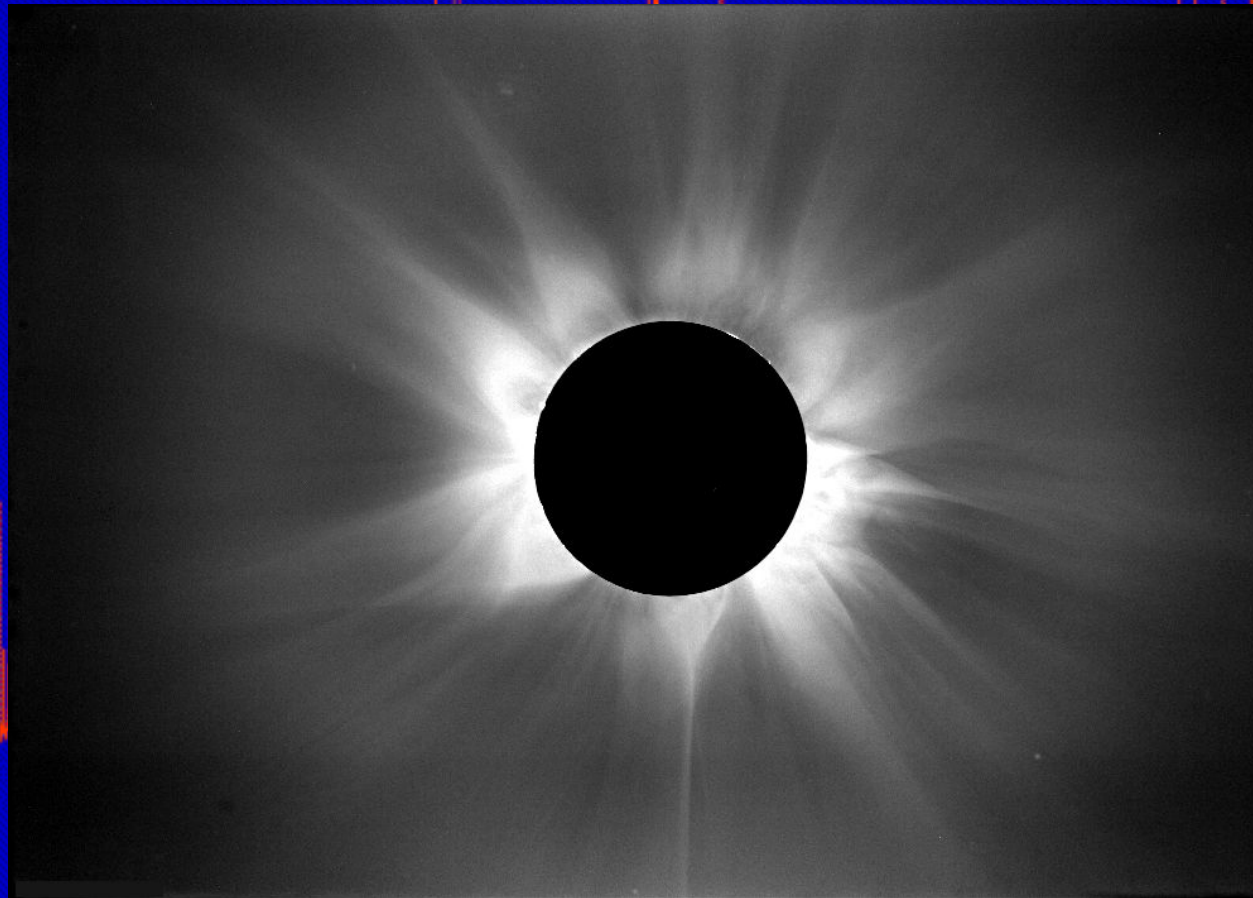
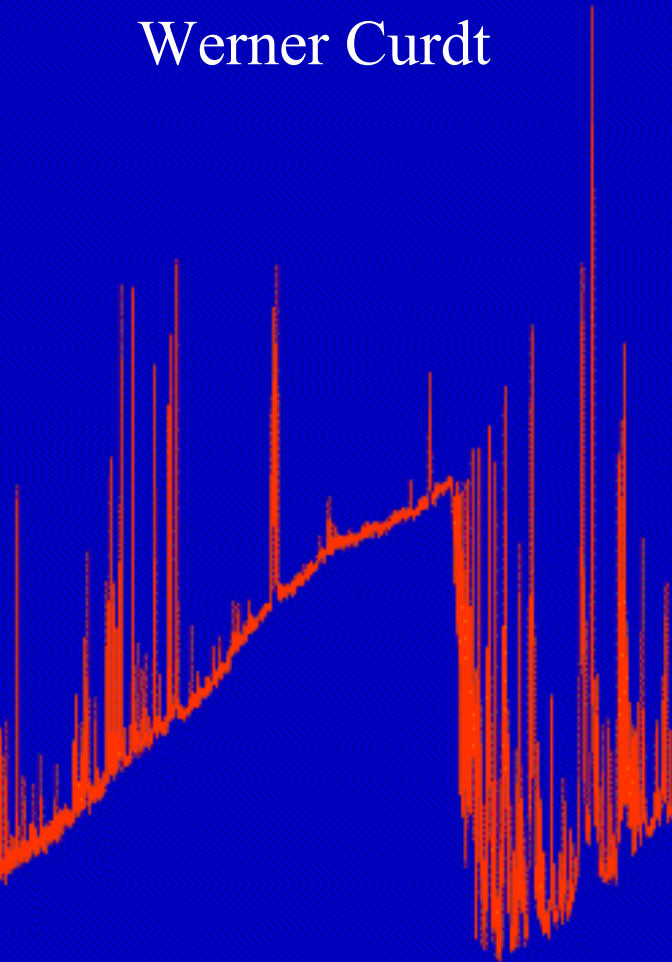




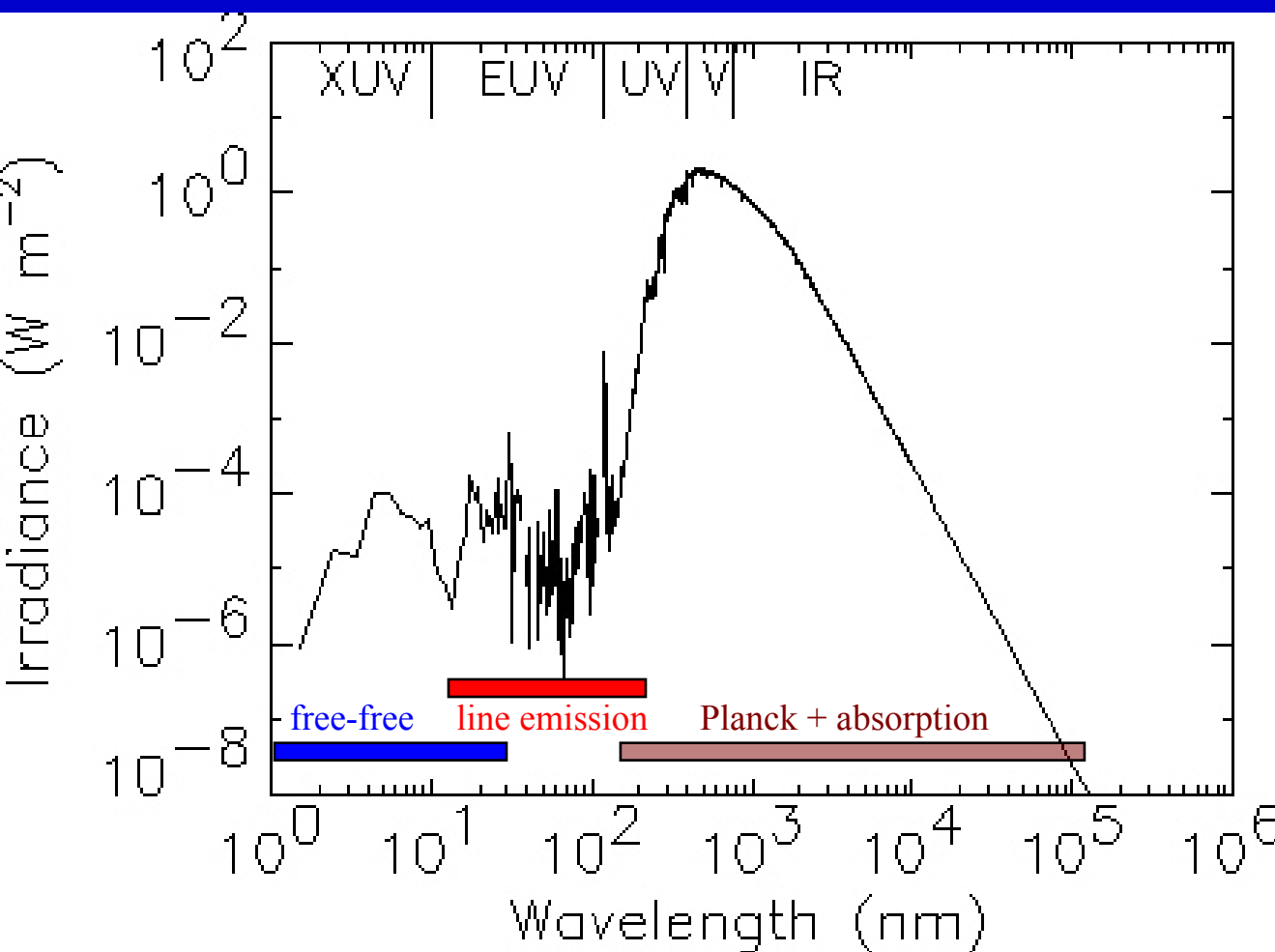
Solar UV Spectroscopy and Coronagraphy

Werner Curdt



Outline

- motivation
 - the Sun's electromagnetic spectrum
 - spectroscopic methods
 - observational examples
- instrumental aspects
 - optical design
 - detectors
 - others
- highlights and outlook
- coronagraphy
 - the solar corona
 - instrumental aspects



spectral categories:

XUV 0.1 – 10 nm

HXR < 0.1 nm

SXR 0.1 – 10

VUV 10 – 200 nm

EUV 10 – 121

FUV 121 – 200

MUV 200 – 300 nm

UV-C 100 – 280

NUV 300 – 400 nm

UV-B 280 – 315

UV-A 315 – 400

VIS 380 – 760 nm

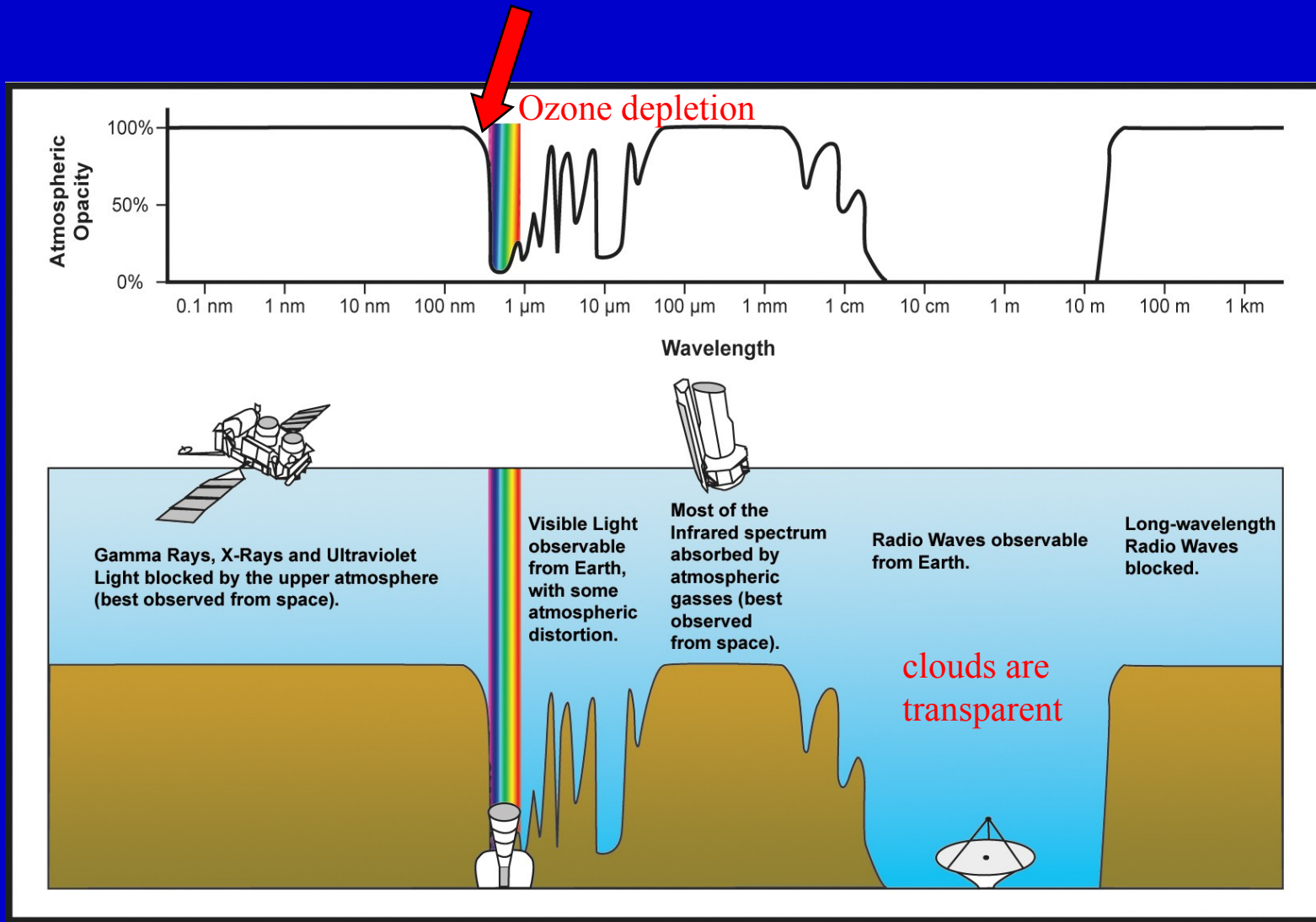
IR 760 nm – 1 mm

radio 1mm – 100 m

The solar irradiance spectrum above earth atmosphere (SOLAR2000)

EUV Spectroscopy

transmission of the Earth atmosphere

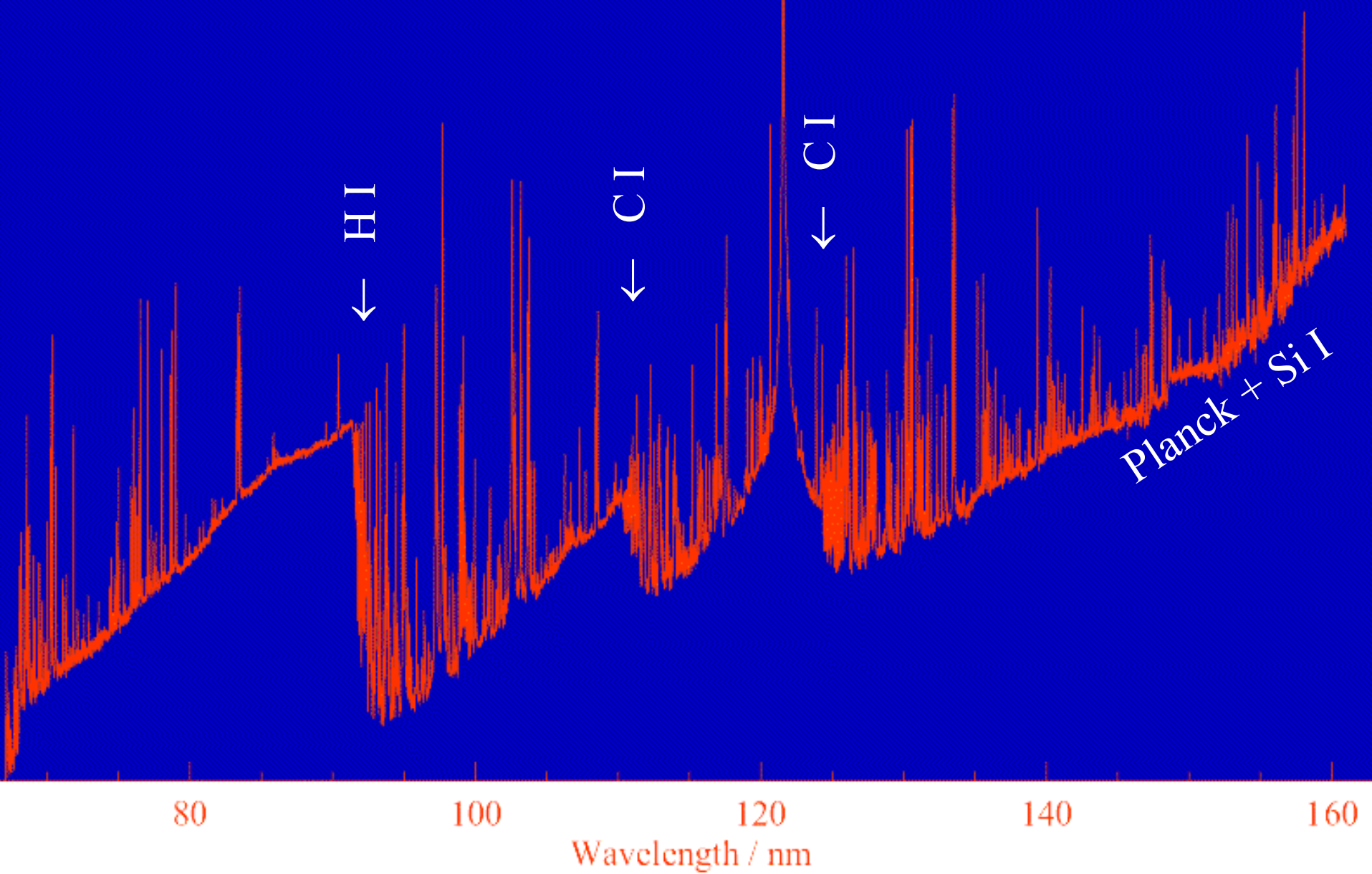


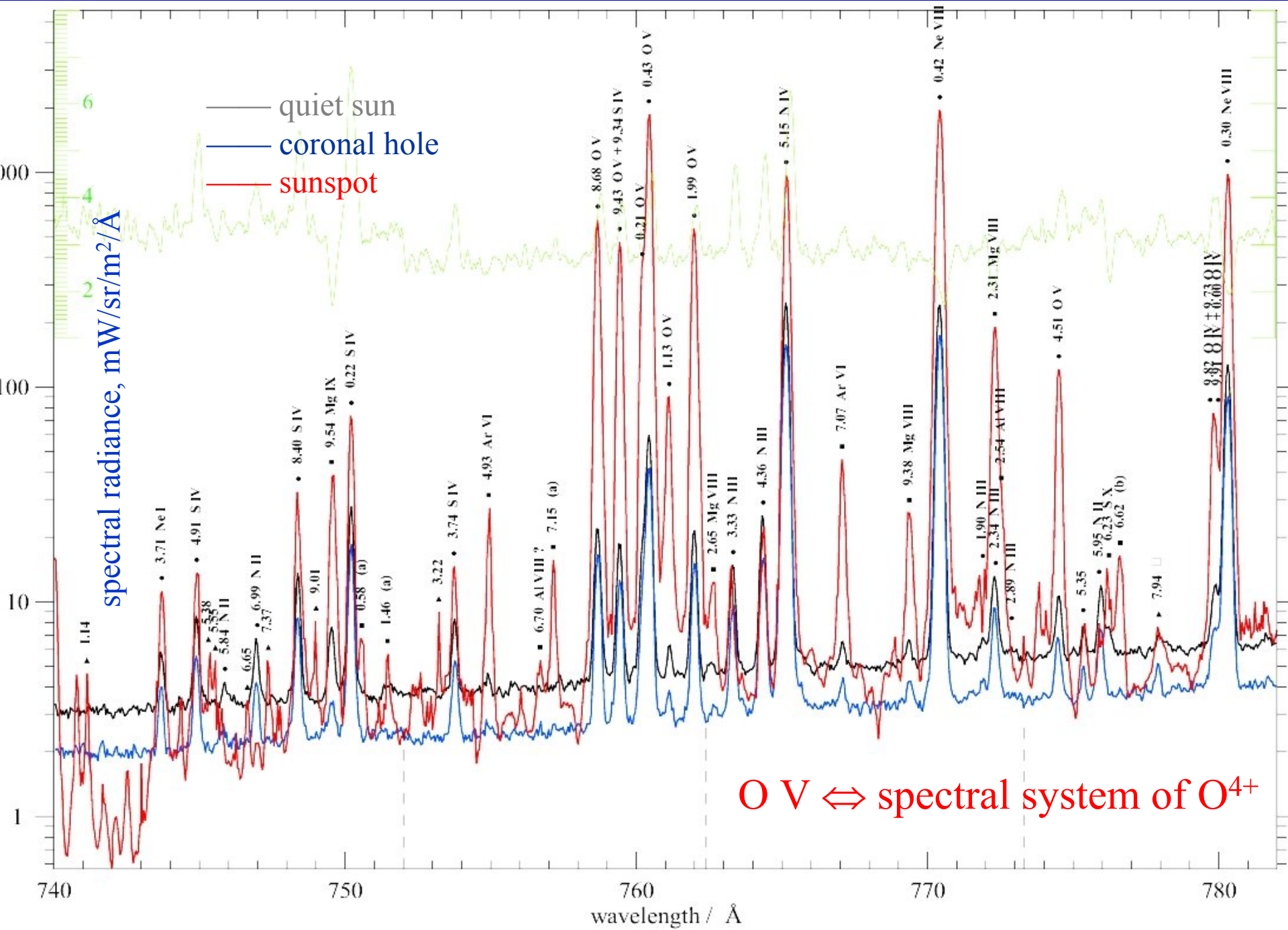
Spectroscopic methods

- line identification / selection
- line shifts / Doppler flows
- line widths / line shape
- plasma diagnostics / line ratios
- raster scans
- drift scans
- abundance measurements / FIP effect
- radiance / irradiance
- atomic physics

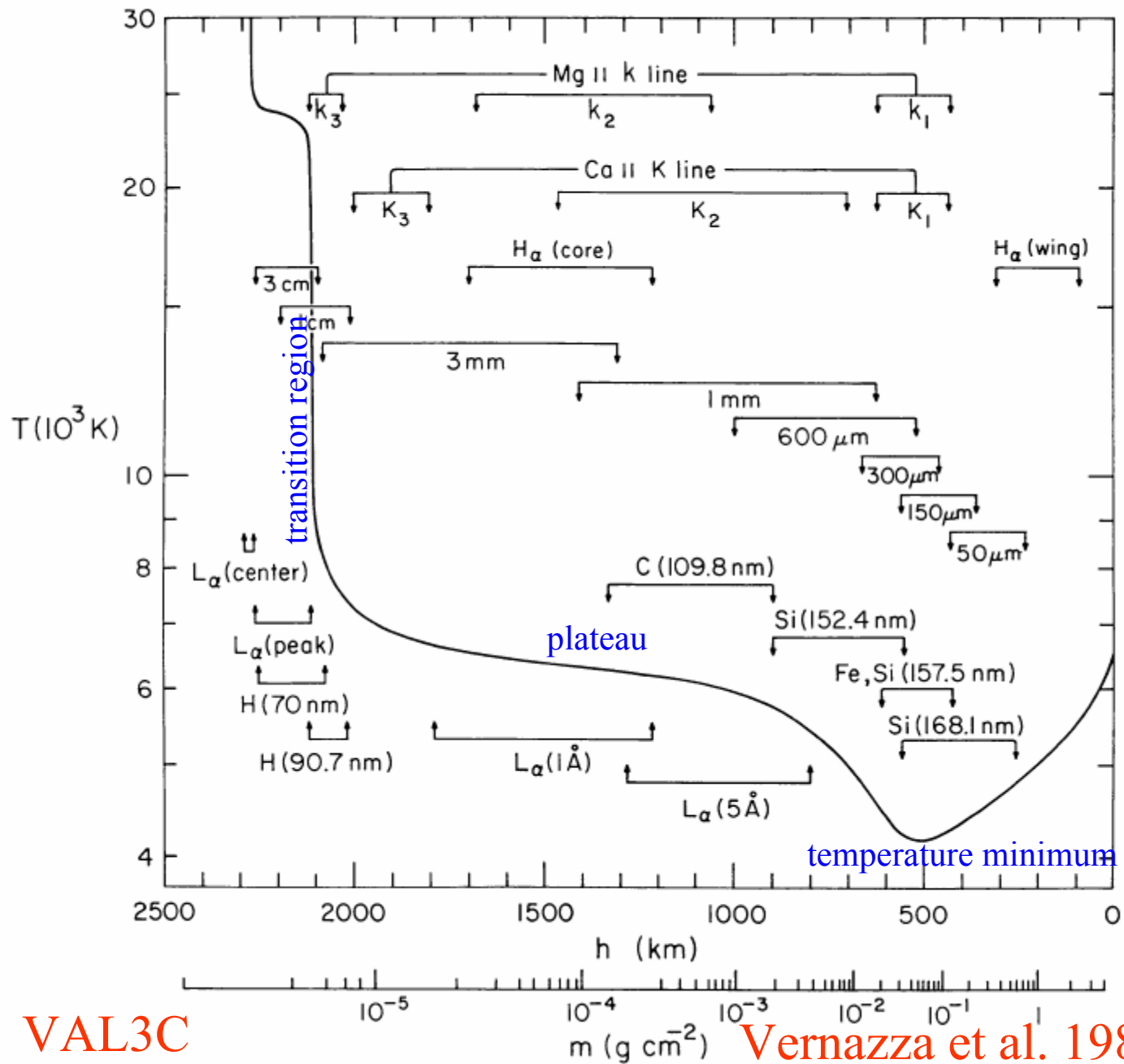
recombination continua:

> 1000 emission lines:



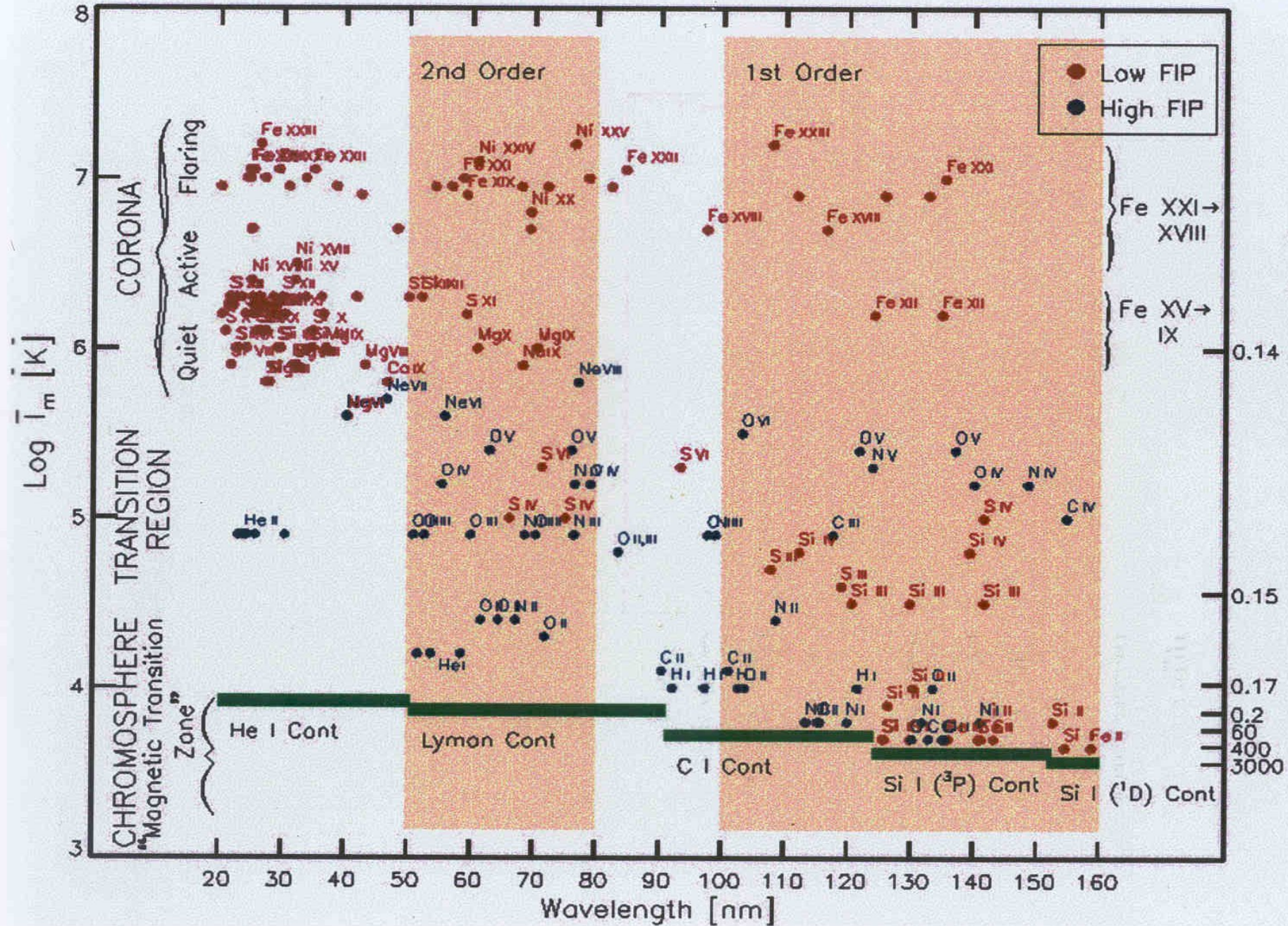


QUIET SUN EUV BRIGHTNESS COMPONENTS



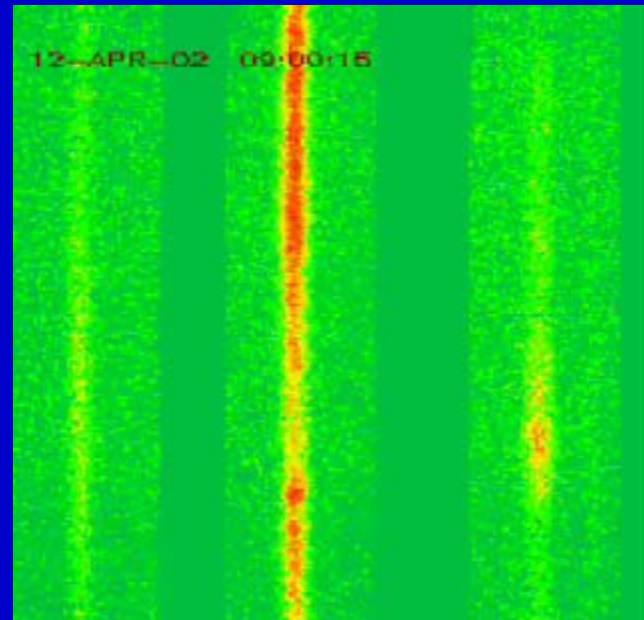
VAL3C

Vernazza et al. 1981



Doppler flows

- $\Delta\lambda / \lambda = v / c$
- Hires spectroscopes can resolve 1- 2 km/s



Si III

Ca X

Fe IXX

EUV Spectroscopy

Line emission

$$P(\lambda) = \int \frac{hc}{\lambda} A_{ul} N_u dV$$

A_{ul} upper/lower level transition probability

$$N_u = \frac{N_u(X^{+p})}{N(X^{+p})} \frac{N_u(X^{+p})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{Ne} Ne$$

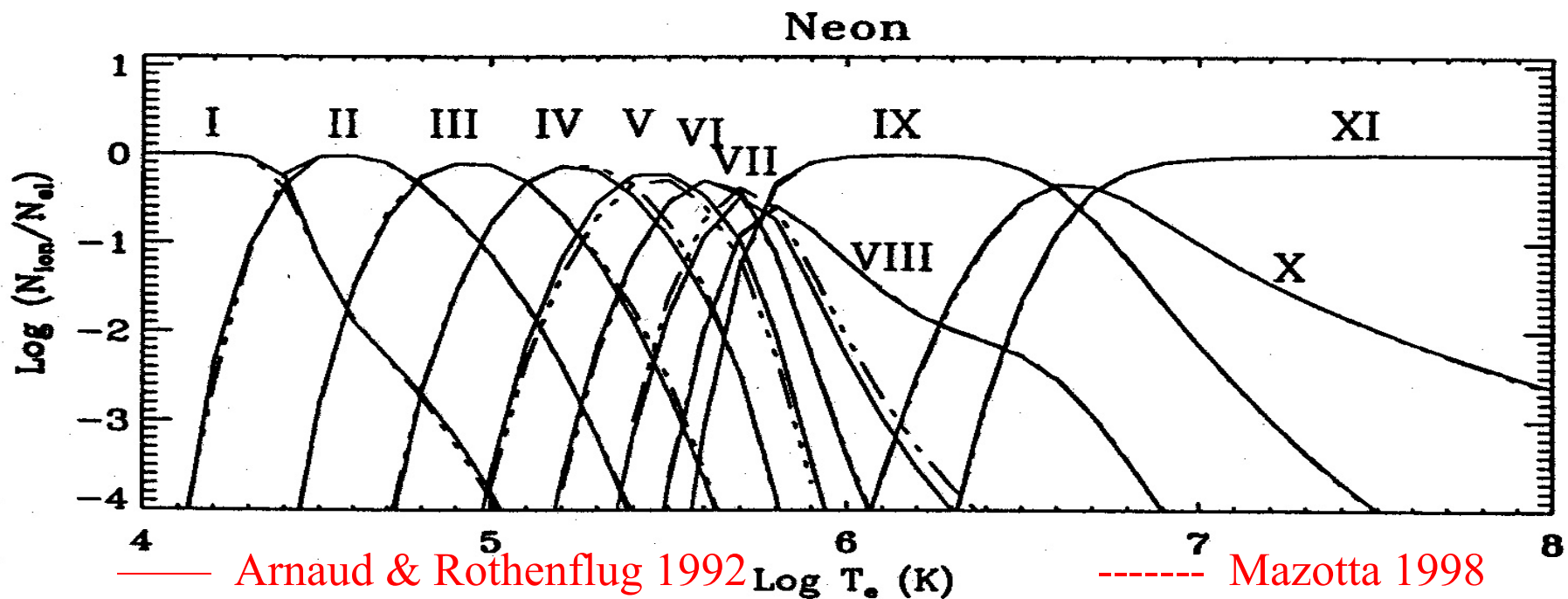
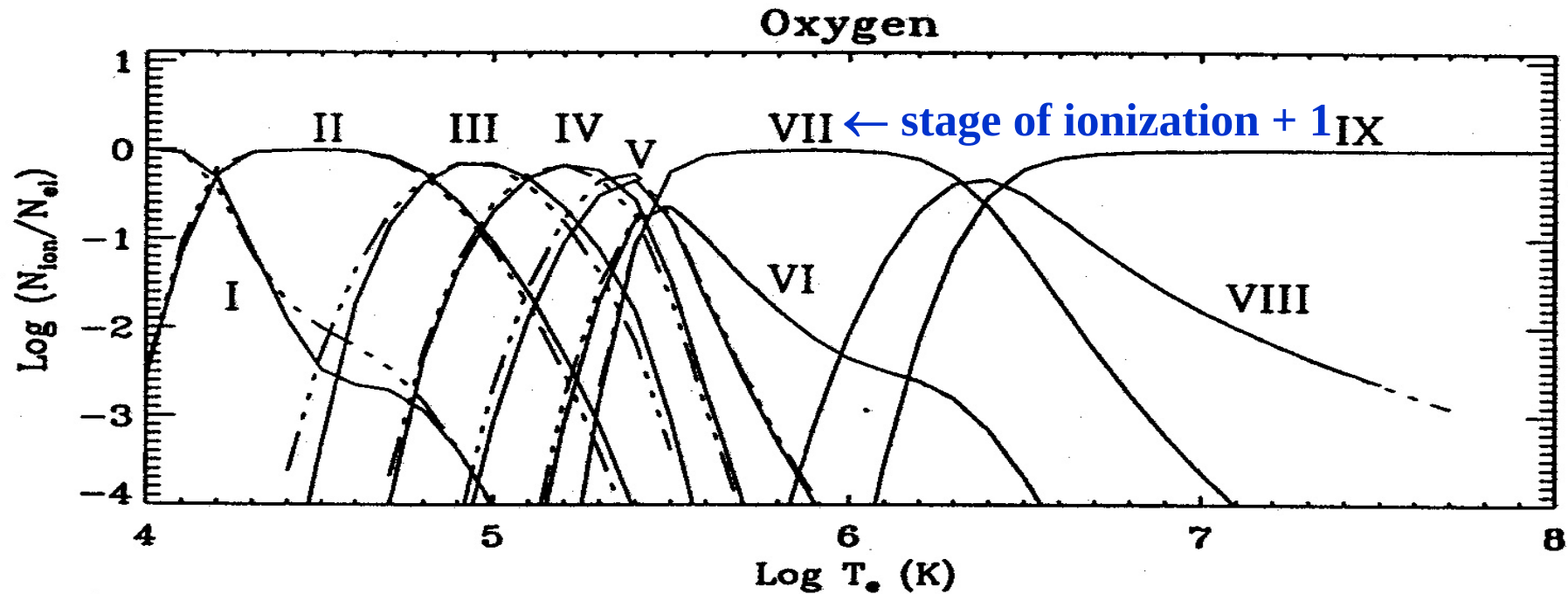
excited level
population

degree of
ionization

elemental
abundance

hydrogen
abundance

Chianti
ADAS
NIST



radiative excitation:

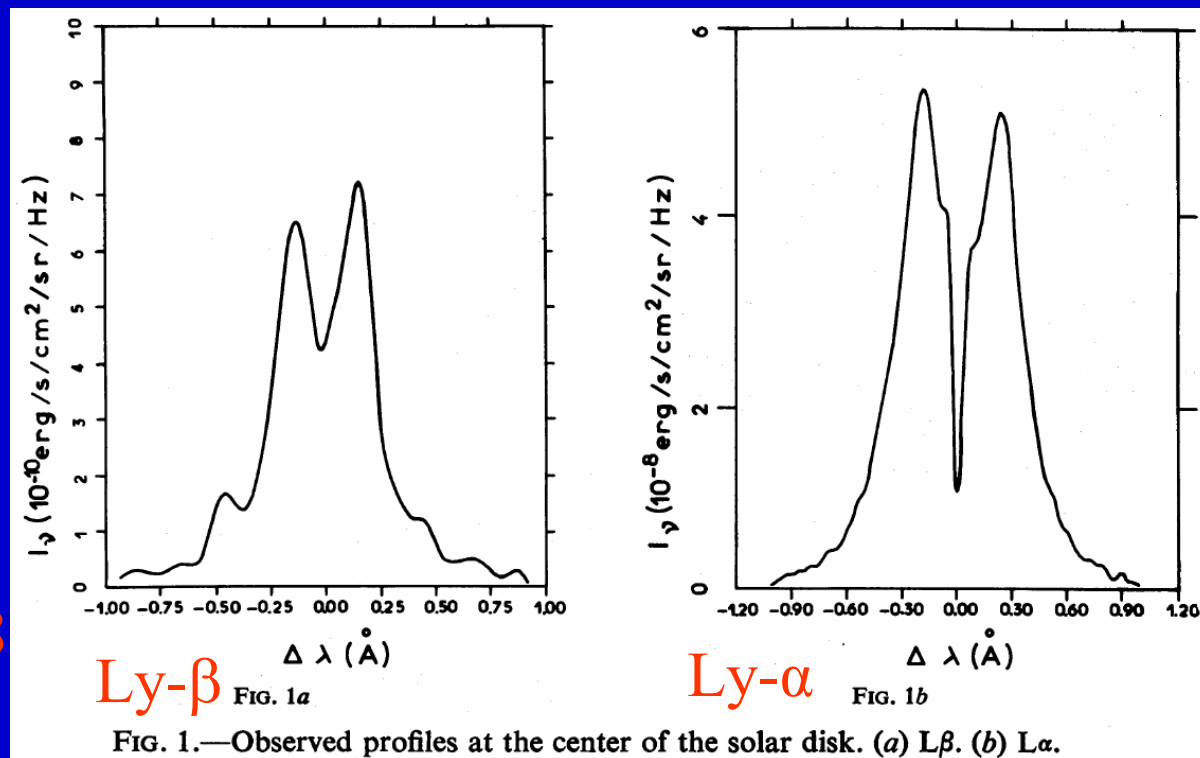
- optical pumping

some atomic systems have transitions into the ground state that coincide with strong lines

heating of the geo-corona

- self-reversal

Gouttebroze 1978



Line shape

- Optically thin emission lines are Gaussians

- emission profile $\Psi(\lambda)$

$$\Psi(\lambda) = \cancel{\Psi(\lambda)_{\text{nat}}} * \cancel{\Psi(\lambda)_{\text{coll}}} * \Psi(\lambda)_{\text{th}} * \Psi(\lambda)_{\text{NT}}$$

- $\Delta\lambda_D = \lambda_0/c (2kT/m + \xi^2)^{1/2}$
 ξ non-thermal velocity (turbulence)

Line ratios

$$P_{ul}(\lambda) \approx N_e^2$$

allowed transitions:

electric dipole transitions

$$\Delta l = \pm 1$$

$$\Delta m = 0, \pm 1$$

$$\Delta s = 0$$

$$P_{ul}(\lambda) \approx N_e$$

metastable levels:

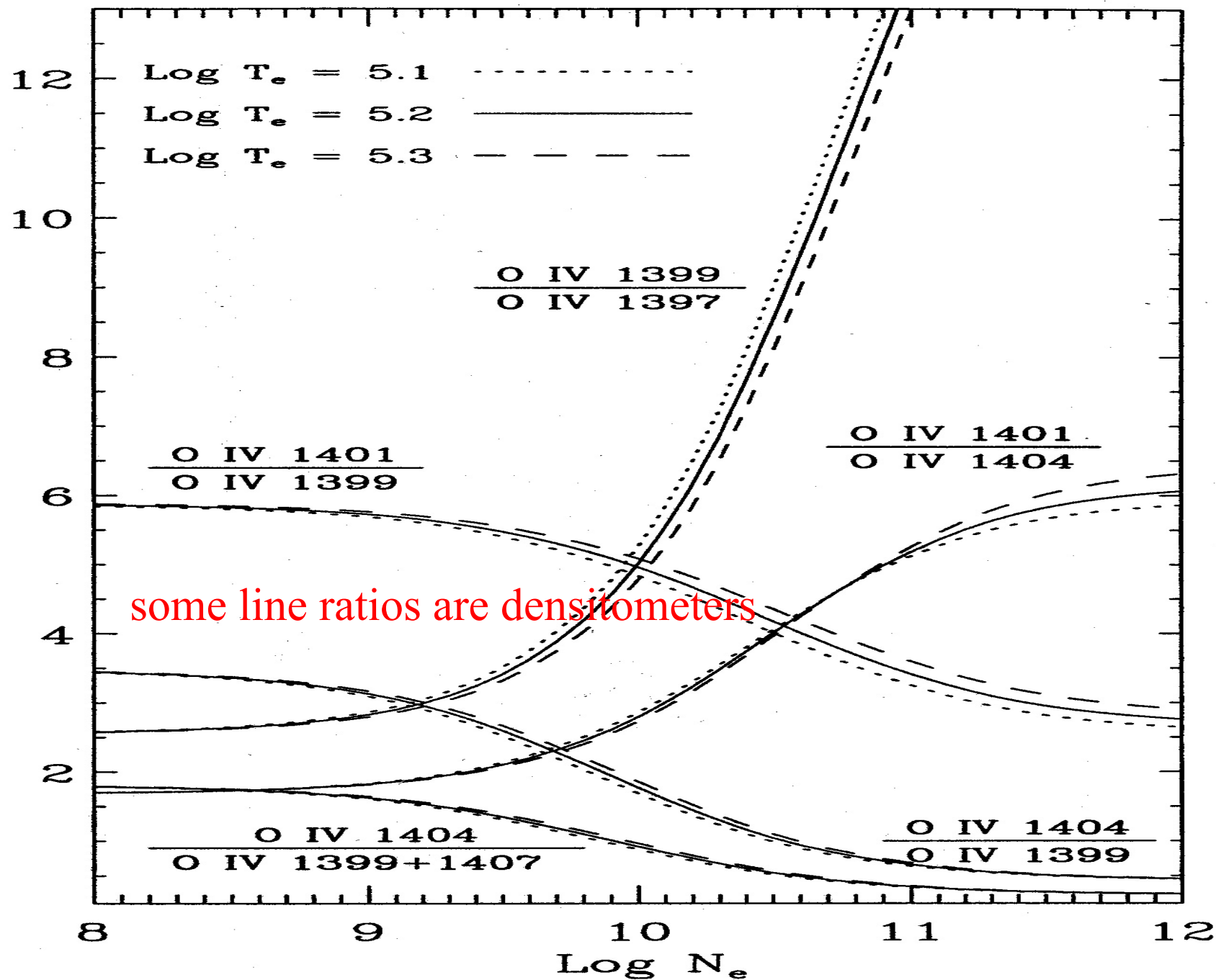
M1, E2, M2, ...

intersystem transition

N_e diagnostics

T_e diagnostics

Line Intensity Ratio



Historical overview

- 1950 Bragg-crystal spectrometers
- 1962 OSO armada
- 1973 Apollo Telescope Mount
- 1975 HRTS, 8 rocket flights
- 1985 HRTS, Spacelab 2
- 1996 SOHO-CDS
- 1996 SOHO-SUMER
- 2006 Hinode-EIS
- 2012 IRIS
- 2018 SO SPICE

