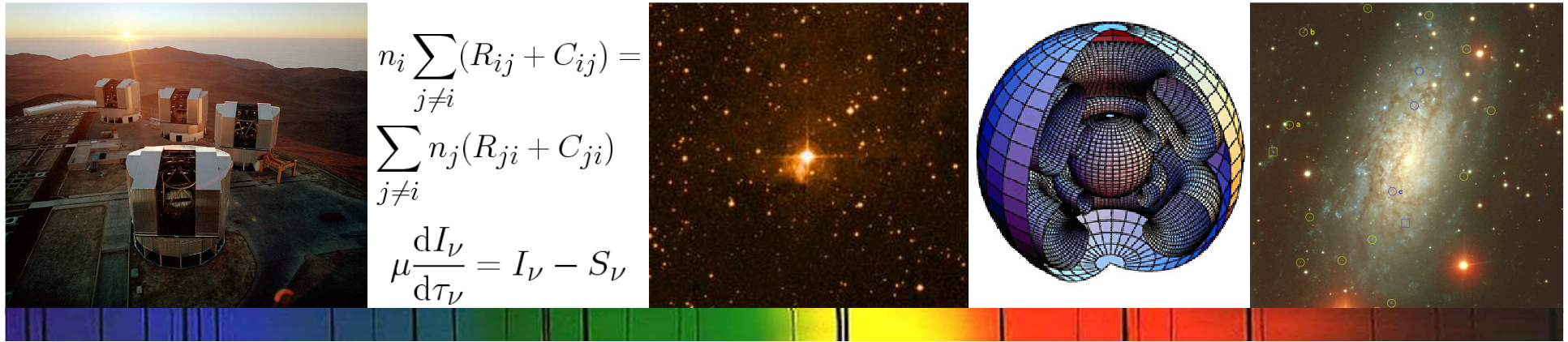




Massive Stars as Tracers for Stellar & Galactochemical Evolution

Norbert Przybilla

Dr. Remeis-Observatory Bamberg

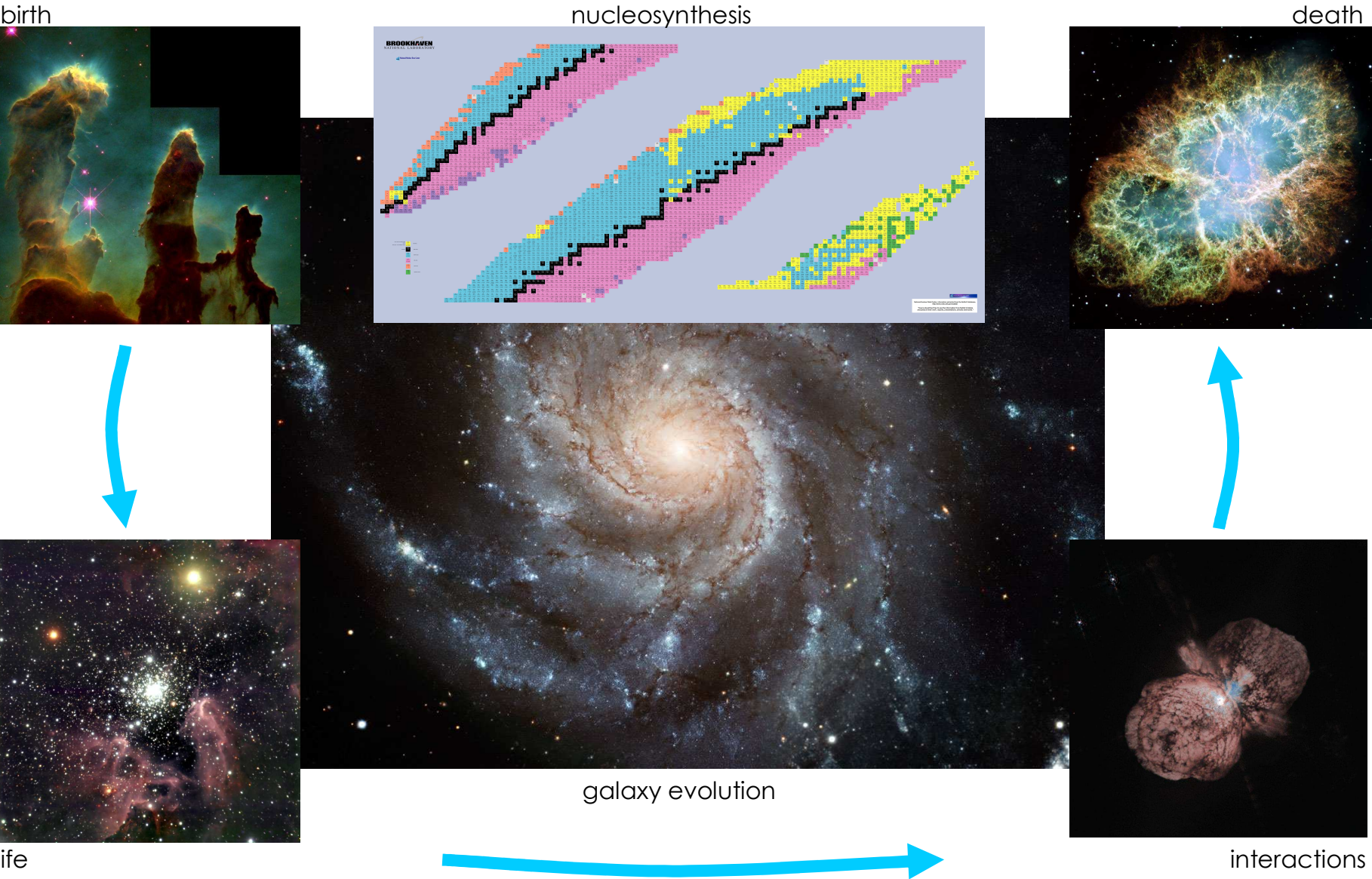
M. Firnstein, M.F. Nieva

K. Butler, R.P. Kudritzki, G. Meynet, A. Maeder

Outline

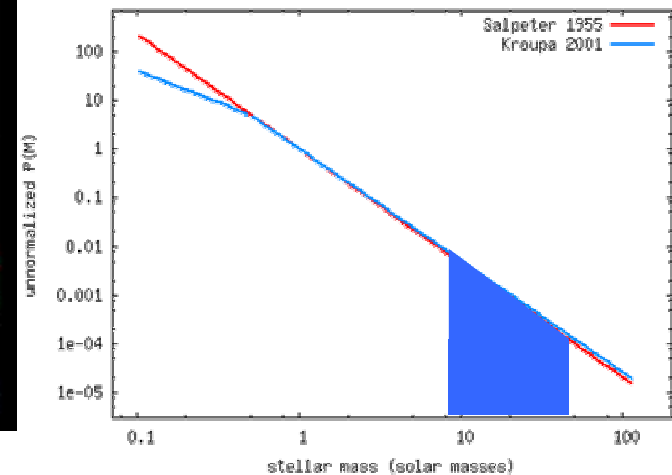
- Intro
- Diagnostics
- Quantitative Spectroscopy @ High Precision & Implications for Stellar/Galactochemical Evolution
- Outlook: Extragalactic Stellar Astronomy

Origins: Cosmic Cycle of Matter

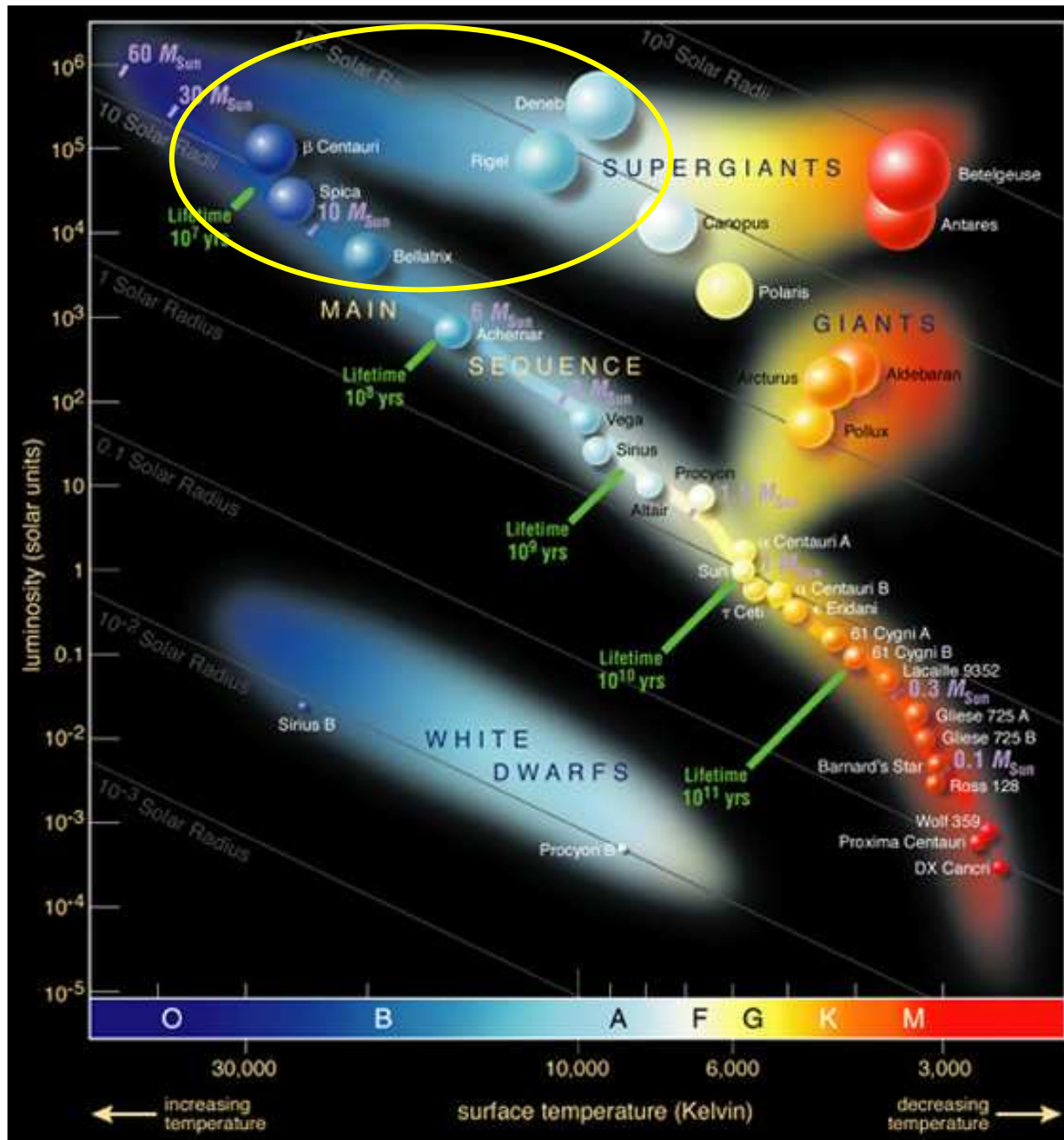


Massive Stars

- dominate **energy** and **momentum budget** of ISM in galaxies
 - SN II, winds, UV photons
- key drivers for **cosmic cycle of matter**
 - star formation, nucleosynth.
- highly luminous
 - **abundance indicators** over large distances: Local Group & beyond

