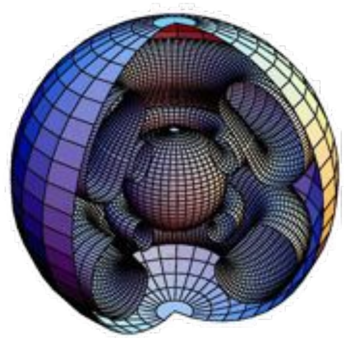
$$n_i \sum_{j\neq i}(R_{ij}+C_{ij}) = \sum_{j\neq i} n_j(R_{ji}+C_{ji})$$

$$\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu$$



Oxygen Abundance Determinations in BA type Supergiants: methods & uncertainties

Norbert Przybilla

K. Butler, S. Becker, M. Firnstein, R.P. Kudritzki, F. Bresolin, M. Urbaneja

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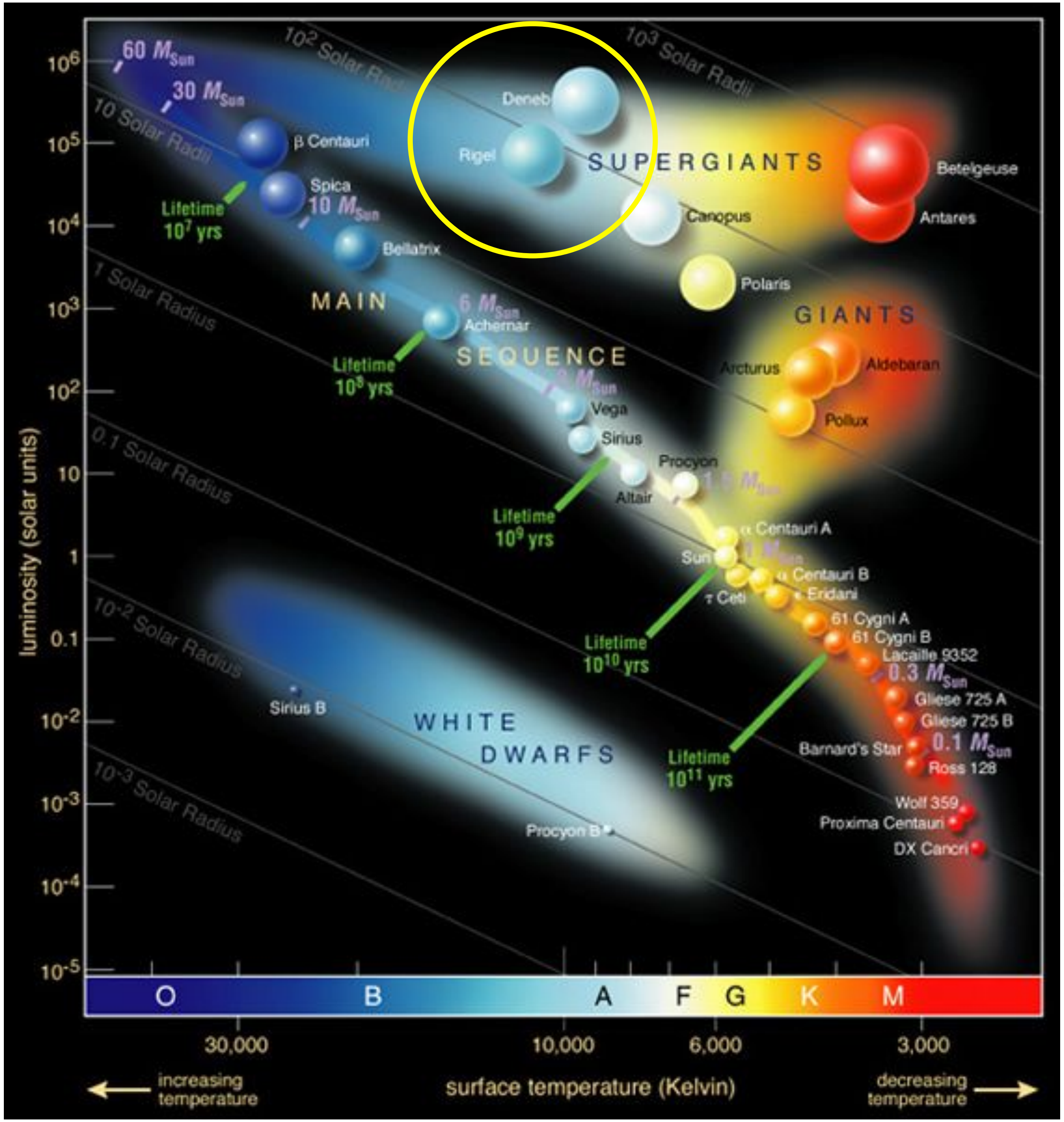
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



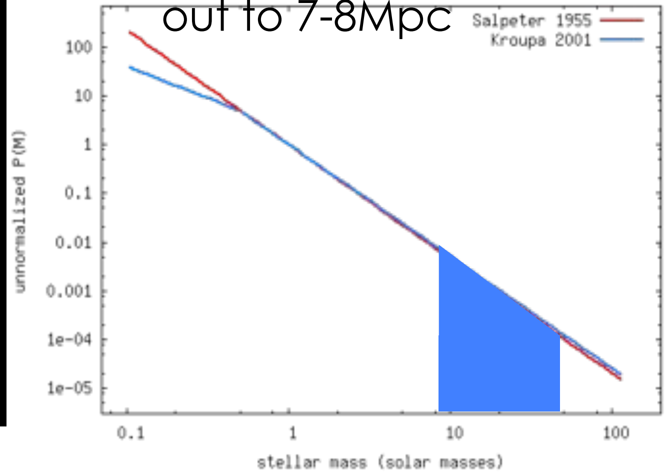
Intro

BA-Supergiants

- evolved progeny of OB main-sequence stars
- T_{eff}: ~ 8000 … 15000 K
- M: ~ 8 … 40 $M_{\odot}$
- L: ~ 10^4 …$10^{5.5}$ $L_{\odot}$
- R: ~ 50 … 400 $R_{\odot}$

→ spectroscopy@high-res throughout Local Group

→ @med-res: out to 7-8Mpc



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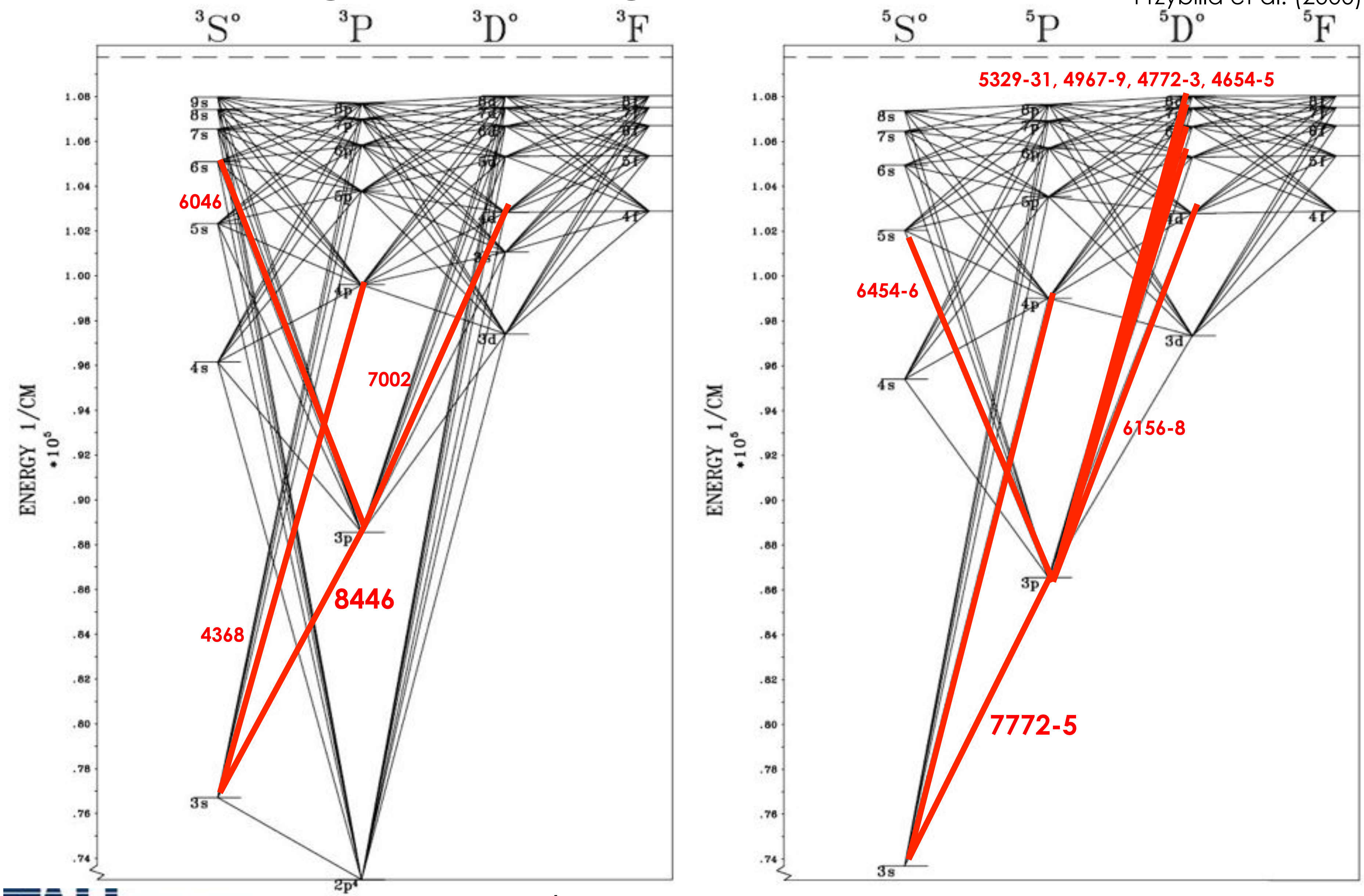
Introducing the protagonists: OI

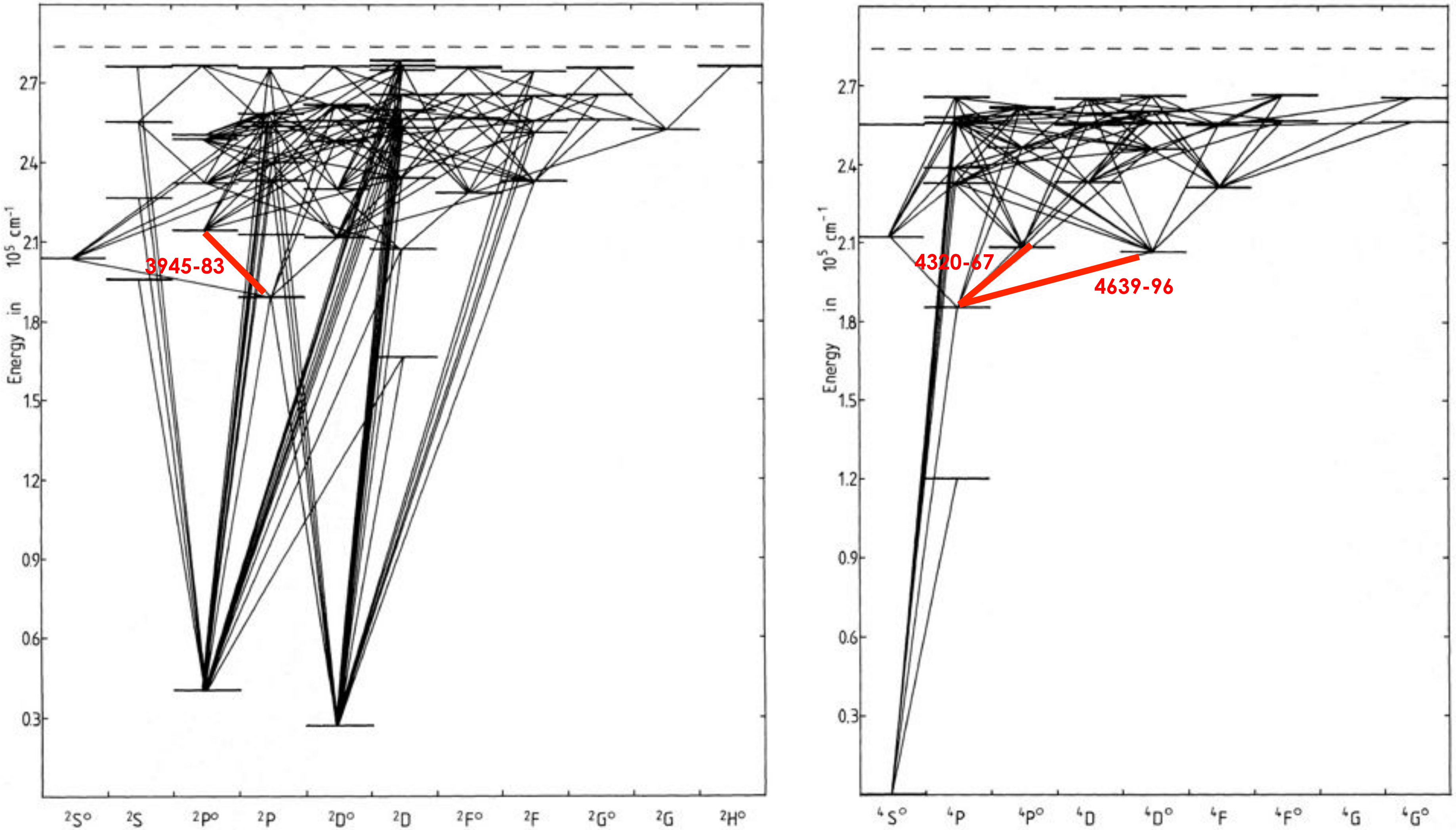
Przybilla et al. (2000)



