Massive Stars:

(1) Carbon Core Masses
(2) Envelope energy deposition

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Planned Activities

Lecture - 40 minutes

- Carbon core masses
- Energy deposition in stellar envelopes during late-stage burning

Mini-Lab - 25 minutes

- All together - 15 M_{sun}, solar metallicity, no rotation, no mass loss

Lecture - 25 minutes

- MESA groups and settings for the Lab

Break - 30 minutes

Lab I - 45 minutes

- Sensitivity of a carbon core mass to physical, numerical, and modeling uncertainties

Lab II - 45 minutes

- Response of a massive star envelope to energy deposition during late-stage burning

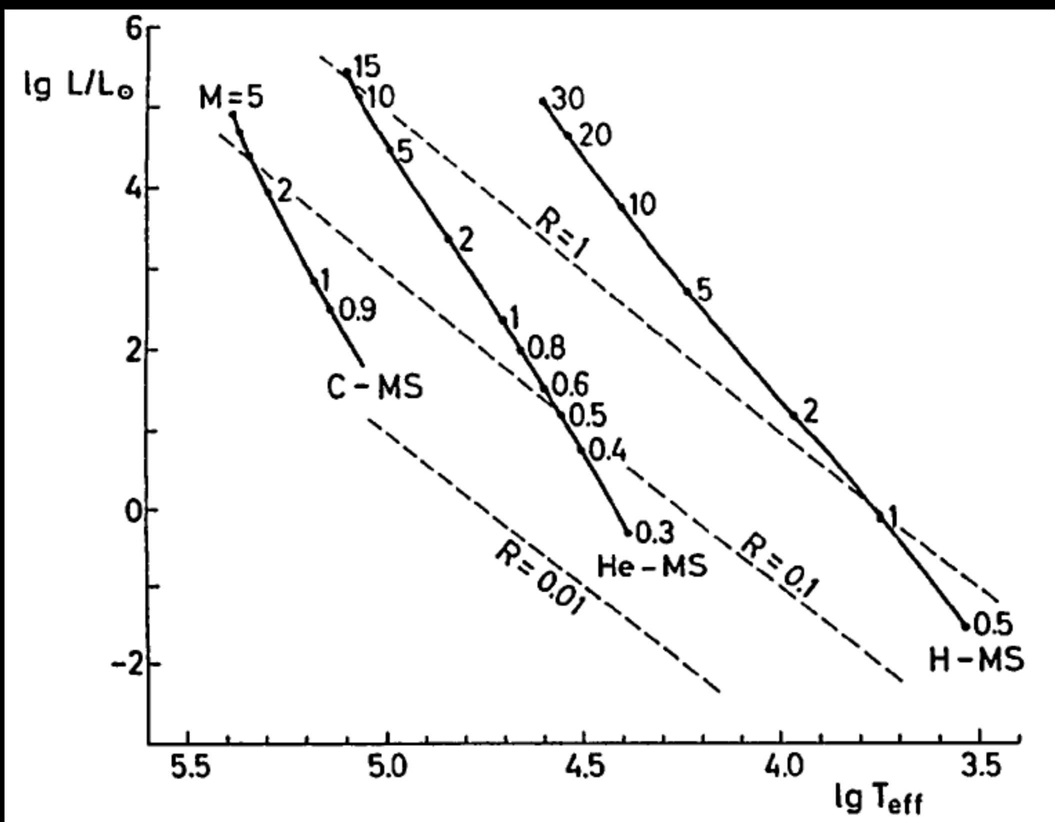
Overnight Lab - a few hours, this is optional

