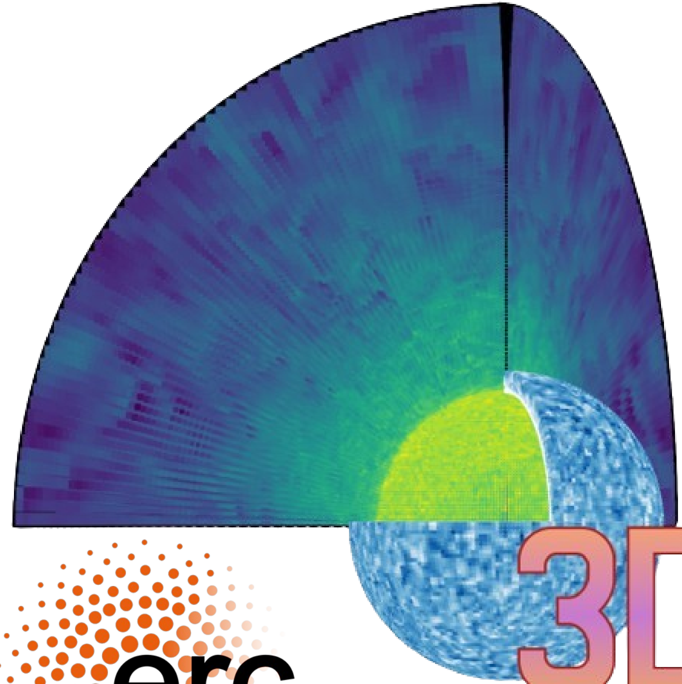
From Multi-D
Atmosphere and Wind models
To spectral synthesis

SUPERSTARS-3D

Massive star winds

In our group:
- 1D Detailed NLTE (Fastwind)
- **3D time-dep. RHD**
- 3D RT, spectral synthesis

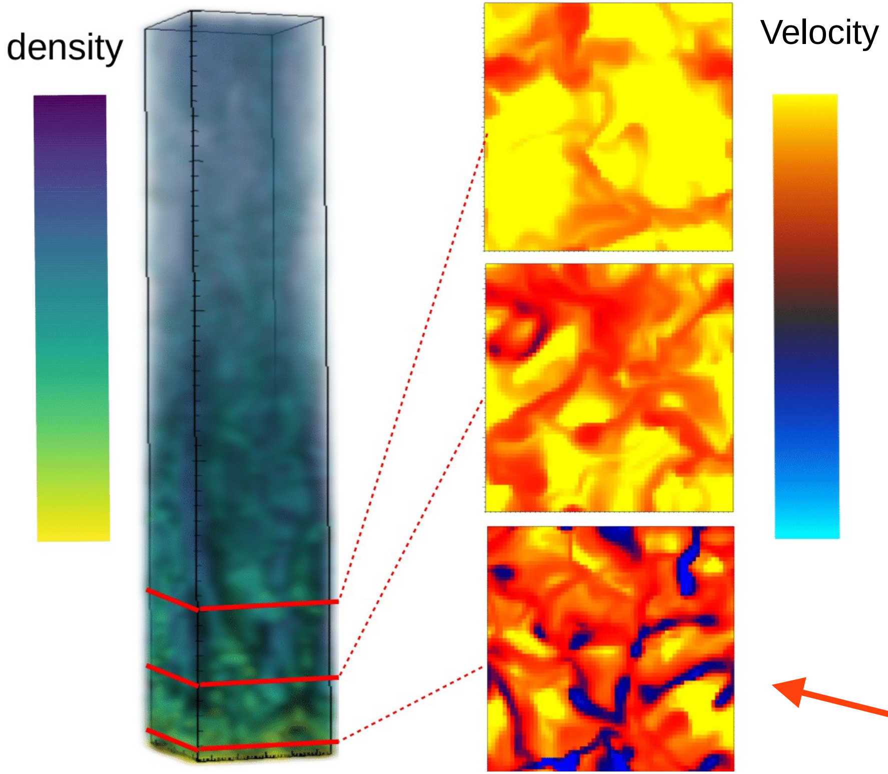
Nicolas Moens
IvS - KU Leuven
POEMS 2024 RJ



The TEAM

Olivier Verhamme, Cassandra Van der Sijpt, Dwaipayan Debnath, Lara Delbroek, Pieter Schillemans, Frank Backs, Luka Poniatowski, Nicolas Moens, Jon Sundqvist

3D RHD Atmospheres and Winds



PhD thesis N. Moens

Multi-D RHD calculations
Built on **mpi-amrvac**

Radiation dominated
Winds and Atmospheres
Of hot massive stars

Local simulation on
Dynamical timescales

Not spherically symmetric

Why do we need 3D models?

1D dynamics: Free parameter hell

Clumping factor *macro-turbulence* *porosity* *thick/thin clumping*

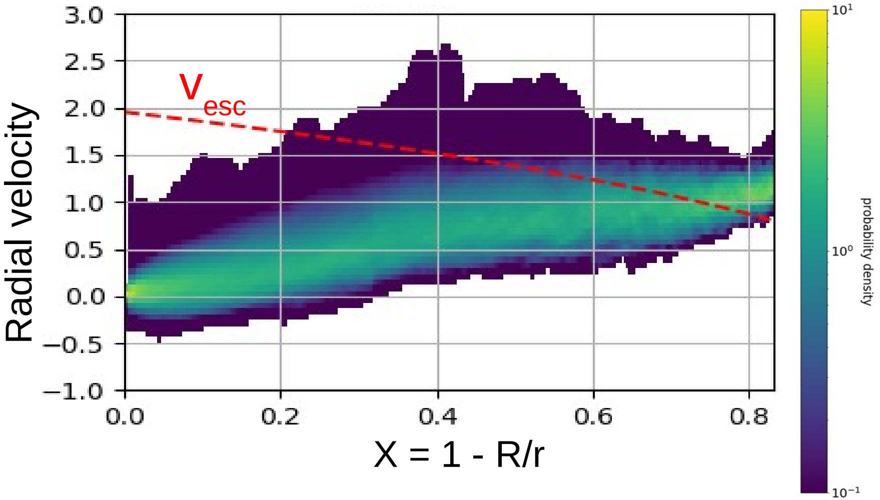
Inter-clump density *micro-turbulence* *Beta-law exponent*

3D spectral effects?

3D model atmosphere → *“New” Solar abundances (Asplund)*

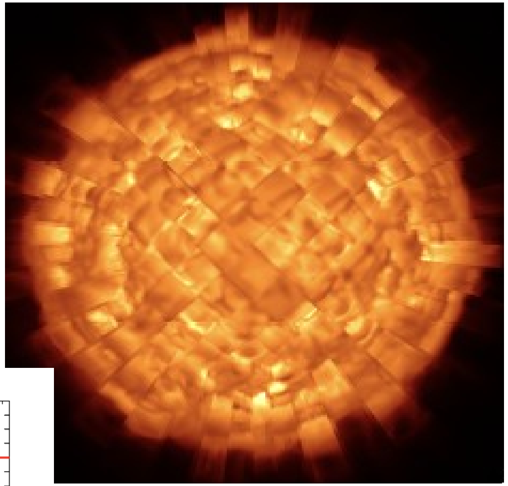
Goals?

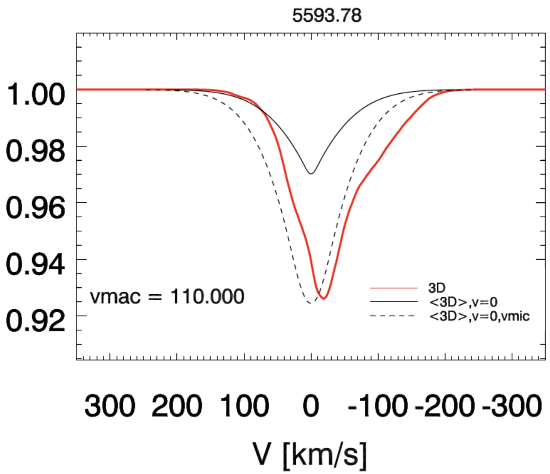
Understanding wind/atmosphere dynamics



Understood for Ostars and WR(?),
How about LBV’s, RSG winds?

Spectral synthesis





Our work this week

This afternoon

Me:

- how to 3D RHD?

Dwaipayan Debnath:

- Ostar atmospheres

Lara Delbroek:

- 3D spectral synthesis

Later this week

Gemma Gonzalez-Tora:

- Feedback to 1D models

Cassandra V.d. Sijpt:

- Structure formation

How do we do?

$$
\begin{aligned}
\partial_t \rho + \nabla \cdot (\rho \vec{v}) &= 0 \\
\partial_t (\vec{v}\rho) + \nabla \cdot (\vec{v}\rho\vec{v} + p) &= -\rho \vec{g}_{grav} - \rho \vec{g}_{rad} \\
\partial_t e + \nabla \cdot (e\vec{v} + p\vec{v}) &= -\rho \vec{v} \cdot \vec{g}_{grav} - \rho \vec{v} \cdot \vec{g}_{rad} + \dot{q}_{rad}
\end{aligned}
$$

Continuity EQ

Momentum EQ

Gas Energy EQ

EOS: gas pressure only:

$$p = \frac{e}{\gamma - 1} + \frac{1}{2}\rho v^2$$

gamma 5/3, NOT Rad. fluid

How do we do?

$$\begin{aligned}\partial_t \rho + \nabla \cdot (\rho \vec{v}) &= 0 \\ \partial_t (\vec{v}\rho) + \nabla \cdot (\vec{v}\rho\vec{v} + p) &= -\rho \vec{g}_{grav} - \boxed{\rho \vec{g}_{rad}} \\ \partial_t e + \nabla \cdot (e\vec{v} + p\vec{v}) &= -\rho \vec{v} \cdot \vec{g}_{grav} - \boxed{\rho \vec{v} \cdot \vec{g}_{rad}} + \boxed{\dot{q}_{rad}}\end{aligned}$$

Radiation source terms

Non-isotropic,
Time-dependent
Radiation field

EOS: gas pressure only:

$$p = \frac{e}{\gamma - 1} + \frac{1}{2}\rho v^2$$

gamma 5/3, NOT Rad. fluid

How do we do?

