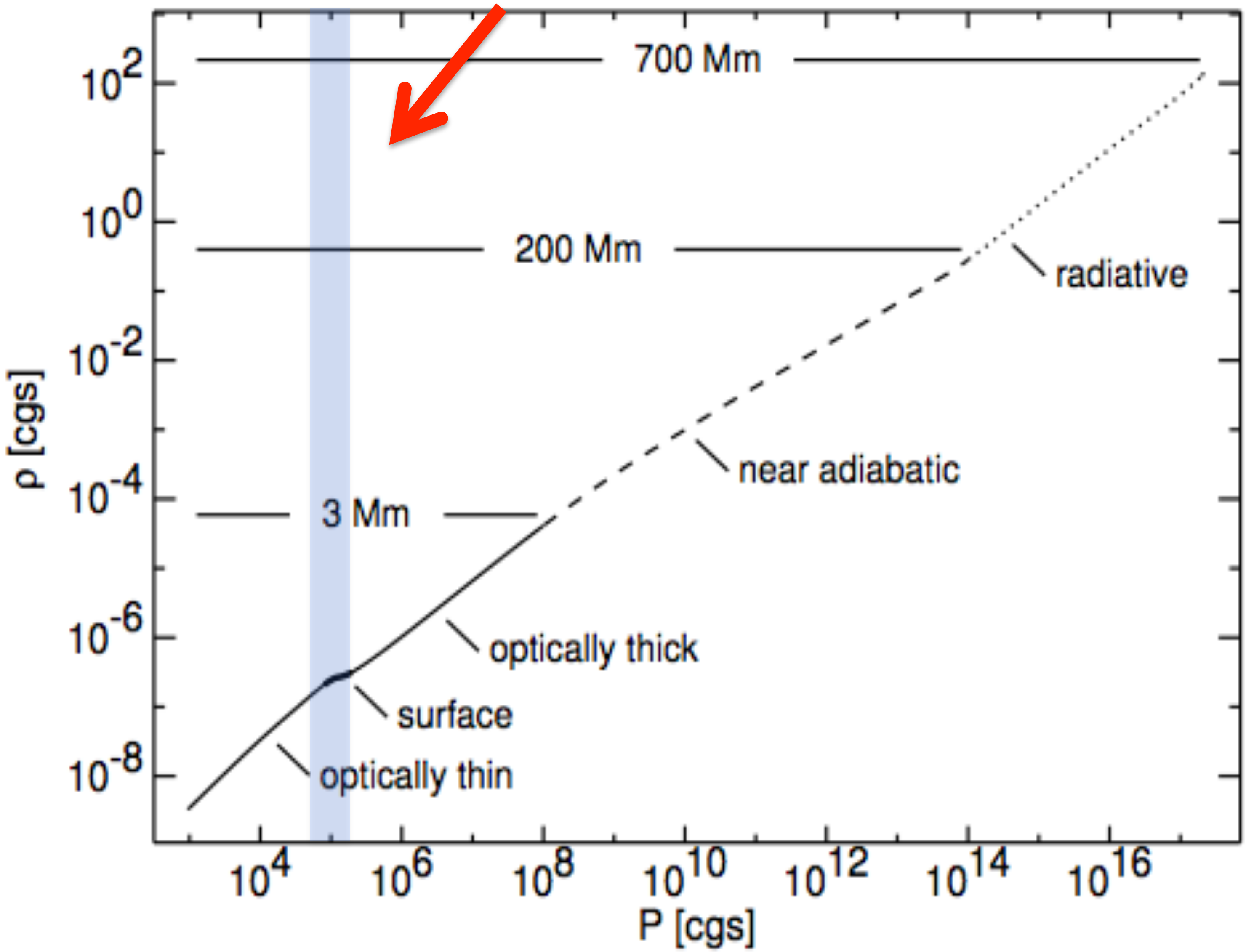
3D NLTE modeling of stellar spectra

Maria Bergemann

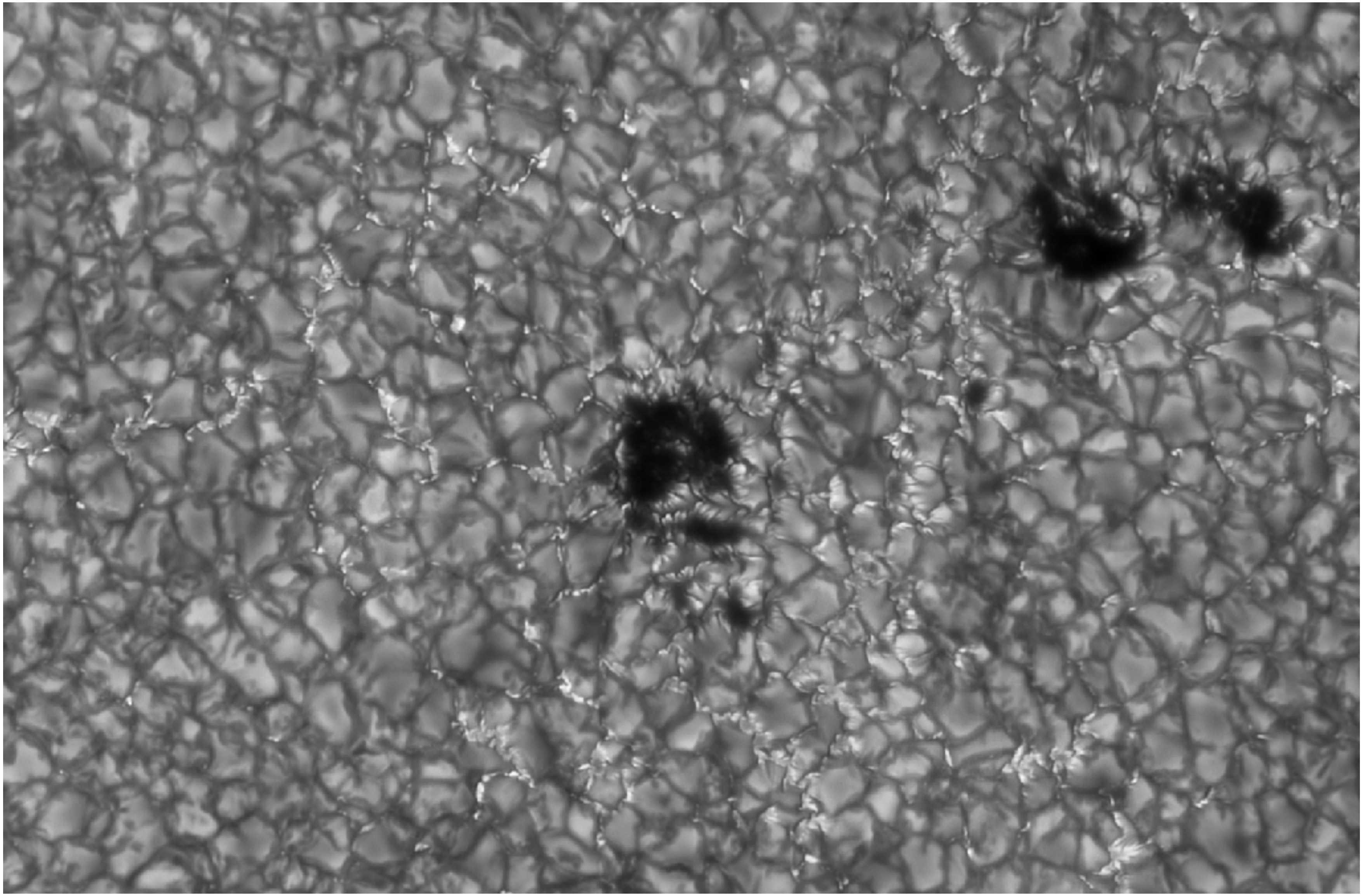
Stellar atmosphere



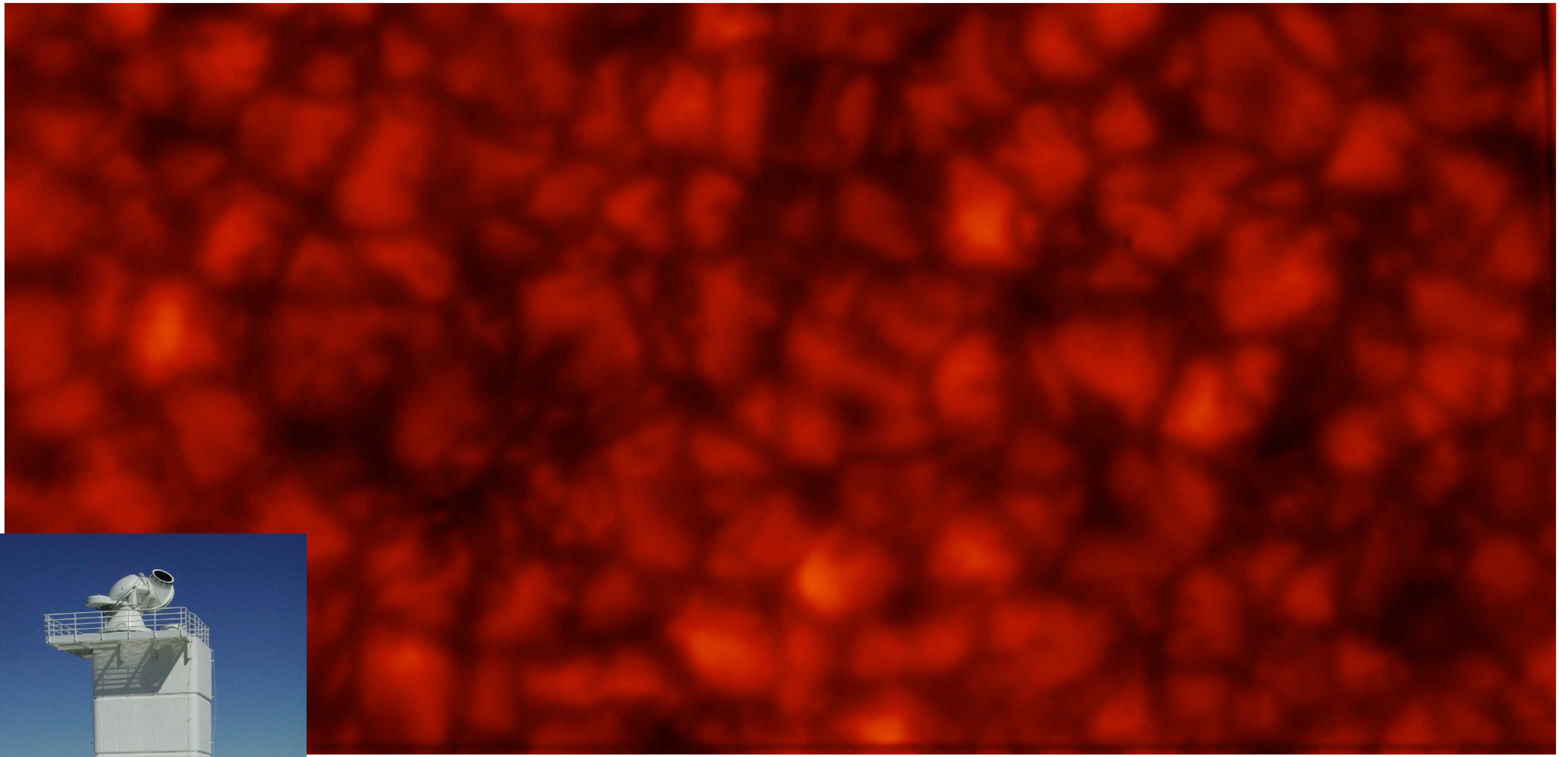
Nordlund et al. 2009

Modeling spectra of cool stars

- **time dependence**
- **Hydrodynamics**
- **Magnetic fields**
- **Chromospheres**
- **Dynamics: inflows and outflows, mass loss**
- **Non-local thermodynamic equilibrium**
- **Non-equilibrium chemistry**



