Understanding the Structures and Evolutions of Massive Stars Based on 3D Radiation Hydrodynamic Simulations

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Outline

- Challenges to understand the structures and evolutions of massive stars

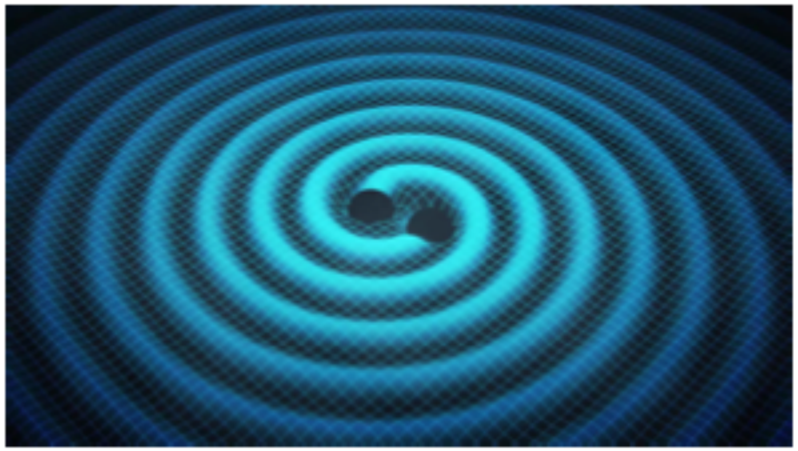
- What can we learn about massive stars based on 3D Radiation hydrodynamic Simulations:

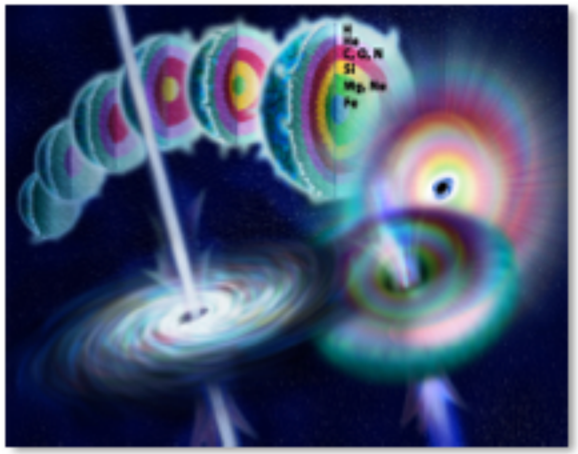
  - Luminous Blue Variables
  - Stochastic low frequency variabilities of massive stars as observed by TESS

- Improve 1D stellar evolution models of massive stars

Massive stars are interesting:

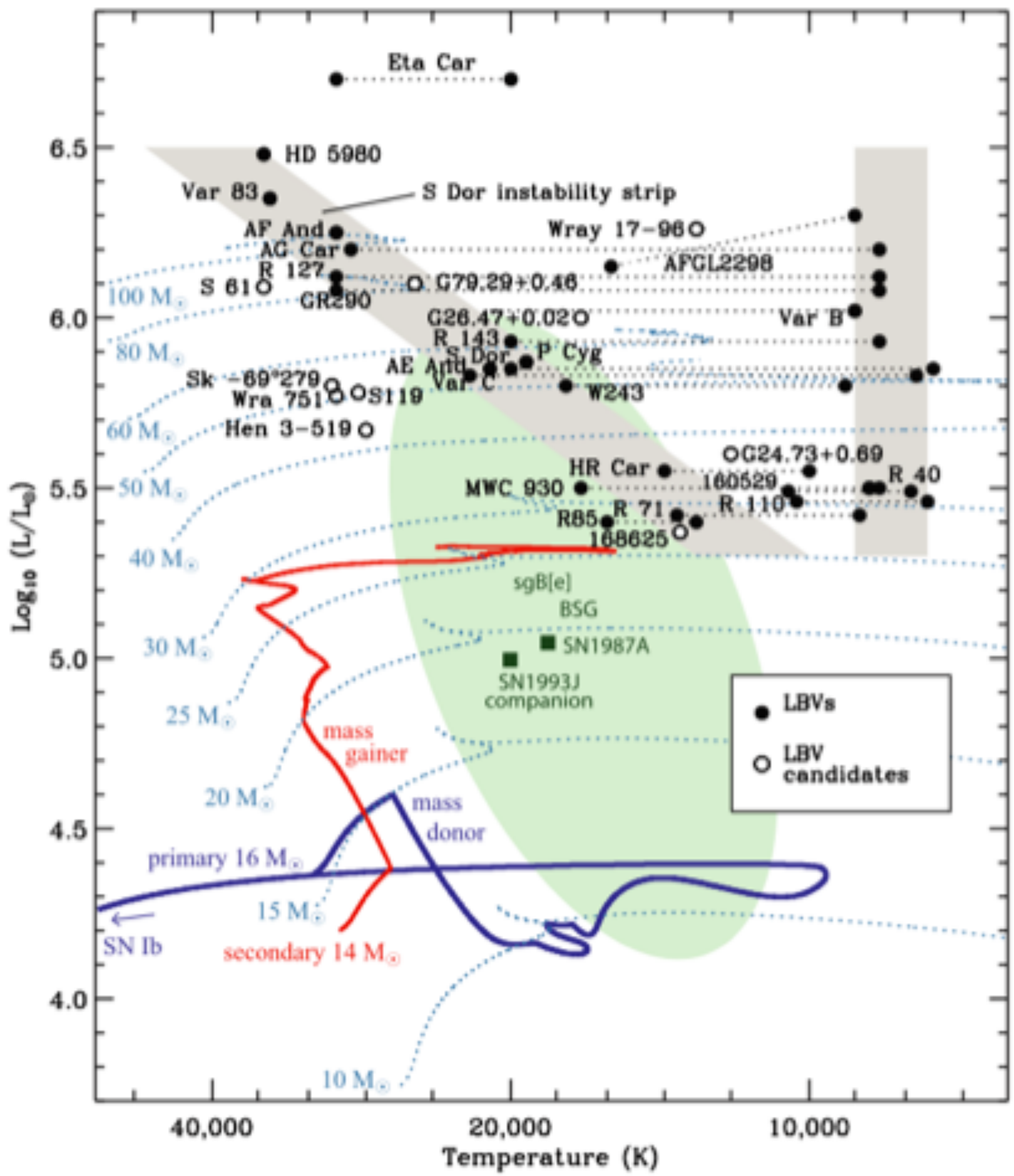
- Provide the bulk contribution of Energy / Momentum to the ISM
  - Through Stellar Winds, SNe Explosions, Ionization photons
- Drivers of Nucleosynthesis
- Remnants: NS and BHs
  - Magnetars, Pulsars, Long GRBs, Gravitational Wave Sources (LIGO)





But massive stars are so hard to understand:

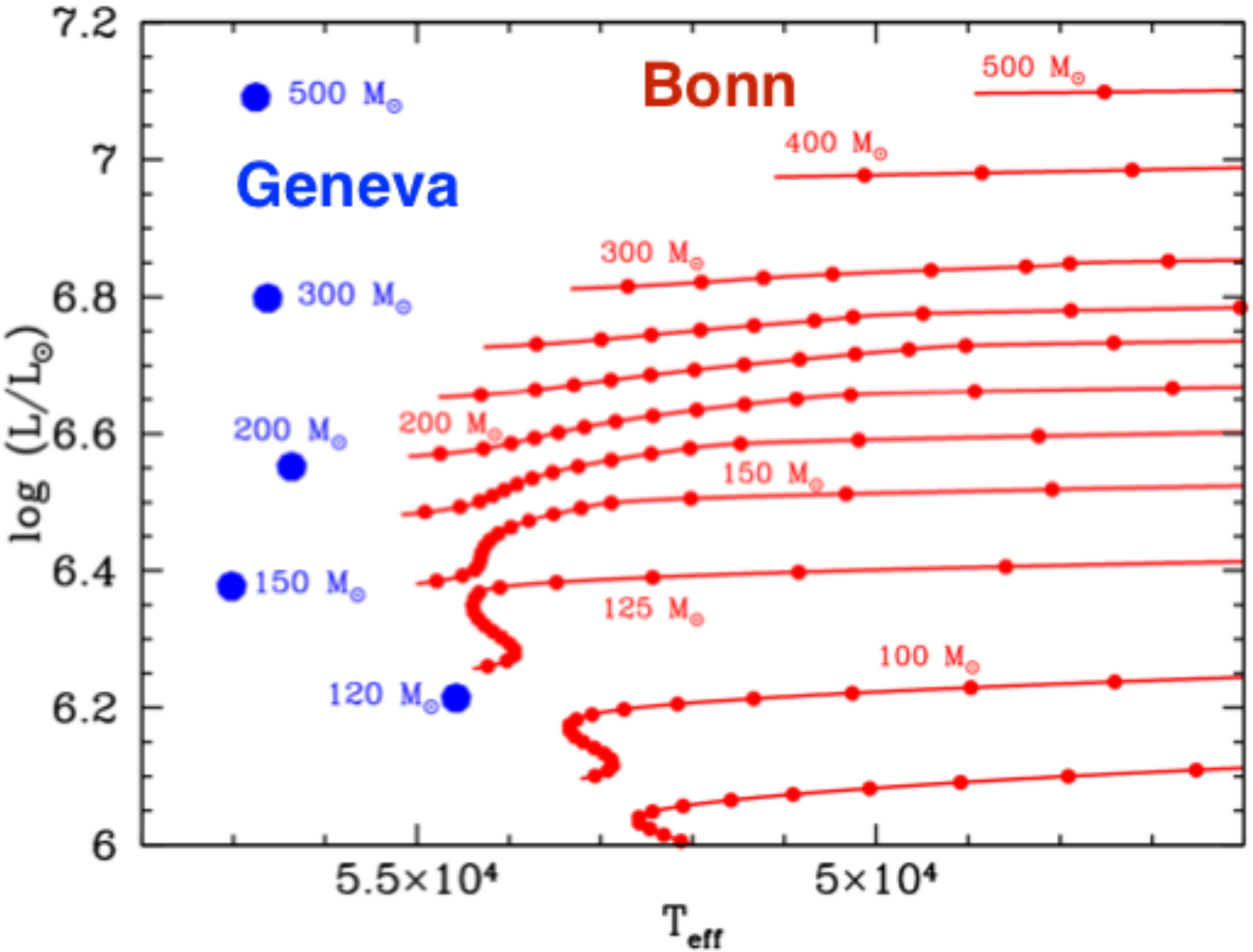
Smith et al. (2004)
Smith & Tombleson (2015)



- Post main sequence evolutions are very complicated.

