Accurate Quantitative Spectroscopy of OB Stars

H, He I/II and C II/III/IV spectrum

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Outline

- Introduction/Aims
- Models/Observations
- Our Analysis
- Controlling Systematics
- Results
- Summary/Conclusions

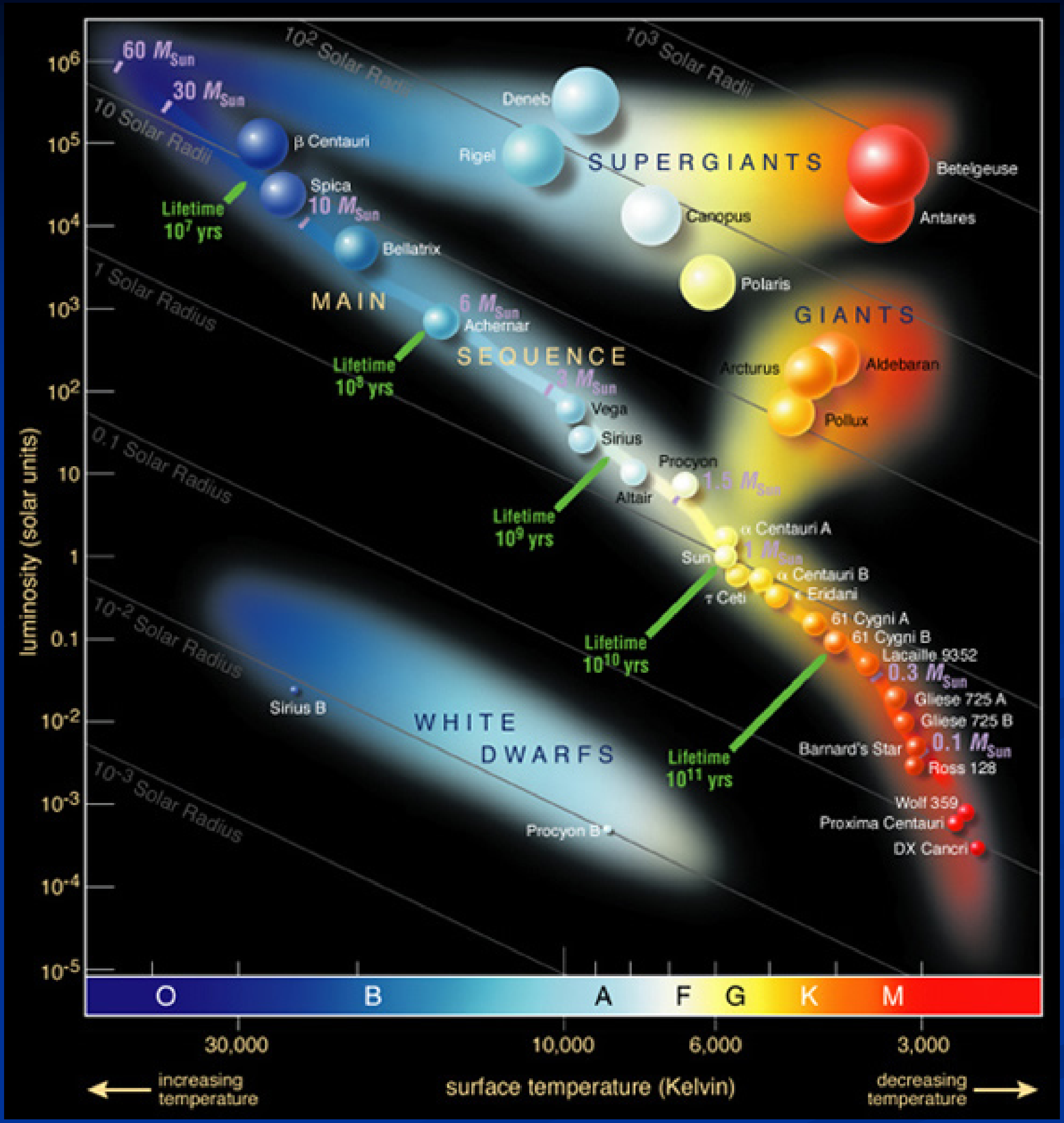
Introduction

- Carbon:
  - one of most abundant ‘metals‘ in universe
  - created in 3α reaction (evolved stars)
  - CNO cycle (H → He massive stars)
  - basis of organic chemistry

- Early-type OB stars:
  - luminous: $\sim 10^4$ L_{sun}
  - young: $\sim 10^7$ yrs
  - massive: ~ 10 M_{sun}

- Carbon abundance OB-stars:
  - present-day abundances (≡ ISM)
  - <u>chemical evolution</u>
  - <u>stellar evolution</u>

