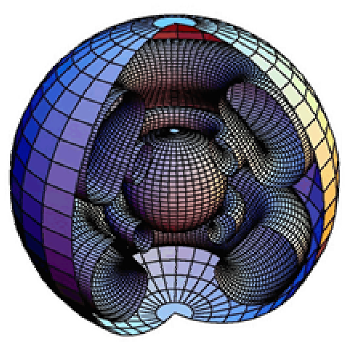
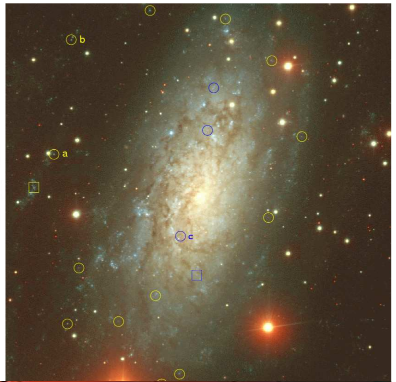
$$n_i \sum_{j\neq i}(R_{ij}+C_{ij}) = \sum_{j\neq i} n_j(R_{ji}+C_{ji})$$

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





Massive Stars
as Tracers for
Stellar & Galactochemical Evolution

Norbert Przybilla

Dr. Remeis-Observatory Bamberg

M. Firnstein, F. Schiller

M.F. Nieva, K. Butler, R.P. Kudritzki, G. Meynet, A. Maeder

Friedrich-Alexander-Universität Erlangen-Nürnberg

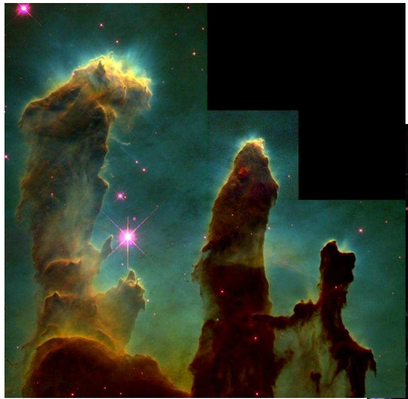
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Outline

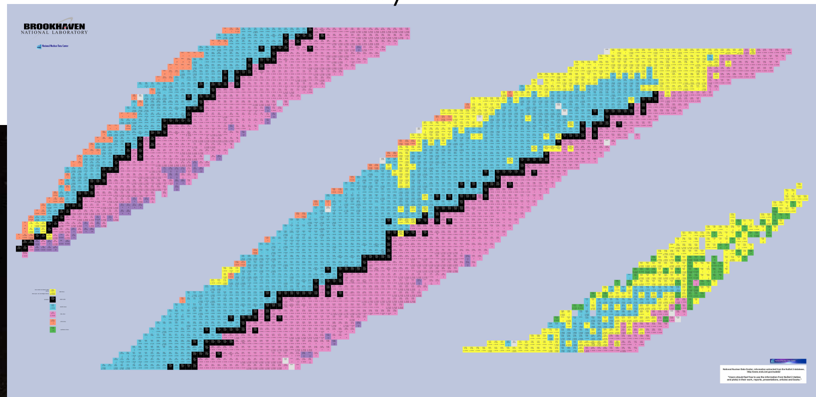
- Intro
- Diagnostics
- Quantitative Spectroscopy @ High Precision & Implications for Stellar/Galactochemical Evolution
- Outlook: Extragalactic Stellar Astronomy

