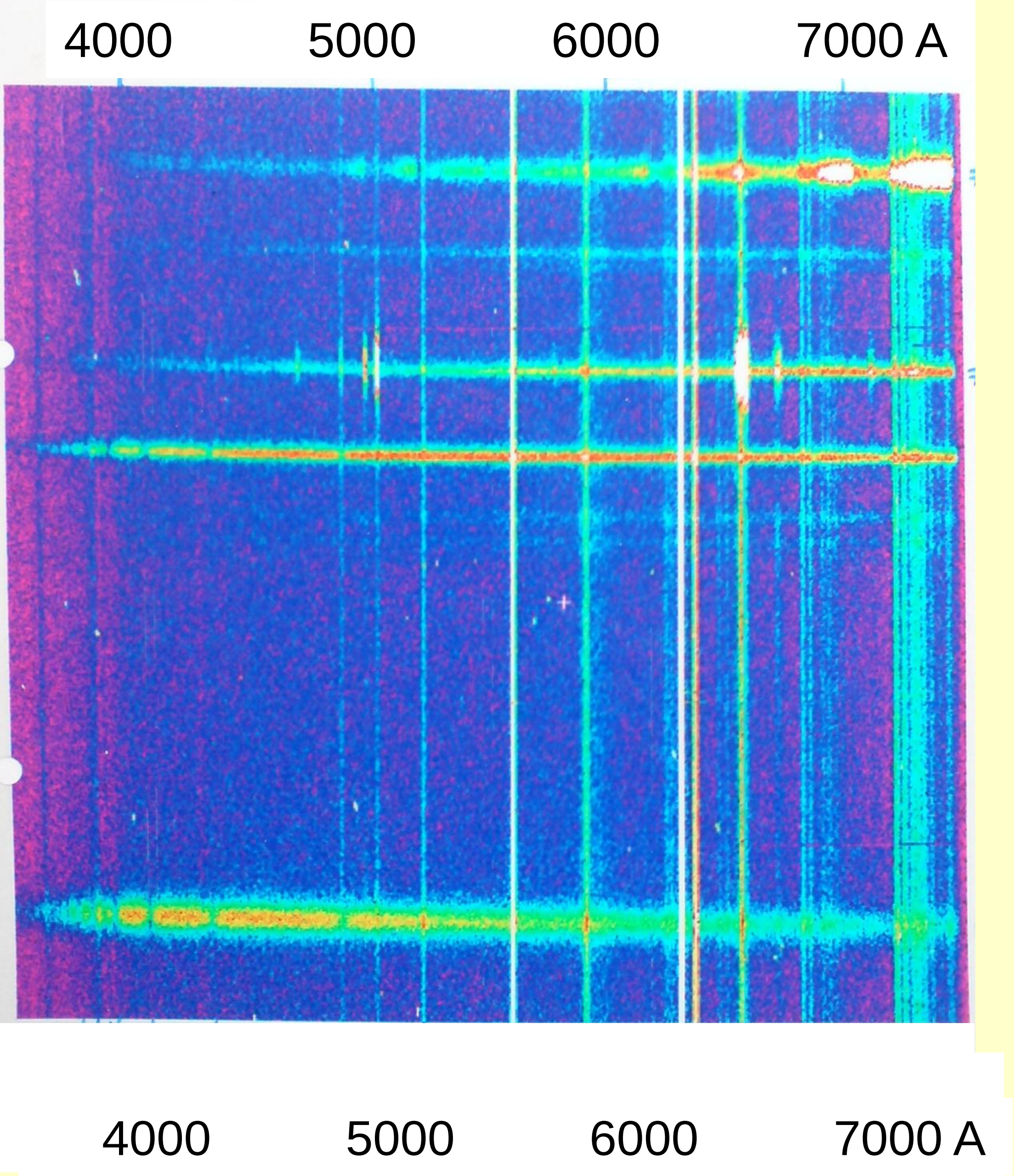
Evolution of Galaxies:
Abundances from stars

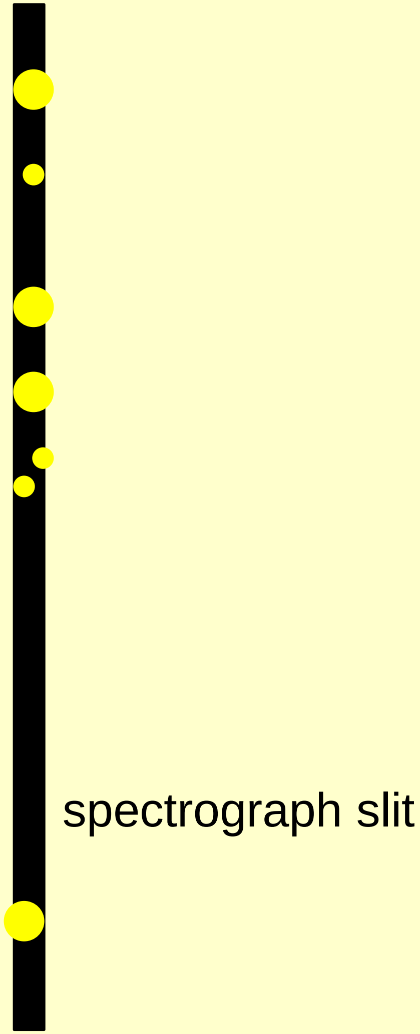
Observatoire astronomique
de Strasbourg

J.Köppen joachim.koppen@astro.unistra.fr

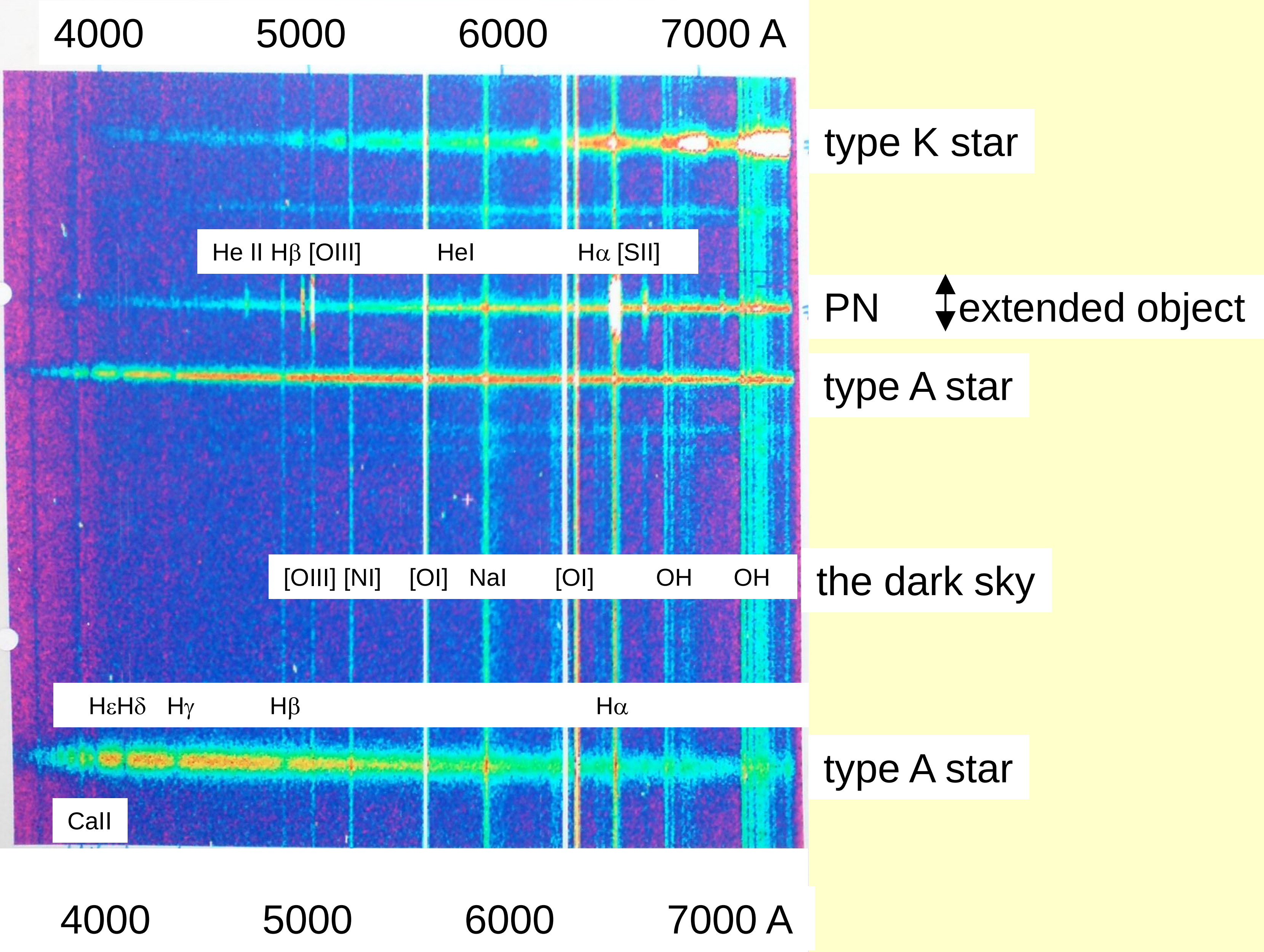
http://astro.u-strasbg.fr/~koppen/JKHome.html

