NLTE analysis of spectra: FG stars

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FG stars

5000 < $T_{eff,Sun}$ < 7000 K

3 < log g_{Sun} < 4.5

… -5 < [Fe/H] < -0.3

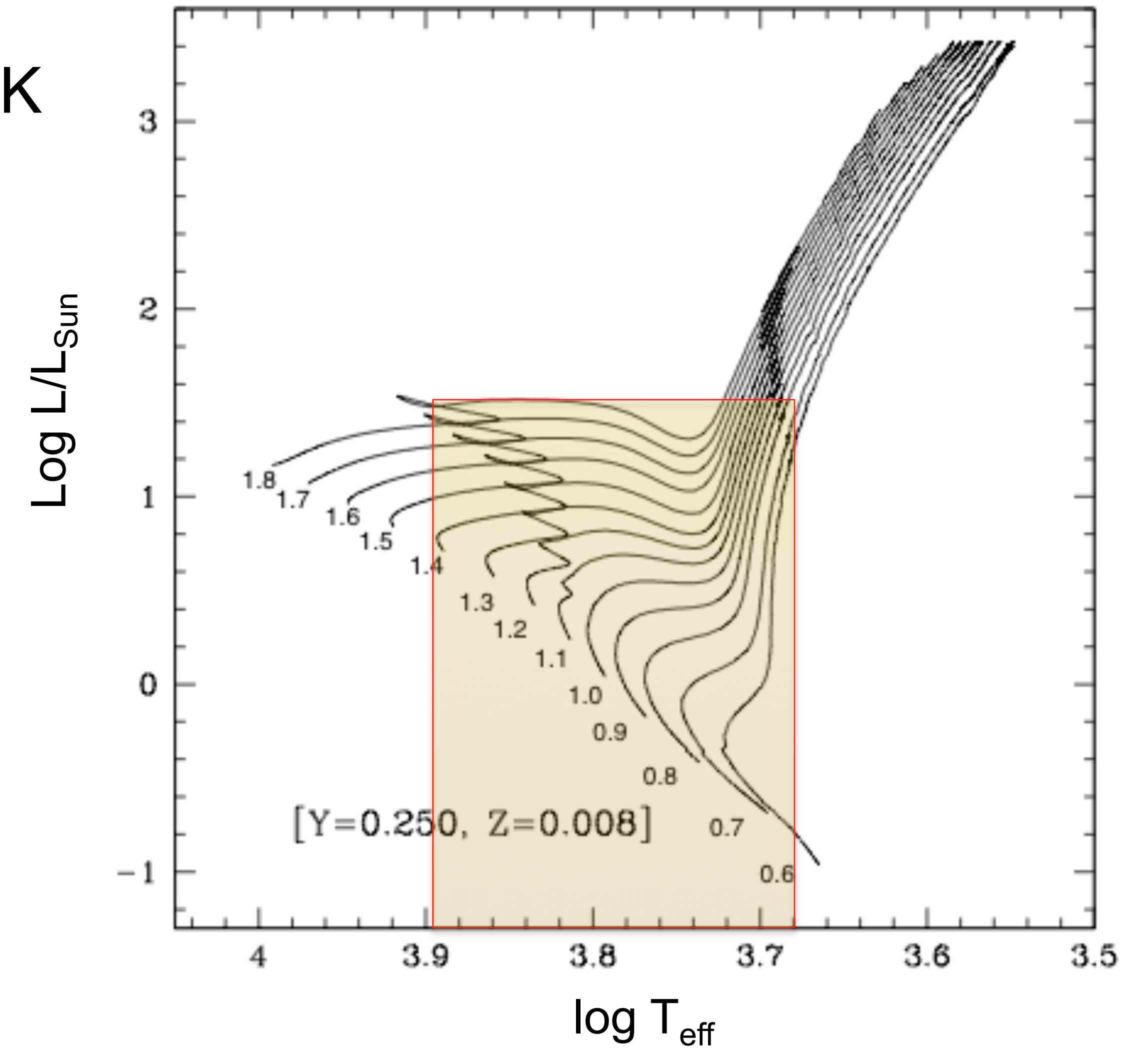


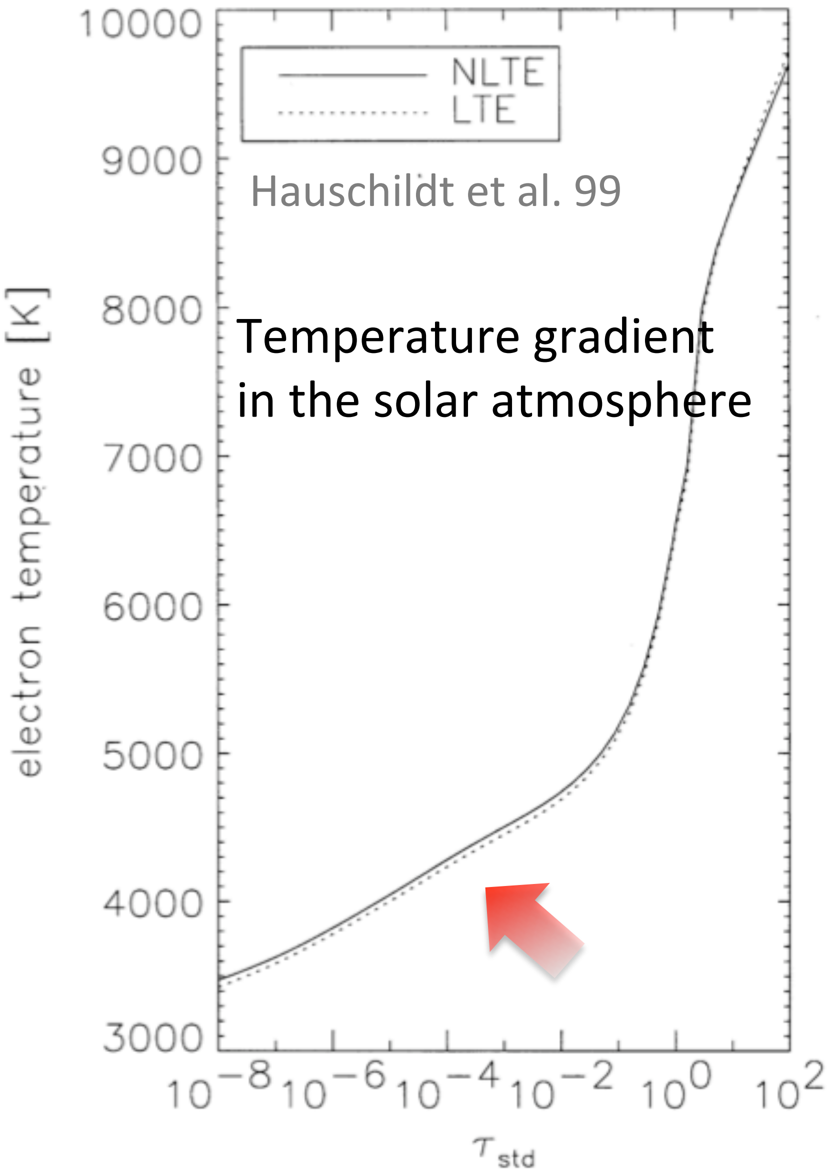
Fig. 5. Evolutionary tracks (same composition as Fig. 4) for low-mass models up to the RGB-tip.

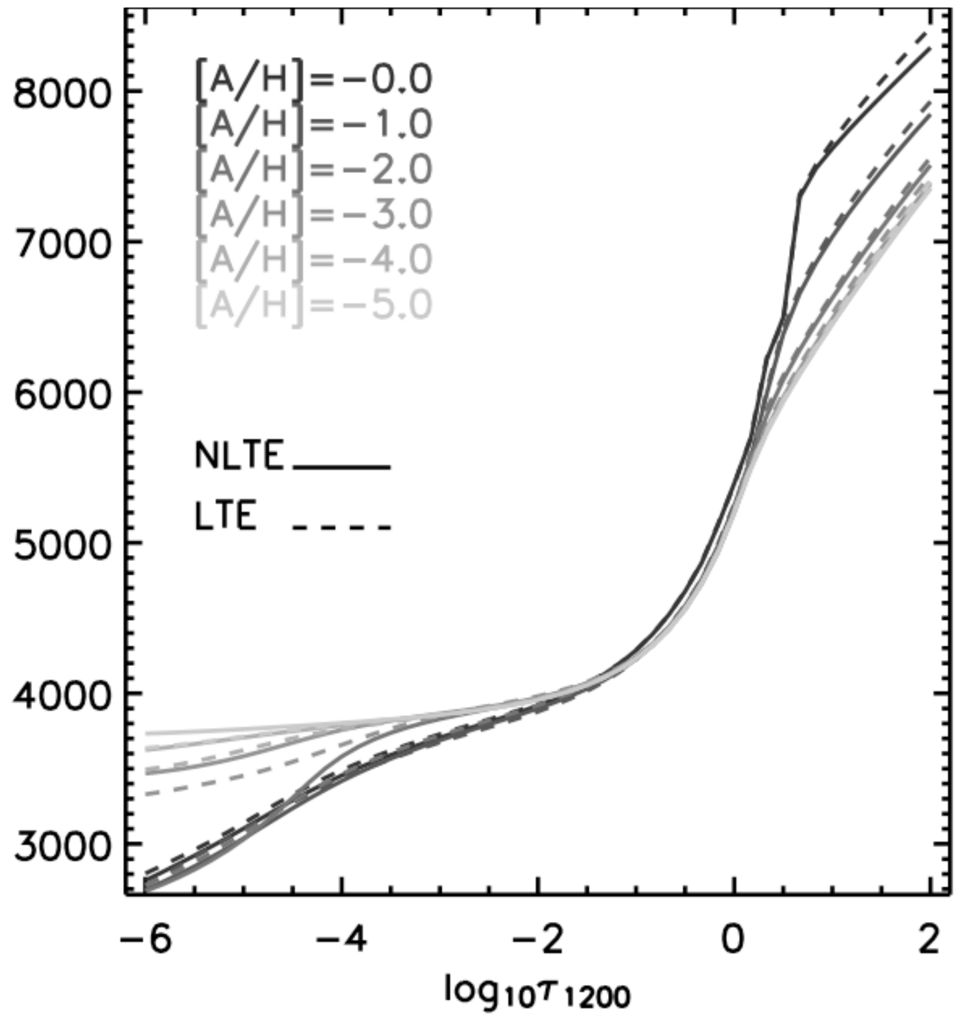
NLTE in FG stellar atmospheres

The key questions to address

- What **atoms/molecules** are sensitive to NLTE conditions?
- Are these **species** important for the atmospheric structure (i.e. opacity, donors of electrons)?

