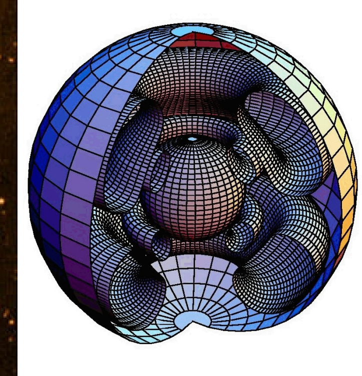
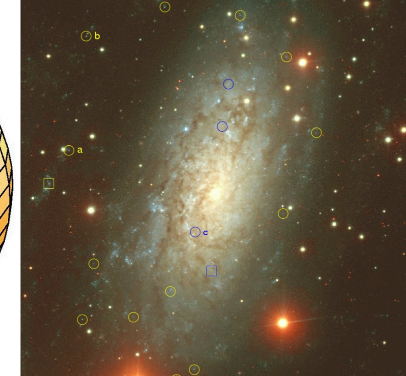
$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji})$$

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





Present-day elemental abundances from OB-type stars

Norbert Przybilla

P. Aschenbrenner, D. Weßmayer, K. Butler, M.F. Nieva

universität innsbruck

Institute for Astro- and Particle Physics

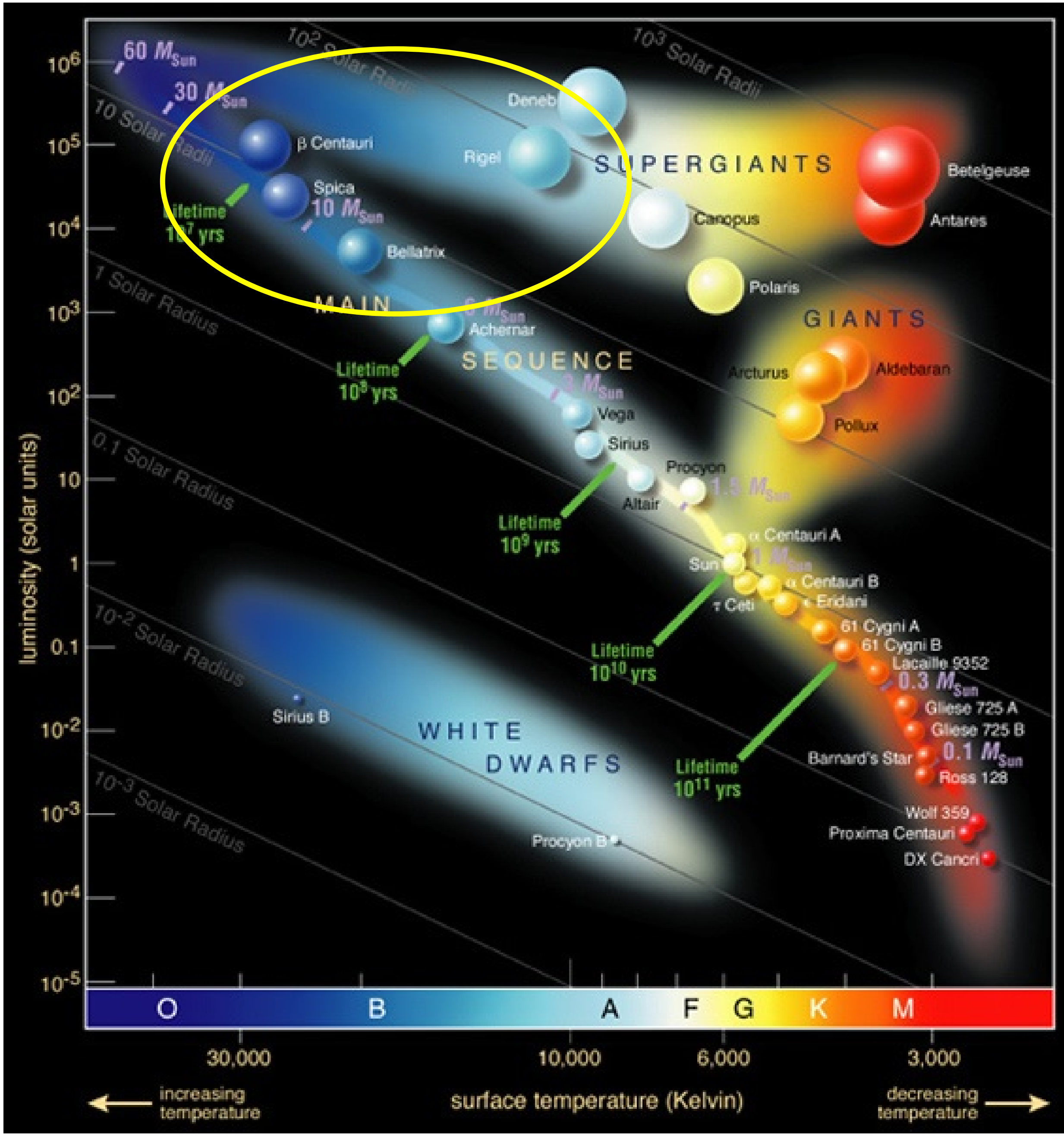
FWF Österreichischer Wissenschaftsfonds

LAND TIROL

Atoms, Light, and Molecules
Innsbruck Physics Research Center

OB-type Stars

(ZAMS to BA-SG stage)



