THE STAGGER-GRID

3D MODEL STELLAR ATMOSPHERES

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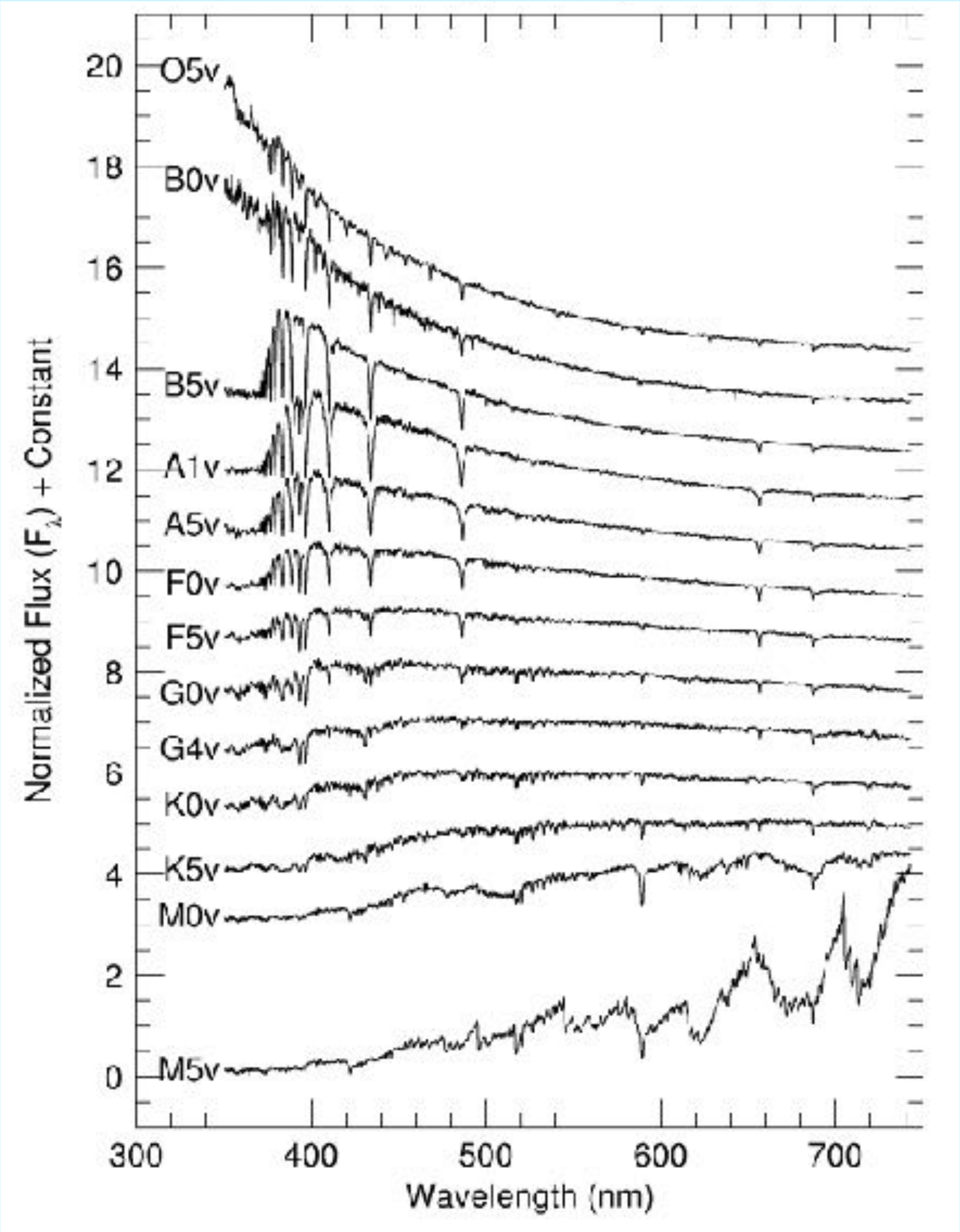
Stellar Characterisation

- **Stellar spectra and light curves** carry information about the physical properties and compositions of stars

- Important for **characterisation of exoplanets** and for **Galactic chemical evolution**

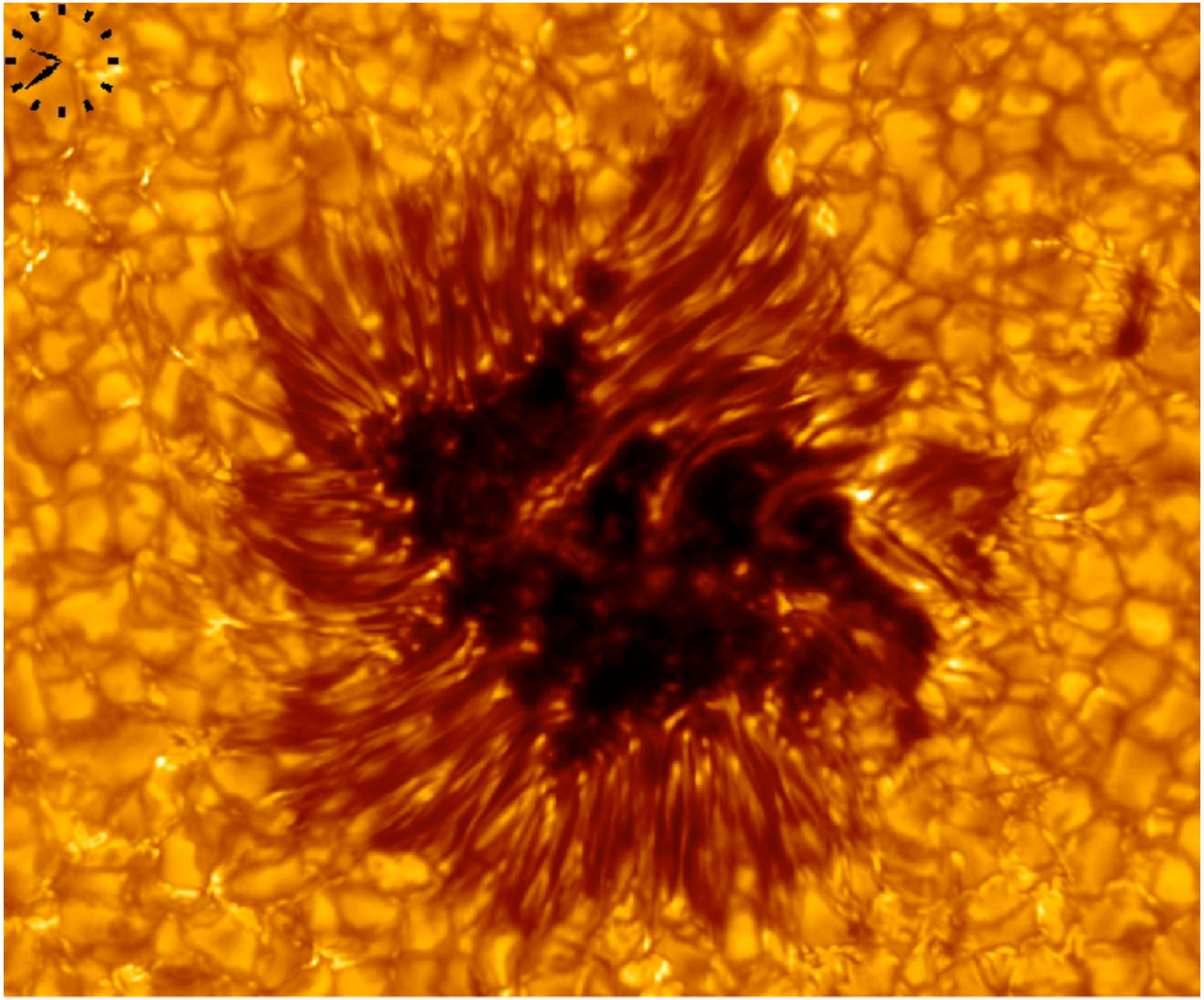
- Quantifying this information requires knowledge of the structure of the **outer layers** (atmospheres) **of stars**



1D model atmospheres

- 1D Homogeneous stratification
- Hydrostatic
- Stationary
- Radiative transfer: 100,000 wavelengths or more
- Convection: simplified treatment (mixing length theory)
- Free tuneable parameters

Real stellar atmospheres



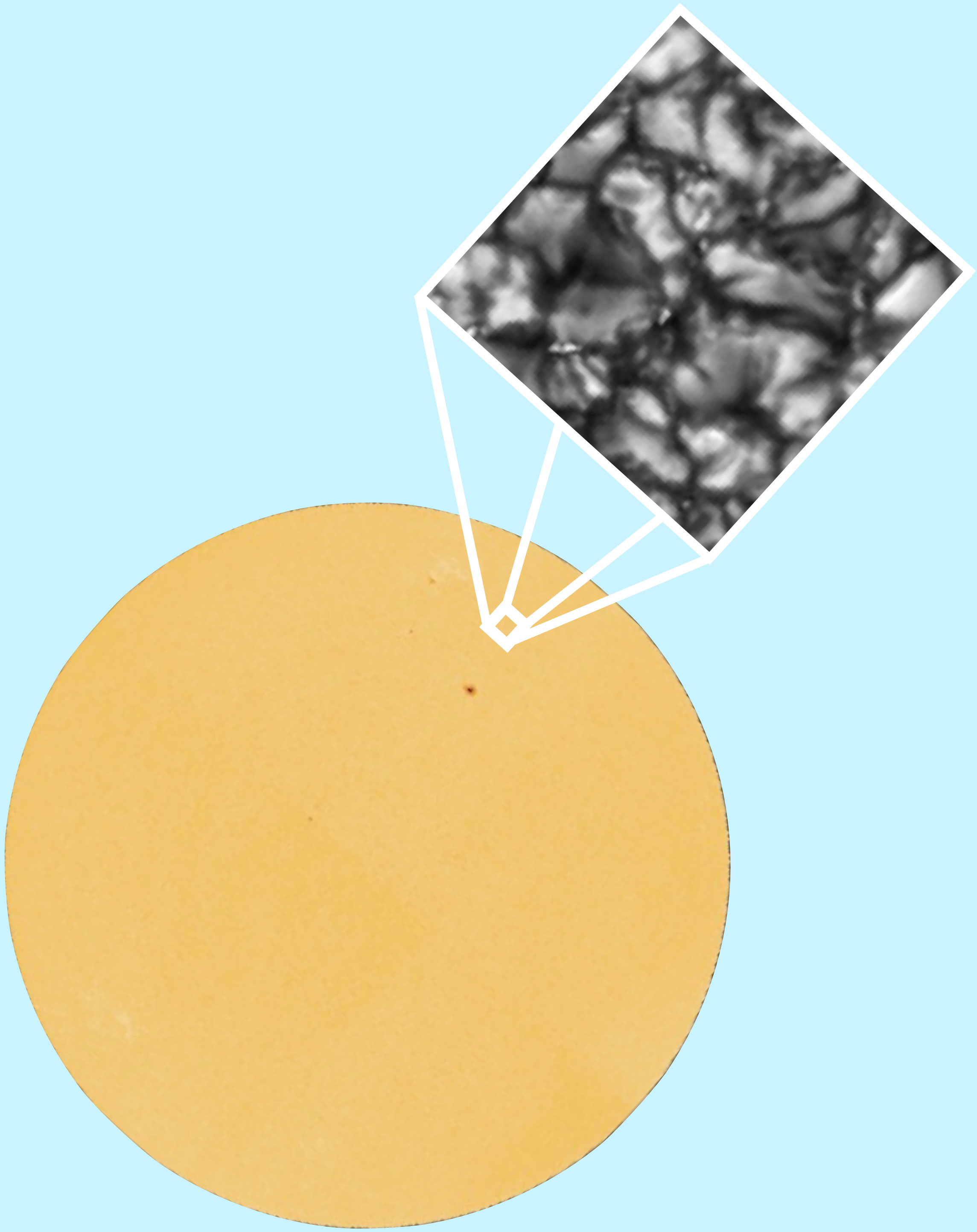
Credit: L. R. van der Voort (Swedish Solar Telescope)

3D models

- Solution of mass, momentum, and energy conservation equations
- 3D geometry
- Time-dependent
- 3D non-grey radiative transfer (with multi-group opacities)
- (Magnetic fields)
- Convection: no need for dedicated free parameters

