Combined efforts: 1D vs multi-dimensional atmospheric model comparison for O and WR stars

Gemma González-Torà

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POEMS, 25th June 2024, Rio de Janeiro

Combined efforts

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1D PoWR model

Postdam Wolf-Rayet stellar atmosphere code (PoWR, Gräfener+02)

1D PoWR model

Spherical

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Full hydrodynamic equations (Sander+17)

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small scale, optically thin clumps surrounded by a void medium.

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1D PoWR model, β-law

- Assume an analytic velocity law for the wind:

$$v(r) = p_1 \left(1 - \frac{1}{r + p_2}\right)^{\beta}$$

- With boundary conditions: $v(r_{max})=v_{\infty}$, $v(r_{con})=v_{con}$ and initially $\beta=0.8$ (Pauldrach+86).
- Using the mass continuity equation with a fixed mass-loss rate, $\dot{M}$:

$$\dot{M} = 4\pi r^2 v(r)\rho(r)$$

1D PoWR model, microturbulence term

- In the subsonic regime, the density and velocity are obtained integrating the hydrostatic equation:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho(r)\left[g(r) - a_{\mathrm{rad}}(r)\right]$$

- To connect density and pressure we use the ideal gas equation of state:

$$P(r) = \rho(r) a_{\mathrm{s}}^2(r)$$

- Including a turbulence term in the speed: $a_{\mathrm{s}}^2(r) = \frac{k_{\mathrm{B}} T(r)}{\mu(r) m_{\mathrm{H}}} + \frac{1}{2} v_{\mathrm{mic}}^2(r)$

- So we obtain a turbulent pressure term: $P_{\mathrm{turb}}(r) = \frac{1}{2}\rho(r) v_{\mathrm{mic}}^2(r) = \rho(r) v_{\mathrm{turb}}^2(r)$

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This turbulence term in the hydrostatic equation is NOT the same as the microturbulent broadening in the line profiles!

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Multi-D radiation hydrodynamic models

Radiation hydrodynamic (RHD) module of MPI-AMRVAC (Xia+18)

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Hybrid approach
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Flux limited diffusion method (FLD, Moens+22a), to reconcile optically thick and thin regimes flux consistency.

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The models go deeper to the *iron-opacity peak* region

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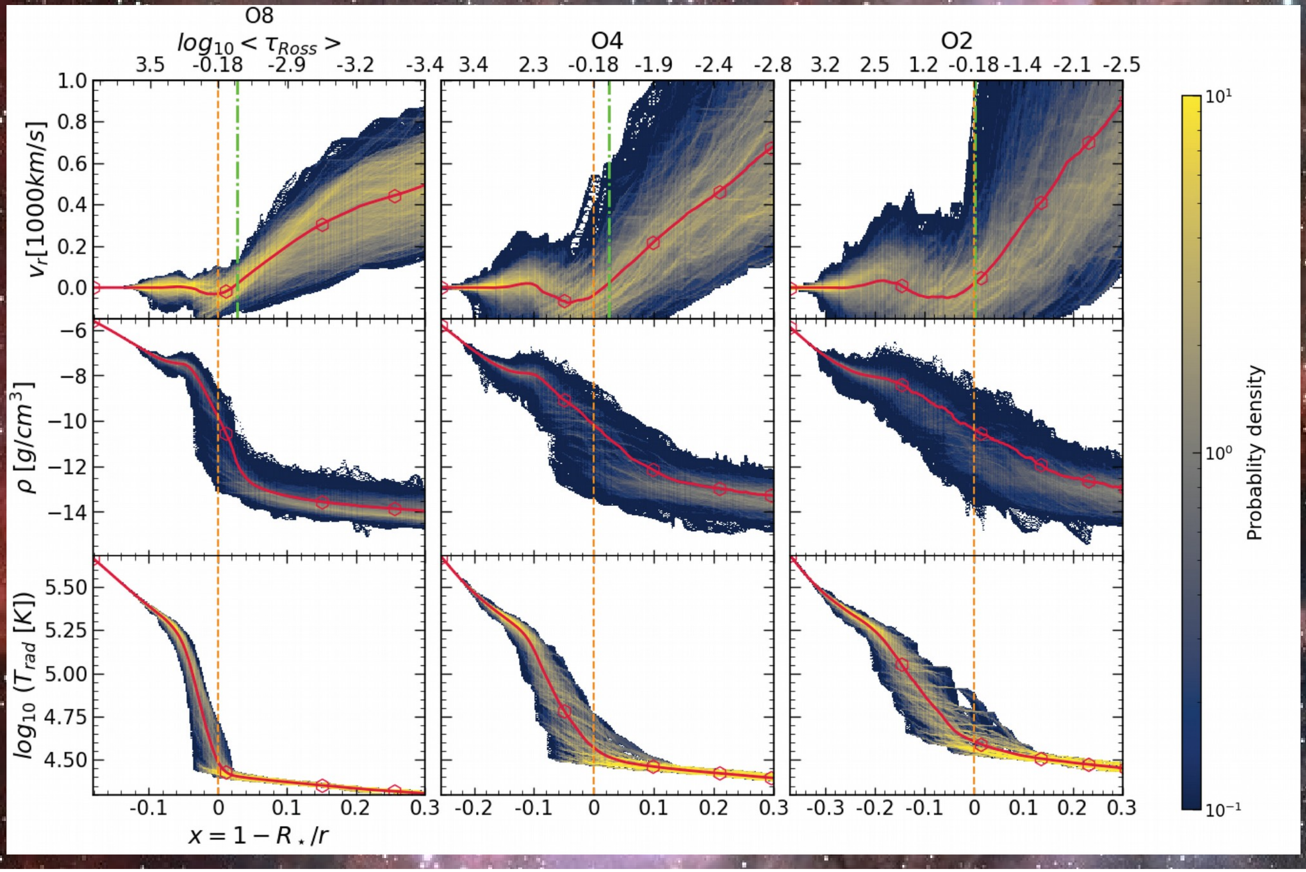
Sub-surface motion, parametrized as turbulent velocity.

Multi-D O-star modelling

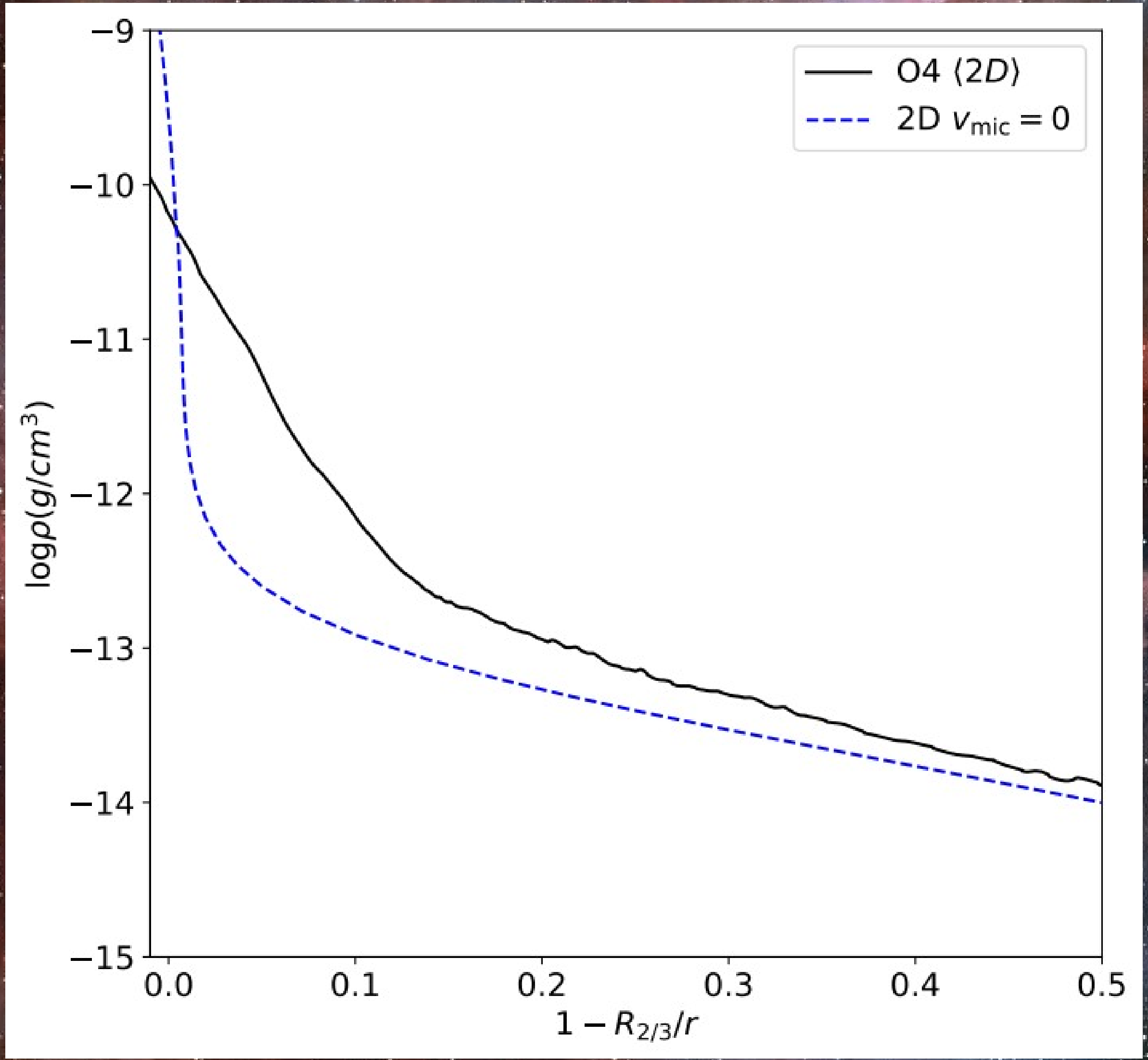


Model	$\langle T_{\rm eff}(\rm kK)\rangle$	$M_\star/M_\odot$	$\langle R_\star\rangle/R_\odot$	$\log_{10}(\langle L_\star\rangle/L_\odot)$	$\langle L_\star\rangle/L_{\rm edd}$	$\log_{10}\langle g_\star\rangle$	$\log_{10}\langle\dot{M}\rangle$ $(M_\odot\,{\rm yr}^{-1})$
O8	33.3	26.9	12.26	5.23	0.16	3.69	–6.86
O4	39.6	58.3	16.98	5.78	0.27	3.74	–5.84
O2	43.8	58.3	15.99	5.93	0.38	3.79	–5.56

Debnath+24

- Debnath+24.
- Multi-dimensional, time-dependent, RHD simulations.
- For O8, O4 and O2 (super-)giants.
- Depth-dependent turbulent velocity:
  - O8 → $v_{turb}(r_{phot})$~30 km/s
  - O4 → $v_{turb}(r_{phot})$~60-80 km/s
  - O2 → $v_{turb}(r_{phot})$~100 km/s