strong vs. weak lines

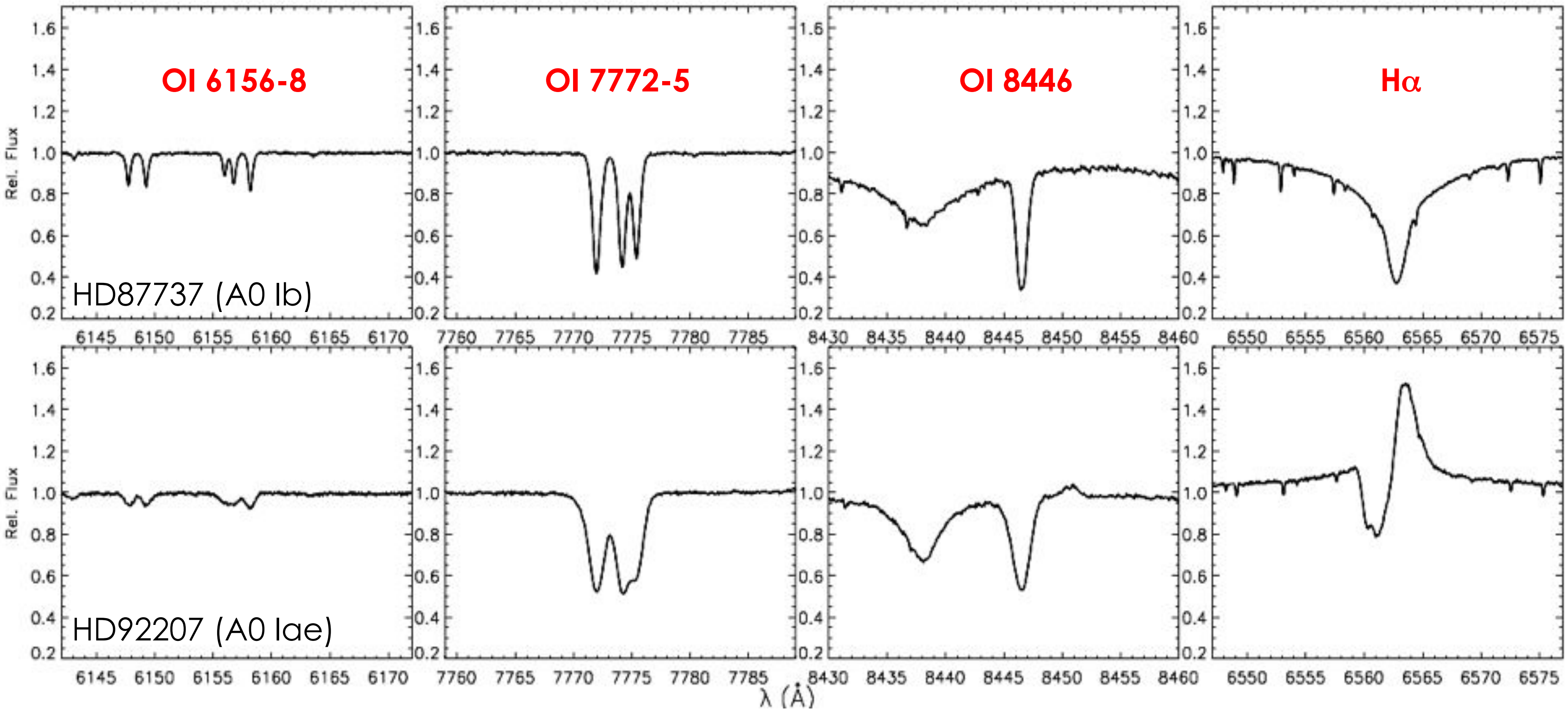
Introducing the protagonists: OII

Becker & Butler (1988)

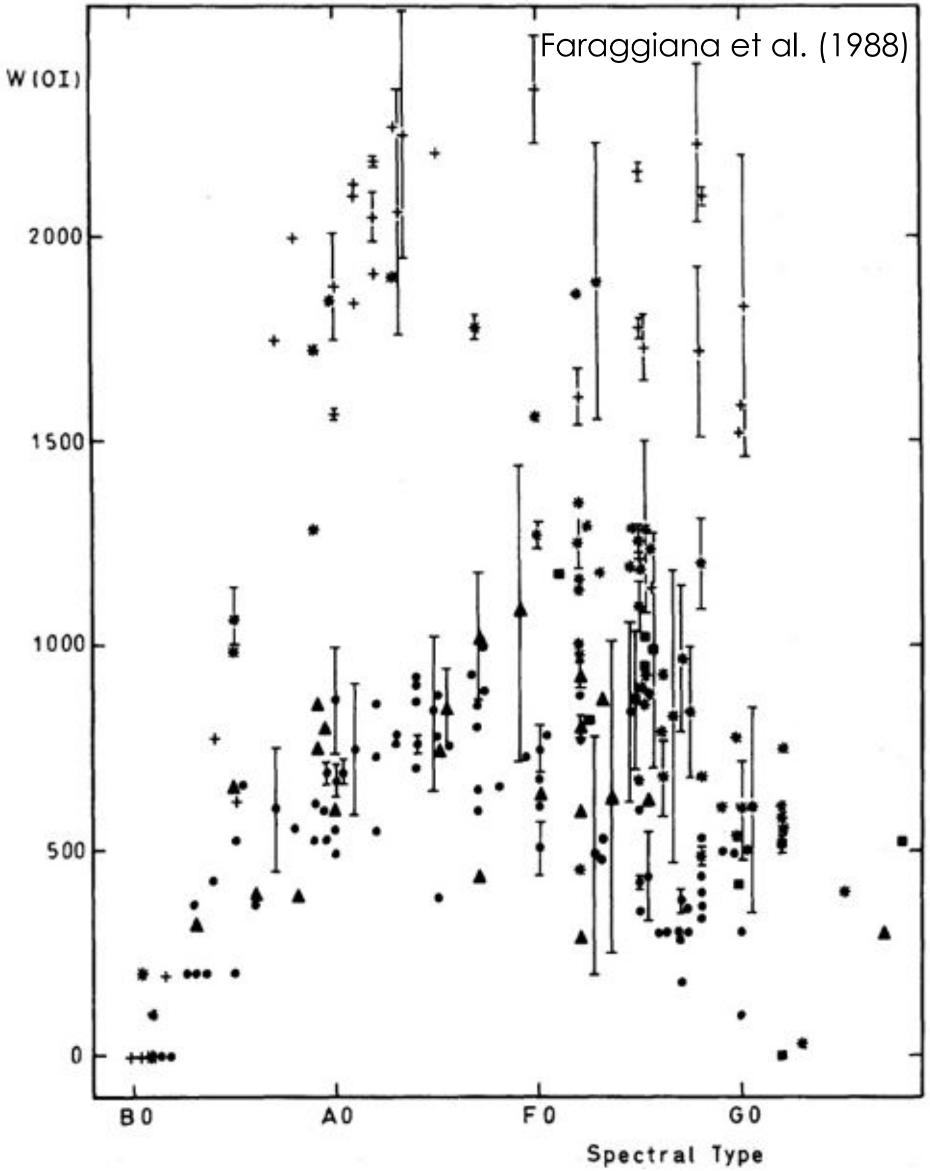


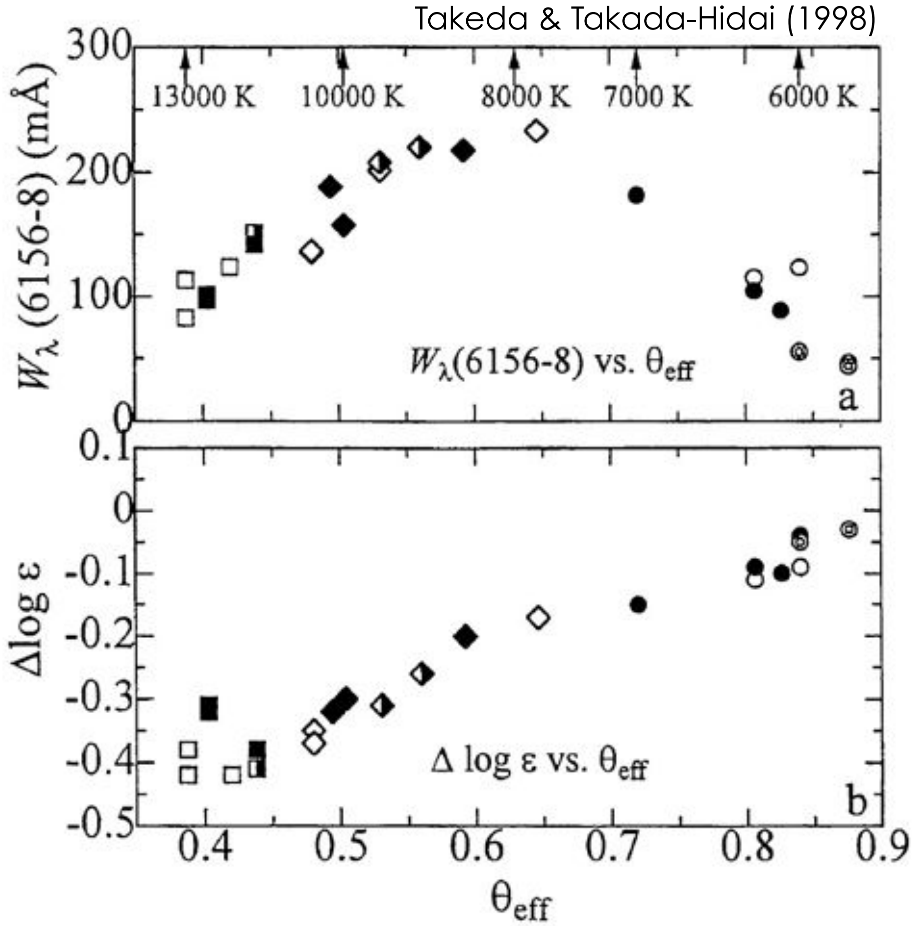
weak lines: late B-SGs

OI: strong vs. weak lines



OI: behaviour of equivalent widths



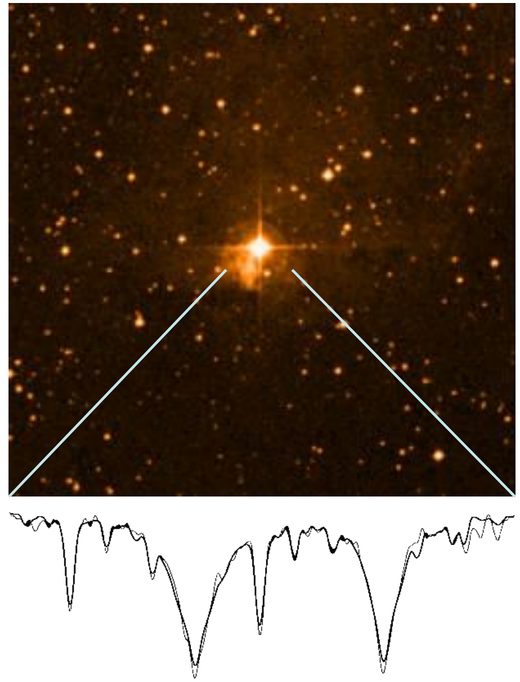


maximum strength of lines:
late A-types

Diagnostics

stellar analyses from
interpretation of observation

→ (spectro)photometry, spectroscopy



- fundamental stellar parameter: L, M, R
- atmospheric parameters: T_{eff}, log g, ξ, Y, Z, etc.
- elemental abundances, e.g. **oxygen**

→ quantitative spectroscopy
via model atmospheres

physical-numerical models

of visible outer layers of stars

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Basic equations of classical stellar atmosphere problem

- radiative transfer equation – **energy transport**:

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \qquad \Rightarrow \qquad J_\nu$$

- radiative equilibrium (+ convective energy transport for cool stars) – **energy conservation**:

$$\int_0^\infty H_\nu \, d\nu = \text{const.} = \frac{\sigma}{4\pi} T_{\text{eff}}^4 \qquad \Rightarrow \qquad T$$

- hydrostatic equilibrium – **momentum conservation**:

$$\frac{dP}{dz} = -\rho \cdot (g - g_{\text{rad}}) \qquad + \text{ideal gas} \qquad \Rightarrow \qquad N$$

- detailed equilibrium (LTE): Saha- & Boltzmann-formula

$$\frac{n_{\text{up}}}{n_{\text{low}}} = \frac{1}{n_e} \cdot 2 \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} \frac{g_{\text{up}}}{g_{\text{low}}} e^{-\left(\frac{E_{\text{up}} - E_{\text{low}}}{kT}\right)}$$

$$\frac{n_i}{n_j} = \frac{g_i}{g_j} e^{-\left(\frac{E_i - E_j}{kT}\right)}$$

- statistical equilibrium (NLTE): rate equations

$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) + n_i(R_{ik} + C_{ik}) = \sum_{j \neq i} n_j(R_{ji} + C_{ji}) + n_k(R_{ki} + C_{ki}) \qquad \Rightarrow \qquad n_i$$

- **charge conservation**:

$$\sum_i n_i Z_i - n_e = 0 \qquad \Rightarrow \qquad n_e$$

Modelling Approaches

usually:

LTE: **L**ocal **T**hermodynamic **E**quilibrium

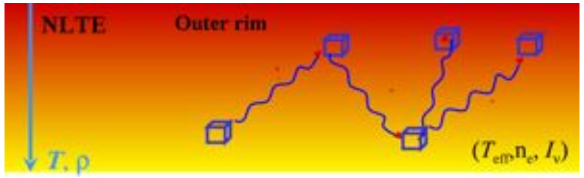
→ Saha-Boltzmann-Formulae, gf-values, line broadening

Limited **T**remendous **E**rror

hot supergiants: strong radiation field, low densities

non-LTE: **non-L**ocal **T**hermodynamic **E**quilibrium

→ rate equations, gf-values, line broadening, detailed level-coupling, zillions of atomic cross-sections



non-Limited **T**remendous **E**rror

(Restricted) non-LTE problem

- transfer equation

$$\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu$$

- statistical equilibrium:

$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji})$$

- radiative rates:

$$R_{ij} = 4\pi \int \sigma_{ij} \frac{J_\nu}{h\nu} \, \mathrm{d}\nu$$

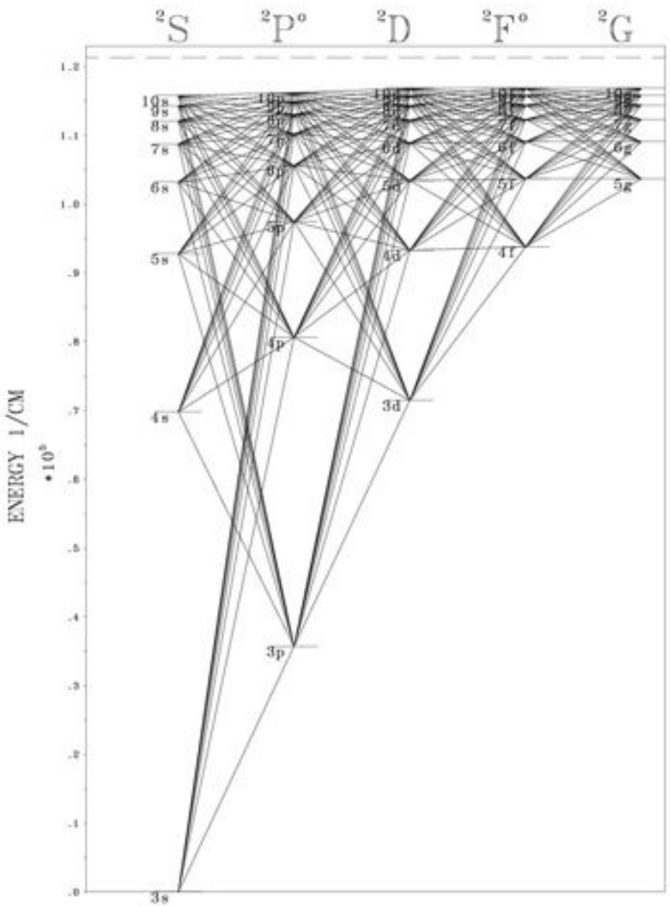
non-local

- collisional rates:

$$C_{ij} = n_e \int \sigma_{ij}(v) f(v) v \, \mathrm{d}v$$

local

- excitation, ionization, charge exchange, dielectronic recombination, etc.



MgII: Przybilla et al. (2001)

→ model atoms ... *required for many elements/ions*

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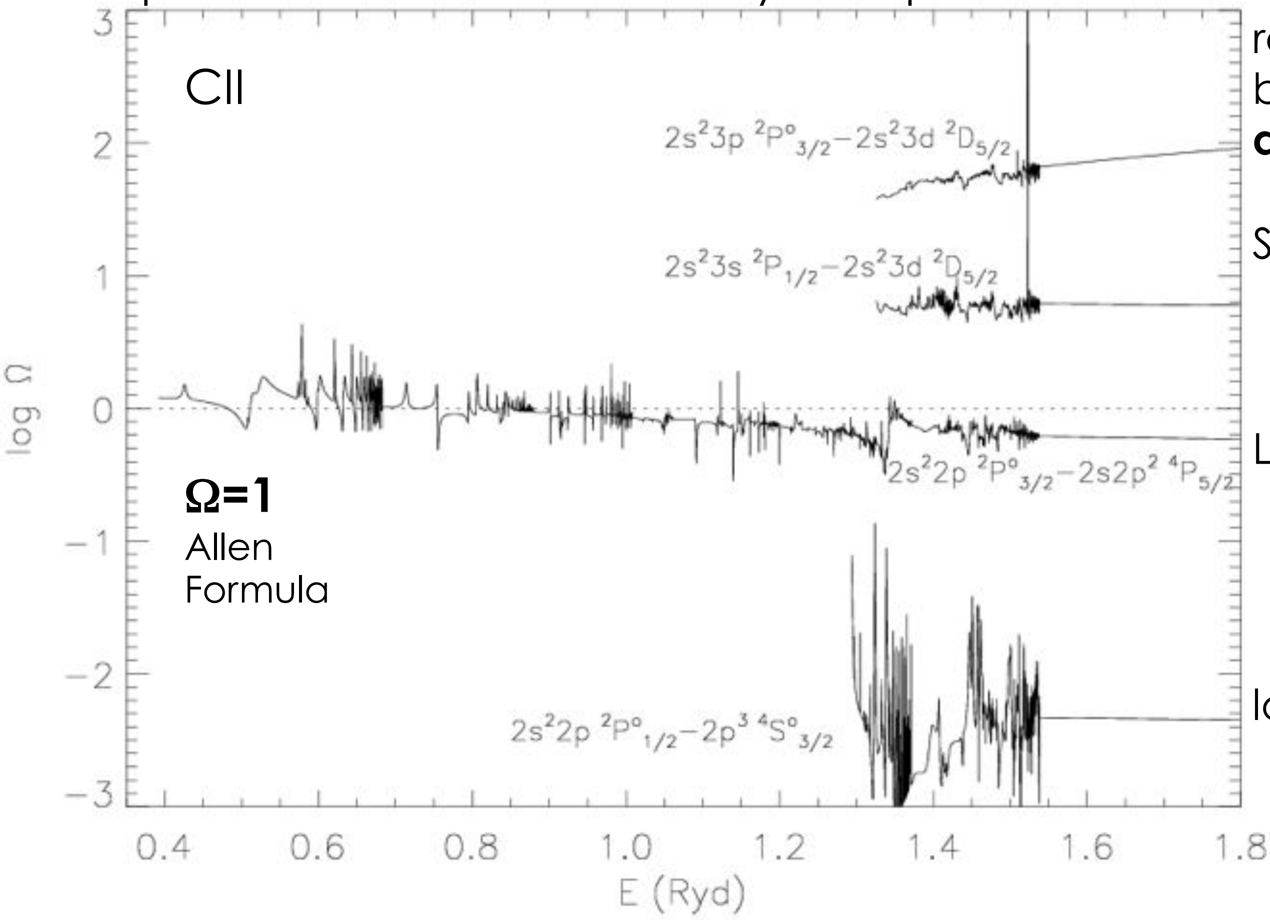
Atomic data

Example: collisional excitation by e⁻-impact



huge amounts of atomic data: OP/IRON Project & own

replacing approximations by **experimental** or **ab-initio data**

Schrödinger equation

$$H_{N+1}\Psi = E\Psi$$

LS-coupling:

$$H_{N+1} = \sum_{i=1}^{N+1}\left\{-\nabla_i^2 - \frac{2Z}{r_i} + \sum_{j>i}^{N+1}\frac{2}{r_{ij}}\right\}$$

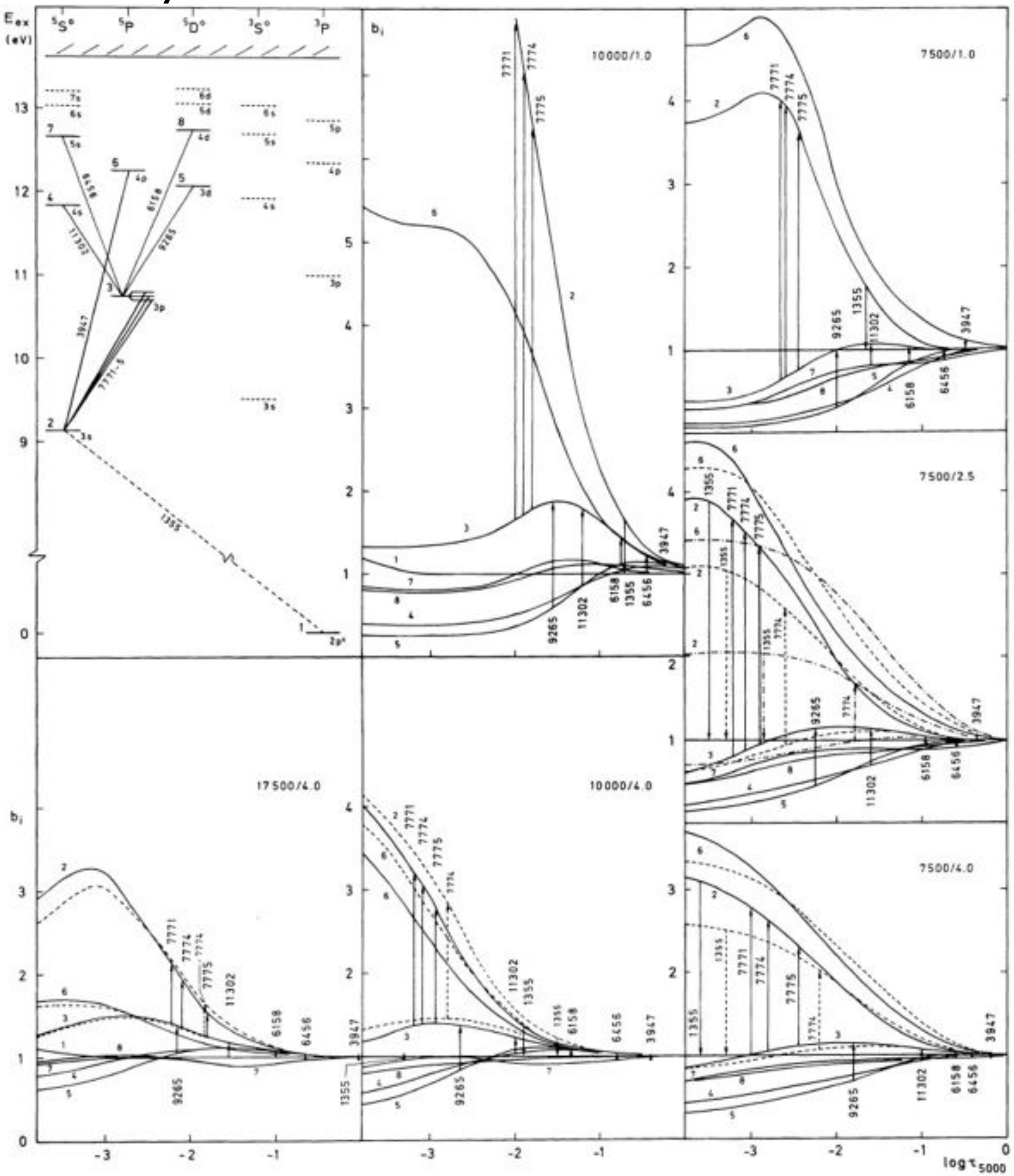
low-Z Breit-Pauli Hamiltonian

$$H_{N+1}^{\mathrm{BP}} = H_{N+1} + H_{N+1}^{\mathrm{mass}} + H_{N+1}^{\mathrm{Dar}} + H_{N+1}^{\mathrm{so}}$$

Methods:

- R-matrix/CC approximation
- MCHF
- CCC

Early non-LTE studies



Baschek et al. (1977)

Non-LTE departure coefficients

$$b_i = \frac{n_i^{NLTE}}{n_i^{LTE}}$$

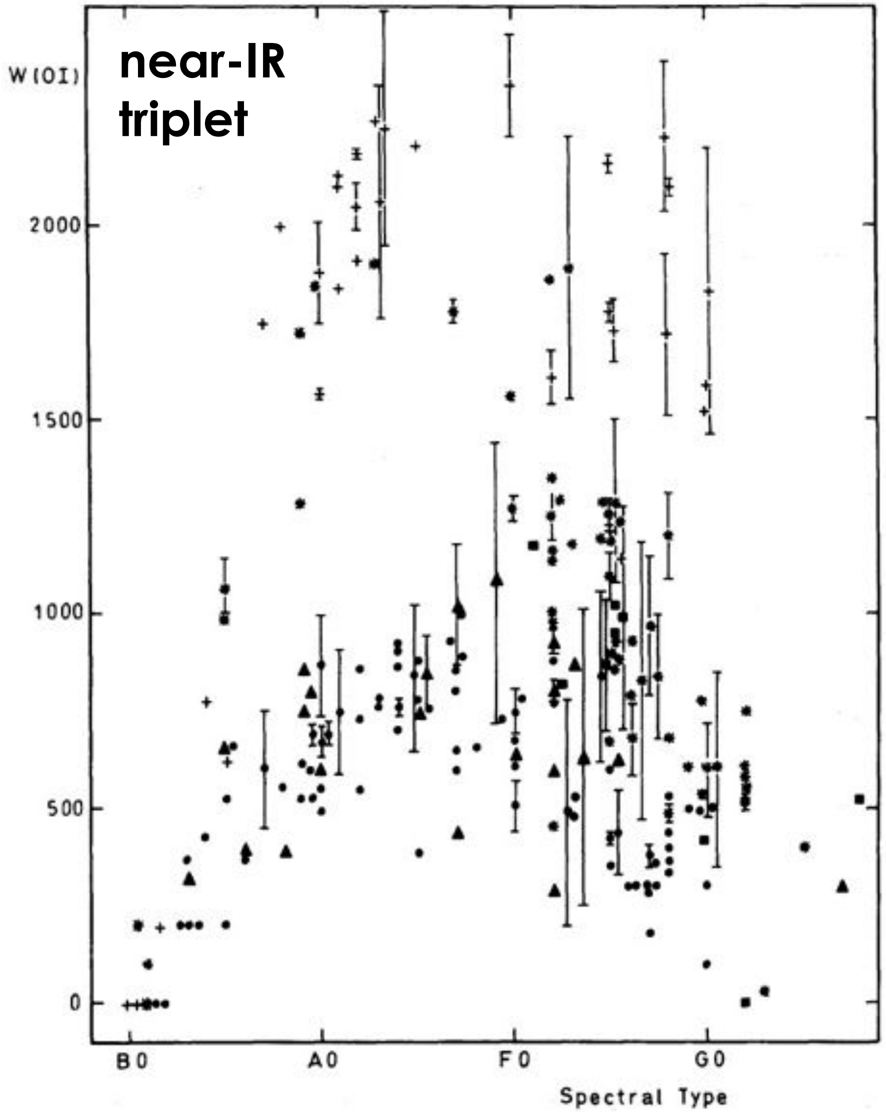
qualitative reproduction of observed trends:
non-LTE line-strengthening

