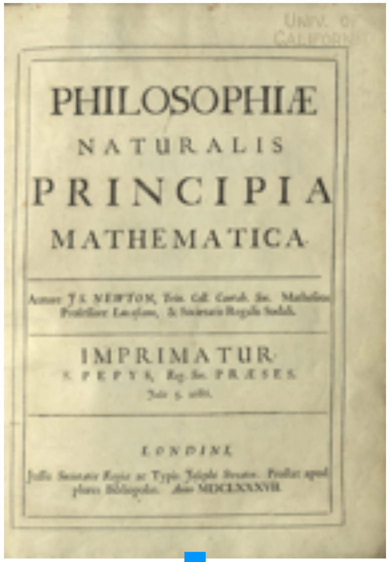
Lecture 2

Models of cool stellar atmospheres and synthetic spectra


Don't leave home without it!
The HUNGRY STUDENT Cookbook
Charlotte Pike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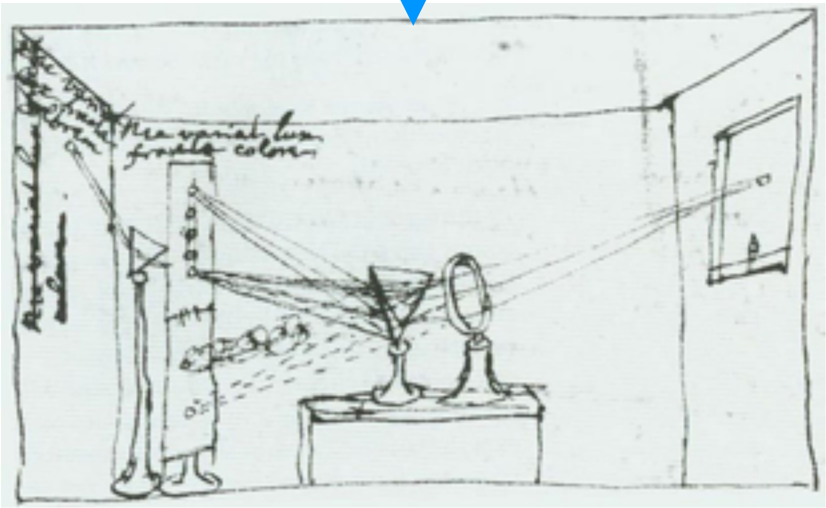


Classical models of stellar atmospheres

Kurucz, Marcs
http://kurucz.harvard.edu
http://marcs.astro.uu.se

- time-independent
- 1D geometry
- a star is flat (spherically-symmetric only for giants)
  local thermodynamic equilibrium
- no sources or sinks of enegry
- hydrostatic equilibrium
- simple convection recipies - MLT
- no winds, magnetic fields
- no chromopsheres

Classical models of stellar atmospheres

$$\cos\theta \frac{dI_\nu}{dz} = \kappa_\nu I_\nu - \eta_\nu$$

$$S_\lambda = \frac{\kappa_\lambda}{\kappa_\lambda + \sigma_\lambda} B_\lambda(T) + \frac{\sigma_\lambda}{\kappa_\lambda + \sigma_\lambda} J_\lambda,$$

$$F = \frac{L}{4\pi R^2} = \sigma T_{\rm eff}^4,$$

$$J_\lambda = \int_0^1 j_\lambda(\mu)\mathrm{d}\mu. \quad \frac{\mathrm{d}^2 j_\lambda}{\mathrm{d}\tau_\lambda^2} = j_\lambda - S_\lambda$$

$$F = F_{conv} + F_{rad}$$

$$K_\lambda = \int_0^1 \mu^2 j_\lambda \mathrm{d}\mu.$$

$$F_{conv} \sim \frac{\alpha_{MLT}}{H_p}$$

$$F_\lambda = 4\pi \left(\frac{\partial K_\lambda}{\partial \tau_\lambda} - \frac{1}{r} \frac{3K_\lambda - J_\lambda}{\kappa_\lambda + \sigma_\lambda} \right)$$

$$F_{\rm rad} = \int F_\lambda \mathrm{d}\lambda$$

at each depth

$$H_{\rm p} = \frac{P}{g\rho} \quad \nabla P_{tot} = -\rho \frac{GM_r}{r^2} = g$$

$$\nabla P_{\rm tot} = \nabla P_{\rm g} + \nabla P_{\rm turb} + \nabla P_{\rm rad},$$

$$\nabla P_{rad} = -1/c \int_0^\infty (\kappa_\nu + \sigma_\nu) F_\nu d\nu$$

$$\nabla P_{turb} \sim \rho \upsilon_t^2$$

Classical models of stellar atmospheres

$$\cos\theta \frac{dI_\nu}{dz} = \kappa_\nu I_\nu - \eta_\nu$$

$$S_\lambda = \frac{\kappa_\lambda}{\kappa_\lambda + \sigma_\lambda} B_\lambda(T) + \frac{\sigma_\lambda}{\kappa_\lambda + \sigma_\lambda} J_\lambda,$$

$$F = \frac{L}{4\pi R^2} = \sigma T_{\rm eff}^4,$$

$$J_\lambda = \int_0^1 j_\lambda(\mu) d\mu, \quad \frac{d^2 j_\lambda}{d\tau_\lambda^2} = j_\lambda - S_\lambda$$

$$F = F_{conv} + F_{rad}$$

Input parameters for a model atmosphere

$$j_\lambda d\mu.$$

$$F_{conv} \sim \frac{\alpha_{MLT}}{H_p}$$

$$F_\lambda = 4\pi\left(\frac{\partial K_\lambda}{\partial \tau_\lambda} - \frac{1}{r}\frac{3K_\lambda - J_\lambda}{\kappa_\lambda + \sigma_\lambda}\right)$$

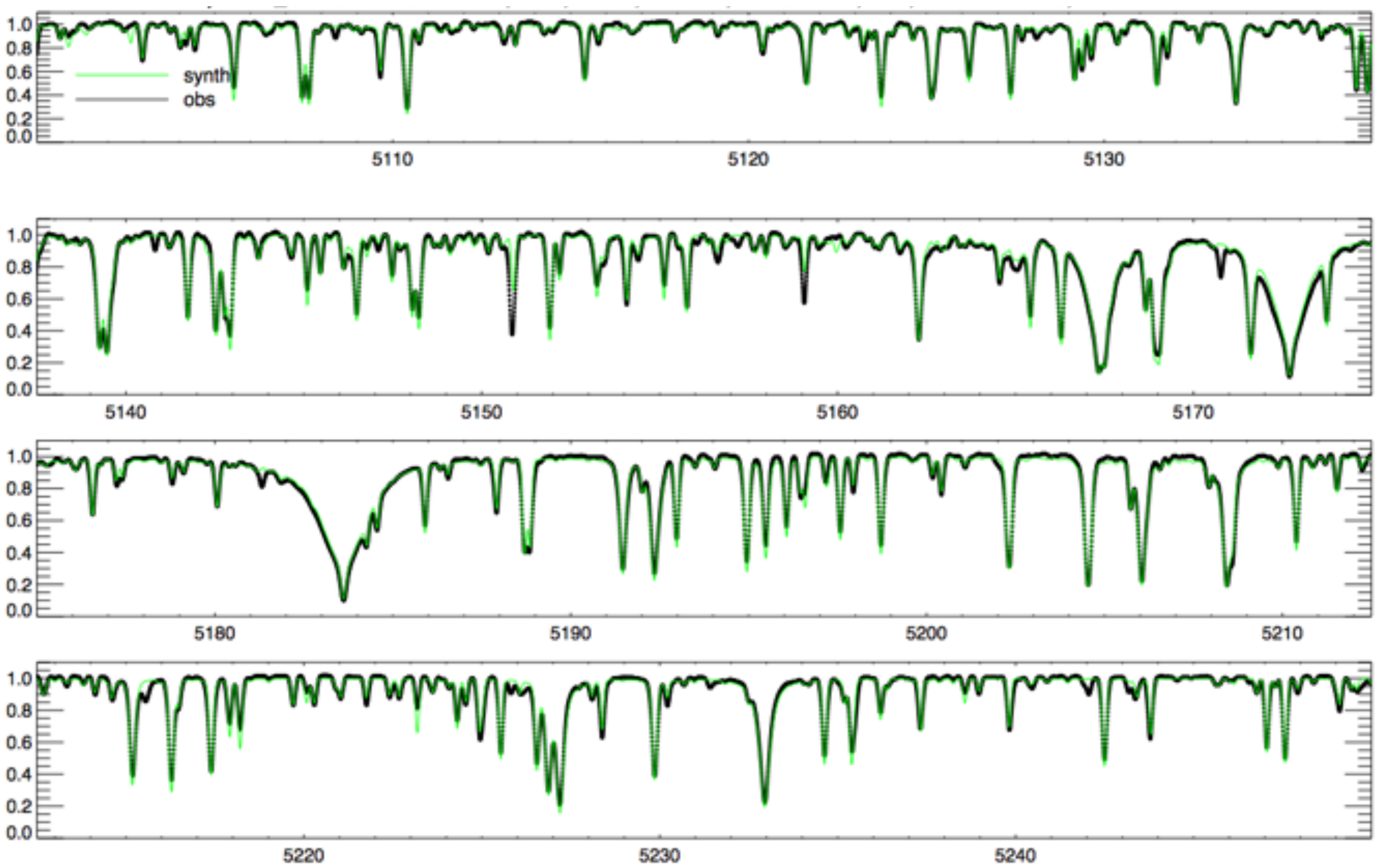
$$H_p = \frac{P}{g\rho} \quad \nabla P_{tot} = -\rho \frac{GM_r}{r^2} = g$$

$$F_{\rm rad} = \int F_\lambda d\lambda$$ at each depth

$$\nabla P_{\rm tot} = \nabla P_{\rm g} + \nabla P_{\rm turb} + \nabla P_{\rm rad},$$

$$\nabla P_{rad} = -1/c \int_0^\infty (\kappa_\nu + \sigma_\nu) F_\nu d\nu$$

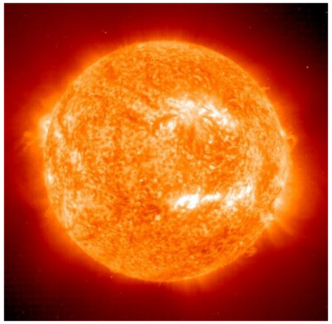
$$\nabla P_{turb} \sim \rho v_t^2$$



synth
obs

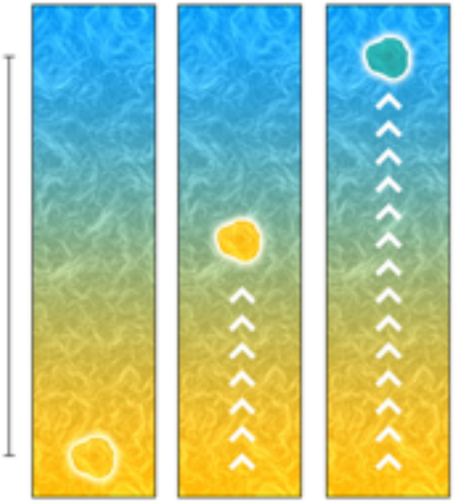
Classical models of stellar atmospheres

'Recipe-based modelling'
making a solar model spectrum is possible



adjusting MANY free parameters:

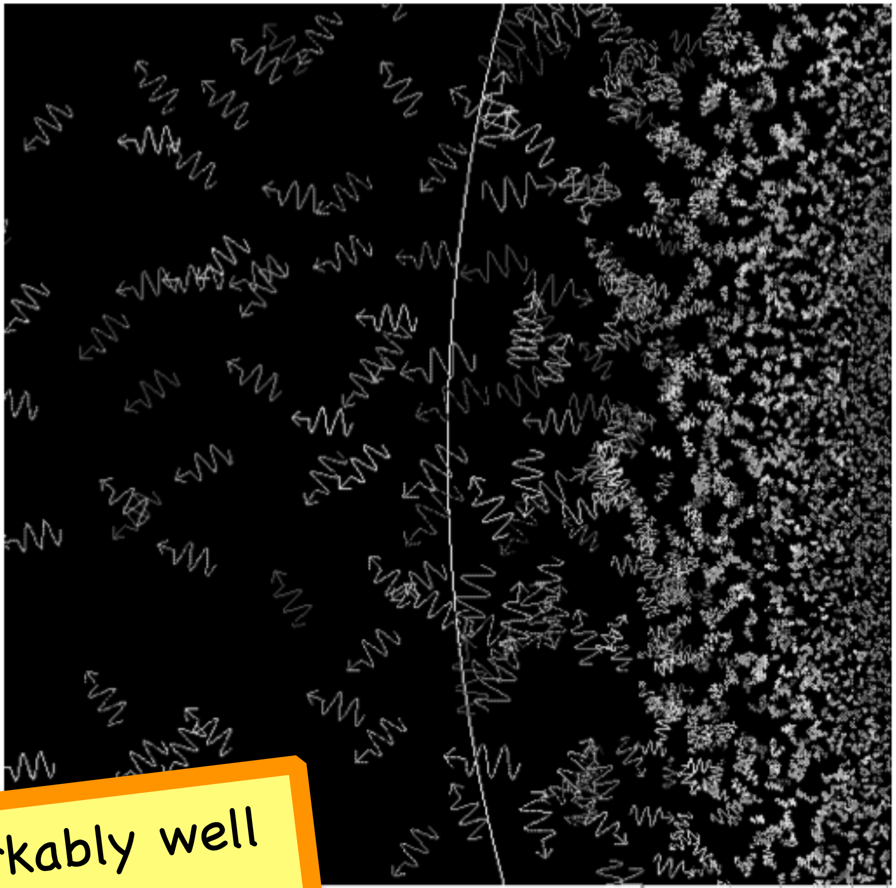
- ✓ abundances to match meteorites
- ✓ mixing length to approximate convective energy transport
- ✓ 'micro-', 'macro-turbulence' to represent turbulent mixing
- ✓ 'astrophysical' atomic data



Models of (cool) stellar atmospheres

- Hydrodynamics and convection
- Non-local thermodynamic equilibrium
- Chromospheres
- Coronae
- Pulsations
- Winds and mass loss
- Terrible amounts of data from atomic and nuclear physics
- Molecular opacities
- Asymmetric shapes with 'hot spots'
- MOLsphere (H_2O, SiO)
- Non-equilibrium chemistry

Non-local thermodynamic equilibrium



LTE works remarkably well
in many cases
but it fails, too, sometimes...