CCD image with spectra of several objects

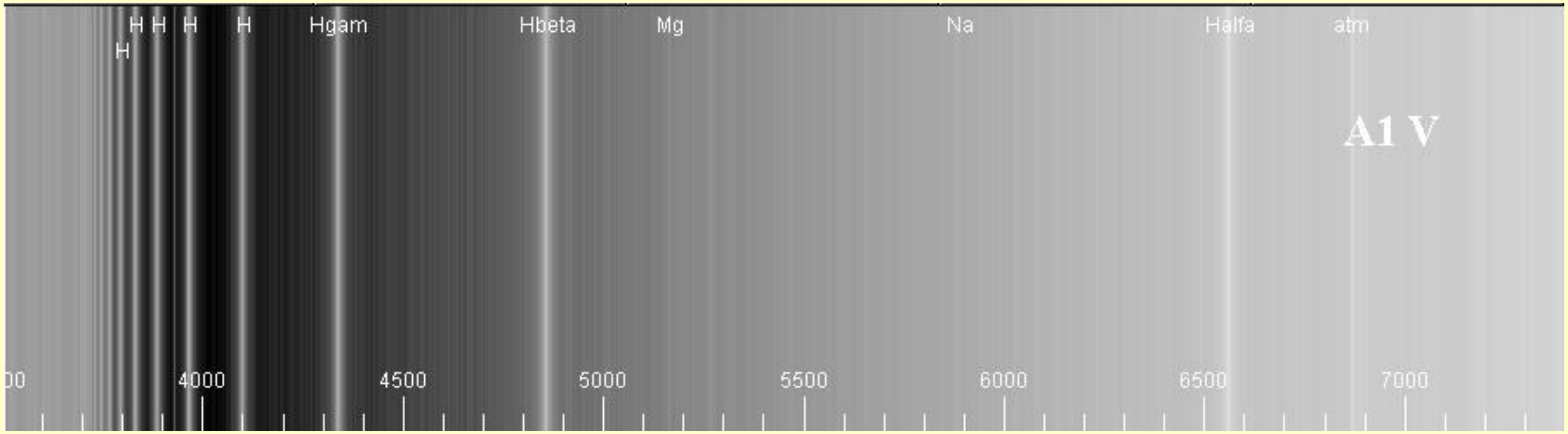


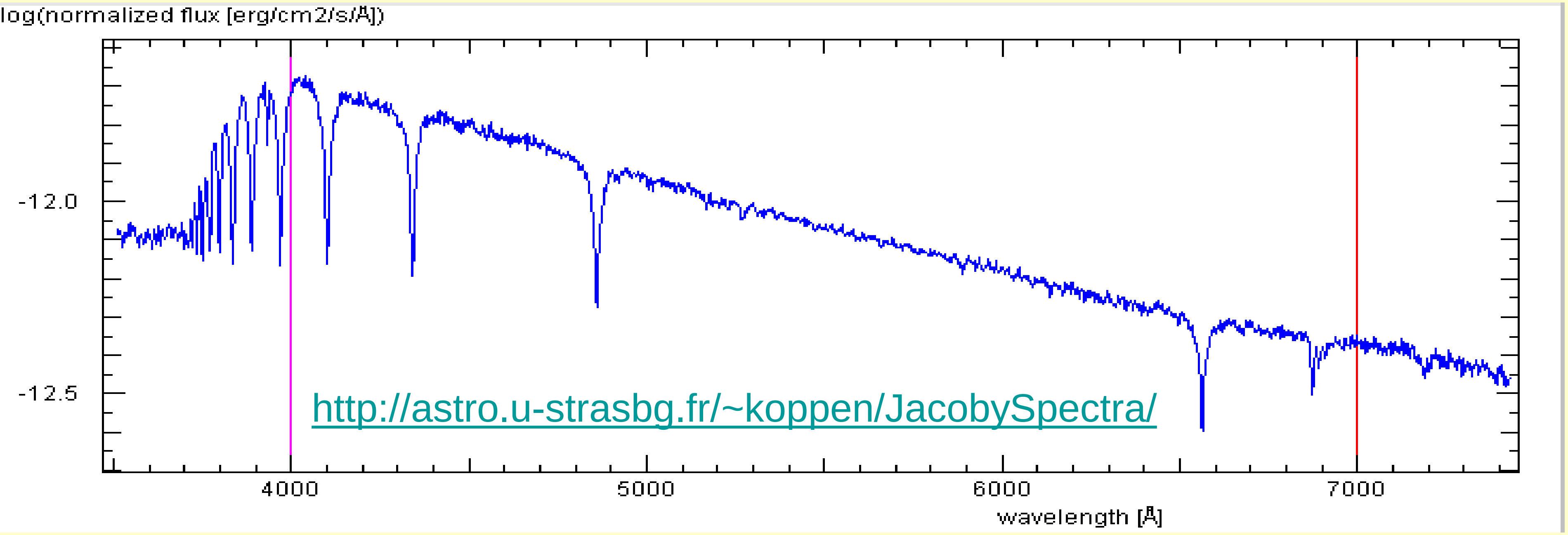


CCD image with spectra of several objects



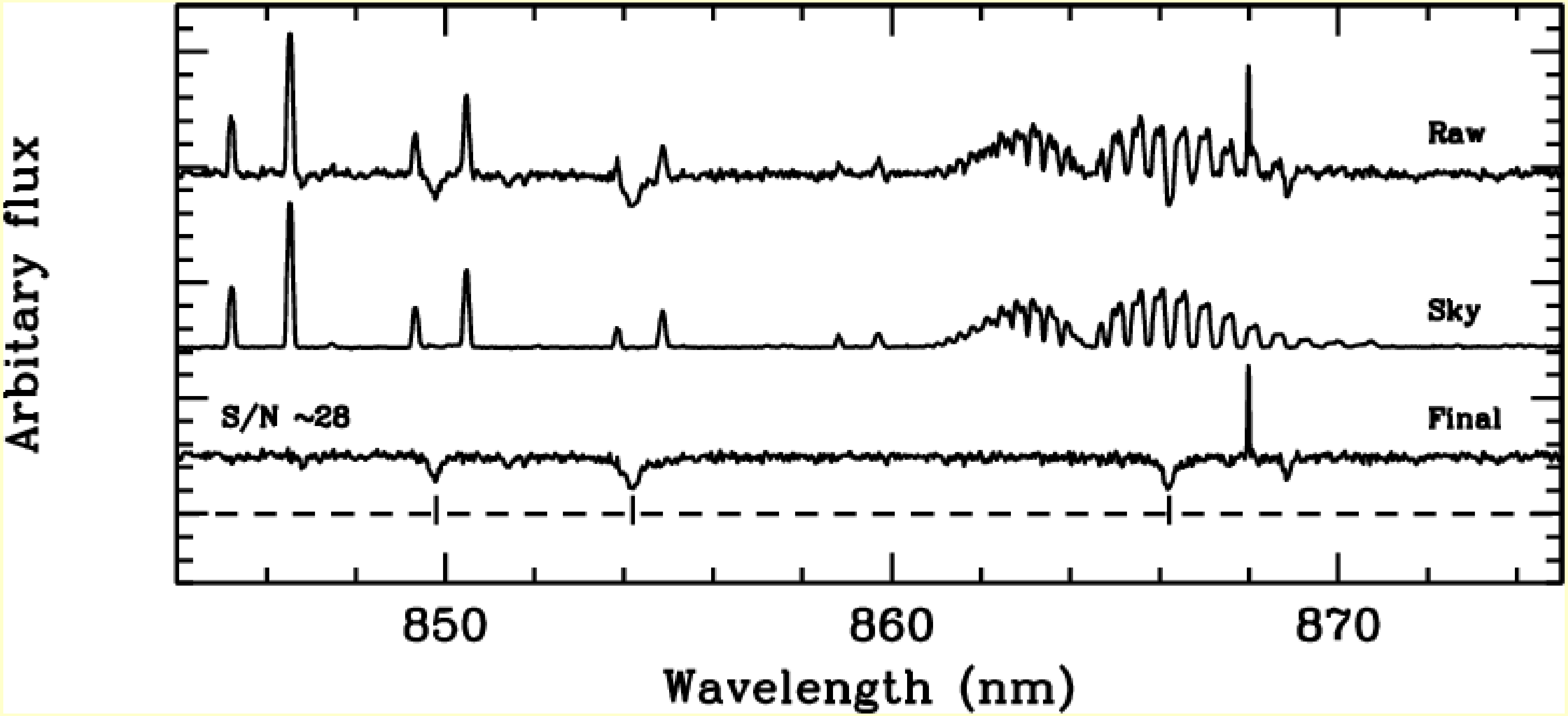
To get a stellar spectrum …



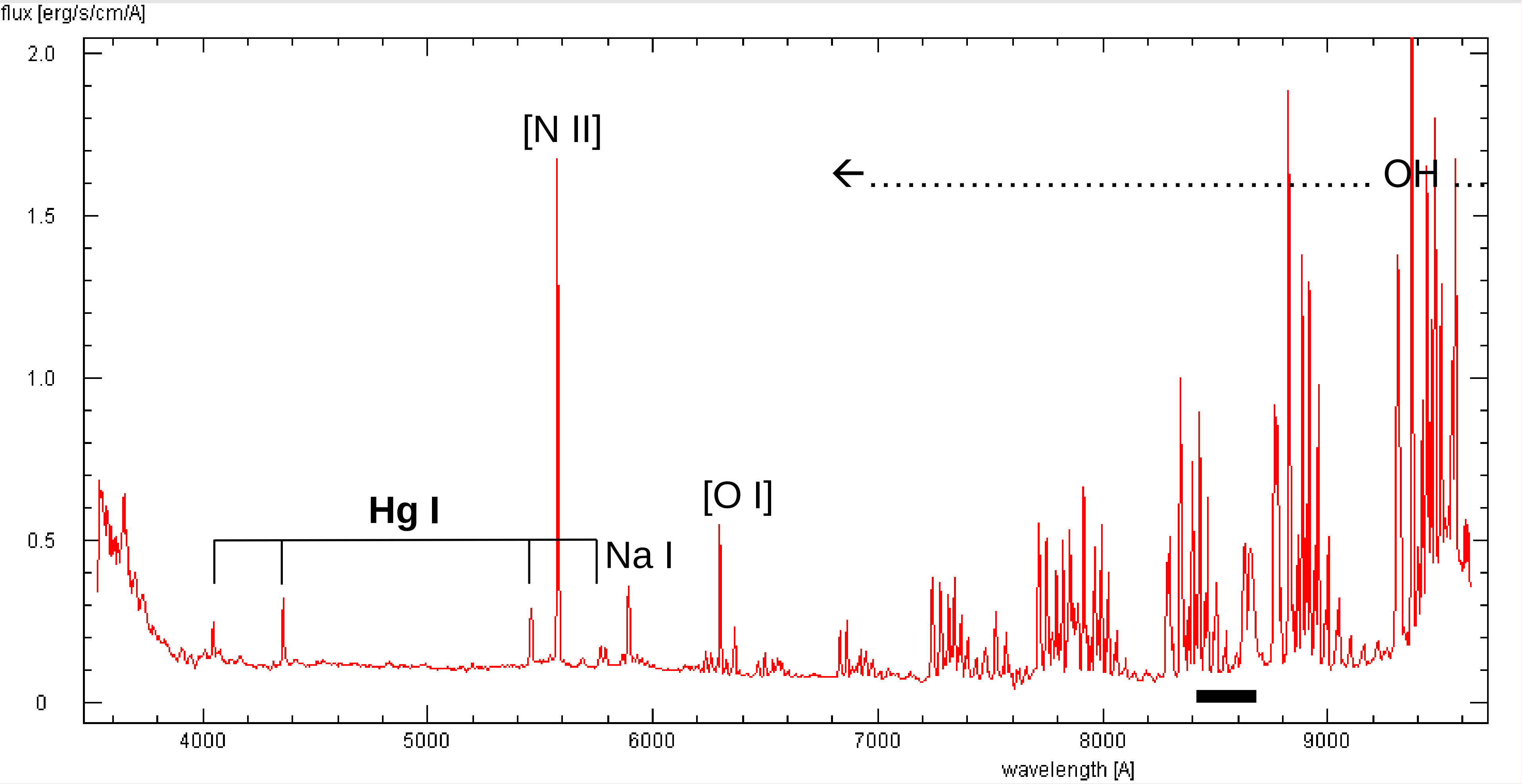


http://astro.u-strasbg.fr/~koppen/JacobySpectra/

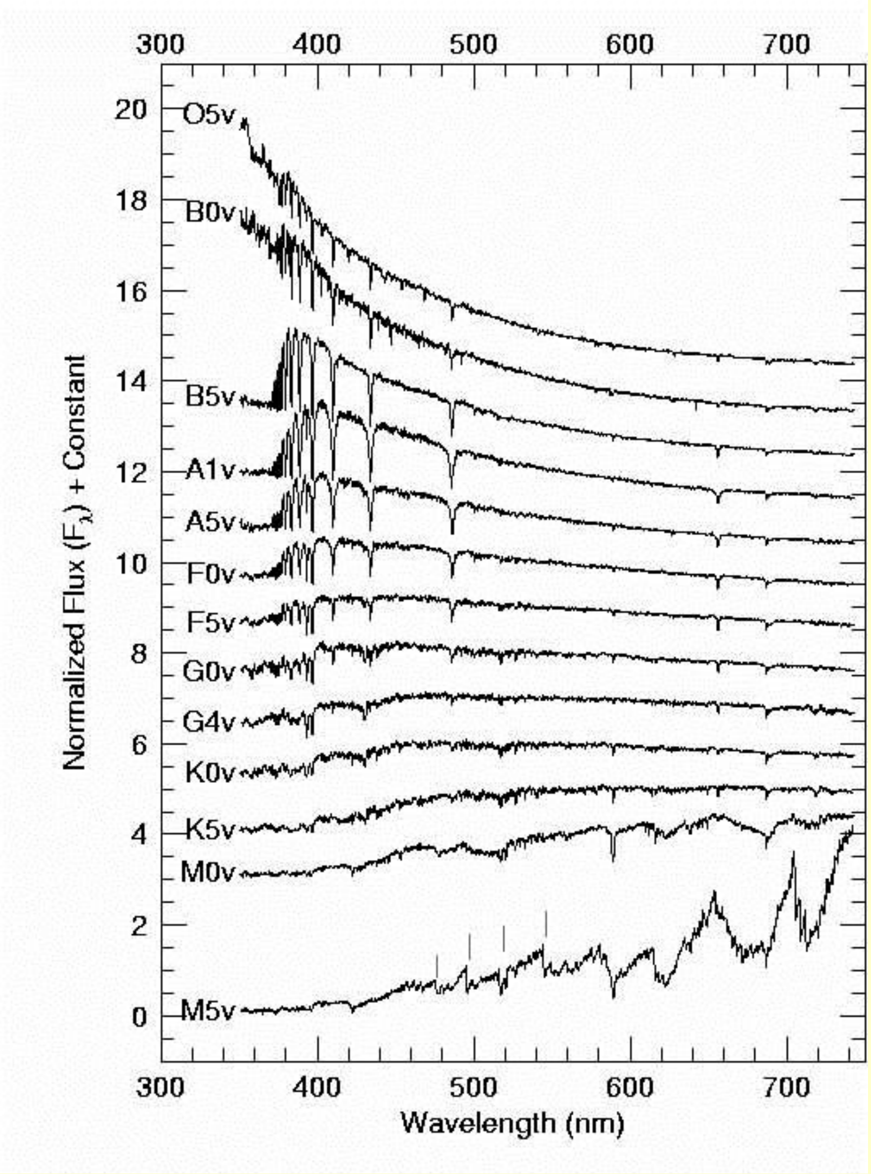
… the raw data needs to be processed



Spectrum of the dark sky



Stellar spectra … spectral class



O: HeII lines

B: HeI lines

A: HI lines strongest

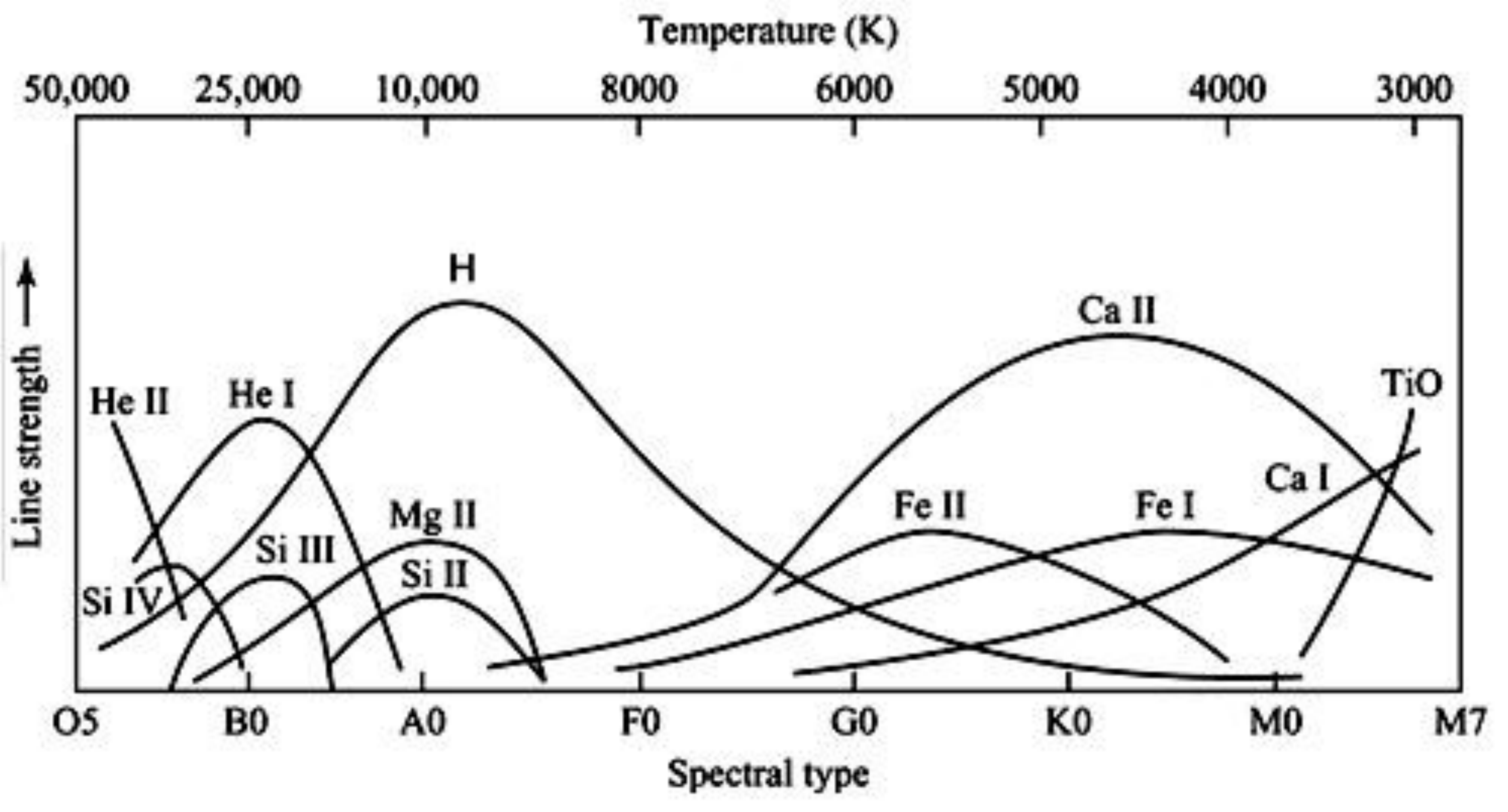
F: H+K,FeII

G: H+K,FeI,FeII

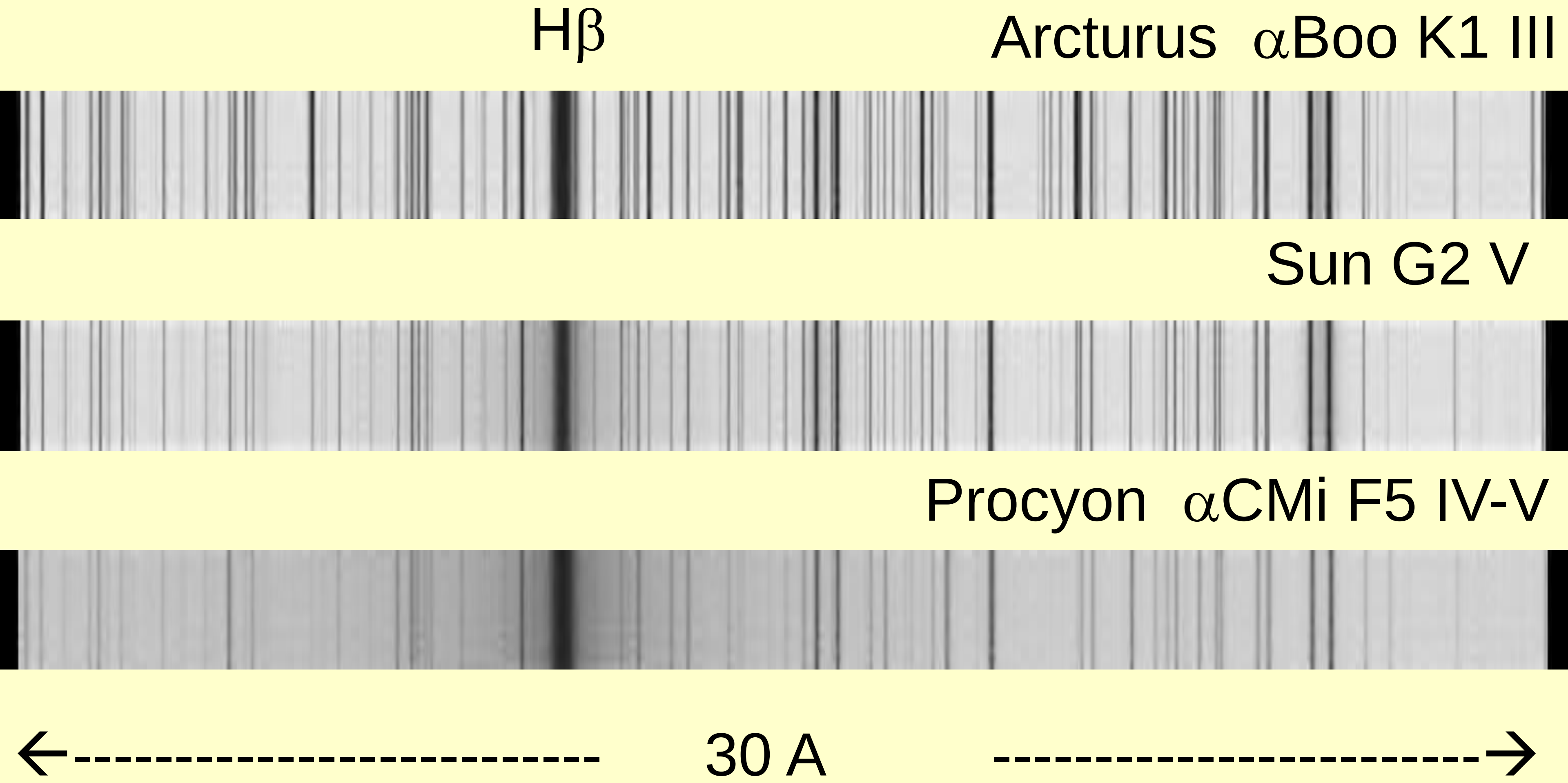
K: H+K strongest

M: TiO bands

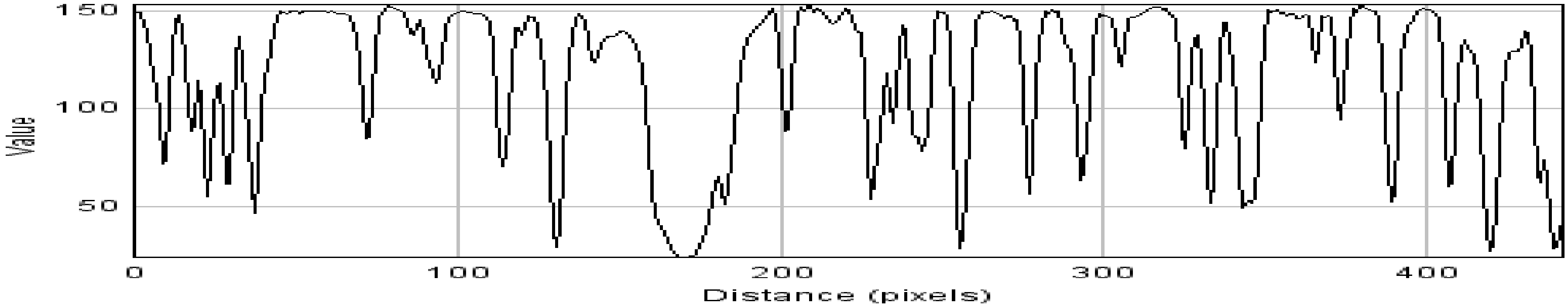
Spectral class & temperature



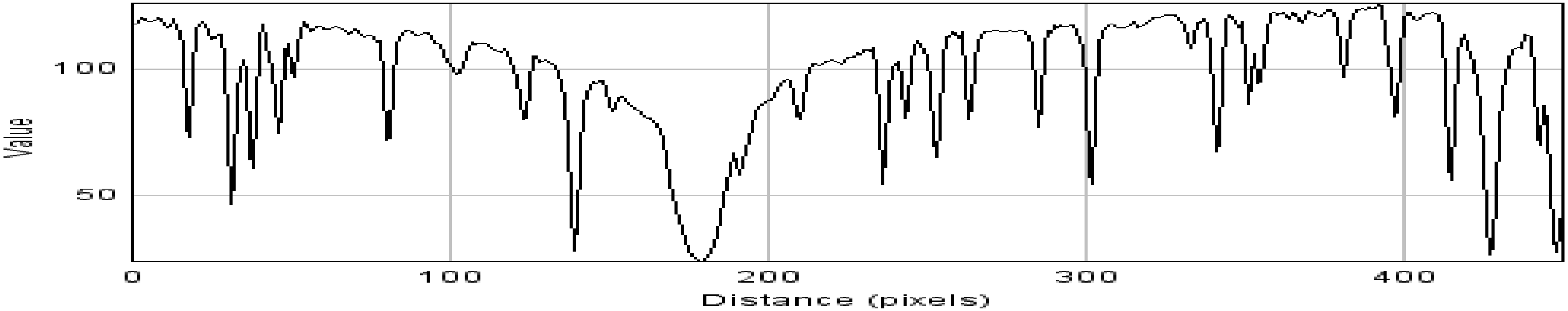
Three stars



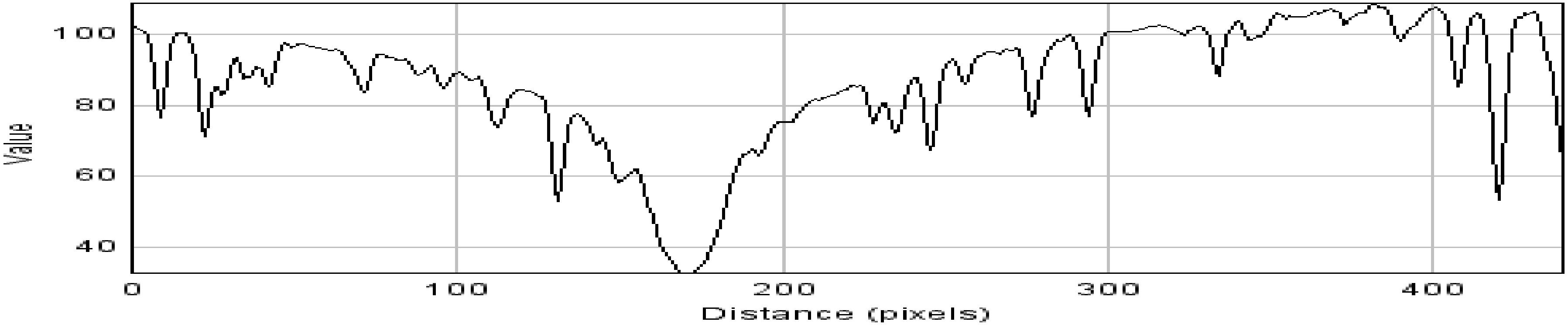
Hβ Arcturus αBoo K1 III



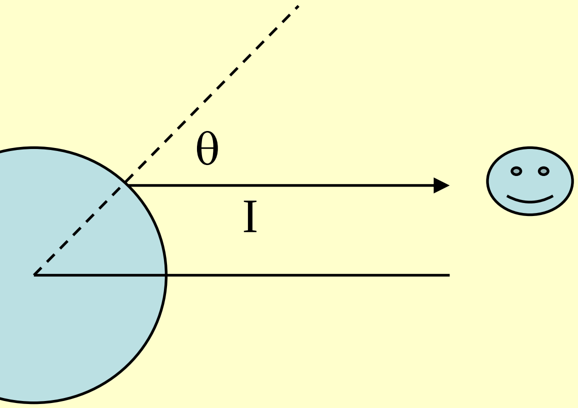
Sun G2 V



Procyon αCMi F5 IV-V

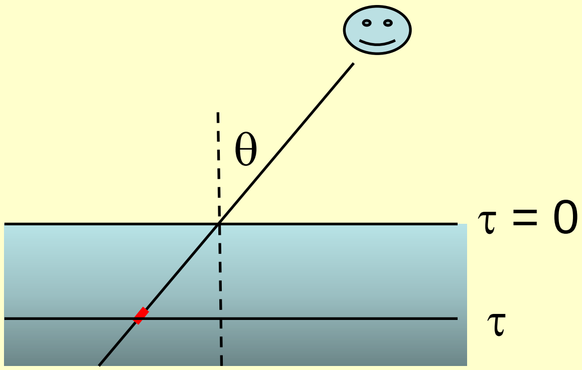


Lines form in stellar atmosphere



Integration over stellar disk gives observed flux

$$F(\Delta\lambda) = \frac{1}{2}\int_0^{\pi/2} I(\Delta\lambda,\theta)\cos\theta\, d\theta$$



Intensity from plane-parallel approx.

$$I(\Delta\lambda,\theta) = \int_0^{\infty} S(\tau(\Delta\lambda))\, e^{-\tau(\Delta\lambda)/\mu} d\theta/\mu$$

$$\mu = \cos\theta$$

Optical depth of layer below the ‘surface’

$$\tau(\Delta\lambda) = \int_0^t \kappa(t,\Delta\lambda)dt$$

N.B.: strictly speaking, $\tau = 0$ is at our eye!