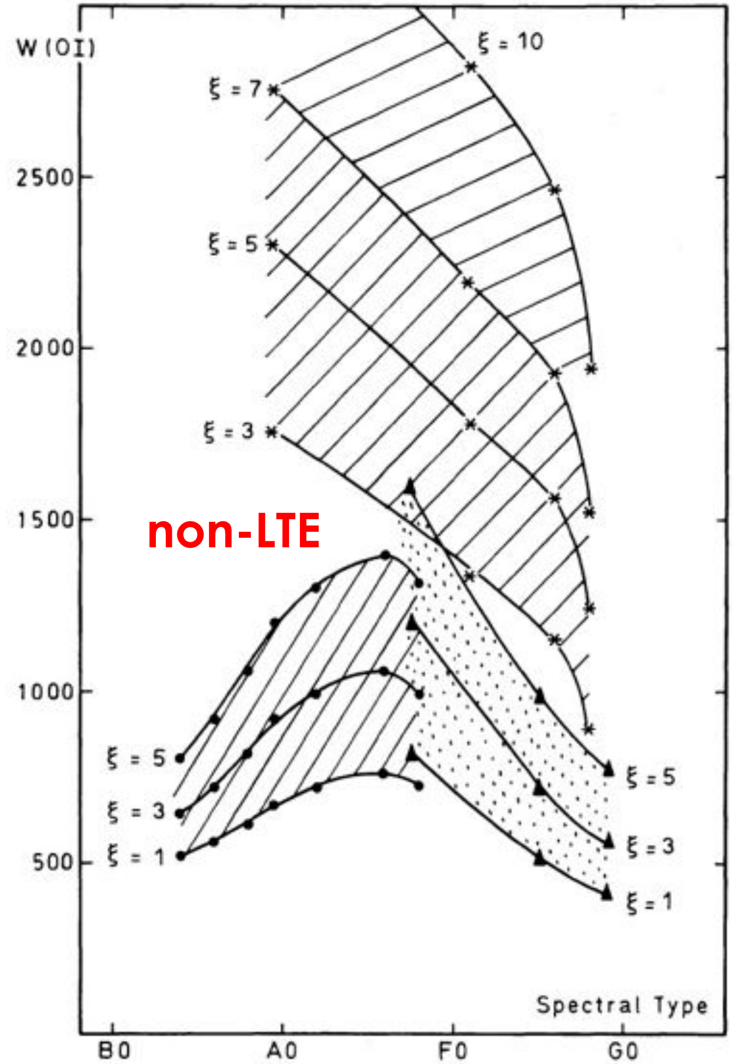
but:

- no metal-line blanketing
- no metal-line blocking
- simplified model atom
- restricted quality of atomic data

Early non-LTE studies

Faraggiana et al. (1988)





interpolation and application of Baschek et al. (1977) results

→ quantitative agreement

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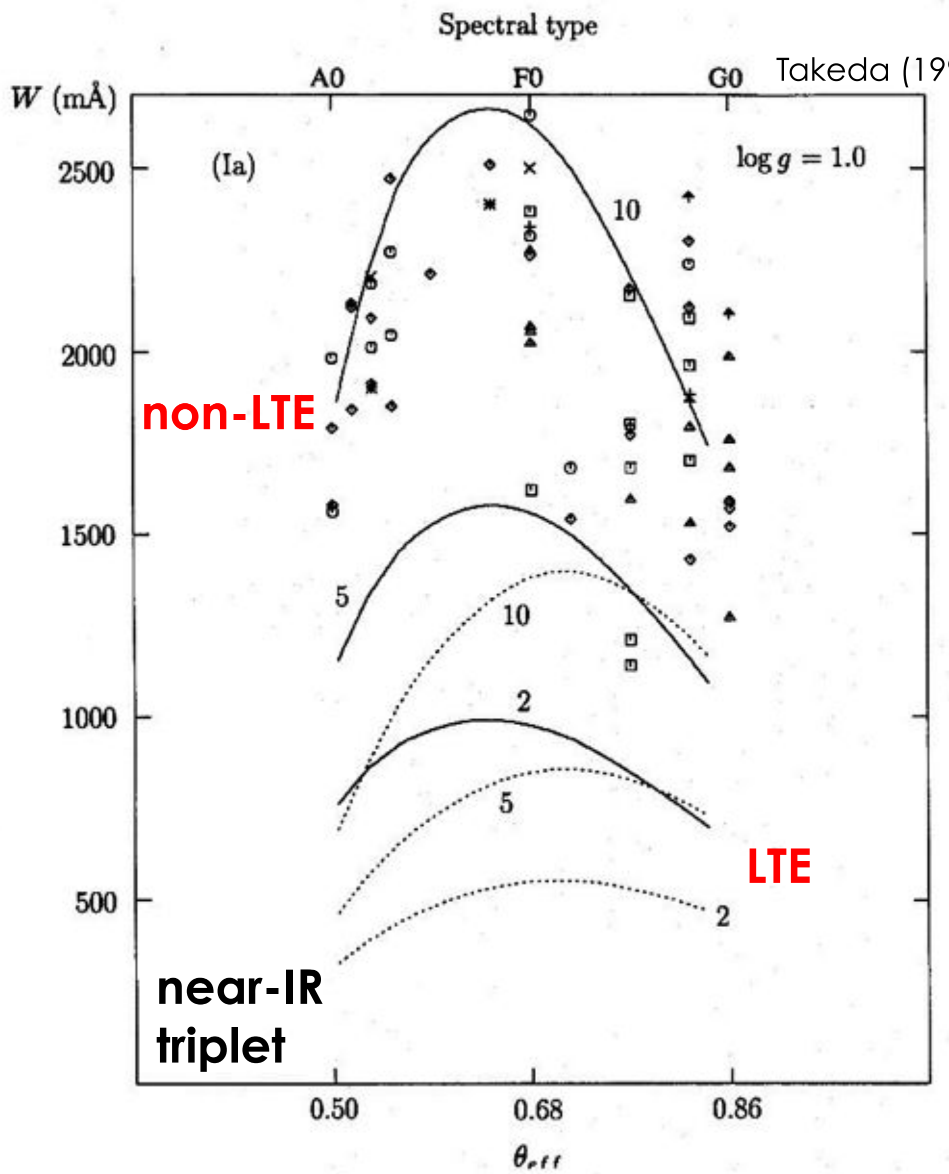
Early non-LTE studies



Takeda (1992)

- improved model atmospheres
- extended model atom
- improved atomic data (OP)

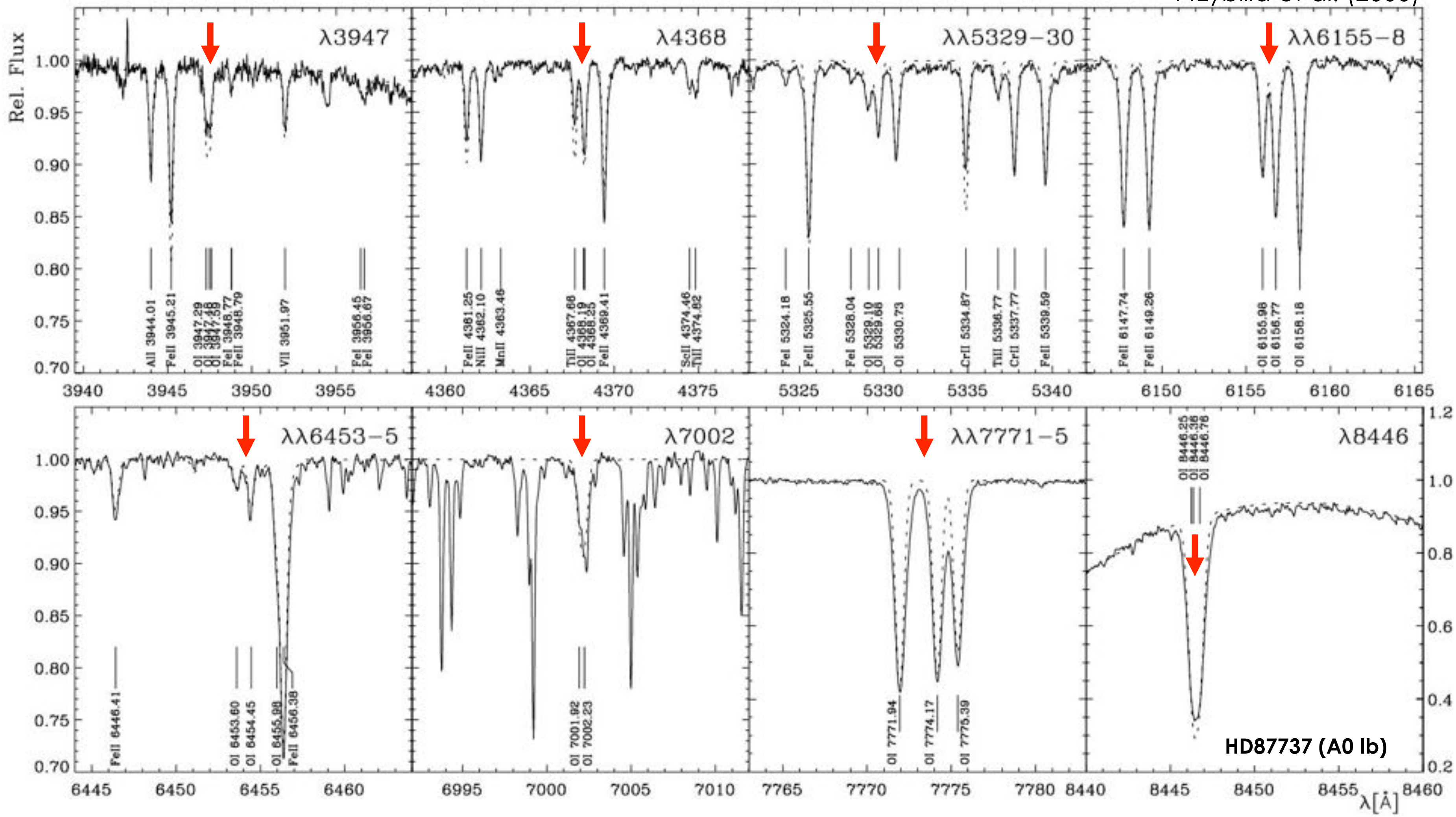
→ quantitative agreement for supergiants

but:

- equivalent widths, no line-profile studies
- consistency from all observable lines?

Most recent non-LTE study: Line Fits

Przybilla et al. (2000)



good overall agreement feasible ... with lots of improvements ...