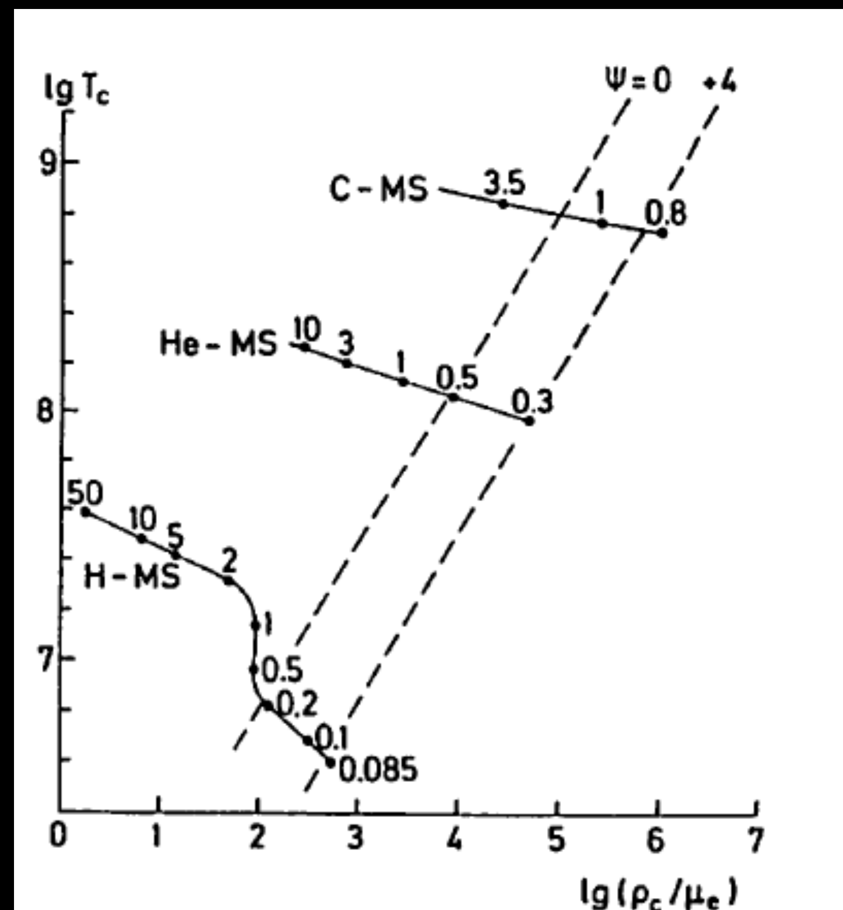
- Onwards to core-collapse

Carbon Core Masses

The carbon core mass left by the He core burning phase strongly influences the further evolutionary phases because it determines the amount of fuel (plus neutron richness of that fuel) available for the central and shell advanced burning stages (Arnett 1972 → Limongi et al. 2012).

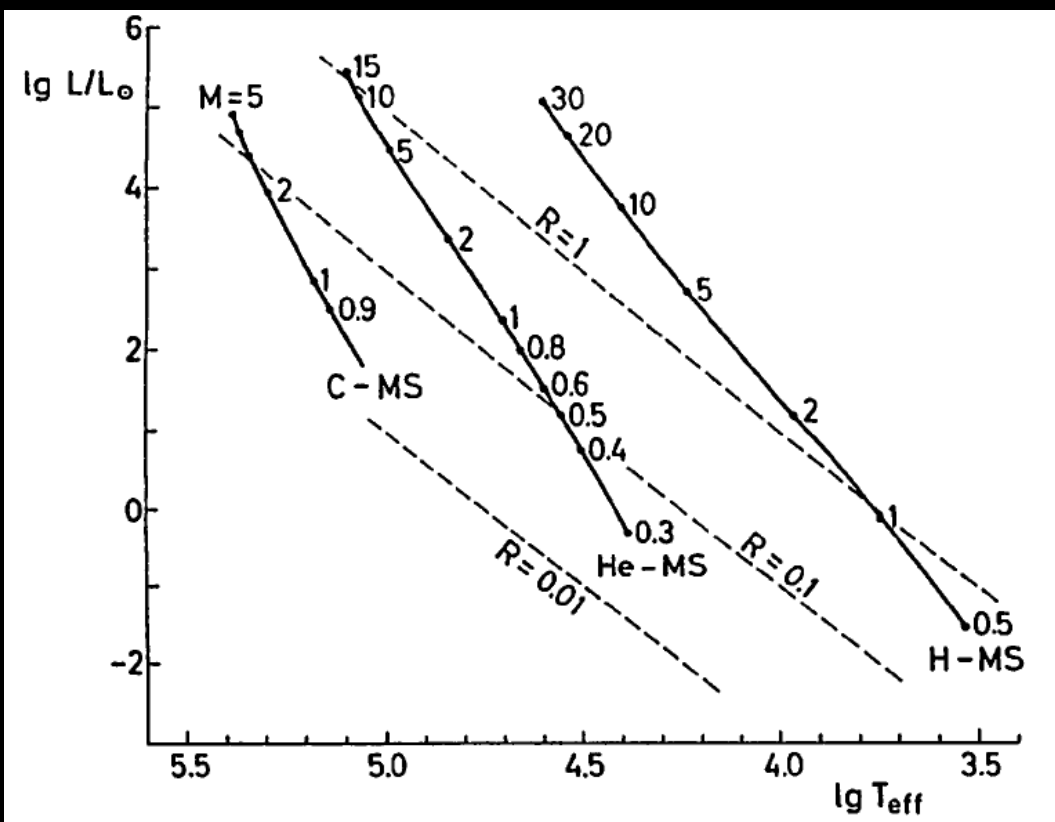
Final He core mass is determined by both the size of the convective core in the H-burning phase and by the advancing of the H shell during the ensuing central He burning phase.

