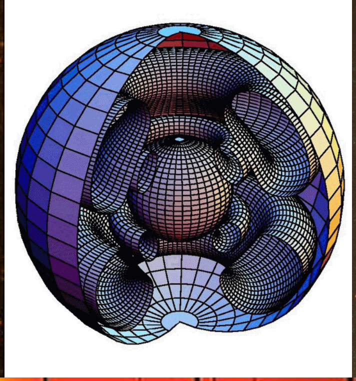
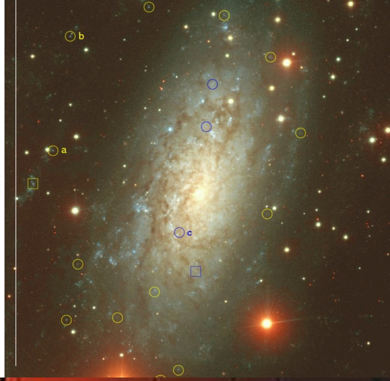
$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) =$$
$$\sum_{j \neq i} n_j (R_{ji} + C_{ji})$$
$$\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu$$





Elemental abundances from massive stars:
The present-day composition of the local Milky Way

Norbert Przybilla

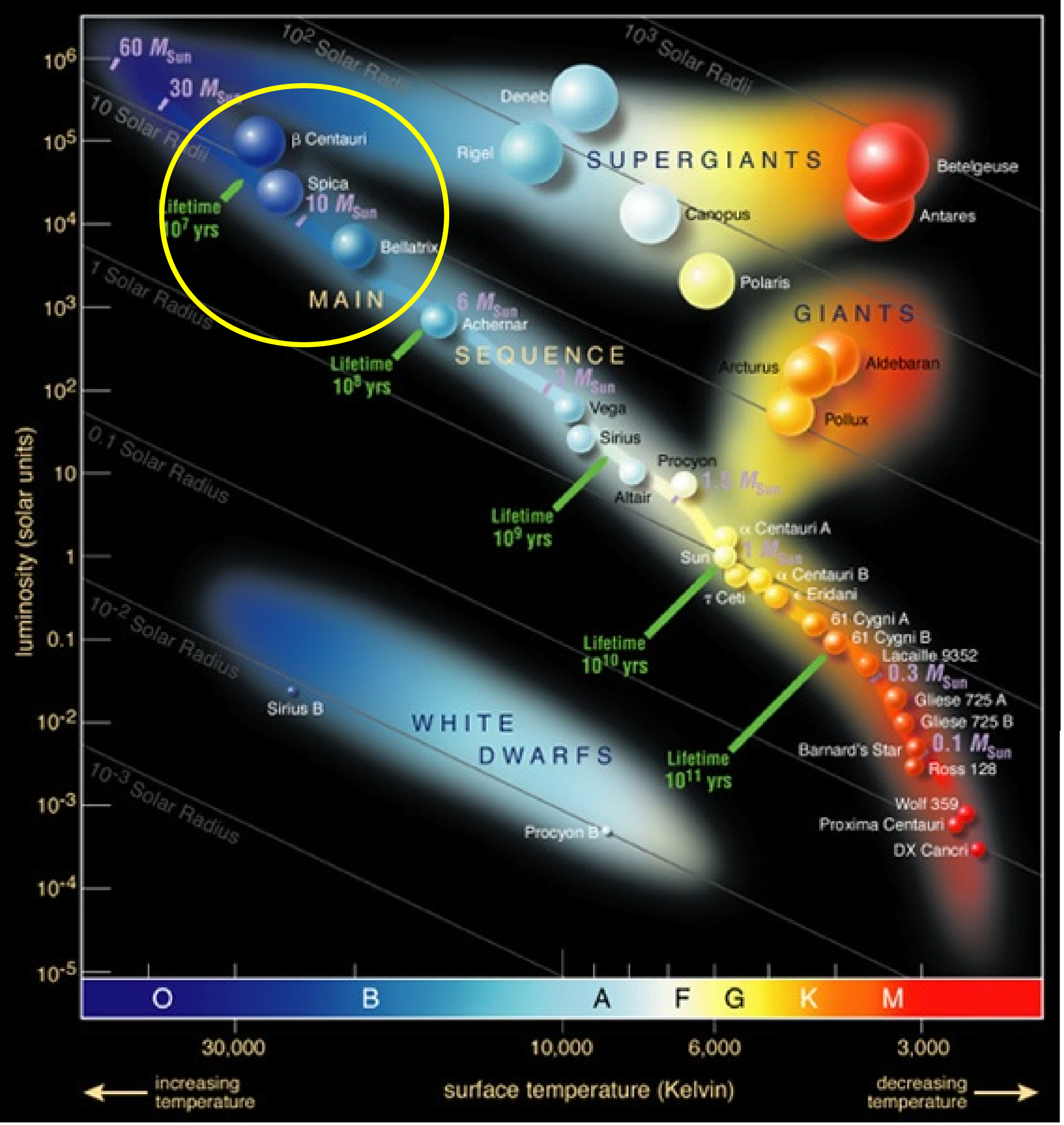
M.F. Nieva, K. Butler, A. Irrgang, V. Schaffenroth

Institute for Astro- and Particle Physics

universität innsbruck

Early B-type Stars

(Main Sequence)



- massive

  M: ~ 8 ... 18 $M_{\odot}$

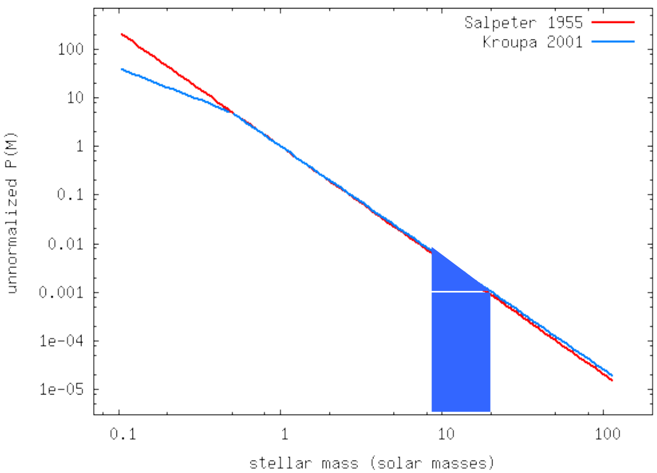
- hot

  T_{eff}: ~ 16000 ... 32000 K

- luminous

  L: ~ several 10^3 ...10^4 $L_{\odot}$

- „numerous"



Abundance Standards: Solar vs. Cosmic

Sun

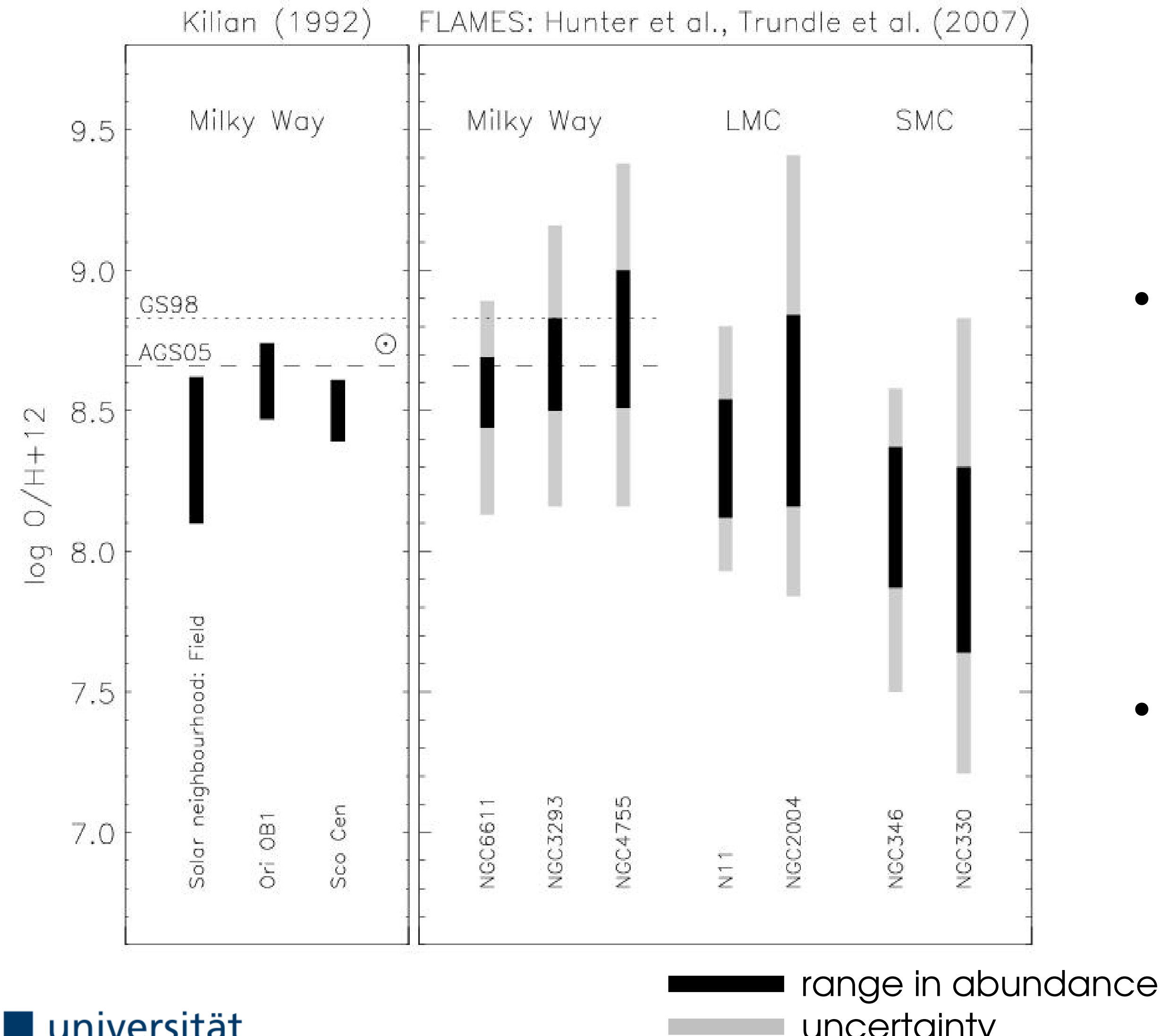
- 4.56 Gyr old
- far from Galactic birth radius
- highly detailed observations
- complex atmosphere: convection (3D), chromosphere
- overall small departures from LTE
- diffusion: photospheric vs. bulk composition
- **laboratory studies of CI chondrites feasible**
- one object: typical or special?

