Towards a high resolution view of infrared line formation

Martin Montelius[1] Nils Ryde[1] Henrik Jönsson[2]

[1]Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Box 43, SE-221 00 Lund
[2]Department of Materials Science and Applied Mathematics, Malmö University, SE-205 06, Malmö

Introduction

High resolution infrared spectroscopy is still in its infancy. There is a lot of work to do: validating that abundances derived from IR spectra are **consistent with optical data**, and investigating **from which processes differences arise**. This is especially important in the context of upcoming IR surveys such as MOONS, but also for IR spectroscopy in general.

Stellar Sample

Number of stars:	34
Spectral class:	K-giants
Spectrometer:	IGRINS
Spectral resolution:	~45000
Spectral range:	1.49 - 1.80 μm
Telescope:	Lowell Discovery
S/N min/median/max:	85/184/413

Method

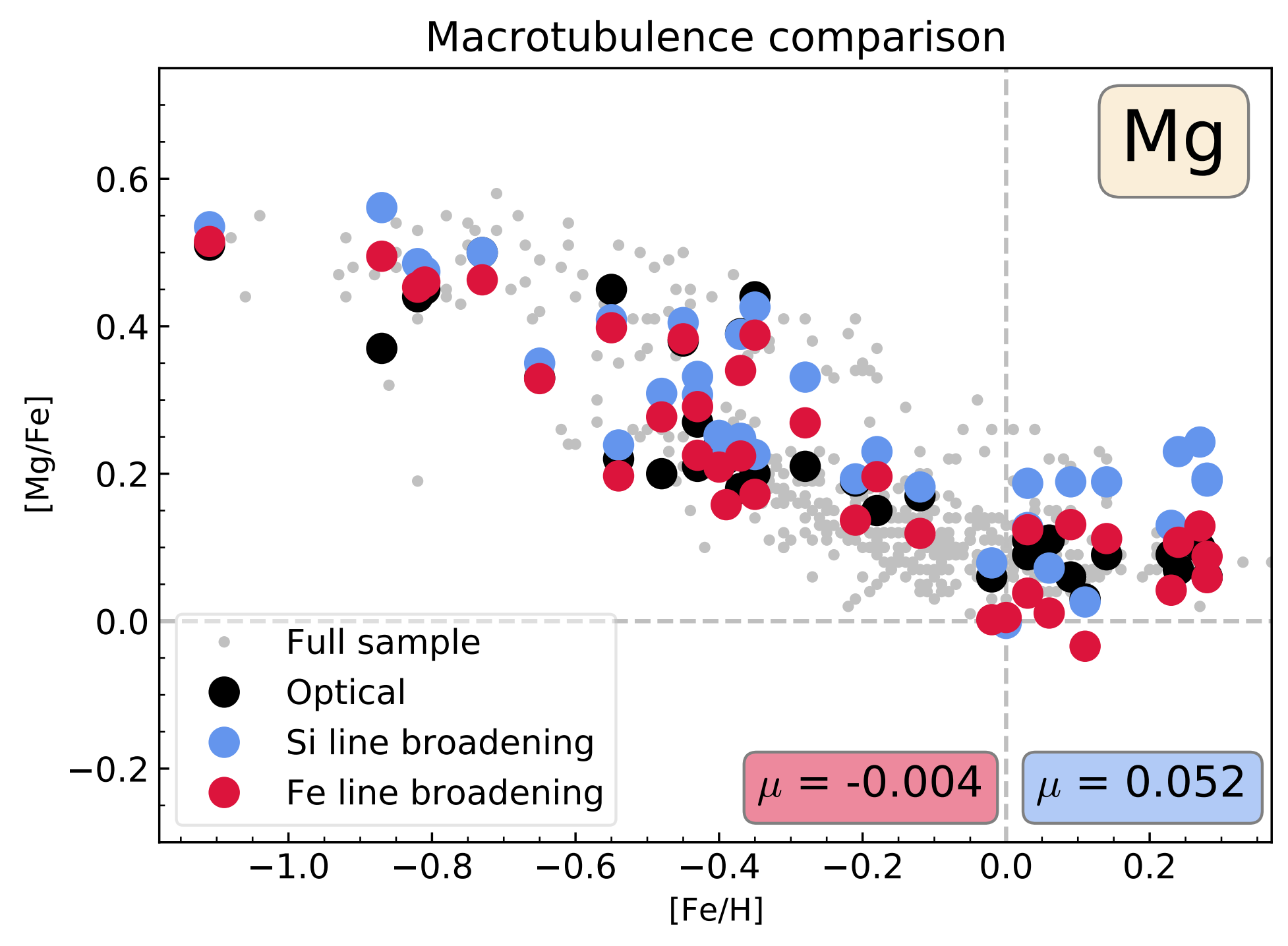
The spectra are manually analysed with the spectral synthesis code **SME** [1]. Stellar parameters have been predetermined from **high resolution optical spectra** [2], as methods for doing so are currently lacking in IR. The same optical analysis has determined abundances, which I **benchmark** my results against.

