X-ray Observations of Cosmic Accelerators

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Outline:

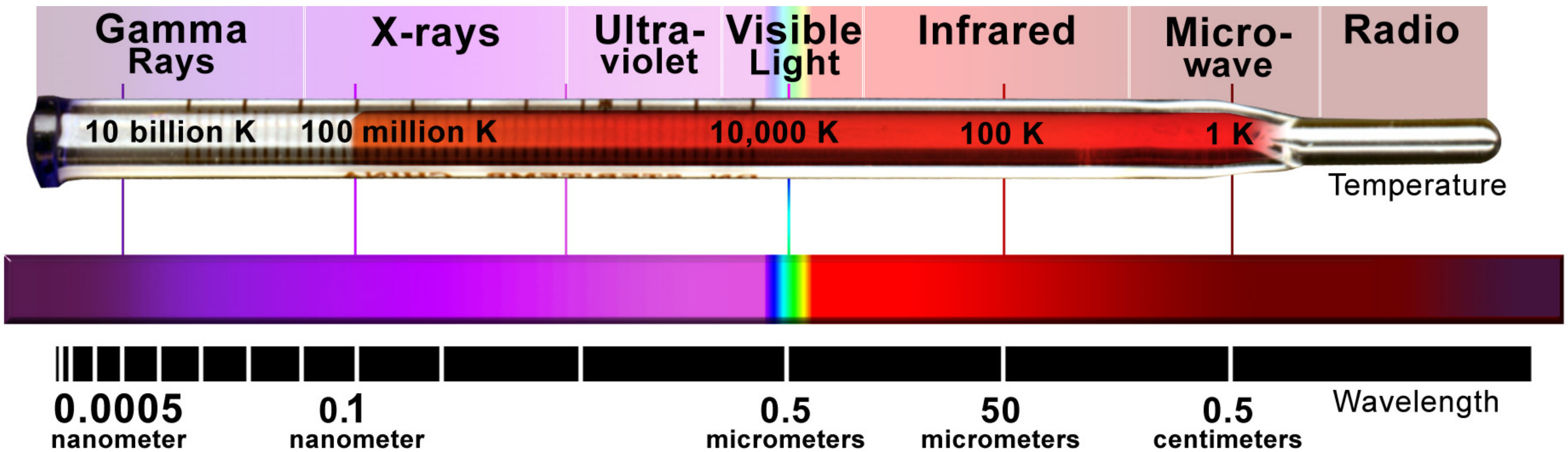
• Why the X-ray band? Motivation and brief history

• Tools of X-ray astronomy: detectors and telescopes

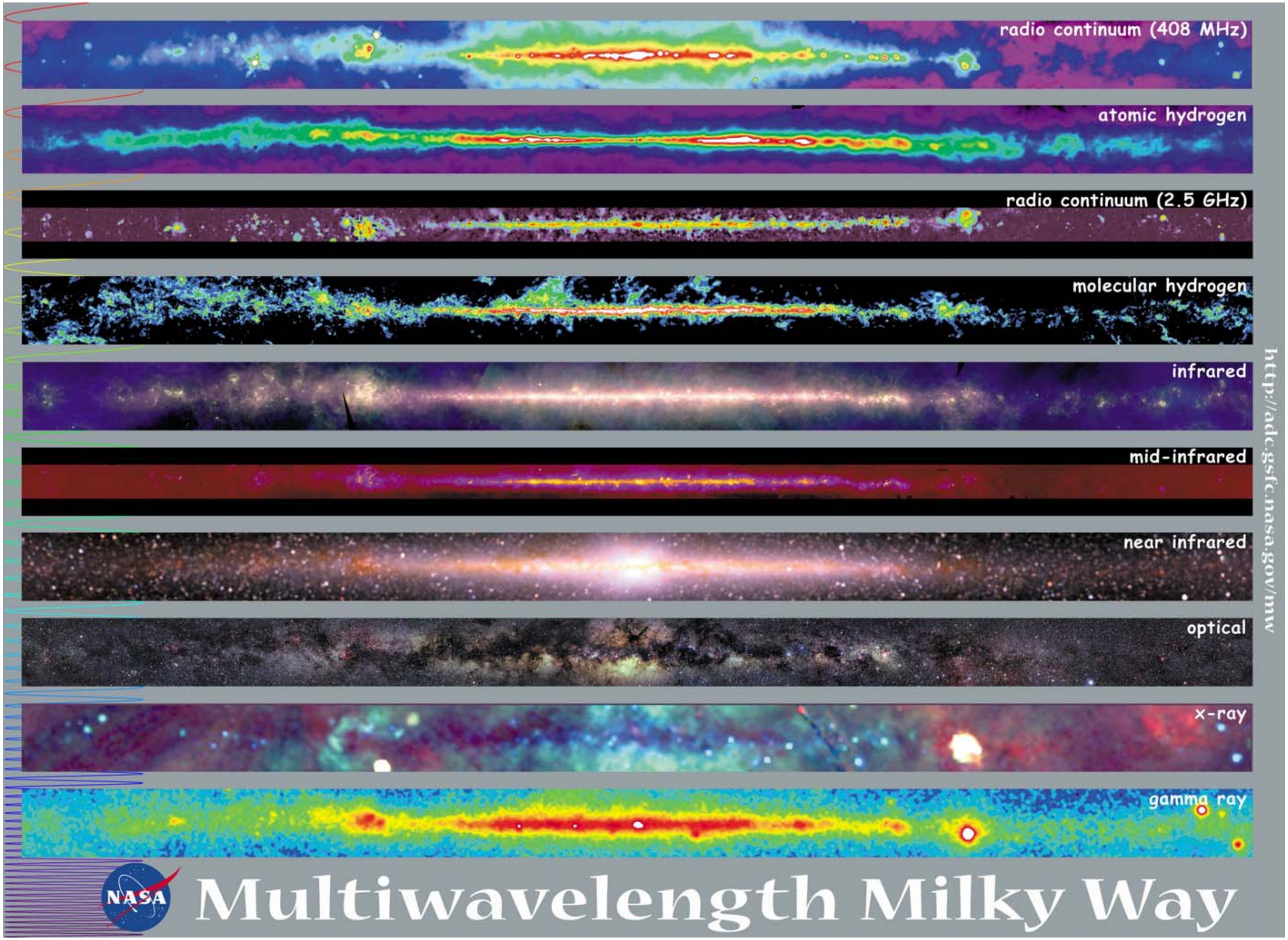
• Observations: Zoo of X-ray sources in the sky

• Case studies and “X-ray insights” into the questions of particle acceleration in the cosmos:
today - supernova remnants and X-ray binaries

X-rays and gamma-rays in perspective

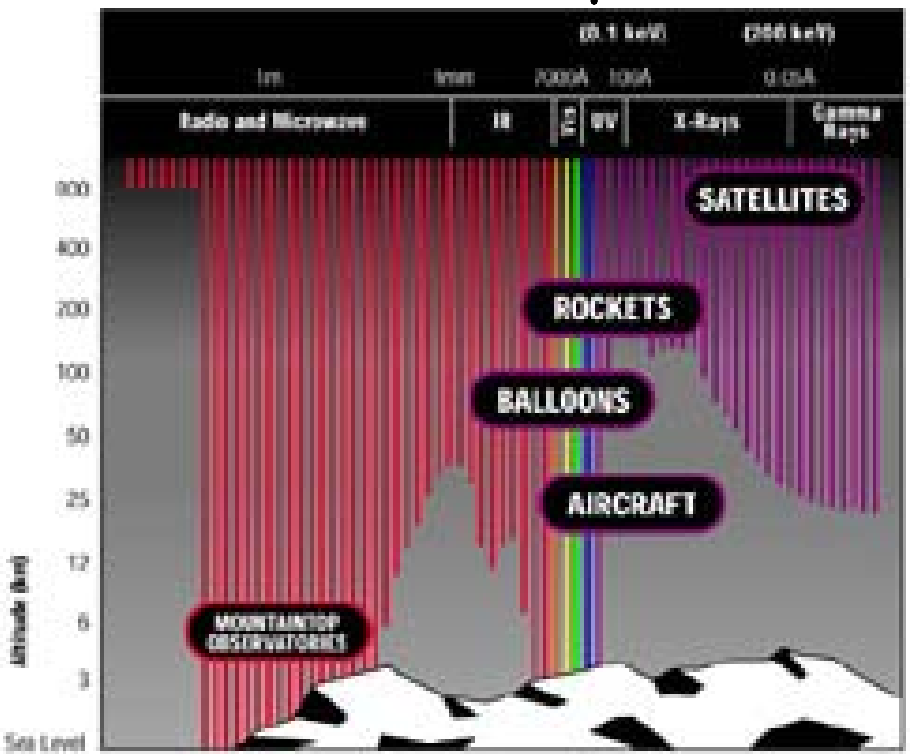


- Optical band is only a small part of the electromagnetic spectrum
- Studying astronomical sources in other spectral ranges besides the optical band can reveal very rich physical phenomena
- Radio band, opened in the 1930s, revealed the world of non-thermal processes
- X-ray and γ-ray data often – but not always – are indicative of non-thermal phenomena -> “violent Universe”



radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

X-ray and γ-ray observations require detectors above the atmosphere

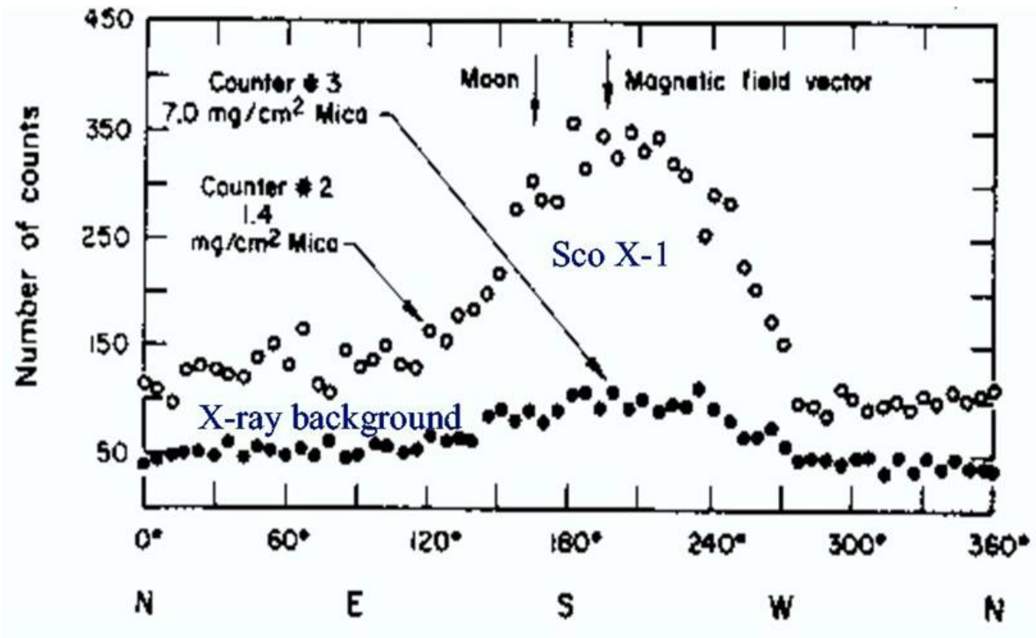


Opacity of the atmosphere
as a function of photon energy

* First observations were conducted using rocket-based, “single shot” (~ 5 min.!) instruments

