# Multi-D Unified Atmosphere and Wind Simulations of O-Stars

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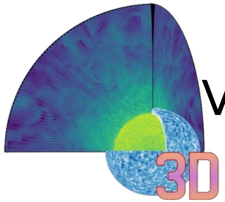


In collaboration with J.Sundqvist, N.Moens, C.Van der Sijpt, Verhamme, L.Poniatowski, F.Backs, L. Delbroek, P. Schillemans..

# Stuck in 'free parameter' HELL

**1D input parameters**

$$M_\star,\ L_\star,\ R_\star,\ \left[\frac{Fe}{H}\right],\ v\sin i$$

$$\dot{M},\ v_\infty, \beta$$

$$v_{micro},\ v_{macro}$$

$$f_{cl},\ f_{vel},\ v_{cl}\ ..$$

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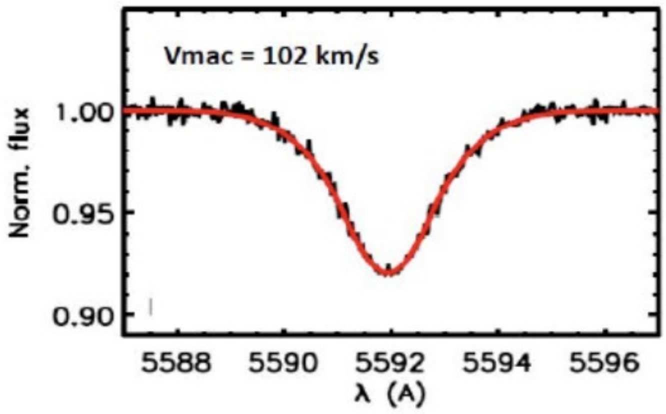
~~$f_{cl},\ f_{vel},\ v_{cl}\ ..$~~

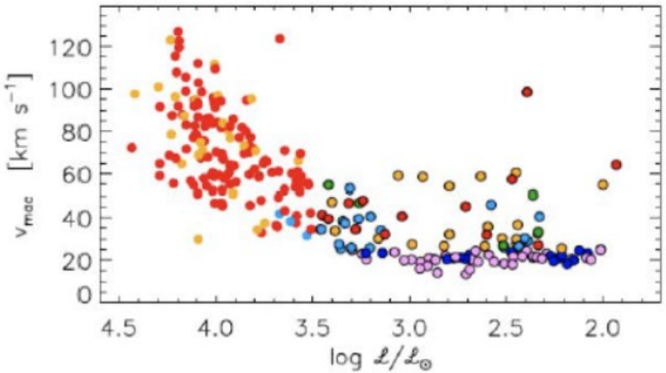
# Observational evidence

- Potential explanation for large **microturbulence** and very large **macroturbulence** needed to fit optical photospheric line profiles

- Effects on e.g. derivation of **chemical abundances**

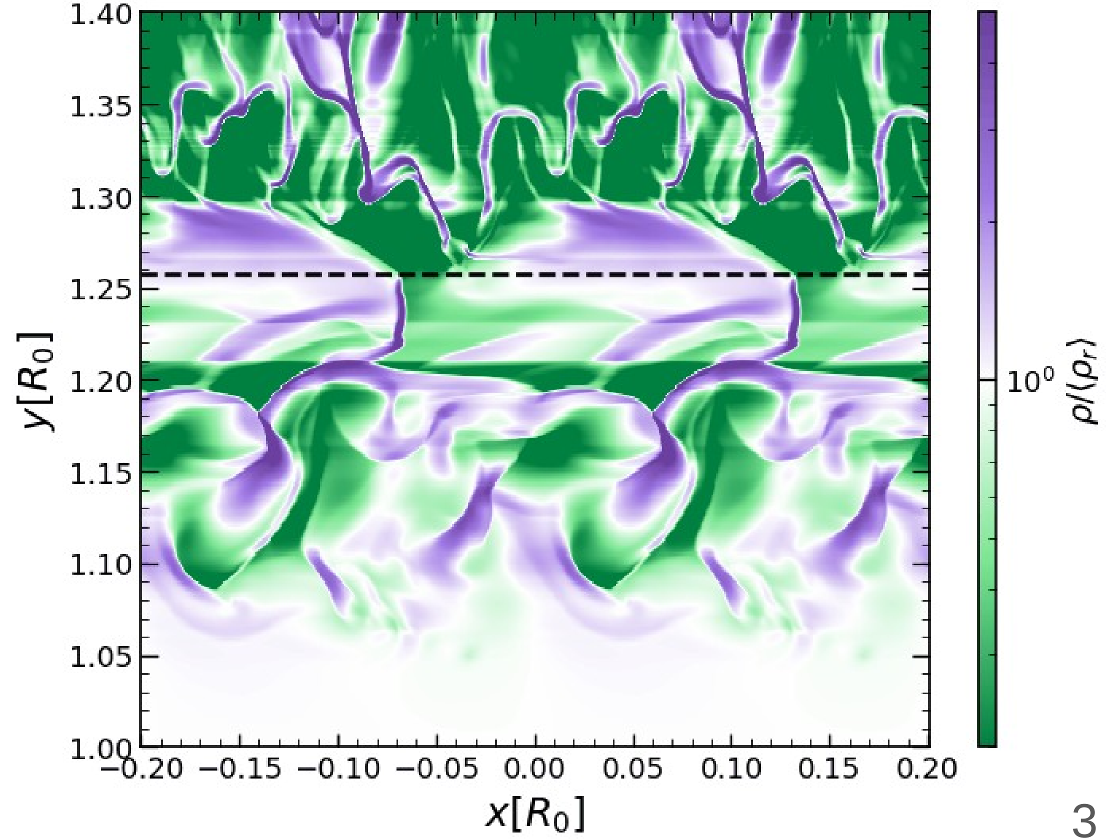
- Log g determination and **mass-discrepancy** (see talk by G. Gonzalez)