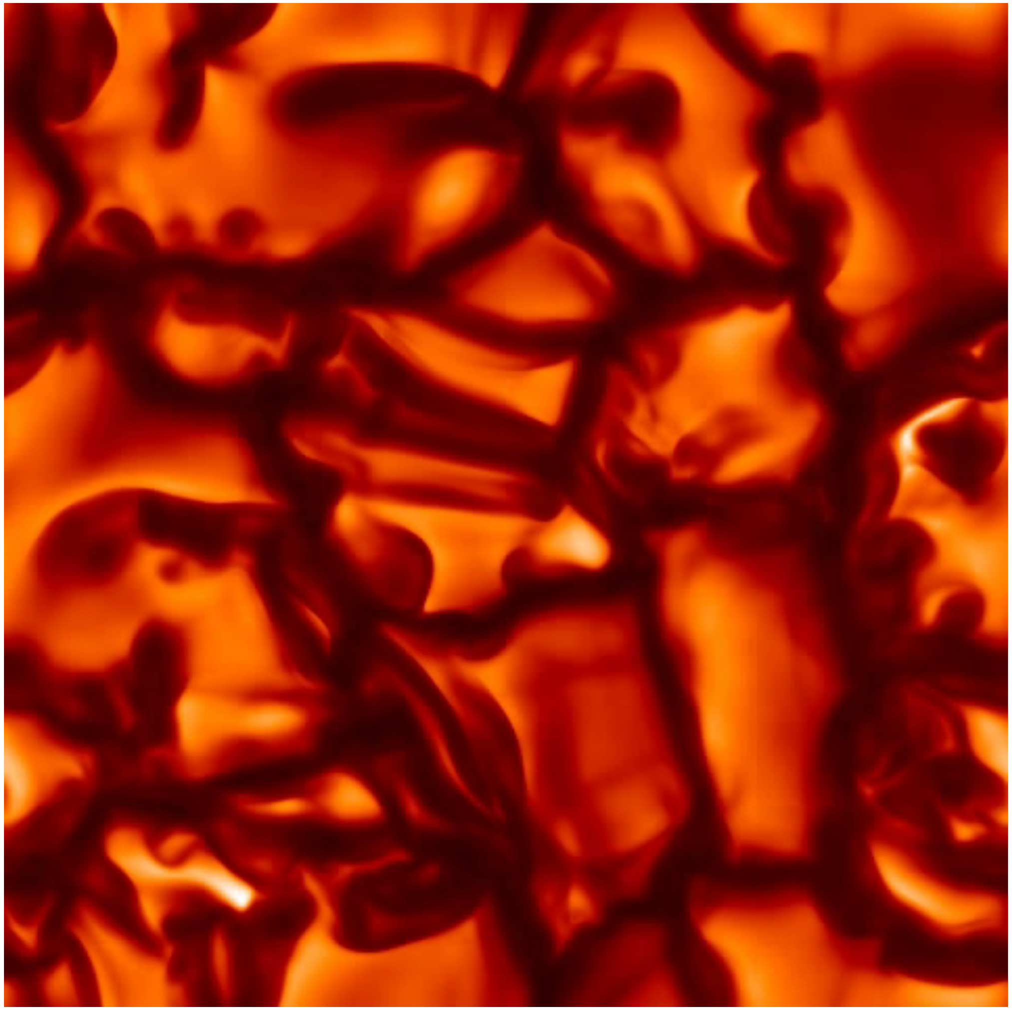
Observations



G-band solar image
Swedish Solar Telescope (La Palma)

Bergemann et al. 2013 in prep.

Surface granulation



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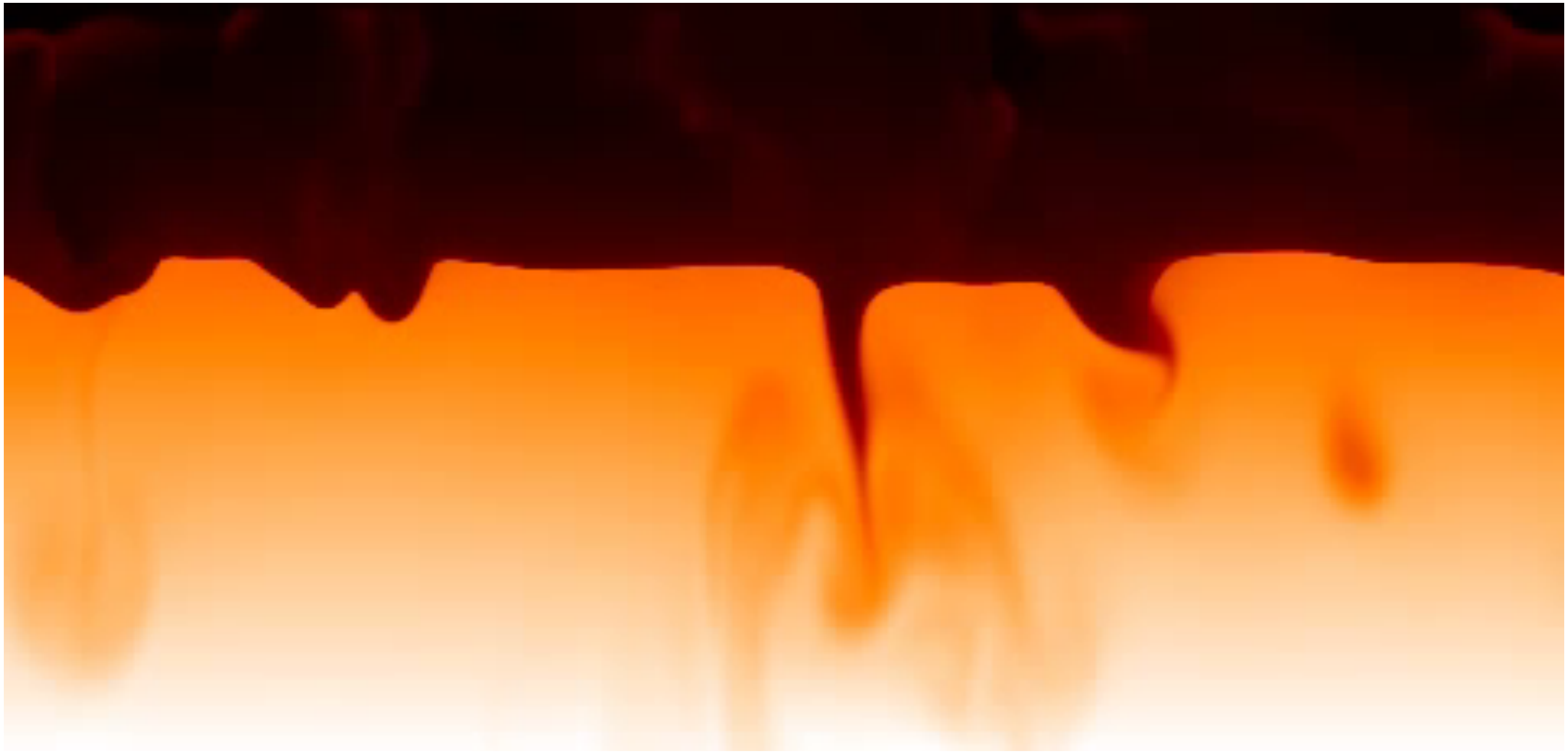
T structure in the 3D convection simulation



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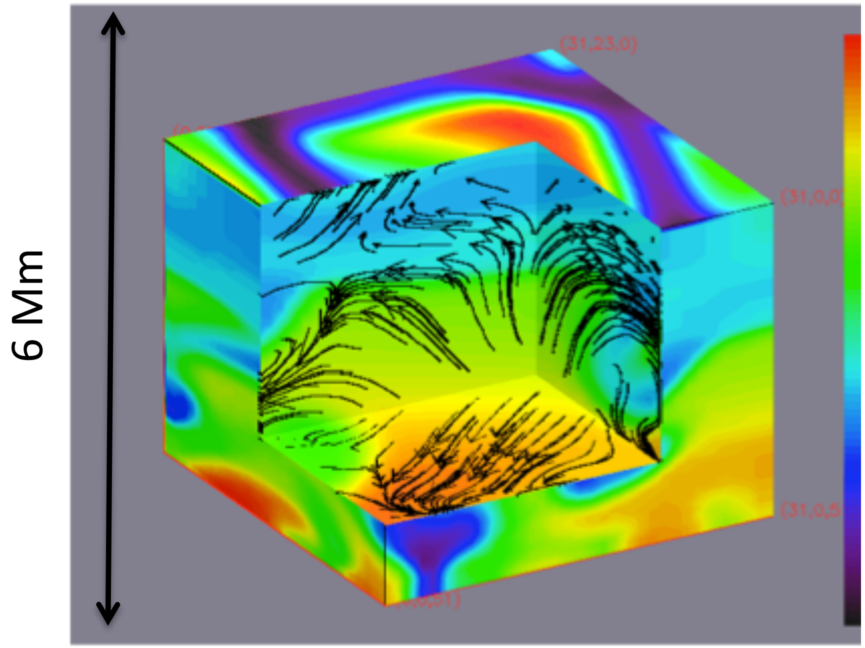
Models



Nordlund et al. (2009)

velocity and temperature structure of a granule in a numerical simulation of the solar convection

Radiative-hydrodynamics in 3D
but
Simplified radiative transfer with LTE

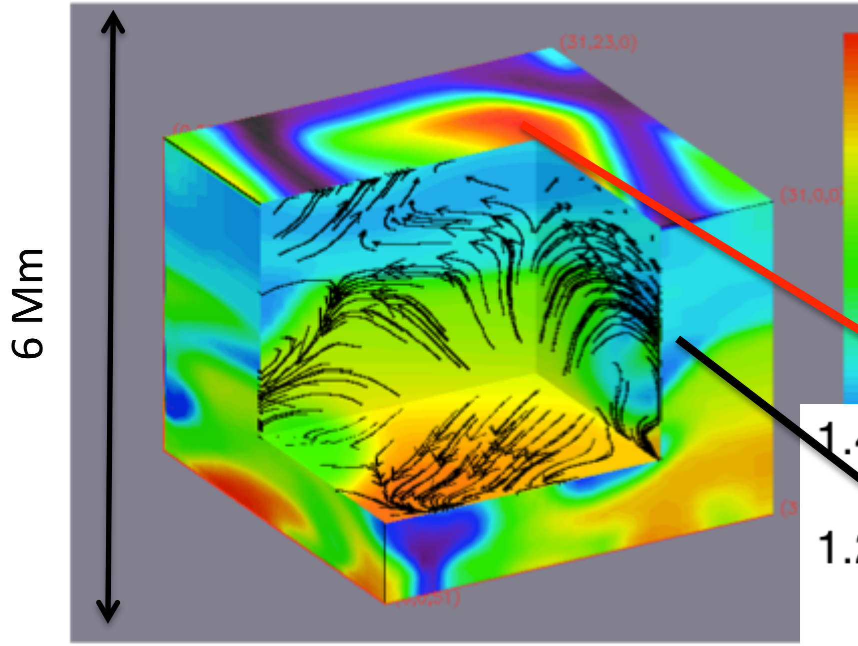
$$\frac{\partial \ln \rho}{\partial t} = -\mathbf{u} \cdot \nabla \ln \rho - \nabla \cdot \mathbf{u} \,,$$

