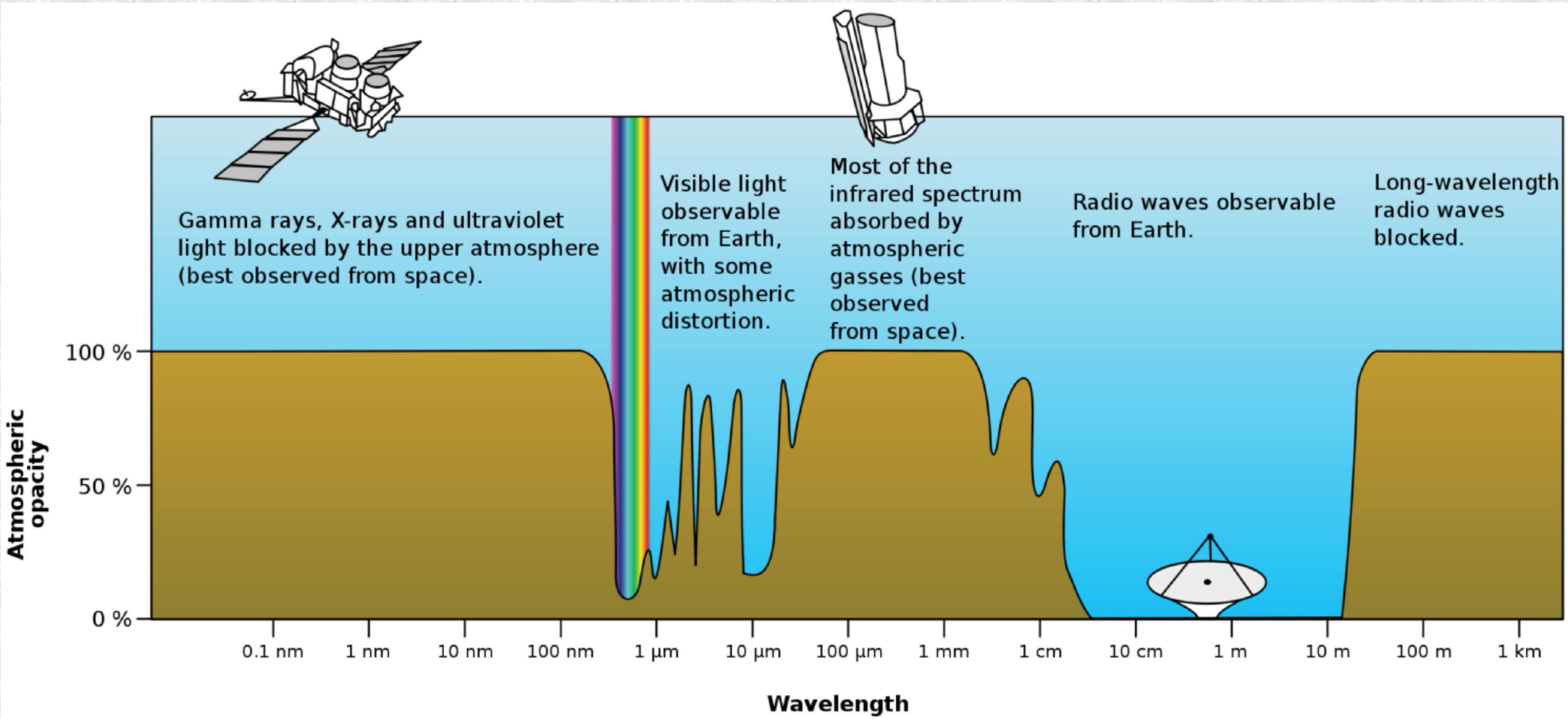
X-ray wavelengths and length scales



X-ray wavelengths are comparable to the dimension of single atoms or small molecules.



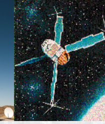
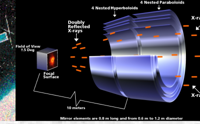
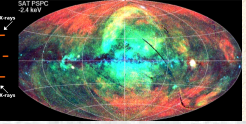
Opacity of the earth's atmosphere



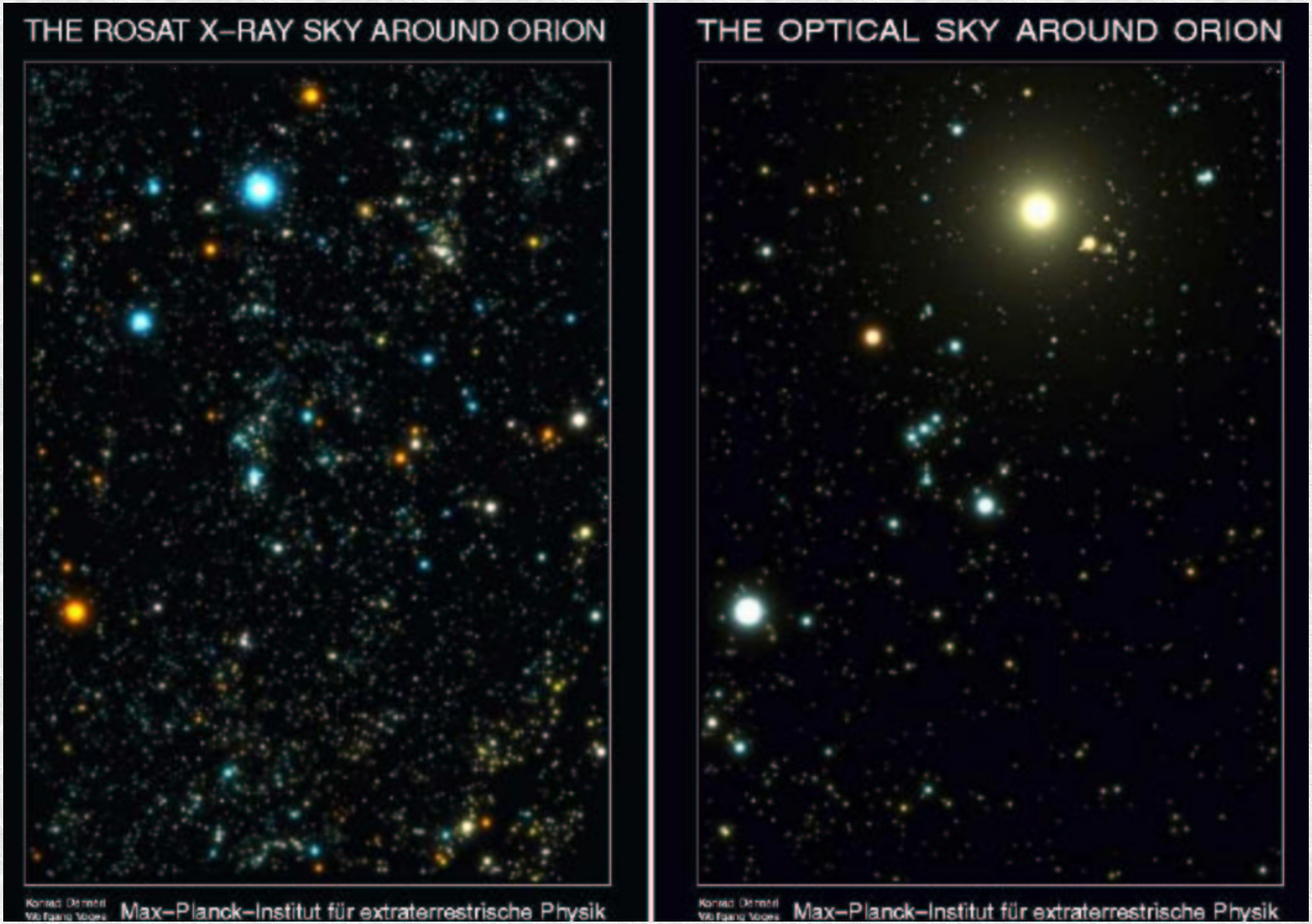
X-ray observations must be taken above the earths atmosphere.

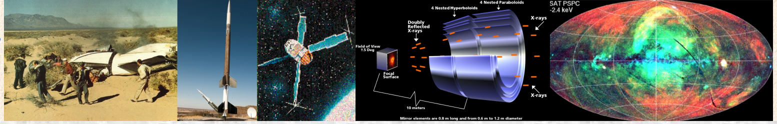
X-ray astronomy derives directly from space exploration.



Comparing the optical to the X-ray sky



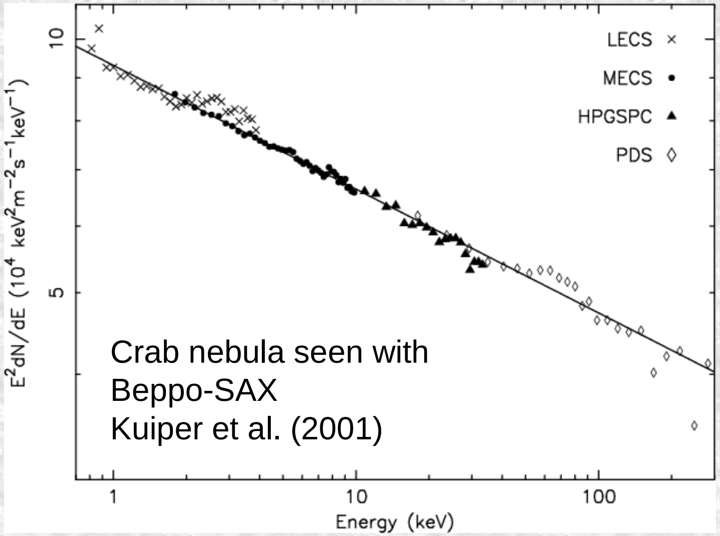


Common units in X-ray astronomy

- Converting wavelength (in **Å**) into photon energy (in **eV** or **keV**):

$$\lambda = hc / E = 12398.4193 \text{ (eV Å)} / E = 12.3984193 \text{ (keV Å)} / E$$

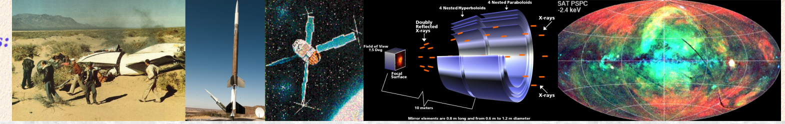
- Typical X-ray spectral range:
  0.1 keV – 100 keV or
  0.12398 Å – 12.398 Å



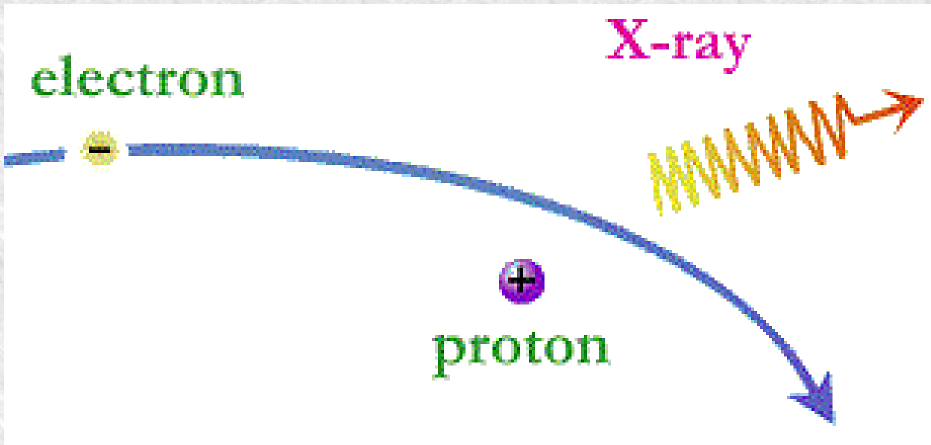
Crab nebula seen with Beppo-SAX
Kuiper et al. (2001)

- Soft X-rays versus hard X-rays: *often* defined as
  0.1 keV – 1 keV and
  1 keV – 100 keV, respectively.

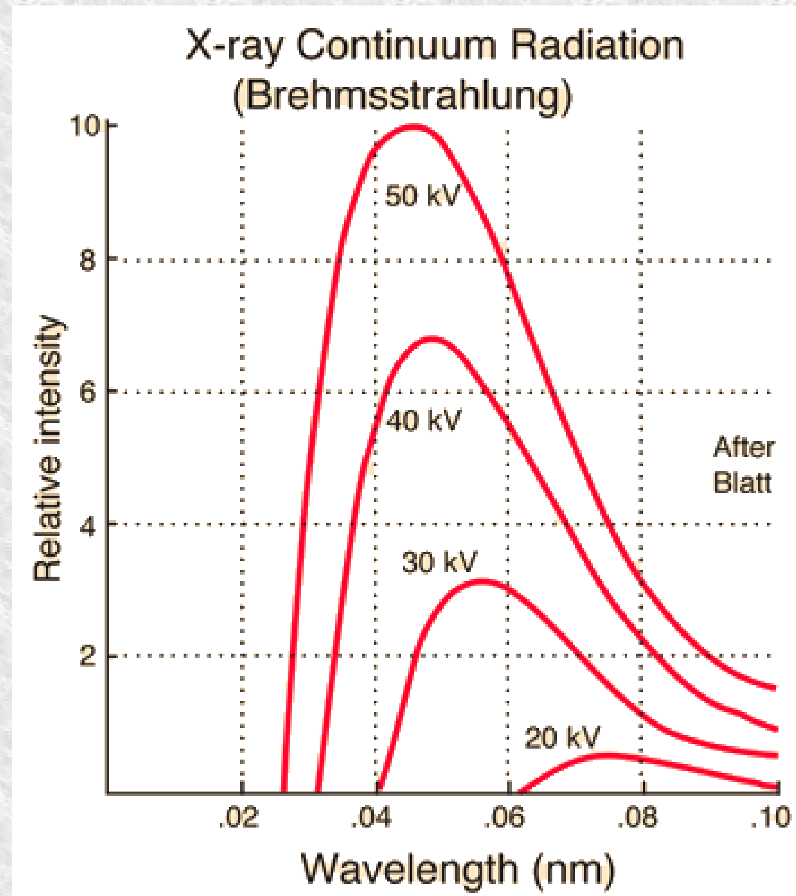
- Flux units:
  photon counts or energy (in erg) per (s cm^2 keV)
  1 erg = 10^{-7} J
  2.42 x 10^{-11} erg/(s cm^2 keV) = 1 μJy ~ 1 mCrab

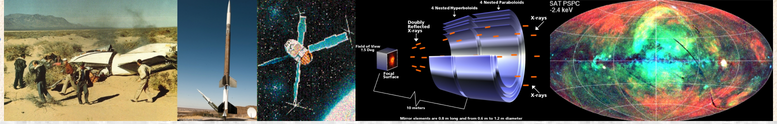


Some X-ray radiative processes: free-free emission

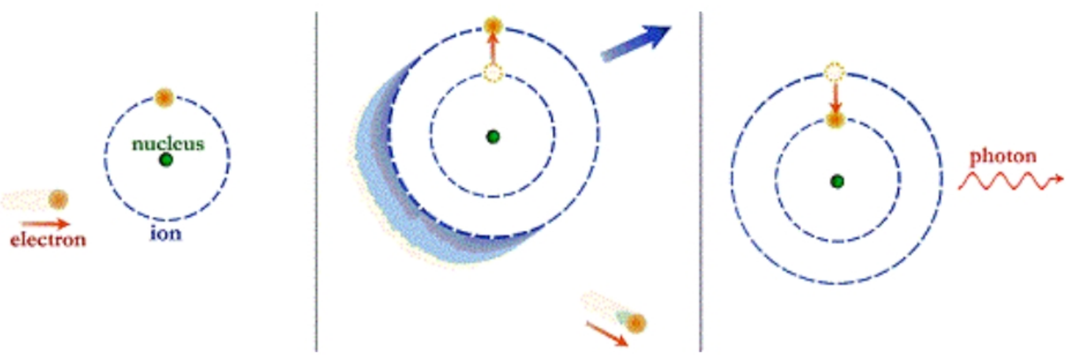


Deceleration of energetic electrons in the electric field of heavier charged particles → emission of a non-thermal spectrum.