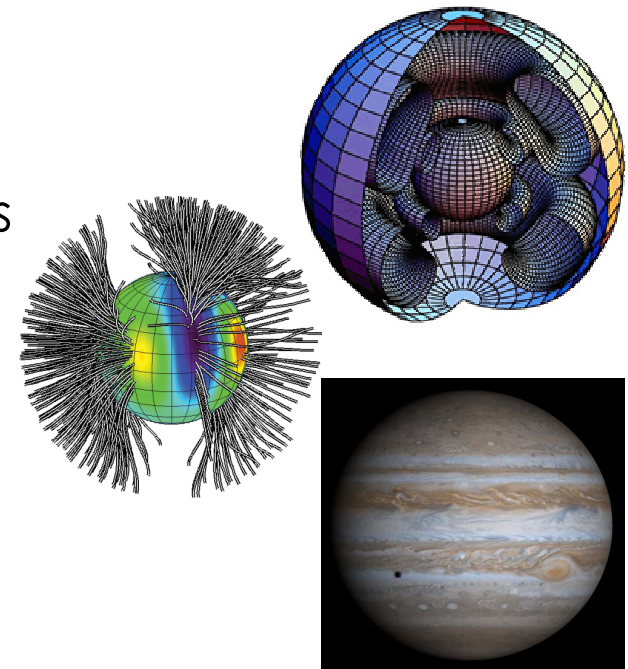
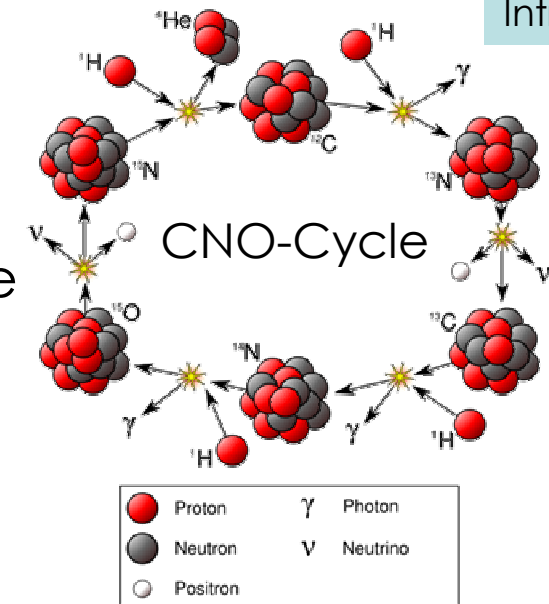


Massive Stars
ESO - 06.04.2011



Massive Stars Evolution: Theory

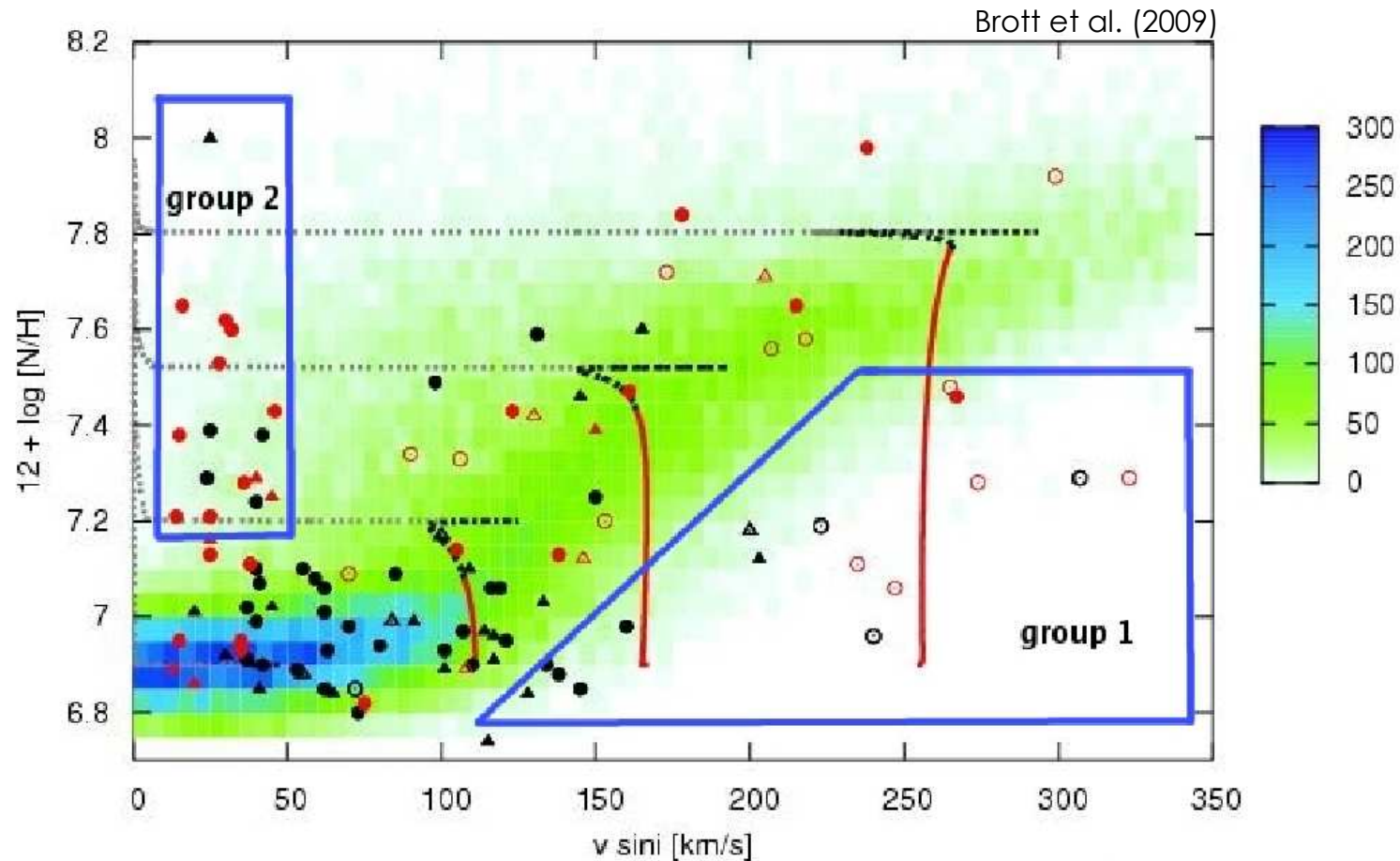
- Context: Cosmic Cycle of Matter
massive stars: sites of nucleosynthesis → SNe
- stellar evolution: $f(M, \dot{M}, Z, \Omega, B)$
- complex (magneto-)hydrodynamic problem:
advances recently in theory
- predicted enrichment of the
stellar atmosphere with nuclear processed
matter via hydrodynamic transport processes
He, N ↗ C ↘
→ empirical **verification** and **calibration**
of stellar evolution models



Massive Stars
ESO – 06.04.2011

Observational Constraints to Stellar Evolution Models

FLAMES survey of massive stars



- many stars with unexpected characteristics

Observational Constraints to Galactic Chemical Evolution

Dispersal and mixing of oxygen in the interstellar medium of gas-rich galaxies

J.-R. Roy^{1,2} and D. Kunth³

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e-mail: jrroy@phy.ulaval.ca

² Observatoire de Paris, DAEC, Unité associée au CRS, DO 173, et à l'Université Paris 7, F-92195 Meudon Cedex, France

³ Institut d'Astrophysique, 98 bis, Blvd. Arago, F-75014 Paris, France

Received 17 March 1994 / Accepted 5 July 1994

Abstract. Stellar and nebular abundance indicators reveal that there exists significant abundance fluctuations in the interstellar medium (ISM) of gas-rich galaxies. It is shown that at the present observed solar level of $O/H \sim 6 \cdot 10^{-4}$, abundance differences of a factor of two, such as existing between the Sun and the nearby Orion Nebula, are many times larger than expected. We examine a variety of hydrodynamical processes operating at scales ranging from 1 pc to greater than 10 kpc, and show that the ISM should appear better homogenized chemically than it actually is: (i) on large galactic scales ($1 \geq l \geq 10$ kpc), turbulent diffusion of interstellar clouds in the shear flow of galactic differential rotation is able to wipe out azimuthal O/H fluctuations in less than 10^9 yr; (ii) at the intermediate scale ($100 \geq l \geq 1000$ pc), cloud collisions and expanding supershells driven by evolving associations of massive stars, differential rotation and triggered star formation will re-distribute and mix gas efficiently in about 10^8 yr; (iii) at small scales ($1 \geq l \geq 100$ pc), turbulent diffusion may be the dominant mechanism in cold clouds, while Rayleigh-Taylor and Kelvin-Helmholtz instabilities quickly develop in regions of gas ionized by massive stars, leading to full mixing in $\leq 2 \cdot 10^6$ yr.

Friedrich-Alexander-Universität
Erlangen-Nürnberg



- massive stars:
inferred from observation

→ chemical
inhomogeneity

BUT

- gas-phase of ISM in
solar neighbourhood
homogeneous
(Sofia & Meyer 2001)

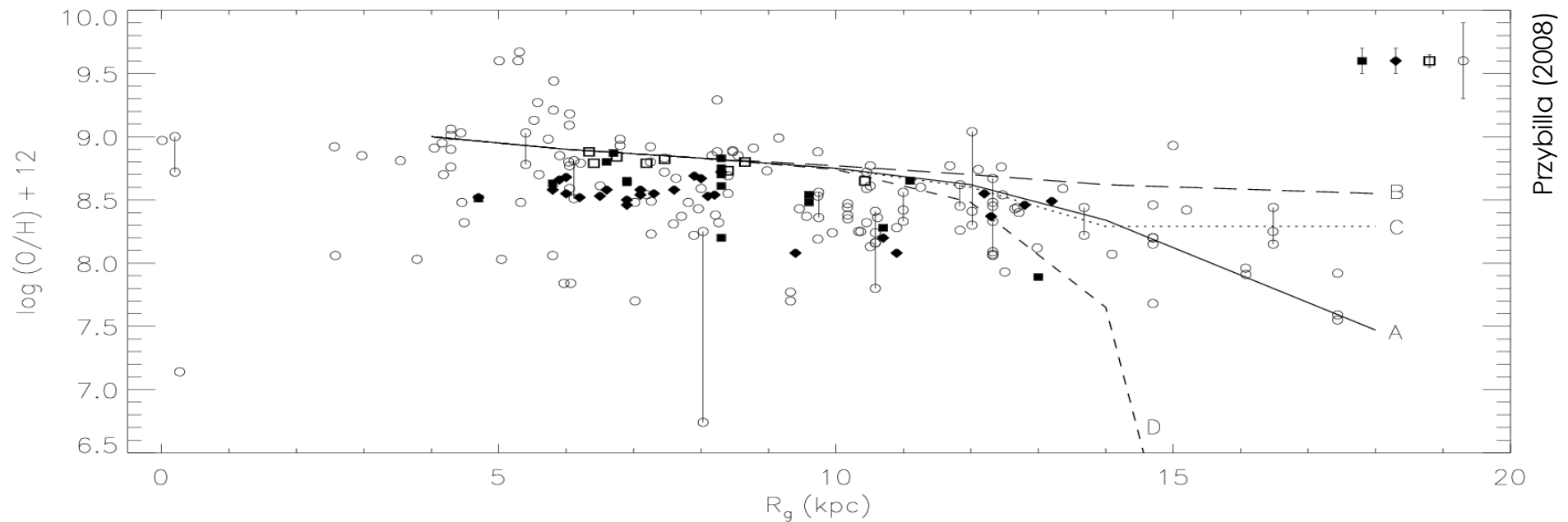
Theory:

- efficient mixing
mechanisms
→ homogeneity
(e.g. Edmunds 1975,
Roy & Kunth 1995)

Observational Constraints to Galactic Chemical Evolution

Present-day abundance gradients in Milky Way

B-stars: Gummersbach+ (1998),
Daflon & Cunha (2004)
HII: Esteban+ (2005), Rudolph+ (2006)
models: Chiappini+ (2001)



