50+ years of cosmic X-ray spectroscopy in the Netherlands

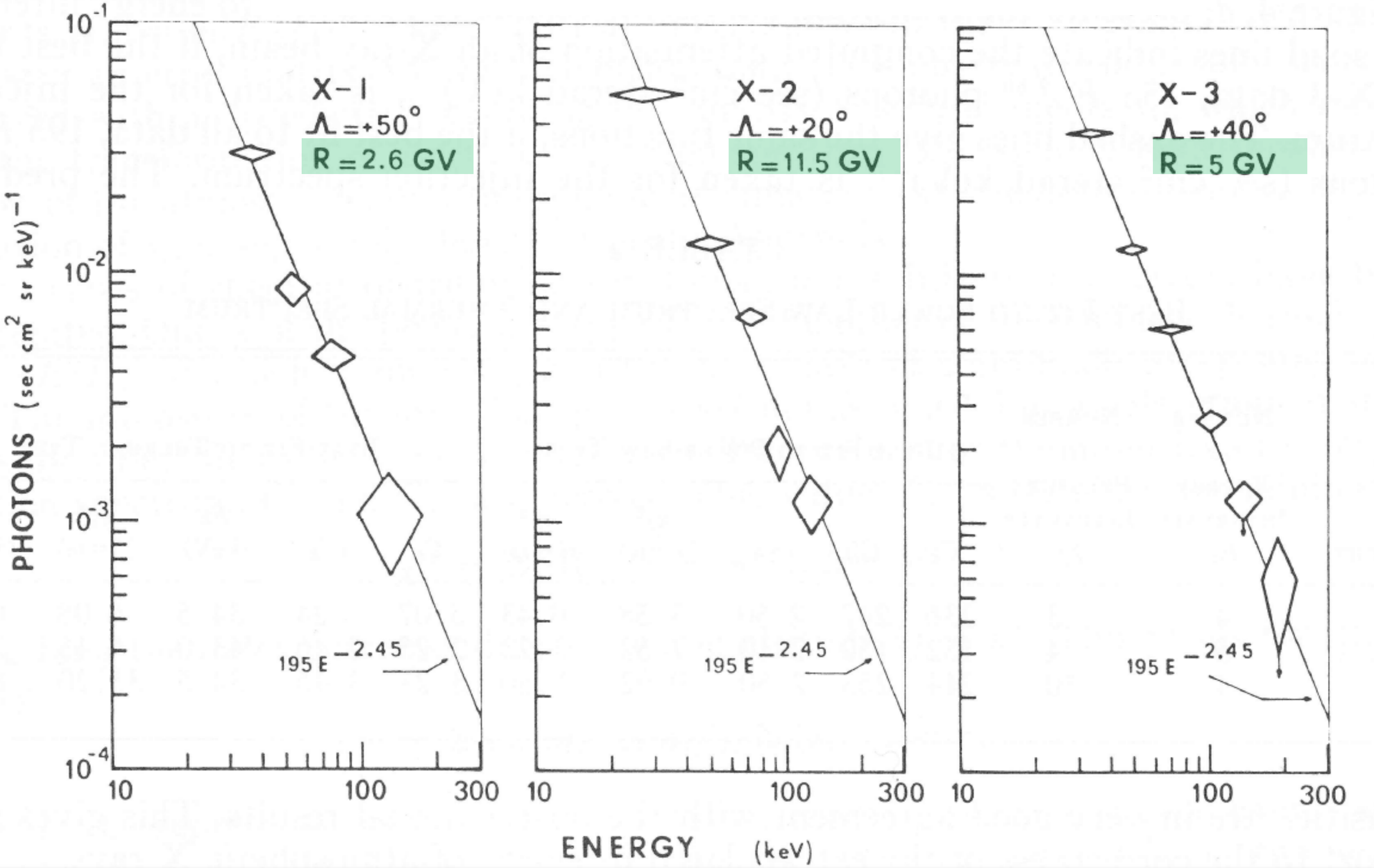
Johan Bleeker SRON/Univ.Utrecht
17 January 2022

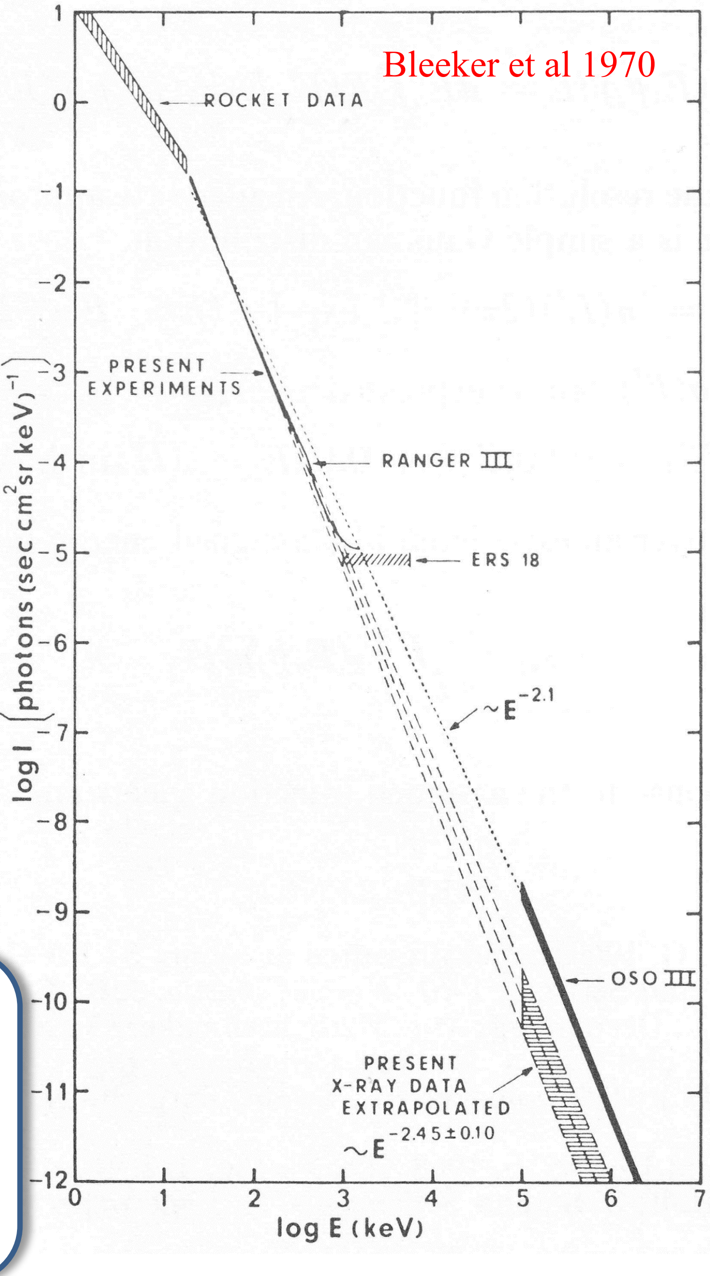
Pioneering phase: early developments

X-ray spectrophotometry:

- 1960’s:
  Surveys of the hard diffuse X-ray background (balloon borne)
- Early 1970’s:
  Surveys of the soft diffuse X-ray background (rocket borne)
- 1974:
  Selected targets (satellite borne: Astronomical Netherlands Satellite ANS)

1960s Leiden-Nagoya: Photometric surveys of the hard diffuse X-ray background

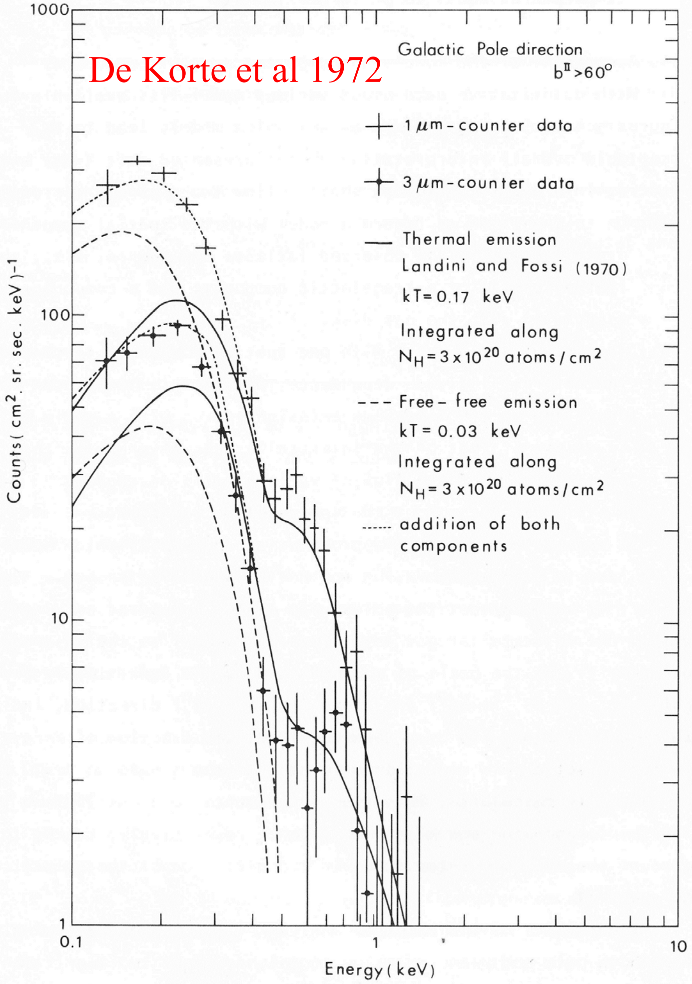


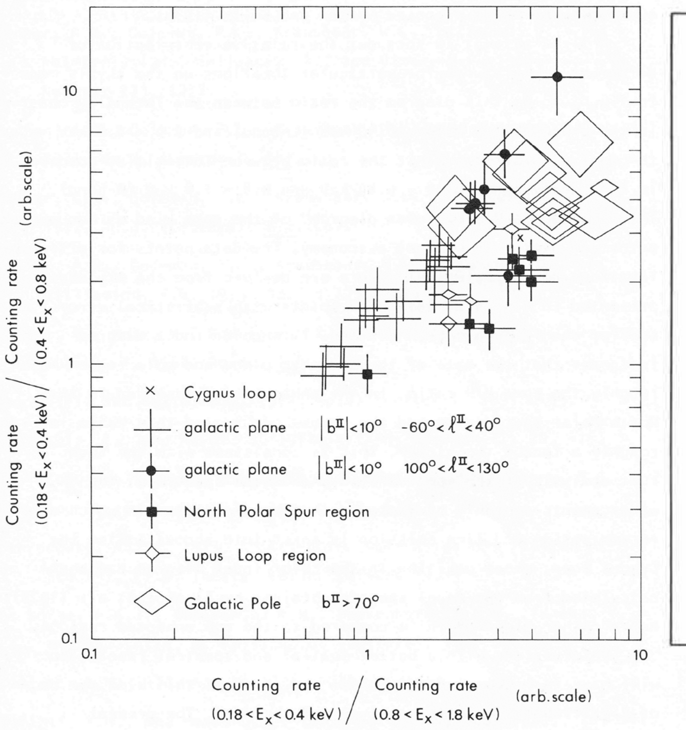

Bleeker et al 1970

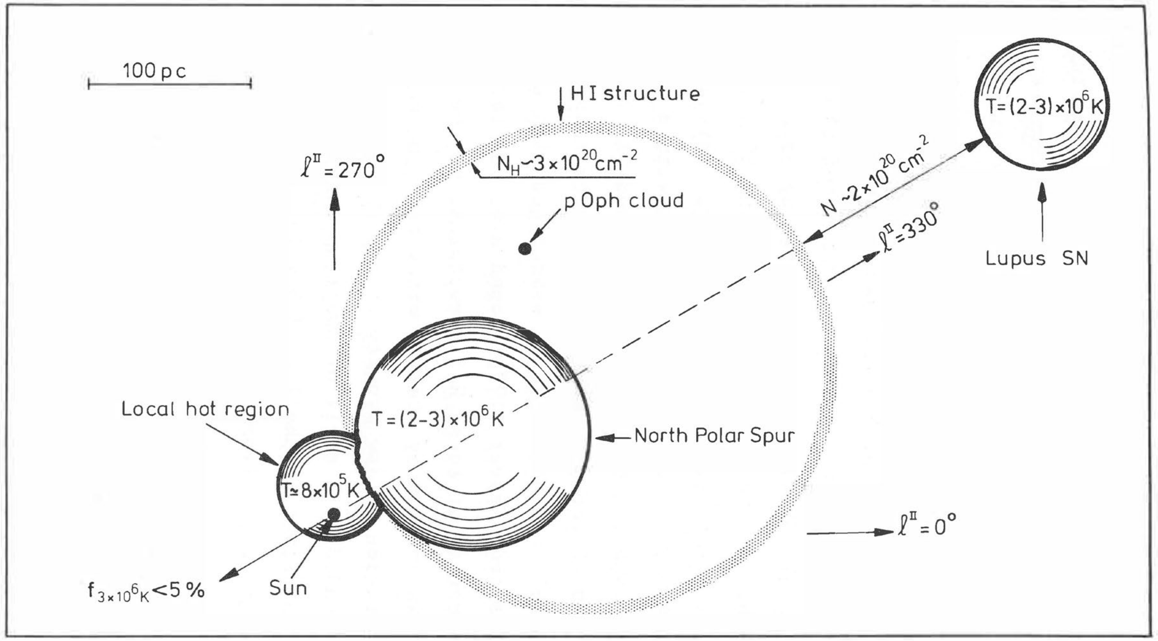
- Unique: chopping beam shutter and radically different radiation environments
- Highly isotropic → extragalactic in origin
- Significant spectral steepening between 2-20 and 20-200 keV
- Diffuse γ-ray background (1968) no extrapolation of hard X-ray background

Photometric surveys of the soft diffuse X-ray background (rocket borne)
(in collaboration with Japanese colleagues at ISAS and Nagoya)

Early 1970s

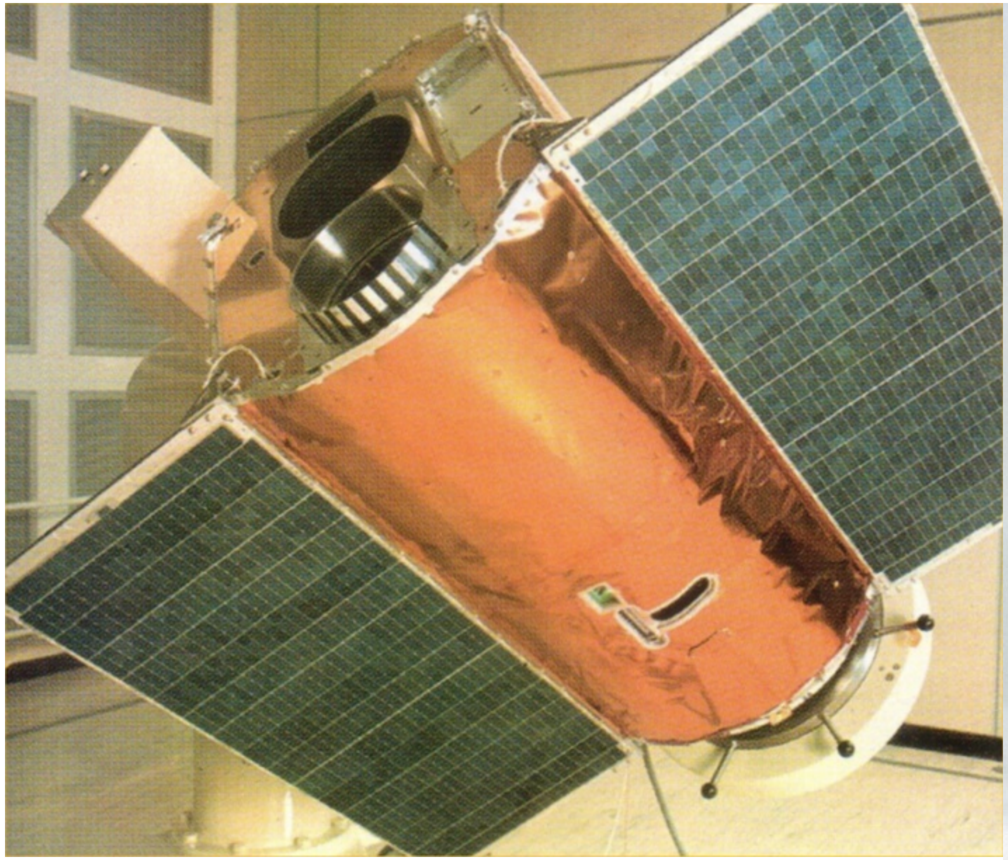
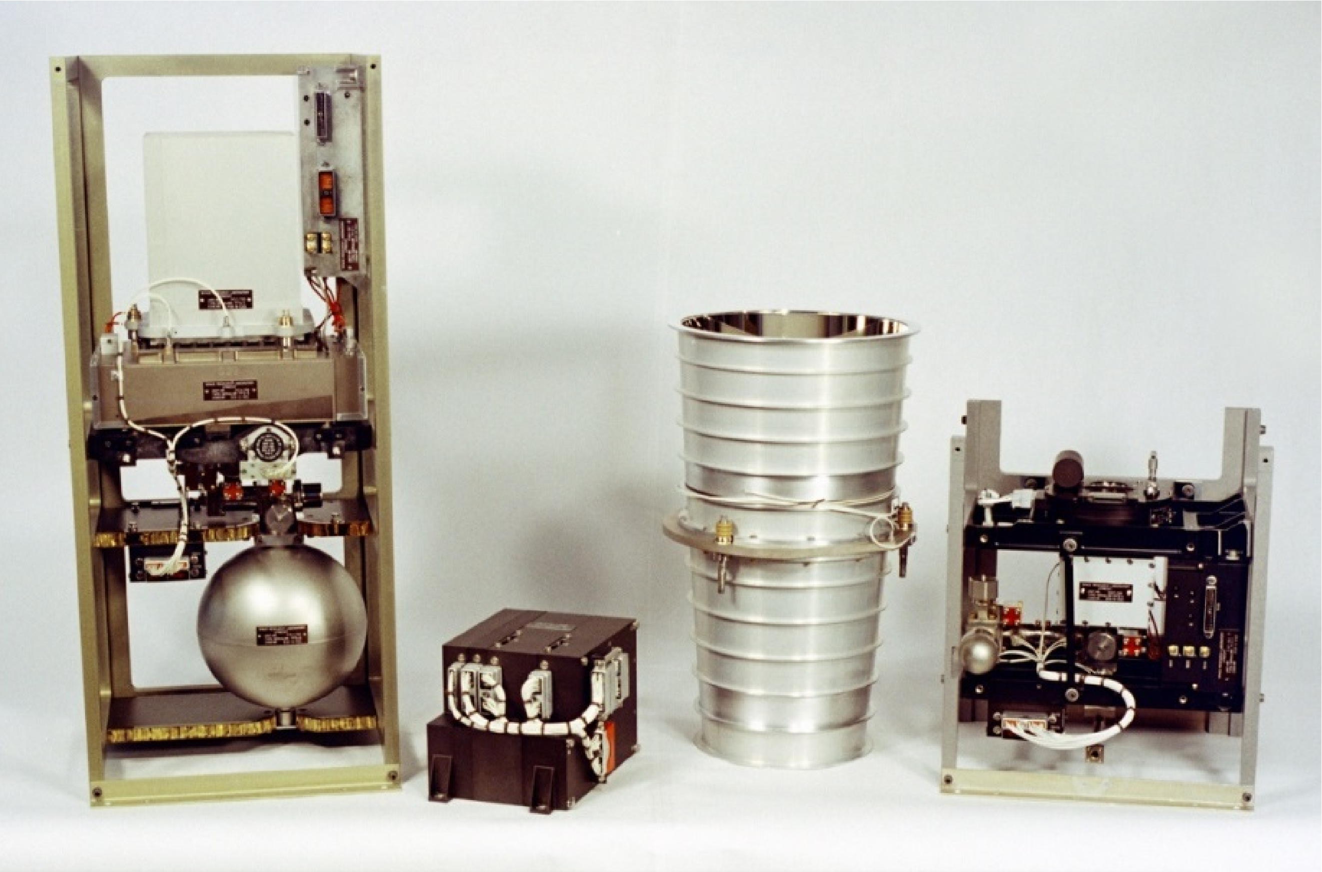