Origins: Cosmic Cycle of Matter

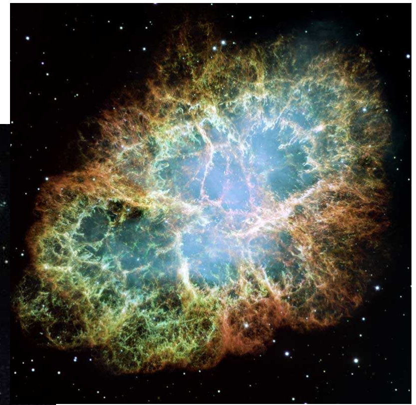
birth

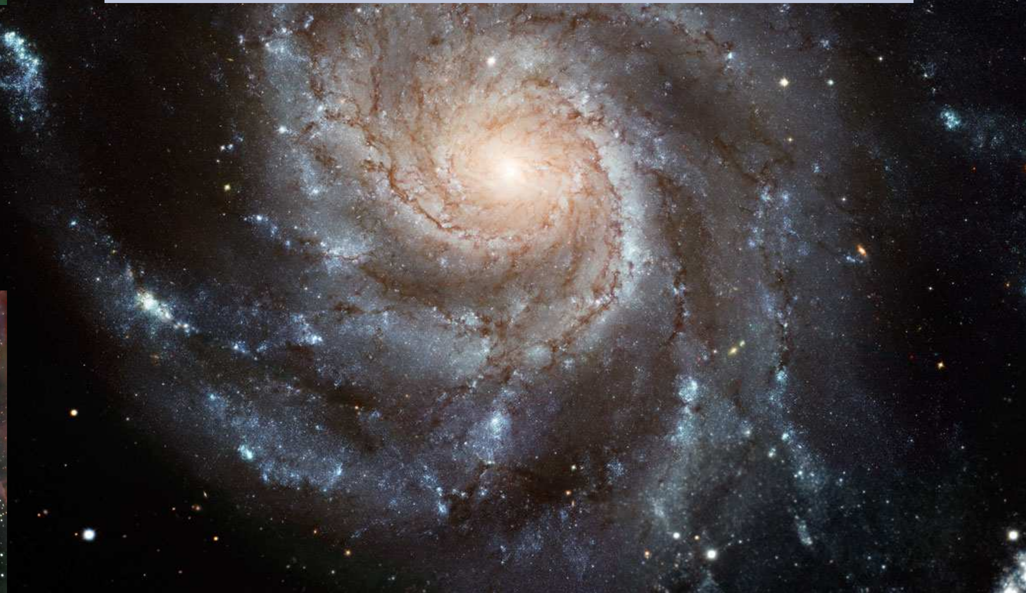


nucleosynthesis

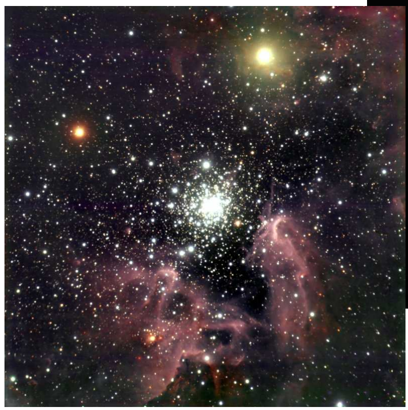


death

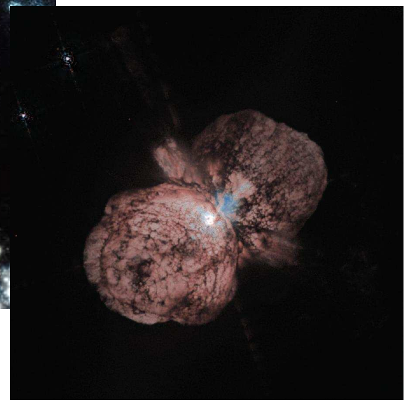




life



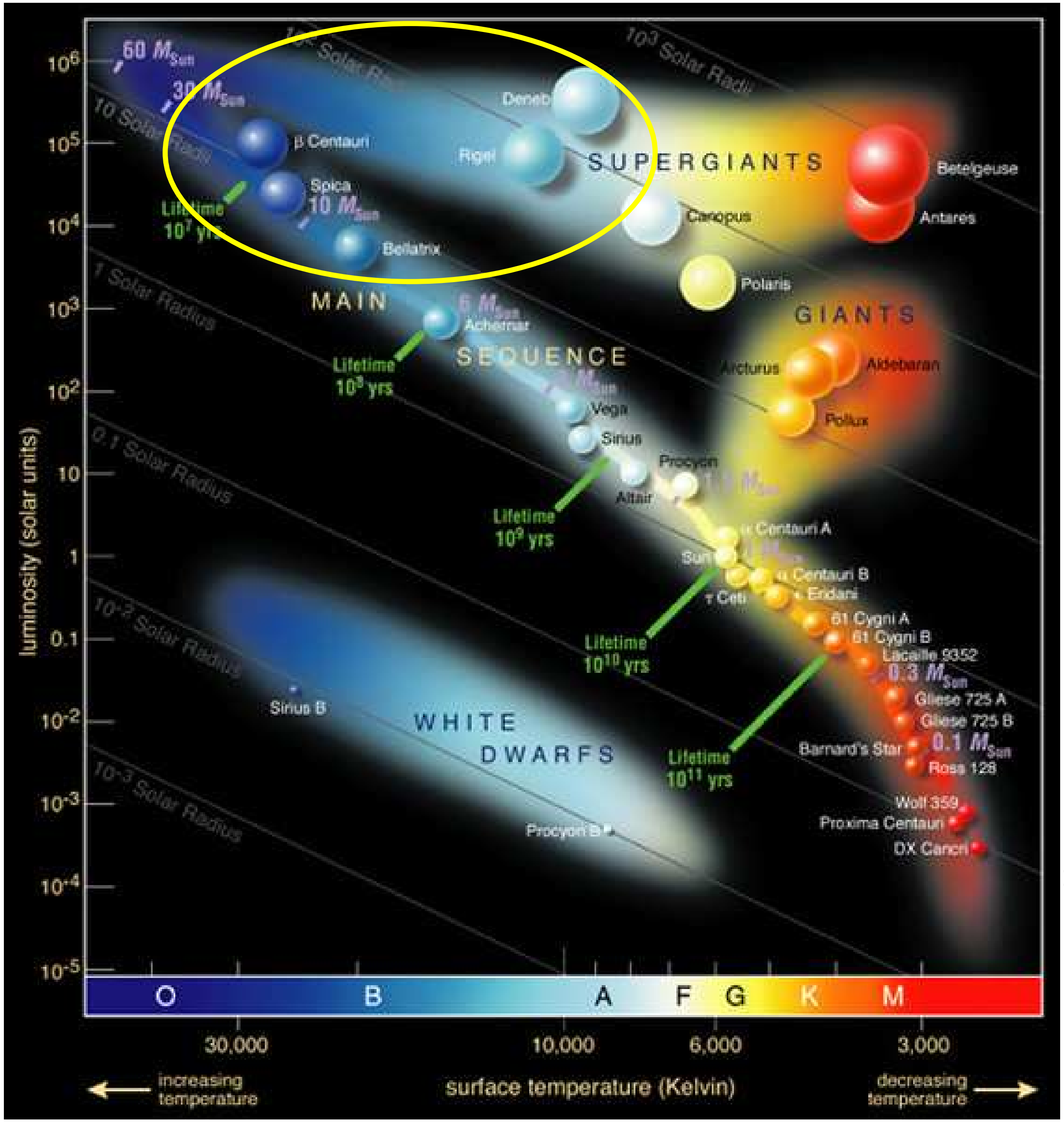
galaxy evolution



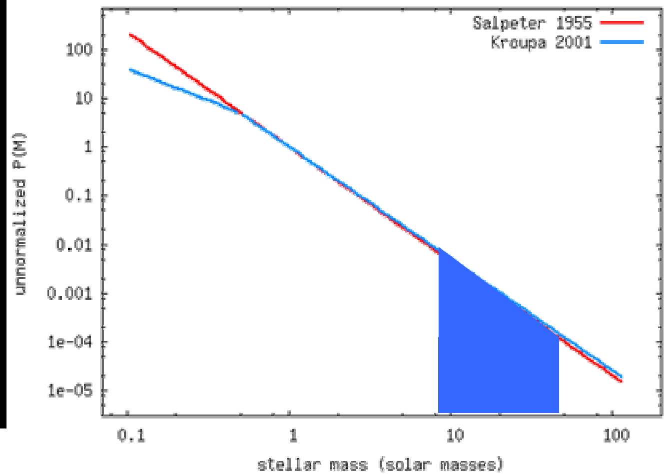
interactions

Friedrich-Alexander-Universität
Erlangen-Nürnberg

Massive Stars



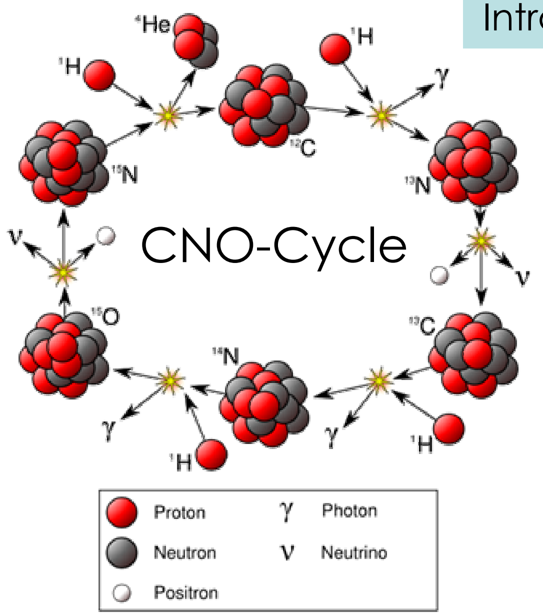
- dominate energy and momentum budget of ISM in galaxies
  - SN II, winds, UV photons
- key drivers for cosmic cycle of matter
  - star formation, nucleosynth.
- highly luminous
  - abundance indicators over large distances: Local Group & beyond

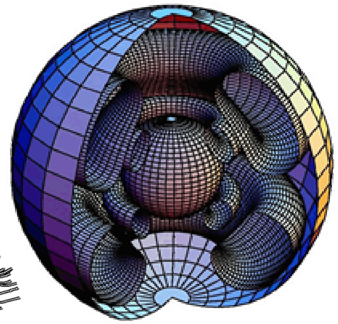


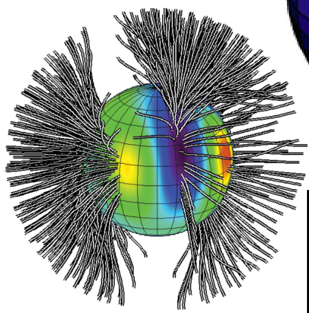
Massive Stars Evolution: Theory

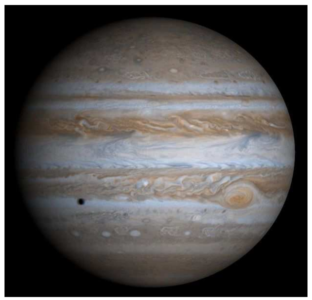
- Context: Cosmic Cycle of Matter
  massive stars: sites of nucleosynthesis ➔ SNe
- stellar evolution: $f(M, \dot{M}, Z, \Omega, B)$
- complex (magneto-)hydrodynamic problem: advances recently in theory
- predicted enrichment of the stellar atmosphere with nuclear processed matter via hydrodynamic transport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

➔ empirical verification and calibration of stellar evolution models





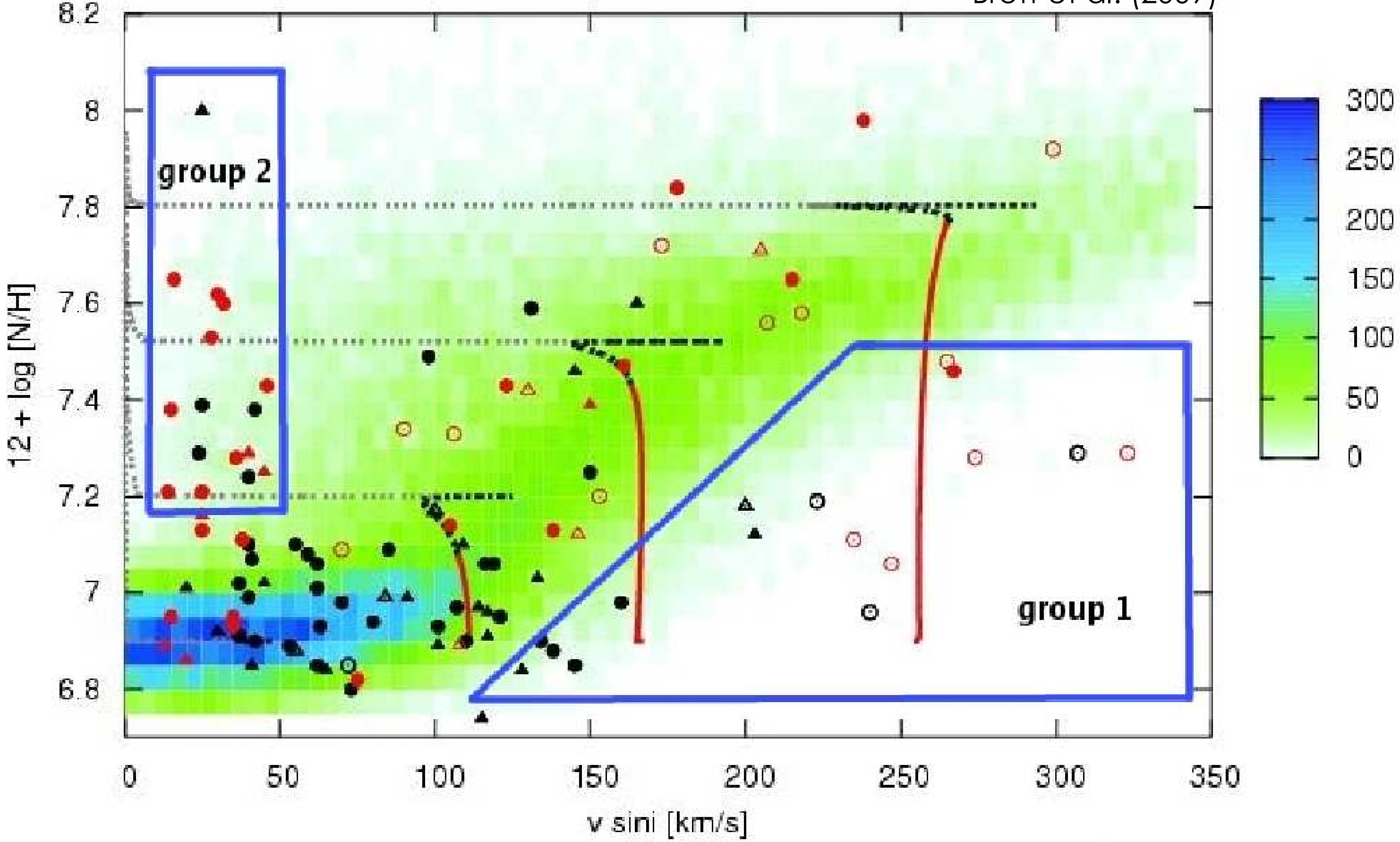




Observational Constraints to Stellar Evolution Models

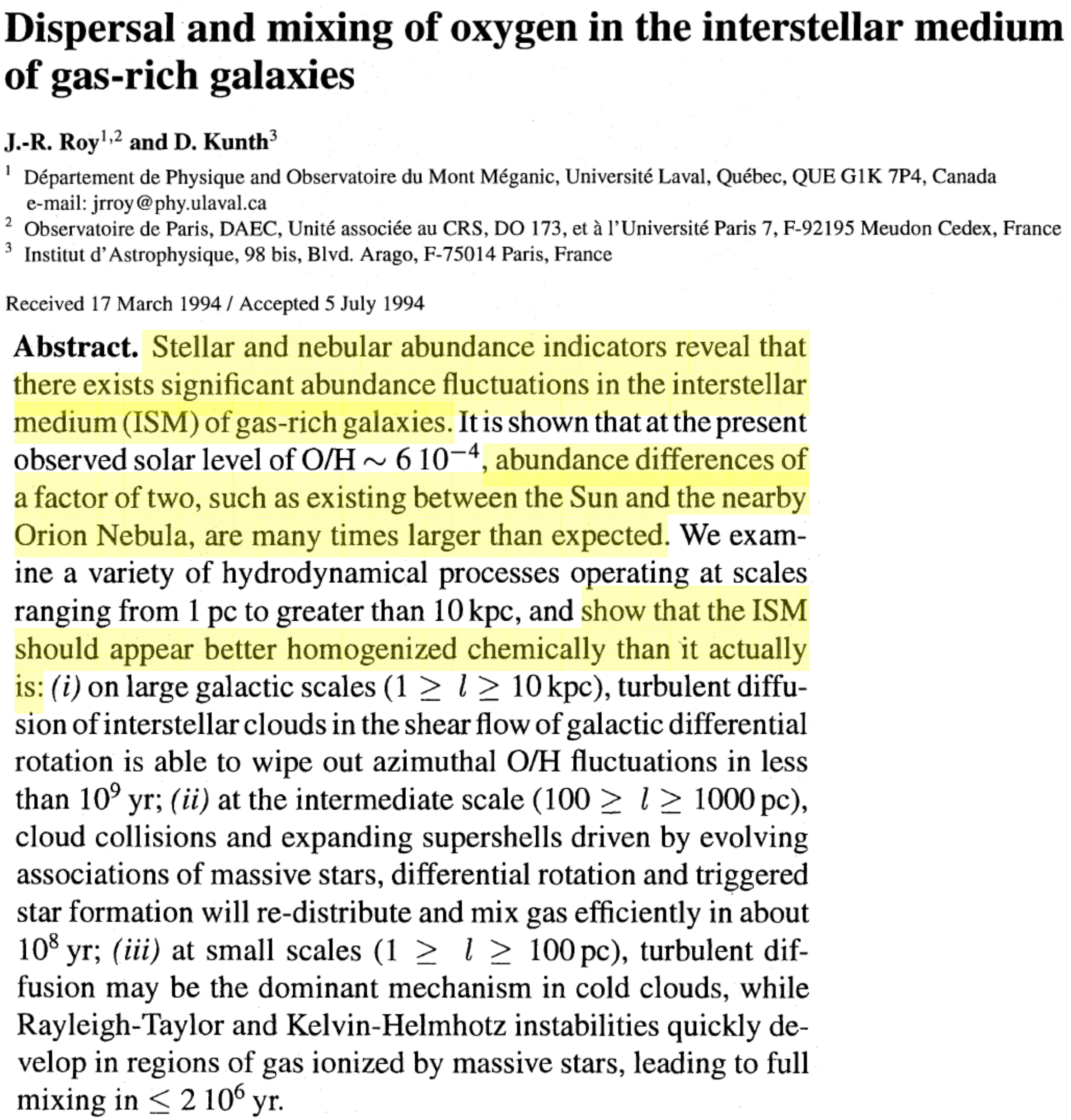
FLAMES survey of massive stars

Brott et al. (2009)



- many stars with unexpected characteristics

Observational Constraints to Galactic Chemical Evolution


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

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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 $\sim 6\,10^{-4}$, 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-Helmhotz instabilities quickly develop in regions of gas ionized by massive stars, leading to full mixing in $\leq 2\,10^6$ yr.