- massive

  M: ~ 8 ... 25 $M_\odot$

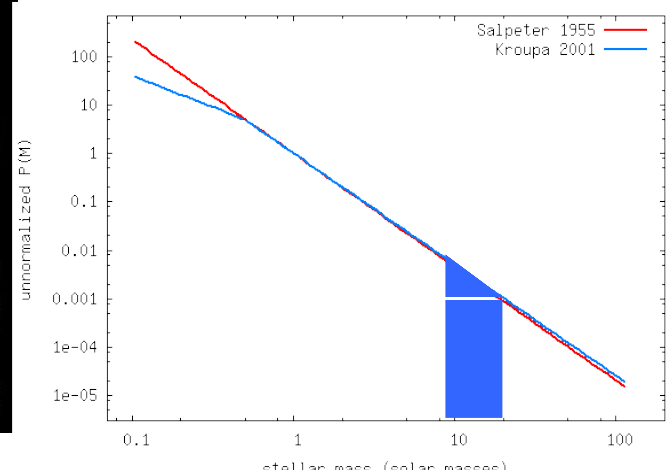
- hot

  T_{eff}: ~ 8000 ... 35000 K

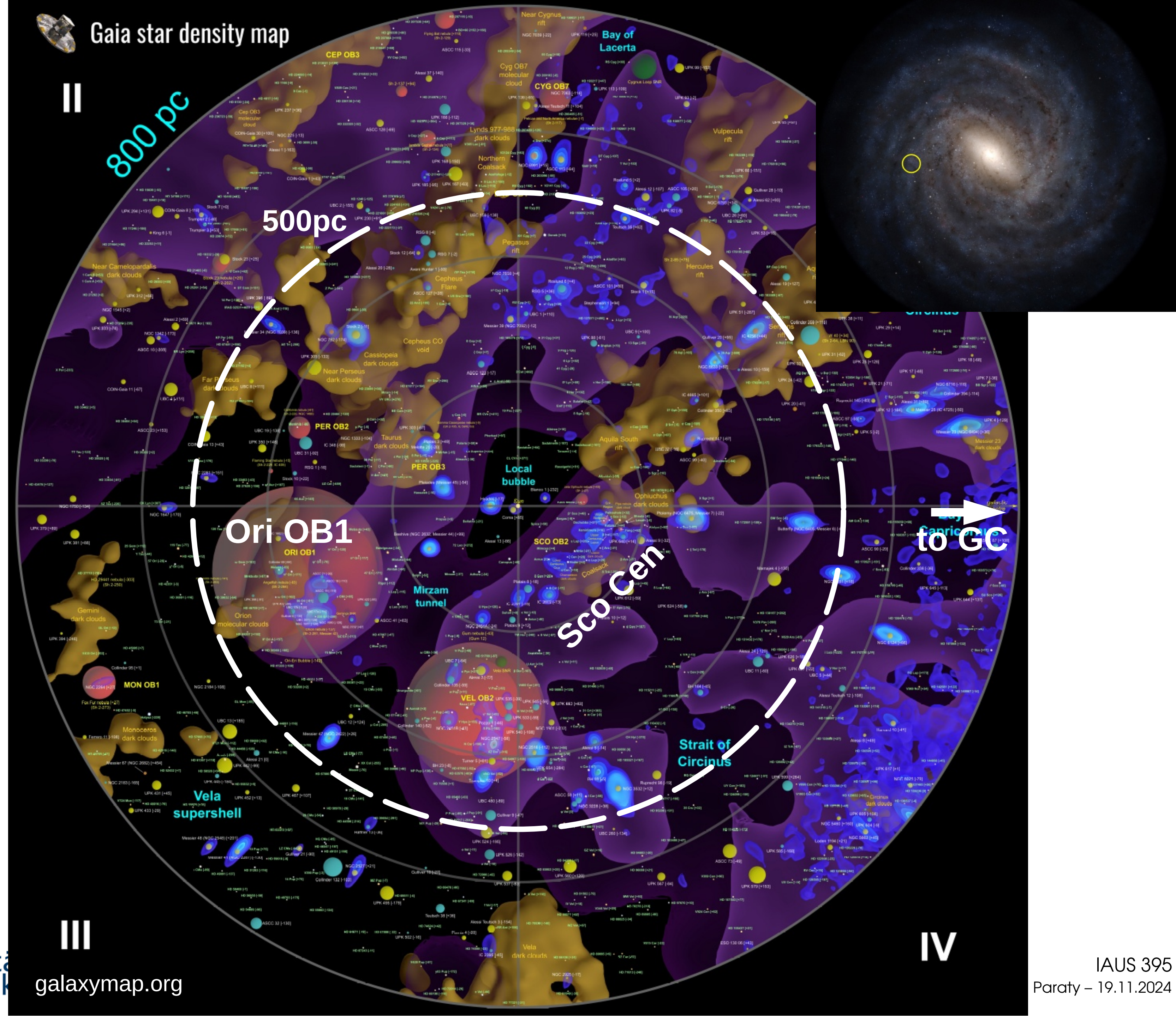
- luminous

  L: ~ several 10^3 ... 10^5 $L_\odot$

- „numerous“



see also P1 (de Burgos+), P65 (Daflon+), P74 (Santos+)



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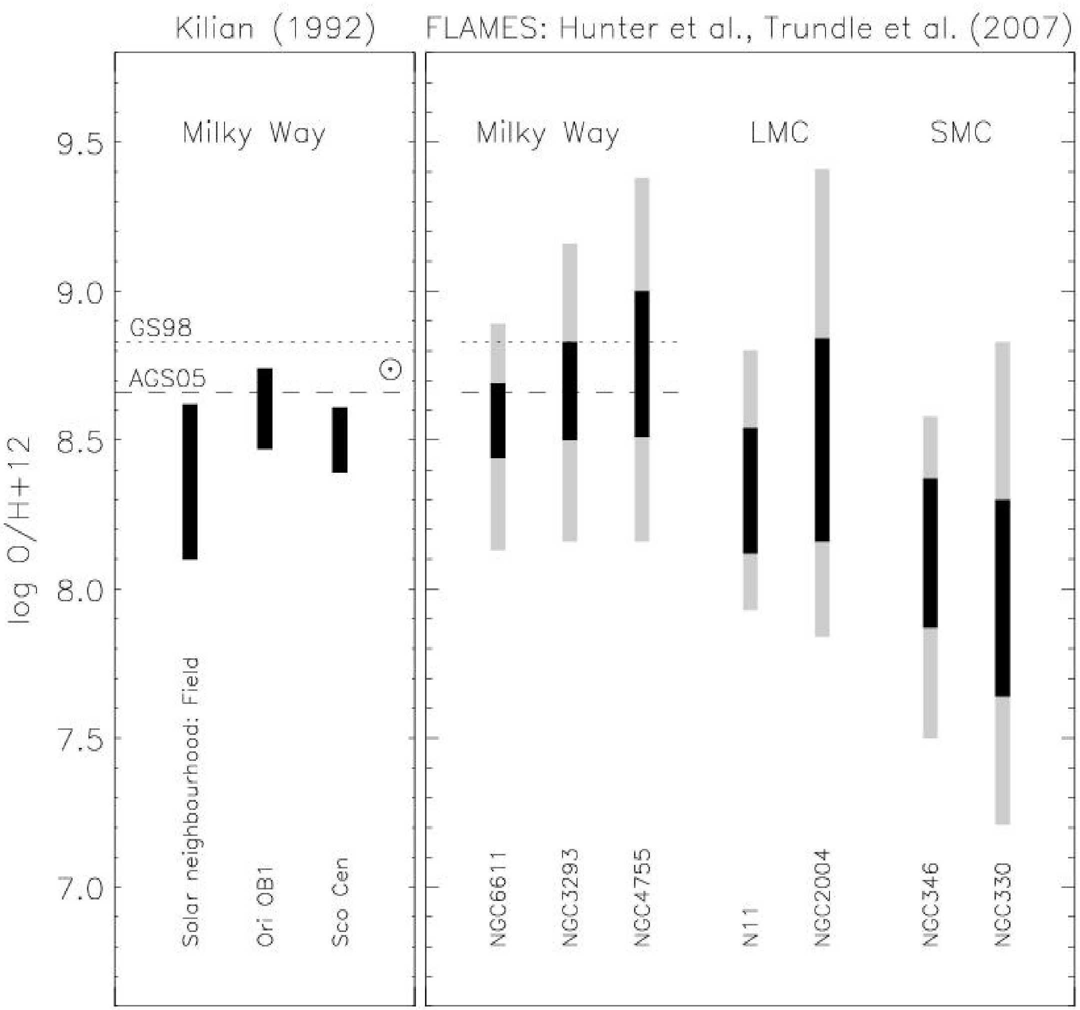
IAUS 395
Paraty – 19.11.2024