Sundqvist et al., 2014;
Simon-Diaz et al., 2017

# Typical simulation set up



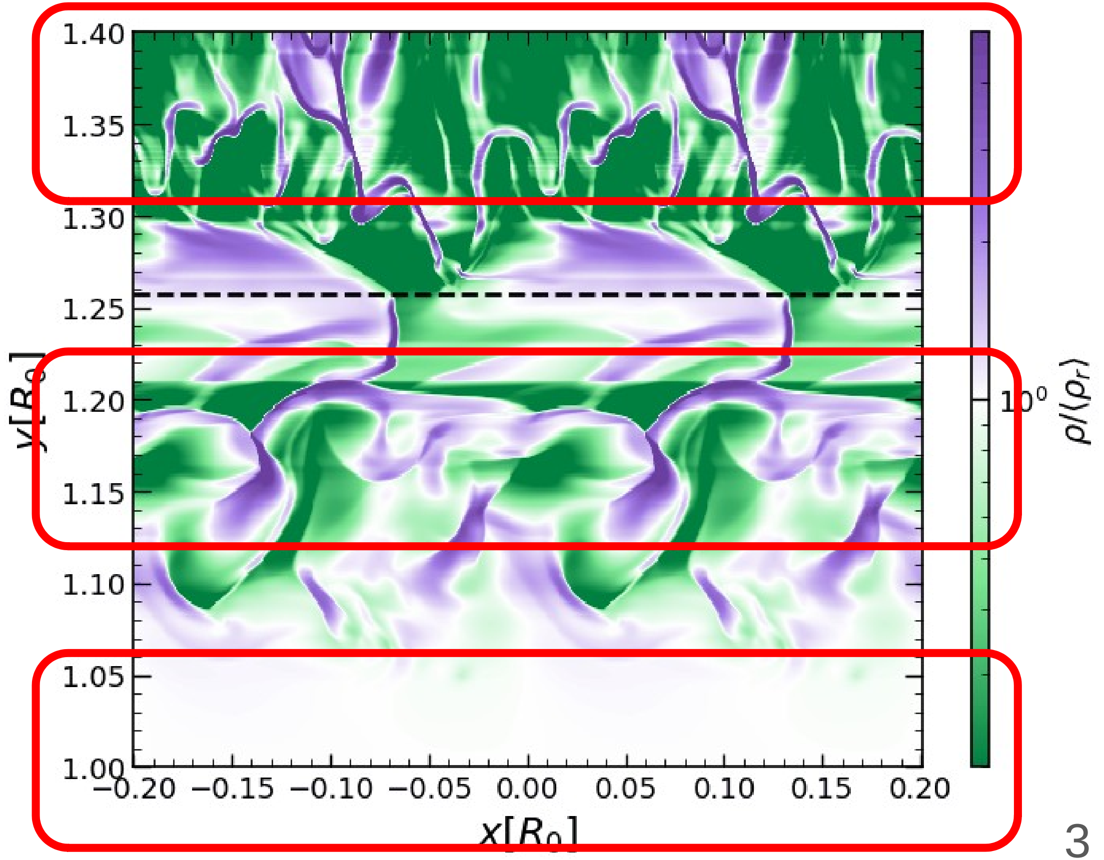
# Typical simulation set up

Outflowing region
20k K

Photosphere
40k K

Turbulent Atmosphere
200k K

Quasi-stable
hydrostatic envelope
400k K

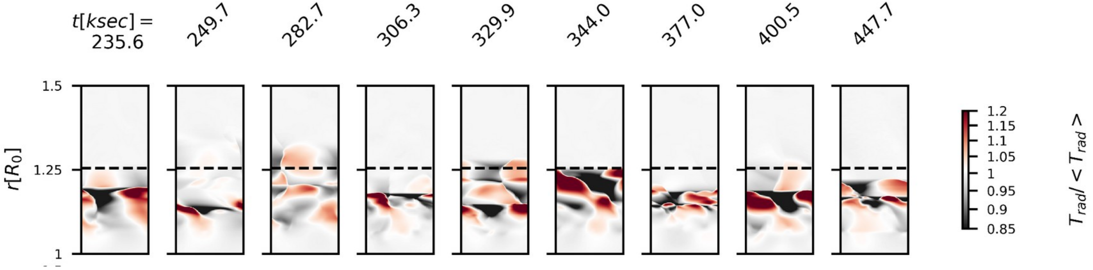


# Simulating ..

MPI-AMRVAC (see talk by N. Moens)

Simulation grid
x-direction (lateral) : 0.2 $R_0$
y-direction (radial) : 3 $R_0$

$$M_\star \sim 58$$
$$R_\star \sim 17$$
$$\Gamma_e \sim 0.27$$

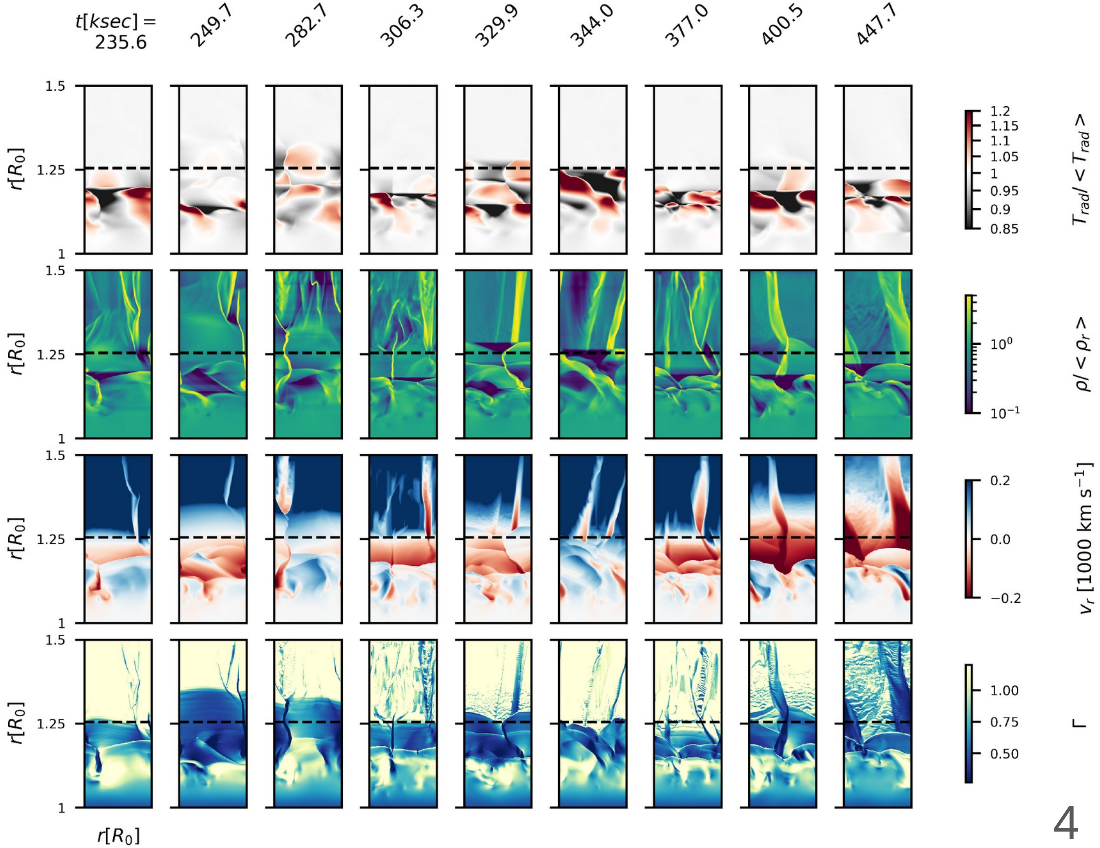



Xia et al., 2018; Keppens et al., 2023; Moens et al., 2022a,b; Debnath et al., 2024

# Simulating ..

Starting from the iron-opacity bump region the atmosphere becomes highly time varying.

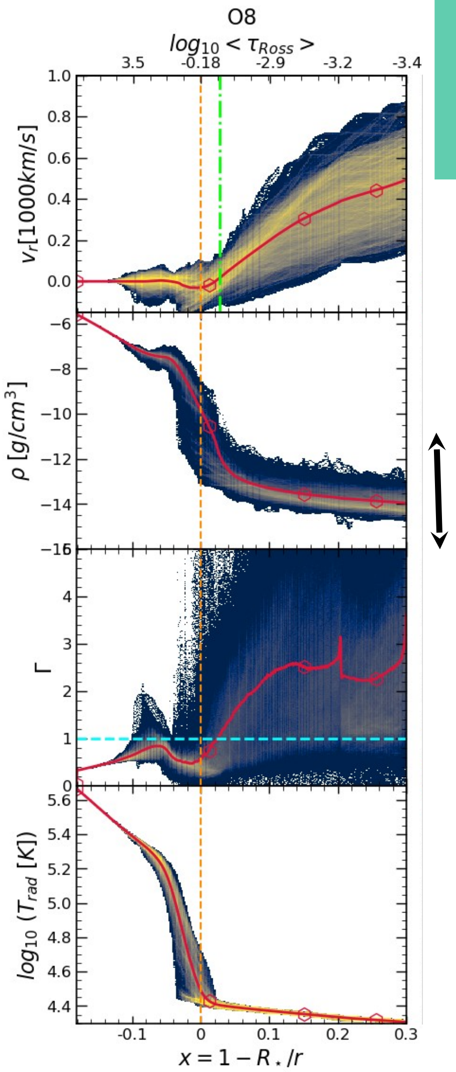
At the iron-opacity bump and outwards the atmosphere becomes highly structured (see the talk by C. Van der Sijpt)




Xia et al., 2018; Keppens et al., 2023; Moens et al., 2022a,b; Debnath et al., 2024

Probability density clouds, likelihood of finding a cell with a specific value for the given quantity at a given radial coordinate.