- massive stars: inferred from observation
  → chemical inhomogeneity

BUT

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

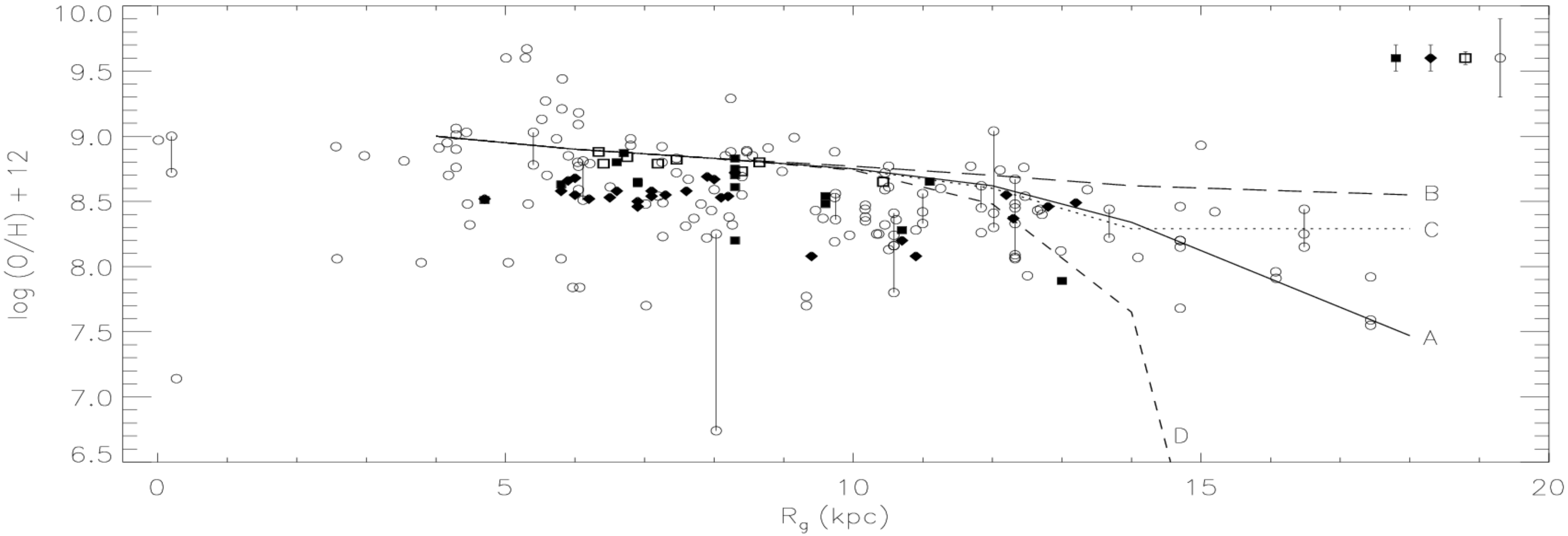
Theory:

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

Observational Constraints to Galactic Chemical Evolution

Present-day abundance gradients in Milky Way

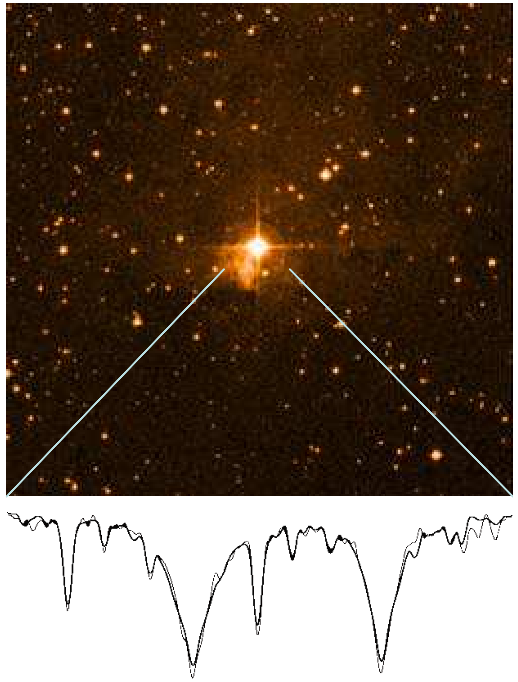
B-stars: Gummersbach+ (1998),
Daflon & Cunha (2004)
HII: Esteban+ (2005), Rudolph+ (2006)
models: Chiappini+ (2001)



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

other galaxies?

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

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

- 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

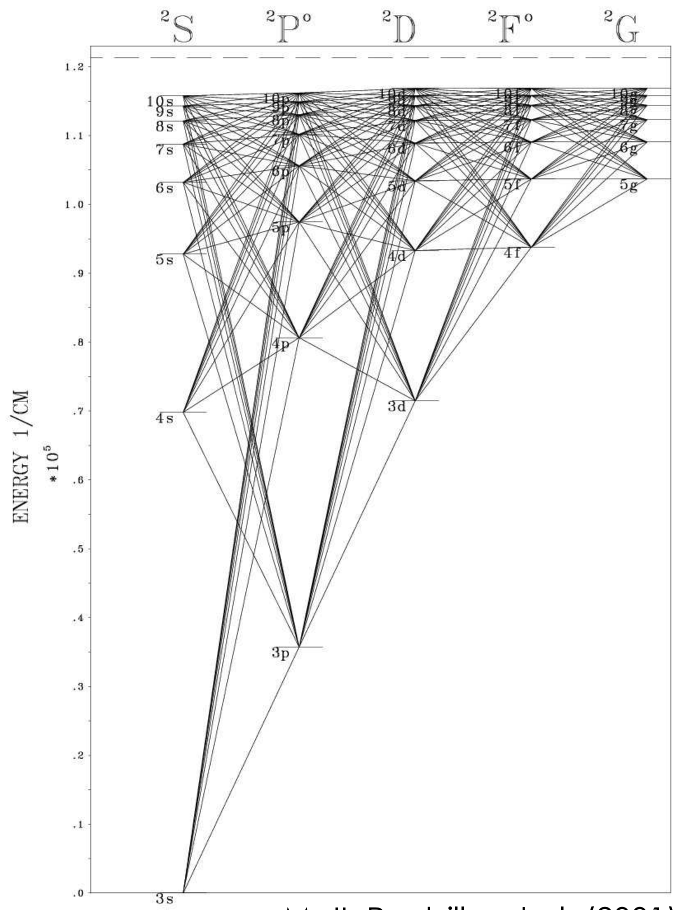
- collisional rates:

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

local

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

→ model atoms

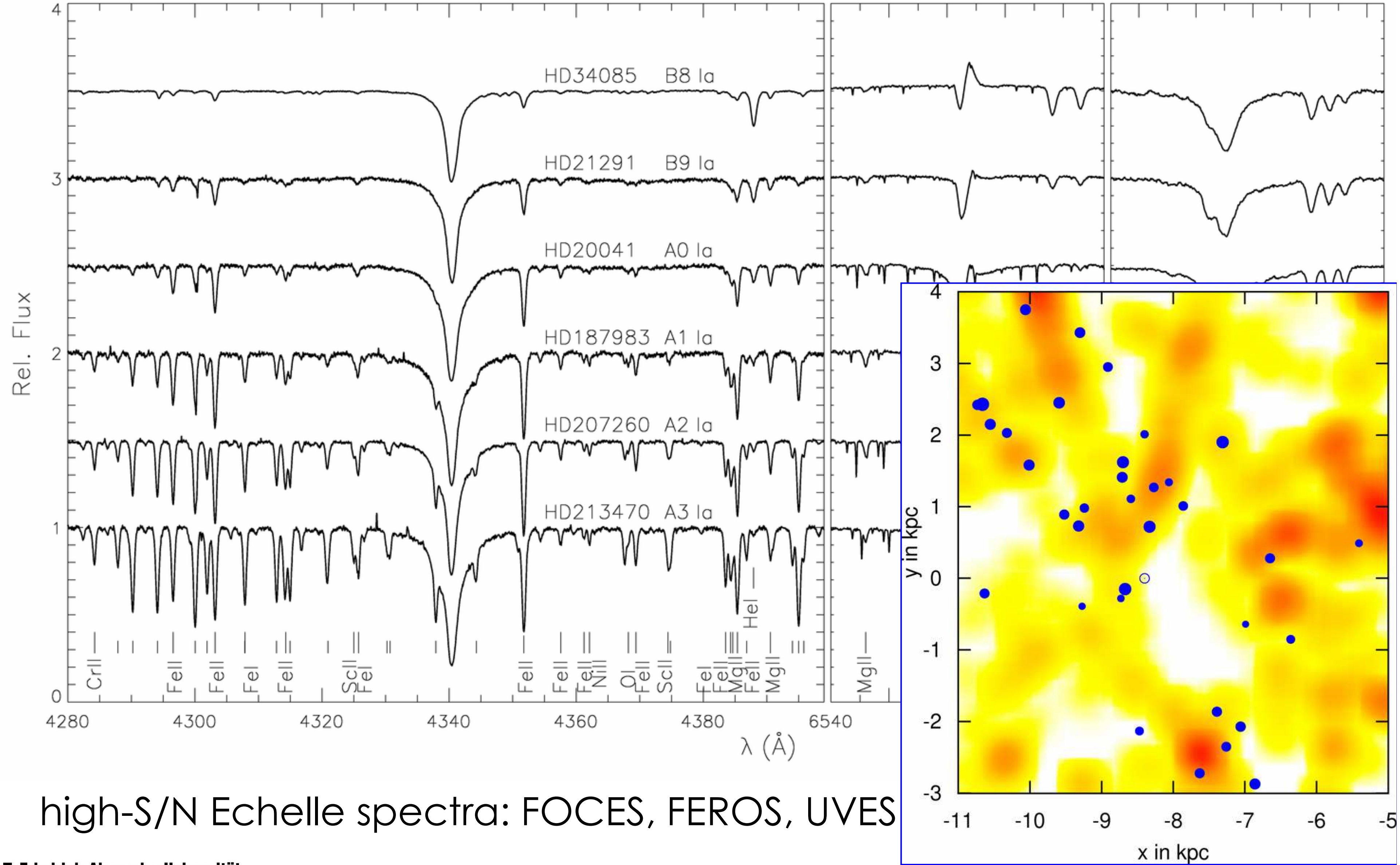


MgII: Przybilla et al. (2001)

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 → T_{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
  $\Delta T_{eff} / T_{eff}$ ~ 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, …