Some X-ray radiative processes: atomic transitions

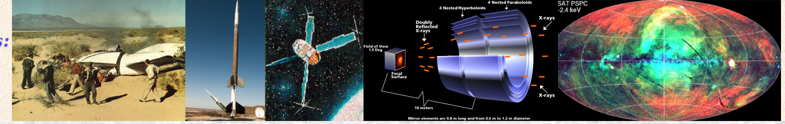


Atomic emission. Image credit: CXC/S. Lee/CC-NC-A.

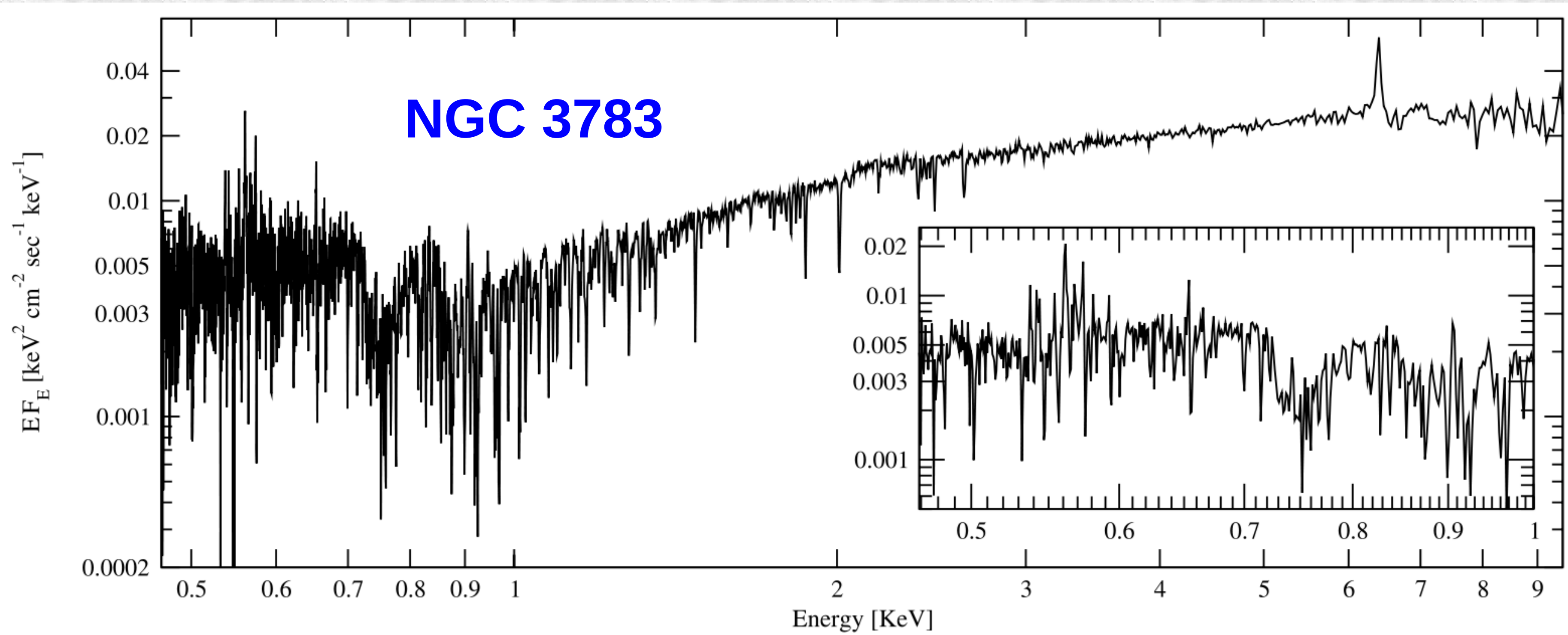
Atomic transitions after collisional or radiative excitation or after photo-ionization and consecutive recombination...

Fluorescence. Image credit: NASA/CXC/M.Weiss/CC-NC-A.

Fluorescence: X-ray photons can knock electrons out of the K-shell → consecutive fluorescence.



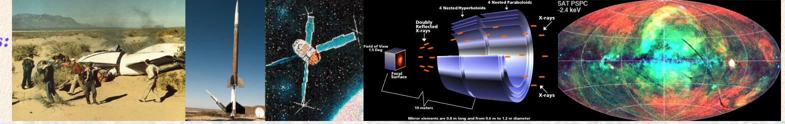
Some X-ray radiative processes: atomic transitions



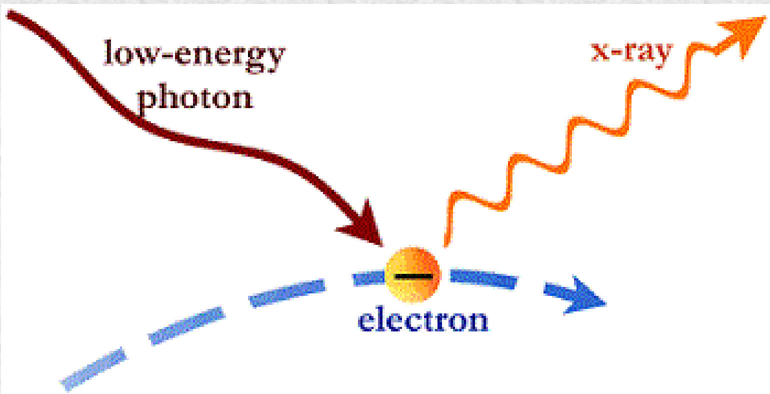
- Strong absorption edges of OVII and OVIII
- Complex sub-structure with many absorption lines
- Lines are blue-shifted v_{shift} ~1000 km/s (outflows)

Kaspi et al. (2002)

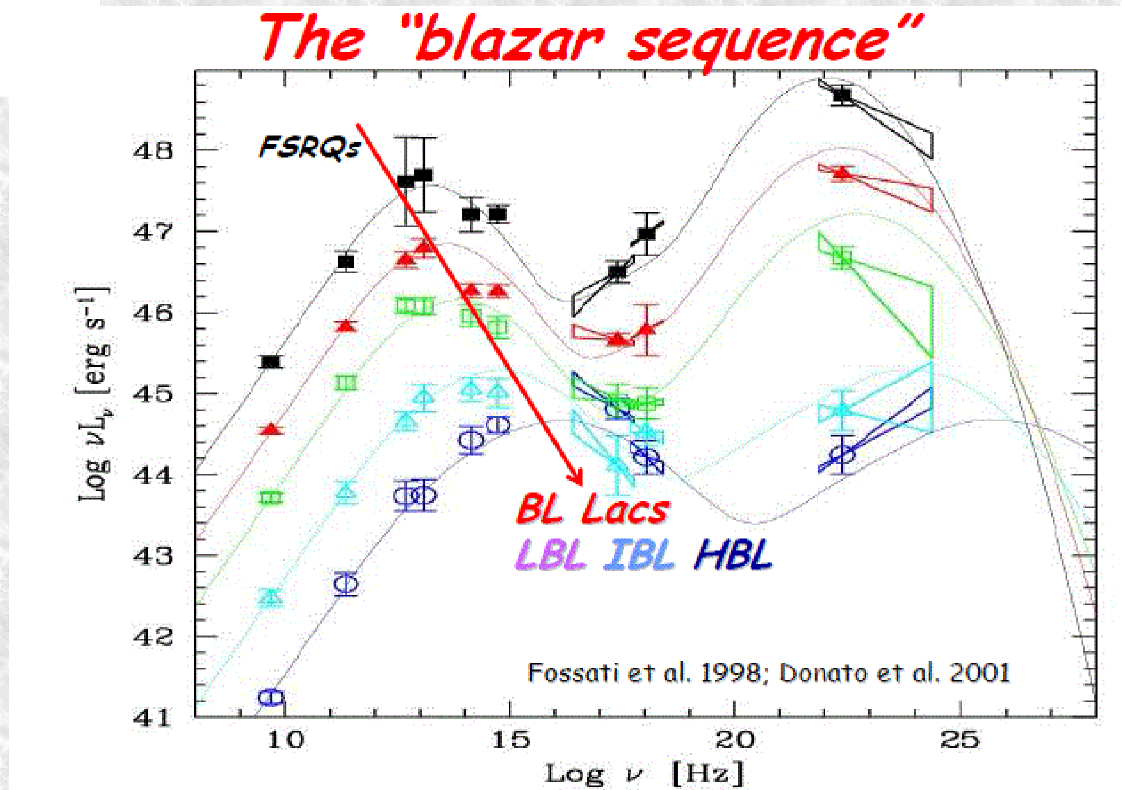
High resolution spectrum of an AGN outflow seen in transmission.



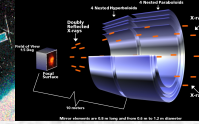
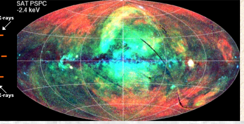
Some X-ray radiative processes: Compton scattering



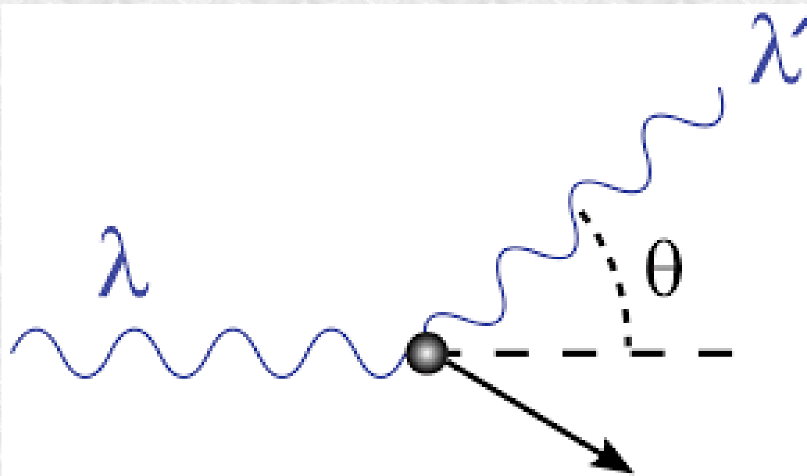
Compton up-scattering by a plasma of fast (hot) electrons. The photon gains energy during each scattering event → emission of a non-thermal continuum that may reach up to gamma rays.





