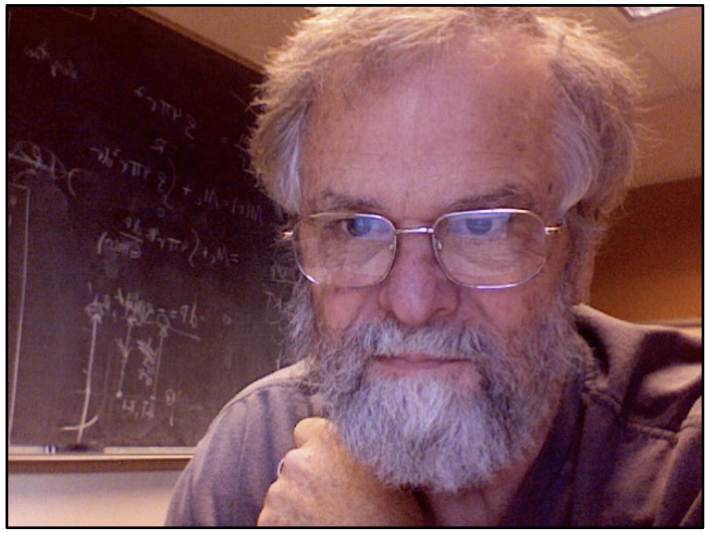
MESA

Modules for Experiments in Stellar Astrophysics

MESA is a state-of-the-art, modular, open source suite for stellar evolution



Bill Paxton, father of MESA

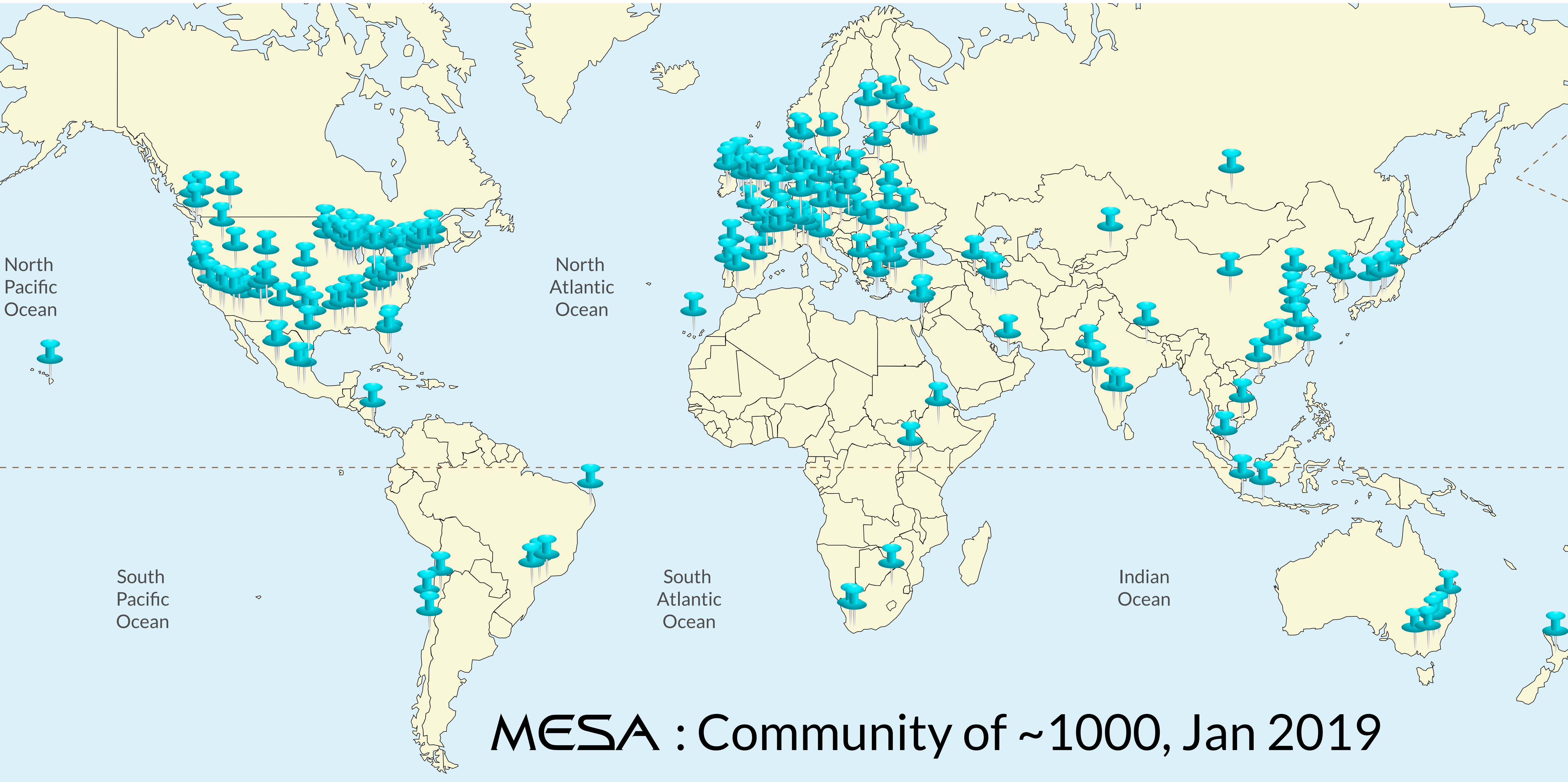
- MESA Stellar Evolution Code: mesa.sourceforge.net
- MESA Instrument Papers (Paxton et al. 2011, 2013, 2015, 2018, 2019)

MESA

- **Openness**: anyone can download sources from the website.
- **Modularity**: independent modules for physics and for numerical algorithms; the parts can be used stand-alone.
- **Wide Applicability**: capable of calculating the evolution of stars in a wide range of environments.
- **Modern Techniques**: advanced AMR, fully coupled solution for composition and abundances, mass loss and gain, etc.
- **Comprehensive Microphysics**: up-to-date, wide-ranging, flexible, and independently useable microphysics modules.
- **Performance**: runs well on a personal computer and makes effective use of parallelism with multi-core architectures.

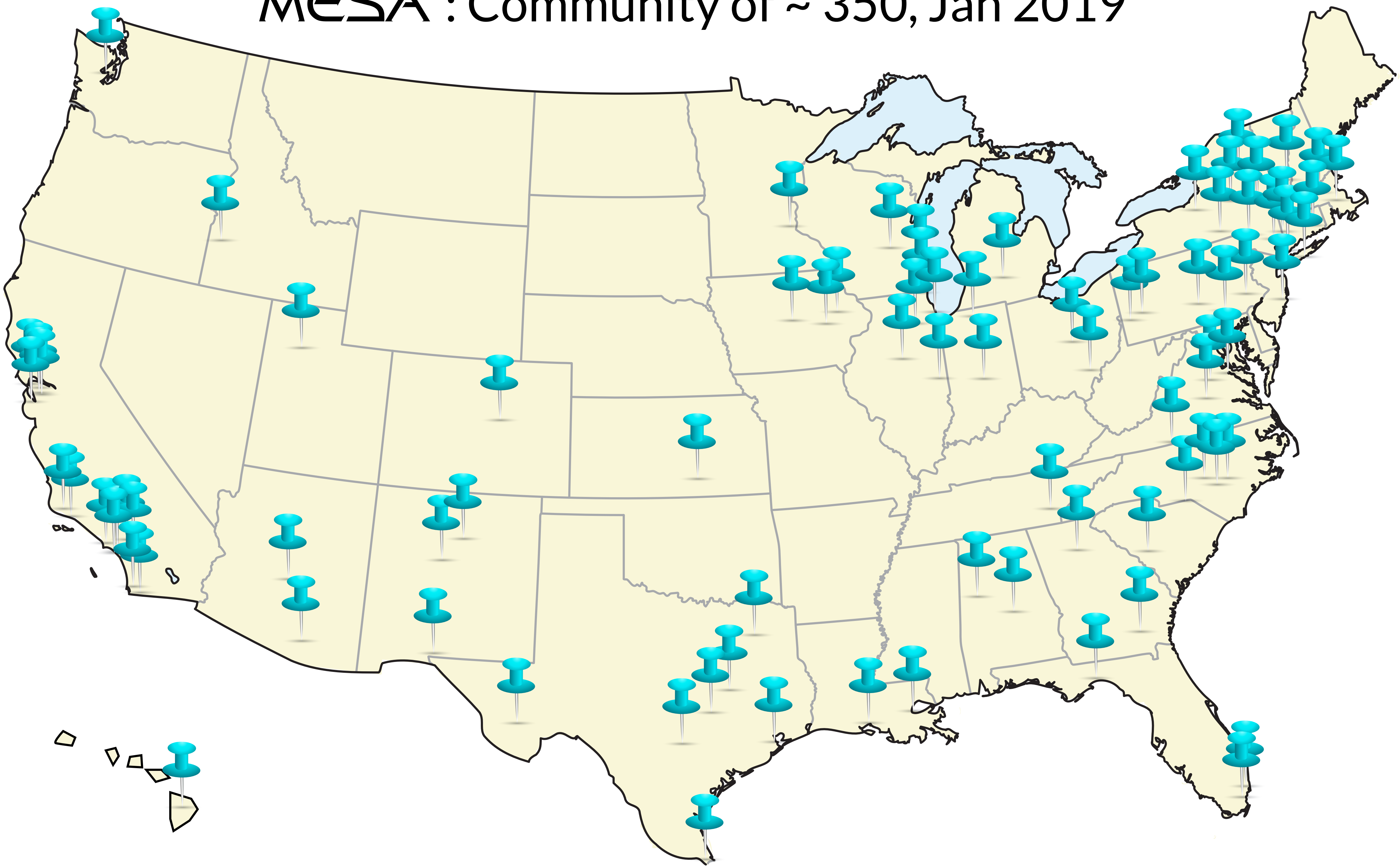
User Base

MESA

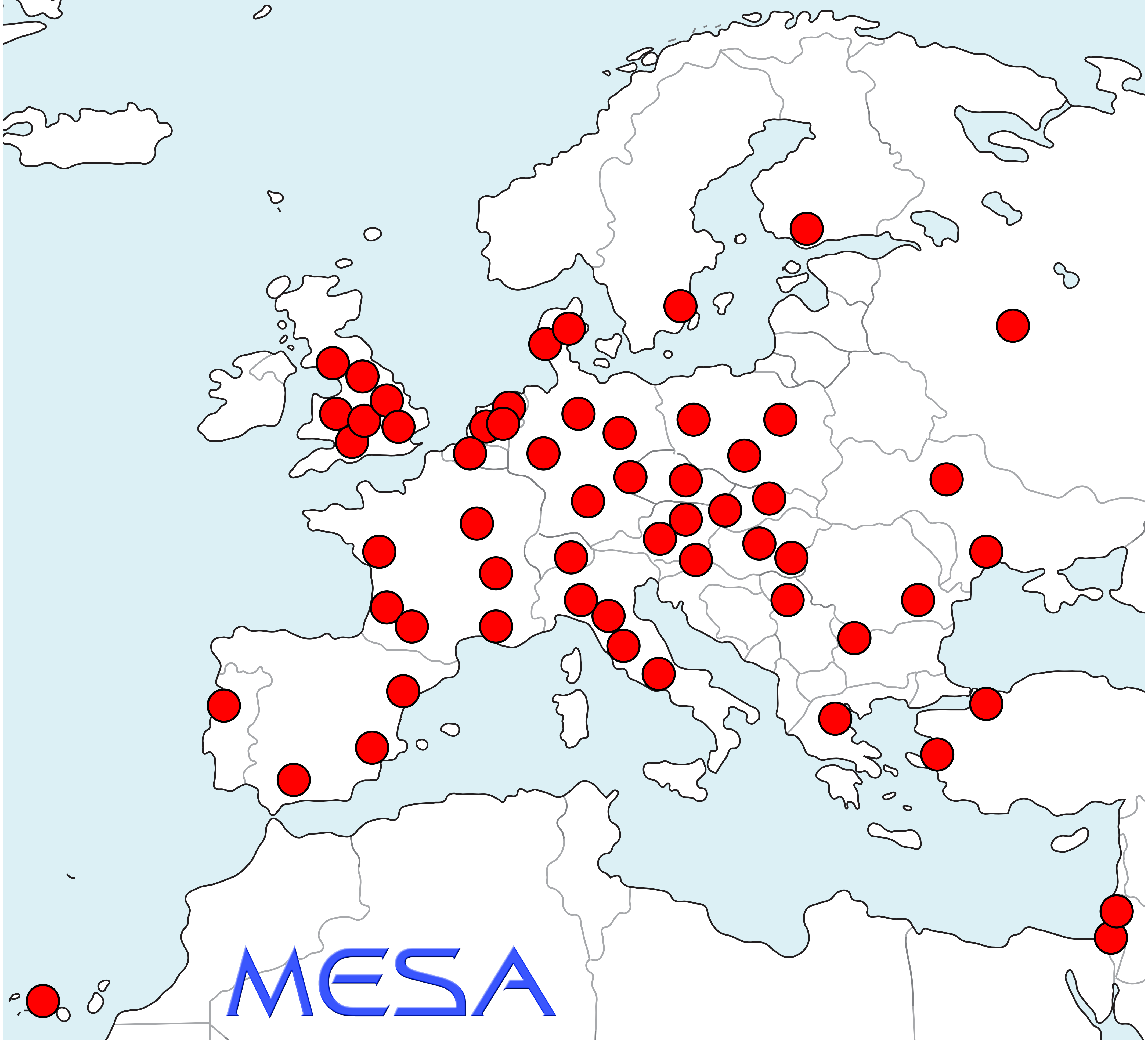

North Pacific Ocean
North Atlantic Ocean
South Pacific Ocean
South Atlantic Ocean
Indian Ocean
MESA : Community of ~1000, Jan 2019