NLTE and atmospheric structure





NLTE and line formation

NLTE is crucial for modelling spectral lines with the goal to determine abundances:

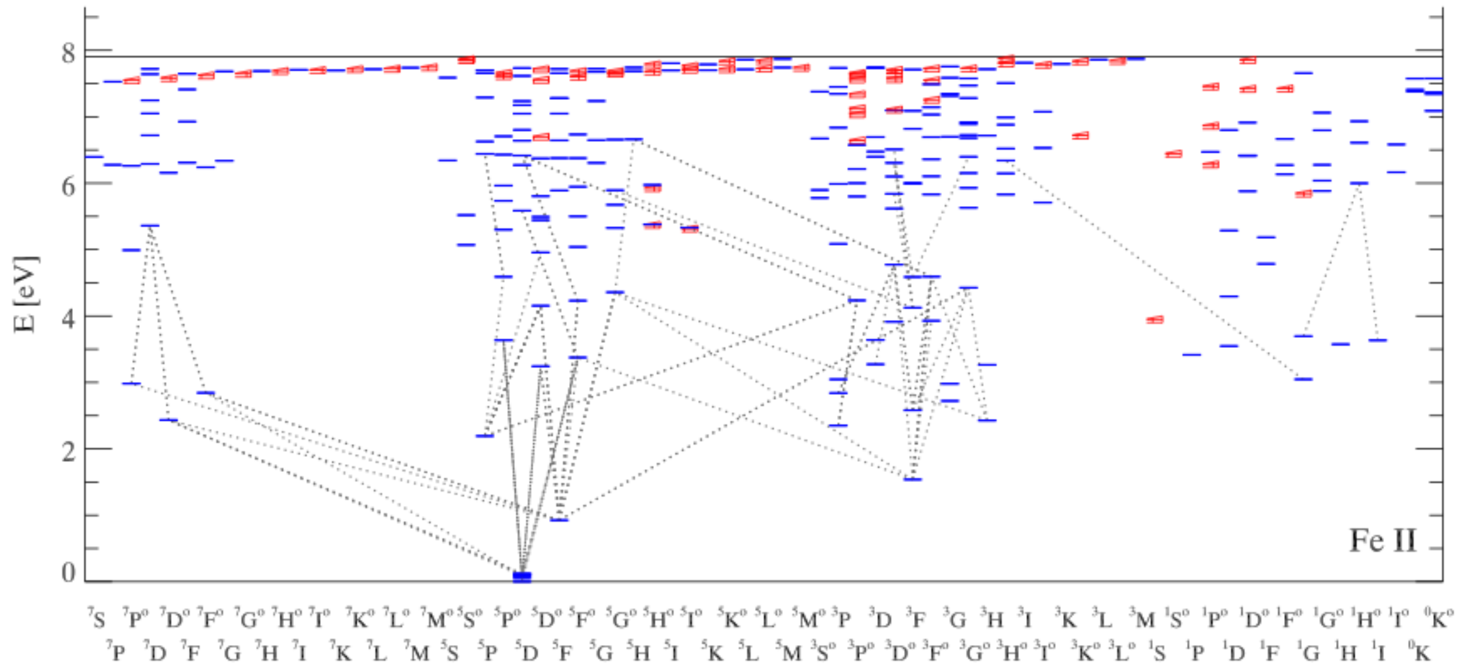
- Li, C, N, O (Asplund et al. 05)
- K, Na, Mg, Al, Si (Gehren et al. 06)
- Mn, Fe, Co, Ni (Korn et al. 03, Bruls et al. 93, Bergemann 08, Bergemann et al. 2011, Bergemann et al. 2012)
- Sr, Ba, Eu, Sr, Pr (Bergemann et al. 2012, Mashonkina et al. 08)

Iron - a key element in astrophysics

- a proxy of stellar metallicity [Fe/H]
- used to derive effective temperature and surface gravity

  the method of **excitation-ionization balance** (S. Sousa's talk)

- Fe I and Fe II have, by far, the largest number of lines in a spectrum of a typical F-type star, thus enabling rigorous tests of the models

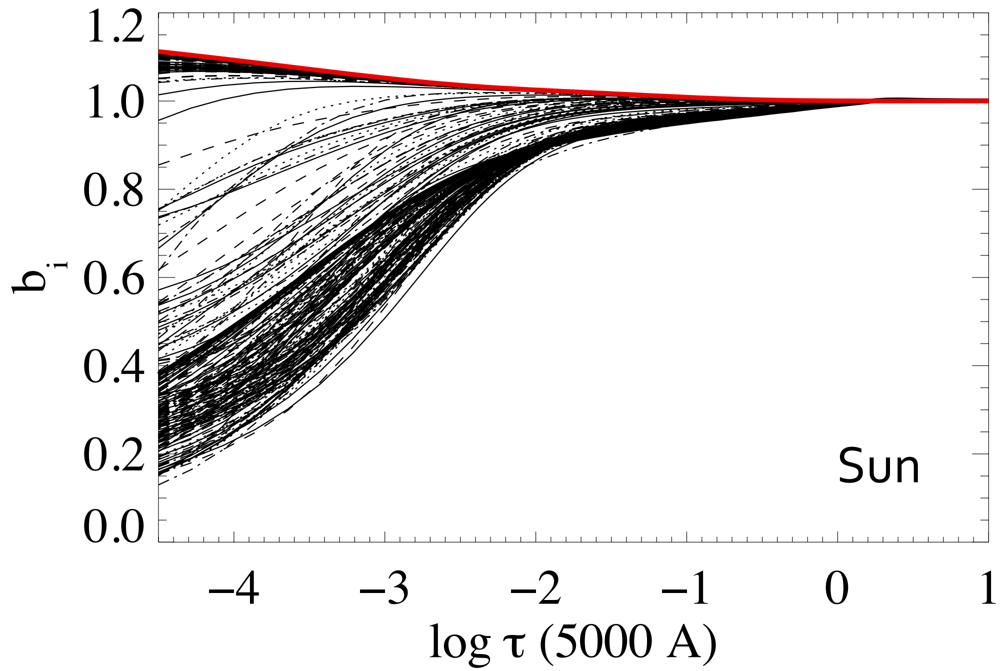


NLTE: excitation balance of Fe

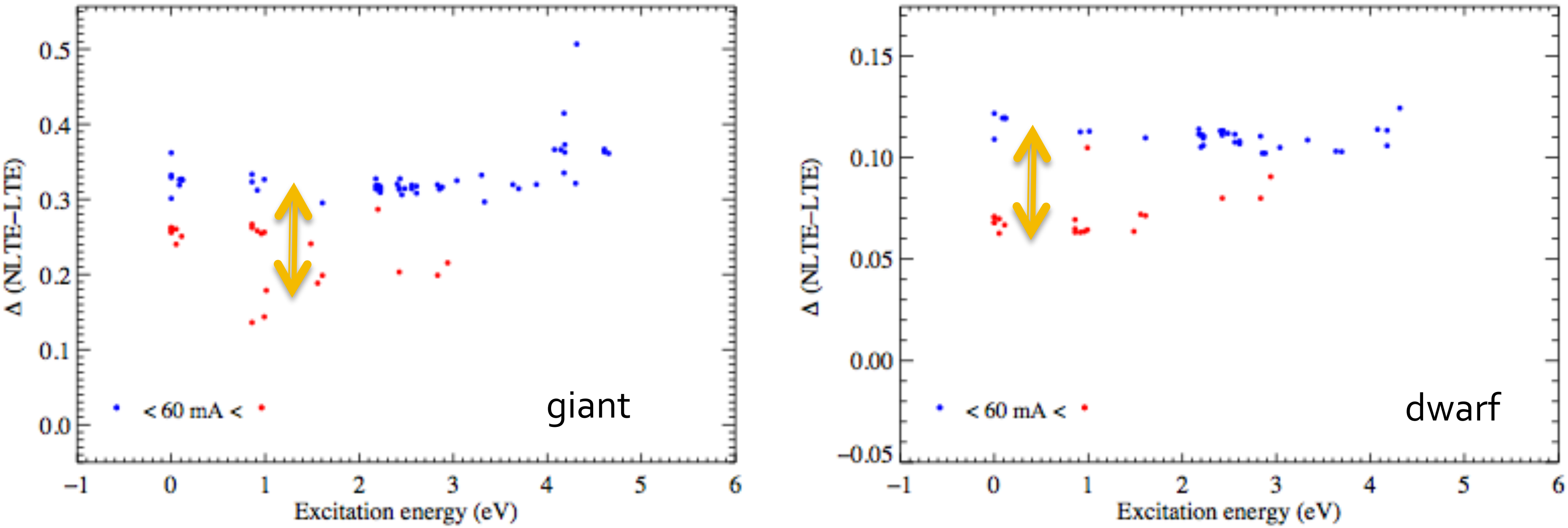
$b_i = N^{NLTE} / N_{LTE}$ Level departure coefficients

Fe I is very sensitive to NLTE effects in FGK atmospheres:

- overionization due to strong non-local UV radiation field
- IR over-recombination



NLTE: excitation balance of Fe

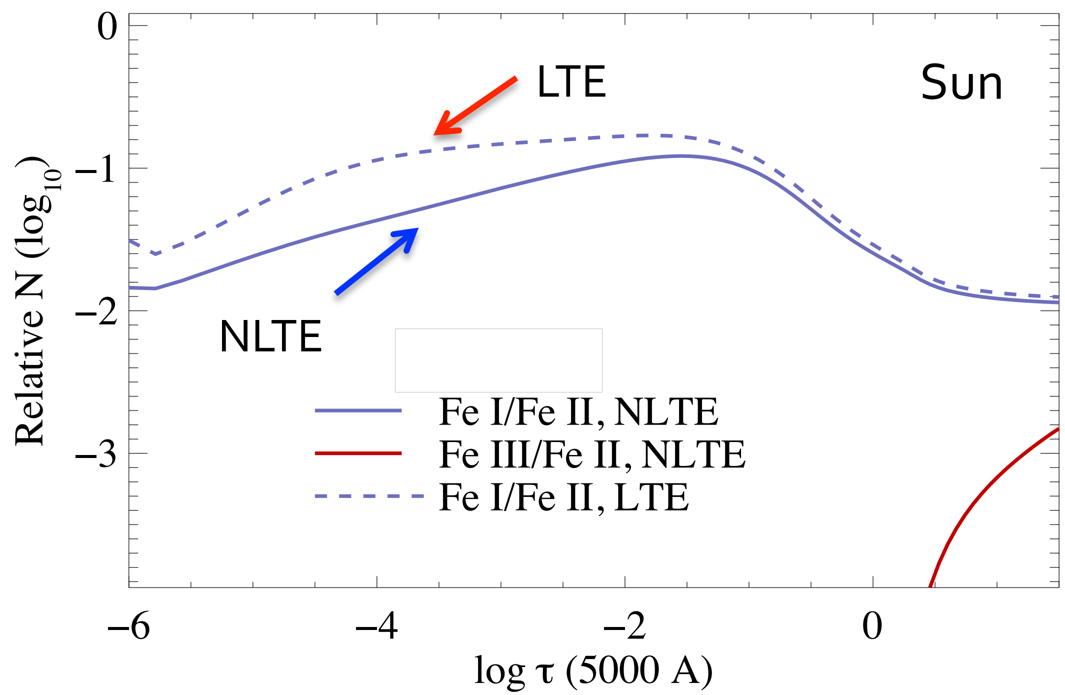


Excitation balance of Fe I is not given by the Saha-Boltzmann statistics → **wrong T_{eff} in LTE**

NLTE: ionization balance of Fe

LTE overestimates ionization fraction of Fe I/ Fe II → major impact on [Fe/H] and log g

- **[Fe/H],** determined either from Fe I or Fe II
- **log g**, since [Fe II/Fe I] – indicator of surface gravity