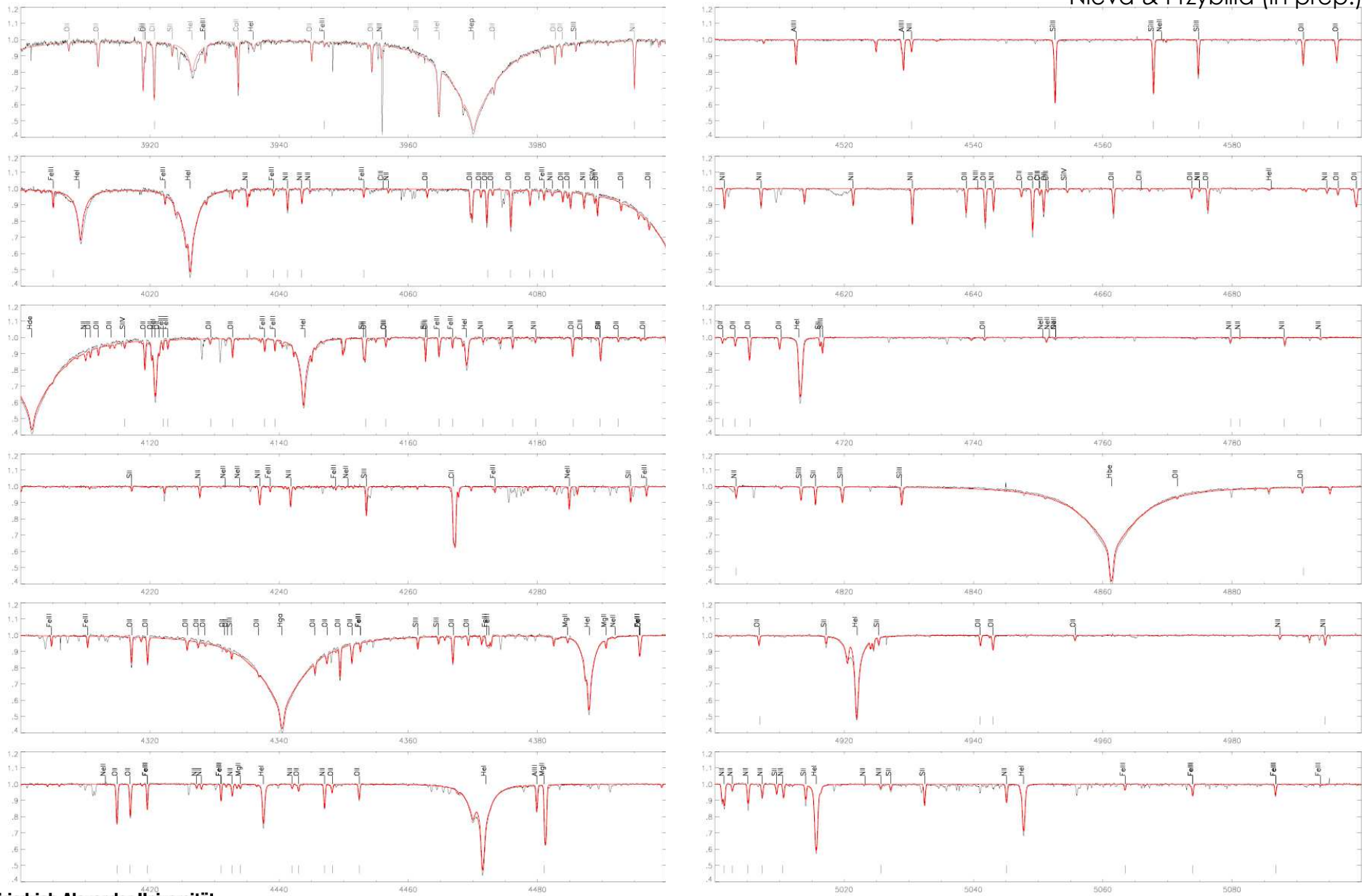
- large scatter @ every R (early-type stars & nebulae)
- test of galacticochemical evolution models?
- gas infall – local retention of metals?

other galaxies?

Quantitative Spectroscopy without Systematics ...

Diagnostics

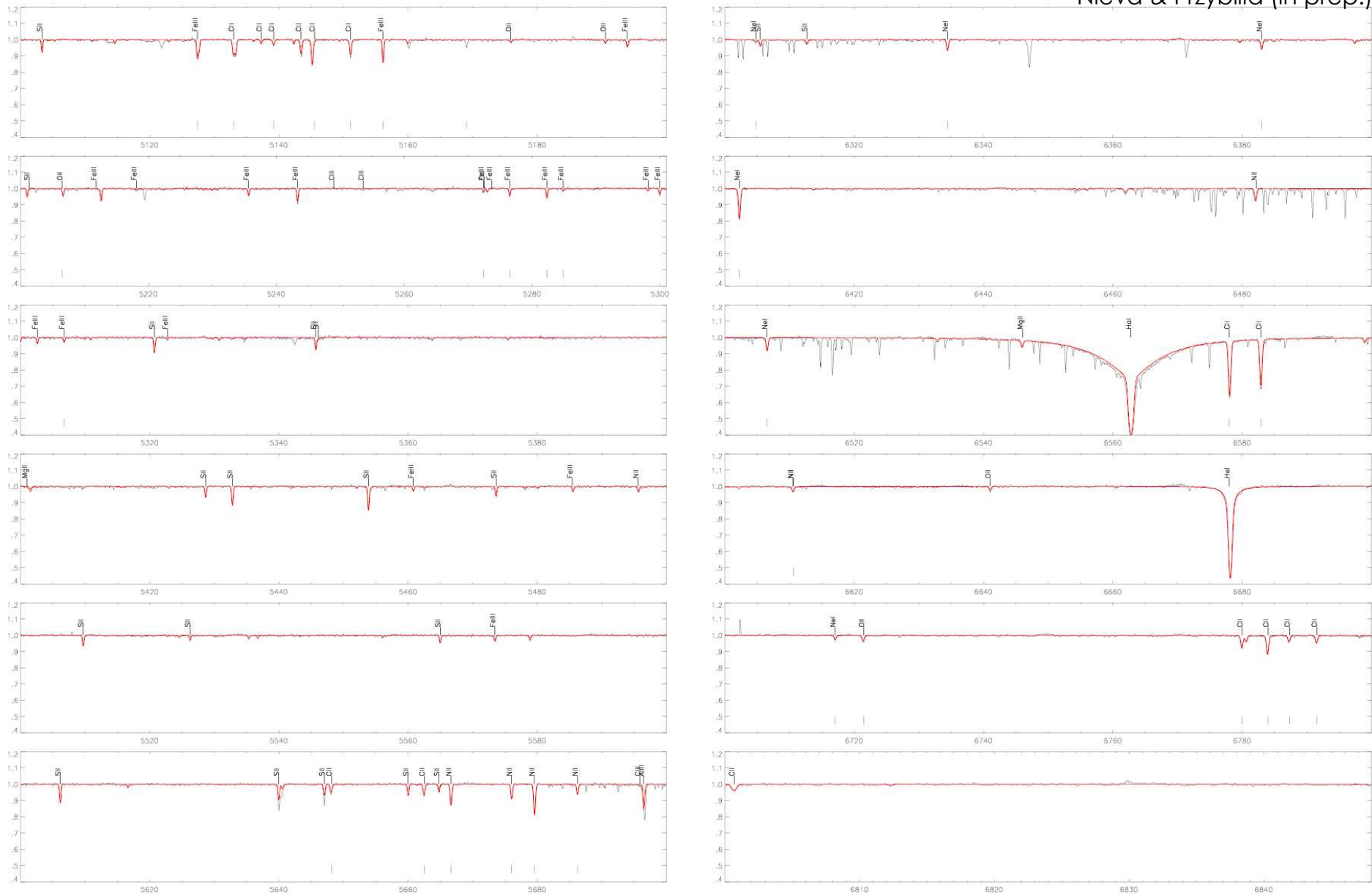
Nieva & Przybilla (in prep.)



... Realisation of a Stellar Astrophysicists's Dream

Diagnostics

Nieva & Przybilla (in prep.)



Diagnostics

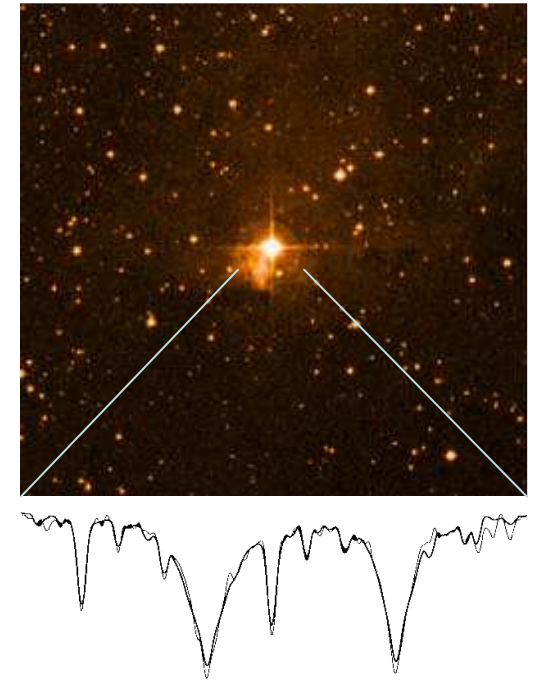
stellar analyses from
interpretation of observation

➔ photometry, spectroscopy

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

➔ quantitative spectroscopy
via model atmospheres

physical-numerical models
of visible outer layers of stars



(Restricted) NLTE Problem

Non-Local Thermodynamic Equilibrium

- transfer equation

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

- statistical equilibrium:

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

- radiative rates:

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

non-local

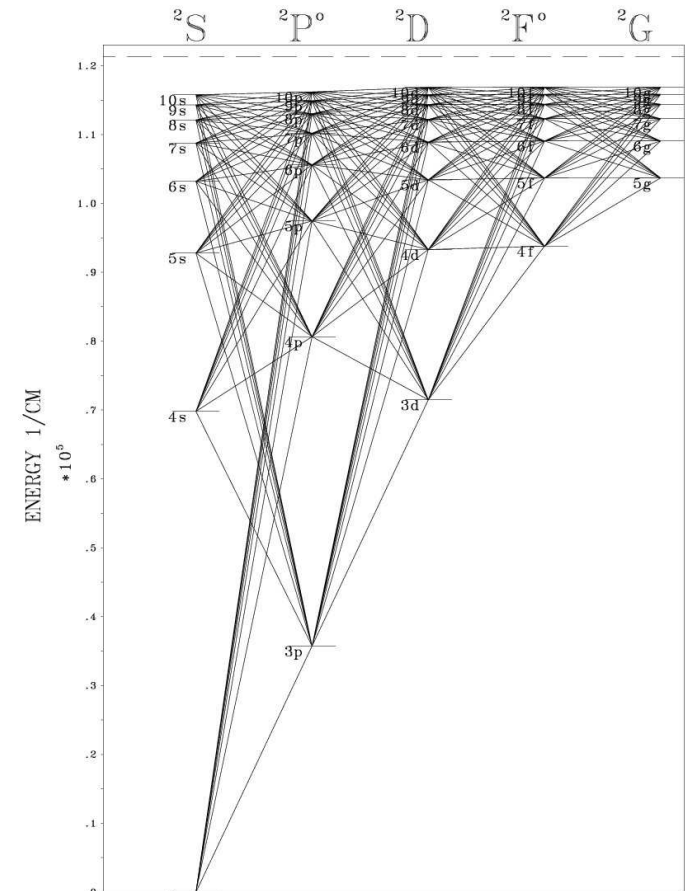
- collisional rates:

