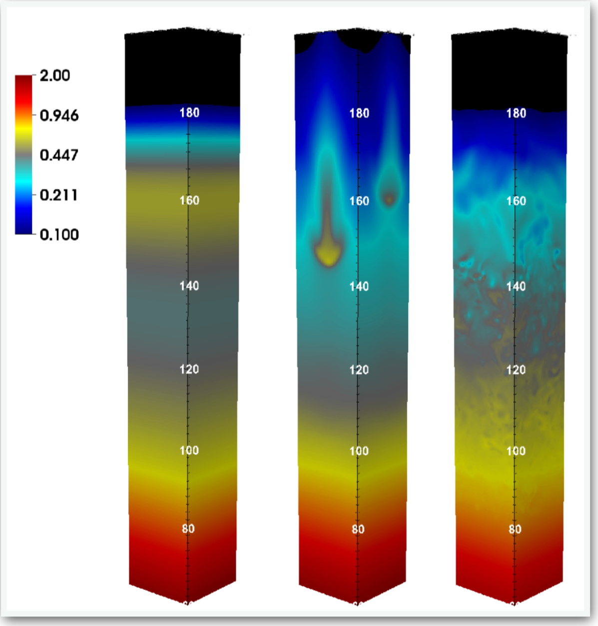
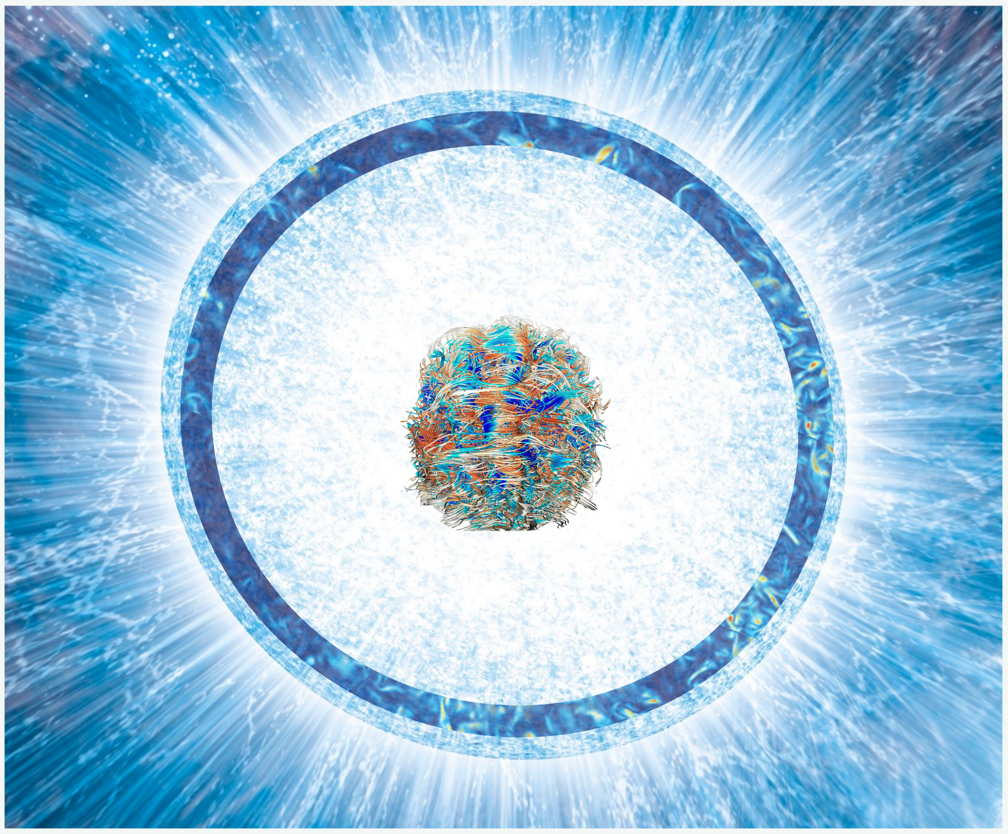
Envelope Convection in Massive Stars





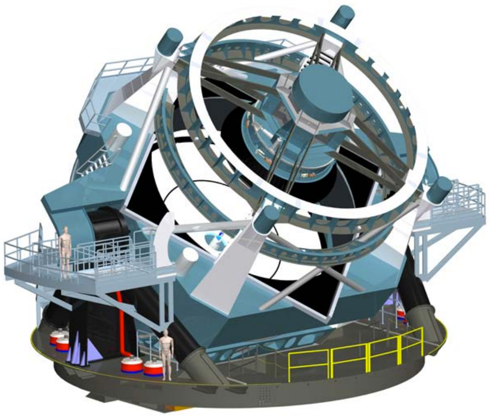
Matteo Cantiello

KITP & Center for Computational Astrophysics, Flatiron Institute

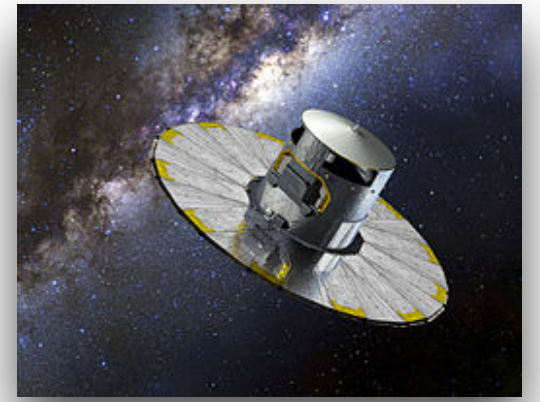
With: Yan-Fei Jiang (姜燕飞), Lars Bildsten, Eliot Quataert, Omer Blaes

Exciting times for Stellar Physics

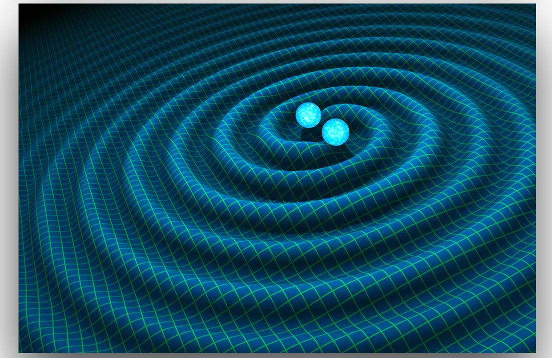
- Transient surveys unraveling unpredicted variety of explosive stellar deaths (e.g. PTF/ZTF, ASAS-SN, Pan-STARRS and soon LSST). We do not understand SN progenitors



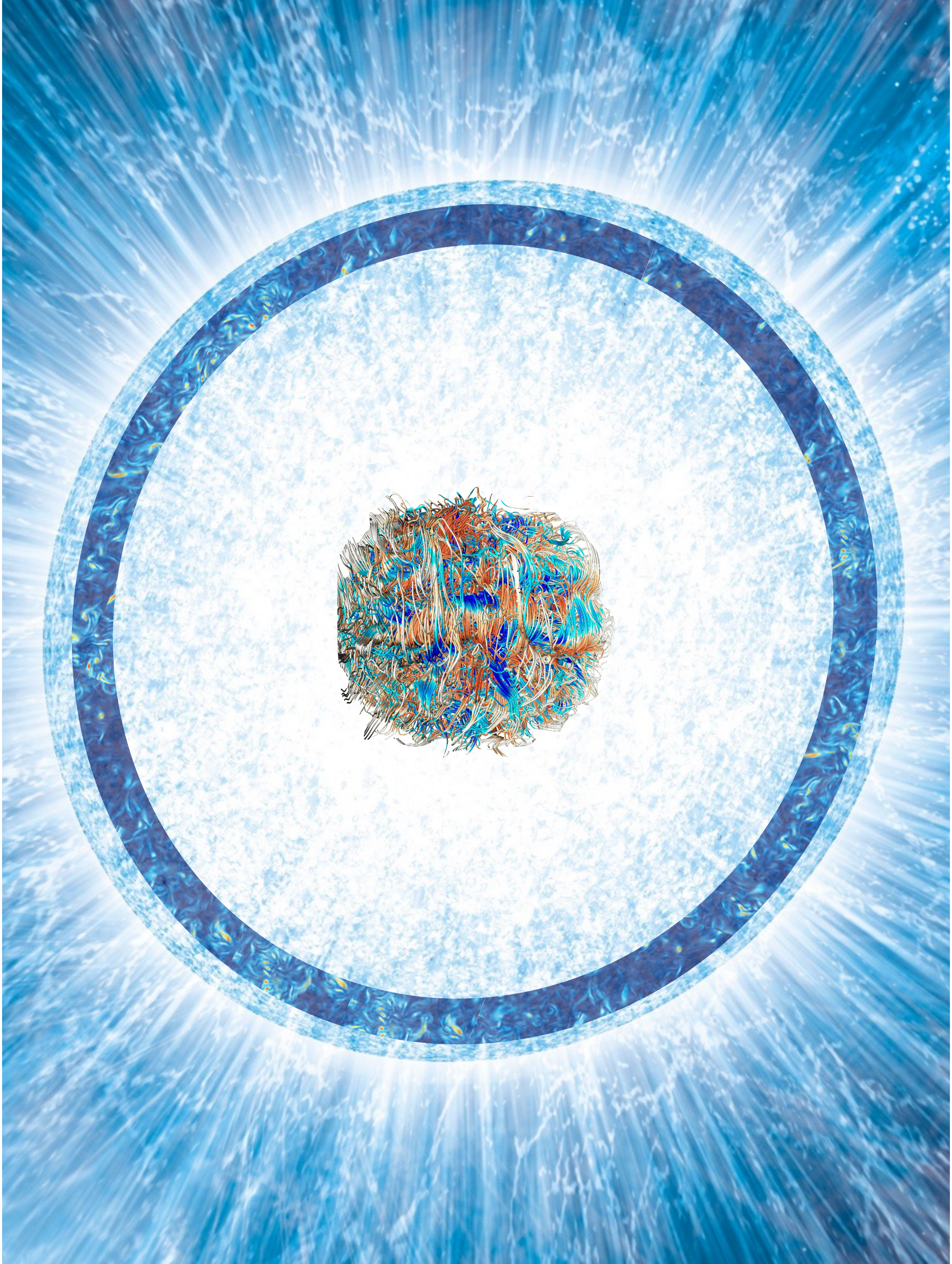
- We are entering the era of high precision stellar physics (Kepler, K2, GAIA, TESS, PLATO). Theory is lagging behind