Chemical (In)Homogeneity from Cosmic Abundance Indicators

Metals in Solar Neighbourhood/Star Clusters



range in abundance
uncertainty

- 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

J.-R. Roy[1,2] and D. Kunth[3]

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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)

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Hybrid non-LTE approach to spectral analysis of OB stars

- LTE model atmospheres:
  ATLAS9/12 (Kurucz)

- non-LTE radiative transfer & statistical equilibrium:
  DETAIL

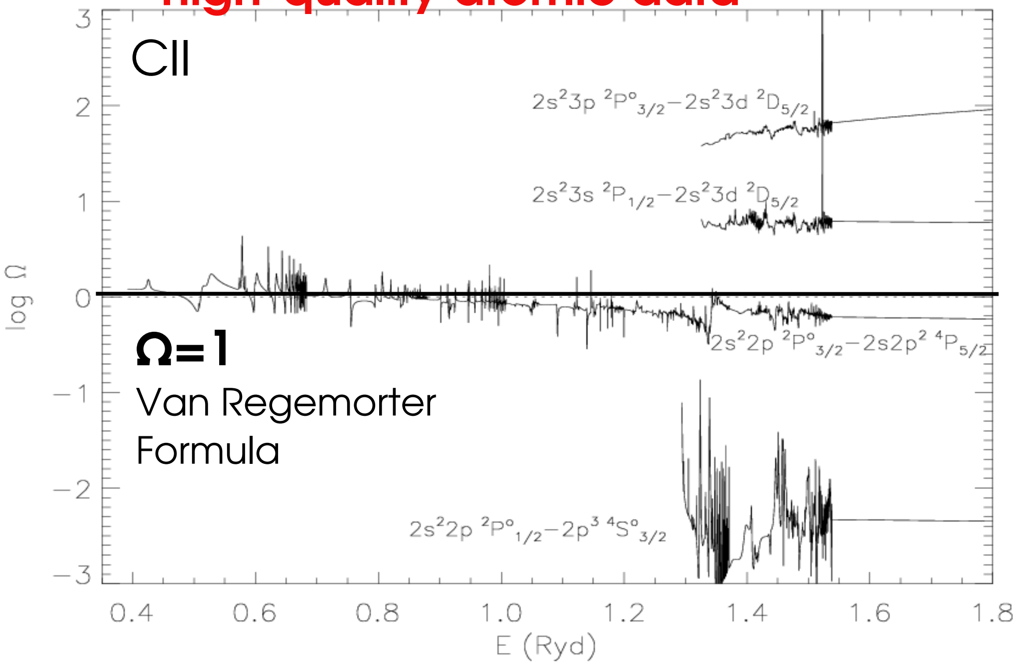
$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$$

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

- non-LTE/LTE spectrum synthesis:
  SURFACE

→ **hybrid non-LTE**: **ADS**

+ comprehensive model atoms/ high-quality atomic data



ab-initio

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

+ high-quality spectra

+ robust spectral analysis techniques

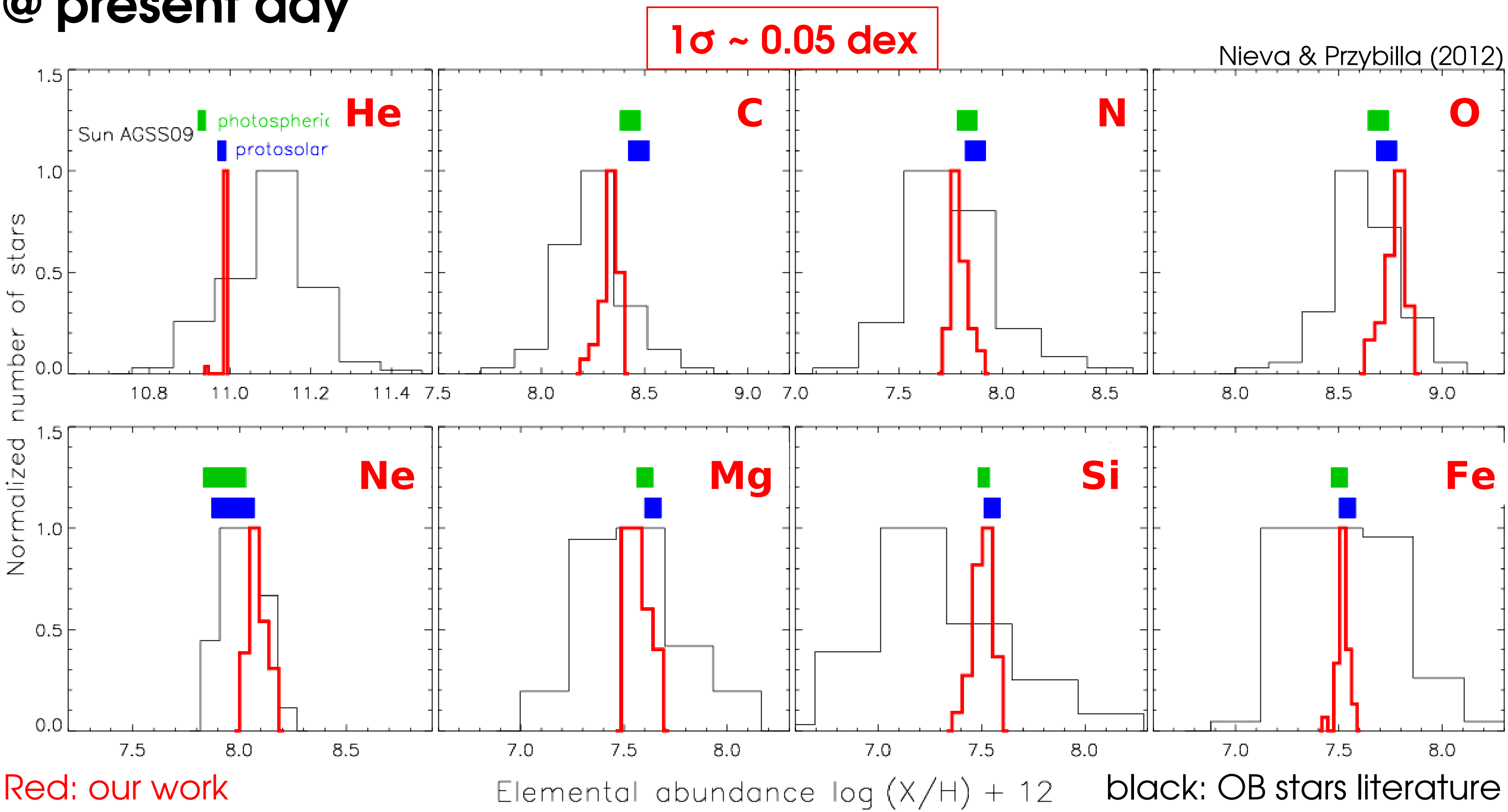
- multiple ionisation equilibria + hydrogen line profiles
- other constraints: SEDs, Gaia, interferometry ...
- analysis of full spectrum

minimising systematics !

