EFFECTS OF MODELING METHODS ON ABUNDANCE DETERMINATION UNCERTAINTIES IN R-PROCESS STARS

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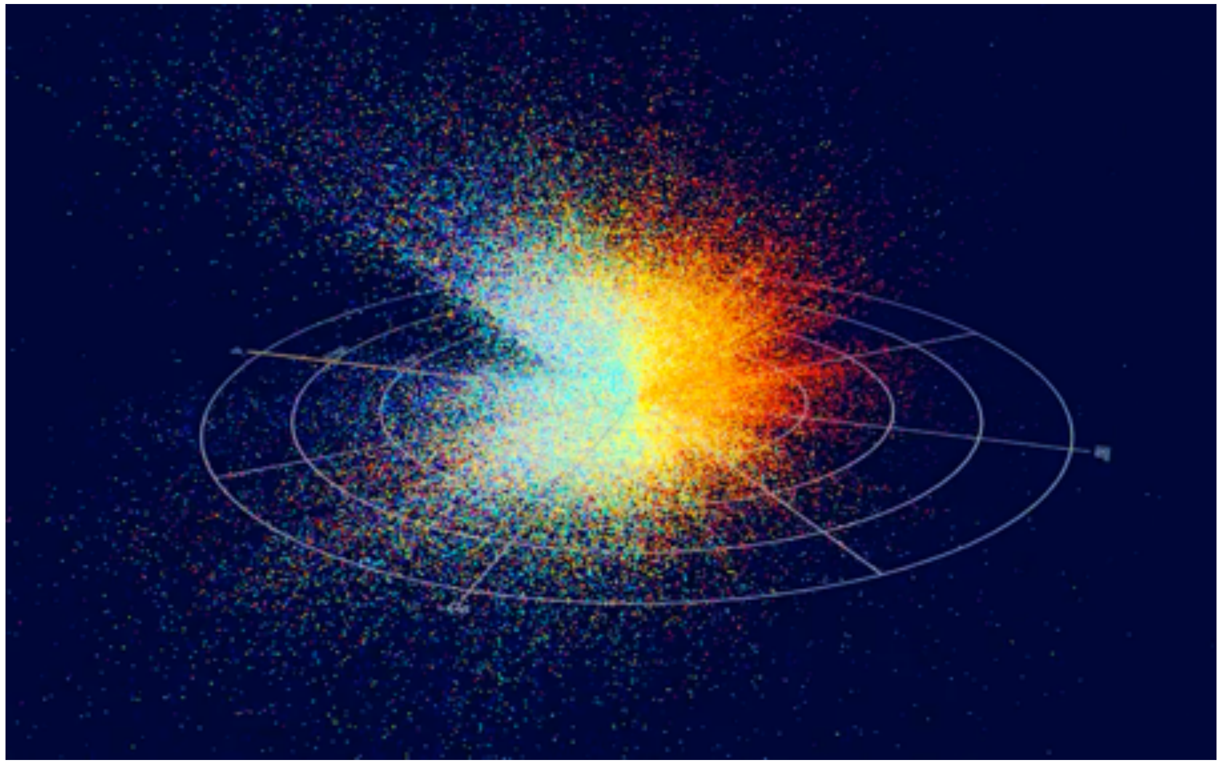
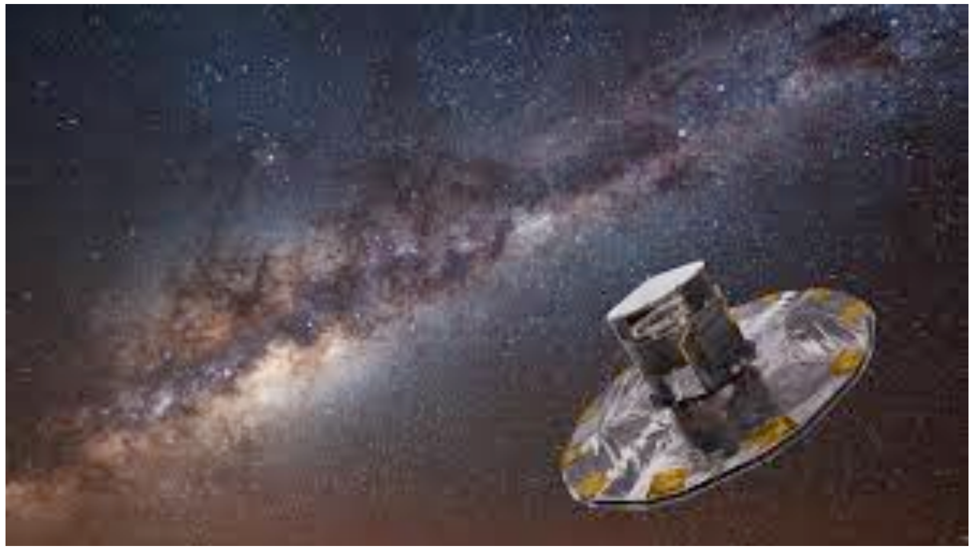
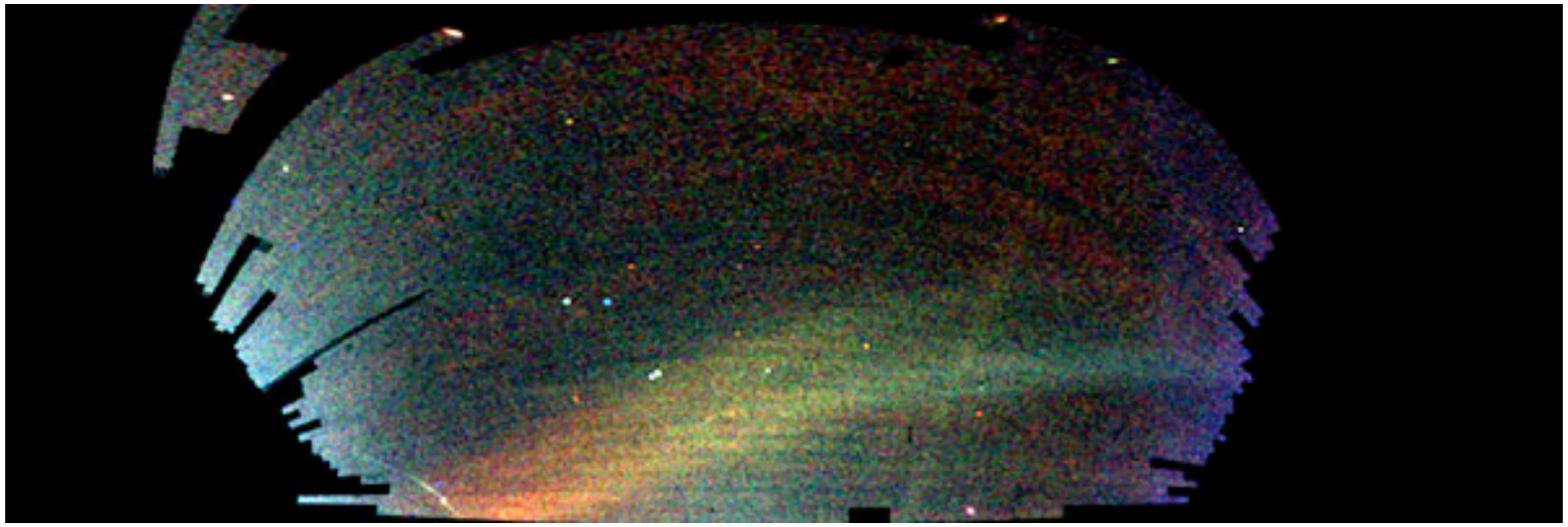
ERA OF LARGE SCALE SURVEYS



RAVE (phys.org)