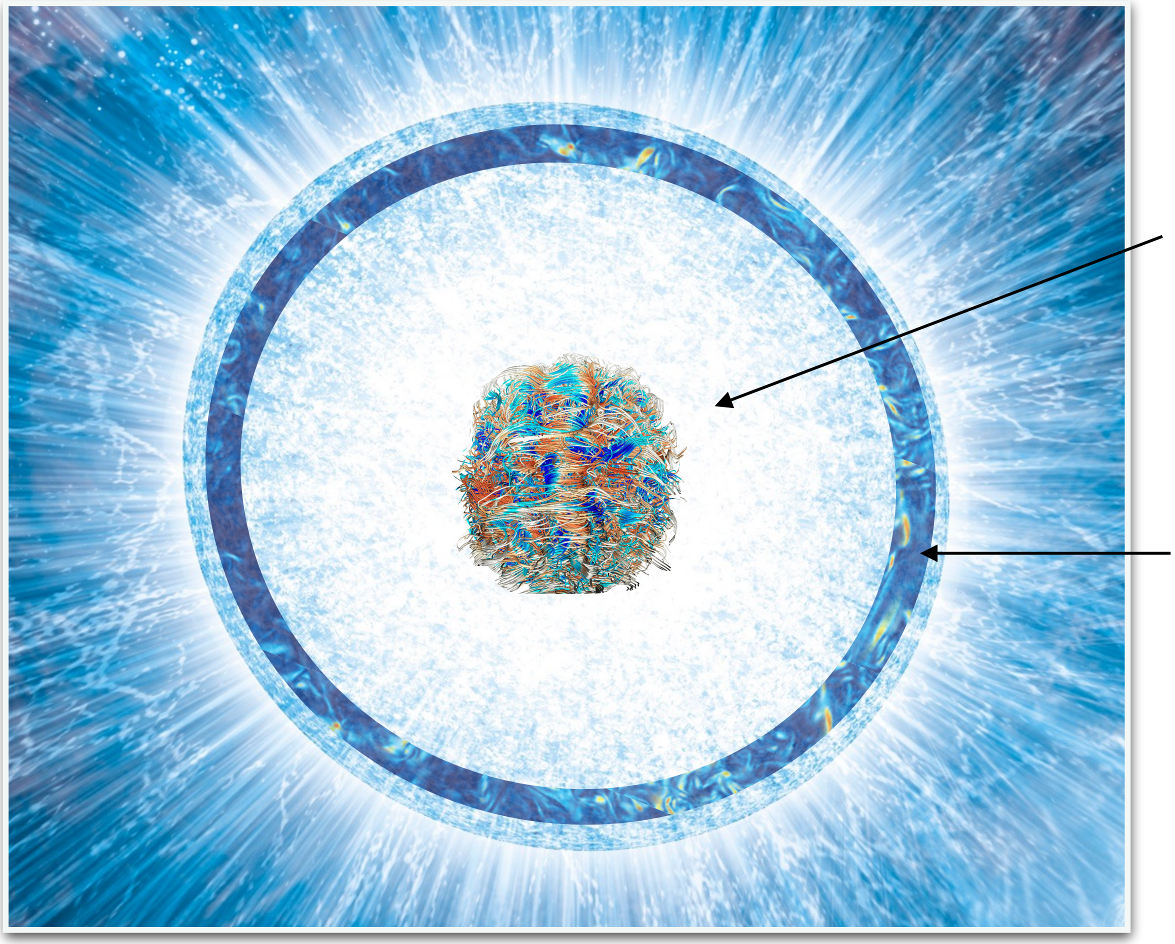
- Dawn of GW-Astronomy



Credit: NASA/C. Reed



For a early MS 60M_{Sun} Star



$R_* \sim 24R_{Sun}$

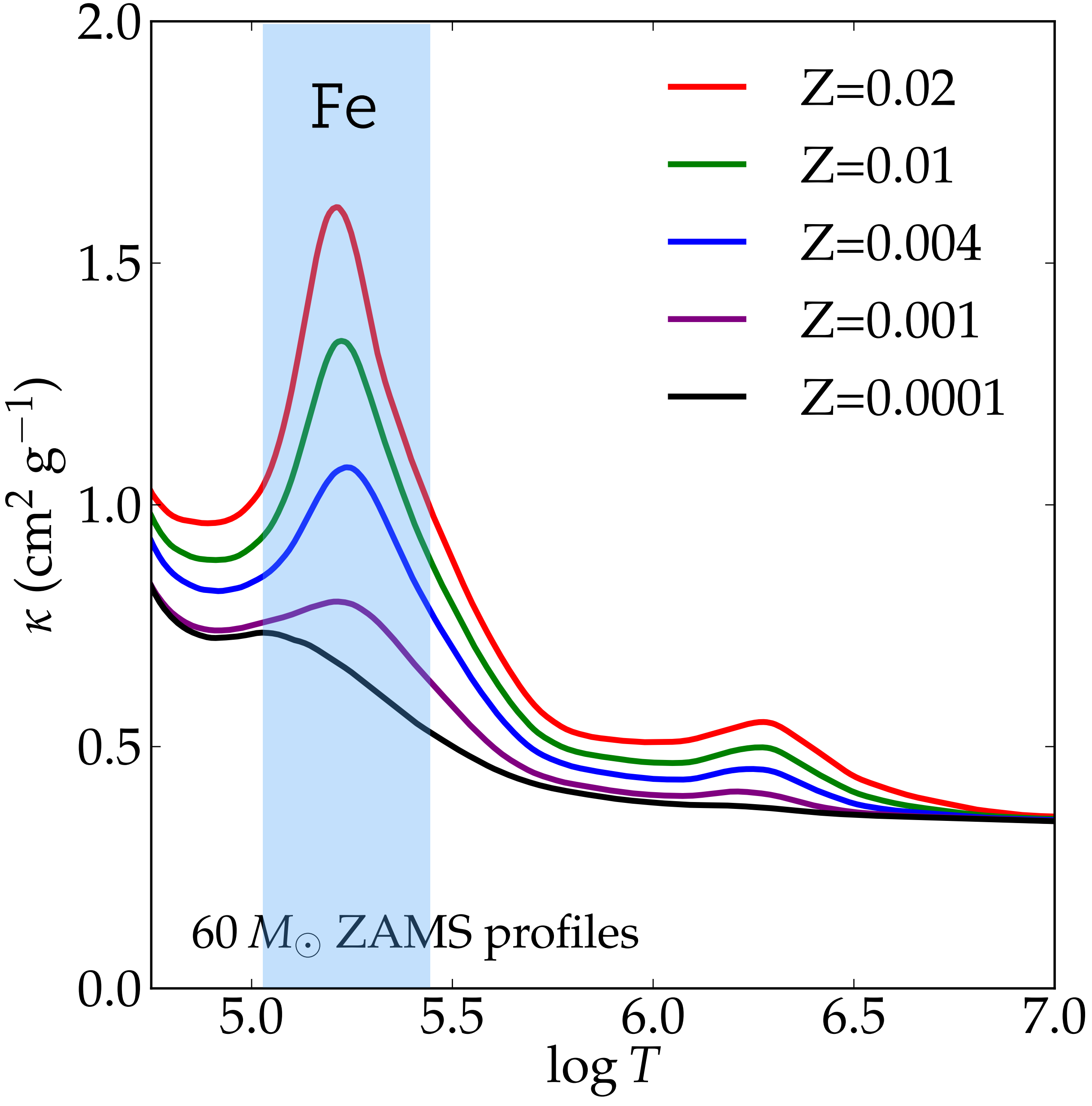
$M_{Core} \sim 40M_{Sun}$
$R_{Core} \sim 6R_{Sun}$

M_{FeCZ}: $\sim 10^{-5}\ M_{Sun}$
Extension CZ: $\sim 2.5\ R_{Sun}$

Core B-fields:
Jim Fuller's talk

Iron Convection Zone (FeCZ): Negligible in mass, but can be the largest convective region in MS massive stars (in volume)

The Opacity: Iron Peak

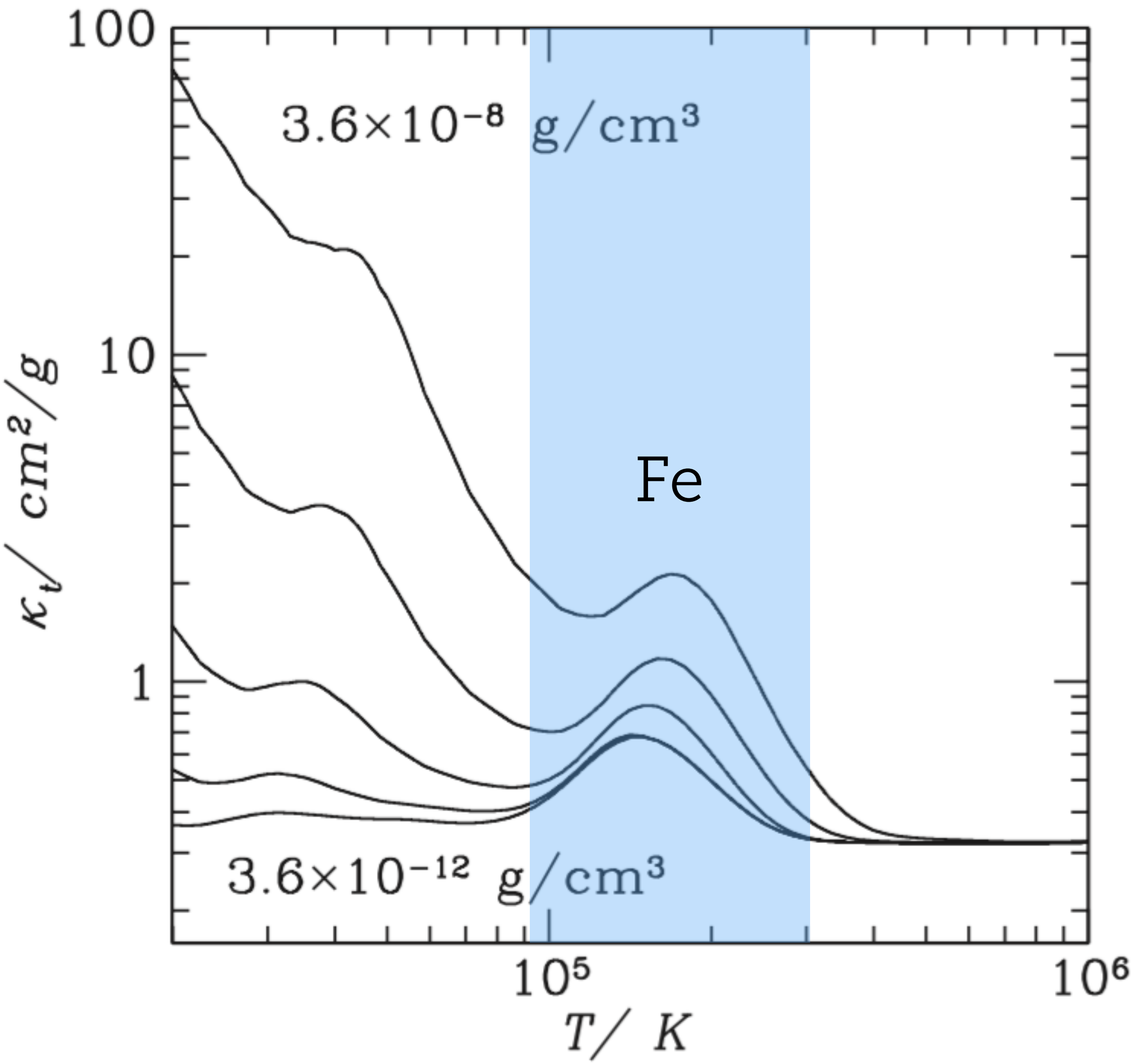


Paxton, MC et al. 2015
Cantiello et al. 2009
Iglesias & Rogers 1996

Strong Metallicity Dependence

Moravveji's talk

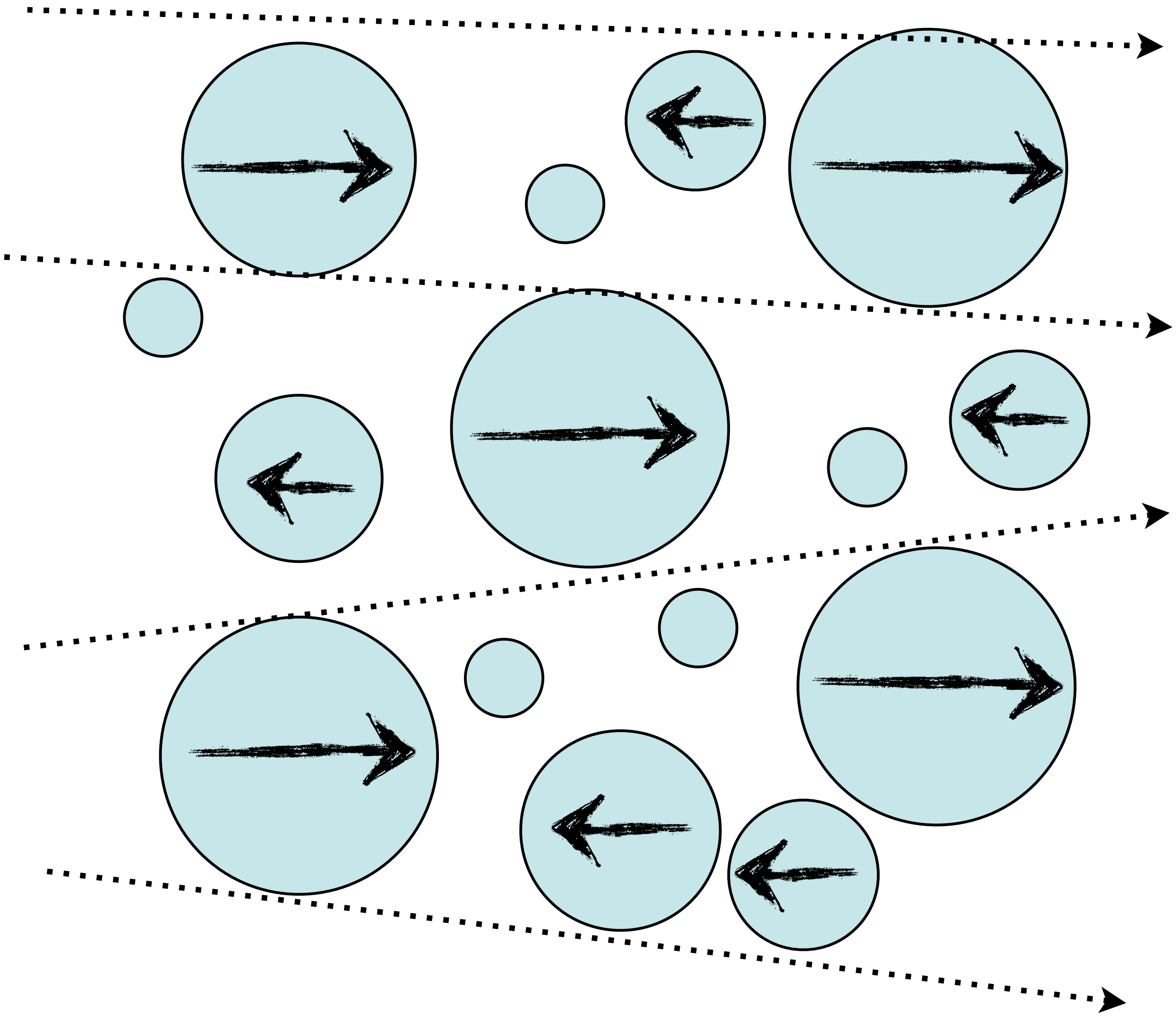
The Opacity: Iron Peak



Jiang et al. 2015

At fixed density
around
Iron Opacity peak.
Neighboring lines:
x10 in rho

Different regimes in Radiation Dominated Convection



Diff Rad Flux ······➤

Advection Flux ⟶
("convection"...)