Early B-type stars

- young: ~ 10 Myr
- close to parental star-formation region
- (bright) point sources
- simple atmospheres: radiative equilibrium (1D)
- line spectra: ubiquous non-LTE effects
- weak stellar winds: no diffusion, no impact on atmospheric structure
- no dust depletion unlike in HII regions & the diffuse ISM
- pollution with CNO-cycled material possible
- several ten objects in solar neighbourhood (d<500pc)

Chemical (In)Homogeneity from Cosmic Abundance Indicators

Metals in Solar Neighbourhood/Star Clusters



- massive stars & HII regions

  → chemical inhomogeneity

BUT

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

Theory:

- efficient mixing mechanisms

  → homogeneity (e.g. Edmunds 1975, Roy & Kunth 1995)

Chemical (In)Homogeneity from Cosmic Abundance Indicators

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

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

→ chemical inhomogeneity

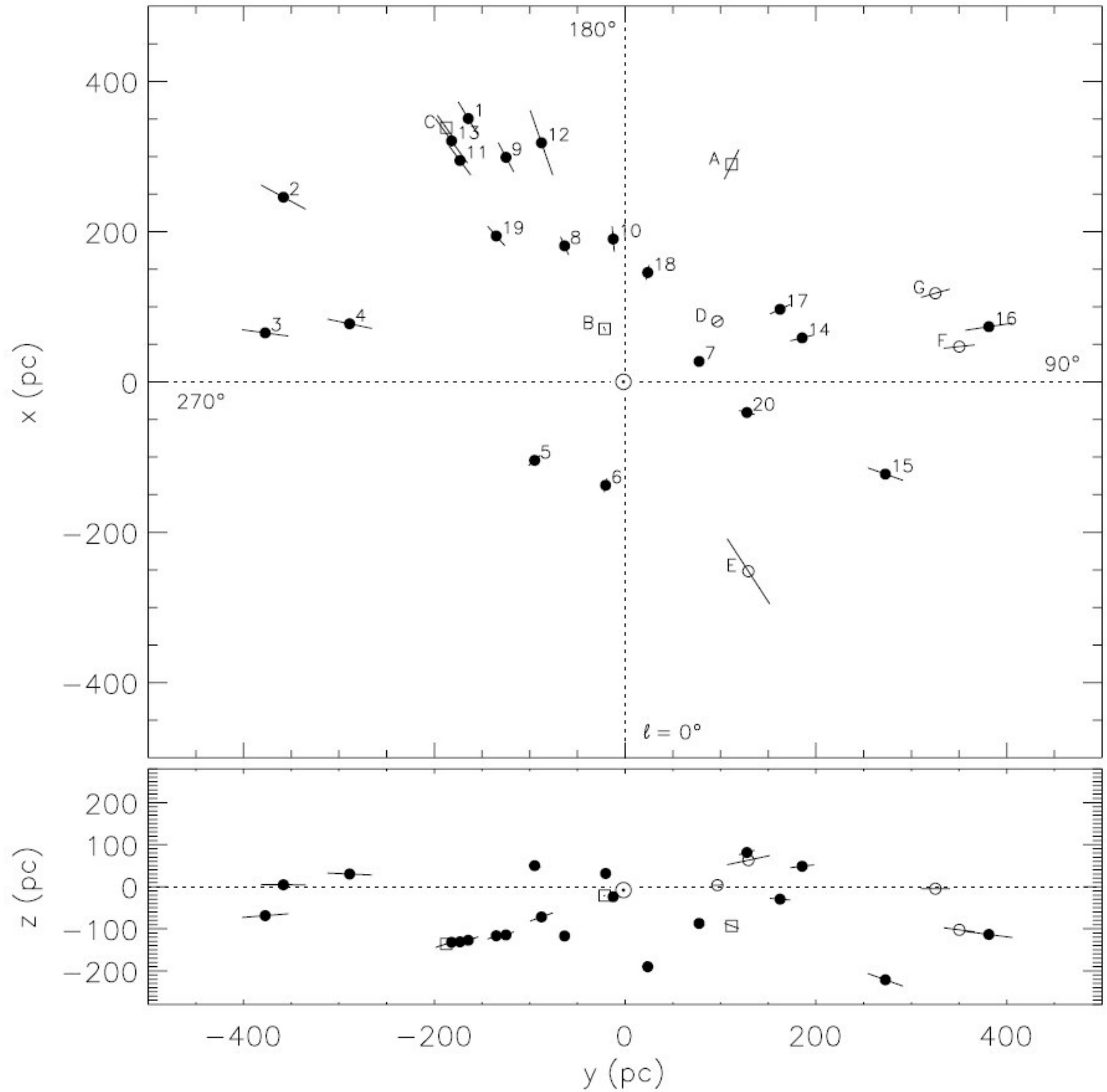
BUT

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

Theory:

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

Location of Sample Stars in Solar Neighbourhood



Nieva & Przybilla (2012)

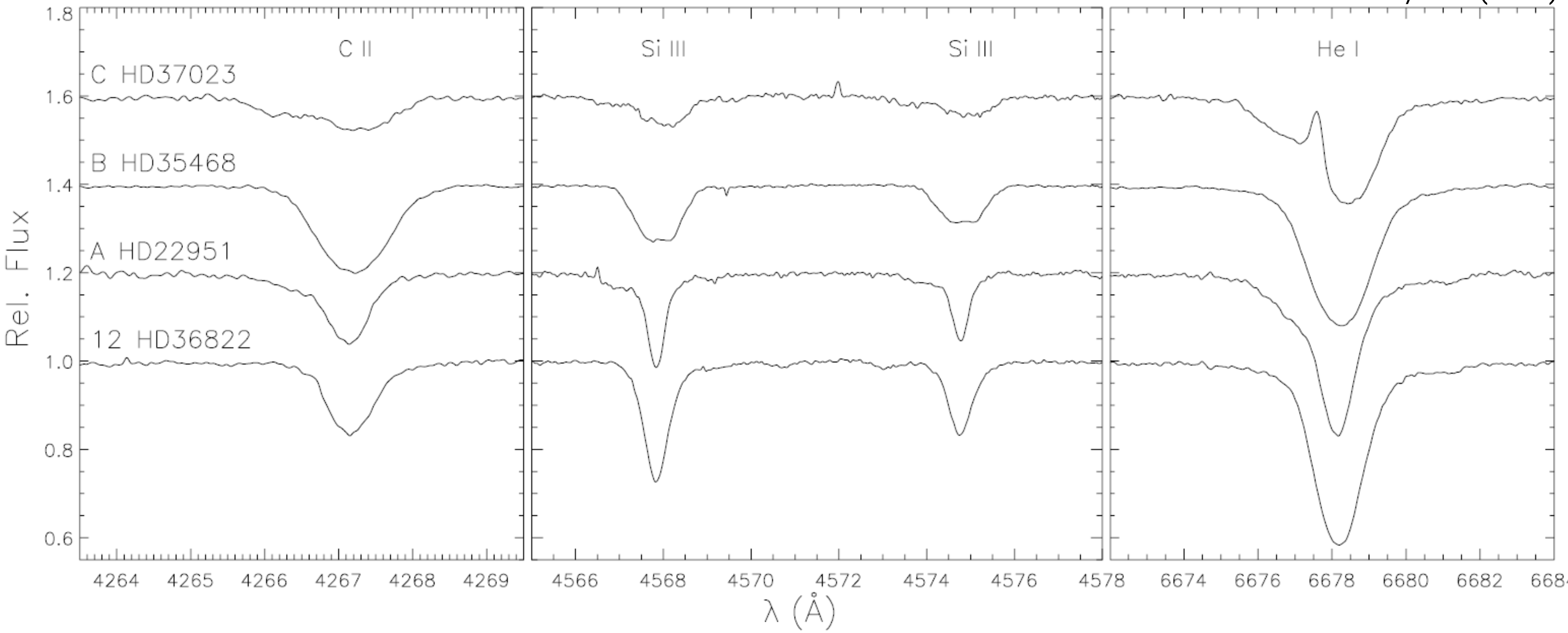
tracing
Gould's Belt

Observational bias

Identification of problematic objects before analysis starts:

- binarity: impact of second light

Nieva & Przybilla (2012)



- Be stars: impact of light from disk on photospheric spectrum: veiling
- CP phenomenon: rare among early B-type stars
  but: He-strong, He-weak stars

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**:

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

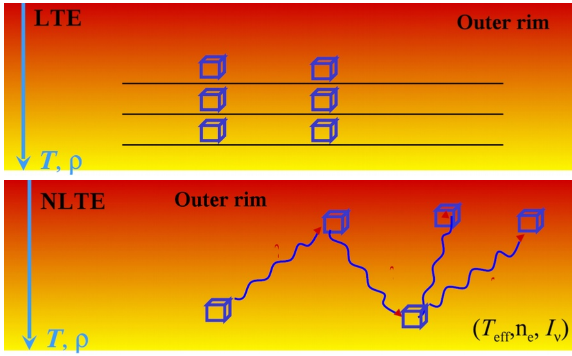
- hydrostatic equilibrium – **momentum conservation**:

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

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

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

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



- 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**:

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

Codes

- LTE model atmospheres:
  ATLAS9 (Kurucz)

- radiative transfer & statistical equilibrium (trace species approx.)
  DETAIL (Giddings, Butler + many recent updates/extensions)

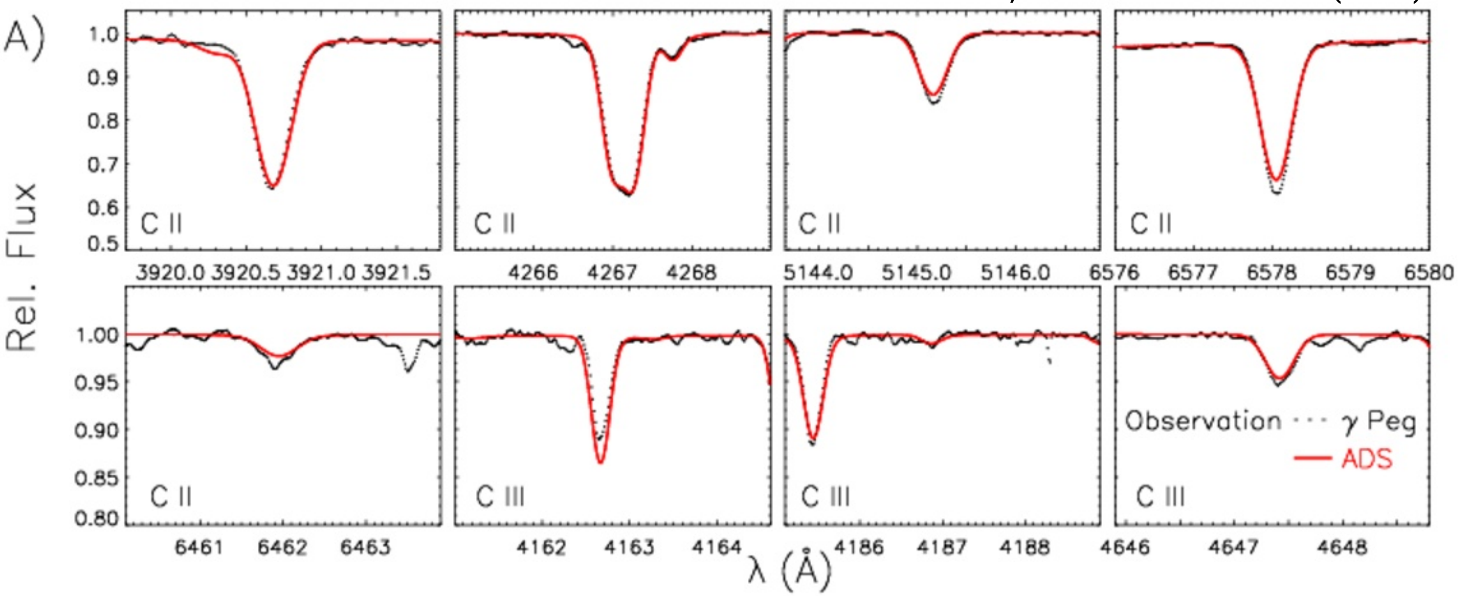
- formal solution:
  SURFACE (Giddings, Butler + many recent updates/extensions)