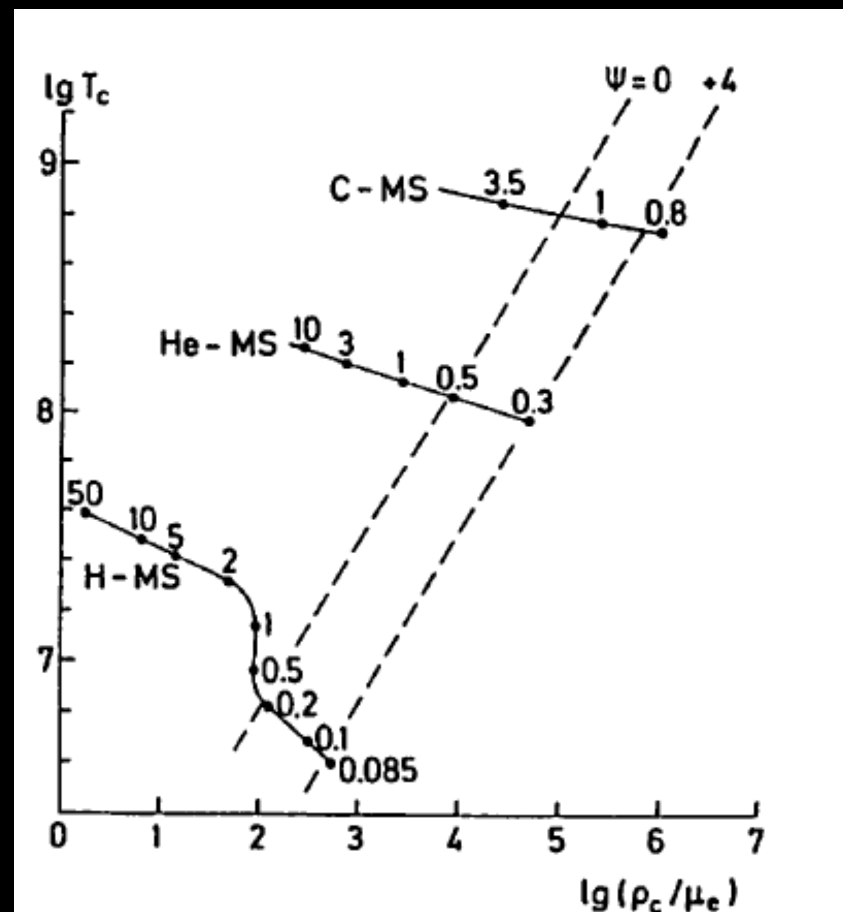




Final CO core mass is determined only by the size of the convective core at the end of the central He burning.

Further evolutionary phases are fast enough that the He convective shell does not have time enough to burn the available fuel and hence add to the CO core mass.





This means that the abundances of ^{12}C and ^{16}O within the whole CO core are essentially flat and fixed by the (convective) central He burning phase and not by shell (radiative or convective) burning.