$$F_{\rm dif} \sim \frac{a_r T^4 c}{\tau}$$

$$F_{\rm adv} \sim c_s a_r T^4$$

Critical optical depth

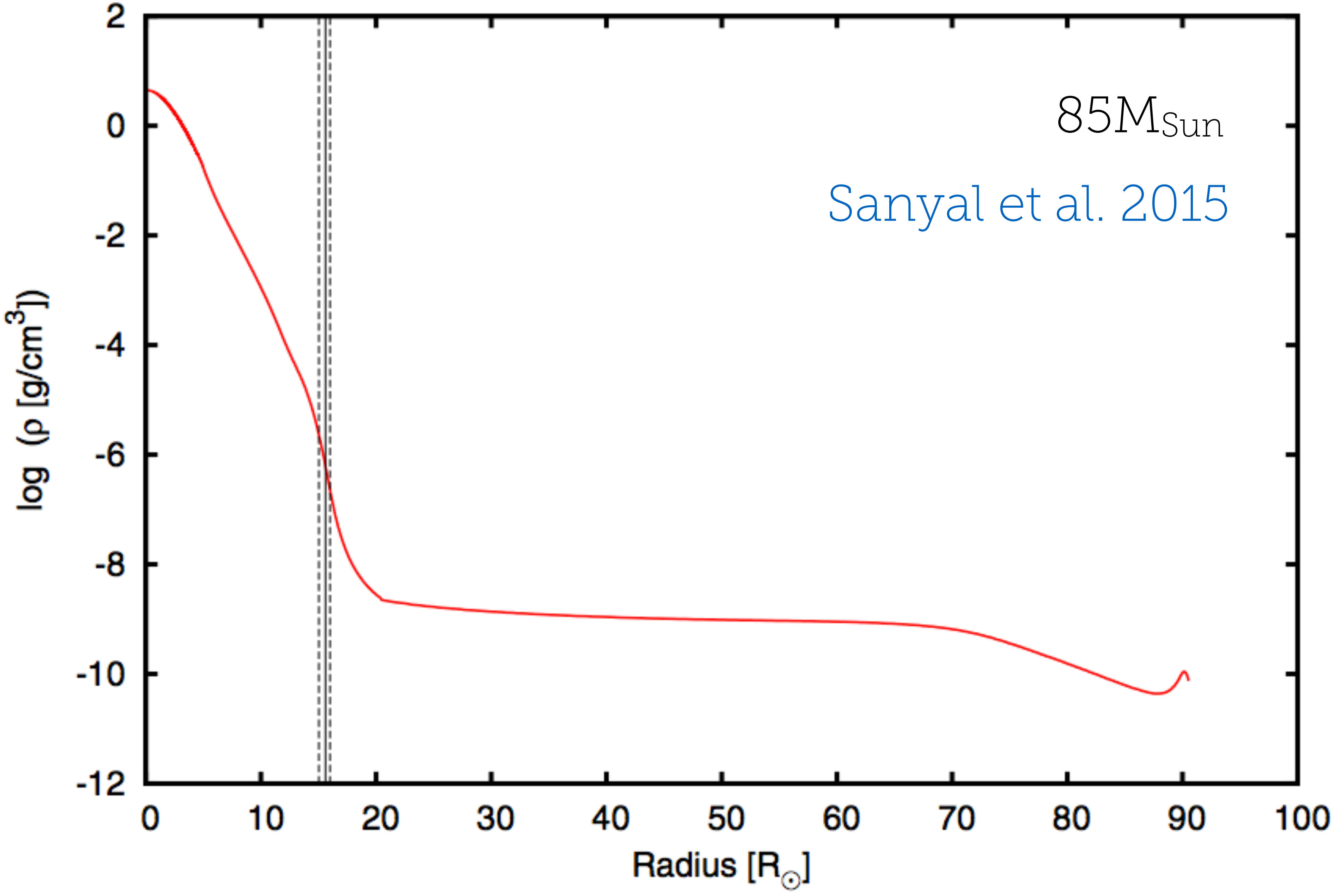
$$\tau_c = c/c_s$$

Optical depth where
radiation diffusion timescale
= dynamical timescale

Radiation Dominated Convection

- Massive stars develop loosely bound envelopes with inefficient convective regions
  e.g Joss et al. 1973, Paxton et al. 2013
- In 1D modeling:
  - Superadiabatic Convection
  - Density Inversions (e.g. Grafener et al. 2012)
  - Gas Pressure Inversions
  - Envelope Inflation (e.g. Sanyal et al. 2015,2017)

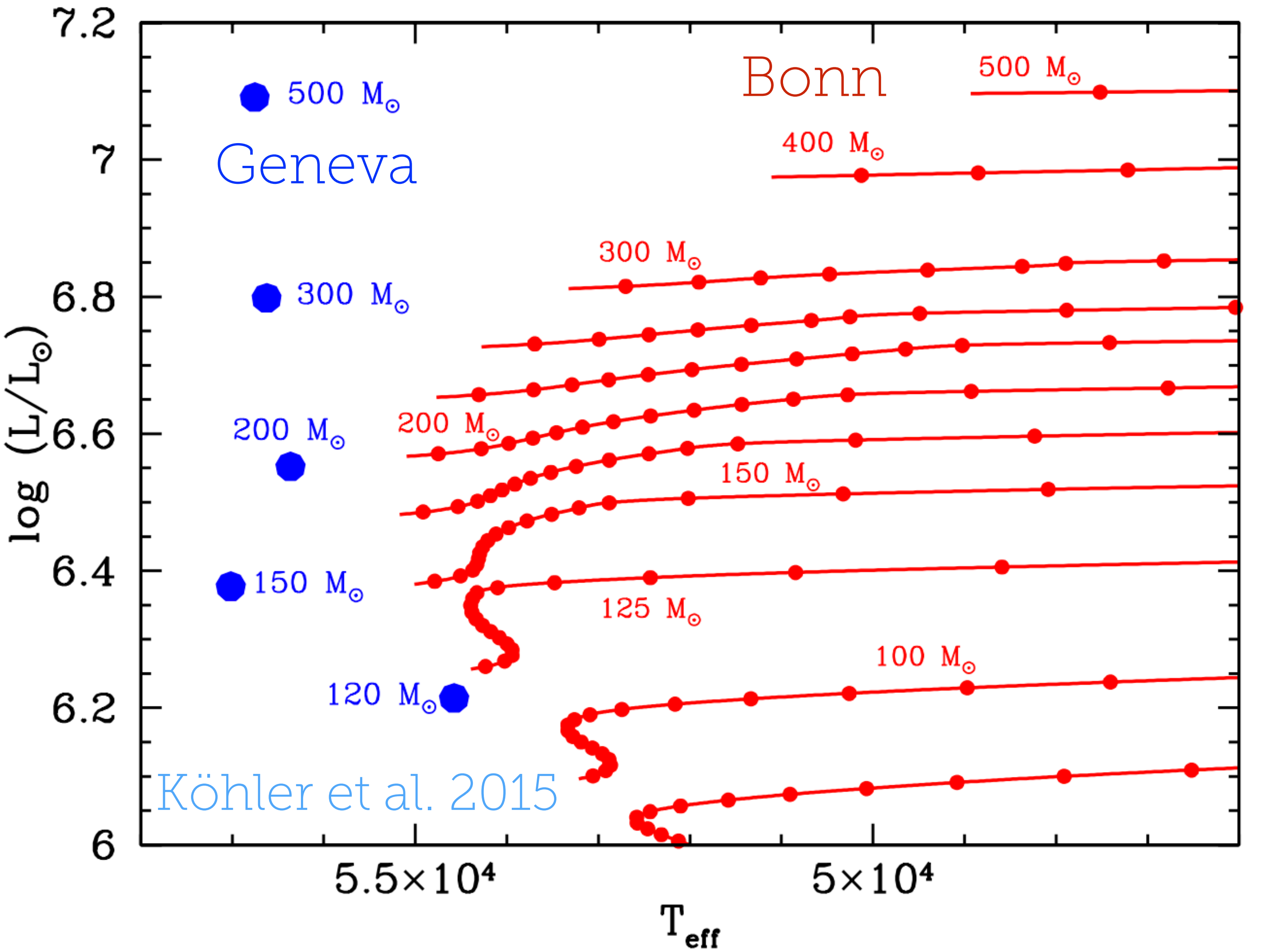
1D: Density Inversions, Envelope Inflation



$85M_{Sun}$

Sanyal et al. 2015

1D MLT: Large Uncertainties



Massive Stars: HRD location, Stellar Radii, Stability, Surface turbulence, MassLoss, Binary Population Synthesis (See e.g. Belczynski+ 2014), BH-BH binary progenitors

Important questions

- Are the density inversions stable in 3D calculation of radiation dominated envelopes?
- How energy is transported in radiation dominated envelopes? MLT not applicable
- Envelope Inflation?
- Potential coupling to mass-loss
- Surface manifestations

3D Radiation
Hydro Calculations

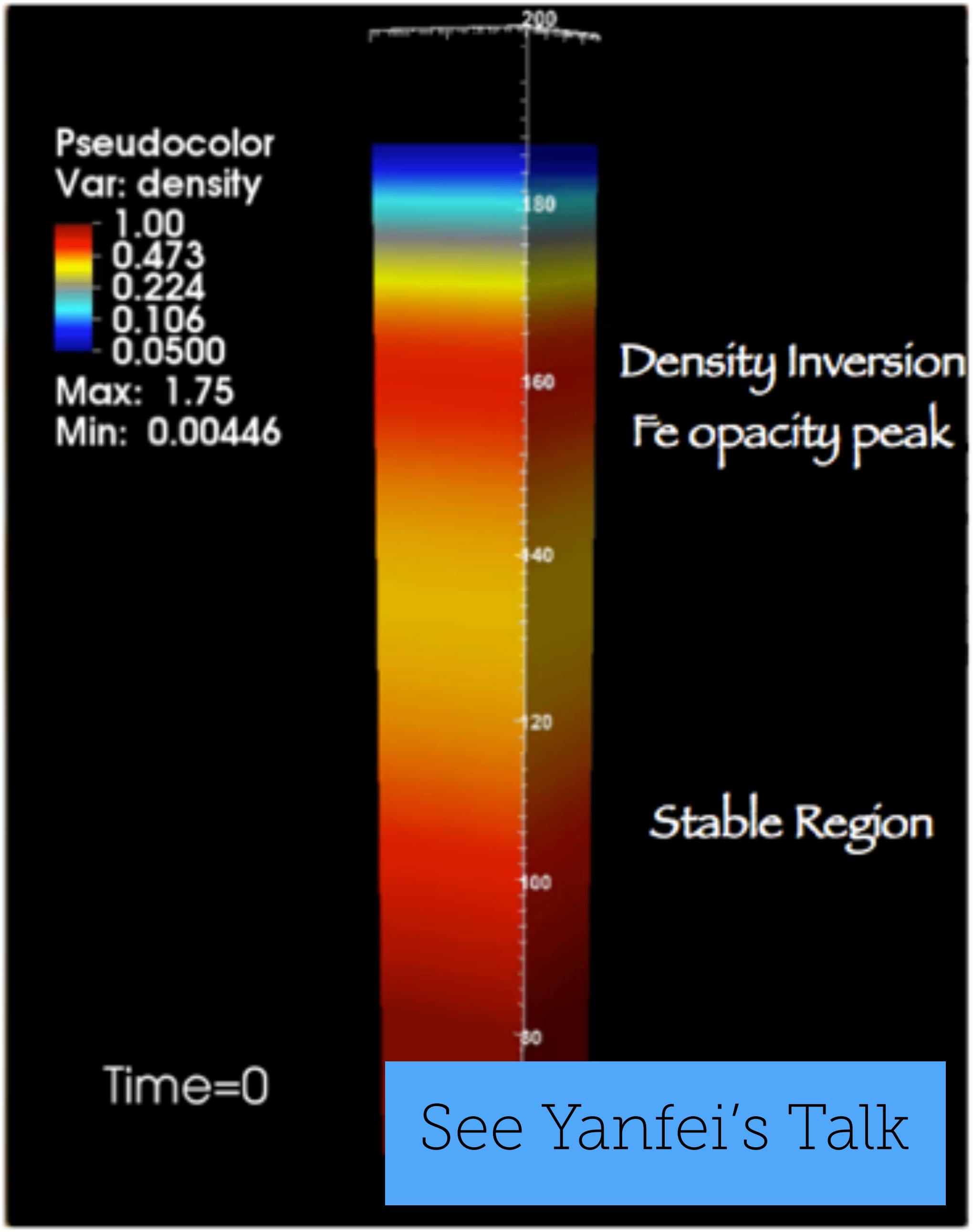
Simulations Setup

ATHENA with VET Radiation Module

Jiang et al. 2015

Open top boundary
(Photosphere can
be included)

