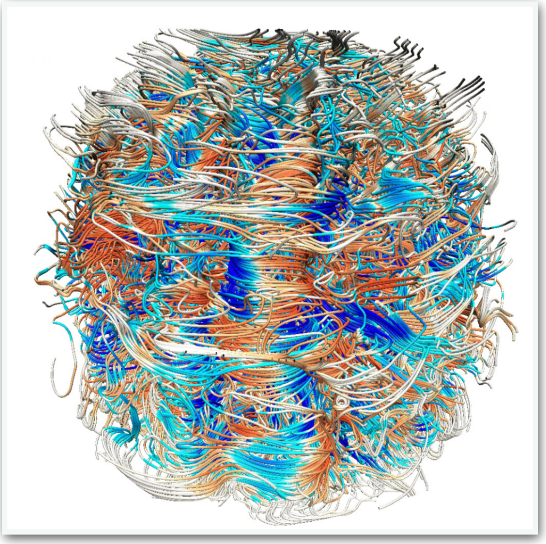
# Open Questions in Massive Stars Evolution




Matteo Cantiello [1,2]

[1] CCA, Flatiron Institute

[2] Princeton University


FLATIRON INSTITUTE
Division of Simons Foundation

# Massive Stars: The most uncertain physics

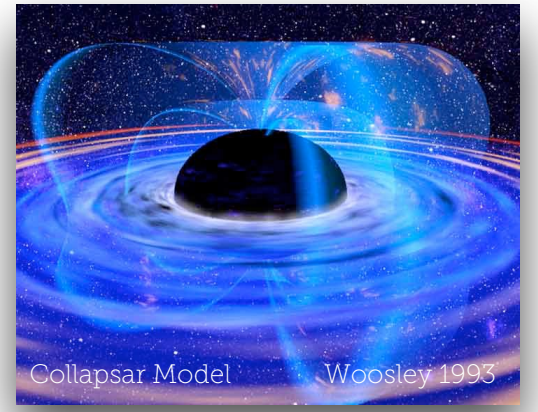
- Stability and energy transport
- Mass loss
- Rotation
- Magnetic Fields
- Binary interactions

Important for central engines (SLSNe, LGRBs...)

See Selma's Talk

# Massive Stars: Rotation & Magnetic Fields

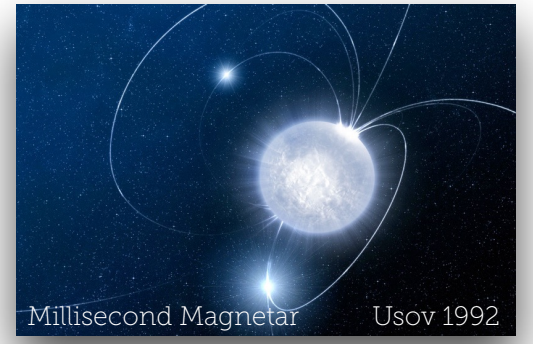
- The final rotation rate and magnetization of stellar cores are important for the physics of central engines (SLSNe, LGRBs...)




- Current models for angular momentum transport relies on 1D diffusion approximation of some (local) physical mechanisms.

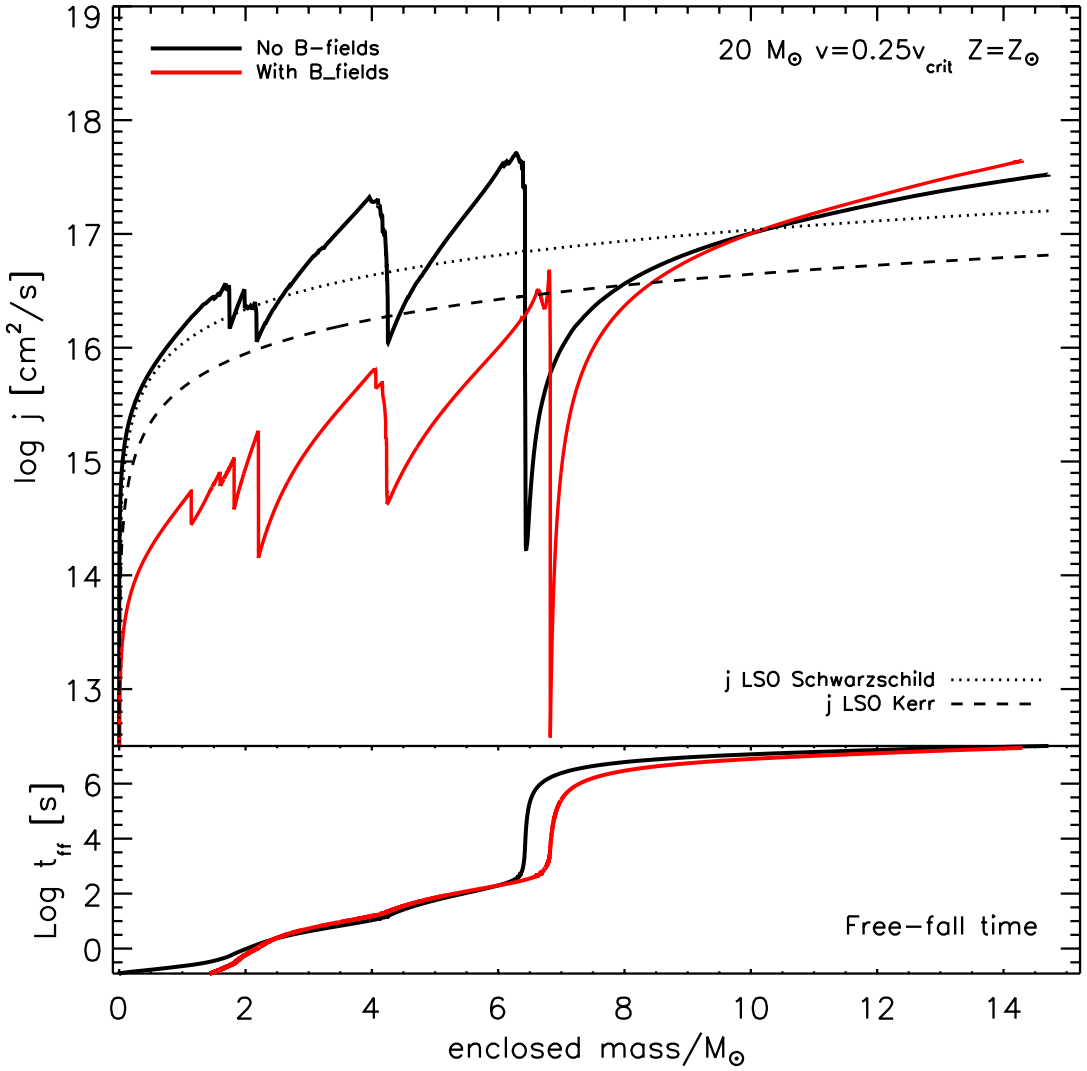
See e.g. Paxton+ 2013

- Large scale magnetic fields are usually not included



# Q: What is the Final j-distribution?

# Q: What is the Final core magnetization?




GRB (?): enough angular momentum in the core to make an accretion disk during collapse / create a rapidly rotating NS

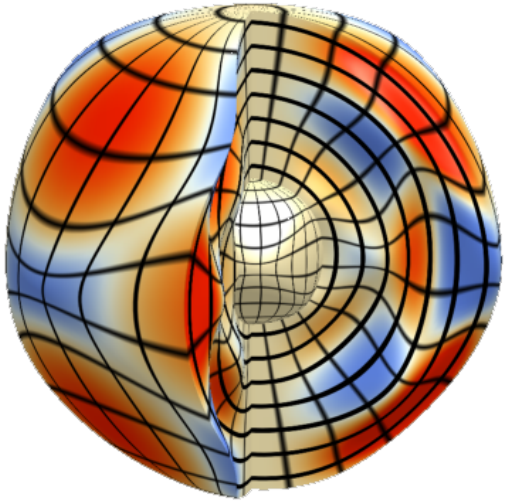
SN: no accretion disk during collapse / no rapidly rotating NS

1D MESA
Stellar evolution calculations

Paxton+ 2011, 2013, 2015

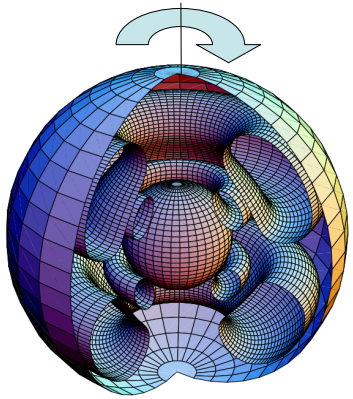
# What the observations say?

