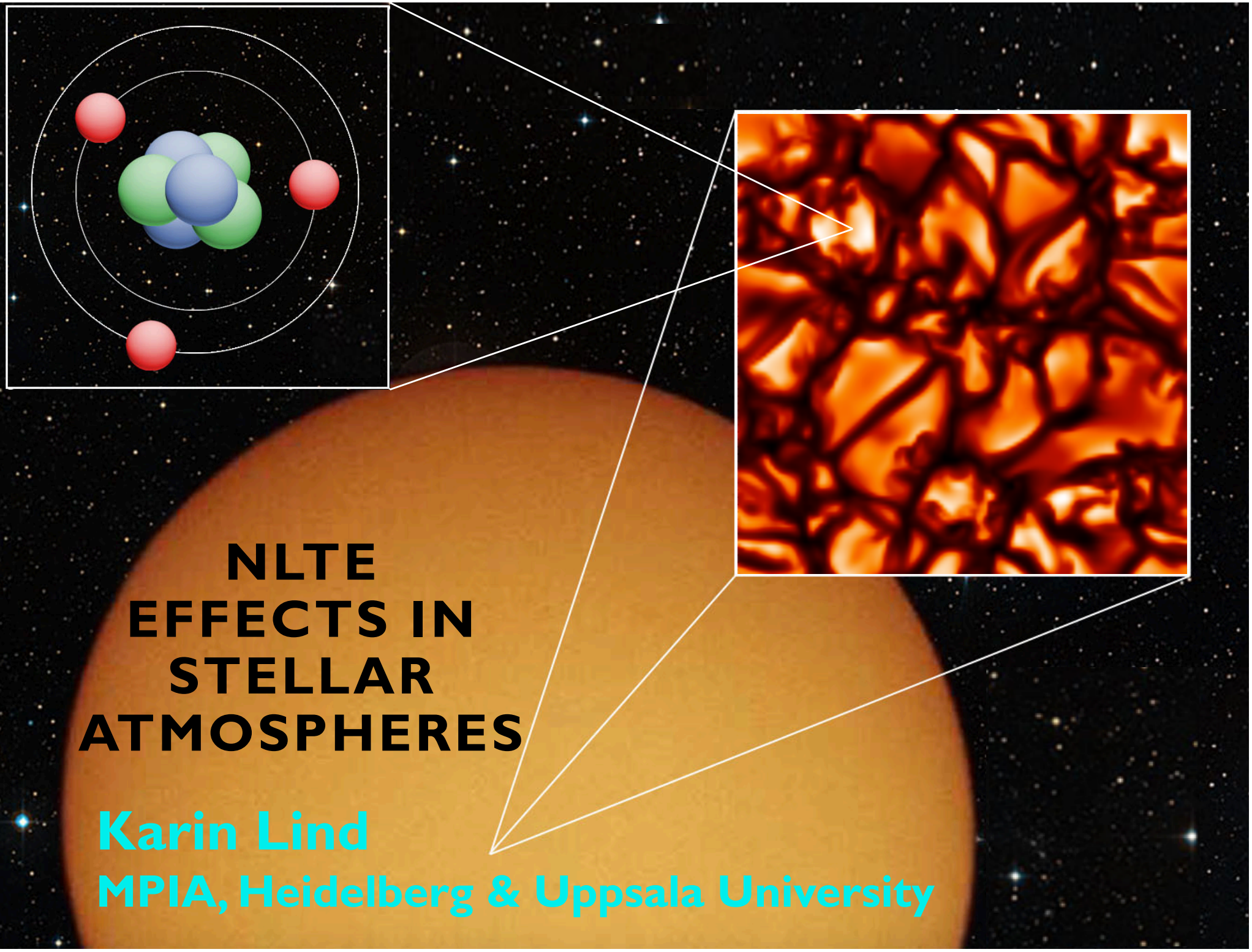
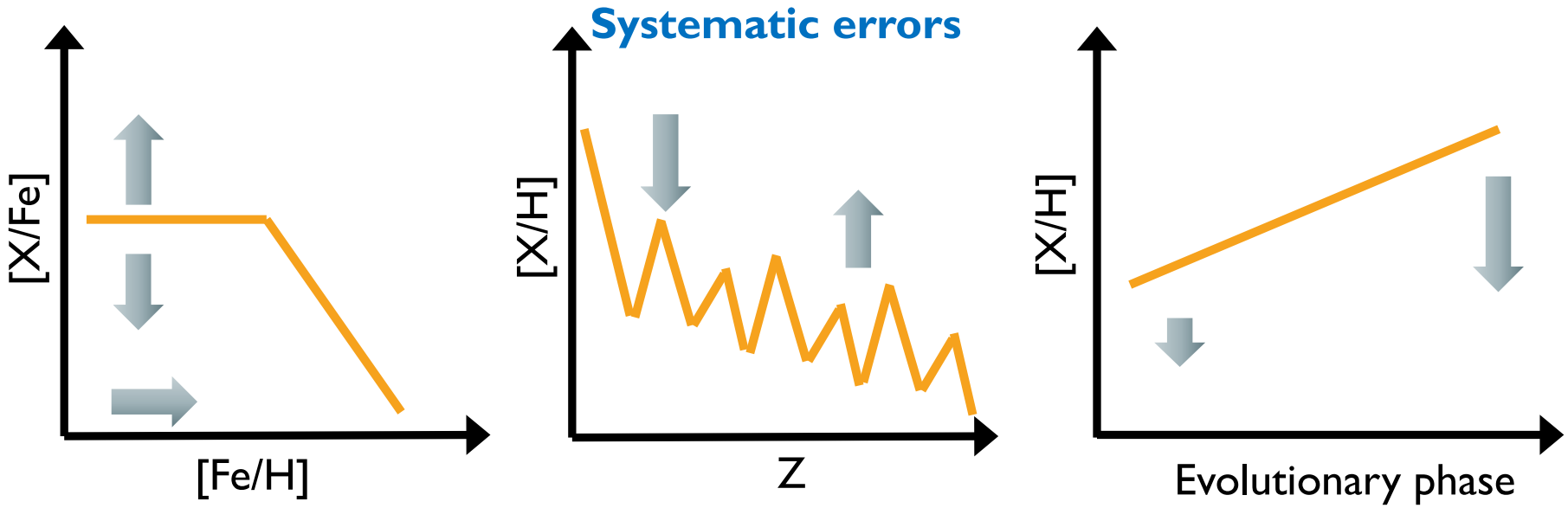

NLTE
EFFECTS IN
STELLAR
ATMOSPHERES
Karin Lind
MPIA, Heidelberg & Uppsala University

# APPLES AND ORANGES

**Comparing hot to cool, dwarf to giant, metal-poor to metal-rich, systematic uncertainties can be almost arbitrarily large -**
**Accurate modelling of stellar spectra is a great challenge!**

# WHAT QUESTIONS CAN BE ANSWERED WITH STELLAR ABUNDANCES?

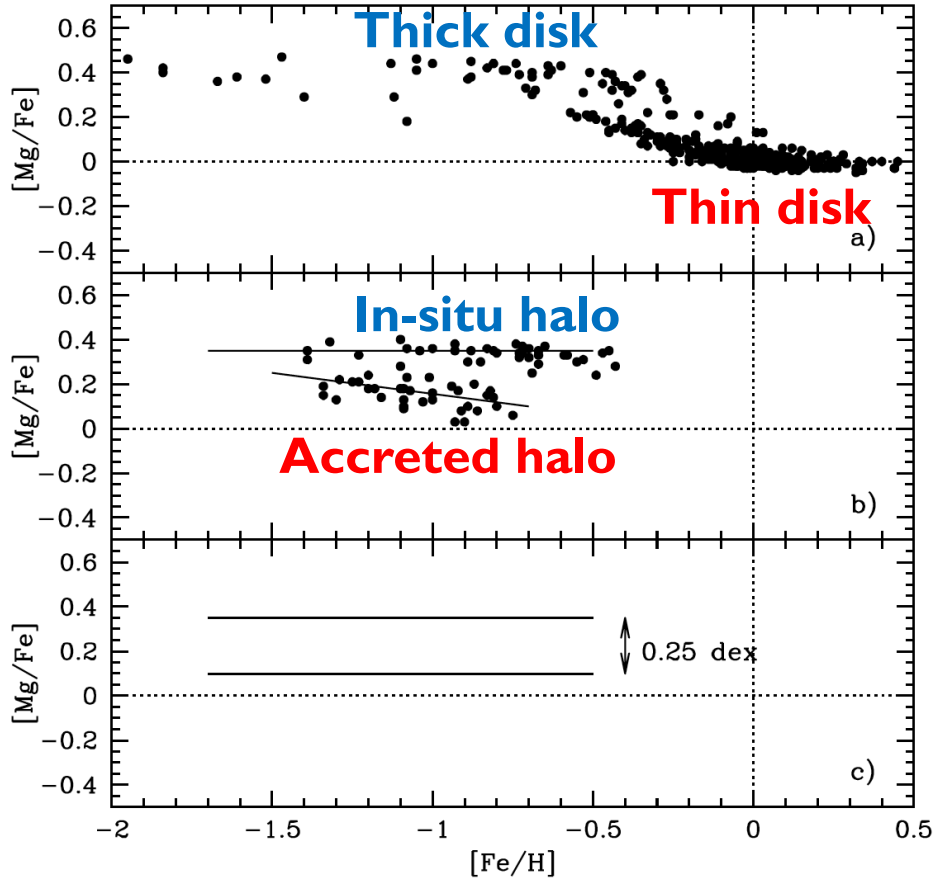



**How do chemical elements build up over time in different nucleosynthesis channels?**

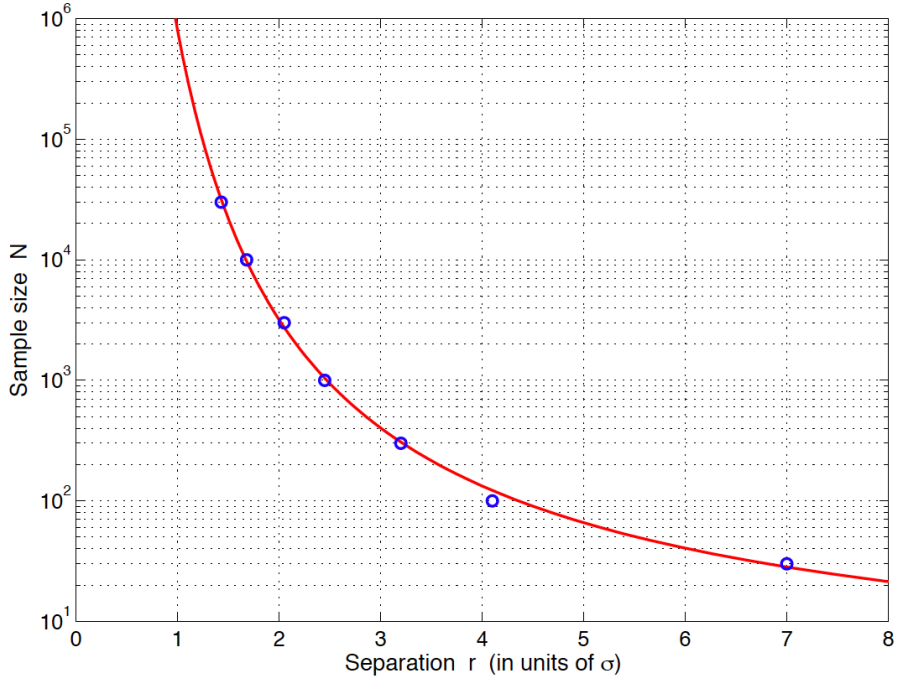
**How massive were the first stars and how did they start enriching the Galaxy with metals?**