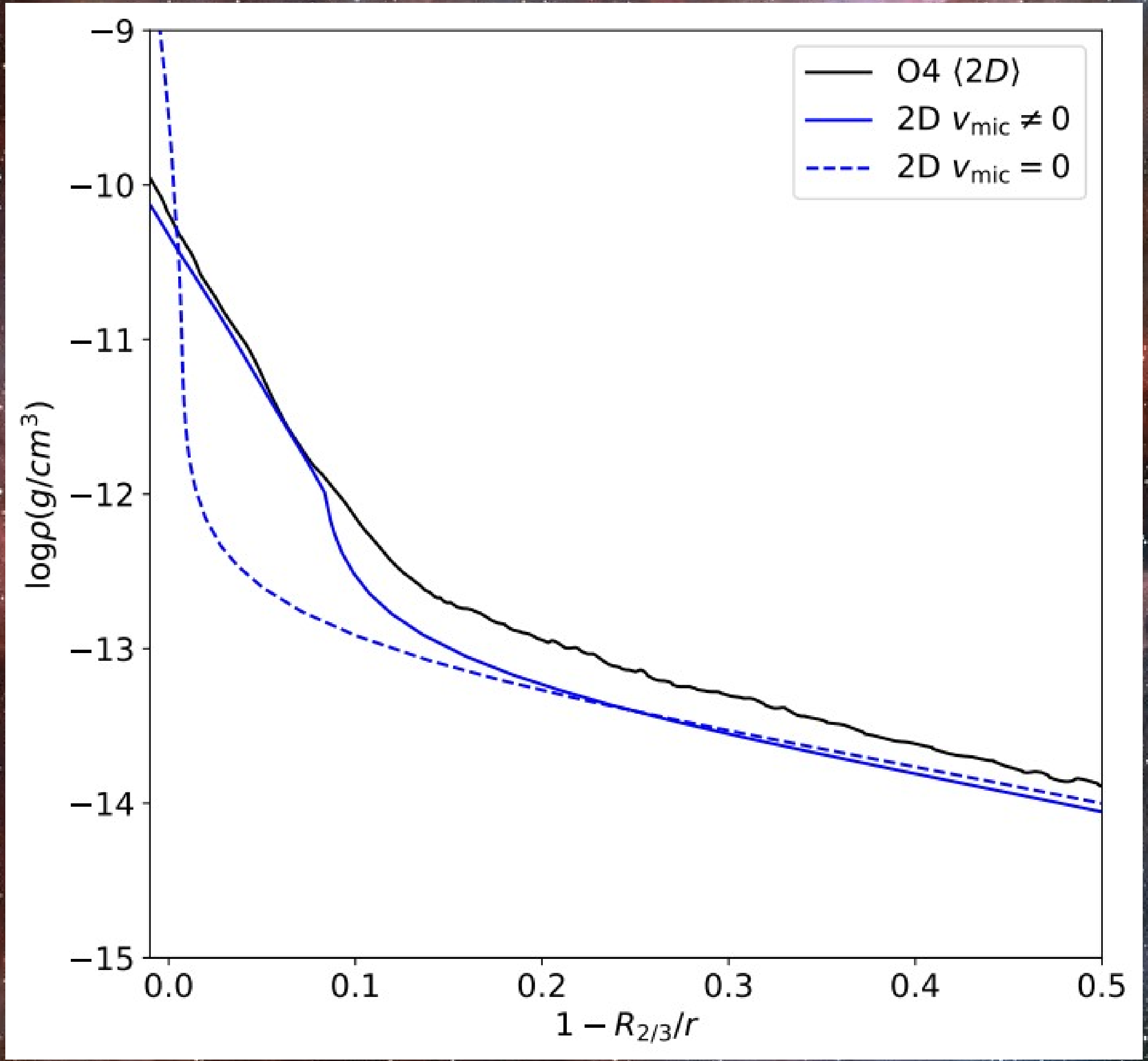
Profile comparison, density



- Same parameters as Debnath+24 averaged 2D models.

González-Torà et al., in prep

Profile comparison, density



- Same parameters as Debnath+24 averaged 2D models.
- Including a v_{mic}=125 km/s (v_{turb}=88.4 km/s).

González-Torà et al., in prep

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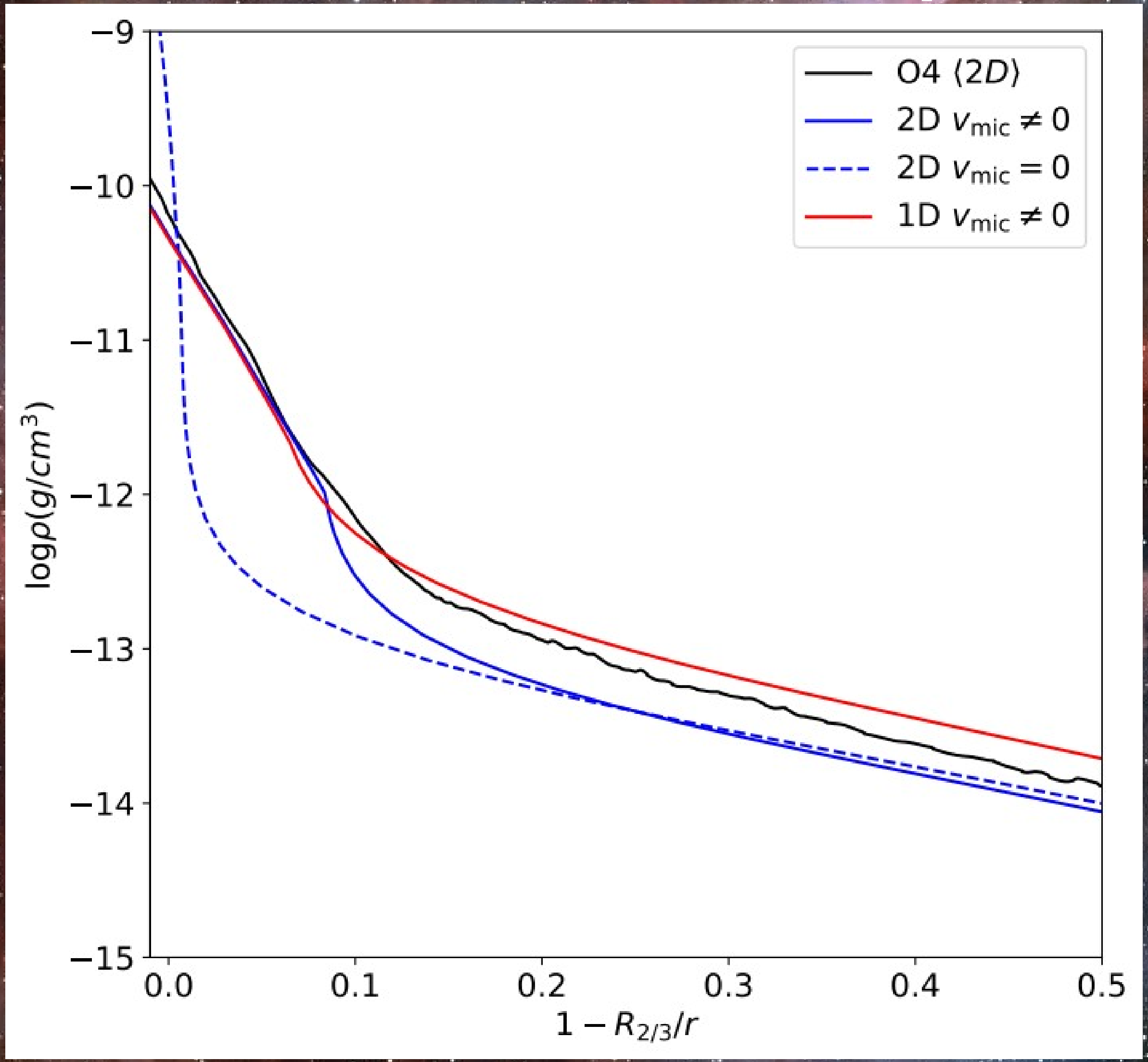
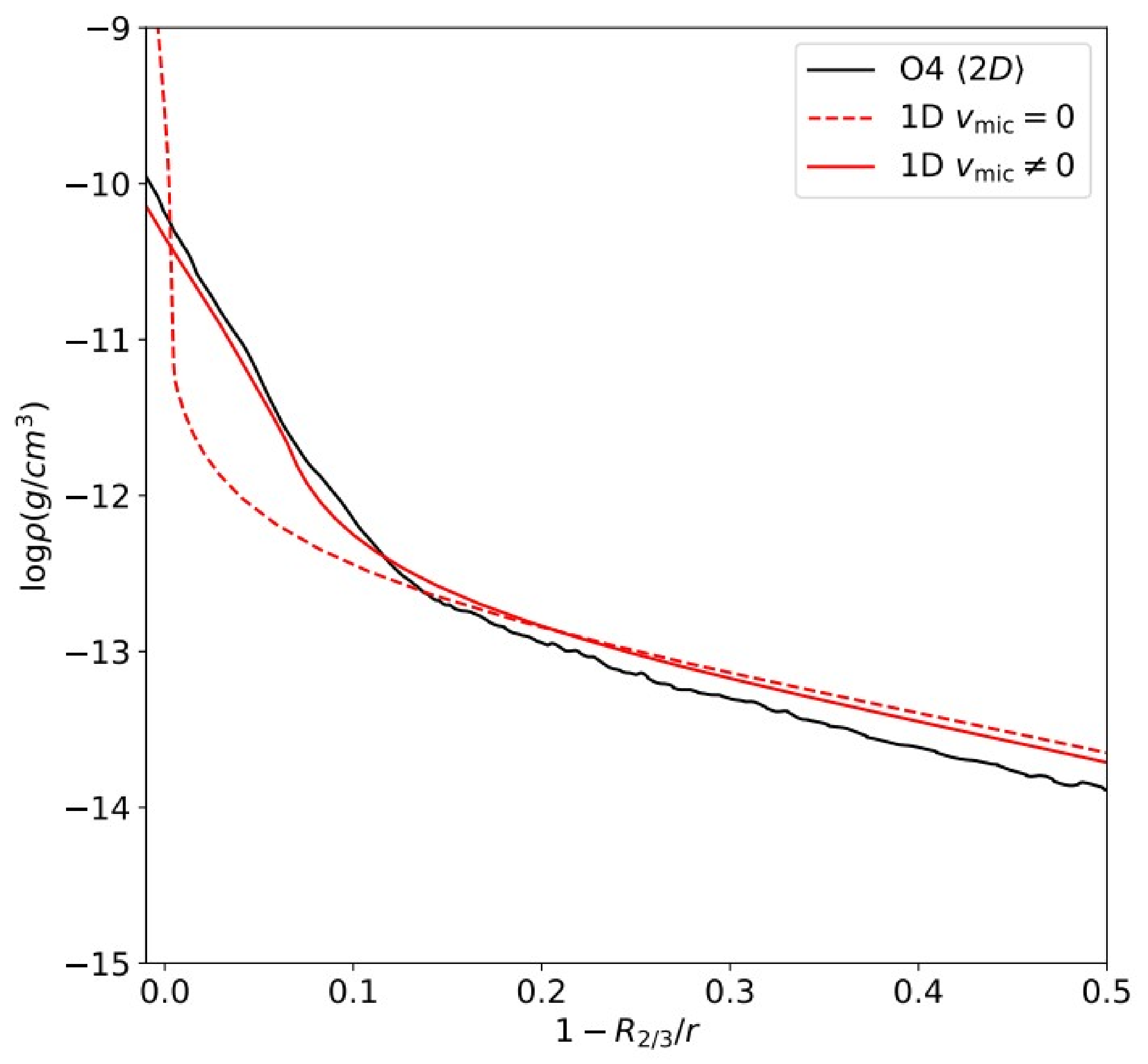


- Same parameters as Debnath+24 averaged 2D models.
- Including a v_{mic}=125 km/s (v_{turb}=88.4 km/s).
- Changing β=1.01.