Asteroseismology now allows to probe the deep interiors of (low-mass) stars and measure properties like radial differential rotation and internal magnetic fields! Important results:



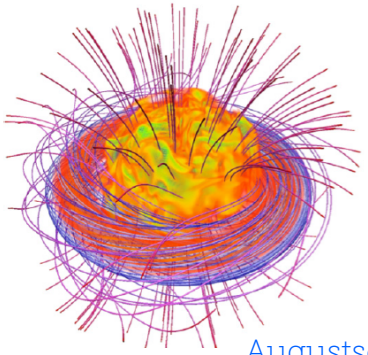
R.Townsend

1. Internal J-transport not fully understood Cantiello et al. (2014) Large coupling core-envelope seems required



Maeder & Meynet

2. Strong core B-fields potentially ubiquitous in massive stars Fuller, MC et al. (2015), Stello, MC et al. (2016)



Augustson

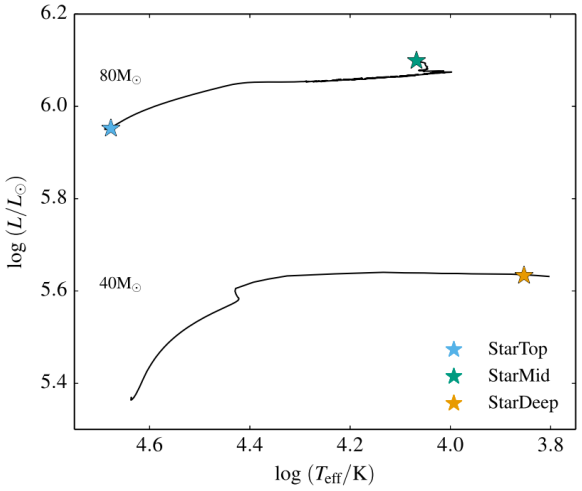
# Massive Stars:
# The most uncertain physics

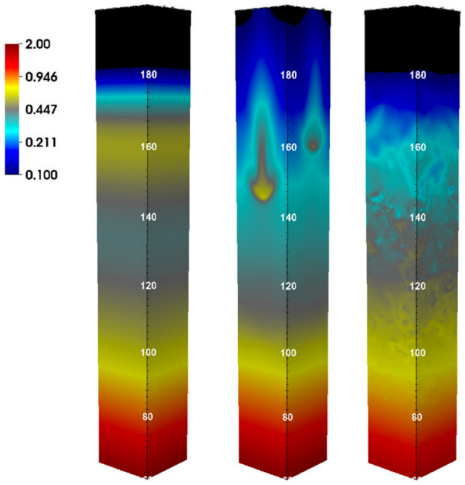
- Stability and energy transport
- Mass loss
- Rotation
- Magnetic Fields
- Binarity

# Stability and energy transport

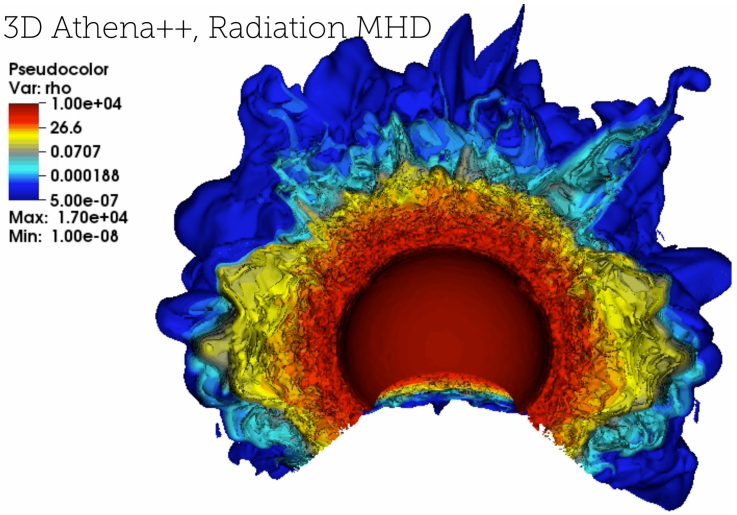
Q: How is the energy transported in massive stars envelopes?
(Radii, stability…)

MLT is not supposed to work!



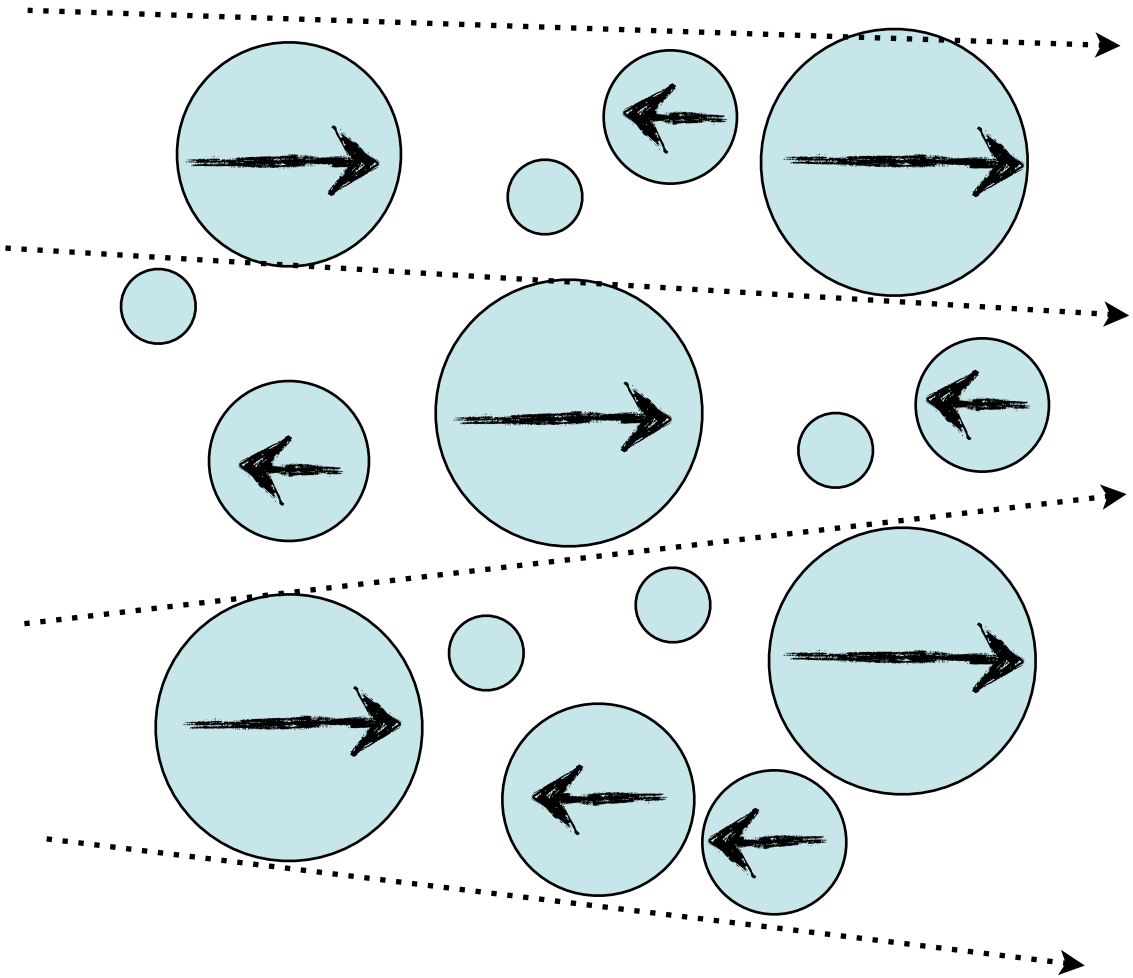

3D Athena++, Radiation MHD




Jiang, MC et al. 2015, 2017

Radii Important:
See e.g. Tony Piro's and Ryan Chornock's Talks

# Different regimes in Radiation Dominated Convection



Diff Rad Flux

Advection Flux
("convection"...)