Radiative transfer equation:

7D Equation:

$$\frac{1}{c}\partial_t I_\nu + \hat{n} \cdot \nabla I_\nu = \kappa_\nu \rho (S_\nu - I_\nu)$$

How do we do?

$$\frac{1}{c}\partial_t I_\nu + \hat{n} \cdot \nabla I_\nu = \kappa_\nu \rho (S_\nu - I_\nu)$$

Frequency integrated,
Angle integrated

0^{th} moment equation:

$$\partial_t E + \nabla \cdot (E\vec{v} + \vec{F}) = -\nabla \vec{v} : P_{rad} - \dot{q}_{rad}$$

+ Computationally cheap
+ Captures dynamics

- No spectral info

Opacity

Source terms:

$$\dot{q} = c\rho\kappa_E E - 4\pi\rho\kappa_B B(T)$$

$$\rho\vec{g}_{rad} = \rho\frac{\kappa_F \vec{F}}{c}$$

Depend on **gas** and **radiation** quantities,
And ...

Opacity

Source terms:

$$\dot{q} = c\rho\kappa_E E - 4\pi\rho\kappa_B B(T)$$

$$\rho\vec{g}_{rad} = \rho\frac{\kappa_F\vec{F}}{c}$$

Frequency-integrated opacities

Opacity

Source terms:

$$\dot{q} = c\rho\kappa_E E - 4\pi\rho\kappa_B B(T)$$

$$\rho\vec{g}_{rad} = \rho\frac{\kappa_F\vec{F}}{c}$$

Frequency-integrated opacities

Atmosphere
(Static, Diffusion Limit)

$$\kappa_E = \kappa_B = \kappa_F$$
$$= \kappa_{Ross}(\rho, T)$$

(e.g. OPAL tables)

Wind
(Sobolev effect, Line driving)

$$\kappa_i = \kappa_i(\rho, T, \tau, E, \partial v/\partial r)$$

Beyond (m-)CAK
Fitted from atomic database
Poniatowski '22

Line driving opacity

Line database

Line data base

Saha-Boltzmann Eq.

Range in
Density and Temperature:
(ρ, T)

Line force calculation

(b)

$$M(t) = \frac{\bar{Q}}{1-\alpha}\frac{(1+Q_0 t)^{1-\alpha} - 1}{Q_0 t}$$

Tabulate fit parameters

$$\alpha \rightarrow \alpha(\rho, T)$$
$$Q_0 \rightarrow Q_0(\rho, T)$$
$$\bar{Q} \rightarrow \bar{Q}(\rho, T)$$

Line database

Line data base

Saha-Boltzmann Eq.

Range in
Density and Temperature:
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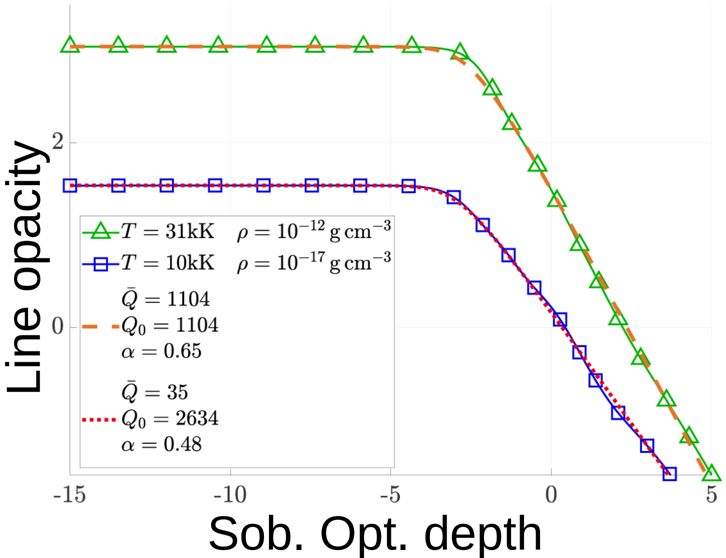
Line force calculation



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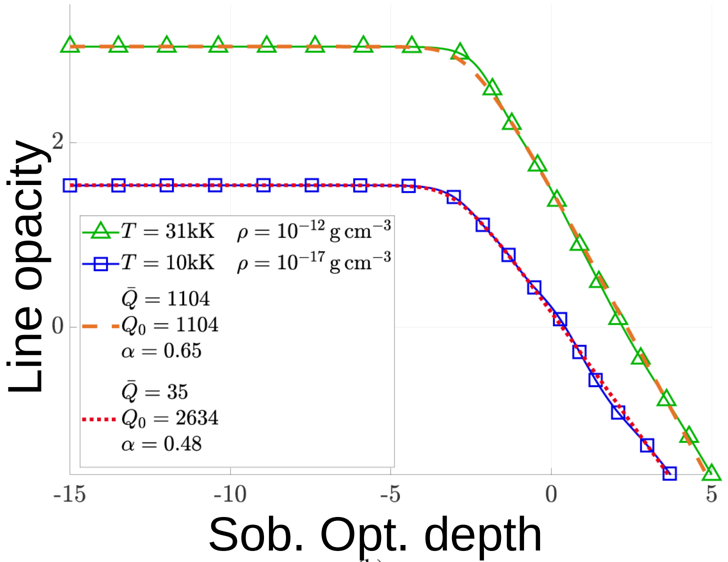

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Line driving opacity

Line database

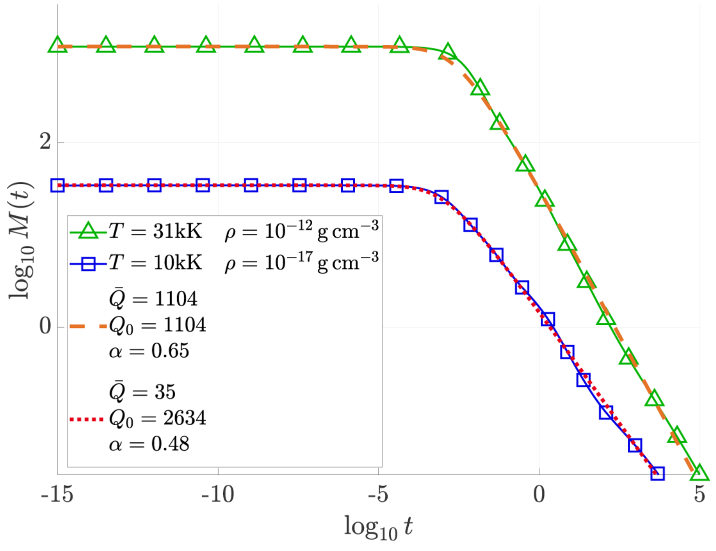
Line data base

Saha-Boltzmann Eq.

Range in
Density and Temperature:
(ρ, T_g, T_r, W)

Approx- NLTE

Line force calculation



(b)

