Compact Binaries

Lecture 2

X-ray Astronomy

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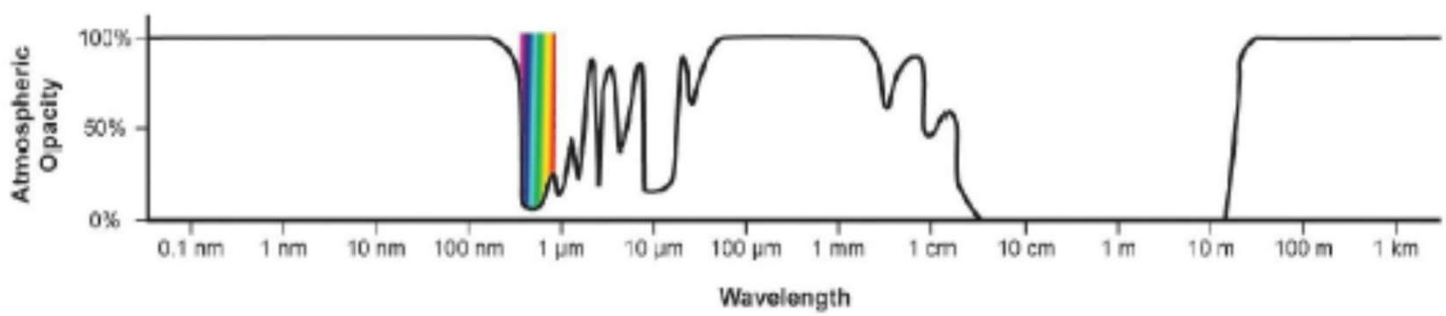
Understanding X-ray Observations

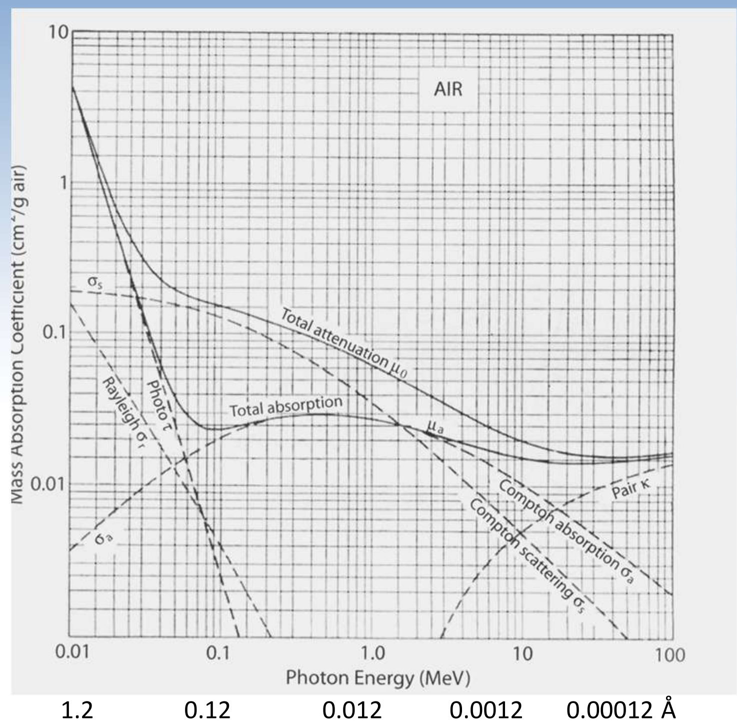
- Important for the study of X-ray binaries (by definition!)
- Also for the study of compact WD binaries
  - Cataclysmic Variable (CVs
  - Super Soft Sources (SSSs)
  - Novae, recurrent novae, symbiotic stars
- Study of many other accretion-driven objects (e.g. AGN)
- Active corona stars

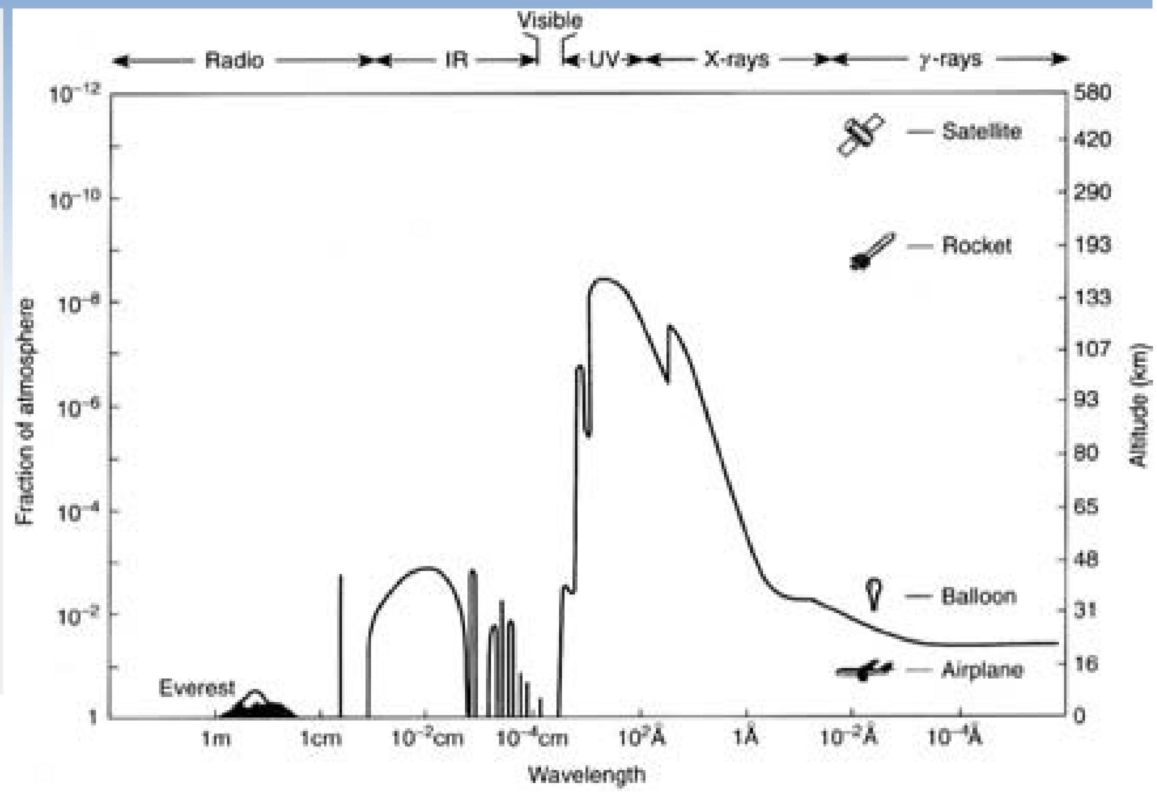
X-ray astronomy

- At very short wavelengths we deal with photon energies instead of λ
  - Measured in electron Volts, eV
- X-rays: energies of approx 100eV to 100keV
  - Absorbed by the atmosphere so observatories are space based



X-ray Absorption in the Atmosphere



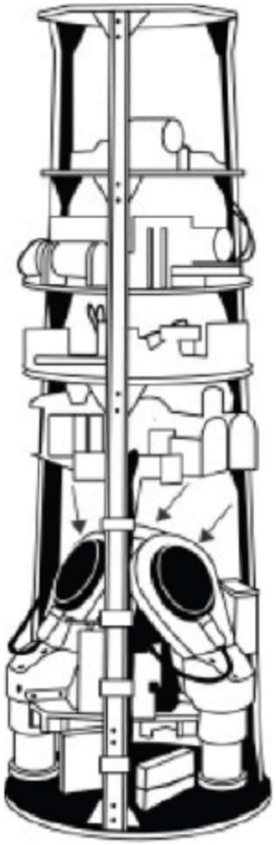


- Photoelectric absorption, Compton effect, pair production
- Height for 50% of attenuation changes with E
- 10 cm of air stops 90% of 3 keV photons (4.1 Å = 0.4 nm)

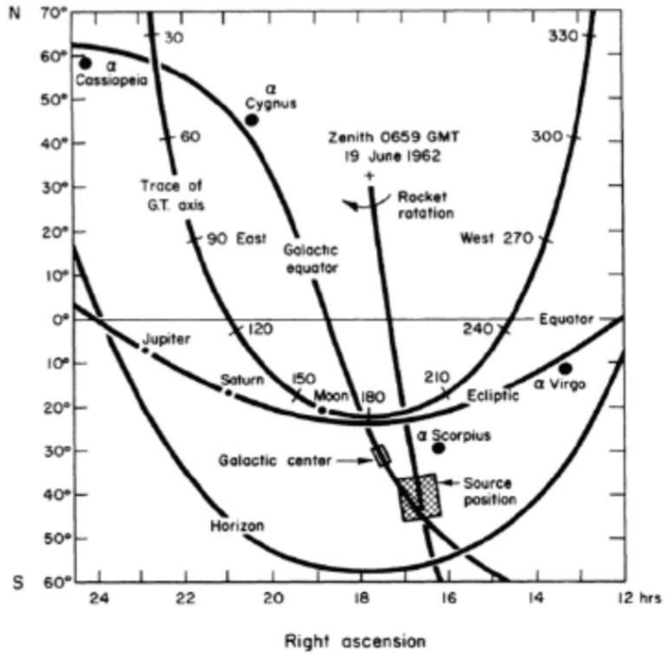
Pioneering Rocket X-ray Observations

Nobel prize 2002: Riccardo Giacconi

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

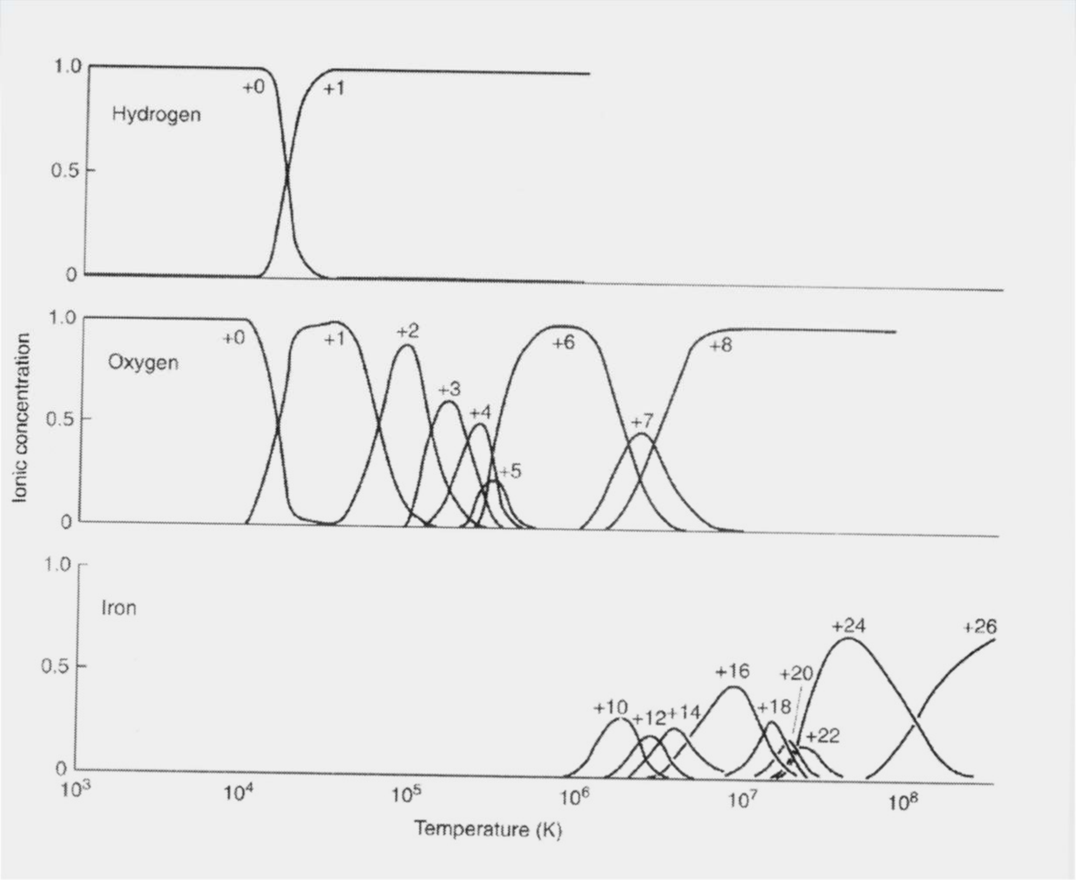


1962: experiment to search for X-rays from the lunar surface: three Geiger counters on a Aerobee rocket



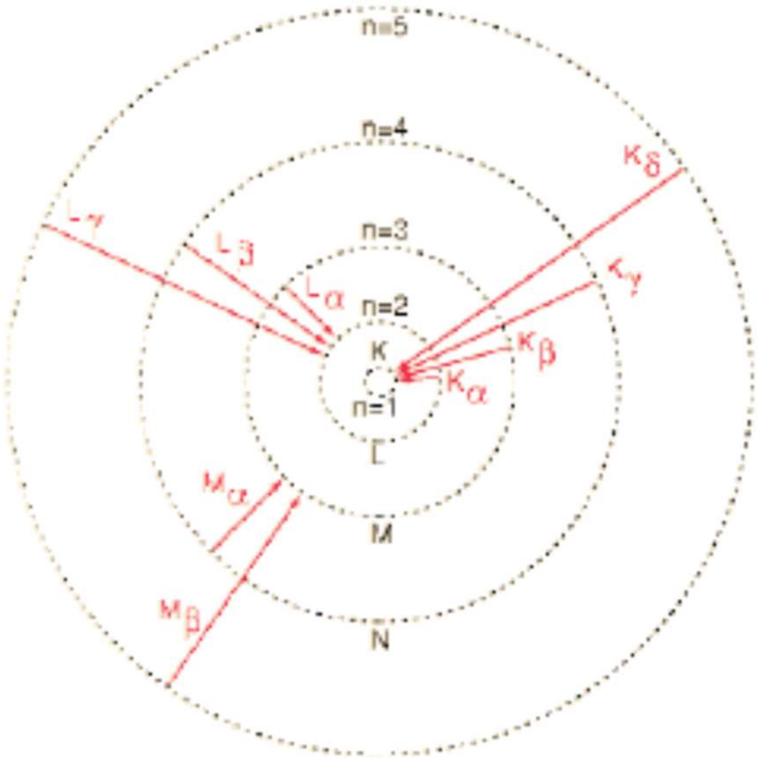
Theory: Ionization

- Ionization temperature (Boltzmann)
- High degrees of ionization require high temp/energy
- Equivalent to high photon energies (X-rays)
- Line emission from electronic transitions



Ionization

- For high Z atoms, K shell electrons require X-ray energies for ionization

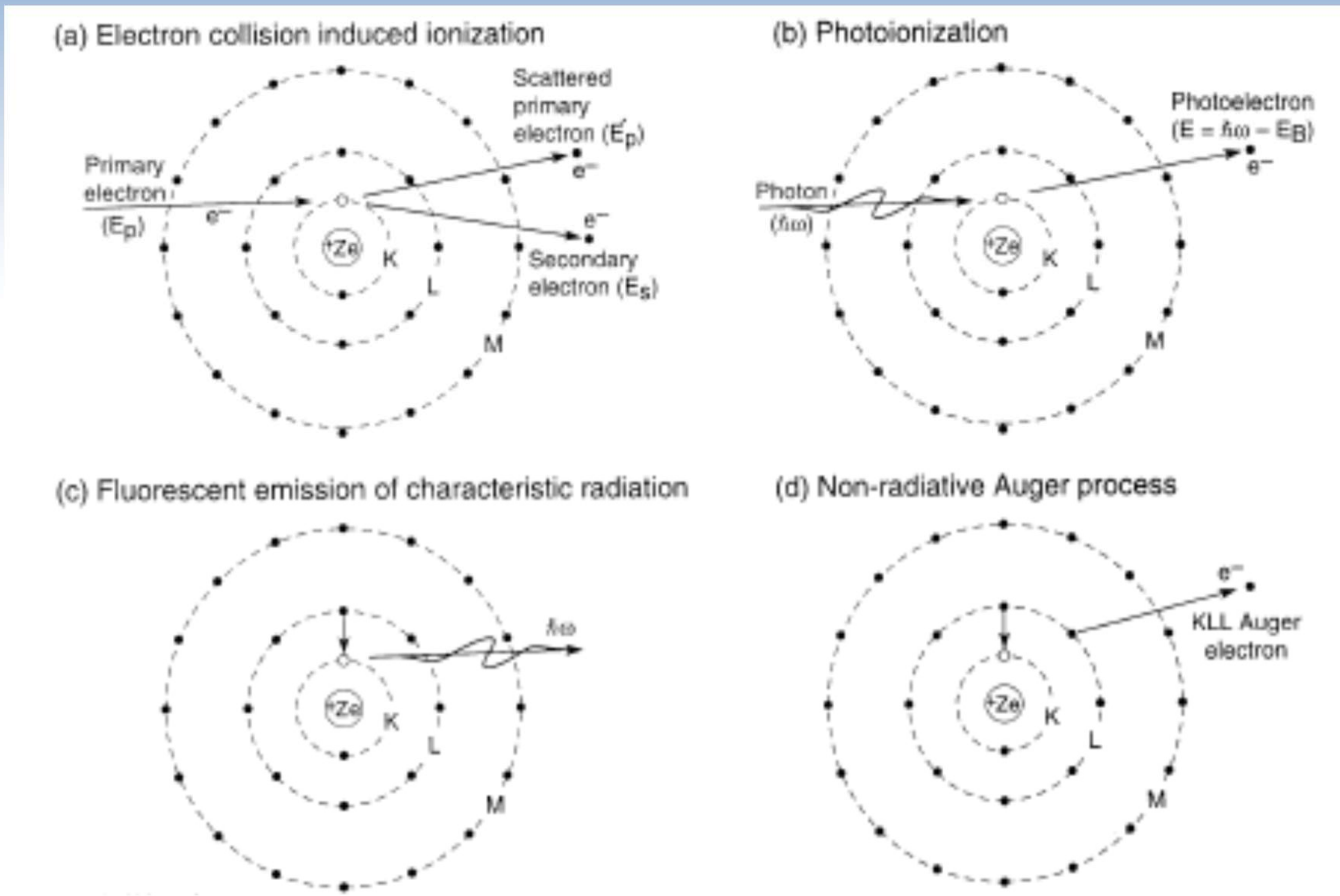


Inner-shell ionization: $\gamma, e^- + I \rightarrow I^{*+} + 2e^- \rightarrow I^+ + e^-, \gamma$