Performance characteristic

Coronal Diagnostic Spectrograph

Solar Ultraviolet Measurement of Emitted Radiation

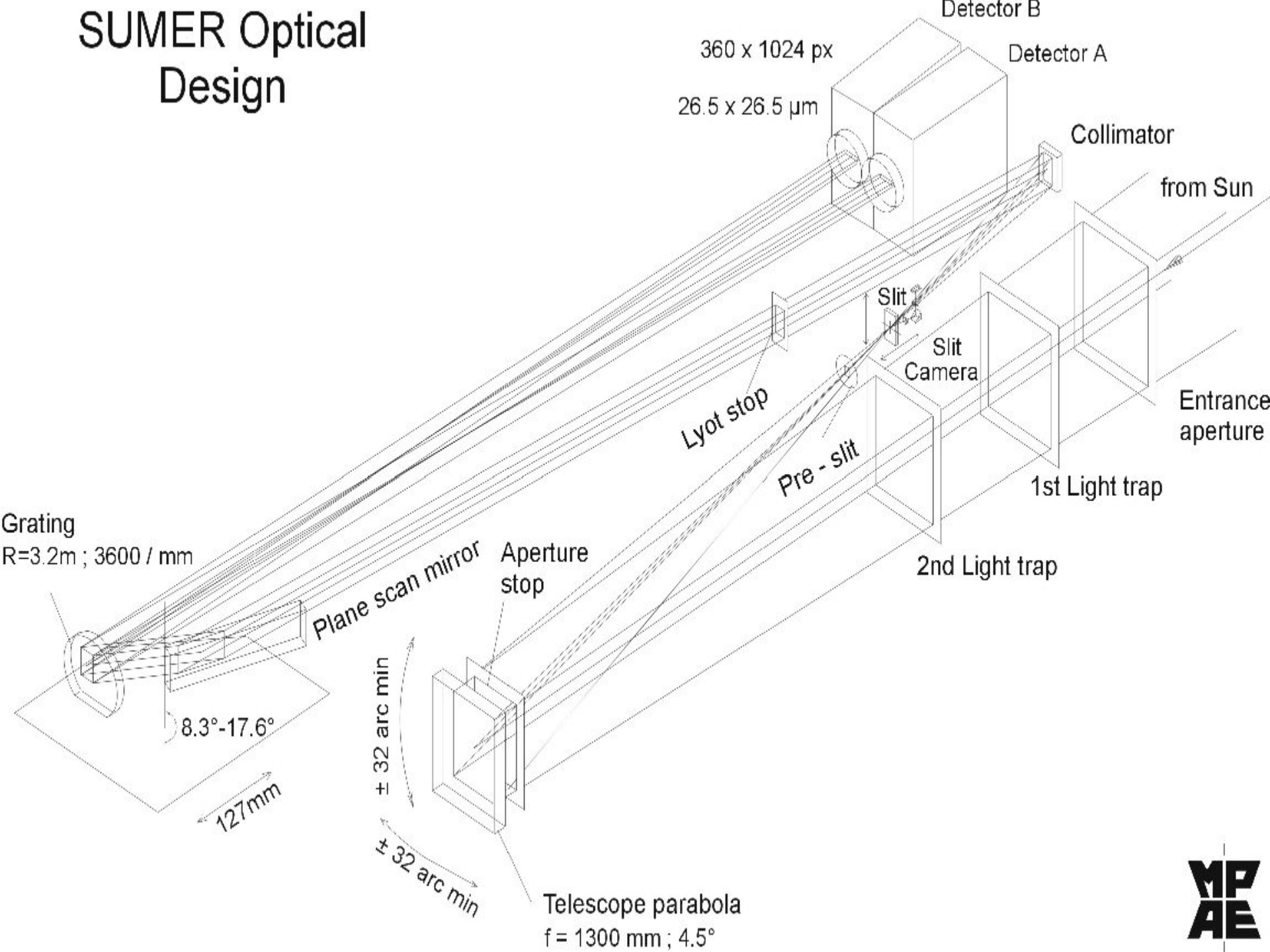
EUV Imaging Spectrograph

	CDS	SUMER	EIS
wavelegth range, Å	308-381 (NI)	790-1608 (1)	180 - 204 (A)
	513-633	465-804 (2)	240 - 290 (B)
	151-221 (GI)		
	256-338		
	393-493		
	656-785		
spatial resolution / "	4 - 8	1.2	1
spectral " / km/s	10	2	2-3
temporal " / s	10	10	1

Instrumental aspects

- Spectroscope:
 - telescope
 - slit
 - dispersive element
 - 2D detector
- infrastructure
 - to bring the instrument into space
 - to bring the data back to Earth

SUMER Optical Design



Telescope primary mirror

- size determines spatial resolution, λ/D
- size $\sim$ photon input $\Rightarrow$ temporal resolution
- figure defines PSF
- micro roughness defines scattered light level
- needs pointing mechanism
- optical surface:
 - $\lambda > 120 \text{ nm} \Rightarrow \text{Al/MgF}_2$
 - $\lambda > 50 \text{ nm} \Rightarrow \text{Si C}$
 - $\lambda < 50 \text{ nm}$ grazing incidence (Wolter) or multilayer coating

Telescope slit

- slit width limits photon input
- slit width limits spectral resolution
- slit: loss of $>99\%$ of photons
 - slitless spectroscopes (strong lines, filters)
 - slot spectroscopes (wide slit)
 - raster scans
 - drift scans (low temporal resolution)

Telescope collimator

- Makes parallel light (classical design)
- defines magnification (pixel adjustment)
- folds the light beam (compactness)

Spectroscope grating

- Bragg crystal systems
- holographic gratings
- ruled gratings
- variable line space technique (TVLS)
 - future 2 reflection designs

Instrument detector(s)

- Films
- CCDs
 - back-illuminated CCDs
 - intensified CCDs
- MCP detectors
 - multianode systems (MAMA)
 - time delay systems (XDL)
- APS sensors
- BOLD detectors

Telemetry issues

16 bit pixels

1 k × 1k

10 s

dynamical range

small and numerous

good time resolution

Example SUMER: $\frac{16 \text{ bit/px} \times 400\,000 \text{ bit}}{10 \text{ s}}$