De Korte et al 1972





- Minimal systematic errors with overlapping 0.5, 1.0 and 3.0 µm ppl X-ray filters
- Soft X-ray background almost exclusively galactic in origin
- Low temperature component ≈ 8.10^5 K pervades the whole sky: local hot gas
- Large scale higher temperature structures ≈ 3.10^6 K: adiabatic SNR shocks

The Astronomical Netherlands Satellite (1974)

Major results

- Type I X-ray bursts
- (soft) X-rays from stellar coronae
- Stellar X-ray flares
- Thermal X-ray distribution in evolved SNRs

The grass roots for spectroscopy

Initiative by Marcel Minnaert at Utrecht

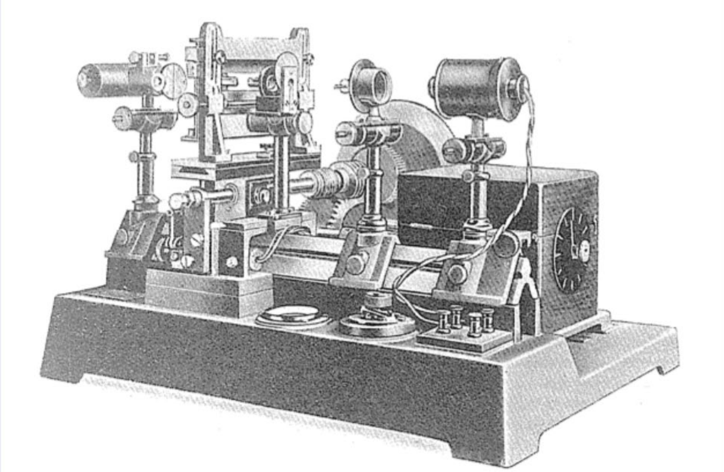
Atlas of the solar spectrum: λ3612 – λ8770

(Appendix: λ3332 – λ3637)

THE SOLAR SPECTRUM 2935Å to 8770Å

Second Revision of Rowland's
Preliminary Table of
Solar Spectrum Wavelengths

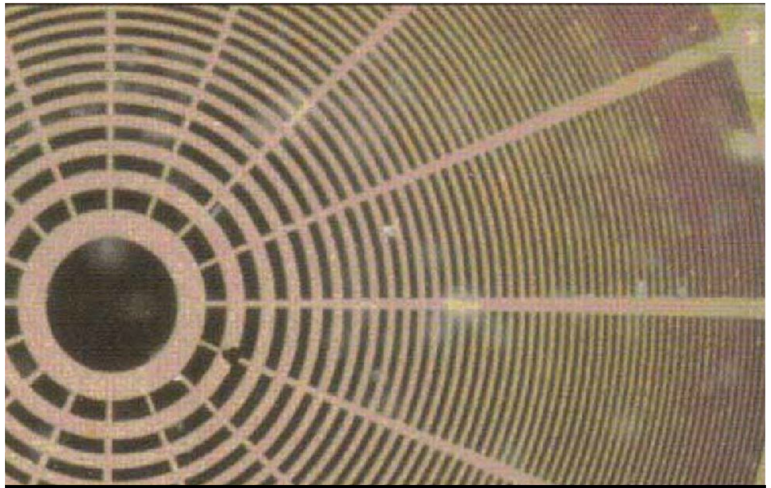
Moll's microphotometer 1919

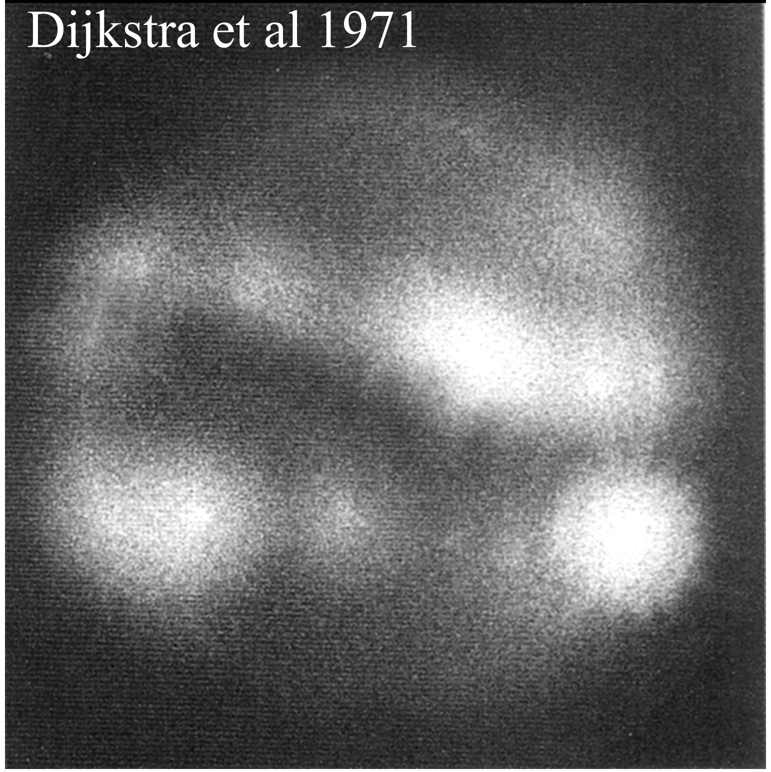


UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

- 1936: ~ 100 photographic plates taken at Mount Wilson Observatory.
- 1940: Utrecht Photometric Atlas of the solar spectrum (Marcel Minnaert et al). Crucial: the innovative micro-photometer designed by Willem Moll in 1919 for calibrating the MWO photographic plates
- 1952: Solar atmosphere temperature model (Kees de Jager)
- 1966: Solar abundances from the solar spectrum (Charlotte Moore et al, NBS)

Mid 1960s Utrecht: Quasi-monochromatic XUV-images of the Sun





Dijkstra et al 1971

X-ray lense employing diffraction: Fresnel zone plate

Photolithography:

Employment of a holographic method that produces a zone pattern resulting from interference of two coherent spherical wave fronts generated by a beam-split Cd-He laser.

1967: Successful sun stabilized Aerobee rocket experiment

4 Zone plates of n = 50 metallic rings

$f_1 = \frac{2 r_n \Delta r_n}{\lambda} = 40$ cm with $\lambda = 5$ nm, $\Delta r_n = 1\,\mu$m, $r_n = 1$ mm

outer diameters 0.90–3.06 mm

→ Solar Q-monochromatic images in Si X, Fe XI, HeII and HeI lines

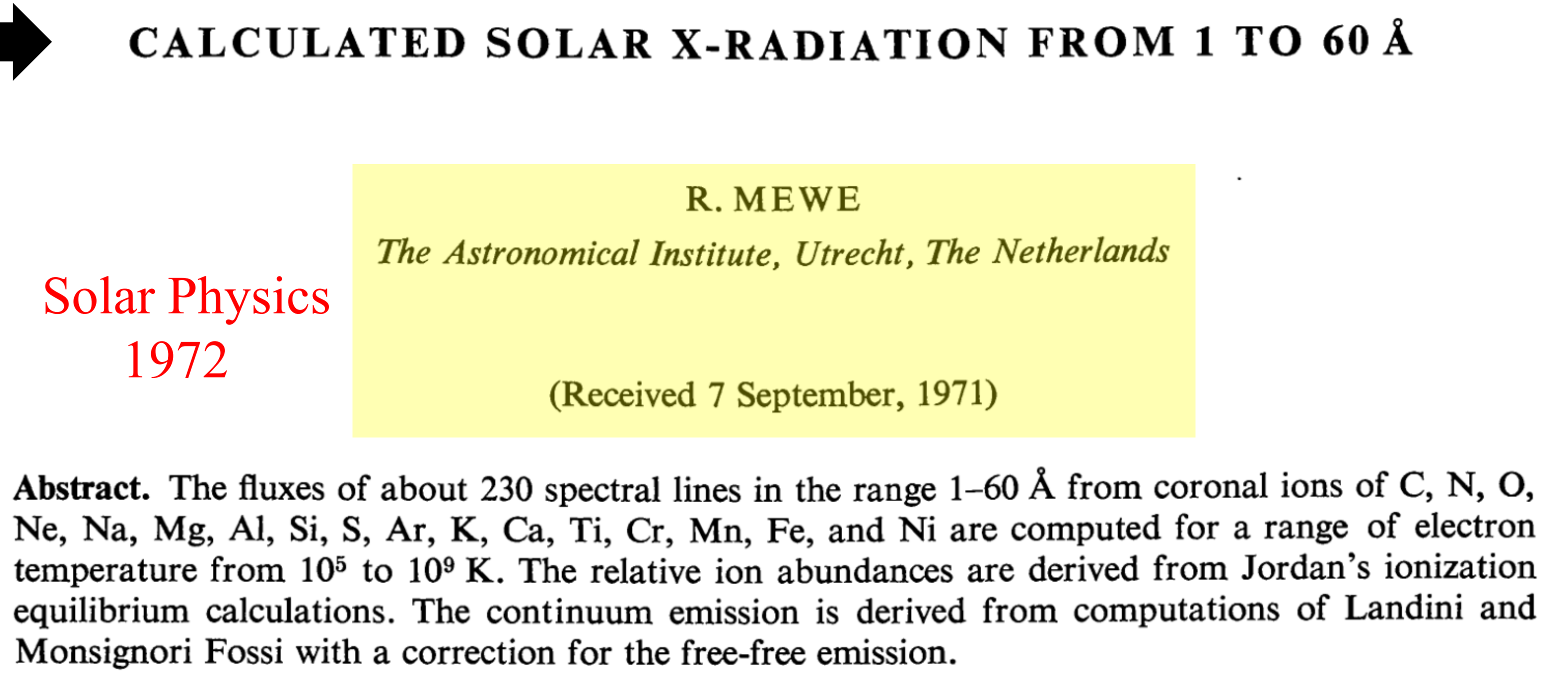
◀ Sun in Si X at 5.1 nm

Seminal papers by Rolf Mewe

Early 1970's:

Start development X-ray spectral codes at Utrecht by Mewe, Kaastra, later joined by Liedahl

MeKaL code
Basis of SPEX fitting



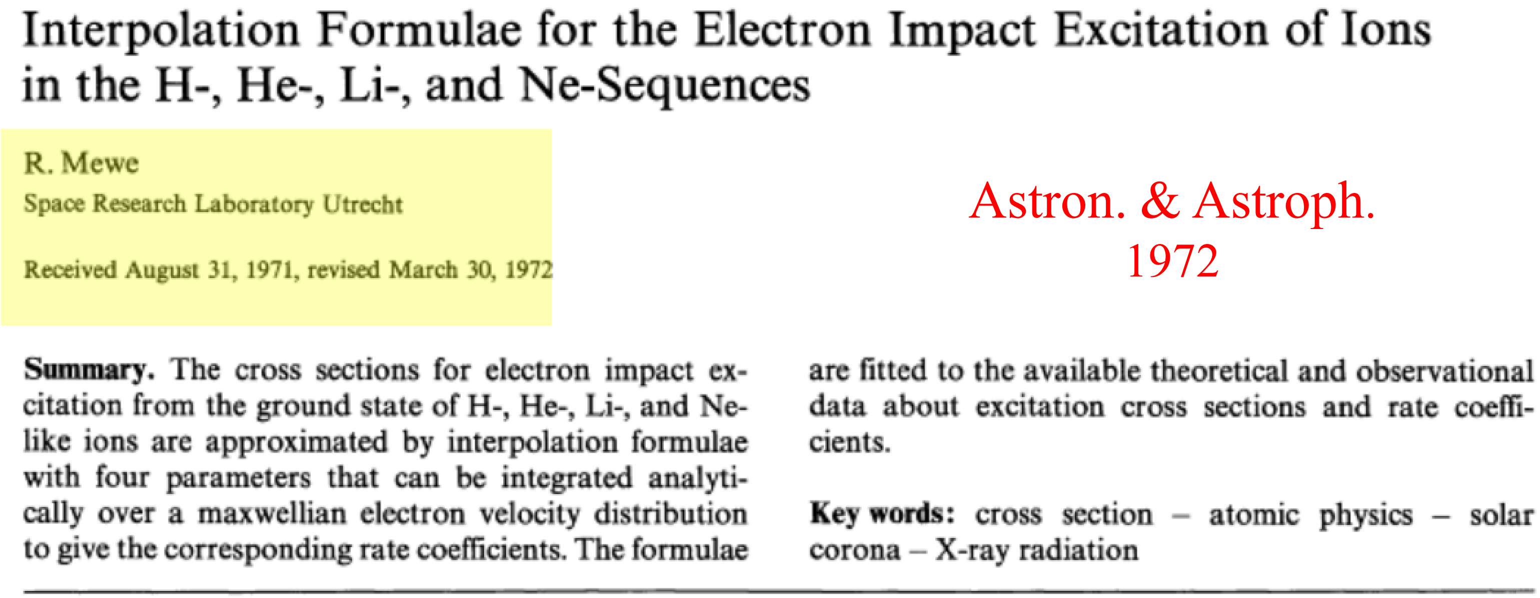
CALCULATED SOLAR X-RADIATION FROM 1 TO 60 Å

R. MEWE
The Astronomical Institute, Utrecht, The Netherlands

(Received 7 September, 1971)

Solar Physics
1972

Abstract. The fluxes of about 230 spectral lines in the range 1–60 Å from coronal ions of C, N, O, Ne, Na, Mg, Al, Si, S, Ar, K, Ca, Ti, Cr, Mn, Fe, and Ni are computed for a range of electron temperature from 10^5 to 10^9 K. The relative ion abundances are derived from Jordan's ionization equilibrium calculations. The continuum emission is derived from computations of Landini and Monsignori Fossi with a correction for the free-free emission.



