How do Massive Stars get their Super-Eddington Luminosity?

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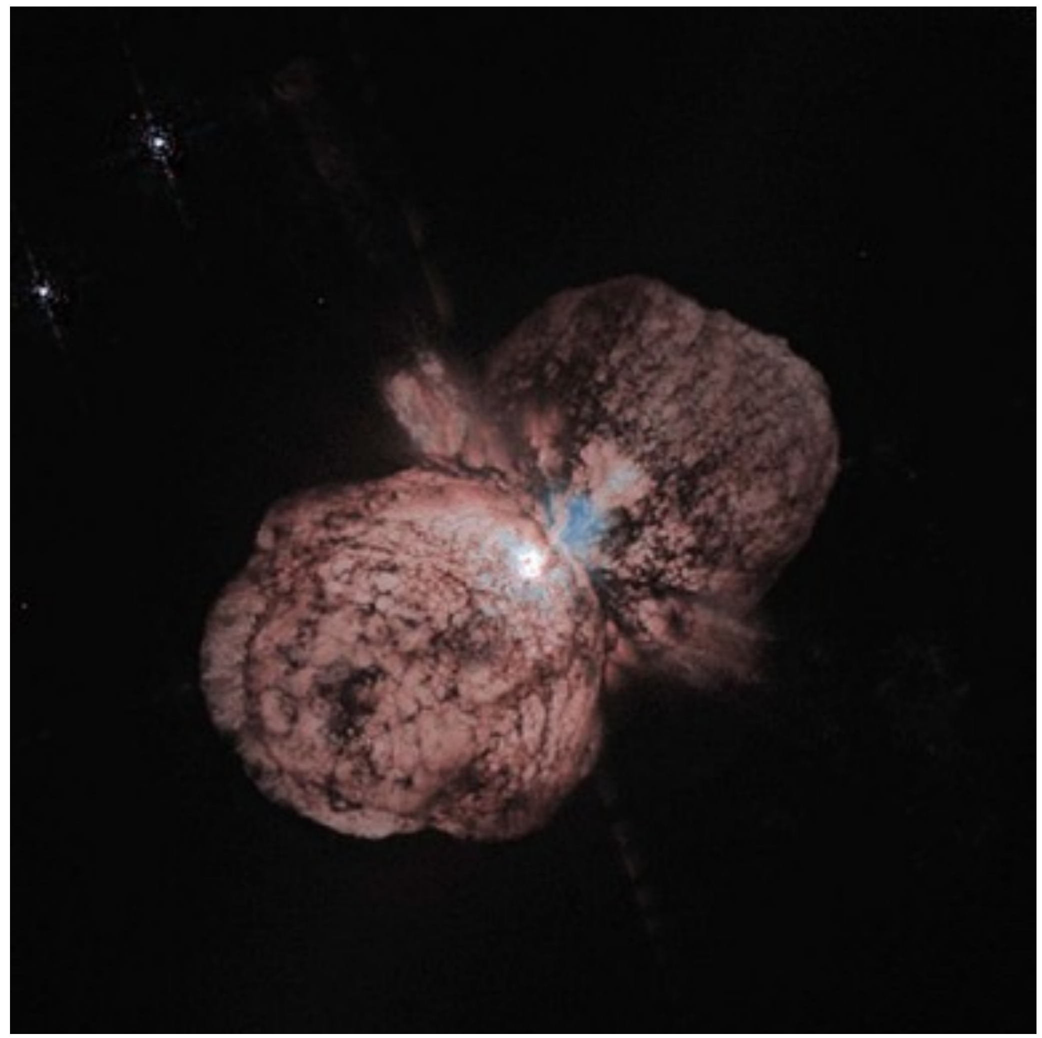
Eta Carinae



Binary Evolution ←

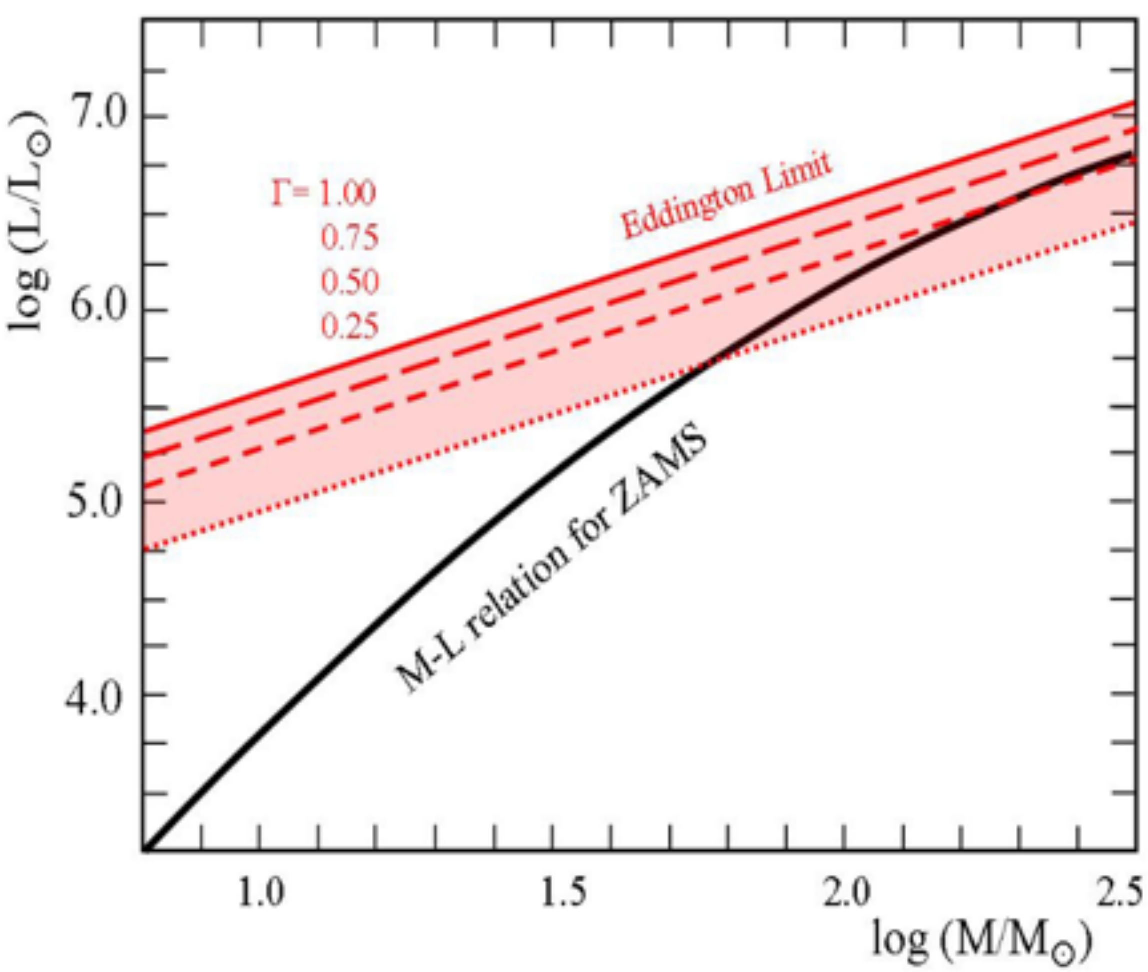
death → Supernova, Black Hole, Neutron Star

↓

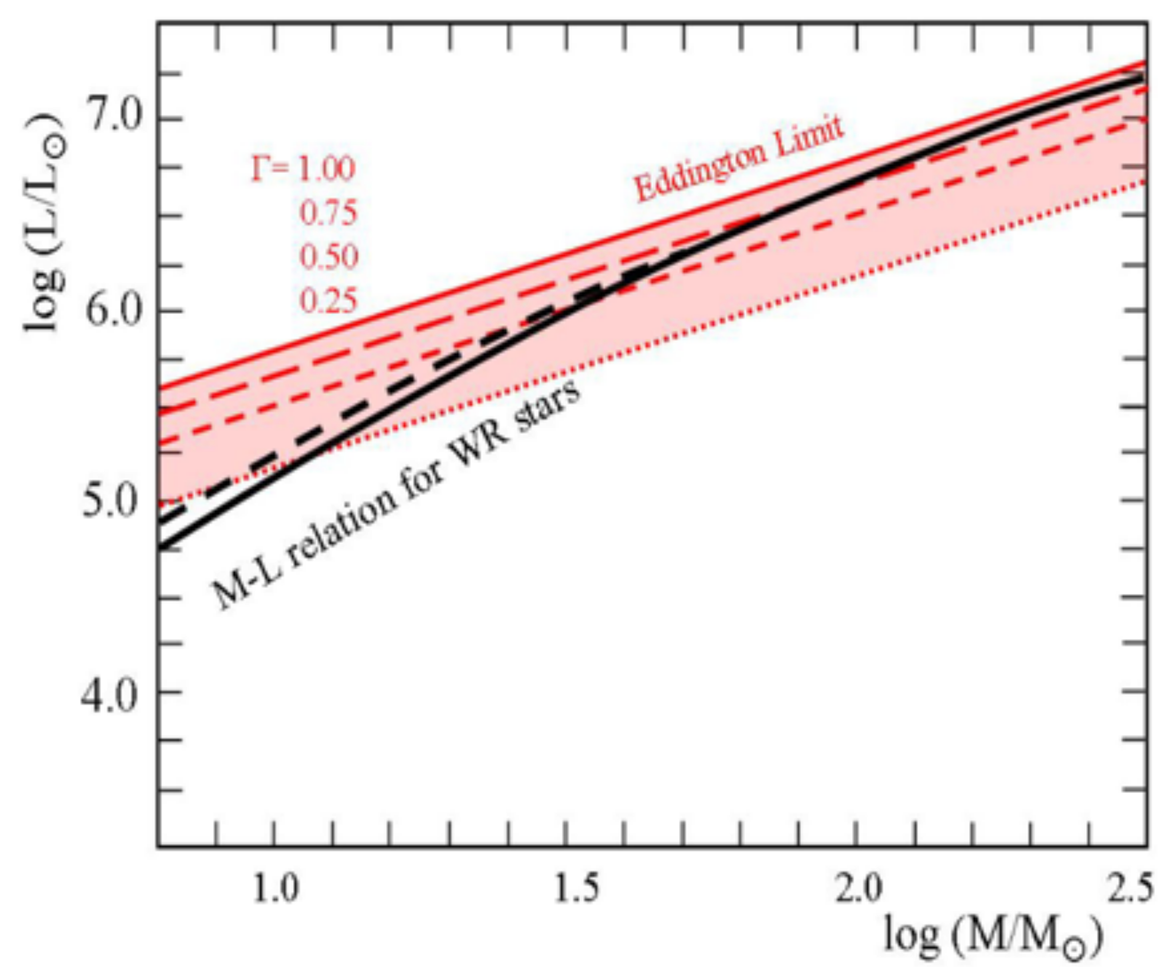
Radiative and mechanic feedback, reionization

Mass-Luminosity Relation

Maeder et al. (2012)