González-Torà et al., in prep

Profile comparison, density

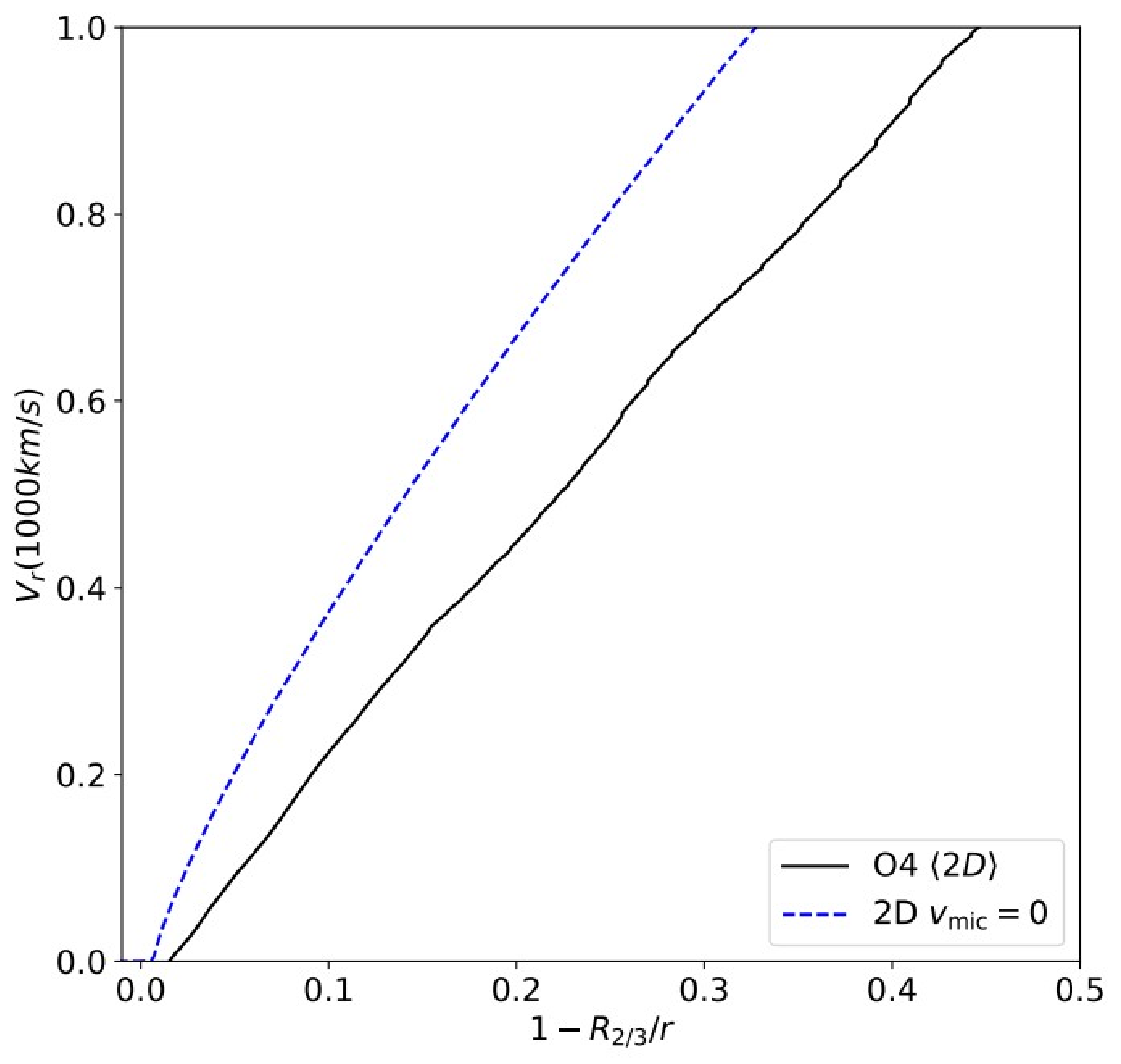


- Final 1D parameters with v_{mic}=0 and with v_{mic}≠0.
- Influence on the v_{mic}:
  - No depth dependence on the v_{mic}.
  - No need to go to very high optical depth.

González-Torà et al., in prep

Profile comparison, velocity

- Same parameters as Debnath+24 averaged 2D models.



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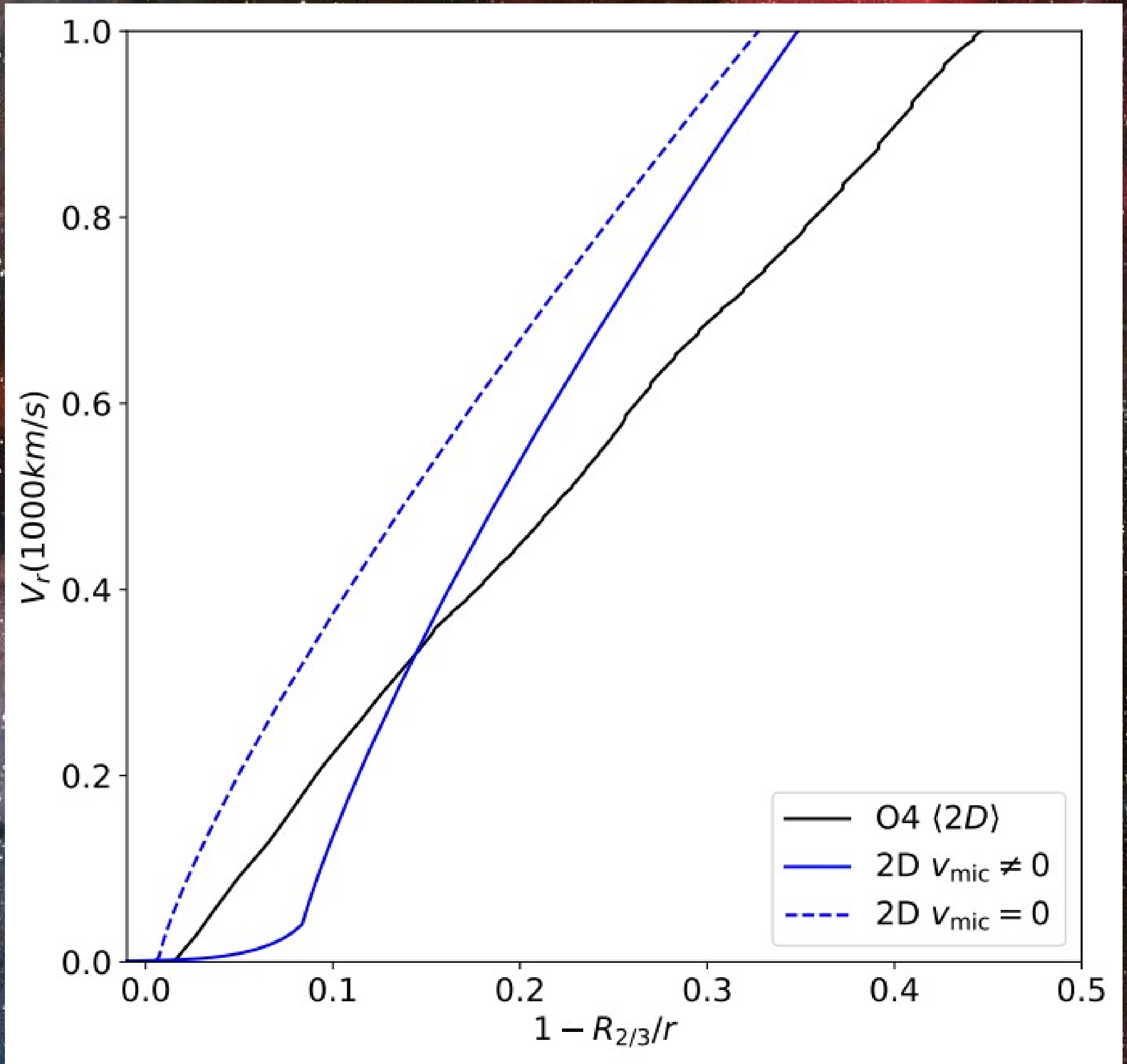