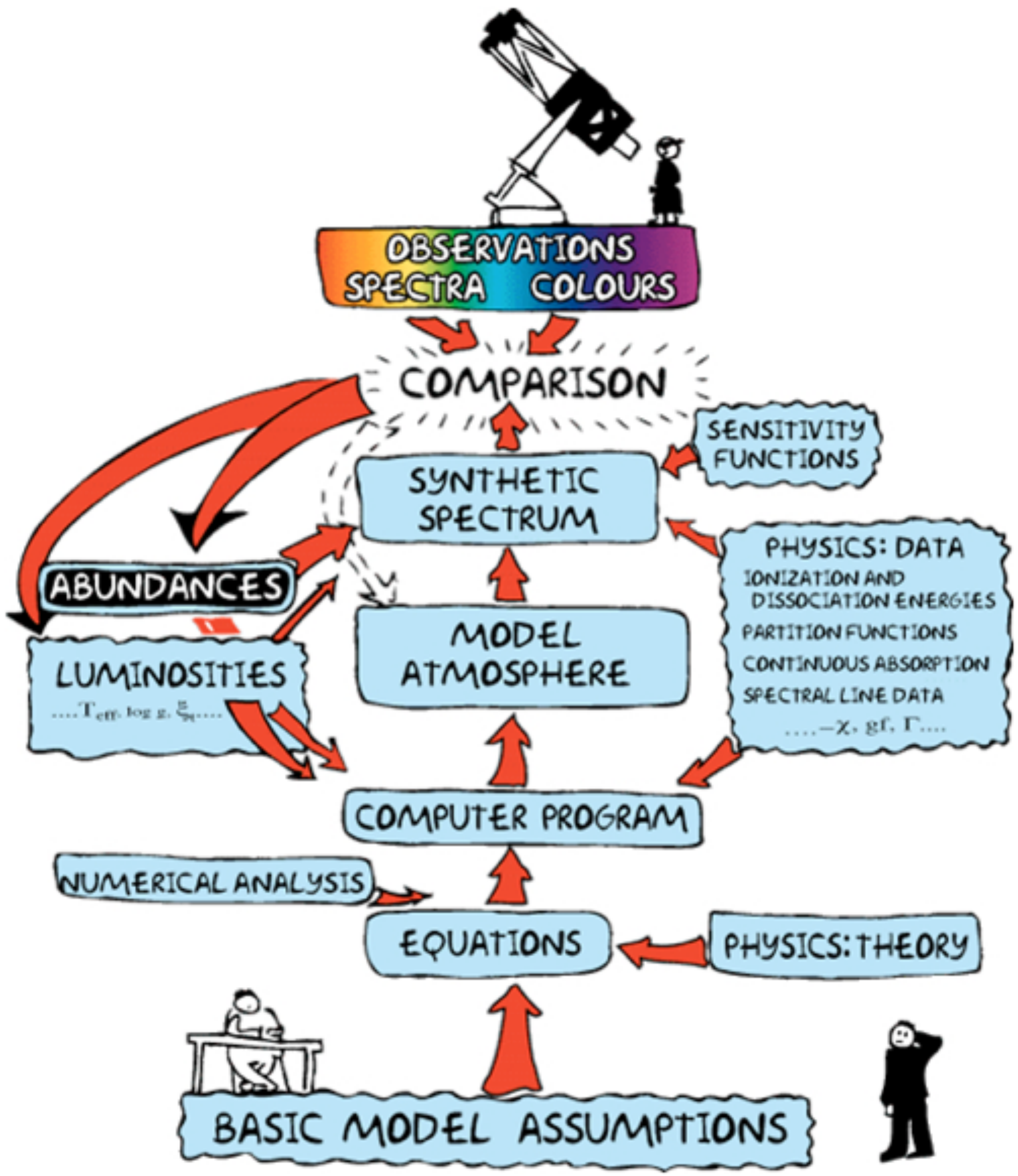


Gaia (esa.int)



SDSS (sdss.org)

ABUNDANCES ARE NOT MEASURED, BUT DERIVED!



B. Gustafsson,
Astronomical Observatory,
Uppsala (2009)

Spectral line formation

To determine relevant properties of a star ($T_{\rm eff}$, log g, [Fe/H], ...) $\Rightarrow$ Compare models of stellar atmosphere (i.e. emergent flux,SED,...) to observable quantities.

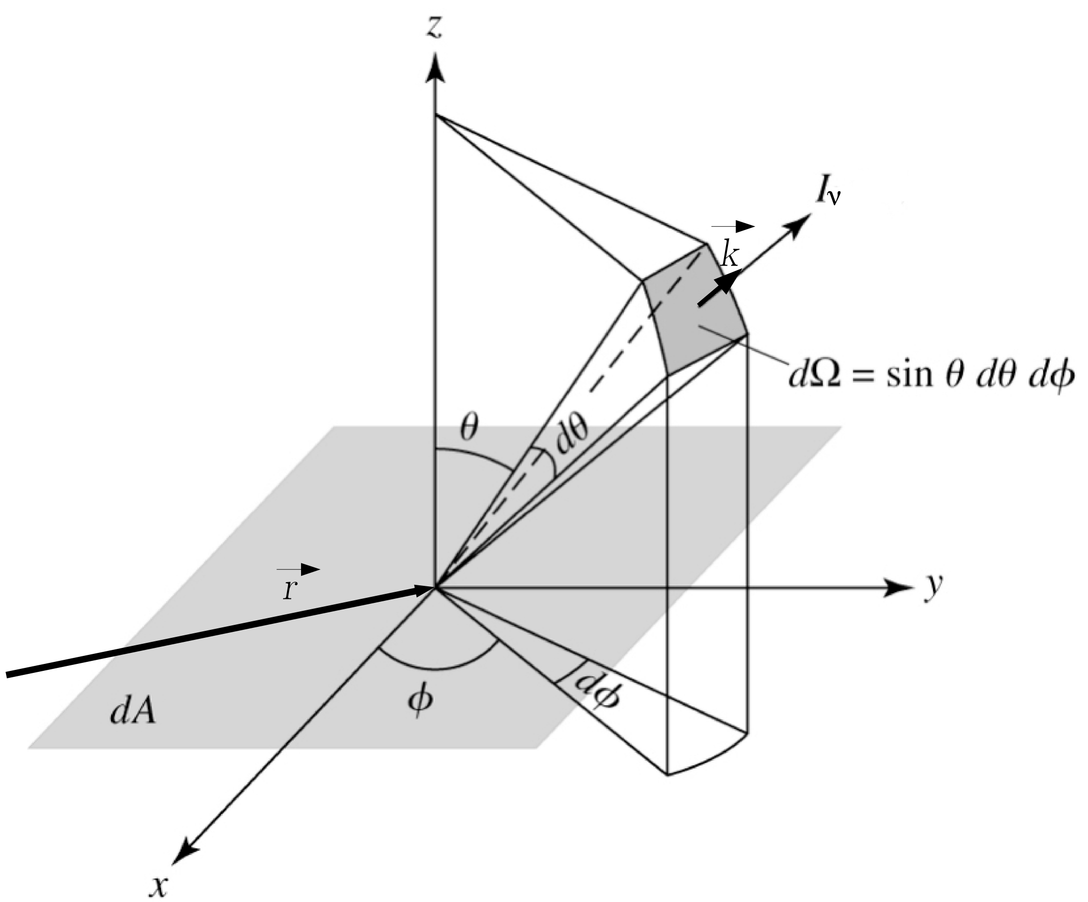
Emergent flux calculation

Radiative transfer equation (plane-parallel) :

$$\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = S_\nu - I_\nu \qquad (1)$$

Optical depth : $$\tau_\nu(z_0) = \int_{z_0}^{\infty} \kappa_\nu \rho \mathrm{d}z \qquad (2)$$

Source function : $$S_\nu = \frac{j_\nu}{\alpha_\nu} \qquad (3)$$



Solution requires adoption of approximations (plane-parallel, monochromatic radiation, static atmosphere, no magnetic fields, ..) and knowledge of source function S_ν.

Abundances are not measured BUT determined using approximations:

- Plane-parallel vs. spherical geometry
- Homogeneity
- Stationarity
- Hydrostatic equilibrium
- 1D vs. 3D atmospheres
- Thermal equilibrium

HOMOGENEITY

$X, Y, Z \neq f(r, \theta, \Phi)$ we assume a homogeneous atmosphere as an averaged model. This average model describes the average stellar properties well.

STELLAR ATMOSPHERES ASSUMPTIONS:

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- Local thermodynamic equilibrium (LTE)

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Special case : Local Thermodynamic equilibrium (LTE)

- Matter assumed in equilibrium with the radiation field over a finite volume of gas.
- Properties of gas defined by one T at each depth.

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Radiation in LTE

Kirchhoff-Planck's law : $$[S_\nu]_{\mathrm{LTE}} = B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_{\mathrm{B}}T}-1} \tag{4}$$

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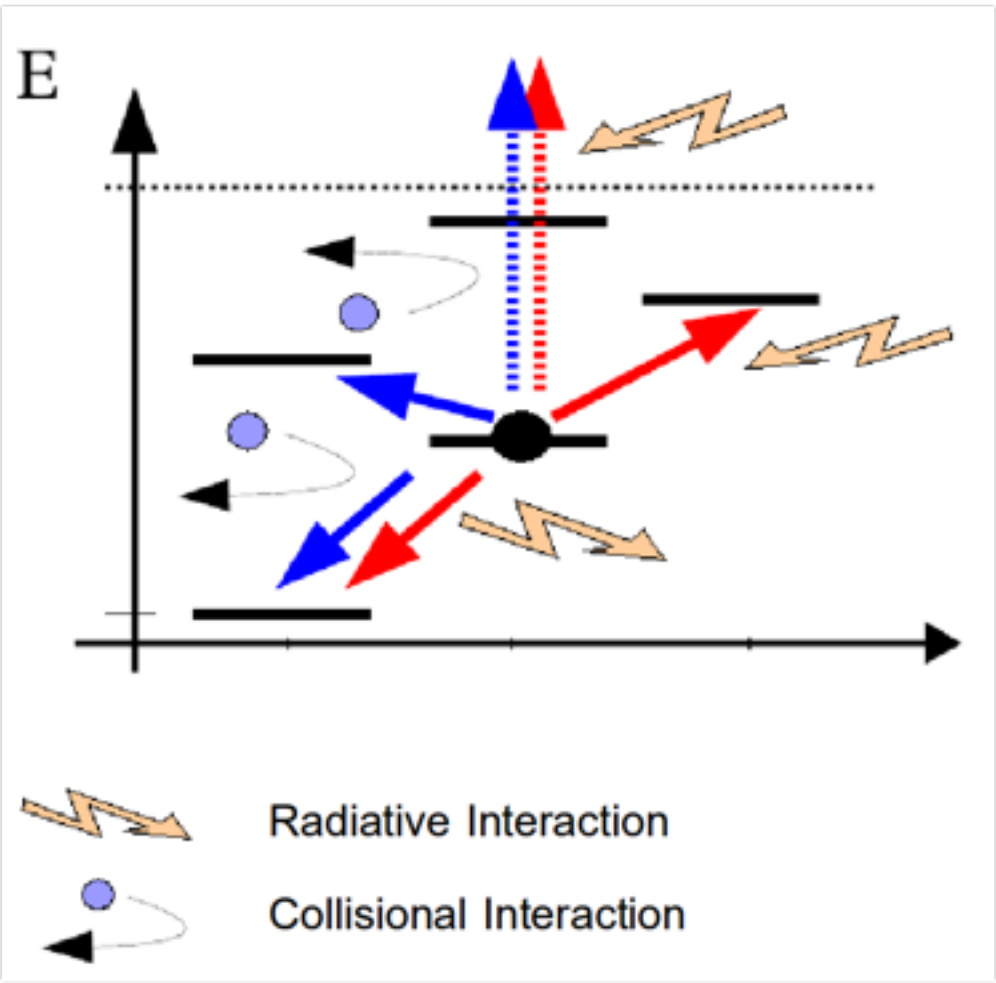
Matter in LTE