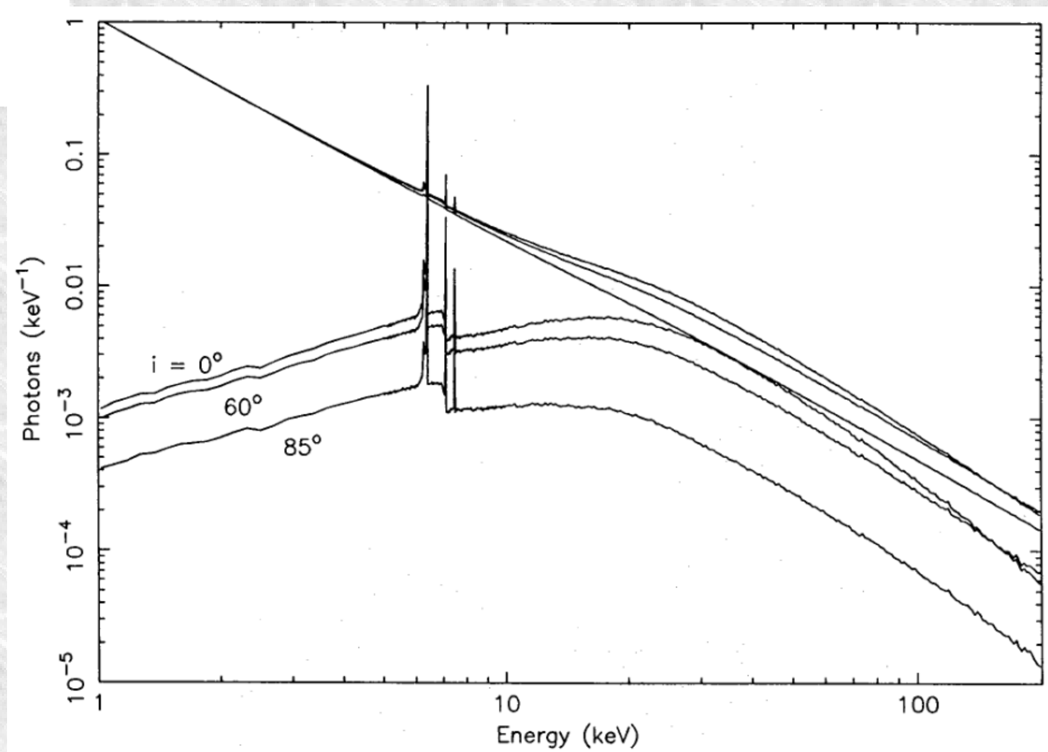




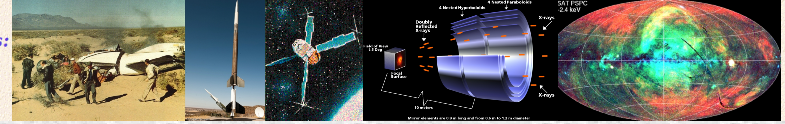
Some X-ray radiative processes: Compton scattering



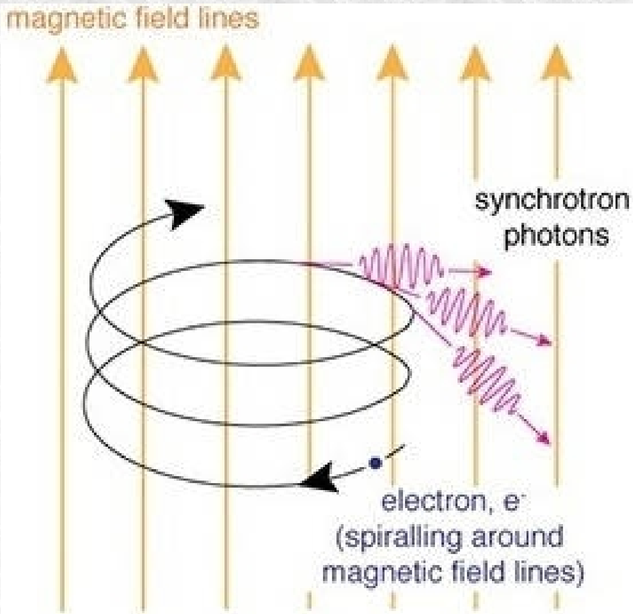
Pioneering modeling in the context of black hole accretion
George & Fabian (1991)

Compton down-scattering of X-ray radiation by a relatively cold matter containing low energy or bound electrons. The photon looses energy at each scattering event → emission of a “reflection” spectrum.





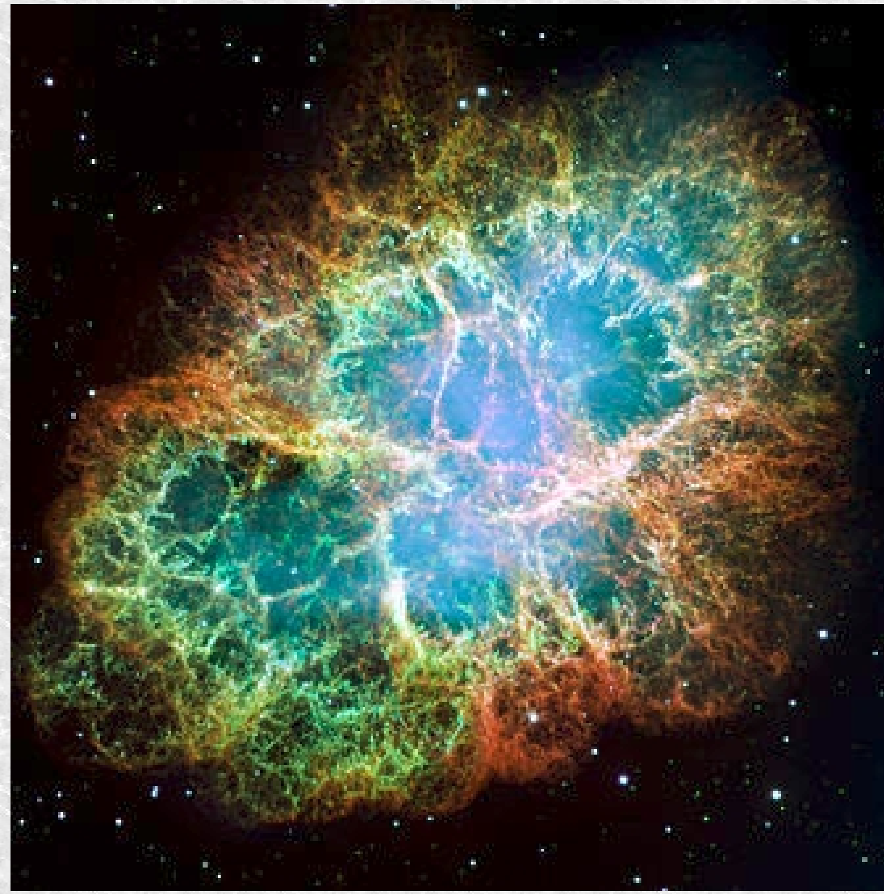
Some X-ray radiative processes: Cyclotron/synchrotron

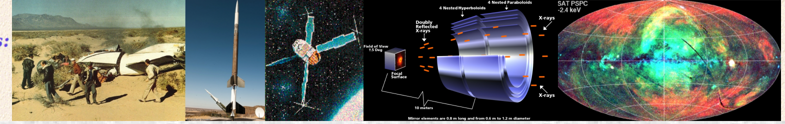


Radiation emitted by electrons spiraling in a magnetic field:

– fast electrons: synchrotron

– slow electrons: cyclotron





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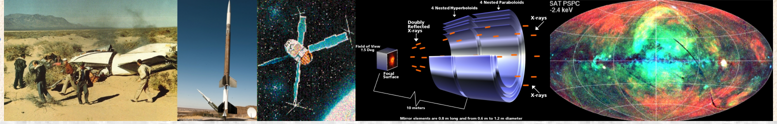
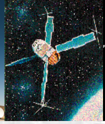
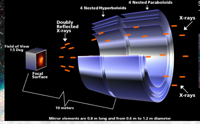
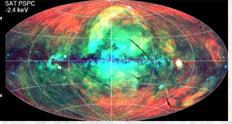


The violent beginning of space exploration

- Wernher von Braun develops the ballistic rocket "Vergeltungswaffe 2" (V2) during the late 1930s

- At the end of World War II, Wernher von Braun and his rocket technology are captured and transferred to the USA → pioneering work for the American Space Program

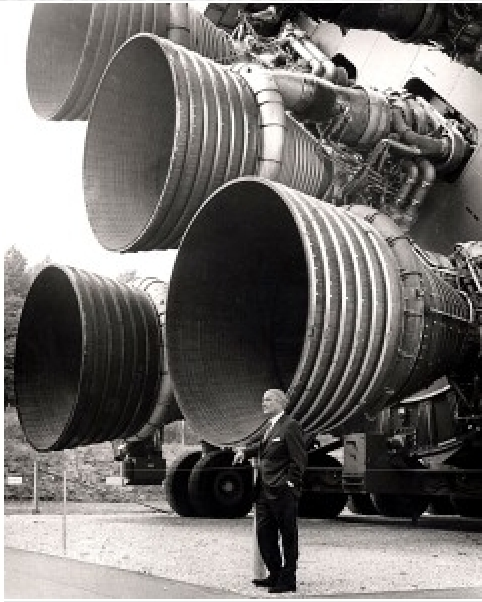


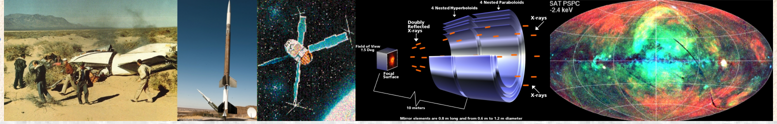
The (violent) beginning of space exploration...

- Earliest rocket experiments by **R. H. Goddard** during the 1920s.
- Leap in technology of the American Space program due to the expertise of the Wernher von Braun team.
- Biggest rocket: Saturn V used for the Apollo program

Dr. Robert H. Goddard and His Rockets: Dr. Goddard and liquid oxygen-gasoline rocket in the frame from which it was fired on March 16, 1926, at Auburn, Massachusetts. It flew for only 2.5 seconds, climbed 41 feet, and landed 184 feet away in a cabbage patch. From 1930 to 1941, Dr. Goddard made substantial progress in the development of progressively larger rockets, which attained altitudes of 7800 feet.
Credit: NASA



Wernher von Braun: A pioneer of America's space program, Dr. von Braun stands by the five F-1 engines of the Saturn V Dynamic Test Vehicle on display at the U.S. Space & Rocket Center in Huntsville, Alabama, circa 1969. Dr. von Braun served as the first director of the NASA Marshall Space Flight Center and was the chief architect of the Saturn V launch vehicle, the superbooster that propelled the Apollo spacecraft to the Moon.
Credit: NASA



1962: Discovery of Sco X-1

Riccardo Giacconi, Bruno Rossi and collaborators

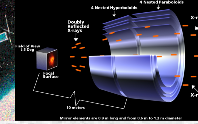
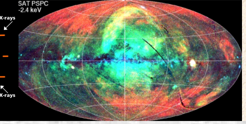
Launch of an **Aerobee** rocket with the purpose to look for X-ray emission from the moon

Payload: 3 large area Geiger counters

Max. altitude of 225 km
Flying higher than 80 km for 350 s
Flight direction: almost straight north for a distance of 120 km

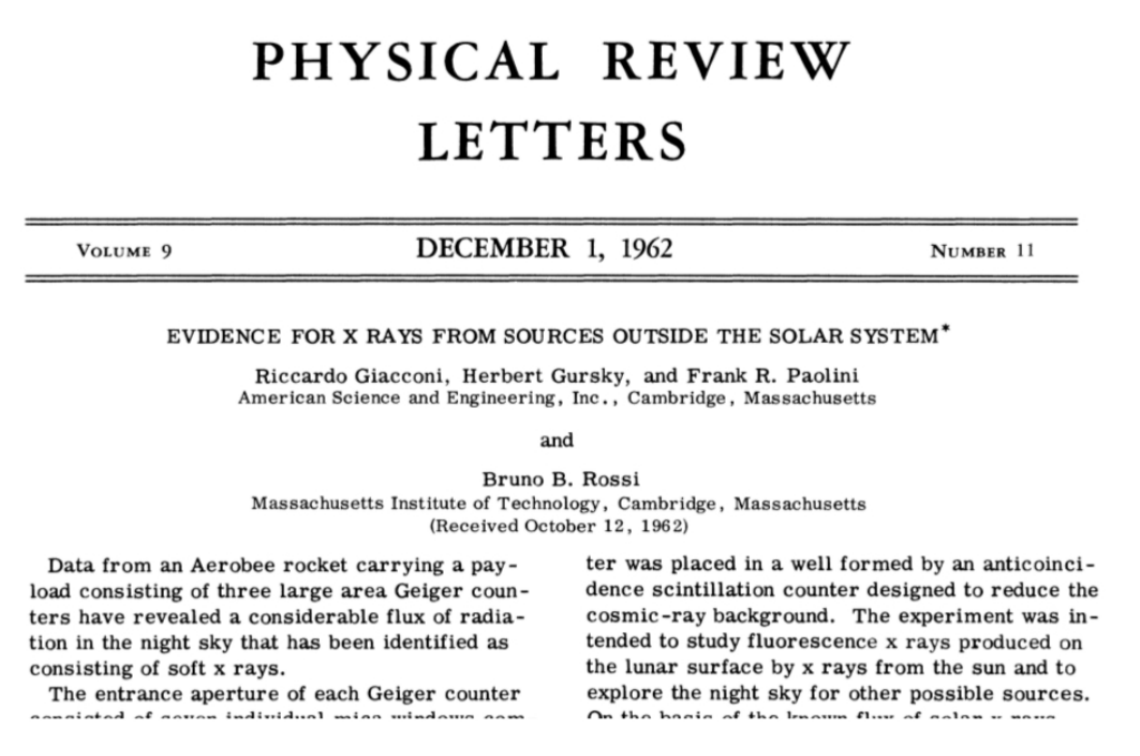
No significant X-ray emission from the moon, but...



1962: Discovery of Sco X-1

Riccardo Giacconi is awarded the Nobel prize in 2002 for his pioneering work and the discovery of the first extra-solar X-ray source.



PHYSICAL REVIEW LETTERS

VOLUME 9 DECEMBER 1, 1962 NUMBER 11

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

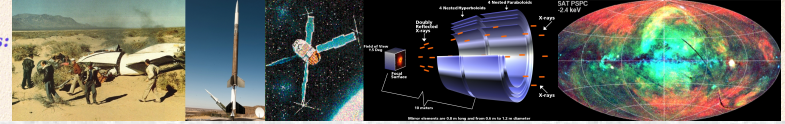
Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

and

Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received October 12, 1962)

Data from an Aerobee rocket carrying a payload consisting of three large area Geiger counters have revealed a considerable flux of radiation in the night sky that has been identified as consisting of soft x rays.