* Covered the band of ~ 1-10 keV (a.k.a. “soft X-ray band”)

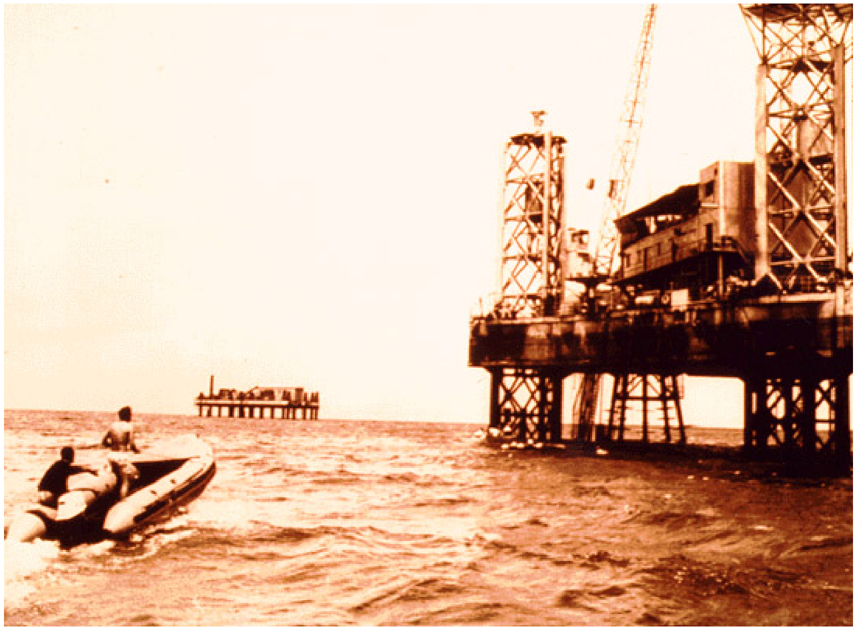
Starting the field of X-ray astronomy…

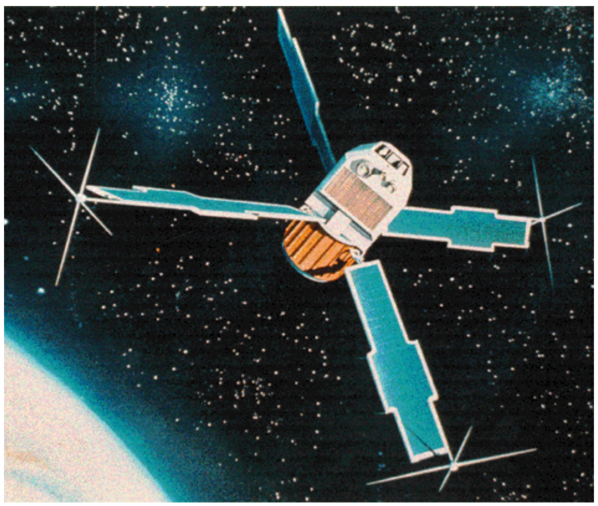


The discovery of non-Solar celestial X-rays by Riccardo Giacconi led to the 2002 Physics Nobel Prize

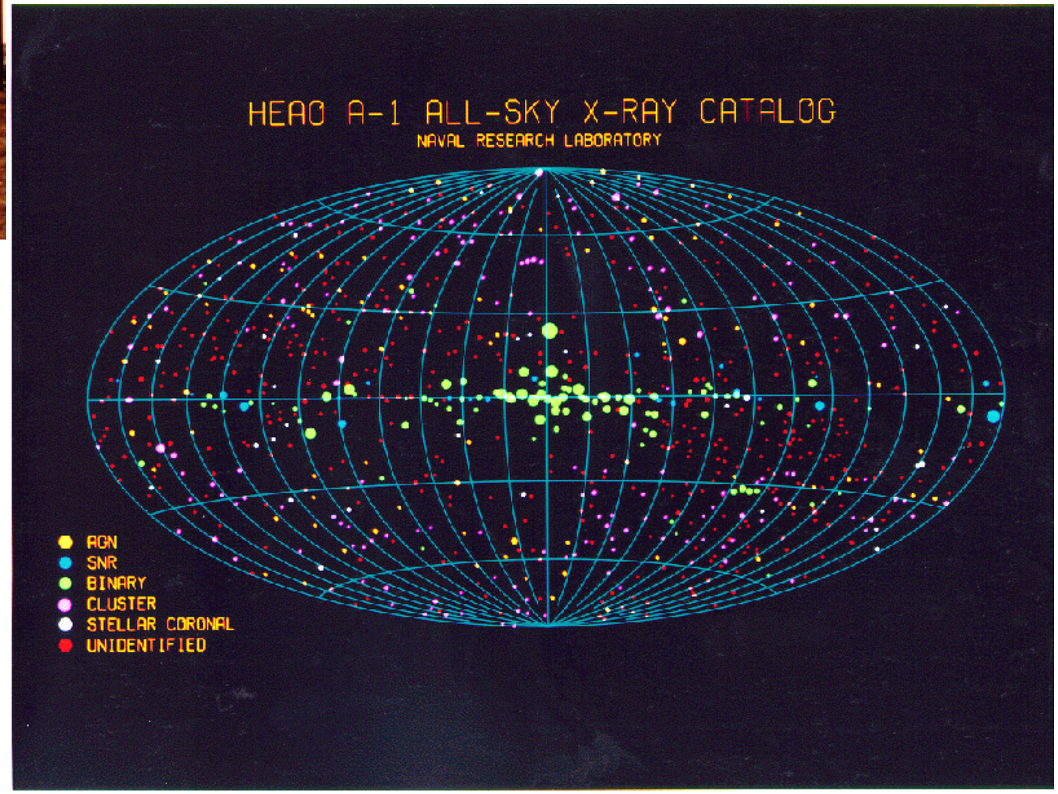
Data from Riccardo's successful rocket flight

Next step: X-ray satellites in orbit



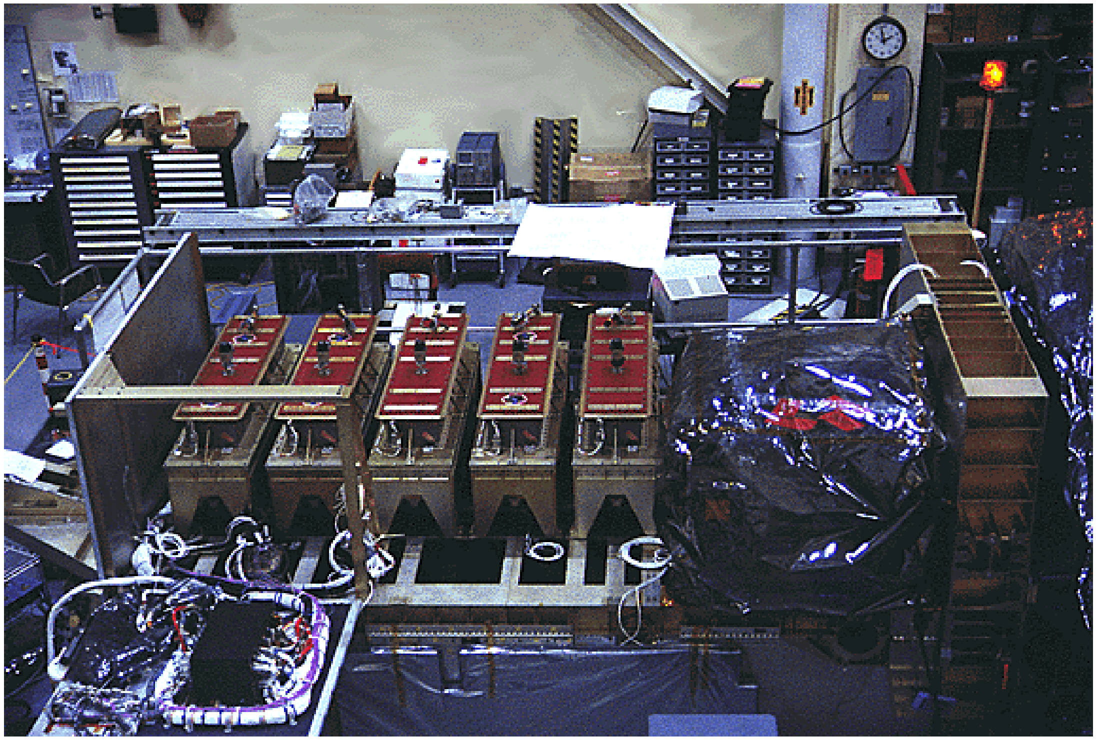


First satellite-based
X-ray – sensitive Observatory:
NASA's UHURU (ca. 1973)



Map of X-ray sources collected by
UHURU's successor, HEAO-A
satellite (ca. 1979)

