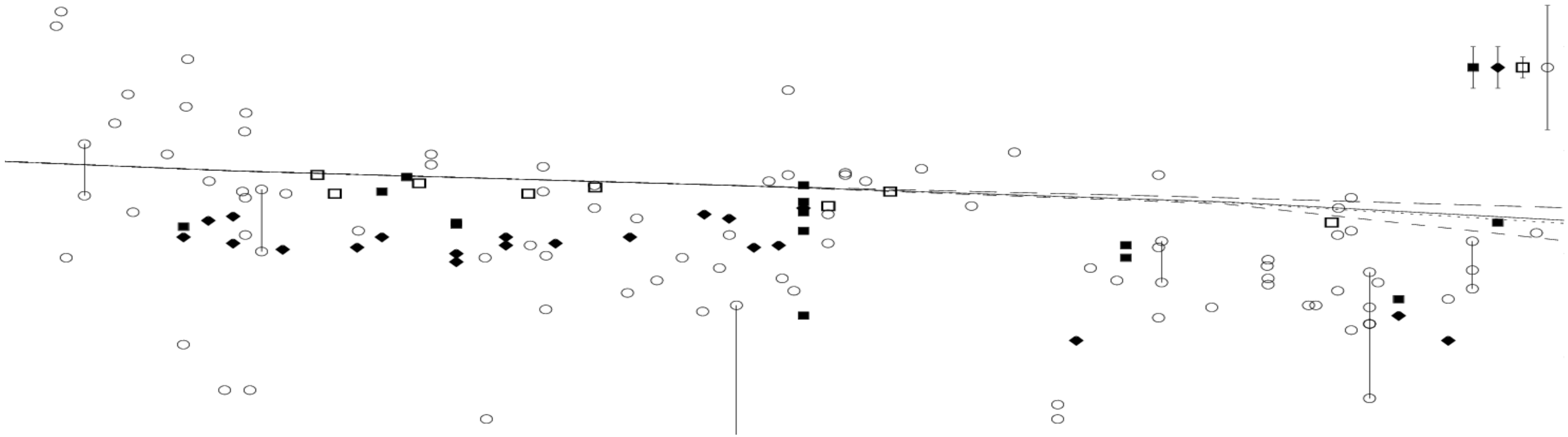

The radial metallicity gradient
from
OB star and HII region studies

Norbert Przybilla

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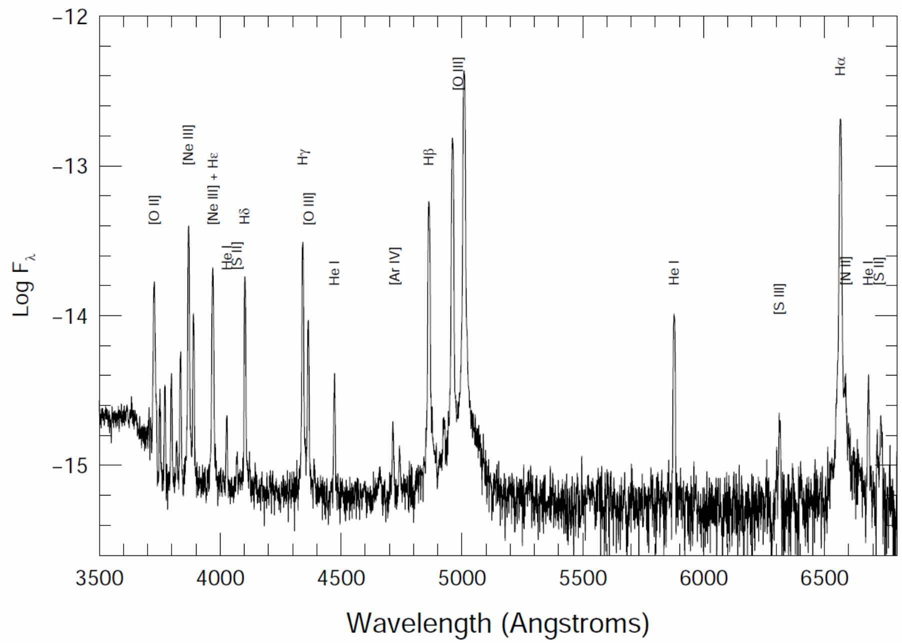
NATURWISSENSCHAFTLICHE FAKULTÄT

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

HII regions



- emission-line spectra:
  He, C, N, O, Ne, S, Ar
- excited by OB stars
  → present-day abundances
- $T_e \sim 10^4$ K, $n_e \sim 10^2 - 10^4$ cm^{-3}

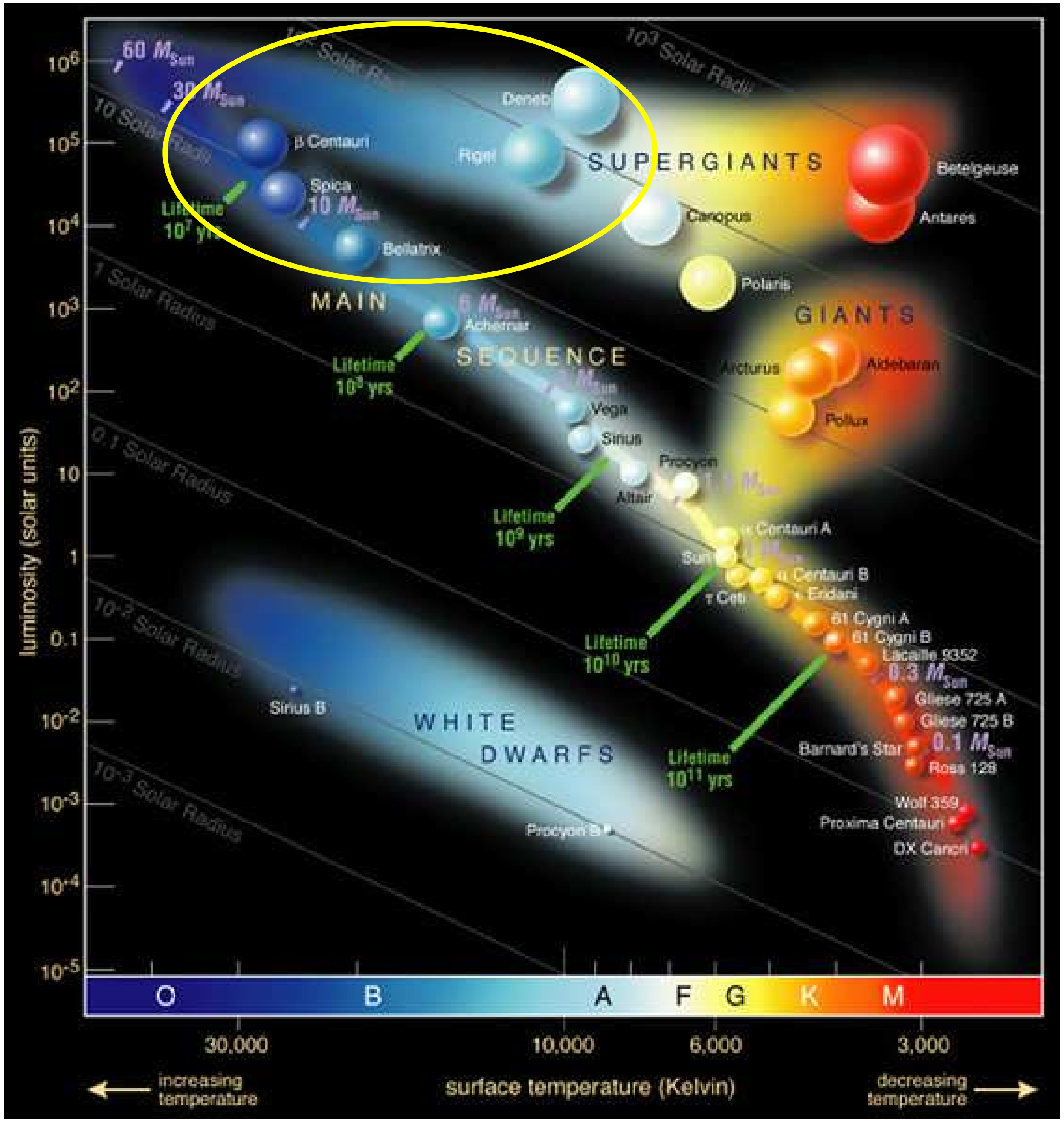
abundance determination from

- Recombination Lines (RL) or Collisionally Excited Lines (CEL)

via
- direct method/requires measurement of weak [OIII] 4363 Å line
- strong-line methods/calibration needed
- photoionisation models

complications: dust depletion & ICF's
temperature fluctuations?