NLTE Diagnostics: Stellar Parameters

using **robust analysis methodology** &
comprehensive model atoms

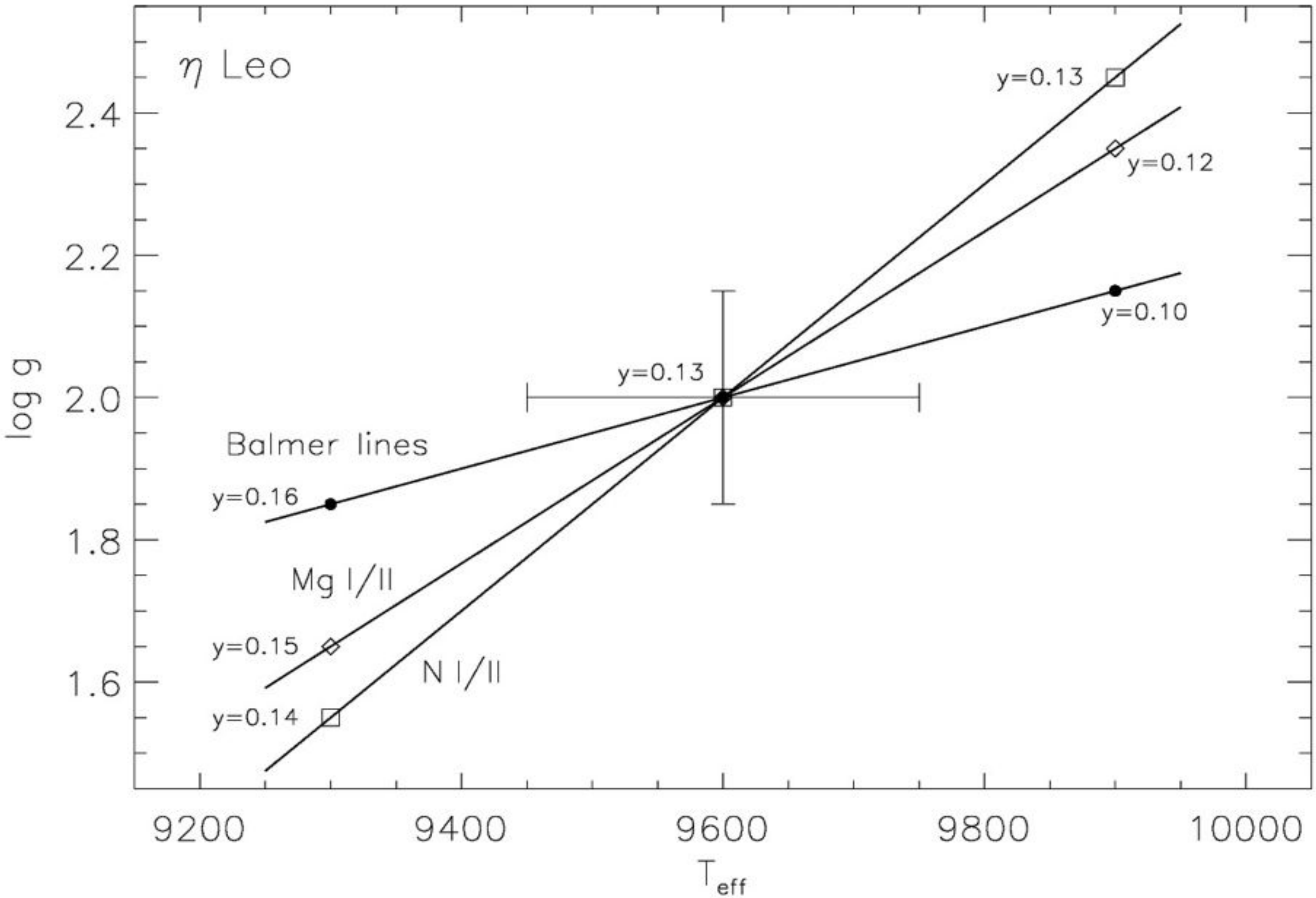
minimising systematics !

- ionization equilibria → T_{eff}
  elements: e.g. C I/II, N I/II, O I/II, Mg I/II, Si II/III, S II/III, Fe II/III
  $\Delta T_{eff} / T_{eff}$ ~ 1…2% usually: 5…10%
- Stark broadened hydrogen lines → log g
  Δ log g ~ 0.05…0.10 (cgs) usually: 0.2
- microturbulence, helium abundance, metallicity

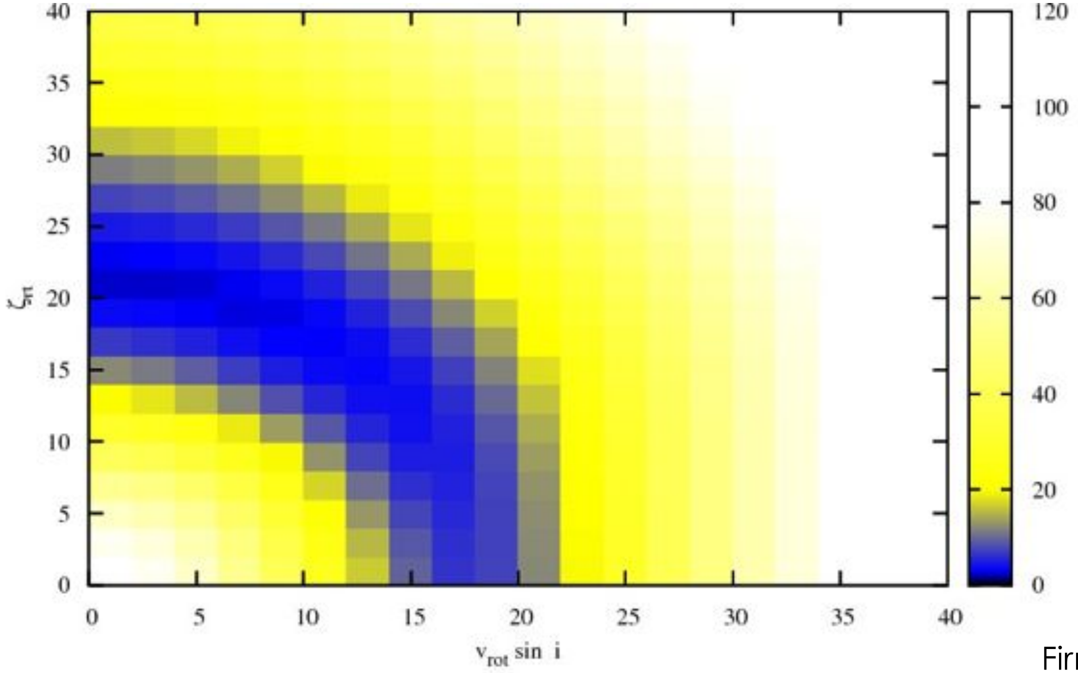
+ other constraints, where available: SED's, near-IR, …

- abundances: **Δlogε ~ 0.05...0.10 dex** (1σ-stat.) usually: factor ~2
  Δlogε ~ 0.07...0.12 dex (1σ-sys.) usually: ???

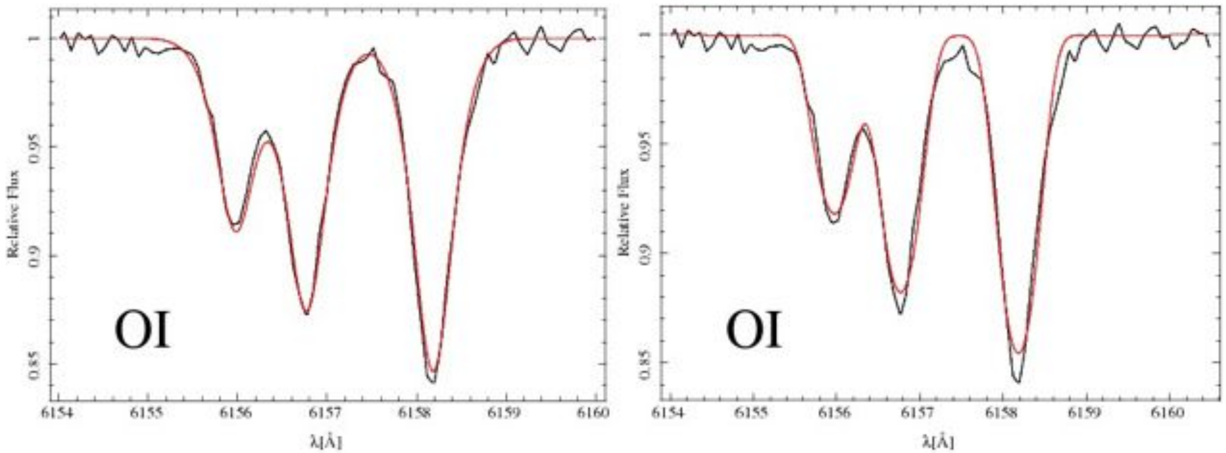
Przybilla et al. (2006)



Przybilla et al. (2006)



Firnstein & Przybilla (2012a)



deviations >0.5 dex at a factor 10

Przybilla et al. (2006)

Przybilla et al. (2000)

Table 1. Uncertainties in the non-LTE analysis of O I

	changes in $\log \varepsilon(\mathrm{O})_{\mathrm{NLTE}}$		
	8500/1.0	10000/1.5	15000/2.0
Atmospheric parameters:			
T_{eff} -150 K	−0.09	−0.04	−0.02
$\log g$ $+0.15$	−0.09	−0.05	−0.06
ξ $+1$ km s^{-1} [a]	−0.05	−0.01	±0.00
Line transitions:			
Oscillator strengths +10%	−0.06	−0.06	−0.05
Damping constant ∗0.5, ∗2	±0.00	±0.00	±0.00
Photoionizations:			
Cross-sections +10%	±0.00	±0.00	±0.00
Cross-sections ∗5	+0.17	+0.23	+0.30
Collisional transitions[b]:			
Cross-sections ∗0.1	−0.05	−0.05	−0.06
Cross-sections ∗0.5	−0.02	−0.03	−0.03
Cross-sections ∗2	+0.04	+0.03	+0.04
Cross-sections ∗10	+0.14	+0.14	+0.17
Collisional ionization:			
Cross-sections ∗0.1, ∗10	±0.00	±0.00	±0.00
Charge exchange reaction:			
Rate coefficients ∗0.1, ∗10	±0.00	±0.00	±0.00
Continuum placement	±0.05	±0.05	±0.05
Estimated total uncertainty	±0.16	±0.11	±0.10

[a] mean values without the near-infrared transitions
[b] mean values without the near-infrared transitions which can show deviations >0.5 dex at a factor 10

→ fine ruler

NLTE Diagnostics: Stellar Parameters

using **robust analysis methodology** &
comprehensive model atoms

minimising systematics !

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  elements: e.g. C I/II, N I/II, O I/II, Mg I/II, Si II/III, S II/III, Fe II/III
  $\Delta T_{eff} / T_{eff}$ ~ 1…2% usually: 5…10%
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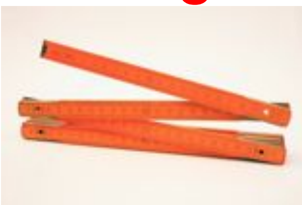


→

→ fine ruler

Elemental Abundances

Przybilla et al. (2006)

artifact

artifact

artifact

- non-LTE:
  absolute abundances
  reduced uncertainties
  Δ log ε:
  ~ 0.05 - 0.10 dex (1σ-stat.)
  ~ 0.10 dex (1σ-syst.)

  reduced systematics

- typical uncertainties in literature:
  factor ~2 (1σ-stat.)
  + unknown syst. errors