Investigated issues

- **Measuring:** C, Na, Mg, Al, Si, P, S, K, Ca, Ti, Cr, Mn, Co, Ni, Cu, Zn
- **Macroturbulence determination**
  - Testing Si and Fe lines
- **Astrophysical line strengths**
  - Measuring lines for all H-band elements
- **NLTE corrections**
  - Investigating C, Na, Mg, Al, Si, K, Ca, Mn
- **Hyperfine structure**
  - Investigating Na, Al, V, Mn, Co, Cu

Macroturbulence – v_{mac}

For R $\gtrsim$50 000 the instrumental profile no longer dominates line broadening, easing investigation of the broadening from the star.

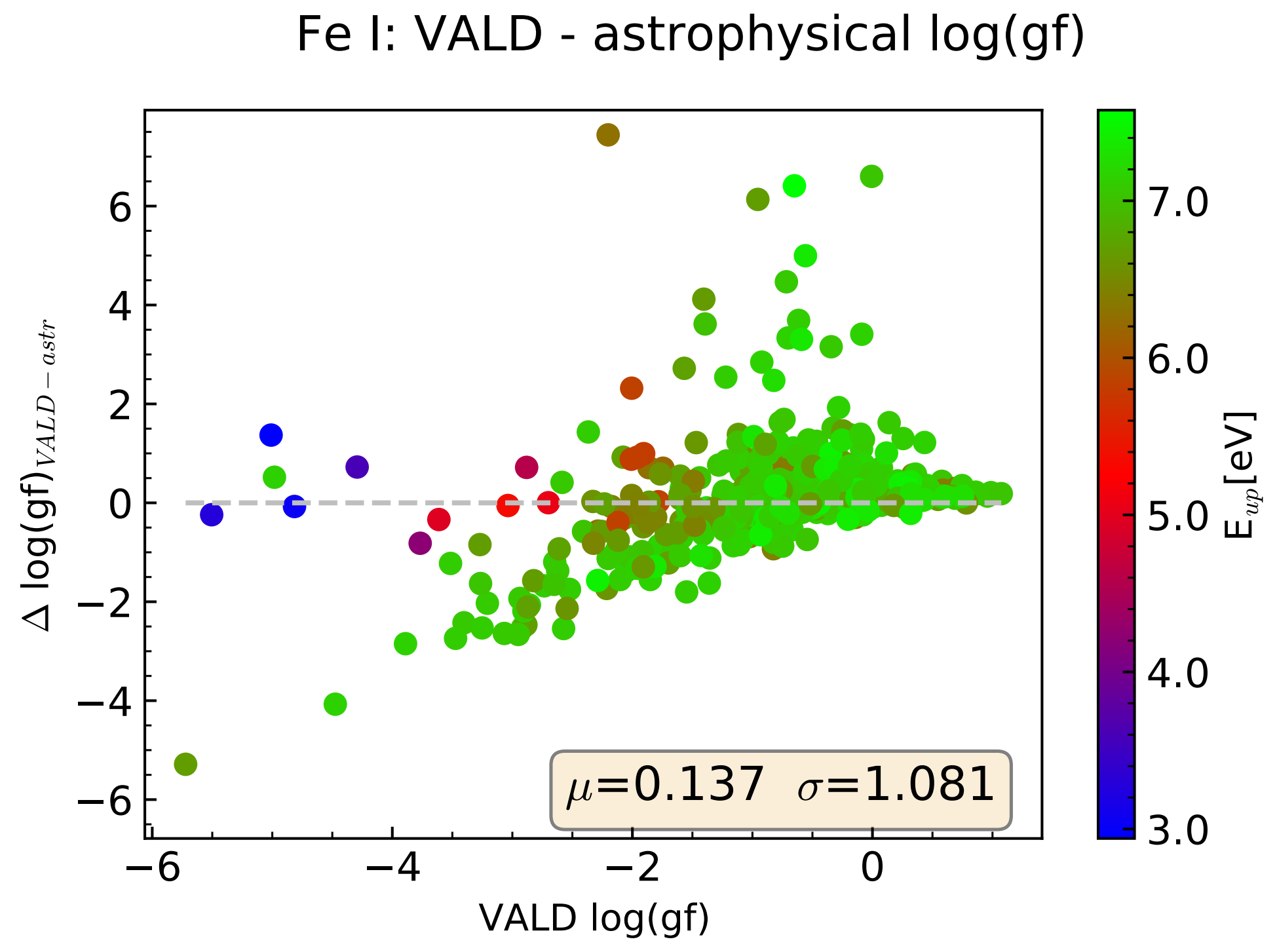


I have tried using both Si and Fe lines to determine v_{mac} for my stars. Highly accurate van der Waals broadening data [3] was used to minimise errors from the other major source of broadening for cool stars. The figure shows the abundance trend for Mg, note the **improved supersolar results using Fe lines**.

Astrophysical line strength

Inaccuracies in atomic data is cited as a top concern for abundance analysis [4], chiefly the line strength – log(gf). **Lab measurements** offer the highest levels of precision, but **are rarely available for IR lines**. Astrophysical log(gf) measurements use the spectra of a star with known abundances (the Sun) and solve for line strength instead of the abundance.