Source function S

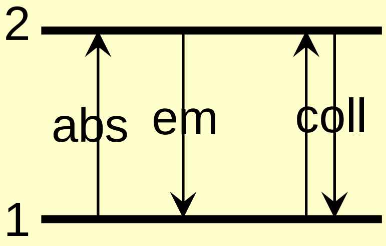
describes emission from layer τ ... $\tau+\Delta\tau$

$$S(\lambda,\tau) = \frac{j(\lambda,\tau)}{\kappa(\lambda,\tau)}$$

Approximation of **L**ocal **T**hermodynamic **E**quilibrium

$$= B\big(\lambda, T(\tau)\big)$$ T-stratification

In general (NLTE)



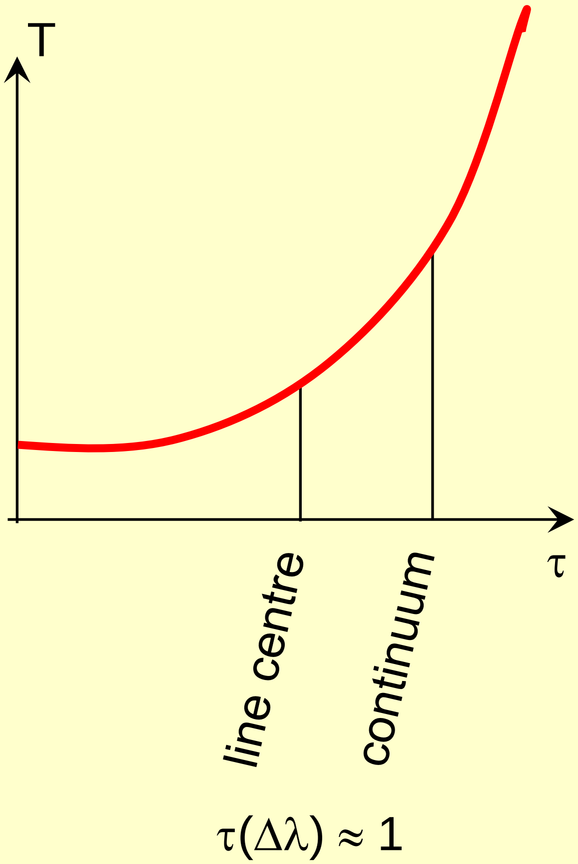
$$= \frac{n_2 A_{21}}{n_1 B_{12} - n_2 B_{21}} = B\big(\lambda, T_{12}(\tau)\big)$$

$n_1, n_2 = f(\tau)$ stratification of level populations

Excitation temperature:

$$\frac{n_2}{n_1} = \frac{g_2}{g_1}\exp(-\frac{E_{12}}{kT_{12}})$$

Temperature decrease upwards



Approximatively:

$$I(\Delta\lambda) \approx S(\tau(\Delta\lambda) \approx 1)$$

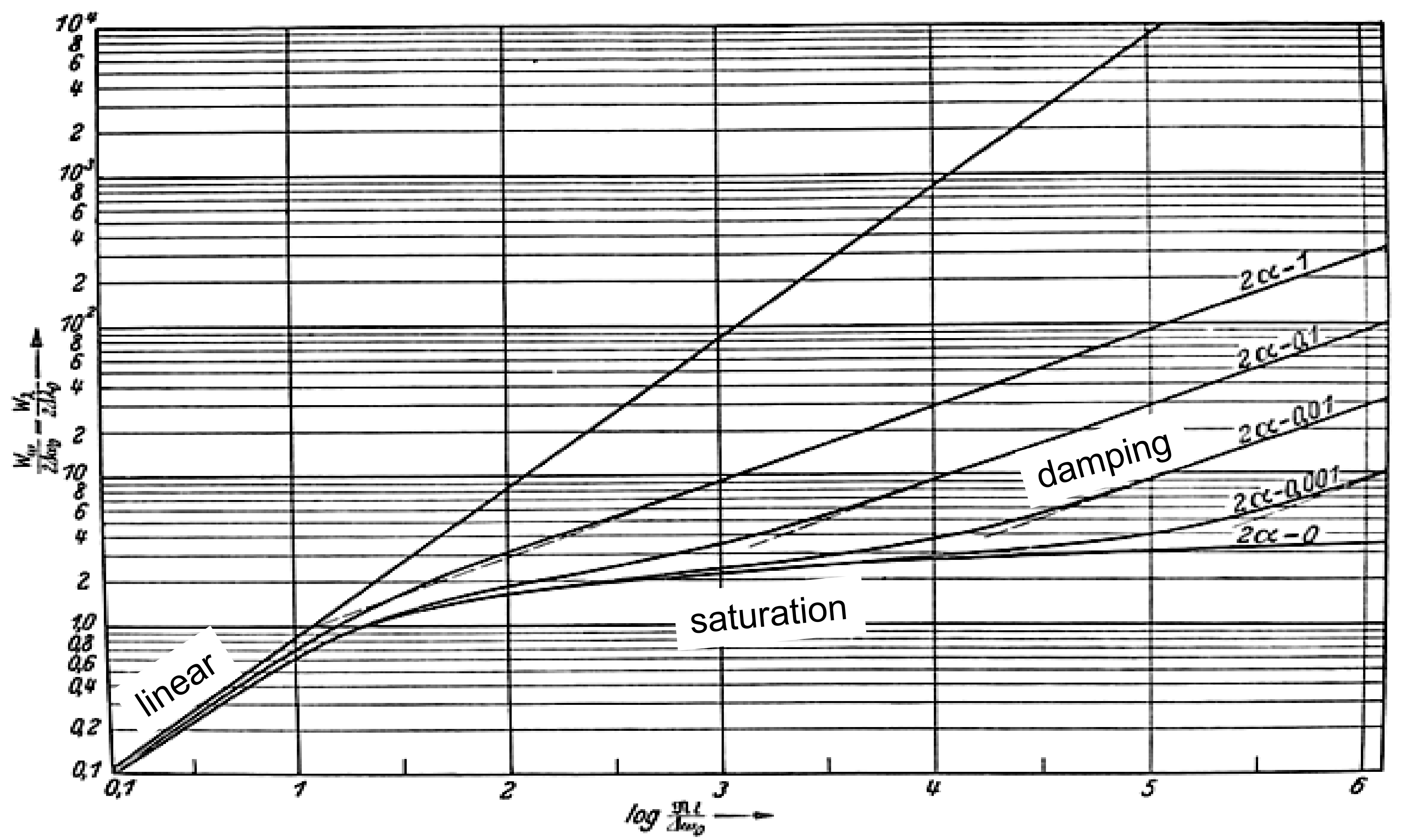
Line centre: has higher absorption ➔ τ=1 occurs higher up in atmosphere

➔lower emission (lower T)

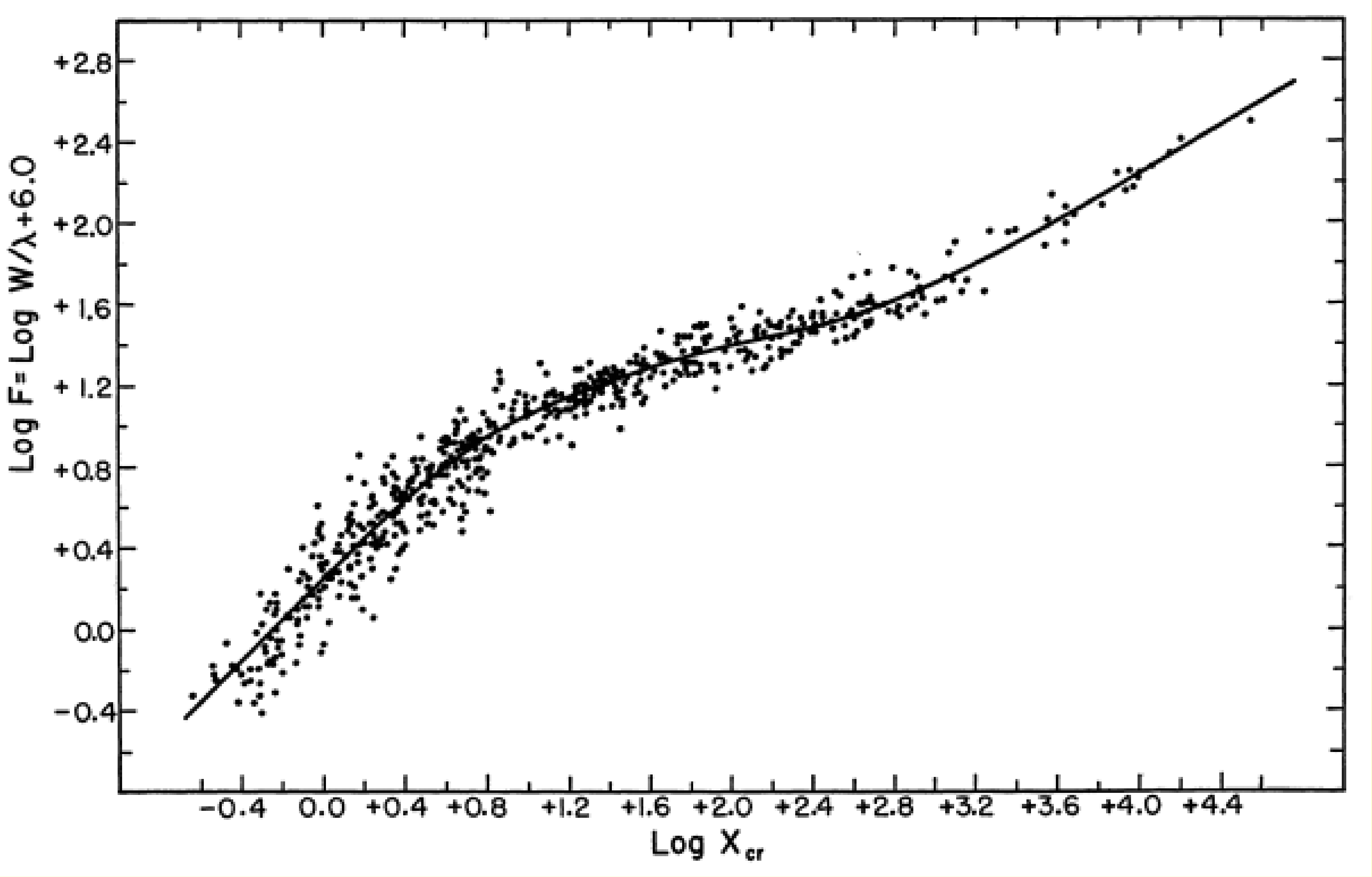
➔line centre darker (‘absorption’)

Equivalent width increases with column density in a **Curve of Growth**

Theoretical COGs



Empirical COG of the Sun (FeI)



Cowley 1964

Stellar spectrum analysis

- COG method (classic):
  - Take empirical COG from similar star or from a model
  - By matching the COGs to observations determine the column densities of all ions and elements
  - Use thermodynamic laws (Boltzmann, Saha) to determine effective temperature and elemental abundances

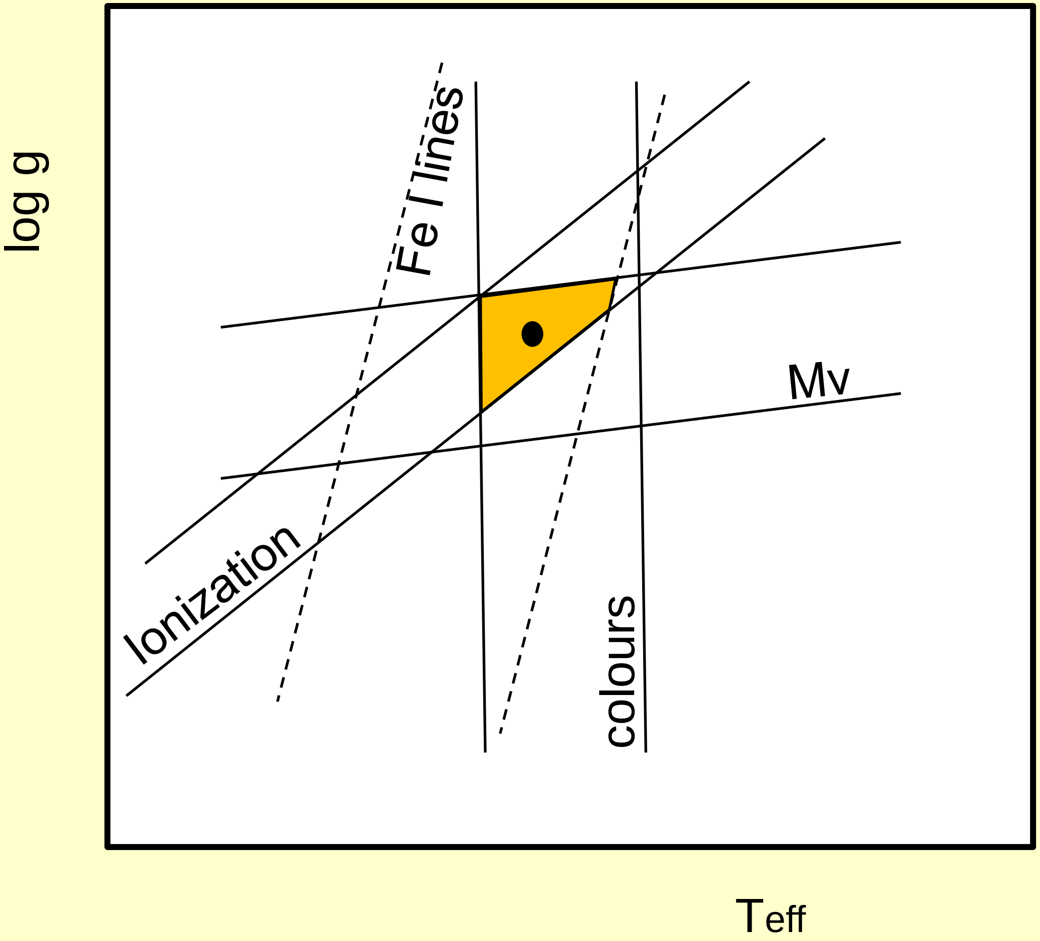
Stellar spectrum analysis

- Model atmosphere approach
  - Get Teff from photometric colours, continuum slope
  - Get log(g) from fitting wings of strong lines (high density ➔ damping ➔ wings)
  - Set elemental abundances
  - Compute model atmosphere (ATLAS: LTE + planar) which gives stratification of n, T, ionisation …
  - Use line formation code to compute
    - line equivalent widths, profiles …
    - Synthetic spectrum
  - compare with observations

Adjust
T, log g,
abundances

Fine tuning
of abundances

Constraints by all observed data determine model (T,g)



Stellar spectrum analysis

Fitting requirement: for a consistent model the same abundances must be obtained by all lines of

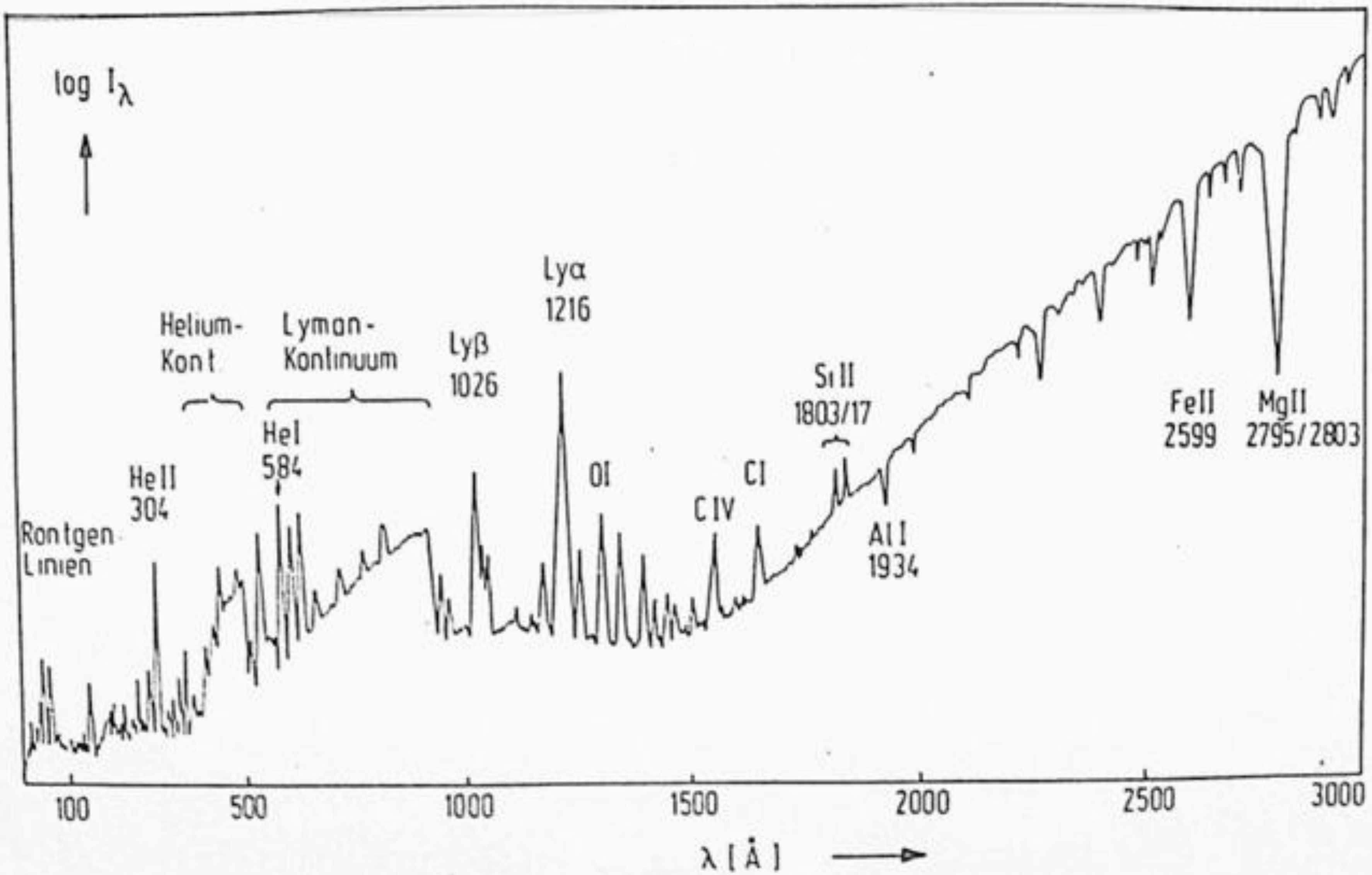
- the same ion
- the same element

independent of the equivalent width, the oscillator strength f, the energy of the lower level, …

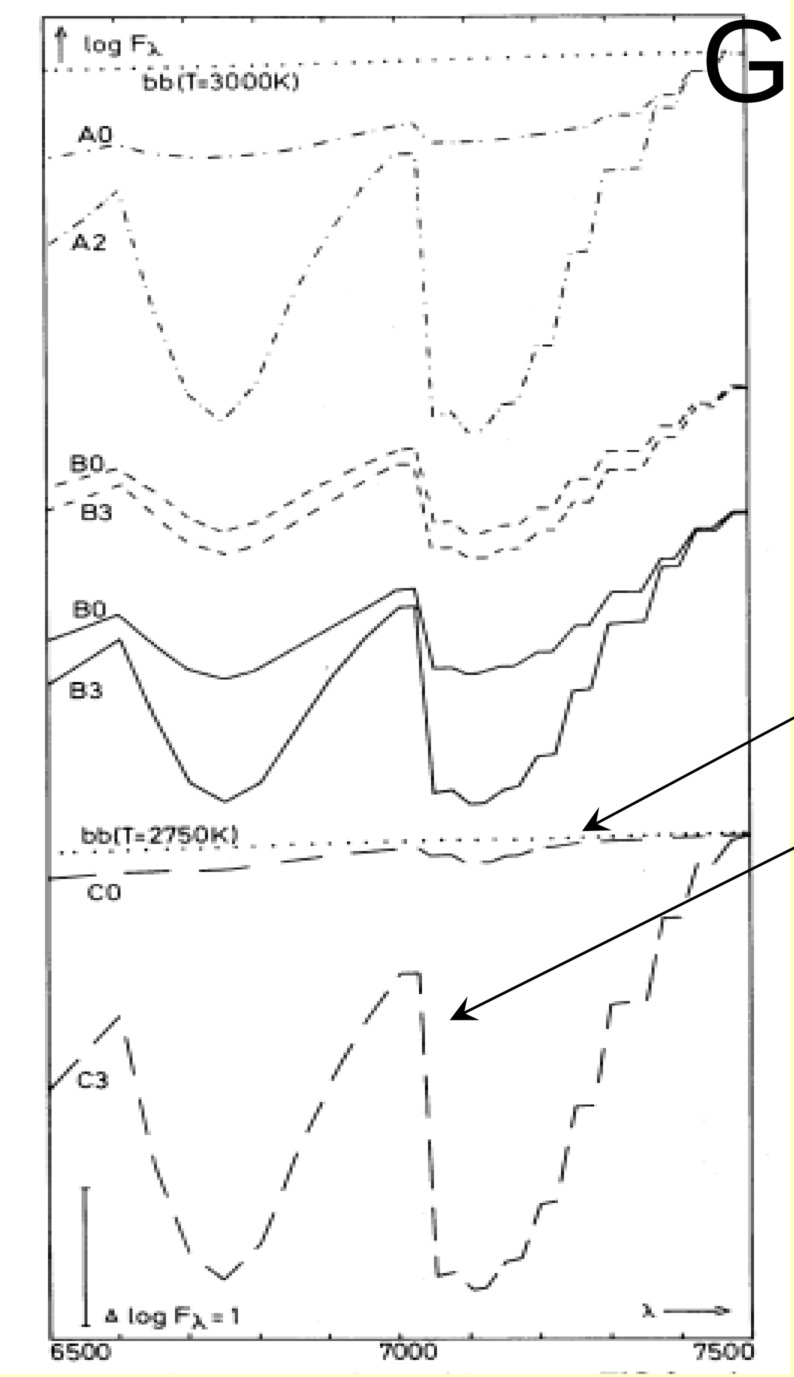
Problems & Difficulties

- Saturation: better observe weak lines (needs high S/N!)
- uncertain f-values
- NLTE is necessary:
  - Hot stars T>25000 K
  - Lines that form high in atmosphere (low density): OI lines in A*
- Rotation: non-spherical stars, Teff varies over surface
- Emission components: circumstellar (HII, PN), chromosphere, corona (UV, Xray)