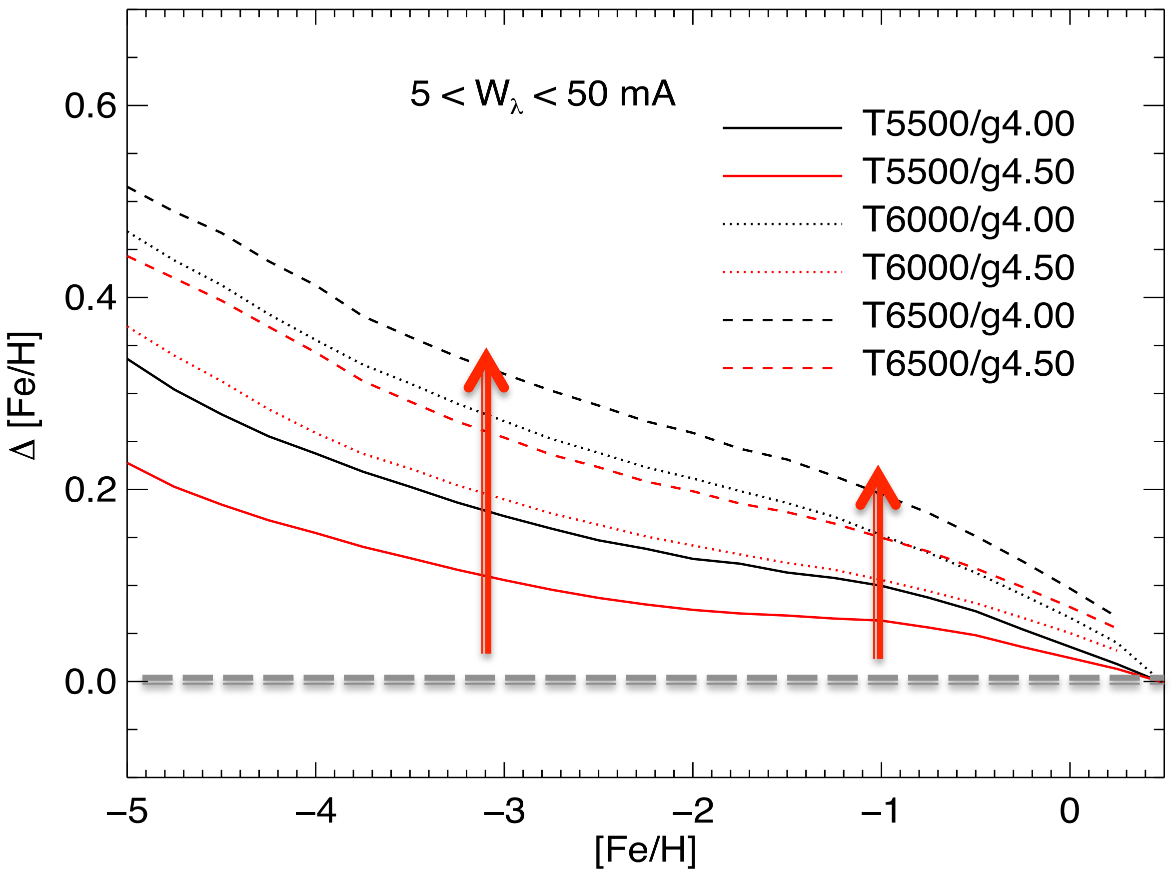


NLTE: abundances

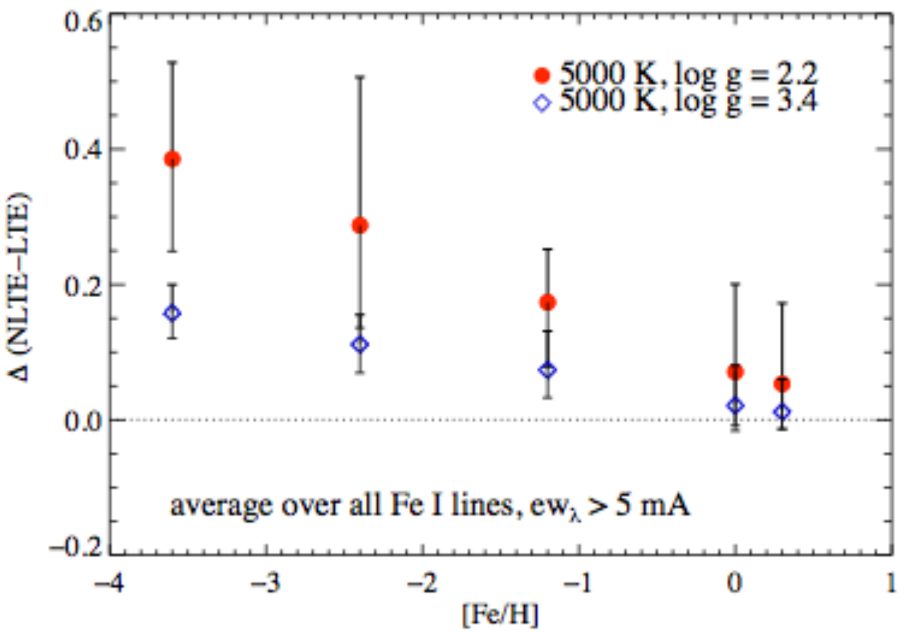
Δ = log A (non-LTE) – log A (LTE)

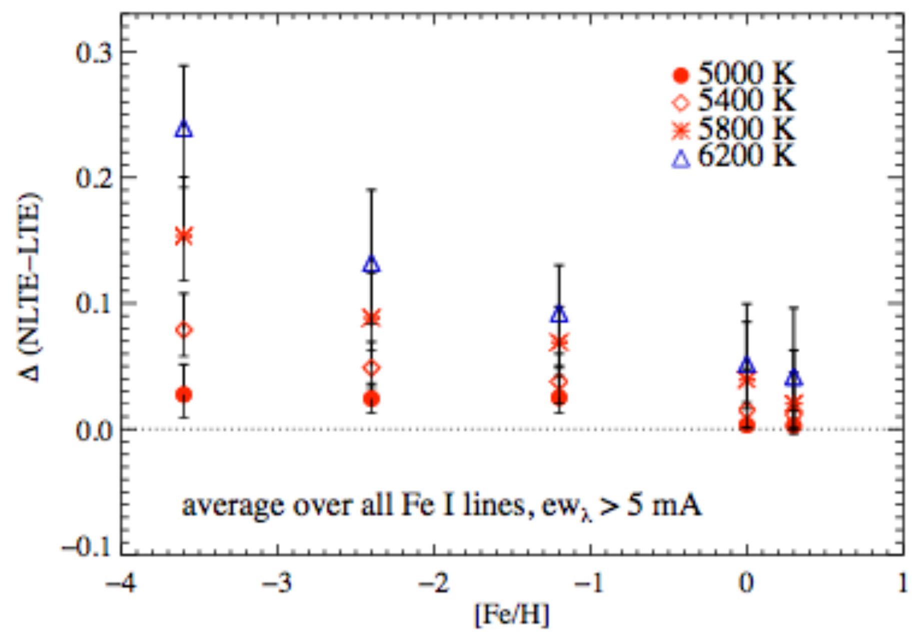
NLTE abundance correction Δ

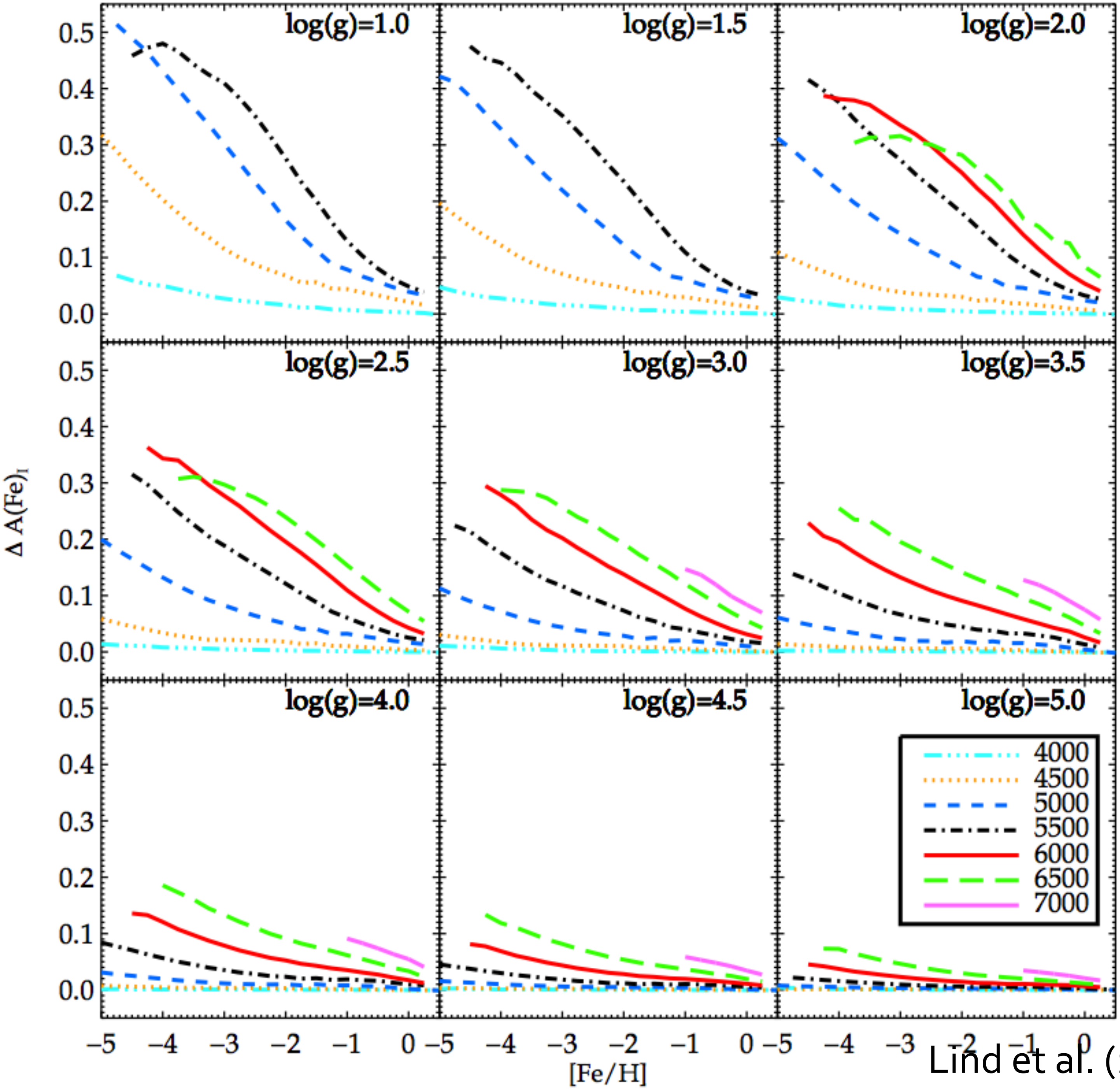
- ↑ with ↓ [Fe/H], log g
- ↑ with ↑ T_{eff}



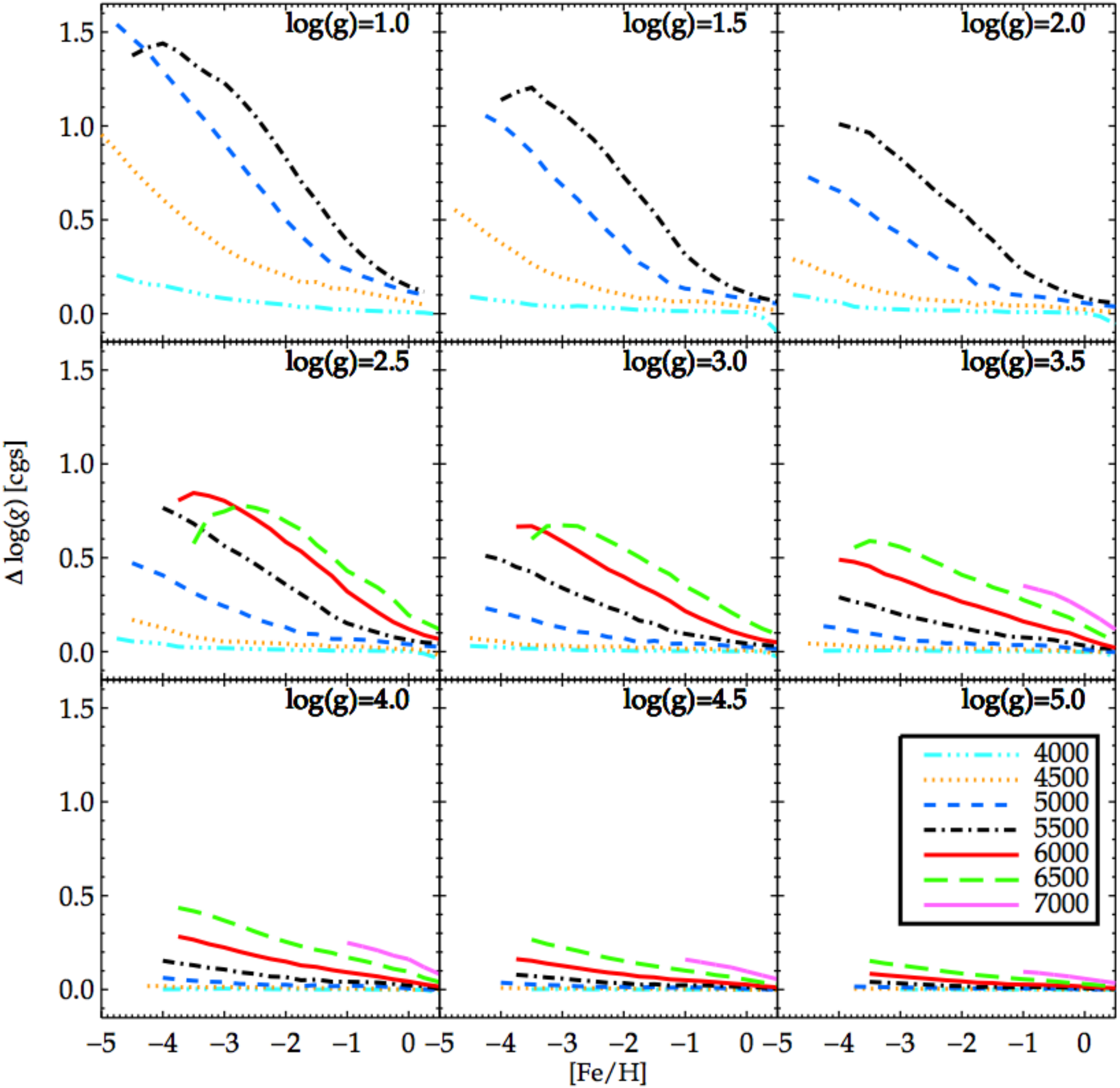
Δ = log A (non-LTE) – log A (LTE)