While the larger the ZAMS mass the larger the final carbon core mass, the $^{12}C/^{16}O$ ratio at the end of central He burning remains almost flat in the mass range 15 to 25 M_{sun} while increasing at lower masses.

The $^{12}C(\alpha,\gamma)^{16}O$ reaction competes with the 3α reaction for α-particles during He burning. The relative strengths of these two rates helps sets the carbon abundance at the end of He burning.

$$\dot{Y}_\alpha = -\frac{1}{2}\rho^2 Y_\alpha^3 R_{3\alpha} - Y_\alpha Y_{\rm C12}\rho R_{\alpha,\gamma}$$

$$\dot{Y}_{\rm C12} = \frac{1}{6}\rho^2 Y_\alpha^3 R_{3\alpha} - Y_\alpha Y_{\rm C12}\rho R_{\alpha,\gamma}$$

$$\dot{Y}_{\rm O16} = Y_\alpha Y_{\rm C12}\rho R_{\alpha,\gamma}$$

If Y_{C12} small or ρ large, then $\alpha \rightarrow {}^{12}C$

If Y_{C12} large or ρ small, then $\alpha \rightarrow {}^{16}O$

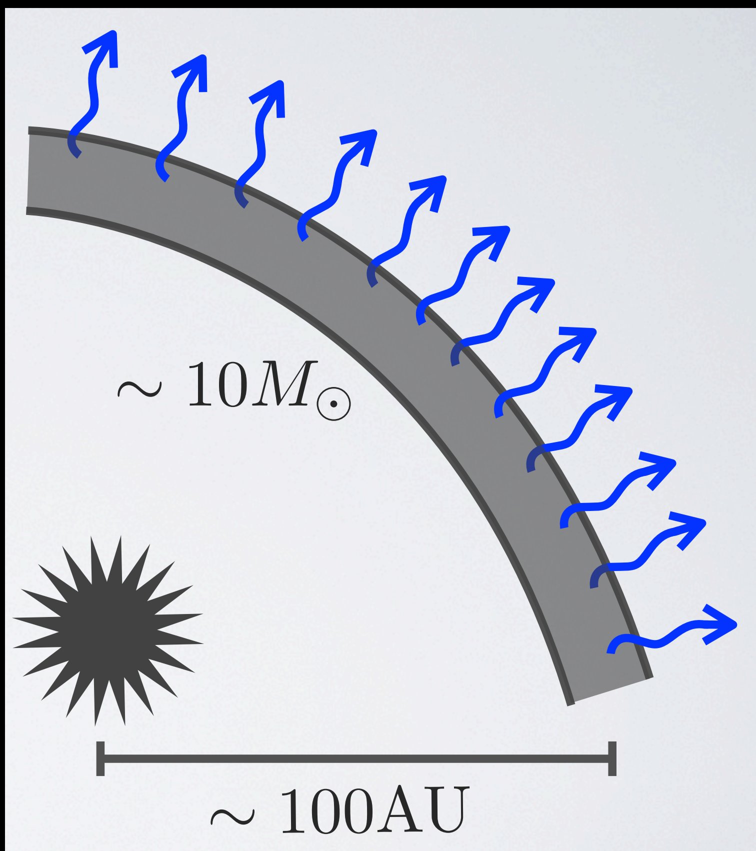
Uncertainty in the $^{12}C(\alpha,\gamma)$ rate is the single most important nuclear physics uncertainty in astrophysics.

Changing the $^{12}C(\alpha,\gamma)^{16}O$ rate or treatment of convection may alter, even significantly, the final carbon core mass.

Lab I will survey the sensitivity of the carbon core mass is to
physical [e.g., $^{12}C(\alpha,\gamma)^{16}O$ rate],
numerical [e.g., the spatial and temporal resolution], and
modeling [e.g., convection criterion and extra mixing] uncertainties.

