X-rays from Neutron Stars: Theory and Observations

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Six Lectures:

Today

1.1 Introduction; ‘seeing’ neutron stars
X-ray astronomy
brief phenomenology of X-ray emitting neutron stars

1.2 X-ray astronomy: instrumentation, techniques, observatories

2.1 interaction of X-rays with matter

2.2 neutron star atmospheres

Tomorrow

3.1 Advanced 1: Applications of the Above.
Observations (mostly *Chandra*, XMM-*Newton*)

3.2 Advanced 2: Plans for NS photospheric spectroscopy:
Astro-H and the SXS spectrometer

1.1 introduction; X-ray astronomy; phenomenology of X-ray emitting neutron stars

We want M **and** R; or combinations:

I, dI/dt, ωR,

$\ddot{Q}$ (GW), g, z_{grav}

have radio pulsars: I, dI/dt, ...;

may get $\ddot{Q}$ (LIGO)

Here, focus on NS surface emission

have to be able to see the stellar surface;
must be X-ray sources!

$$L = 4\pi R^2\ \sigma_{\rm SB} T_{\rm eff}^4\ \Rightarrow L/L_\odot = 1.8 \times 10^{-9} (T_{\rm eff}/10^4\ {\rm K})^4$$

$$\Rightarrow M = 26.5\ (d \equiv 10\ {\rm pc})$$

(R = 10 km)

$$m = 36.5\ (d = 1\ {\rm kpc})$$

compare: faintest objects with HST *m* ~ 31

To be observable, need *much* higher $T_{\rm eff}$!

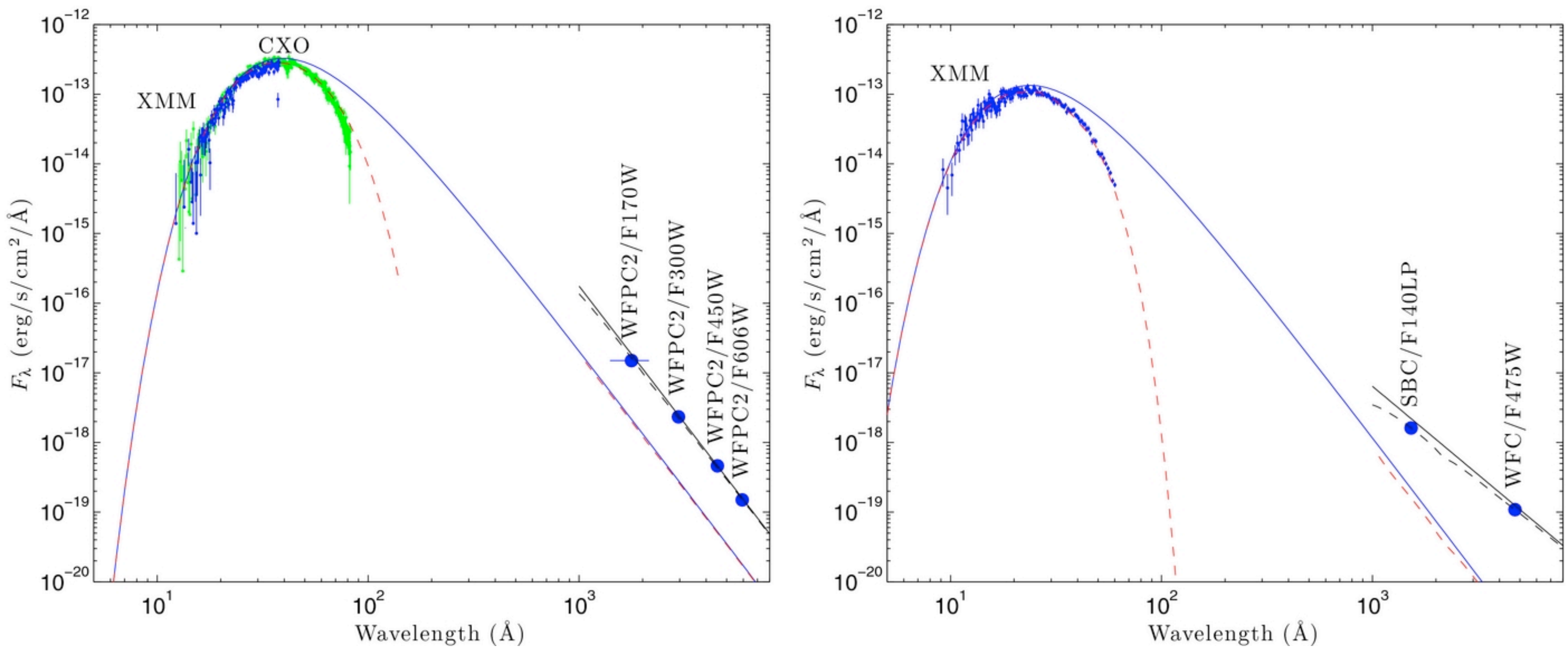
(we can't do much about *d* and *R*)

parsec? 3.1×10^{18} cm, or about three light years; Galactic Center is at 8.5 kpc

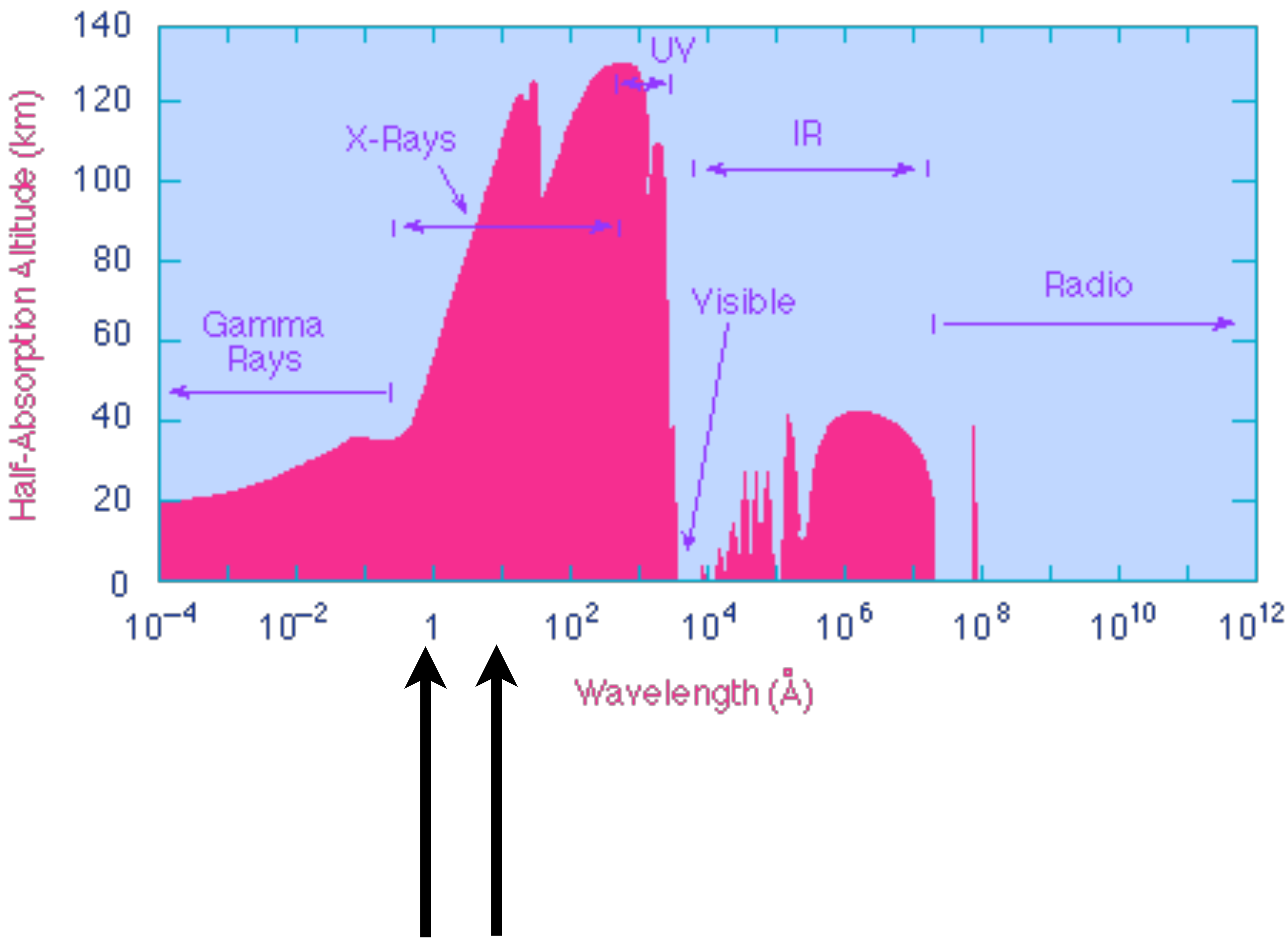
have to be able to see the stellar surface;
must be X-ray sources!

neutron stars start showing up as X-ray sources, once T_{eff} > few 10^5-10^6 K; Wien: $\lambda_{max} = 29\ (T/10^6\ \mathrm{K})^{-1}$ Angstrom

at that point, some NS also optically detectable (m ~ 26-28)



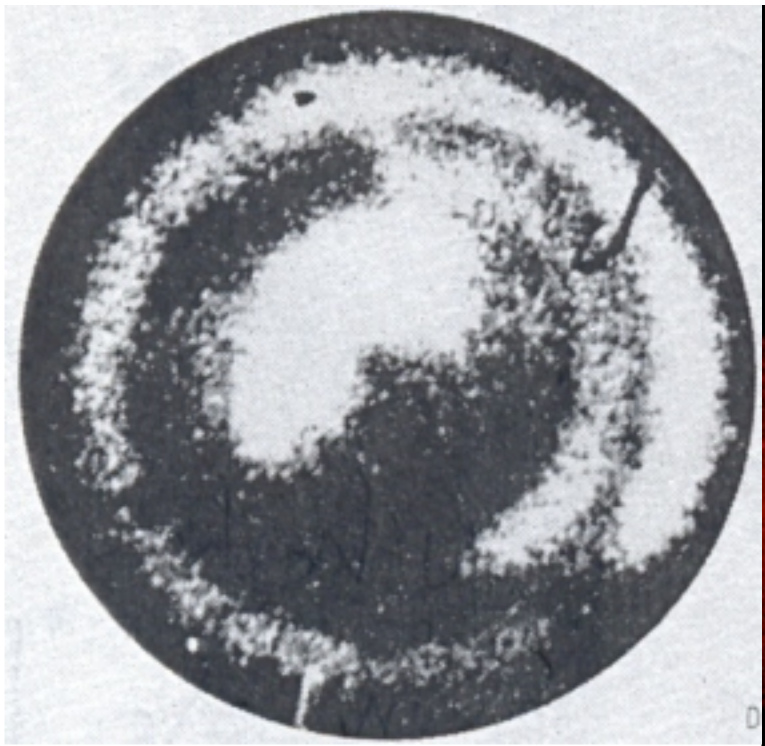
X-rays from outer space



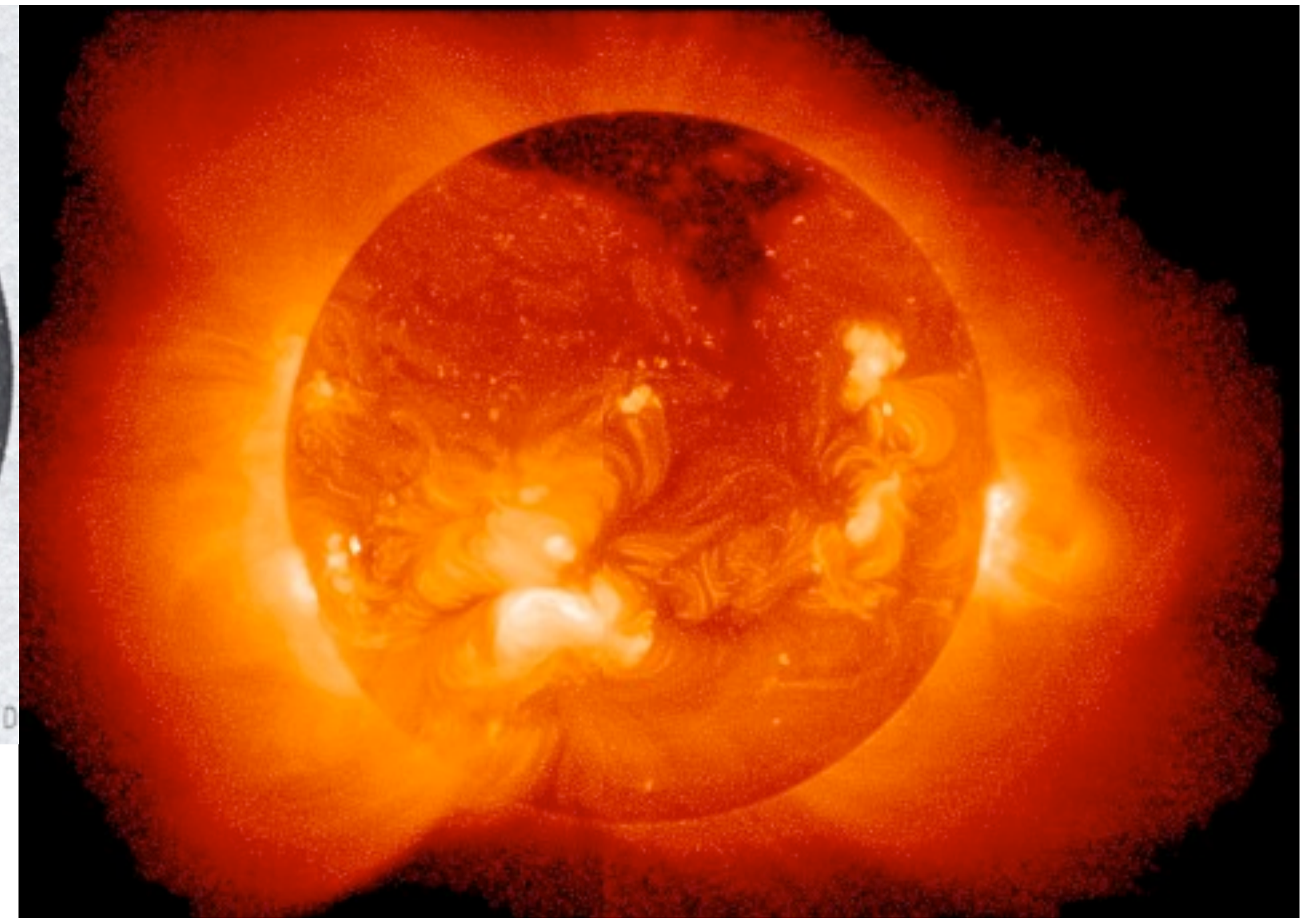
2-10 keV

credit: NRAO

X-rays from outer space



April 1960, rocket (NRL)



Yohkoh (ISAS), early 1990's

first object in high energy astrophysics: the Sun

X-ray astronomy

first extrasolar source: Sco X-1 (1962)

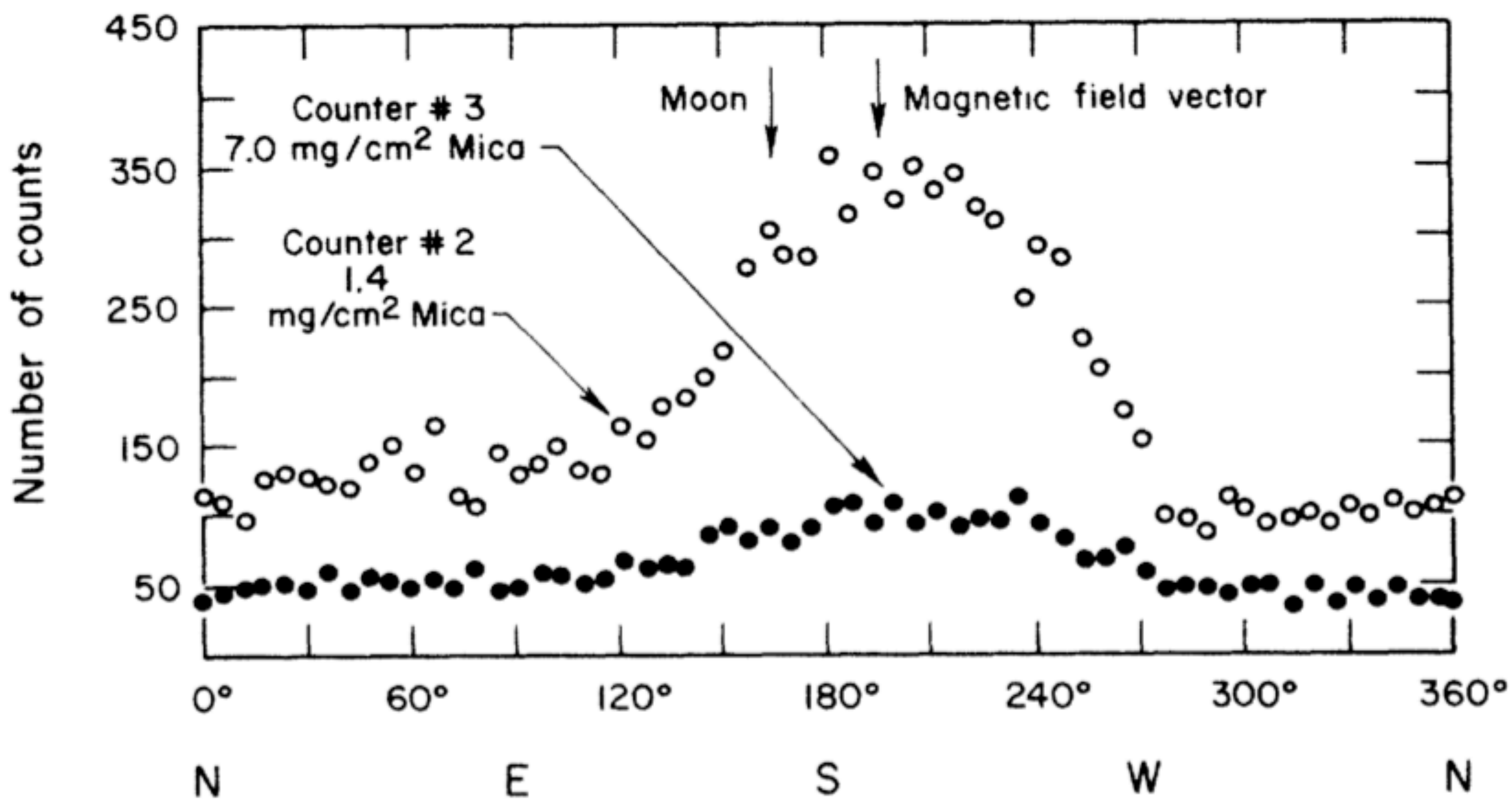


FIG. 1. Number of counts versus azimuth angle. The numbers represent counts accumulated in 350 seconds in each 6° angular interval.

No. 4, 1978 FOURTH *UHURU* CATALOG 409

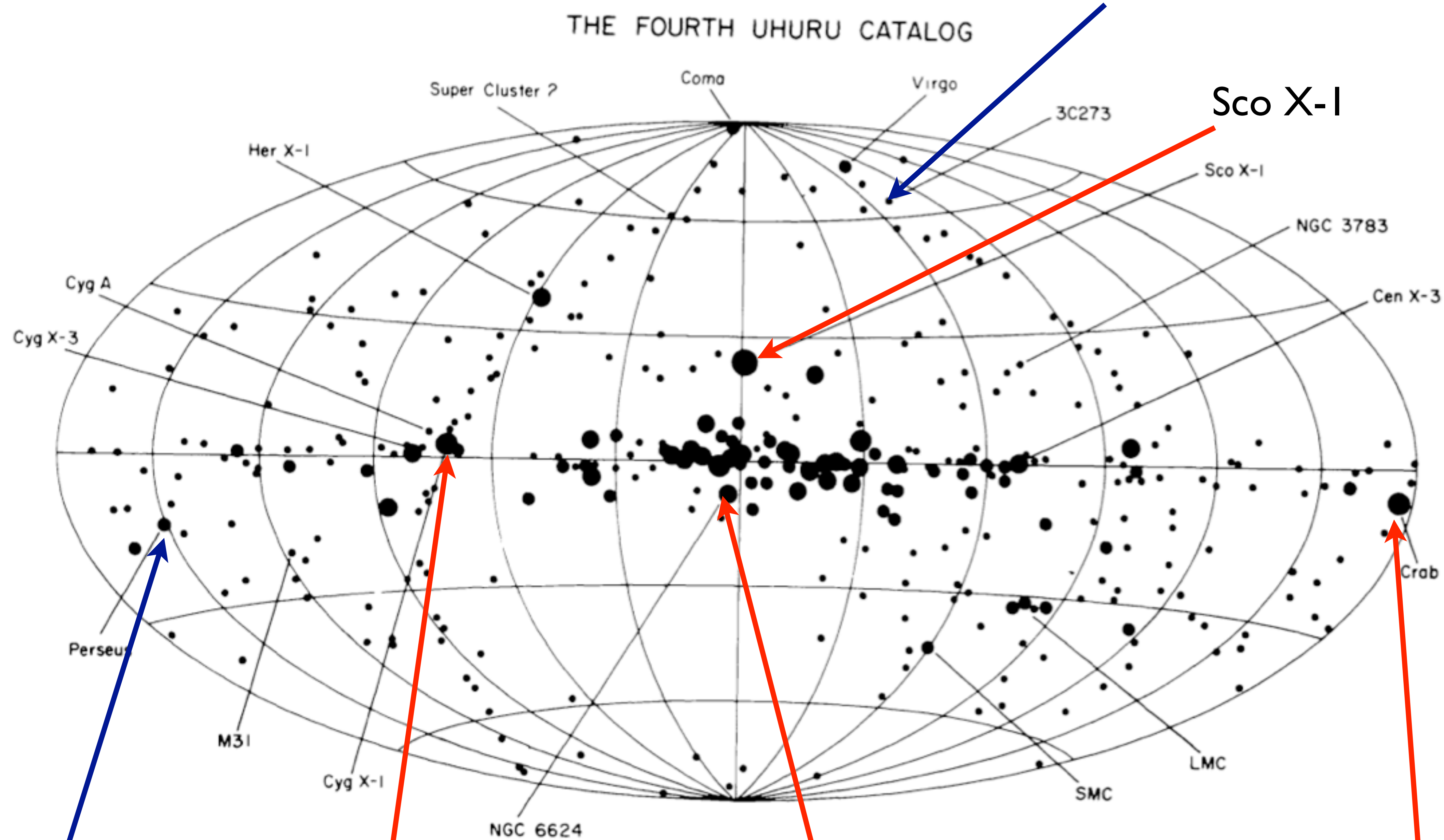


FIG. 5.—The sources listed in Table 1 are displayed in galactic coordinates. The size of the symbols representing the sources is proportional to the logarithm of the peak source intensity.

Perseus Cluster
(first Fe K line)

Cyg X-1

Globular Cluster NGC 6624
(first X-ray bursts)

Crab

Forman et al., ApJS, 1978

Uhuru (~1970): bright sources survey

the brightest sources are all Galactic-
but how do we know most of them involve compact objects?

brightest sources; $F_X \sim 10^{-8}$ erg/cm^2/s (2-10 keV):

$L_X \sim 10^{38}$ (d/10 kpc)^2 erg/s

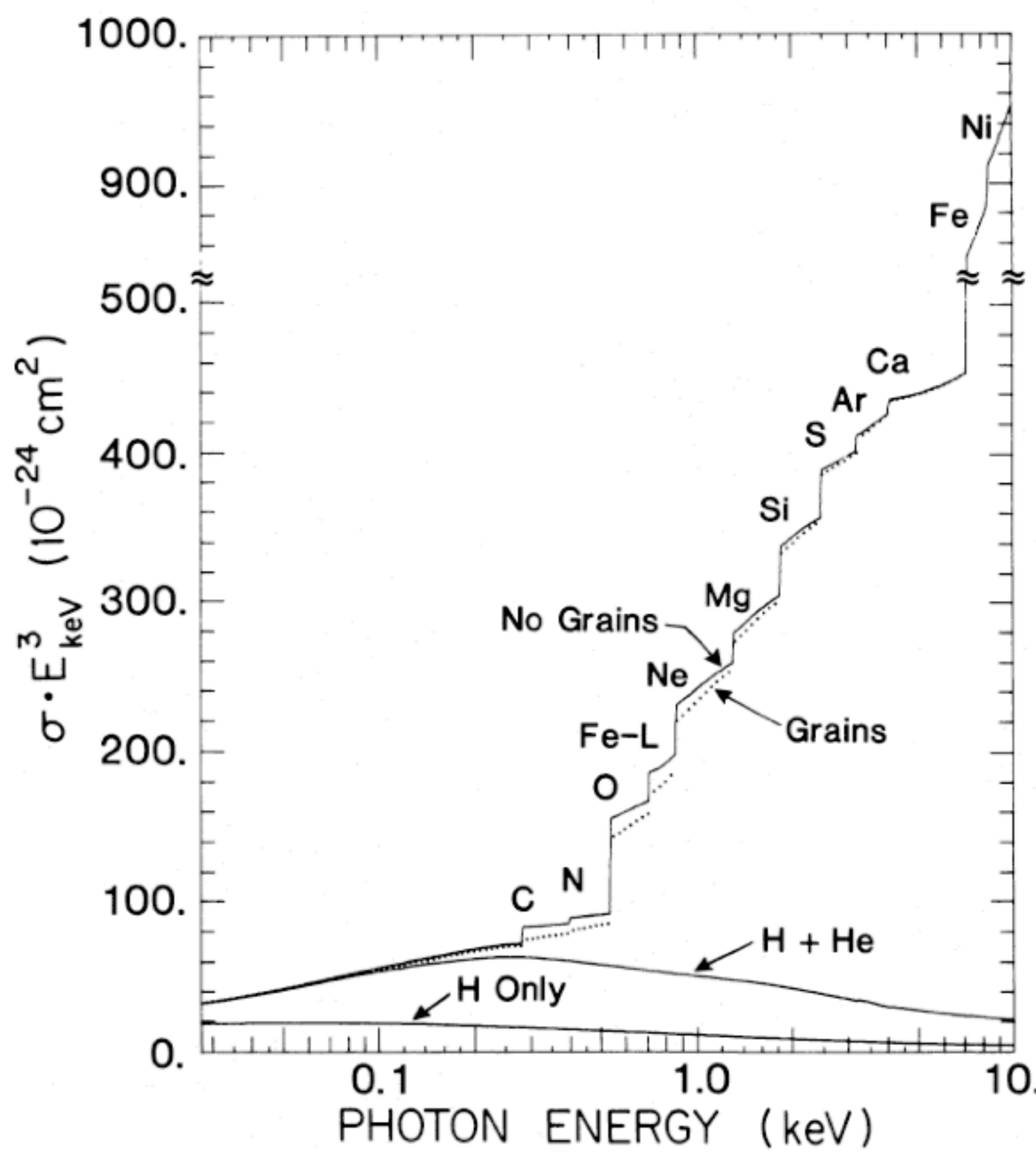
Strong clue:

that is the Eddington luminosity for a $1 M_\odot$ object!

$$\left(F_{\rm rad} = F_{\rm grav} \Rightarrow L = \frac{4\pi G M m_p c}{\sigma_{\rm T}} \right)$$

weak clue that *distances* are correct: photoelectric absorption by the interstellar gas of the Galaxy

