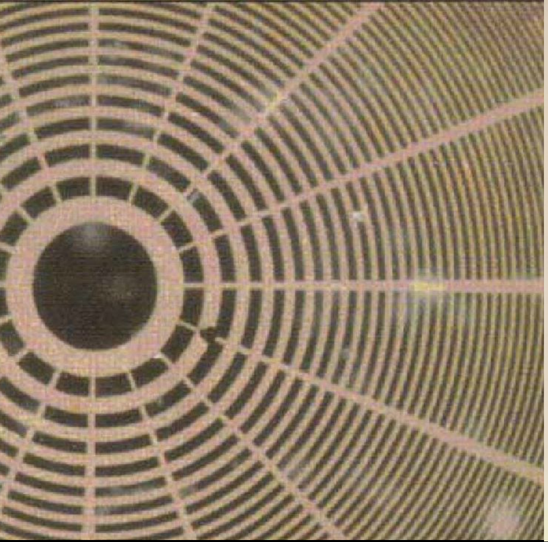
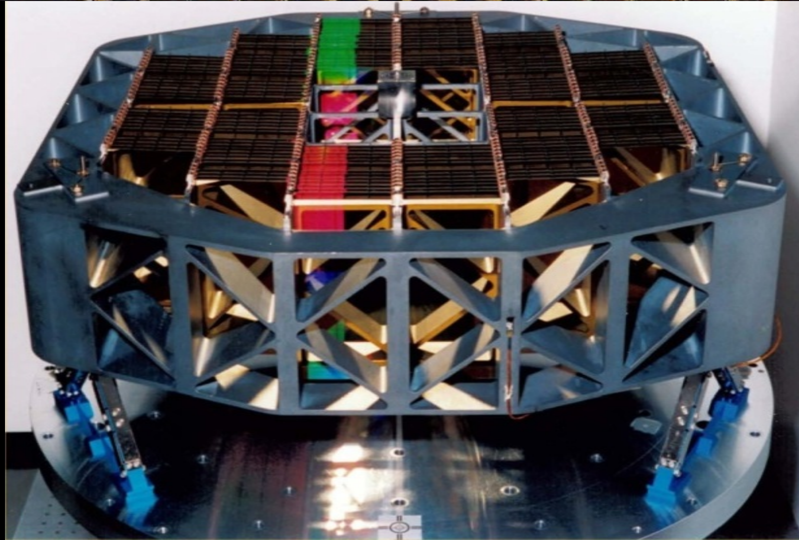


X-ray spectrometry with Exosat and beyond



Johan Bleeker
SRON/Utrecht University

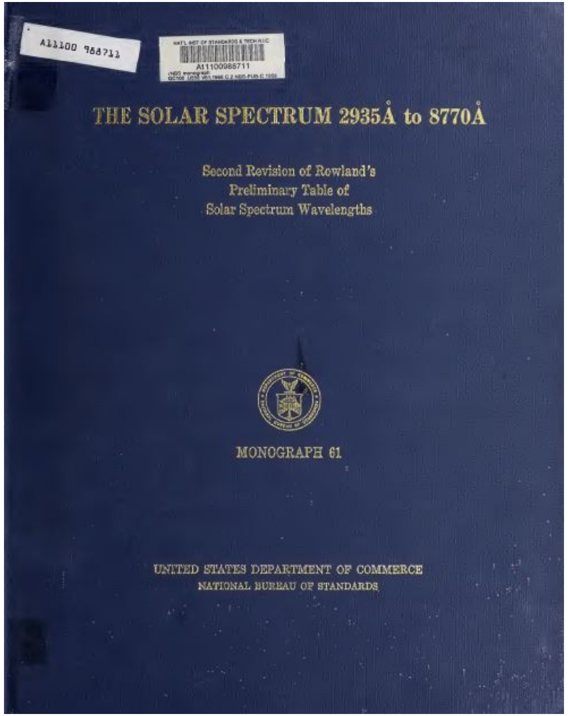
EXOSAT-Reunion, ESAC May 25, 2018

The grass roots at Utrecht

Atlas of the solar spectrum: $\lambda3612 - \lambda8770$, $\lambda3332 - \lambda3637$

Initiative by Marcel Minnaert

- 1936: ~ 100 photographic plates taken at Mount Wilson Observatory
- 1940: Utrecht Photometric Atlas of the solar spectrum (Minnaert et al)
- 1952: Solar atmosphere temperature model (de Jager 1952)
- 1966: Solar abundances from The Solar Spectrum (Moore et al)



Mid 1960's: Monochromatic XUV-images of the Sun

X-ray lense employing diffraction: Fresnel zone plate

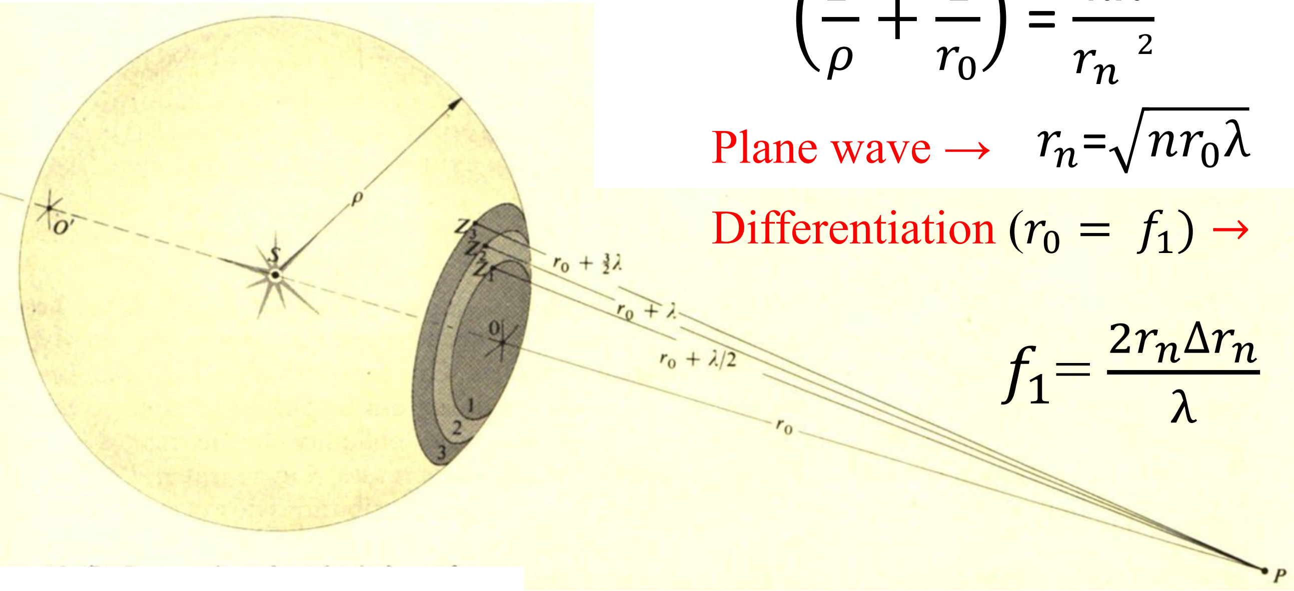
Principle: zone partition of spherical wavefront → block even/odd zones

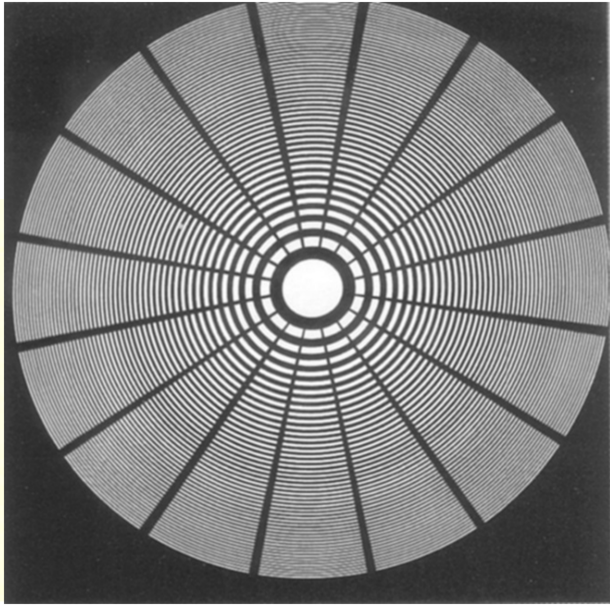
$$\left(\frac{1}{\rho}+\frac{1}{r_0}\right)=\frac{n\lambda}{r_n{}^2}$$