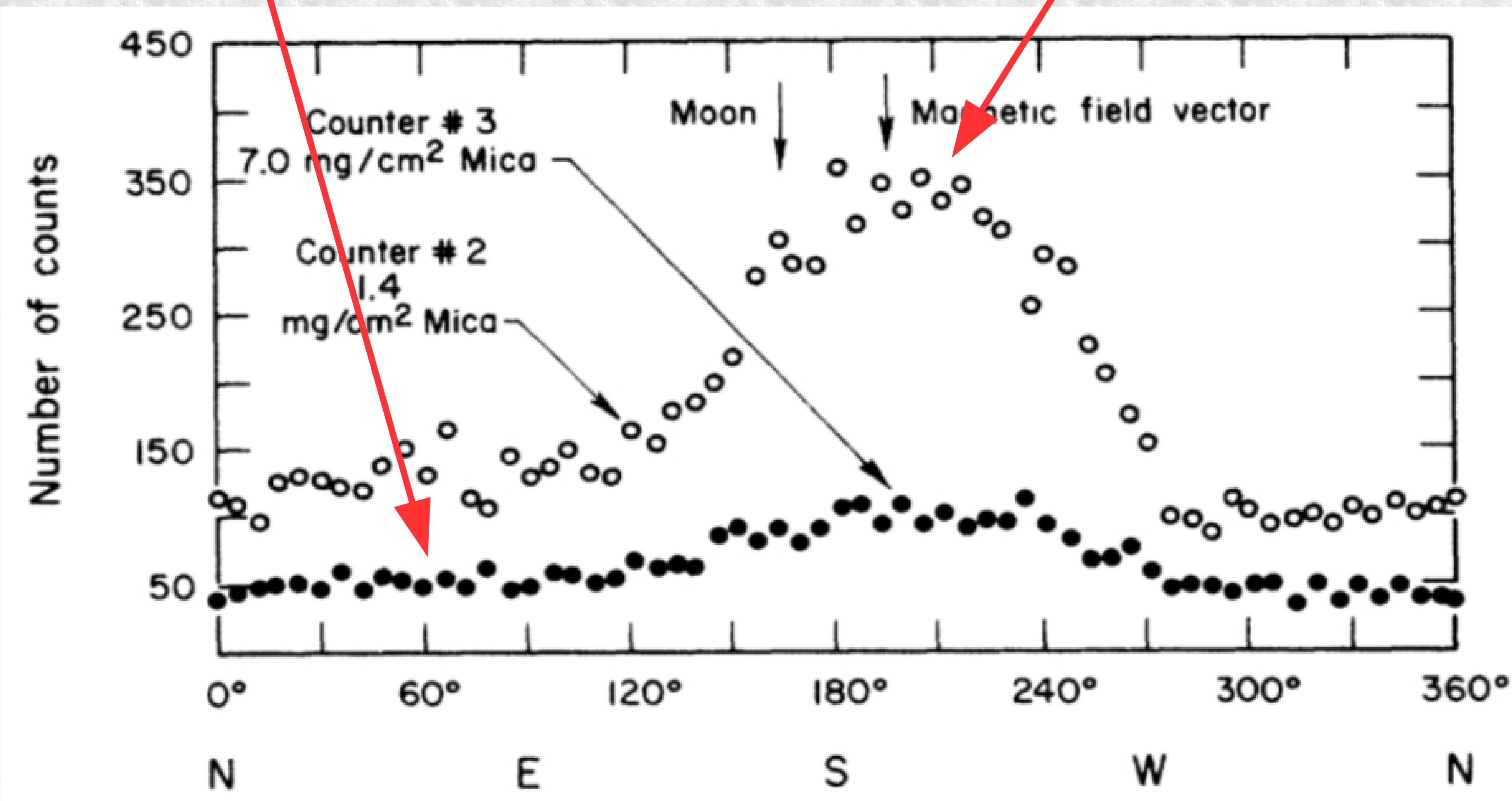
The entrance aperture of each Geiger counter [illegible] ter was placed in a well formed by an anticoincidence scintillation counter designed to reduce the cosmic-ray background. The experiment was intended to study fluorescence x rays produced on the lunar surface by x rays from the sun and to explore the night sky for other possible sources.



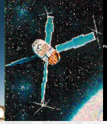
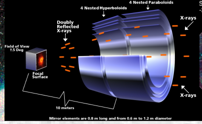
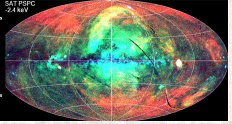
1962: Discovery of Sco X-1

Sco X-1

“isotropic (?)” X-ray background





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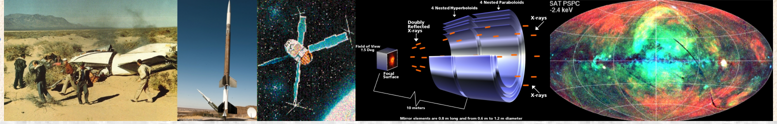
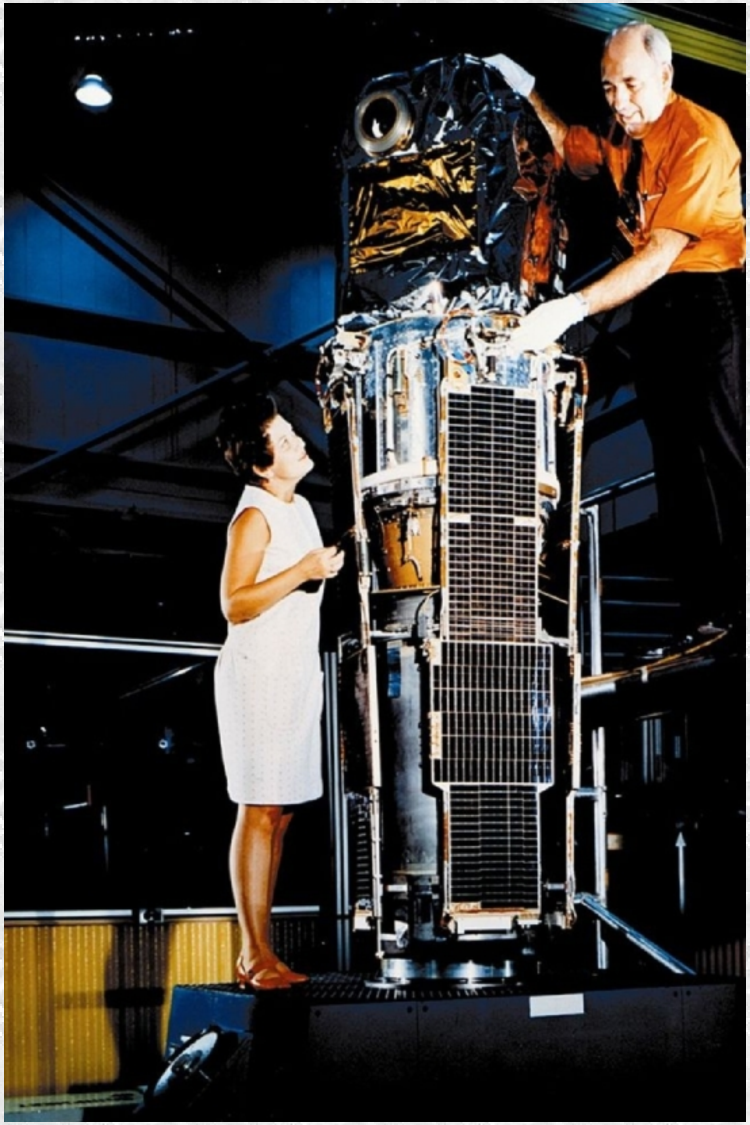
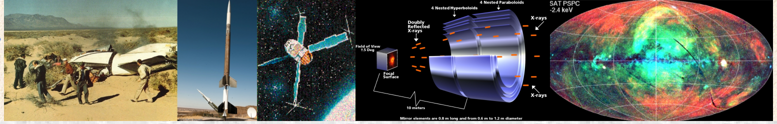


The step to X-ray observatories: UHURU

- Rocket flights above 100 km are limited to a few minutes.
- For considerable observation time a satellite is needed.
- 12 Dec 1970: launch of UHURU as the first X-ray space observatory.
- Live time until March 1973
- First systematic X-ray surveys ever conducted





The step to X-ray observatories: UHURU

- Spectral band 2 .. 20 keV
- Focusing instrument
- Payload: two proportional counters
- Flux limit 10^{-4} of Sco X-1
- $A = 0.084\ m^2$
- Angular res. = 0.54°
- First black holes Cyg X-1, Her X-1, X-ray pulsars
- Extragalactic X-ray sources & galaxy clusters
- Total of 339 sources in the 4th Catalog (denominations like 4U1957+11 etc..)

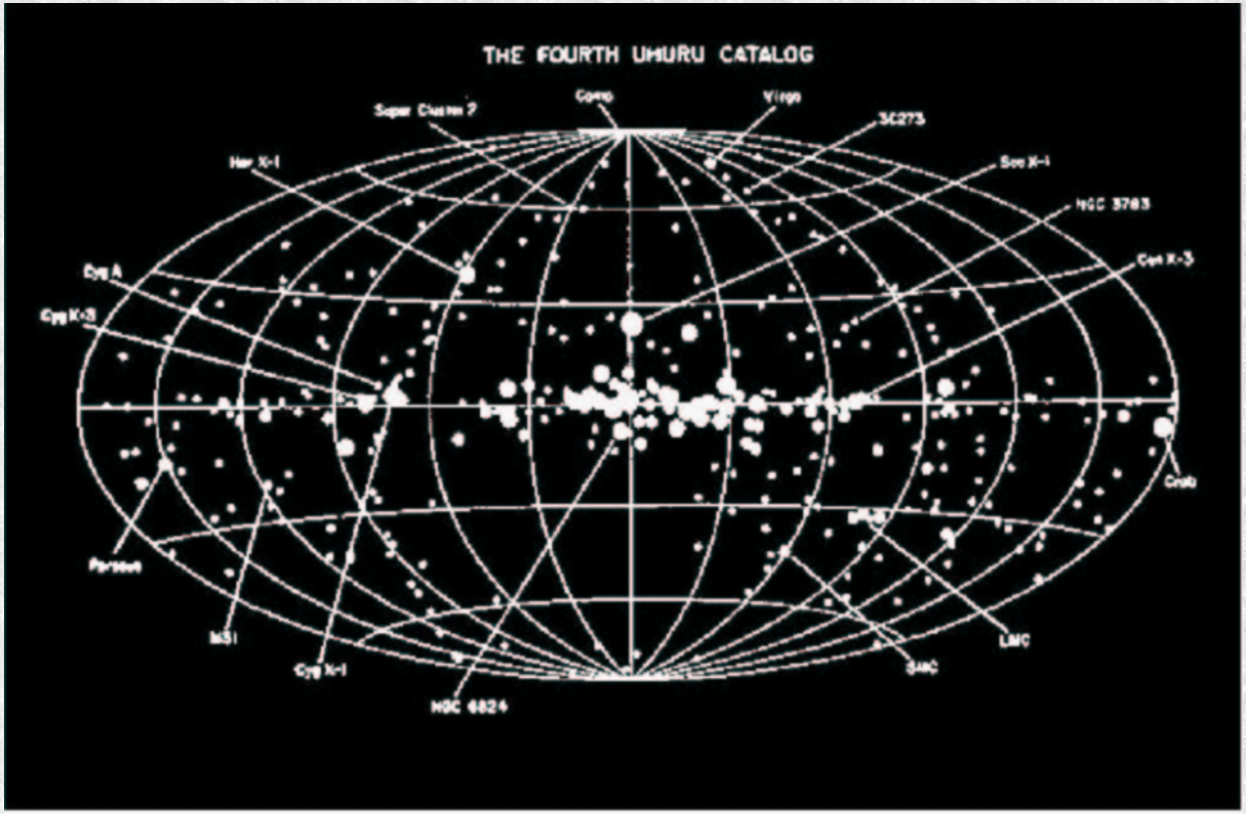
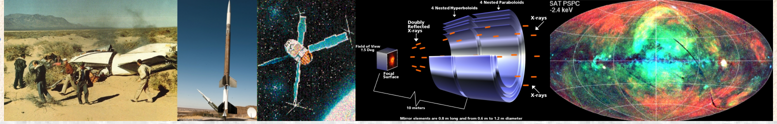
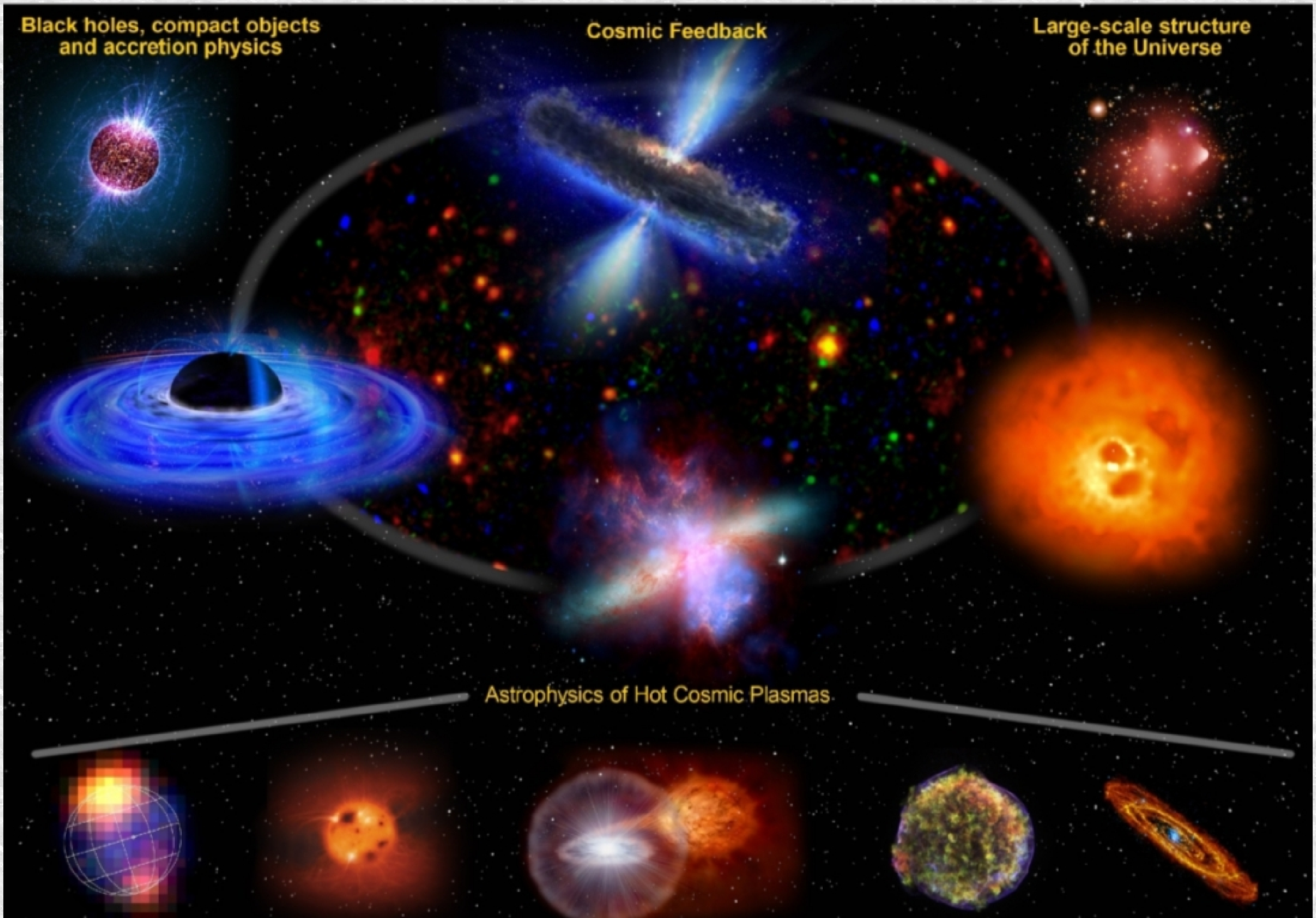
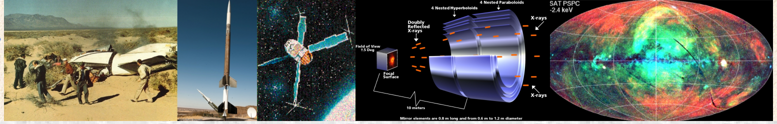


Figure 4. The x–ray sources observed by UHURU plotted in galactic coordinates. The site of the dot is proportional to intensity on a logarithmic time scale. From X-ray Astronomy (Eds. R. Giacconi, H. Gursky), 1974, Riedel, Dordrecht, p. 156.