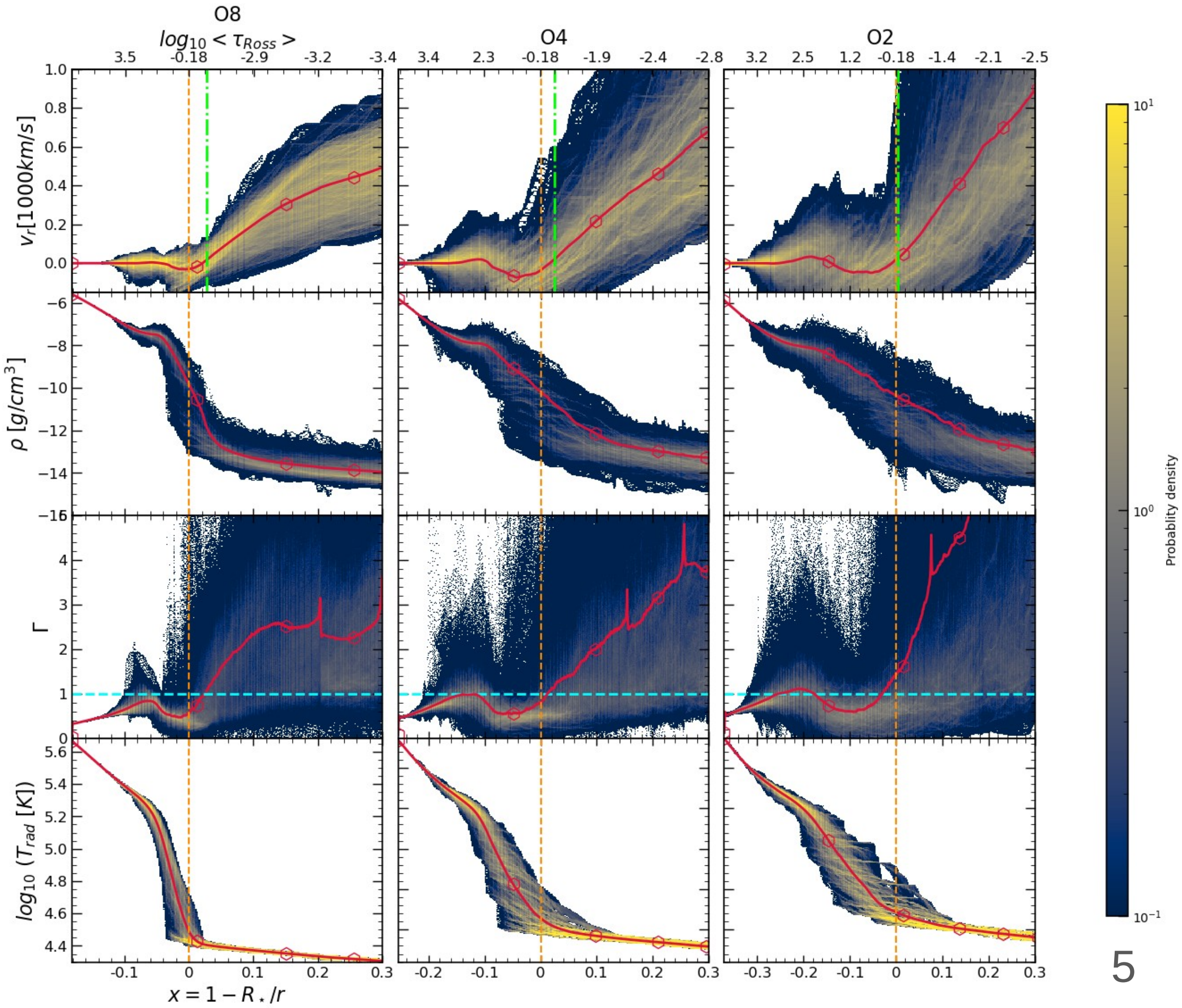
The red curves are the lateral and time averaged quantity




Higher spread signifies a structured atmosphere, and wind outflow

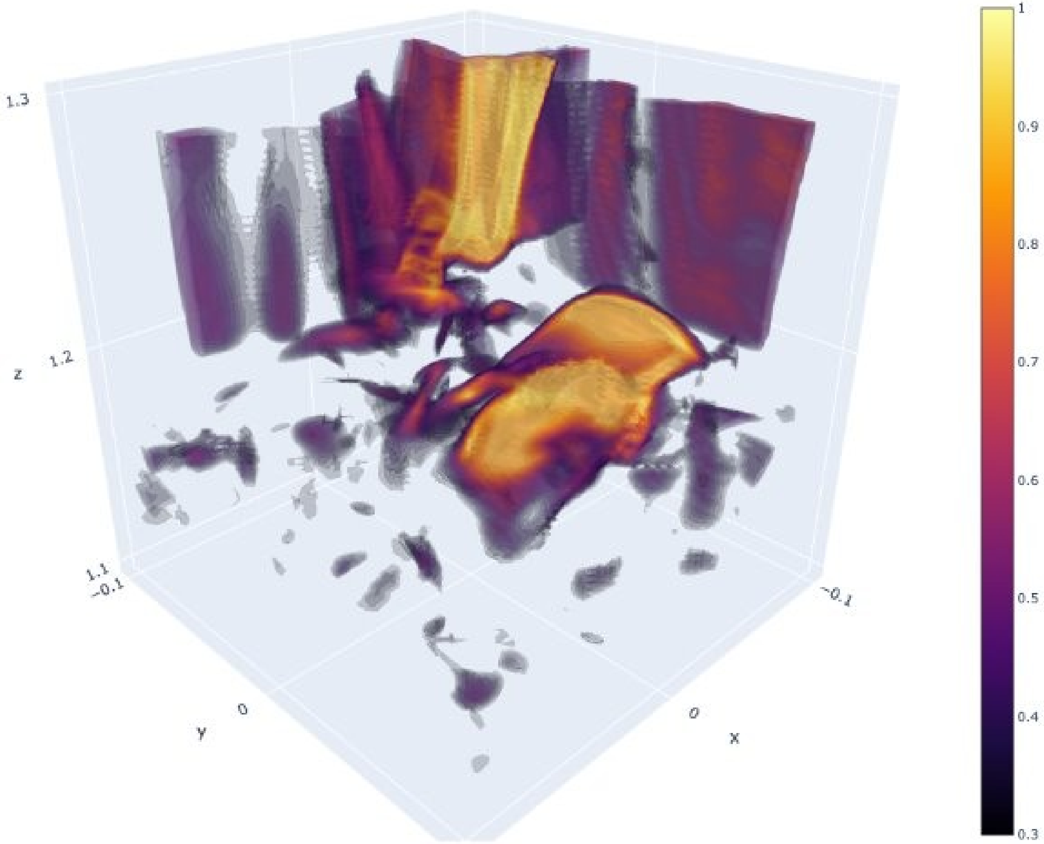
At the iron bump as the eddington $\Gamma \sim 1$, we start observing a lot of dispersion - can’t be captured in 1D.

The higher $\Gamma$ models exhibit larger dispersion from the mean.




