Centre-to-Limb Variation Calculations with 3D Model Stellar Atmospheres

REMO COLLET
Stellar Astrophysics Centre, Aarhus University

1D model atmospheres

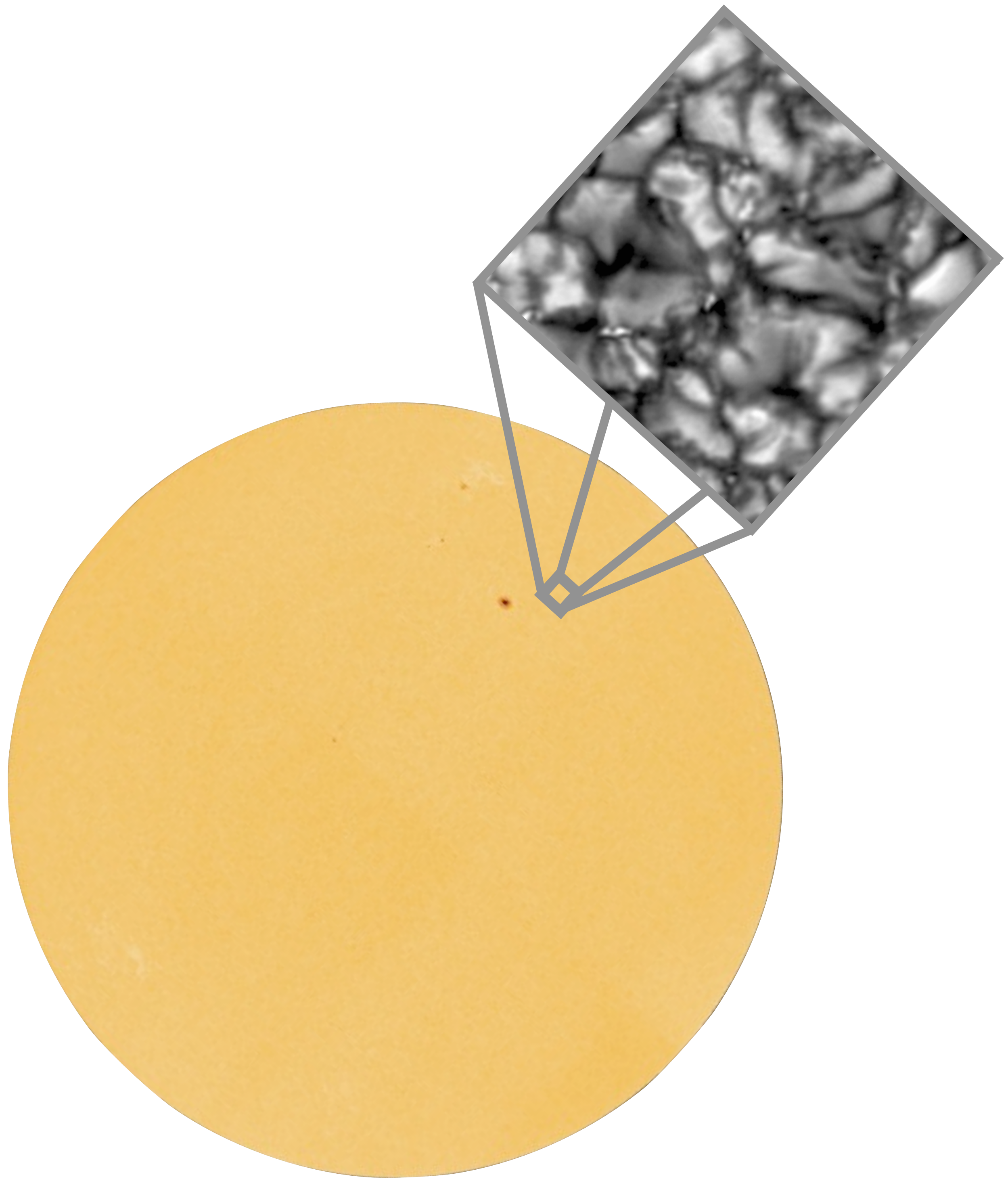
- Classical model atmospheres of FGKM stars (MARCS, Gustafsson et al. 2008; ATLAS, Kurucz 1979; NextGen/ PHOENIX, Hauschildt et al. 1999)
- 1D Homogeneous stratification
- Hydrostatic
- Stationary
- Radiative transfer: 100,000 wavelengths or more
- Convection: mixing-length theory, free parameters

3D models

- **STAGGER** (Nordlund & Galsgaard 1995; Collet et al. 2018); CO5BOLD (Freytag et al. 2012); MURaM (Vögler et al. 2005)
- 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

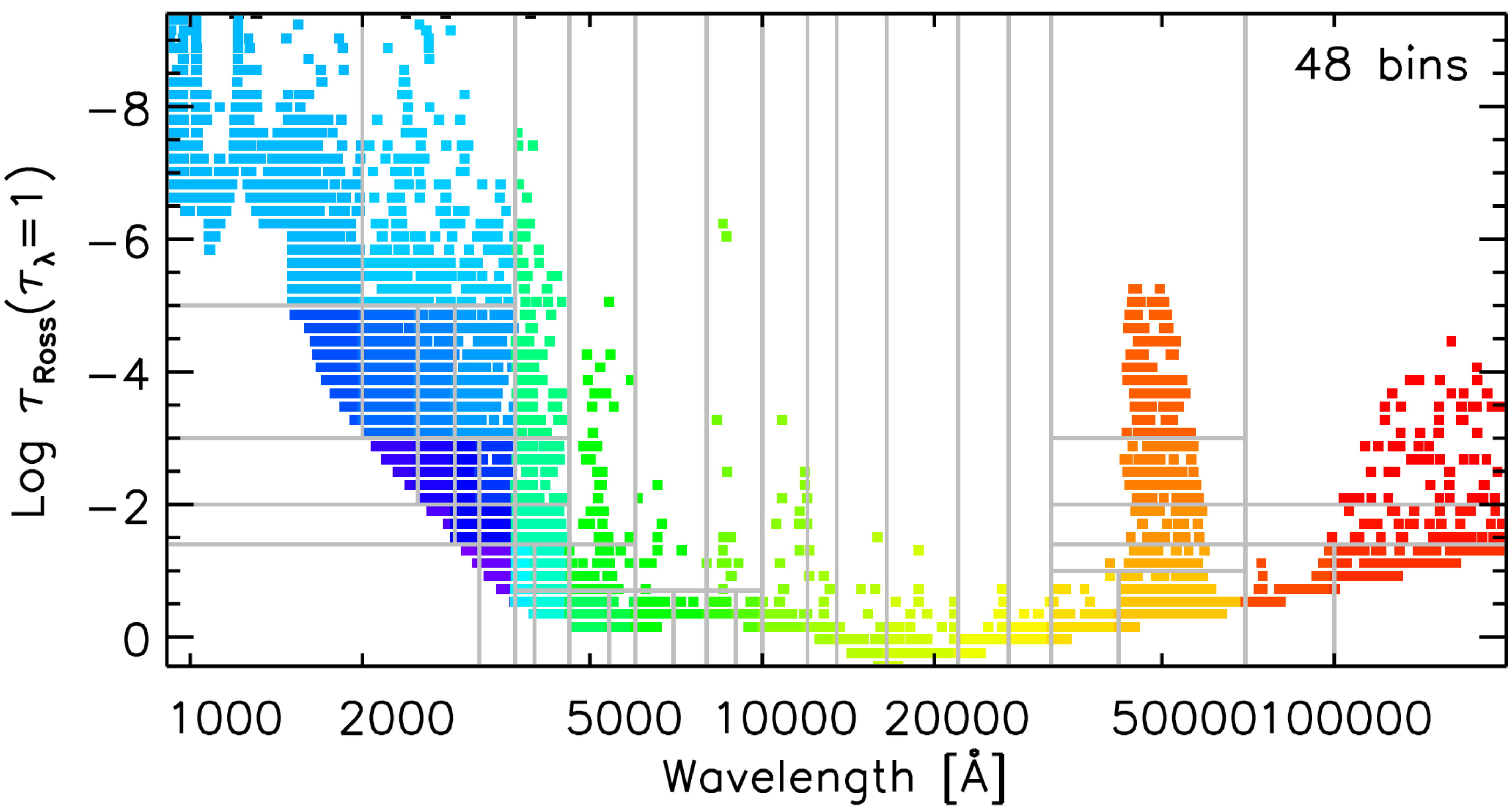
Simulations: setup and input physics

- “Box in the star”
- Equation of state: Mihalas et al. 1988 with updates
- Opacities: Uppsala/MARCS package (Gustafsson et al. 1975, 2008; B. Plez et al.)
- Radiative transfer: ~10-20 inclined rays per surface point

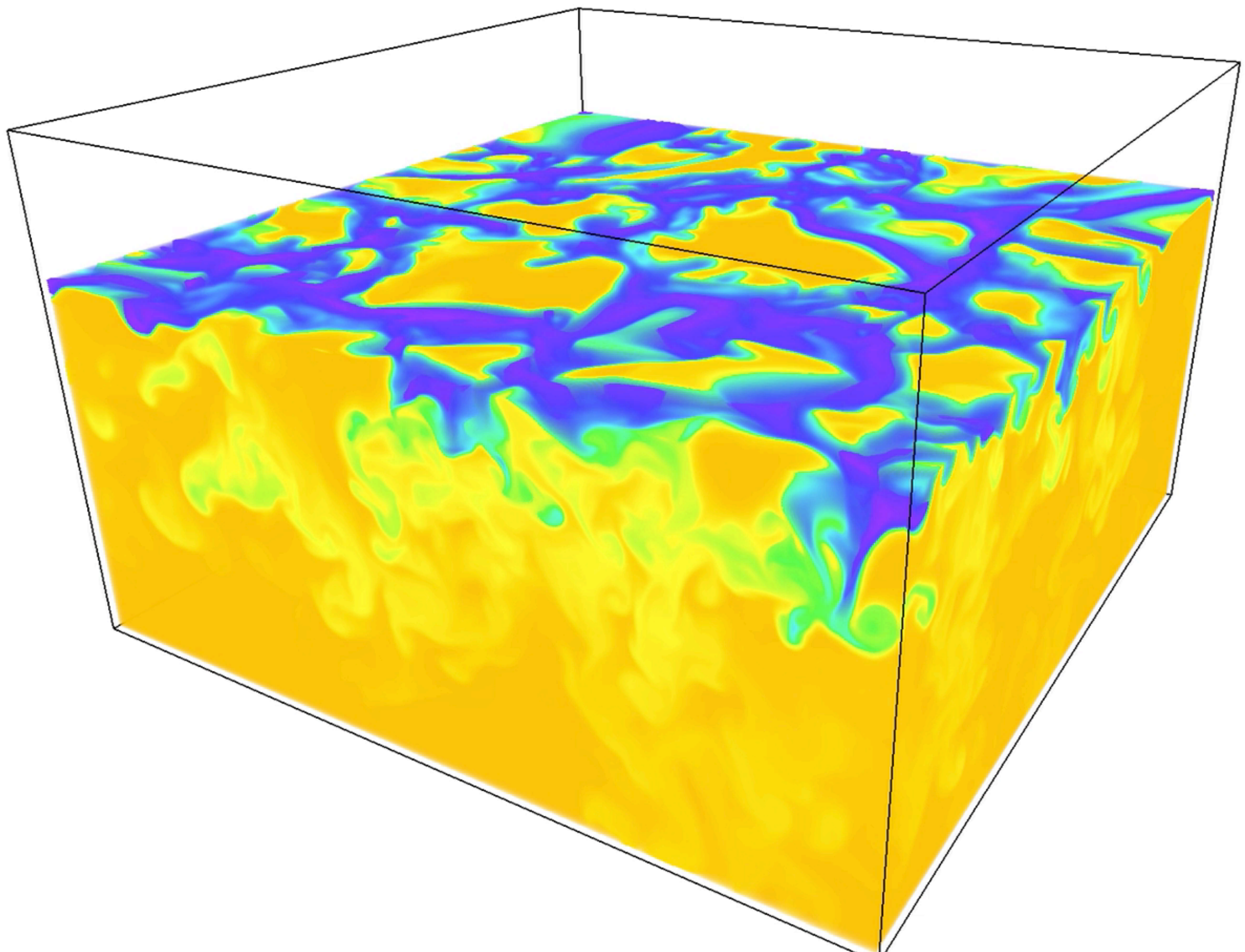


Opacity binning

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

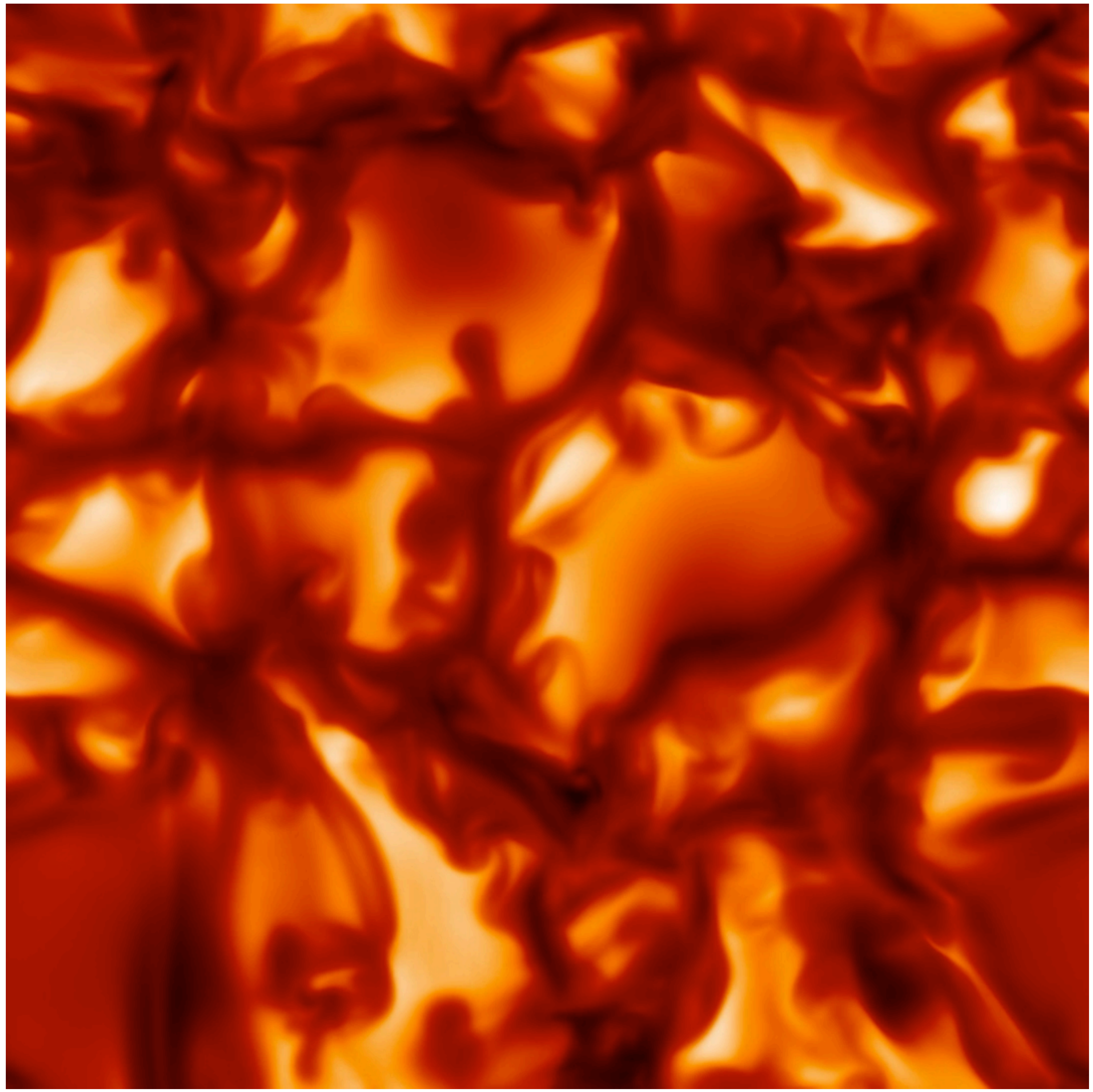


3D simulations: surface convection



STAGGER solar surface convection simulation (R. Collet)