MESA

MESA : Community of ~ 350, Jan 2019



MESA: ~410 Europe Users April 2014



MESA Capabilities

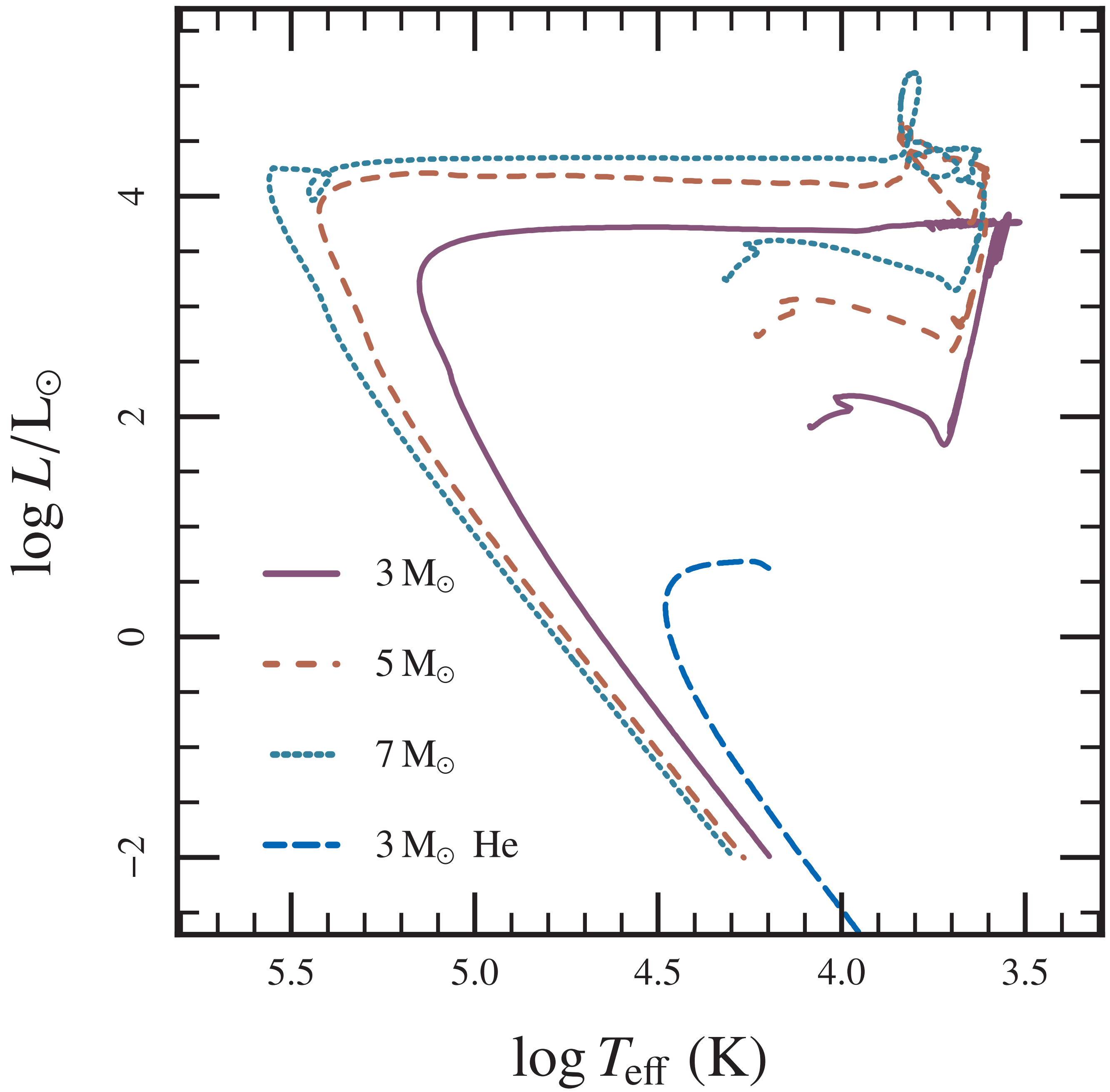
MESA Capabilities

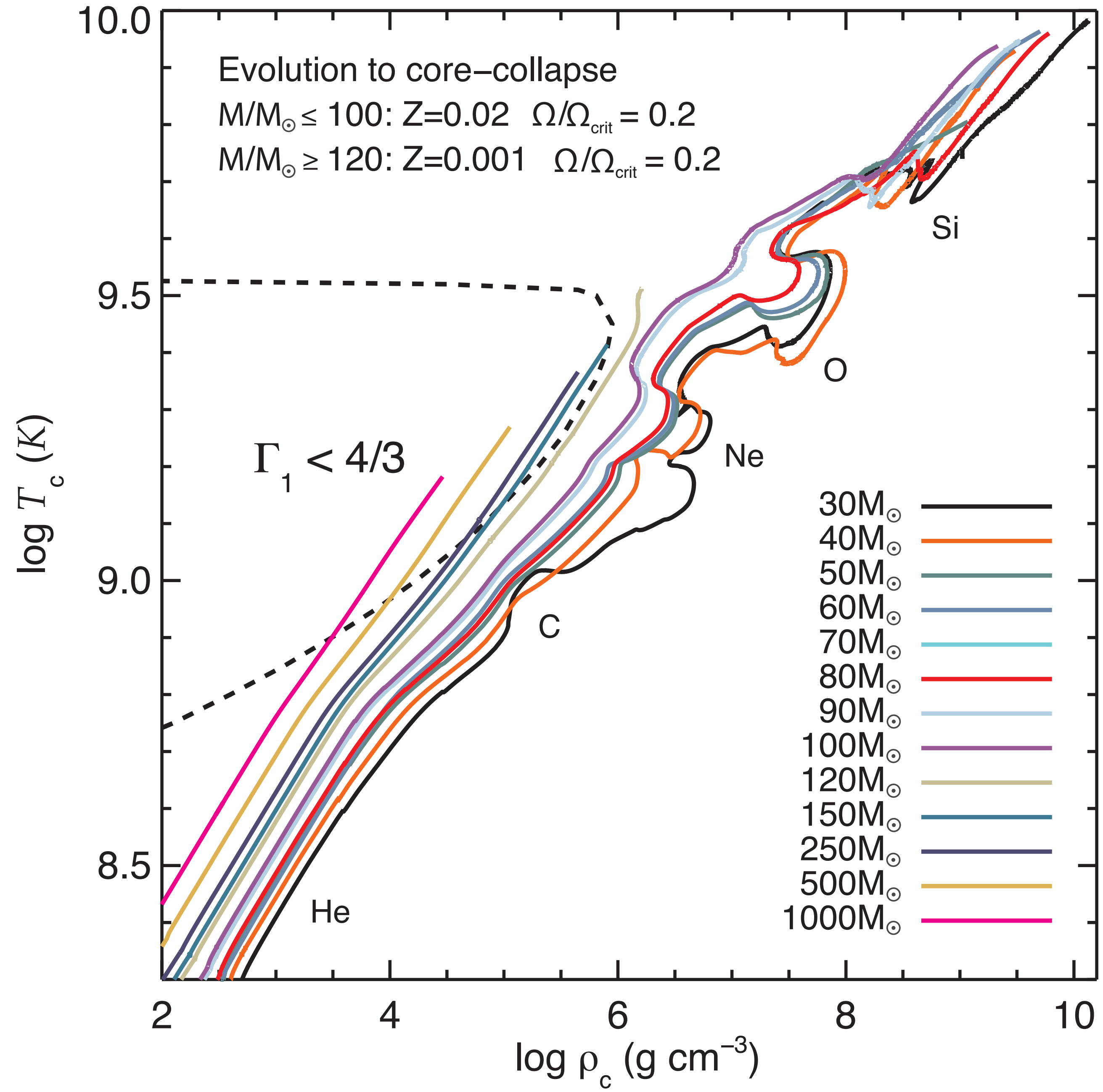
- Mass loss/gain, Schwarzschild/Ledoux, diffusion, double diffusion, gravitational settling, radiative levitation.
- It includes the physics of rotation (in a diffusion approximation) and of dynamo generated magnetic fields in radiative zones (Tayler-Spruit dynamo)
- Asteroseismology : MESA is natively coupled with two oscillations codes: ADIPLS (J. Christensen-Dalsgaard 2008) and the non-adiabatic code GYRE (Townsend & Teitler 2013)
- Giant planets, Low-mass stars, Massive Stars, Compact Objects, Asteroseismology, Accretion / Massloss...
- Binary stars evolution (accretion, tides, angular momentum transfer...)
- Implicit hydrodynamics, shocks. SN light curves (with STELLA)
- Radial Stellar Pulsations (with RSP)

(Paxton+ 2011, 2013, 2015, 2018, 2019)

Single stars with MESA

- Uninterrupted evolution to WD and core-collapse



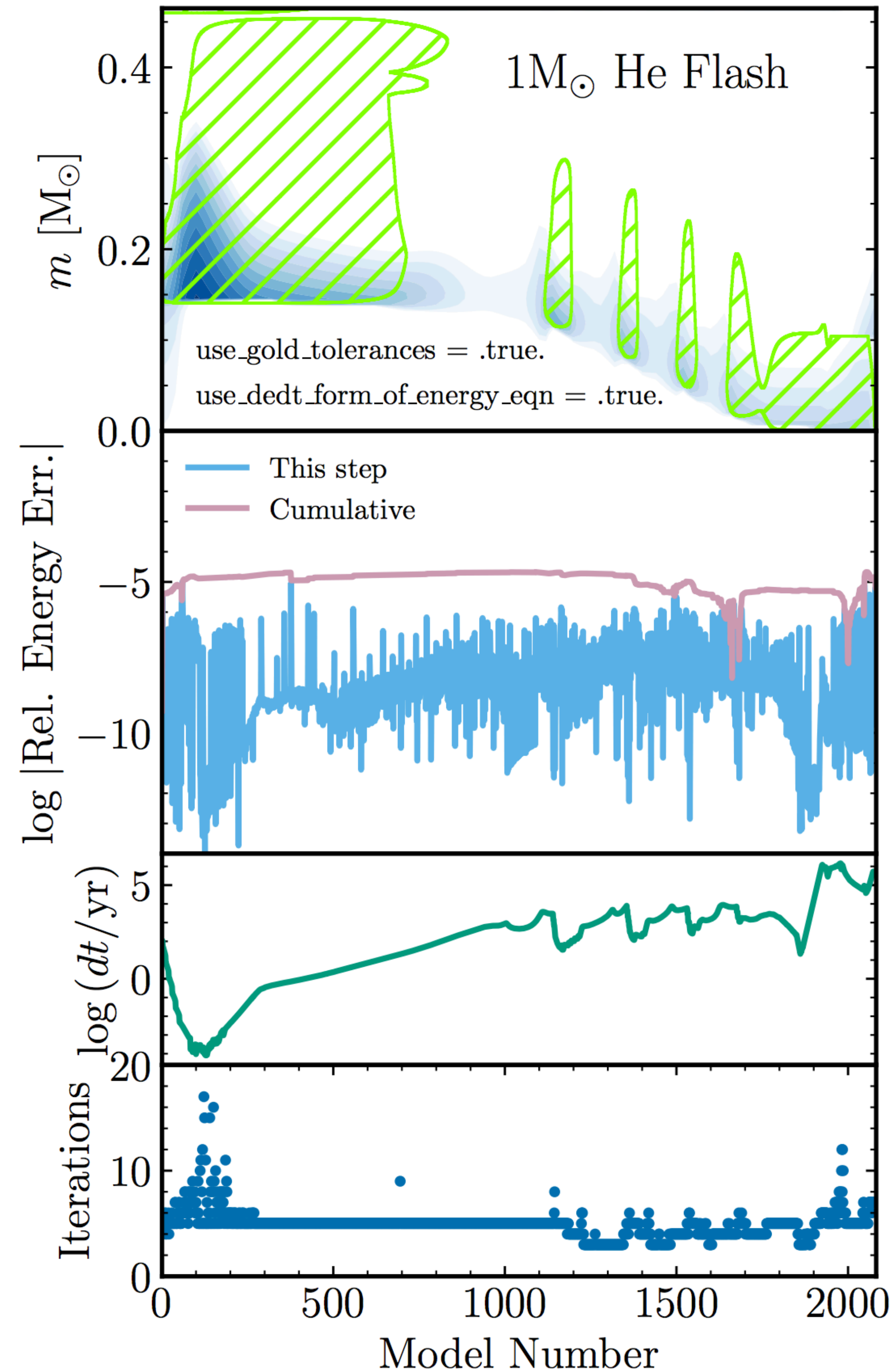


(Paxton+ 2013, 2015, 2018, 2019)

Energy Conservation

MESA performs uninterrupted calculations through the He flash that conserve energy to better than 0.001%

(Paxton+ 2019)



Single stars with MESA

- Mass loss/gain, Schwarzschild/Ledoux, overshooting, double diffusion, gravitational settling, radiative levitation…