“Workhorse” sensor for the early X-ray astronomy instruments: proportional counter behind an egg-crate collimator



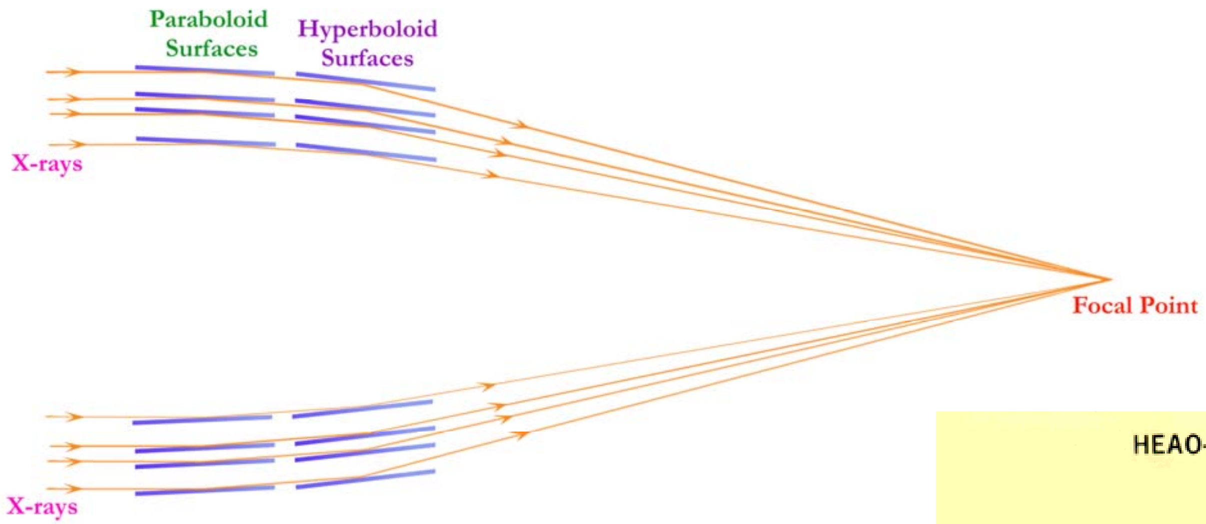
X-ray proportional counters for the Rossi X-ray Timing Explorer

Proportional counters have many advantages: simple to build, reliable and stable in space, provide good energy bandpass (typically ~1 - ~50 keV)

But they are sensitive to interaction with energetic particles: background!

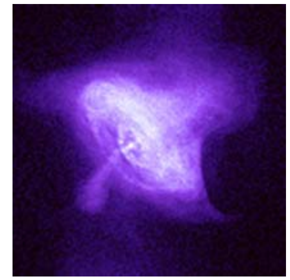
Background is proportional to the detector volume -> try to focus / image X-rays

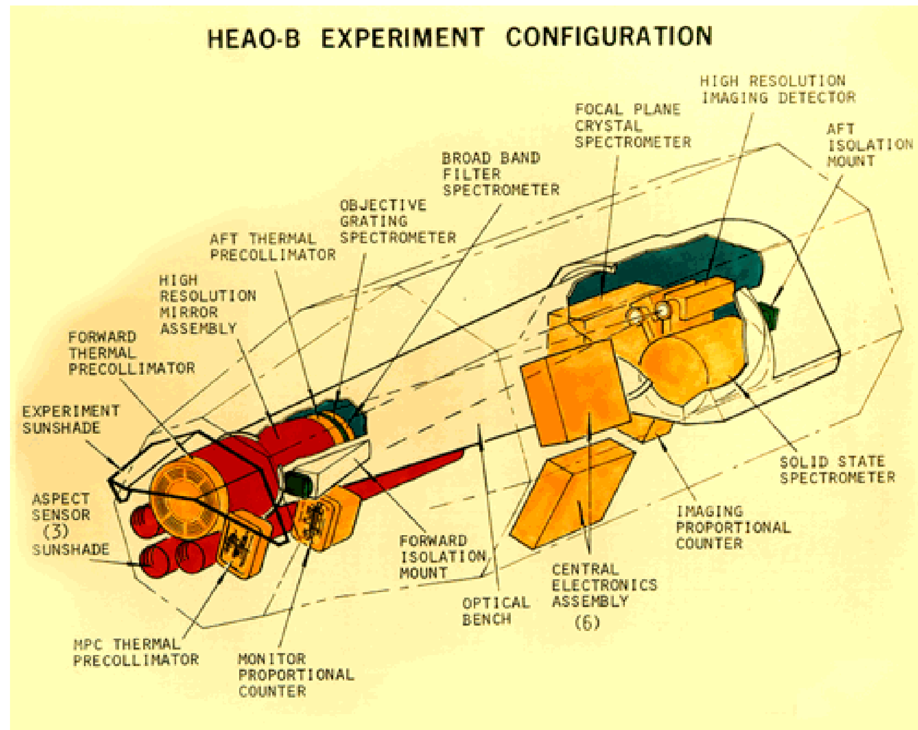
Next breakthrough: imaging of celestial soft X-rays



Principle of operation of X-ray mirrors used in X-ray astronomy: grazing incidence reflection

X-ray image



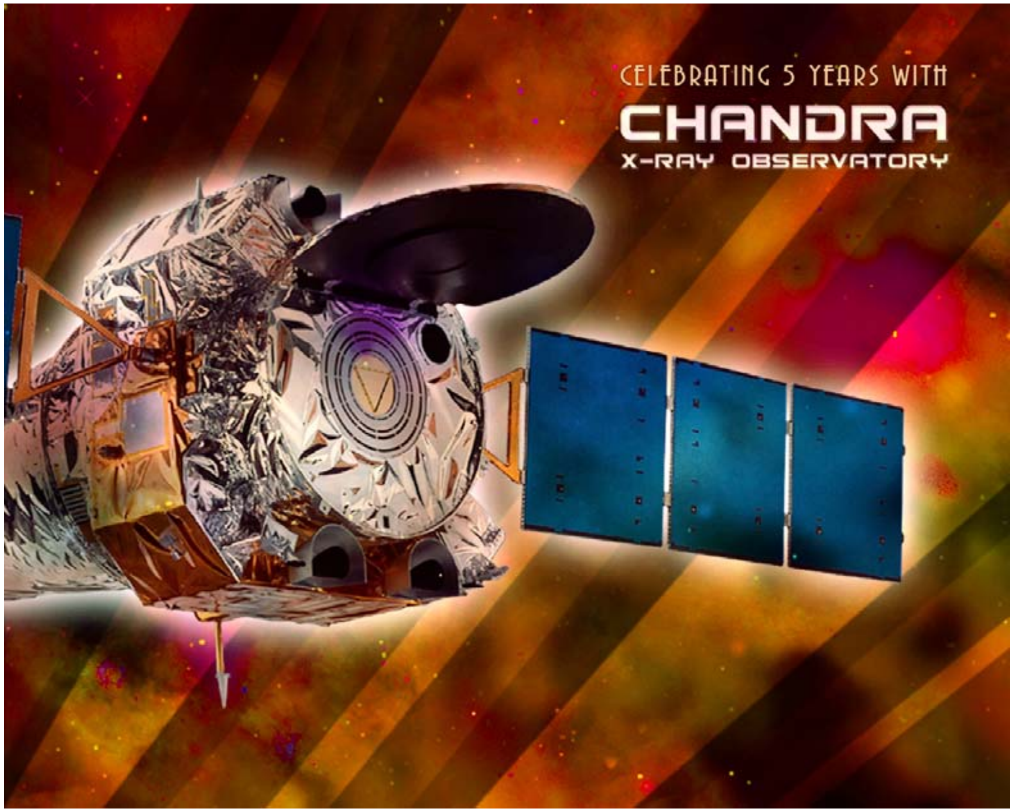


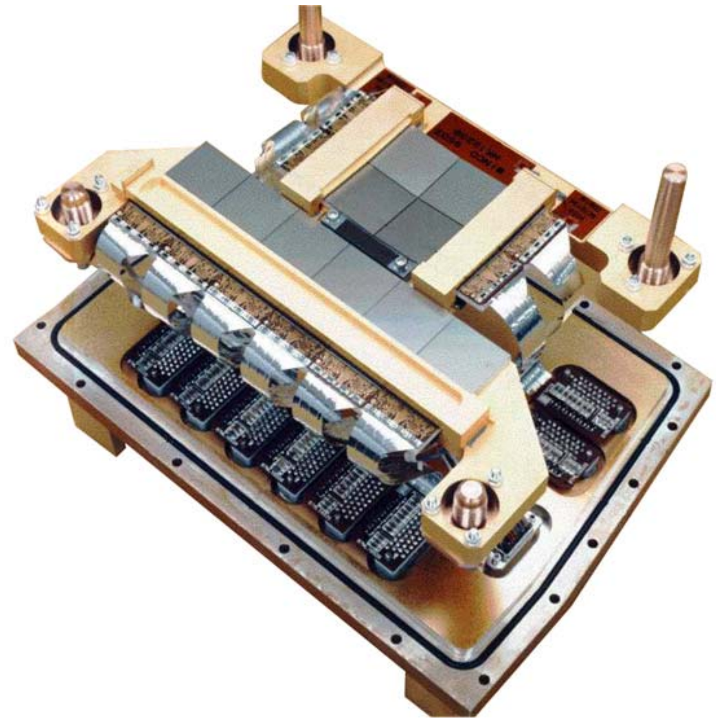
HEAO-B (=Einstein) X-ray Observatory (ca. 1981)
First satellite-based *X-ray imaging* instrument

* Can provide large collecting area (mirror) with small detector volume -> reduction of background!