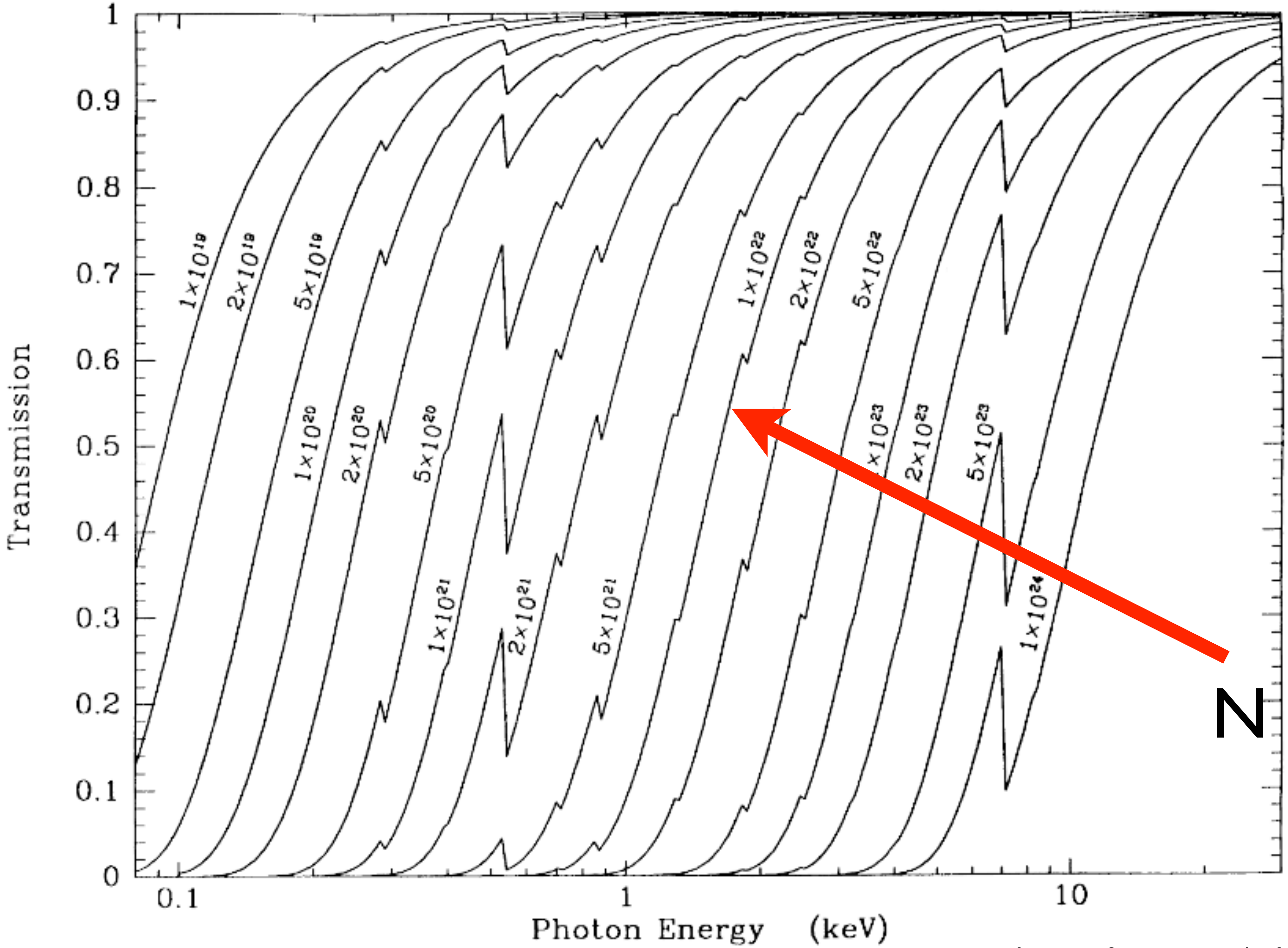
$n \sim 1\ \mathrm{cm^{-3}}$, so $N \sim 3\mathrm{x}10^{22}\ \mathrm{cm^{-2}}$ to Galactic Center



photoelectric absorption cross section for interstellar gas;
'cosmic' element abundances

Morrison &McCammon 1983

transmission of the interstellar gas



N = 10^{22} cm^{-2}

from Seward (1999)

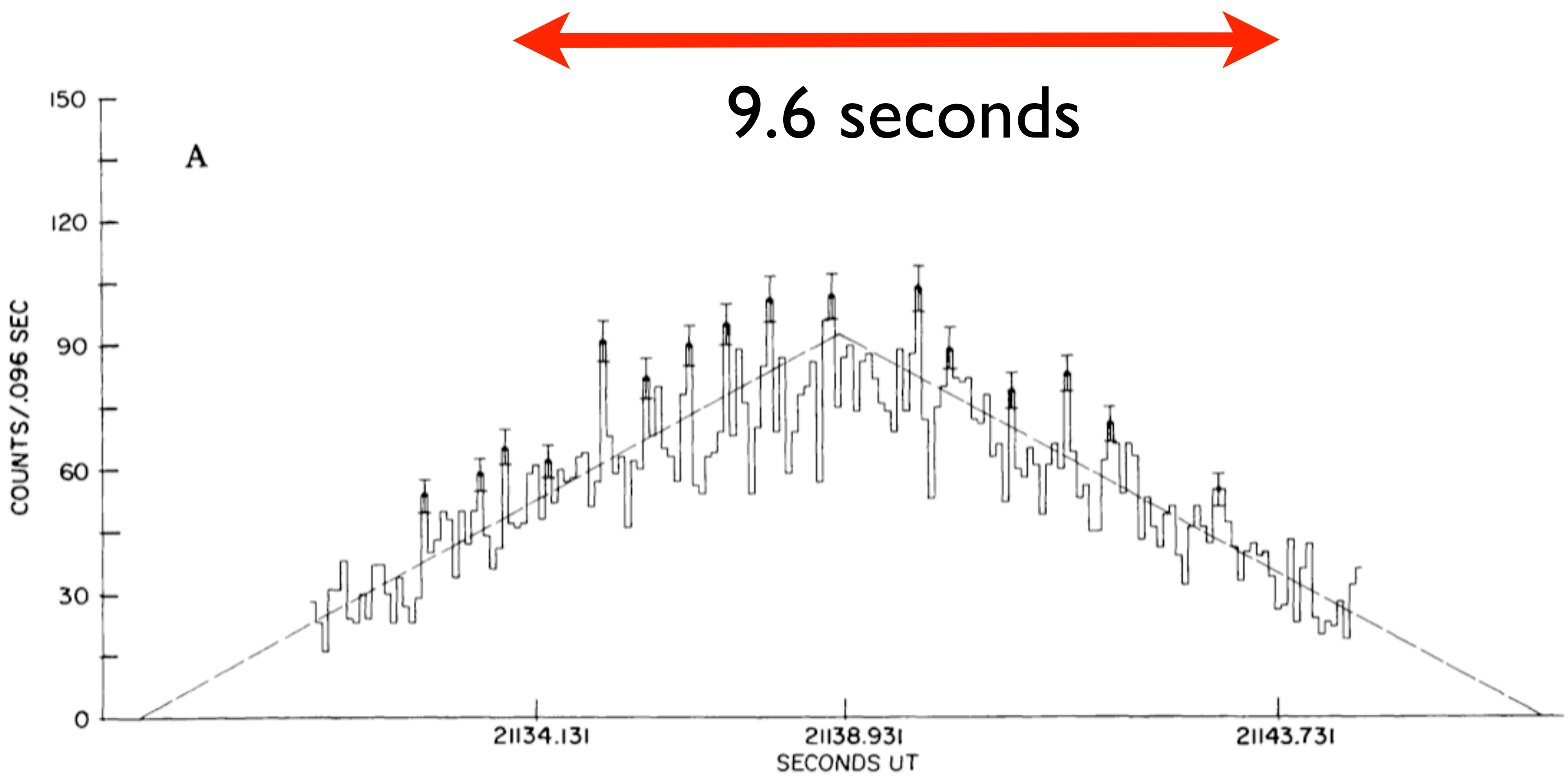
and you can see this in the spectra of the sources but of course a $1M_\odot$ *star* does not emit 10^{38} erg/sec in X-rays!

For compact objects,
conversion of gravitational energy is much more efficient than thermonuclear fusion:

$$\eta_{\mathrm{H}\rightarrow\mathrm{He}} = 0.007; \quad \eta_{\mathrm{grav}} \sim \frac{GM}{c^2 R} = 0.15 \left(\frac{M}{M_\odot}\right) \left(\frac{R}{10\ \mathrm{km}}\right)^{-1}$$

so *accretion of gas* at a moderate rate onto a neutron star can easily power the luminous Galactic X-ray sources

further early proof for the correctness of this idea



Cyg X-1 showed rapid variability
Oda, M., et al. 1971

and Cen X-3 is *periodic* (4.8 sec): spin!

Giacconi et al. 1971

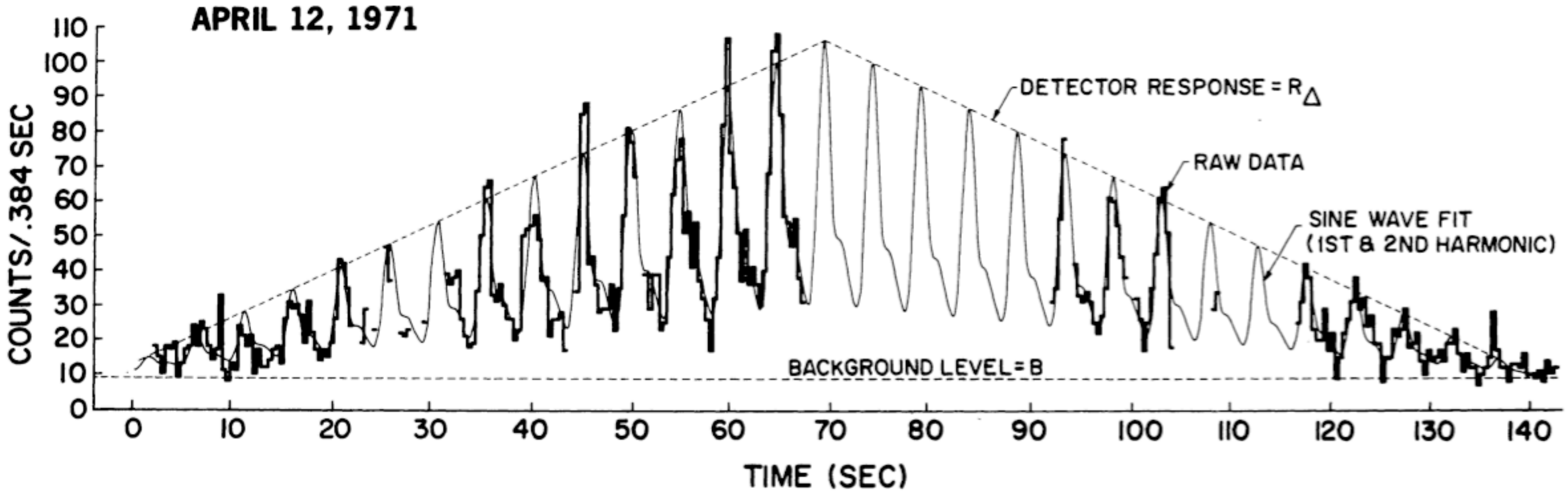


FIG. 2.—Histogram shows counts accumulated in 0.384-s intervals in the 2–6-keV energy range as a function of time on 1971 April 12. Missing portions of the data are due to quick-look transmission dropout. The spacecraft spin rate during this observation was about 0°.07 s^{-1}. The sinusoidal function fit to the data is shown as the continuous curve and is given analytically by the function $f = B + R_\Delta[A_0 \sin(\omega t + \phi_1) + A_1 \sin(2\omega t + \phi_2) + A_2 \sin(3\omega t + \phi_3) + C]$.

and the period is periodically modulated: *binary motion!*

Schreier et al. 1972

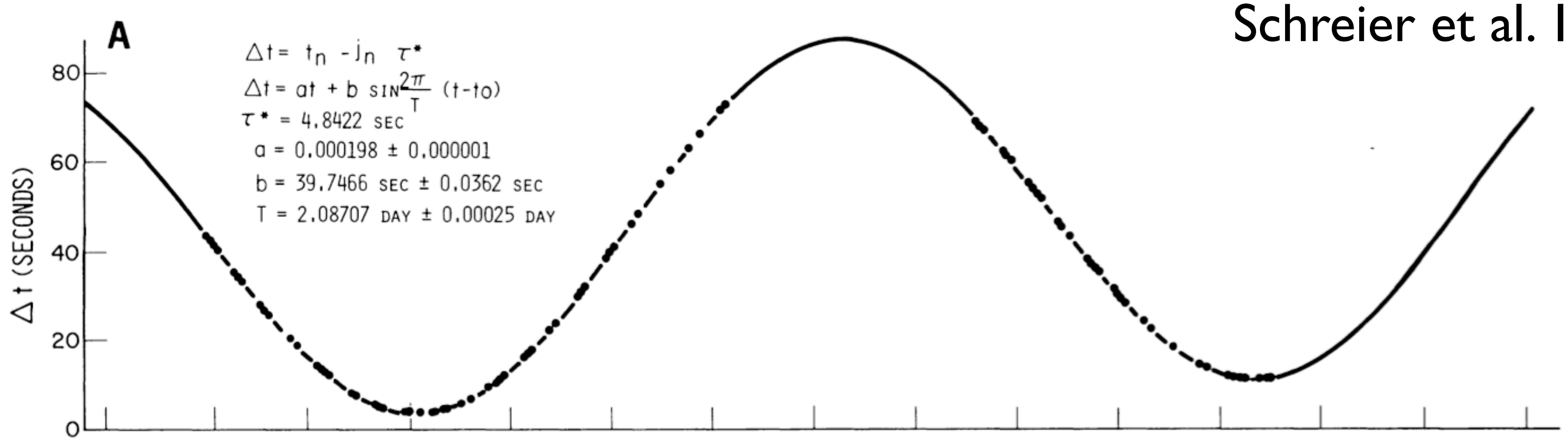


FIG. 4.—(*a*) The difference Δt between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. A best-fit function and the values of the parameters are given. (*b*) The dependence of the pulsation period τ on time as derived from the best-fit phase function above is shown and the values of the parameters given. (*c*) The intensity observed and the light curve predictions are shown for the same set of data. Note the coincidence of the null points of the period function with the centers of the high- and low-intensity states.

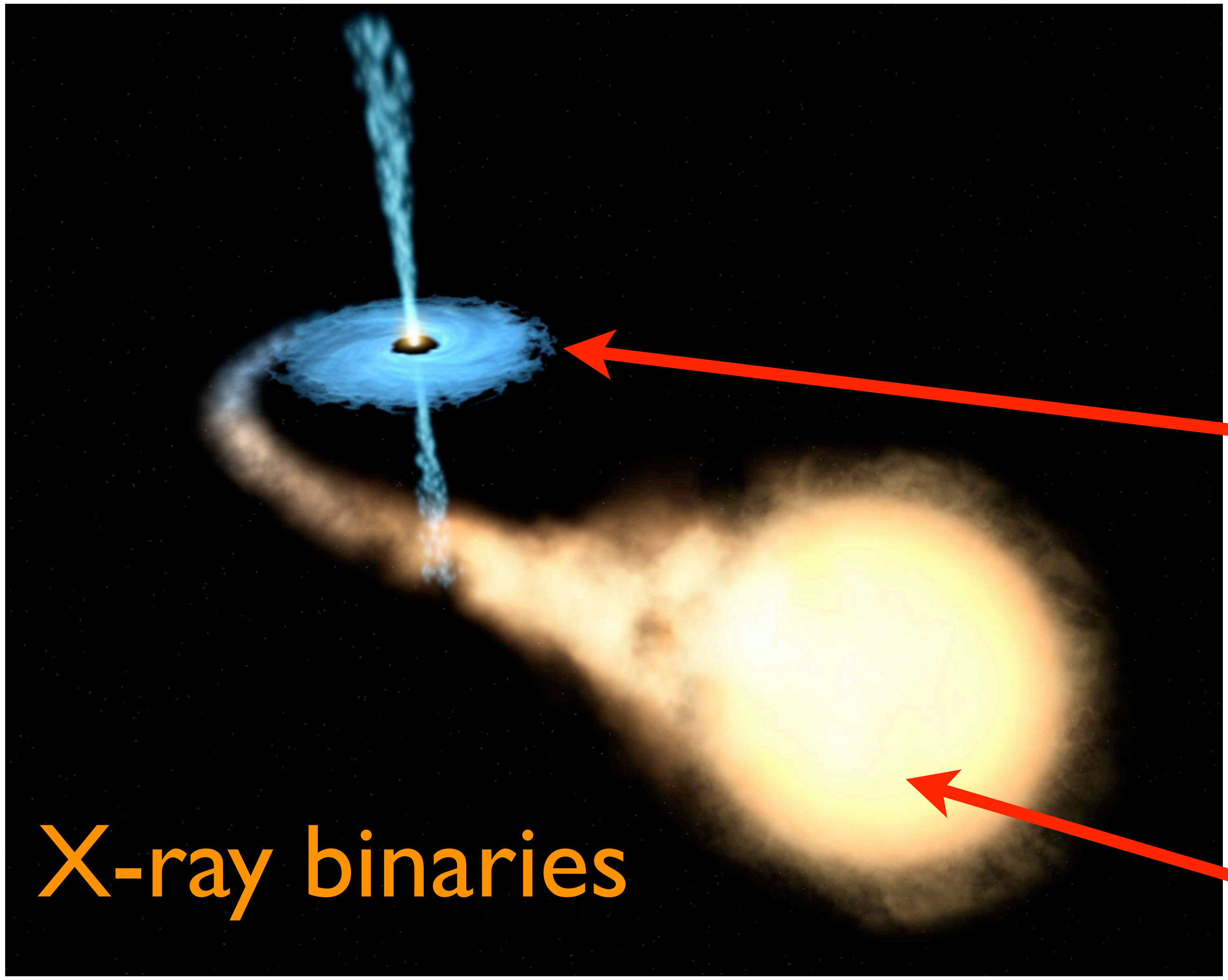
Massive companion star

young neutron star
usually large *B*:
accretion onto NS
B-pole(s)

stellar wind

binary periods ~ days
spin period of the
compact star ~ ms-sec:
neutron star or black hole
compact object accretes from stellar wind

Low-mass companion



accreting gas has
J wrt compact object
(binary motion):
often results in
disk accretion

secondary fills
critical Roche surface

binary periods ~ days
evolution of the normal star
drives mass transfer

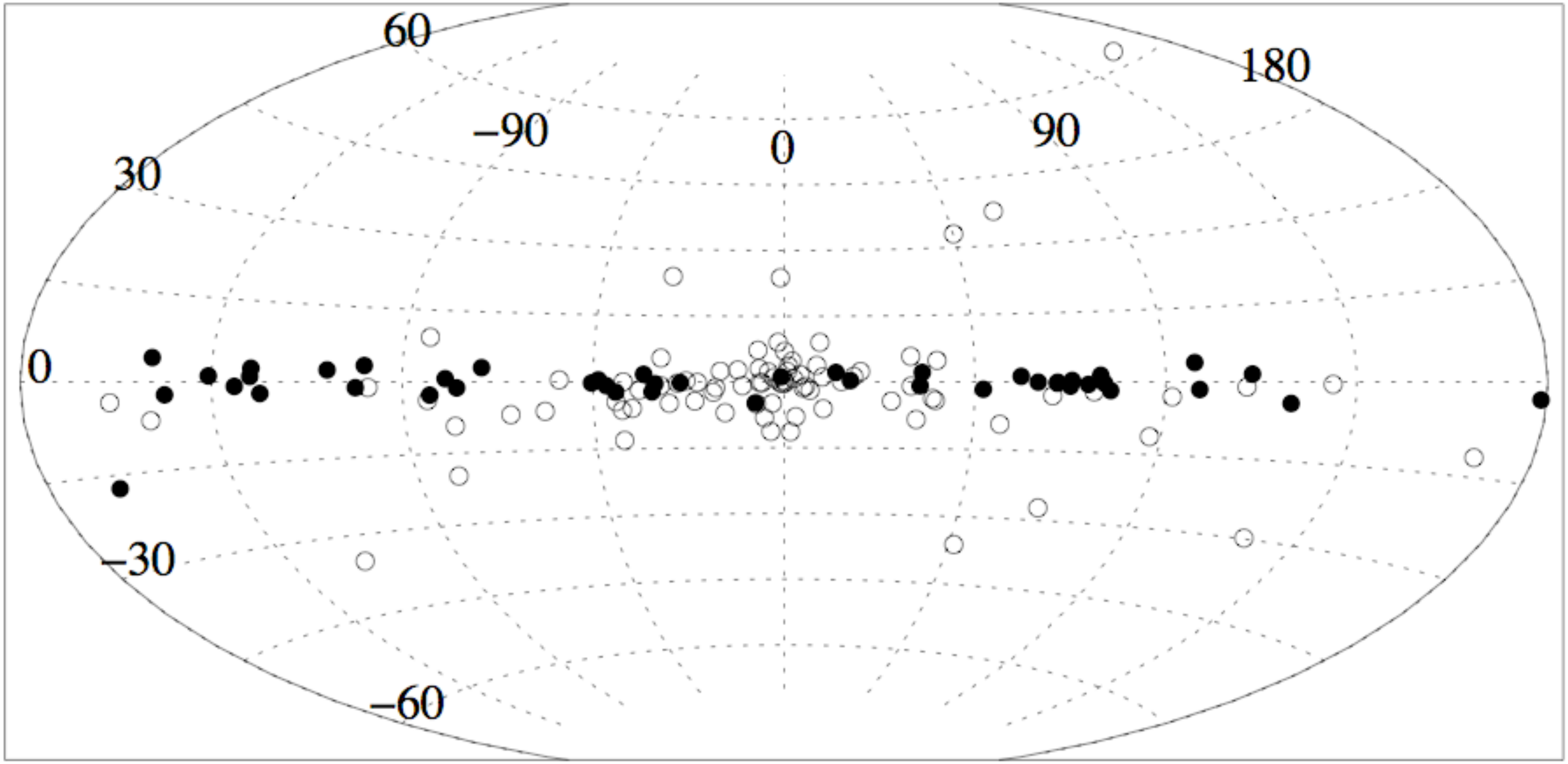


FIGURE 2.1.: Distribution of LMXBs (open circles) and HMXBs (filled circles) in the Galaxy. In total 86 LMXBs and 52 HMXBs are shown. Note the significant concentration of HMXBs towards the Galactic Plane and the clustering of LMXBs in the Galactic Bulge.

accreting neutron stars in the Galaxy

Hans-Jakob Grimm, PhD Thesis 2003

Stellar Structure and Evolution

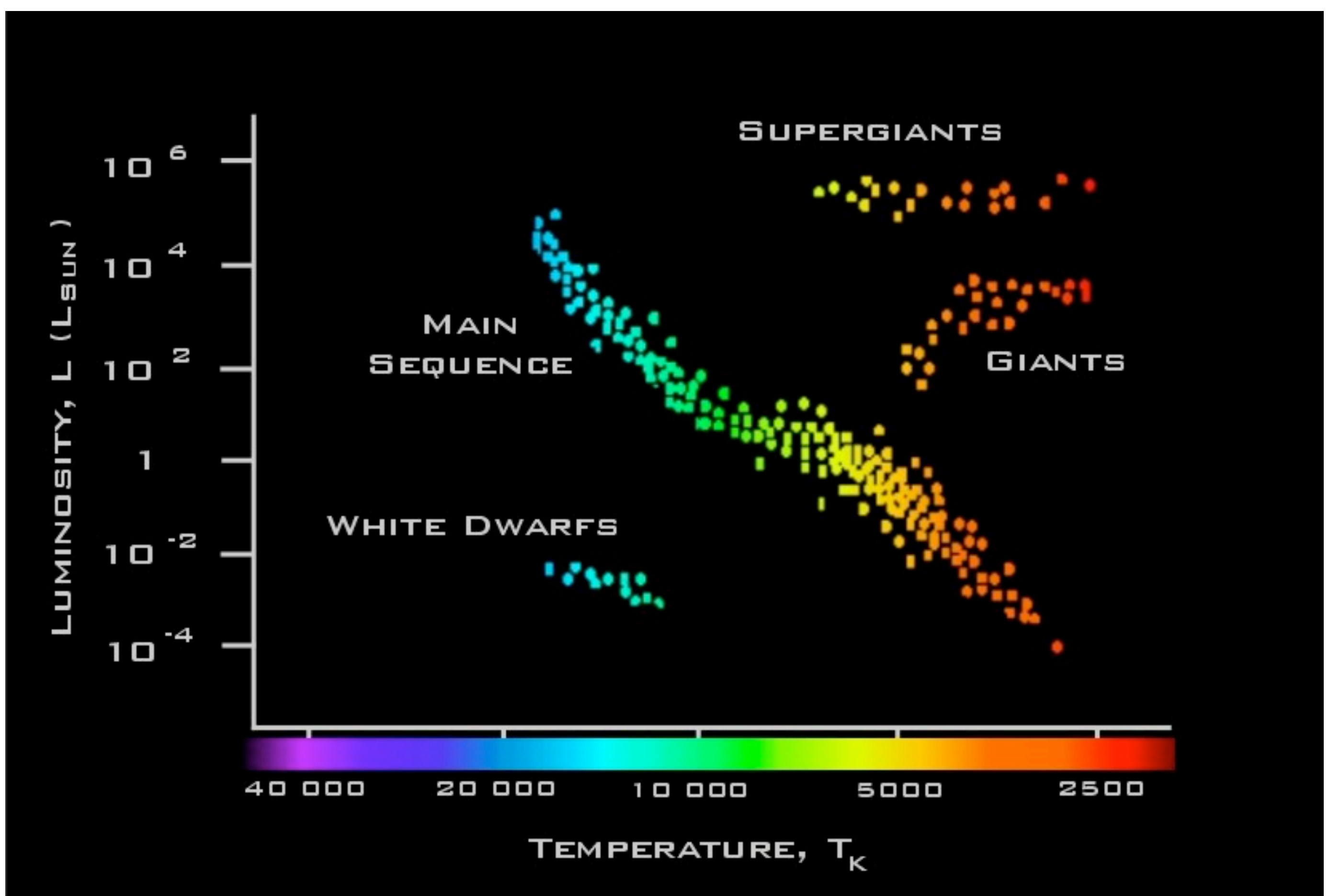
Most stars on the *Main Sequence* in luminosity-surface temperature diagram ('Hertzsprung-Russell Diagram')

Empirically: $L \propto M^4$: massive stars are luminous

Since nuclear fuel reservoir $\propto M$:

lifetime $\propto M^{-3}$: massive stars burn out fast; are therefore 'young'

t(Sun) ~ 10 billion years; $M \sim 10\ M_\odot$: t ~ 10 million years



High-mass X-ray binaries

Massive companion star;
luminous, outshines accretion opt/UV
short-lived as X-ray binary: NS young
high B-field: X-ray pulsars
BH most likely in these binaries

So high-mass binaries are recent descendants from massive stars

while low-mass binaries are old descendants from massive stars

Low-mass X-ray binaries

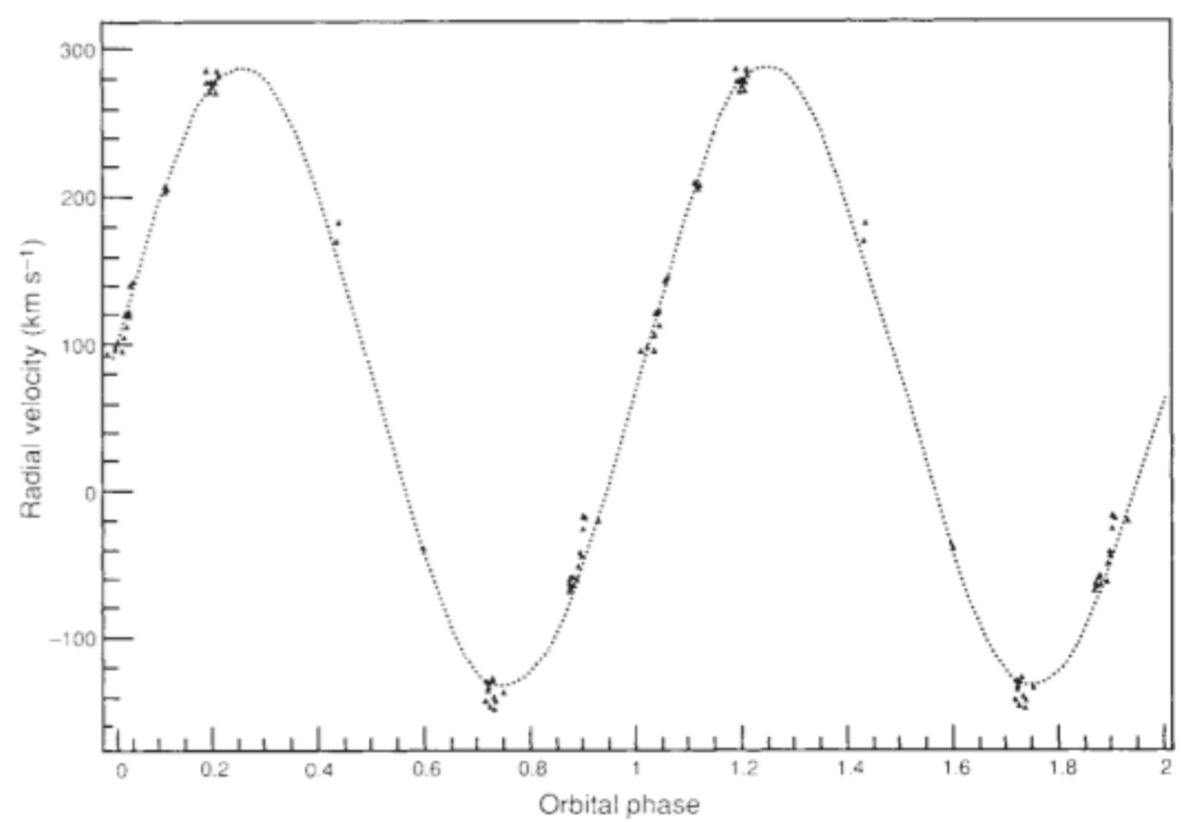
low-mass companion star;
faint, accretion outshines star
long-lived as X-ray binary: NS old
B-field low/gone: no pulsations
host 'bursters' (*see later*)

constraints on NS masses from orbital dynamics of binary stars

$$m_1 + m_2 = \frac{4\pi^2}{G}\frac{a^3}{P^2} \qquad \text{(Kepler)}$$

our case: cannot resolve *a*;
all we usually have is periodic radial velocity for companion

FIG. 1 Radial velocity curve and best sine fit for the secondary of V404 Cyg with respect to the rest frame of 61 Cyg A (the template used in the initial cross-correlation analysis), which has a gamma velocity of $-64.5 \pm 2.2\ \mathrm{km\ s^{-1}}$. The ephemerides given in the text have been corrected for this.