González-Torà et al., in prep

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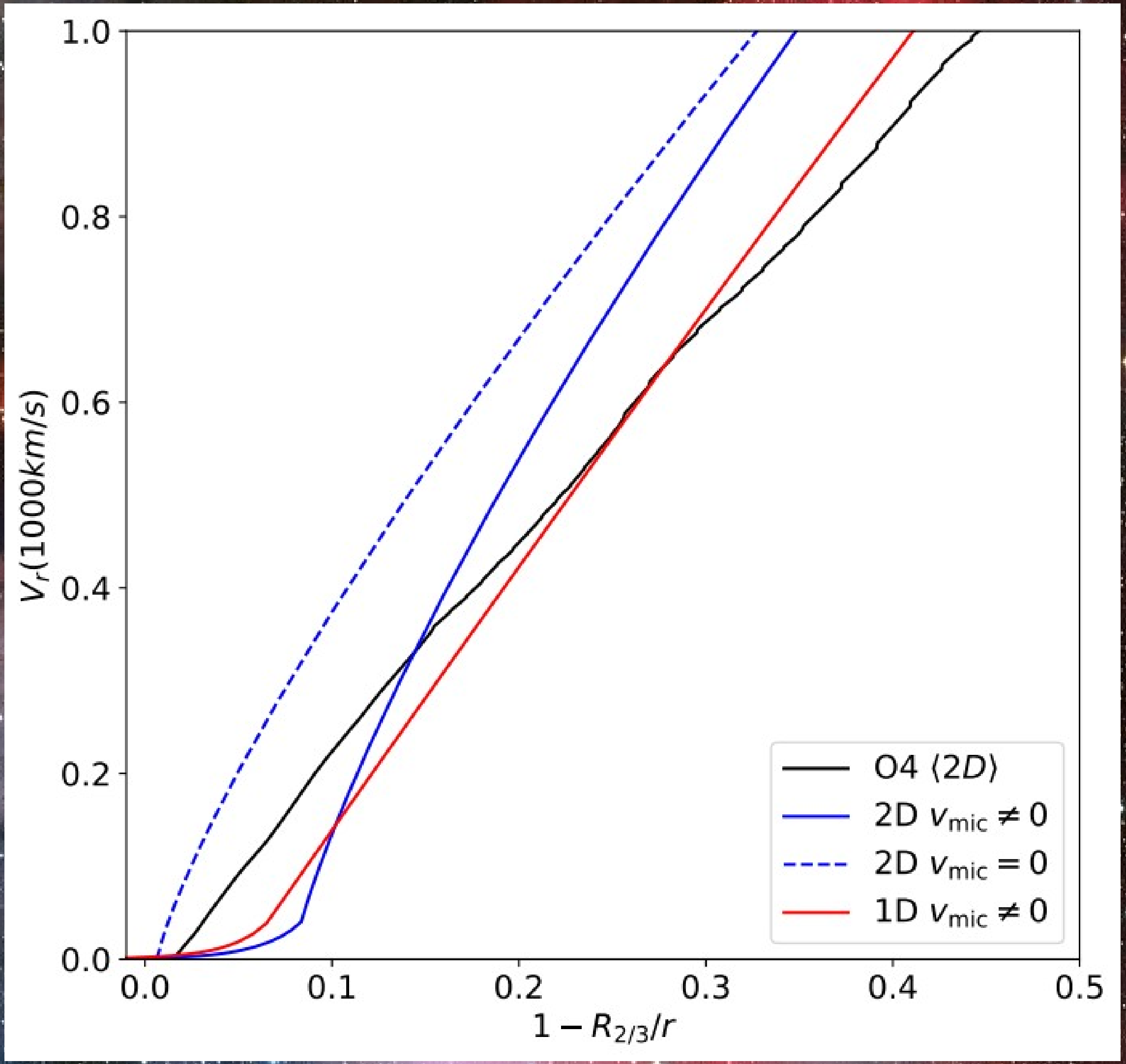
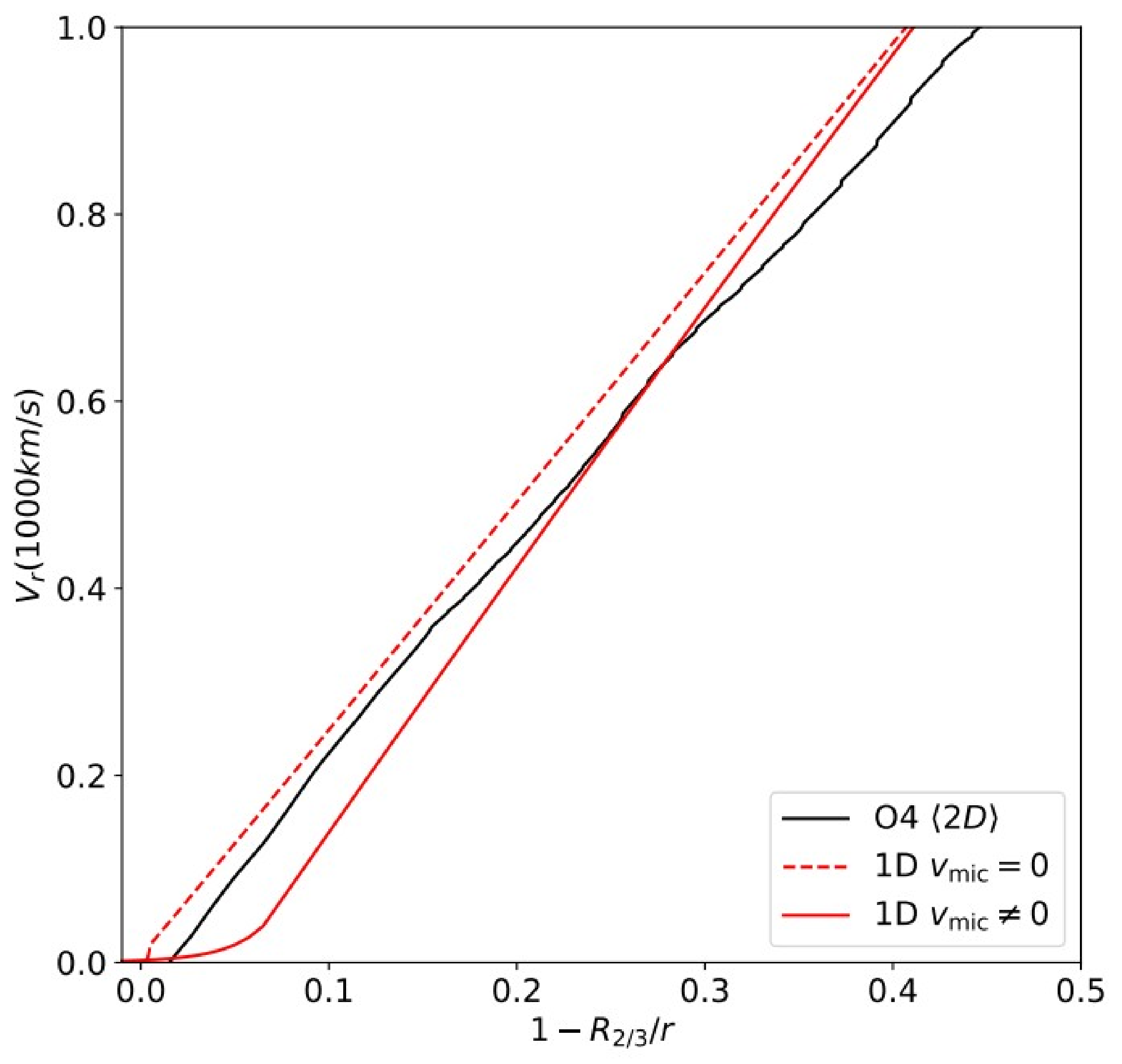
- Changing β from 0.8 to 1.01.



González-Torà et al., in prep

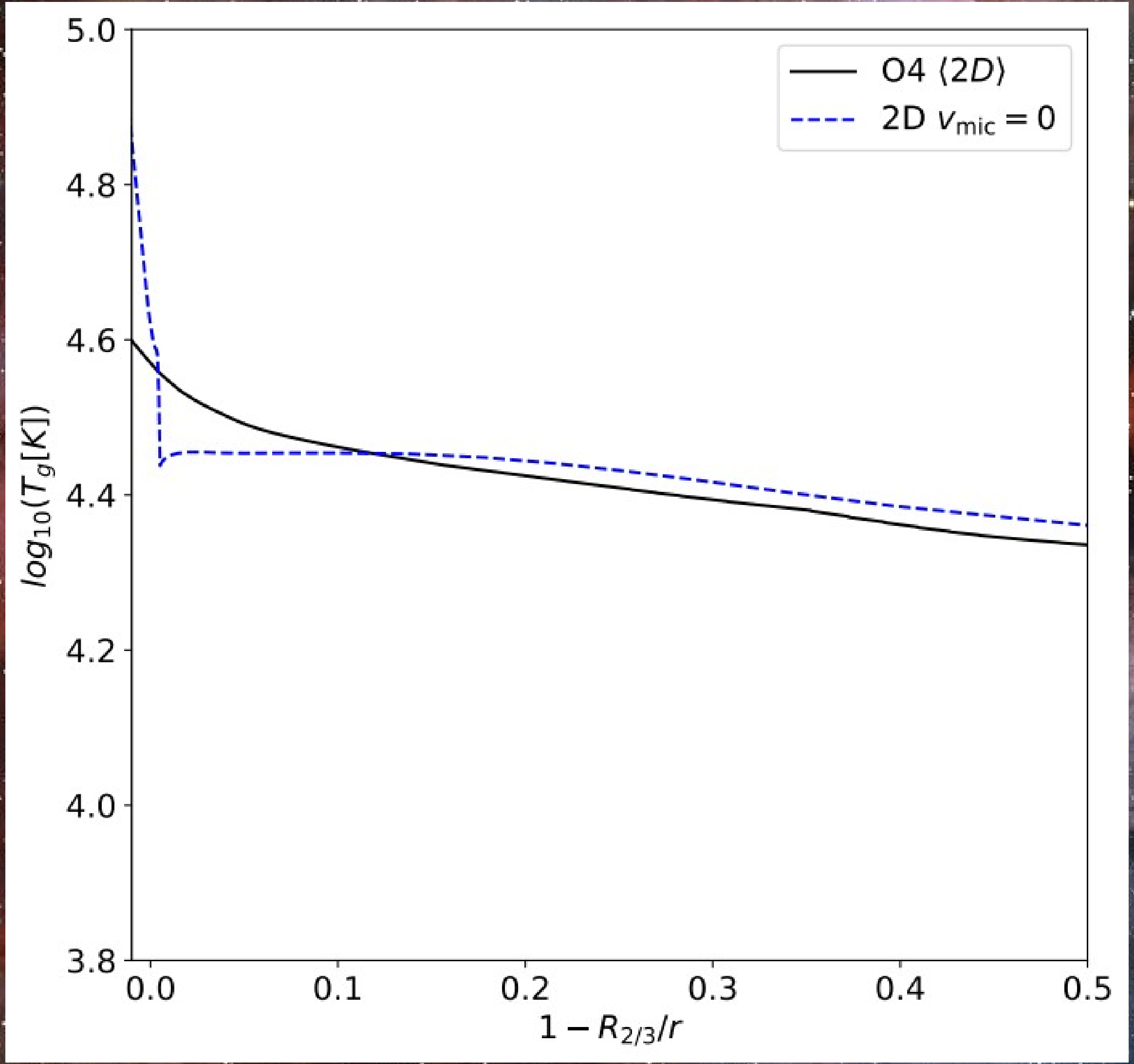
Profile comparison, velocity

- Final 1D parameters with v_{mic}=0 and with v_{mic}≠0.
- Influence on the v_{mic}:
  - Creates a shifted onset further out of the atmosphere.



González-Torà et al., in prep

Profile comparison, temperature



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González-Torà et al., in prep

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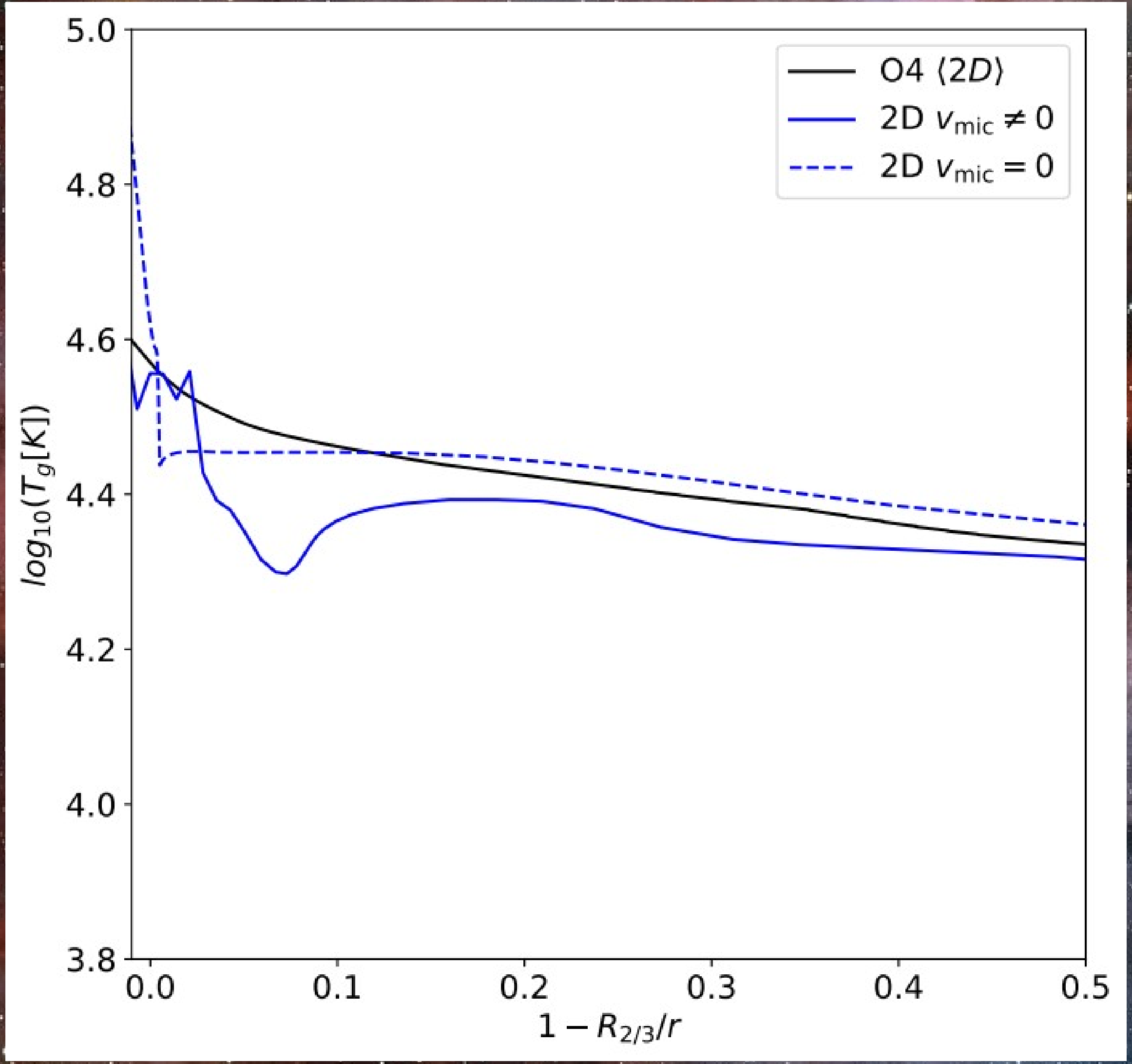