Injecting energy into the envelopes of massive stars during late-stage (C, Ne, O) burning

Interaction in SNe IIn (SN2006gy, SN2011ht)



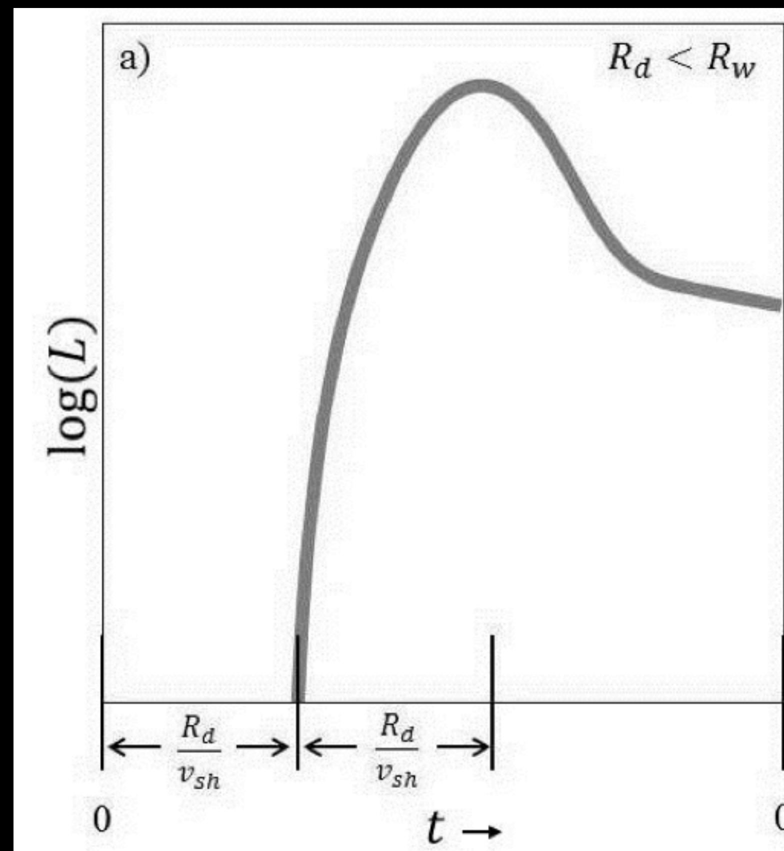
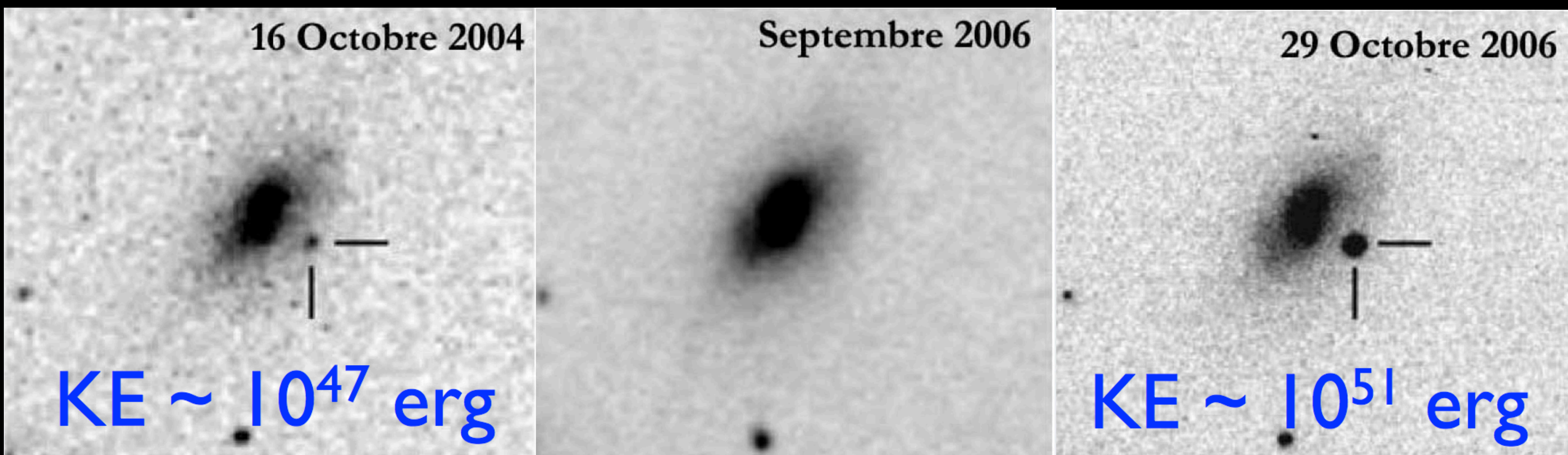


