Hydrodynamical model atmospheres: Their impact on stellar spectroscopy and asteroseismology

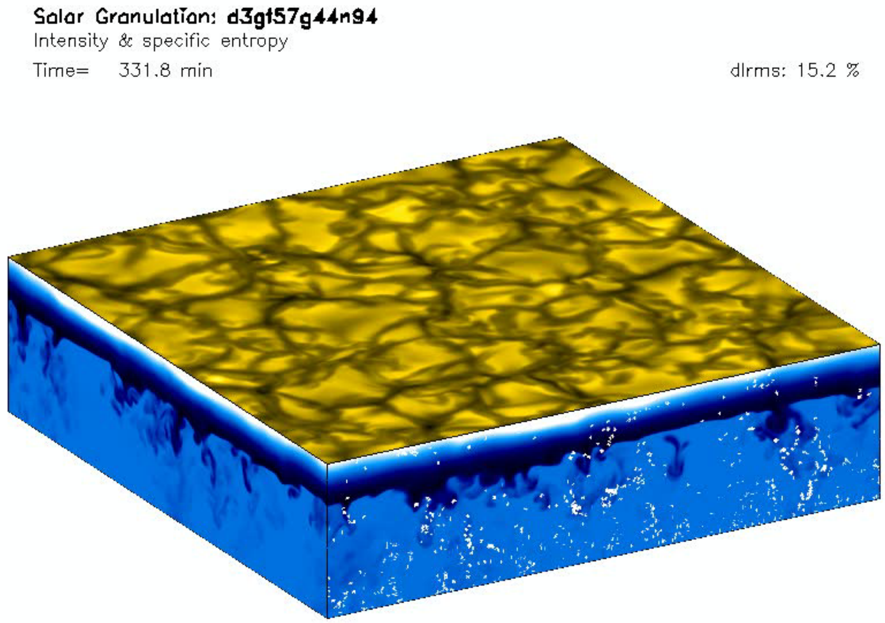
Hans-G. Ludwig

ZAH – Landessternwarte, University of Heidelberg, Germany

Overview

- 3D model atmospheres in a nutshell
  - contrasting 3D with situation in standard 1D models
- CO^5BOLD 3D model grid
- Applications in asteroseismology and spectroscopy?
  Not exhaustive list but trying to be illustrative
  - work on the percentage level
- Examples from work *in progress* ...
  - diagnostic potential of the so-called granulation background → Ludwig et al. ↓
  - microturbulence and collisional cross-sections of neutral hydrogen with oxygen → Steffen et al. ↓
  - corrections to theoretical oscillation frequency due to surface effects → Sonoi et al. ↑
- Leaving out 3D abundance corrections, in particular of molecular species

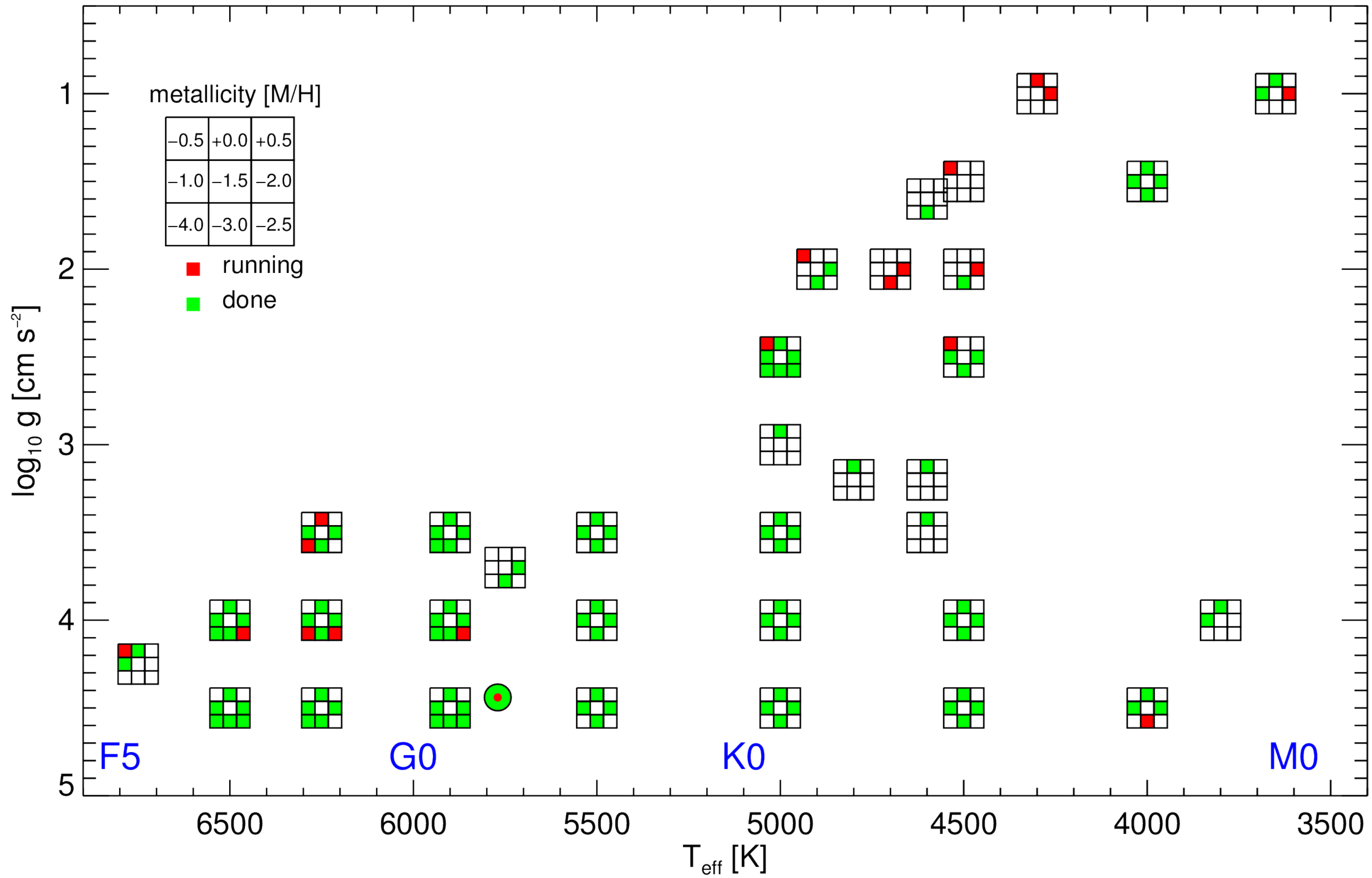
1D and 3D model atmospheres of late-type stars



1D model atmospheres	3D model atmospheres
plane-parallel or spherical symmetry	no assumptions on symmetry
	small representative patch of surface layers
time-independent	time-dependent
CT with mixing-length theory	solution of M(HD) equations
RT with 10^5 frequencies	up-to 25 frequency bands (or bins)
radiative-convective equilibrium	follows flow evolution
	quasi-stationary, fluctuations
CPU time $\approx$ 1 min	$10^5 \ldots 10^6$ min $\rightarrow$ grids?

. . . and many more technical details

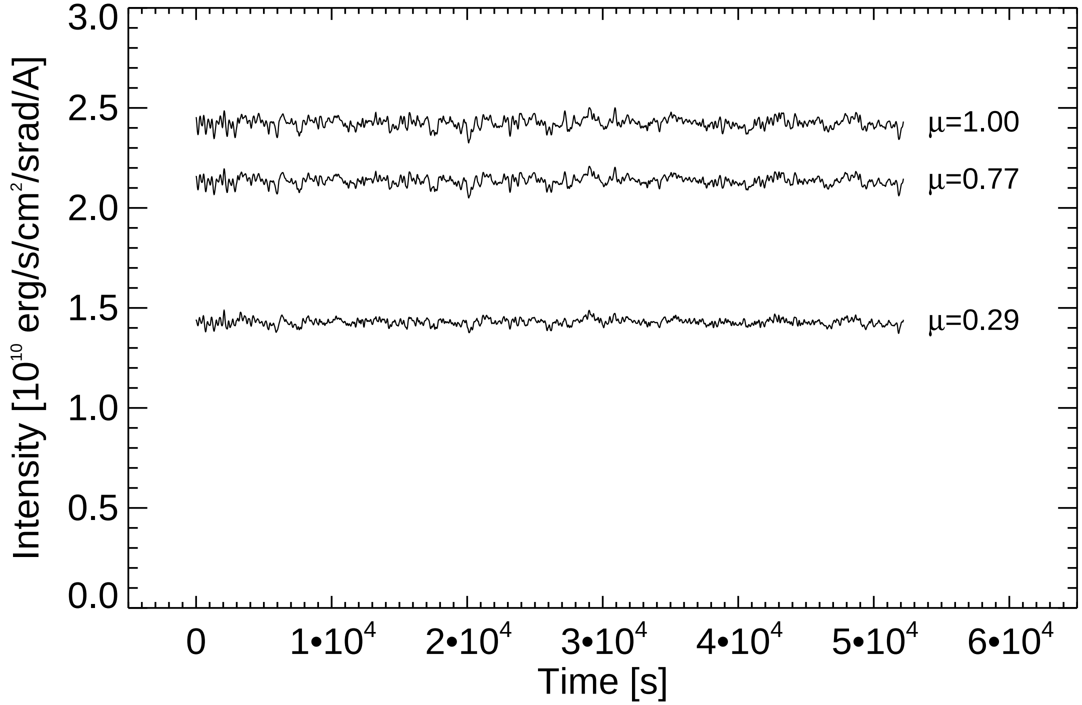
CO^{5}BOLD **3D model atmosphere grid of non-degenerate objects**

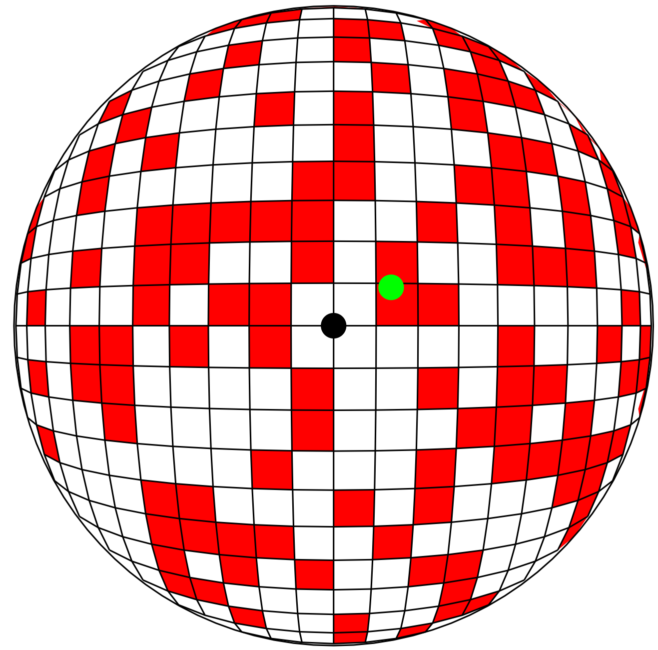


(Ludwig, Caffau, Steffen, Freytag, Bonifacio, Kučinskas)

- Filling of parameter space mostly project driven
- In addition: M-dwarfs, AGB giants, brown dwarfs, white dwarfs . . .

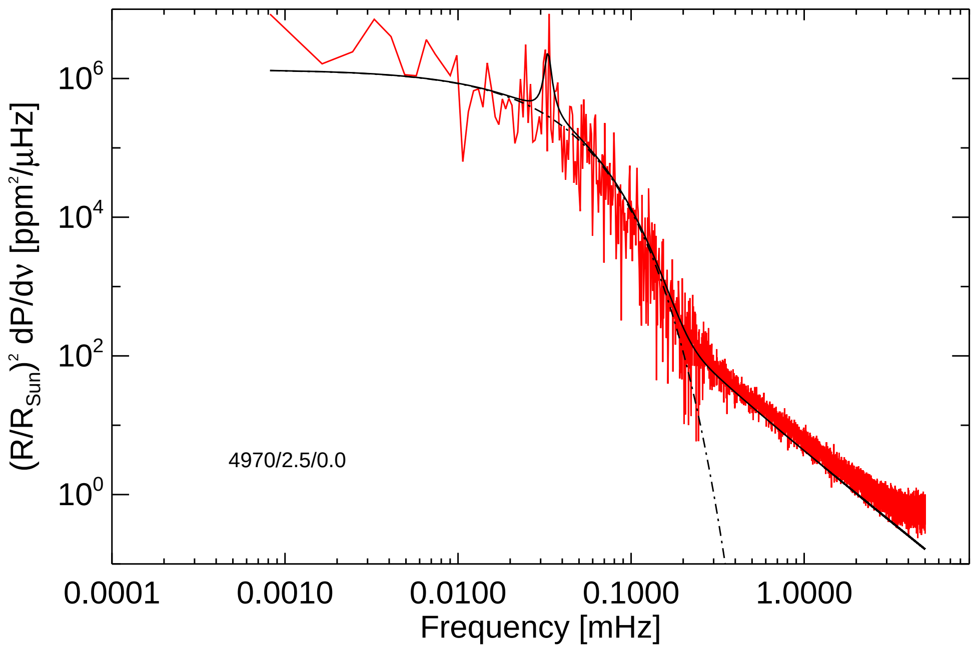
Granulation background across the Hertzsprung-Russell diagram