$$M(t) = \frac{\bar{Q}}{1-\alpha} \frac{(1+Q_0 t)^{1-\alpha} - 1}{Q_0 t}$$

Tabulate fit parameters

$\alpha(\rho, T_g, T_r, W)$

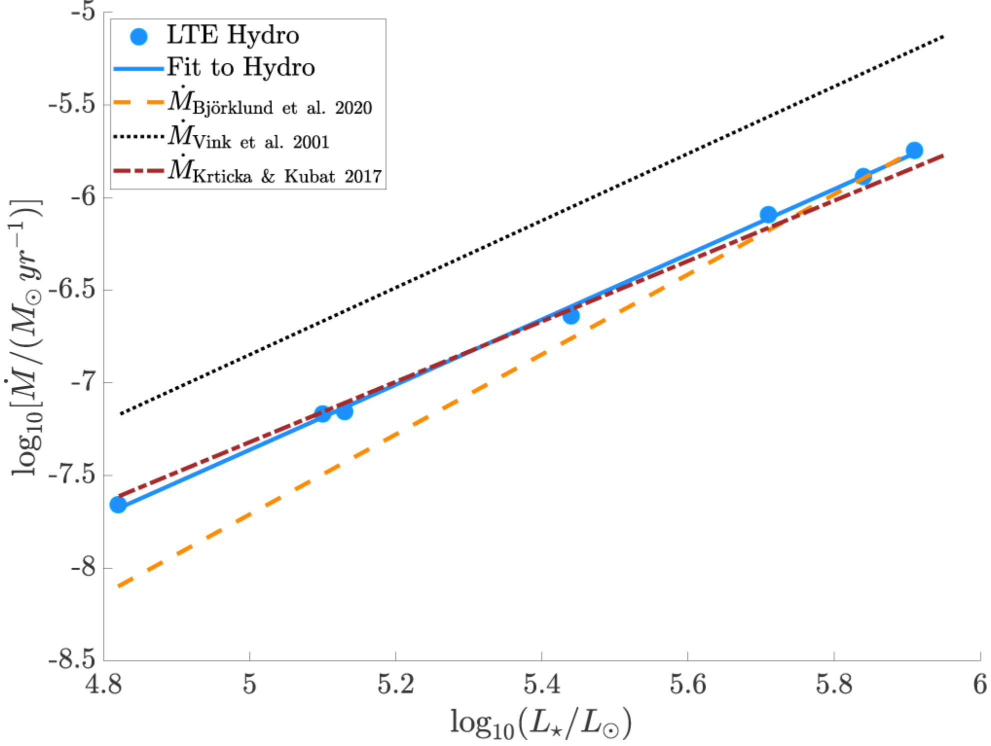
$Q_0(\rho, T_g, T_r, W)$

$\bar{Q}(\rho, T_g, T_r, W)$

Approx- NLTE

Opacity recovers Mdot recipes

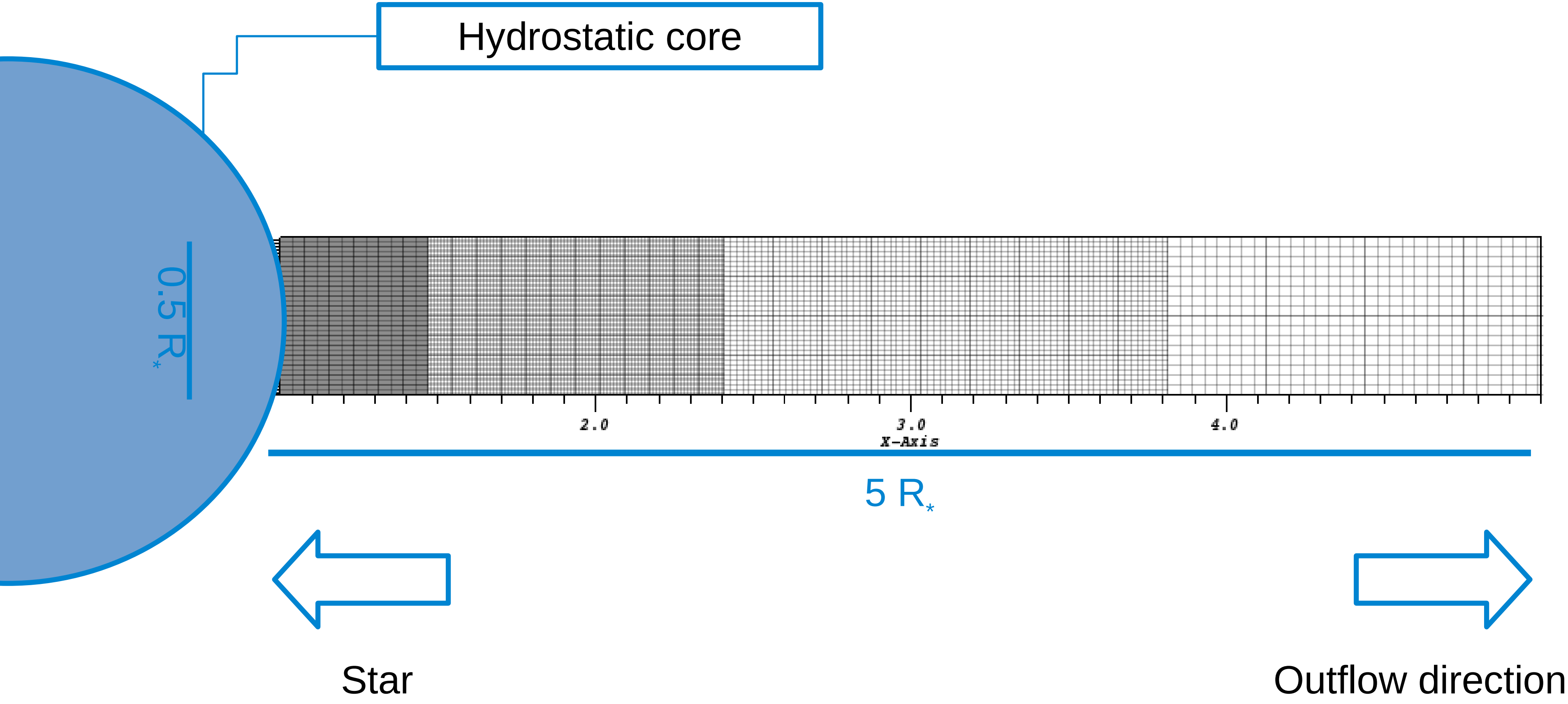
[Poniatowski '22]



- No CMF RT
- No NLTE

+ Recover general wind dynamics

Simulation setup

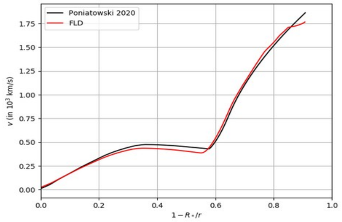


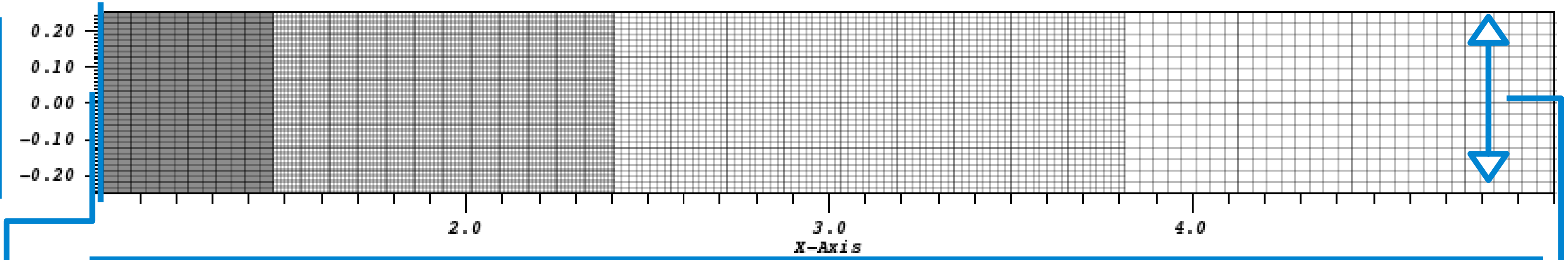
Simulation setup

Refinement near base

Initial conditions:

1D steady state model





$0.5\ R_*$

$5\ R_*$

Boundary conditions:

- fixed density
- fixed radiation flux
- self consistent T_{core}
- self consistent Mdot

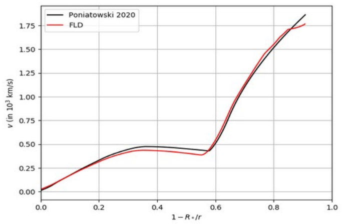
Periodic boundary

Simulation setup

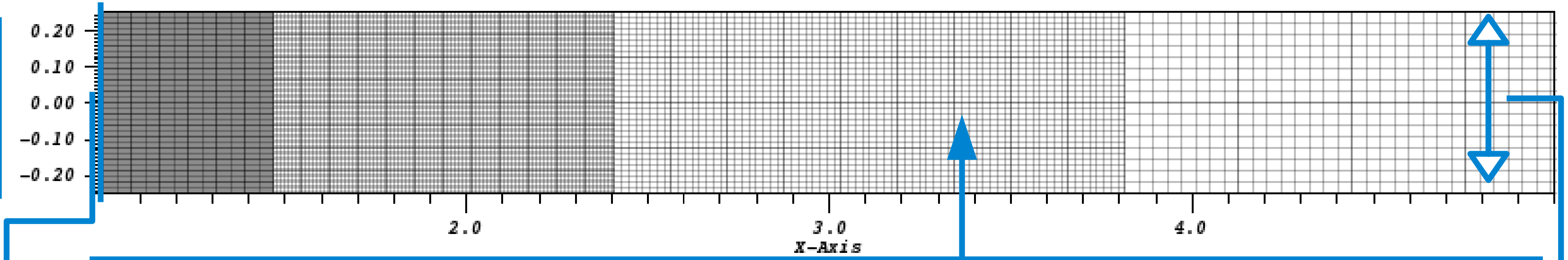
Refinement near base

Initial conditions:

1D steady state model



0.5 R_*



5 R_*

Boundary conditions:

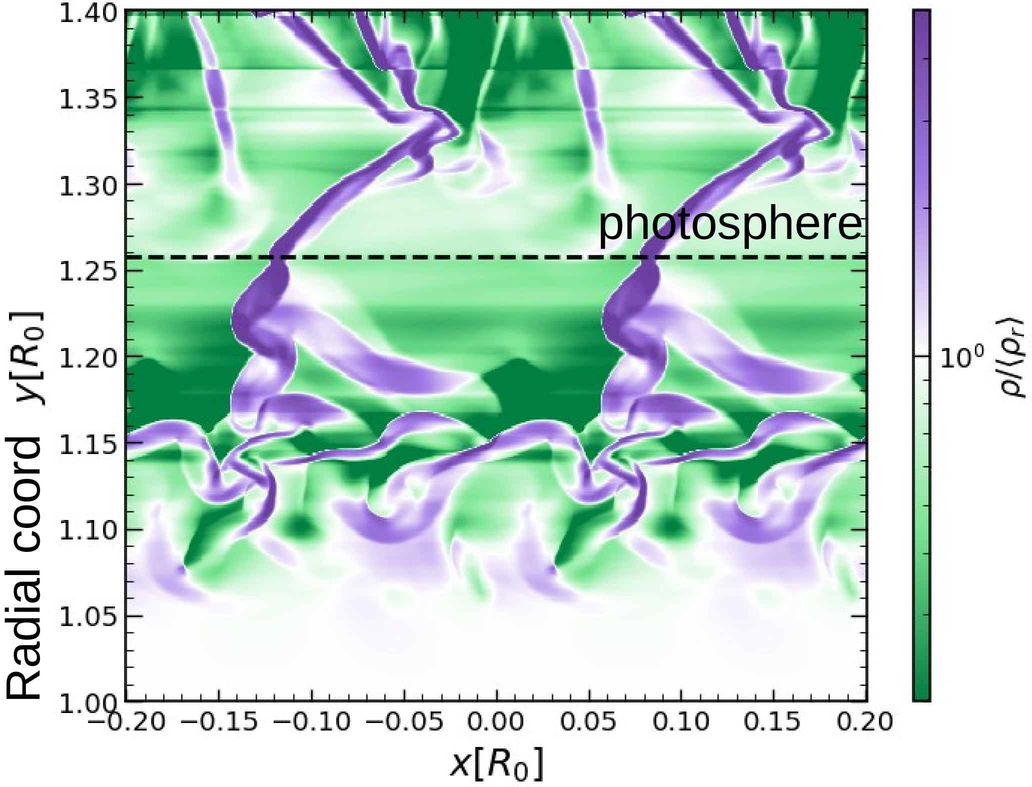
- fixed density
- fixed radiation flux
- self consistent T_{core}
- self consistent Mdot