  } Galactic & extragalactic


60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
3 M_Sun
1.5 M_Sun
1 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

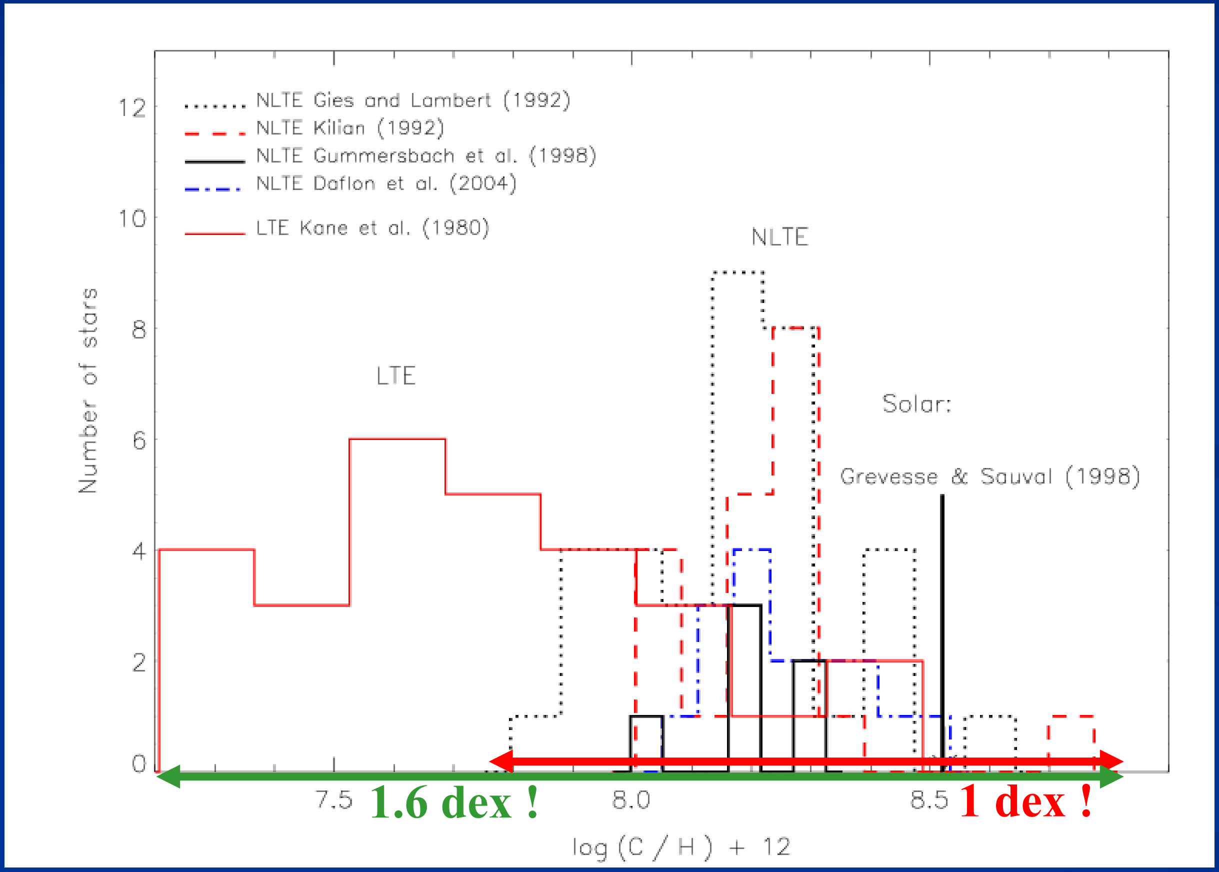
Introduction

$\varepsilon(C)=\log(C/H)+12$

- History of Abundances ε(C) in OB-type Stars
  - Long-standing problem: last ~ 40 years
  - non-LTE effects: not well understood
  - **ε(C II)** **strong lines** **≠ ε(C II)** **weak lines**
  - Strong lines: **C II 4267, 6578/83** Å:
    - very sensitive to non-LTE effects
    - important for extragalactic applications
  - **ε(C II) ≠ ε(C III)**: no ionization equilibrium

Introduction

Carbon Abundances of OB stars in the Solar Vicinity



large scatter

Real from stellar/chemical evolution ??

Artifact from the analysis ??

sub-solar

Also N, O, Mg, Si, etc.

Young OB stars: metal poor ??

Inconsistent with chemical evolution !

Aims of this work

- Solution classical non-LTE problem ε(C) OB-stars
- Construct a reliable C II/III/IV model atom calibrated with Galactic stars
- Special emphasis:

 - selection input atomic data

 - accurate atmospheric parameters (T_{eff}, log g, etc.)