What is there to be observed in the X-rays?

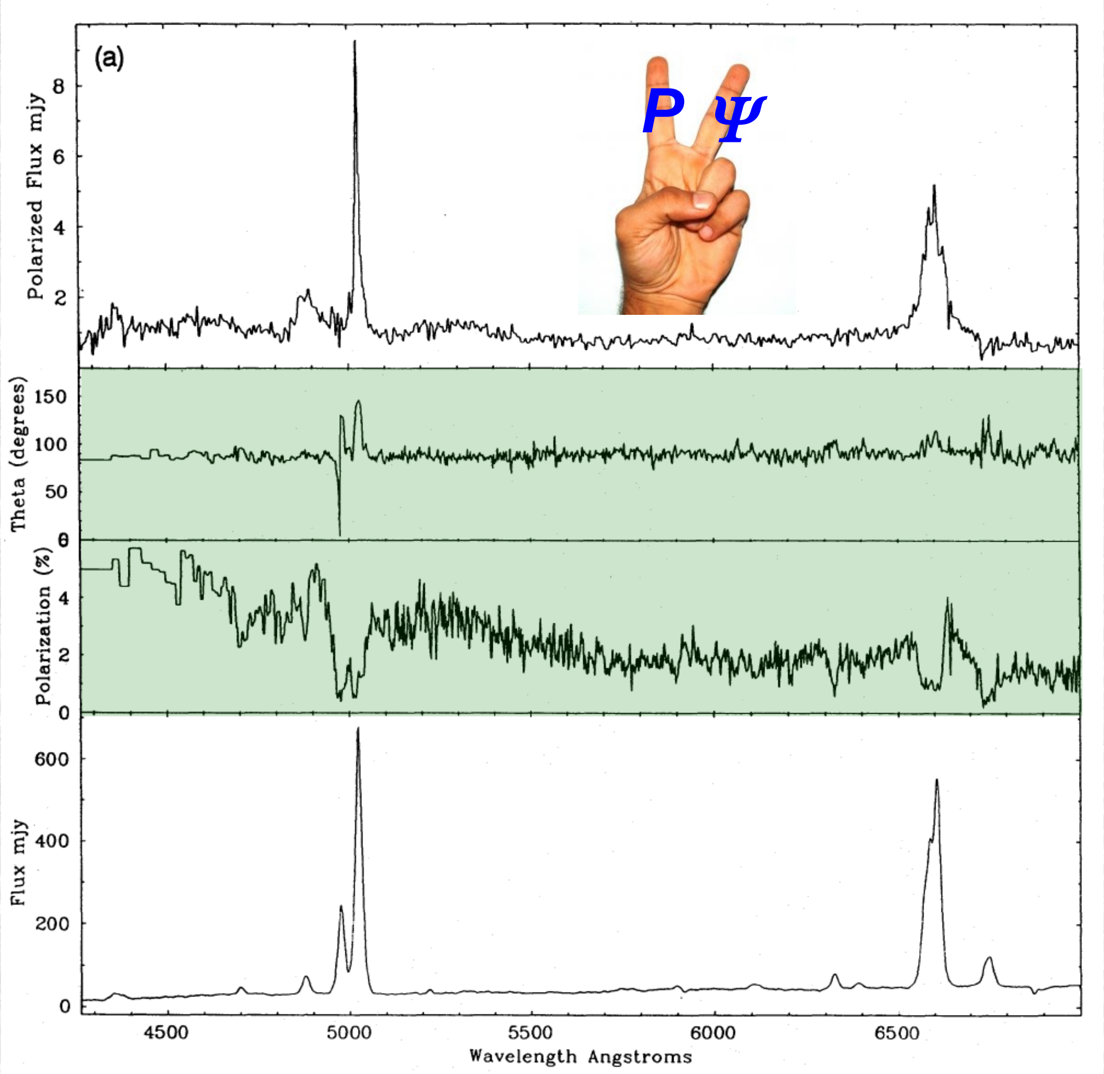




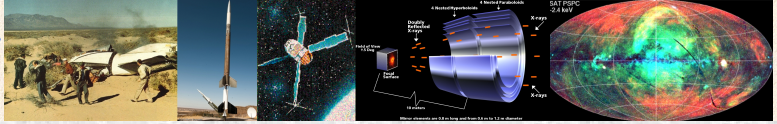
Why should we care about X-ray polarization?

Note: almost any interaction of EM radiation with matter also modifies its polarization state!

ERGO: Considering the polarization state of light gives us a set of **two additional, independent observables** as a function of photon wavelength, time, and space.



Inglis et al. 1995



Processes producing X-ray (de-)polarization

Electron scattering

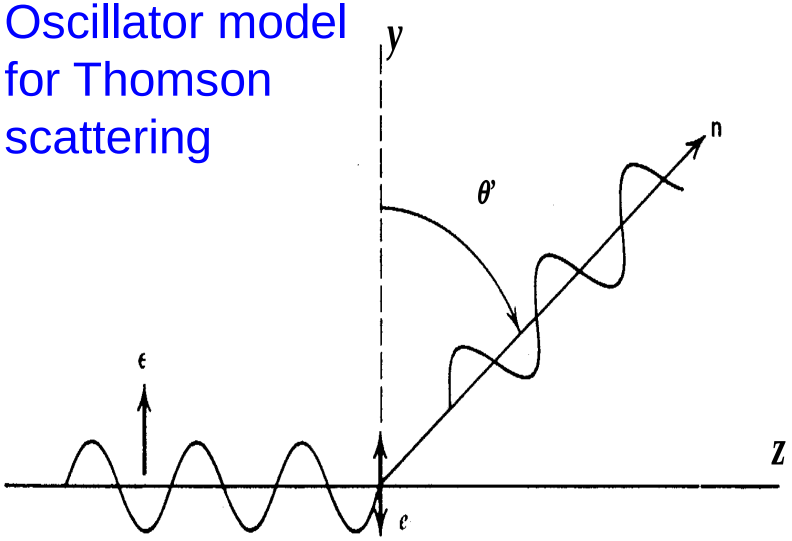
Resonant line scattering

Dilution (by unpolarized radiation)

General Relativity

Synchrotron and SSC emission

Oscillator model for Thomson scattering



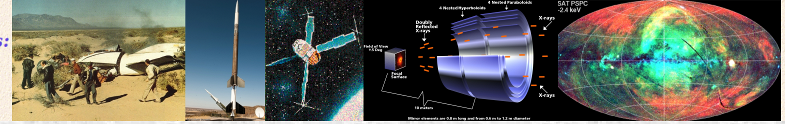
$$\frac{\partial\sigma}{\partial\omega}(\alpha)_{tot} = \frac{1}{2} r_0 \left(1+\cos^2\theta\right).$$

Scattering

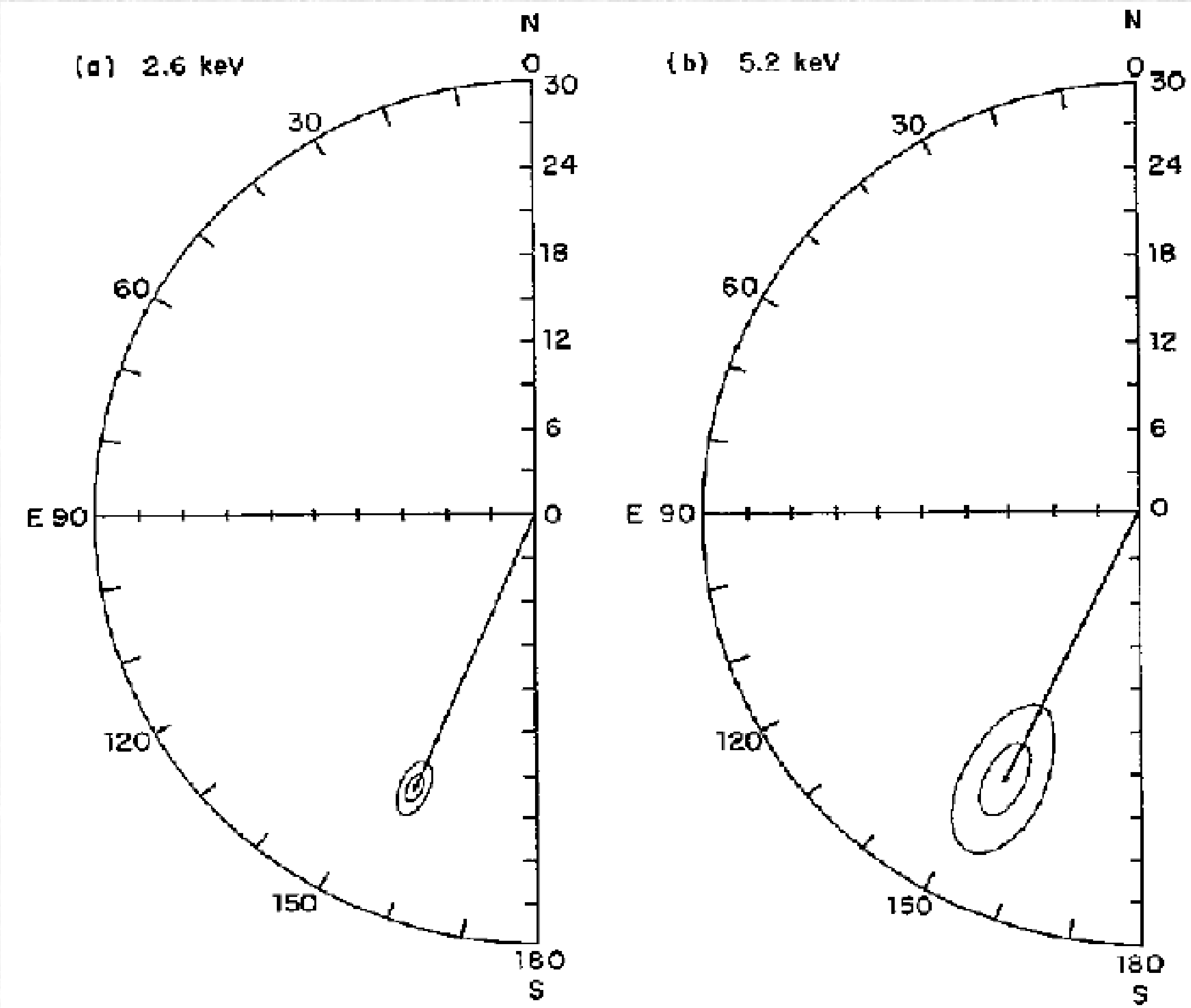
Strong polarization: Θ = 90° (Reflection)
Weak polarization: Θ = 0° (Transmission)

$$P = \frac{1-\cos^2\theta}{1+\cos^2\theta}.$$

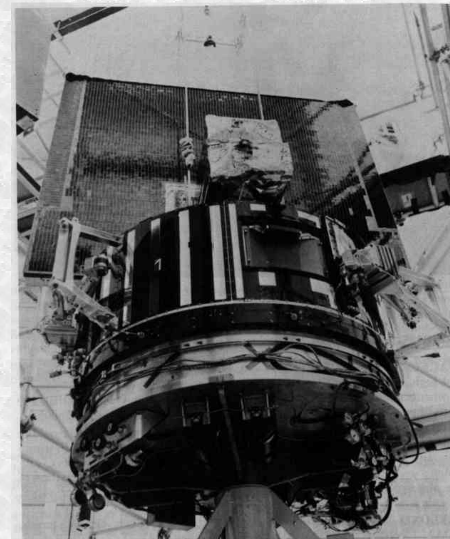
$$\sigma_T = \frac{8\pi}{3} r_0^2 = \frac{8\pi e^4}{3m^2c^4}.$$



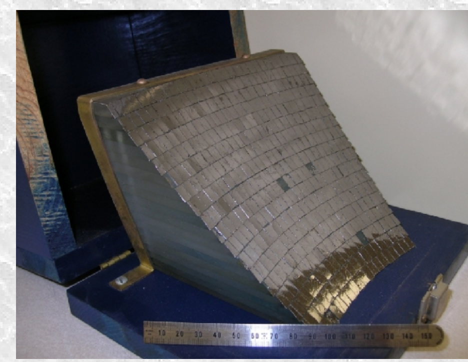
So-far (soft) X-ray polarization experiment



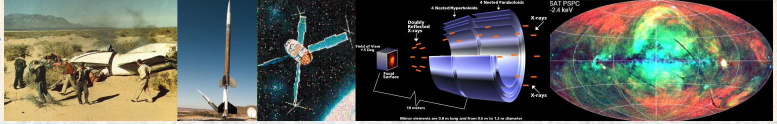
Crab Nebula (OSO-8), Weisskopf et al (1978)



OSO-I undergoes launch preparation. (NASA photo)