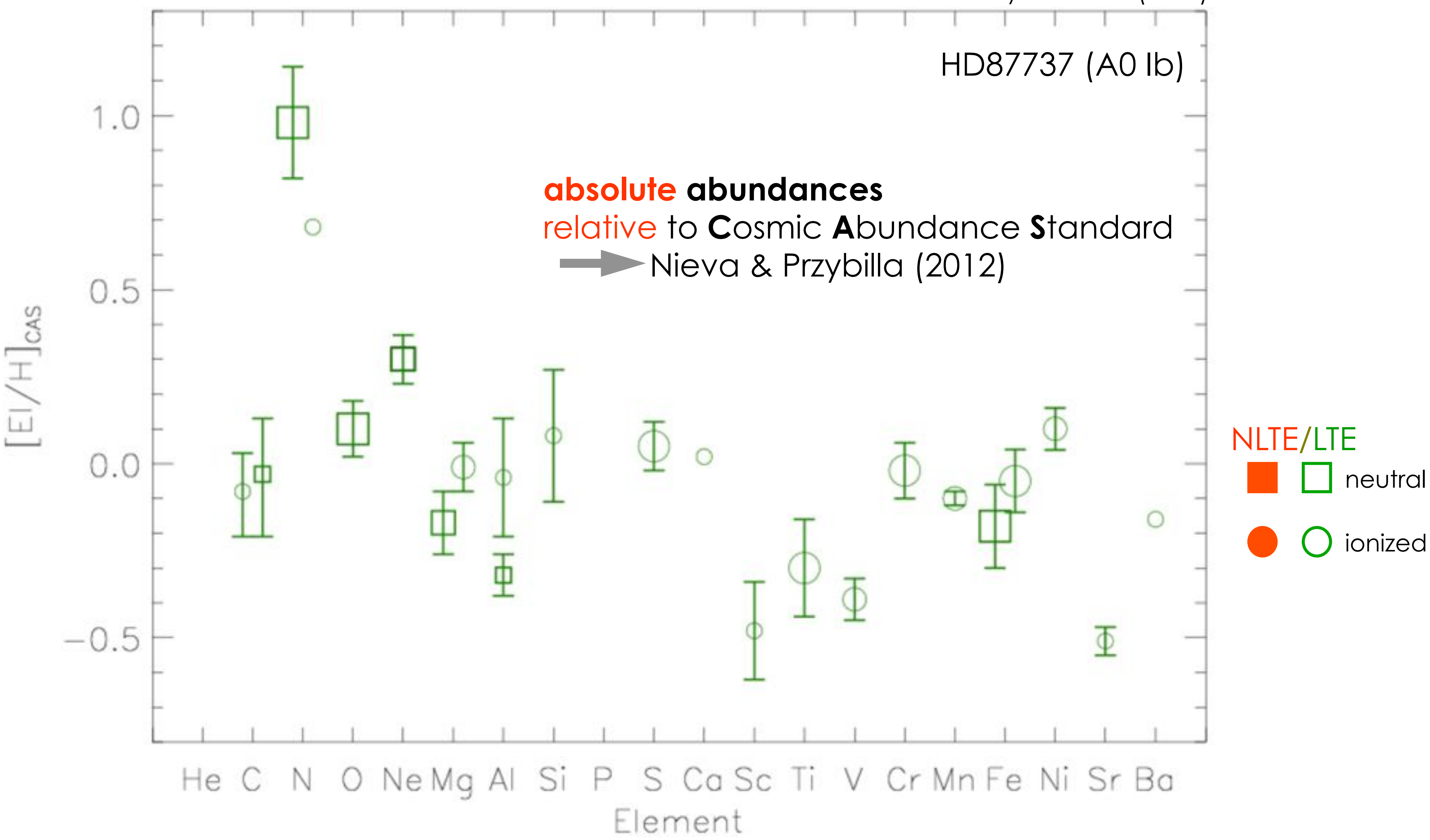
NLTE/LTE

■ □ neutral

● ○ ionized

Elemental Abundances

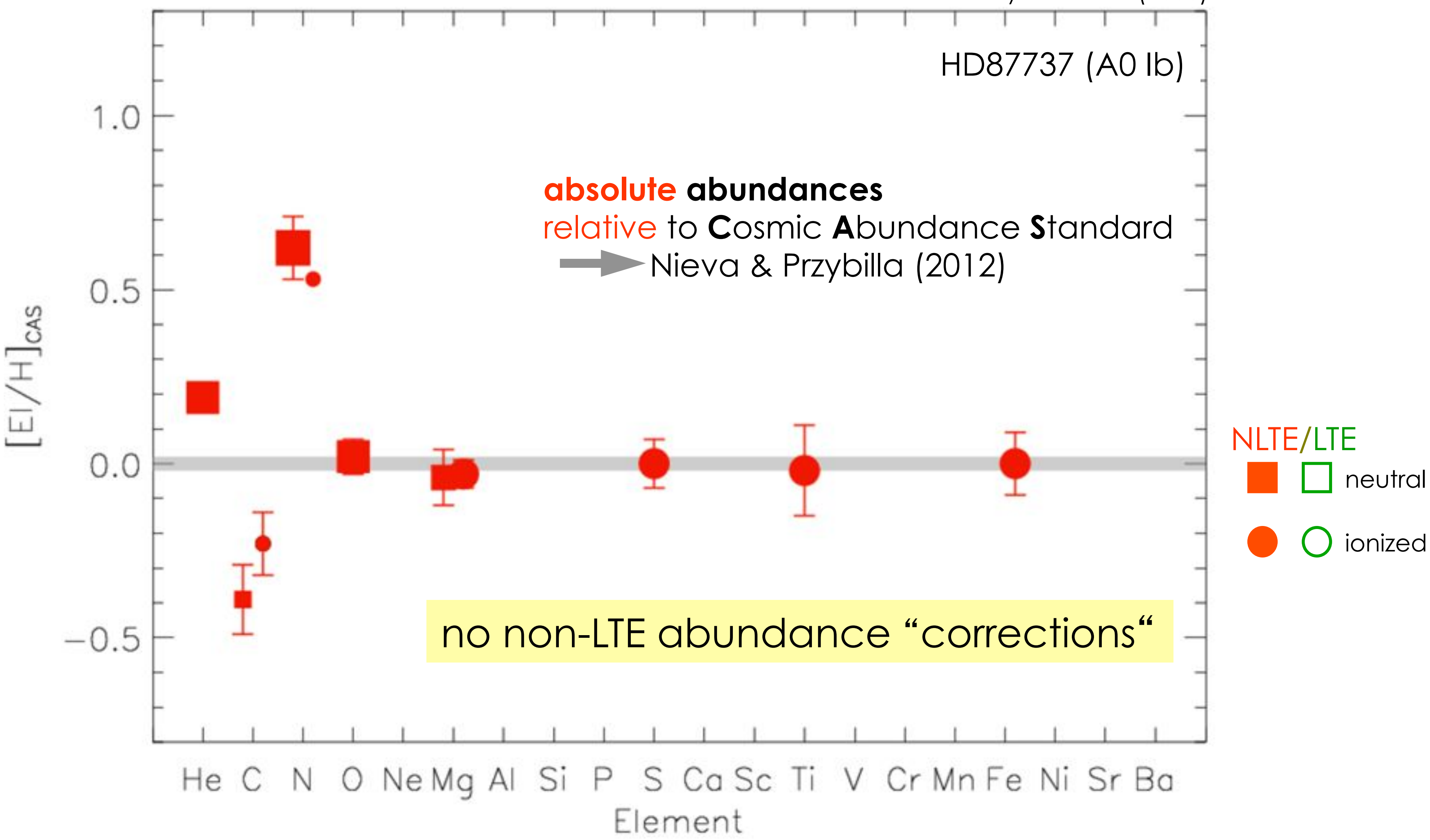
Przybilla et al. (2006)



- LTE: abundance pattern? - large uncertainties

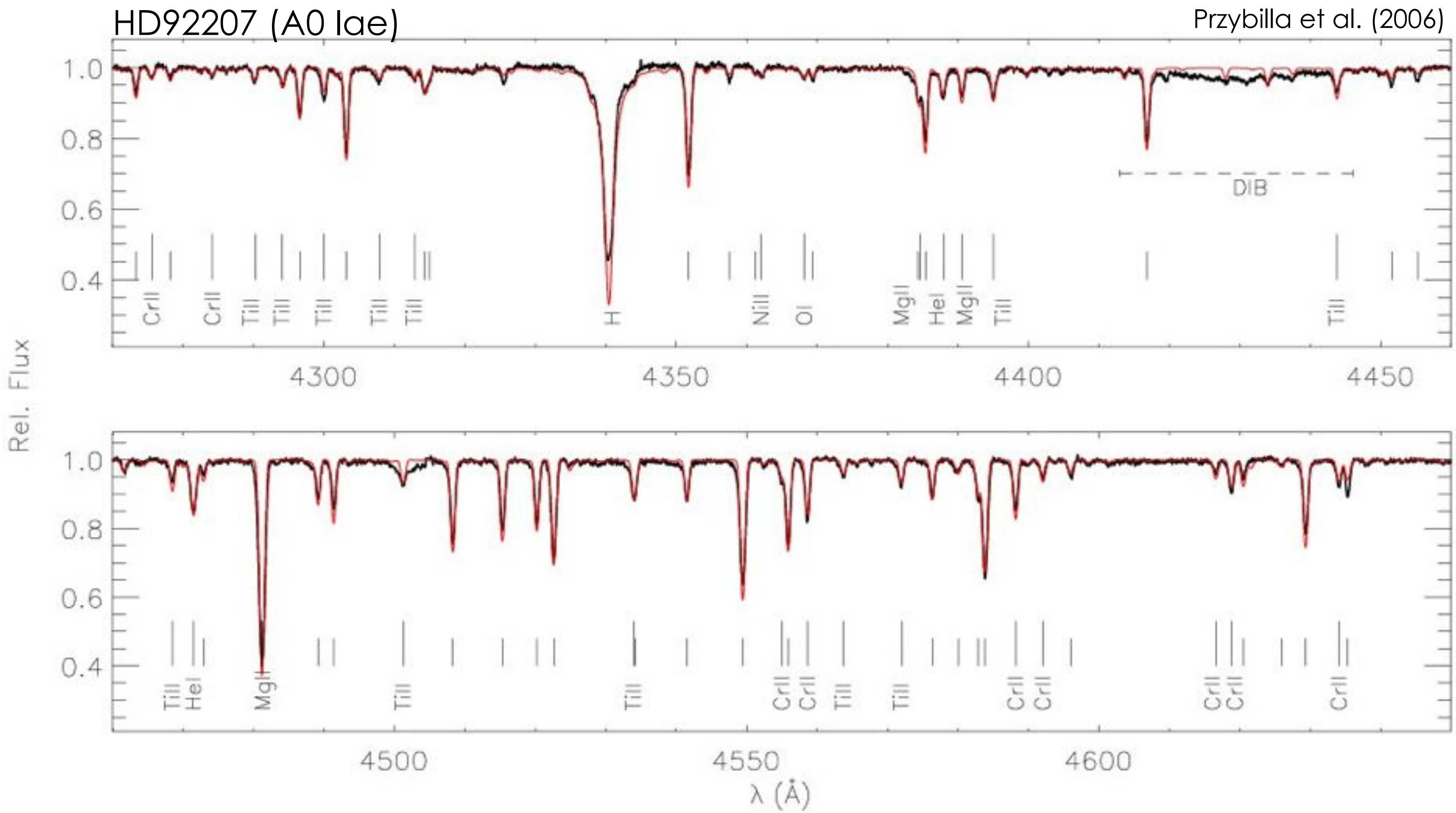
Elemental Abundances

Przybilla et al. (2006)



- non-LTE: consistency & reduced uncertainties

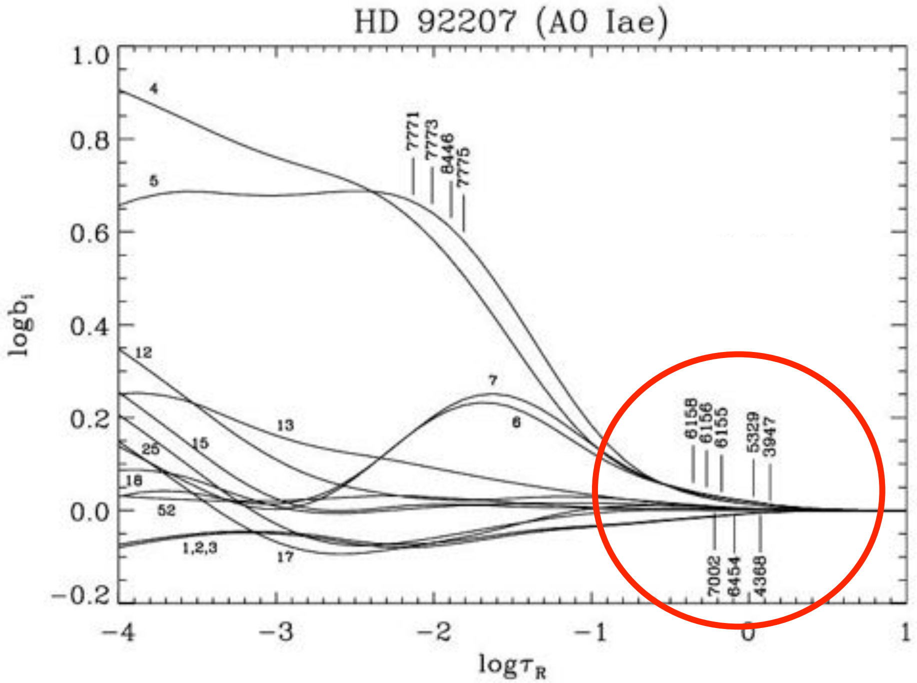
Spectroscopy @ High-res & High-S/N

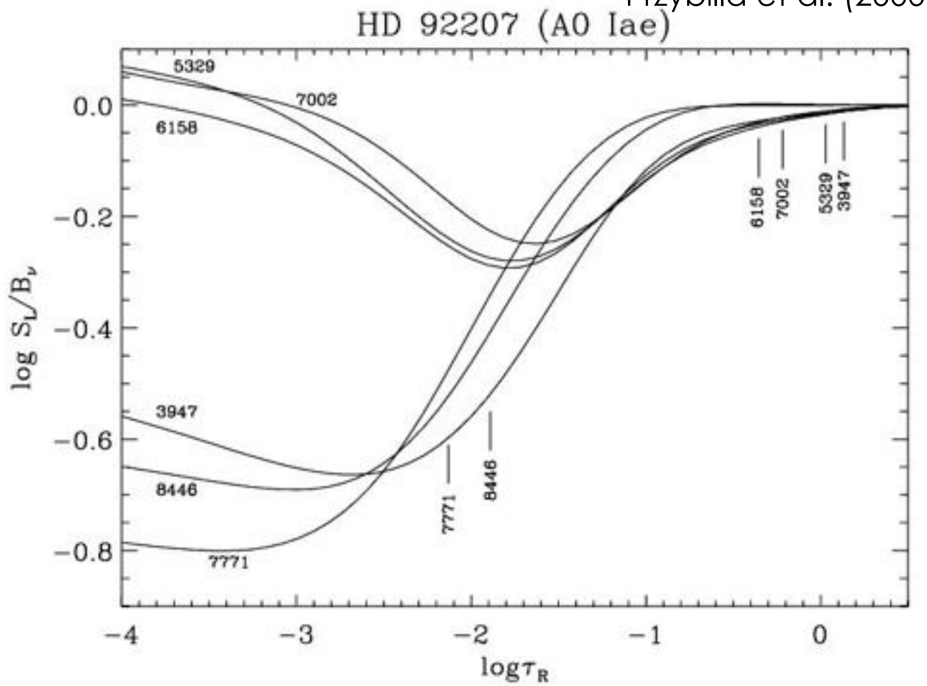


- several 10^4 lines: ~30 elements, 60+ ionization stages
- complete spectrum synthesis in visual (& near-IR) ~70-90% in NLTE

