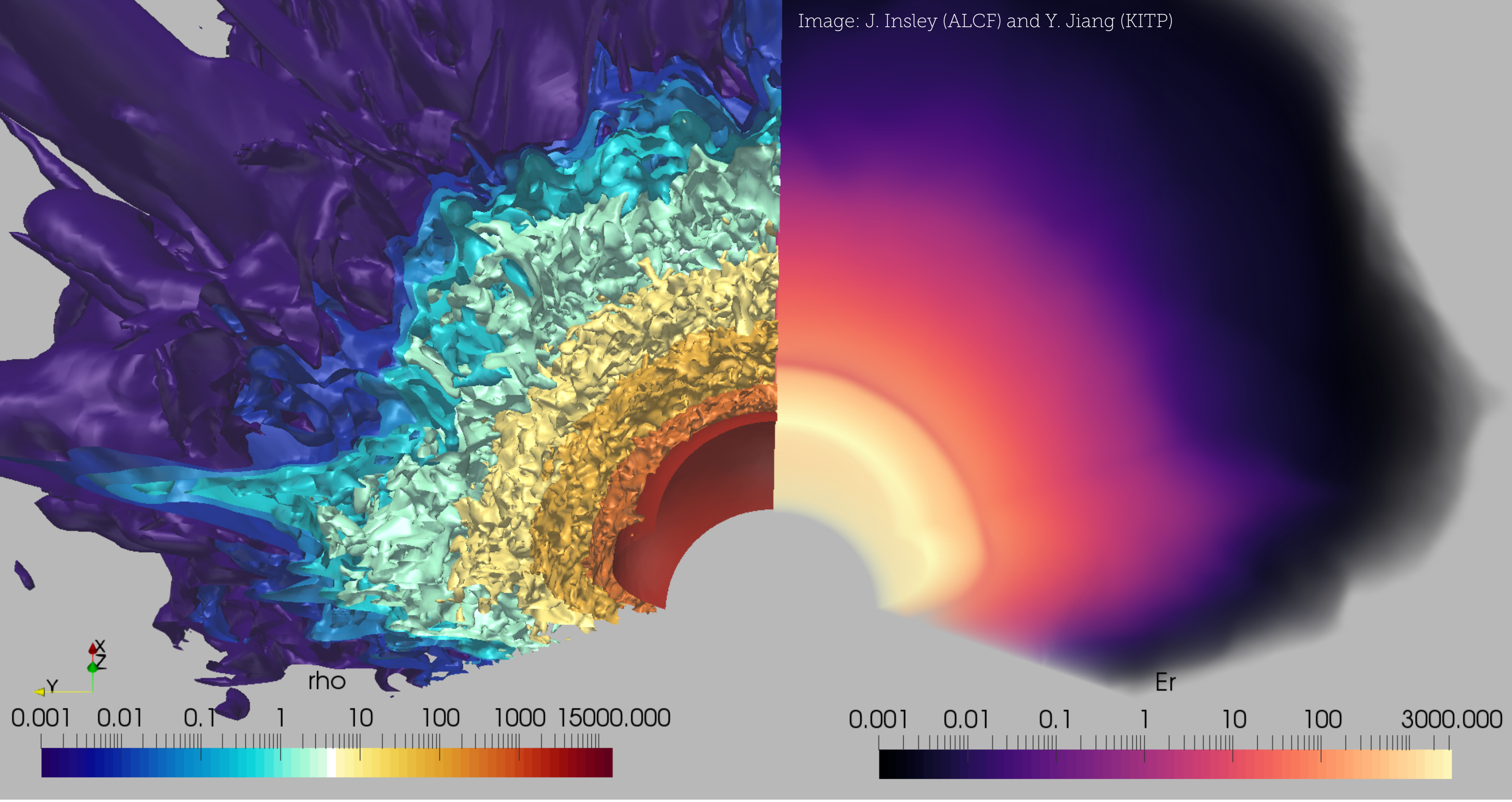


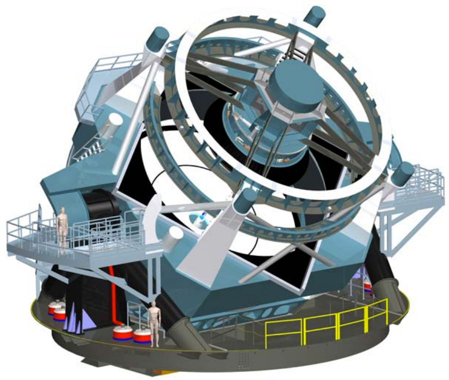
Local and Global Radiation Hydrodynamics Simulations of Massive Star Envelopes

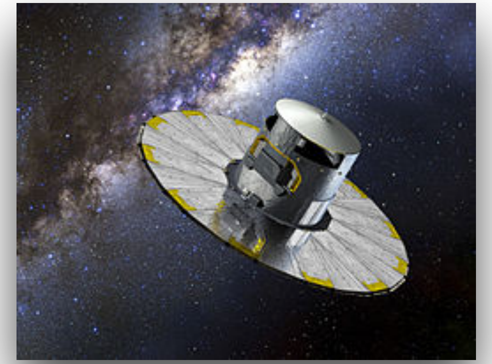
Matteo Cantiello (CCA, Flatiron Institute & Princeton University)

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

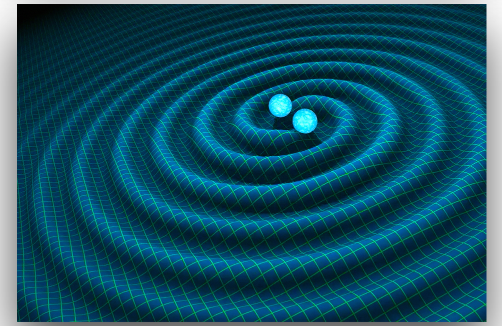
Exciting times for Stellar Physics

- 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





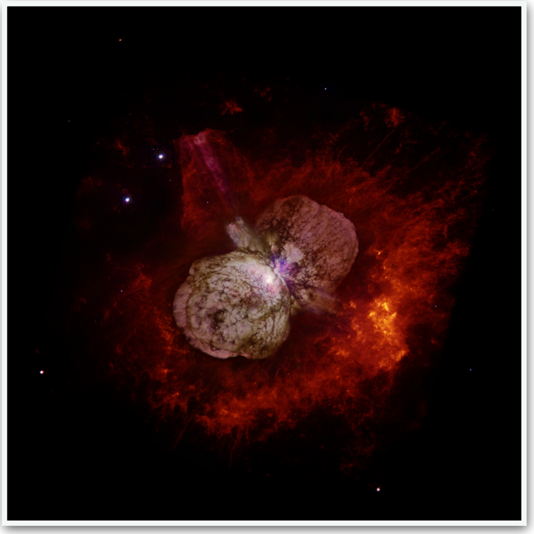
- We are entering the era of high precision stellar physics (Kepler, BRITE, K2, GAIA, TESS, PLATO). Theory is lagging behind



- Dawn of GW-Astronomy

Massive Stars Evolution: The most uncertain physics

- Stability and energy transport
- Mass loss (See e.g. J. Vink & E. Beasor's Talk)
- Rotation
- Magnetic Fields
- Binarity (Talks from Van Dyk, Hirai, Zapartas, Schneider...)

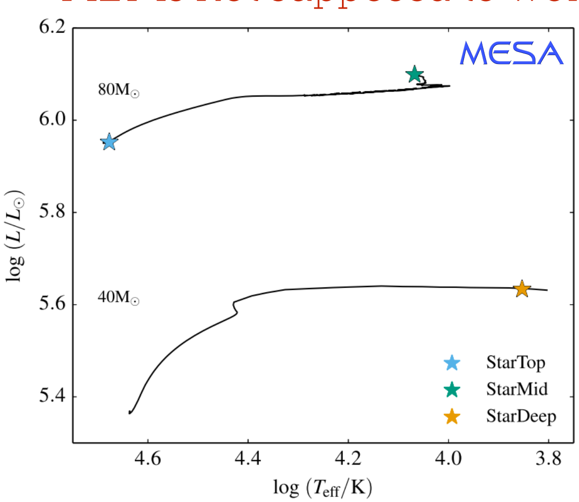


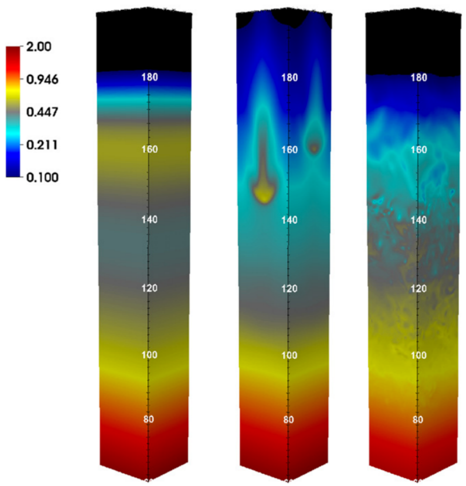
To Understand CCSNe, GRBs and LIGO GW sources we need to understand the structure, mass loss and binary interactions in massive stars

Stability and energy transport

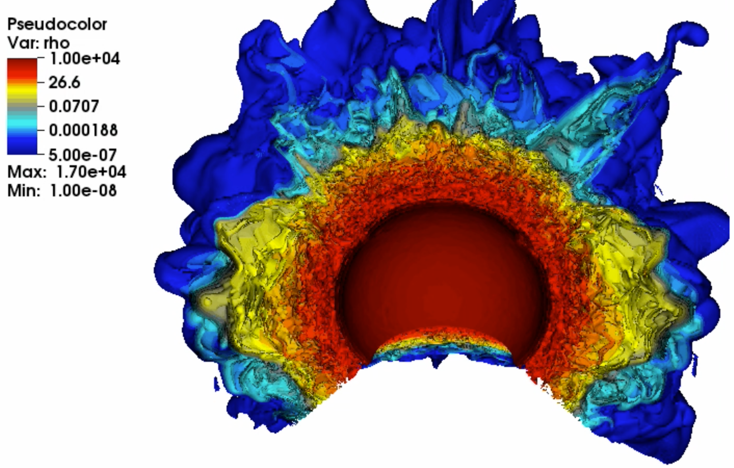
Q: How is the energy transported in massive stars envelopes?
(Impact on radii and stability)

MLT is not supposed to work!