- Broad application of model atom to other objects

Quantitative Spectroscopy

Our Methodology

Theory: synthetic lines

Atomic Physics	⟷	Model Atoms	⟷	Stellar Atmospheres

↕

Observations

Spectra

Line fits

⬇

Chemical Abundances

- Absolute values (Physics)
- Not relative to other stars or Sun

- ➢ Non-trivial process (at all !)
- ➢ Accuracy depends on all steps of analysis
- ➢ Difficult: controlling systematic effects

Theory

- **Model atmospheres:** LTE hydrostatic metal-blanketed in plane parallel geometry (ATLAS9: Kurucz 1993)
- **NLTE line formation:**
  Recent versions of
  DETAIL (Giddings, 1981)
  SURFACE (Butler & Giddings 1985)
- **State-of-the-art model atoms:**
  C II/III/IV (Nieva & Przybilla, 2006d, in prep.)
  H (Przybilla & Butler 2004)
  He I/II (Przybilla 2005)

Hybrid non-LTE approach

(Nieva & Przybilla 2006b, A&A, accepted)

radiative transfer & statistical equilibrium

for non-LTE calculations

Observations

- 6 early-B III-V apparently slow-rotators
- 21500 < T_{eff} < 32000 K
- 3.1 < log *g* < 4.3 dex
- randomly distributed in solar vicinity (< 1 Kpc)
- from associations and field
- Spectra: high S/N FEROS (ESO) data
- Spectra: near-IR (FOCES, SUBARU: Calar Alto, Hawaii) for 2 stars