$$
\begin{aligned}
\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\partial_t (\mathbf{v}\rho) + \nabla \cdot (\mathbf{v}\rho\mathbf{v} + \mathbf{p}) &= \rho \frac{\kappa \mathbf{F}}{c} - \rho \mathbf{g} \\
\partial_t e + \nabla \cdot (e\mathbf{v} + \mathbf{p}\mathbf{v}) &= \dot{q} + \mathbf{v} \cdot \rho \frac{\kappa \mathbf{F}}{\mathbf{c}} - \mathbf{v} \cdot \rho \mathbf{g} \\
\partial_t E + \nabla \cdot (E\mathbf{v} + \mathbf{F}) &= -\dot{q} - \nabla \mathbf{v} : \mathbf{P}
\end{aligned}
$$

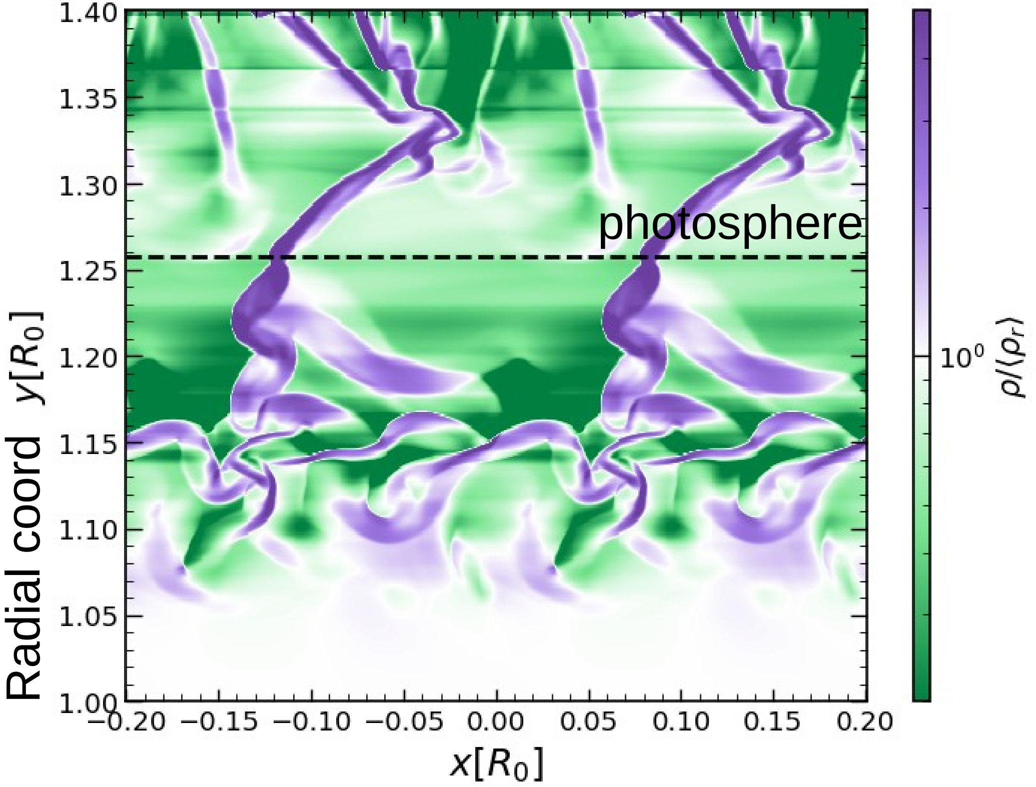
+ Hybrid opacity

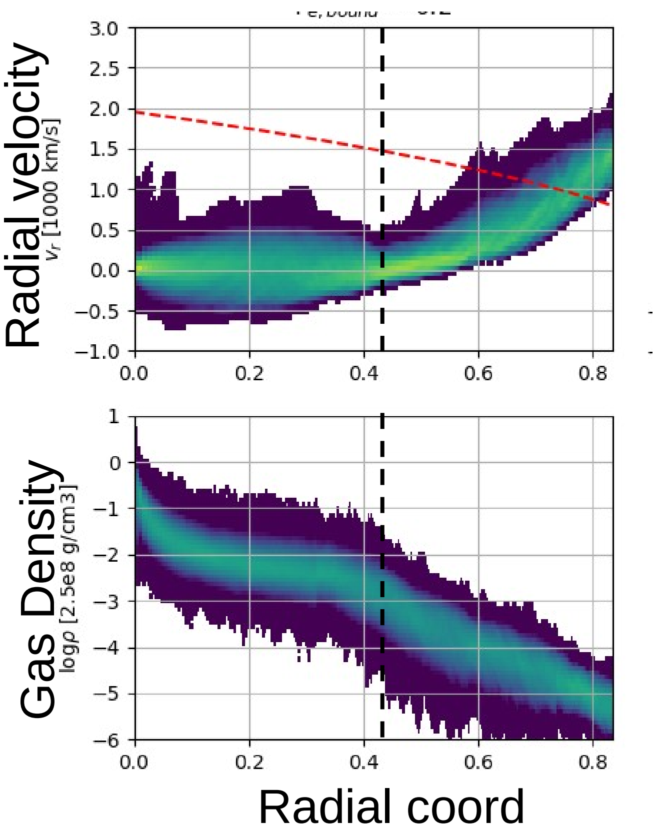
Periodic boundary

Example model



Example model





Results

WR stars:
Understanding wind dynamics

Moens '22

O stars:
Understanding atmosphere inflation

Debnath '24

LBV stars:
S-dor like variability?

Schillemans (work in progress)

Results

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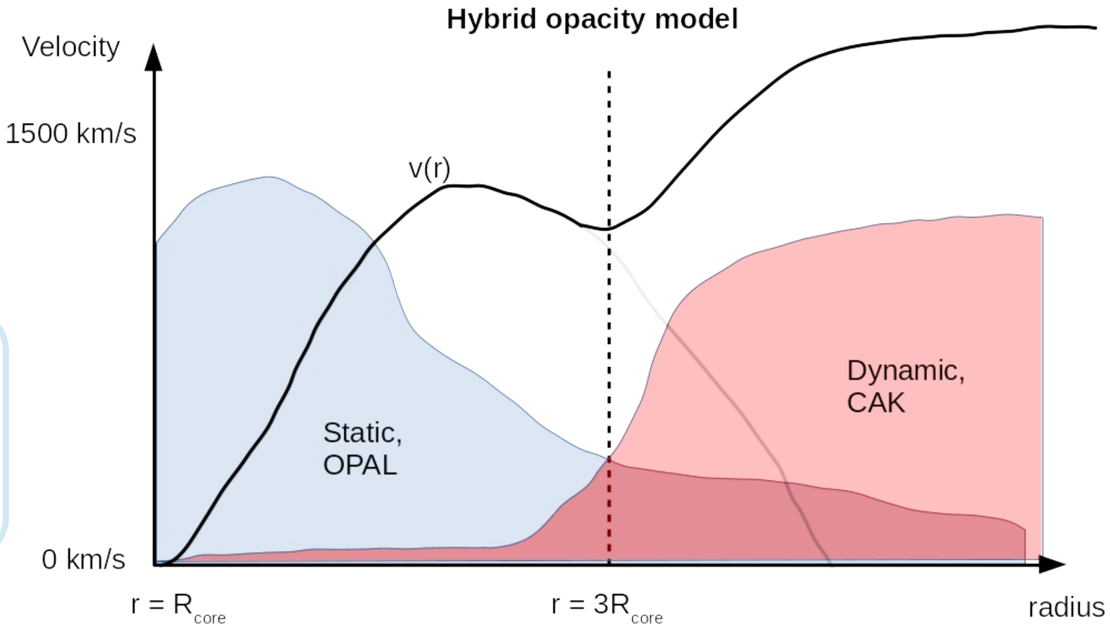

Driving enhanced by structure formation

Results

WR stars:
Understanding wind dynamics

Moens ‘22

O stars:
Understanding atmosphere inflation

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LBV stars:
S-dor like variability?

Schillemans (work in progress)

Dwaipayan Debnath:

Next talk

Results

WR stars:
Understanding wind dynamics

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O stars:
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LBV stars:
S-dor like variability?