$$C_{ij} = n_e \int \sigma_{ij}(v) f(v) v dv$$

local

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

➔ model atoms

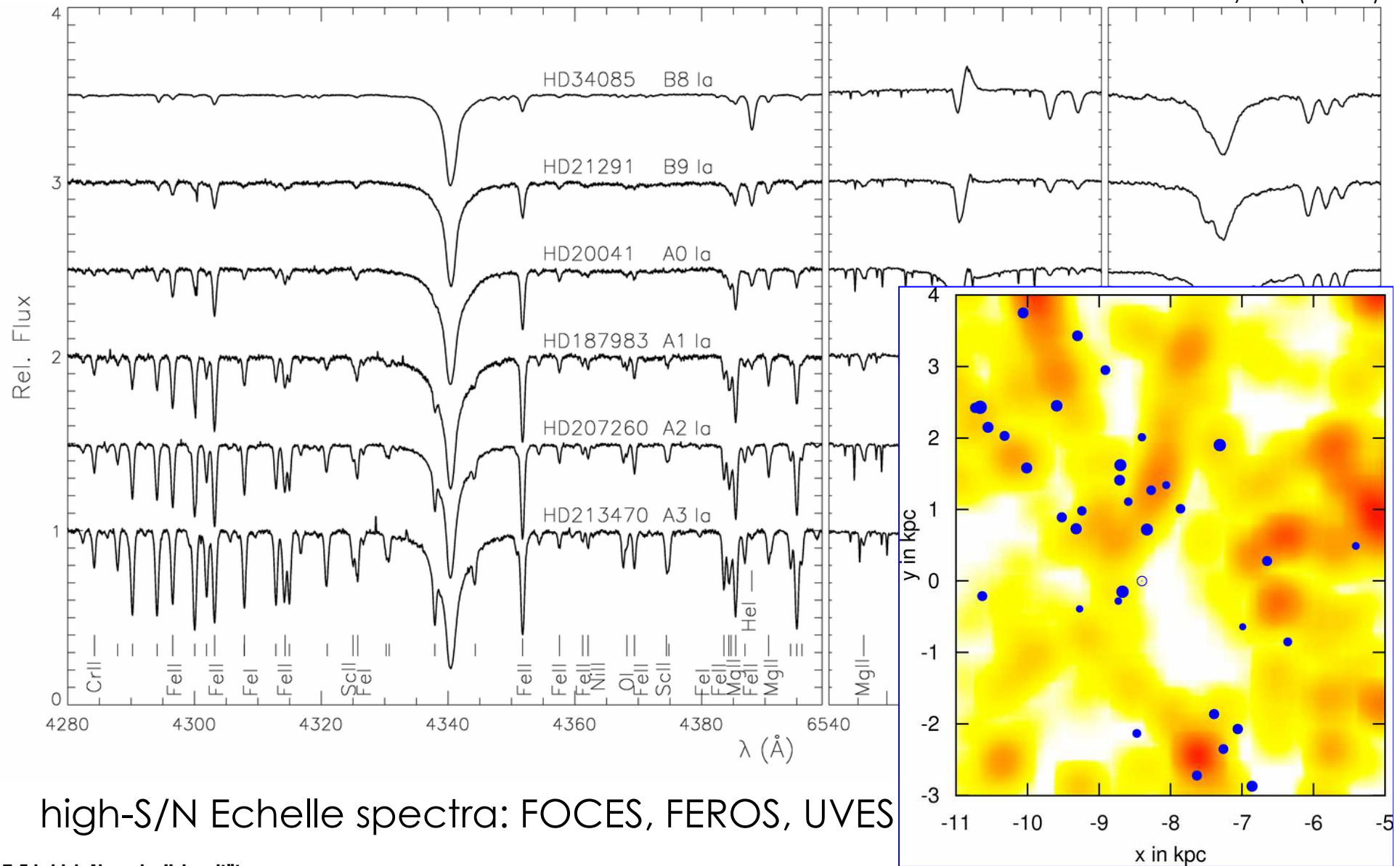


MgII: Przybilla et al. (2001)

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

Galactic BA-Type Supergiants: Spectroscopy

Firnstein & Przybilla (2011a)



high-S/N Echelle spectra: FOCES, FEROS, UVES

NLTE Diagnostics: Stellar Parameters

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

minimising
systematics !

- ionization equilibria $\rightarrow T_{\text{eff}}$
elements: e.g. He I/II, C II/III/IV, N I/II, O I/II, Ne I/II, Mg I/II, Si II/III/IV, S II/III, Fe II/III
 $\Delta T_{\text{eff}} / T_{\text{eff}} \sim 1...2\%$ usually: 5...10%
- Stark broadened hydrogen lines $\rightarrow \log g$
 $\Delta \log g \sim 0.05...0.10$ (cgs) usually: 0.2
- microturbulence, helium abundance, metallicity
+ other constraints, where available: SED's, near-IR, ...
- abundances: $\Delta \log \epsilon \sim 0.05...0.10$ dex (1σ -stat.) usually: factor ~ 2
 $\Delta \log \epsilon \sim 0.07...0.12$ dex (1σ -sys.) usually: ???

$\rightarrow$ **fine ruler**

Simultaneous Establishment of Ionization Equilibria

Nieva & Przybilla (in prep.)

#	HD	T_{eff} 10 ³ K	H	He I	He II	C II	C III	C IV	O I	O II	Ne I	Ne II	Si III	Si IV	Fe II	Fe III
11	36512	33.4	•	•	•	•	•	•		•		•	•	•		•
6	149438	32.0	•	•	•	•	•	•		•	•	•	•	•		•
3	63922	31.2	•	•	•	•	•	•		•		•	•	•		•
19	34816	30.4	•	•	•	•	•			•	•	•	•	•		•
12	36822	30.0	•	•	•	•	•	•		•	•	•	•	•		•
13	36960	29.0	•	•	•	•	•			•	•	•	•	•		•
1	36591	27.0	•	•	•	•	•			•	•	•	•	•		•
14	205021	27.0	•	•	•	•	•			•	•	•	•	•		•
2	61068	26.3	•	•	•	•	•			•	•	•	•	•		•
9	35299	23.5	•	•		•	•		•	•	•	•	•	•	•	•
16	216916	23.0	•	•		•	•		•	•	•	•	•	•	•	•
4	74575	22.9	•	•		•	•		•	•	•	•	•	•	•	•
7	886	22.0	•	•		•	•		•	•			•	•	•	•
8	29248	22.0	•	•		•	•		•	•	•		•	•	•	•
18	16582	21.3	•	•		•	•		•	•	•		•	•	•	•
5	122980	20.8	•	•		•	•		•	•	•		•		•	•
10	35708	20.7	•	•		•	•		•	•	•		•	•	•	•
17	3360	20.7	•	•		•	•		•	•	•		•	•	•	•
20	160762	17.5	•	•		•			•	•	•		•		•	•
15	209008	15.8	•	•		•			•	•	•		•		•	•

NLTE Diagnostics: Stellar Parameters

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

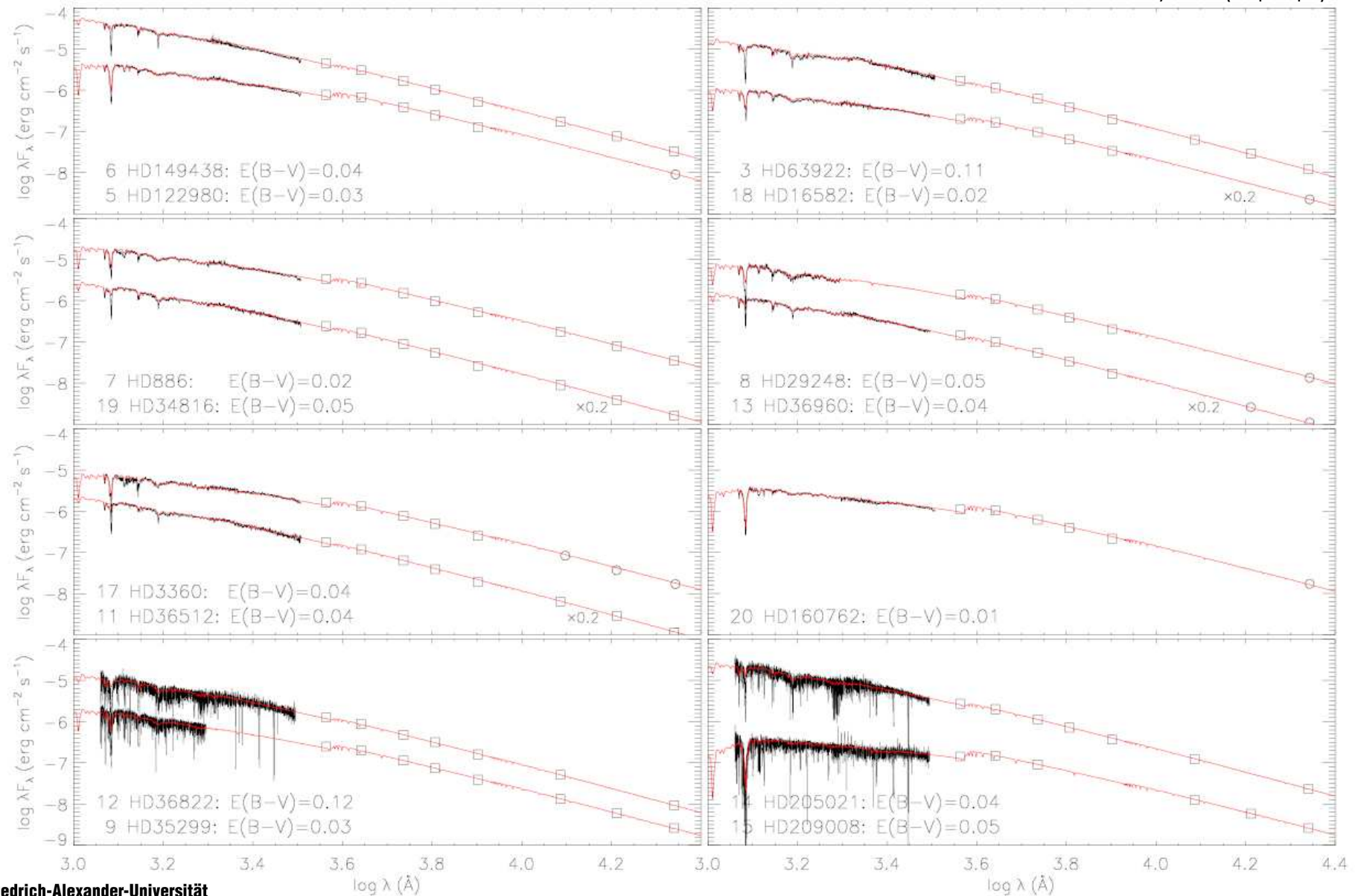
minimising
systematics !

- ionization equilibria $\rightarrow T_{\text{eff}}$
elements: e.g. He I/II, C II/III/IV, N I/II, O I/II, Ne I/II, Mg I/II, Si II/III/IV, S II/III, Fe II/III
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$\rightarrow$ **fine ruler**

Test: SEDs

Nieva & Przybilla (in prep.)



NLTE Diagnostics: Stellar Parameters

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

minimising
systematics !

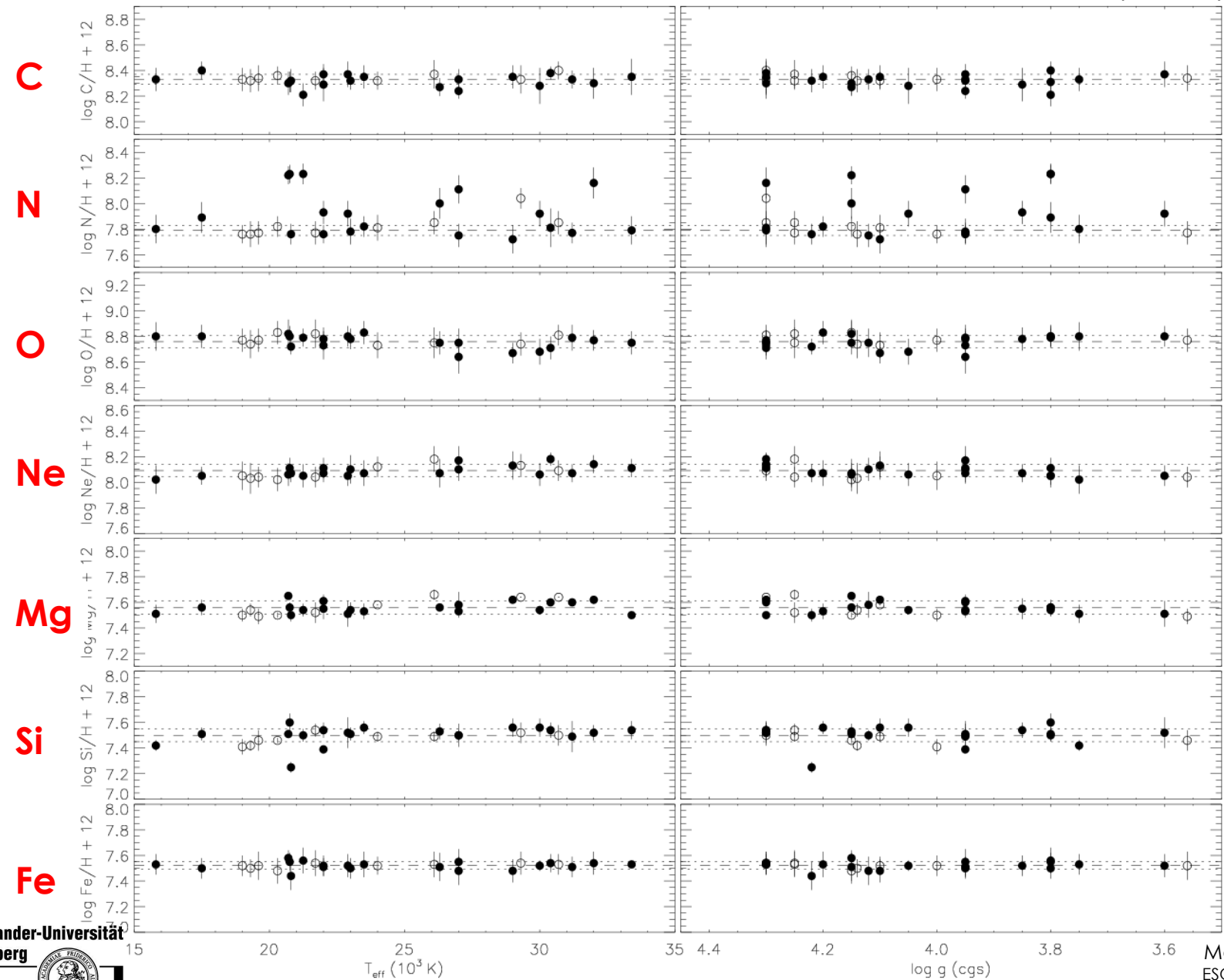
- ionization equilibria $\rightarrow T_{\text{eff}}$
elements: e.g. He I/II, C II/III/IV, N I/II, O I/II, Ne I/II, Mg I/II, Si II/III/IV, S II/III, Fe II/III
 $\Delta T_{\text{eff}} / T_{\text{eff}} \sim 1...2\%$ usually: 5...10%
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 $\Delta \log \epsilon \sim 0.07...0.12$ dex (1σ -sys.) usually: ???

