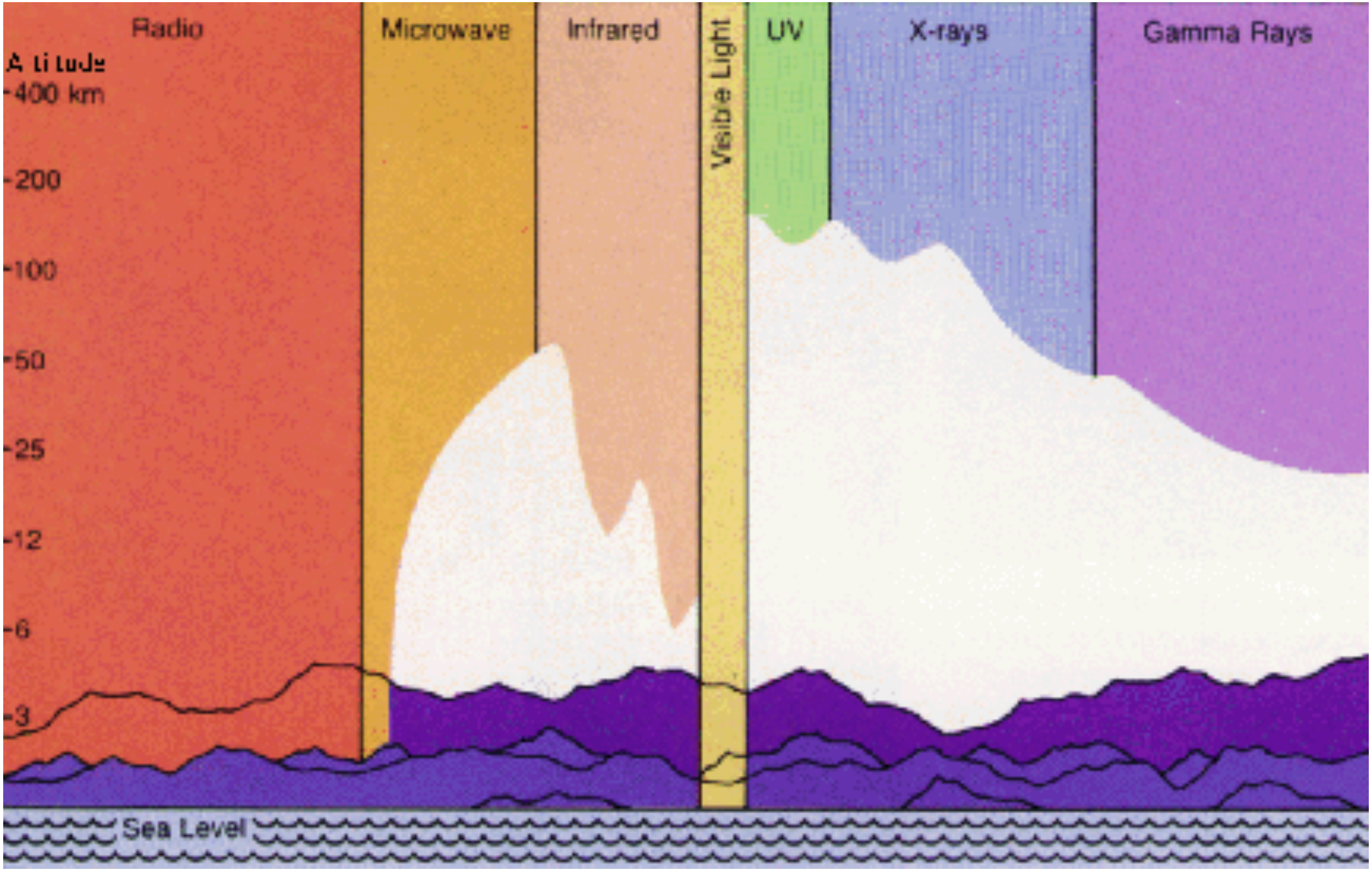
X-ray astronomy

Peter Wheatley

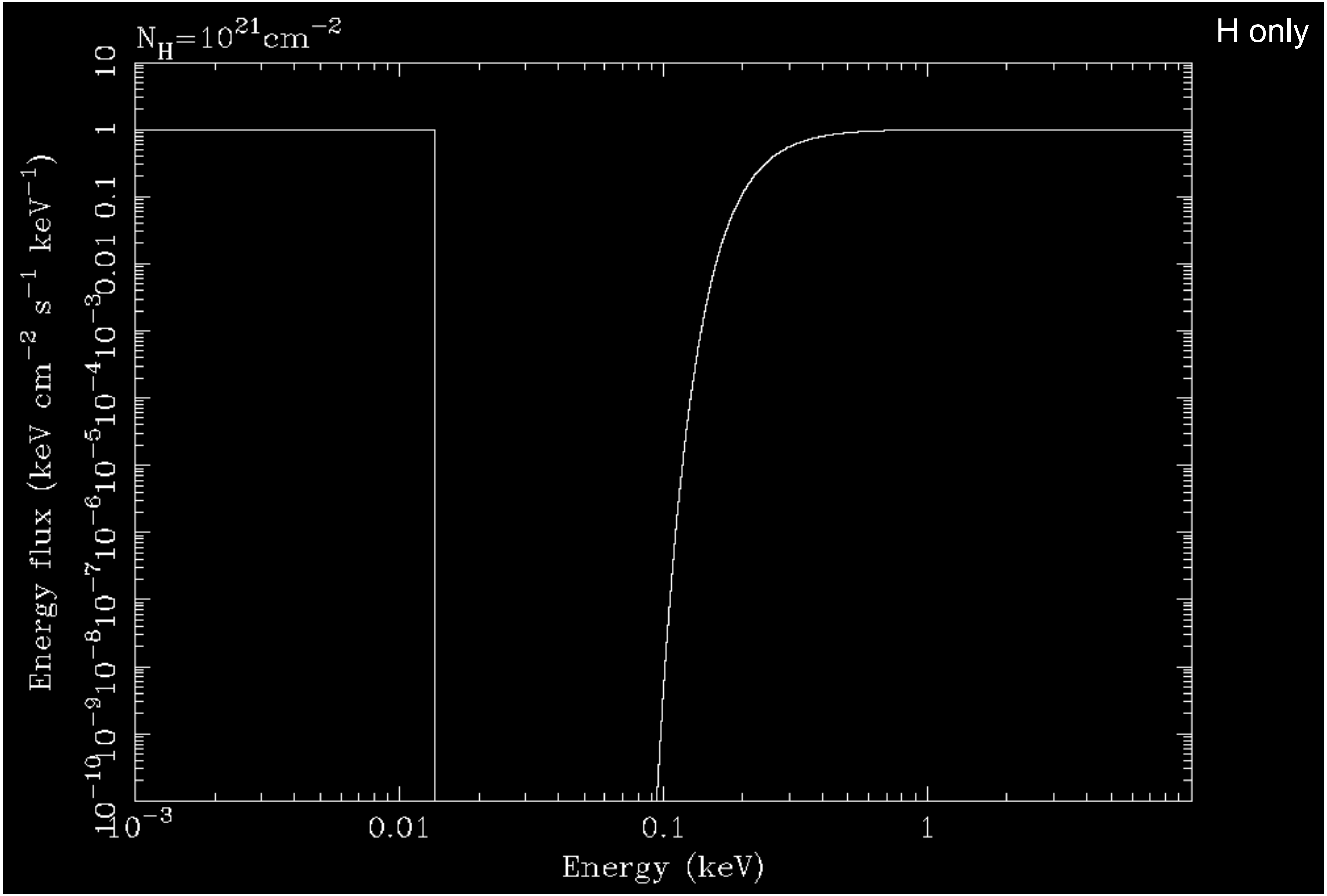
Outline

- Introduction
- X-ray emission processes
- Instrumentation
- Practicalities

Multi-wavelength astronomy

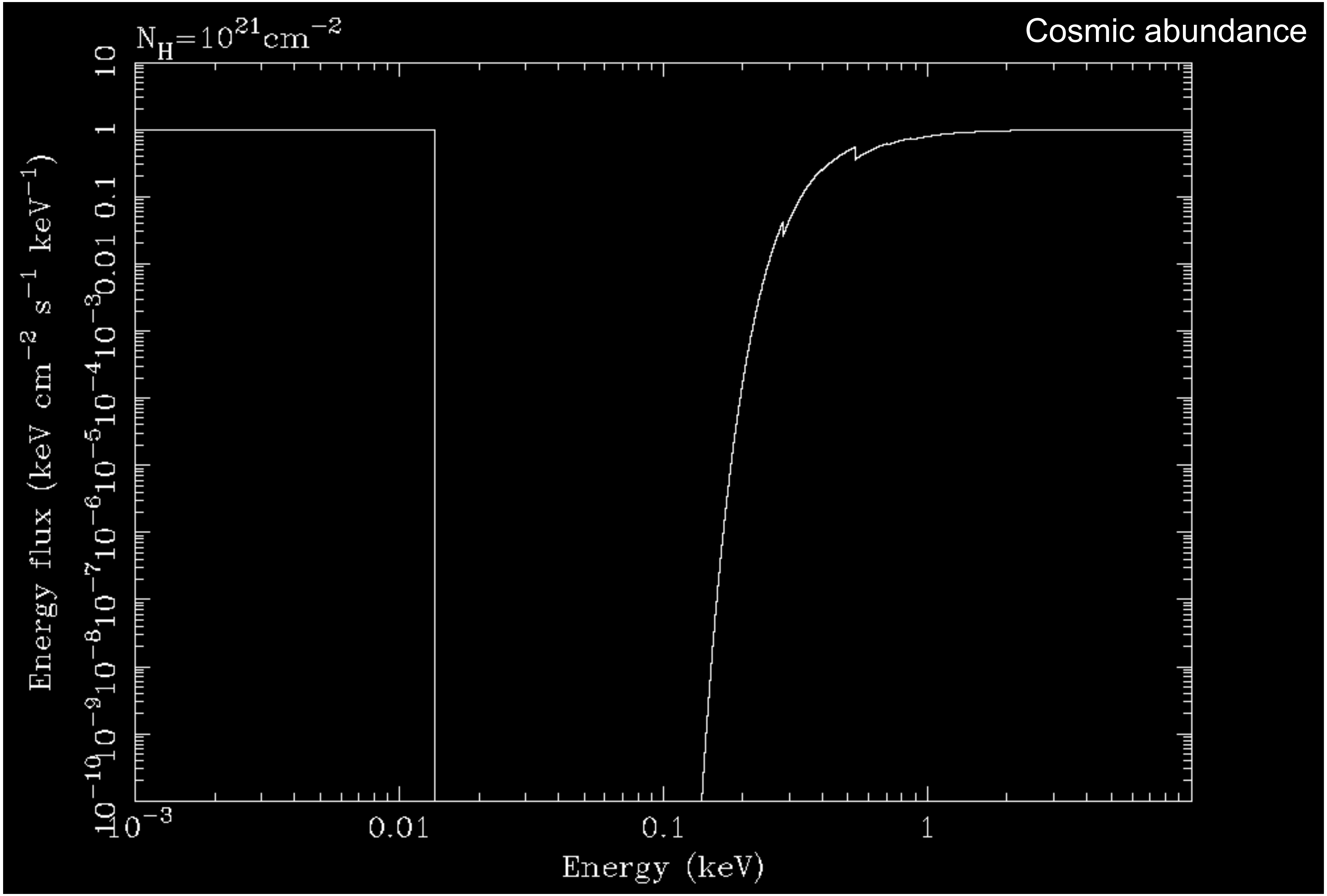


UV / EUV / X-ray



N_H=10^21 cm^-2
H only
Energy flux (keV cm^-2 s^-1 keV^-1)
10
1
0.1
0.01
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-3
0.01
0.1
1
Energy (keV)

UV / EUV / X-ray



$N_H = 10^{21} cm^{-2}$
Cosmic abundance
Energy flux (keV cm^{-2} s^{-1} keV^{-1})
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
10^{-3}
0.01
0.1
1
Energy (keV)

X-ray emission

- X-rays in range 0.1-100 Angstroms or more usually 0.1-100 keV
  - Useful to remember that 100 A = 124 eV
  - 13.6-100 eV is extreme-ultraviolet (EUV)
  - >~100 keV is gamma rays
  - Low/high energy corresponds to *soft/hard* X-rays

- Thermal emission
  - $E = hc/\lambda \sim kT$ (for any thermal process)
  - So for emission at 3 Angstrom, $T \sim 10^7$ K

Compared with optical/IR

- Count rates are low
  - Each photon has ~1000x energy, so 1000x fewer photons for same energy flux
  - Effective area of X-ray telescopes tends to be small (e.g. XMM is ~0.1m^2)
  - So data tends to be Poisson dominated

- X-ray detectors tend to give time, energy and location of each photon
  - Can collapse *event lists* to images, light curves or spectra
    - Or combinations thereof

- Fluxes often quoted in standard bands (cf BVRIZ bands), e.g.
  - E.g. 2-10keV
  - Typical units of erg s^{-1} cm^{-2}
  - Sometimes in Crabs or mCrabs !

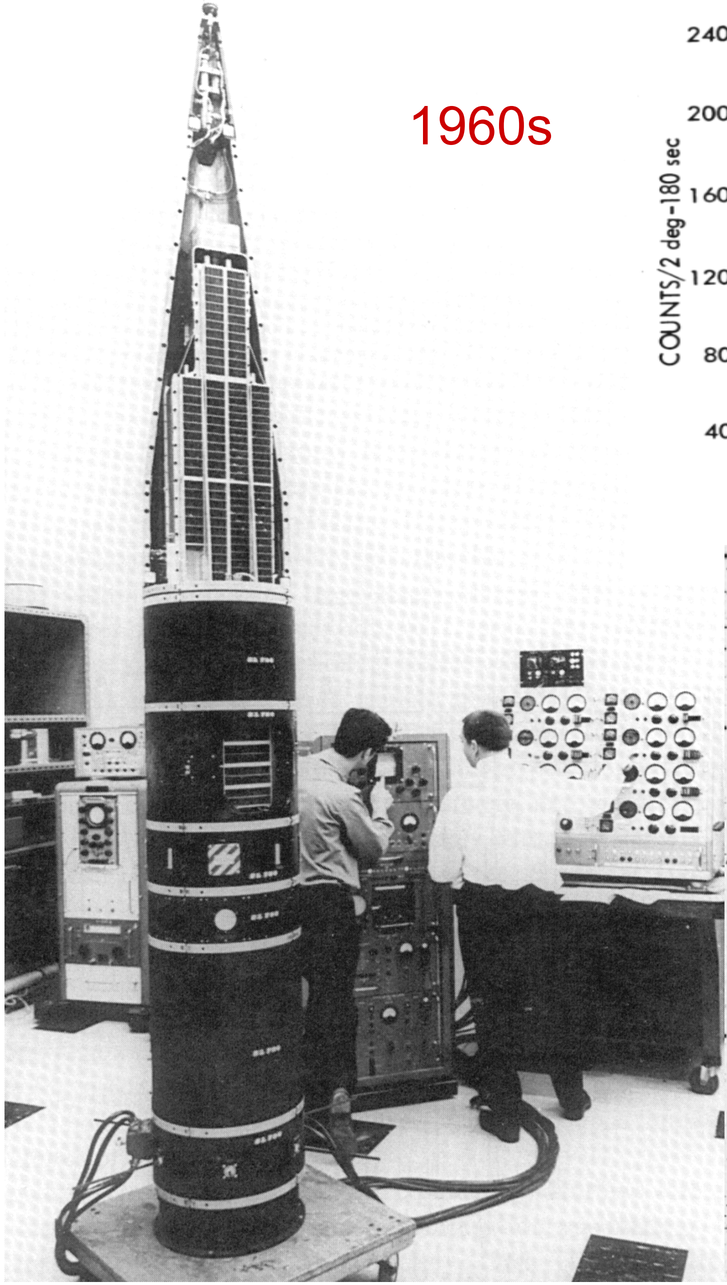
Early X-ray astronomy

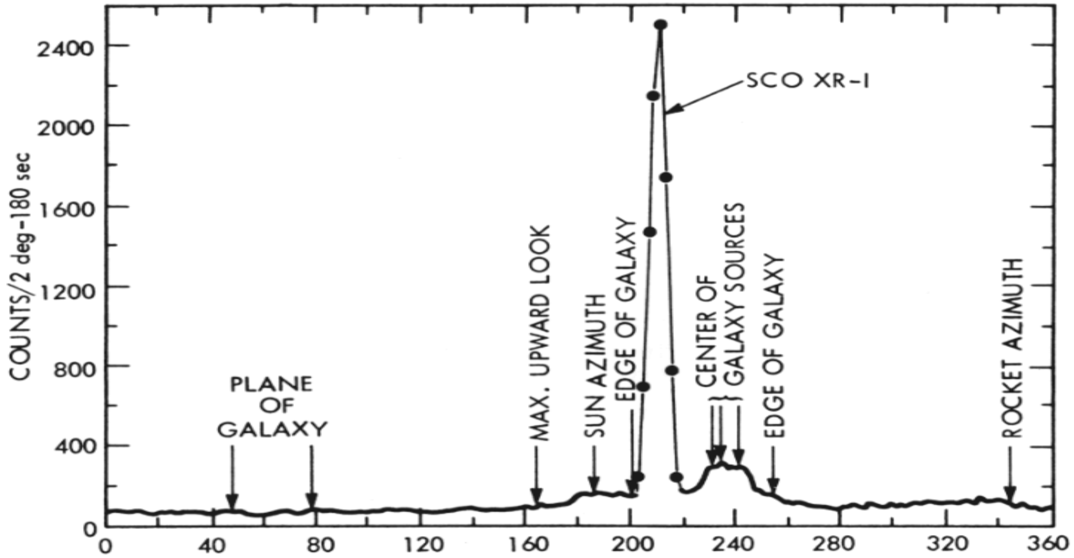
1960s

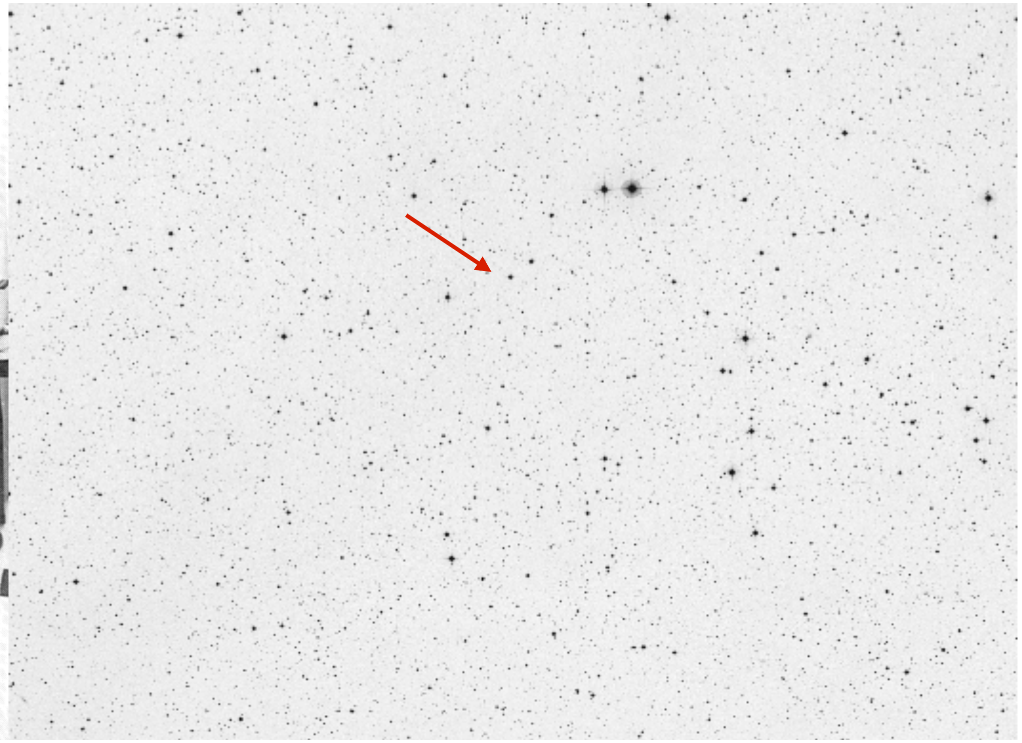
- Sun detected in 1950s, but luminosity implied other stars would be too faint
- 1962: Sco X-1 discovered while searching for scattered X-rays from Moon

Early X-ray astronomy

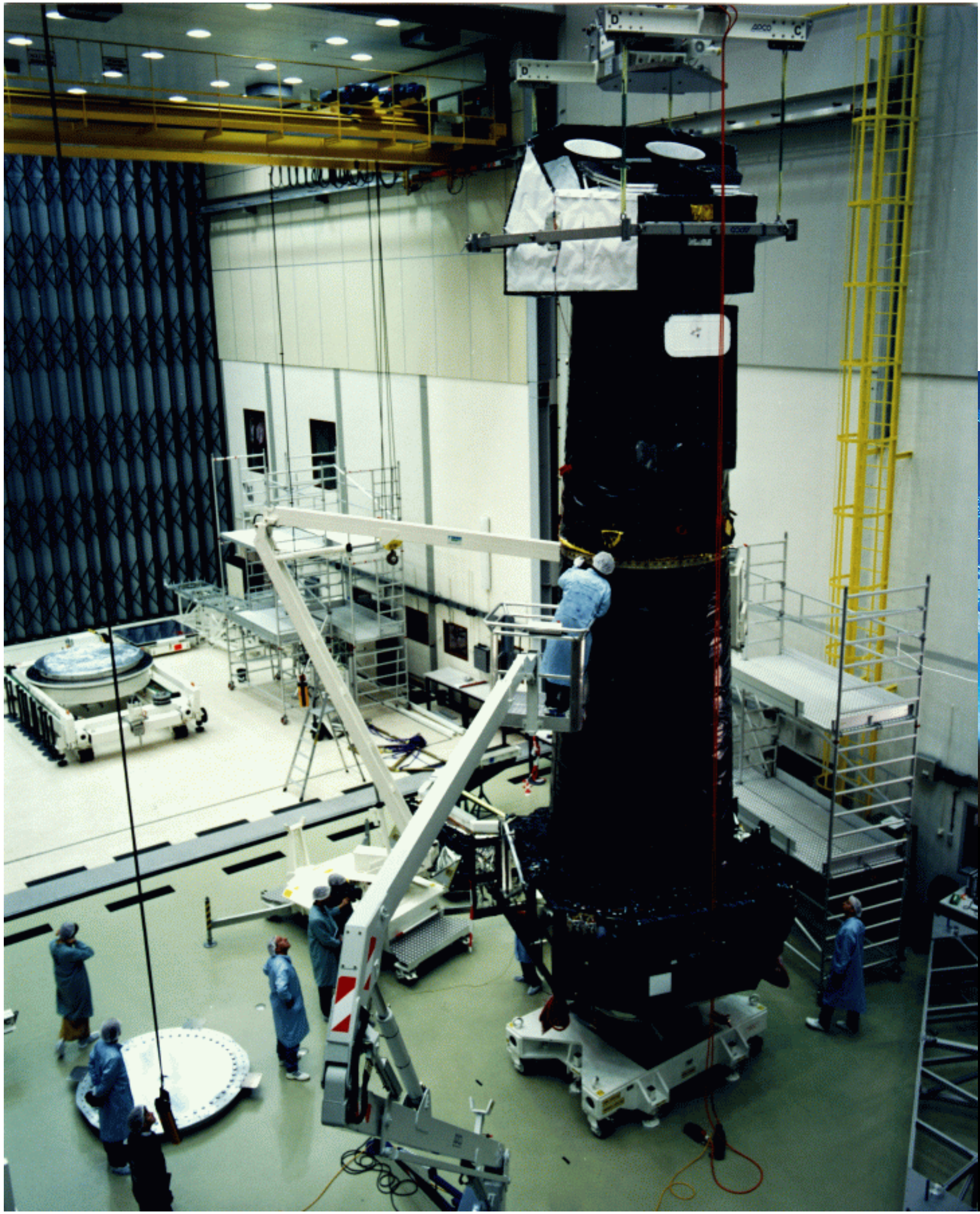
1960s







Modern X-ray astronomy



XMM-Newton

Chandra

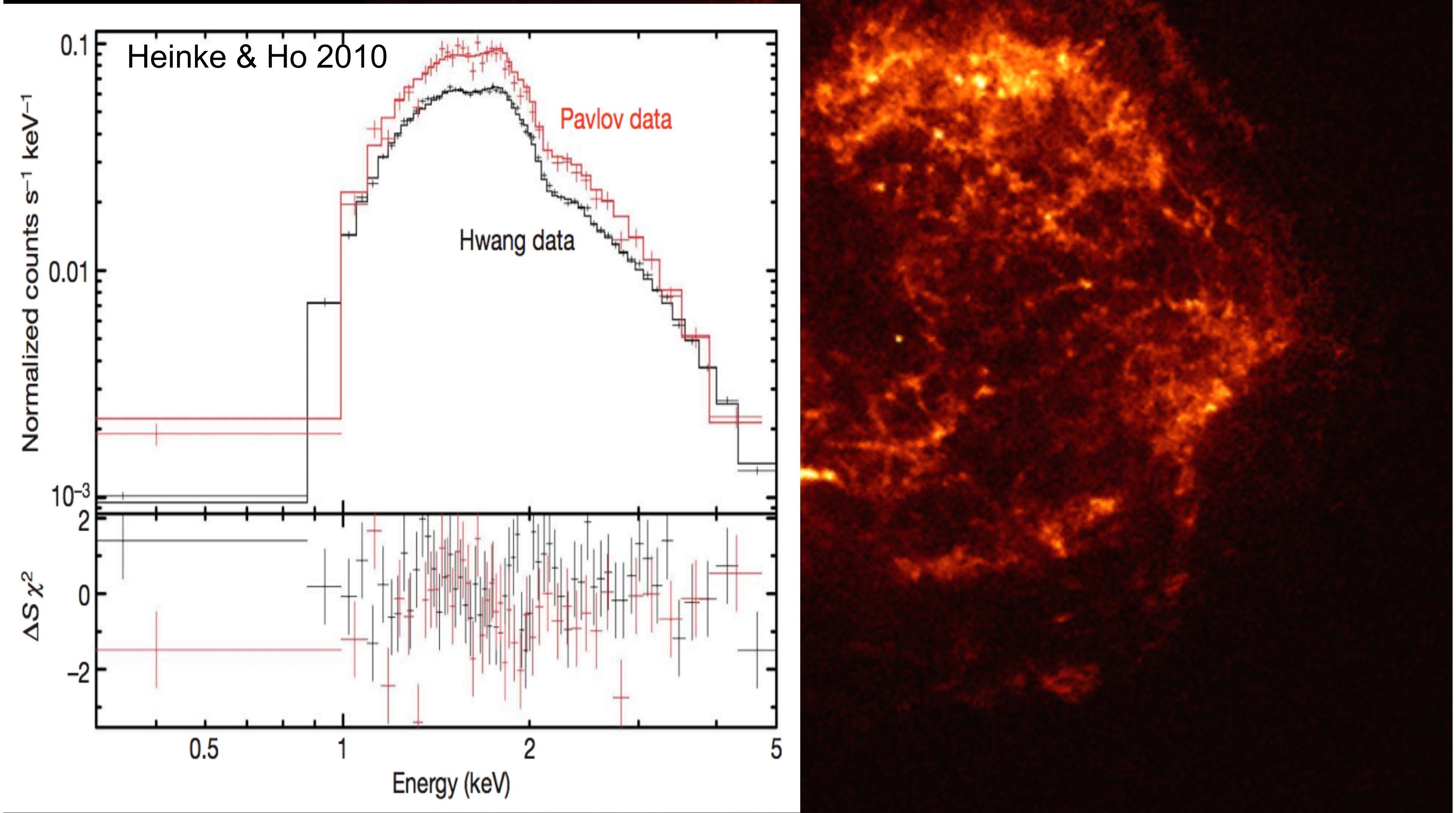
X-ray processes

Optically-thick thermal emission

- Black-body emission (modified by atmospheric opacities)
- Wien's displacement law: $T = 0.0029 / \lambda_{peak}$
  - For 100 A, T = 300,000 K
  - For 0.1 A, T = 300,000,000 K
- But temperatures cannot exceed Eddington limit
  - $T^4 \leq g\, m_p\, c / \sigma_T\, \sigma$
  - So high temperatures require high surface gravity