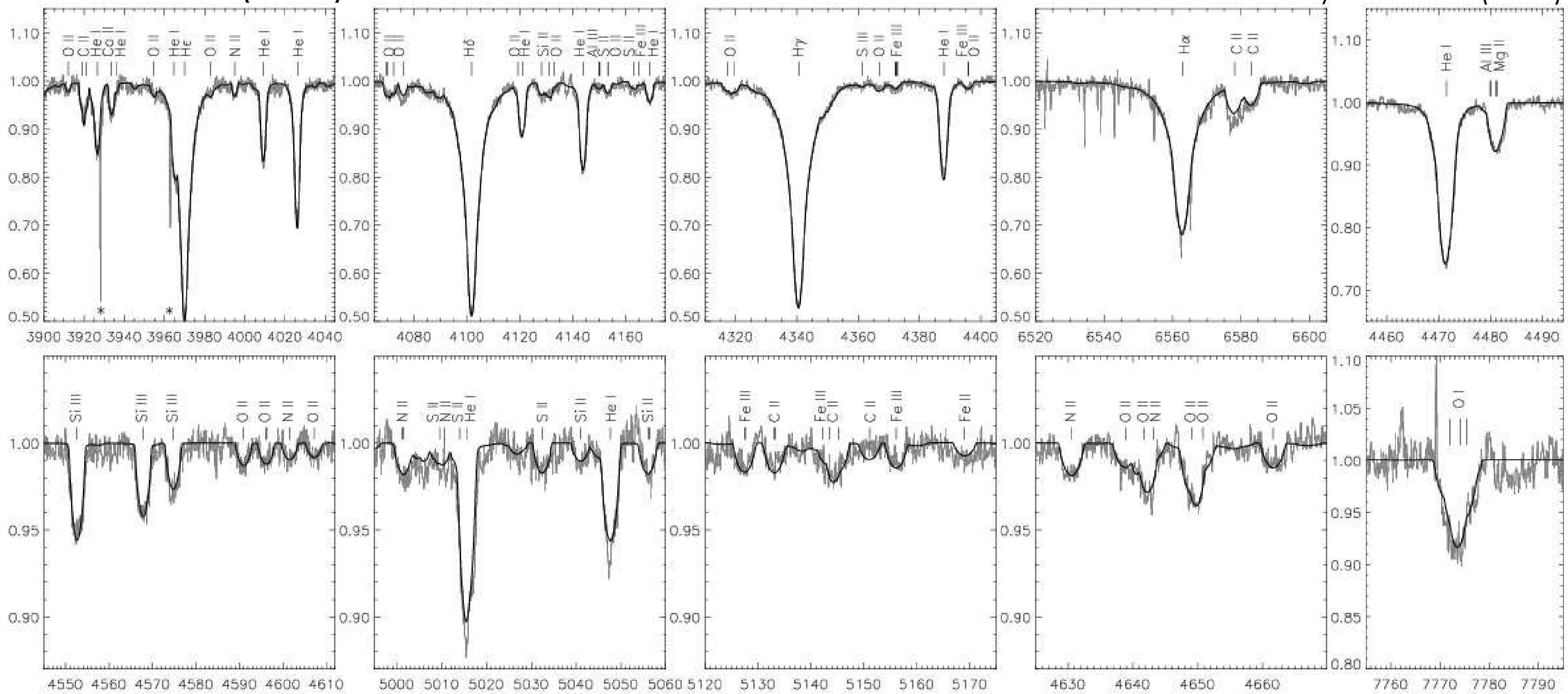
- abundances: **$\Delta\log\varepsilon$ ~ 0.05...0.10 dex** (1σ–stat.) usually: factor ~2
  $\Delta\log\varepsilon$ ~ 0.07...0.12 dex (1σ–sys.) usually: ???

→ **fine ruler**

Spectroscopy @ High-res & High-S/N

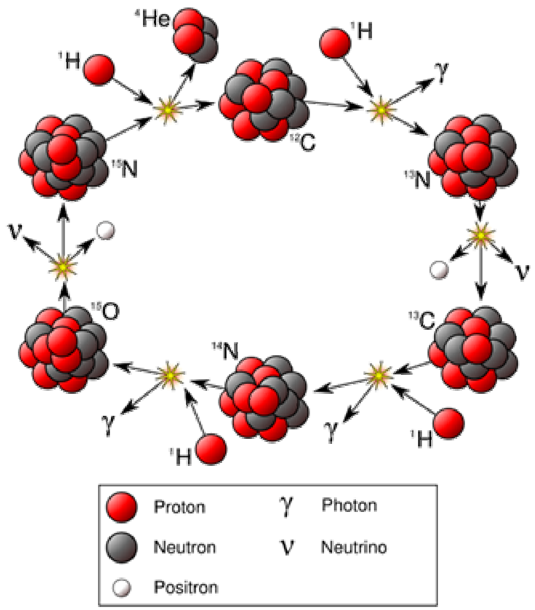
HD271791 (B3 III)

Przybilla et al. (2008)



- several 10⁴ lines: ~30 elements, 60+ ionization stages
- complete spectrum synthesis in visual (& near-IR) ~70-90% in NLTE

Nuclear path of the CNO-cycles



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

initially CN-cyle: $\mathrm{d}C = -\frac{6}{7}\mathrm{d}N$, O const.

$$\mathrm{d}(N/O) = \mathrm{d}N/O$$

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

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

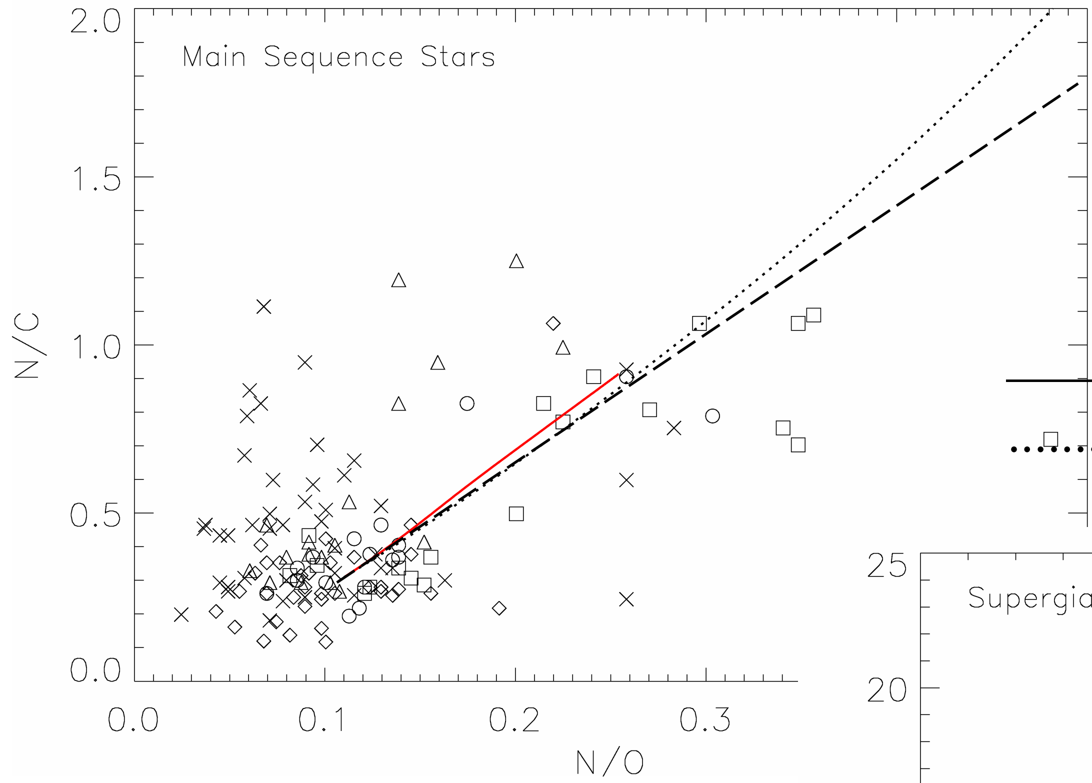
$$\frac{\mathrm{d}(N/C)}{\mathrm{d}(N/O)} \sim 4$$

- for initial (scaled) solar composition
- for cosmic abundance standard

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

Literature: NLTE Studies

- large scatter observed

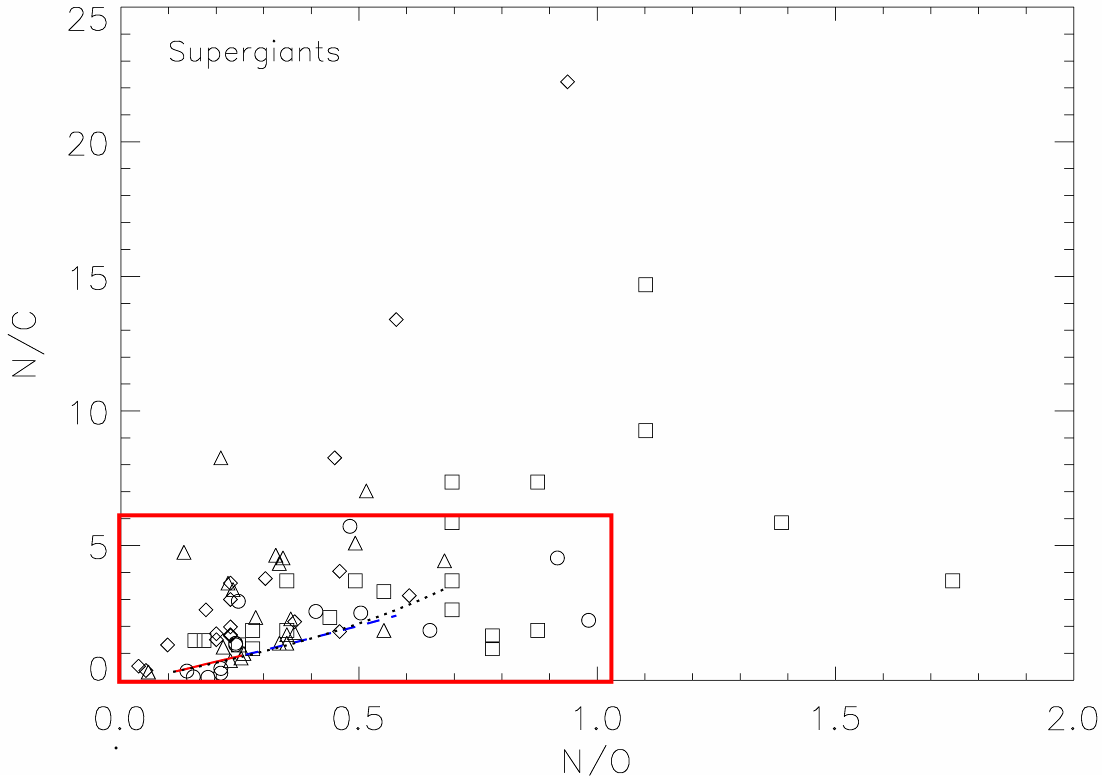


Tracks: 15 $M_\odot$

v_{rot}=300 km/s Meynet & Maeder (2003)