Plane wave → $r_n=\sqrt{n r_0 \lambda}$

Differentiation $(r_0 = f_1)$ →

$$f_1=\frac{2r_n\Delta r_n}{\lambda}$$



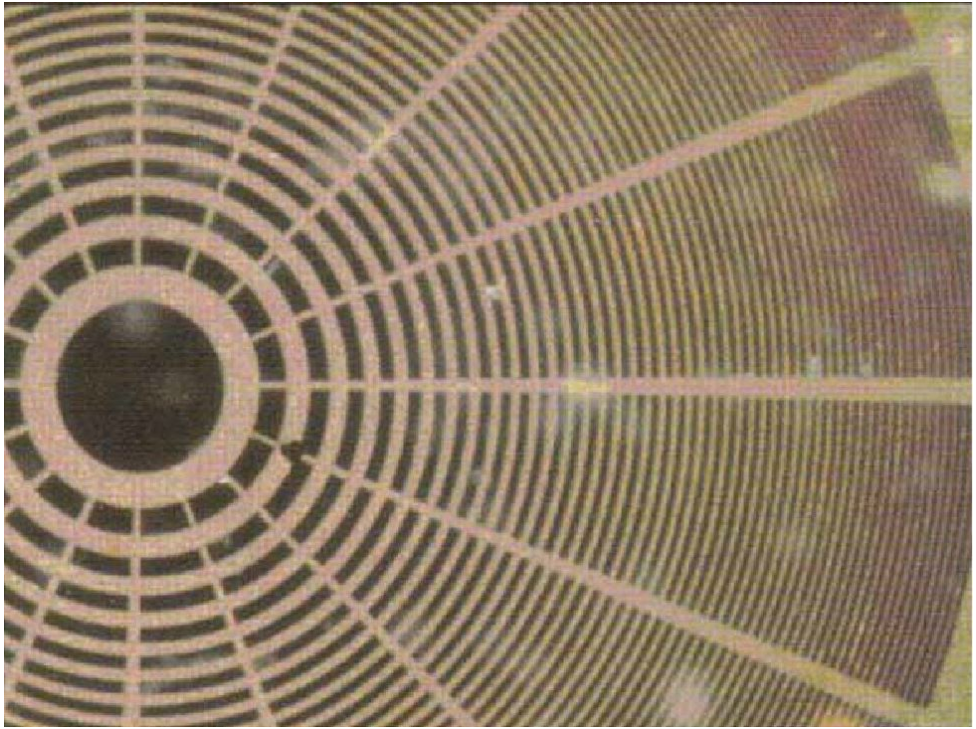


Focal length $\boldsymbol{f_1}$ *(*λ*=5nm,* $\Delta \boldsymbol{r_N}$*=1µm,* $\boldsymbol{r_N}$*=1mm): 40 cm*

Mid 1960s: Q-monochromatic XUV-images of the Sun

X-ray lense employing diffraction: Fresnel zone plate

Requirement: transparent zones completely open, width 1-2 µm → radial support
First successful trials with electron-optical imaging:



◀ Non-apodized zone plate manufactured by electron-optics early 1960's

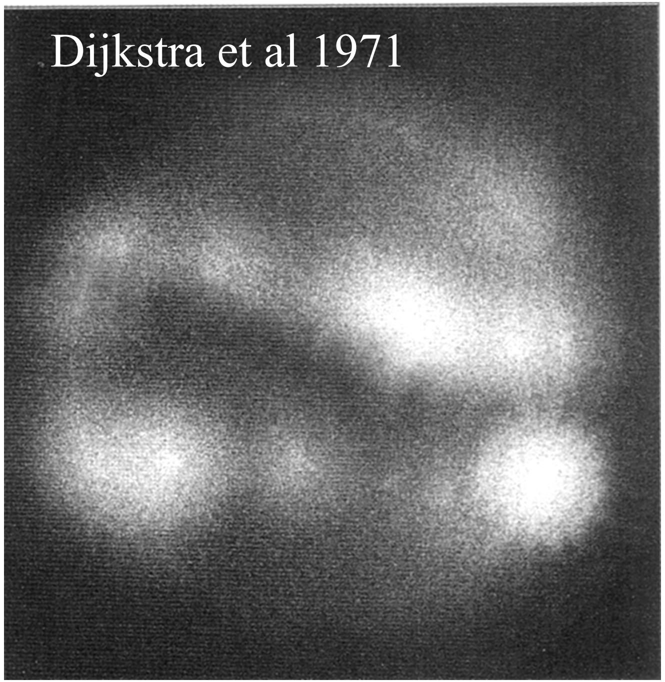
Problem: FOV of the available system too small for the production of larger ring shaped zone plates with a sufficiently large opaque central section to avoid distortion of the image by zero-order radiation from the sun.

Mid 1960s: Q-monochromatic XUV-images of the Sun

X-ray lense employing diffraction: Fresnel zone plate

Photolithography:

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



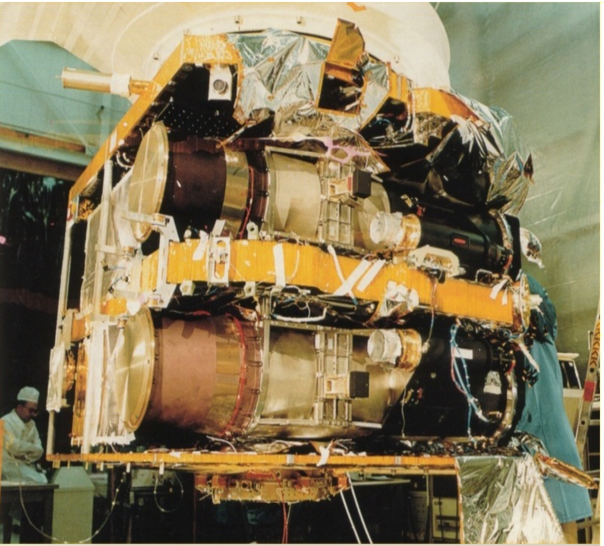
1967: Successful sun stabilized Aerobee rocket experiment

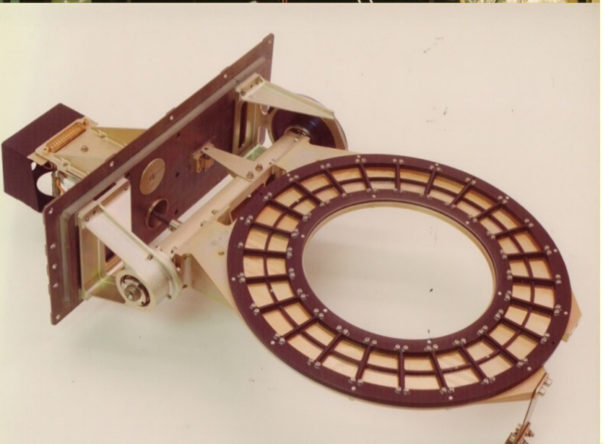
4 Zone plates of 50 metallic rings
f = 40 cm, outer diam. 0.90–3.06 mm

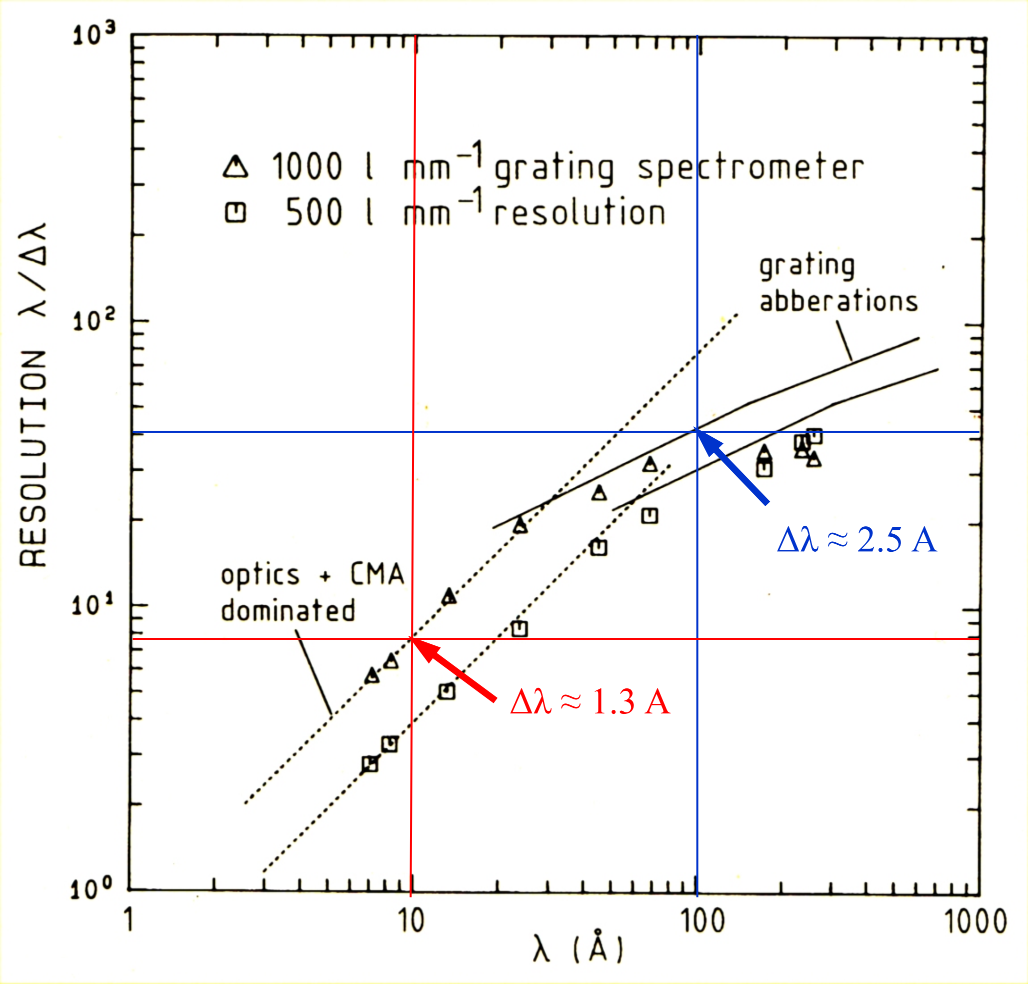
→ Solar Q-monochromatic images in Si X, Fe XI, HeII and HeI lines