→ hybrid non-LTE: **ADS**

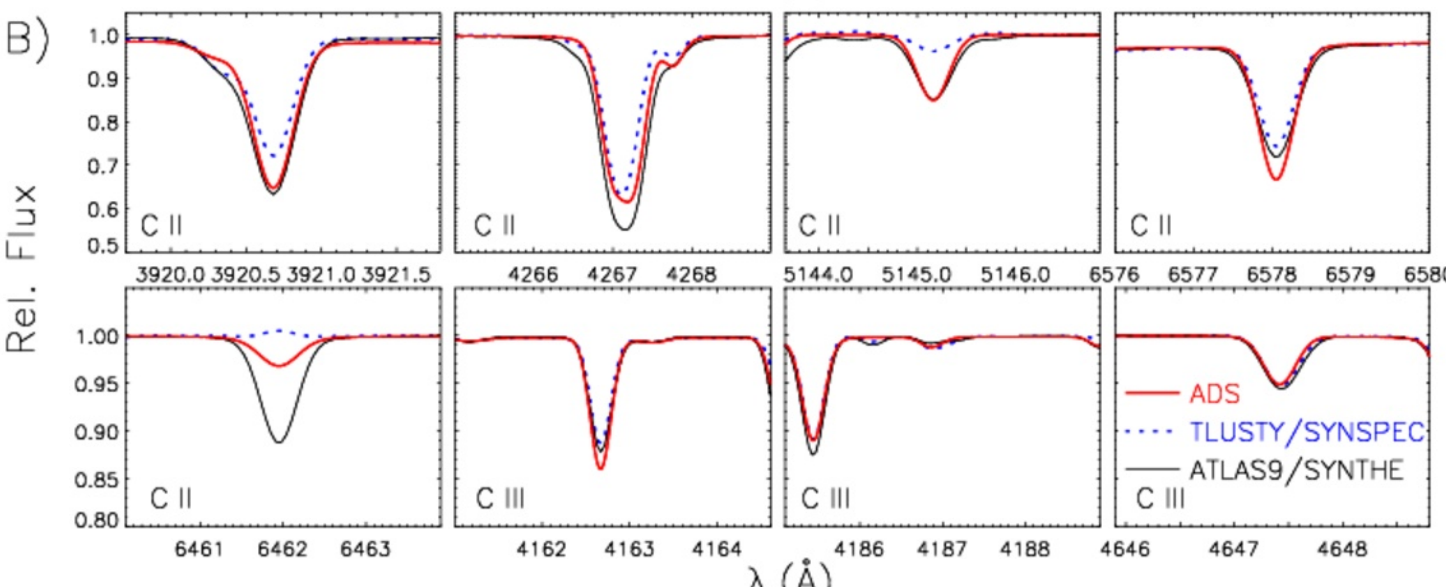
huge amounts of
atomic data:
OP/IRON Project, physics literature & own

Consequences for models

Przybilla, Nieva & Butler (2011)



fit to observation: our model, using model atom of Nieva & Przybilla (2008)

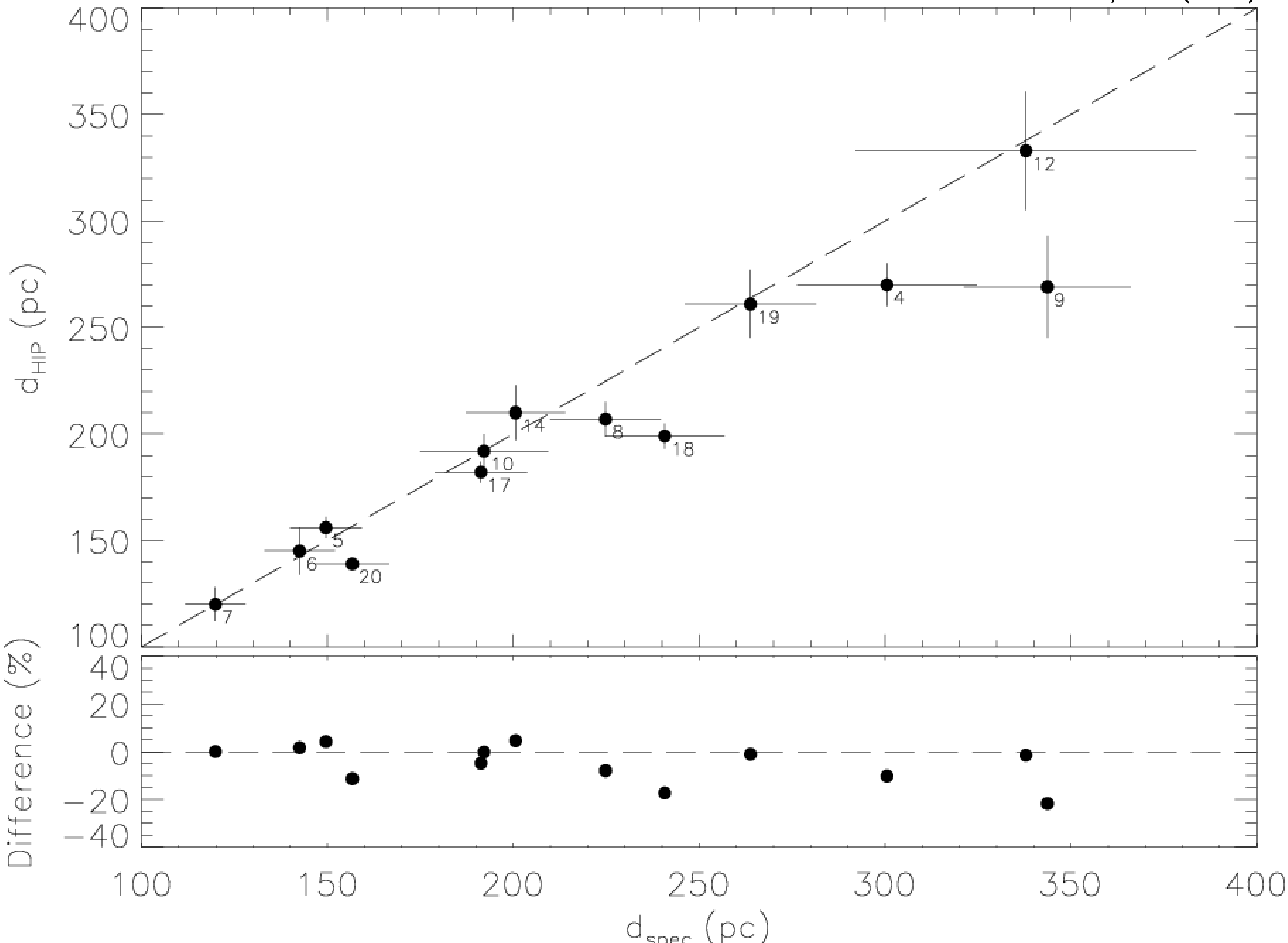


model comparison

→ **input atomic data crucial**

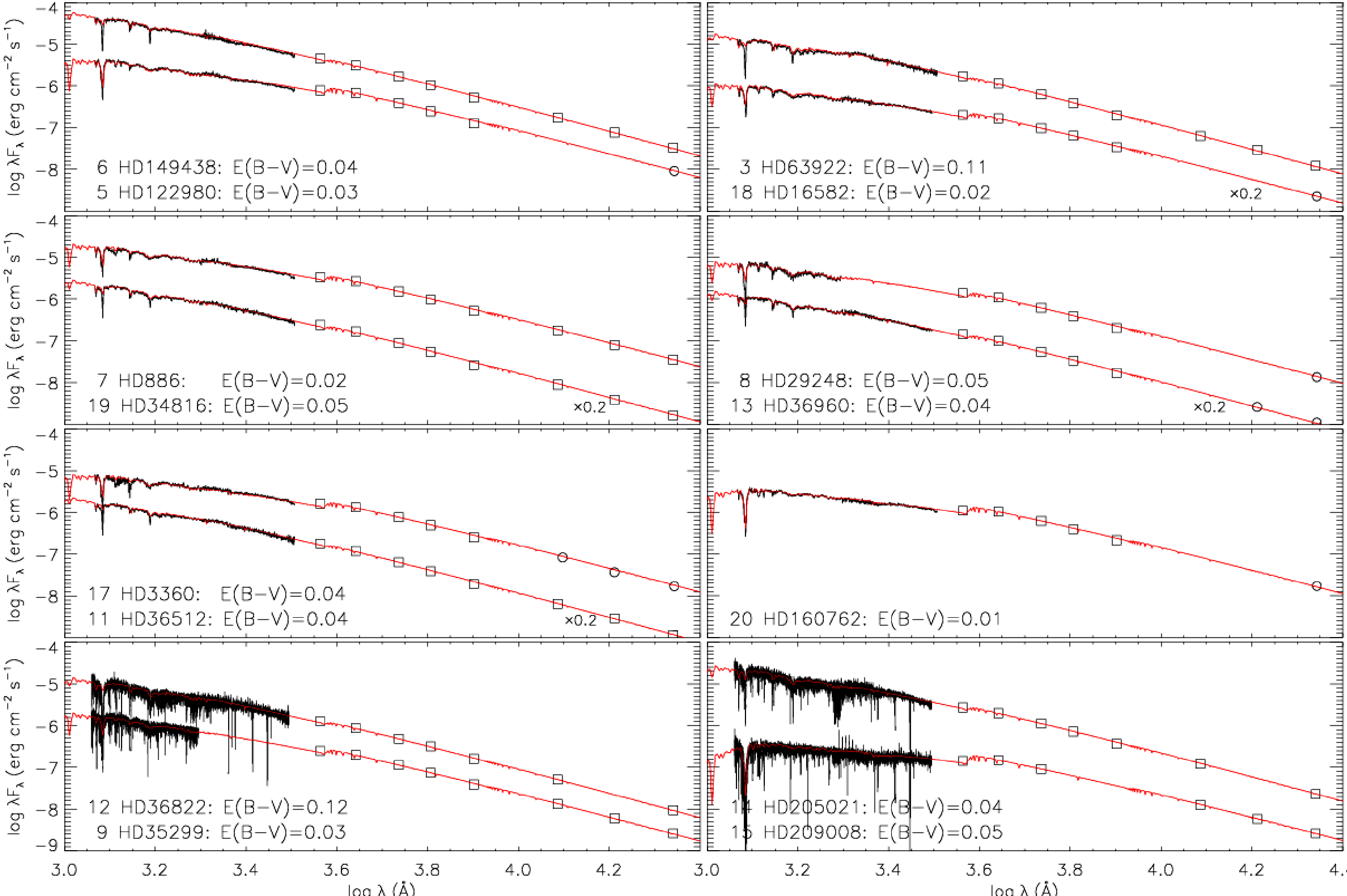
Test: Spectroscopic vs. Hipparcos Distances