V404 Cyg; Casares, Charles, Naylor, (1992)

constraints on NS masses from orbital dynamics of binary stars

orbital inclination

$$\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i = \frac{P}{2\pi G} v_{1,\mathrm{r}}^3$$

radial velocity of companion star

measurable combination of parameters: 'mass function',
puts **lower** limit on mass of compact object, m_2

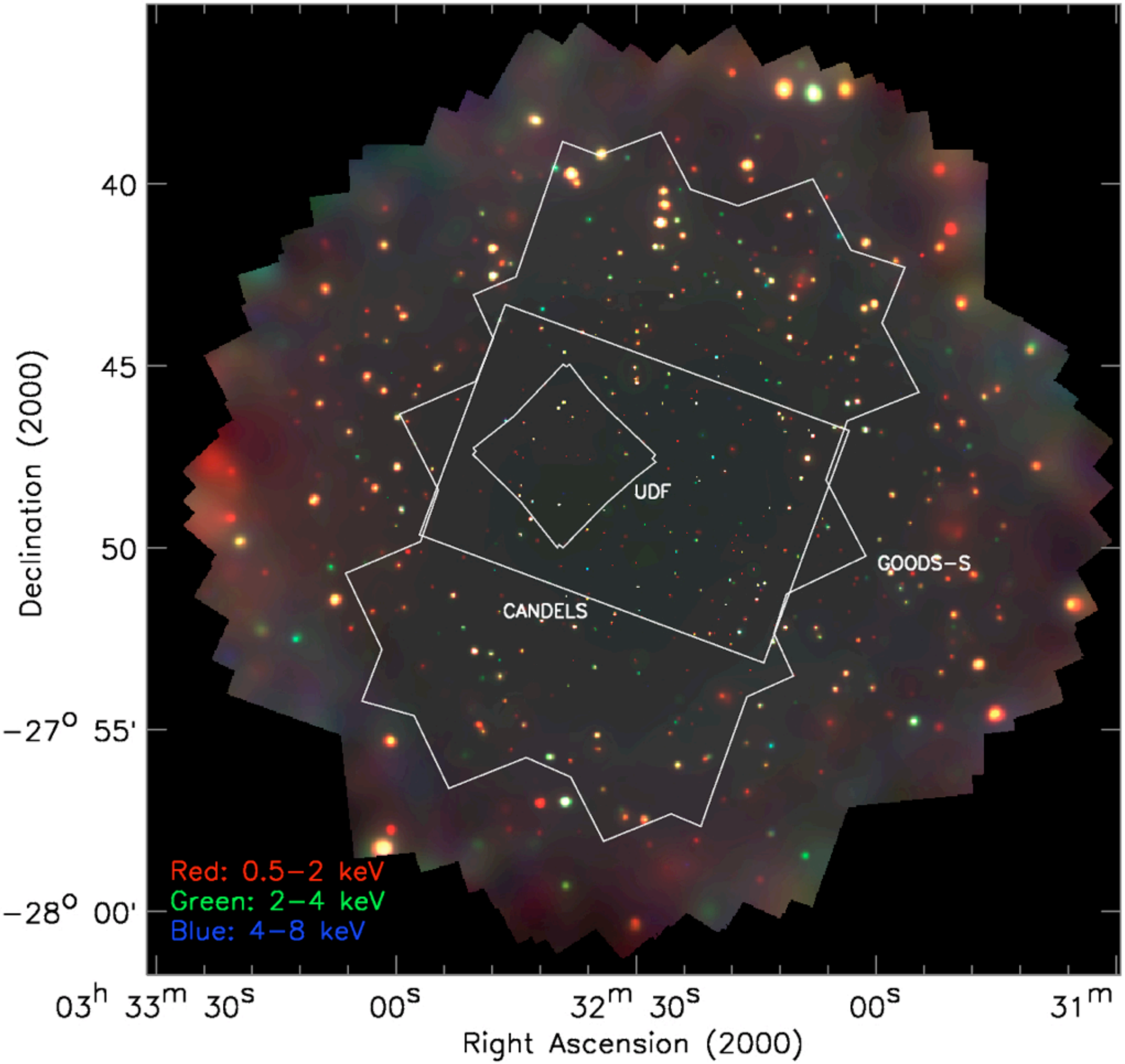
(and so, in V404Cyg, m_2 > 6.8 Solar masses)

NB: relativistic NS-NS binaries different: either see GR effects, and/or have two radial velocities (both NS)

OK, back to X-ray astronomy

more recently: **imaging**, imaging surveys-
faint sources (faint NS in Globular Clusters! isolated neutron stars!), extragalactic astronomy

a few illustrative examples

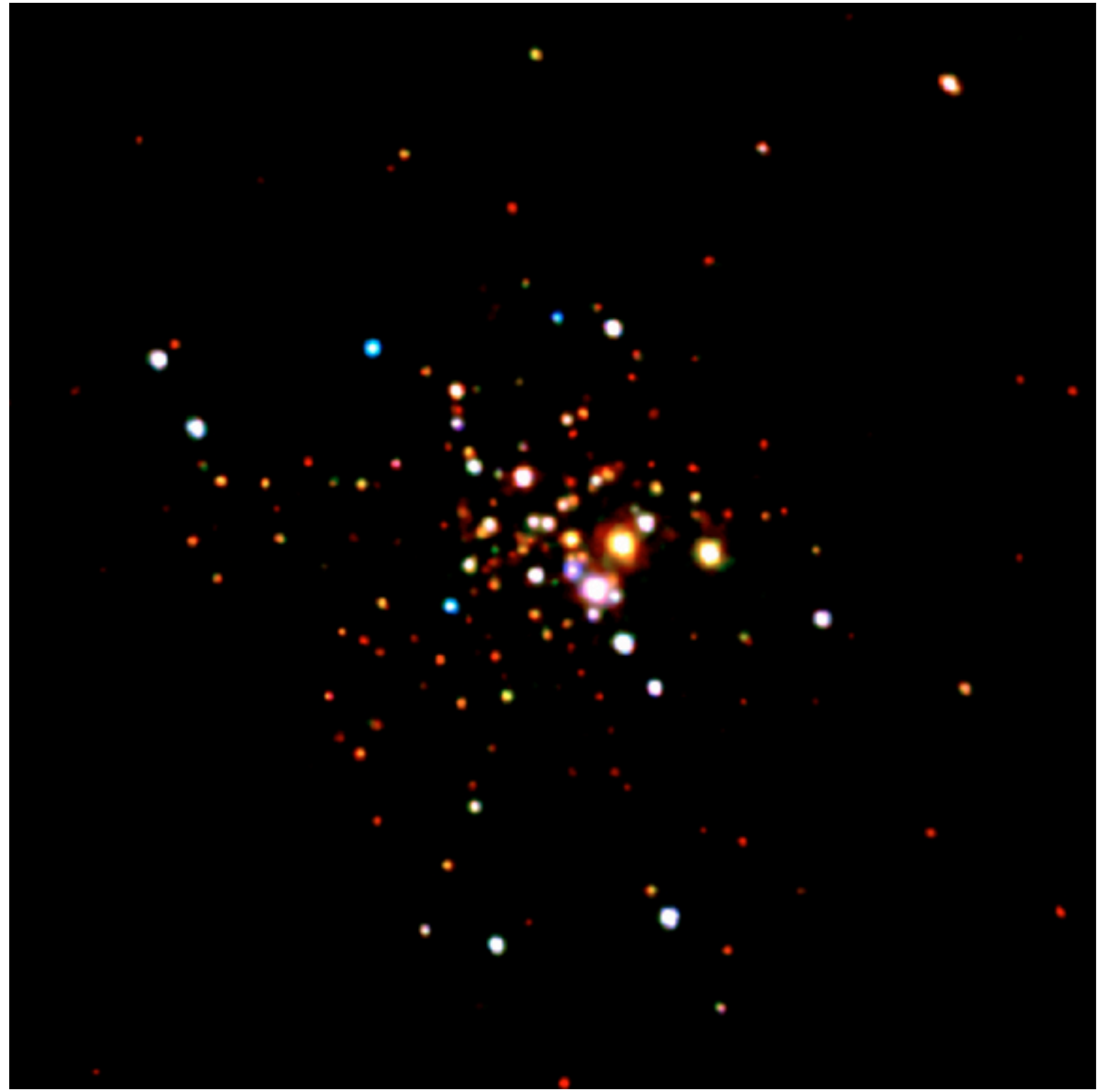


Extragalactic astronomy and cosmology: very deep survey with *Chandra* X-ray telescope

X-ray sources
in globular cluster
47 Tucanae

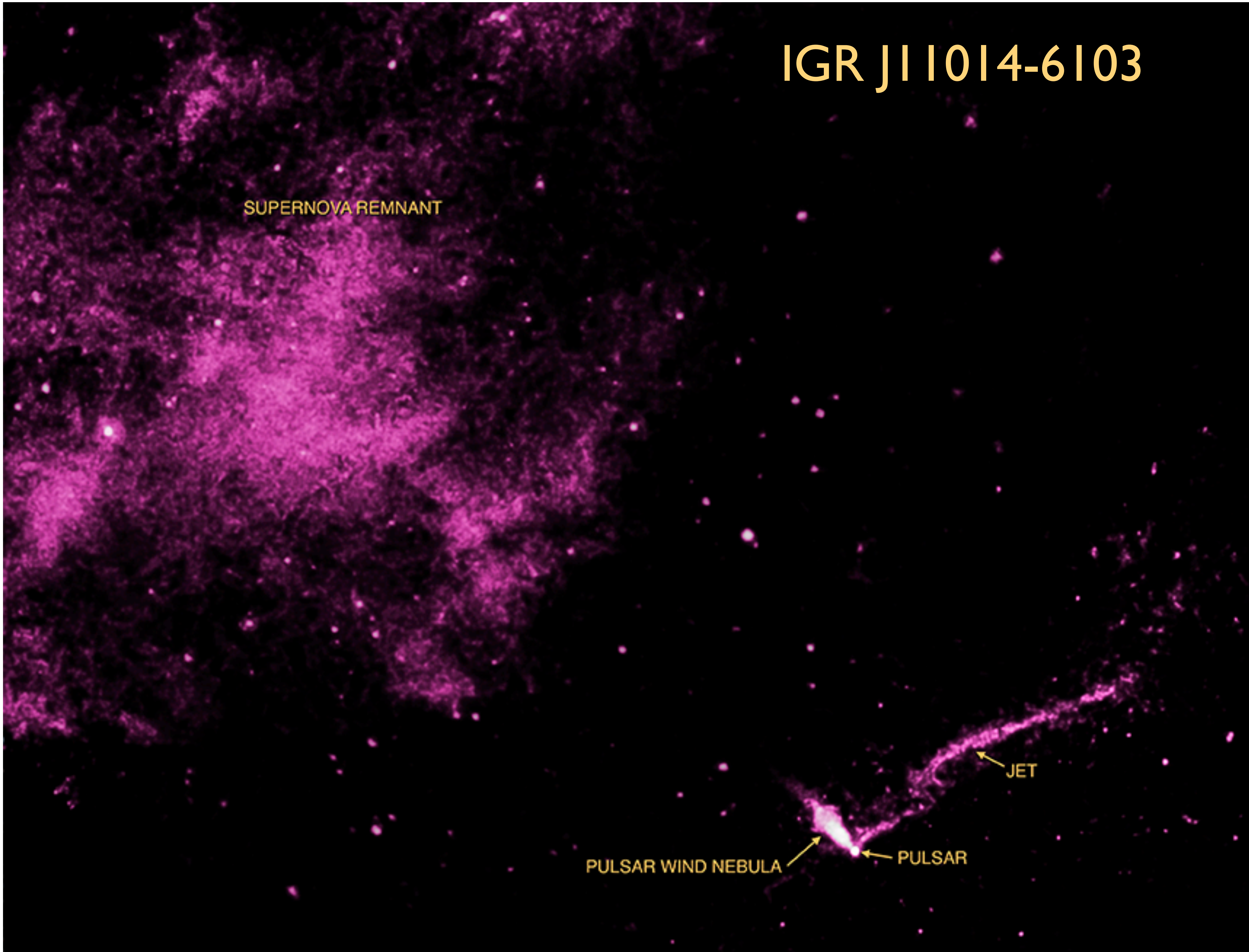
msec pulsars,
quiescent X-ray
binaries, ...

(Heinke et al. 2005)



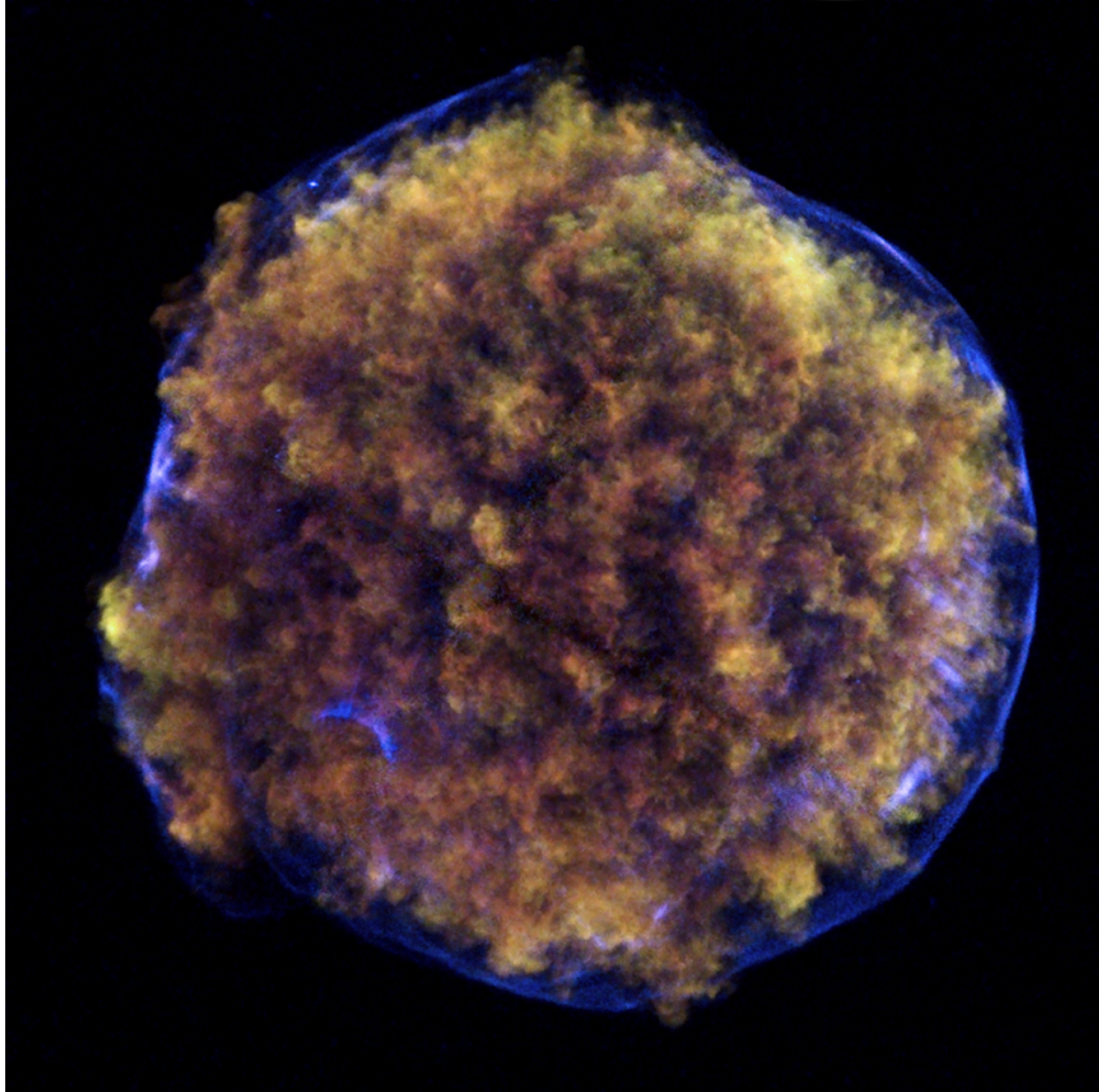
2.5 arcmin

Chandra X-ray Observatory



press reselase Feb 18, 2014: a pulsar shooting out of a Supernova remnant
Chandra Observatory, Pavan et al. (2014)

Chandra X-ray images



remnant of Tycho's supernova

galaxy cluster 1E0657-56
(the 'Bullet Cluster') at z = 0.3

X-ray Emitting Neutron Stars: small Zoology

accreting NS in binaries
single accreting NS (from the ISM)
single NS, rotation powered or cooling

X-ray Emitting Neutron Stars: small Zoology

accreting NS in massive binaries:
X-ray emission from accretion outshines NS surface;
much of the accretion stream dominated by strong B-field
not much use for present purpose *(except classical optical binary orbital dynamics studies! but that does not give R!)*

accreting NS in low-mass binaries:
accretion disk outshines NS surface most of the time,
except in ‘X-ray bursters’ and ‘quiescent LMXB’

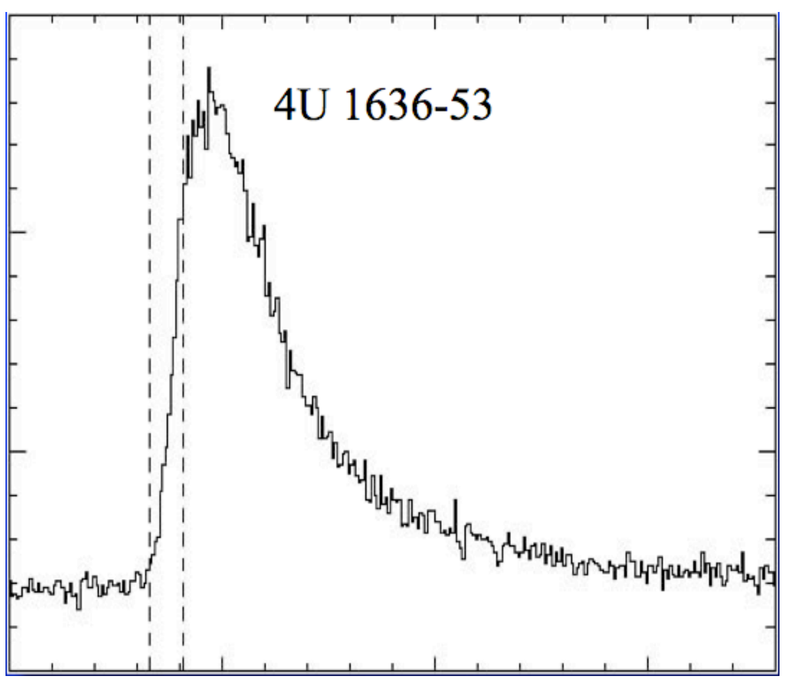
X-ray Emitting Neutron Stars: small Zoology

X-ray burst sources

when accretion rate is right, accreted gas accumulates, becomes unstable to runaway thermonuclear burning:

episodic 'flashes' (tens of seconds) in X-rays
burning heats stellar surface to $\sim 10^7$ K,
outshines accretion by factor ~10

X-ray flux



time

example: burster 4U 1636-53

empirical evidence for low *B*-fields!
but.... rapidly spinning NS!!

from Markwardt (2007)

X-ray Emitting Neutron Stars: small Zoology

single NS accreting from the ISM:
'Coulomb stopping' heats stellar surface
first suggested by Zeldovich & Shakura
(1967! *before radio pulsars!!*)

given prevalence of NS in Galaxy, had expected to discover
many of these (*ROSAT* All Sky Survey- see later)
but in fact, not a single confirmed example known
(velocities of NS higher than optimistically assumed?)

SOVIET ASTRONOMY – AJ VOL. 13, NO. 2 SEPTEMBER-OCTOBER, 1969

X-RAY EMISSION ACCOMPANYING THE ACCRETION OF GAS BY A NEUTRON STAR

Ya. B. Zel'dovich and N. I. Shakura

Institute of Applied Mathematics, Academy of Sciences of the USSR
Physics Department, Moscow University

Translated from Astronomicheskii Zhurnal, Vol. 46, No. 2,
pp. 225–236, March–April, 1969
Original article submitted August 19, 1968

X-ray Emitting Neutron Stars: small Zoology

single NS, rotation powered:

several X-ray emitting NS known (radio- and gamma-ray pulsars)

X-ray emission evidently results from heating by (poorly understood) magnetospheric processes

problems with interpretation (strong B-field; small hot surface area << star)

cf. Table 4, Kaplan and van Kerkwijk, *ApJ*, **705**, 798 (2009)

X-ray Emitting Neutron Stars: small Zoology

Single, or Isolated NS;
and 'Central Compact Objects'

Table 4
Properties of the Isolated Neutron Stars and Related Rotation-powered Pulsars

Source	Timing[a]				Spectrum[b]					d[c]	Age[d]	Refs.
	P (s)	B_{dip} (10^{12} G)	τ_{char} (Myr)	$\log_{10} \dot{E}$ (erg s^{-1})	PSPC (s^{-1})	kT (eV)	R_{BB} (km)	$\log_{10} L_{X,BB}$ (erg s^{-1})	$\log_{10} L_{X,tot}$ (erg s^{-1})	(pc)	(Myr)	
Isolated neutron stars												
RX J1308.6+2127	10.31	34	1.5	30.6	0.3	102	4.1	32.4	32.4	500	0.8–1.2	1, 2, 3, 4, 5, 6
RX J0720.4−3125	8.39	24	1.9	30.7	1.6	87	6.4	32.5	32.5	360	0.5–1.0	7, 8, 9, 10, 11, 12
RX J0806.4−4123[e]	11.37	25	3.3	30.2	0.4	92	1.3	31.2	31.2	250	...	13, 14, this work
RX J2143.0+0654	9.44	20	3.7	30.3	0.2	102	3.2	32.1	32.1	430	...	15, 16, 17, 18, 19
RX J1856.5−3754	7.06	15	3.8	30.5	3.6	62	6.2	31.9	31.9	160	0.4	20, 21, 22
RX J1605.3+3249	...	...	...	...	0.9	93	4.7	32.3	32.3	390	0.1–1.0	23, 24, 14, 25, 26
RX J0420.0−5022	3.45	...	...	...	0.1	45	3.3	30.8	30.8	345	...	13, 14

the isolated NS: 'Magnificent Seven' (all RX sources!)
'cooling': shining by residual thermal energy

X-ray Emitting Neutron Stars: small Zoology

Central Compact Objects (CCO) in Supernova remnants

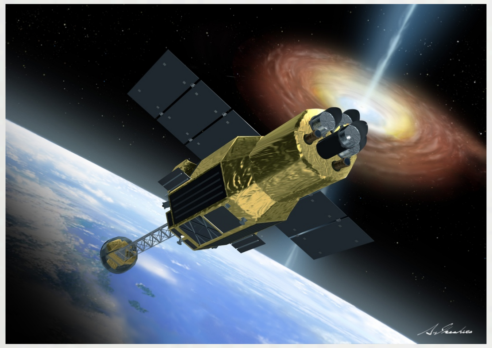
Table 1. Central Compact Objects in Supernova Remnants

CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{10} G)	$L_{x,\,\mathrm{bol}}$ (erg s^{-1})	References
RX J0822.0−4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}	1,2,3,4,5,6
CXOU J085201.4−461753	G266.1−1.2	1	1	⋯	<7	⋯	2.5×10^{32}	7,8,9,10,11
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	9.8	2.5×10^{33}	6,12,13,14,15,16,17
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	⋯	<40	⋯	1.5×10^{33}	18,19
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	⋯	<7	⋯	$\sim 1 \times 10^{33}$	11,20,21
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	⋯	⋯	⋯	3.9×10^{33}	22,23
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	3.1	5.3×10^{33}	24,25,26,27
CXOU J232327.9+584842	Cas A	0.33	3.4	⋯	<12	⋯	4.7×10^{33}	27,28,29,30,31,32,33
2XMMi J115836.1−623516	G296.8−0.3	10	9.6	⋯	⋯	⋯	1.1×10^{33}	34
XMMU J173203.3−344518	G353.6−0.7	~27	3.2	⋯	<9	⋯	1.3×10^{34}	35,36,37,38
CXOU J181852.0−150213	G15.9+0.2	1–3	(8.5)	⋯	⋯	⋯	$\sim 1 \times 10^{33}$	39