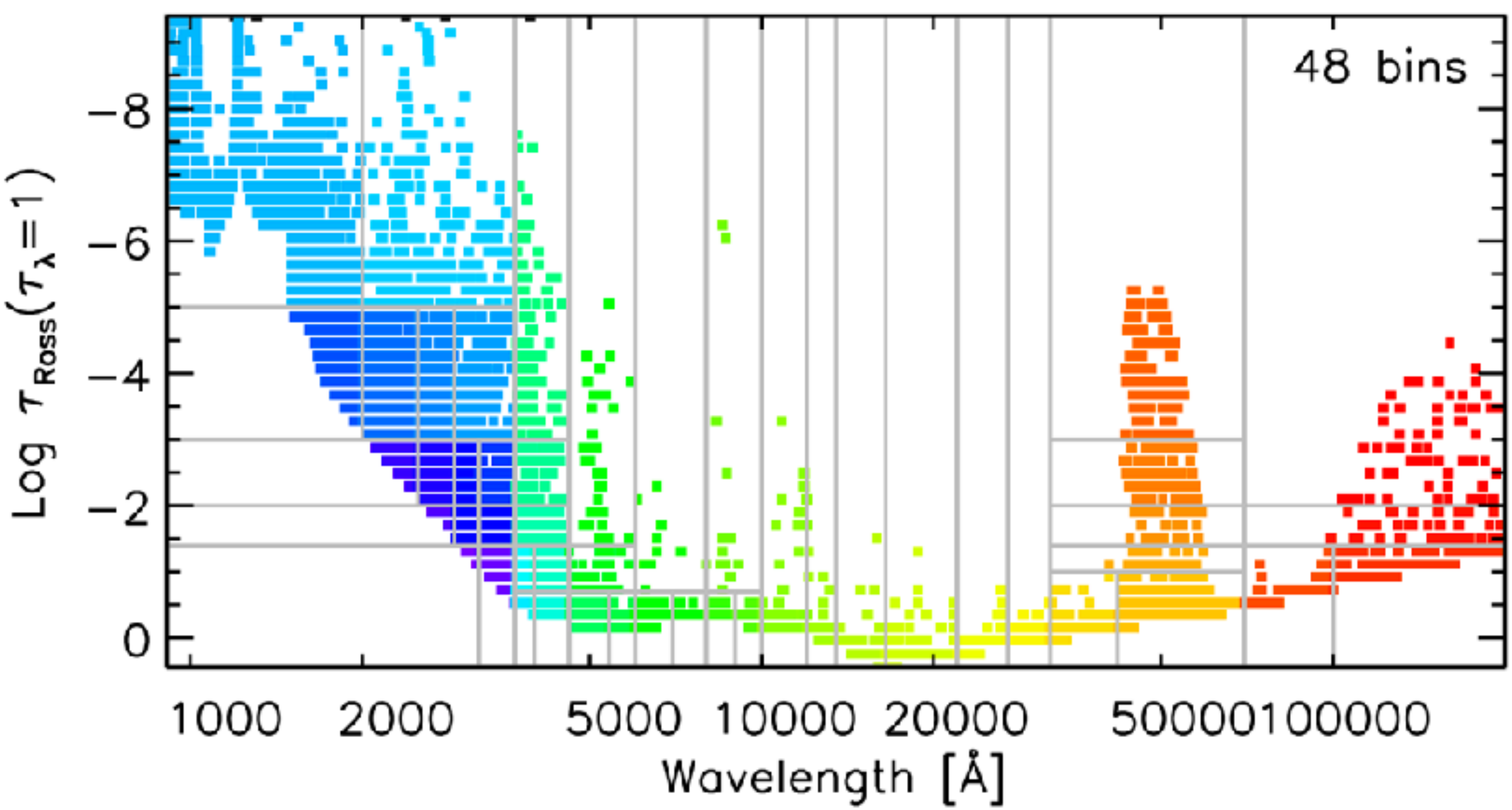
Simulations: setup and input physics

- 3D radiation-MHD code (e.g. Stagger, Nordlund et al.)
- “Box in the star”:
  - periodic horizontally,
  - constant pressure at bottom,
  - constant entropy in inflows at bottom,
  - open boundary at top
- Equation of state: Mihalas et al. 1988, updated
- Opacities: Uppsala/MARCS package (Gustafsson et al. 1975, 2008; Plez et al.)

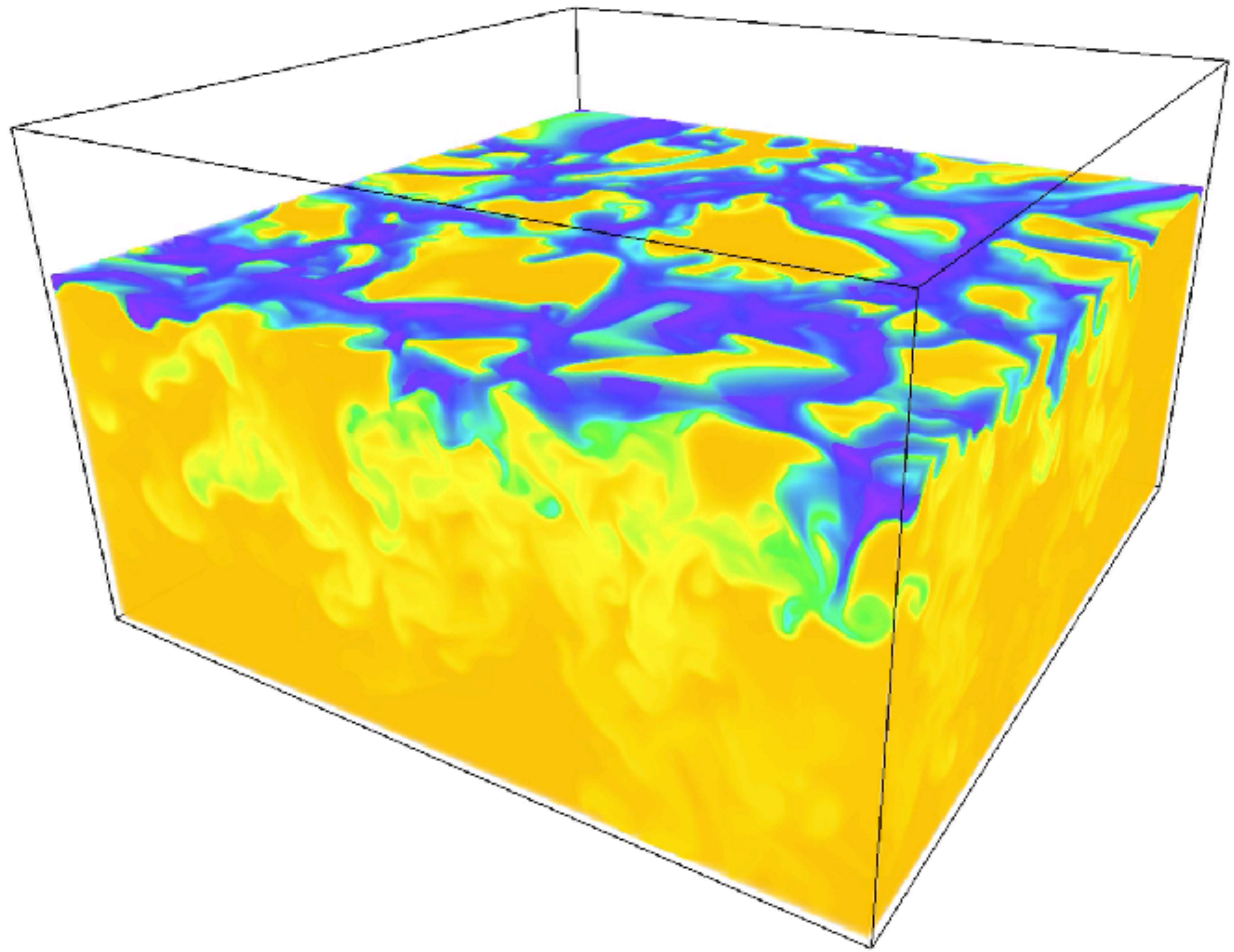


Opacity binning

- Sort monochromatic wavelengths into groups (opacity bins)
- Solve radiative transfer for average opacities and integrated source functions in bins

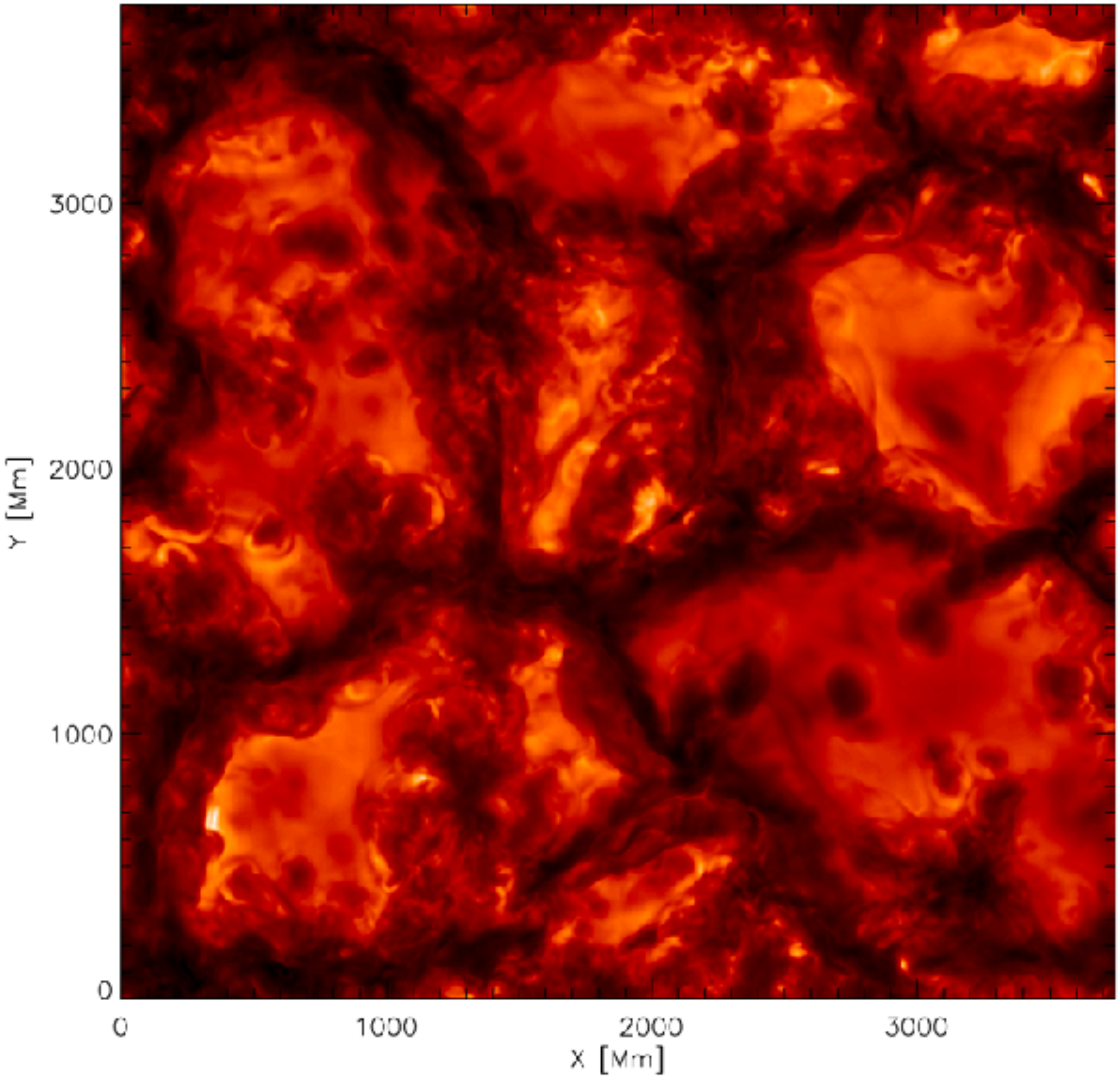


3D simulations: surface convection



Stagger-code solar surface convection simulation (R. Collet)

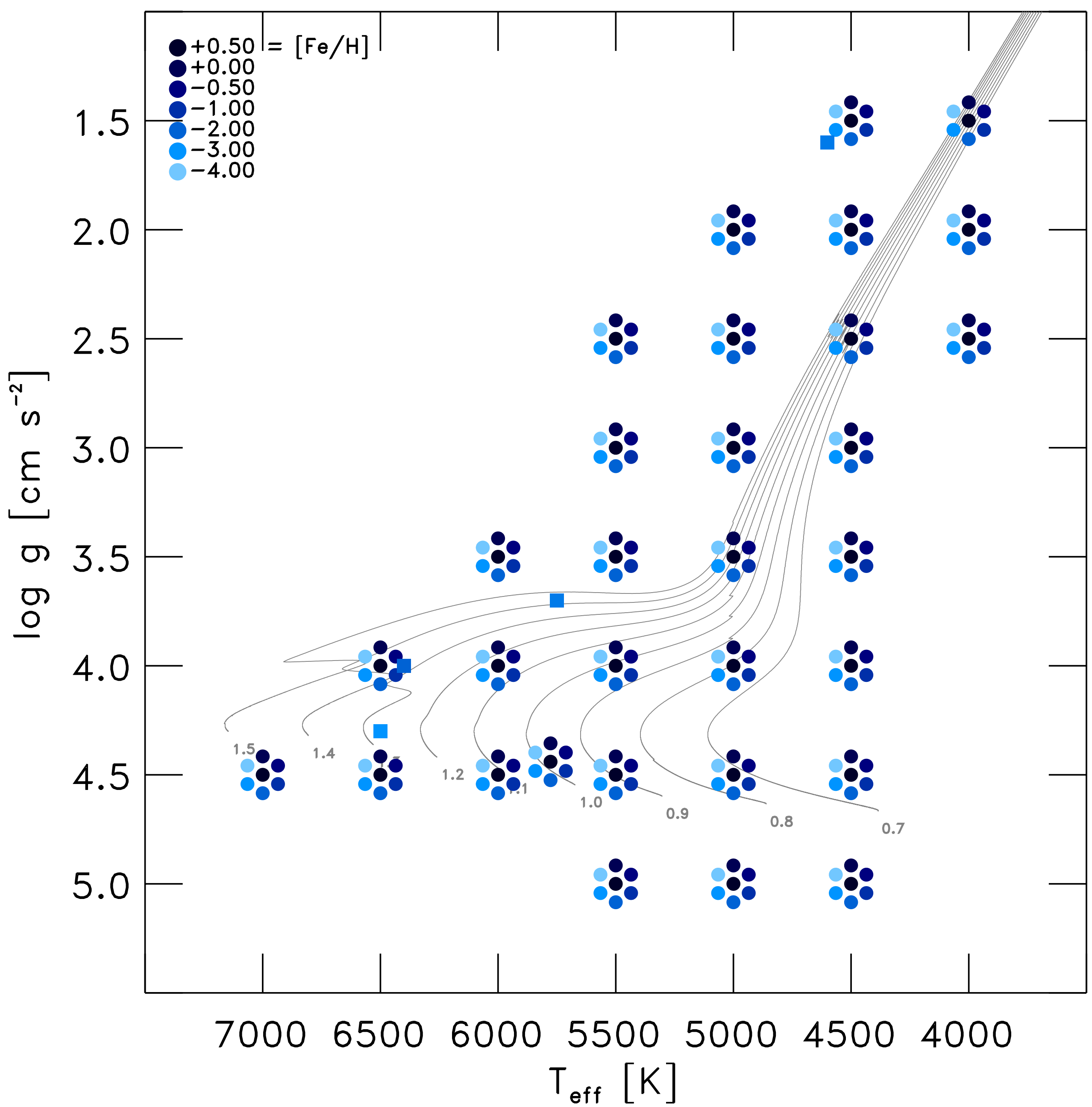
Surface intensity



HD122563 (Collet et al. 2018)

