Hydrodynamical model atmospheres of cool stars: recent progress and lingering problems

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Overview

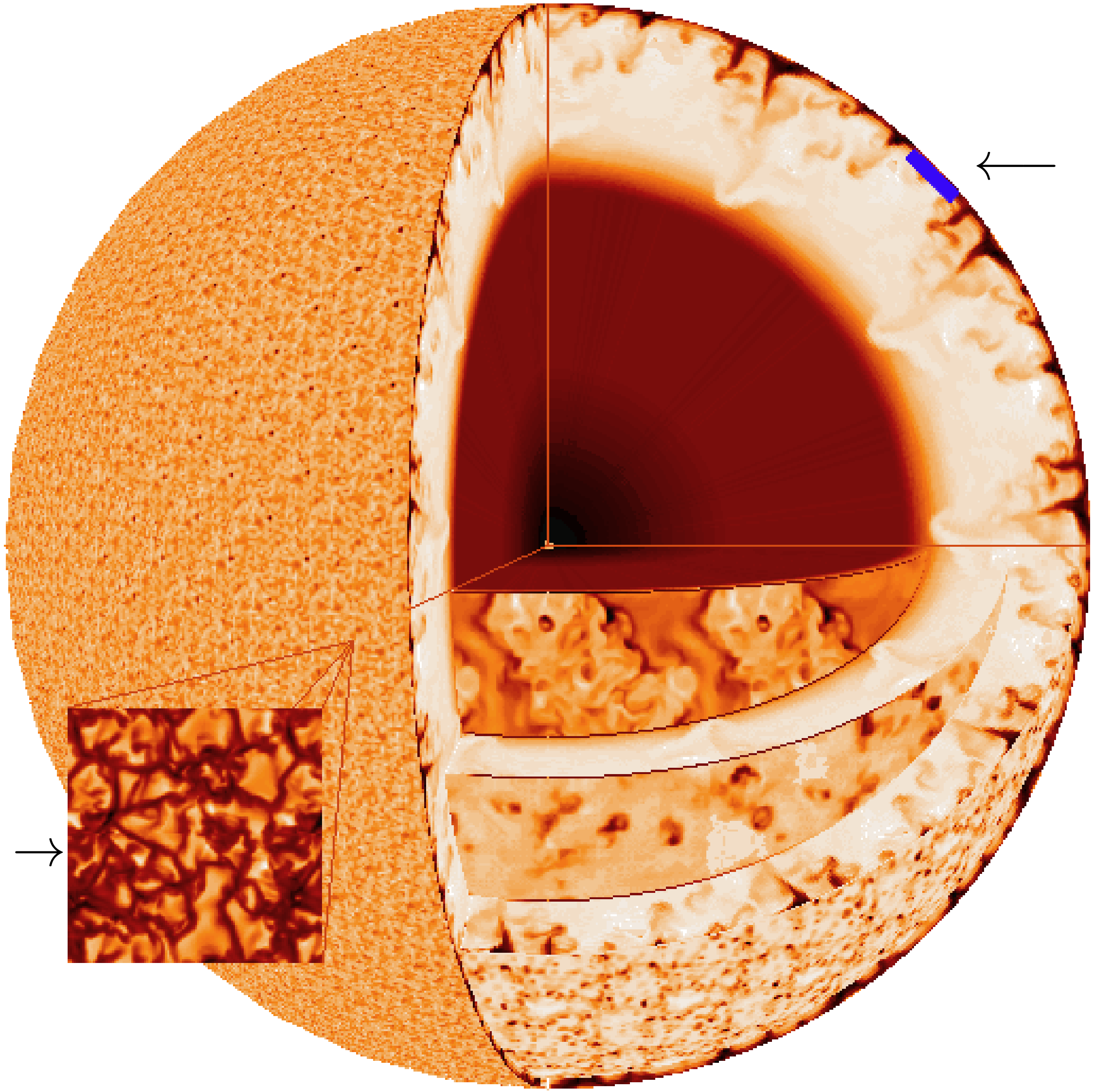
- CO^{5}BOLD radiation-magnetohydrodynamics code, 3D spectral synthesis

- Status of CIFIST 3D model atmosphere grid
  Cosmological Impact of the FIrst STars
  - continued and hopefully completed soon at Heidelberg and Vilnius

- Applications of hydrodynamical model atmospheres of different flavor
  - O abundance in binary CS 22876-032 $\rightarrow$ galactic chemical evolution
  - Solar abundances $\rightarrow$ helioseismic trouble
  - 3D atmospheres for giants and abundance corrections

- Leaving out ...
  ^{6}Li in the metal-poor halo dwarfs, micro-variability of late-type stars, stellar T_{eff} from Balmer lines, convective blueshifts for GAIA, surface structures and interferometry, chromospheres of M-dwarfs, cloud formation in brown dwarfs, predictions of the atmospheric microturbulence, high-mass problem in DA white dwarfs

Scale separation in cool stars → “box-in-a-star” setup



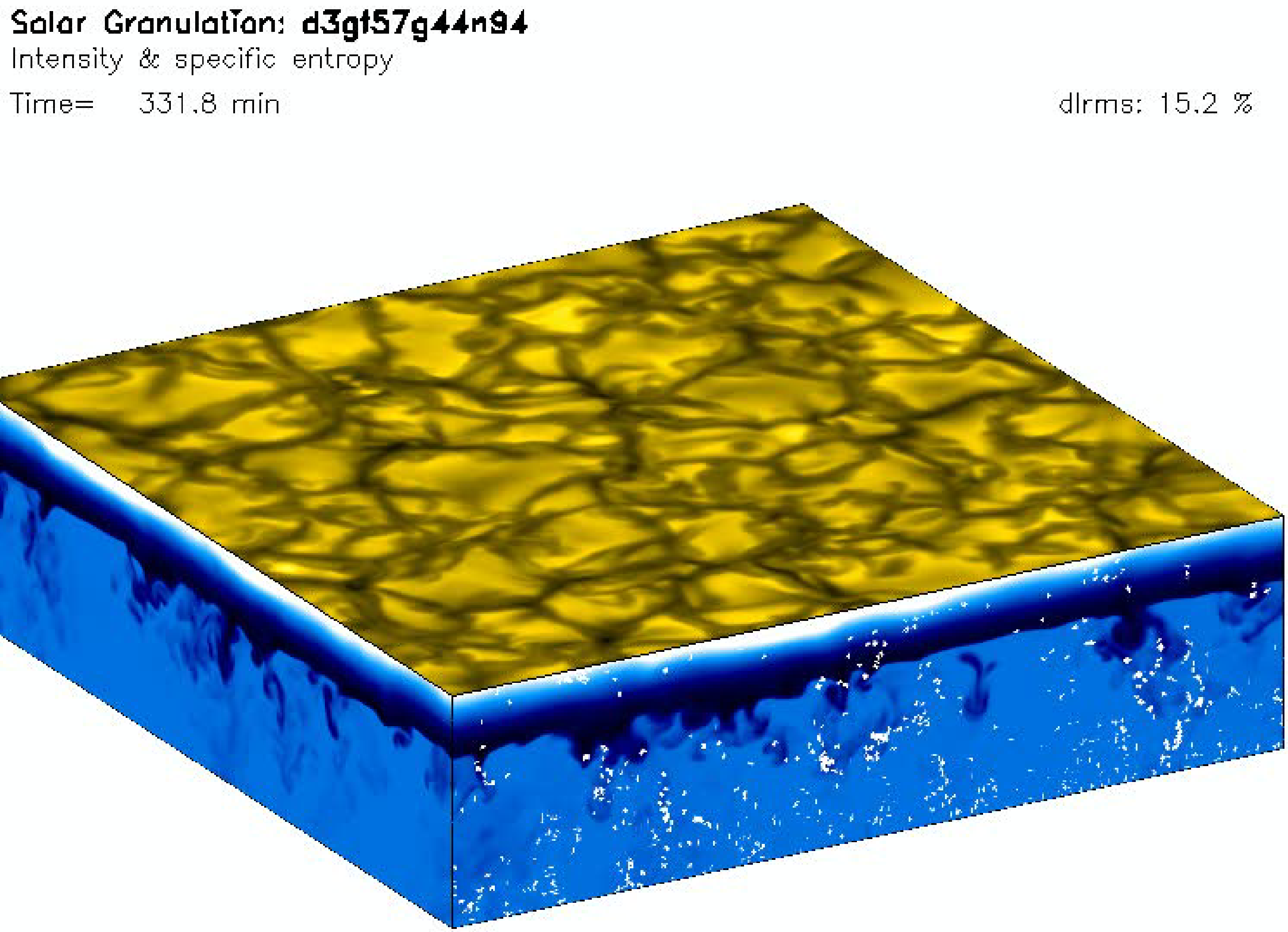
Cartesian simulation box with periodic side boundaries