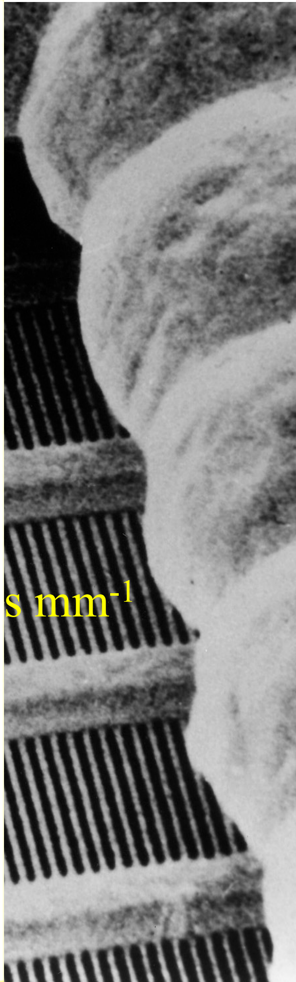
◄ Sun in Si X at 5.1 nm

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









TGS: Observational targets

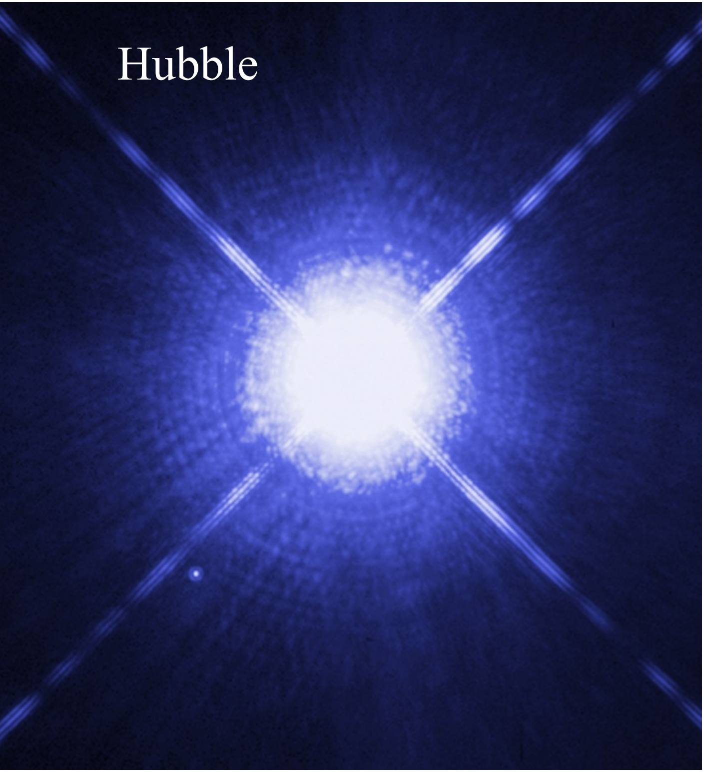
Distinguishing feature from previous instruments:
Unprecedented dynamic range over the soft-X and EUV band (8 - 400 A), with a superior combination of sensitivity and spectral resolution in the XUV band (50 - 400 A).

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 ($\Delta\lambda \approx$ 3A) ionic coronal emission lines over a wide temperature range → temperature and emission measure distribution of the hot stellar coronal plasma.

TGS-spectroscopy of hot WDs: Sirius B, the WD star closest to the earth



Sirius A + B

The Sirius system, brightest star in the night sky (m_v +1.42)

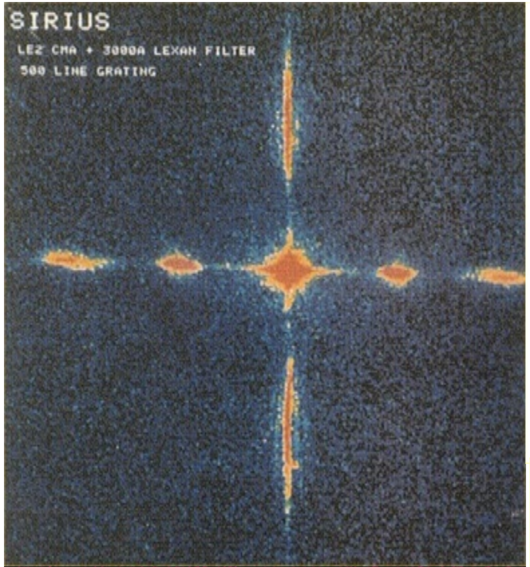
Binary: Sirius A (MS A1) + Sirius B (DA white dwarf)
Distance: 2.6 pc, 8.6 ly (Hipparcos)
Solar units: $M_{Sirius\ A} \approx 2\ M_{\odot}$, $L_{Sirius\ A} = 25\ L_{\odot}$

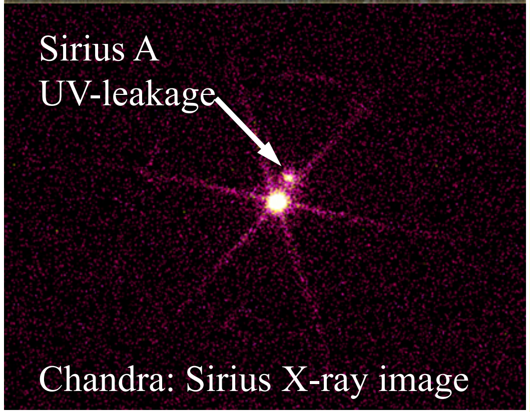
Discovery of soft X-ray emission by ANS (Mewe et al, 1975)
Interpretation:

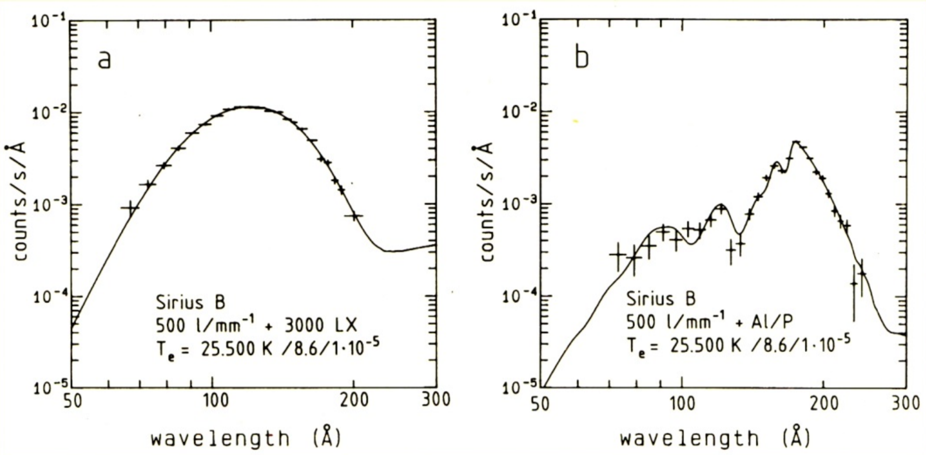
1. Miniature corona DA dwarf (Hearn and Mewe, 1976)
   Corona of an exotic kind: scale height ≈ 100 cm,
   $L_X > 5L_{phot}$ (Martin et al., 1982)
2. Hot pure-H-Photosphere (Shipman, 1976)

EXOSAT TGS →XUV spectrum → atmospheric parameters
Full EM spectral data → photospheric parameters + R_{WD}

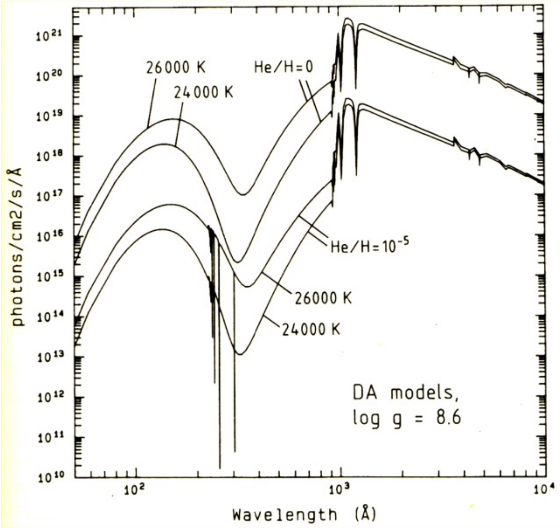
TGS-spectroscopy of hot WDs: Sirius B, the WD star closest to the earth







(Paerels et al, 1988)



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

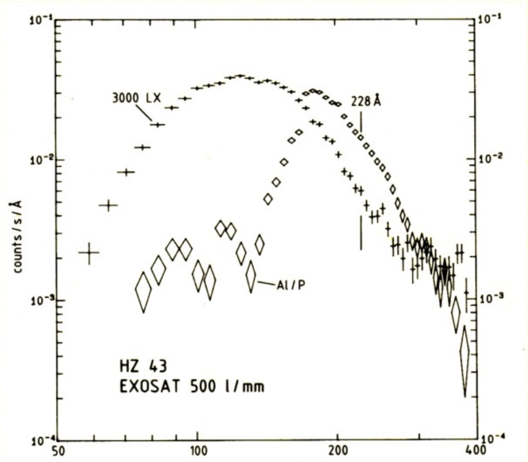
from $M/M_\odot$ = 1.053 ± 0.028

log g = 8.53 – 8.73 (≈ 400,000g_{earth})

He/H < 2.10^{-5}

N_H = (1.1 – 5.0).10^{18} cm^{-2}

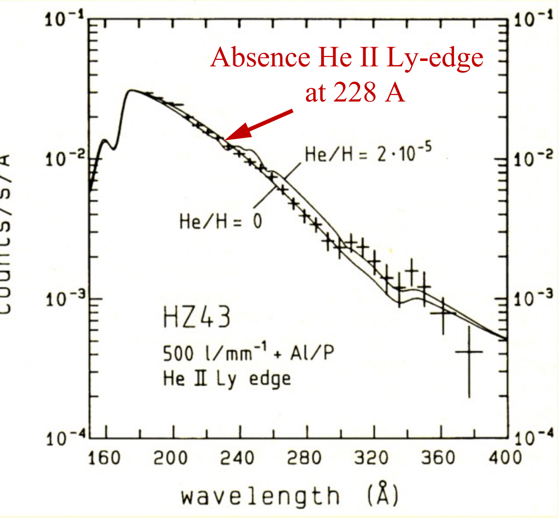
TGS-spectroscopy of hot WDs: HZ 43, a very young luminous hot WD!