* the stellar parameters provided in Debnath et al., 2024

# What about 3D ?

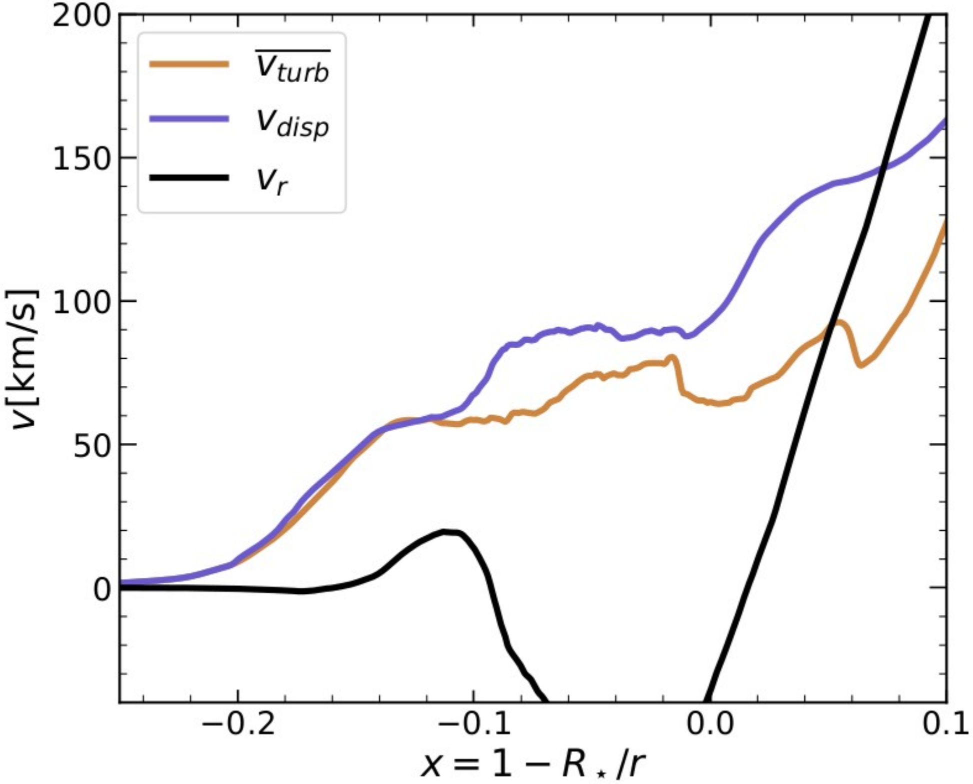



Qualitatively, we find similar structural behaviour in 3D as in 2D.

Lot of under and over dense structures, originating from the iron bump region.

Highly turbulent atmosphere

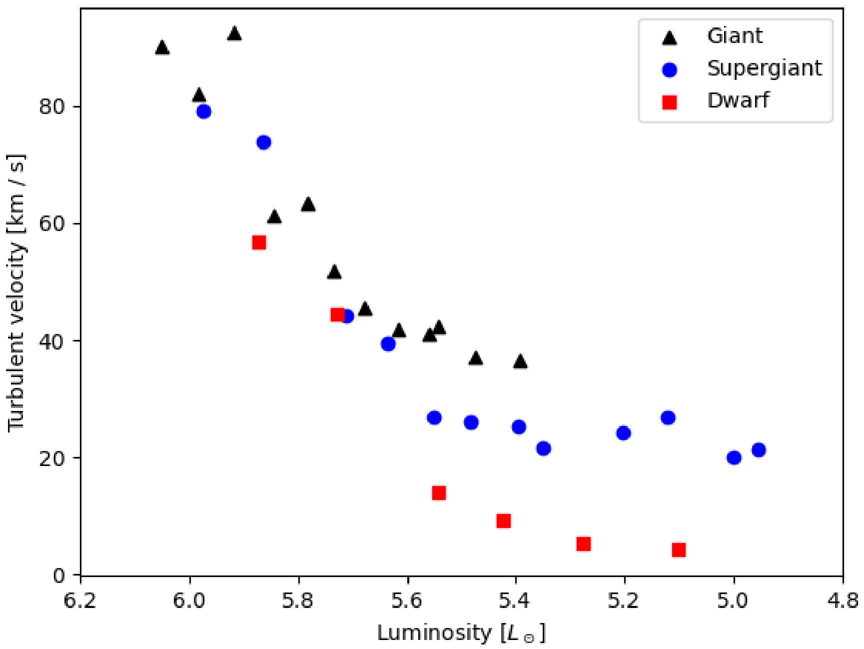
# Hold on! We got turbulence

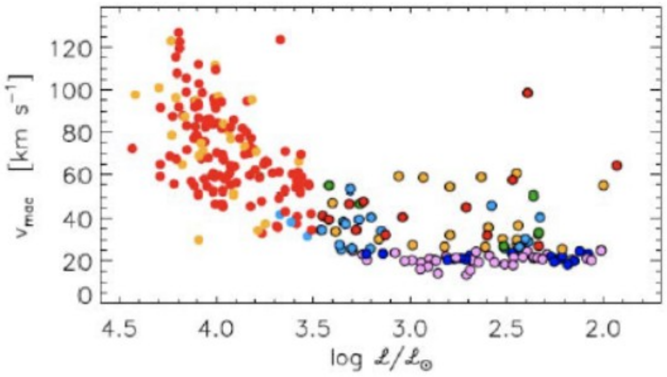



Turbulent velocities are in the range of the ad-hoc extra broadening terms used in 1D codes.

Turbulence as the natural explanation for macro-turbulent velocities used to match observations in 1D atmospheric models (See the talk by L. Delbroek)

# Hold on! We got turbulence

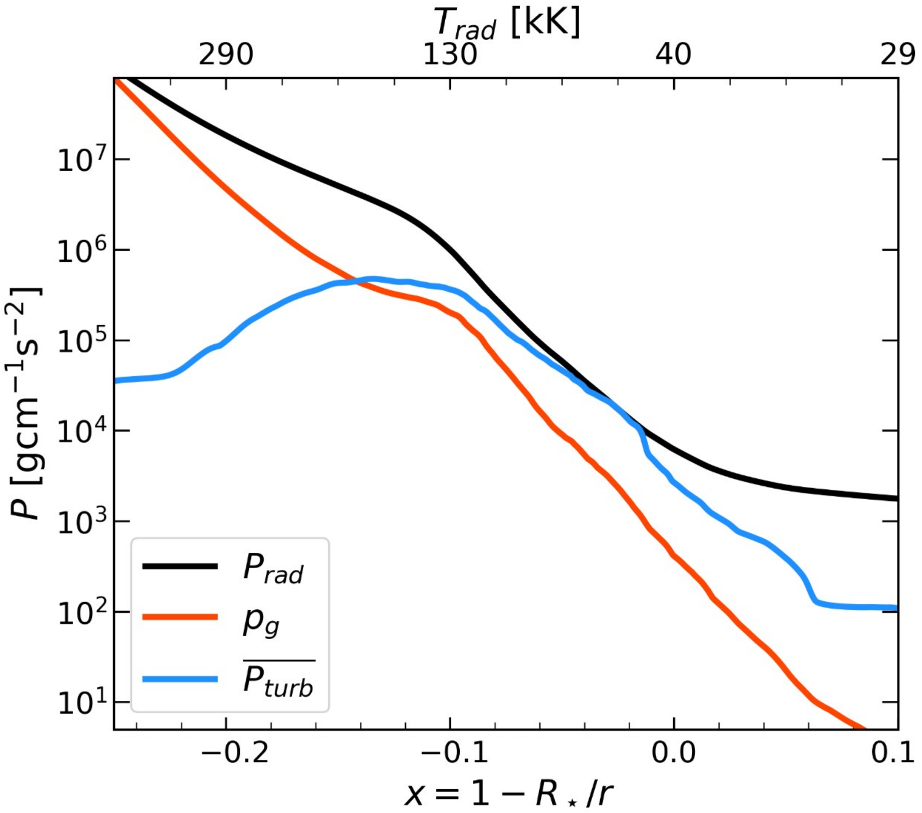



Turbulent velocities scales with luminosity, following the same trend as the ad-hoc macro turbulence.