Important 6.4 keV line from Fe I - Fe XVI

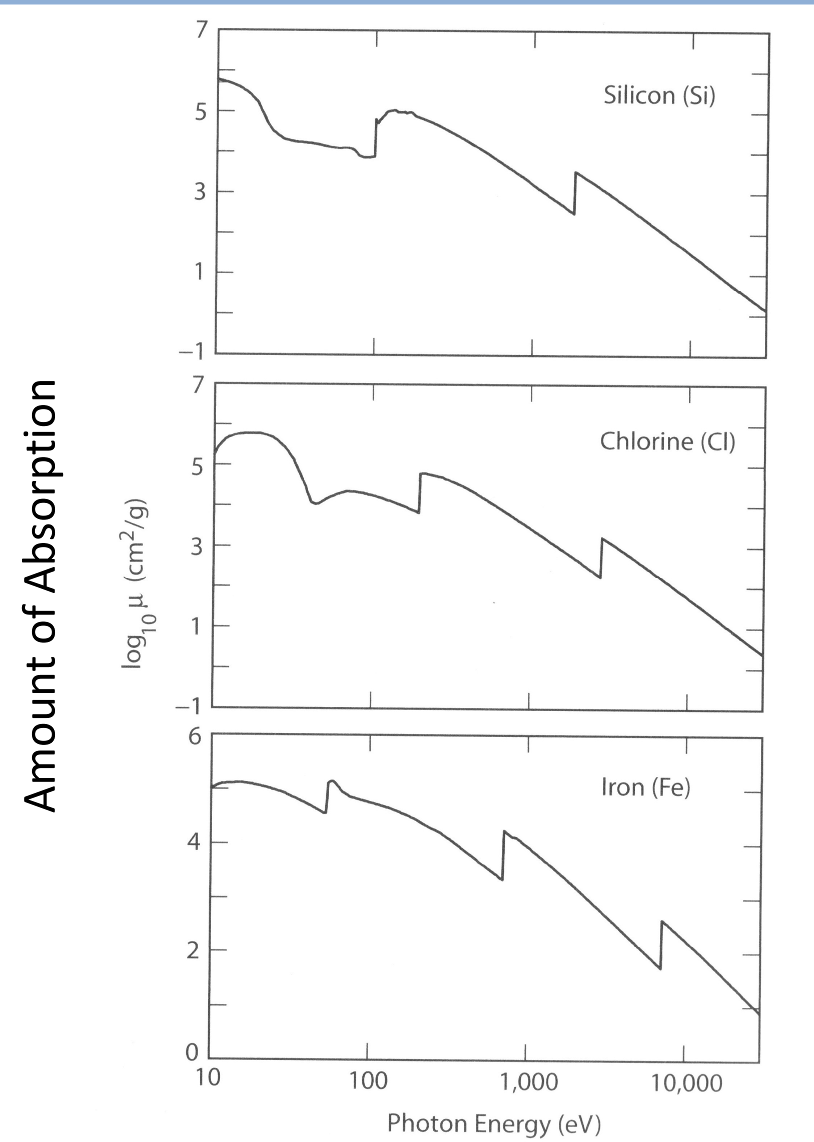
Ionization

- Basic ionization and emission processes in atoms



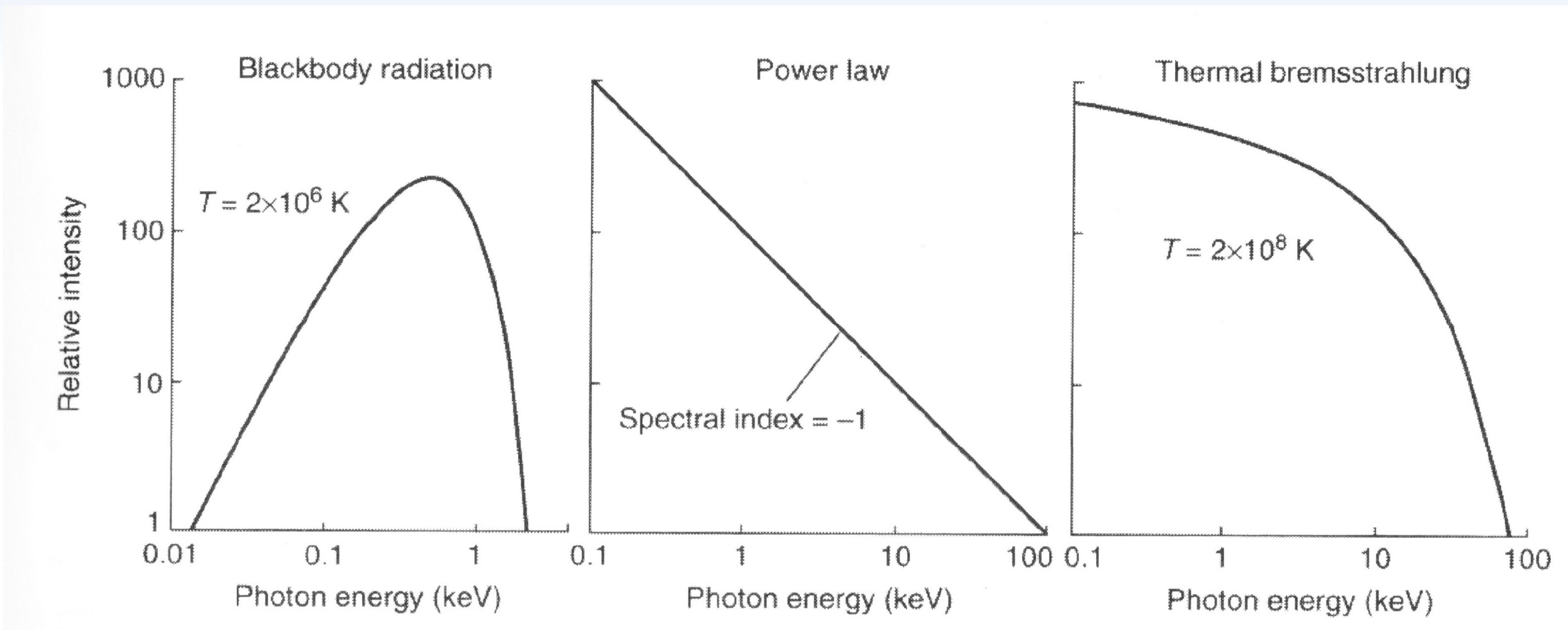
Ionization: Spectra

- Absorption “edges” from K, L, M shells



X-ray Emission Processes: Spectra

- Blackbody emission
- Power Law emission (synchrotron processes)
- Thermal bremsstrahlung (free-free emission)



X-ray Emission Processes: Spectra

energy range:
0.1- 100 keV (0.12-120 Å)
(hard X-rays up to 500 keV)

continuum

bremsstrahlung
blackbody
synchrotron
(inverse) Compton scattering
radiative recombination

lines

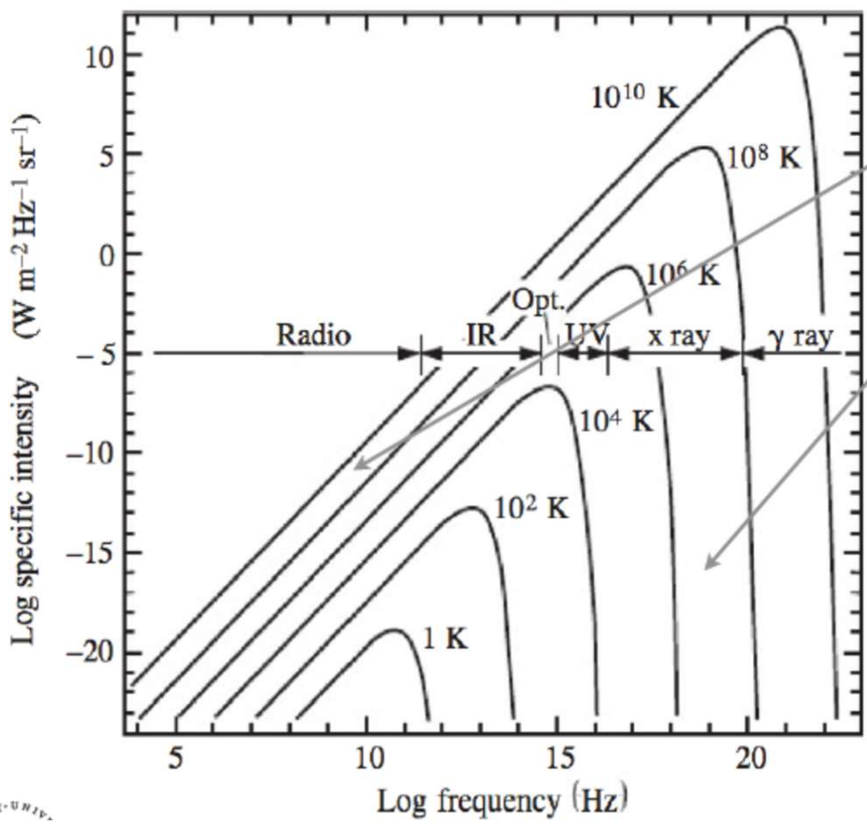
charges exchange
fluorescence
thermal

X-ray band includes K-shell transitions (n=2 to 1) for all elements heavier then He

Black Body Emission

- The Planck function

Plank radiation law $$I(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{\exp^{h\nu/kT}-1}$$



Rayleigh Jeans approximation

$$I(\nu,T)\approx\frac{2\nu^2}{c^2}k_BT$$

Wien approximation

$$I(\nu,T)\approx\frac{2h\nu^3}{c^2}\exp^{-h\nu/kT}$$

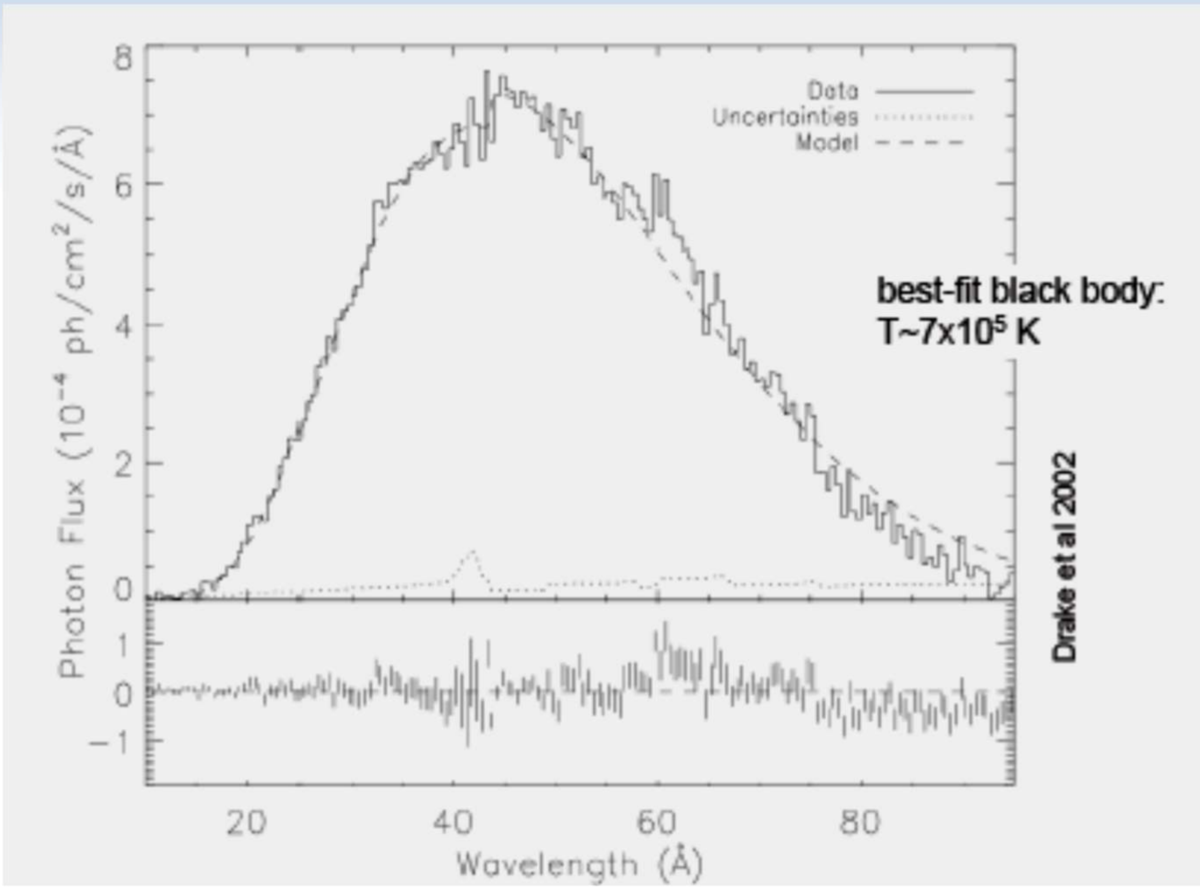
total energy flux

$$F=\sigma T^4$$

Star temperatures:
red dwarf: 2500 K
O star: 40 000 K
Newly formed neutron star: 10^6 K (?)

Black Body Emission

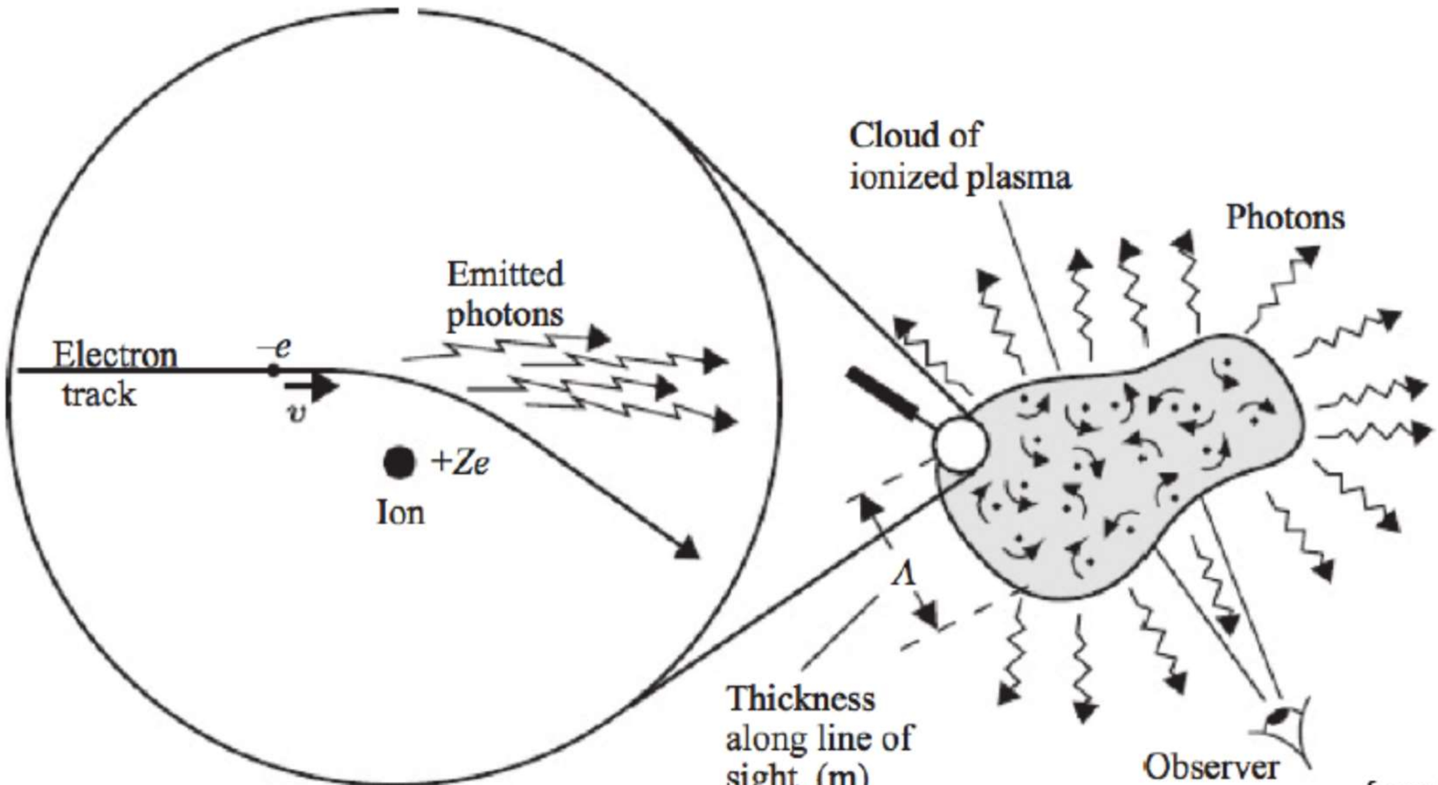
- Example of a hot black body: isolated neutron star at 700,000K
- Accreting from the Interstellar Medium (ISM)



Thermal Bremsstrahlung Emission

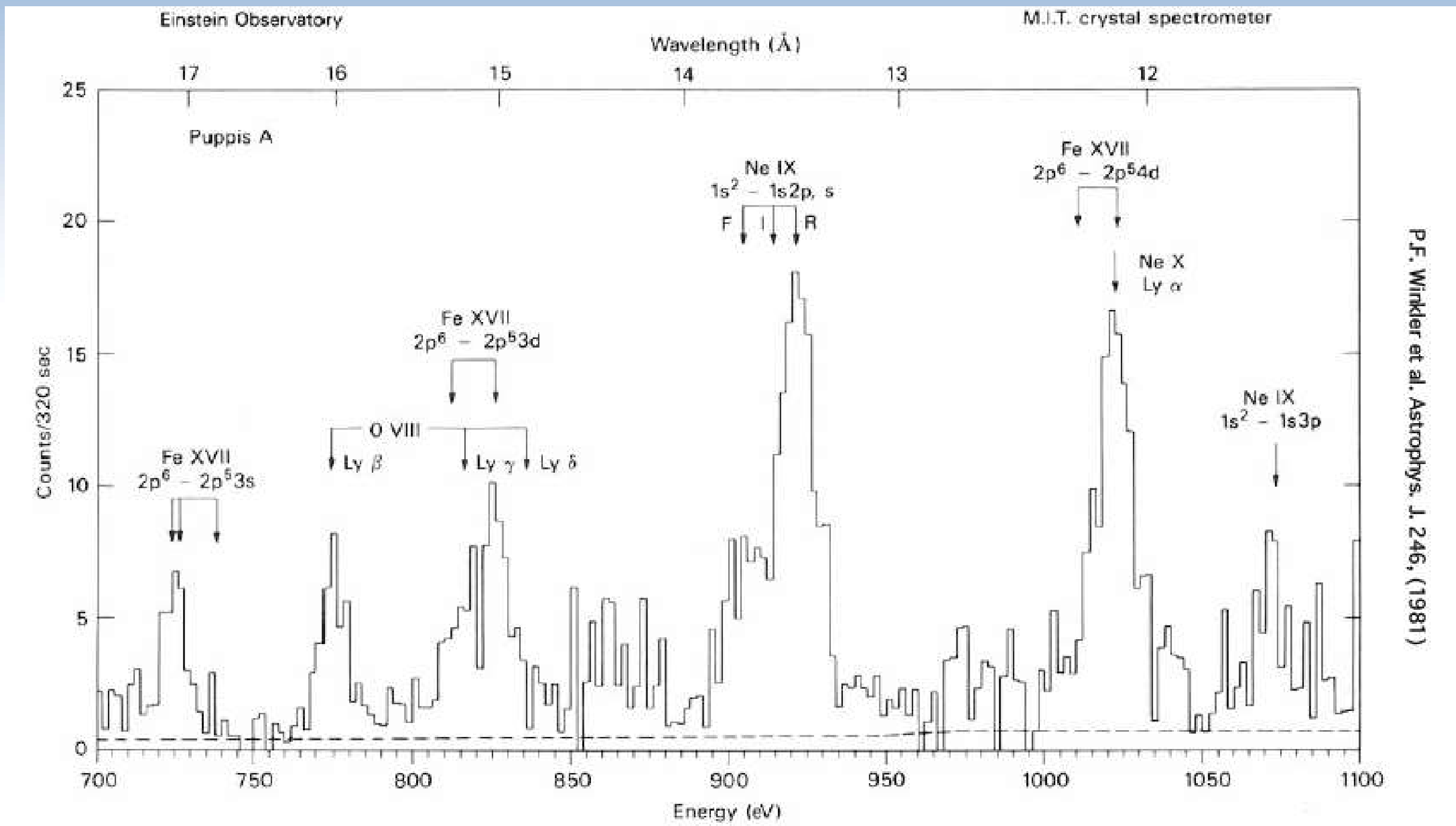
consider a hot optically thin plasma transparent to its own radiation in thermal equilibrium

Thermal Bremsstrahlung by electrons (Maxwellian velocity distribution)