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{g} - \frac{P}{\rho} \nabla \ln P + \underline{\underline{\tau}} \,,$$

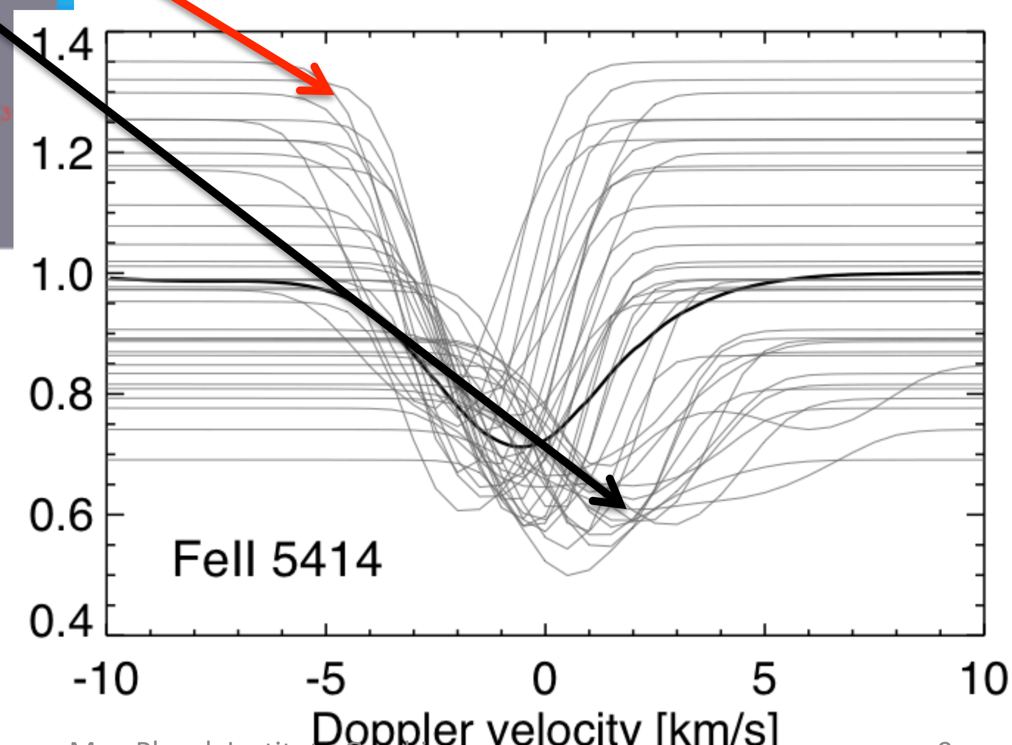
$$\frac{\partial e}{\partial t} = -\mathbf{u} \cdot \nabla e - \frac{P}{\rho} \nabla \cdot \mathbf{u} + Q_{rad} + Q_{visc} \,,$$

rising and descending gas volumes have different line-of-sight velocities

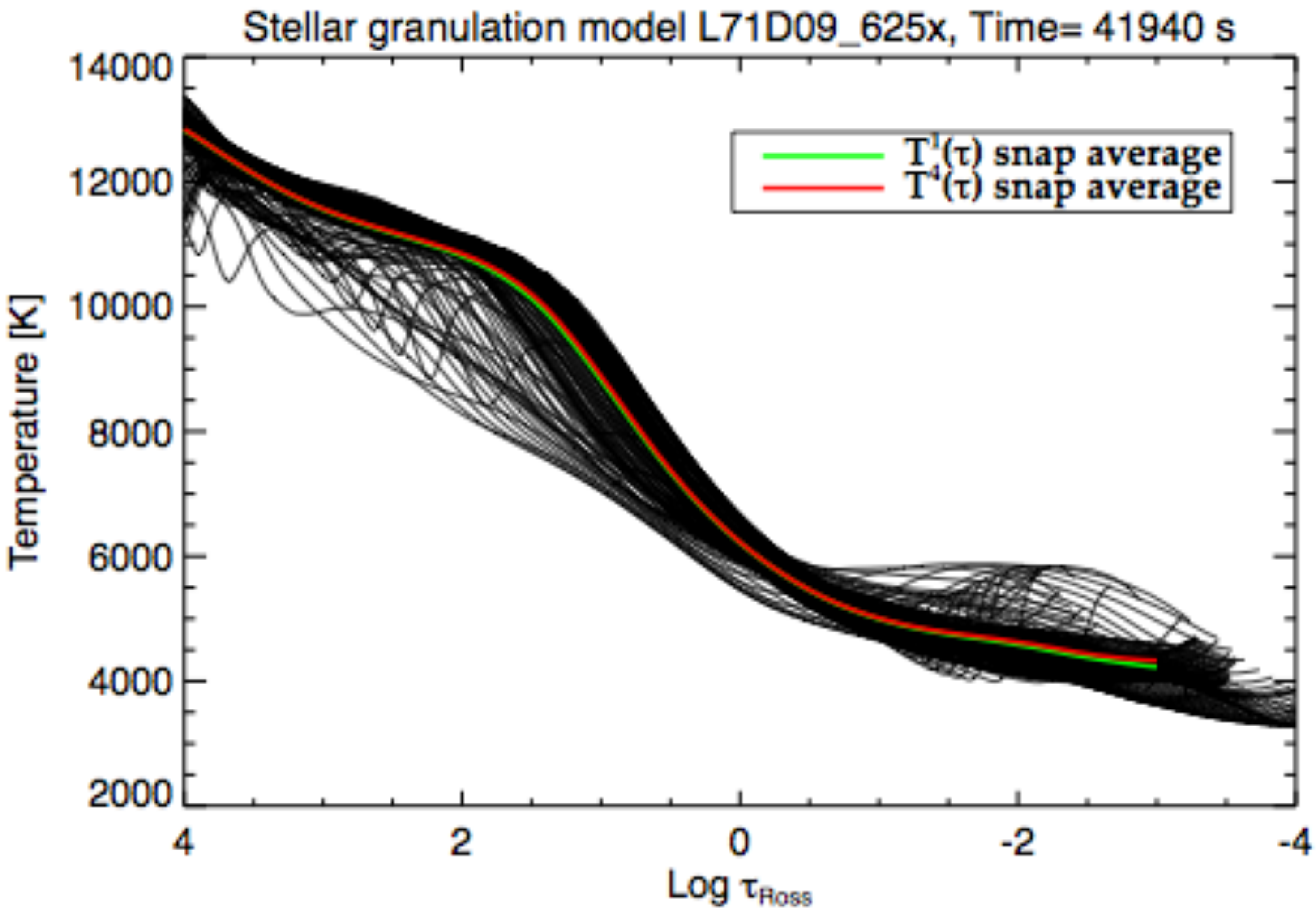
spectral lines are shifted and asymmetric



Nordlund et al. (2009)



Fe II line profile in a 3D simulation of solar surface convection

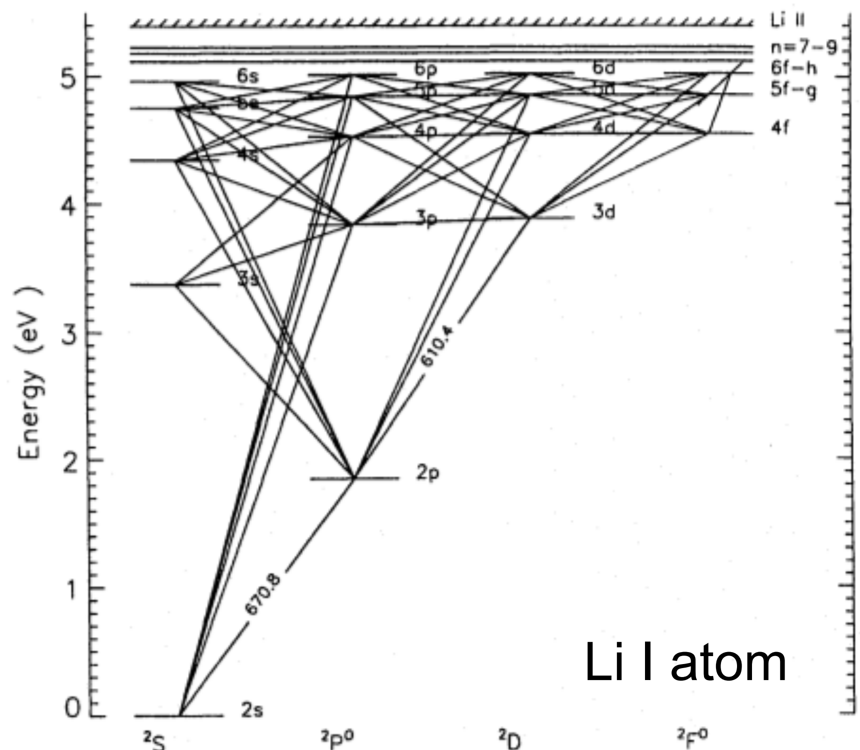


Steffen & Holweger 2002

Full 3D NLTE radiative transfer

computationally prohibitive

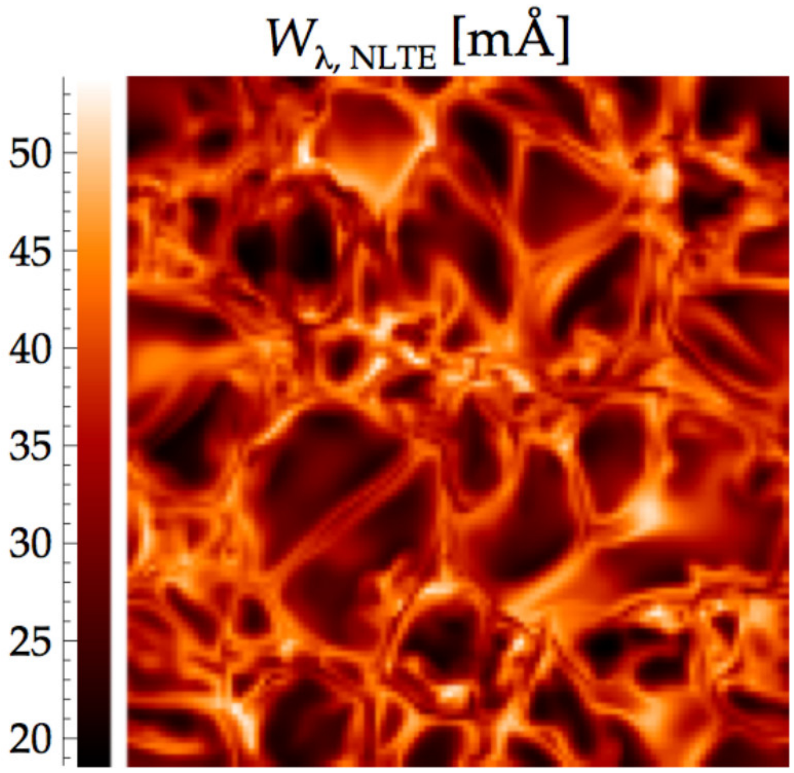
→ applied only to ~10 stars so far and only simplest atoms (Li and Oxygen)