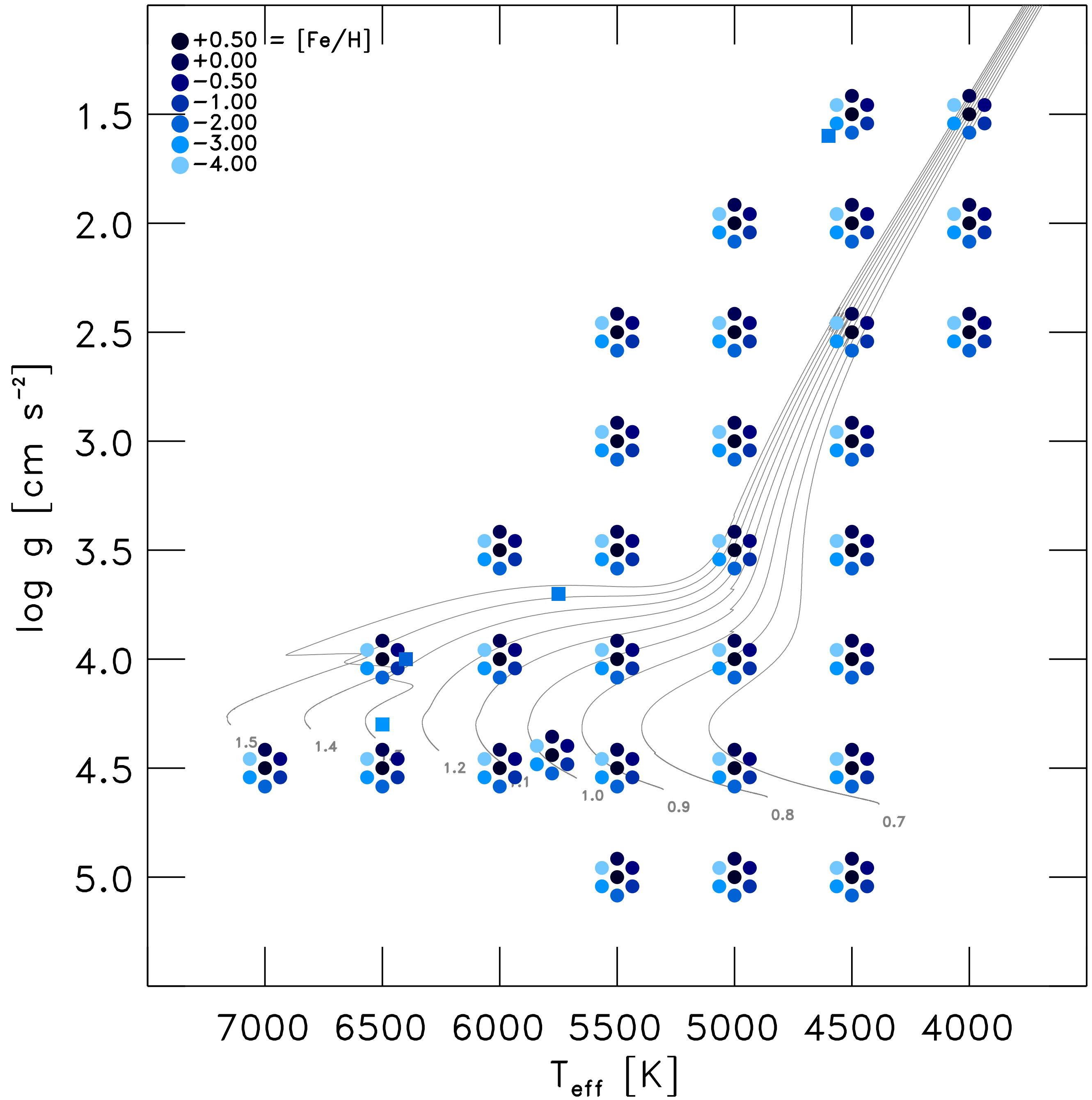
Surface intensity



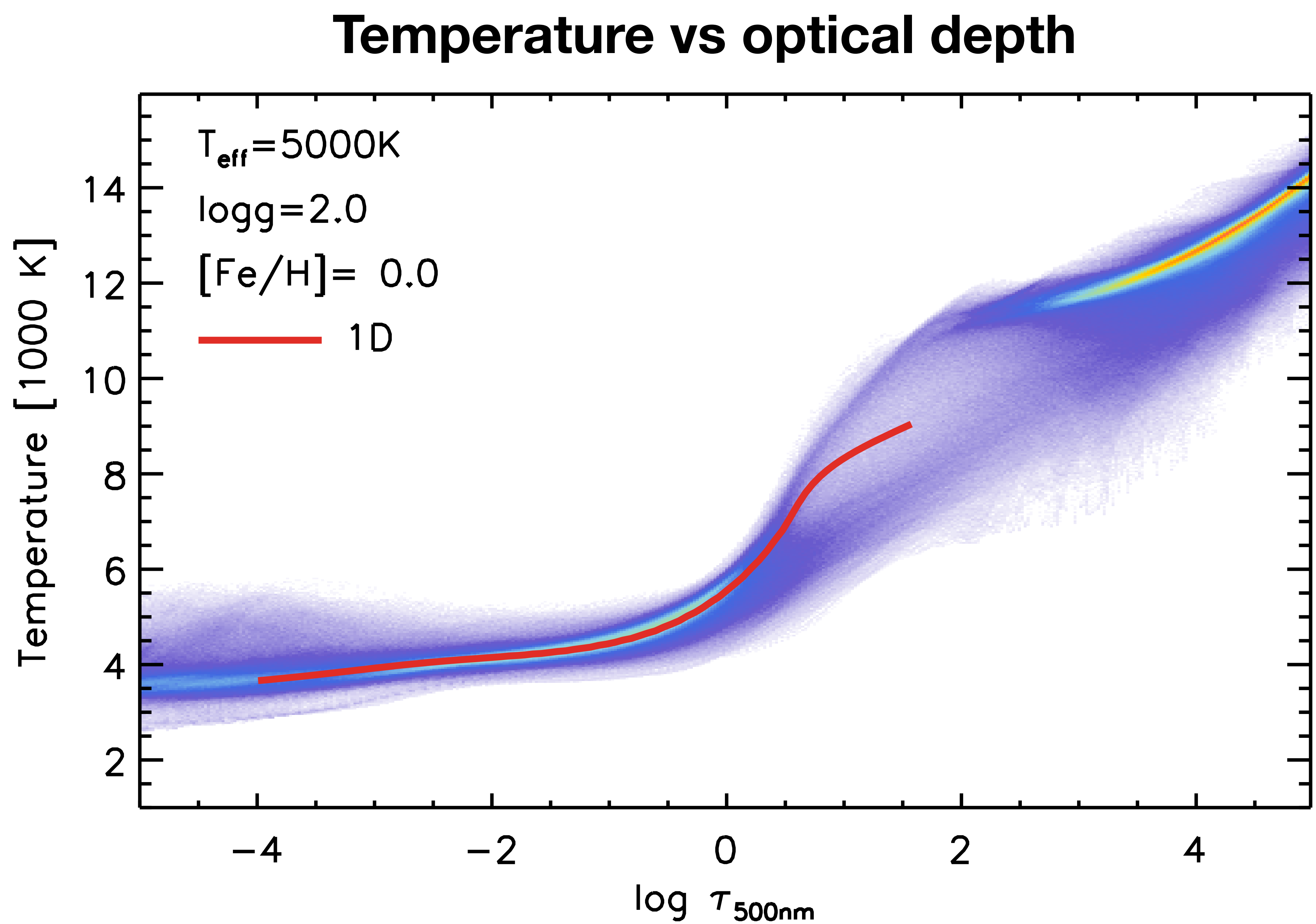
Solar simulation, 6 Mm x 6 Mm, (R. Collet)

Grid of 3D simulations

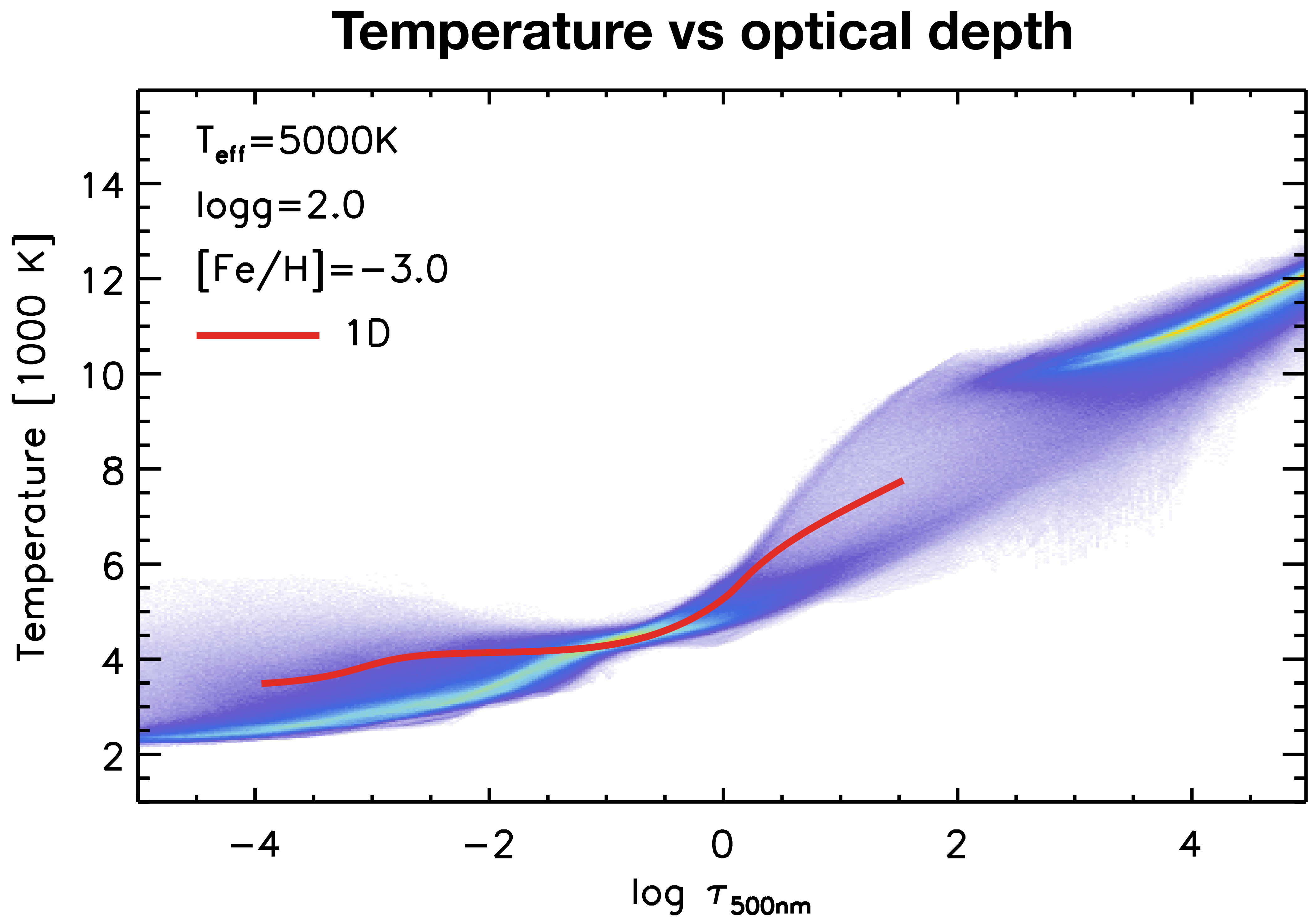
- STAGGER (Collet et al. 2011; Magic et al. 2013;): ~200 3D convection simulations of FGK stars
- Trampedach et al. (2013); CO^{5}BOLD/CIFIST (Tremblay et al. 2013); MURaM (Beeck et al. 2013)
- Systematic study of 3D-1D differences in synthetic spectra and colours



Solar metallicity

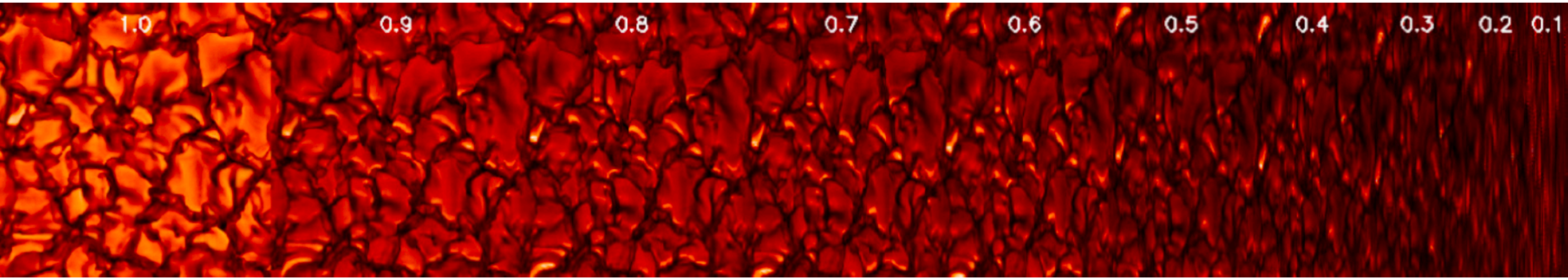


Low metallicity



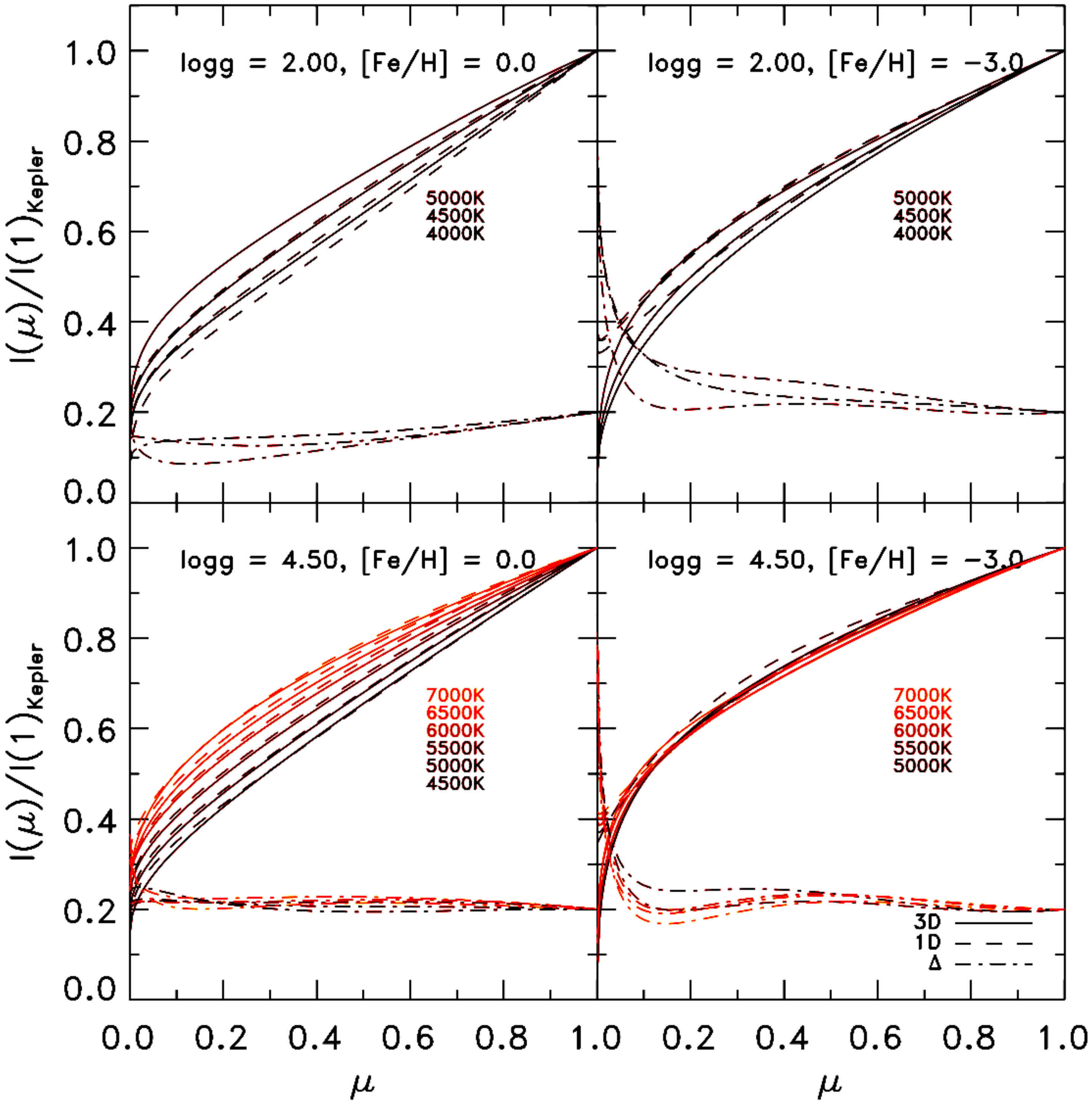
Limb darkening

- The diameter of CoRoT target HD49933: limb-darkening calculations with 3D models combined with interferometric and asteroseismic observations (Bigot et al. 2011)