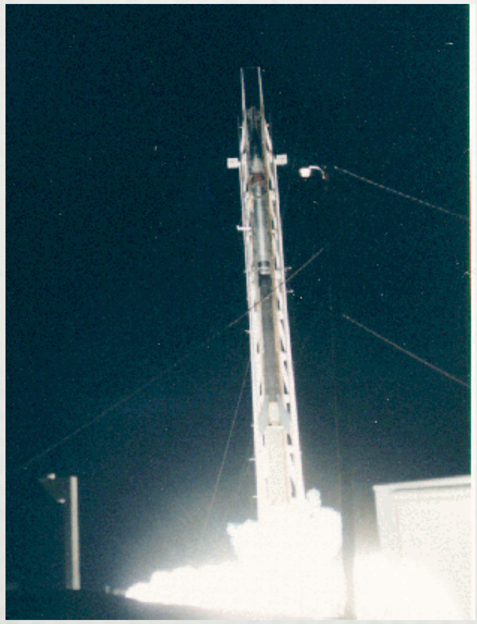
Gotthelf et al. (2013)

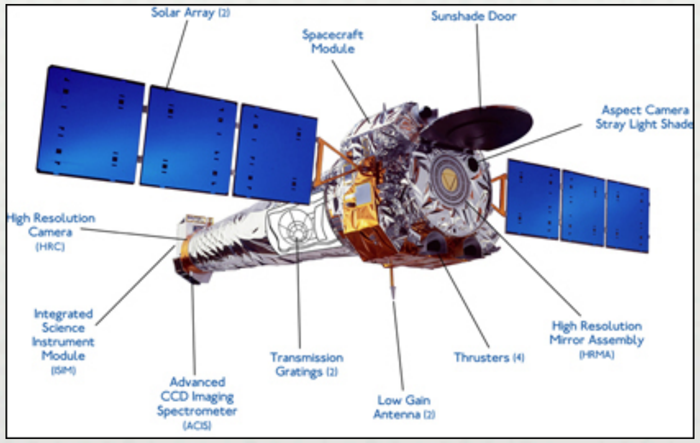
brief break

1.2 X-ray astronomy: instrumentation, techniques, observatories



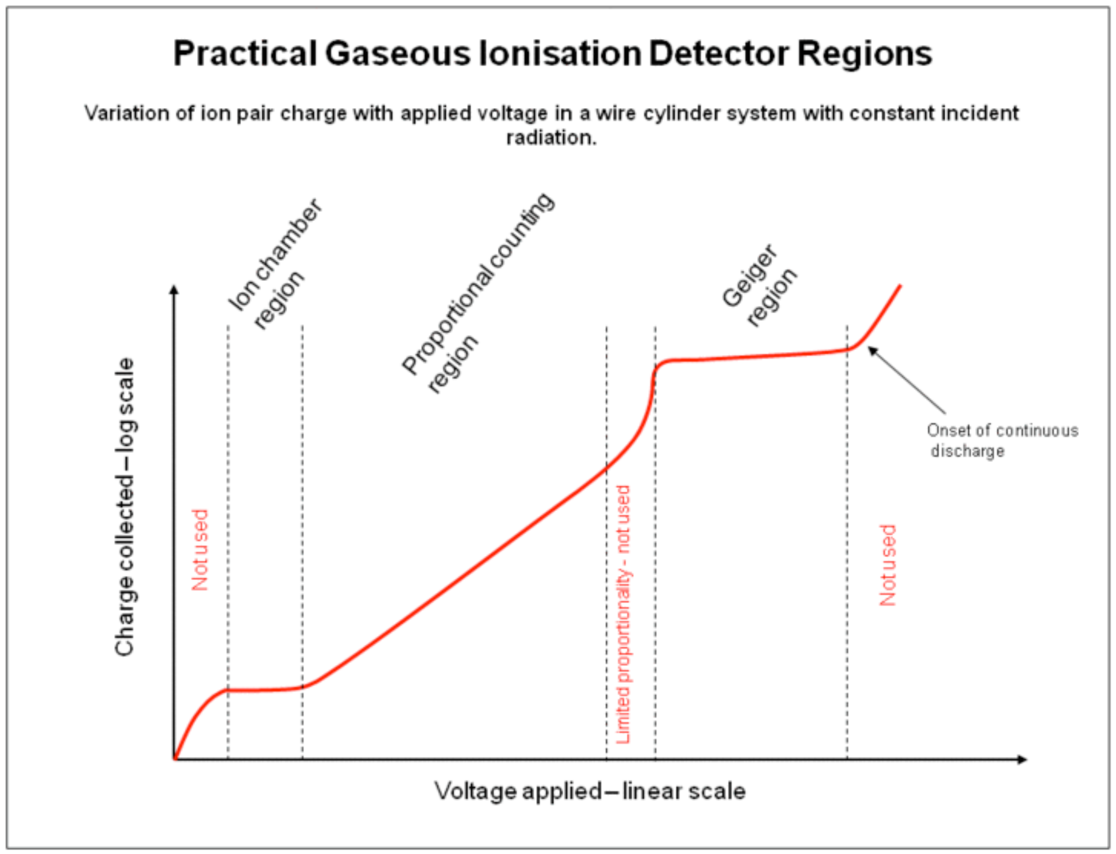
Detectors
Imaging (telescopes)
Spectroscopy
Surveys
Observatories

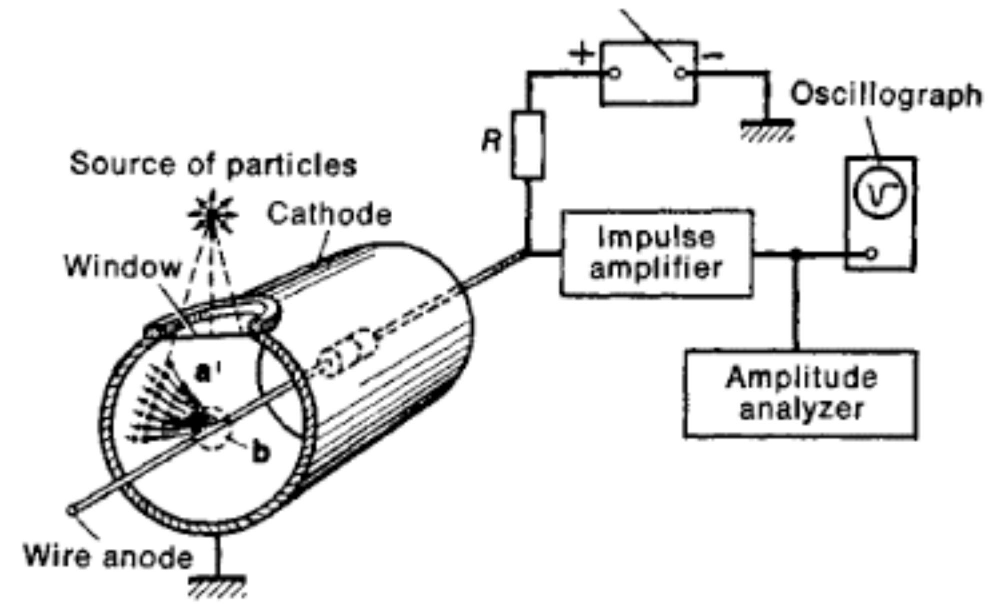




Detectors

Ionization detectors: proportional counters



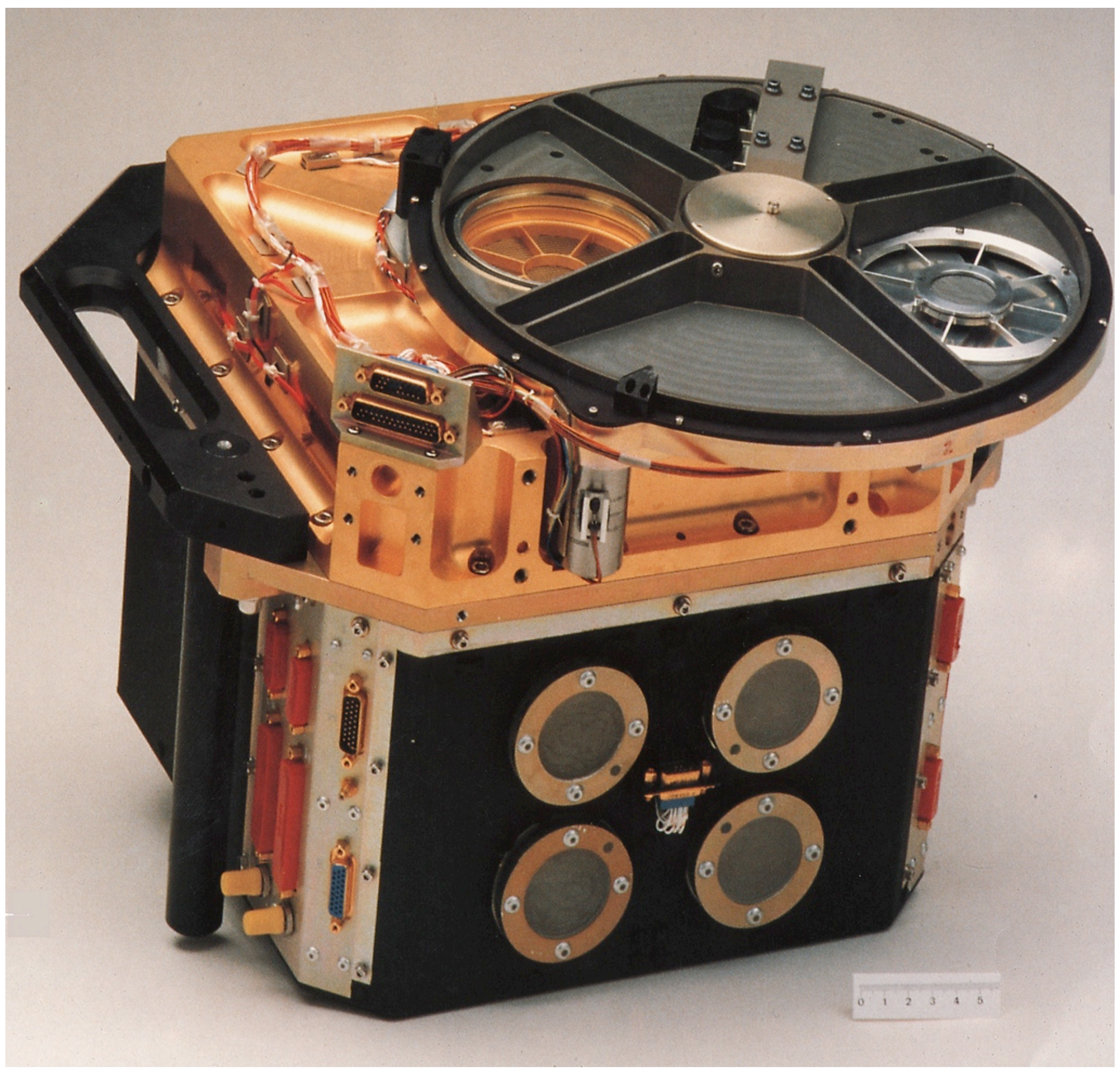


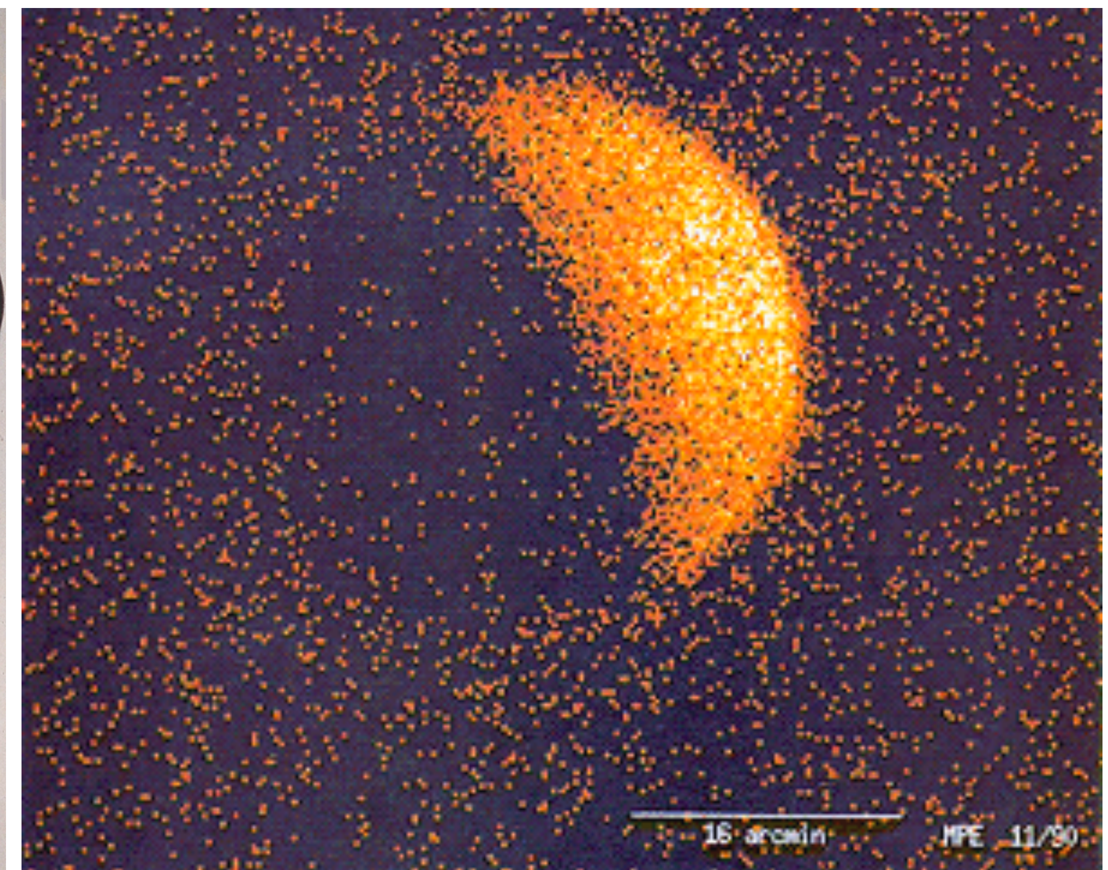
(this image from the Great Soviet Encyclopedia! copyright holder has expired)

Very sensitive; nice background rejection;
but poor energy resolution

Poisson statistical fluctuation on nr of electrons
set by ionization potential of counter gas (30 eV for Ar);
typically $E_\gamma/\Delta E_\gamma \approx 10\sqrt{E_\gamma}$ (photon energy E_γ in keV)

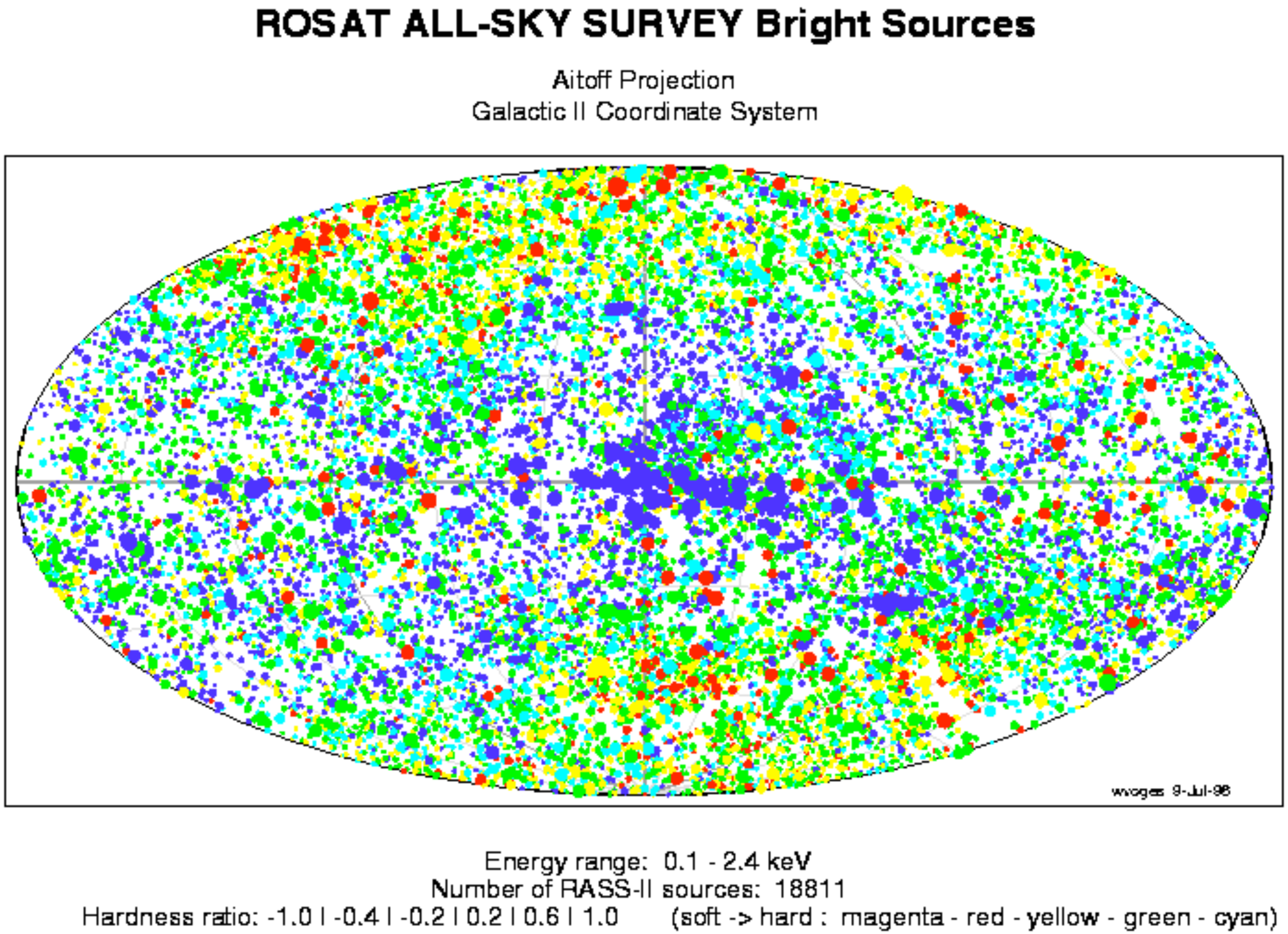
But low background makes imaging proportional counters still interesting. Example:
The Position Sensitive Proportional Counter (PSPC) on the US/German *ROSAT* observatory (1990-1999)



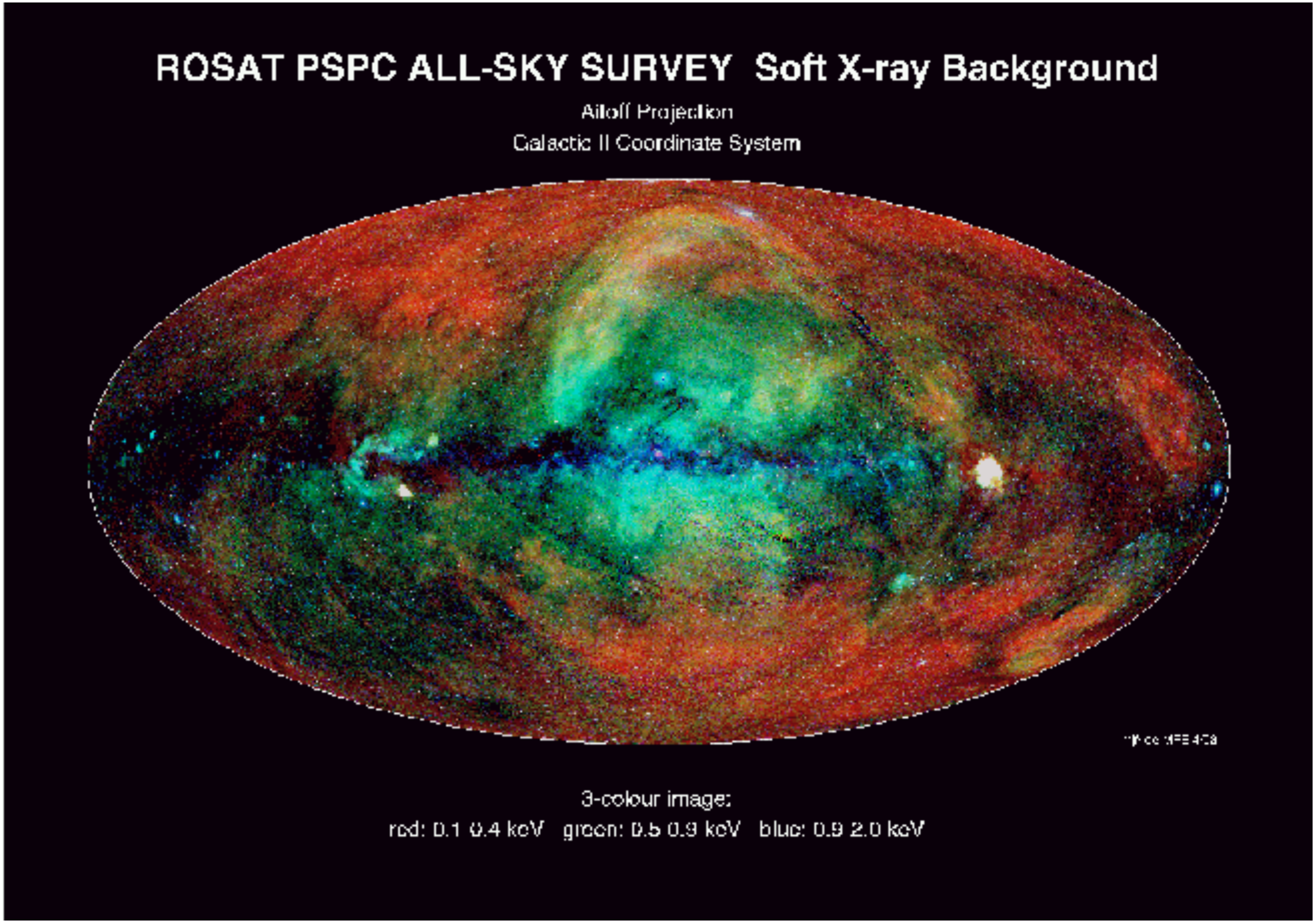


(finally: the Moon in X-rays- note the Dark Side!! those are real X-rays, not background!)

ROSAT All Sky Survey: Point Sources



(only bright sources plotted; N ~ 150,000 total)



a map of the diffuse soft X-ray background

example of use:
color/color and F_X/F_{opt} selection: *isolated NS*

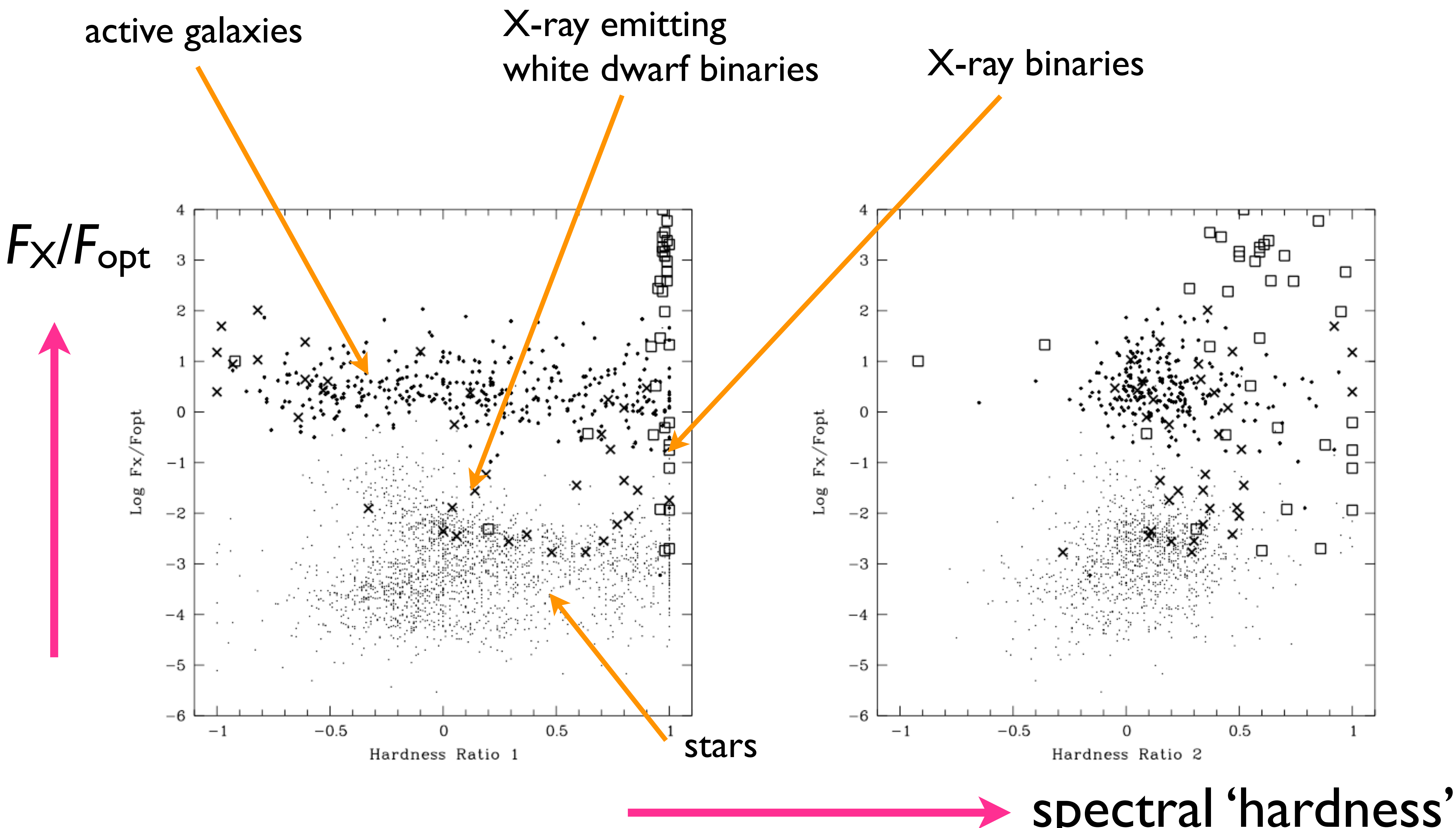
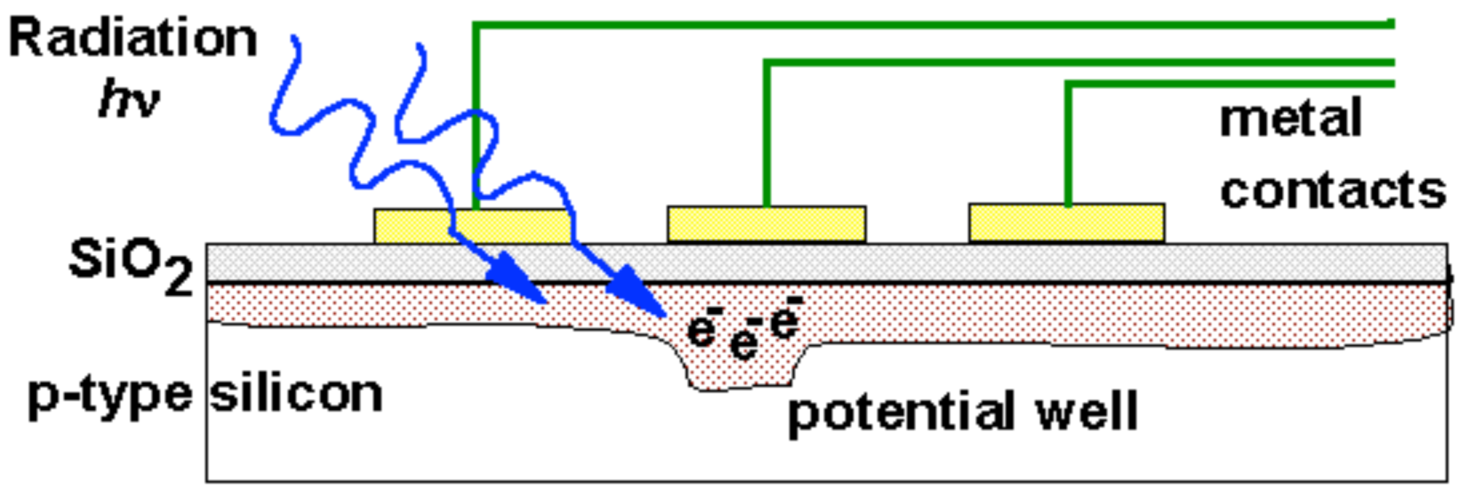