OB Stars $M \sim 8 \ldots 30\ M_\odot$



- dominate energy and momentum budget of ISM in galaxies
- key drivers for cosmic cycle of matter
- highly luminous
  - abundance indicators over large distances CNO/α-elements/iron-group
- short-lived → present-day abundances
- simple atmospheres:
  - radiative envelopes
  - weak winds
  - no diffusion
  - NLTE treatment required

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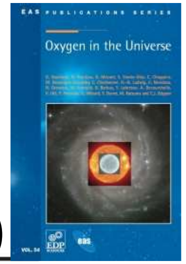


Metallicity gradient from HII regions

- oxygen as metallicity substitute for HII regions and OB stars

Stasinska et al. (2012)

d log(O/H) / dR [dex kpc^{-1}]	$A(O)_0$	range [kpc]	number of objects	references
-0.13 ± 0.04	8.9	8–14	5	Peimbert *et al.* (1978)[a]
-0.067 ± 0.017	9.38 ± 0.04	4–14	35	Shaver *et al.* (1983)[b]
-0.064 ± 0.009	9.15 ± 0.06	0–12	34	Afflerbach *et al.* (1997)[c]
-0.040 ± 0.005	8.82 ± 0.05	5–15	34	Deharveng *et al.* (2000)[d]
-0.044 ± 0.010	9.04 ± 0.08	6–10	6	Esteban & Peimbert (1995)[e]
-0.035 ± 0.006	8.77 ± 0.05	6–10	6	Esteban & Peimbert (1995)[f]
-0.060 ± 0.010	9.19 ± 0.04	6–18	70	Rudolph *et al.* (2006)[g]
-0.041 ± 0.014	8.67 ± 0.05	0–15	68	Rudolph *et al.* (2006)[h]
-0.03 ... -0.07 azimuthal variation		5-22	133	Balser *et al.* (2011)

- ‘steep‘ and ‘shallow‘ solutions for abundance gradient
- wide variation of (extrapolated) central oxygen abundance

Metallicity gradient from OB stars

Stasinska et al. (2012)

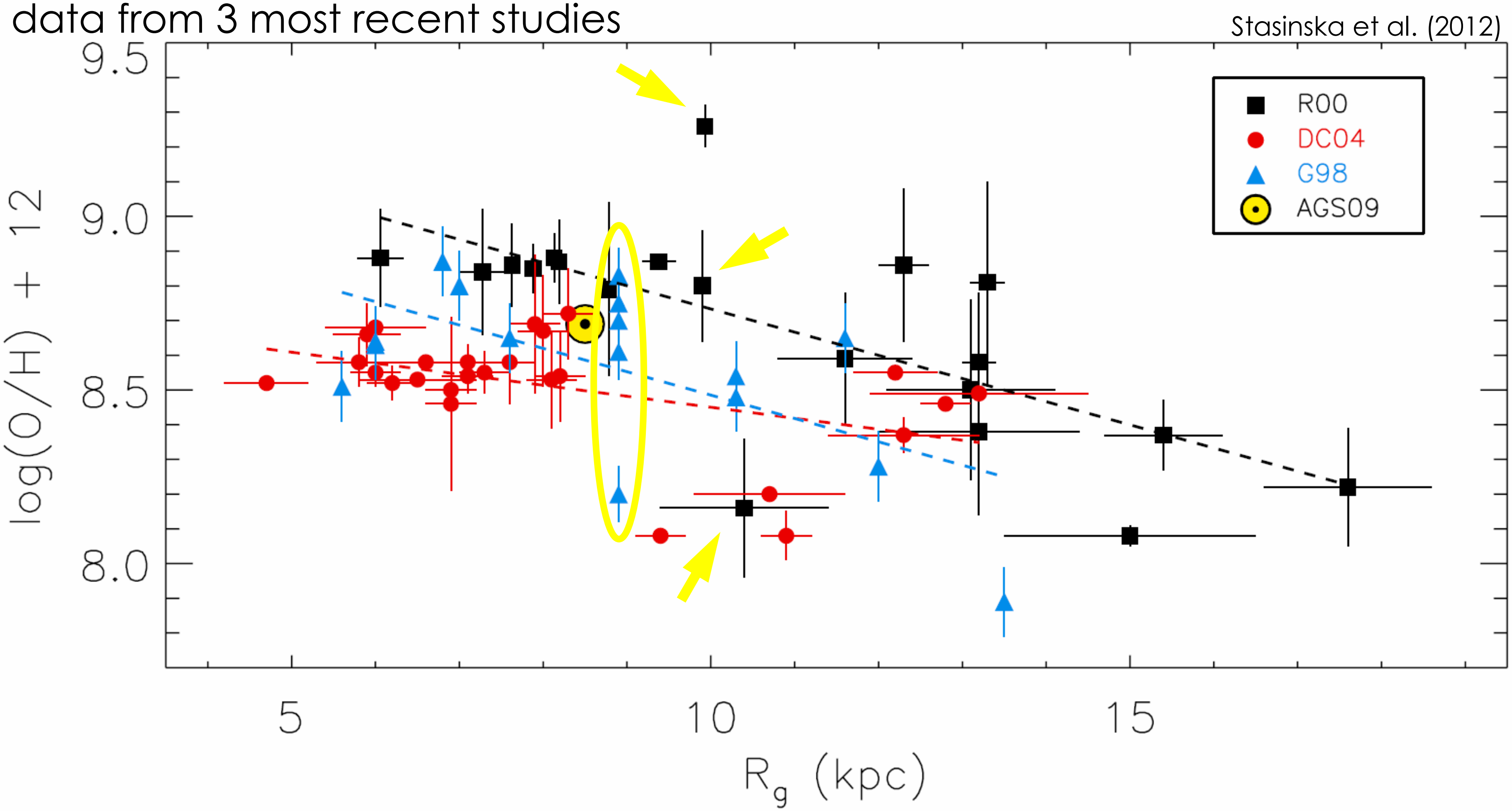
	Author	Range in R_g [kpc]	# stars	# assoc.	$\Delta A(O)/\Delta R$ [dex kpc^{-1}]	$A(O)_0$ [dex]
	G85	8.5 – 17.0	10		−0.012 ± 0.024	
	F90	5.5 – 10.3	20	4	−0.015 ± 0.014	
	KM94	5.0 – 15.0	38	4+loc	−0.021 ± 0.012	
	K94	7.0 – 16.0	16/55	10/20	−0.000 ± 0.009	
	SR97	6.0 – 18.0	80	22	−0.07 ± 0.01	
*	G98	5.0 – 14.0	16	10	−0.07 ± 0.02	9.16
*	R00	6.0 – 18.0	80	22	−0.067 ± 0.008	9.40
*	DC04	4.7 – 13.2	69	25	−0.031 ± 0.012	8.76
*	F11	7.0 – 9.8	35		−0.033 ± 0.005	

References: F90 (Fitzsimmons *et al.* 1990), SR97 (Smartt & Rolleston 1997), R00 (Rolleston *et al.* 2000), G85 (Gehren *et al.* 1985), KM94 (Kilian-Montenbruck *et al.* 1994), K94 (Kaufer *et al.* 1994), G98 (Gummersbach *et al.* 1998), DC04 (Daflon & Cunha 2004), F11 (Firnstein 2011).