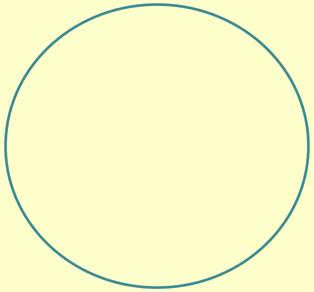
Solar Xray and UV spectrum



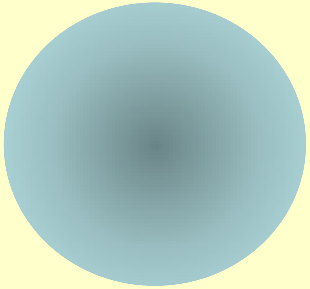
Giants have extended atmospheres



Plan-parallel model



Extended atmosphere model



Schmid-Burgk 1981

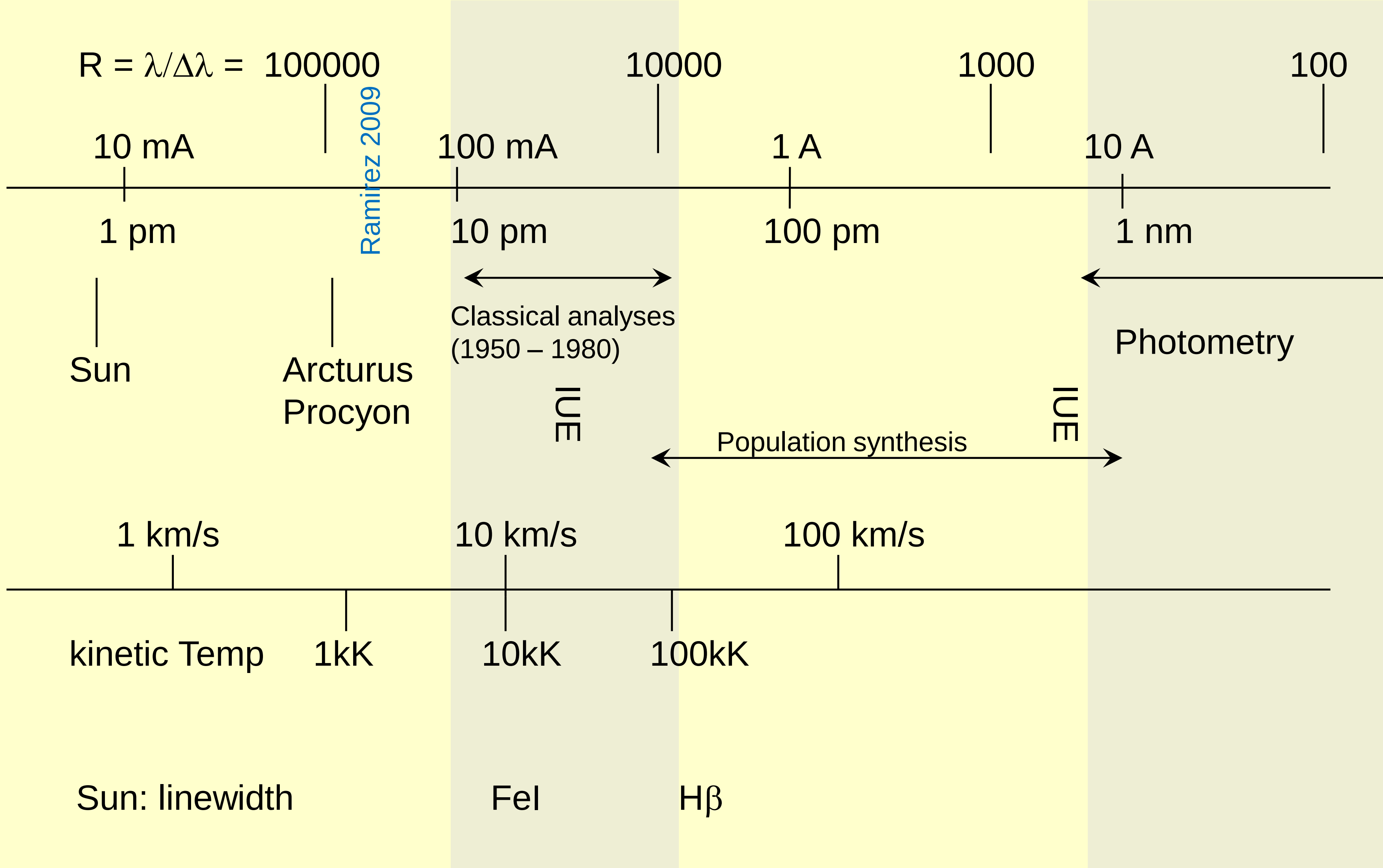
Problems & Difficulties

- Extended atmospheres
- Microturbulence ξ remains a fudge parameter!
- Chemically inhomogeneous atmospheres, starspots, …

Accuracy: better than 0.3 dex is possible

NB: **differential analysis** of similar stellar spectra is possible, and detects small differences

Spectral resolution (~5000 A)



R = λ/Δλ = 100000 10000 1000 100

10 mA 100 mA 1 A 10 A

1 pm 10 pm 100 pm 1 nm

Ramirez 2009

Sun

Arcturus
Procyon

Classical analyses
(1950 – 1980)

IUE

Population synthesis

IUE

Photometry

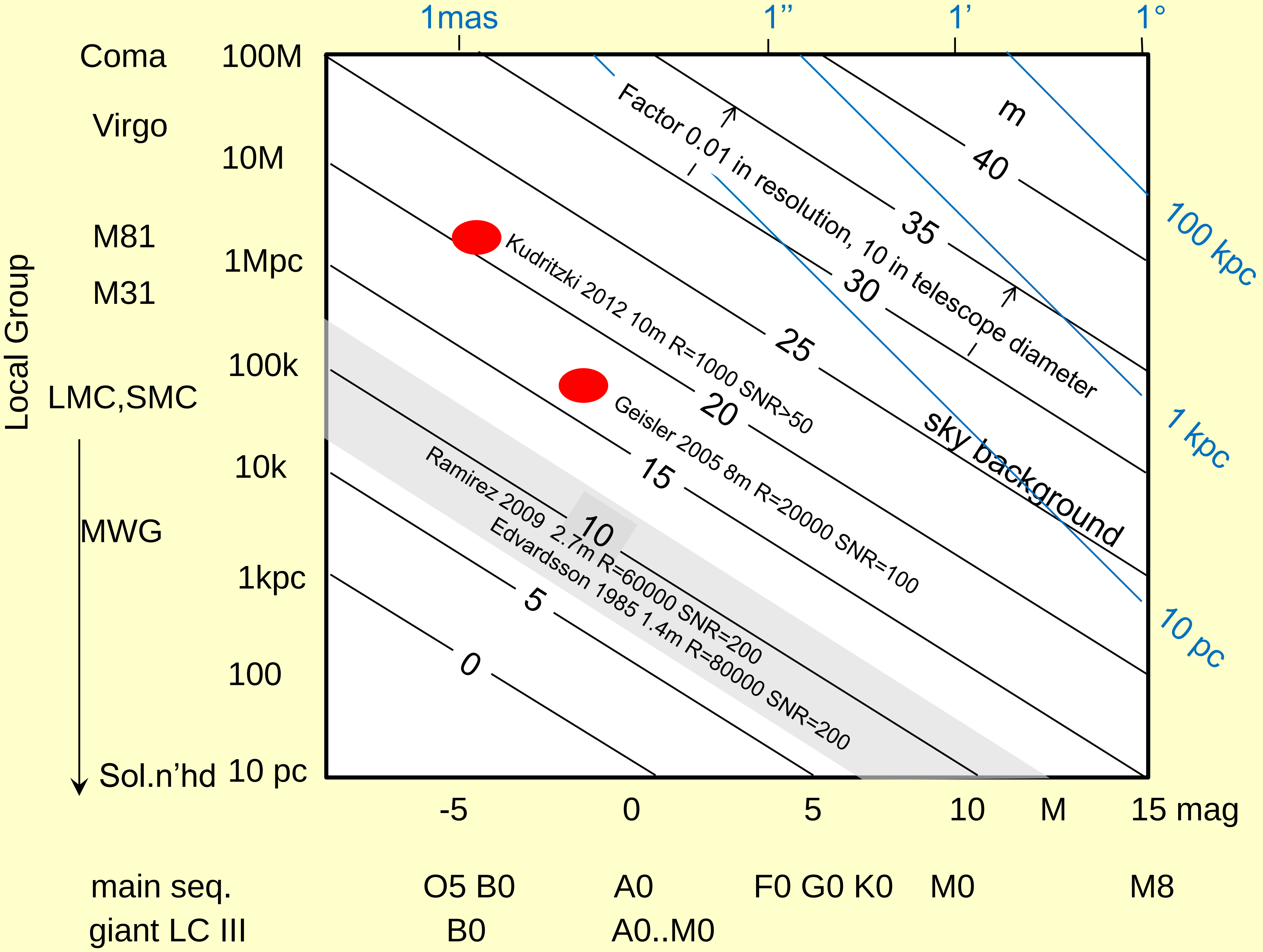
1 km/s 10 km/s 100 km/s

kinetic Temp 1kK 10kK 100kK

Sun: linewidth

FeI

Hβ



1mas
1”
1’
1°
Coma
Virgo
M81
M31
Local Group
LMC,SMC
MWG
Sol.n’hd
100M
10M
1Mpc
100k
10k
1kpc
100
10 pc
m
40
35
30
25
20
15
10
5
0
Factor 0.01 in resolution, 10 in telescope diameter
sky background
Kudritzki 2012 10m R=1000 SNR>50
Geisler 2005 8m R=20000 SNR=100
Ramirez 2009 2.7m R=60000 SNR=200
Edvardsson 1985 1.4m R=80000 SNR=200
100 kpc
1 kpc
10 pc
-5
0
5
10
M
15 mag
main seq.
O5 B0
A0
F0 G0 K0
M0
M8
giant LC III
B0
A0..M0

Methods for more distant stars

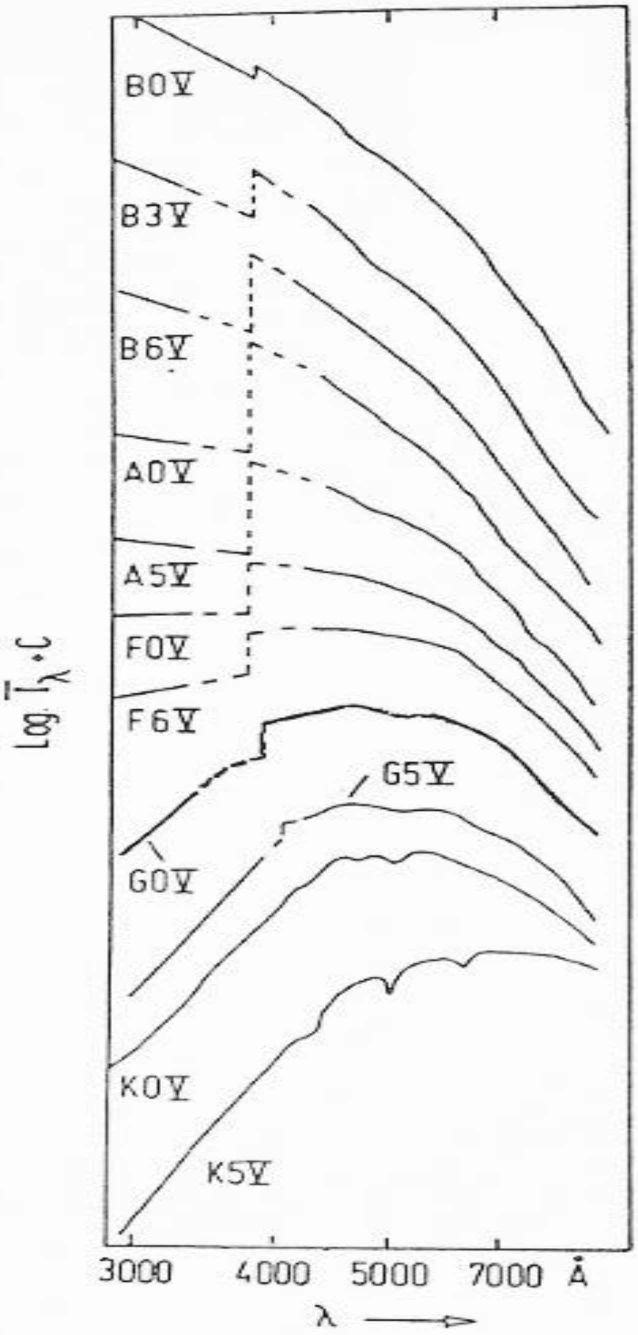
- Spectroscopy needs good S/N → limited range
- Integrated spectra of entire stellar population
  - + no angular resolution needed
  - -- modeling of population required
- Photometric methods (single stars / stellar pop.)

principle: elements like Fe, Ni, Ti, V, … have complex level diagrams with many lines in optical and UV.

Higher metallicity →more absorption → depression of continuum → detectable in intermediate and narrowband photometry

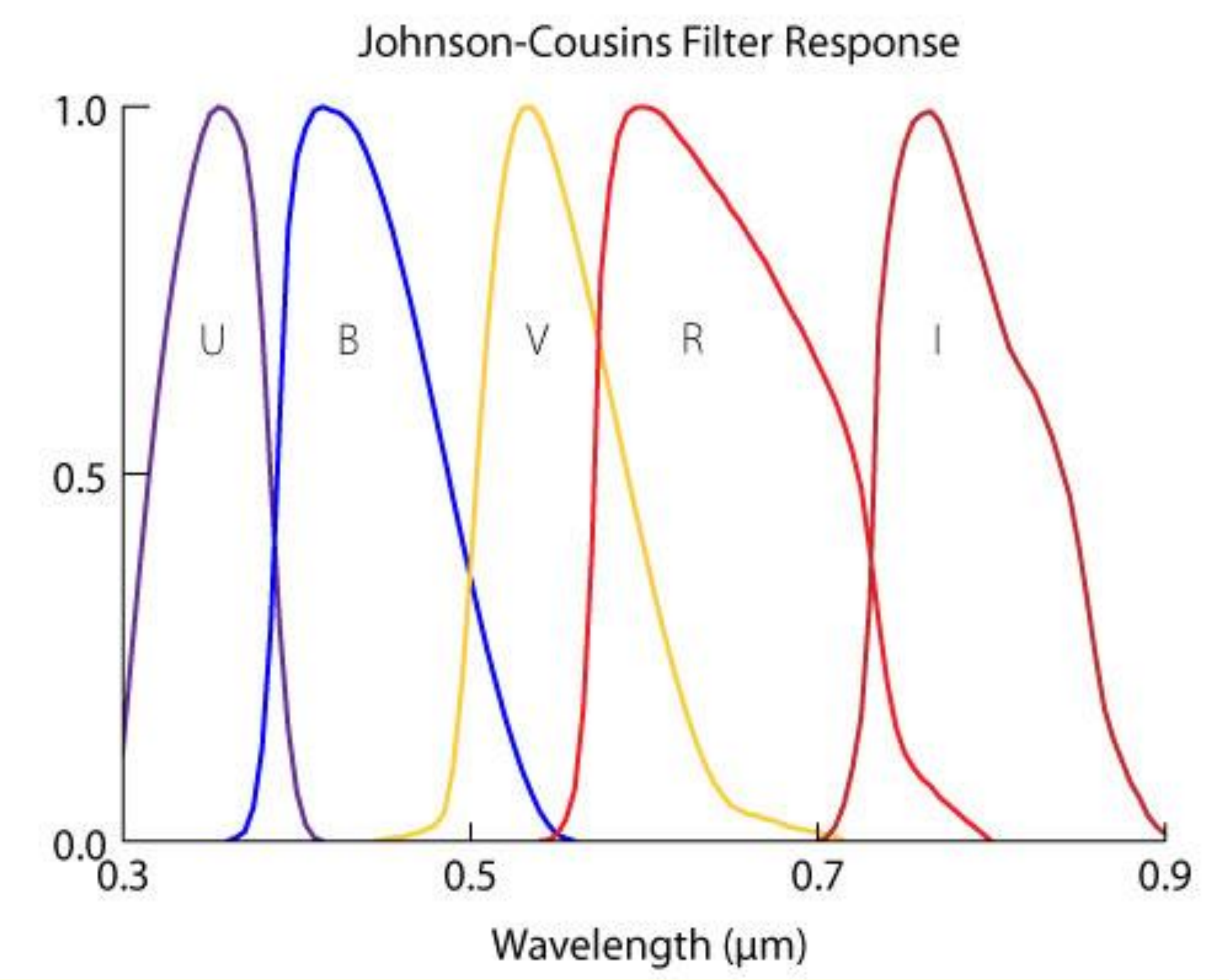
How to get parameters

- Effective temperature: from continuum slope, Balmer jump (hot stars), Balmer line strength in FG*
- log g or L: Balmer lines (hot stars), Balmer jump&molecule features in FGK*
- [Fe/H]: Johnson $\lambda/\Delta\lambda$~5, Geneva 10, Strömgren 40, DDO (Toronto), Lick $\Delta\lambda=8$A