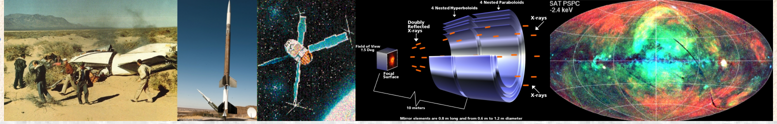


Bragg-reflection polarimeter

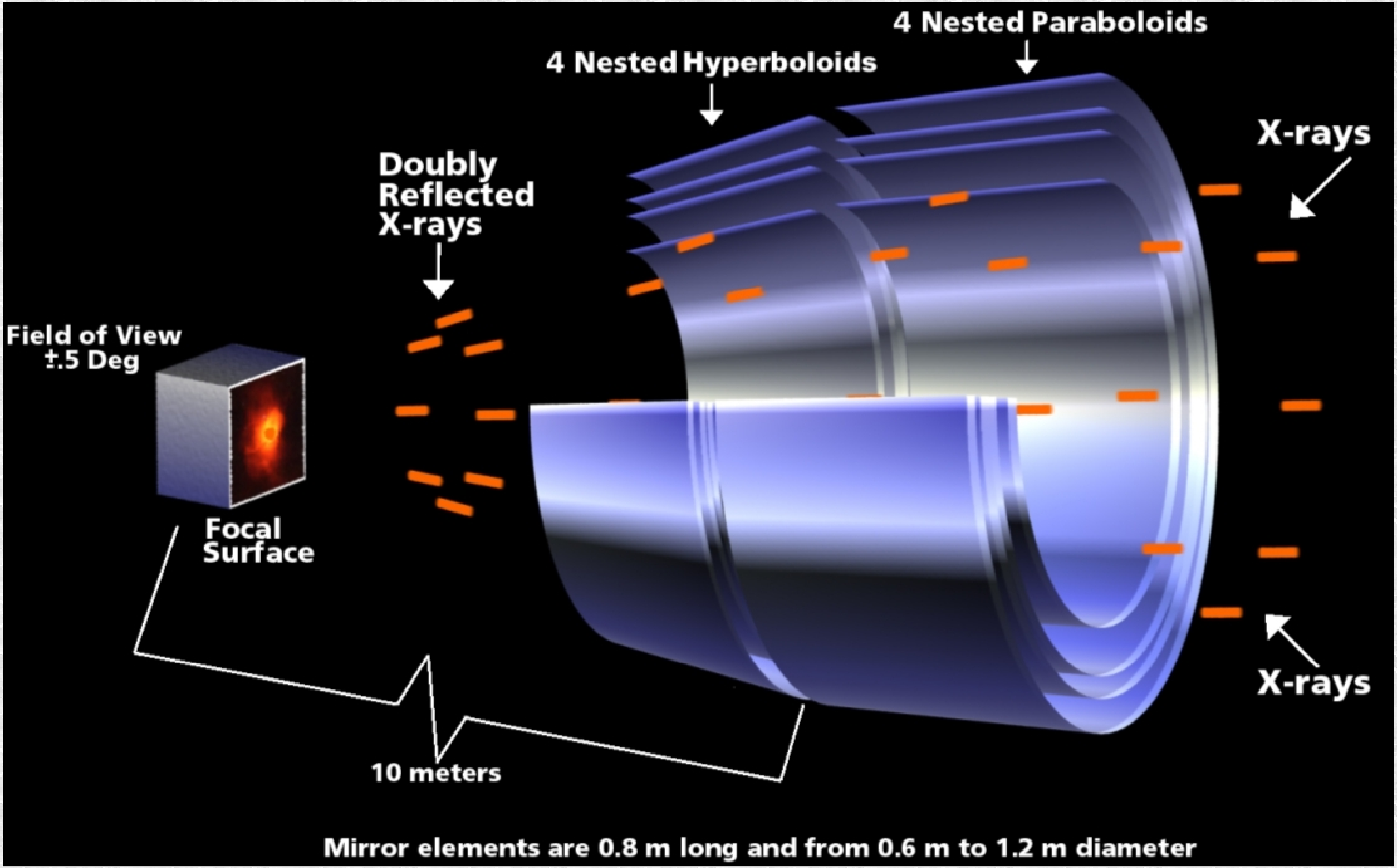


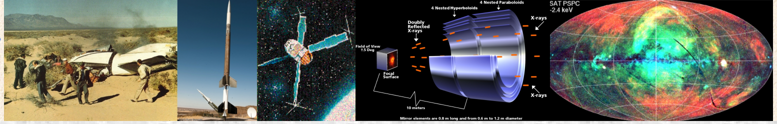
Widening the field of view

- To discover new and possibly transient X-ray sources, it is important that X-ray telescopes also have a significant field of view.
- It is then necessary to enable X-ray imaging together with spectroscopy.
- This requires focusing instruments and two-dimensional detectors → CCD cameras



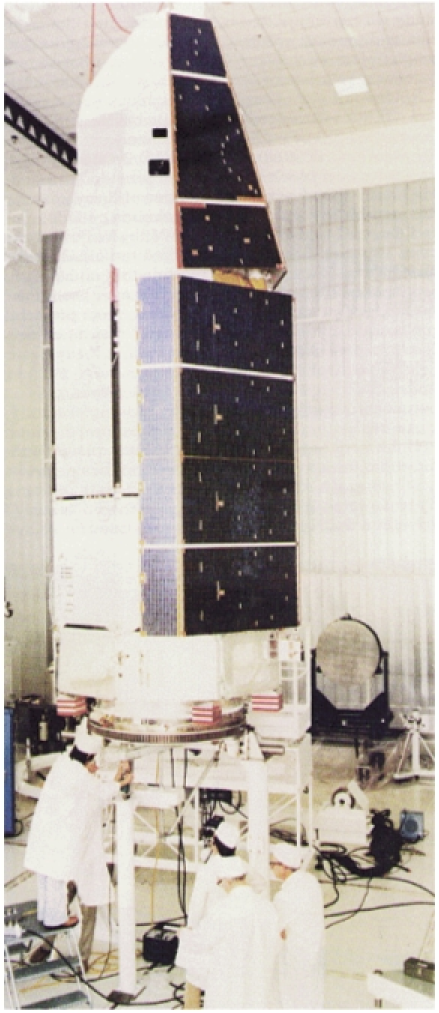
Focusing instruments: how to build an X-ray lens?

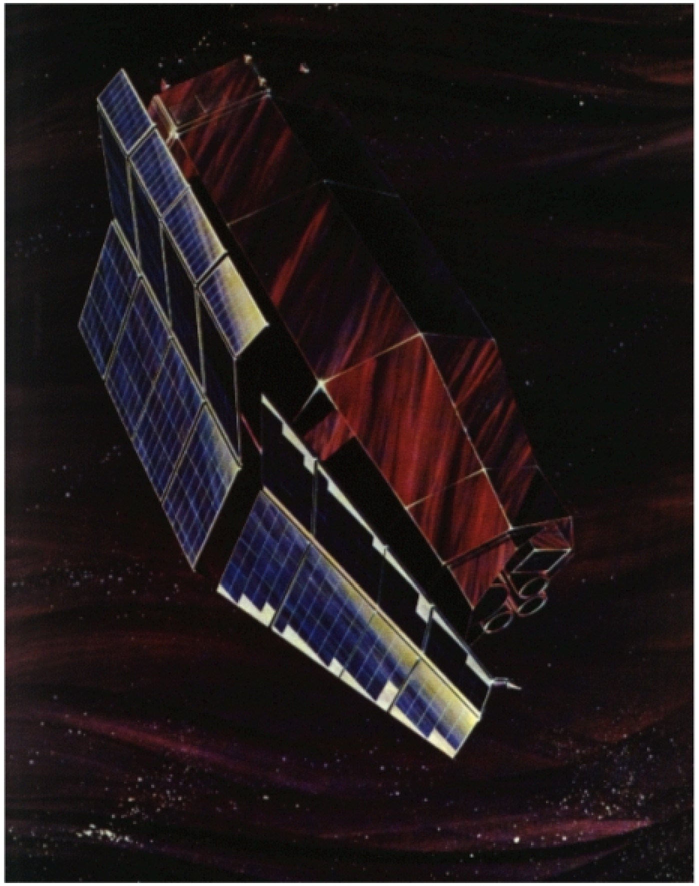


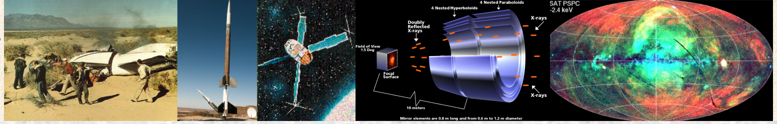


1978-1982: NASA's Einstein satellite

- First X-ray imaging observatory ever
- P.I. Riccardo Giacconi
- Set of 4 Wolter type-1 nested mirrors focusing X-rays up to 8 keV in energy
- Angular resolution: 5 arcsec on axis, degrading to 1.5 arcmin at the edge of the 1 degree field of view







1978-1982: The Einstein satellite (and a Chandra preview)

- First X-ray imaging observatory ever
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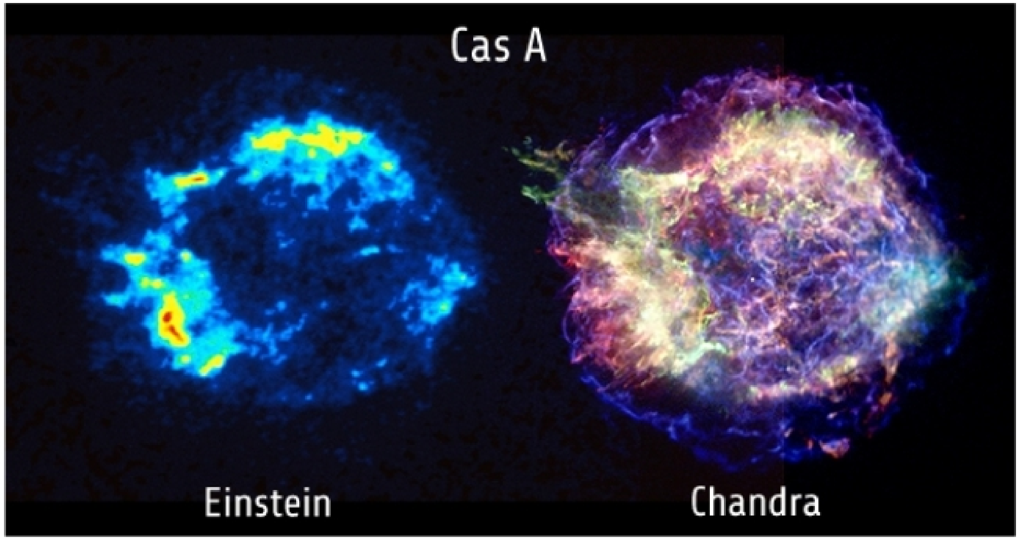
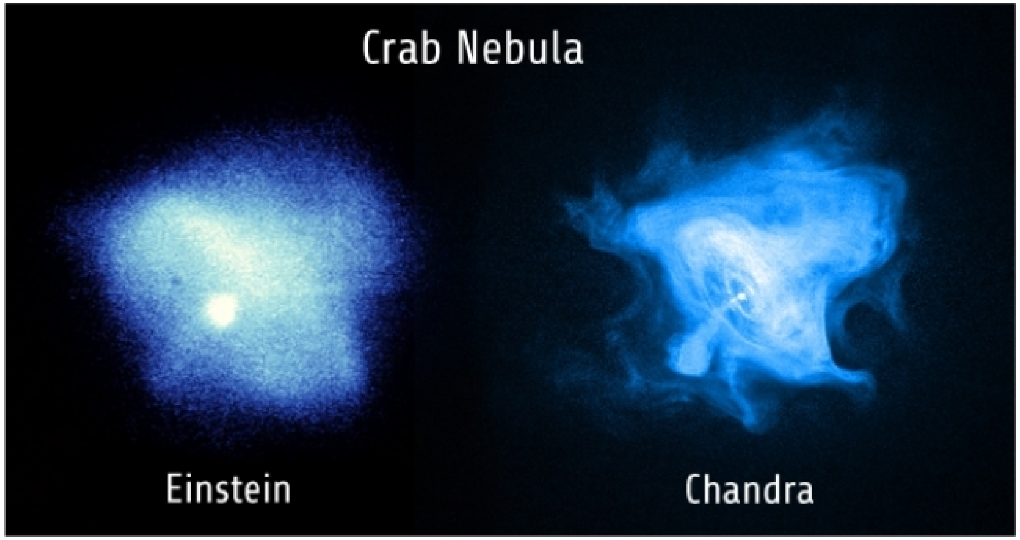
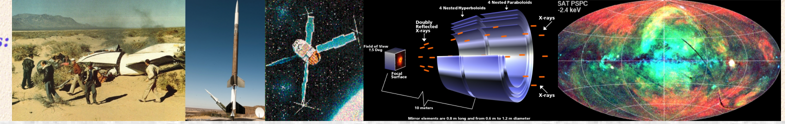
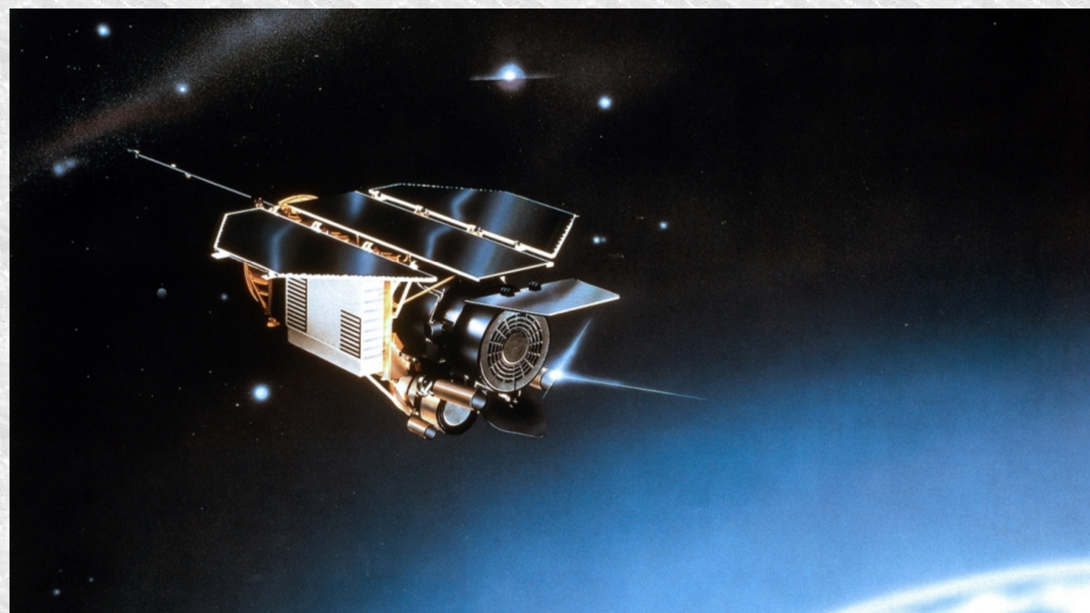