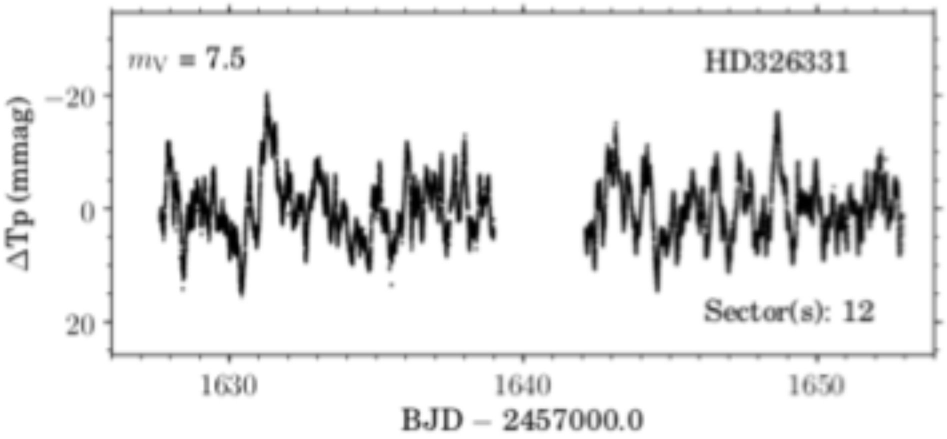
But massive stars are so hard to understand:

Köhler et al. 2015



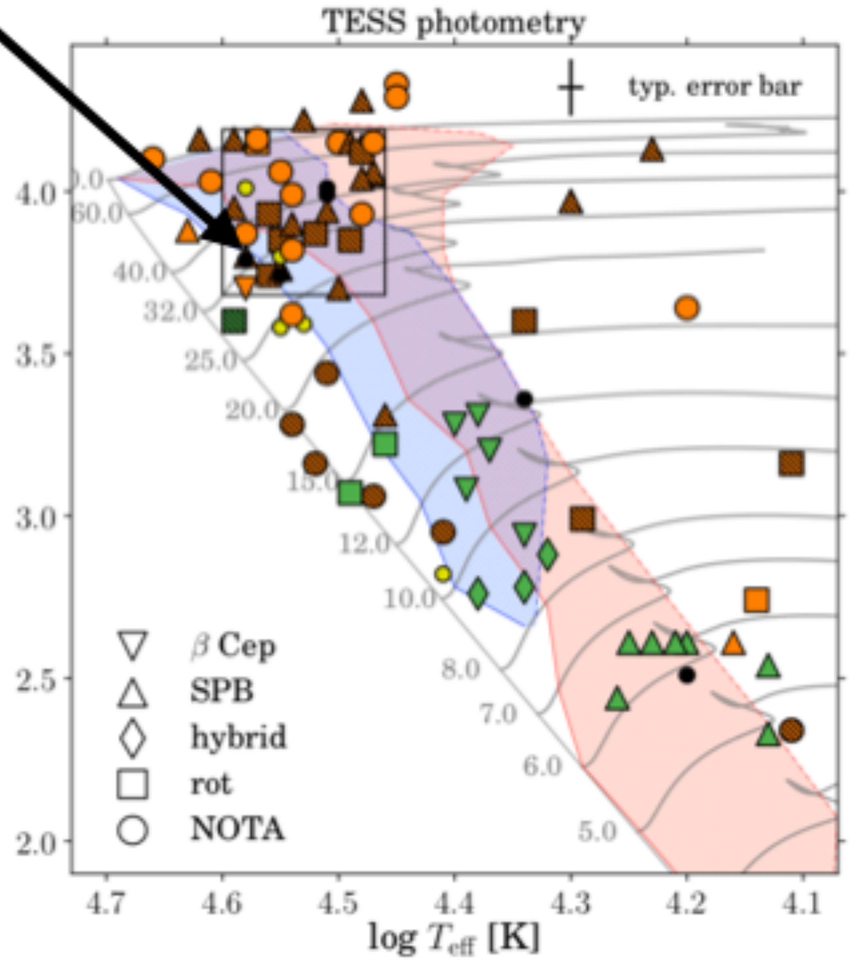
- 1D stellar evolution models are very uncertain.

But massive stars are so hard to understand:



Burssens et al (2020)

Burssens et al. (2020)

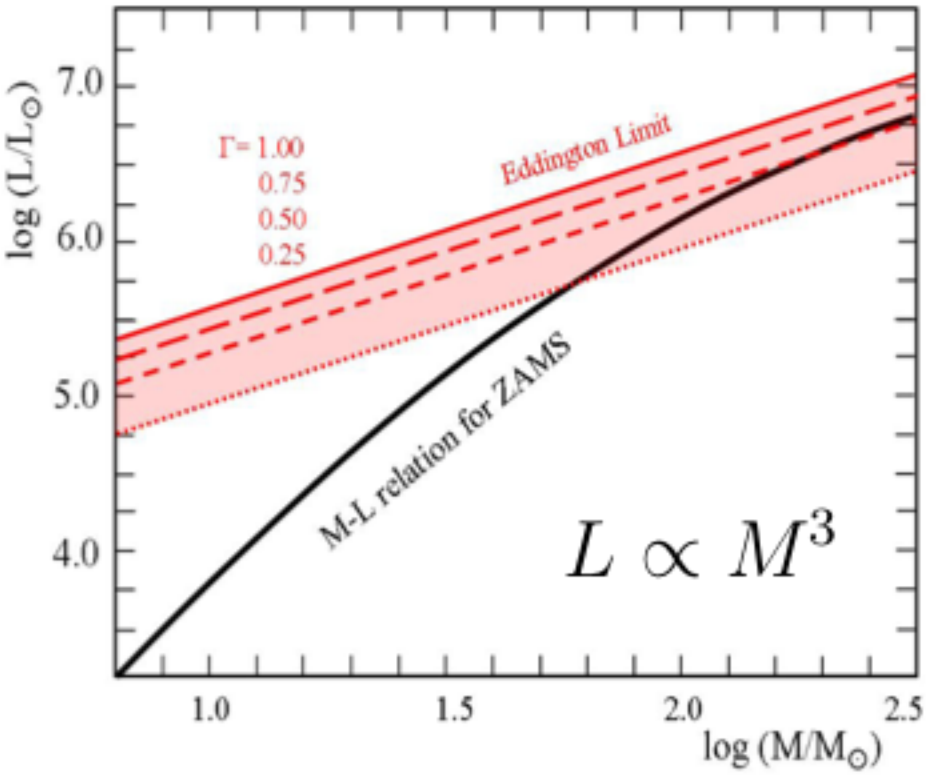


- Stochastic, low frequency variability as observed by TESS.

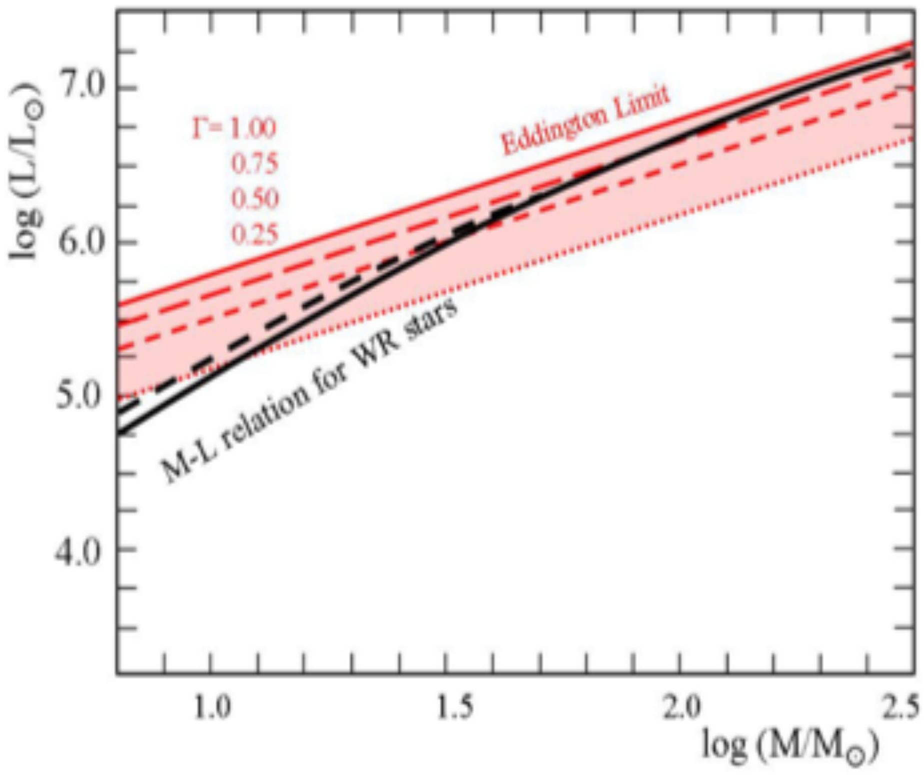
But massive stars are so hard to understand:

Maeder et al. (2012)

- Close to Eddington limit for electron scattering opacity



Zero–Age Main Sequence Stars



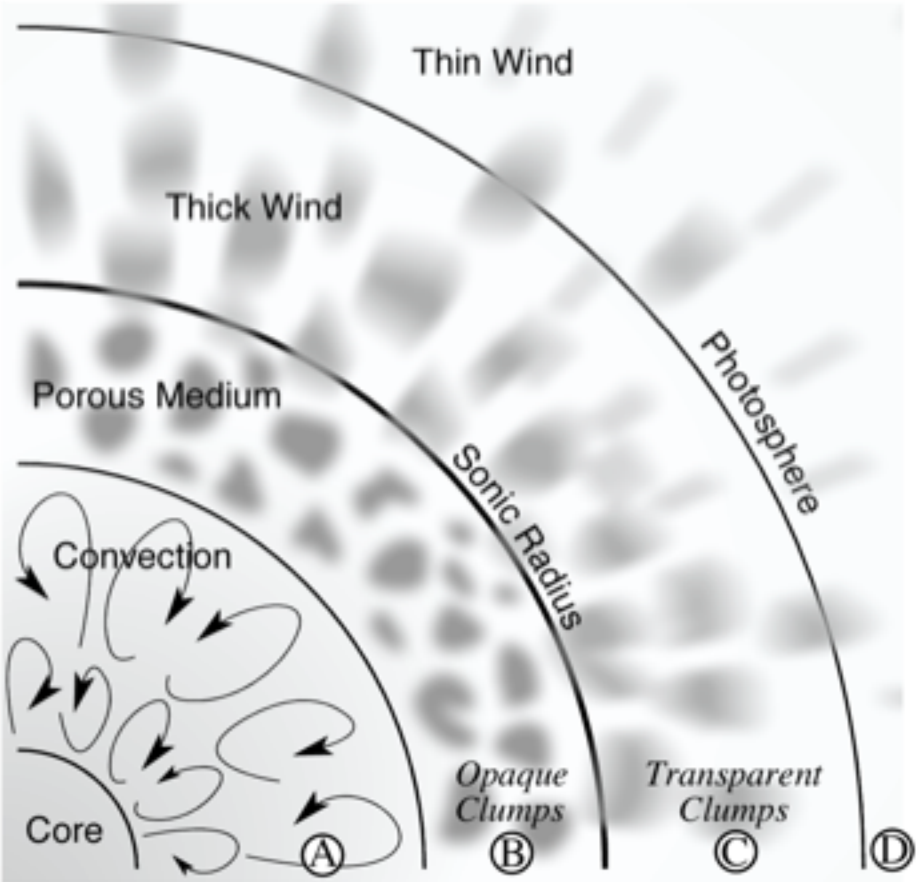
Evolved Stars

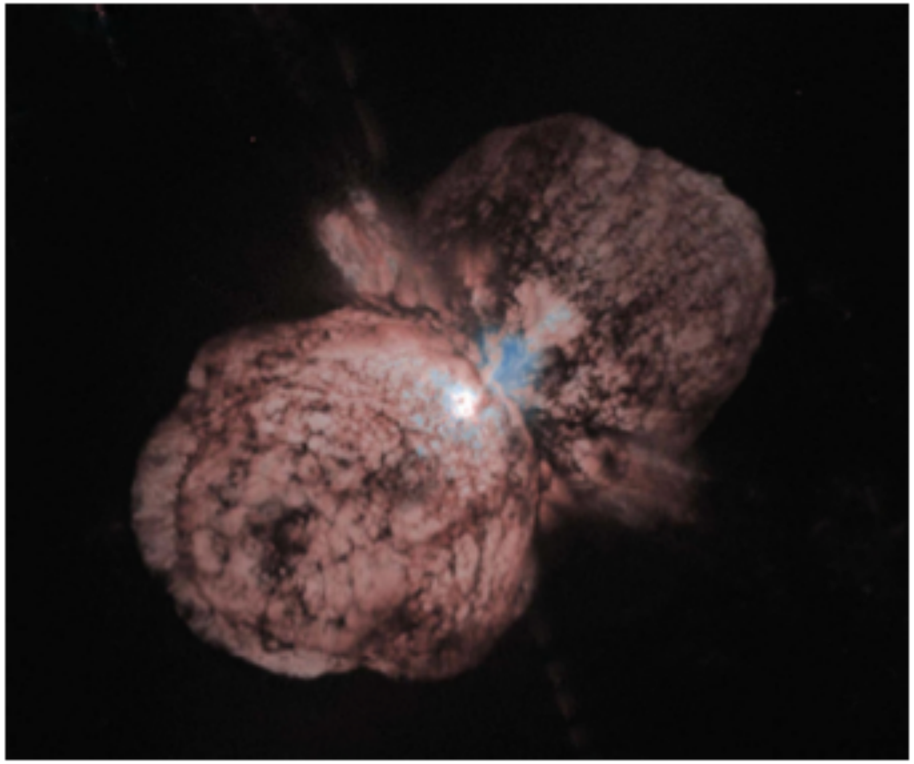
Mass–Luminosity Relation

But massive stars are so hard to understand:

- Significant mass loss

Puls et al. (2008)
Owocki (2014)



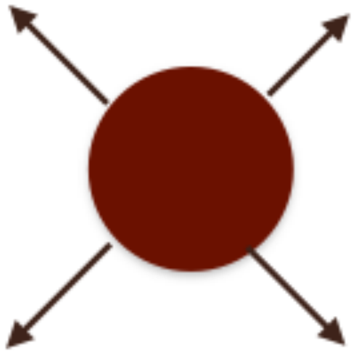


Eta Carinae

1D Stellar Evolution Studies

Paxton et al. (2013)
Joss et al. (1973)

- Thermal equilibrium: how to transport the energy out



$$L = 4\pi r^2 F_r = 4\pi r^2 \left[F_{r,0} + v\left(E_r + P_r\right)\right]$$

Diffusive radiation flux | Advective flux

- Hydrostatic equilibrium

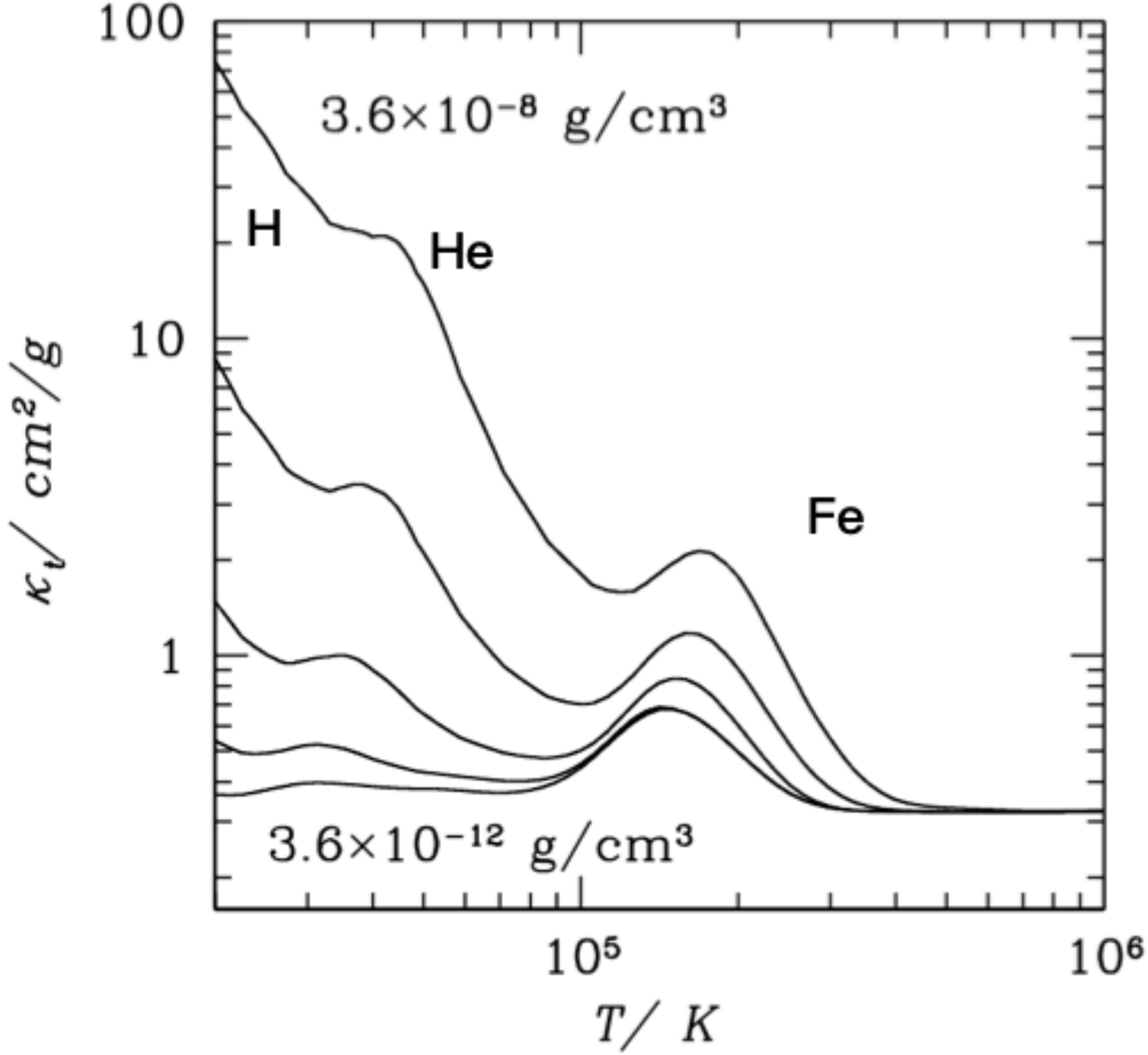
$$\frac{\mathrm{d}P_{\mathrm{gas}}}{\mathrm{d}r} = \left(\frac{\mathrm{d}P_{\mathrm{rad}}}{\mathrm{d}r}\right)\left[\frac{L_{\mathrm{Edd}}}{L_{\mathrm{rad}}} - 1\right].$$

$$a_r = \frac{\kappa F_{r,0}}{c}$$

$$\frac{dP_{\mathrm{rad}}}{dr} = -\rho a_r$$

Super-Eddington due to the opacity

Super-Eddington due to the opacity peaks

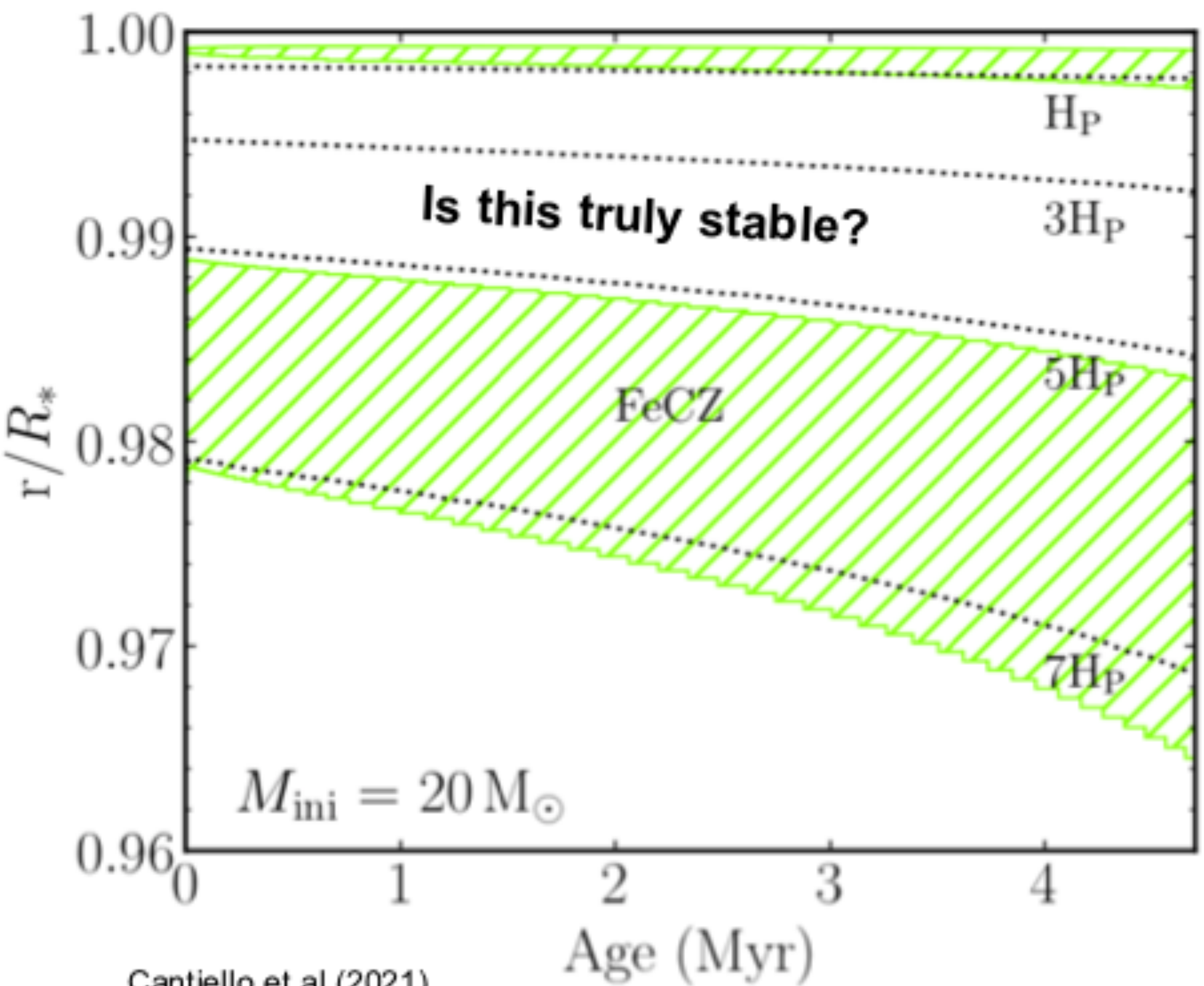


Paxton et al. (2013)
Jiang et al. (2015)

constant
density lines

Opacity Peaks cause near surface

Opacity Peaks cause near surface convection zone



Cantiello et al (2021)

Cantiello et al. (2021)