Slope (=colour) of the Spectral Energy Distribution (SED) indicates temperature

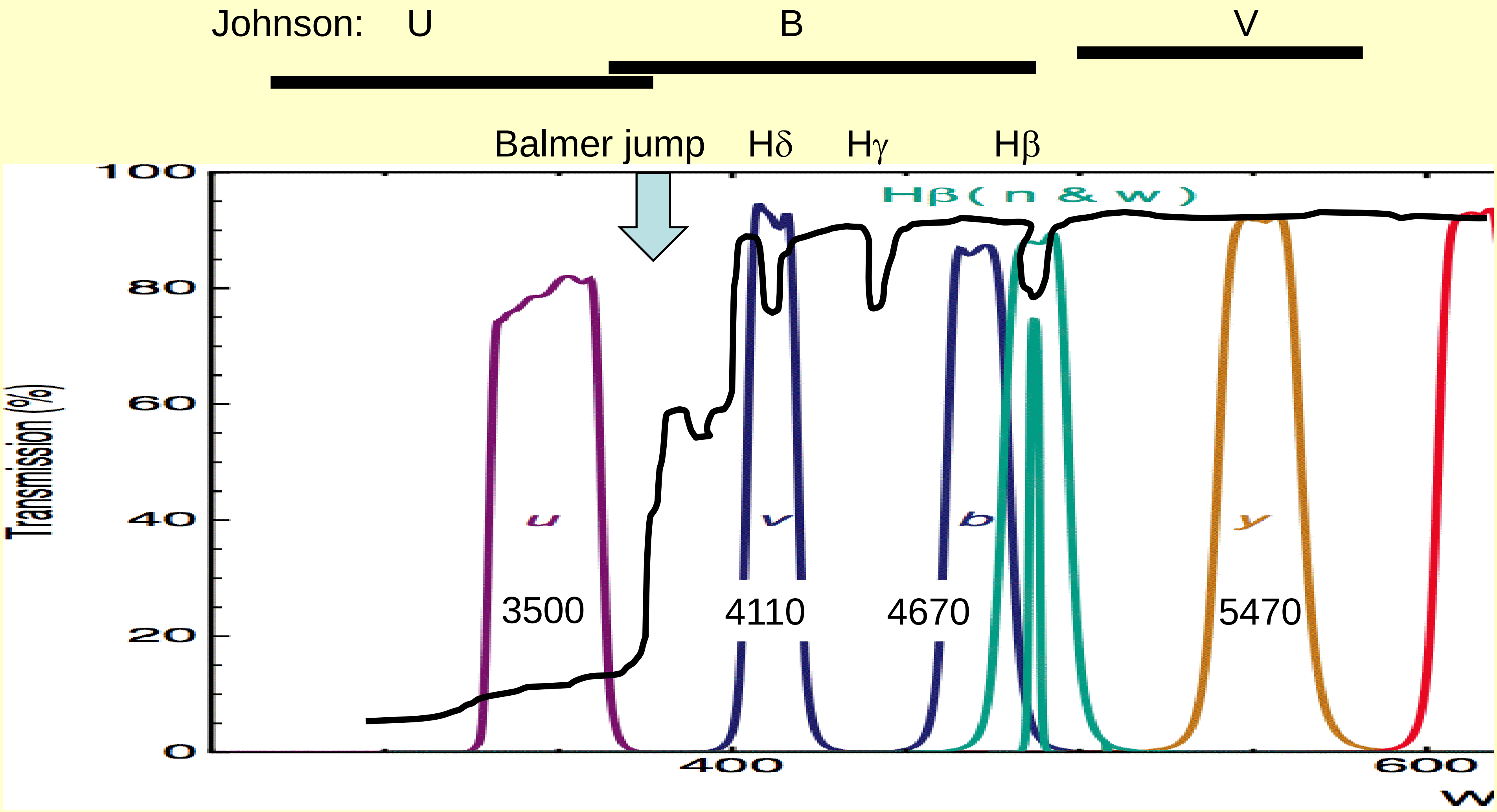
Johnson UBVRI



Central wavelengths:

U	365 nm
B	440
V	548
R	0.7 µm
I	0.9
J	1.25
H	1.63
K	2.2
L	3.6
M	5.0
N	10.6
Q	21

Strömgren photometry

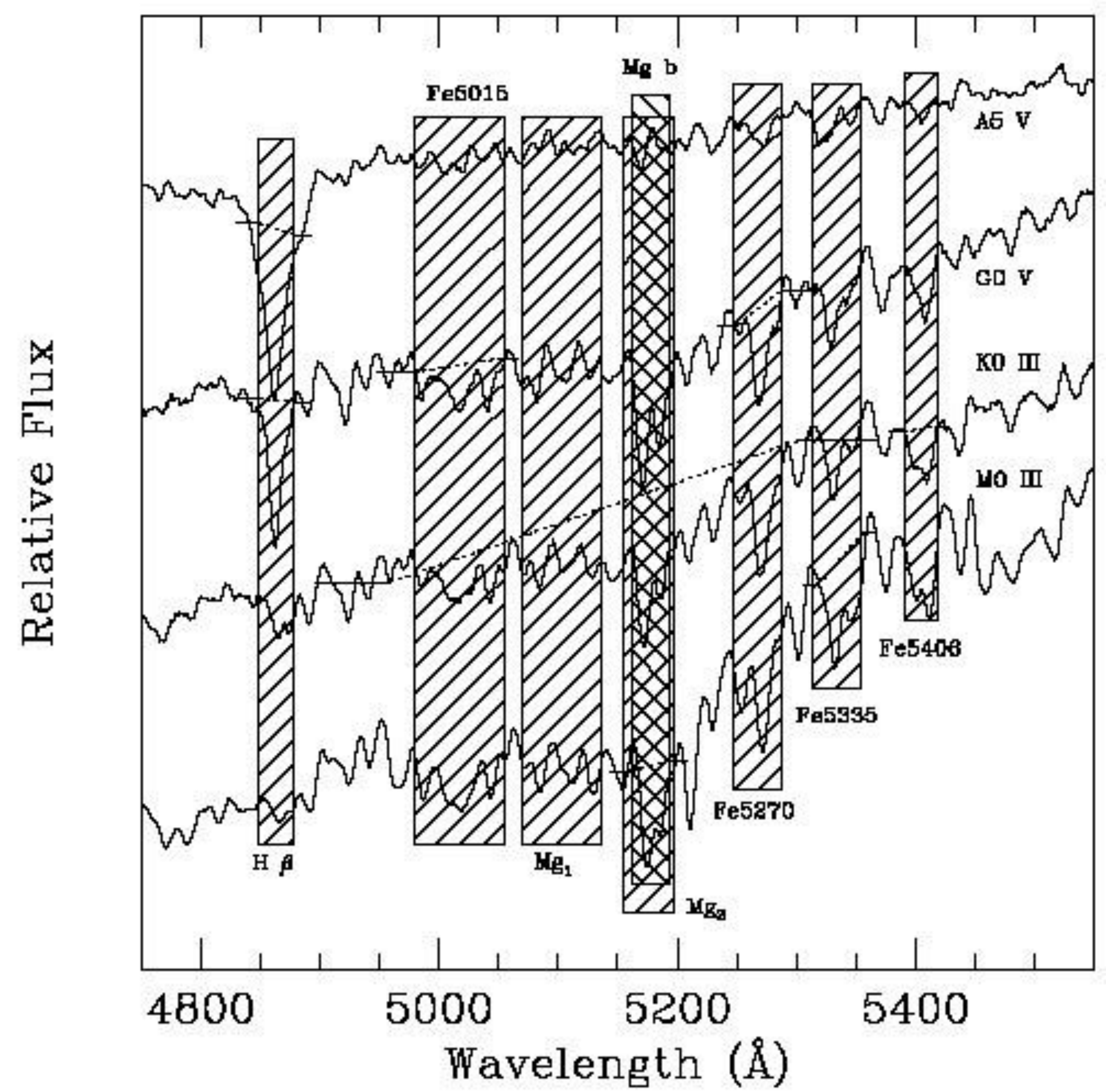


Johnson: U B V

Balmer jump Hδ Hγ Hβ

3500 4110 4670 5470

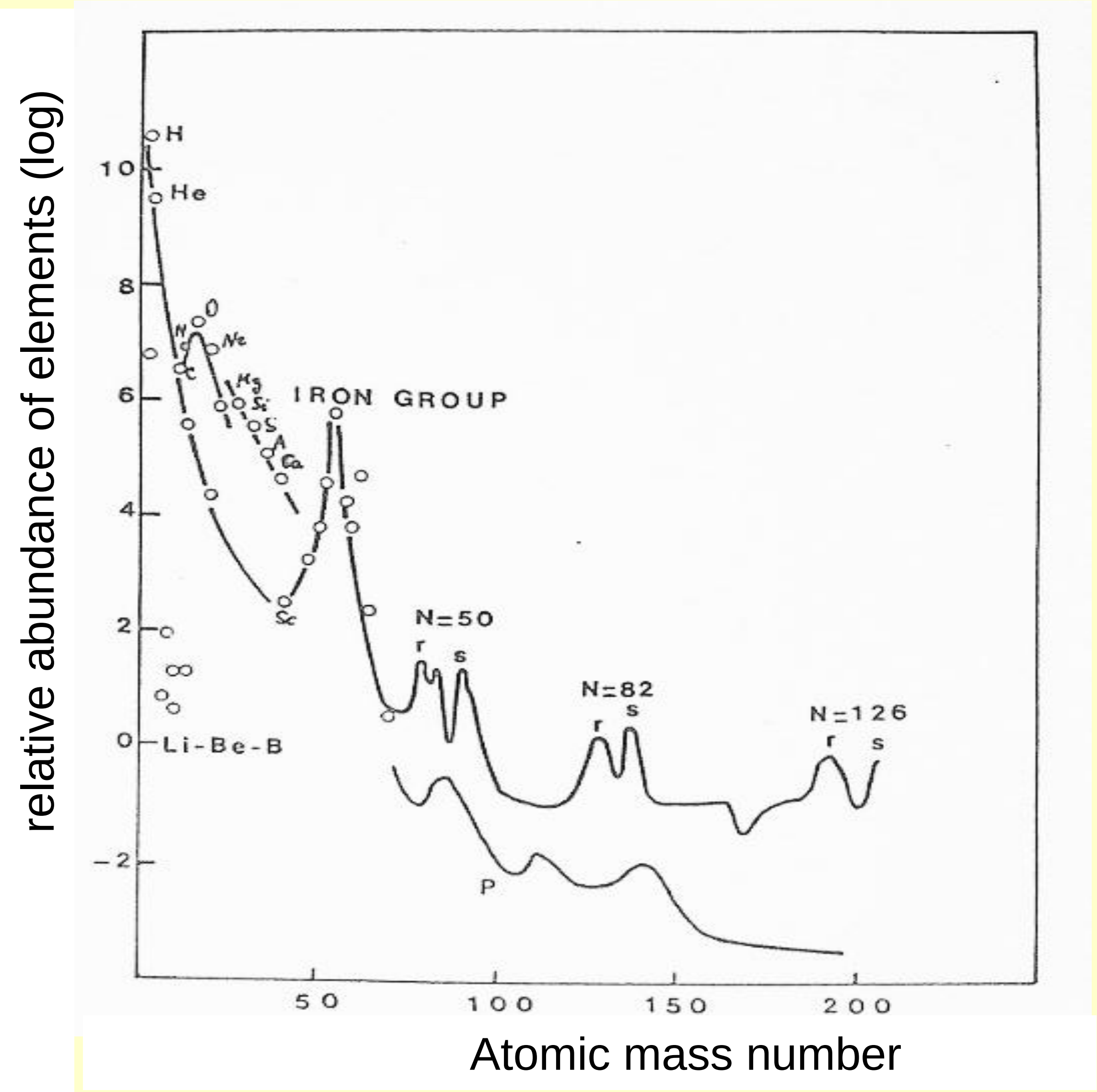
Lick narrowband photometry



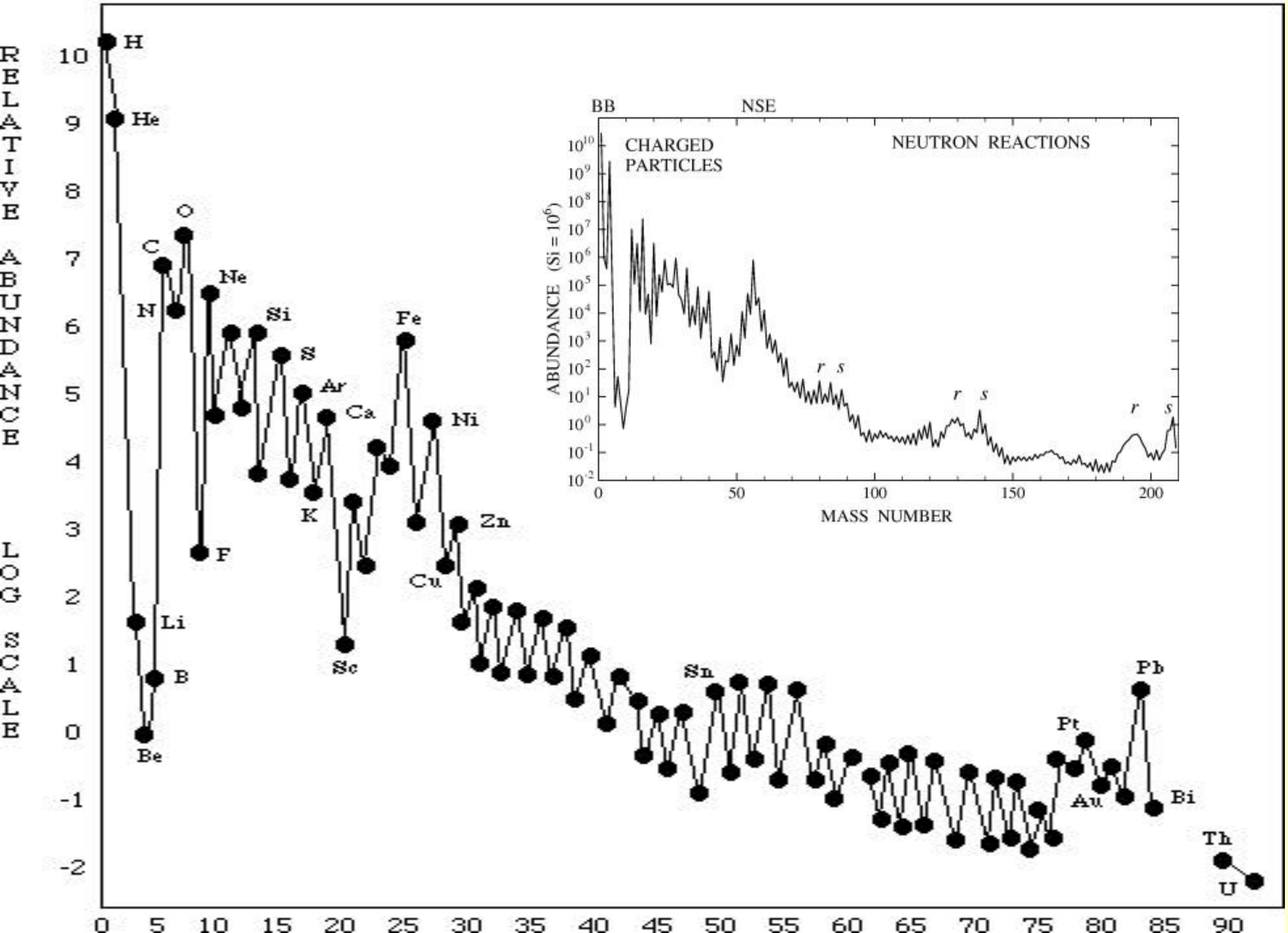
Results: MWG, spectroscopy

- Universal abundance pattern
  - He
  - CNO
  - O,Ne,Mg,Si,S,Ar,Ca,Ti,Cr,Fe
  - Ti,Fe,Ni,Co
  - beyond Fe: r+s elements (Eu)
- [metals/Fe] < ±0.5 dex

Universal ‘cosmic’ abundance



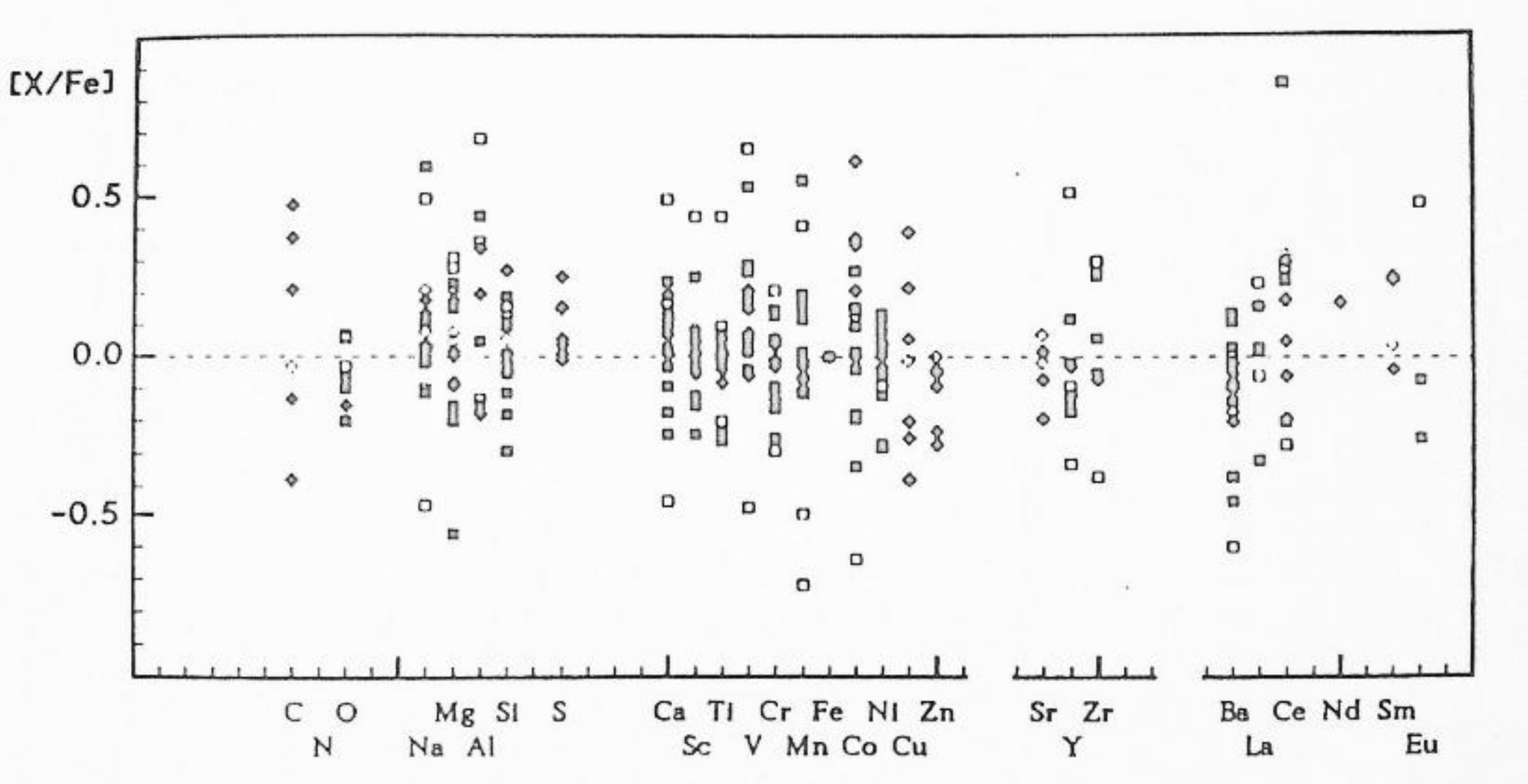
Universal ‘cosmic’ abundance



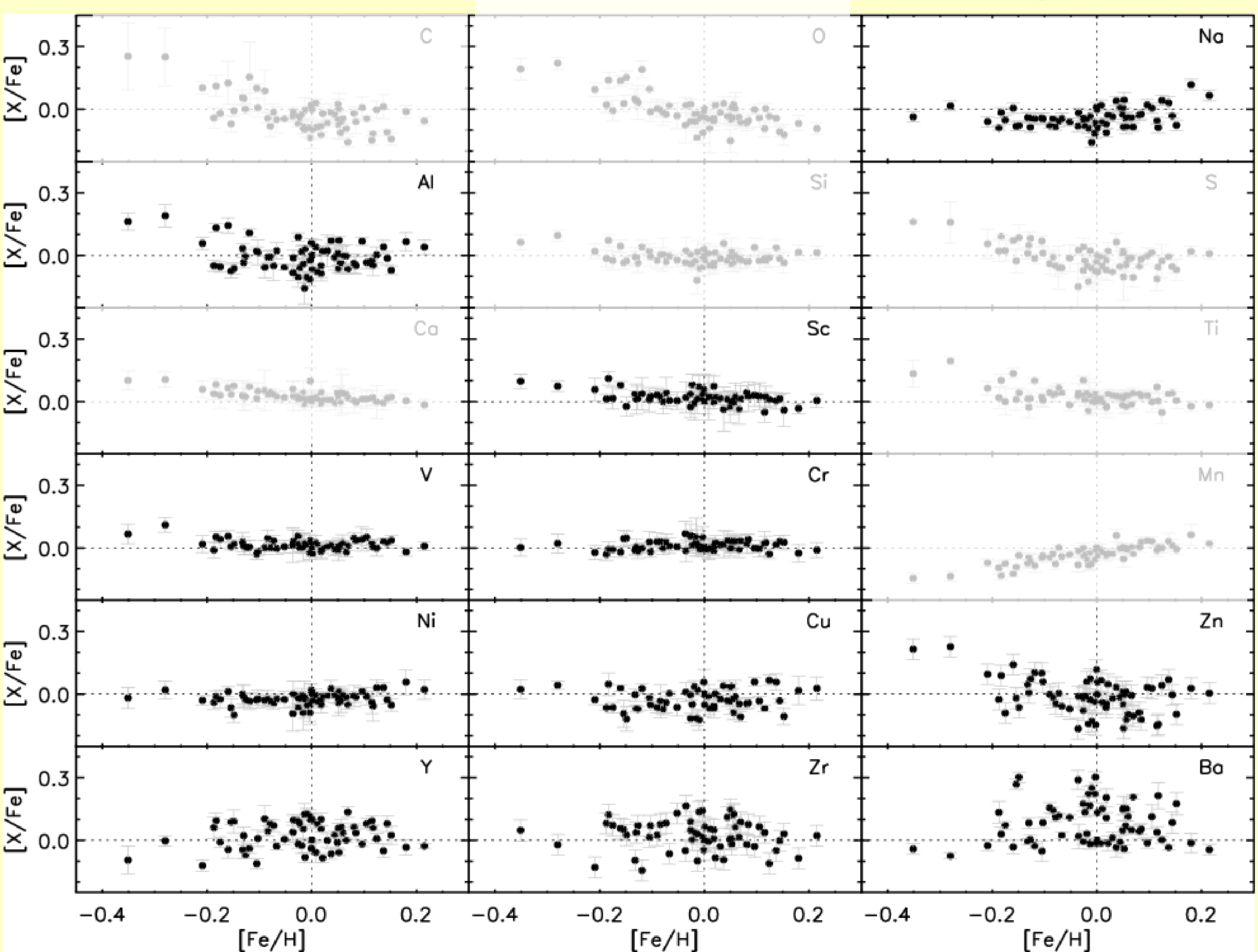
Relations between elements

- In lockstep with Fe: C, Na, Sc,V,Cr, Mn, Co, Ni, Zn
- α-process elements: O,Ne,Mg,Si,S,Ar,Ca,Ti
  - halo: high [M/Fe]
  - disk: [M/Fe] decreases with [Fe/H]
- other elements: N, Eu …