$\approx 500 \text{ kbit/s}$

Data selection

windows, binning

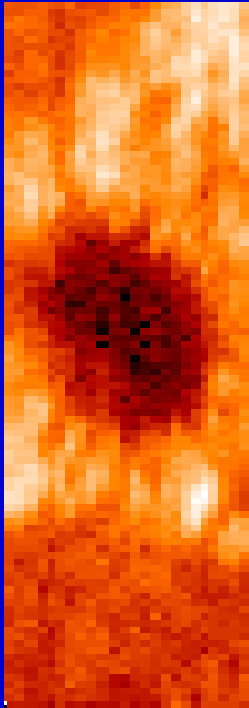
Data compression

sqrt, JPEG, MPEG

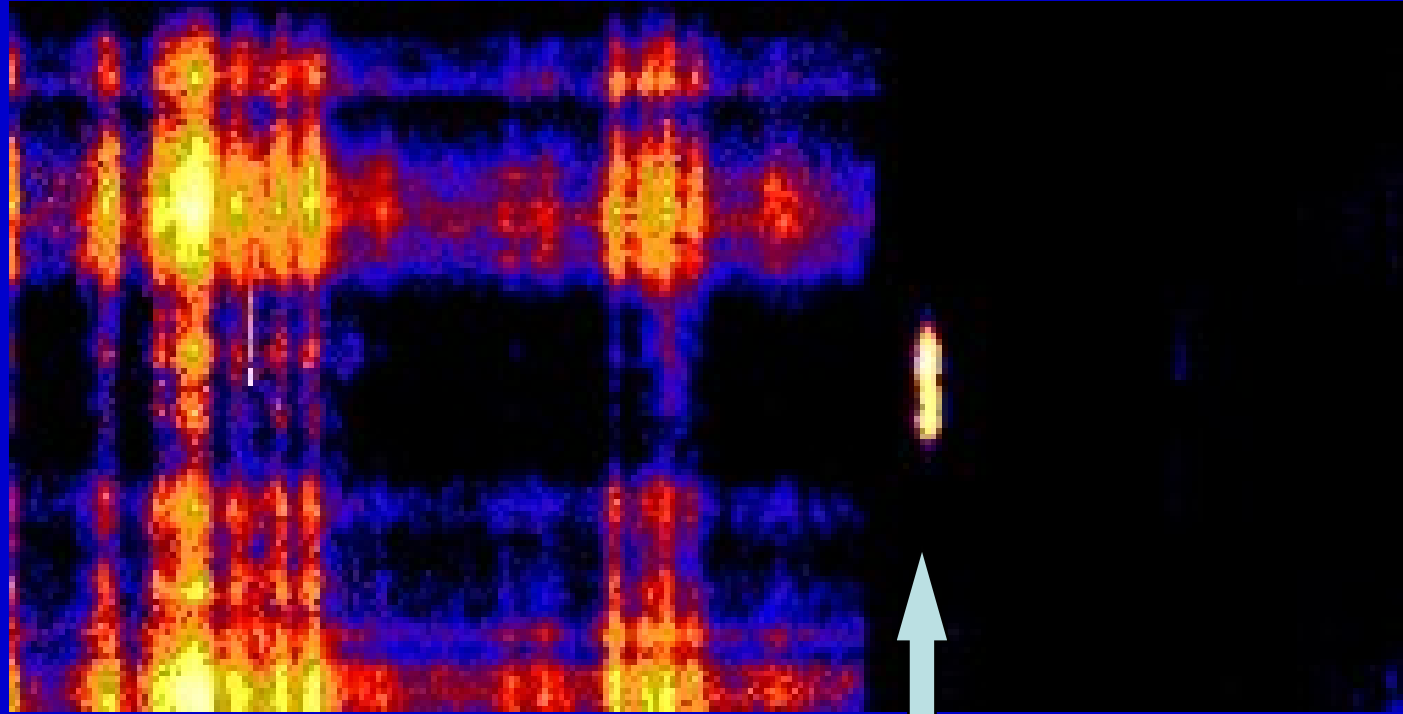
Data reduction

moments

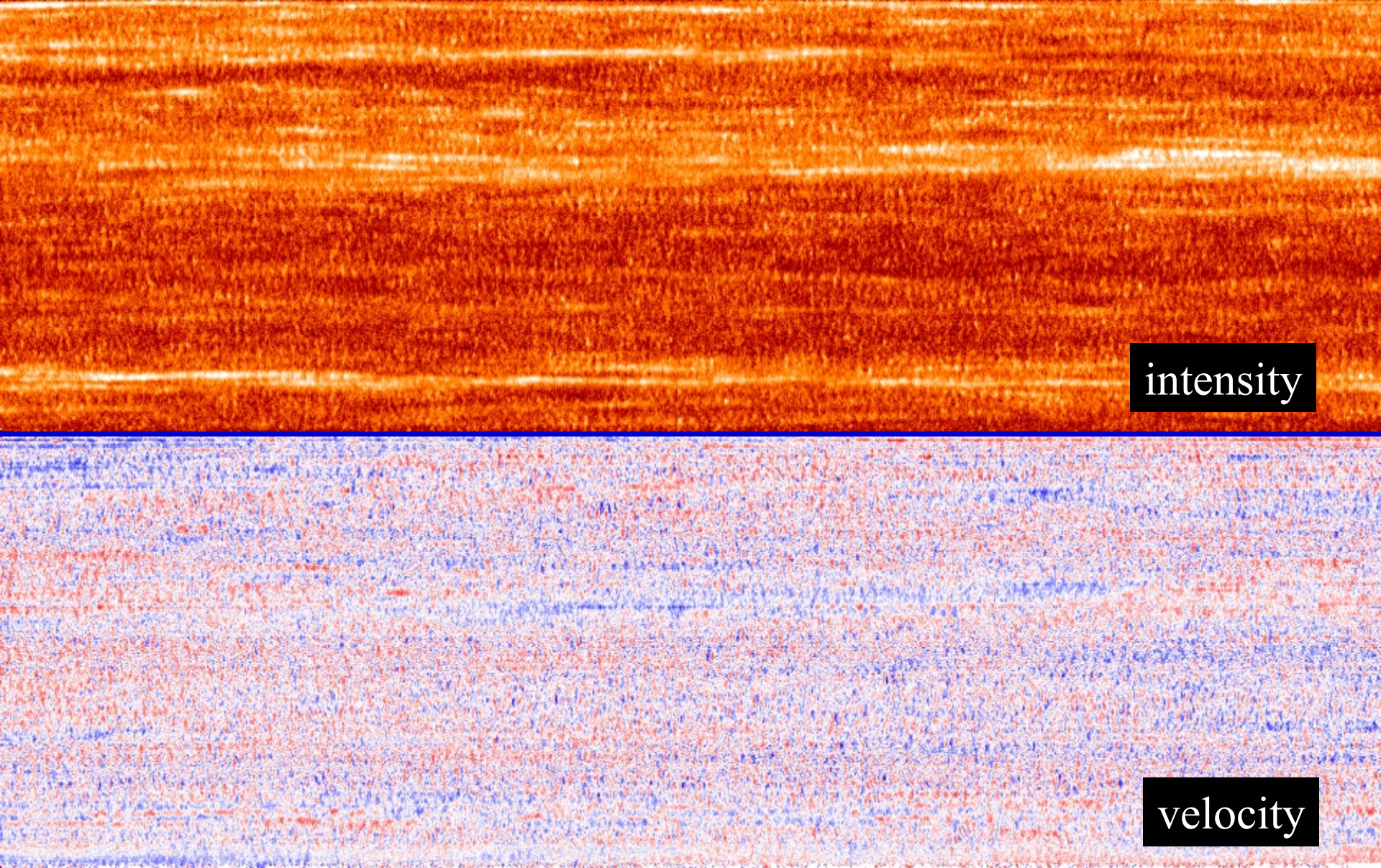
Sunspot onbserveed on Mar 18, 1999



Raster scan in the
continuum @ 1478 Å



Spectrum around 1163 Å with
strong H₂ fluorescence emission



Drift scan (x-t map) over 9 hours

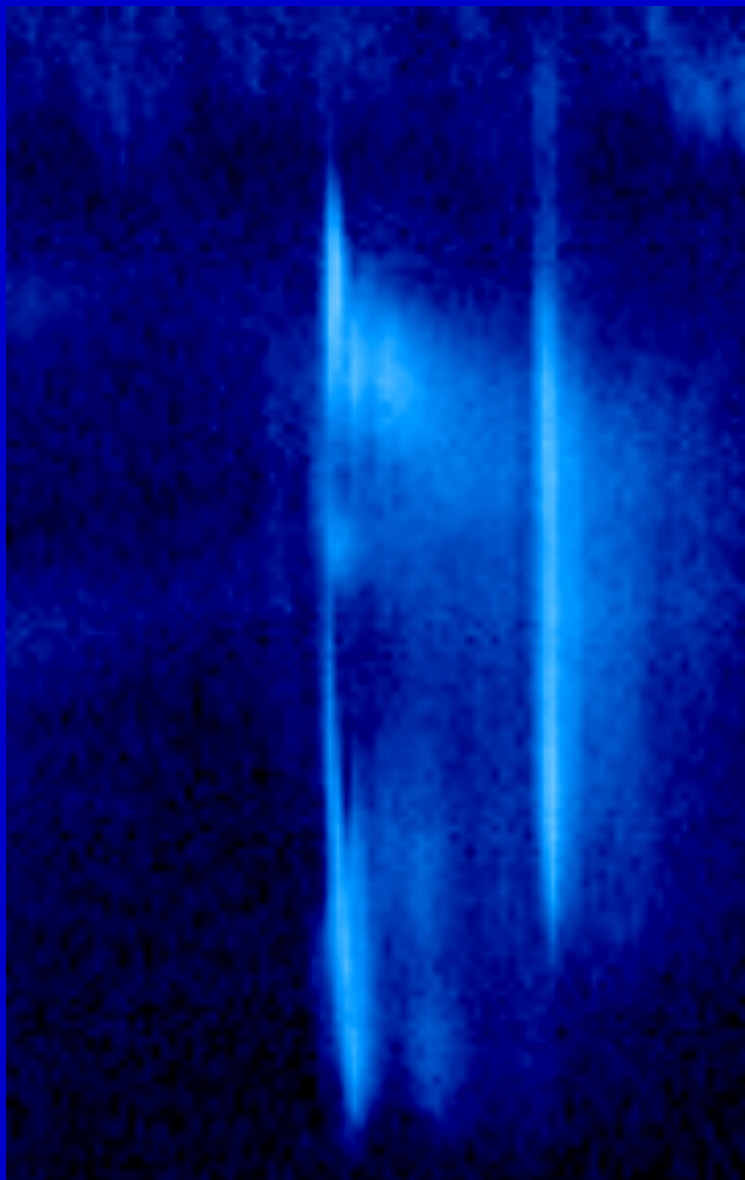
Si II 130.9 nm

EUV Spectroscopy

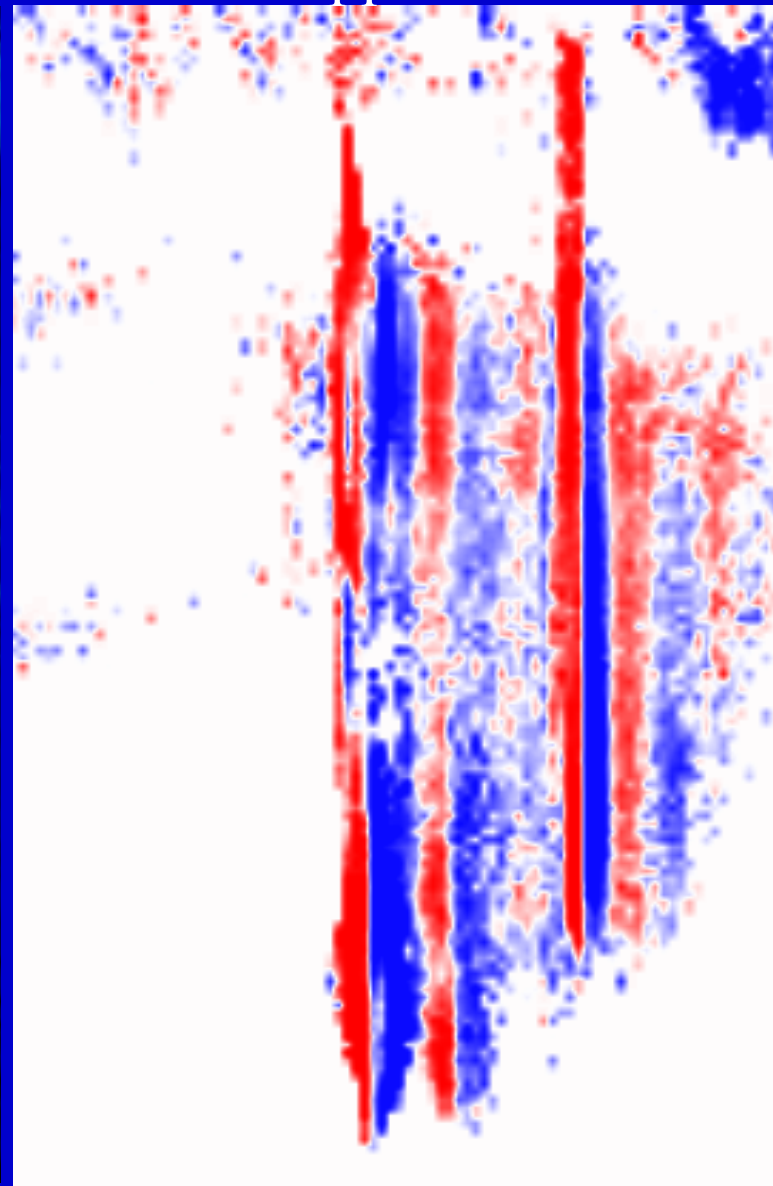
Fe XIX radiance

Fe XIX Doppler flow

distance



time

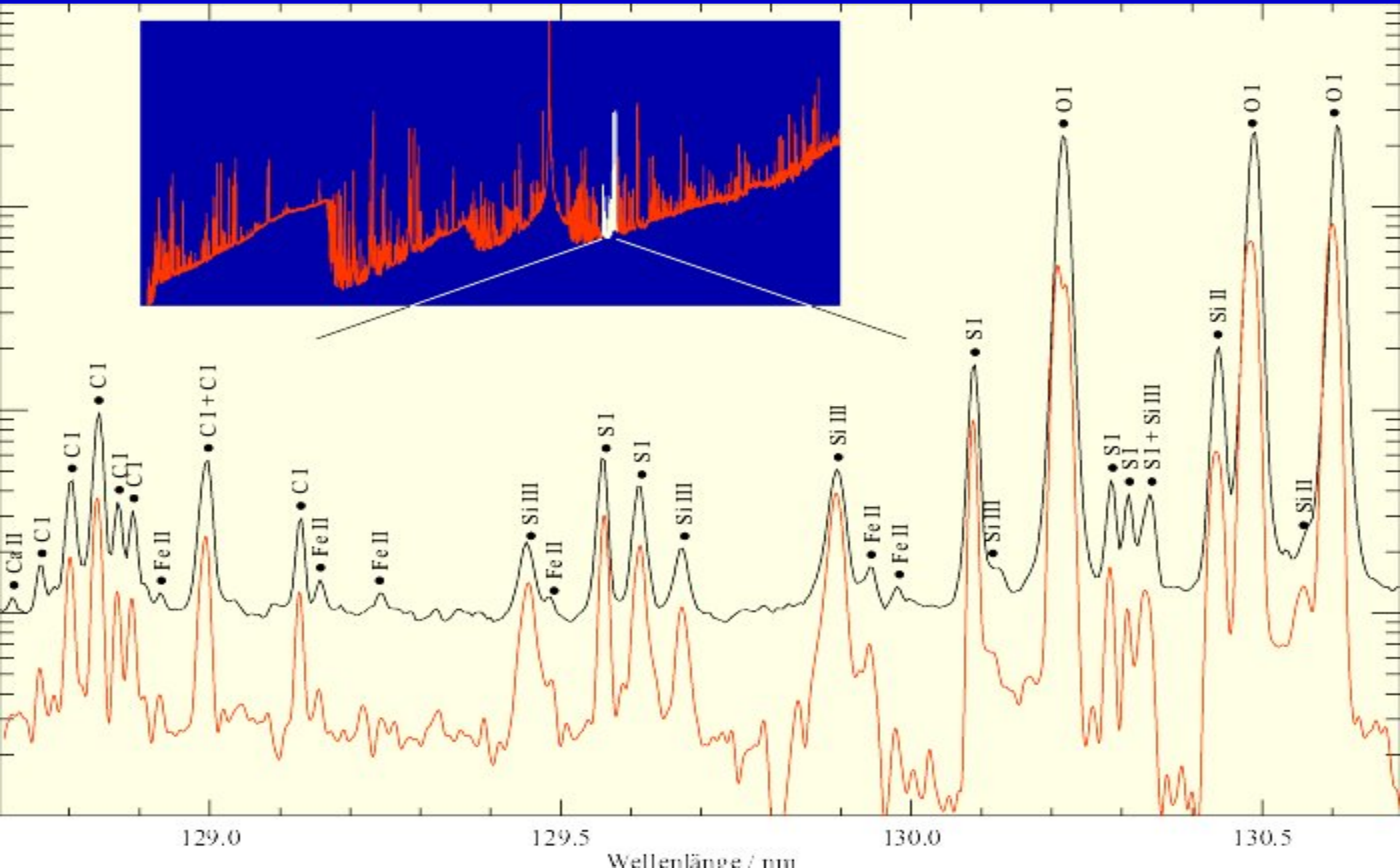


time

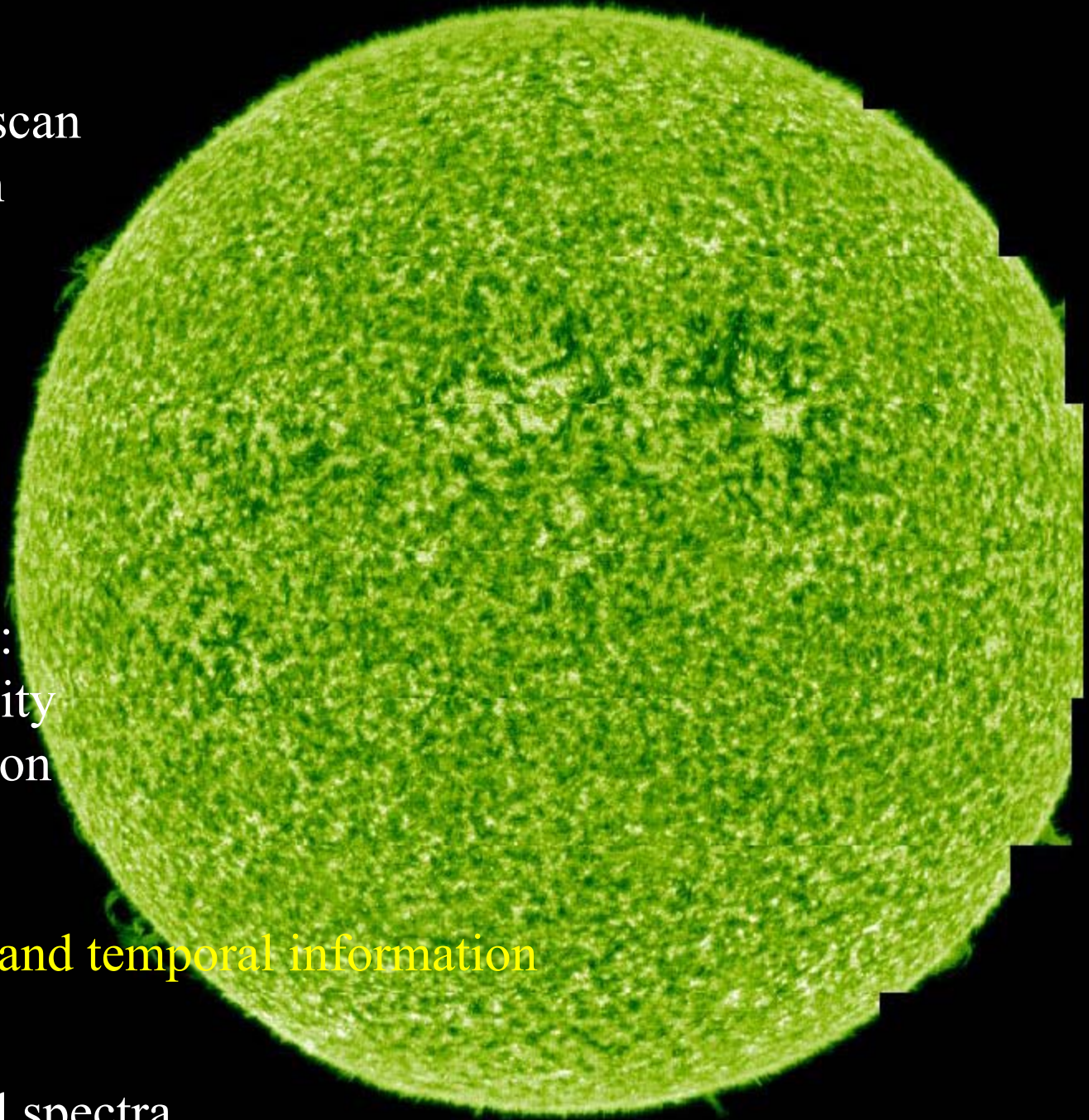
28 Sep 2000

EUV Spectroscopy

Sun @ 130 nm (black) / α Cen A (red)