- ‘zero‘, ‘steep‘ and ‘shallow‘ solutions for abundance gradient
- wide variation of (extrapolated) central oxygen abundance

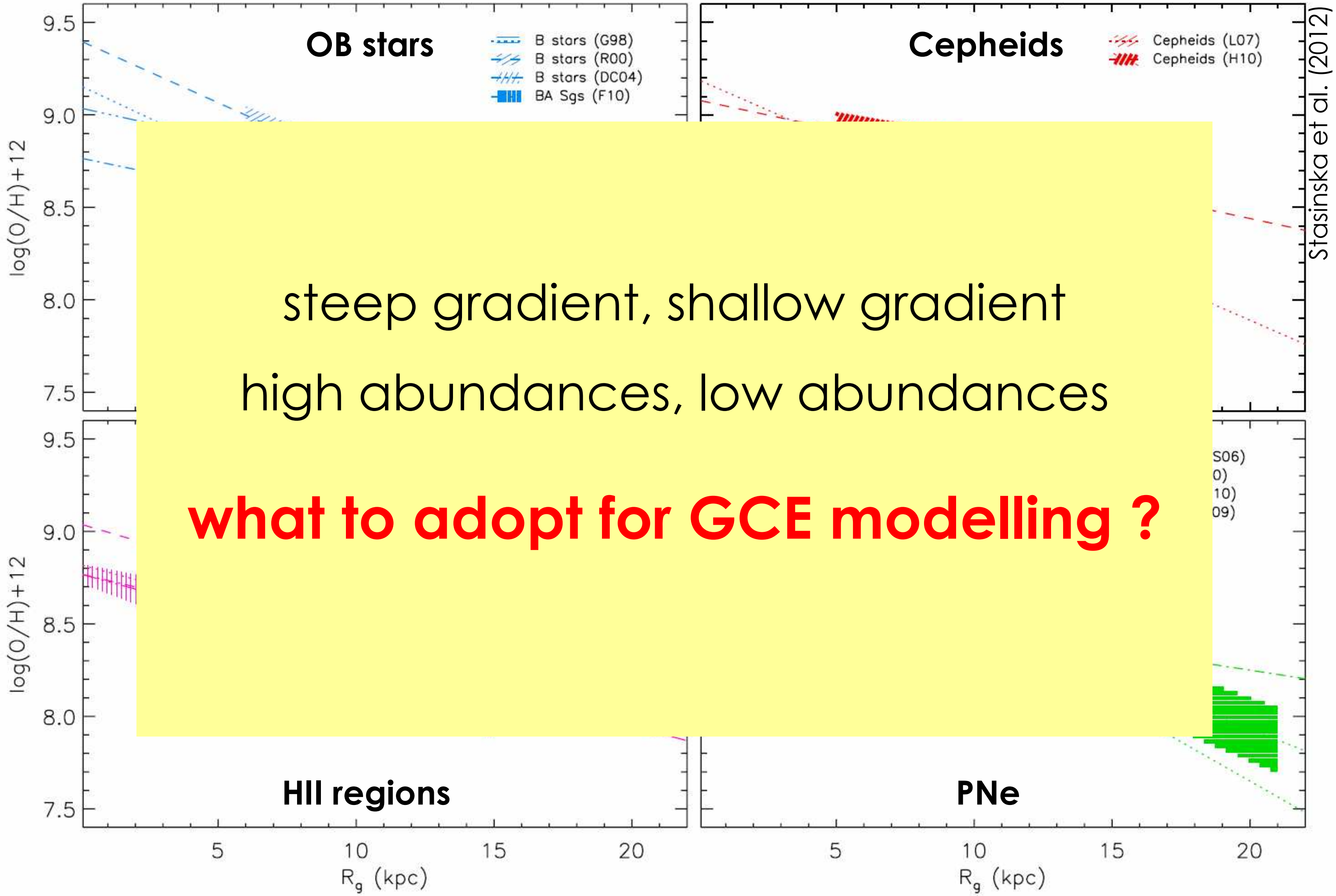
Metallicity gradient from OB stars

data from 3 most recent studies



- large scatter > 0.5dex within single clusters/associations
- large scatter > 1dex for clusters @ similar R_g ... effect of 12+Gyr GCE

Metallicity gradient from different indicators



steep gradient, shallow gradient

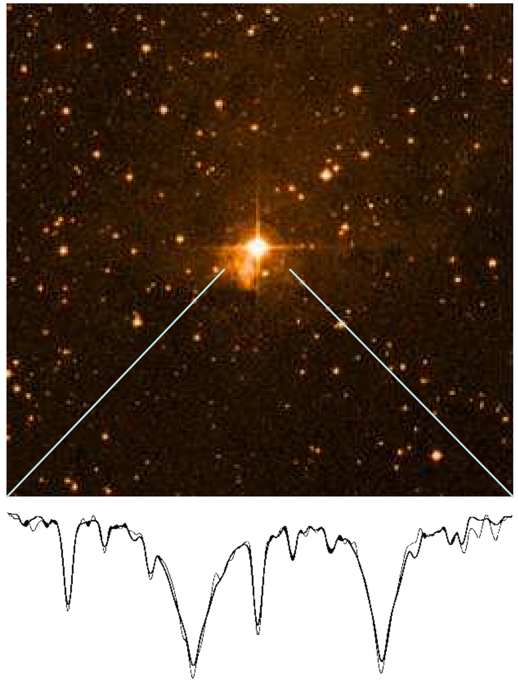
high abundances, low abundances

what to adopt for GCE modelling ?

Diagnostics

HII region and stellar analyses from
interpretation of observation

→ (spectro)photometry, spectroscopy



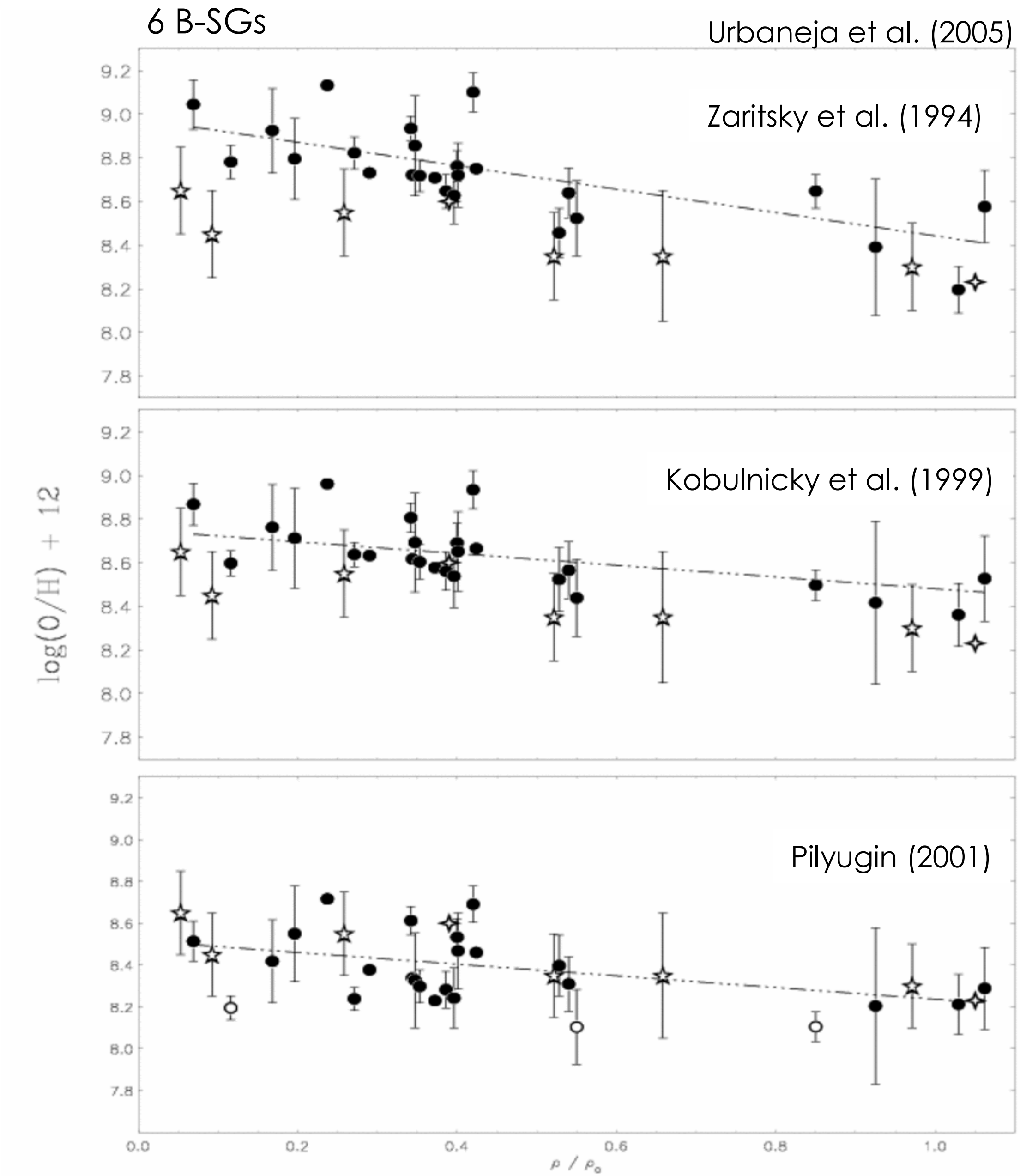
- plasma parameters: T_e, n_e
- elemental abundances