Maxwell velocity distribution :
$$f(v)\mathrm{d}v = \left(\frac{m}{2\pi k_\mathrm{B}T}\right)^{3/2} 4\pi v^2 e^{-(1/2)mv^2/k_\mathrm{B}T}\mathrm{d}v \qquad (5)$$

Boltzmann distribution :
$$\frac{n_i}{n_j} = \frac{g_i}{g_j}e^{-\Delta\chi/k_\mathrm{B}T} \qquad (6)$$

The Saha equation :
$$\left[\frac{N_1}{N_0}P_e\right] = \frac{(2\pi m_e)^{3/2}(k_\mathrm{B}T)^{5/2}}{h^3}\frac{2u_1(T)}{u_0(T)}e^{-\chi_0^\infty/k_\mathrm{B}T} \qquad (7)$$

Photons carry non-local information:
Everything depends on everything,
everywhere else!



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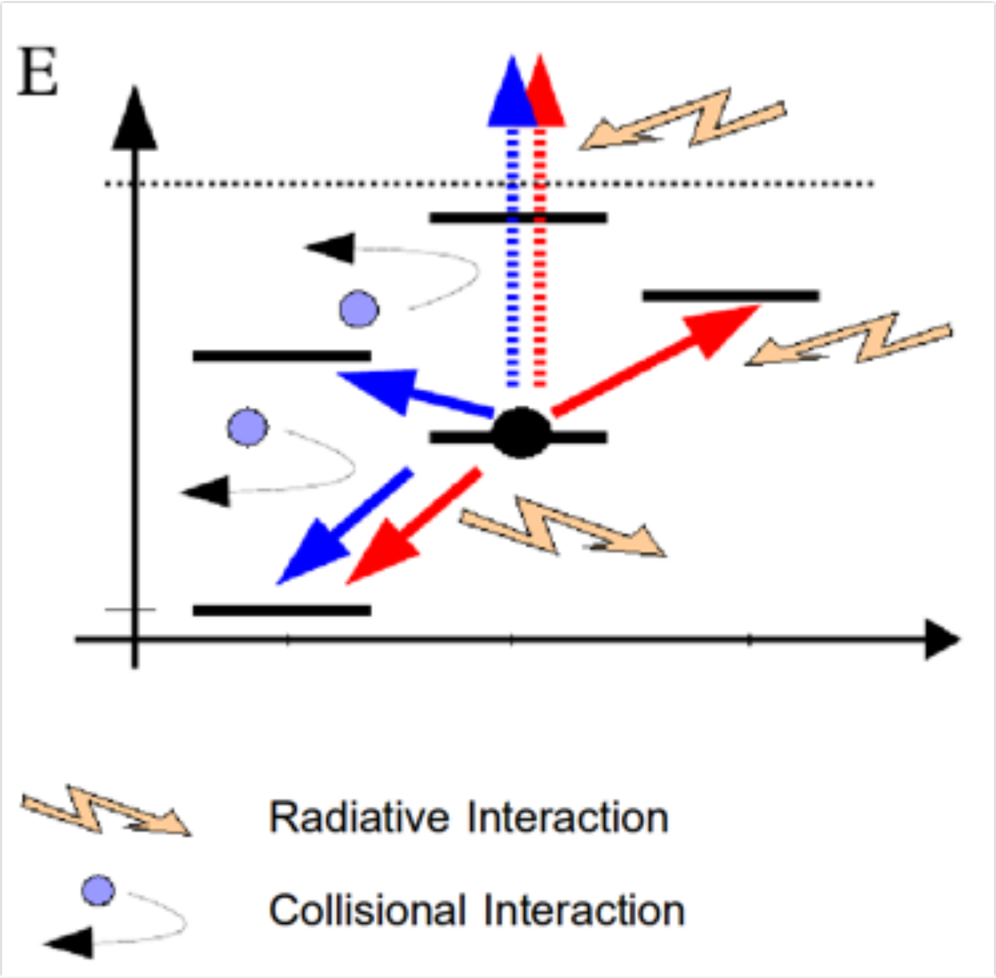
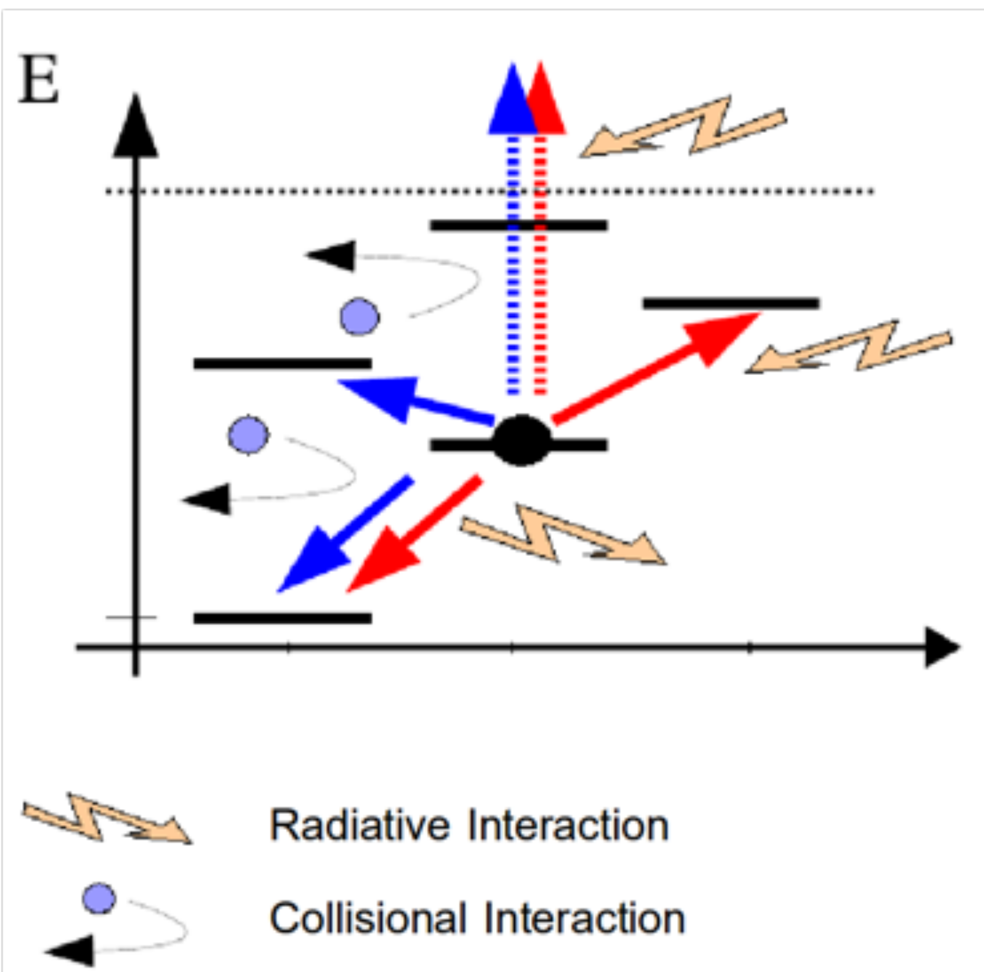


Statistical Equilibrium Equation has to be solved simultaneously with the radiative transfer equation:

$$\boxed{n_i \sum_{j \neq i} (\mathbf{R}_{ij} + \mathbf{C}_{ij}) = \sum_{j \neq i} n_j (\mathbf{R}_{ji} + \mathbf{C}_{ji})}$$

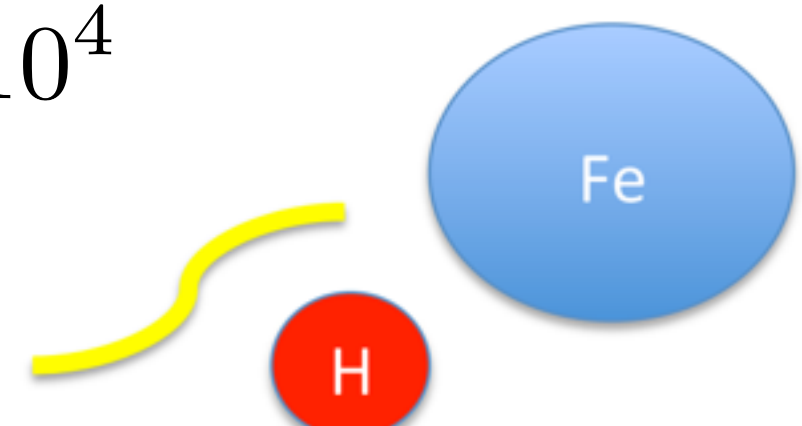
Bulk of atomic data required in NLTE calculations.