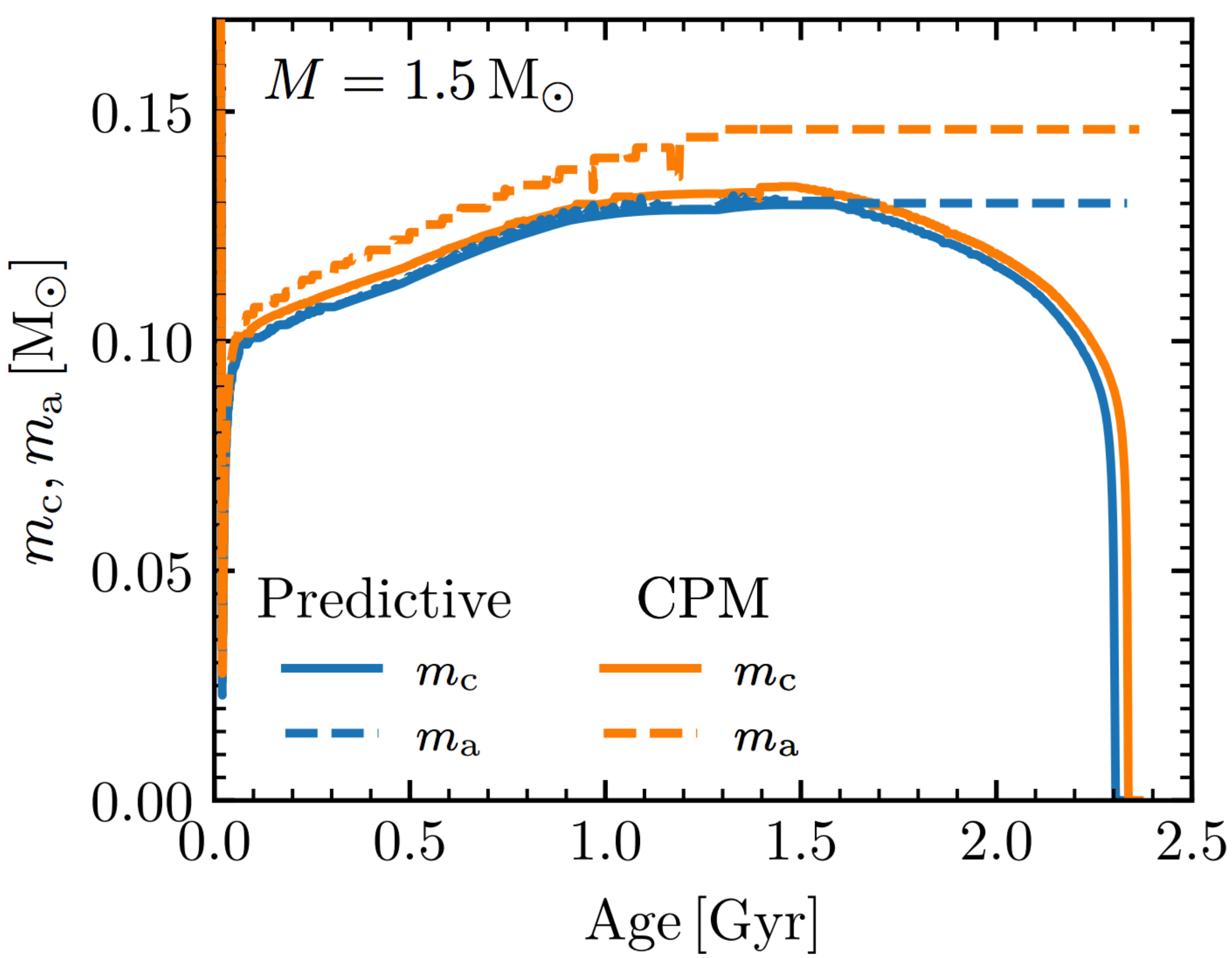
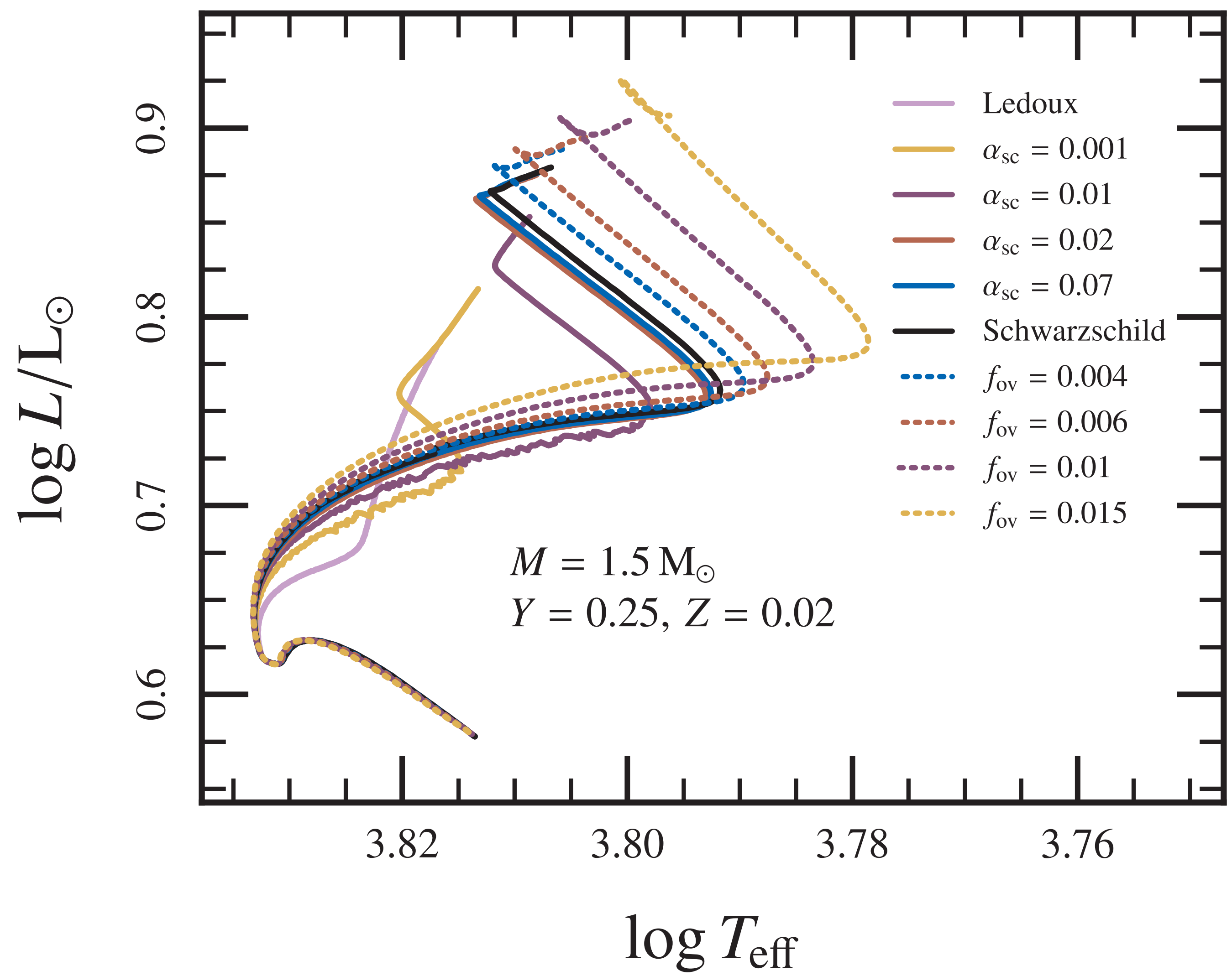


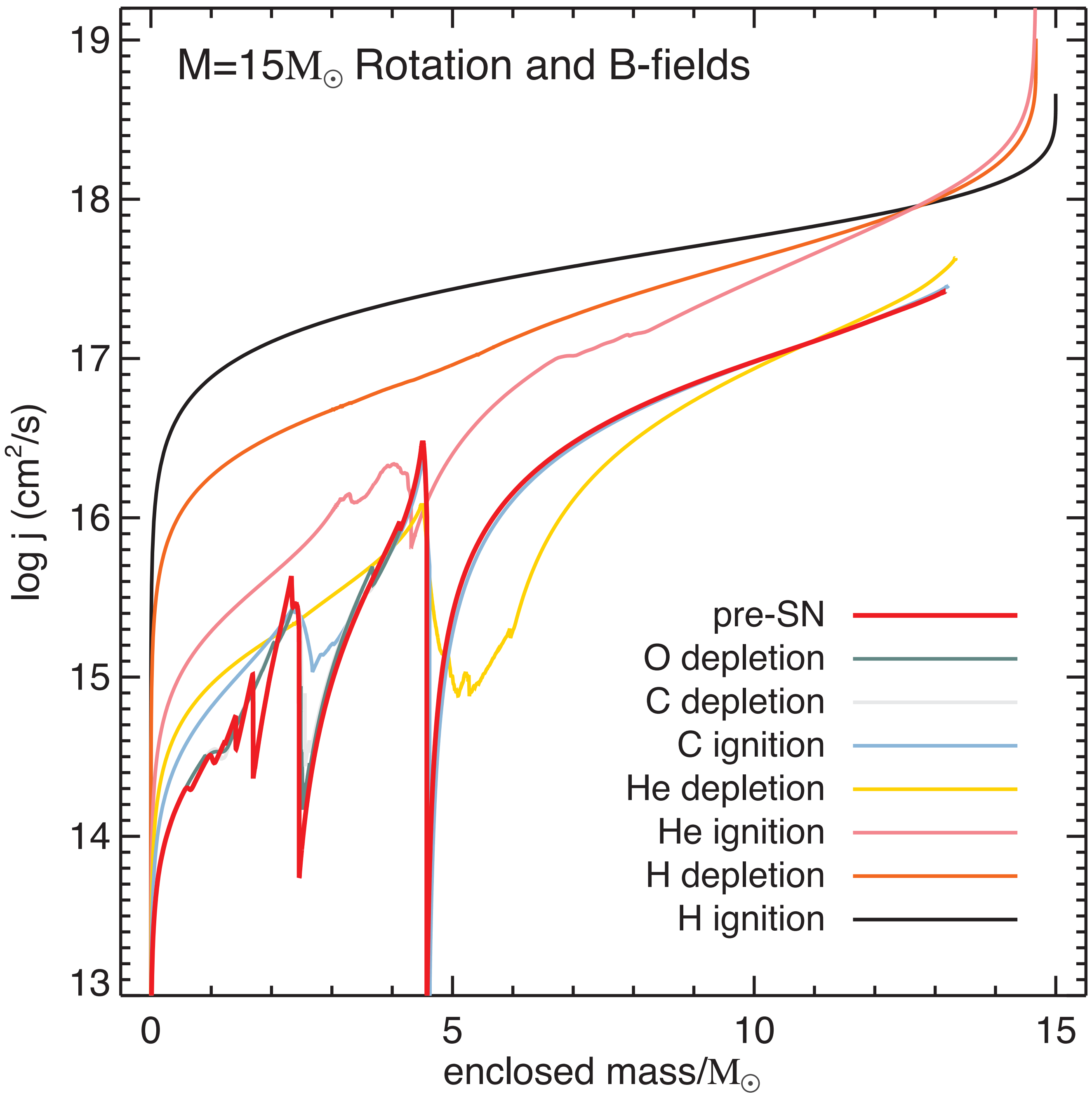
Figure 46. Mass coordinates of the convective core boundary (m_c) and the top of the abundance-gradient region (m_a) as a function of MS age, for the $1.5\,\mathrm{M}_\odot$ star. Different line colors show the separate runs discussed in the text.