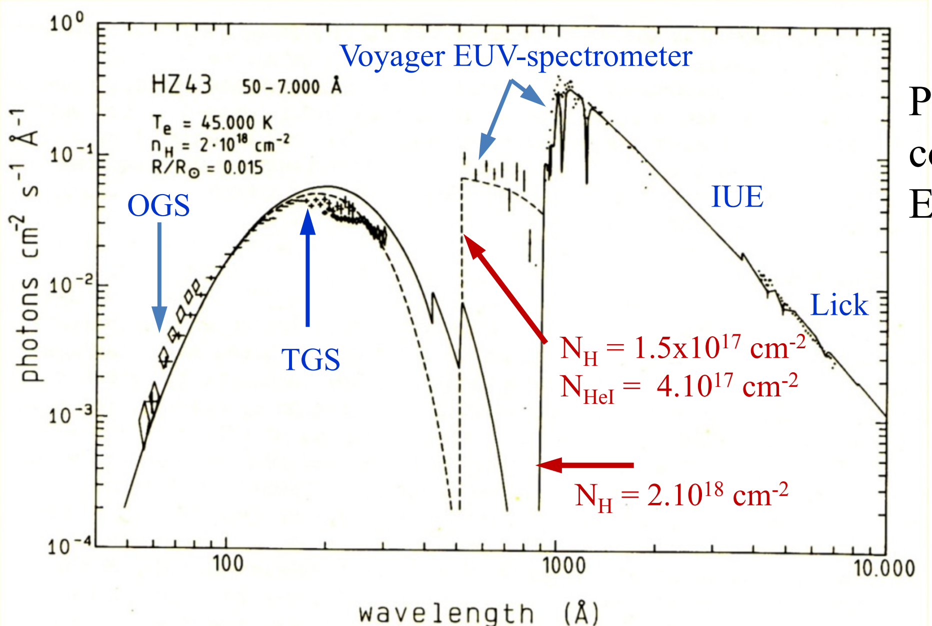


Rocket EUV- spectrometer (Malina et al, 1982) detects He in HZ 43 EUV spectrum: He/H = (1.5 – 6.0).10^{-5} ? Kahn et al (1984), from comparison of Einstein IPC-fluxes for 4 DA WDs with IUE spectra, find evidence for He/H =10^{-5}-10^{-3}. Petre et al (1986) find similar results for another 5 WDs.

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

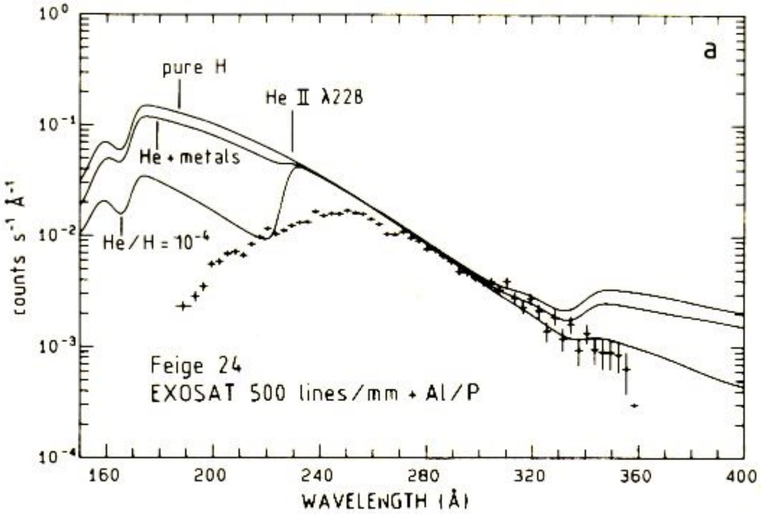
log g = 7.8 – 8.4

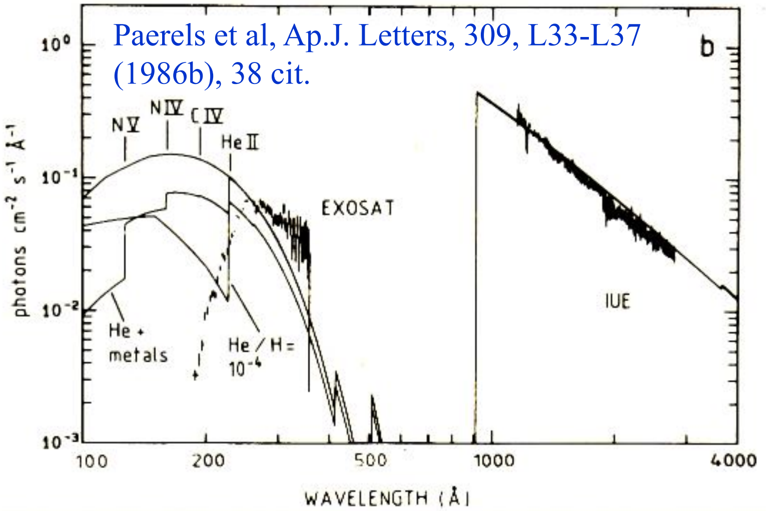
He/H < 1.0 x 10^{-5}

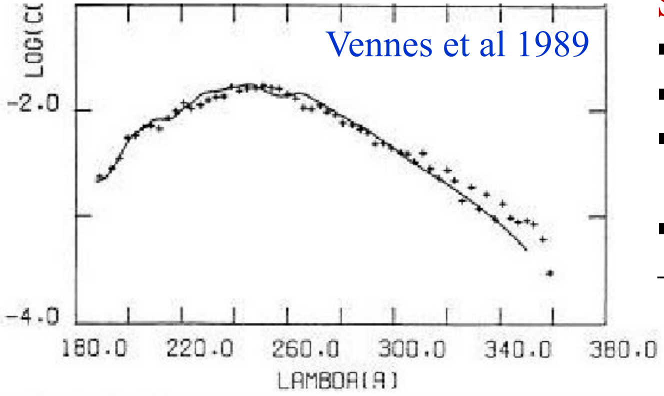
(Paerels et al, 1986a)

(Heise et al 1988)

TGS-spectroscopy of hot WDs: Feige 24, a surprising photosphere!





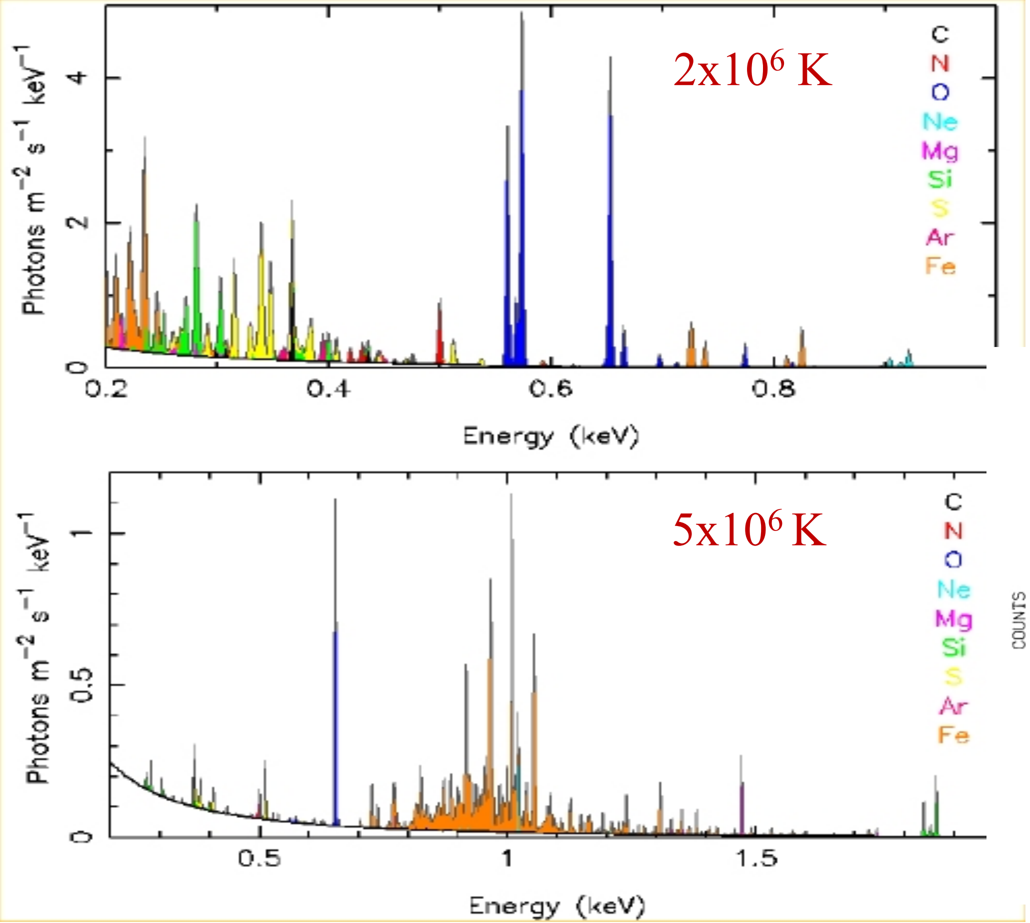


Surprise: Steep decline towards short wavelengths:

- No fit with He II Ly-edge possible (Paerels et al, 1986b)
- No improvement by adding traces of C, N and Si (Paerels, et al, 1986b)
- Improved fit with heavier trace elements up to Ca consistent with IUE abundances (Vennes et al, 1989)
- A later deep 31 hour IUE exposure indicated Fe/H = $(5\text{-}10).10^{-6}$

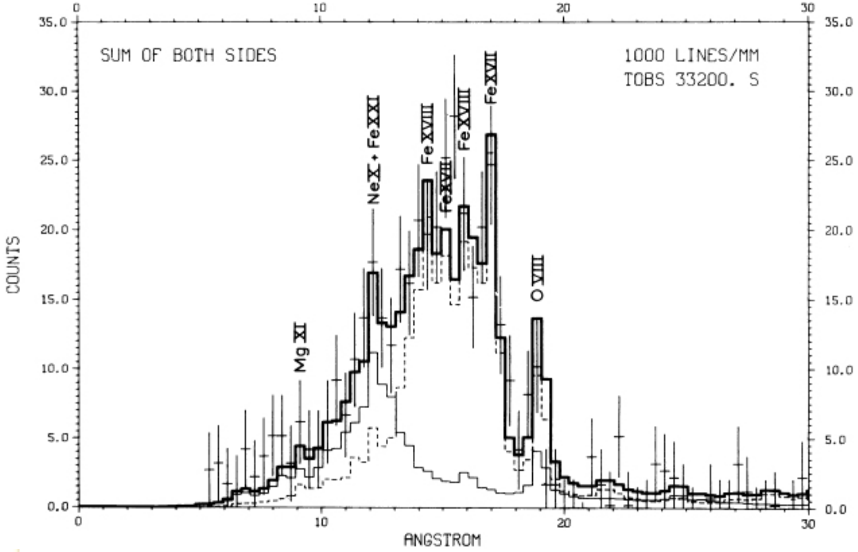
→ A complex of hundreds of Fe IV, FeV and FeVI resonance lines may be causing the Feige XUV deficiency. The relatively high Fe-abundance significantly exceeds the prediction of selective radiation pressure models (Vennes et al 1992)

Hot Coronal Plasma: X-ray line spectra for cosmic abundance

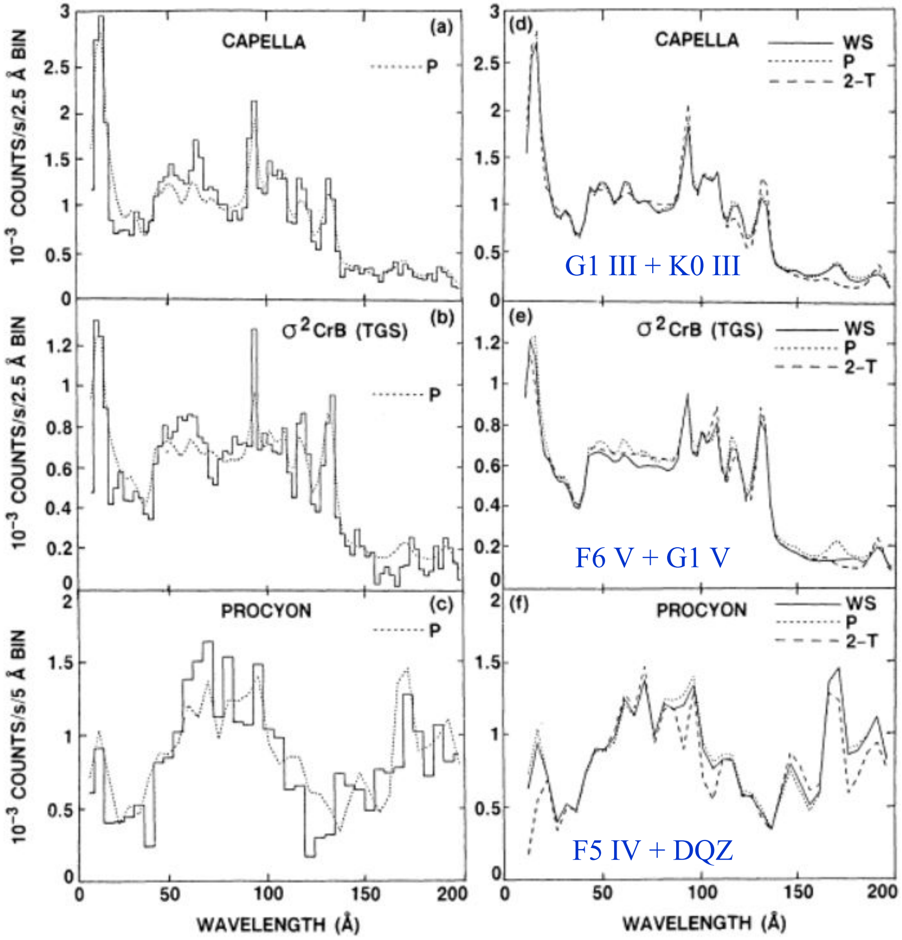


First high resolution X-ray spectrum of the corona of Capella taken with the 1000 l/mm OGS on the Einstein Observatory (Mewe et al, 1982).

The soft X-ray emission was discovered in 1975 by Mewe et al (ANS) and Catura et al (rocket flight).



Coronal activity in three late type stars: DEM distributions (TGS 1000 l/mm R ≈ 3A)



Lemen et al, Ap.J. **341**,474 (1989), 128 cit.

Spectral fits:

T1, T2: 2 temperatures

P : Polynomial

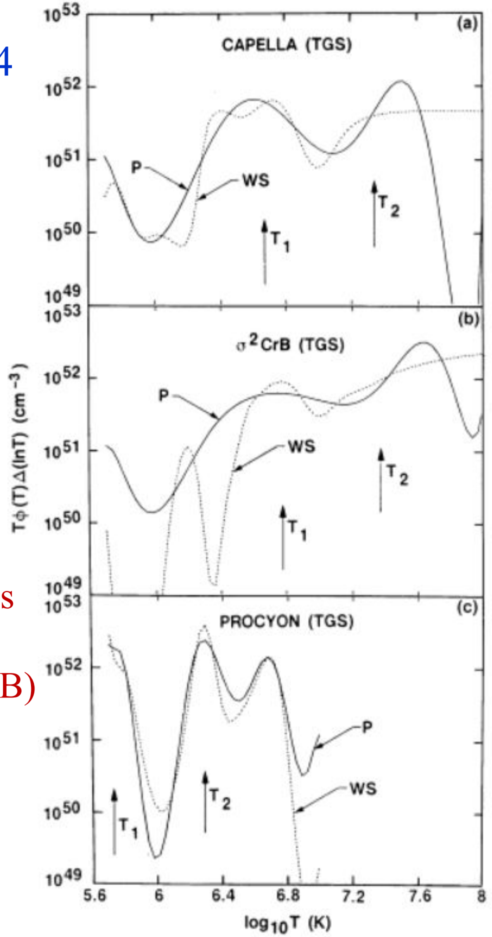
WS: Multi-thermal

Conclusion:

Bimodal temperature intervals centered on:

5 MK and 25 MK (Cap, σ^2CrB)

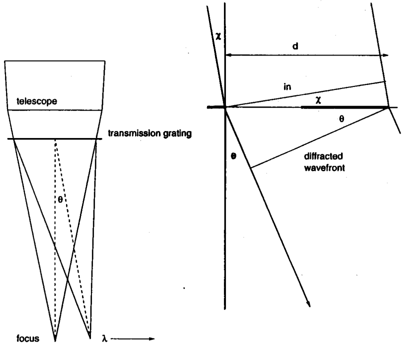
0.6 Mk and 3 MK (Procyon)



Post-EXOSAT generation grating spectrometers

Chandra LETGS/HETGS

Transmission grating



“Normal” incidence

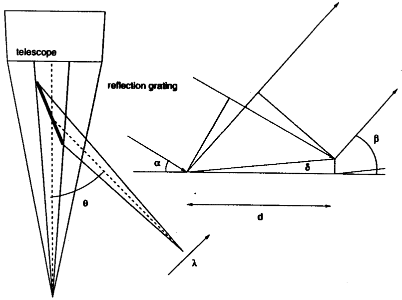
DE: $m\lambda = d(\sin\theta - \sin\chi)$

BW: $\Delta\chi \to \Delta\theta \to \Delta\lambda = \frac{d}{m}\cos\theta\Delta\theta$