**Do stars preserve their birth composition in the surface layers?**

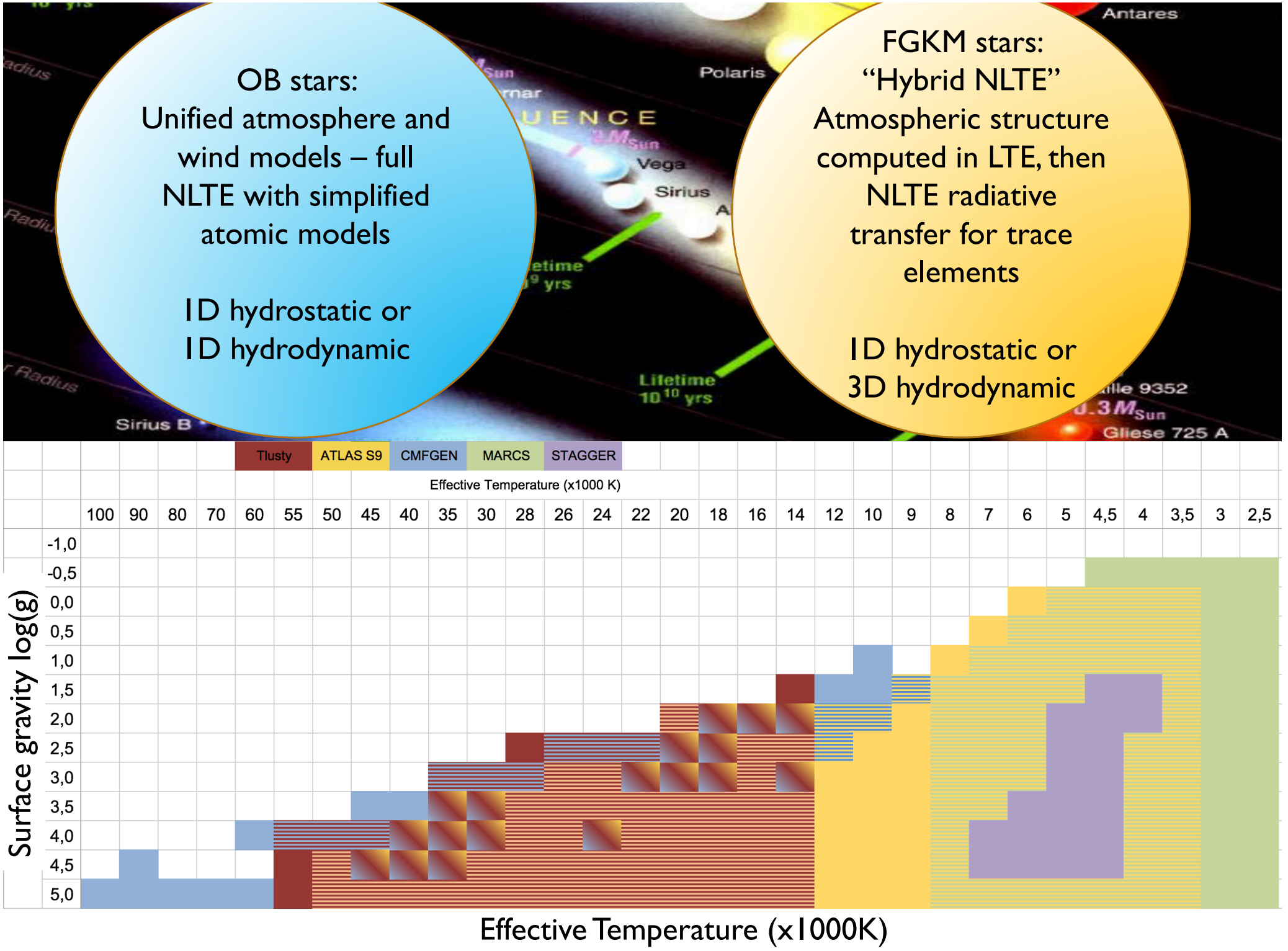
# WHAT CAN BE GAINED BY INCREASED PRECISION?

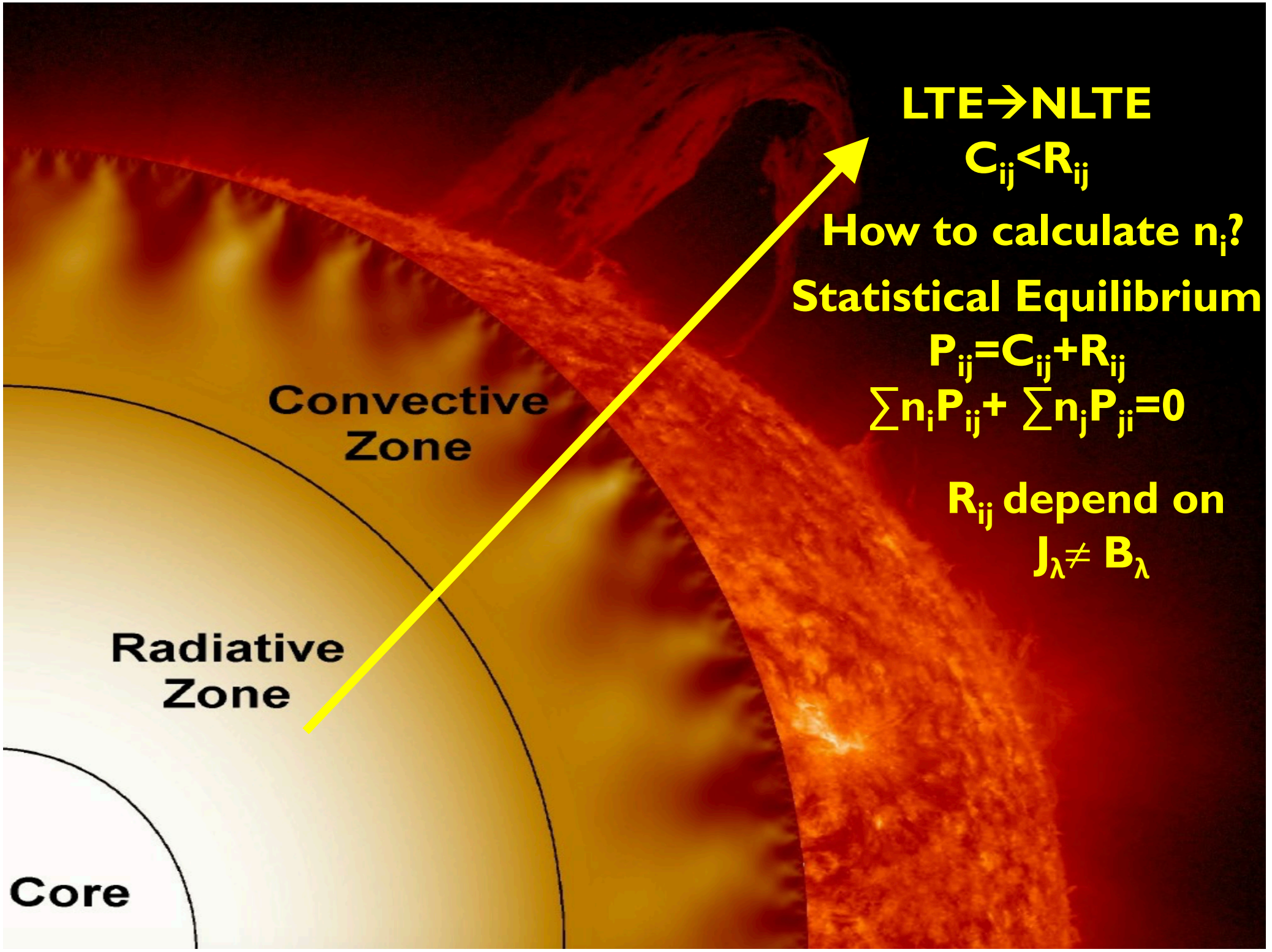


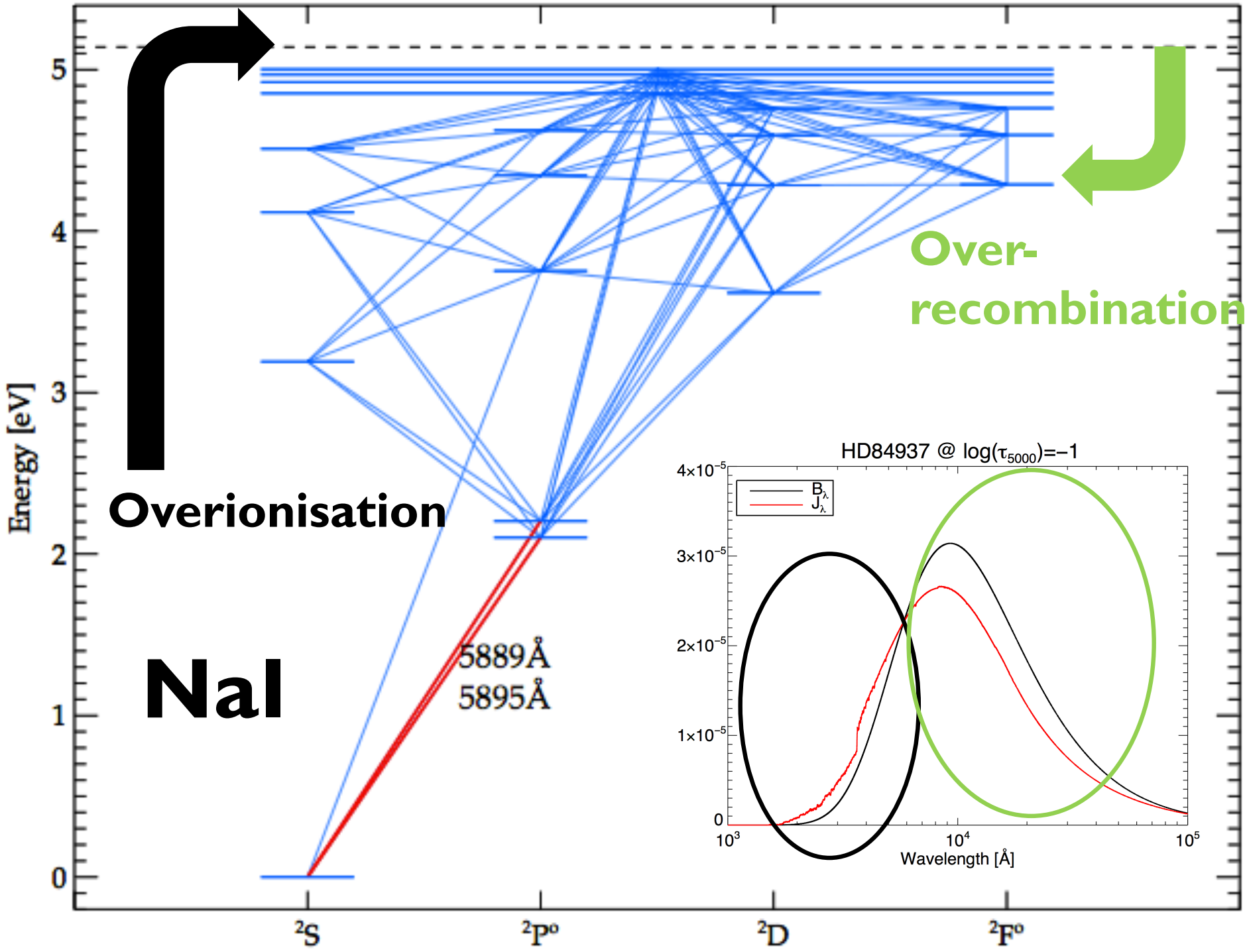

The sample size needed to separate two Gaussian populations grows exponentially with decreasing separation in units of σ (abundance precision)