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

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

Critical optical depth

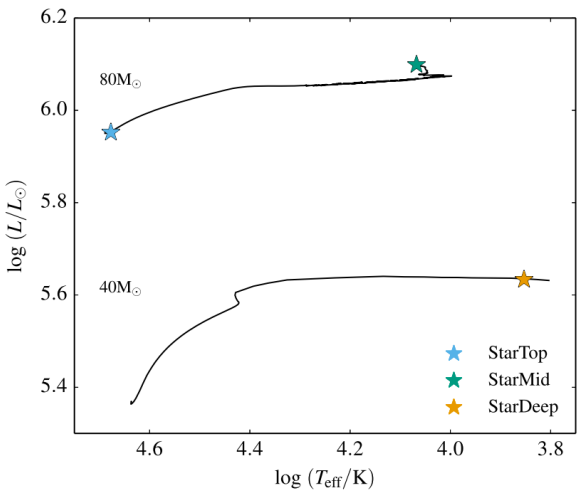
$$\tau_c = c/c_s$$

Optical depth where radiation diffusion timescale = dynamical timescale

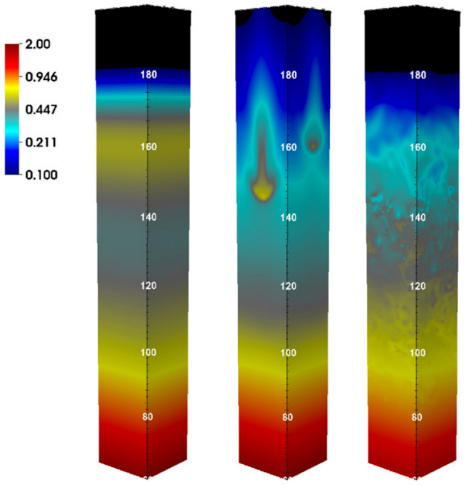
MLT is not supposed to work!

# Stability and energy transport

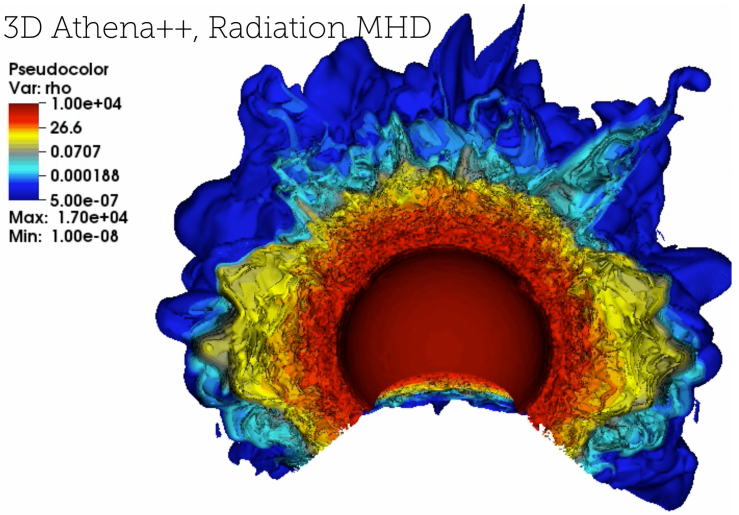
## 1D Stellar Evolution (MESA)