3D Athena++, Radiation MHD



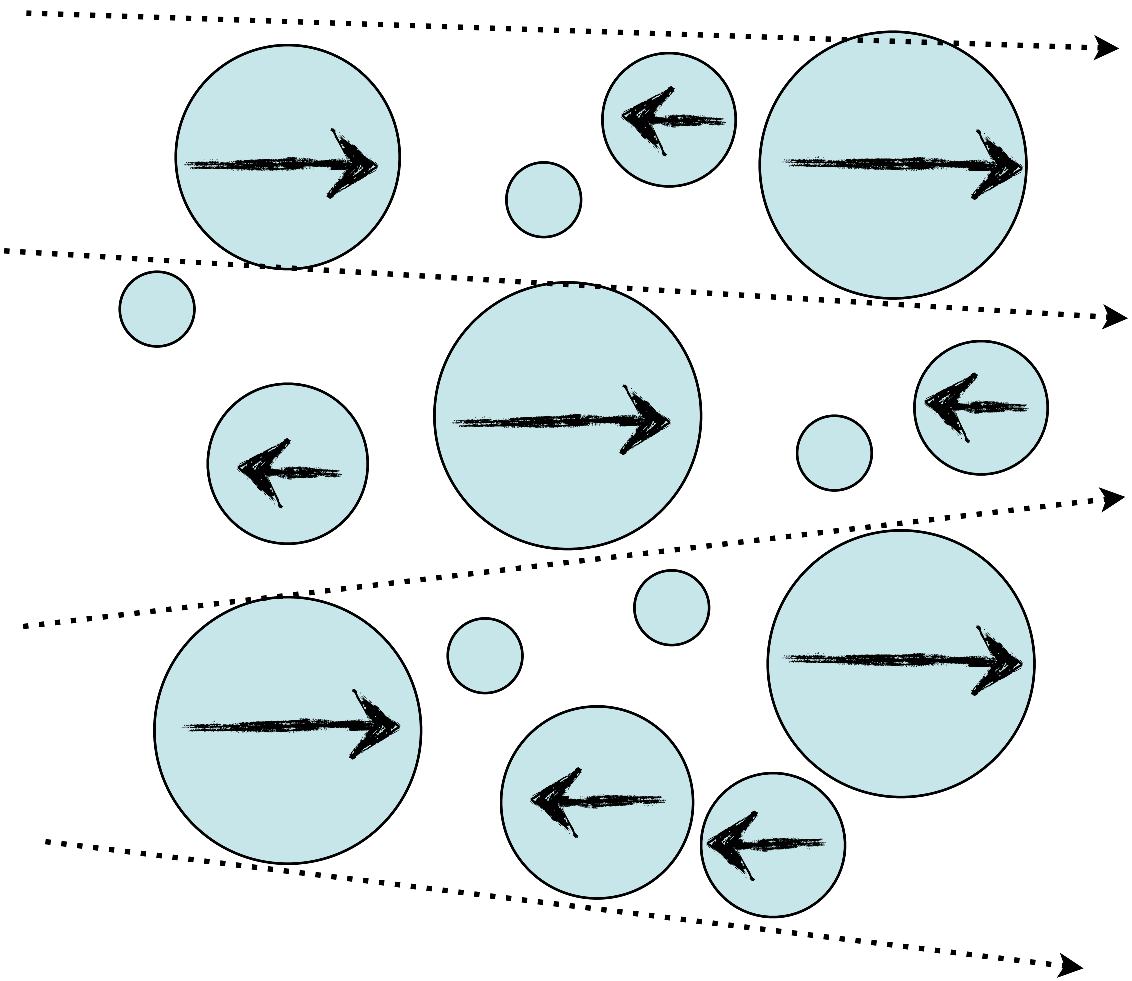
Jiang, MC et al. 2015, 2017

Radii Important to understand SN light curves
See e.g. Lars Bildsten's Talk

Massive Star Envelopes

- Massive stars can develop radiation dominated, loosely bound envelopes
  e.g Joss et al. 1973, Paxton et al. 2013
- In 1D models such envelopes are characterized by:
  - Superadiabatic Convection
  - Density Inversions (e.g. Grafener et al. 2012)
  - Gas Pressure Inversions
  - Envelope Inflation (e.g. Sanyal et al. 2015)
- What about 3D?

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

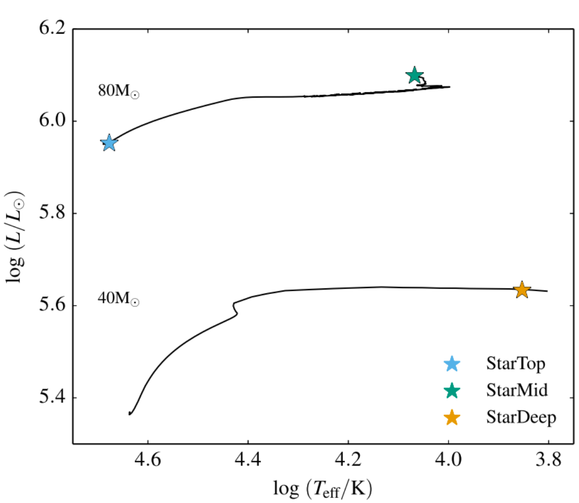
MLT is not supposed to work!

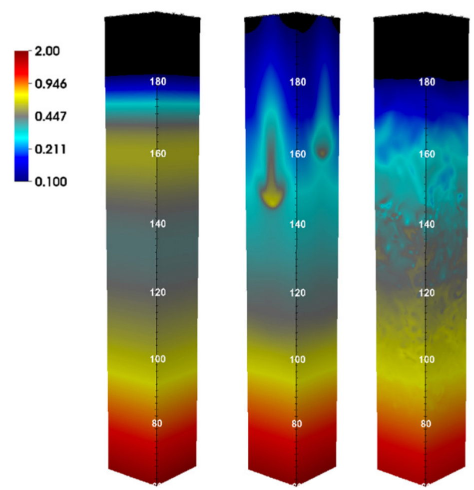
Stability and energy transport

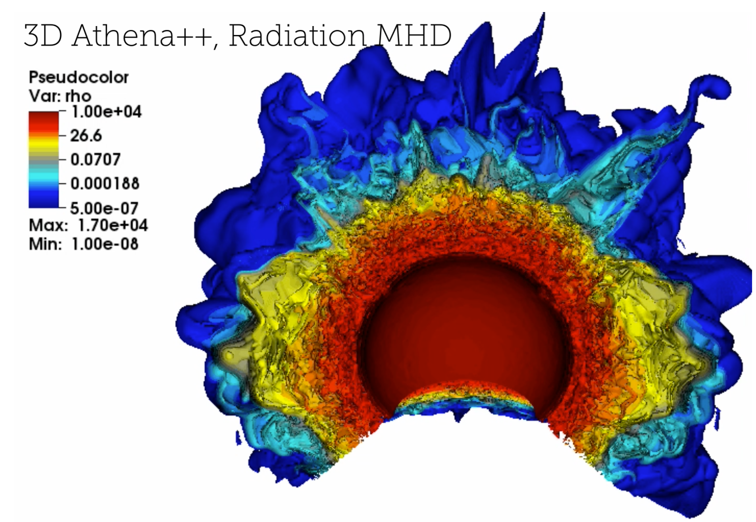
1D Stellar Evolution (MESA)

3D Local Radiation MHD (ATHENA)

3D Global Radiation MHD (ATHENA++)