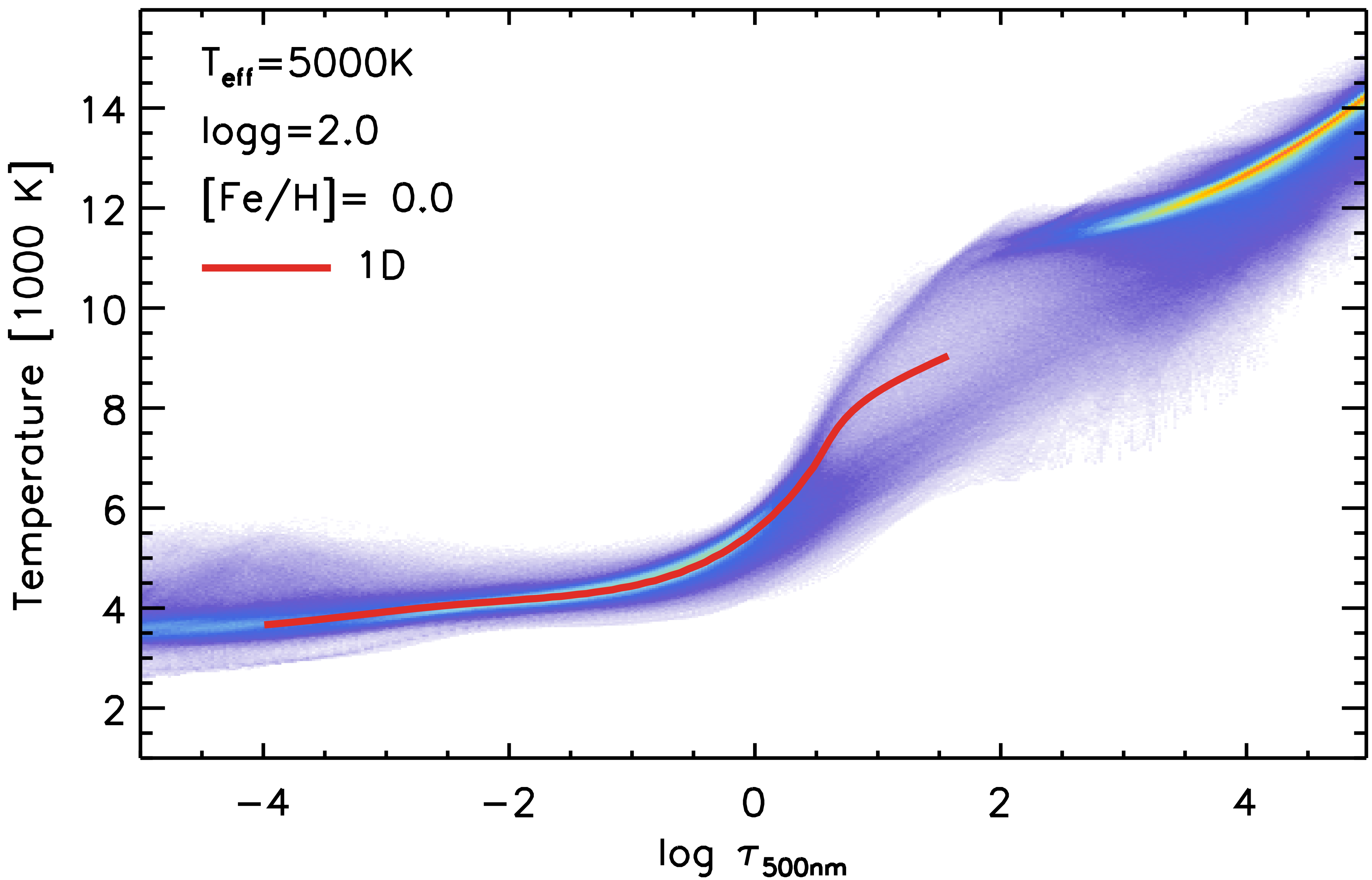
Grid of 3D simulations

- Stagger, Magic et al. (2013), Collet et al. (2011), but also Trampedach et al. 2013; CIFIST, Tremblay et al. 2013; MURaM, Beeck et al. 2013; ANTARES, Kupka et al.
- Stagger: over 200 3D surface convection simulations of FGK stars
- Systematic study of 3D-1D differences (spectroscopy and photometry)
- Calibration of MLT and improved boundary conditions for 1D stellar structure models



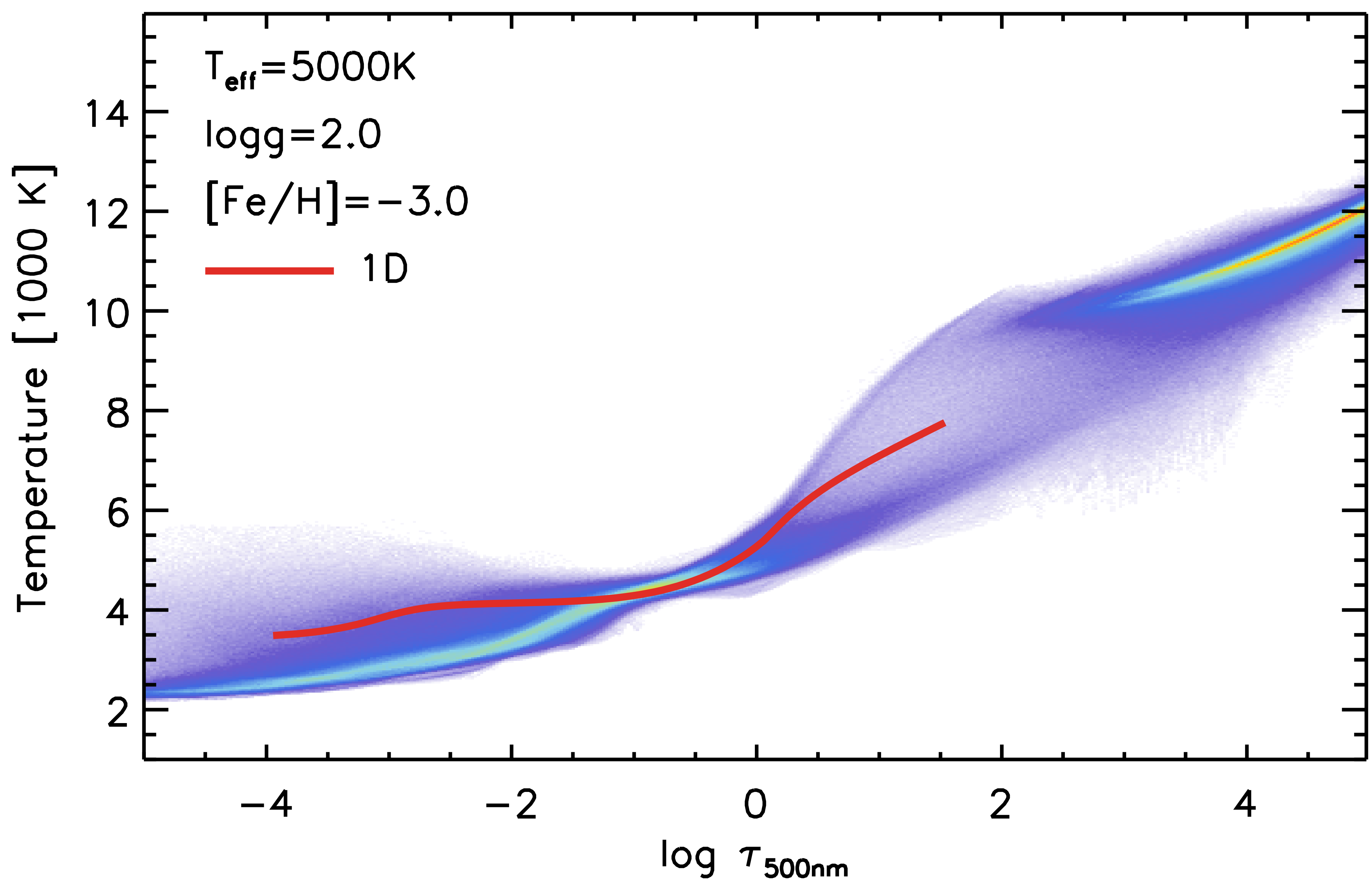
Solar metallicity

Temperature stratification vs optical depth



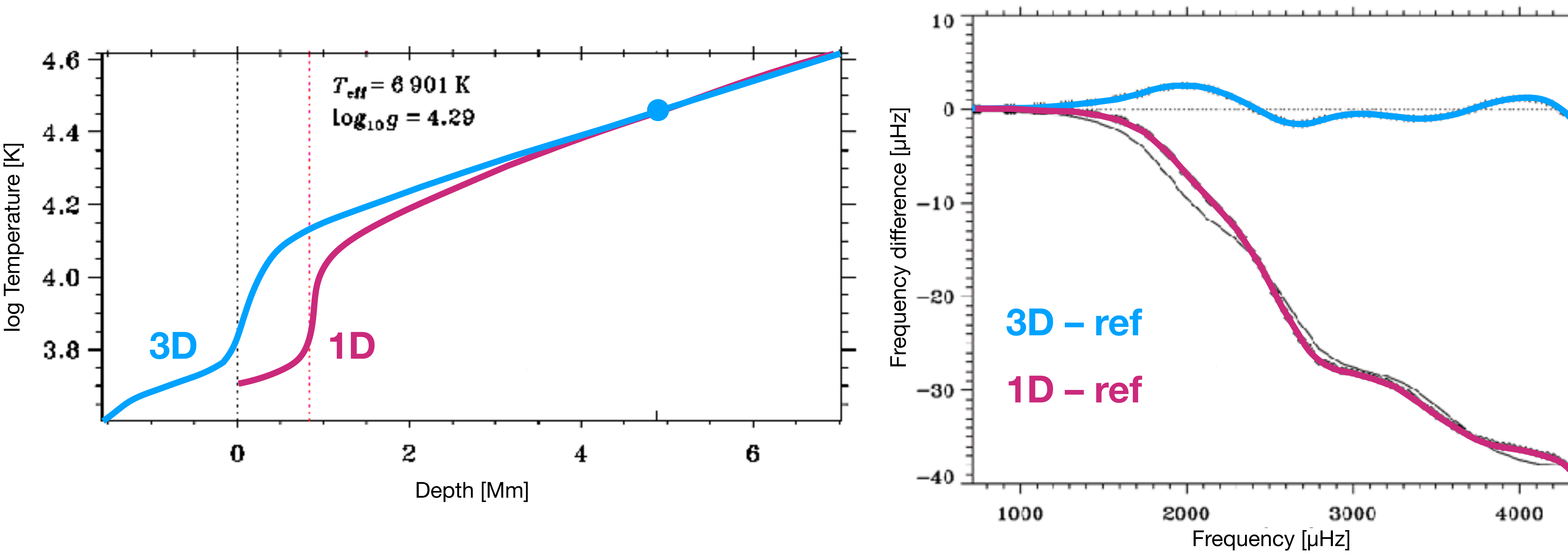
Low metallicity

Temperature stratification vs optical depth



3D structural surface effect

- 3D: convective expansion of the outer stellar layers
- Improved boundary conditions for model stellar interiors
- More accurate predictions of stellar oscillation frequencies and asteroseismic characterisation of stars

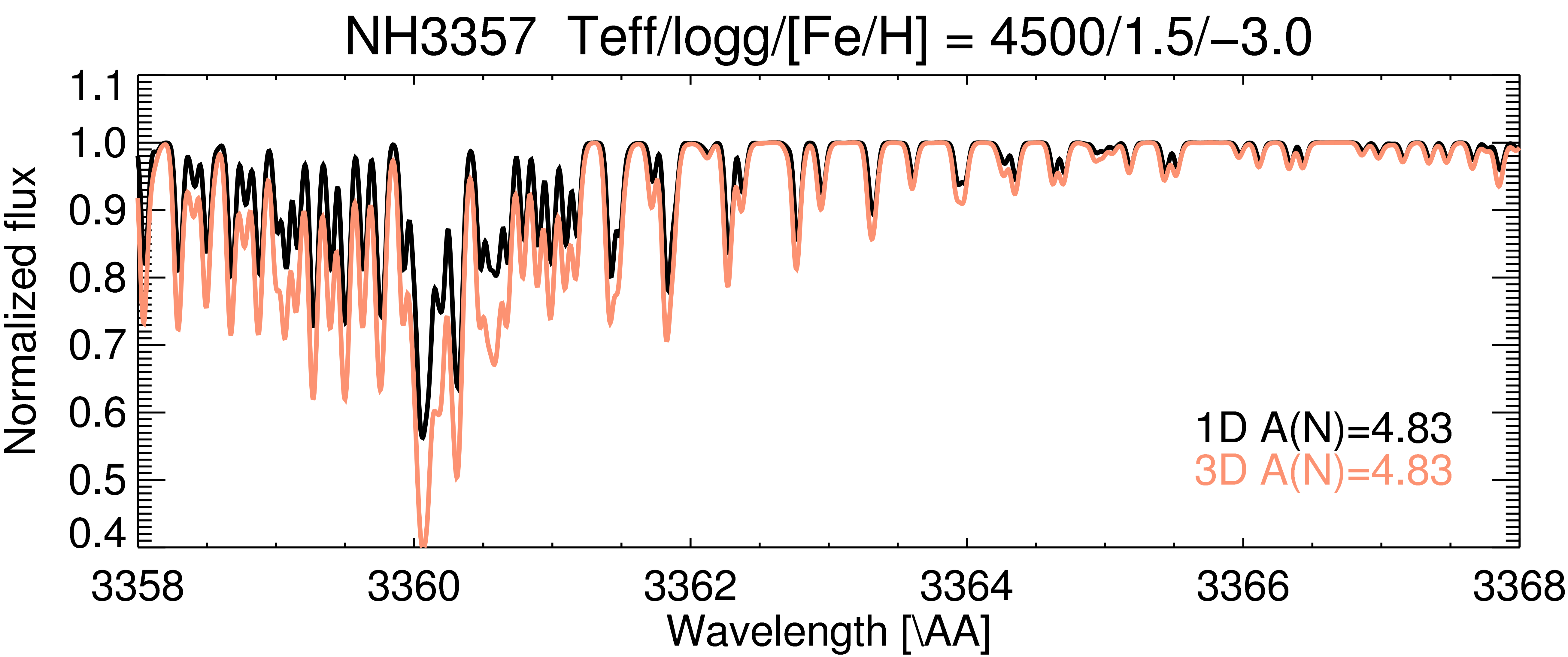


(Trampedach et al. 2017)