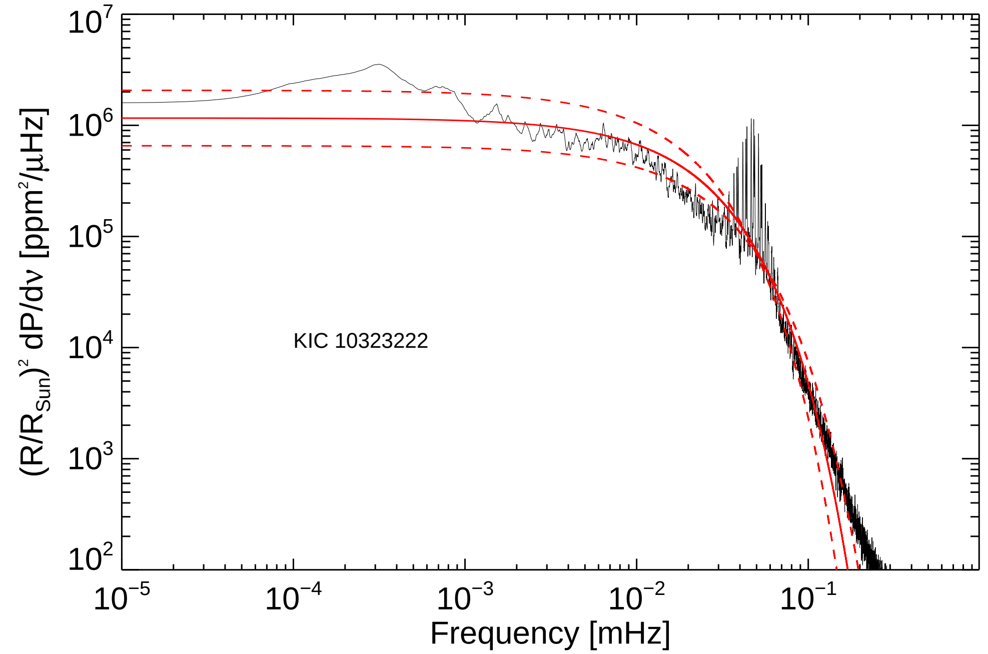


- 3D model provides realization of radiative output of “patch” on the stellar surface
  - only horizontal average considered, dependence on limb-angle included: $I_{\rm bol}(t,\mu)$
- Assuming *incoherent action* of (perhaps many) patches $\rightarrow$ stellar radius
  - ok for random granulation pattern, inadequate for oscillatory modes
- Outcome: estimate of power spectrum of observable, global brightness fluctuations

Simulated and observed power spectra



simulation & fitted model



comparison with observation (Kepler)

- Exponential background model

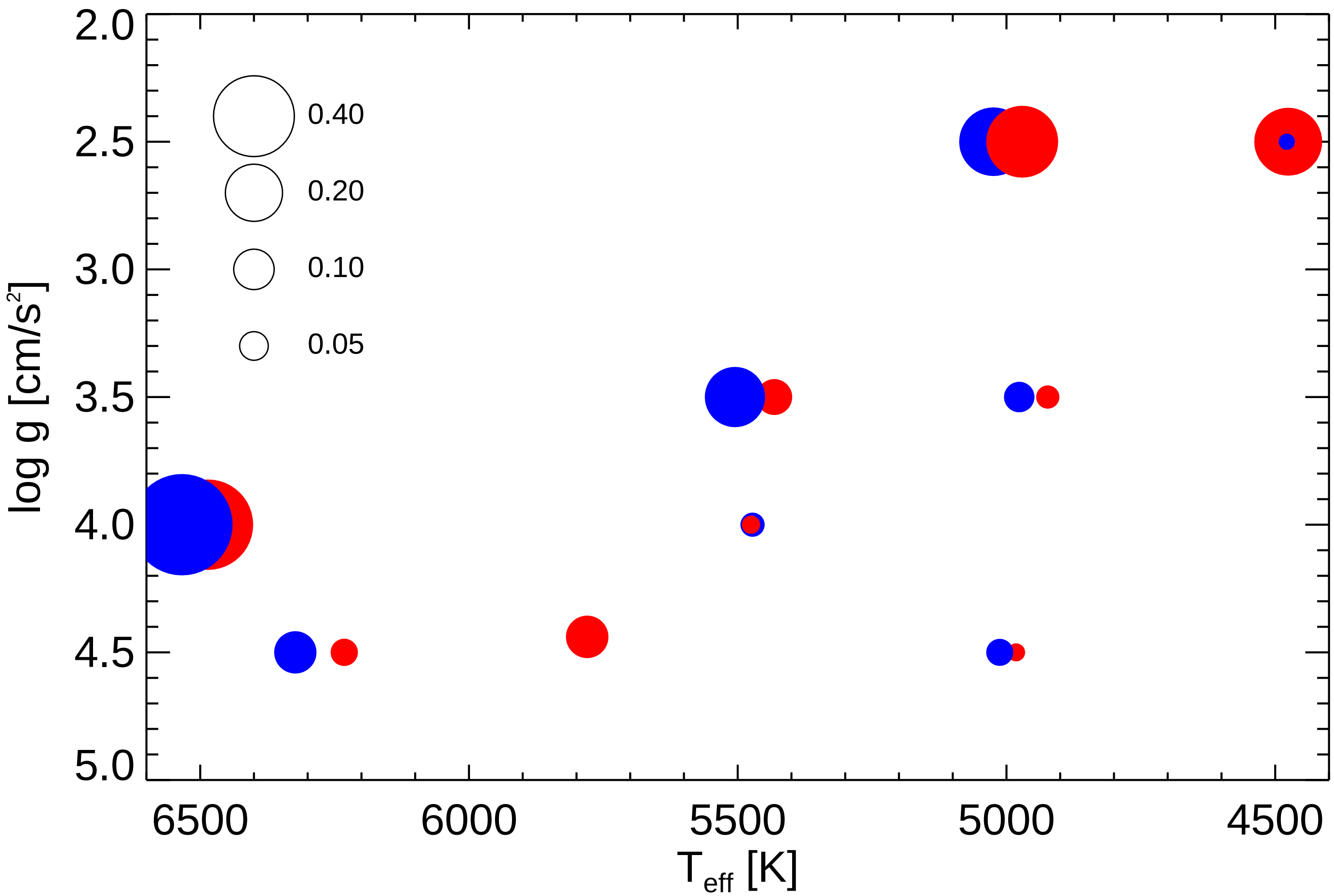
  $\frac{dP}{d\nu}(\nu) = b \exp\left(-\nu/\nu_{\rm gran}\right) +$ sum of Lorentzian box modes

  - characteristic granular frequency $\nu_{\rm gran}$, frequency-integrated fluctuation $\sigma_{\rm gran}$

- Rather: scaled frequency-integrated fluctuation $\tilde{\sigma}_{\rm gran} \equiv \frac{R}{\rm R_\odot}\,\sigma_{\rm gran}$

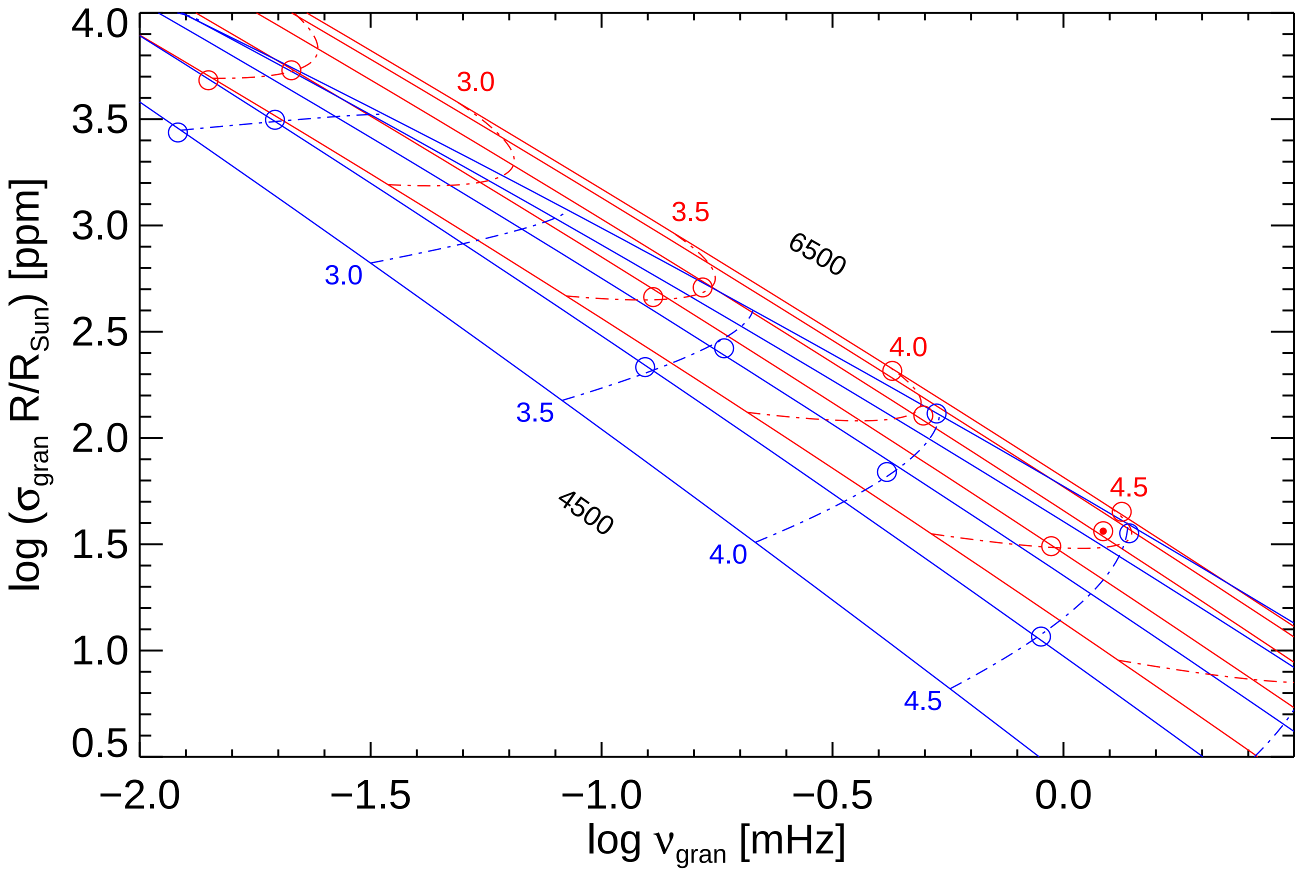
  - stellar radius R not control parameter of the 3D model atmospheres
  - external piece of information, e.g. $R(T_{\rm eff}, \log g, [{\rm M/H}])$ from evolutionary models

The (small) sample of 3D model atmospheres



- 17 3D models: (ignore size of symbols)
  - 9 solar metallicity red cirles
  - 8 sub-solar metallicity blue circles ($[\mathrm{M/H}] = -2$)

“Inverse” Hertzsprung-Russell diagram of convective properties



- 17 3D models: solar metallicity red cirles, sub-solar metallicity blue circles ($[M/H] = -2$)
- *Bi-quadratic power law* fit in $\log(T_{\rm eff})$ and $\log g$ separately for both metallicities

- Dependence of brightness fluctuations on gravity well known $\rightarrow$ *8-hour flicker*
- Theoretical quantification of T-sensitivity: significant difference with metallicity
- Fine structure in the shown fit not significant (yet) $\rightarrow$ curvature at $[M/H] = 0$

Microturbulence and H-collisions – microturbulence?

An abundance analysis of the Hyades giant γ Tauri: an exercise in caution

R.E.M. Griffin[1] and H. Holweger[2]

[1] Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA, England
[2] Institut für Theoretische Physik und Sternwarte der Universität Kiel, Olshausenstrasse 40, D-2300 Kiel, Federal Republic of Germany

Received June 13, accepted October 18, 1988

3.1.2. Microturbulence

This seemingly innocent but potent parameter deserves more respect than it usually gets, as its abuse can produce drastic effects on abundance results.

Microturbulence $\xi_{\rm micro}$

- In 1D abundance analyses $\xi_{\rm micro}$ is usually considered a “nuisance” parameter
  - influences the strength of strong, saturated lines
  - interpreted as effect of unknown (in 1D!), small-scale atmospheric velocity field
  - also compensates offsets in thermal structure between model and observation
  - usually modelled by a depth-independent Gaussian of fixed width $\xi_{\rm micro}$
  - adjusted to make weak and strong lines provide the same abundance
- Spectroscopic determination of $T_{\rm eff}$, $\log g$, abundances, and $\xi_{\rm micro}$ interrelated
- At low spectral resolution or S/N abundance analysis relies on strong lines $\rightarrow$ survey work
- No determination of $\xi_{\rm micro}$ possible, in need of calibration
- 3D models predict atmospheric velocity field $\rightarrow$ can provide theoretical guidance
  - longish story in itself, exploitation of this feature is worked on
  - observational picture rather messy (line parameters? activity? rotation?)

Another exercise in caution: ξ_{micro} and S_{H}

- Departures from local thermodynamic equilibrium (LTE) limits accuracy of spectroscopic abundance determinations – also in cool stars

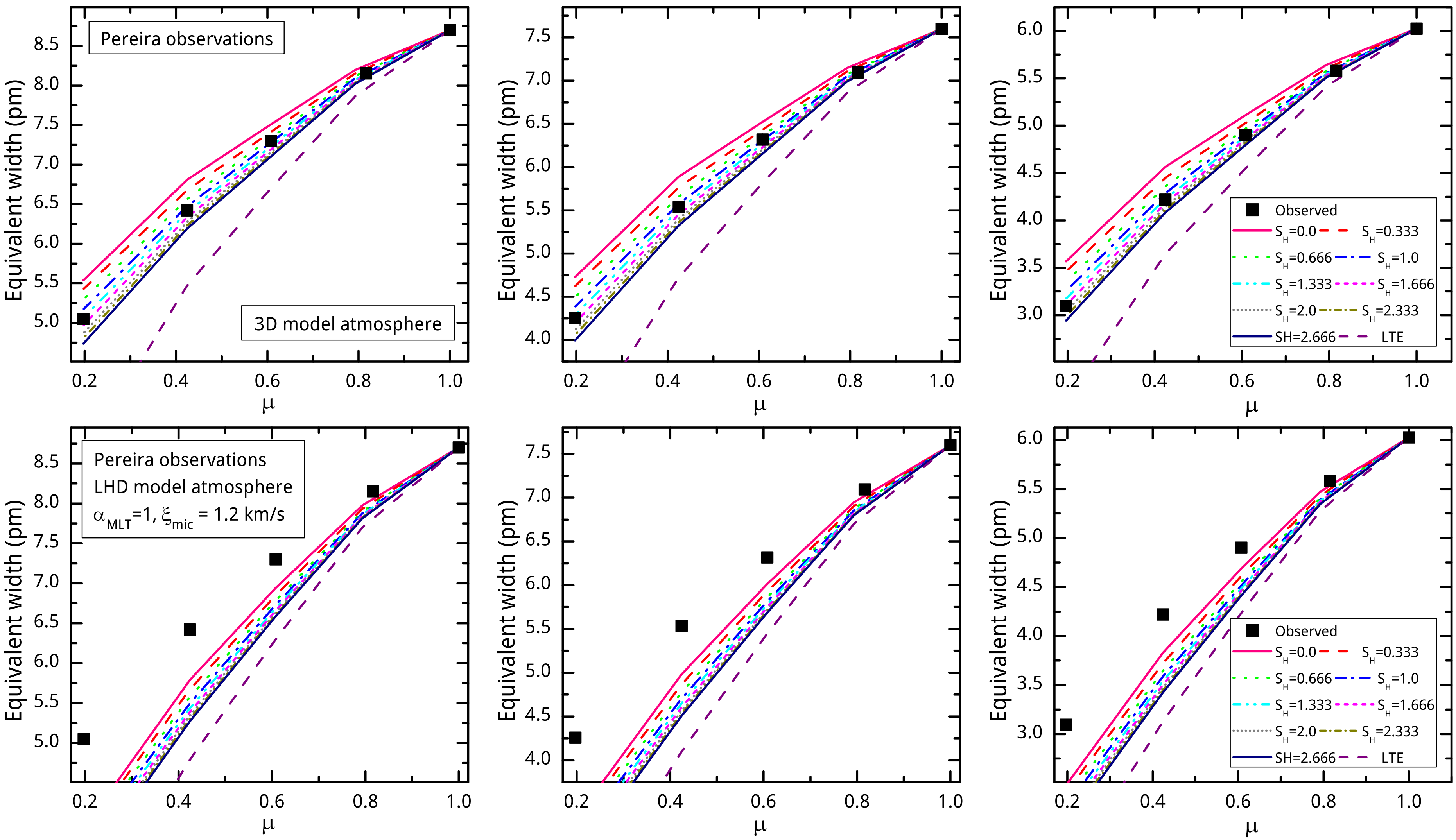
- Collisions with neutral H-atoms important for establishing of LTE