RP: $\lambda/_{\Delta\lambda} = \theta/_{\Delta\theta}$

XMM-Newton RGS

Reflection grating



“Grazing” incidence

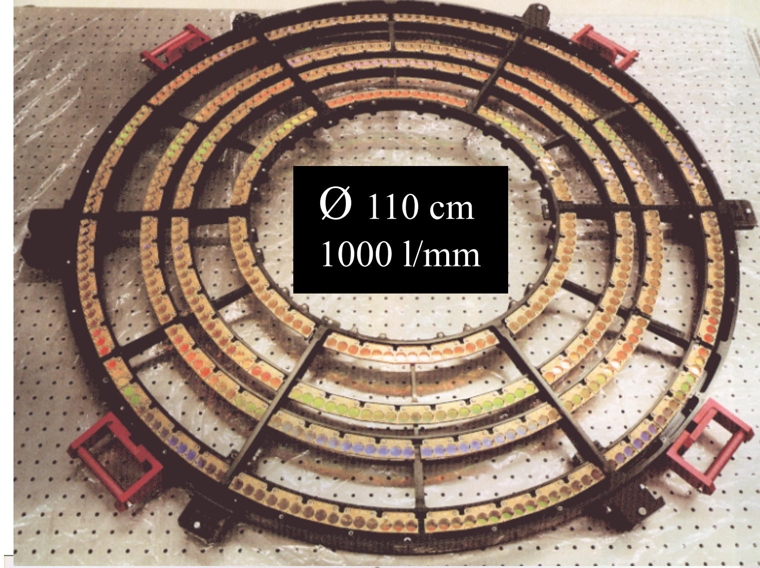
DE: $m\lambda = d(\cos\beta - \cos\alpha)$

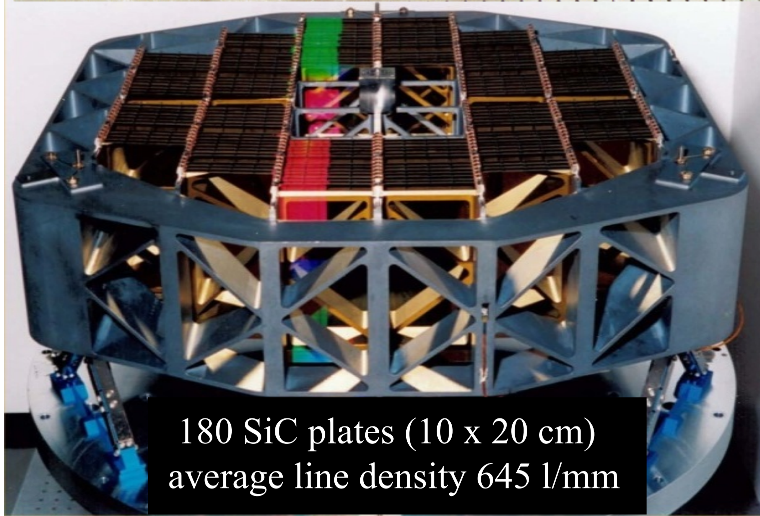
BW: $\Delta\alpha \to \Delta\lambda = \frac{d}{m}\sin\alpha\Delta\alpha$

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

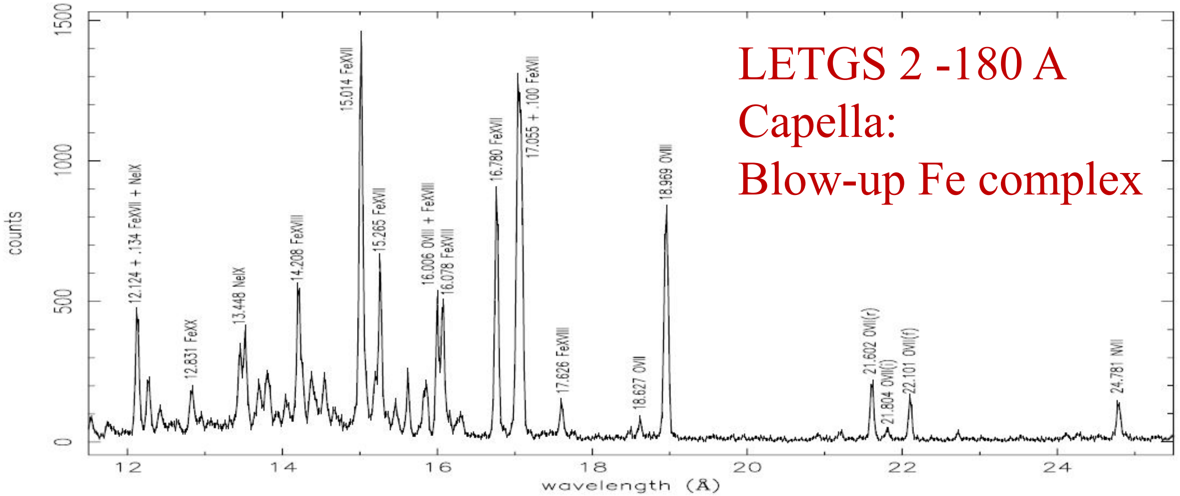
→ effective grating period: $d\sin\alpha$

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

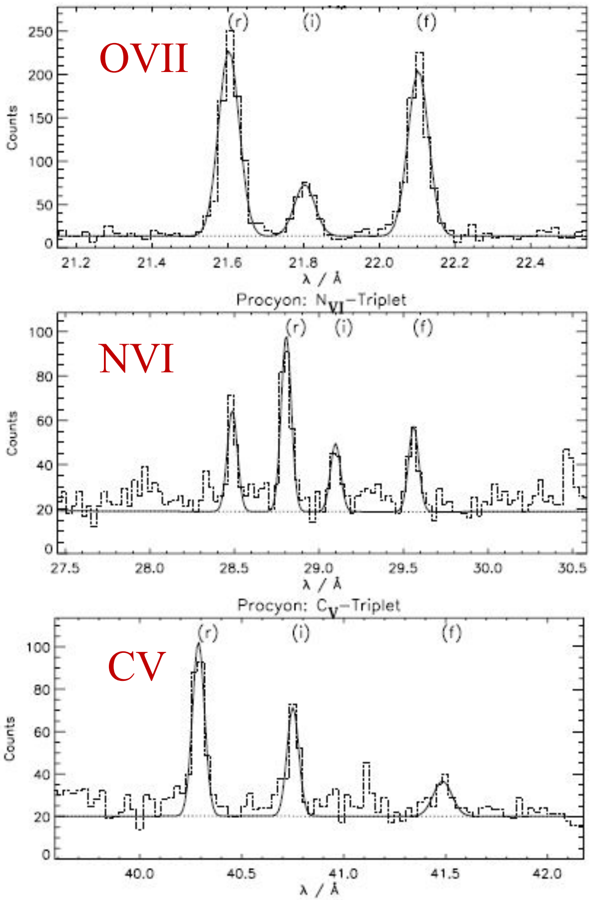




HR spectroscopy with Chandra LETGS, plasma density diagnostics with He-like triplets



PROCYON



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

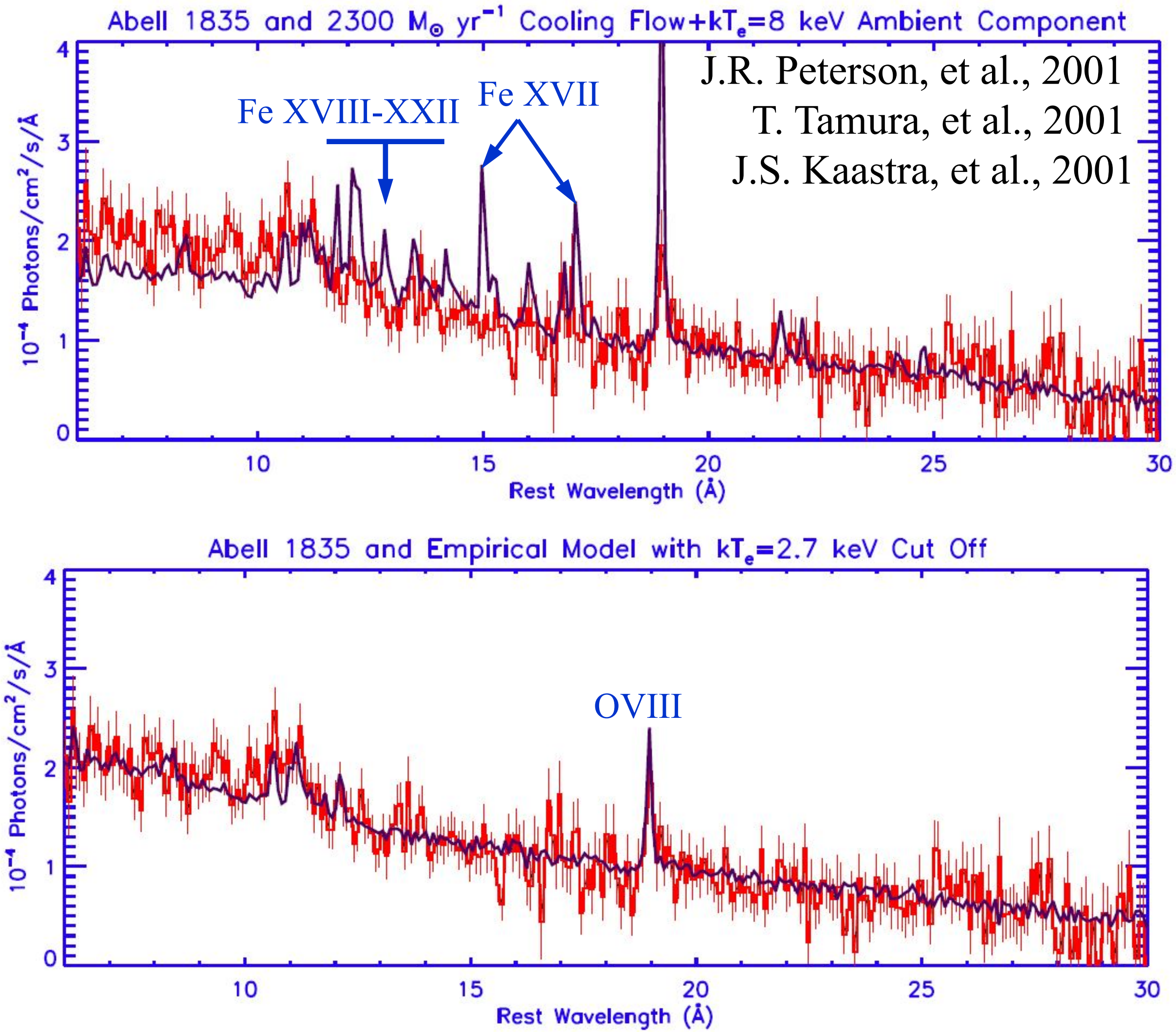
Capella OVII: $n_e = 3.10^9$, NVI: 7.10^9, CV $= 3.10^9$
Procyon OVII: $n_e = 2.10^9$, NVI: 9.10^9, CV $<10^9$