Interpolation Formulae for the Electron Impact Excitation of Ions in the H-, He-, Li-, and Ne-Sequences

R. Mewe
Space Research Laboratory Utrecht

Received August 31, 1971, revised March 30, 1972

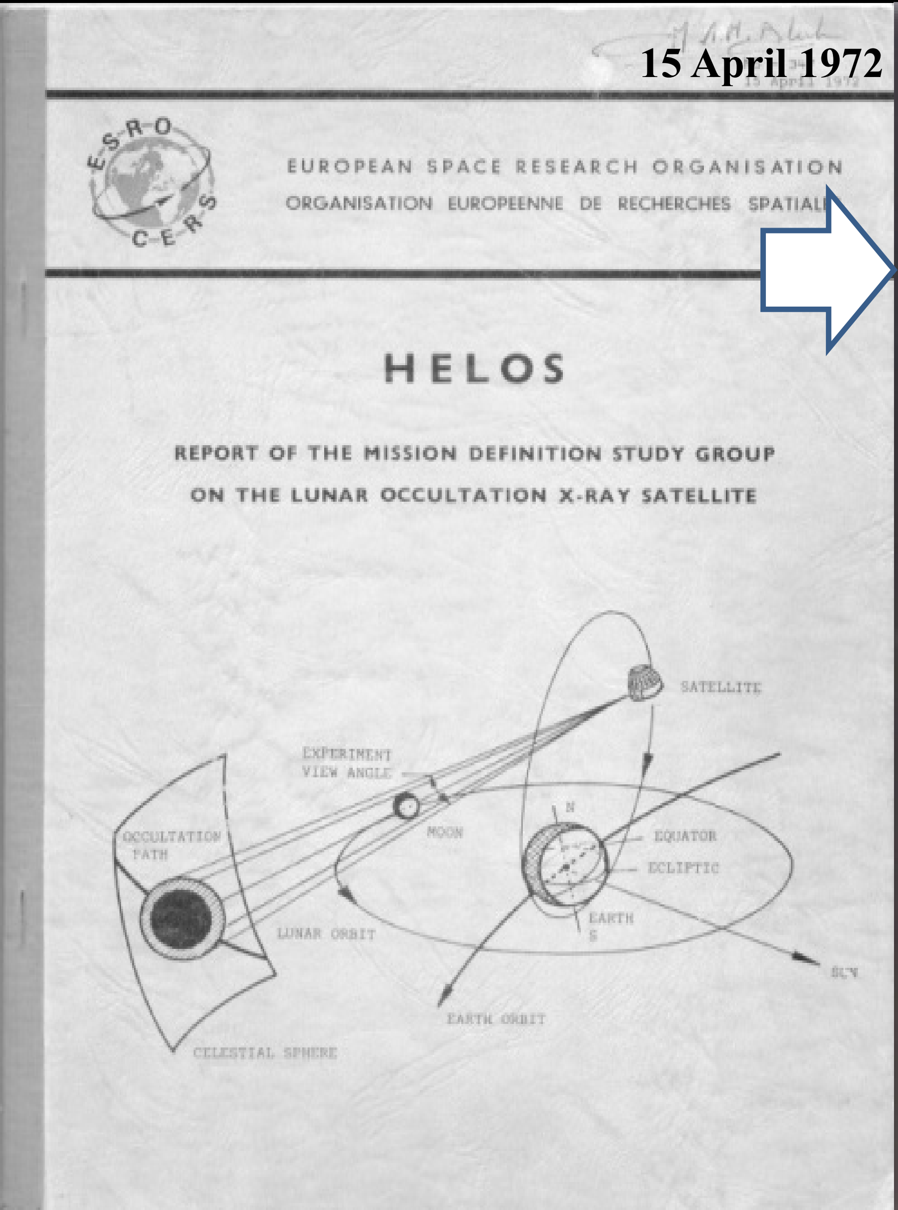
Astron. & Astroph.
1972

Summary. The cross sections for electron impact excitation from the ground state of H-, He-, Li-, and Ne-like ions are approximated by interpolation formulae with four parameters that can be integrated analytically over a maxwellian electron velocity distribution to give the corresponding rate coefficients. The formulae are fitted to the available theoretical and observational data about excitation cross sections and rate coefficients.

Key words: cross section – atomic physics – solar corona – X-ray radiation

Grating spectrometers OGS/TGS on Einstein (1978) & EXOSAT (1983):

Photolithographic zone plate technology ➡ from QM-image to HR-spectrum



15 April 1972

ESRO CERS

EUROPEAN SPACE RESEARCH ORGANISATION
ORGANISATION EUROPEENNE DE RECHERCHES SPATIAL

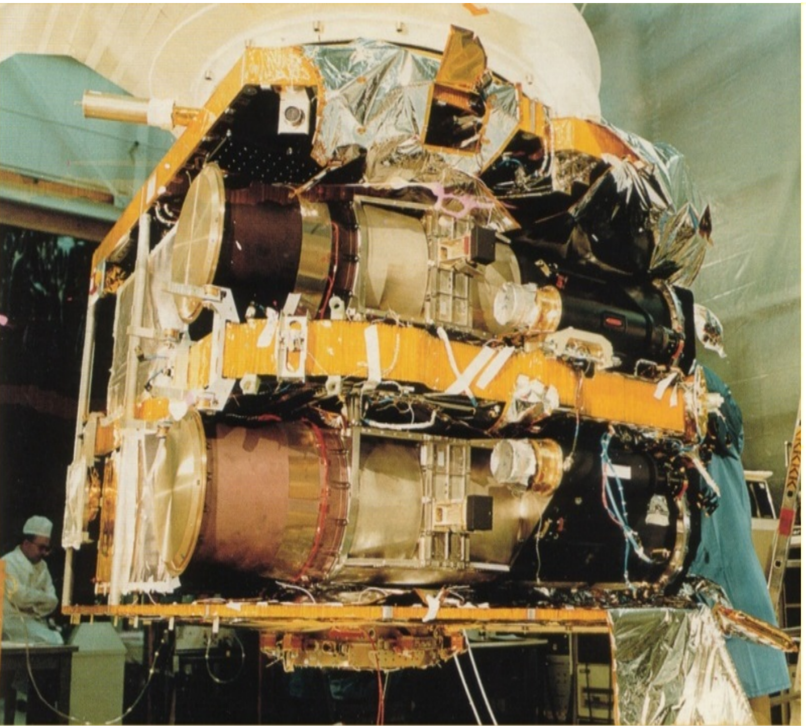
HELOS

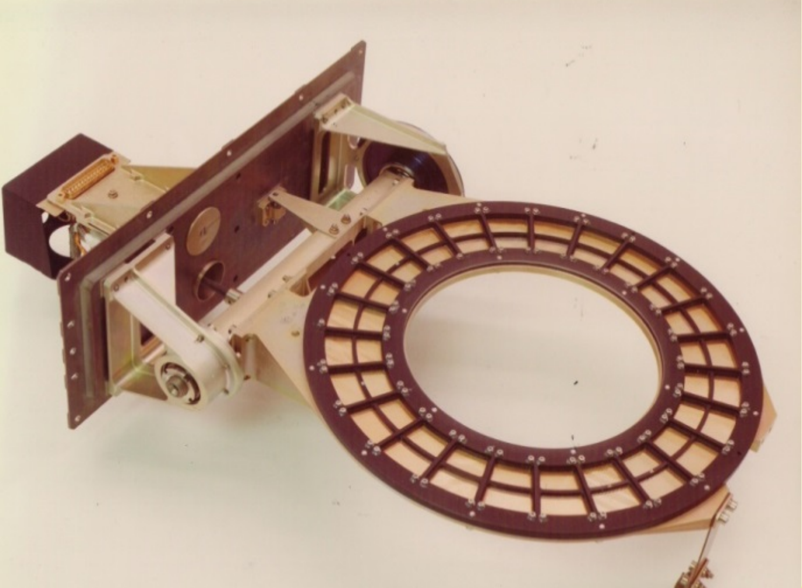
REPORT OF THE MISSION DEFINITION STUDY GROUP
ON THE LUNAR OCCULTATION X-RAY SATELLITE

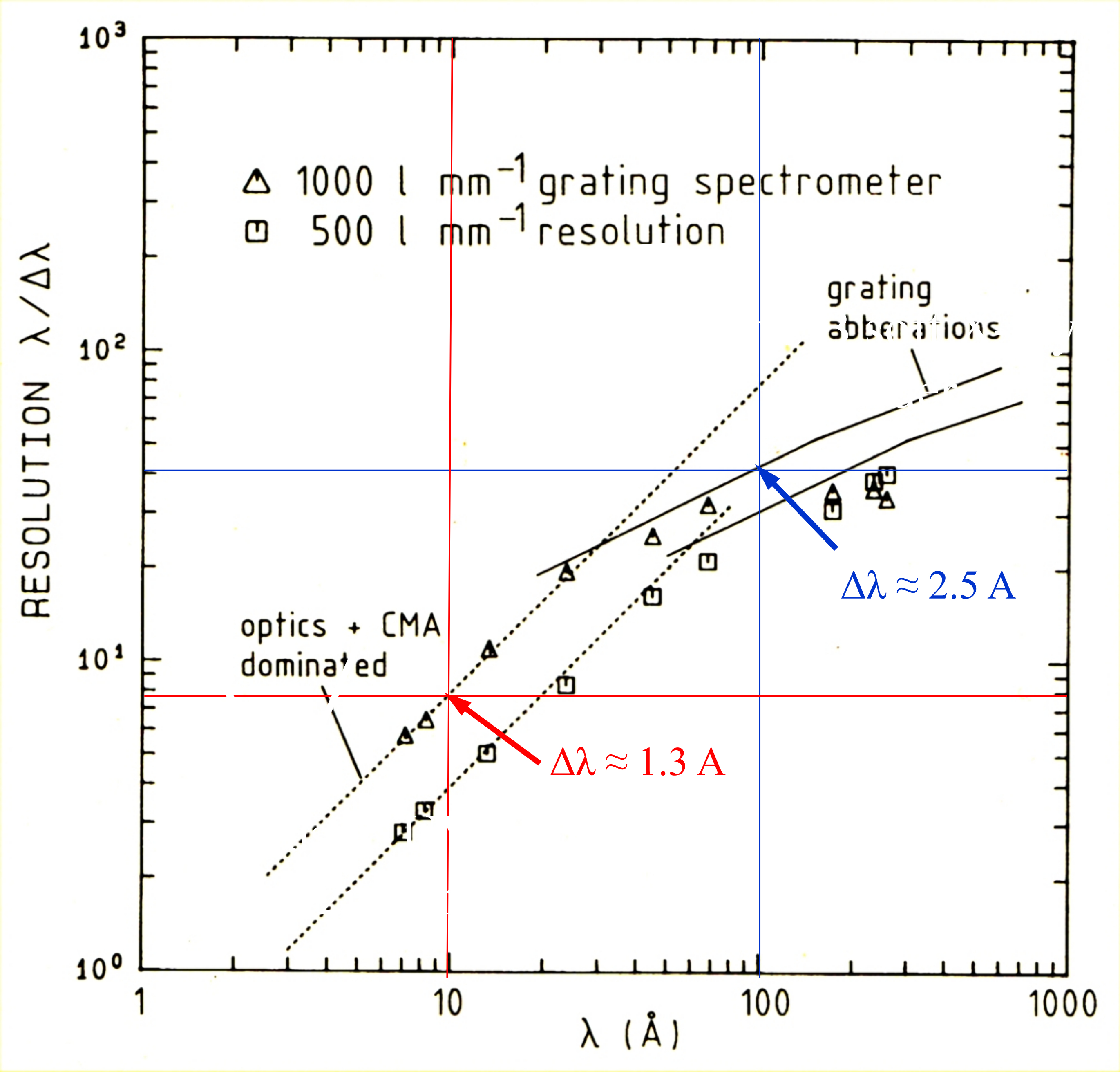
EXOSAT

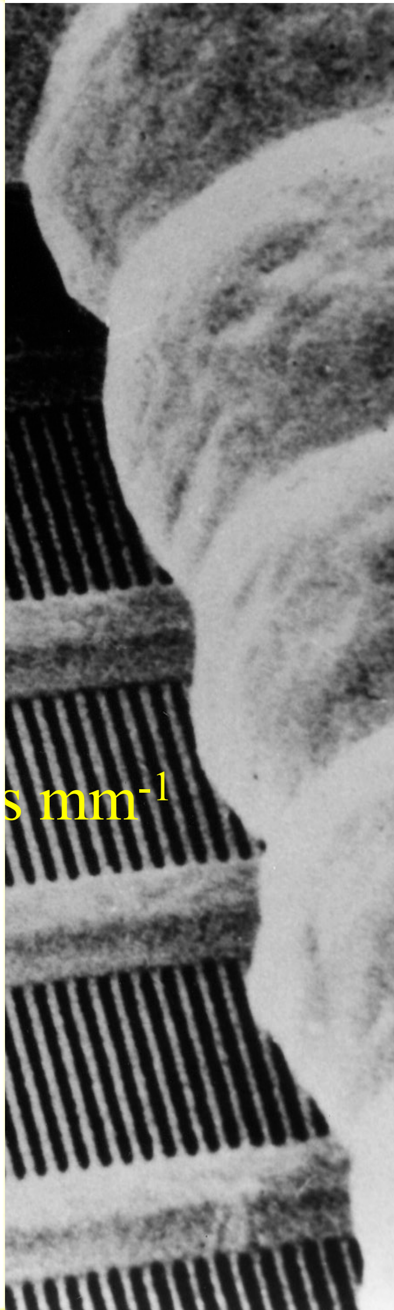
First development of
light -weight replica
Wolter I X-ray optics:
Carrier : Beryllium
Layer : Epoxy
Coating : Gold