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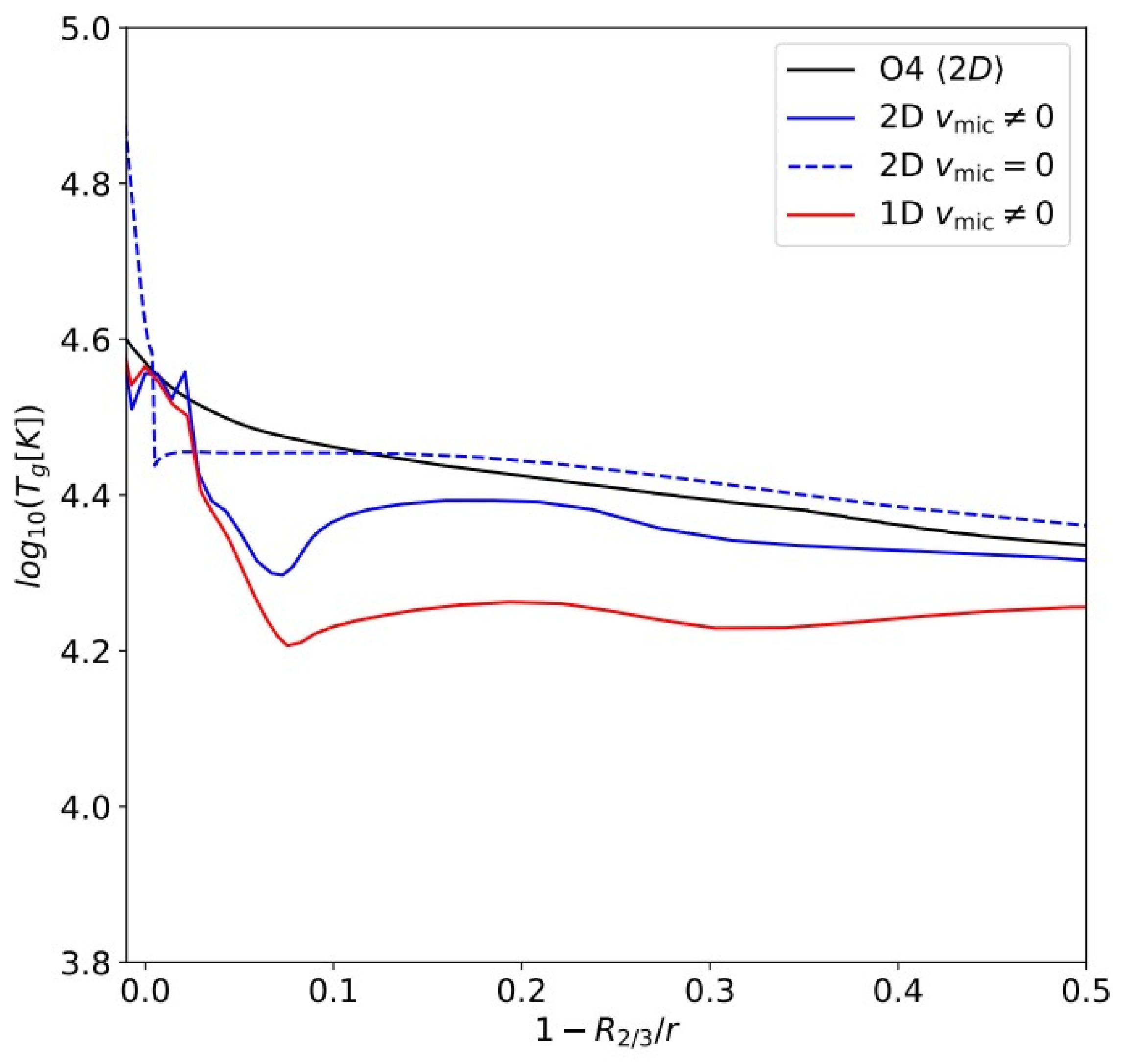

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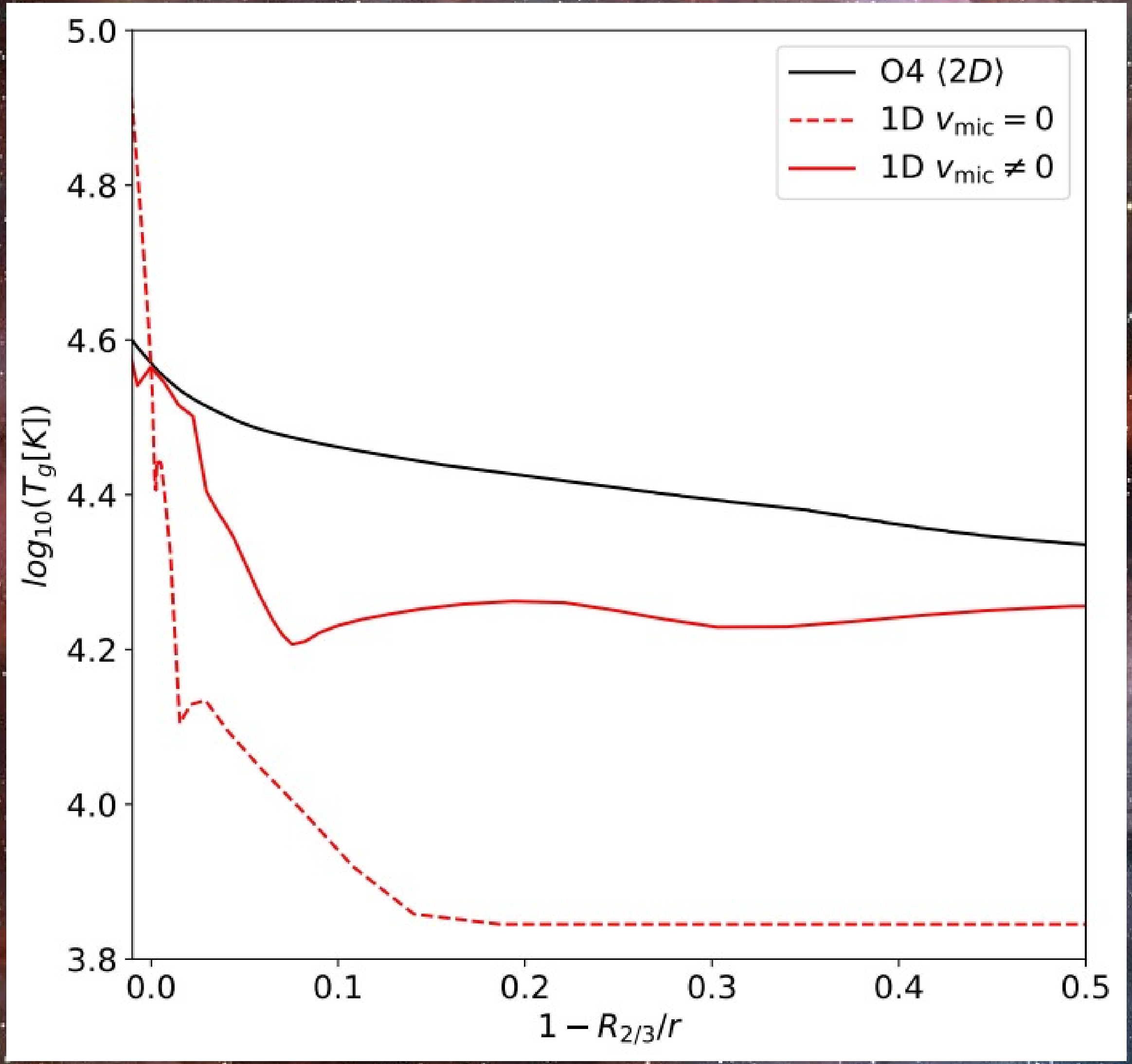
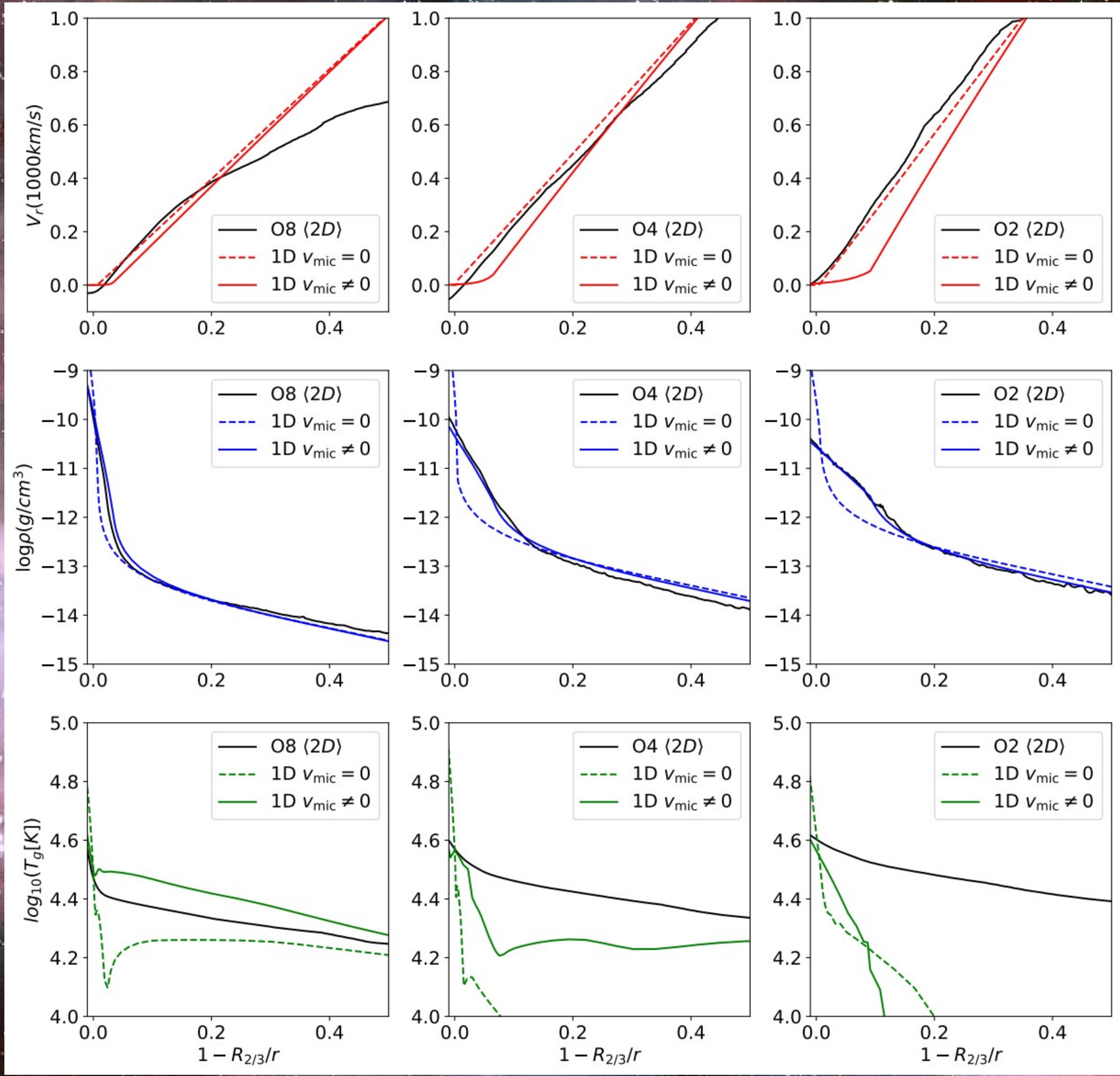