Molecular bands: 3D vs 1D

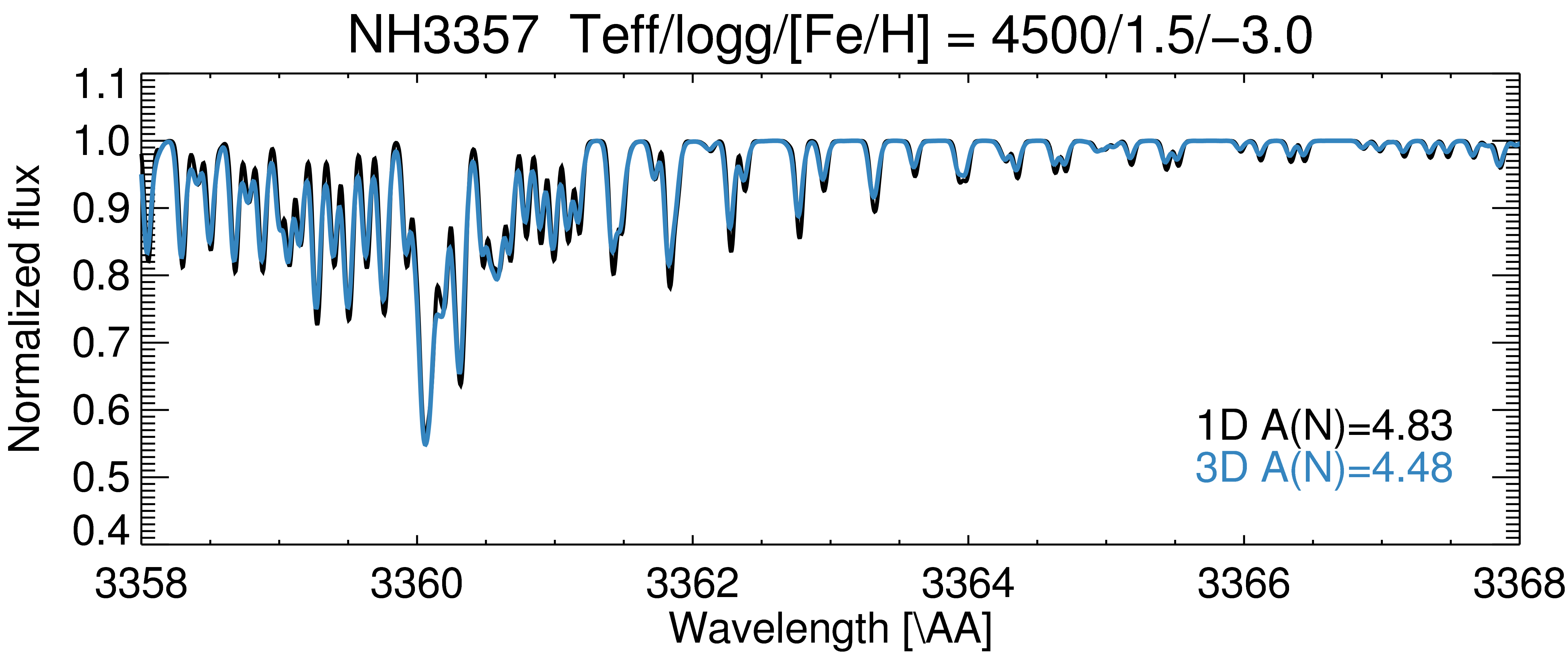
Example: NH UV band in low-metallicity red giant

3D and 1D: same nitrogen abundance



Molecular bands: 3D vs 1D

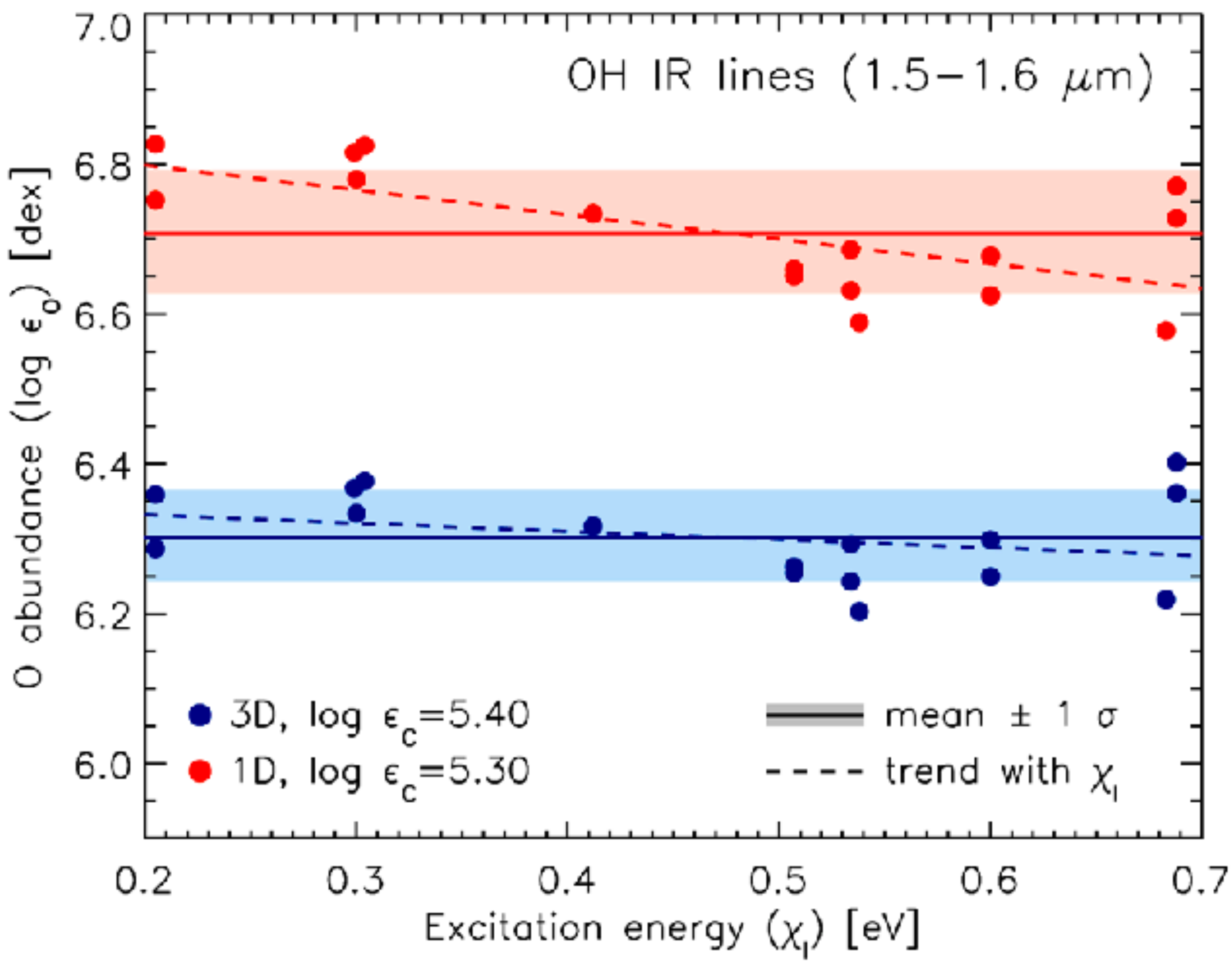
3D: lower nitrogen abundance needed to fit the band