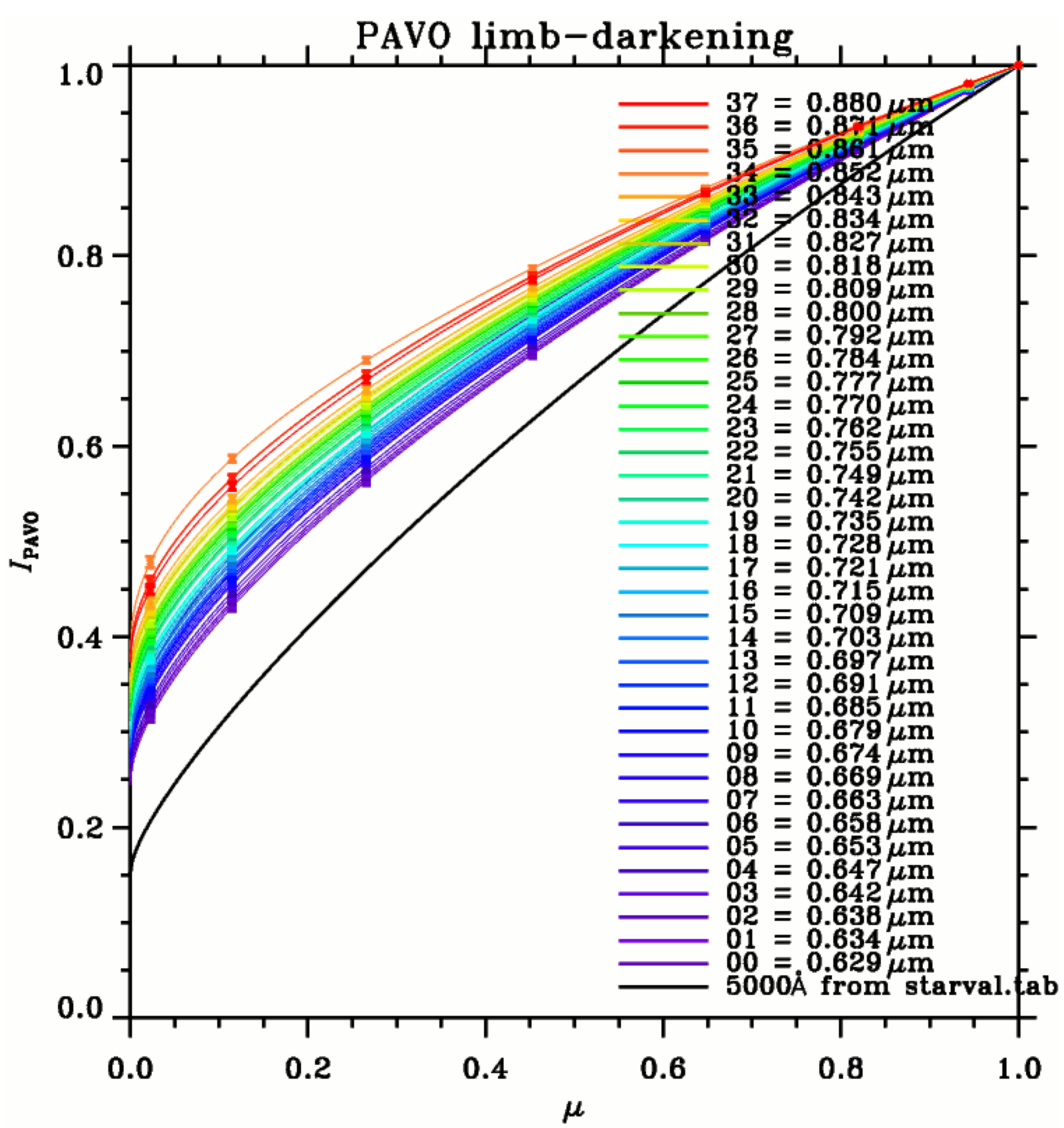
Limb darkening, 1D-3D

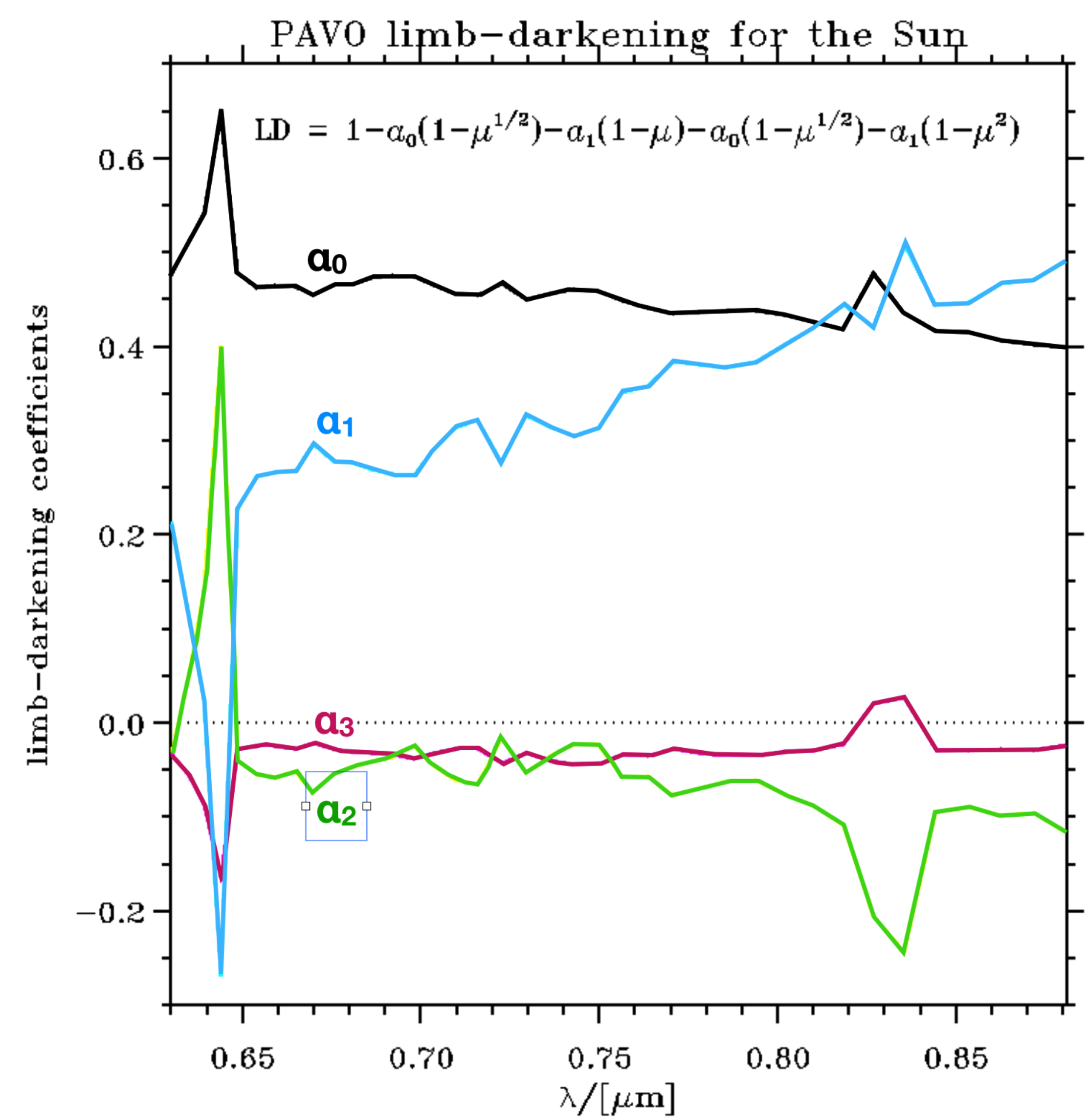
Centre-to-limb variations, Kepler band, 3D vs 1D (STAGGER; Magic et al. 2015)



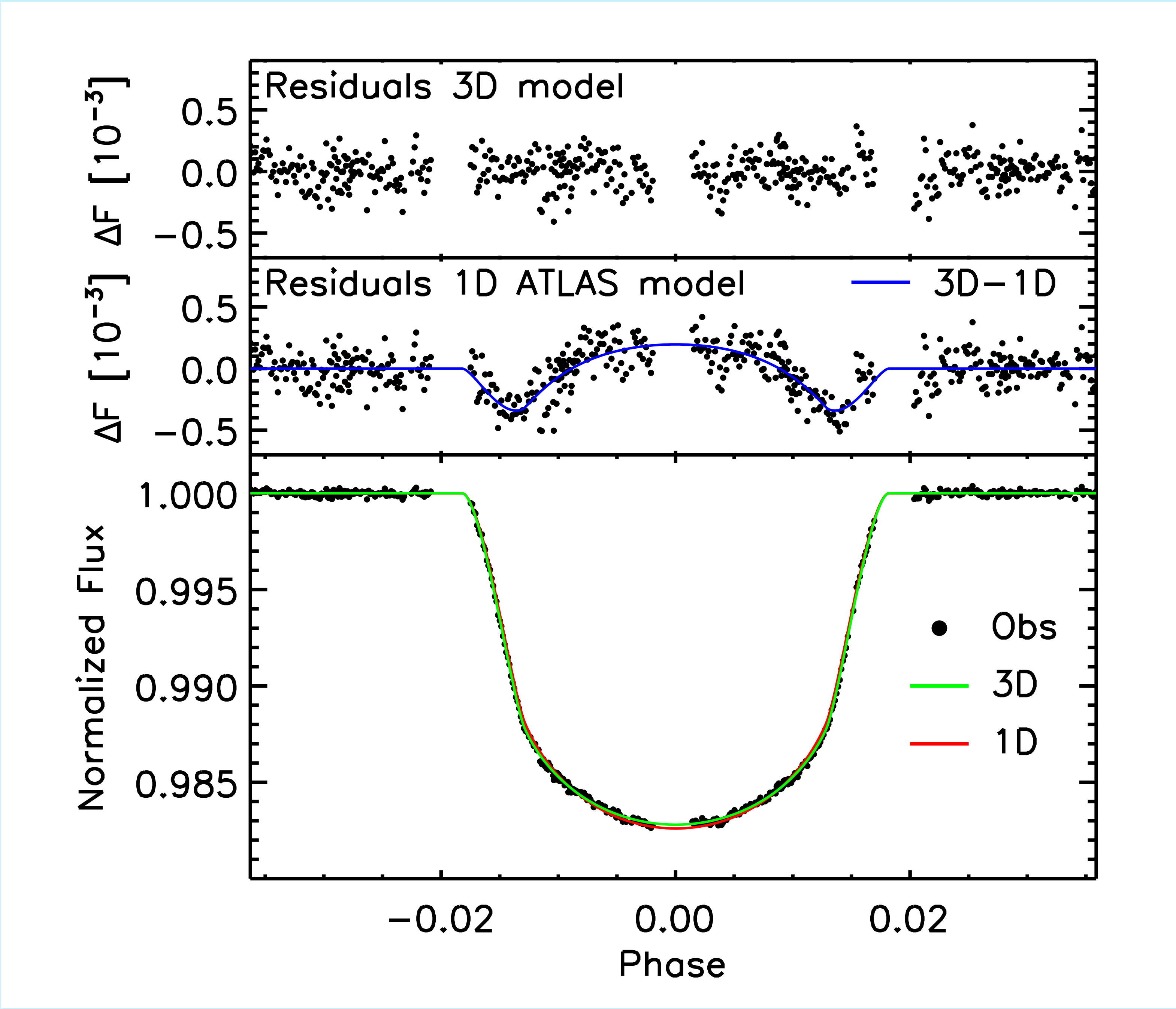
Limb-darkening coefficients

- 3D solar simulation: fit to 4-term Claret (2000) limb-darkening law for 38 CHARA/PAVO channels (Trampedach et al. in prep.)
- Wavelength dependence (especially α_1 coefficient)
- Strong molecular features at 0.64 µm and at 0.83 µm





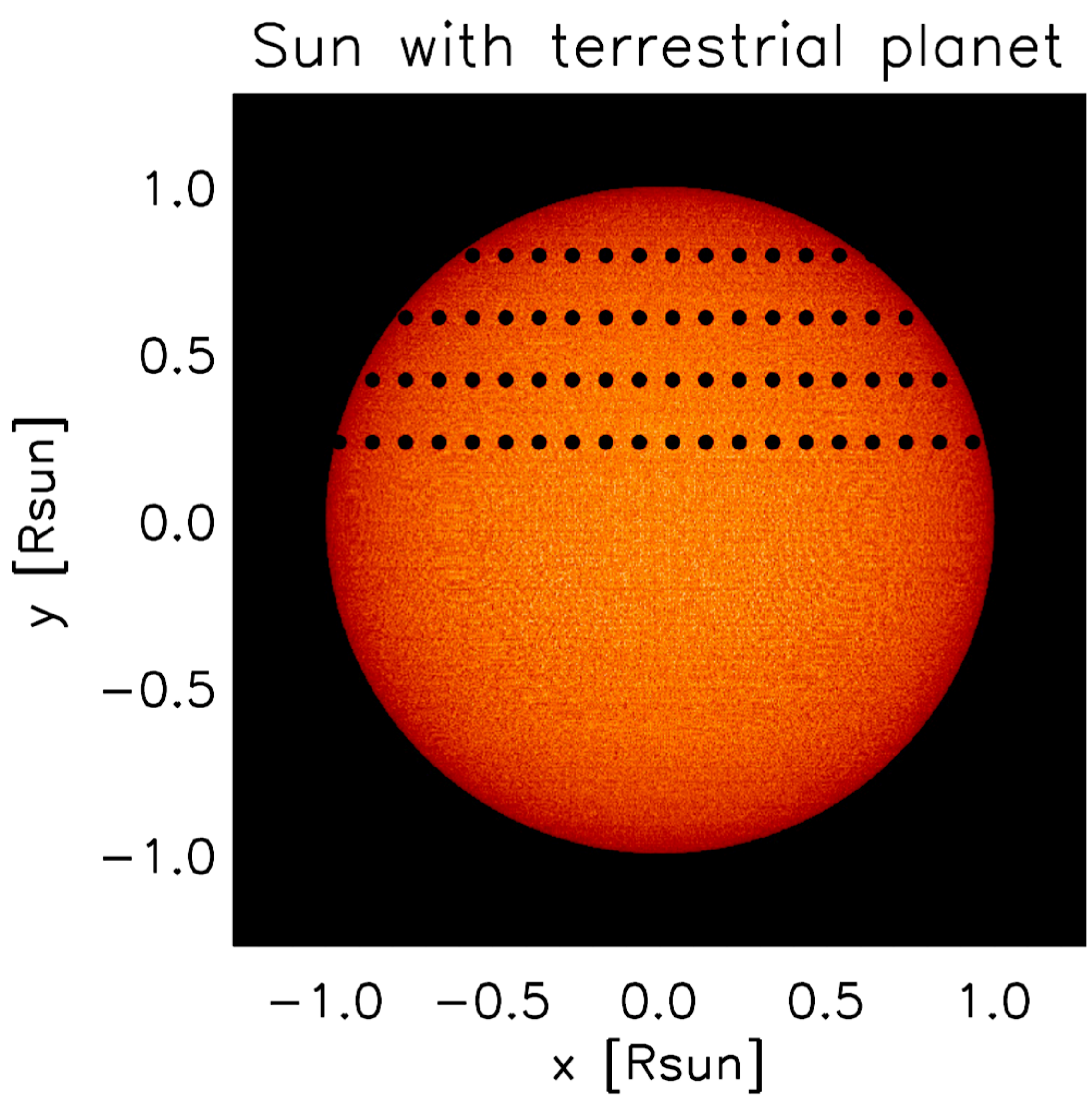
Exoplanet transits

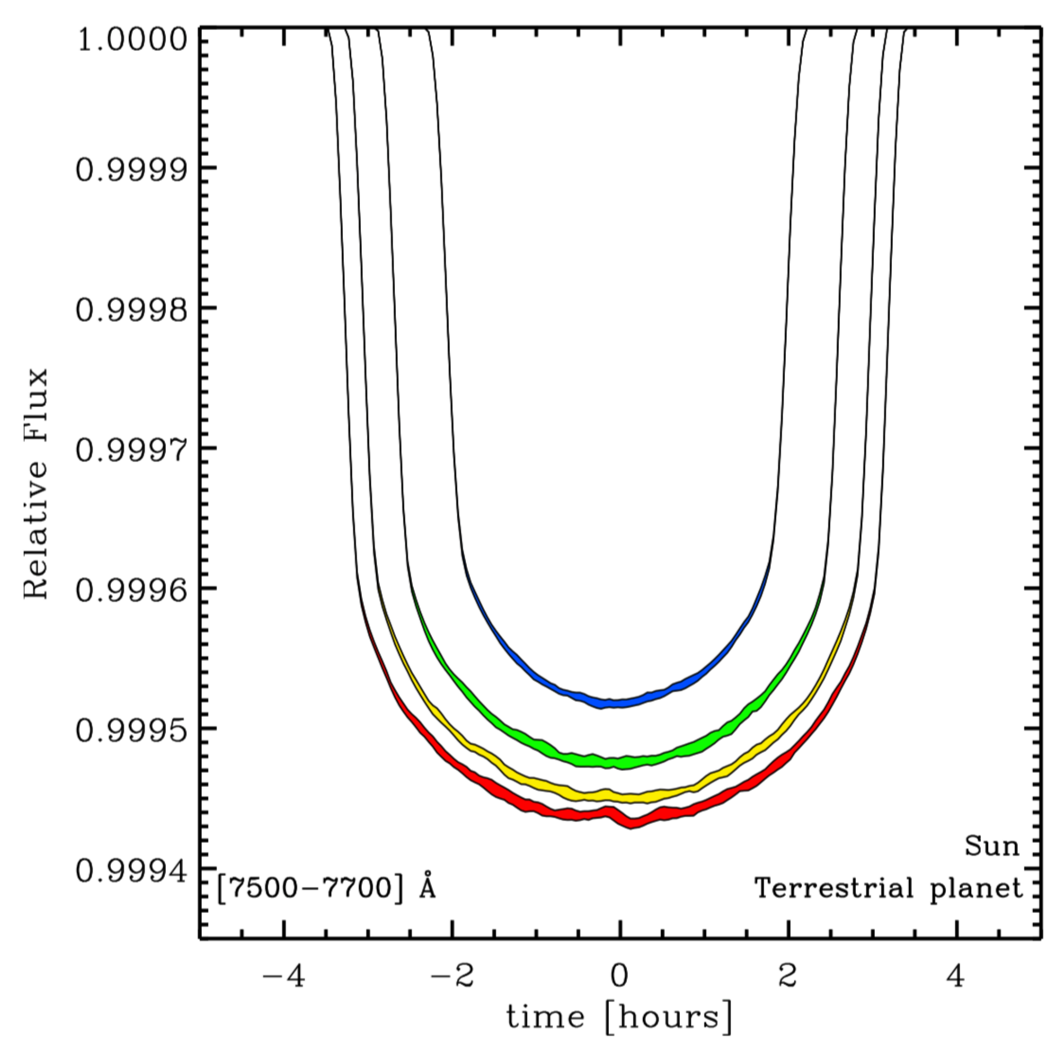


HD209458b transit, HST 2900 Å - 5700 Å band (Hayek et al. 2012)

Exoplanet transits (2)

- Simulated transits with synthetic stellar disc images from 3D simulations: granulation noise