- Few accurate laboratory measurements or quantum-mechanical calculations available
  - standard recipe: approximate Drawin formula times a global scaling factor S_{H}
  - empirical calibration of S_{H} necessary

- Wording: *global* means here for all transitions in a particular model atom in the same way

- Here: 1D and 3D calibration of S_{H} for oxygen infrared triplet lines in the Sun
  - observation of lines at various limb-angles $\mu = \cos\theta$
  - unique abundance of oxygen assumed
  - ξ_{micro} in 1D model: Gaussian, depth-independent, μ-independent

Center-to-limb variation of O-triplet in 3D-NLTE and 1D-NLTE

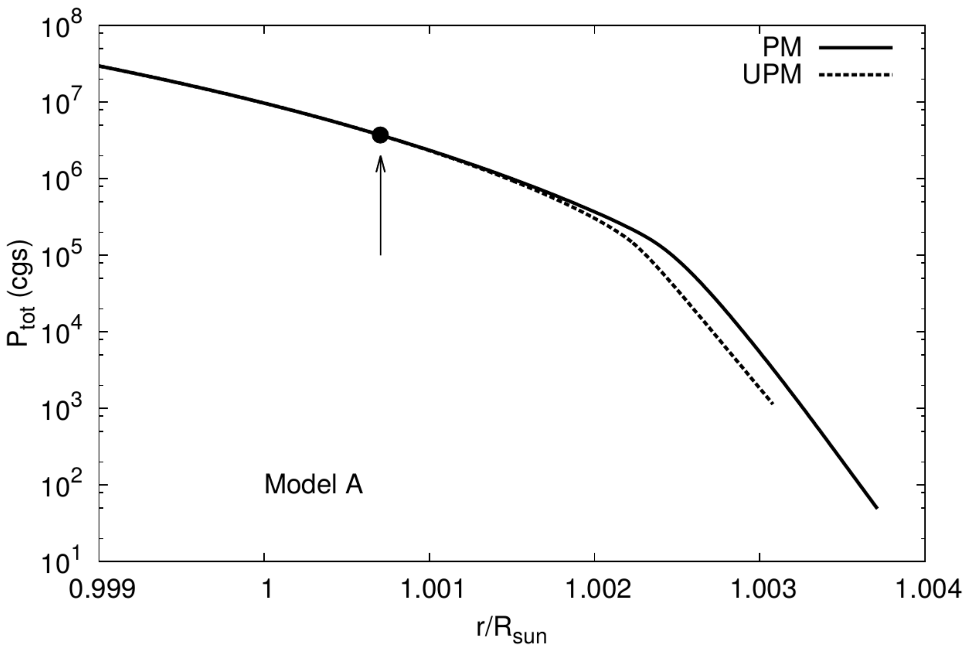


- 3D: $S_{\mathrm{H}} = 1.2 \ldots 1.8$, oxygen abundance $\log \epsilon_{\mathrm{O}} = 8.76 \pm 0.02$
- 1D: no reasonable fit possible $(S_{\mathrm{H}} < 0)$! $\rightarrow$ μ-independent ξ_{micro} problematic

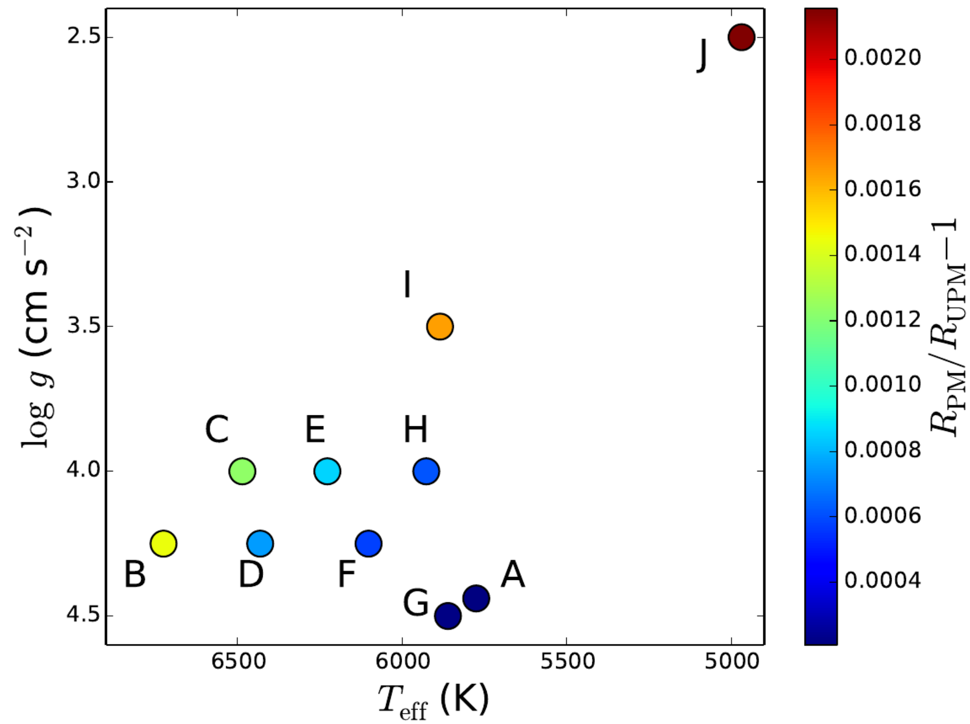
Stellar models and turbulent pressure

- In standard 1D stellar models convective transport is described by mixing-length theory (MLT)
  - approximate treatment of energy transport by gas flows
- Momentum transport, in particular turbulent pressure is usually ignored
  - in fact local nature of MLT make it difficult to include turbulent pressure
  - naturally included in multi-D hydrodynamical approach
- Effects limited to regions of significant flow speed (Mach numbers)
  $\rightarrow$ stellar surface
- Idea . . .
  - combine interior 1D model with horizontally averaged 3D structure in the outer layers $\rightarrow$ combined or patched model
  - compare combined with standard model to derive changes in mode frequencies
- Correct for "surface effect"

3D model atmospheres and surface effects on mode frequencies



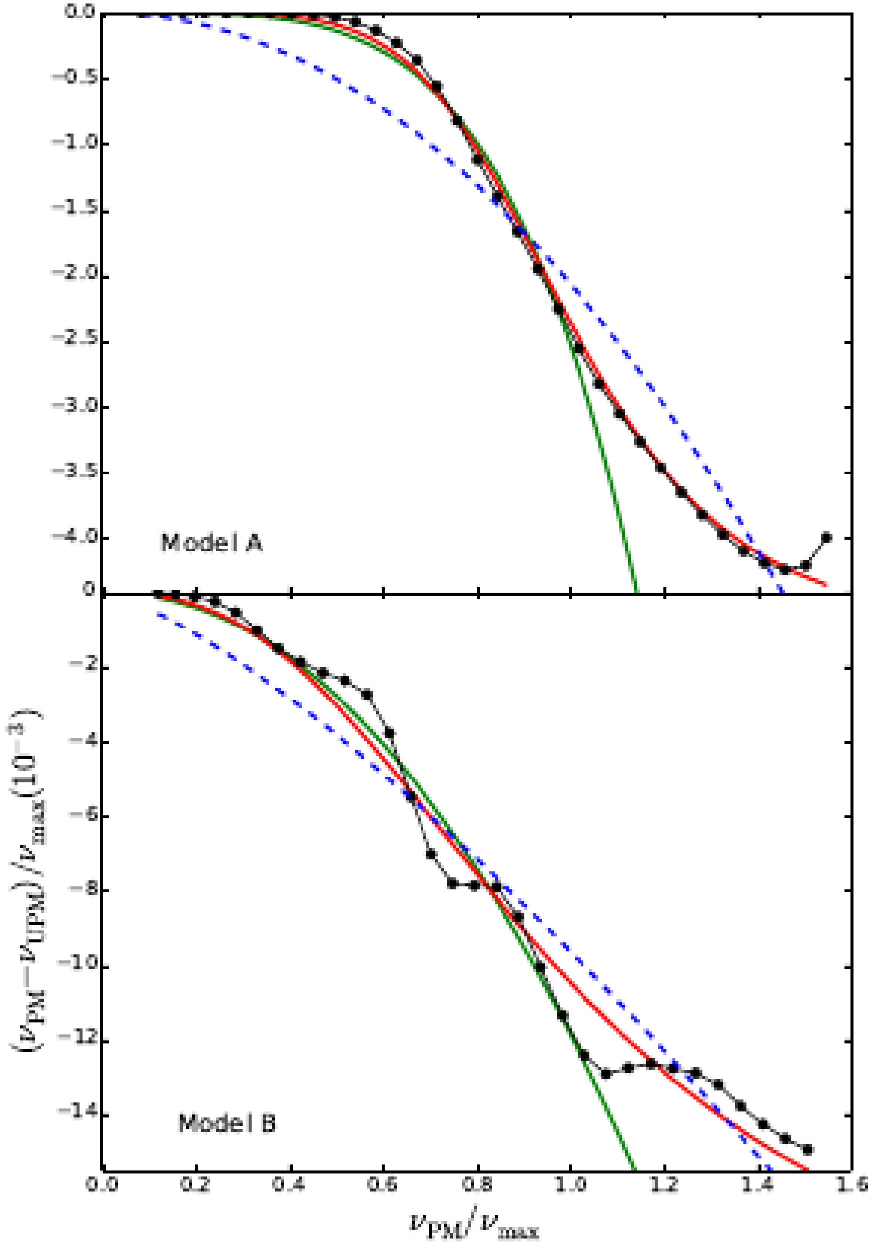
standard (UPM) & combined model (PM)



radius increase

- In 3D, turbulent pressure “lifts” outer layers wrt 1D standard model
- Increase of size of resonant cavity, effect pronounced in red giants ($\Delta R/R \approx 10^{-3}$)
- Systematic lowering of mode frequencies
  - frequency change dependent on upper turning point of waves

Examples: frequency changes of radial modes



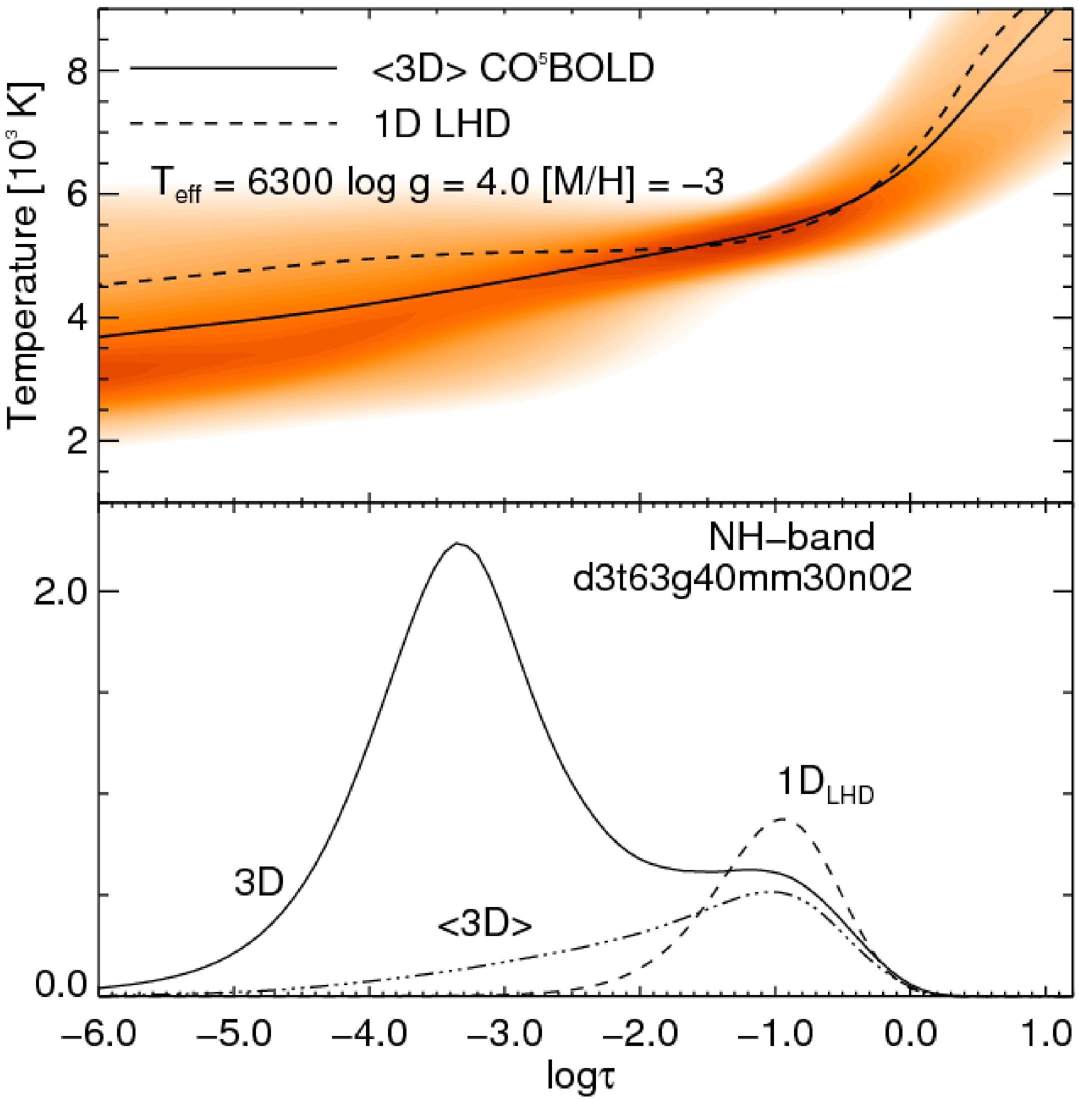
- Green and dashed blue lines: power law fits to frequency differences as suggested by Kjeldsen et al. (2008)
- Red line: Lorentzian gives better fit
- Hot F-dwarf model B shows effects of acoustic glitch (H-ionization)
  - → wiggly shape makes analytical fit difficult
- Here 10 models across HRD

Final remarks

- 3D model atmospheres provide . . .
  - a natural path to achieve higher accuracy in studies of stellar surface structure
  - the possibility to quantify the impact of approximations in 1D
- Exploitation of existing model grids to support survey work ongoing
  - systematic investigation of larger model basis
  - transfer of obtained information into analyses
- Observational tests?
- Where is this needed?