**Lindegren & Feltzing (2013)**

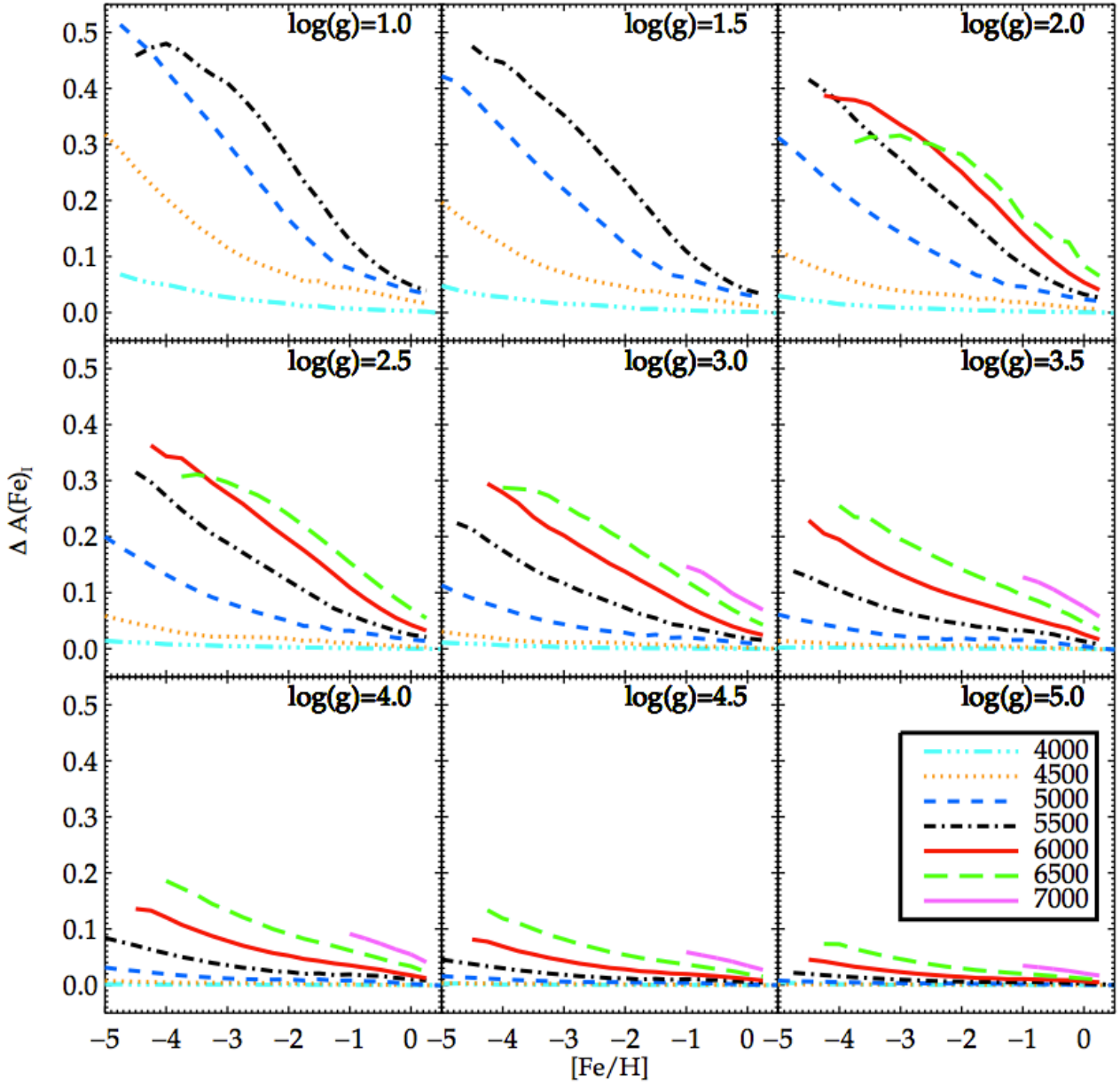

OB stars:
Unified atmosphere and wind models – full NLTE with simplified atomic models
1D hydrostatic or
1D hydrodynamic
FGKM stars:
"Hybrid NLTE"
Atmospheric structure computed in LTE, then NLTE radiative transfer for trace elements
1D hydrostatic or
3D hydrodynamic
Antares
Polaris
Vega
Sirius
Sirius B
Lifetime
$10^{10}$ yrs
Gliese 725 A
Tlusty
ATLAS S9
CMFGEN
MARCS
STAGGER
Effective Temperature (x1000 K)
100 90 80 70 60 55 50 45 40 35 30 28 26 24 22 20 18 16 14 12 10 9 8 7 6 5 4,5 4 3,5 3 2,5
-1,0 -0,5 0,0 0,5 1,0 1,5 2,0 2,5 3,0 3,5 4,0 4,5 5,0
Surface gravity log(g)
Effective Temperature (x1000K)


LTE→NLTE
$C_{ij}<R_{ij}$
How to calculate $n_i$?
Statistical Equilibrium
$P_{ij}=C_{ij}+R_{ij}$
$\sum n_i P_{ij} + \sum n_j P_{ji}=0$
$R_{ij}$ depend on
$J_\lambda \neq B_\lambda$
Convective Zone
Radiative Zone
Core


Energy [eV]
0
1
2
3
4
5
$^2$S
$^2$P$^o$
$^2$D
$^2$F$^o$
Overionisation
Over-
recombination
NaI
5889Å
5895Å
HD84937 @ log(τ5000)=−1
4×10$^{-5}$
3×10$^{-5}$
2×10$^{-5}$
1×10$^{-5}$
0
$B_\lambda$
$J_\lambda$
10$^3$
10$^4$
10$^5$
Wavelength [Å]

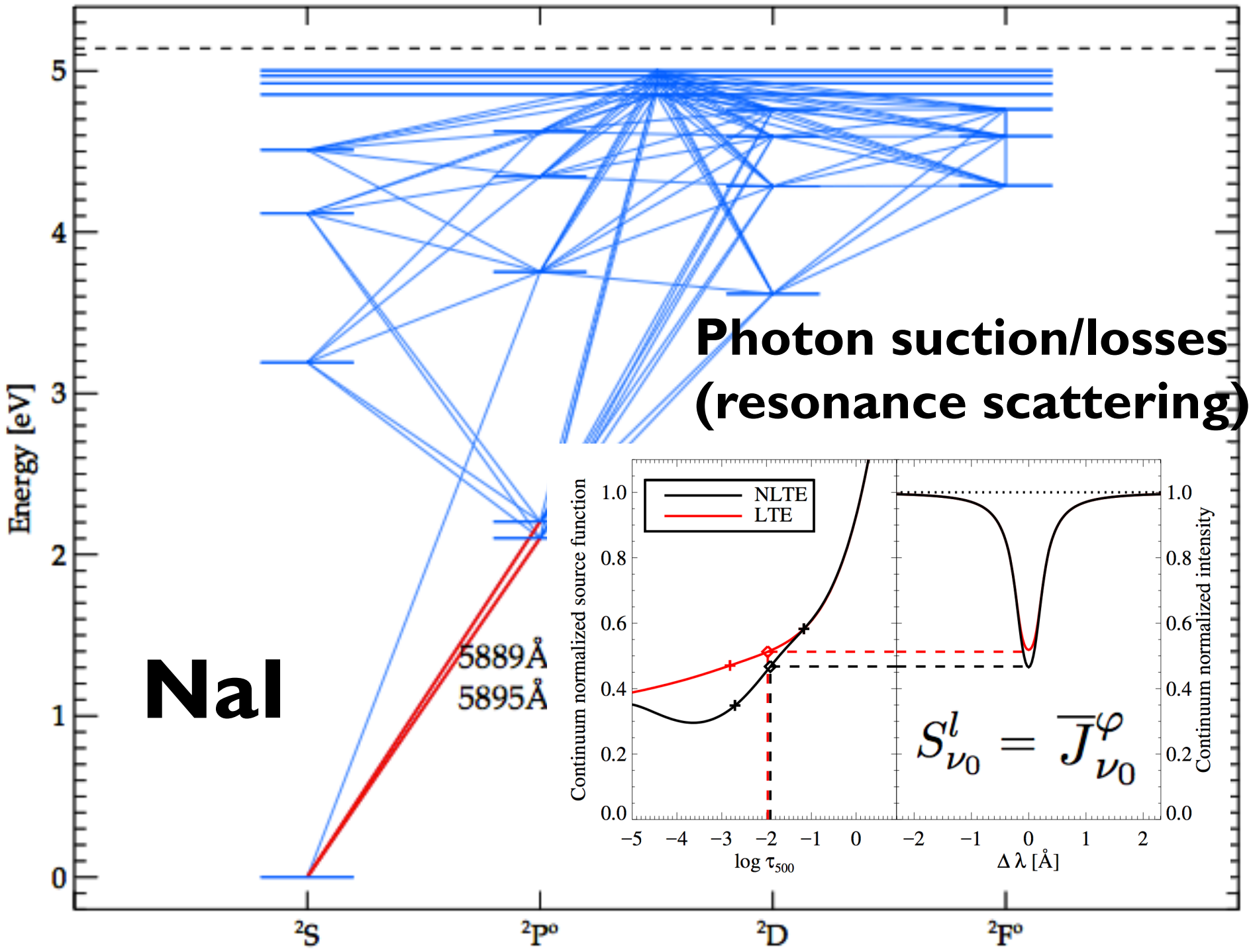
# NLTE EFFECTS ON [FE/H]