- **abundances: Δlogε ~ 0.05...0.10 dex (1σ-stat.)**
  Δlogε ~ 0.1 dex (1σ-sys.)

standard error: ~0.01...0.02 dex

Chemical composition of the solar neighborhood @ present day



Chemical homogeneity → cosmic abundance standard

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

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Comparison CAS & Solar Standard

Element	CAS	Sun (photospheric) Asplund et al. (2021)	Δ(CAS-⊙)
C	8.33±0.04	8.46±0.04	-0.13
N	7.79±0.04	7.83±0.07	-0.04
O	8.76±0.05	8.69±0.04	0.07
Ne	8.09±0.05	8.06±0.05	0.03
Mg	7.56±0.05	7.55±0.03	0.01
Al (prelim.)	6.28±0.07	6.43±0.03	-0.15
Si	7.50±0.05	7.51±0.03	-0.01
S (prelim.)	7.16±0.06	7.12±0.03	0.04
Ar	6.58±0.05	6.38±0.10	0.20 Keiler et al. (in prep.)
Fe	7.52±0.03	7.46±0.04	0.06

- Sun a bit more metal rich according to Caffau et al. (2010)
- confirmation of CAS from a few BA-type supergiants, late O-stars
- Protosun is even more metal rich (diffusion @ bottom conv. zone)

... no GCE over past 4.56 Gyrs ?

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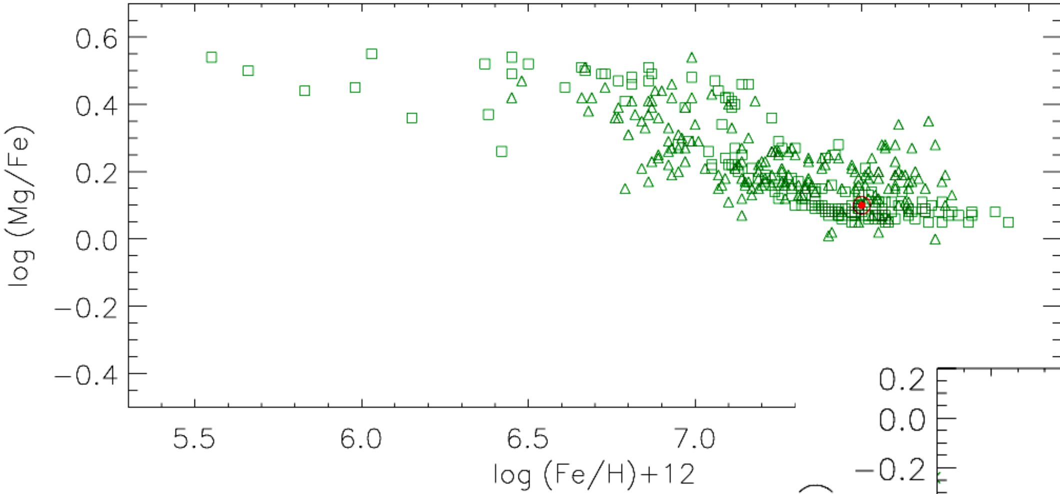
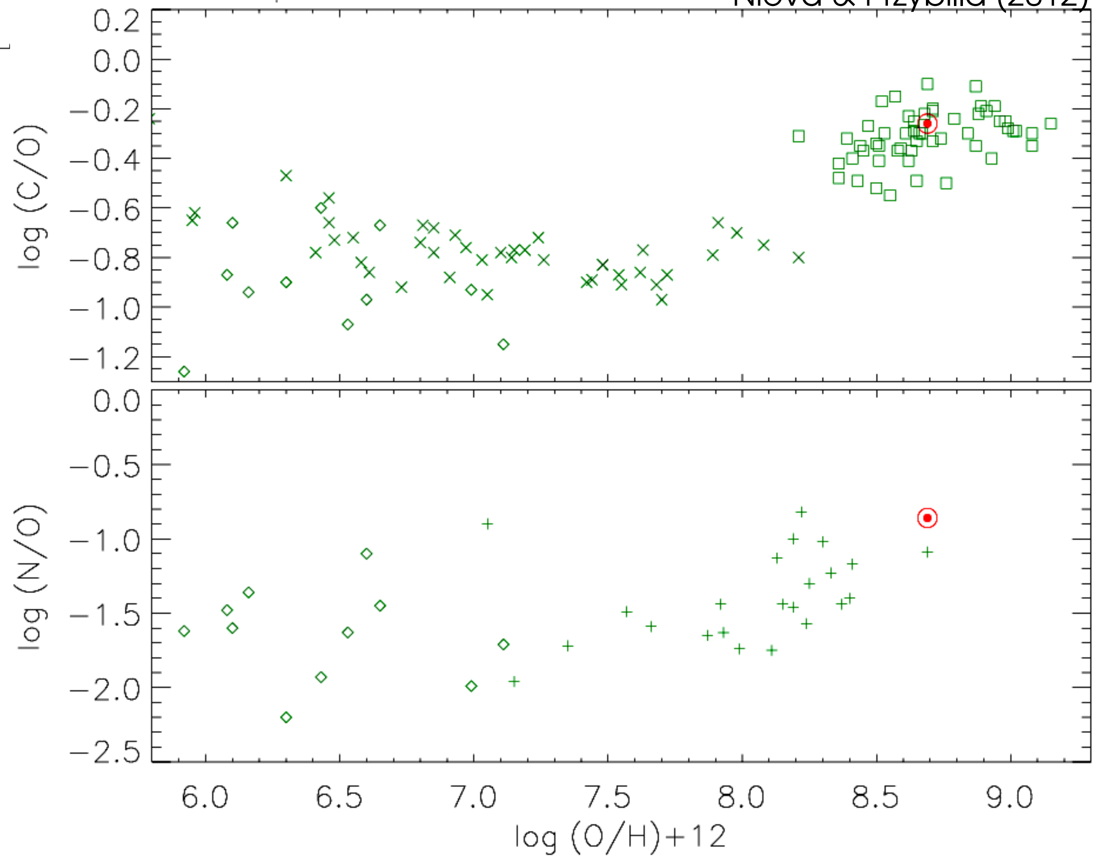
Genesis of Heavy Elements over Cosmic History



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

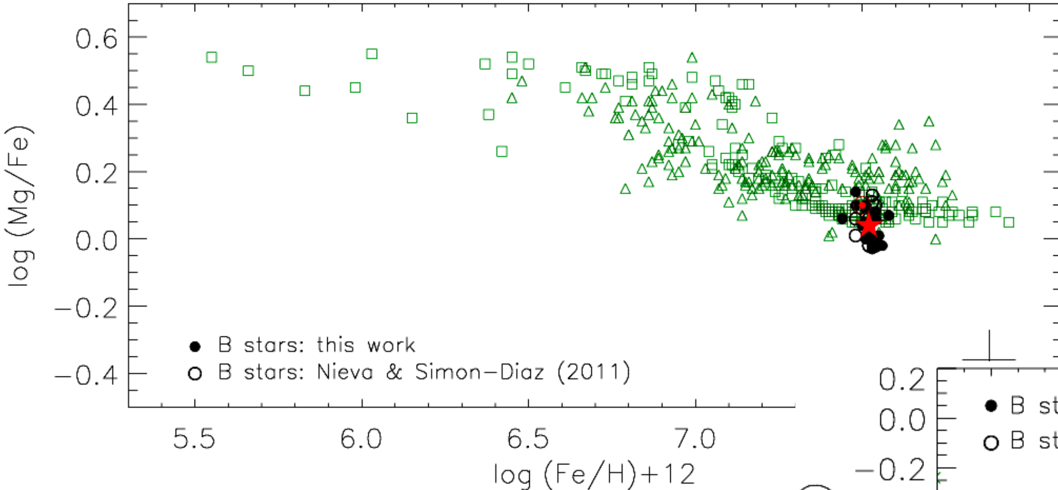
Nieva & Przybilla (2012)