Talking of molecules . . .

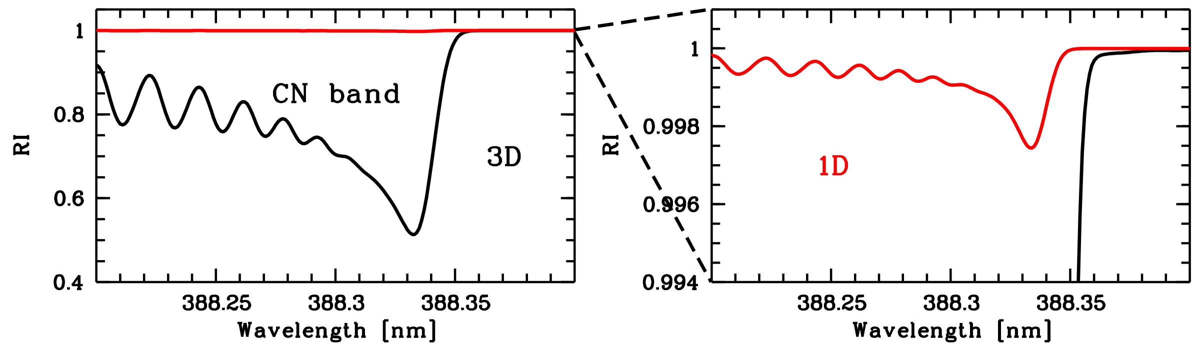
Molecular line formation and temperature fluctuations

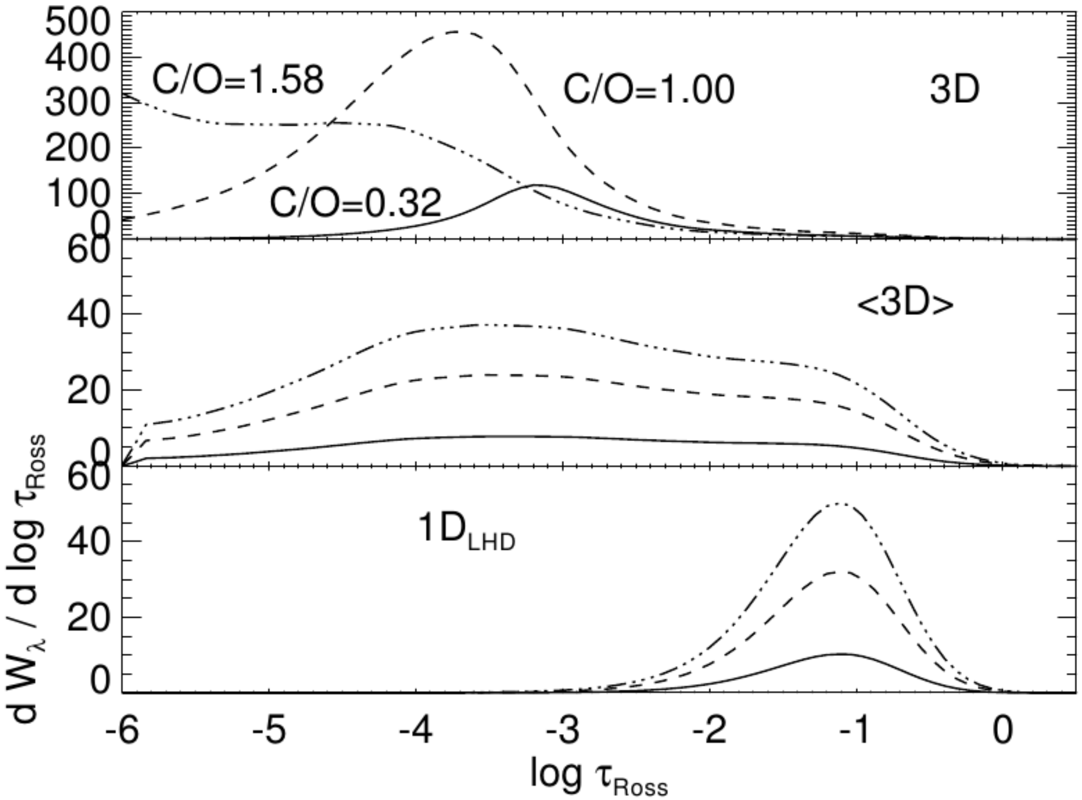


(Bonifacio et al. 2013)

- Binary molecules CH, NH, OH, C_2, CN, CO important abundance indicators
- Dissociation equilibria rather T-sensitive
- Example: contribution function to equivalent width of NH band
- 3D vs. ⟨3D⟩ emphasizes role of T-fluctuations
- Coupled via reaction network

Molecular line formation and C/O ratio

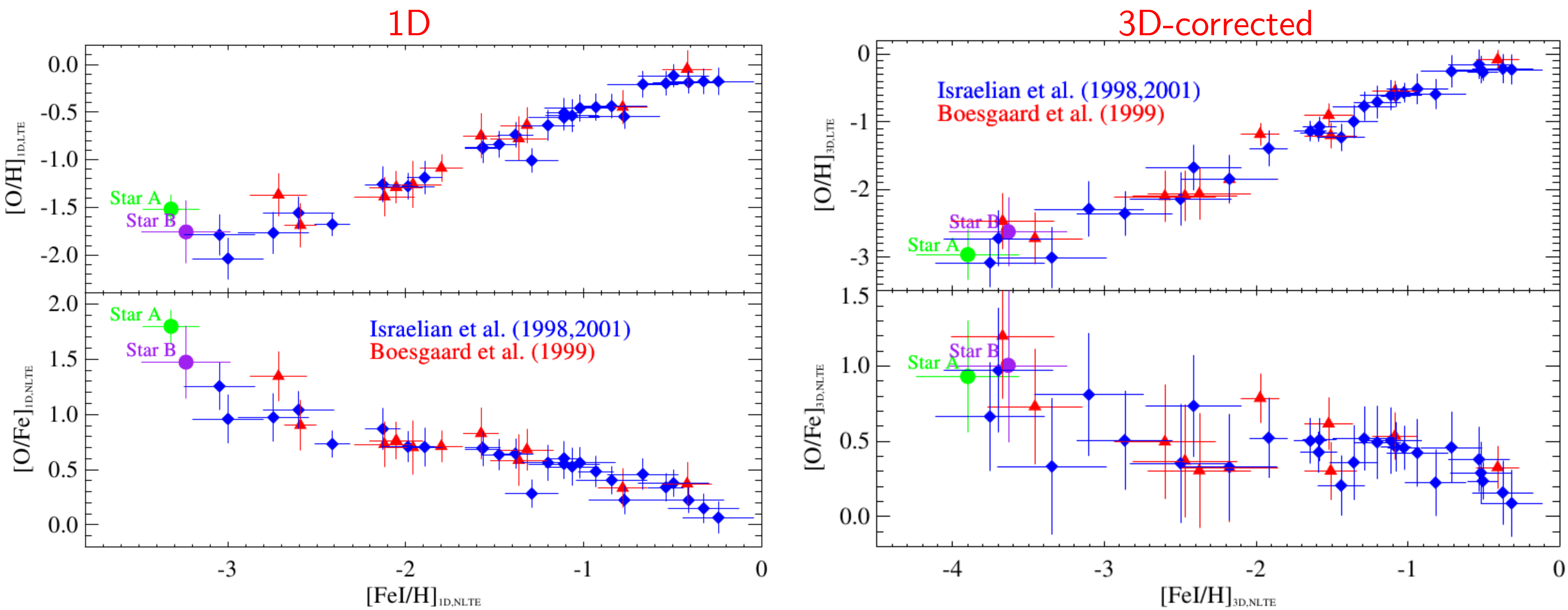




(all figures from Bonifacio et al. 2013)

- CN 388.3 nm band
- ≈ 2 dex difference in EW
- Extreme sensitivity to carbon-to-oxygen ratio
- CO formation (most stable molecule) controls available C for other molecules
- Pure 3D effect!
- Frequency of CEMP stars? (from CH-band)

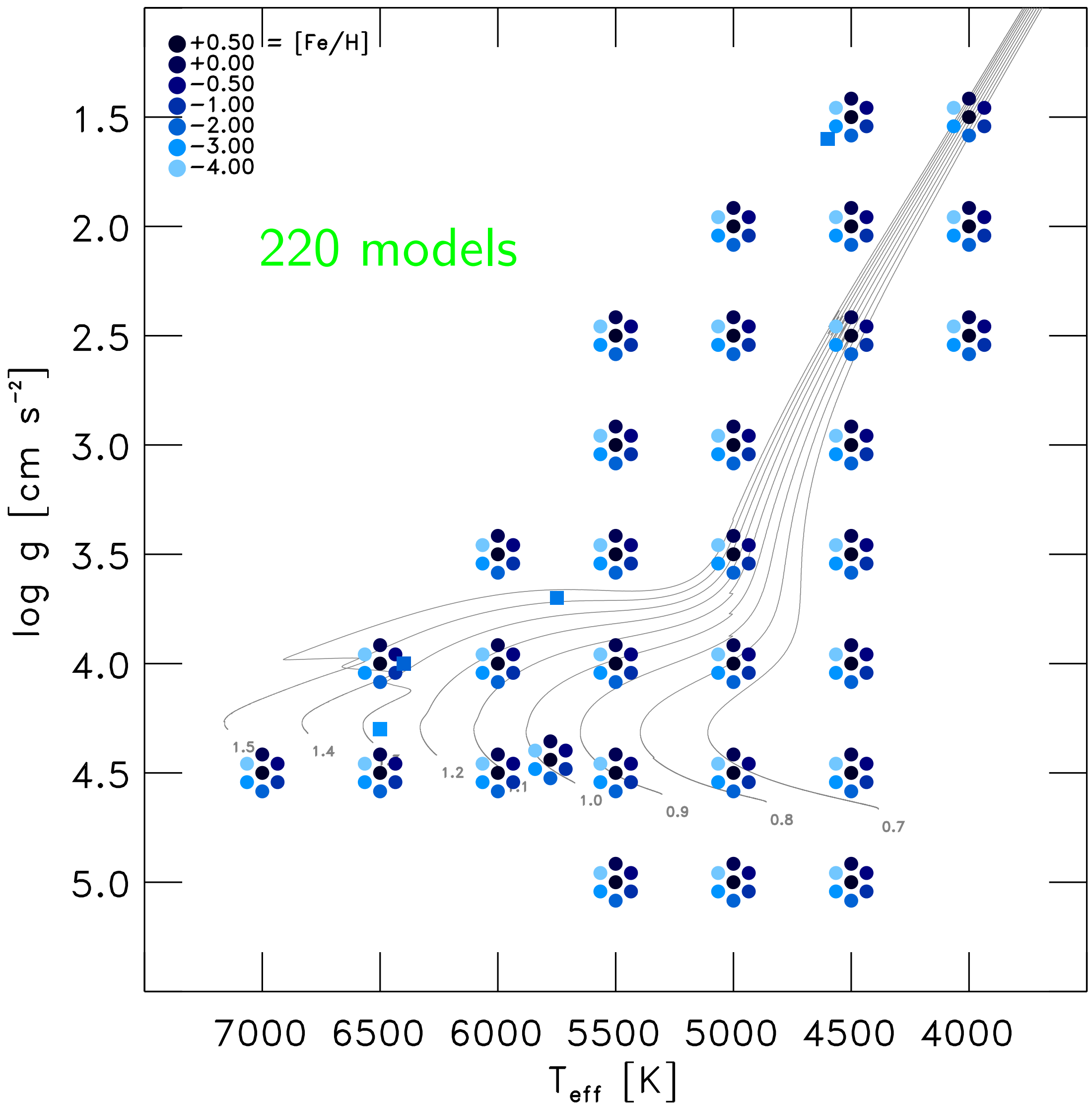
Galactic evolution of oxygen from OH lines in dwarfs



(González Hernández et al. 2010)

- UV-lines of OH in metal-poor dwarf stars last available abundance indicator of O
- Above example record work using 52 3D models to derive abundance corrections
- Downward revision by factor 10 at low metallicity, better consistency with giants
- Fine print: in 3D departures from LTE for Fe and molecules largely unexplored →talk of Lyudmila Machonkina