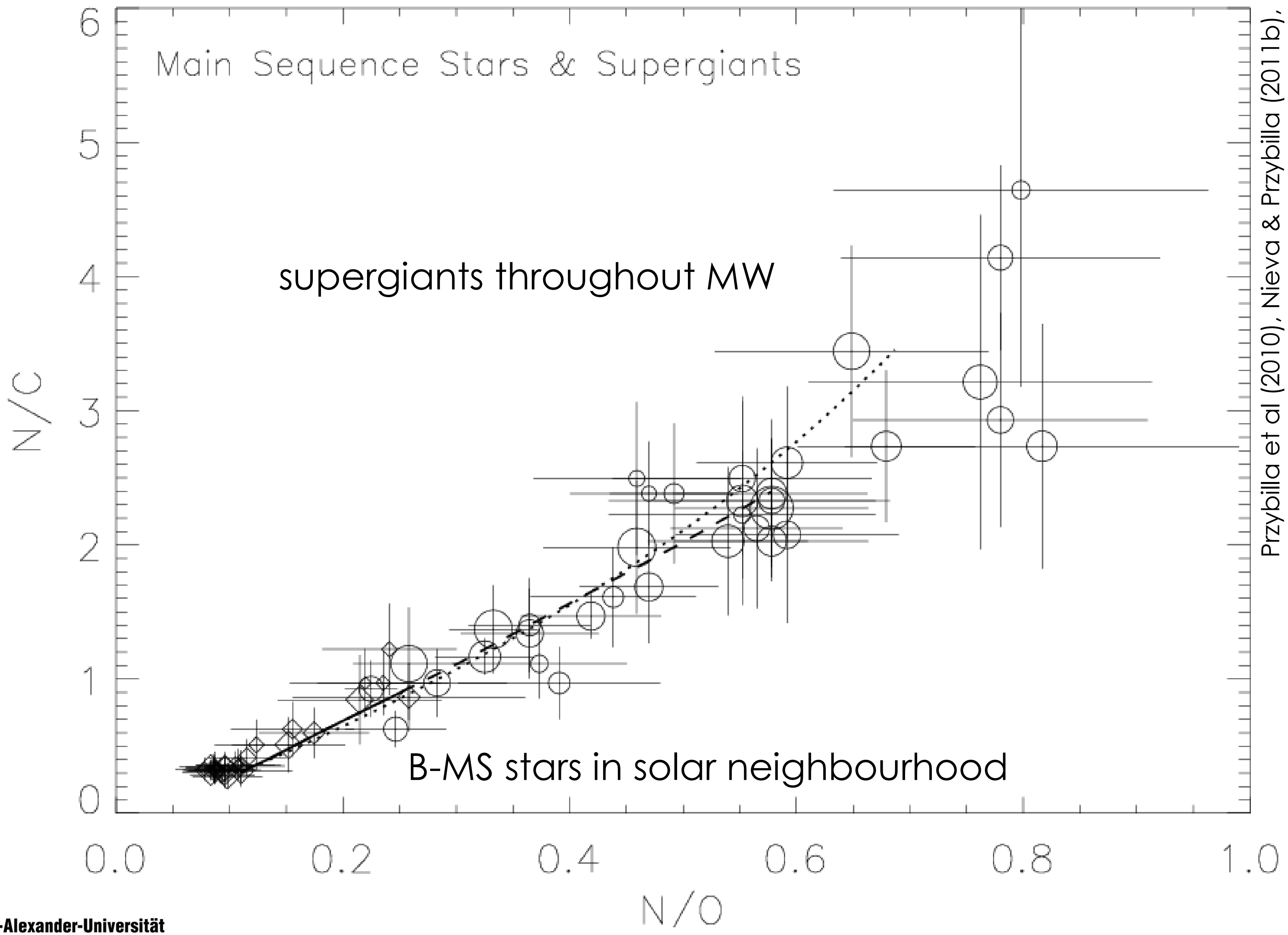
v_{rot}=300 km/s + B Maeder & Meynet (2005)

Przybilla et al. (2010)



constraints on models ?

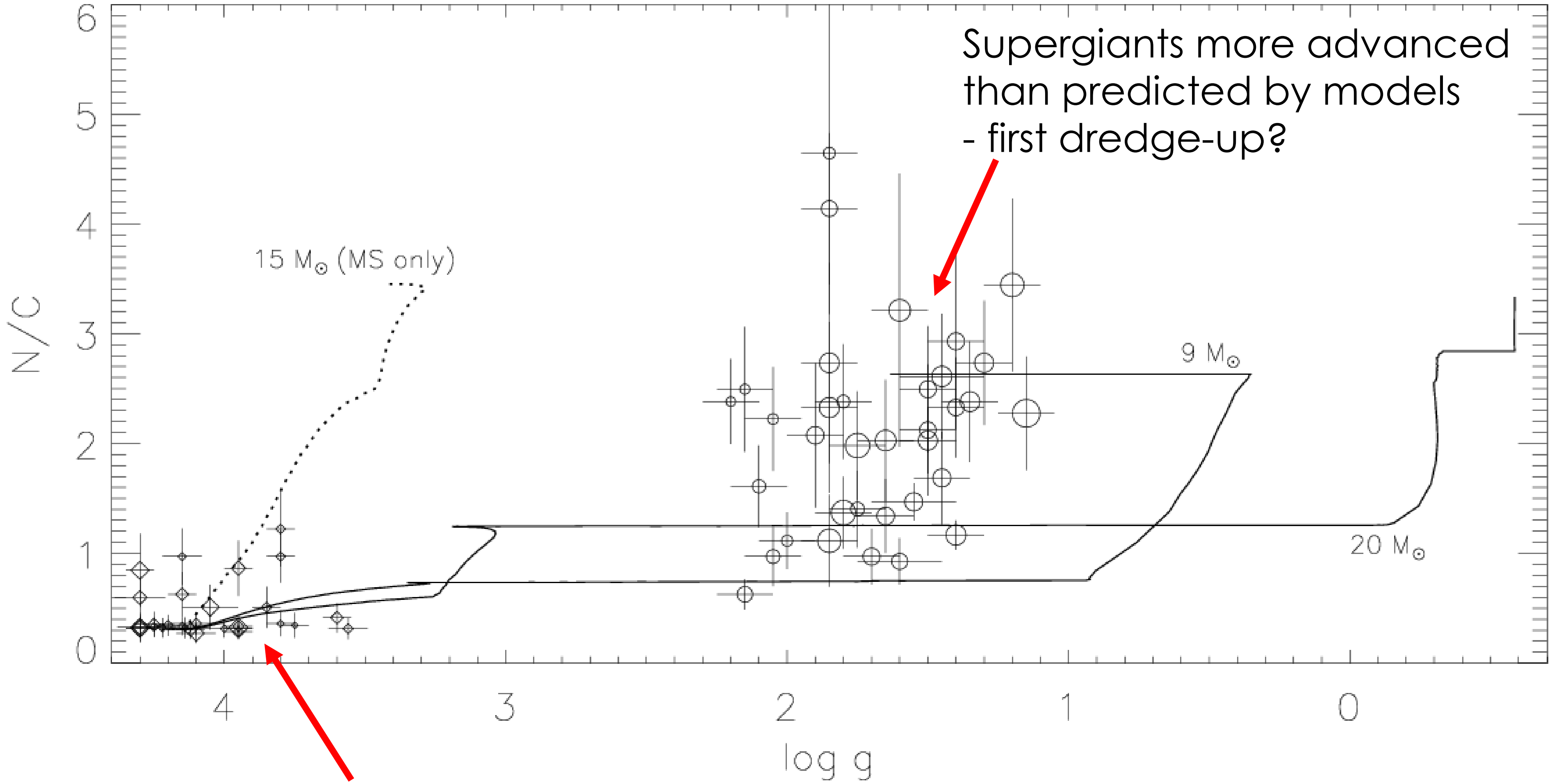
Mixing of CNO: New NLTE Data



Przybilla et al (2010), Nieva & Przybilla (2011b), Firnstein & Przybilla (2011b)

Mixing vs. Evolutionary Status

Data from Przybilla et al (2010), Nieva & Przybilla (2011b), Firnstein & Przybilla (2011b)
Tracks: Meynet & Maeder (2003), Maeder & Meynet (2005)

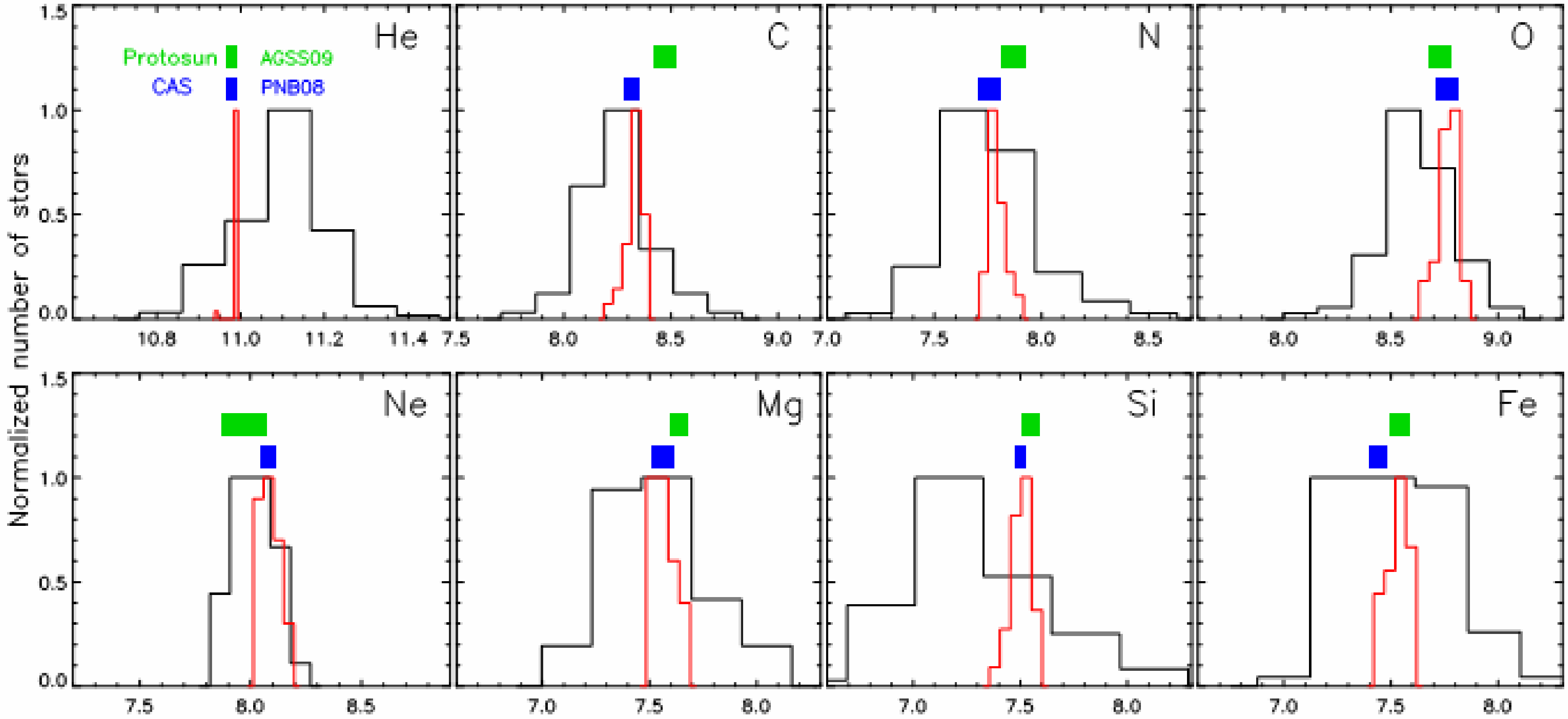


MS evolution compatible with models

Chemical composition of the solar neighborhood @ present day

1σ ~ 0.05 dex

Nieva & Przybilla (2011a)