* "Standard" version (surface of precisely polished high Z material) good only up to ~ 10 keV

The most precise X-ray imager: Chandra X-ray Observatory





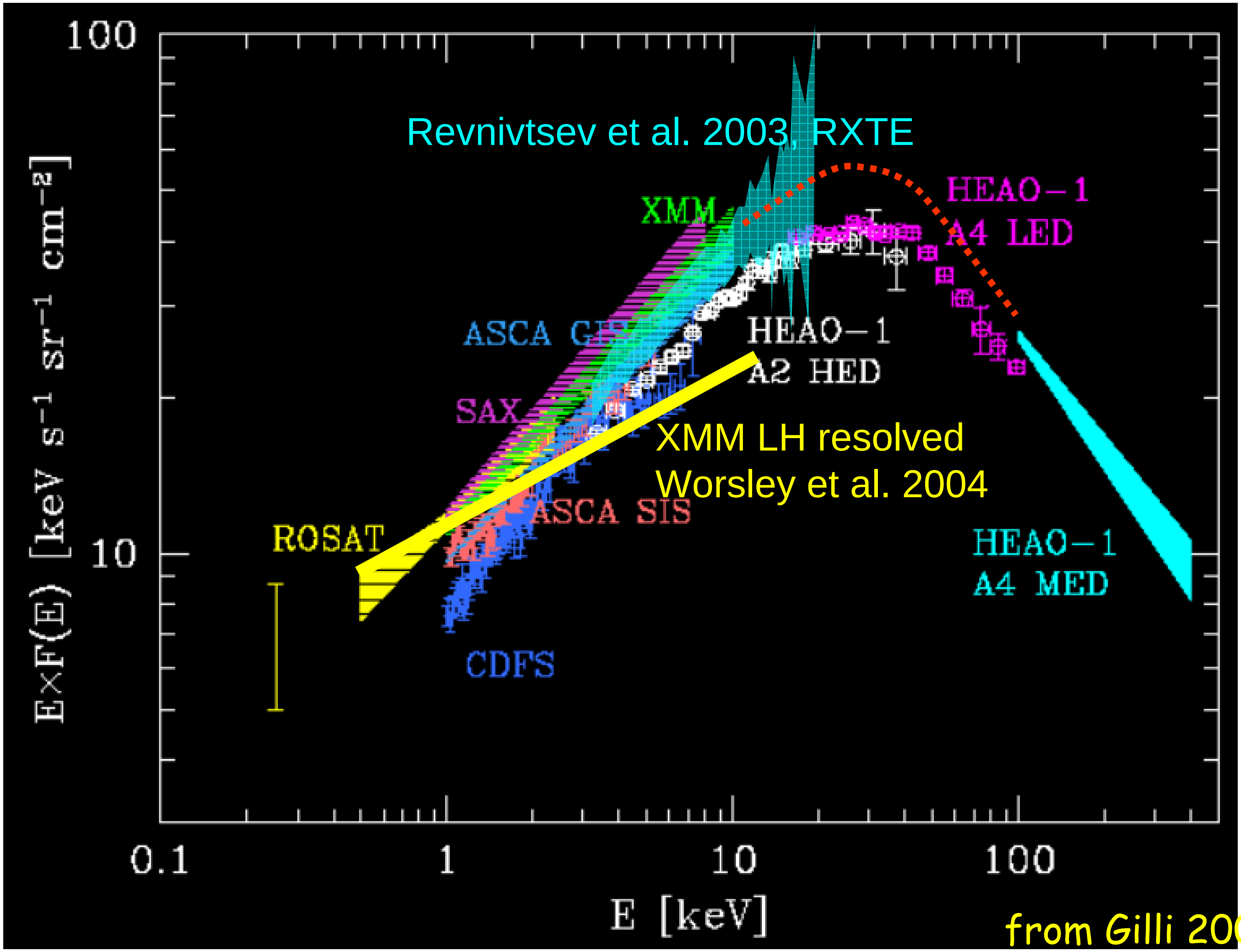
Chandra Observatory: sensitive in the 0.3 – 10 keV band

Chandra's "workhorse" detector: X-ray sensitive CCDs

Chandra's main science goal: what is the origin of the Cosmic X-ray Background, originally discovered in Giacconi's 1962 rocket flight?

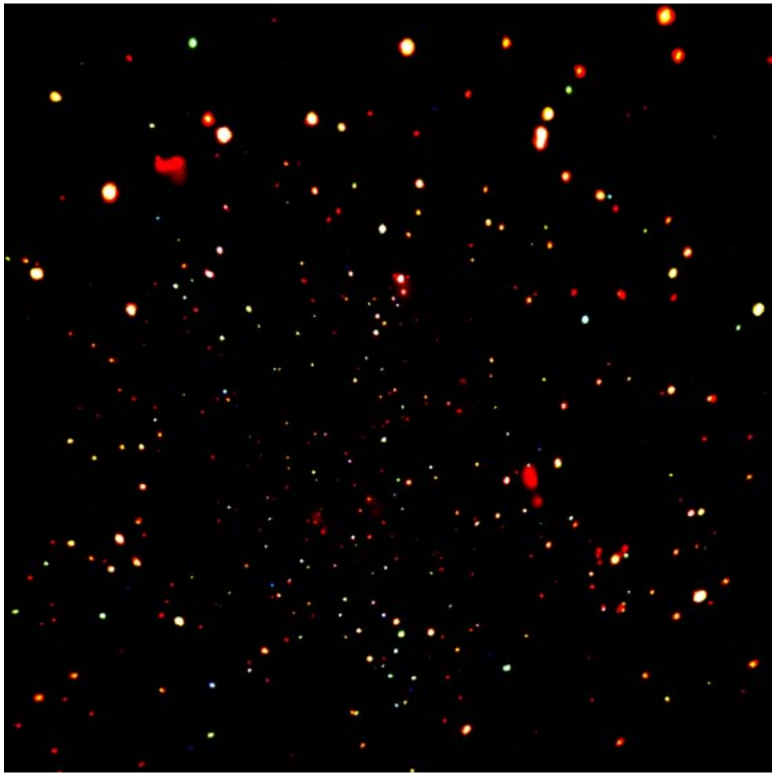
* Can it be attributed to a superposition of discrete sources, or truly diffuse component is needed?

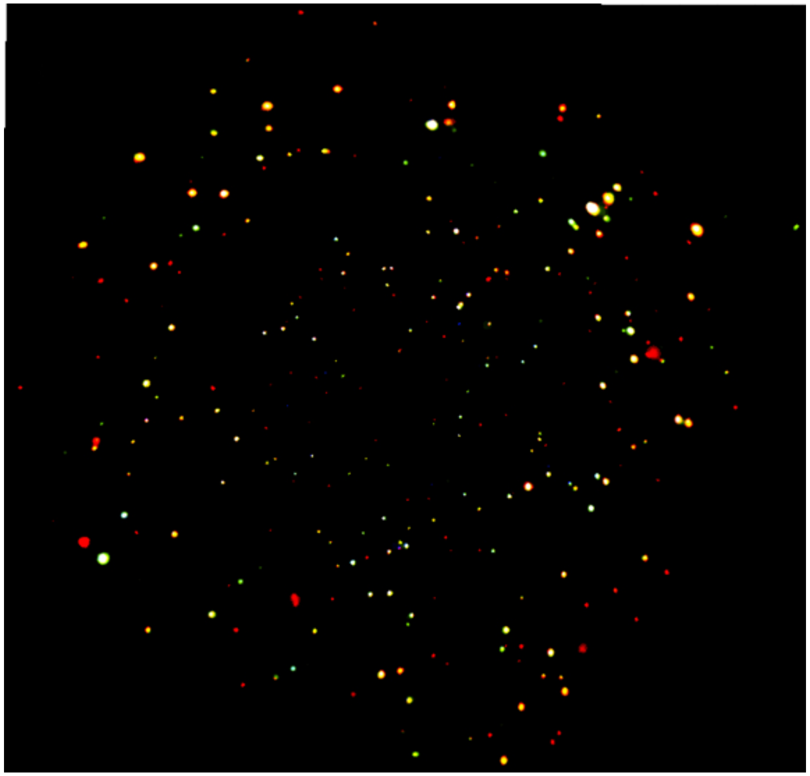
Cosmic X-ray Background Spectrum



from Gilli 2003

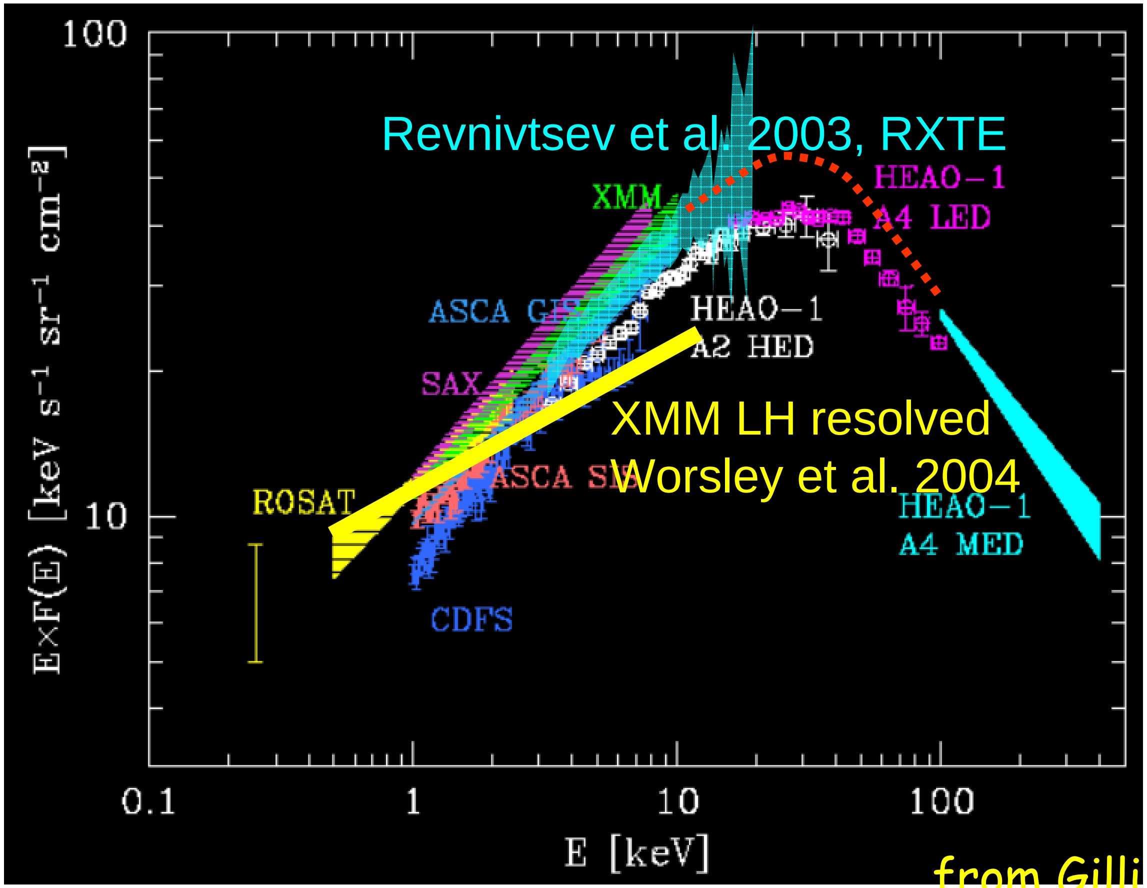
Cosmic X-ray Background: superposition of many distant / faint X-ray emitting Active Galactic Nuclei?