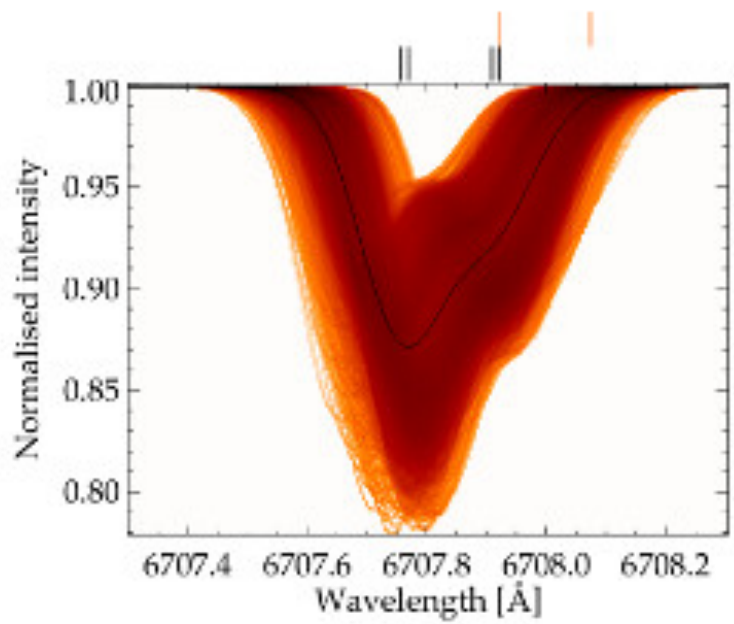
Carlsson et al. 1994

Full 3D NLTE radiative transfer

Li: consistent 3D NLTE radiative transfer



Li I line



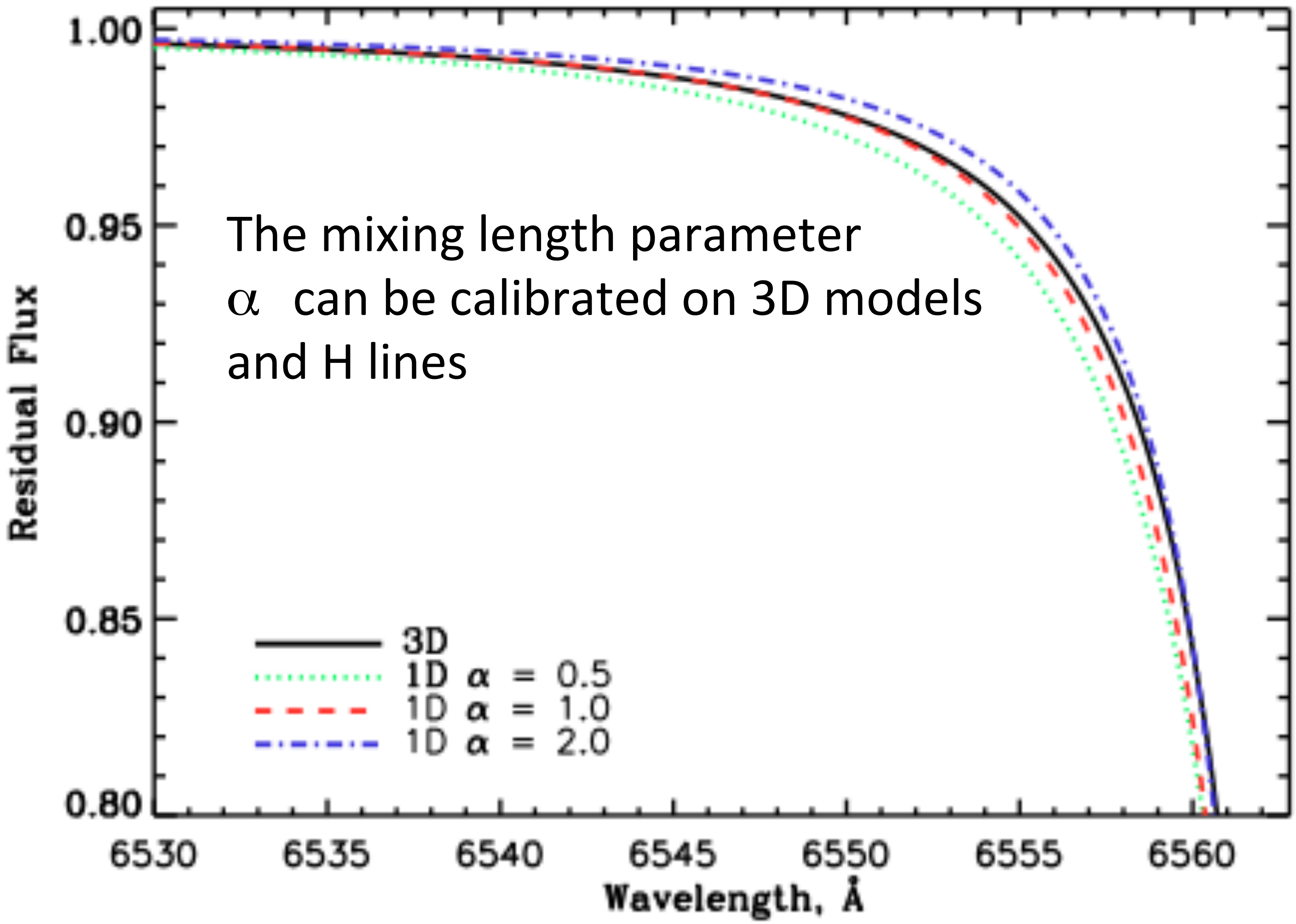
Lind et al. 2013

3D in Hydrogen line profiles

		3D – $1D_{LHD}$					
		$\alpha_{MLT} = 0.5$		$\alpha_{MLT} = 1.0$		$\alpha_{MLT} = 2.0$	
$T_{eff}/\log g/[M/H]$ (K/c.g.s/dex)	line	ΔT	QF/σ	ΔT	QF/σ	ΔT	QF/σ
5500/3.50/–2.00	H_α	235	89/26	119	99/19	–76	80/16
	H_β	20	35/11	–94	48/10	–251	54/10
	H_γ	–10	31/10	–144	44/8	–309	51/9
5780/4.40/0.00	H_α	34	21/9	24	16/8	–21	44/10
	H_β	39	15/9	–23	52/9	–164	72/9
	H_γ	36	19/9	–64	41/7	–263	76/9

Ludwig et al. 2009

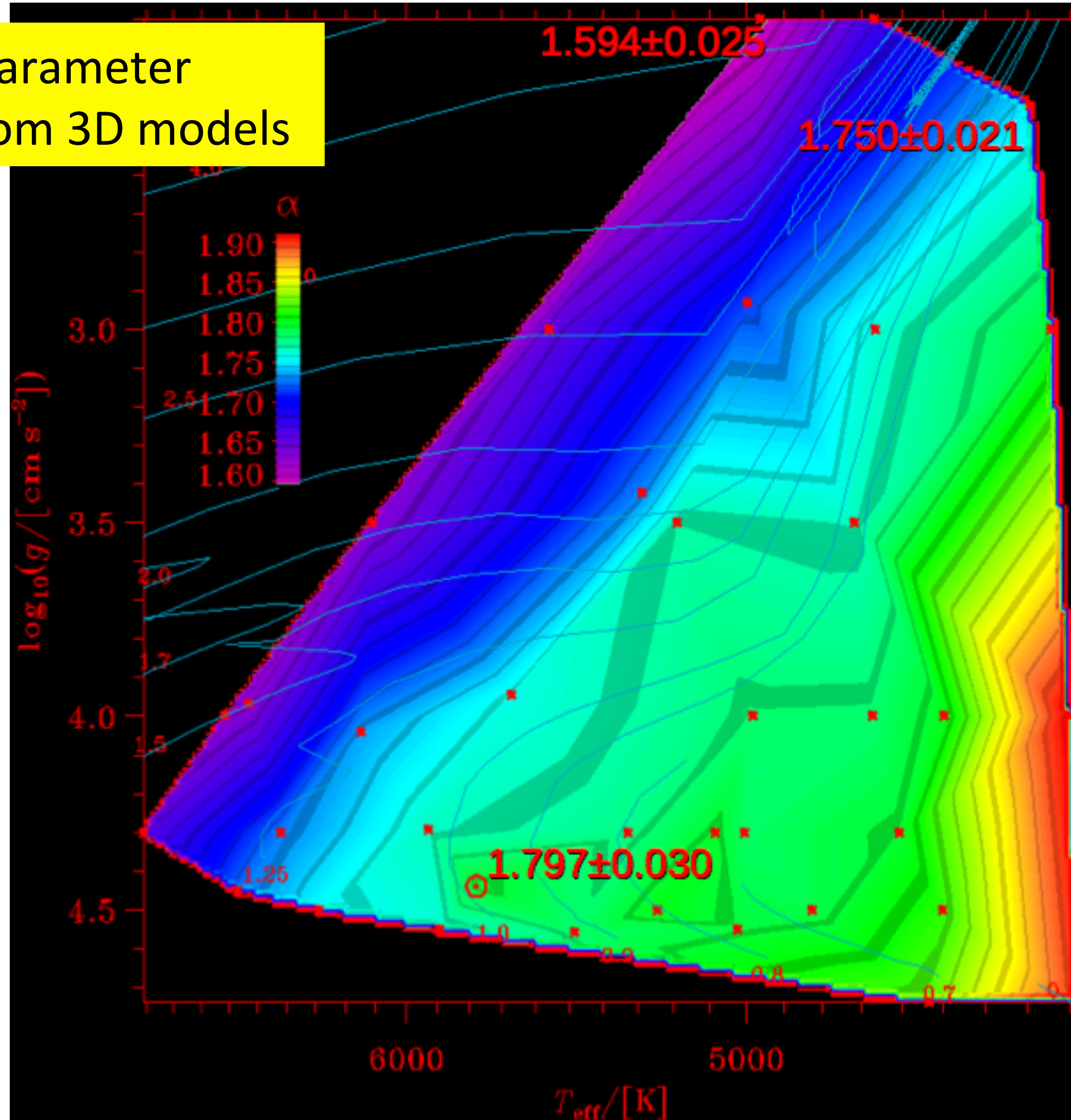
3D on Hydrogen line profiles



The mixing length parameter α can be calibrated on 3D models and H lines

Ludwig et al. 2009

The mixing length parameter
α reconstructed from 3D models



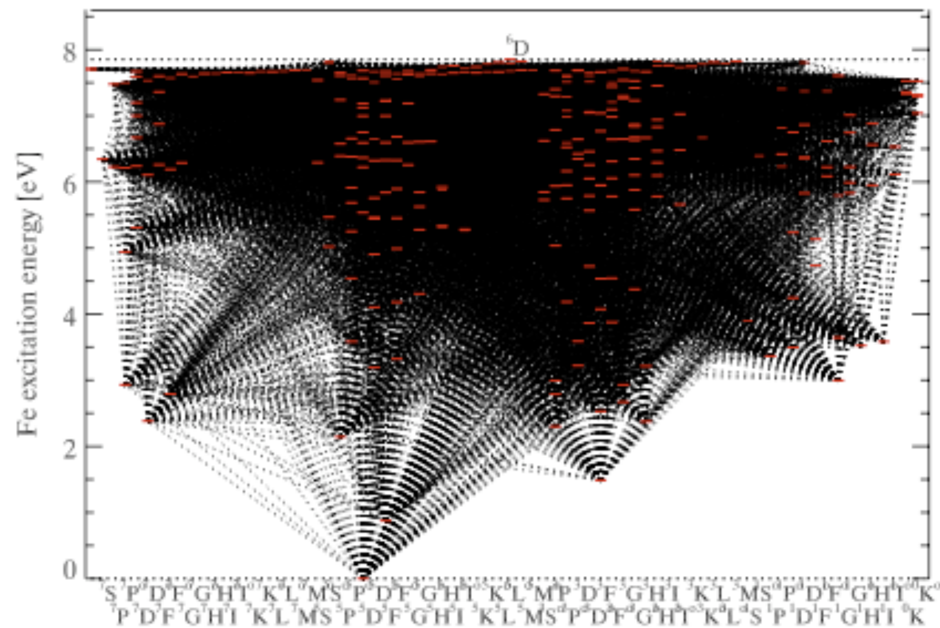
Trampedach 2009

Full 3D NLTE radiative transfer

computationally prohibitive

→ applied only to ~10 stars so far and only simplest atoms (Li and Oxygen)