- **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

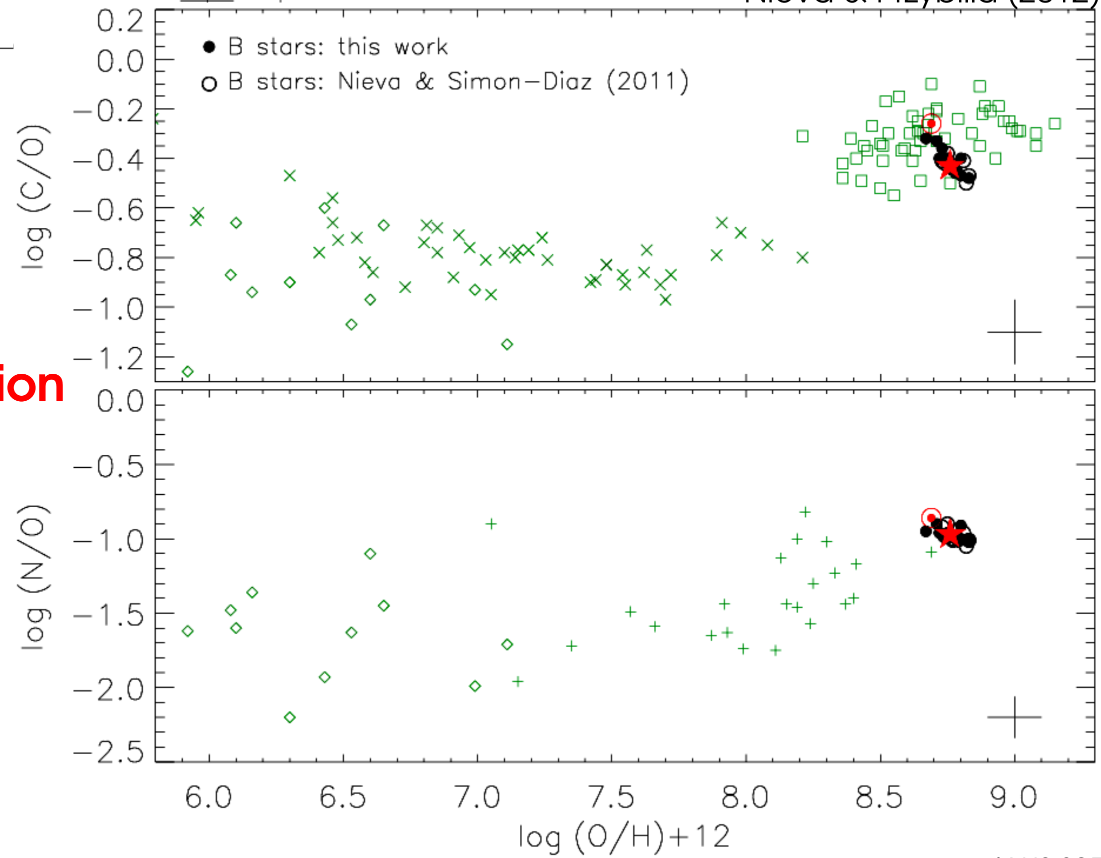


- comparison with our data on early B stars

tight constraints !

present-day chemical composition of solar neighbourhood at odds with solar composition in view of GCE

Nieva & Przybilla (2012)



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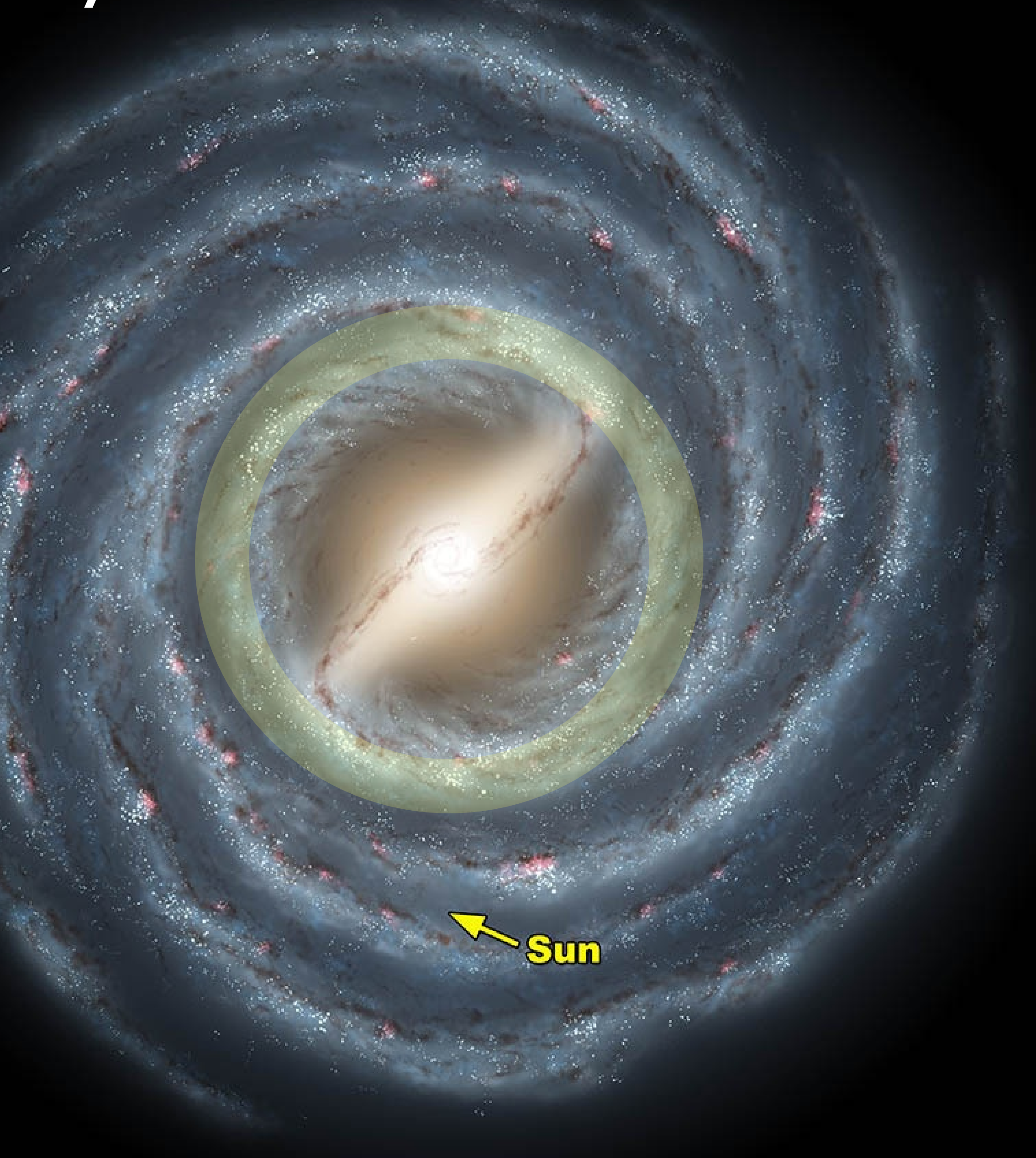
Place of birth of the solar system