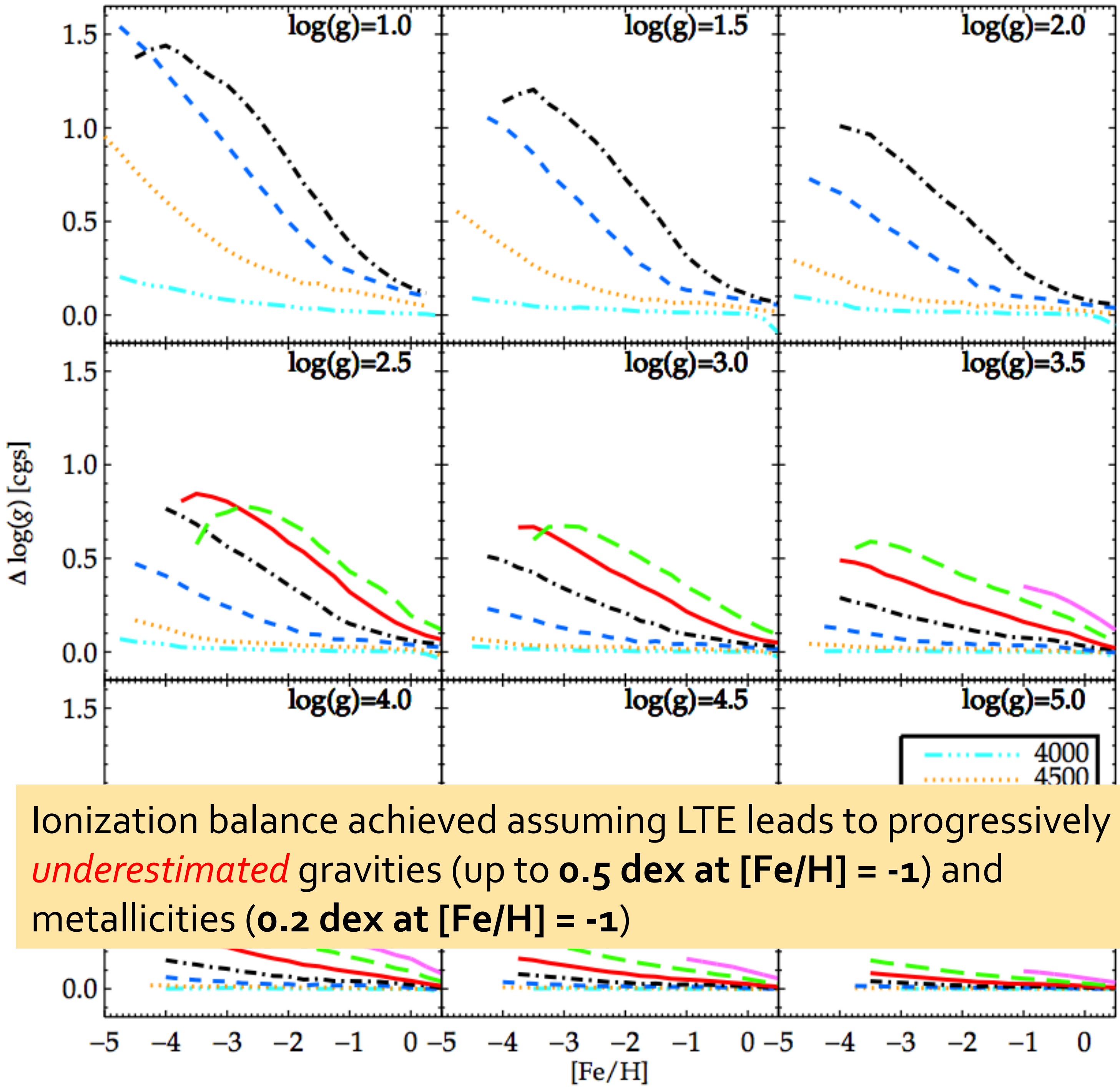




Lind et al. (2012)



log(g)=1.0
log(g)=1.5
log(g)=2.0
log(g)=2.5
log(g)=3.0
log(g)=3.5
log(g)=4.0
log(g)=4.5
log(g)=5.0
Δ log(g) [cgs]
[Fe/H]
4000
4500
5000
5500
6000
6500
7000

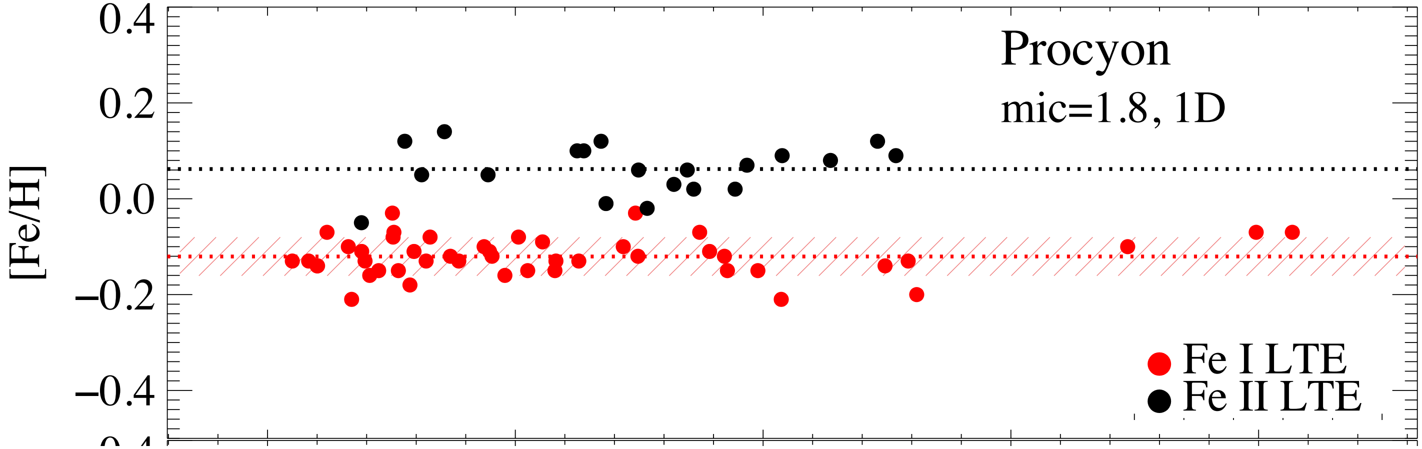


Ionization balance achieved assuming LTE leads to progressively *underestimated* gravities (up to **0.5 dex at [Fe/H] = -1**) and metallicities (**0.2 dex at [Fe/H] = -1**)

Metallicity = Fe abundance

Procyon: visual binary, astrometric mass + interferometric ang. diameter

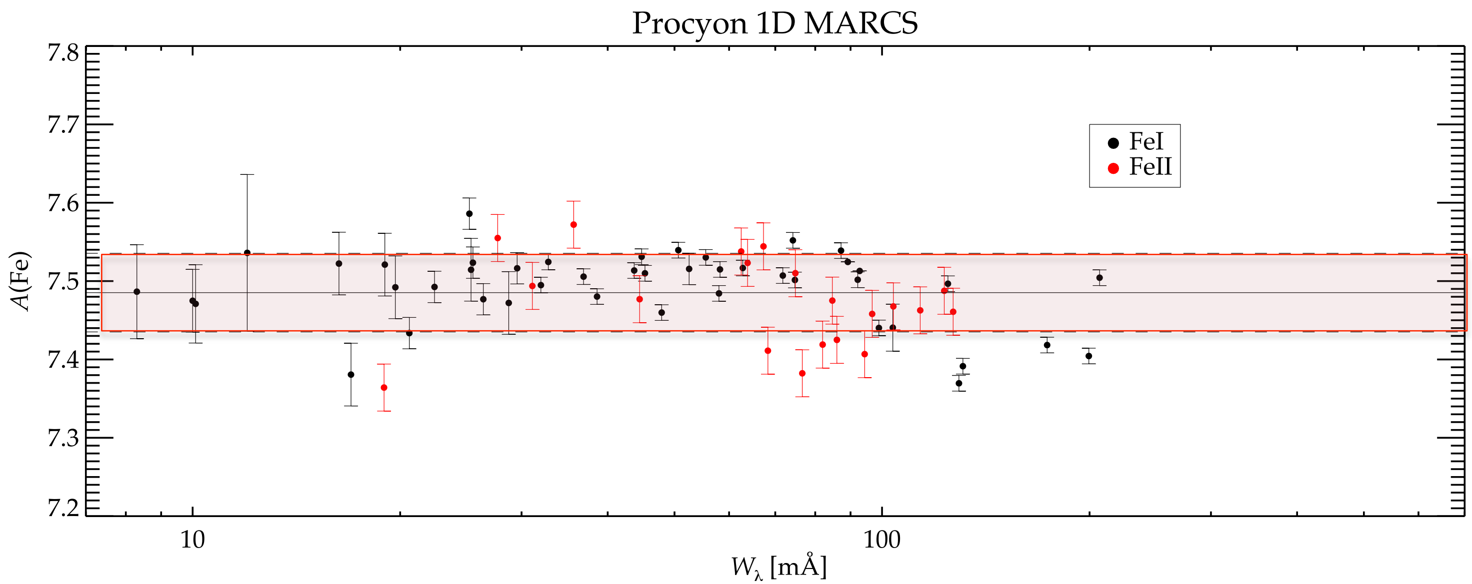
- super-solar metallicity (if LTE & Fe II) [Fe/H] = + 0.08 … + 0.12
- sub-solar metallicity (if LTE & Fe I) [Fe/H] = - 0.12 … - 0.03