Solar granulation →

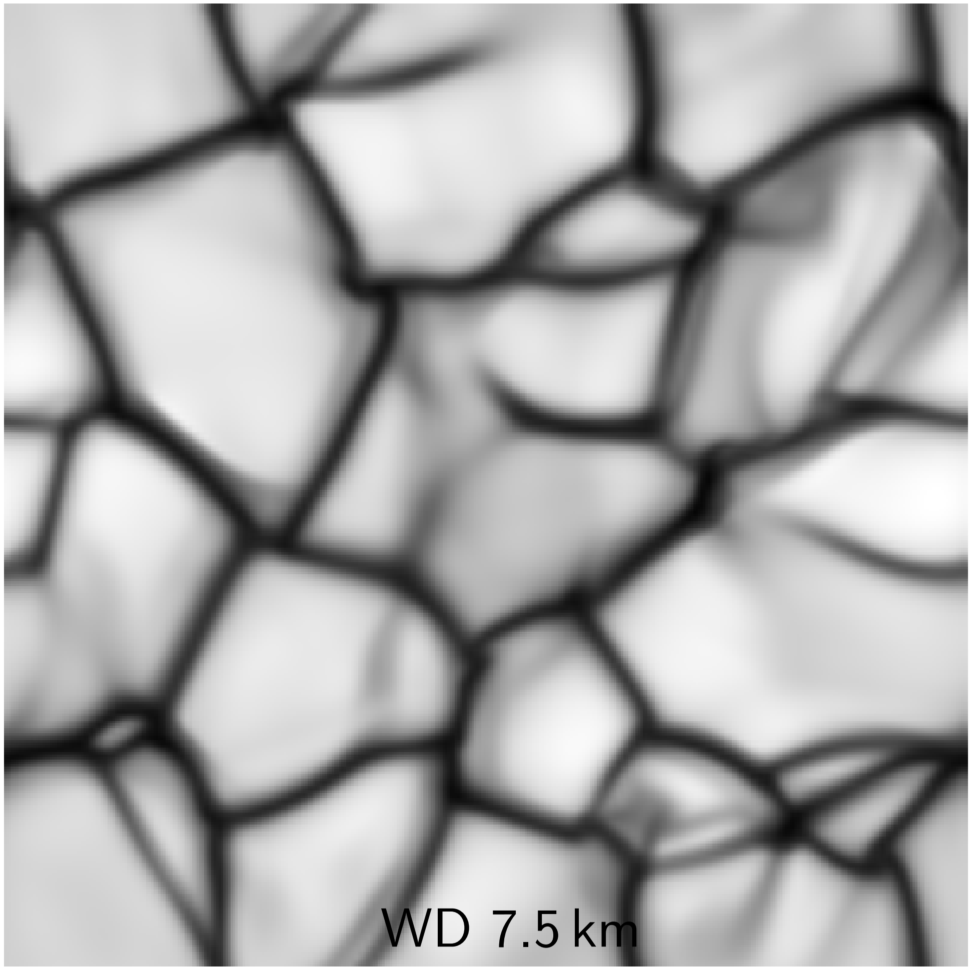
The radiation-magnetohydrodynamics code CO^{5}BOLD

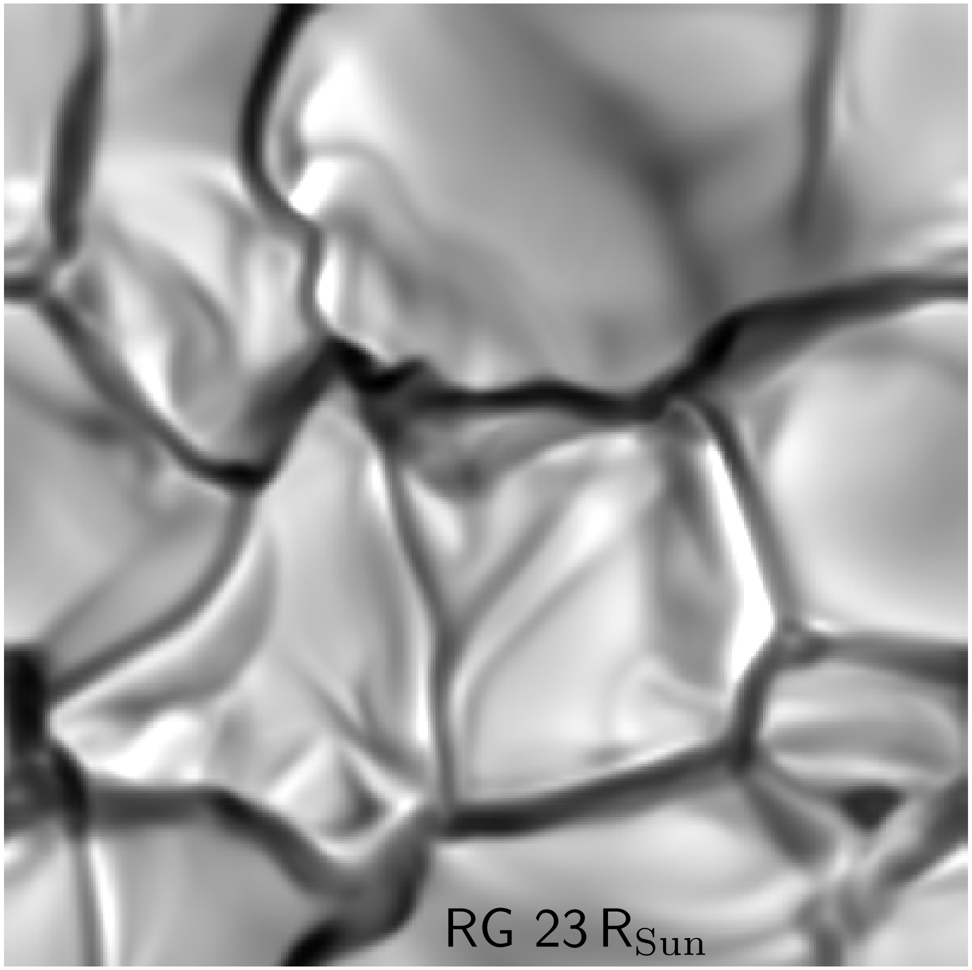
- COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions with l=2,3
- B. Freytag & M. Steffen, with contributions from S. Wedemeyer-Böhm, J. Leenaarts, W. Schaffenberger, HGL
- Solution of the HD or MHD equations coupled to equation of radiative transfer
  - HD/MHD, approximate Riemann solvers → low intrinsic dissipation, "shock-proof"
  - wavelength dependence of radiation field treated by multi-group approach
  - realistic equation-of-state (tables)
- Kinetics & transport for molecules and dust grains, non-equilibrium chemistry
- Strictly conservative in mass, momentum, and energy
- Open top (waves) and bottom (convection) boundaries
- CO^{5}BOLD not limited to local models "box-in-a-star" → "star-in-a-box"
- Result: statistical realization of flow from sub-photosphere to chromosphere

Schematic close-up of 3D model



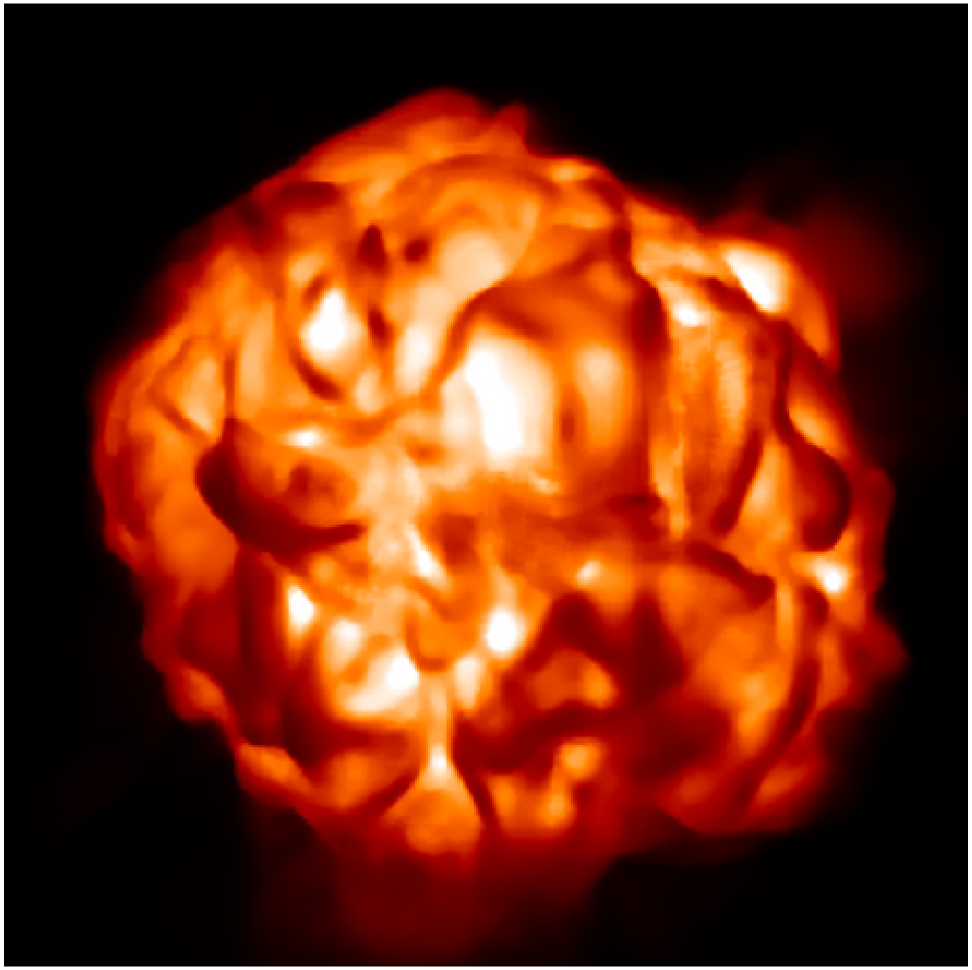
Granulation across the Hertzsprung-Russell diagram