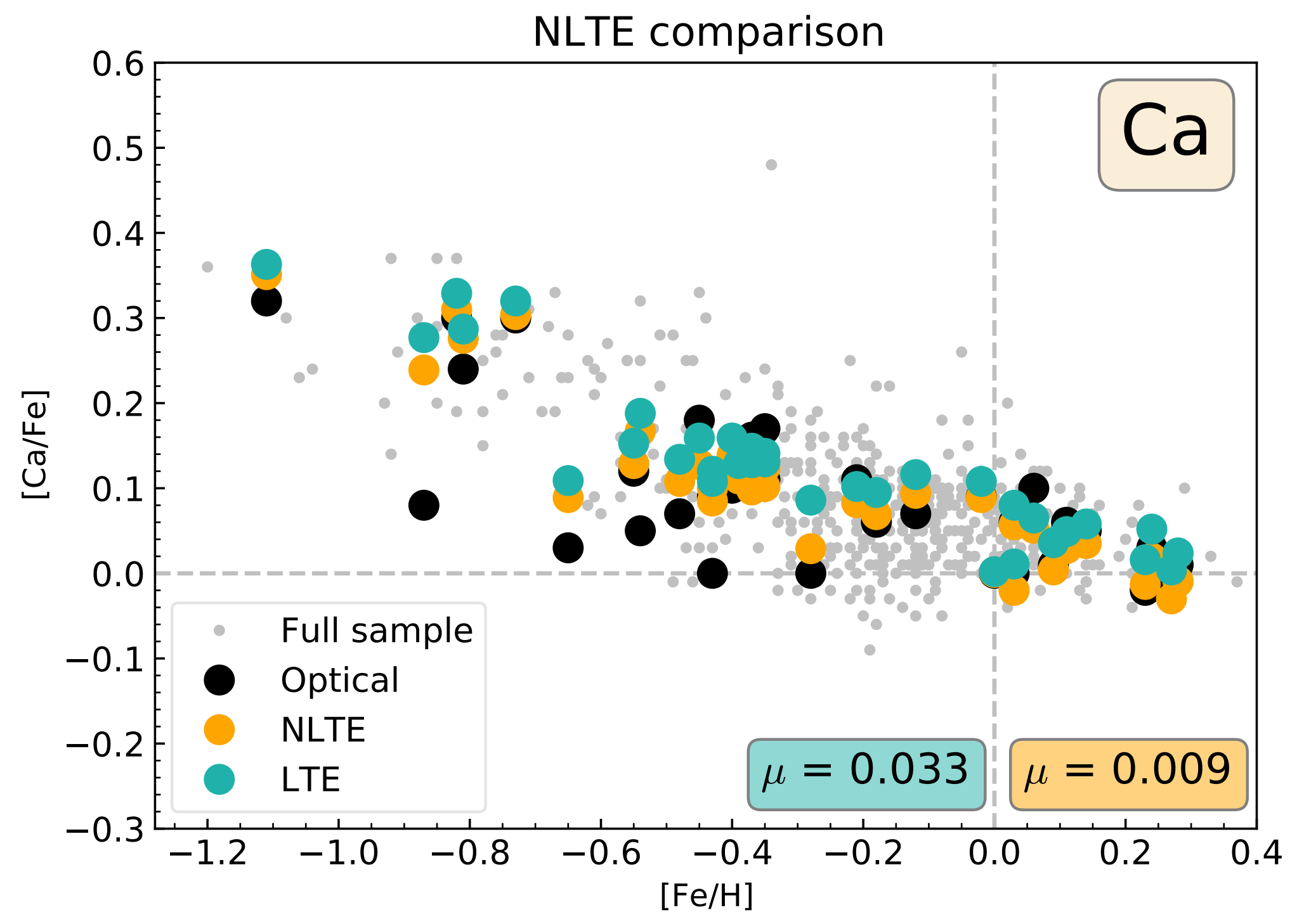
I have developed a method that **takes fine and hyperfine structure into account** when performing astrophysical log(gf) measurements, building on relative line strengths in LS multiplets to adjust secondary lines log(gf) [5].



Astrophysical measurements **can be very important**; above, the differences between astrophysical measurements and values from the VALD database for 551 Fe I lines are shown. Not accounting for the inaccuracies in database values, risks the accuracy of studies.