Moens et al. (in prep),
Simon-Diaz et al., 2017

# Missing Turbulent Pressure in 1D models




Such high turbulent velocities gives rise to high turbulent pressure

Around the photosphere the main contribution to the total pressure is from the radiation and turbulent pressure

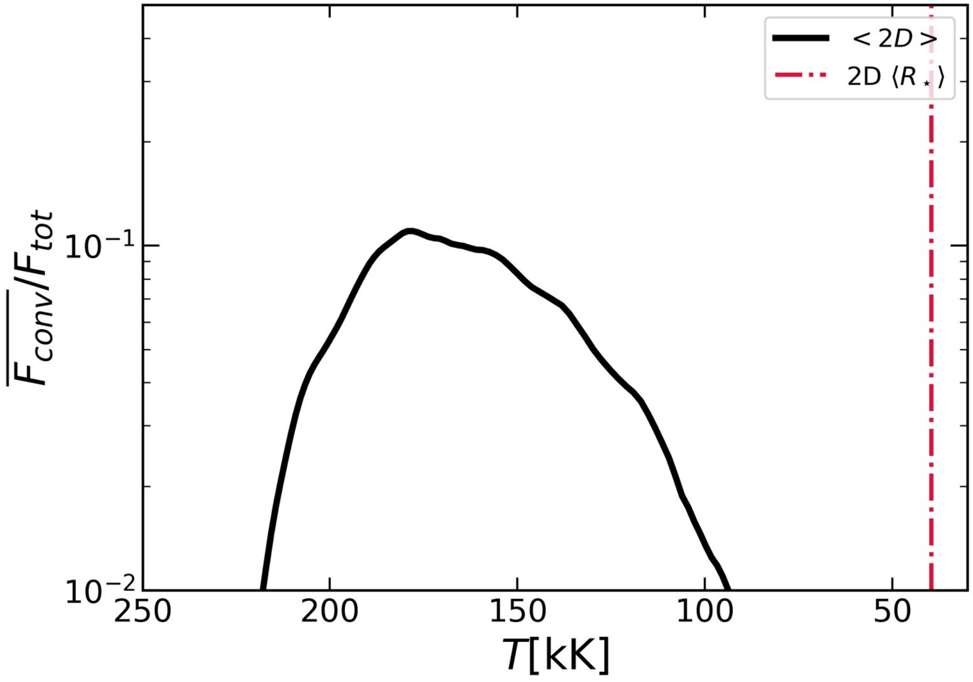
# Energy transport via convection

$$\overline{F_{\rm conv}} = \langle v_r(p_{\rm g} + e_{\rm g}) + v_r(P_{\rm rad} + E_{\rm rad})\rangle$$

Gas enthalpy

Radiation enthalpy

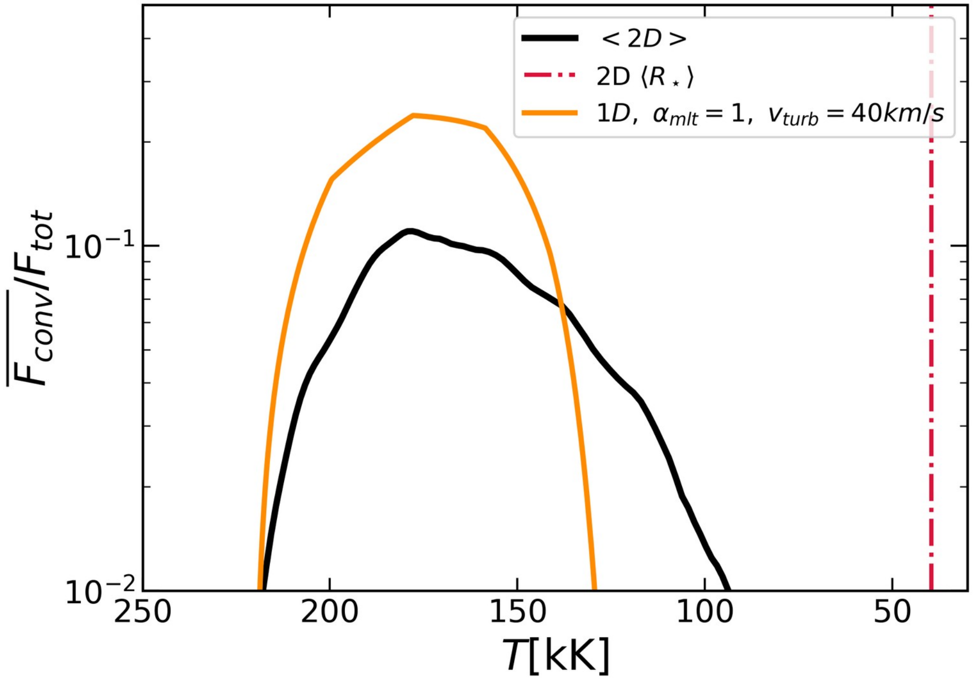
Only **10%** of the total energy is transported at maximum in the O4 model (Debnath et al., 2024) (at the iron-opacity peak region) by convection. Similar findings by Jiang et al., 2015, their STARTOP model.



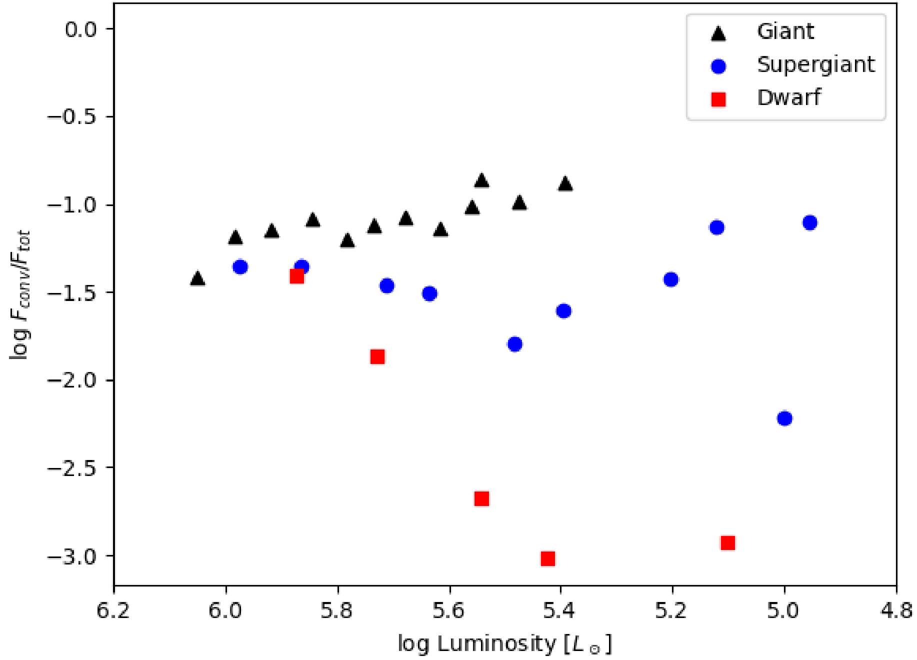
# Energy transport via convection

$$\overline{F}_{\rm conv} = \langle v_r(p_{\rm g} + e_{\rm g}) + v_r(P_{\rm rad} + E_{\rm rad})\rangle$$

In standard mixing length theory they try to reproduce such an effect by the MLT $\alpha$. To match our 2D simulation we only need $\alpha \sim 0.5$ in our simplified 1D model.