- Final 1D parameters with v_{mic}=0 and with v_{mic}≠0.
- Influence on the v_{mic}:
  - Bumps present in the 1D.
  - Cooling effect?

González-Torà et al., in prep

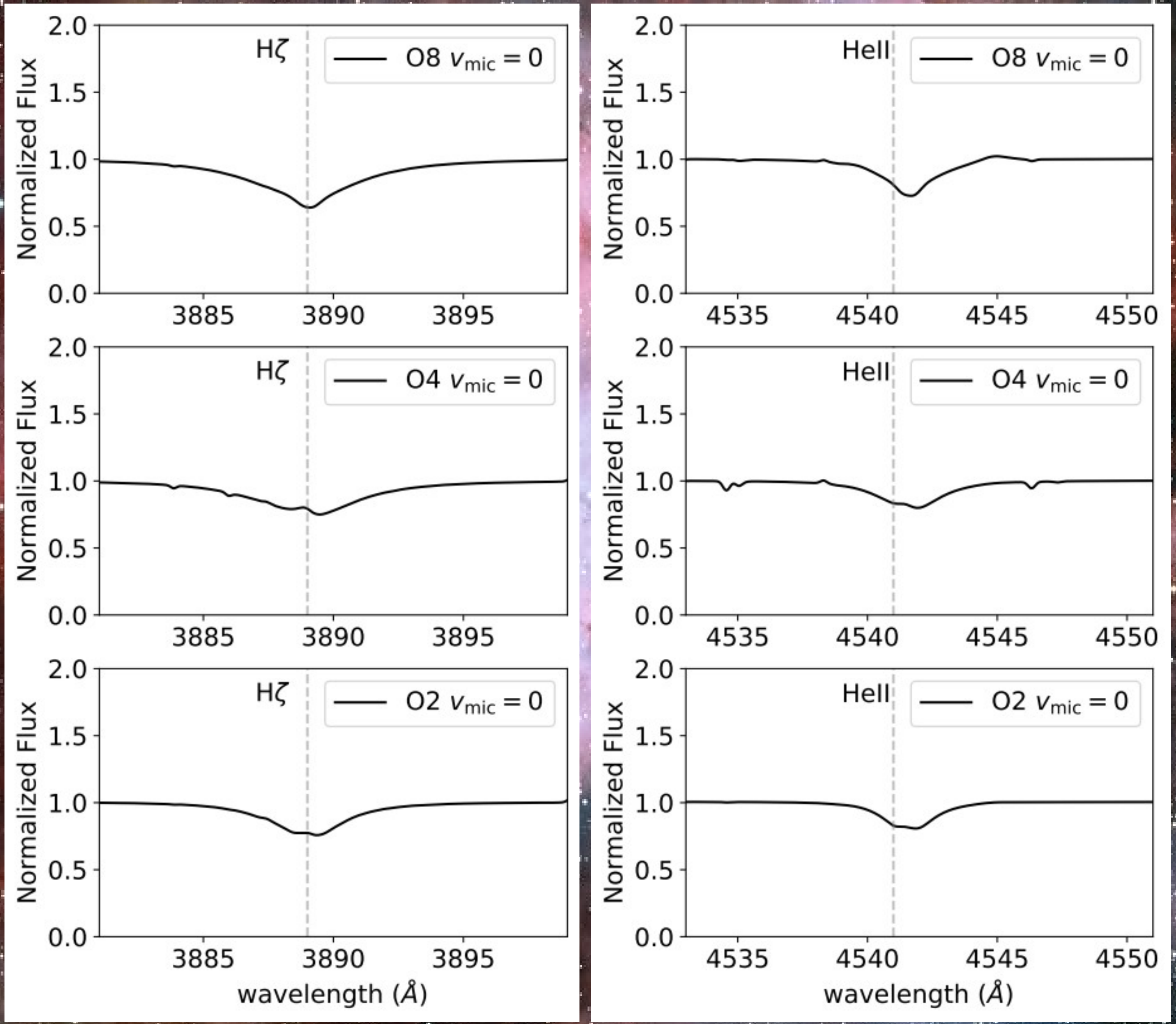
Profile comparison for all 3 models



- O8 → vmic=50 km/s (vturb=35.4 km/s).
- O4 → vmic=125 km/s (vturb=88.4 km/s).
- O2 → vmic=150 km/s (vturb=106.1 km/s).

González-Torà et al., in prep.

Spectral synthesis



- Lines with v_{mic}=0.

González-Torà et al., in prep.

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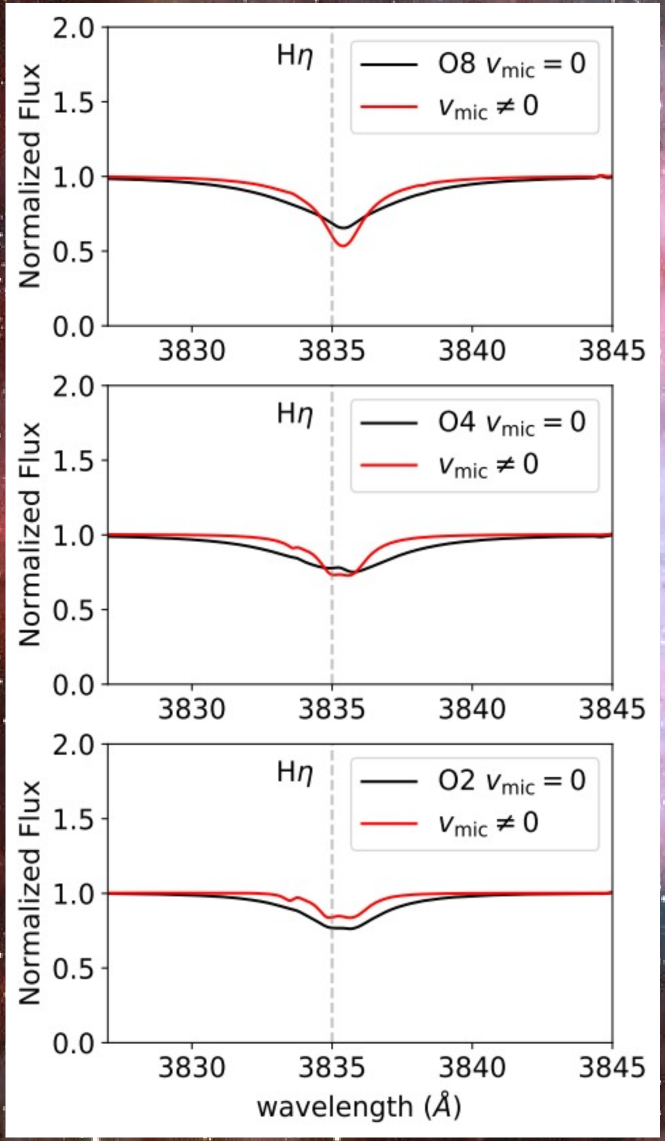
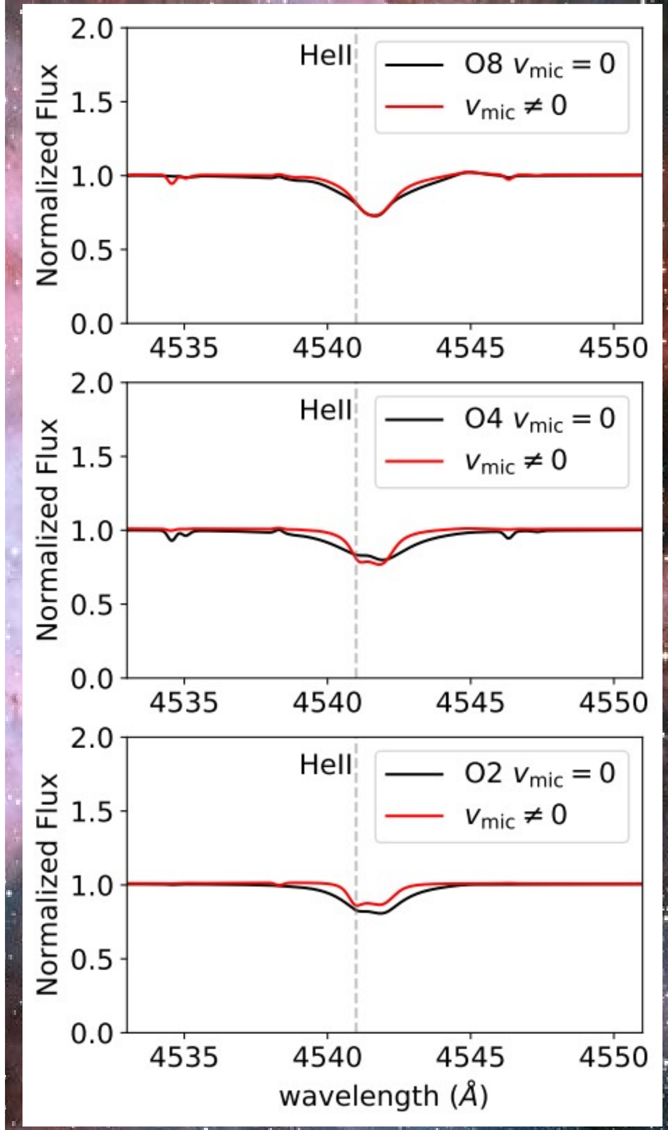




- Lines with v_{mic}=0.
- Including v_{mic}≠0.
- This turbulence term in the hydrostatic equation is NOT the same as the microturbulent broadening in the line profiles!