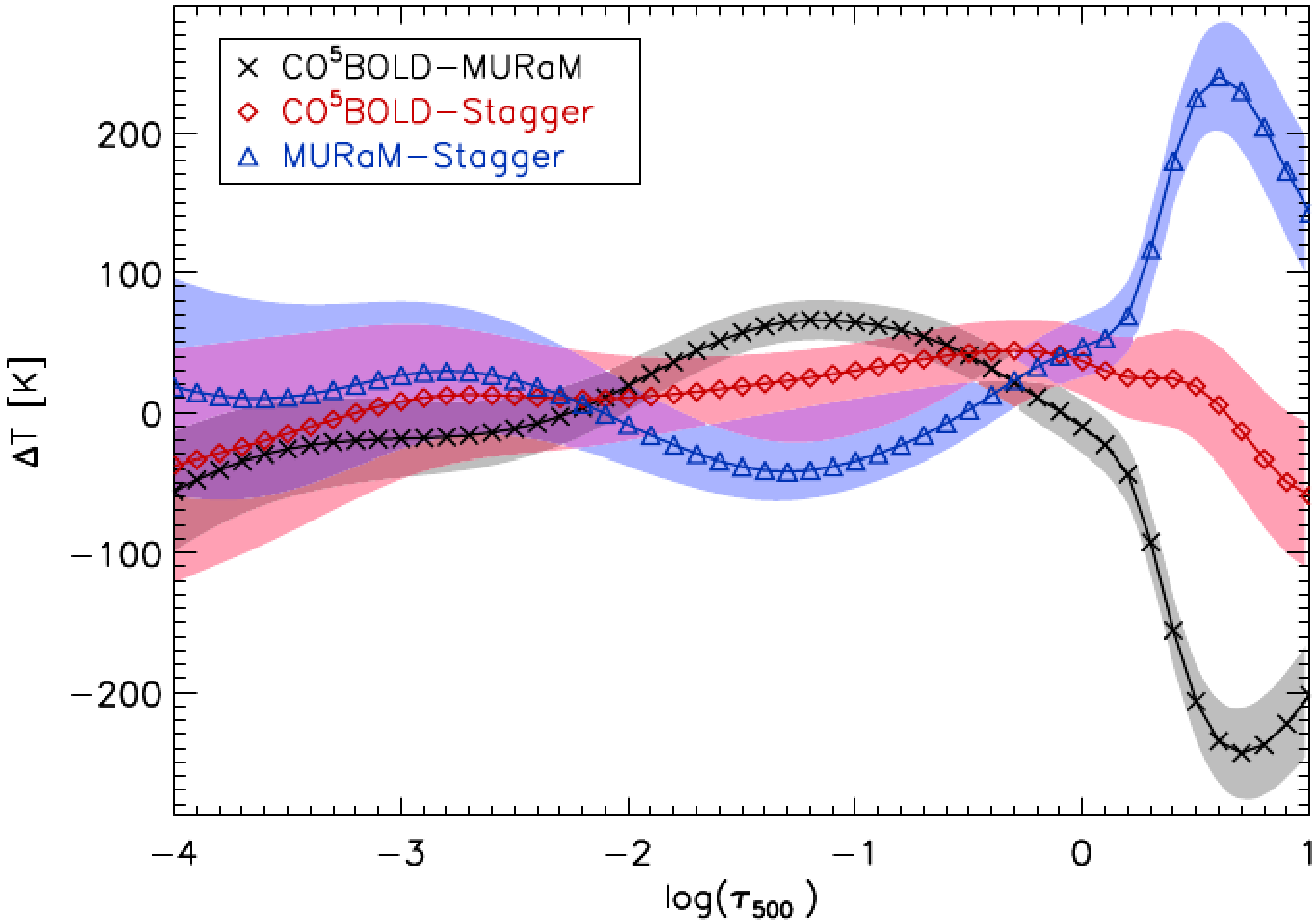
STAGGER **3D model atmosphere grid**



(Magic et al. 2013)

- More metallicities, typically higher resolution → talk by Remo Collet

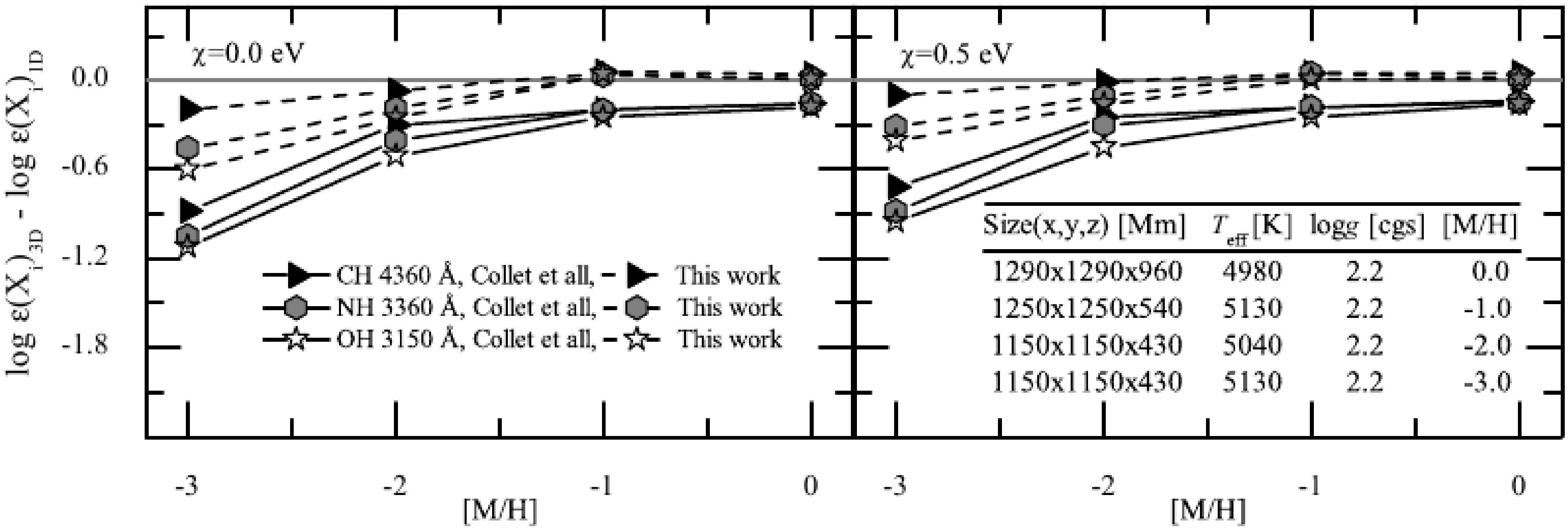
3D model systematics: getting closer – for the Sun



(Beeck et al. 2012)

- CO^{5}BOLD and STAGGER (Collet et al. 2011) agree within 50 K for $\tau_{500} < 1$
- Discrepancies reduced by about factor 2 over recent years

Situation for giants less favorable



(Ivanauskas et al. 2010, Collet et al. 2007)

- Abundance corrections of molecules in CO^5BOLD models smaller in magnitude than in Nordlund-Stein/STAGGER models
- Indicative of different T-structure
- Likely related to different approaches in opacity binning scheme

Comparison between 1D and 3D models
3D abundance corrections

- Comparison between 1D and 3D model of the same atmospheric parameters effective temperature, surface gravity, overall metallicity

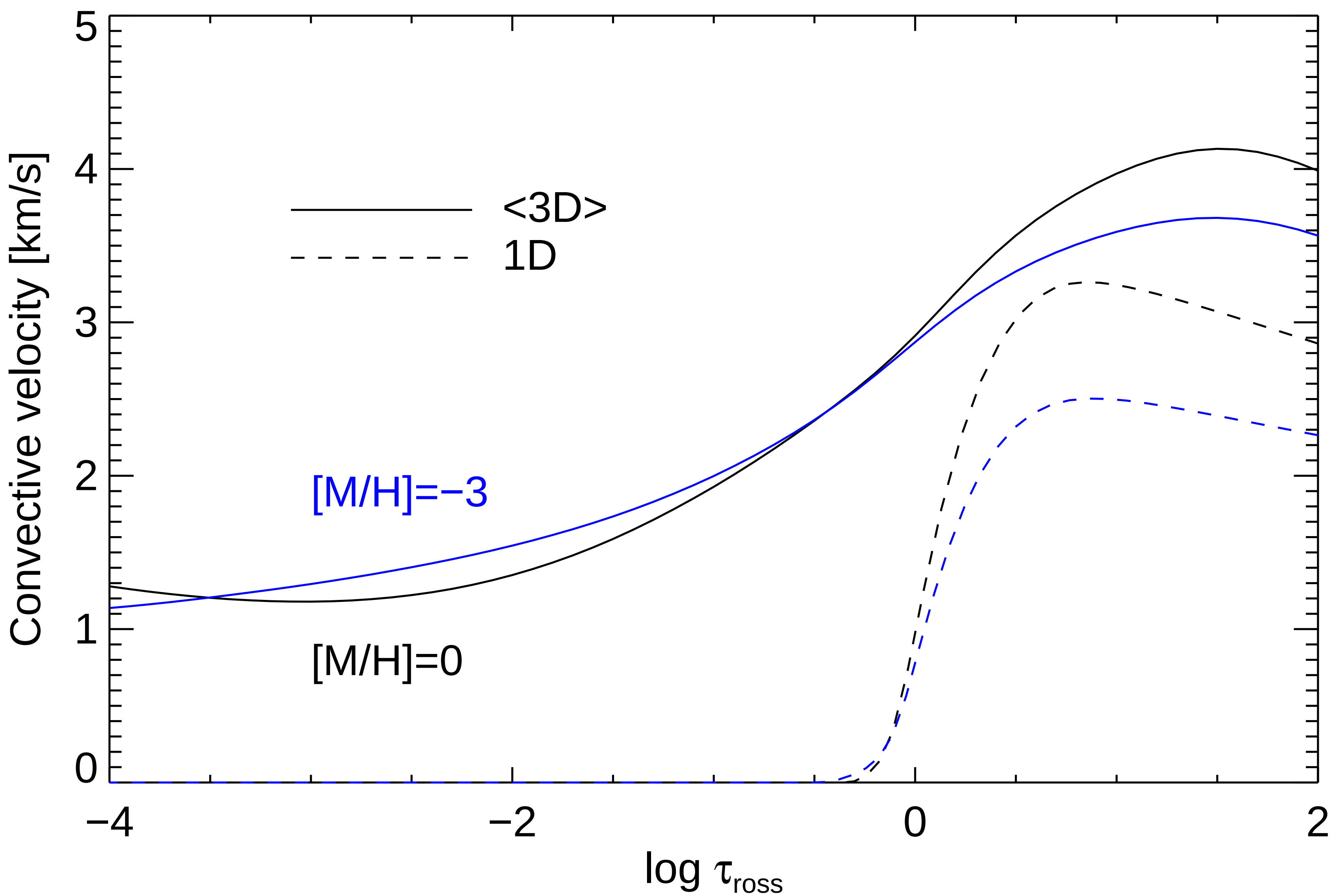
- 1D model has further free parameters, mixing-length parameter, microturbulence ξ_{micro} for spectroscopic applications

- Further diagnostics: $\langle$3D$\rangle$ model obtained by horizontal and temporal averaging

- 3D abundance corrections . . .
  - spectral synthesis of spectral lines of interests in 1D and 3D
  - space-time averaging of 3D spectra

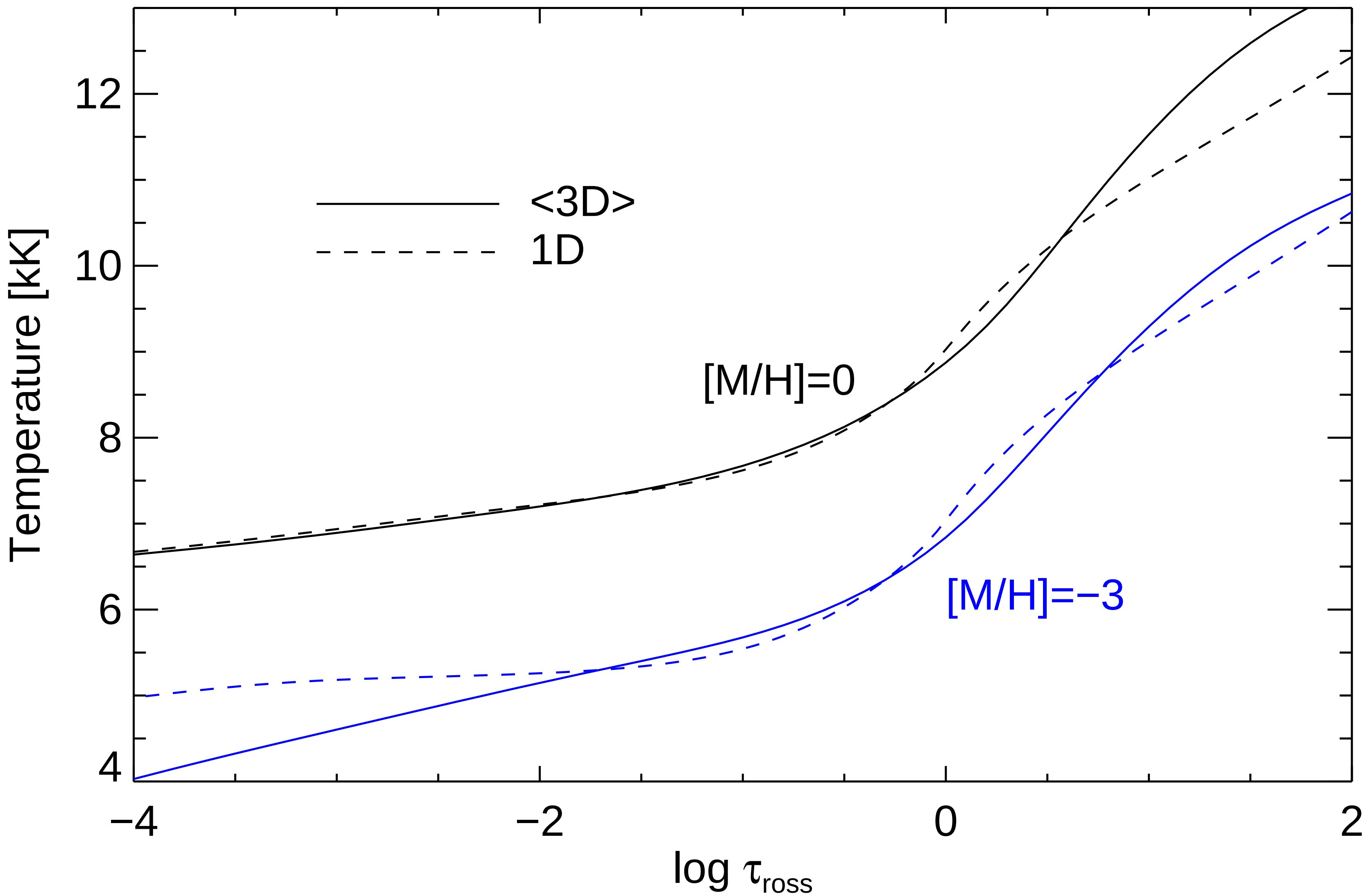
- 3D-1D (total) correction: difference between 3D and 1D abundance for given line strength
  - 3D-$\langle$3D$\rangle$: effects due to horizontal inhomogeneities only
  - $\langle$3D$\rangle$-1D: effects due to differences in mean structure only