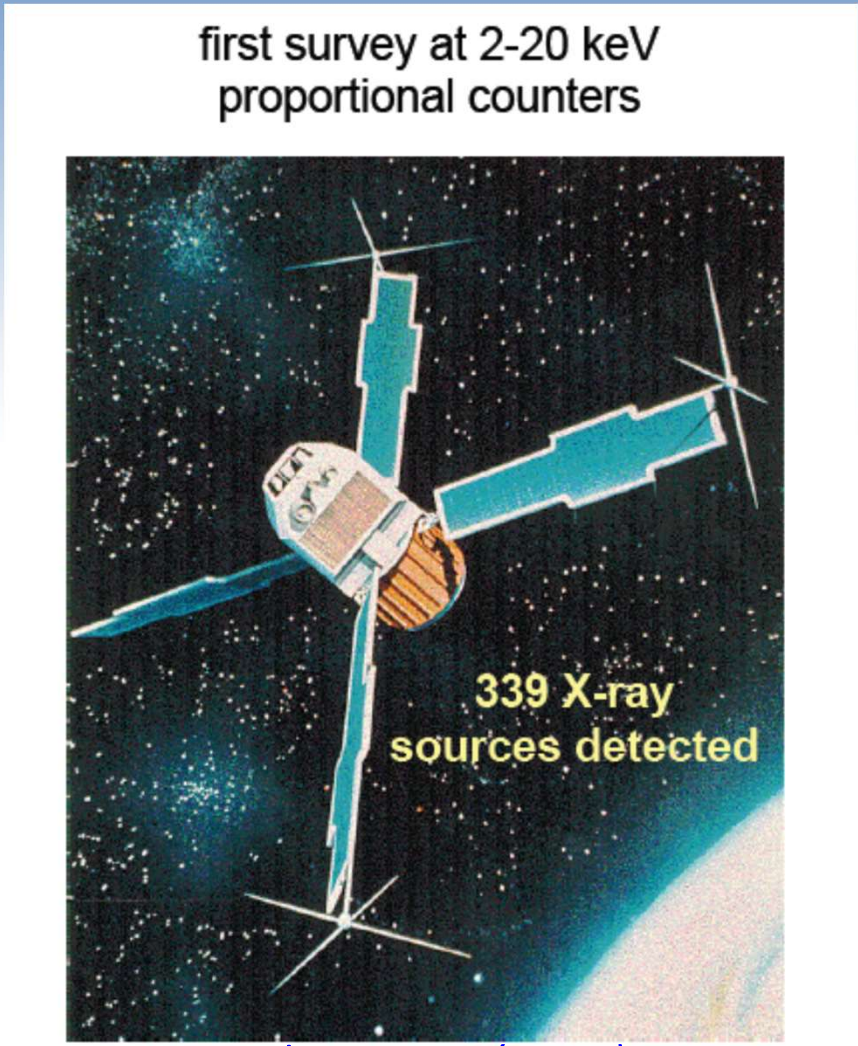
from Bradt 2008

X-ray Line Emission



Temperature: Bremsstrahlung cut off and/or presence of lines
Composition: strength and energies of lines

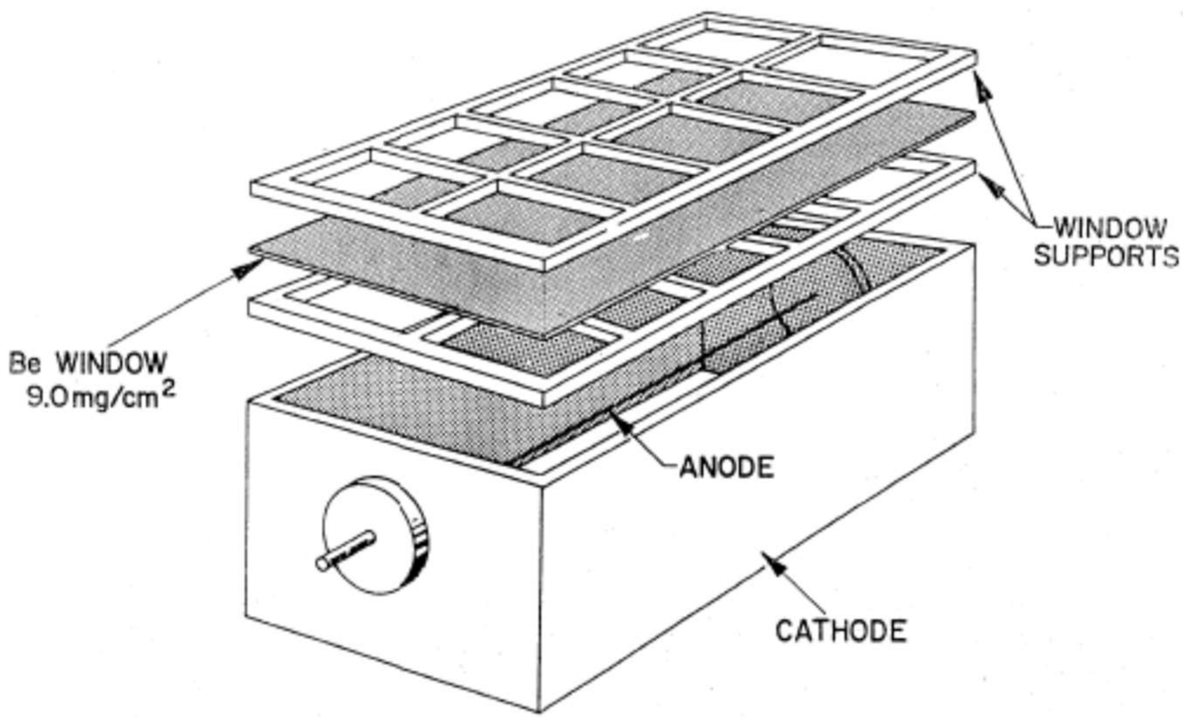
The First X-ray Astronomy Satellites



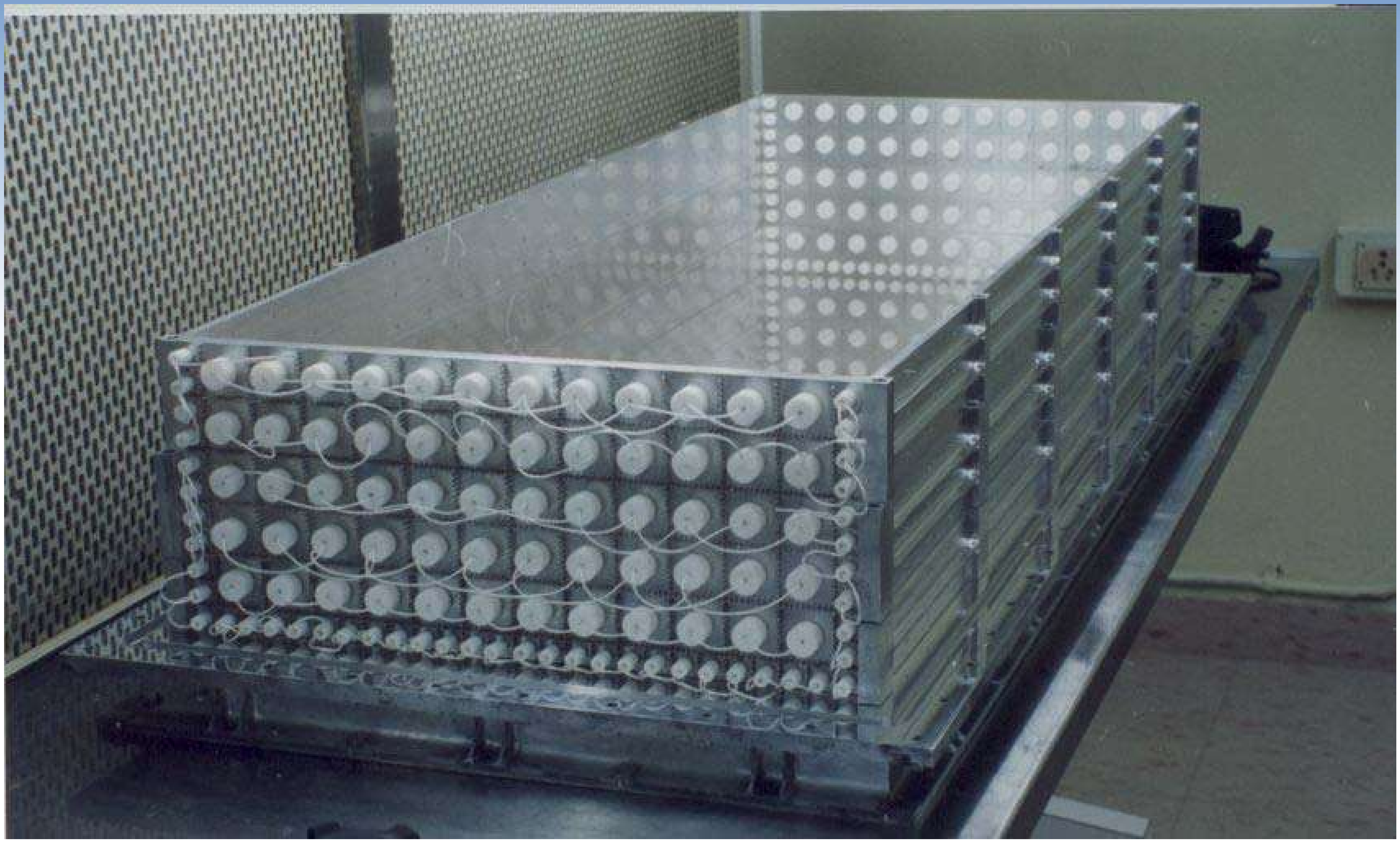
#1: Uhuru 1970 (NASA)

X-ray Detection

- First detectors were proportional counters
- Based of photoionization of a Nobel gas (e.g. Ar)
- Gain of $10^3 – 10^5$
- Single photon event are detected (need to be!)



Example: LAXPC on *AstroSat*



LAXPC X-ray detecting anode assembly with veto layer on 3 sides mounted on the back plate.

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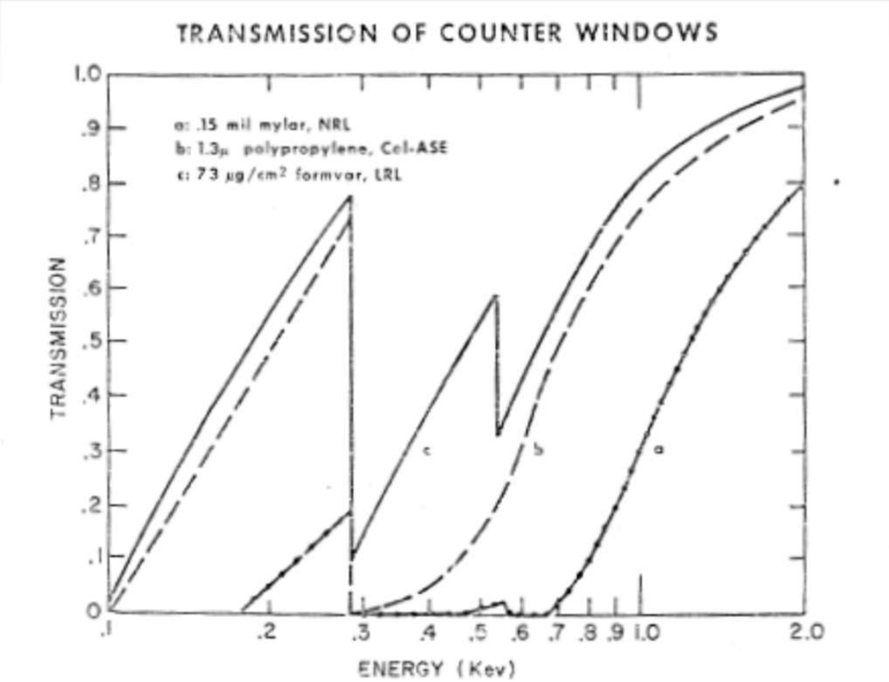
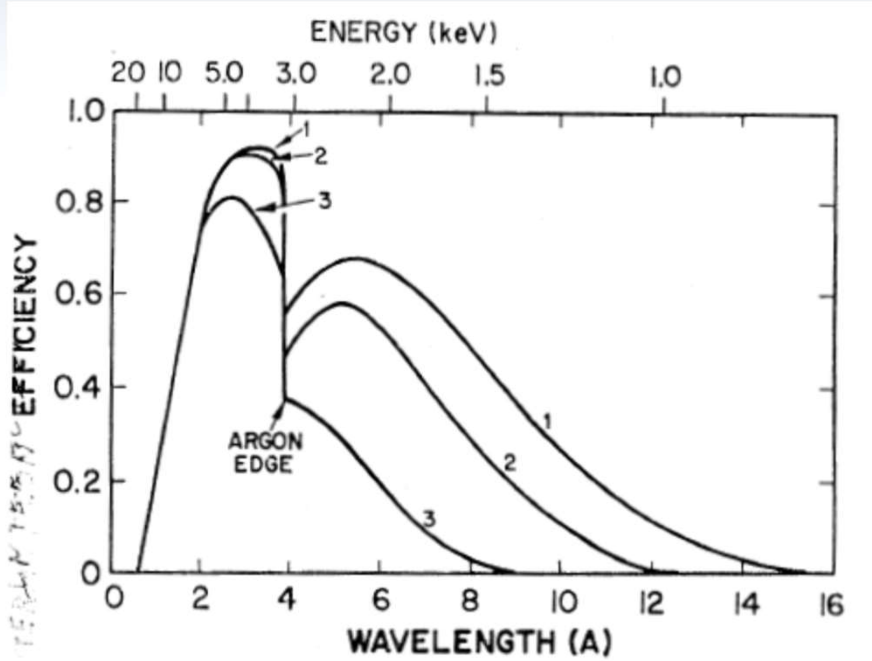
Proportional Counters

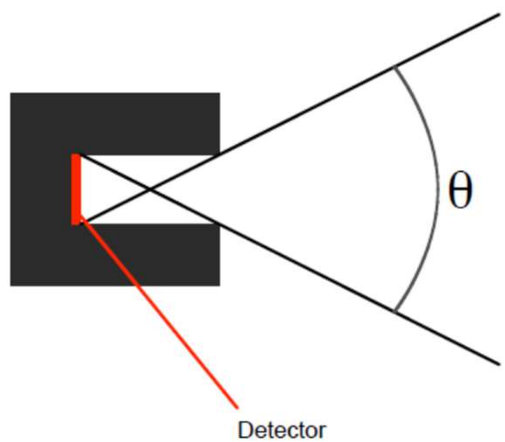
- Need transparent window
- Need absorptive gas

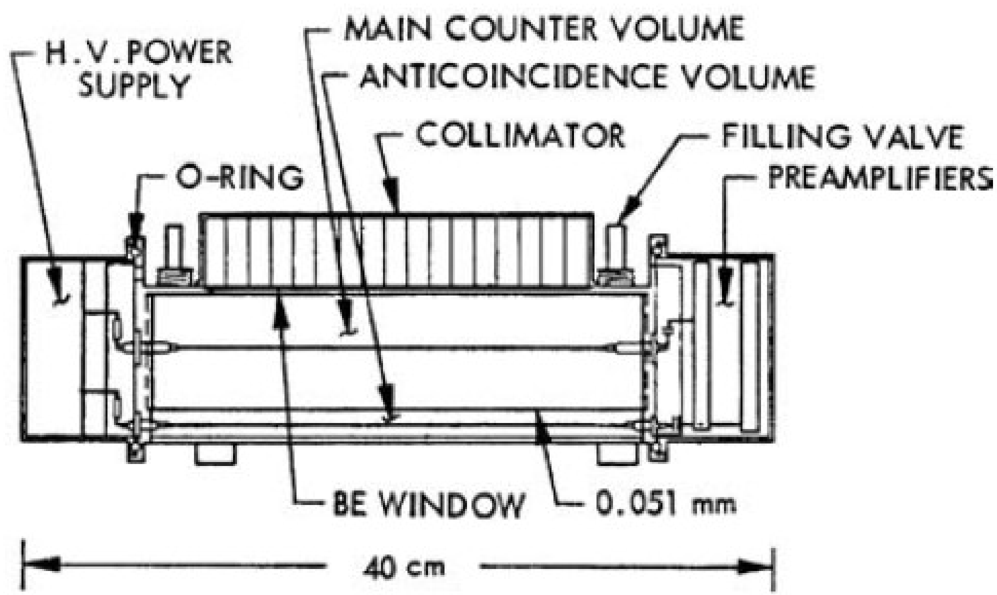




X-ray Source Location

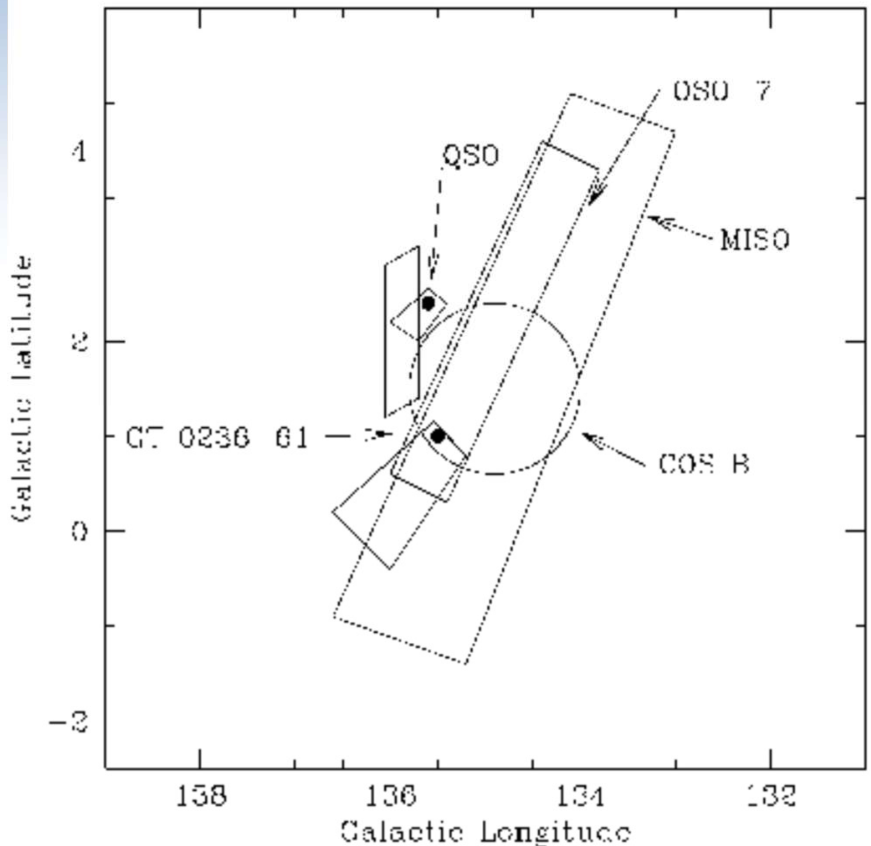
- Crude collimation by means of mechanical obstructions (slats or "egg crate" collimators)