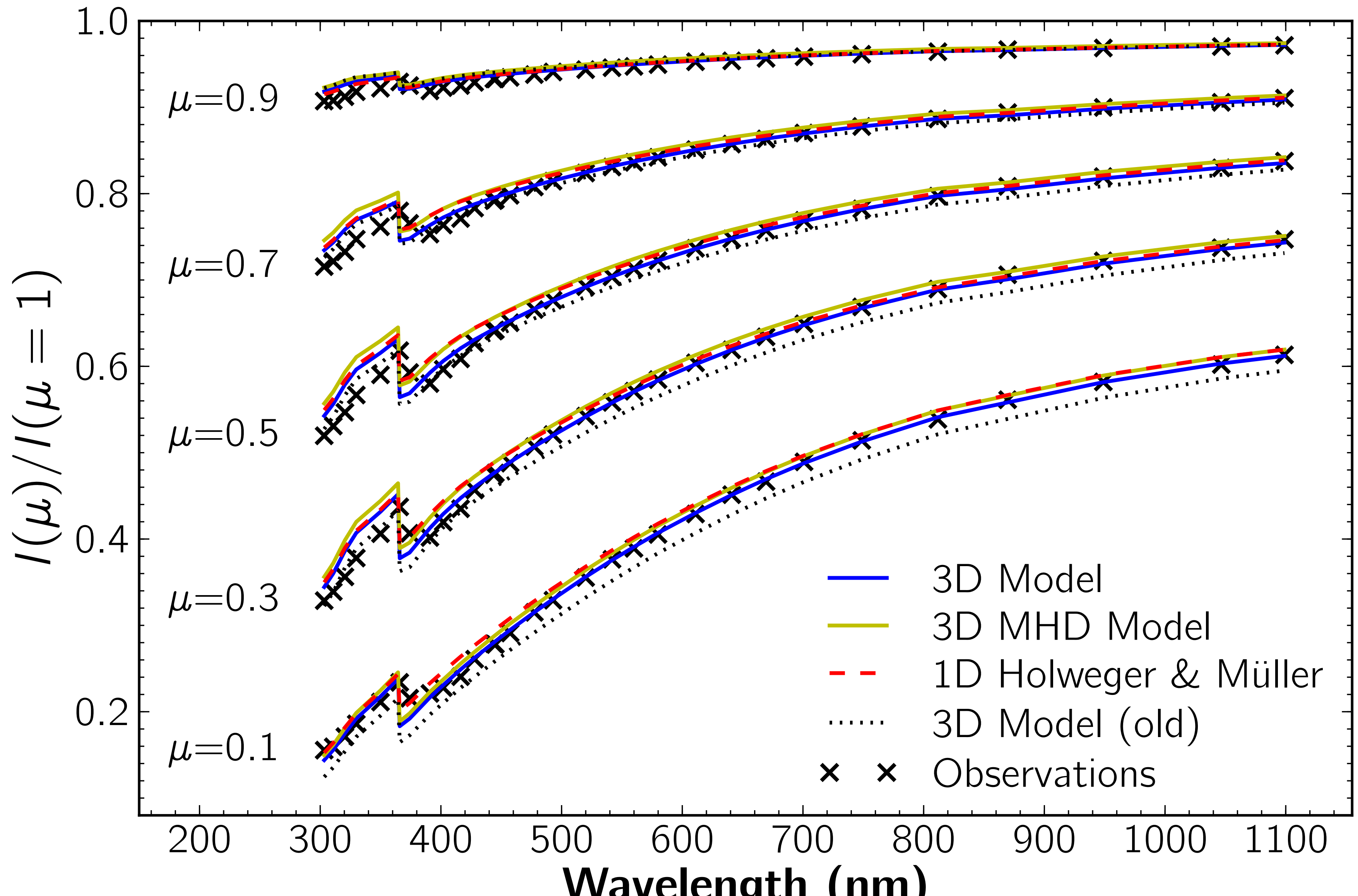




Chiavassa et al. 2017

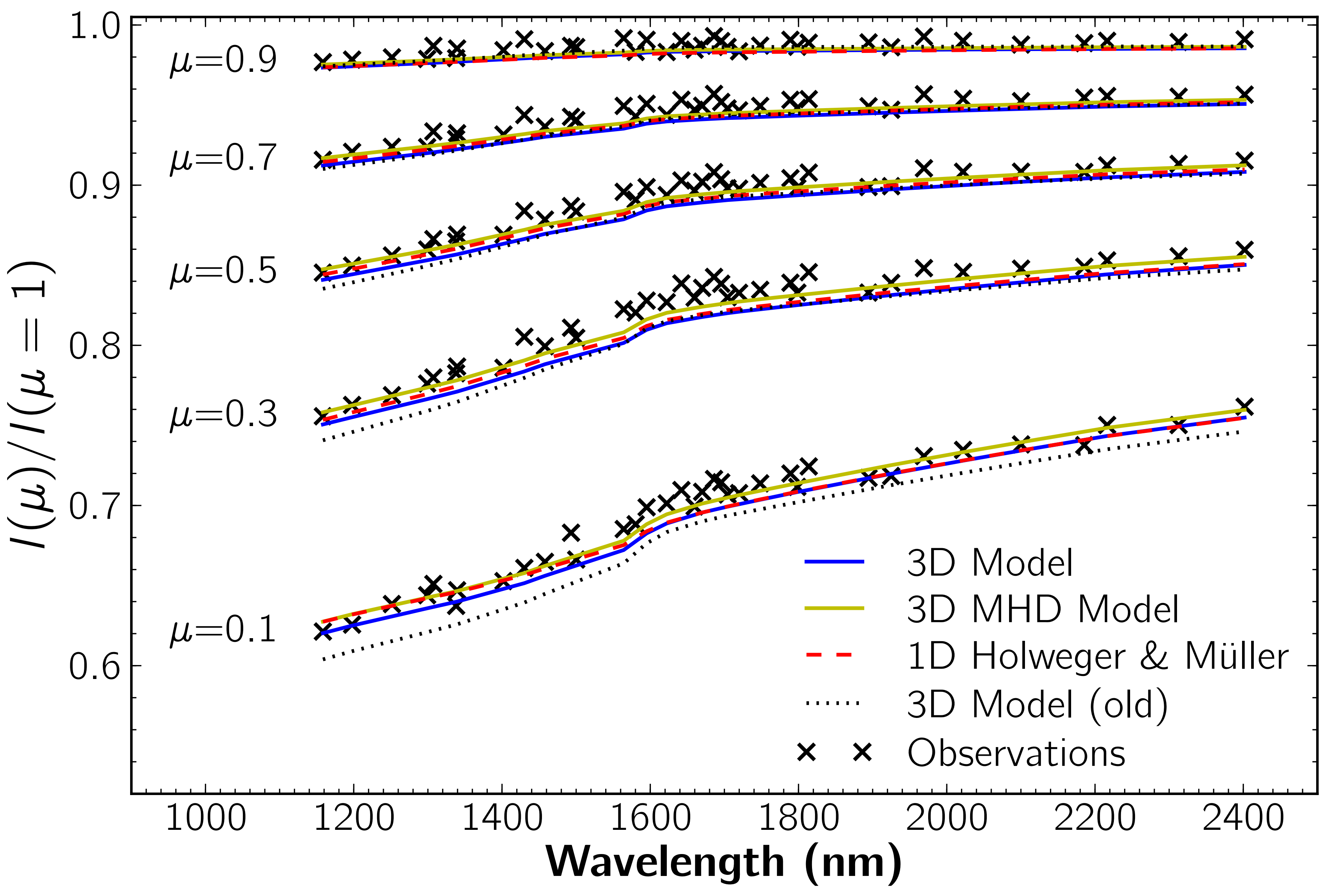
Limb darkening: Sun

- Very good agreement between limb-darkening curves from 3D models and observations at UV and visible wavelengths (Pereira, Asplund, Collet et al. 2013; data: Pierce & Slaughter 1977; Neckel & Labs 1994)



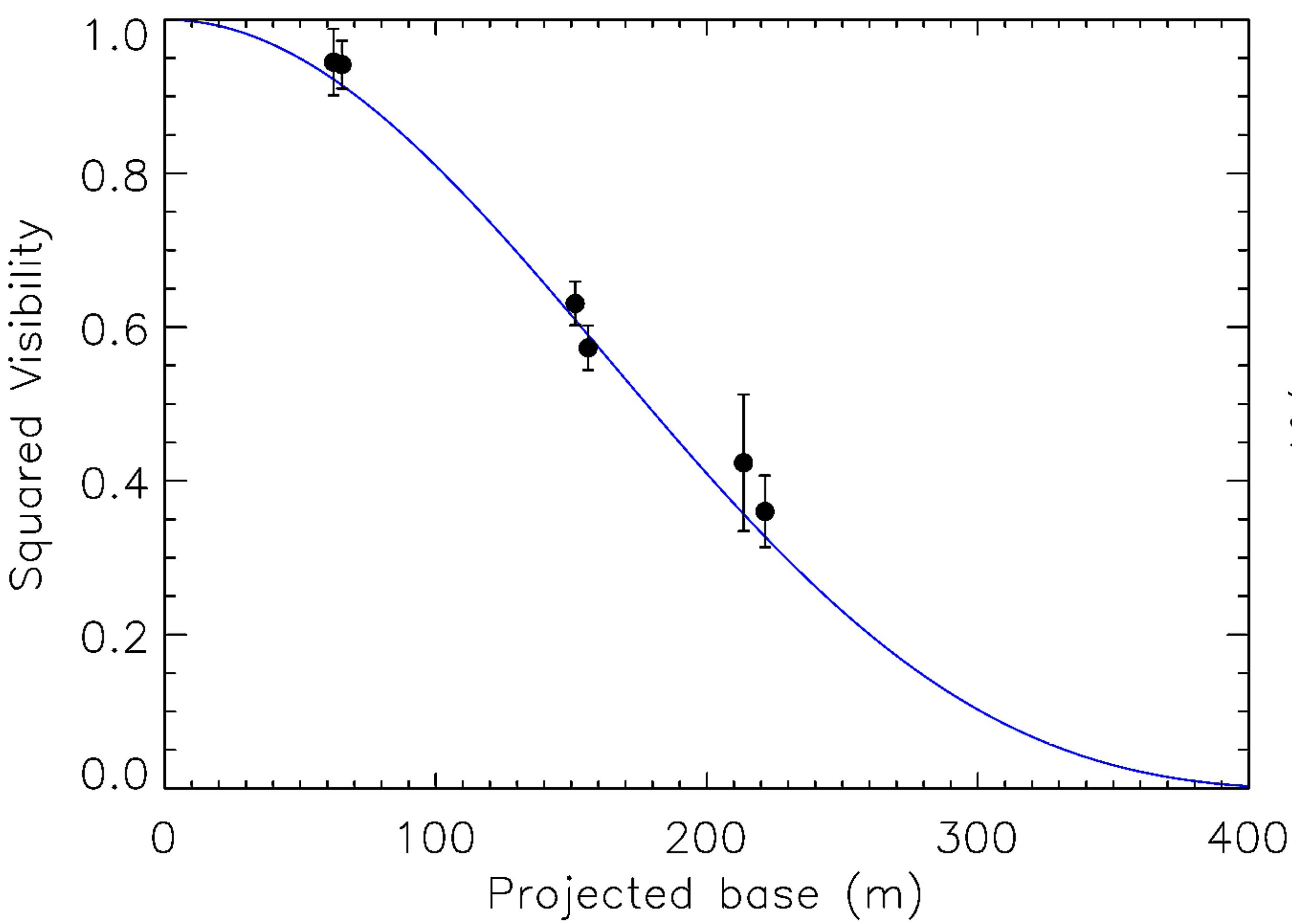
Limb darkening: Sun (2)

- Poorer agreement with observations at long wavelengths (Pereira et al. 2013; data: Pierce et al. 1977)

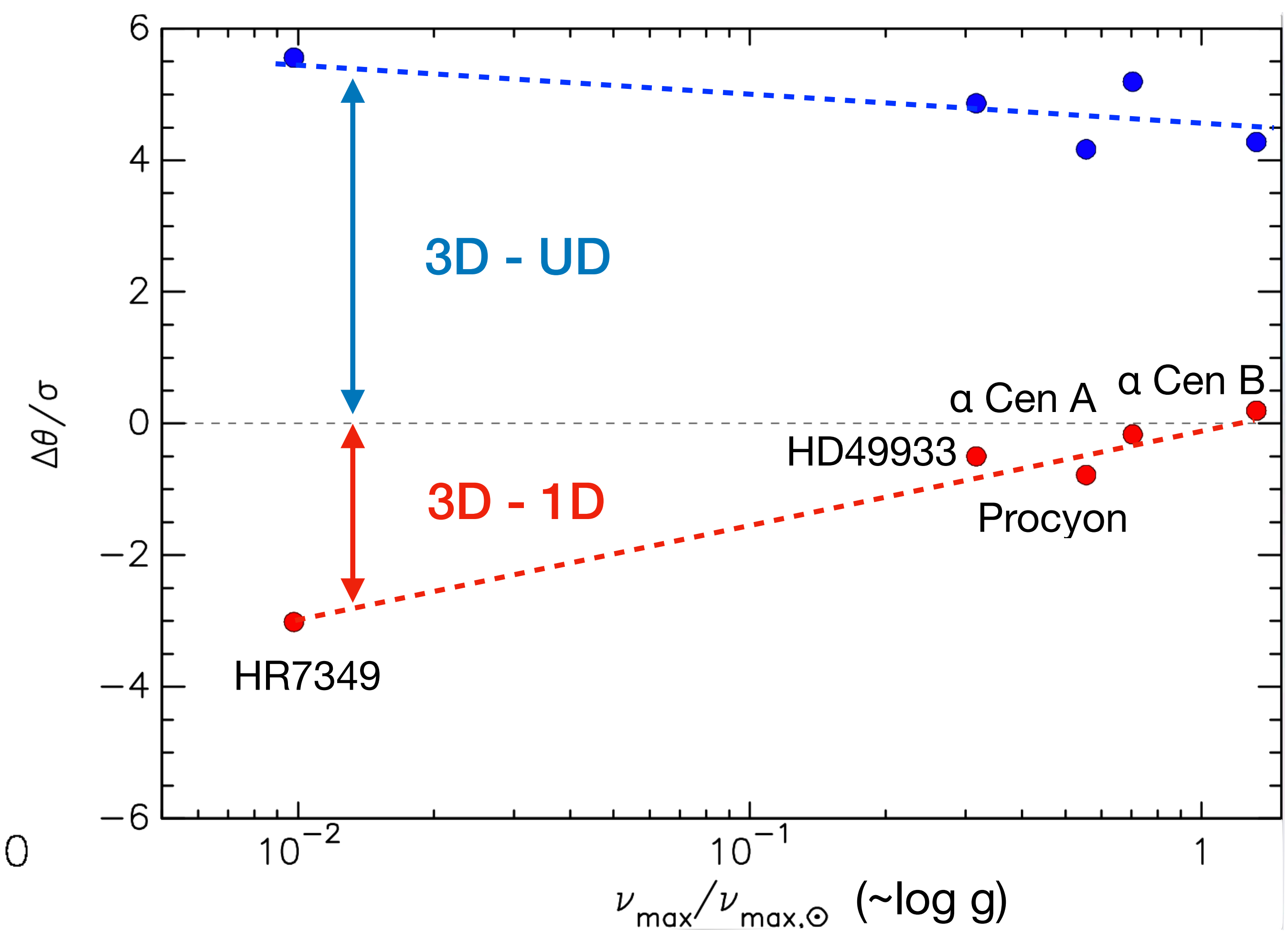


Interferometric stellar angular diameters

- In general: $\theta_{UD} < \theta_{3D} < \theta_{1D}$
- Significant (3 σ) 3D-1D limb-darkening corrections for giants



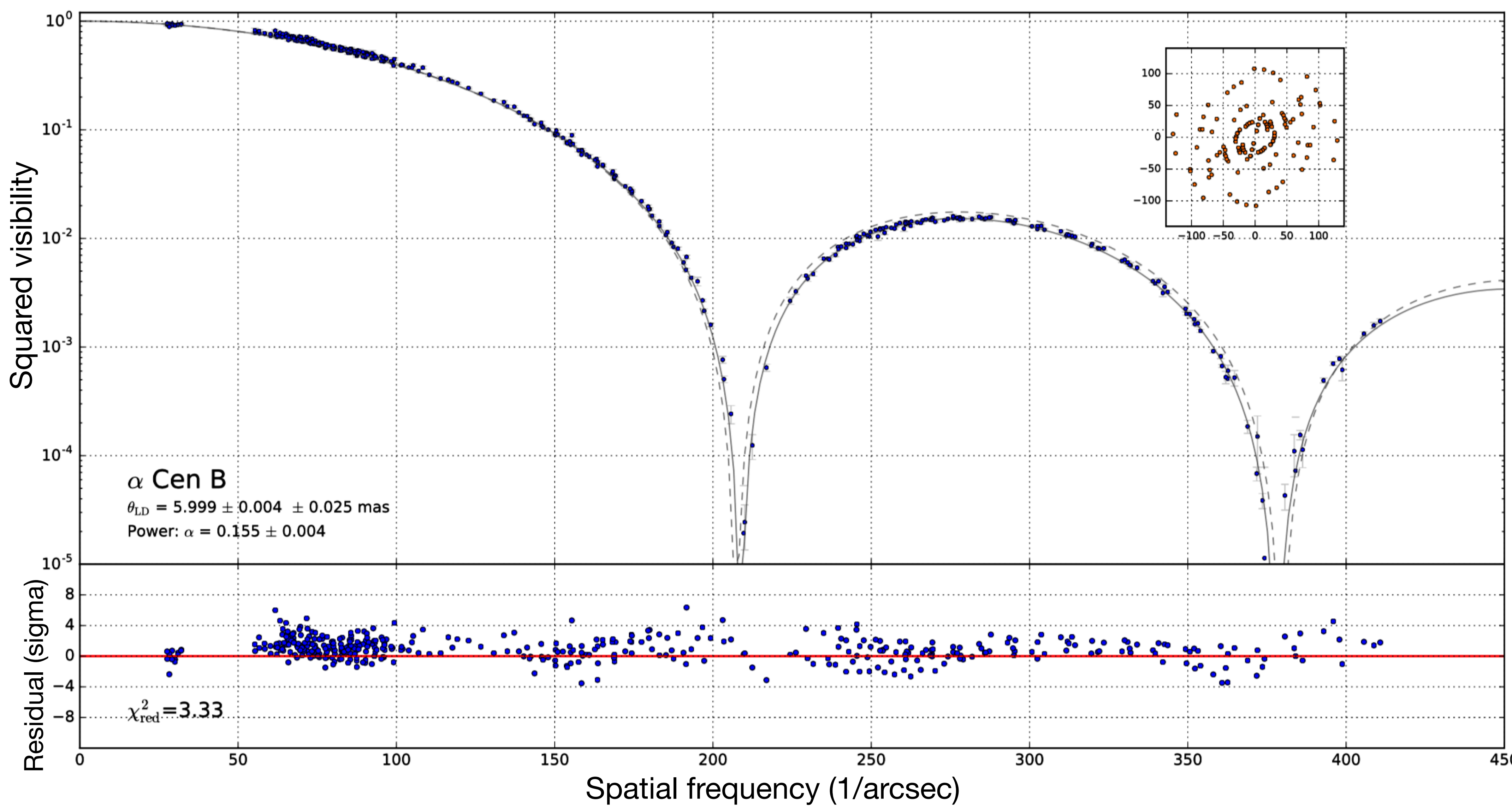
HD49933 (Bigot et al. 2011)