→ But we need an approach, which works for other (complex) elements, e.g. Fe



Reducing complexity

- non-LTE radiative transfer

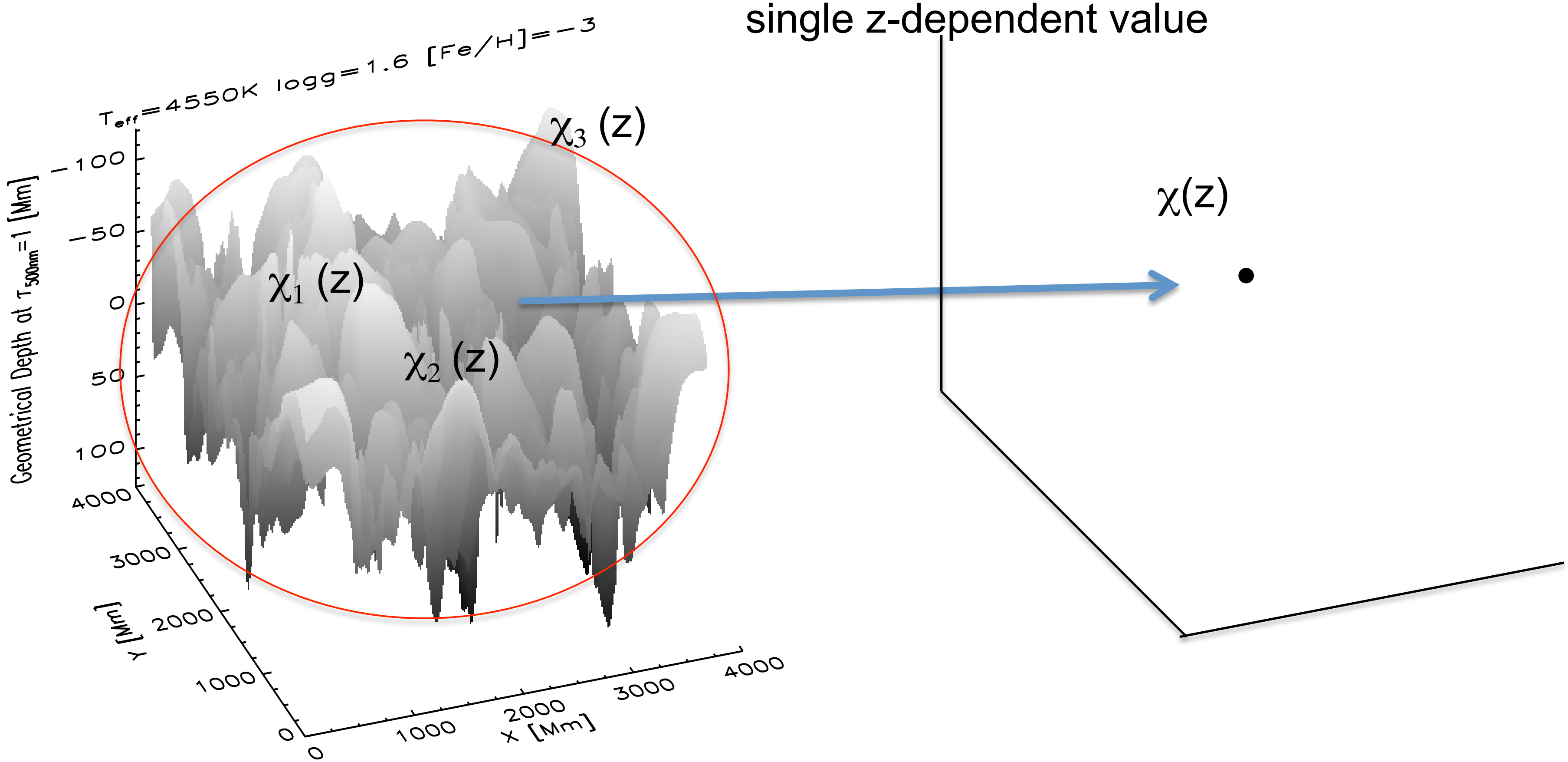
‘trace element assumption’ – single element treated at a time