Ubiquitous to nearly all massive stars throughout many stages of their lifetime

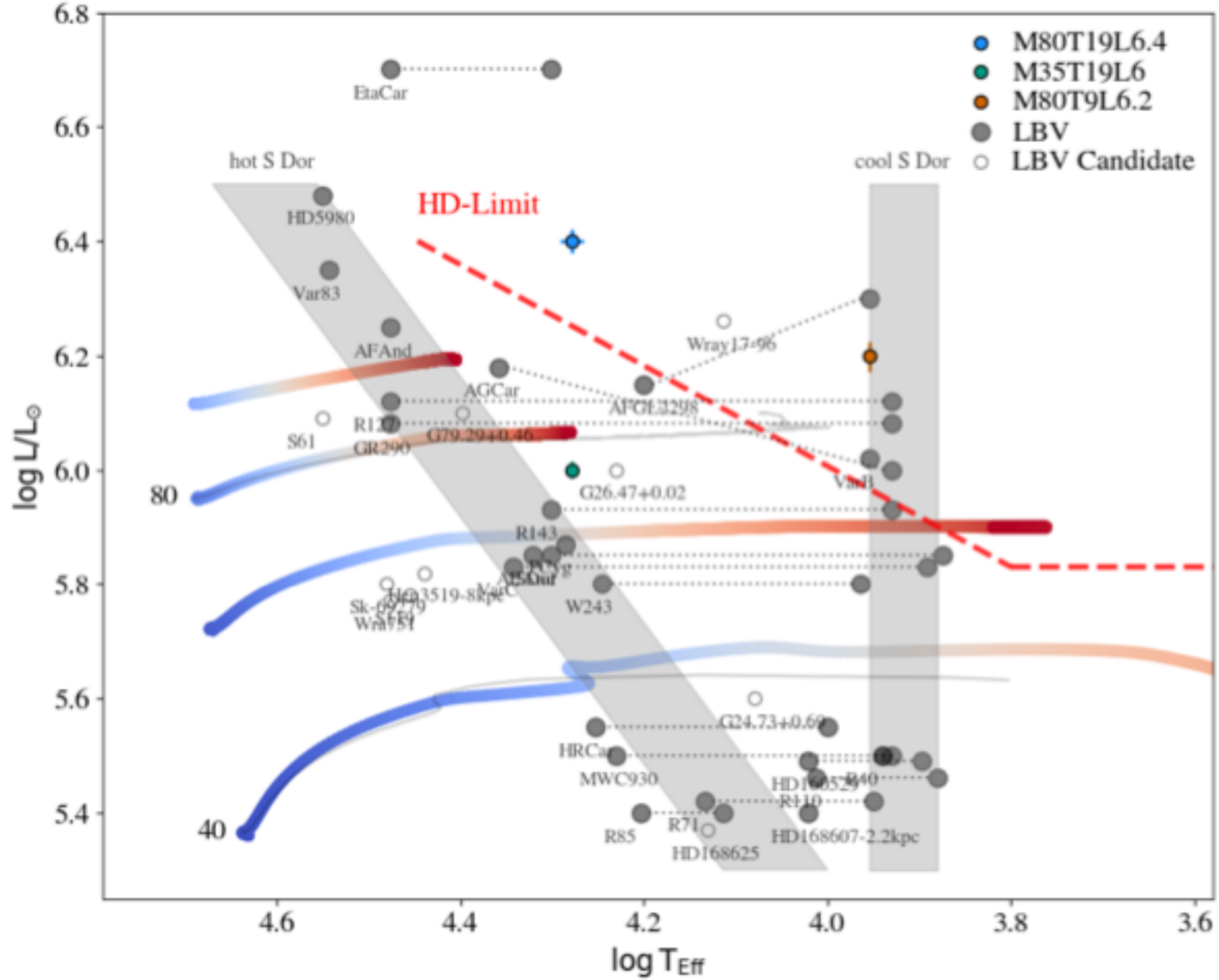
Put the star in 3D

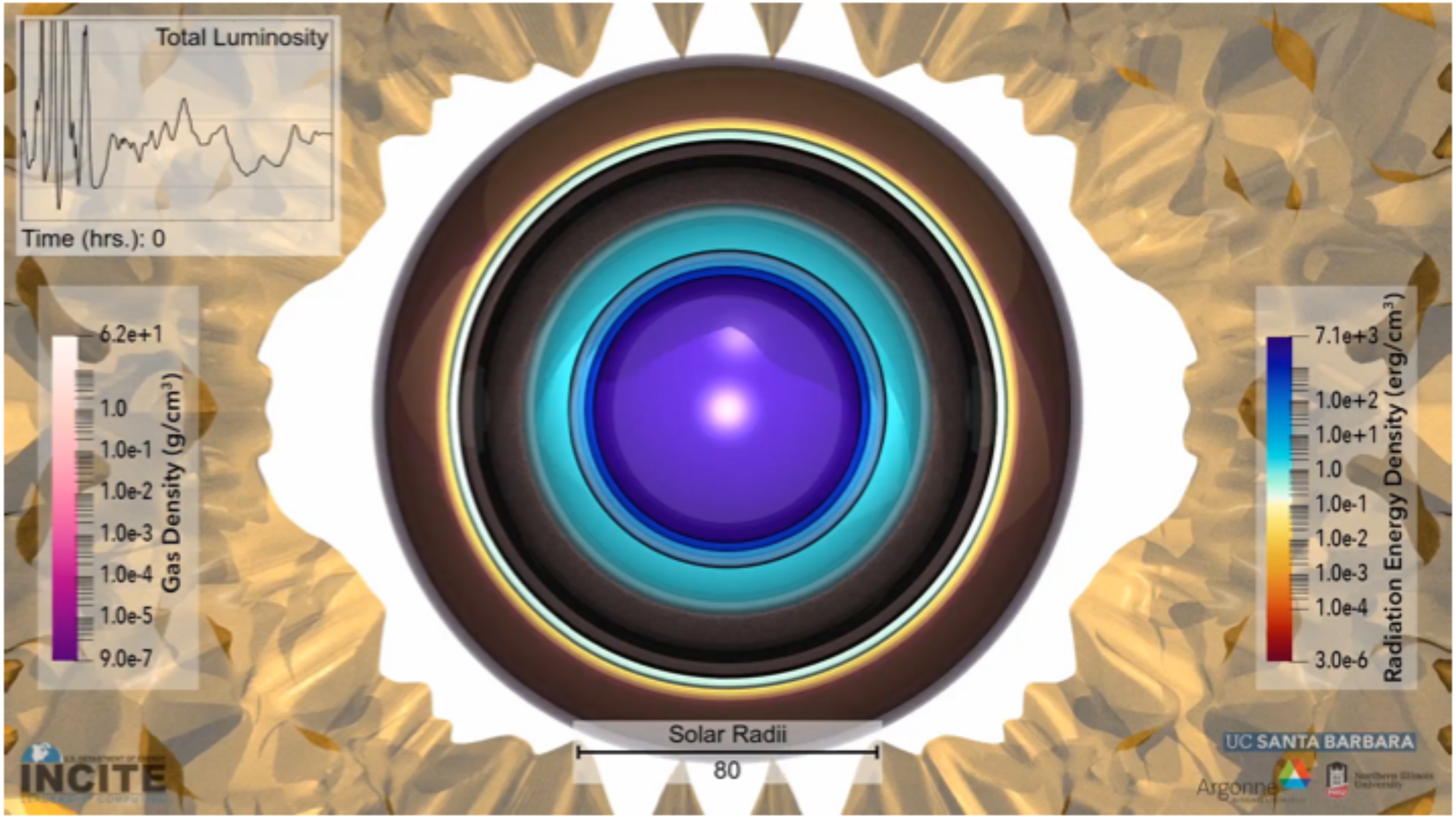
Jiang et al. (2012, 2014)
Jiang (2021)

- 3D hydrodynamics for ideal gas
- Solving the time–dependent Boltzmann equation for radiative transfer (frequency integrated)
- Gas and photons are thermally and dynamically coupled self–consistently.

- No mixing length type convection model
- No radiation force due to ultraviolet lines in the optically thin regime

Model Selection

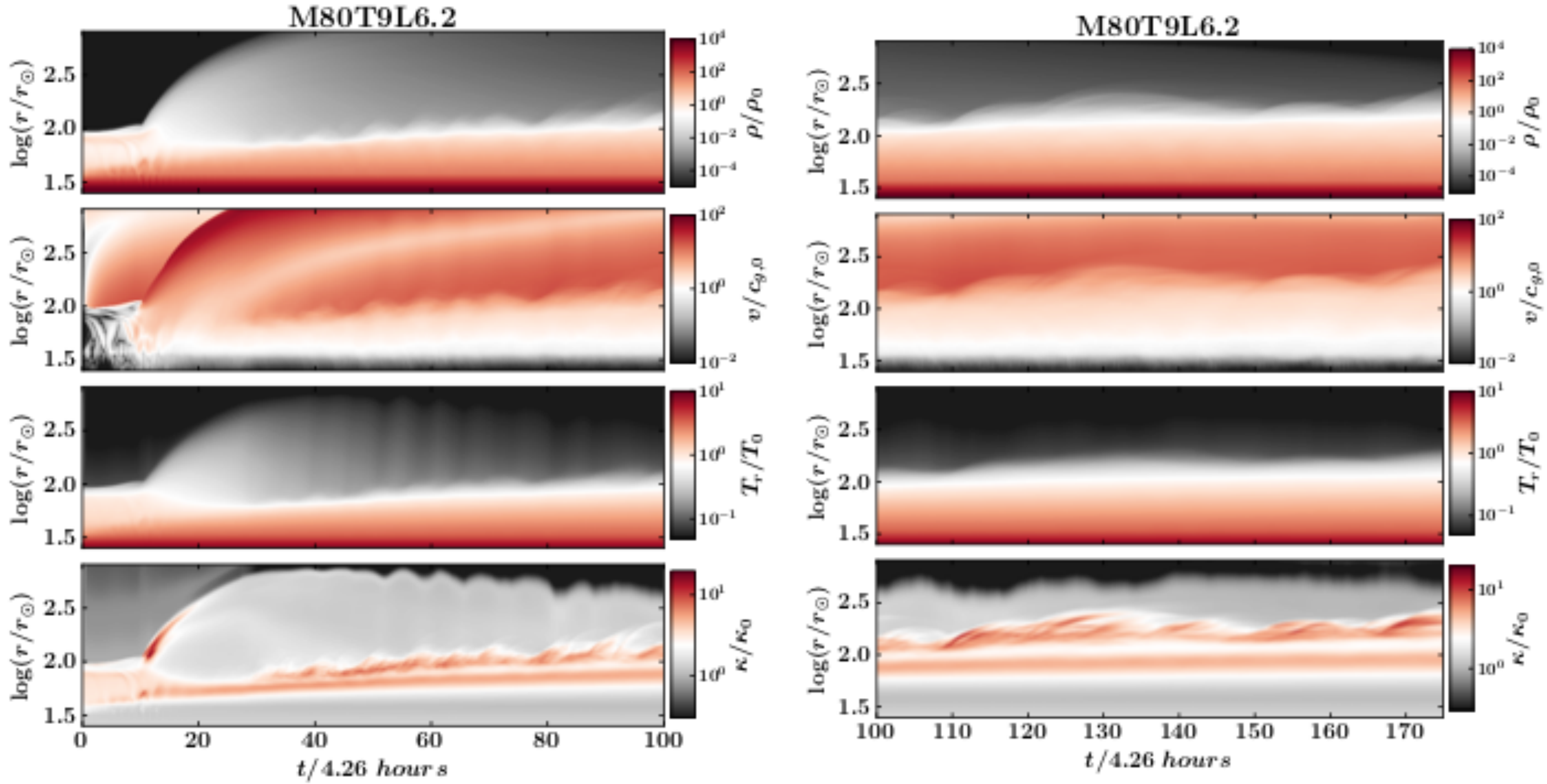




Jiang et al. (2018)