Nieva & Przybilla (2012)



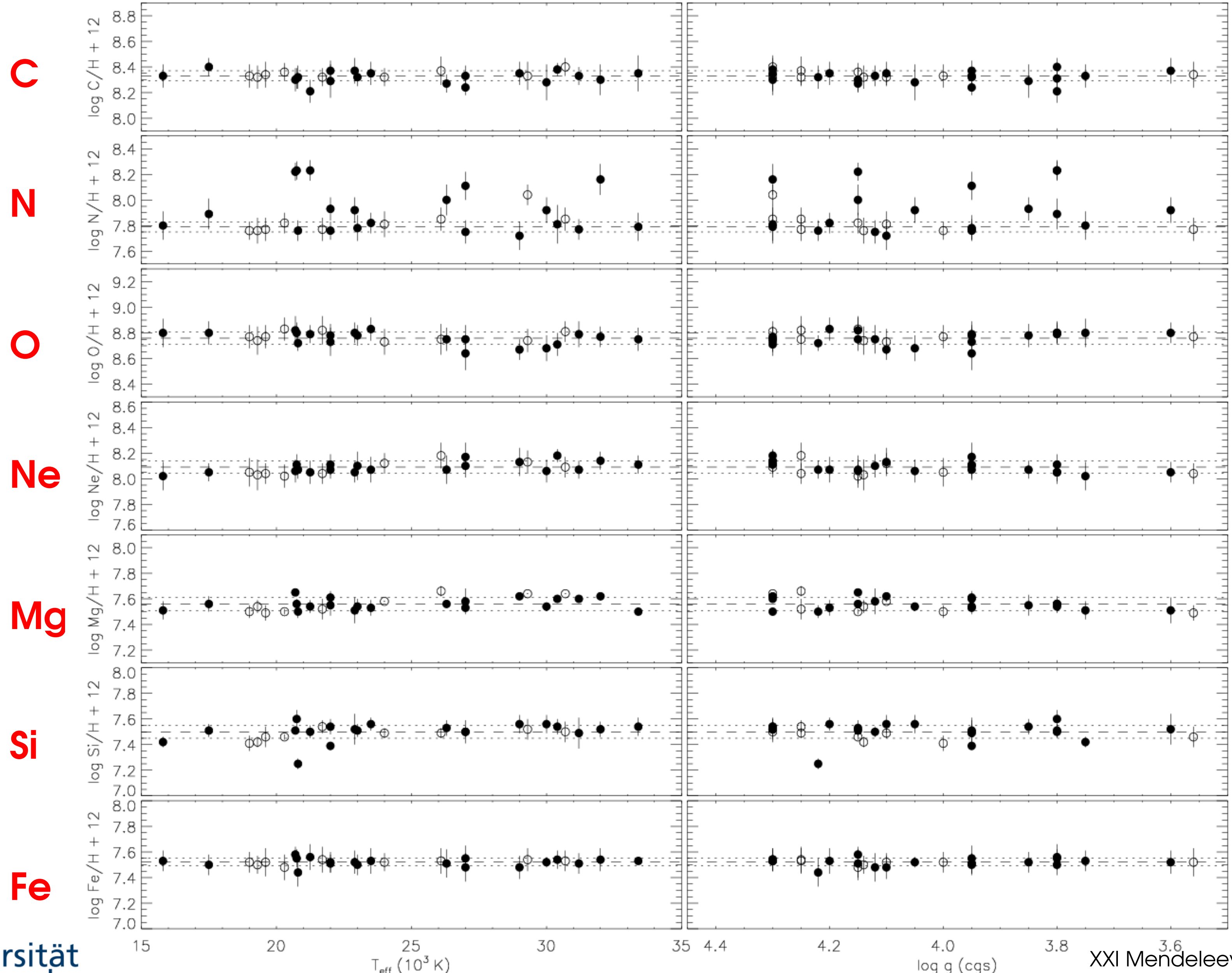
Test: SEDs

Nieva & Przybilla (2012)



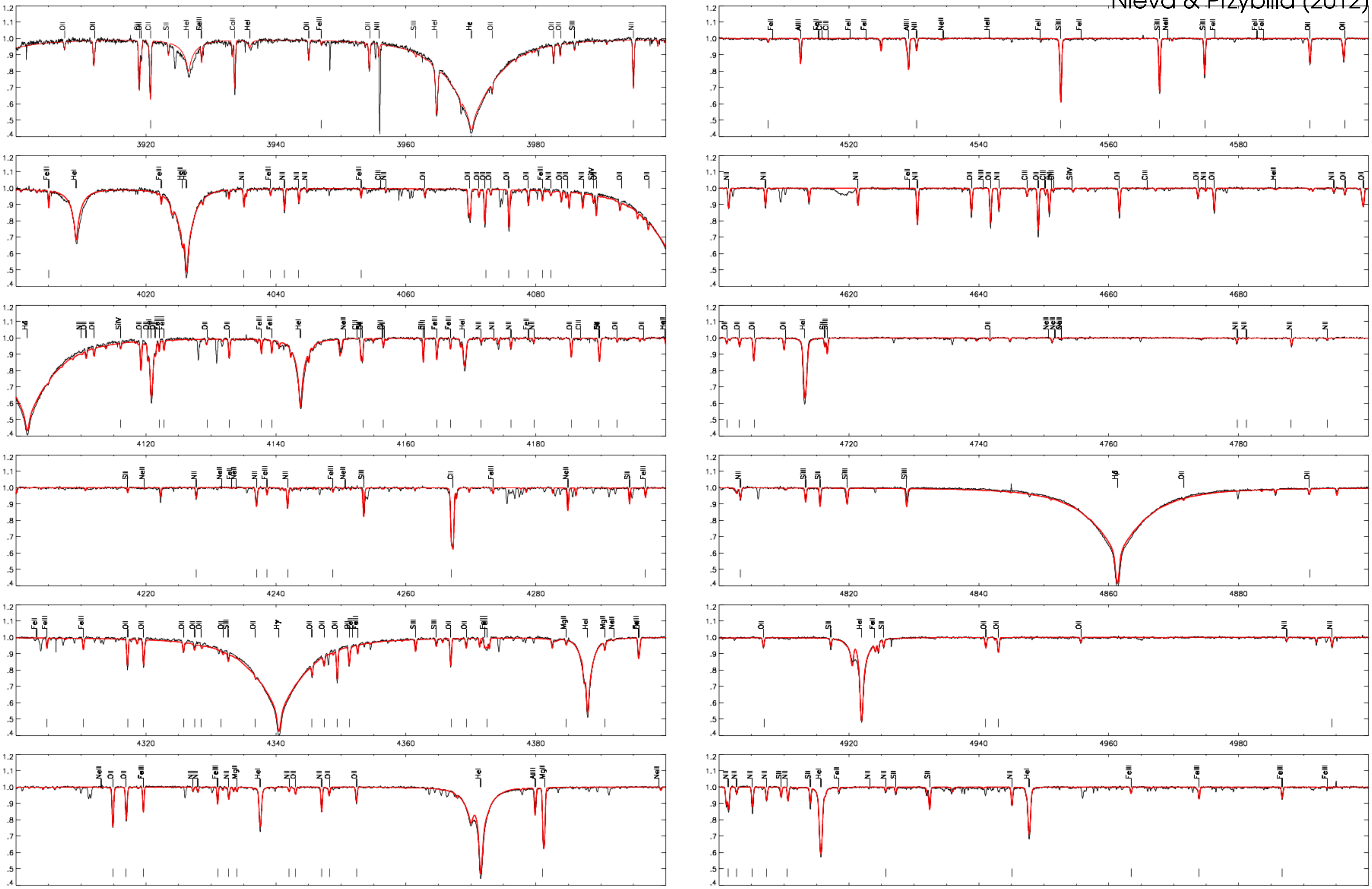
Test: Abundance Trends

Nieva & Przybilla (2012)



Quantitative Spectroscopy with Little Systematics

Nieva & Przybilla (2012)