Red: our work   Elemental abundance log (X/H) + 12   black: OB stars literature

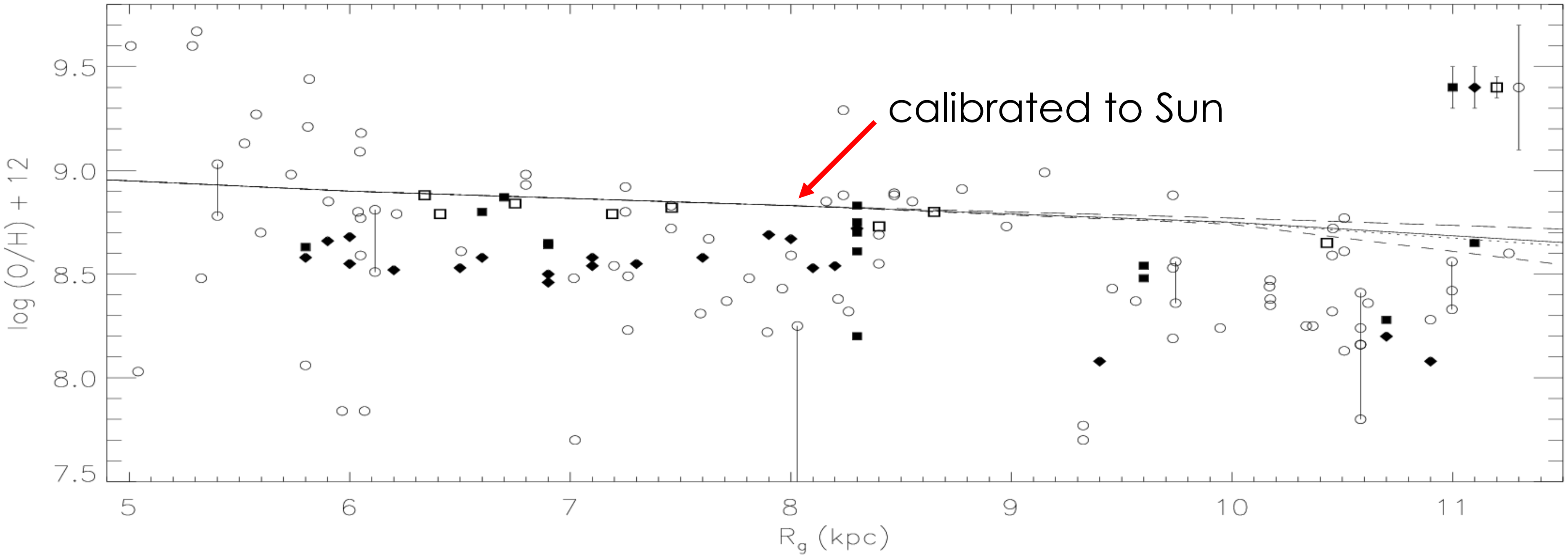
chemical homogeneity = ISM → **cosmic abundance standard**

→ dust composition   X=0.715   Y=0.271   **Z=0.014**

Milky Way: Abundance Gradients

Literature: HII regions & B-stars

Przybilla (2008)



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

Models:
Chiappini et al. (2001)

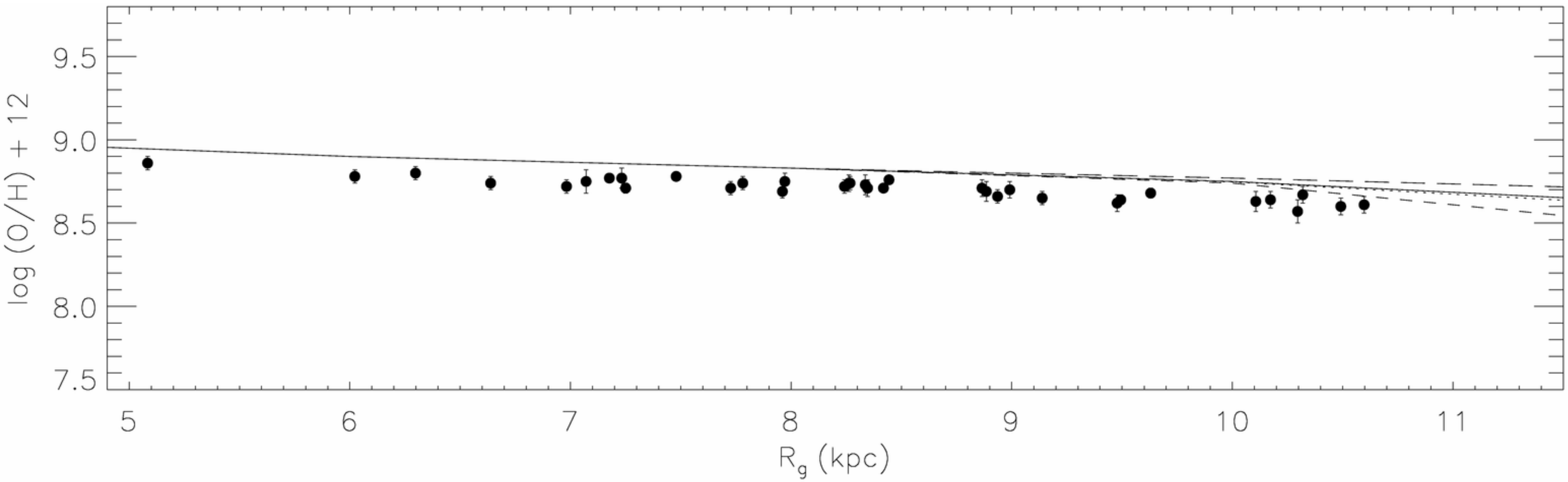
B-Stars (NLTE):
■ Gummersbach et al. (1998)
♦ Daflon & Cunha (2004)

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

Milky Way: Abundance Gradients

our sample: BA-type supergiants

Firnstein & Przybilla (2011c)

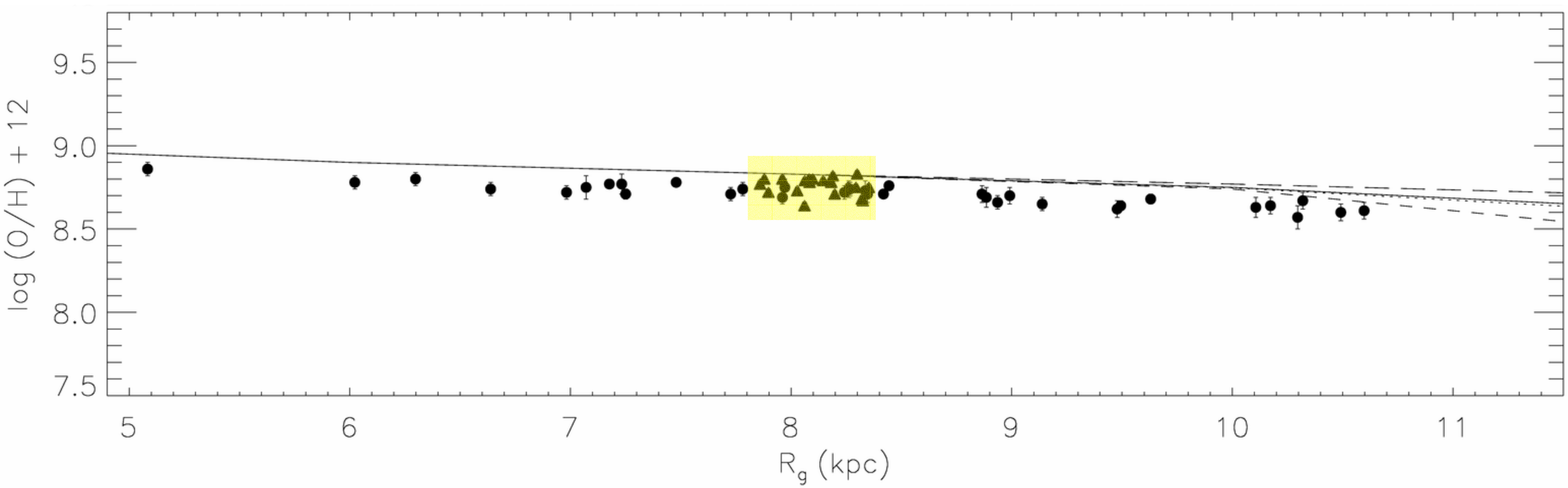


- tight abundance gradient: low scatter @ every R
- O abundance @ solar circle:
  intermediate between "old" and "new" solar values

Milky Way: Abundance Gradients

our sample: BA-type supergiants + B-stars

Firnstein & Przybilla (2011c)
+ Nieva & Przybilla (2011a)



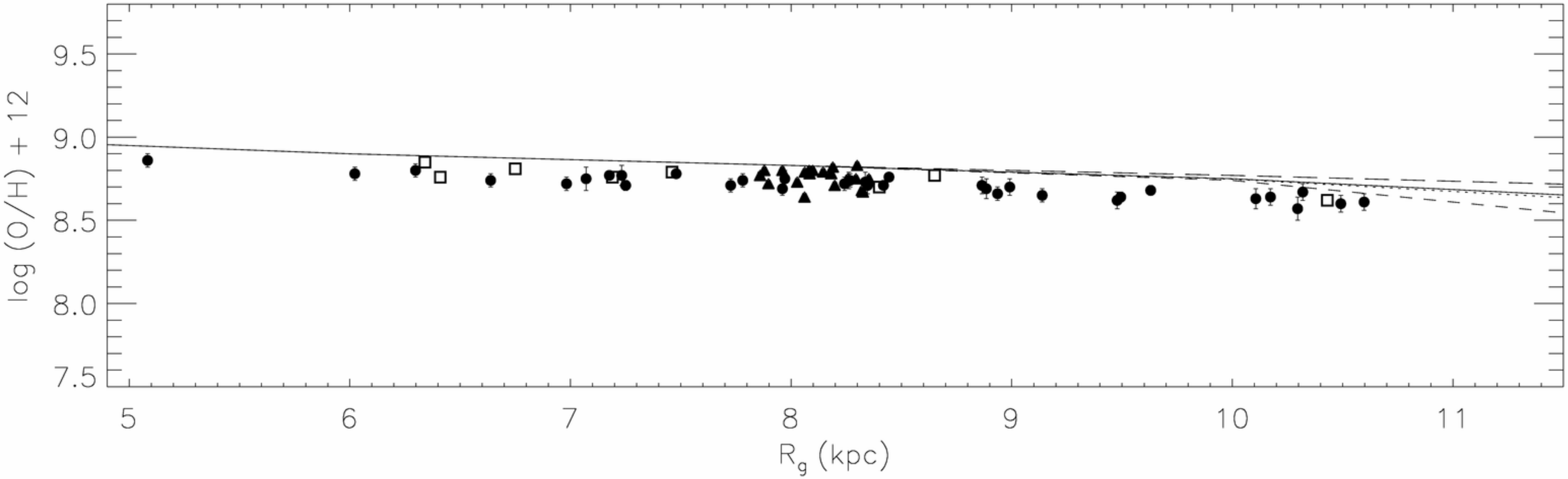
- agreement from 2nd independent indicator