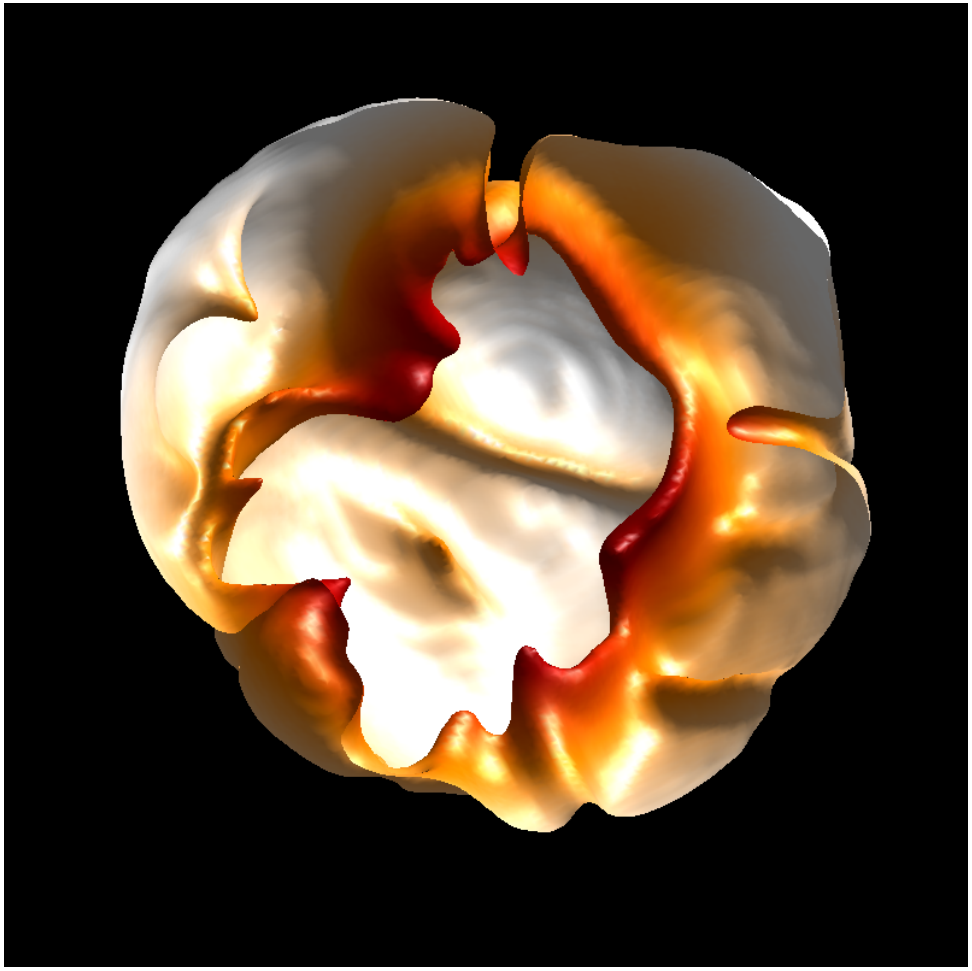




- From the Sun to stars with largely different parameters $\rightarrow$ robustness
- Here: spatial scale ratio 2×10^6

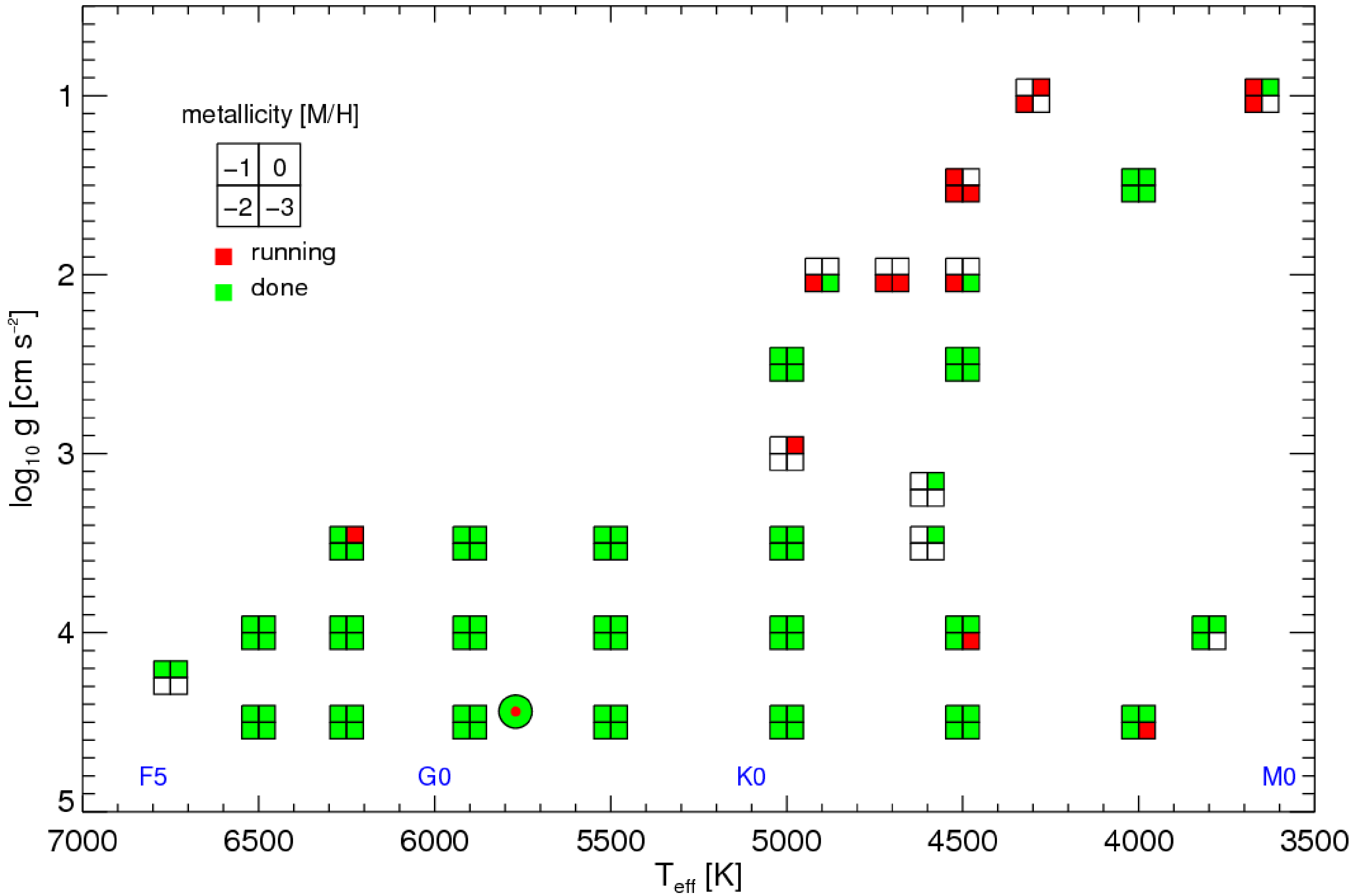
"Star in a Box"





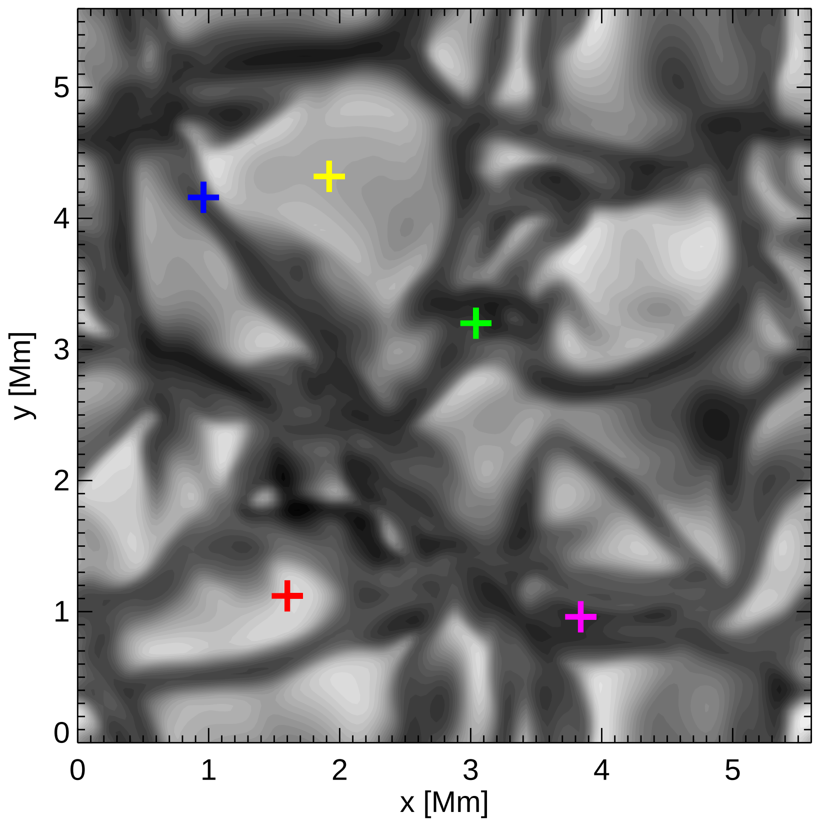
- CO^{5}BOLD model of red supergiant; © B. Freytag (Lyon)
  - complete stellar envelope, cubic box, Cartesian grid
  - observable radiation intensity (left), entropy-isosurface (right)