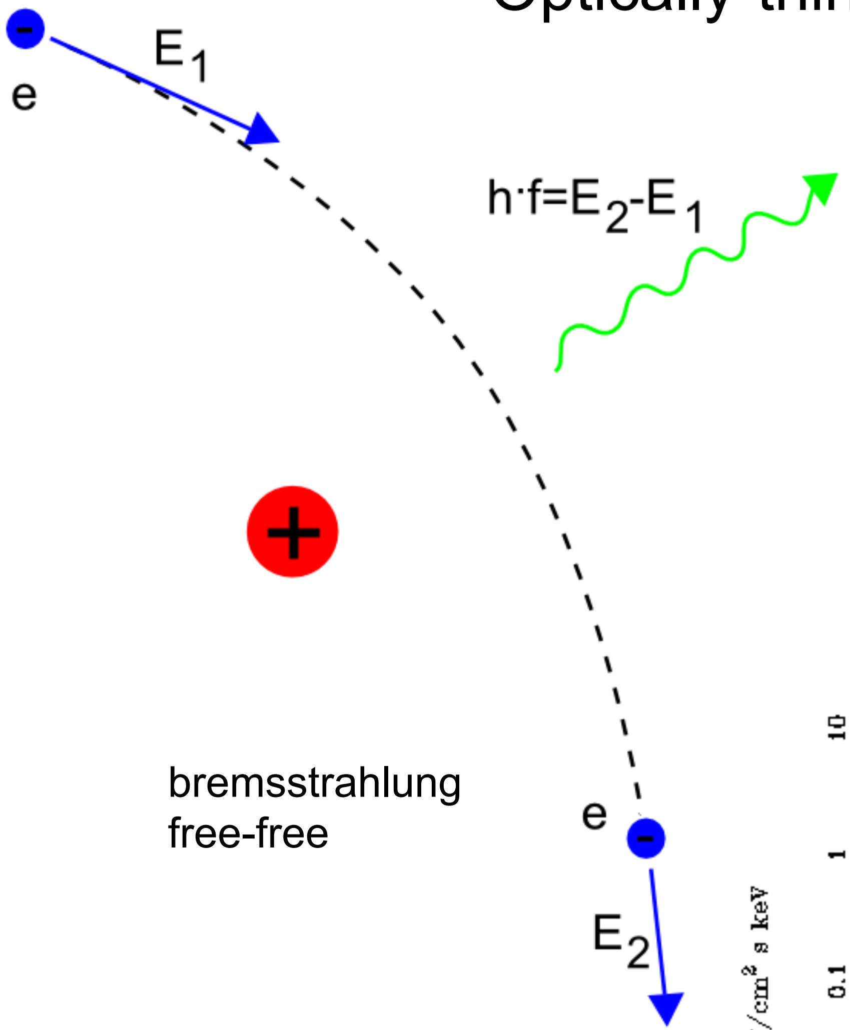
  - For Sun, T_{Edd}= 80,000 K
  - For WDs, T_{Edd}~ 500,000 K, so can be supersoft/ultrasoft X-ray sources
  - For NSs and stellar mass BHs, T_{Edd}~ 20,000,000 K, can be X-ray sources
  - For supermassive BHs, T_{Edd}~ 300,000 K, so can only be EUV sources

Thermal emission from a young NS in a Supernova remnant



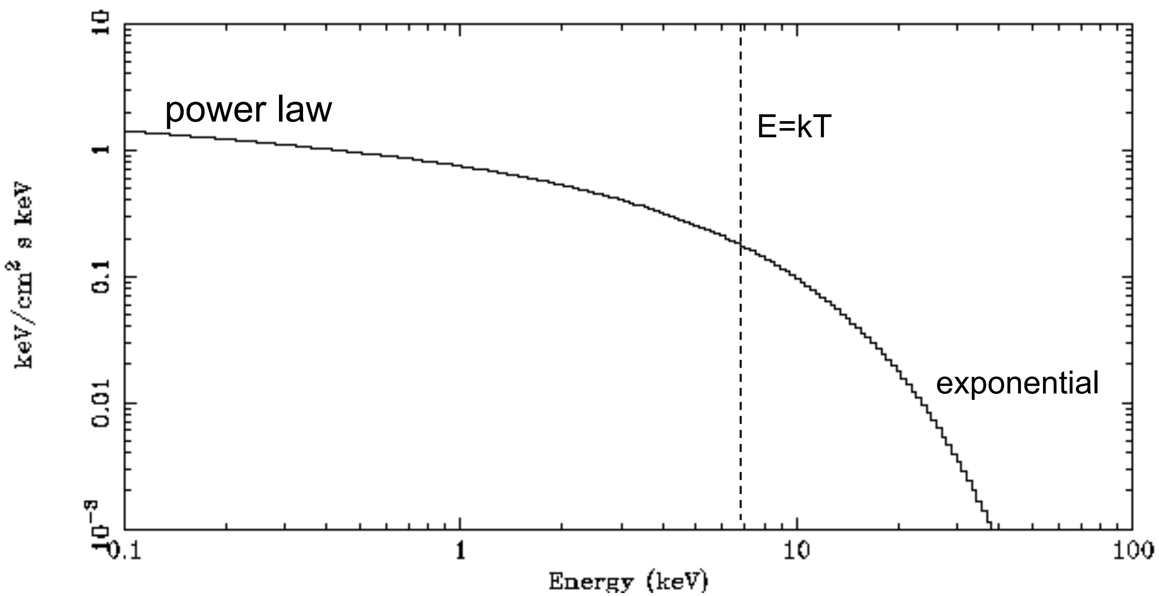
Cas A

Optically-thin thermal emission

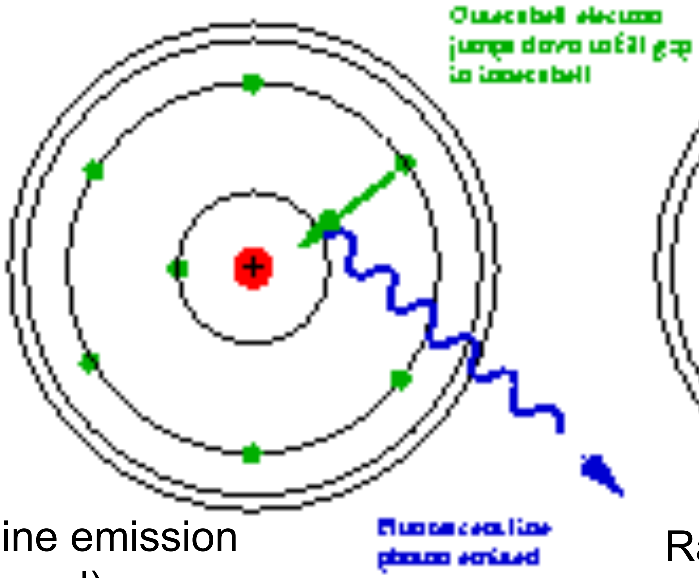


bremsstrahlung
free-free

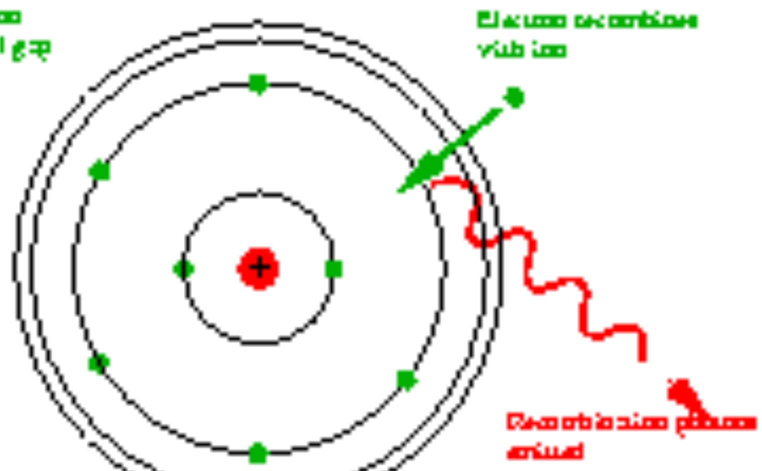
- $L \propto T^{1/2} n_e n_i Z^2$
  - luminosity increases only slowly with T
  - low density plasma can cool on v long timescales



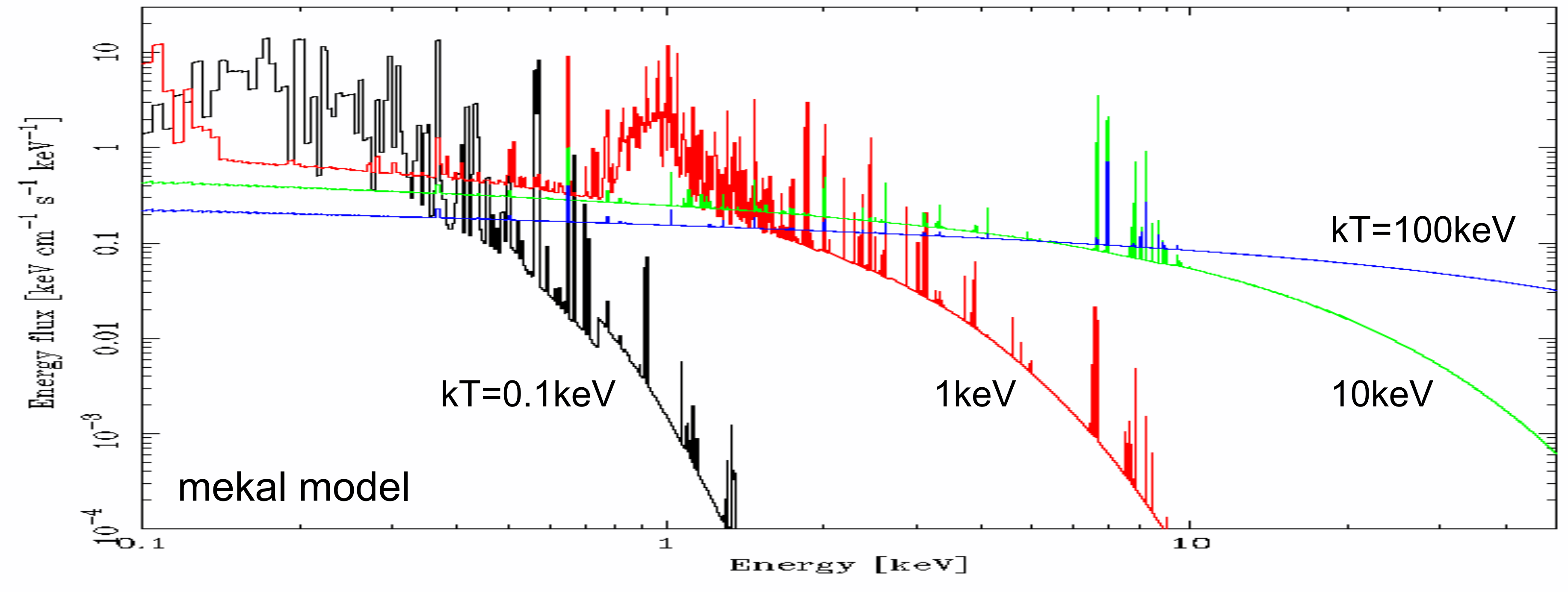
Optically-thin thermal emission



Thermal line emission
(bound-bound)



Radiative recombination (free-bound)



X-ray atomic energy levels

X-ray atomic energy levels (eV)

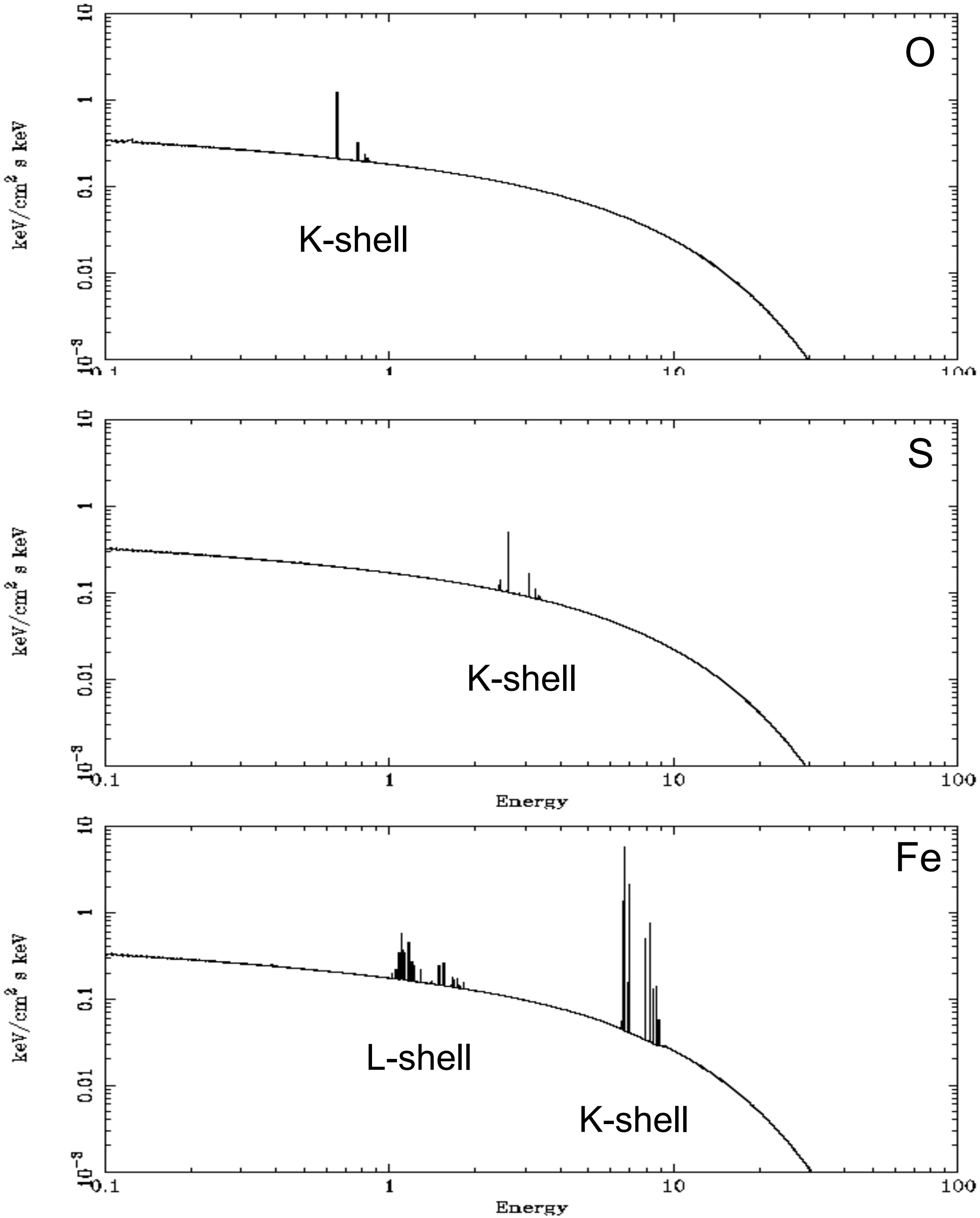
Z	element	K	L_I	$L_{II,III}$
1	H	13.598		
2	He	24.587		
3	Li	54.75		
4	Be	111.0		
5	B	188.0		4.7
6	C	283.8		6.4
7	N	401.6		9.2
8	O	532.0	23.7	7.1
9	F	685.4	31	8.6
10	Ne	866.9	45	18.3
11	Na	1072.1	63.3	31.1
12	Mg	1305.0	89.4	51.4
13	Al	1559.6	117.7	73.1
14	Si	1838.9	148.7	99.2
15	P	2145.5	189.3	132.2
16	S	2472.0	229.2	164.8

Z	element	K	L_I	L_{II}	L_{III}	M_I	$M_{II,III}$	$M_{IV,V}$
17	Cl	2822.4	270.2	201.6	200.0	17.5	6.8	
18	Ar	3202.9	320.	247.3	245.2	25.3	12.4	
19	K	3607.4	377.1	296.3	293.6	33.9	17.8	
20	Ca	4038.1	437.8	350.0	346.4	43.7	25.4	
21	Sc	4492.8	500.4	406.7	402.2	53.8	32.3	6.6
22	Ti	4966.4	563.7	461.5	455.5	60.3	34.6	3.7
23	V	5465.1	628.2	520.5	512.9	66.5	37.8	2.2
24	Cr	5989.2	694.6	583.7	574.5	74.1	42.5	2.3
25	Mn	6539.0	769.0	651.4	640.3	83.9	48.6	3.3
26	Fe	7112.0	846.1	721.1	708.1	92.9	54.0	3.6

Permitted transitions

K series	L series
$K\alpha_1 = K - L_{III}$	$L\alpha_1 = L_{III} - M_V$
$K\alpha_2 = K - L_{II}$	$L\alpha_2 = L_{III} - M_{IV}$
$K\beta_1 = K - M_{III}$	$L\beta_1 = L_{II} - M_{IV}$
$K\beta_3 = K - M_{II}$	
$K\beta_2 = K - N_{II,III}$	

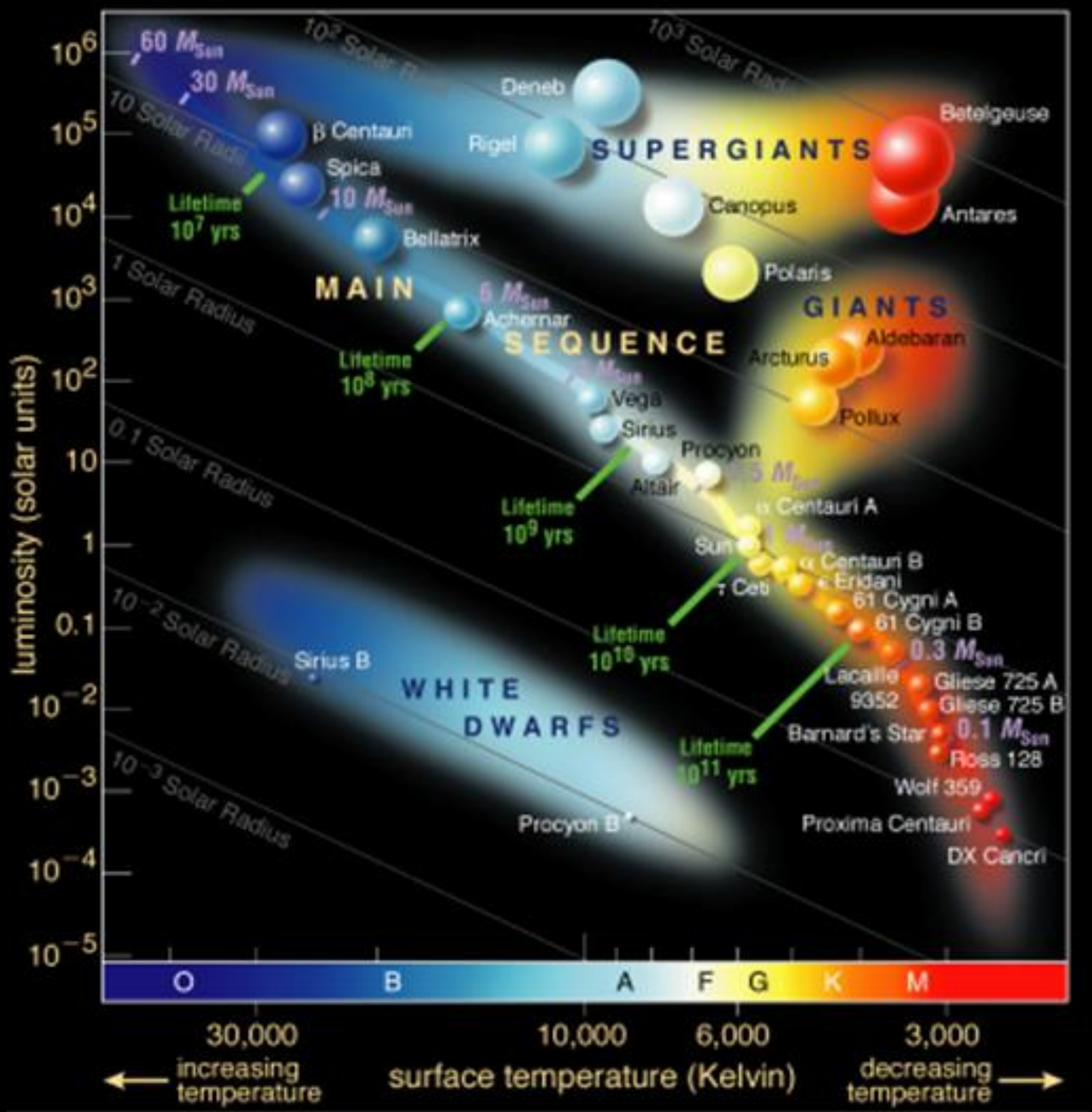
X-ray atomic transitions



Mekal model with individual elements

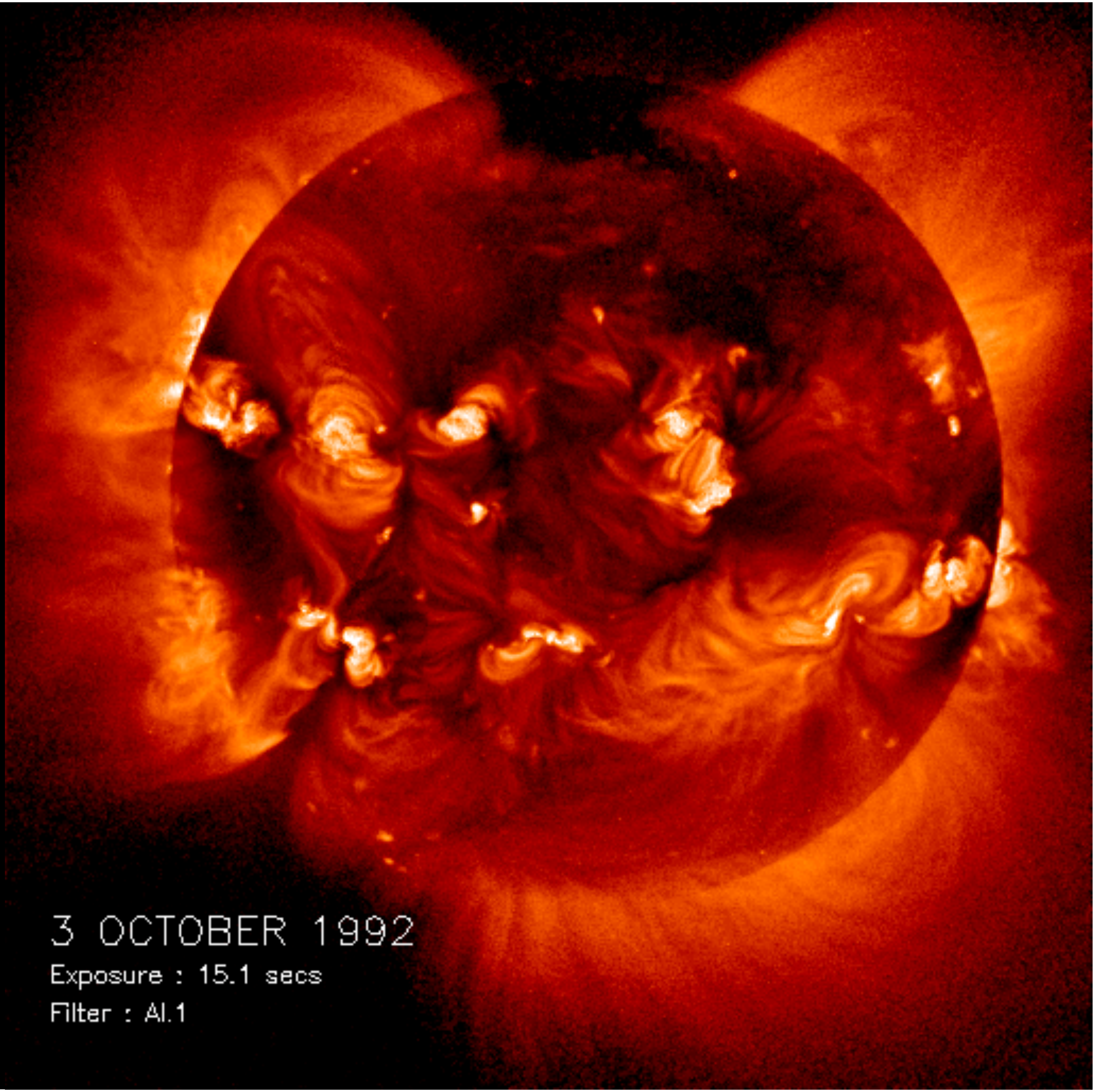
Examples: Stars

:



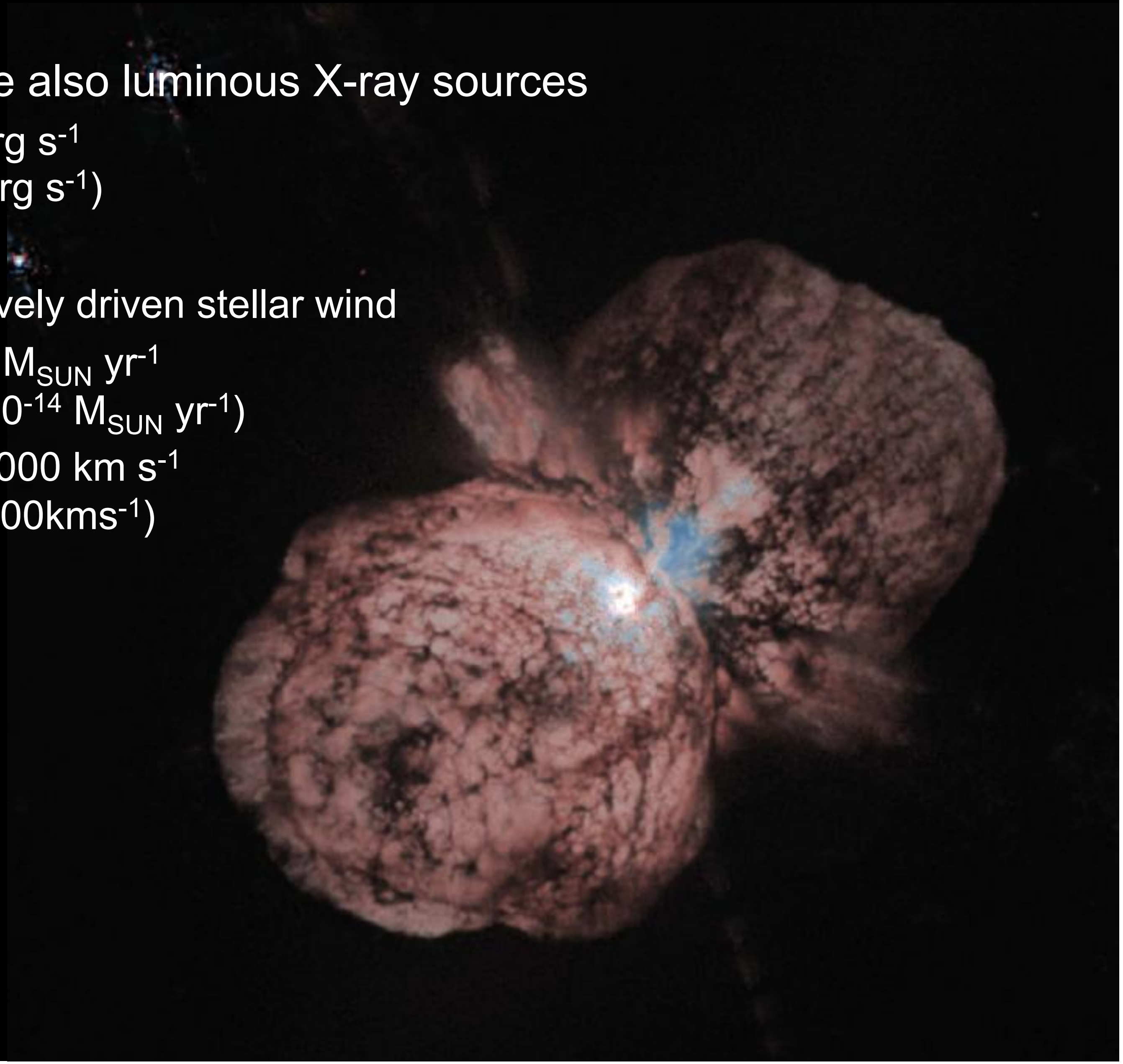
- O - early B STARS
  - $L_x \sim 10^{-7} L_{bol}$
  - little variability
- B - A STARS
  - no X-ray emission
- F - M STARS
  - $L_x \sim 10^{-7}$ - $10^{-3} L_{bol}$
  - highly variable

The Sun
(G-type star)



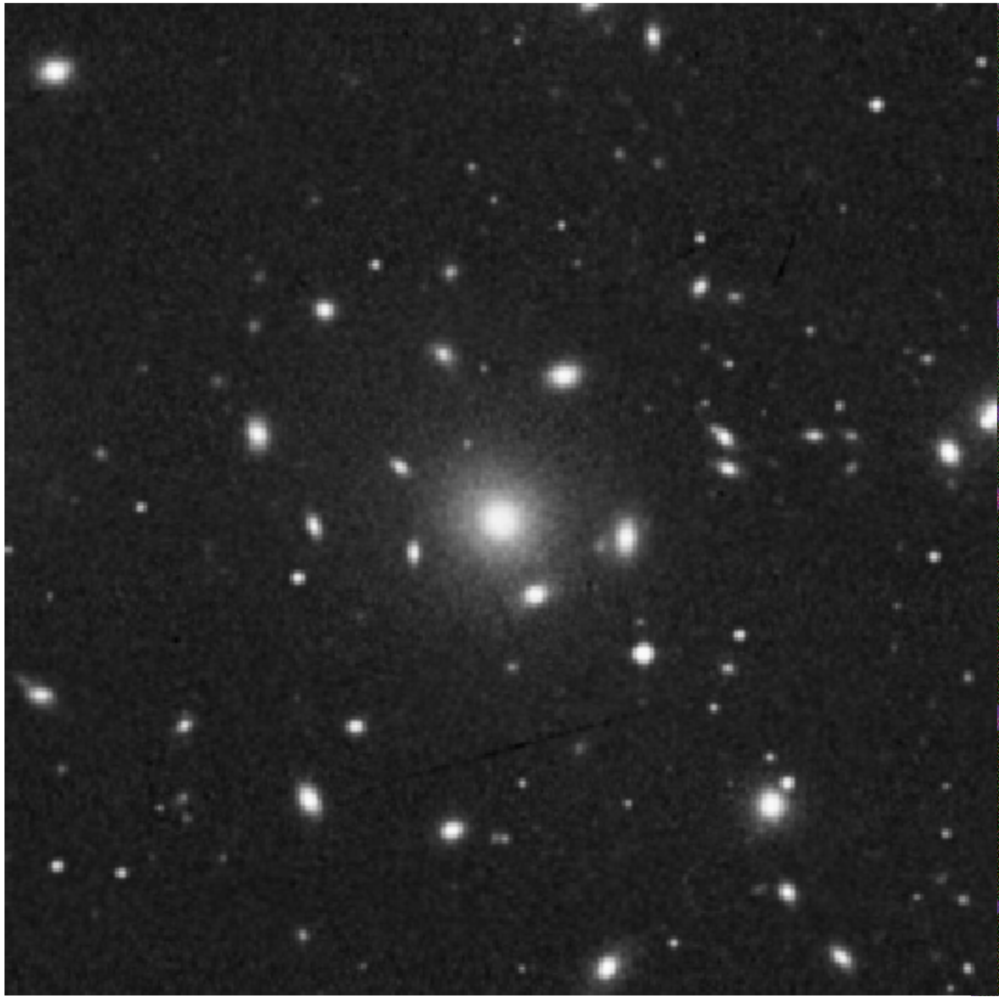
Early type stars

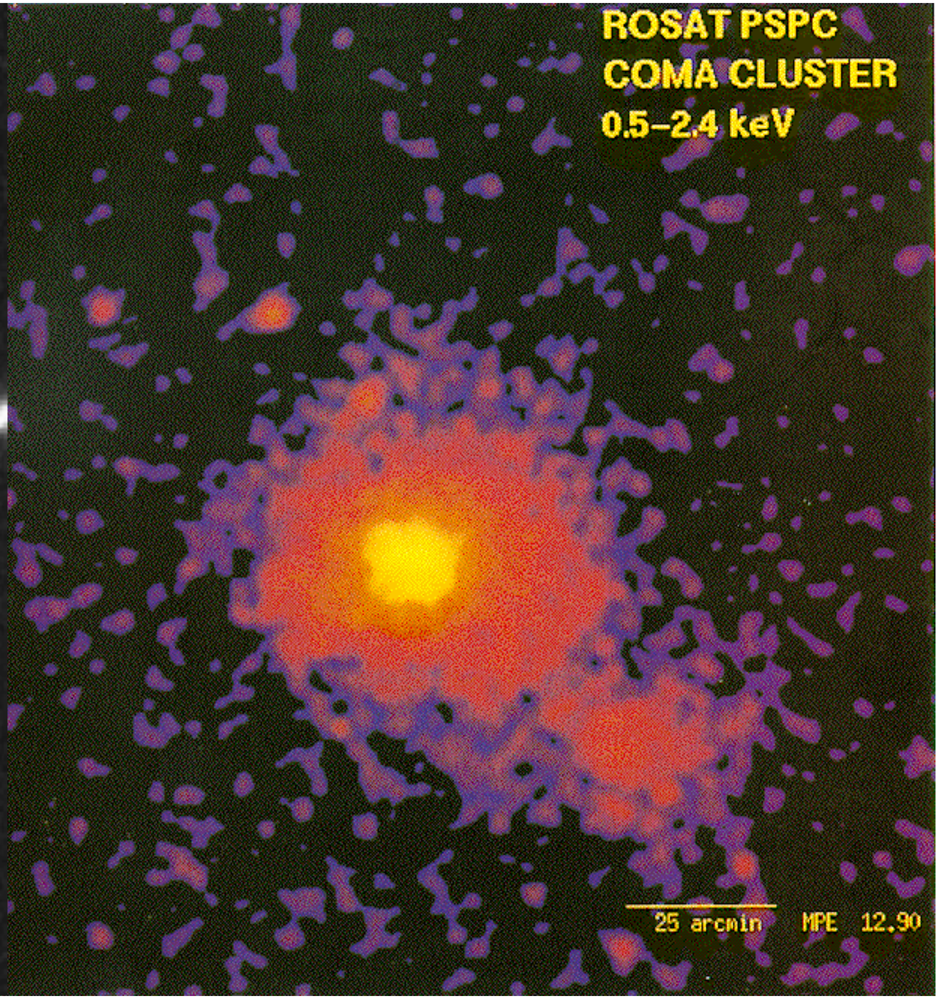
- Early-type stars are also luminous X-ray sources
  - $L_x \sim 10^{31} - 10^{33}$ erg s^{-1}
    (solar $L_x \sim 10^{27}$ erg s^{-1})
  - $L_x/L_{bol} \sim 10^{-7}$
  - Shocks in radiatively driven stellar wind
  - Mass loss $\sim 10^{-6}$ M_{SUN} yr^{-1}
    (The Sun loses 10^{-14} M_{SUN} yr^{-1})
  - wind velocity ~ 3000 km s^{-1}
    (solar velocity~ 300kms^{-1})



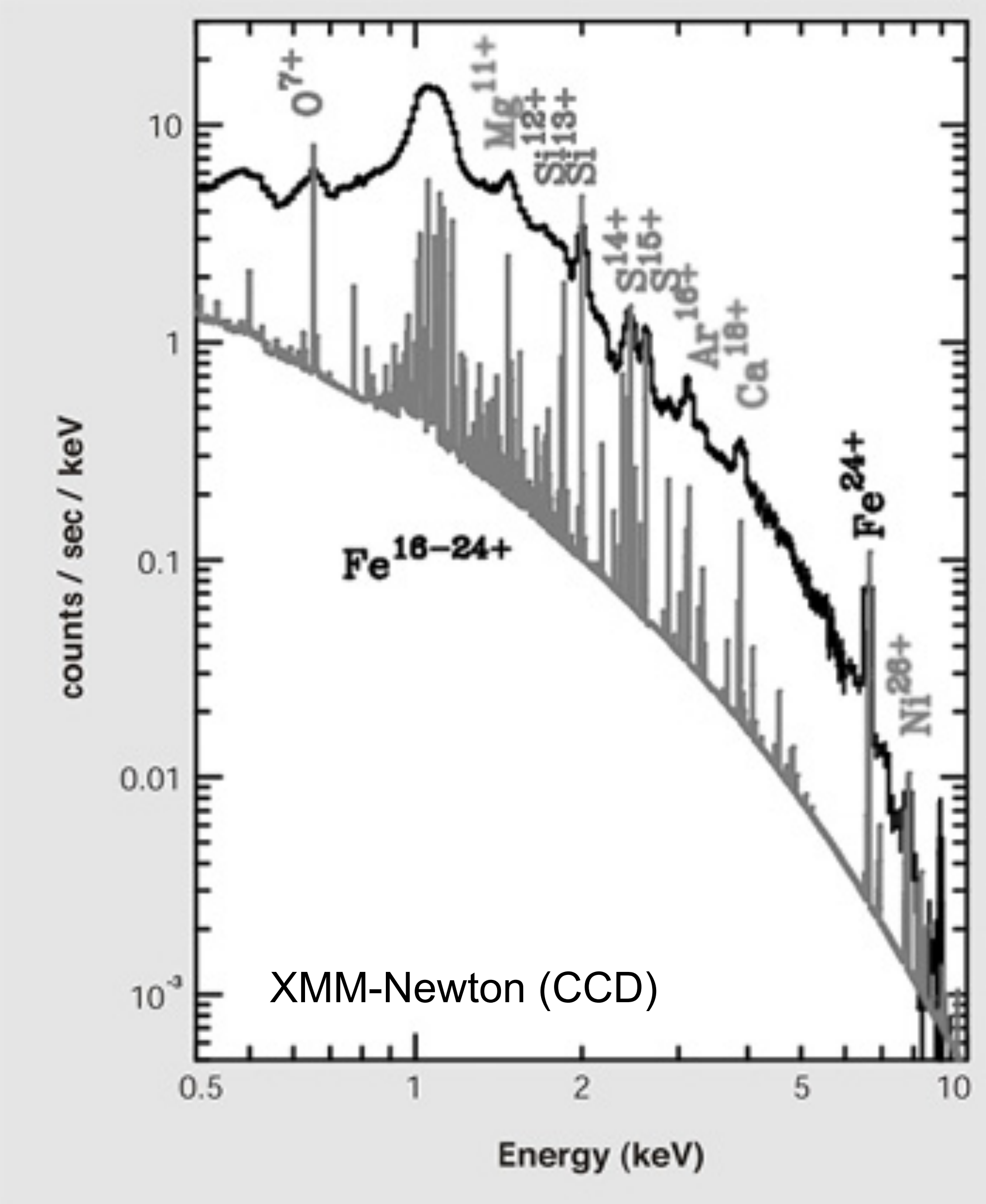
Examples: Clusters of galaxies

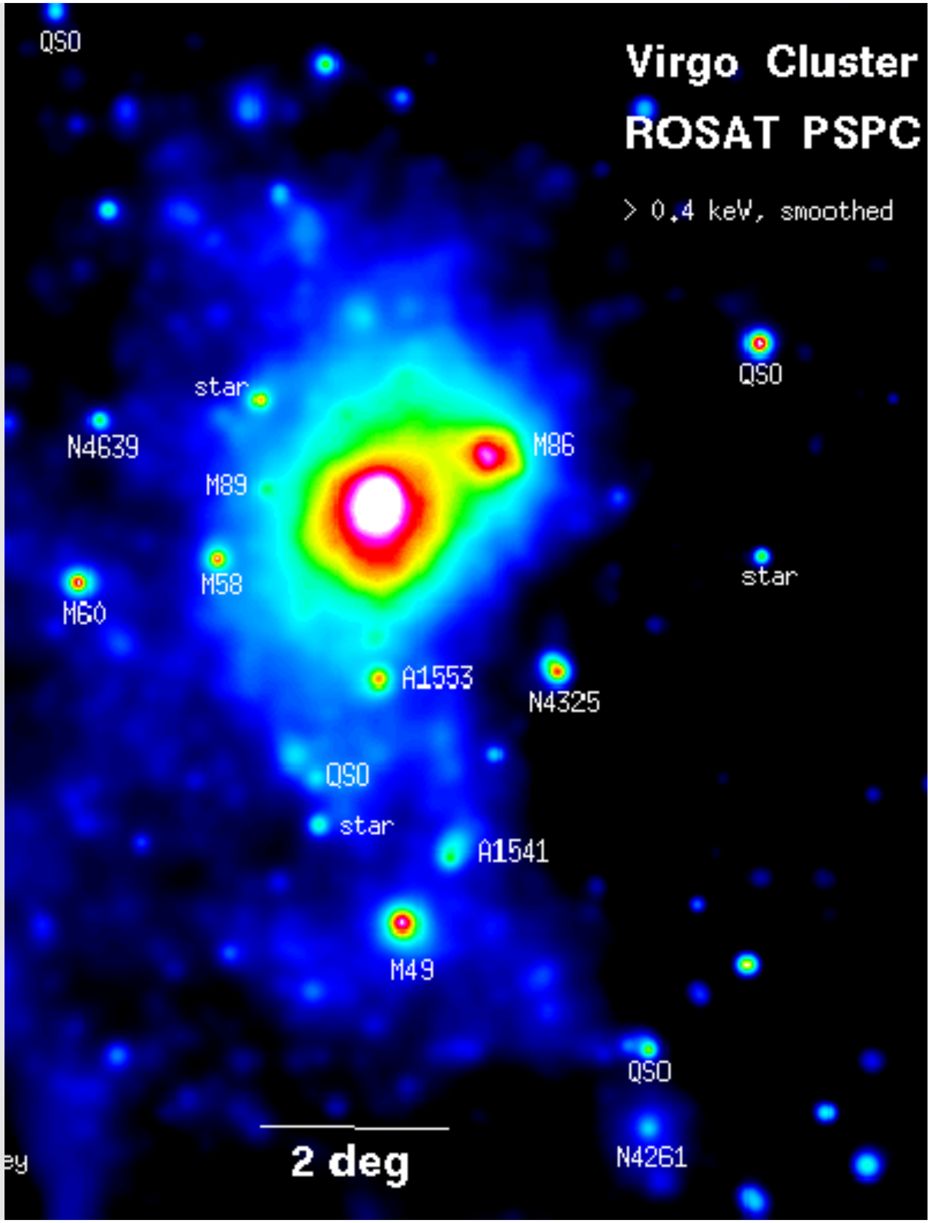
Most baryons in hot gas; cooling time ~ age of Universe