González-Torà et al., in prep.

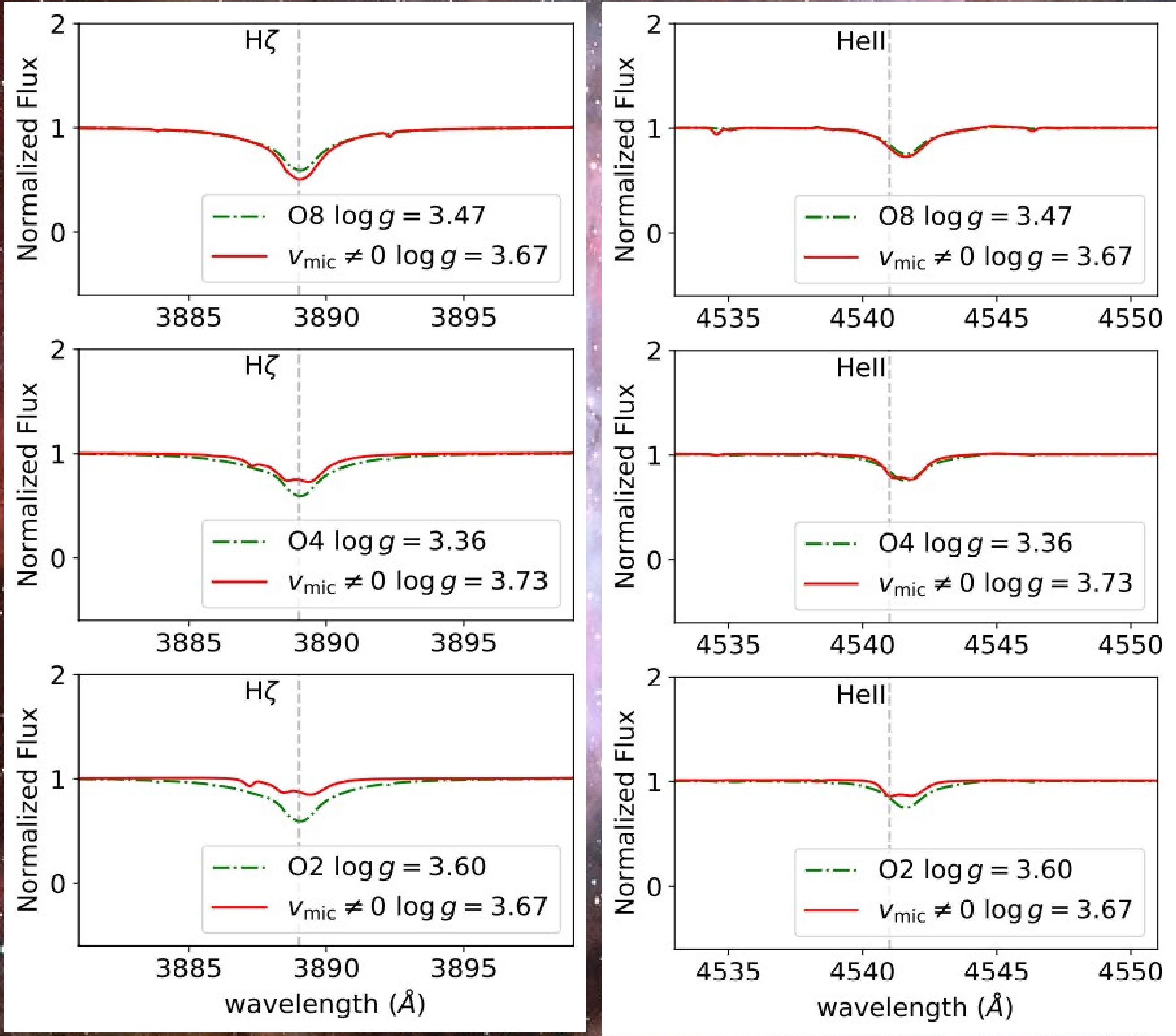
Surface gravity

- Using a v_{mic} term in the solution of the hydrostatic equation will lead to larger log*g* values:

$$\Delta(\log g) = \log\left(1 + \frac{v_{\rm mic}^2 \mu m_{\rm H}}{2 k_{\rm B} T_{\rm phot}}\right)$$

- Using the expression: $\Delta(\log g) \sim 0.4, 0.9, 1.0$ for O8, O4 and O2.

Spectral synthesis



- Fit the spectral lines with v_{mic}=0 and lower log*g*.
- From the spectra:

  Δlogg~0.2, 0.4 for O8 and O4.
- Obtain a **higher** mass with v_{mic}≠0 than with v_{mic}=0 and lower log*g*.

González-Torà et al., in prep.

Surface gravity

Model	$\log g_{\rm mic}$	$M_{\rm mic}/M_\odot$	$\log g_0$	$M_0/M_\odot$
O8	3.67	26.9	3.47	17.17
O4	3.73	60.5	3.36	27.03

González-Torà et al., in prep.

Surface gravity

Model	$\log g_{mic}$	$M_{mic}/M_{\odot}$	$\log g_0$	$M_0/M_{\odot}$
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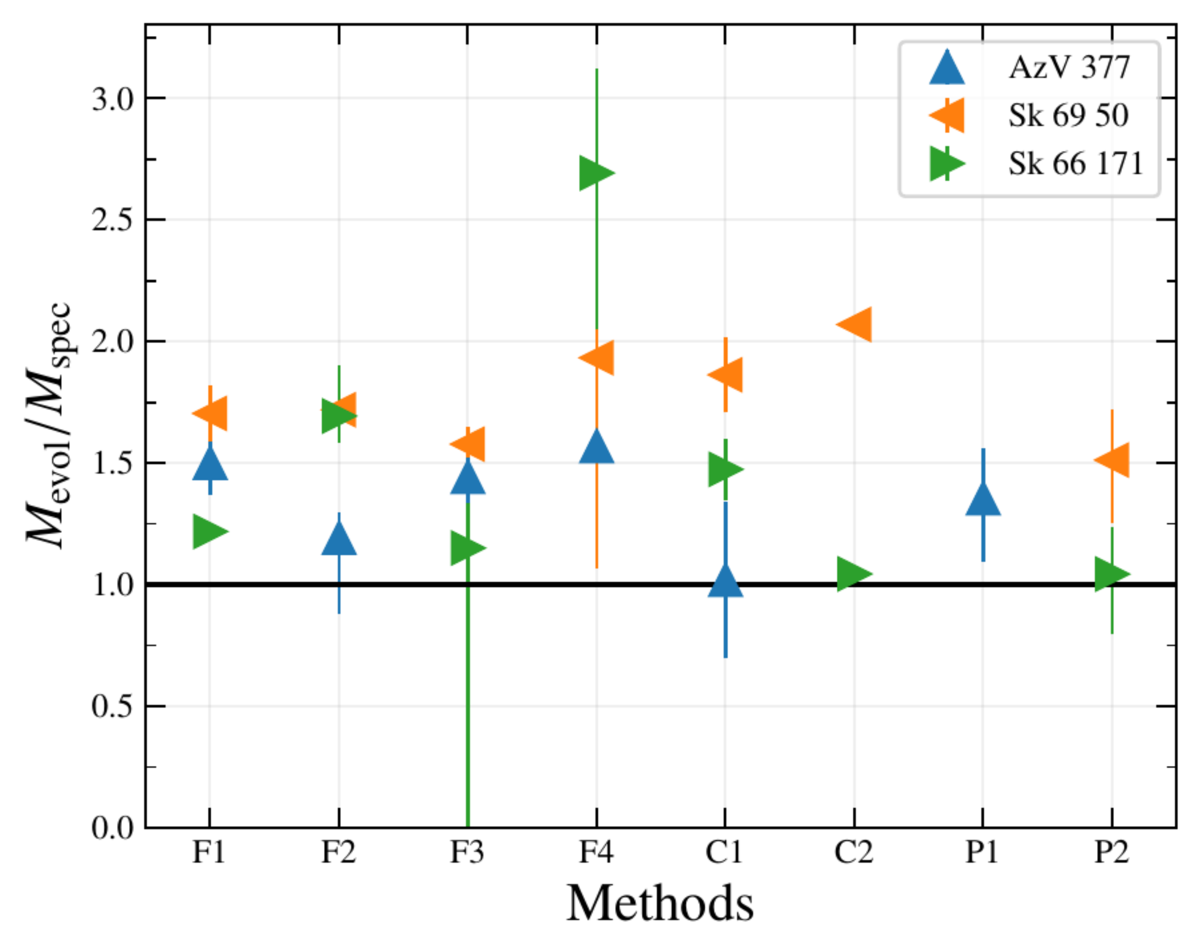
González-Torà et al., in prep.

Mass discrepancy (Herrero+92)

Markova+18 analysed a galactic O4 V star ~comparable to our O4 model

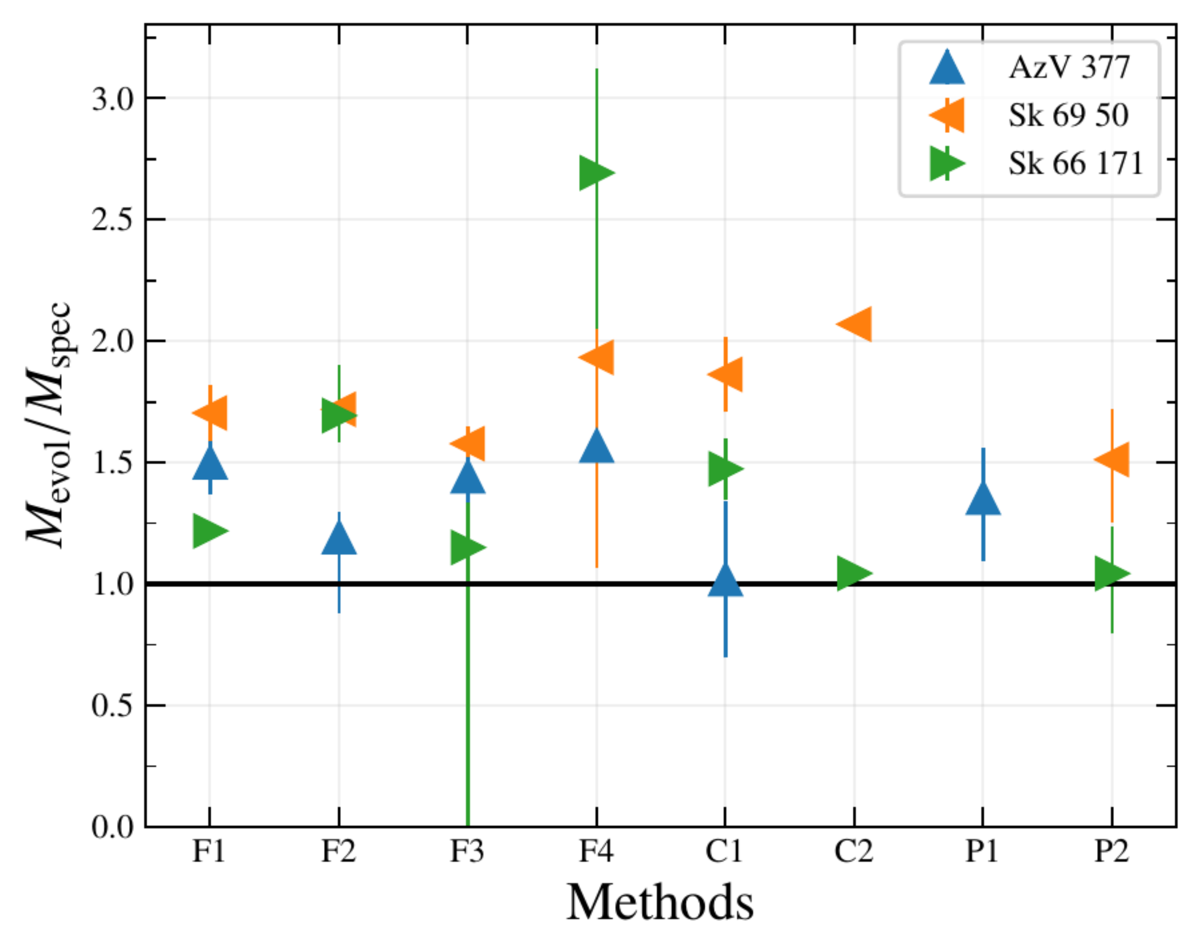


Sander et al., (XshootU IV, sub.)