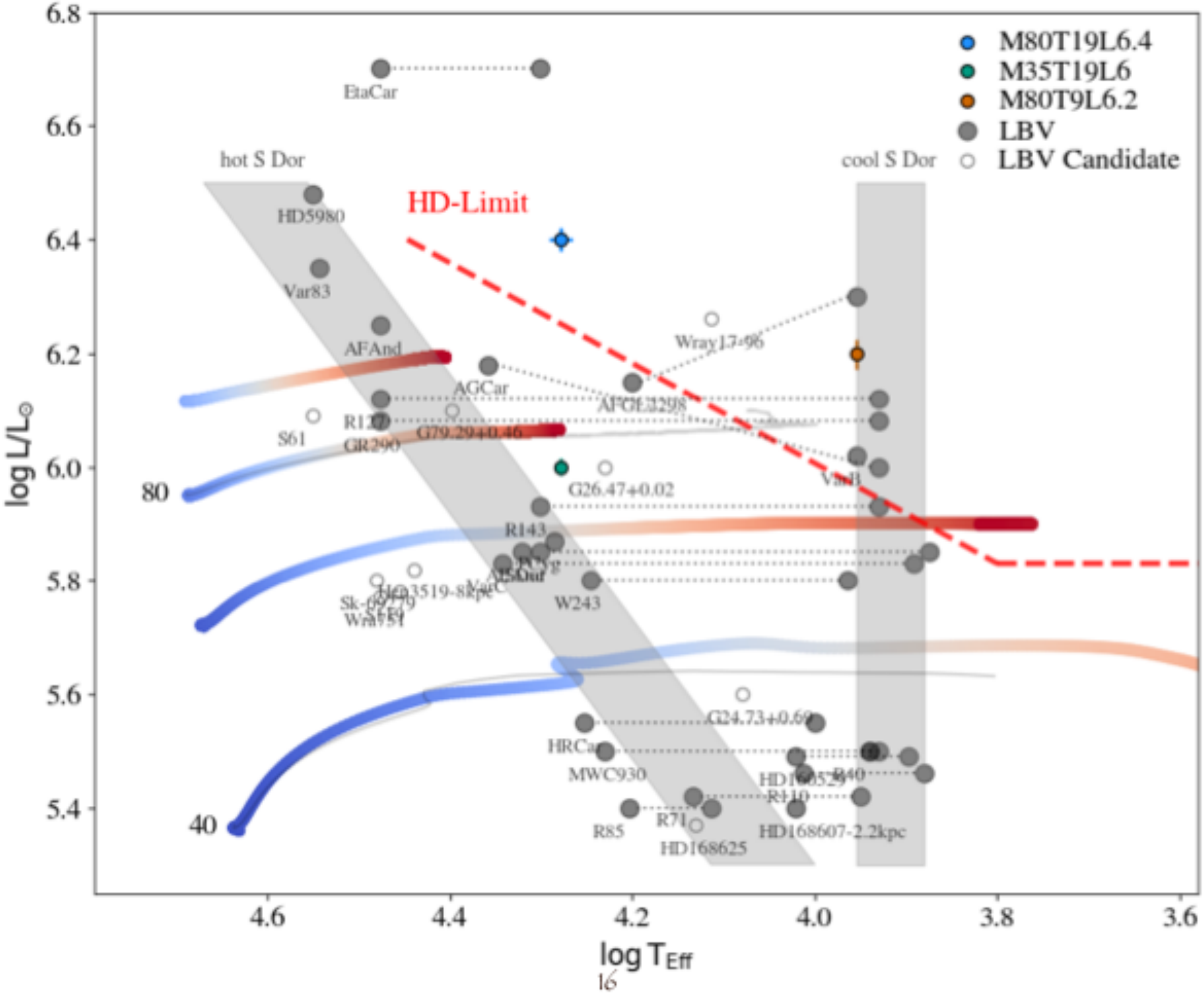
Global Structures of the

Massive Star Envelopes

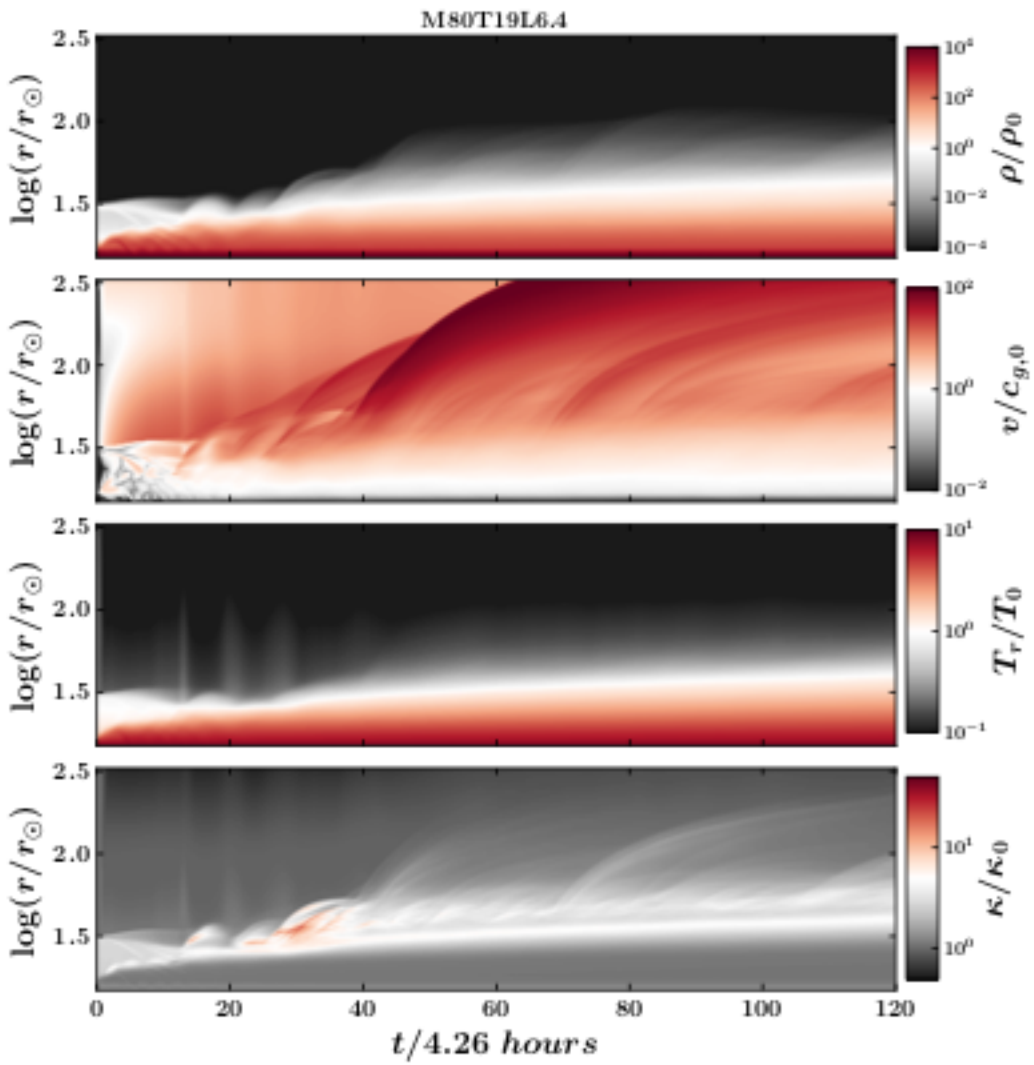


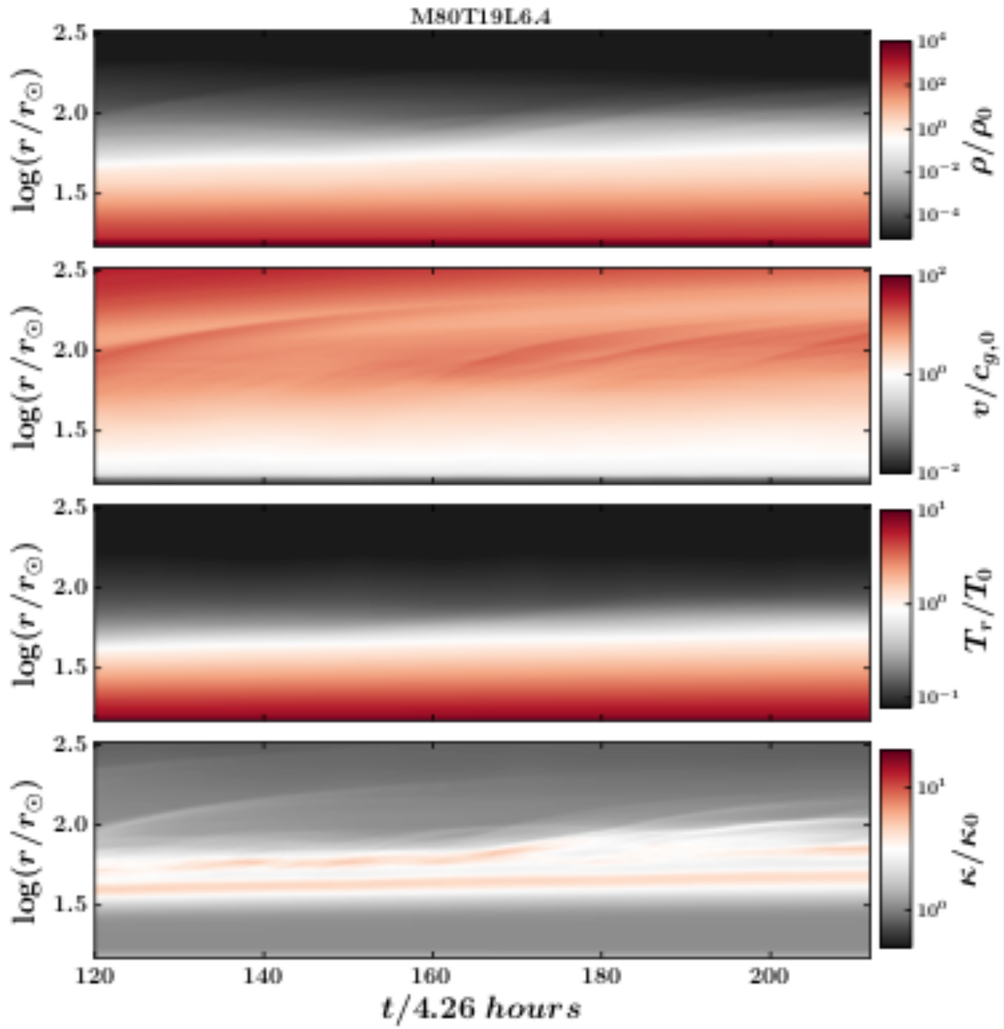
Comparison Run

Comparison Run



Comparison Run

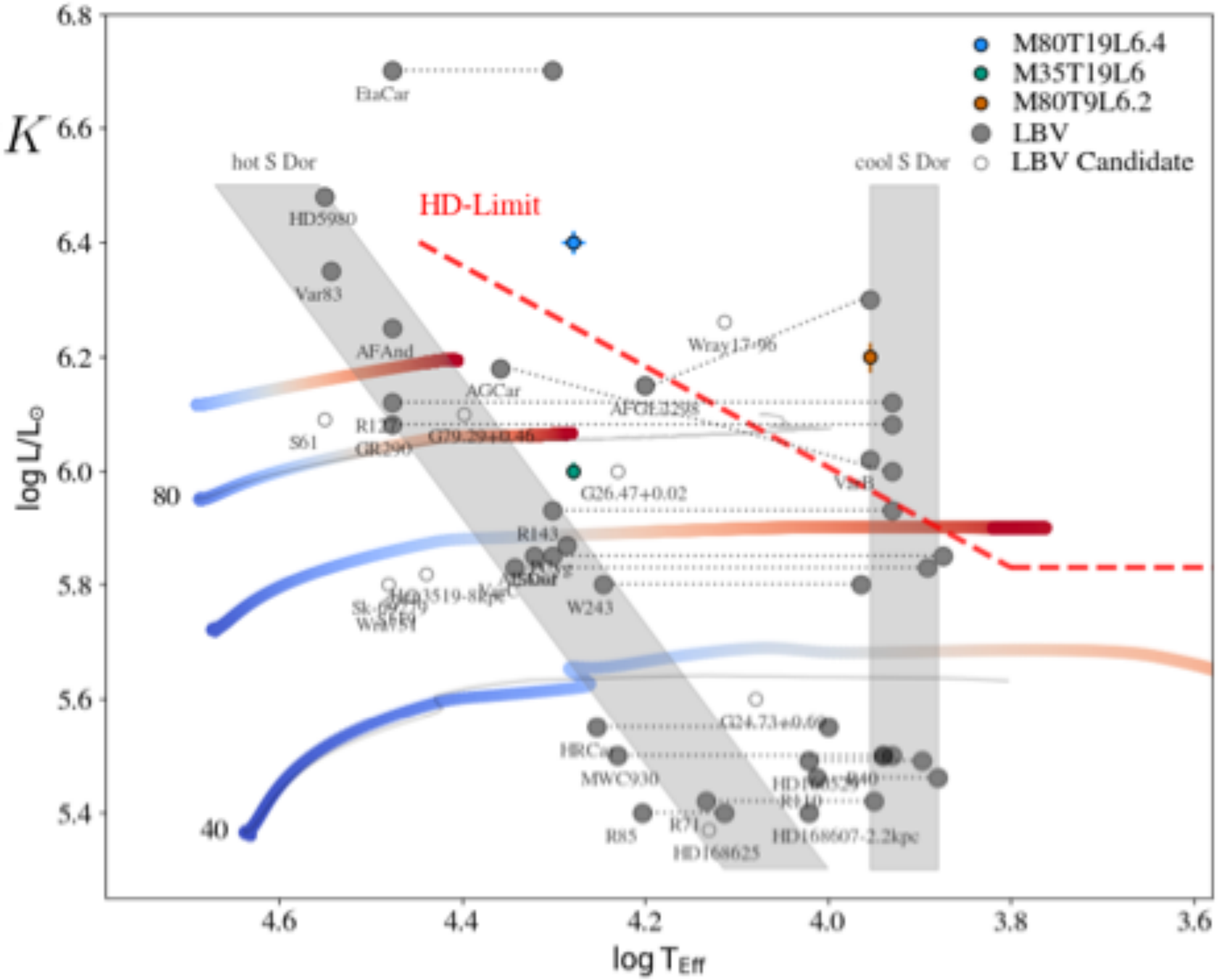




Comparison Run

Comparison Run

$R_{\rm ph} = 102.2 R_\odot$
$T_{\rm ph} = 1.9 \times 10^4 K$
$R_{\rm Fe} = 44.6 R_\odot$
$H_{\rm Fe} = 3.7 R_\odot$



$R_{\rm ph} = 342.3 R_\odot$
$T_{\rm ph} = 9.1 \times 10^3 K$
$R_{\rm Fe} = 85.9 R_\odot$
$H_{\rm Fe} = 11.2 R_\odot$

$R_{\rm ph} = 64 R_\odot$
$T_{\rm ph} = 1.9 \times 10^4 K$
$R_{\rm Fe} = 25.7 R_\odot$
$H_{\rm Fe} = 3.5 R_\odot$

Continuum Radiation

Driven Mass Loss Rate

- Initial mass above the iron opacity peak region is lost with the rate $\sim 10^{-2} M_{\odot}/yr$
- In the steady state, cooler star can drive mass loss rate