no effect on the structure of a model atmosphere

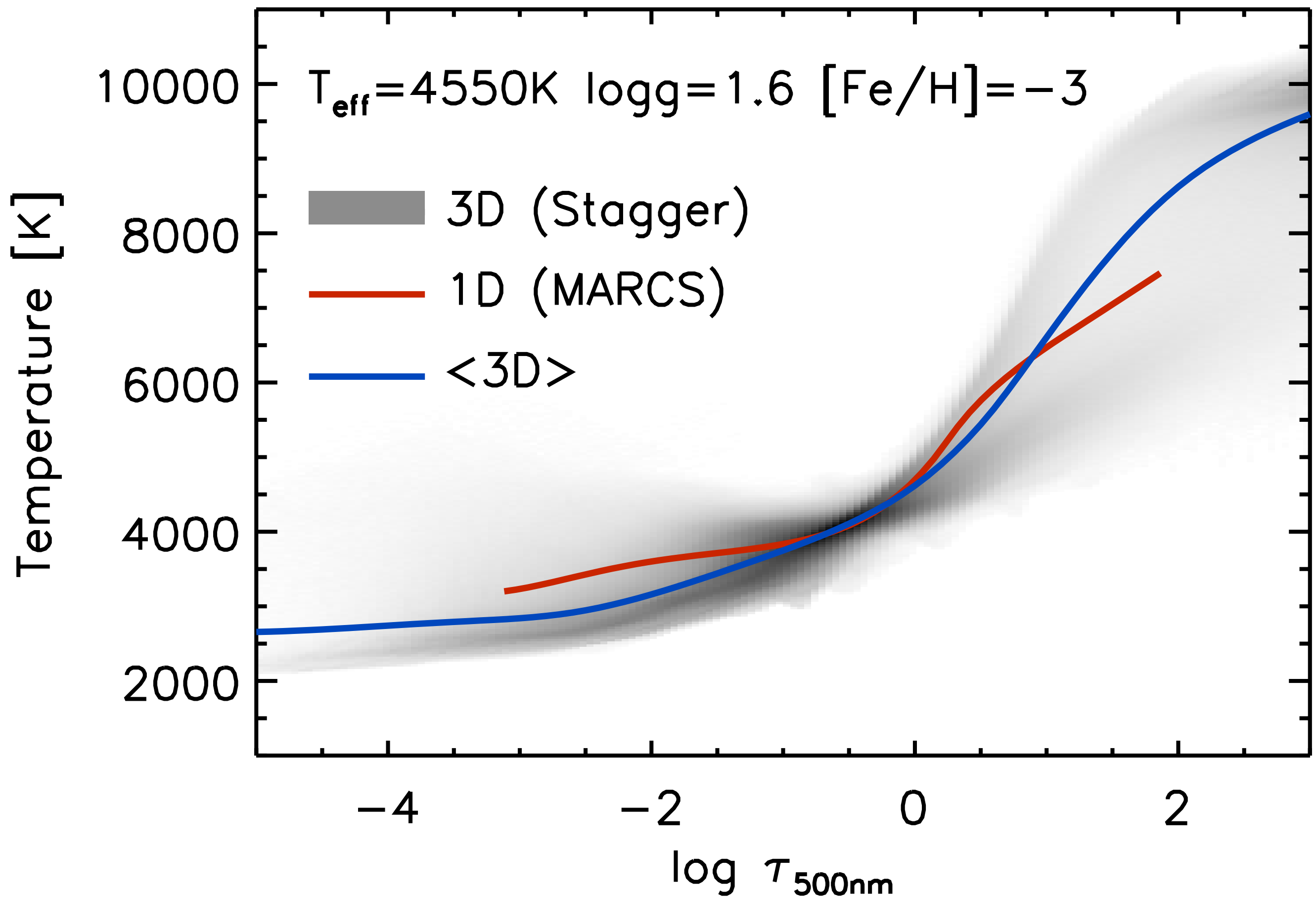
Reducing complexity

3D RHD simulations of stellar convection
→ temporal and spatial averaging

e.g., collapsing **opacity surface** to a single z-dependent value

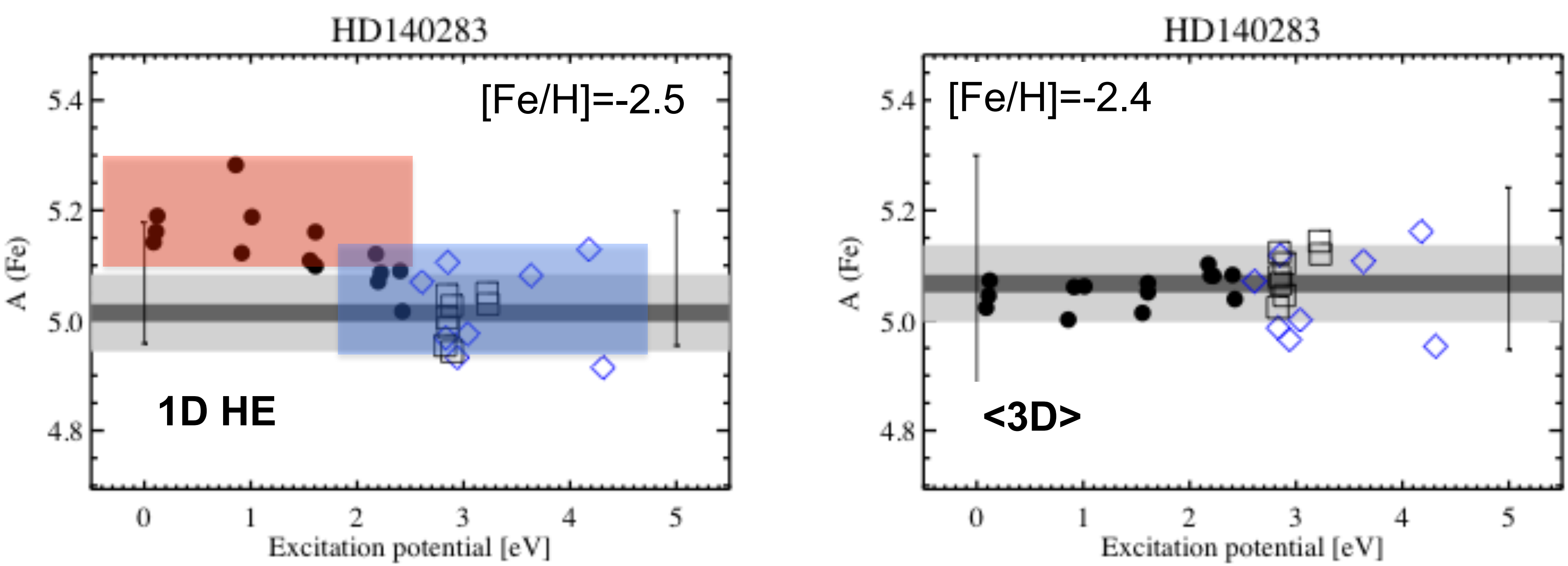


1D-averages of 3D radiation-hydrodynamic models of stellar convection



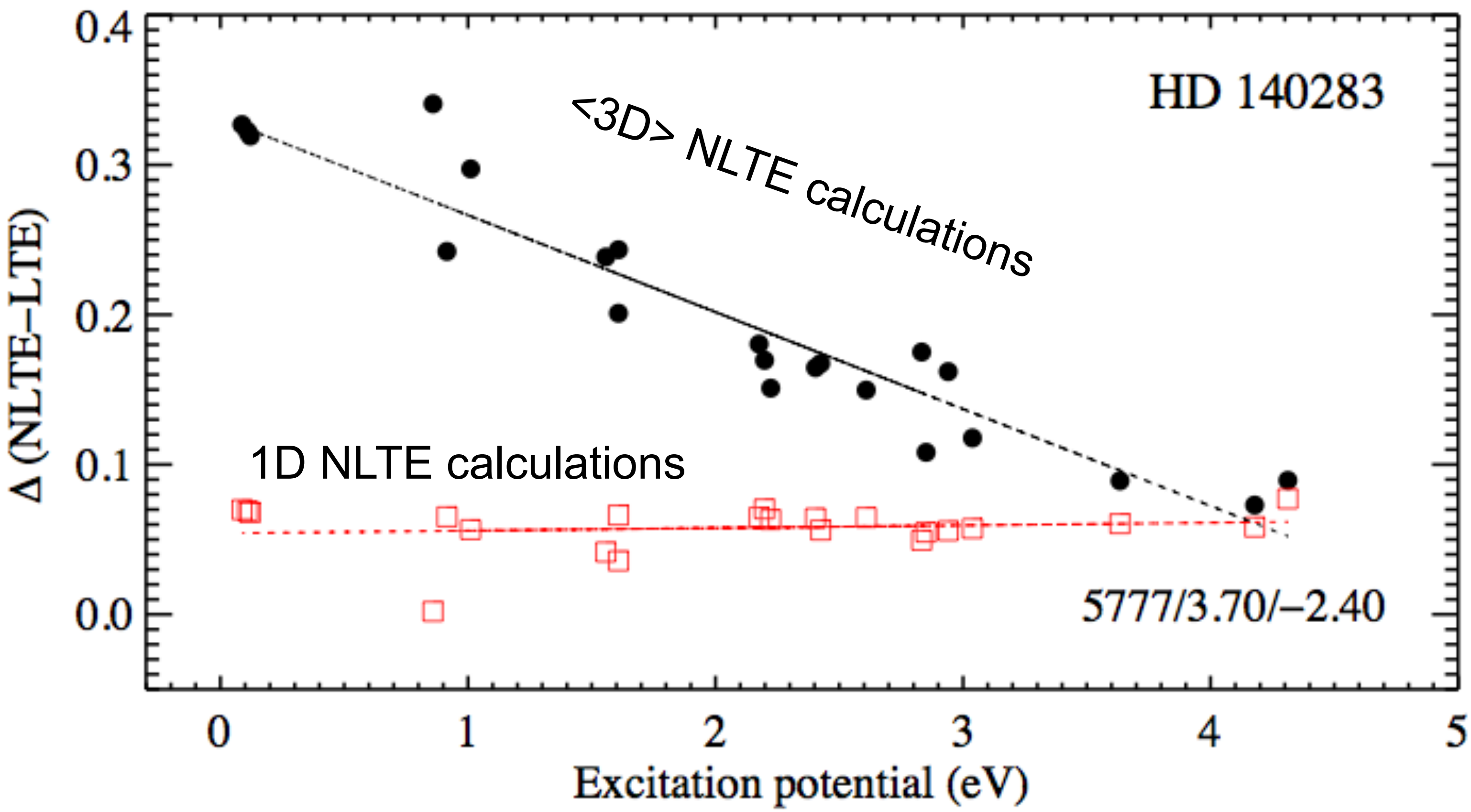
Fe lines

- LTE: discrepancy between Fe I and Fe II lines
- 1D NLTE: discrepancy between Fe I lines
- <3D> NLTE OK

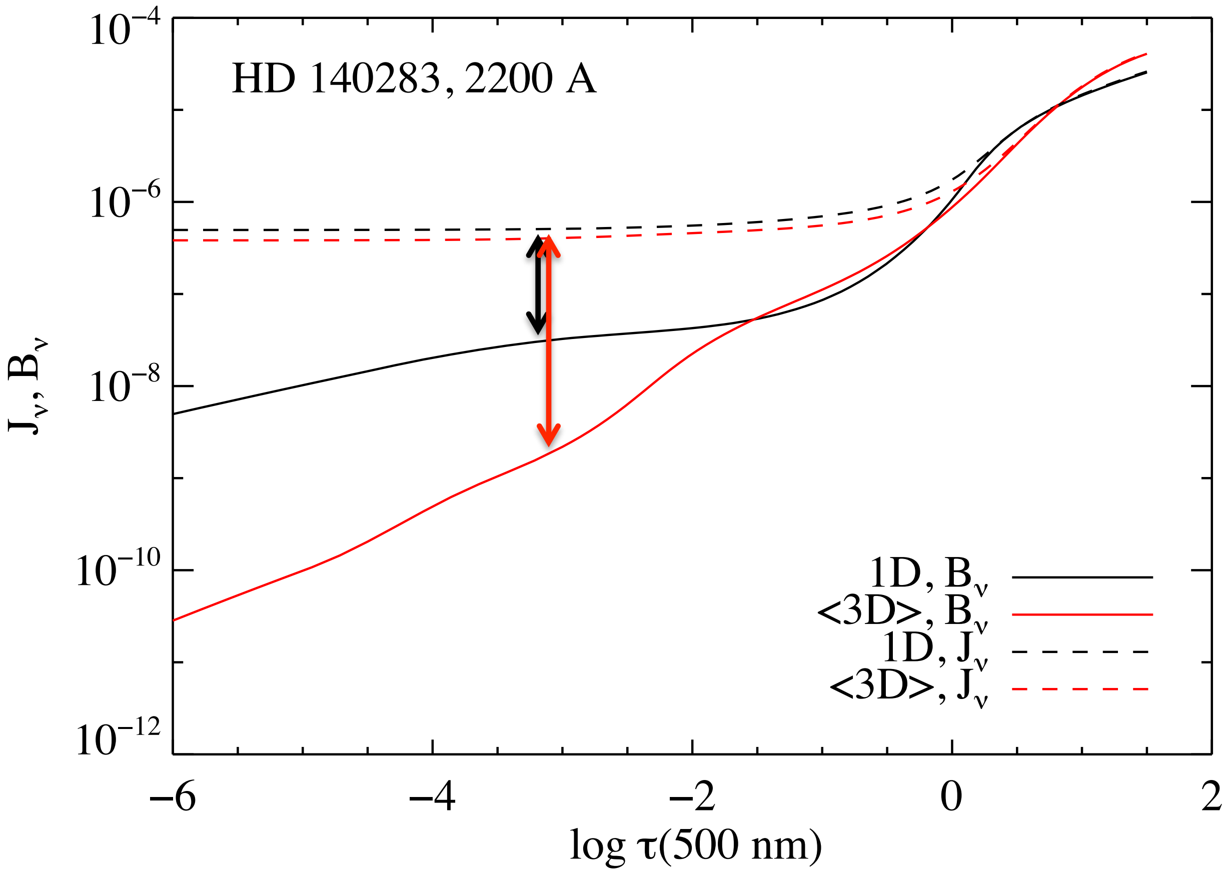


Bergemann et al. 2012

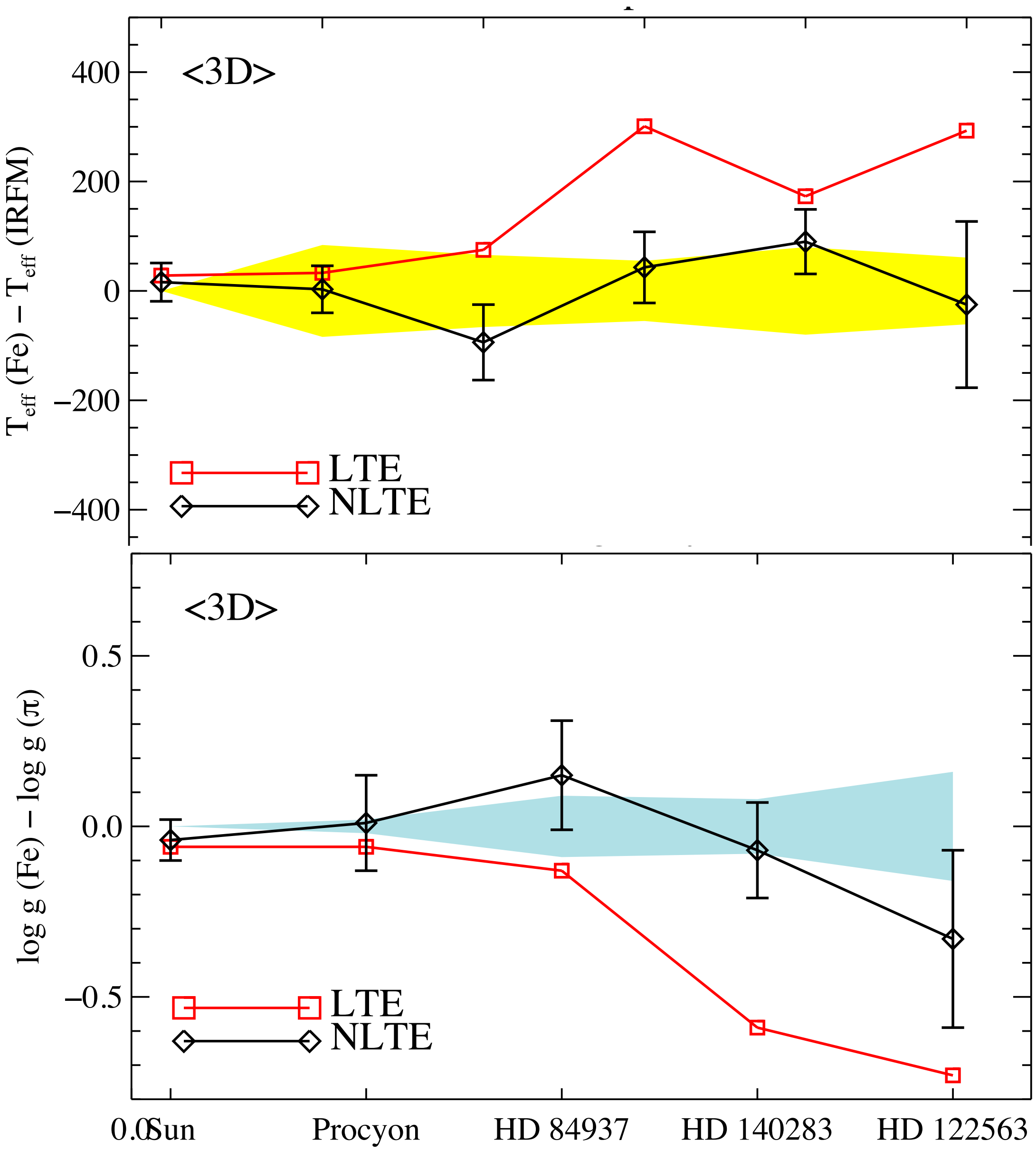
Fe: 1D NLTE and <3D> NLTE



Why are NLTE effects different in 1D and <3D>?