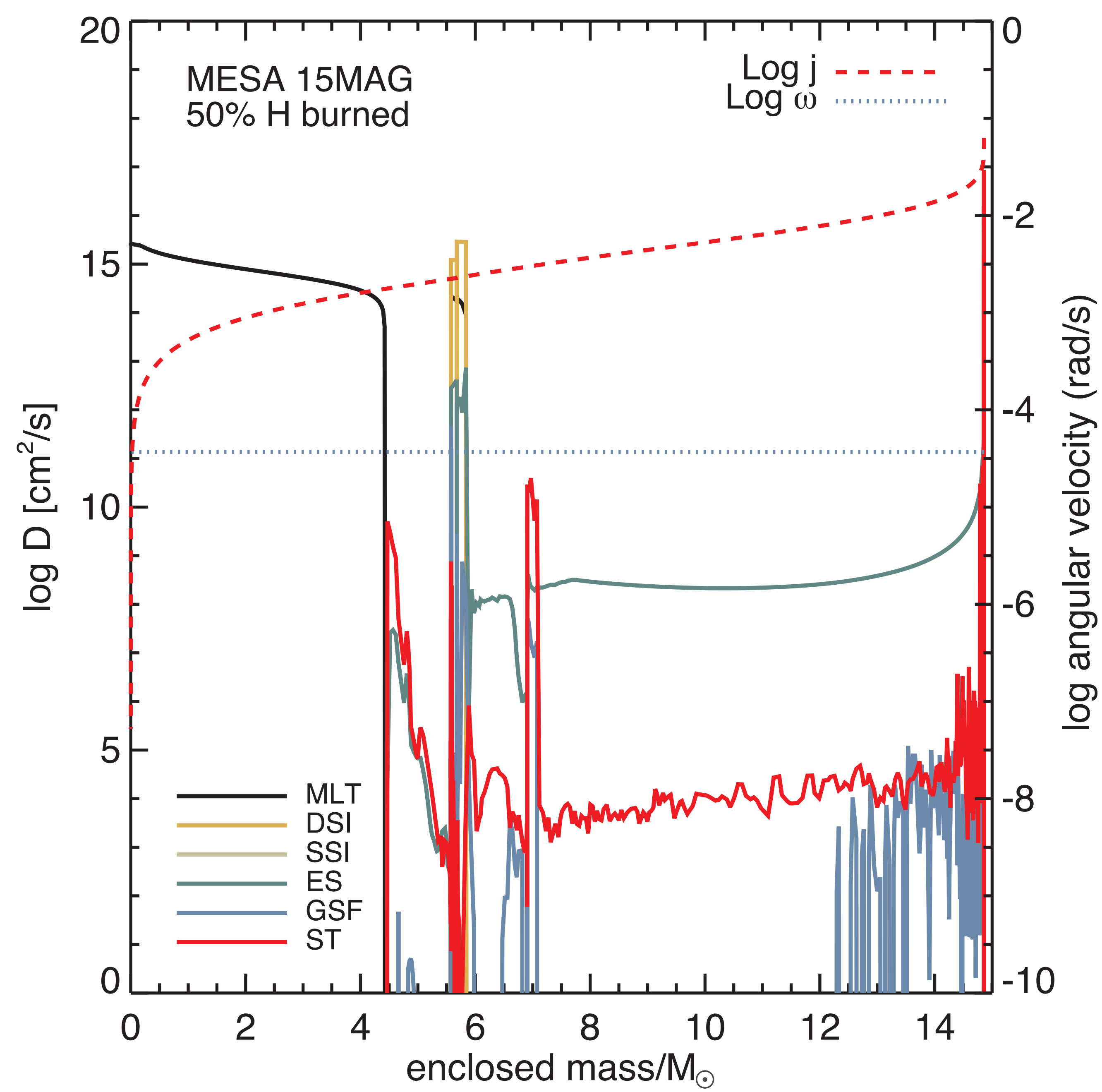


(Paxton+ 2013,2018,2019)

Single stars with MESA

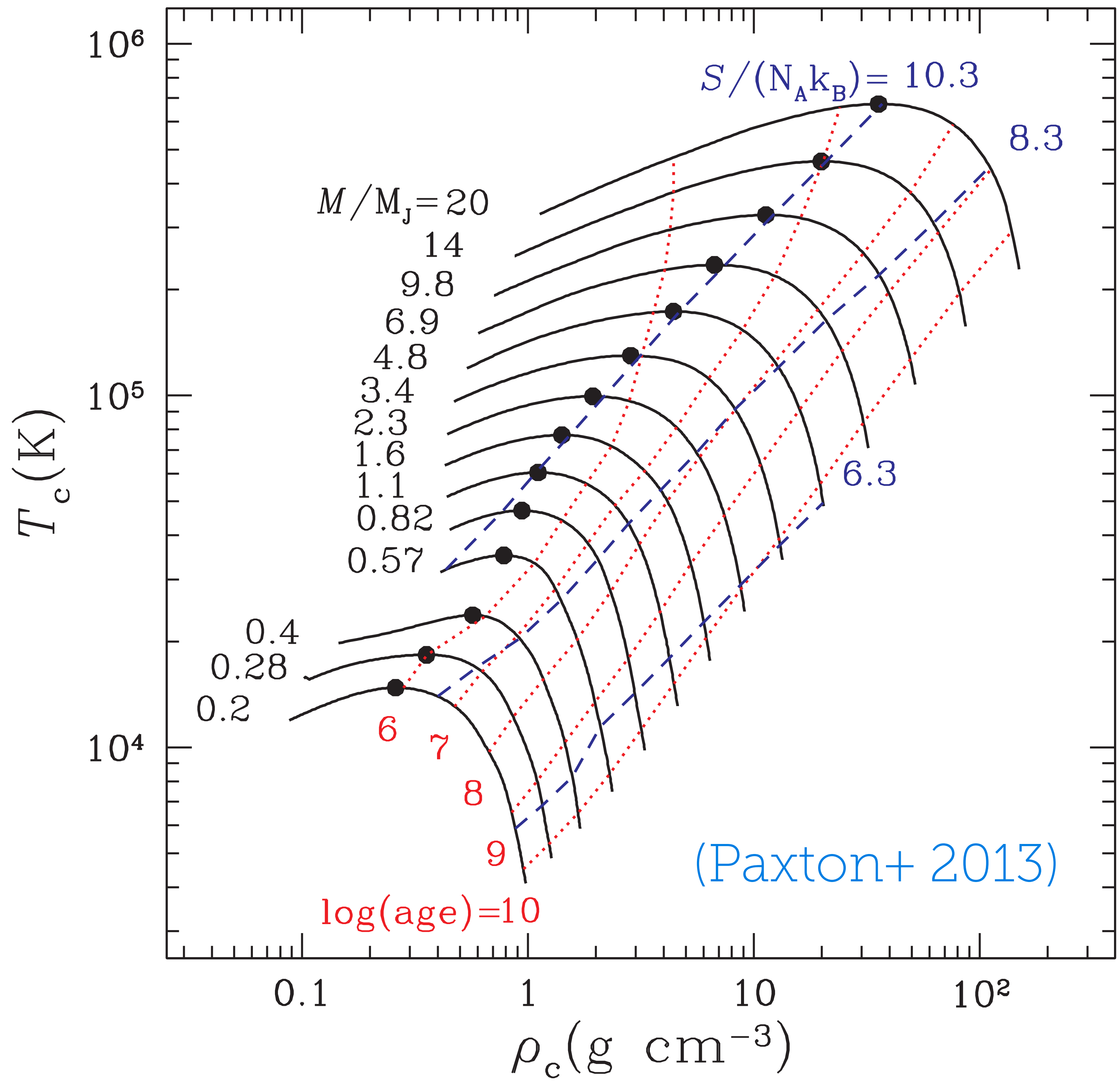
- Includes the physics of rotation (in a diffusion approximation) and of dynamo generated magnetic fields in radiative zones



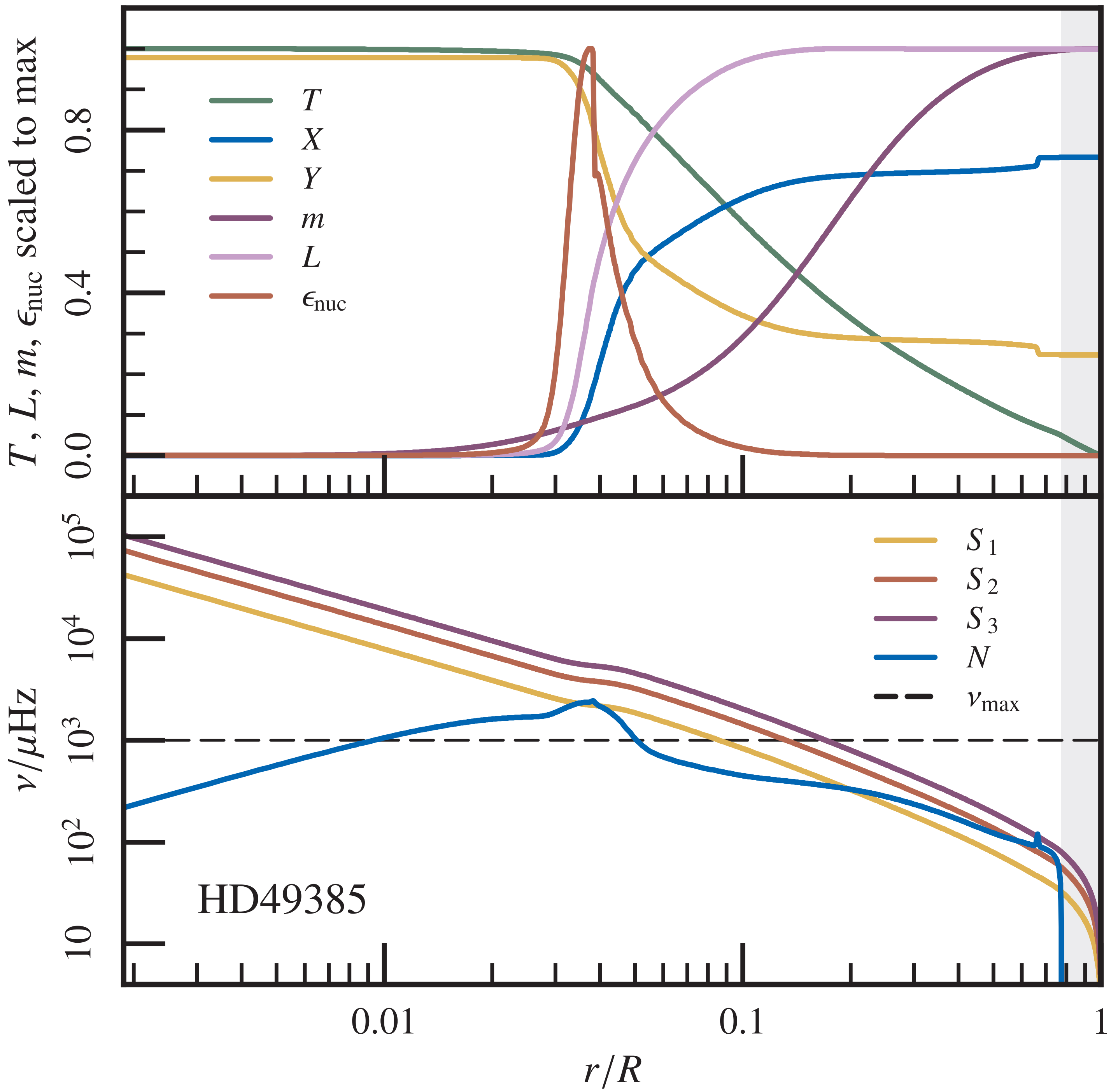


(Paxton+ 2013, 2019)

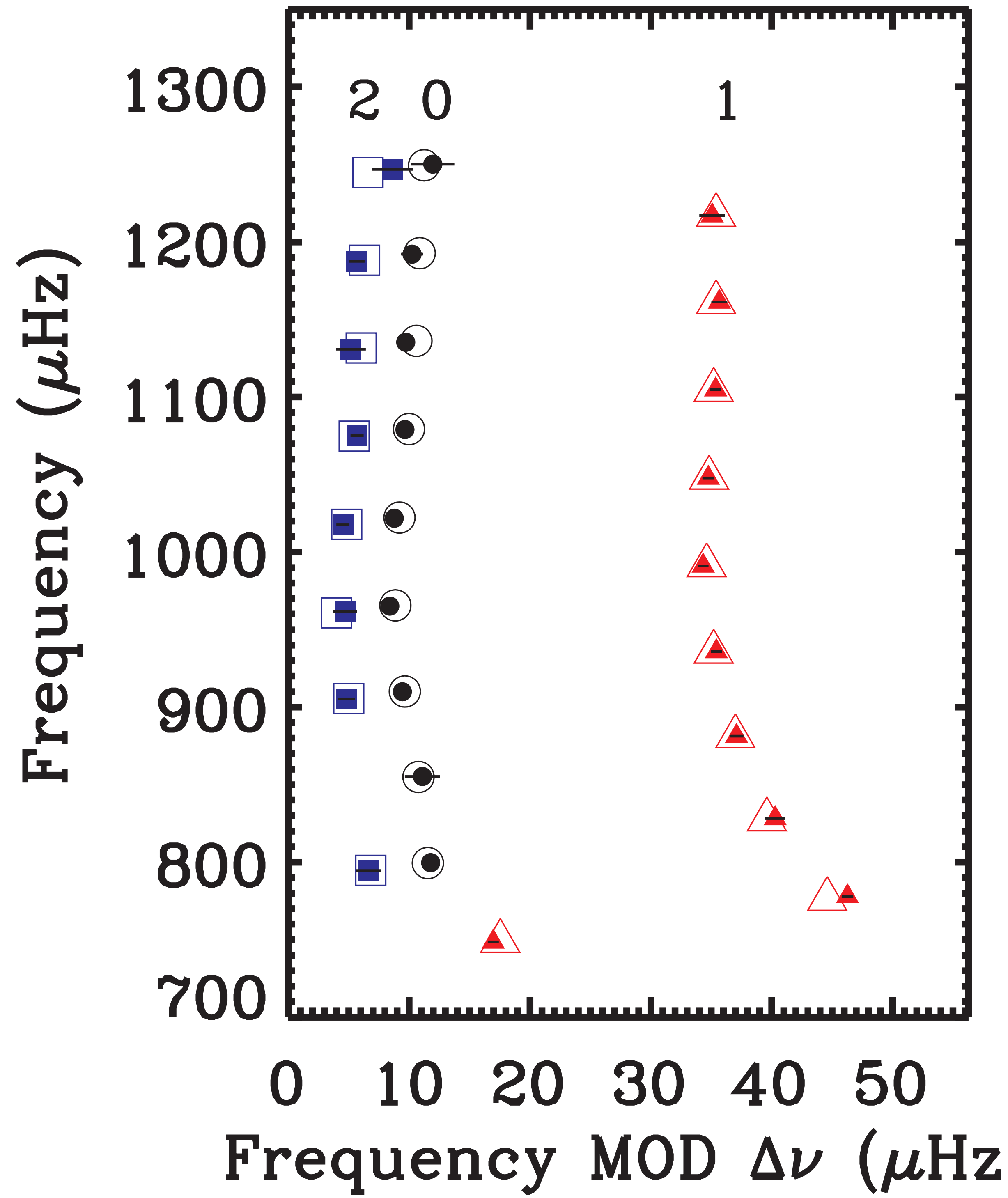
Giant Planets with MESA



Asteroseismology with MESA



(Paxton+ 2013)