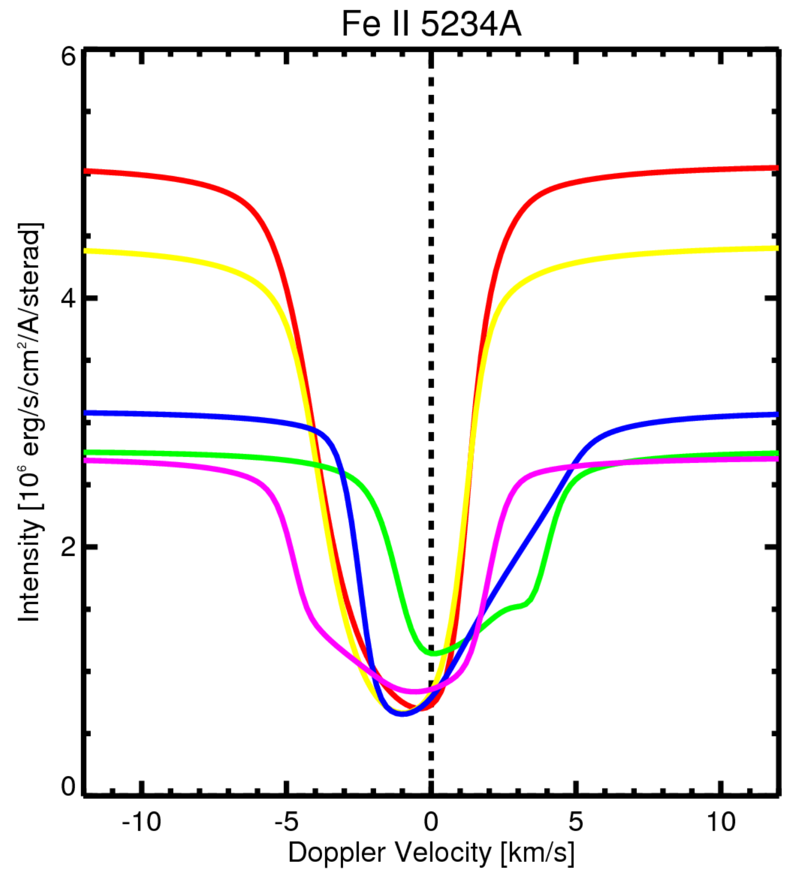
CIFIST **3D model atmosphere grid**



- Filling of parameter space mostly project driven

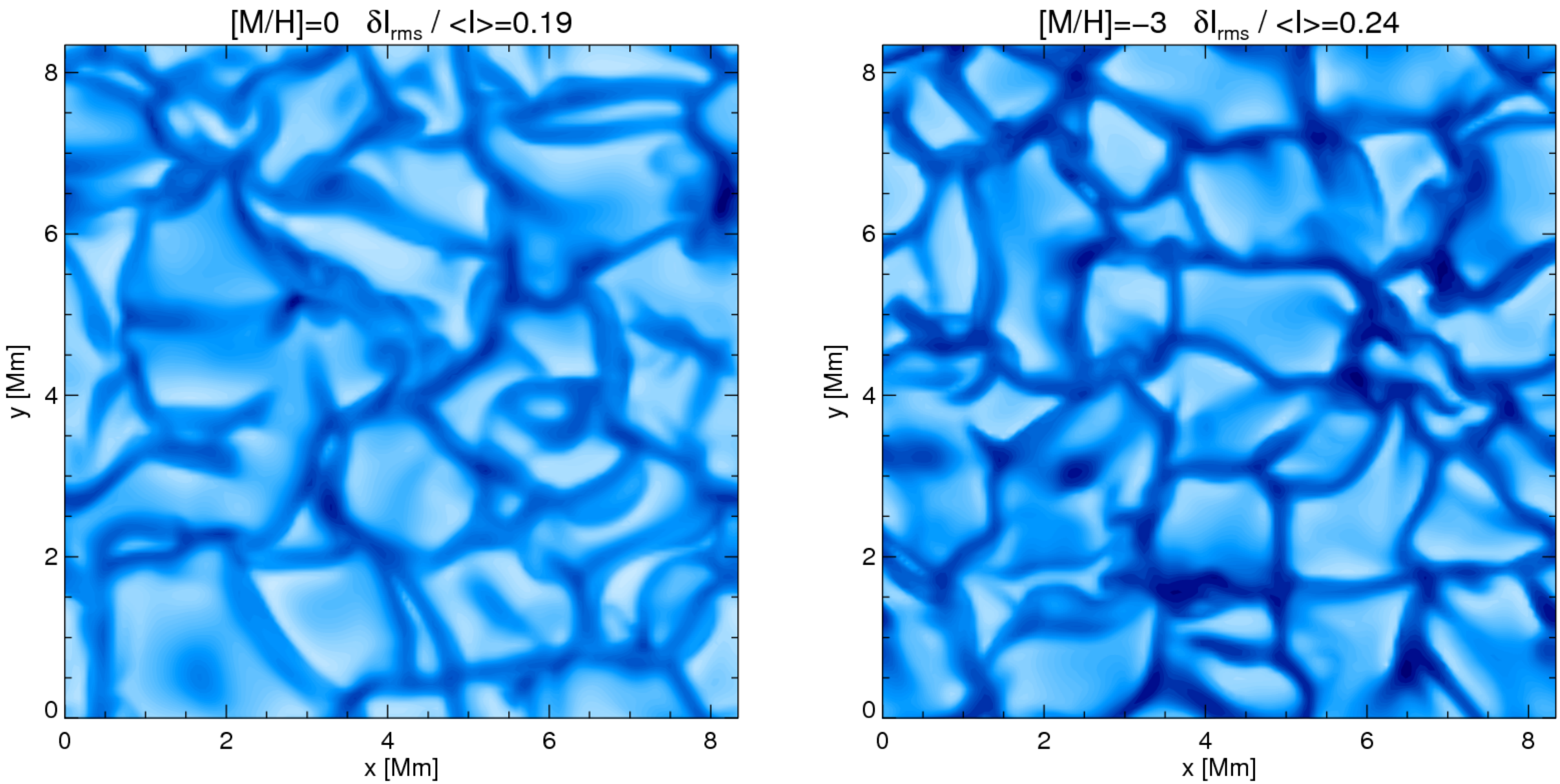
3D spectral line formation with the Linfor3D package





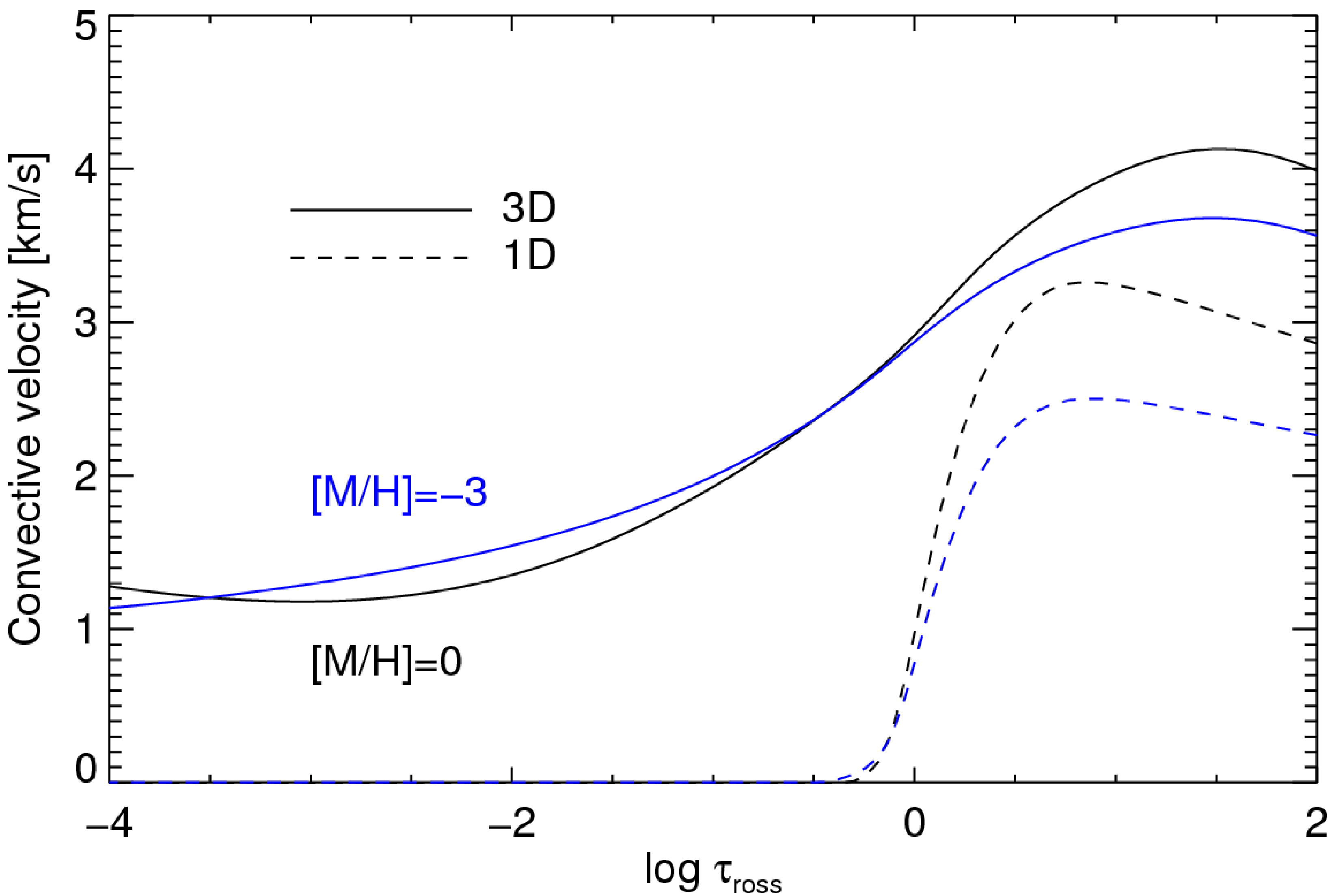
- Variations in line strength, width, shift, asymmetry across granulation pattern
- Non-linearities cause net effects in disk-integrated light
- Knowledge of detailed line shapes $\rightarrow$ no micro/macro-turbulence