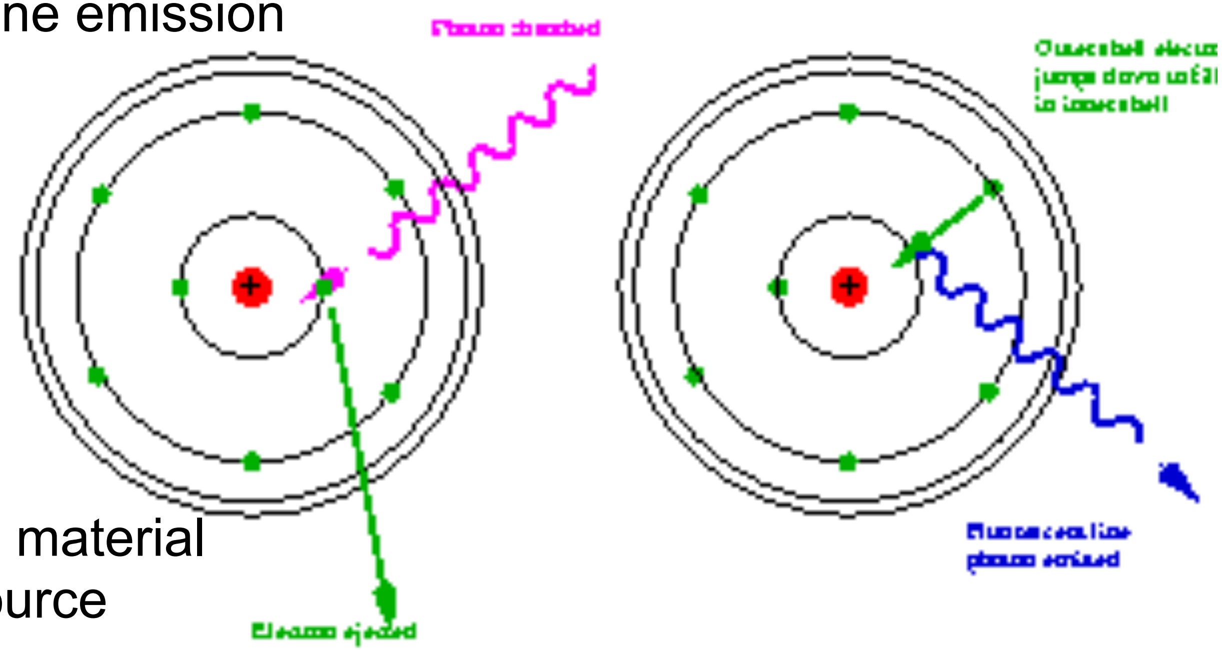
Virgo cluster: thermal emission



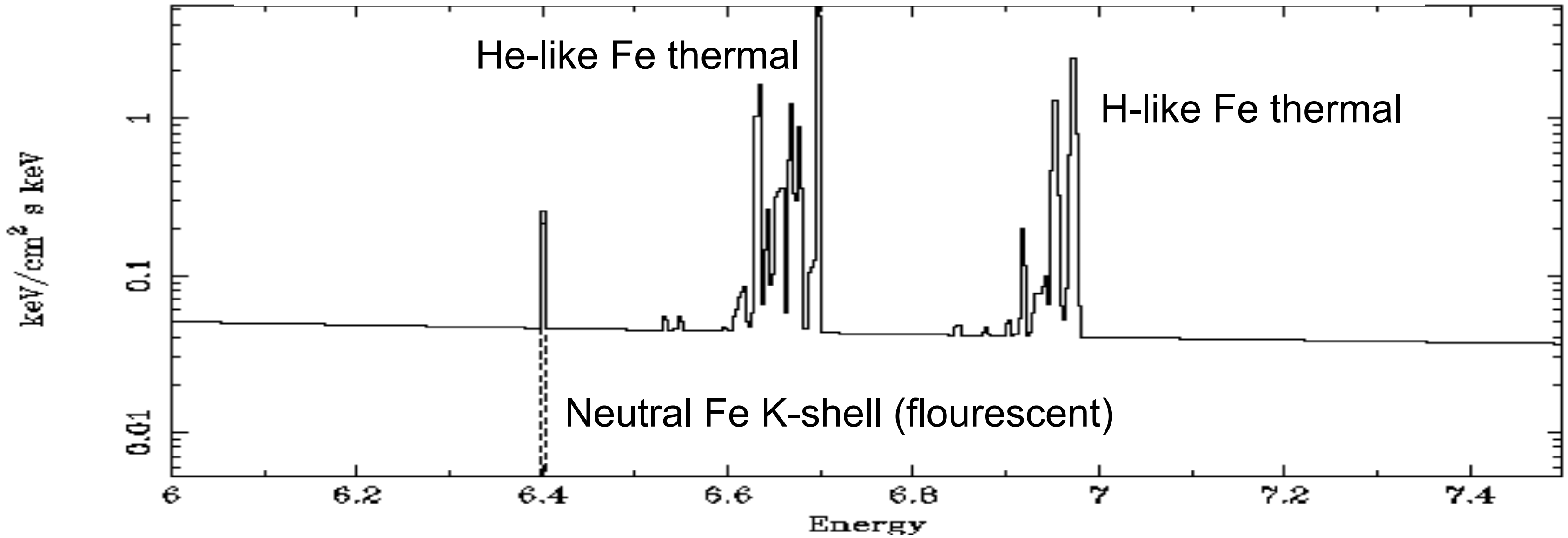


Non-thermal processes

Fluorescent line emission

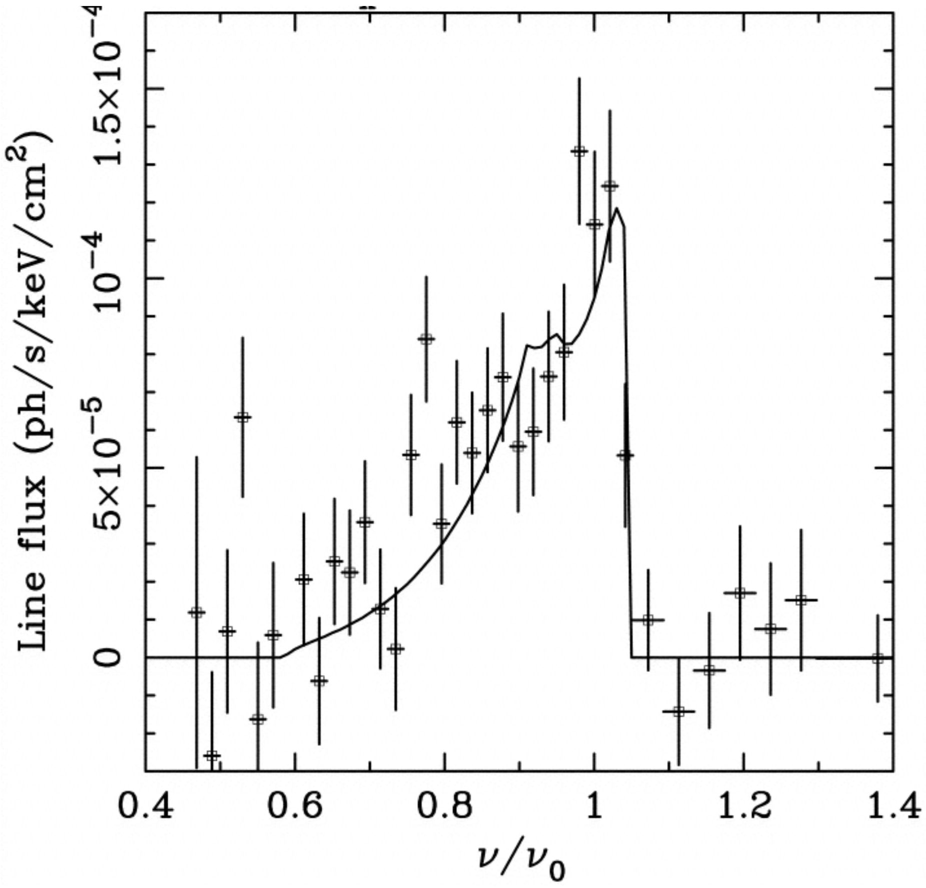


Probes “cold” material
near X-ray source

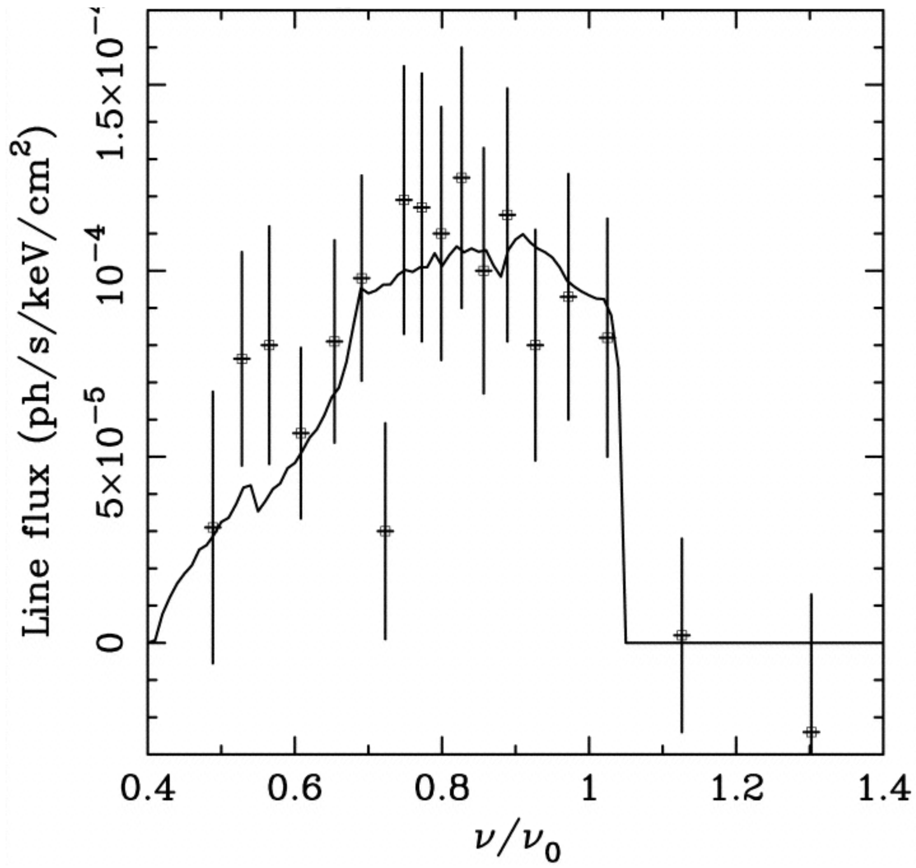


Example: Relativistic line smearing in accretion disc

Schwarzschild black hole model



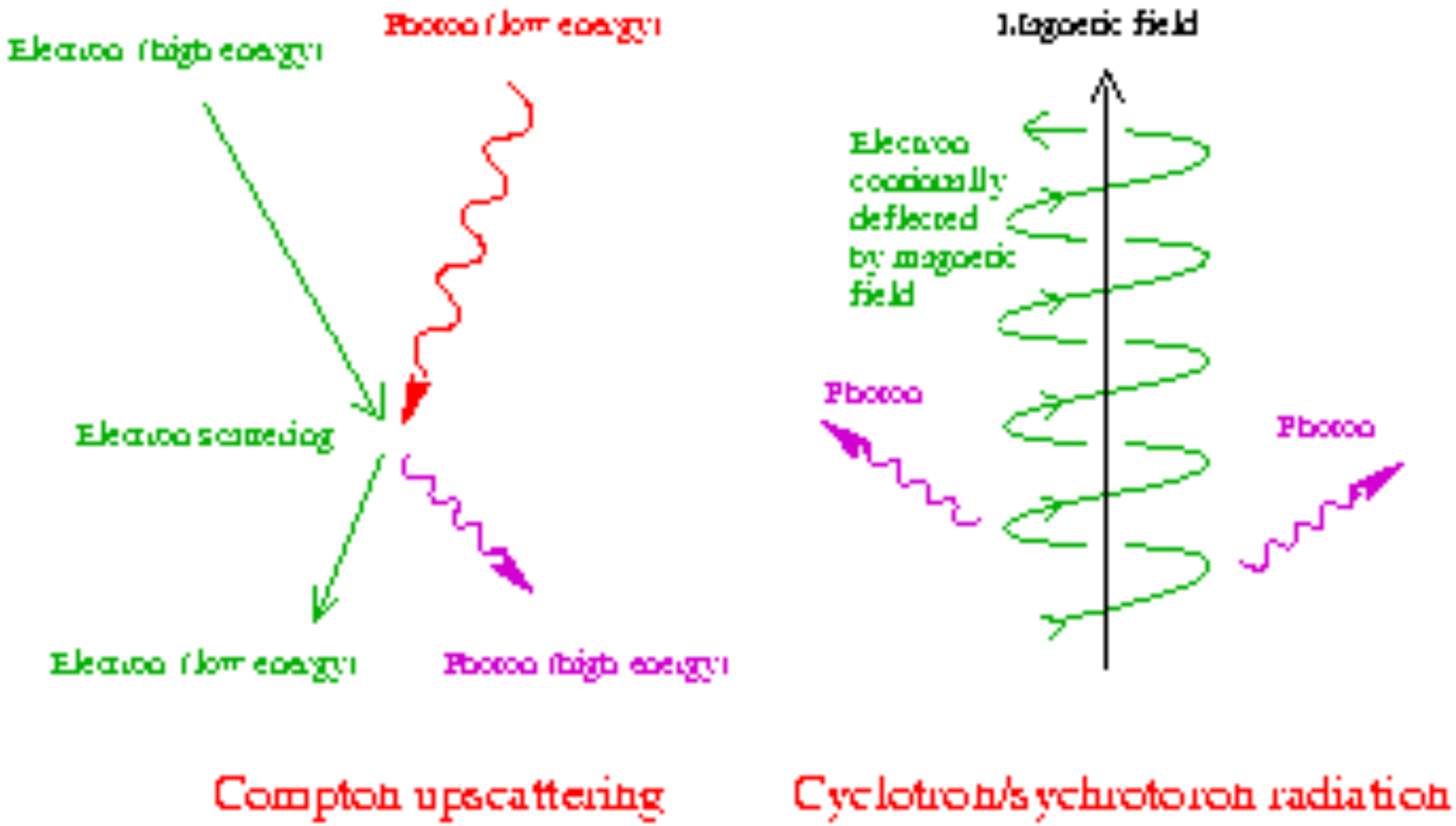
Kerr black hole model



Non-thermal emission processes

Compton upscattering

synchrotron

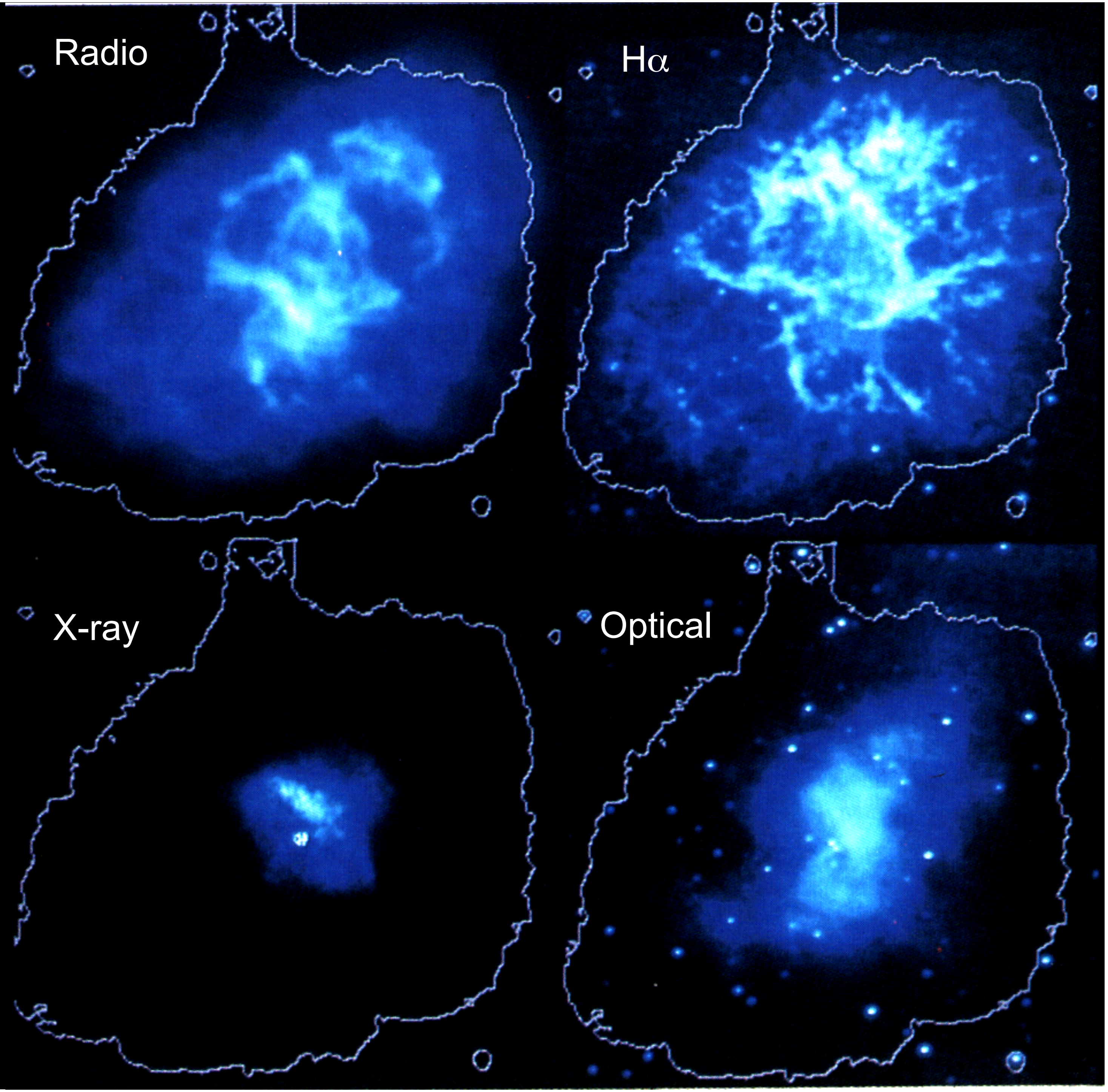


Both require relativistic electrons and typically result in power law spectra. Difficult to determine underlying emission process.

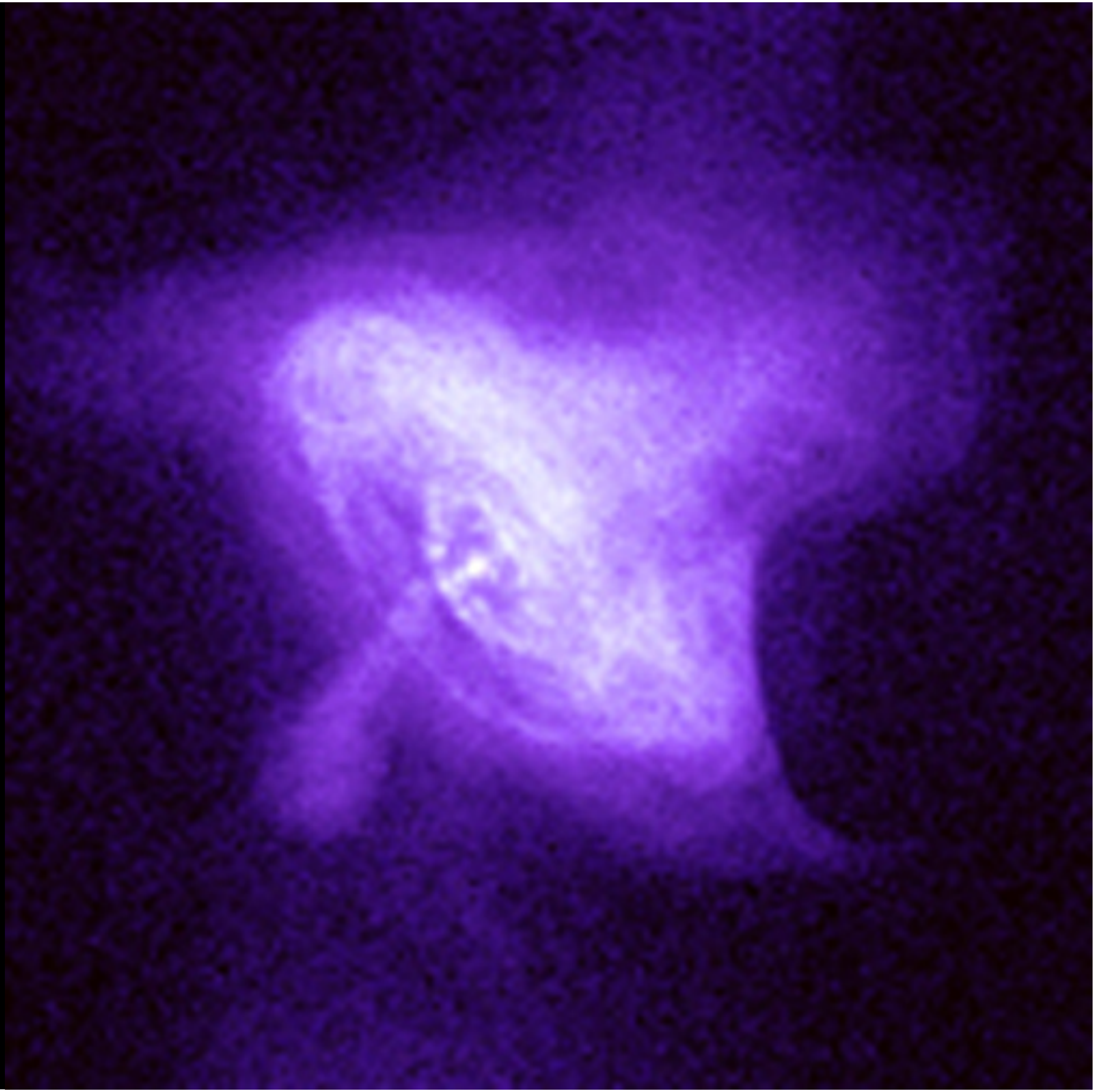
Example:

Crab pulsar

(synchrotron)