OH IR lines: 3D vs 1D

Example: HD122563

Δ log O abundance ≈ –0.4 dex



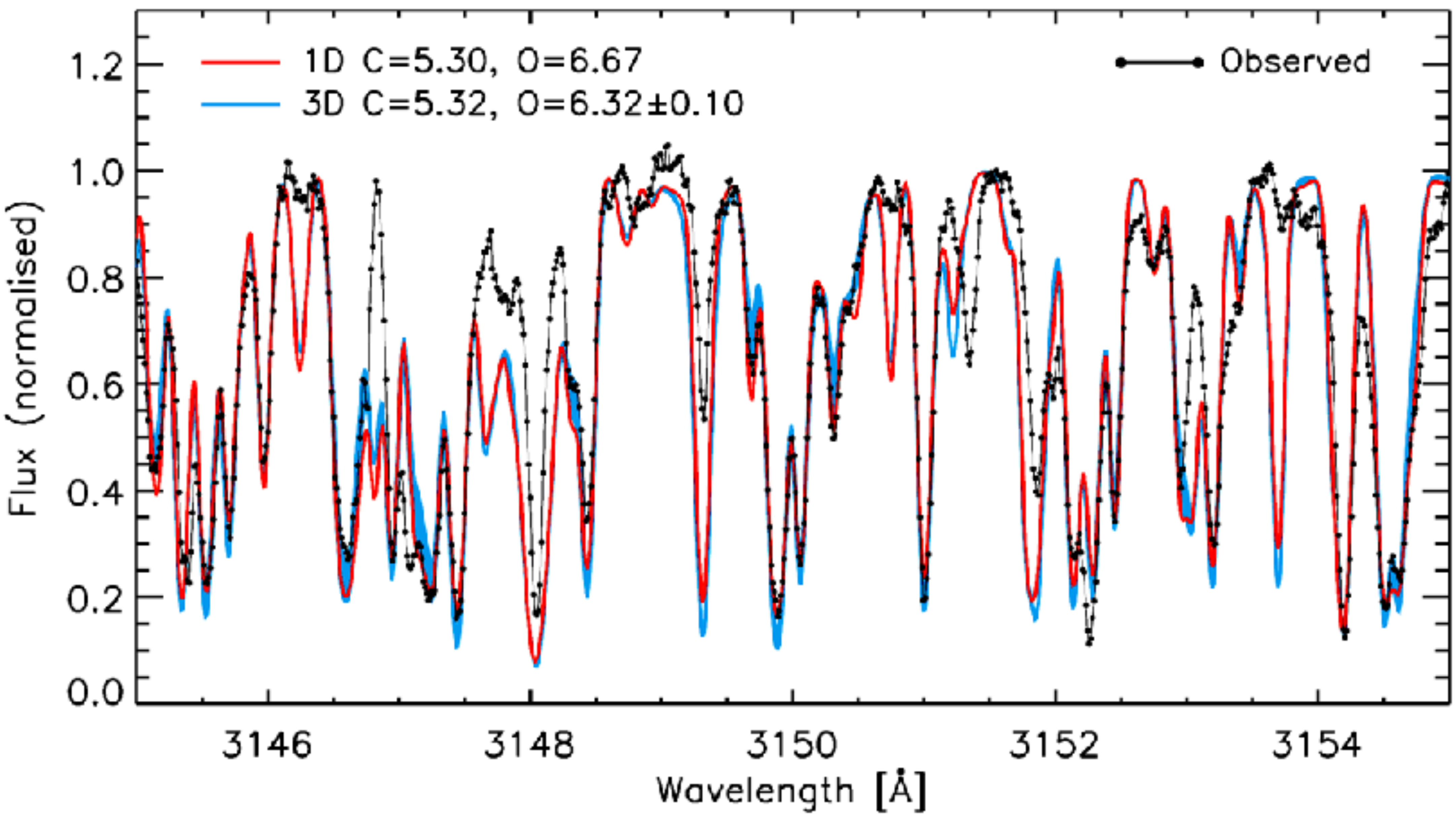
Collet et al. 2018

OH UV band: 3D vs 1D

Example: HD122563

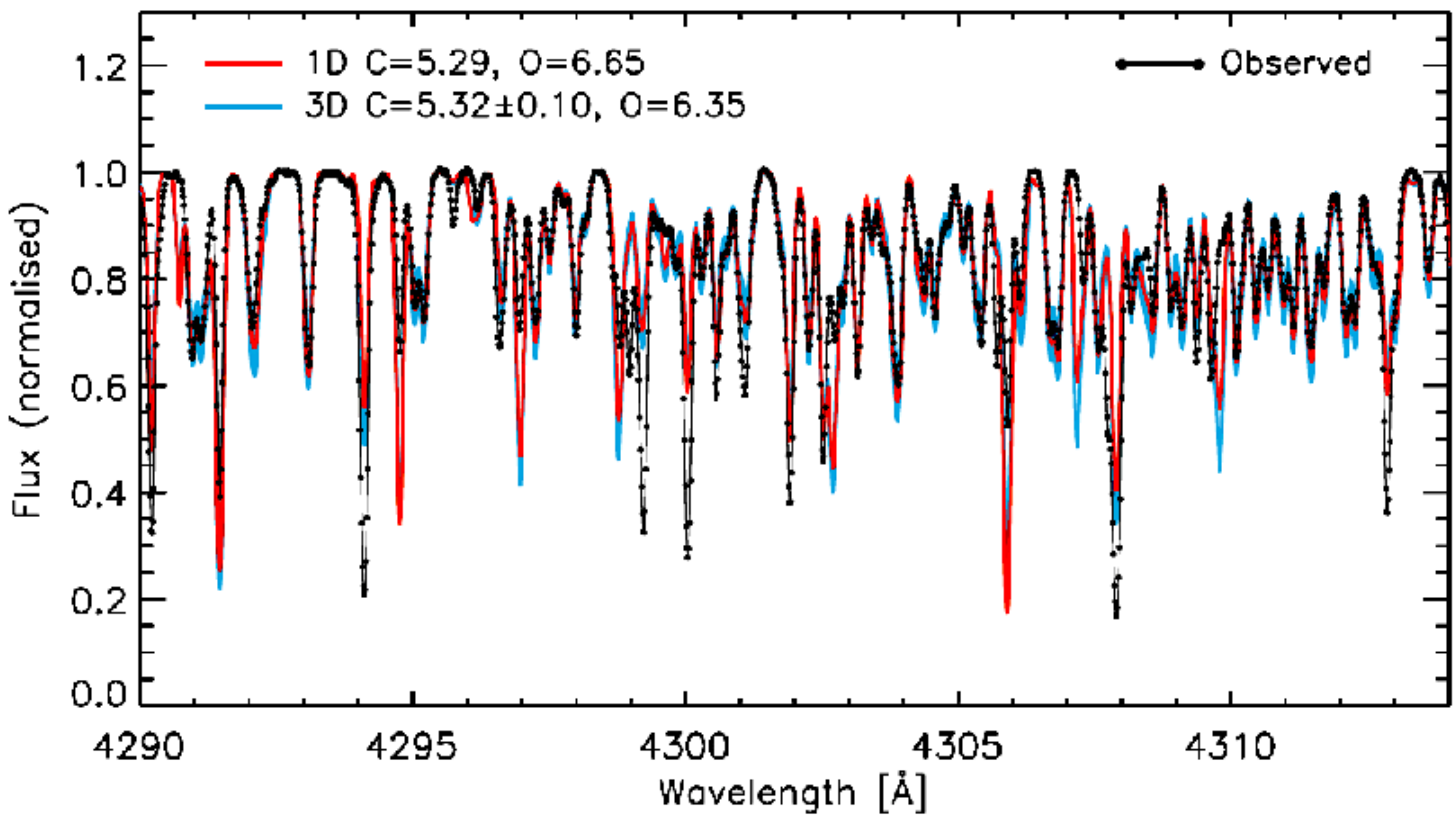
Δ log C abundance ≈ +0.03 dex

Δ log O abundance ≈ −0.35 dex

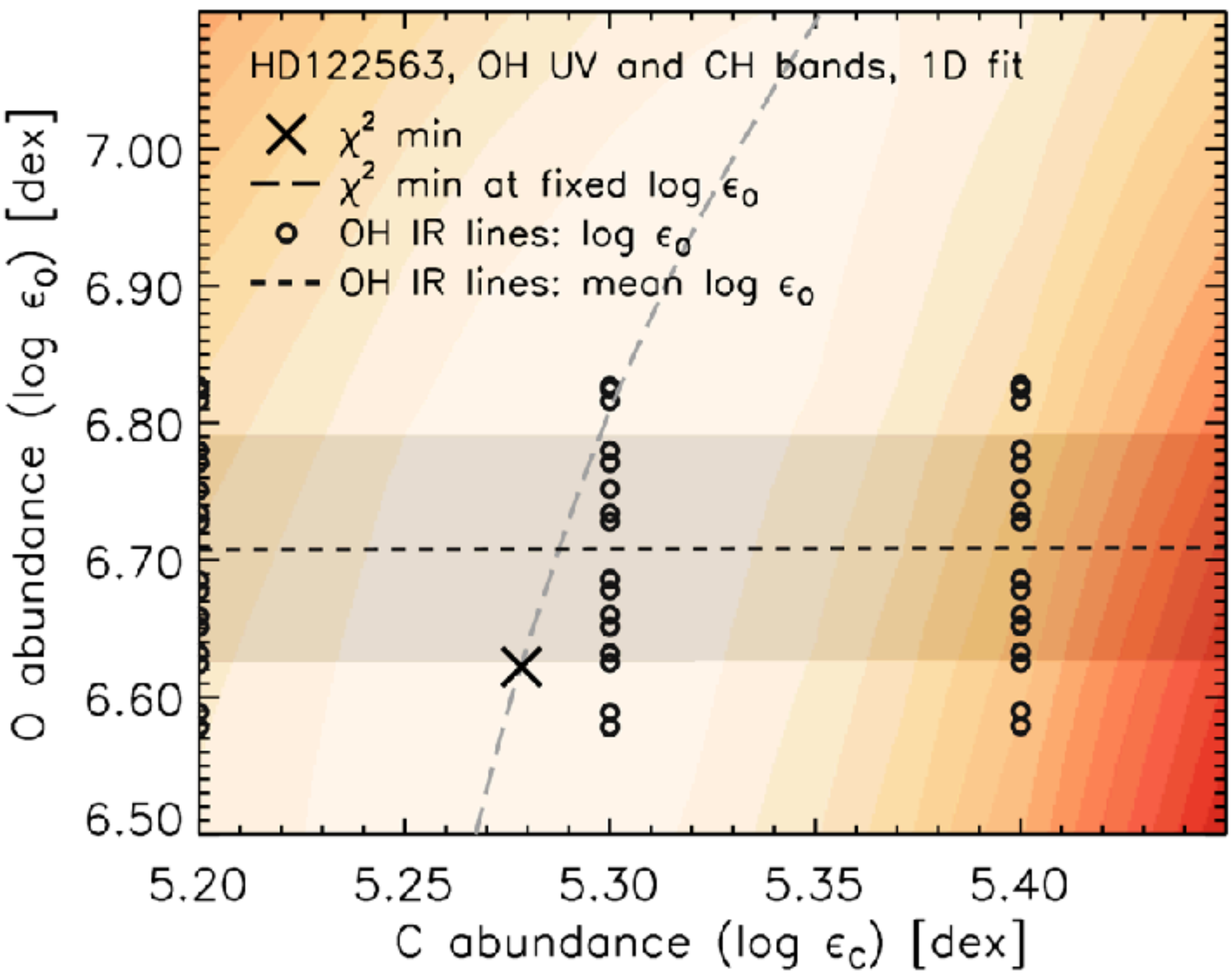


CH G band: 3D vs 1D

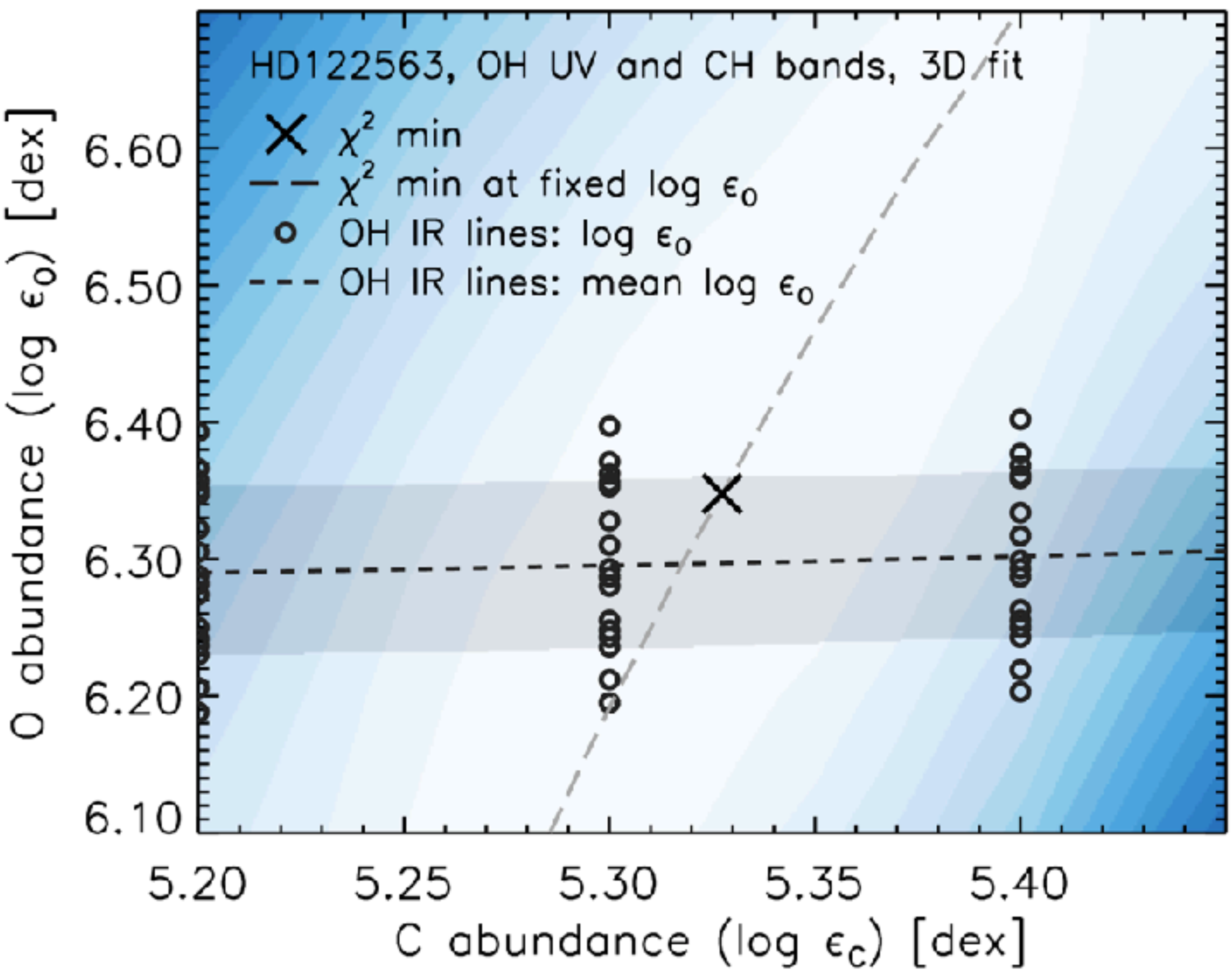
Example: HD122563
Δ log C abundance ≈ +0.03 dex
Δ log O abundance ≈ –0.30 dex



C and O abundances: 1D fit

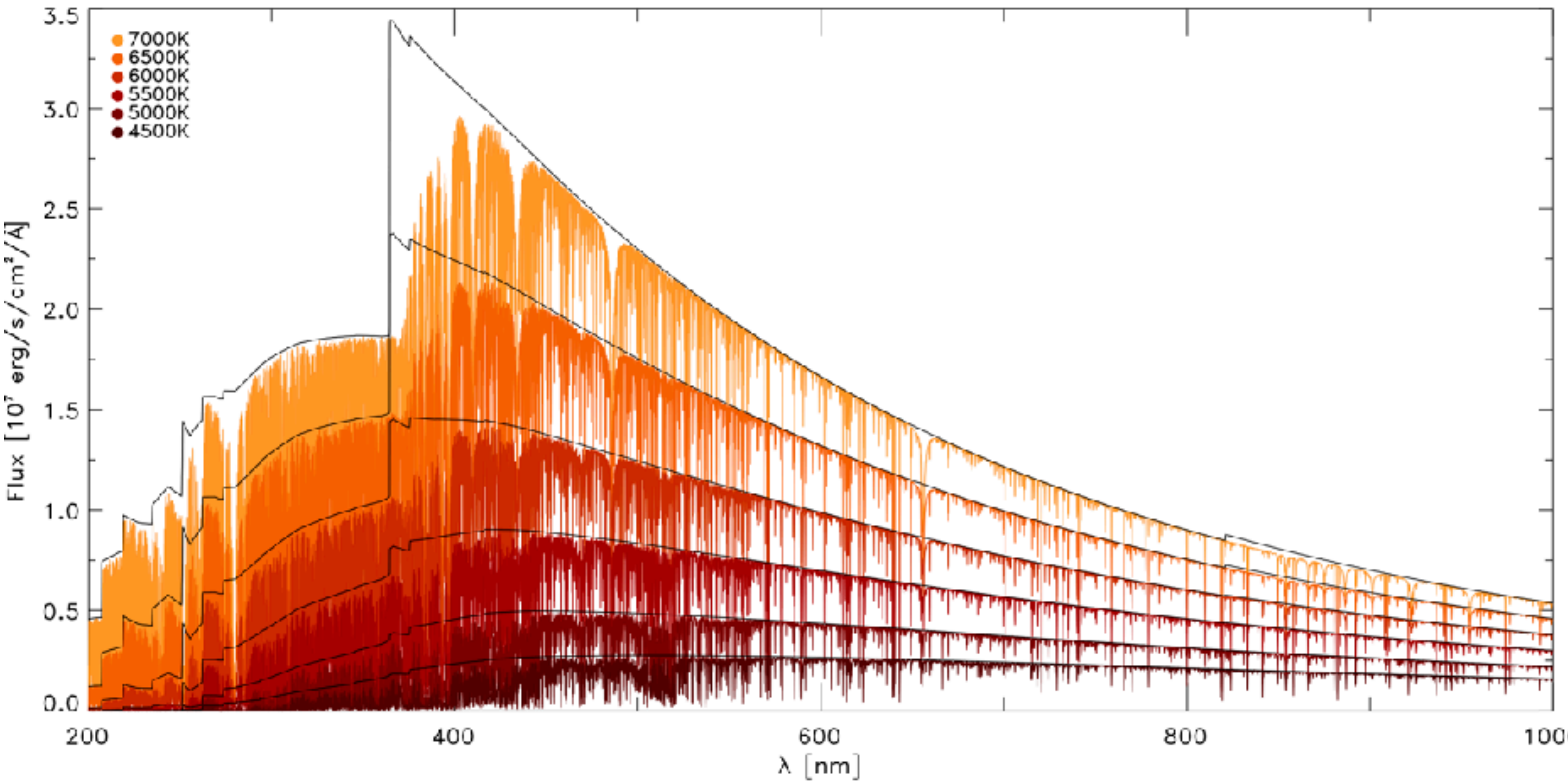


C and O abundances: 3D fit



3D synthetic fluxes

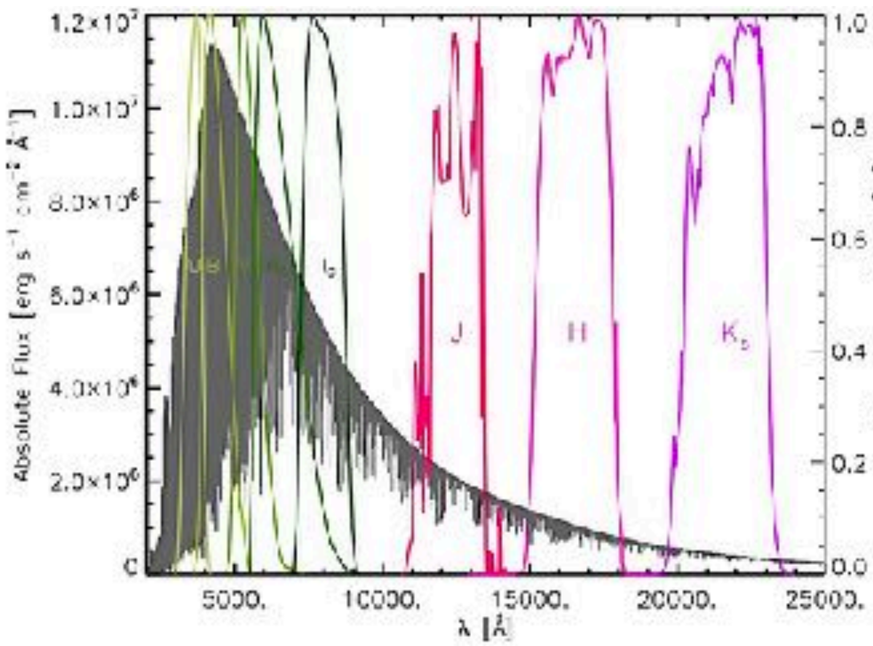
- Spectral energy distributions computed using 3D models (Magic et al. 2015; Chiavassa et al. 2018; see also Allende Prieto et al. 2013; Bonifacio et al. 2018)