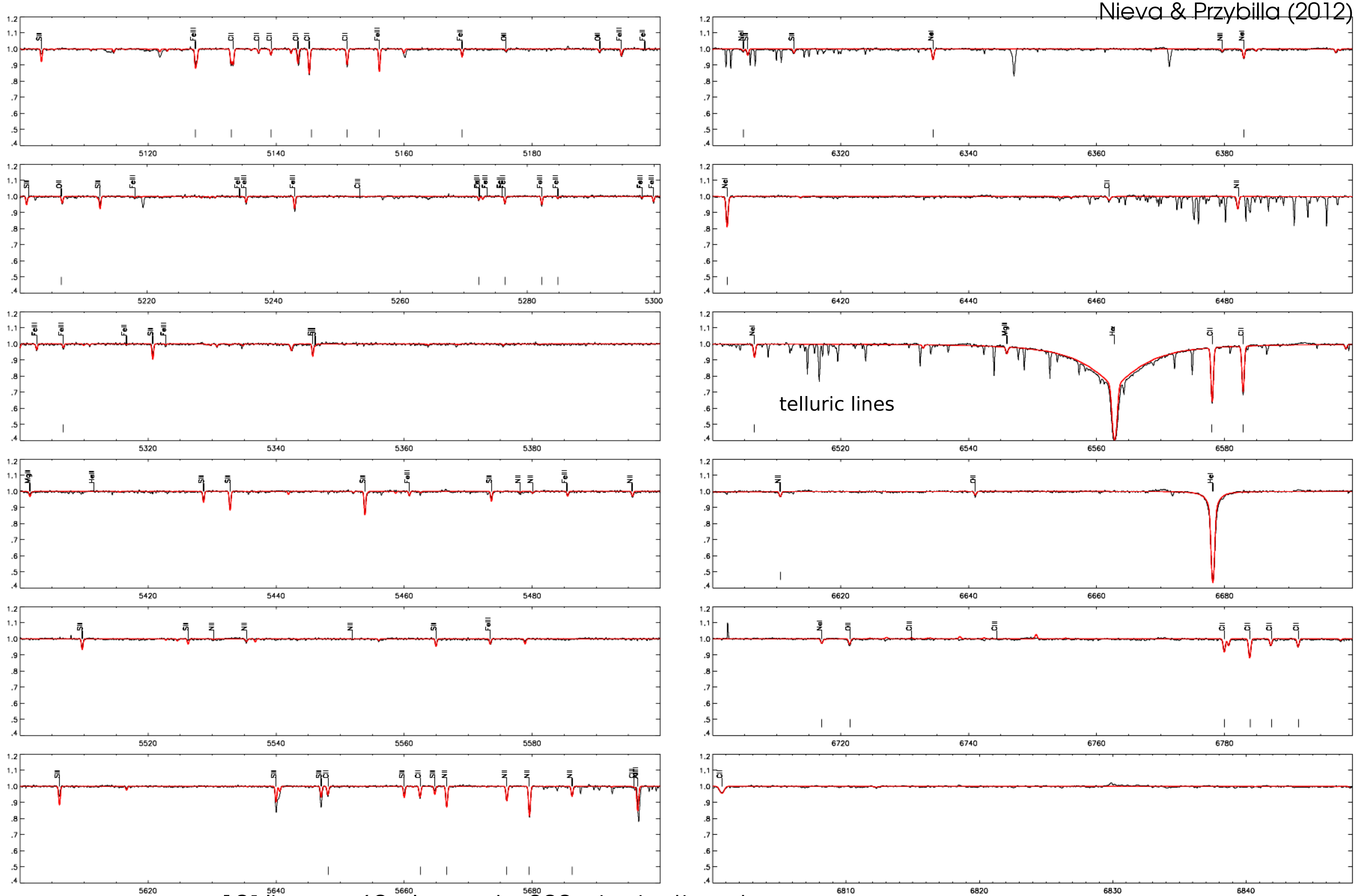


- ~10^5 lines: ~60 elements, 200+ ionization stages
- OB stars: complete spectrum synthesis in visual & near-IR, up to ~95% in NLTE

07 HD886 07 HD886

Quantitative Spectroscopy with Little Systematics

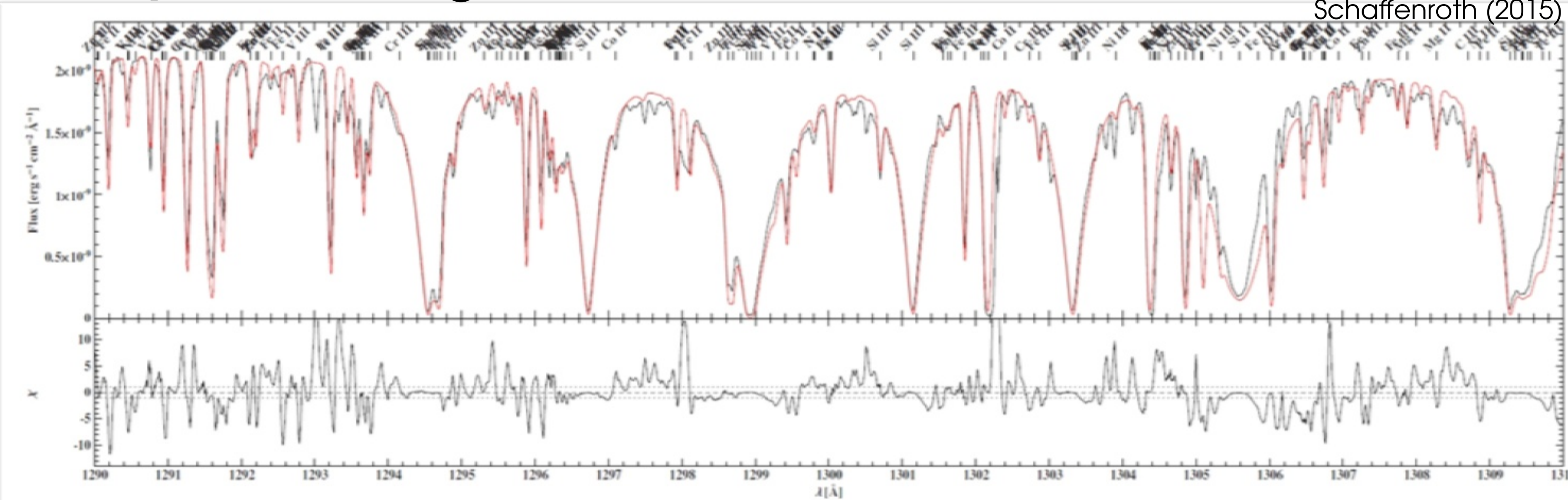
Nieva & Przybilla (2012)

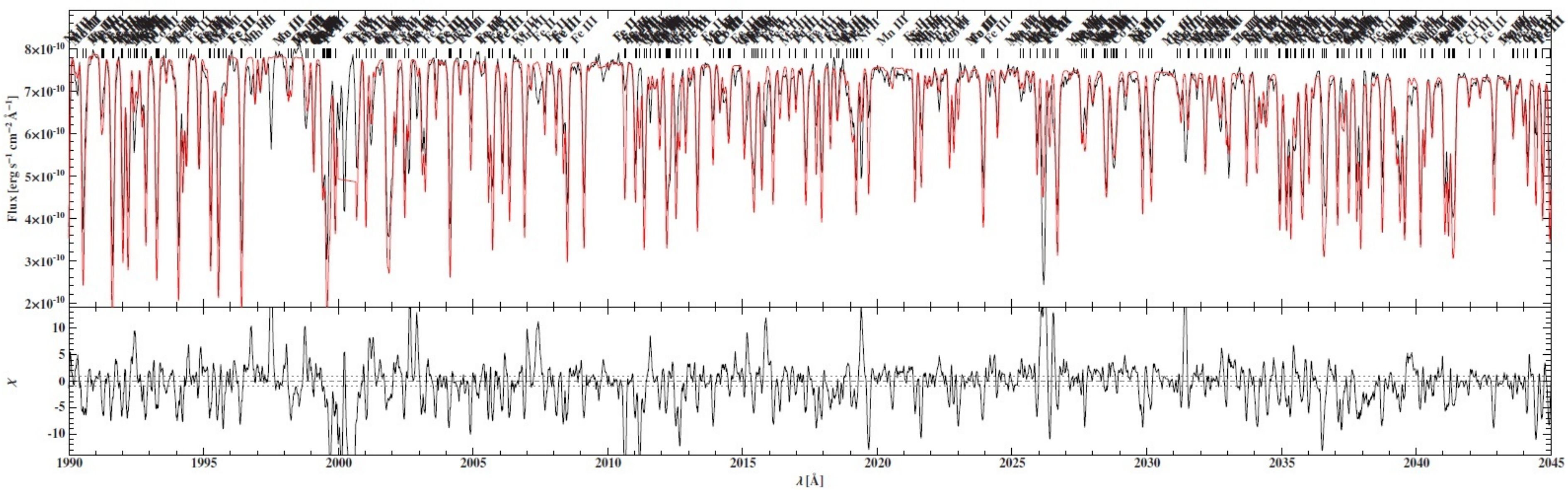


- ~10^5 lines: ~60 elements, 200+ ionization stages
- OB stars: complete spectrum synthesis in visual & near-IR, up to ~95% in NLTE

UV Spectral Range with HST/STIS

Schaffenroth (2015)





- ~10^5 lines: ~60 elements, 200+ ionization stages
- OB stars: UV ~50% of lines in NLTE, rest LTE **– atomic data missing**, high-quality observations

Extending the elemental coverage in the UV

Schaffenroth (2015)

Z Symbol Atomic Weight Element Name

- included in LTE
- included in NLTE
- not included in the model

1 H 1.01 Hydrogen																		2 He 4.00 Helium
3 Li 6.94 Lithium	4 Be 9.01 Beryllium												5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
11 Na 22.99 Sodium	12 Mg 24.31 Magnesium												13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
19 K 39.10 Potassium	20 Ca 40.08 Calcium		21 Sc 44.96 Scandium	22 Ti 47.87 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.69 Nickel	29 Cu 63.55 Copper	30 Zn 65.39 Zinc	31 Ga 69.72 Gallium	32 Ge 72.61 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium		39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.76 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
55 Cs 132.91 Caesium	56 Ba 137.33 Barium	57–70 *	71 Lu 174.97 Lutetium	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.84 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra (226) Radium	89–102 **	103 Lr (262) Lawrencium	104 Rf (261) Rutherfordium	105 Db (262) Dubnium	106 Sg (266) Seaborgium	107 Bh (264) Bohrium	108 Hs (269) Hassium	109 Mt (268) Meitnerium	110 Ds (271) Darmstadtium	111 Rg (272) Roentgenium	112 Cn (283) Copernicium	113 Uut [286] Ununtertium	114 Fl (287) Flerovium	115 Uup [288] Ununpentium	116 Lv (289) Livermorium	117 Uus [294] Ununseptium	118 Uuo (293) Ununoctium
		* Lanthanoids	57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.36 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium		
		** Actinoids	89 Ac (227) Actinium	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np (237) Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium		

Quantitative Spectroscopy using NLTE Diagnostics

using **high-quality spectra**,
robust analysis methodology &
comprehensive model atoms

getting rid of systematics !!!

- ionization equilibria → T_{eff}
  elements: e.g. He I/II, C II/III/IV, O I/II, Ne I/II, Si II/III/IV, S II/III, Fe II/III
  $\Delta T_{eff} / T_{eff} \sim 1\%$
- Stark broadened hydrogen lines → log g
  $\Delta \log g \sim 0.05...0.10$ (cgs)
- microturbulence, helium abundance, metallicity