Full Sun raster scan in C III 97.7 nm



spectroscopy basics:

- line-of-sight velocity
- „in situ“ information
- spectrally clean
- waste of photons
- mixture of spatial and temporal information

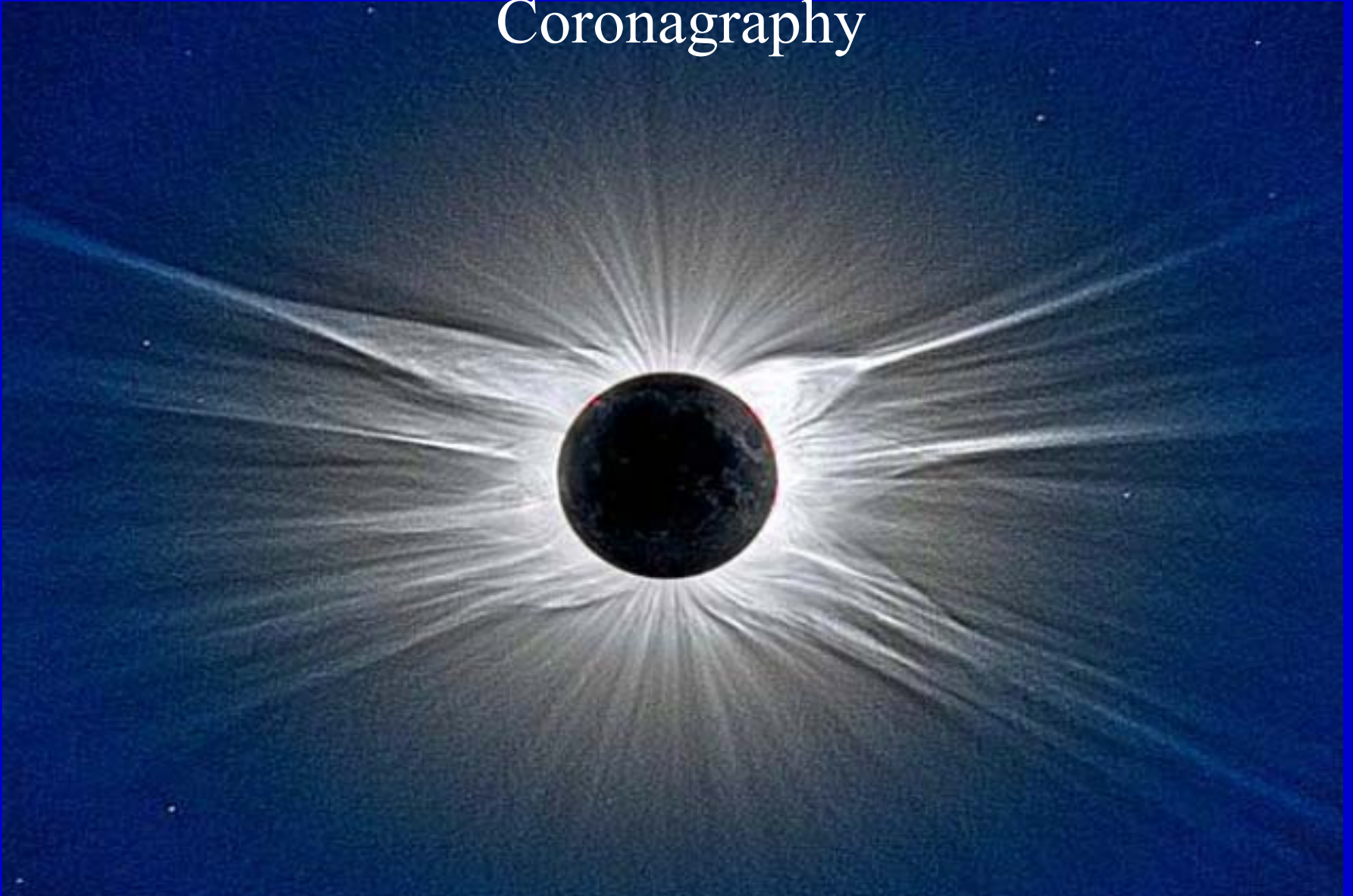
25 hours

12338 individual spectra

Outlook

- SUMER and CDS still in operation
- HINODE EIS
- IRIS
- Solar orbiter SPICE
- SOLAR C

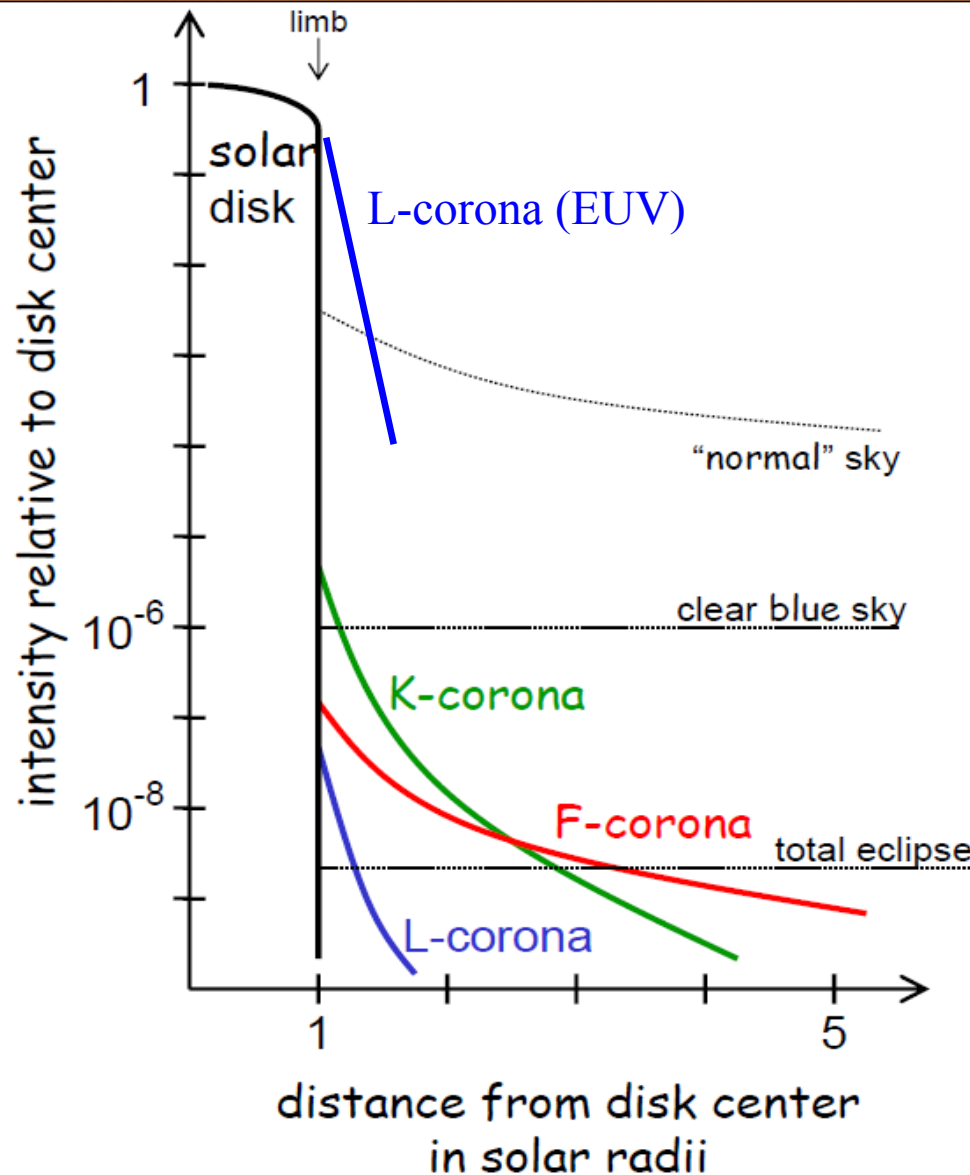
Coronagraphy



Schwenn 2006

EUV Spectroscopy

The solar corona: the 3 main types



(K) continuum corona

- no absorption lines
- polarised:
free electron scattering

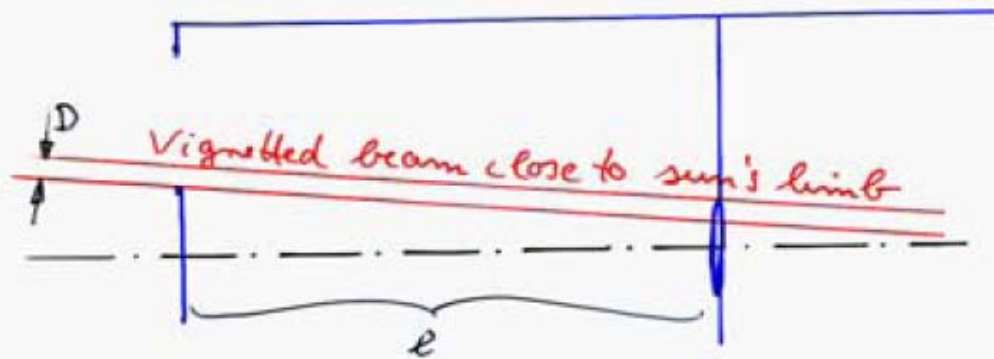
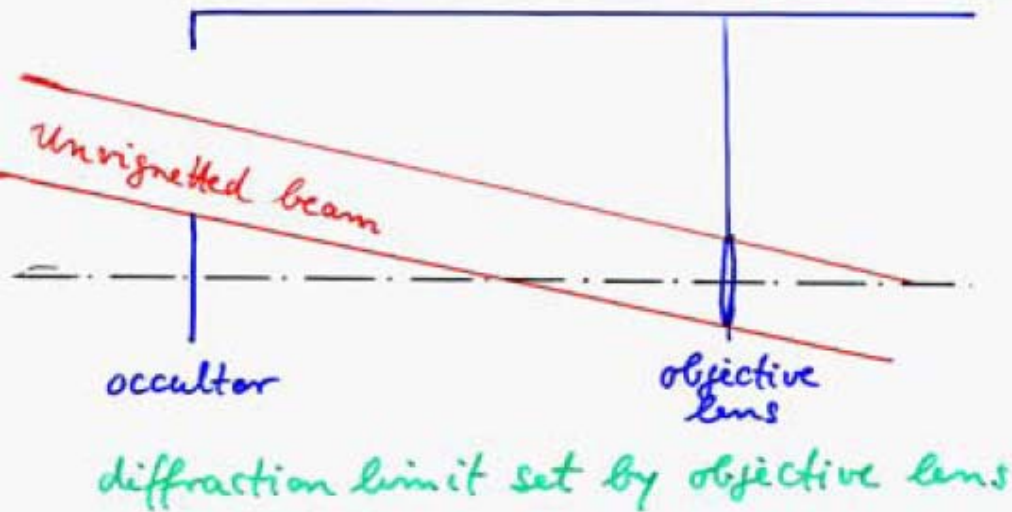
(F) Fraunhofer corona

- absorption lines visible
- not polarized:
dusk scattering
- Zodiac light...