Asteroseismology: MESA + GYRE

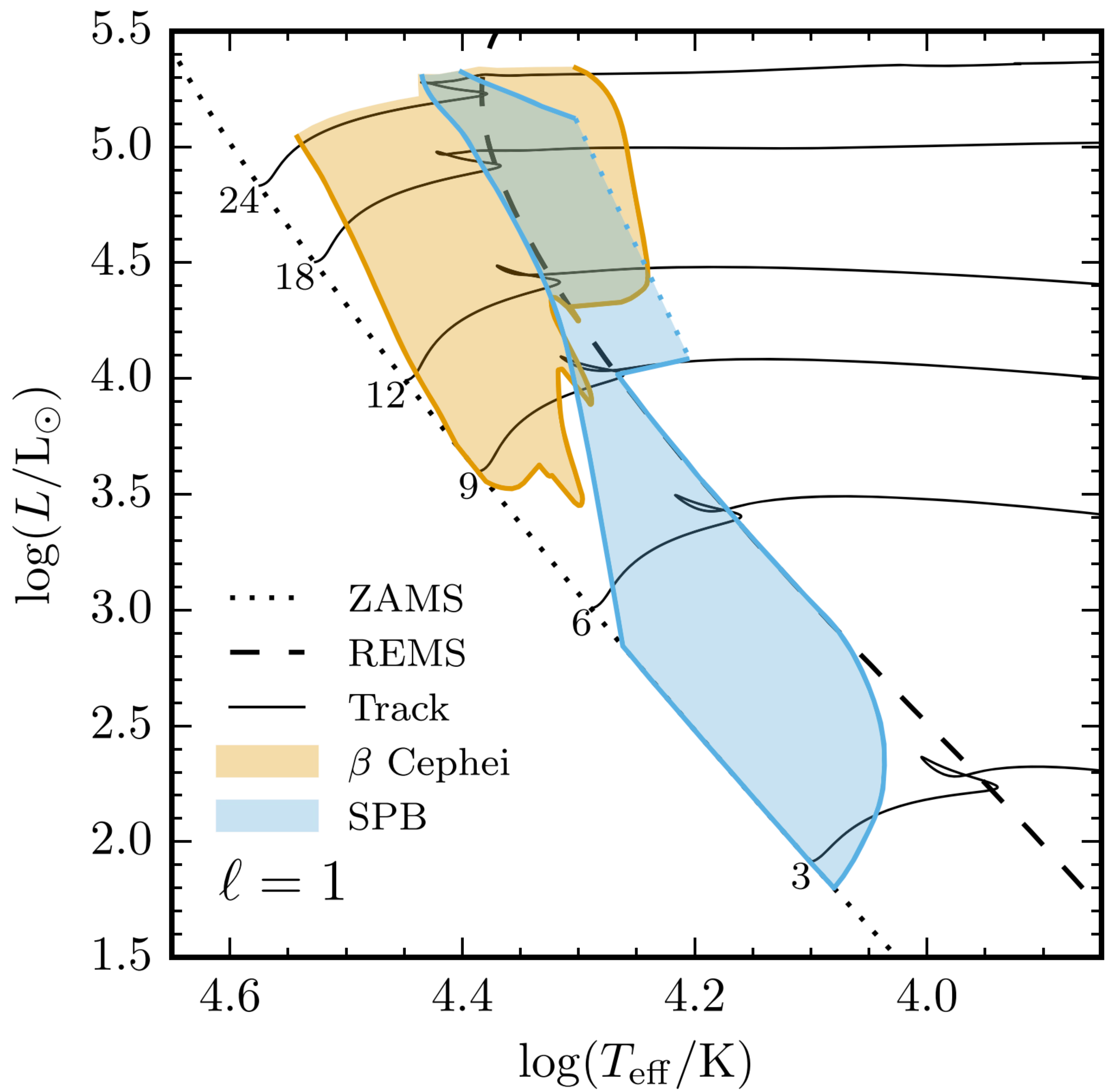


Figure 11. Instability strips for dipole ($\ell = 1$) oscillation modes in the upper part of the HR diagram, but calculated using OP rather than OPAL opacities (cf. Figure 9).

(Paxton+ 2015)

Binary Stars with MESA

- 2 stars evolved at the same time
- Implicit mass transfer
- Magnetic Braking (Rappaport, Verbunt & Joss 1983)
- GW-Braking
- Irradiation
- Tides (Zahn 1977, Tassoul & Tassoul)
- Angular momentum accretion
- L-S coupling

(Paxton+ 2013, 2015)

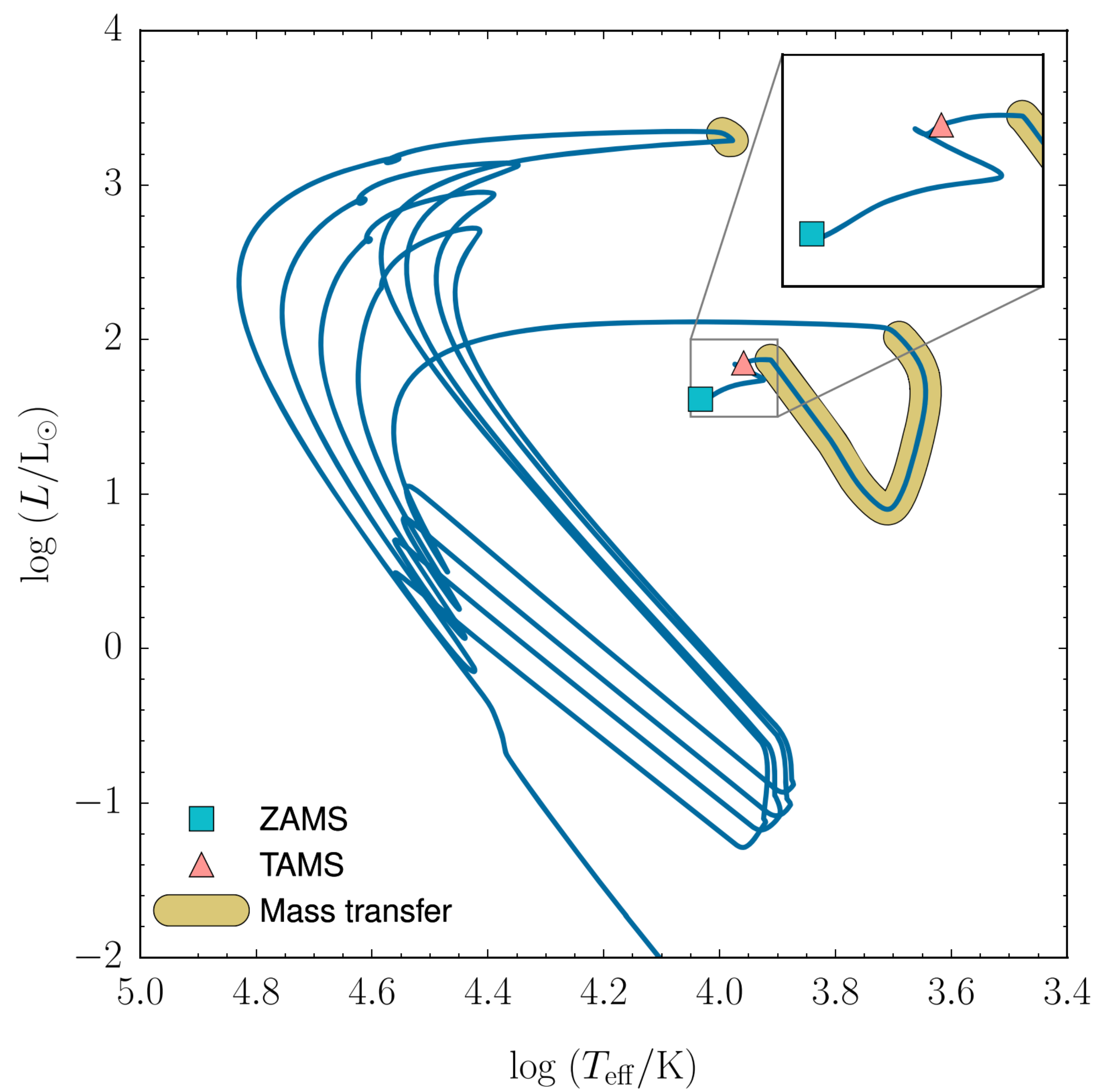


Figure 1. Evolution in the Hertzsprung-Russell (HR) diagram for a 2.5 $M_\odot$ star transferring mass to a 1.4 $M_\odot$ point mass, assuming a mass transfer efficiency of 1%. Symbols are shown at zero-age main sequence (ZAMS) and terminal-age main sequence (TAMS), together with parts of the track where RLOF is occurring. The inset shows evolution from ZAMS up to the beginning of the first phase of mass transfer.

Binary Stars with MESA

- 2 stars evolved at the same time
- Implicit mass transfer

(Paxton+ 2013, 2015)

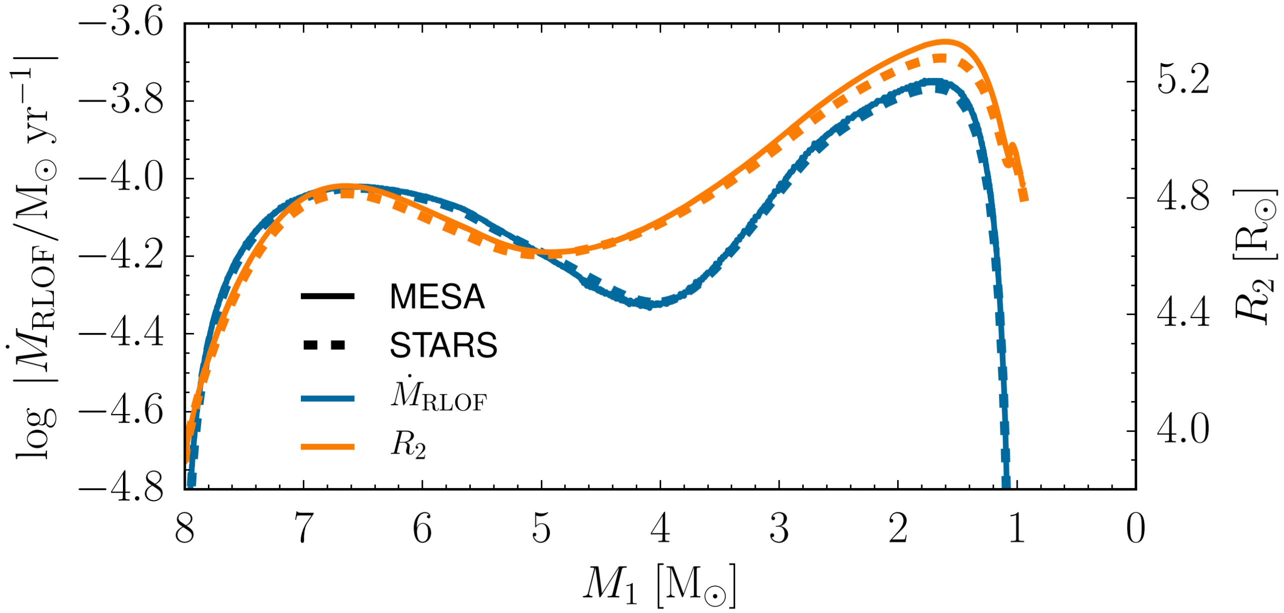


Figure 4. Mass transfer rate and accretor radius as computed by MESA and STARS for an 8 $M_\odot$ + 6.5 $M_\odot$ binary with an initial orbital period of 3 days. All internal mixing processes (including convective mixing) are turned off in the calculations.