Convection introduces horizontal temperature fluctuations at all metallicities



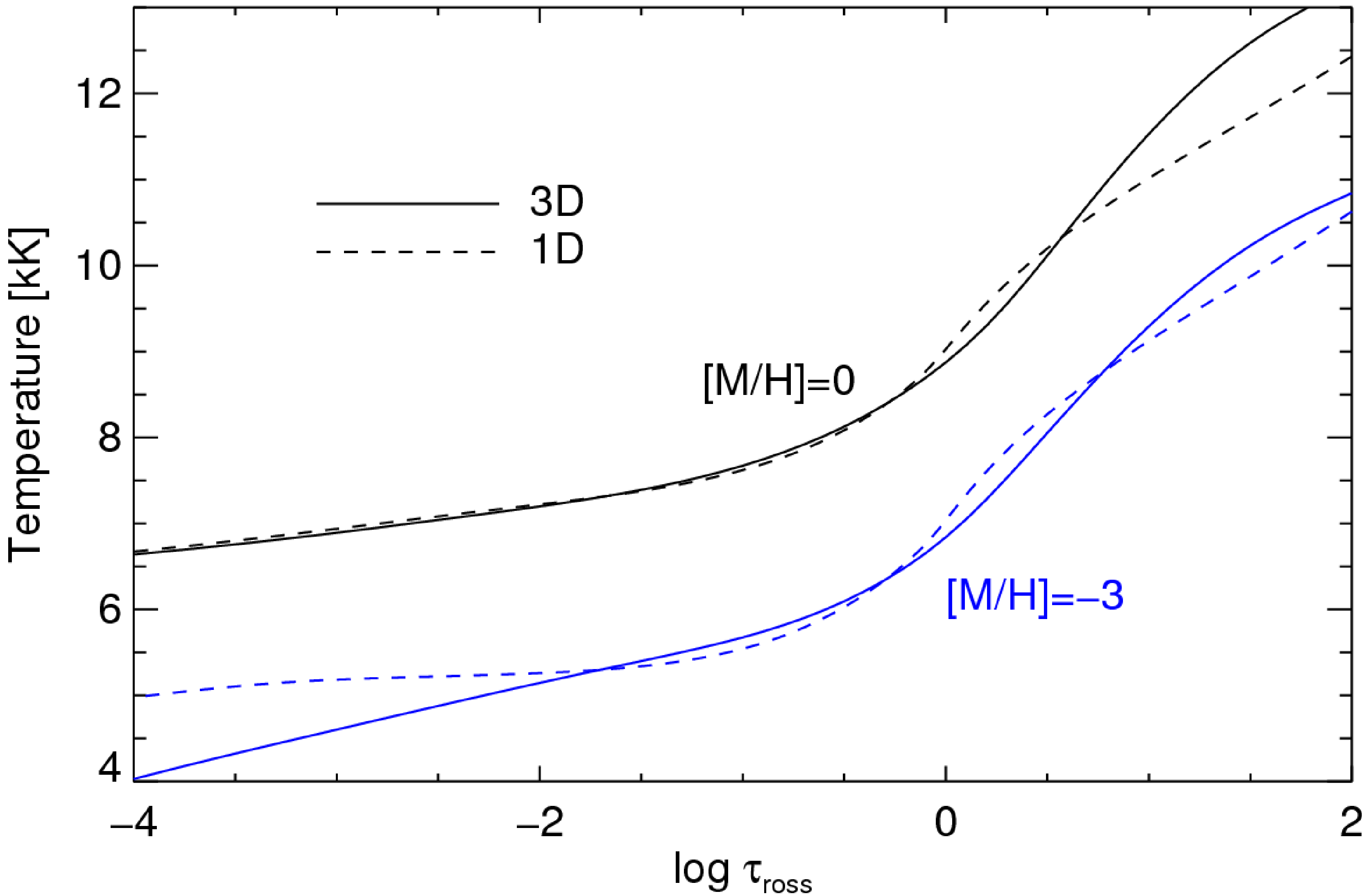
($T_{\rm eff}$=6500 K, $\log g$=4.5)

Convective overshooting takes place at all metallicities



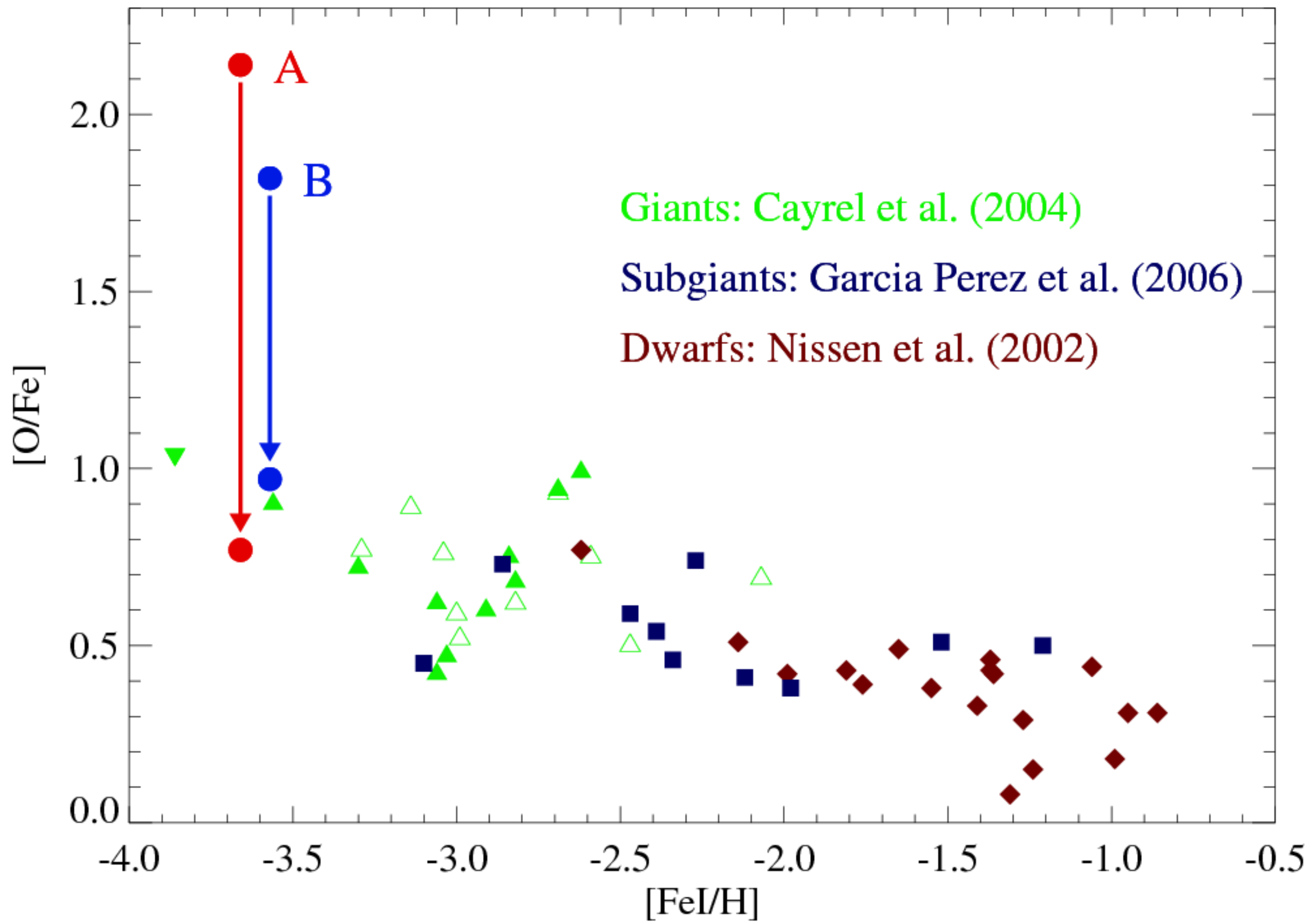
- 3D models predict strong overshooting ($v_{\rm z}^{\rm rms}$) → micro/macro-turbulence

Response to convective overshooting depends on metallicity



- Cooling/heating of outer/deeper photospheric layers stronger at low metallicity