Schillemans (work in progress)

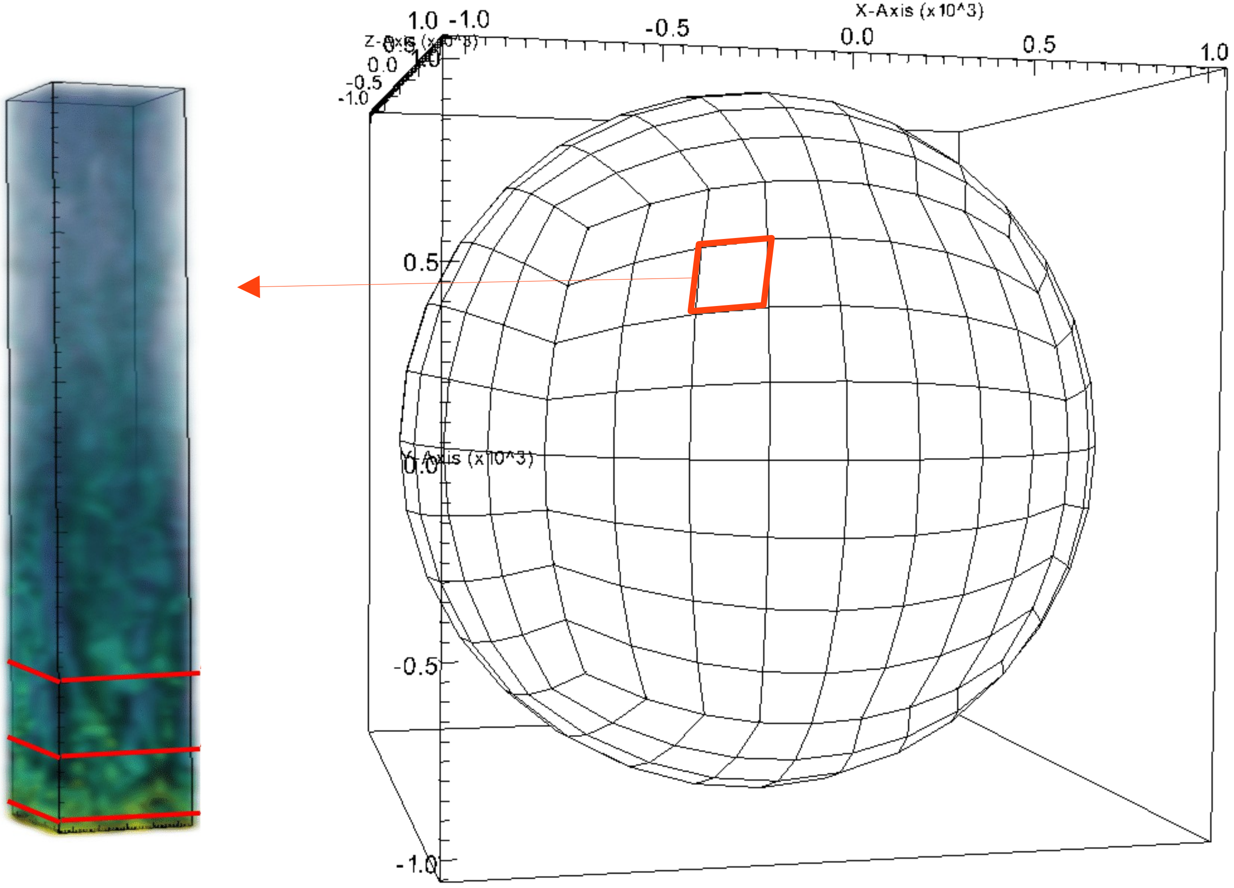
Work in progress

Towards spec synth: Global reconstruction

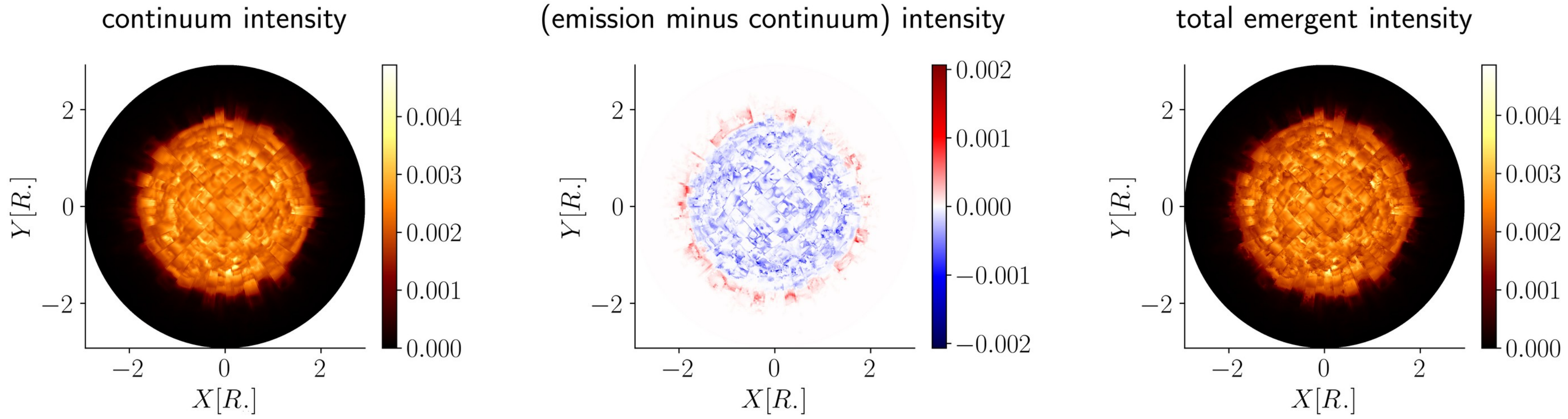
Fill the full sphere with multiple “local” simulation boxes for spectral synthesis

Short/Long Characteristics solver

Line3D (Hennicker 2022)



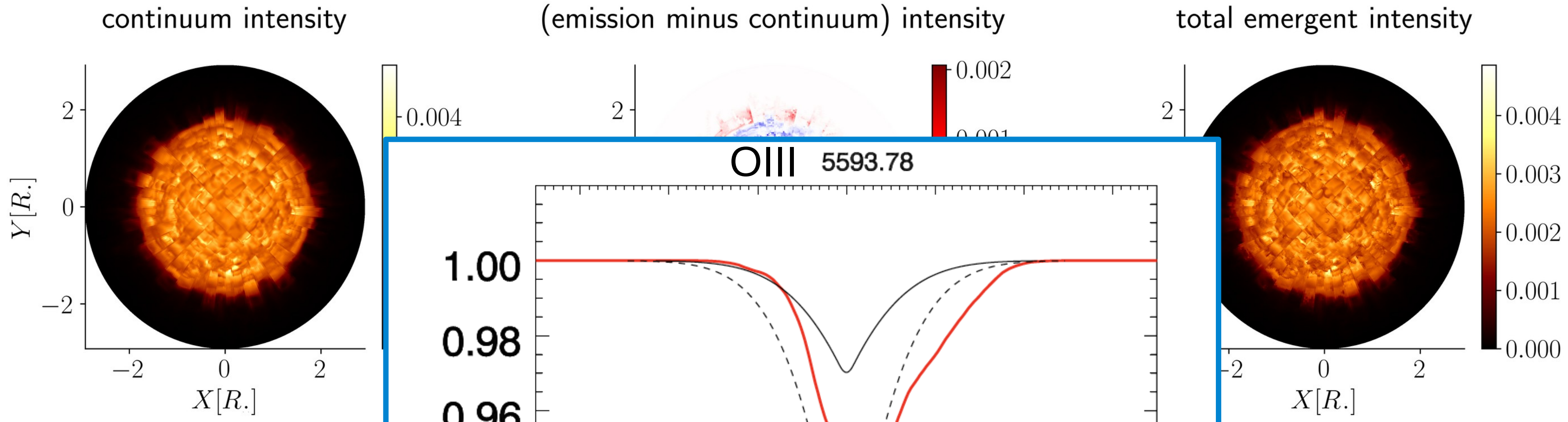
Spectral synthesis

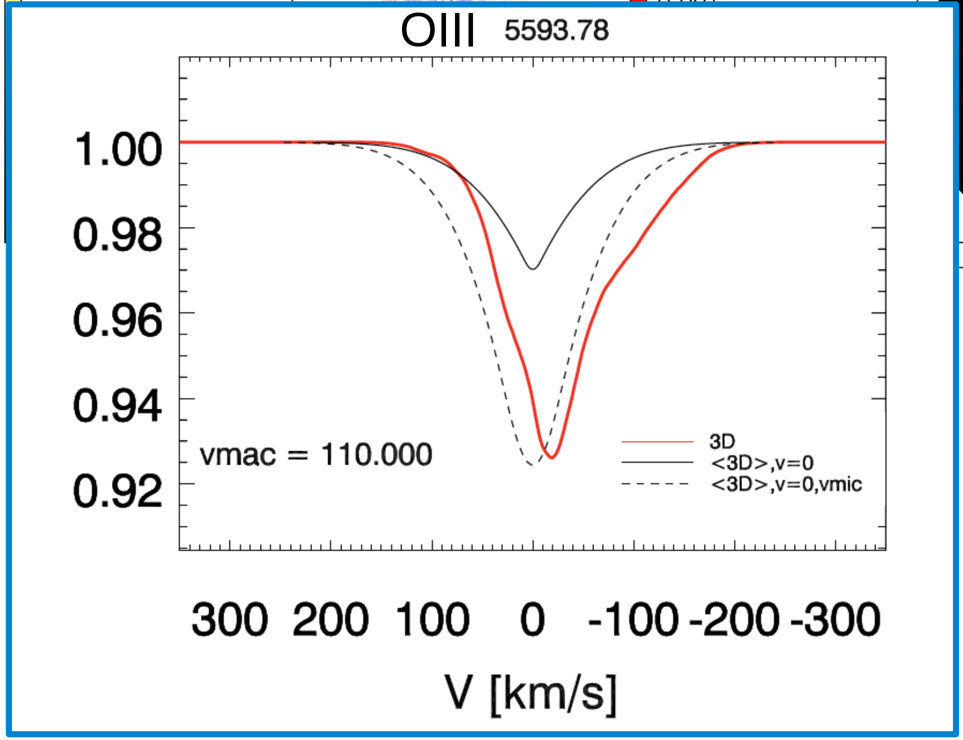


$$\frac{1}{c}\partial_t I_\nu + \hat{n} \cdot \nabla I_\nu = \kappa_\nu \rho (S_\nu - I_\nu)$$

*Without assuming micro/macro turbulence, clumping, ...