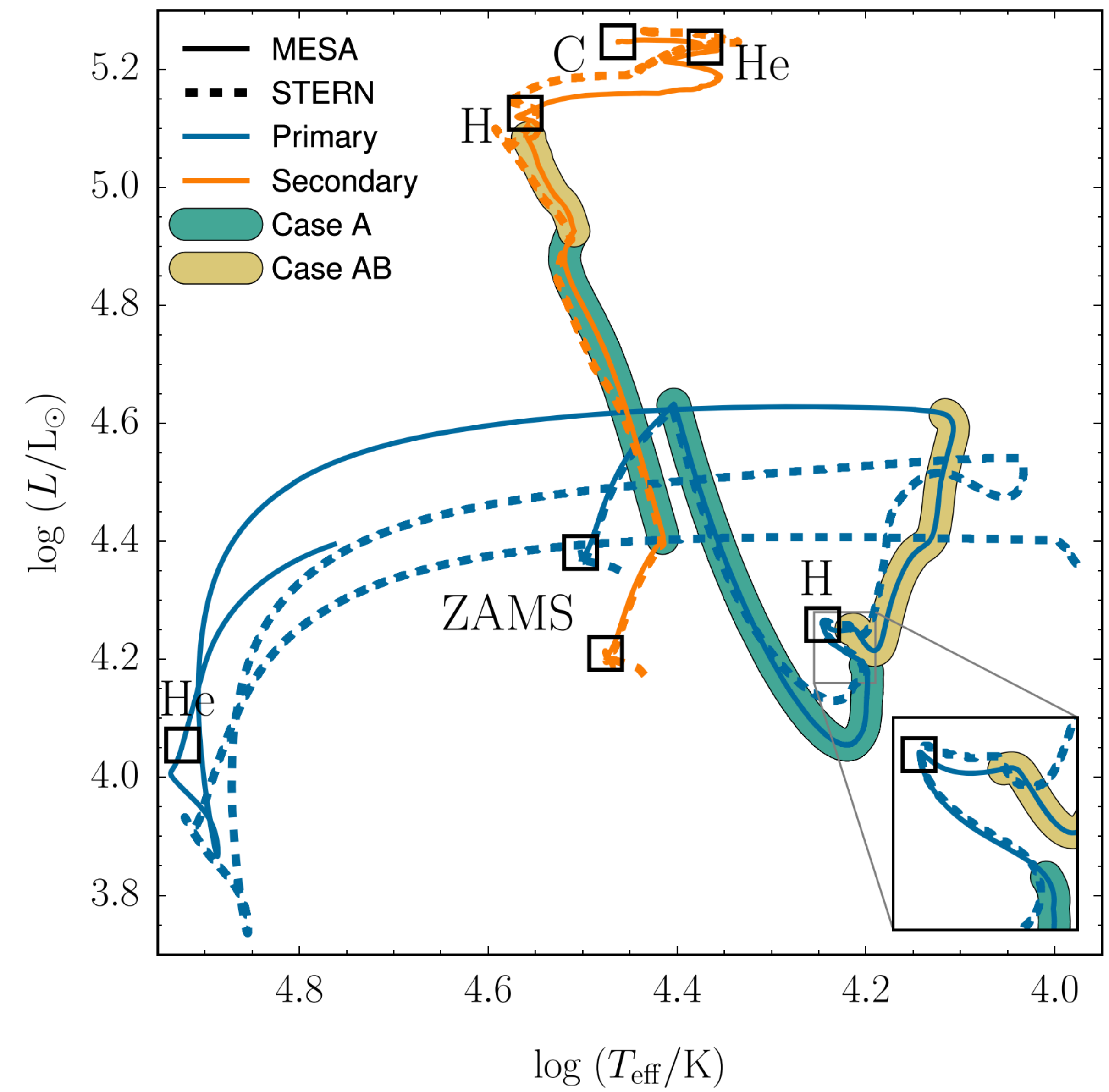


Figure 6. Evolution of a 16 $M_\odot$ + 14 $M_\odot$ system with a 3 day initial orbital period. MESAbinary models are compared to the results of Wellstein et al. (2001), which were calculated using the STERN code. The terms primary and secondary are used throughout the evolution to describe the initially more massive and the less massive components, respectively. For each component in the MESAbinary model, squares mark the ZAMS and the depletion of the indicated nuclear fuel in the core.

Binary Stars with MESA

- Tides
- J-accretion/loss
- L-S coupling

(Paxton+ 2013, 2015)

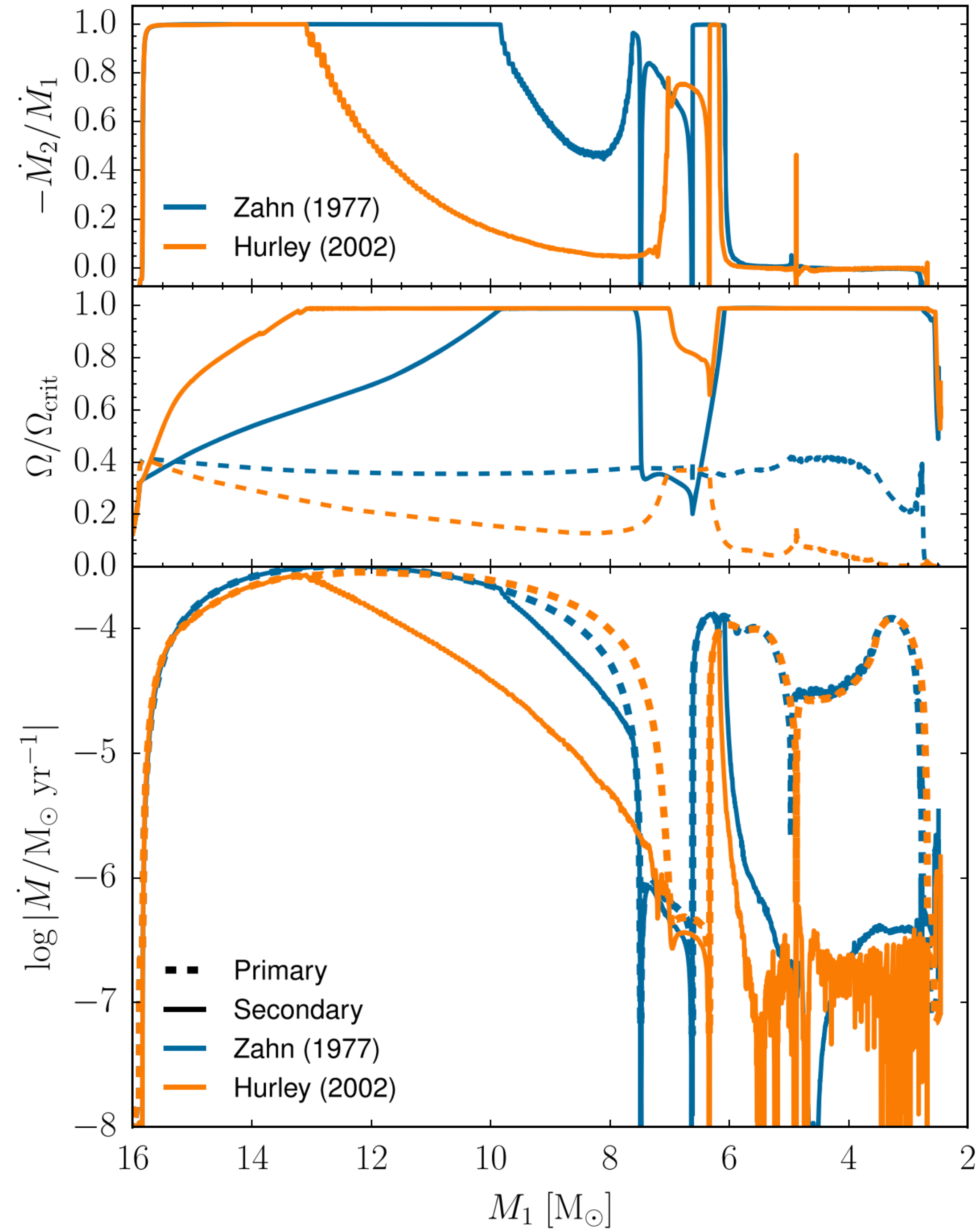


Figure 8. Efficiency of mass transfer in a 16 $\mathrm{M}_\odot$ + 15 $\mathrm{M}_\odot$ binary system including differential rotation. The system is modeled with tides as described by Hurley et al. (2002) for radiative envelopes, and also with the simple tidal timescale given by Zahn (1977). The upper panel shows the efficiency of mass transfer, the middle panel the angular frequency of each star in terms of its critical value, while the lower panel shows the evolution of $\dot{M}$ for both components.

Binary Stars with MESA

- 2 stars evolved at the same time
- Implicit mass transfer
- Magnetic Braking (Rappaport, Verbunt & Joss 1983)
- GW-Braking
- Irradiation
- Tides (Zahn 1977, Tassoul & Tassoul)
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(Paxton+ 2013, 2015)

Implicit Hydrodynamics MESA

- Sedov Blast Wave

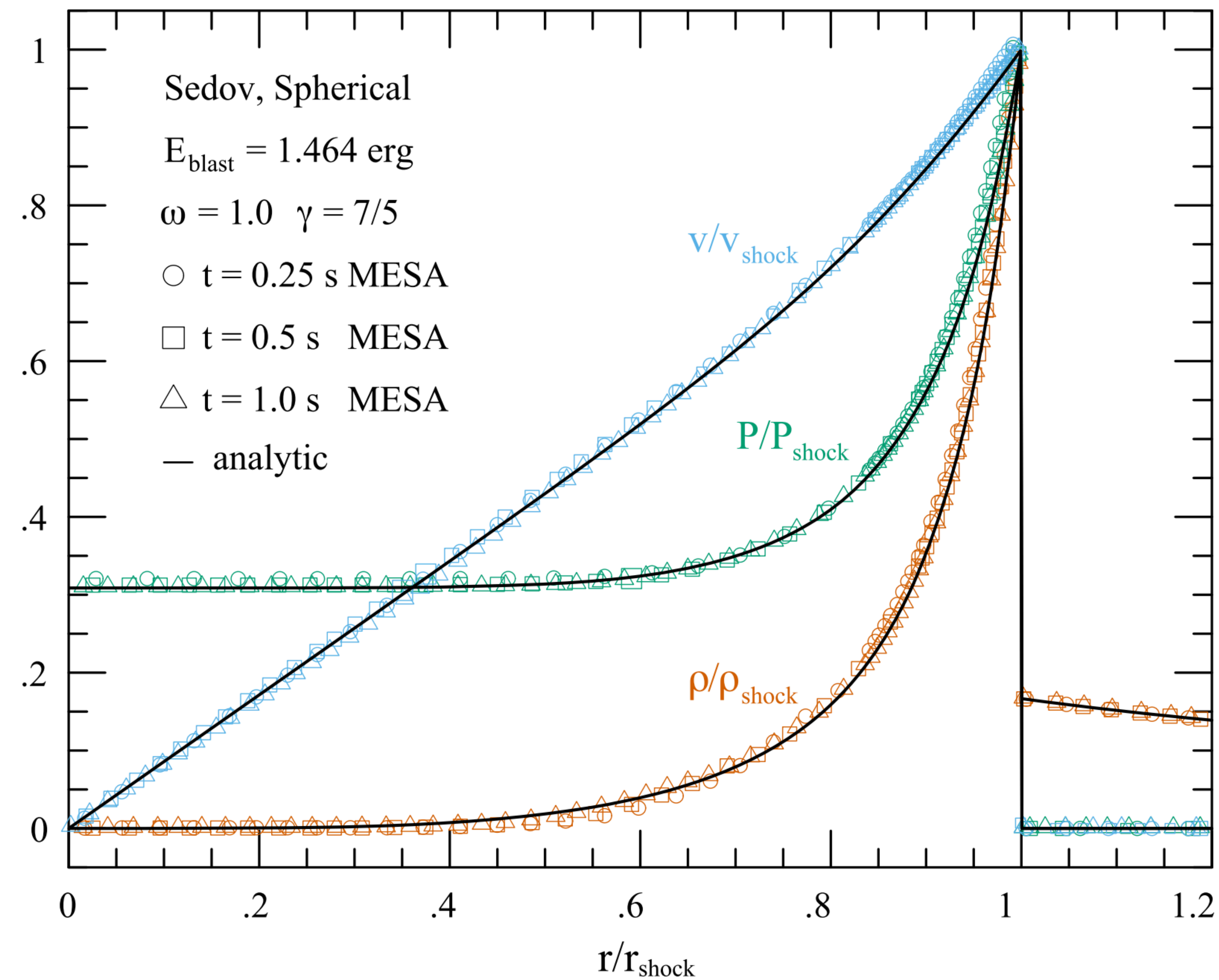


Figure 21. Sedov blast wave self-similarity of the analytic (black curves) and MESA (colored symbols) solutions. Scaled velocity $v/v_{\rm shock}$, pressure $P/P_{\rm shock}$, and density $\rho/\rho_{\rm shock}$ profiles for a shock propagating down a $\rho = \rho_0 r^{-1}$ density profile at the three different times are overlaid. Symbols for each epoch mark cell locations. Deviations from the analytic self-similar solutions are $\lesssim$2%.