<3D> NLTE stellar parameters



<3D> LTE:

- over-estimated T_{eff}
- under-estimated log g

Bergemann et al. 2012

Spectroscopic distances

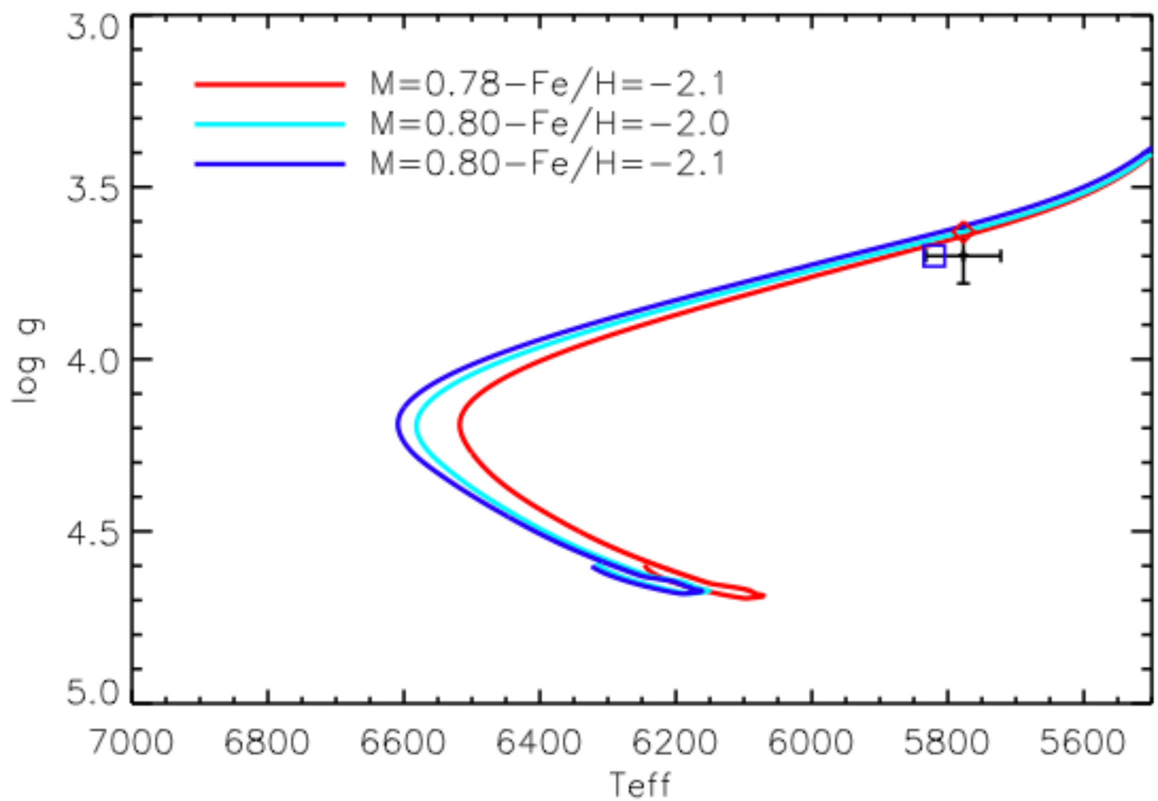
T_{eff}, log g, [Fe/H] from stellar spectra

+ evolutionary tracks

+ photometry

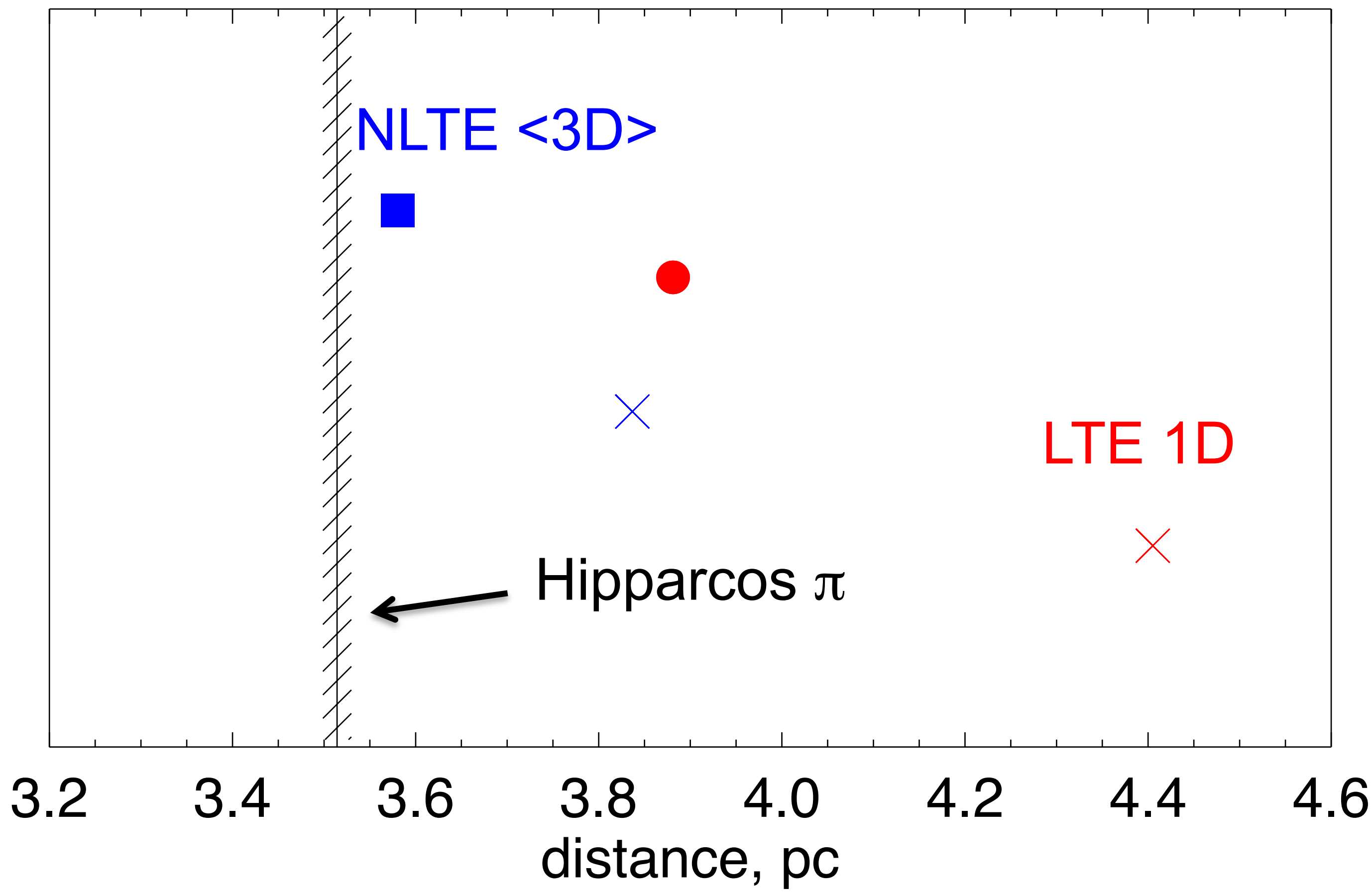
$$\log g = \log g_{\odot} + \log \frac{M}{M_{\odot}} - \log \frac{L}{L_{\odot}} + 4 \log \frac{T_{\rm eff}}{T_{\rm eff,\odot}}$$