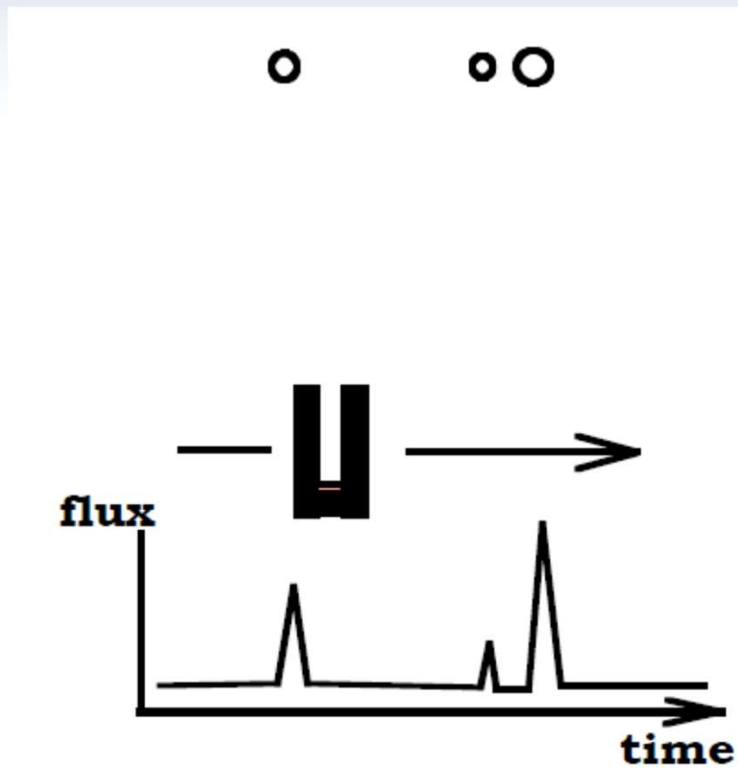
X-ray Source Location

- Non-imaging proportional counter only gave crude source postions
- Source confusion issues



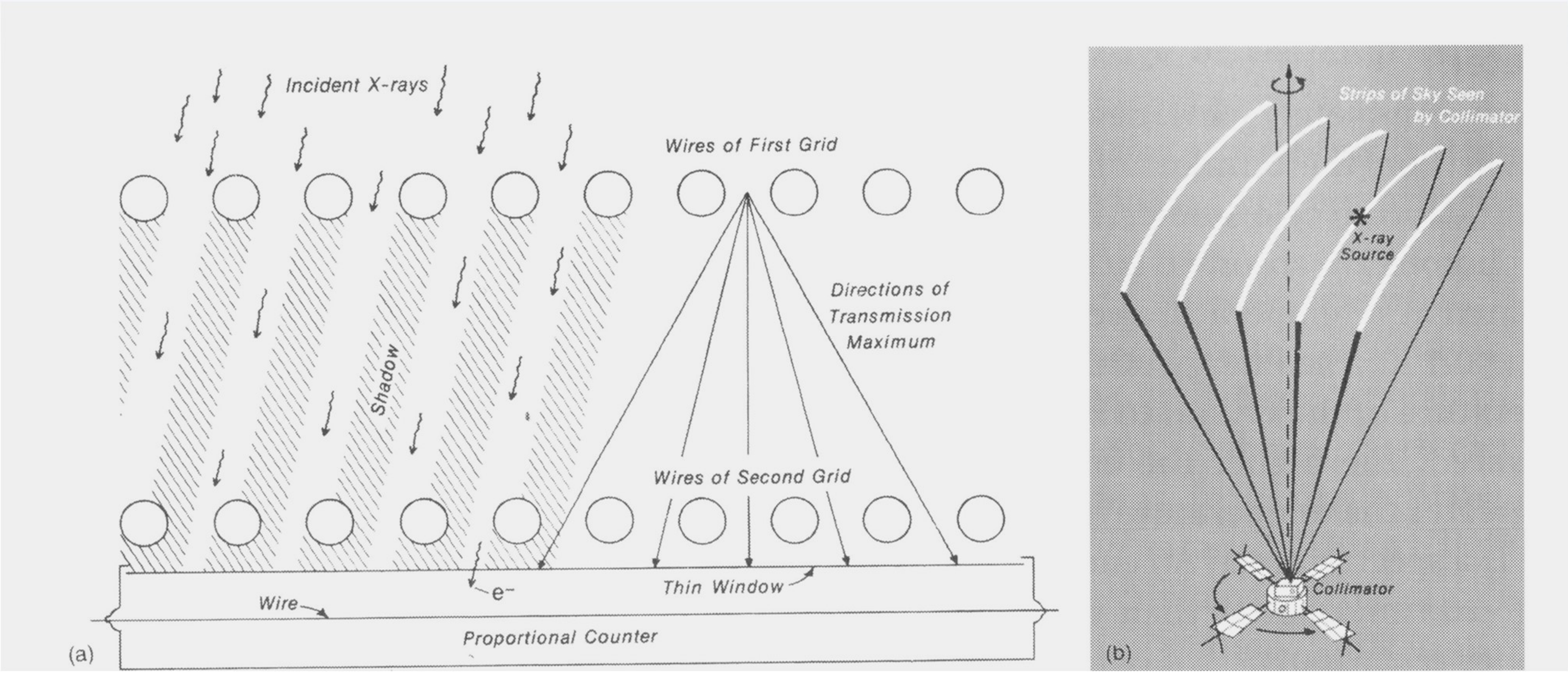
X-ray Source Location

- Improvements from using *modulation* collimators
- Rotate the satellite and periodically occult the X-ray source



X-ray Source Location

- *Scanning Modulation Collimator*
- *Rotating Modulation Collimator*

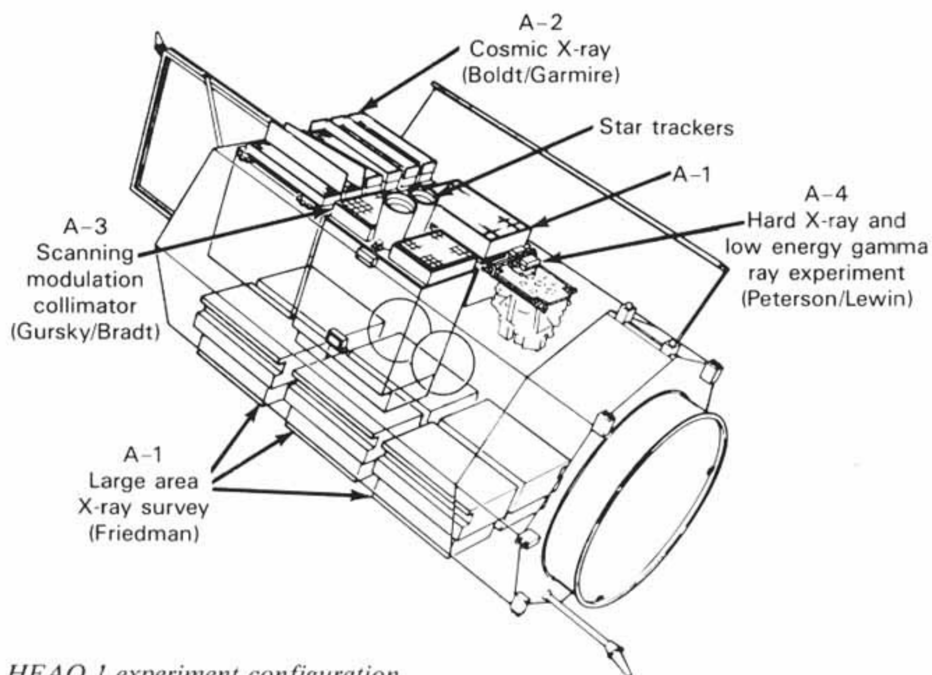


The First X-ray Astronomy Satellites

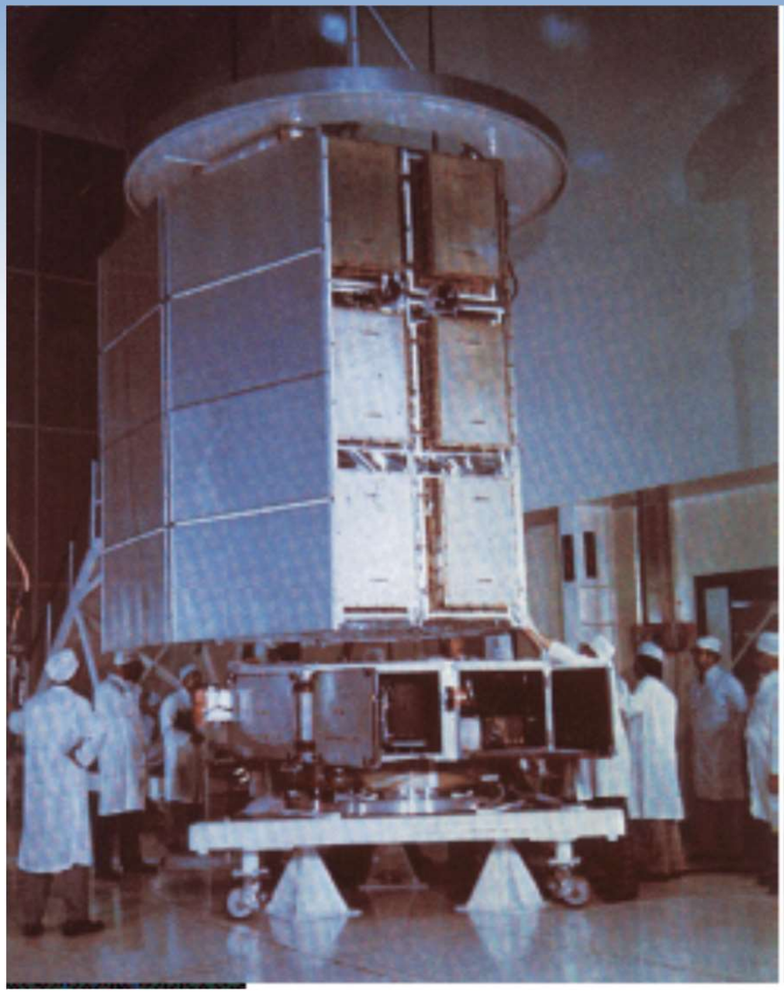
- **A number of smaller X-ray satellite missions (Ariel, SAS, OAO)**
- **All using PCs, some with modulation collimators**
- **Culminating eventually in the NASA *High Energy Astronomy Observatory* missions:**
  - **HEAO-1 (scanning collimation; first hard X-ray all-sky survey)**
  - **HEAO-2 (renamed *Einstein Observatory;* first imaging X-ray telescope)**
  - **HEAO-3 (cosmic rays)**

HEAO-1

- **4 different instruments**
  - A1: hard X-ray large area PCs
  - A2: soft X-ray PCs
  - A3: hard X-ray scanning PCs
  - A4: gamma ray detectors

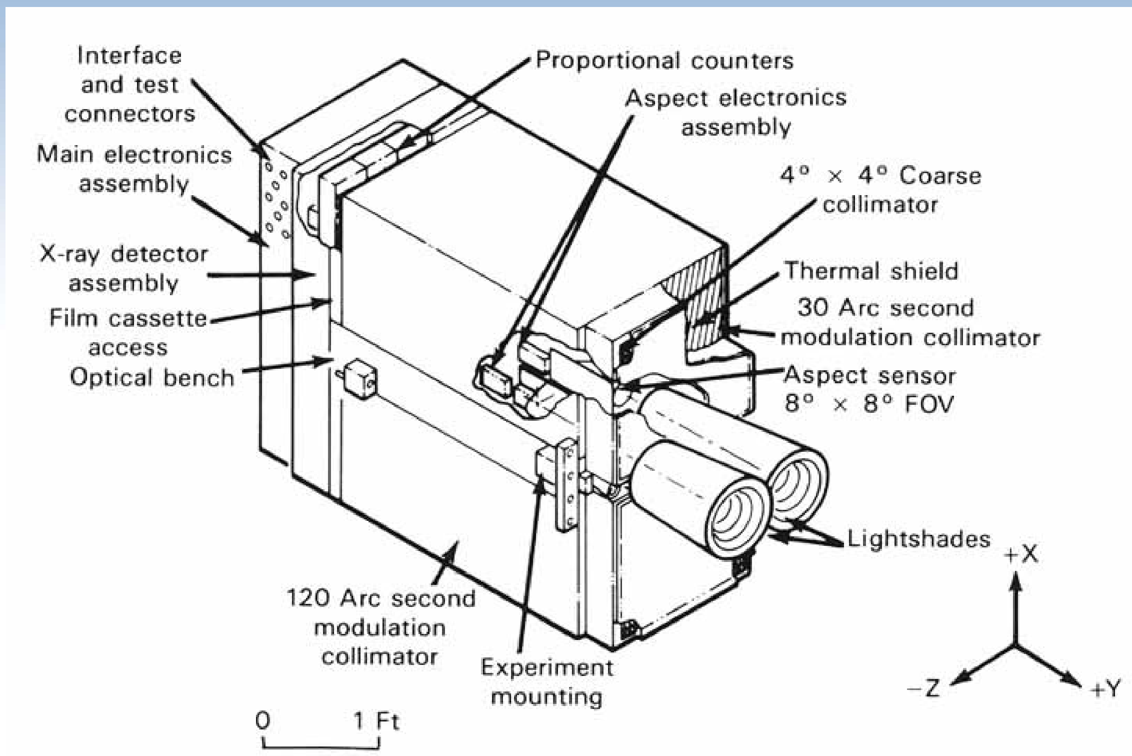


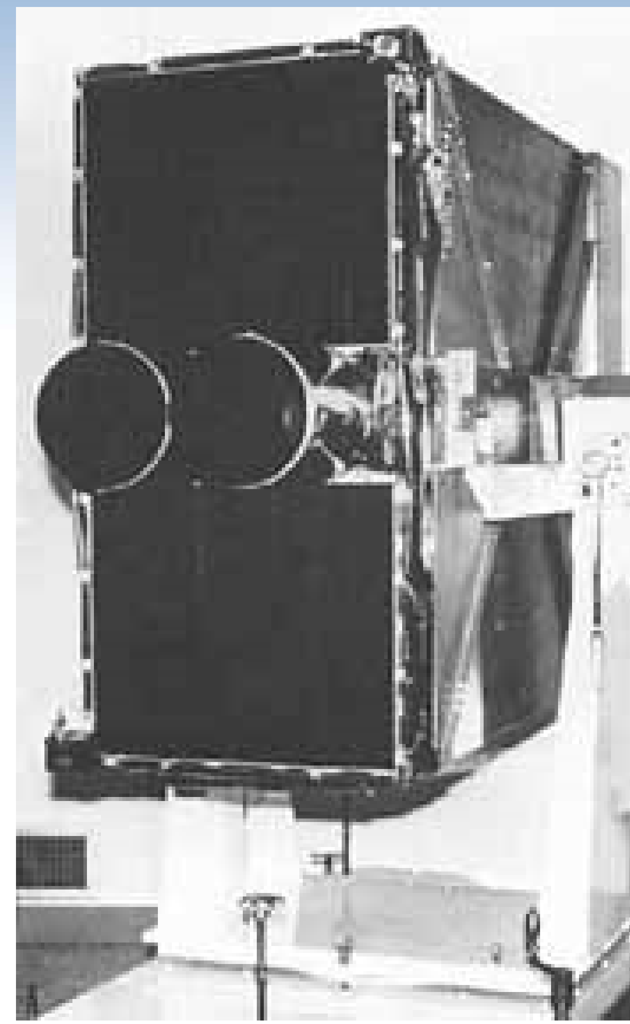
HEAO 1 experiment configuration.



HEAO-1

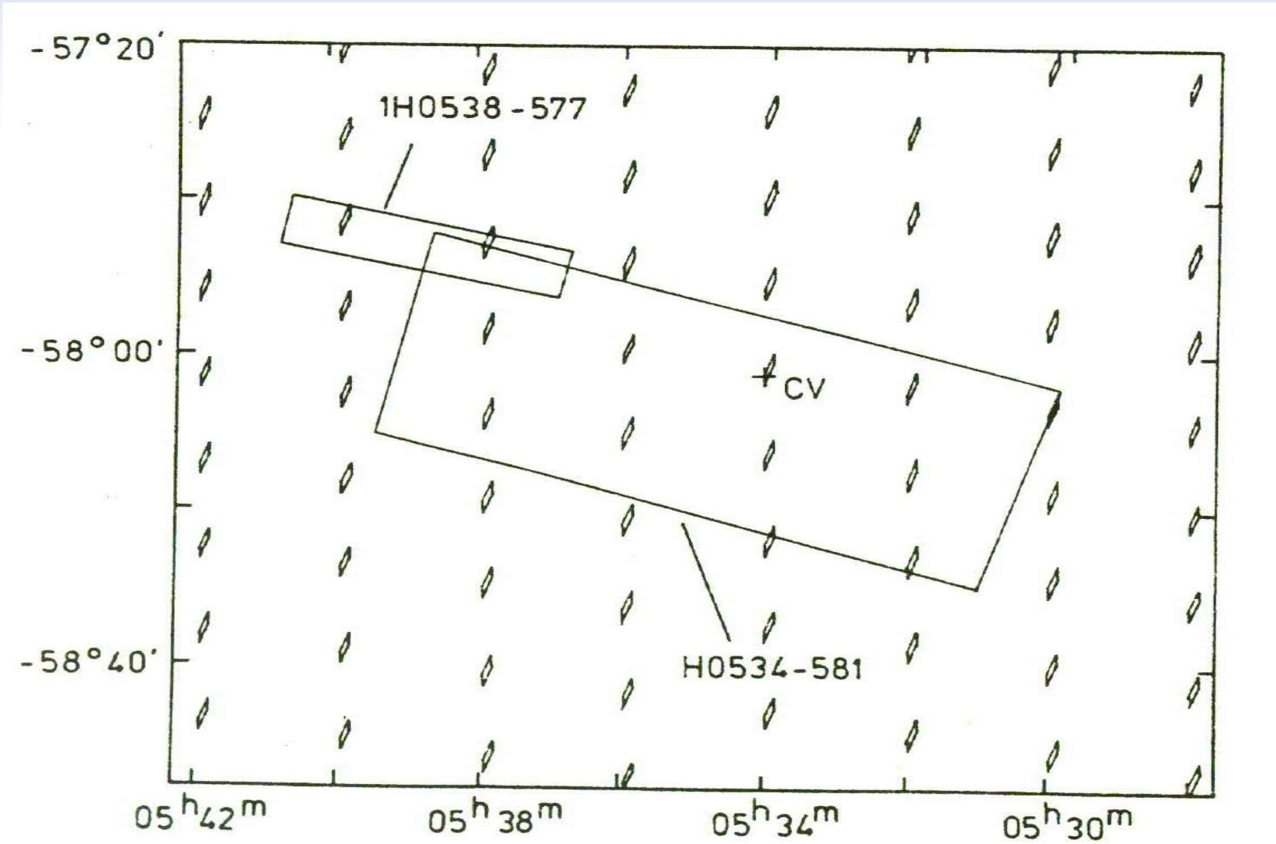
- *Scanning Modulation Collimator (A3)*





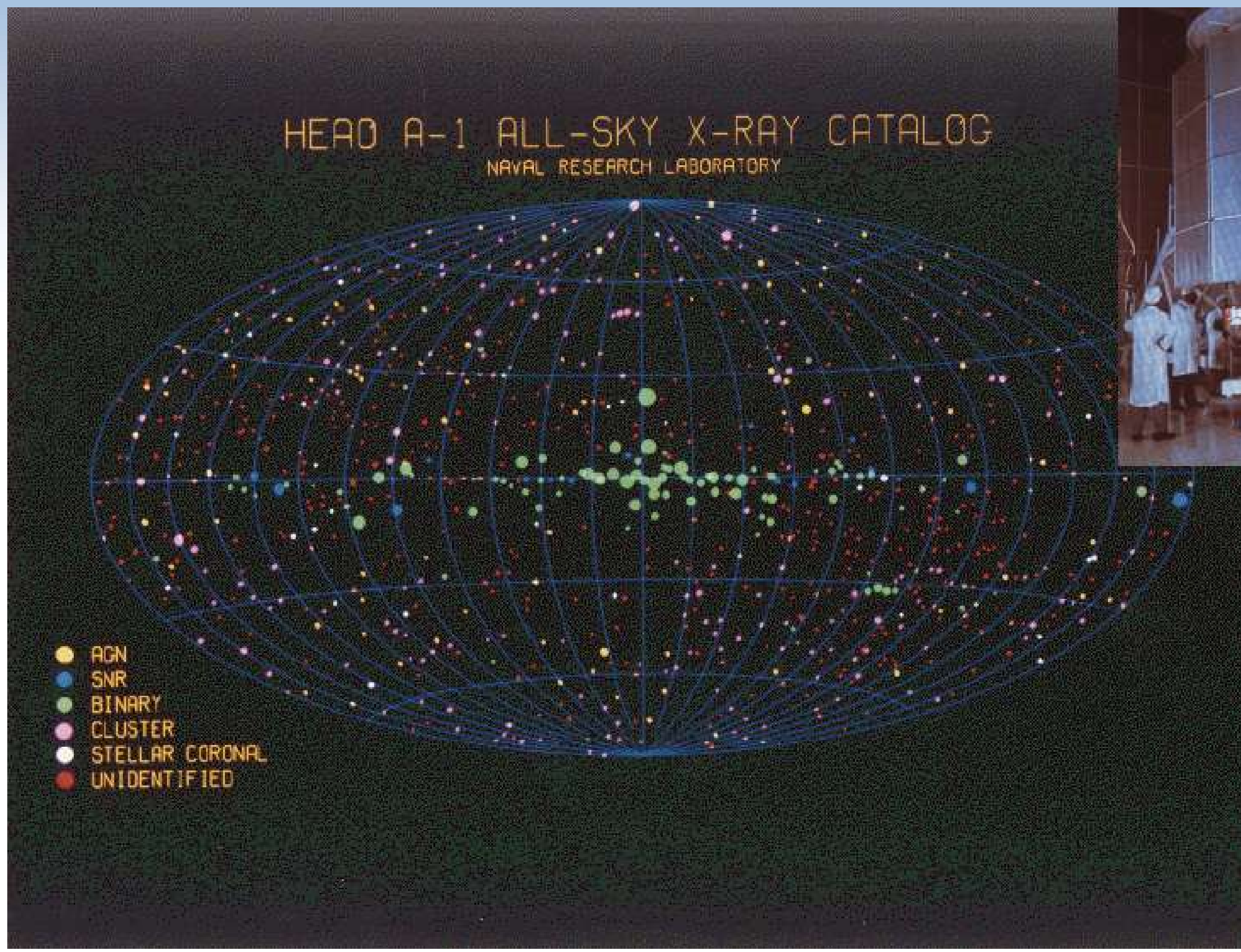
HEAO-1

- *Produced a regular grid of possible non-unique error boxes*
- *~1 x 2 arcmin over 4 x 4 degrees*
- *Any one of them could contain the source!*