➔ chemical homogeneity of solar neighbourhood

➔ **cosmic abundance standard**

Milky Way: Abundance Gradients

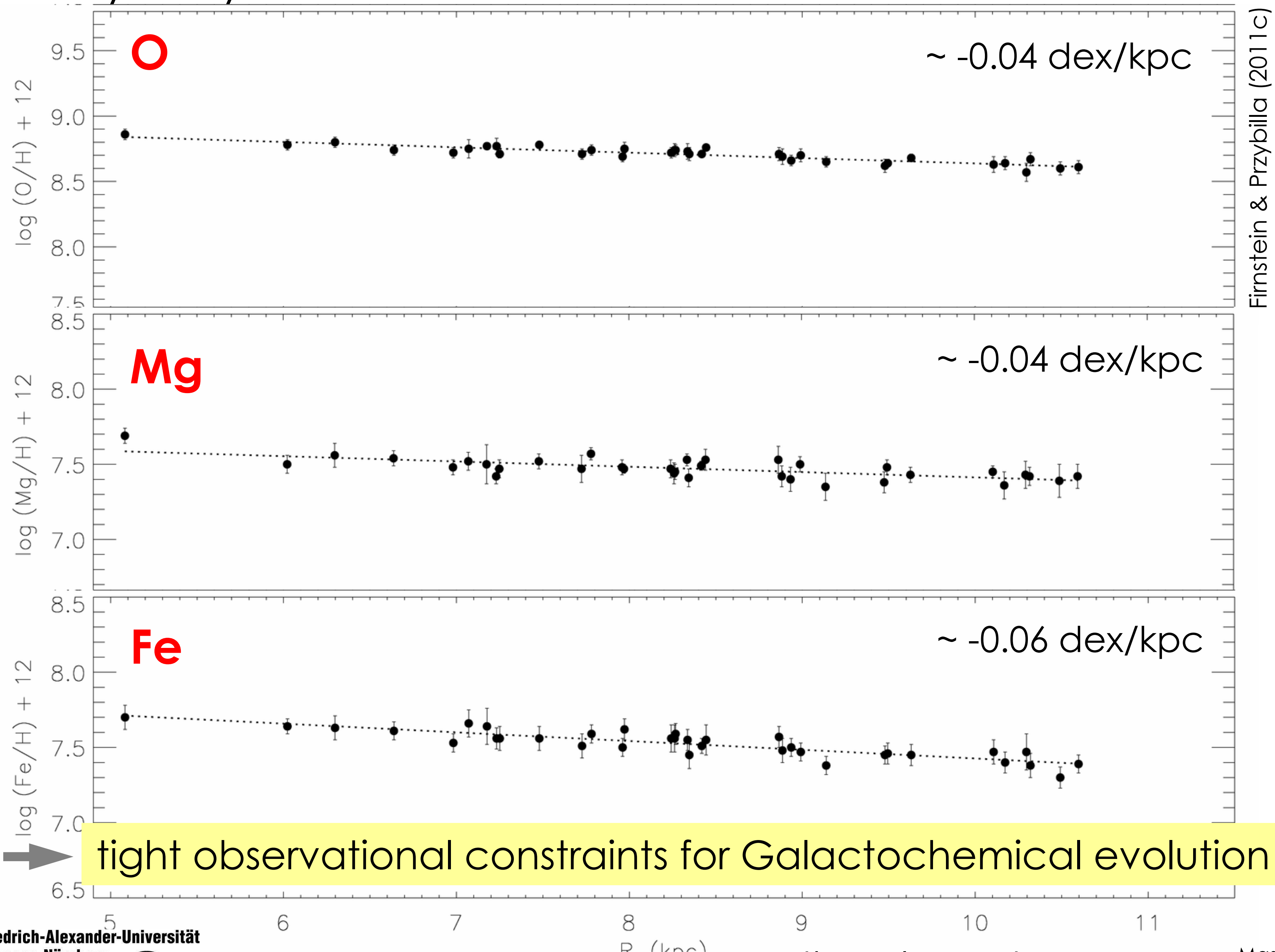
our sample: BA-type supergiants + B-stars & HII-regions (Esteban+ 2005)



- 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

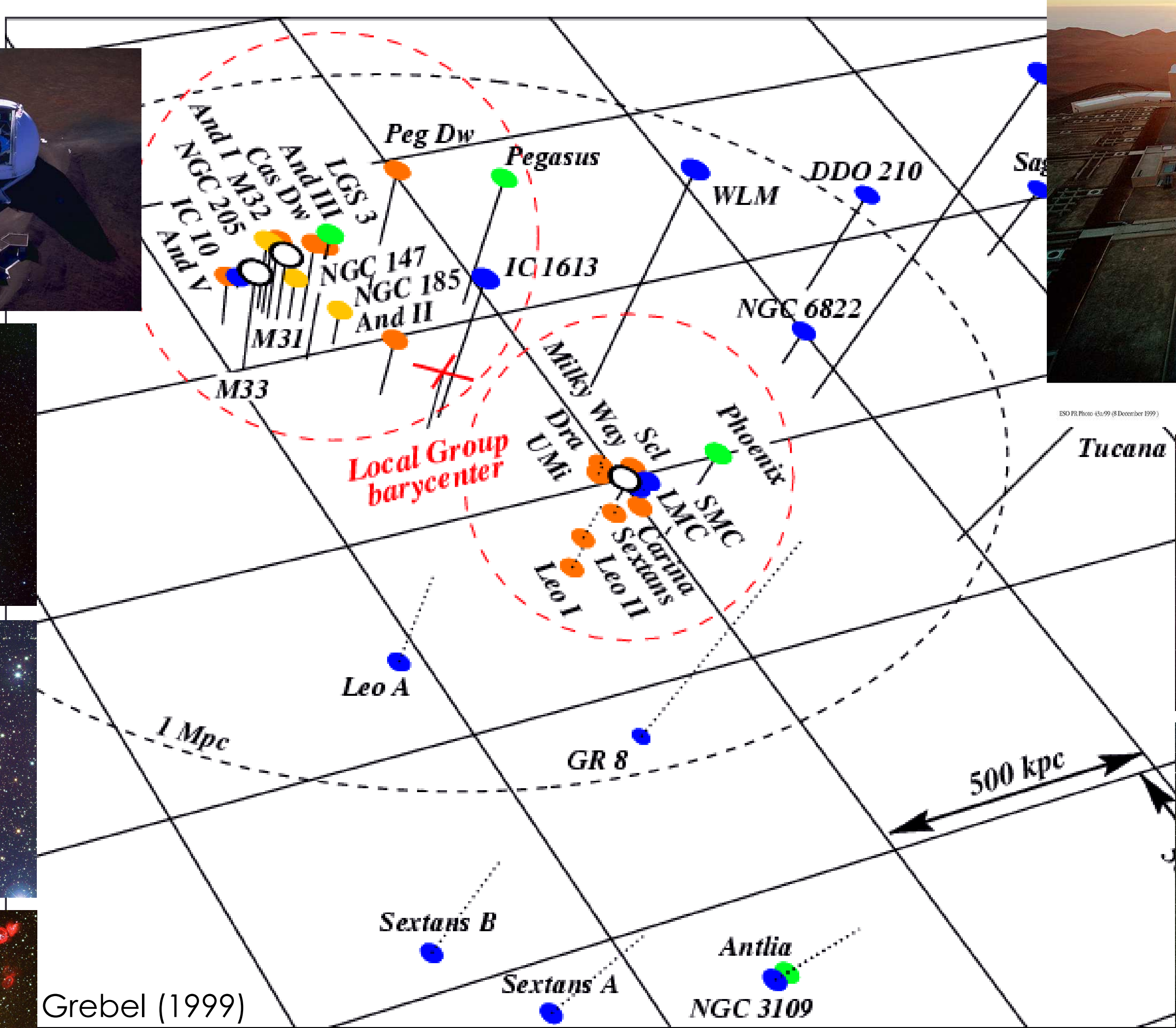
Milky Way: Abundance Gradients

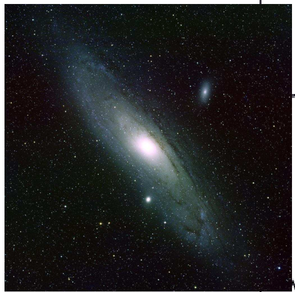


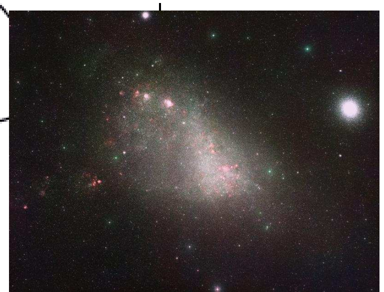
tight observational constraints for Galactochemical evolution