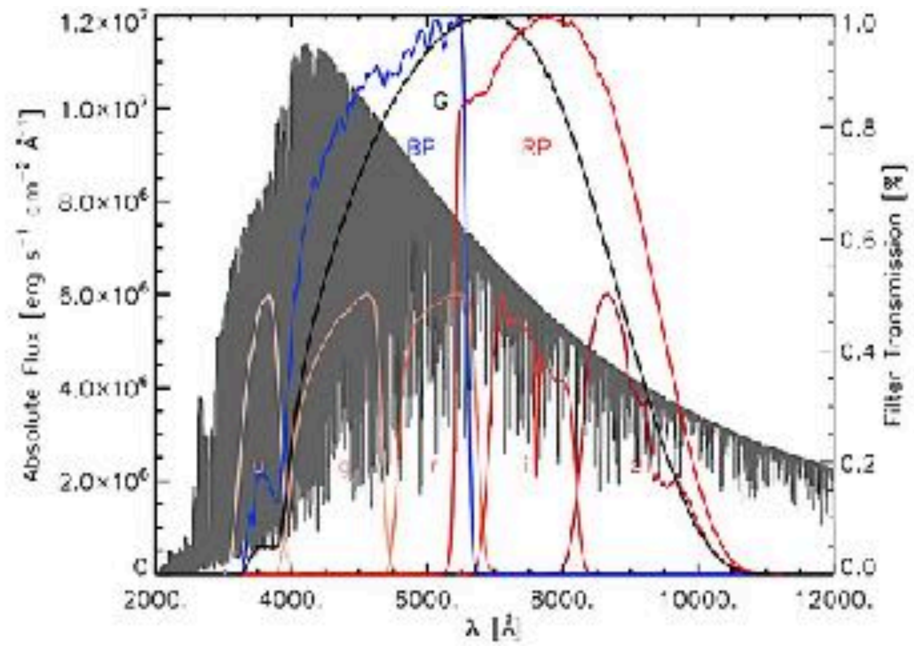
3D broad-band photometry

- 3D–1D bolometric corrections generally small: less than 5%, depending on filter, 3% for Gaia, but ~10% for SDSS u and g (Chiavassa et al. 2018)