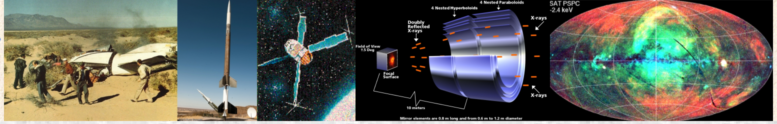




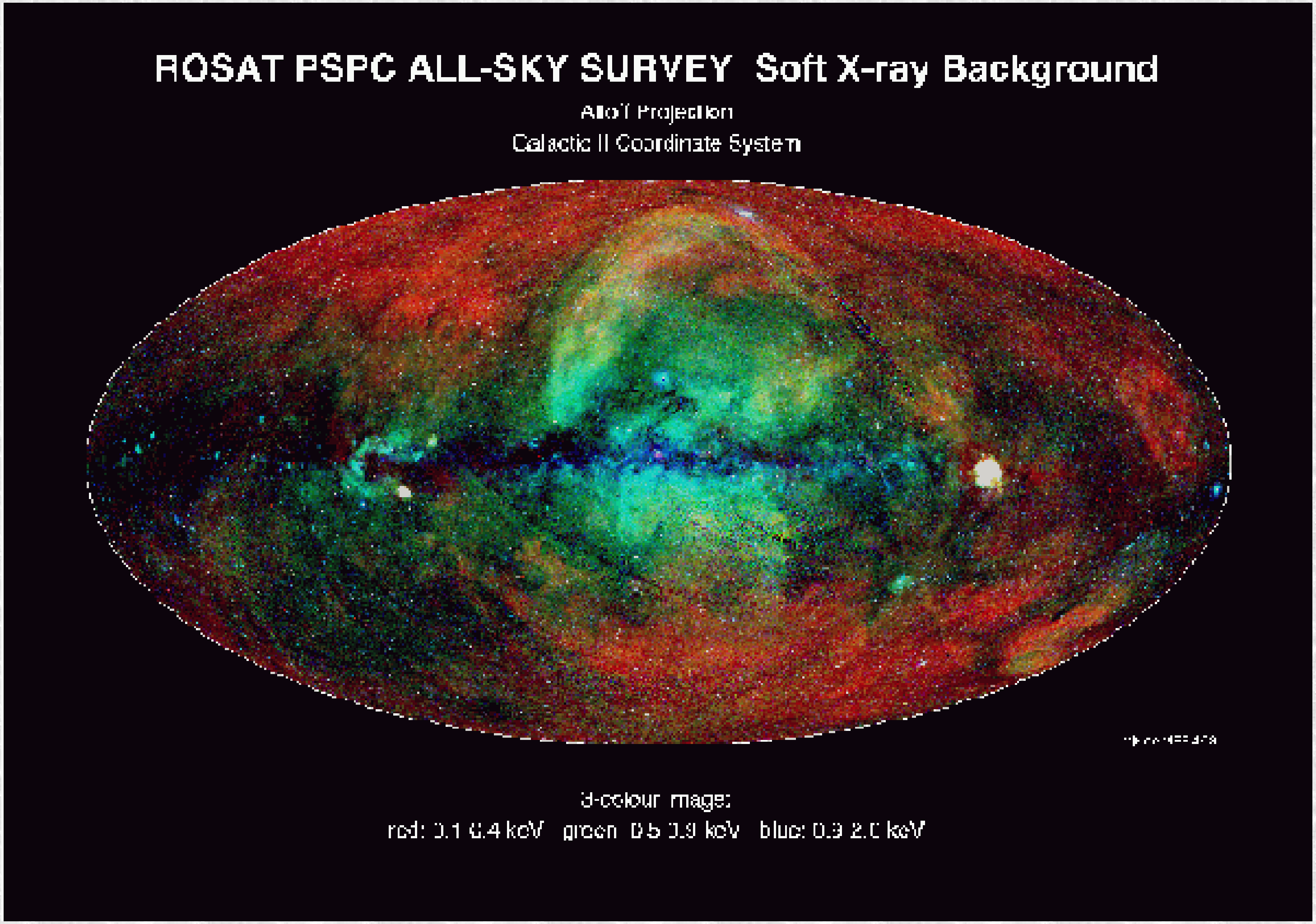
1990s: The ROSAT satellite

- Germany, USA, UK
- 0.2 - 2.4 keV
- Θ = 2 arcsec
- X-ray all-sky survey catalog, more than 150000 sources
- detection of isolated neutron stars
- Comets
- Collision of Comet Shoemaker-Levy with Jupiter

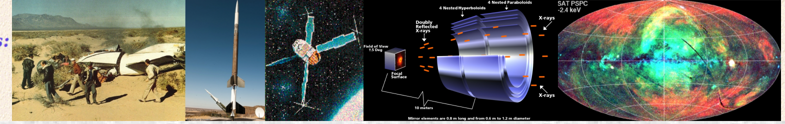




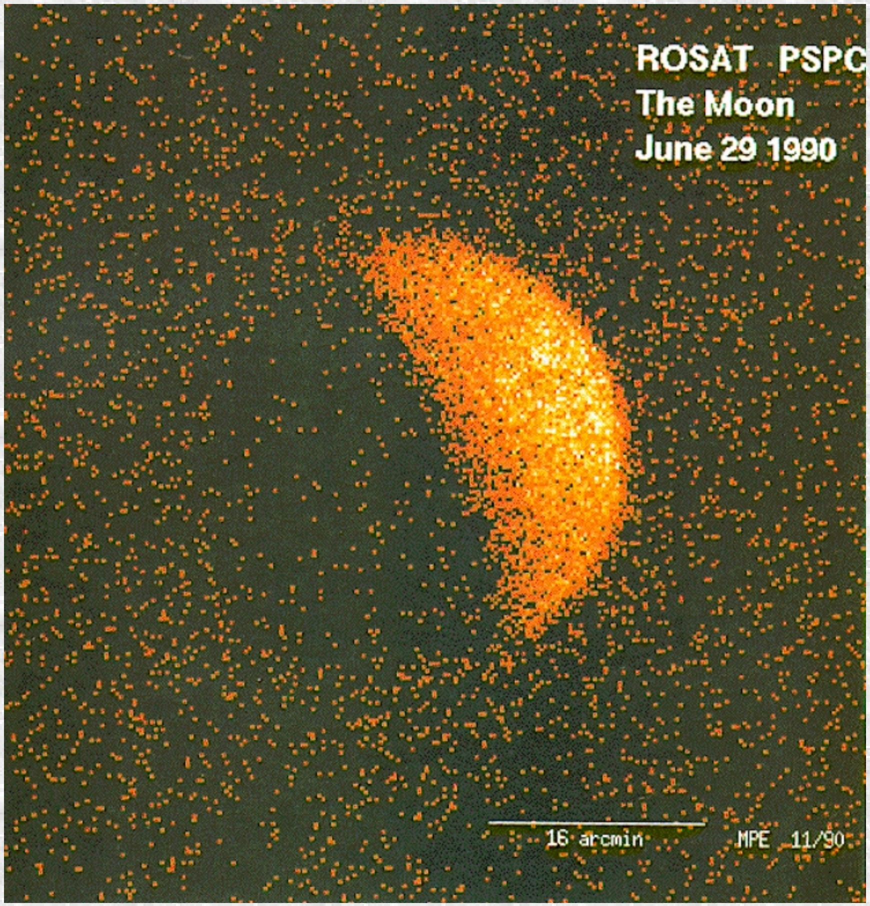
Low energy (soft) X-ray background



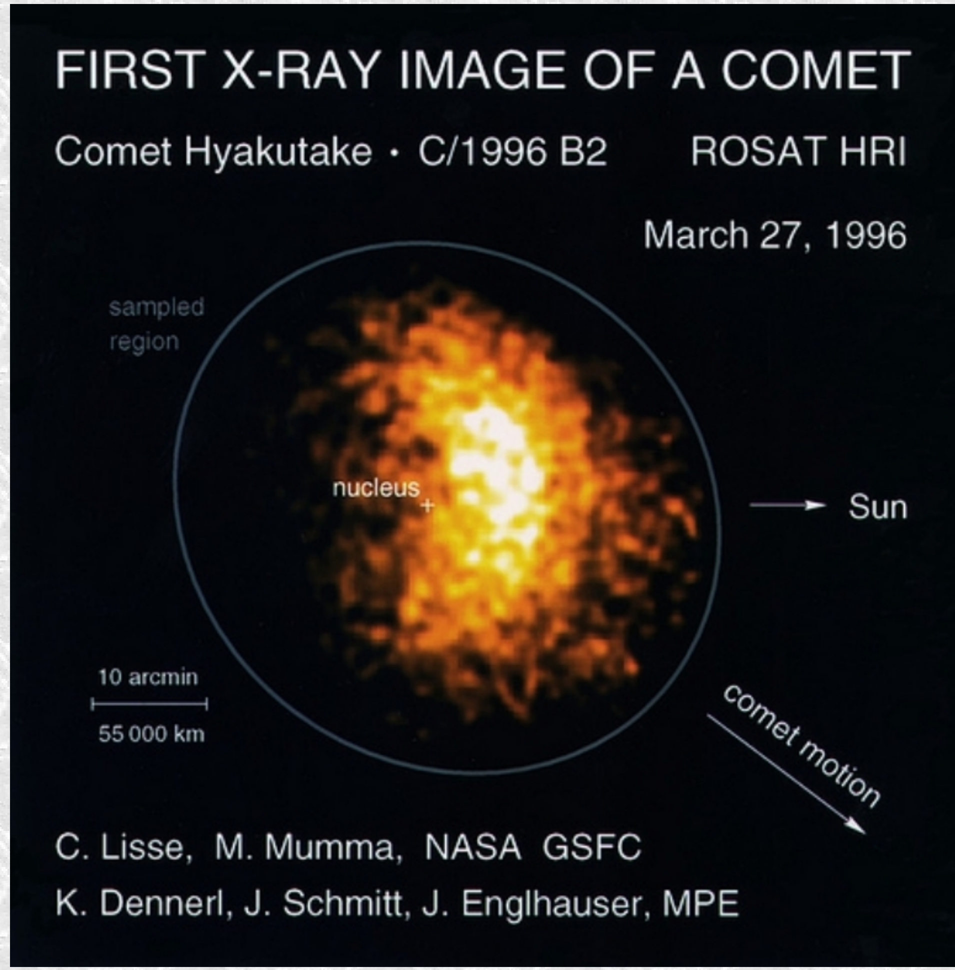
Color code from red to white represents average photon energy
T~ a few 100 000 K (red), T ~ 20 million K (white)



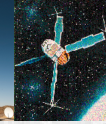
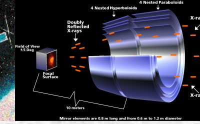
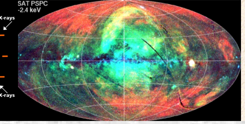
Exploring the solar system with ROSAT



Scattered solar X-rays from the moon.





1993-2001: The Japanese ASCA satellite

- The sensitivity of ASCA's instruments allowed for the first detailed, broad-band spectra of distant quasars to be observed.

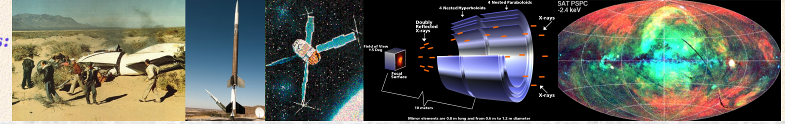
- ASCA's suite of instruments provided the best opportunity at the time for identifying the sources whose combined emission makes up the cosmic X-ray background.

- ASCA saw broad iron lines proving that the active nucleus of a galaxy is a super-massive black hole.

- ASCA provided analysis of the elemental composition, heterogeneity and particle acceleration of supernova remnants by dispersing X-rays.

- ASCA saw X-ray emission from a newly-formed protostar.

- ASCA saw a two-temperature structure of hot plasma in a galaxy cluster.