$\rightarrow$ **fine ruler**

$\rightarrow$ **solid results**

Test: Abundance Trends

Nieva & Przybilla (in prep.)



NLTE Diagnostics: Stellar Parameters

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

minimising
systematics !

- ionization equilibria $\rightarrow T_{\text{eff}}$
elements: e.g. He I/II, C II/III/IV, N I/II, O I/II, Ne I/II, Mg I/II, Si II/III/IV, S II/III, Fe II/III
 $\Delta T_{\text{eff}} / T_{\text{eff}} \sim 1...2\%$ usually: 5...10%
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$\rightarrow$ **fine ruler**

Nuclear path of the CNO-cycles

diagnostic diagram: mass ratios N/C vs. N/O

initially CN-cyle: $dC = -\frac{6}{7}dN$, O const.

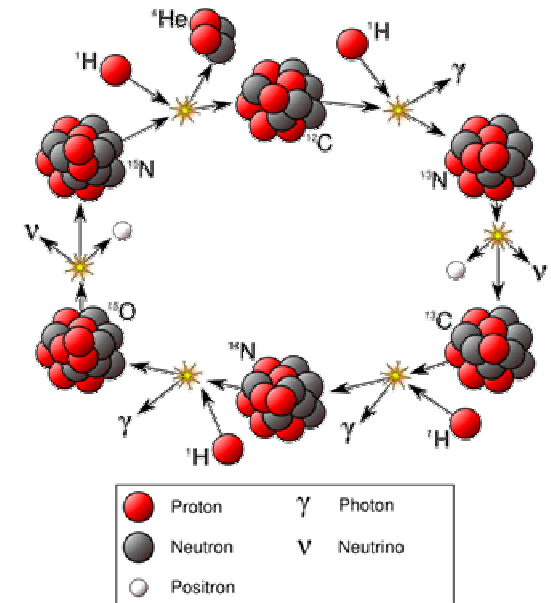
$$d(N/O) = dN/O$$

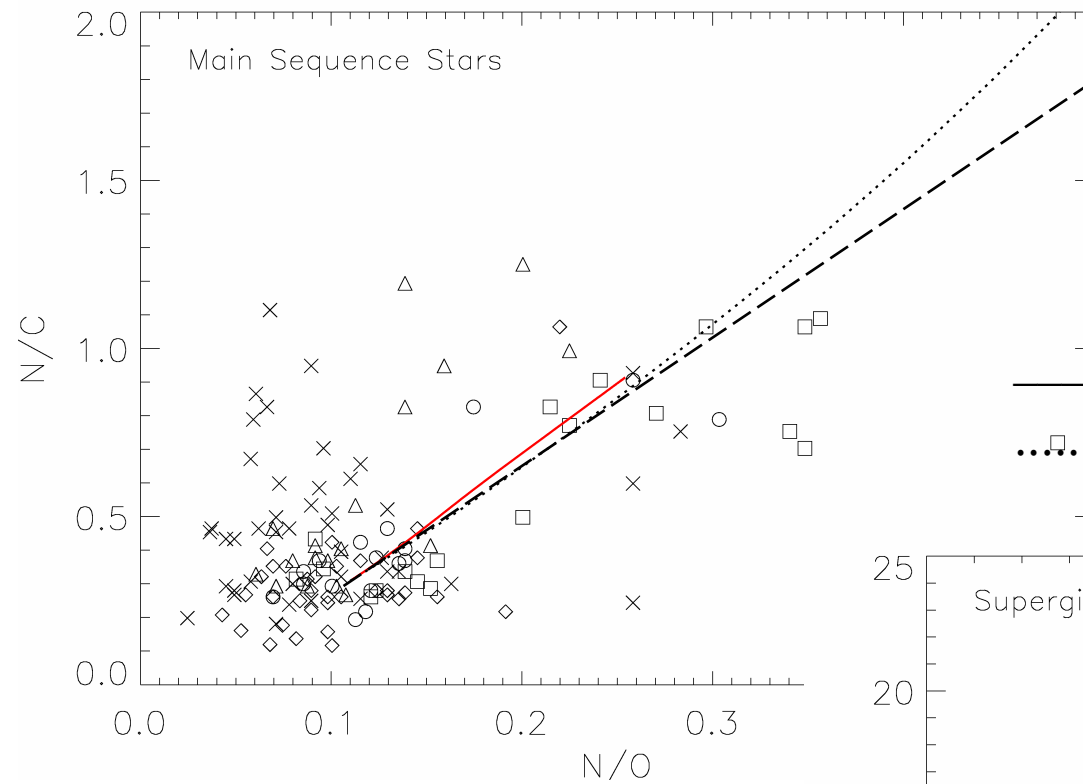
$$d(N/C) = \frac{dN}{C} - \frac{N}{C^2} \frac{dC}{dN} dN = \frac{dN}{C} \left[1 + \frac{6}{7} \frac{N}{C} \right]$$

$$\frac{d(N/C)}{d(N/O)} = \frac{(N/C)}{(N/O)} \left[1 + \frac{6}{7} \frac{N}{C} \right]$$

$$\frac{d(N/C)}{d(N/O)} \sim 4$$

- for initial (scaled) solar composition
- for cosmic abundance standard
 $X=0.715 \quad Y=0.271 \quad \mathbf{Z=0.014}$





Literature: NLTE Studies

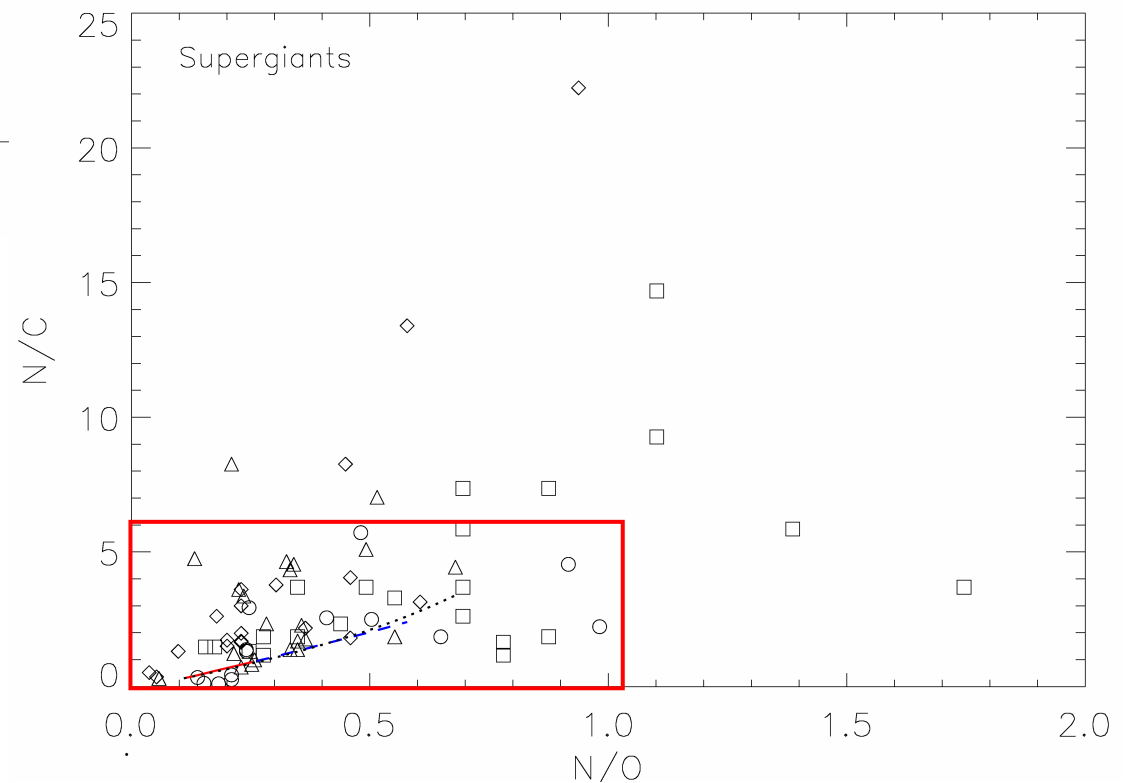
- large scatter observed

Tracks: 15 M_⊙

— $v_{\text{rot}}=300$ km/s Meynet & Maeder (2003)

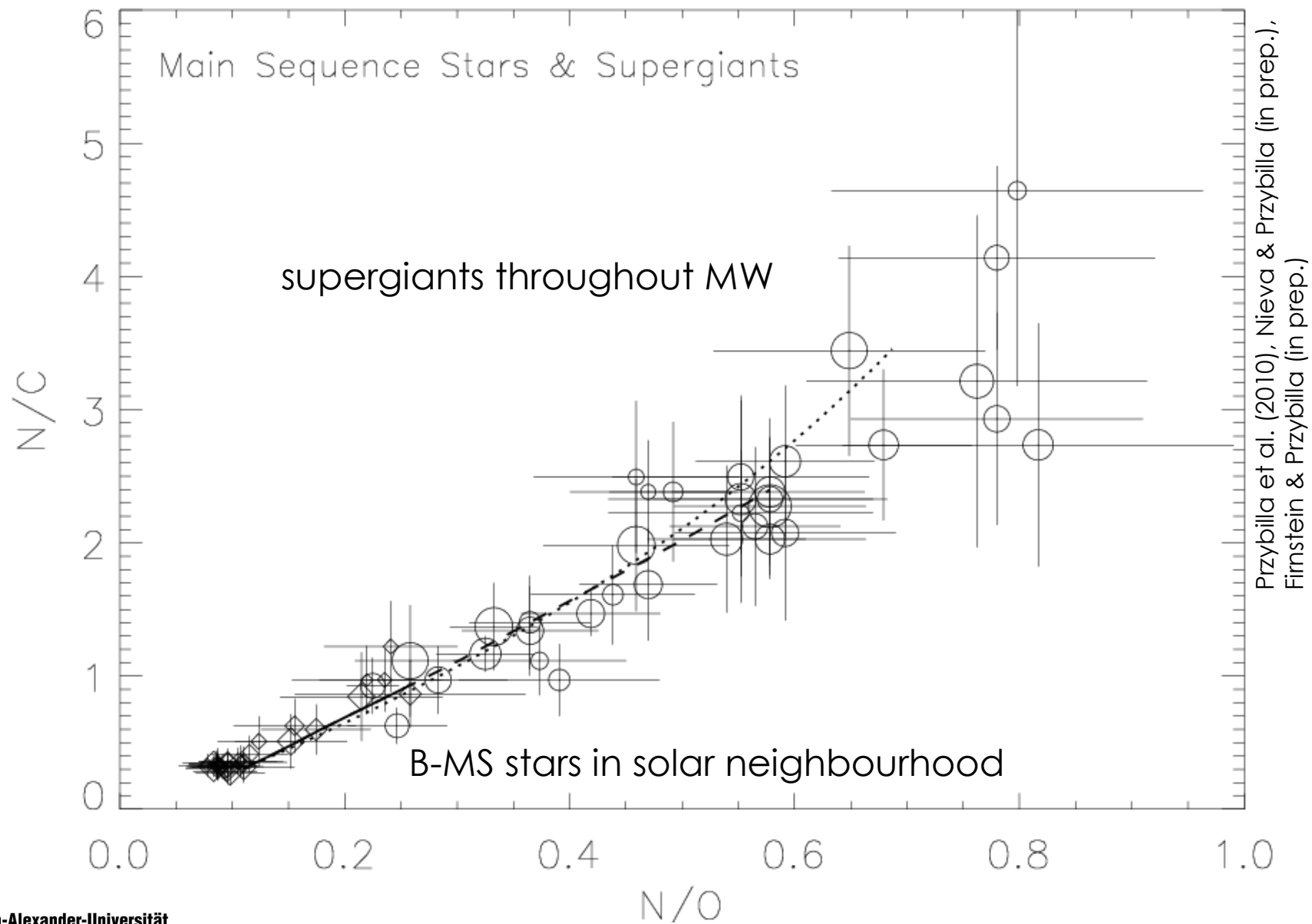
..... $v_{\text{rot}}=300$ km/s + B Maeder & Meynet (2005)

Przybilla et al. (2010)



constraints on models ?