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

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

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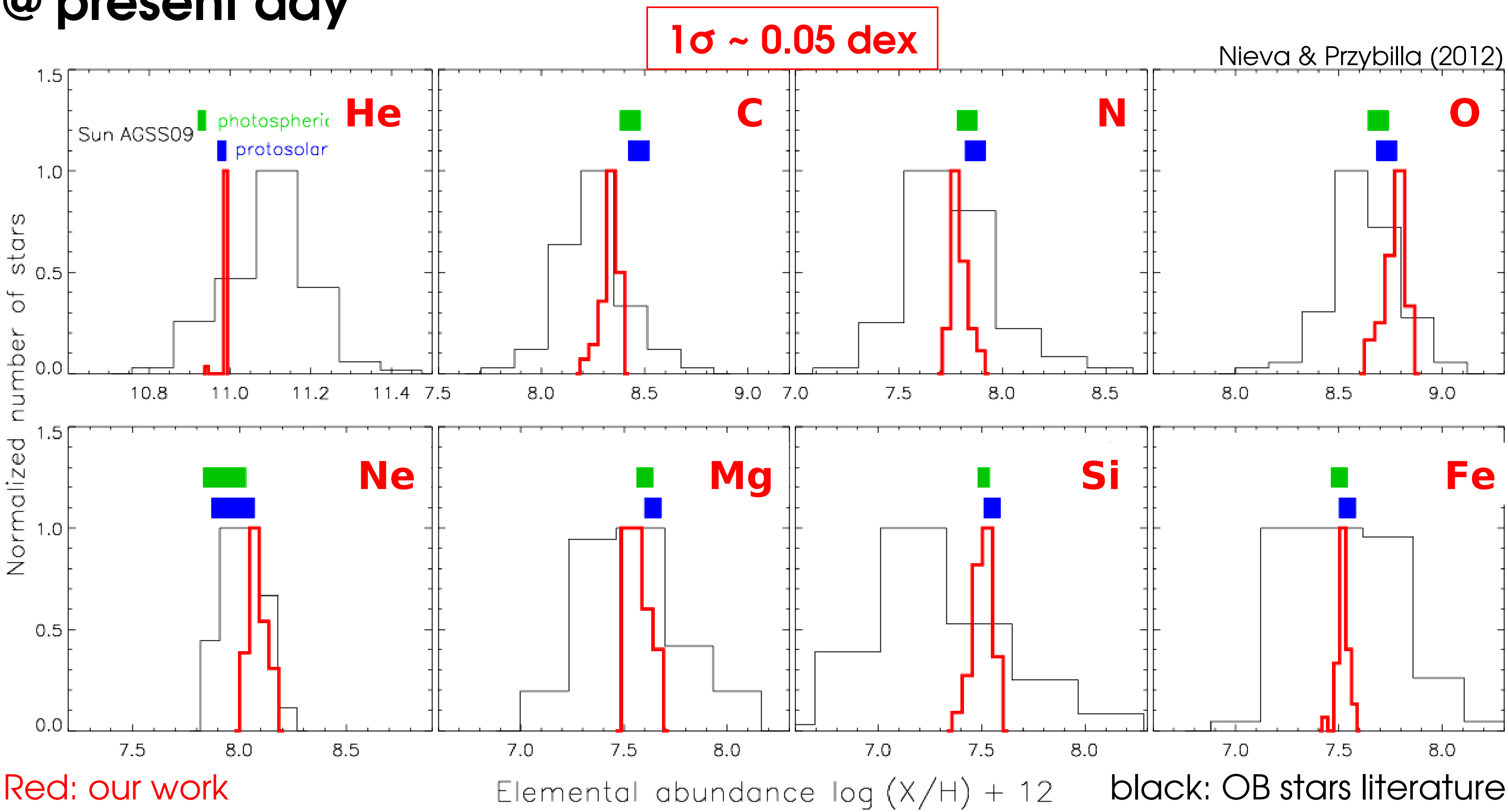
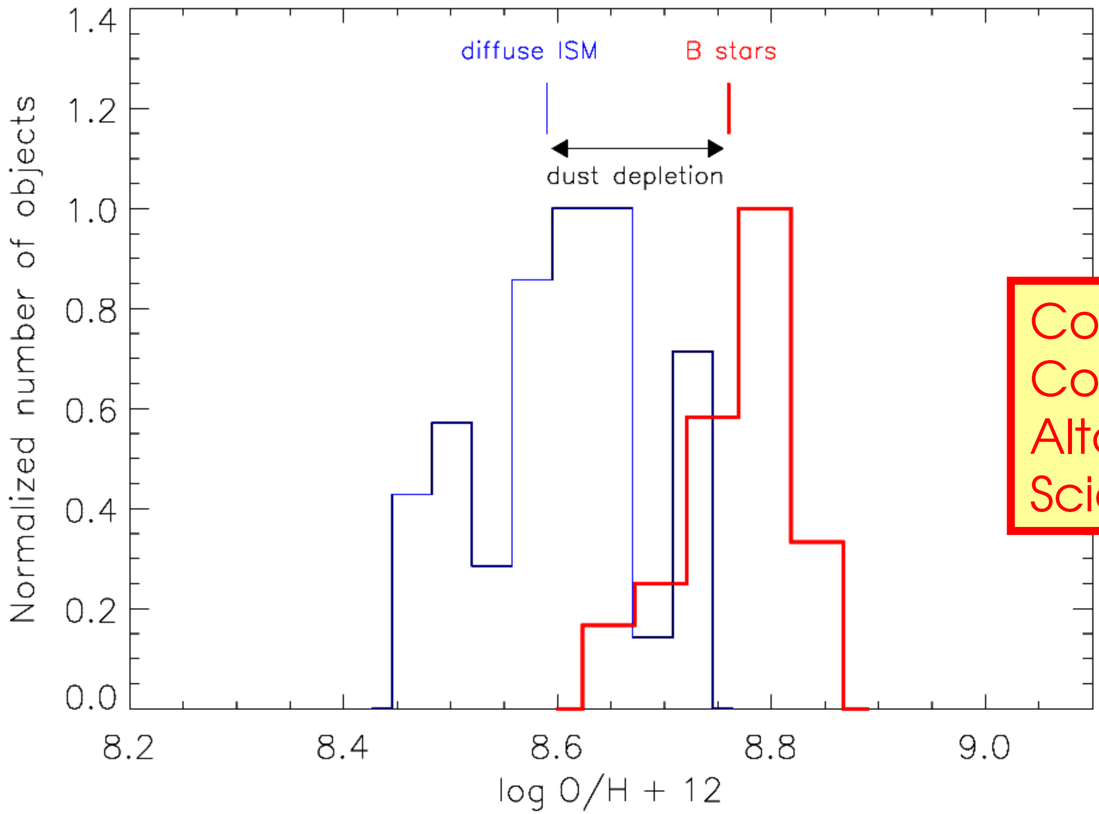
Chemical composition of the solar neighborhood @ present day



Chemical homogeneity → cosmic abundance standard

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

Chemical composition of interstellar dust



Nieva & Przybilla (2012)

Confirmed by Cassini`s Cosmic Dust Analyzer: Altobelli et al. 2016, Science, 352, 312

- **chemical homogeneity** of ISM and OB-stars

  difference → dust composition

- homogeneity over hundreds of parsecs: **highly efficient mixing**

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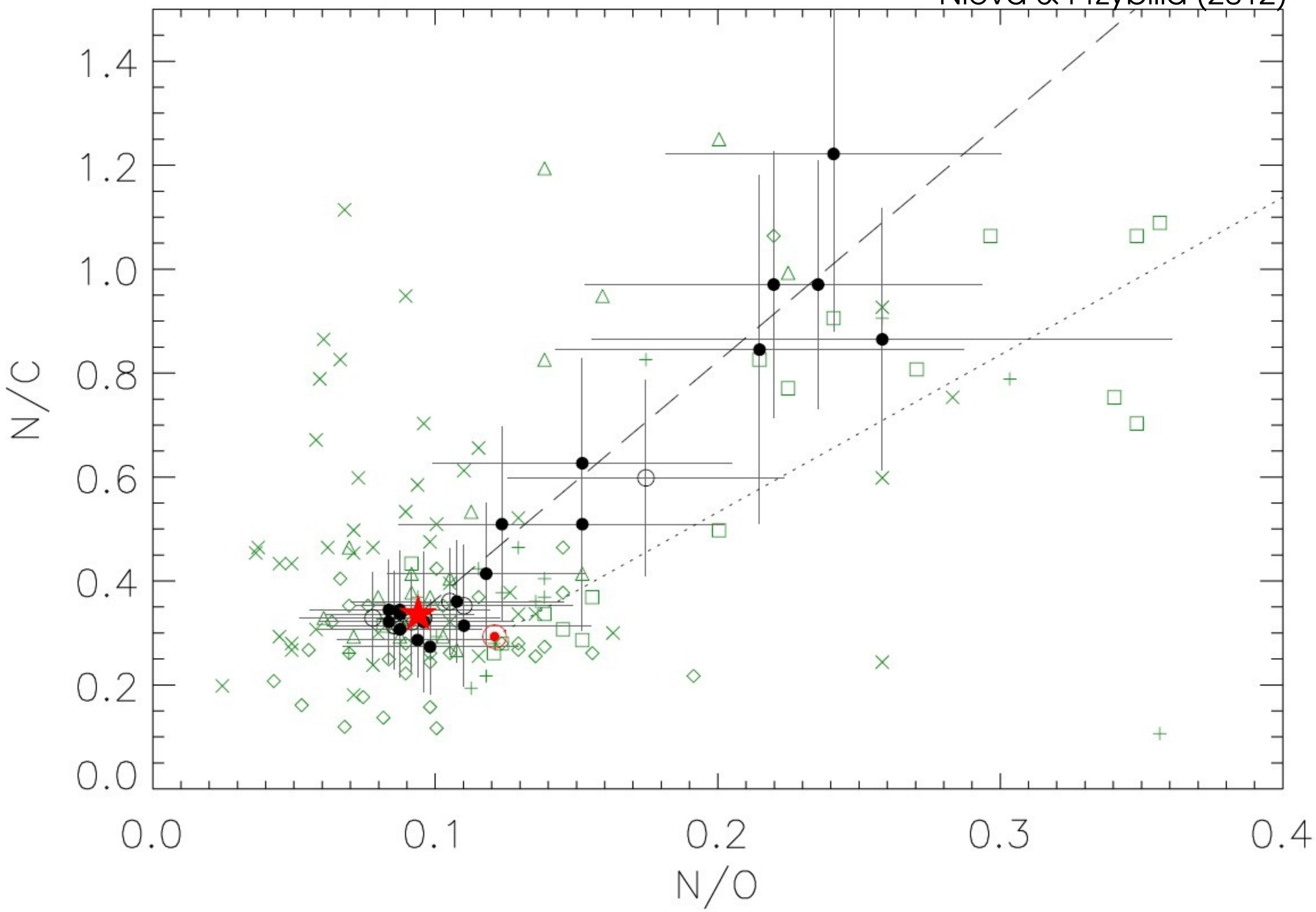
Mixing with CNO-processed matter

- theory predicts very tight relation in N/C vs. N/O diagram

→ nuclear path of the CNO cycles (Przybilla et al. 2010; Maeder et al. 2014)

Nieva & Przybilla (2012)