Our Analysis

Step 1: H, He I/II

Solve the atmosphere

Step 2: Carbon

Fine tunning for atmospheric parameters

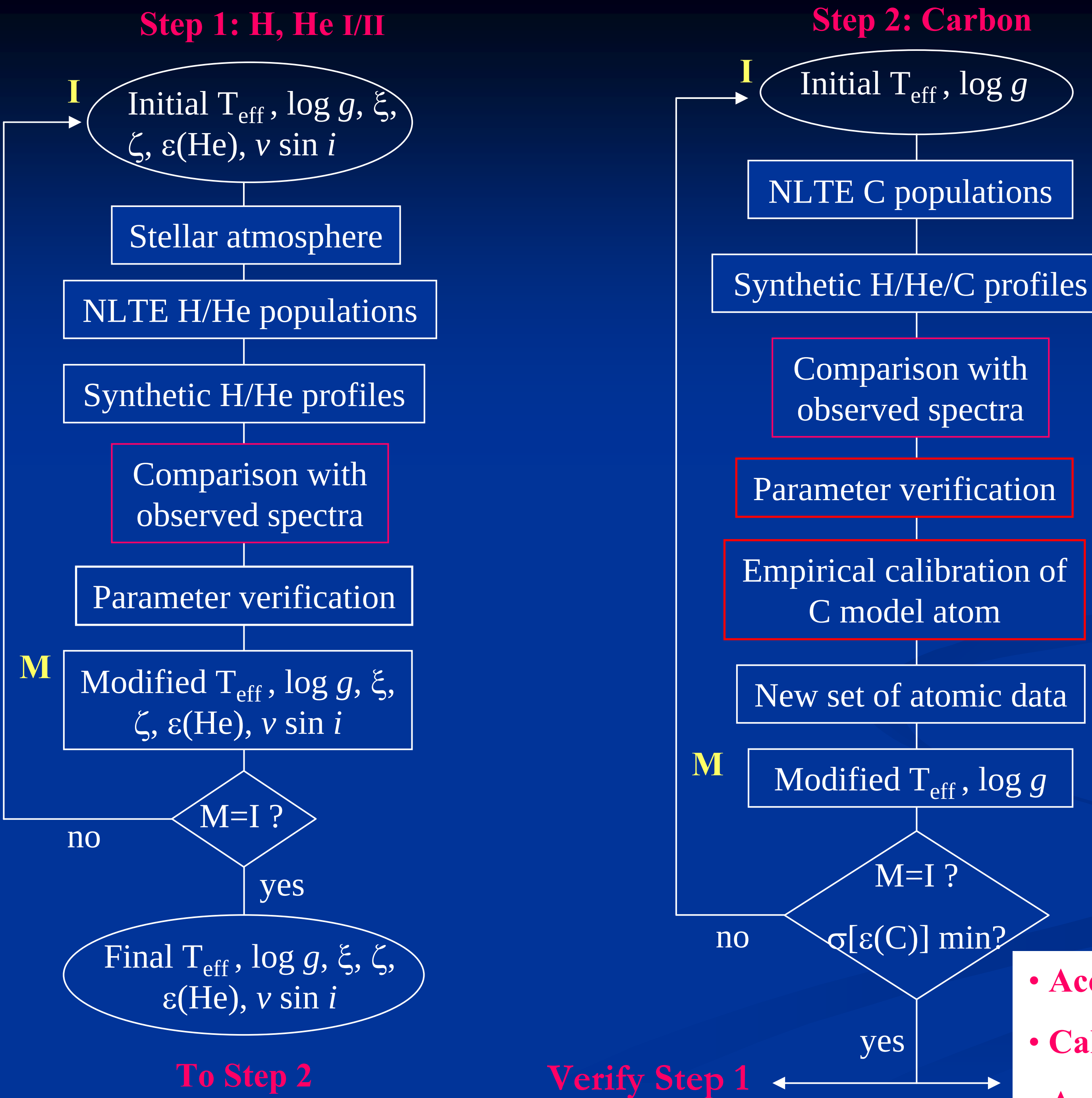
+

Calibration of model atom

No grids !

Detailed analysis for each star !

Our Analysis



No grids !

Detailed analysis for each star !

Variables:

T_{eff} , log *g*, ξ, ζ, ε(C), *v* sin *i*

~200 levels

> 1300 radiat. transitions

> 5300 collis. transitions

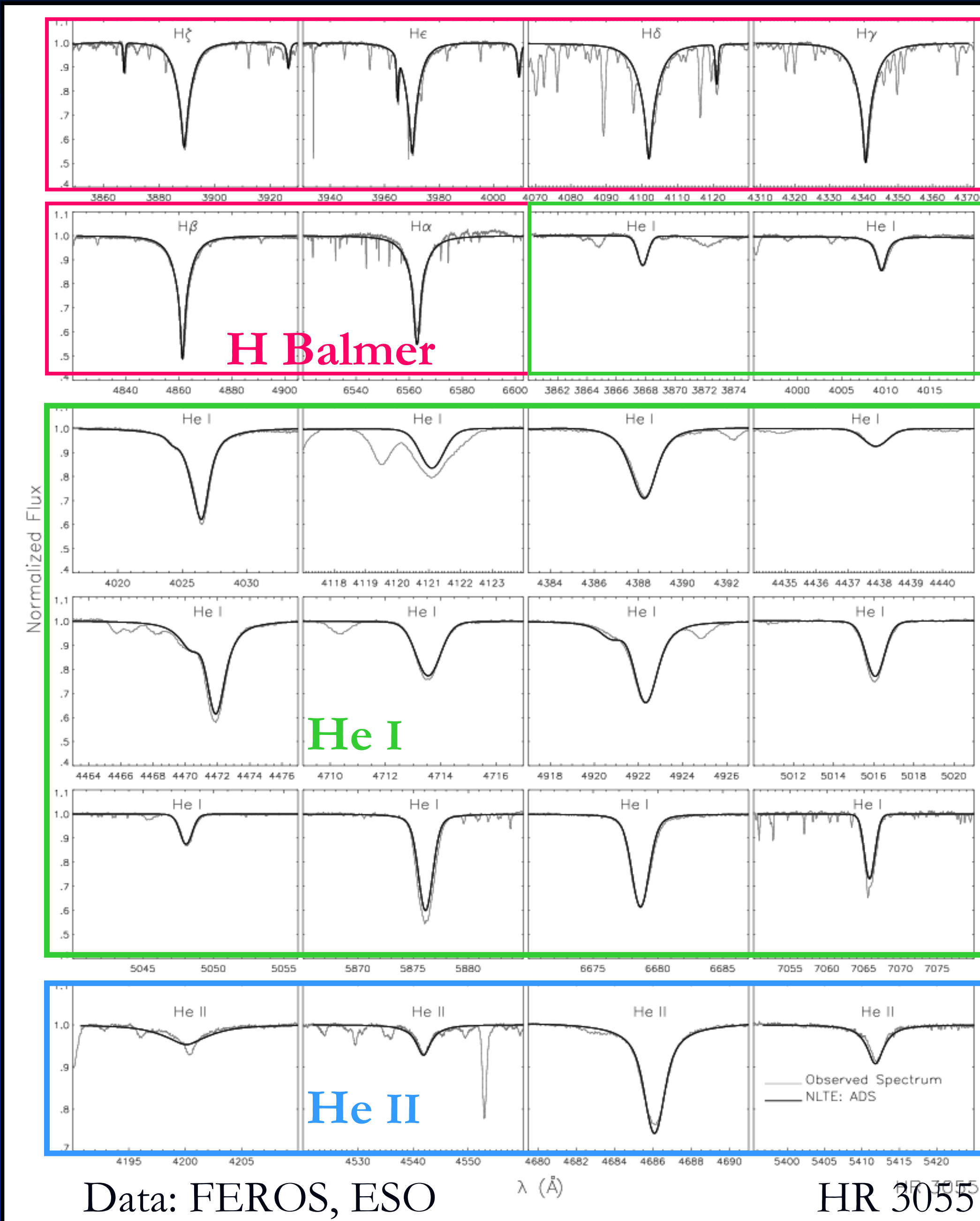
Same procedure for:

- **6 early-B III-V stars**
- **21500 < T_{eff} < 32000 K**
- **3.1 < log *g* < 4.3 dex**

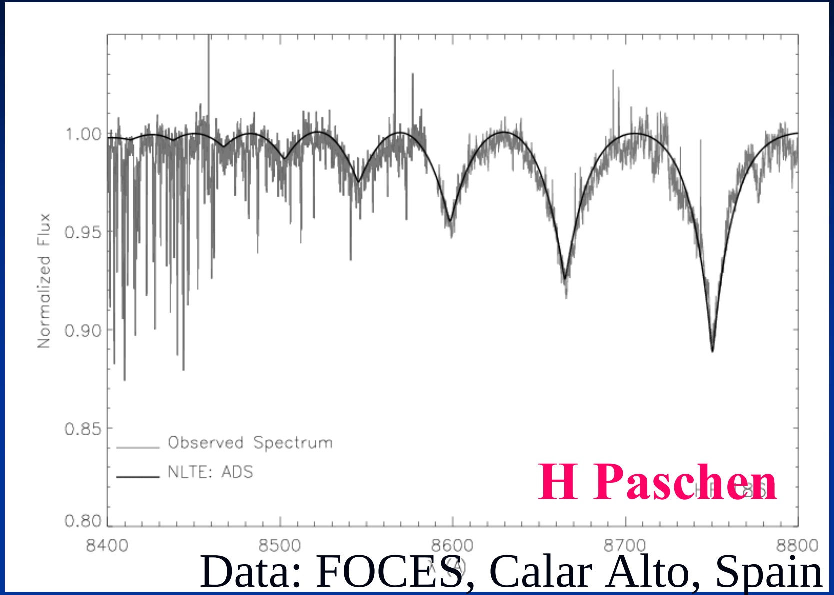
- **Accurate Stellar Parameters**
- **Calibrated C model for 1 Star**
- **Accurate Carbon Abundance**

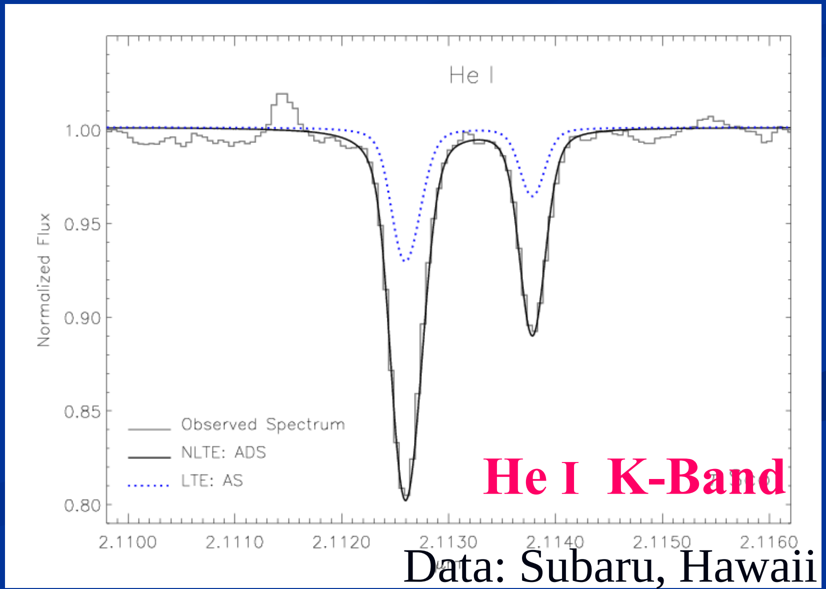
Simultaneous fits to all mesurable H/He lines