# Energy transport via convection



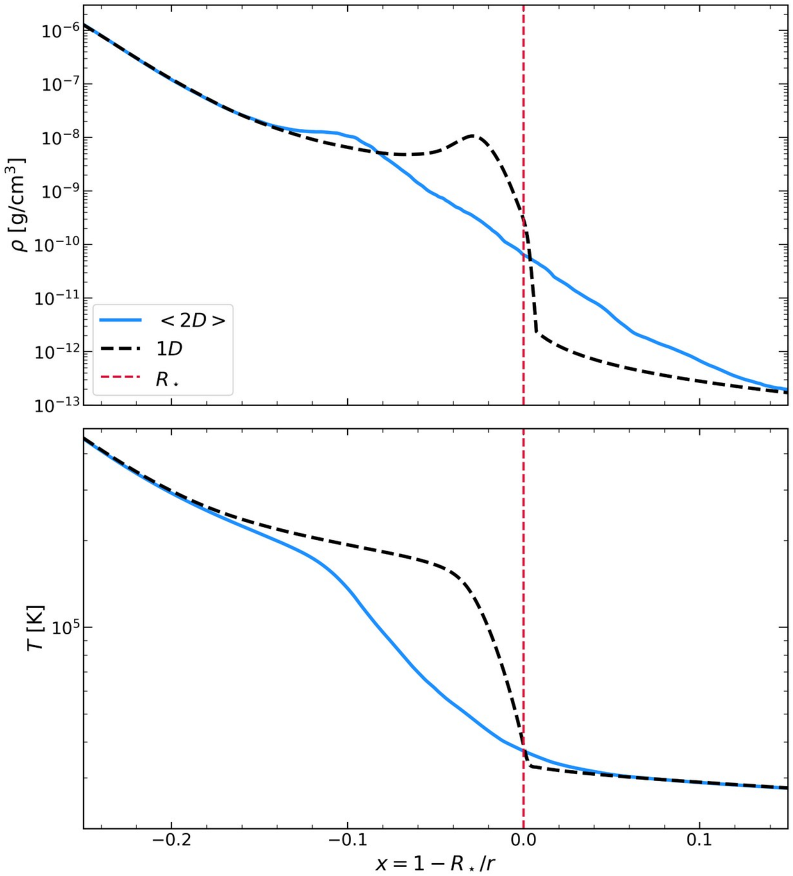

Unlike Sun where it can reach much values of almost 100% the convective fluxes are much lower. Although, unlike Sun, it’s an opacity effect rather than classical convection.

There is no clear trend with luminosity, although preliminary results tends to point towards a log g dependence.

Moens et al. (in prep)

# 1D calibration and comparison to 2D

Calibrating our models to have same Teff and Rstar

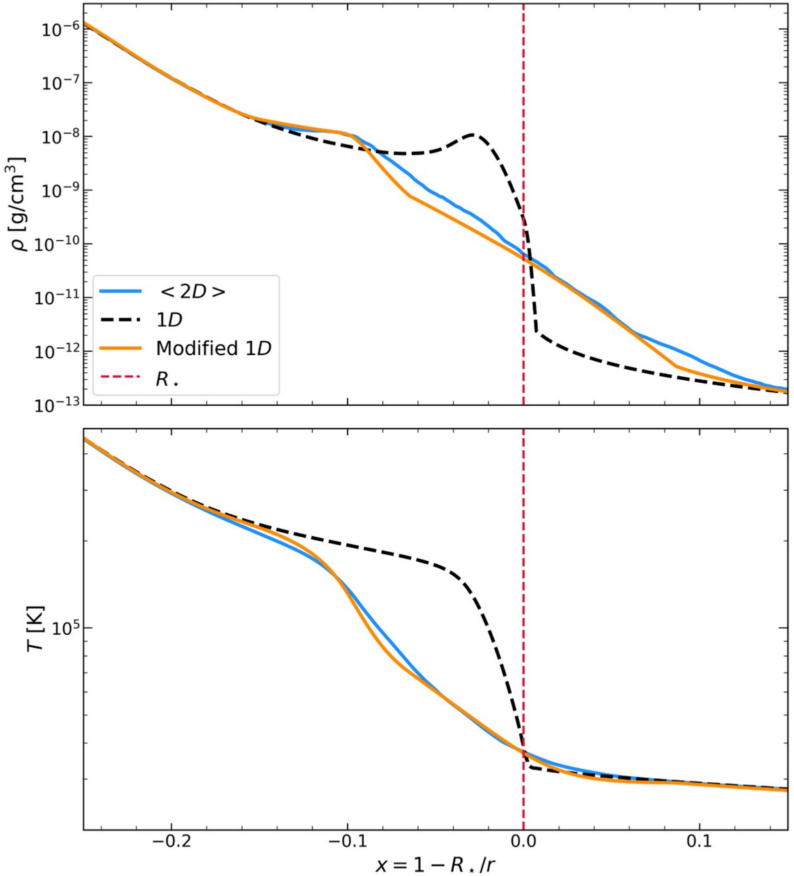


# 1D calibration and comparison to 2D

Calibrating our models to have same Teff and Rstar

We modify the 1D by adding in a simplified prescription of convection, using Schwarzschild criterion, with $\alpha \sim 0.5$

We also add turbulent pressure to the total pressure. Done by adding a turbulent velocity of ~90 km/s at the photosphere, reducing to 0 inwards.



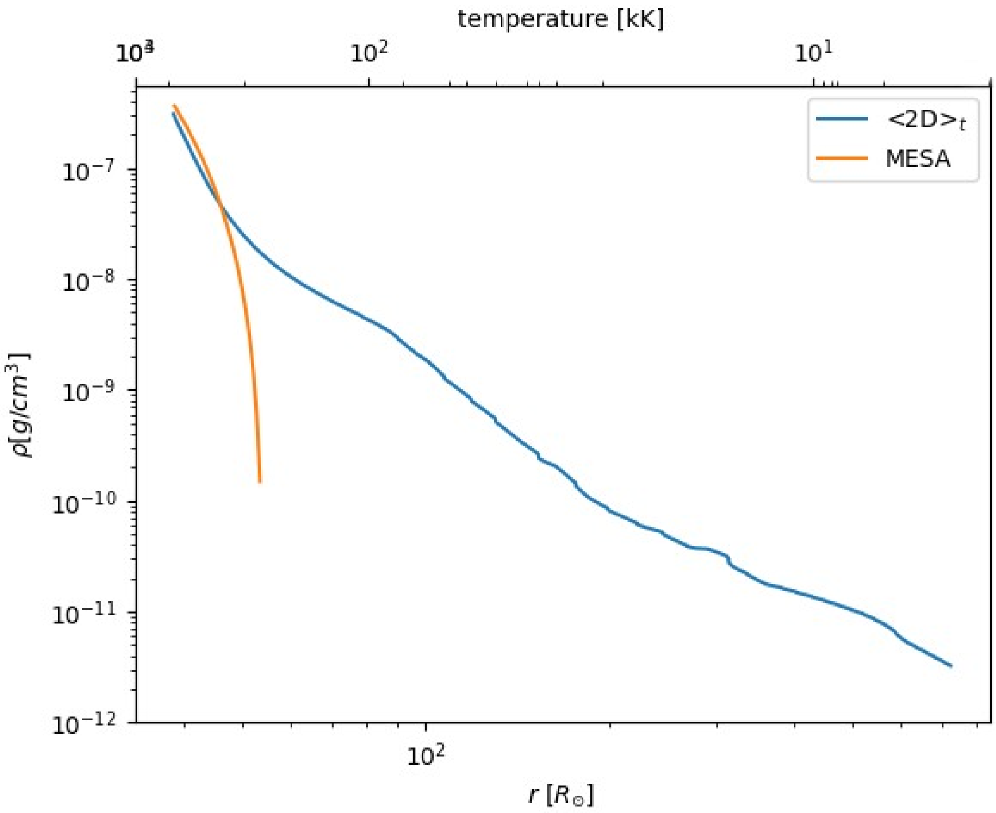
# Final thoughts and implications

**Structure** appears at around the **iron-bump region**, results in a lot of variability (see also talk by C. Van der Sijpt).