→ CNO-mixed stars easily identified

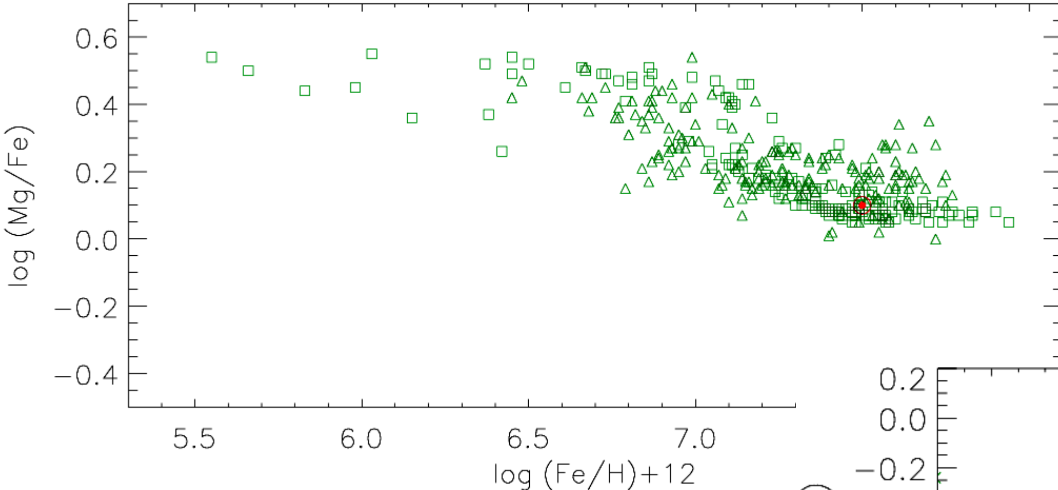
Comparison CAS & Solar Standard

Element	CAS	Sun (photospheric) Asplund et al. (2009)	Δ(CAS-⊙)
C	8.33±0.04	8.43±0.05	-0.10
N	7.79±0.04	7.83±0.05	-0.04
O	8.76±0.05	8.69±0.05	0.07
Ne	8.09±0.05	[7.93±0.10]	0.16
Mg	7.56±0.05	7.60±0.04	-0.04
Al (prelim.)	6.28±0.07	6.45±0.03	-0.17
Si	7.50±0.05	7.51±0.03	-0.01
S (prelim.)	7.16±0.06	7.12±0.03	0.04
Ar (prelim.)	6.50±0.06	[6.40±0.13]	0.10
Fe	7.52±0.03	7.50±0.04	0.02

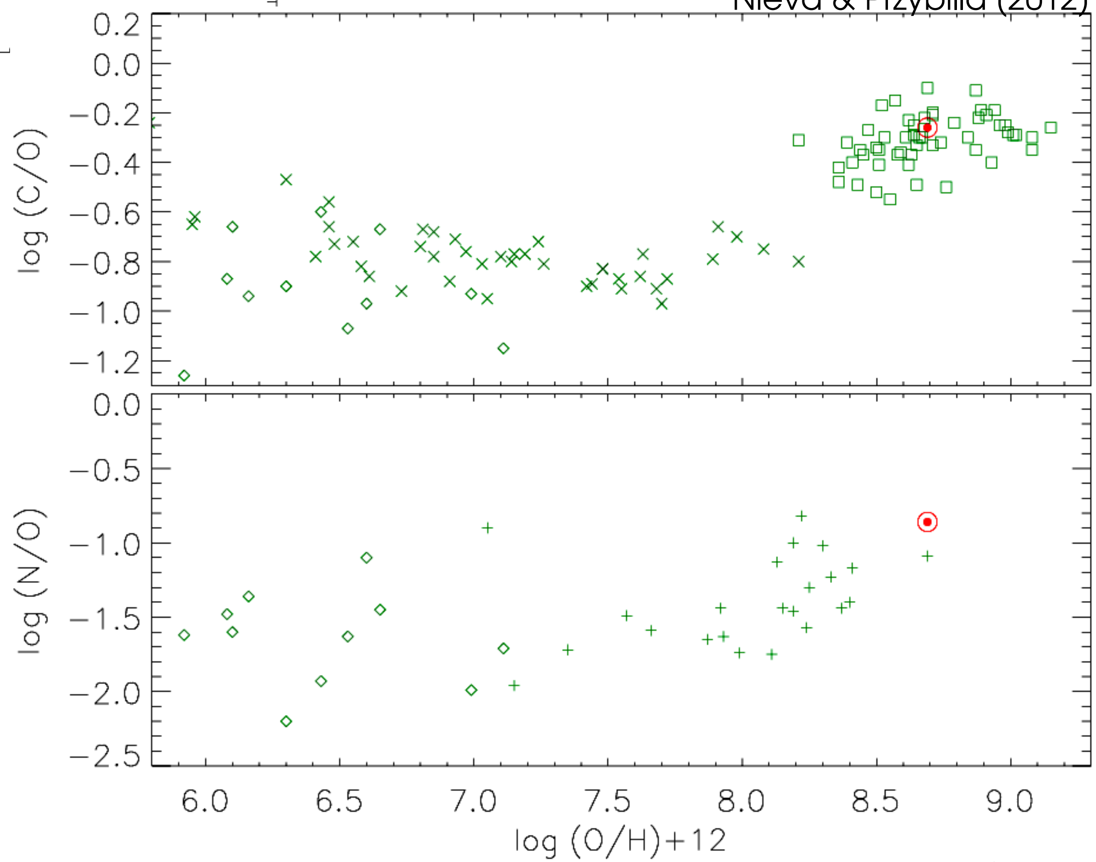
- Sun a bit more metal rich according to Caffau et al. (2010)
- confirmation of CAS from a few BA-type supergiants
- **surprising good agreement ... suspicious**
- Protosun is even more metal rich

... no GCE over past 4.56 Gyrs ?

Genesis of Heavy Elements over Cosmic History



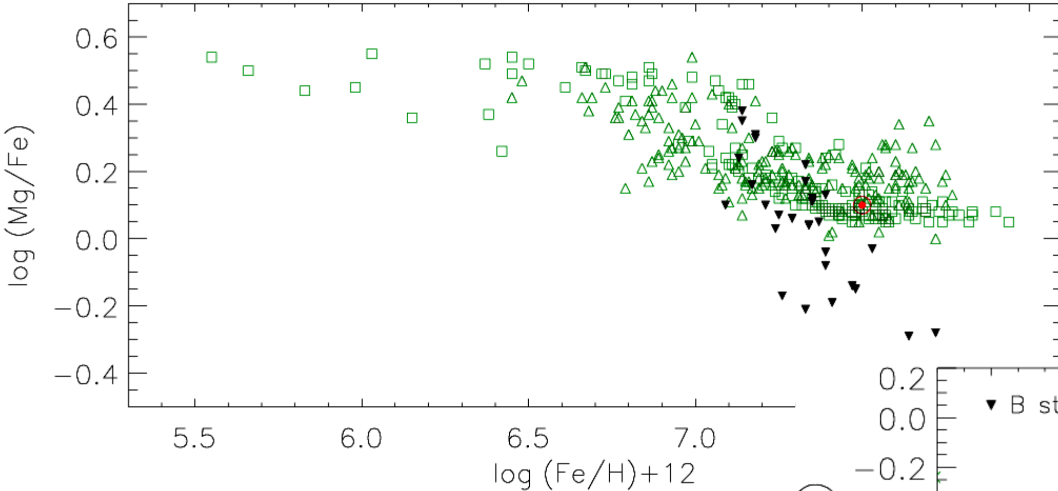
α-enhancement:
delay of **SN Ia** w.r.t. **SNII**



- **solar-type stars** (long-lived): constraints on Galactochemical evolution over time

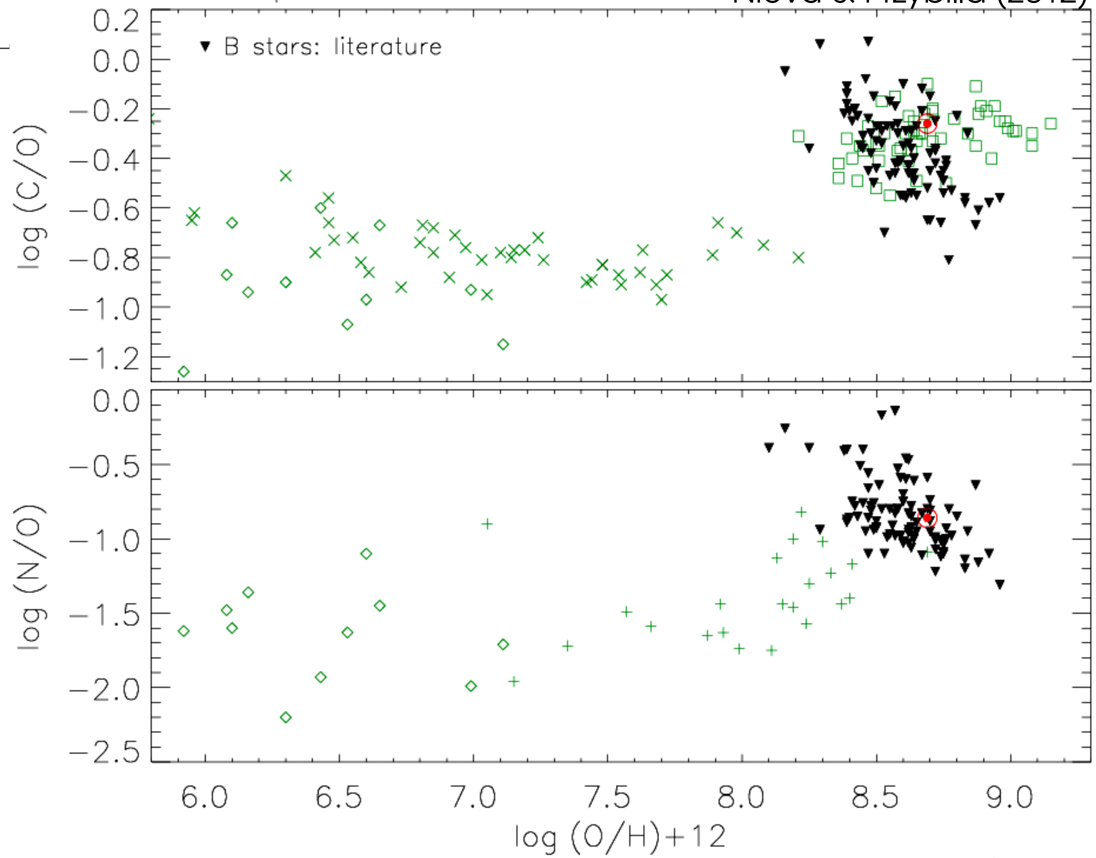
delayed CN-production in intermediate-mass stars

Genesis of Heavy Elements over Cosmic History



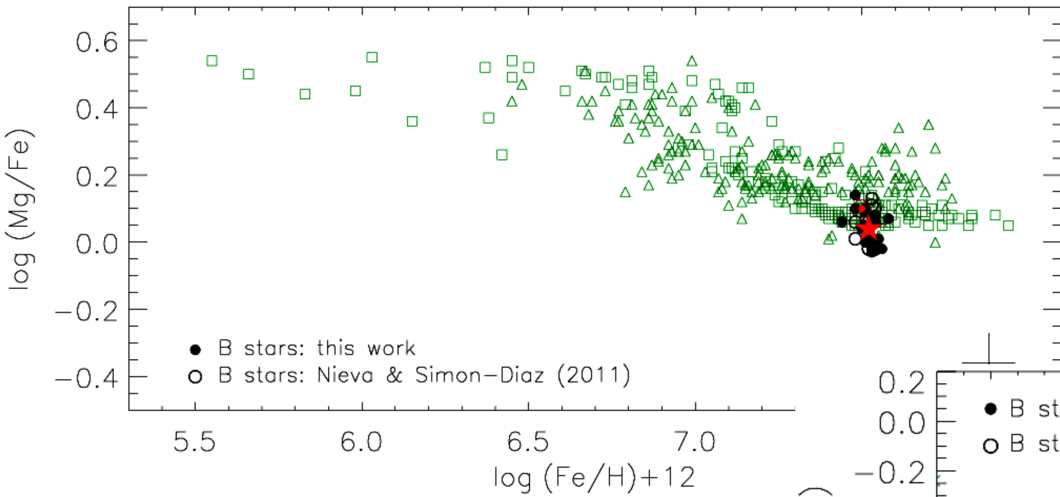
- comparison with literature on early B stars