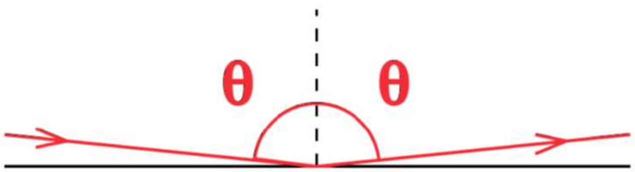
HEAO-1

- *Total of ~1000 sources detected*



First X-ray Telescope: *Einstein Observatory (HEAO-2)*

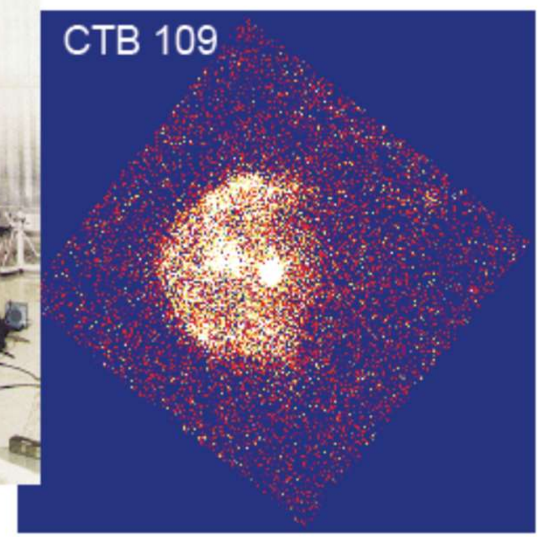
- First use of mirrors to focus X-ray
- Grazing incidence optics



- Pointed observations rather than all-sky survey
- Softer energies

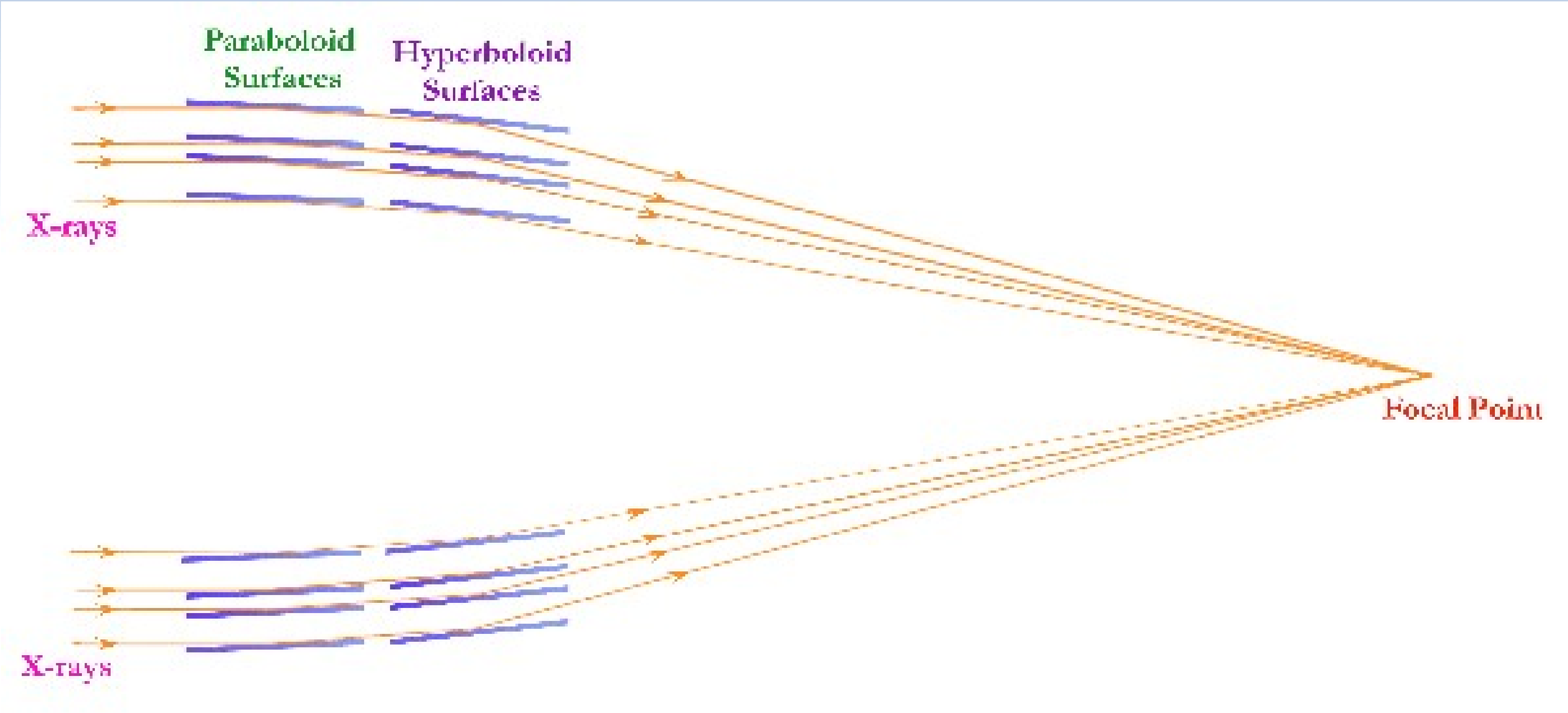
first imaging at 2-20 keV
several instruments (5-200 cm^2)

1000s of X-ray sources, discovery of jets (M87), spectroscopy



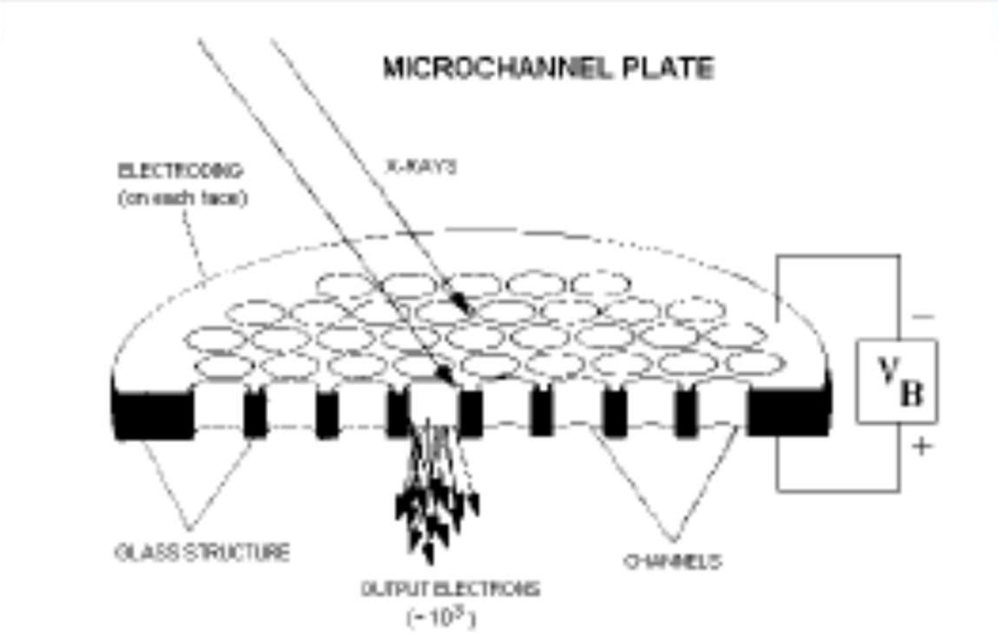
Einstein Observatory

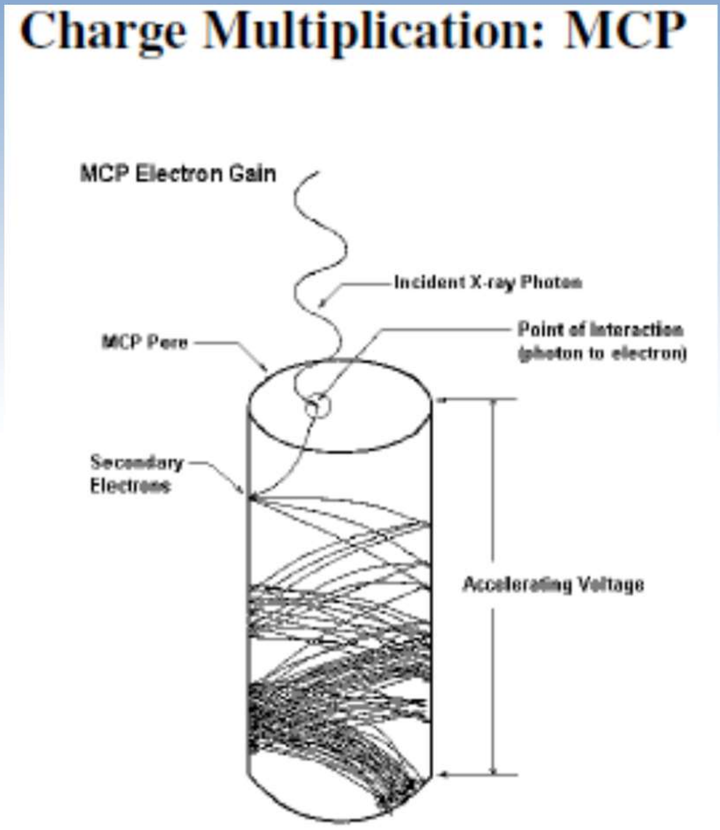
- The telescope design:



Einstein Observatory

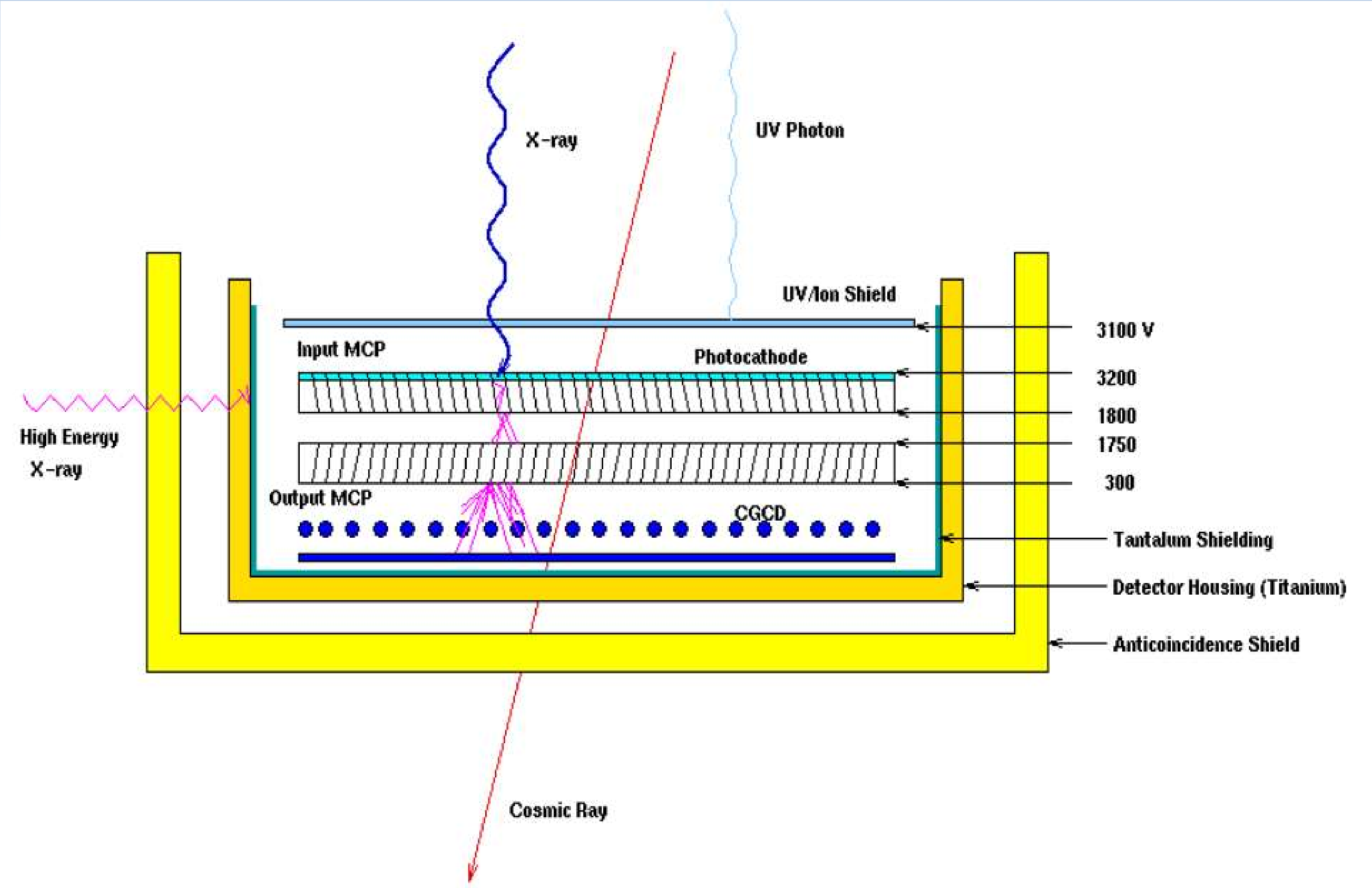
- New types of detectors
  - Micro-Channel Plate
  - Solid State Spectrometer





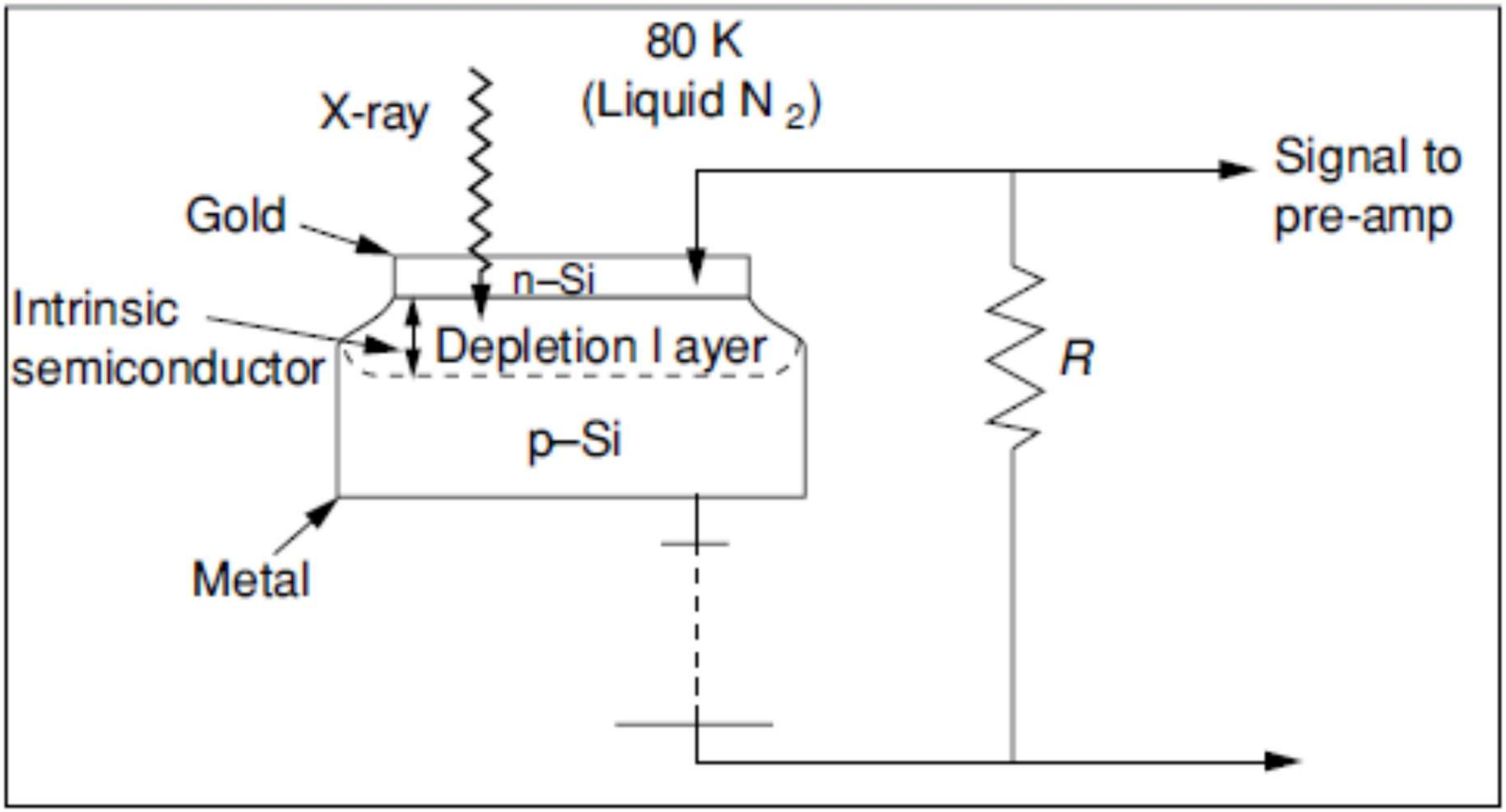
Einstein Observatory

- New types of detectors
  - Micro-Channel Plate



Einstein Observatory

- New types of detectors
  - Solid State Spectrometer (CCD principle)