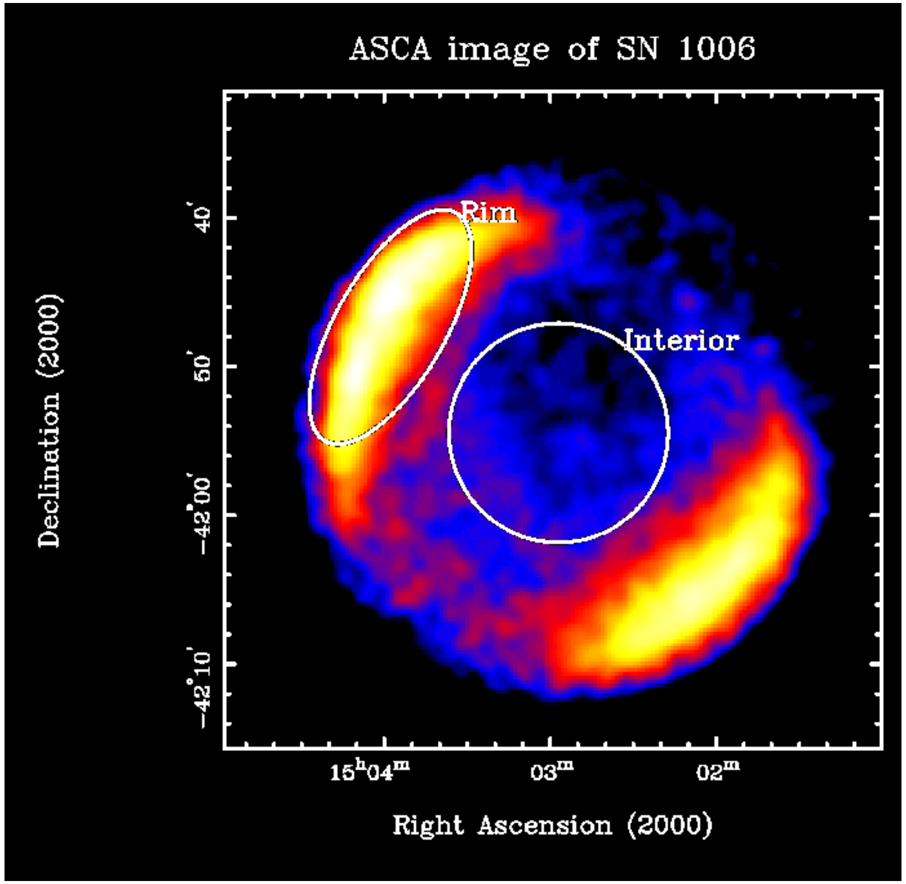


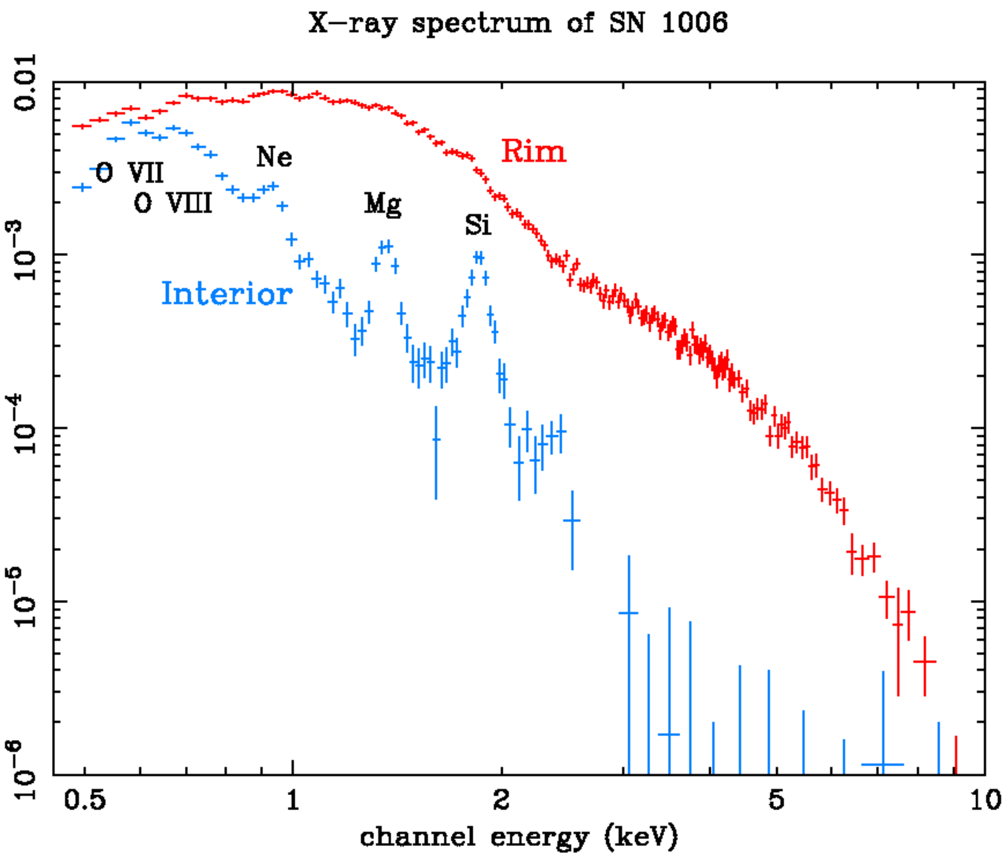
Crab pulsar



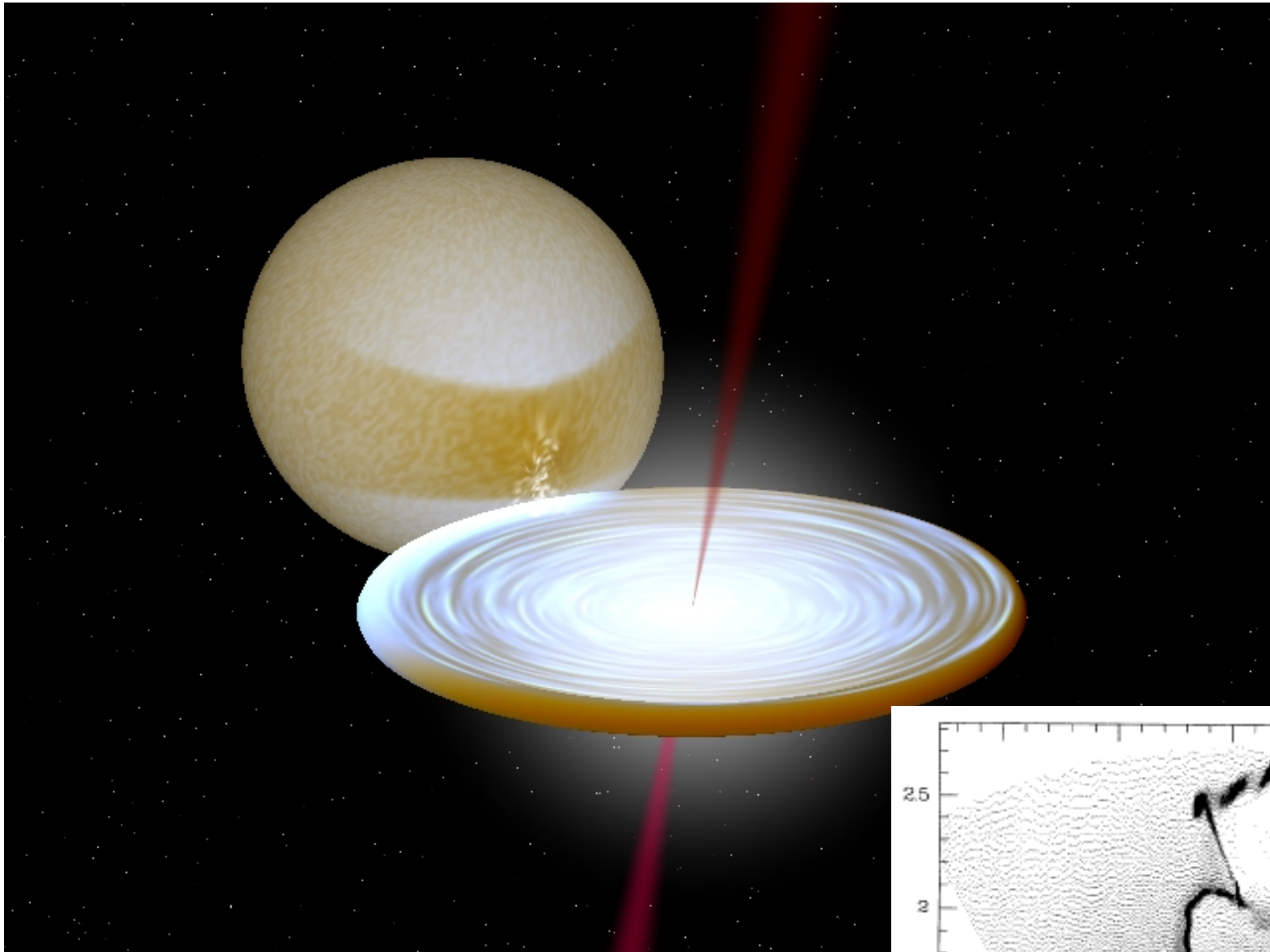
Chandra

SN 1006: thermal and non-thermal X-rays



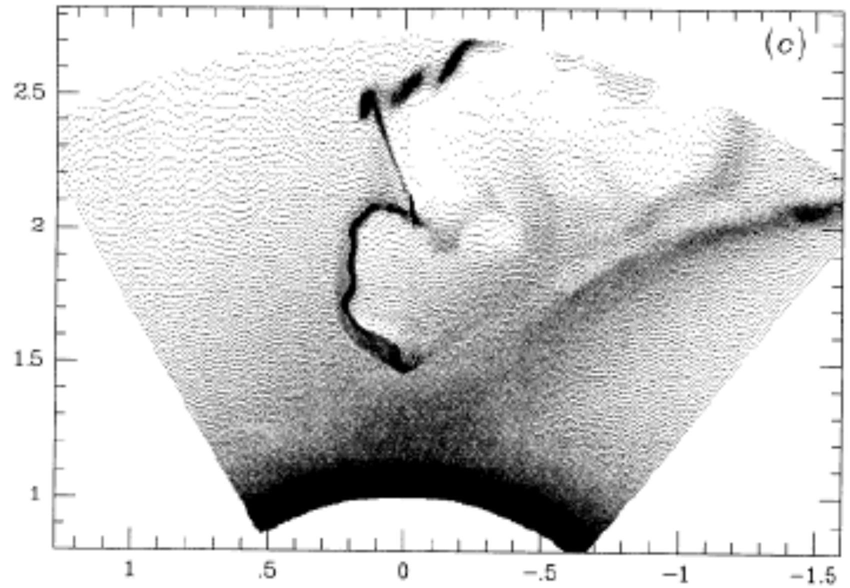


X-ray binaries

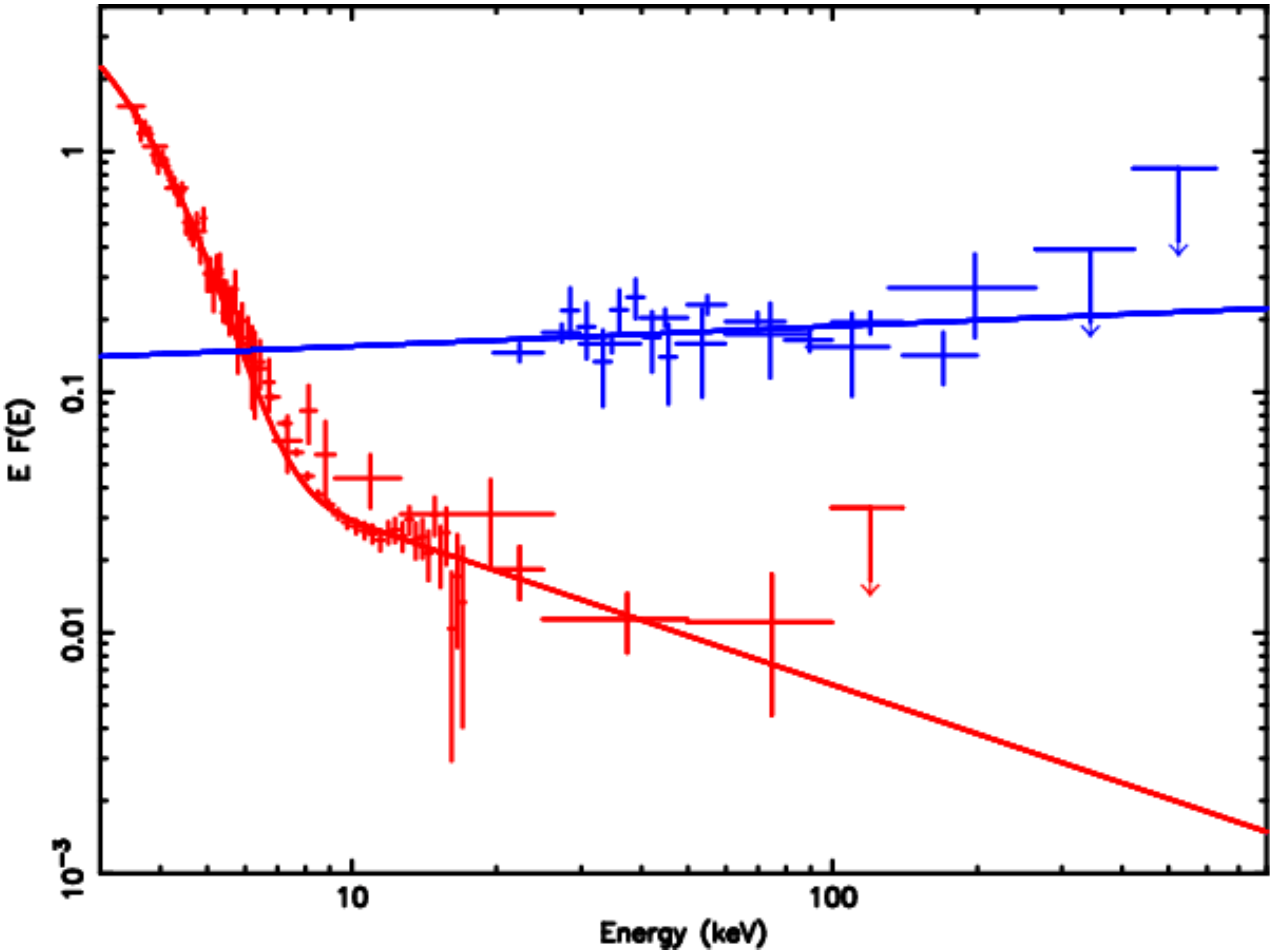


Low mass XRB

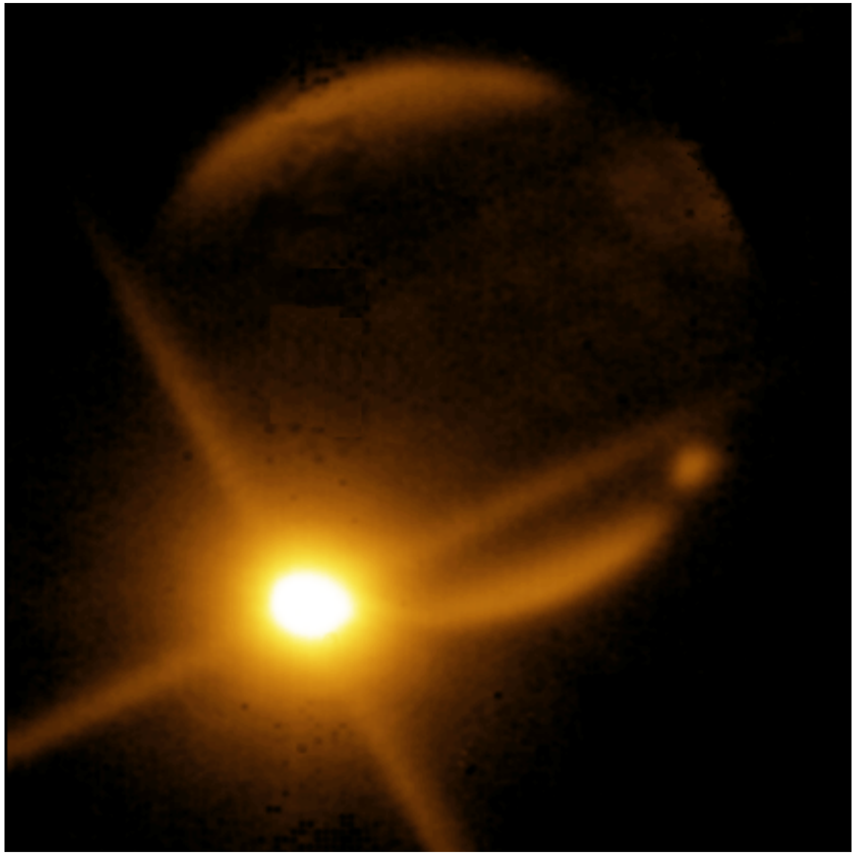
High mass XRB



X-ray binaries: hard states (comptonisation)



Accretion powered sources



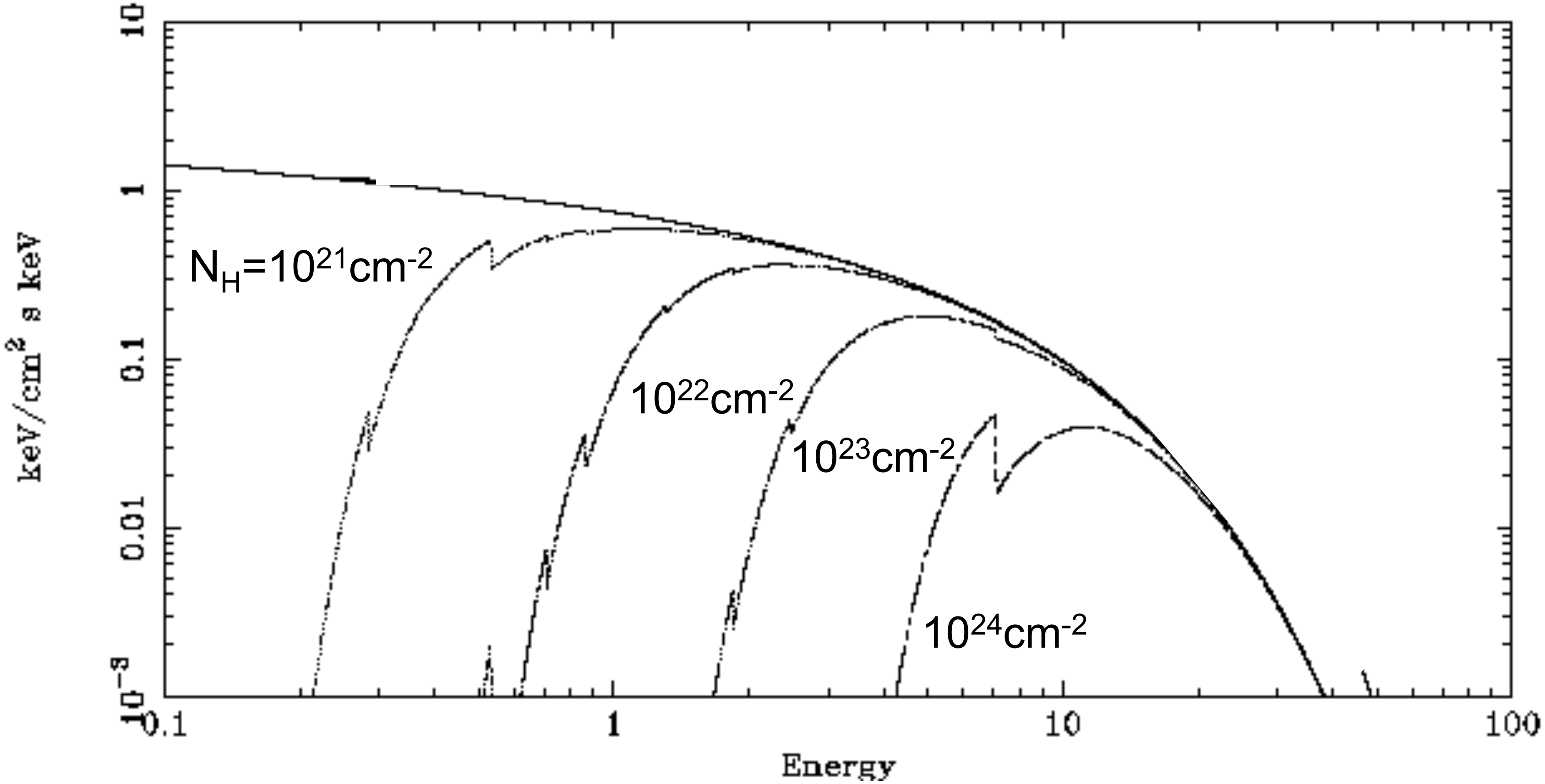
Thermal and non-thermal X-ray sources often powered by accretion

$$\dot{E} = L_{acc} = \frac{GM\dot{m}}{R}$$

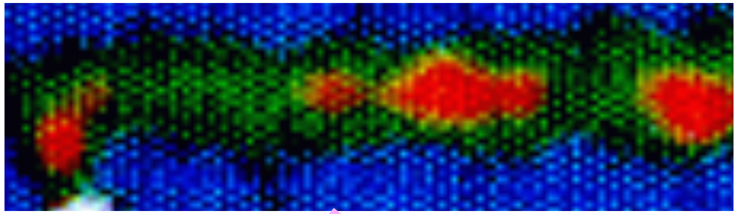
- Cataclysmic variables (CVs)
  - White dwarfs
- X-ray binaries
  - Neutron stars and stellar mass black holes
  - Up to 30% of rest mass energy
- Active galactic nuclei (AGNs)
  - Supermassive black holes

X-ray processes: photoelectric absorption

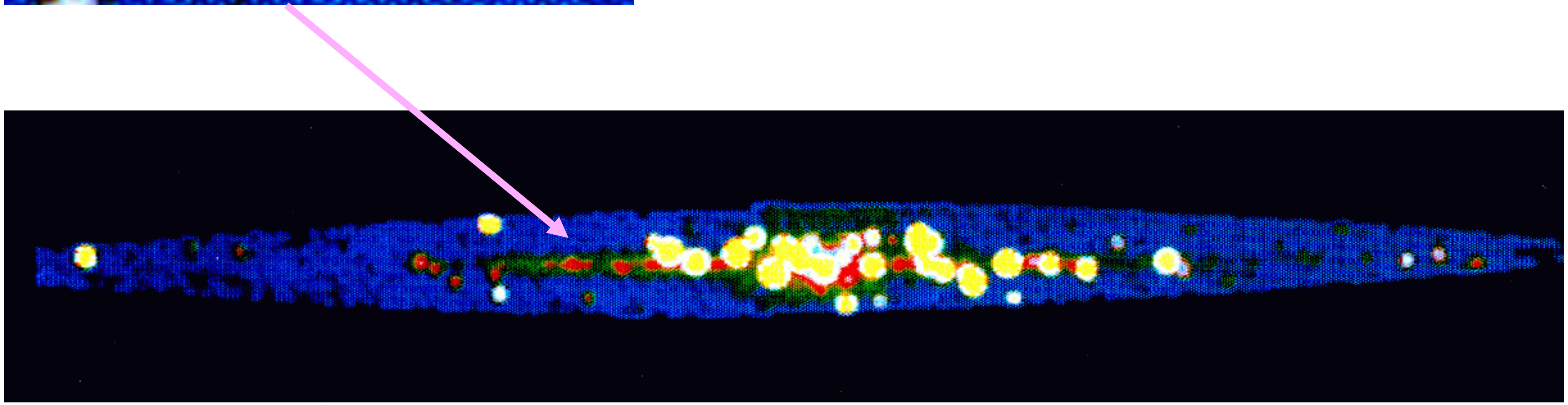
- Photoelectric absorption
- Can be interstellar and/or intrinsic
- Measured in terms of H column, but dominated by metals in X-rays



Other X-ray emitting objects



Our Galaxy



90 **EXOSAT Map of Galactic Plane** 270

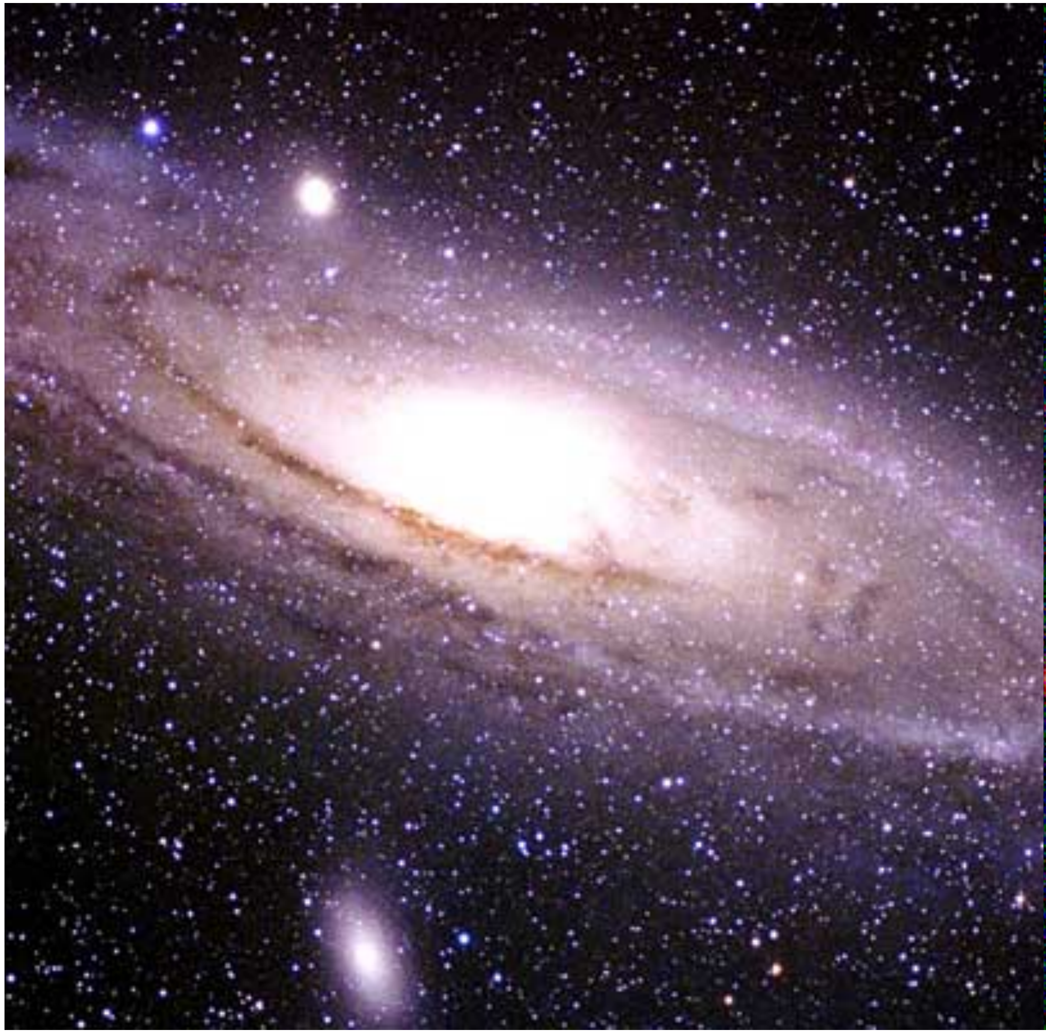
- Dominated by X-ray binaries

- Also Galactic ridge X-ray emission
  - CVs ?
  - Diffuse hot gas ?

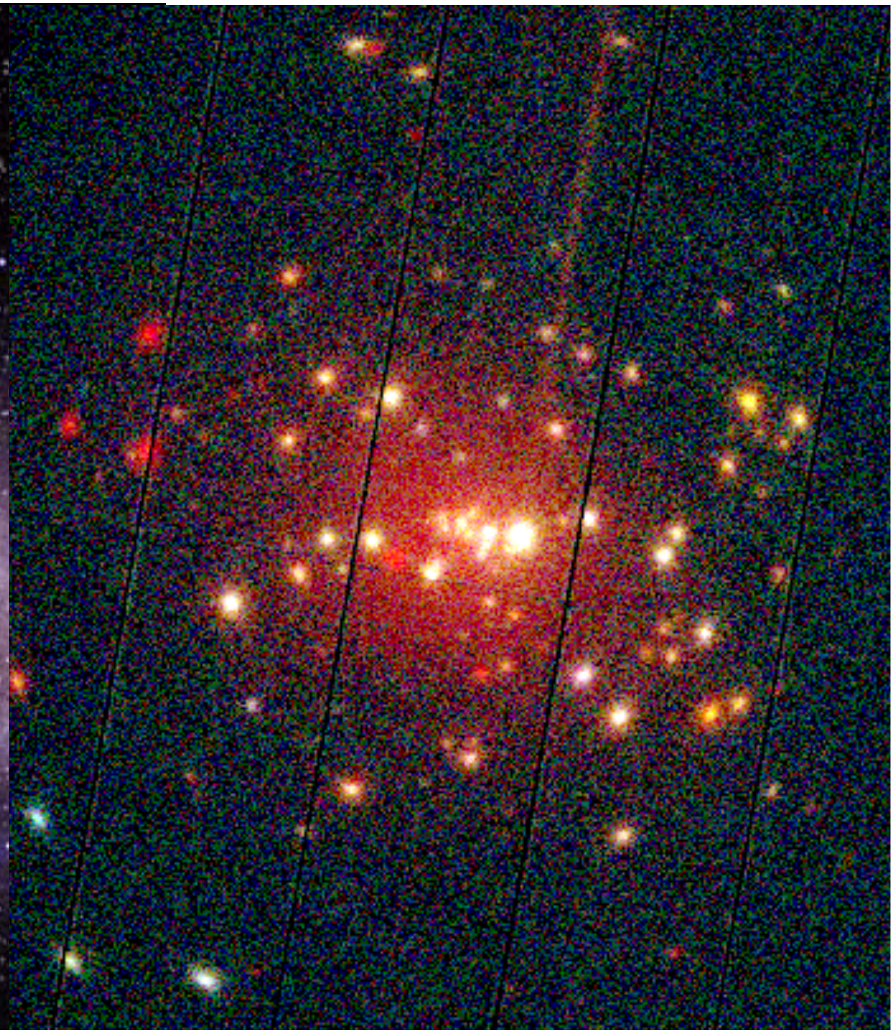
Nearby galaxies

- XRBs
- SNRs
- Diffuse emission: stars and CVs?

M31

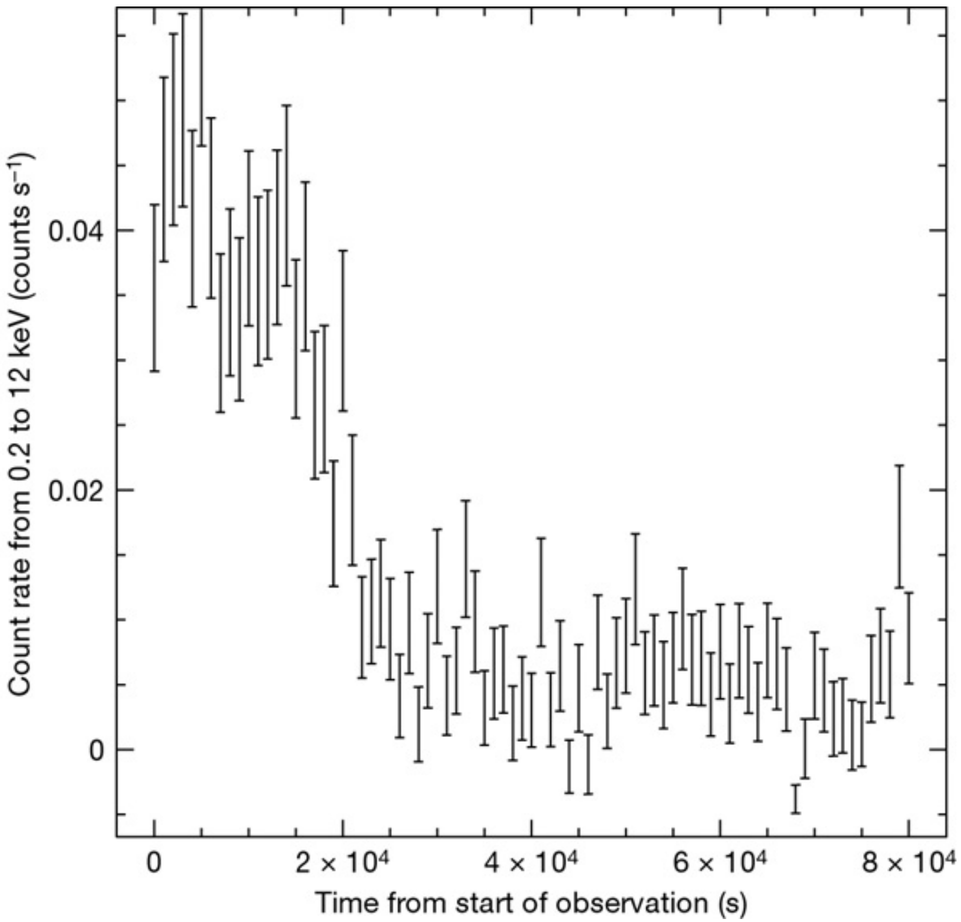


XMM-Newton



Ultra-luminous X-ray sources (ULXs)

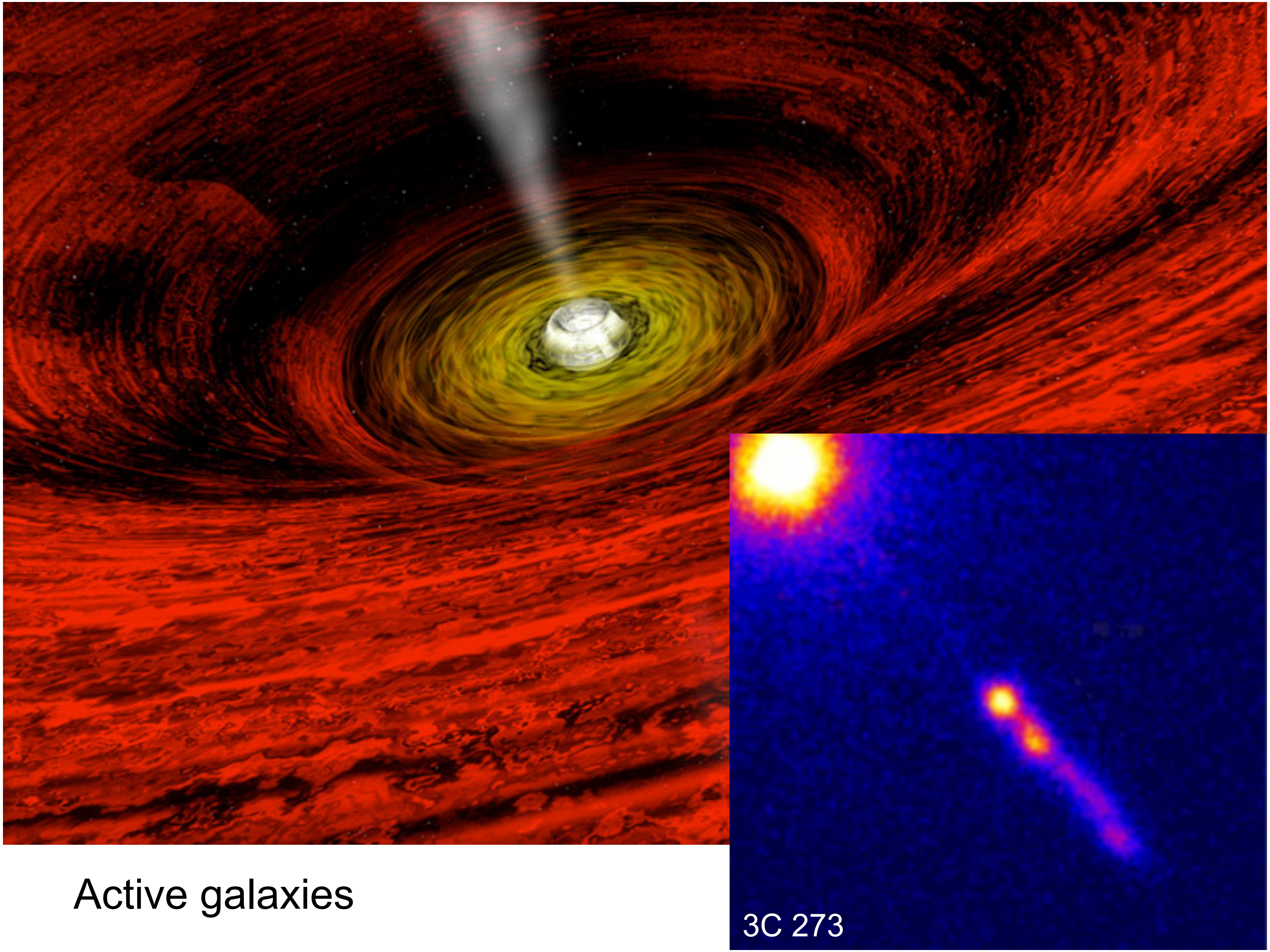
- $L_x > L_{Edd} = 1.3 \times 10^{38}$ erg s^{-1} M_{sun}
  - Beamed?
  - Intermediate mass black holes?