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

quantitative spectroscopy

- direct method (T_e)
- strong line methods
- photoionization models

- model atmospheres



NGC300: abundance gradient from strong-line method

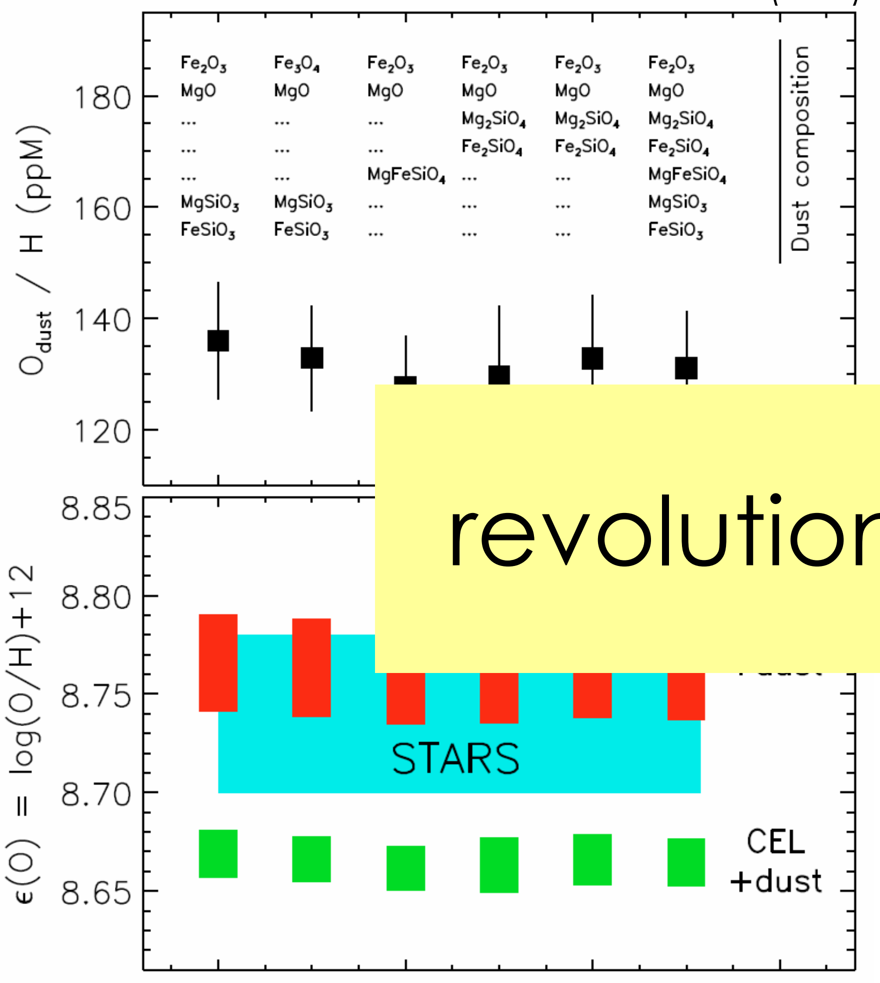
- HII regions vs. B-SGs
- different trends for HII-regions from 3 different R_{23}-calibrations

$$R_{23} = ([OII]_{\lambda 3727} + [OIII]_{\lambda 4959,5007})/H\beta$$

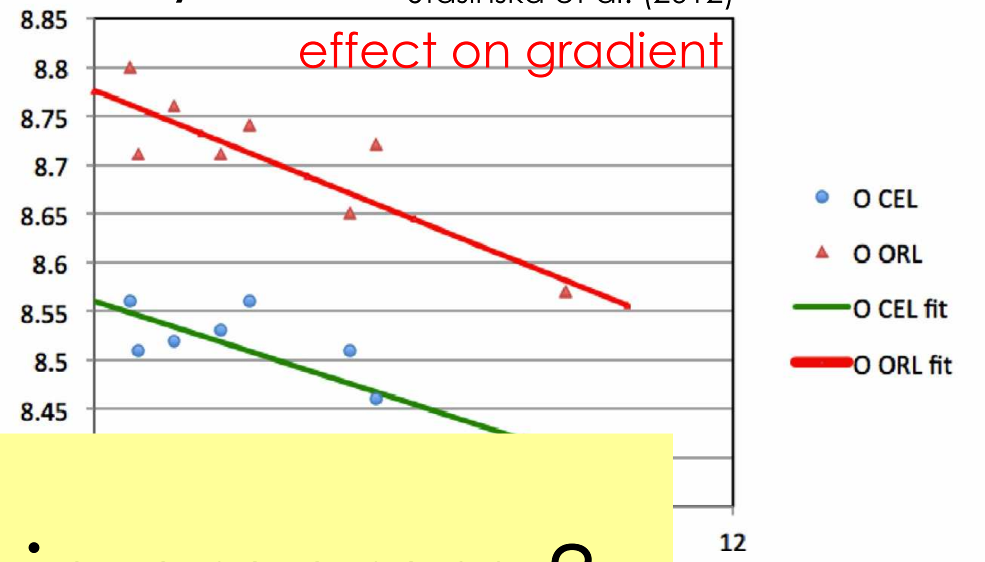
- independent verification and extension via stellar analyses
- systematic bias in published gradients!?

HII regions: RL/CEL dichotomy

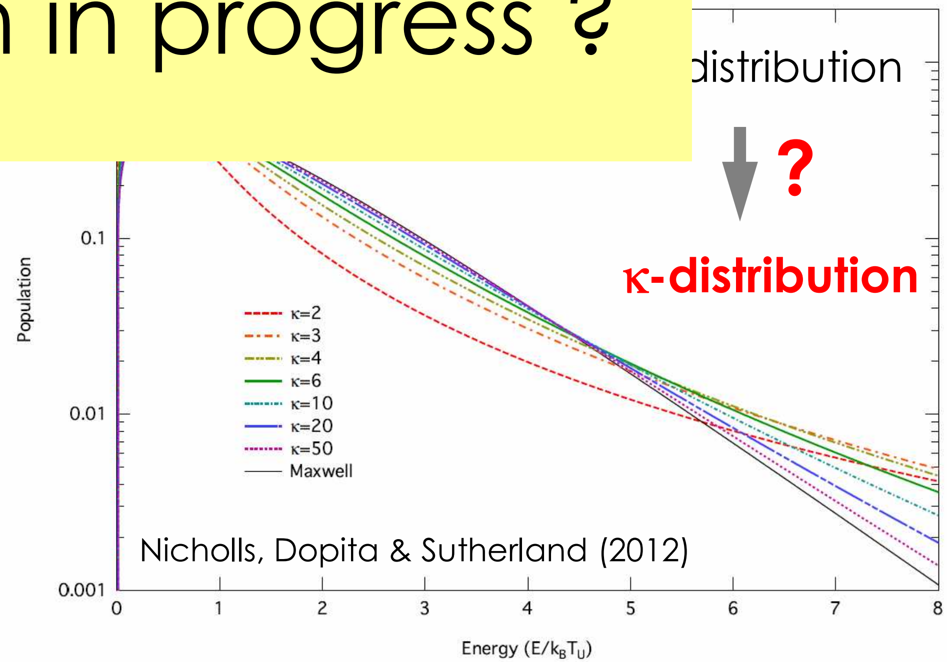
Simon-Diaz & Stasinska (2011)



Stasinska et al. (2012)



revolution in progress ?



stellar and nebular abundances in Orion

→ RL/CEL dichotomy characteristic for Milky Way

(Restricted) NLTE 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:

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

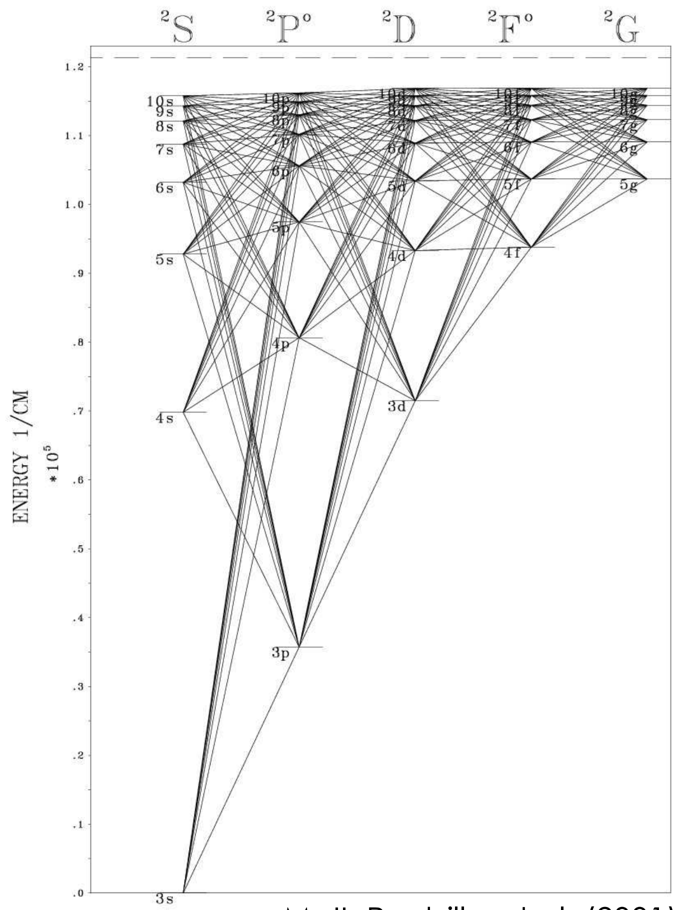
non-local

- collisional rates:

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

local

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

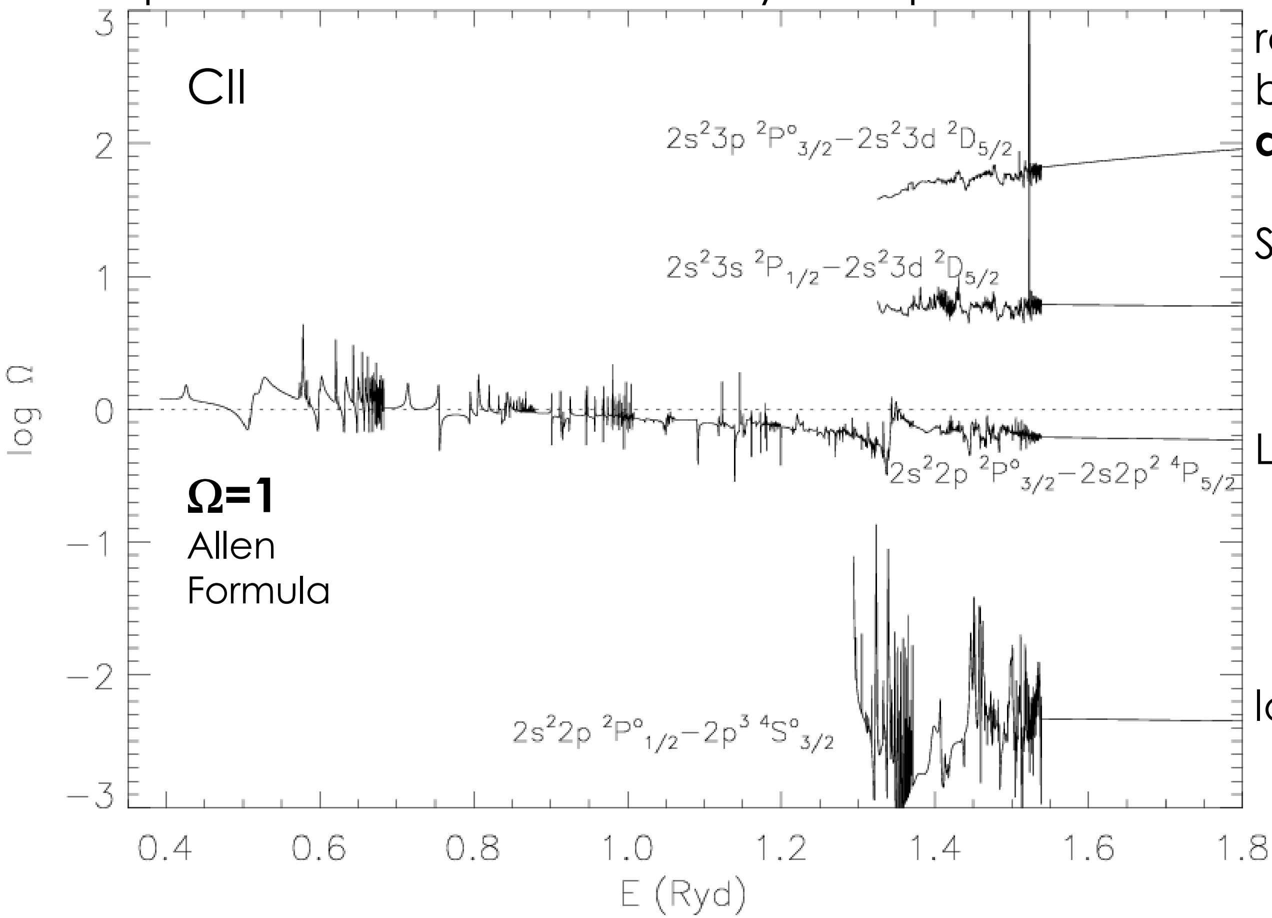


MgII: Przybilla et al. (2001)

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

Atomic data

Example: collisional excitation by e⁻-impact



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

$$H^{\rm BP}_{N+1} = H_{N+1} + H^{\rm mass}_{N+1} + H^{\rm Dar}_{N+1} + H^{\rm so}_{N+1}$$

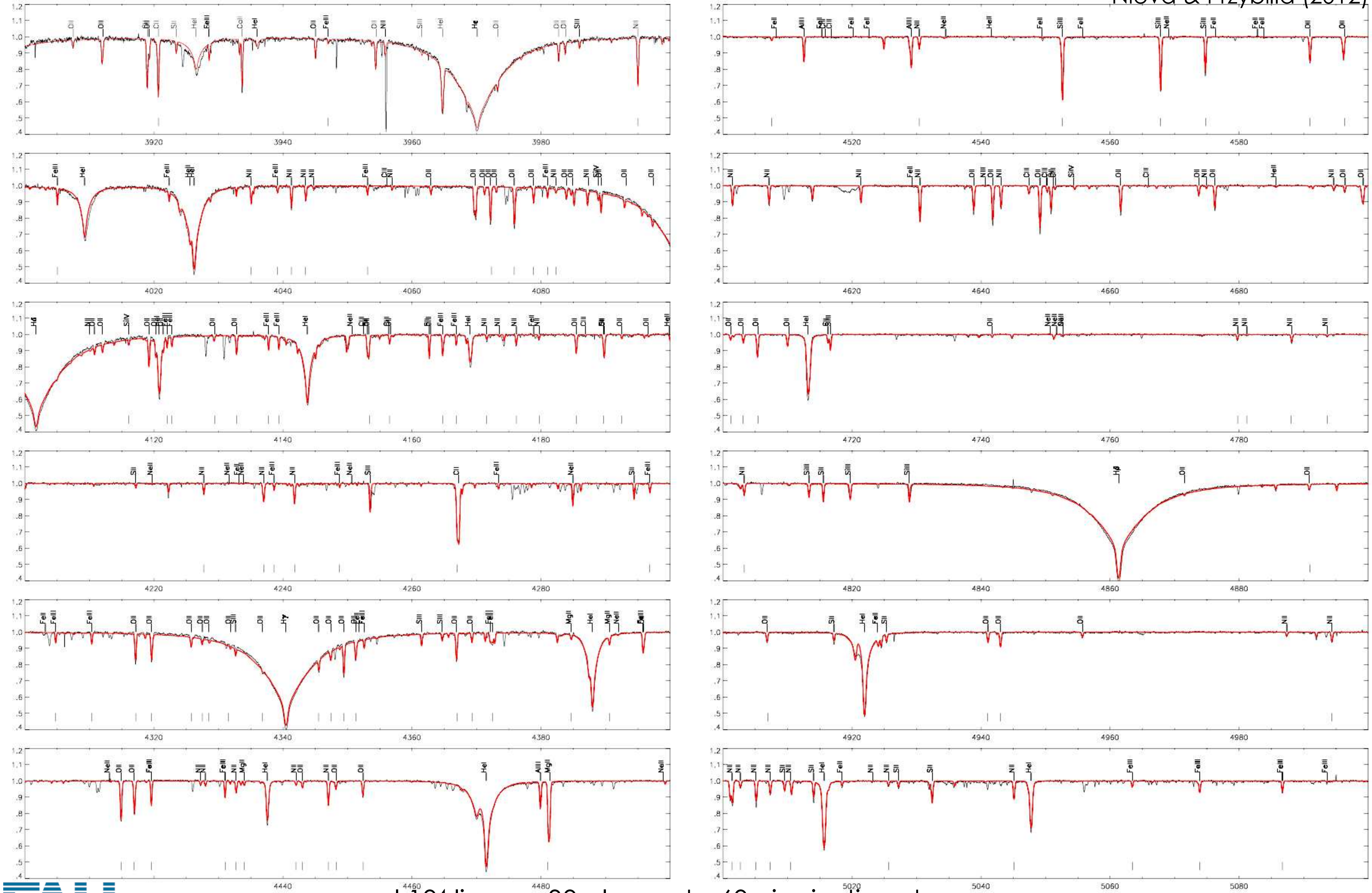
huge amounts of atomic data: OP/IRON Project & own

Methods:
- R-matrix/CC approximation
- MCHF
- CCC

Diagnostics

Quantitative Spectroscopy without Systematics ...