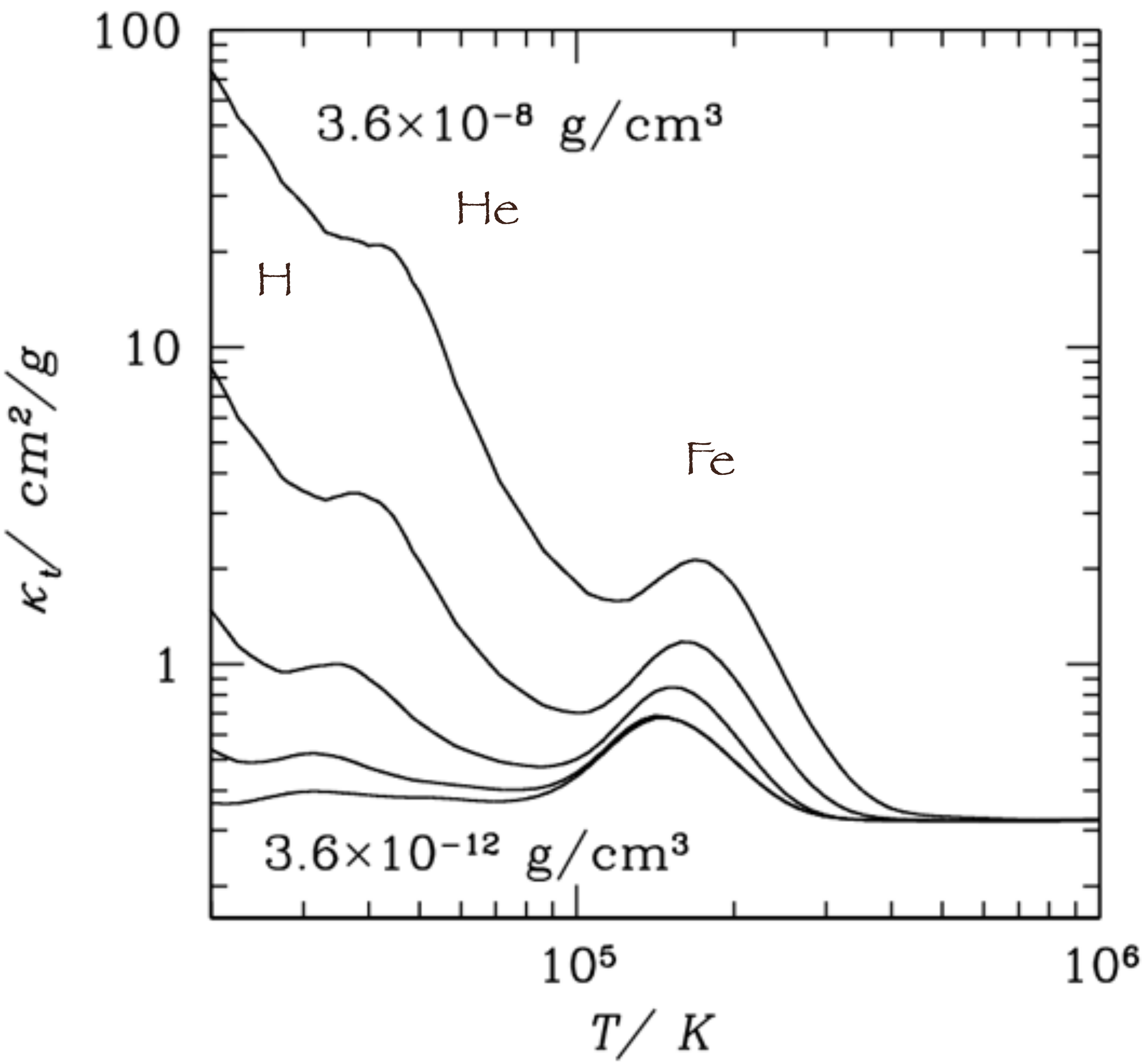
Zero-Age Main Sequence Stars



Evolved Stars

The Opacity

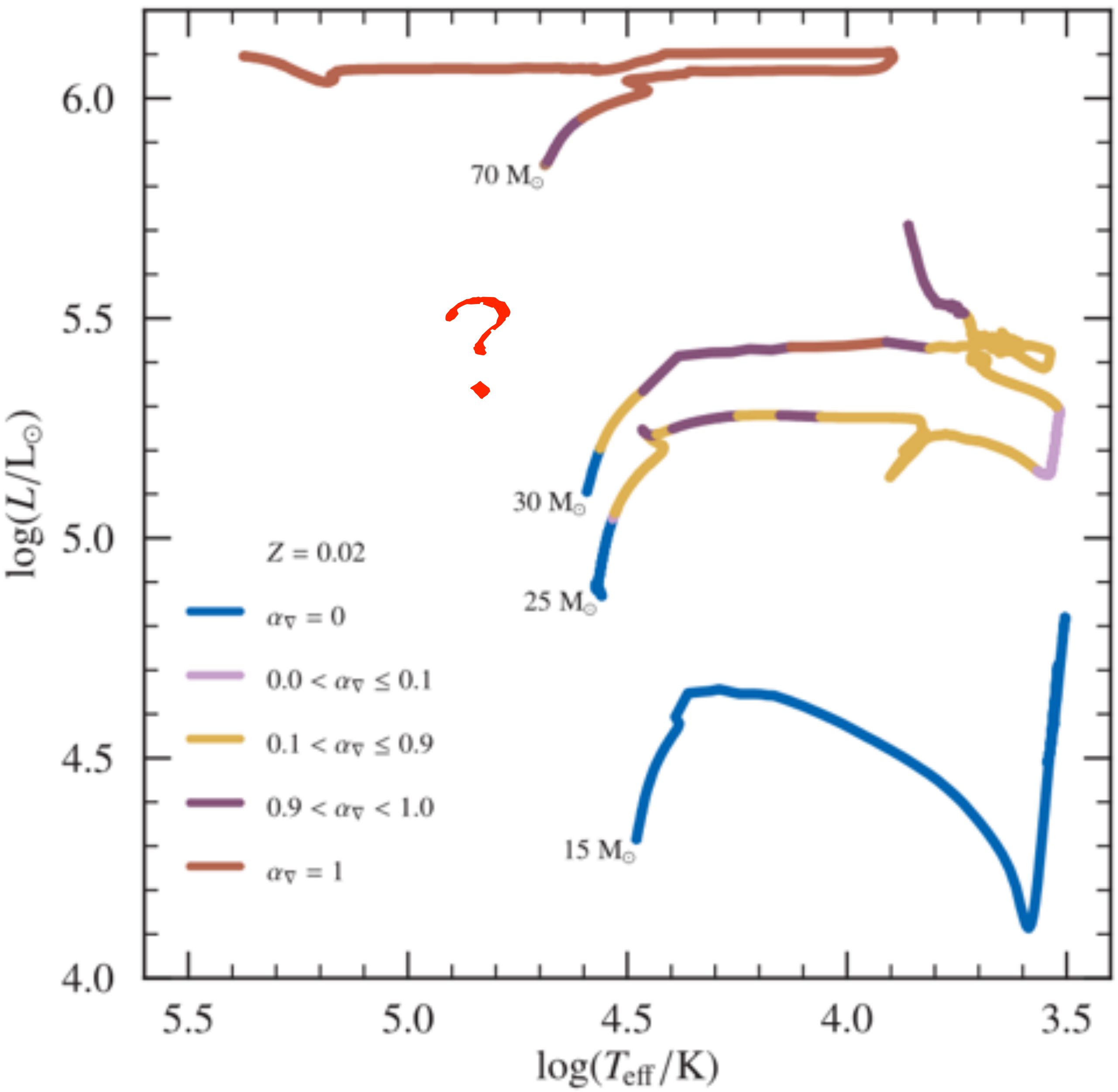
Paxton et al. (2013)
Jiang et al. (2015)



1D Stellar Evolution Studies

Paxton et al. (2013)

Joss et al. (1973)



- Hydrostatic Equilibrium with Super-Eddington flux

$$\frac{dP_{\rm gas}}{dr} = \left(\frac{dP_{\rm rad}}{dr}\right)\left[\frac{L_{\rm Edd}}{L_{\rm rad}} - 1\right].$$

- Radiation and gravitational acceleration:

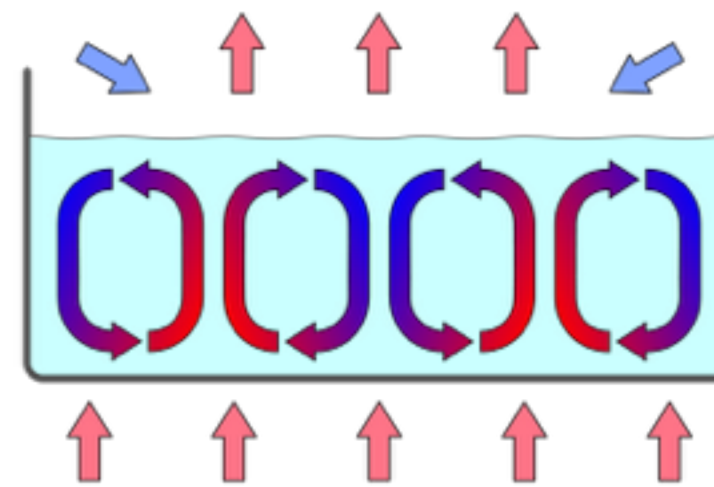
$$F_r = \frac{L}{4\pi r^2}, \quad a_r = \frac{\kappa F_{r,0}}{c}, \quad a_g = \frac{GM}{r^2}.$$

- Convection

$$\frac{L_{\rm rad}}{L_{\rm Edd}} > \frac{L_{\rm onset}}{L_{\rm Edd}} \equiv \left(1 - \frac{P_{\rm gas}}{P}\right)\left(\frac{\partial \ln P_{\rm rad}}{\partial \ln P}\right)_s.$$

The Theoretical challenges

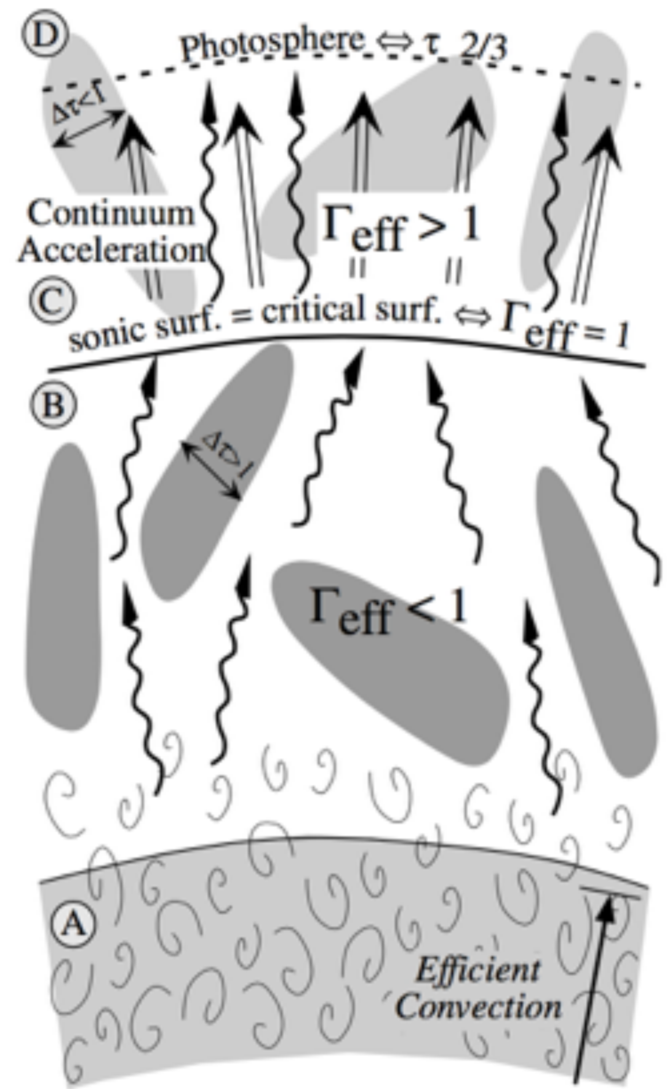
- What is the Convection flux in the radiation pressure dominated regime



$$F_r = \frac{L}{4\pi r^2},\ a_r = \frac{\kappa F_{r,0}}{c}$$

- The "Porosity effect"