Status Quo?

Large uncertainties still associated with collisional rates due to lack of experimental cross-section data, esp. collisions with Hydrogen in cool stars which plays an important role esp. in metal-poor stars.

$$\frac{n_{\rm H}}{n_{e-}} \sim 10^4$$



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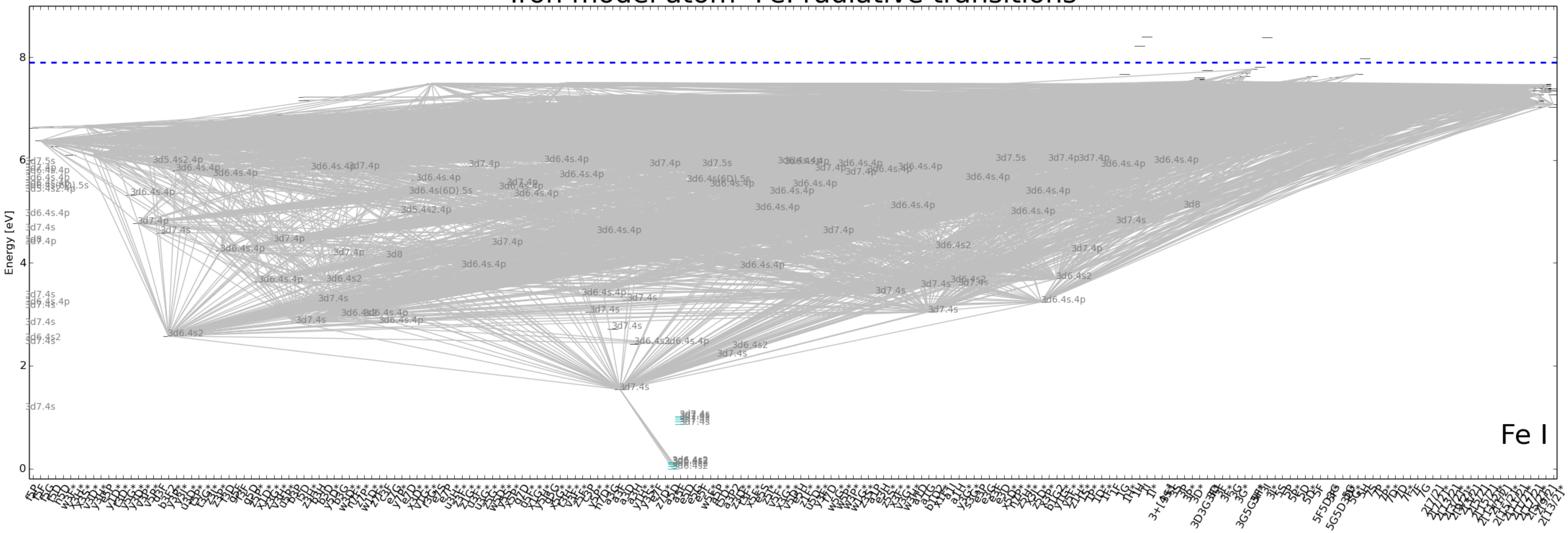
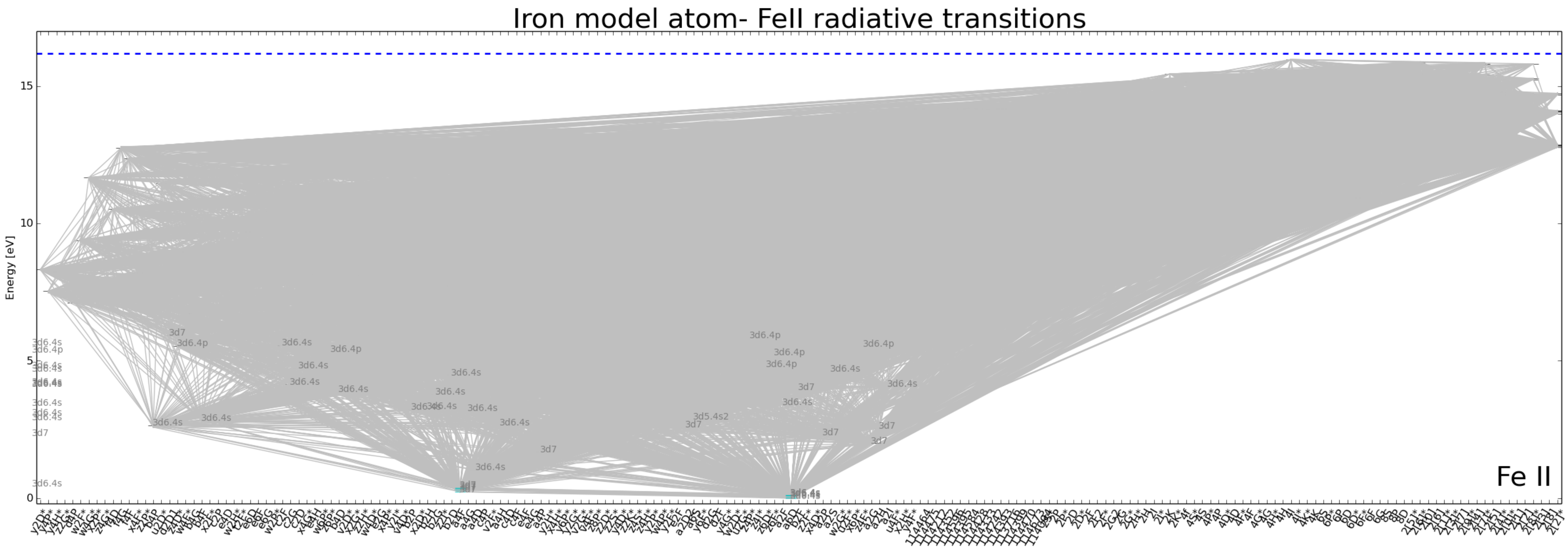
Iron model atom- FeI radiative transitions