## 3D Local Radiation MHD (ATHENA)




## 3D Global Radiation MHD (ATHENA++)

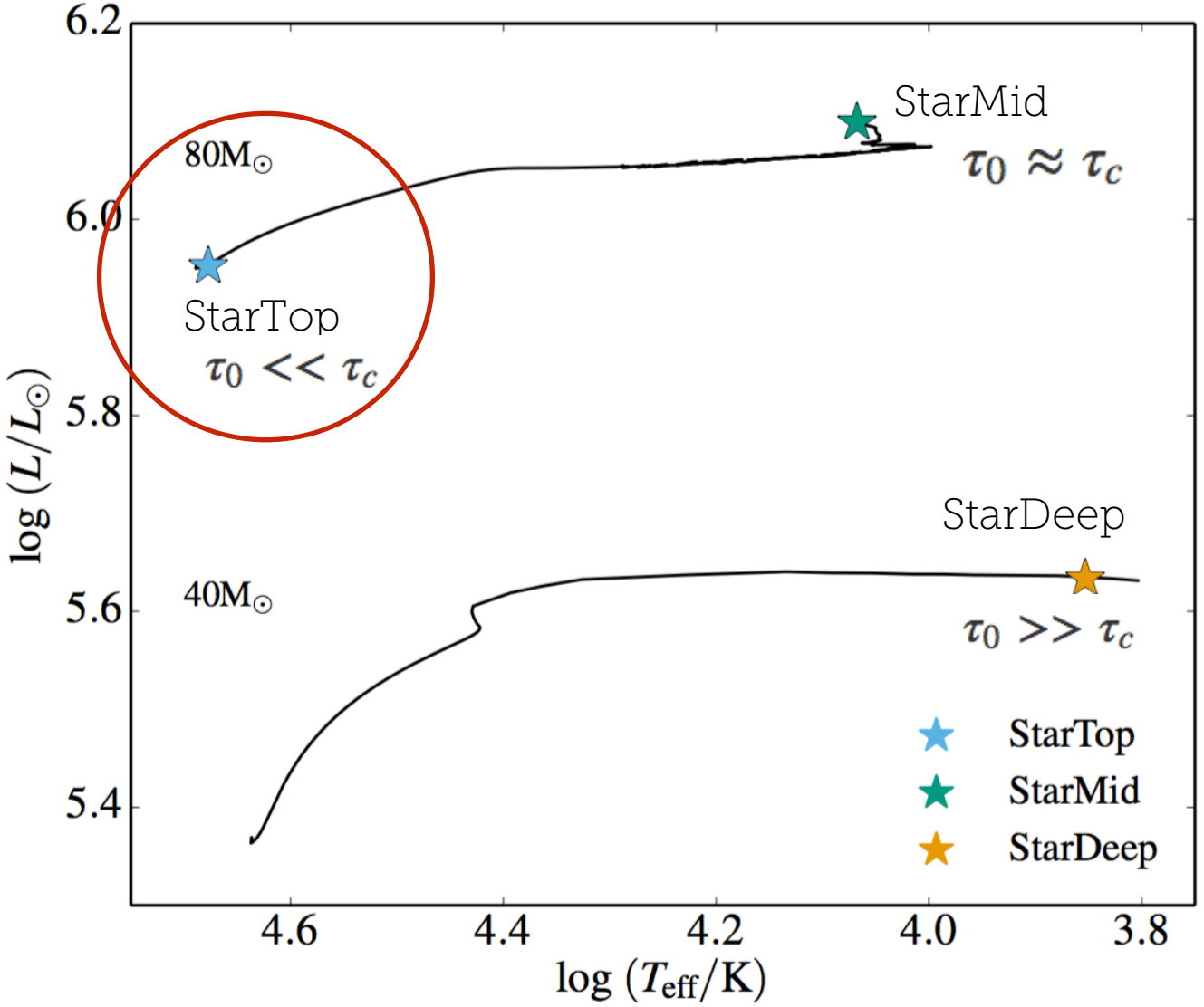



Jiang, MC et al. 2015, 2017

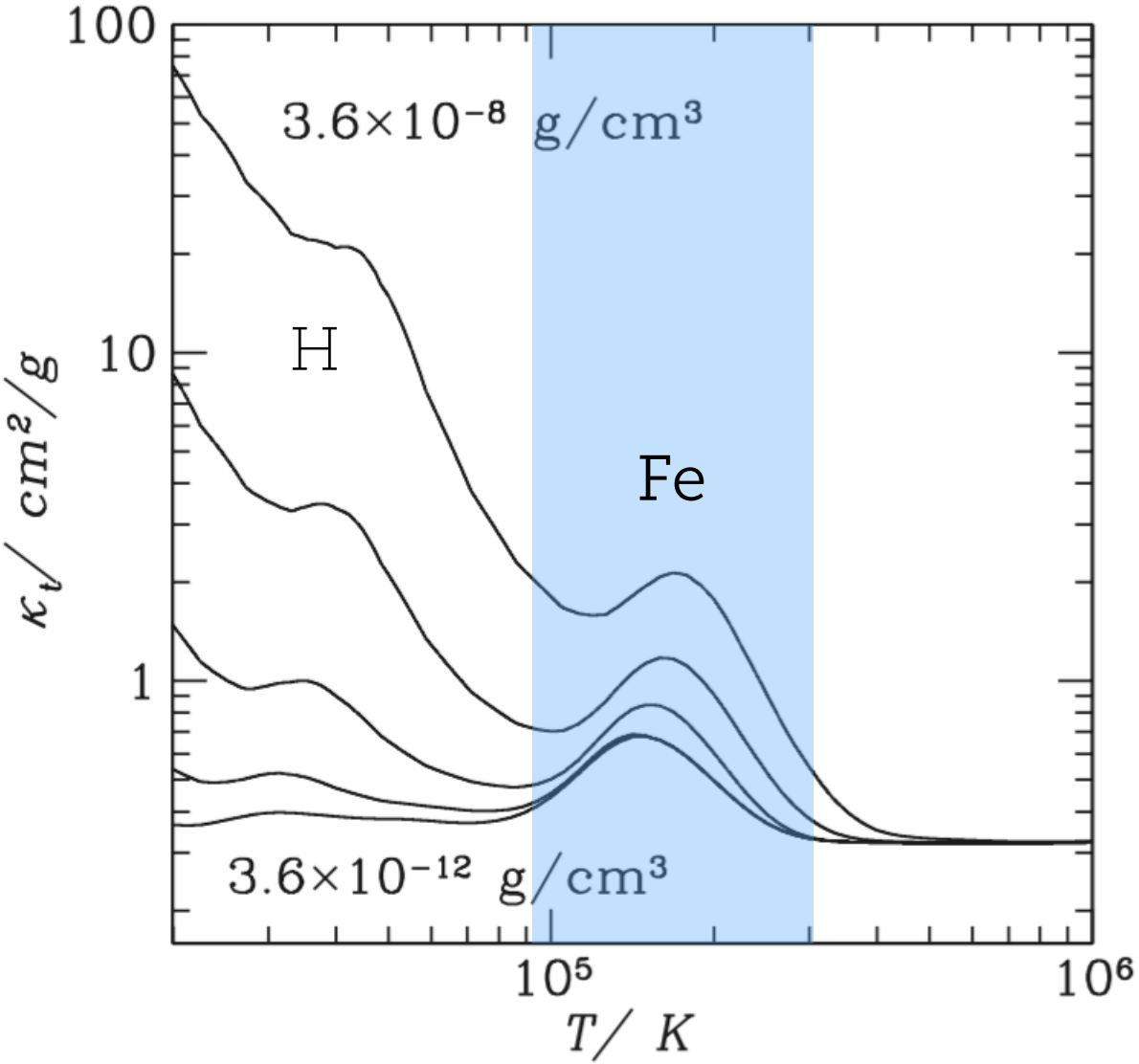
# Initial Conditions

Jiang, MC et al. 2015

## Guided from MESA 1D models

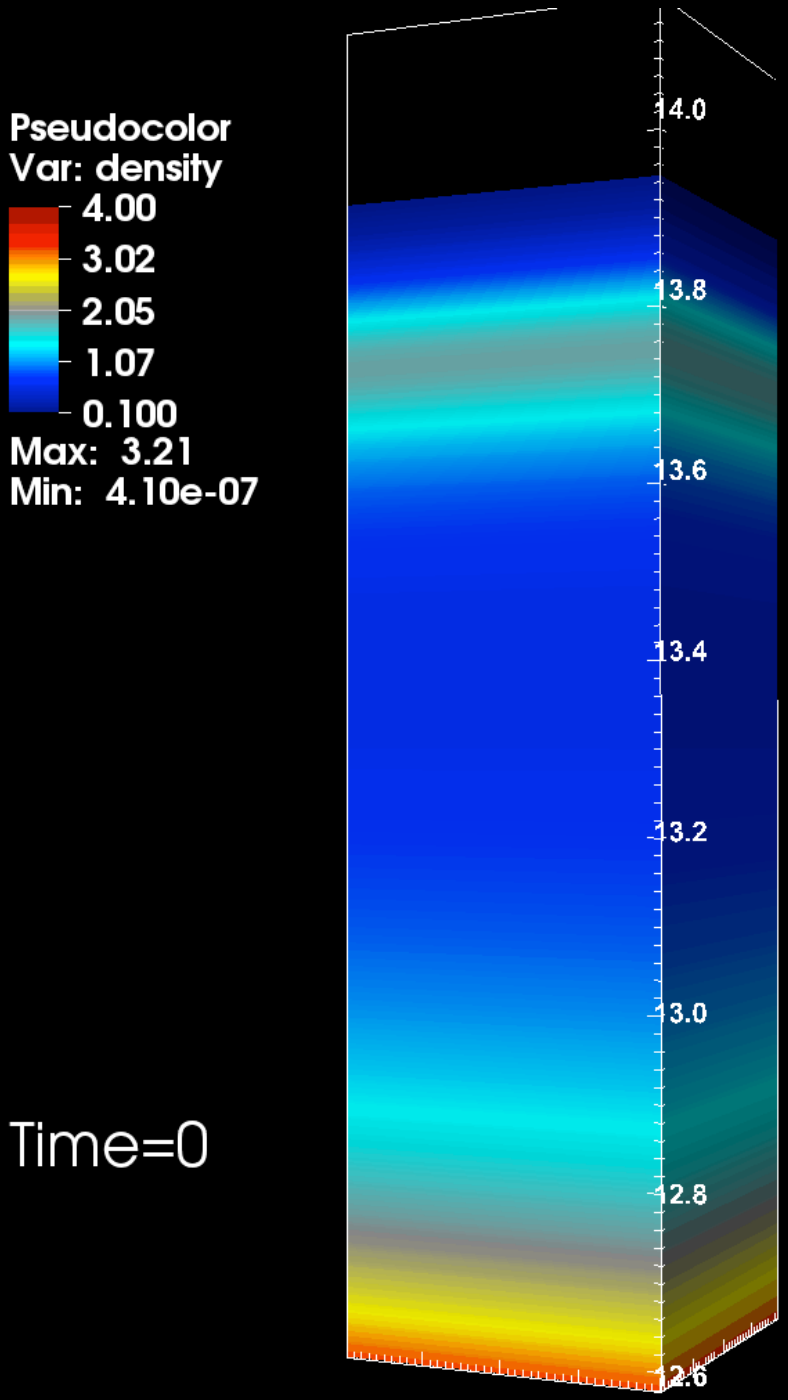


# The Opacity: Iron Peak




Cantiello et al. 2009,
Paxton, MC et al. 2013,
Jiang, MC et al. 2015

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




# STARTOP

## The case with inefficient convection

ATHENA + VET

| Variables/Units | StarTop |
|---|---|
| $r_0/r_\odot$ | 13.6 |
| $T_0/\mathrm{K}$ | $1.57 \times 10^5$ |
| $\rho_0/(\mathrm{g\ cm^{-3}})$ | $5.52 \times 10^{-9}$ |
| $g/(\mathrm{cm\ s^{-2}})$ | $1.17 \times 10^4$ |
| $F_{r,i}/(\mathrm{erg\ cm^{-2}\ s^{-1}})$ | $3.06 \times 10^{14}$ |
| $H_0/\mathrm{cm}$ | $2.37 \times 10^{10}$ |
| $t_0/\mathrm{s}$ | $1.42 \times 10^3$ |
| $\tau_c \equiv c/c_{g,0}$ | $6.54 \times 10^3$ |
| $\tau_0$ | 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