Mixing of CNO: New NLTE Data

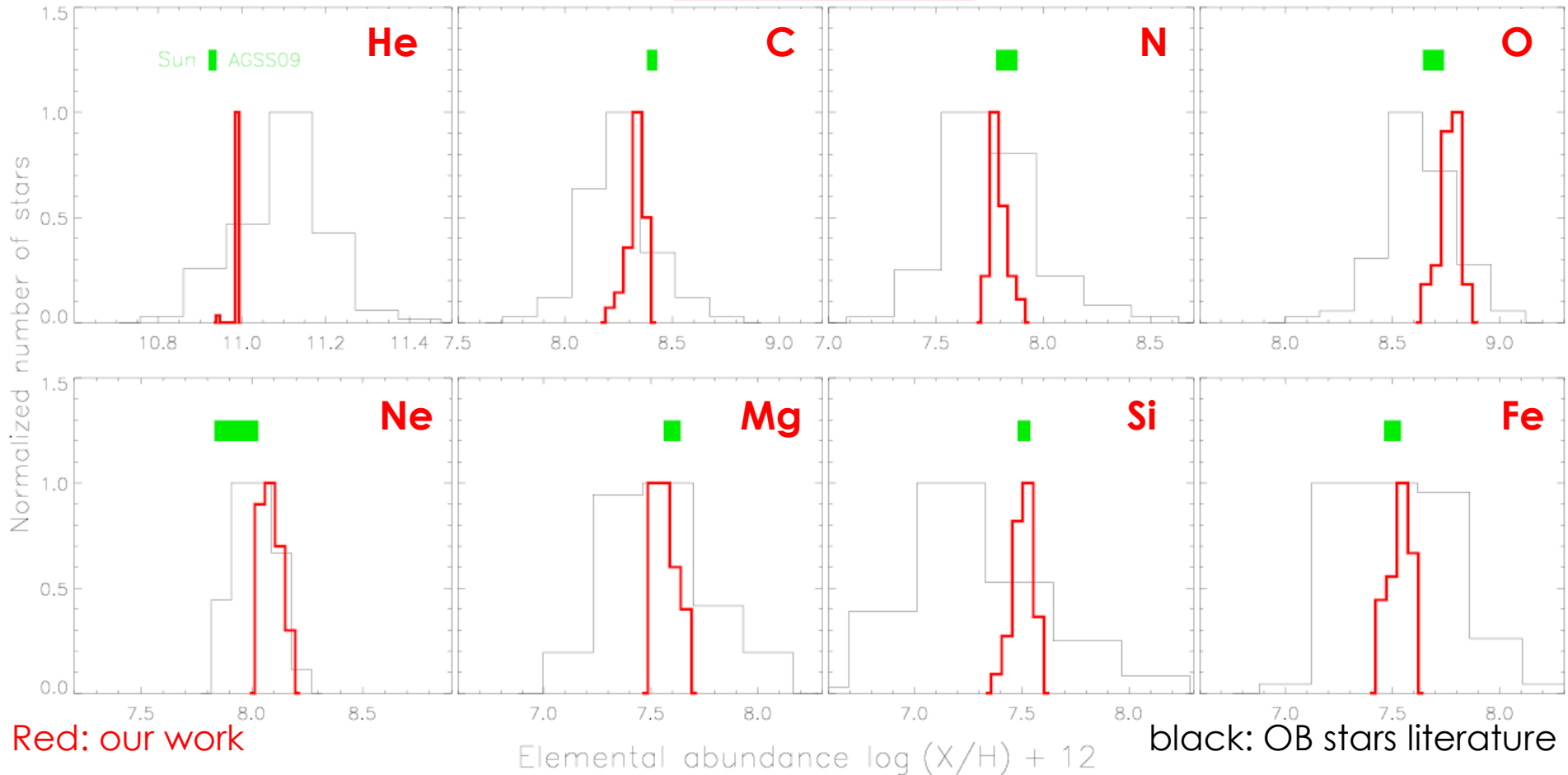


Chemical composition of the solar neighborhood

@ present day

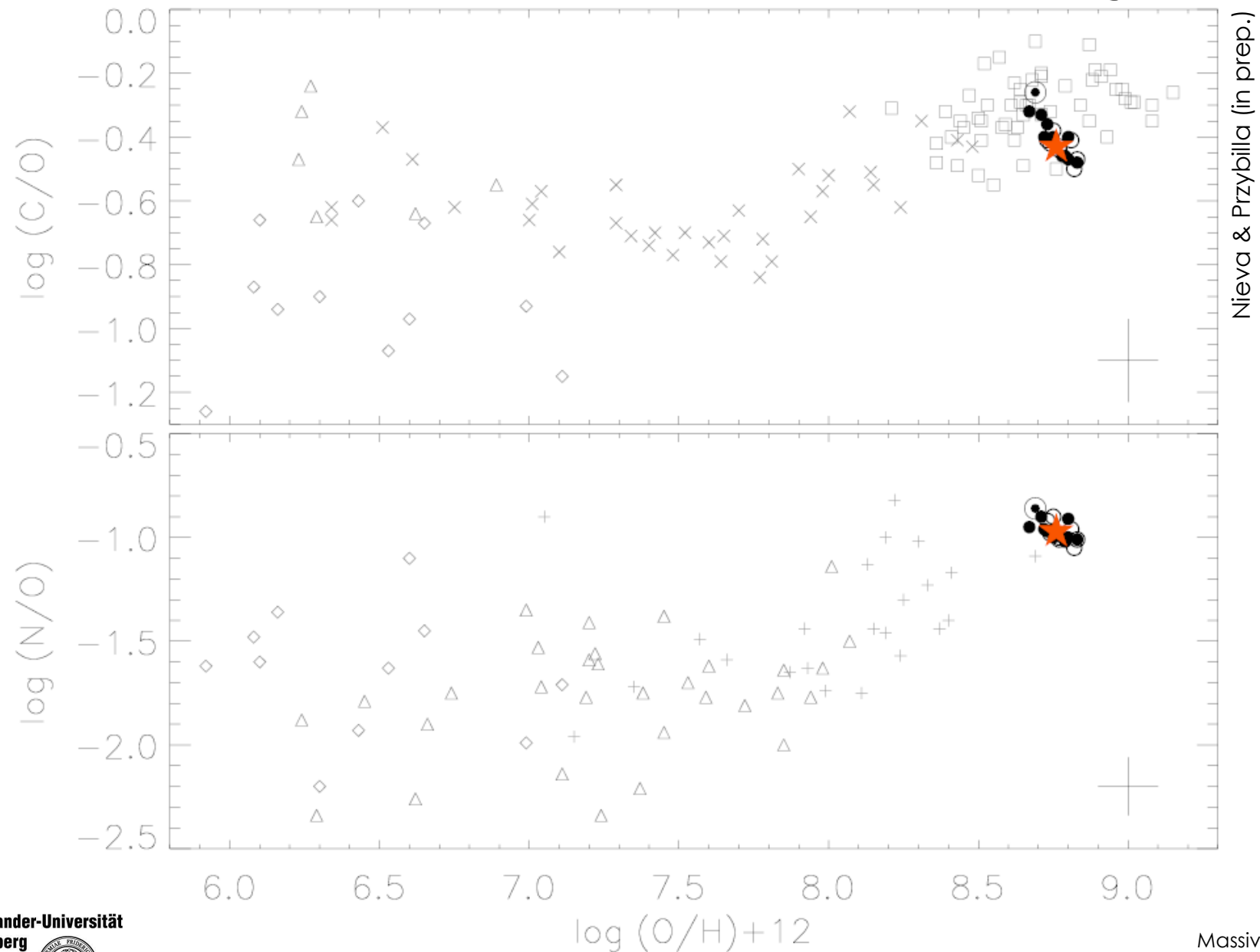
$1\sigma \sim 0.05$ dex

Nieva & Przybilla (in prep.)