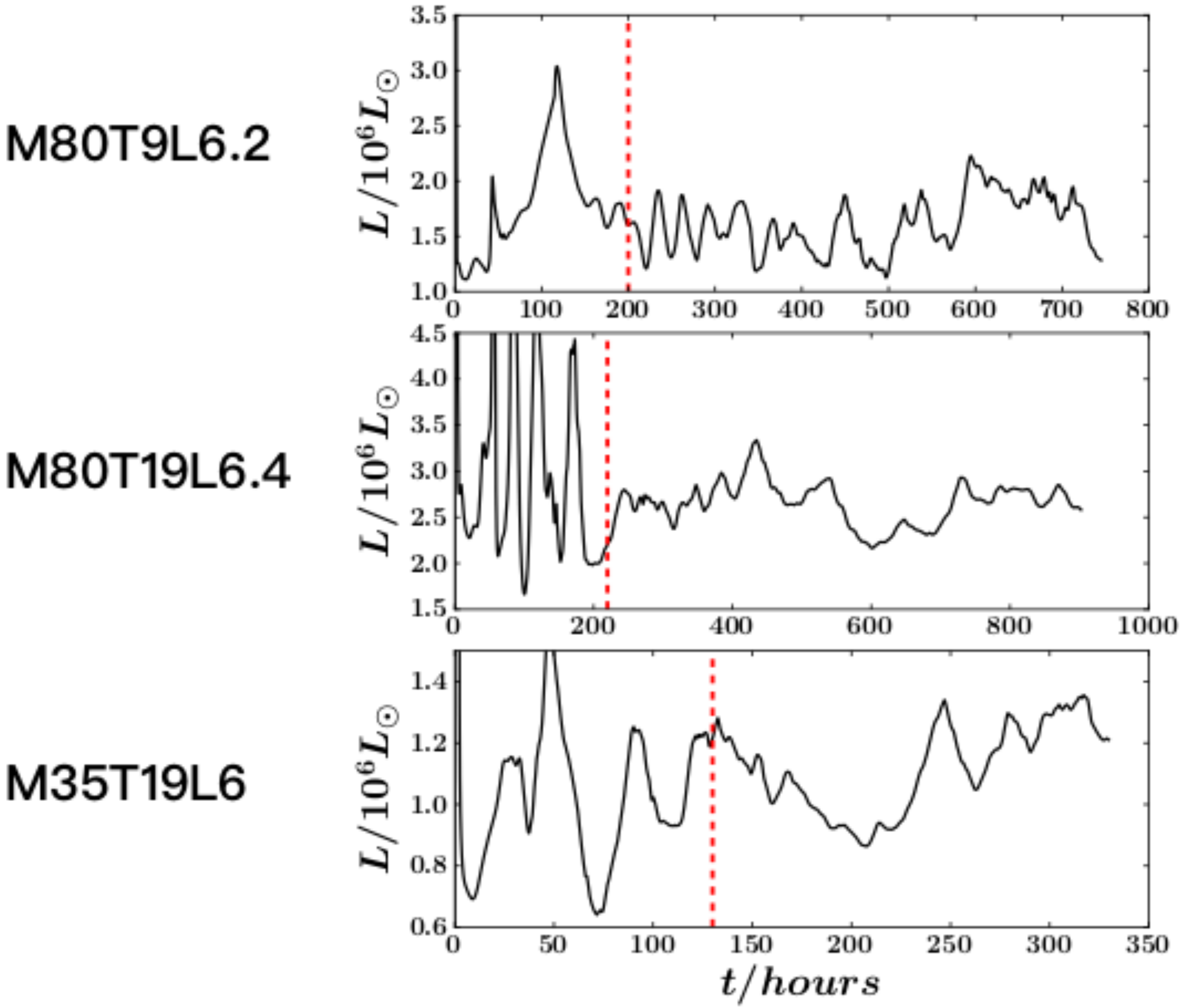
$$\sim 10^{-5} M_{\odot}/yr$$

- Mass loss rate for the hotter star in the steady state is smaller

$$\sim 10^{-6} M_{\odot}/yr$$

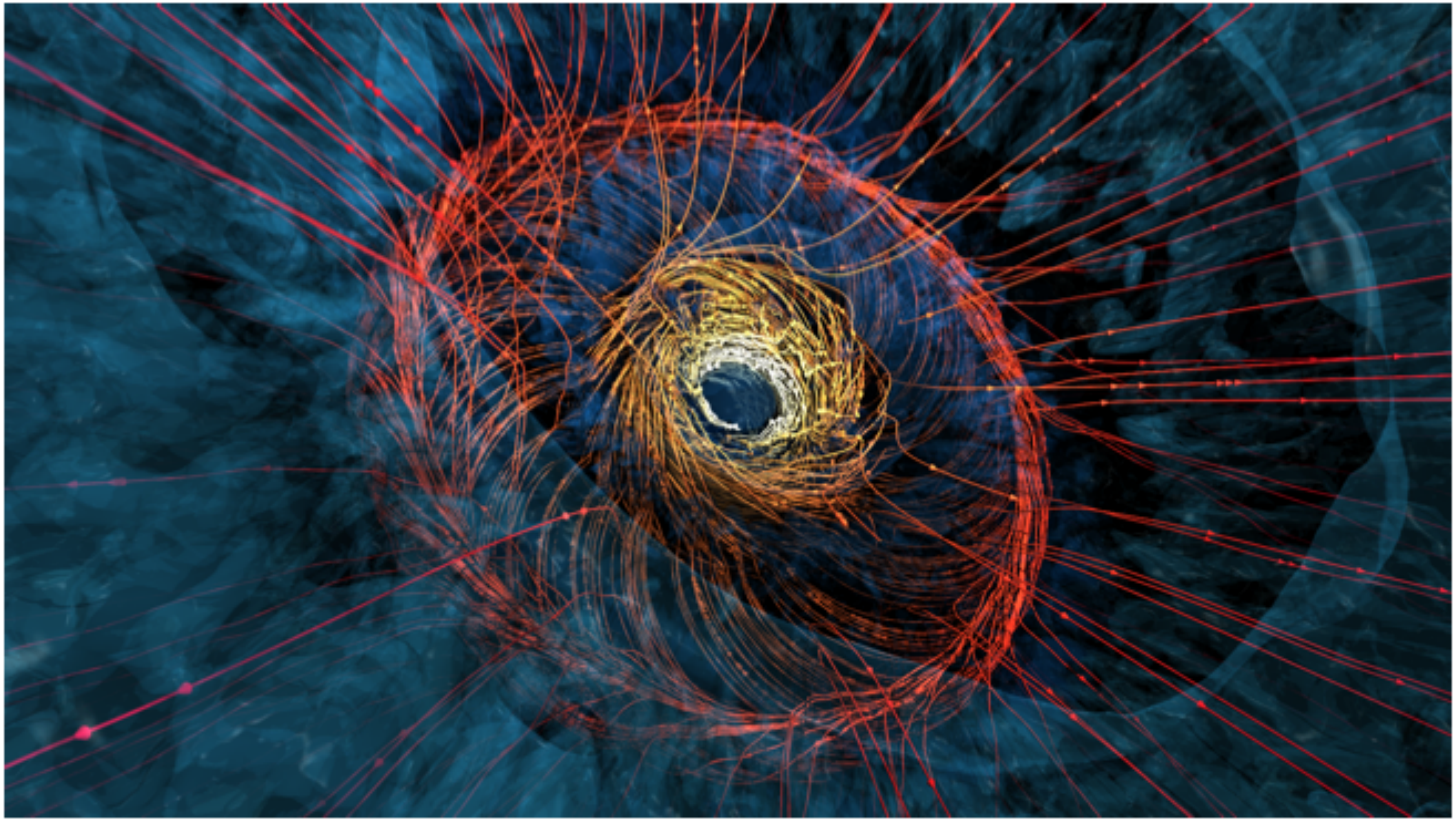
Variability Properties

Variability Properties



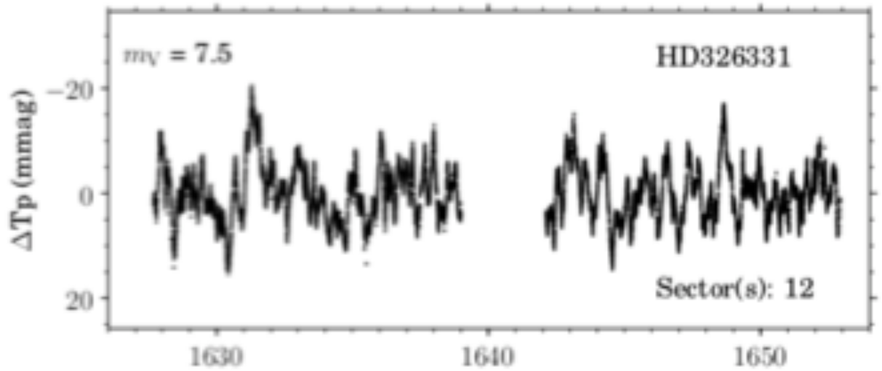
Effects of Rotation