Back to oxygen: non-LTE effects

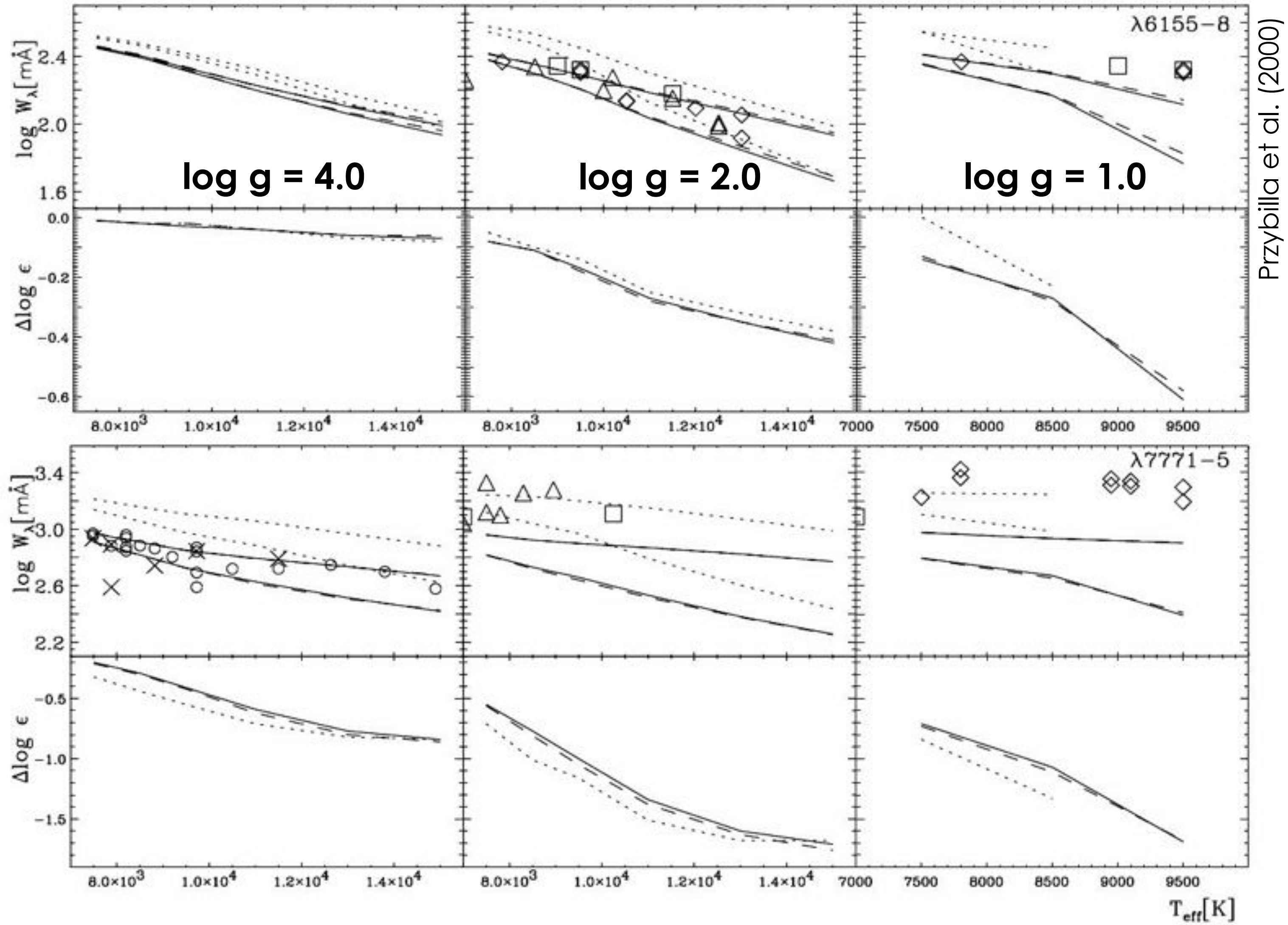
Przybilla et al. (2000)





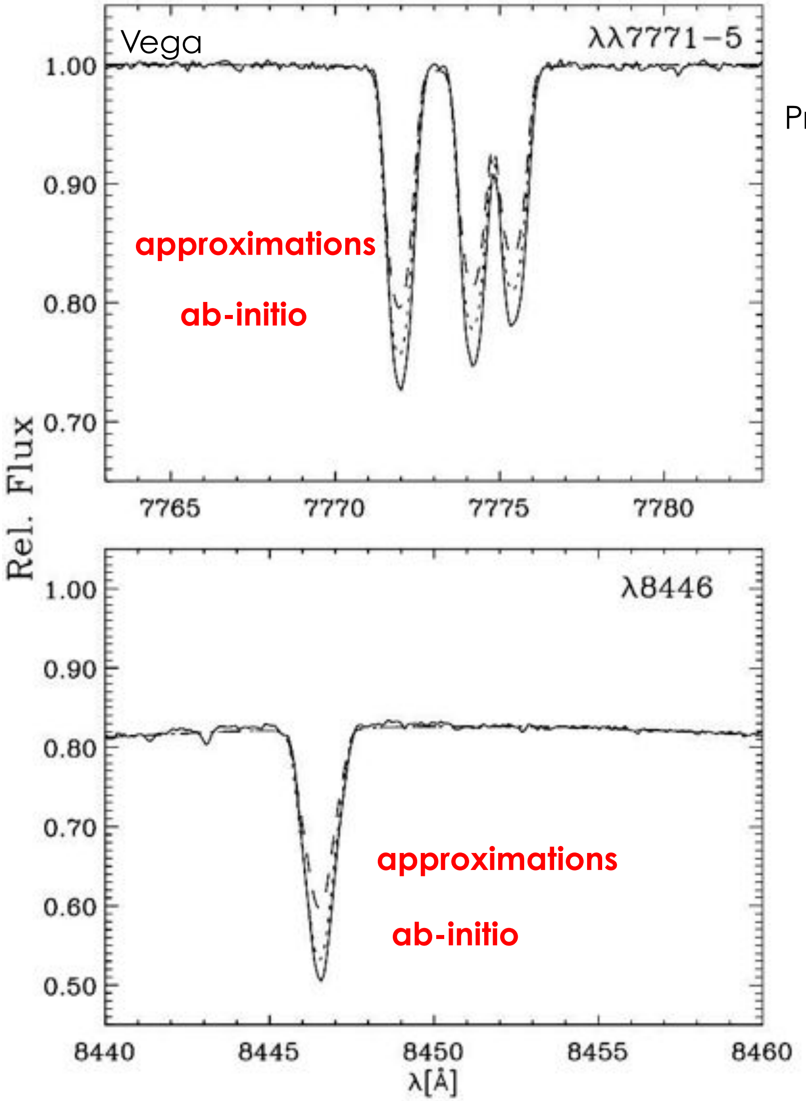
- non-LTE overpopulation of lower levels of transitions
- photon losses lead to outward drop of line source function
  deeper line cores in NLTE
- ~10% NLTE overpopulation → 0.5 dex change in abundance
- up to ~2 dex changes in abundances from strong lines

Back to oxygen: non-LTE effects



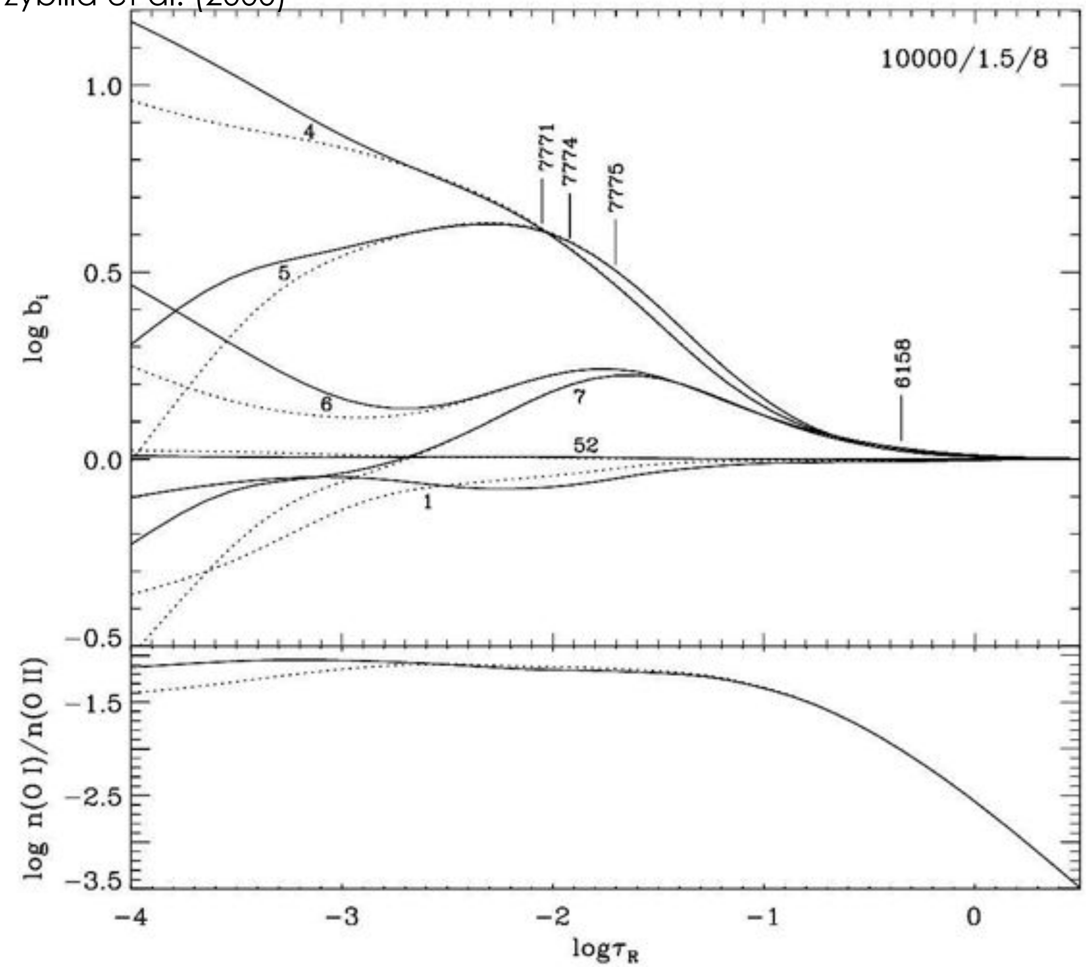
Non-LTE effects

- collisional data



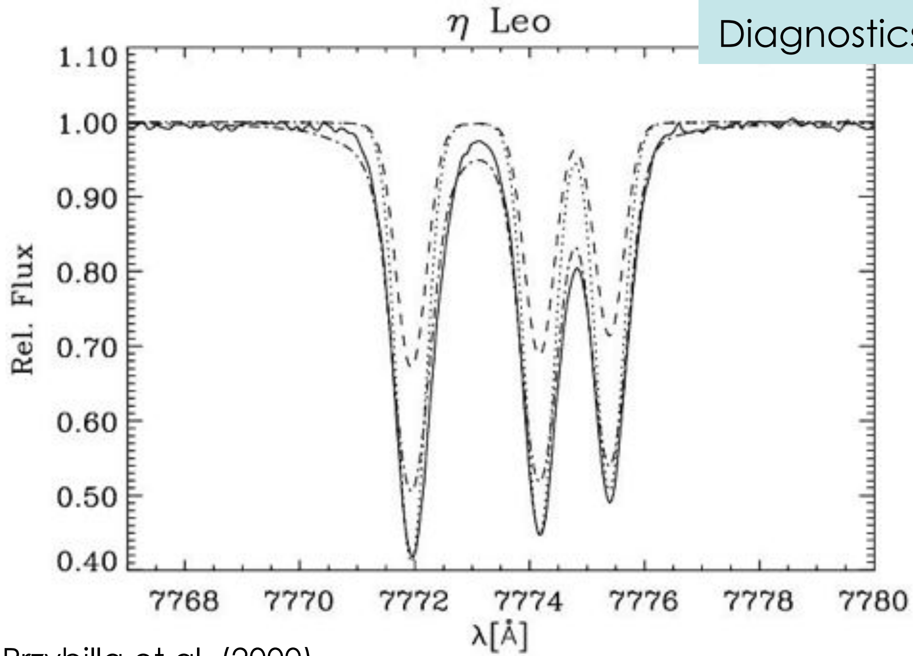
- charge exchange reaction with hydrogen near-resonant

Przybilla et al. (2000)

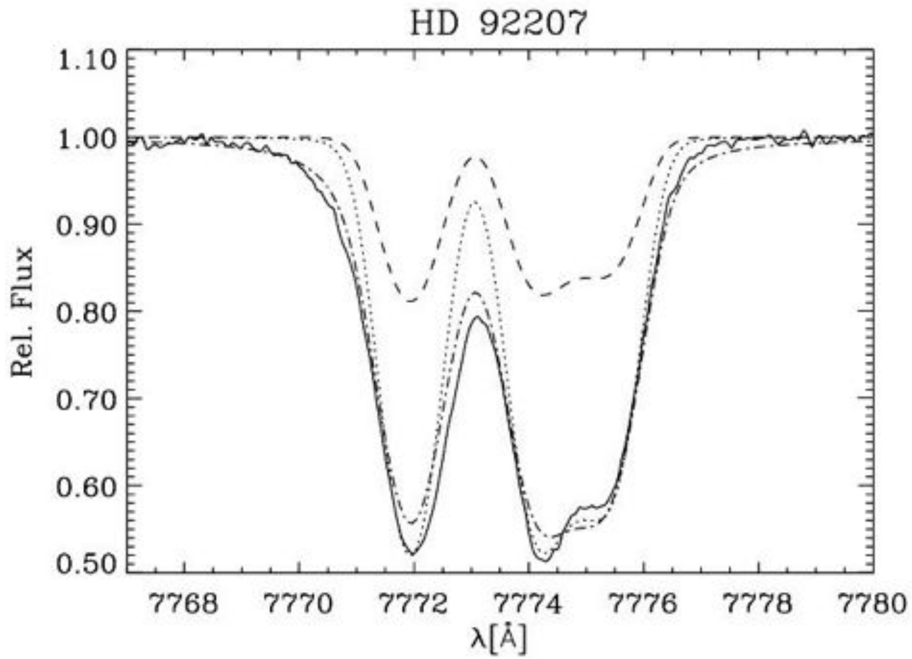


A grain of salt: strong near-IR lines

- LTE line profiles never fit despite observed EW reproduced
- non-LTE line depth ~ ok
- non-LTE profiles not broad enough: quest for
  - detailed line-broadening tabes?
  - depth-dependent turbulence/ hydrodynamic models?
- analogy to Hα/hydro models