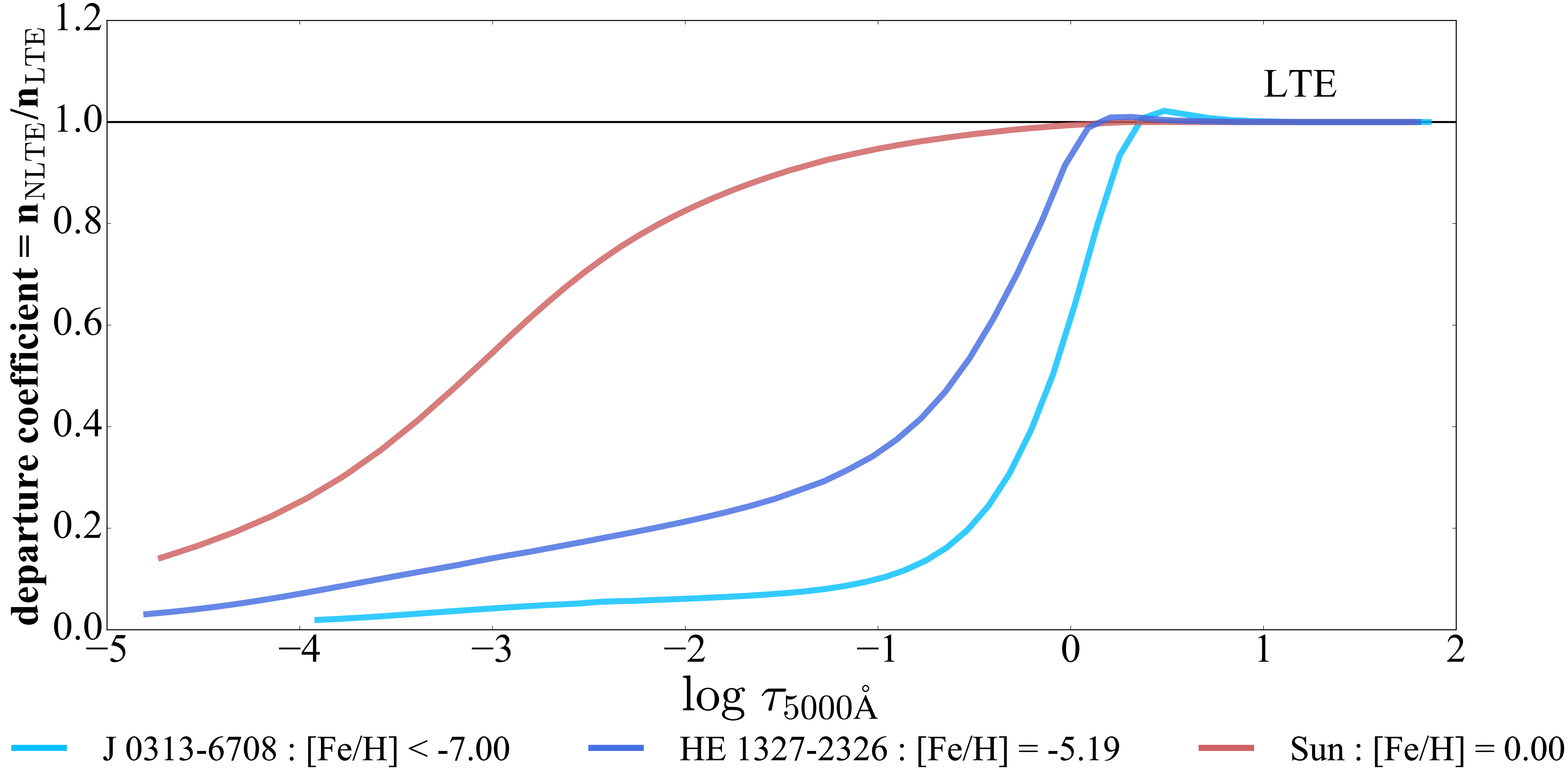


Rana Ezzeddine, PhD, 2015



Rana Ezzeddine, PhD, 2015

departure coefficient (b)= level population density (NLTE)/level population density (LTE)



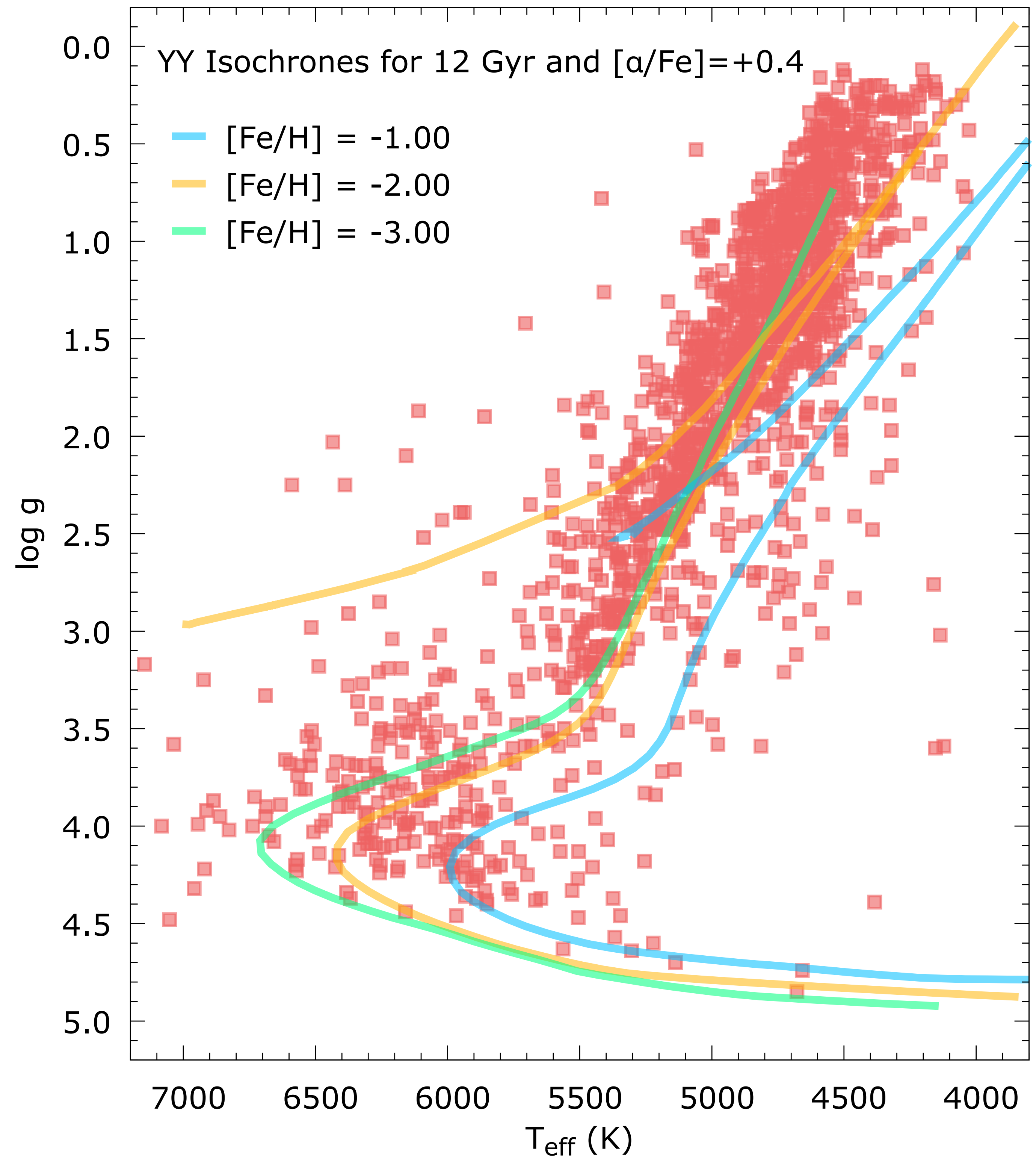
Deviations from LTE increase toward lower metallicities

MOST R-PROCESS STARS ARE OLD AND METAL-POOR

1694 RAVE r-process stars

Placco et al. 2018

NLTE can be important!



Iron abundance

Its importance

1- Proxy to the total metal content $\sim$ [Fe/H]

2- Wealth of lines in most stellar spectra

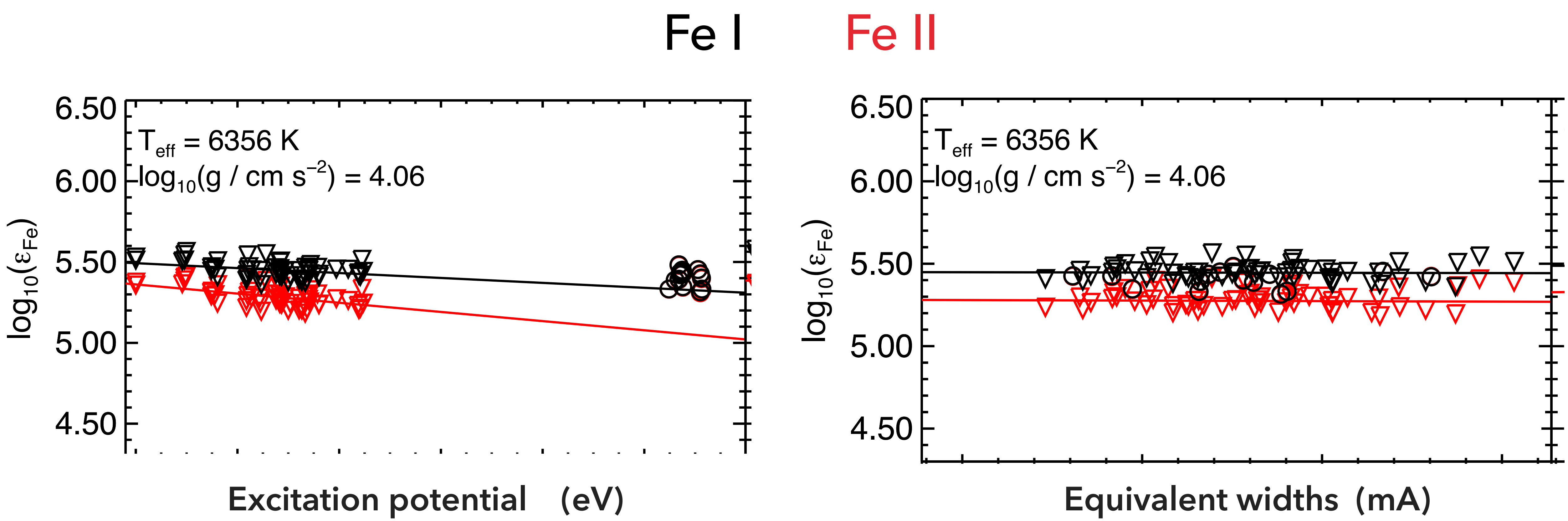
3- Opacity contribution

4- Relative elemental abundances [X/Fe] used in galactic chemical evolution studies

5- Used to determine spectroscopic Teff, logg, .. iteratively

SPECTROSCOPIC STELLAR PARAMETERS (FE)