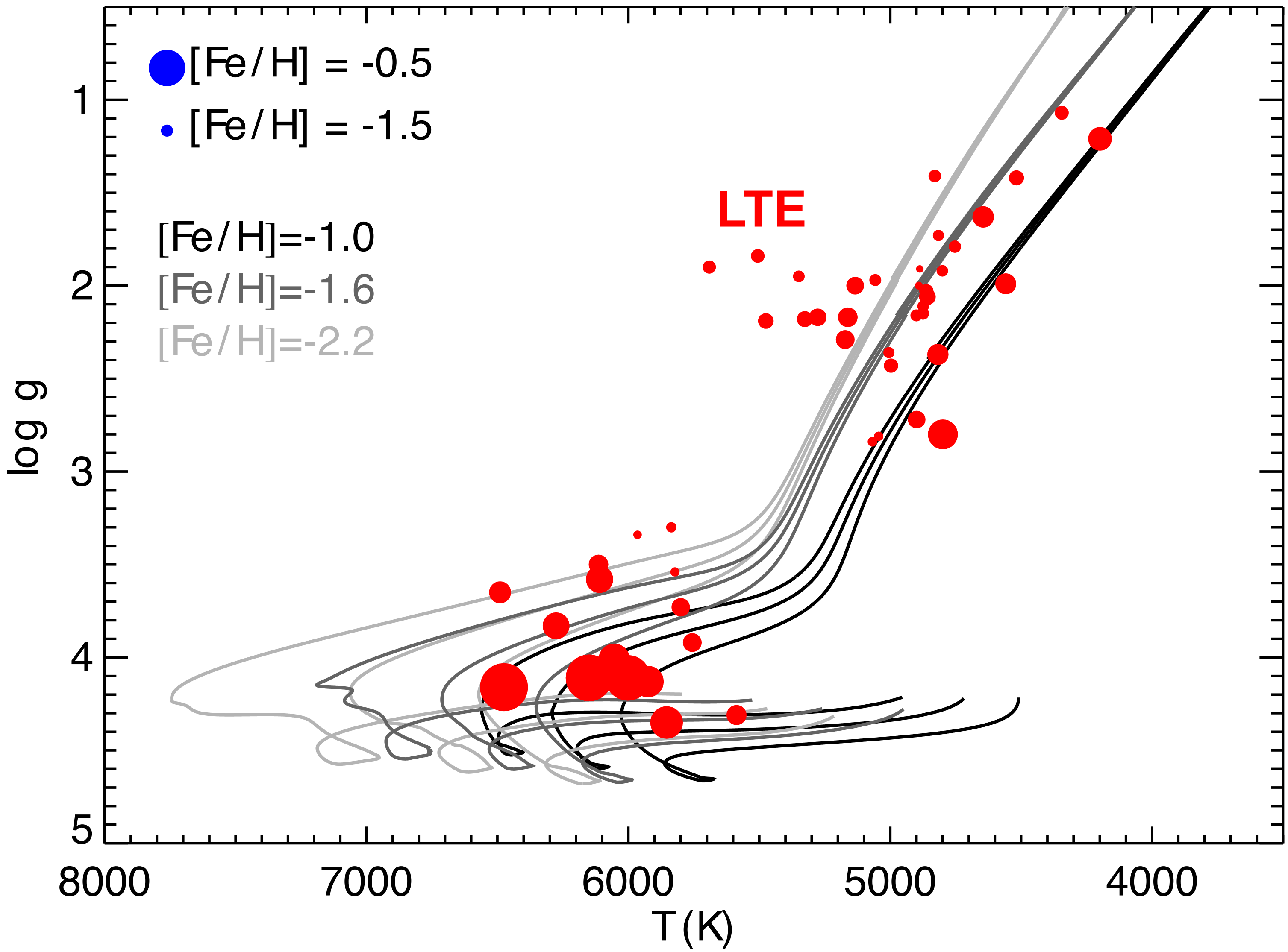
Metallicity = Fe abundance

Procyon: visual binary, astrometric mass + interferometric ang. diameter

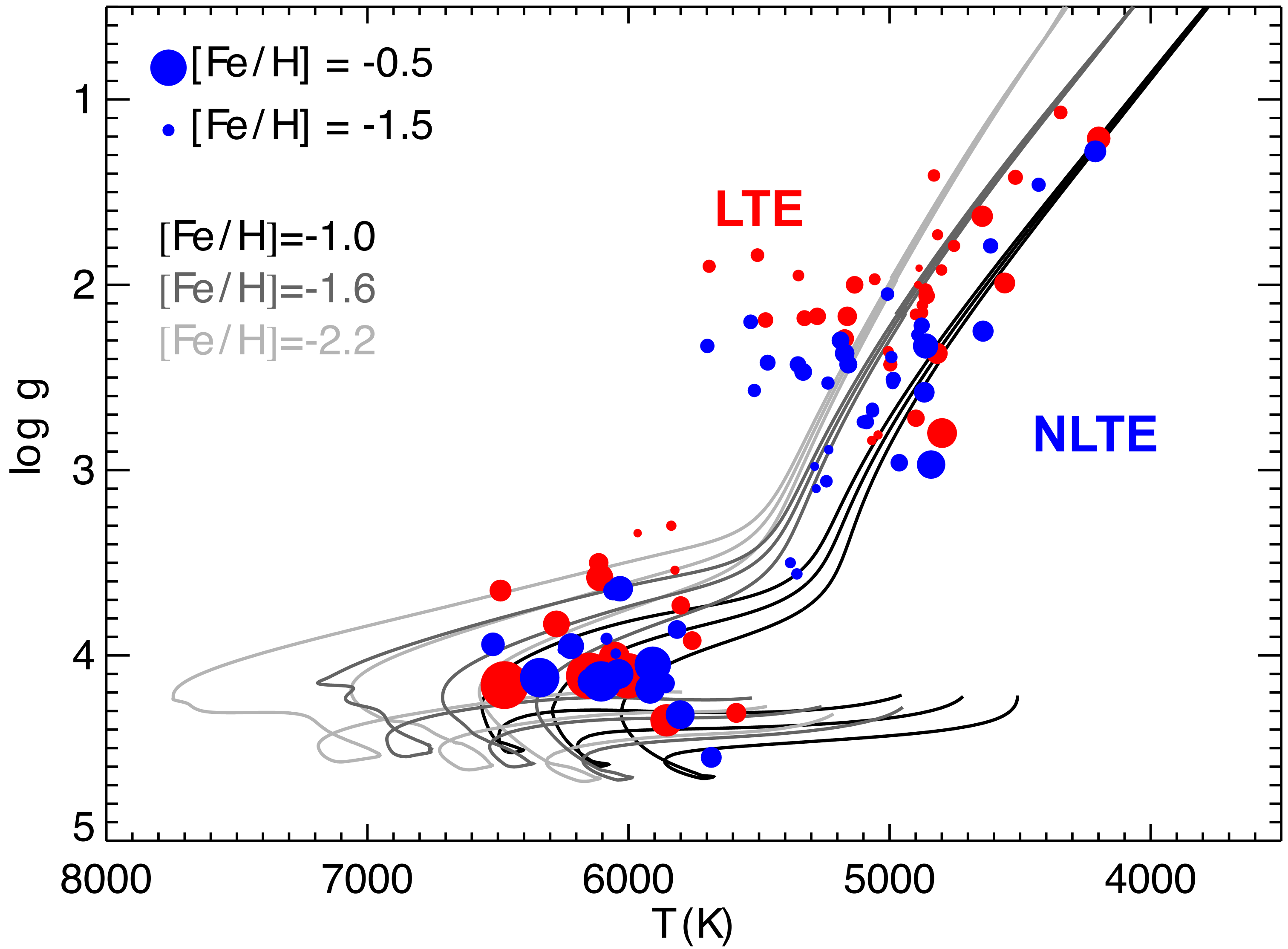
Metallicity from Fe I and Fe II lines: [Fe/H] = -0.03



Stellar parameters



Stellar parameters



Abundances of trace elements

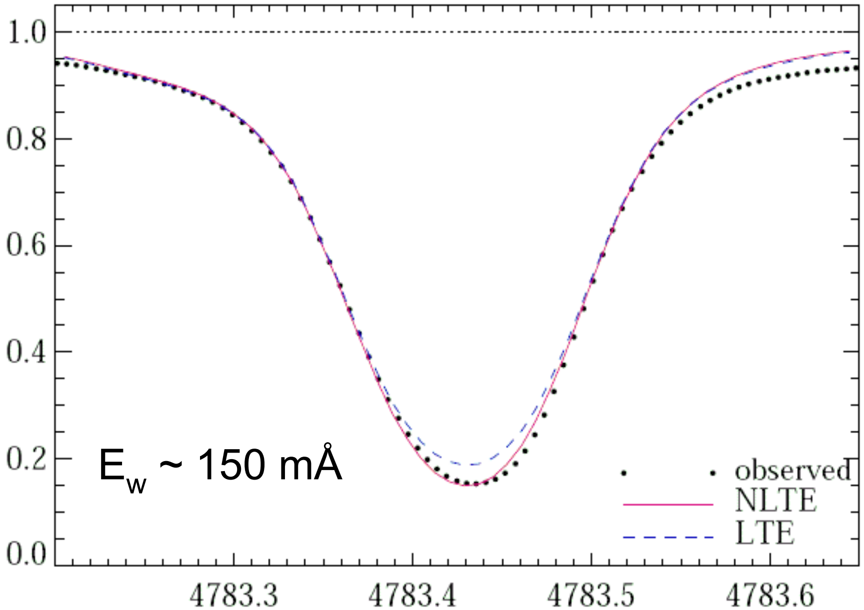
$\Delta = \log A\,(\text{non-LTE}) - \log A\,(\text{LTE})$

NLTE abundance corrections are a function of T_{eff} , log g, and [Z], but also depend on the atomic properties:

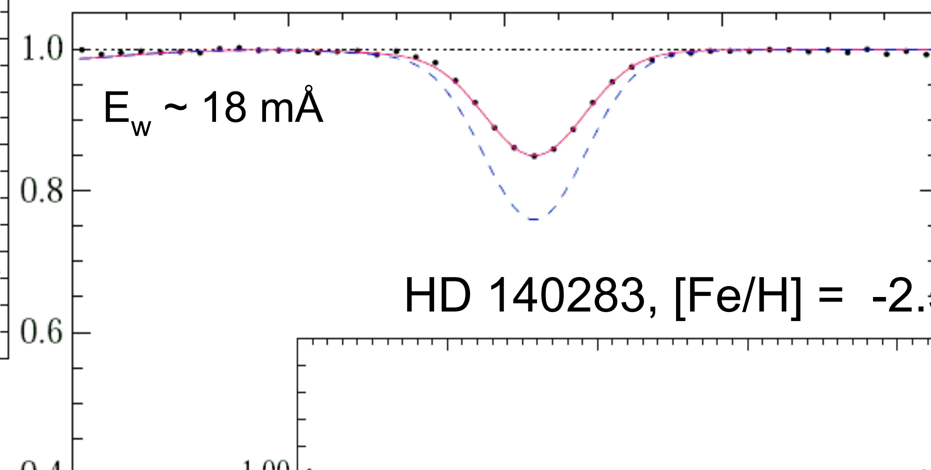
- Ti I: $-0.05 < \Delta < +0.3$
- Mn I : $-0.1 < \Delta < +0.5$
- Co I: $-0.1 < \Delta < +0.7$

Mn in NLTE

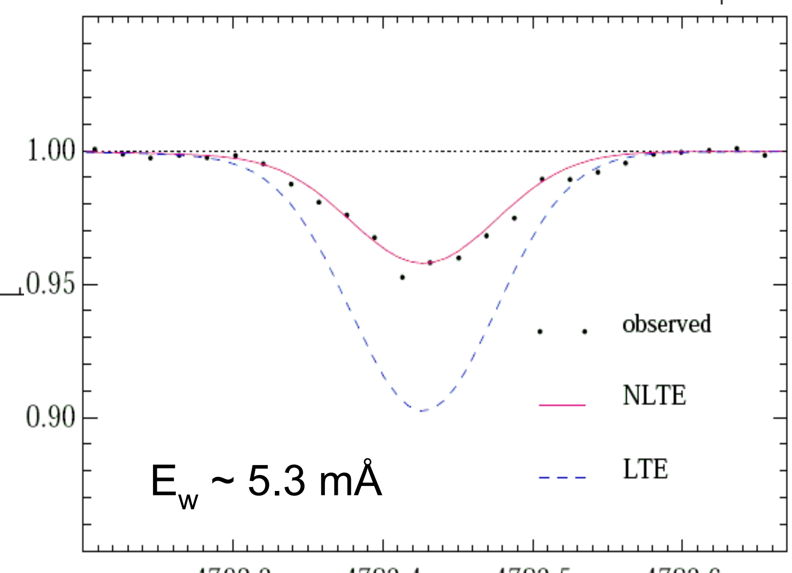
The Sun



HD 34328, [Fe/H] = -1.5



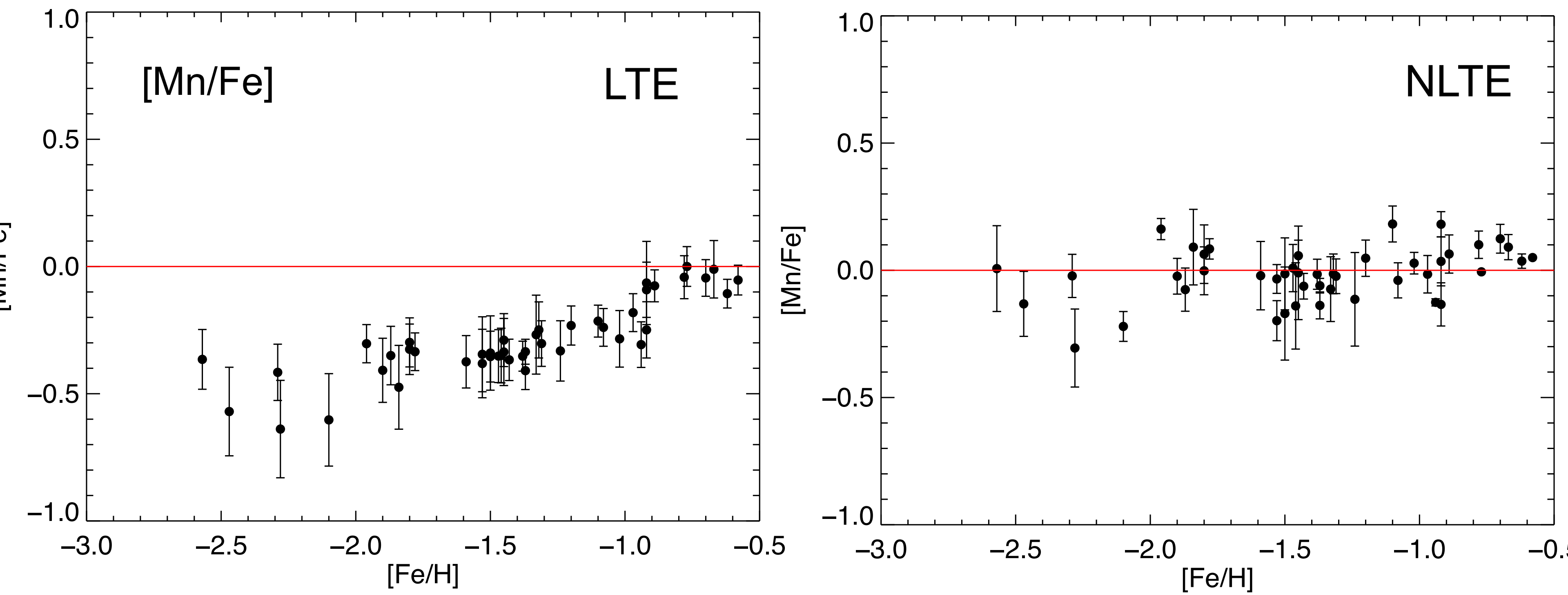
HD 140283, [Fe/H] = -2.5



Metal-poor stars: inter-atomic collisions are sparse and radiation field is much stronger due to the absence of line blanketing, thus NLTE effects are extreme.