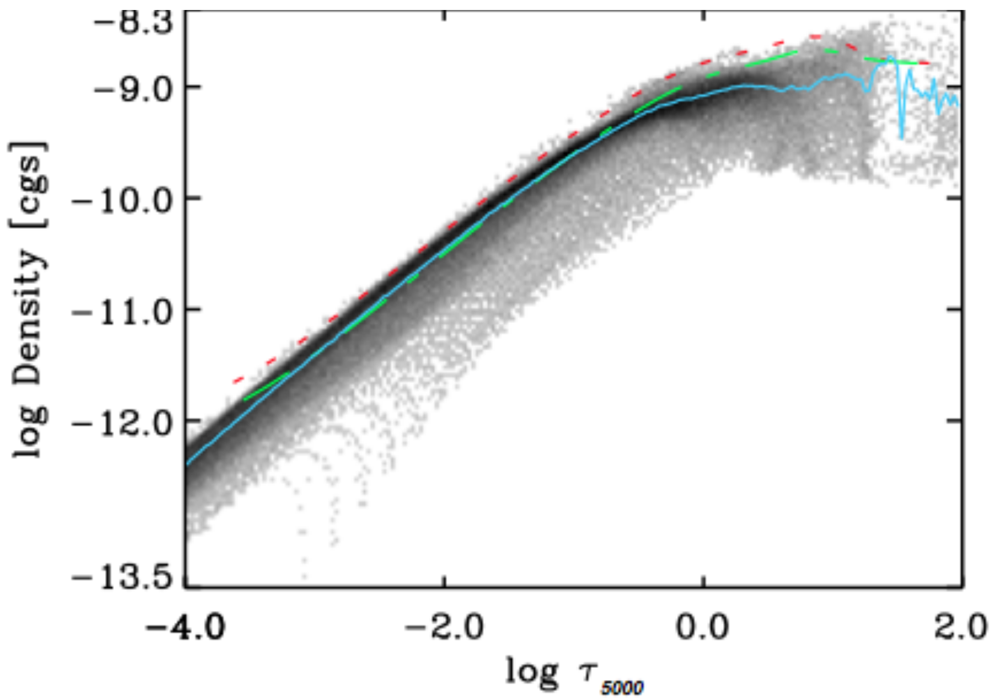
Non-local thermodynamic equilibrium

very low densities in the atmospheres

collisions between gas particles are too weak to establish LTE

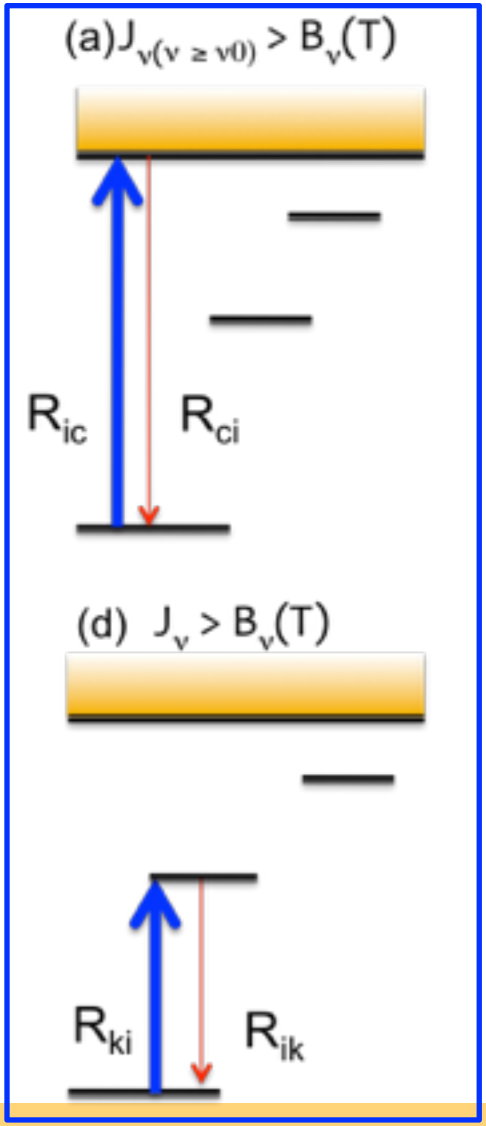
$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i v) = \sum_{j \neq i} n_j P_{ji} - n_i \sum_{j \neq i} P_{ij}$$

$$n_i \sum_{j \neq i} P_{ij} = \sum_{j \neq i} n_j P_{ji}$$



Non-LTE reaction channels

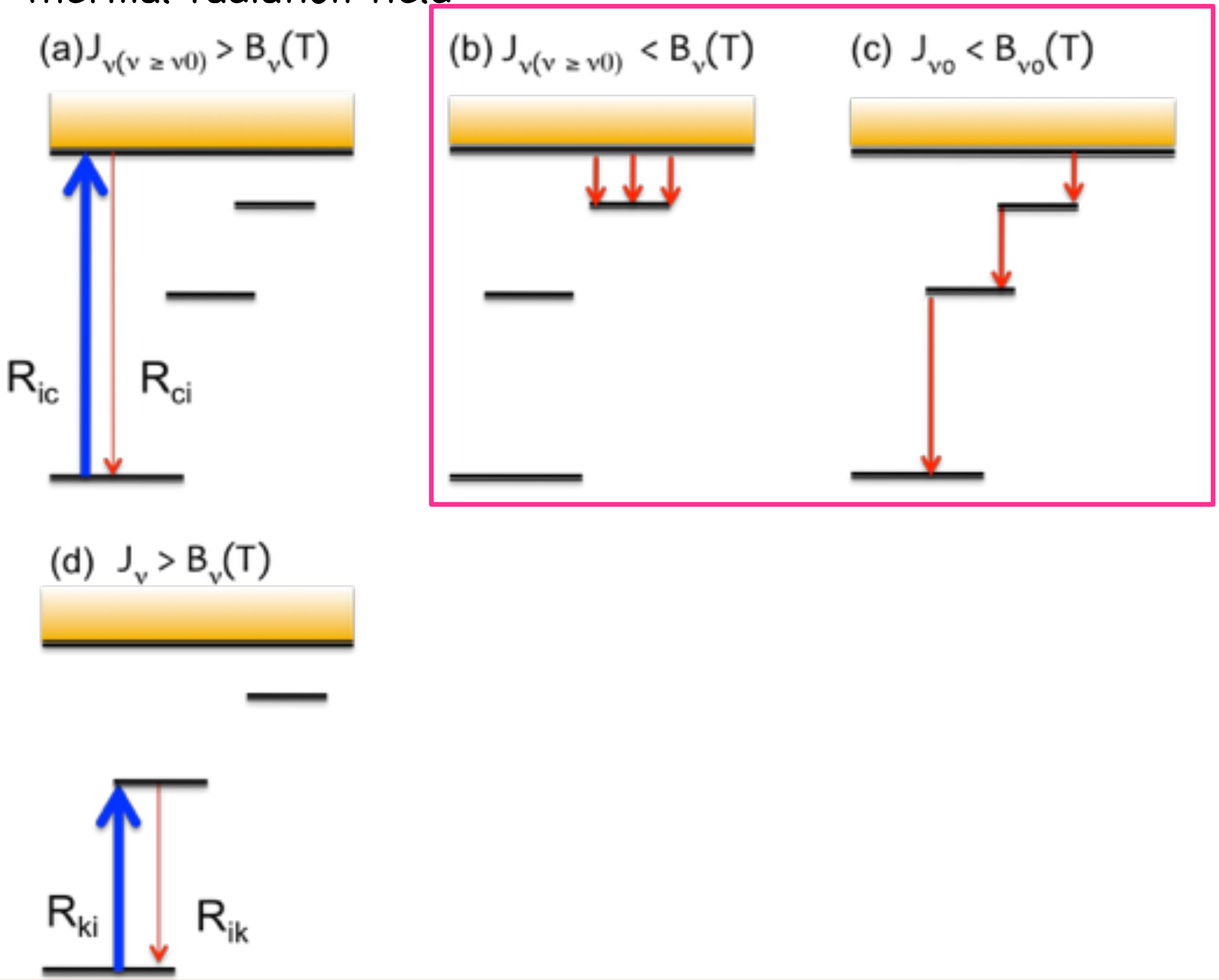
overionization and photon pumping
by super-thermal radiation field