Nieva & Przybilla (2012)



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

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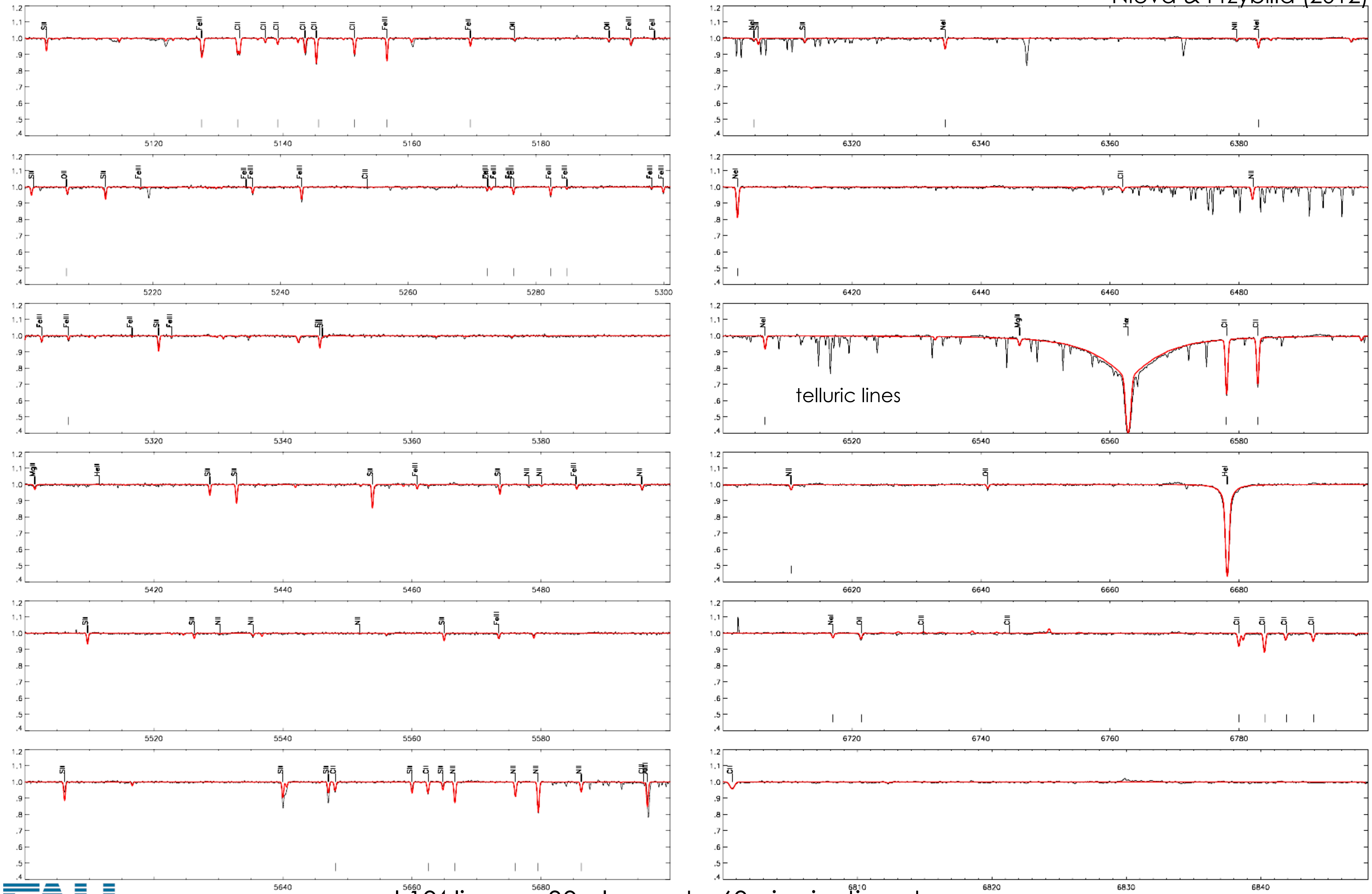
Diagnostics

... Realisation of a Stellar Astrophysicists's Dream

Nieva & Przybilla (2012)



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

NLTE Diagnostics: Stellar Parameters

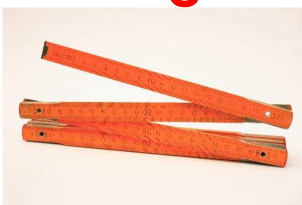
using **robust analysis methodology** & **comprehensive model atoms**

minimising systematics !

- ionization equilibria → T_{eff}
  elements: e.g. He I/II,C I/II, N I/II, O I/II, Ne I/II, Mg I/II, Si III/IV, 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, …