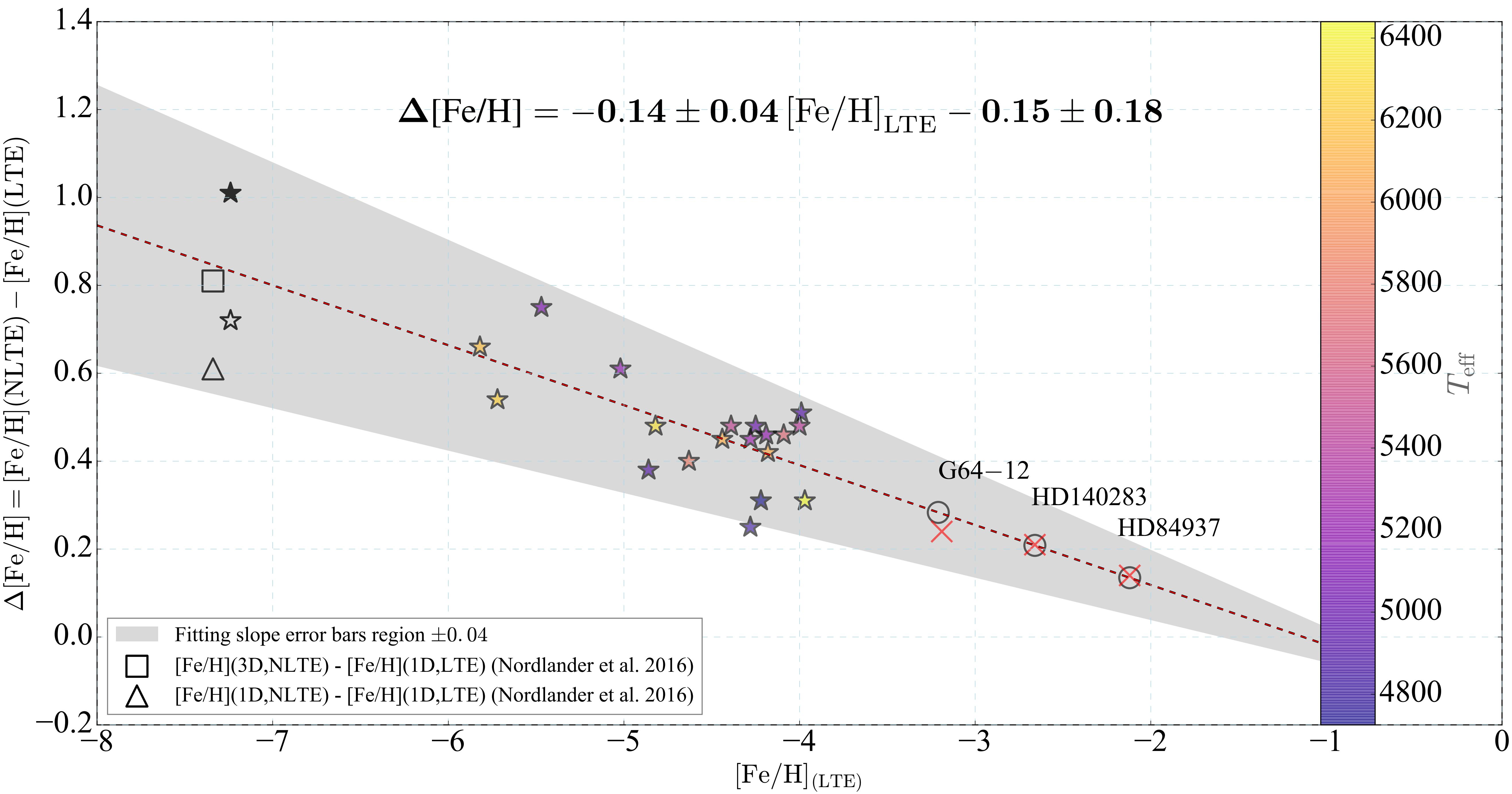
Amarsi et al. (2016)



Parameters determined iteratively by removing trends between Fe I and Fe II

Departure from LTE can be severe in iron-poor stars!

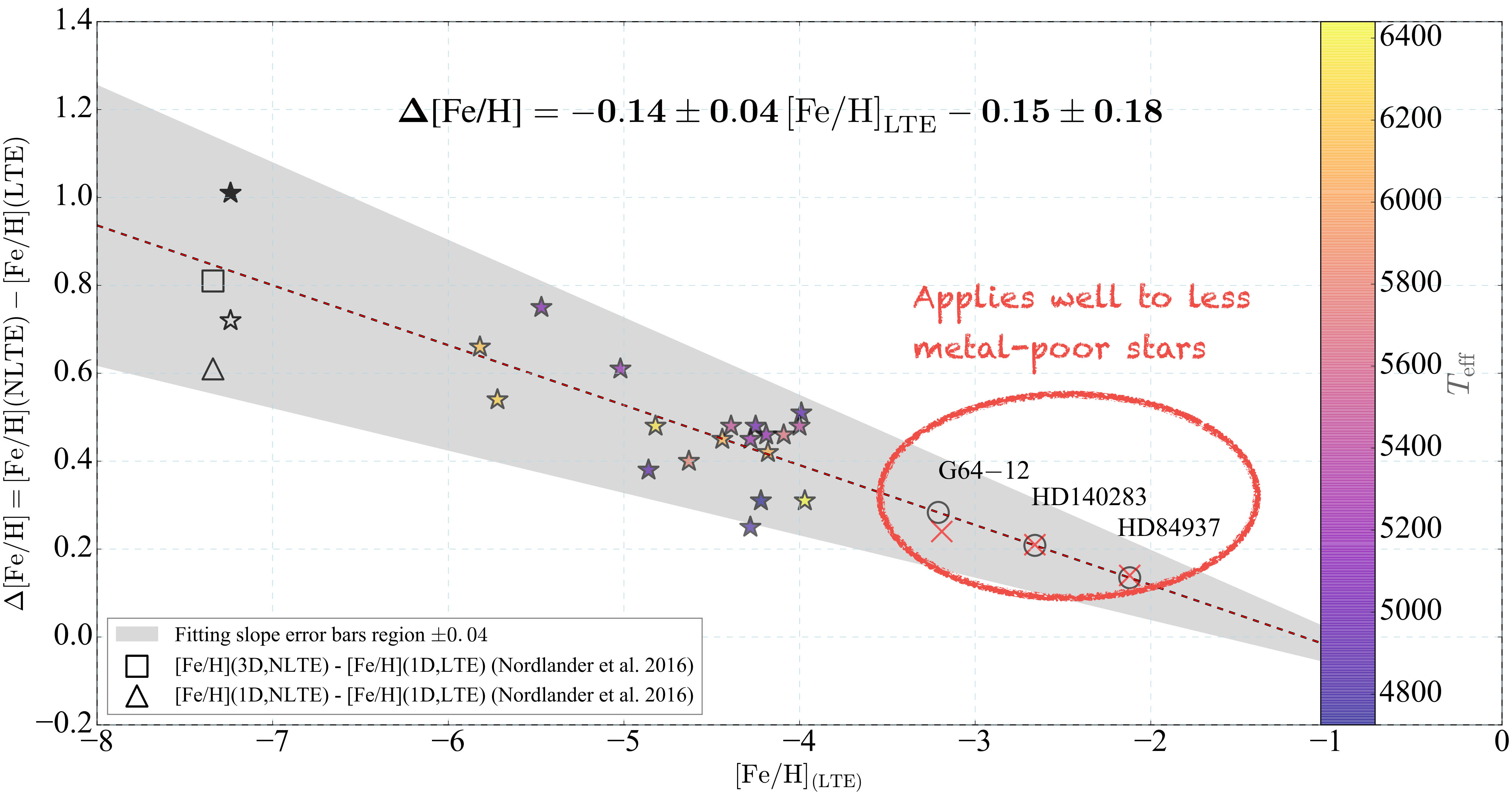
Ezzeddine et al. 2017



NLTE EFFECTS : IRON

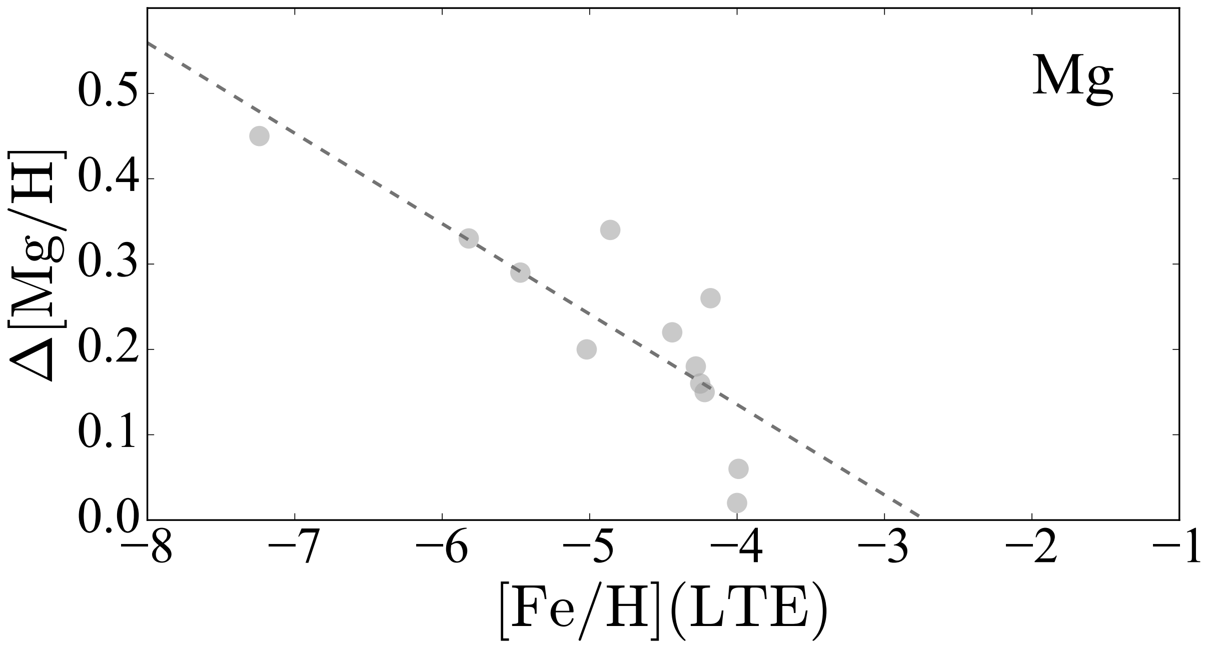
Departure from LTE can be severe in UMP stars!