Non-LTE reaction channels

overionization and photon pumping by super-thermal radiation field

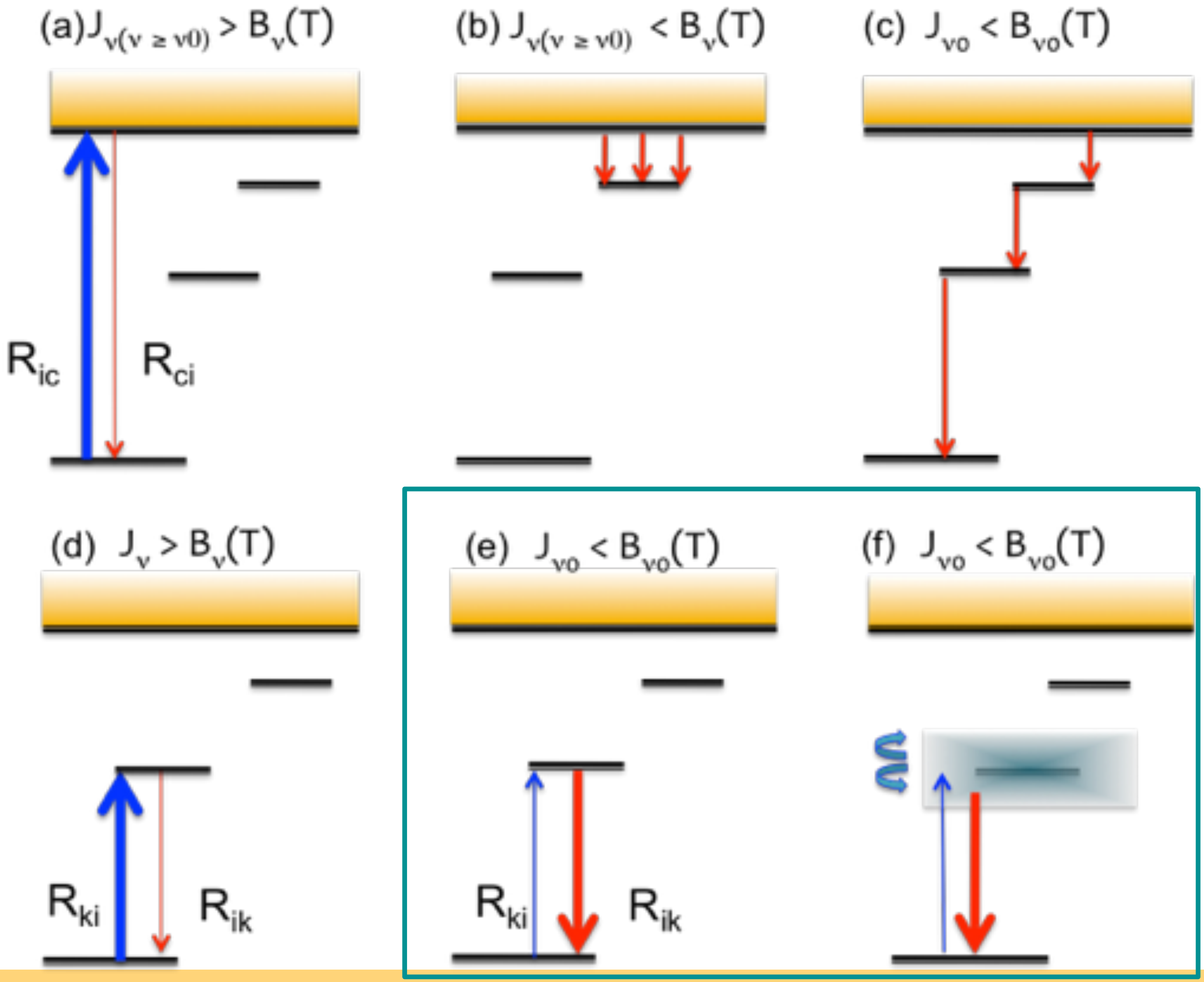
overrecombination and photon suction

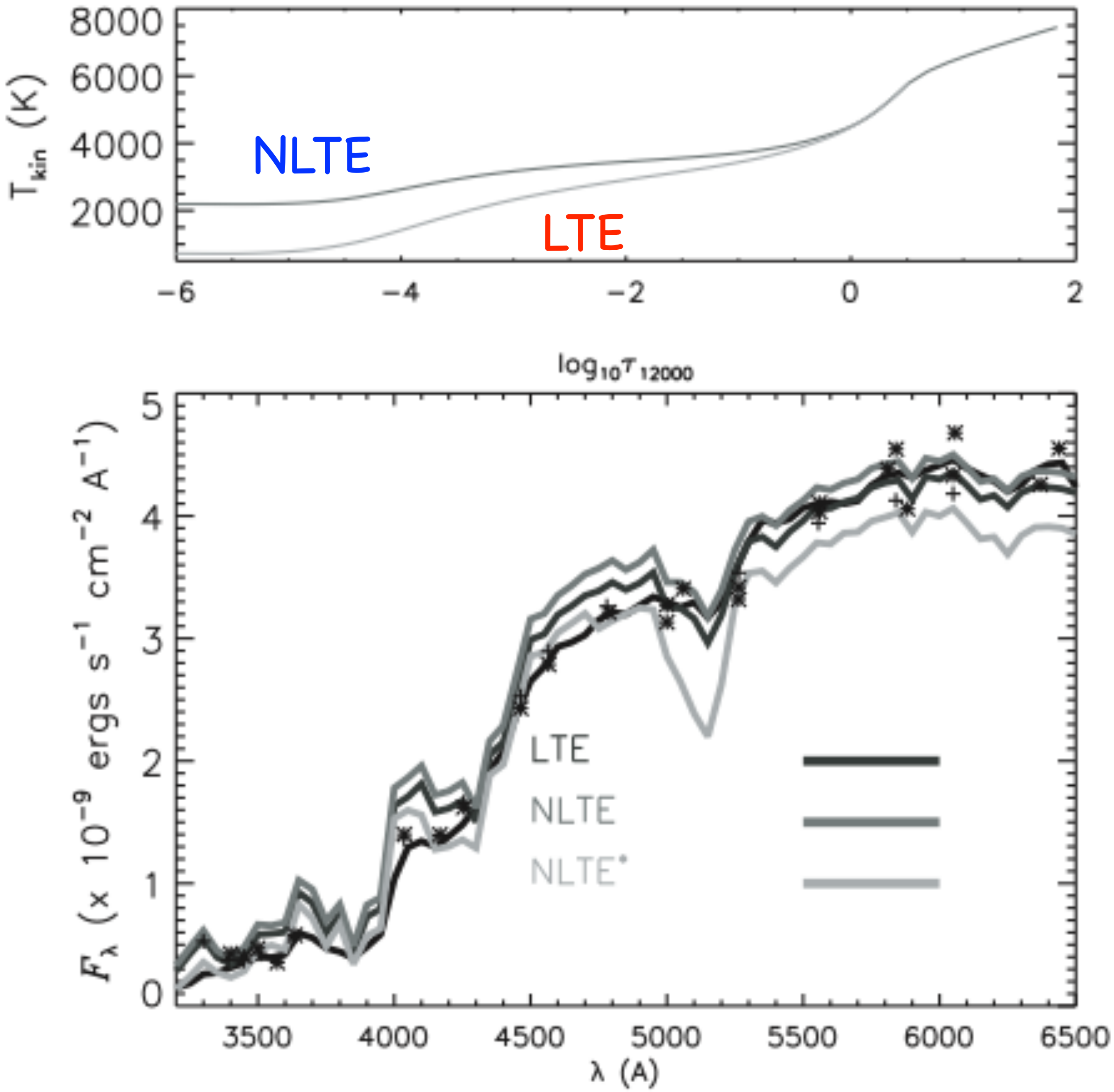


Non-LTE reaction channels

overionization and photon pumping
by super-thermal radiation field

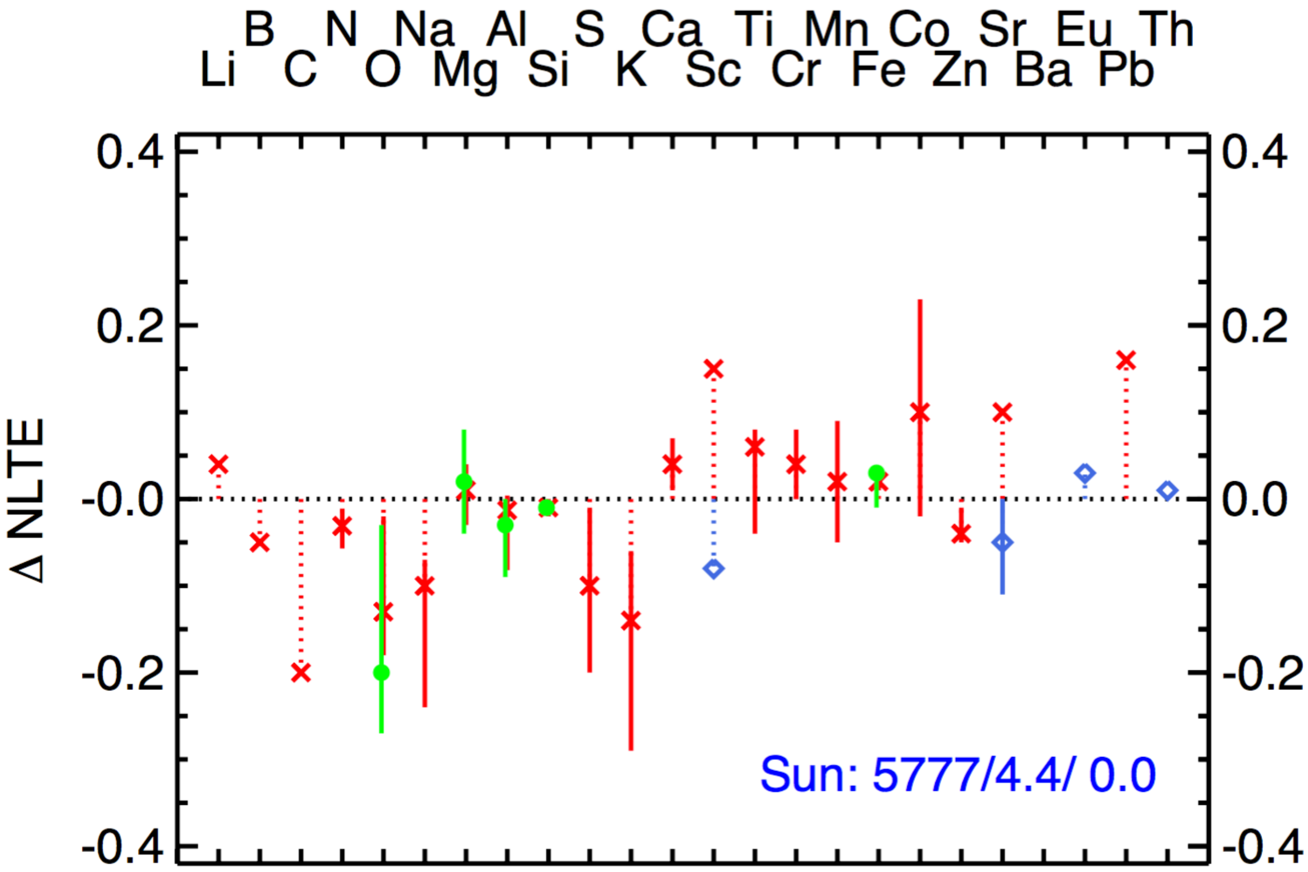
overrecombination and photon suction
resonance line scattering & photon loss




8000
6000
4000
2000
T_{kin} (K)
NLTE
LTE
−6
−4
−2
0
2
$\log_{10}\tau_{12000}$
5
4
3
2
1
0
F_λ (x 10^{-9} ergs s^{-1} cm^{-2} A^{-1})
LTE
NLTE
NLTE*
3500
4000
4500
5000
5500
6000
6500
λ (A)

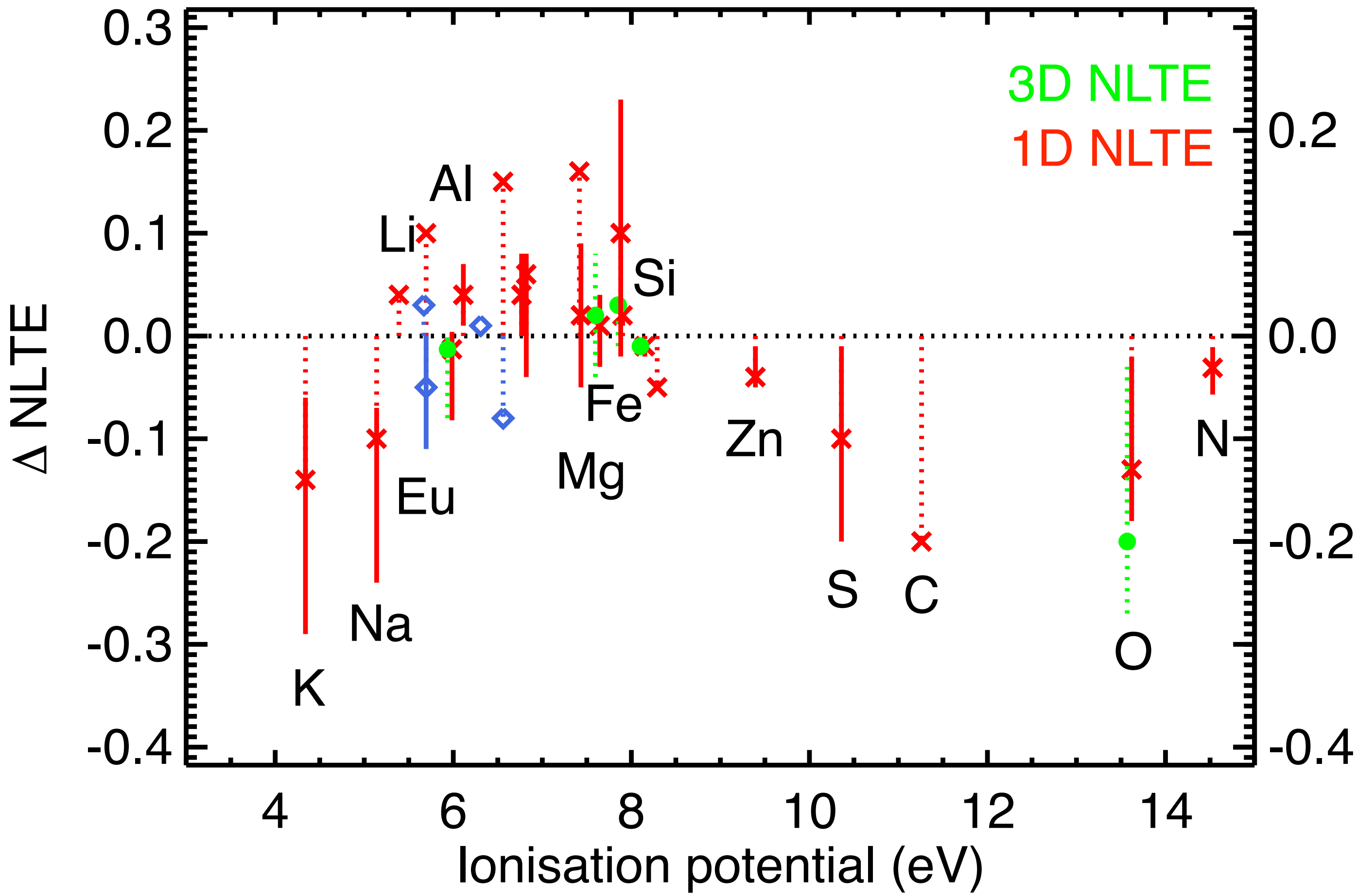
Non-local thermodynamic equilibrium

effect on solar elemental abundances
from -0.3 to +0.2 dex



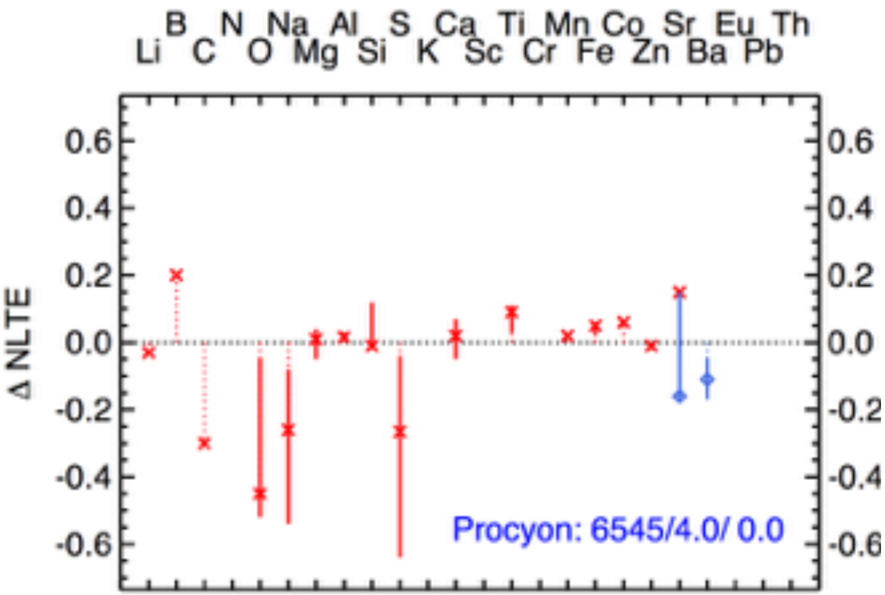
Non-local thermodynamic equilibrium

effect on <u>solar elemental abundances</u>
from −0.3 to +0.2 dex

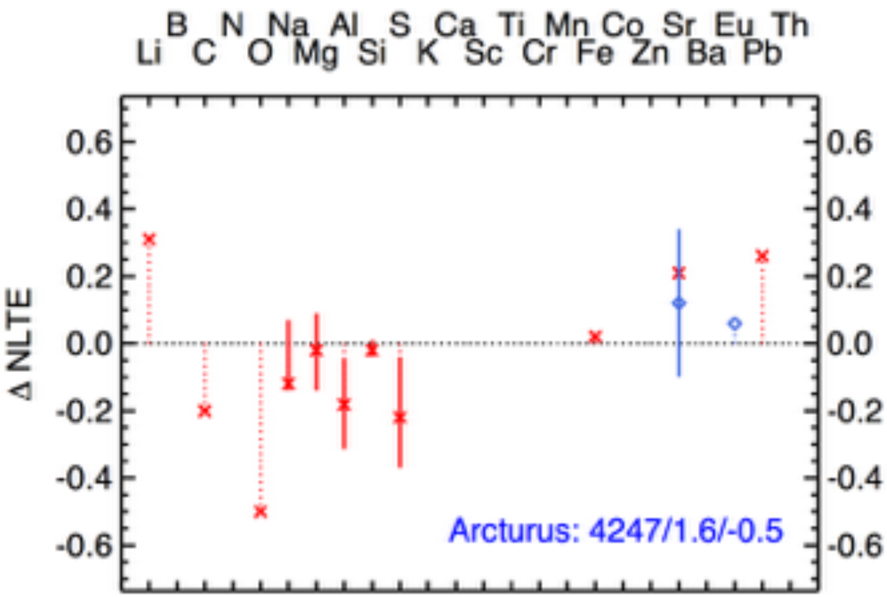


NLTE effects grow with ↑ Teff, ↓ log(g), and ↓ [Fe/H]