Shaviv (1998)
Shaviv (2001)

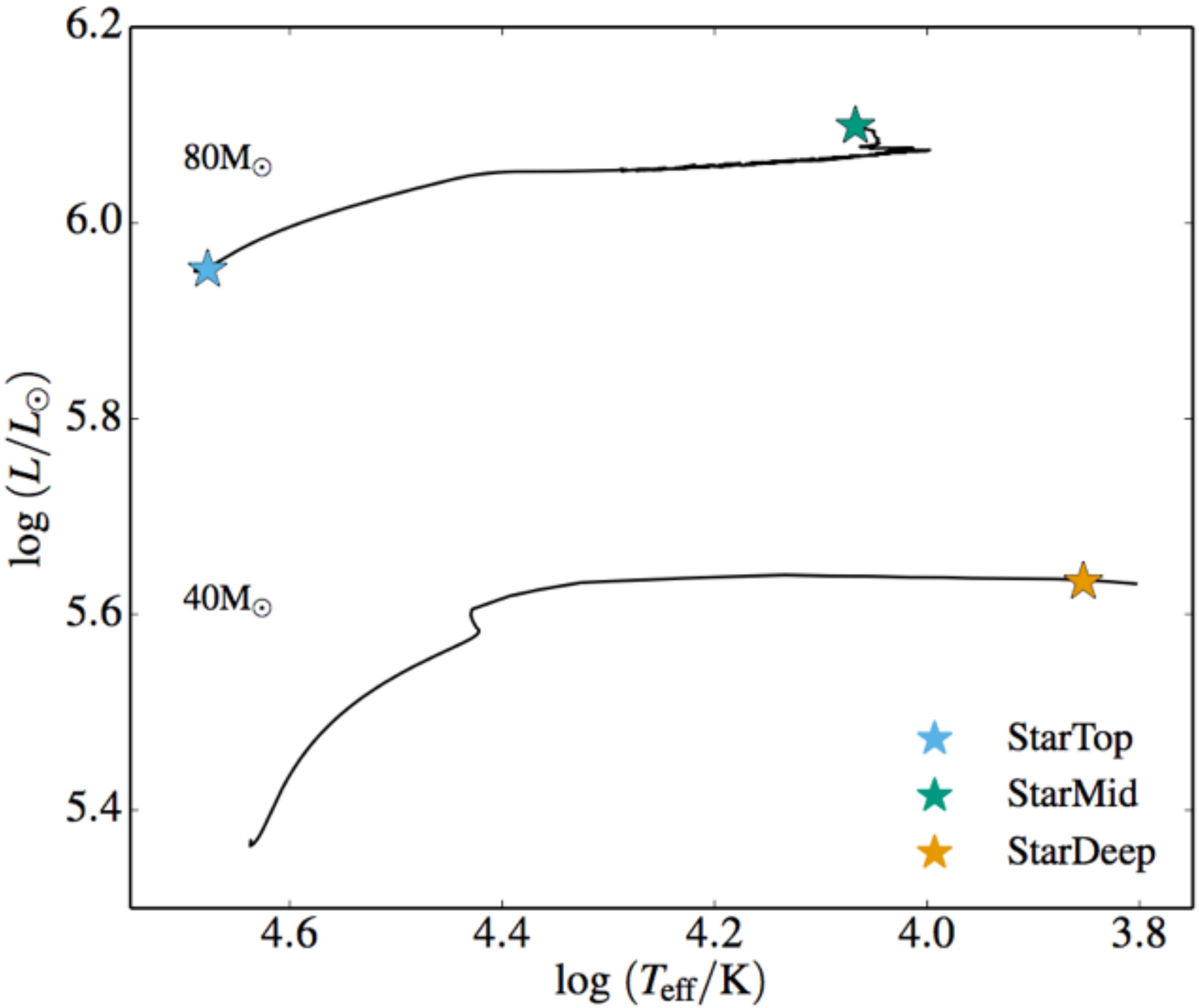


$$\tilde{a}_r = \frac{\langle \rho \kappa_t F_{r,0z} \rangle}{c \langle \rho \rangle}.$$

$$a_r = \frac{\kappa_t}{c} F_{r,0z}.$$

Photons tend to go through the low density regions.

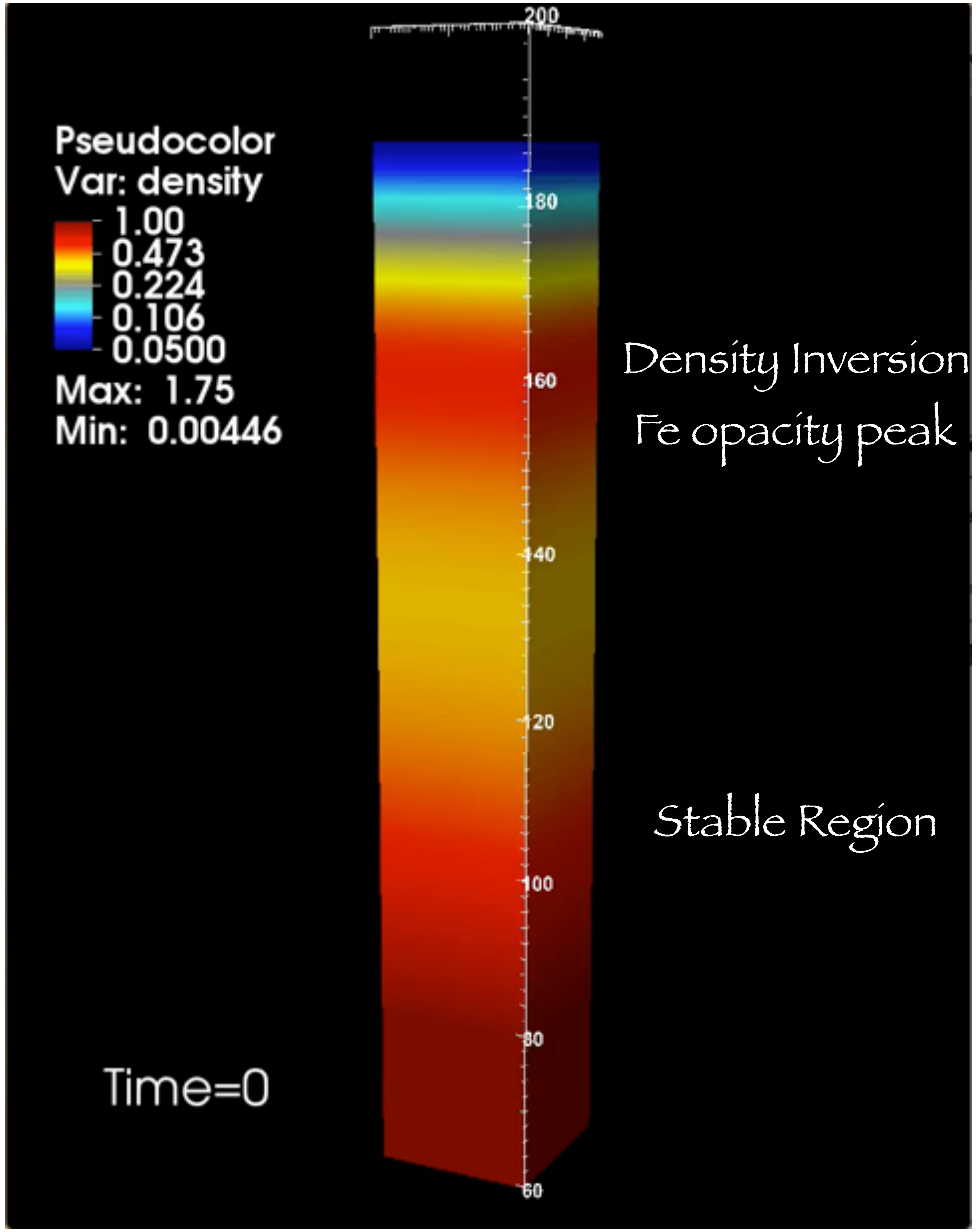
The Stellar Models



Pick the parameters of stellar models from MESA.

Simulation Setup

Open top boundary
(Photosphere can
be included)