Reflection bottom
boundary



See Yanfei's Talk

g

Constant gravity

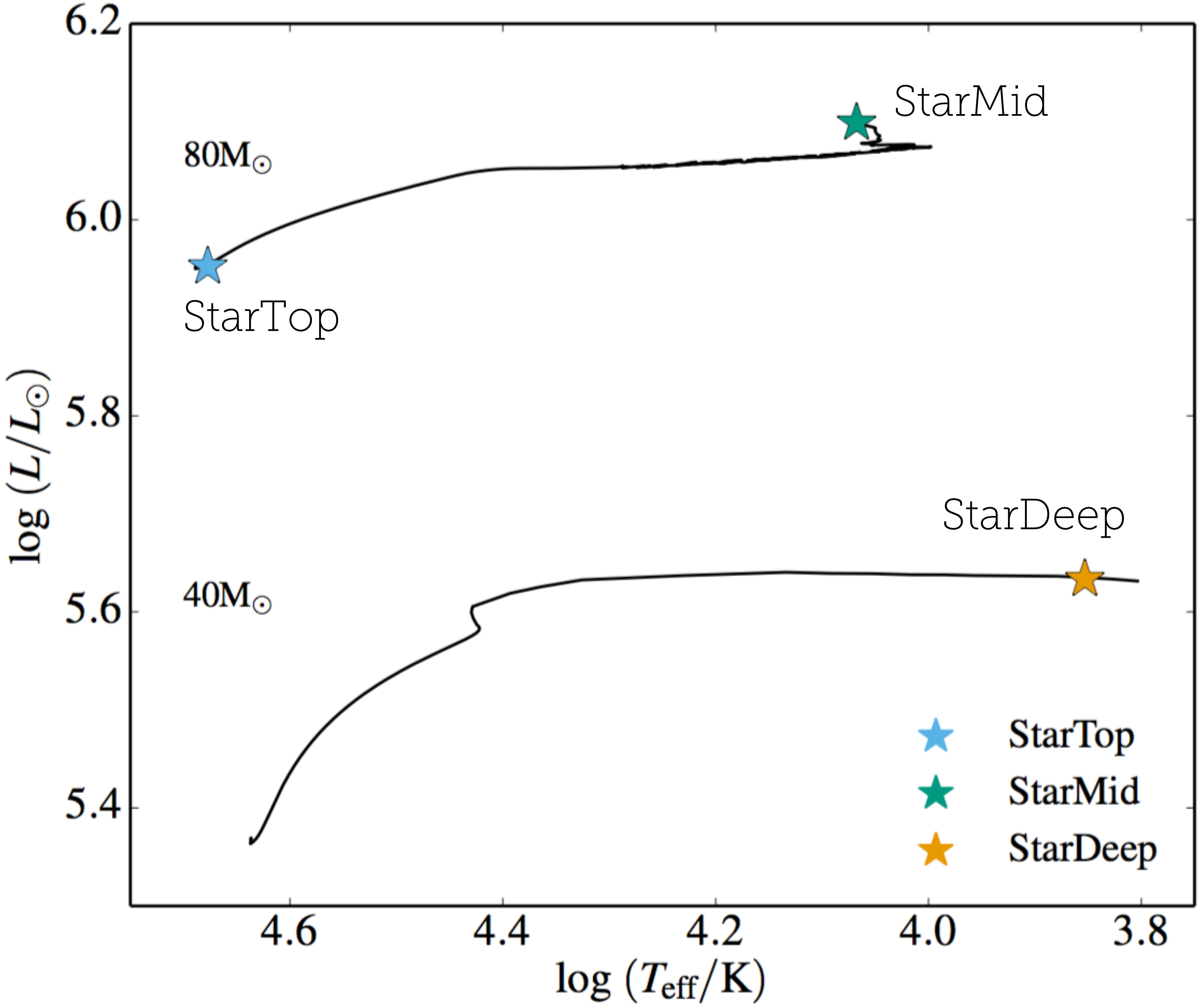
Fr

Constant radiation flux
coming from the bottom

Initial Conditions

Guided from MESA 1D models

Jiang et al. 2015



Initial Conditions

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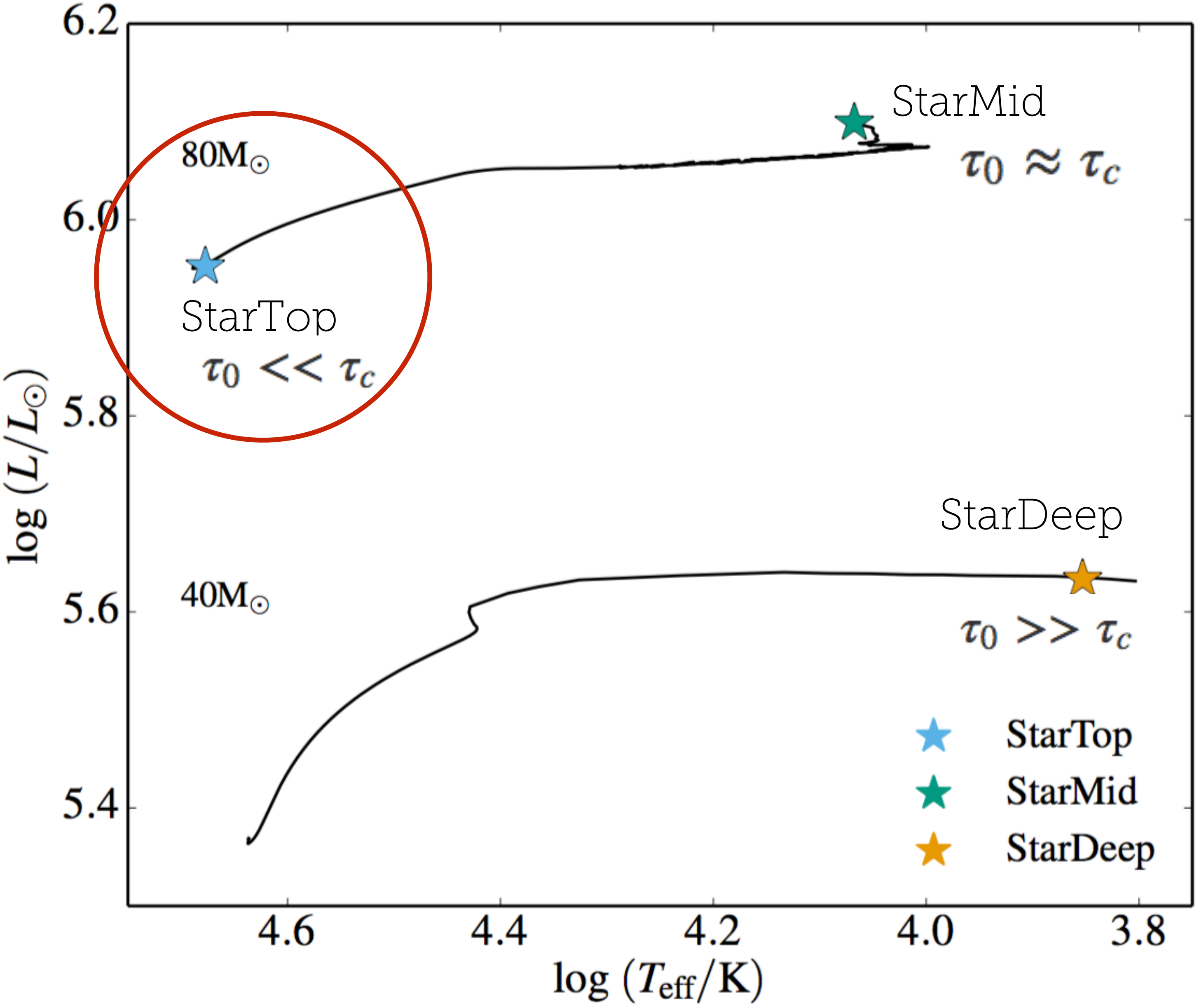
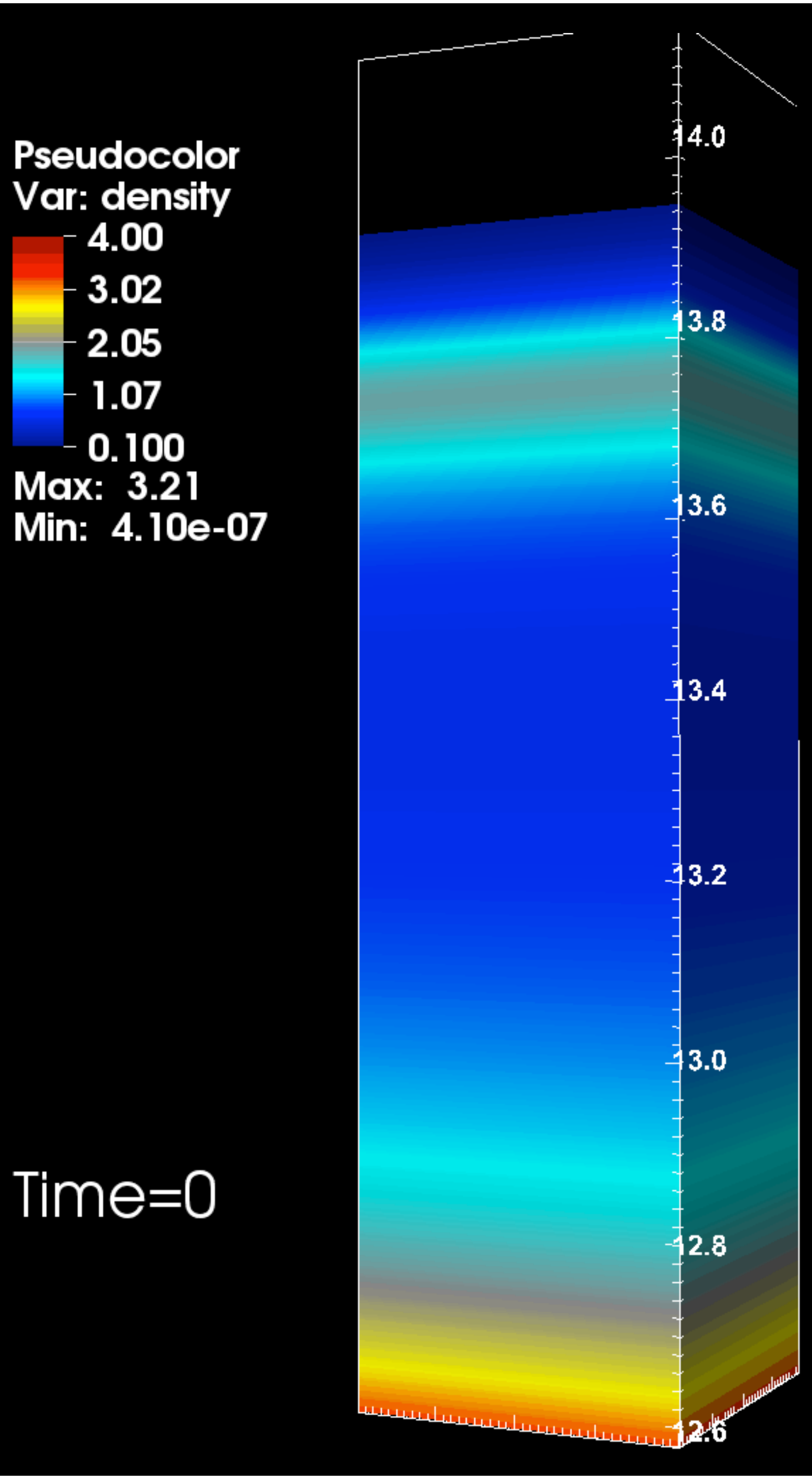


STARTOP

The case with inefficient convection

$\tau_0 \ll \tau_c$



Jiang et al. 2015

STARTOP

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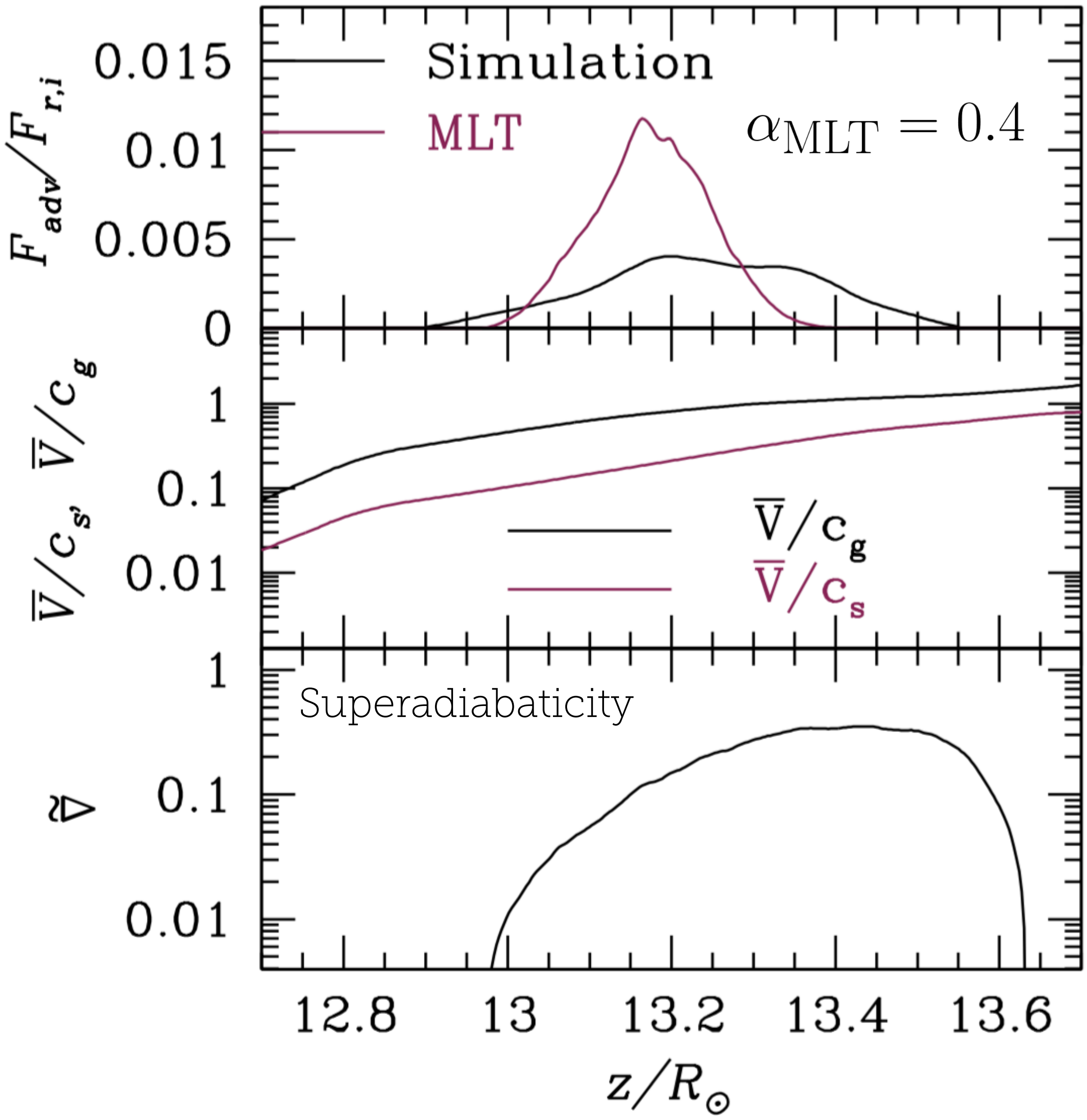