ULX in NGC4472

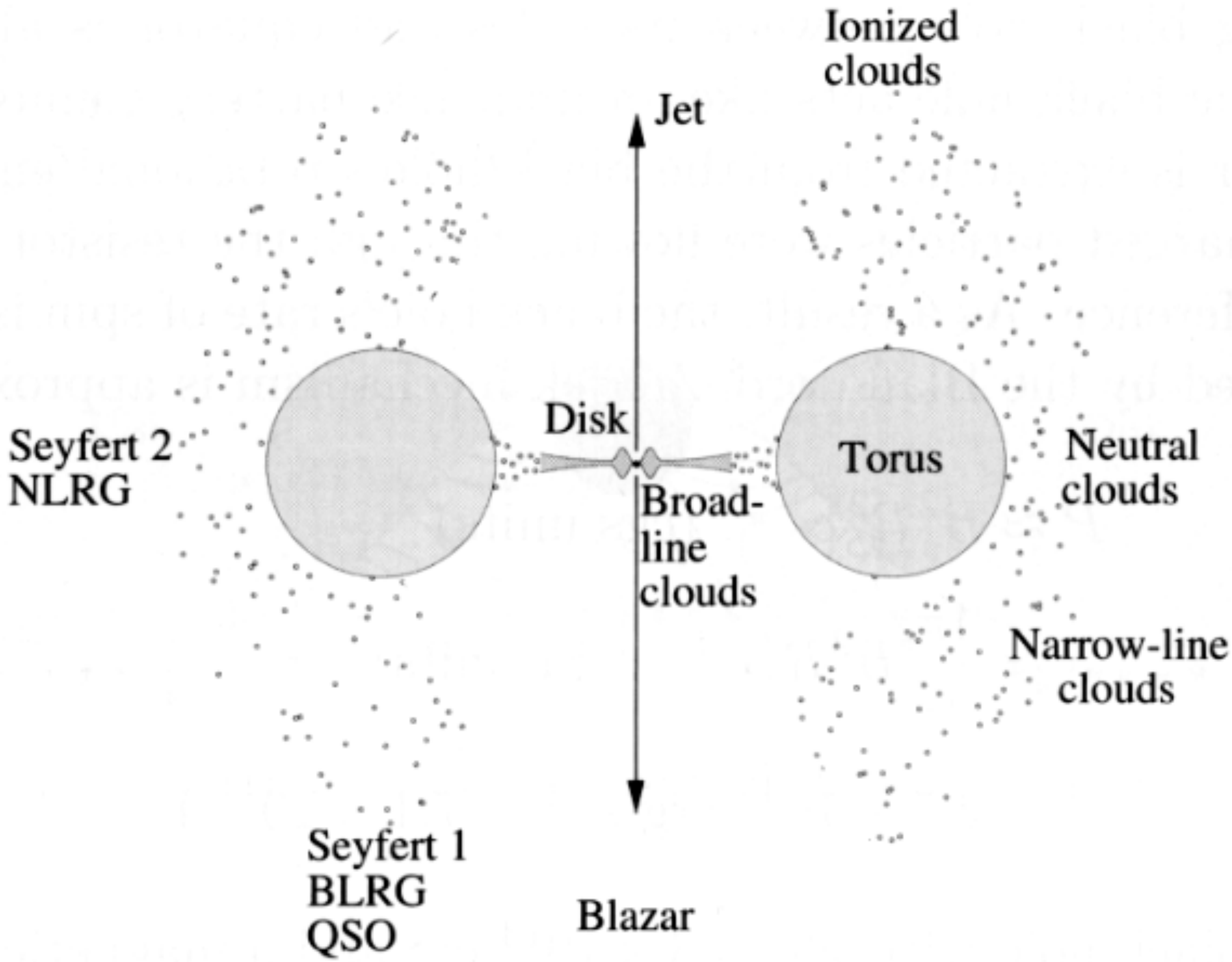
$L_x = 4 \times 10^{39}$ erg s^{-1}

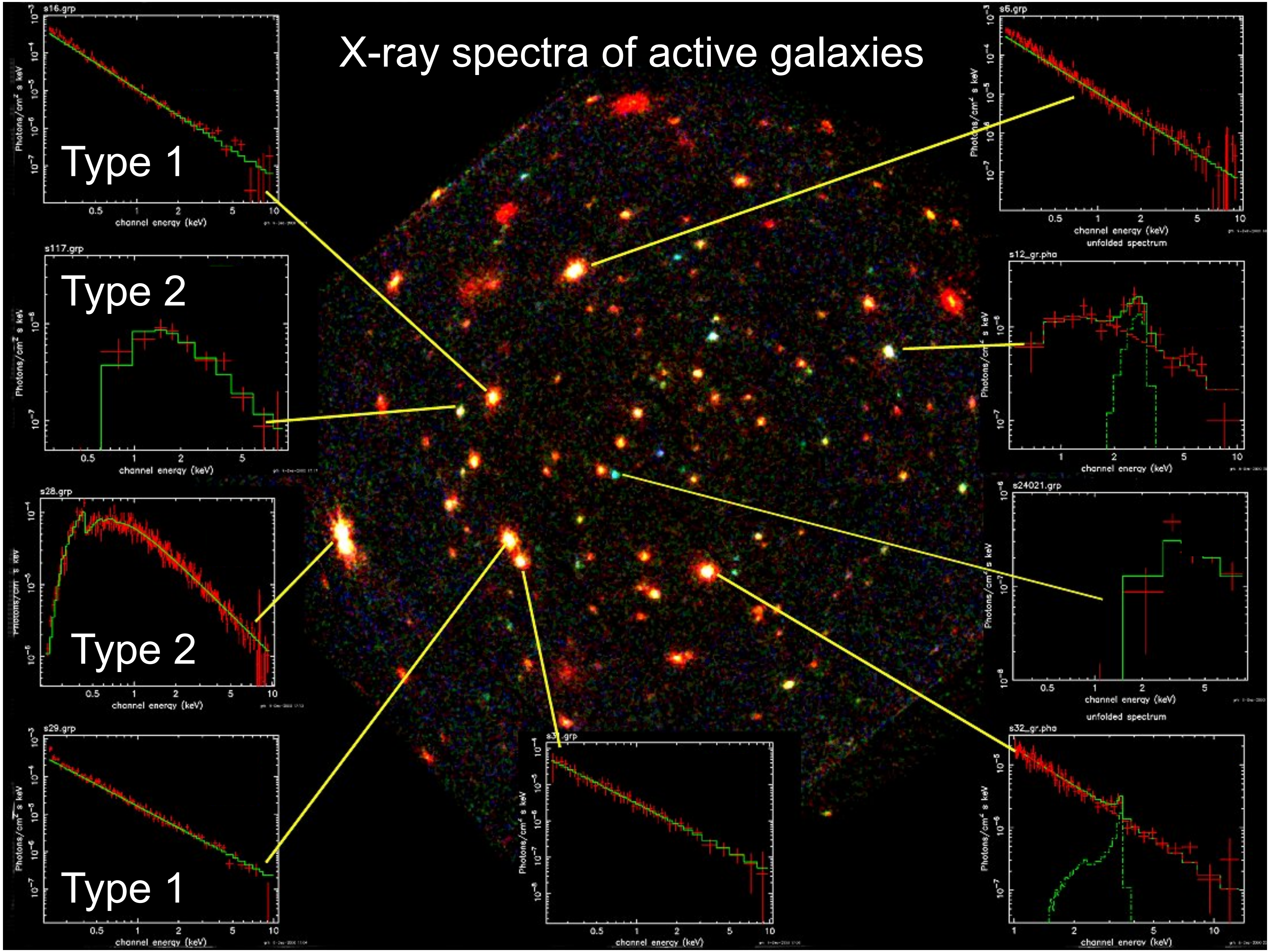
Variability demonstrates a single object



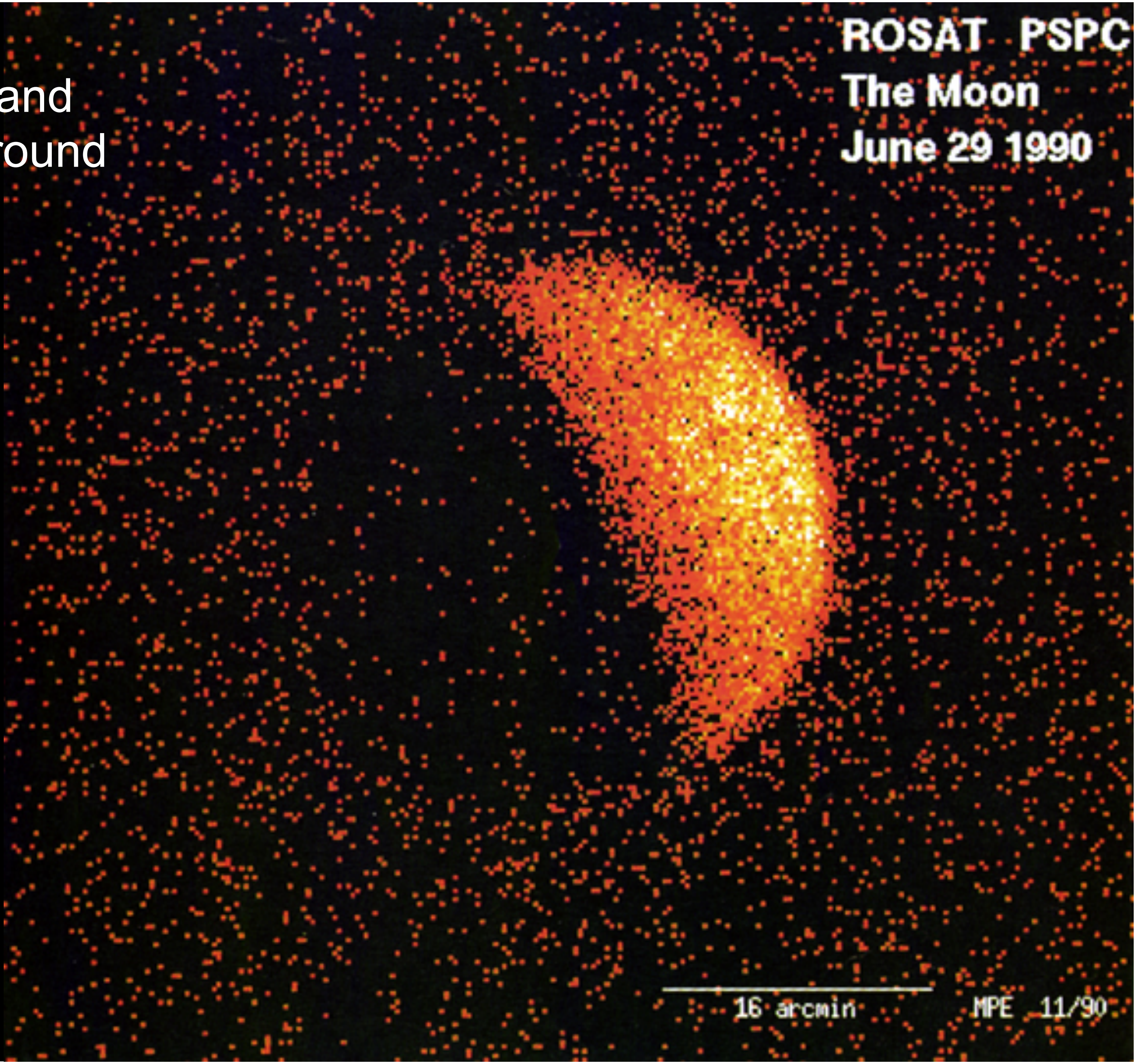
Active galaxies

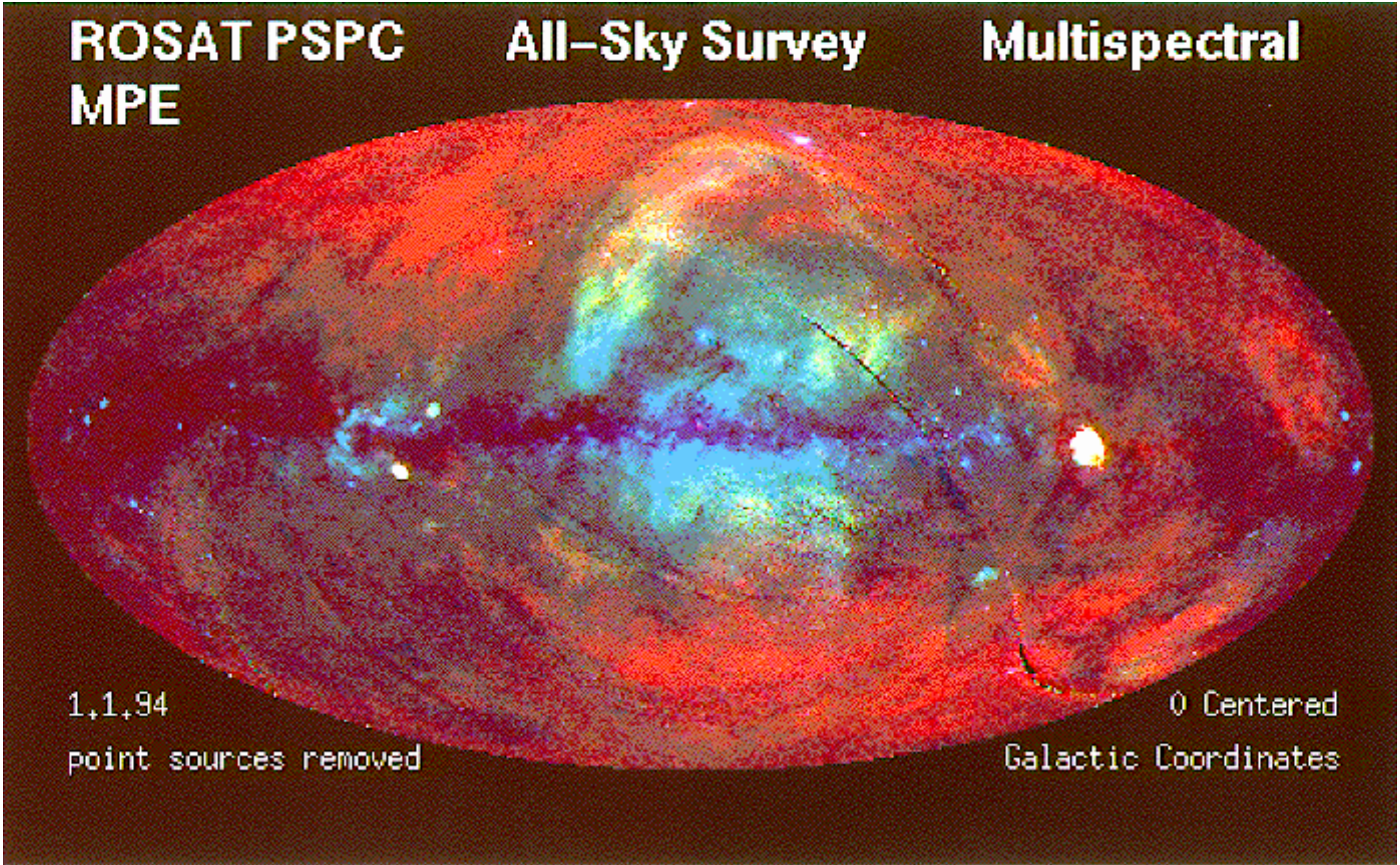
Active galactic nuclei



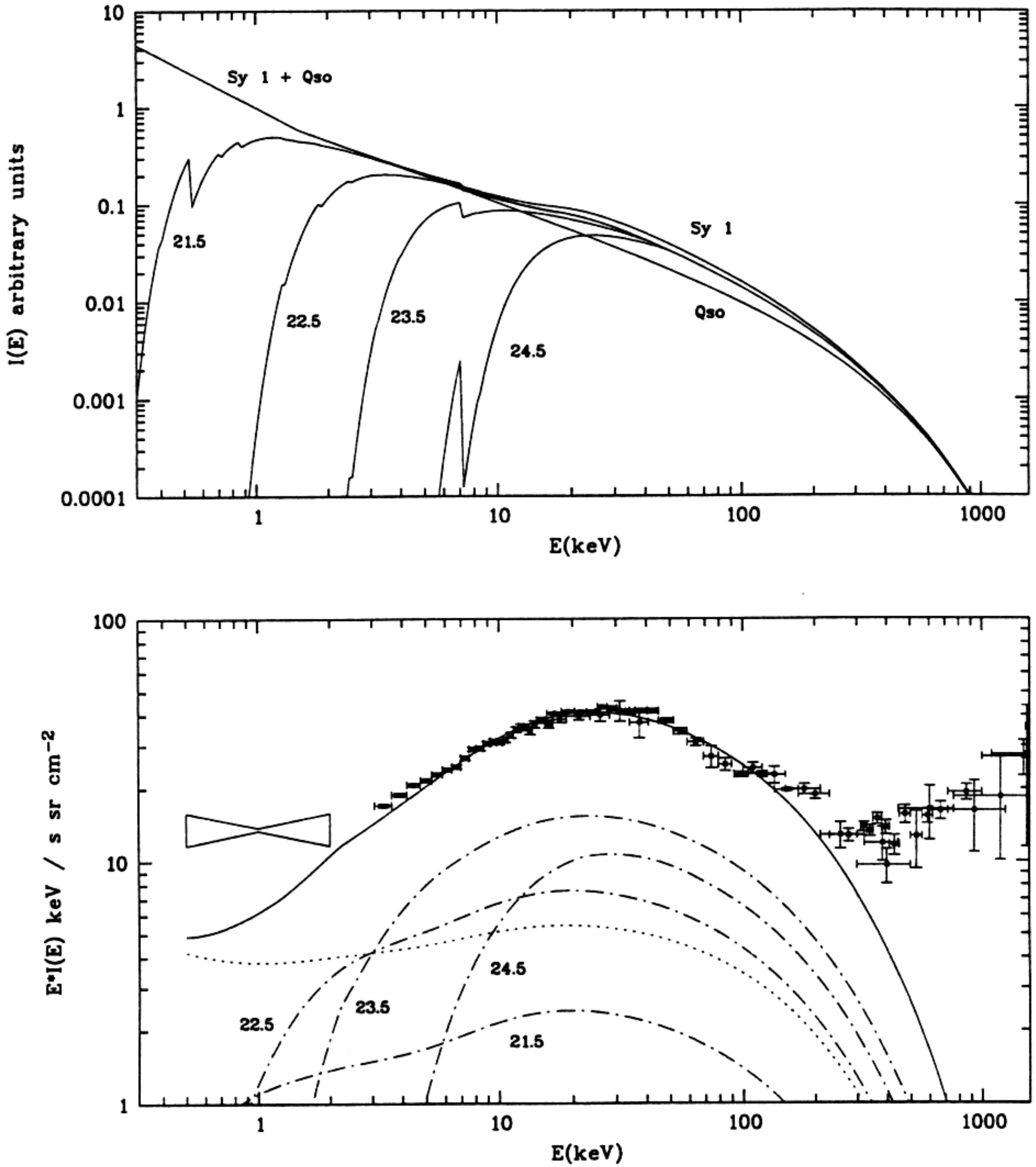

X-ray spectra of active galaxies
Type 1
Type 2
Type 2
Type 1
s16.grp
s117.grp
s28.grp
s29.grp
s6.grp
s12_gr.pha
s24021.grp
s32_gr.pha
channel energy (keV)
unfolded spectrum
Photons/cm² s keV

The Moon and
X-ray background





Soft X-ray background dominated by hot gas in “local bubble” (an old SNR) plus Solar Wind Charge Exchange in Solar System

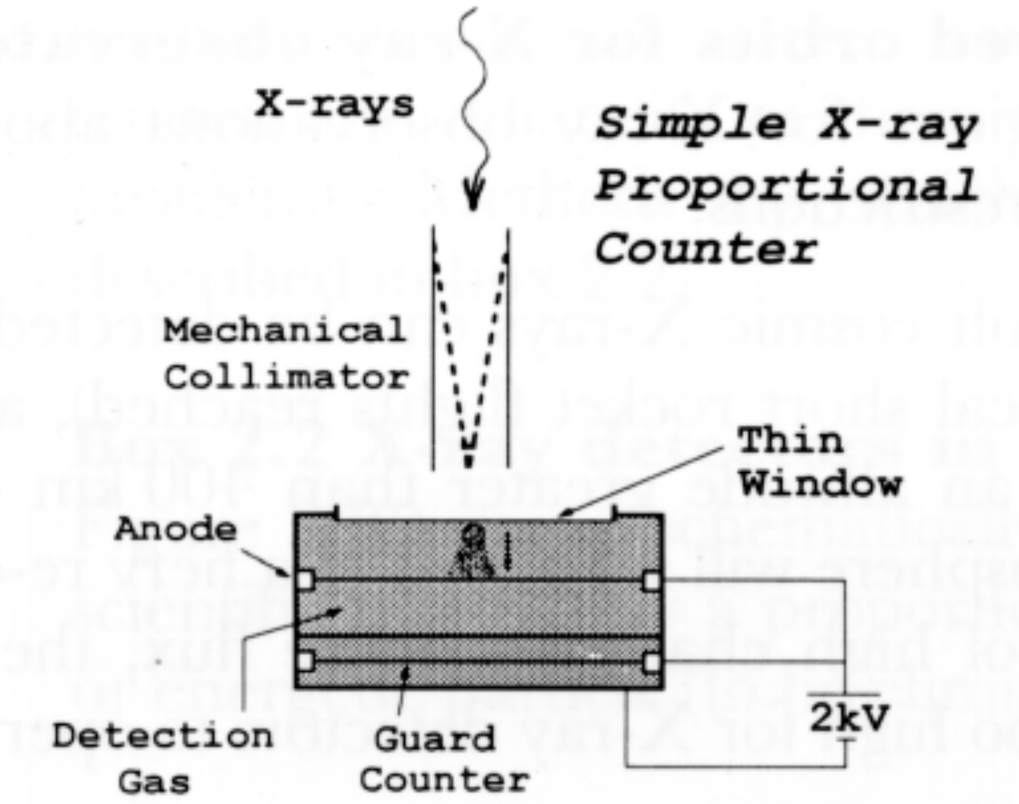


Hard X-ray background dominated by type II AGN

Instrumentation

Detectors I: proportional counters

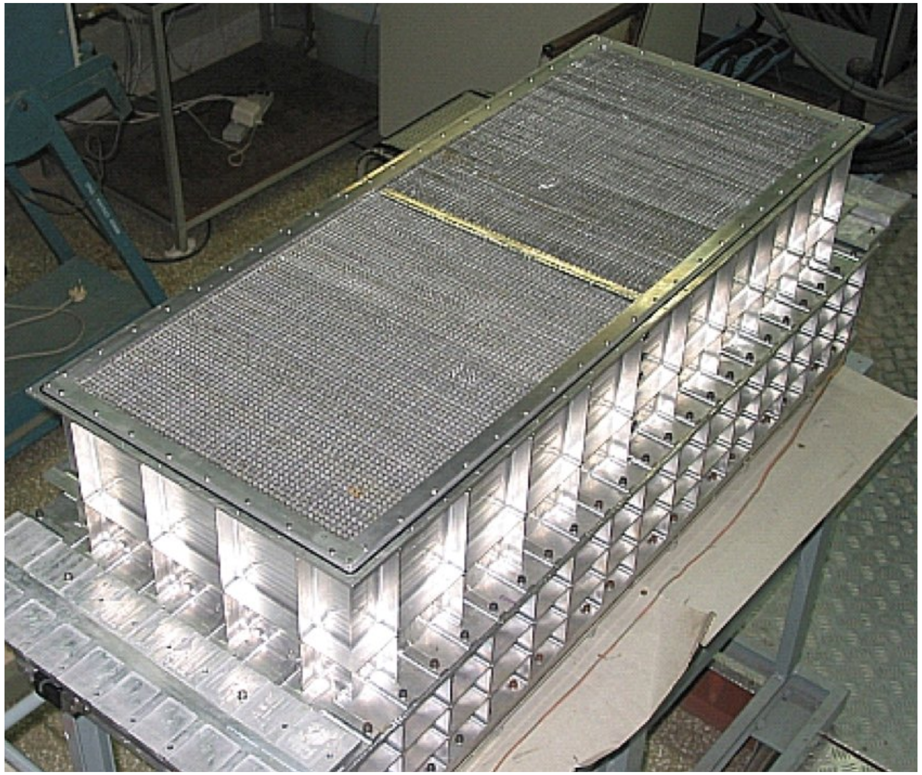
- Workhorse of the 1960s-80s and still used on NASA's RXTE mission
- X-ray photon => electron cloud via photoelectric effect => accelerated by electric field => cloud amplification => charge pulse detected at anode



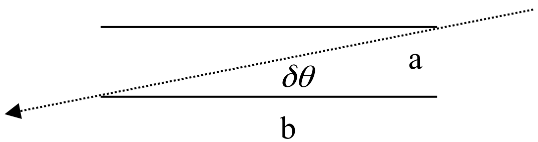
- Pros:
  - large collecting area
  - high time resolution
  - high counting rates
- Cons:
  - Poor spatial resolution
  - Poor spectral resolution
    $E / \Delta E \propto E^{1/2} \sim 2\text{-}10$

Optics I: collimators

Astrosat collimator

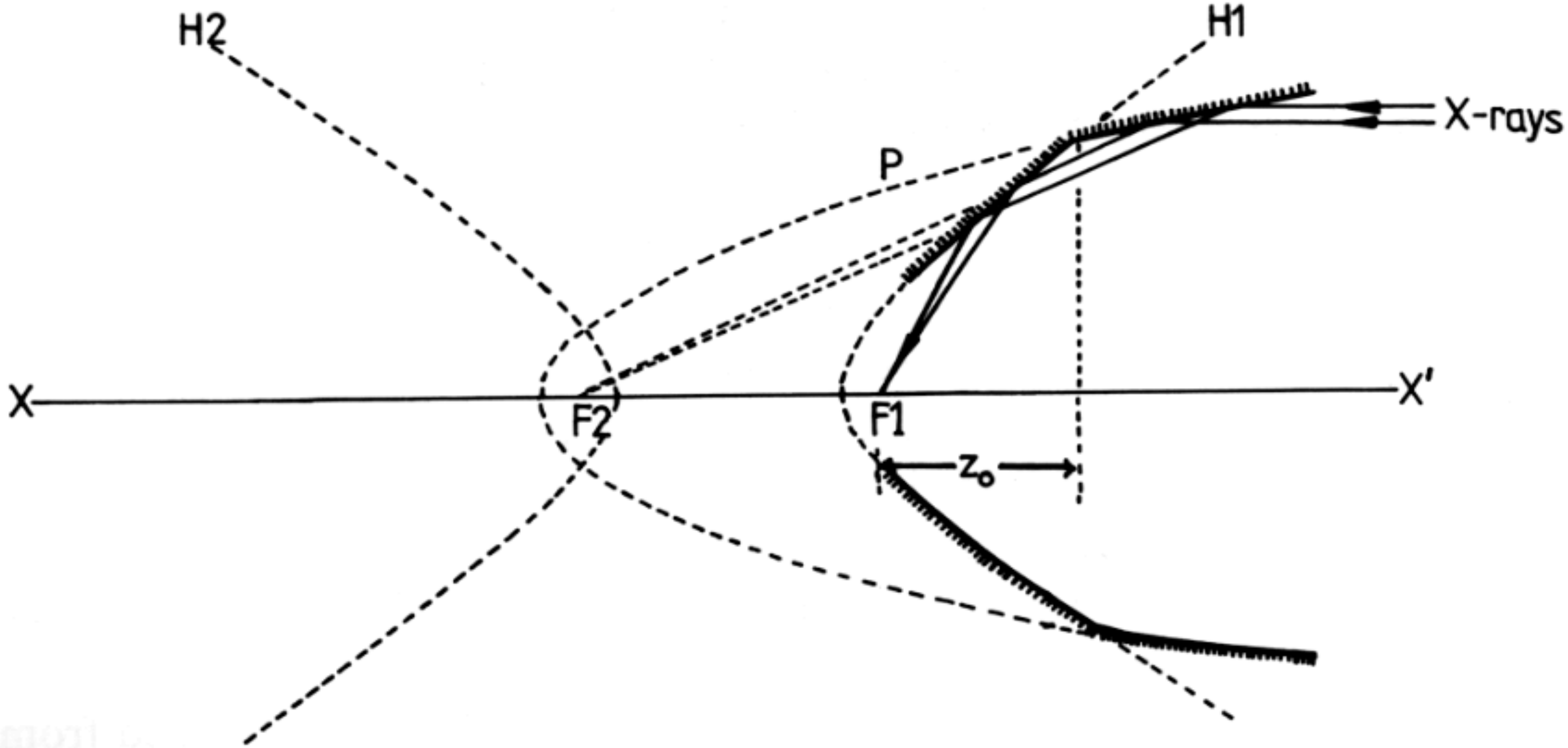


- Pros:
  - Simple and cheap
  - Large collecting area
  - Low mass
- Cons:
  - Poor spatial resolution
  - No imaging
  - No background rejection