Reflection bottom
boundary

$$c_{g,0} = \sqrt{\frac{P_0}{\rho_0}},$$

$$c_{s,0} = \sqrt{\frac{a_r T_0^4}{3\rho_0}},$$

$$H_0 = \frac{c_{s,0}^2}{g} = \frac{a_r T_0^4}{3\rho_0 g},$$

$$\tau_0 = \kappa_t(\rho_0, T_0)\rho_0 H_0,$$

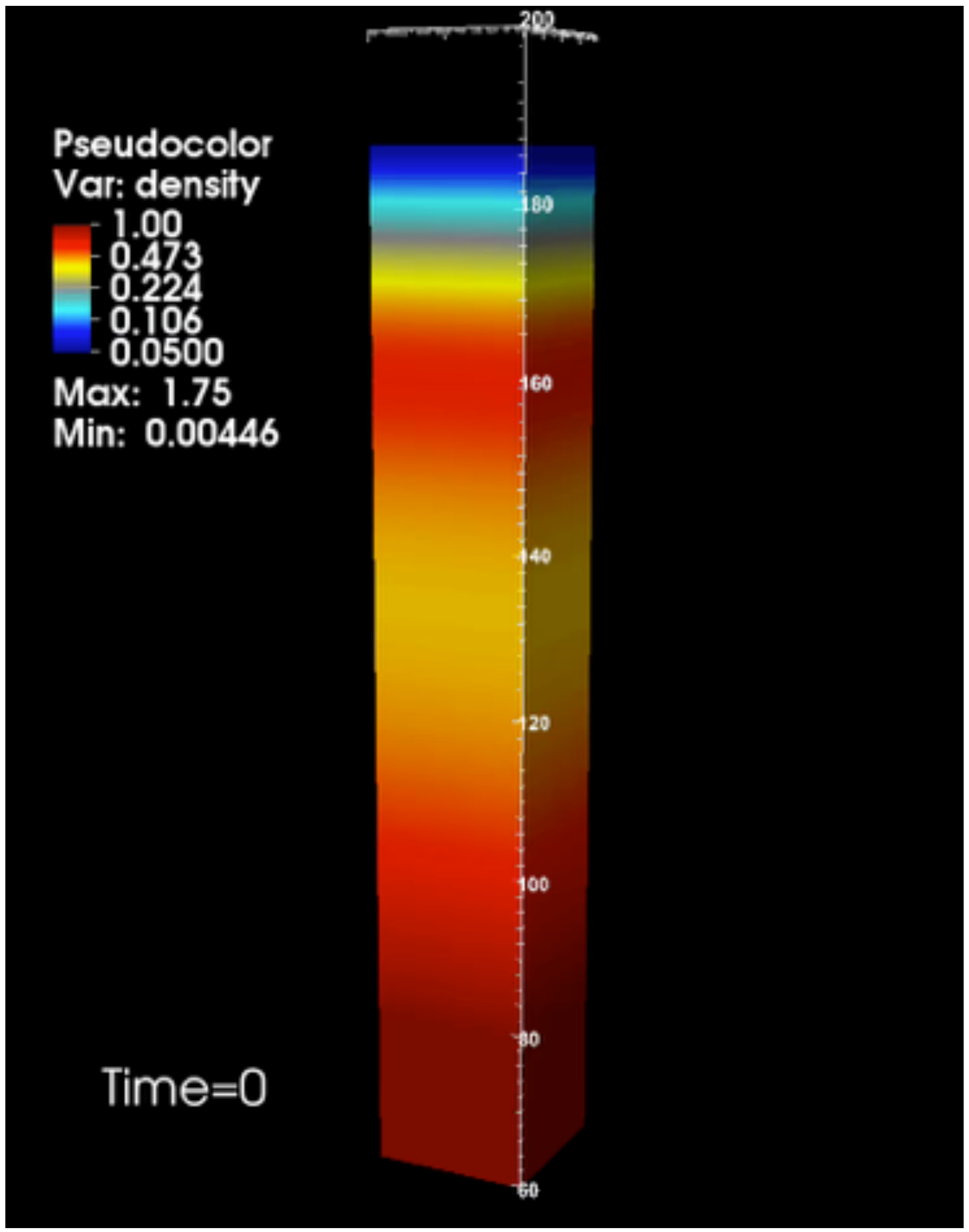
g

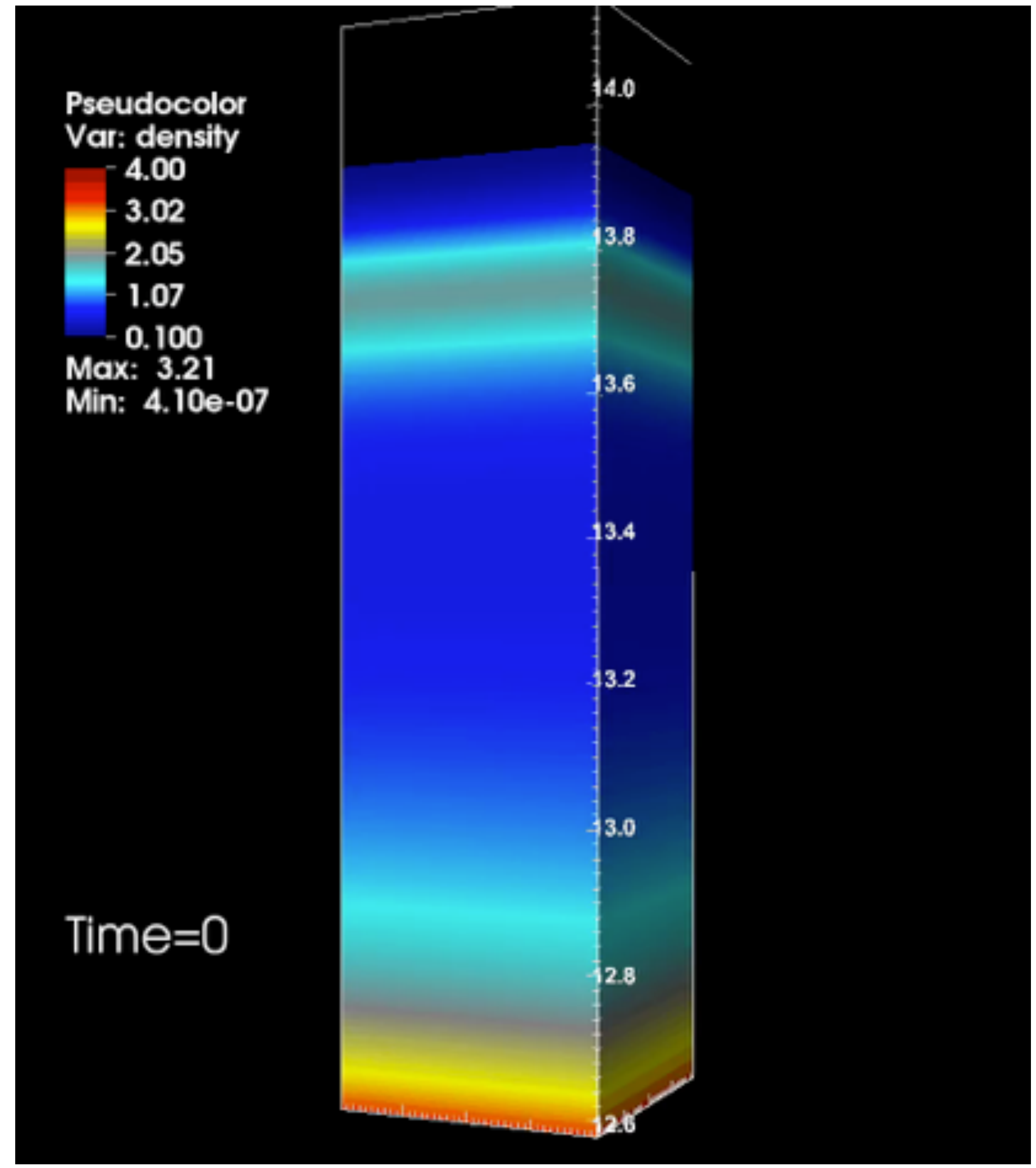
Constant gravity

Fr

Constant radiation flux
coming from the bottom

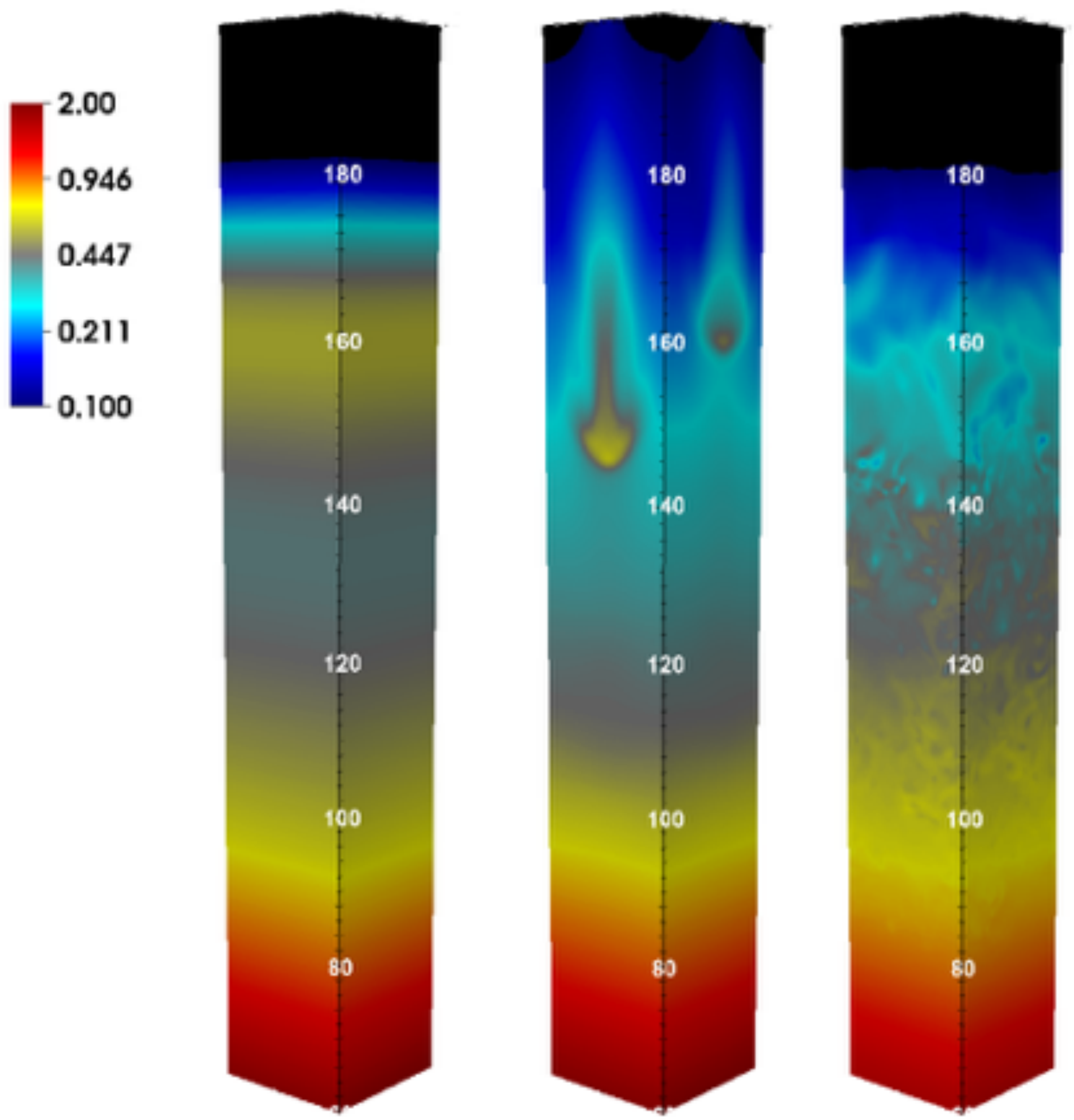
Results for Two Different Cases

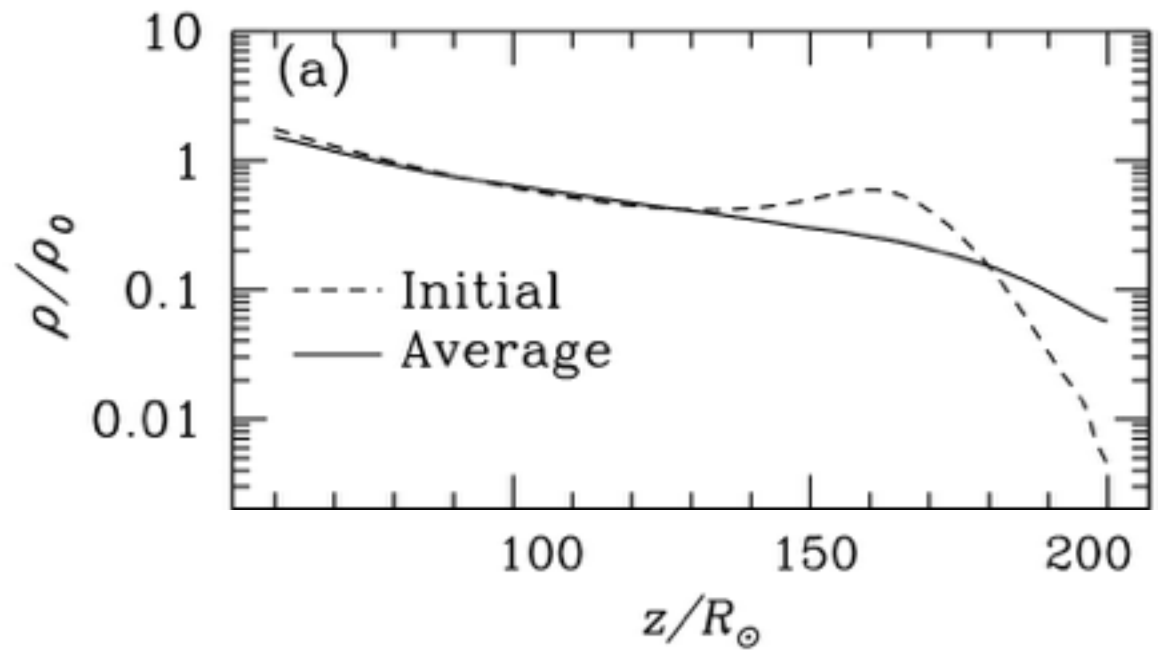