Applications: Galactic Archaeology

Chemical evolution of Mn: [Mn/Fe] with [Fe/H]



NLTE online database

INSPECT

http://www.inspect-stars.net/

- Home
- Documentation
- FAQ
- Philosophy
- Release Notes
- Contact Us
- Team

pmwiki.org

edit SideBar

Welcome to the INSPECT project

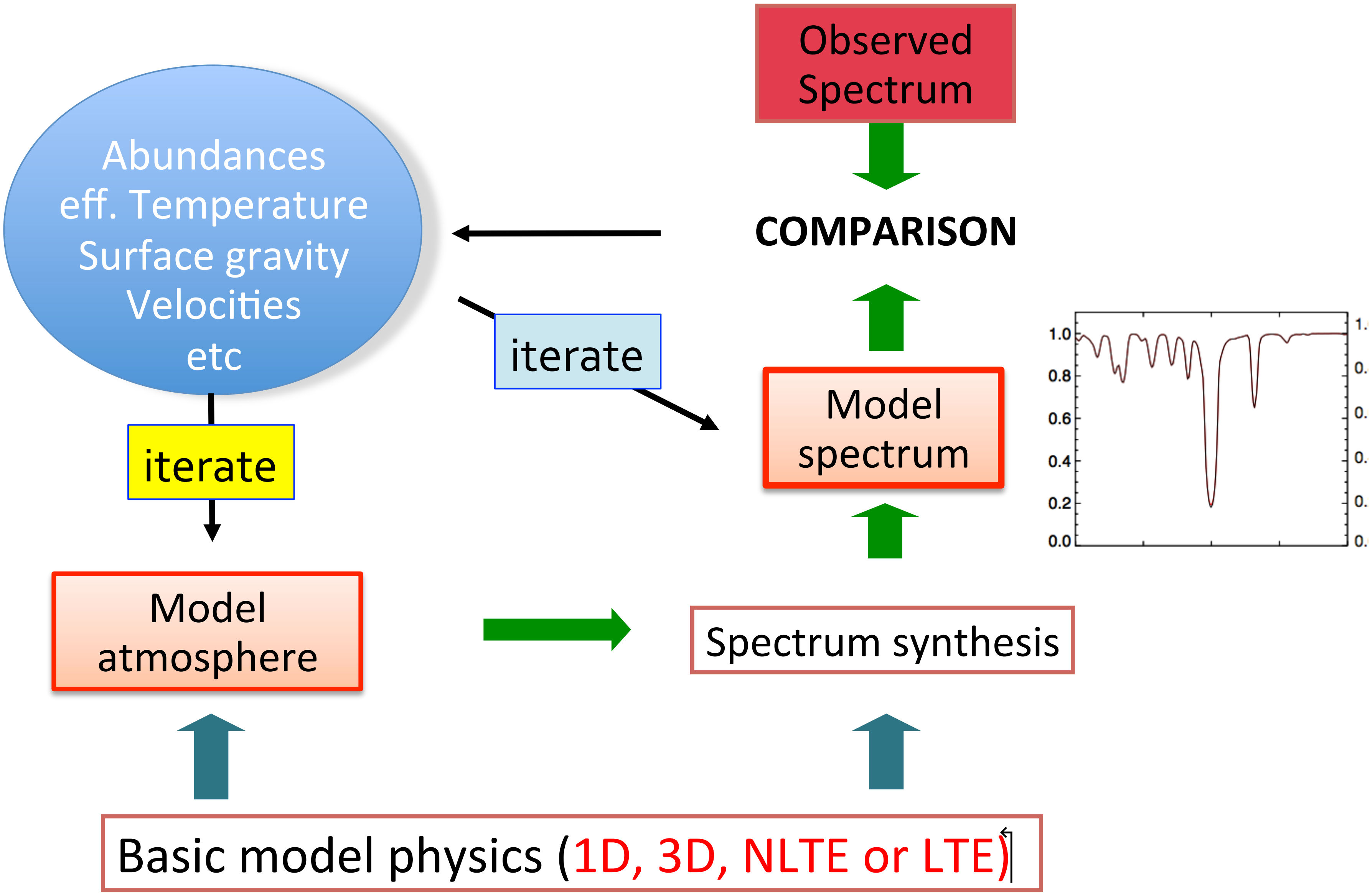
A database for Interactive NLTE Spectroscopy of late-type stars.

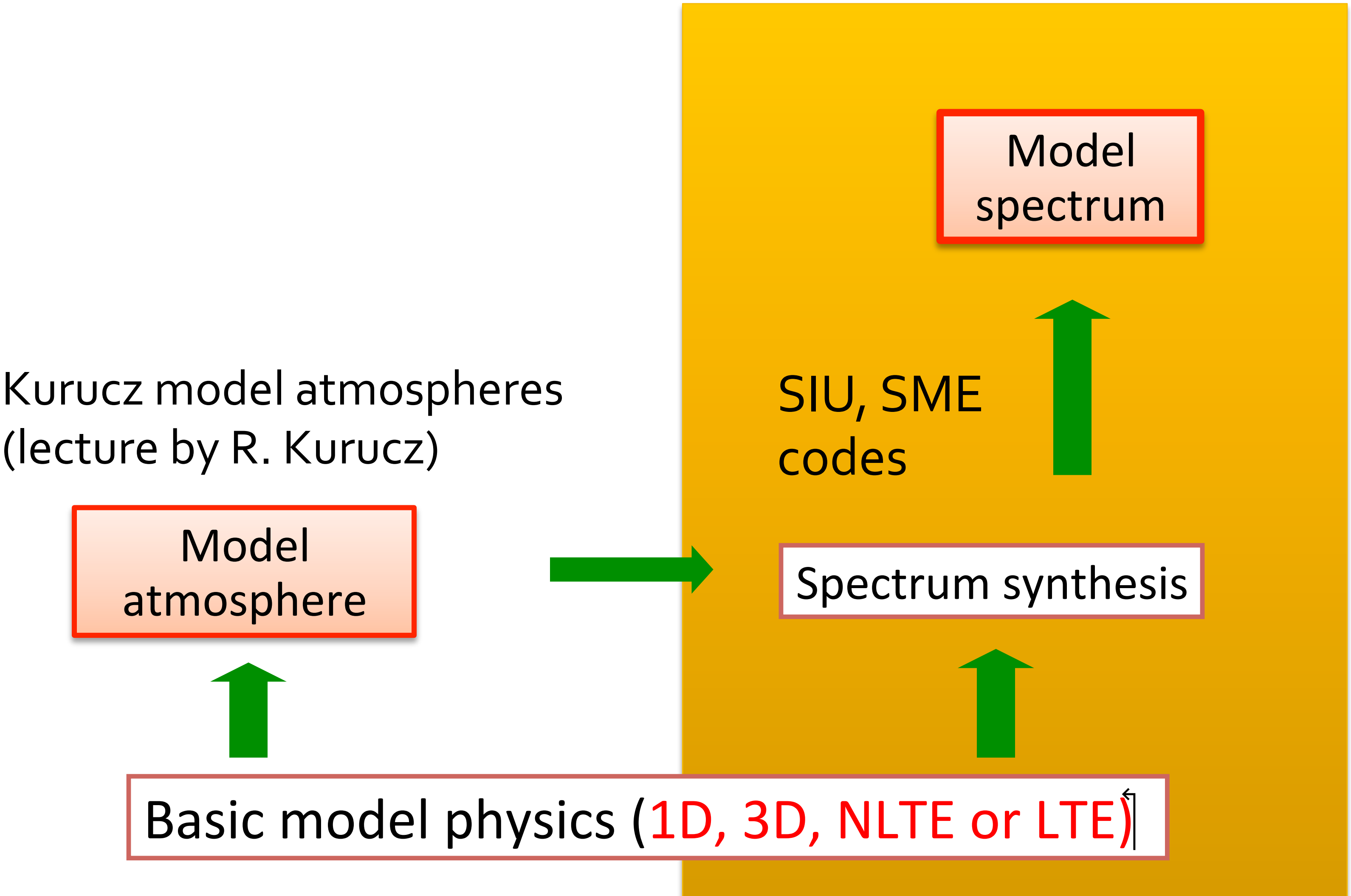
Get started by choosing your element from the periodic table.

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

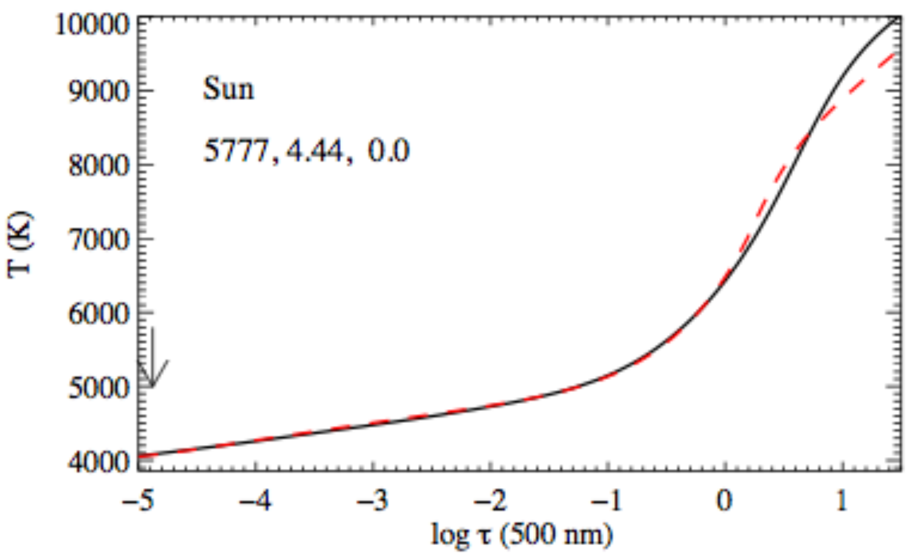
Introduction

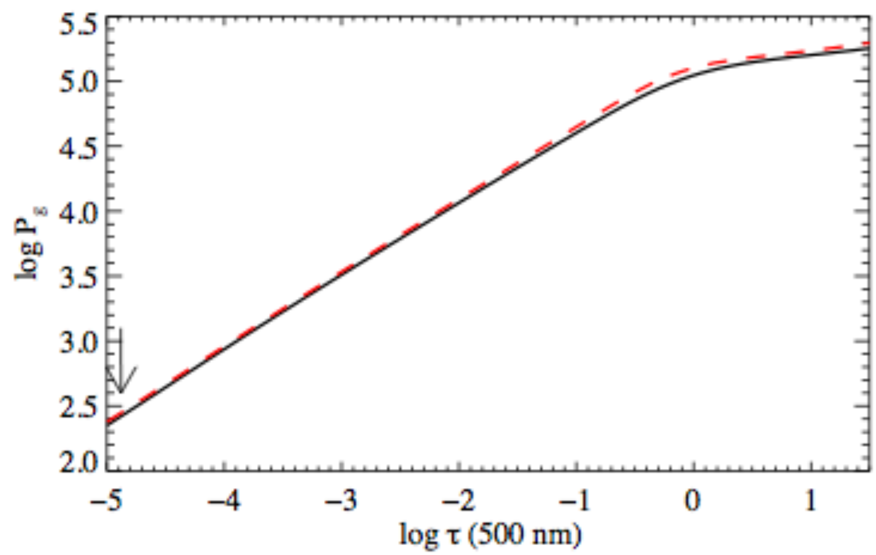
The idea


Observed Spectrum
Abundances
eff. Temperature
Surface gravity
Velocities
etc
COMPARISON
iterate
Model spectrum
iterate
Model atmosphere
Spectrum synthesis
Basic model physics (1D, 3D, NLTE or LTE)
1.0
0.8
0.6
0.4
0.2
0.0