Turnoff star

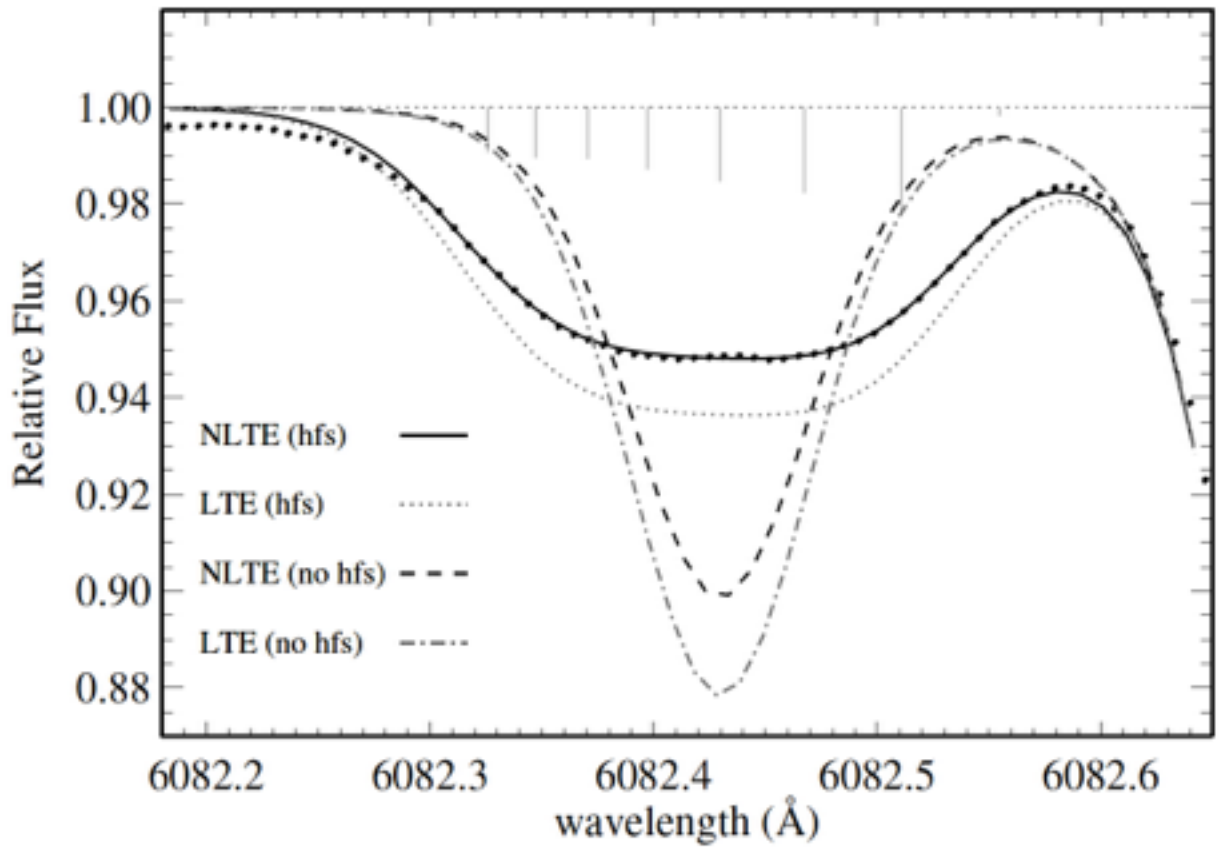


Red giant



Modelling spectral lines

modelling spectra of cool stars: lines are not simple gaussians
Hyperfine structure, isotopic shifts, pressure broadening



Radiative hydrodynamics (RHD)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}),$$ ← mass conservation

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v} \boldsymbol{v}) - \nabla P - \rho \nabla \Phi - \nabla \cdot \tau_{visc},$$ ← momentum conservation

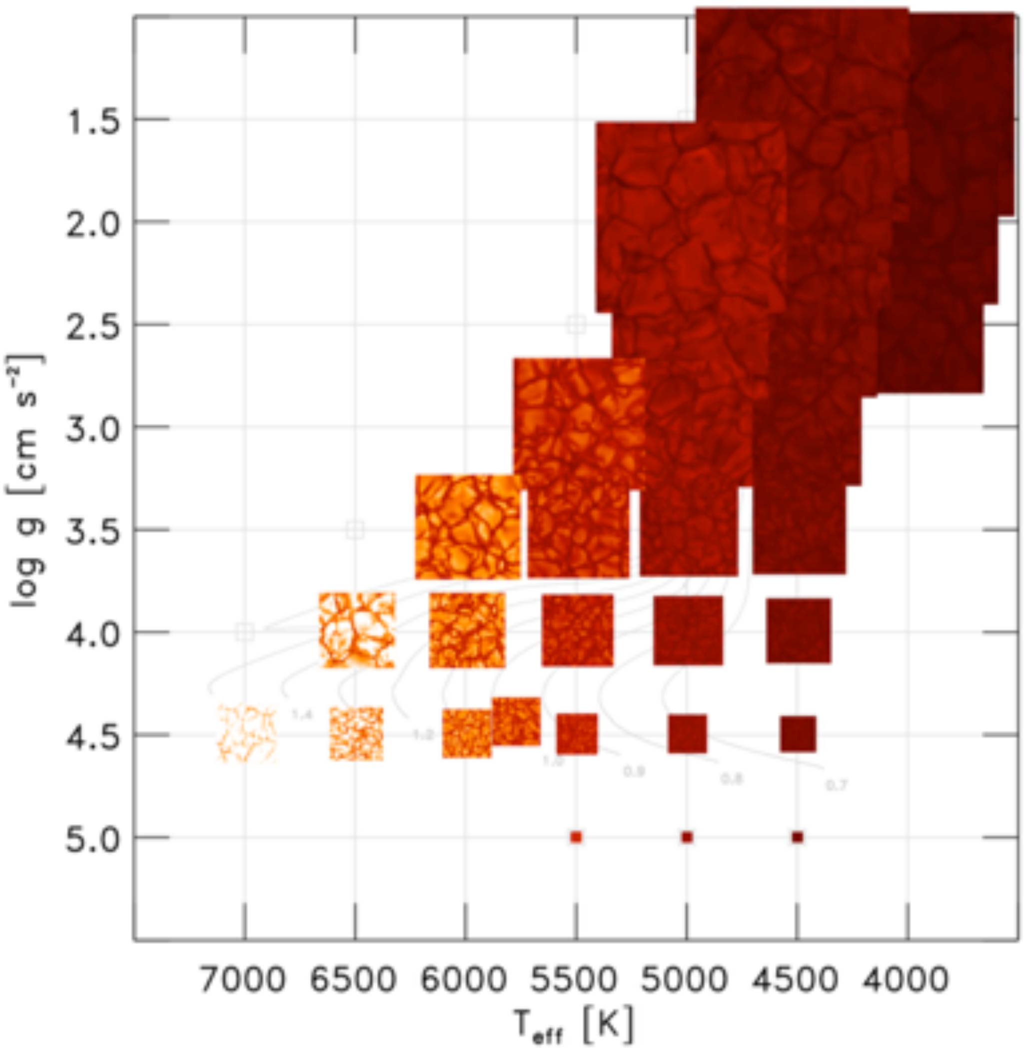
$$\Phi = -\frac{GM}{(r_0^4 + r^4/\sqrt{1 + (r/r_1)^8})^{1/4}} \qquad d\Phi/dz = g,$$

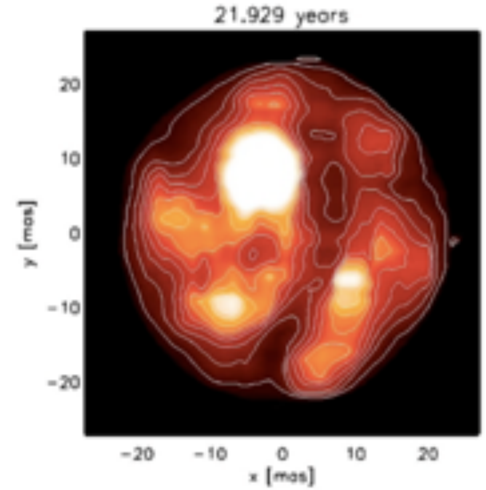
$$\frac{\partial e}{\partial t} = -\nabla \cdot (e \boldsymbol{v}) - P(\nabla \cdot \boldsymbol{v})/\rho + Q_{\rm rad} + Q_{\rm visc}$$ ← energy conservation

$$Q_{\rm rad} = \int_\nu \int_\Omega \rho \kappa_\nu (I_\nu - S_\nu) d\Omega \, d\nu,$$ ← radiative energy exchange

Grids of 3D RHD models

https://staggergrid.wordpress.com





Convection and granulation:
- all FGKM stars
- granules larger for lower log(g) and [Fe/H]
- contrast larger for higher T_{eff}

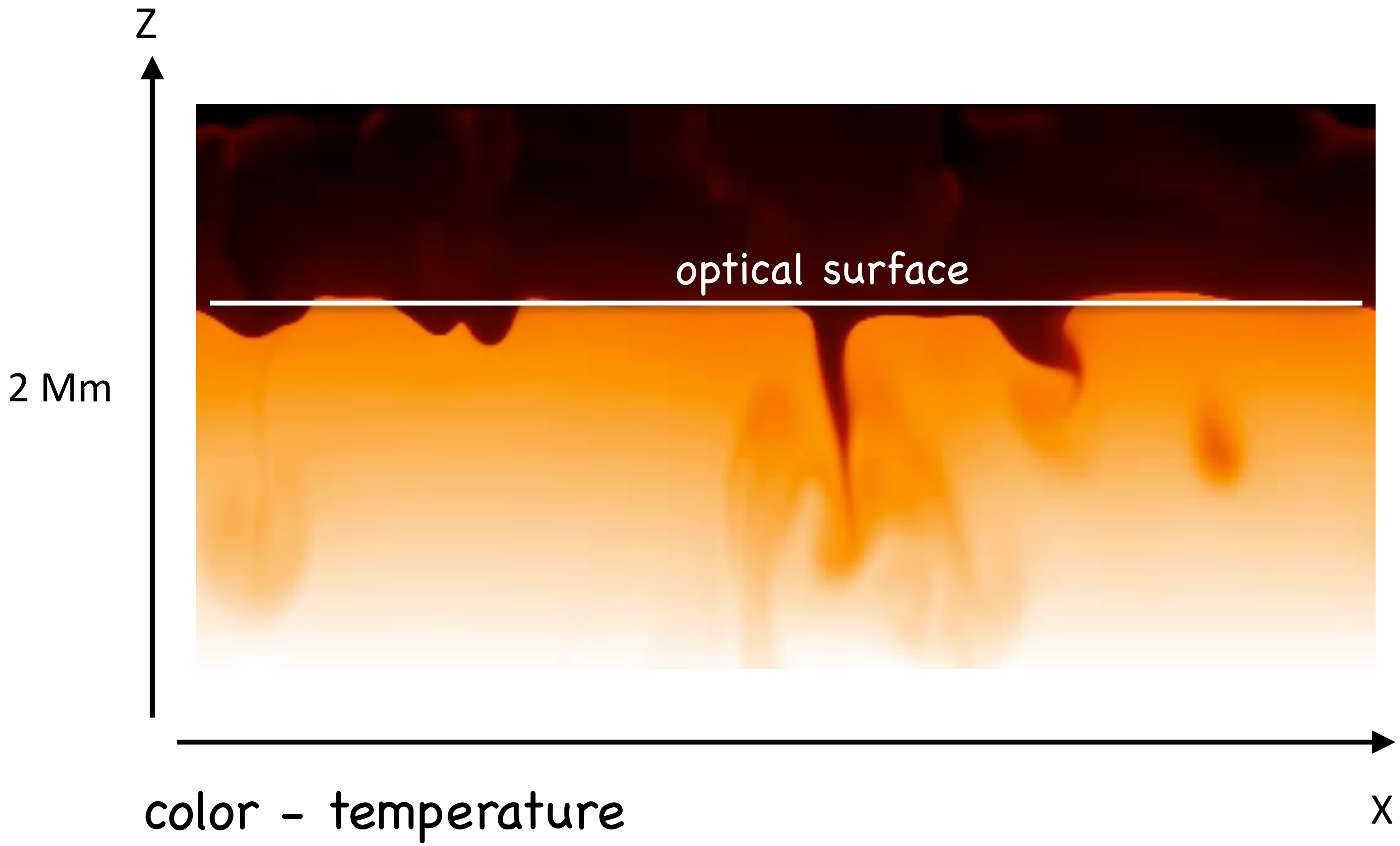
$$\frac{x_{\rm gran}}{R_*} \approx 0.0025 * \frac{R_*}{R_\odot}\frac{T_{{\rm eff},*}}{T_{{\rm eff},\odot}}\frac{M_\odot}{M_*}$$

Freytag et al. (1997)

3D RHD or hydrostatic?