Bigot et al., in prep; Chiavassa et al. 2012;
Bigot et al. 2011; Kervella et al. 2017; Bigot et al. 2006

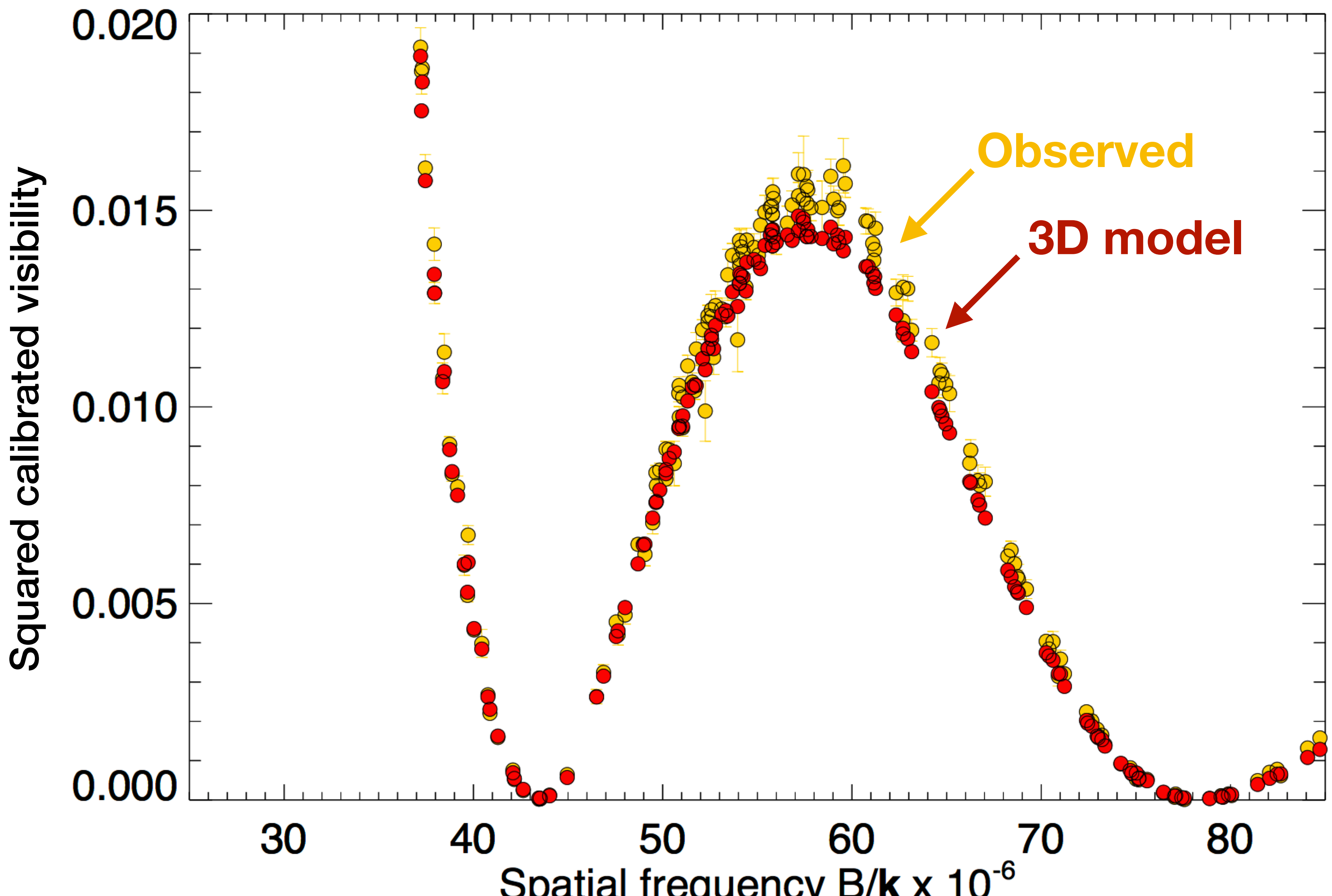
Interferometric tests

- α Cen B (K0 dwarf), VLTI/PIONIER observations in H band (1.65 μm) (Kervella, Bigot, Gallene, & Thévenin 2017)
- Observed squared visibilities: two side lobes



Interferometric tests

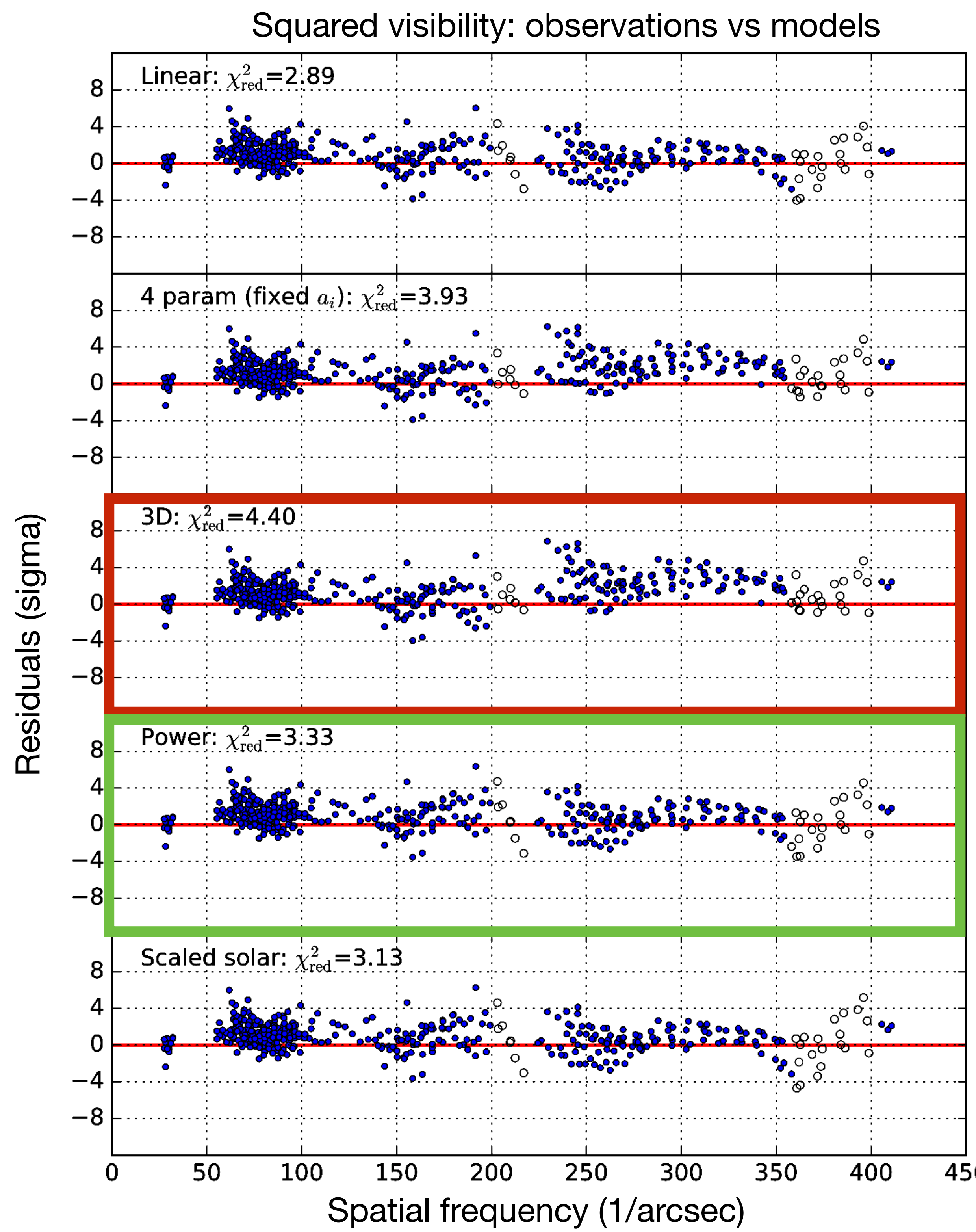
- α Cen B, limb darkening from 3D (and 1D) models: **predicted interferometric square visibility of first side lobe lower than observed**



Kervella et al. (2017)

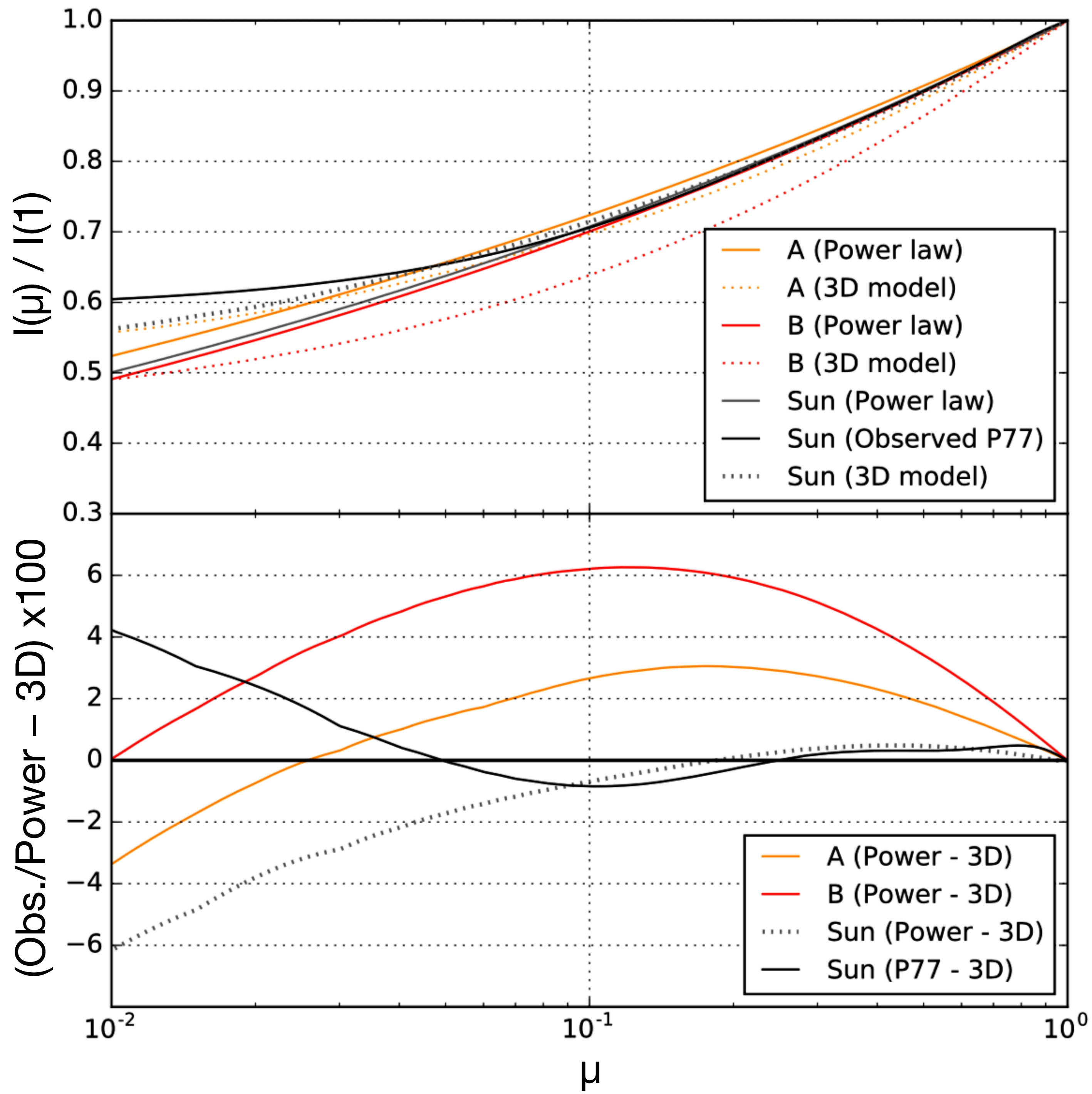
Interferometric tests

- α Cen B, comparative study of limb darkening models (Kervella et al. 2017)
- Simple power-law model (μ^α) for limb darkening performs better than models



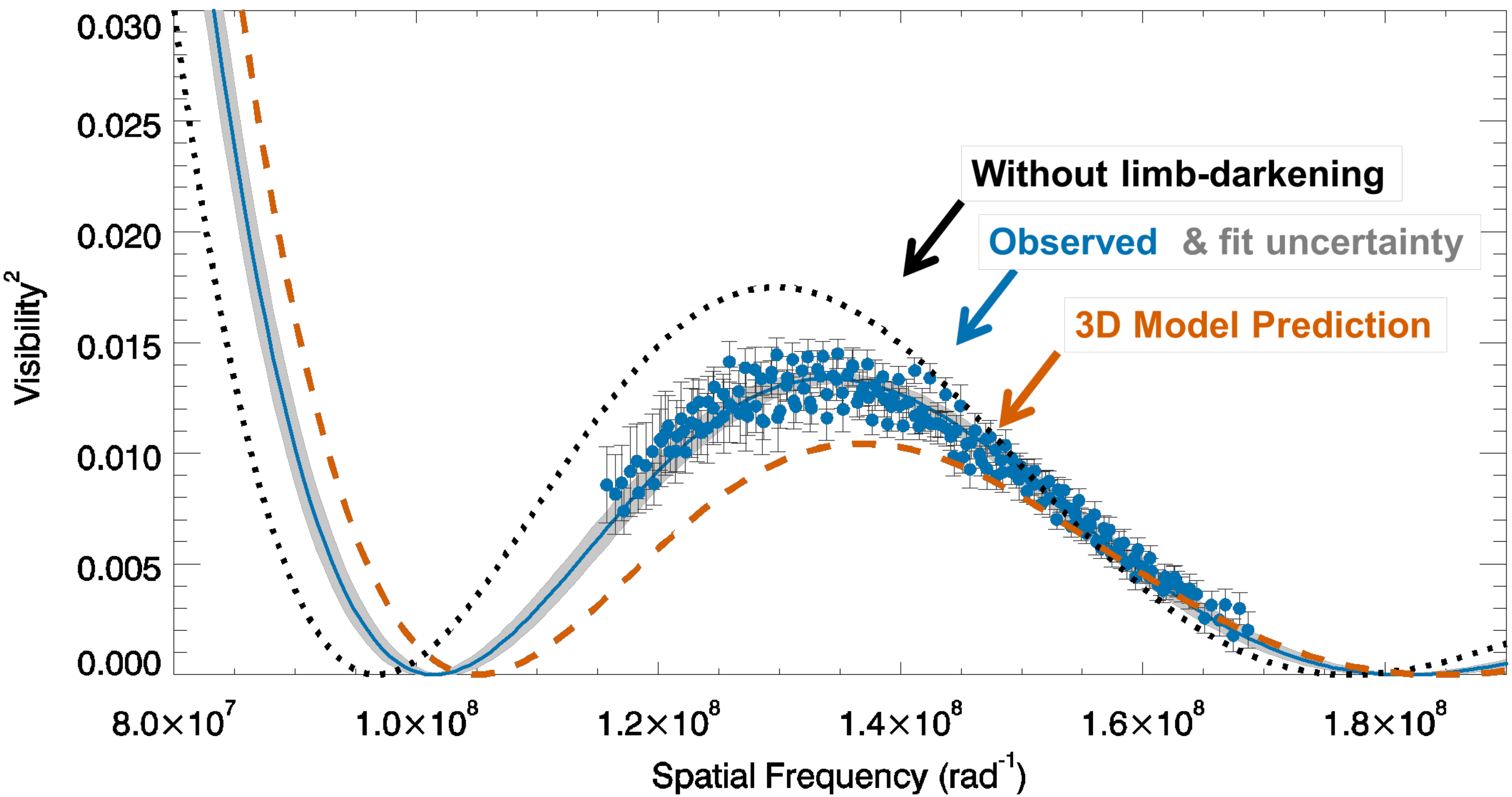
Limb-darkening models

Comparison between α Cen A & B and the Sun, power law vs 3D (Kervella et al. 2017)