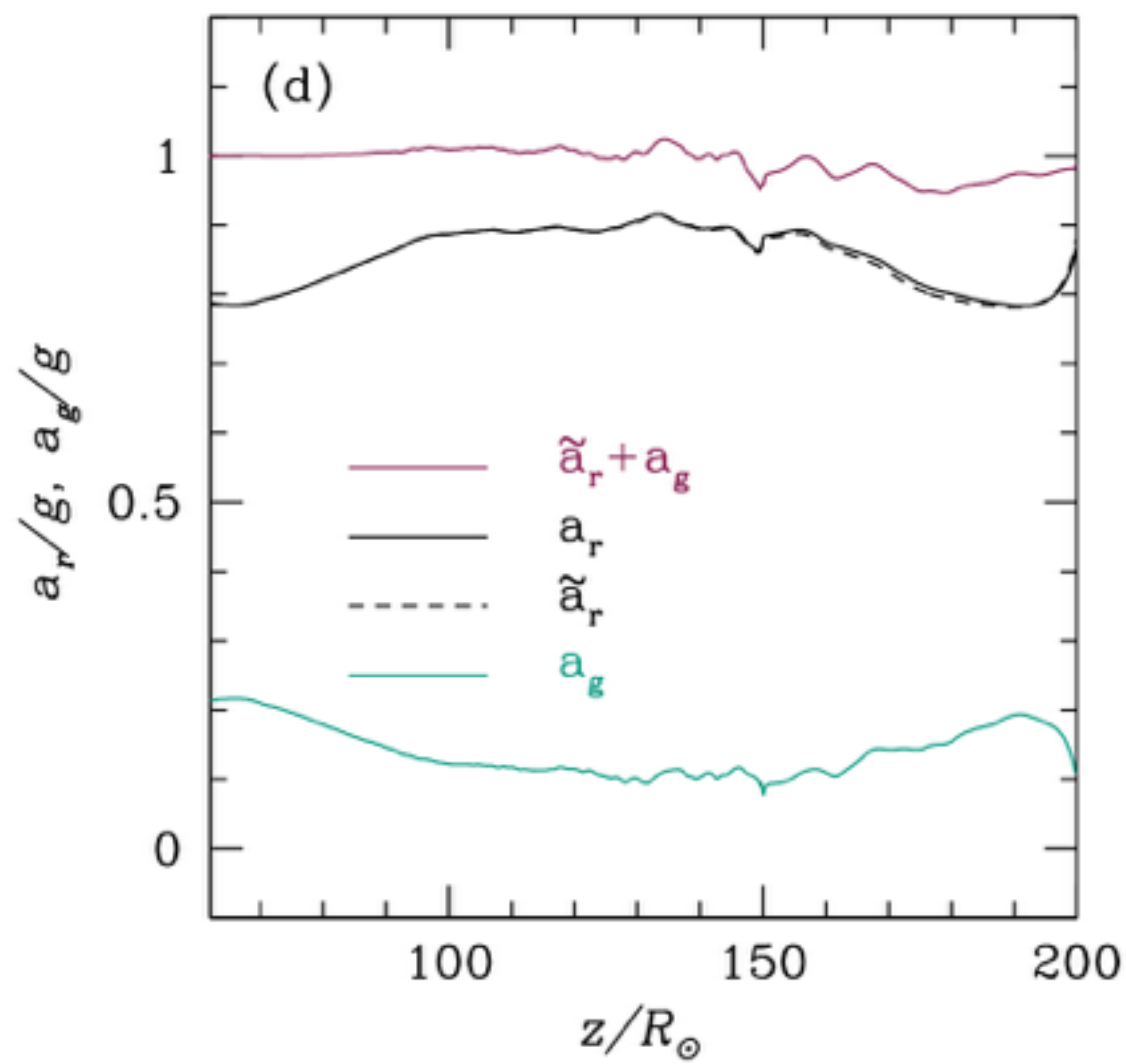


$\tau_c \equiv c/c_{g,0}$	5.99×10^3	6.54×10^3
τ_0	9.12×10^4	166.5

The Case with Efficient Convection





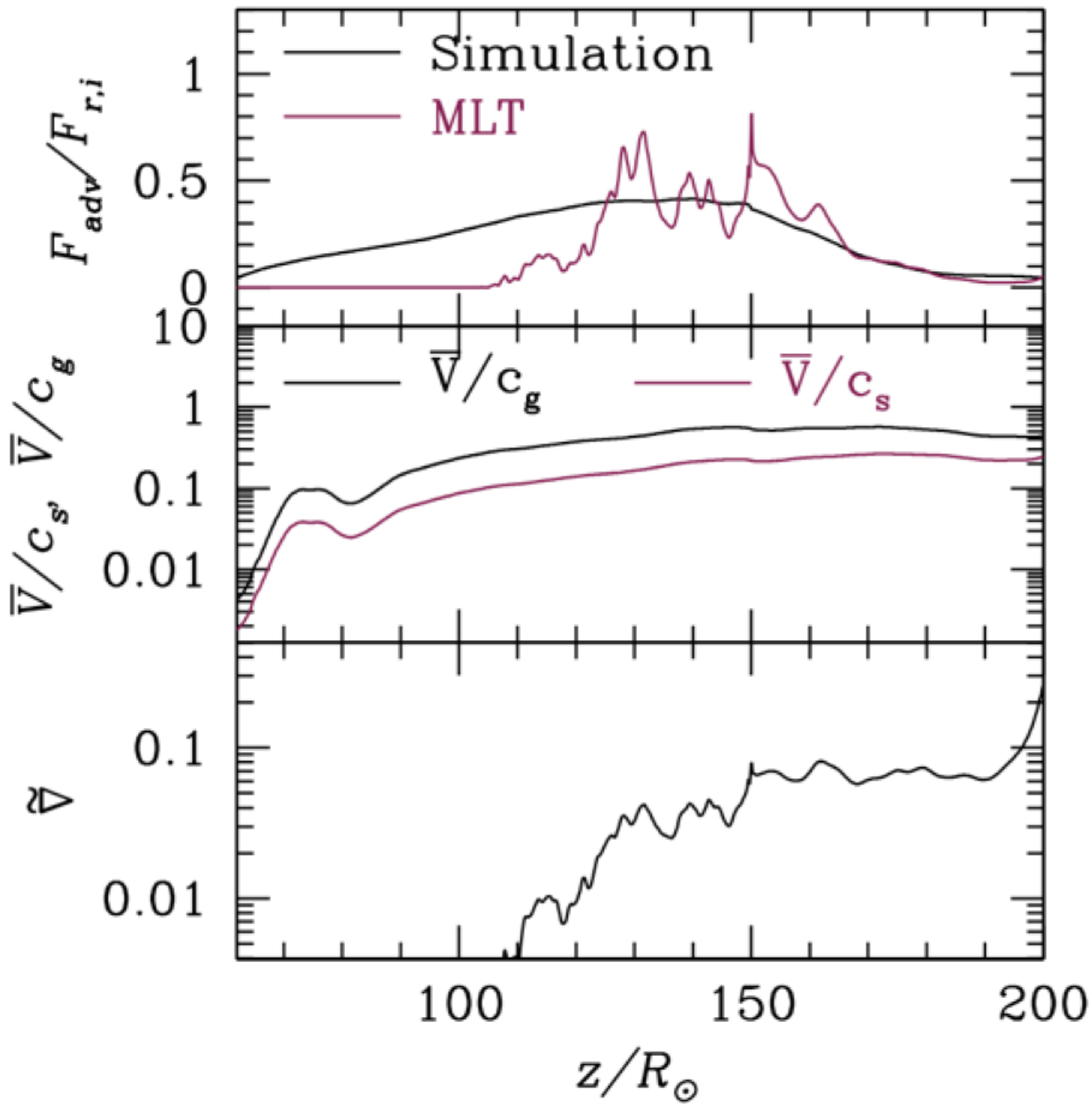


Compared with MLT

$$F_{\rm conv} = \frac{Q^{1/2} c_p}{4\sqrt{2}} \frac{k_B \rho T}{\mu} \left(\frac{P+P_r}{\rho}\right)^{1/2} \alpha^2 (\nabla - \nabla_{\rm ad})^{3/2},$$

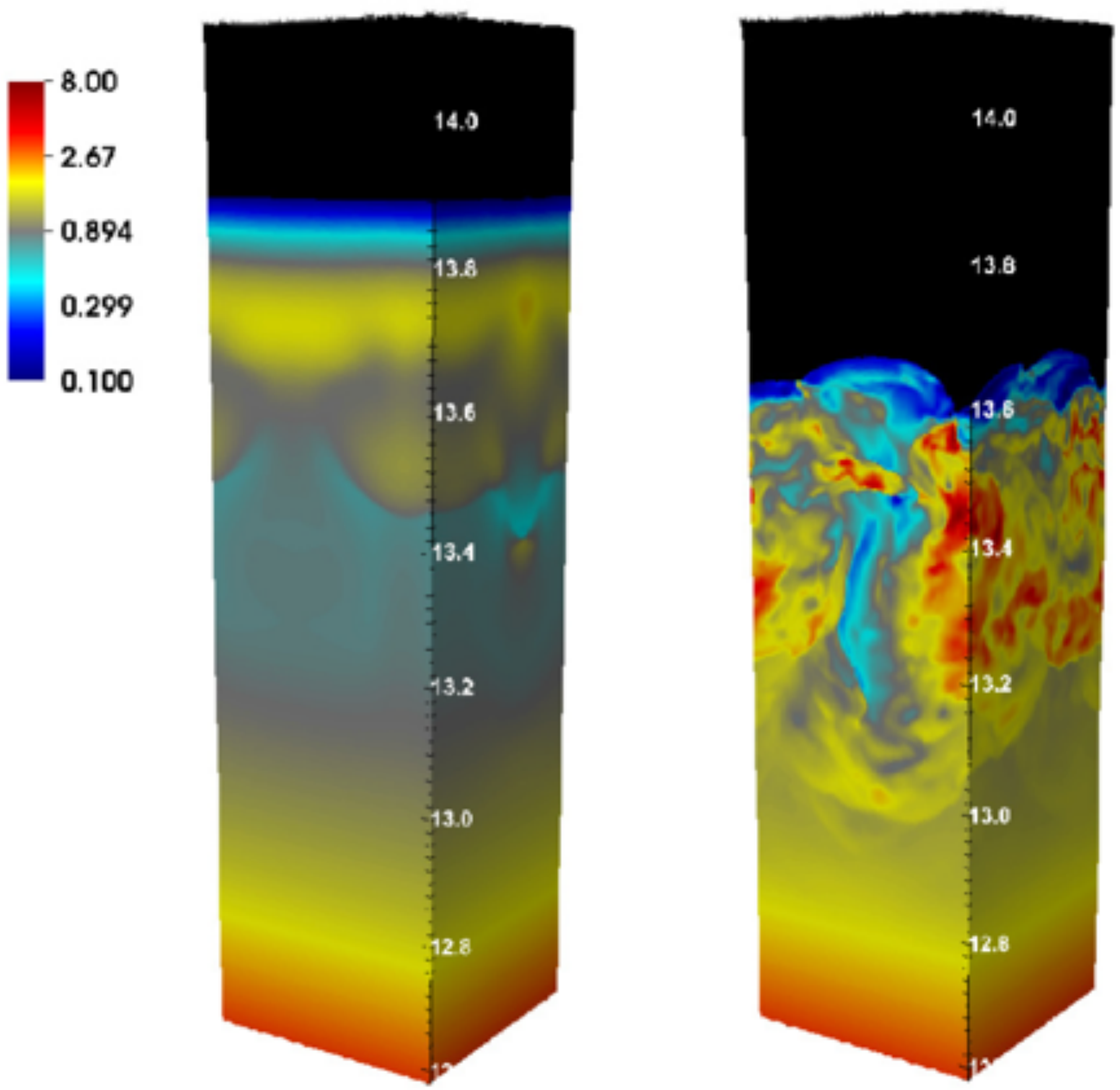
$$\nabla_{\rm ad} \equiv \left.\frac{d\ln T}{d\ln(P+P_r)}\right|_{\rm ad} = \frac{\Gamma_2 - 1}{\Gamma_2}.$$