TGS (500 lines mm^{-1} and 1000 lines mm^{-1}) on EXOSAT

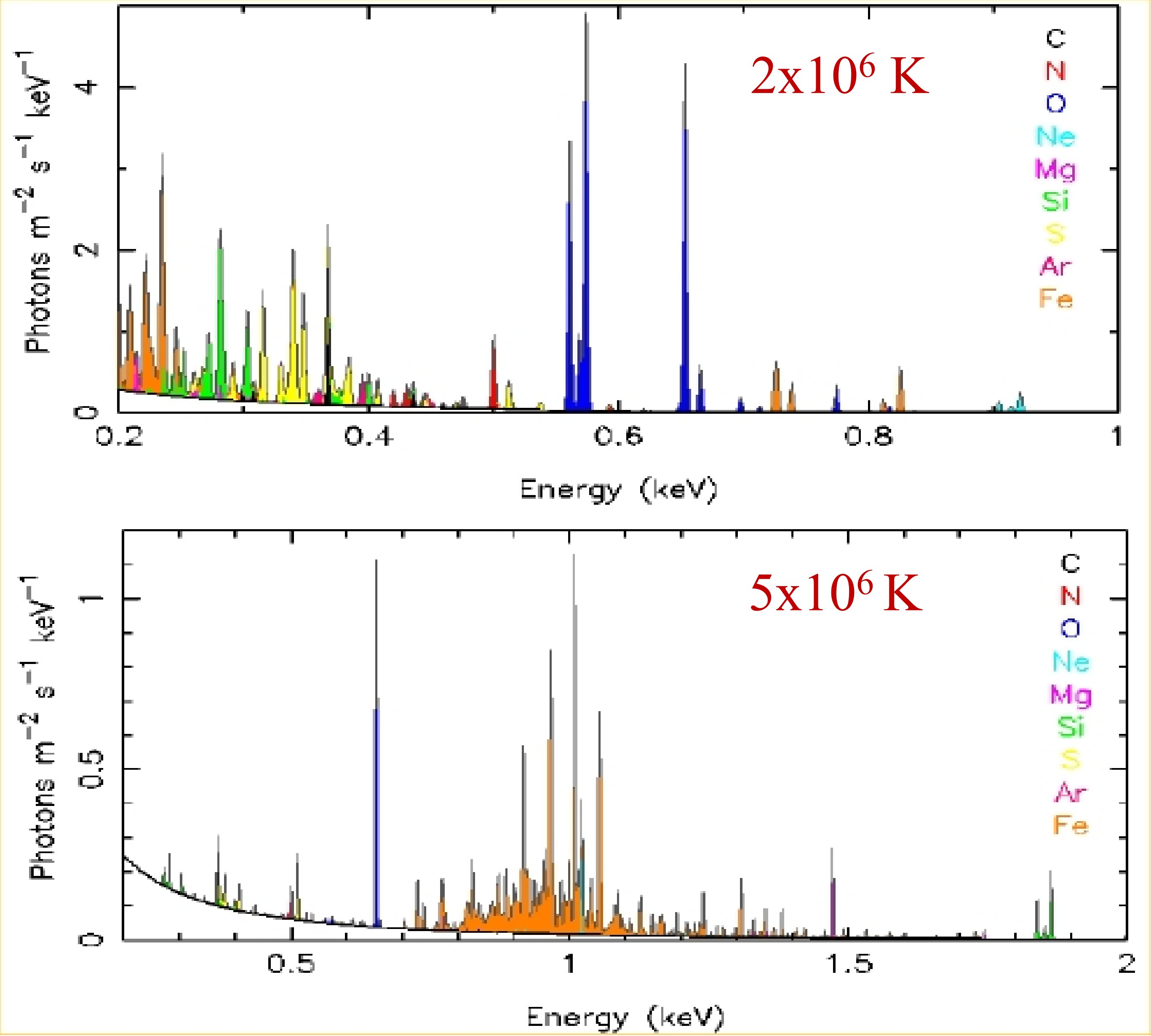




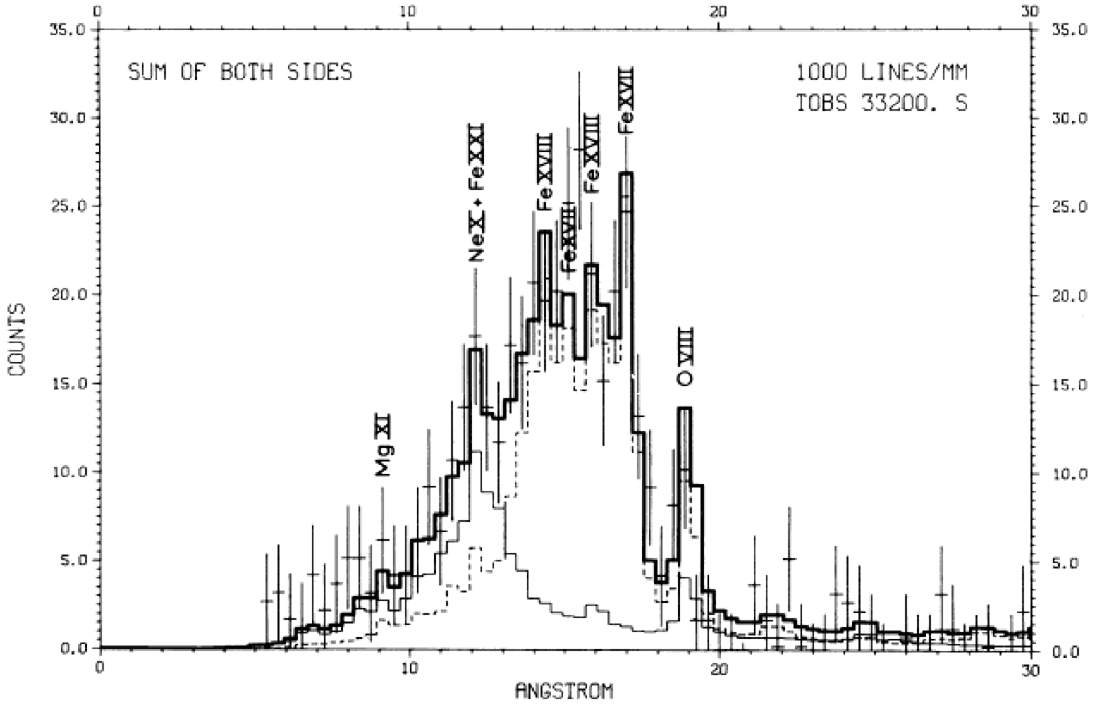




Coronal spectra: Differential Emission Measure DEM) as a function of Temperature



First high resolution X-ray spectrum of the corona of Capella taken with the 1000 l/mm OGS on the Einstein Observatory (Mewe et al, 1982).
The soft X-ray emission was discovered in 1975 by Mewe et al (ANS) and Catura et al (rocket flight).



TGS: unique features

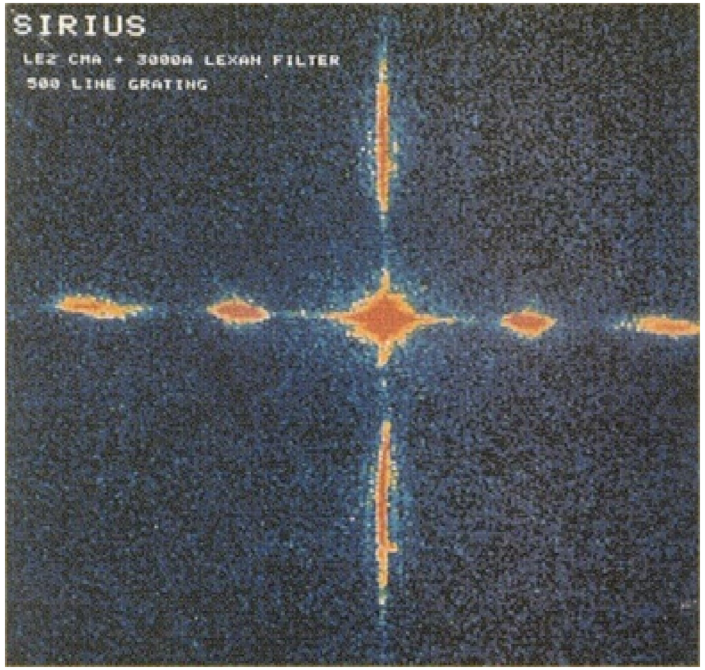
Distinguishing feature from previous instruments:
Unprecedented dynamic range over the soft-X and EUV band (8 - 400 A), with a superior combination of sensitivity and spectral resolution in the XUV band (50 - 400 A).

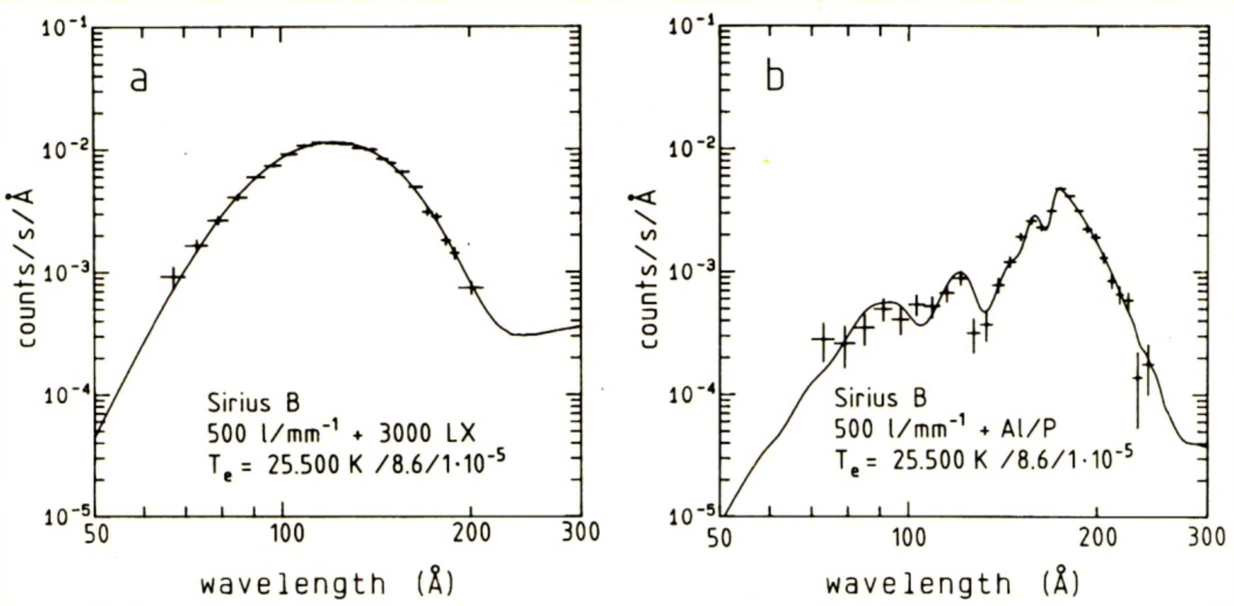
Priority targets:

- Hot photospheres of nearby white dwarfs
  TGS covers the full XUV spectrum between the intrinsic short wavelength cut-off of the stellar spectrum (at ≈ 50 A) and the cut-off in the EUV band due to interstellar absorption.

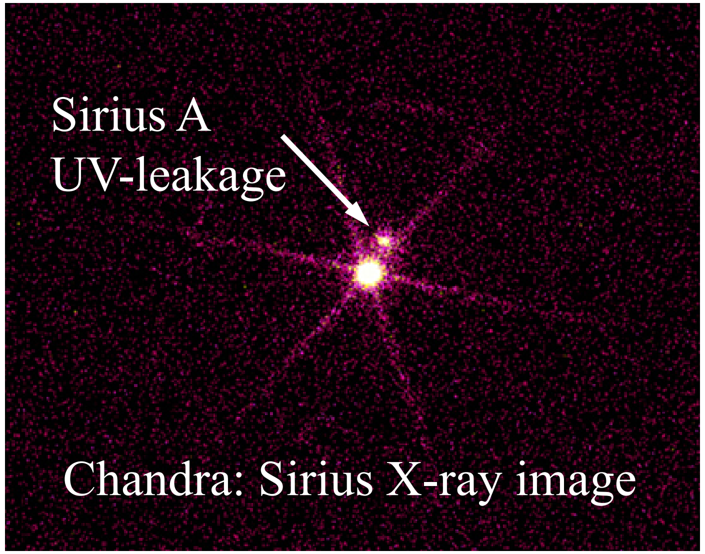
- Hot coronae of nearby late-type stars
  TGS resolves ($\Delta\lambda \approx 3$A) ionic coronal emission lines over a wide temperature range → temperature and emission measure distribution of the hot stellar coronal plasma.

WD atmospheres: Sirius B ➡ He-abundance and interstellar absorption

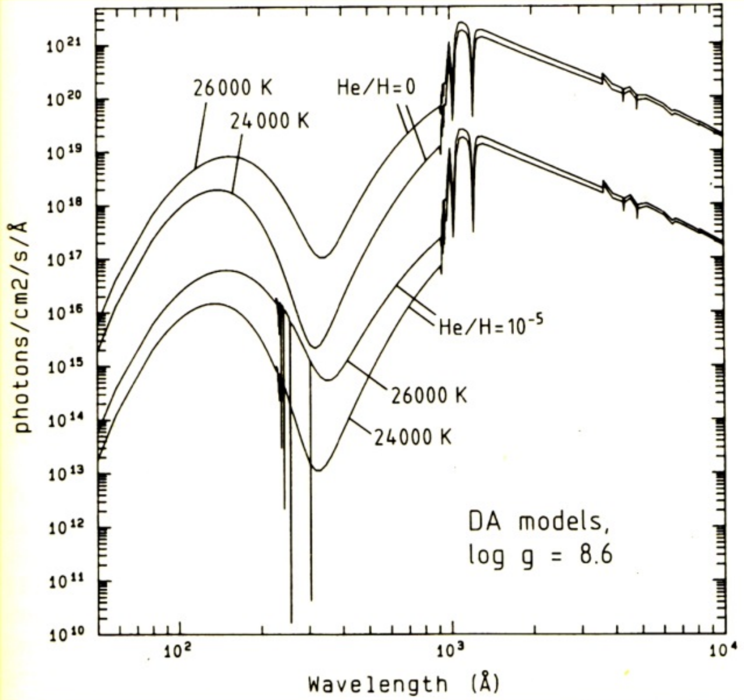




(Paerels et al, 1988)



Chandra: Sirius X-ray image



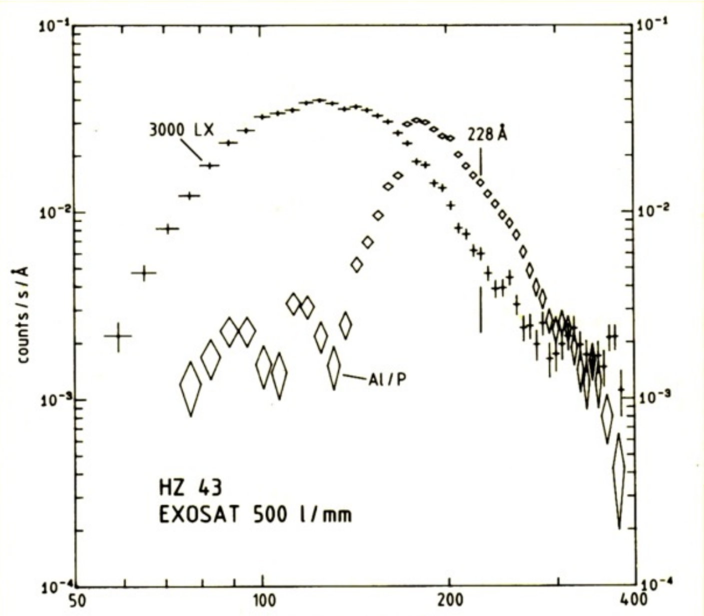
EXOSAT spectroscopy, 99% confidence limits:

T_e = 24,500 – 26,000
$R/R_\odot$ = 0.008 – 0.012
log g = 8.3 – 8.7
He/H < 2.10^{-5}

Parameter set for a consistent model covering the full EM spectrum: optical, UV, EUV, soft-X:

T_e = 25,000 ± 500 K
$R/R_\odot$ = 0.0079 – 0.0085
from $M/M_\odot$ = 1.053 ± 0.028
log g = 8.53 – 8.73 (≈ 400,000g_{earth})
He/H < 2.10^{-5}
$N_H = (1.1 – 5.0).10^{18}$ cm^{-2}

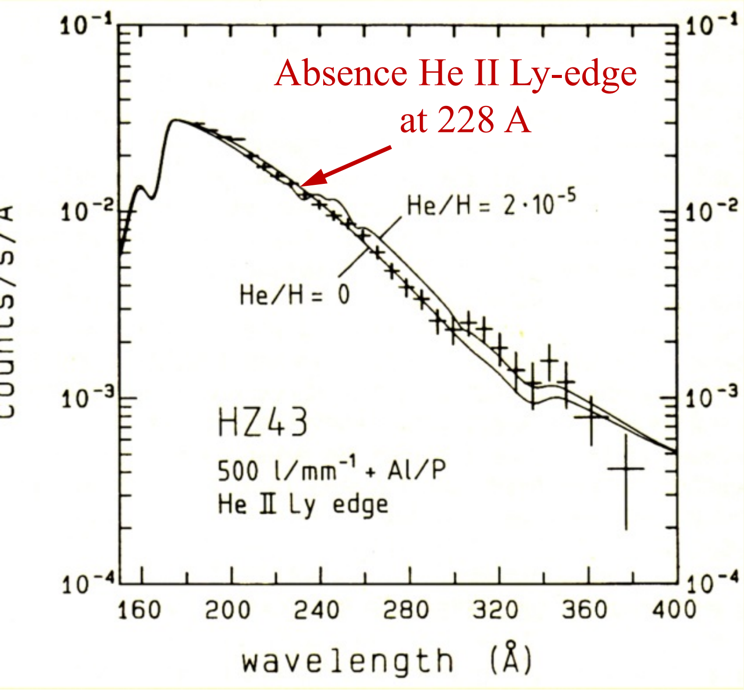
Hot WDs: HZ 43 ➡ Atmospheric model fit with full EM-spectrum

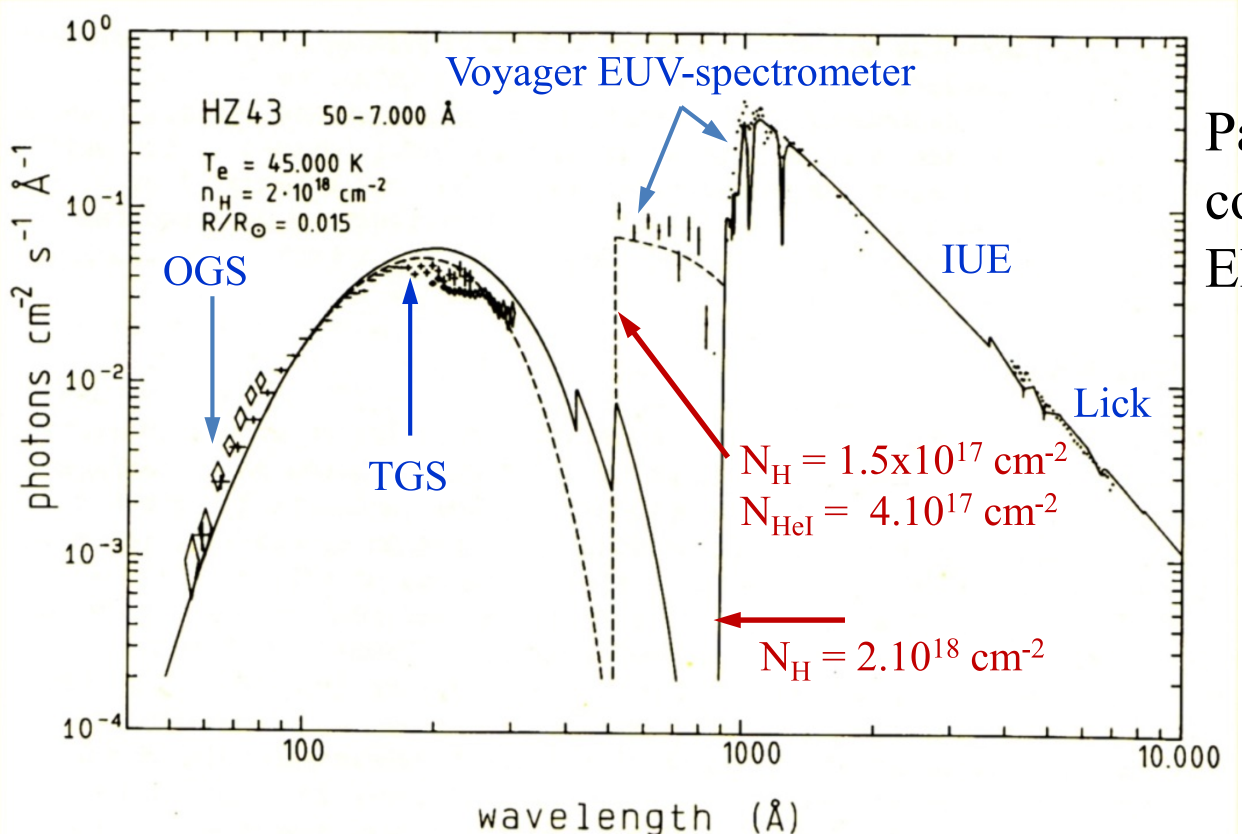


Rocket EUV- spectrometer (Malina et al, 1982) detects He in HZ 43 EUV spectrum: He/H = $(1.5 – 6.0).10^{-5}$? Kahn et al (1984), from comparison of Einstein IPC-fluxes for 4 DA WDs with IUE spectra, find evidence for He/H $=10^{-5}-10^{-3}$. Petre et al (1986) find similar results for another 5 WDs.