Galactochemical evolution
over cosmic history
&
Galactic abundance gradients

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

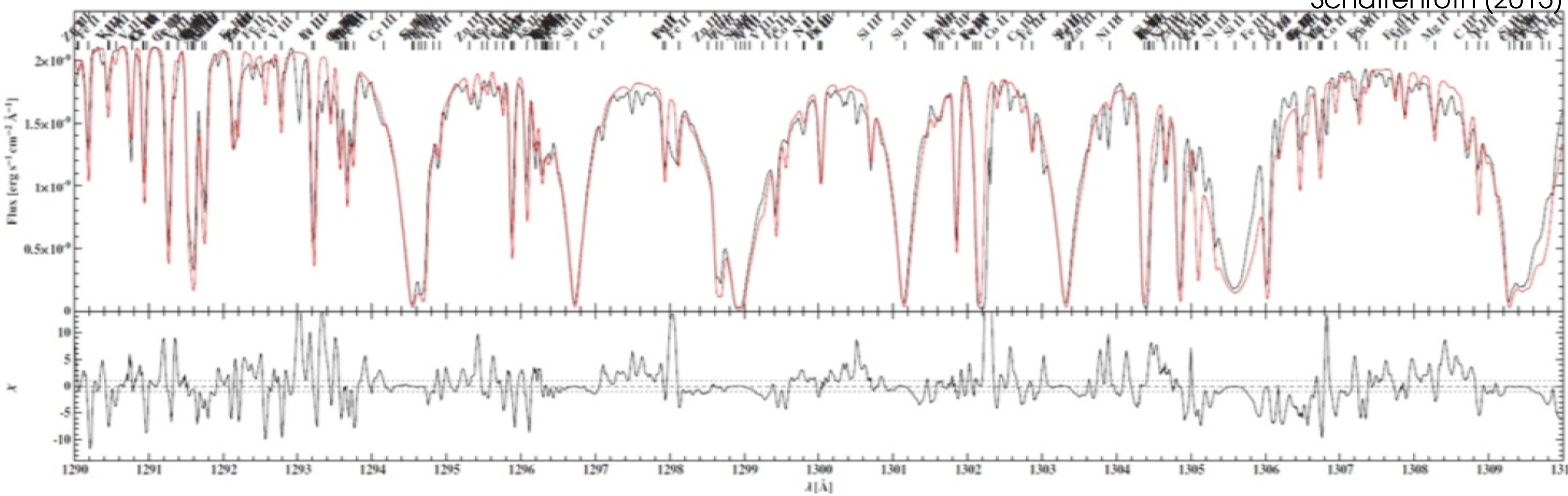
birth radius of Sun at R_g~5-6 kpc

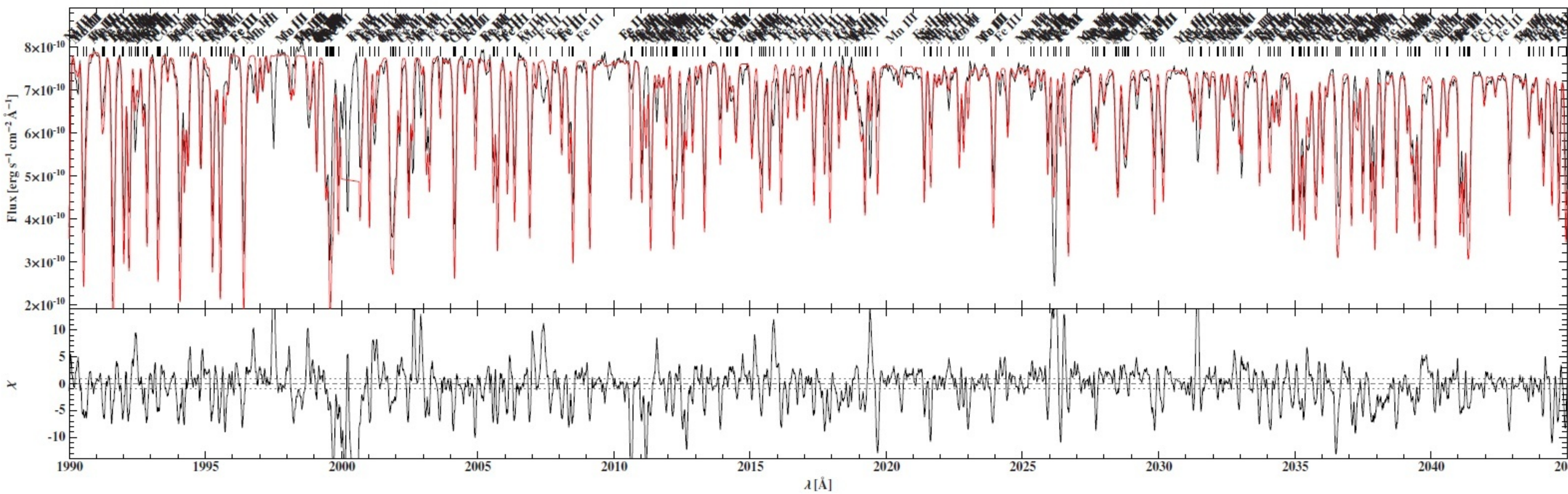


see also:
Wielen et al. (1996)
Minchev et al. (2013),
Minchev et al. (2018),
Feltzing et al. (2020),
Frankel et al. (2020),
Tsujimoto & Baba (2020),
Baba et al. (2023),
Lu et al. (2024)

UV (HST/STIS)

Schaffenroth (2015)