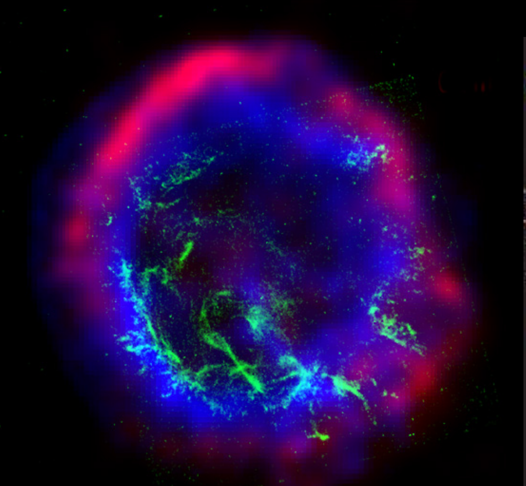
- Electron density values typical for solar active regions
- No densities as high as in solar flares
- Flux generated in Magnetic Loops: filling factor exceeds solar >10

From Cooling Flows to Cool Cores in galaxy clusters.

Characteristically:
temperatures < $T_{max}/3$ missing
(Peterson & Fabian, 2006)

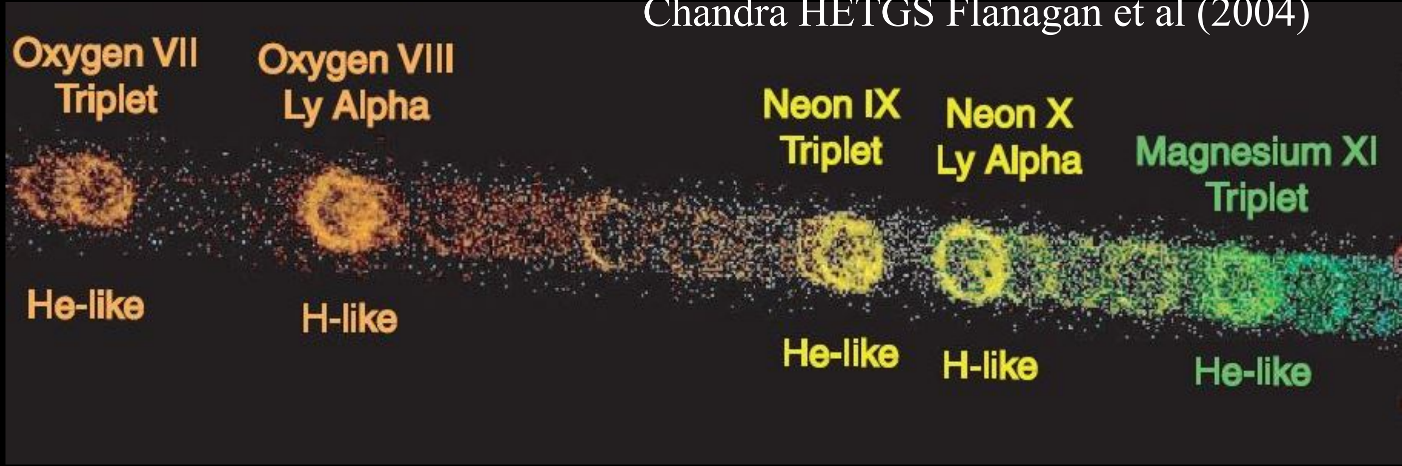
Abell 1835 (Chandra)

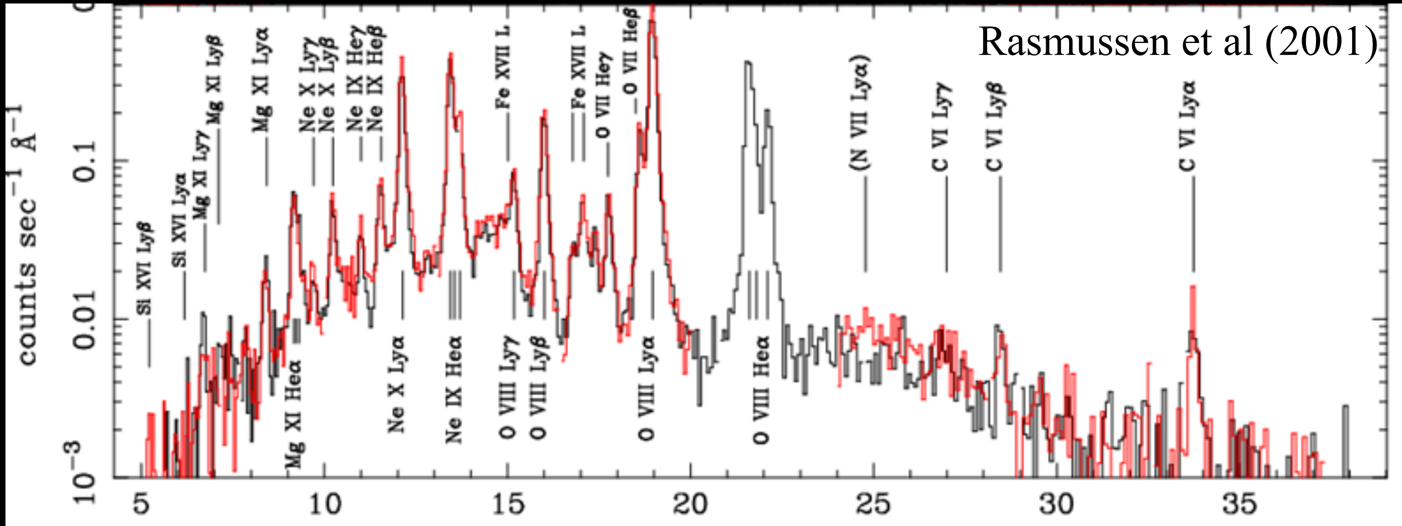




Gaetz et al (2000)

Chandra HETGS Flanagan et al (2004)