Effects of Rotation

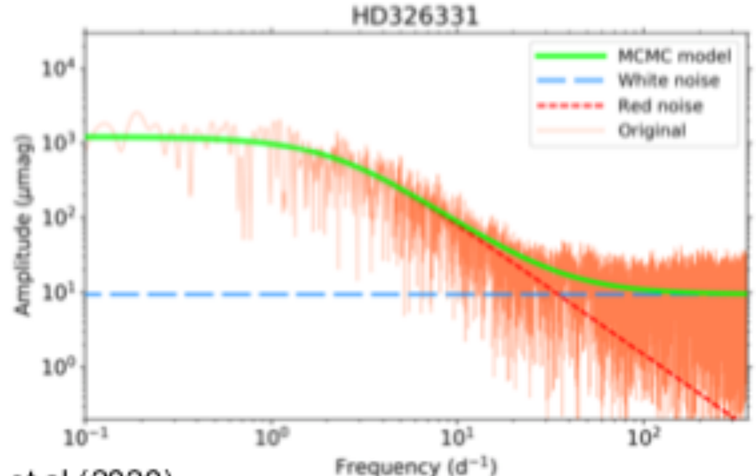


TESS Characterizations

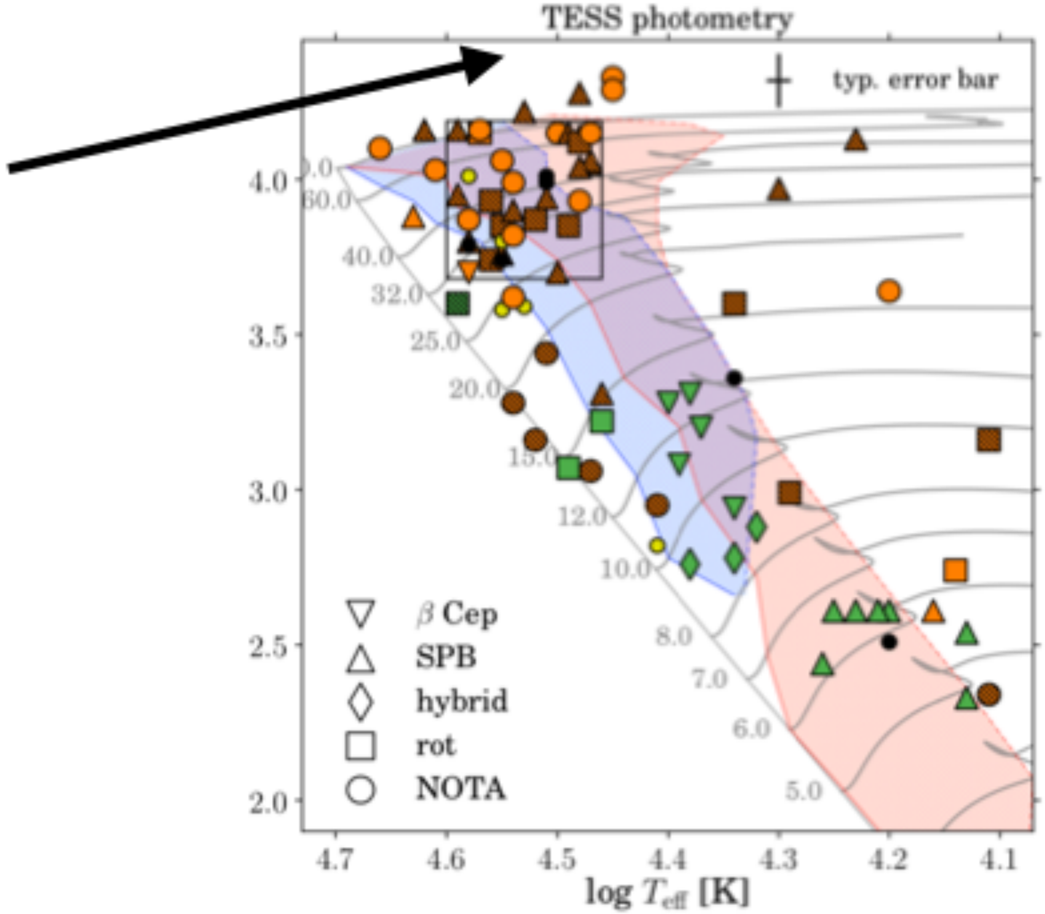
of Massive Stars



Burssens et al (2020)



Bowman et al (2020)

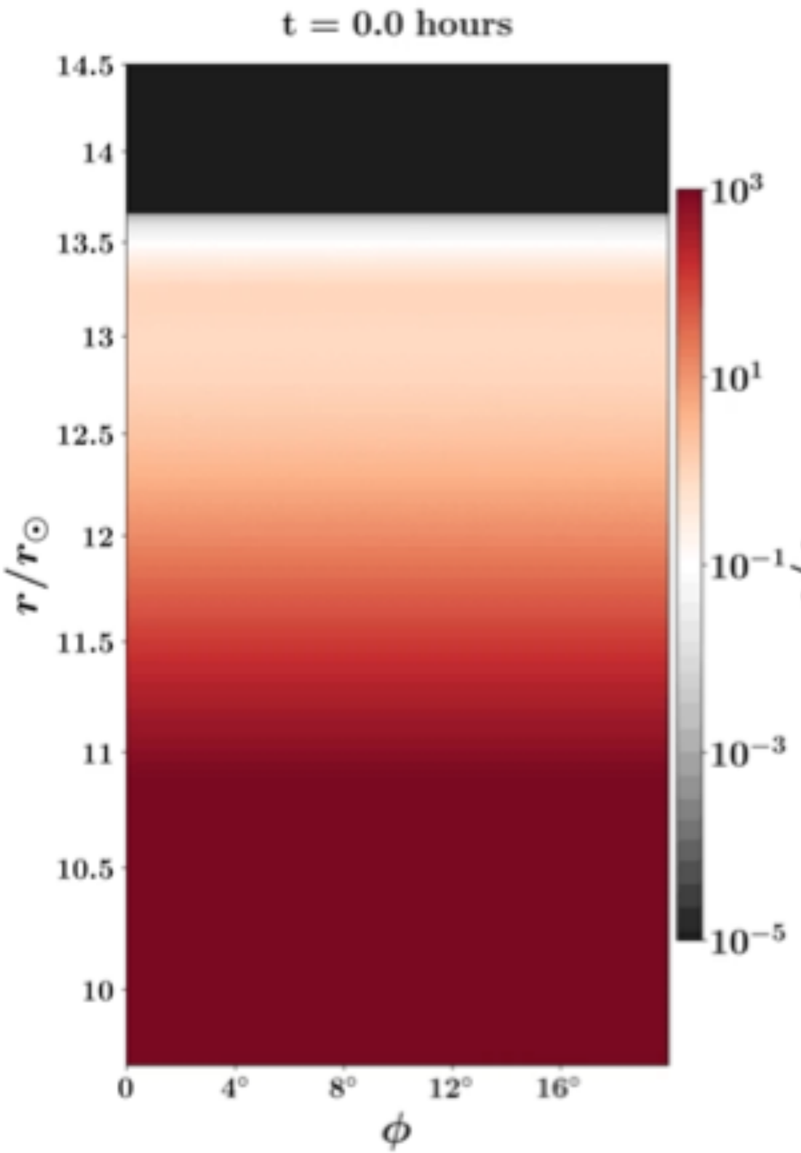


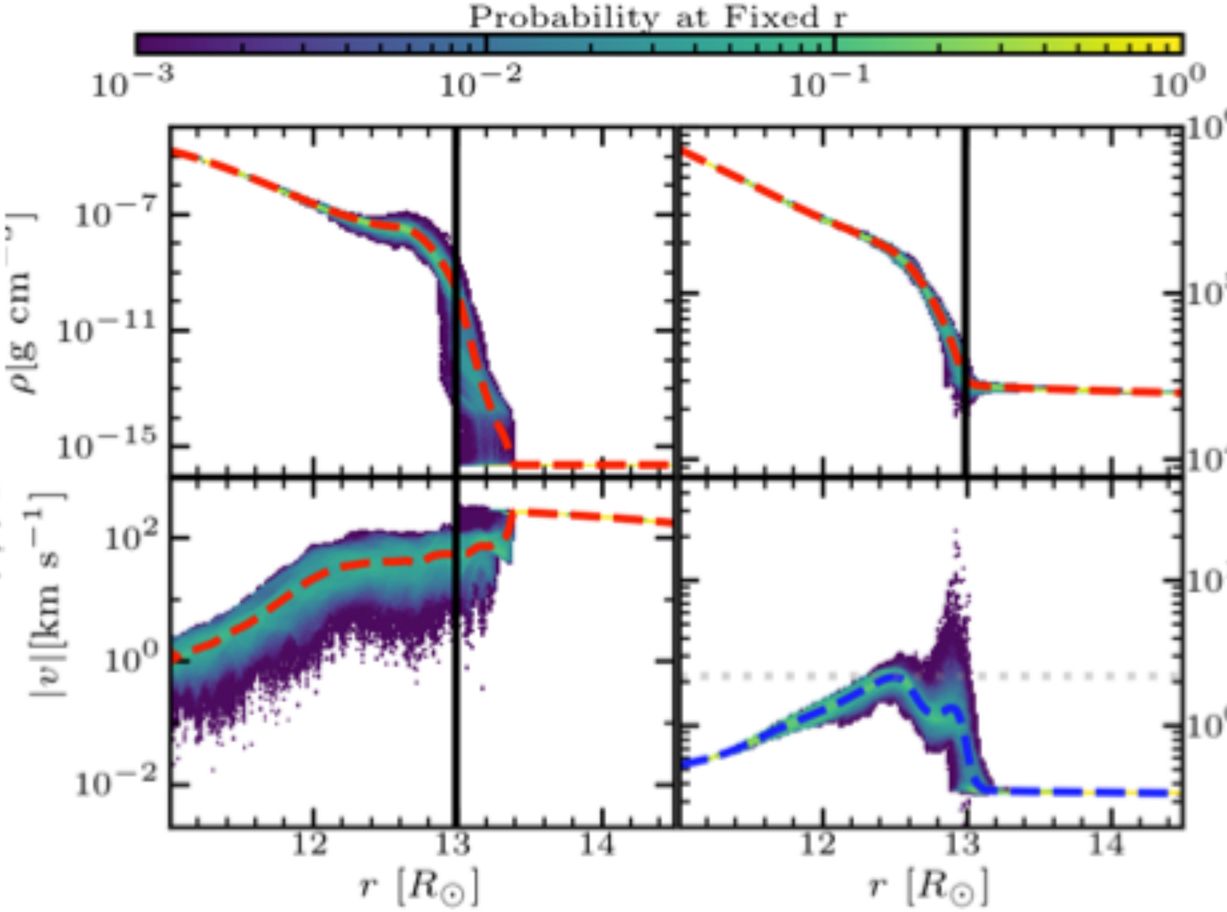
1.Internal gravity waves (IGWs)