Visual



Near-IR

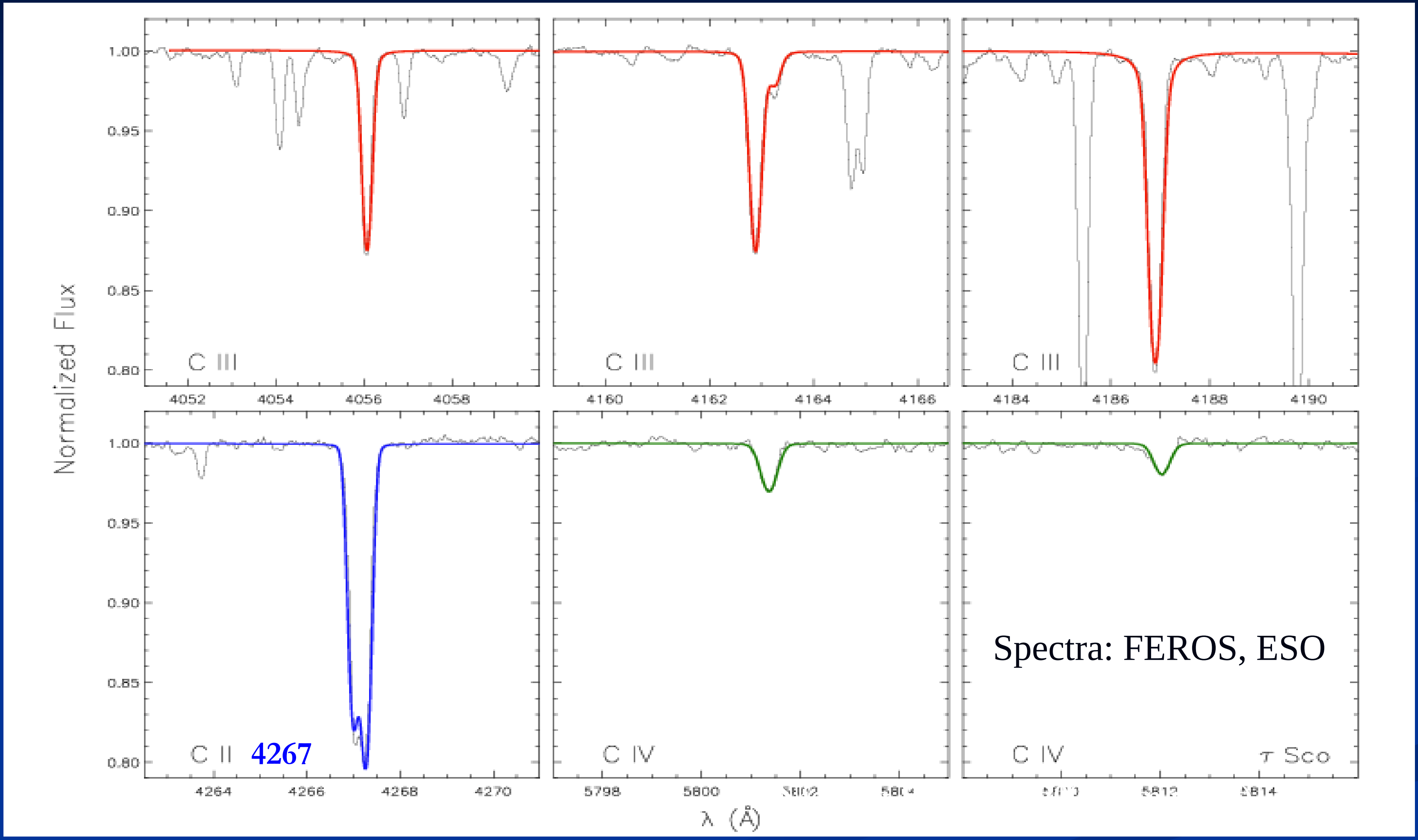




Nieva & Przybilla, 2006b, A&A, accepted

Carbon: quality of spectra/fits

up to 40 lines !!



Abundances from line profile fits (similar values)

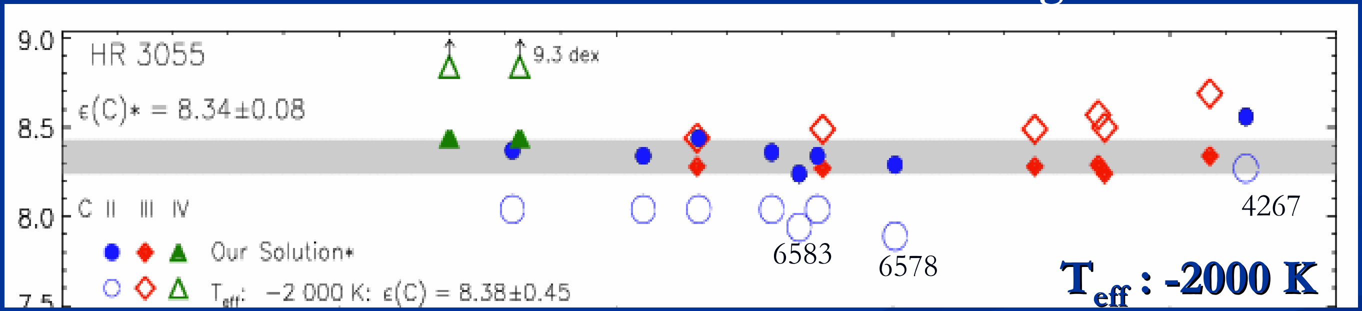
Sensitivity of Carbon Abundance to Atmospheric Parameters