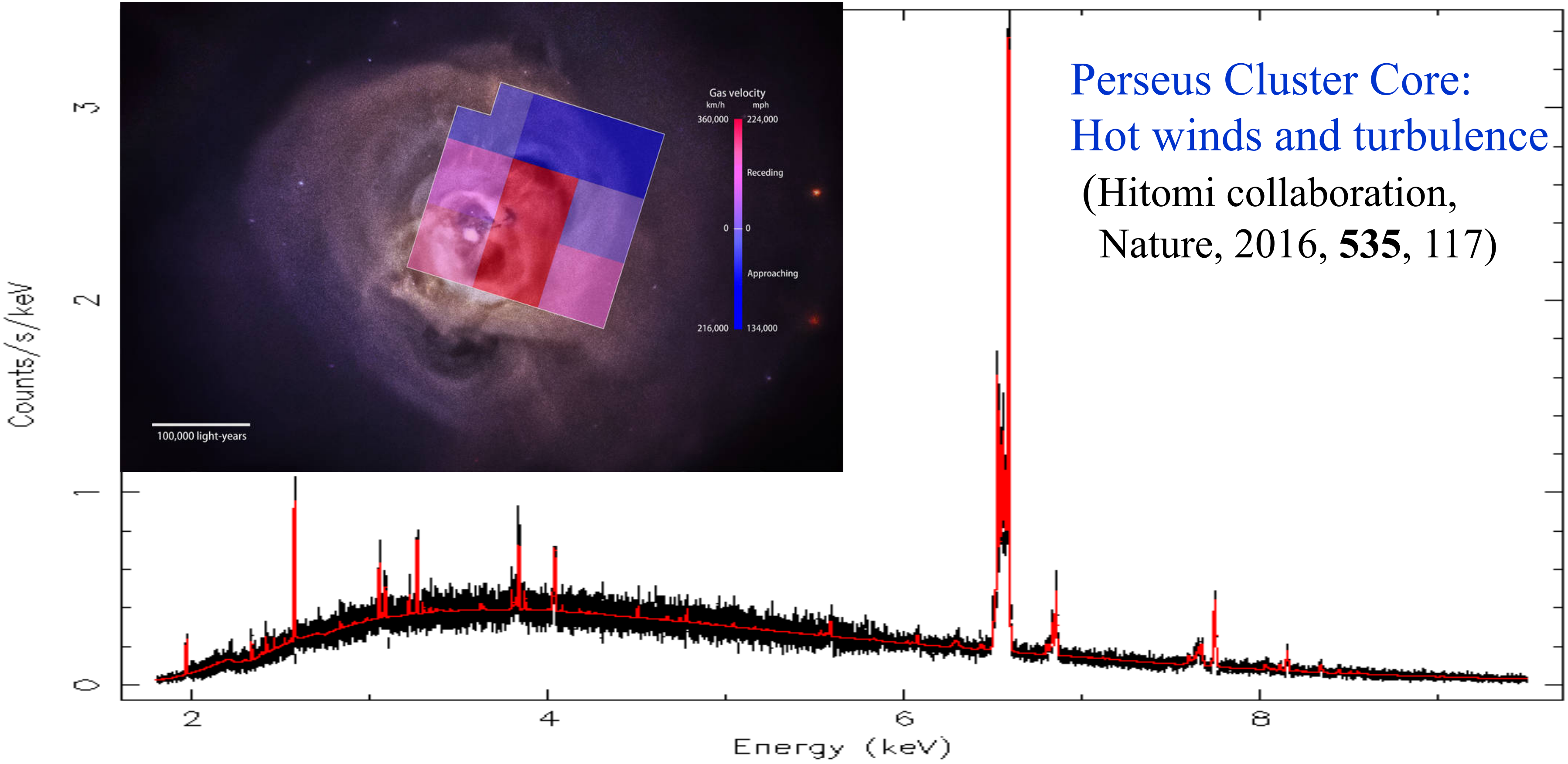


XMM-Newton

SNR shocks

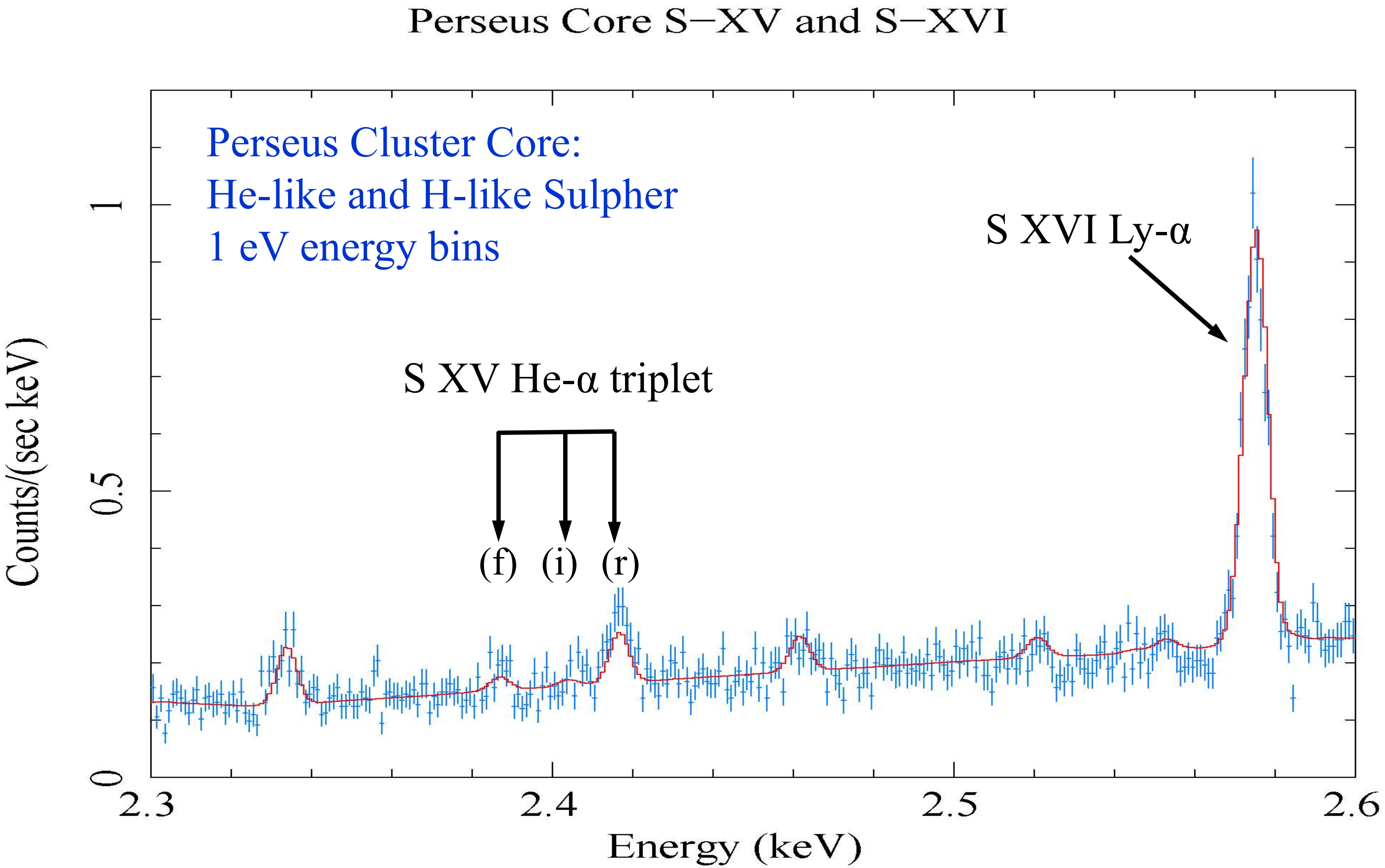
The magnificent case of 1E0102-73 in the Small Magellanic Cloud

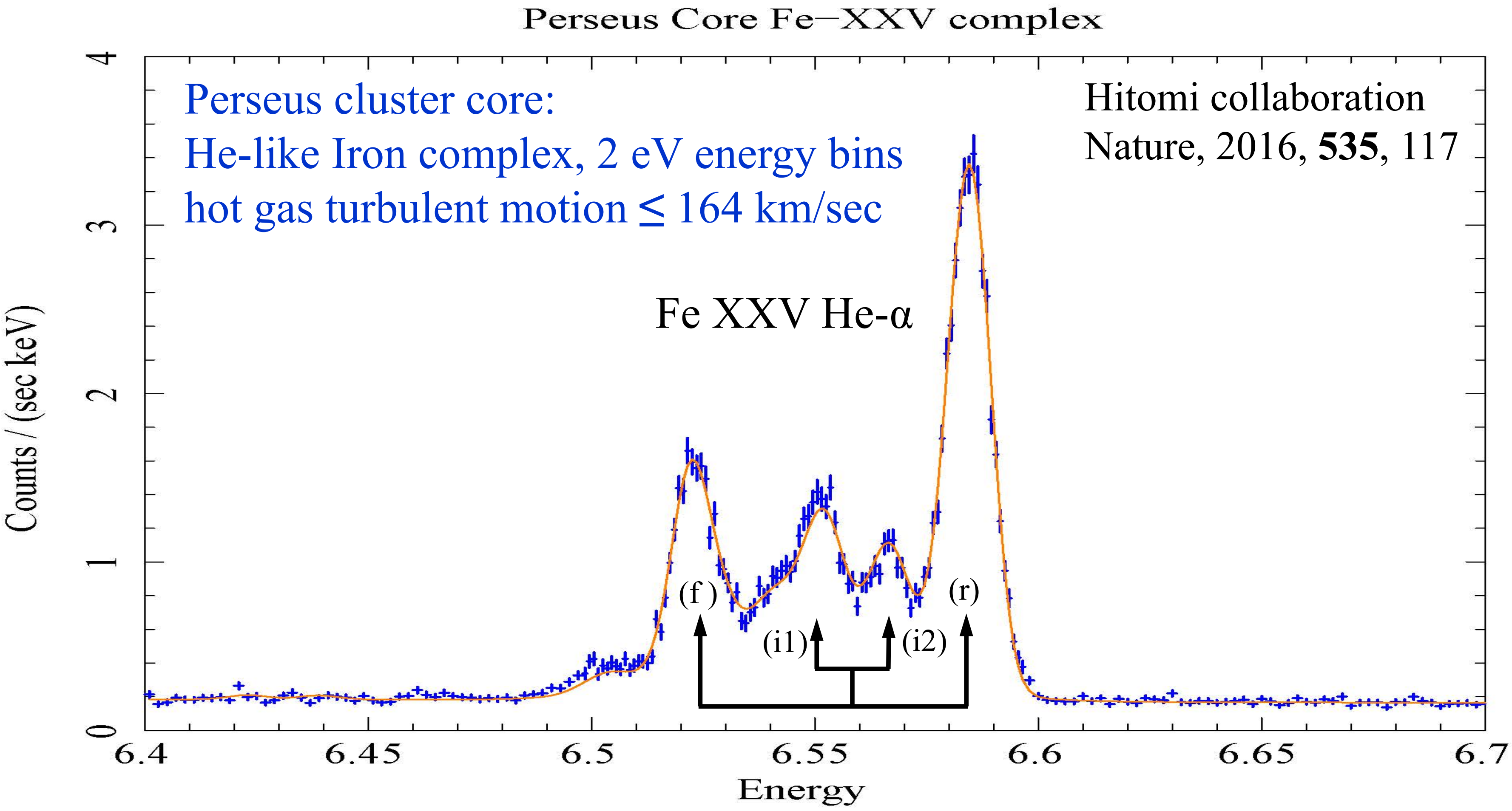
Energy-dispersive HR-spectroscopy: the Microcalorimeter on Hitomi



Perseus Cluster Core:
Hot winds and turbulence

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


Perseus Core S−XV and S−XVI
Perseus Cluster Core:
He-like and H-like Sulpher
1 eV energy bins
S XVI Ly-α
S XV He-α triplet
(f)
(i)
(r)
Counts/(sec keV)
0
0.5
1
2.3
2.4
2.5
2.6
Energy (keV)


Perseus Core Fe−XXV complex
Perseus cluster core:
He-like Iron complex, 2 eV energy bins
hot gas turbulent motion ≤ 164 km/sec
Hitomi collaboration
Nature, 2016, **535**, 117
Fe XXV He-α
(f)
(i1)
(i2)
(r)
Counts / (sec keV)
Energy
0
1
2
3
4
6.4
6.45
6.5
6.55
6.6
6.65
6.7