Binary CS 22876-032 ([Fe/H]≈-3.7): OH vs [OI] 630nm



plot courtesy of J. González Hernández

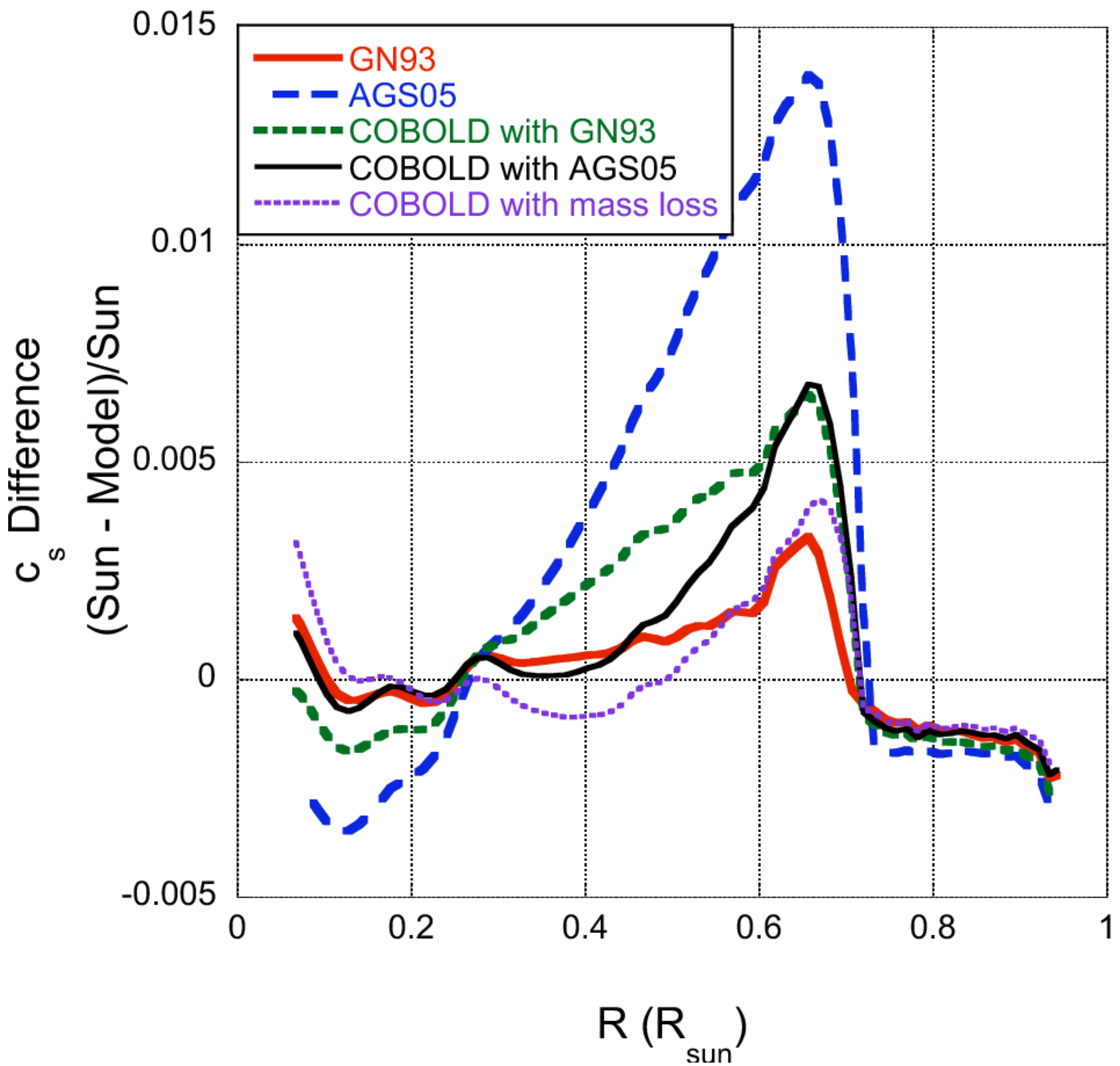
- O abundances from OH lines in the UV, 3D abundance corrections -1.0. . .-1.5 dex
- Binary components (Star A/B) support the notion of a slope in the O/Fe ratio

CO^5BOLD 3D abundances (E. Caffau) in comparison to others

EL	N	CO^5BOLD	AG89	GS98	AGS05	AGSS09
Li	1	1.02 ± 0.02	1.16 ± 0.10	1.10 ± 0.10	1.05 ± 0.10	1.05 ± 0.10
C	43	8.50 ± 0.11	8.56 ± 0.04	8.52 ± 0.06	8.39 ± 0.05	8.43 ± 0.05
N	12	7.86 ± 0.12	8.05 ± 0.04	7.92 ± 0.06	7.78 ± 0.06	7.83 ± 0.05
O	10	8.76 ± 0.07	8.93 ± 0.035	8.83 ± 0.06	8.66 ± 0.05	8.69 ± 0.05
P	5	5.46 ± 0.04	5.45 ± 0.04	5.45 ± 0.04	5.36 ± 0.04	5.41 ± 0.03
S	9	7.15 ± 0.06	7.21 ± 0.06	7.33 ± 0.11	7.14 ± 0.05	7.12 ± 0.03
Eu	5	0.52 ± 0.03	0.51 ± 0.08	0.51 ± 0.08	0.52 ± 0.06	0.52 ± 0.04
Hf	4	0.87 ± 0.04	0.88 ± 0.08	0.88 ± 0.08	0.88 ± 0.08	0.85 ± 0.04
Th	1	0.08 ± 0.03	0.12 ± 0.06	*0.09 ± 0.02*	*0.06 ± 0.05*	0.02 ± 0.10
K	6	5.10 ± 0.09	5.12 ± 0.13	5.12 ± 0.13	5.08 ± 0.07	5.03 ± 0.09
Fe	15	7.51 ± 0.08	7.67 ± 0.03	7.50 ± 0.05	7.45 ± 0.05	7.50 ± 0.04
Os	3	1.15 ± 0.06	1.45 ± 0.10	1.45 ± 0.10	1.45 ± 0.10	1.25 ± 0.07
Z		0.0154	0.0189	0.0171	0.0122	0.0134
Z/X		0.0211	0.0267	0.0234	0.0165	0.0183

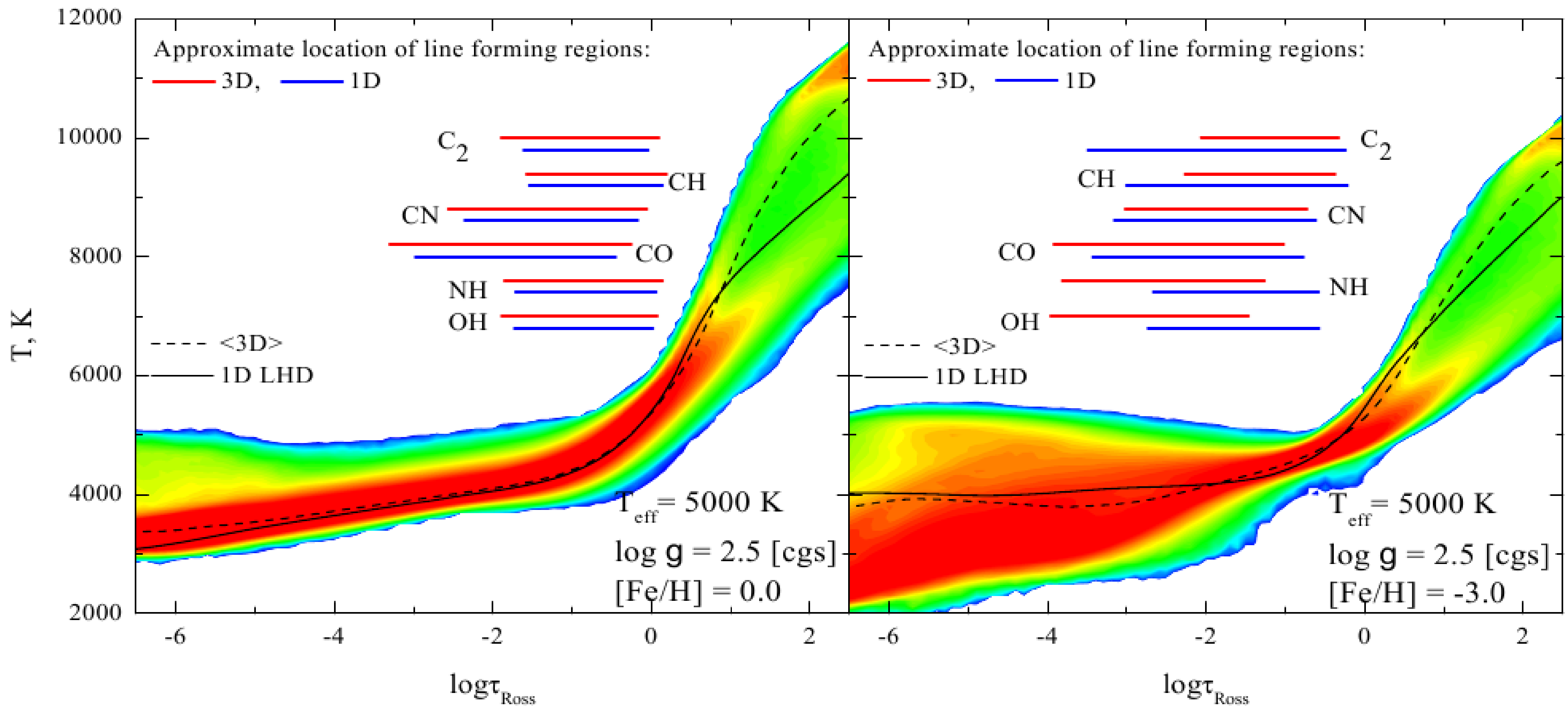
AG89 Anders & Grevesse Geochemica et Cosmochimica acta, 1989 Vol. 53 (6th place)
GS98: Grevesse et Sauval; Space Science Reviews 85: 161-174, 1998
AGS05: Asplund et al.; ASP Conferences Series, Vol. 336, 2205
AGGS09: Asplund, Grevesse, Sauval, & Scott, 2009, ARAA 47, 481