# Initial Conditions

Jiang, MC et al. 2015

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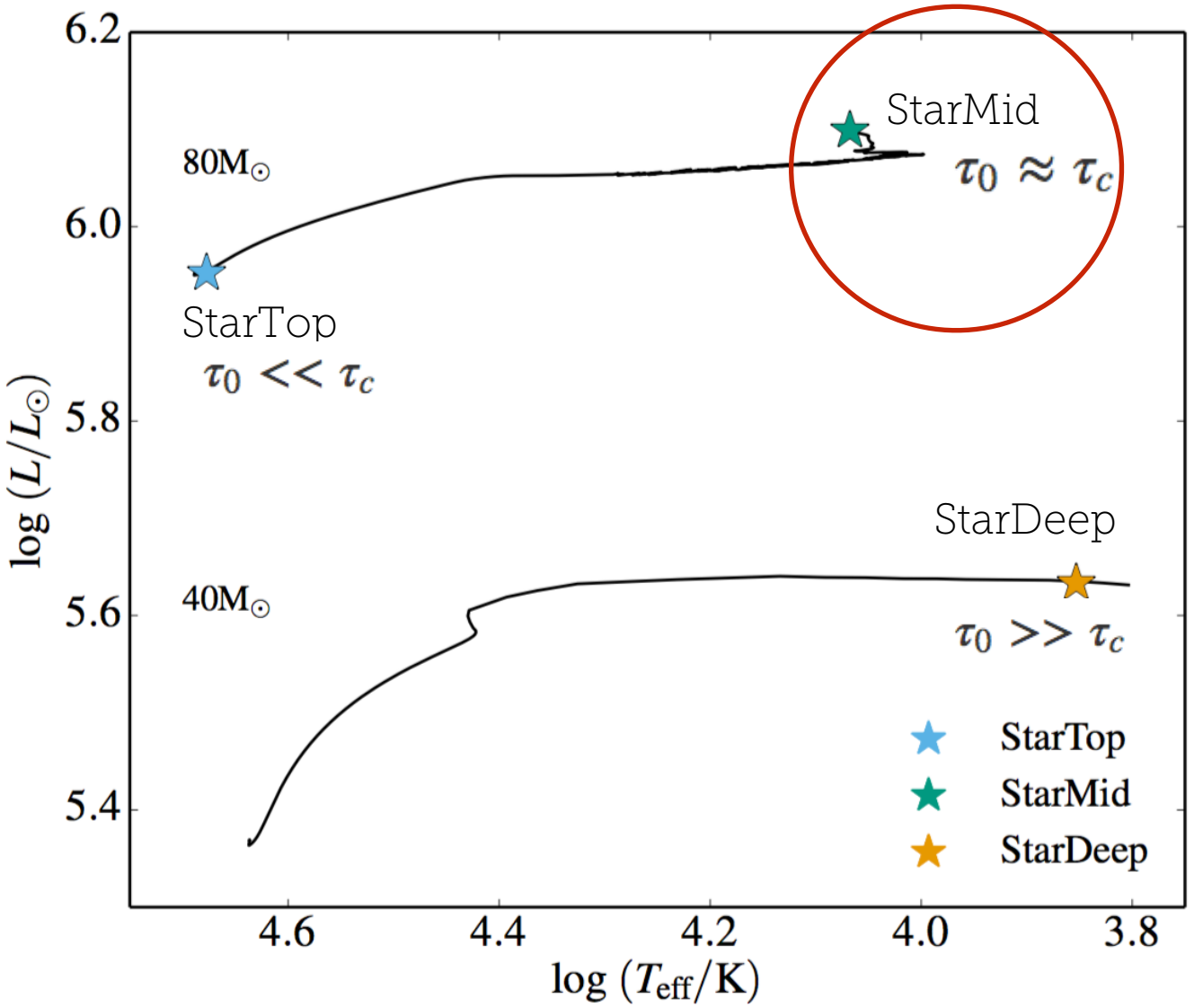

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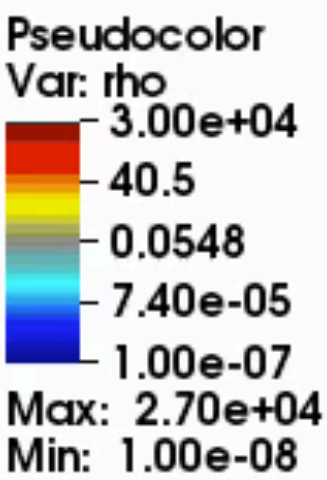
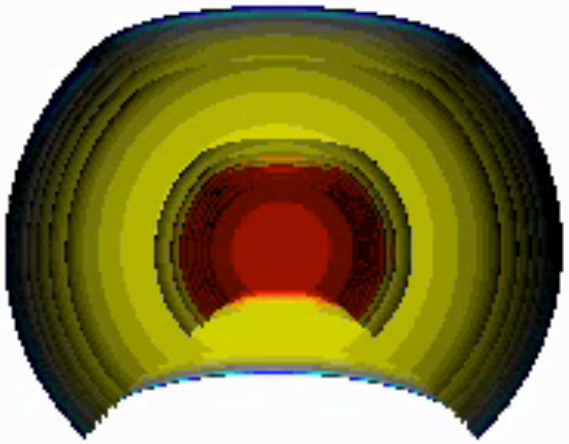
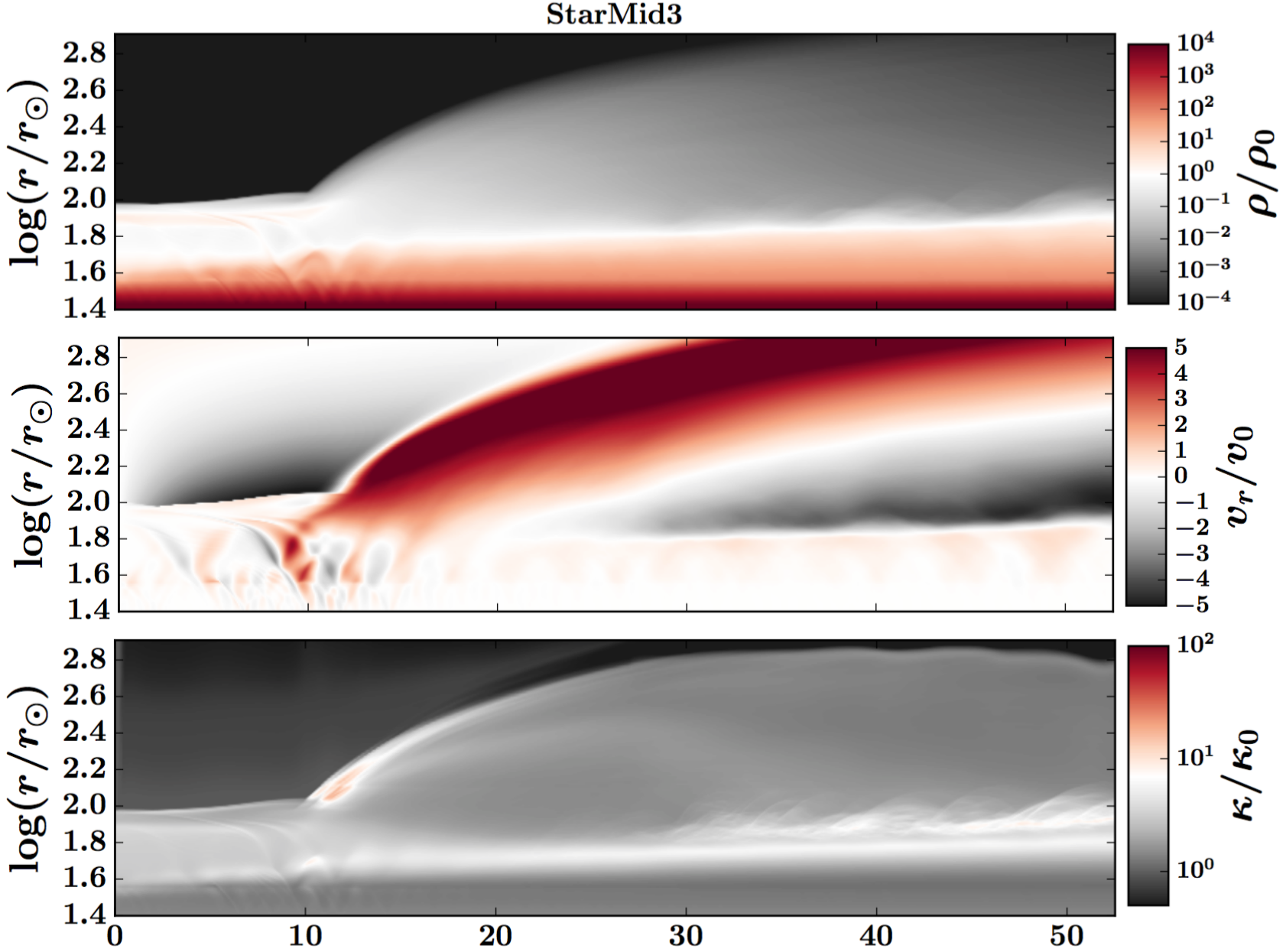