Nieva & Przybilla (2012)



- **early B-type stars** (short lived): boundary values @present time

Genesis of Heavy Elements over Cosmic History

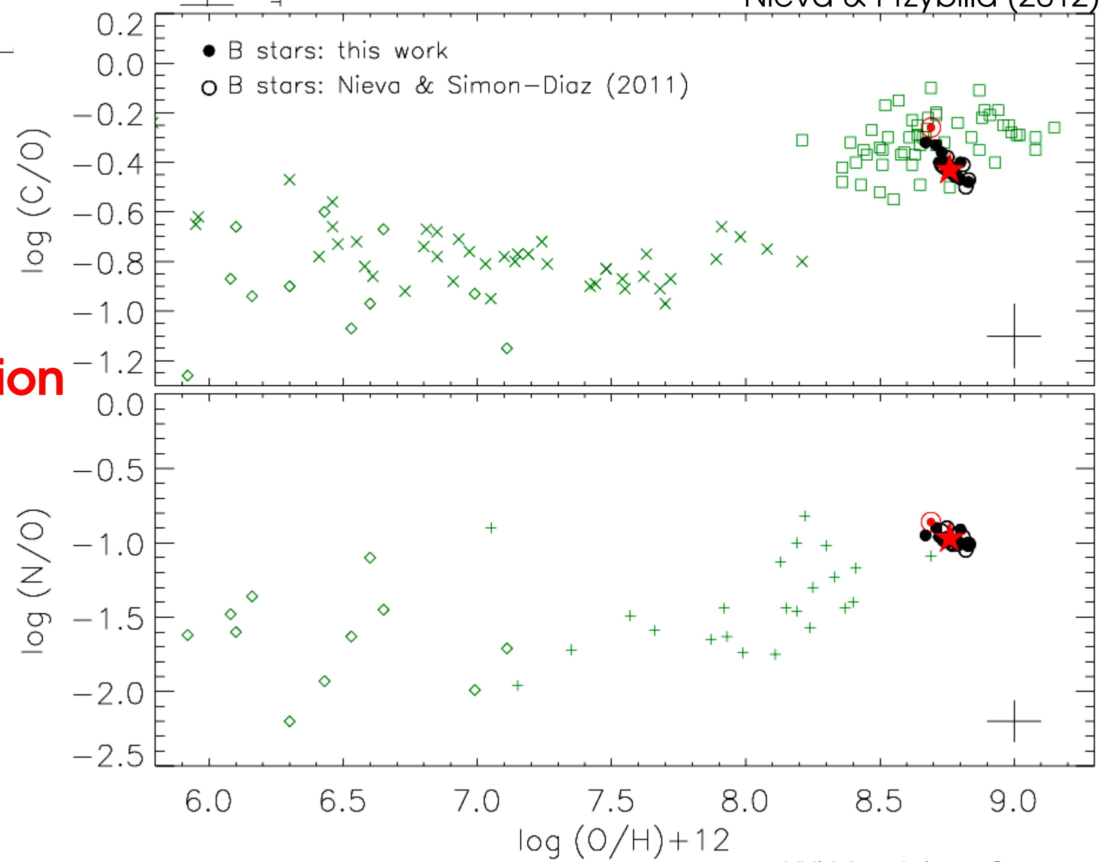


- comparison with our data on early B stars

tight constraints !

present-day chemical composition of solar neighbourhood at odds with solar composition

Nieva & Przybilla (2012)



Place of birth of the solar system

- method: chemical tagging – orbit tracing not working: radial migration
- available data: CAS, present-day abundance gradients,
  solar abundances (4.56 Gyr)

diffusion → Protosun

Sun, if born today → Protosun, GCE corrected

present-day solar neighbourhood → CAS

Galactic abundance gradients → $d\varepsilon(El.)/dR_g$

present-day inner Galaxy → CAS+$d\varepsilon(El.)/dR_g$

Element	Protosun		Protosun, GCE corrected[a]		CAS	$d\varepsilon(\mathrm{El.})/dR_g$	CAS+$d\varepsilon(\mathrm{El.})/dR_g$	
	AGSS09	CLSFB10	AGSS09	CLSFB10		dex kpc^{-1}	$R_g = 6$ kpc	$R_g = 5$ kpc
C	8.47 ± 0.05	8.54 ± 0.06	8.53 ± 0.05	8.60 ± 0.06	8.33 ± 0.04	-0.103 ± 0.018[b]	8.54 ± 0.05	8.64 ± 0.05
N	7.87 ± 0.05	7.90 ± 0.12	7.95 ± 0.05	8.01 ± 0.12	7.79 ± 0.04	-0.085 ± 0.020[c]	7.96 ± 0.05	8.05 ± 0.05
O	8.73 ± 0.05	8.80 ± 0.07	8.77 ± 0.05	8.84 ± 0.07	8.76 ± 0.05	-0.035[d,e]	8.83 ± 0.05	8.87 ± 0.05
Mg	7.64 ± 0.04	…	7.68 ± 0.04	…	7.56 ± 0.05	-0.039[d]	7.64 ± 0.05	7.68 ± 0.05
Si	7.55 ± 0.04	…	7.63 ± 0.04	…	7.50 ± 0.05	-0.045[d]	7.59 ± 0.05	7.64 ± 0.05
Fe	7.54 ± 0.04	7.56 ± 0.06	7.68 ± 0.04	7.70 ± 0.06	7.52 ± 0.03	-0.052[d]	7.62 ± 0.03	7.68 ± 0.03

Notes. [a] Applying values from Table 5 of AGSS09, based on GCE models of Chiappini et al. (2003); [b] Esteban et al. (2005); [c] Carigi et al. (2005); [d] Cescutti et al. (2007), based on Cepheid observations of Andrievsky et al. (2004, and references therein); [e] a slightly steeper – though compatible – gradient, by -0.044 ± 0.010 dex kpc^{-1}, is given by Carigi et al. (2005).

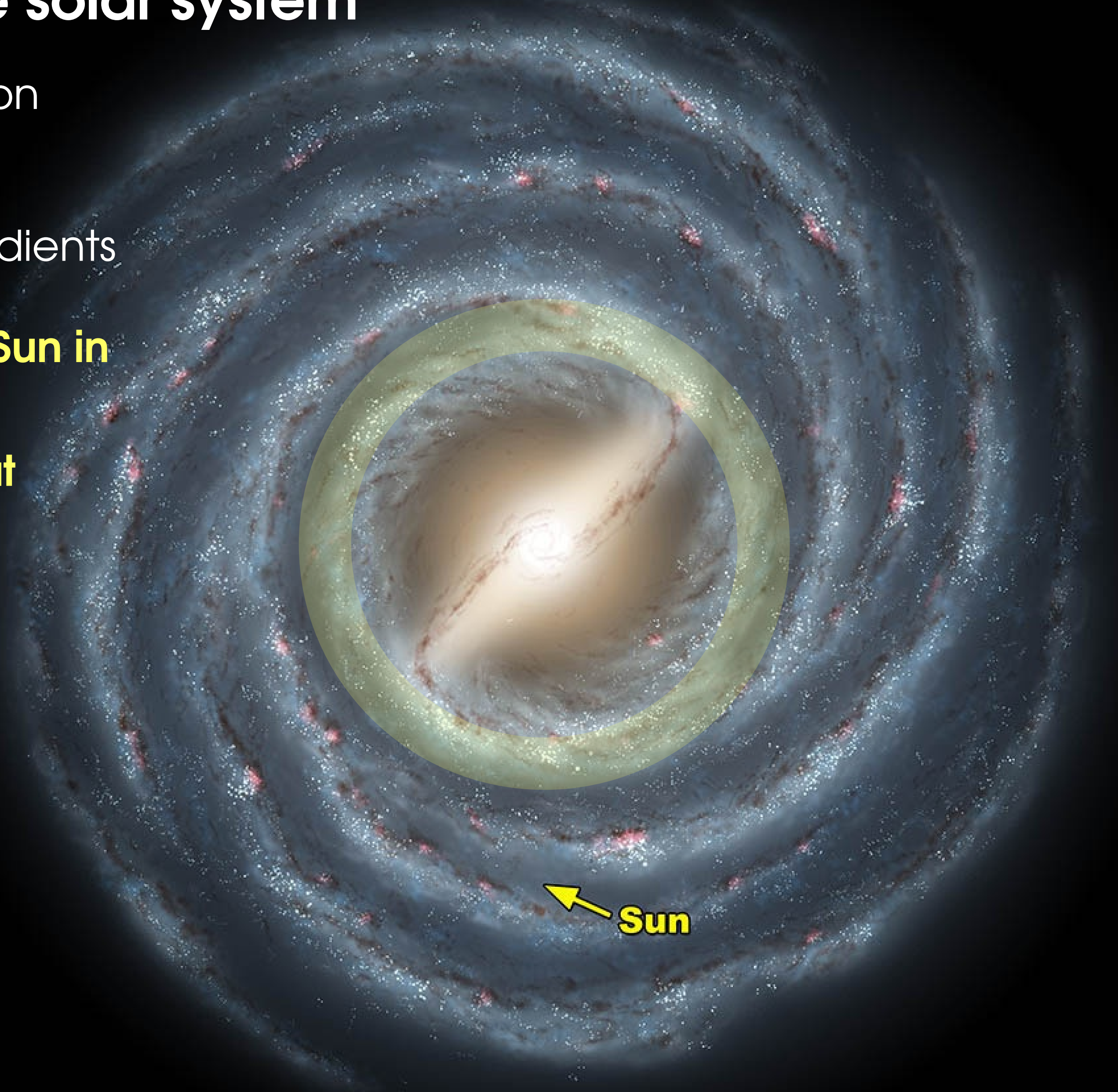
Nieva & Przybilla (2012)

Place of birth of the solar system

Galactochemical evolution
over cosmic history
&
Galactic abundance gradients

→ **radial migration of Sun in Milky Way disk**

birth radius of Sun at R_g~5-6 kpc



Summary

- early B-type stars excellent probes for spatial distribution of chemical abundances @ present day

- early B-stars in solar neighbourhood chemically hogeneous

  → **C**osmic **A**bundance **S**tandard

- similarities and differences with respect to solar standard

  → chemical tagging of the Sun`s birth radius

- many applications, e.g.
  - quantifying depletion onto dust grains in the ISM
  - spatial distribution of elemental abundances in Milky Way
  - initial composition for modelling stellar evolution
  - boundary condition for GCE modelling