(L) Line corona

- emission lines:
e.g.: "green coronal line"
- emission of atoms / ions:
new elements?
helium, "coronium"

Diffraction limit for externally occulted coronagraph



for the inner field of view, the diffraction limit is set by distance and size of external occulter.

$$\sin \theta_{\min} = 1.22 \cdot \frac{\lambda}{D}$$

Diffraction limit of spatial resolution

The problem with external occultation in coronagraphs of limited size: For regions close to the limb there is substantial vignetting.

External occulter systems are perfect to view the outer corona, but suffer from vignetting near the inner edge (loss of spatial resolution).

Wait for solar eclipse!
Formation flying spacecraft!

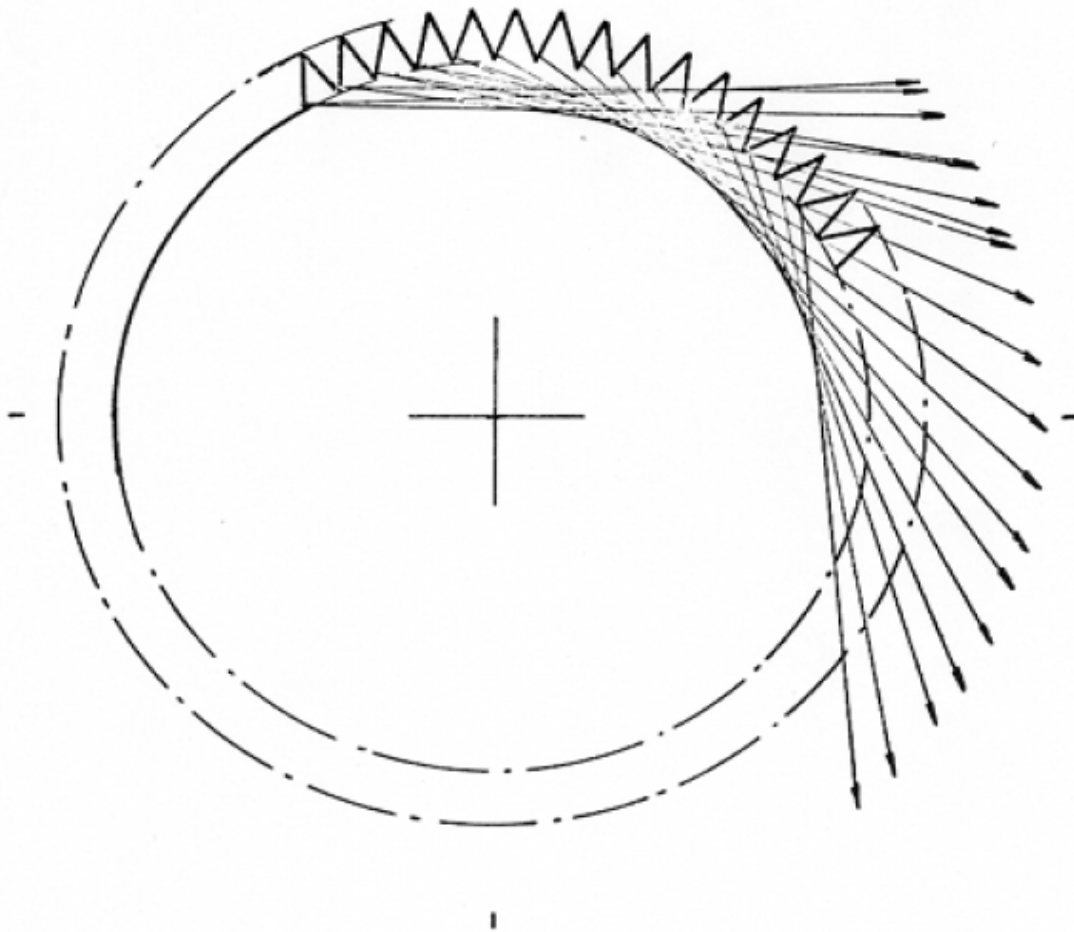
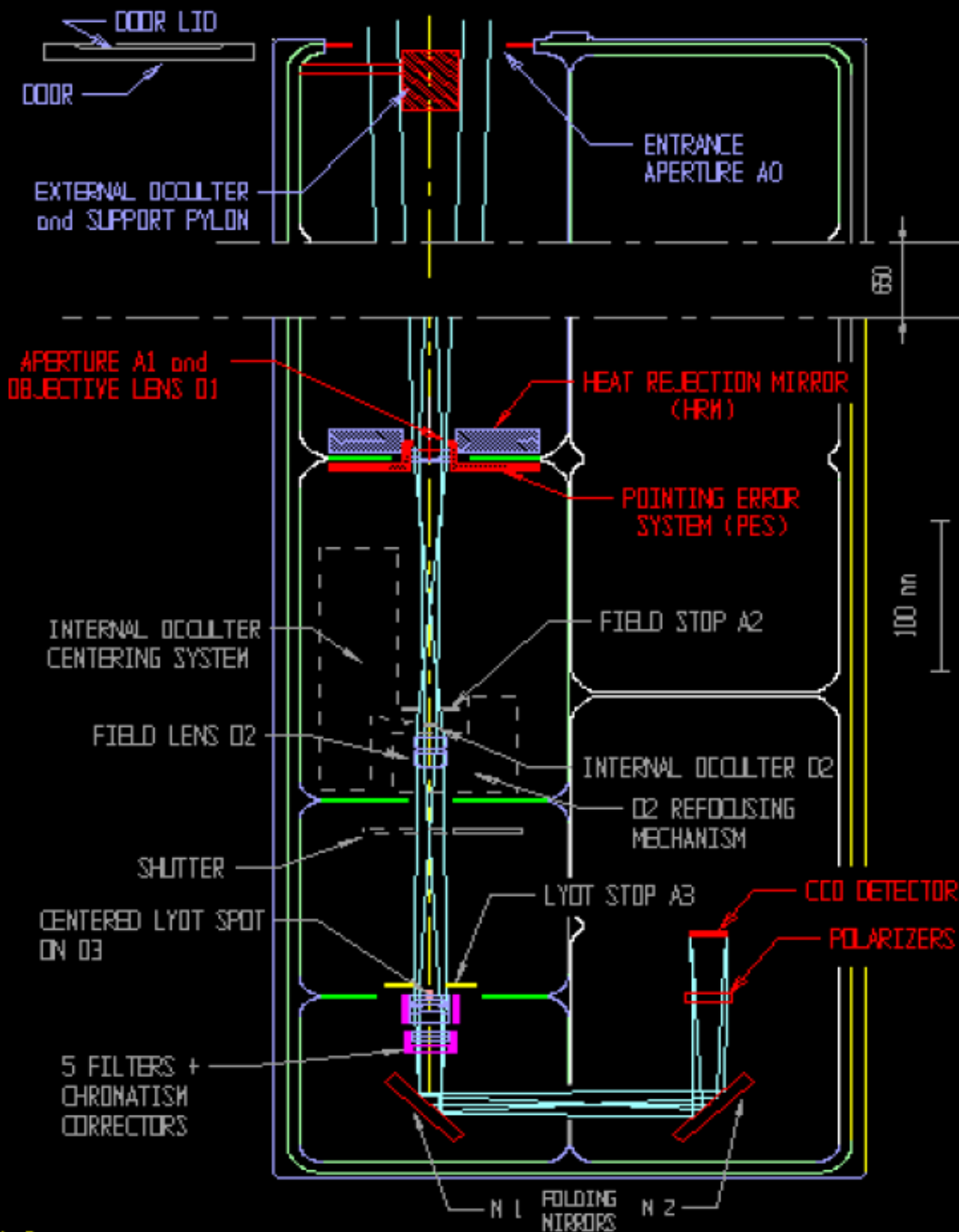


Fig. 7. Direction of diffracted parallel light from the periphery of a sawtooth disk or serrated edge (from Purcell and Koomen, 1962). The incident beam is perpendicular to the plane of the figure and the directions of the diffracted rays are shown in projection on the plane of the figure, so they do not reach the optical system of a coronagraph.

Straylight reduction by a serrated occulter:
diffracted rays have a component to leave the optical system

EUV Spectroscopy

LASCO C2

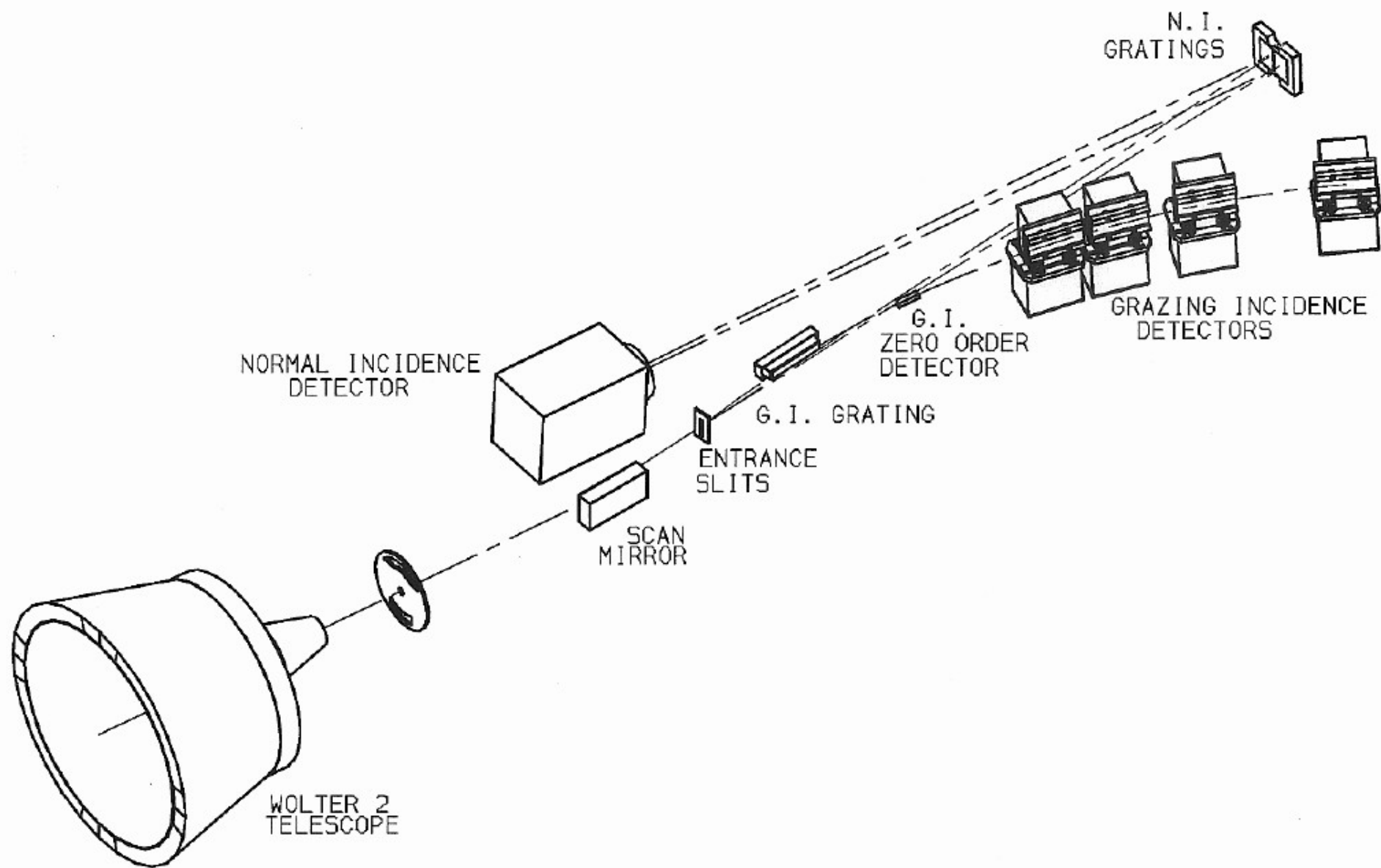


The problem of internally occulted systems:

the full illumination leads to

- straylight of the aperture and the main mirror

- heat



CDS OPTICS