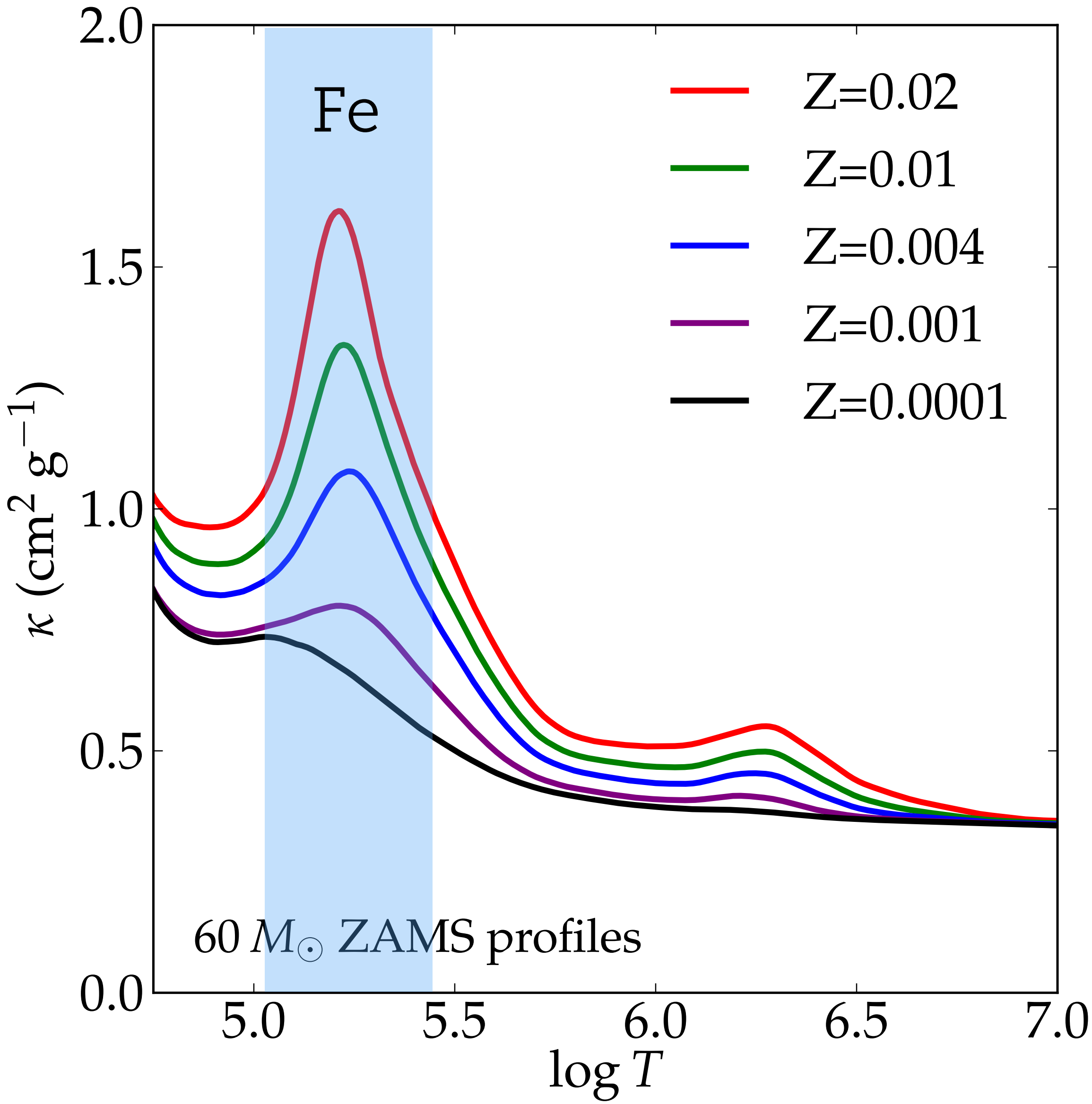






Jiang, MC et al. 2015, 2017

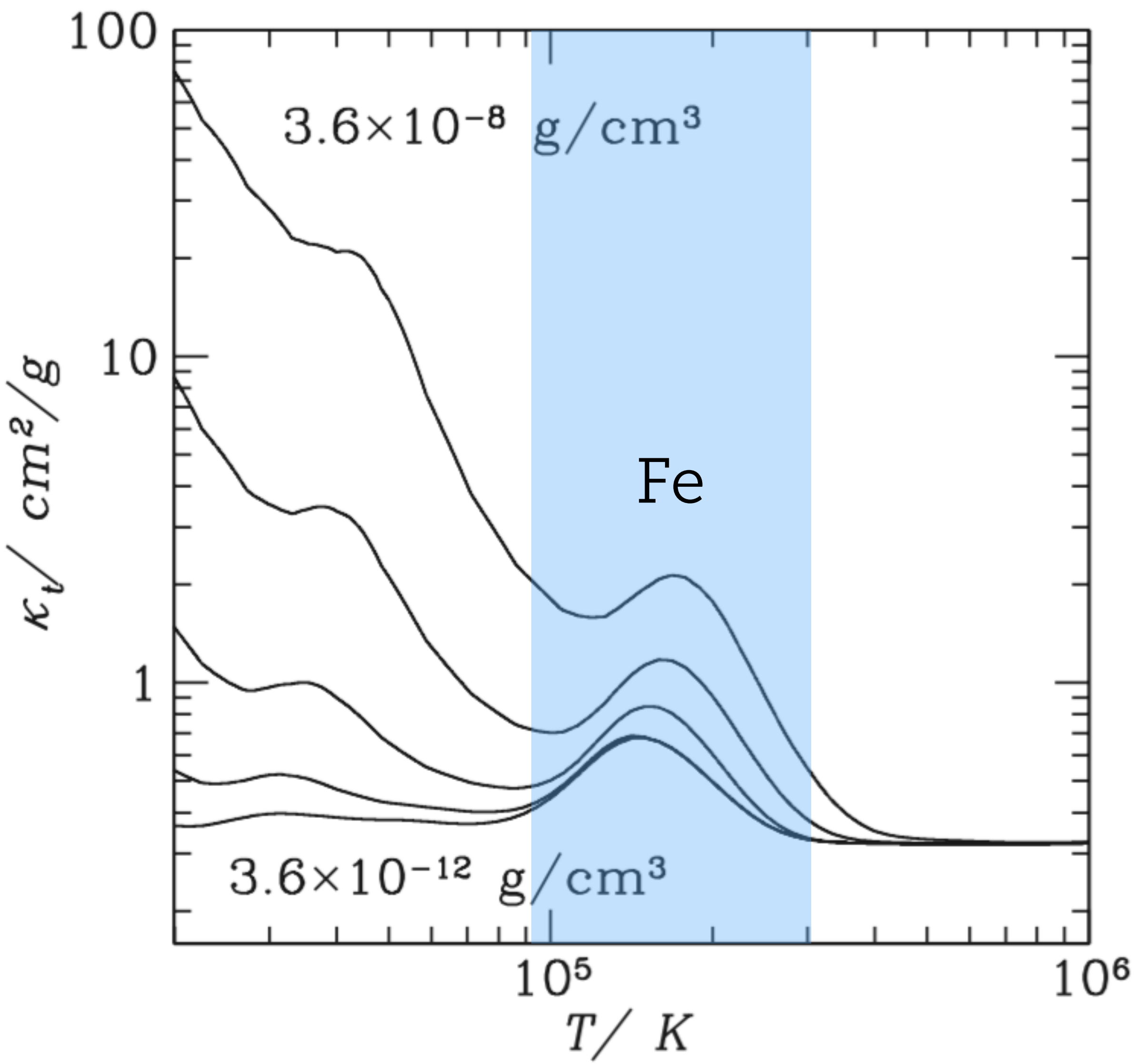
The Opacity: Iron Peak



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

Strong Metallicity Dependence

The Opacity: Iron Peak



Jiang, MC et al. 2015

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

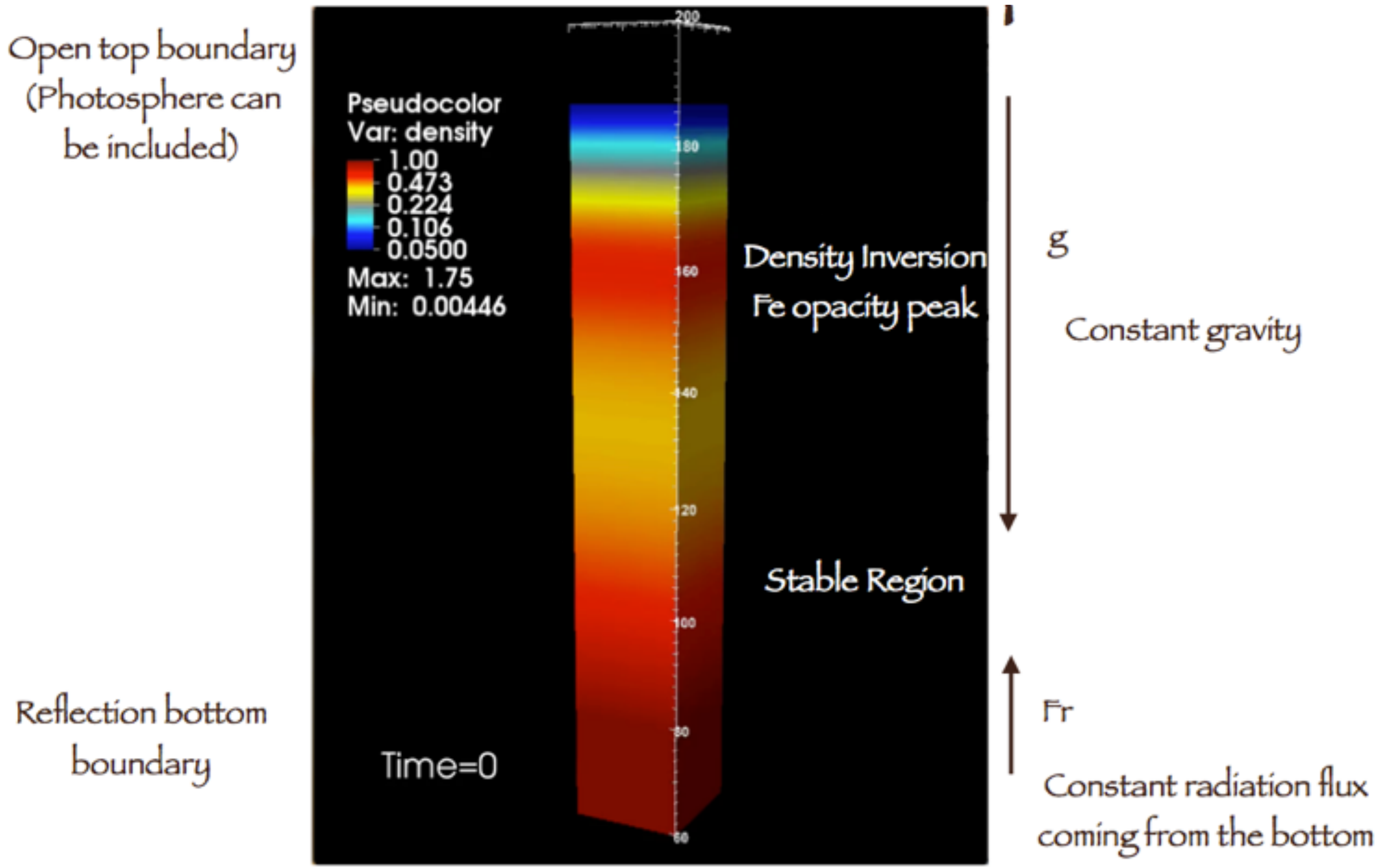
3D Radiation Hydro Calculations:

Energy Transport & Stability

Simulations Setup

ATHENA with VET Radiation Module

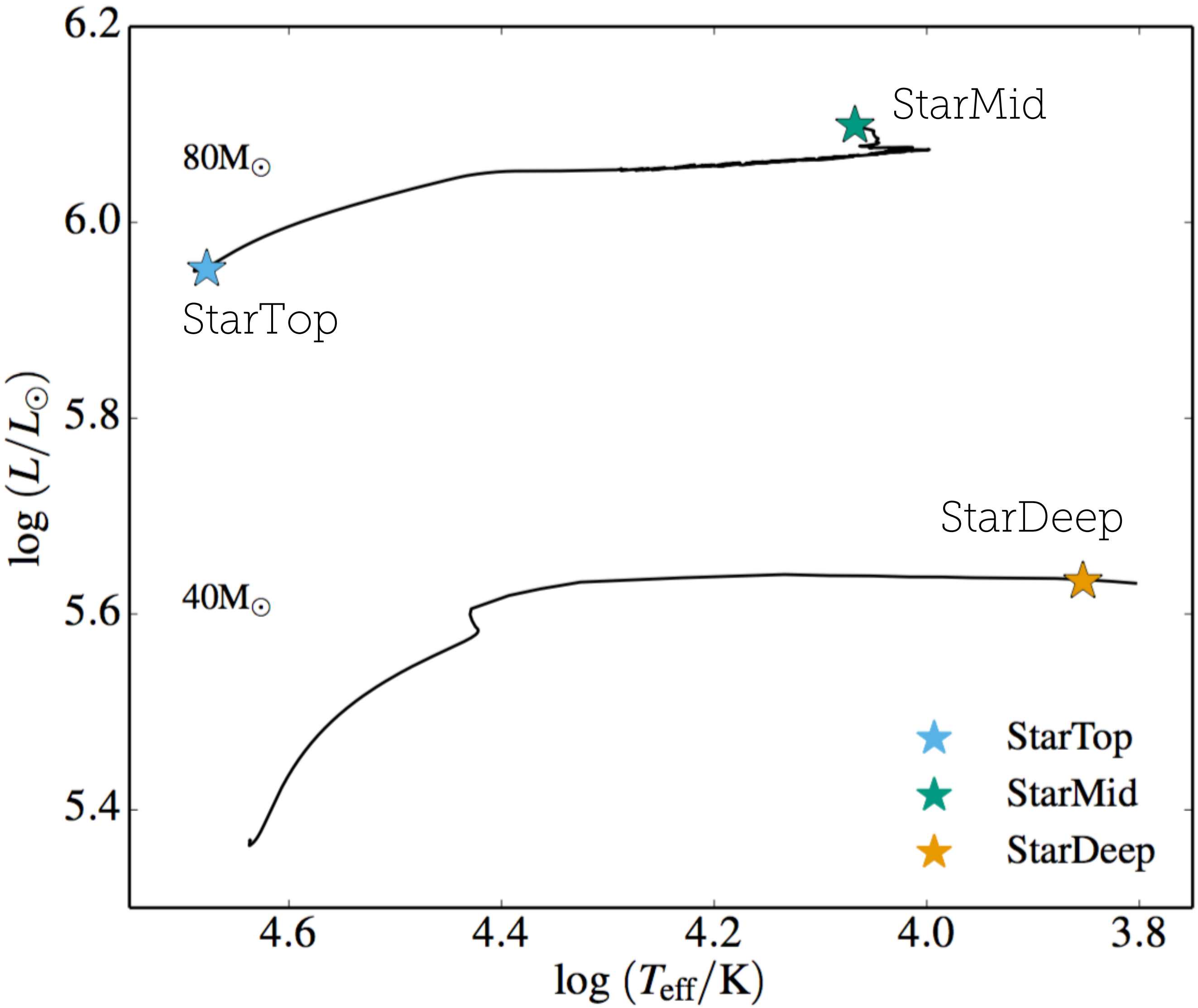
Davis et al. 2014
Jiang et al. 2014
Jiang, MC et al. 2015