3D RHD simulation of a metal-poor red giant star

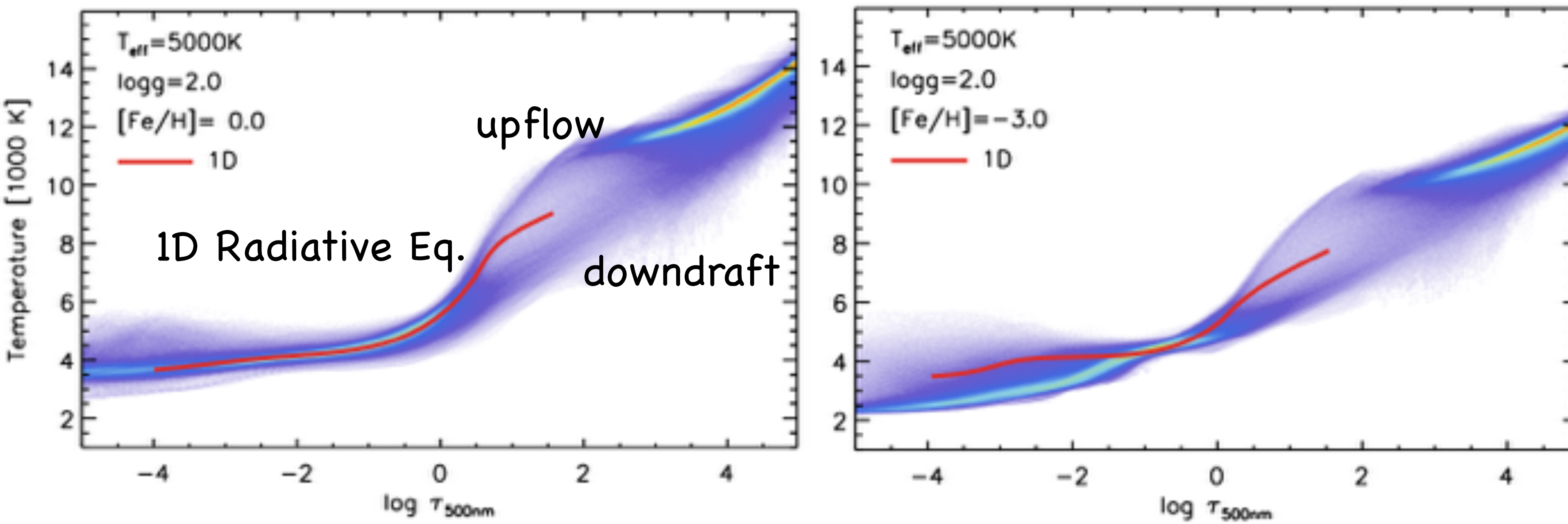
→ no well-defined stellar surface



color - temperature

3D RHD model atmospheres

Convective overshoot into the photosphere
the concept of a 'mean' 1D hydrostatic structure is meaningless



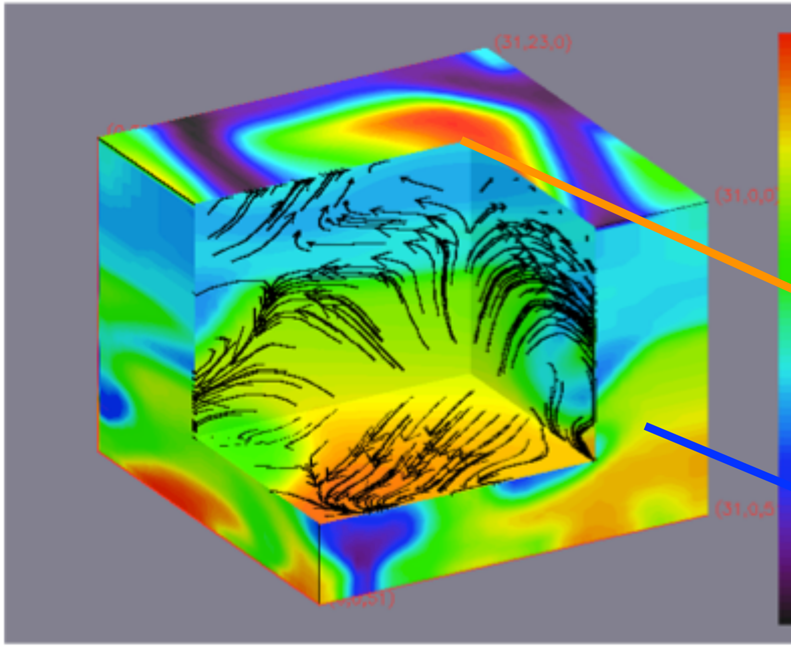
Collet (2008)

$$\partial E / \partial t = -\nabla \cdot E\mathbf{u} \;\; -P\, \nabla \cdot \mathbf{u} \;\; + Q_{rad} \;\; + Q_{visc}$$

in metal-poor stars, adiabatic cooling dominates over radiative heating Q_{rad}

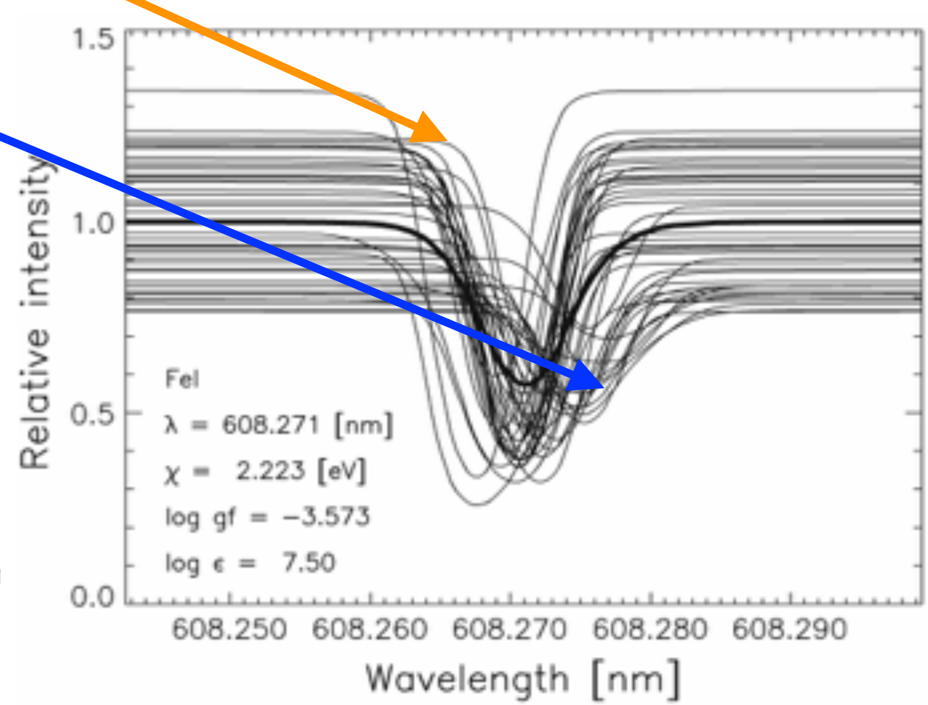
3D RHD model atmospheres

Colour - Temperature



Nordlund et al. (2009)

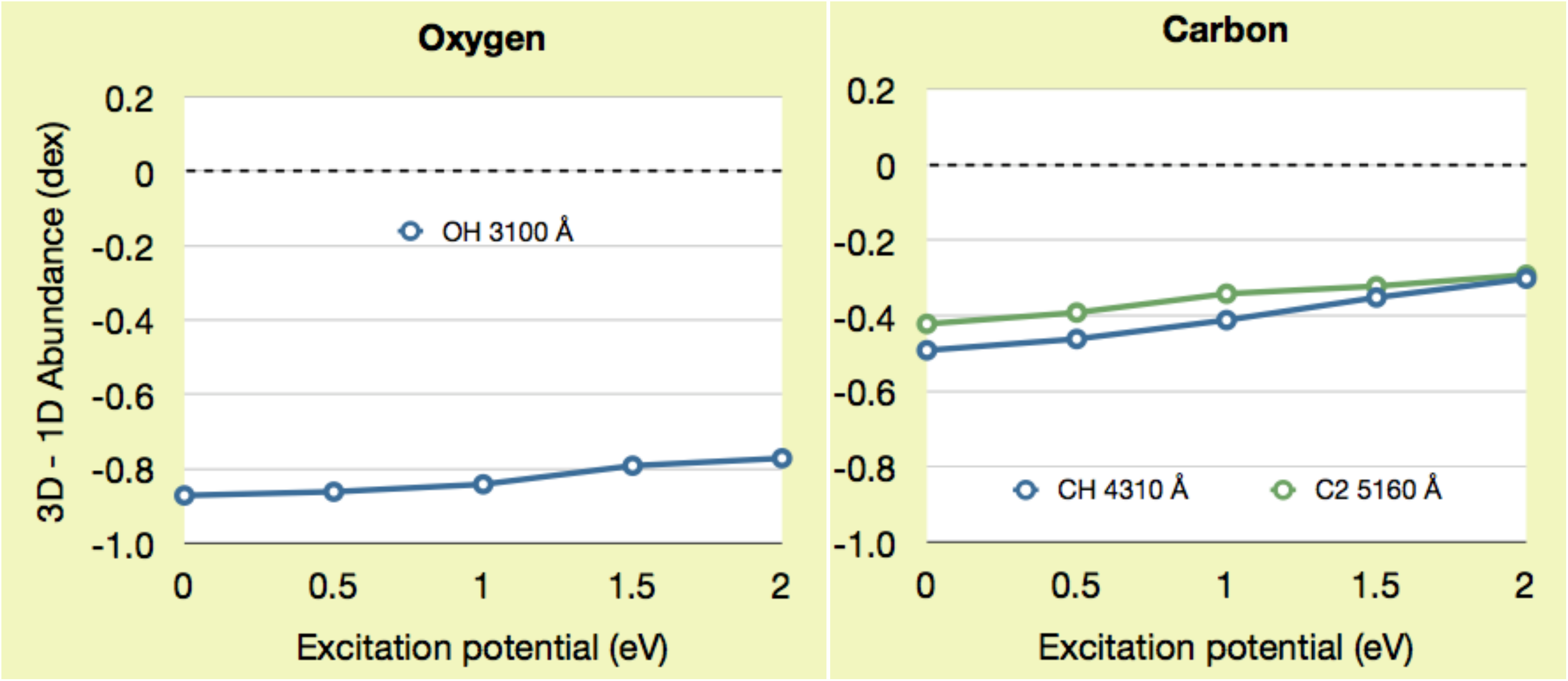
- rising and descending gas volumes have different line-of-sight velocities
- spectral lines are shifted and asymmetric



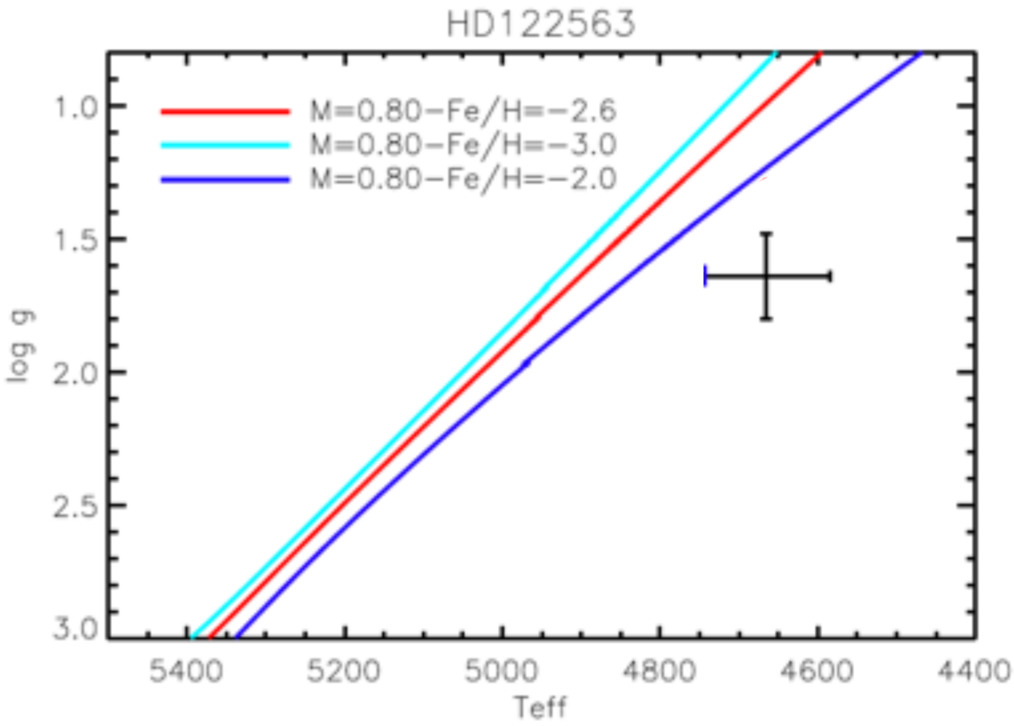
Fe II line profile in a 3D simulation of solar surface convection

3D RHD model atmospheres

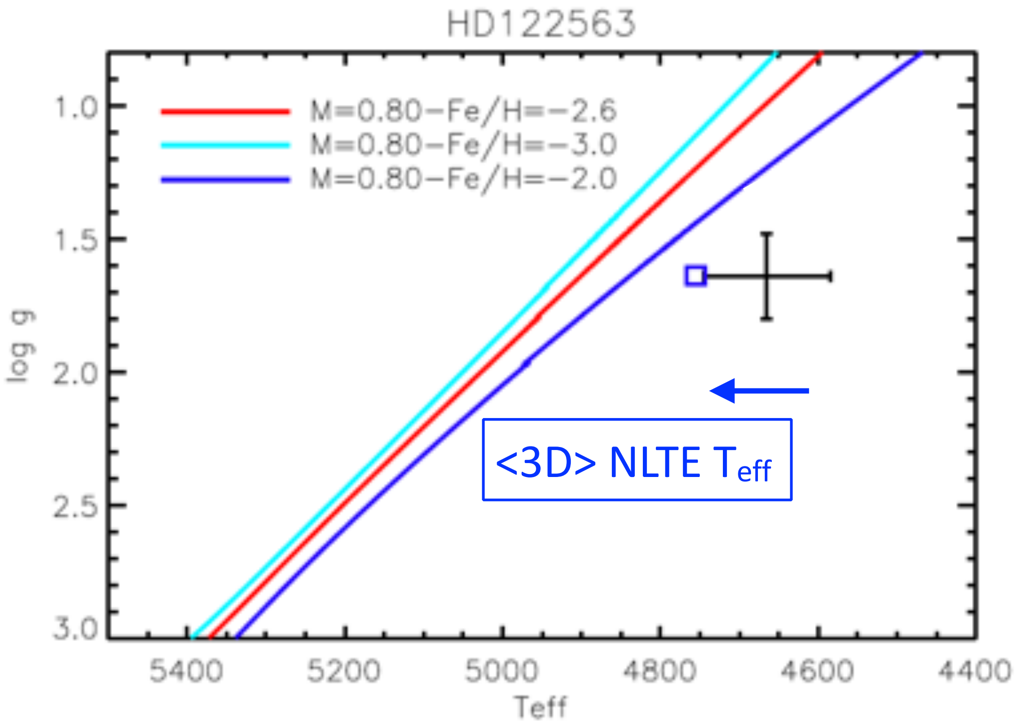
Elemental abundances from molecular lines are lower than predictions of 1D hydrostatic models