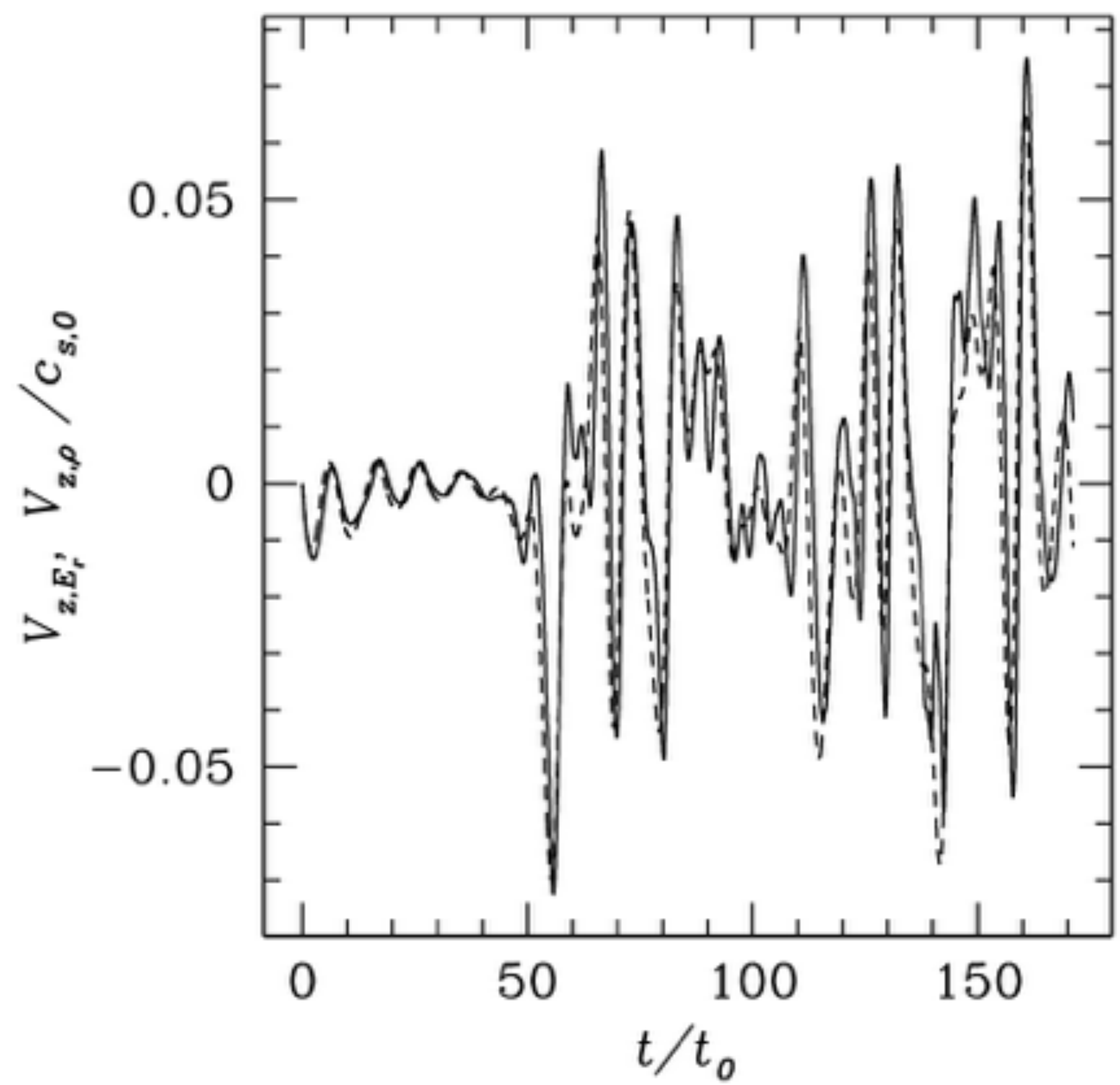
$$\nabla \equiv d\ln T / d(\ln(P+P_r))$$