Initial Conditions

Jiang, MC et al. 2015

Guided from MESA 1D models



Initial Conditions

Jiang, MC et al. 2015

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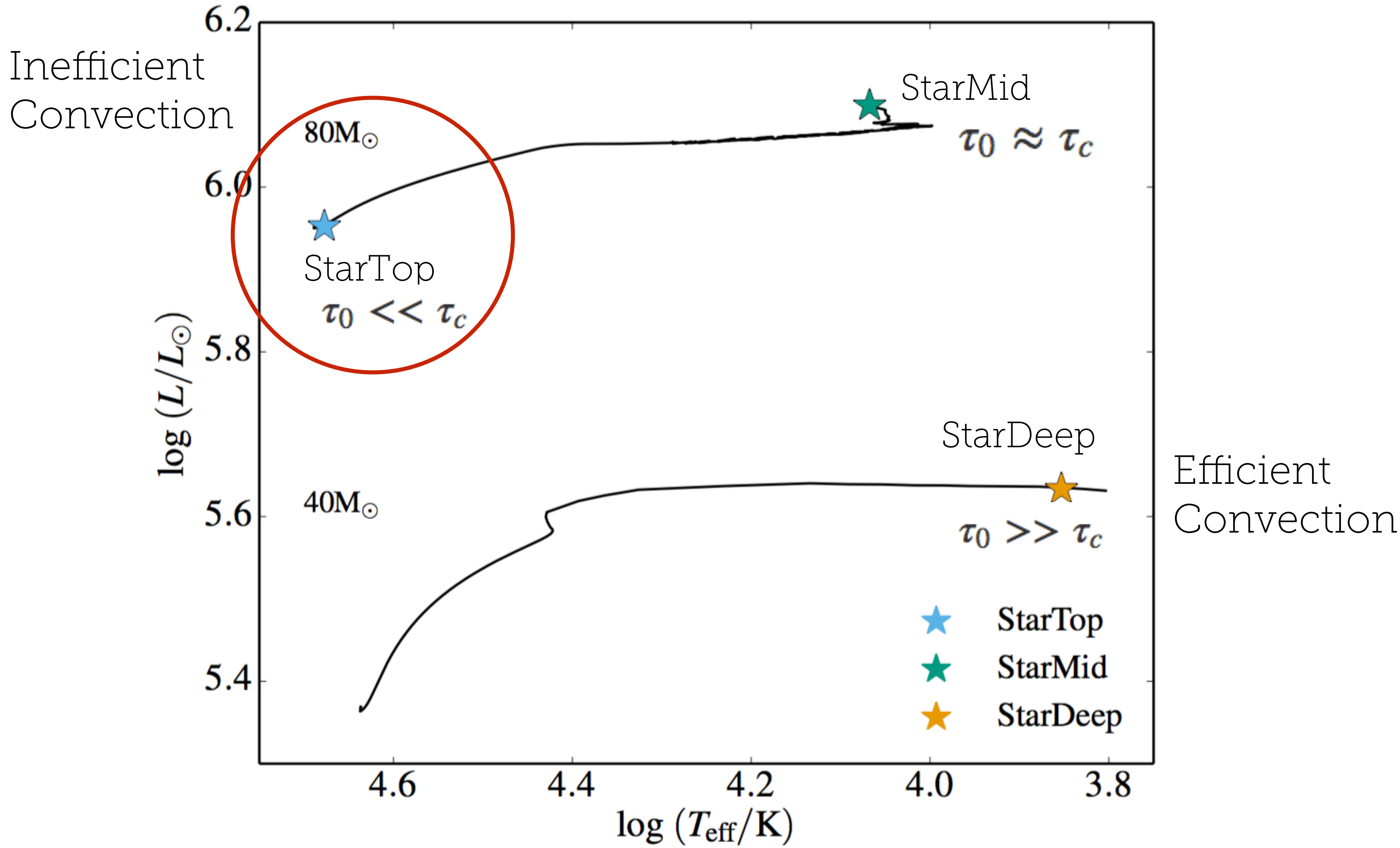
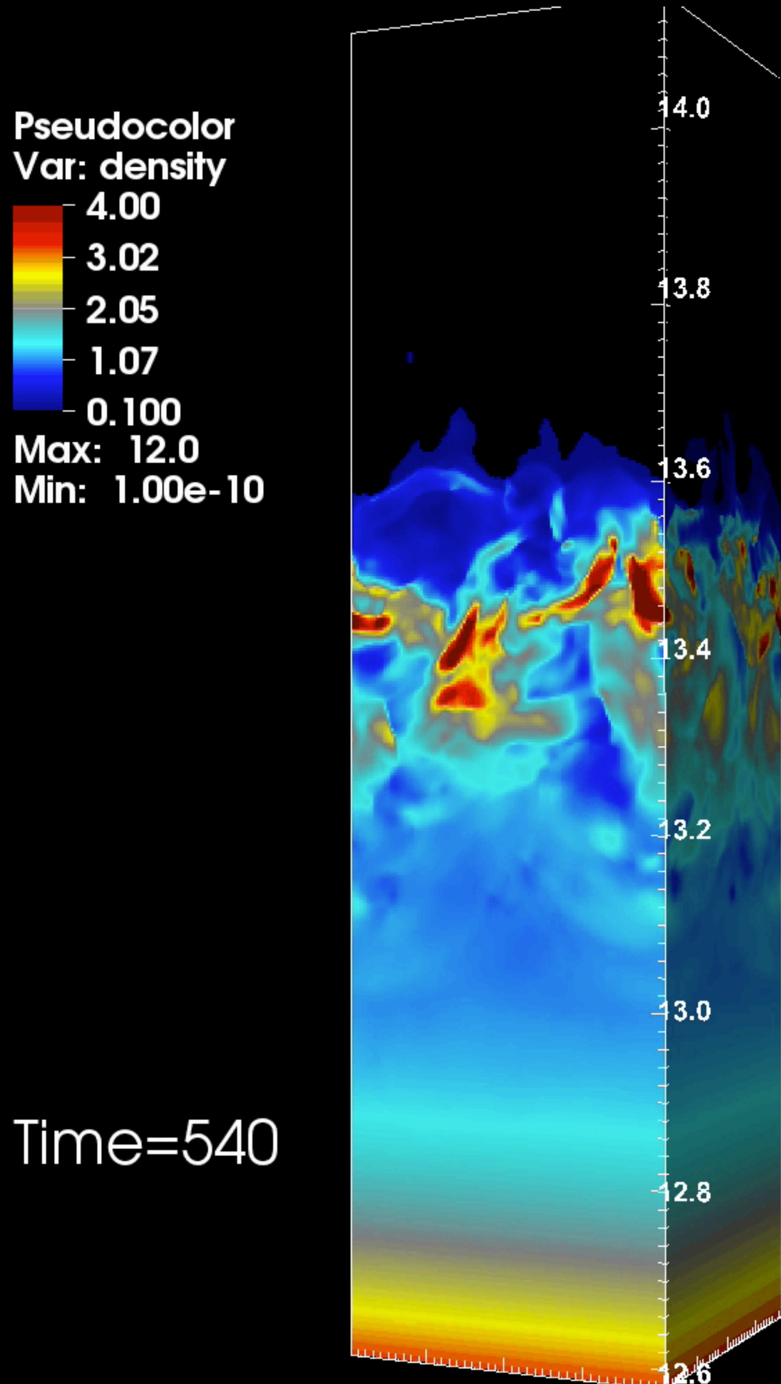




STARTOP

The case with inefficient convection

$\tau_0 \ll \tau_c$

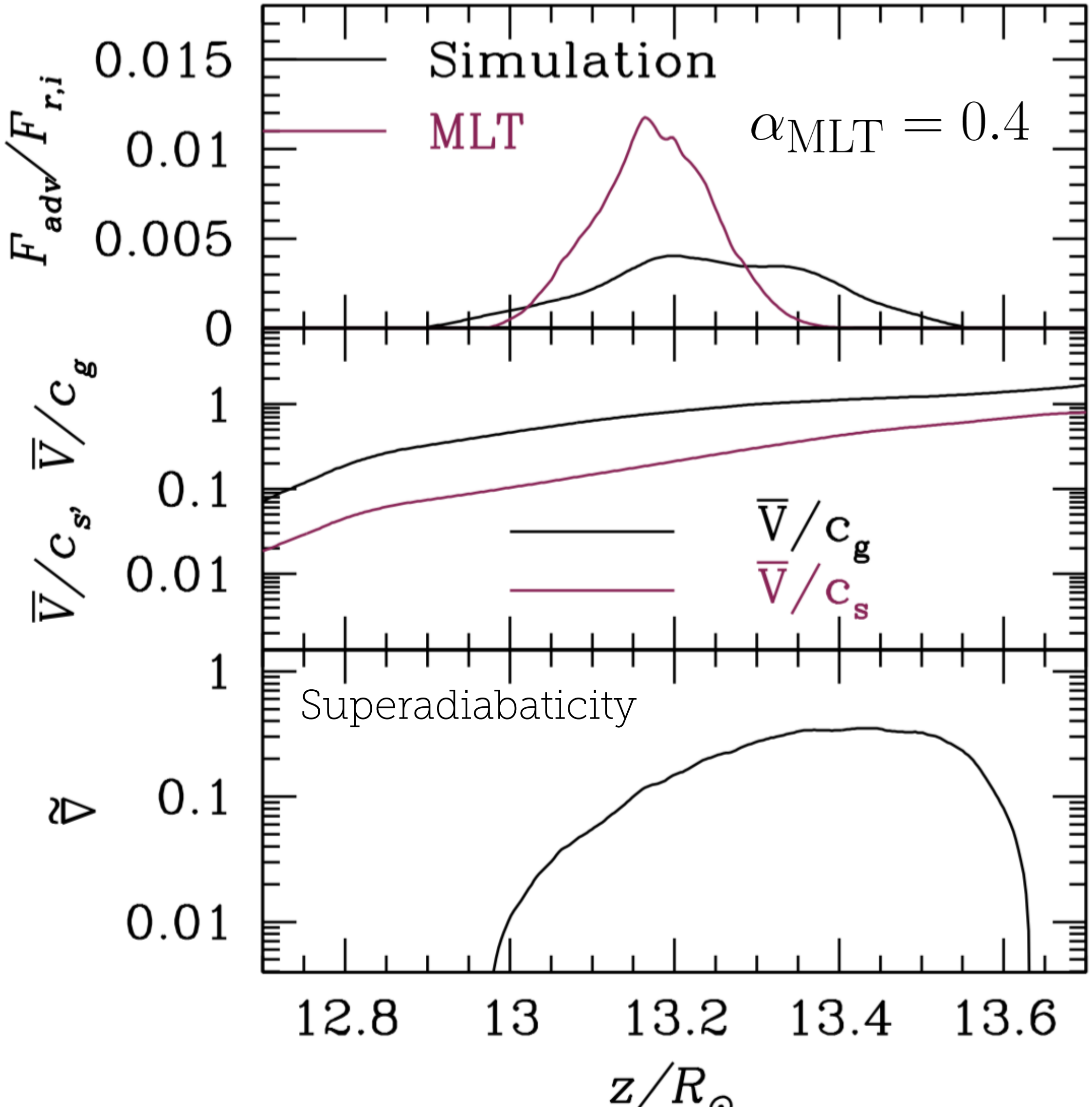
Variables/Units	StarTop
$r_0/r_\odot$	13.6
T_0/K	1.57×10^5
$\rho_0/(\mathrm{g\ cm^{-3}})$	5.52×10^{-9}
$g/(\mathrm{cm\ s^{-2}})$	1.17×10^4
$F_{r,i}/(\mathrm{erg\ cm^{-2}\ s^{-1}})$	3.06×10^{14}
H_0/cm	2.37×10^{10}
t_0/s	1.42×10^3
$\tau_c \equiv c/c_{g,0}$	6.54×10^3
τ_0	166.5
$P_{r,0}/P_0$	13.22
$L_{x,y}/H_0$	1.17
L_z/H_0	4.60
$N_{x,y}$	128
N_z	512