Kurucz model atmospheres
(lecture by R. Kurucz)
Model atmosphere
Model spectrum
SIU, SME codes
Spectrum synthesis
Basic model physics (1D, 3D, NLTE or LTE)

Model atmosphere





Model atmosphere

```
 'TEFF   4300.  GRAVITY 1.50000 LTE '
 'TITLE  [0.0] VTURB=1.0 KM/SEC  L/H=1.50 MARCS-OS      ASPLUND ABUNDANCES
' OPACITY IFOP 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 0 0 0 0 0'
' CONVECTION ON   1.50 TURBULENCE OFF  0.00  0.00  0.00  0.00'
'ABUNDANCE SCALE   1.00000 ABUNDANCE CHANGE 1 0.92080 2 0.07837'
' ABUNDANCE CHANGE  3 -10.99  4 -10.66  5  -9.34  6  -3.65  7  -4.26  8  -3.38'
' ABUNDANCE CHANGE  9  -7.48 10  -4.20 11  -5.87 12  -4.51 13  -5.67 14  -4.53'
' ABUNDANCE CHANGE 15  -6.68 16  -4.90 17  -6.54 18  -5.86 19  -6.96 20  -5.73'
' ABUNDANCE CHANGE 21  -8.99 22  -7.14 23  -8.04 24  -6.40 25  -6.65 26  -4.59'
' ABUNDANCE CHANGE 27  -7.12 28  -5.81 29  -7.83 30  -7.44 31  -9.16 32  -8.46'
' ABUNDANCE CHANGE 33  -9.75 34  -8.71 35  -9.48 36  -8.76 37  -9.44 38  -9.12'
' ABUNDANCE CHANGE 39  -9.83 40  -9.45 41 -10.62 42 -10.12 43 -20.00 44 -10.20'
' ABUNDANCE CHANGE 45 -10.92 46 -10.35 47 -11.10 48 -10.27 49 -10.44 50 -10.04'
' ABUNDANCE CHANGE 51 -11.04 52  -9.85 53 -10.53 54  -9.77 55 -10.97 56  -9.87'
' ABUNDANCE CHANGE 57 -10.91 58 -10.46 59 -11.33 60 -10.59 61 -20.00 62 -11.03'
' ABUNDANCE CHANGE 63 -11.52 64 -10.92 65 -11.76 66 -10.90 67 -11.53 68 -11.11'
' ABUNDANCE CHANGE 69 -12.04 70 -10.96 71 -11.98 72 -11.16 73 -12.21 74 -10.93'
' ABUNDANCE CHANGE 75 -11.81 76 -10.59 77 -10.66 78 -10.40 79 -11.03 80 -10.91'
' ABUNDANCE CHANGE 81 -11.14 82 -10.04 83 -11.39 84 -20.00 85 -20.00 86 -20.00'
' ABUNDANC                                               20.00 92 -12.51'
' ABUNDANC                                               20.00 98 -20.00'
' ABUNDANC
'READ DECK6 ',dep,' RHOX,T,P,XNE,ABROSS,ACCRAD,VTURB, FLXCNV,VCONV,VELSND'
```

A – abundance of an element, $A = \log N/N_H + 12$

N - total number density of an element

Model atmosphere

Column mass density m(t)

Gas pressure P(t)

Temperature T(t)

Electron concentration N_e (t)

```
READ DECK6 72 RHOX,T,P,XNE,ABROSS,ACCRAD,VTURB, FLXCNV,VCONV,VEL
 1.11438611E-03   4303.3 1.114E+01 1.188E+09 1.197E-04 5.762E-03
 1.46933430E-03   4325.0 1.469E+01 1.499E+09 1.309E-04 5.781E-03
 1.90642161E-03   4338.1 1.906E+01 1.806E+09 1.404E-04 5.788E-03
 2.44338350E-03   4355.4 2.443E+01 2.200E+09 1.541E-04 5.798E-03
 3.09334096E-03   4372.8 3.093E+01 2.664E+09 1.704E-04 5.816E-03
 3.87393779E-03   4391.0 3.874E+01 3.217E+09 1.900E-04 5.851E-03
 4.80510076E-03   4409.4 4.805E+01 3.867E+09 2.128E-04 5.891E-03
 5.91112062E-03   4428.0 5.911E+01 4.629E+09 2.393E-04 5.939E-03
 7.22091430E-03   4446.5 7.221E+01 5.515E+09 2.698E-04 5.995E-03
 8.76903374E-03   4464.8 8.769E+01 6.544E+09 3.046E-04 6.061E-03
 1.05970558E-02   4482.7 1.060E+02 7.729E+09 3.440E-04 6.141E-03
 1.27556538E-02   4500.1 1.276E+02 9.088E+09 3.885E-04 6.240E-03
 1.53040028E-02   4517.4 1.530E+02 1.066E+10 4.389E-04 6.356E-03
 1.83113451E-02   4534.4 1.831E+02 1.246E+10 4.961E-04 6.489E-03
```

... 72 depth points - t

LTE line formation

- the profile function

$$\psi(\nu-\nu_0)=\phi(\nu-\nu_0)=\frac{H(a,v)}{\sqrt{\pi}\Delta\nu_D} \quad \text{with} \quad a=\frac{\gamma_R+\gamma_3+\gamma_4+\gamma_6}{4\pi\Delta\nu_D} \quad v=\frac{\nu-\nu_0}{\Delta\nu_D}$$

- line absorption coefficient

$$\kappa_\lambda^l=\frac{\pi e^2}{m_e c}\frac{\lambda}{c}b_i\frac{N_i^{\mathrm{LTE}}}{N_{\mathrm{El}}}N_{\mathrm{H}}\log\varepsilon f_{ij}\frac{H(a,v)}{\Delta\lambda_D}\left(1-\frac{b_j}{b_i}\mathrm{e}^{-hc/\lambda kT}\right)$$

$$\kappa_\lambda=\kappa_\lambda^l+\kappa_\lambda^c,$$

$$S_\nu\equiv\frac{2hc^2}{\lambda^5}\frac{1}{\mathrm{e}^{hc/kT\lambda}-1}=B_\nu$$

Line source function, assumed to be Planck function

$$I_\lambda(\tau_\nu=0,\mu)=\int_0^\infty S_\lambda(\tau_\lambda)e^{-\tau_\lambda/\mu}d\tau_\lambda/\mu$$

Emergent intensity

$$F_\lambda(0)=2\pi\int_0^\infty S_\lambda(T(\tau_\lambda))E_2(\tau_\lambda)d\tau_\lambda$$

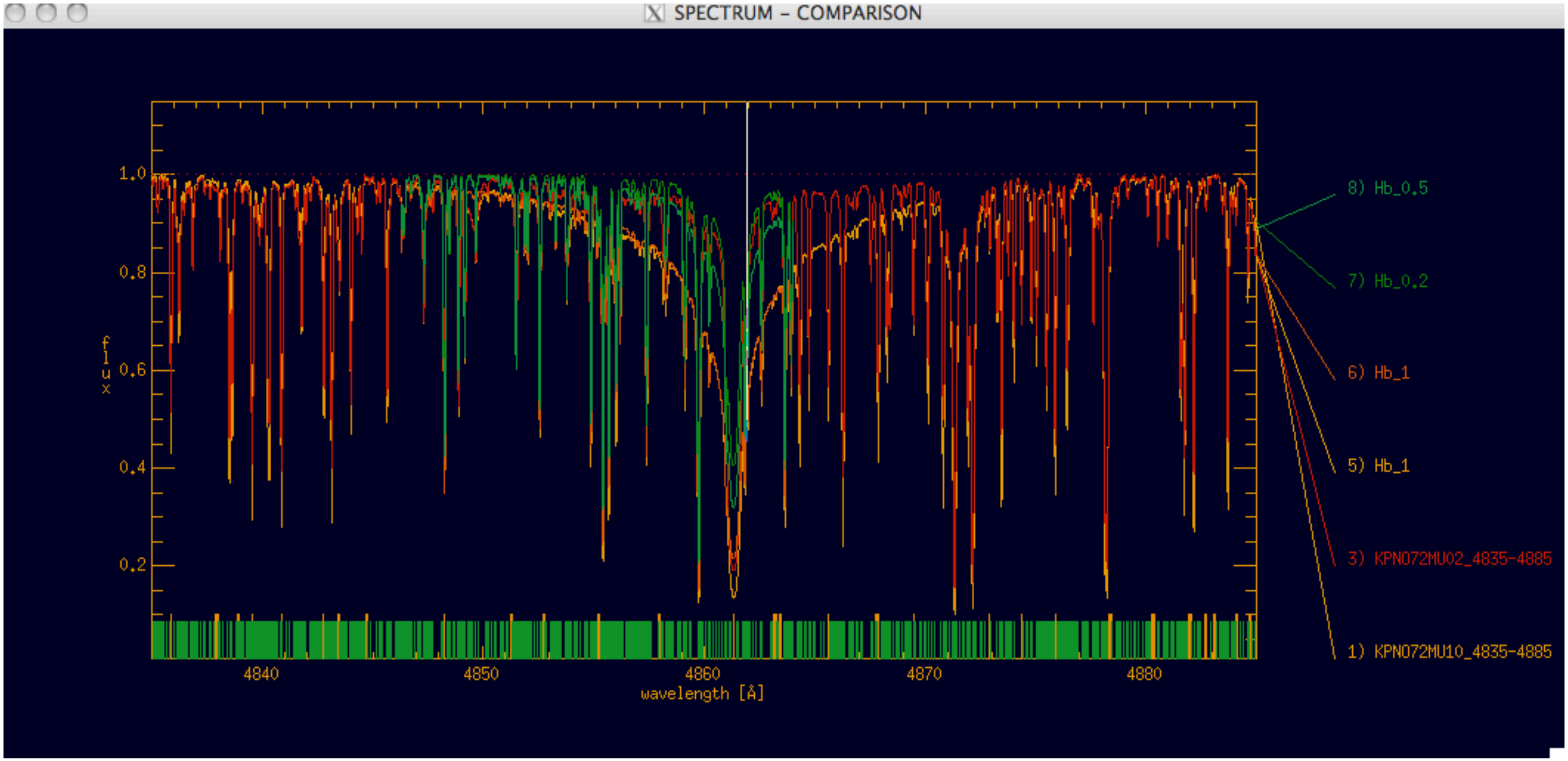
Surface flux

NLTE line formation

$$b_i(\tau_0) = \frac{n_i(\tau_0)}{n_i^*(\tau_0)} ,$$

$$\kappa_\nu^l = b_l \kappa^{*l} \frac{1 - \frac{b_u}{b_l} \mathrm{e}^{h\nu/kT}}{1 - \mathrm{e}^{h\nu/kT}} .$$

$$S_\lambda = \frac{2h\nu_0^3}{c^2} \frac{1}{\frac{b_l}{b_u} \mathrm{e}^{h\nu_0/kT} - 1} .$$