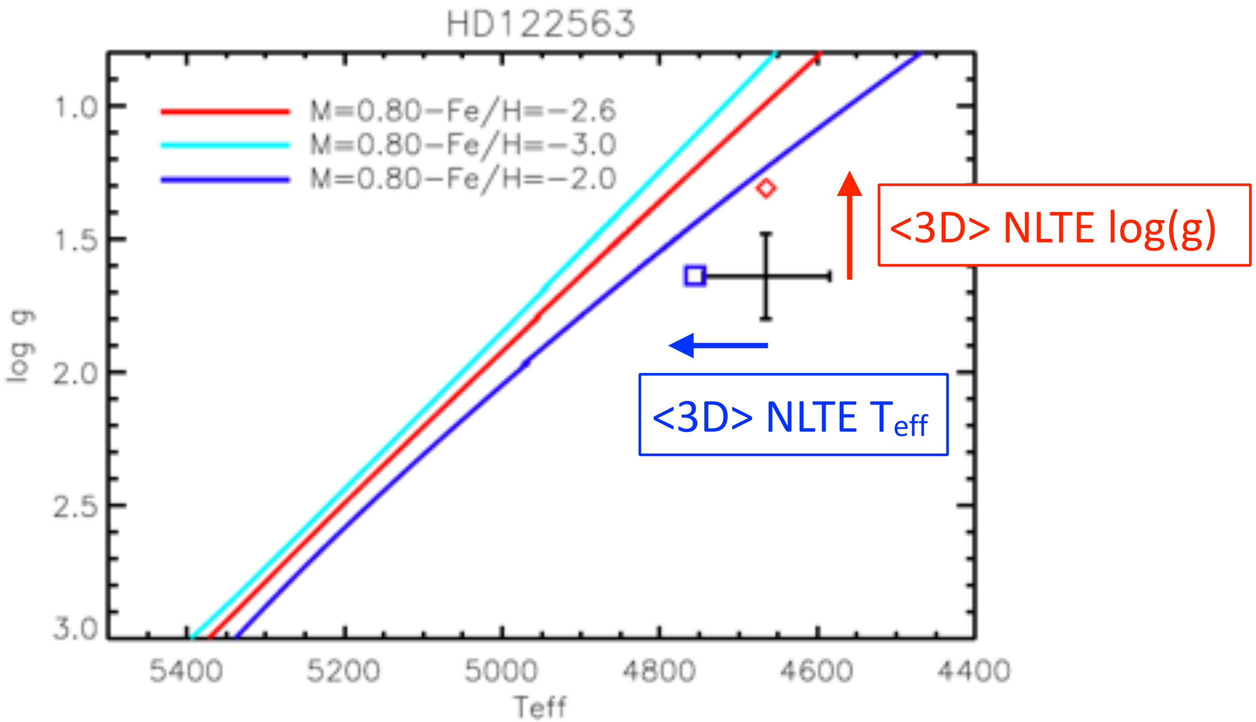
Stellar parameters

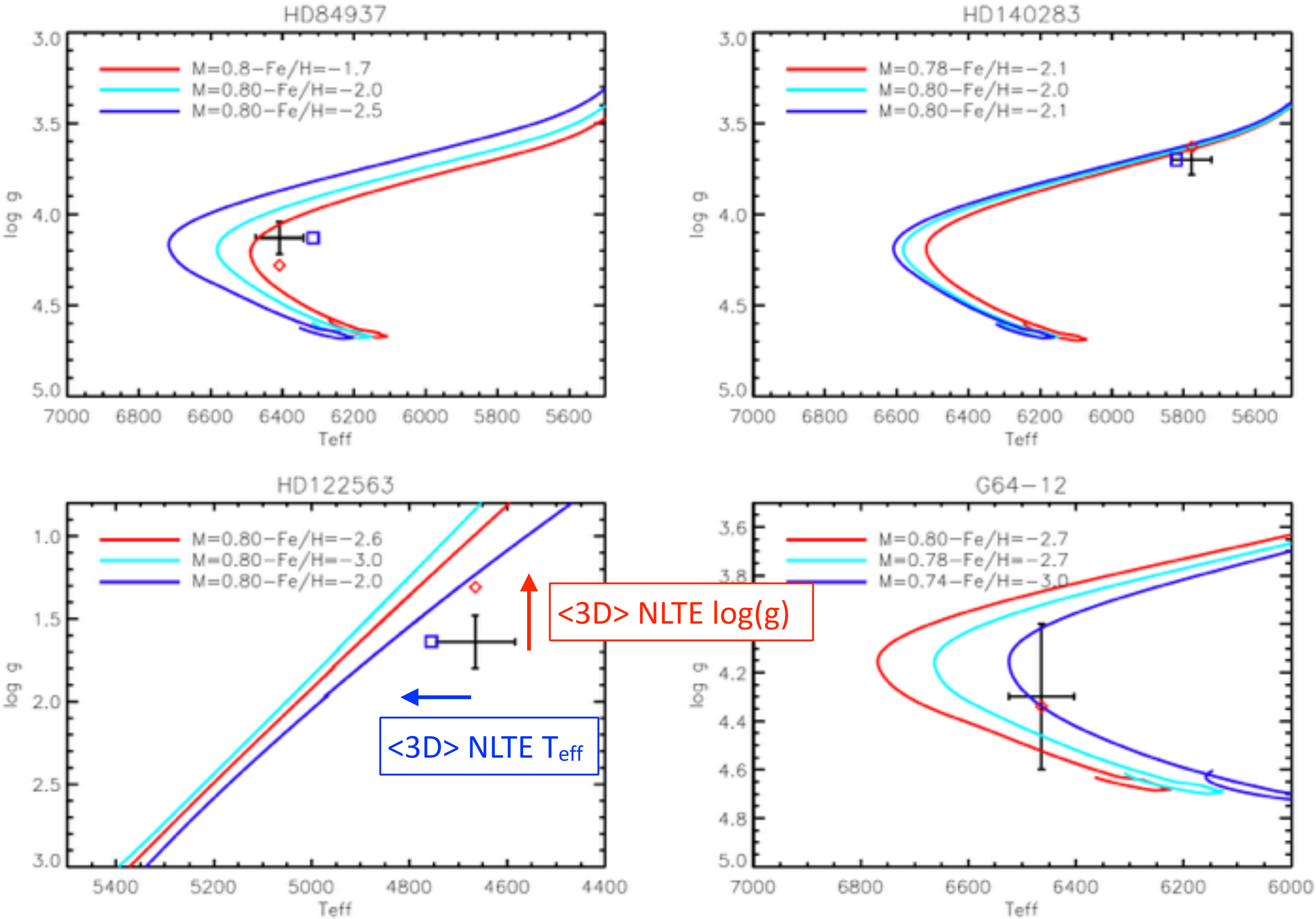


1D LTE estimate of Teff and log(g)



HD122563
M=0.80−Fe/H=−2.6
M=0.80−Fe/H=−3.0
M=0.80−Fe/H=−2.0
1.0
1.5
2.0
2.5
3.0
log g
5400
5200
5000
4800
4600
4400
Teff
<3D> NLTE Teff

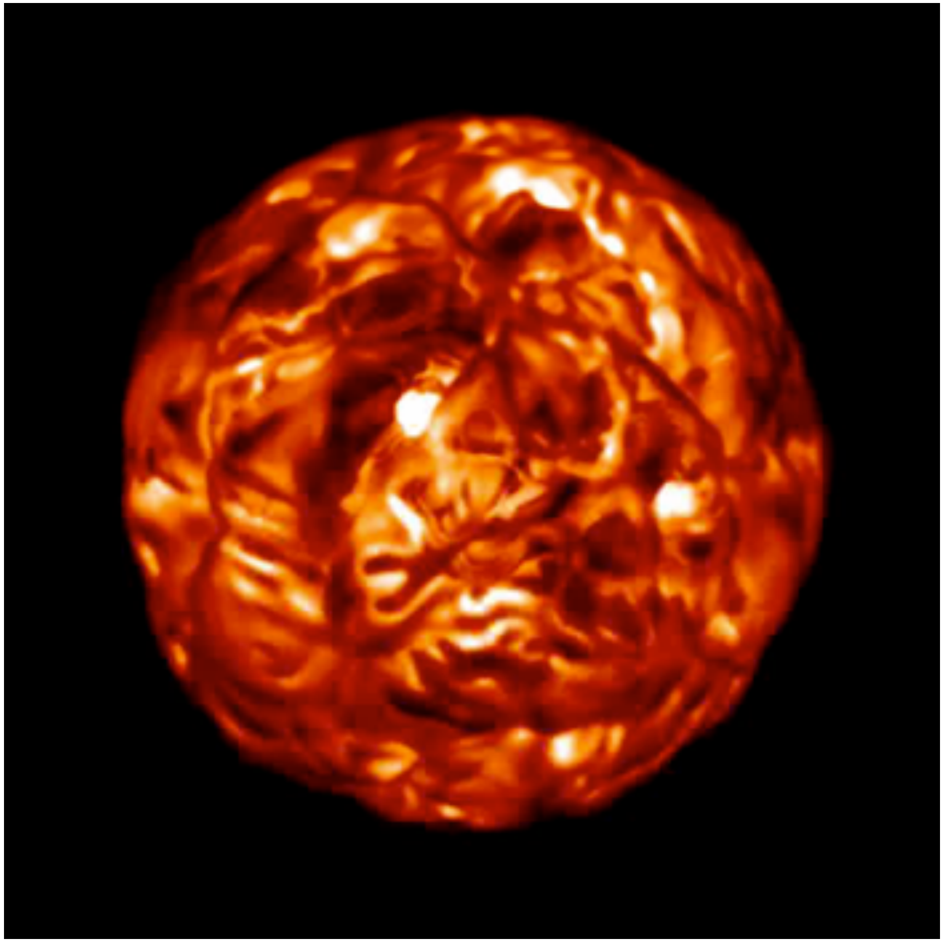

HD122563
M=0.80−Fe/H=−2.6
M=0.80−Fe/H=−3.0
M=0.80−Fe/H=−2.0
log g
1.0
1.5
2.0
2.5
3.0
5400
5200
5000
4800
4600
4400
Teff
<3D> NLTE log(g)
<3D> NLTE Teff



Bergemann et al. (2012)

Red Supergiants: atmospheres

- Global 3D RHD simulations
  star-in-a-box
  star completely enclosed in simulation domain
- Boundary conditions:
  - central luminosity source,
  - open external boundaries
- Low spatial resolution
- Gravity: prescribed potential
- Opacities: grey or binning
- Time per model: months

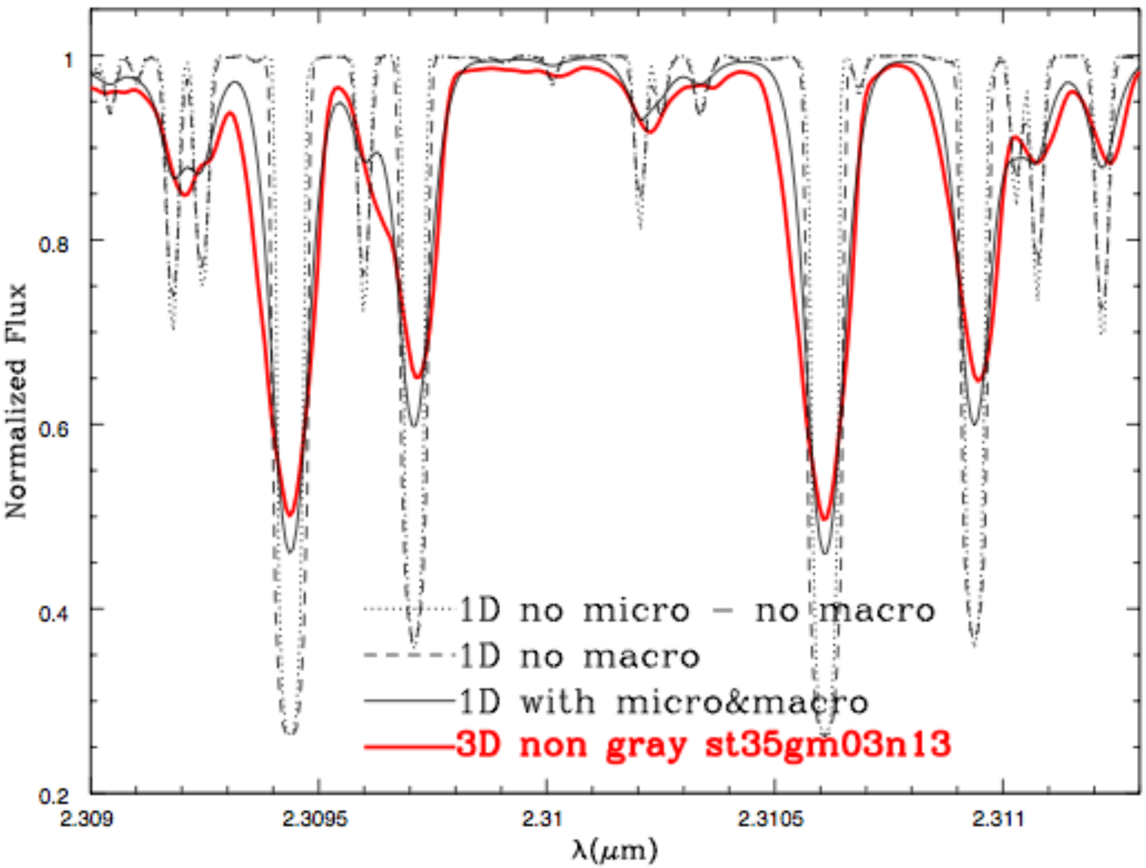


Chiavassa et al. (2011,2013)

3D RHD model atmospheres

Velocity fields have an effect on the structure of atmosphere through the line blanketing