Przybilla et al. (2000)



Results

using **non-LTE modelling** and **comprehensive analysis techniques**
absolute oxygen abundance determinations feasible for BA-SGs
@ high precision and accuracy:

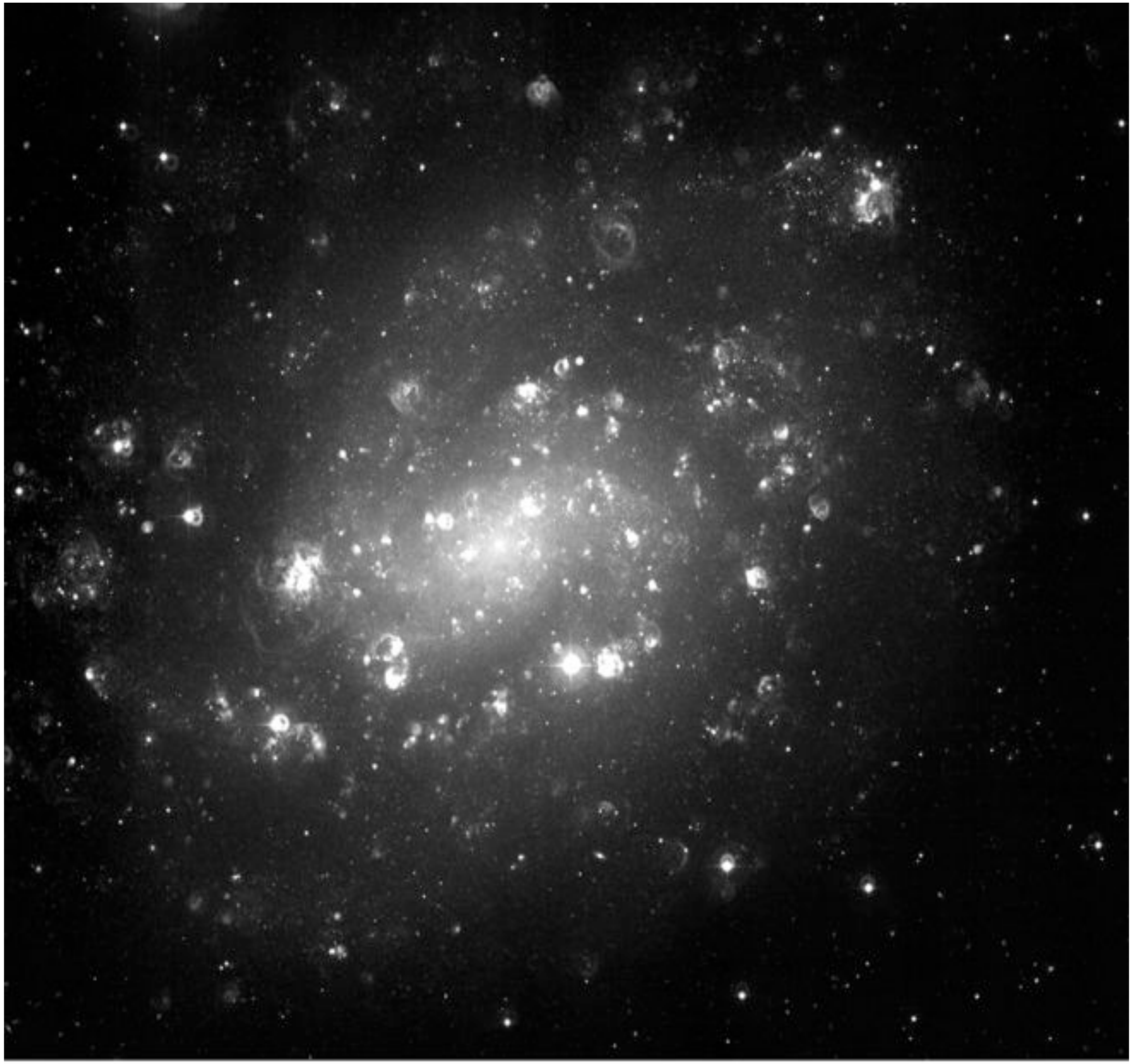
- **0.05-0.10 dex (1σ statistical uncertainty)**
- **~0.10 dex (1σ systematic uncertainty)**

- mean oxygen abundance from BA-supergiants
  in **solar neighbourhood** (<1kpc distance):
  $(\log O/H + 12)_{SN} = 8.78 \pm 0.03$ (19 targets)

CAS: **8.76 ± 0.05** (Nieva & Przybilla 2012)

Extragalactic Abundances

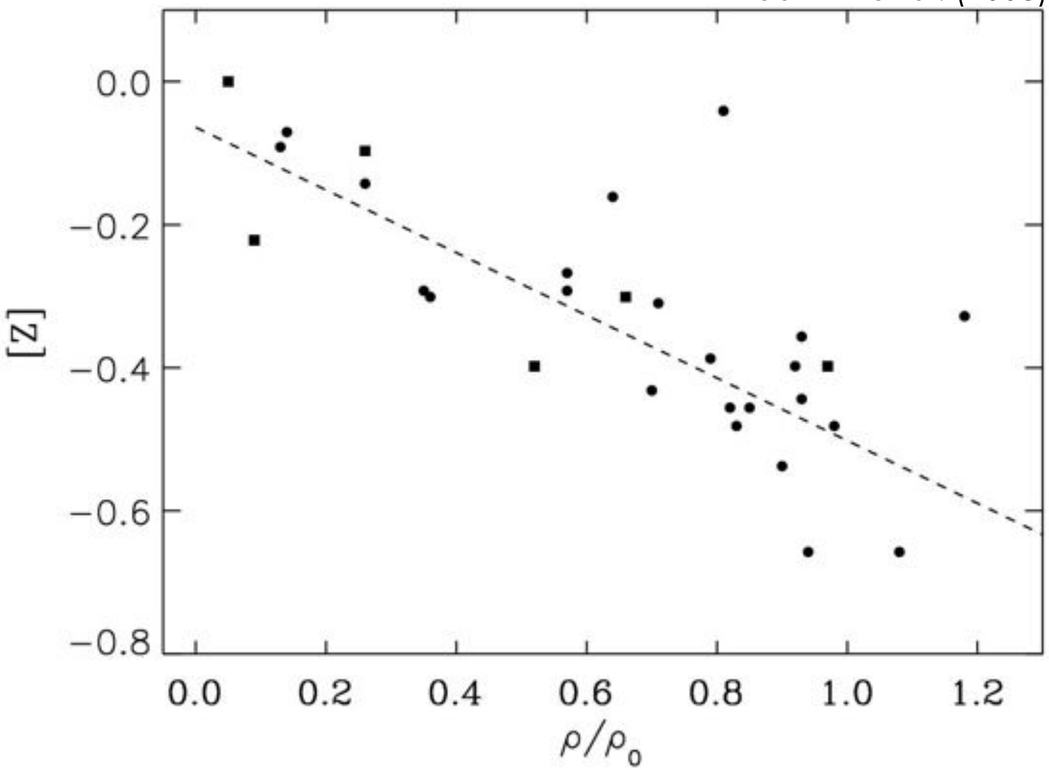
- so far:
  HII regions
  only indicators for abundances
  in nearby galaxies:
  He, N, O, Ne, S
- **verification** and **extension** via **stars**



ESO PR Photo 18c/02 (7 August 2002)

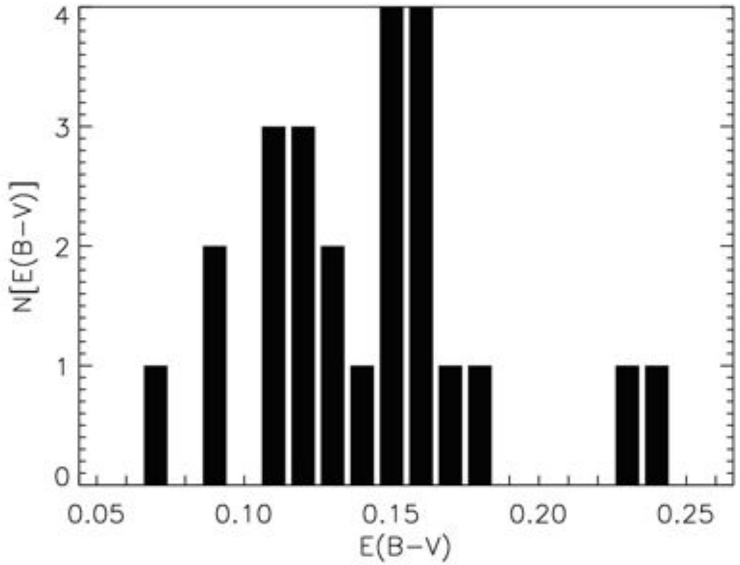
Spiral Galaxy NGC 300 (H-alpha band)
(MPG/ESO 2.2-m + WFI)

Kudritzki et al. (2008)



NGC300

- radial trend of chemical abundances
- azimutal variation?
- investigate interstellar absorption
- distance determination → FGLR



metallicity gradient:
30 B & A-type supergiants

To be expected:
improvements on
Cepheid distance scale

interstellar
extinction
within NGC300

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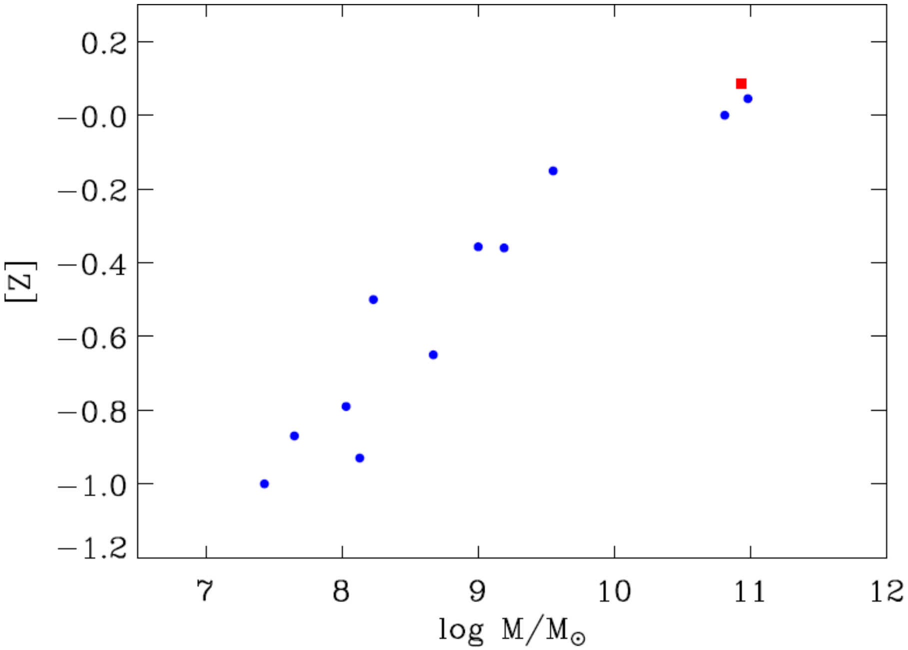
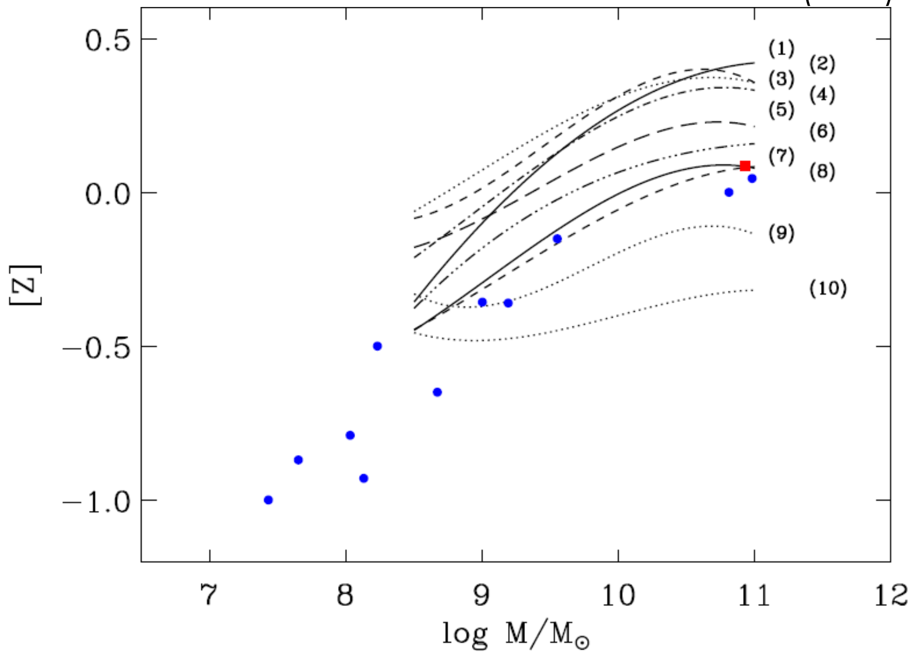
Mass-metallicity relationship



stellar

Local Group and beyond

Kudritzki et al. (2012)



stellar
vs.
strong line analyses of HII regions

→ investigate and minimise
systematic bias of extragalactic metallicities