Our solution for HR 3055:
T_{eff} = 31200±200 K
log *g* = 3.95±0.05 dex

Typical systematic discrepancy from the literature in T_{eff}

Weak lines — Strong lines

ε(C)



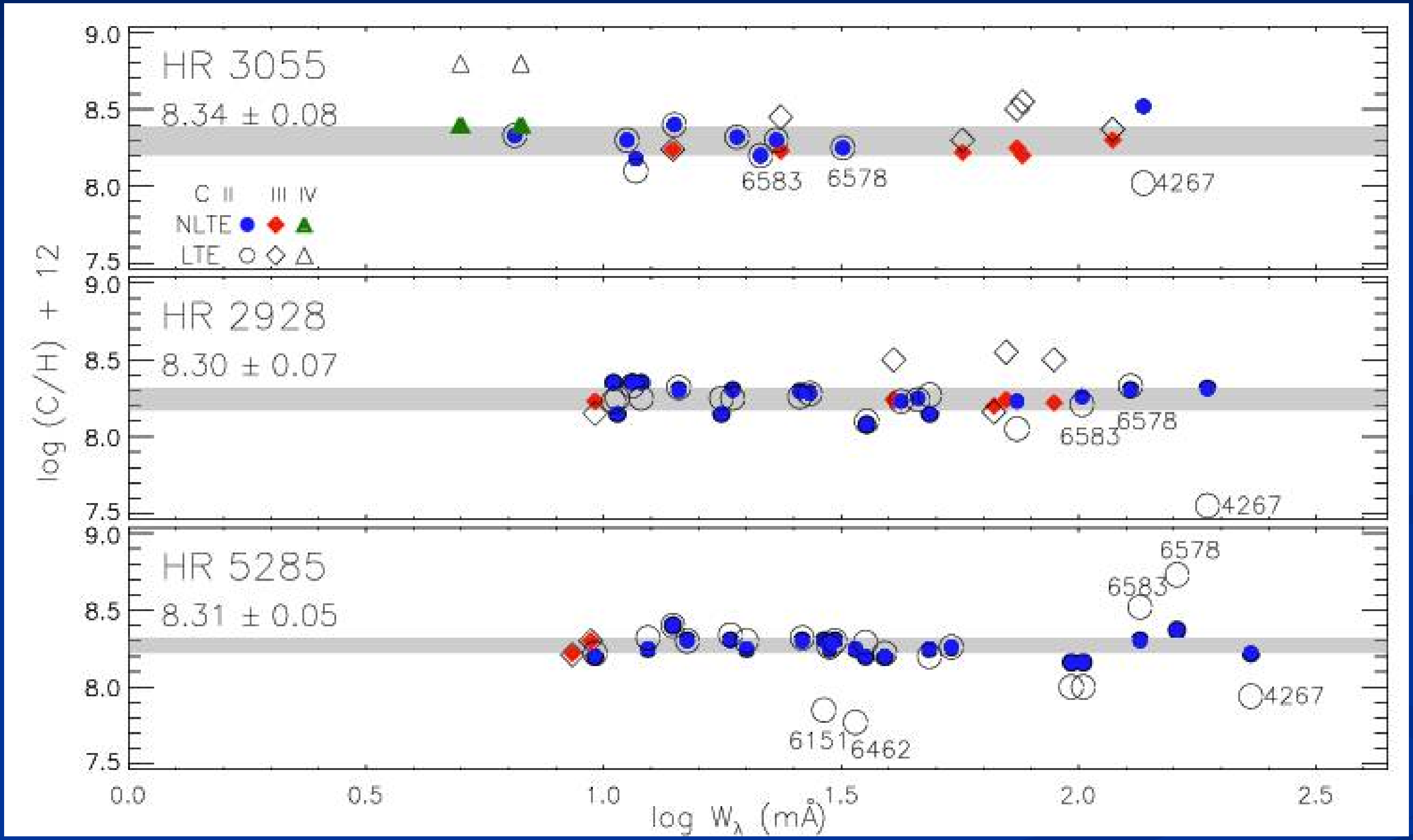
log W_λ

C IV up to +1.1 dex!
C III up to +0.35 dex!
C II up to -0.35 dex!

Discrepancies increase with ≠ atomic data !!

Results: Non-LTE C abundances from individual lines

Non-LTE vs. LTE



Solution to C II/III/IV and C II/III ionization equilibrium even for lines very sensitive to non-LTE effects !!