Close scaling with Iron

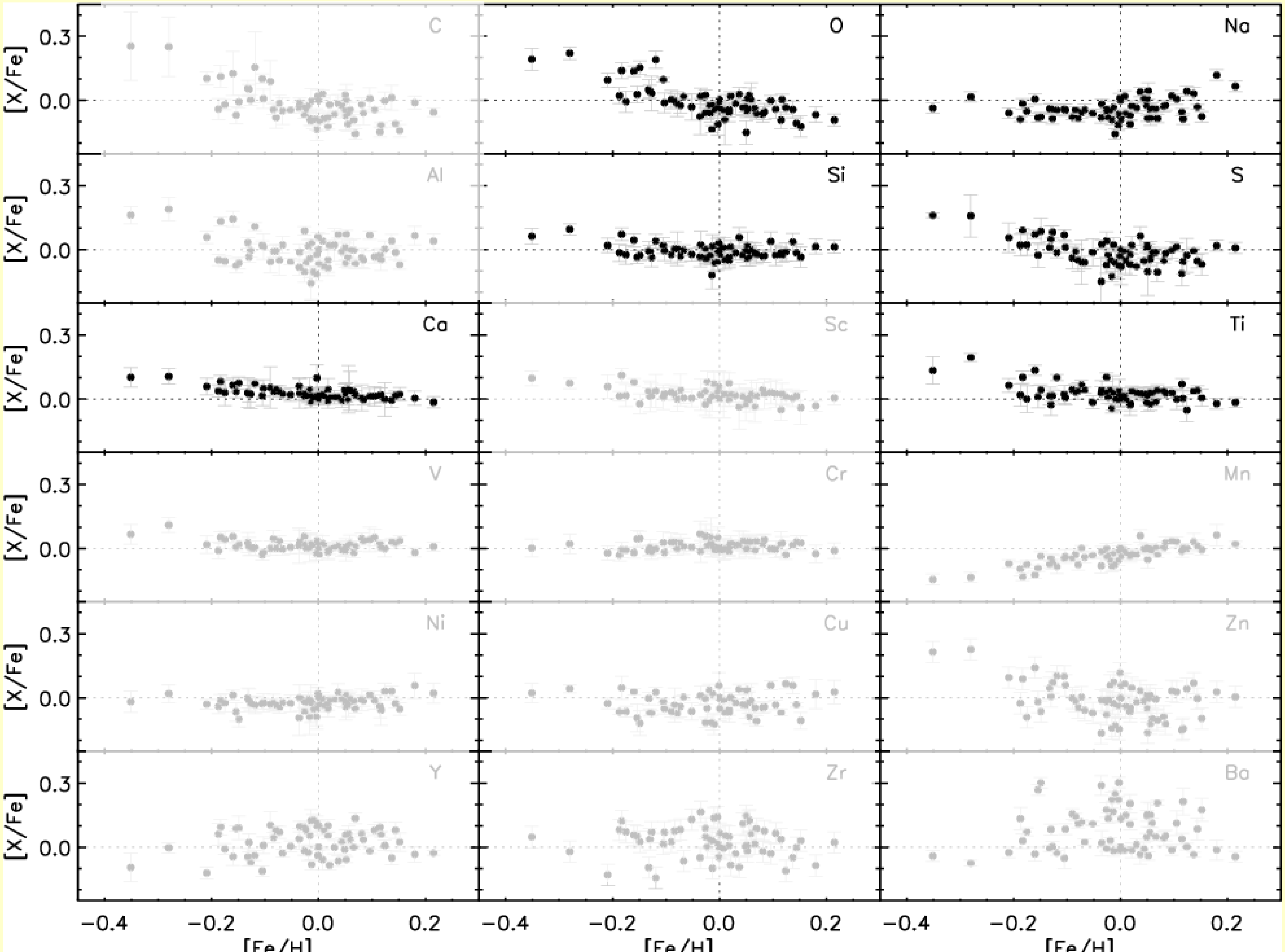


Sun-like stars: In lockstep with Fe



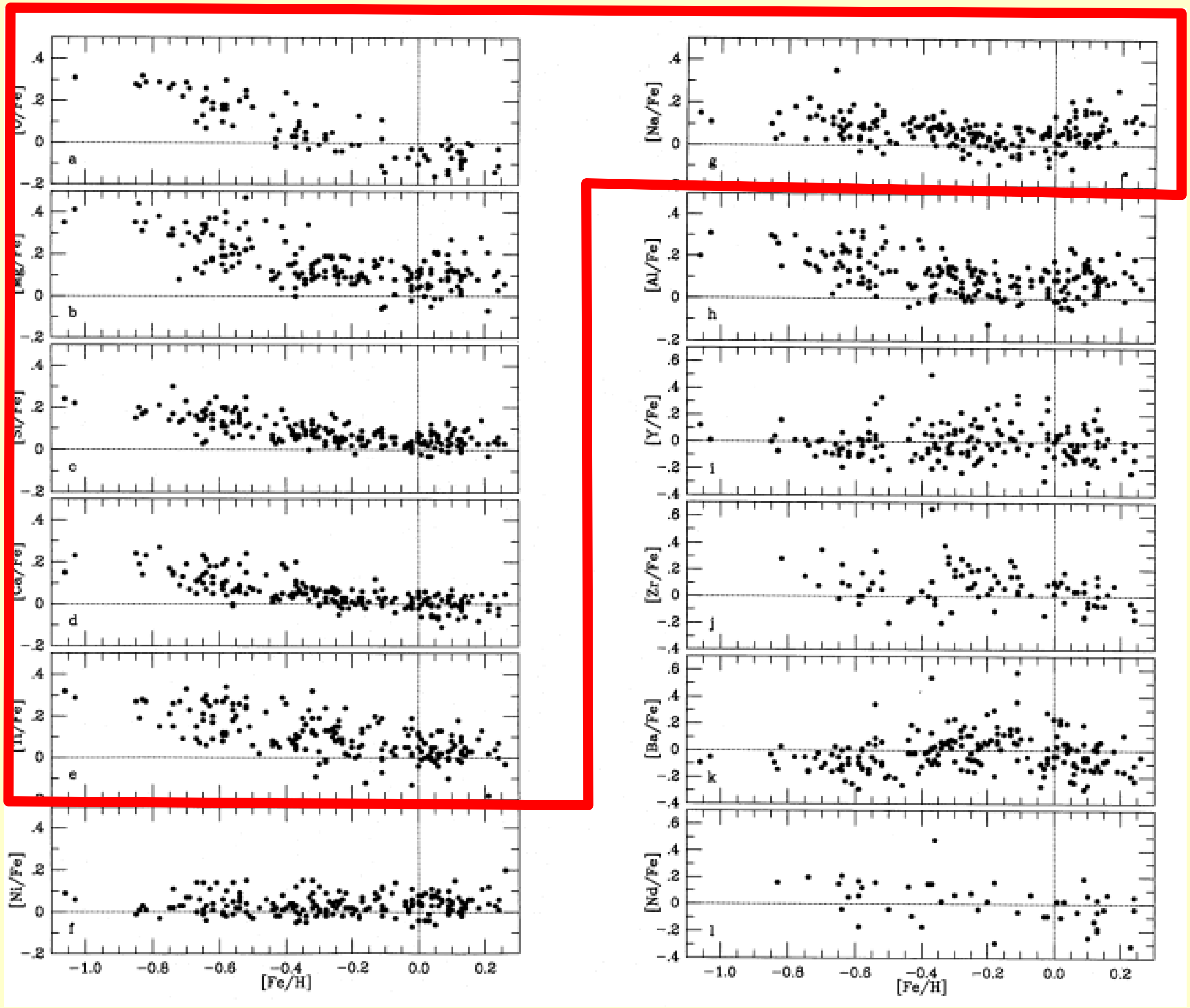
Ramirez 2009

α elements in solar-type stars



Ramirez 2009

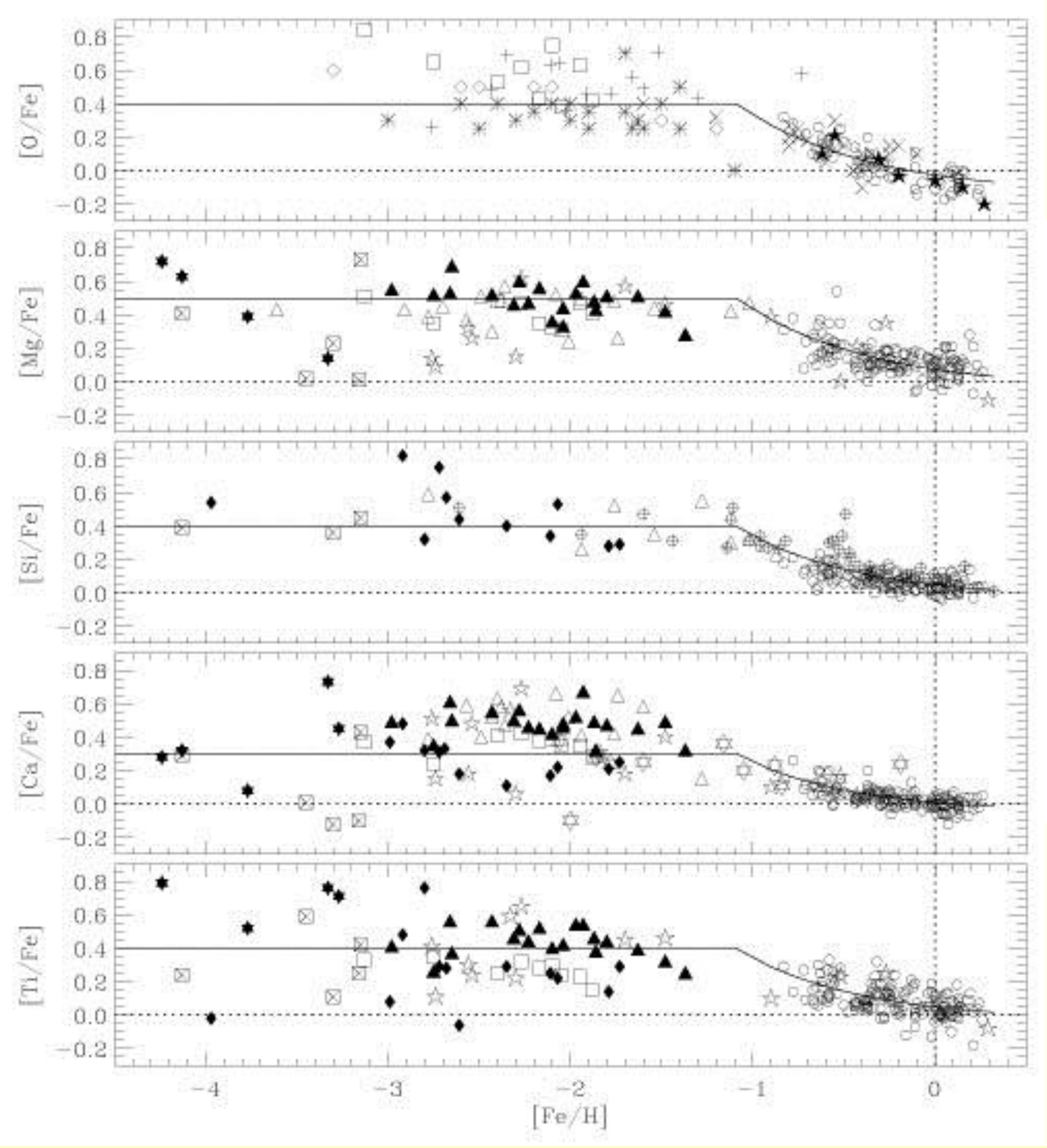
Abundance patterns in disk FG*

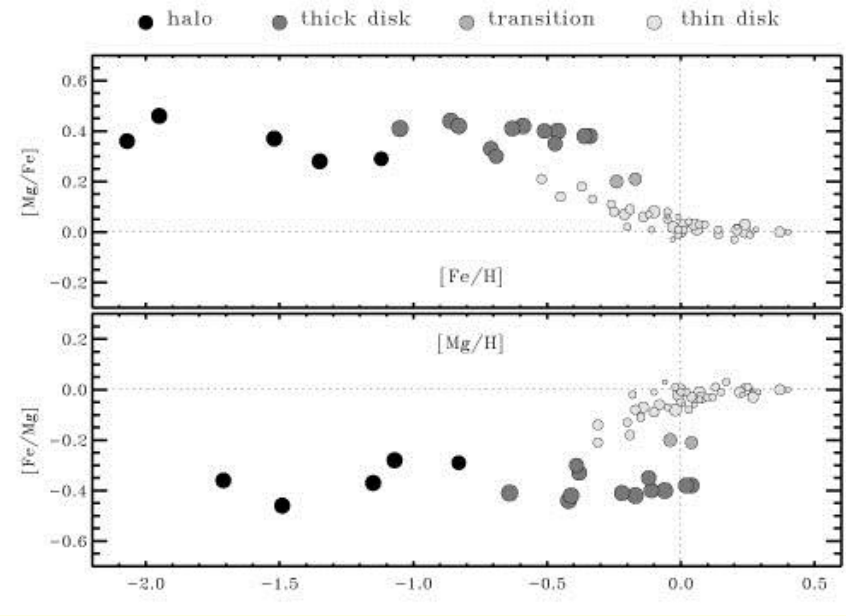


α elements

Edvardsson 1994

α elements: disk + halo stars





Fuhrmann 1998

Pagel 1995

Radial abundance profile

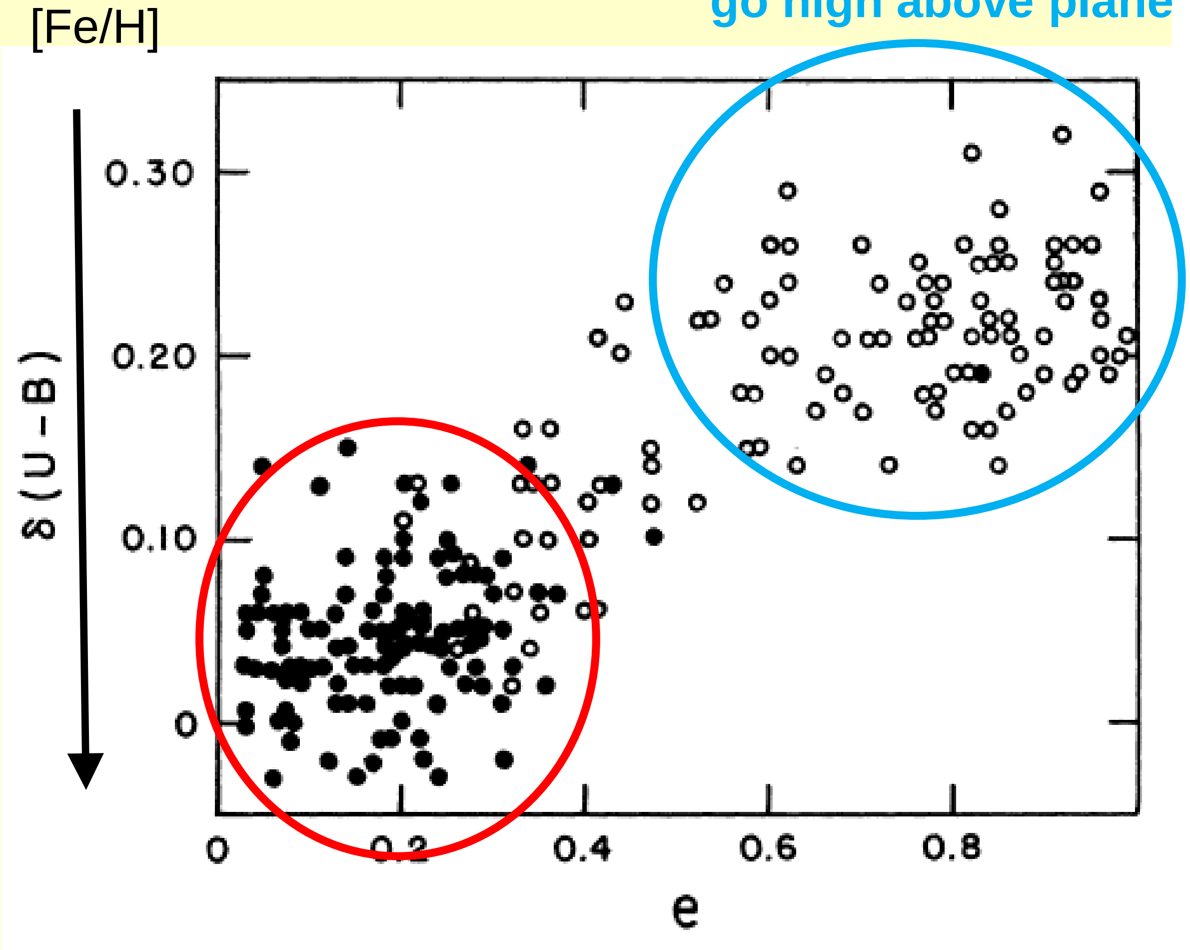
- Thin disk: open clusters ([Fe/H]) and B stars (O/H, NLTE!!!): gradient like HII regions
- Halo: no gradient
- Globular Clusters:
  - Inner, metal-rich system: ‘disk clusters’
  - Outer, metal-poor system: ‘halo clusters’
- Thick disk: [Fe/H] $\approx$ -1 … -1.6; no radial or vertical gradient in [Fe/H]