Helioseismic trouble: mismatch to the solar sound speed profile



(from Guzik et al. 2010)

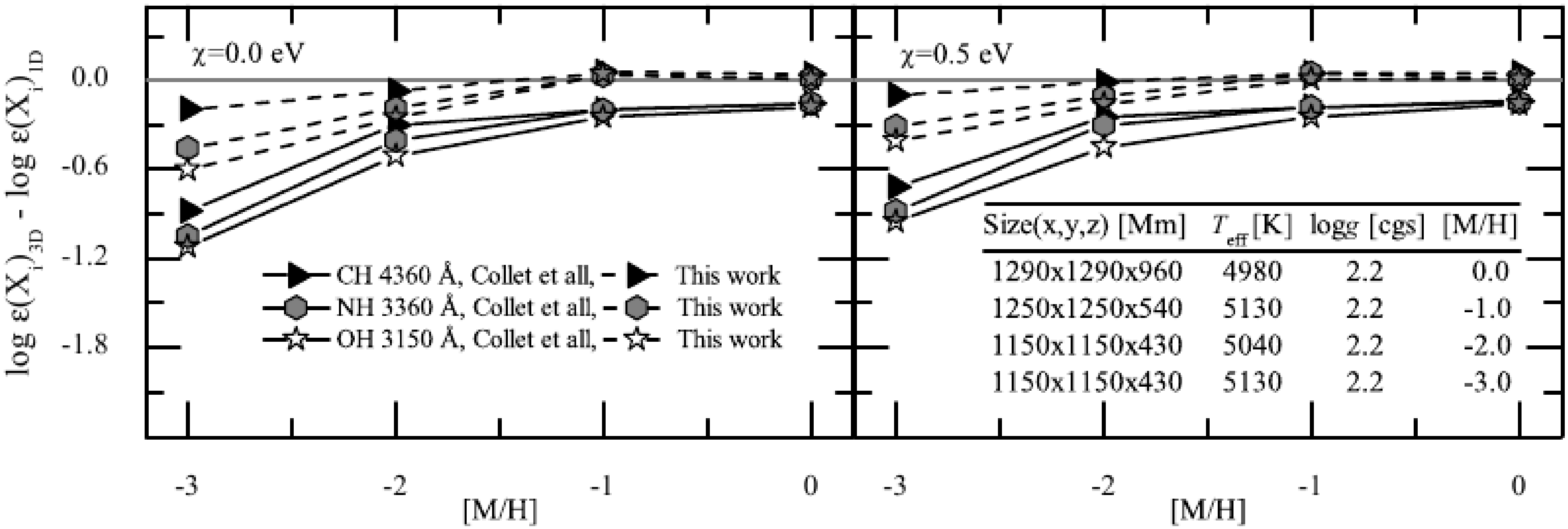
3D effects on RG temperature structure



(from Ivanauskas et al. 2010)

- Two 3D effects on T-structure
  - change of mean temperature with respect to 1D MLT model
  - strong fluctuations around the mean
- Rather modest change of mean structure at rather low metallicity

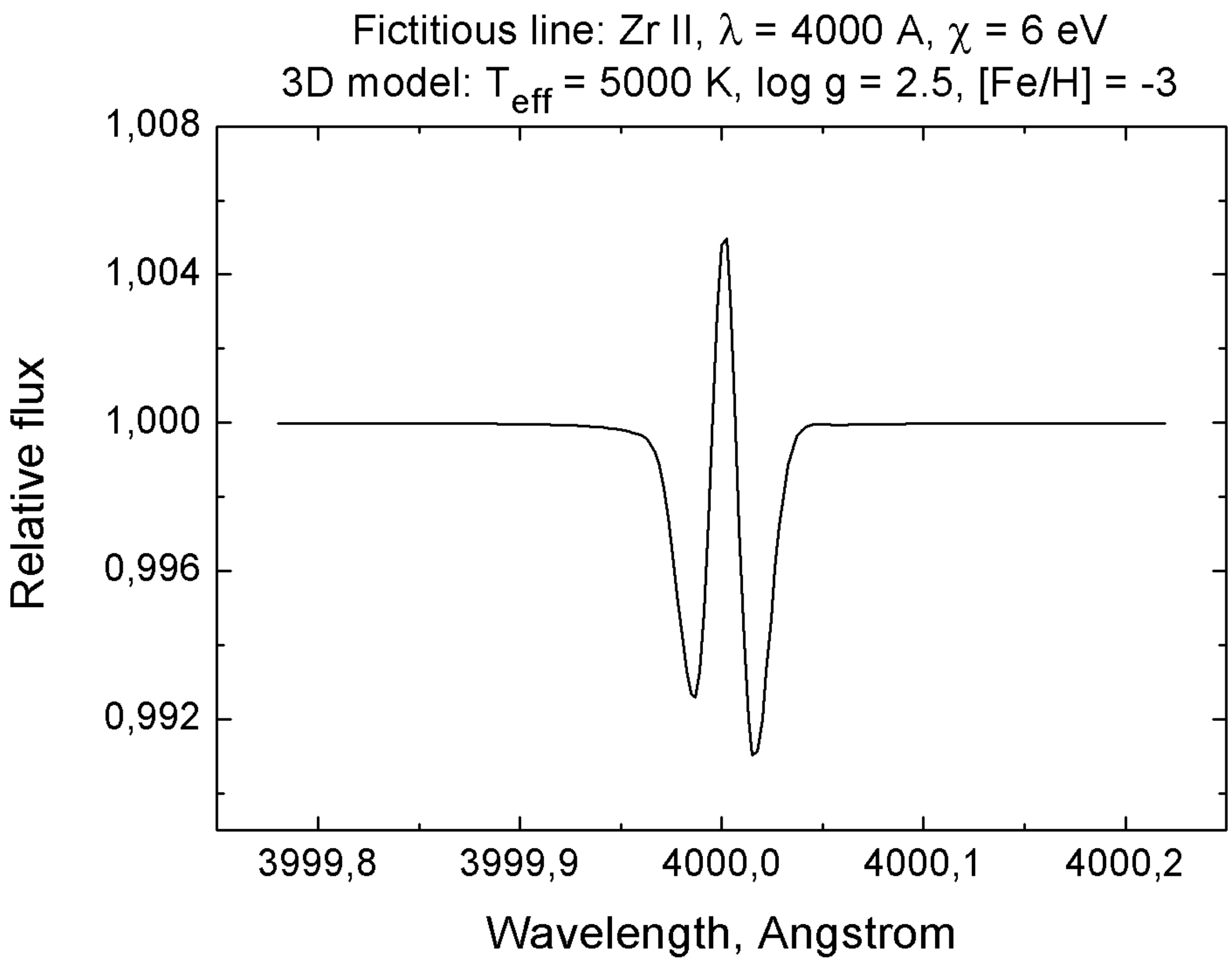
3D effects on abundances



(from Ivanauskas et al. 2010)

- 3D-1D abundance corrections smaller than in Nordlund-Stein 3D models (comparison to work of Collet et al. 2007)
- Treatment of scattering effects? (H Rayleigh scattering)
- Models sometimes predict emission features in line profiles
  - horizontal T-inhomogeneities realistic? departures from LTE?

Flow structure of metal-poor RG models tends to generate emission lines



(from Prakapavicius 2011, priv. comm.)

- Emission features not observed. NLTE effects important?

Take away ...

- Multi-D time-dependent model atmospheres have reached a high level of realism
  - most stars with outer convective envelopes can be modelled
  - some limitations persist at high $T_{\rm eff}$ and low $\log g$
- Metal-poor stellar atmospheres more easily affected by gas-dynamics
- Refined insight into stellar physics and more reliable use of stars as probes of astrophysical processes
- Provide higher-fidelity abundances which sometimes change physical conclusions $qualitatively$
- Further development efforts necessary

Compute cluster GODOT – hardware

- 14 *identical* PCs, standard ethernet switch (1 Gb/s), no rack!
- 2× dual core AMD Opteron processor 285, 2.6 Ghz, 4 Gb RAM, 120 Gb disk