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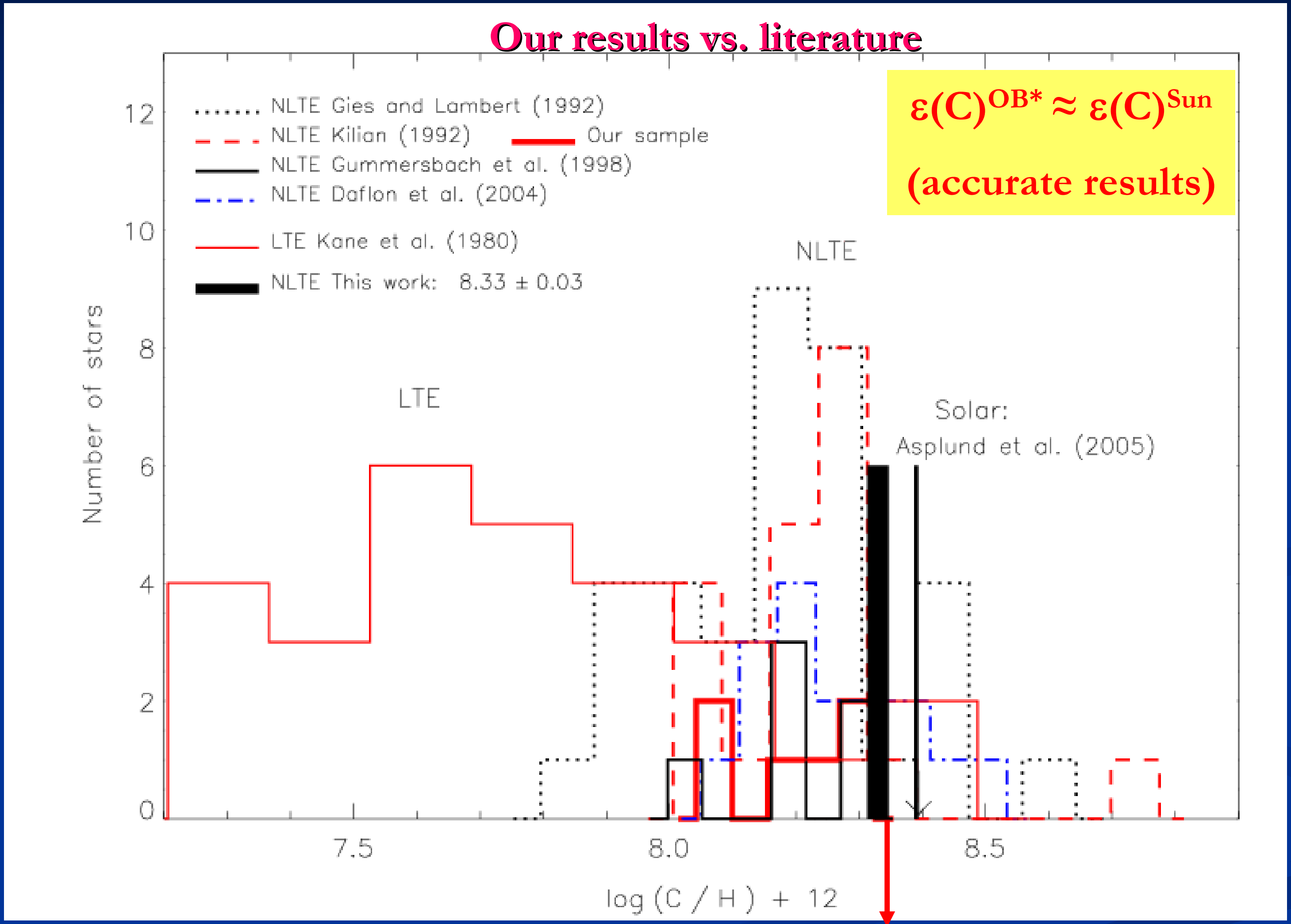
Accurate Present-Day Carbon Abundances in the Solar Vicinity



$\varepsilon(C)^{OB*} = 8.33 \pm 0.03$ (only uncertainties)

$\varepsilon(C)^{Sun} = 8.39 \pm 0.05$ (total error)

avoids systematic errors in atmospheric parameters and atomic data

Summary

- State-of-the-art C II/III/IV model atom empirically calibrated (for NLTE calculations)
- Critically selected input atomic data
- Highly accurate stellar parameters/C abundances almost free of systematic errors
- Metal abundances (C,N,O,Si,Mg,Al,...) of different kind of objects: HVS, EHS, SdBs, LMC (see References)

Conclusions

- Solution to C II/III/IV ionization equilibrium
- Solution to classical C II λλ 4267/6578-82 Å problem
- possible applications to fast-rotators and extragalactic objects
- Unprecedent and highly uniform C abundance for 6 early B-type stars (nearly solar!): agreement with chemical evolution for the first time!

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