Chandra X-ray Observatory "deep fields" –
observations designed to resolve the Cosmic X-ray Background

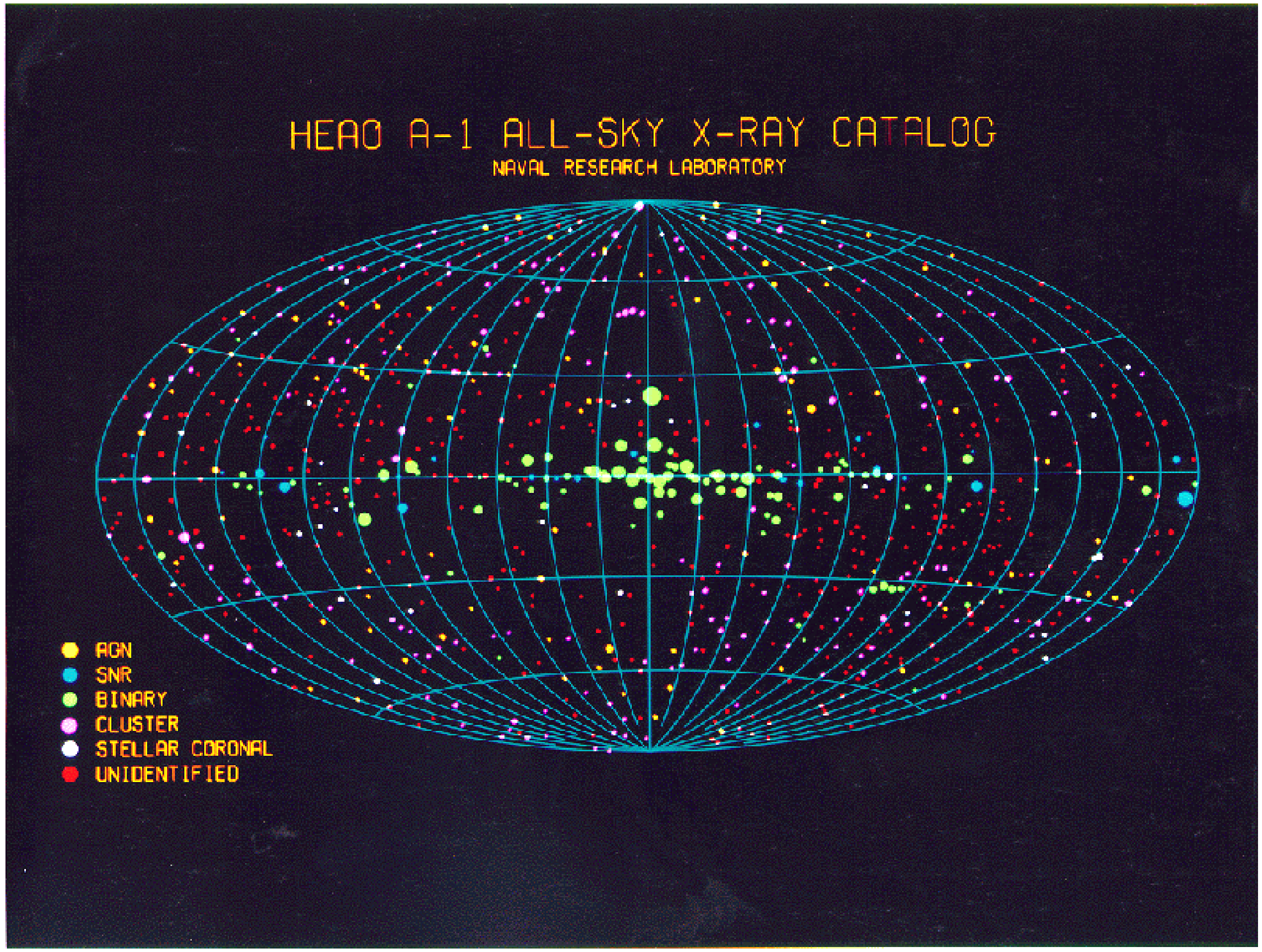
Cosmic X-ray Background Spectrum



from Gilli 2003

* While at E < 2 keV the CXB is resolved to originate from active galaxies,
  at E > 5keV – still quite uncertain (more on active galaxies later)
* Sensitive observations in the hard X-ray band are needed
  difficult for experimental reasons!

X-ray sources in the sky



Even early X-ray observations revealed rich variety of celestial X-ray sources:

•Binary stars with "compact" companions

•Supernova remnants (thermal and neutron star – powered "pulsar wind nebulae")

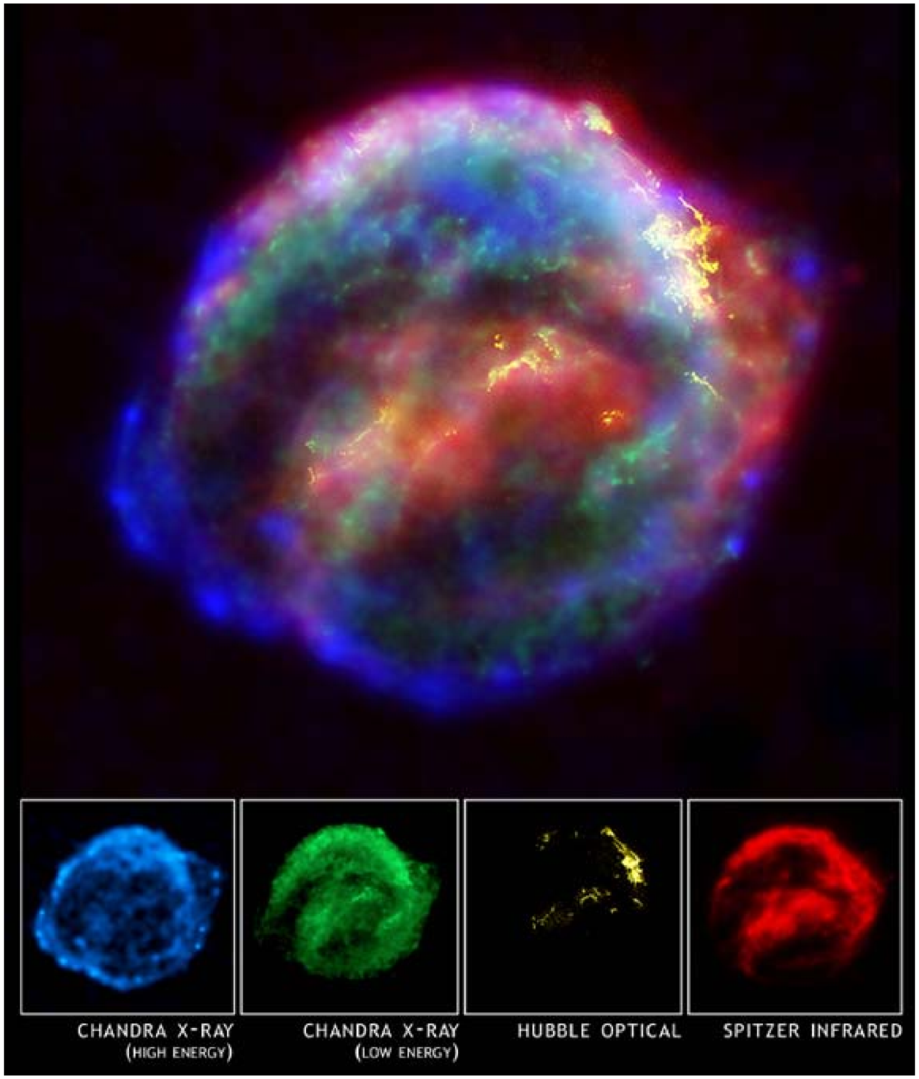
•Active galactic nuclei

•Clusters of galaxies

•Even ordinary stars…

Nearly all celestial X-ray sources are powerful X-ray accelerators

Supernovae and their remnants



Composite image of the Kepler's supernova remnant

* Early Universe contained only the lightest elements: hydrogen, helium

* "Heavy" elements were all "cooked" in stars and ejected into the interstellar space via *supernova explosions*

* The velocity of the ejecta, v is roughly 10,000 km/s

* How do we know that v is ~10,000 km/s and not say, 100 or 10^5 km/s?