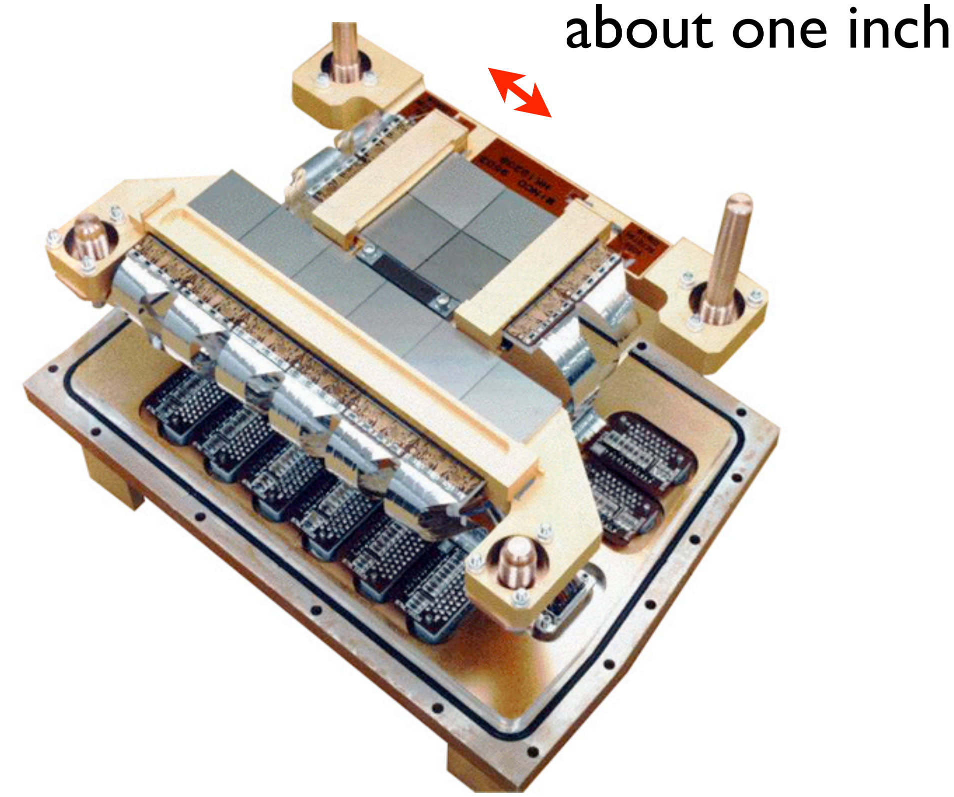
Fig. 3. Position of various classes of identified BRASS sources in the $HR1$ (left) or $HR2$ (right) / Log(F_X/F_{opt}) diagram. Small dots represent stars, large dots AGN, squares are X-ray binaries and crosses are cataclysmic variables. For stars and AGN only sources having errors on $HR1$ or $HR2$ smaller than 0.2 are plotted

Motch et al., 1998

CCD's



© 2000 by Brian M. Tissue



principle same as optical CCD, but: number of e^- per photon proportional to photon energy, so also a spectrometer (optical: 1 e^- per photon)

Advanced CCD Imaging Spectrometer on *Chandra* observatory

First CCD Imaging Spectrometer for astrophysics: ASCA (ISAS; 1993-1999)

supernova remnant Cas A
(Holt, Gotthelf, Tsunemi, Negoro 1994)

ASCA Observations of Cassiopeia A

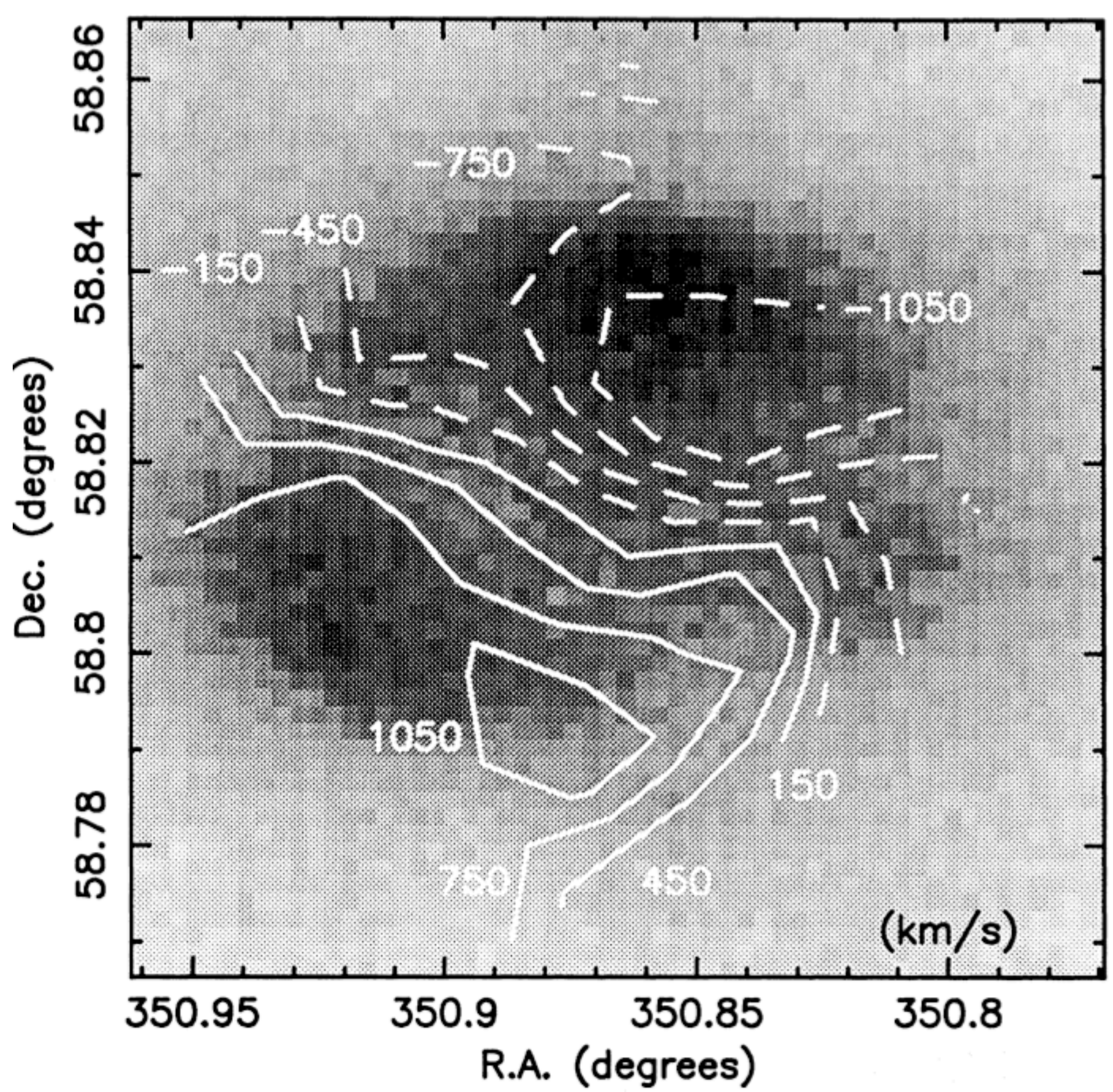


Fig. 3. Doppler contour map (equinox J2000) of the peak energy of the 1.85 keV Si line of Cassiopeia A.

Doppler velocity map

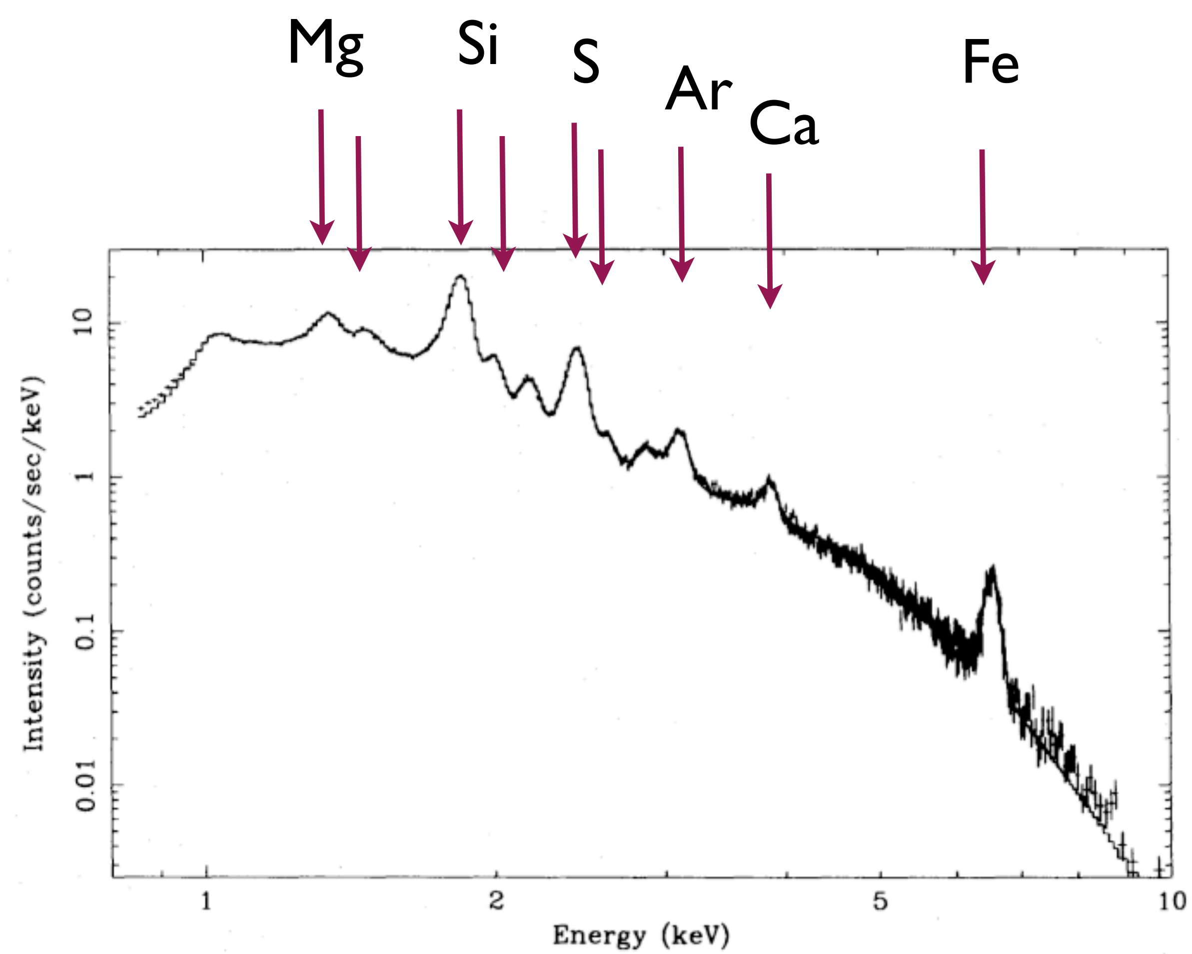


Fig. 2. The ASCA SIS 0 pulse-height spectrum of the bright NW knot of Cassiopeia A.

spectrum

cgs, Gaussian units

Focusing and Imaging

focusing requires *reflecting* the radiation
X-ray reflectivity zero at large angles of incidence
solution: *grazing incidence optics*

reflectivity of metals:
write wavelike solutions to Maxwell's Equations;
find that $\varepsilon(\omega) = \boldsymbol{n}^2(\omega)$; $\boldsymbol{n}$ is the complex index of refraction

use the relation between $\boldsymbol{E}$, $\boldsymbol{D}$, and $\boldsymbol{P}$ to calculate $\varepsilon(\omega)$; use harmonic oscillator as model for the response of the charges to incident $\boldsymbol{E}$:

$$\mathbf{p} = -e\mathbf{r} = \frac{e^2}{m}\left(\omega_0^2 - \omega^2 - i\omega\gamma\right)^{-1}\mathbf{E}$$

ω_0: resonance frequency; γ: damping

e.g. Jackson, 3d Ed., Chapter 7

$$\epsilon(\omega) = 1 + \frac{4\pi N e^2}{m} \sum \frac{f_i}{\omega_{0,i}^2 - \omega^2 - i\omega\gamma_i}$$

N: density of atoms; f_i: oscillator strength; $\Sigma f_i = Z$ (nuclear charge)

at high frequencies ($\omega \gg \omega_0$) and small damping:

(note the minus sign on ω^2!!)

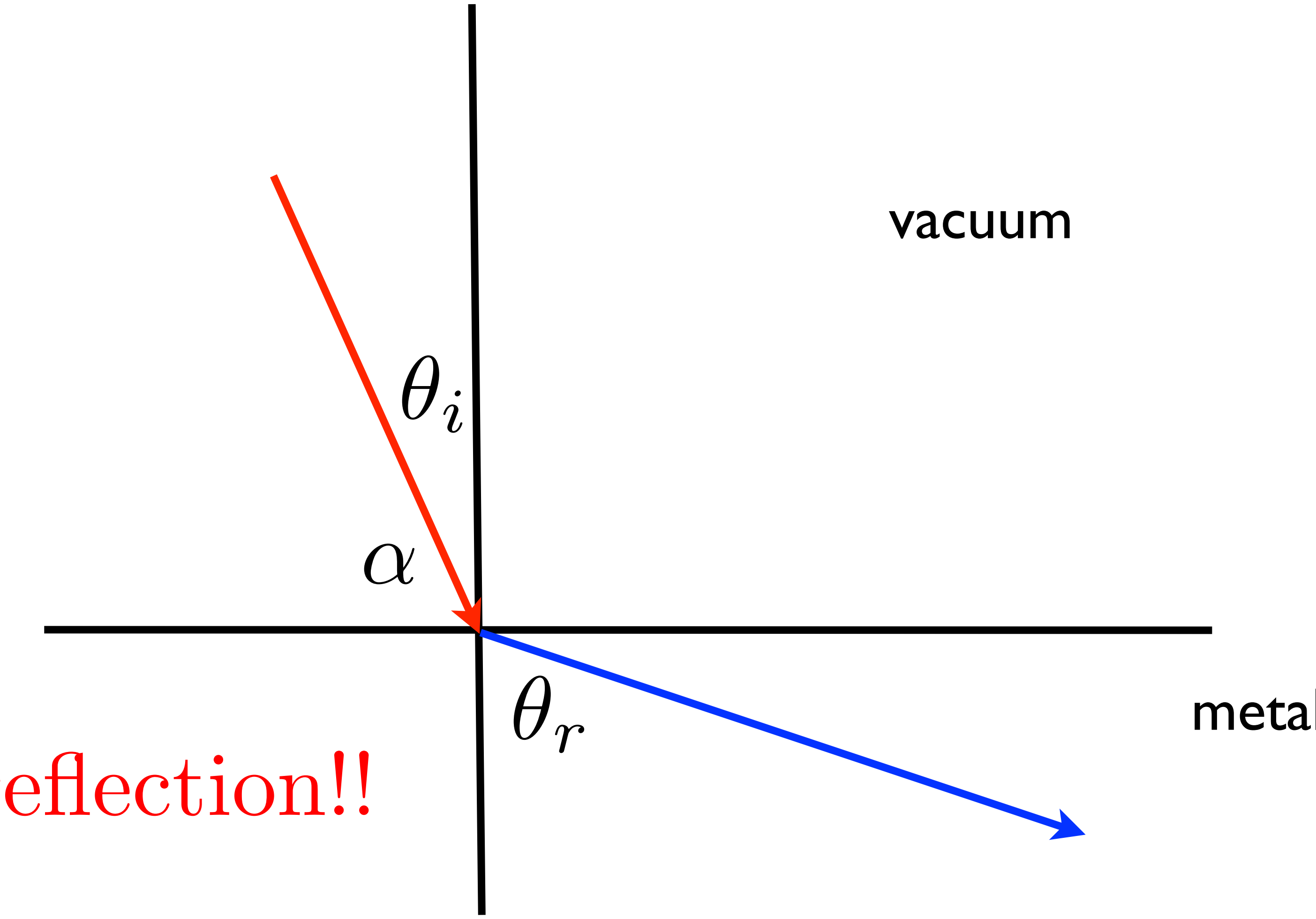
$$\epsilon(\omega) \approx 1 - \frac{\omega_p^2}{\omega^2}; \quad \omega_p \equiv \frac{4\pi N Z e^2}{m}$$

and for $\omega \gg \omega_p$, *n* is approximately real, and

$$\epsilon(\omega) = n^2 \approx 1 - \frac{\omega_p^2}{\omega^2} \Rightarrow \boxed{n \approx 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}}$$

Snell's Law has strange consequence if *n* < 1:

$$\frac{\sin\theta_i}{\sin\theta_r} = n$$



$$\color{red}{\theta_r \to \frac{\pi}{2} : \text{total external reflection!!}}$$

$$\sin\theta_i = \cos\alpha = n$$

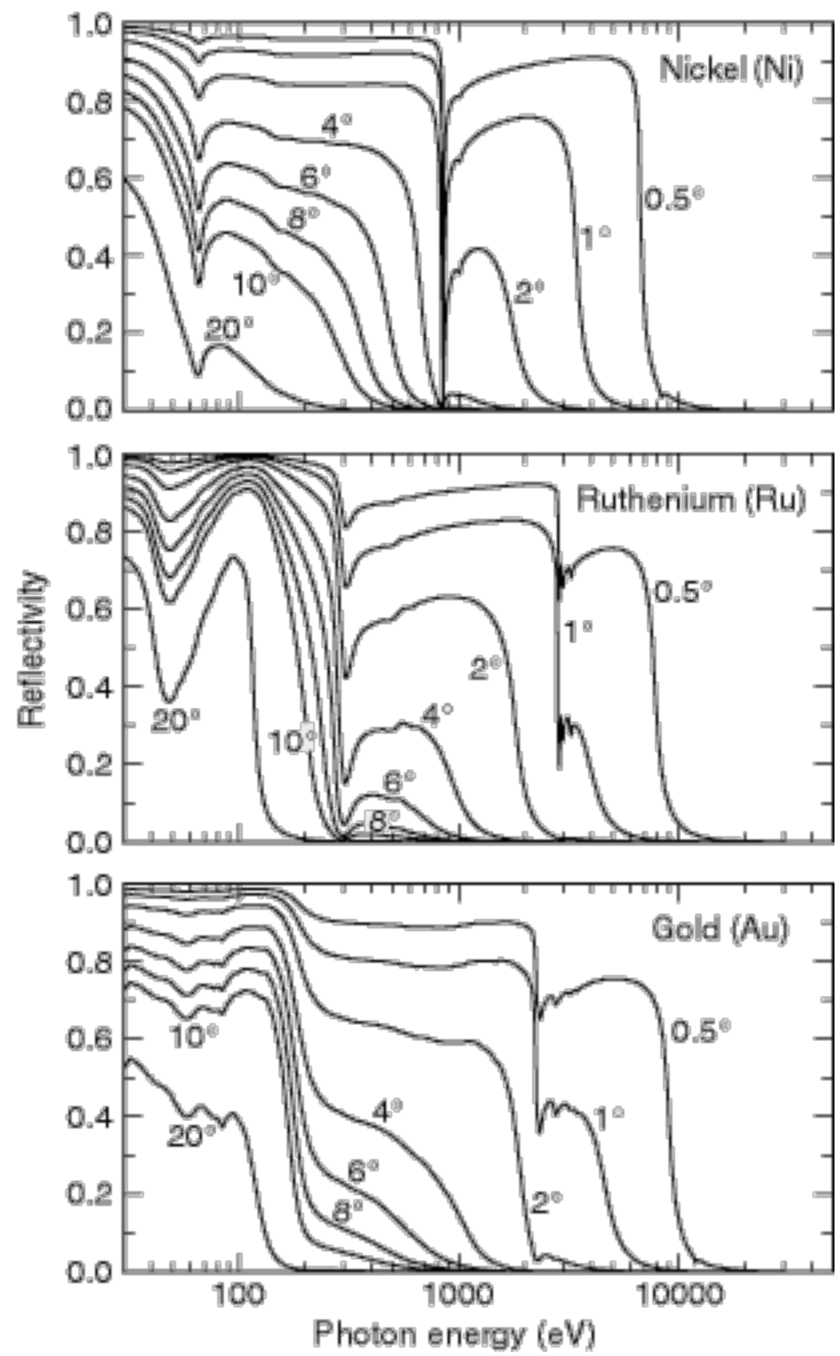
and since n-1 << 1,

$$\cos\alpha \approx 1 - \frac{1}{2}\alpha^2 \Rightarrow \alpha \approx \frac{\omega_p}{\omega}$$

so $\boxed{\text{reflection for angles} < \frac{\omega_p}{\omega}}$

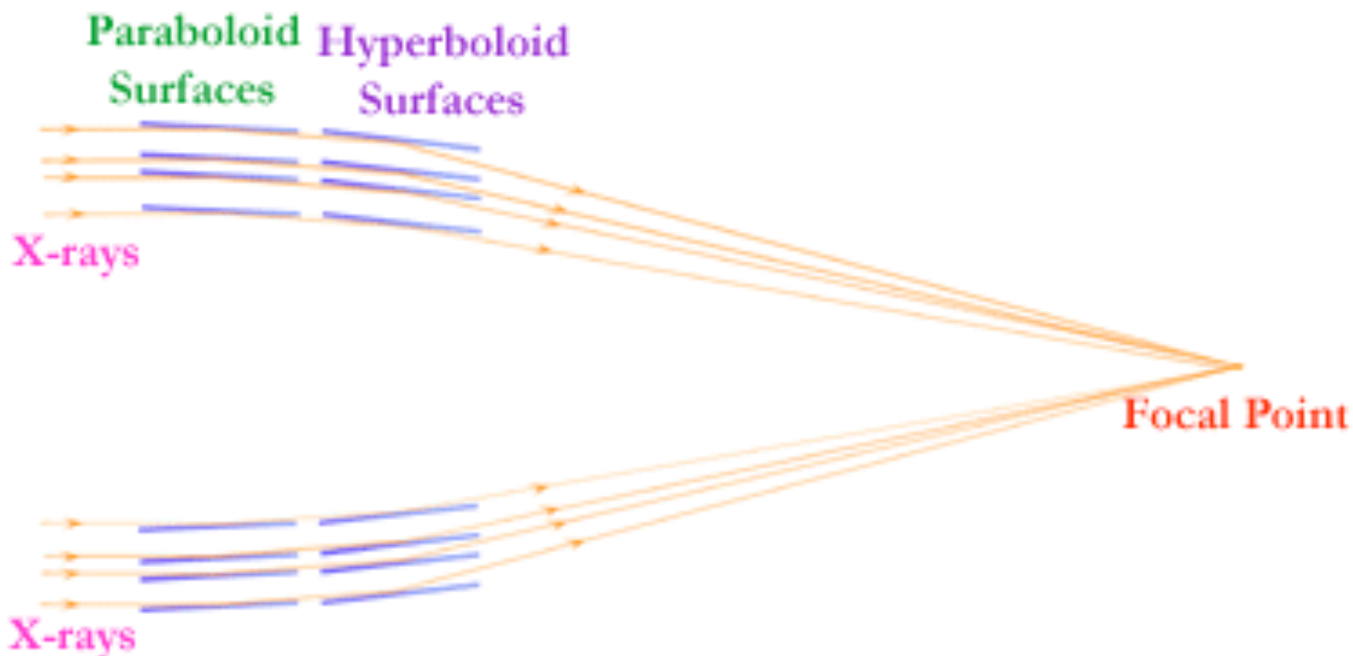
Grazing Incidence Optics

practically, for Au and similar metals, with E_γ in keV $$\alpha_{\mathrm{critical}} \sim \frac{1}{E_\gamma}$$