Figure Credits: Shiode; Chevalier & Irwin (2012)

Precursor Events (SN2006jc, SN2009ip)

Eruptions ~years before SN with energy scales capable of unbinding significant part of envelope



Pastorello et al. 2007

Late Stage Burning

Timescale of ~years before core-collapse is good. There is so much energy being generated in the core that tapping into a tiny fraction would be sufficient to unbind the envelope.

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

Quataert & Shiode 2012 [25 Msun]

Example Mechanism

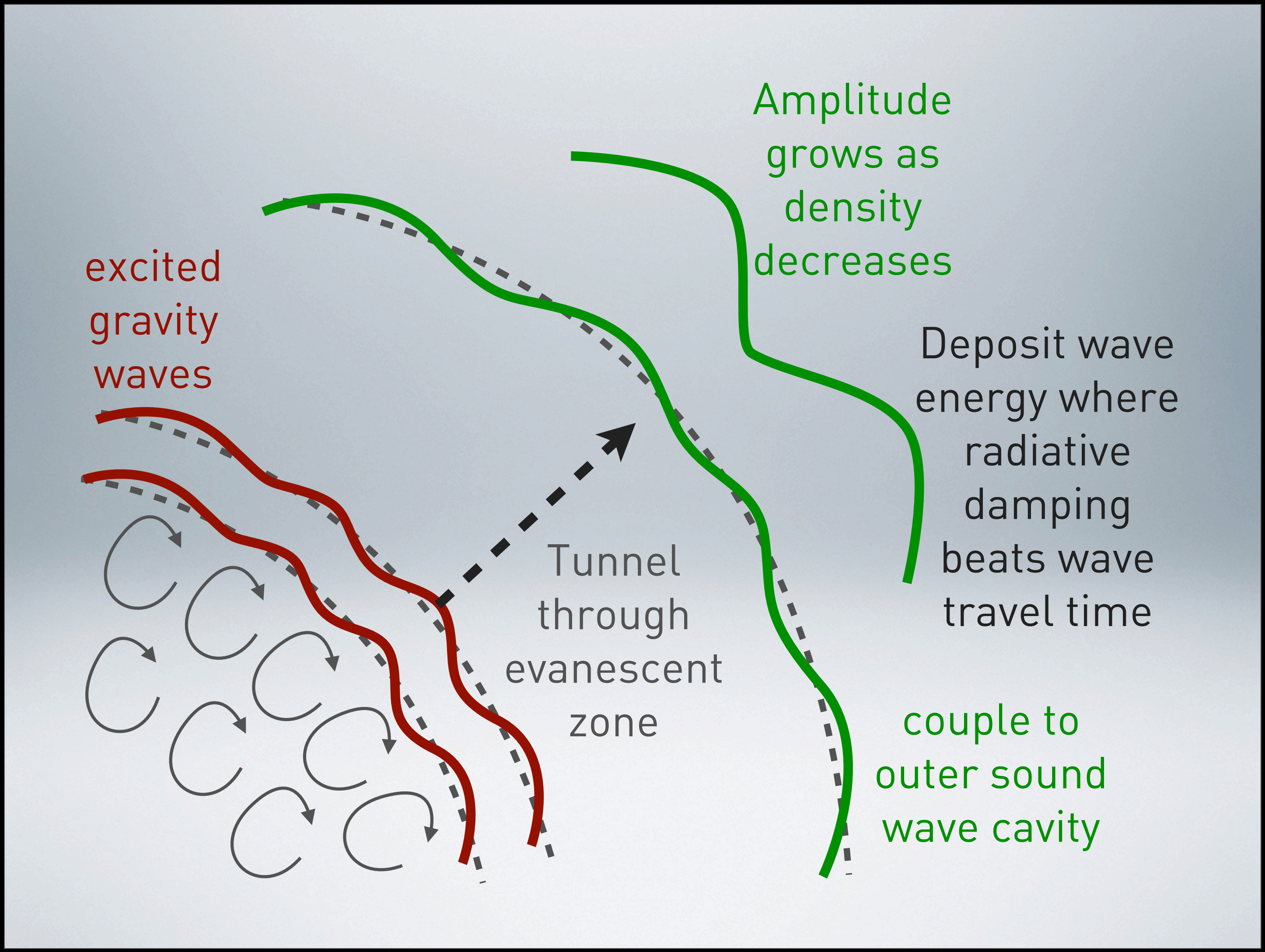


Figure Credit: Josh Shiode

Mini-Lab

Run a 15 M_{sun}, solar metallicity, no rotation, no mass loss to the end of helium burning.

Get inlist from
http://mesastar.org/documentation/mesa-summer-school-2013/massive-stars

Report your carbon core masses and your central $X(^{12}C)/X(^{16}O)$ ratio

Optional : Show a Kippenhahn Diagram of evolution.
Example python code from same URL.

MESA Groups and Settings for Labs I and II

Lab I - Sensitivity of a carbon core mass to physical, numerical, and modeling uncertainties

Start: from your mini-lab 15 M_{sun} inlist

Goal: report carbon core mass at the end of helium burning.

physical uncertainties:

try $^{12}C(\alpha,\gamma)^{16}O$ rate of 0.8 1.2, 1.5, 1.7, 2.0 times the nominal rate

numerical uncertainties: spatial and temporal resolution

try mesh_delta_coeff = 1.5, 1.2, 0.8, 0.5, 0.3

try convergence thresholds varcontrol_target 5×10^{-5} 3×10^{-4} 1×10^{-3}

modeling uncertainties: 1d mixing treatments, rotation, and mixing

schwartzchild + overshoot above H burning
try values of 0.003, 0.005, 0.01, 0.02

ledoux + semiconvection
try values of 0.0 10^{-3} 10^{-2} 10^{-1}

ledoux + overshoot
try values of 0.003, 0.005, 0.01, 0.02

slow rotators
try values Ω/Ω_{crit} of 0.01 0.02 0.05 0.1

minimum mixing diffusion coefficient as a proxy for rotation