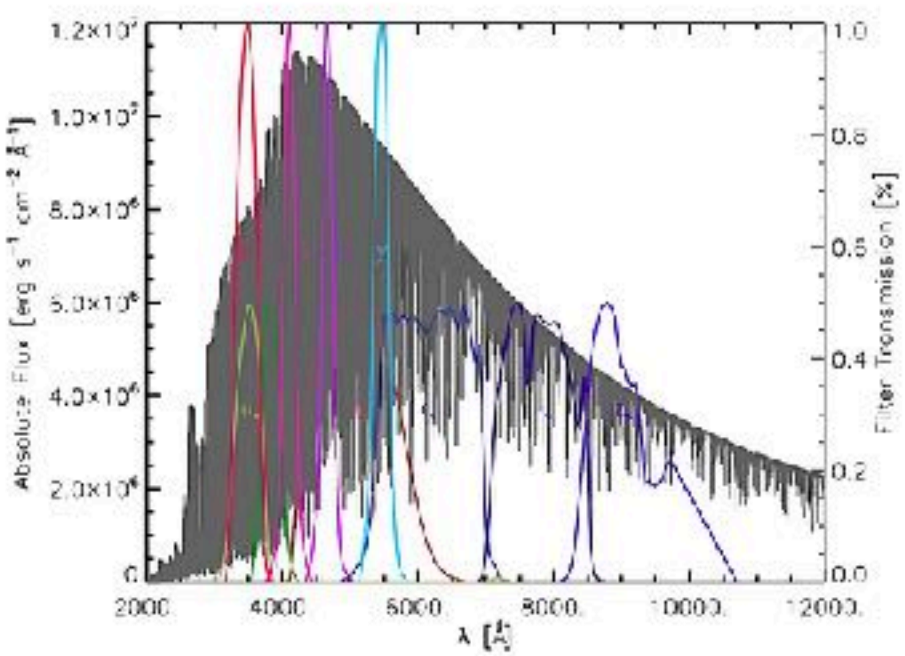
Johnsons-Cousins; 2MASS



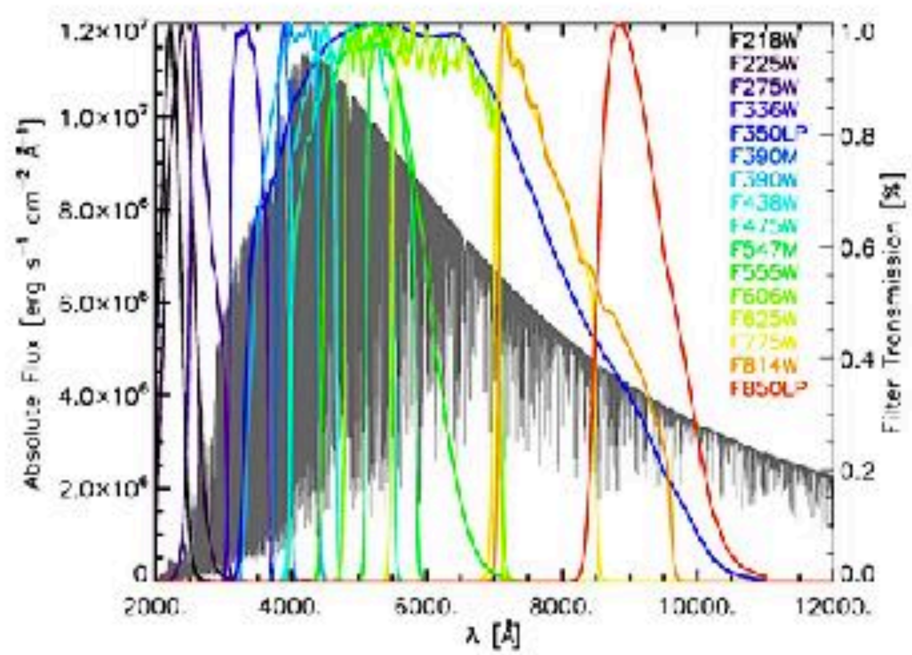
Gaia; SDSS



Strömgren; Skymapper

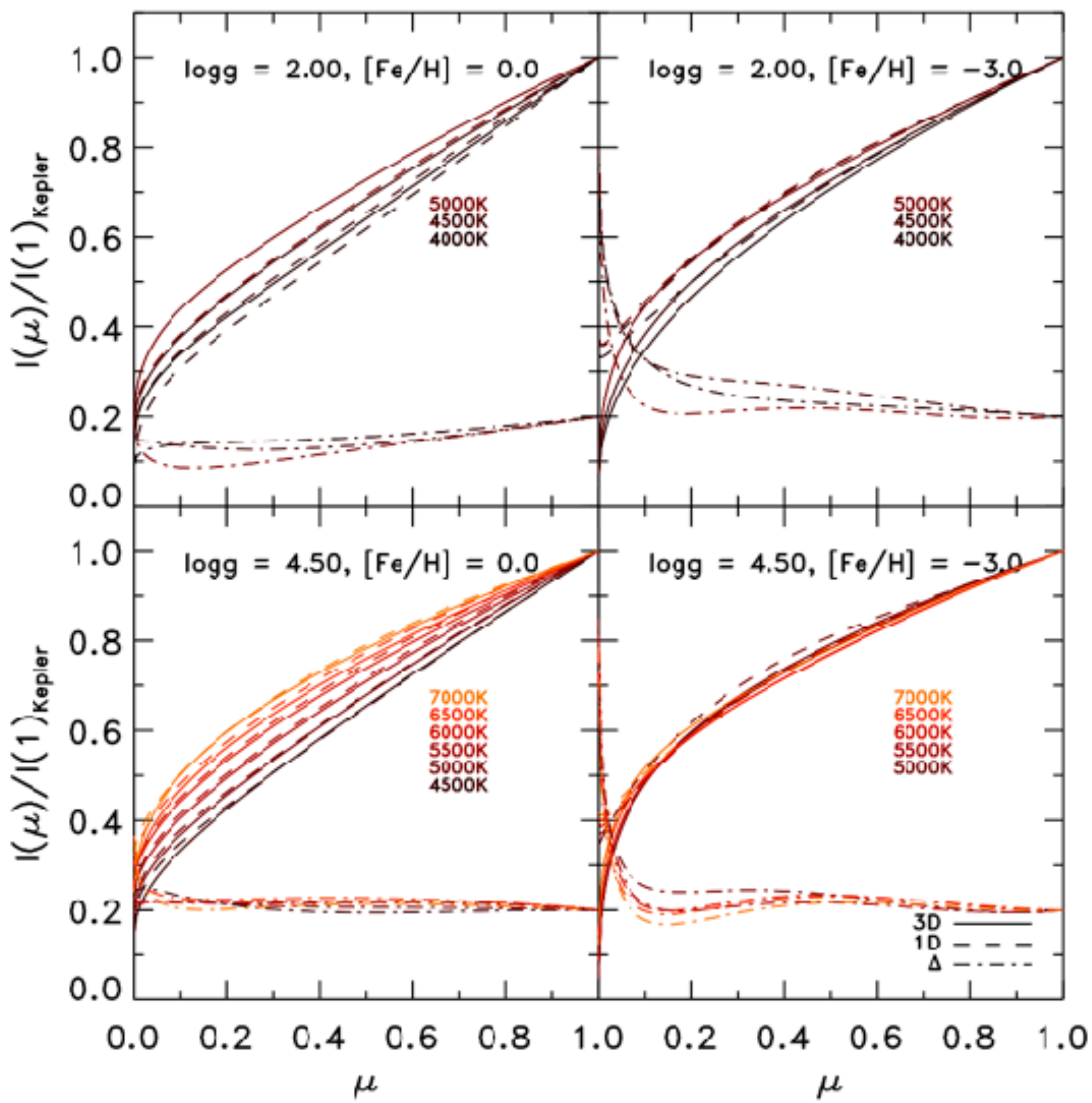


HST-WFC3



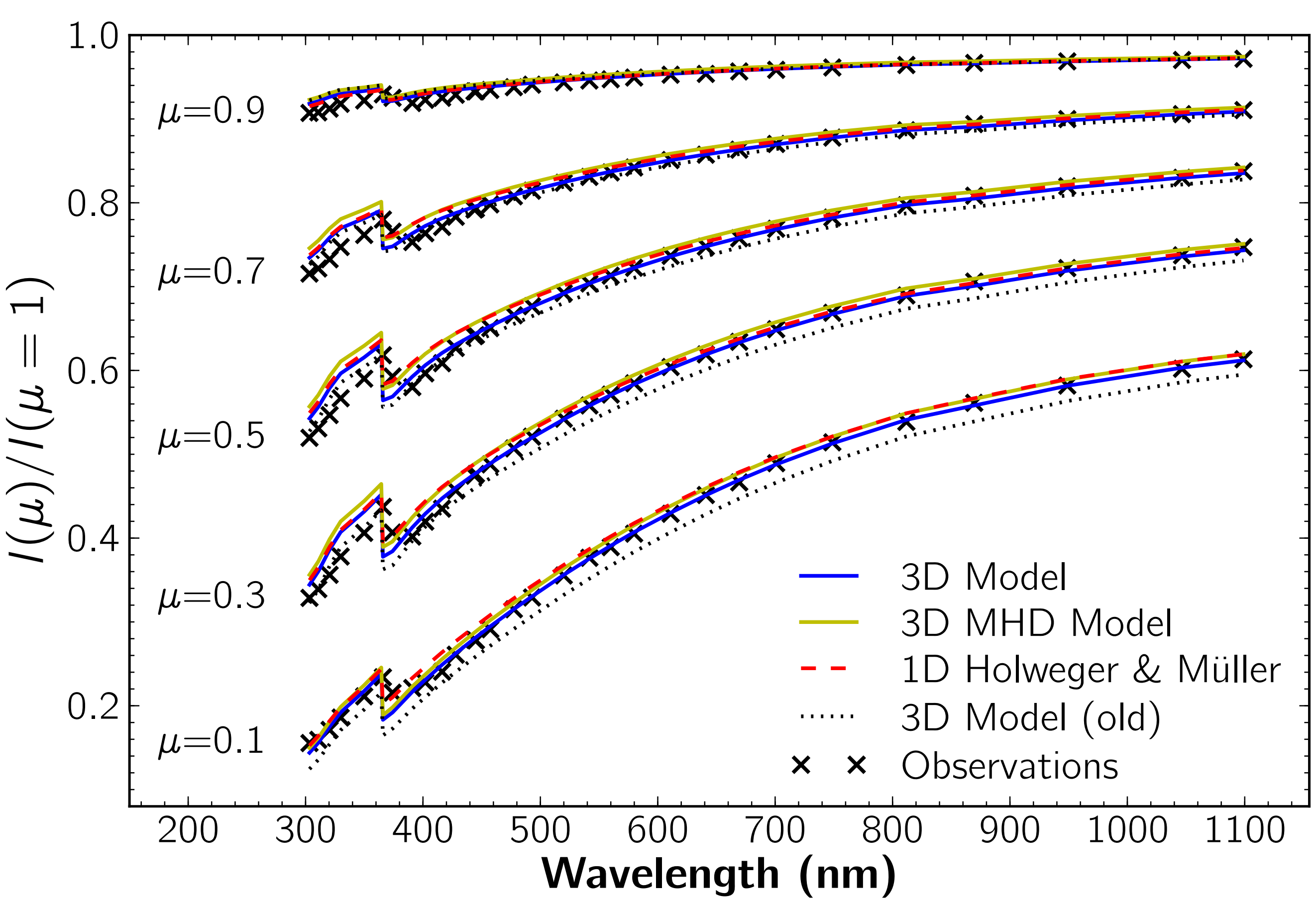
Limb darkening

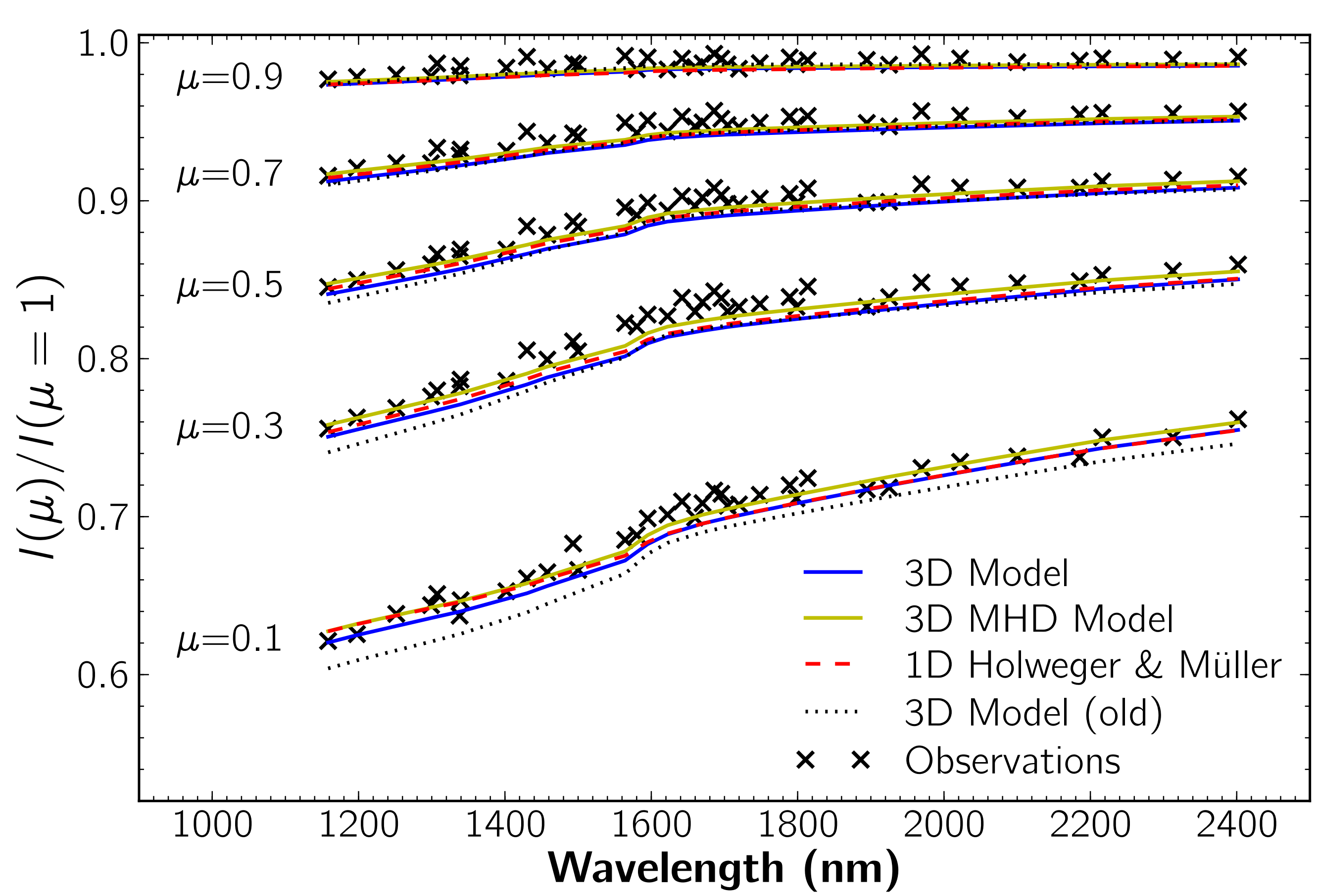
3D vs 1D centre-to-limb variations, Kepler band (Magic et al. 2015)



Limb darkening: Sun

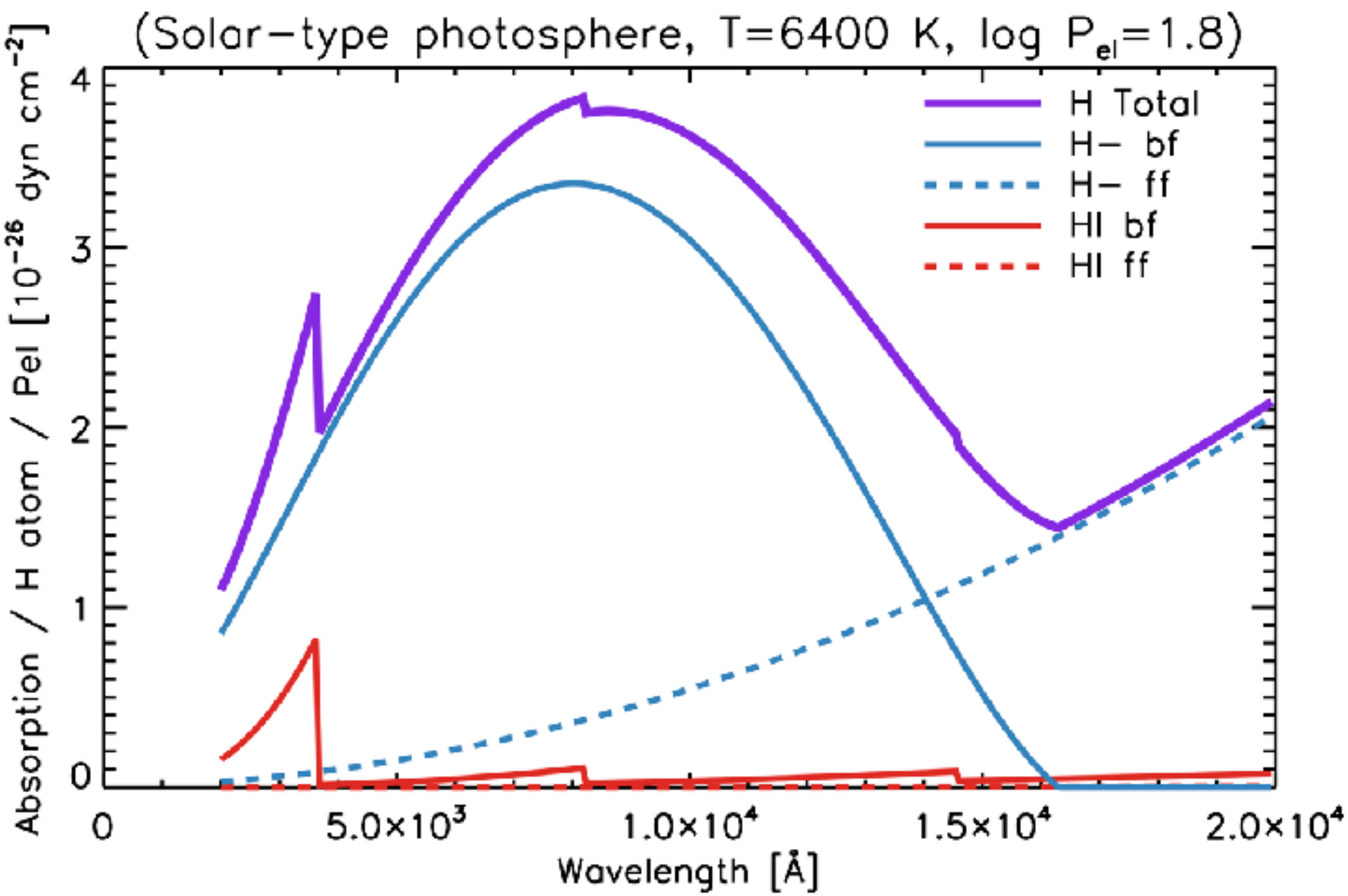
- Excellent agreement between 3D calculations and observations at UV and visible wavelengths (Pereira et al. 2013)
- Deviations at near-IR infrared





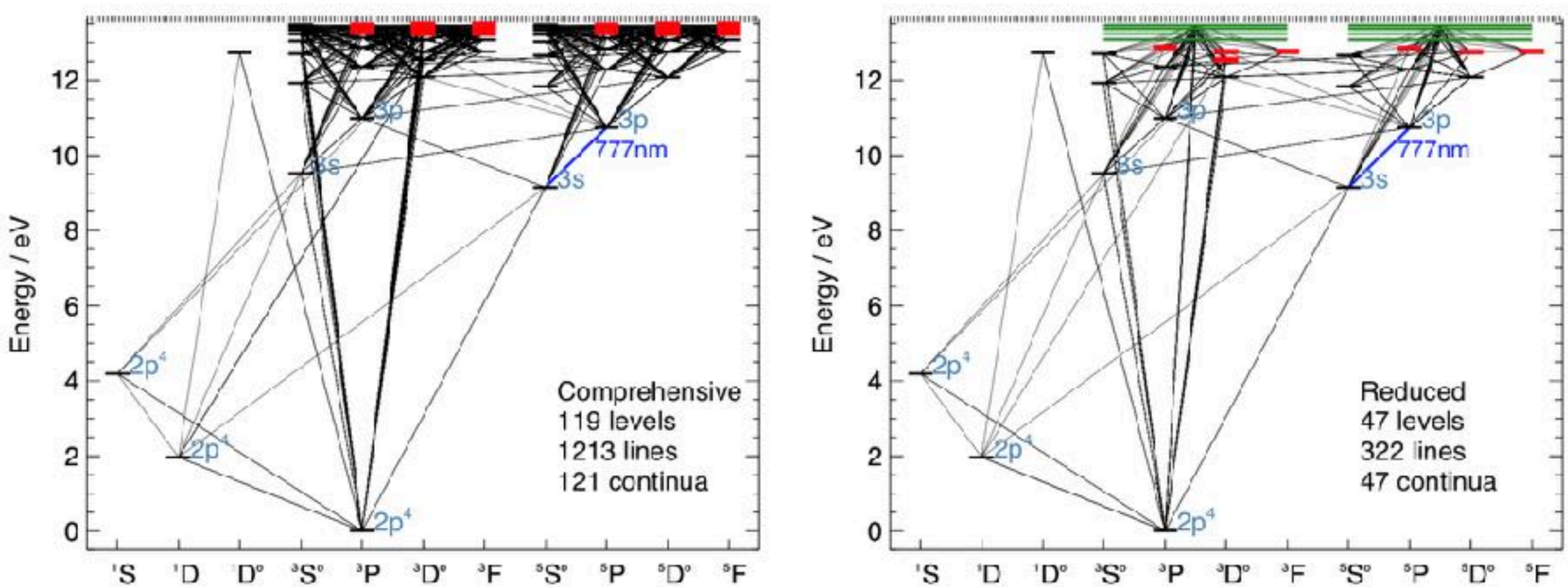
Continuous opacities

- H- bound-free: (direct/indirect) effects of departures from LTE?



3D Non-LTE spectral synthesis

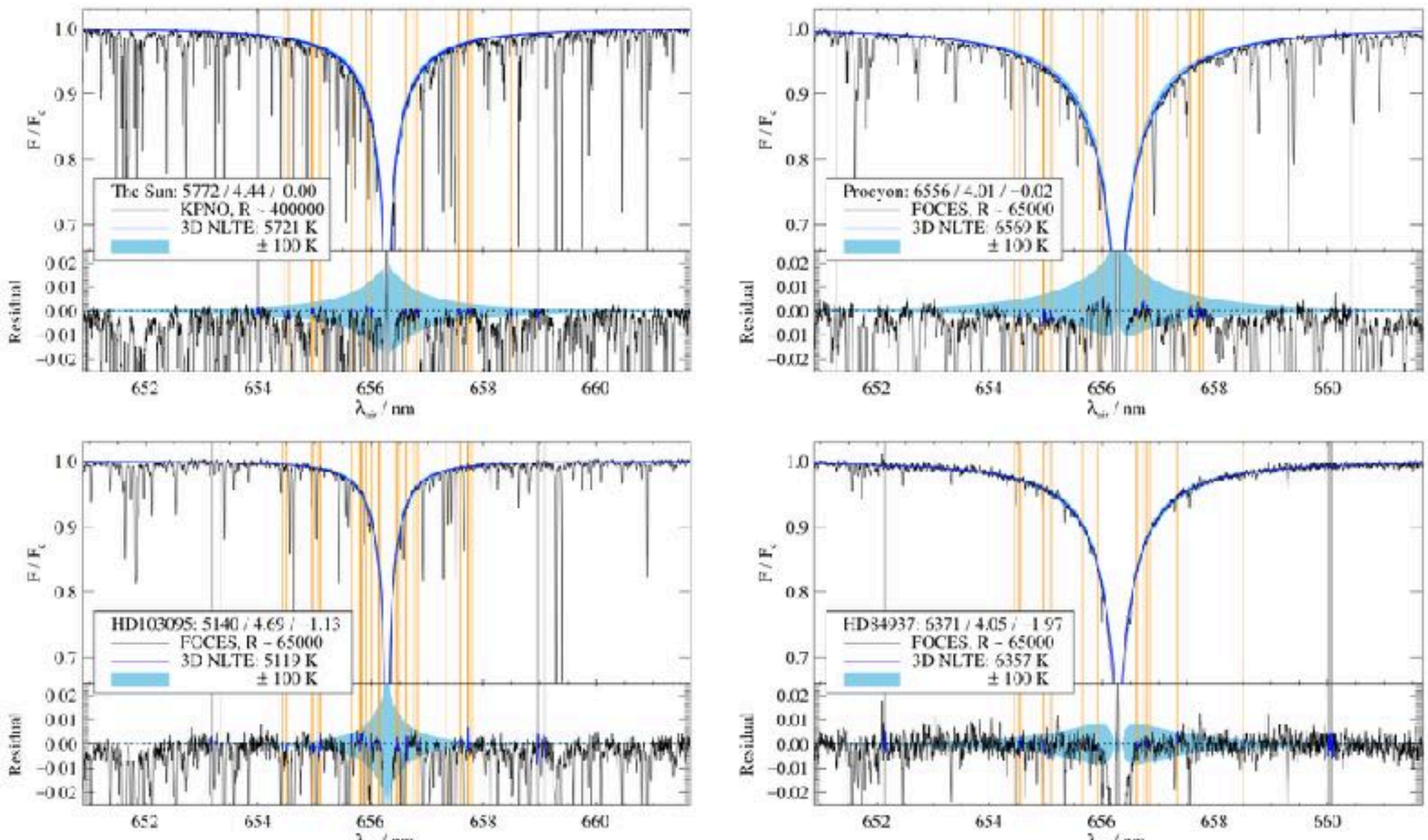
- Departure of atomic level populations and radiation field from LTE
- Statistical equilibrium, inhomogeneous 3D atmosphere
- Balder code: Multi3D variant, improved MPI and scaling to large atoms, independent opacity package (Amarsi et al. 2016, 2018)