Spectral synthesis





In 20 min.

Conclusions

We developed a self-consistent **3D** massive star **atmosphere and wind** model for **dynamics** and **spectral synthesis**

Pro’s:

- Self-consistent
- No ad-hoc parameters
- Capture important 3D effects
- Inform 1D methods
- Computationally cheap

Con’s:

- Computationally expensive
- Sobolev approximation
- Not fully NLTE

Thank you

Flux-limited diffusion

0^{th} moment equation:

$$\partial_t E + \nabla \cdot (E\vec{v} + \vec{F}) = -\nabla\vec{v} : P_{rad} - \dot{q}_{rad}$$

Flux limited diffusion:

$$\mathbf{F} = -\frac{c\lambda}{\kappa\rho}\nabla E$$

Recovers diffusive limit
Recovers free streaming limit

+ Computationally cheap
+ Captures dynamics

- No spectral info
- **Analytic approximation**

Radiation-hydrodynamics

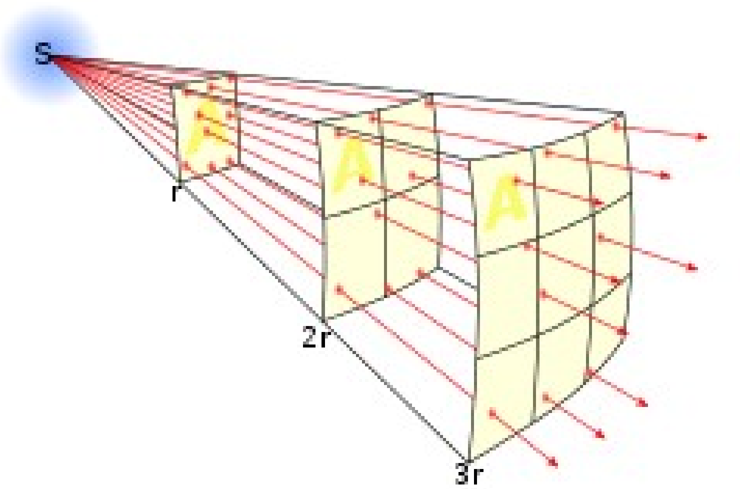
$$
\begin{aligned}
\partial_t \rho + \nabla \cdot (\rho \vec{v}) &= 0 \\
\partial_t (\vec{v}\rho) + \nabla \cdot (\vec{v}\rho\vec{v} + p) &= -\rho \vec{g}_{grav} - \rho \vec{g}_{rad} \\
\partial_t e + \nabla \cdot (e\vec{v} + p\vec{v}) &= -\rho \vec{v} \cdot \vec{g}_{grav} - \rho \vec{v} \cdot \vec{g}_{rad} + \dot{q}_{rad} \\
\partial_t E + \nabla \cdot (E\vec{v} + \vec{F}) &= -\nabla \vec{v} : P_{rad} - \dot{q}_{rad}
\end{aligned}
$$

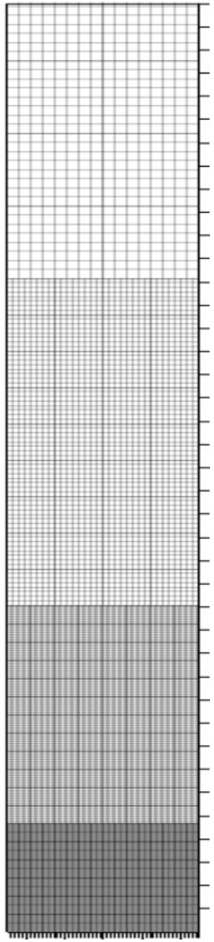
Solved with **MPI-AMRVAC**
In 1D, 2D or 3D setting

- Finite volume solver
- AMR, mpi-parallel

Moens ‘21

Pseudo-Planar correction

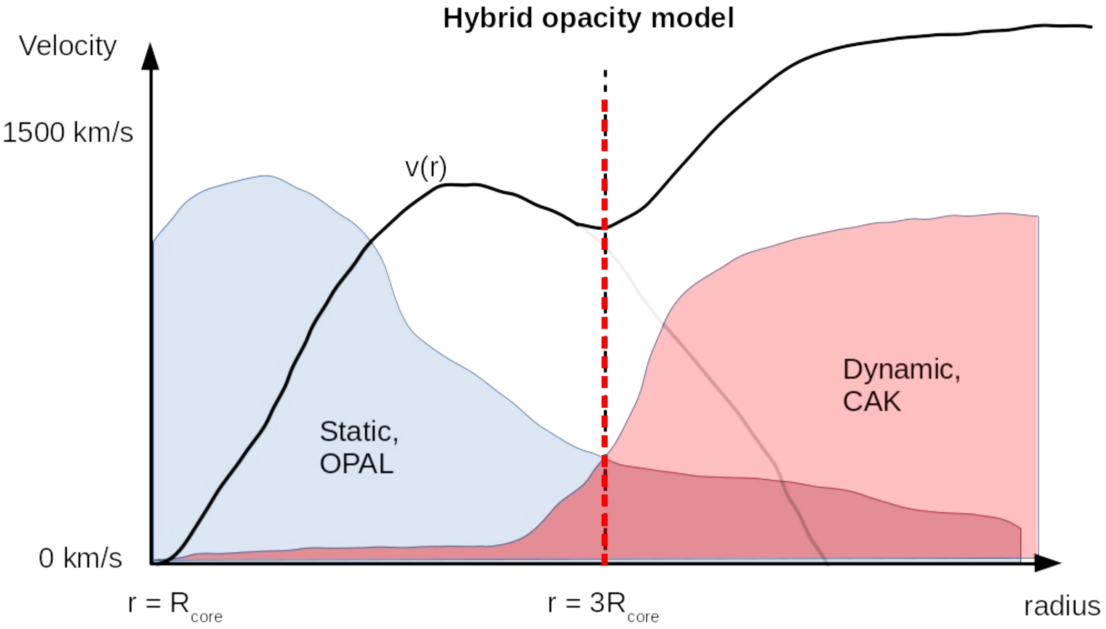




$$\nabla \cdot \vec{v} = \boxed{\frac{1}{x^2}\partial_x(x^2 v_x)} + \partial_y v_y + \partial_z v_z$$

As in spherical radial coordinate

WR wind morphology

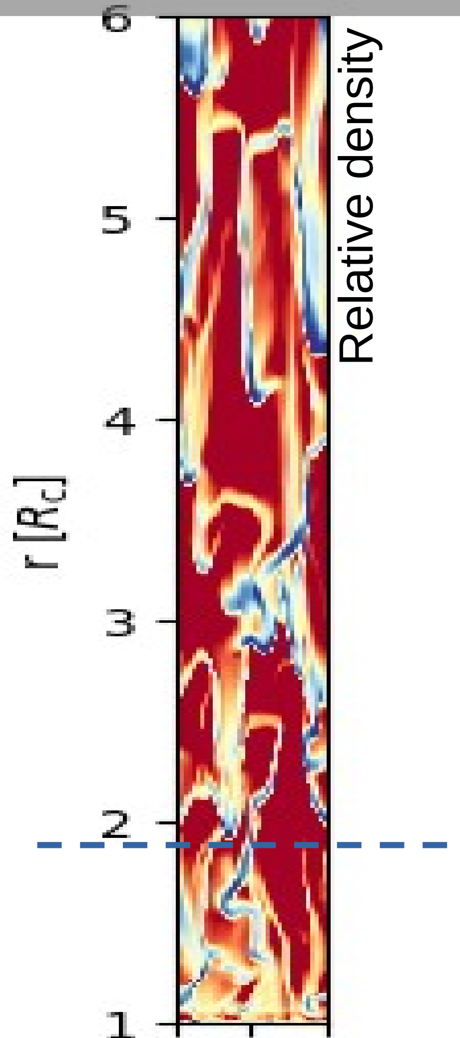


Only IRON BUMP does not suffice to lift gas from gravitational well

Solution: Take into account stretched line opacities (driving force behind O,B-star winds)

Hybrid opacity model by Poniatowski et. al. ‘21

WR wind morphology



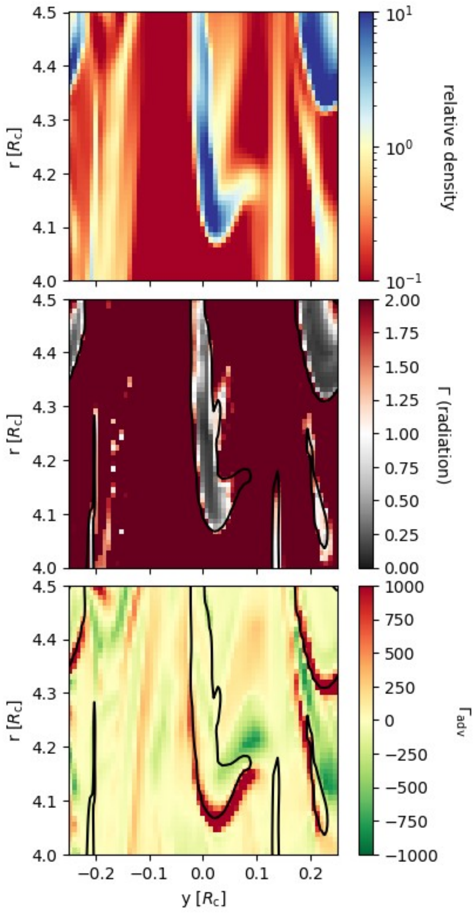
Line-driven: $\kappa \sim 1/\rho^a$

OPAL dominated: $\kappa \sim \rho$
Radiation-Convective Unstable [Langer 97, Castor 04]