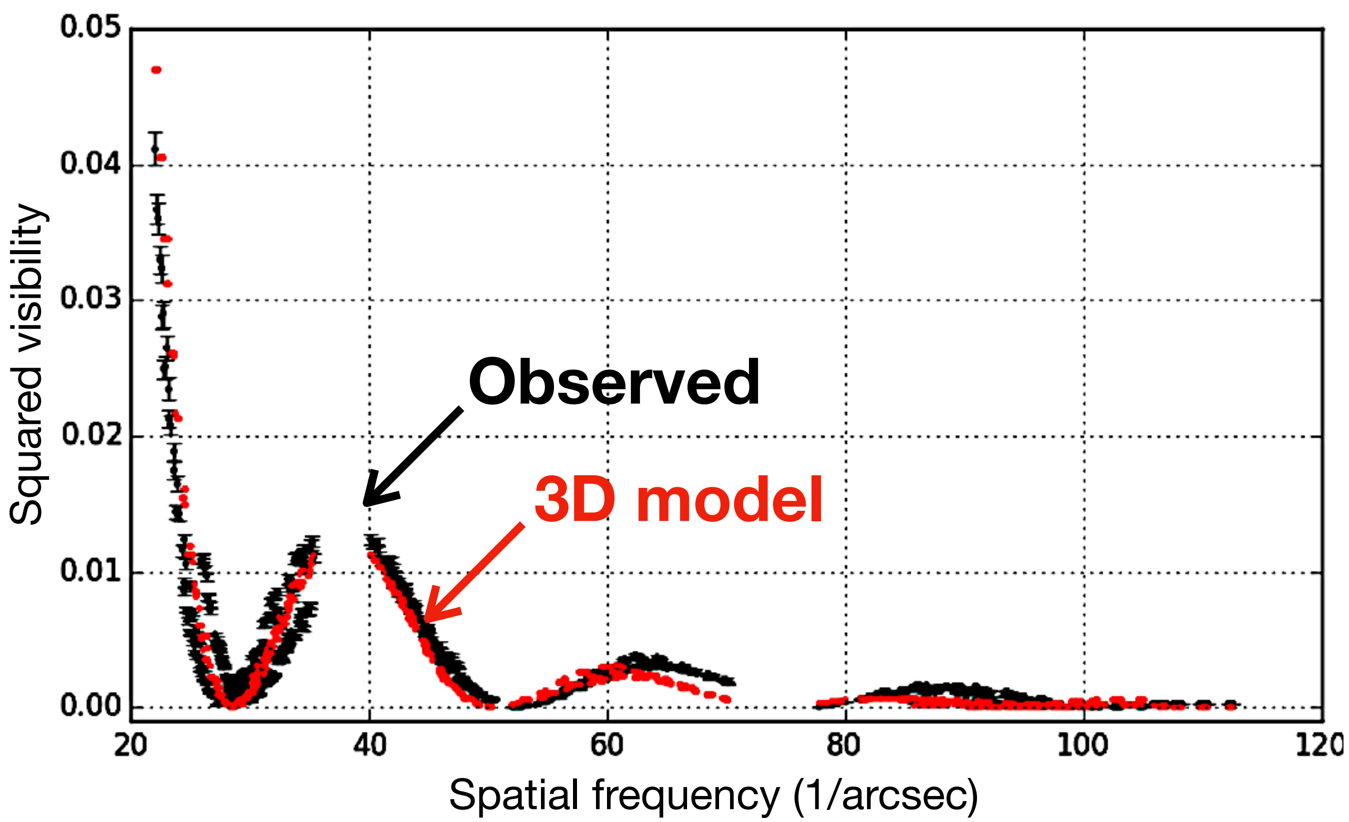
Interferometric tests (2)

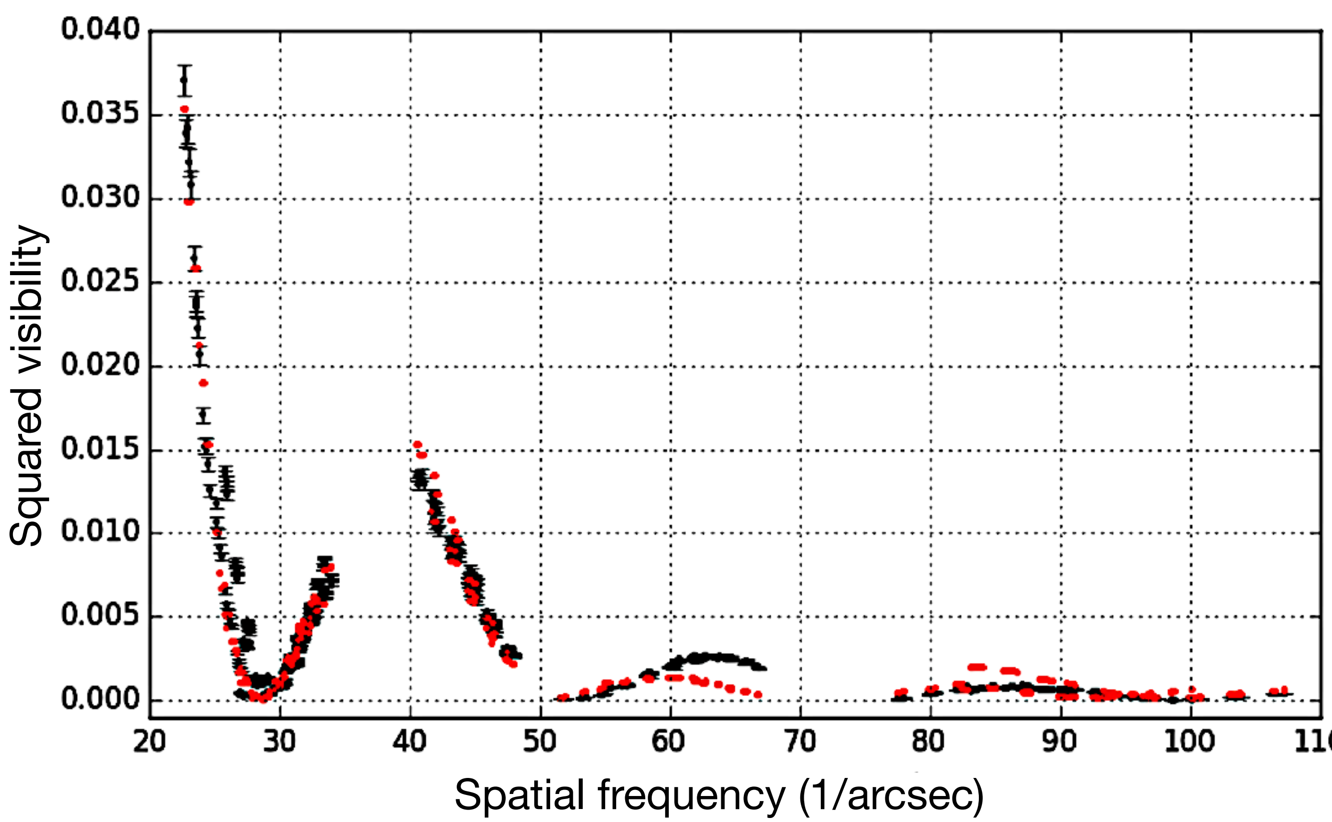
- Evolved star η Cep (K0 subgiant), CHARA/PAVO observations, visible wavelengths (T. White et al., in prep.)



Interferometric tests (2)

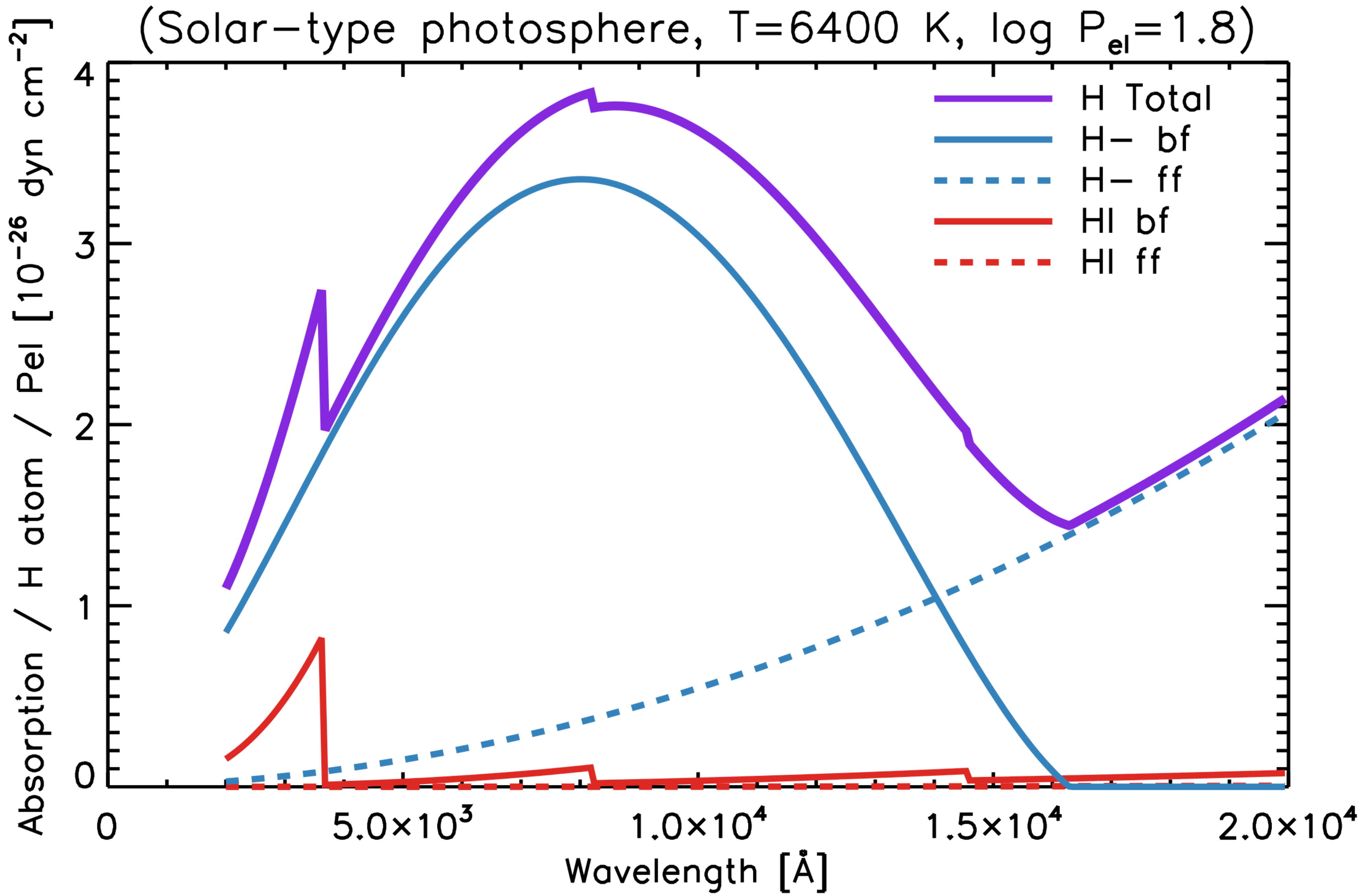
- Antares (M0.5 supergiant),VLTI/PIONIER observations (Montargès et al. 2017)
- 3D “star-in-the-box” CO5BOLD simulations (Freytag et al. 2012)
- Squared visibilities and angular stellar diameter determinations: dependence on epoch and sampled position angles





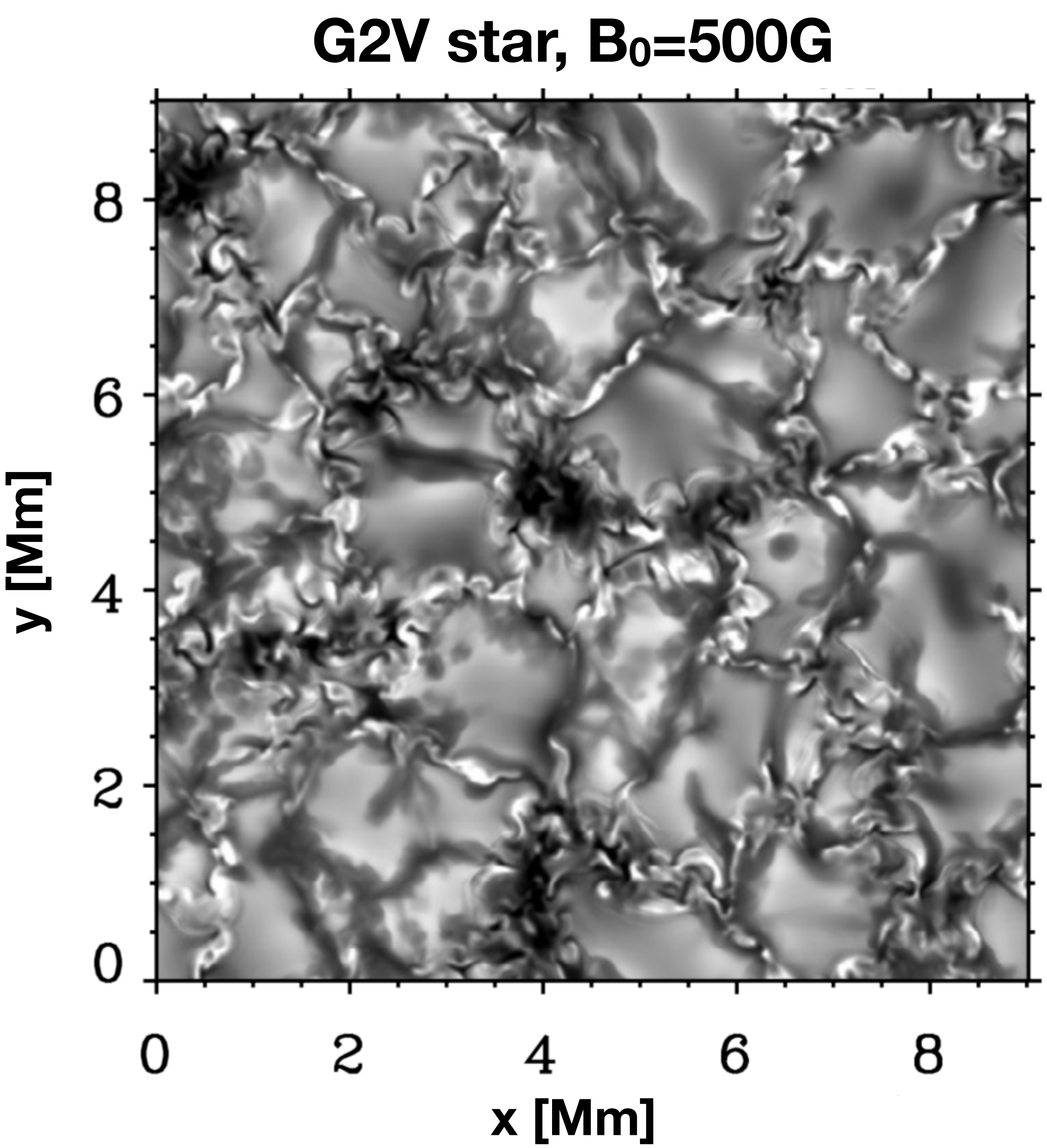
Continuous opacities

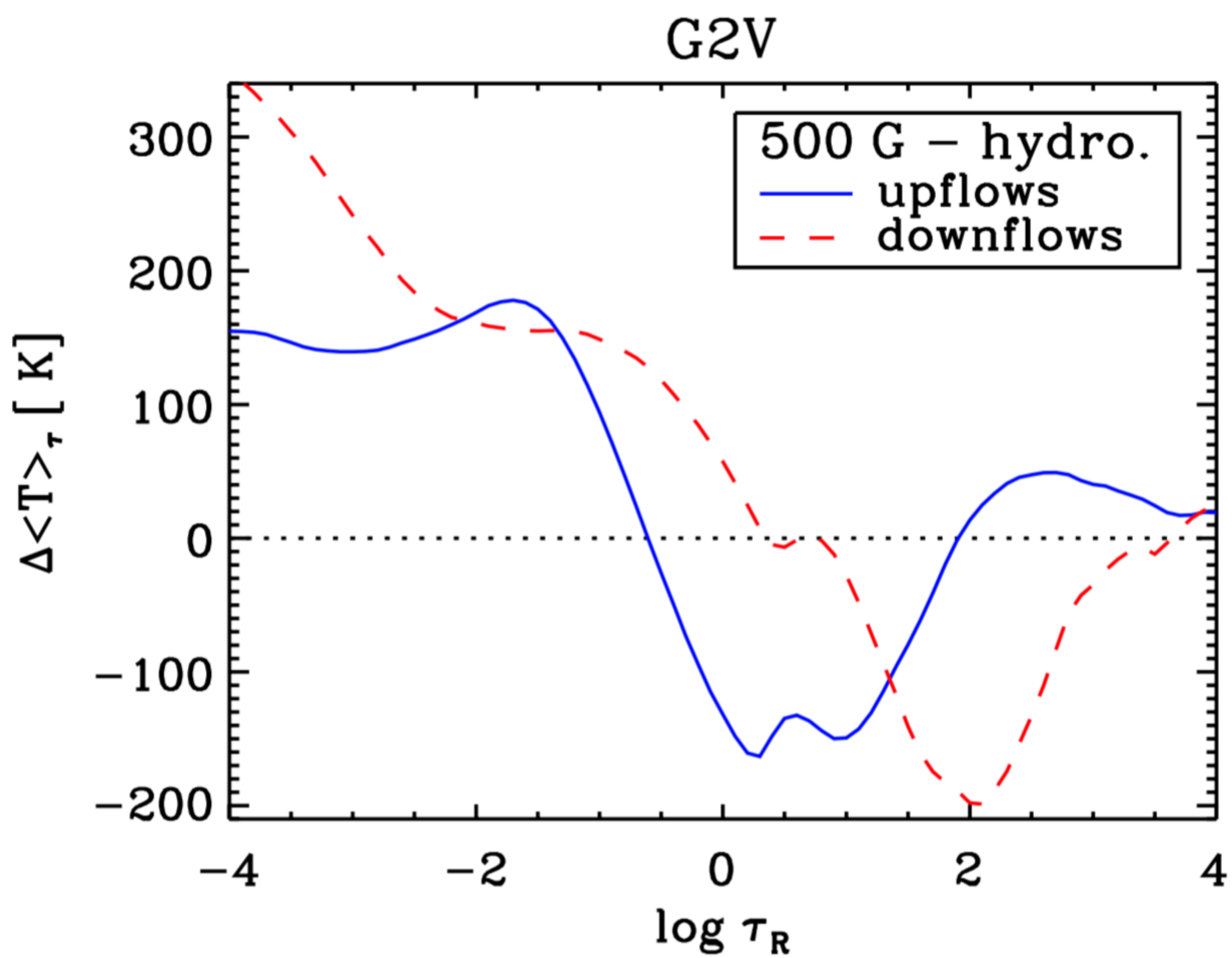
- H- bound-free: cross-section? (direct/indirect) effects of departures from LTE on H- or electron number density?