Model oxygen atom (Amarsi et al. 2018)

Balmer lines

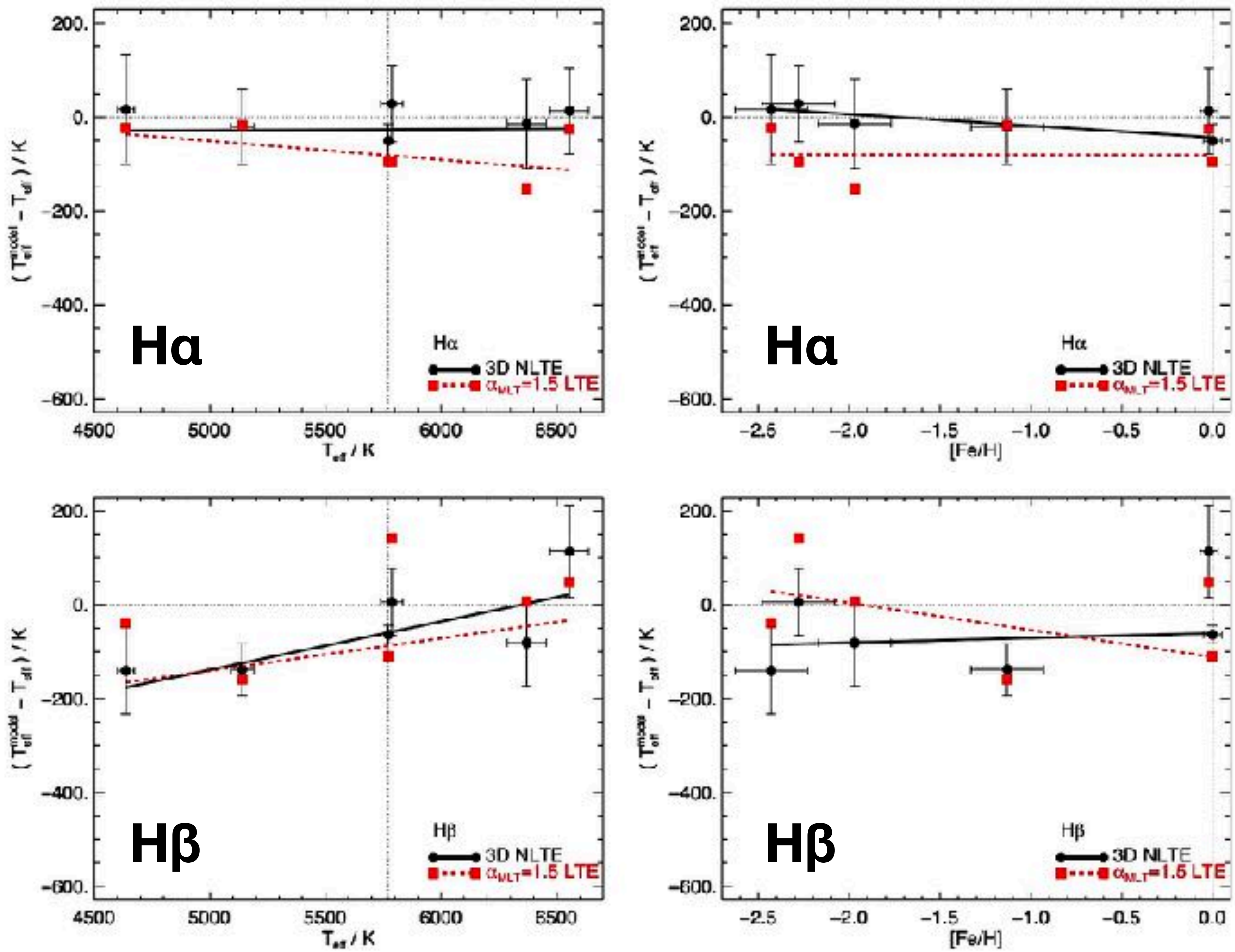
Fitting of Balmer line profiles in the spectra of benchmark stars through 3D non-LTE H spectral synthesis



Hα: Sun, Procyon, HD103095, HD84937 (Amarsi et al. 2018)

Balmer lines

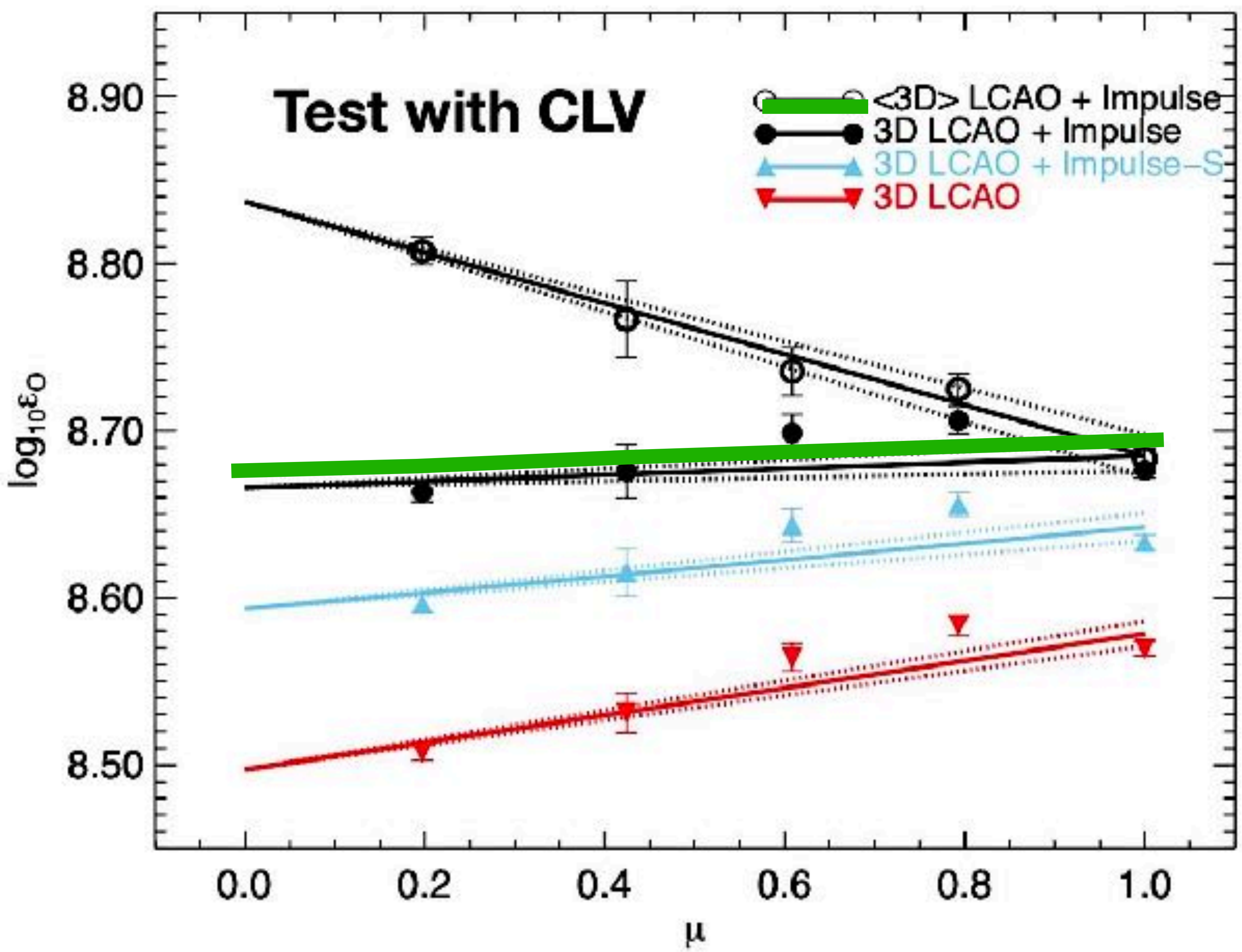
Effective temperatures from Hα and Hβ profile fitting, 3D non-LTE vs 1D LTE



Amarsi et al. 2018

Solar oxygen abundance

- 3D/<3D> non-LTE with different state-of-the-art quantum mechanical O+H collisional rates

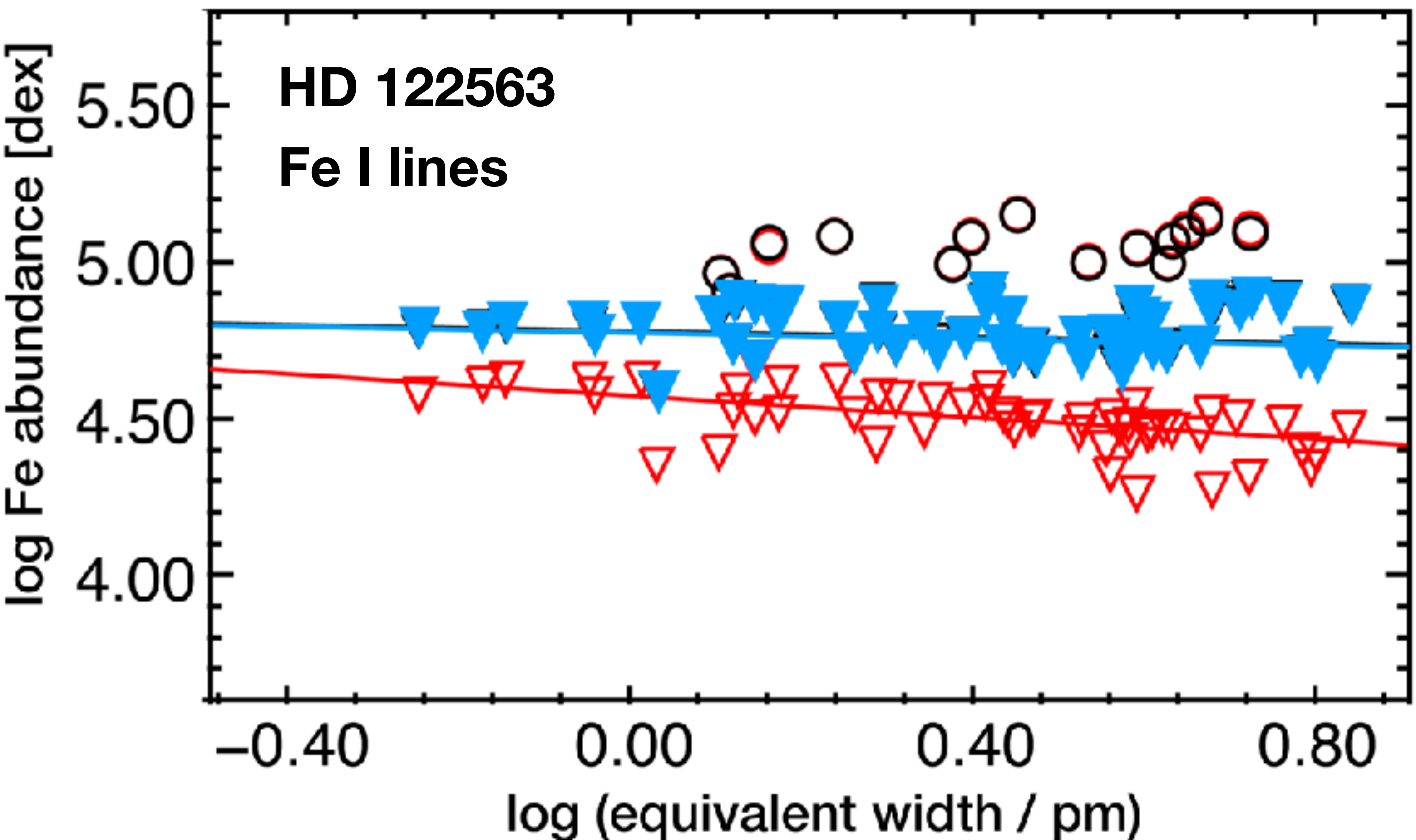


Amarsi et al. (2018)

Fe lines: 3D Non-LTE

3D LTE log Fe abundance = 4.5 dex

3D non-LTE log Fe abundance = 4.8 dex



Amarsi et al. (2016)

Summary

- Systematic differences between 3D and 1D: inhomogeneities, velocity fields, temperature gradients, expanded atmosphere
- 3D models at low metallicity: steeper and cooler upper atmospheres, significant abundance differences for molecular lines
- Importance of 3D non-LTE effects on e.g. O, Fe
- Limb darkening: very good agreement with observations but some open issues at long wavelengths (uncertainties in continuous opacities?)

Credits

WP122200 team and Stagger crew:

Remo Collet
Zazralt Magic
Martin Asplund
Regner Trampedach
Wolfgang Hayek
Aake Nordlund
Robert F. Stein
Andrea Chiavassa
Lionel Bigot
Anish Amarsi
Damian Fabbian
Yixiao Zhou
Andreas C. S. Jørgensen
Robert Cameron