**Fel overionisation**



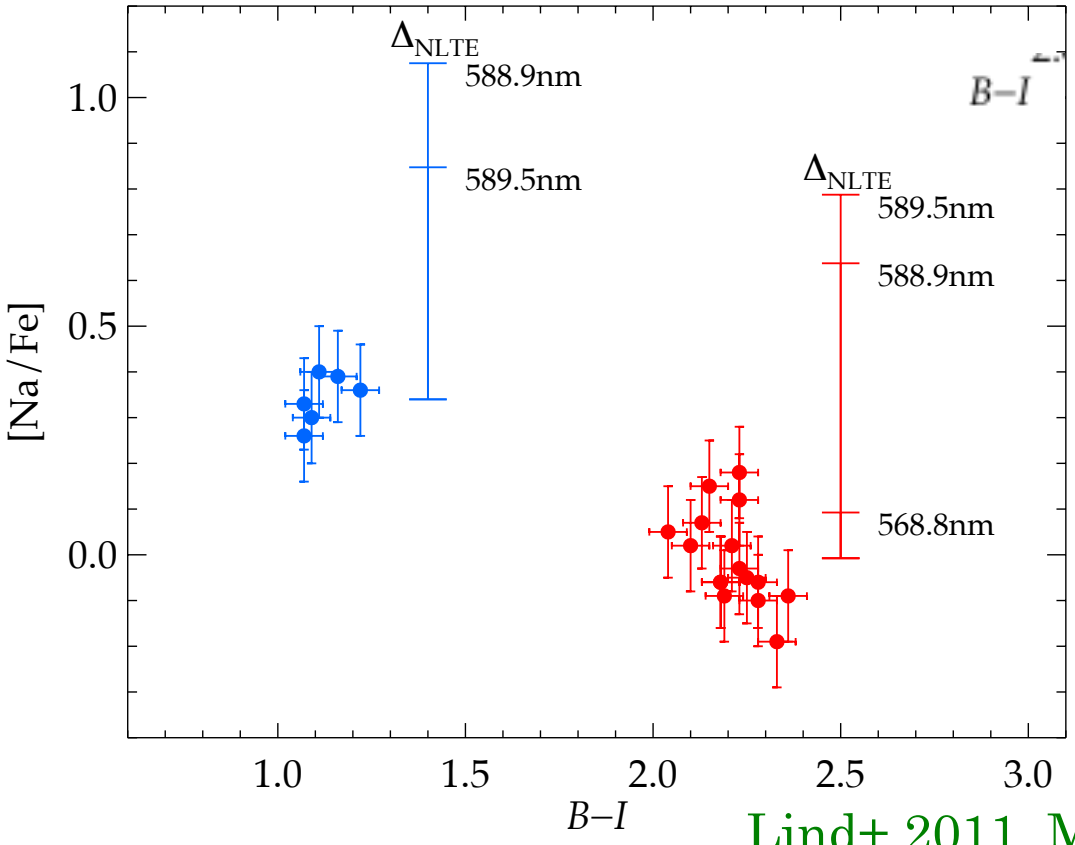

**Effects increase with:**
Decreasing [Fe/H]
Increasing $T_{eff}$
Decreasing log(g)

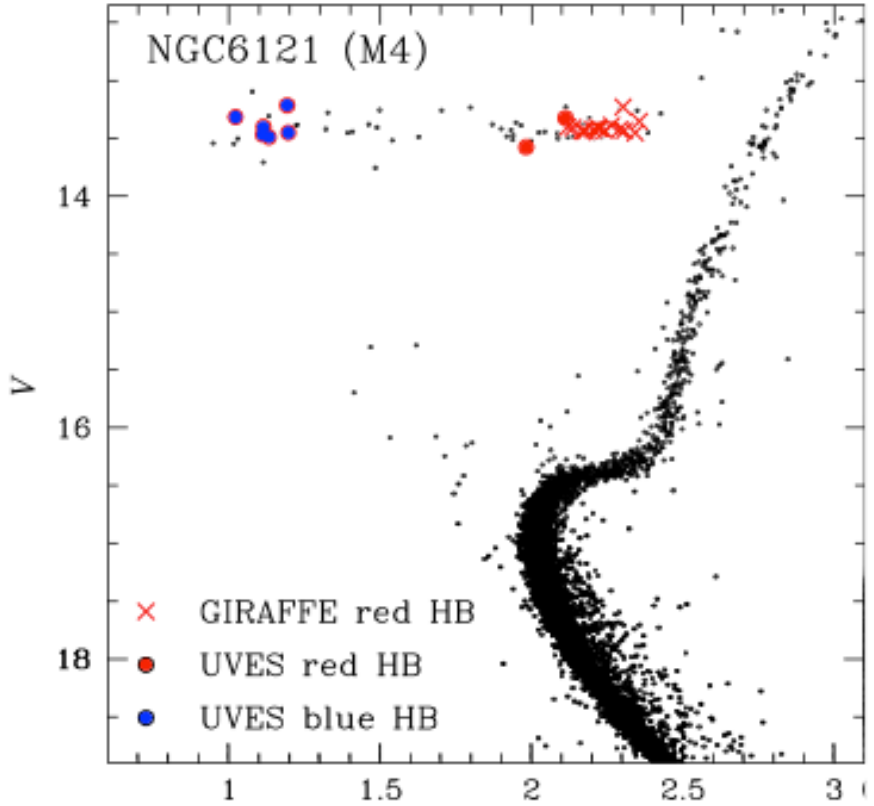
Lind+ (2012)


Energy [eV]
0
1
2
3
4
5
$^2$S
$^2$P$^o$
$^2$D
$^2$F$^o$
NaI
5889Å
5895Å
Photon suction/losses
(resonance scattering)
NLTE
LTE
Continuum normalized source function
log $\tau_{500}$
Δ λ [Å]
Continuum normalized intensity
$S^l_{\nu_0} = \overline{J}^{\varphi}_{\nu_0}$

# NLTE EFFECTS FOR [NA/H]

**NLTE effects grow with line strength, largest at maximum saturation, e.g. on the HB of M4 ([Fe/H]=-1)**

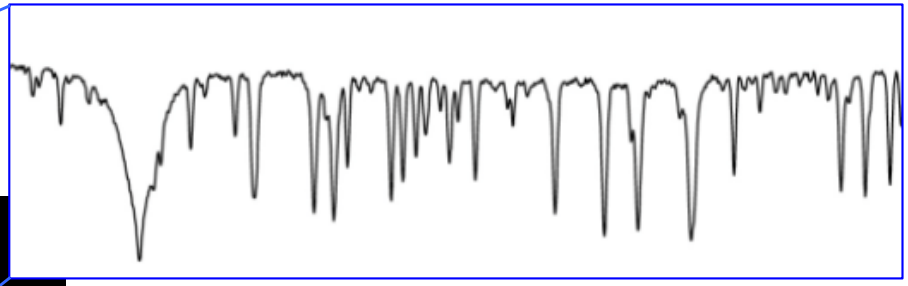


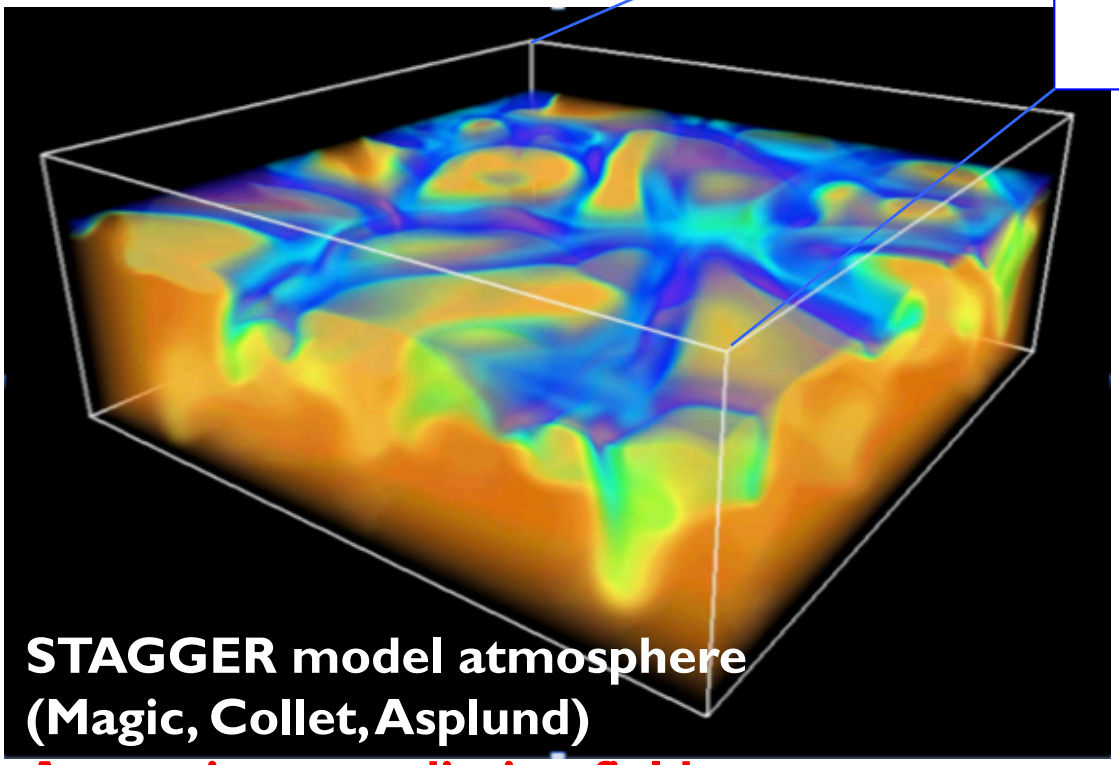

Lind+ 2011, Marino+ 2011

# MODELLING DEVELOPMENTS

**Goal is "3D NLTE": realistic modelling of convection, radiation, and the statistical equilibria of atoms, without important free parameters**