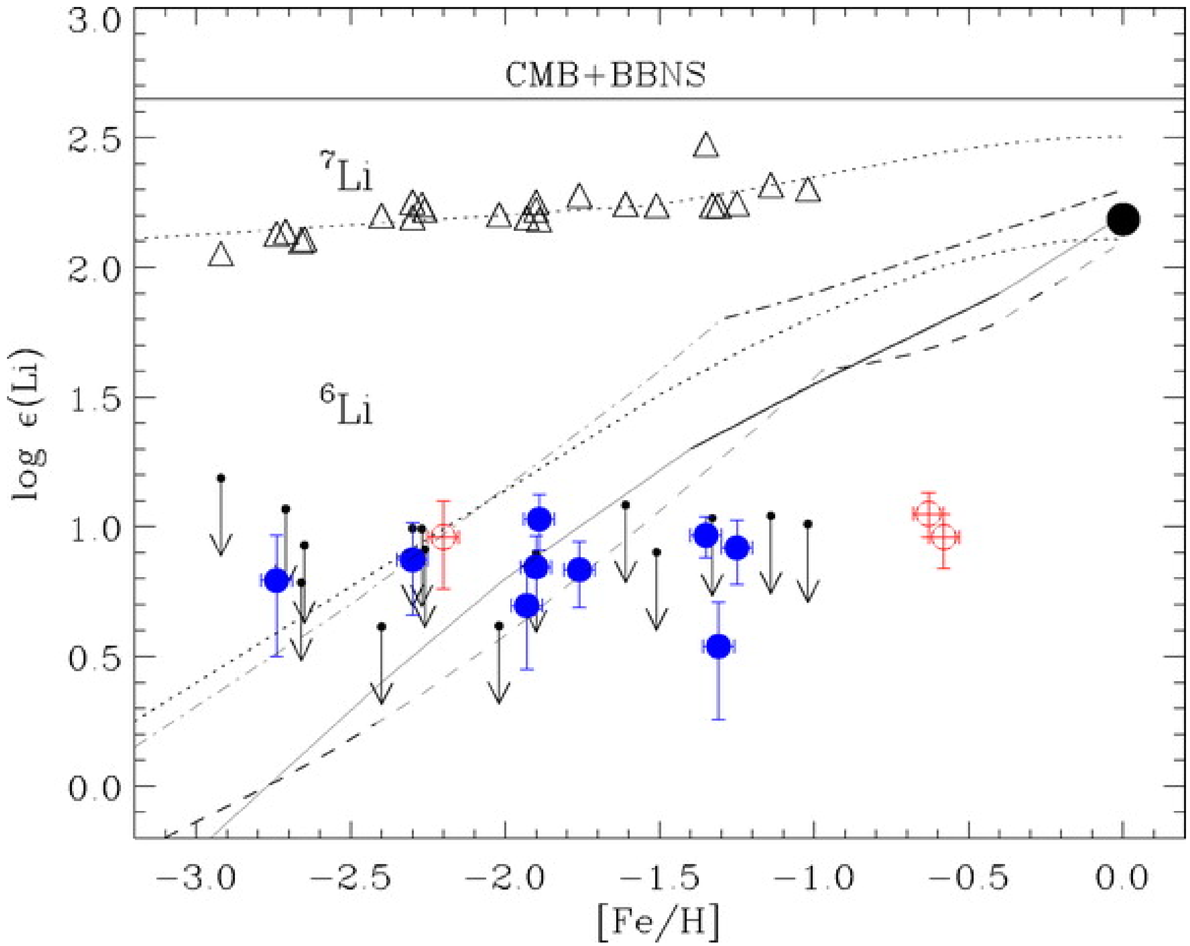
Balance between convective (adiabatic) and radiative equilibrium

$$t_{\mathrm{rad}} = \frac{c_{\mathrm{p}}}{16\sigma\, T^3\, \chi}$$

$$t_{\mathrm{con}} = \frac{H_{\mathrm{p}}}{v_{\mathrm{con}}}$$

- Lack of metal lines in metal-poor atmospheres: $\chi \downarrow \quad t_{\mathrm{rad}} \uparrow$
- T and $\chi(\rho, T)$ dependence causes rapid transition to cool state
- Larger H_{p} at lower gravities makes giants less prone to deviations from radiative equilibrium
  - v_{con} not largely different between dwarfs and giants
  - t_{rad} not sensitively dependent on density

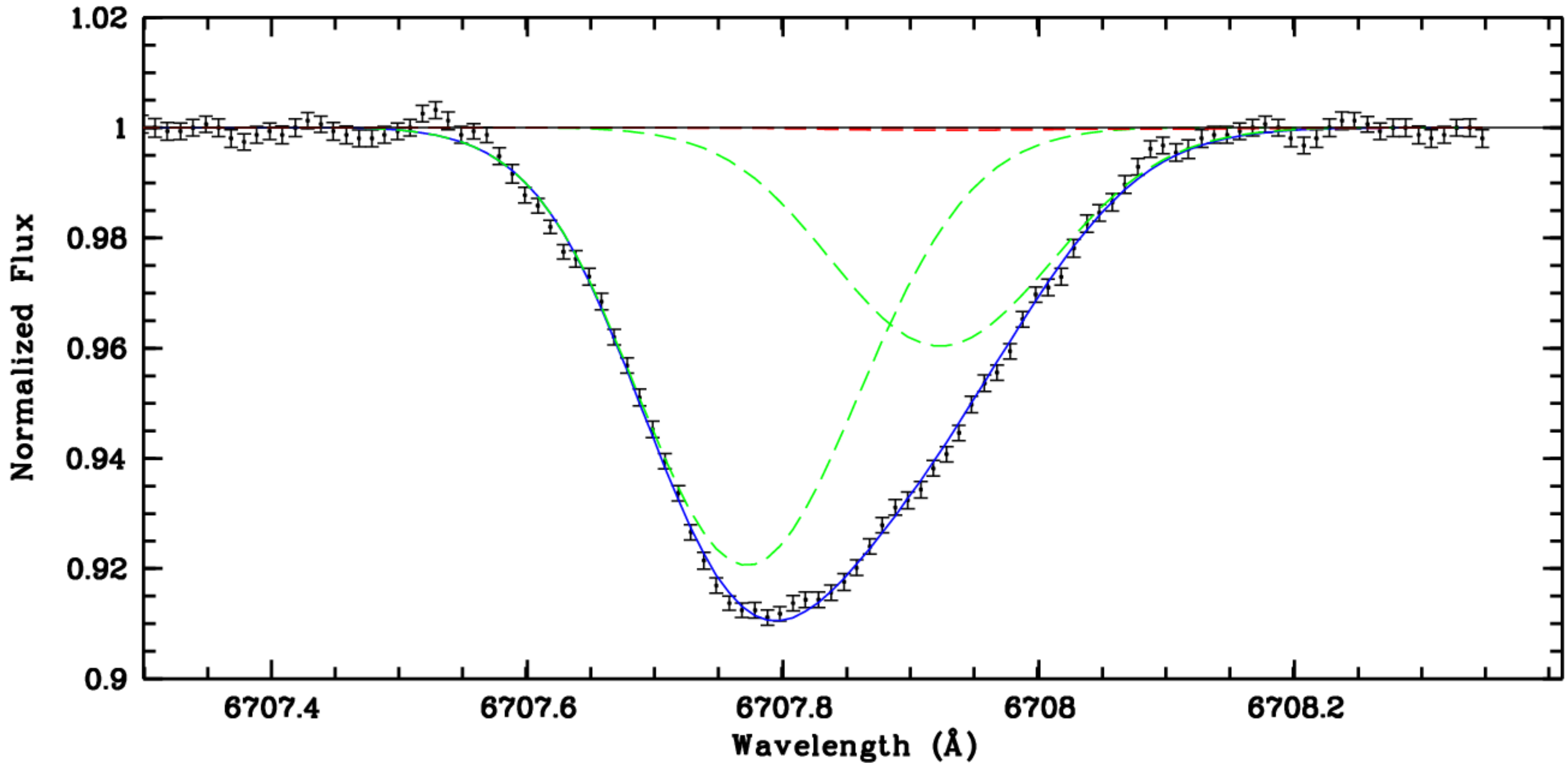
^{6}Li and ^{7}Li in metal-poor halo stars



(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)

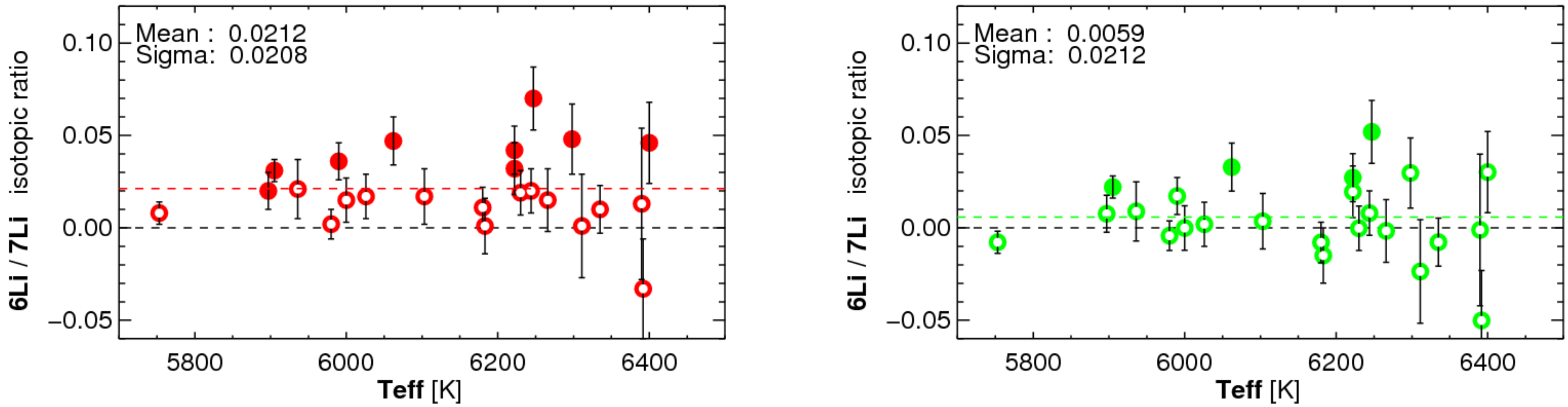
- Not corrected for stellar endogenic depletion; arrows indicate 3σ upper limits
- Essentially no ^{6}Li production during Big Bang; but measured isotopic ratio ≈ 0.05

Case study of difficult spectroscopic measurement: ^{6}Li/^{7}Li isotopic ratio in the metal-poor halo dwarf HD74000



- Outstanding observational material: 20h HARPS, $\lambda/\Delta\lambda \approx 110\,000$, $\mathrm{S/N} \approx 600$
- 3D convective line asymmetry and NLTE effects mimic presence of ^{6}Li
- Casts doubts on all previous 1D measurements

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