Density

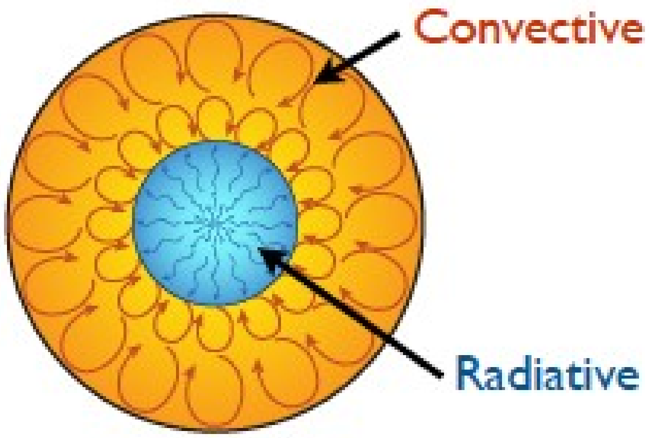
Eddington Gamma

Ram-Pressure

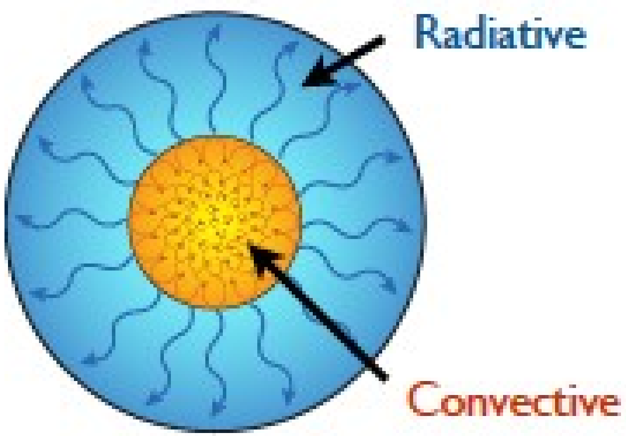


Ostars

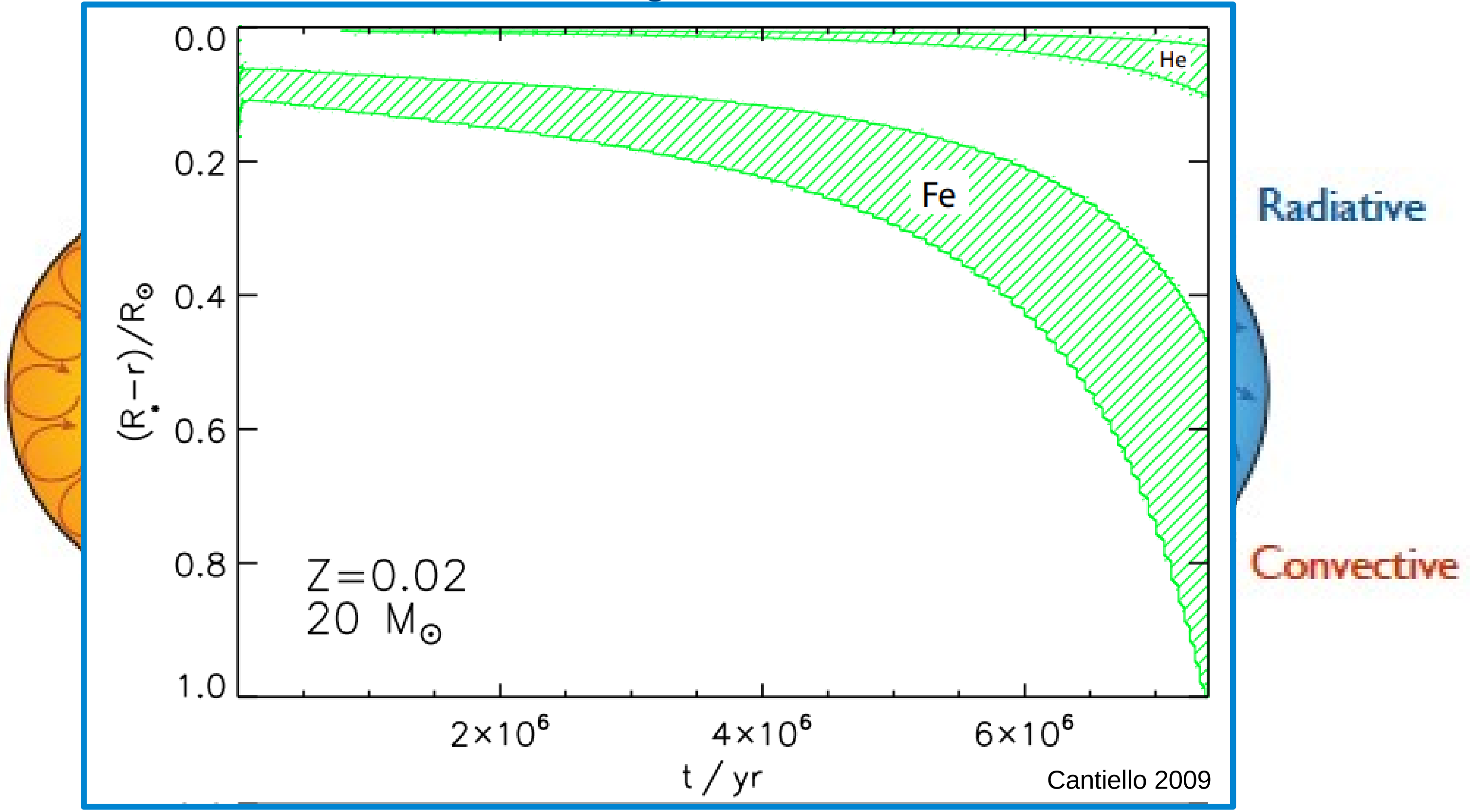
Low Mass



Higher Mass



Even Higher Mass



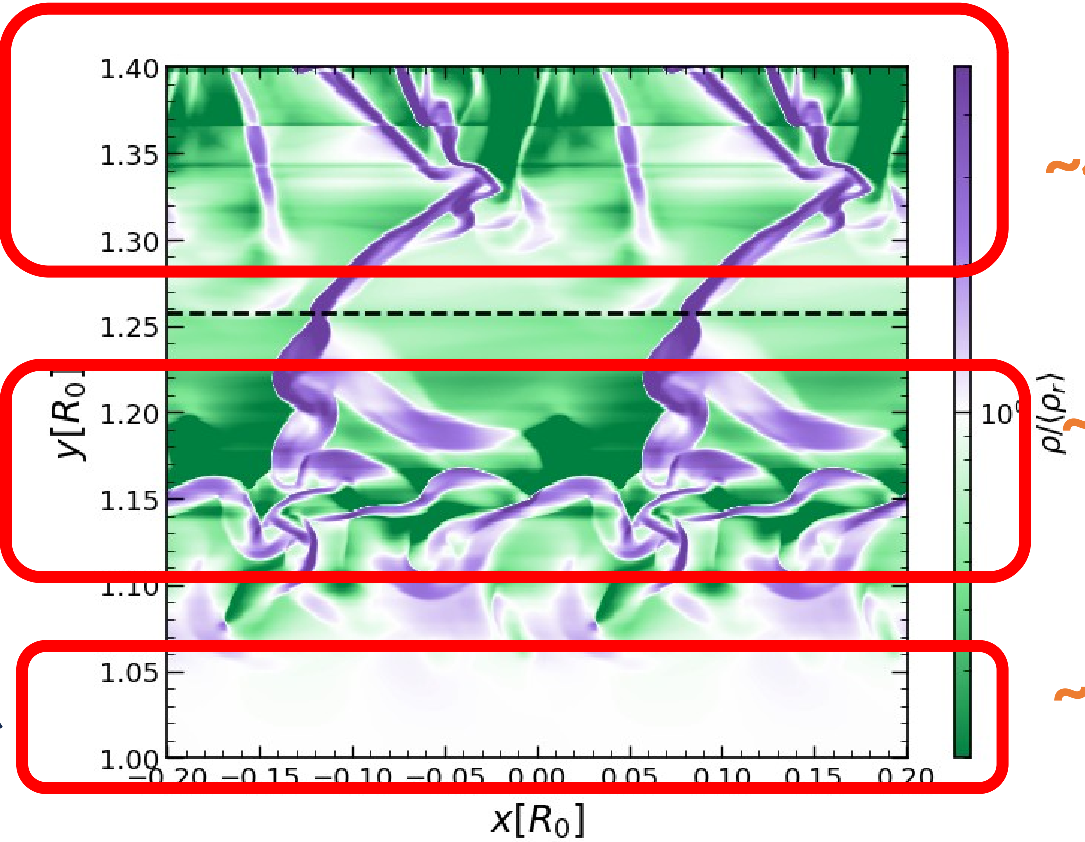
Cantiello 2009

Ostars

Outflowing part

Turbulent atmosphere

Quasi-stable hydrostatic envelope/ lower atmosphere



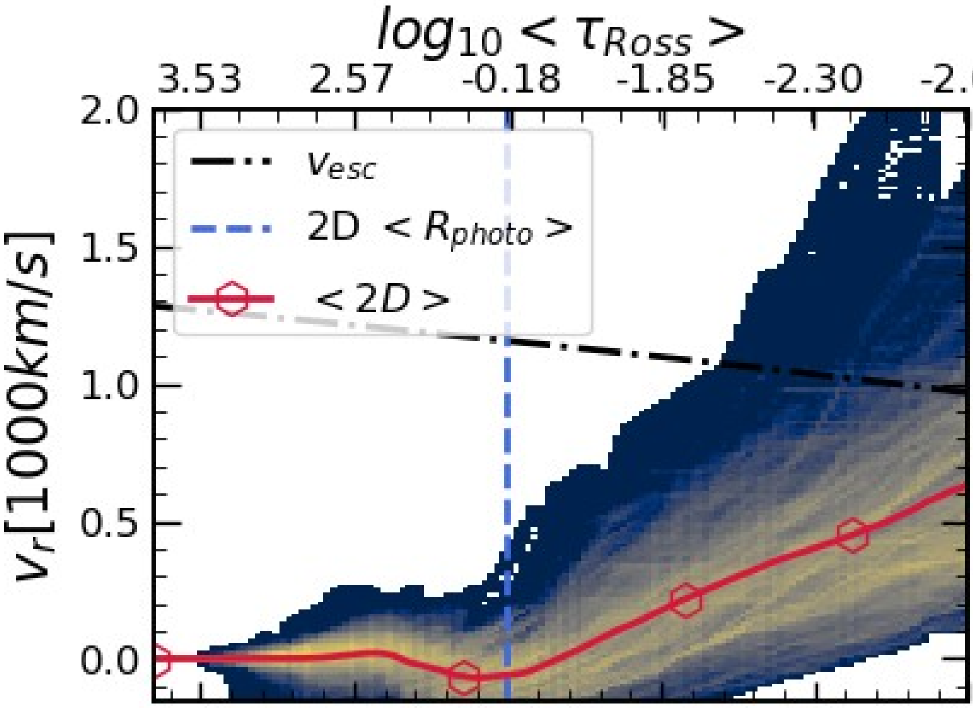
~40kK

~150k K

~400k K

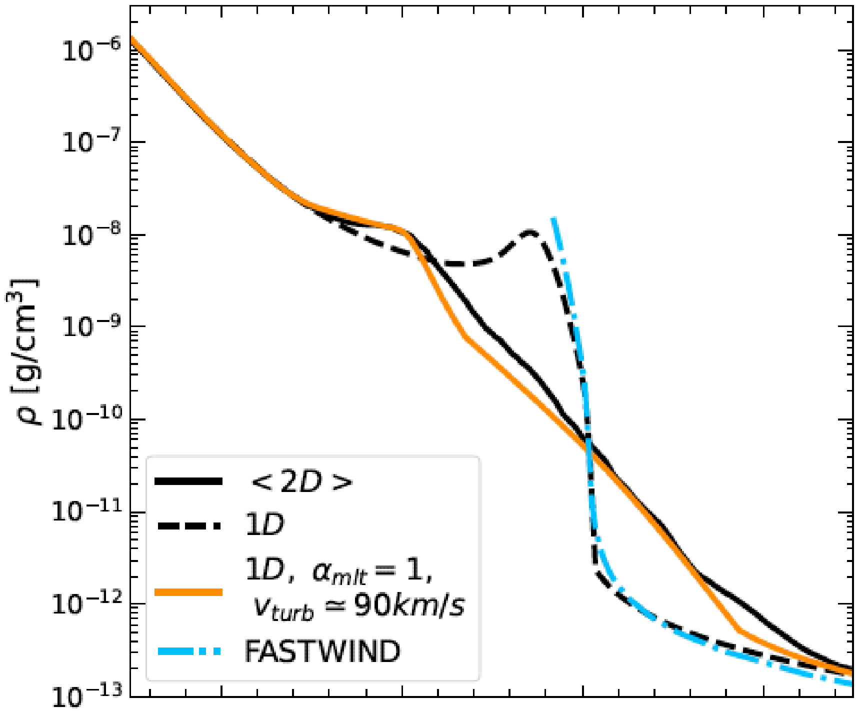