**Synthetic spectrum:**
**High resolution, non-LTE**

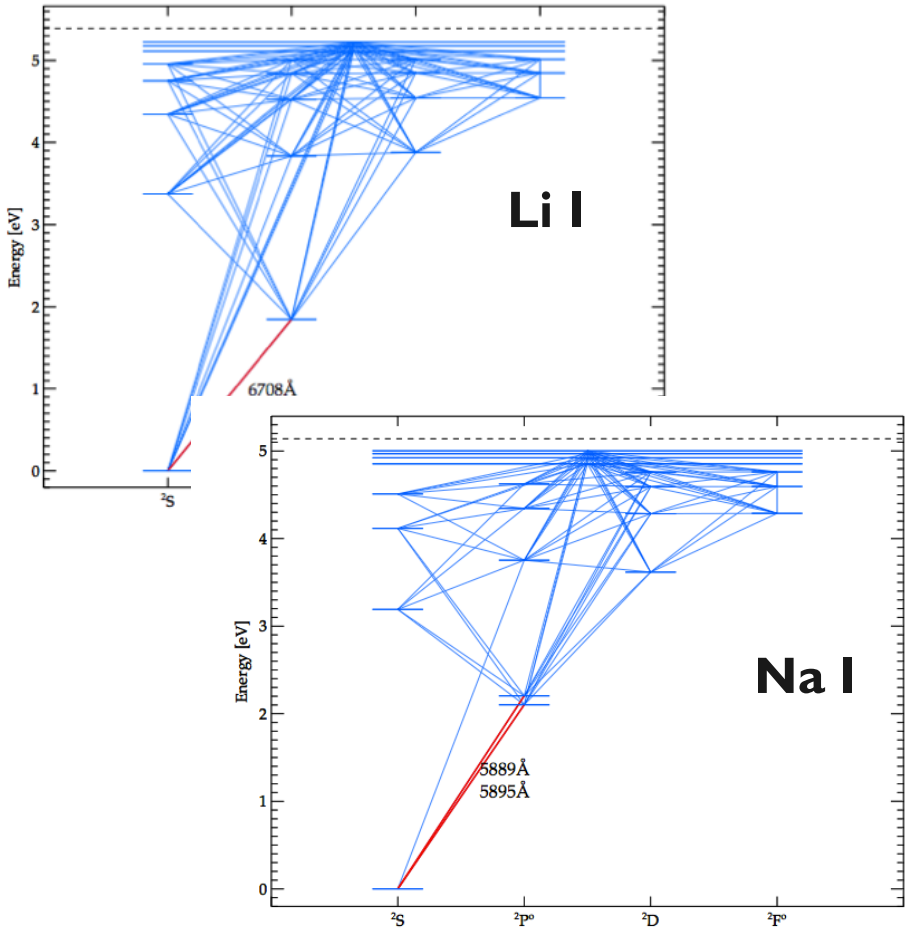


**STAGGER model atmosphere**
**(Magic, Collet, Asplund)**

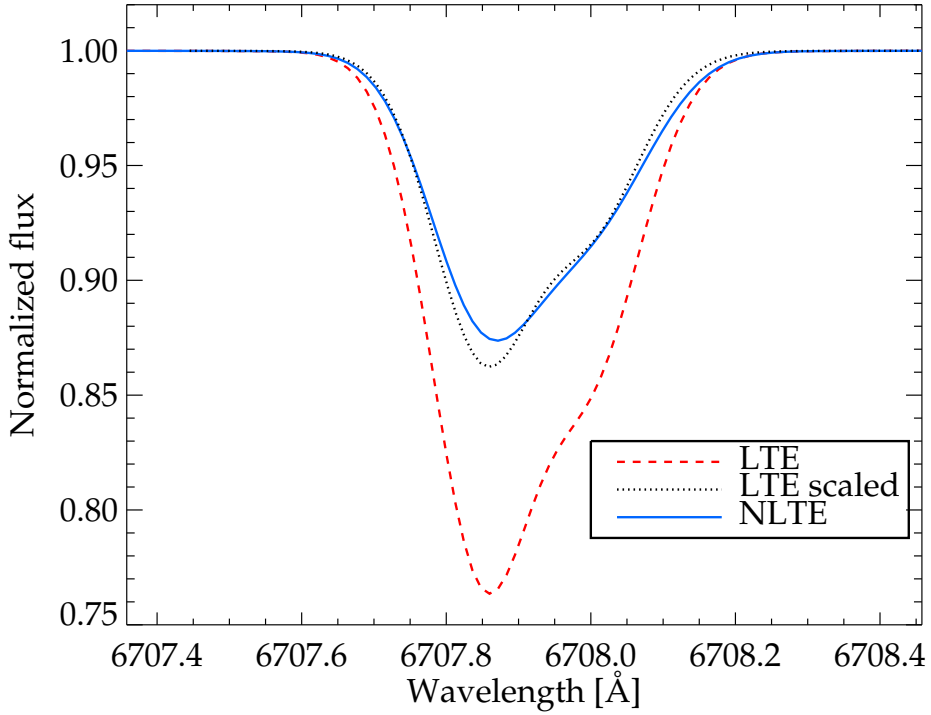
**Approximate radiation field**

# 3D NLTE

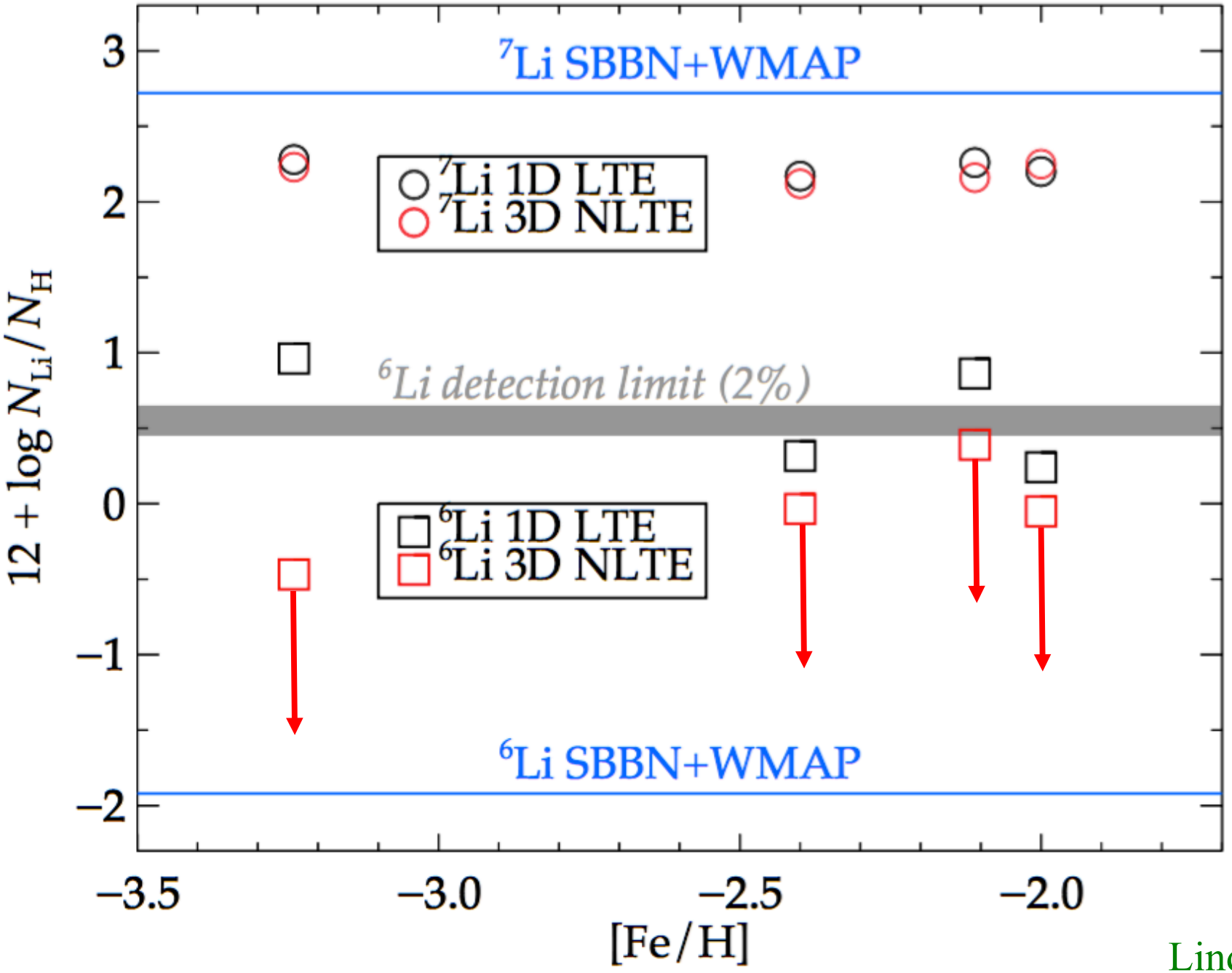
## 2013




## 3D synthesis of the LiI resonance line to determine $^{6}Li/^{7}Li$ ratio



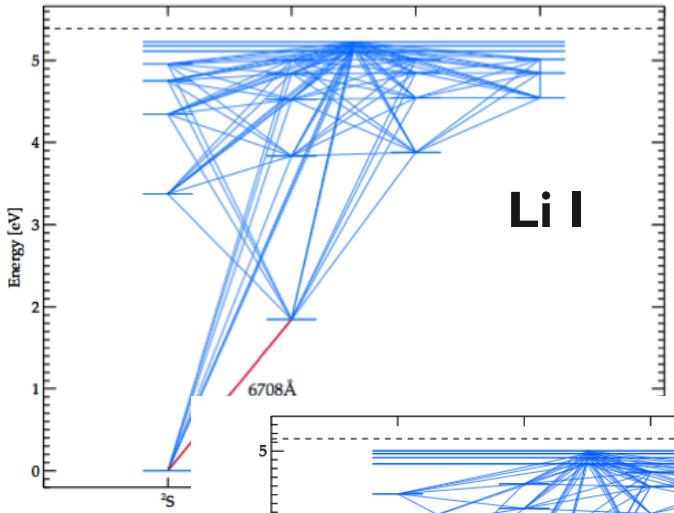
# The 2nd cosmological lithium problem

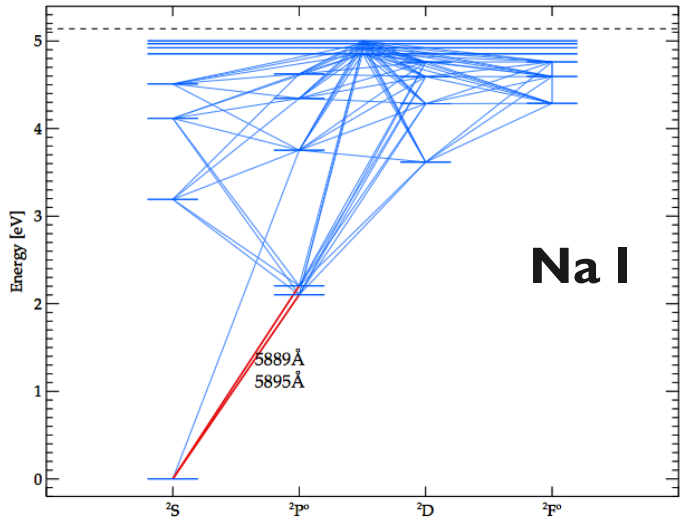



Lind+ 2013

# 3D NLTE

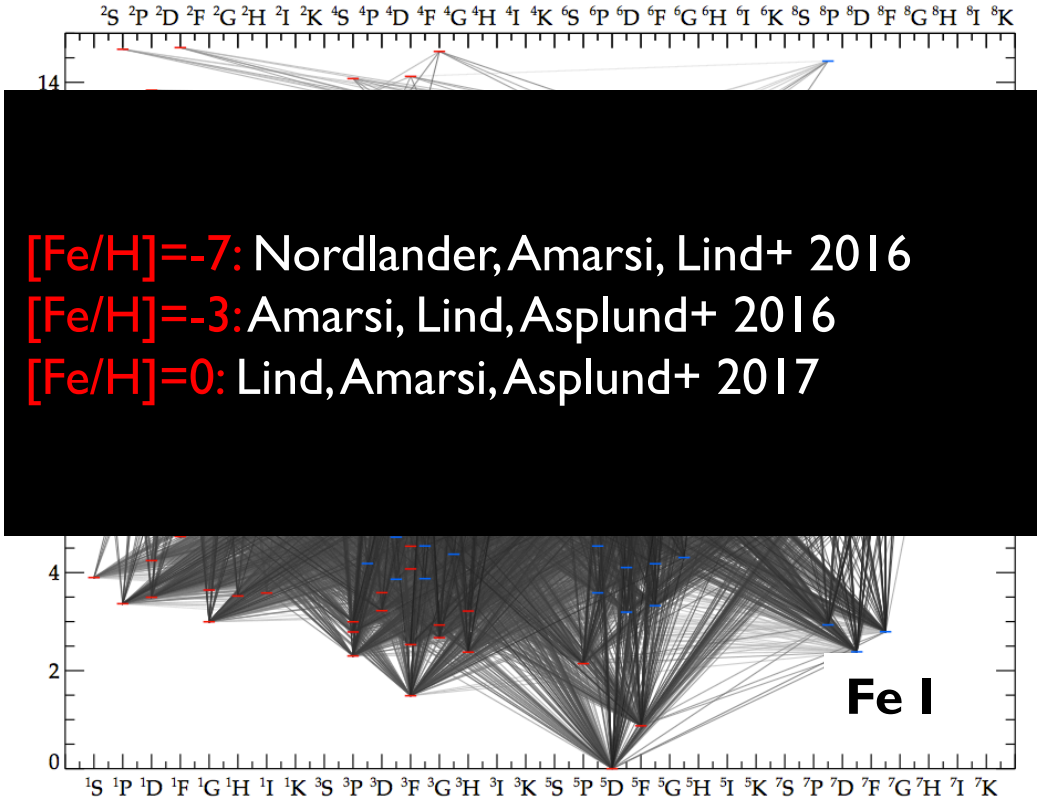
**2013** → **2016**




## A new atomic model for Fe

**Oscillator strengths/photoionisation**
**Collisional cross-sect. with H**




[Fe/H]=-7: Nordlander, Amarsi, Lind+ 2016
[Fe/H]=-3: Amarsi, Lind, Asplund+ 2016
[Fe/H]=0: Lind, Amarsi, Asplund+ 2017