Non - LTE corrections

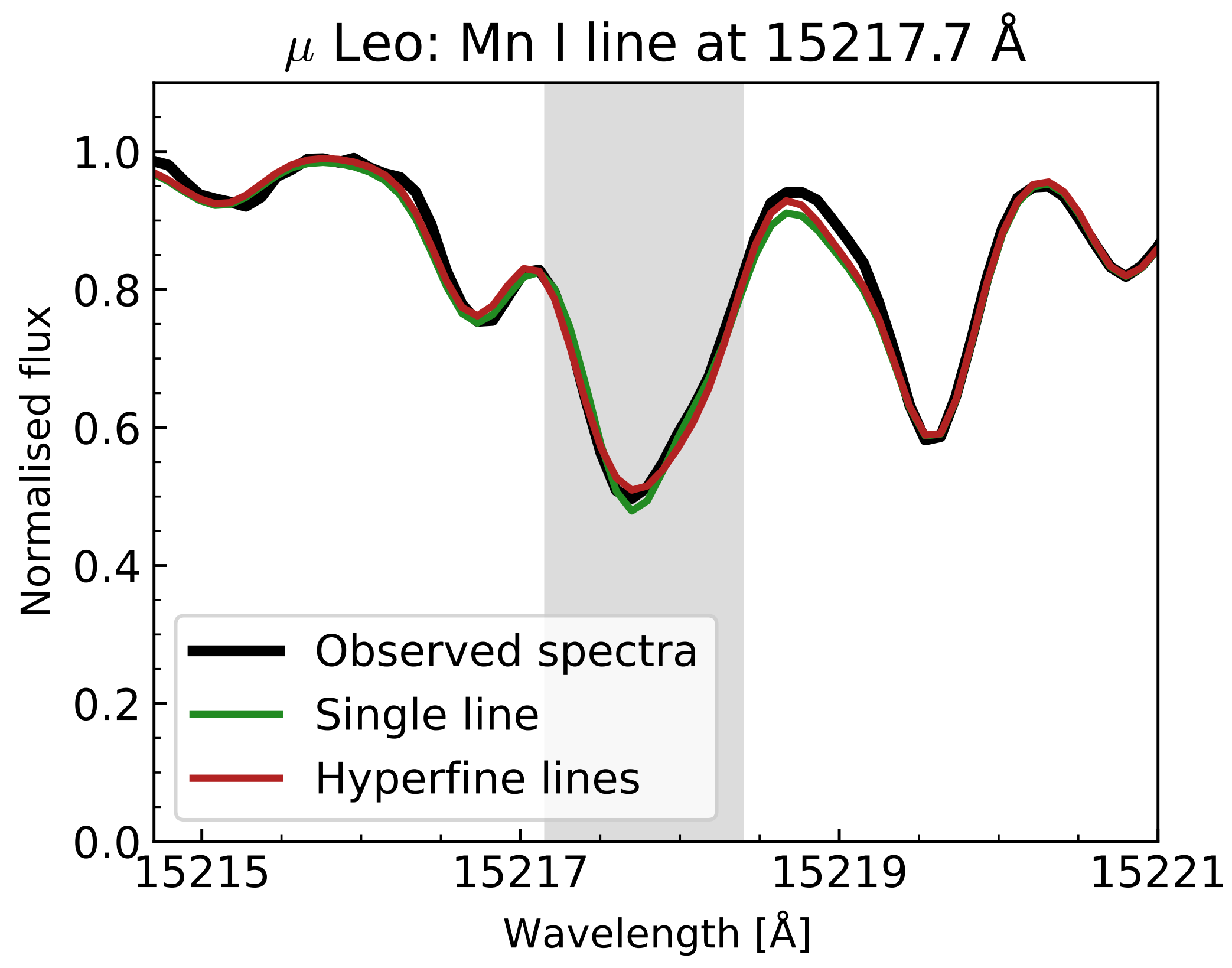
To simplify calculations, spectral synthesis codes typically assume Local Thermodynamic Equilibrium (LTE), that temperature changes happen slowly enough that equilibrium can be assumed at each point. Further out in a star's photosphere, that assumption breaks down. Corrections to account for the resulting Non - LTE effects can be estimated, with updated values published in 2020 [6].