Interpretation: 1. High T_e radiation field prevents He from quick downward diffusion due to large gravity?

2. Accretion of interstellar He onto DA photosphere?





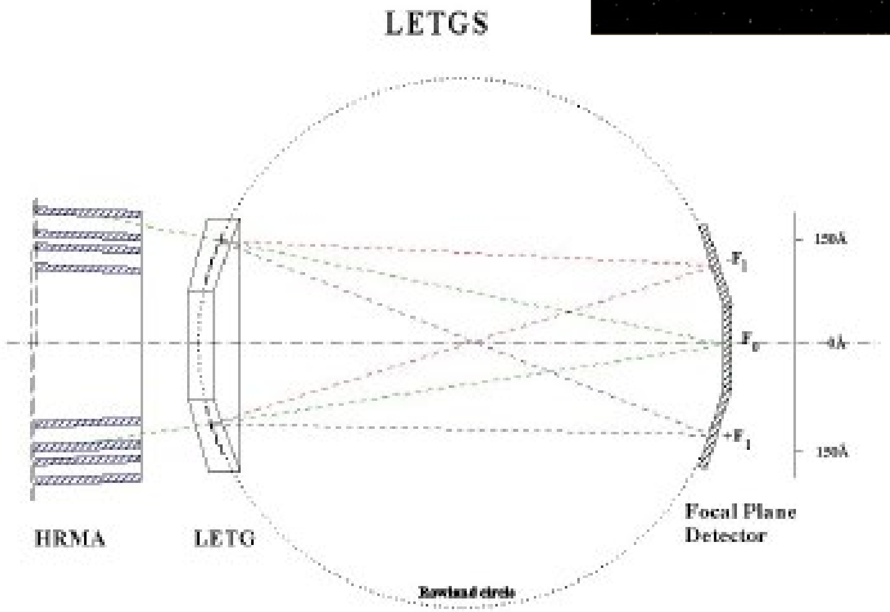
Parameter set for a model consistent with the full EM spectrum of HZ 43:

$T_e = 45,000 – 54,000$ K
$R/R_\odot = 0.0140 – 0.0165$
$\log g = 7.8 – 8.4$
$He/H < 1.0 \times 10^{-5}$

(Paerels et al, 1986a)
(Heise et al 1988)

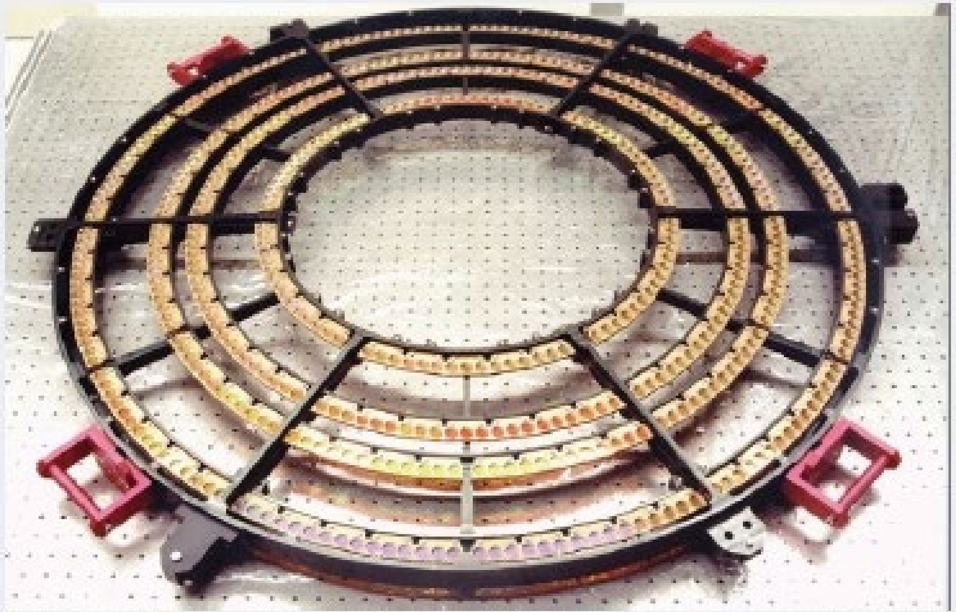
LETG on Chandra: SRON (PI) & MPE-Garching

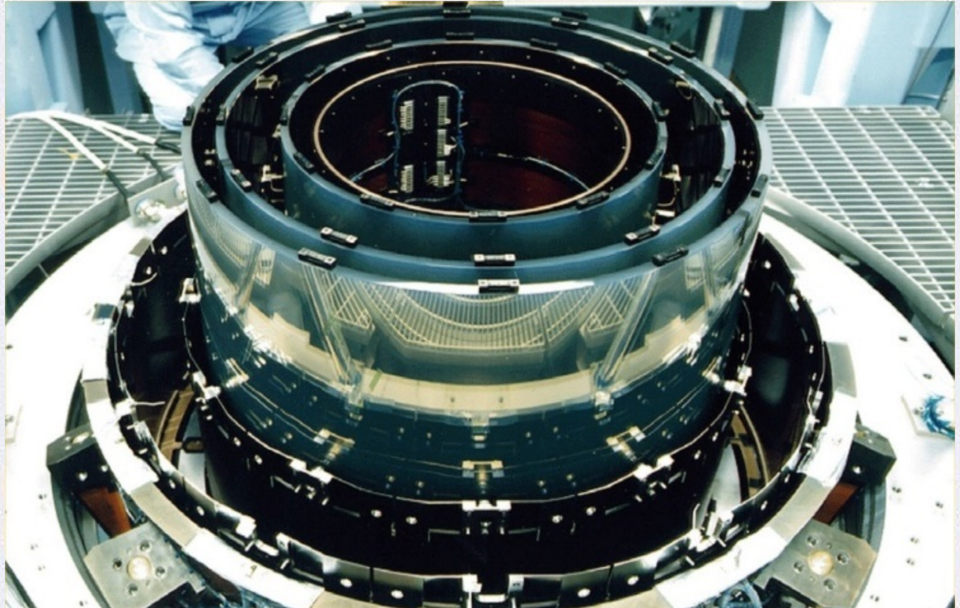
optical configuration



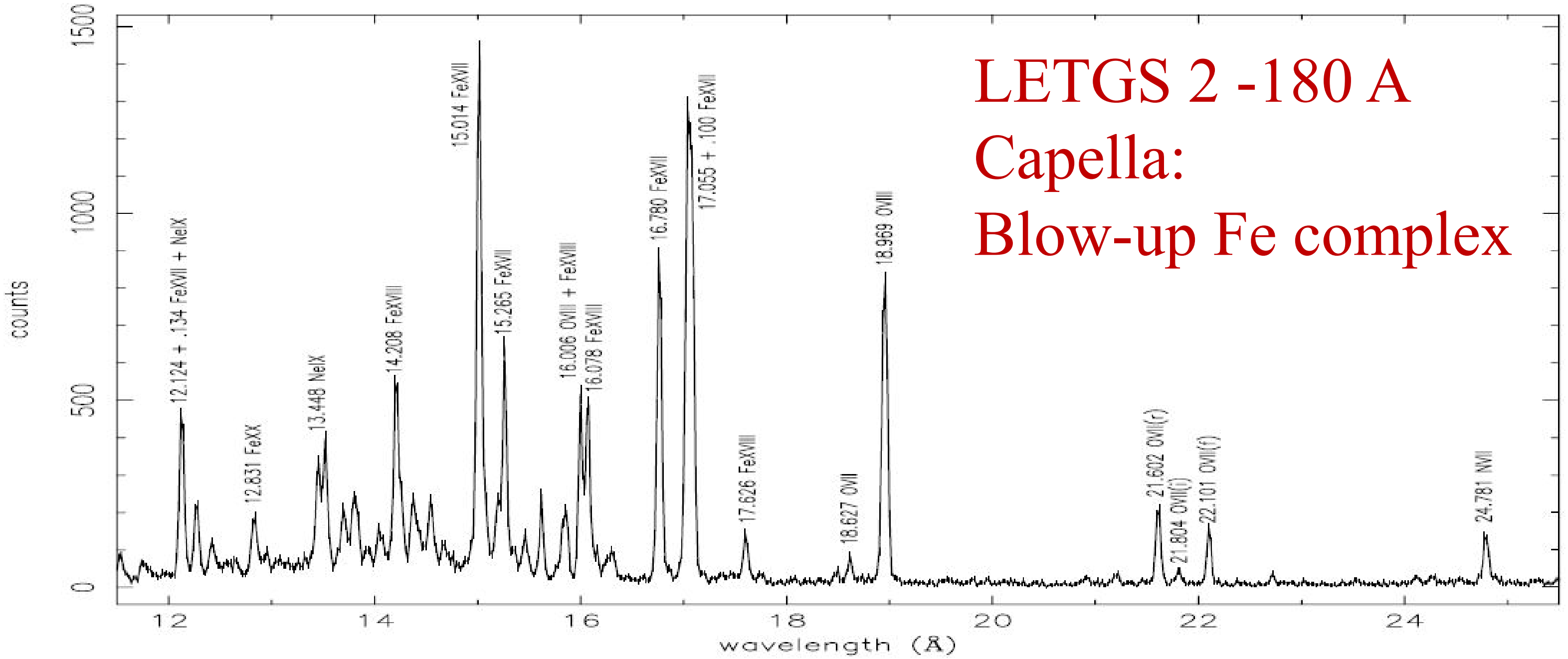
grating ⇒

- 1000 lines/mm (Au)
- 25 μm/2 mm pitch supports





HR spectroscopy with Chandra LETGS, plasma density diagnostics with He-like triplets

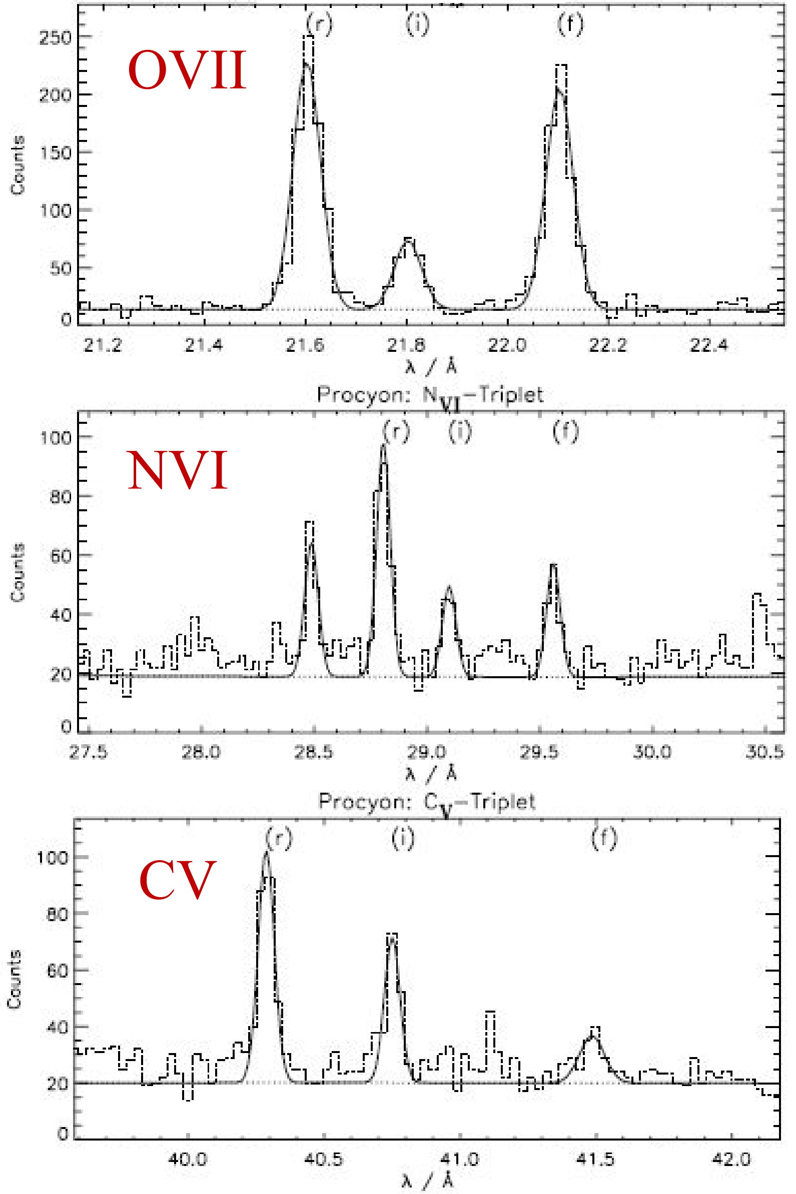


LETGS 2 -180 A

Capella:

Blow-up Fe complex

PROCYON



Plasma electron density n_e from the triplet f/i ratio of the He-like ion

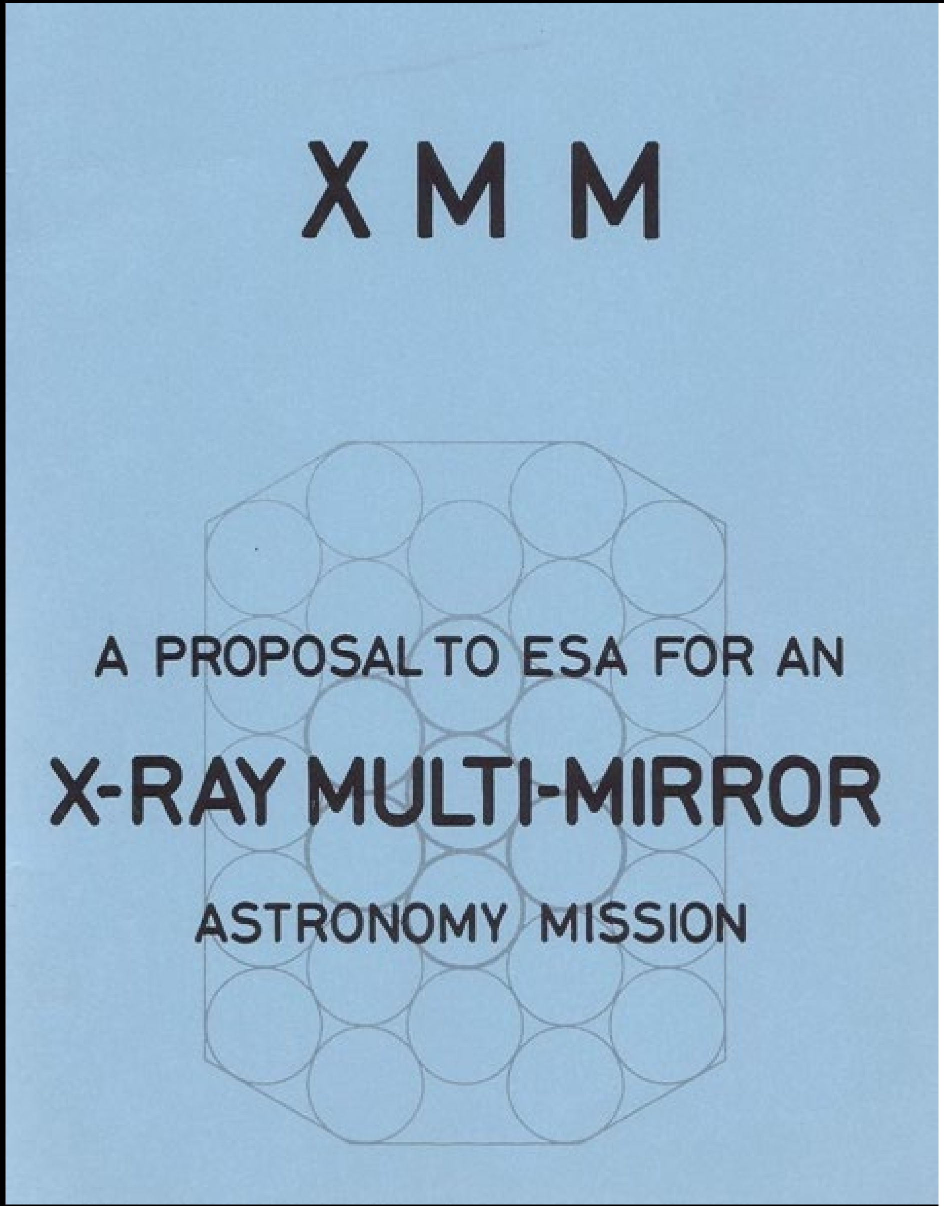
Capella OVII: $n_e = 3.10^9$, NVI: 7.10^9, CV = 3.10^9