ROSAT: The next imaging X-ray satellite (1990)

- German-UK-US collaboration
- Soft X-ray survey (0.2 – 2.5KeV)
- Greatly improved sensitivity
- ~80,000 sources

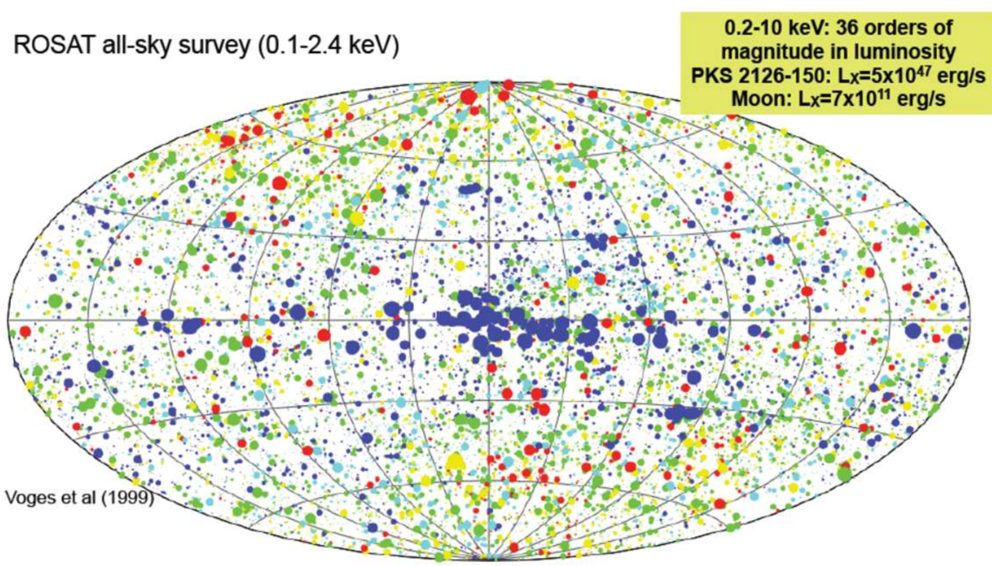
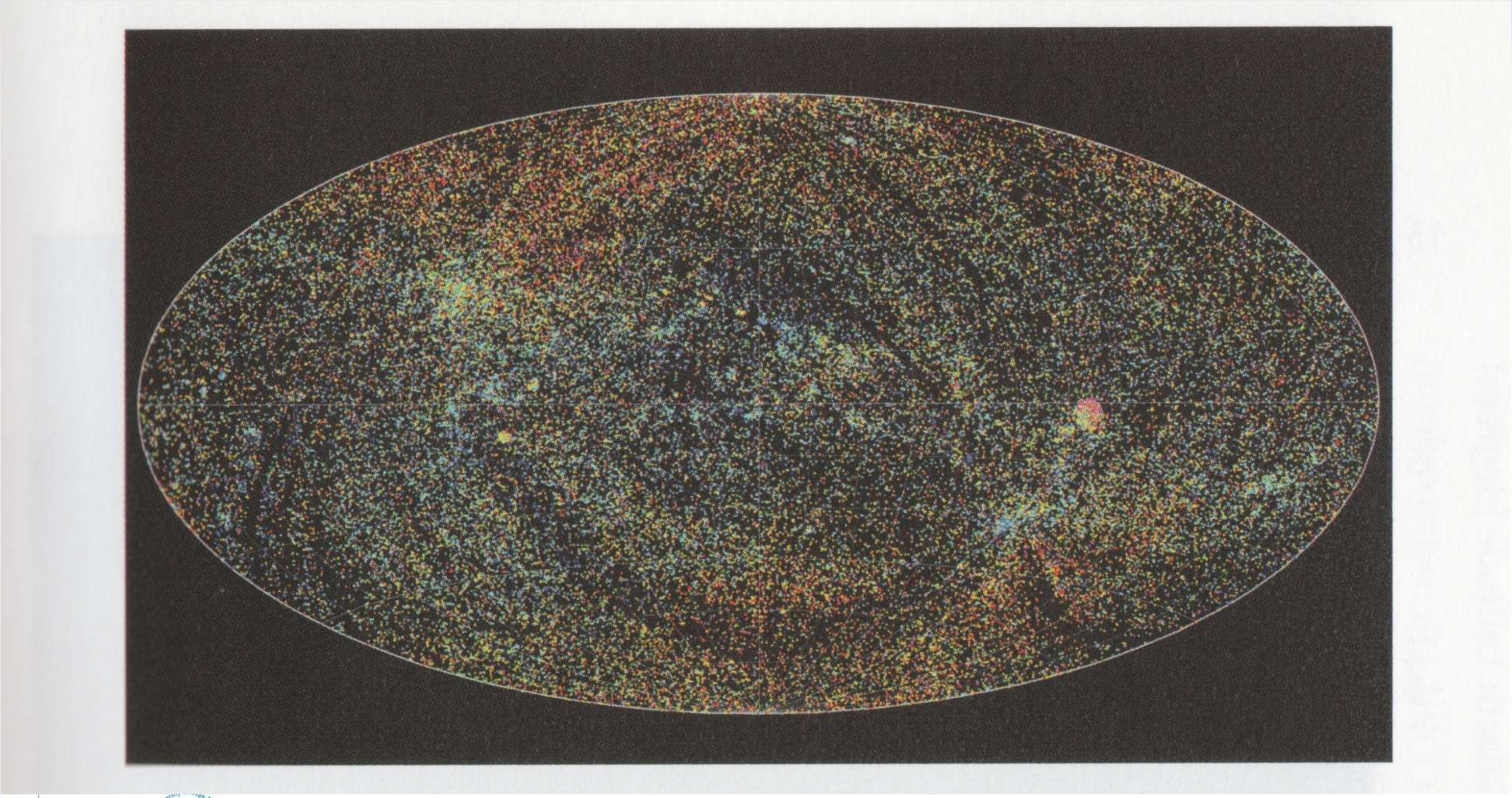


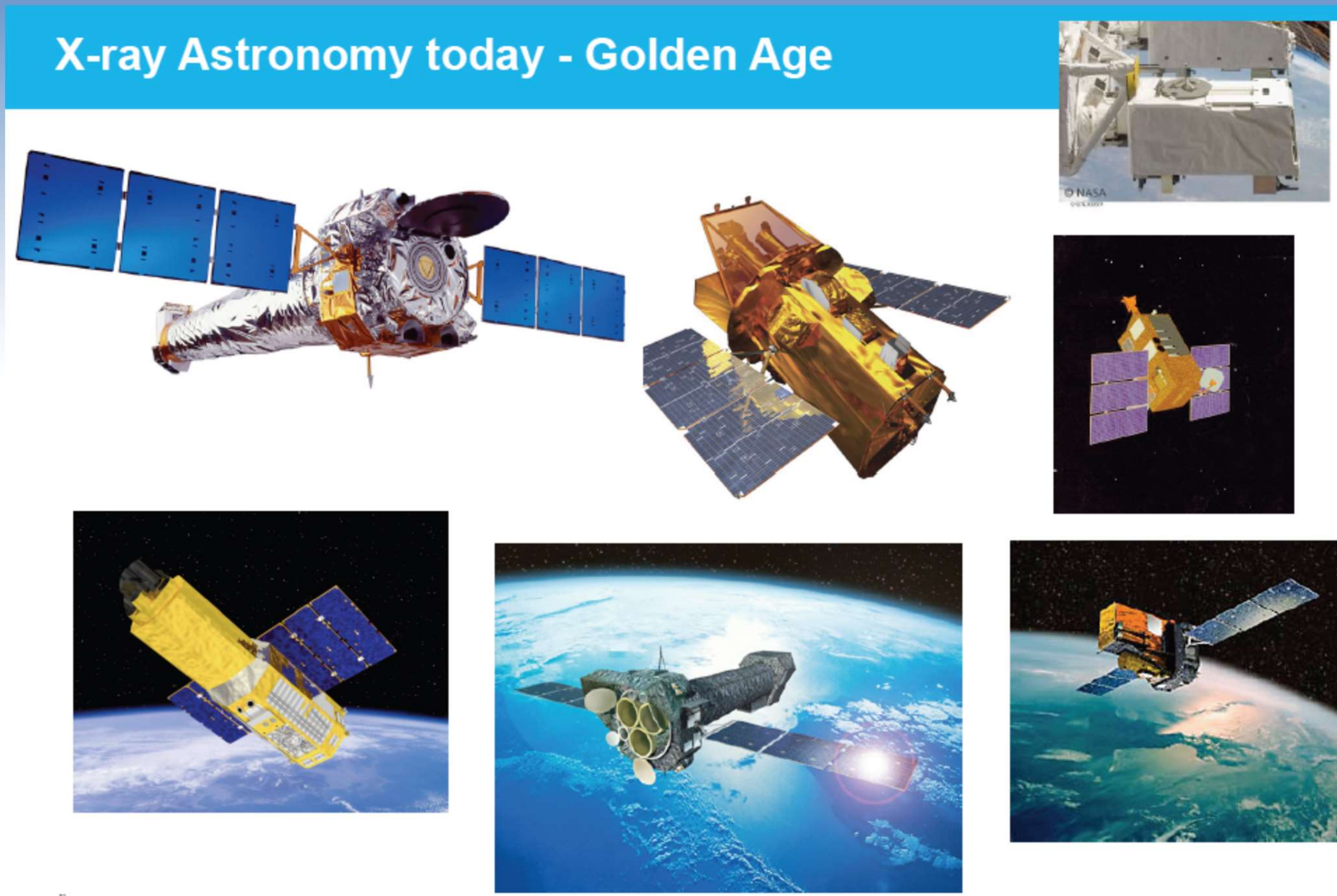
Fig. 5. Aitoff projection of the distribution of all RBSC sources obtained in the ROSAT All-Sky Survey observations until August 13, 1991 in galactic coordinates. The size of the symbols scales with the logarithm of the count-rate and the colours represent 5 intervals of the hardness ratio HR1: red ($-1 \leq$ HR1 < -0.6); yellow ($-0.6 \leq$ HR1 < -0.2); green ($-0.2 \leq$ HR1 $<$ 0.2); blue ($0.2 \leq$ HR1 < 0.6) and violet ($0.6 \leq$ HR1 ≤ 1.0).

ROSAT

- Greatly improved sensitivity
- Also did first Extreme UV (EUV) survey
- Lots of source IDs and optical follow-up done at SAAO



New Missions of the Millenia



Current X-ray Missions

Key Points

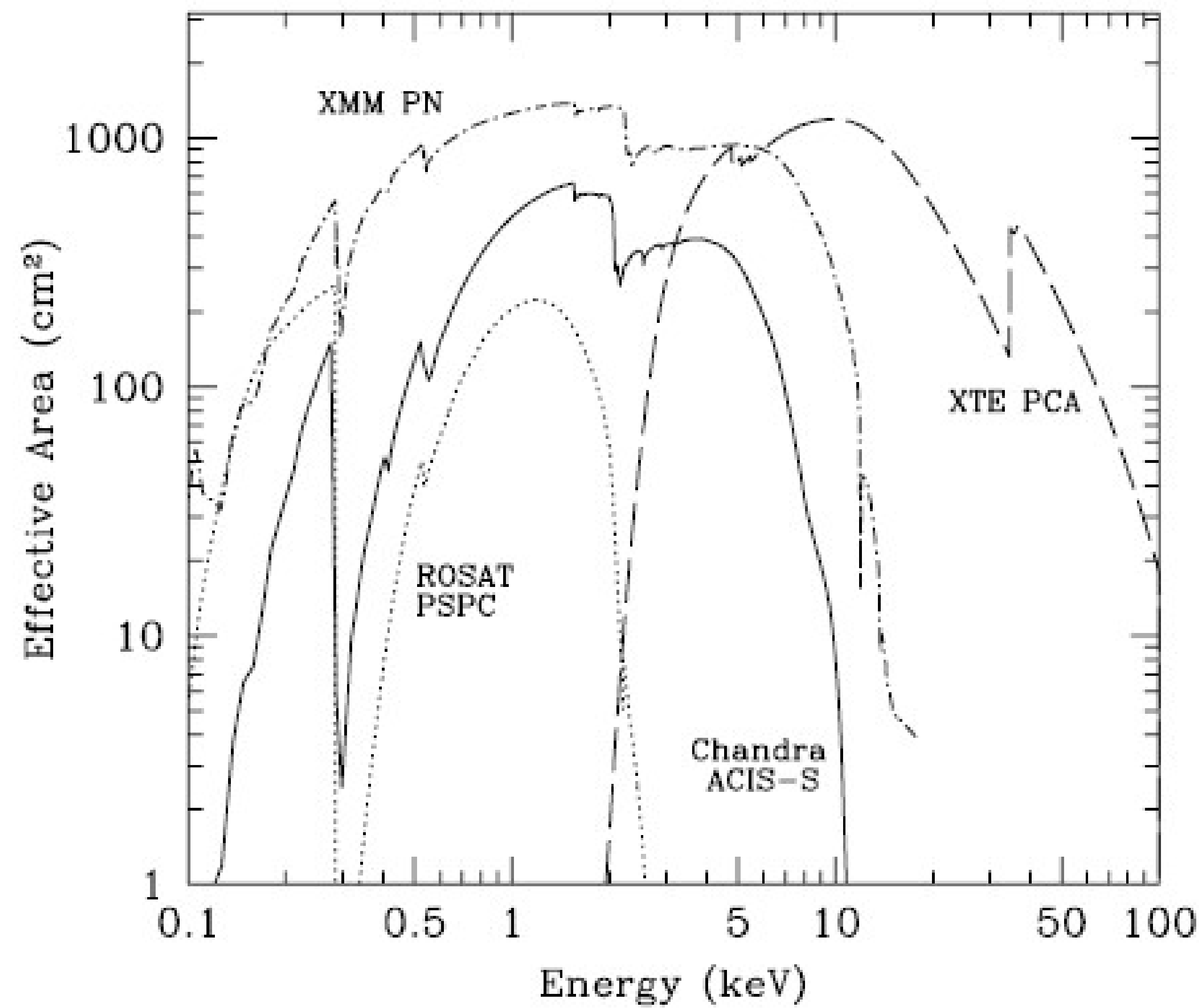
- X-ray telescopes use grazing reflections
- Most modern detectors are arrays of CCDs
- Energy of X-ray determines charge released in pixel
- Use grating spectrometers for higher energy resolution
- Record position, energy, time of each photon

Co

New Millennium

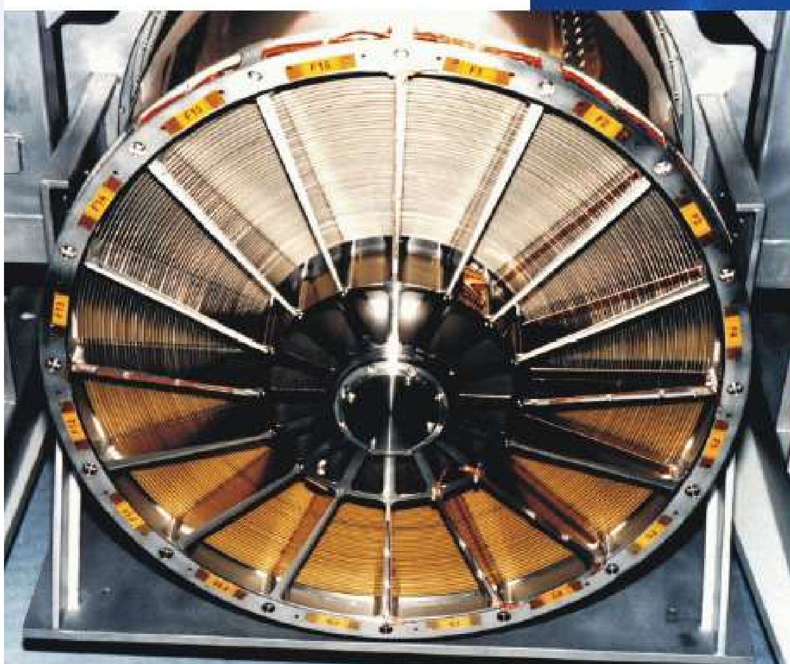
- 1999 saw launch of Chandra and XMM-Newton
  - NASA's Chandra high spatial resolution
  - ESA's XMM high sensitivity
- 2005: Japan's Suzaku mission launched
  - High resolution X-ray spectrometer failed after launch, imager still performing useful science