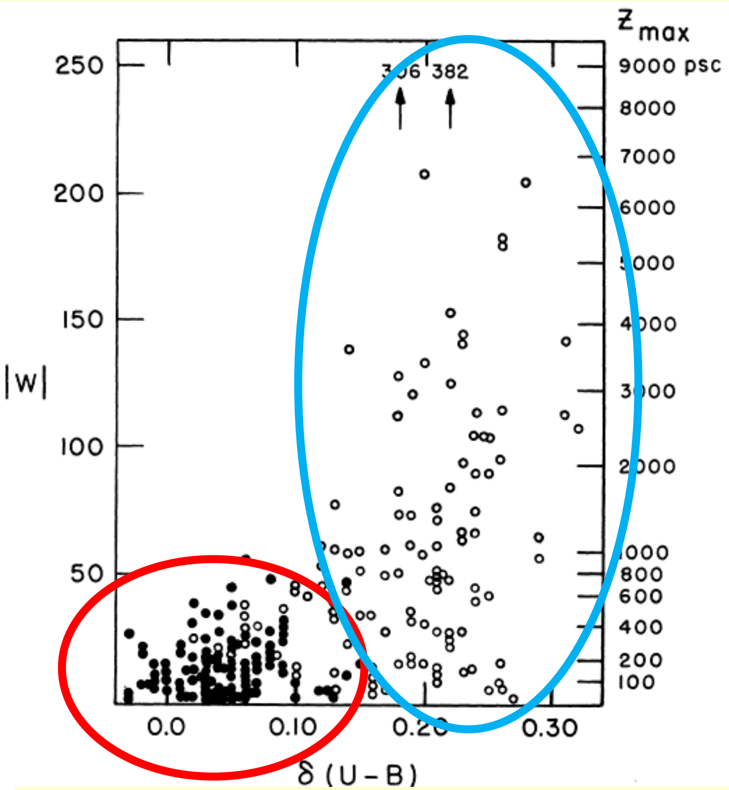
Disk and Halo

- Eggen, Lynden-Bell & Sandage (1962) find that the photometric UV-excess (measure of [Fe/H]) is correlated with eccentricity of orbit and vertical velocity
- Scenario for formation of MWG:
  - Collapse from single protogalactic cloud ➔ metal-poor stars on radial orbits
  - Gas settles into rotating disk, forms metal rich stars

ELS

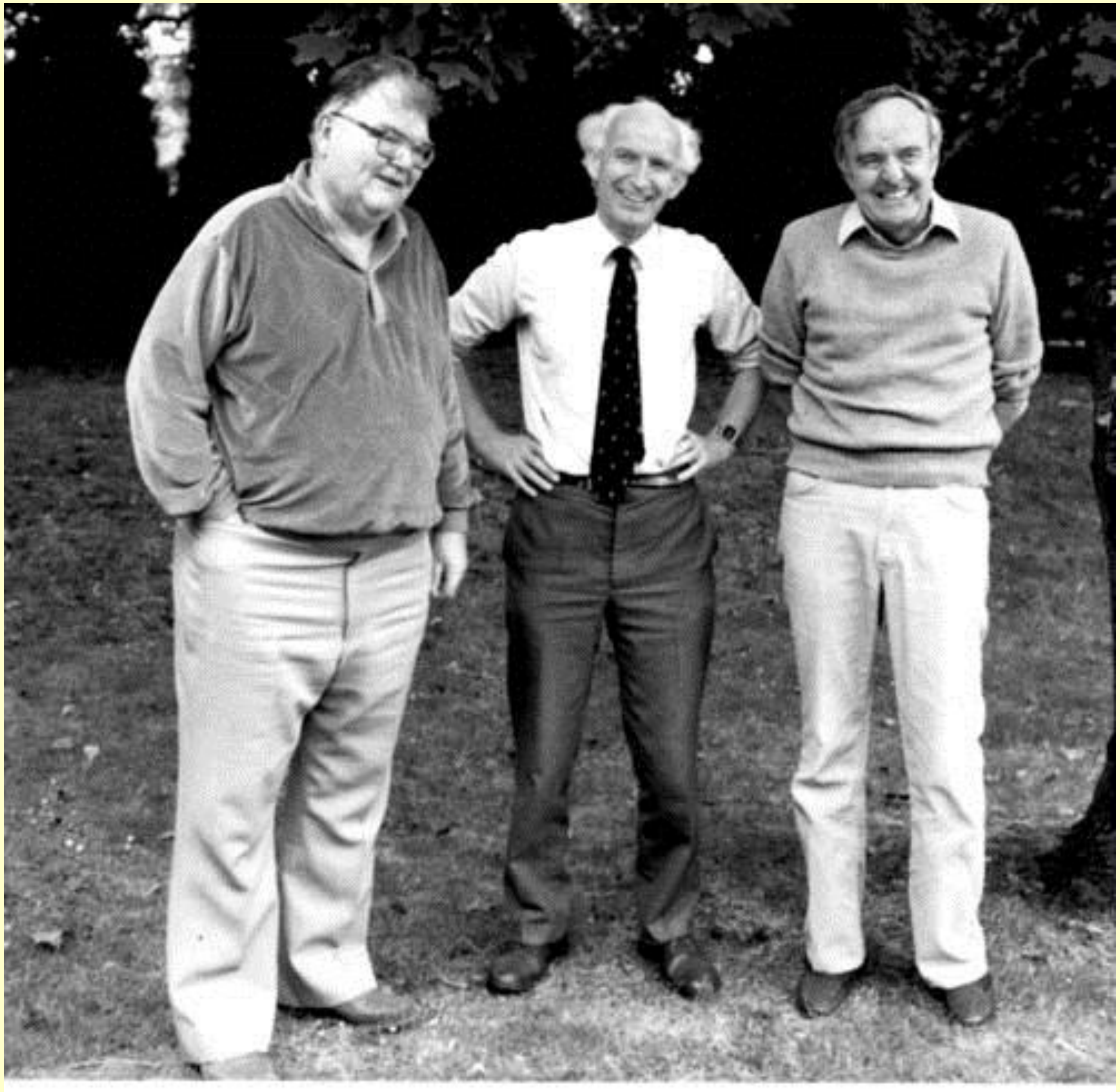
Metal-poor stars on nearly radial orbits and go high above plane





Metal-rich stars on nearly circular orbits and stay in plane

E L S

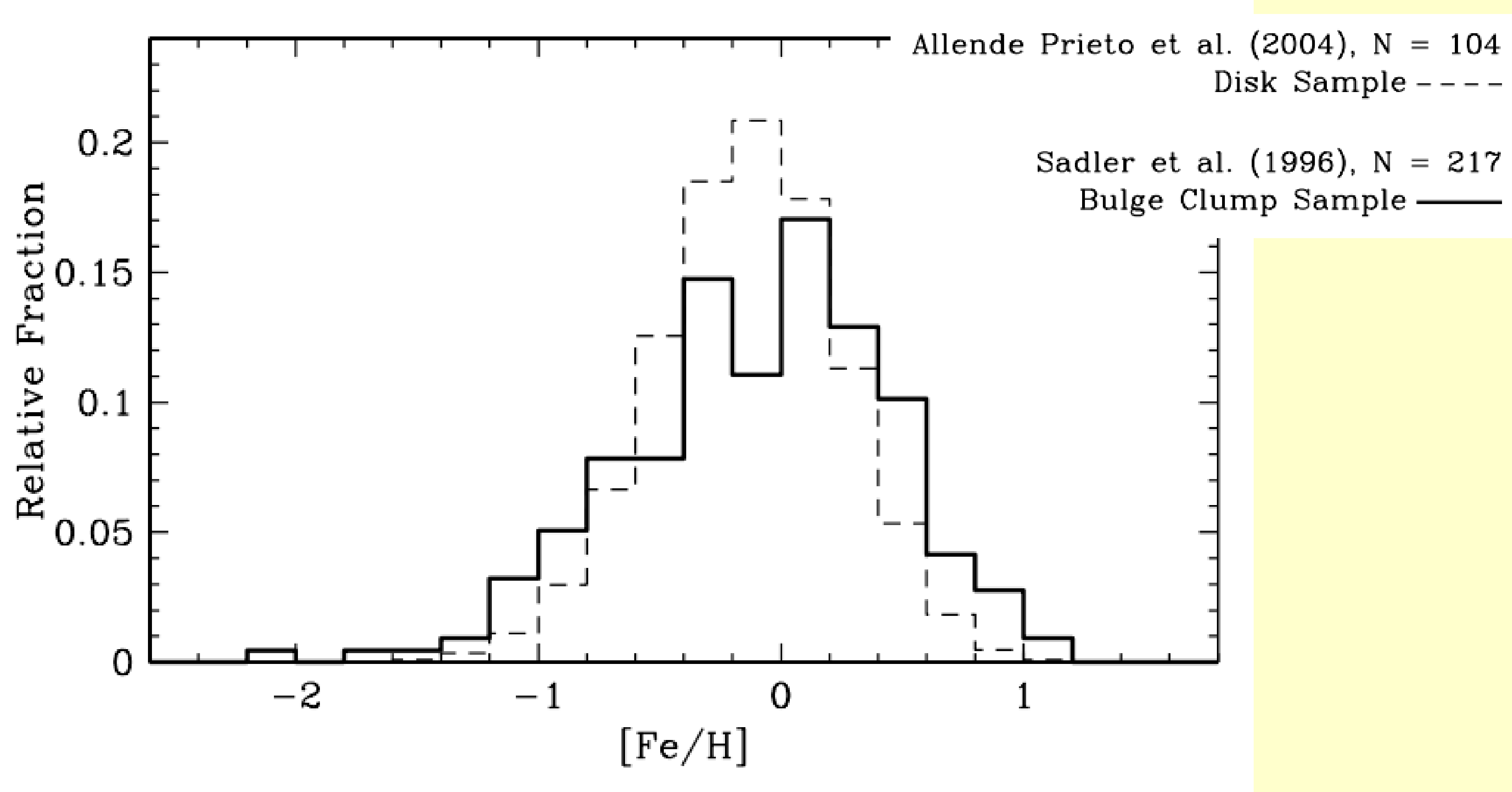


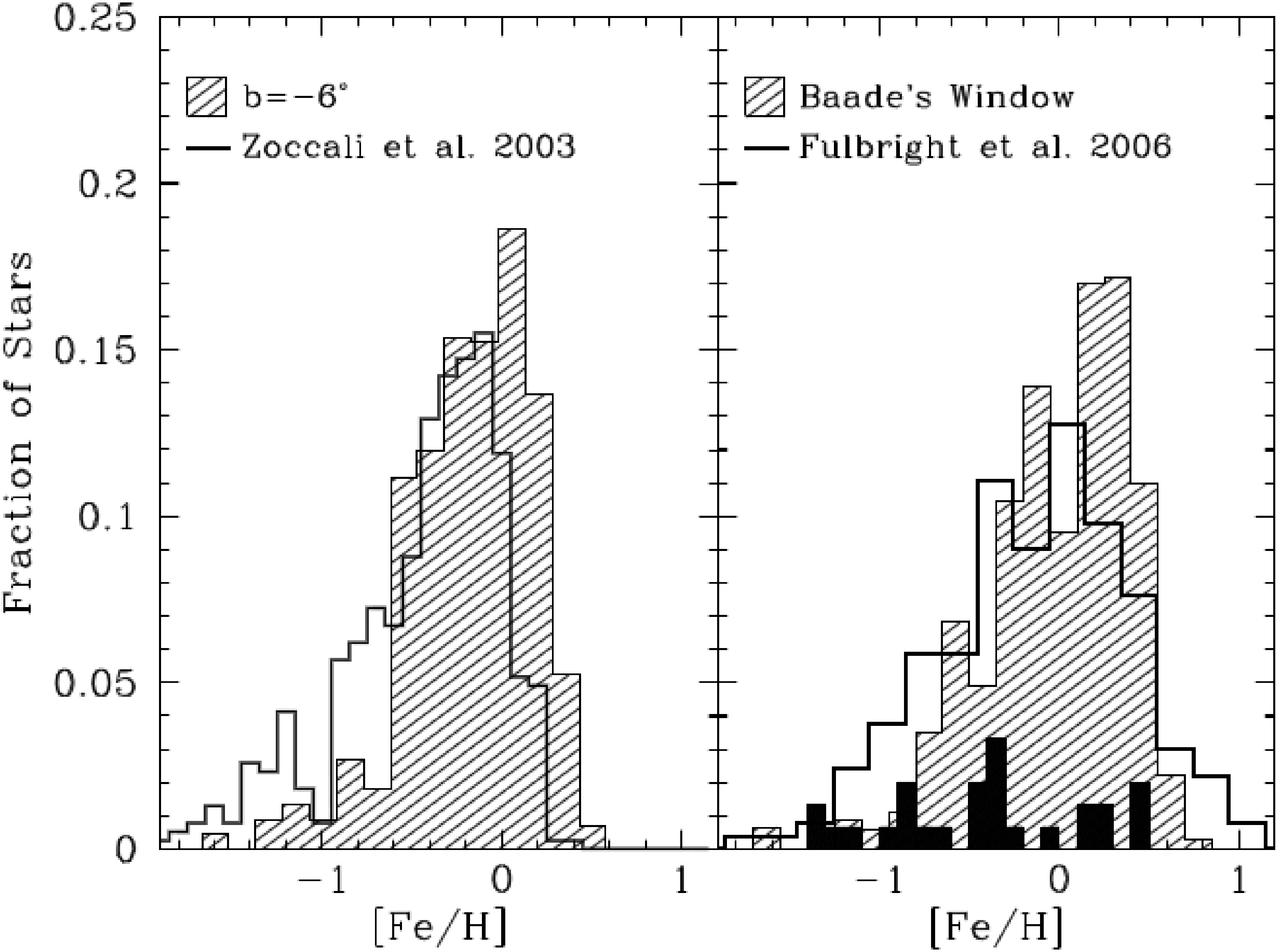
The Bulge

	[Fe/H]
Rich 1988: K giants, Mg, FeI indices	-1…+0.8
Terndrup 1991: M giants, R=1000	+0.3
Geisler+Friel 92: giants, photometry	+0.17
McWilliam+Rich 94: spectro	-0.25
– ➔ Rich 88 overestimate Fe/H in metal-rich stars	
– Solar neighbourhood	-0.17
Terndrup 95, Sadler 96; lo-R spectro	-0.1
Fulbright 06/07: Keck spectro	-1.2…+1.1
Zoccali et al. 03: photom.	-1.5…+0.4
Zoccali et al. 09: spectro	-1.4…+0.3

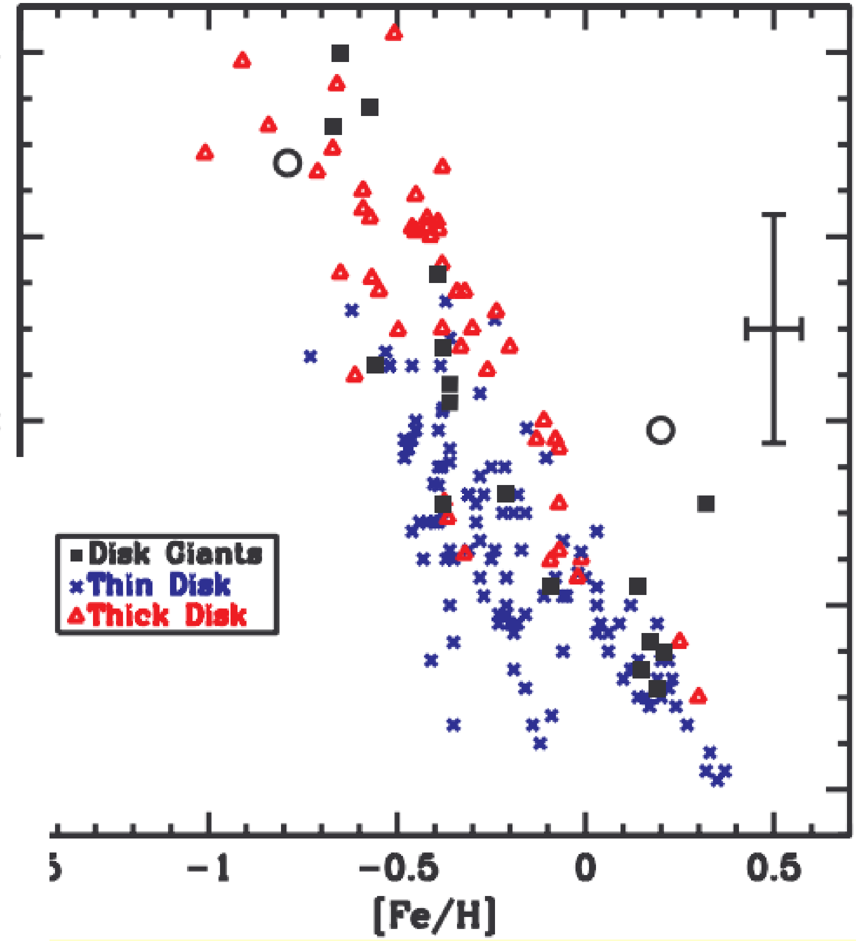
Metallicity distribution functions

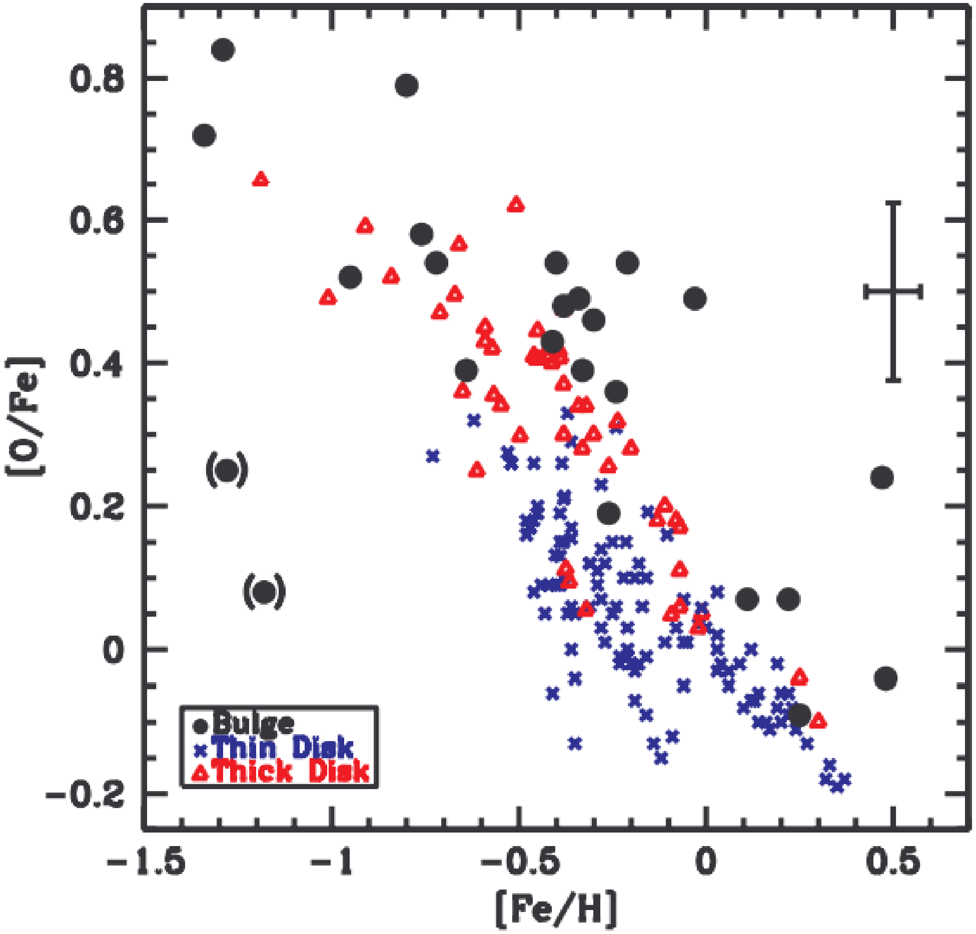
Count the number of stars in each metallicity bin …
useful for comparison with models (cf. later …)




0.25
0.2
0.15
0.1
0.05
0
Fraction of Stars
b=−6°
Zoccali et al. 2003
Baade's Window
Fulbright et al. 2006
−1
0
1
[Fe/H]
−1
0
1
[Fe/H]