Preliminary Results!

Jiang, MC et al. In Prep



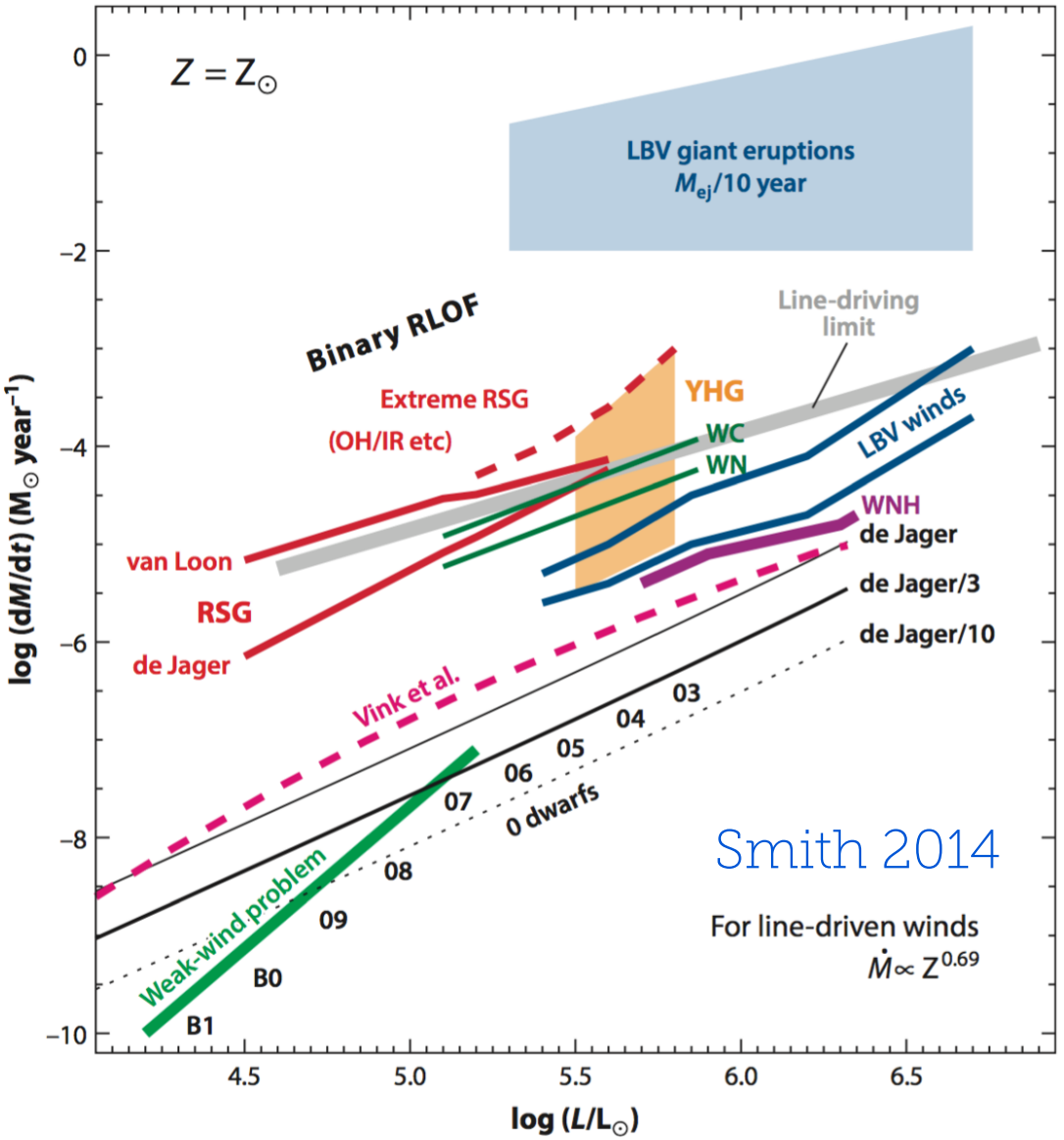

Jiang, MC et al. In Prep

Preliminary Results!

# Massive Stars: Mass Loss

Q: How massive stars loose their mass?

- Line Driven Winds
- "Cool" Winds
- LBV eruptions
- Pulsationally enhanced winds
- Binary RLOF
- Pre SN massloss



# Pre SN Mass Loss and Outbursts

Type IIn: e.g. Smith 2016, heterogenous class. But large mass loss rates required in last phases of stellar life