Overshooting beyond Schwarzschild boundary at all metallicies



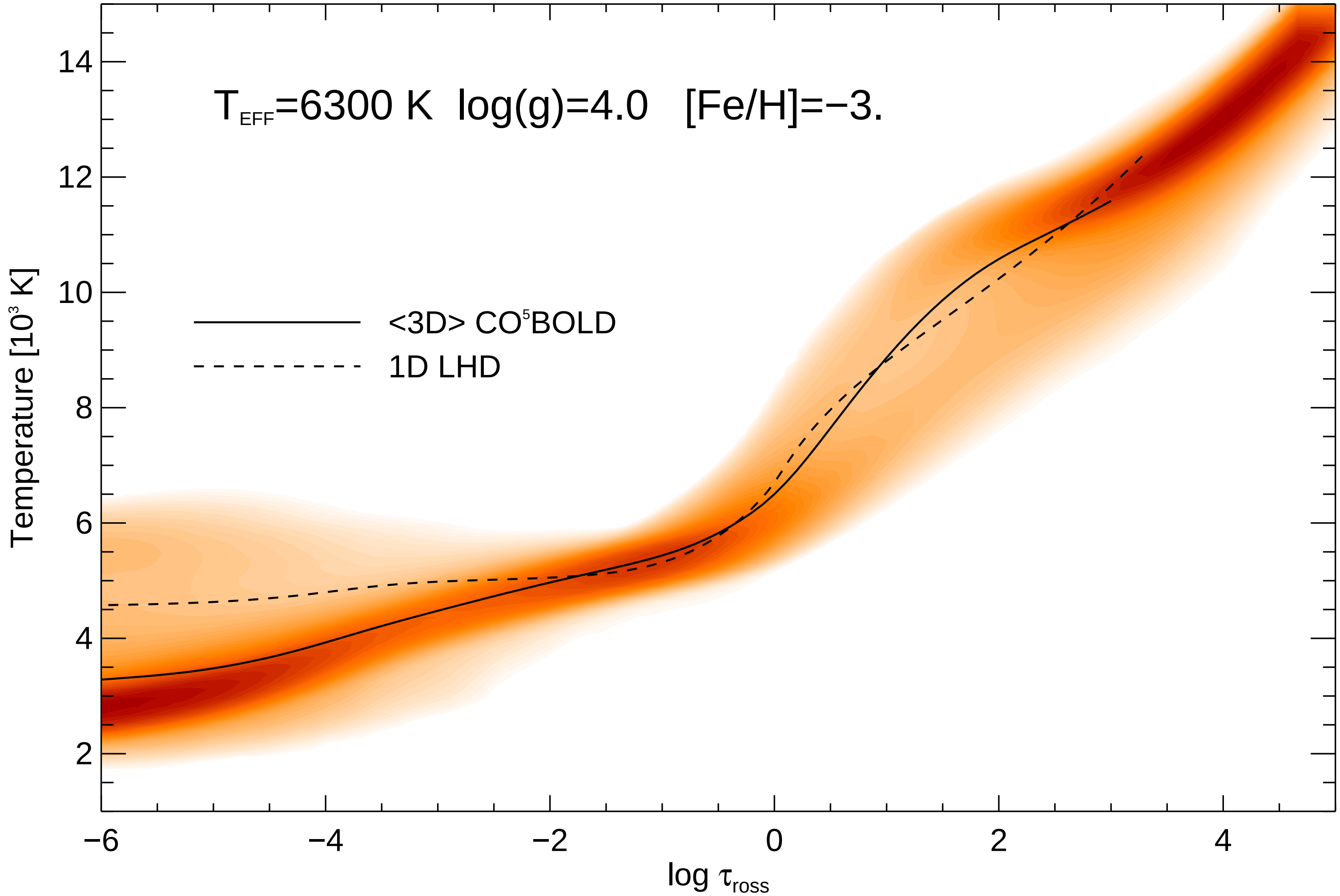
- 3D models predict strong overshooting $(v_z^{rms}) \rightarrow$ micro/macro-turbulence

T-response to convective overshooting depends on metallicity



- In 3D balance between convective cooling and radiative heating
- Dependent on atmospheric parameters, in particular metallicity

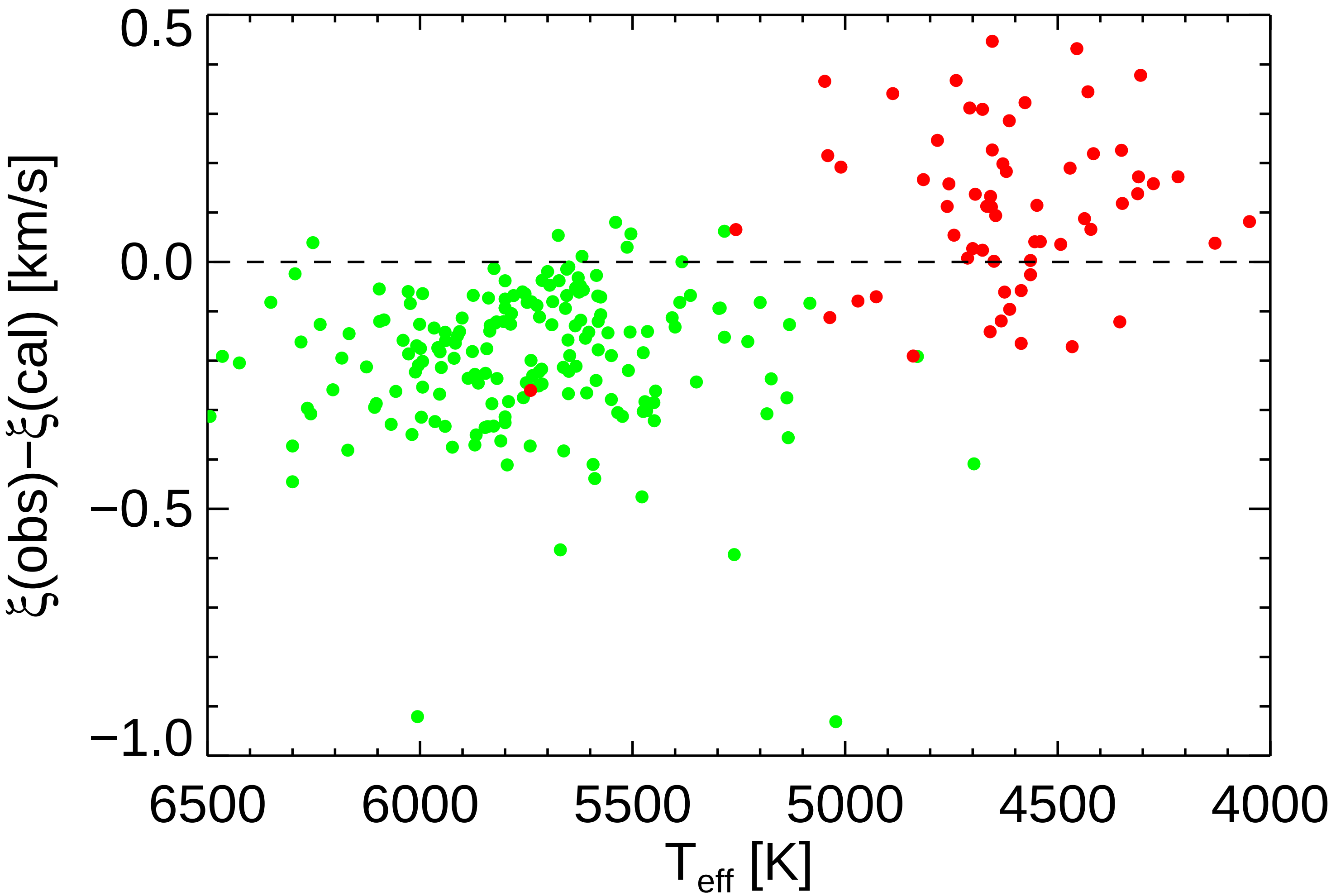
Temperature fluctuations



(González Hernández et al. 2010)

- Flow dynamics induces temperature fluctuations

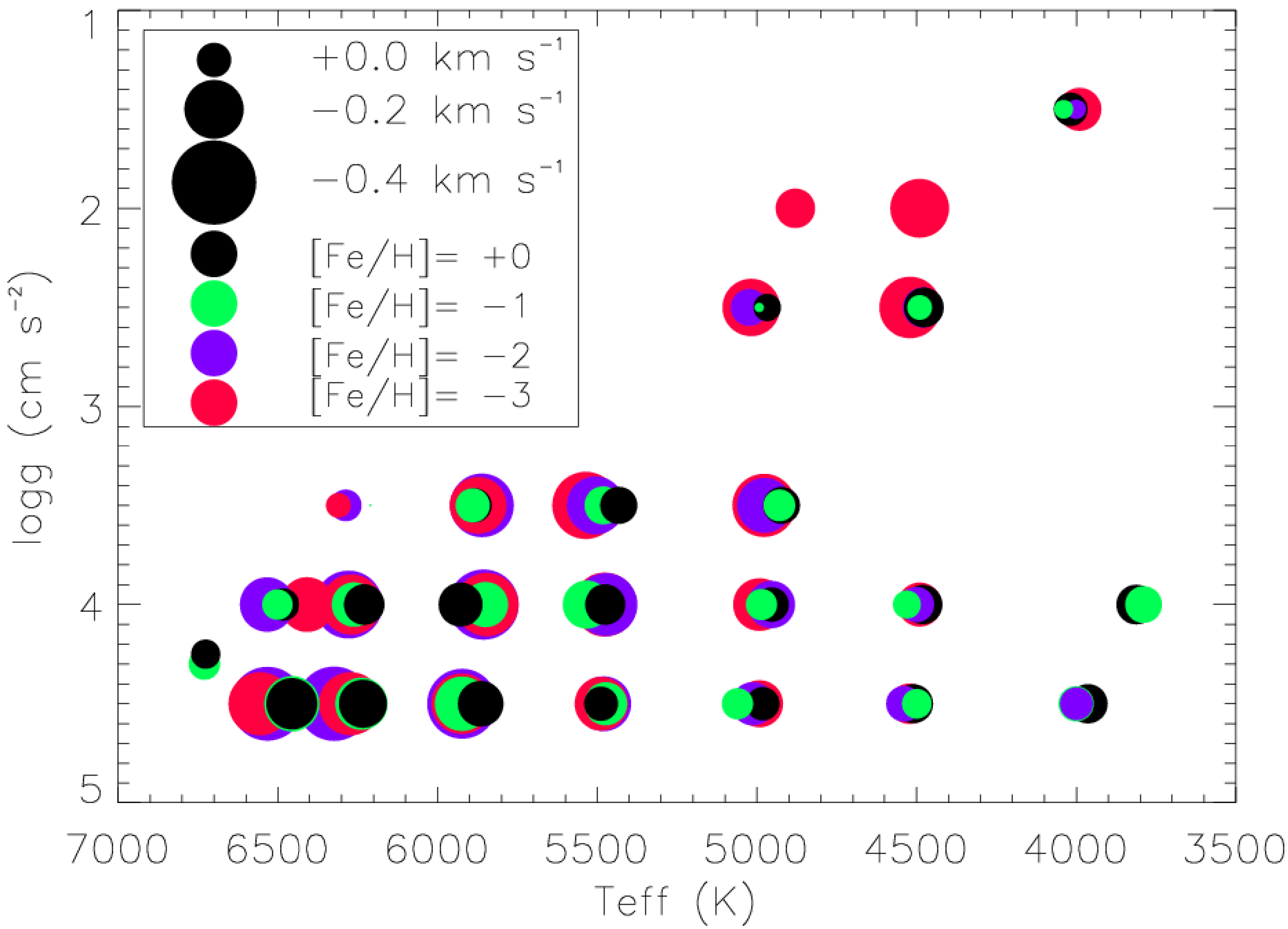
GES UVES stars: measured $\xi_{\rm micro}$ vs. recommended calibration



(red points: giants $\log g < 3.5$)

- Dispersion does not show obvious correlation with atmospheric parameters??

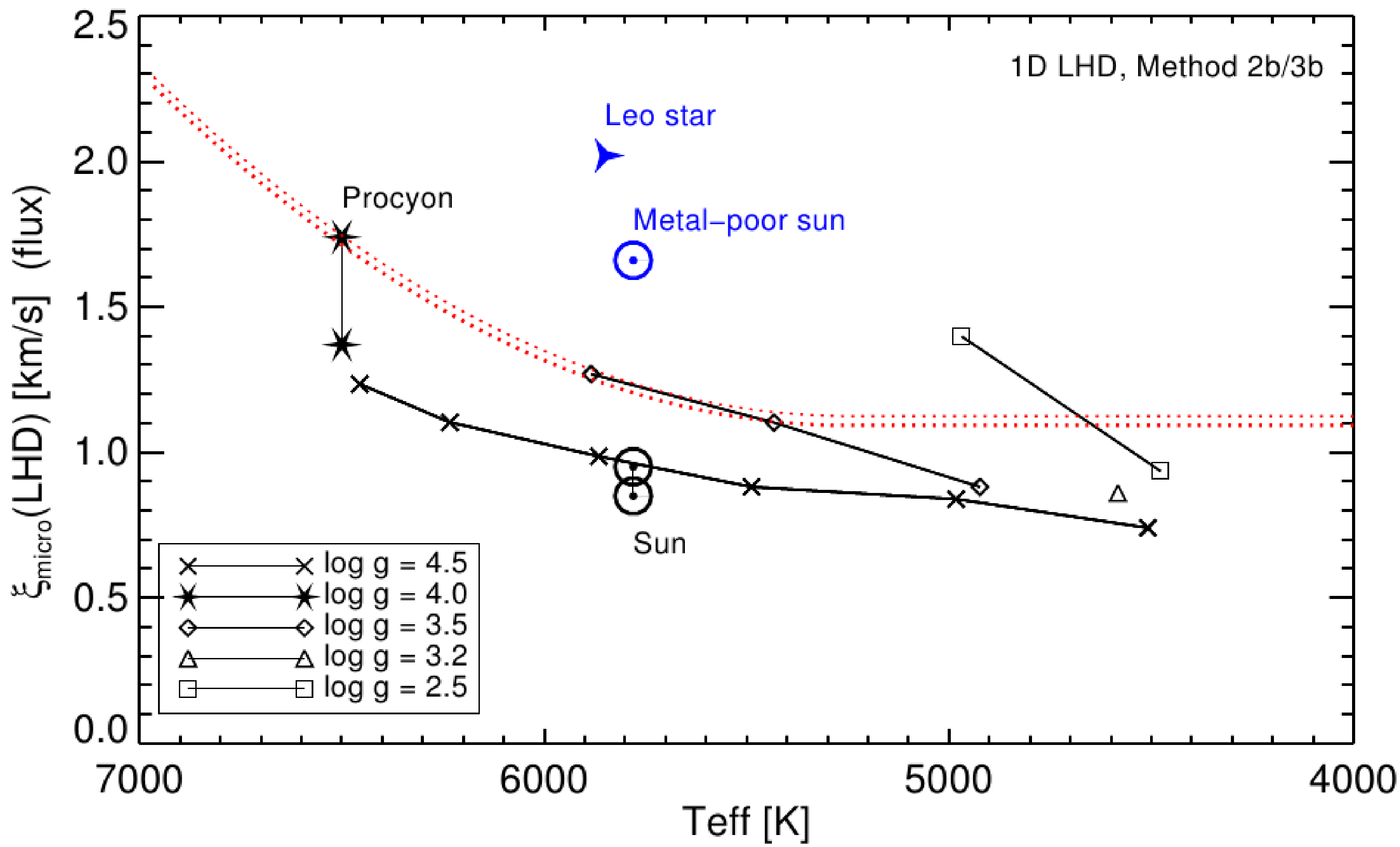
Predicted line shifts for Gaia's Radial Velocity Spectrometer