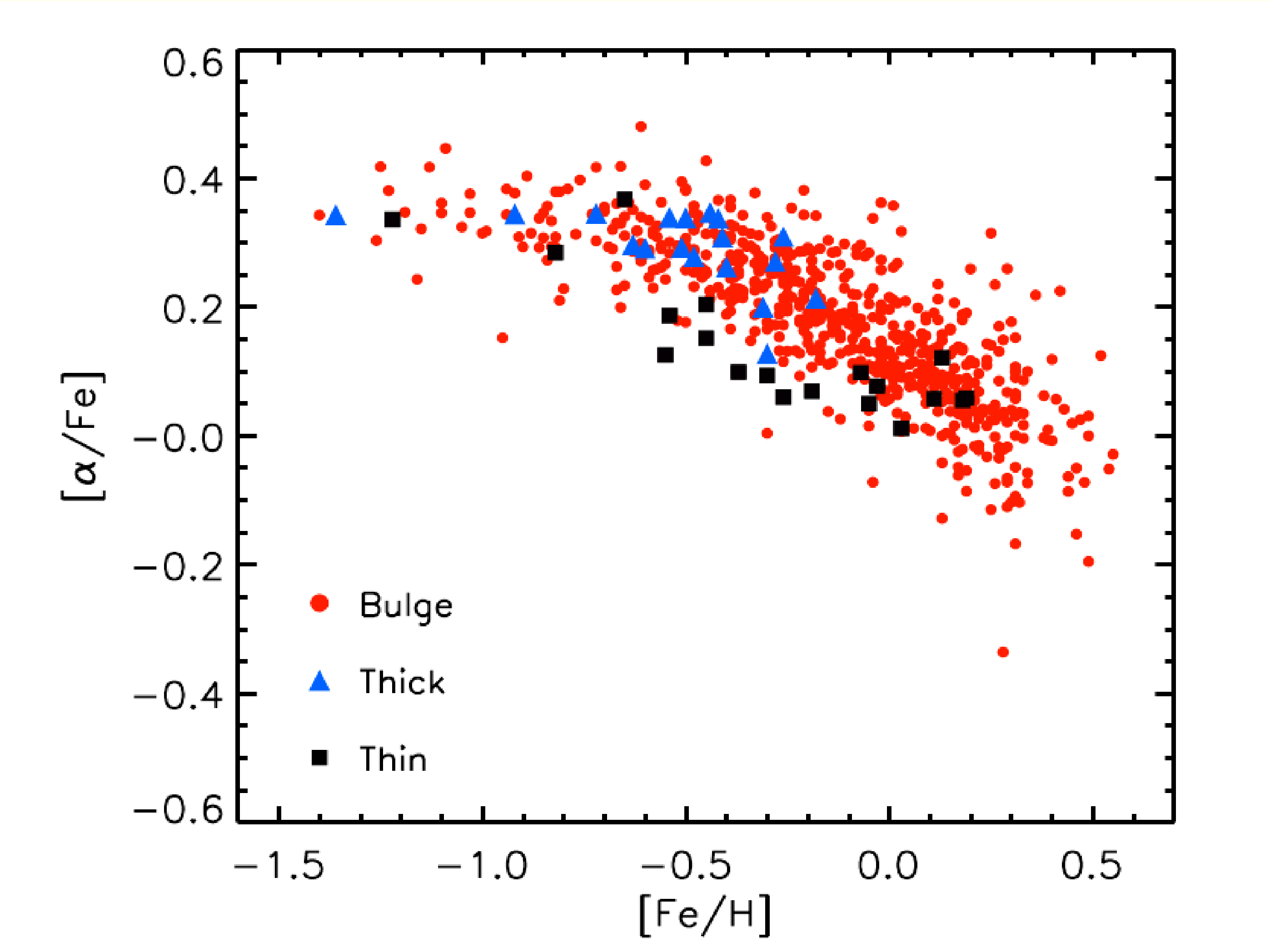
Bulge, Thin & Thick Disk





(Keck spectra)
Fulbright et al. 2006/07

650 K giants of the Bulge



Spectro R=20000
ESO VLT
S/N= 40..90

Similar [Fe/H] range as thin disk

[α/Fe] is higher than in the disk

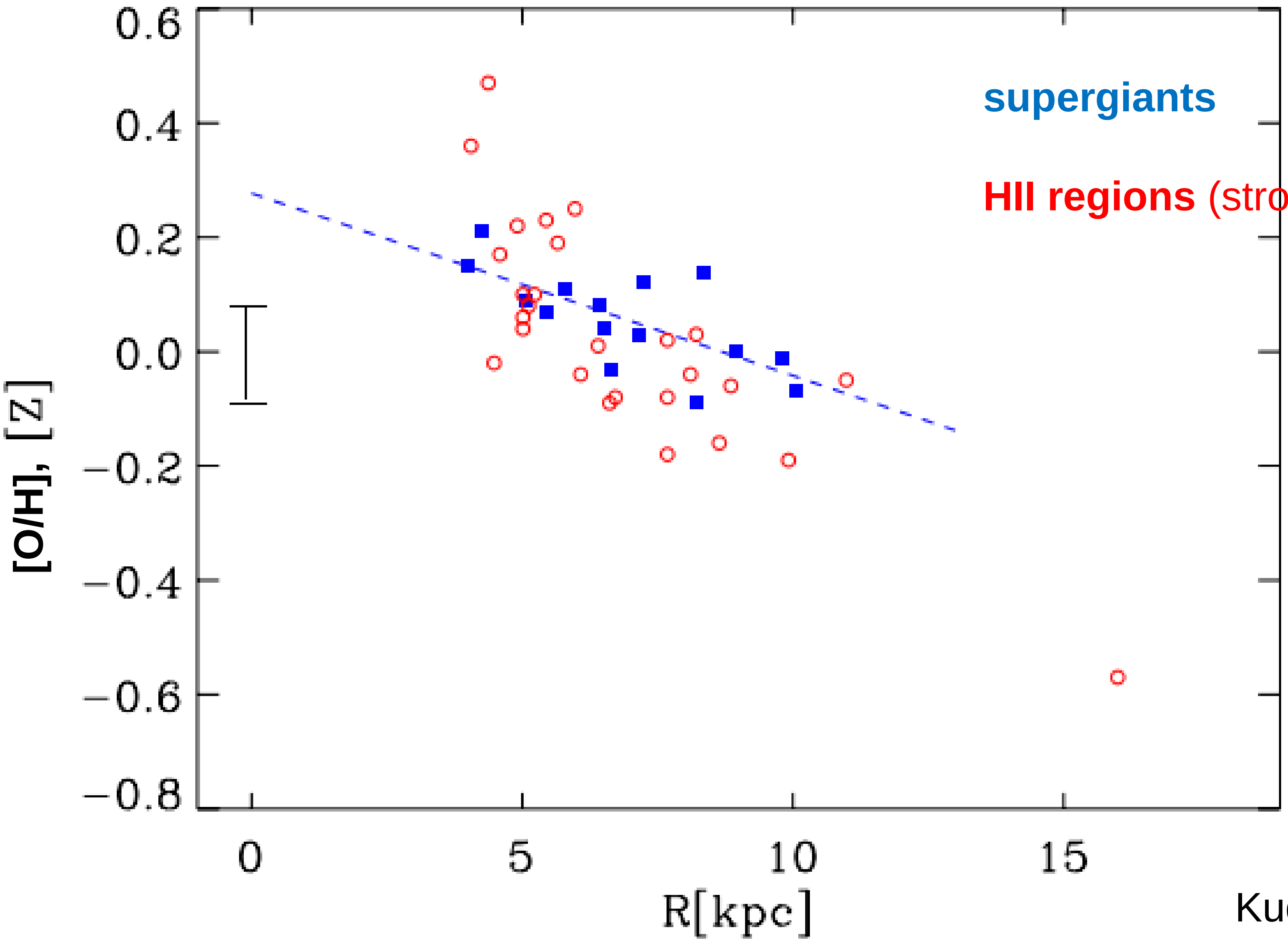
Thick disk:
- [Fe/H] = -1.5 … -0.2
- [α/Fe] like bulge

Gonzales et al. 2011

External spiral galaxies

- Spectra of individual supergiants in M31, M33, M81
  - ±0.2 dex
  - Radial gradient like HII regions
- Colours of red giants (RGB gets redder with metallicity): M31 halo [Fe/H] > 0.6; no radial gradient; outer disk resembles solar neighbourhood

M81 abundance gradient

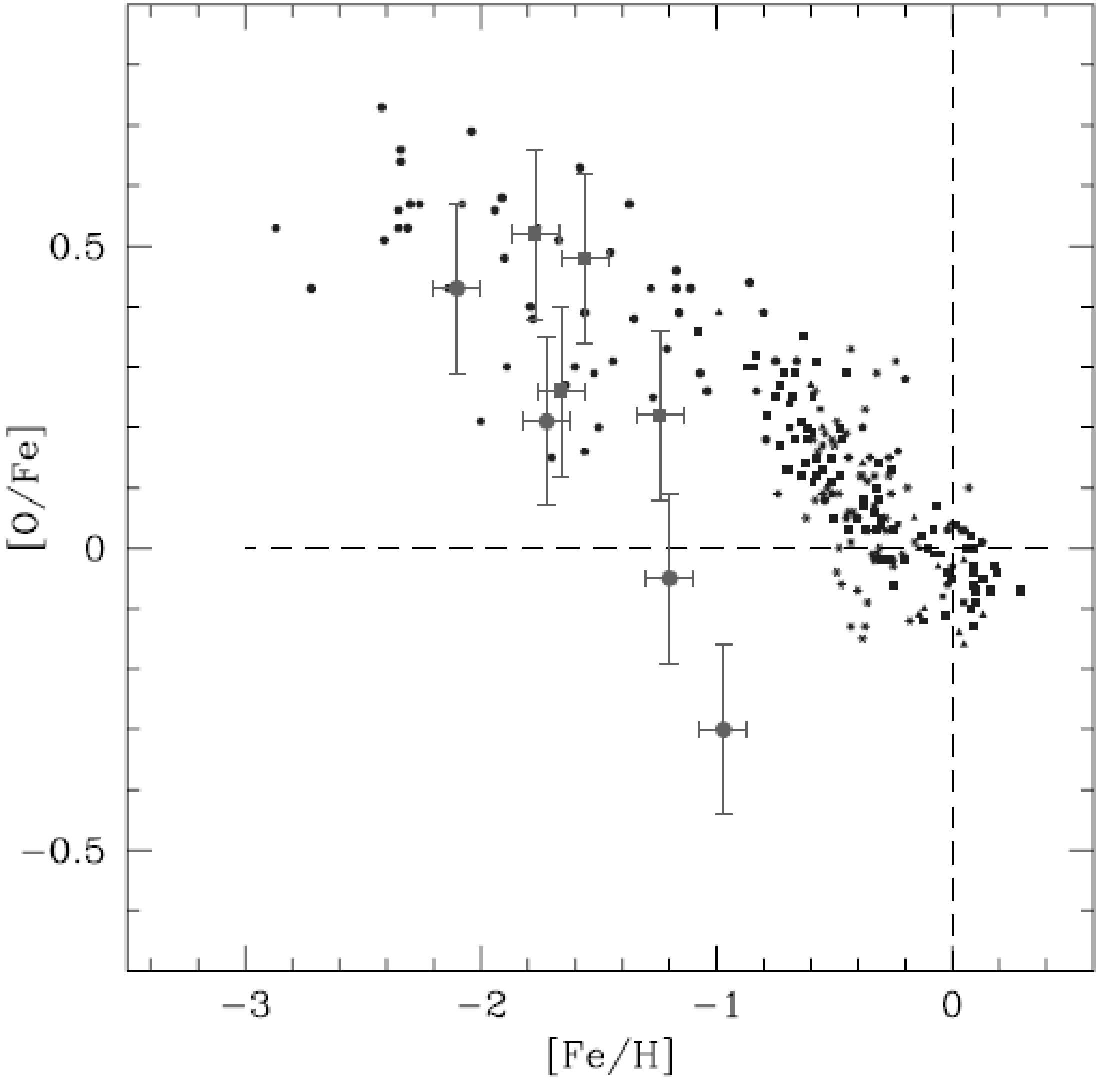


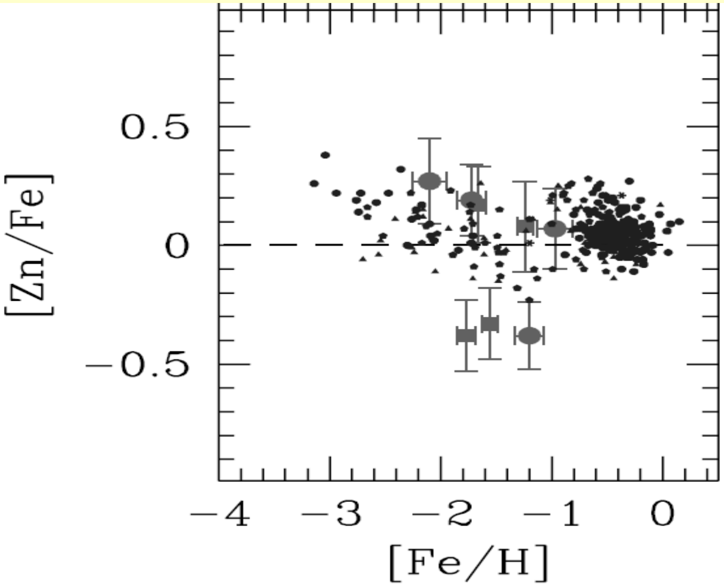
supergiants

HII regions (strong line method)

Kudritzki et al. 2012

Sculptor dSph galaxy





Giant stars compared to solar neighbourhood:

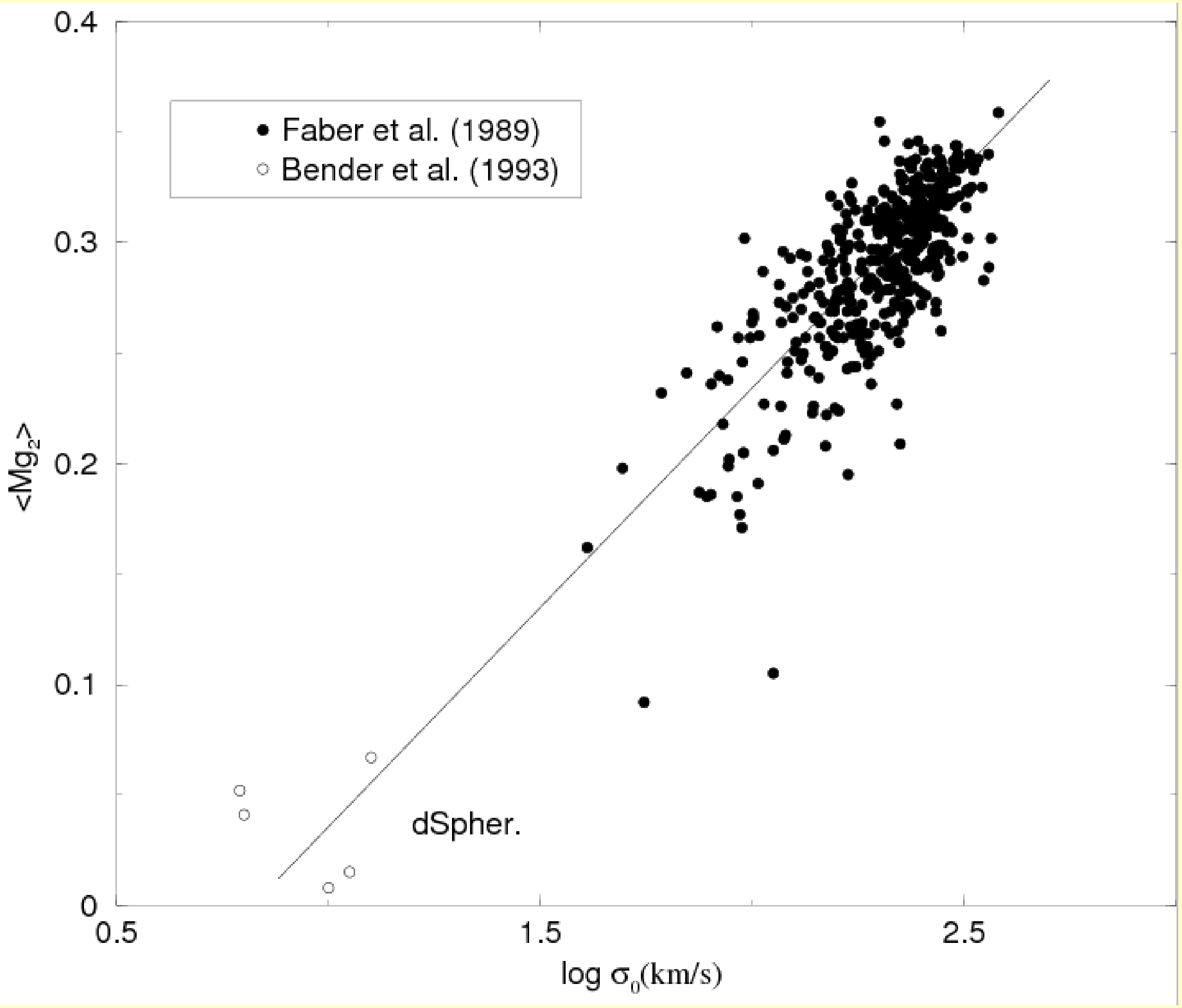
➔ lower [Fe/H]
➔ steeper O/Fe-Fe/H relation!

Geisler 2005

Elliptical galaxies: photometry

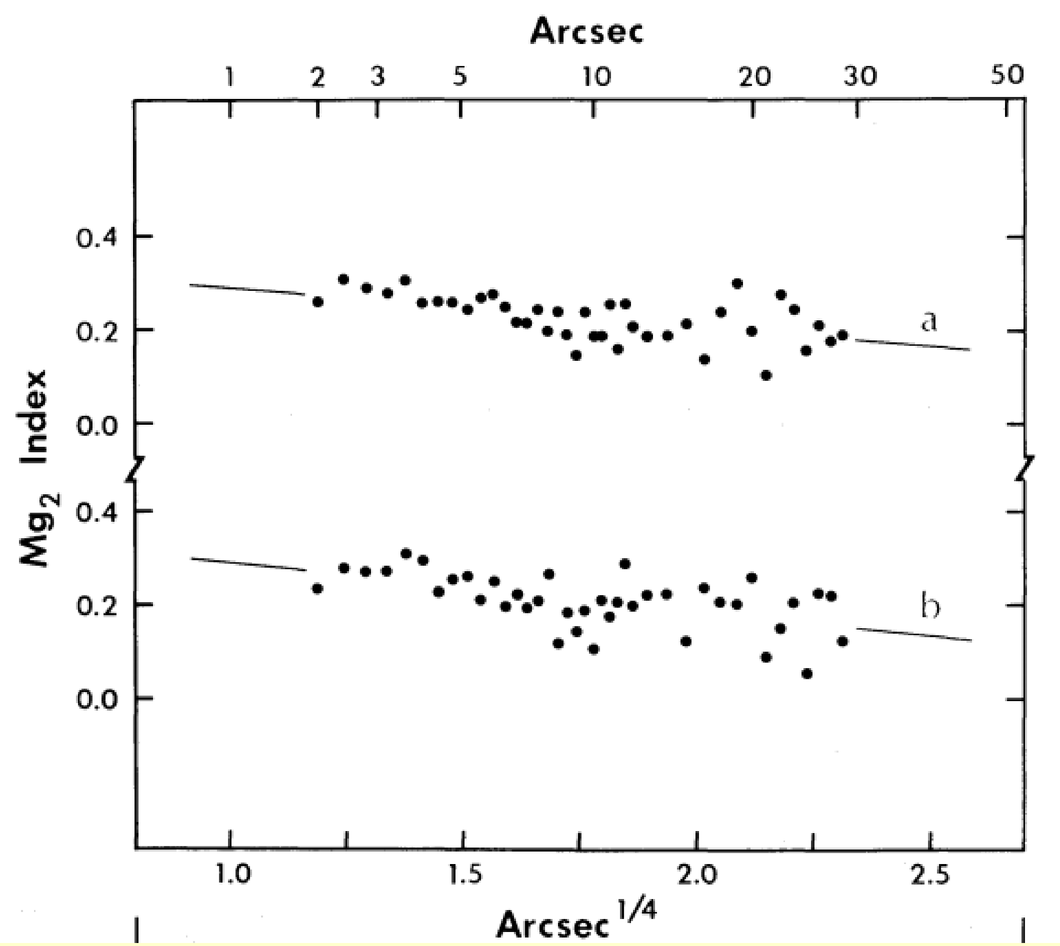
- [Z/H] ~ 0 … +0.4 in centers of large E
- Mass-metallicity relation
- Radial gradients (NB. Need population models to compute theoretical colour profile) $\Delta \lg Z / \Delta \lg R \approx -0.2$
- Abundance ratios: Mg, Na, N larger than expected from scaled solar pattern

Mass-metallicity relation



Henry+Worthey 1999

Elliptical galaxies: gradients



Thomsen+Baum 1987