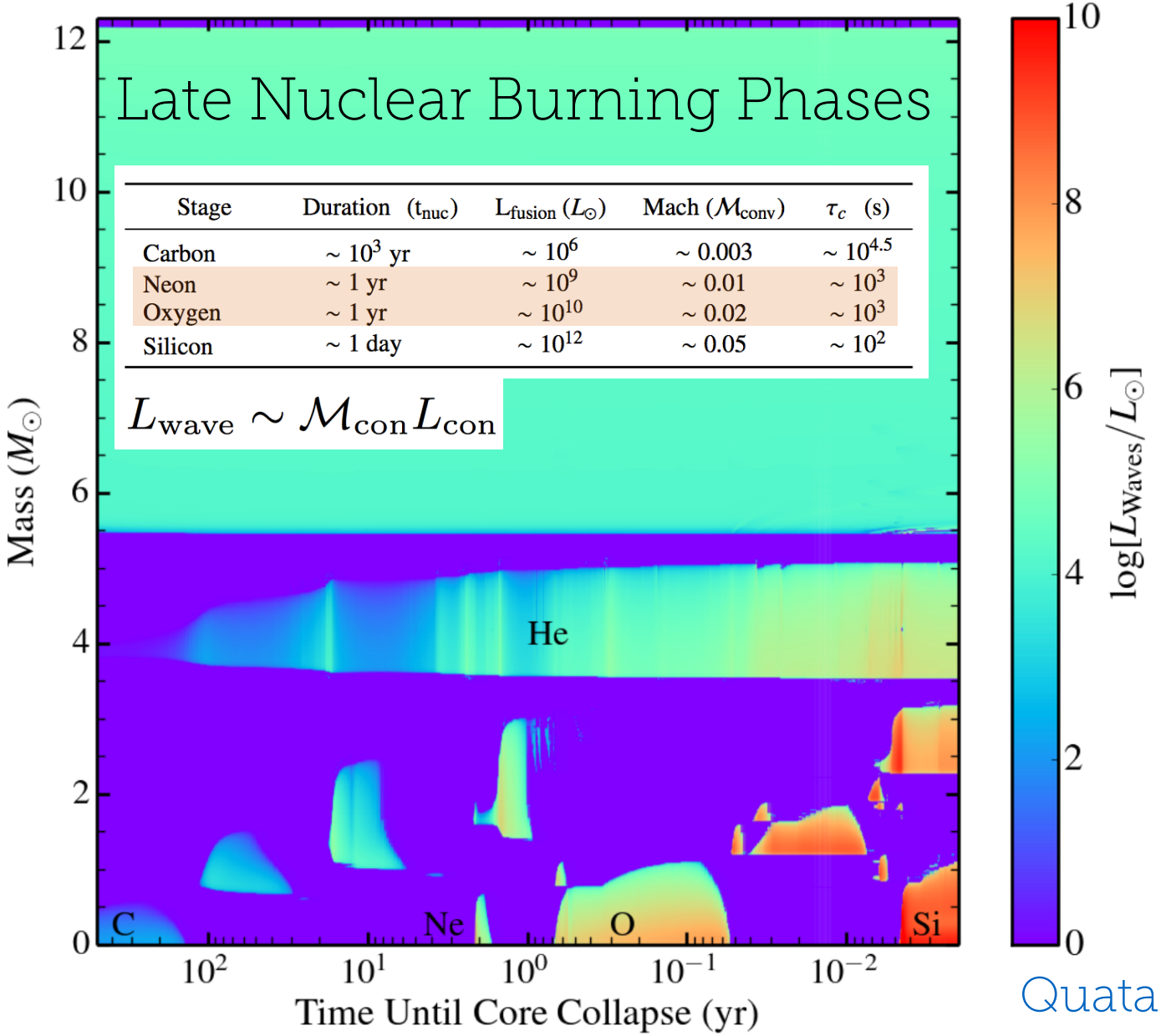
Pre SN Outbursts: 2009ip (e.g. Margutti et al. 2014), 2010mc (Ofek et al. 2013), LSQ13zm (Tartaglia et al. 2016), 2015bh (e.g. Ofek et al. 2016)

Type Ibn: e.g. SN 2014C transitioned into a IIn, due to H-rich CSM ejected by its progenitor in its final ~decades of life (Milisavljevic et al. 2015, Margutti et al. 2017 )

Type IIP: SN 2013fs Early time flash spectroscopy reveals modest mass ejection ($10^{-3}$ $M_{Sun}$/yr) in final year of progenitor's life (Yaron et al. 2017)

See e.g. Maria Drout and Ori Fox talks

# Wave Driven Heating & Mass Loss




| Stage | Duration ($t_{nuc}$) | $L_{fusion}$ ($L_\odot$) | Mach ($\mathcal{M}_{conv}$) | $\tau_c$ (s) |
|---|---|---|---|---|
| Carbon | ~ $10^3$ yr | ~ $10^6$ | ~ 0.003 | ~ $10^{4.5}$ |
| Neon | ~ 1 yr | ~ $10^9$ | ~ 0.01 | ~ $10^3$ |
| Oxygen | ~ 1 yr | ~ $10^{10}$ | ~ 0.02 | ~ $10^3$ |
| Silicon | ~ 1 day | ~ $10^{12}$ | ~ 0.05 | ~ $10^2$ |




15 $M_{Sun}$ RSG

Fuller 2017,
Quataert & Shiode 2012

# Wave Driven Heating & Mass Loss

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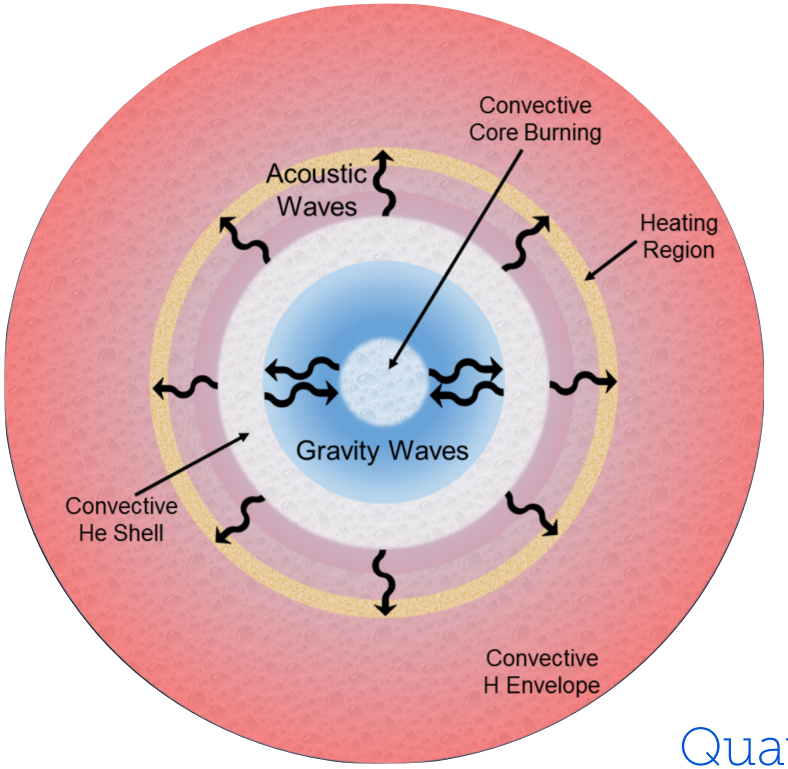
Quataert & Shiode 2012