Magnetic fields

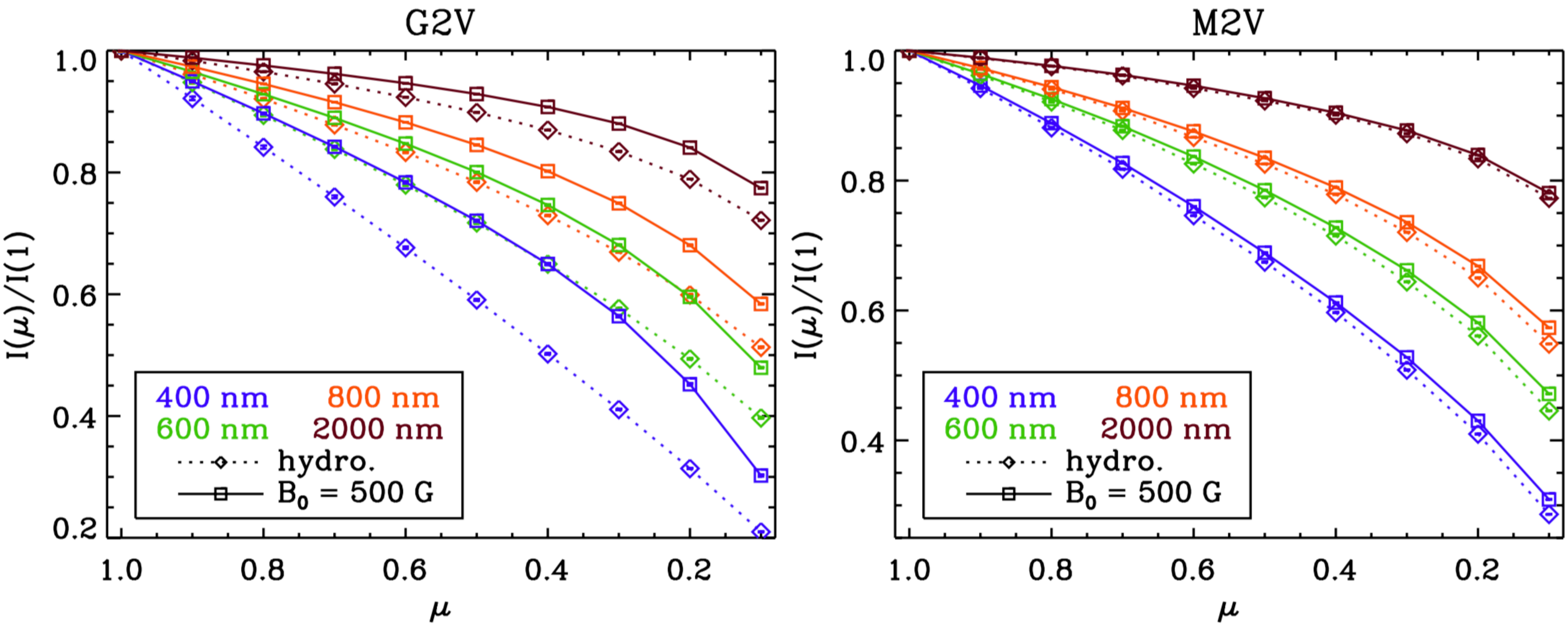
- Effect of vertical magnetic fields on physical stratification in main-sequence stars (e.g. Beeck et al. 2015; Rempel 2014; Pereira et al. 2013)





Magnetic fields

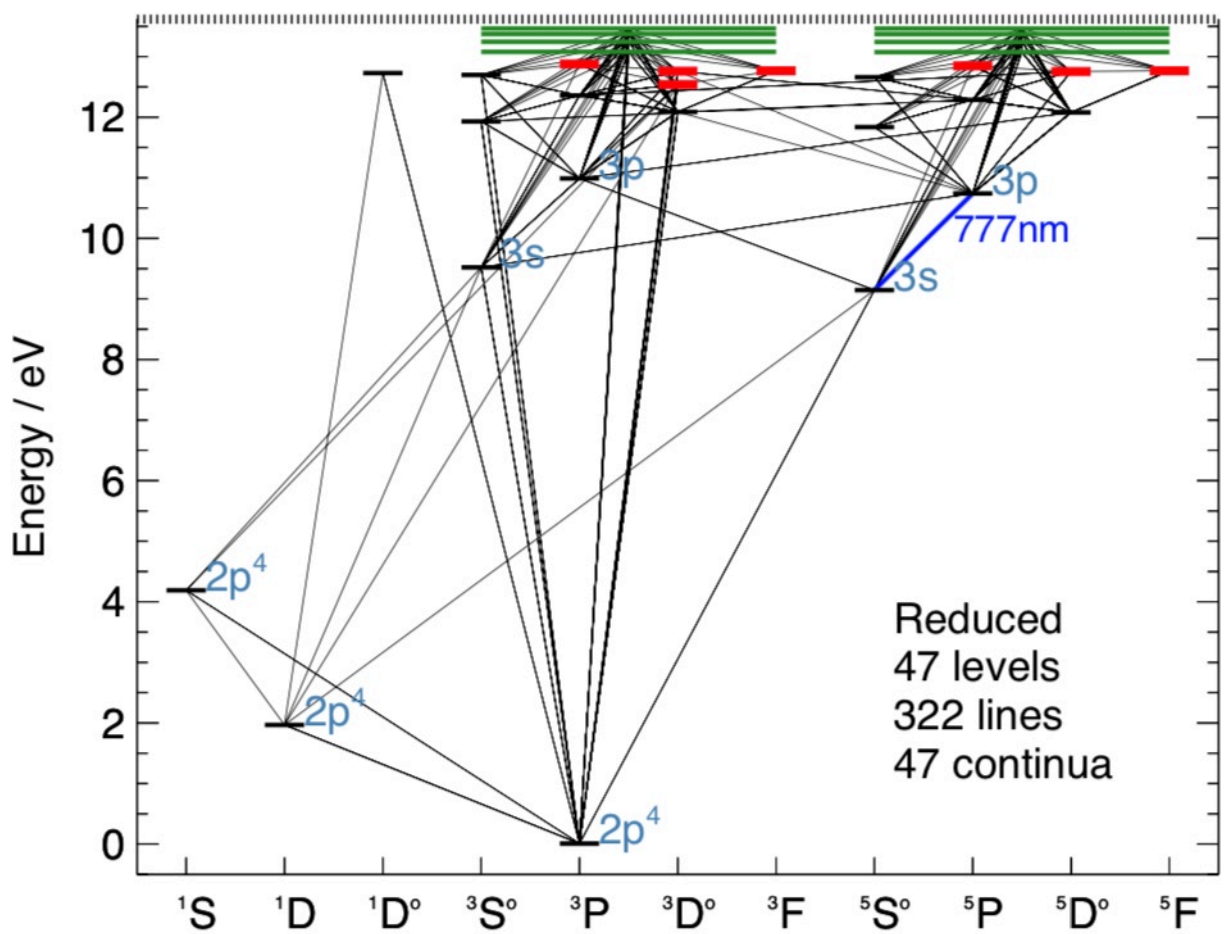
Effect of magnetic fields on limb-darkening curves

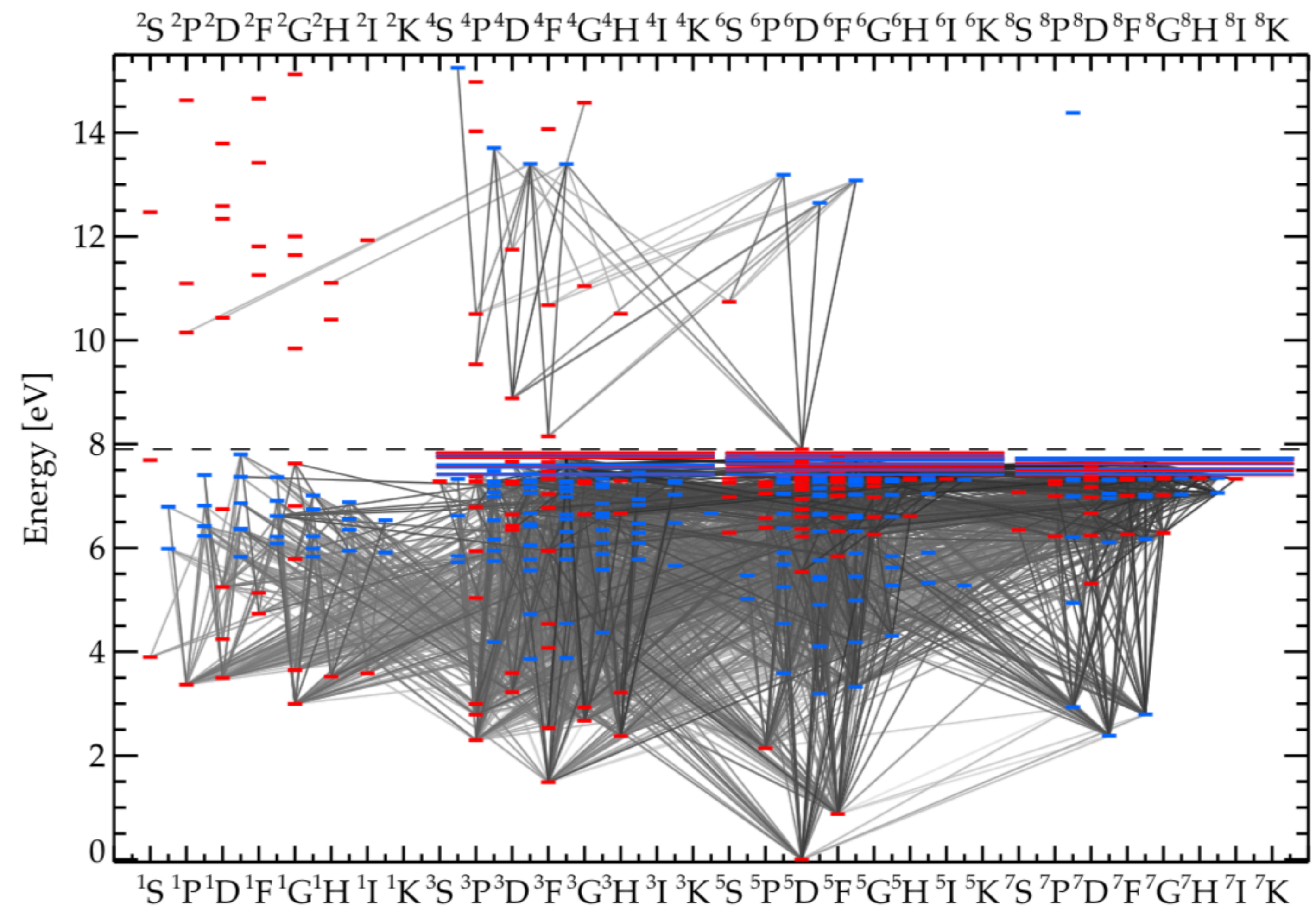


Beeck et al. (2015)

Spectral lines, CLV and non-LTE

- Departure of atomic level populations and radiation field from local thermodynamic equilibrium (LTE) in stellar atmospheres
- BALDER/MULTI3D code (Amarsi et al. 2016, 2018), scaling to large model atoms (C, O, Si, Fe, …)

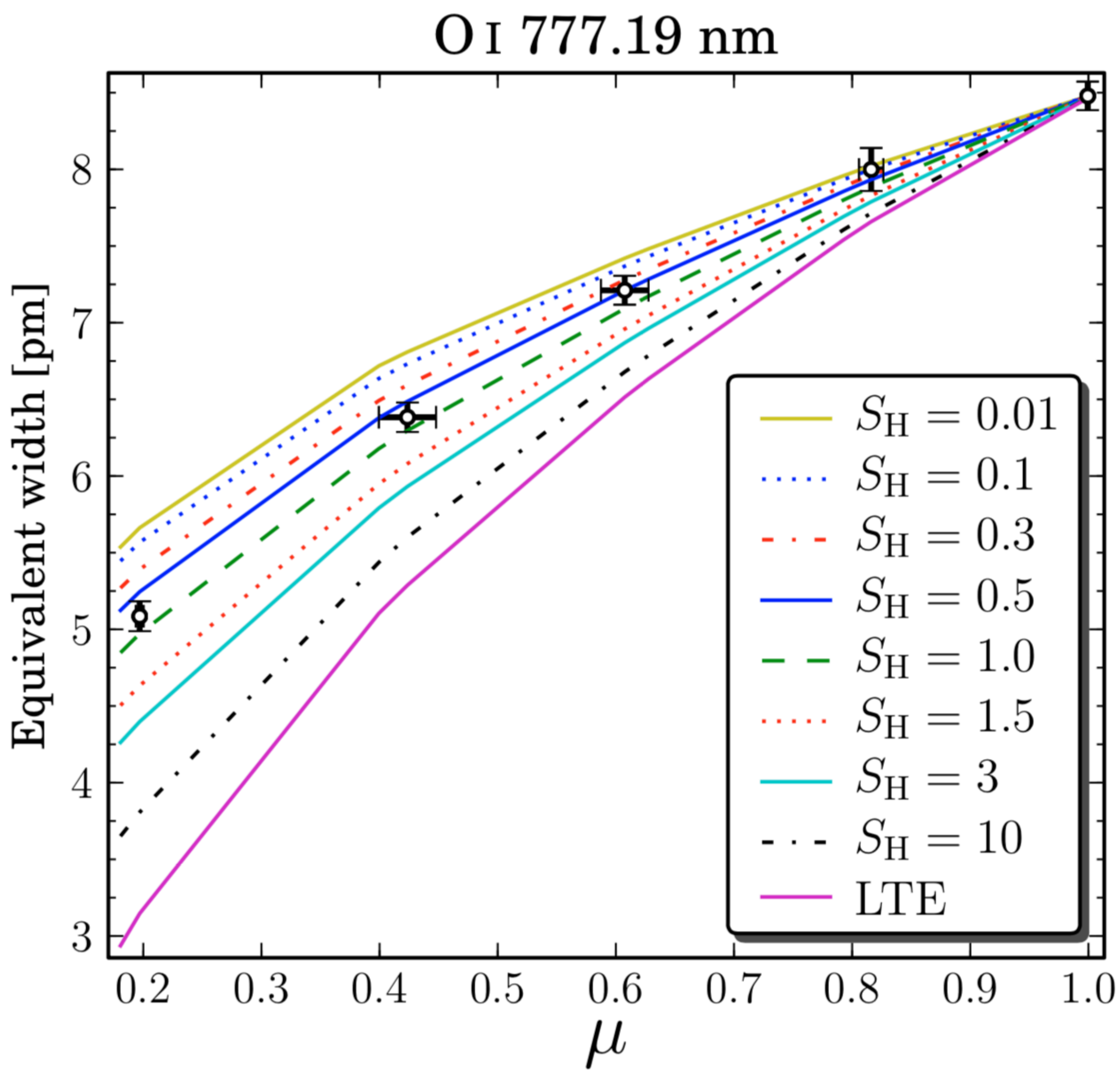




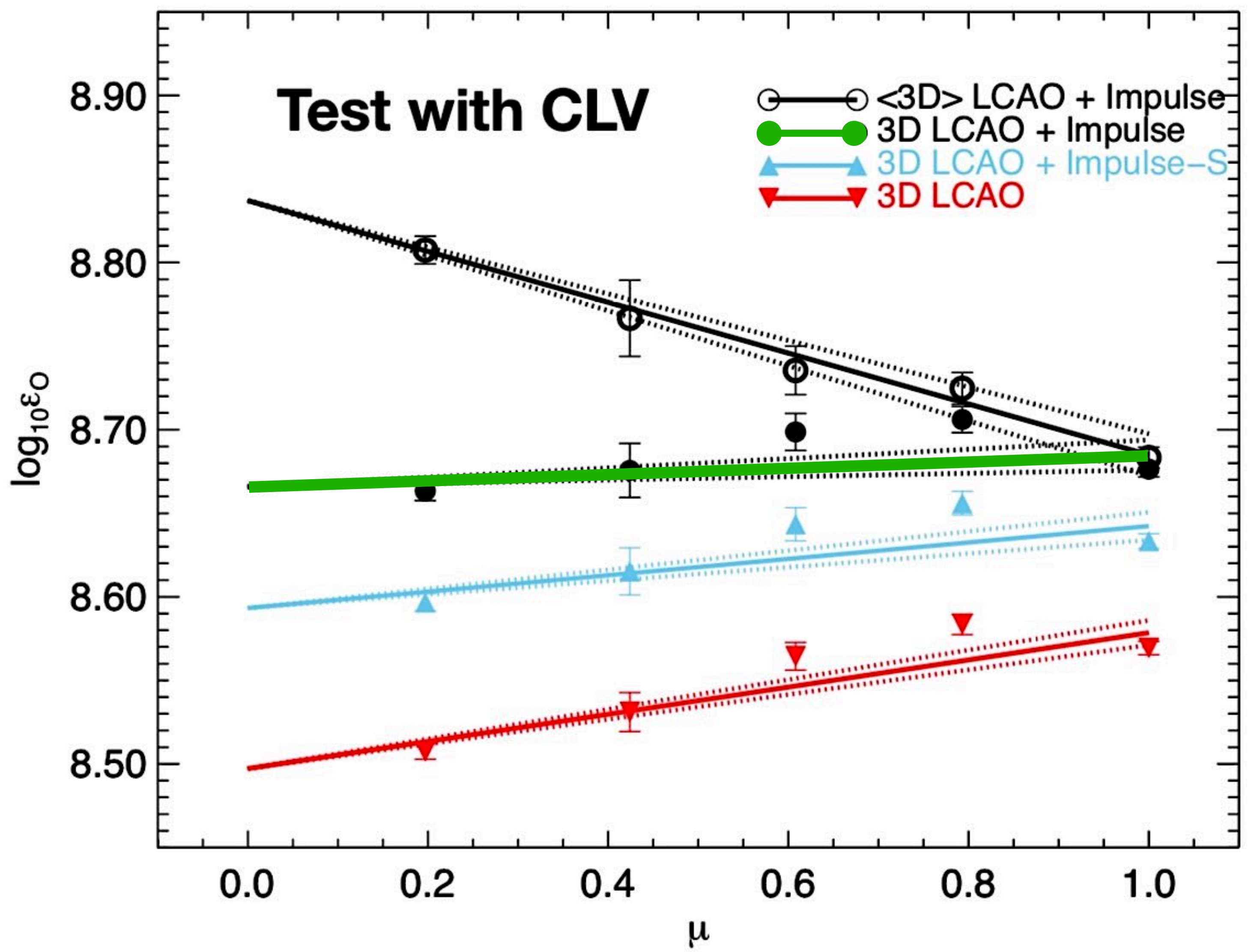
Model O and Fe atoms (Amarsi et al. 2018; Lind et al. 2017)