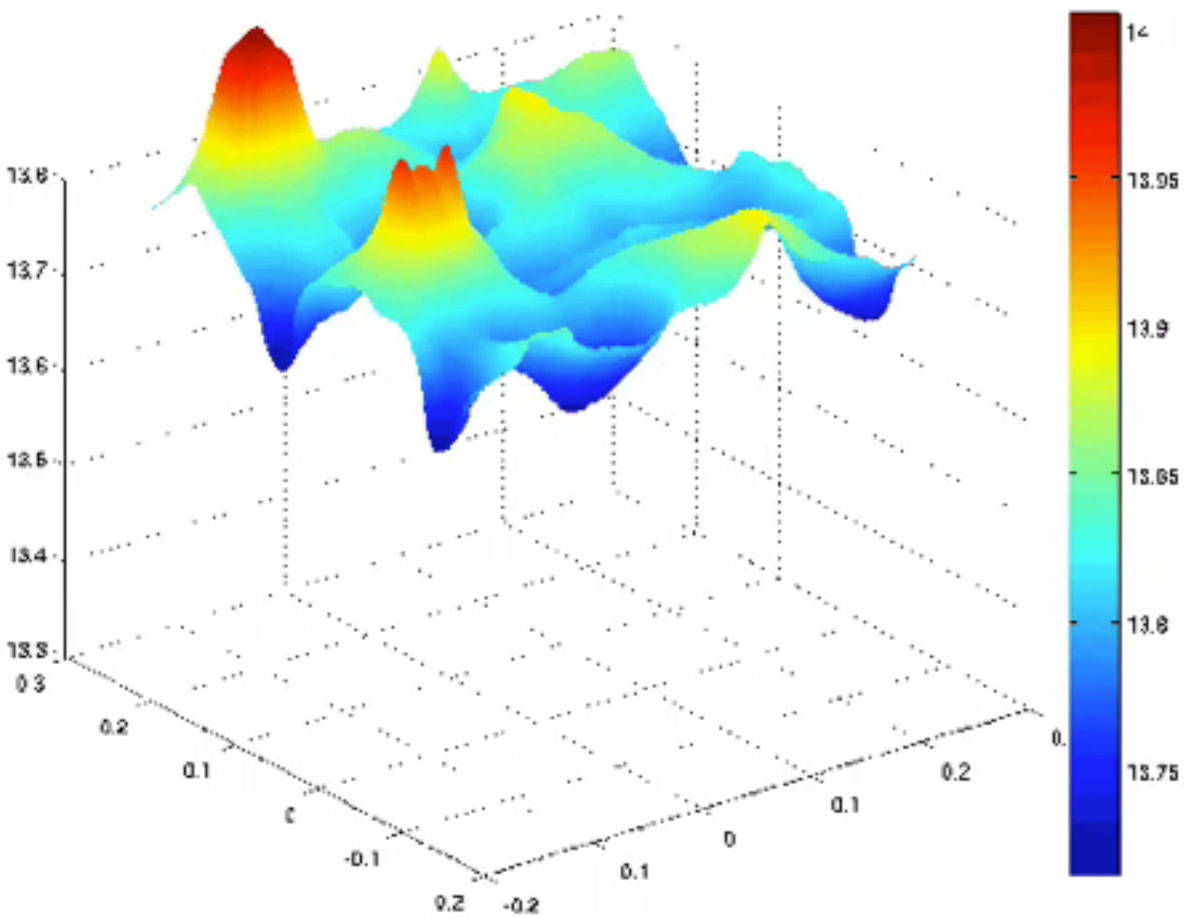
$$\alpha = 0.55$$

The Case with Inefficient Convection

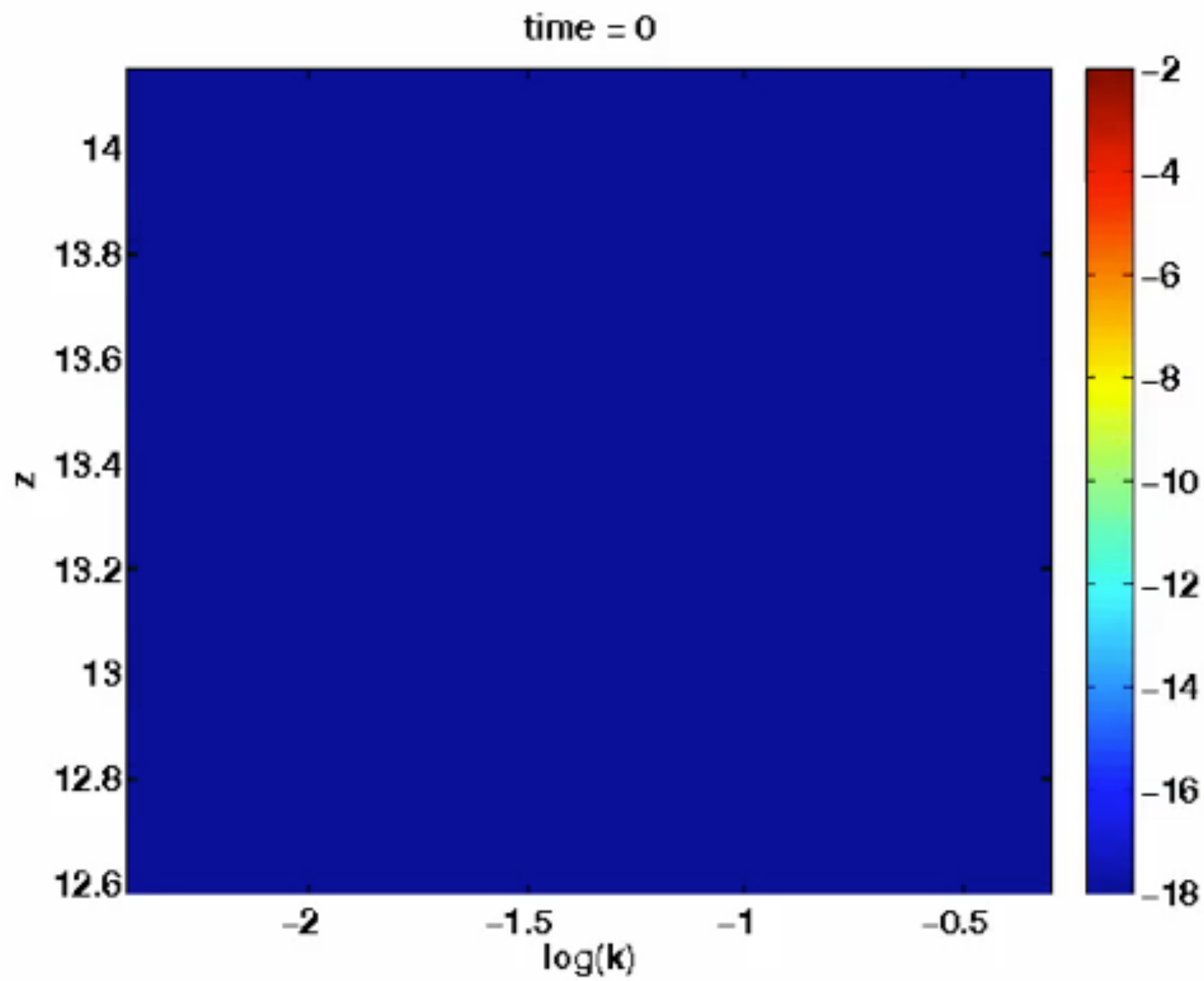




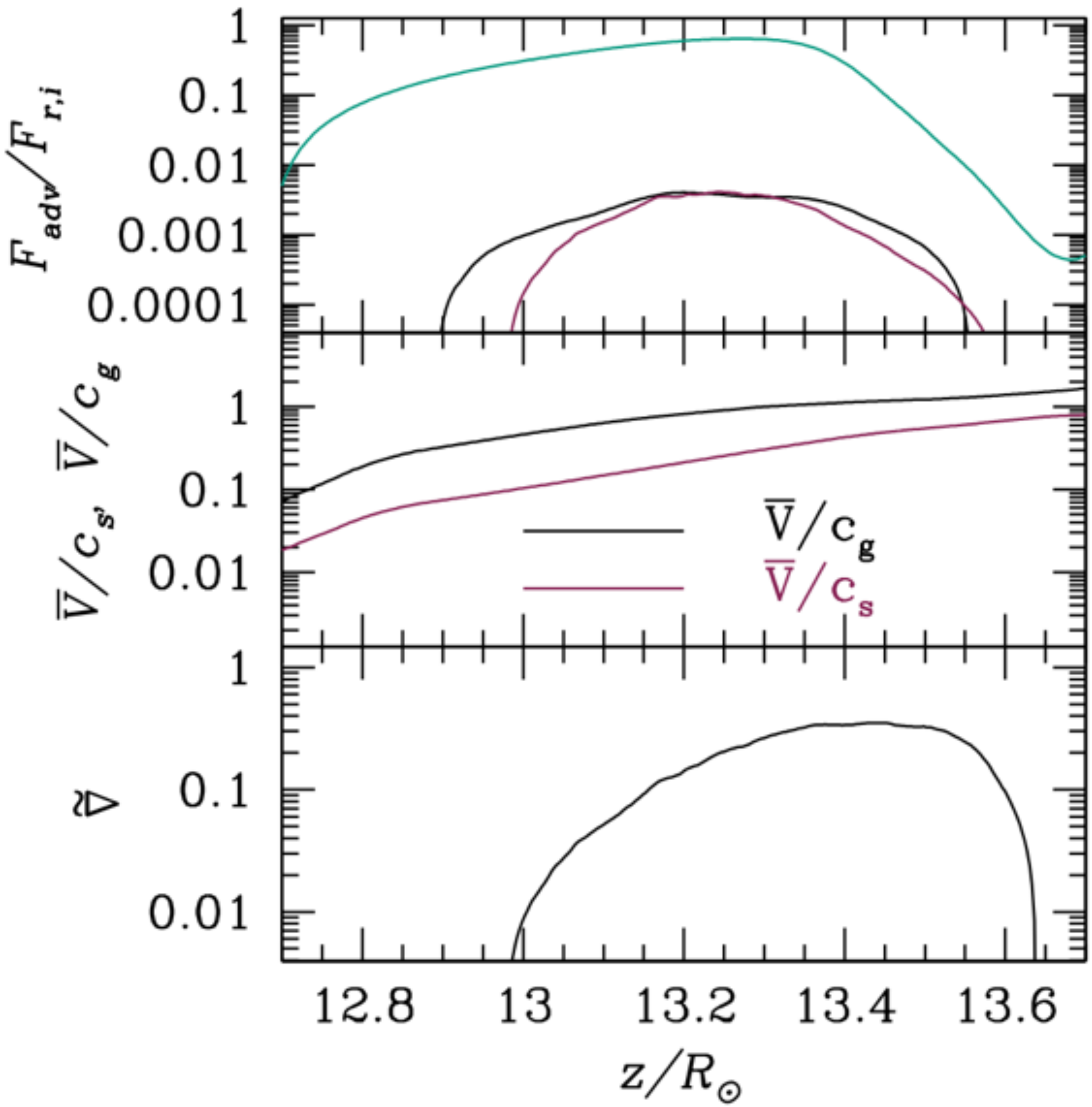
Photosphere



Power Spectrum



Very Small Convection Flux $\tau_0 \ll \tau_c$

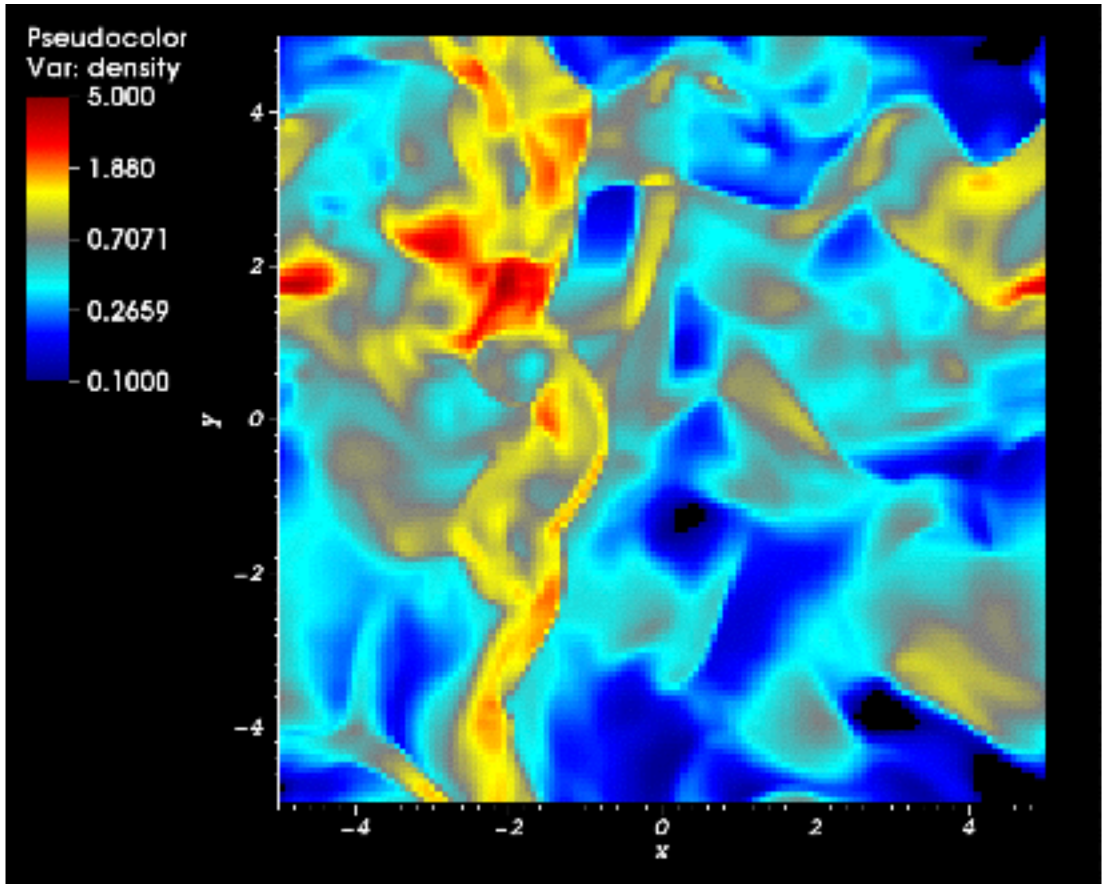


$\alpha = 0.1$

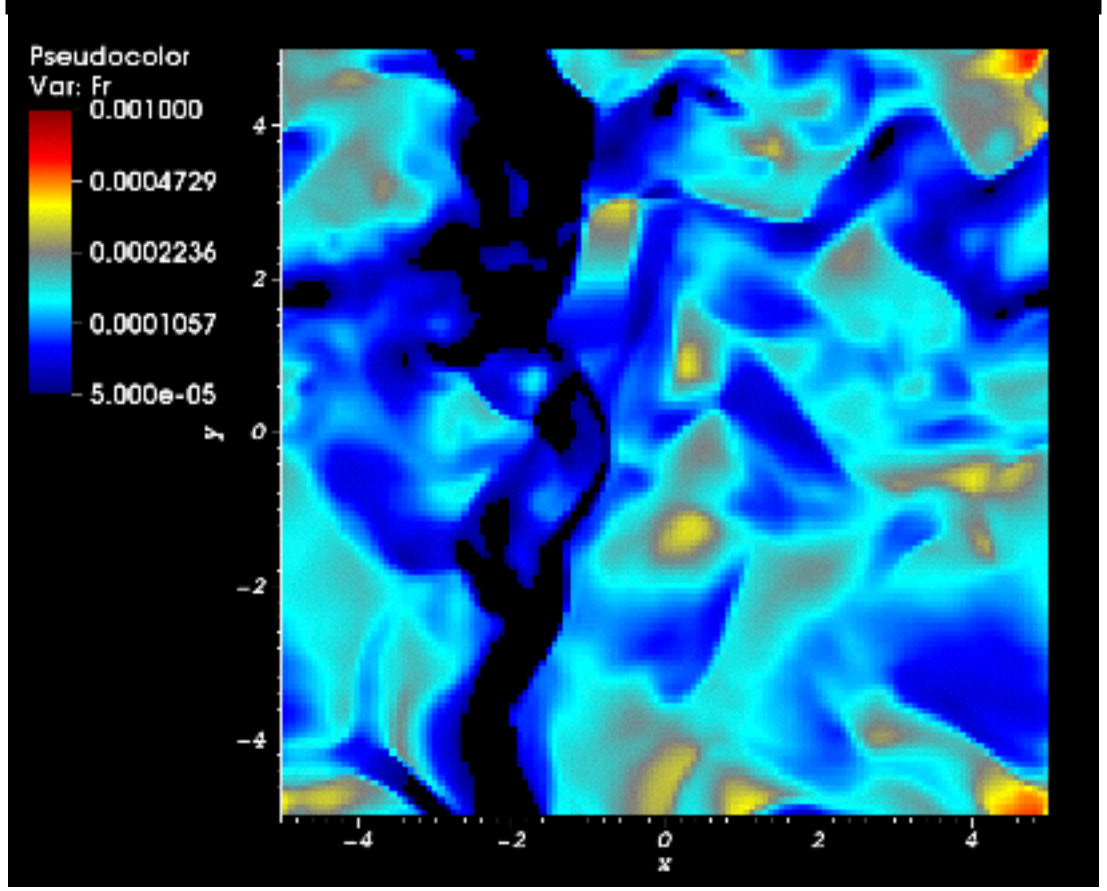
Porosity Effects exits, but not that strong