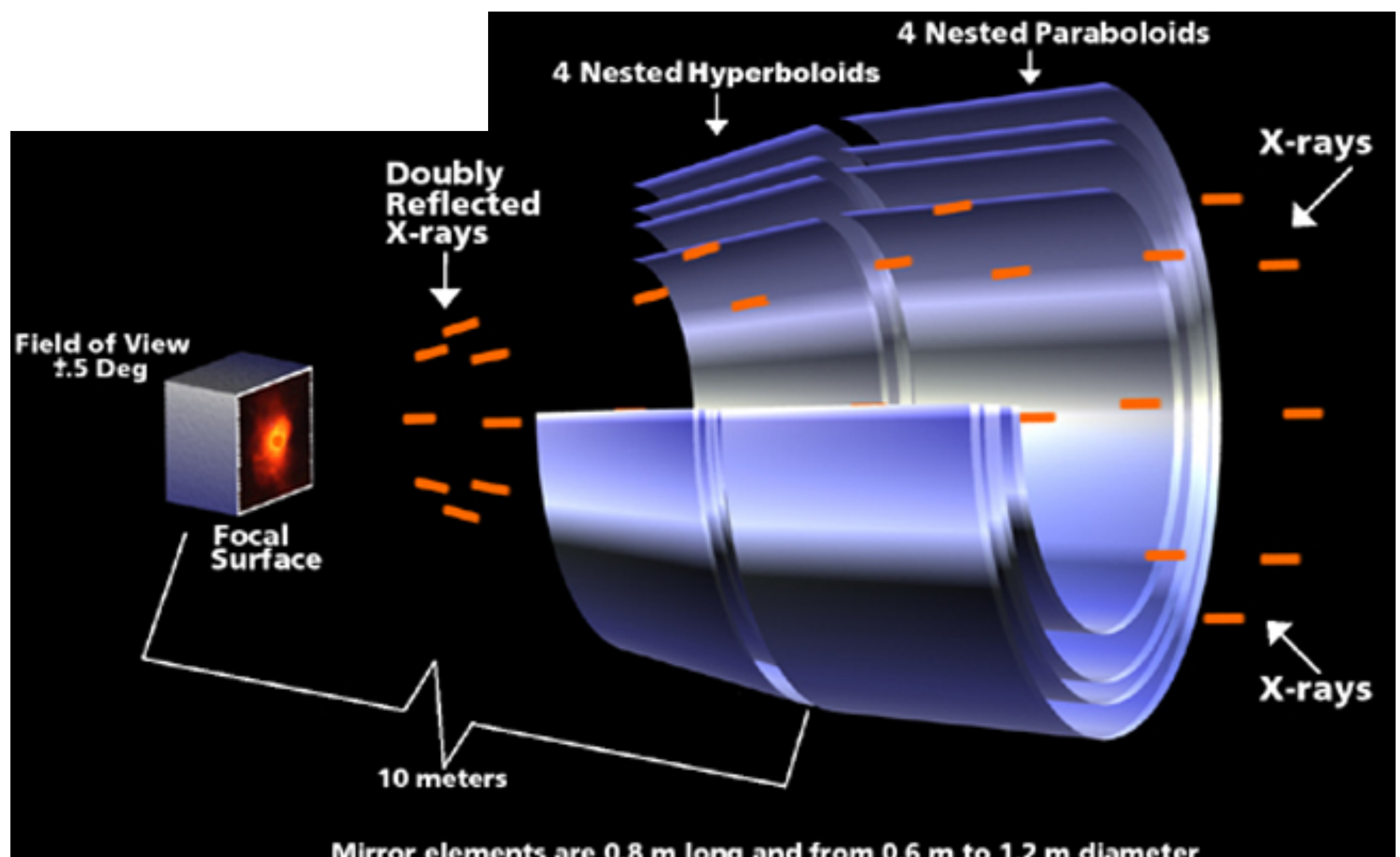


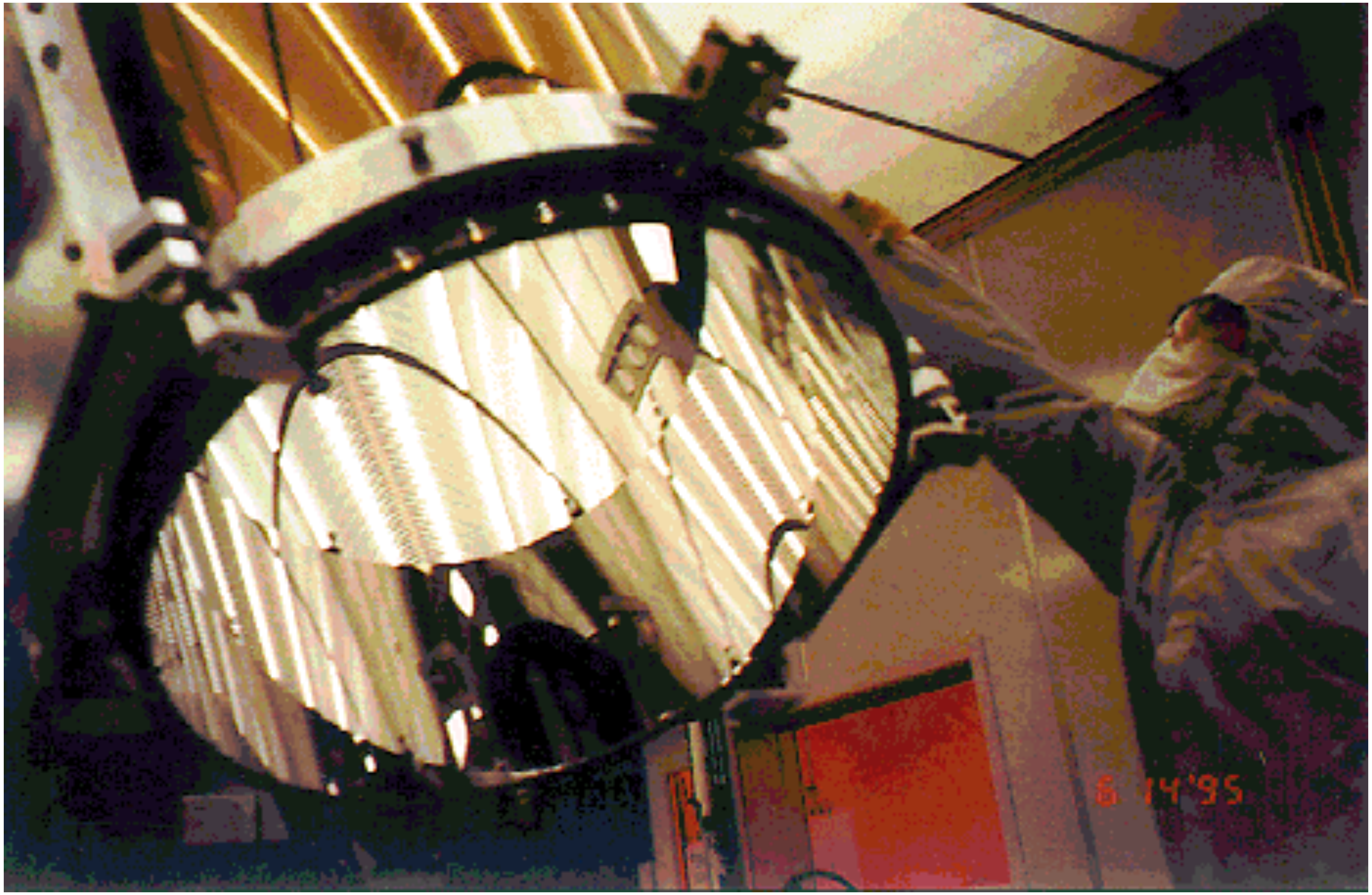
But how do you get to focus the radiation?

Wolter geometry mirrors



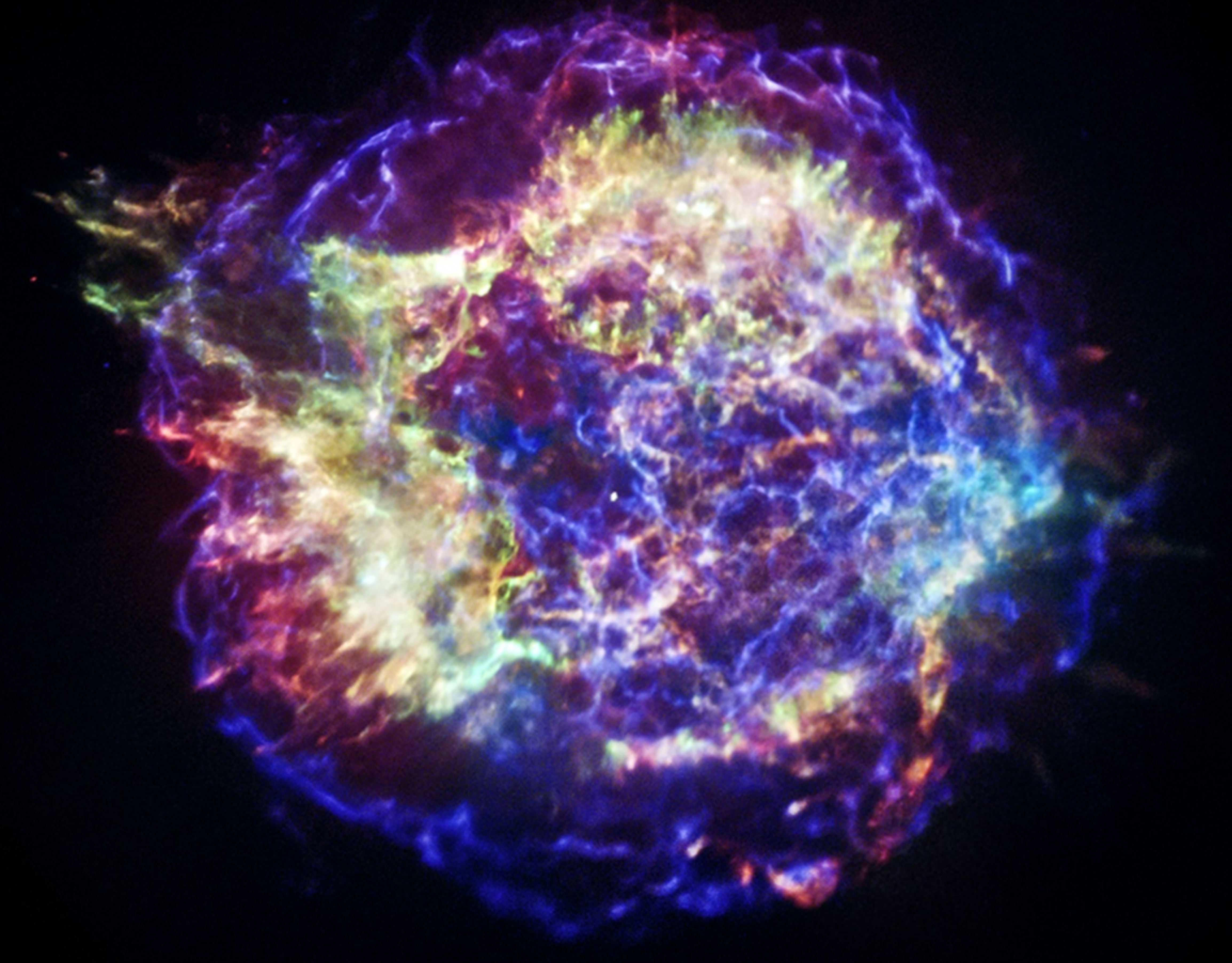
long focal length
small efficiency
limited field of view
but can be made with high angular resolution (1 arcsec)





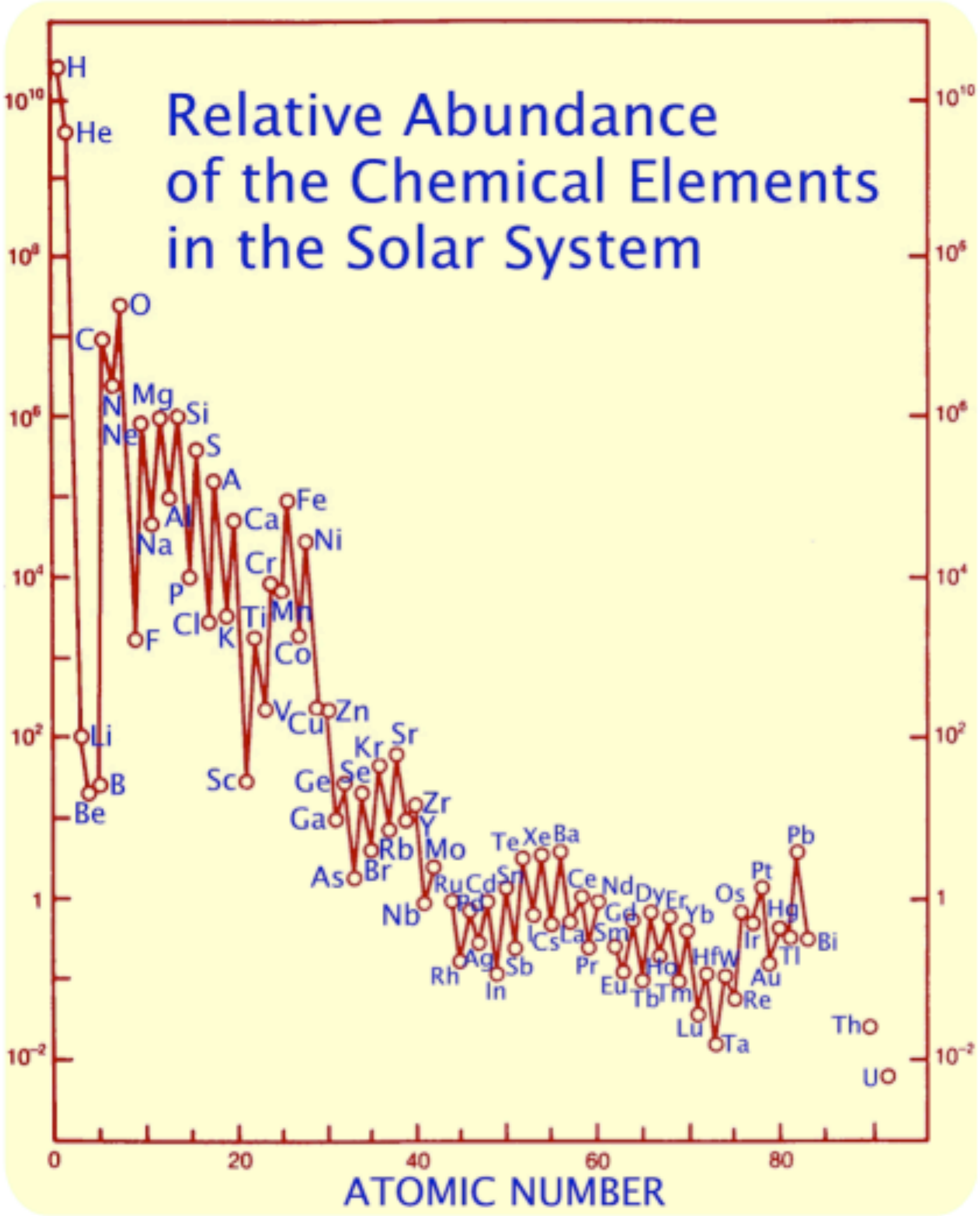
Ir-coated mirrors for *Chandra* Observatory

Chandra image of Cas A (1 Msec exposure)

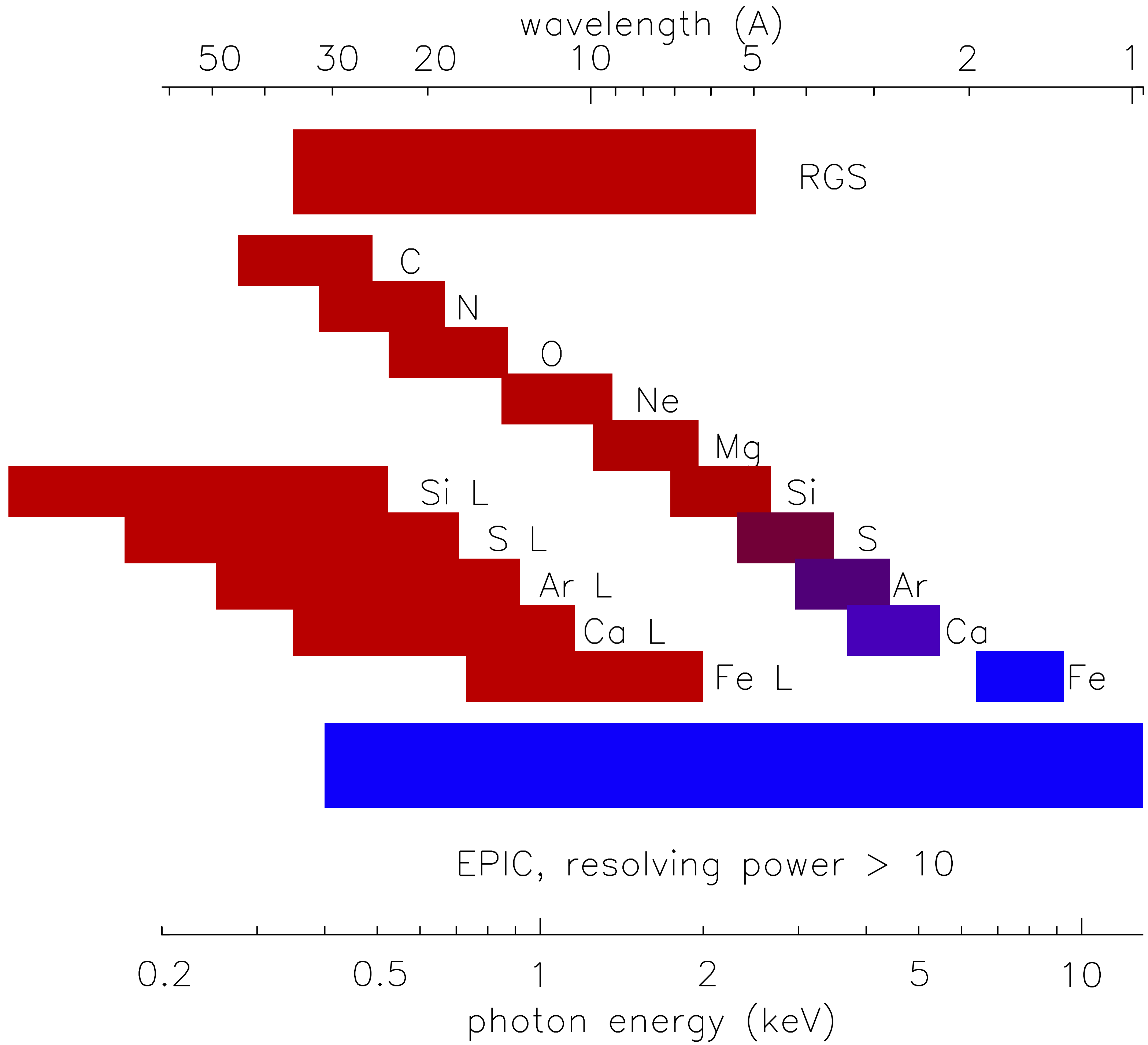


also note the central point source!

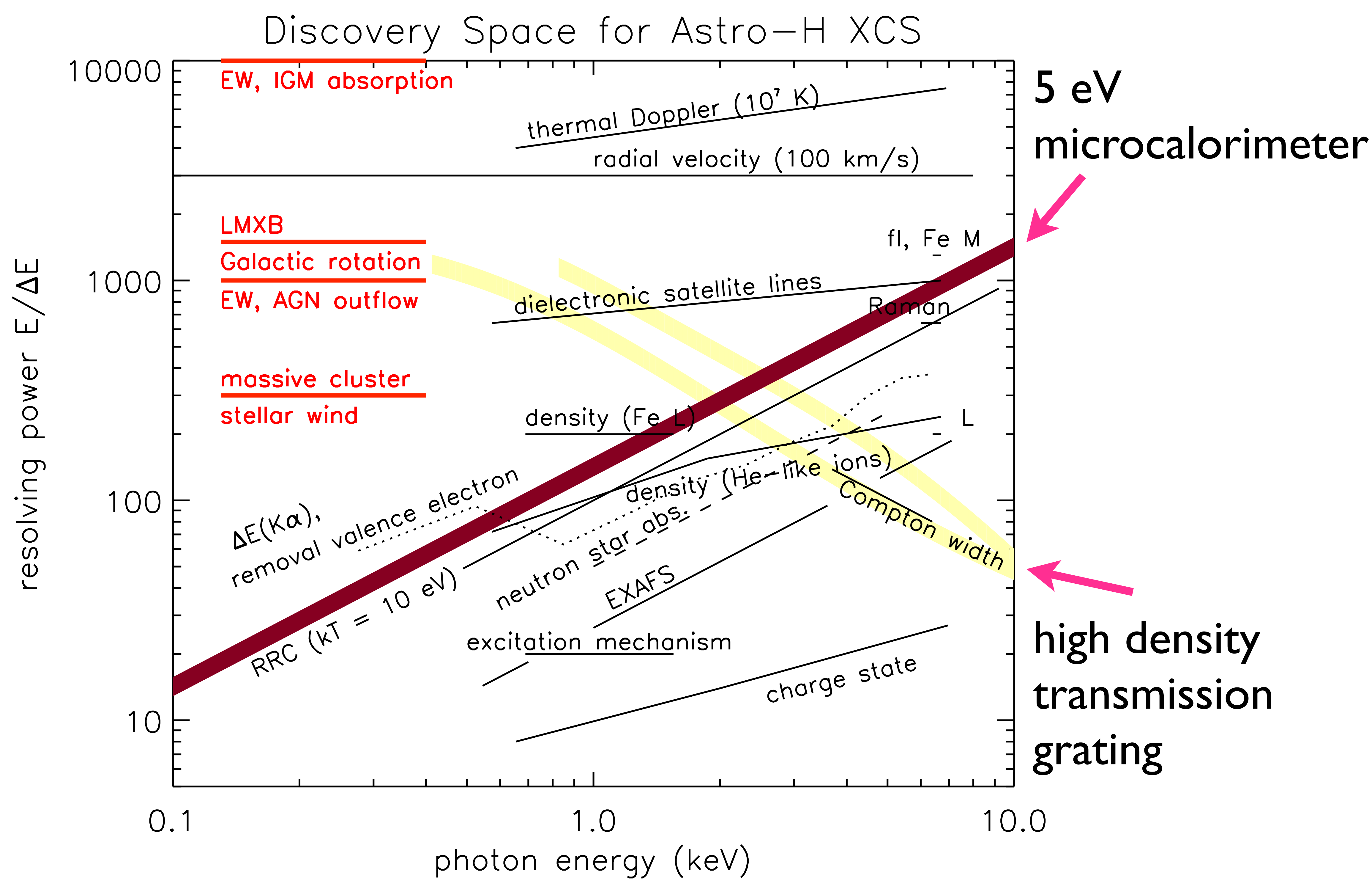
Spectroscopy



atomic spectroscopy:
which elements count in astrophysics?



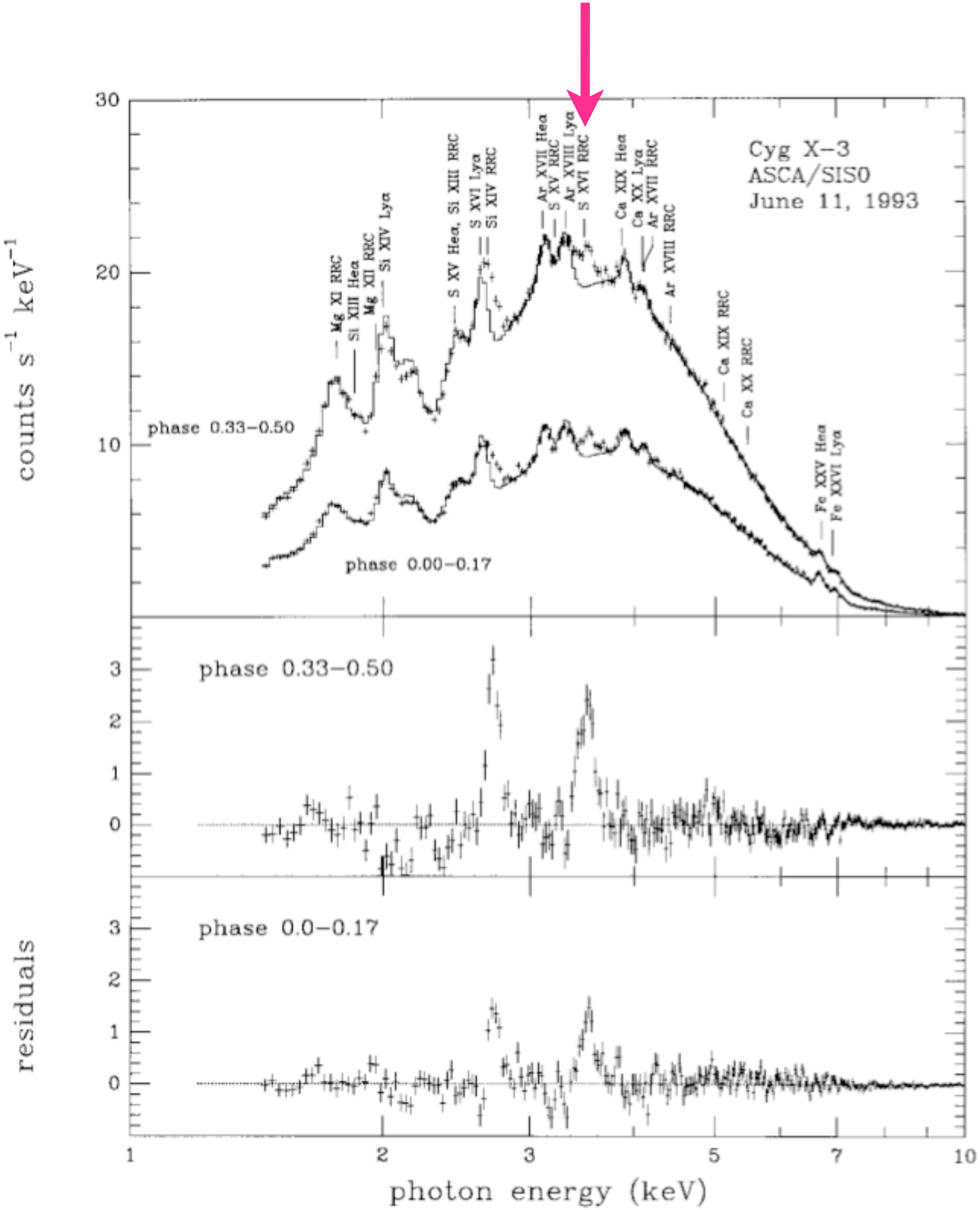
where are the X-ray spectra of these elements?



resolving powers of interest for astrophysical X-ray spectroscopy

Spectrometers I: Ionization
Si-based detectors

CCD's again: but this time as spectrometers

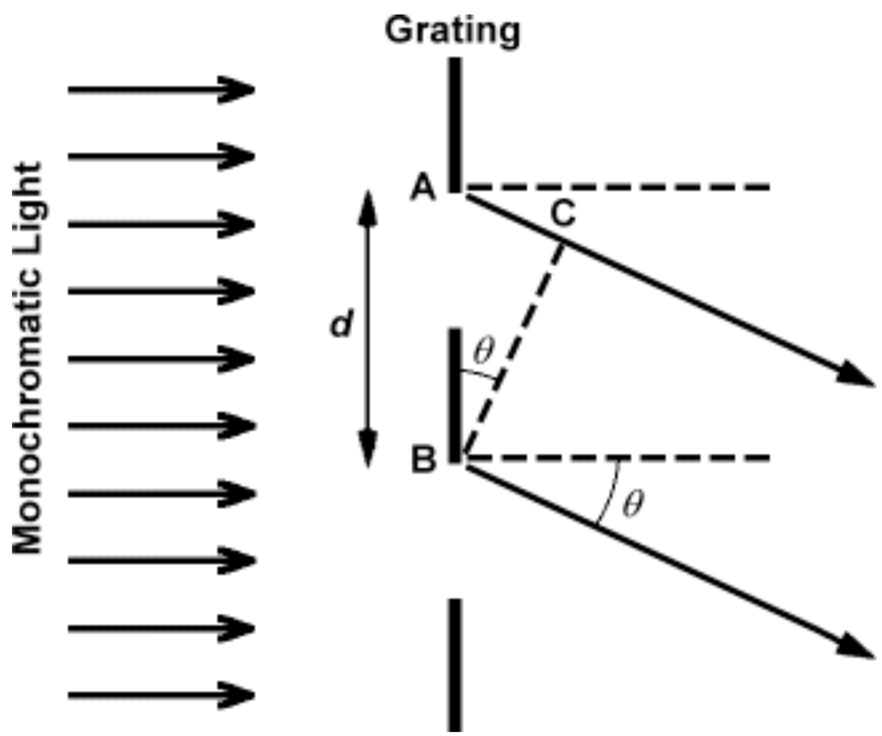


X-ray photoionized gas in massive X-ray binary Cygnus X-3:

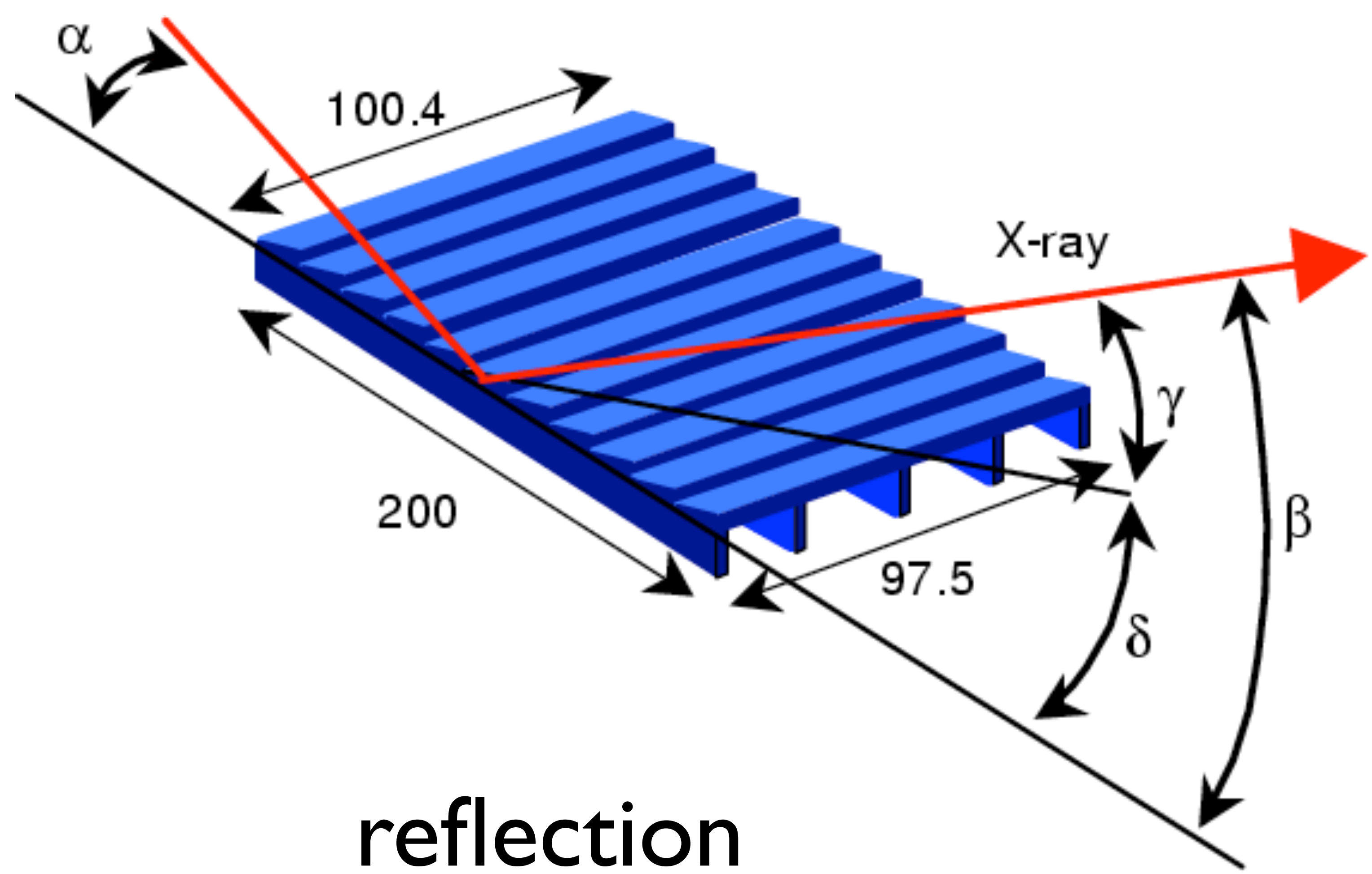
note the radiative recombination continua

Liedahl and Paerels (1996)

Spectrometers II: Diffraction Gratings



transmission



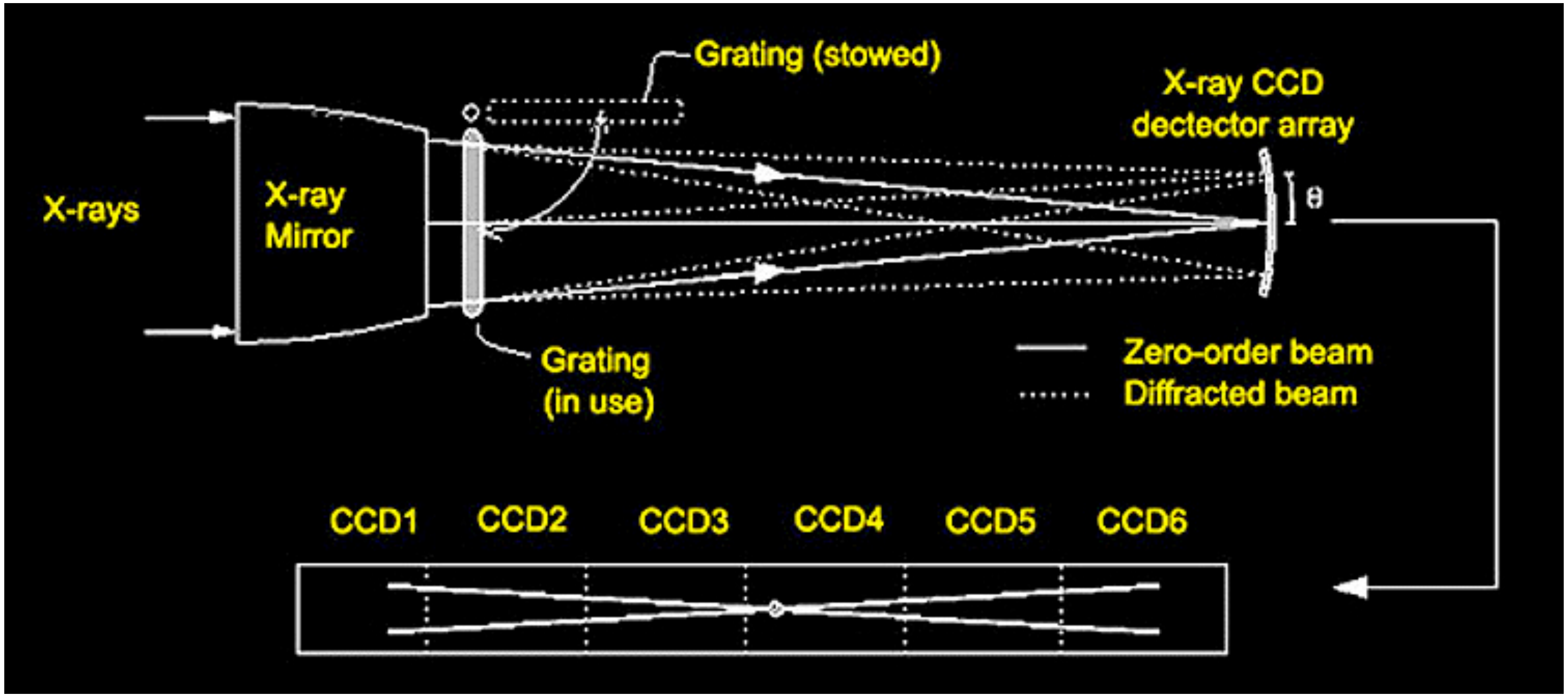
reflection

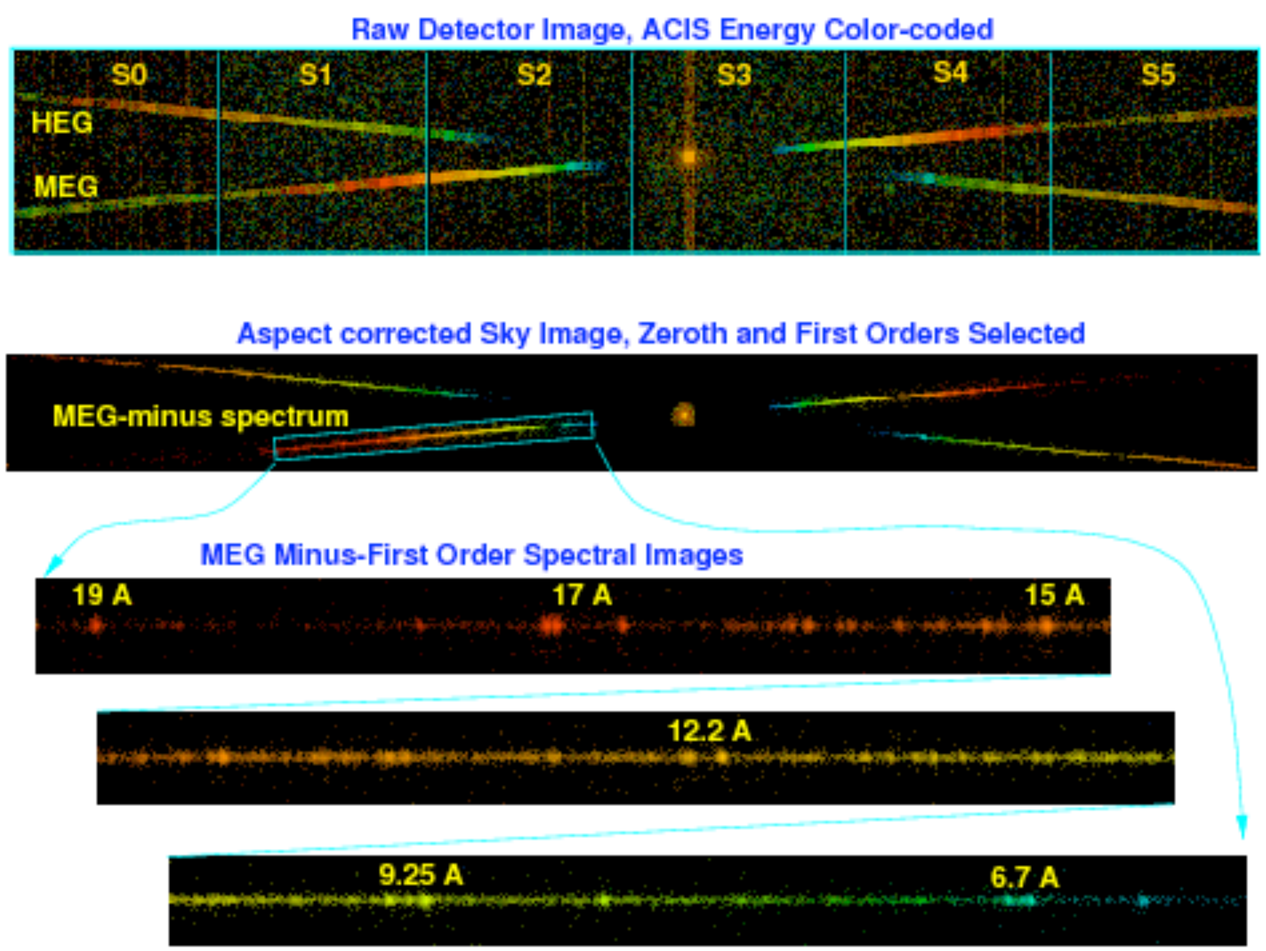
$$d \sin \theta = m\lambda$$

resolving power:

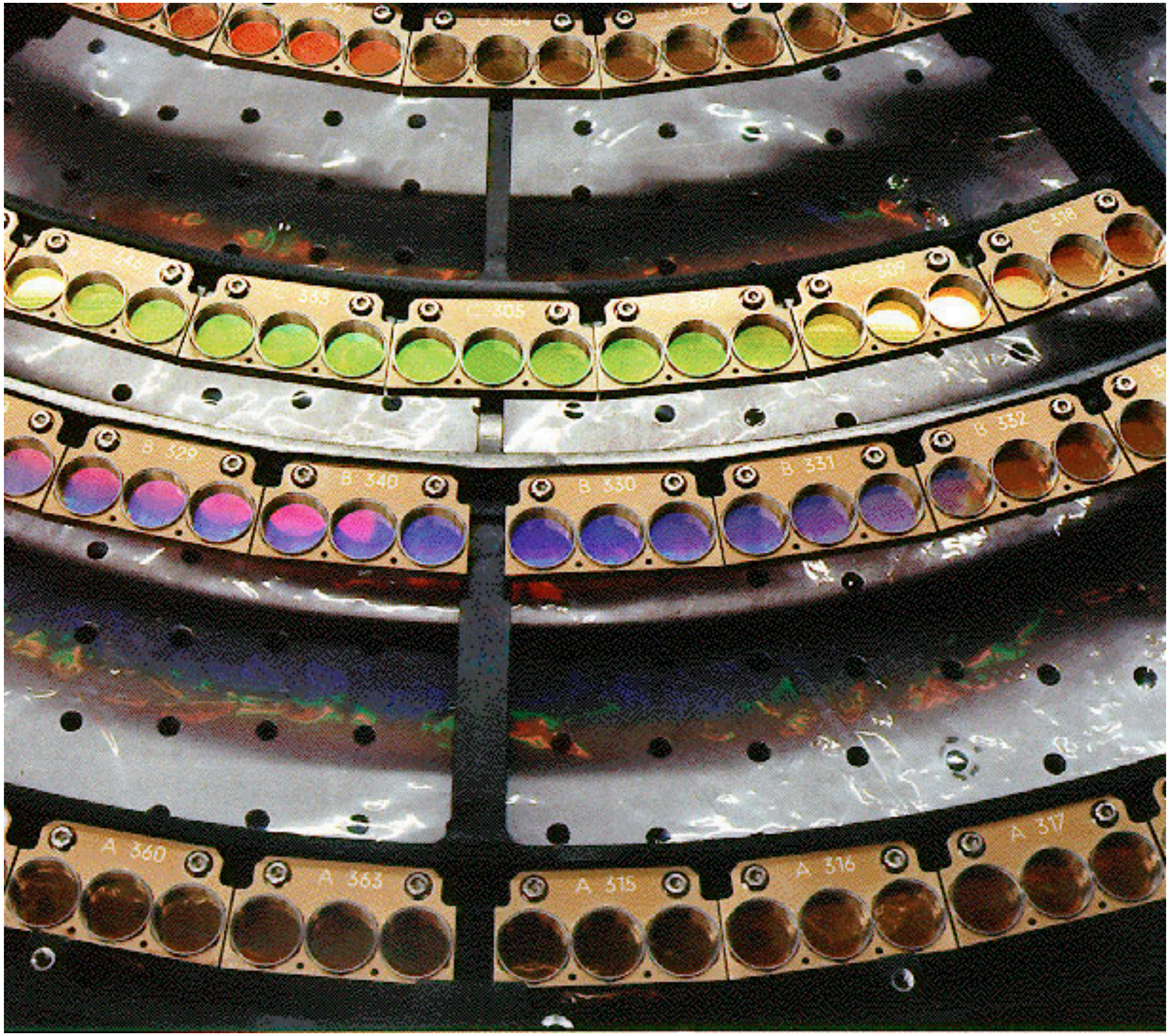
$$\lambda/\Delta\lambda = \theta/\Delta\theta$$

(if telescope resolution $\Delta\theta$ dominates)



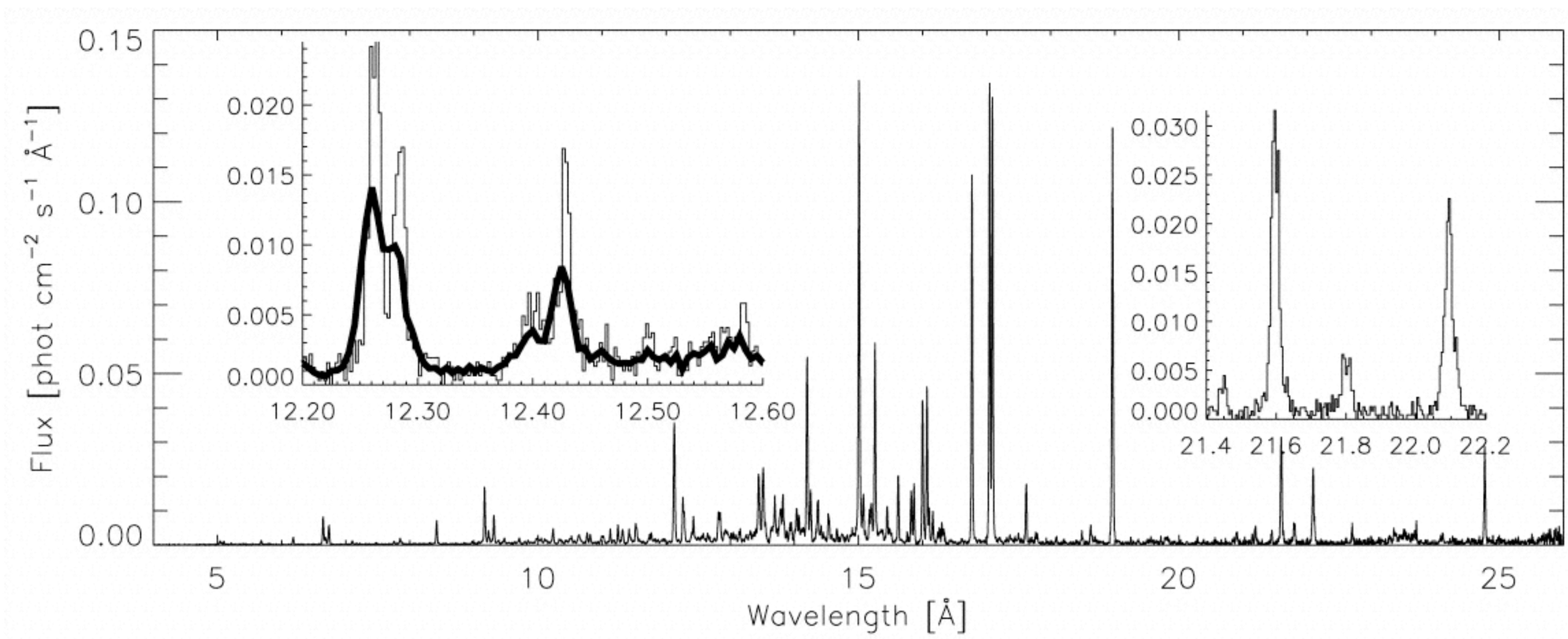


the High Energy Transmission Grating Spectrometer on *Chandra* (MIT)



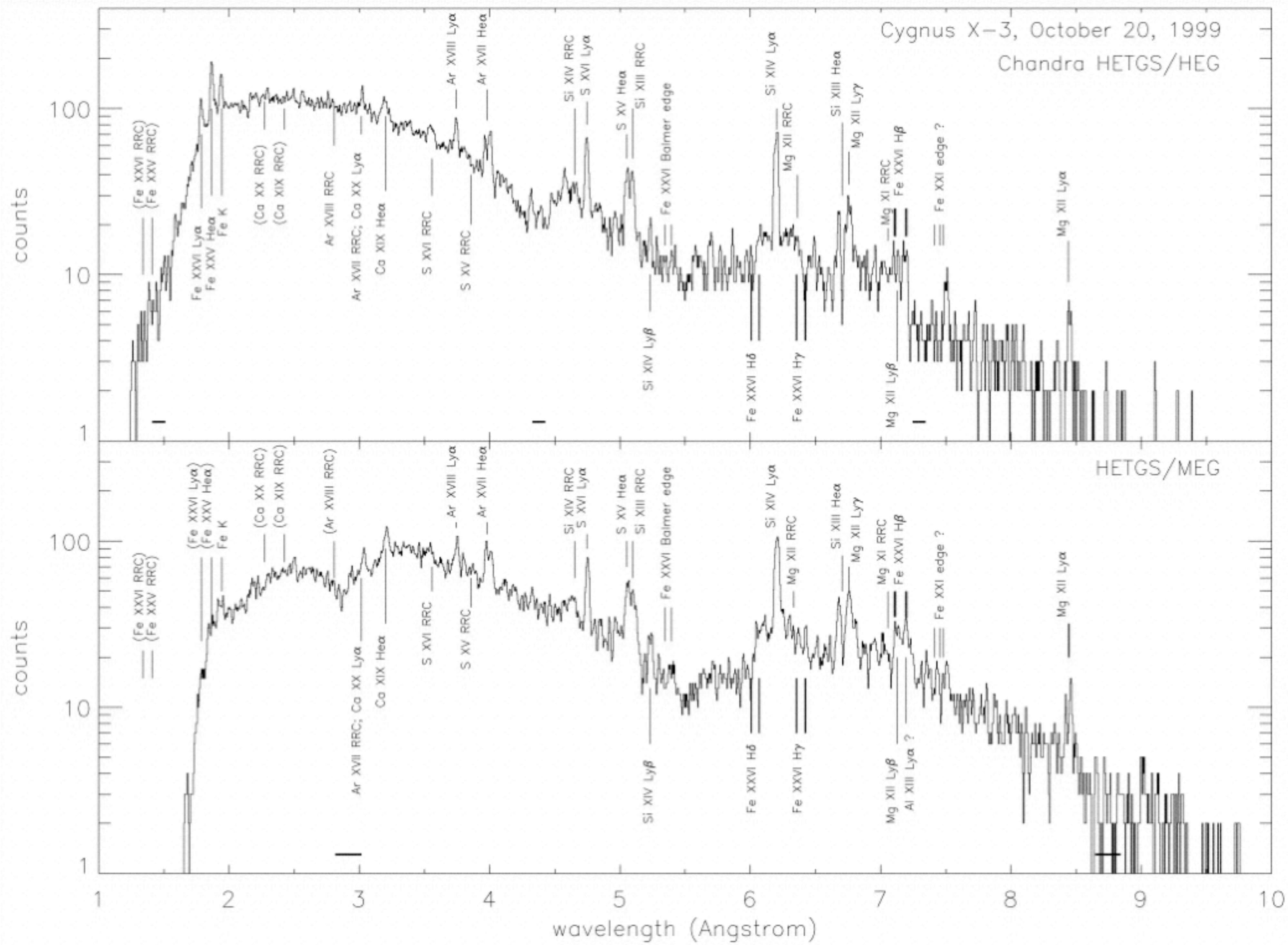
picture of the HETGS gratings

X-ray astrophysical spectroscopy: state of the art
a few random examples



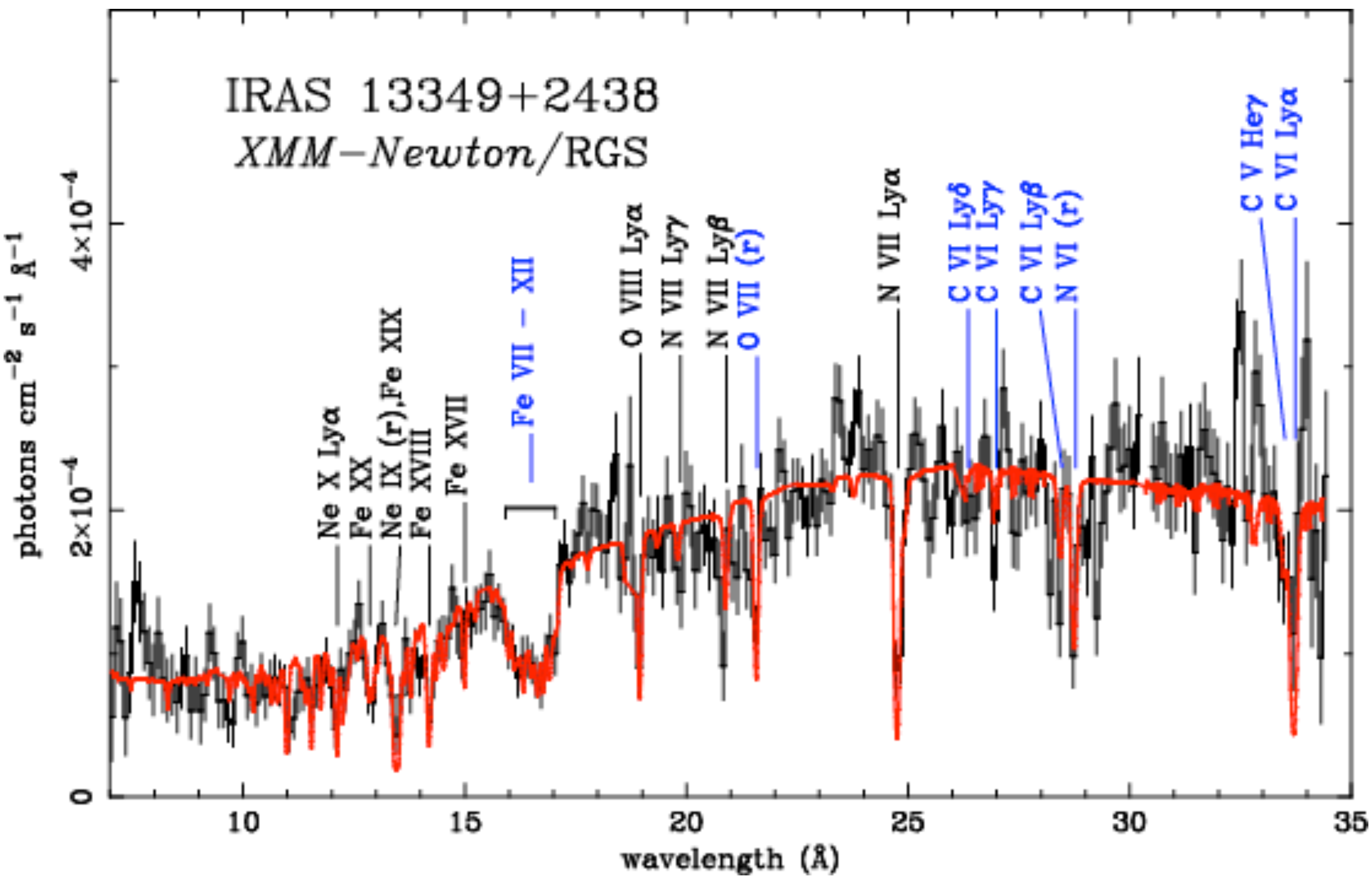
stellar coronal emission: Capella with the *Chandra*/HETGS (Huehnemoerder et al., 2001)

X-ray astrophysical spectroscopy: state of the art



X-ray photoionized gas in Cygnus X-3; *Chandra* HETGS (Paerels et al. 2000)

X-ray astrophysical spectroscopy: state of the art



highly ionized outflow in nucleus of quasar; XMM/RGS (Sako et al. 2001)

Spectrometers III: single photon heat equivalent ("calorimetry")

tomorrow!