Procyon OVII: $n_e = 2.10^9$, NVI: 9.10^9, CV $<10^9$

- Electron density values typical for solar active regions
- No densities as high as in solar flares
- Flux generated in Magnetic Loops: filling factor exceeds solar >10

⇨ High throughput cosmic X-ray spectroscopy in Europe

HERITAGE: the successful development of light-weight replica-optics for EXOSAT

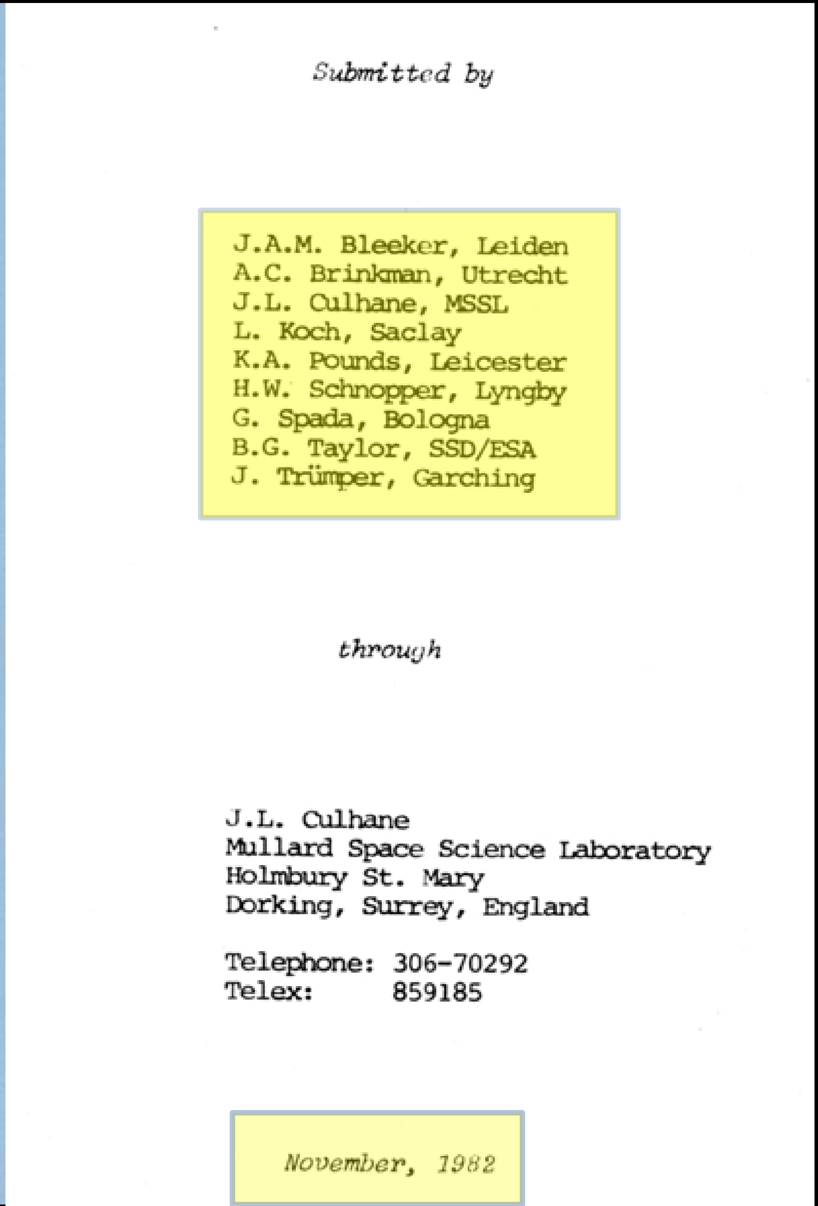


XMM

A PROPOSAL TO ESA FOR AN

X-RAY MULTI-MIRROR

ASTRONOMY MISSION



Submitted by

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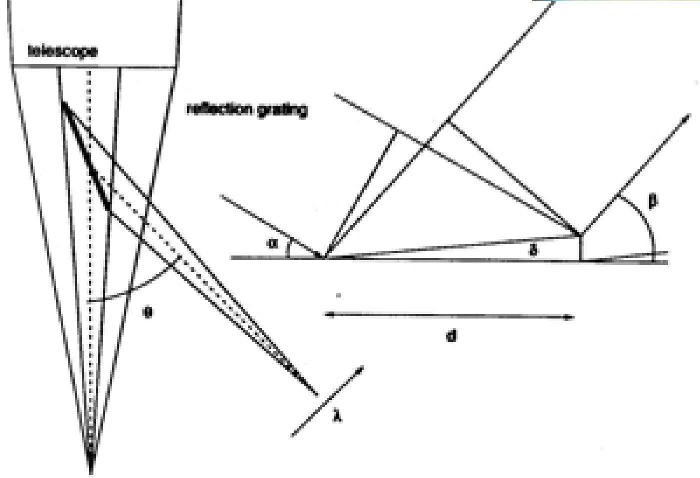
November, 1982

HD-X-ray spectroscopy on XMM: SRON(PI) & UCBerkeley/LawLiv NL

Reflection grating



"Grazing" incidence

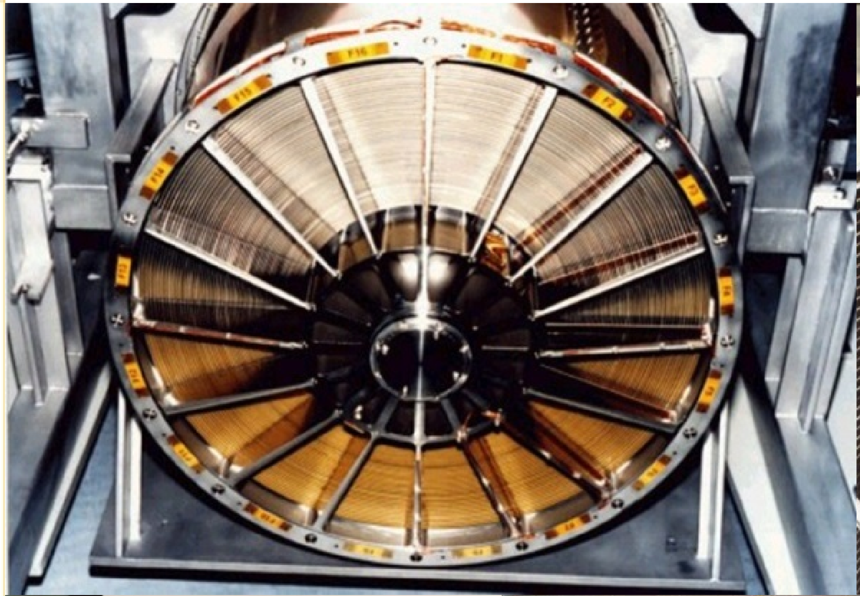
DE: $m\lambda = d(\cos\beta - \cos\alpha)$

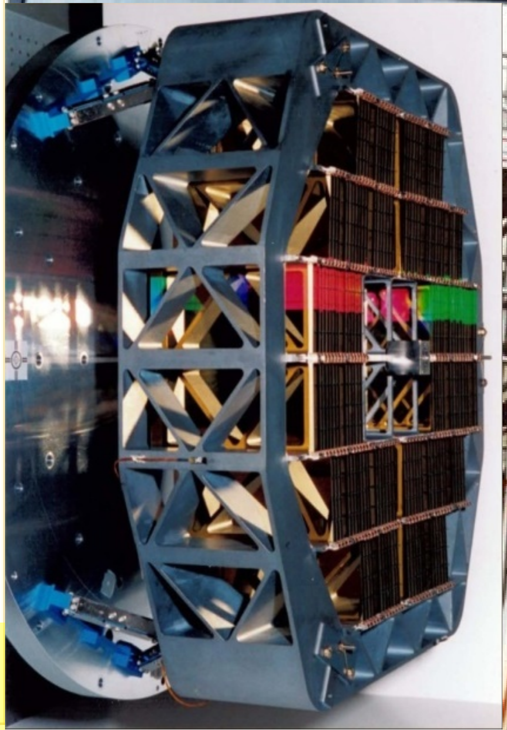
BW: $\Delta\alpha \rightarrow \Delta\lambda = \frac{d}{m}\sin\alpha\Delta\alpha$

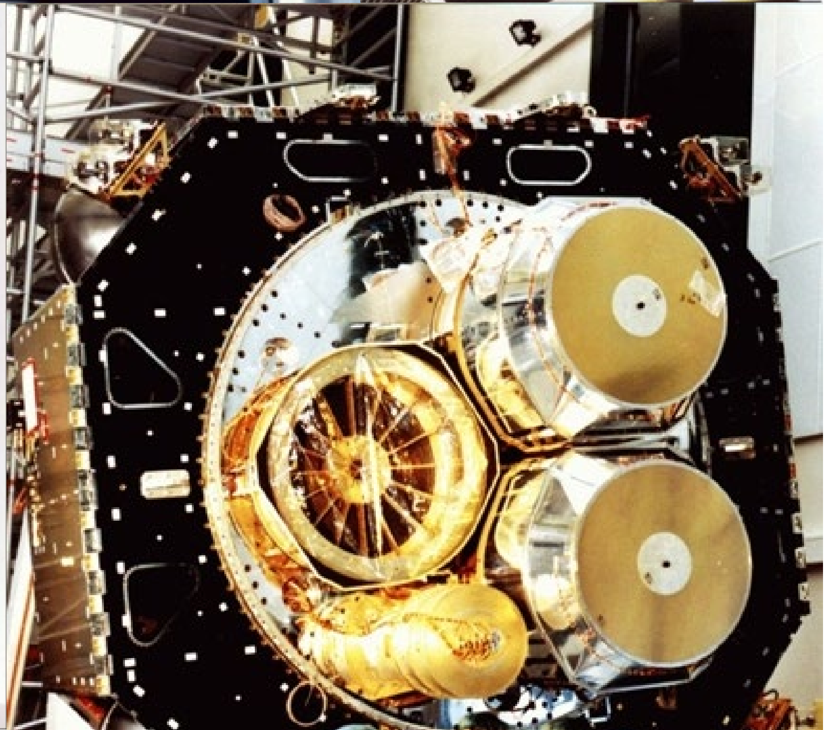
RP: $\lambda/\Delta\lambda = \frac{\cos\alpha - \cos\beta}{\sin\alpha\Delta\alpha}$

→ effective grating period: $d\sin\alpha$

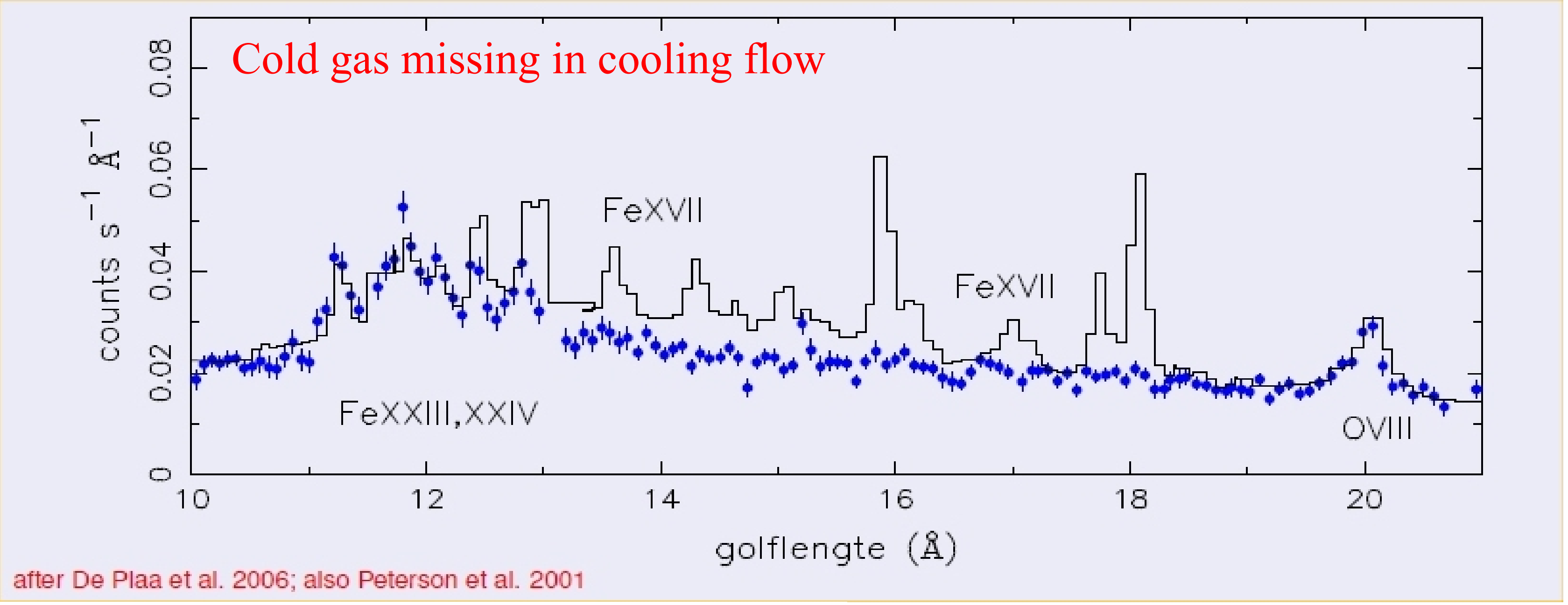
→ effective line density: $\rho = \frac{\rho_r}{\sin\alpha}$ (ρ_r = ruling density)