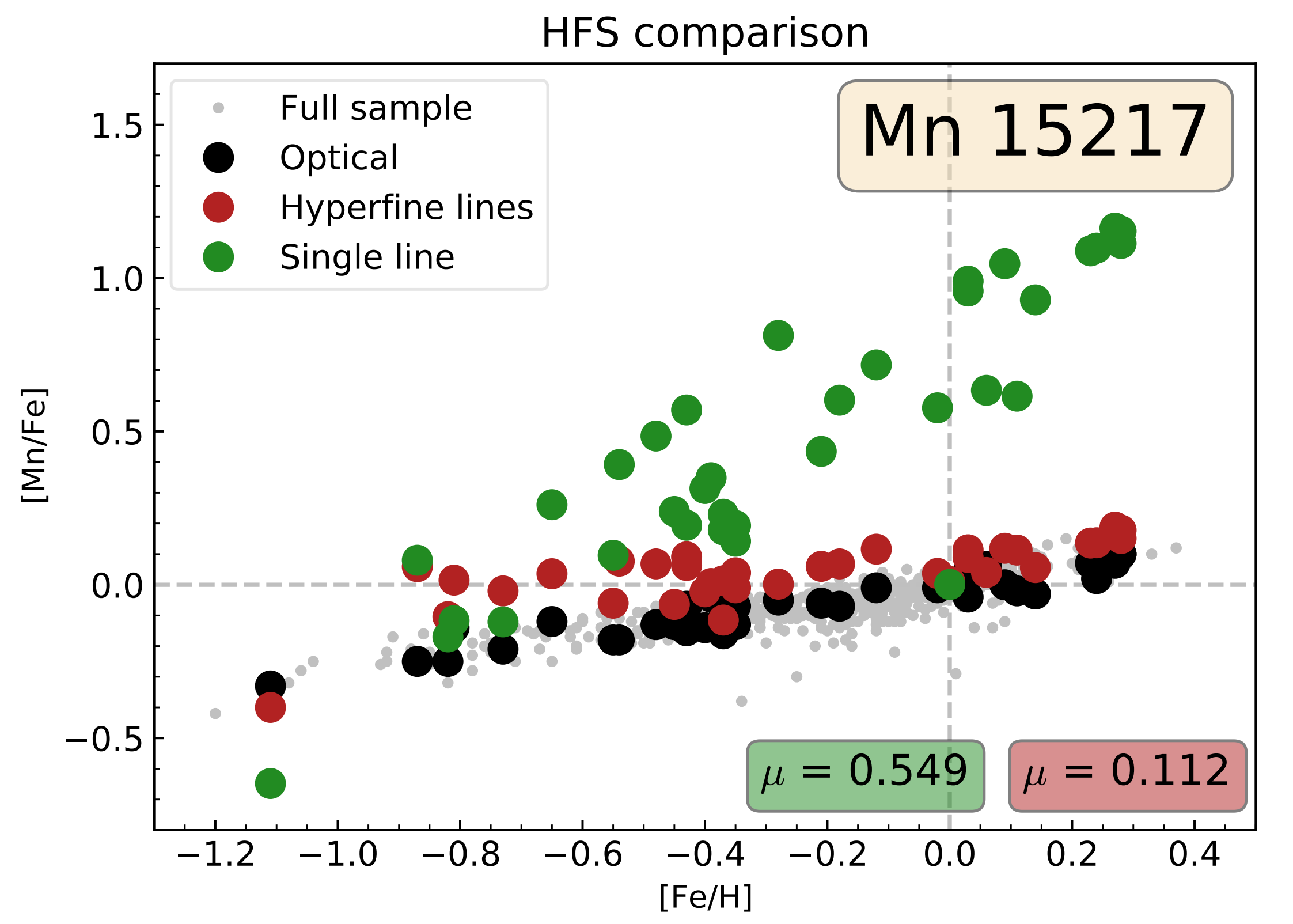


Above is an example of how I have assessed the impact of NLTE corrections. The two sets of results have been computed with and without NLTE corrections, including when measuring the astrophysical log(gf) values, with otherwise identical input. The difference in the Ca abundances are significant, with the LTE results showingm systematically higher abundances compared to the optical results.

Hyperfine structure – HFS

The nuclear spin of nuclei with odd Z or A, interacts with the angular momentum of the electrons, and splits the atom's energy levels into their hyperfine components. The HFS can warp the line profile, but also **desaturate strong lines, drastically affecting the derived abundance**.





In the example shown above, two synthetic spectra of the star μ Leo have been computed, one with a single Mn I line and one with 16 hyperfine Mn I lines. The two synthetic **spectra appear similar**, but the **derived abundances differ by almost a whole order of magnitude!** The abundance trends shows the stark difference for the rest of the stars; the HFS effect shows a strong metallicity dependence, resulting in everything from similar abundances to an order of magnitude in difference.

Future prospects

- Investigating and comparing techniques for parameter determination in the IR
- Extending studies to available K band data
- Replicating studies for stars of different spectral classes, investigating differences
- Consistently studying the impact of HFS / NLTE / v_{mac} on optical spectra
- Calculating van der Waals broadening data for IR lines to test v_{mac} determination
- Extending laboratory measurements of more IR spectral lines

References

[1] Piskunov, N. Valenti, J. (2017). "Spectroscopy Made Easy: Evolution". *AA* 597

[2] Jönsson, H., et al. (in prep.)

[3] Barklem, P. (private communication)

[4] Barklem P. (2016) "Accurate abundance analysis...". *Astron. Astrophys. Rev.* 21:9.

[5] Cowan, R. D. (1981). "The theory of atomic structure and spectra".

[6] Amarsi, A., et al. (2020). "The GALAH Survey: non-LTE departure coefficients for large spectroscopic surveys". *AA* 642.