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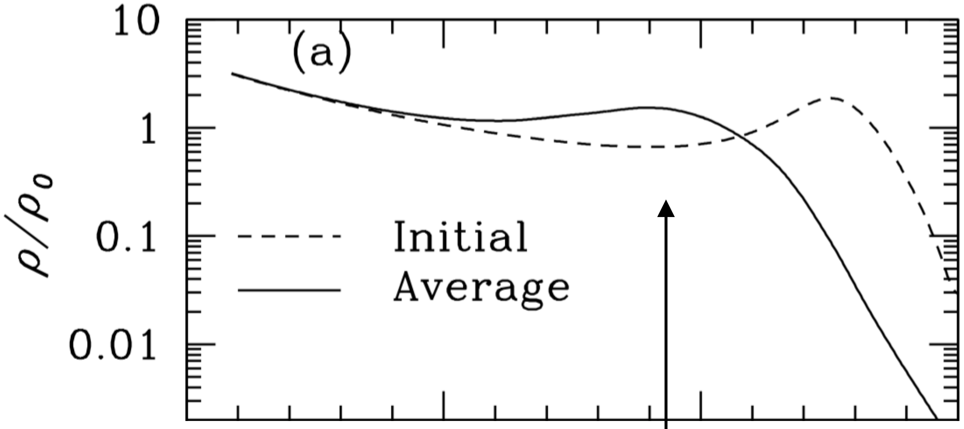
Jiang et al. 2015

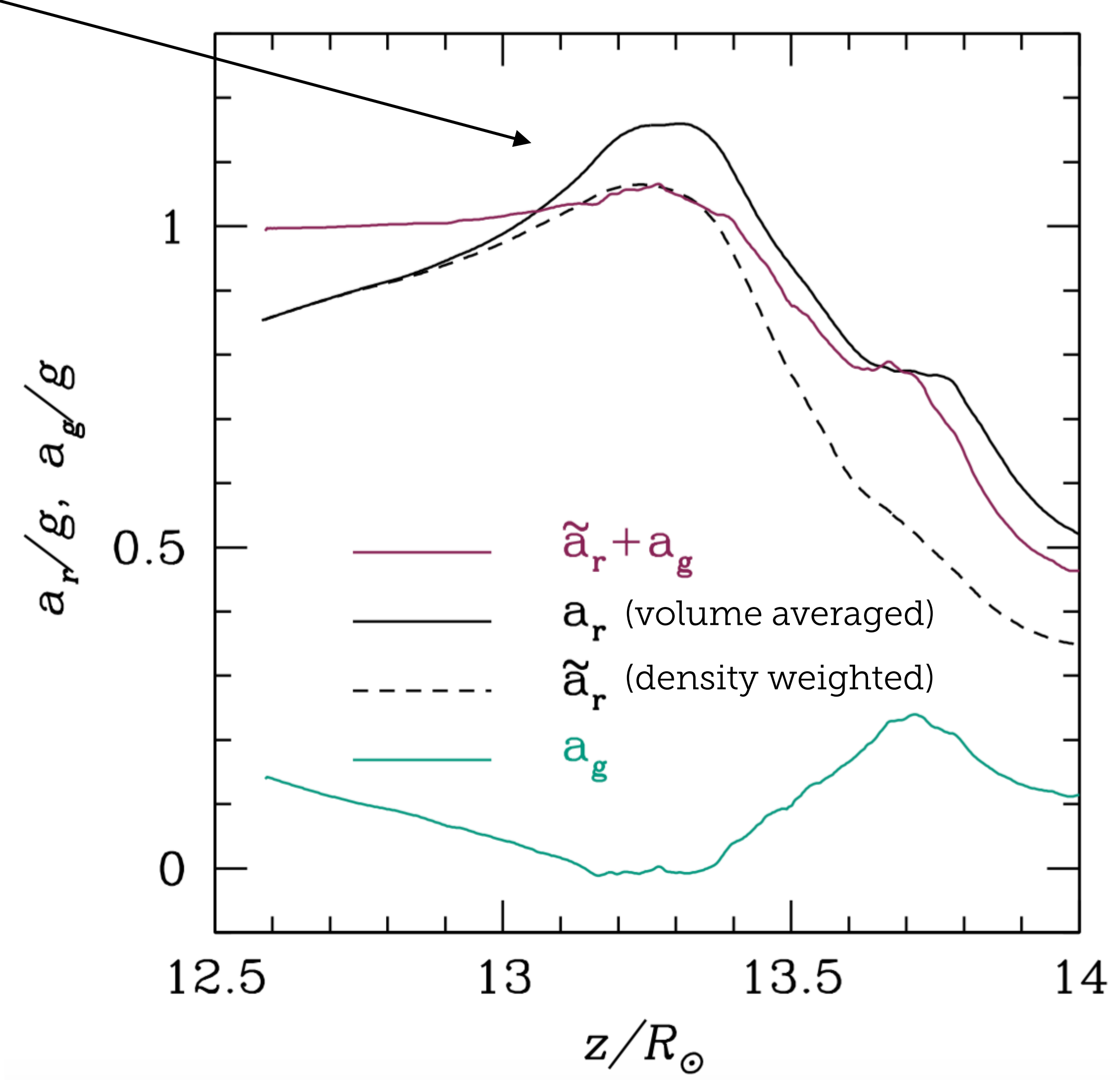
The case with inefficient convection

$\tau_0 \ll \tau_c$

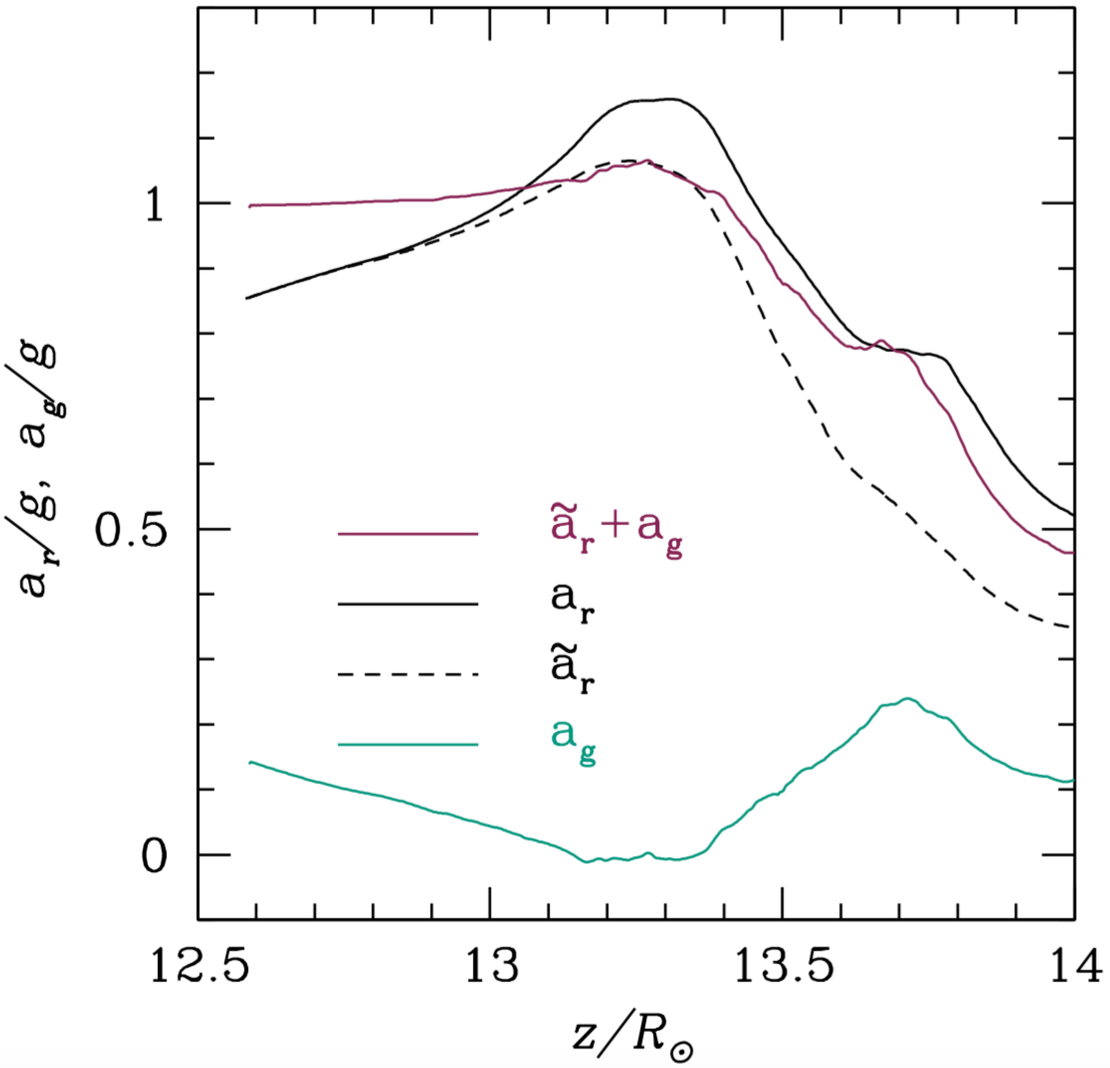
Porosity reduces radiative acceleration, but not enough to make it sub-Eddington



Density Inversion still present (in average)



The Porosity Factor



$$\mathscr{F} \equiv \frac{a_r}{\tilde{a}_r} \geq 1$$

Density weighted radiation acceleration

$$\tilde{a}_r = \frac{< \rho \kappa F_{\text{rad}} >}{c < \rho >}$$

3D -> 1D

The Porosity Factor:

Preliminary 1D implementation

- Use calibrated alpha MLT (using the advection flux calculated in ATHENA)

$$\alpha_{\mathrm{MLT}} = 0.4 - 0.5$$

Larger in the presence of B-fields (0.6-1.0)

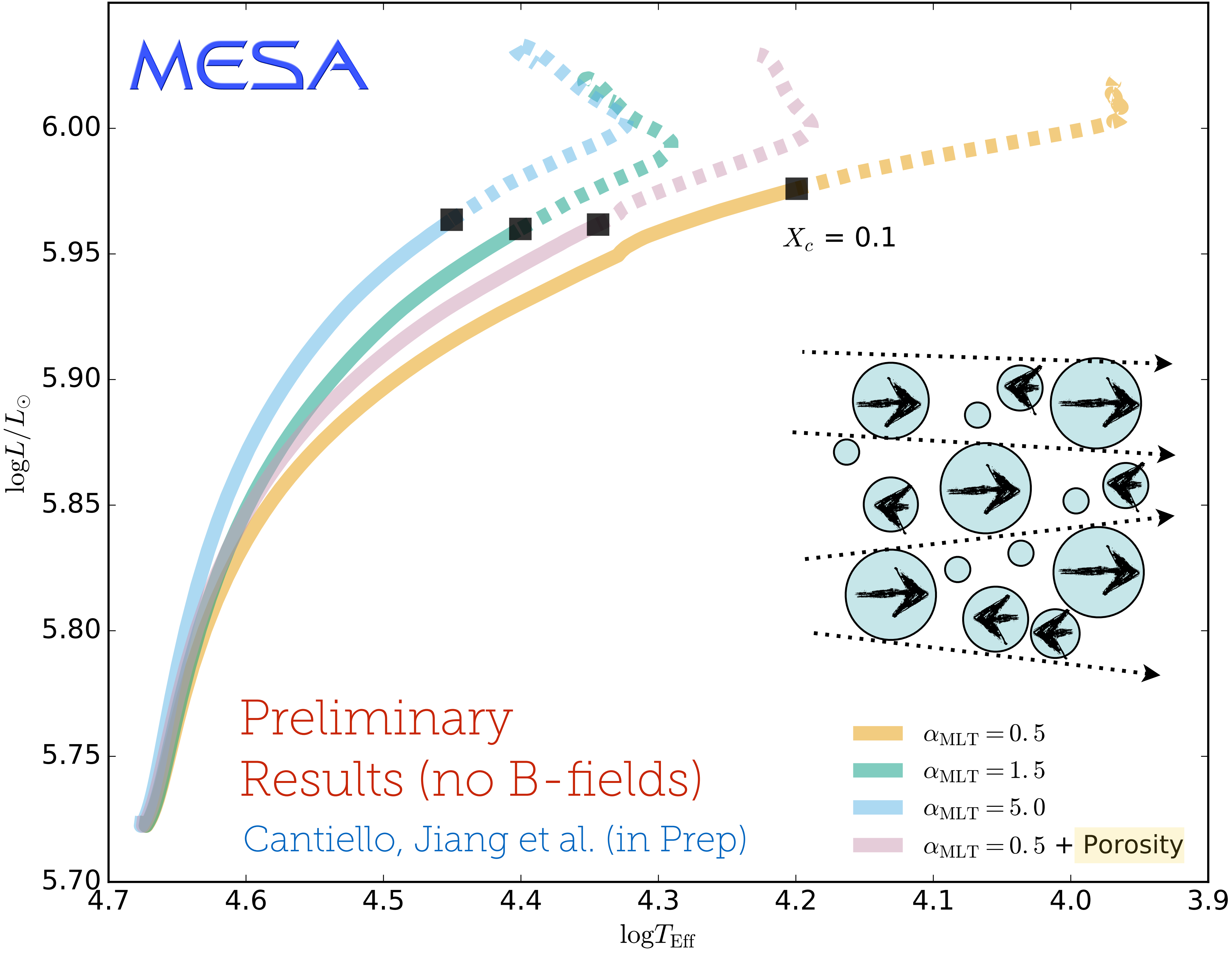
- Include Porosity Factor (Calibrated from ATHENA calculations)

$$\frac{dP_{\mathrm{rad}}}{dm} = -\frac{\kappa L}{c4\pi r^2}\frac{1}{\mathscr{F}}$$

$$<\kappa>_{\mathrm{MLT}} = \frac{\kappa}{\mathscr{F}}$$

Cantiello, Jiang et al. (in Prep)