Ostars

Debnath '24



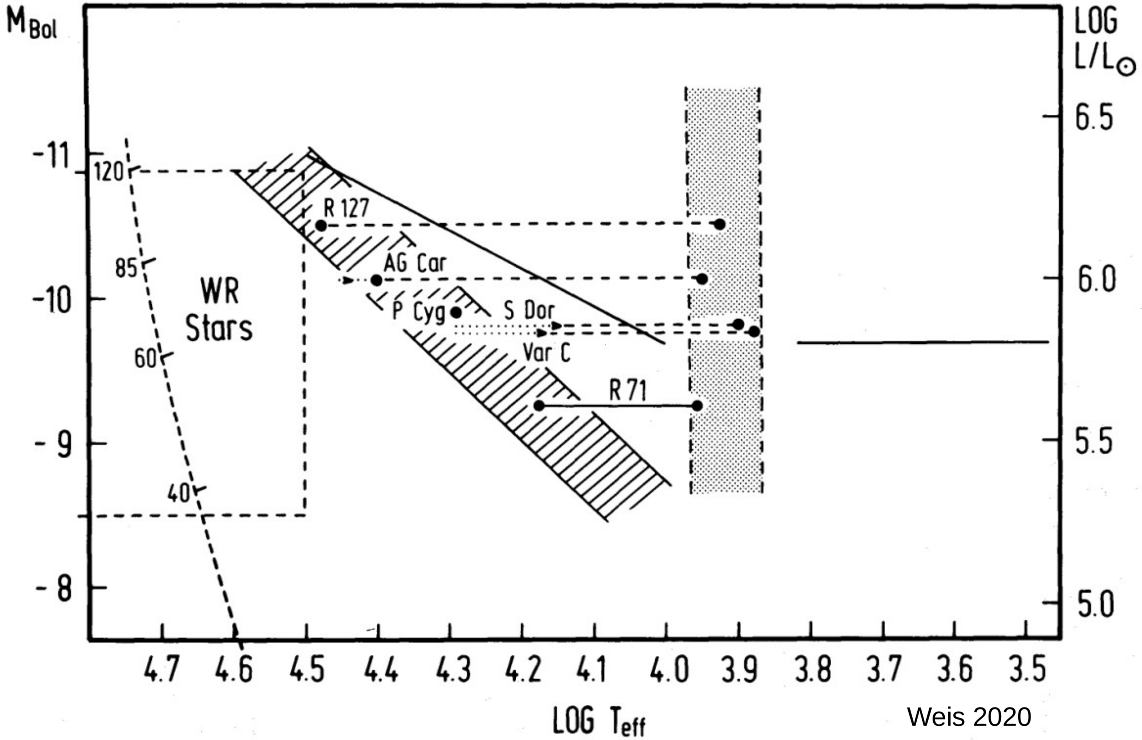
Scaled Radius

Debnath '24



Scaled Radius

LBV stars

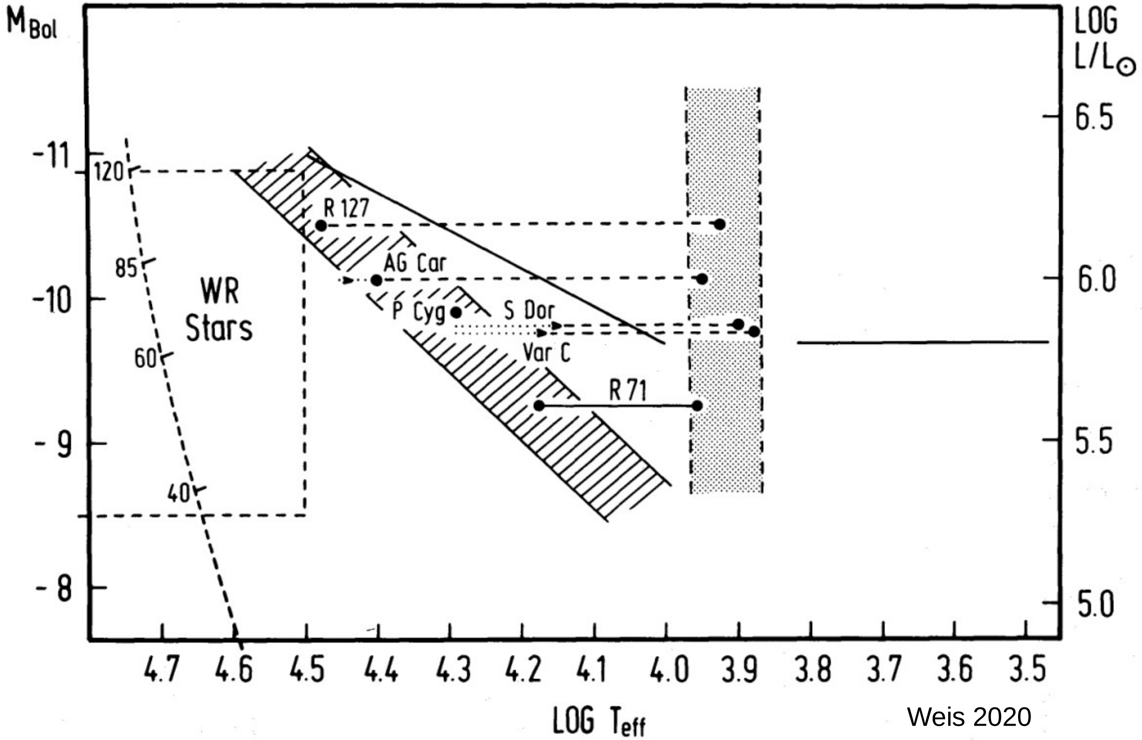


Weis 2020

S Dor-like
Luminous Blue Variables:

Move left-right on HRD
On (atmosphere's)
thermal timescale

LBV stars



Weis 2020

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Move left-right on HRD
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thermal timescale

VIDEO TIME