Jiang, MC et al. 2015

STARTOP

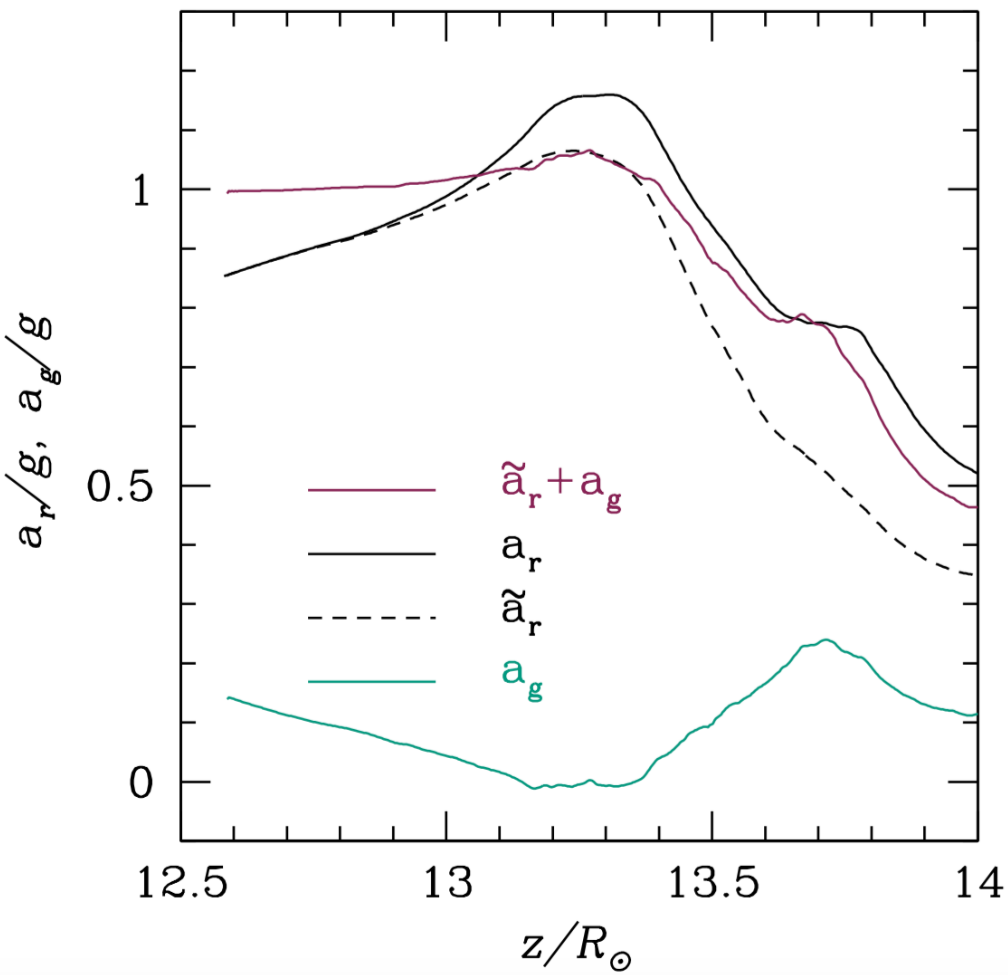
Jiang, MC et al. 2015

The case with inefficient convection



$\tau_0 \ll \tau_c$

The Porosity Factor



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

Density weighted radiation acceleration

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

Jiang, MC et al. 2015

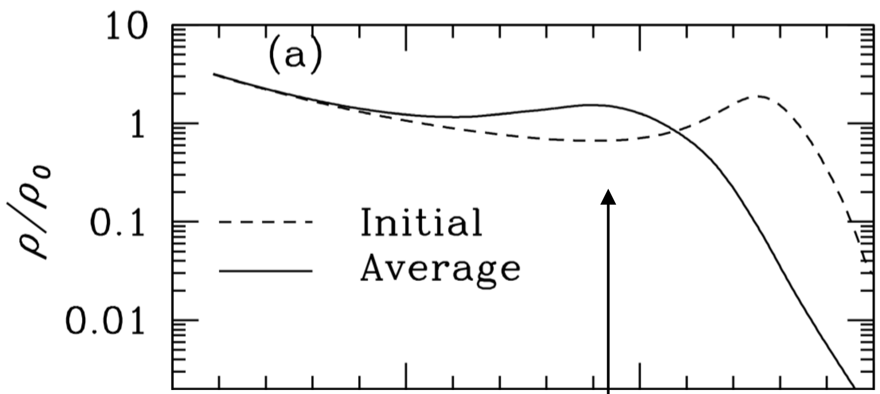
See e.g. Owocki et al. 2004

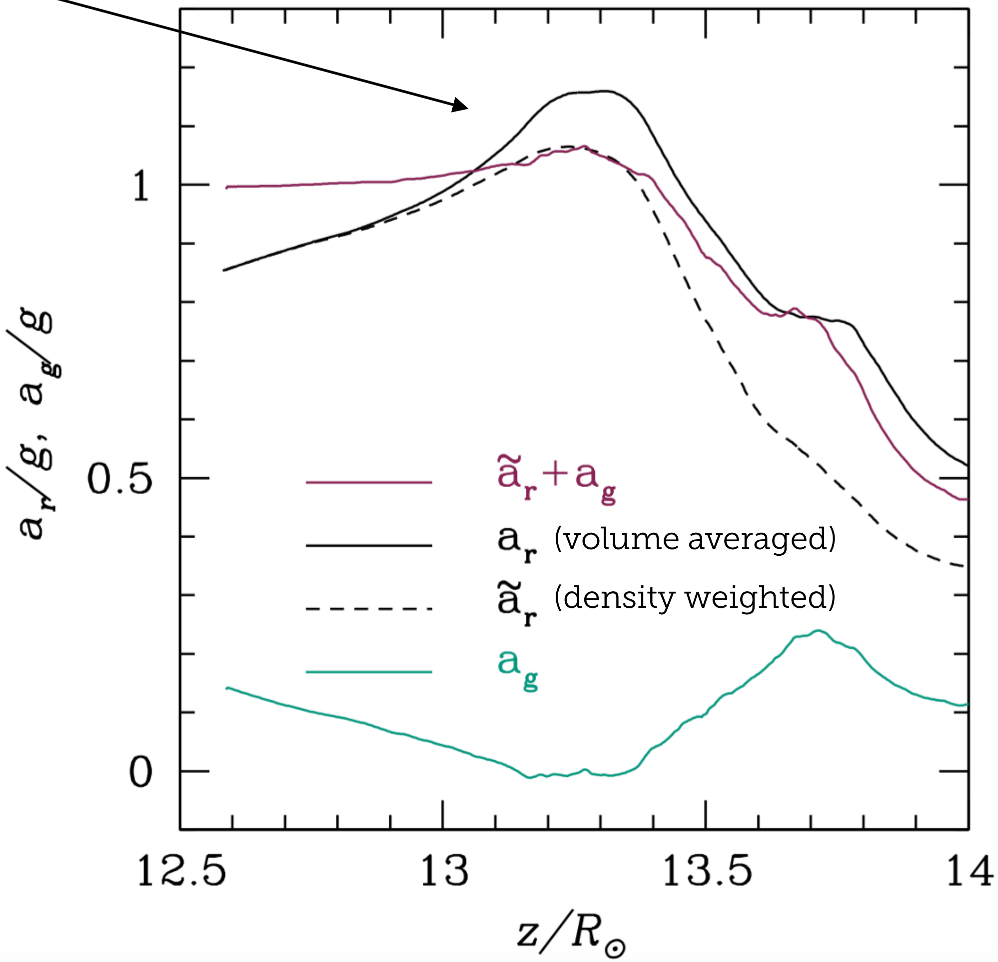
STARTOP

The case with inefficient convection

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

$\tau_0 \ll \tau_c$





Density Inversion still present (in average)

Jiang, MC et al. 2015

3D -> 1D

The Porosity Factor:

Preliminary 1D implementation

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

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

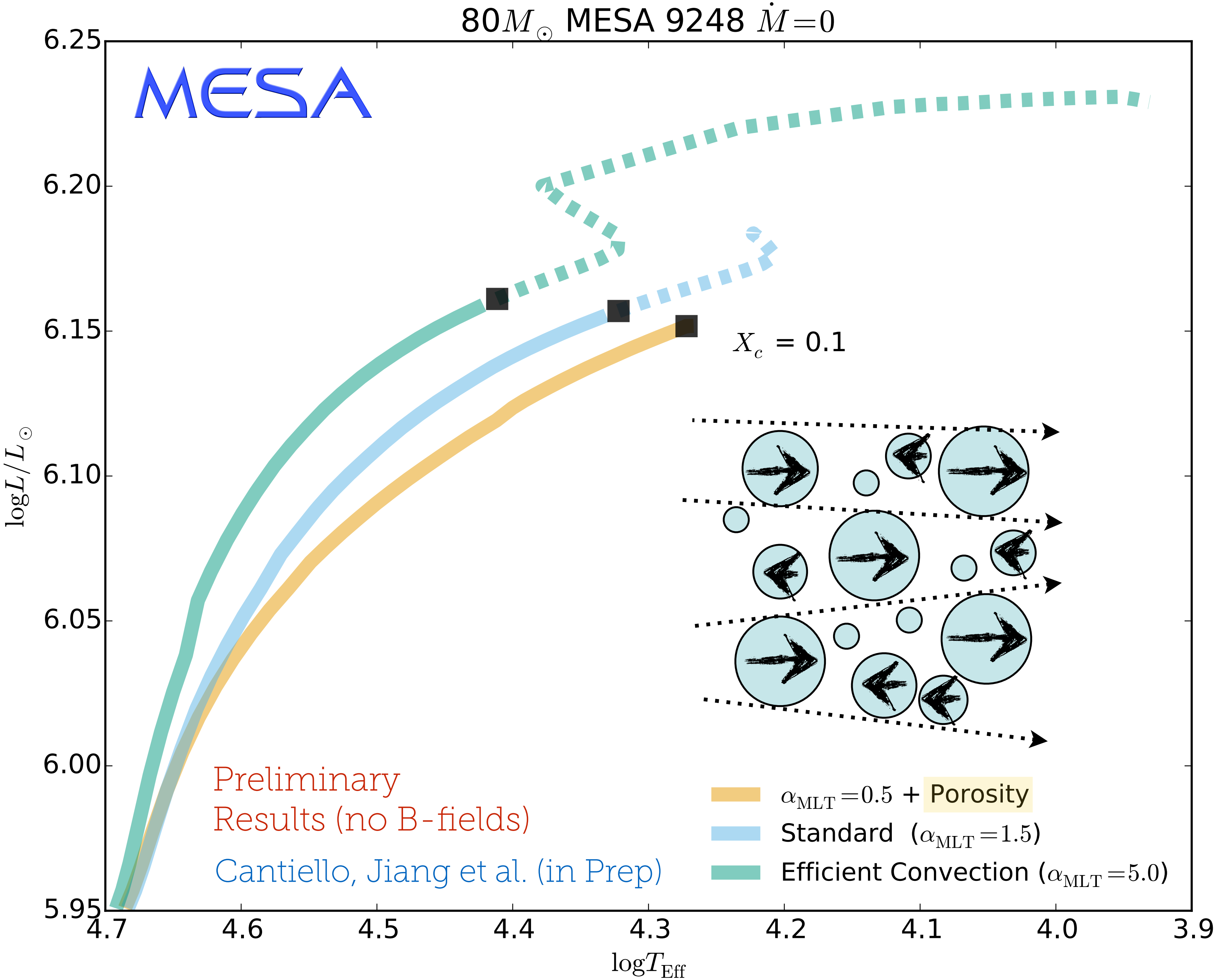
Larger in the presence of B-fields (0.6-1.0)
Jiang, MC et al. 2017

- Include Porosity Factor (Calibrated from ATHENA calculations)

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

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

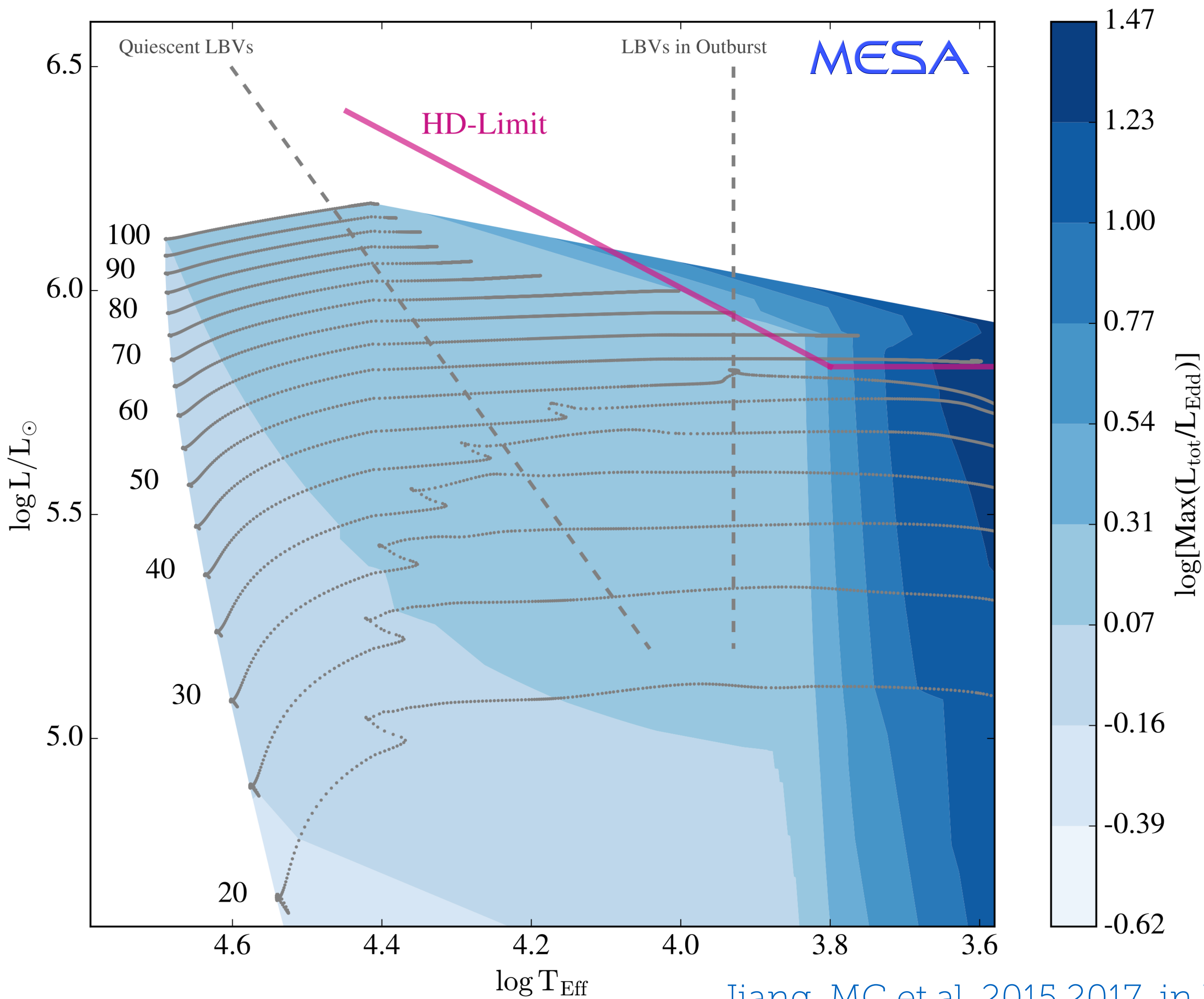
Cantiello, Jiang et al. (in Prep)