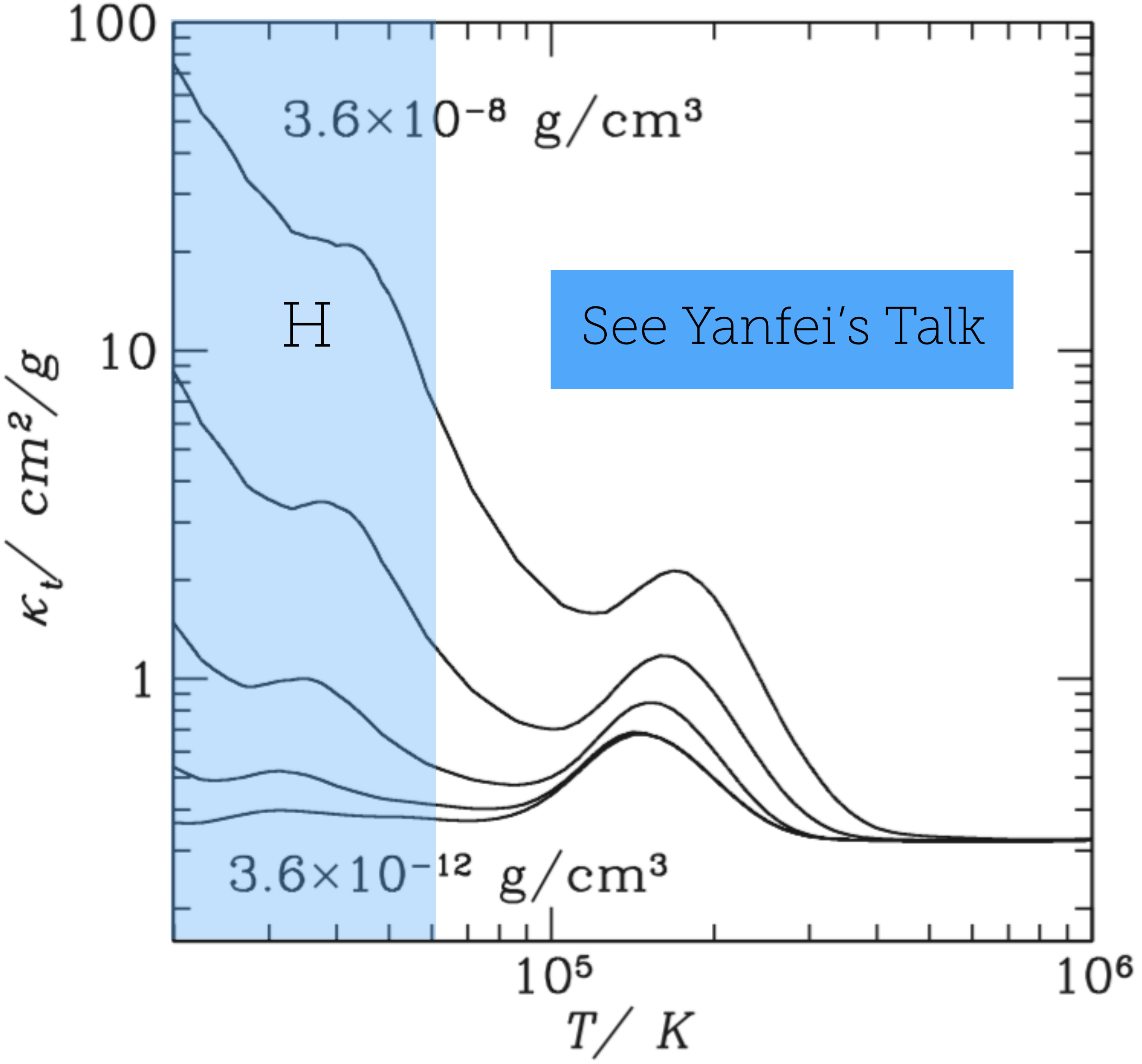
$60 M_\odot$ MESA 9248 Z=0.02



Preliminary
Results (no B-fields)

Cantiello, Jiang et al. (in Prep)

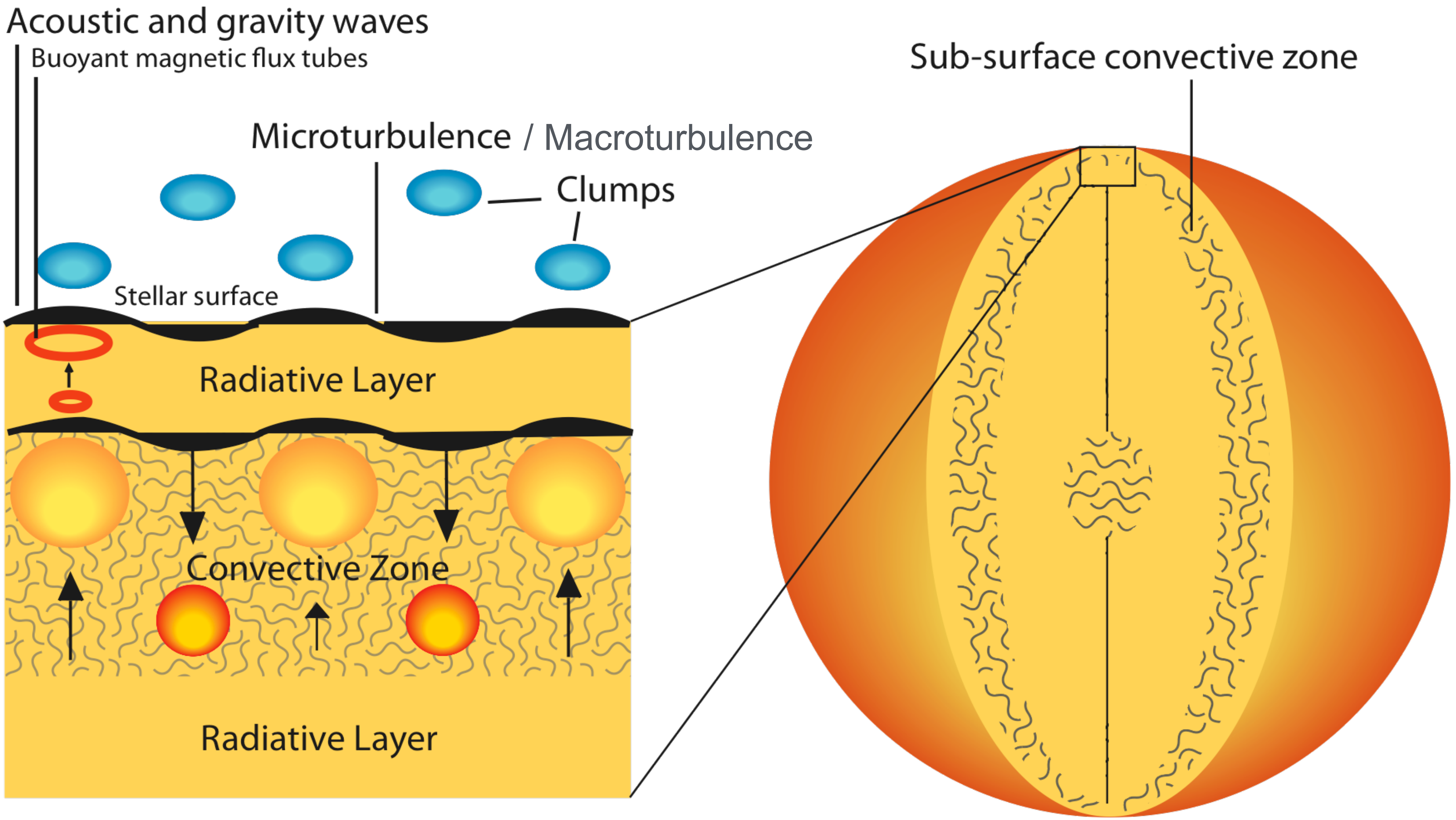
In later evolutionary phases, things might get even more interesting!



See Yanfei's Talk

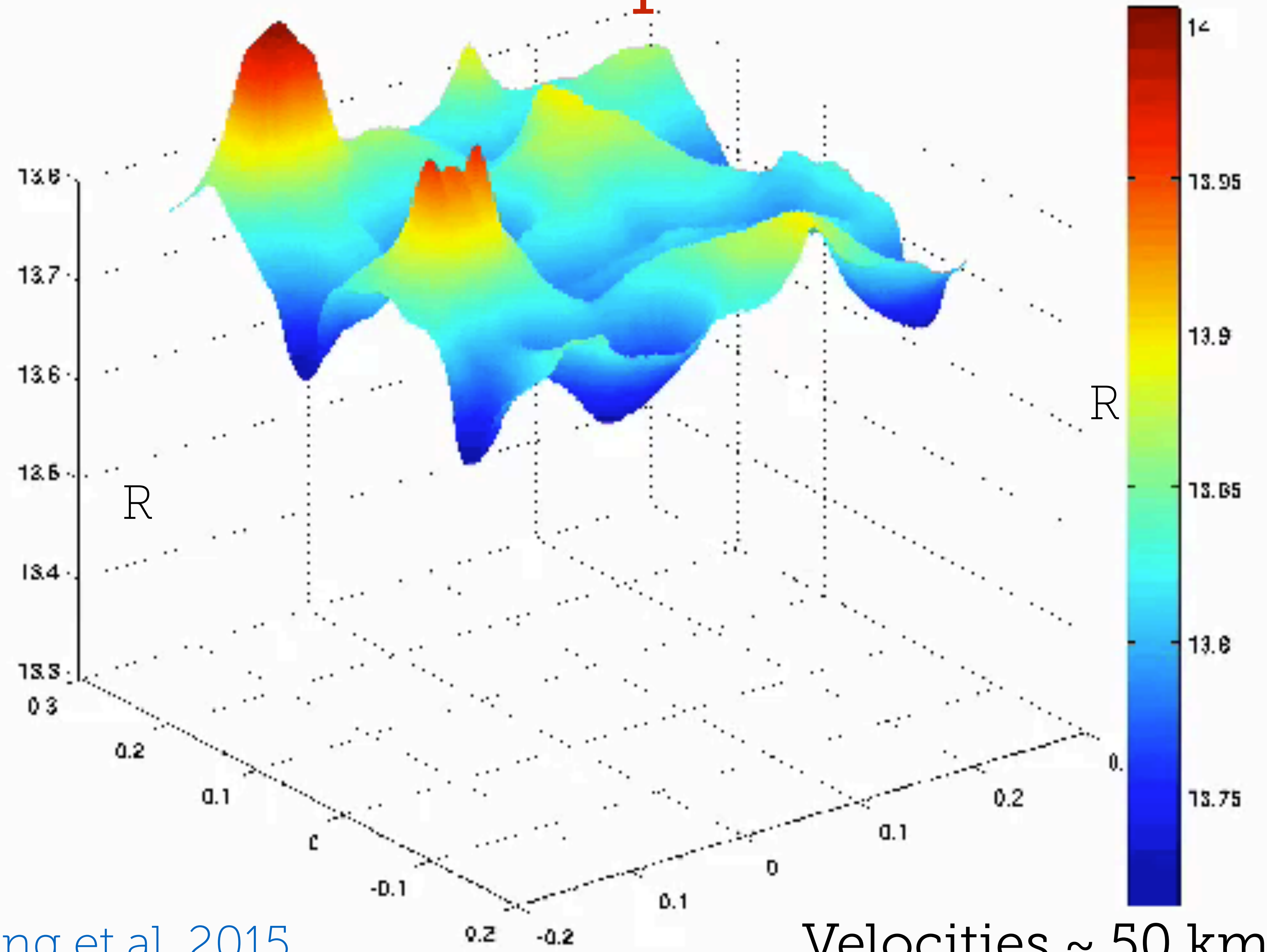
Surface Manifestations

Observable Consequences of Sub-Surface Convection?