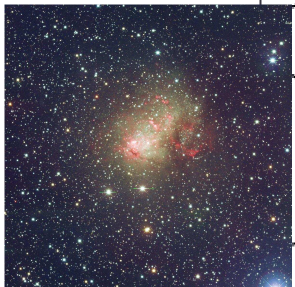
+ other elements

Extragalactic Stellar Astronomy: The Local Group

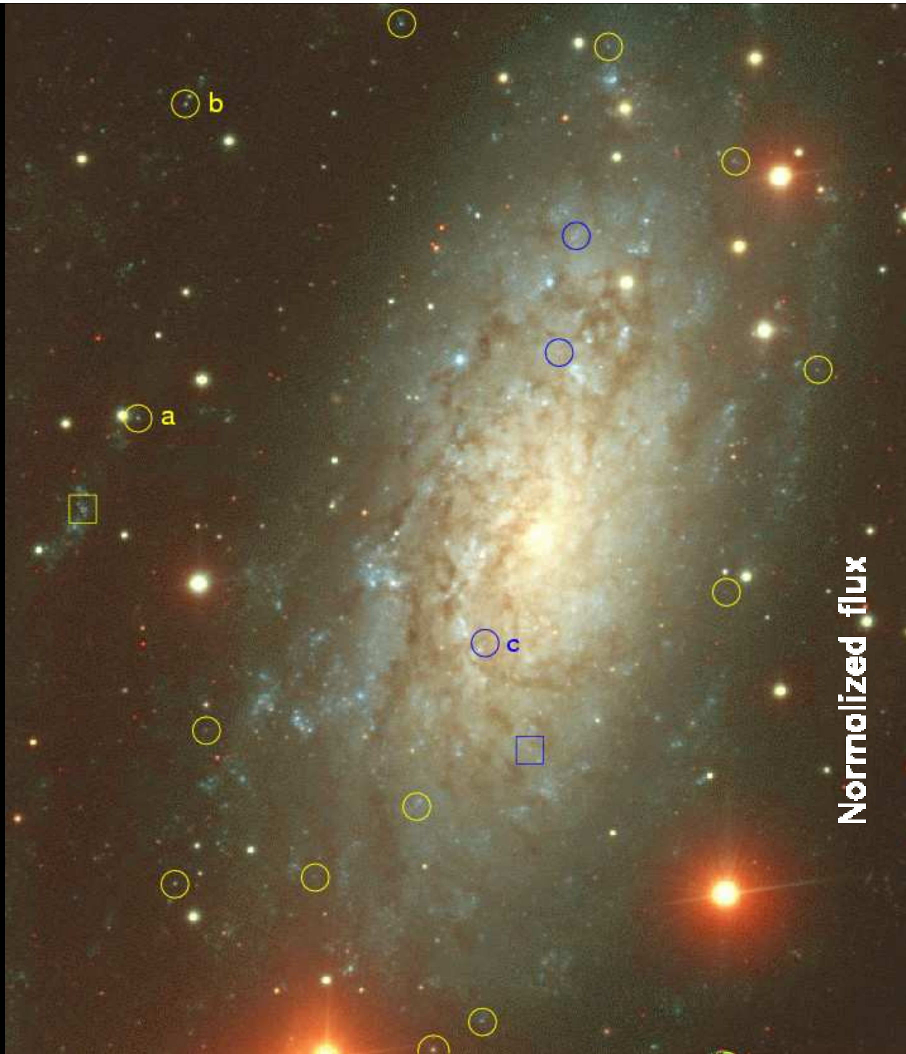


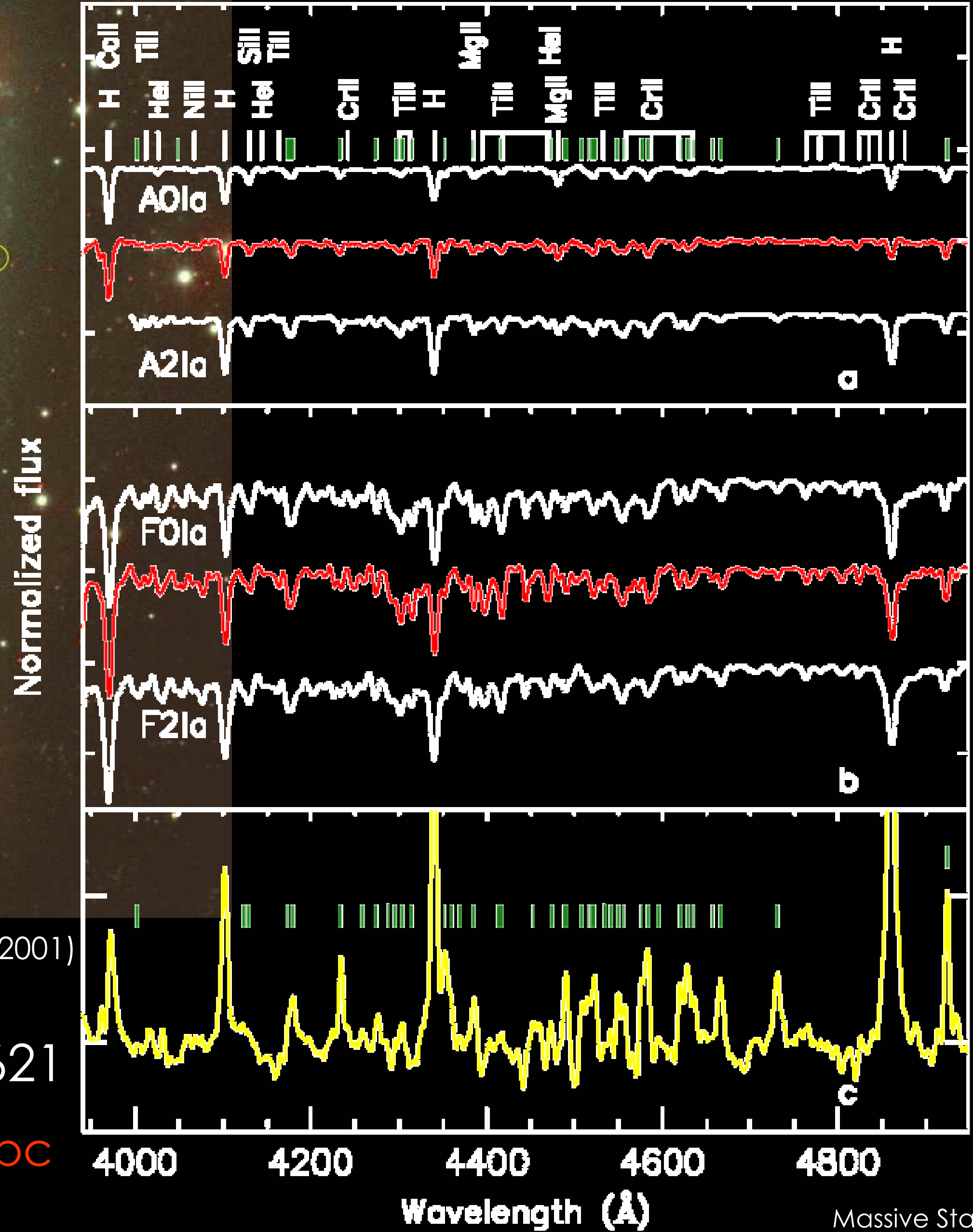






Grebel (1999)





Bresolin, Kudritzki, Méndez & Przybilla (2001)

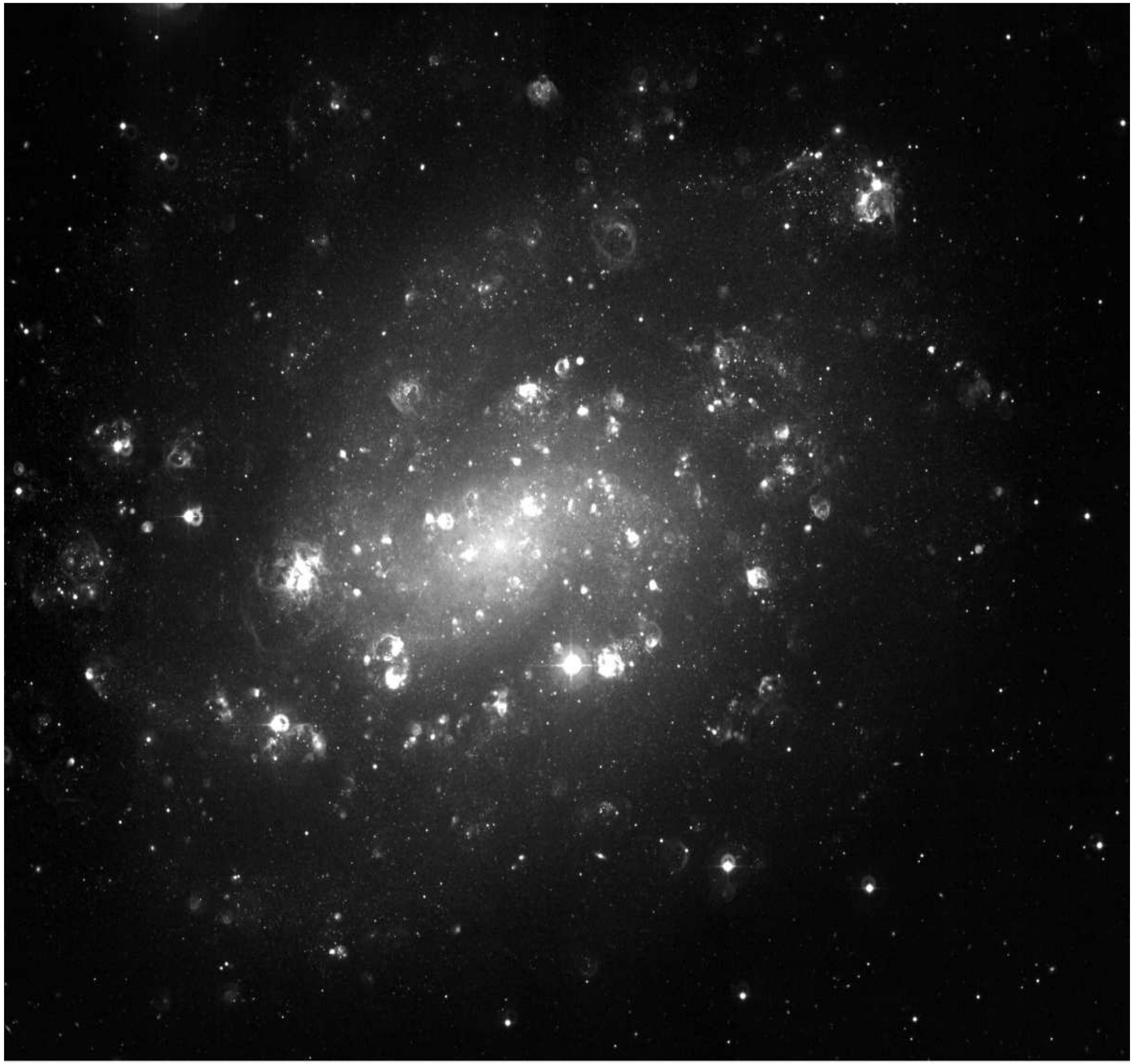
... and beyond

NGC 3621

VLT/FORS1

d ~ 6.6 Mpc

Extragalactic Abundances

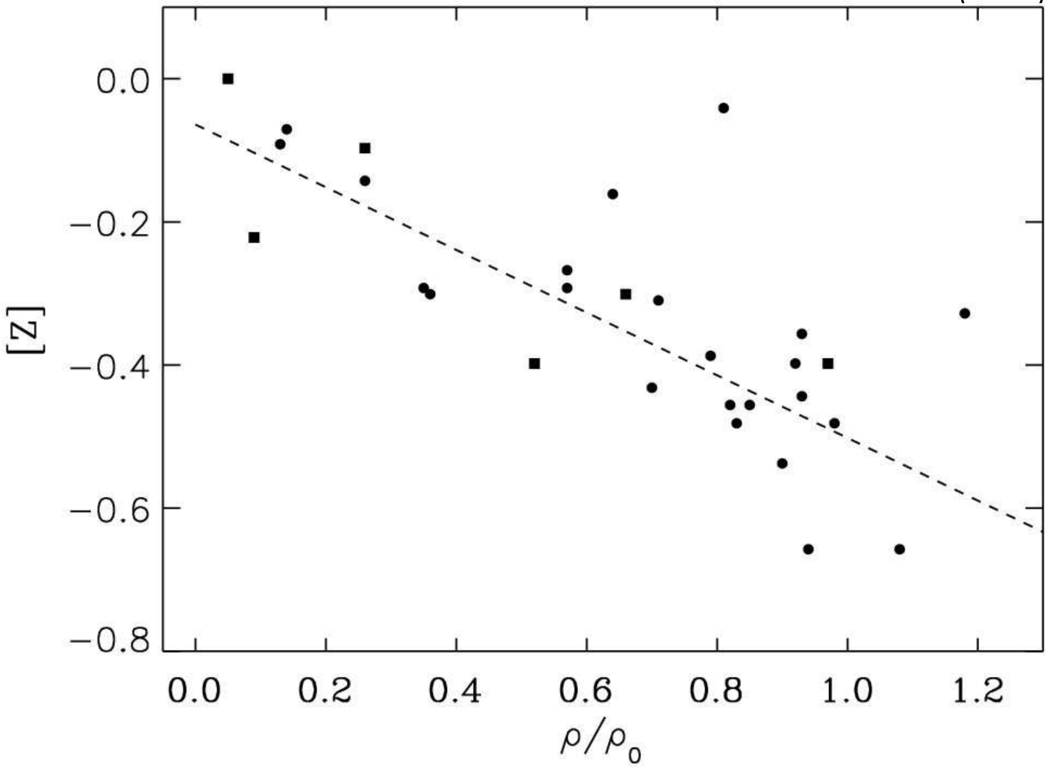


Spiral Galaxy NGC 300 (H-alpha band)
(MPG/ESO 2.2-m + WFI)

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

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

Kudritzki et al. (2008)

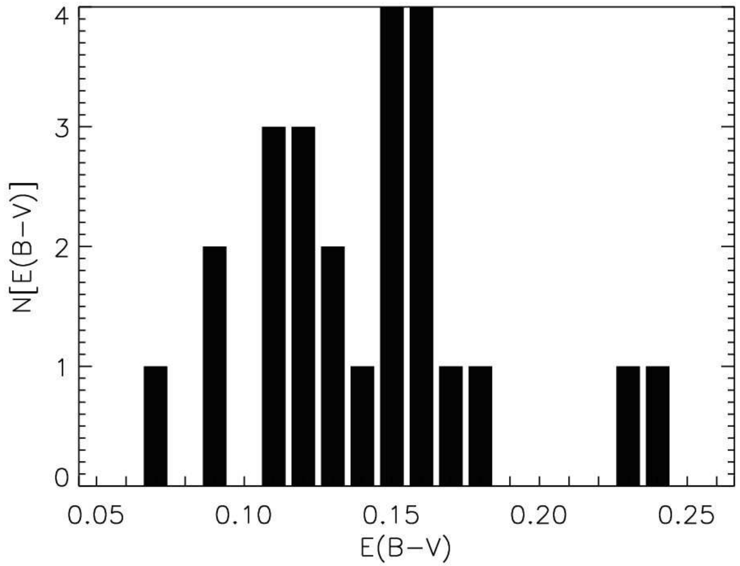


metallicity gradient:
30 B & A-type supergiants

To be expected:
improvements on
Cepheid distance scale

NGC300

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



interstellar
extinction
within NGC300

Summary

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

Stellar Evolution

- MS evolution well understood, supergiants not

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