# ATOM REDUCTION FOR 3D

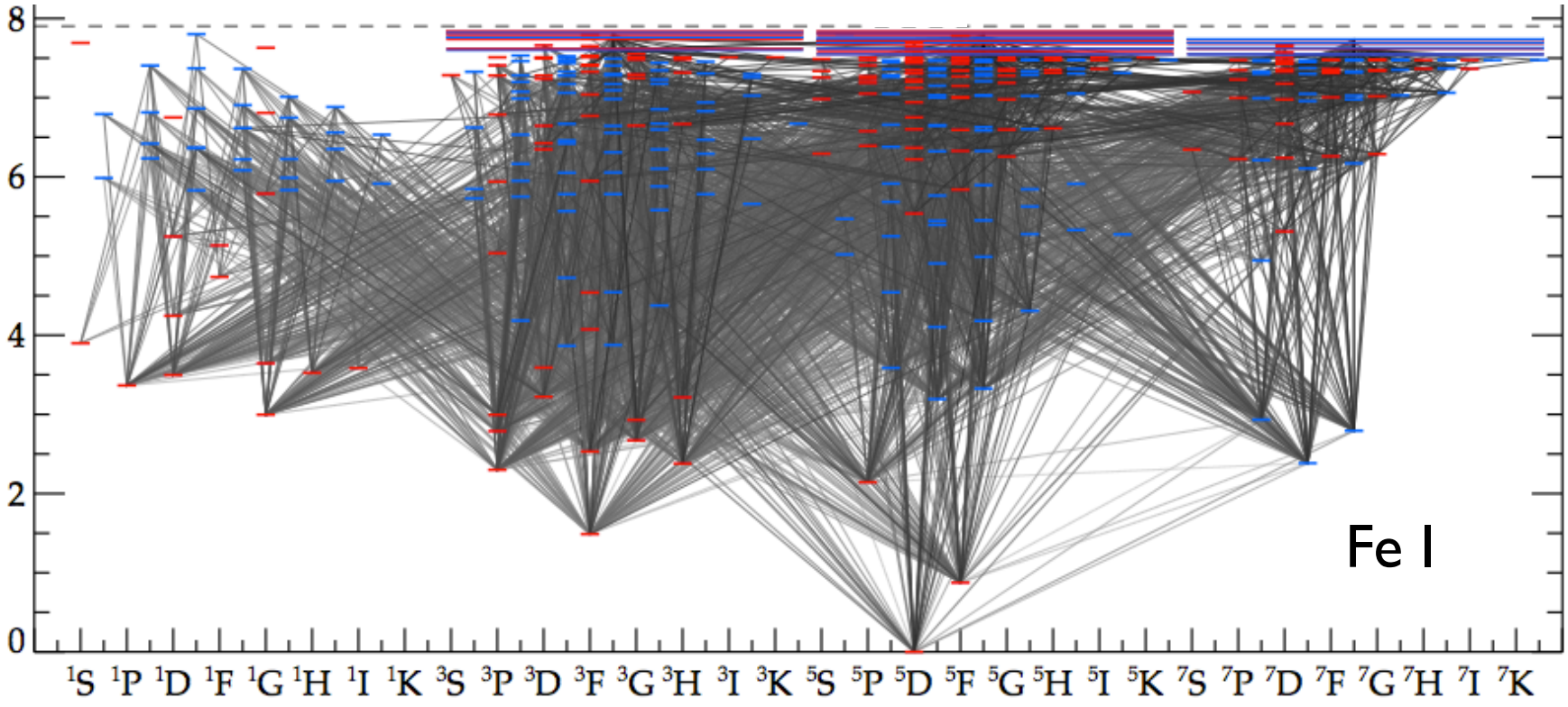
$$\sum_{j \neq i} n_j P_{ji} - \sum_{j \neq i} n_i P_{ij} = 0$$

$$P_{ij} = R_{ij} + C_{ij}$$

$$\Delta_{ij} = n_i R_{ij} - n_j R_{ji}$$

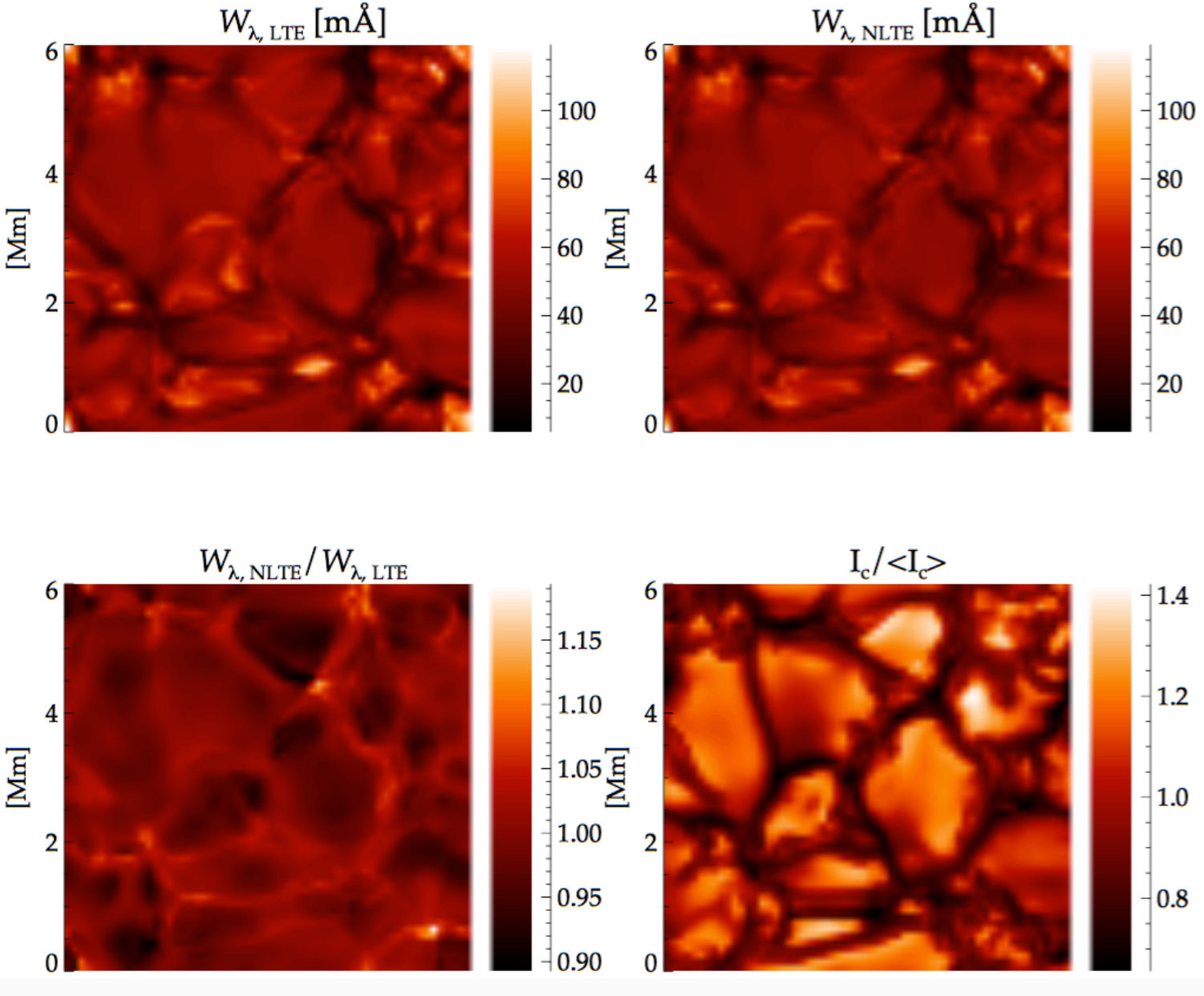
**Kurucz 2014 : 93,000 b-b radiative transitions**