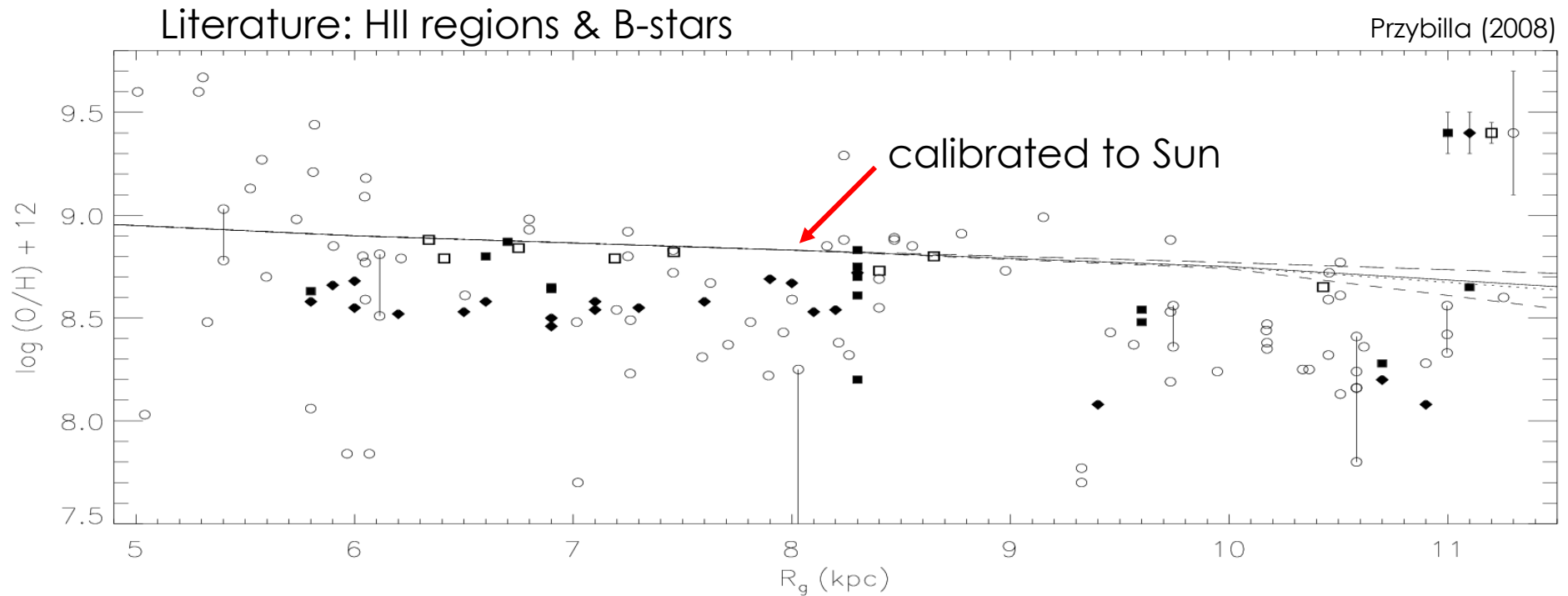


chemical homogeneity = ISM → **cosmic abundance standard**

Genesis of Heavy Elements over Cosmic History: e.g. CNO



Milky Way: Abundance Gradients

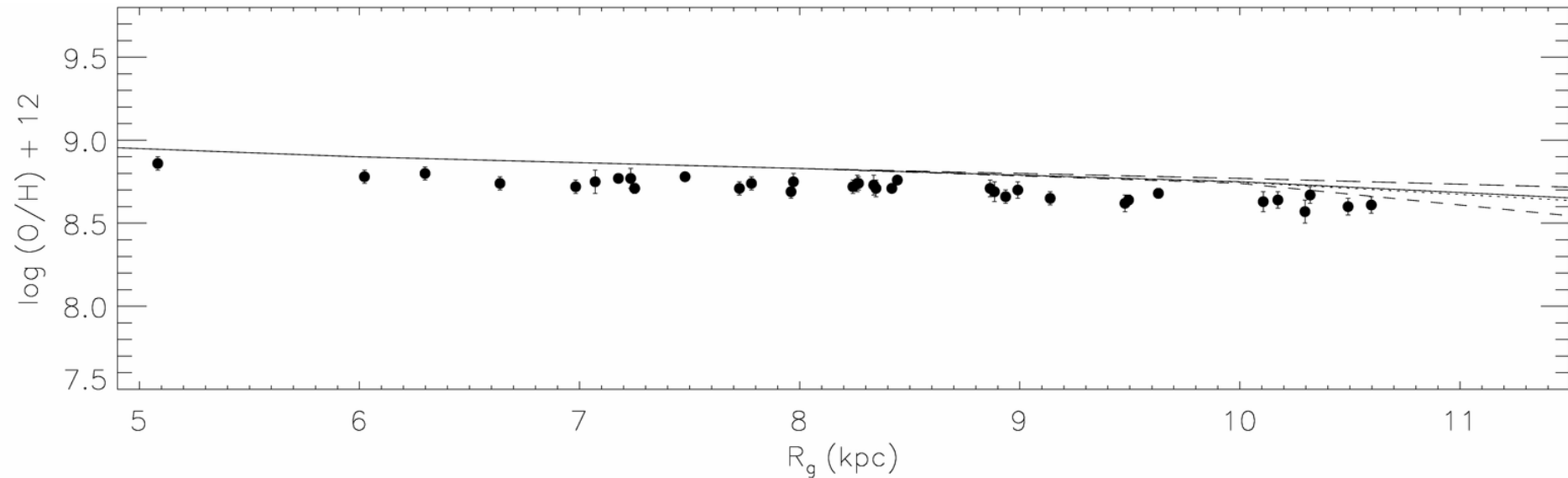


- large scatter @ every R
- complex picture from “simple” analysis

Milky Way: Abundance Gradients

our sample: BA-type supergiants

preliminary

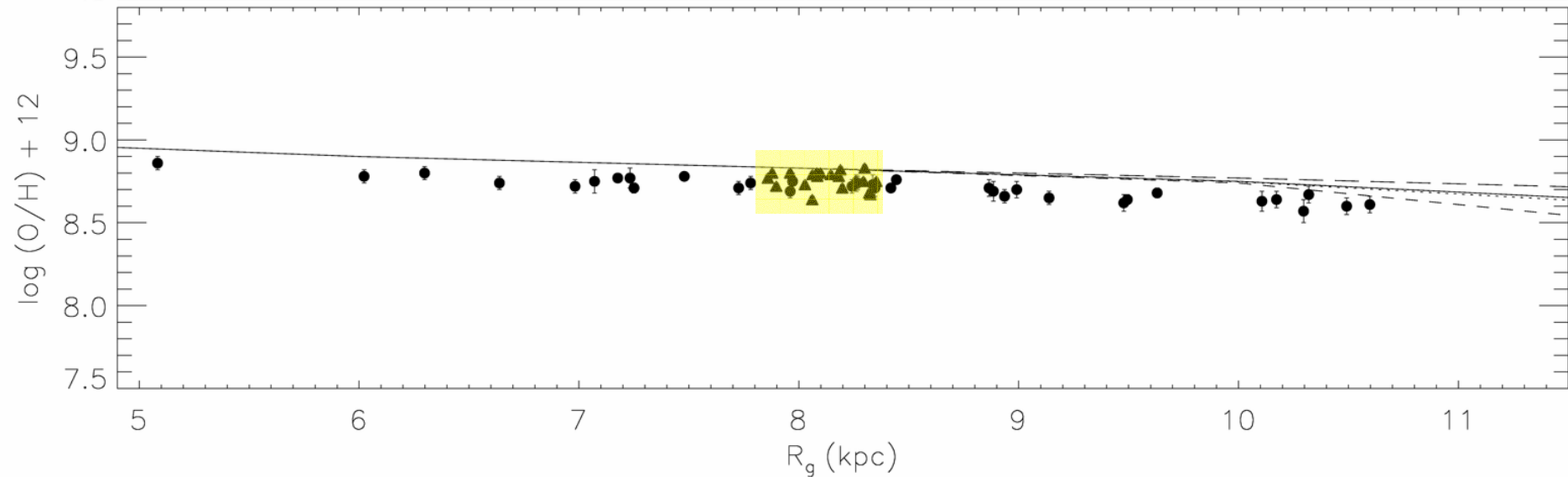


- tight abundance gradient: **low scatter @ every R**
- O abundance @ solar circle:
intermediate between “old” and “new” solar values

Milky Way: Abundance Gradients

our sample: BA-type supergiants + B-stars

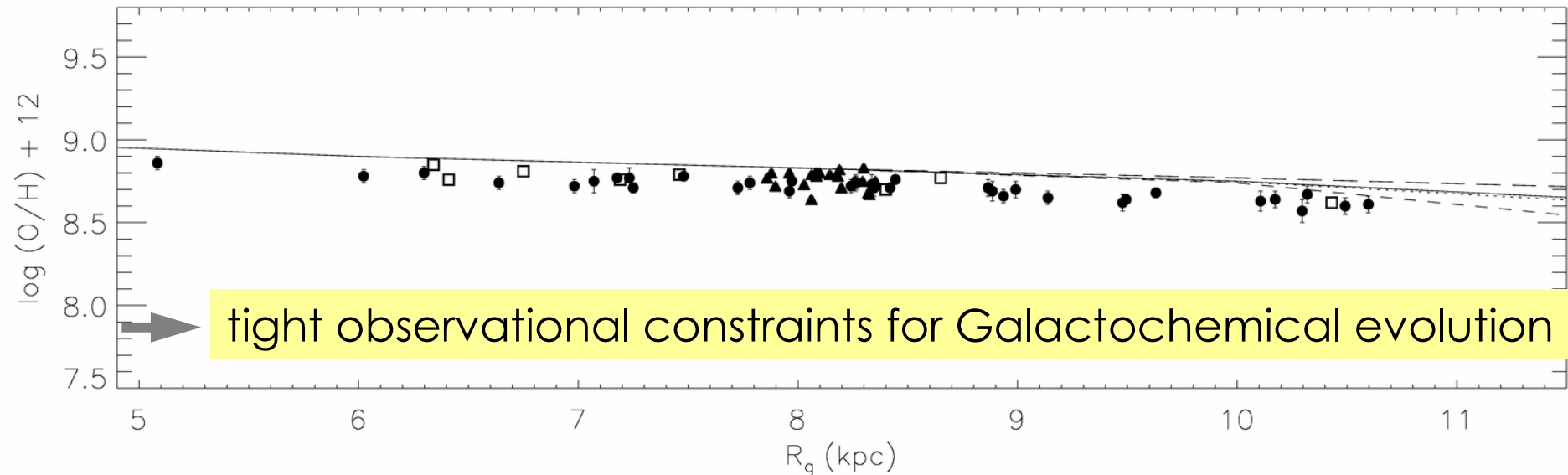
preliminary



- agreement from 2nd independent indicator
 - ➔ chemical homogeneity of solar neighbourhood
 - ➔ **cosmic abundance standard**

Milky Way: Abundance Gradients

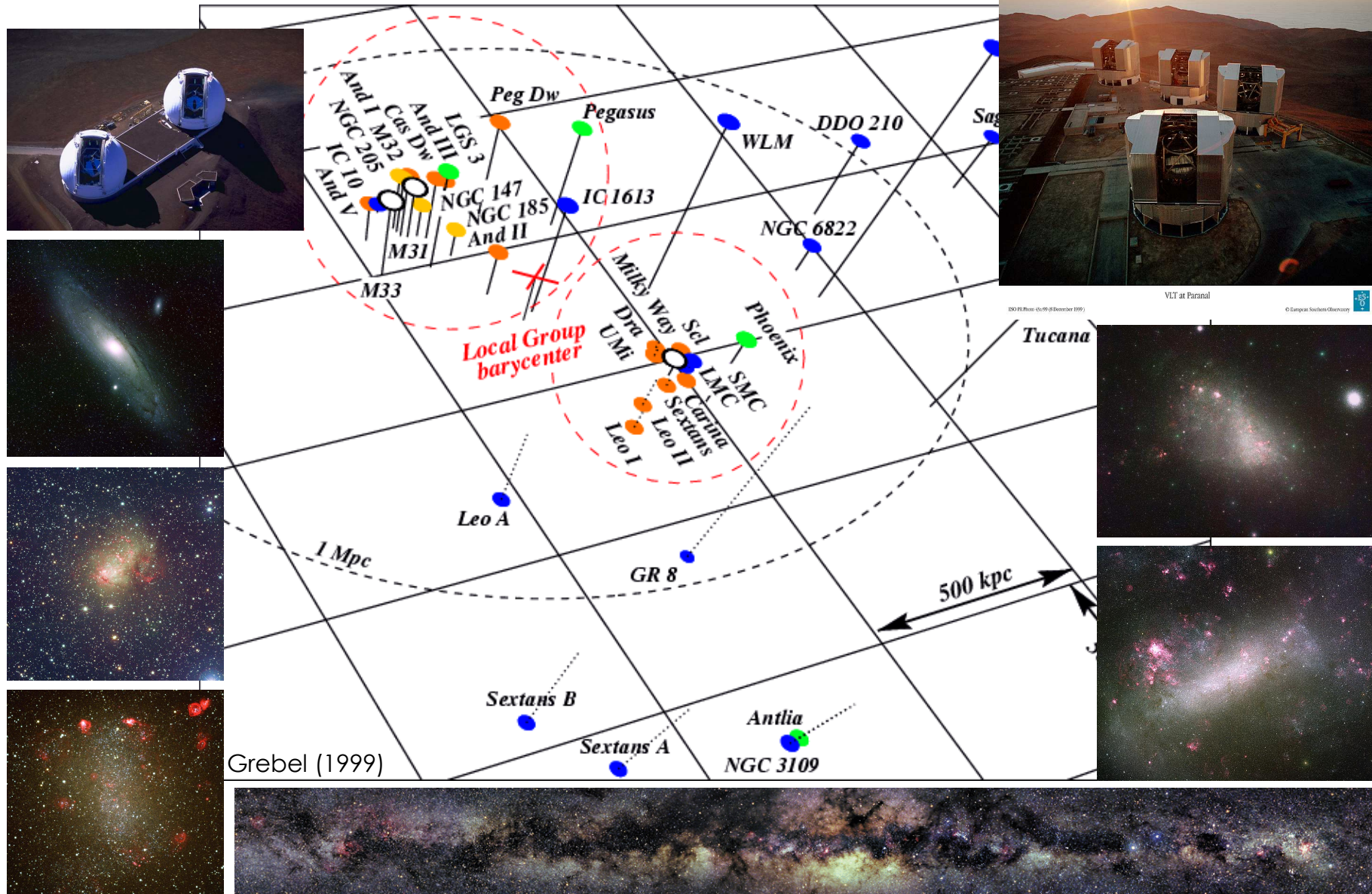
our sample: BA-type supergiants + B-stars & HII-regions (Esteban+ 2005)