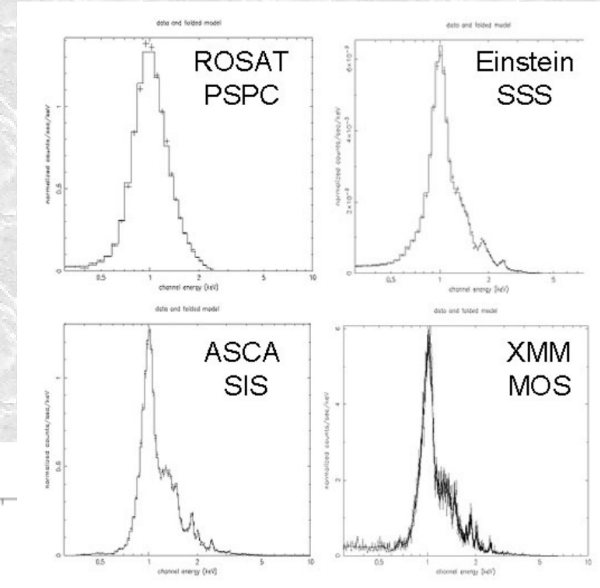


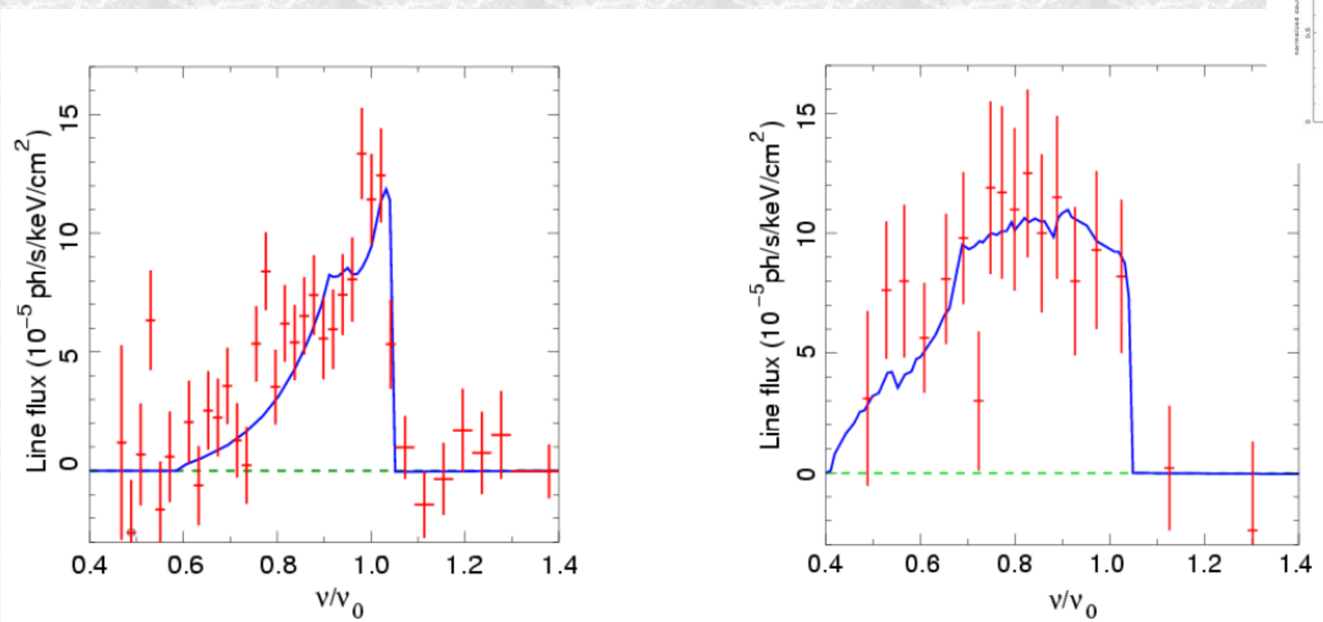
1993-2001: The Japanese ASCA satellite

- Window opened on X-ray spectroscopy of emission lines

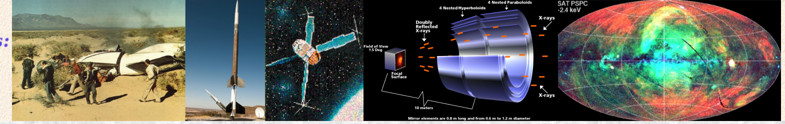
- First indication ever of a relativistic iron emission line in an active galactic nucleus

- One key motivation for the science case of XMM-Newton...



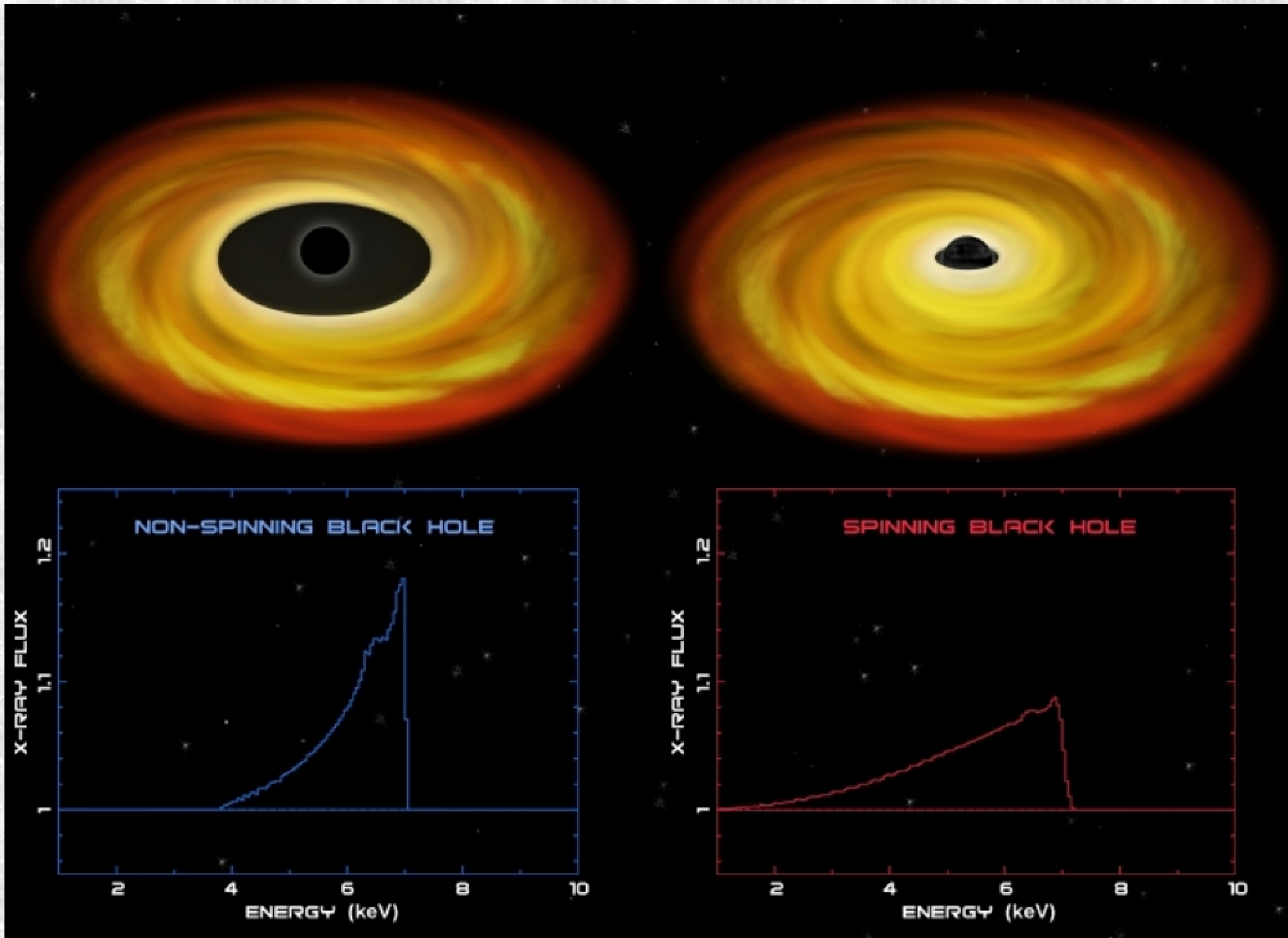


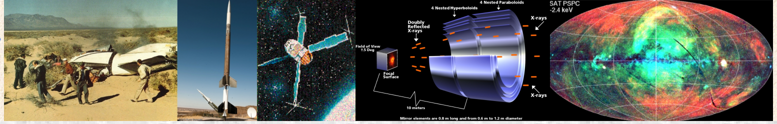
MCG−6-30-15 ($z = 0.008$): first AGN with relativistic disk line



1993-2001: The Japanese ASCA satellite

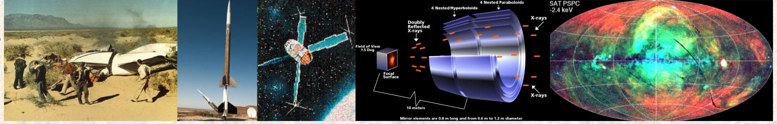
- First indication ever of a relativistic iron emission line – how to interpret it?



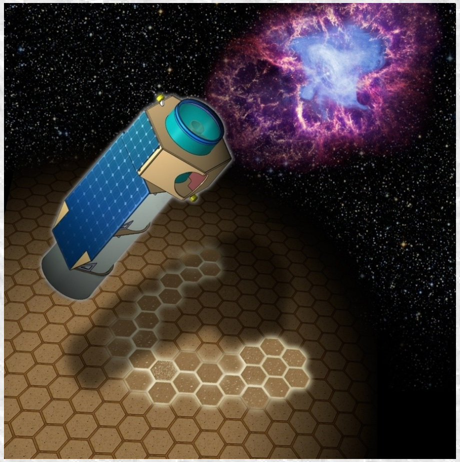


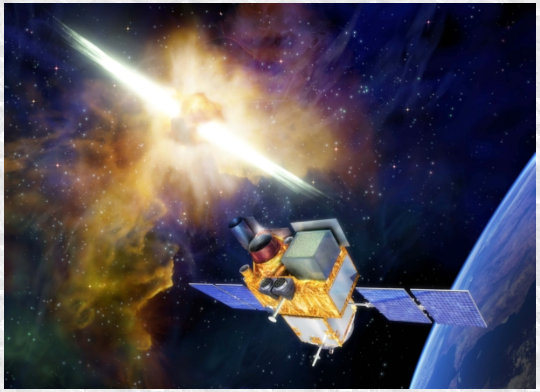
Outline

- X-rays in astronomy and how they are produced
- The beginnings of X-ray astronomy: rocket experiments
- Space-born X-ray observatories
- **Towards the future**



(Selected) future mission (projects)

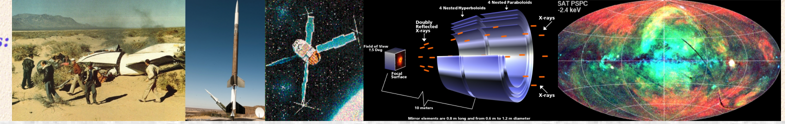




- XIPE (X-ray Imaging Polarimetry Explorer) – ESA M4 candidate, launch 2025

- Two more X-ray polarimetry missions competing for the NASA SMEX program, launch for 2022

- SVOM (Gamma burst mission) with very broad (and fast) multi-lambda coverage, launch 2022



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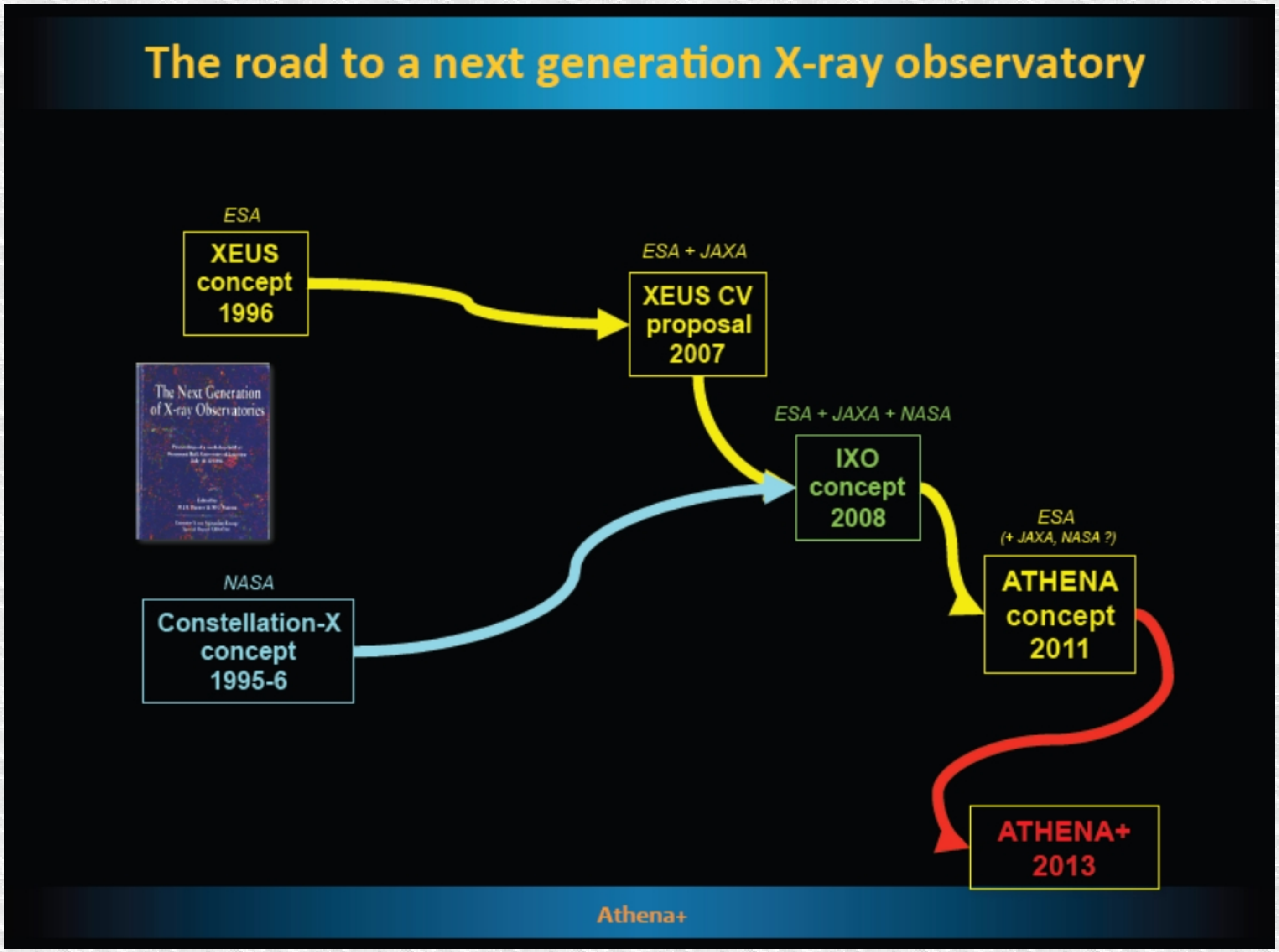

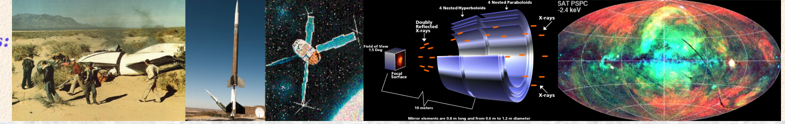

(Selected) future mission (projects)