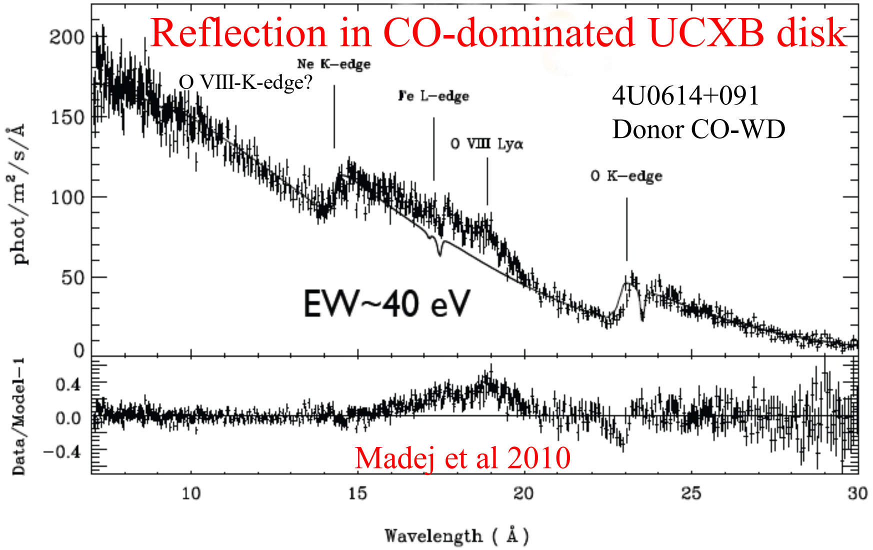


XMM-Newton: cooling flows, accretion disk reflection, ionized outflows



Cold gas missing in cooling flow

after De Plaa et al. 2006; also Peterson et al. 2001

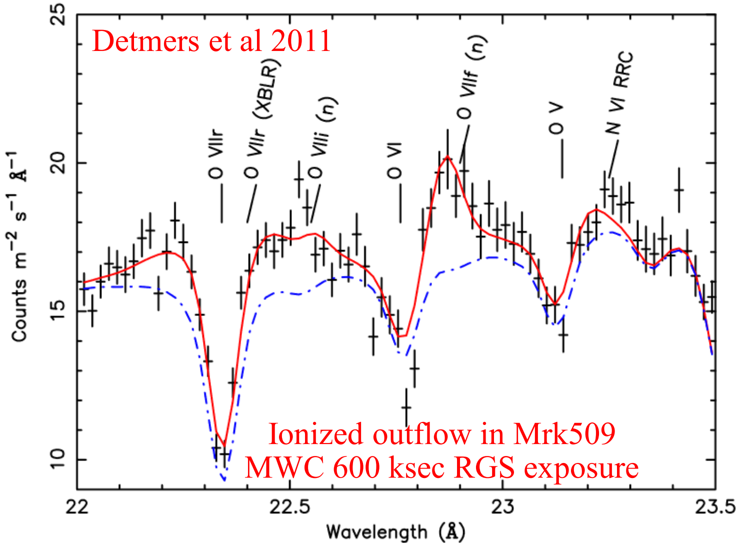


Reflection in CO-dominated UCXB disk

4U0614+091
Donor CO-WD

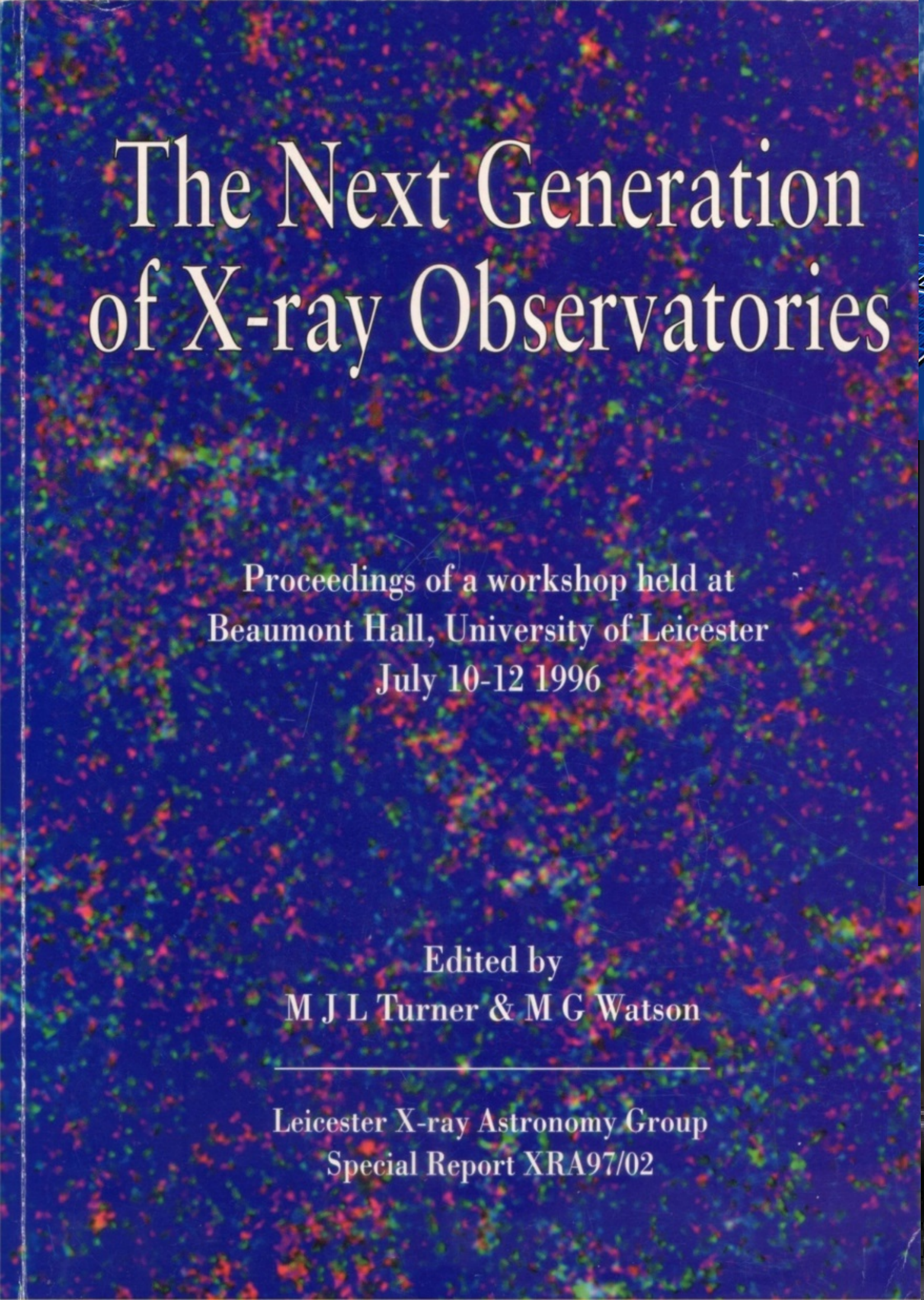
EW~40 eV

Madej et al 2010



Detmers et al 2011

Ionized outflow in Mrk509
MWC 600 ksec RGS exposure



The Next Generation
of X-ray Observatories

Proceedings of a workshop held at
Beaumont Hall, University of Leicester
July 10-12 1996

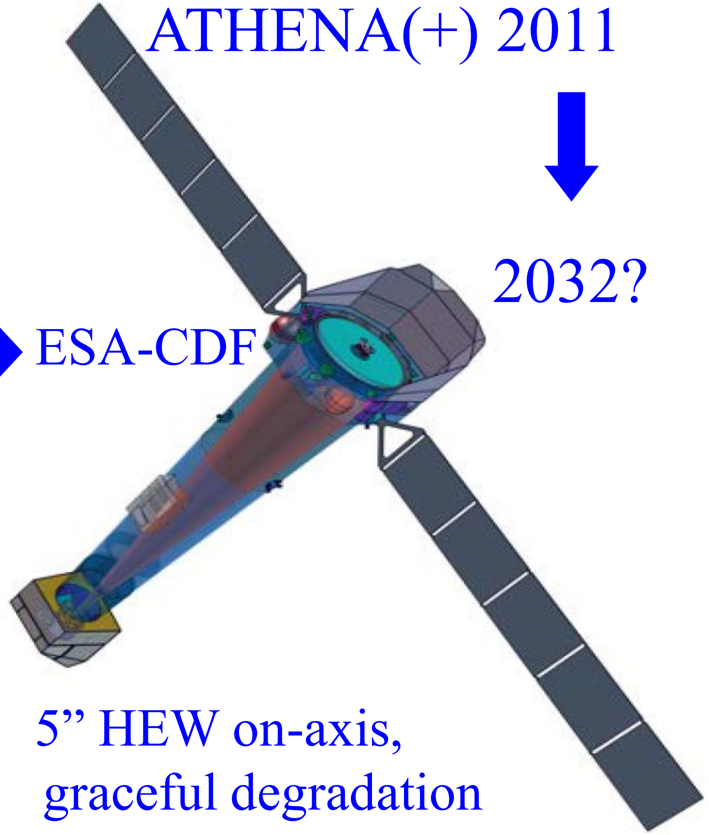
Edited by
M J L Turner & M G Watson

Leicester X-ray Astronomy Group
Special Report XRA97/02

XEUS 1996-2008

IXO 2008-2011

Constellation-X 1996-2008



ATHENA(+) 2011

↓

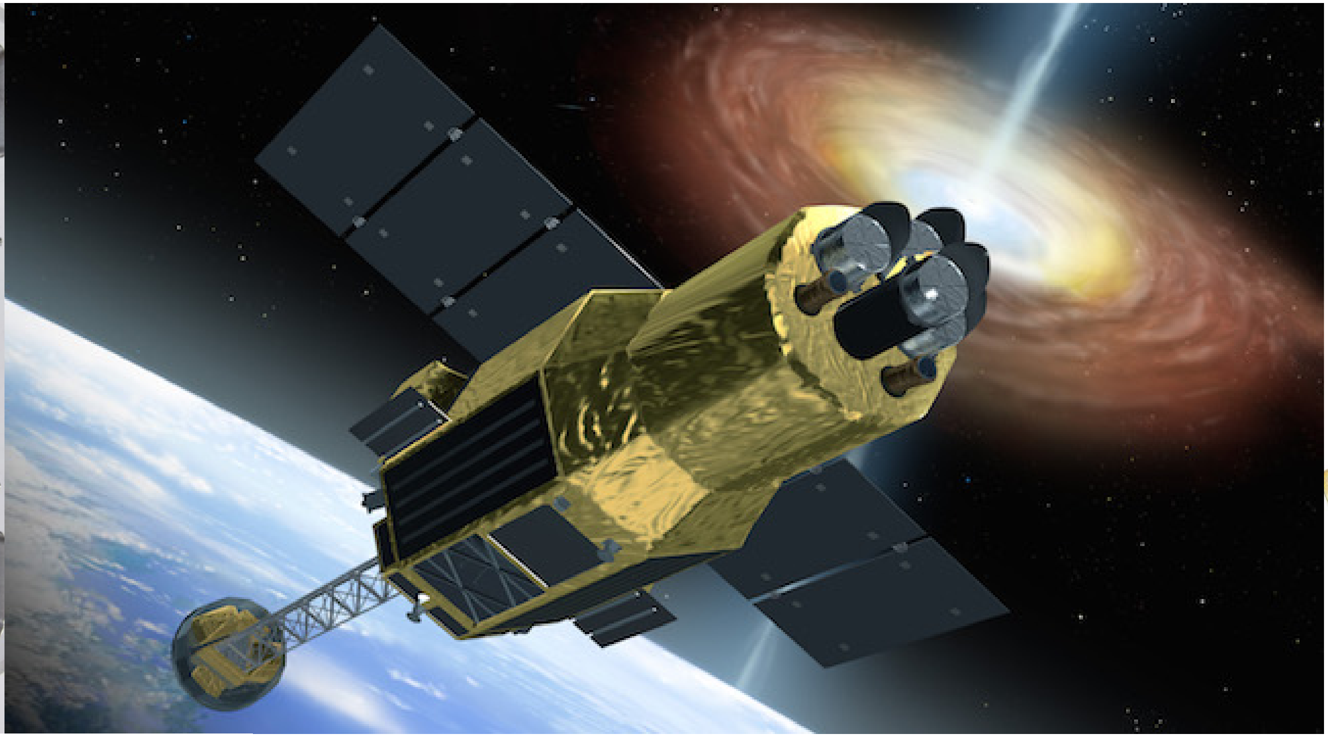
2032?

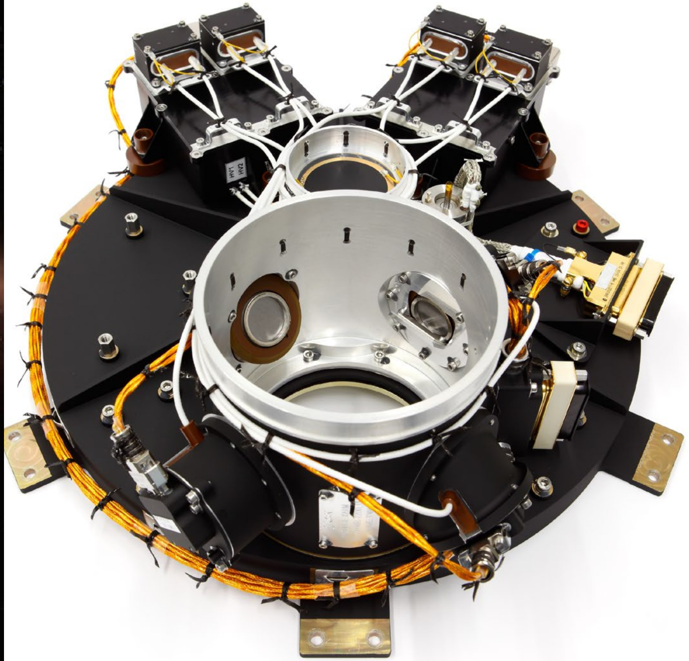
ESA-CDF

- 5” HEW on-axis,
  graceful degradation
  off-axis: ≈ 10” at 30 arcmin
- X-IFU spectrometer effective area:
  ≈ 1.05 m^2 at 1 keV,
  ≈ 0.16 m^2 at 7 keV,
  ≈ 0.11 m^2 at 0.35 keV
- X-IFU energy resolution:
  $\Delta E \leq 2.5$ eV at 7 keV (RP ≥ 2800)

Recovery Hitomi science: XRISM (JAXA, NASA, with ESA/SRON participation)

Expected launch: April 2023





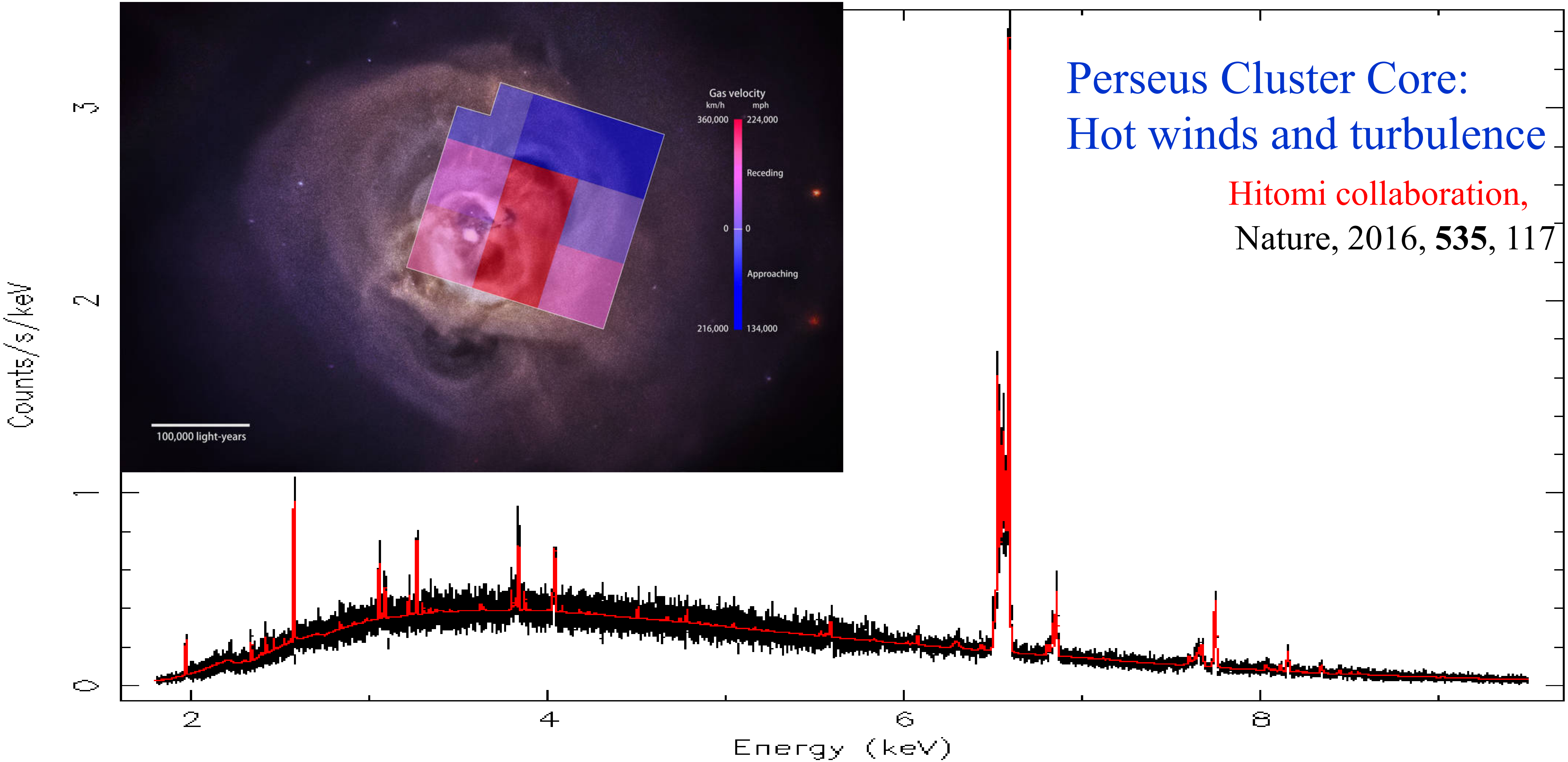
XRISM

X-Ray Imaging and Spectroscopy Mission

Filterwheel and in-flight calibration source assembly:

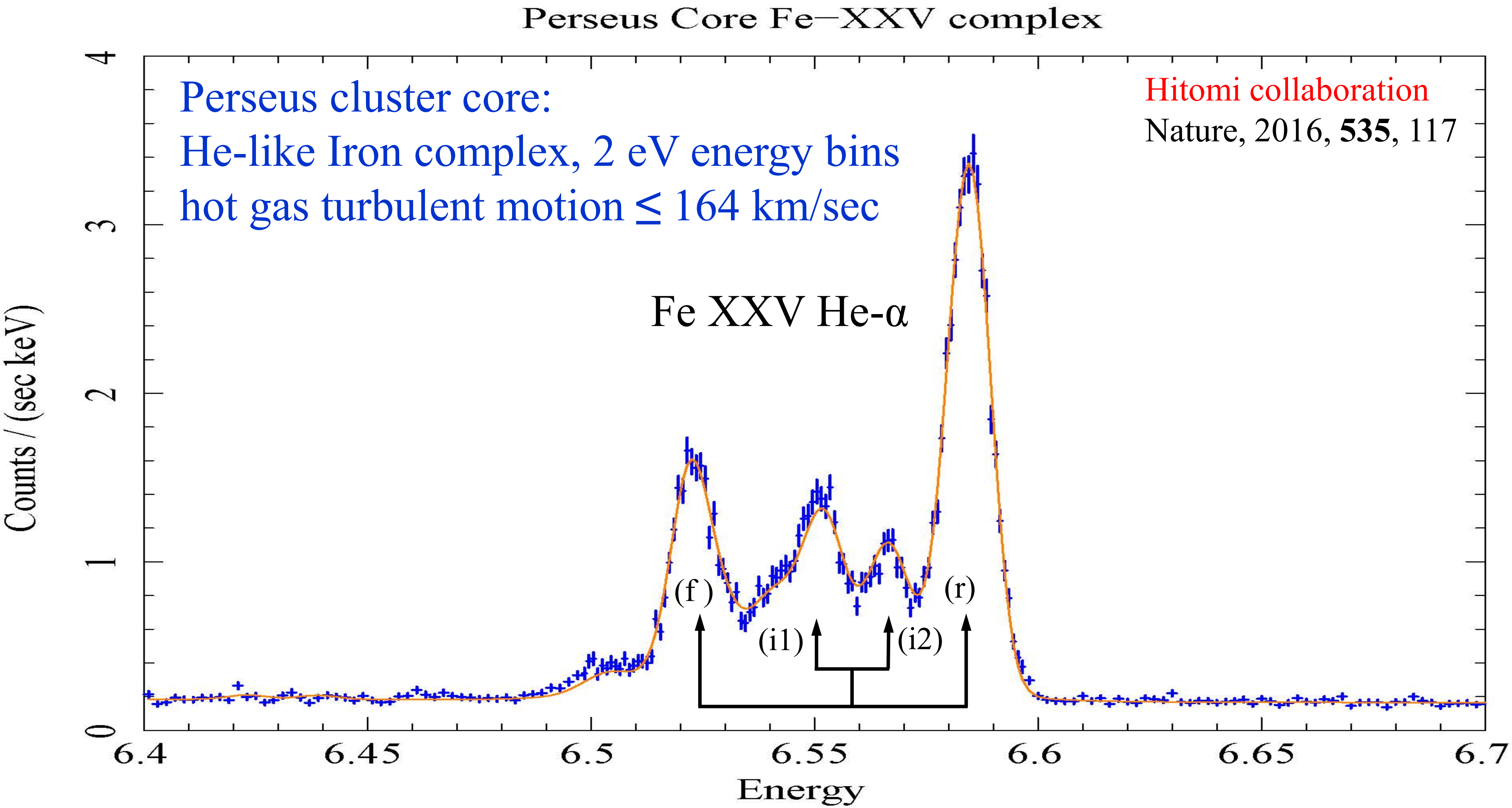
ΔE_X at Mn K-α_1 (5898.75 eV) ≈ 4.2 eV 588765

Energy-dispersive HR-spectroscopy: the Microcalorimeter on Hitomi



Perseus Cluster Core:
Hot winds and turbulence

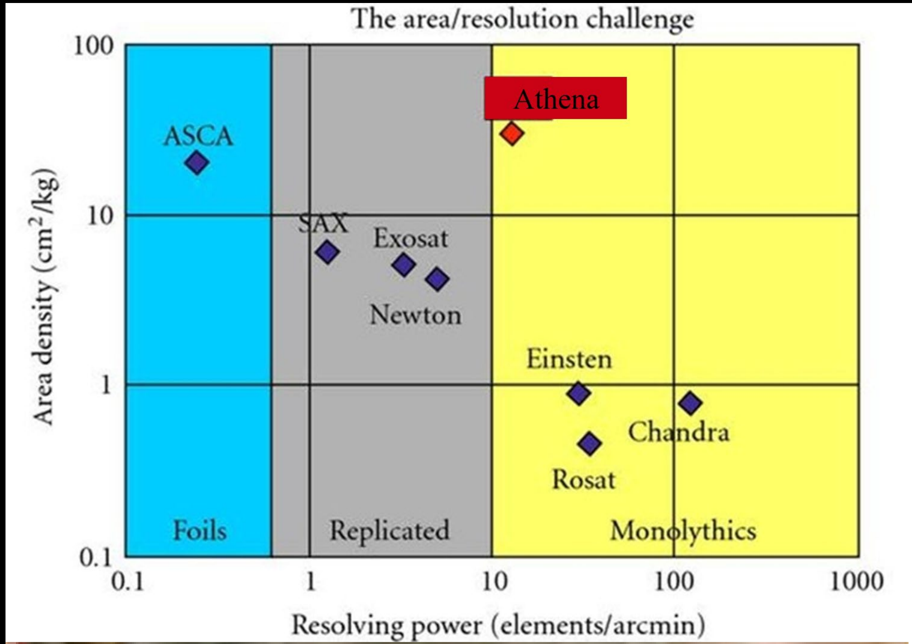
Hitomi collaboration,
Nature, 2016, **535**, 117



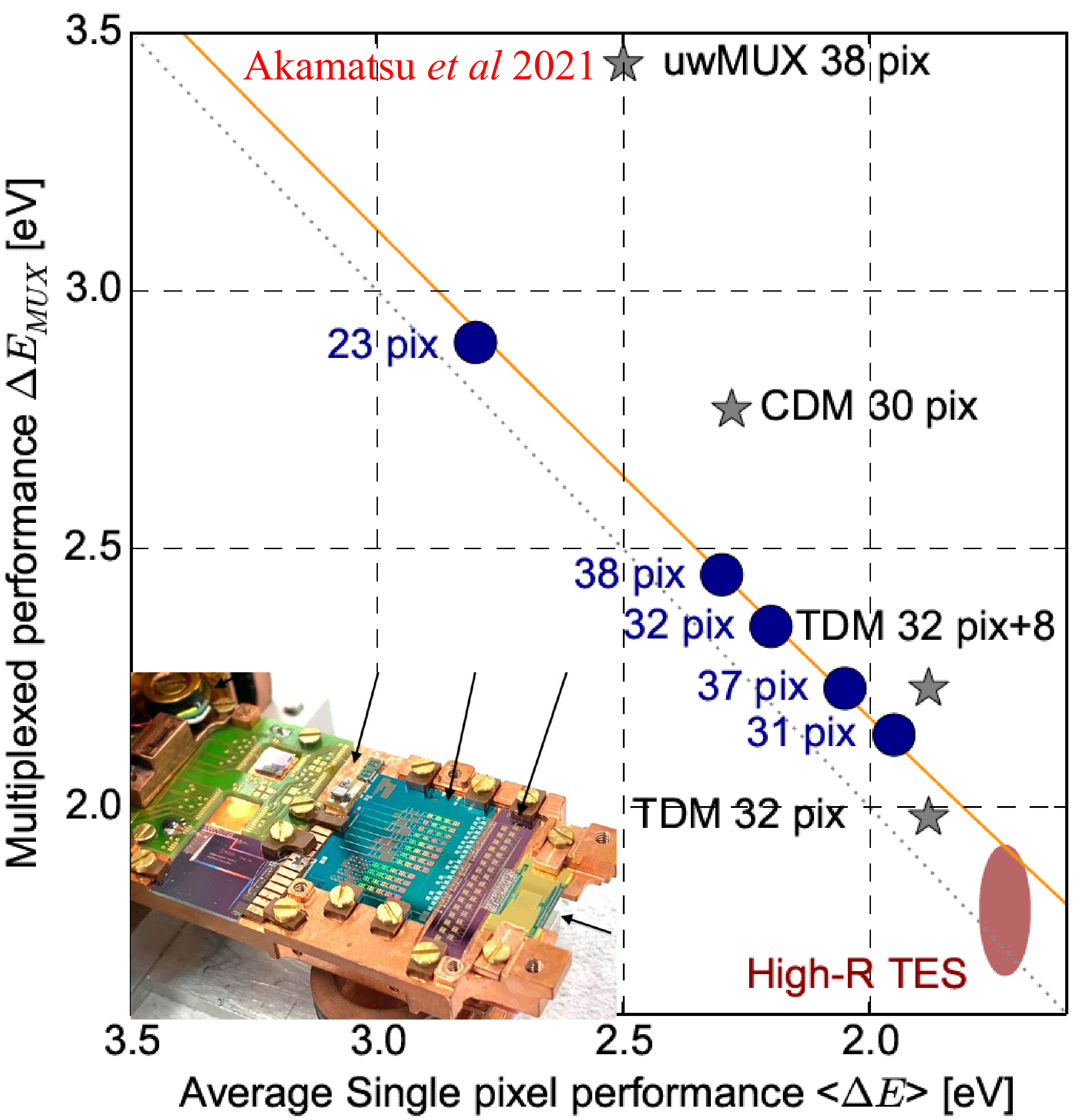
Perseus cluster core:
He-like Iron complex, 2 eV energy bins
hot gas turbulent motion ≤ 164 km/sec

Hitomi collaboration
Nature, 2016, **535**, 117

Enabling technologies for the next generation X-ray Observatory



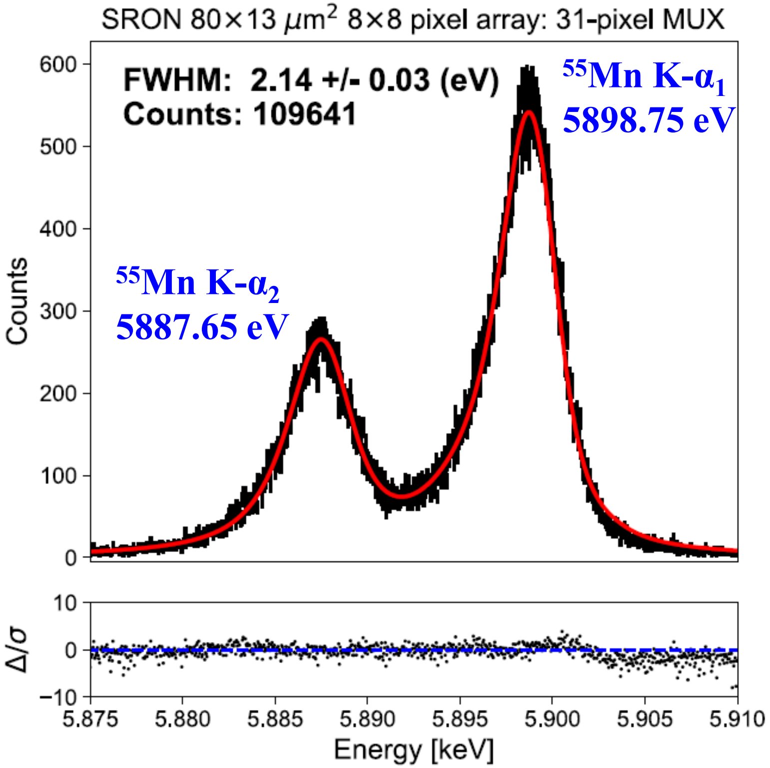
- No conventional technology: excessive mass
- New technologies: Si-pore optics, slumped glass
- Si-pore most mature, baseline → ATHENA

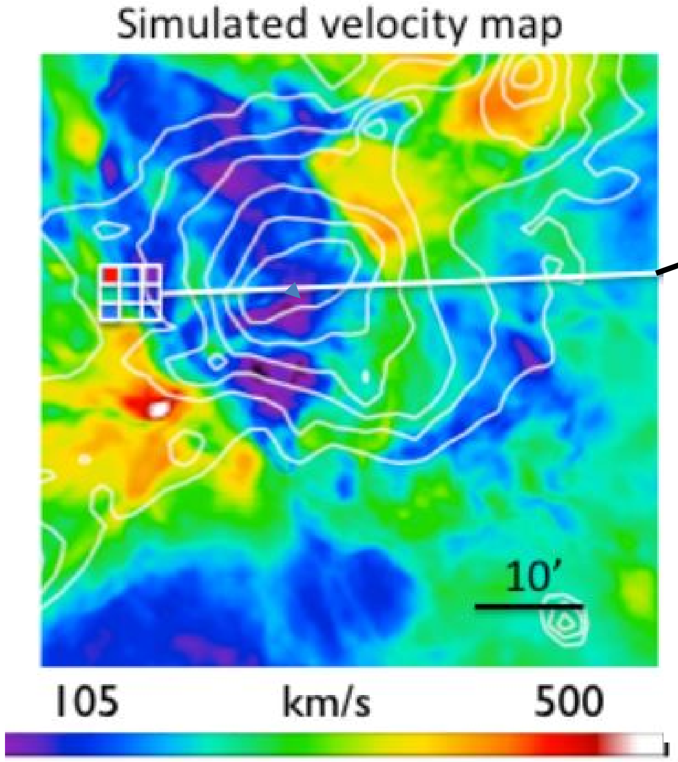


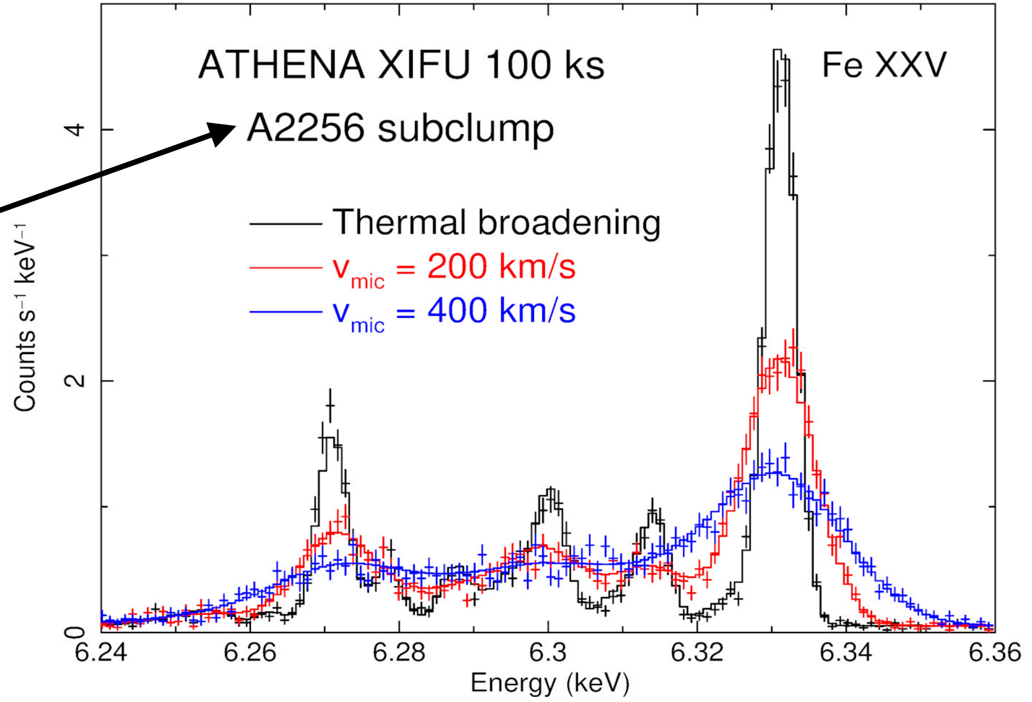
Dissipation of gravitational energy in intra-cluster gas

Potential broadening of hot plasma emission lines by turbulence in the intra-cluster gas, induced by infalling mass concentrations towards the core of the A2256 cluster (z = 0.058)

Akamatsu *et al* 2021

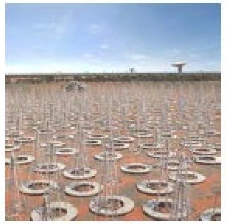






In Conclusion

SKA



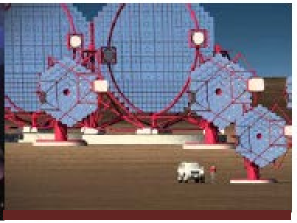
ALMA

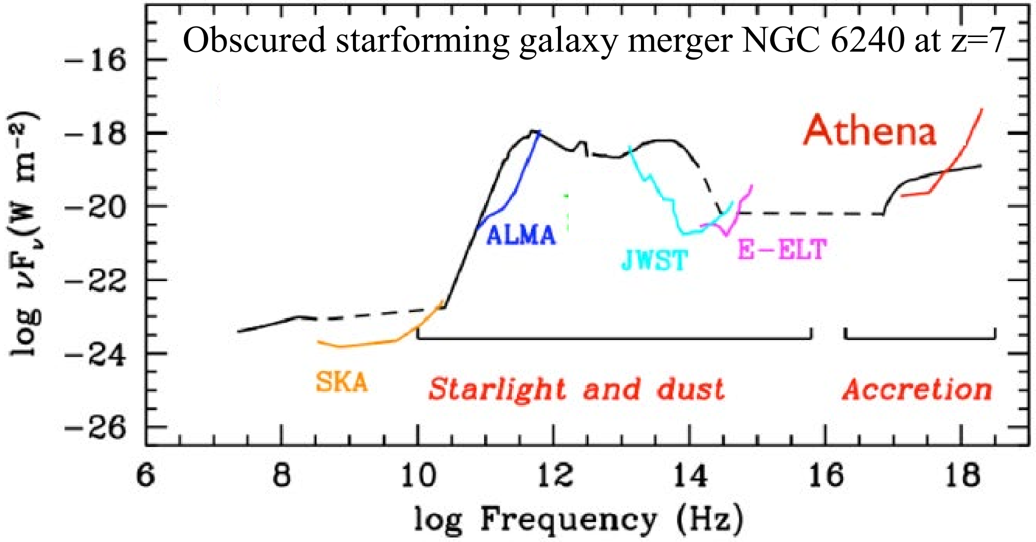
JWST

E-ELT

Athena

CTA





- Horizon 2000 and Cosmic Vision were vital for bringing Europe at the forefront of cosmic X-ray spectroscopy
- X-ray spectroscopic observations are nowadays central to many astrophysical investigations.
- Chandra and XMM-Newton have become the workhorses for global X-ray astronomy.
- The future is Athena, bridged by XRISM, and in synergy with other large observational facilities