Cantiello et al. 2009

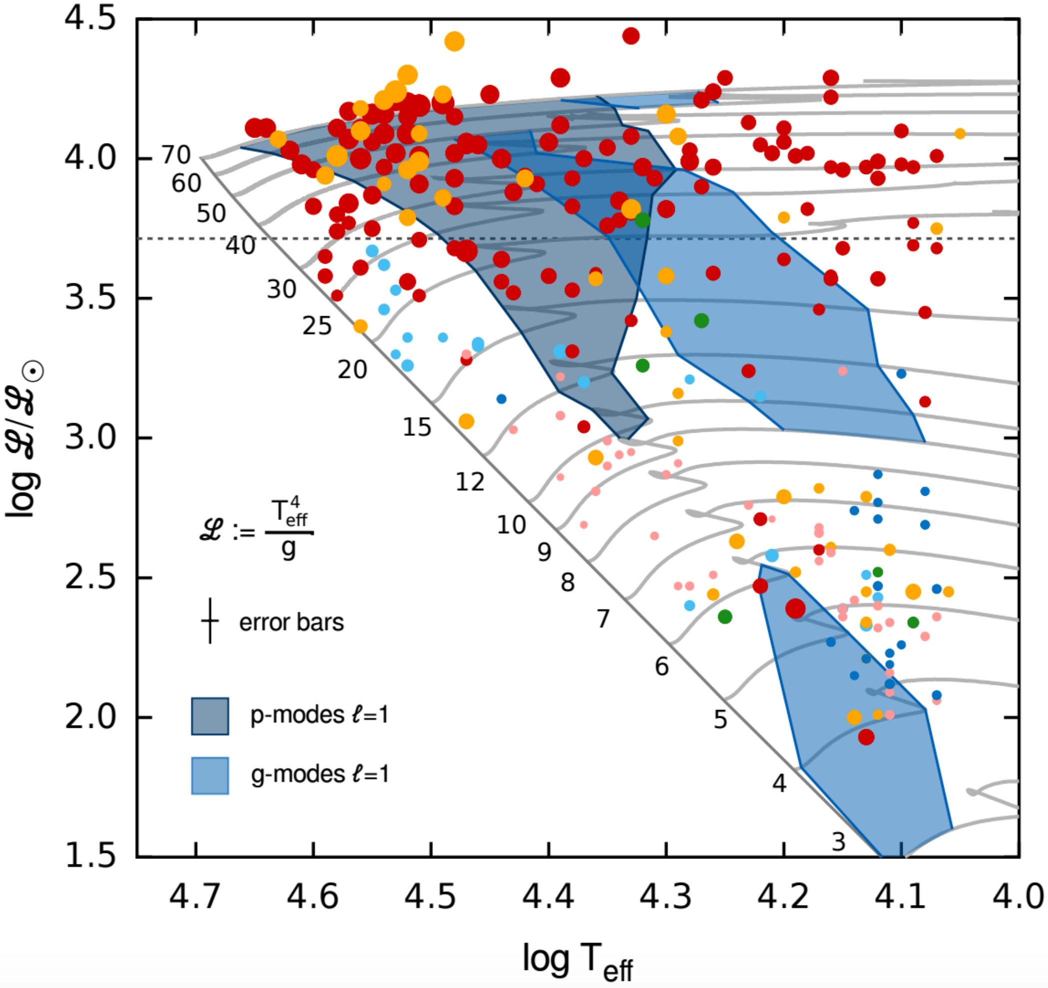
STARTOP Photosphere

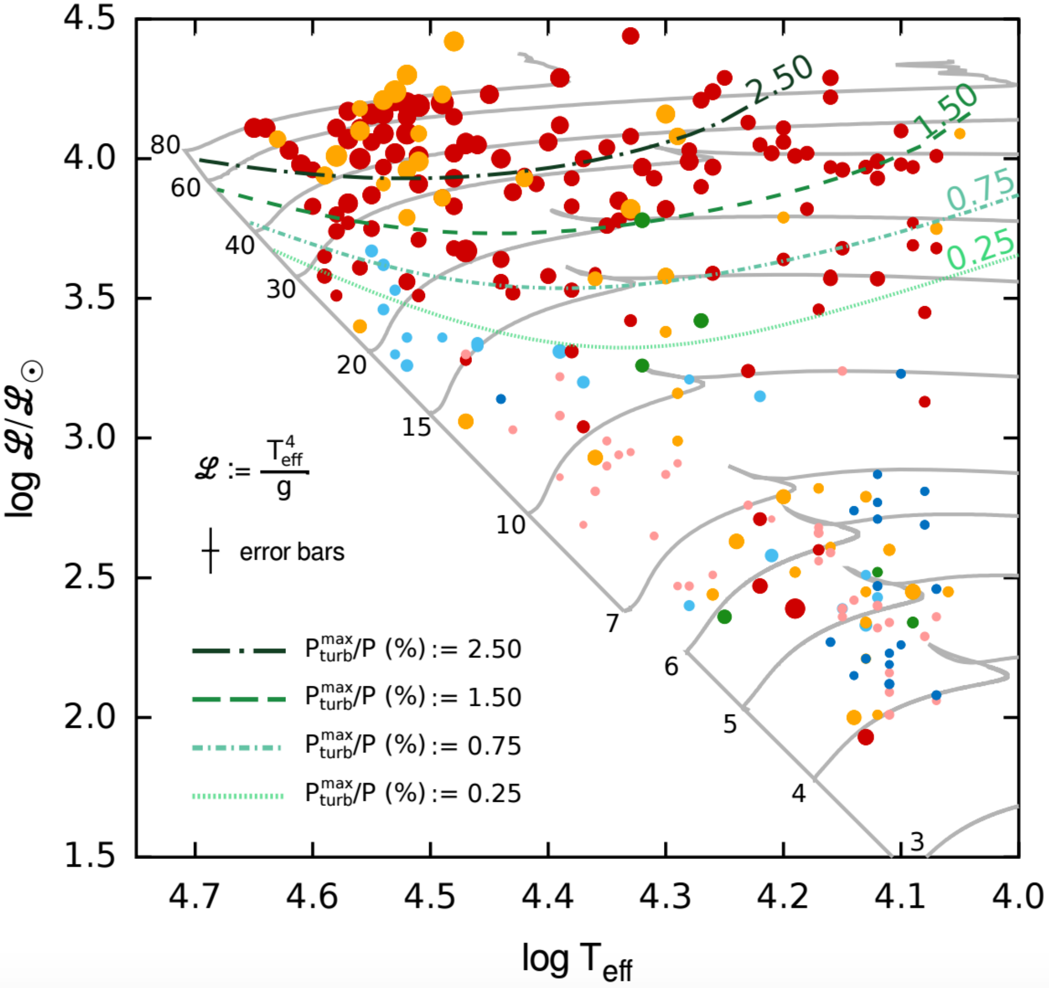


Jiang et al. 2015

Velocities ~ 50 km/s

Macroturbulent broadening in OB stars

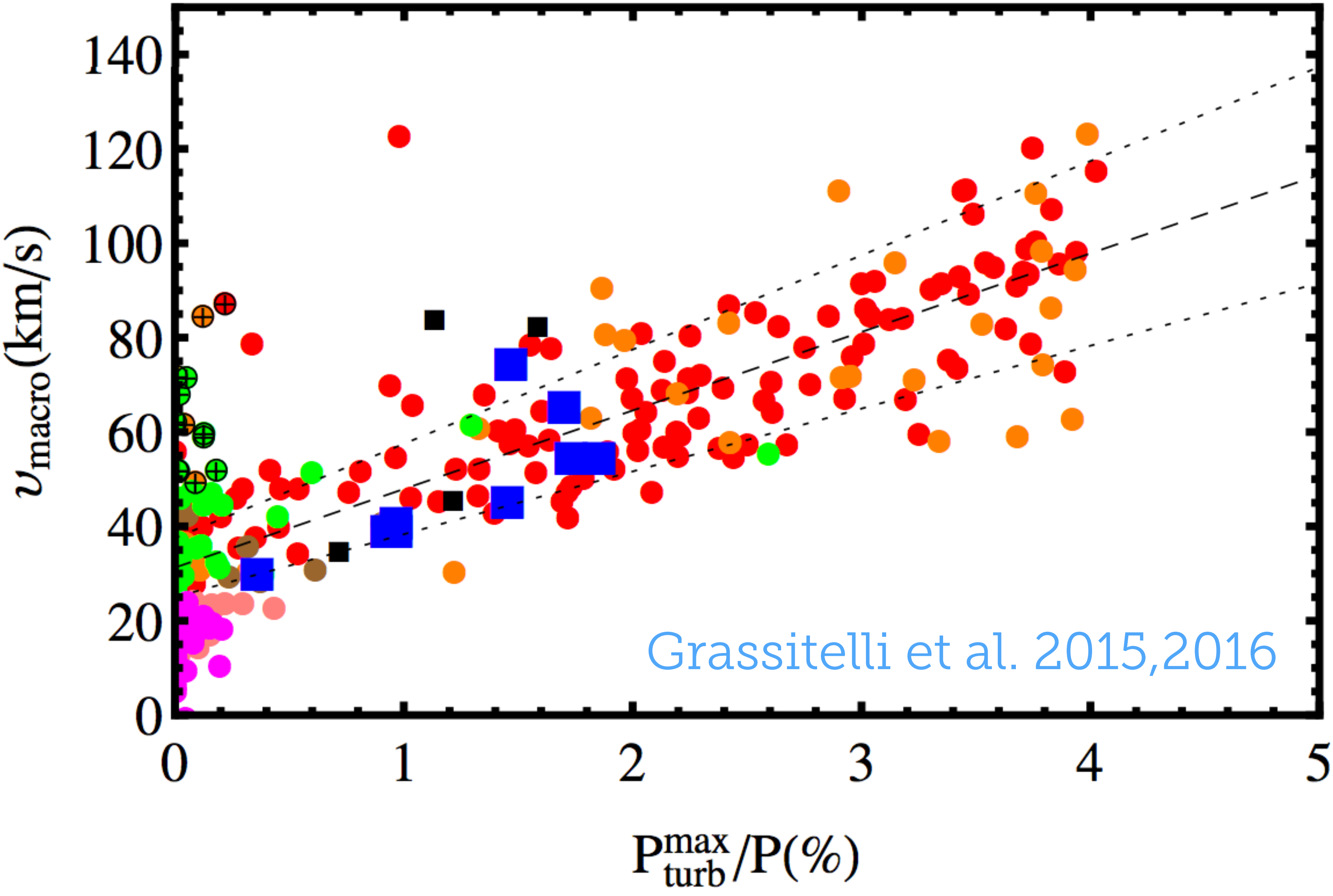




Simon-Diaz et al. 2017

Grassitelli et al. 2015,2016

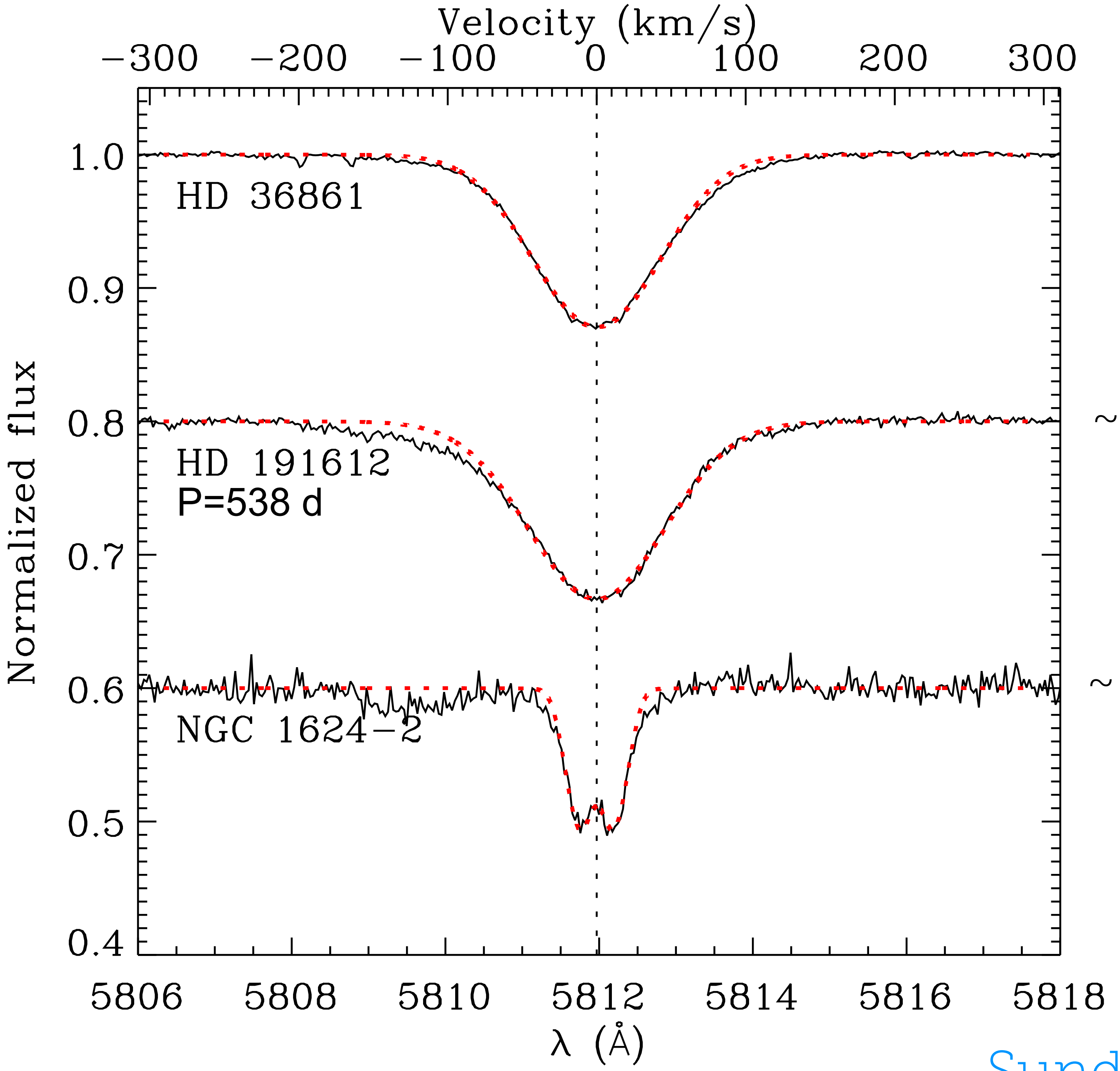
Inefficient Convection and Surface Velocity fields