(Allende Prieto et al. 2013)

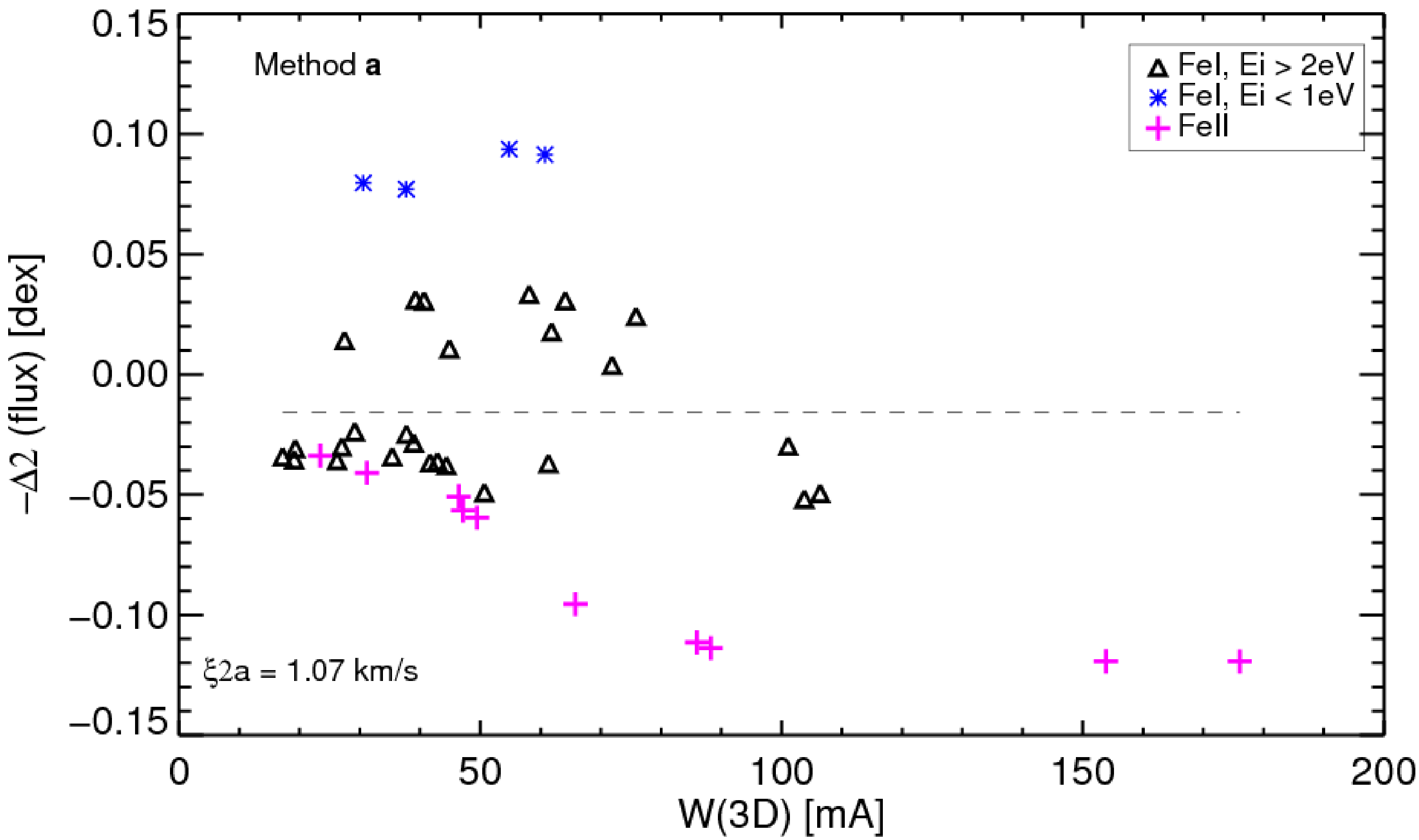
- Correcting spectroscopic radial velocities to actual stellar space motion
- 3D synthesis of RVS spectral range serious computational effort → Ranger@TACC

Microturbulence from 3D models (Steffen et al. 2013)



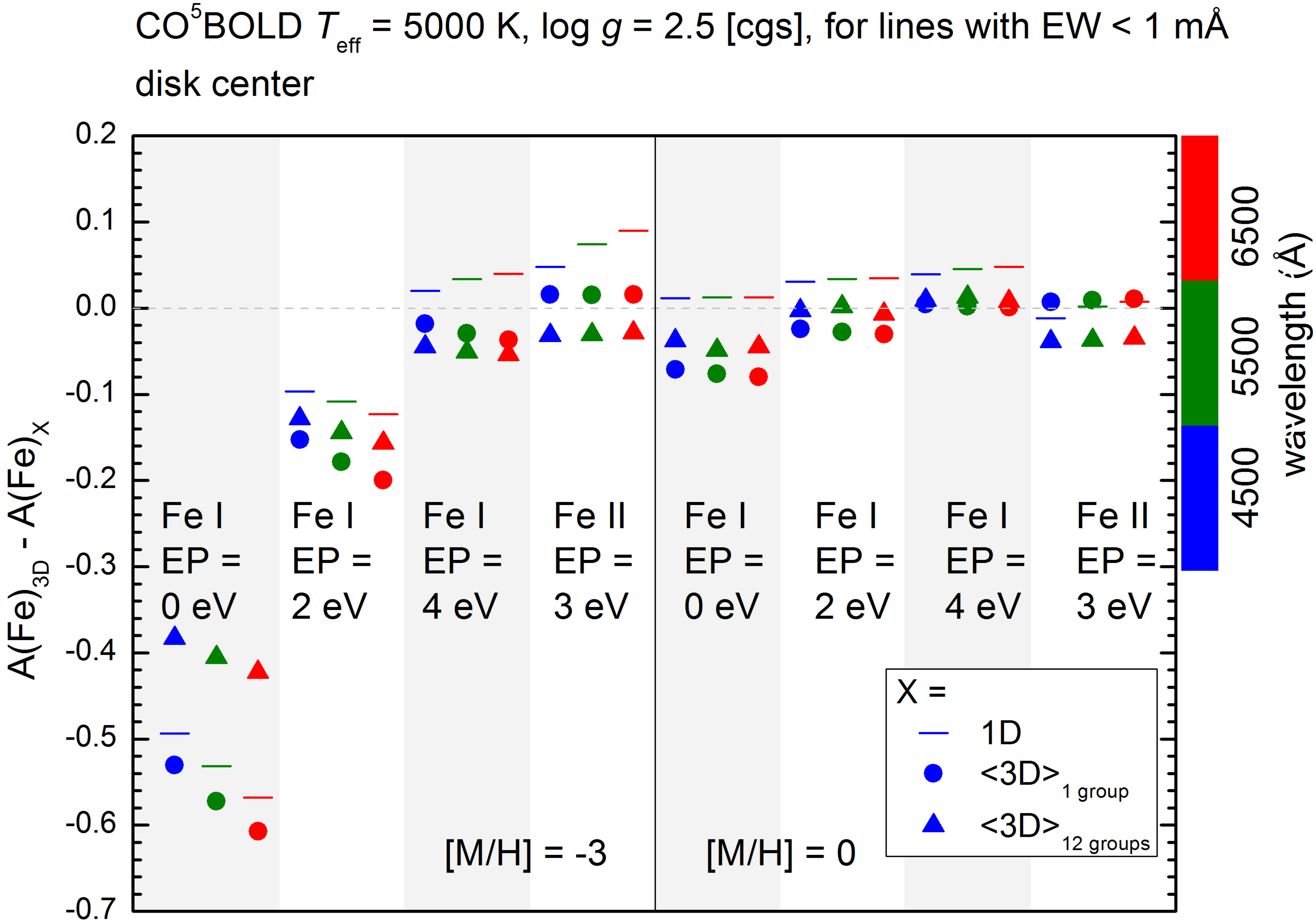
- CO[5]BOLD 3D model to provide "observation", here mostly $[\mathrm{M/H}] = 0$
- Interpret 3D line strength with help of 1D model
  - resolution of 3D models?
  - mismatch between 1D and 3D model in thermal structure?

Precision limits to 1D analysis: e.g. solar-metallicity F-dwarf



- Ideal situation: perfect LTE, line strengths and parameters exactly known
- Model of solar metallicity: 1D and ⟨3D⟩ model very similar
  → T-fluctuations drive differences and significant dispersion

Best 1D representation of 3D model? (intensity)

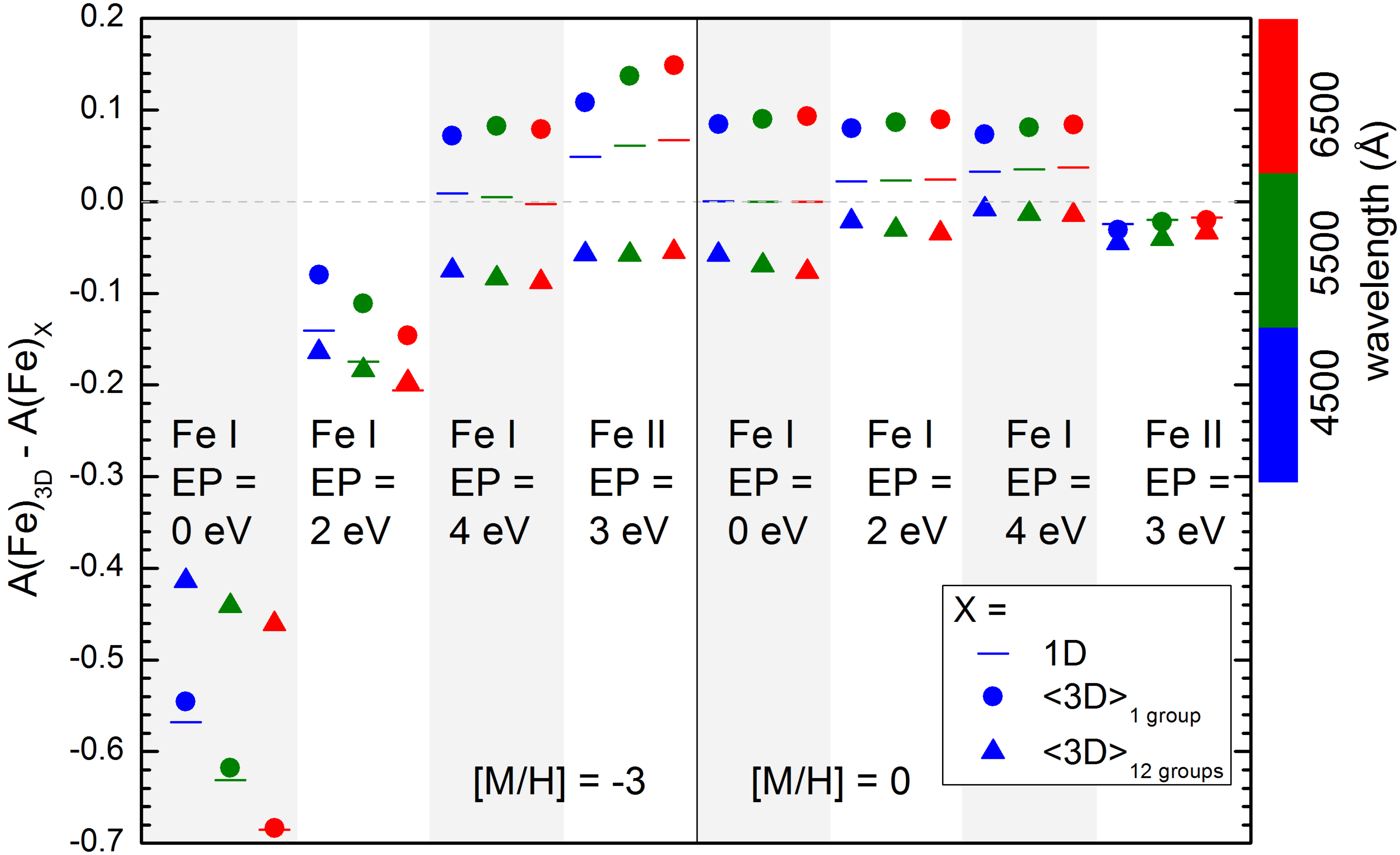


(Klevas 2013, priv. comm.)