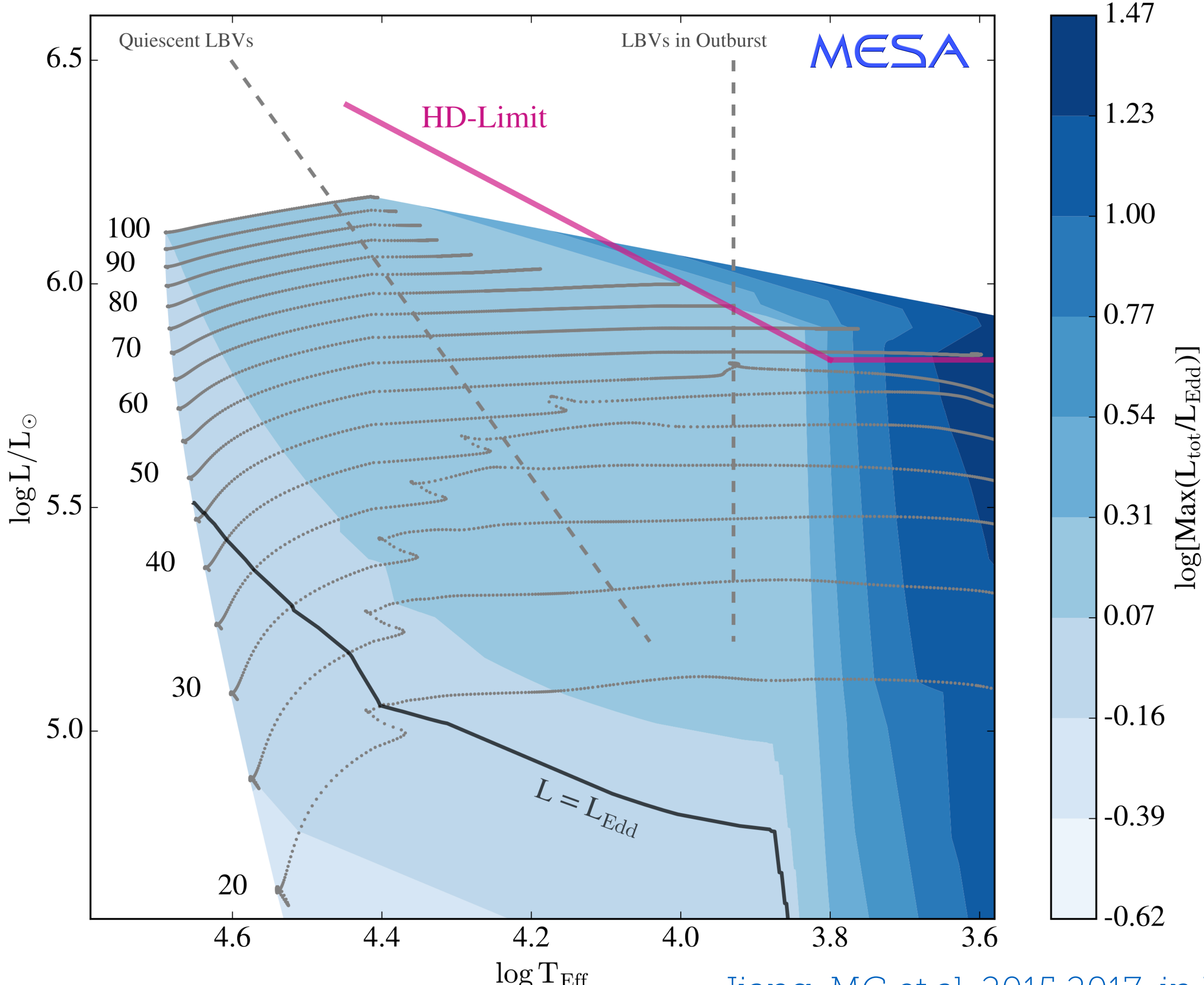
$80 M_\odot$ MESA 9248 $\dot{M}=0$
MESA
X_c = 0.1
Preliminary
Results (no B-fields)
Cantiello, Jiang et al. (in Prep)
$\alpha_{\rm MLT}=0.5$ + Porosity
Standard ($\alpha_{\rm MLT}=1.5$)
Efficient Convection ($\alpha_{\rm MLT}=5.0$)
$\log L/L_\odot$
$\log T_{\rm Eff}$
6.25
6.20
6.15
6.10
6.05
6.00
5.95
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9

3D Radiation Hydro Calculations:

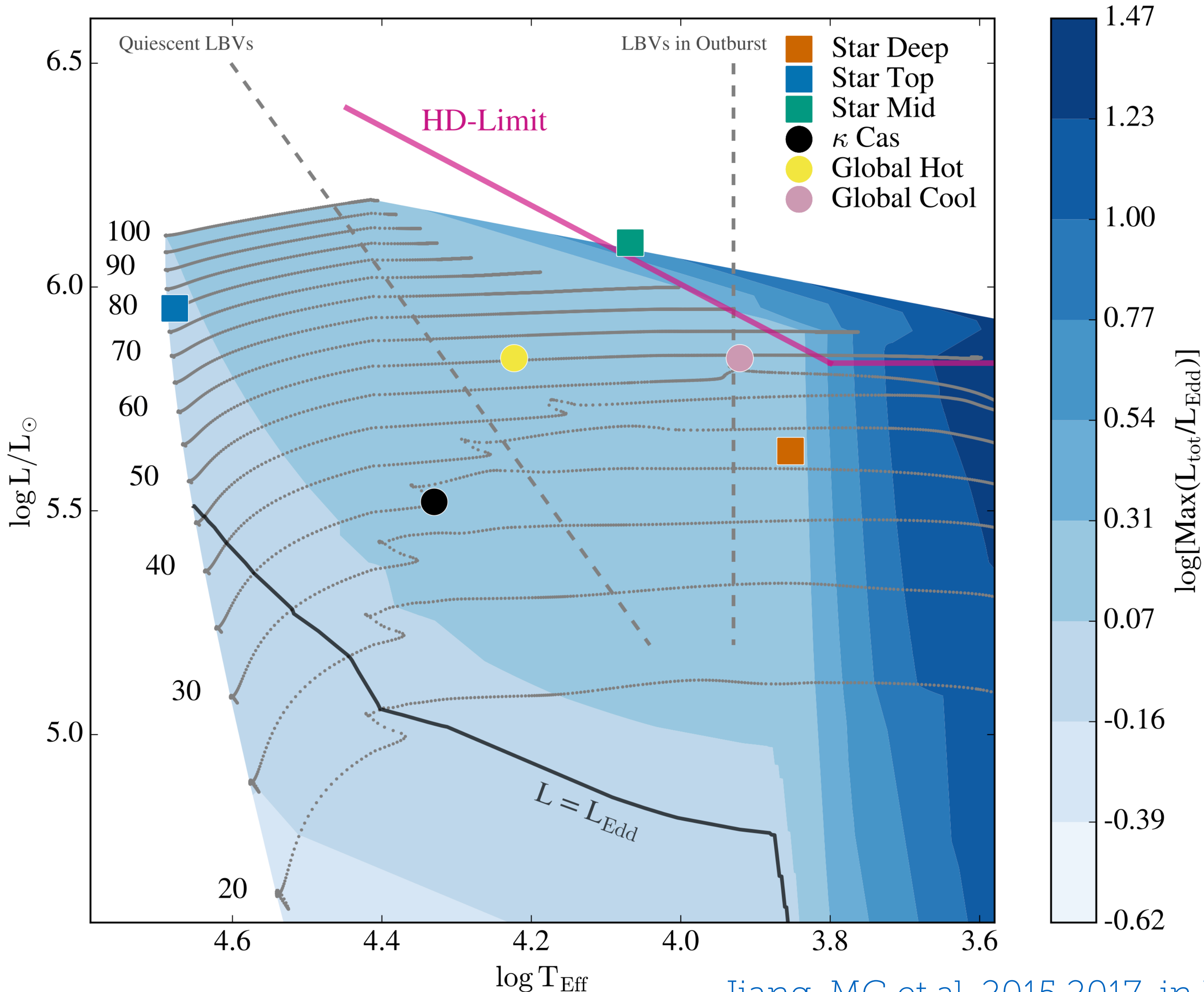
Global Calculations and Mass Loss



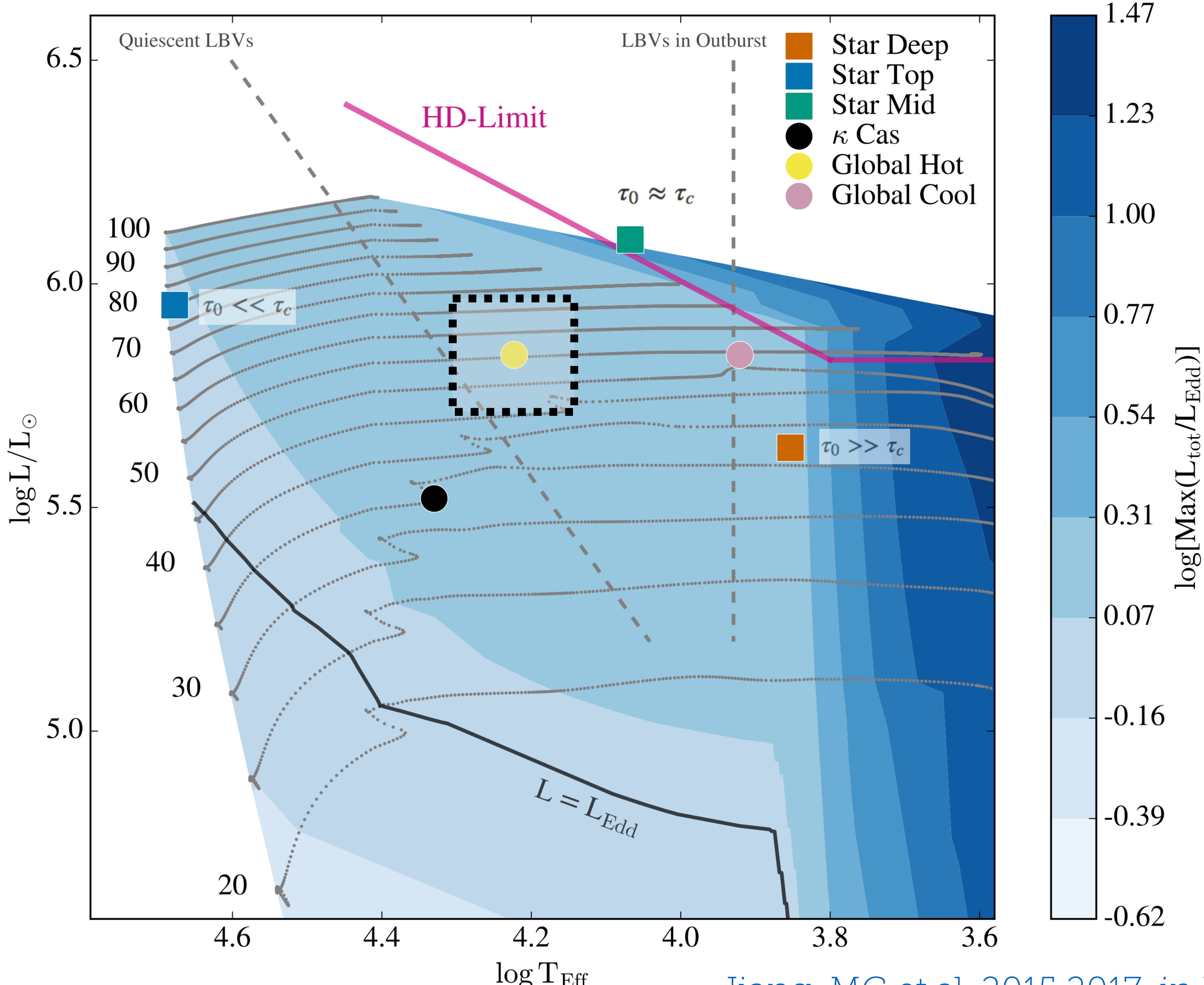
Jiang, MC et al. 2015,2017, in Prep



Jiang, MC et al. 2015,2017, in Prep



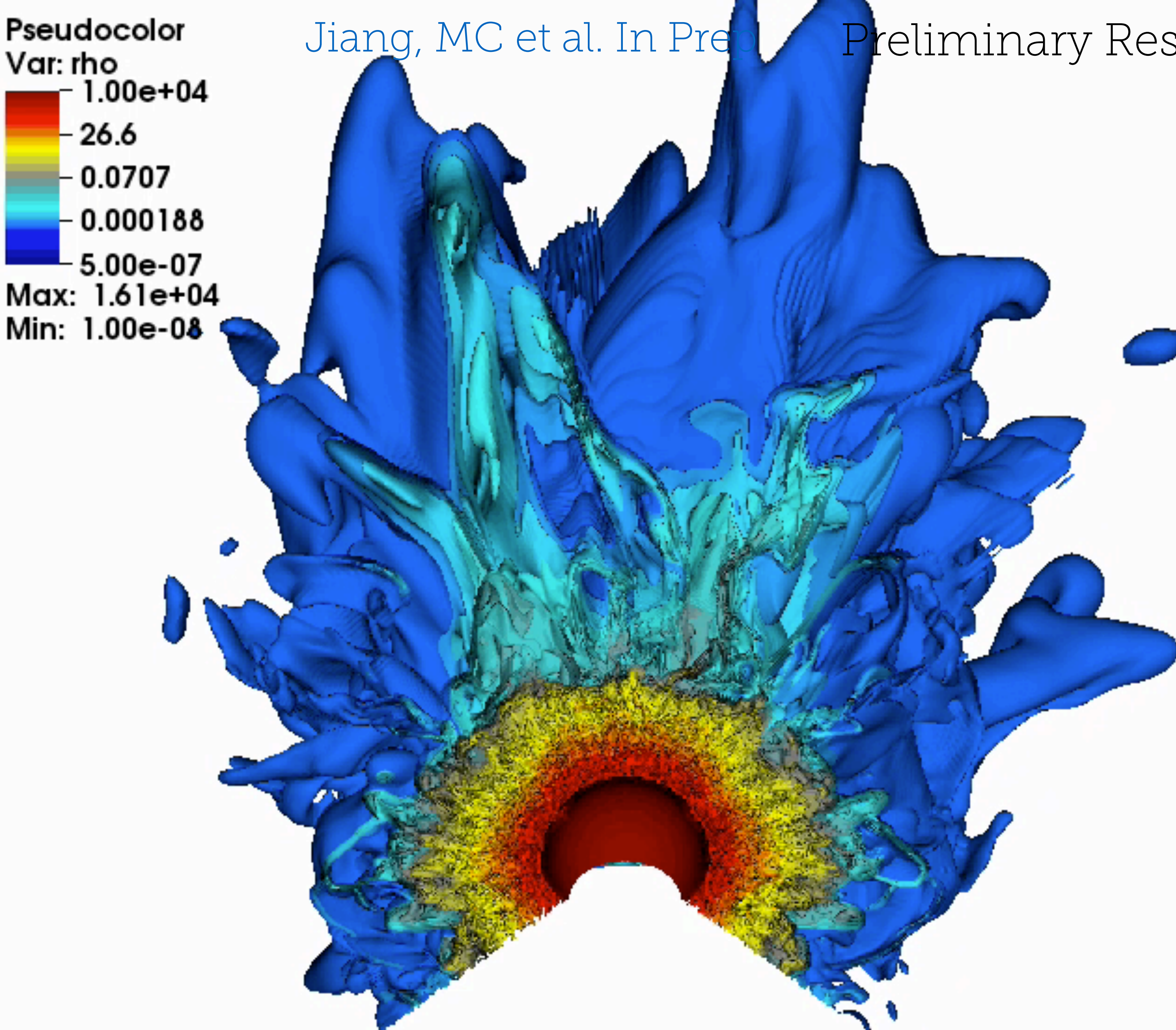
Jiang, MC et al. 2015,2017, in Prep

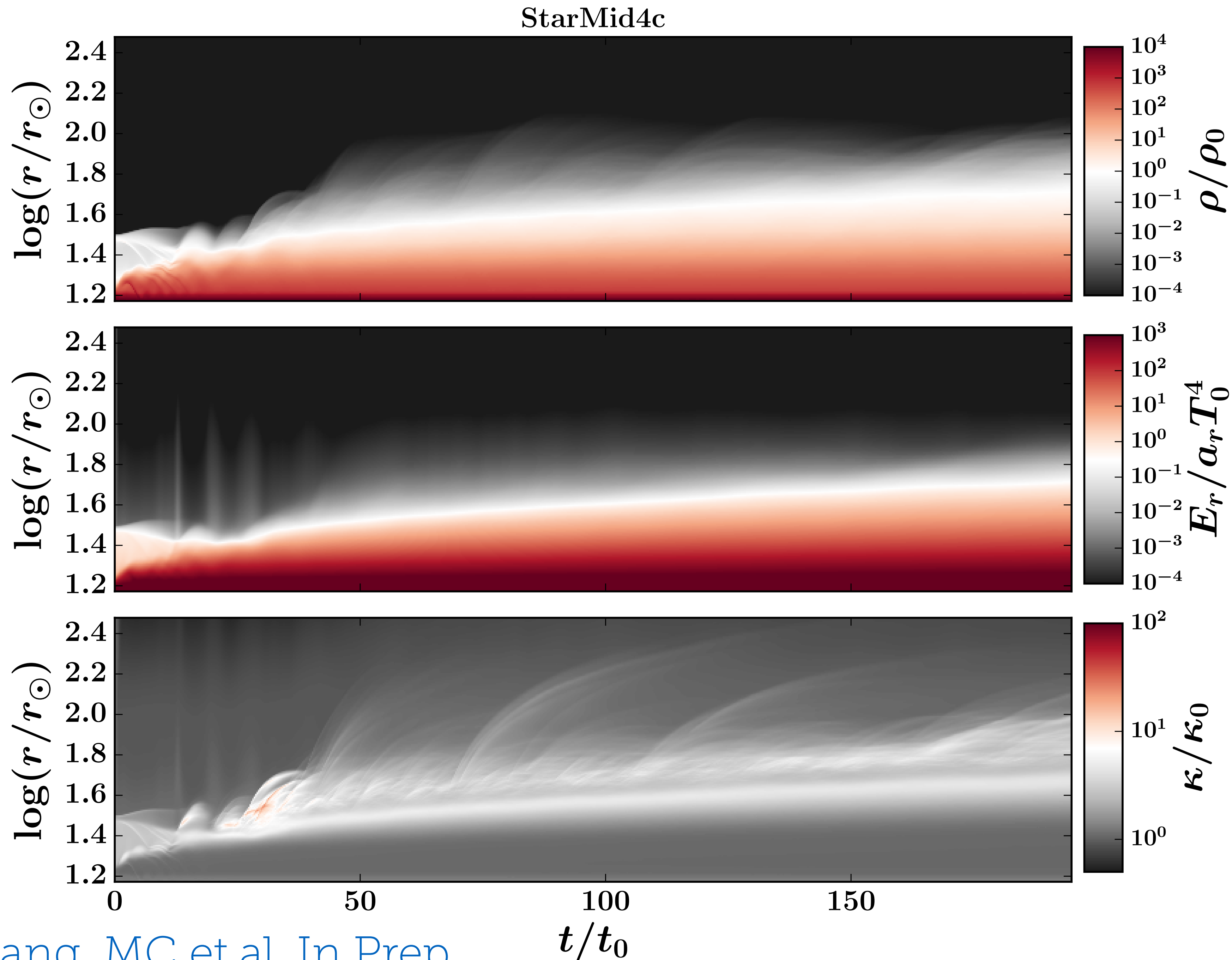


Jiang, MC et al. 2015,2017, in Prep

Jiang, MC et al. In Prep

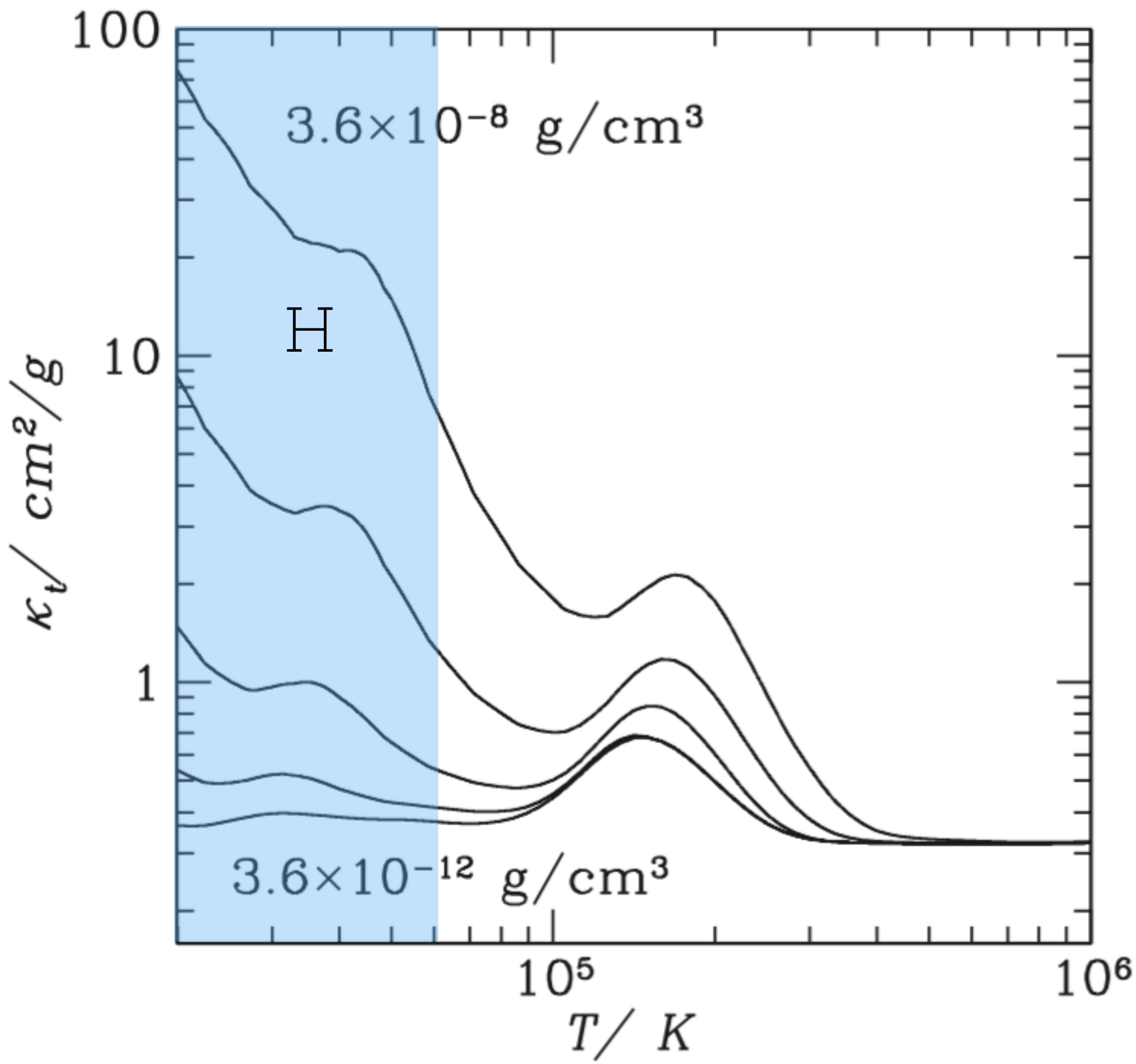
Preliminary Results!