(Paxton+ 2018)

Implicit Hydrodynamics MESA

- Supernova Shock

(Paxton+ 2018)

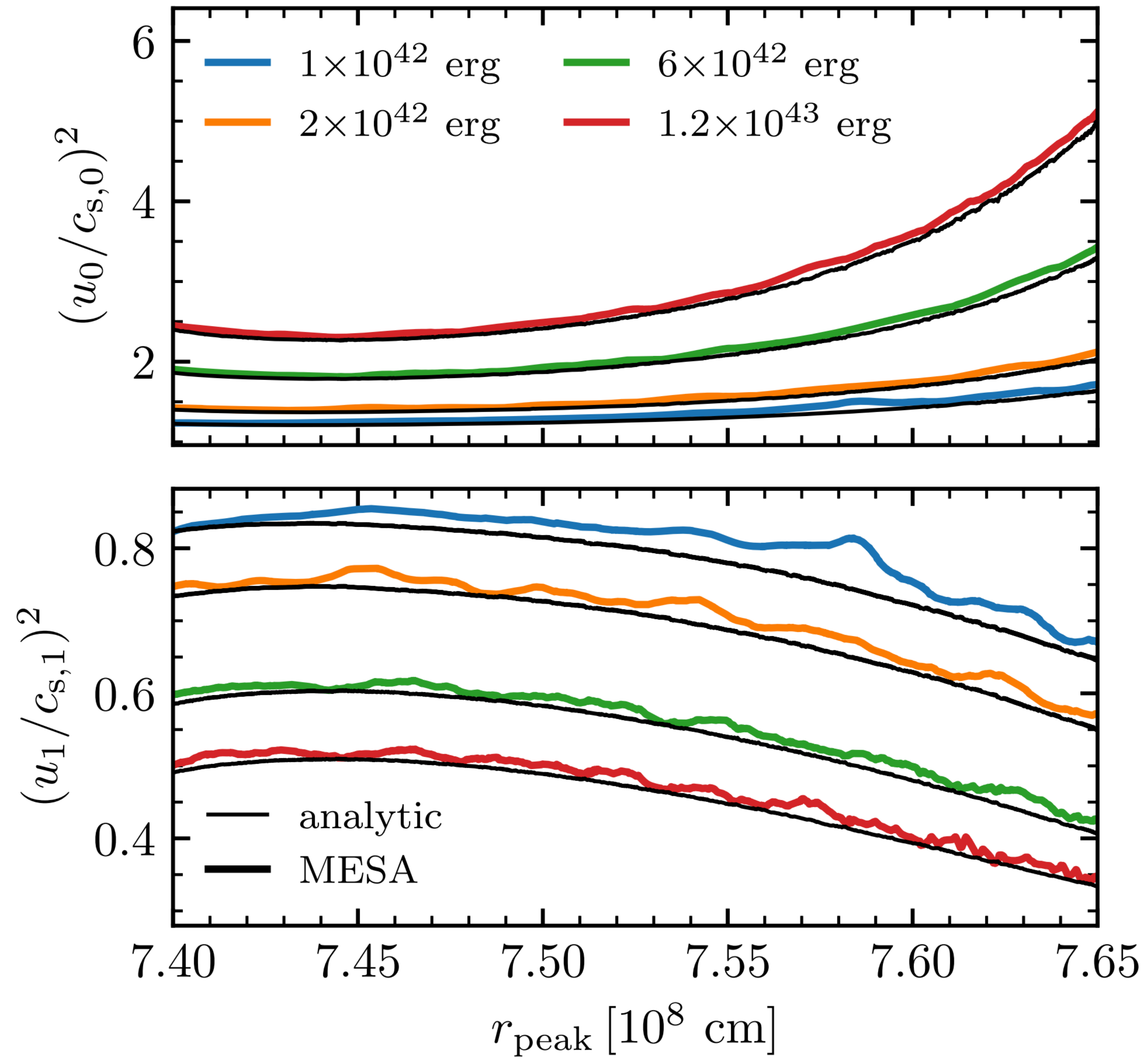


Figure 25. Comparison of the MESA calculation (colored lines) with analytic expressions (thin black lines) for $(u_0/c_{s,0})^2$ (upper) and $(u_1/c_{s,1})^2$ (lower) for different energies injected.

Rayleigh-Taylor Instability (RTI)

- RTI: Duffel (2016) advection-diffusion 1D scheme

(Paxton+ 2018)

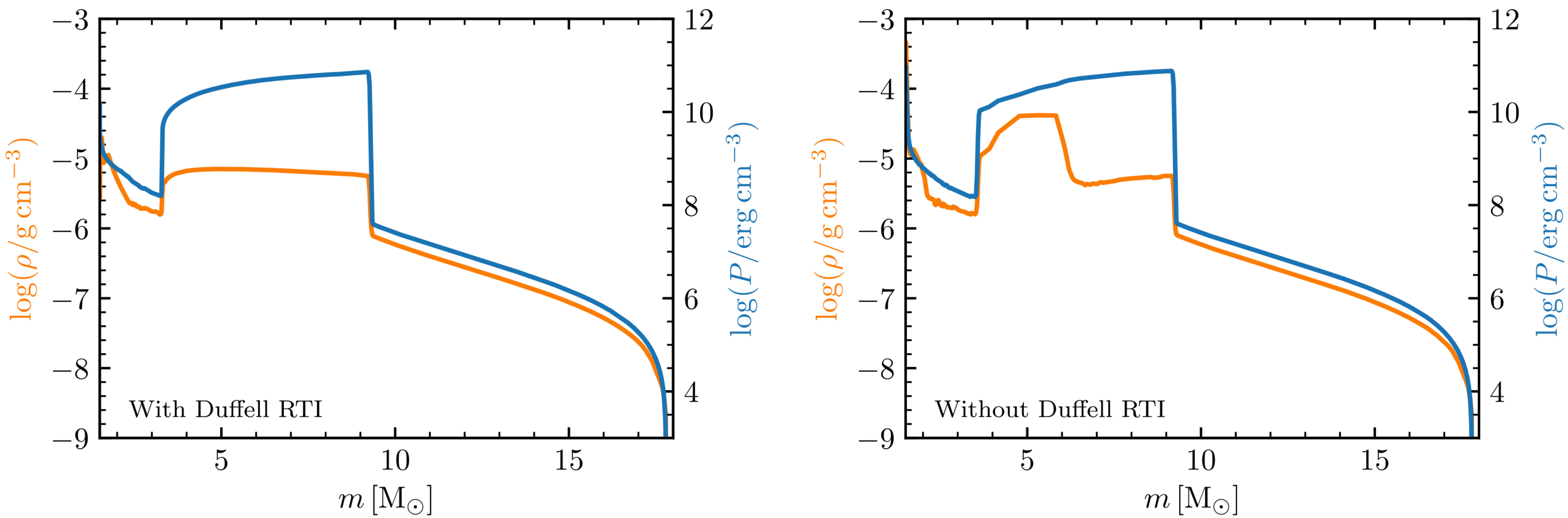


Figure 29. Density (left y-axis, orange curves) and pressure (right y-axis, blue curves) for MESA models with the Duffell RTI (left panel) and without any RTI effects (right panel) at a time when the forward shock is approximately halfway through the star. The animated figure shows the time evolution of these and other quantities for each case.

SN Lightcurves: MESA + STELLA

- The STELLA code (Blinnikov+ 1998) is included with the MESA distribution, and the interface from MESA to STELLA has been customized for ease of use.

(Paxton+ 2018)

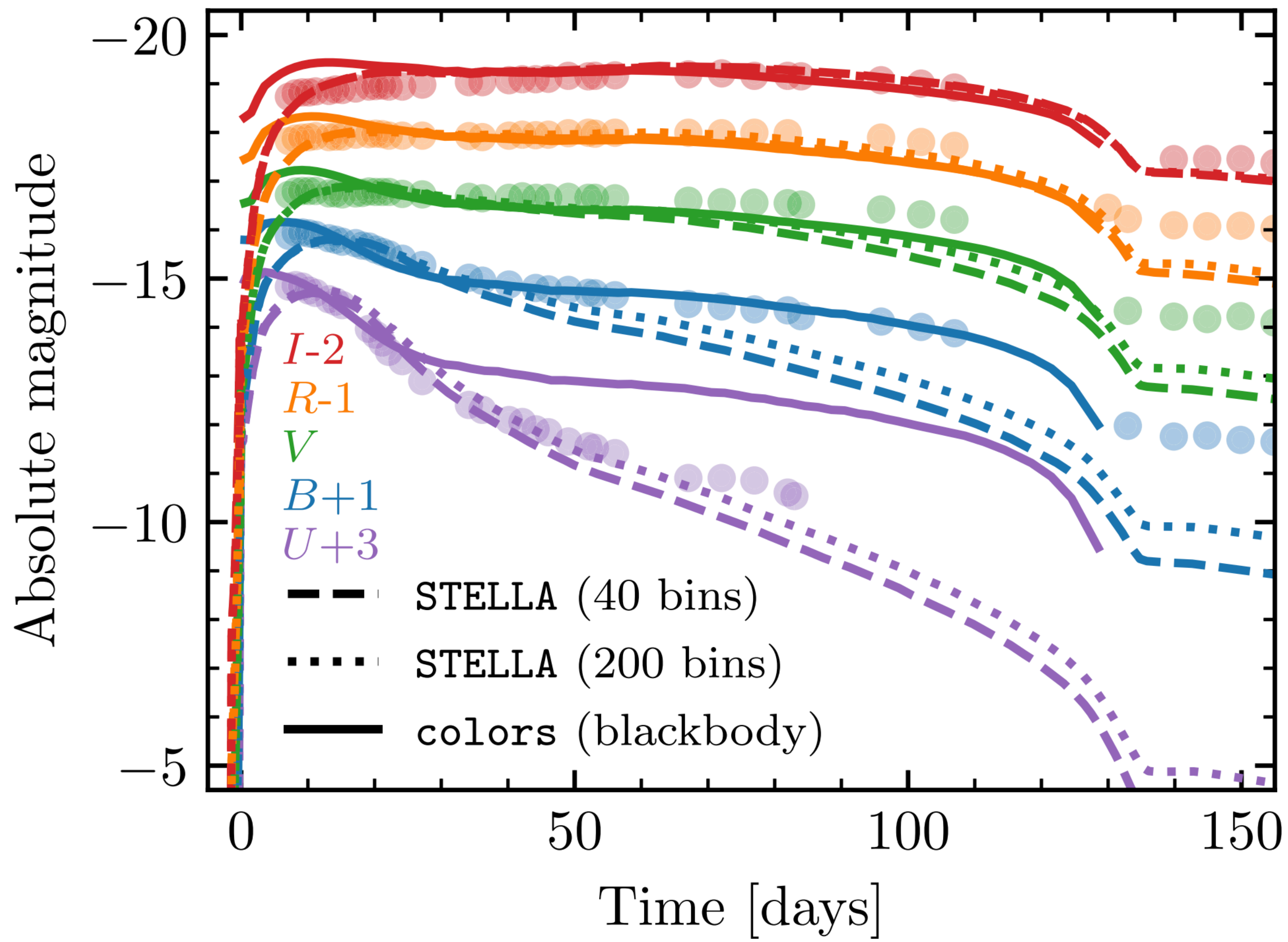


Figure 35. Comparison of model 99em_19 with the multicolor light curve of SN 1999em, showing colors from STELLA and blackbody colors from MESA. Circles indicate observational data. This demonstrates the effect of the number of STELLA frequency bins on the predicted colors.

PPISN

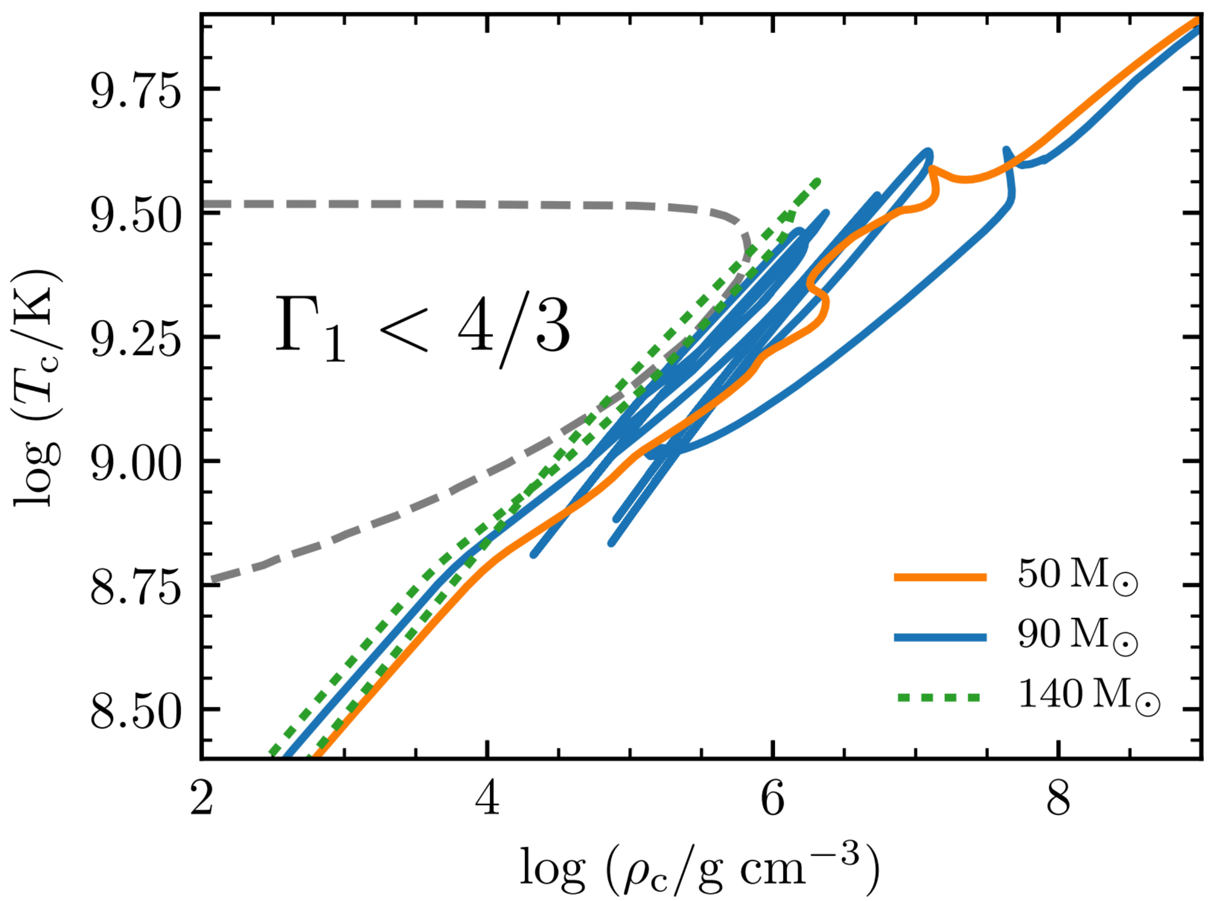


Figure 49. Central temperature and density for models with metallicity $Z = 0.001$ undergoing core collapse (50 M$_\odot$), PPISN (90 M$_\odot$), and PISN (140 M$_\odot$).