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

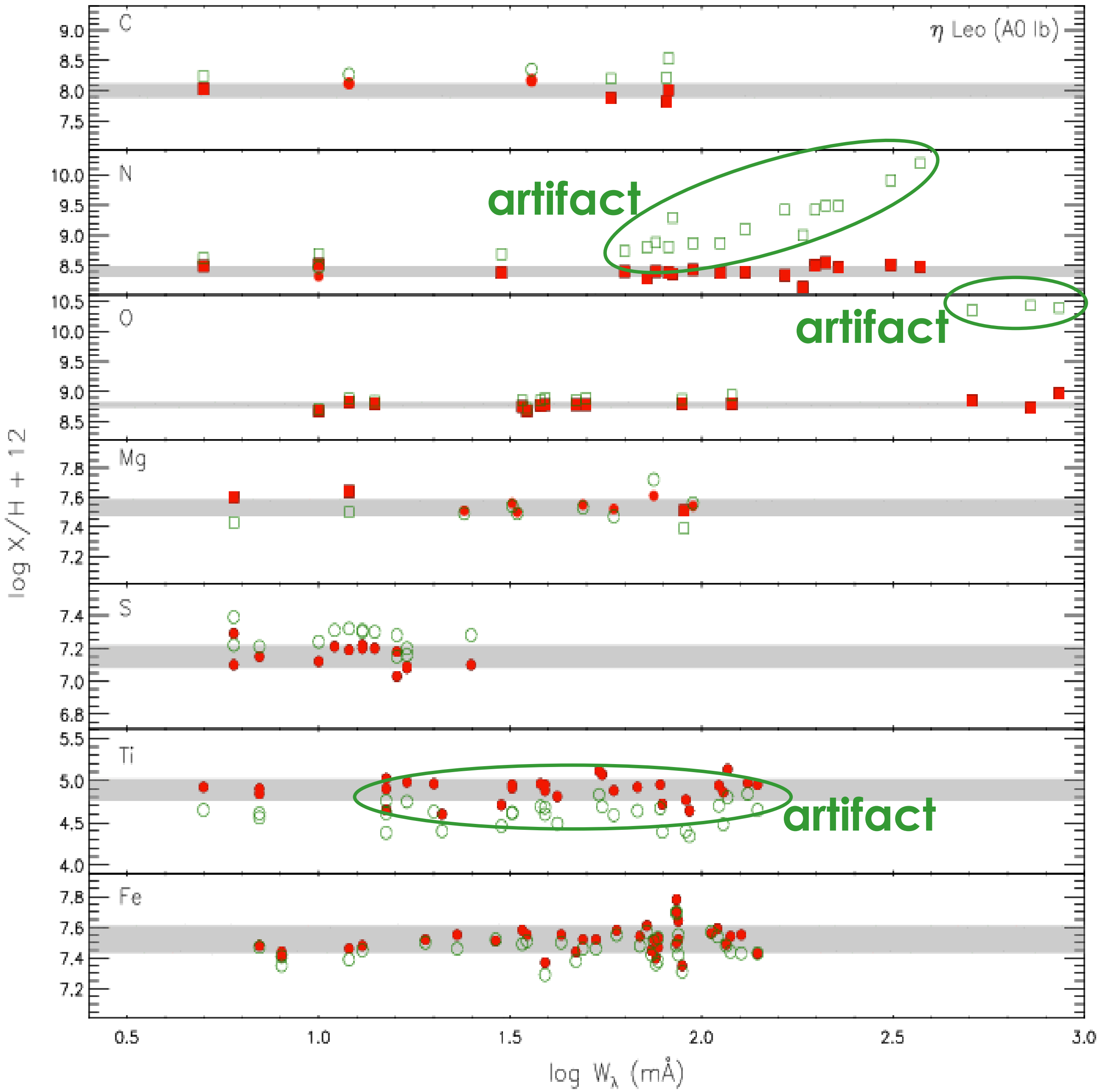


→

→ fine ruler

Elemental Abundances

Przybilla et al. (2006)



- NLTE:
  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

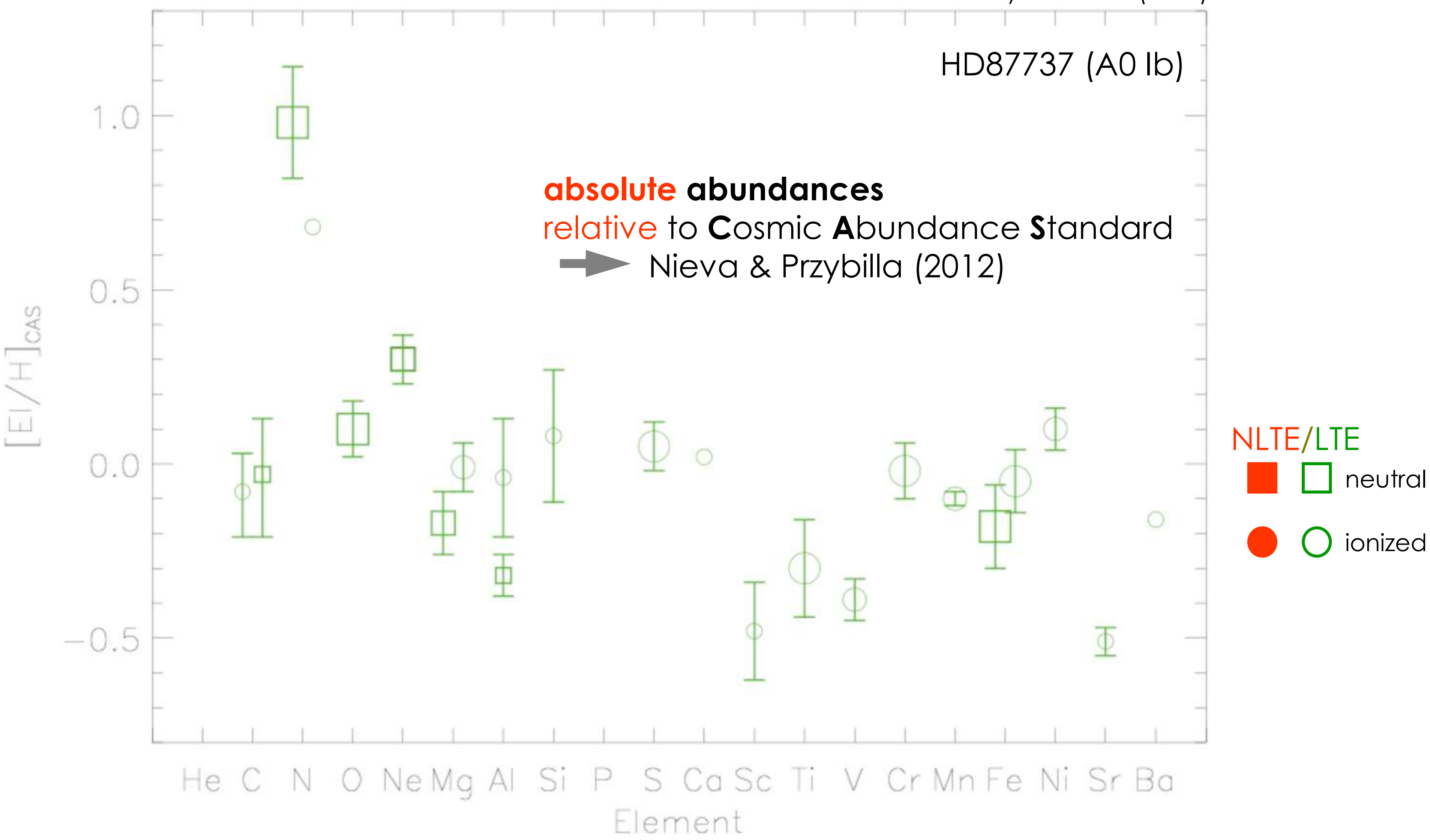
NLTE/LTE

neutral

ionized

Elemental Abundances

Przybilla et al. (2006)



- LTE: abundance pattern? - large uncertainties

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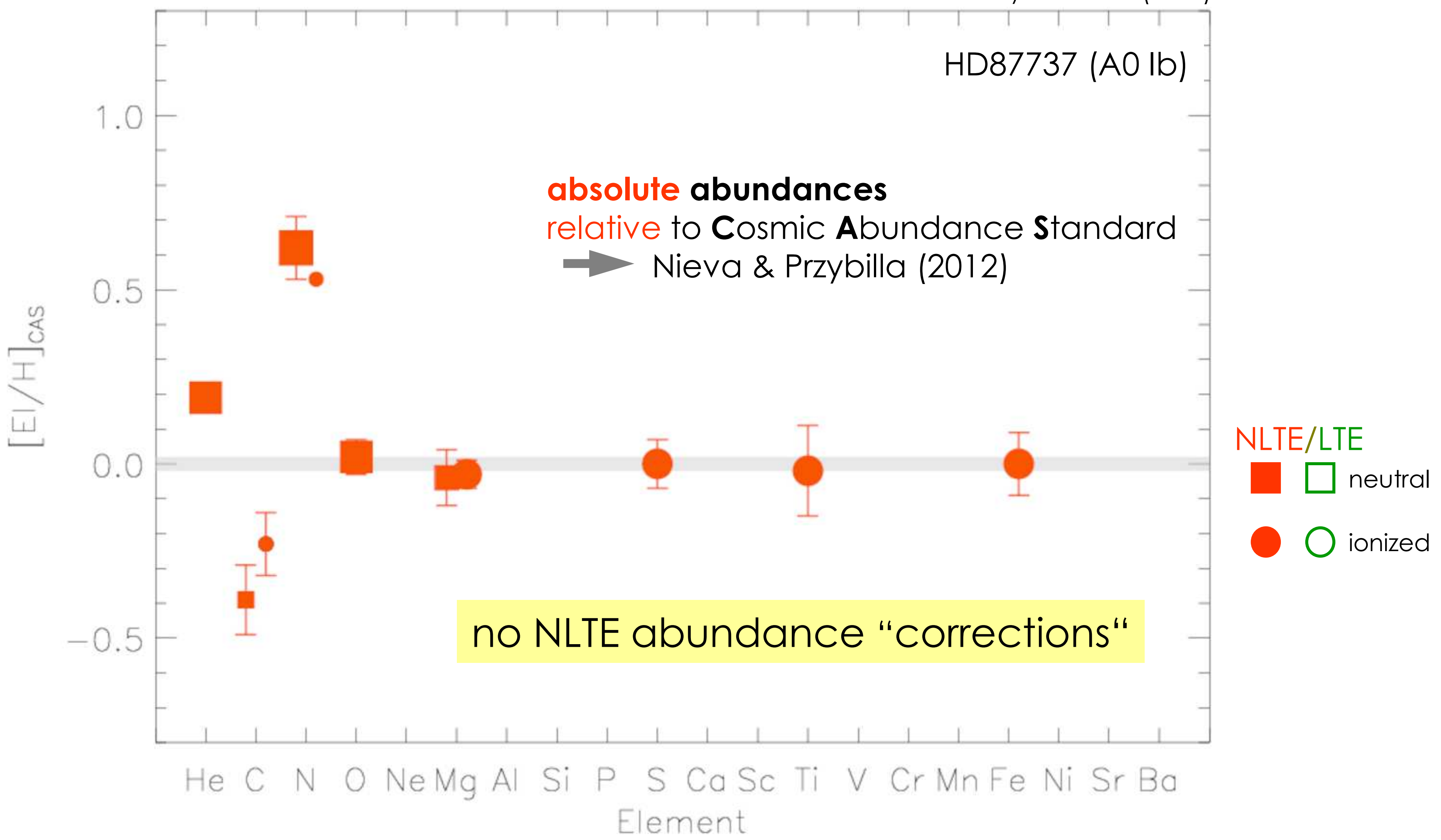
Elemental Abundances