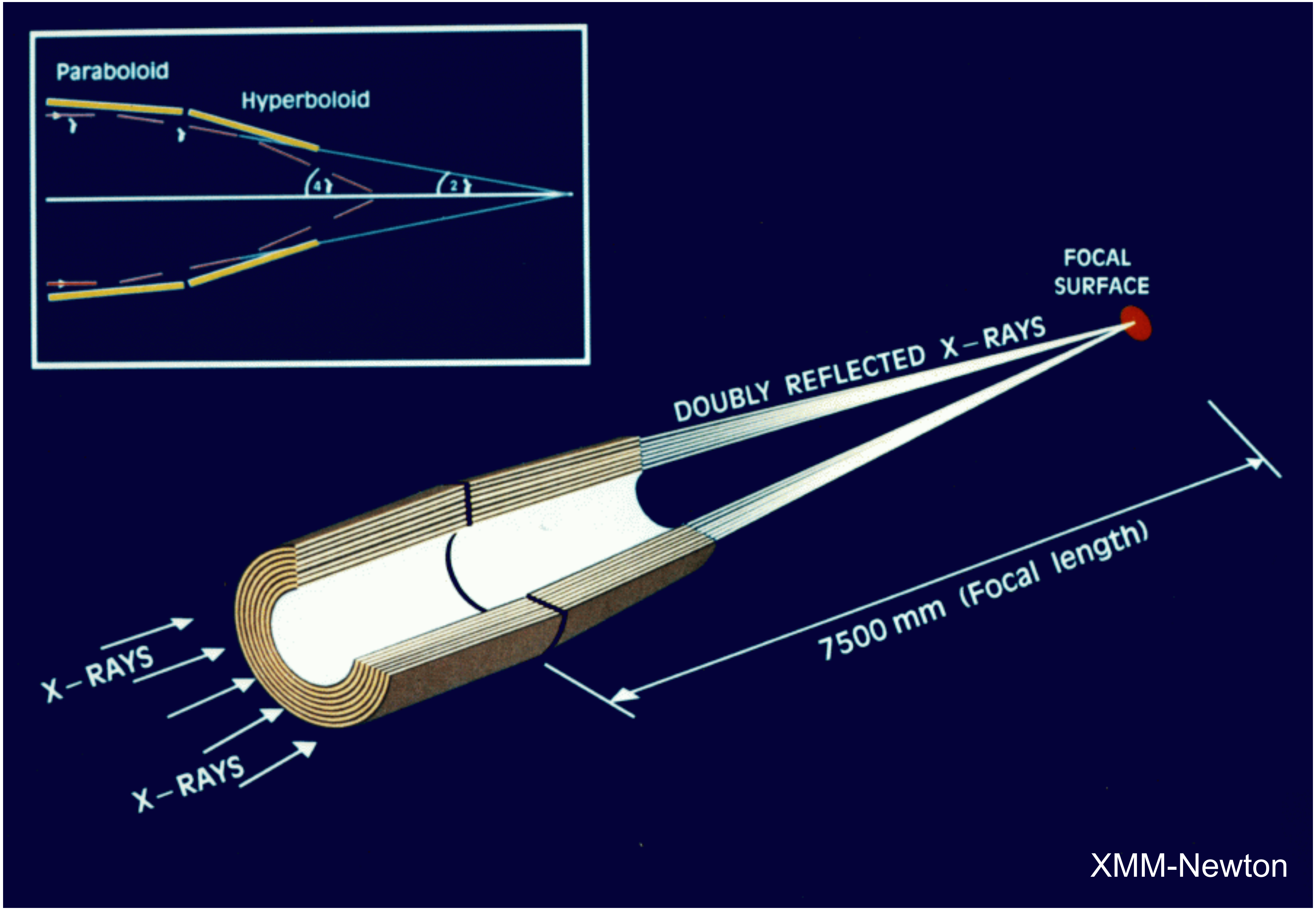
$$\delta\theta = \tan(\frac{a}{b})$$

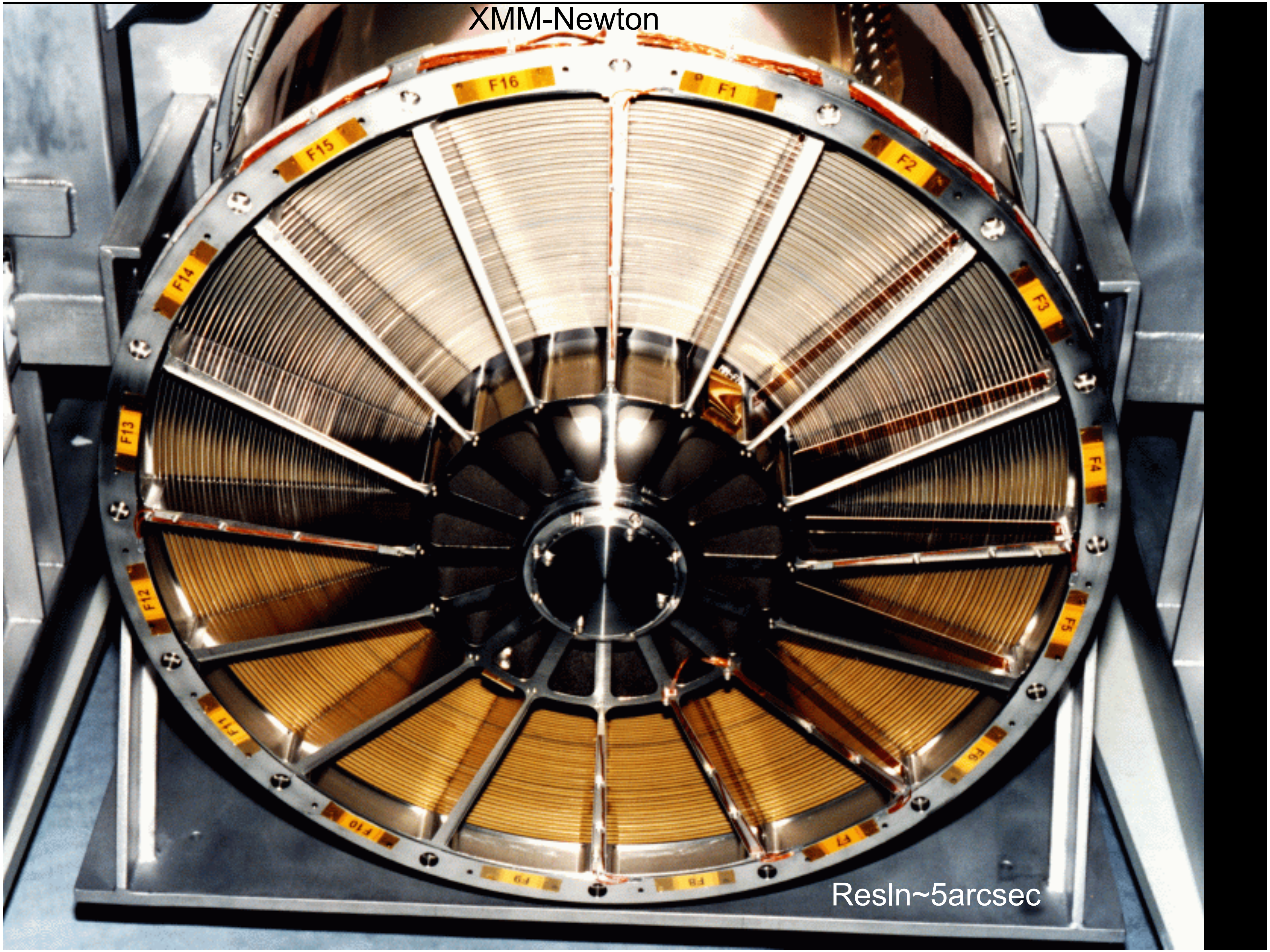
Optics II: grazing incidence optics



- X-rays only reflected at *grazing incidence*
- Wolter type-I design
  - parabolic mirror
  - additional hyperbola to shorten focal length
- Hard X-ray response limited by quality and focal length
- Multiple mirrors nested to provide useful *effective area*

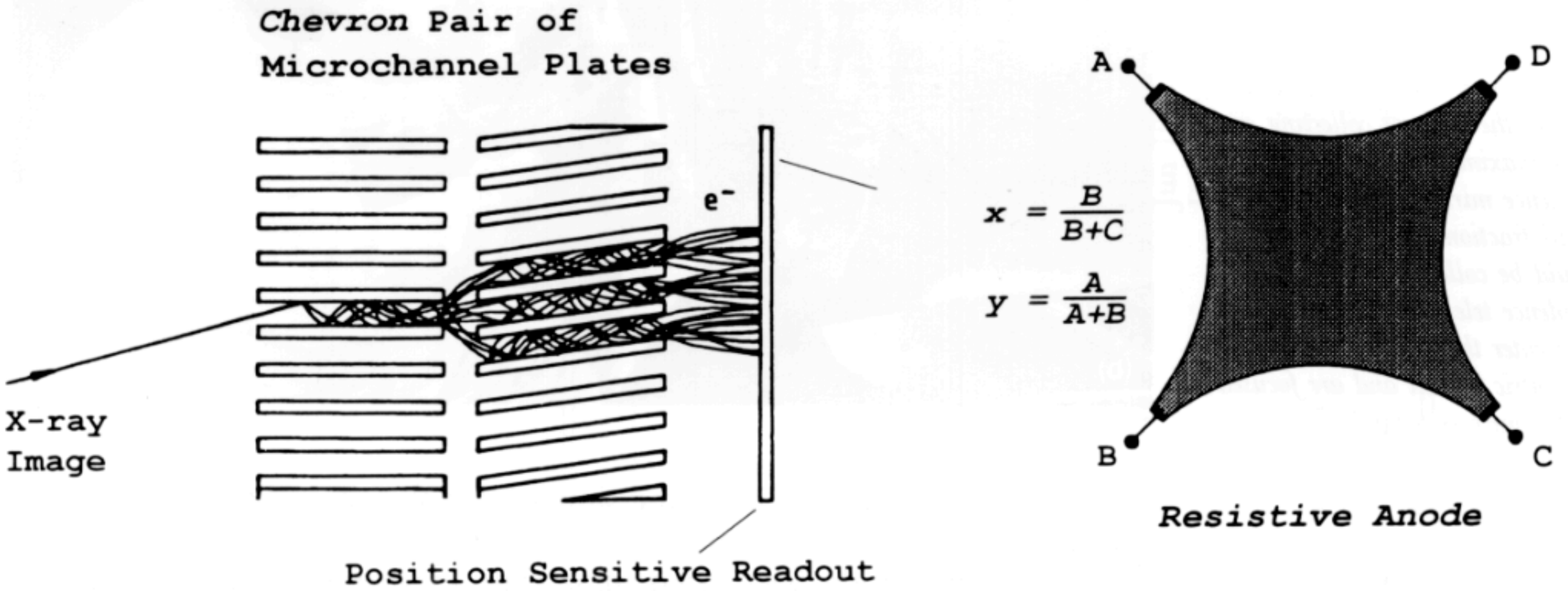
Optics II: grazing incidence reflection




XMM-Newton
Resln~5arcsec

Chandra mirror: resln ~ 0.5arcsec

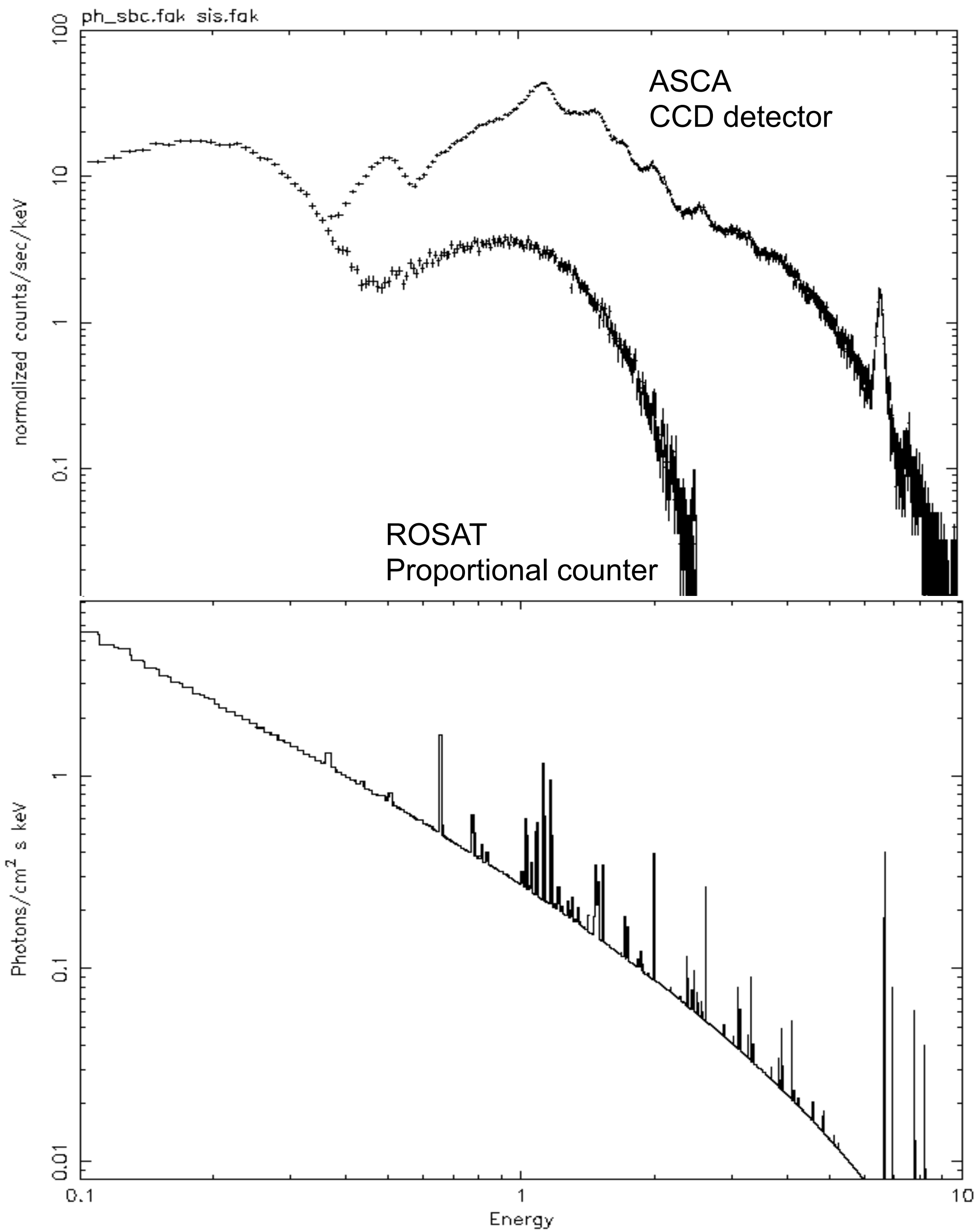
Detectors II: microchannel plates



- Millions of fine co-aligned glass tubes
  - X-ray photon => liberates electrons from tube wall => electron cloud => accelerated by electric field along tube
  - typical amplification along tube ~10^5
  - position sensitive anode readout preserves spatial resolution
- Pros: excellent spatial resolution
- Cons: essentially no spectral resolution

Detectors III: CCDs

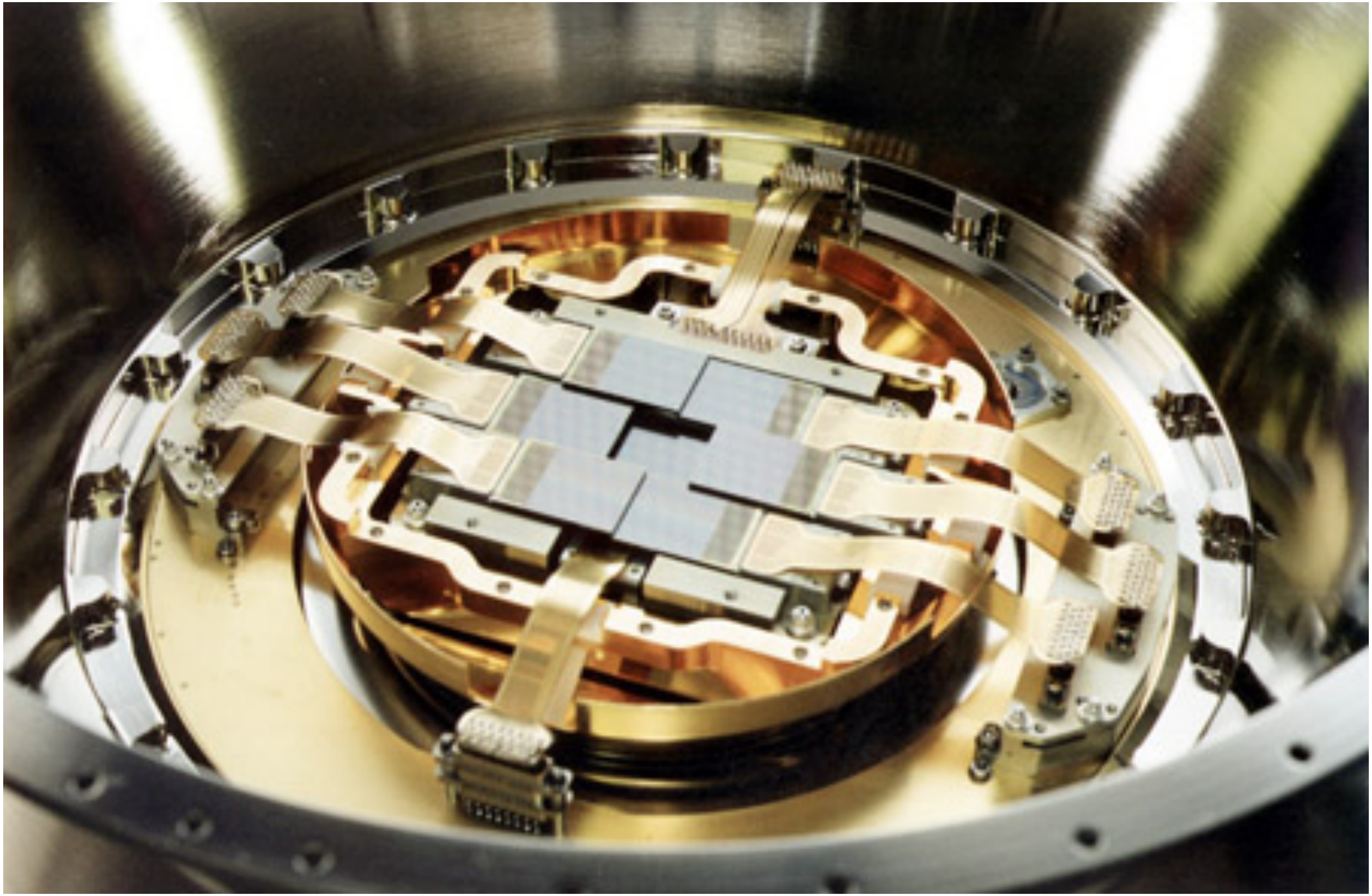
- Essentially the same as optical CCDs except read out quickly to achieve photon counting
- Number of photoelectrons proportional to photon energy
  - $E/\Delta E \propto E^{1/2} \sim 10\text{-}100$
  - Still modest but allows direct detection of strong emission lines
  - Better than prop counters because band gap smaller than ionisation potential



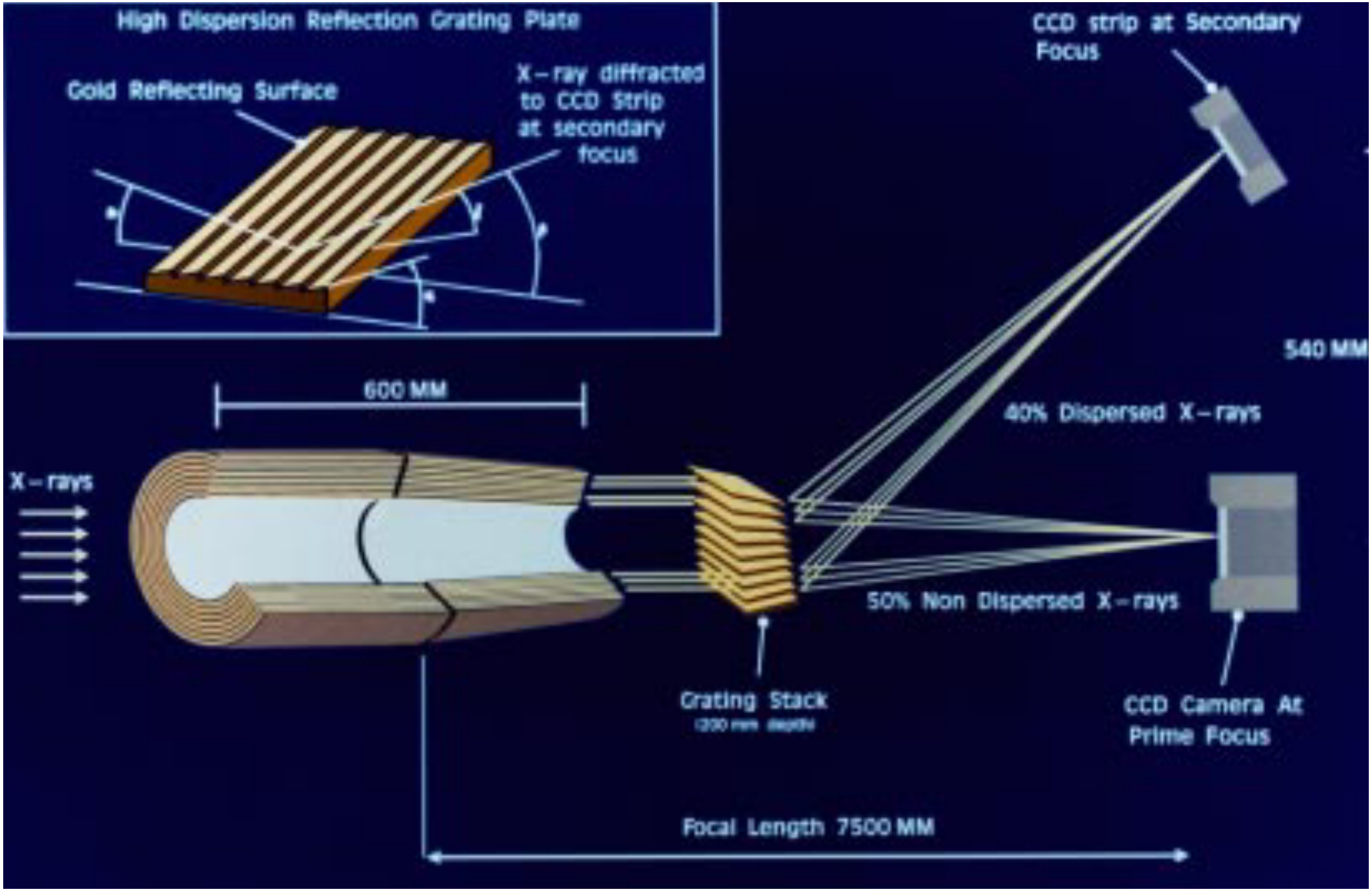
- Pros
  - Relatively good spectral resln
  - Good spatial resolution
- Cons
  - Limited count rate (pile up)
  - Limited soft x-ray response
  - Susceptible to radiation damage