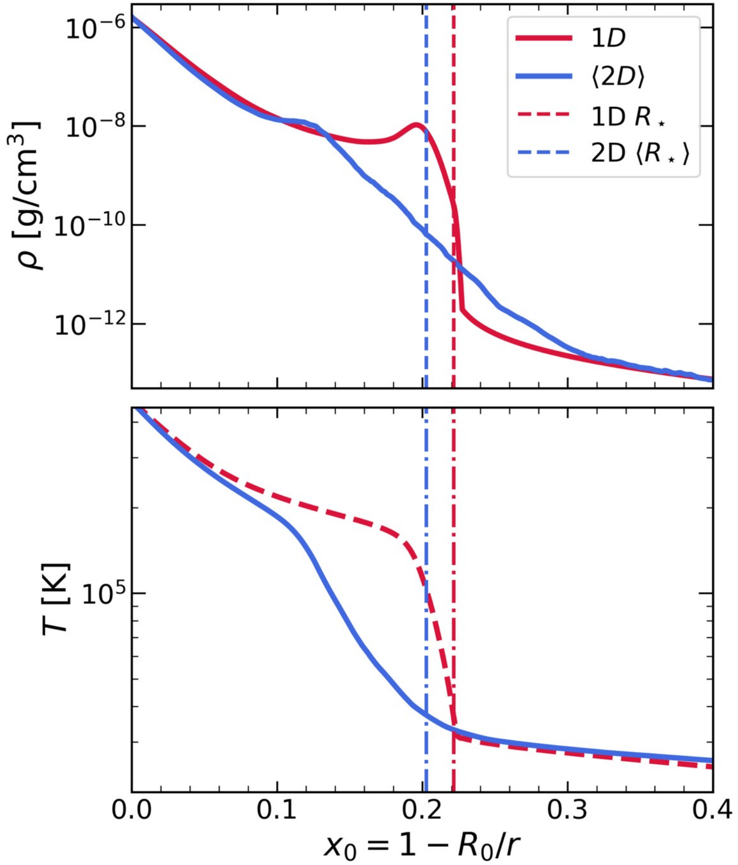
<2D> show **stark differences** compared to 1D profiles, can be replicated by adding **turbulent pressure** and **convective flux.**

**Turbulence** can be a natural explanation of macro-turbulence broadening (see also talk by L. Delbroek).

# Comparison with MESA



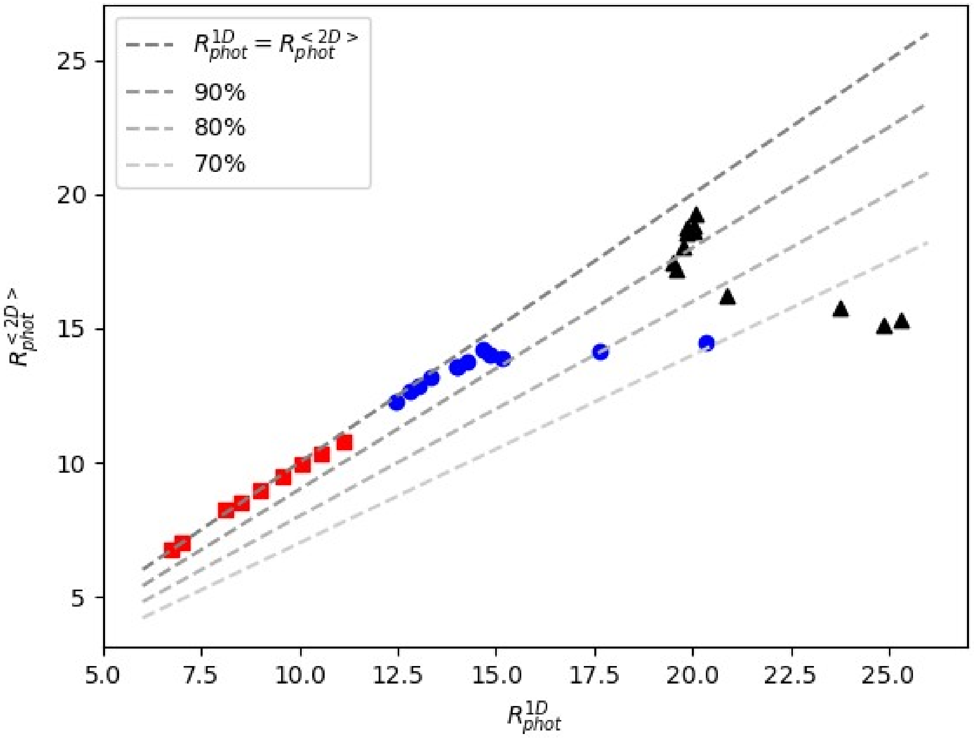
# Deflation ?




When compared with the input 1D with averaged <2D> has,

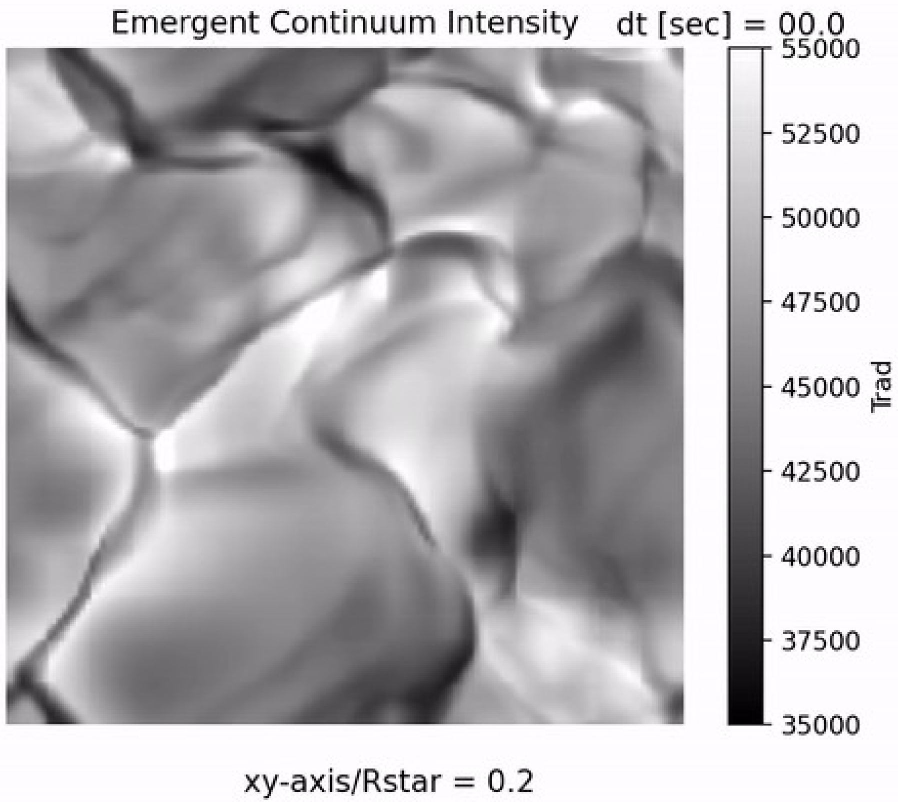
- ➢ Less envelope expansion than 1D, thus higher effective temperature.
- ➢ Sharp density inversion is no longer present in <2D>. Much shallower slope around the photosphere. Different density height scale.