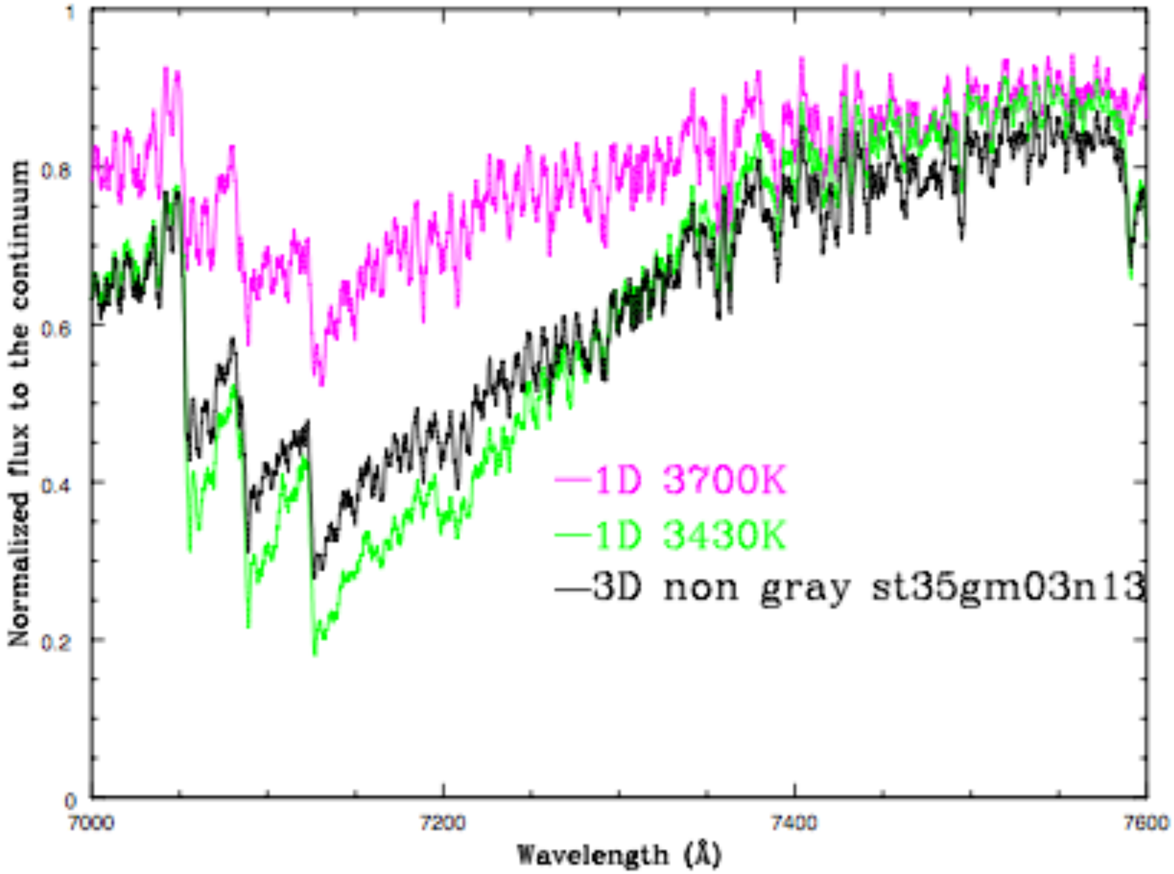
CO lines



in 1D hydrostatic models,
V fields are represented by
'micro-turbulence'
and
'macro-turbulence'

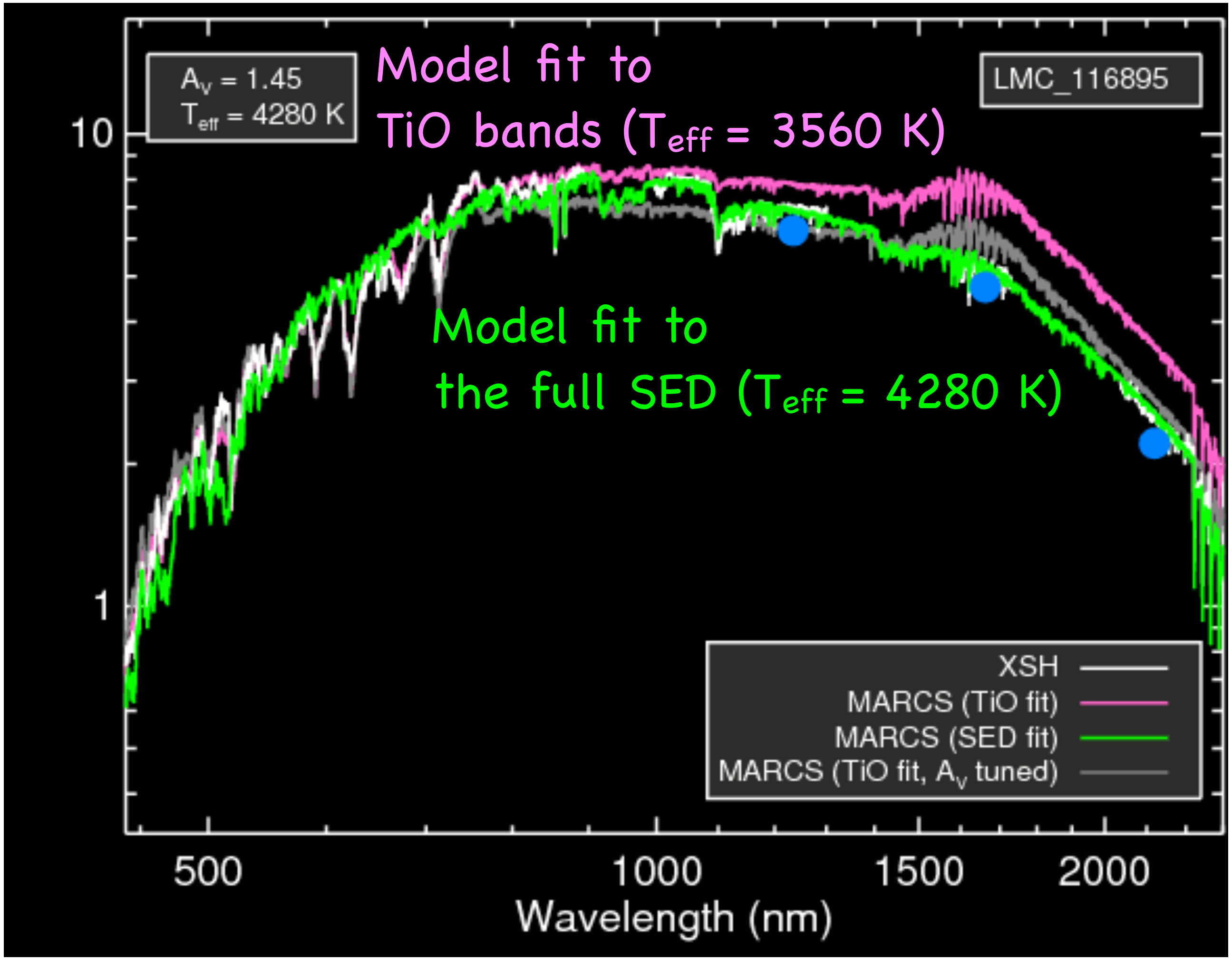
3D RHD model atmospheres

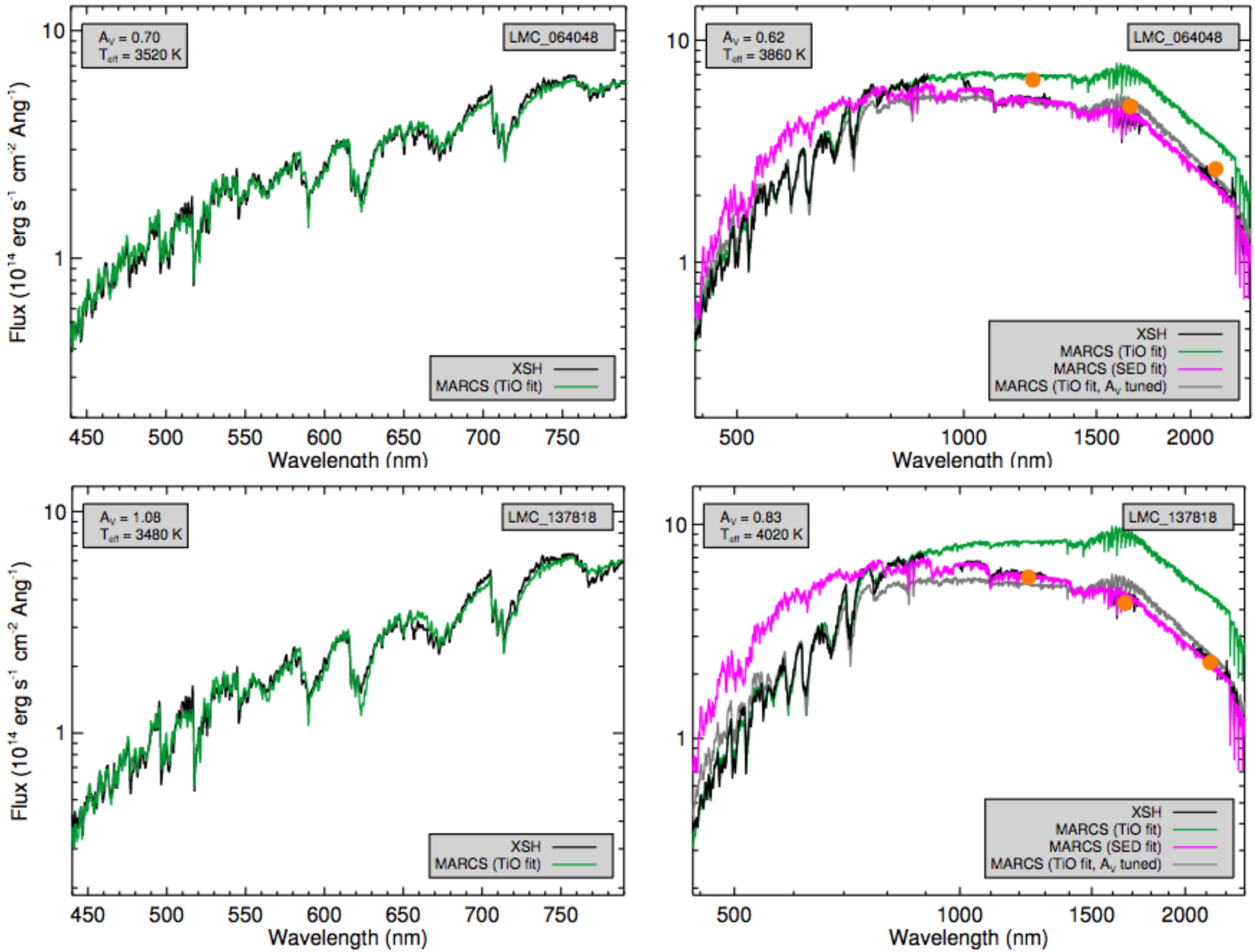
The effect of convection on the radiation field is huge in the frequencies of strong molecular absorption (e.g. TiO)



TiO: overestimate the flux in the near IR

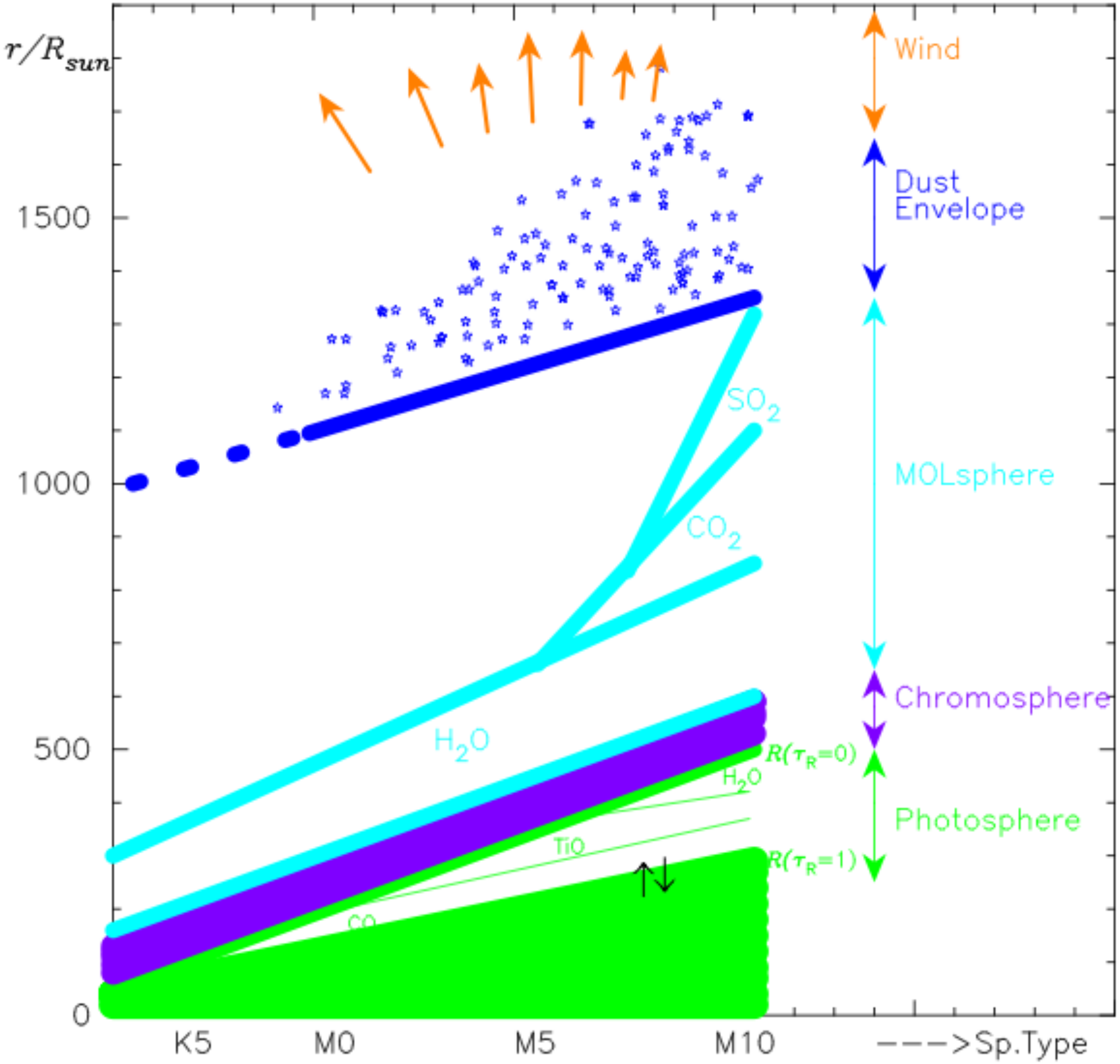
optical/IR SED: under-predict the TiO strengths





A_V = 0.70
T_eff = 3520 K
LMC_064048
XSH
MARCS (TiO fit)
A_V = 0.62
T_eff = 3860 K
LMC_064048
XSH
MARCS (TiO fit)
MARCS (SED fit)
MARCS (TiO fit, A_V tuned)
A_V = 1.08
T_eff = 3480 K
LMC_137818
XSH
MARCS (TiO fit)
A_V = 0.83
T_eff = 4020 K
LMC_137818
XSH
MARCS (TiO fit)
MARCS (SED fit)
MARCS (TiO fit, A_V tuned)
Flux (10^14 erg s^-1 cm^-2 Ang^-1)
Wavelength (nm)

Red Supergiants: atmospheres



Tsuji (2003)