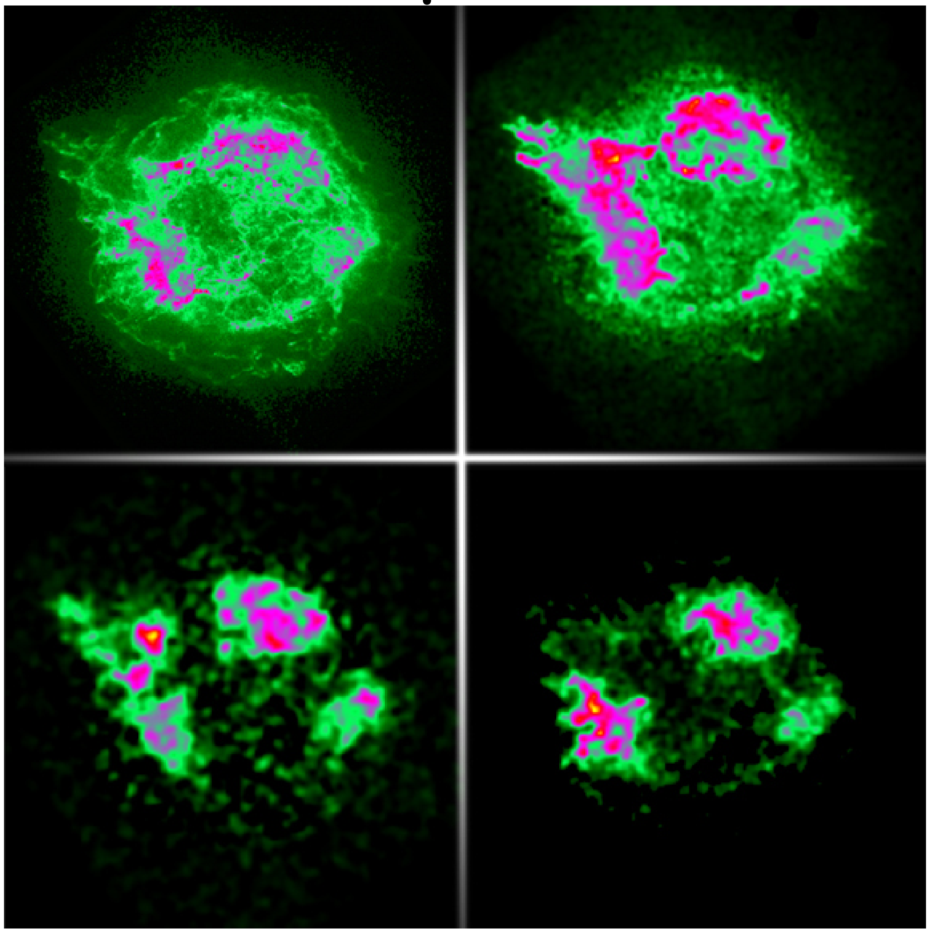
-> know the age t; also know the angular size θ, distance D –> linear size ~ $D*\theta$ and thus $v = D*\theta/t$

* Doppler – broadening of emission lines is also a probe of kinematics of the ejecta, inferred v consistent with the above

* Multiple observations of SNR separated by ~ years also clearly show the expansion

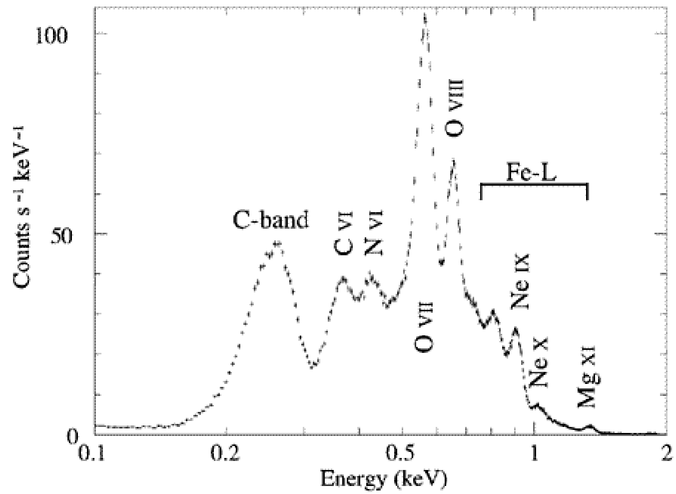
* *Since the temperature of the ambient medium is at most ~ hundreds of K -> expansion is clearly supersonic -> forms a shock*

Supernovae and their remnants



Supernova remnant Cassiopeia A in X-rays as seen by Chandra: Broad-band (UL), silicon (UR), calcium (LL) and iron (LR)

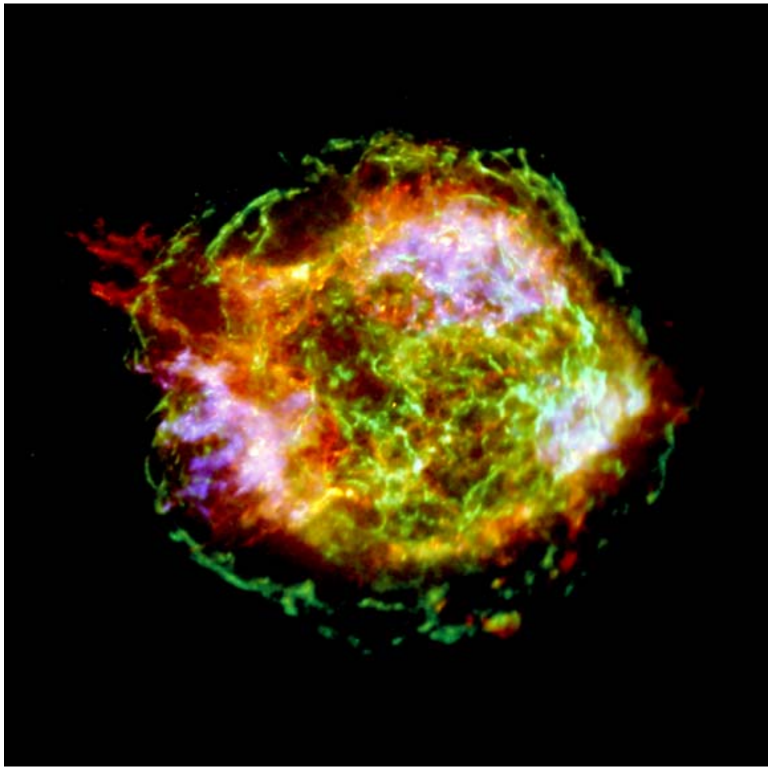
- The enriched supernova ejecta result in elemental “pollution” of the interstellar space
- Kinetic energy of the ejecta heat the interstellar medium to temperatures of ~ 10^7 K, as expected from the energy balance
- The observed photon spectrum is well described by thermal bremsstrahlung with associated elemental emission lines

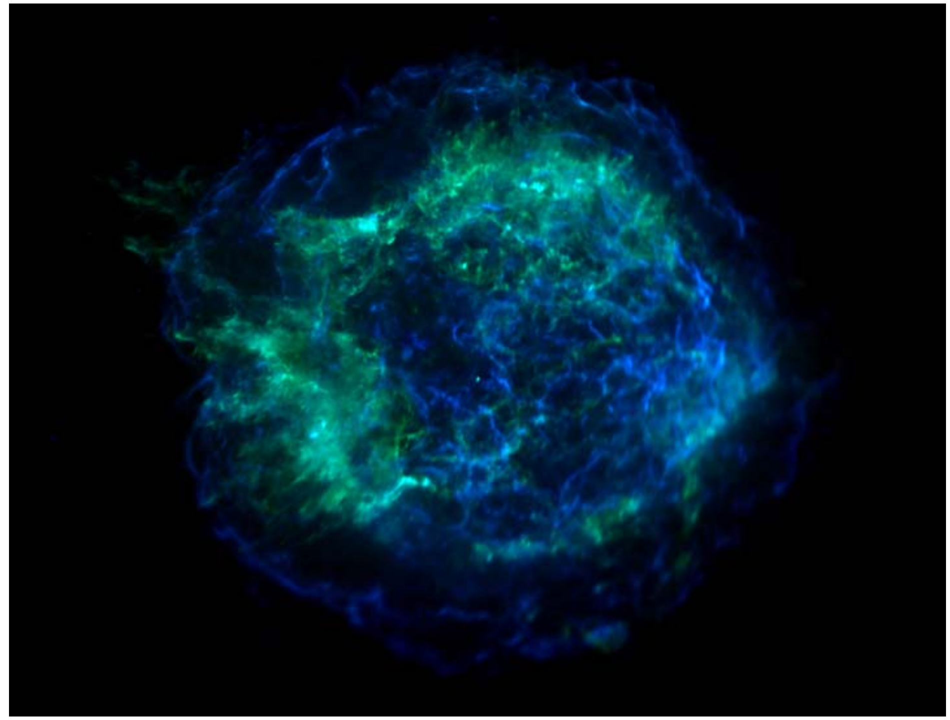


X-ray spectrum of N132D

* Elemental composition of a remnant
  - from the progenitor + those already present in the ambient medium
  - can be studied via narrow-band imaging corresponding to energies of atomic transitions for specific elements

Supernova remnants and neutron stars





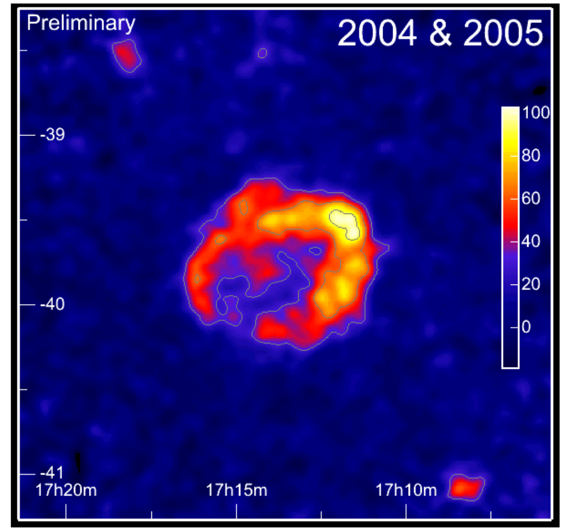
Cassiopeia A supernova remnant: composite (left) and X-ray (right), with the NS at the center

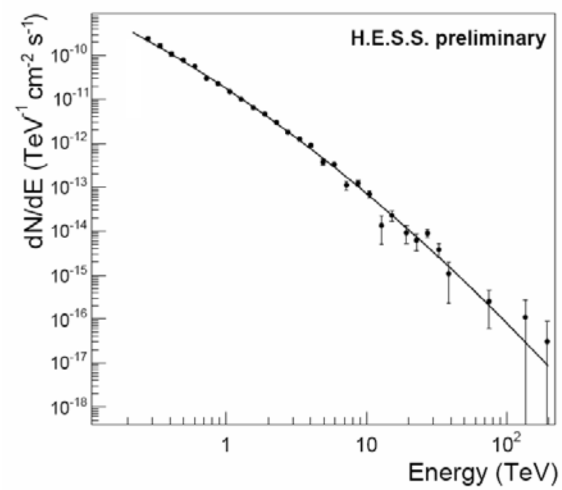
* *Neutron stars* left behind the explosion may manifest themselves as pulsars;
  they gradually cool, radiating thermal continuum