Mass discrepancy (Herrero+92)

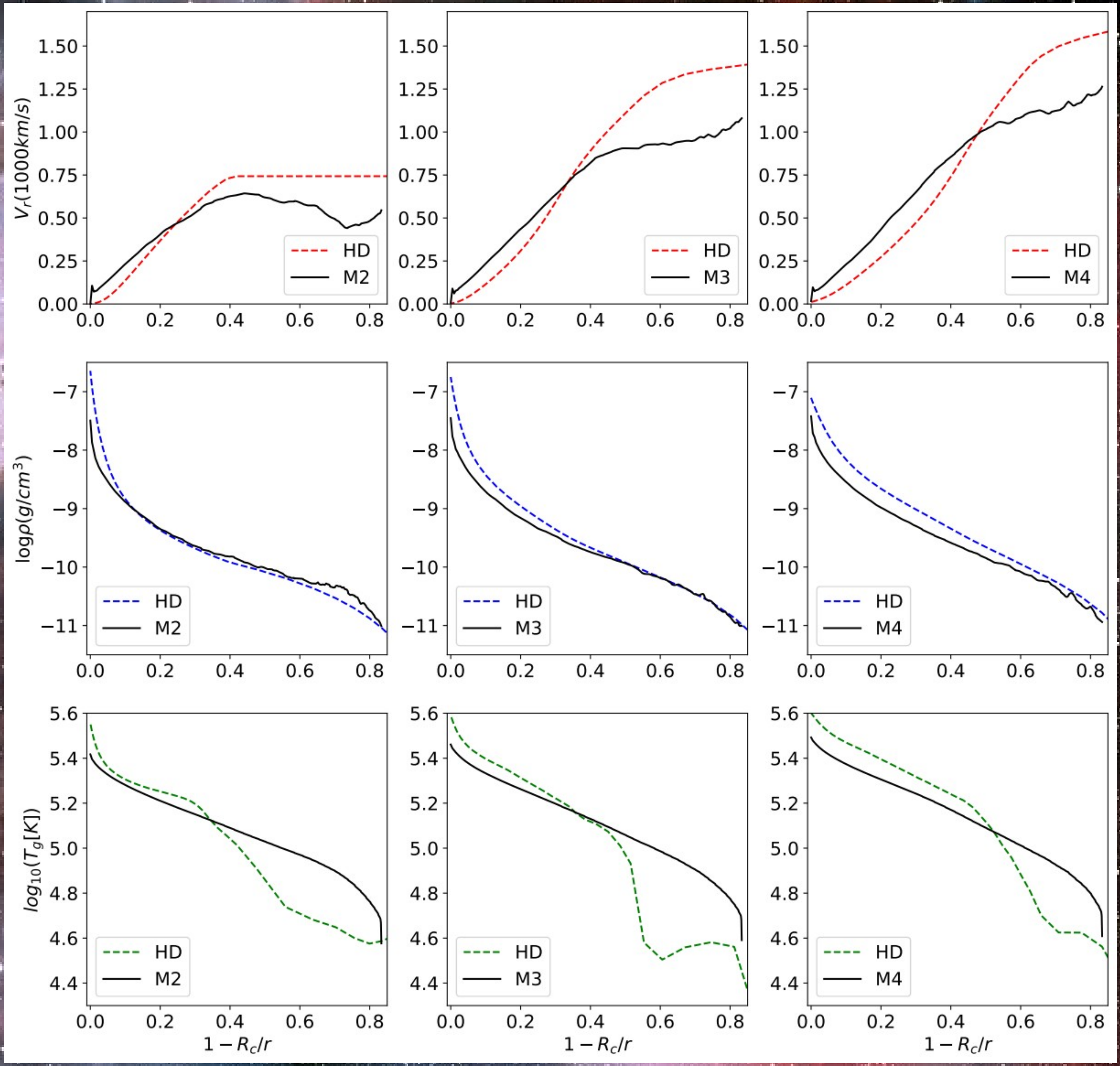
Markova+18 analysed a galactic O4 V star ~comparable to our O4 model

For vmic≠0: evolutionary mass is comparable, spectroscopic mass is ~20 M⊙ lower.



Sander et al., (XshootU IV, sub.)

WR stars…
Stay tuned



- Compared with averaged 3D models for WR stars in Moens+22b.
- PoWR branch solving the full hydrodynamic equations (Sander+17).

González-Torà et al., in prep.

Conclusions

- Compared 1D PoWR models with averaged 2D RHD profiles for three O stars and three WR stars.
- Density profiles can be well reproduced with a fixed v_{mic} in the hydrostatic equation.
  - Future work: Include a depth dependence on v_{mic}.
- Increasing β parameter from 0.8 to 1.01 helps reproduce the velocity profile.
- Including a v_{mic} affects the spectral lines and line diagnostics.
- This turbulence term could reconcile the ‘Mass discrepancy’ between evolutionary and spectroscopic mass determinations.

Spectral synthesis, ξ

- The microturbulence broadening in the spectral computation, ξ.
- It cannot fit the depth of the lines.

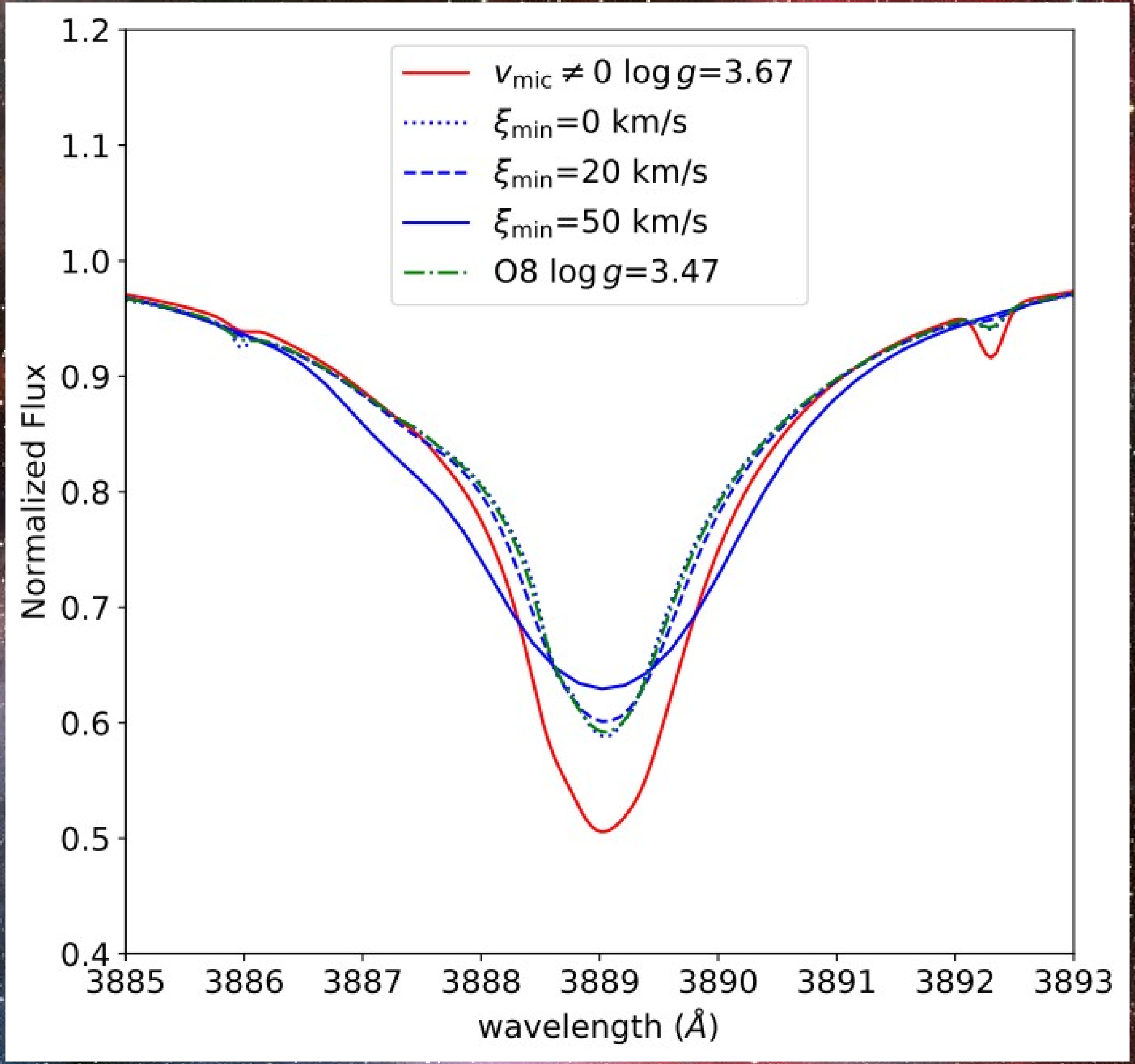


Table 1 Gonzalez-Tora et al., in prep.

Model	$\log(L_\star/L_\odot)$	$L_\star/L_{edd}$	$\log \dot{M}/M_\odot yr$	T_{eff} (kK)	$M_\star/M_\odot$	$R_{\tau=2/3}/R_\odot$	$\log g$	$\log g_0$	v_{turb} (km/s)	β
O8	5.23	0.16	-6.75	33.1	26.9	12.56	3.67	3.47	35.4	1.01
O4	5.78	0.27	-5.55	38.4	60.5	17.55	3.73	3.36	88.4	1.01
O2	5.93	0.39	-5.26	40.9	58.3	18.39	3.67	3.5	106.1	1.01

Model	$\langle T_{eff}(kK)\rangle$	$M_\star/M_\odot$	$\langle R_\star\rangle/R_\odot$	$\log_{10}(\langle L_\star\rangle/L_\odot)$	$\langle L_\star\rangle/L_{edd}$	$\log_{10}\langle g_\star\rangle$	$\log_{10}\langle\dot{M}\rangle$ ($M_\odot\,yr^{-1}$)
O8	33.3	26.9	12.26	5.23	0.16	3.69	–6.86
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Debnath+24