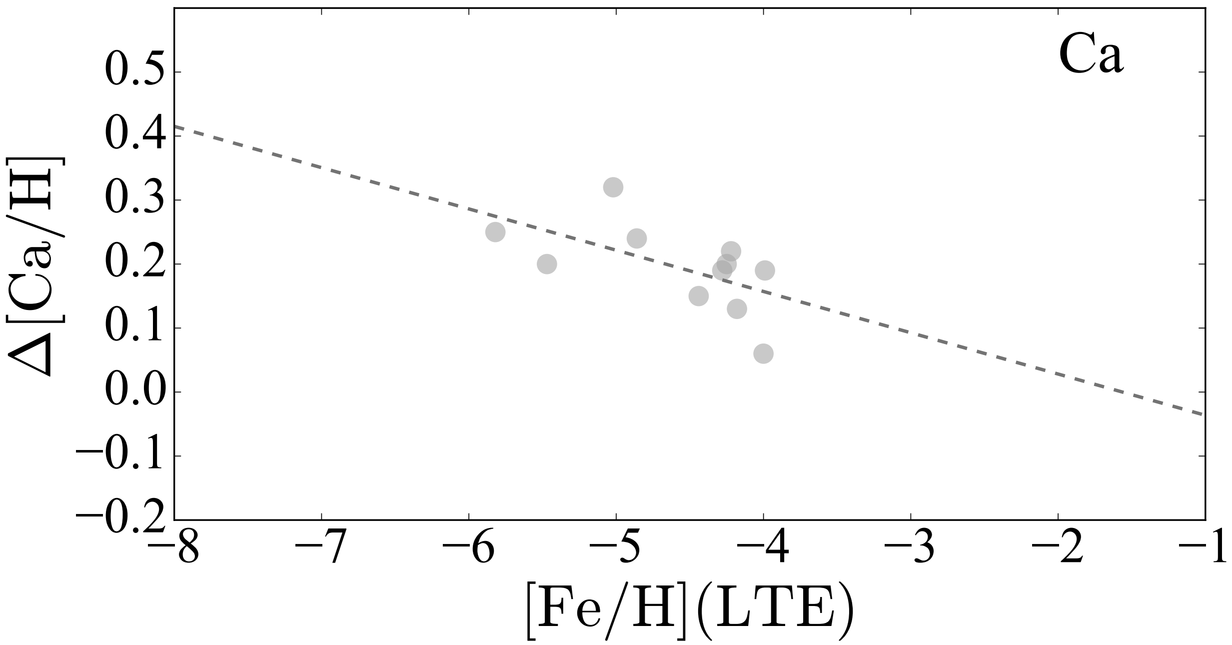
Ezzeddine et al. 2017

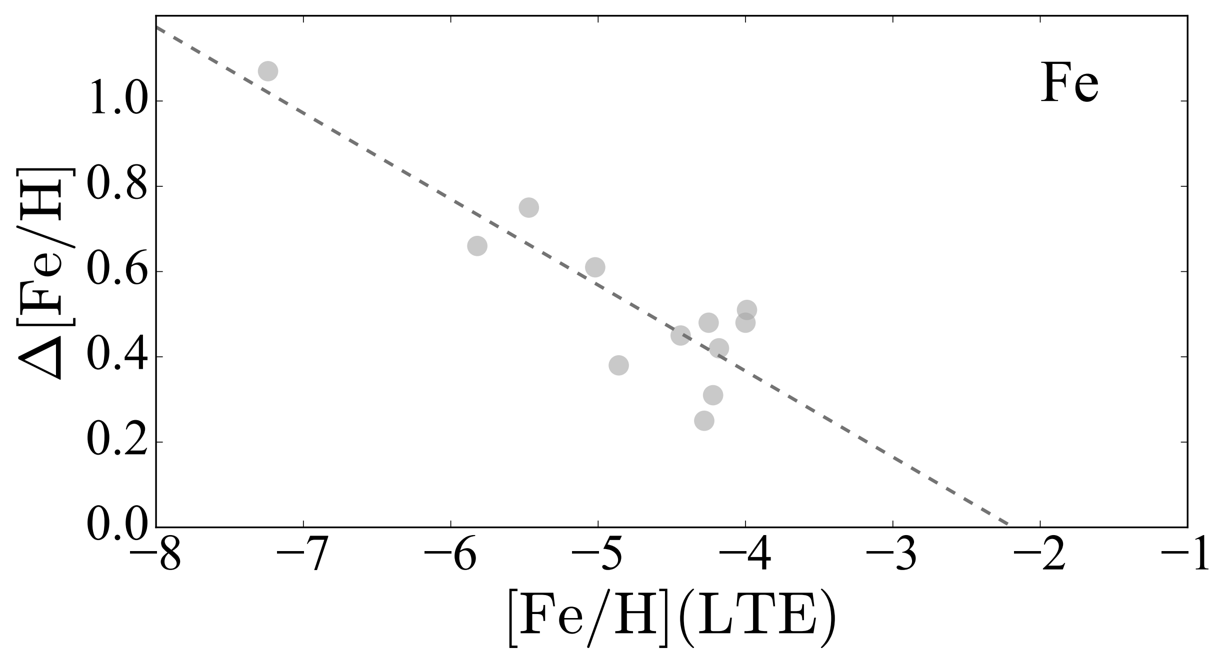


NLTE EFFECTS : MG & CA

Sitnova, Ezzeddine et al. (in prep.)







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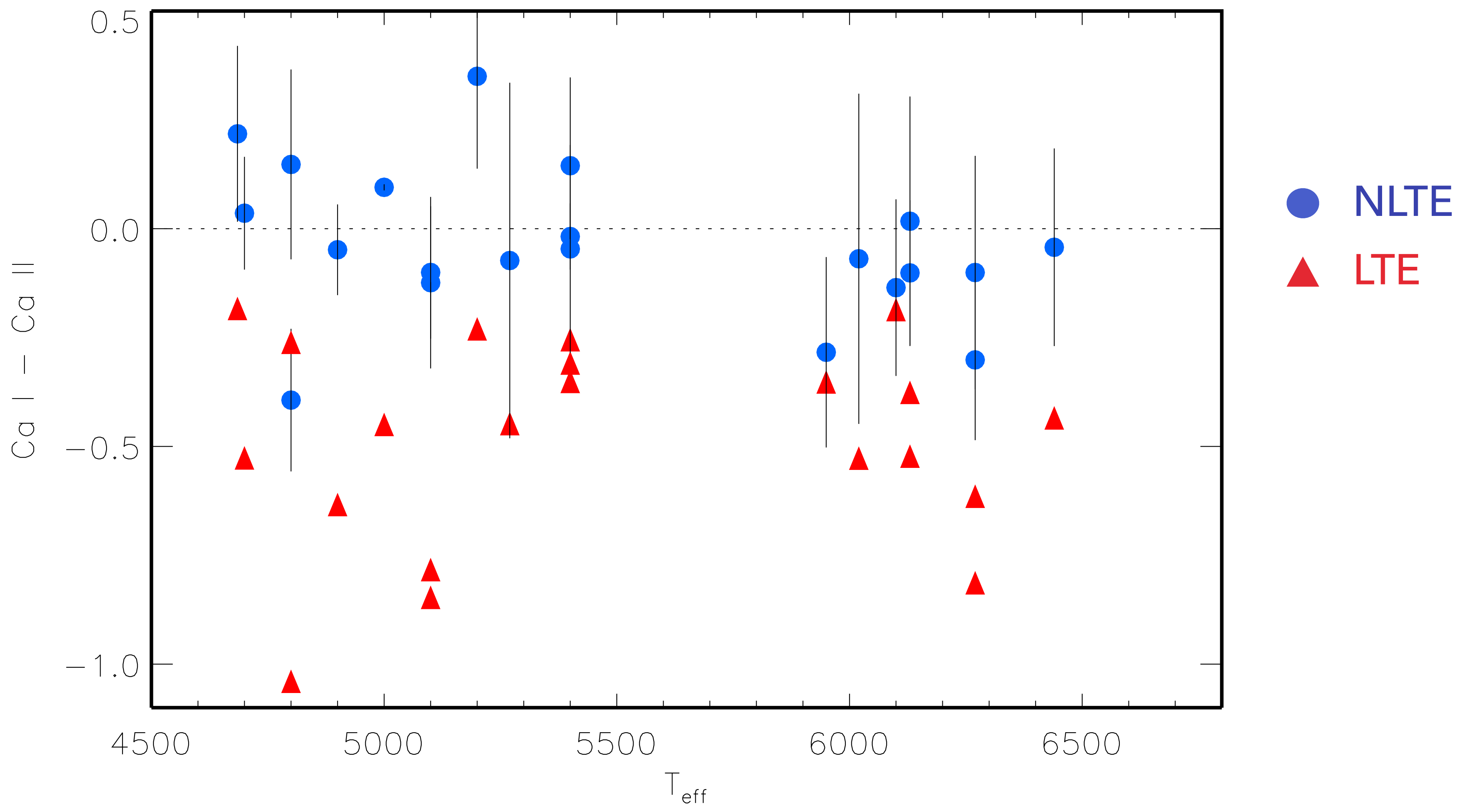