try min D_mix of 10^4 10^8 10^{12} 10^{16} 10^{20}

Lab II- Response of a massive star envelope to energy deposition during late-stage (C, Ne, O) burning

Get inlist & initial models from
http://mesastar.org/documentation/mesa-summer-school-2013/massive-stars

Goal: report stellar radius at end of run
(either when $X_{Si} > 0.3$ or MESA gives up).

We will (artificially) dump energy into the envelope. MESA provides simple routines for introducing and controlling extra heating sources.

If we had MESA report a mass loss rate, it would depend on the super-Eddington wind model, etc.

So to keep things simple, we won't have MESA do any mass loss. Instead we'll observe the effects on the envelope structure and can then evaluate whether it could potentially drive significant mass loss.

I prepared 3 model files by running our mini-lab model up until central O-ignition and artificially stripping the envelope.

- 15 M_{sun} Red Supergiant
- 5 M_{sun} Red Supergiant
- 4 M_{sun} Wolf Rayet star (stripped down to He)

Your task is to use run_star_extras.f to dump varying amounts of energy into the envelope:
try Luminosity: 10, 30, 100 × L_{edd}

and vary the location of the energy deposition
try 15 M_{sun} & 5 M_{sun}: 0.1, 1.0, 10.0 × R_{sun}
4 M_{sun}: 0.1, 1.0, 2.0 × R_{sun}

Break

Lab I - Sensitivity of a carbon core mass to physical, numerical, and modeling uncertainties

Reiterate groupings and parameter values.

Report your carbon core mass at the end of He burning.

Optional: show a Kippenhahn Diagram of evolution.

Lab II - Response of a massive star envelope to energy deposition during late-stage (C, Ne, O) burning

Reiterate groupings and parameter values.

Report stellar radius at end of run.

Optional: show how the star's structure varies as energy is deposited

Overnight Lab - this is optional

Run your Lab I or Lab II model to core-collapse

Report your iron core mass and central Y_e in the morning