$$M_V = V + 5 + 5 \log \pi - A_V$$



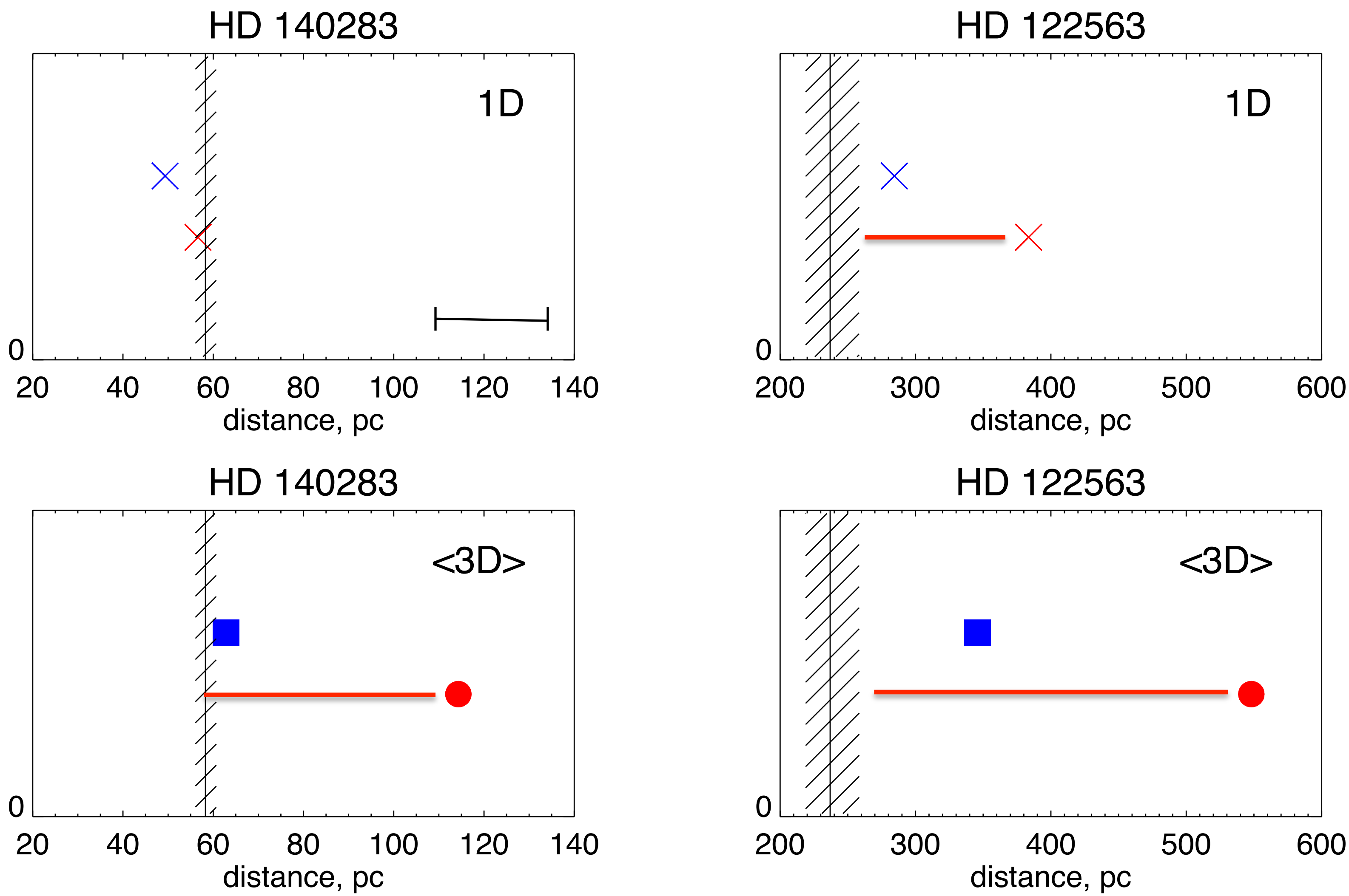
Spectroscopic distances

Visual binary: F-type sub-giant + white dwarf
T_{eff} from interferometry



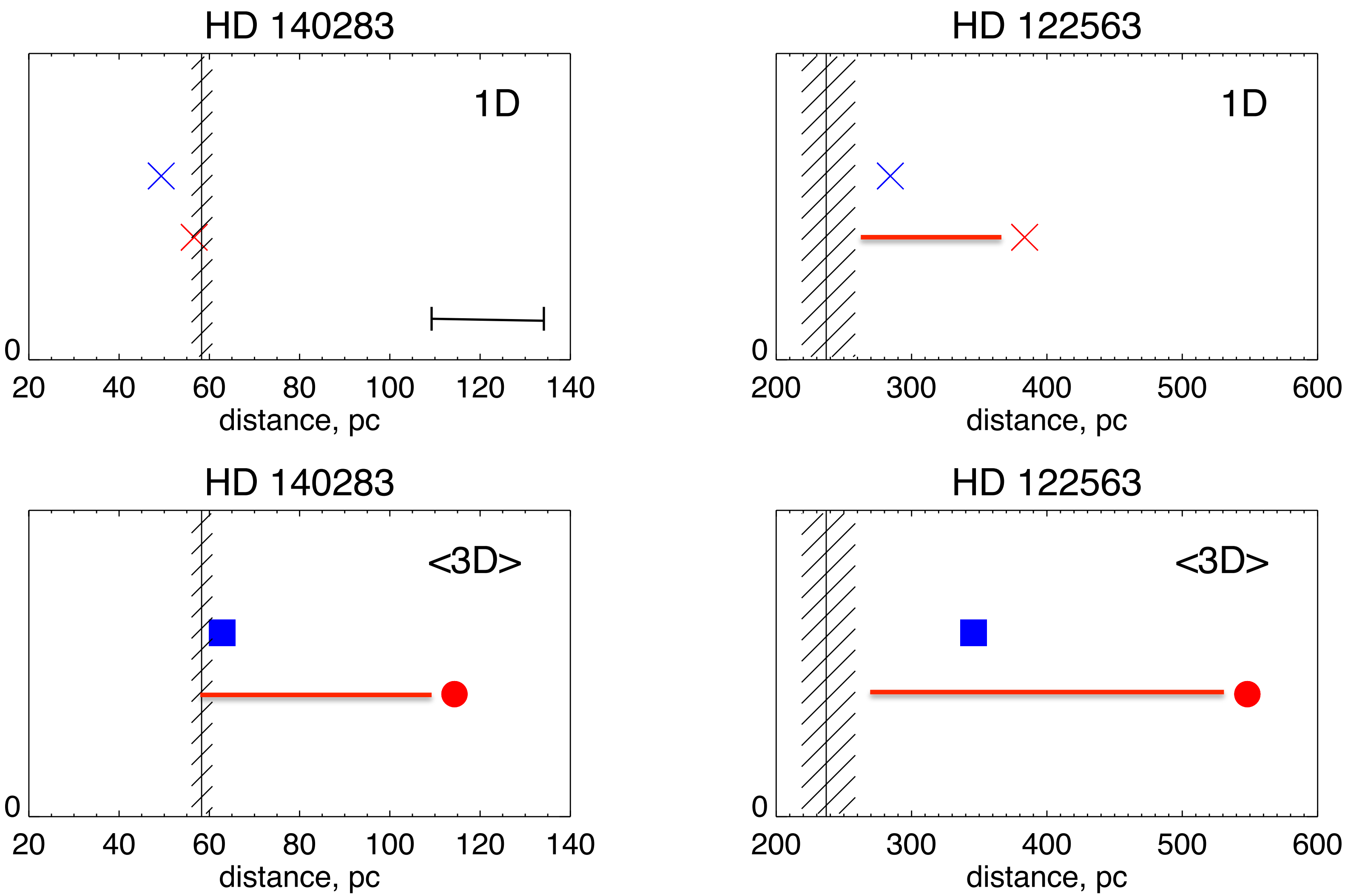
Spectroscopic distances

LTE over-estimates distance, especially with <3D> models

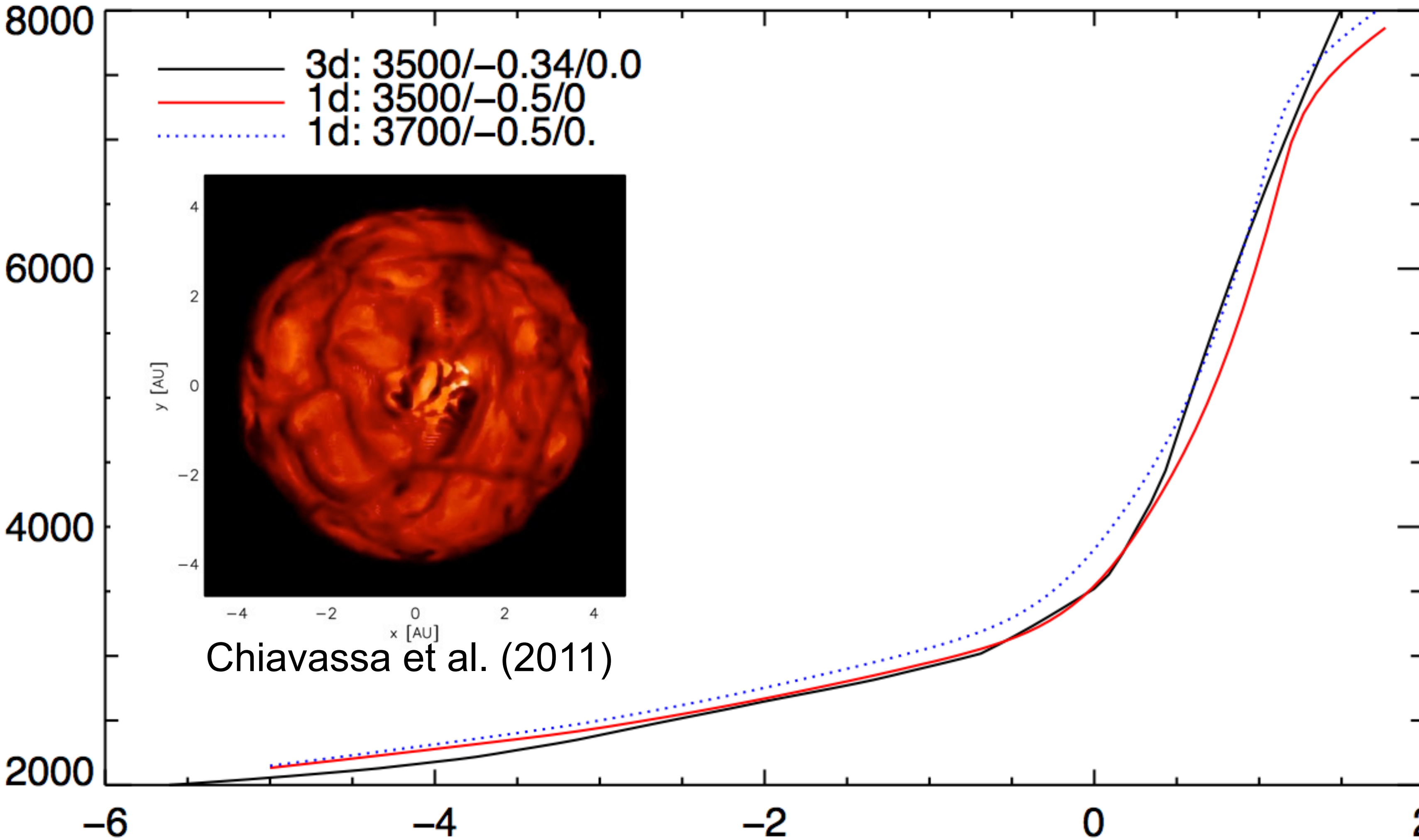


Spectroscopic distances

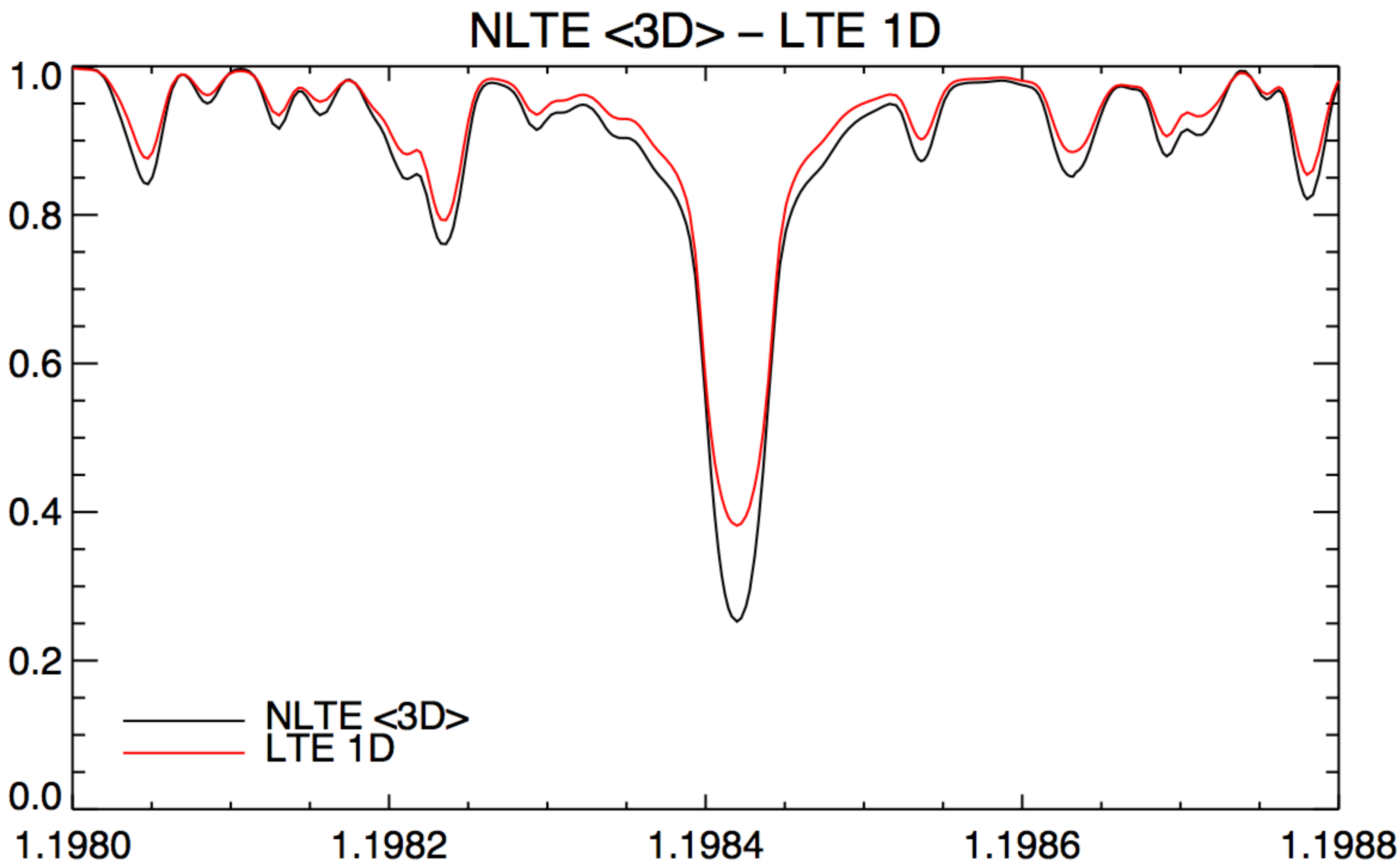
1D models are OK, if NLTE is taken into account



Red supergiants



Abundance diagnostics in the near-IR



Bergemann et al. (2013)

Conclusions

- FGKM stars: photospheres are non-equilibrium systems
- sub-photospheric convection affects emergent radiation
- classical 1D LTE approach in the determination of basic stellar parameters is **not valid:**

systematic effect on Teff, log g, [Fe/H], abundances