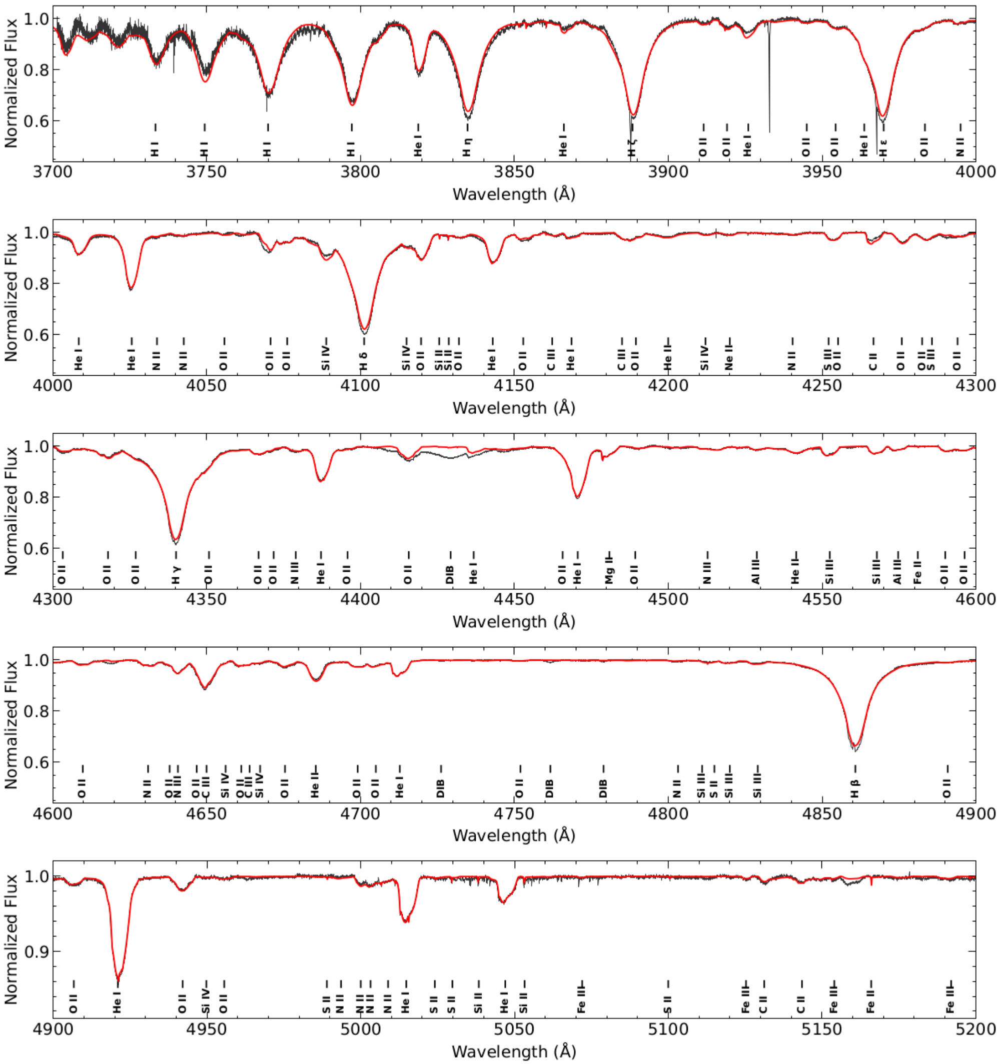
- ~10^5 lines: ~60 elements, 200+ ionization stages
- OB stars: UV ~50% of lines in non-LTE, rest LTE **– atomic data missing**, high-quality observations

Extension Work

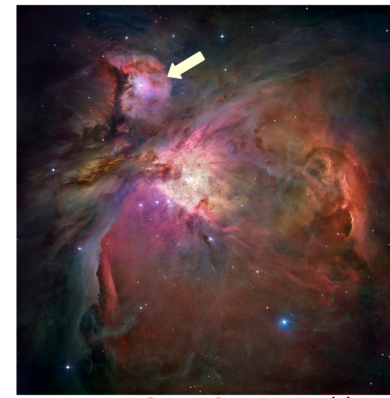
+ B-type supergiants (Weßmayer et al. 2022,2023)

+ weak wind late O-type stars (Aschenbrenner et al. 2023)

+ early-type binary/multiple stars (Aschenbrenner et al. 2024)

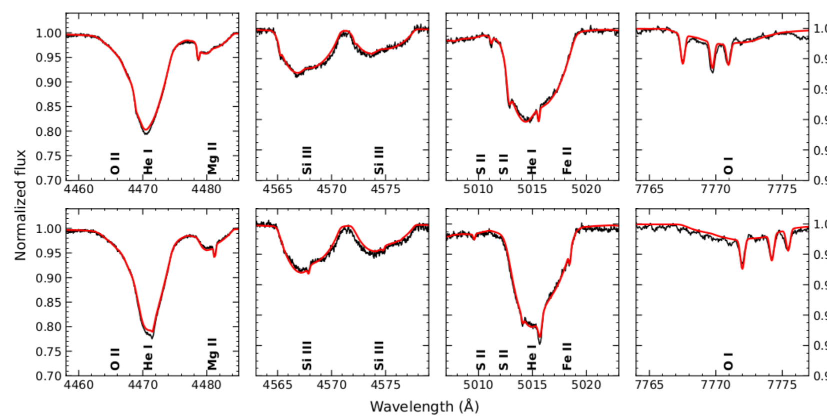


quadruple system HD37061 in M43



NASA, ESA, M. Robberto

2 epochs:



Aschenbrenner et al. (2024)

- ~10^5 lines: ~60 elements, 200+ ionization stages
- OB stars: complete spectrum synthesis in visual & near-IR, 100% in non-LTE

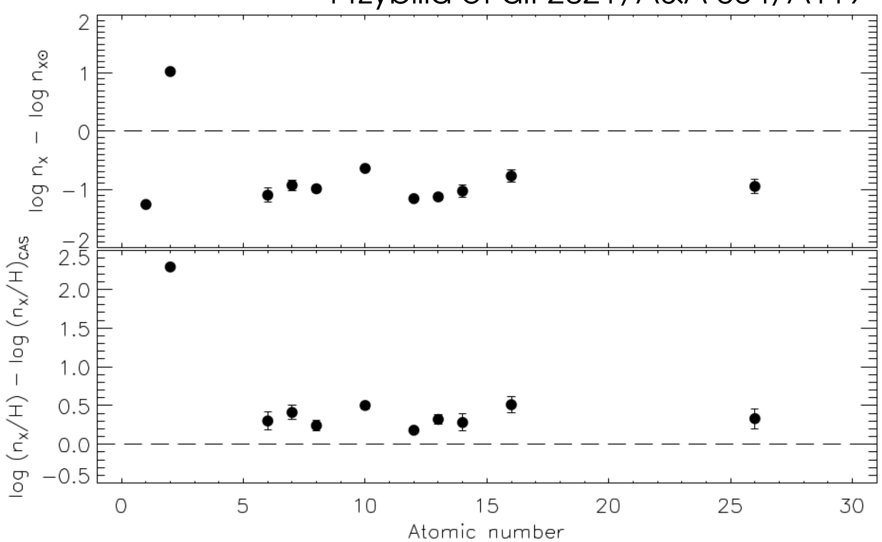
all confirm CAS

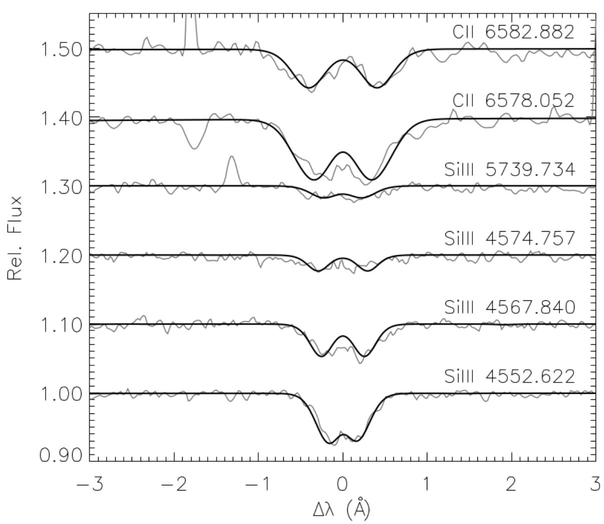
All confirm CAS? – The unique outliers

Extension Work

HD144941 – early B star @ $Z = 1/10\ Z_\odot$?