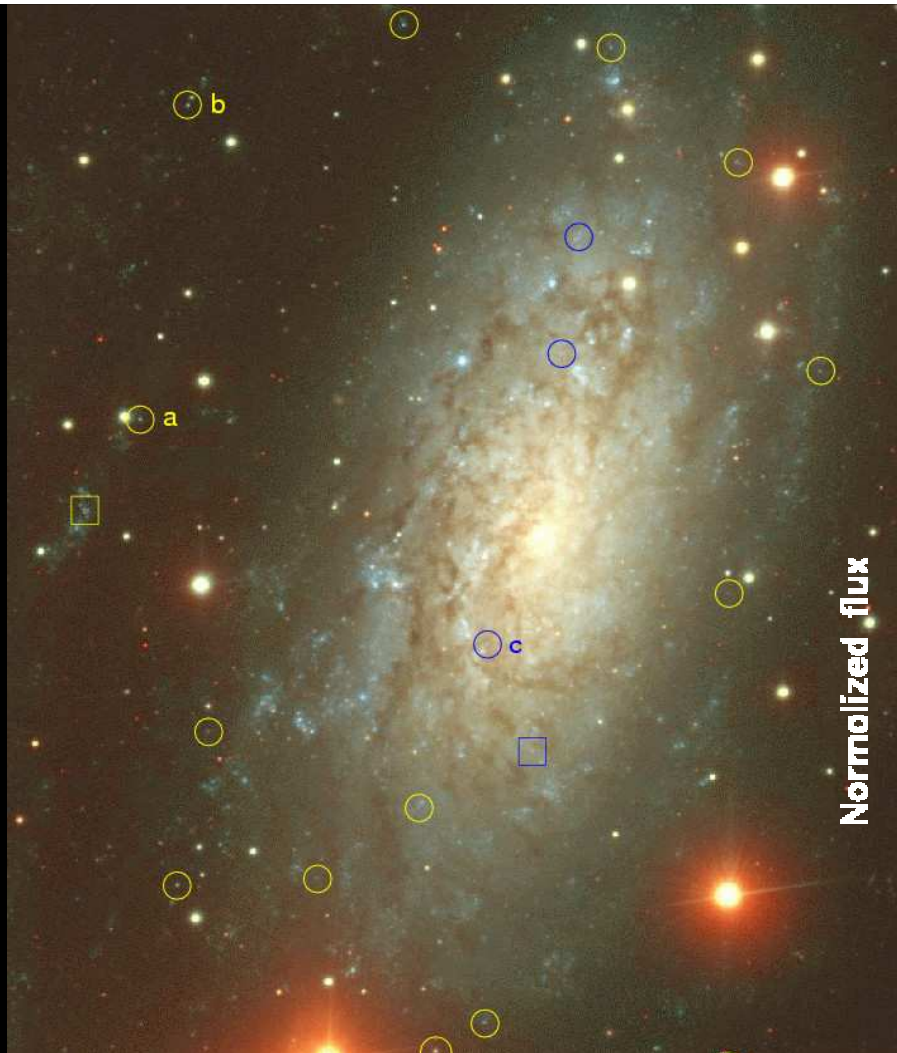


- 3rd independent indicator (HII-regions)
- absolute values from HII-regions problematic: dust depletion
- O abundance @ solar circle:
intermediate between “old” and “new” solar values
- simple picture from complex analysis

Extragalactic Stellar Astronomy: The Local Group

Extragalactic Stellar Astronomy





Bresolin, Kudritzki, Méndez & Przybilla (2001)

... and beyond

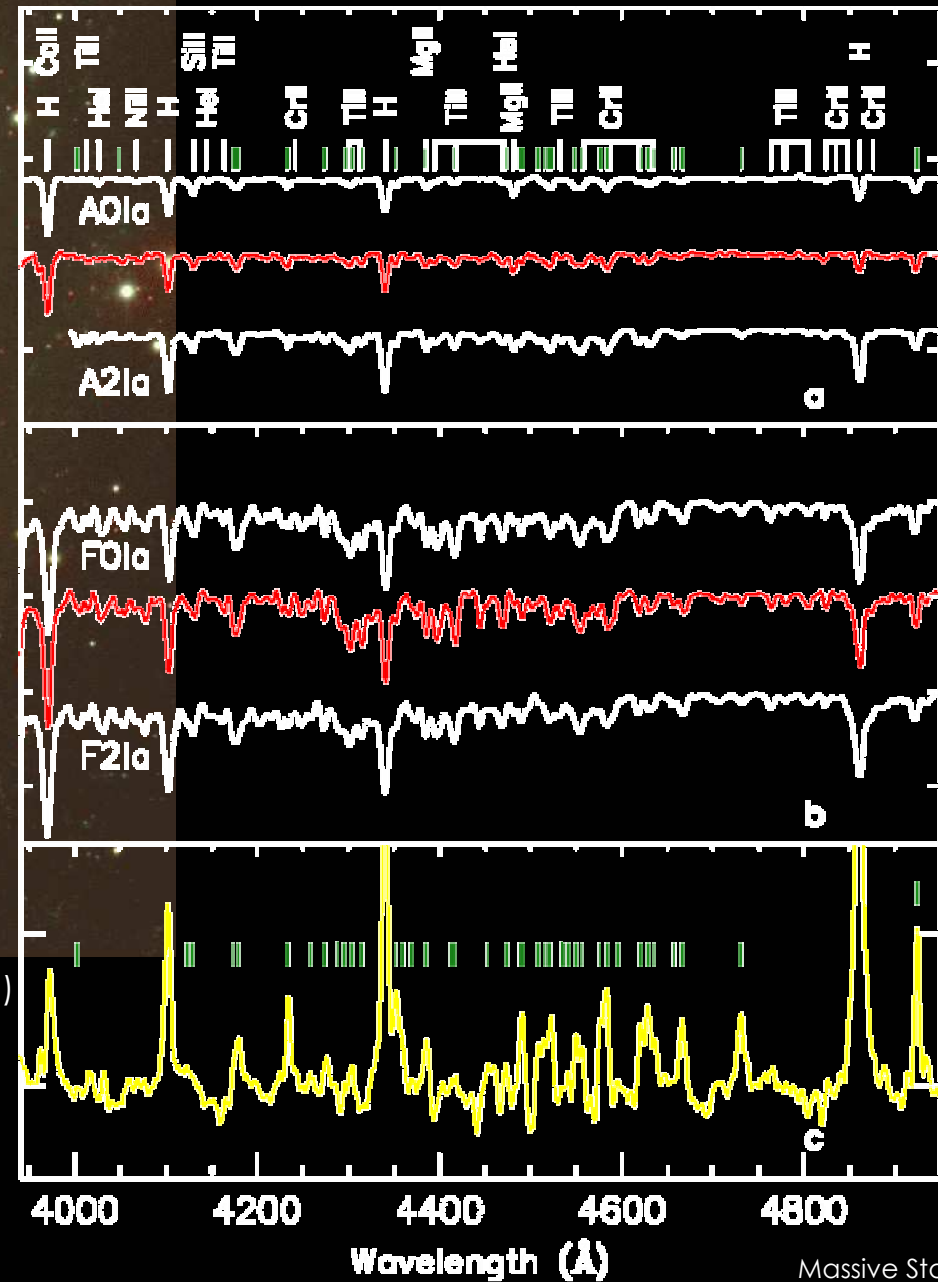
NGC 3621

d ~ 6.6 Mpc

VLT/FORS1



Normalized flux



Extragalactic Abundances

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



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

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

**Friedrich-Alexander-Universität
Erlangen-Nürnberg**



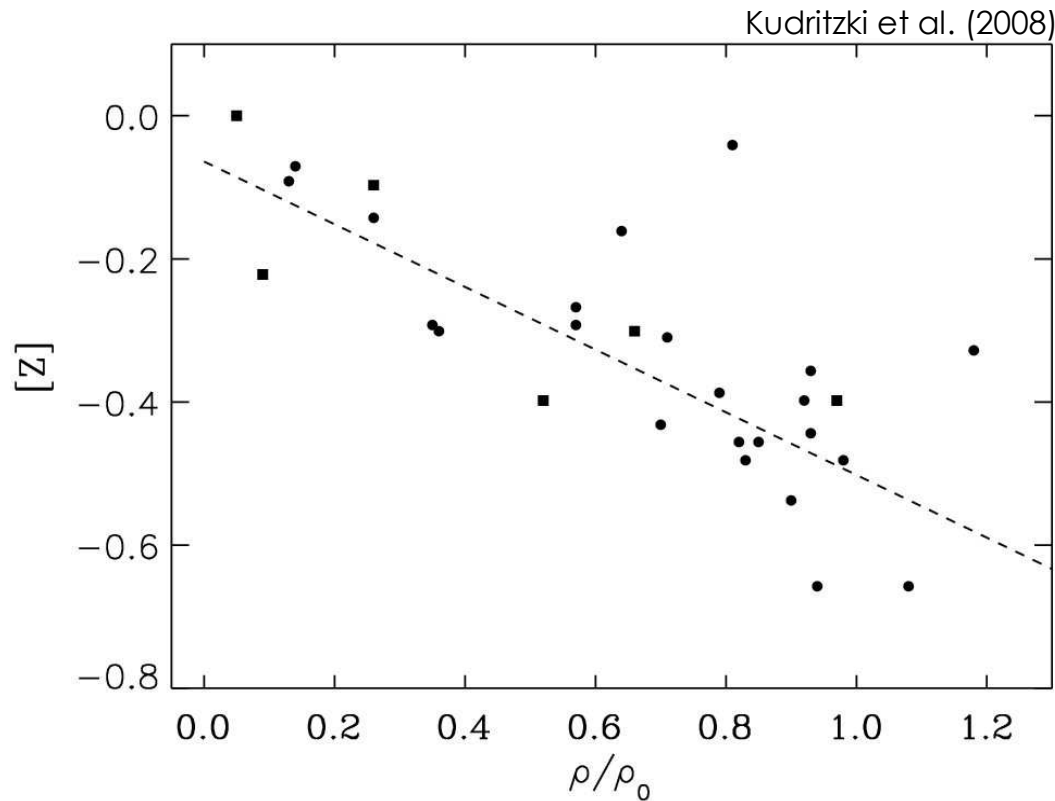
© European Southern Observatory



Massive Stars
ESO – 06.04.2011

NGC300

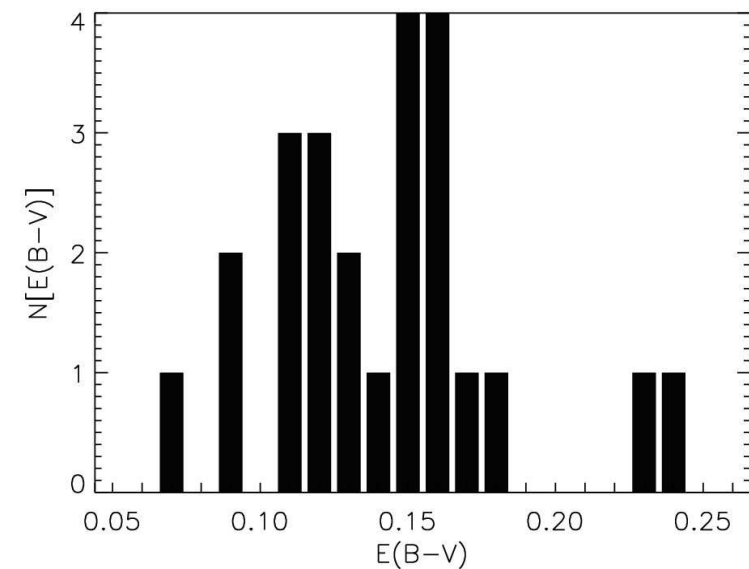
- radial trend of chemical abundances
- azimuthal variation?
- investigate interstellar absorption
- distance determination
➔ FGLR



metallicity gradient:
30 B & A-type supergiants

To be expected:
improvements on
Cepheid distance scale

interstellar
extinction
within NGC300



Summary

- precise & accurate quantitative spectroscopy feasible
- simple picture from complex analysis

Stellar Evolution

- tight observational constraints on horizon for testing models

Galactochemical Evolution

- highly uniform abundances in solar vicinity
→ cosmic abundance standard
- tight Galactic abundance gradients

Extragalactic Stellar Astrophysics

- stellar/galactic studies out to Virgo & Fornax clusters