**Reduced atom: only 4,000 needed !**



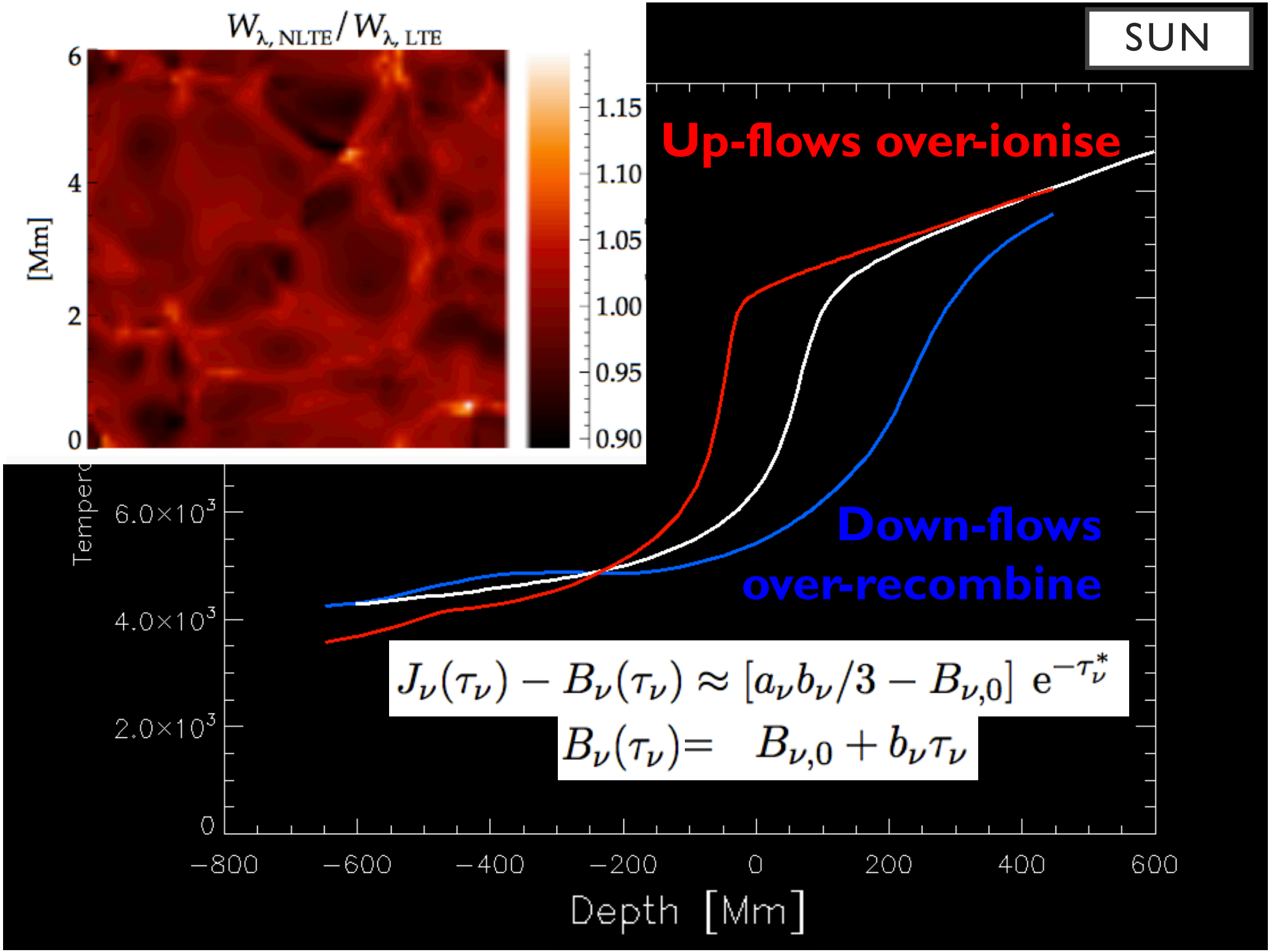

Lind+ 2017

# 3D NLTE ANALYSIS OF FE IN THE SUN

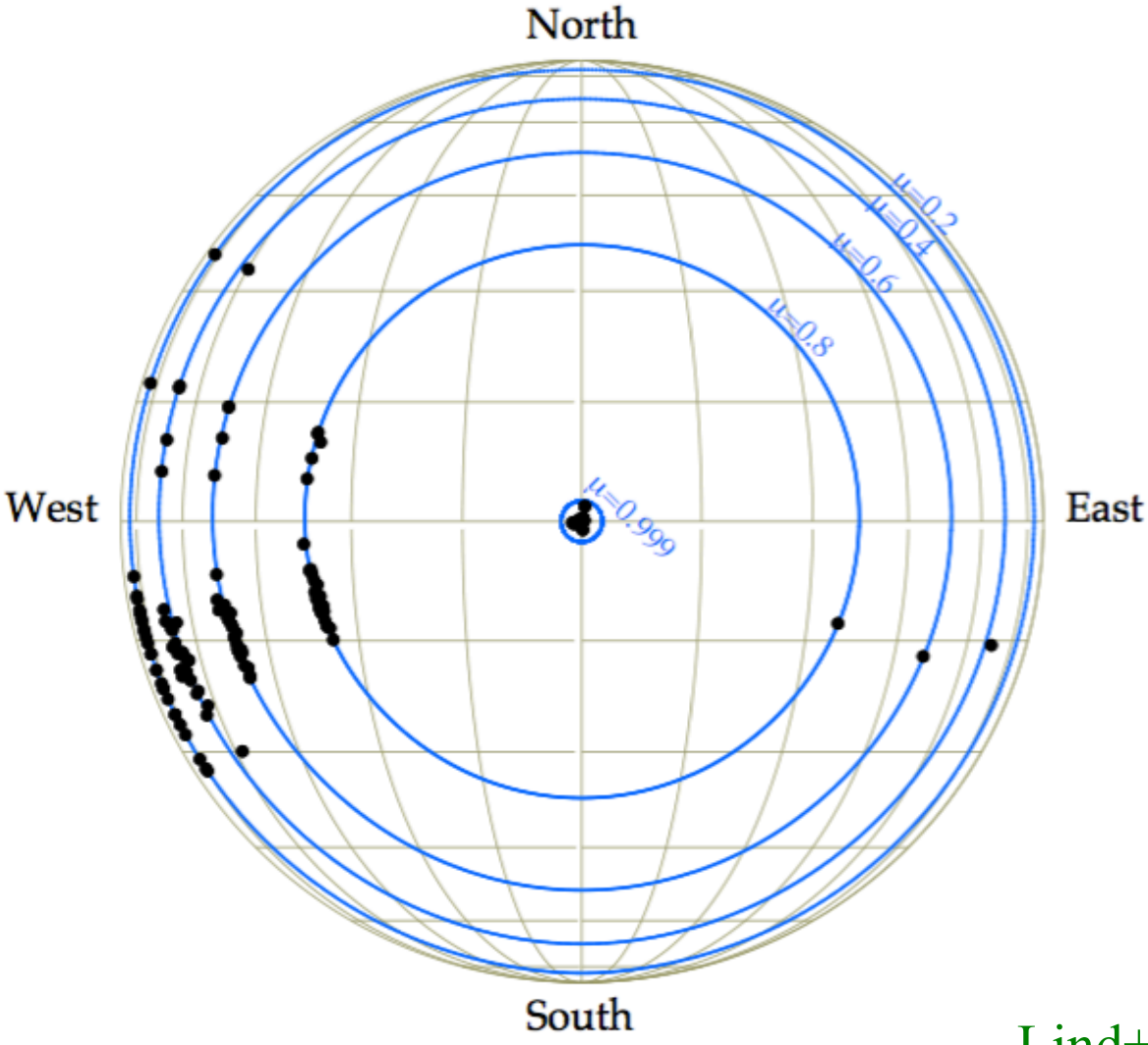



**Predicted line strength of Fe I 6151Å at disk centre**

Lind+ 2017

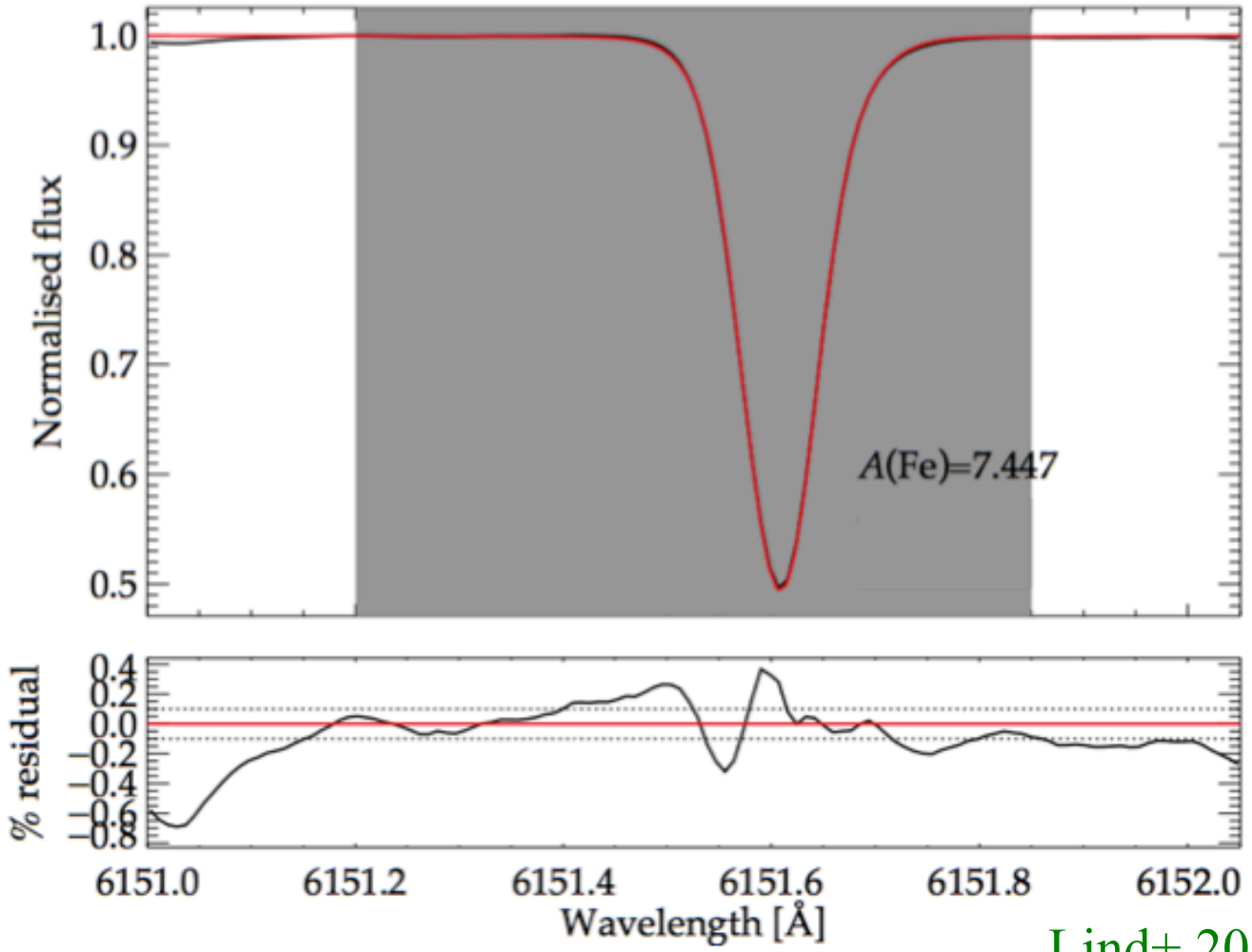

SUN
$W_{\lambda,\,\mathrm{NLTE}} / W_{\lambda,\,\mathrm{LTE}}$
[Mm]
0
2
4
6
0.90
0.95
1.00
1.05
1.10
1.15
Up-flows over-ionise
Down-flows over-recombine
$J_\nu(\tau_\nu) - B_\nu(\tau_\nu) \approx [a_\nu b_\nu/3 - B_{\nu,0}]\ \mathrm{e}^{-\tau_\nu^*}$
$B_\nu(\tau_\nu) = B_{\nu,0} + b_\nu \tau_\nu$
Tempera
$6.0\times10^3$
$4.0\times10^3$
$2.0\times10^3$
0
−800
−600
−400
−200
0
200
400
600
Depth [Mm]