Oxygen lines and CLV (Sun)

- 3D non-LTE O abundance and CLV: sensitivity to model atmosphere structure and atomic/electronic collisions



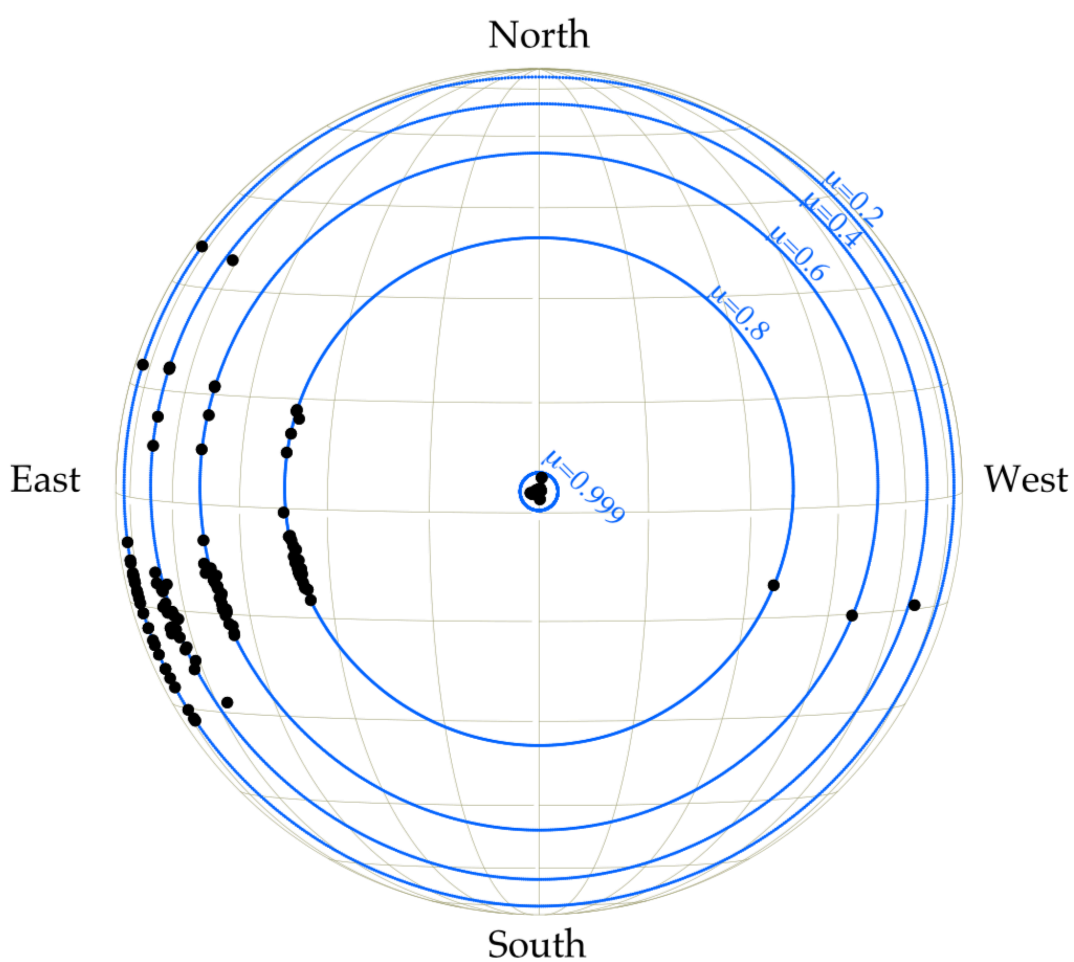
Pereira et al. (2013)

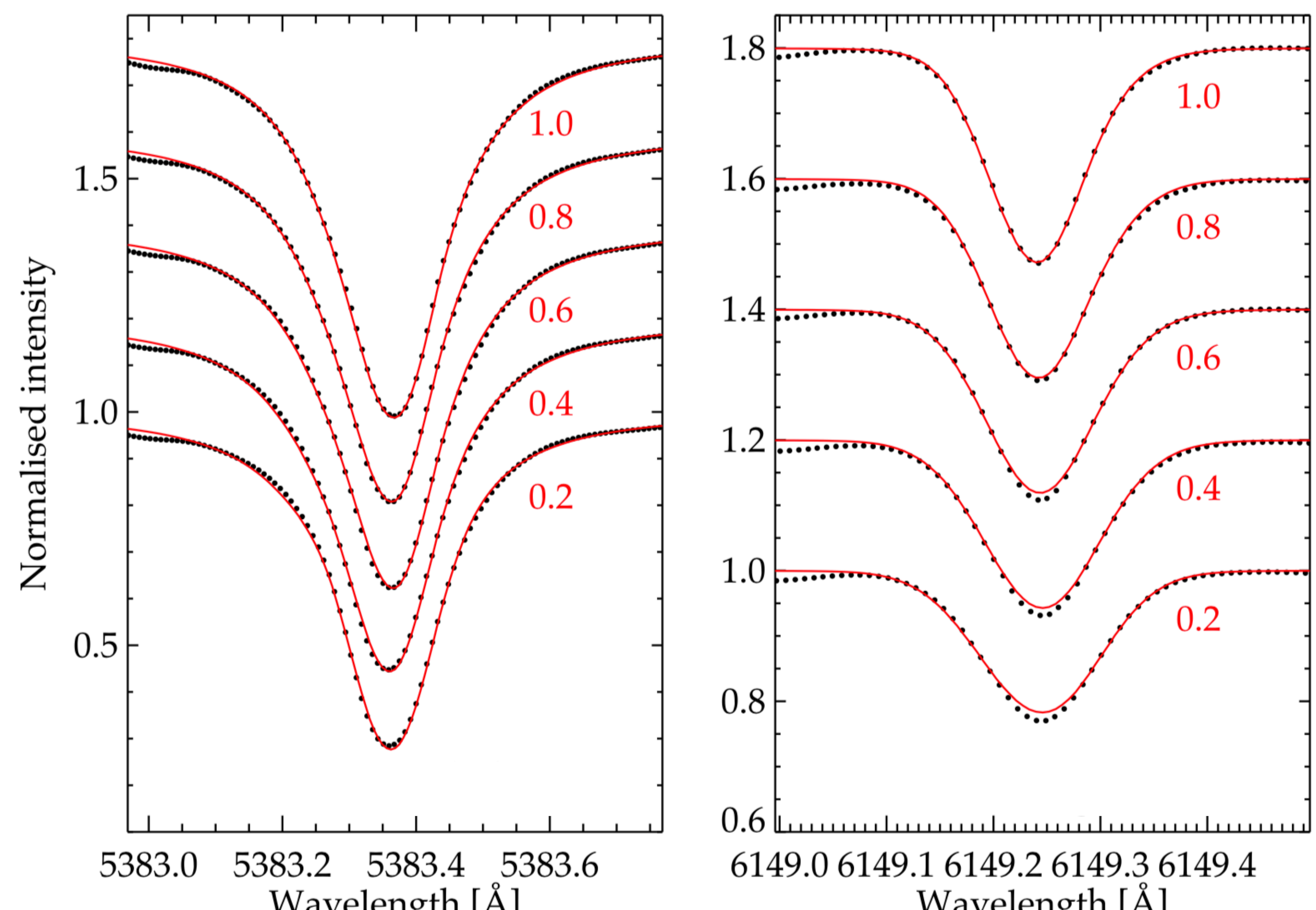


Amarsi et al. (2018)

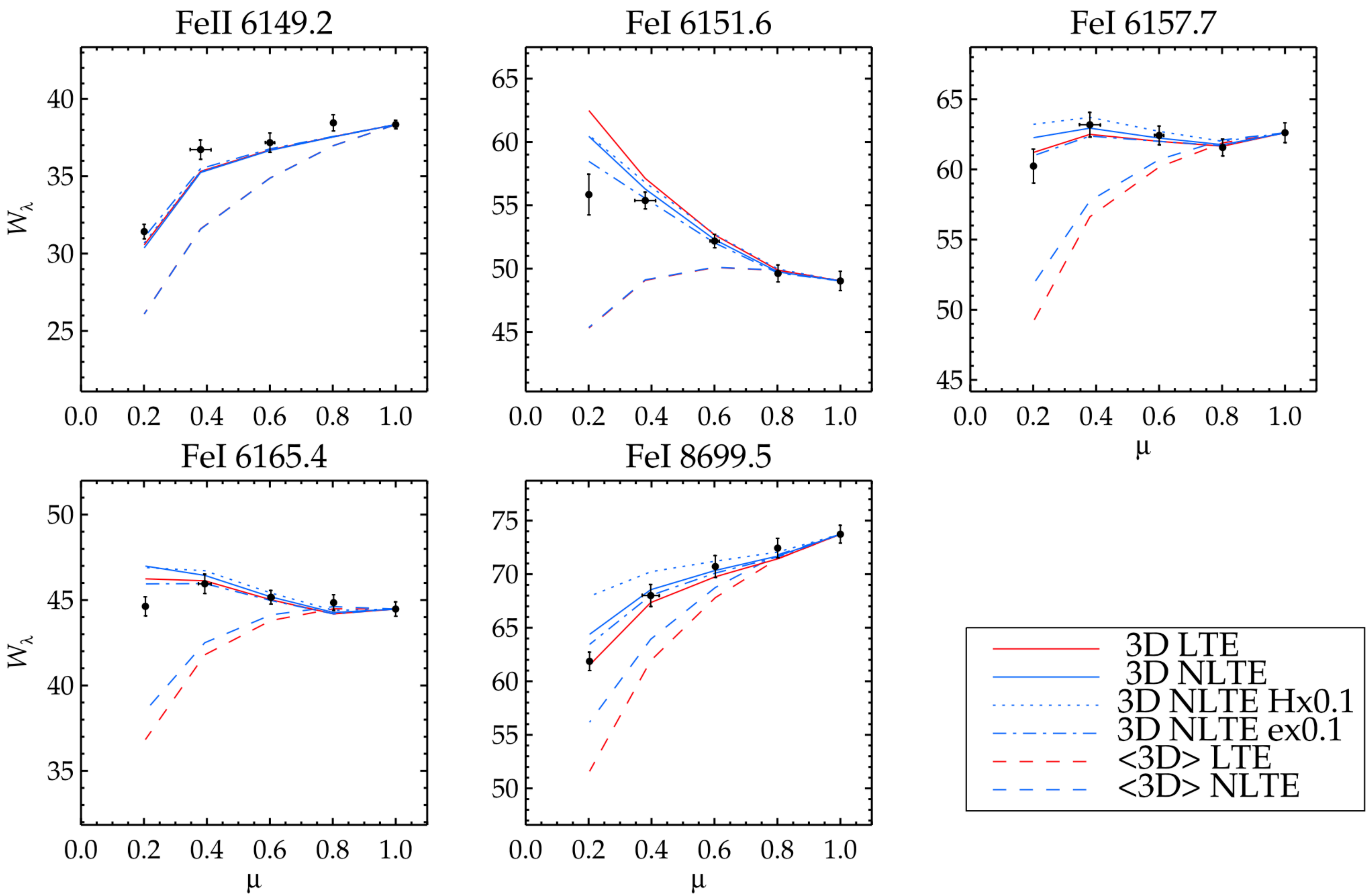
Iron lines and CLV (Sun)

- Observations with Swedish Solar Telescope (Lind et al. 2017)
- 3D non-LTE modelling of Fe I and II spectral lines
- Quantum mechanical Fe+H collisional rates



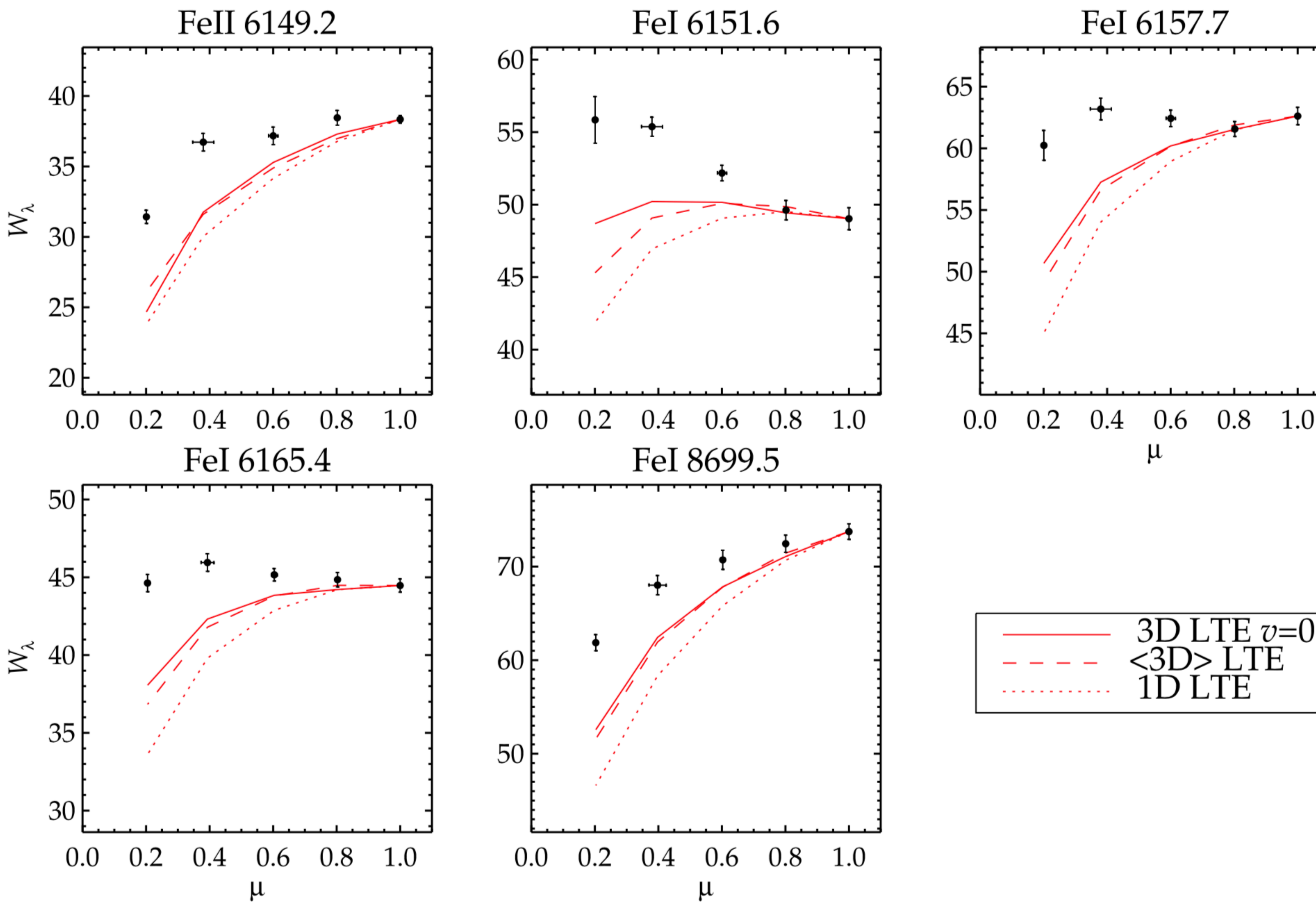


Iron lines and CLV (Sun)



Lind et al. (2017)

Iron lines and CLV (Sun)



Lind et al. (2017)

Collaborators

WP122200 and STAGGER teams:

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