2. Near Surface Convective Zones (CZs)

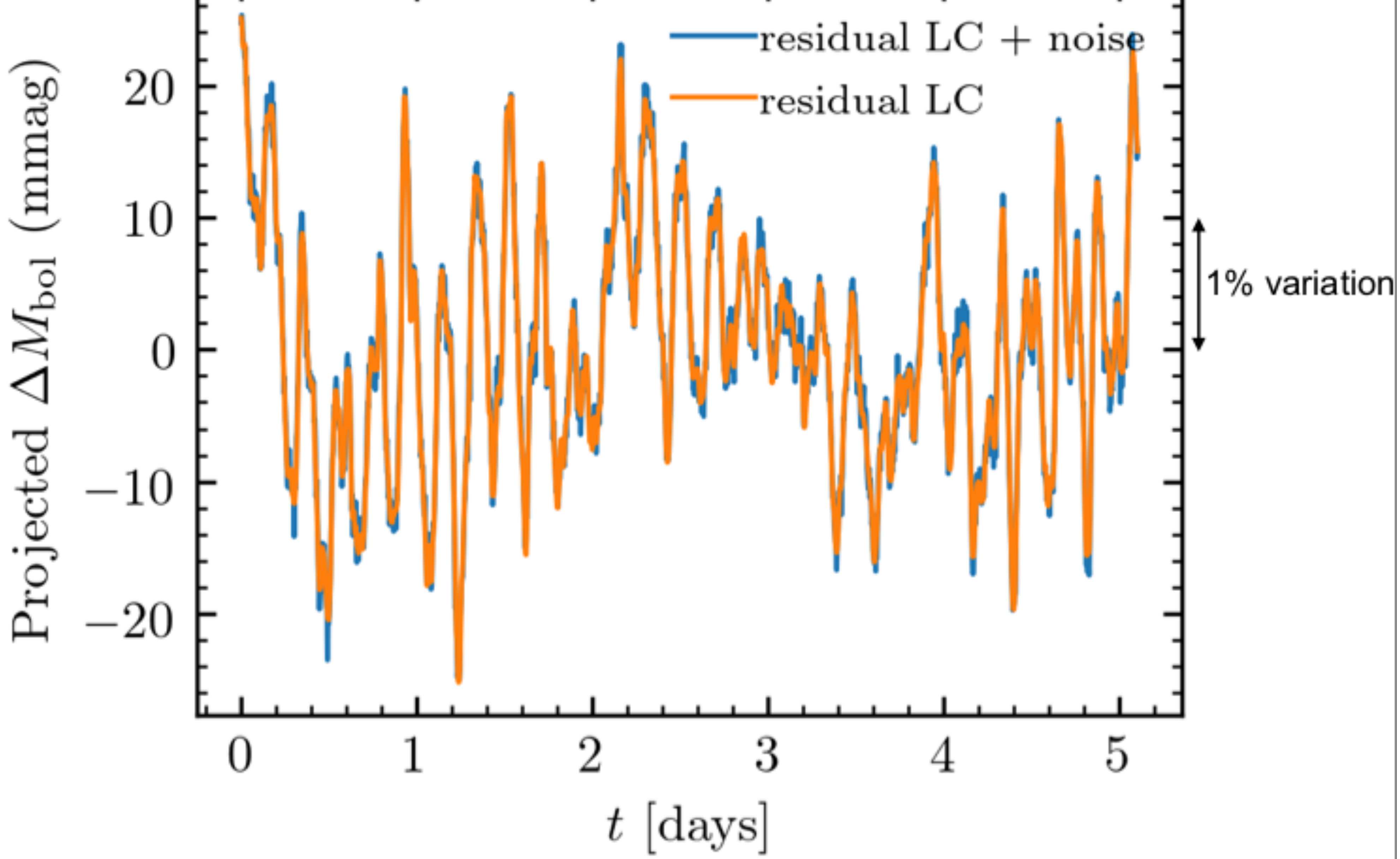
Simulation of a 35 Solar

Mass Star

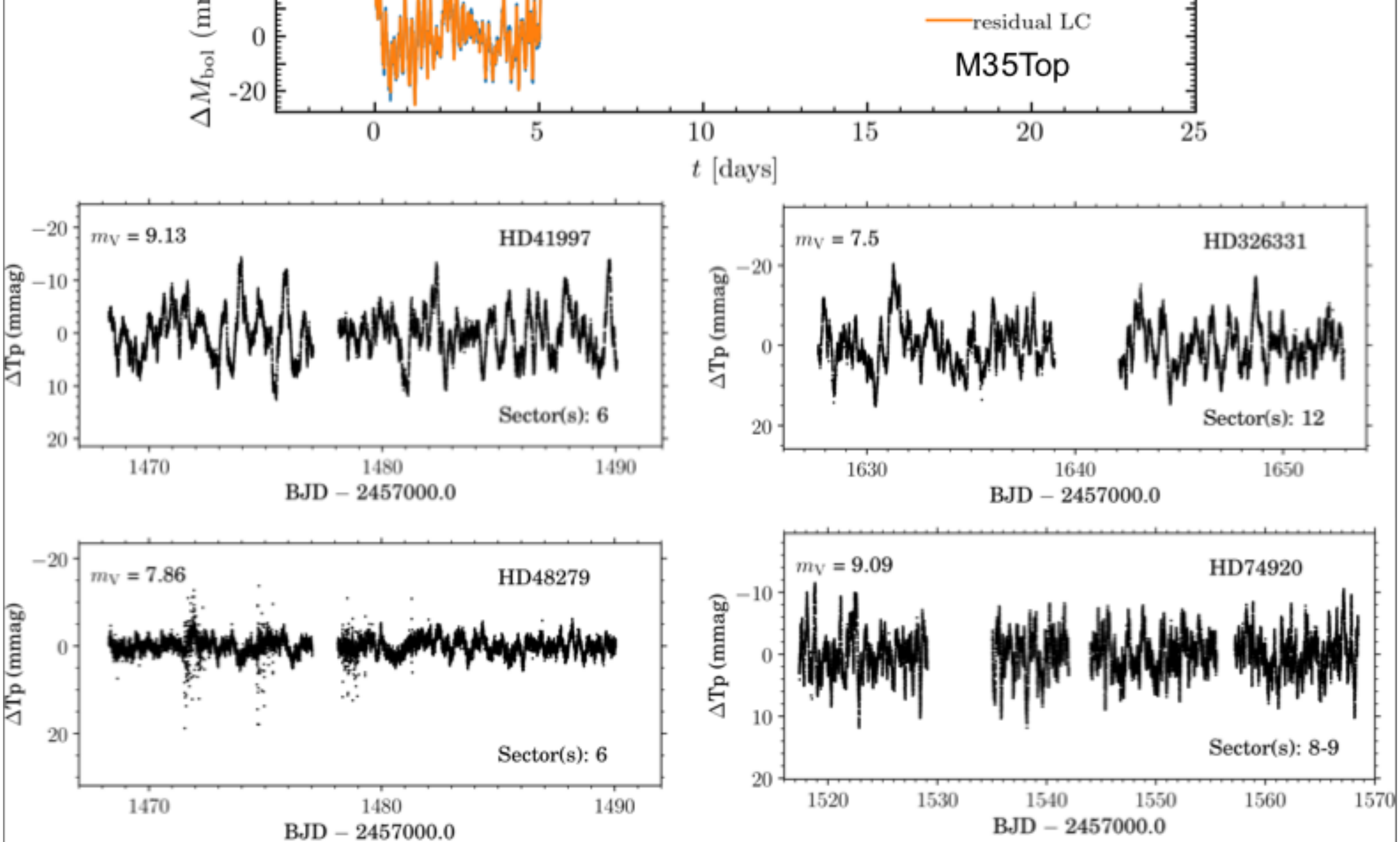




Projected 3D Light Curve



Light Curve Comparisons



Burssens et al (2020)

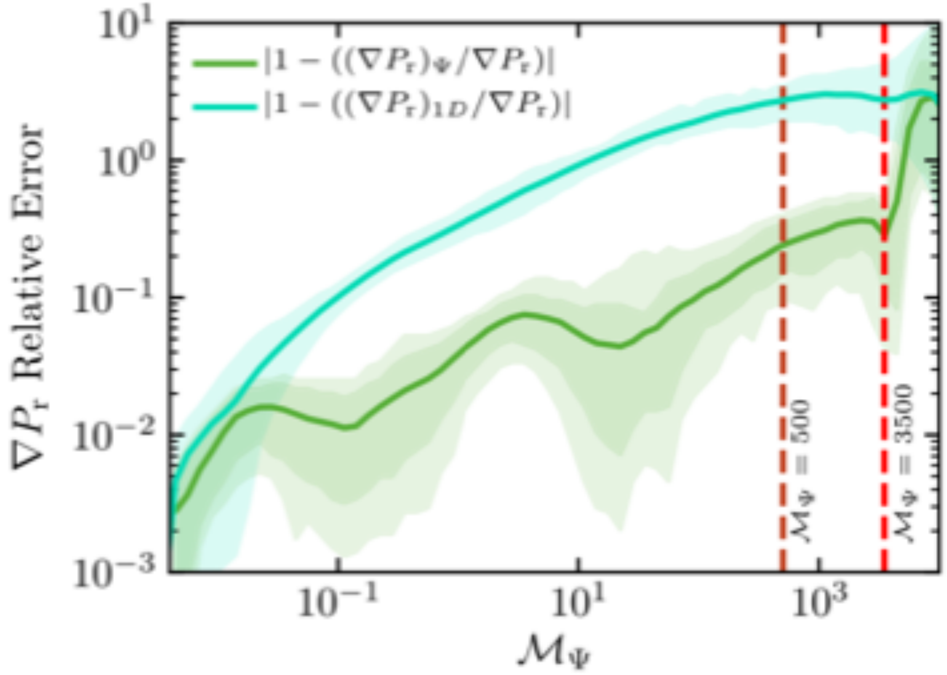
From 3D Simulations to 1D Modeling

- Reduction of radiation force due to convection

$$(\nabla P_{\rm r})_\Psi \equiv -\frac{1}{c}\langle F_{\rm r}\rangle \langle \kappa\rangle \langle \rho\rangle \Psi.$$

- Correct formula for convective energy transport

- Significant turbulent pressure support near the photosphere



Schultz, Bildsten & Jiang (2020)

Summary

- 3D radiation hydrodynamic simulations are the way to learn the physical processes in massive stars.
- Iron opacity peak causes strong convection, density as well as effective temperature fluctuations on the surfaces of massive stars
- Helium/hydrogen opacity peaks cause the effective temperature quickly moving to the cold S Dor instability strip for evolved massive stars.
- Cooler stars show stronger variability in the time scale of a day
- Continuum radiation field alone can drive mass loss rate

$$\sim 10^{-7} - 10^{-5} M_{\odot}/yr$$