SPECTRUM – COMPARISON
1.0
0.8
0.6
0.4
0.2
flux
4840
4850
4860
4870
4880
wavelength [Å]
8) Hb_0.5
7) Hb_0.2
6) Hb_1
5) Hb_1
3) KPN072MU02_4835-4885
1) KPN072MU10_4835-4885

```
LINEFORMATION
START
CANCEL
Atmos.    : t<Teff><logg><logz>.dat OR grid interpolation
Teff      :  5777    K
log(g)    : 4.44     [cm/s^2]
[Fe/H]    :  0.00
Xi        :  0.90    km/s
CONSTANT MICROTURBULENCE
XI-file   : hm-micro.xi
LTE - LINEFORMATION
Departures:
Termdesig.:
------------------------------------------------------
Wmin      :    4834.500  A
Wmax      :    4885.500  A
Stepwidth-crit.:      0.100000
Min.stepwidth  :     5.    mA / 5000 A
Max.stepwidth  :     1.50     A / 5000 A
------------------------------------------------------
FLUX
Cos(theta) :  1.00000
NORMALIZED
ALL EXISTING LINES
ATOMIC AND MOLECULAR LINES
IGNORE   QUADRATIC STARK EFFECT
------------------------------------------------------
SEARCH EXACT ATMOSPHERE  ON
INTEGRATION:  GAUSS-QUADRATURE
```

- define a model atmosphere or provide

T_{eff}
logg
[Fe/H]
Xi: microturbulence

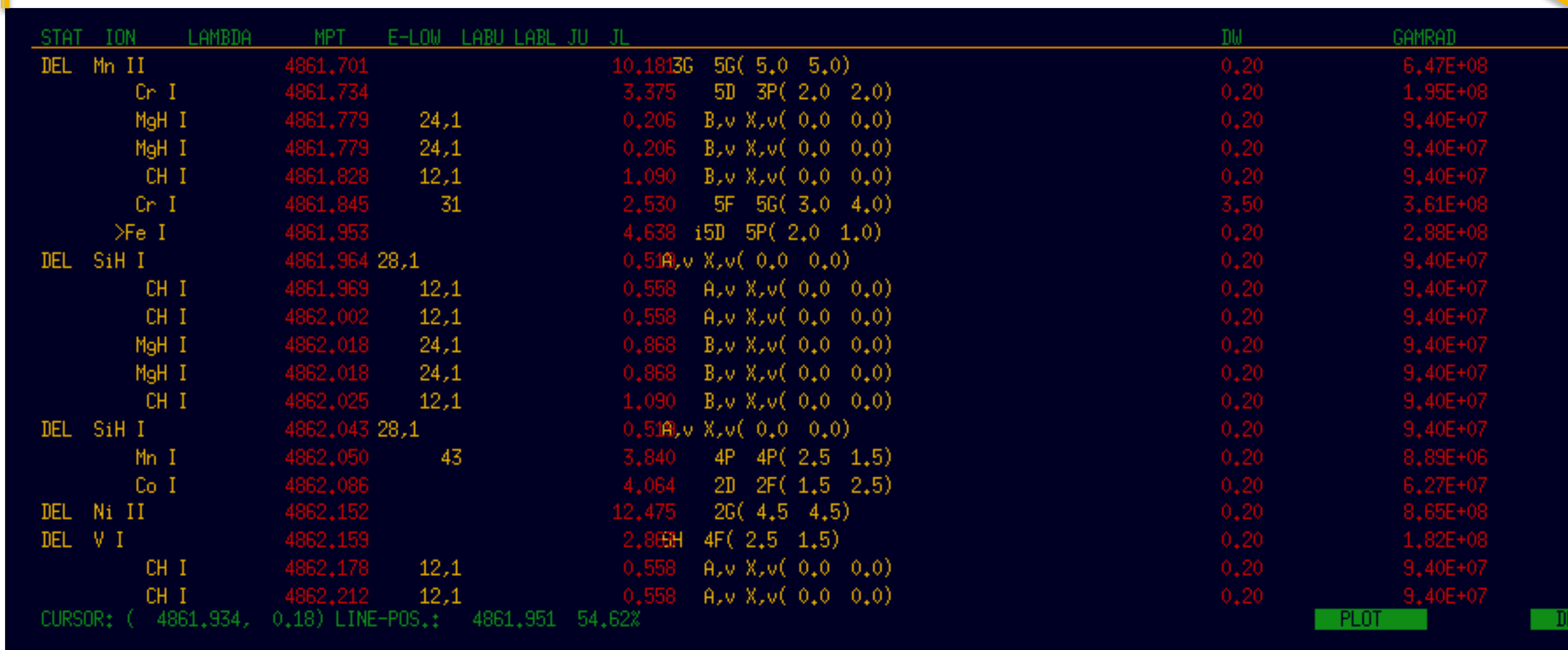
- Min wavelength
- Max wavelength

- Flux or Intensity?

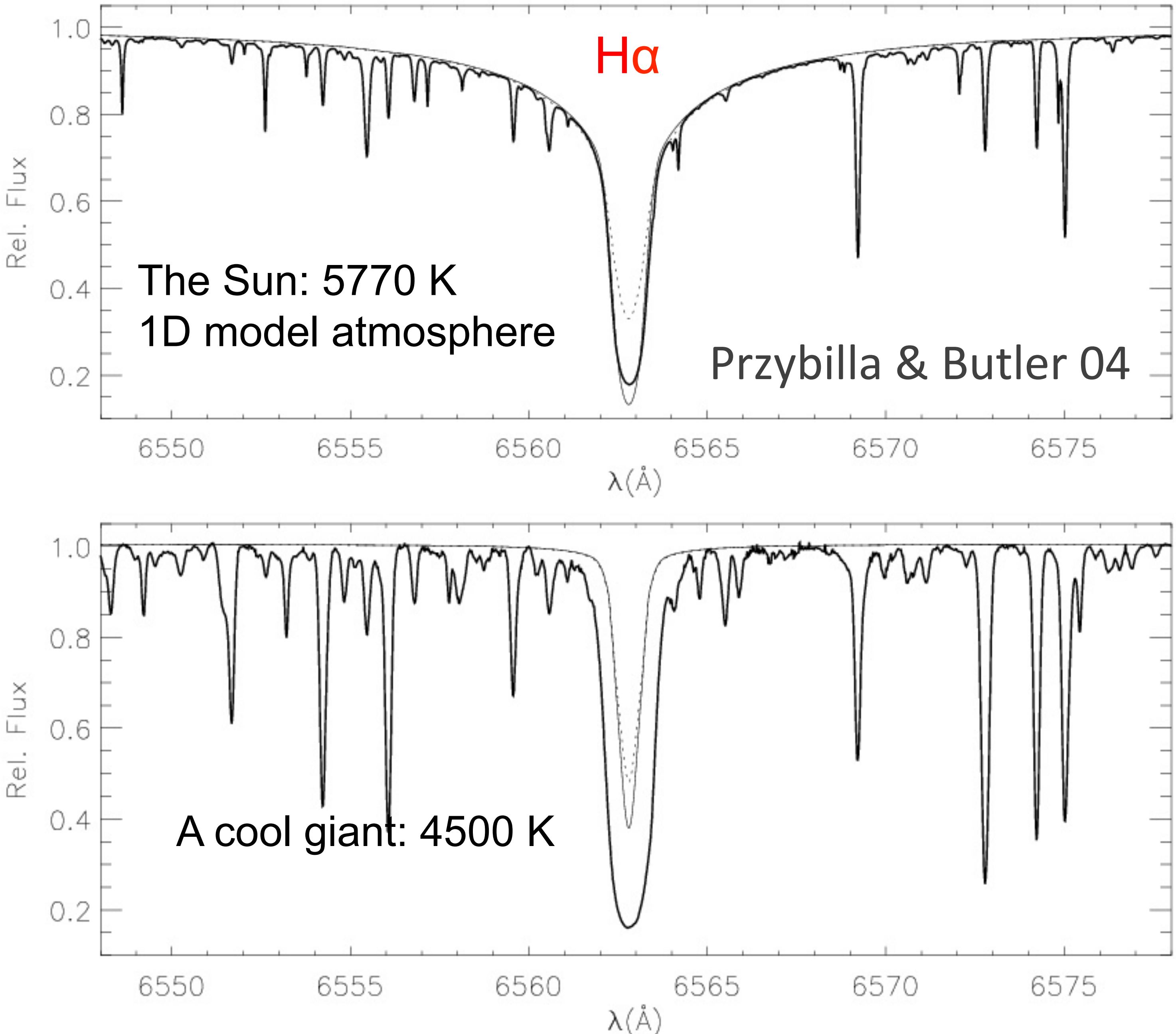
$\cos\theta$ = ?

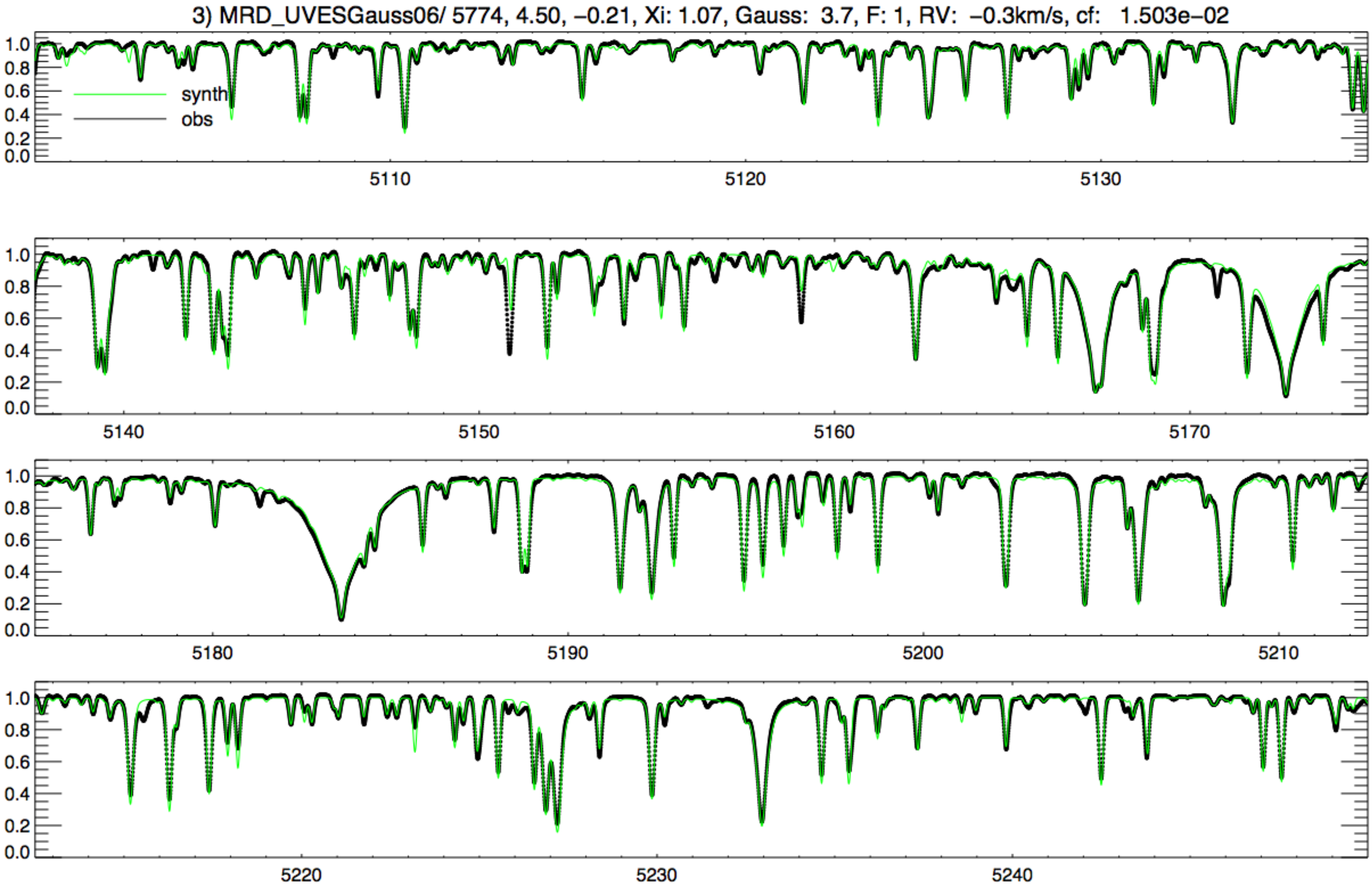
- **Linelist?**

LINELIST – atomic data for each line



Hydrogen lines – T_{eff} diagnostics




3) MRD_UVESGauss06/ 5774, 4.50, −0.21, Xi: 1.07, Gauss: 3.7, F: 1, RV: −0.3km/s, cf: 1.503e−02
synth
obs
0.0
0.2
0.4
0.6
0.8
1.0
5110
5120
5130
5140
5150
5160
5170
5180
5190
5200
5210
5220
5230
5240