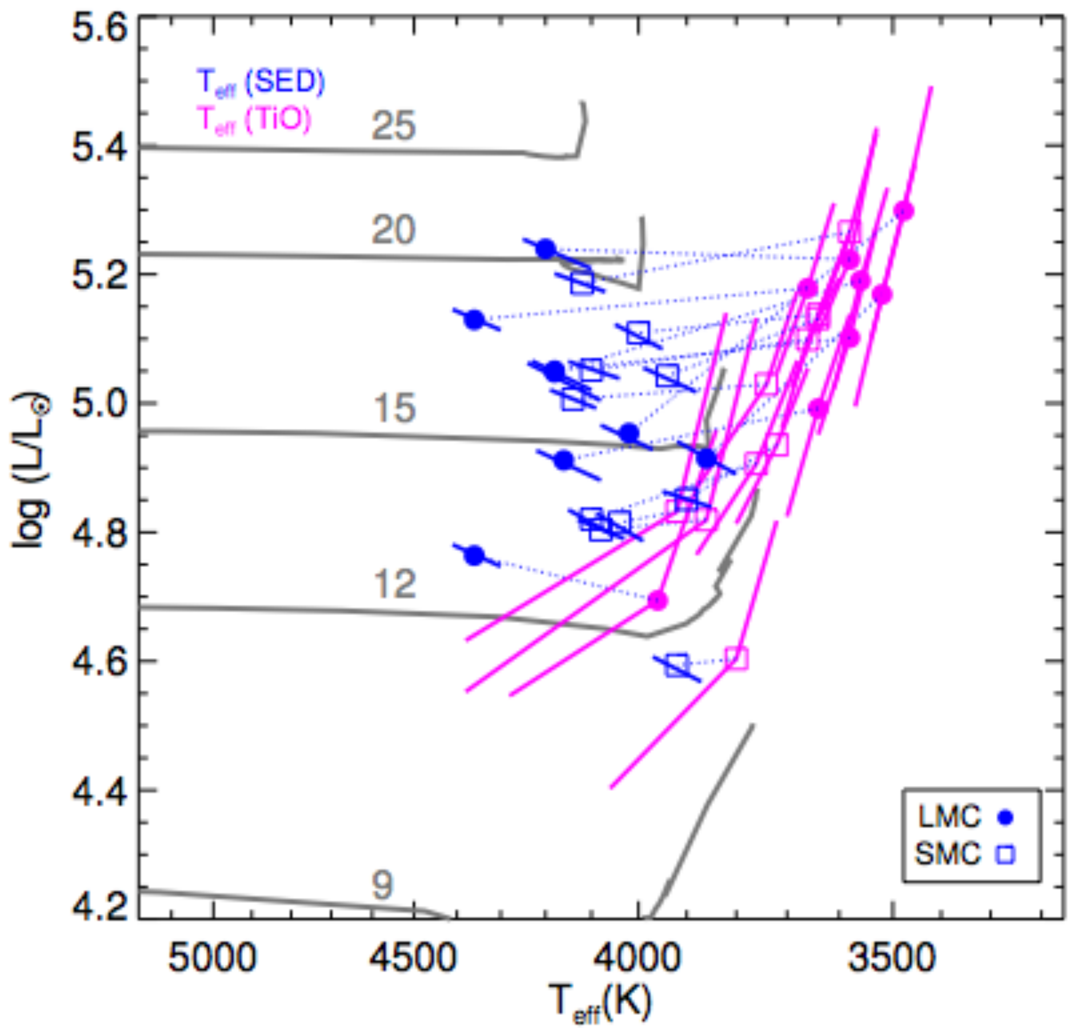
Unsolved problems

are RSG warm or cool?

SED fitting

TiO fitting

impact on evolution of massive stars and SNe



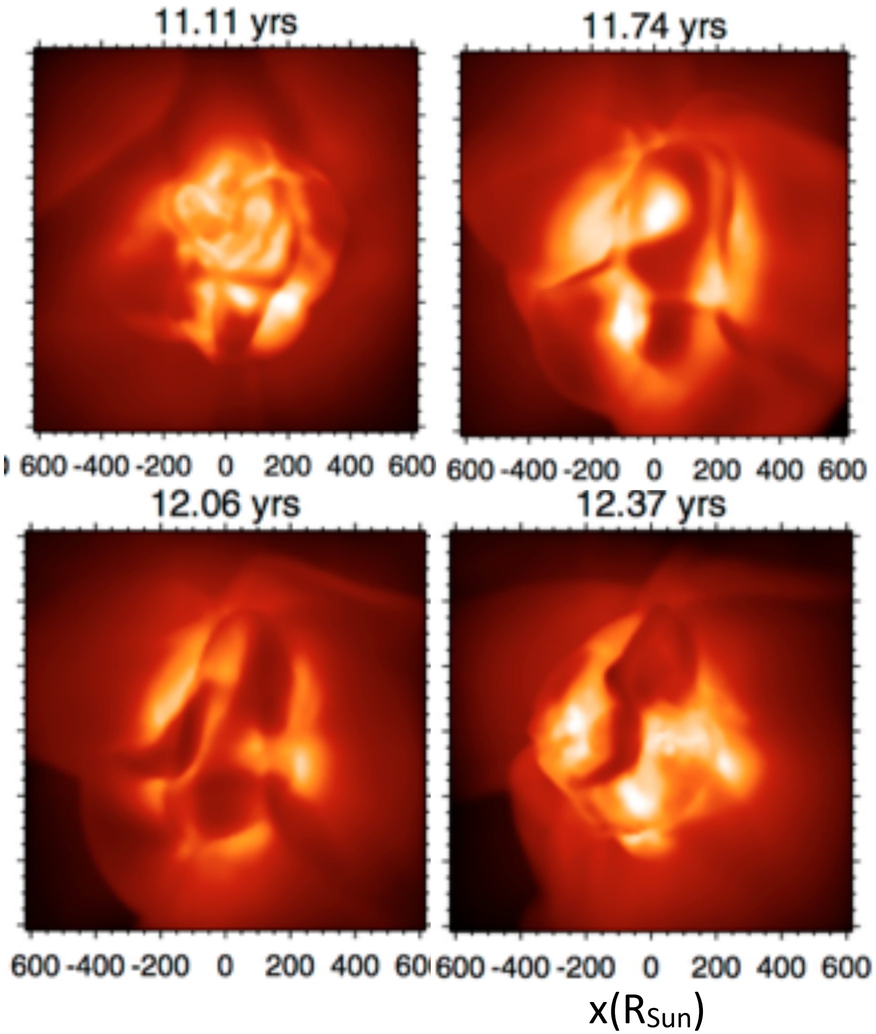
Davies et al. (2013)

AGB stars

3D RHD simulations
of the outer envelope and
atmosphere

- long-lasting giant
convection cells, ~years
- short-lived surface granules
- strong radial pulsations

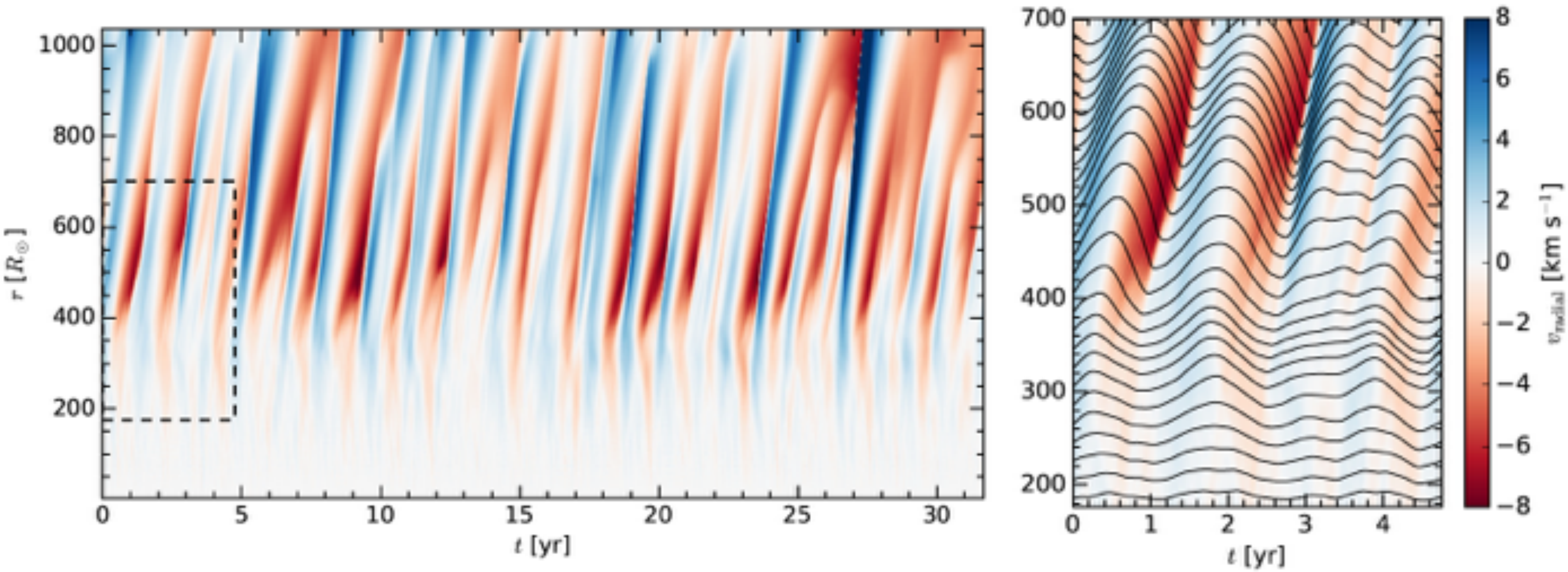
→ shocks
→ radiation pressure on dust
winds



Freytag et al. (2017)

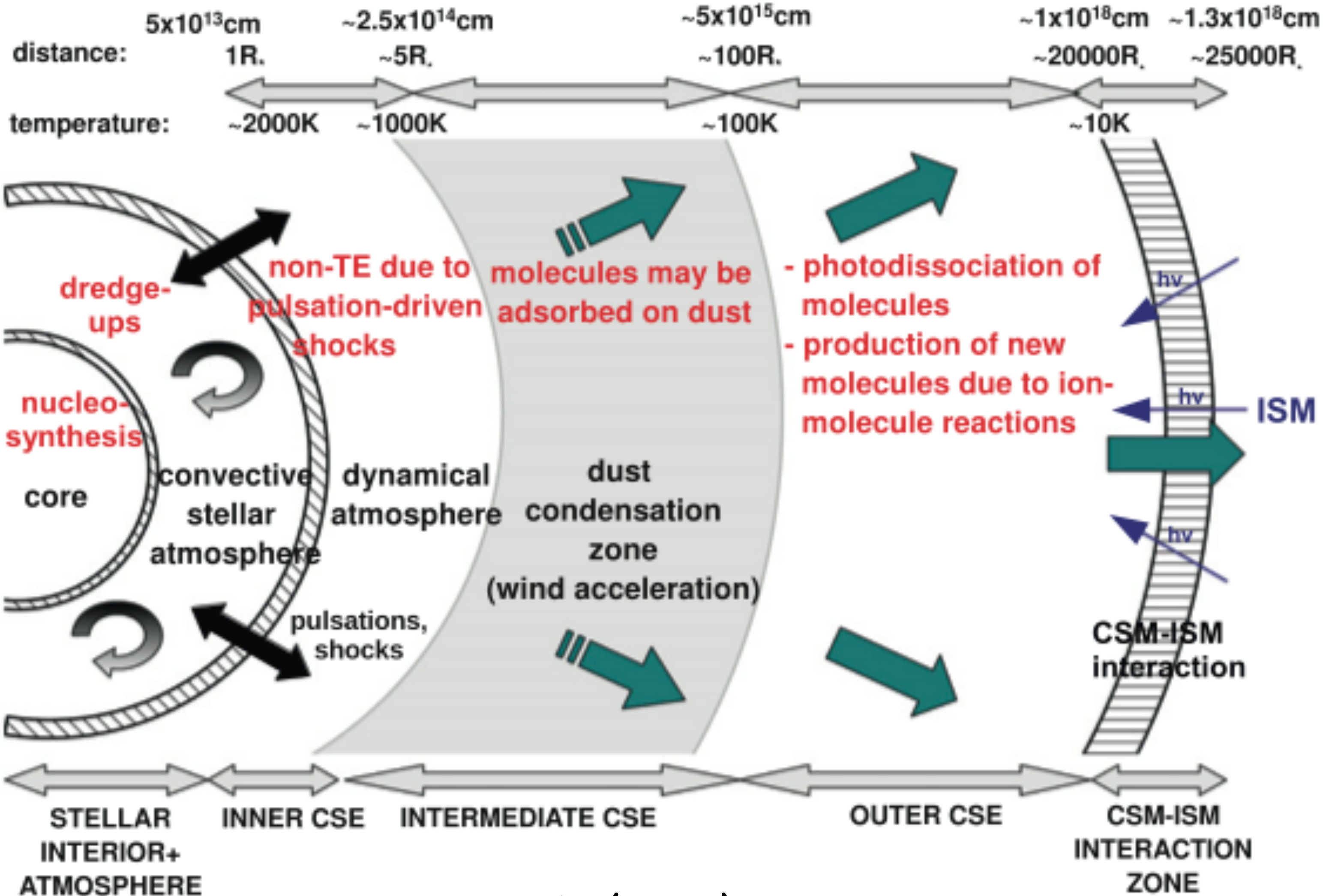
AGB stars

Left: The spherically averaged radial velocity V(r; t) for the full run time and radial distance.
Right: mass-shell movements plotted as iso-mass contour lines



Freytag et al. (2017)

Schematic view of an AGB atmosphere



Decin (2003)

Stars and winds

	The Sun	RSG	Blue Supergiants
Driving mechanism	d P_{gas}/dr	P_{rad} on ions and dust	P_{rad} on ions
mass (M_{Sun})	1	8 ... 40	10 ... 100
luminosity (L_{Sun})	1	10^4 ... 10^6	10^5 ... 10^6
radius (R_{Sun})	1	500 ... 1500	10 ... 200
T_{eff} (K)	5777	3000	10^4 ... 5 10^4
wind temperature (K)	10^6	1000	8000 ... 40000
mass loss rate (M_{Sun}/yr)	10^{-14}	10^{-6} ... 10^{-4}	10^{-6} ... 10^{-5}
life time (yr)	10^{10}	10^5	10^7
total mass loss (M_{Sun})	10^{-4}	< 0.5	90 %