Better agreement between Ca I and Ca II in NLTE vs. LTE

FE NLTE GRID

[TEFF, LOGG, [FE/H], MICROTURBULENT VELOCITY (VT)]

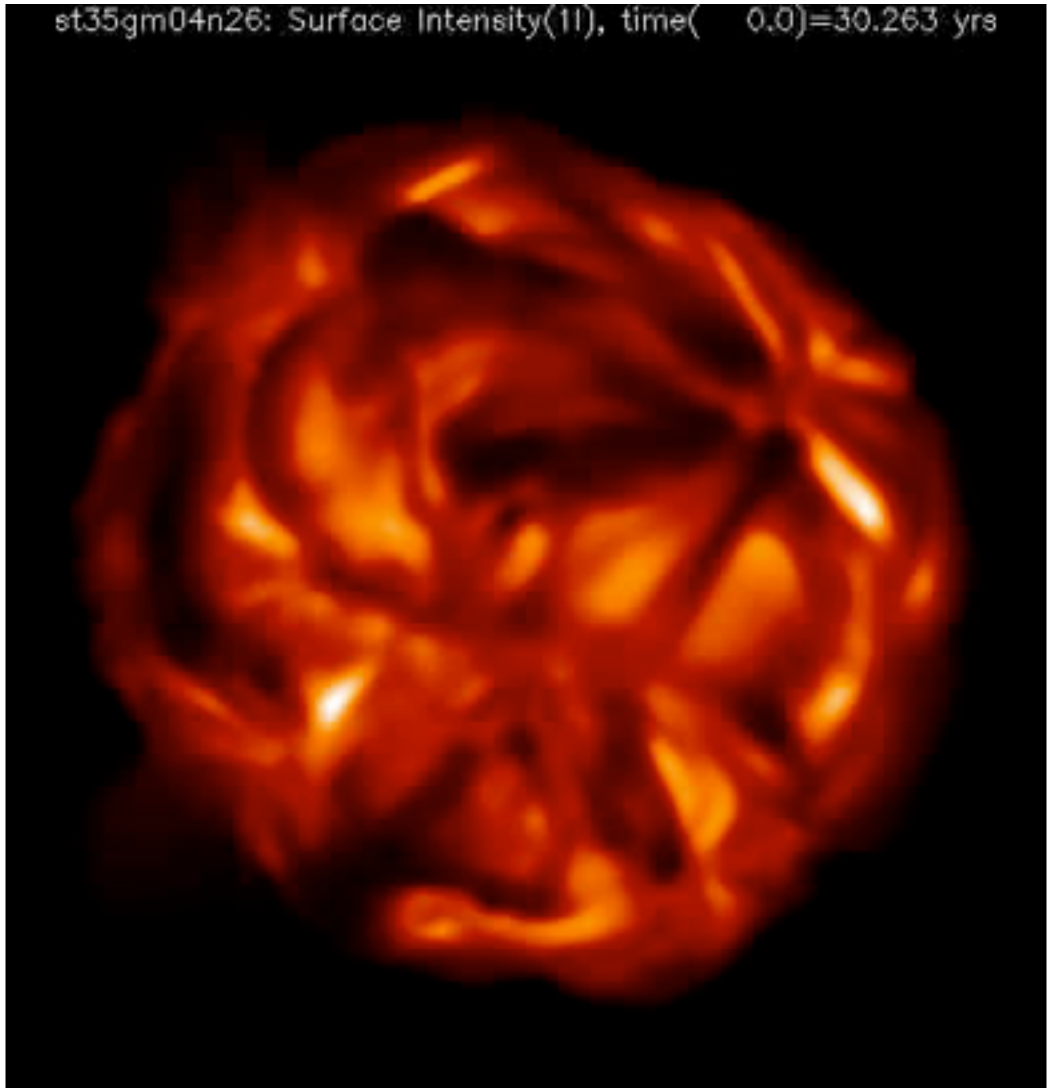
SPACE SMALL STEPS OF

- 50K FOR TEMPERATE
- 0.1 DEX FOR GRAVITY
- 0.2 DEX FOR [FE/H] (TO BE REDUCED TO 0.1)
- 0.5 DEX FOR VT

–> TESTED ON BENCHMARK STARS

–> LOGG AGREE WITH GAIA DR2 PARALLAXES

–> CAN BE USED TO DETERMINE NLTE STELLAR PARAMETERS AND FE ABUNDANCES

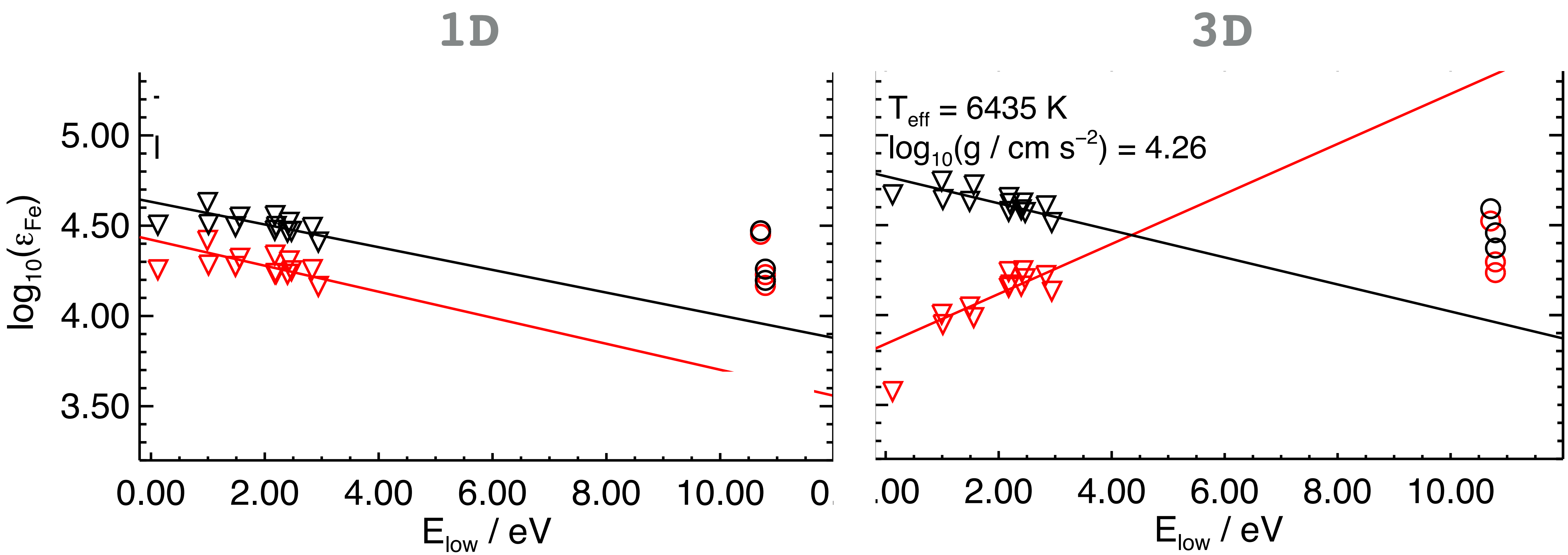


Matthias Steffen
3D COBOLD simulations

3D important for CNO elements : large 3D effects

STELLAR ATMOSPHERES ASSUMPTIONS : IS 1D OKAY VS 3D?

Amarsi et al. (2016)



NLTE **LTE**

1D, NLTE better than 3D, LTE!

- Our abundances are only as good as our models

- Extra care has to be taken when modeling metal-poor stars (i,e, r-process stars)

- Departures from LTE abundances for Fe can be severe

- Accurate modeling of atmospheres in iron-poor stars (NLTE) is important. Ignoring NLTE effects can:

  - underestimate log g ~ 0.2 - 1 dex
  - overestimate Teff ~ 50- 600 K
  - underestimate [Fe/H] ~ 0.2 – 1.0 dex
  -underestimate [Mg/H] up to 0.5 dex
  -underestimates [Ca/H] from Ca II lines up to 0.5 dex

- NLTE effects important to include in Spectroscopic Surveys.