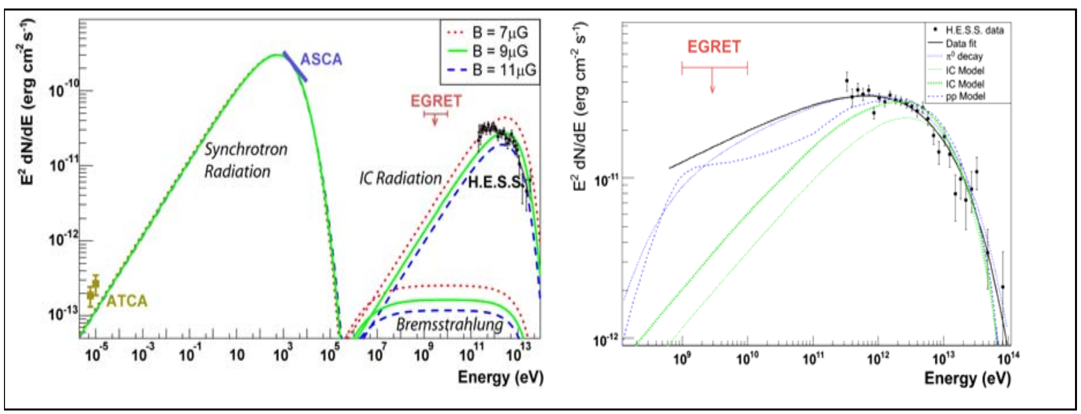
* Measurements of the flux + distance (=luminosity, or emitted power)
  and neutron star surface temperature determine radius and thus with mass
  measuremets provide hints to determine the *equation of state*

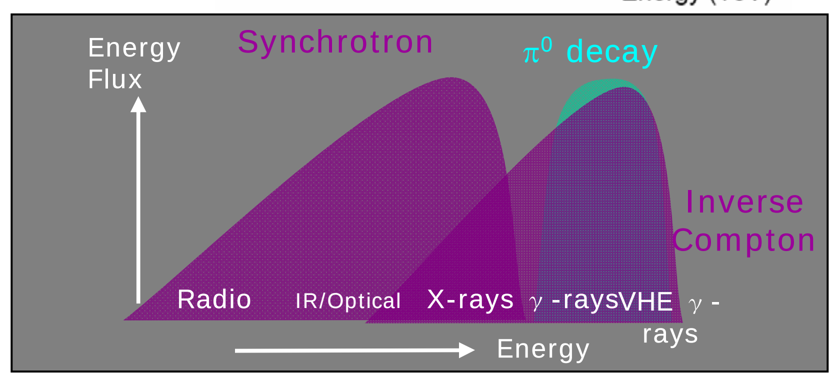
γ-ray emitting supernova remnants: the origin of cosmic rays?

- Among the most prominent Galactic γ-ray sources (besides pulsars!) are shell-type supernova remnants - accelerators of the Galactic cosmic rays?
- Example: RX J1713.7-3946
- First object resolved in TeV γ-rays (H.E.S.S., Aharonian et al. 2004)
- Emission mechanism: up to the X-ray band – synchrotron process
- Gamma-ray emission mechanisms - ambiguity between leptonic (inverse Compton) vs. hadronic (π^0-decay) processes

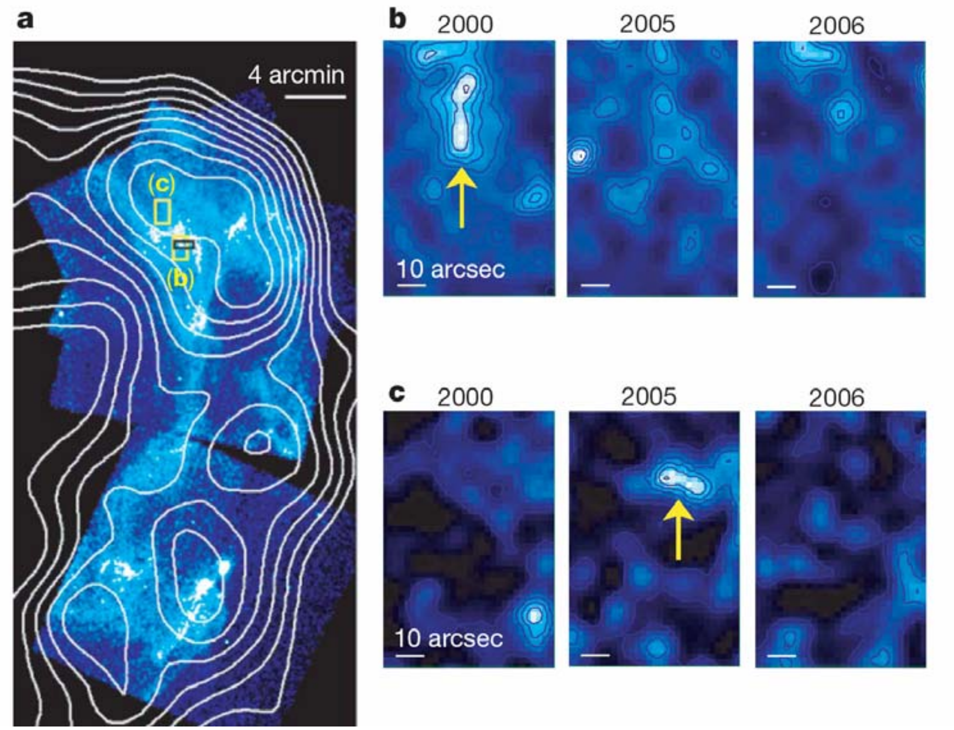








Models of SNR: X-rays to the rescue!



* Chandra imaging data reveal relatively rapid (time scale of years) X-ray variability of large-scale knots (Uchiyama+ 2008) ->

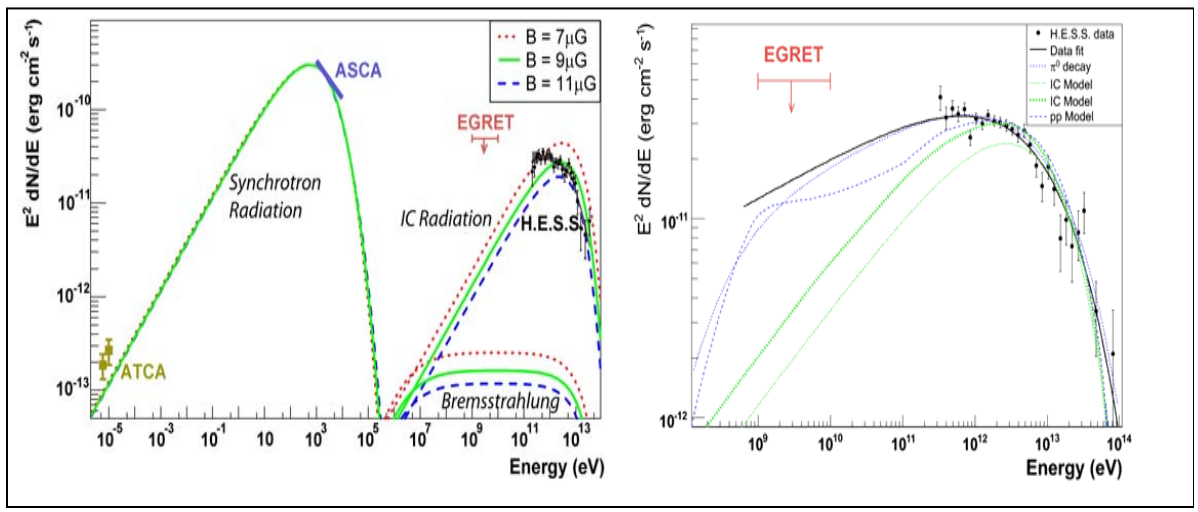
•This indicates strong (milliGauss!) B field, because:

$$\nu_{synch} = 1.3 \times 10^6\, B \times \gamma_{el}^2 \text{ Hz}$$

$$\tau_{loss} \sim \sim 5 \times 10^8\, \gamma_{el}^{-1}\, B^{-2} \text{ sec}$$

• Two equations, two unknowns – solvable!