# 3D NLTE ANALYSIS OF FE IN THE SUN

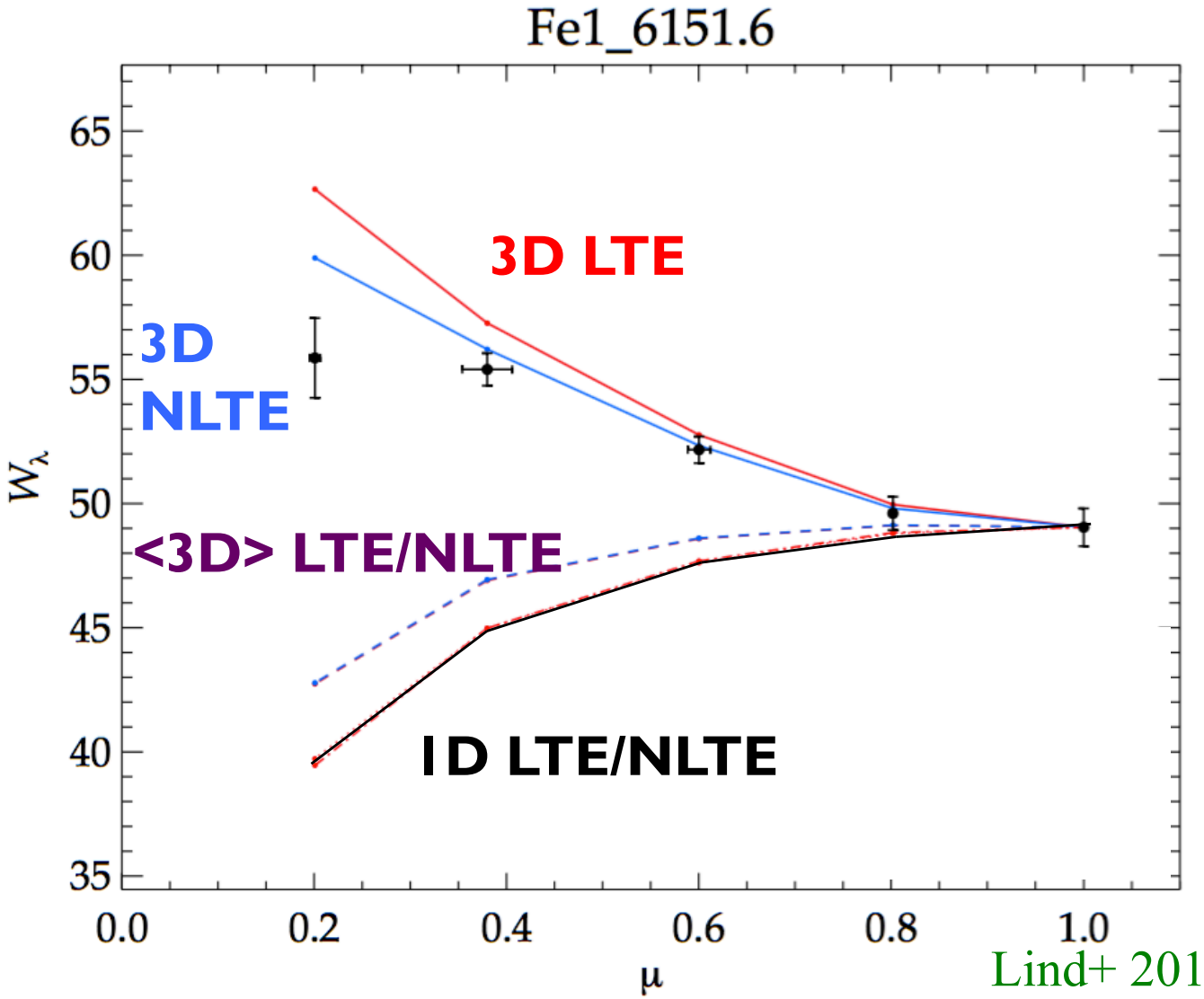

Lind+ 2017

# 3D NLTE ANALYSIS OF FE IN THE SUN


Lind+ 2017

# 3D NLTE ANALYSIS OF FE IN THE SUN

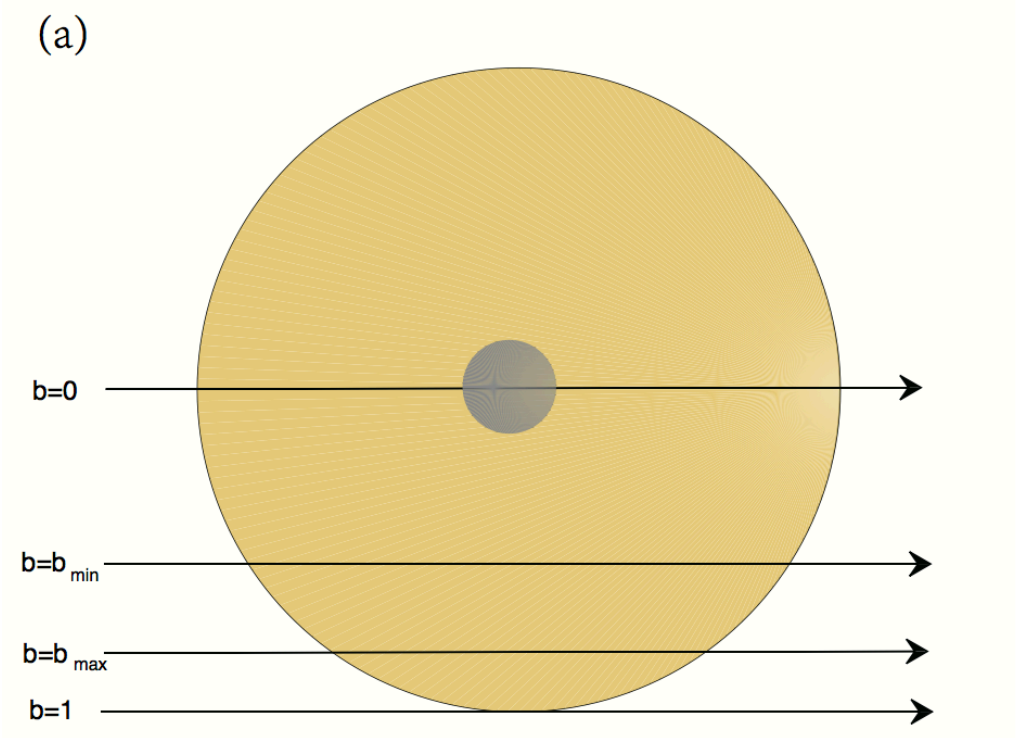



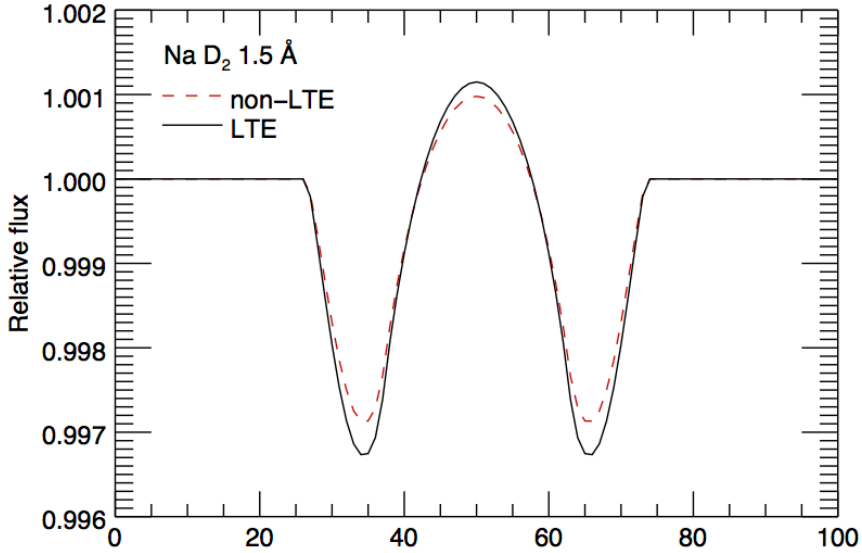

Lind+ 2017

# The effect of the stellar absorption line centre-to-limb variation on exoplanet transmission spectrum observations

F. Yan[1], E. Pallé[2,3], R. A. E. Fosbury[4], M. G. Petr-Gotzens[4], and Th. Henning[1]

[1] Max Planck Institute for Astronomy, Königstuhl 17, 69117, Heidelberg, Germany
e-mail: fyan@mpia.de
[2] Instituto de Astrofísica de Canarias, C/ vía Láctea, s/n, 38205 La Laguna, Tenerife, Spain
[3] Dpto. de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain
[4] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany



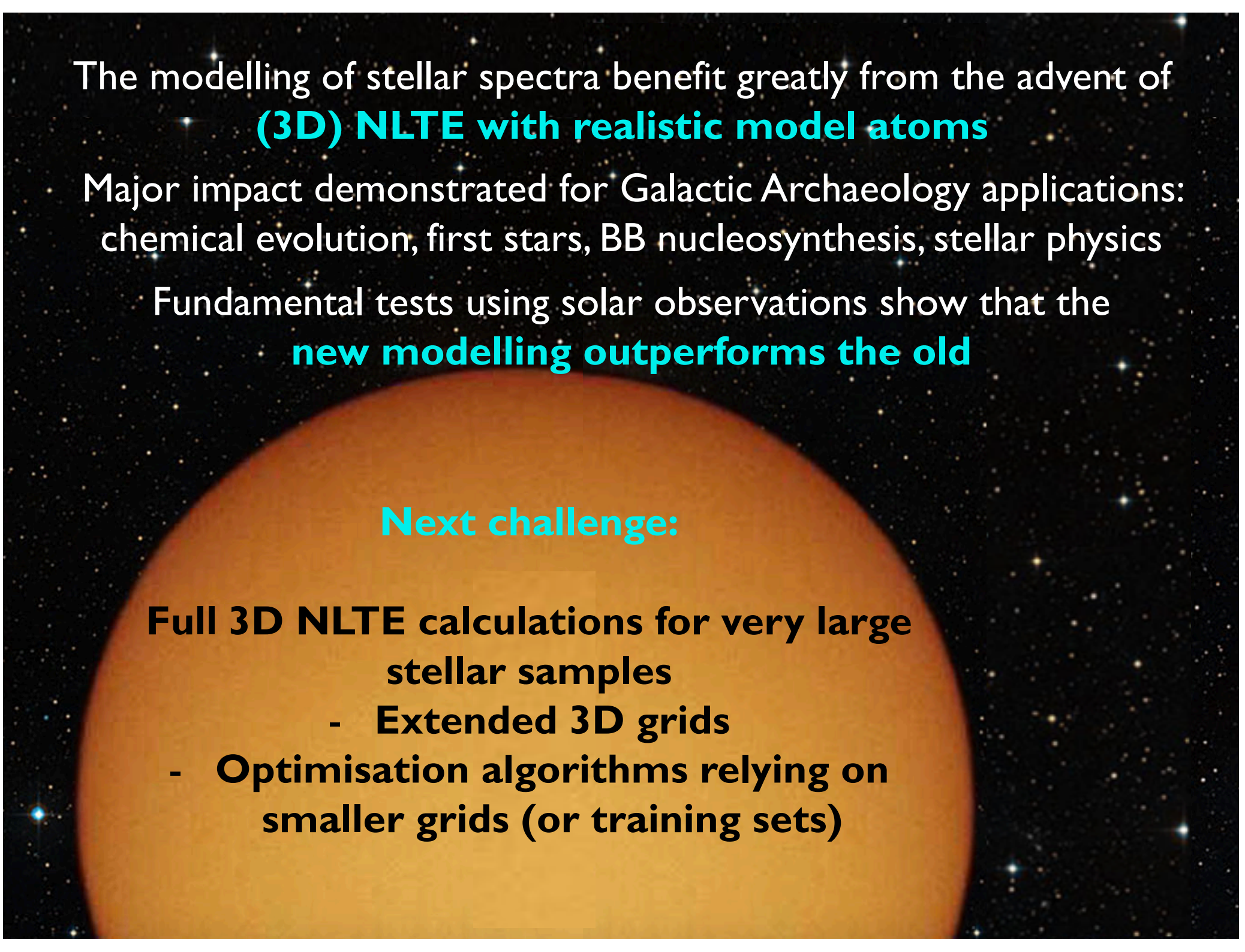
The modelling of stellar spectra benefit greatly from the advent of

**(3D) NLTE with realistic model atoms**

Major impact demonstrated for Galactic Archaeology applications: chemical evolution, first stars, BB nucleosynthesis, stellar physics

Fundamental tests using solar observations show that the

**new modelling outperforms the old**



**Next challenge:**

**Full 3D NLTE calculations for very large stellar samples**

- **Extended 3D grids**
- **Optimisation algorithms relying on smaller grids (or training sets)**