Best 1D representation of 3D model? (flux)

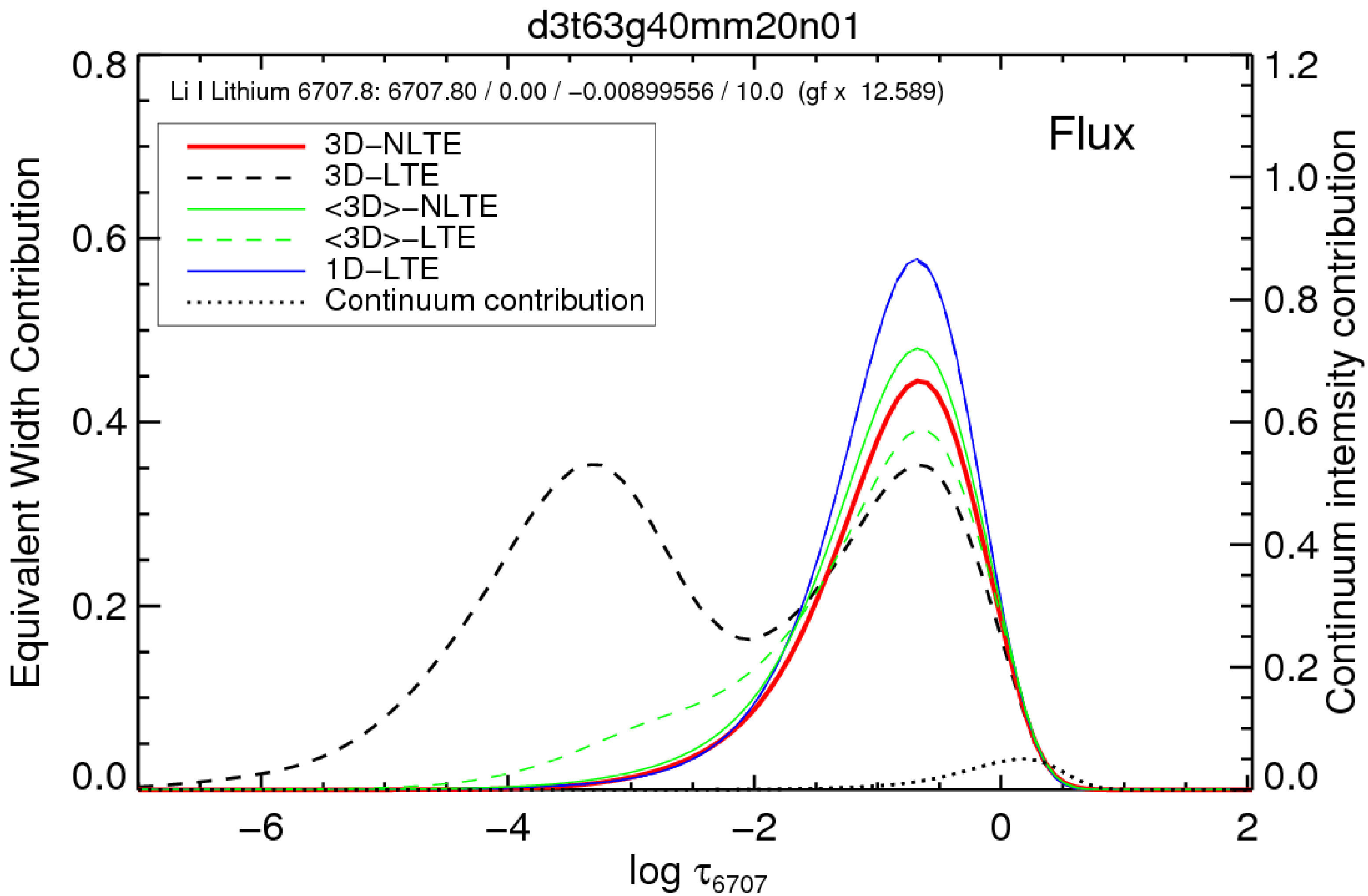
CO^{5}BOLD T_{eff} = 5000 K, log g = 2.5 [cgs], for lines with EW < 1 mÅ

disk-integrated



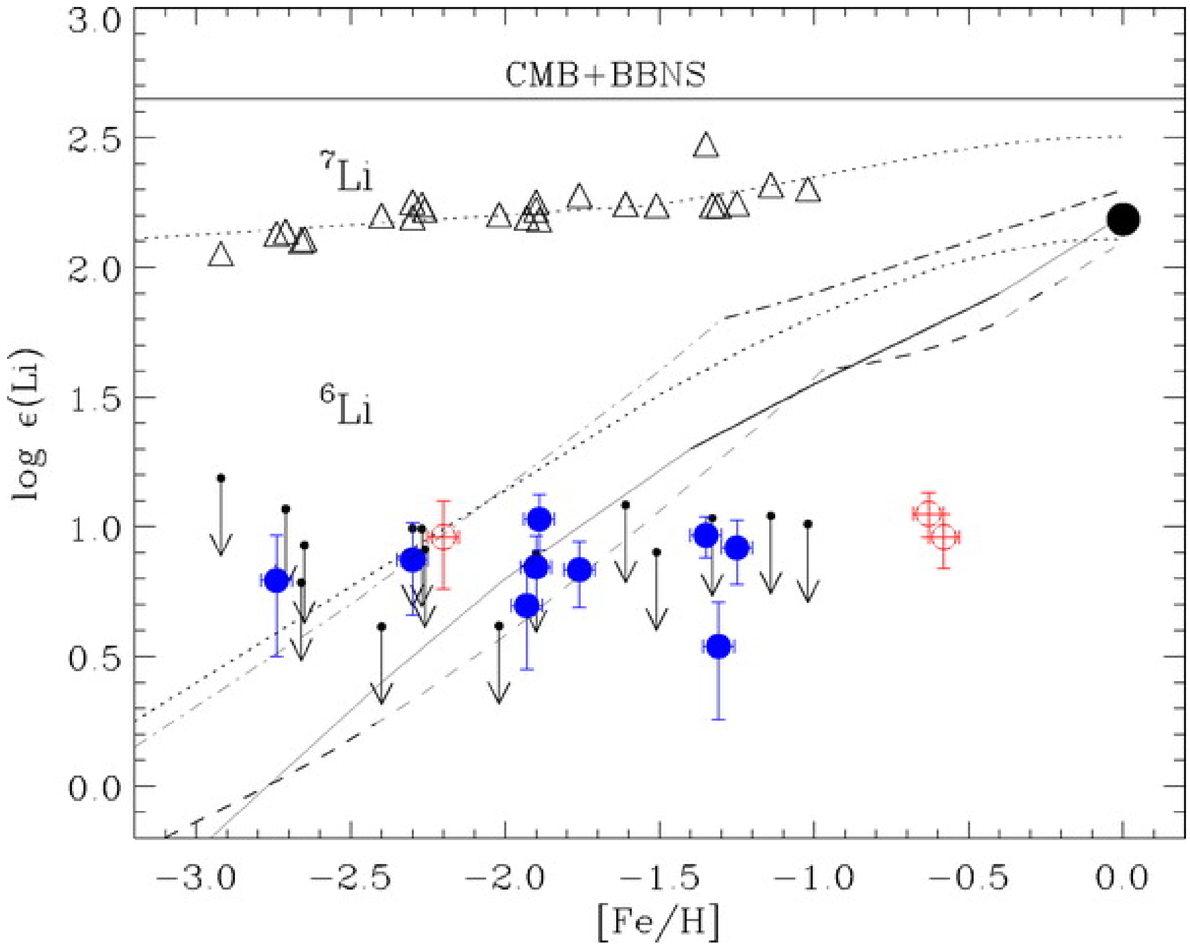
(Klevas 2013, priv. comm.)

Departures from LTE 3D, ⟨3D⟩, and 1D



(Steffen 2013, priv. comm.)

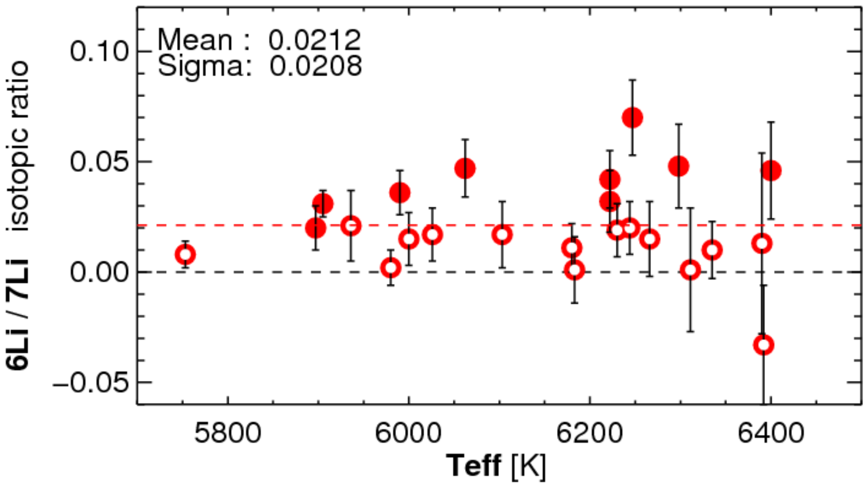
^{6}Li and ^{7}Li in metal-poor halo stars

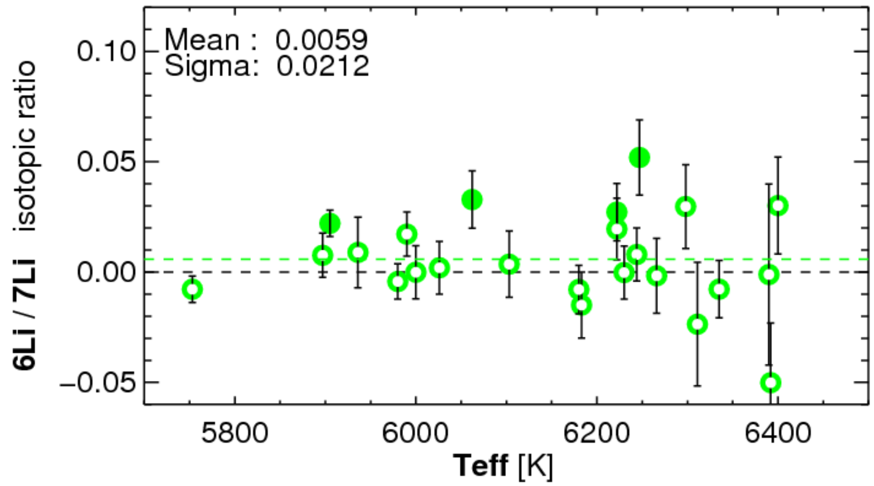


(Asplund et al. 2006; Smith et al. 1993, 1998; Cayrel et al. 1999; Nissen et al. 1999; chemical evolution models: Prantzos 2006; Ramaty et al. 2000; Fields & Olive 1999; Vangioni-Flam et al. 2000)

- Not corrected for stellar endogenic depletion; arrows indicate 3σ upper limits
- Essentially no ^{6}Li production during Big Bang; but measured isotopic ratio ≈ 0.05

Detections when accounting for 3D and NLTE effects

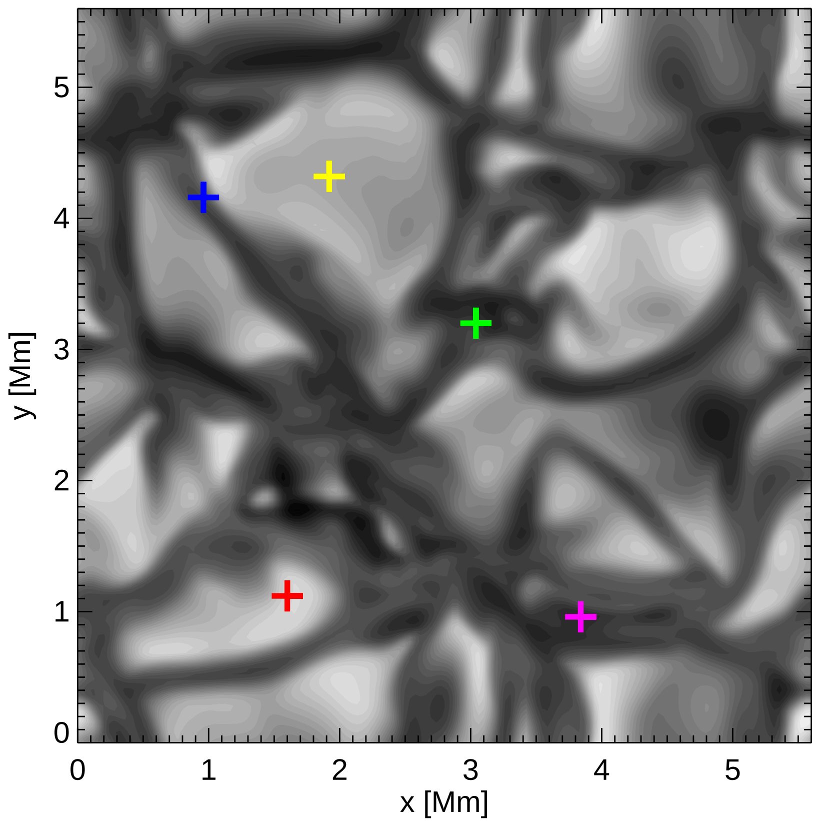


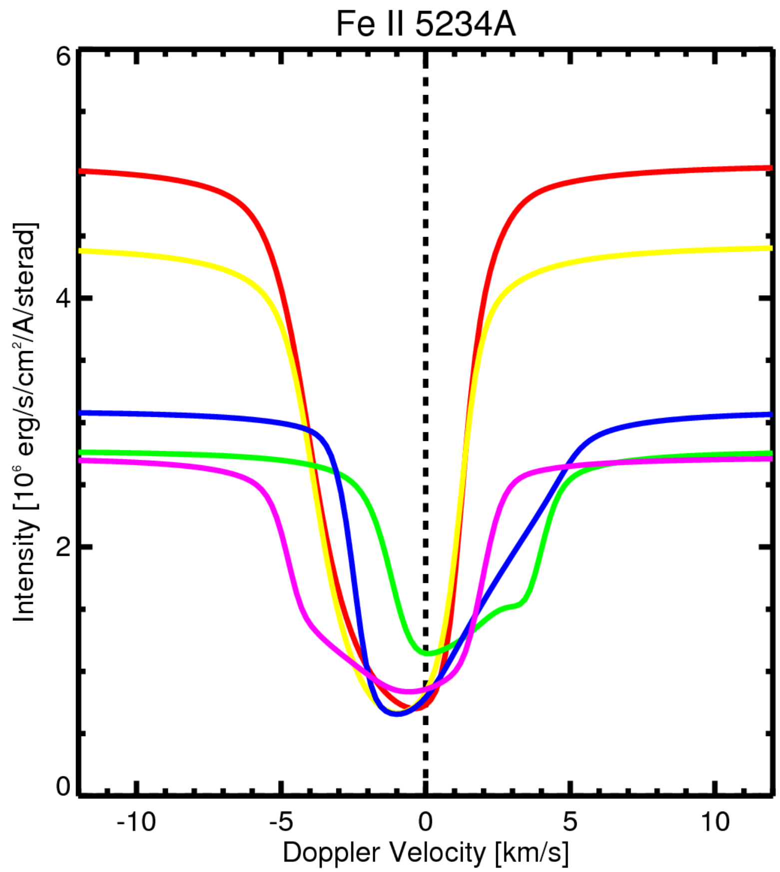


solid: detections / open: non-detections / left: Asplund et al. 2006 / right: corrected

- Reduction from 9 to 2-4 detections out of 24 2σ observations
- ^{6}Li in metal-poor halo stars rather the exception than the rule

3D spectral line formation with the Linfor3D package





- Variations in line strength, width, shift, asymmetry across granulation pattern
- Non-linearities cause net effects in disk-integrated light
- Knowledge of detailed line shapes $\rightarrow$ no micro/macro-turbulence