Detectors III: CCDs

XMM-Newton EPIC MOS



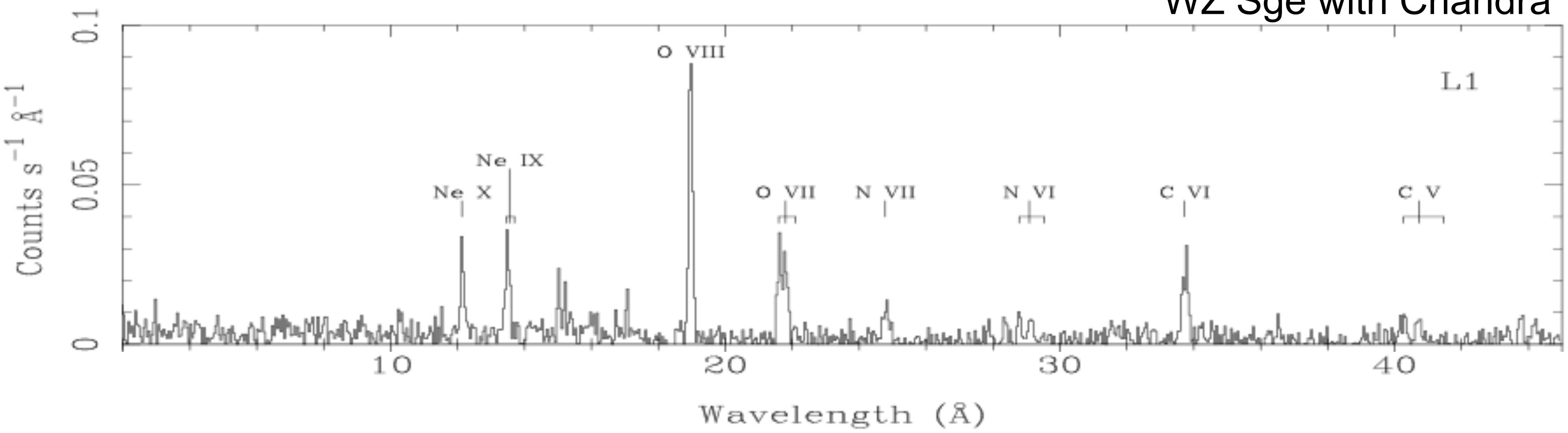
Optics III: diffraction gratings



Optics III: diffraction gratings

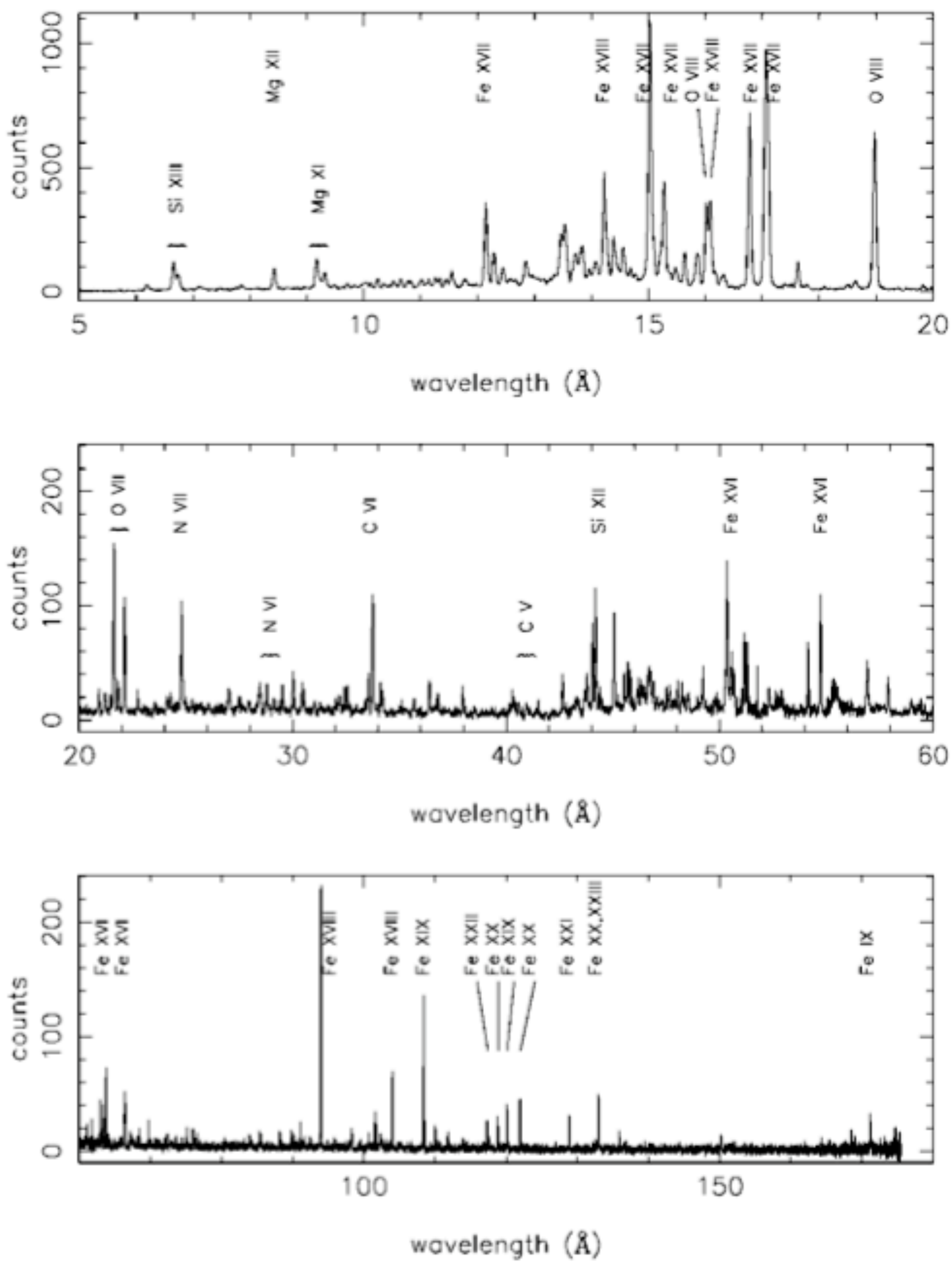
- Conventional dispersed spectroscopy possible using transmission or reflection gratings (at grazing incidence)
- Grating equation
  - $2d \sin \theta = m\lambda$
  - Typical line spacing: $1/d \approx 500 - 5000$ lines/mm
  - Resolving power $E/\Delta E = \lambda/\Delta\lambda \propto E^{-1} \propto \lambda \sim 100-1000$
    - So usually plot against log λ rather than log E
- Pros: real spectroscopy possible for bright sources
- Cons: high bgd and multiple orders limit sensitivity

WZ Sge with Chandra



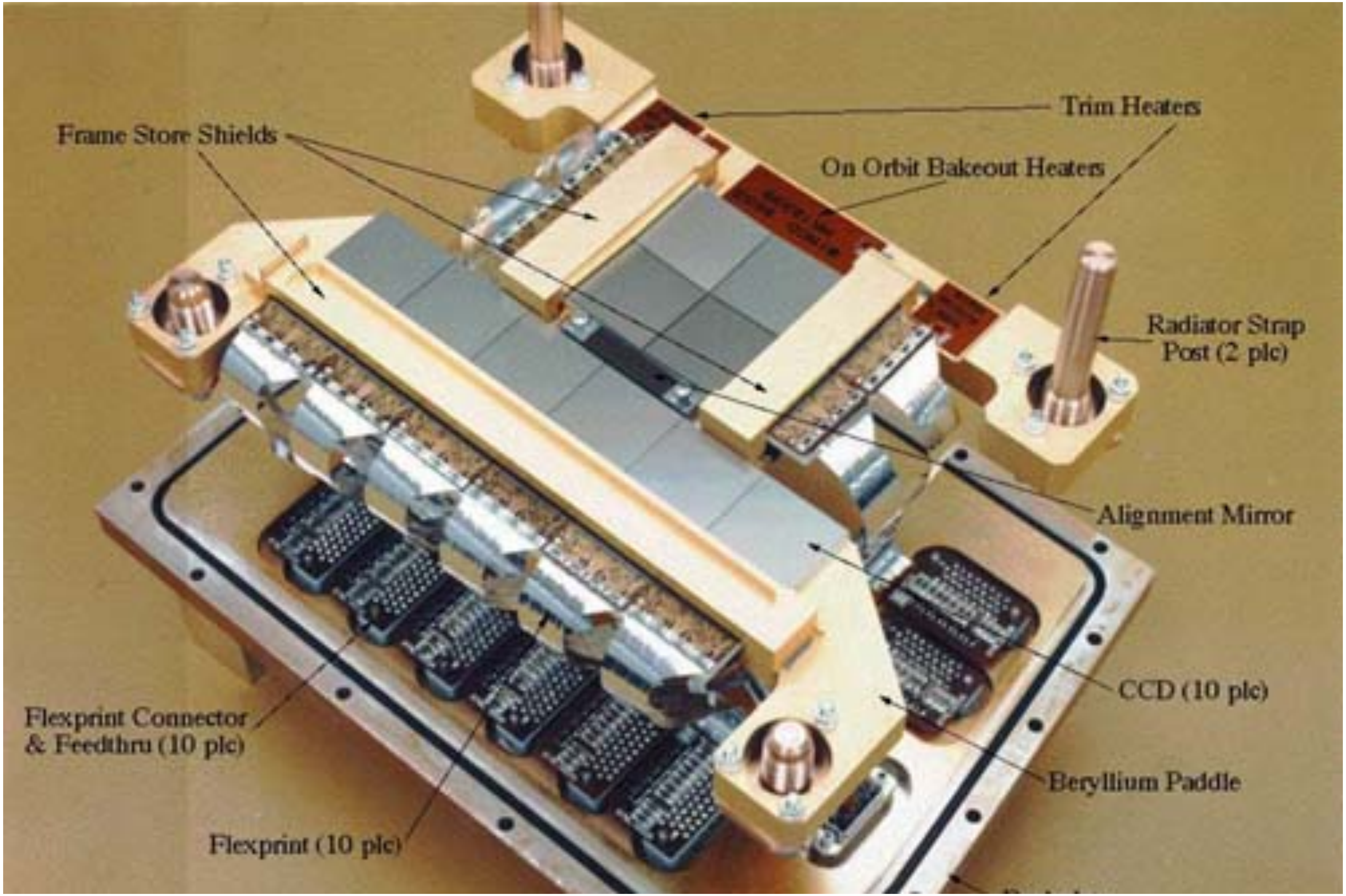
Example: Late type star

- Chandra LETG grating spectrum of Capella
- Thermal spectrum
- Brinkman et al. 2000



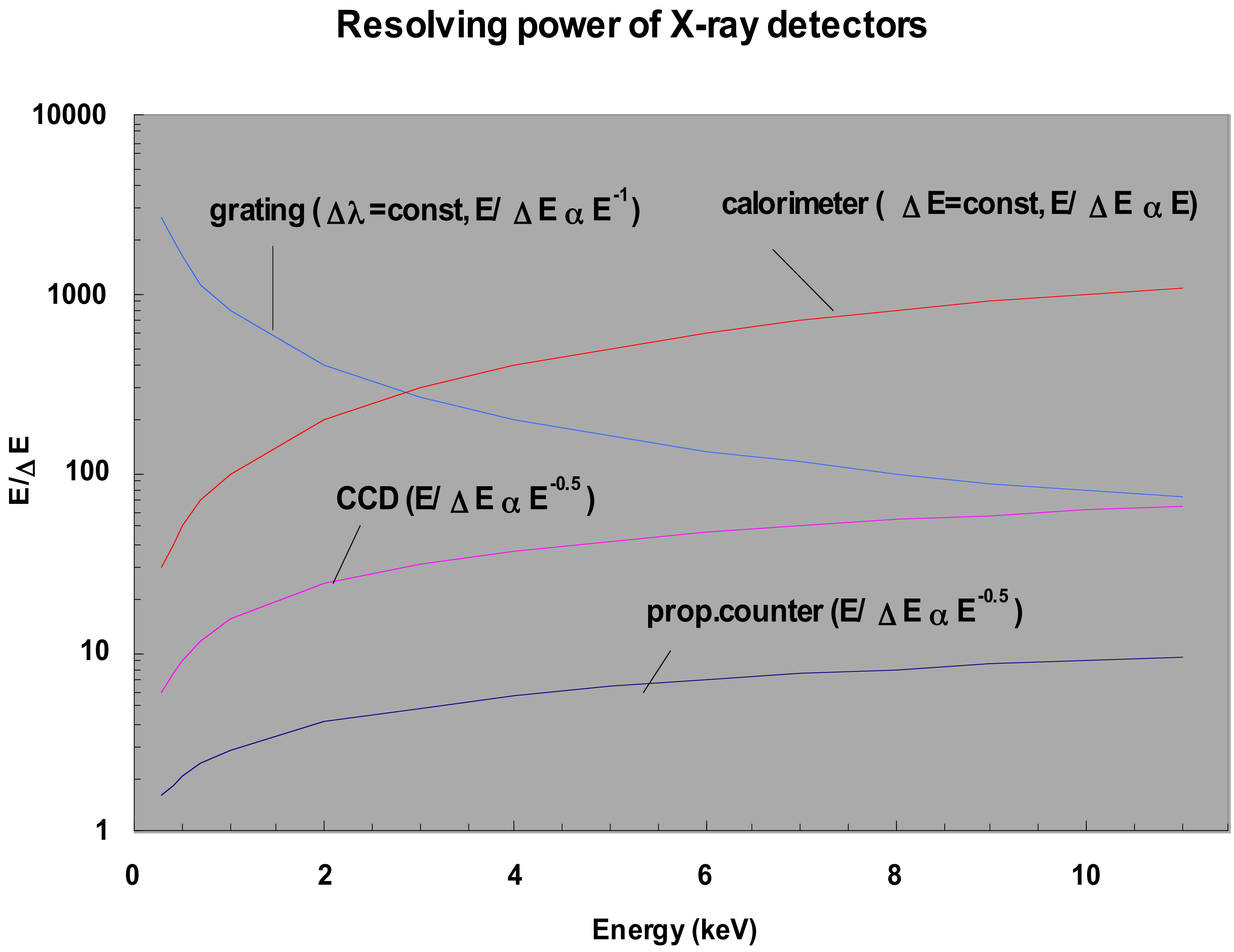
Detectors III: CCDs

Chandra ACIS



Detectors IV: micro-calorimeters

- Detector senses the temperature increase when an individual photon is absorbed
- Temperature increase is proportional to photon energy
  - energy resolution maximised by using low heat capacity absorber
  - $E/\Delta E \propto E \sim 100\text{-}1000$
  - limiting resolution ~ 1 eV (currently 6 eV)
  - requires cryogenic temperatures, $T < 0.1$ K
- Not yet successfully flown
  - Astro-E crashed
  - Suzaku (Astro-E2) lost cryogen
- Pros:
  - Very high spectral resolution (especially at high energies)
  - Non-dispersive so low background
- Cons:
  - Limited cryogen lifetime



Resolving power of X-ray detectors
grating (Δλ =const, E/ Δ E α E^-1)
calorimeter (Δ E=const, E/ Δ E α E)
CCD (E/ Δ E α E^-0.5)
prop.counter (E/ Δ E α E^-0.5)
E/Δ E
10000
1000
100
10
1
0
2
4
6
8
10
Energy (keV)

Key missions

UHURU	1970-1973	First satellite dedicated to X-ray astro
HEAO-1	1977-1979	
Einstein	1978-1981	First imaging telescope
EXOSAT	1983-1986	4 day elliptical orbit (long continuous obs)
Ginga	1987-1991	
ROSAT	1990-1999	Most sensitive all-sky survey
ASCA	1993-2001	First use of CCDs
BeppoSAX	1996-2002	
RXTE	1996-	Optimised for time resolution
XMM-Newton	1999-	Optimsed for sensitivity + spec resln
Chandra	2000-	Optimised for imaging spec resln
Swift	2004-	Optimised for rapid response
Suzaku	2005-	Planned to be optmised for spectral resln

Practicalities

Access to X-ray data

- Guest observer (GO) mode
  - Opportunities ~once per year
    - XMM-Newton
    - Chandra
    - Suzaku
    - Swift

- Target of opportunity (ToO) observations
  - Pre-approved (GO cycle)
  - Responsive
    - Swift in hours
    - XMM-Newton and Chandra ~days

- Archival
  - Data from old missions available
  - Uniform data format, calibration and analysis recipes
  - High level products often available

Key missions

UHURU	1970-1973	First satellite dedicated to X-ray astro
HEAO-1	1977-1979	
Einstein	1978-1981	First imaging telescope
EXOSAT	1983-1986	4 day elliptical orbit (long continuous obs)
Ginga	1987-1991	
ROSAT	1990-1999	Most sensitive all-sky survey
ASCA	1993-2001	First use of CCDs
BeppoSAX	1996-2002	Broad energy range
RXTE	1996-	Optimised for time resolution
XMM-Newton	1999-	Optimsed for sensitivity + spec resln
Chandra	2000-	Optimised for imaging spec resln
Swift	2004-	Optimised for rapid response
Suzaku	2005-	Planned to be optmised for spectral resln

NASA's HEASARC
High Energy Astrophysics Science Archive Research Center

Guest Observer Facilities & Science Centers

AGILE	ASCA
Astro-H	BeppoSAX
COBE	CGRO
Chandra	EUVE
Fermi	GALEX
GEMS	HETE-2
INTEGRAL	MAXI
NuSTAR	ROSAT
RXTE	Suzaku
Swift	WMAP
XMM-Newton	

NASA Archives

ADS	AstroGravS
EOSDIS	HORIZONS
IRSA	KOA
LAMBDA	MAST
NExScI	NED
NSSDC	NStED
PDS	SDAC
SPDF	SSC

The High Energy Astrophysics Science Archive Research Center (HEASARC) is the primary archive for NASA missions dealing with extremely energetic phenomena, from black holes to the Big Bang. Having recently merged with the Legacy Archive for Microwave Background Data Analysis (LAMBDA), it includes data obtained by NASA's high-energy astronomy missions from the extreme ultraviolet through gamma-ray bands, along with missions that study the relic cosmic microwave background.

HEASARC Picture of the Week

APOD: Astronomy Picture of the Day

More Images

Archive Data Search Form

More Search Options

Search criteria:

Enter positions, times, missions, ... to Browse.
Try **ROSAT 3c273** to get ROSAT data on 3c273 or **chandra bii>80 status=archived** to get archived Chandra data near the north galactic pole. Use quotes around targets that have embedded white space (e.g., **'ar lac'**).

- More examples and interactive feedback
- Detailed help on the options

Latest News

- **Chandra COSMOS (C-COSMOS) Survey Photometric Redshift Catalog** (23 Nov 2011)
This catalog providing photometric redshifts for 1694 Chandra X-ray sources in the COSMOS field (from Salvato et al. 2011, ApJ, 742, 61), as well as the **XMM-Newton COSMOS Survey Photometric Redshift Catalog** providing photometric redshifts for 1735 XMM sources (from the same reference), are both now available in Browse.
- **Lambda Ori Cluster XMM-Newton X-Ray Source Catalog** (21 Nov 2011)
This catalog of 167 X-ray sources (and their optical/IR identifications) towards the Lambda Ori Cluster (from Franciosini & Sacco 2011, A&A, 530, A150) is now available in Browse.
- **An INTEGRAL view of the high-energy sky (the first 10 years)** (14 November 2011)
The 9th INTEGRAL workshop will take place from October 15-19, 2012, in Paris.
- **Press Release: Swift's UV/Optical Telescope Catches Asteroid YU55 Flyby** (14 Nov 2011)
As asteroid 2005 YU55 swept past Earth in the early morning hours of Wednesday Nov. 9, the telescopes on Swift joined professional and amateur astronomers around the globe in monitoring the fast-moving space rock. The unique ultraviolet data will aid scientists in understanding the asteroid's surface composition.
- **Swift CALDB Data updated Again** (10 Nov 2011)
The Swift Caldb has been updated for the SC (update version 20111031).
- **Ultraluminous X-Ray Sources in**

XMM-Newton

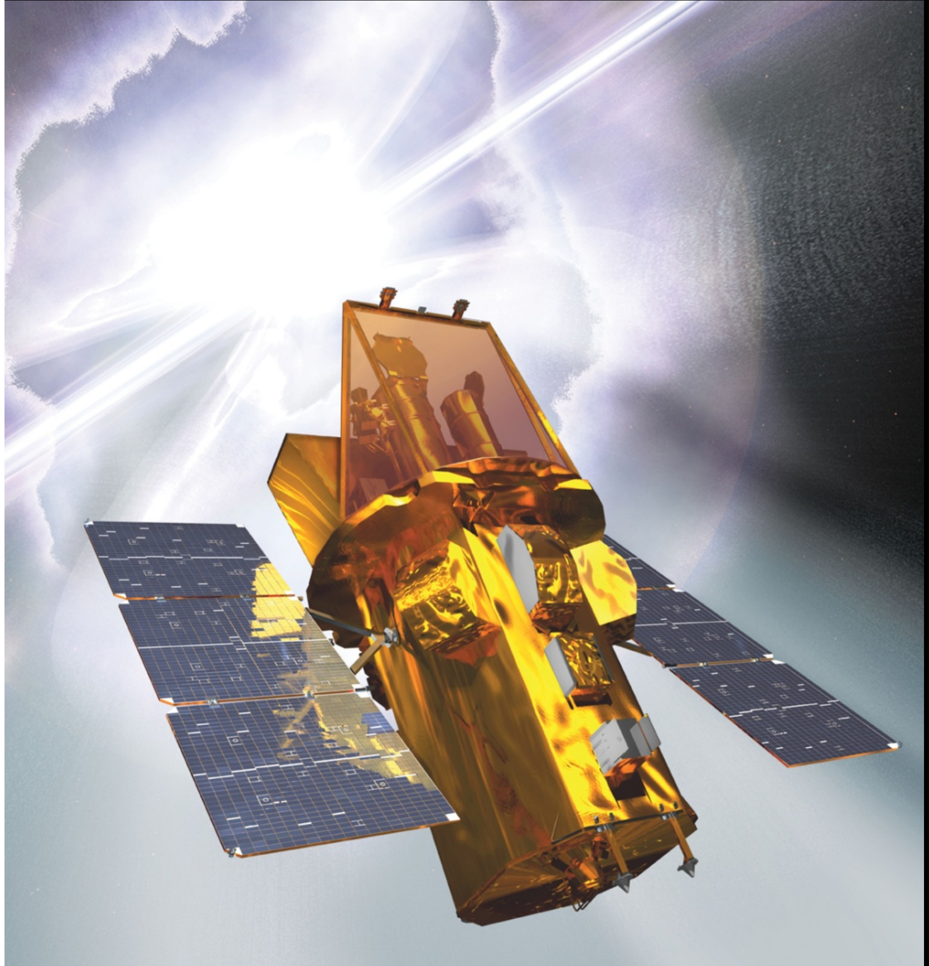
- 3 co-aligned X-ray telescopes
  - All with CCD detectors (EPIC) ~0.2-12 keV
  - Two with additional fixed Reflection Grating Spectrographs (RGS)
  - One optical telescope (OM)
- Analysis with XMM SAS software

Chandra

- One X-ray telescope
  - Micro-channel plate and CCD detectors
  - Movable diffraction gratings
    - High-energy transmission grating (HETG)
    - Low-energy transmission grating (LETG)
  - Analysis using CIAO software

Swift

- Gamma-ray, X-ray and optical telescopes
  - CCD detector in X-rays



- Analysis using ftools

ROSAT

- X-ray and EUV telescopes
  - Micro-channel and proportional counter detectors

Horses for courses

- ROSAT
  - All sky coverage – soft X-ray observations (or limits) for everything
- XMM-Newton
  - Highest collecting area
  - Best for high quality CCD observations of most sources
  - Soft X-ray grating spectrum always available (RGS)
  - Simultaneous optical / UV coverage with OM
- Chandra
  - Exceptional imaging capabilities
  - Allows detection of faintest objects due to background rejection
    - Significant detection even with 2 photons !
  - Flexible choice of gratings, including hard and very soft X-rays
- Swift
  - Very rapid response and flexible scheduling possible

Archival data

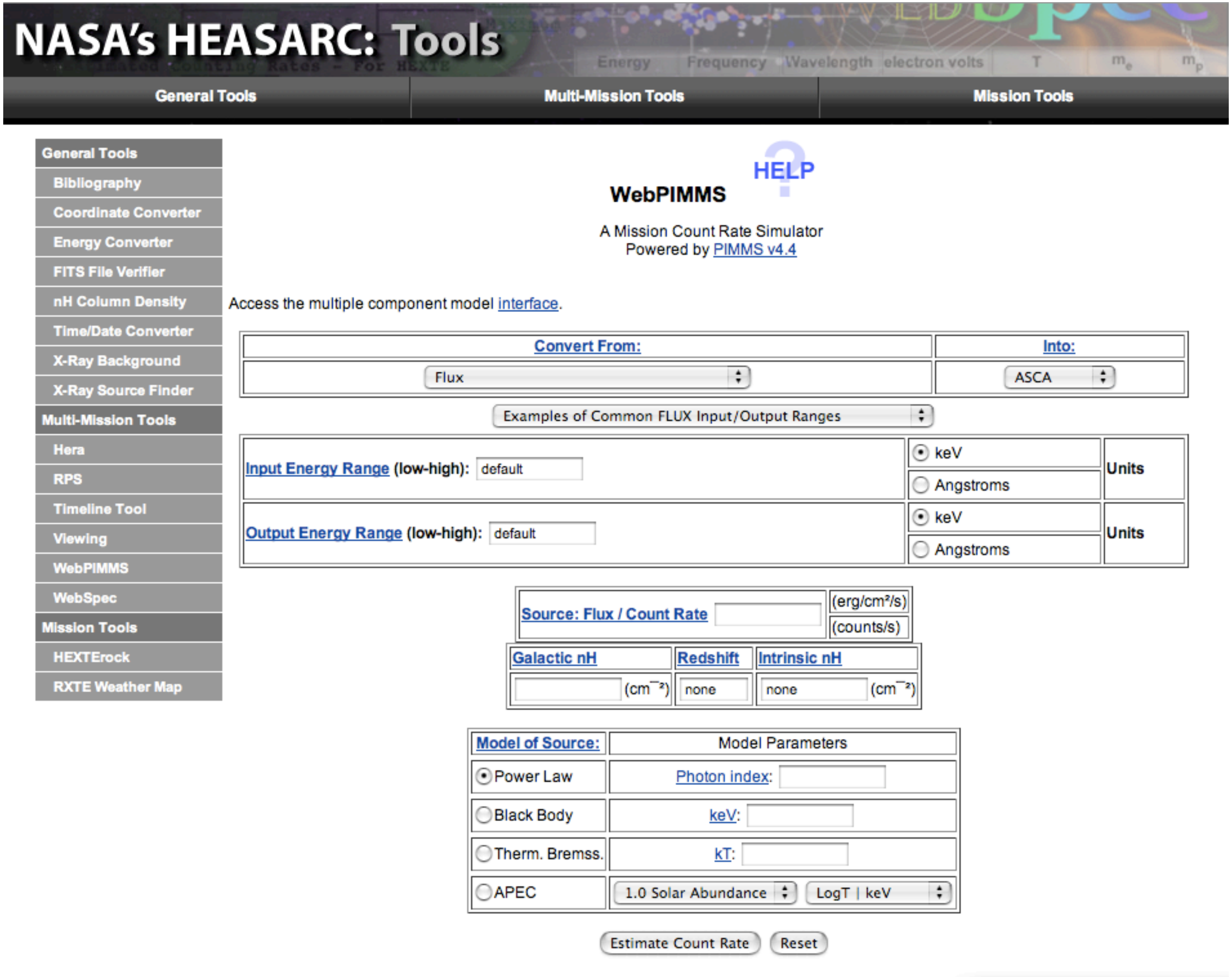
- One stop shop: NASA HEASARC
  - High Energy Astrophysics Archive
  - Easy to search for observations

- XMM-Newton
  - Science Operations Centre (SOC) at European Space Agency

- Chandra
  - Chandra X-ray Center (CXC) at CfA Harvard

- Swift
  - Swift Science Center at HEASARC
  - UK Swift Science Data Centre at Leicester

Compare count rates with WebPIMMS



Assignment

- Look up the ROSAT all-sky survey count rate of the cataclysmic variable star SU UMa
- Assuming optically-thin thermal plasma emission with kT=6 keV and interstellar absorption of $N_H=10^{20} cm^{-2}$, estimate the 2-10 keV energy flux of SU UMa
- Further calculate the XMM-Newton RGS count rate, and determine how long an observation is required to accumulate 20,000 RGS counts
- Find out when such an observation could be made during 2014