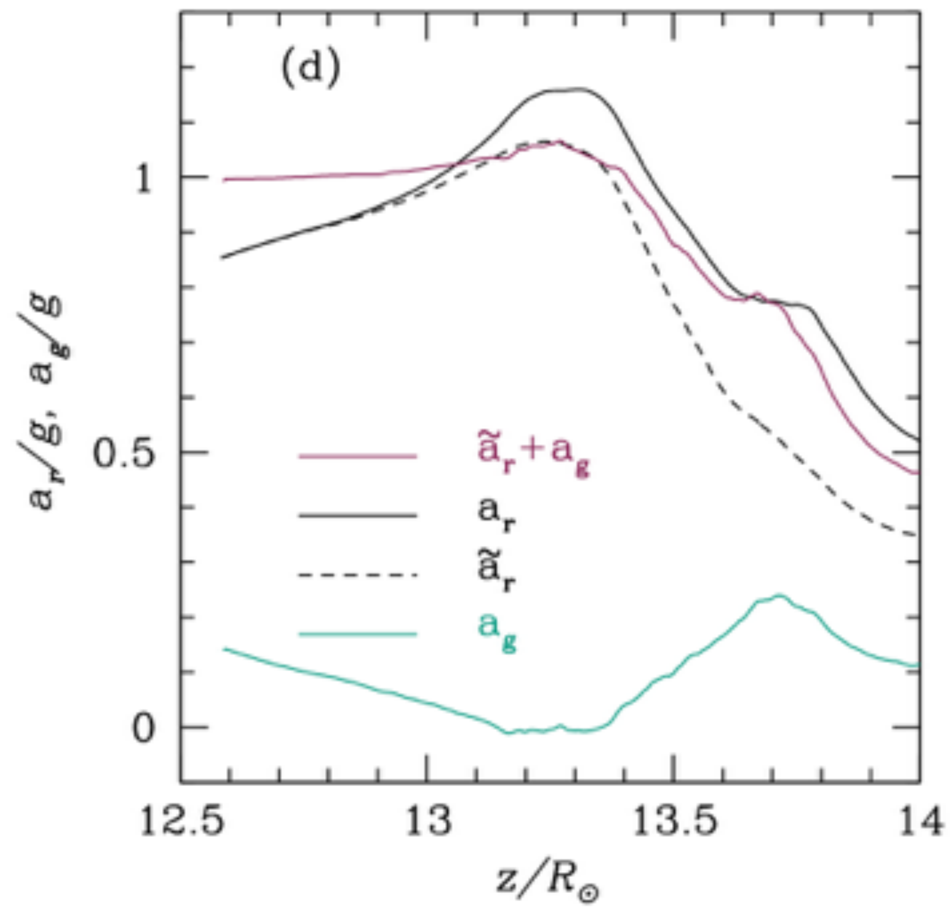
Horizontal Slice

Density



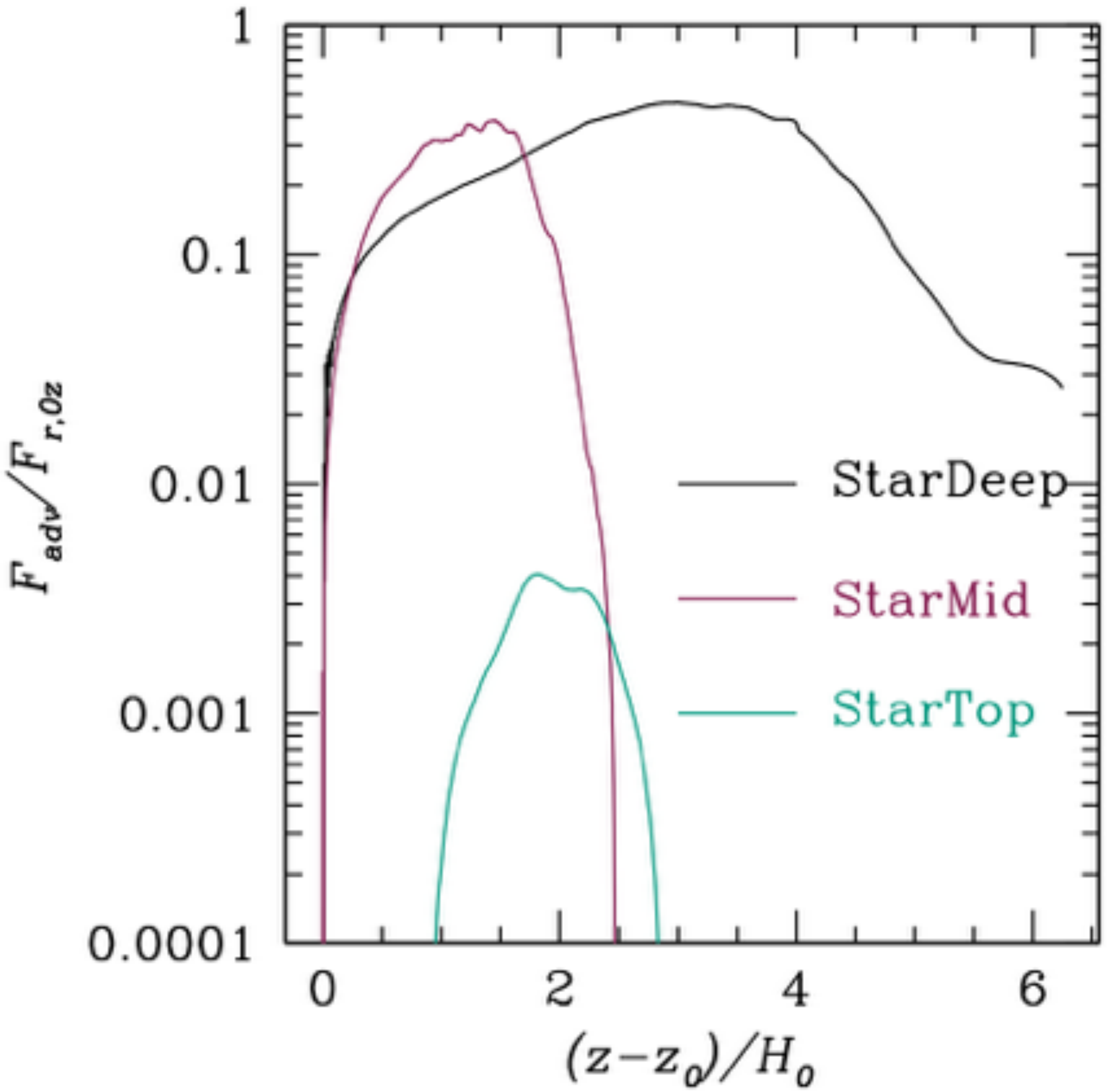
Radiation Flux



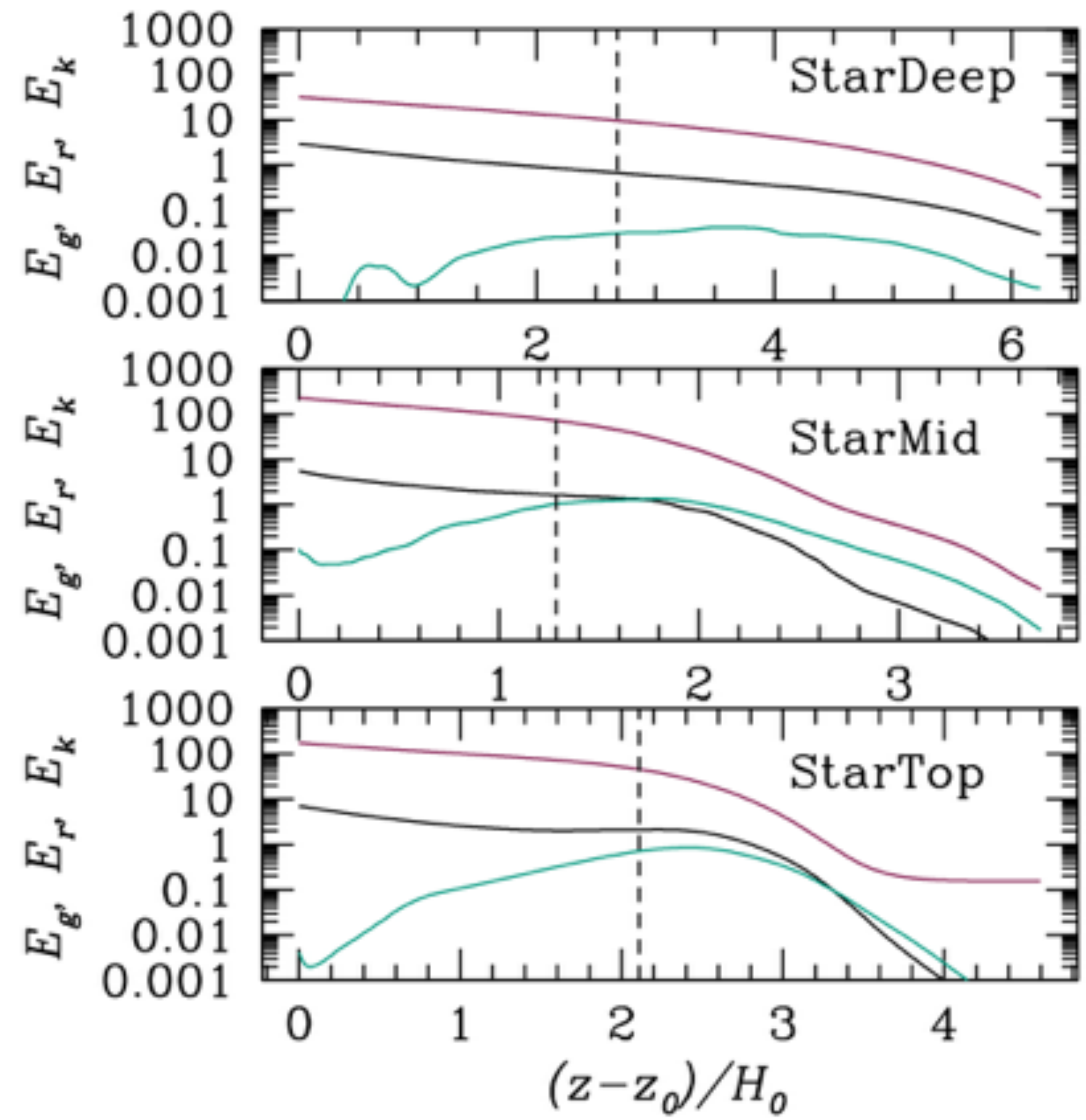


- Density weighted radiation acceleration is reduced.
- But it is still super-Eddington on average sense.

Summary



1
0.1
0.01
0.001
0.0001
0
2
4
6
$(z-z_0)/H_0$
$F_{adv}/F_{r,0z}$
StarDeep
StarMid
StarTop



1000
100
10
1
0.1
0.01
0.001
$E_g,\ E_r,\ E_k$
StarDeep
0
2
4
6
StarMid
0
1
2
3
StarTop
0
1
2
3
4
$(z-z_0)/H_0$

Summary

- This is the first time to calibrate convection in radiation pressure dominated regime.
- We give a criterion on the efficiency of convection
- In inefficient convection regime, radiation acceleration causes large amplitude oscillation with a period of a few hours.
- The supersonic convection will impact the estimate of rotations in massive stars.