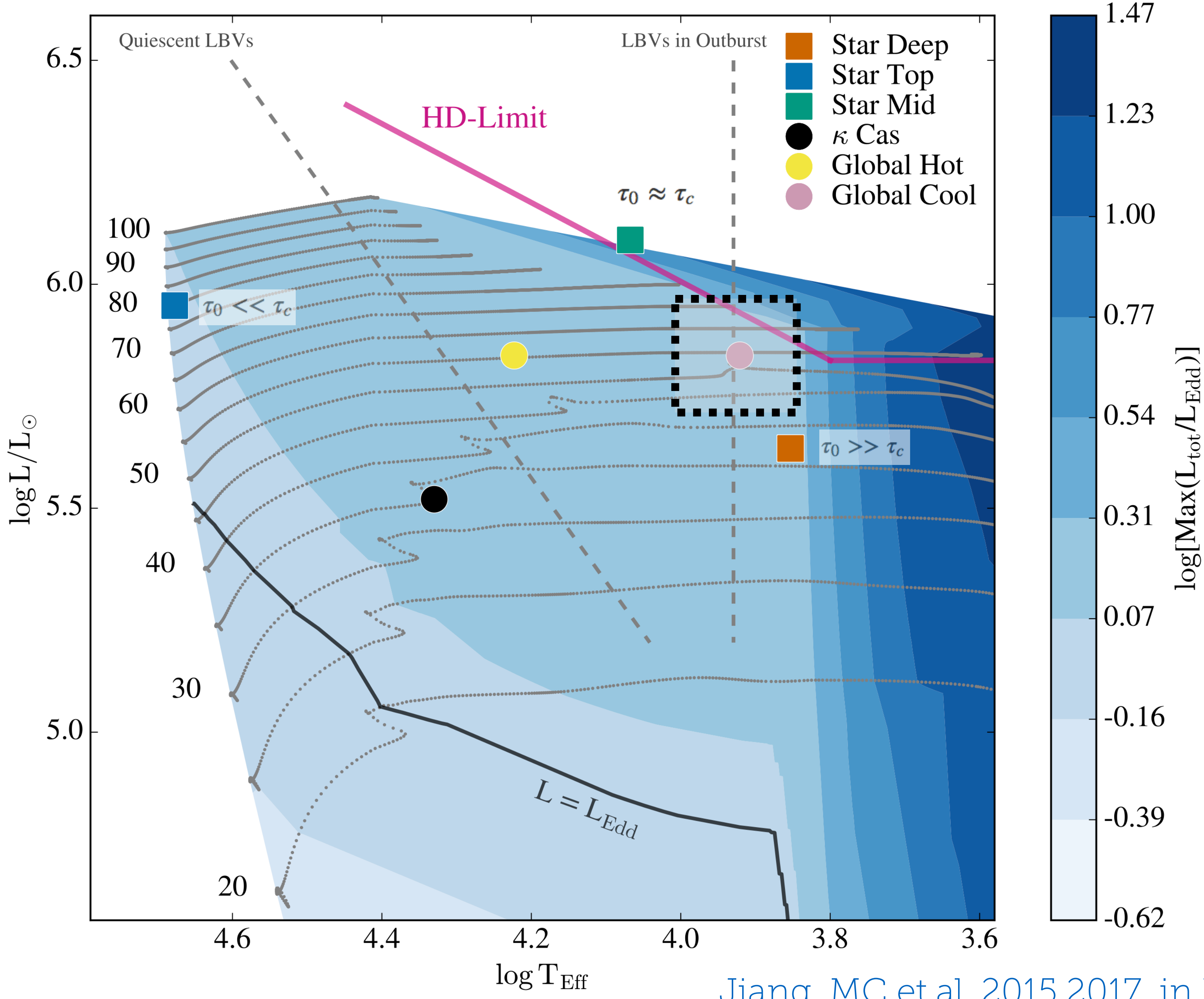




Jiang, MC et al. In Prep

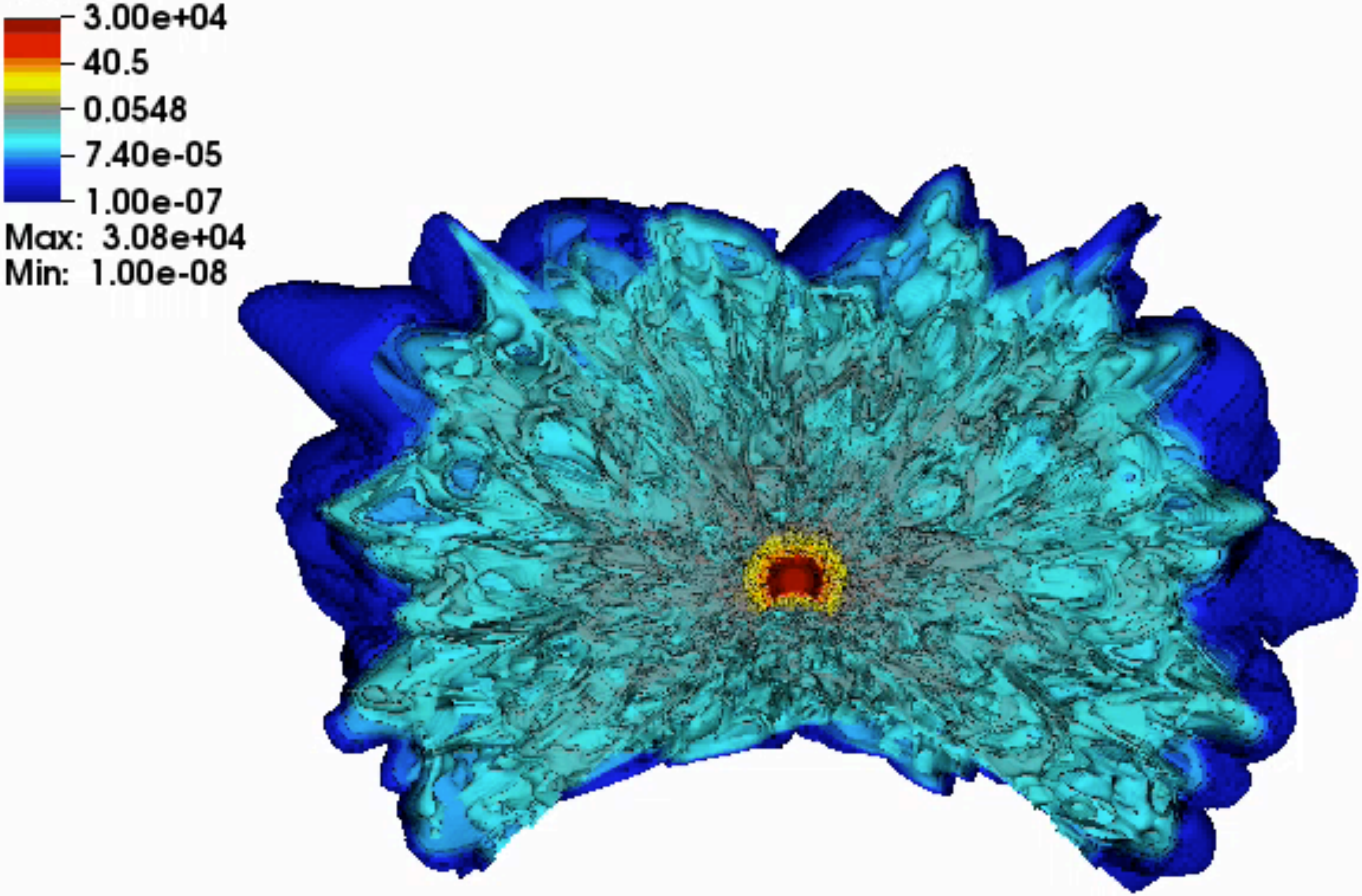
At lower temperatures / later evolutionary phases, things might get even more wild!





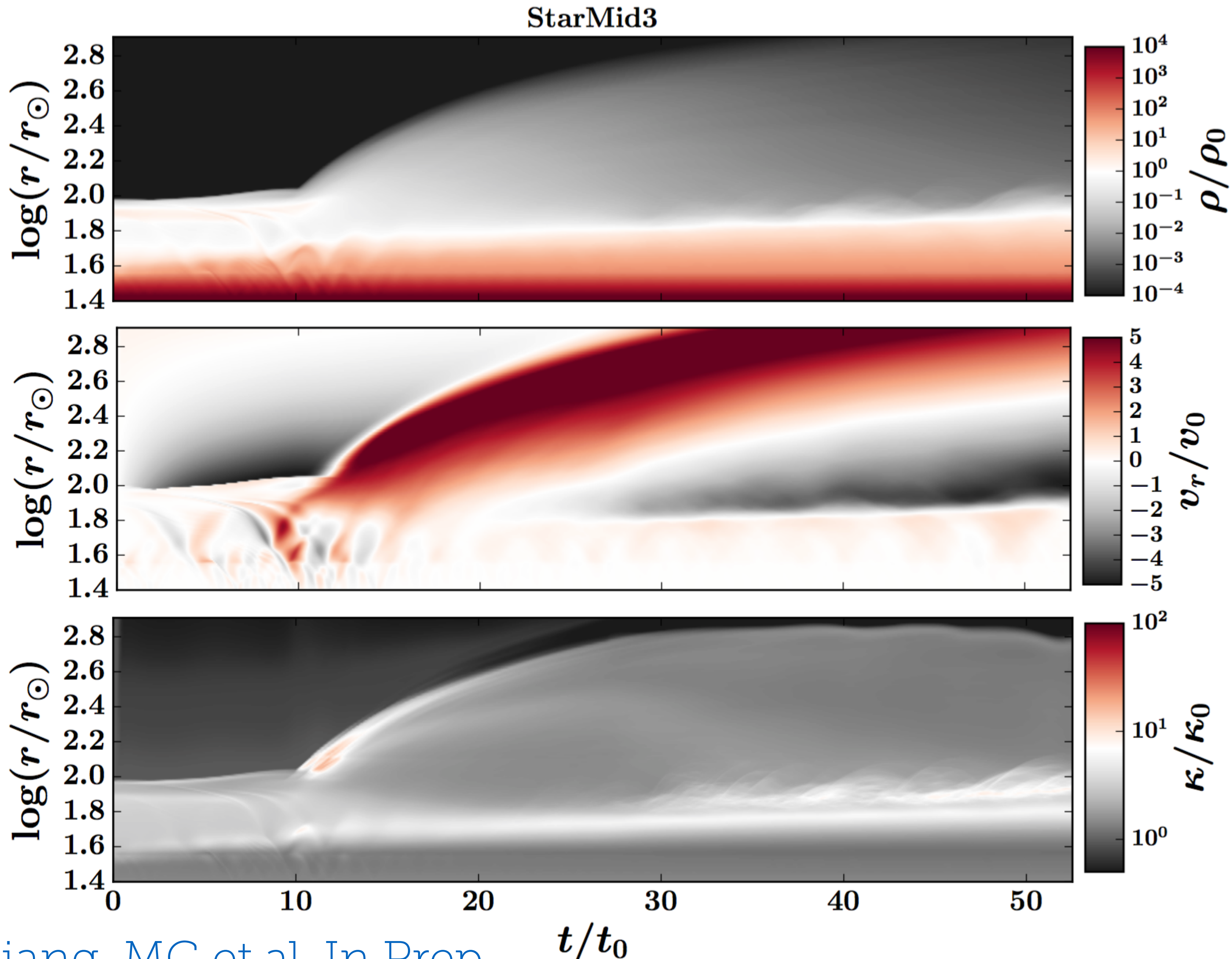
Jiang, MC et al. 2015,2017, in Prep

"Global Cool" 3D Athena++, Radiation Hydro



Jiang, MC et al. In Prep

Preliminary Results!



Jiang, MC et al. In Prep

Summary

1. Density inversions observed in 1D codes unstable in 3D
2. Porosity of density fluctuations reduce the effective radiation acceleration, but density inversions can persist in a time-averaged sense
3. Realistic stellar structures require implementing the porosity factor and calibrating MLT to the values observed in the 3D calculations
4. First 3D global radiation hydro calculations used to study the stability and mass loss of very luminous stars

What's Next?

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