# Deflation ?



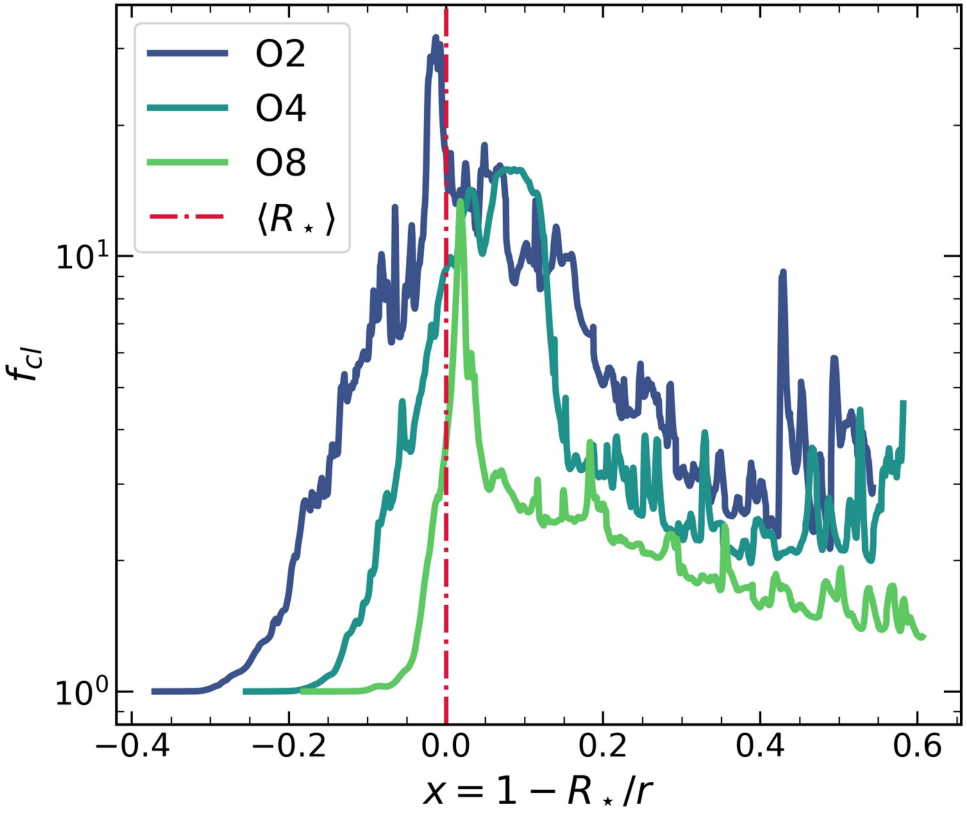

Moens et al. (in prep)

# Surface Brightness

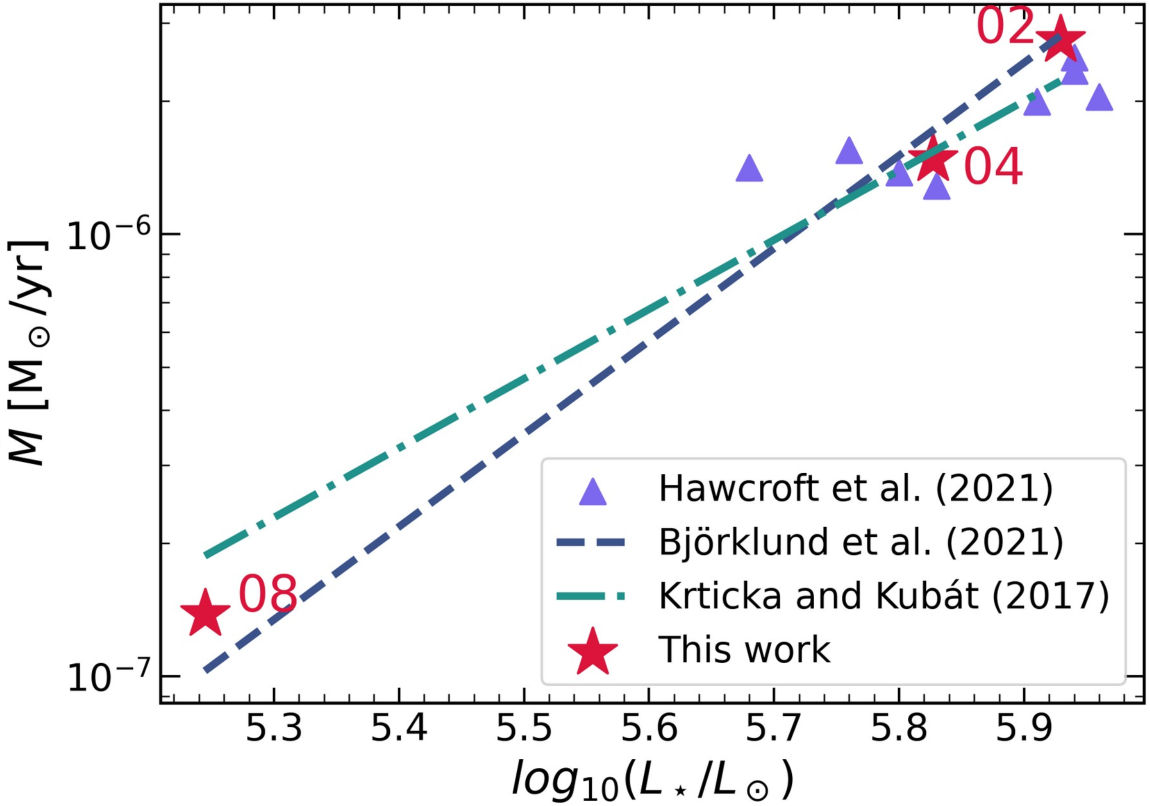



- ➢ Such structured atmosphere also gives rise to a variable emergent intensity
- ➢ The plot shows the surface brightness profile with darker regions being colder and vise versa (see talk by Delbroek)
- ➢ Quite reminiscent to the solar-surface like granulation

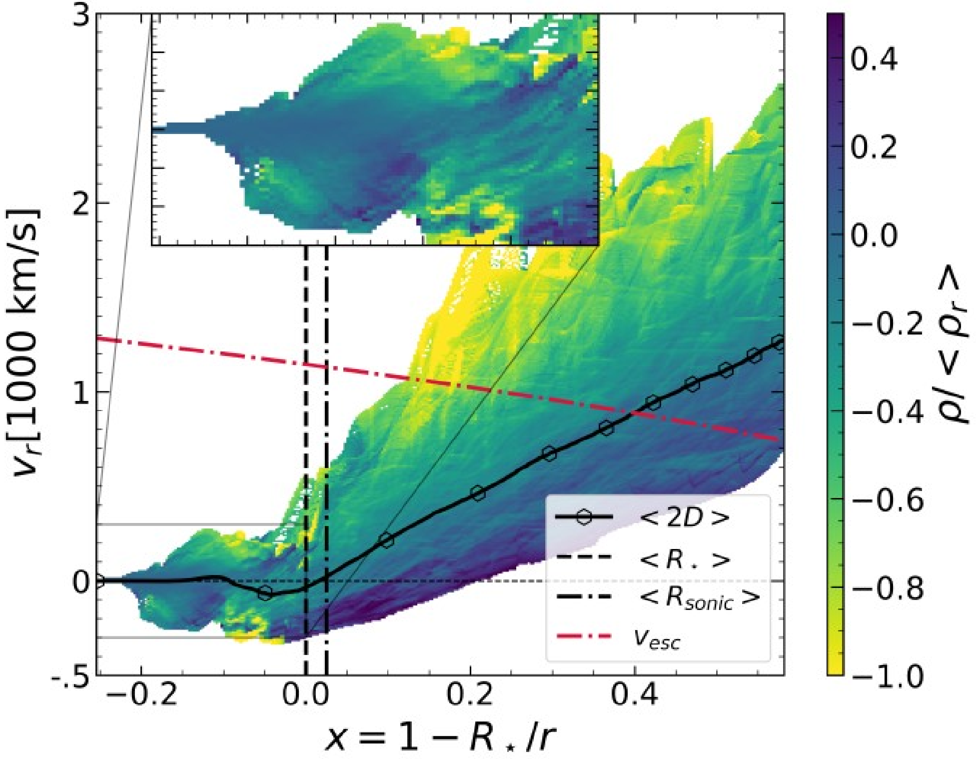
# Clumping factors



# Mass loss rates



# Anti correlation between density and line-driving



# Hybrid Opacity