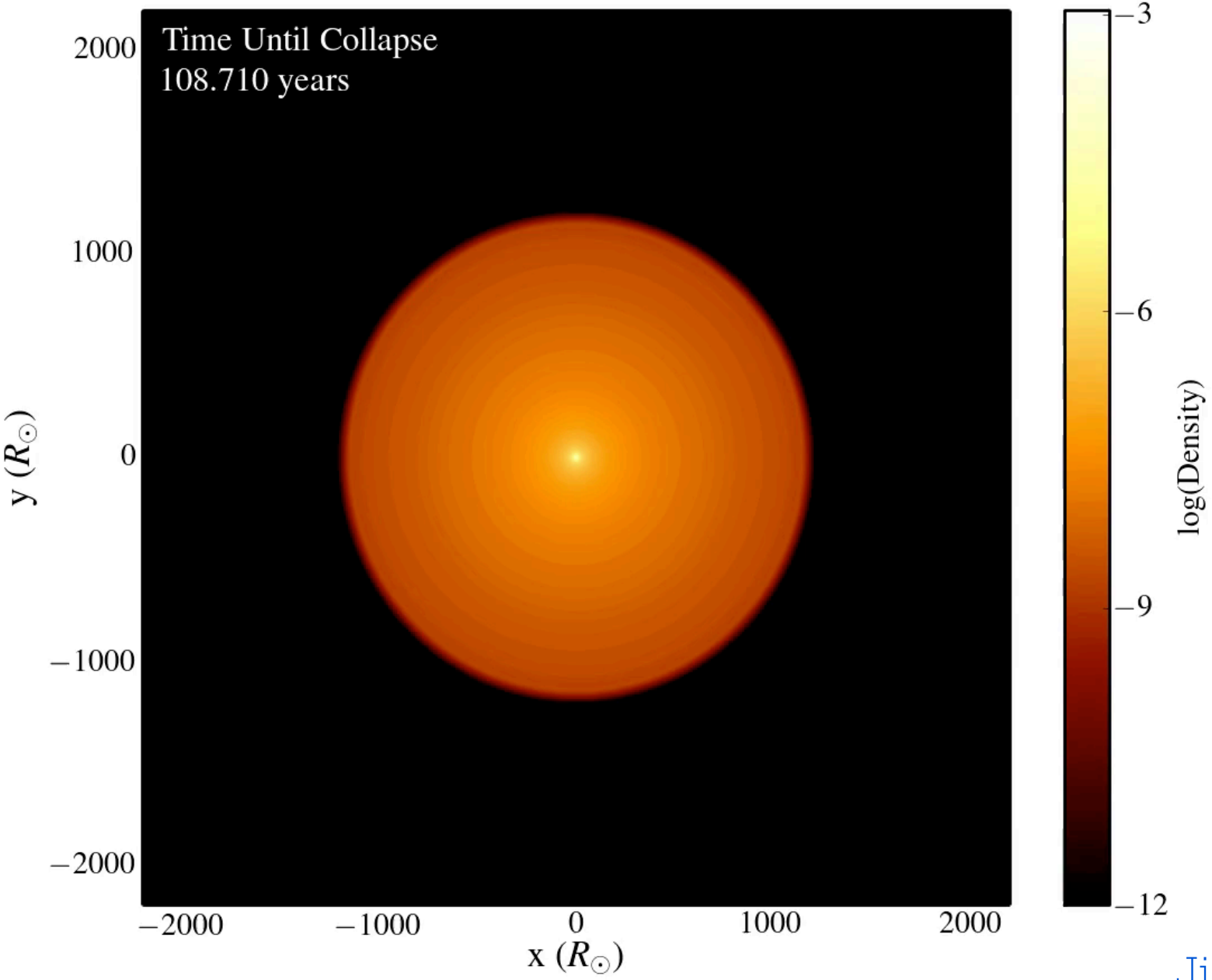

$$L_{\rm wave} \sim \mathcal{M}_{\rm con} L_{\rm con}$$

Waves can deposit ~$10^{48}$ ergs in the envelope in the last months to years before SN explosion

Shiode & Quataert 2014, Fuller 2017

Quataert et al. 2016 (SuperEddington outflows)

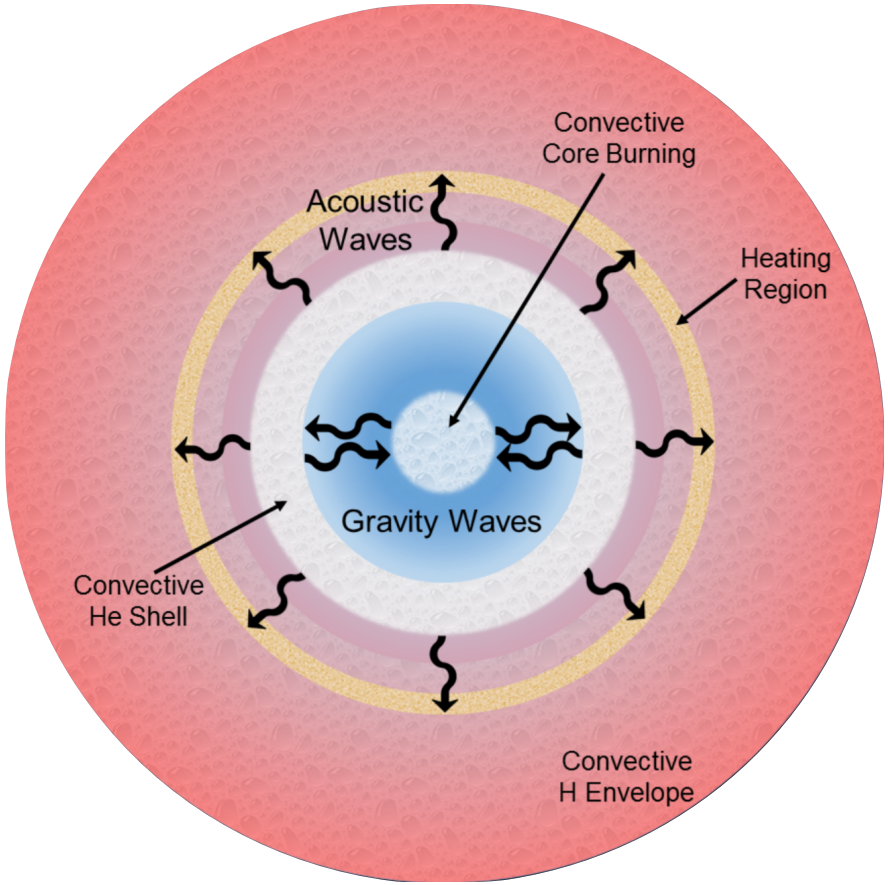
# 15 $M_{Sun}$ RSG




Jim Fuller

# Wave Driven Heating & Mass Loss

For a typical Type IIP progenitor

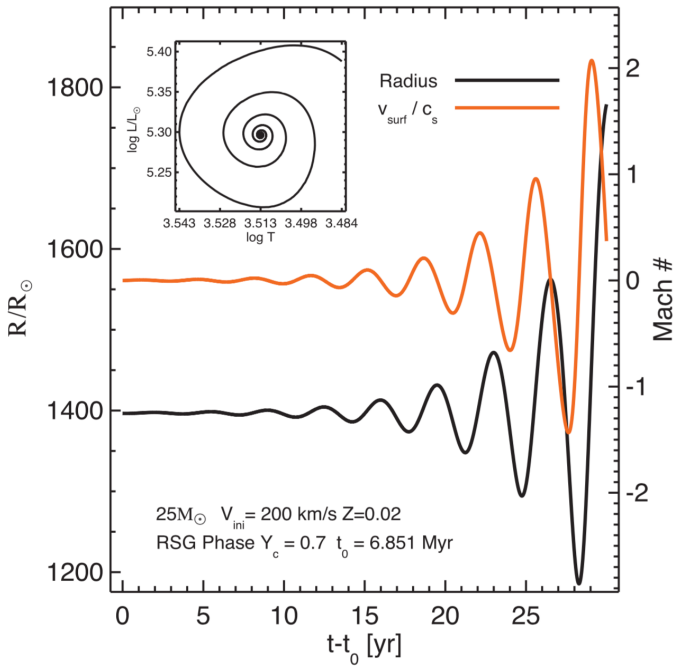


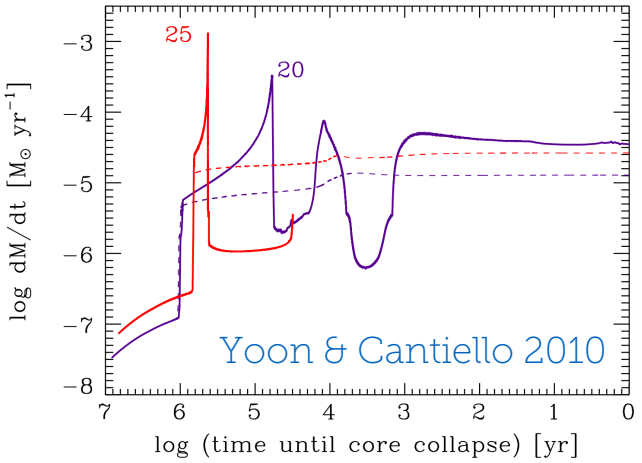

- Modest luminosity excursions (less than 2 mags during last few years)
- Impact on radius and envelope structure (Important for light curve, in particular early peak luminosity). See Tony Piro's Talk
- Can explain mild Pre SN outbursts in RSGs, leading to observed flash spectroscopy
- Ejecta masses small (< $1M_{Sun}$, and with velocity < 50 km/s)

Fuller 2017

# Other Pre SN Mass Loss Mechanisms

- Pulsationally enhanced winds in RSG (Heger+ 1997, Yoon & Cantiello 2010, Moryia & Langer 2017)
- Pulsation Pair Instability (Woosley 2017)
- Burning Shell Instabilities (e.g. Meakin & Arnett 2006, 2007)
- Si-Burning Flashes (Woosley & Heger 2015)



Large Synoptic Survey Telescope

# Q: How massive stars loose their mass?

LSST: Pre SN outbursts. Early(?) and Late time light curves, to probe CSM interaction

# Q: Are the cores of (some) massive stars magnetized and/or rapidly rotating?

LSST: Early(?) and Late time light curves, to probe energetics of central engines (vs other energy sources)