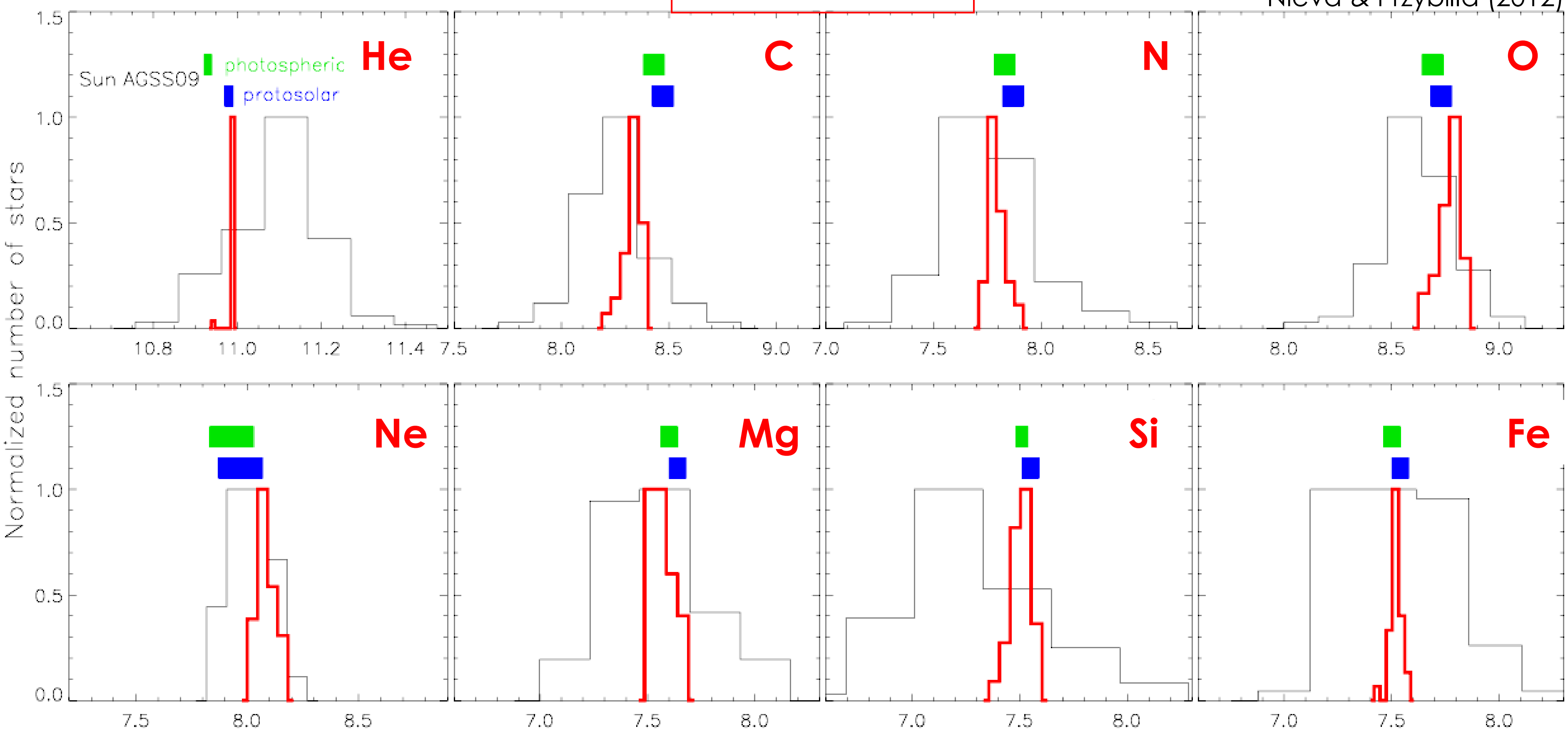
Przybilla et al. (2006)



- NLTE: consistency & reduced uncertainties

Chemical composition of the solar neighborhood @ present day

1σ ~ 0.05 dex



Red: our work 29 stars

black: OB stars literature

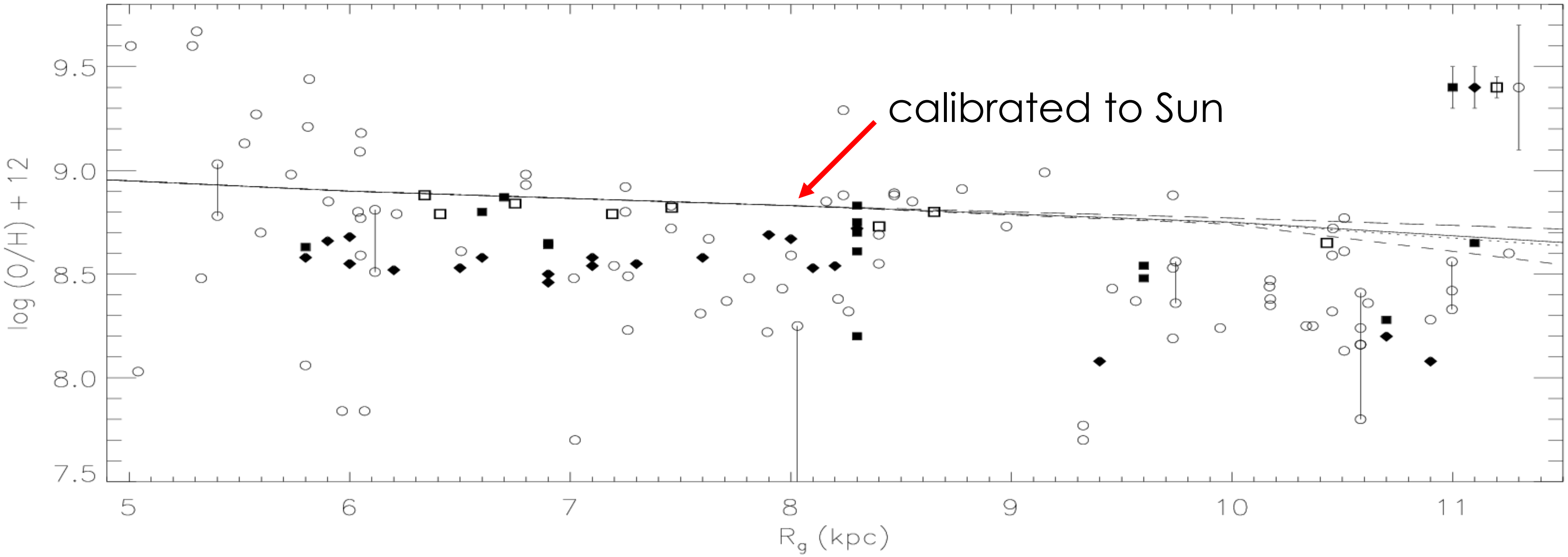
Chemical homogeneity ➜ cosmic abundance standard

X=0.715 Y=0.271 **Z=0.014**

Milky Way: Oxygen Abundance Gradient

Literature: HII regions & B-stars

Przybilla (2008)



HII Regions:
○ Rudolph et al. (2006)
□ Esteban et al. (2005)

Models:
Chiappini et al. (2001)

B-Stars (NLTE):
■ Gummersbach et al. (1998)
♦ Daflon & Cunha (2004)

- large scatter @ every R
- complex picture from “simple“ analysis

Some slides on work in progress removed

Quote, insted of conclusions

"It is also a good rule not to put overmuch confidence in the observational results that are put forward until they are confirmed by theory."

A.S. Eddington