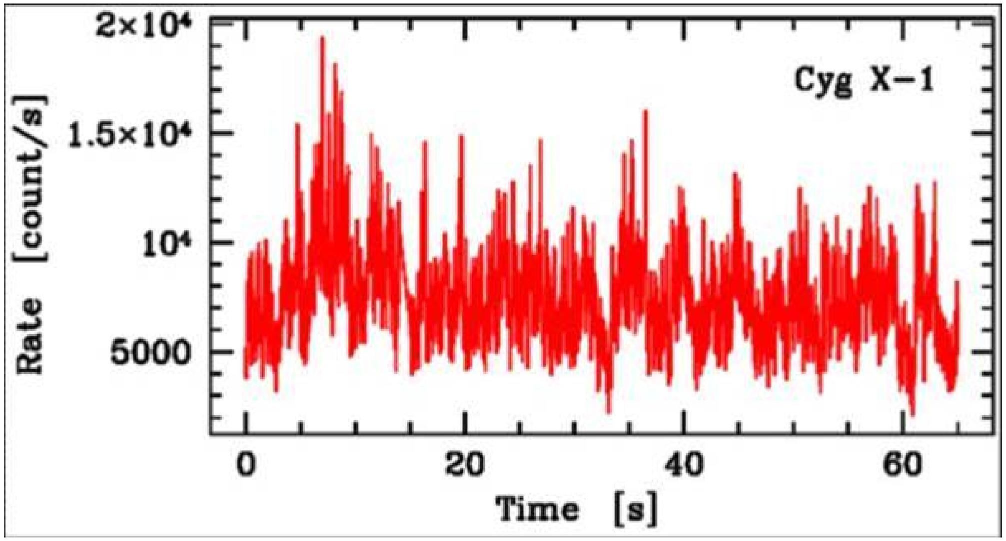
• Strong B-field -> weaker emission via Inverse Compton process -> hadronic models probably favored



* Hadronic models -> extremely energetic protons (VHE cosmic ray range)

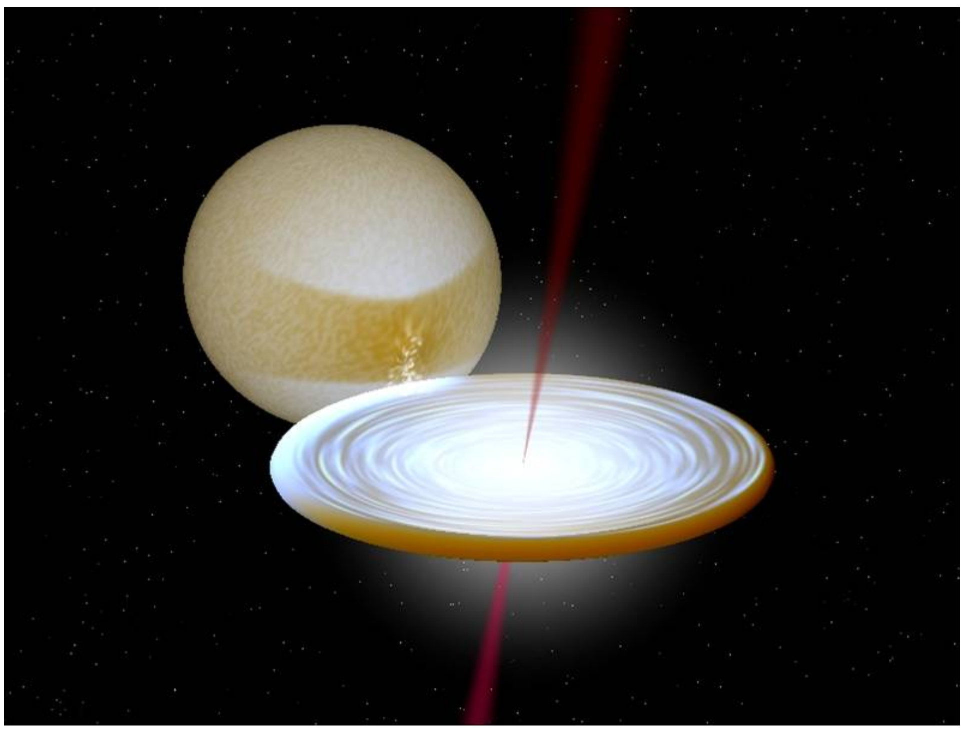
-> MULTI-BAND STUDIES (GLAST!) ESSENTIAL

X-rays from accreting black hole/neutron star binaries



* X-rays emitted in flares (bursts) of radiation: random, non-periodic variability in the X-ray band, in addition to orbital modulation seen in the optical

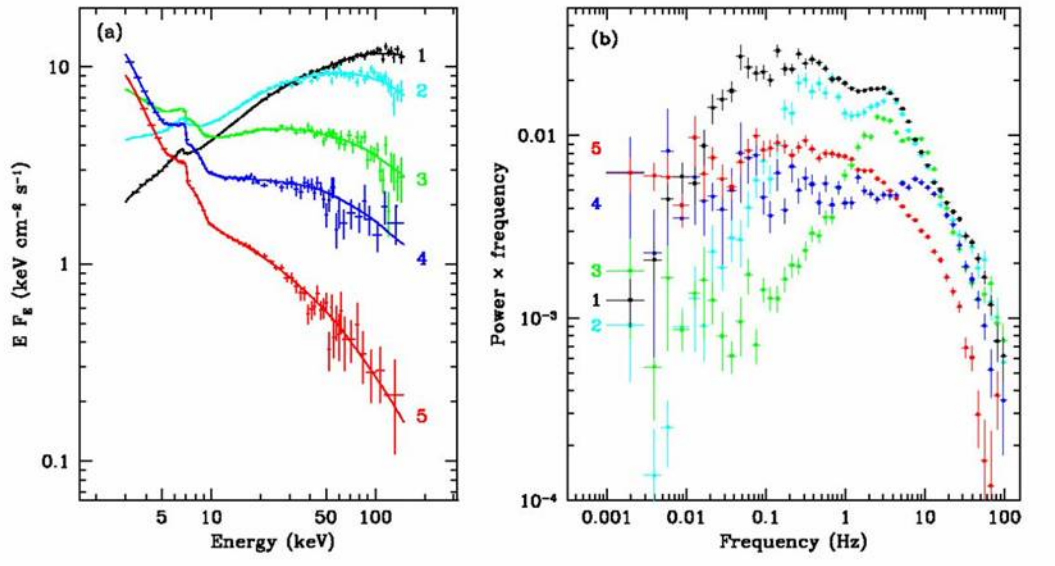
* Example: black hole binary Cygnus X-1 (RXTE data from Zycki et al. 2008)



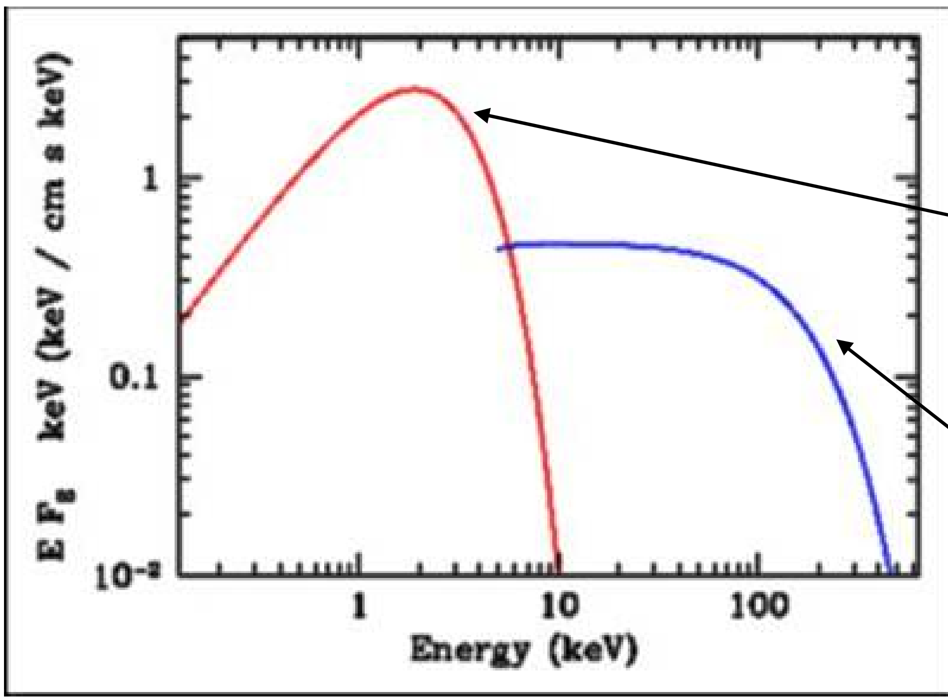
Artist's conception of an X-ray binary: Compact source (black hole, neutron star) "accretes" matter from the "normal" companion star

Matter flows in a disk-like structure ("accretion disk")

X-rays from accreting neutron star / black hole binaries



Actual RXTE data for Cyg X-1:
spectrum and variability (Zycki et al. 2008)

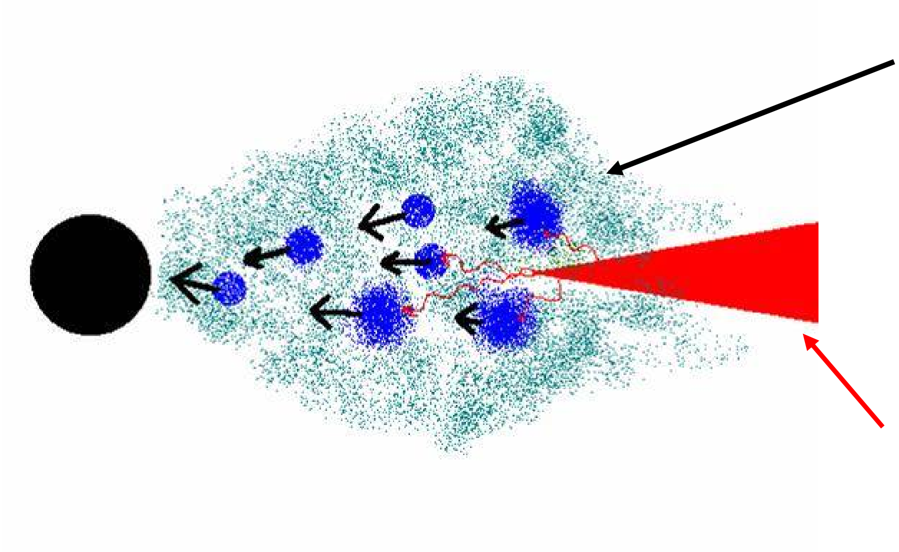


Energy spectra with two components:

Thermal, ~1 keV, emission from an accretion disk

Hard power law spectrum (with cutoff at ~100 keV) – Comptonization of disk photons in a hot plasma
- much hotter than expected from "thermal" disk!

General model of X-ray emission for low/hard state of X-ray binaries



Best model: hot (100 keV) plasma producing the hard component via inverse Compton upscattering of disk photons

Cold (0.1-1 keV) accretion disk producing thermal radiation (also “seed” photons for Compton upscattering)

Variability: Radially propagating emitting structures
(fragmentation of the accretion disk plasma)
-> Flares come from dissipation of gravitational energy

What is the origin of the hot plasma?
Observed X-ray spectra (up to at least 100 keV) indicate that accretion disks must be sites of vigorous particle acceleration

- Most likely associated with “plasma viscosity” provided by the magneto-rotational instabilities (necessary to transport outwards the angular momentum)