Przybilla et al. 2021, A&A 654, A119





Zeeman splitting
15 kG
magnetic field

most extreme
He-strong star

fallback of HeI,
95% surface He

normal [Fe/H]

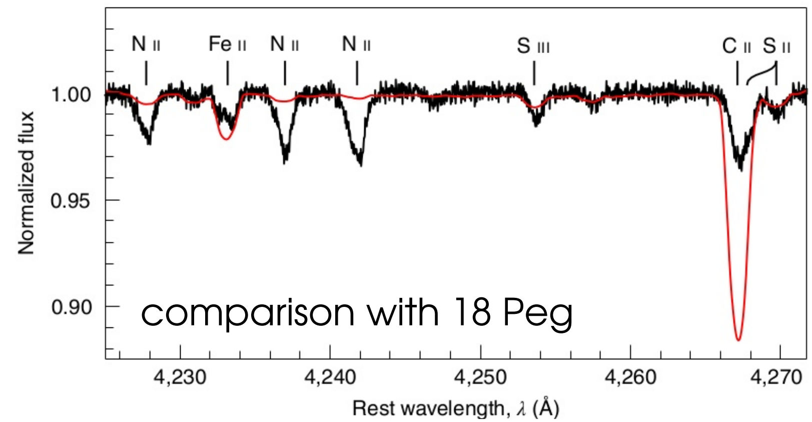
Article

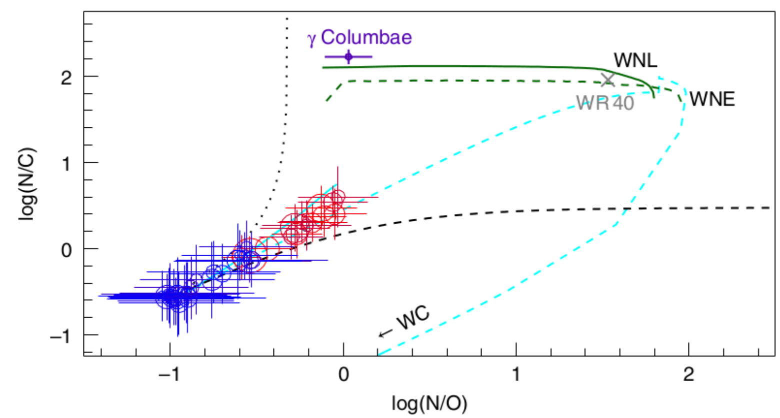
https://doi.org/10.1038/s41550-022-01809-6

γ Columbae as a recently stripped pulsating core of a massive star

Andreas Irrgang[1], Norbert Przybilla[2] and Georges Meynet[3]

Nature Astronomy | Volume 6 | December 2022 | 1414–1420

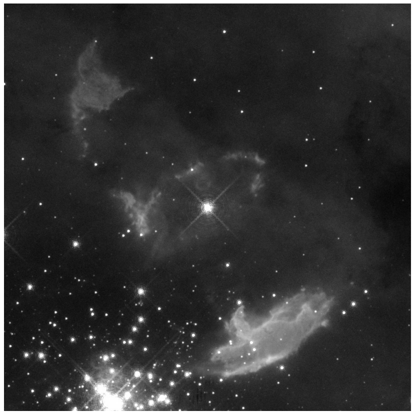


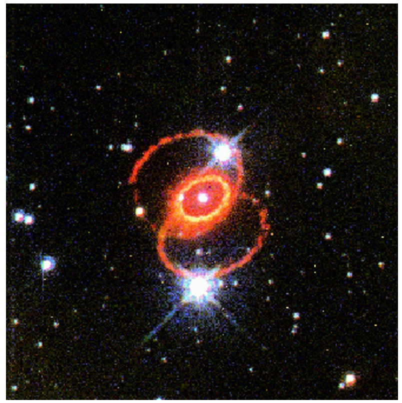


exposed CN-burning layers

All confirm CAS? – The unique outliers

Weßmayer et al. 2023, A&A 677, A175:
Sher 25 in NGC3603 – SN1987A lookalike


NASA/ESA Hubble; Robert O'Connell et al.

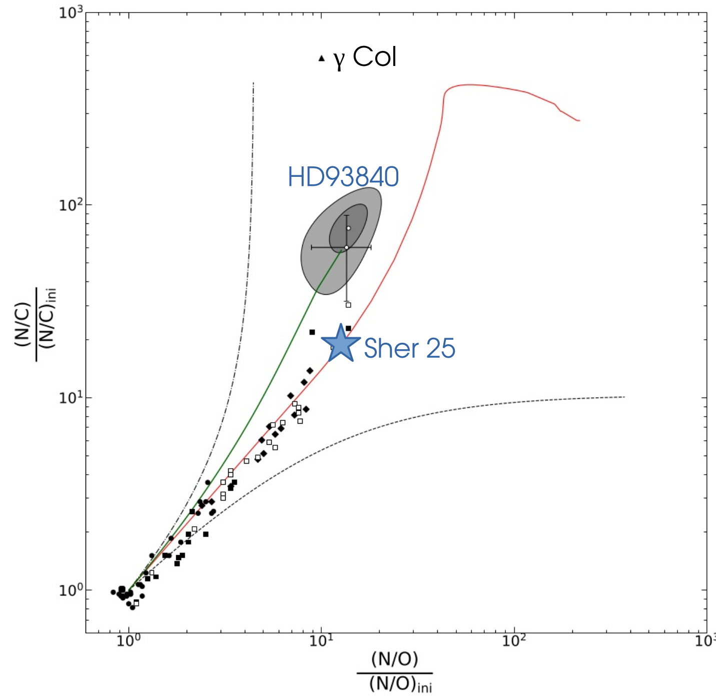

George Sonneborn (Goddard), Jason Pun (NOAO); NASA/ESA

- unrelated to NGC3603 – in foreground, older
- revision:
  ~60M$_\odot$ (Smartt et al. 2002),
  50±10M$_\odot$ (Hendry et al. 2008)

→ ~25M$_\odot$, much closer to Sk–69°202

- bipolar nebula ejection likely from merger ~6600yr ago (Brandner et al. 1997)

Weßmayer et al. 2024, A&A 687, L7:
Runaway BN-SG HD93840
– blue cc-SN progenitor



- impostor of a ~20M$_\odot$ star

→ real mass ~8-11M$_\odot$

- product of binary evolution, overluminosity by factor ~7
- high μ, very advanced in He-burning

Summary

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

- OB-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 for the future:

tight observational constraints for
- massive star evolution
- GCE

- unique outliers