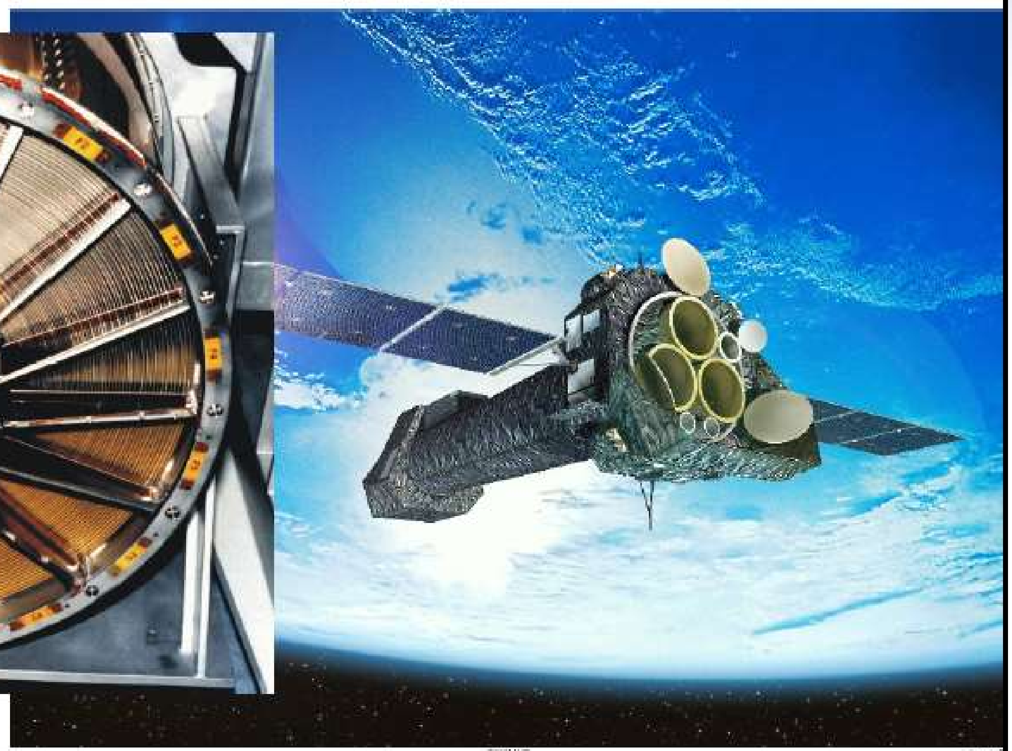
Improved Collecting Area



XMM-Newton 1999-

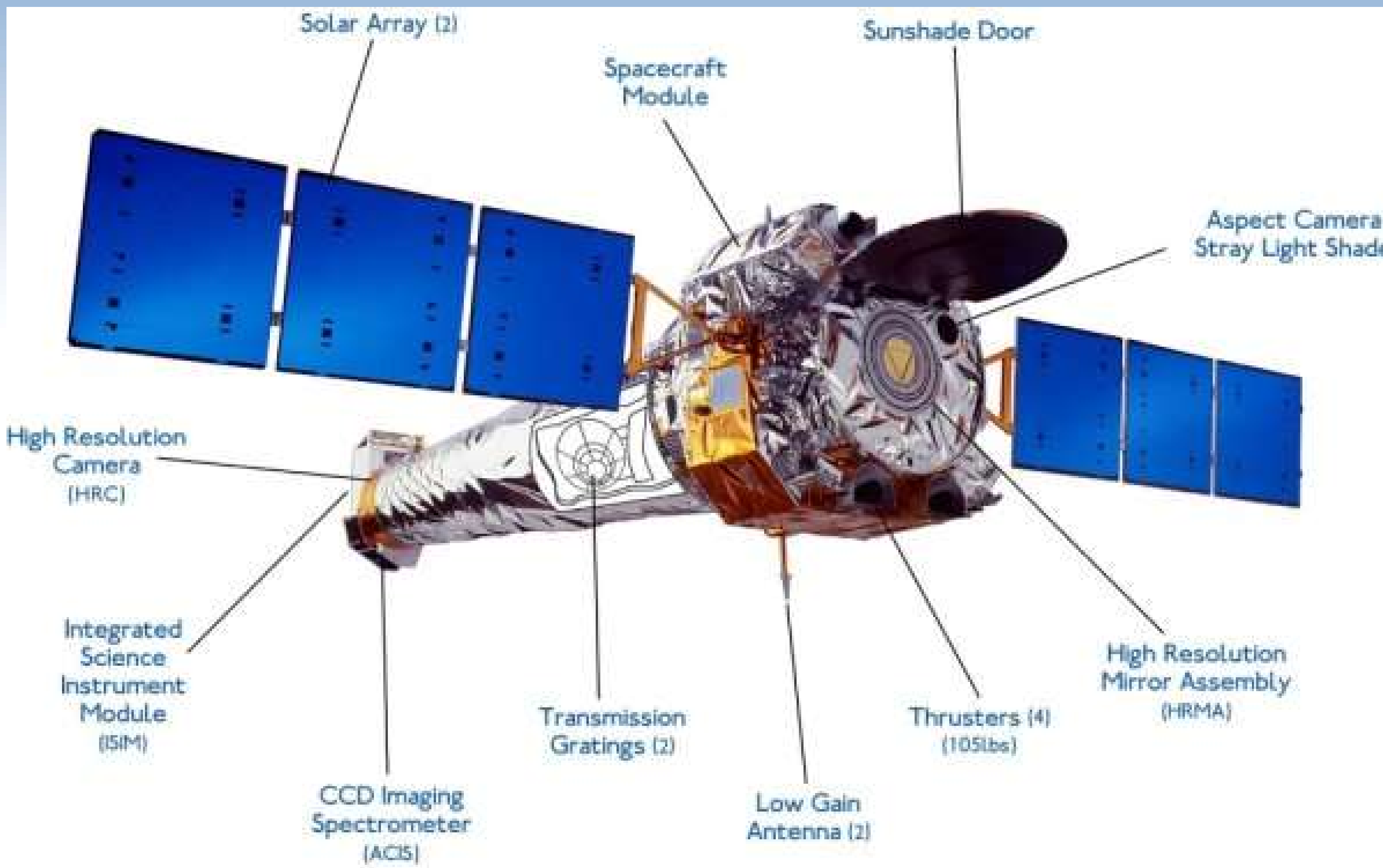
- 3 X-ray telescopes each with 58 nested Wolter mirrors
- Effective area approx 0.4 m^2





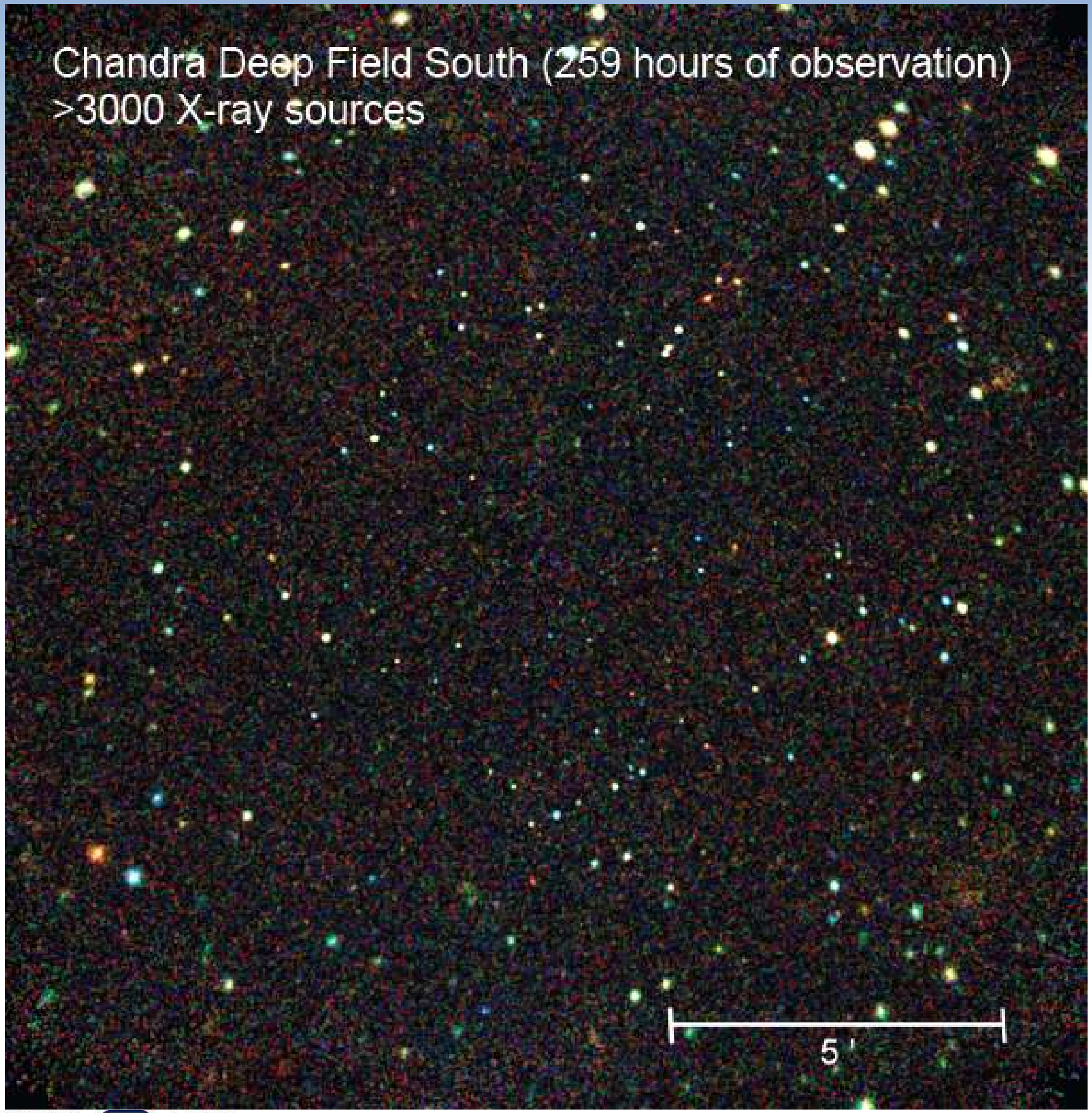
Chandra

Chandra



Solar Array (2)
Sunshade Door
Spacecraft Module
Aspect Camera Stray Light Shade
High Resolution Camera (HRC)
Integrated Science Instrument Module (ISIM)
CCD Imaging Spectrometer (ACIS)
Transmission Gratings (2)
Low Gain Antenna (2)
Thrusters (4) (105lbs)
High Resolution Mirror Assembly (HRMA)

Chandra Results:
best resolution images to date



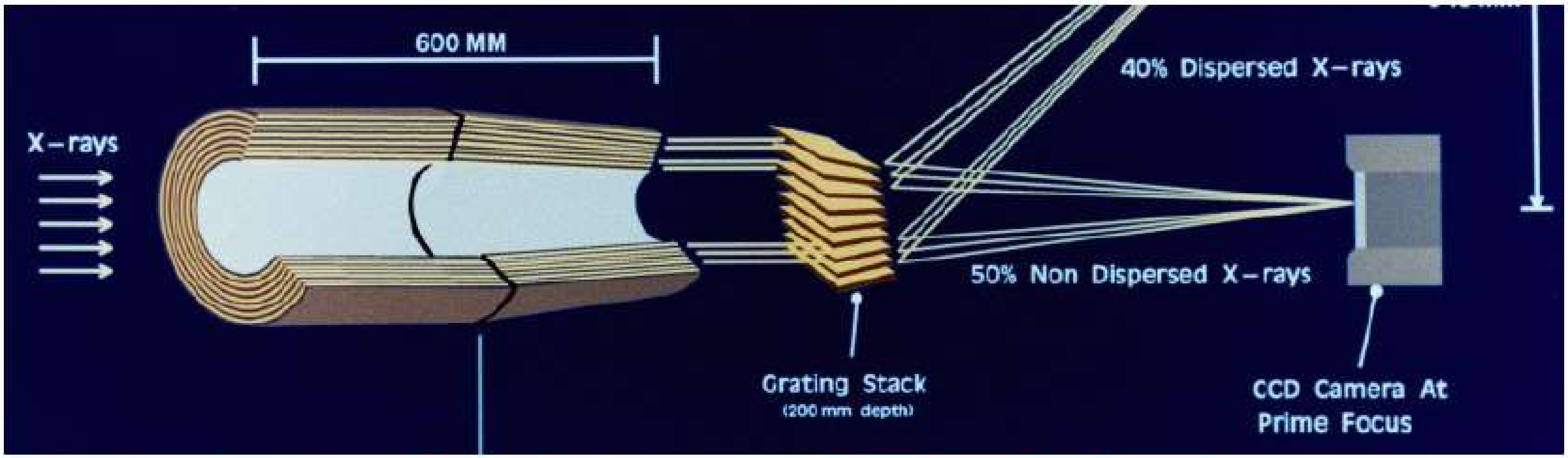
Com

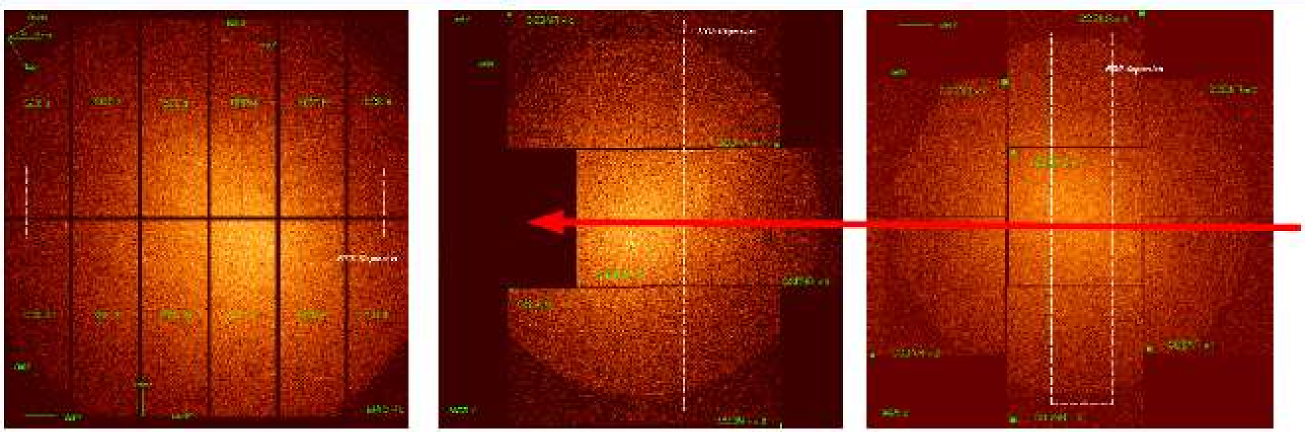
X-ray CCDs

- Energy of single X-ray sufficient to release many electrons in pixel
- Charge on a pixel when read out gives energy of photon
  - Providing only one photon detected by pixel
- Even brightest X-ray sources emit few photons per unit time compared to optical sources
- In a short exposure (~1s), each CCD pixel receives 0 or maybe 1 photon
- Long exposure built up from many short exposures and readouts
- Record position, energy and time of each photon

XMM-Newton 1999-

- 1 EPIC-pn BI CCD camera
- 2 EPIC-MOS FI CCD cameras with gratings

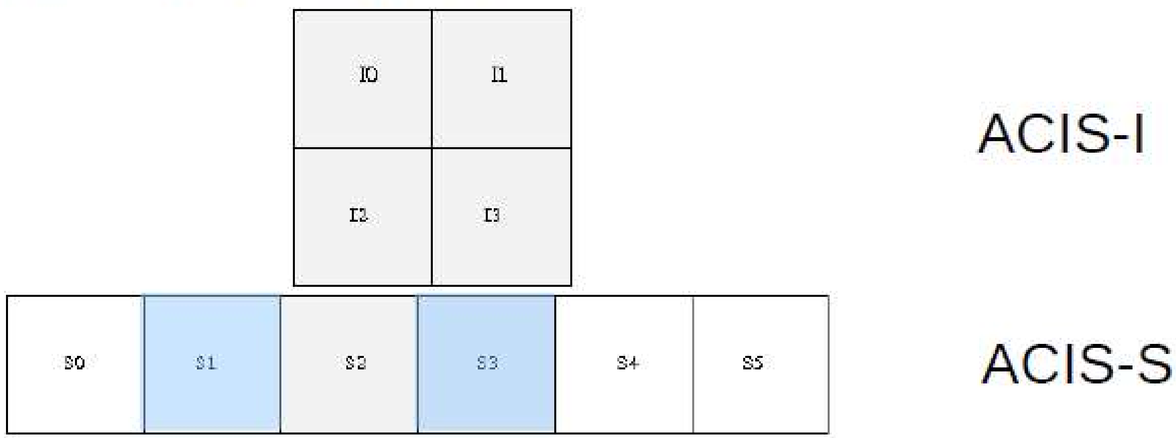




MOS1 CCD damaged by micrometeorite in 2005

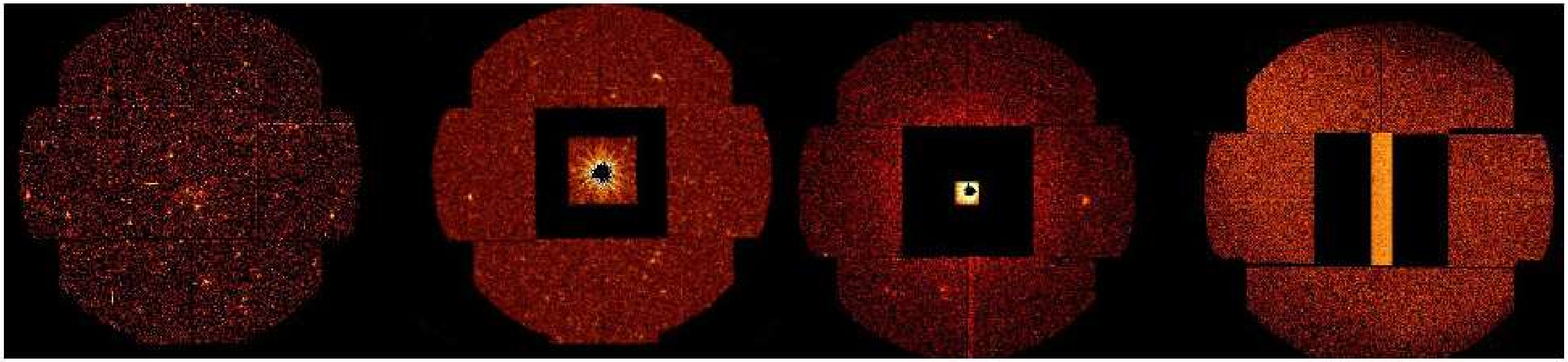
Chandra ACIS

- ACIS Camera consists of 2 CCD arrays (I & S)
- Optional transmission gratings disperse X-rays along ACIS-S
- Use subset of 6 chips for observations
- 2 BI CCDs, rest FI
  - FI chips suffered radiation damage early in mission
  - Slightly degraded energy resolution



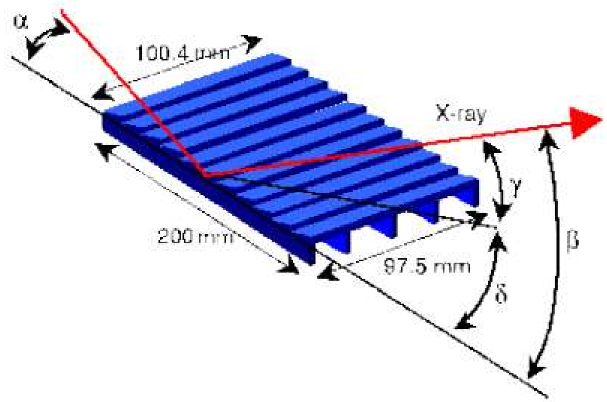
Time Resolution

- Time of arrival of photon determined from which short exposure & readout it was detected in
- The time taken to shuffle the charges between pixels to read out CCD places limit on time resolution
- Improve by only activating small part of CCD
  - reduces readout time
  - e.g. different timing modes of EPIC MOS camera on XMM-Newton

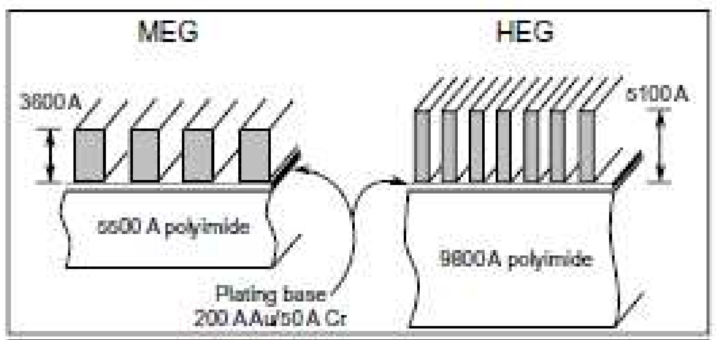


X-ray Gratings

- While CCDs provide good energy resolution, high energy resolution requires grating spectrometers
- Transmission or reflection gratings diffract X-rays



- Reflection gratings on XMM have ~650 lines/mm

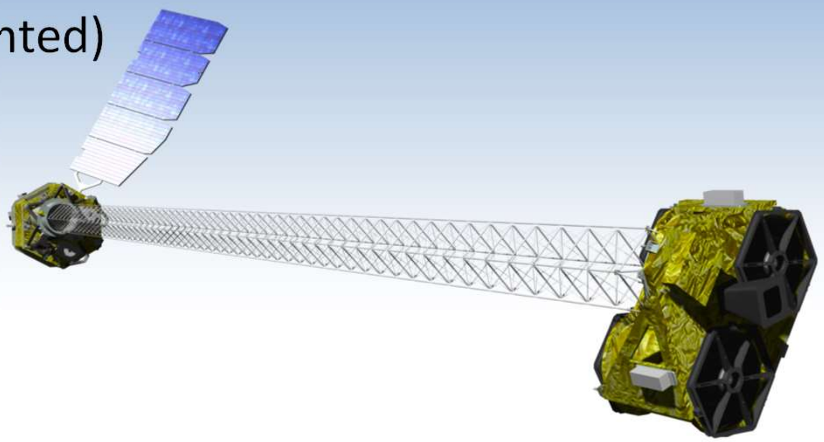


X-ray Data

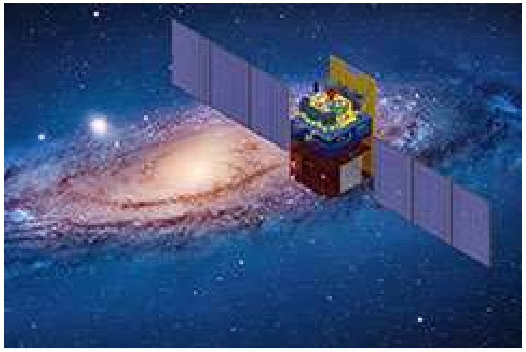
- X-ray observatories record position, time and energy of every event detected in an **events list**
- Extract information we are interested in from events list
  - Take N(x,y) and make image
  - Take N(t) and make lightcurve
  - Take N(E) and make spectrum
- In practice, perform additional filtering
  - e.g. make image in particular energy band
  - e.g. extract spectrum from spatial region