Important Observatories

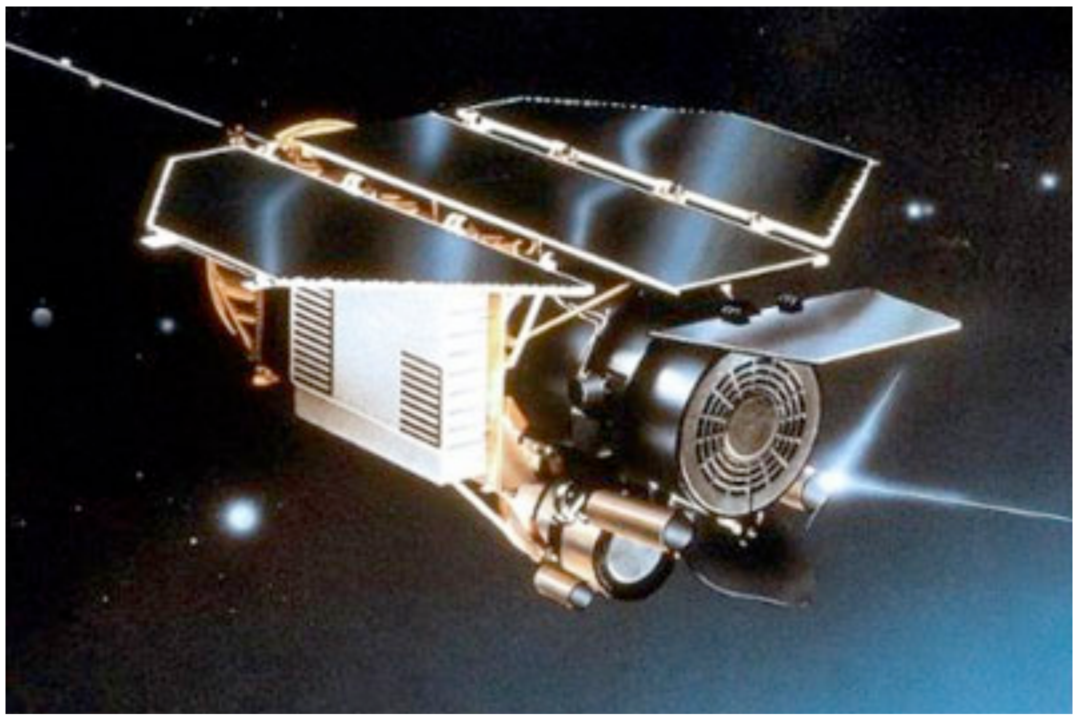
first focusing X-ray telescope in space:
Einstein Observatory (NASA;1979-1981)

focusing telescope, 0.2-4 keV
Imaging Proportional Counter
High-resolution Imager
Transmission gratings
Focal Plane Crystal Spectrometer
'Solid State Spectrometer' (Si)

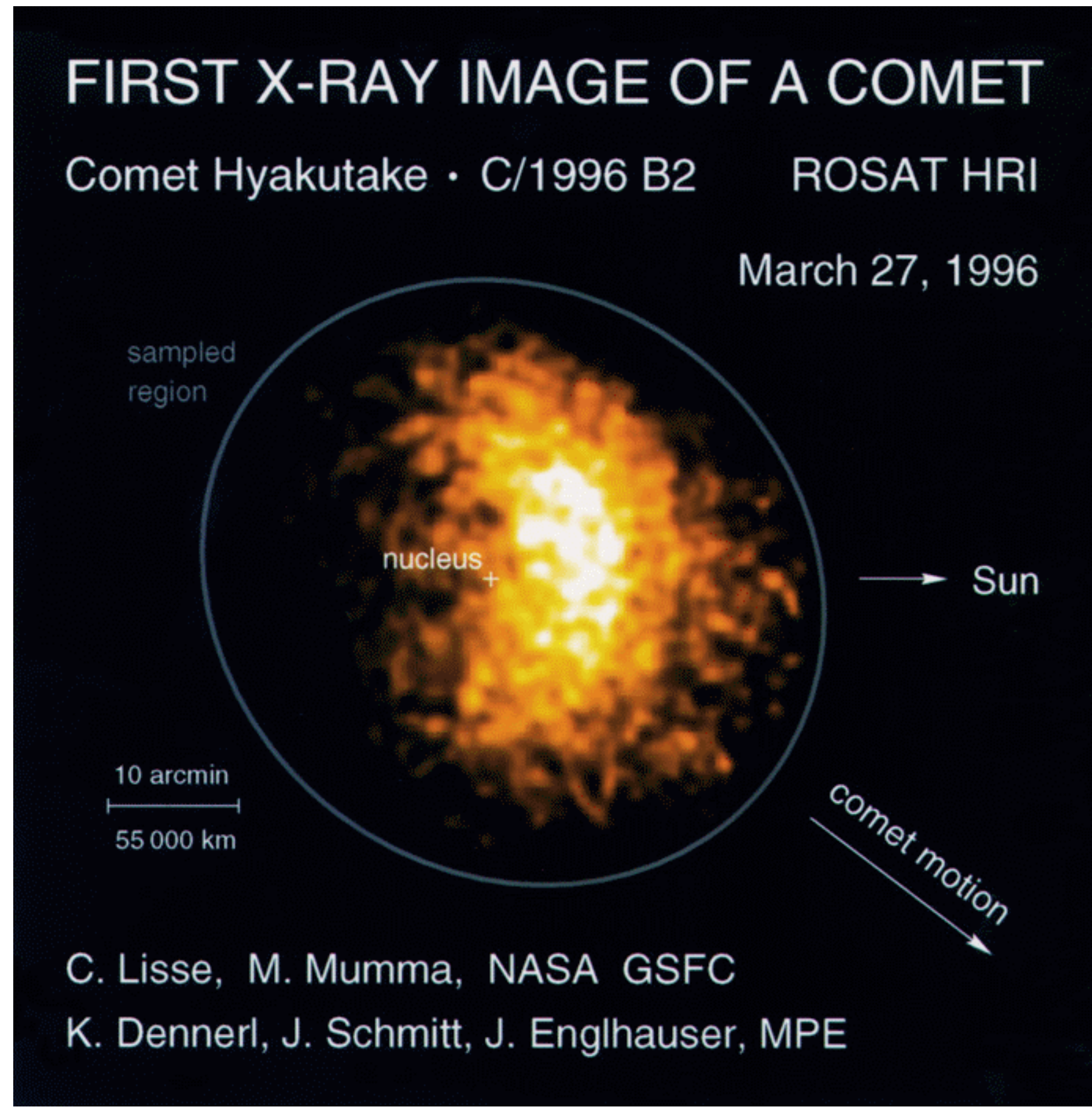
Important Observatories

ROSAT Observatory (MPG/NASA; 1990-1999)

First All-Sky Survey with sensitive telescope

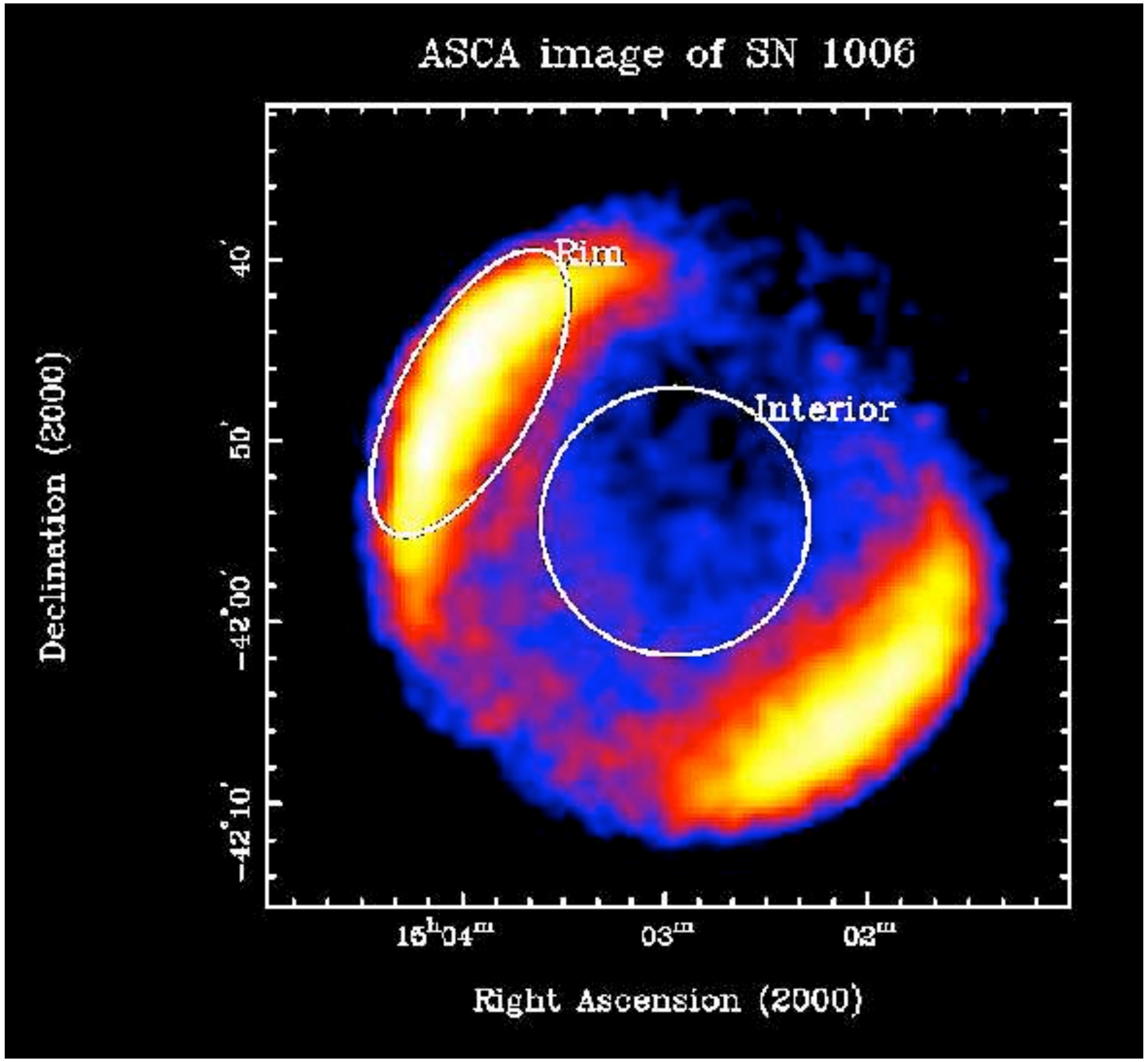


telescope, 0.2-2.4 keV
imaging proportional counters (PSPC)
high resolution imager (HRI)



Important Observatories

First CCD Imaging Spectrometer for astrophysics: ASCA (ISAS, NASA; 1993-1999)

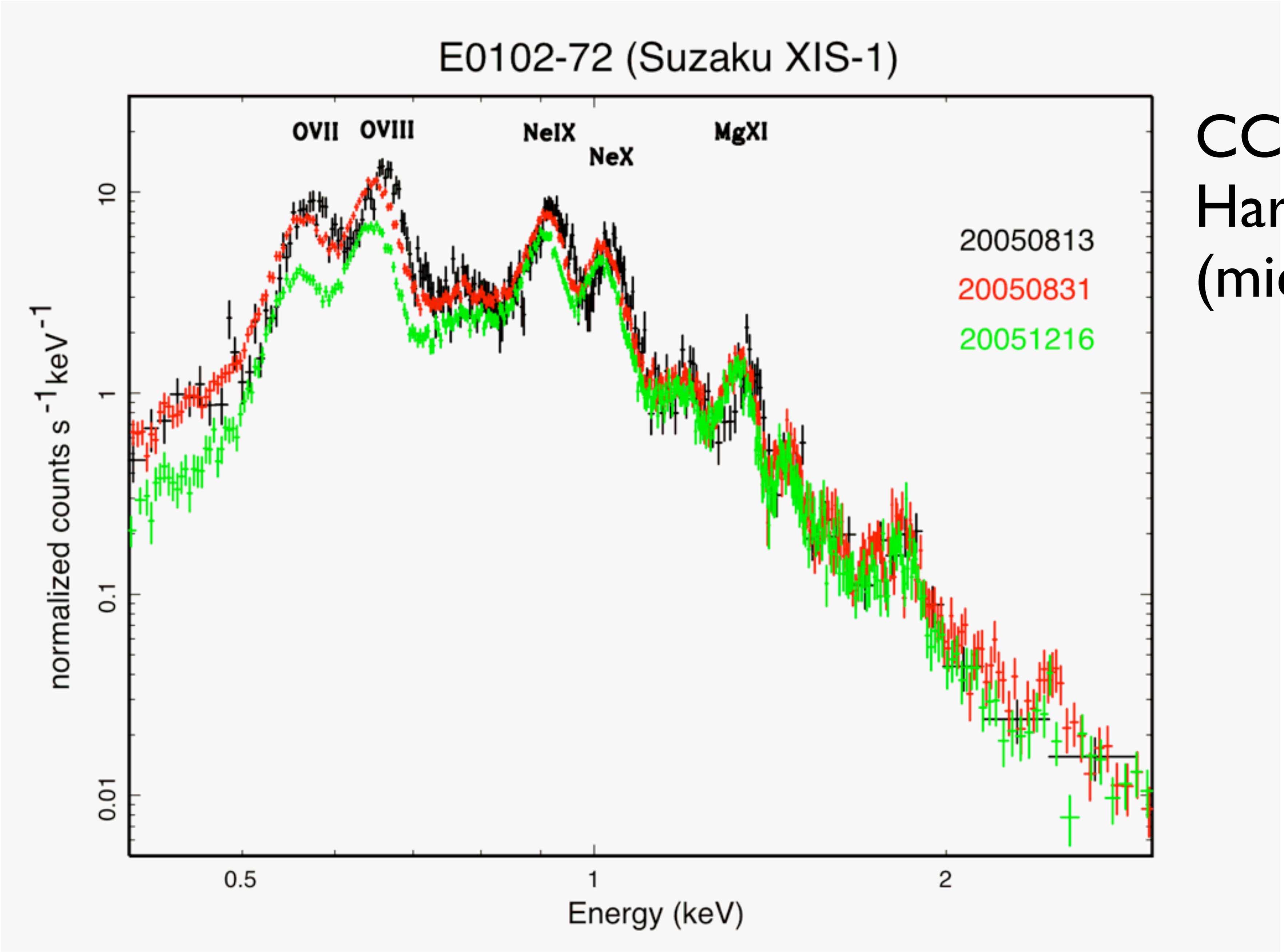


focusing optics, 0.2-10 keV
CCD imagers
gas-scintillation imagers
hard X-ray experiment

Important Observatories

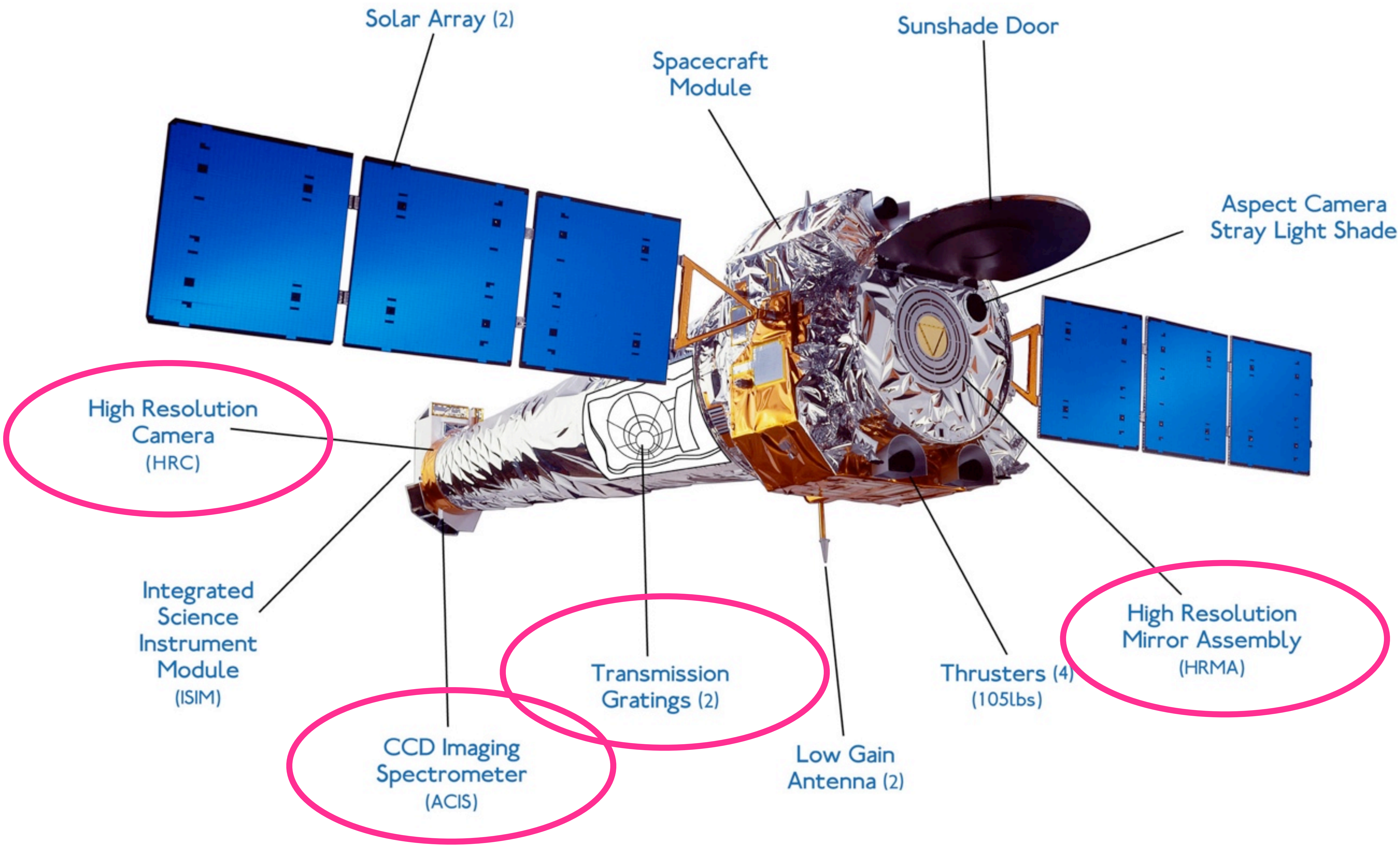
Suzaku (JAXA, NASA; 2005-)

CCD spectrometers with near-theoretical performance at low energies

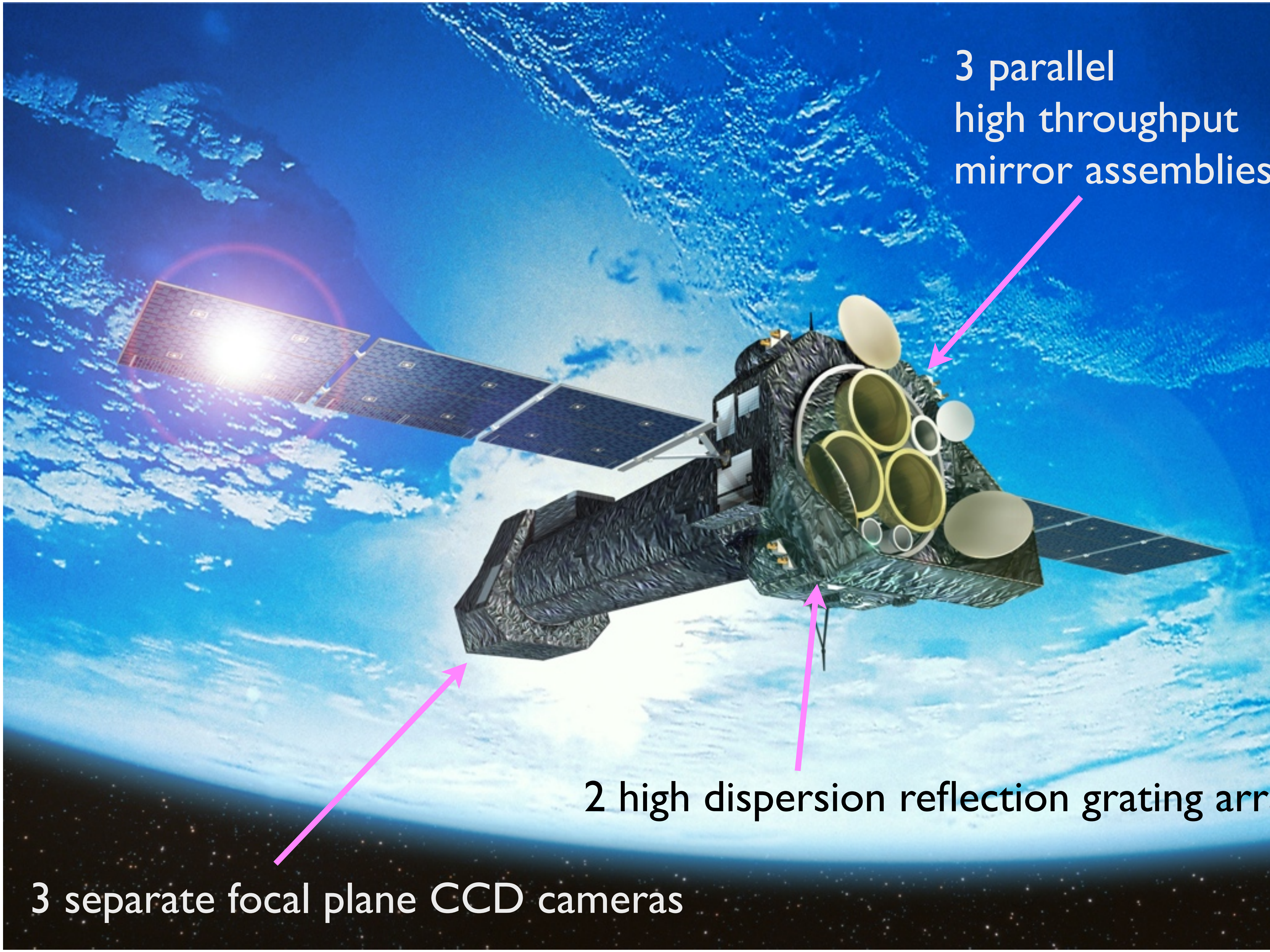


CCD imagers
Hard X-ray experiment (microcalorimeter)

Important Observatories



Chandra X-ray Observatory (NASA, 1999-)



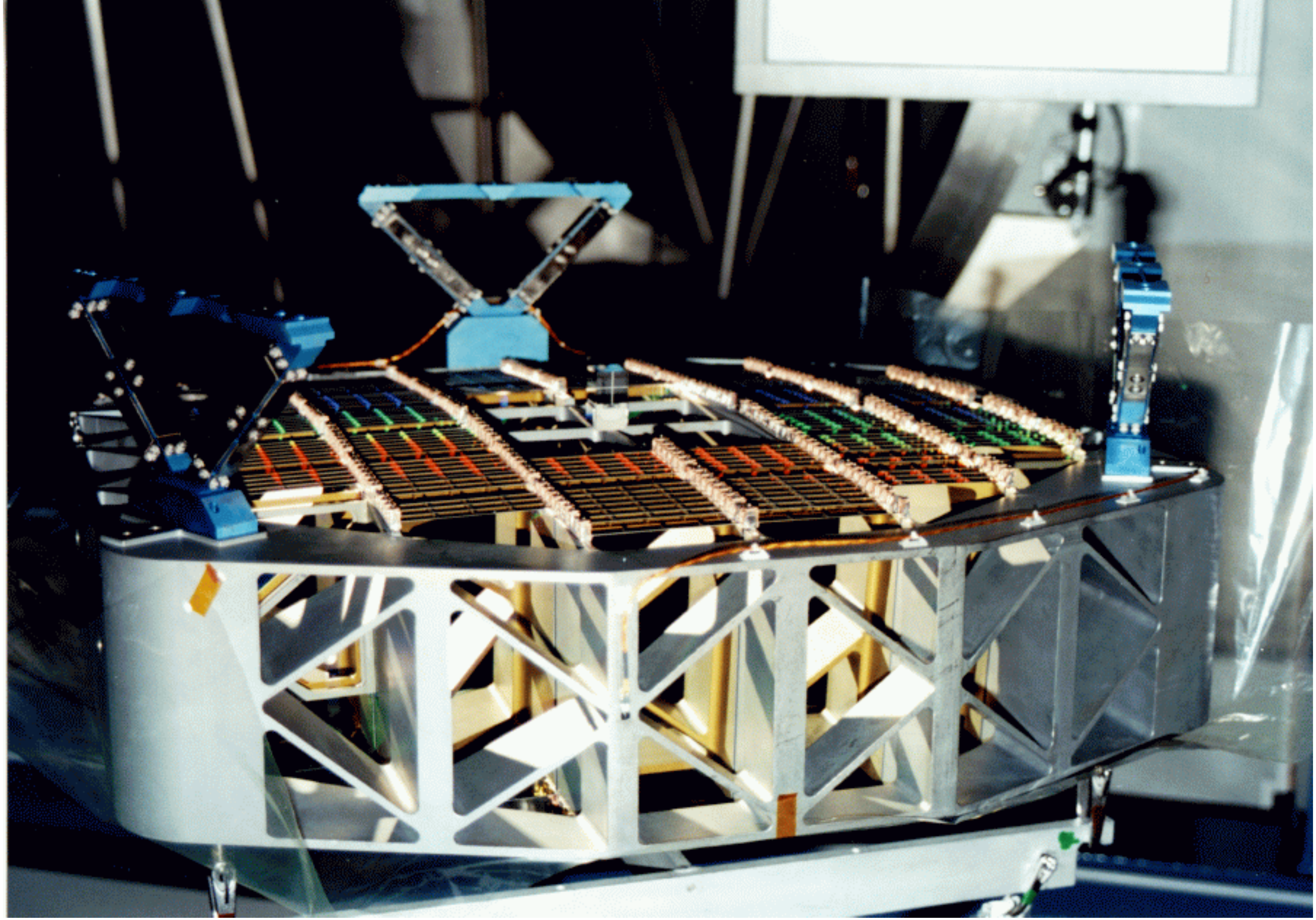
XMM-*Newton* (ESA; 1999-   )

XMM-*Newton*

XMM-Newton preparation

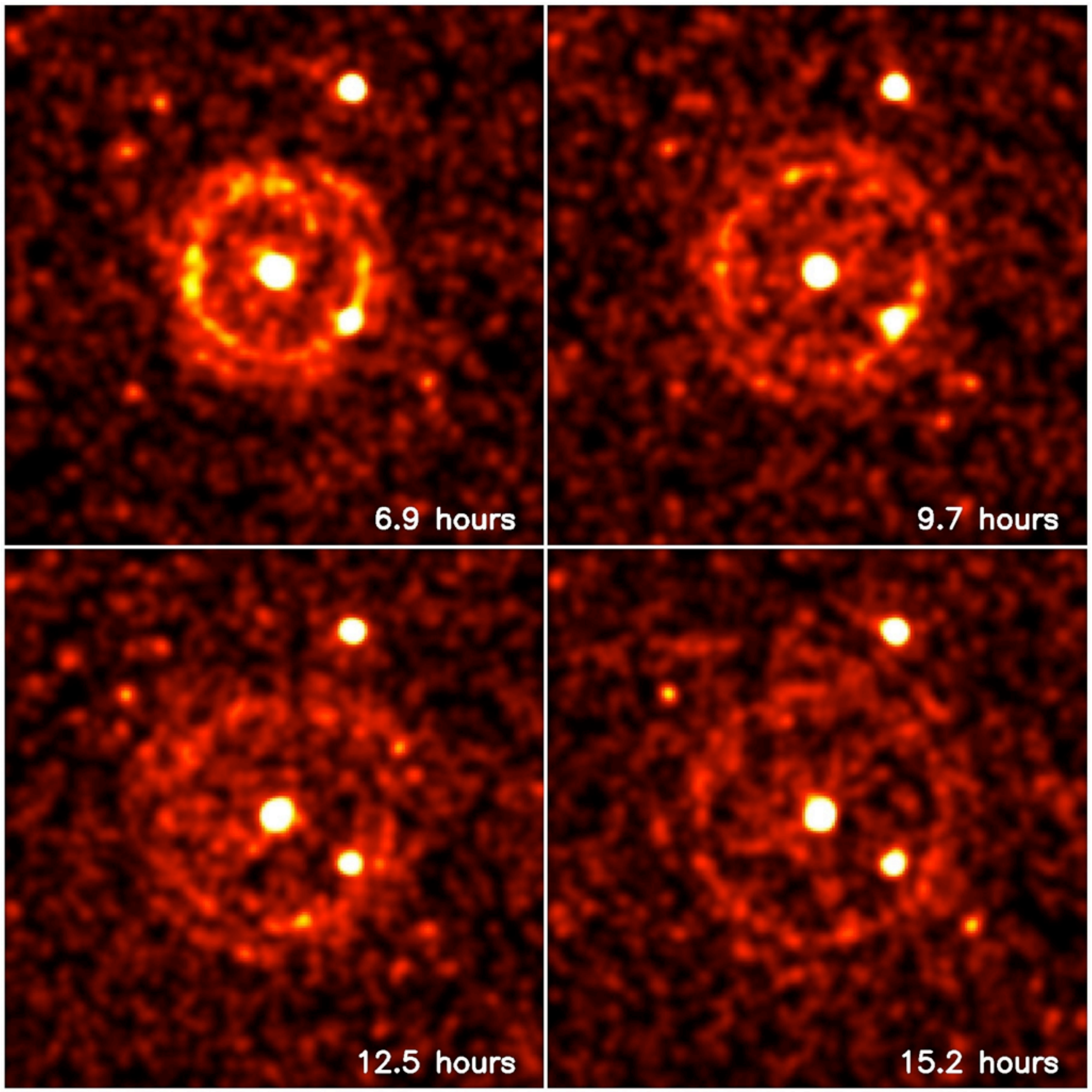
Image courtesy of D. Parker

European Space Agency



array of reflection gratings for the
Reflection Grating Spectrometer (XMM-RGS; 5-35 Å)
(SRON/Columbia University)

last slide of the day: has nothing to do with neutron stars



X-ray shout echoing through space from GRB 031203

Image courtesy of Simon Vaughan (University of Leicester)

European Space Agency

XMM observed the X-ray afterglow of gamma-ray burst GRB 031203 (z = 0.105); detected an expanding halo due to scattering by Galactic interstellar dust!

(Vaughan et al. 2004)