Grassitelli et al. 2015,2016

Observations? Spectroscopy

C IV line



non-
magnetic

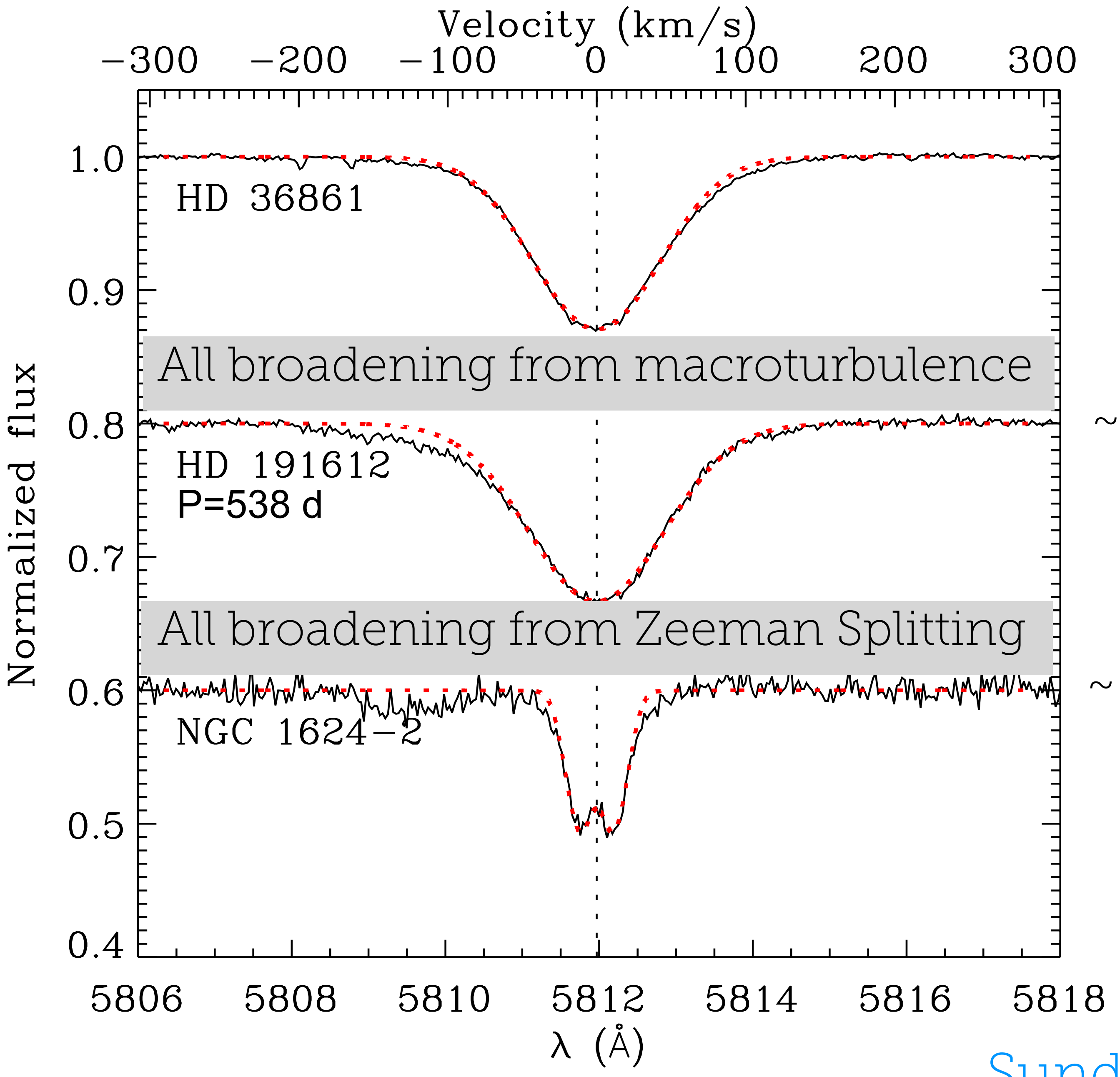
Dipole
~ 2.5 kG

Dipole
~ 20 kG

Sundqvist al. (2013)

Macroturbulence in magnetic OB stars

C IV line



All broadening from macroturbulence

All broadening from Zeeman Splitting

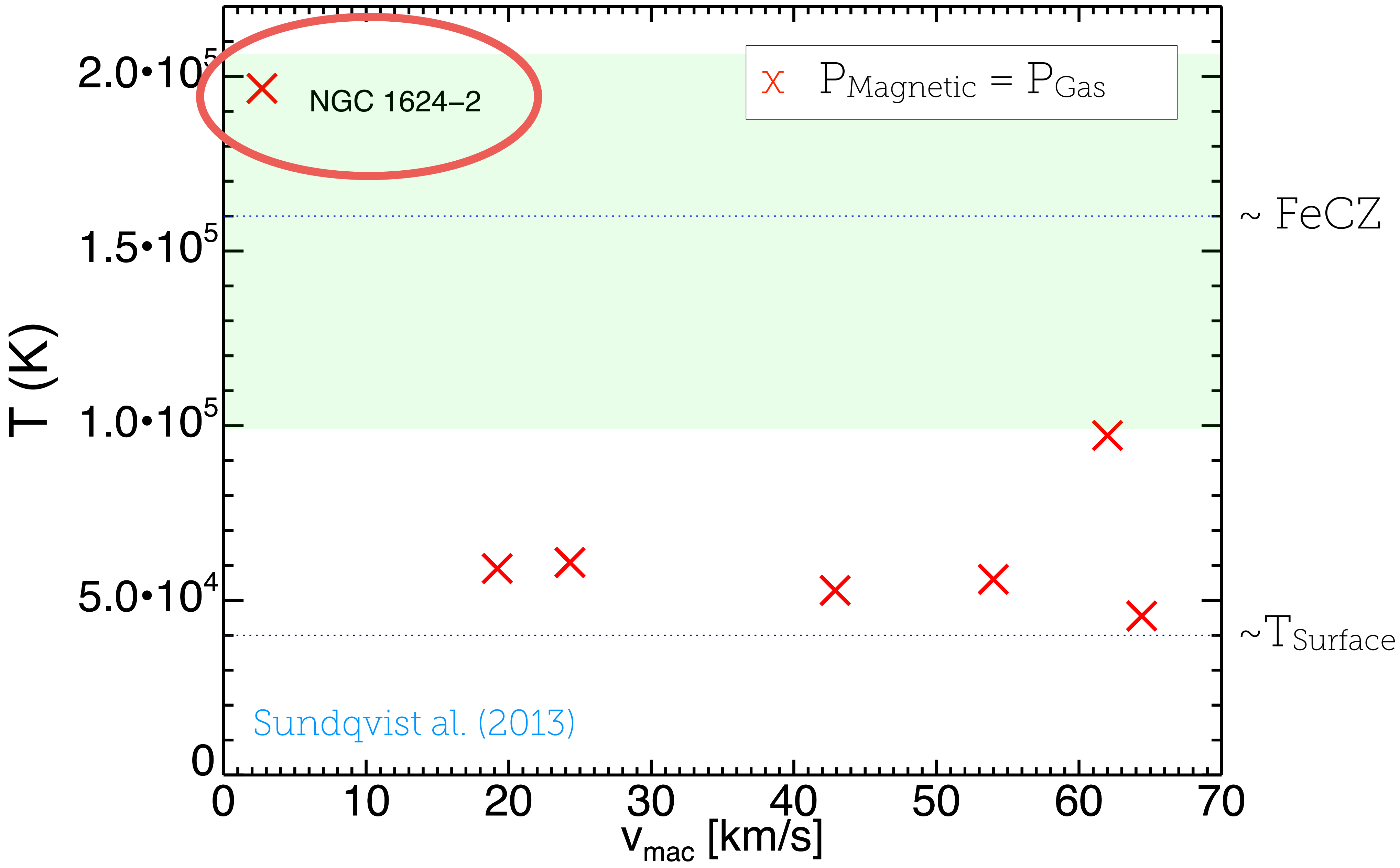
non-
magnetic

Dipole
~ 2.5 kG

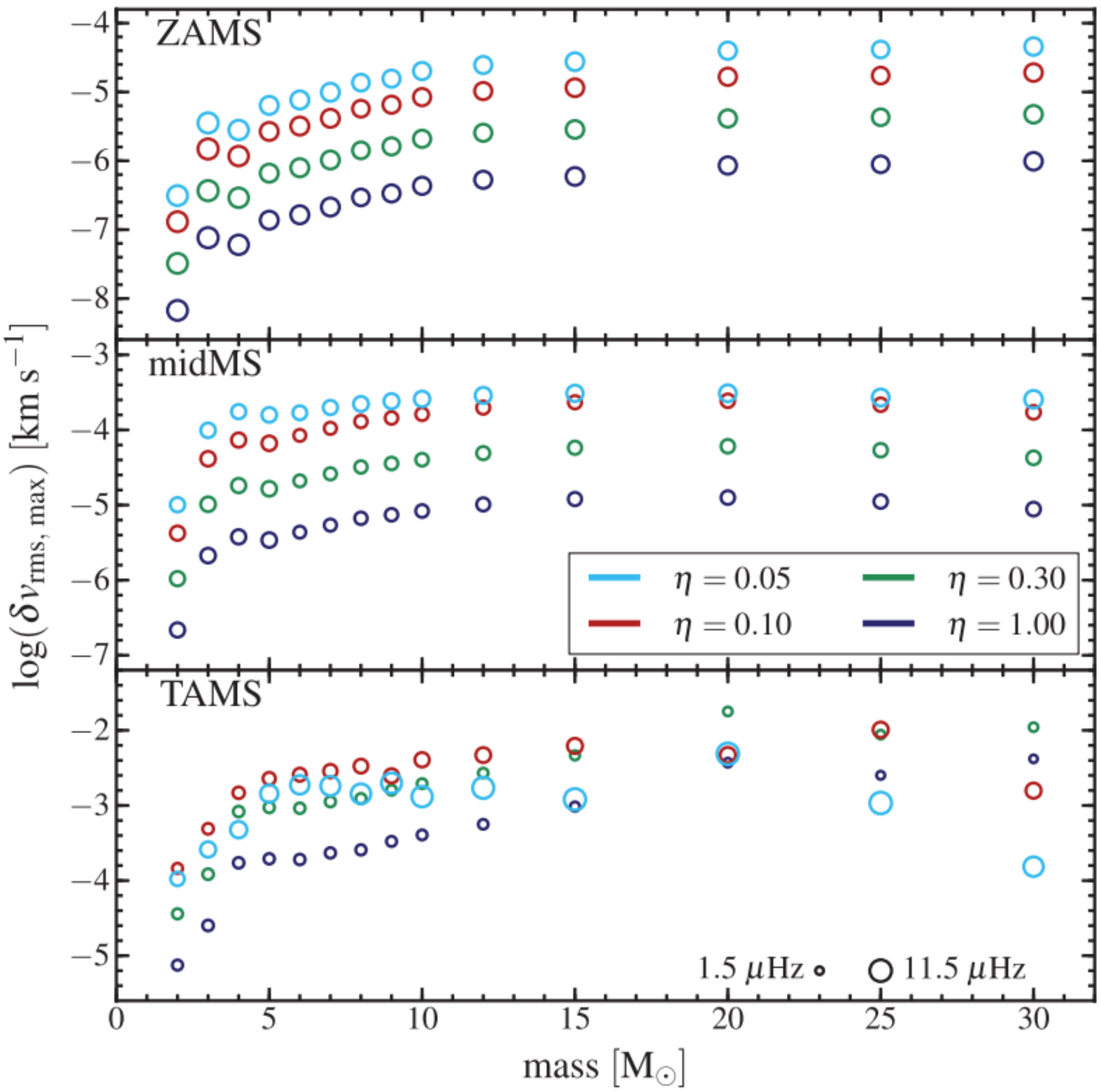
Dipole
~ 20 kG

Sundqvist al. (2013)

Macroturbulence in magnetic OB stars



Core IGWs or Sub-Surface Driving?



Surface velocity amplitudes from convectively excited g-modes are tiny

Shiode et al. 2013

Role of rotation neglected, but non-rotating stars also show large macroturbulent velocities

Summary

1. Iron opacity peak is responsible for inefficient convective regions close to the surface of massive stars
2. Density inversions observed in 1D codes are unstable in 3D
3. Porosity of density fluctuations reduce the effective radiation acceleration, but density inversions can persist in a time-averaged sense
4. Realistic stellar structures require implementing the porosity factor and calibrating MLT to the values observed in the 3D calculations
5. Radiation pressure dominated envelopes have time dependent, large amplitude oscillations. Could explain observed velocity fields (surface turbulence)

What’s Next

1. 3D->1D To improve predictions of massive star evolution
2. Effects of magnetic fields (Jiang et al. 2017)
3. Effects on line-driven winds (e.g. clumping)
4. Continuum driven winds / Eruptions?

Thanks!