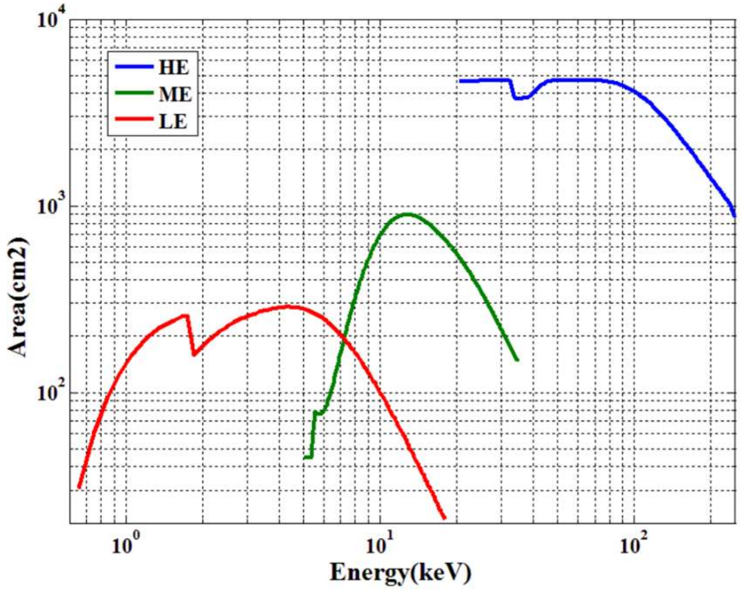
Recent X-ray Missions

- MAXI - instrument on the ISS since 2009
- NICER (0.2 – 10 keV; pointed) – another instrument on the ISS
- NuSTAR (3 – 79 keV; pointed)



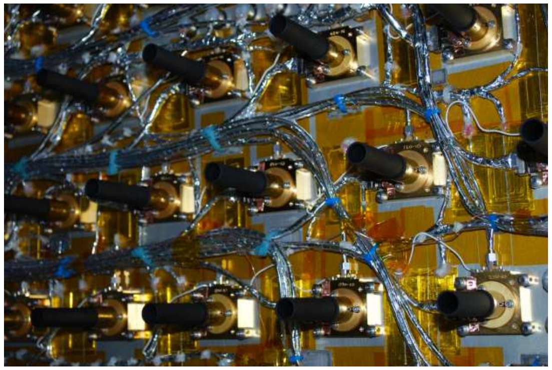
- HXMT/Insight (3 instruments covering 1 – 250 keV)





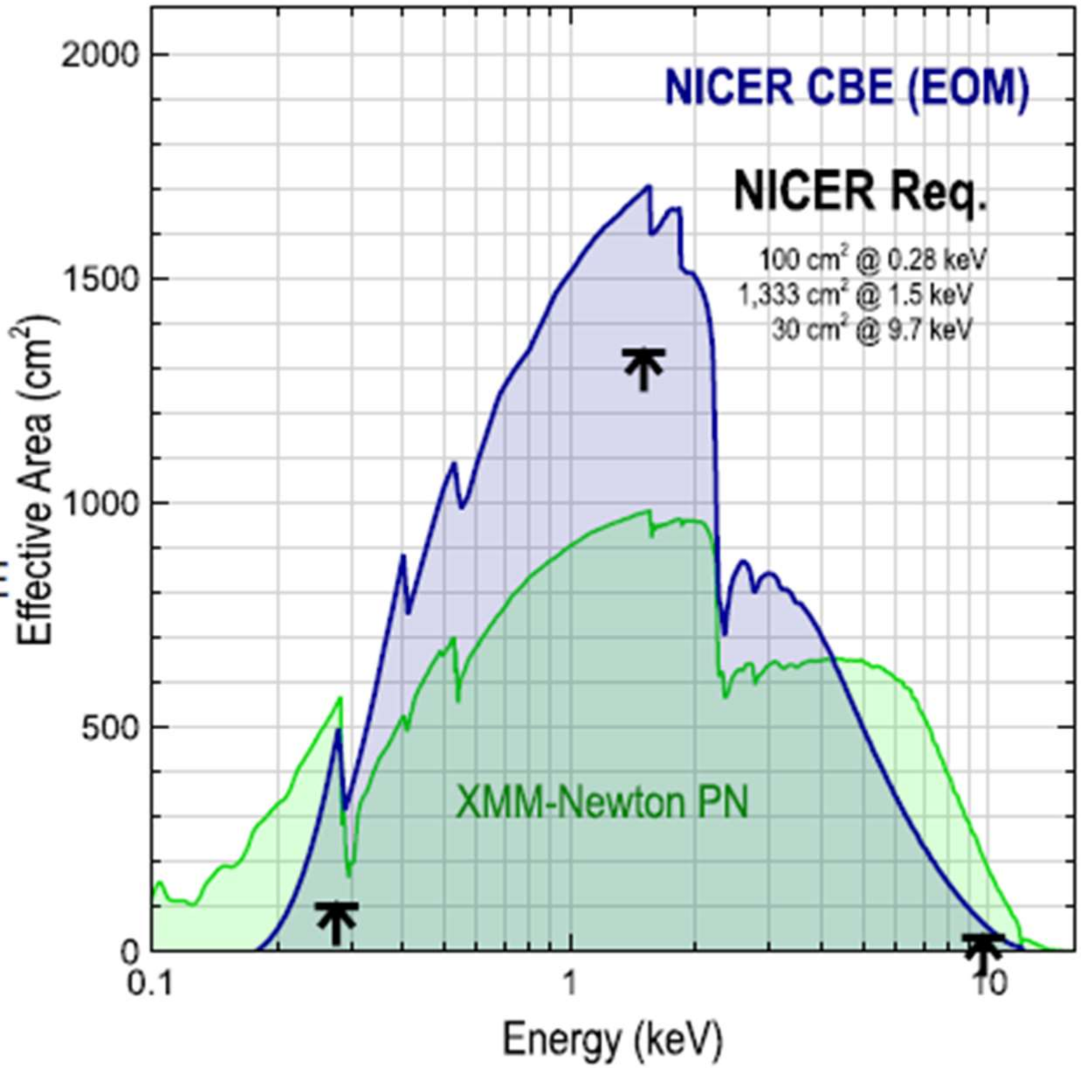
Example NICER

- Very efficient soft X-ray instrument
- Utilizing Si based detectors
- Installed on ISS in 2017



NICER

- Most sensitive to X-ray QPOs (2x XMM)
- Most sensitive to soft X-ray lines (better than gratings < 1 keV)
- 25x better timing than RXTE
- CCD-like energy resolution
- High sensitivity to faint sources (low bg) while handling brightest sources
- *No Pileup (!)*



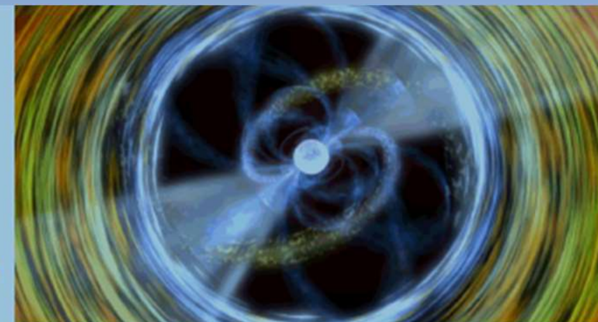
NICER: Science Goals

Primary Targets: non-accreting pulsars

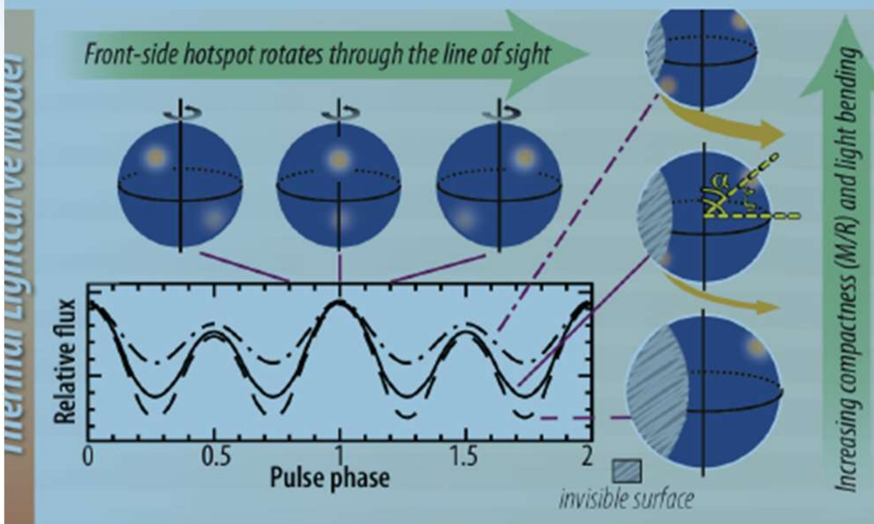
(they drive Baseline Science Requirements)

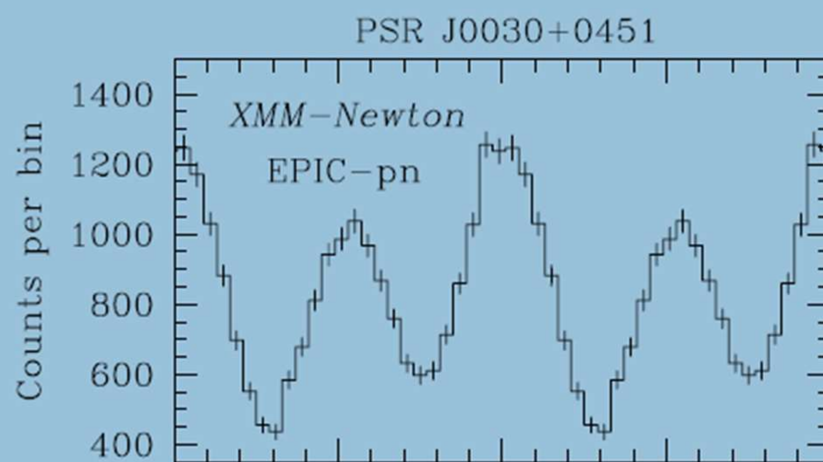
Typically < 0.1 mCrab

Goal: 5% radii and 10% masses to constrain NS EoS



credit: Dana Berry/NASA

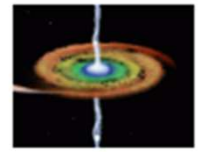




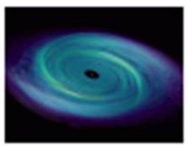
NICER: Science Goals

Prime Targets: Galactic X-ray binaries

Flux can be > 1 Crab !

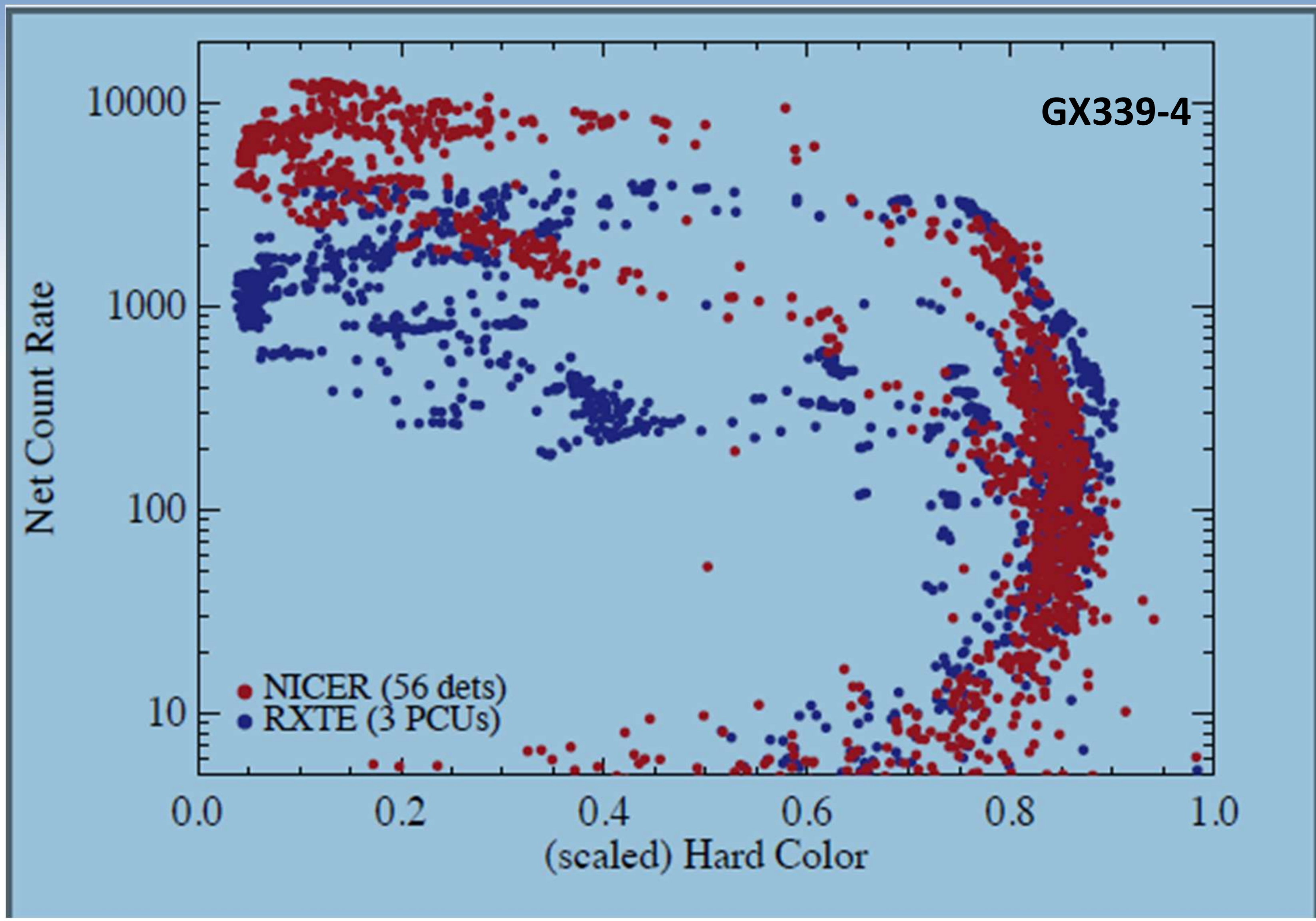


Driving largest programs in "observatory science" group



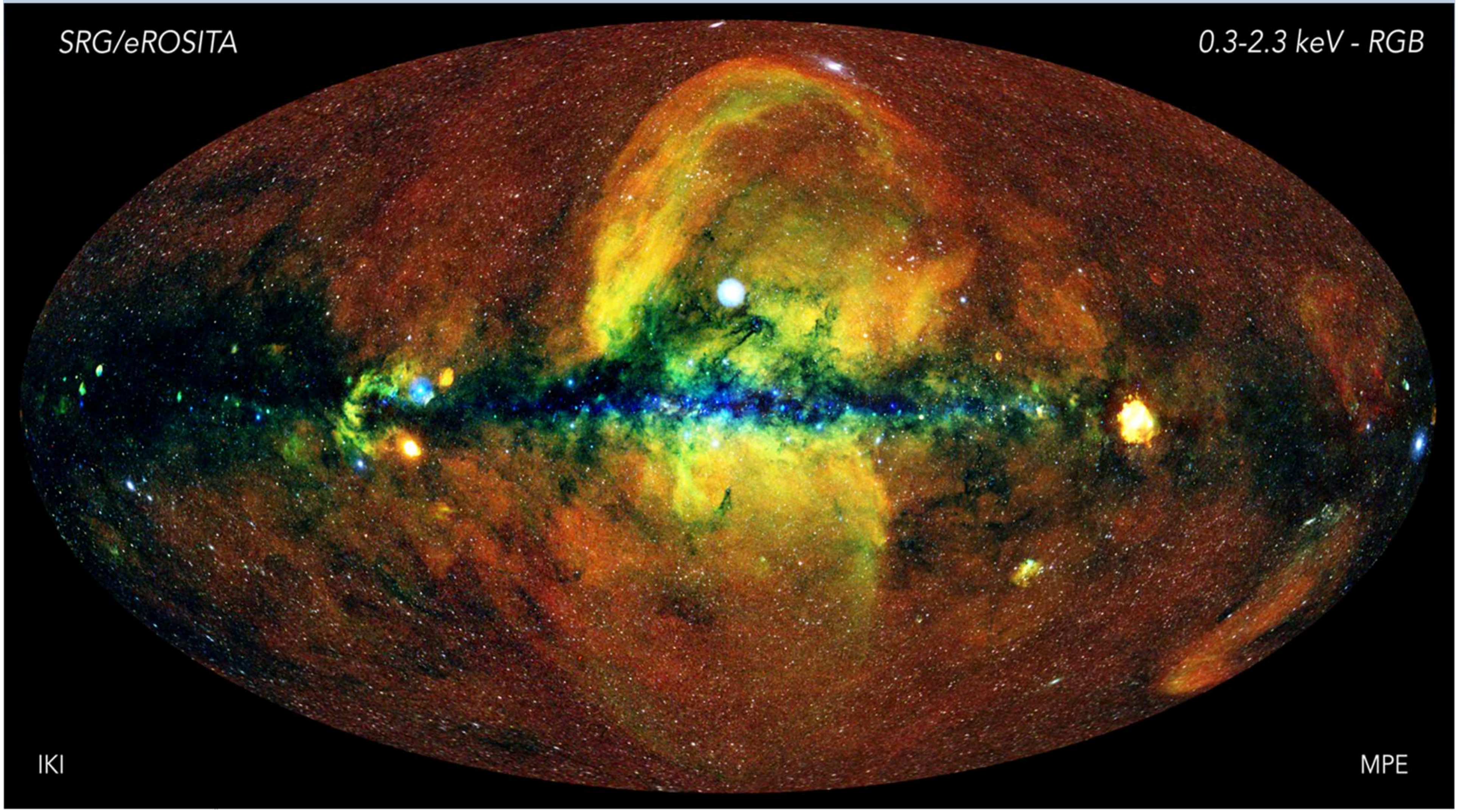
- Time variability constrains size-scales, magnetic activity (e.g., flares), accretio models, stochastic nature of systems
  - Via Fourier and spectral-timing techniques: PDS spectra, reverberation, lag-spectra, et
- Outflows, winds, and X-ray plasmas (column, ionization, abundance, warm absorbers, density, temperature, launch mechanism & speed)
- Thermal features provide size constraints (spin, etc.)
- Nonthermal emission, power-law and reflection components, constrains size-scales, geometry of coronae, jets (spin, abundances, accretion variation, jet/coronal geometry)

NICER: LMXB outbursts



The next big thing: eROSITA

- A sensitive hard X-ray instrument on-board Spectrum-Röntgen-Gamma satellite (Russian – German collaboration
- Most sensitive survey yet of the entire sky (will survey 8 times over 4 years)



References/Acknowledgements

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- *The Universe in X-rays:* Joachim E. Trümper & Günther Hasinger (eds). Springer (2008).

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