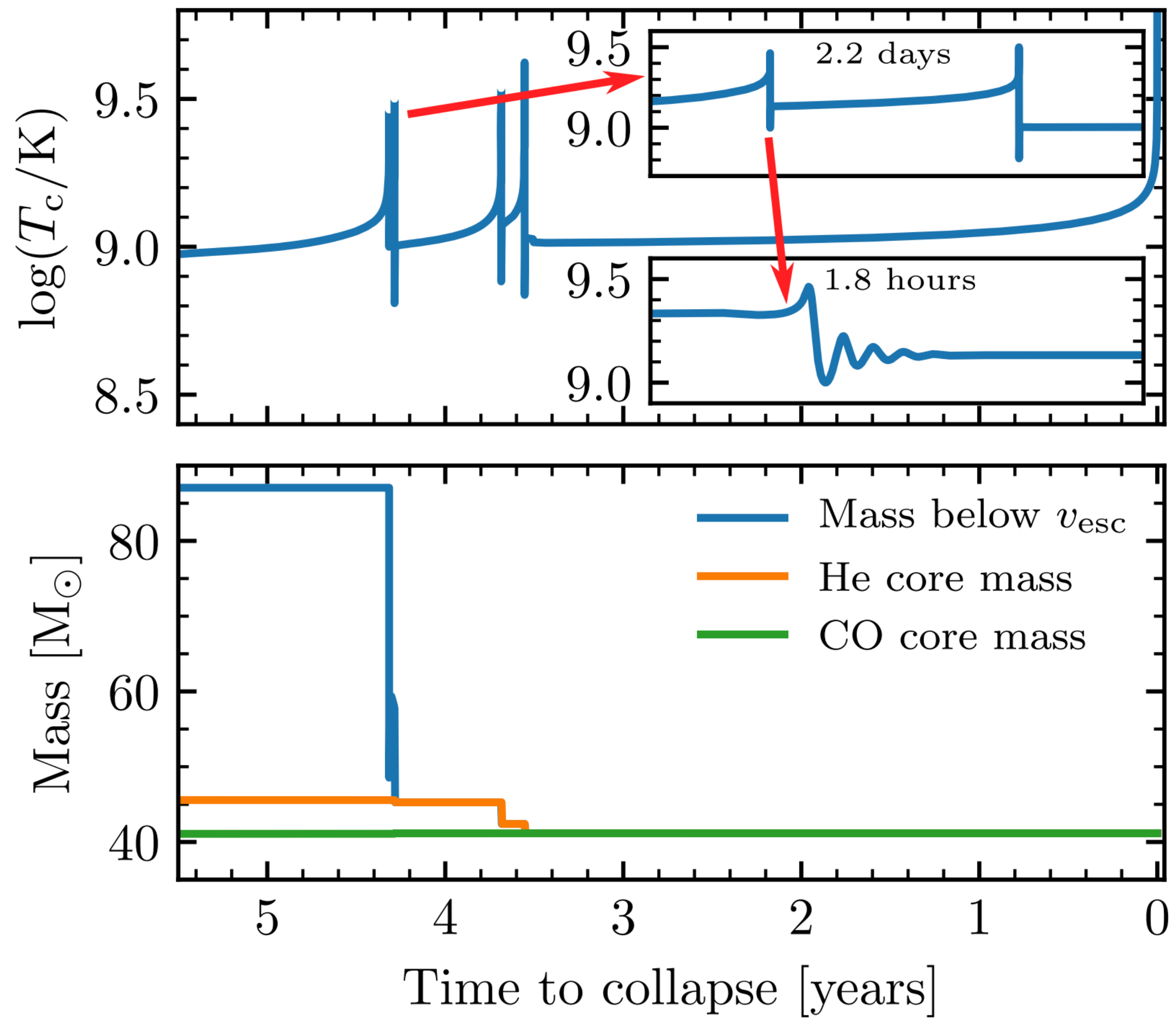


Figure 50. Late-time evolution of an $M_{\mathrm{ZAMS}} = 90$ M$_\odot$ star with metallicity $Z = 0.001$ undergoing a PPISN. (Upper panel) Evolution of the central temperature showing a zoomed-in region, covering 2.2 days, which contains the first two pulses, as well as an additional zoomed-in region covering 1.8 hr, which shows the first pulse and its ring-down into hydrostatic equilibrium. (Lower panel) Total mass of the star below the escape velocity, He core mass, and CO core mass during pulsations. The animated figure shows the time evolution of these quantities and the interior structure of the star.

(Paxton+ 2018)

Radial Pulsations: MESA + RSP

RSP models large amplitude, self-excited, nonlinear pulsations. RSP is closely integrated with the MESA environment. Instead of calling the standard MESAstar routine to evaluate equations and solve for a new model using Newton-Raphson iterations, a separate routine does the same for RSP using a different set of equations and a different NewtonRaphson solver. The different equations include time dependent convection in a form appropriate for modelling nonlinear pulsations

(Paxton+ 2019)

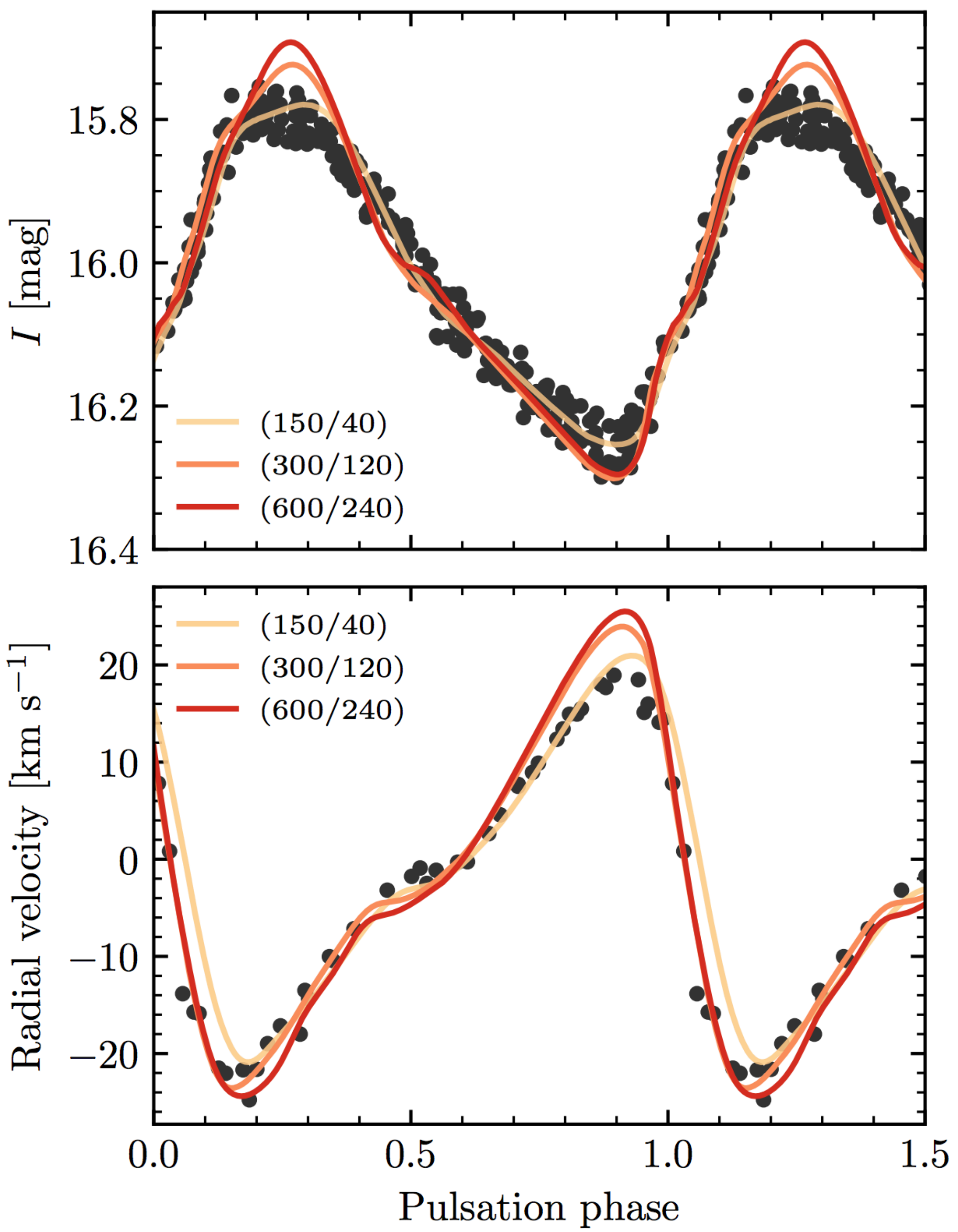


Figure 19. I-band light (upper panel) and radial velocity (lower panel) curves of the BEP OGLE-BLG-RRLYR-02792 as a function of pulsation phase. Observations are shown as circles (Pietrzynski et al. 2012) with the radial velocity multiplied by a projection factor of $p = 1.2$. Model curves are shown at three resolutions labeled by $(N/N_{\rm outer})$.

Radial Pulsations: MESA + RSP

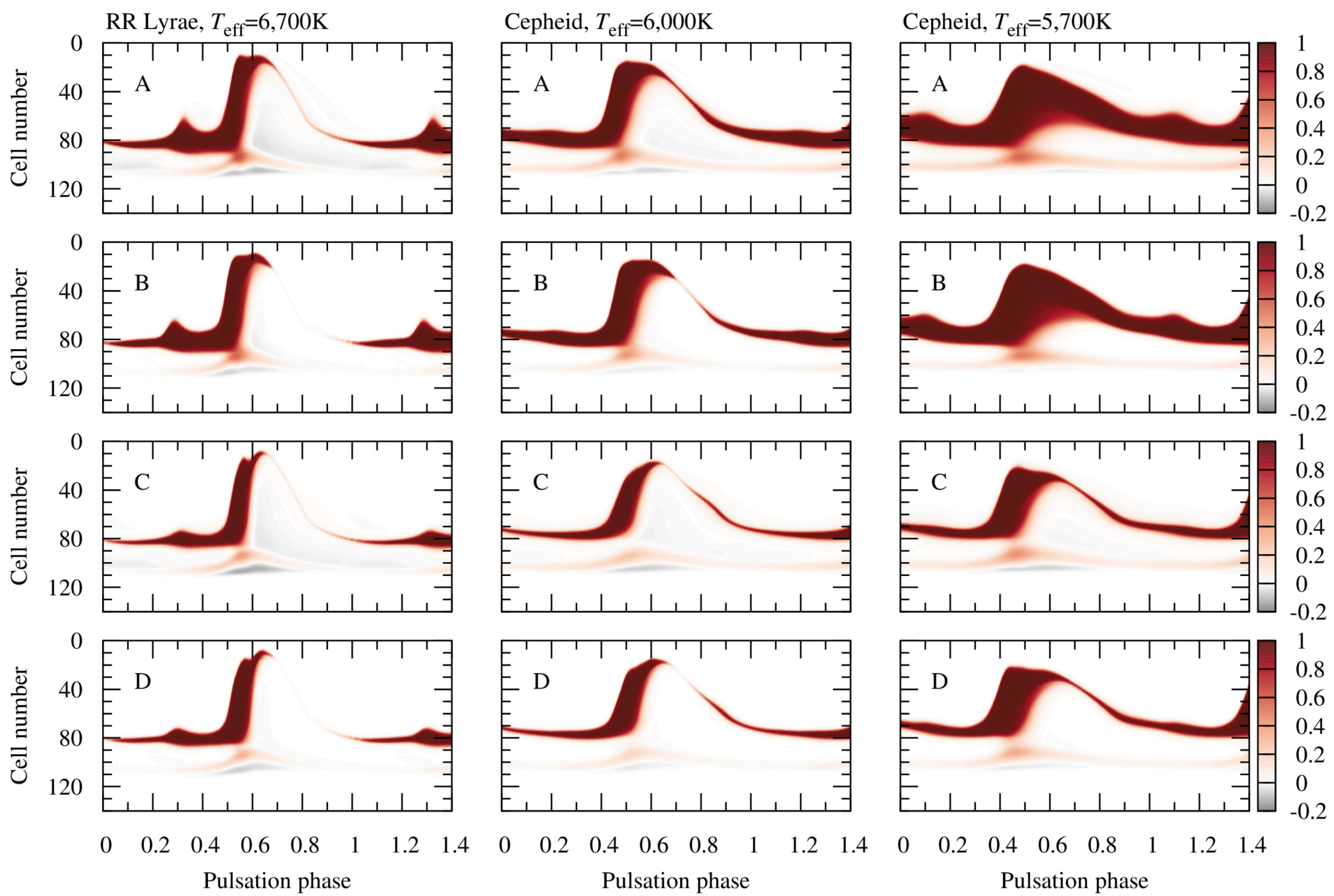
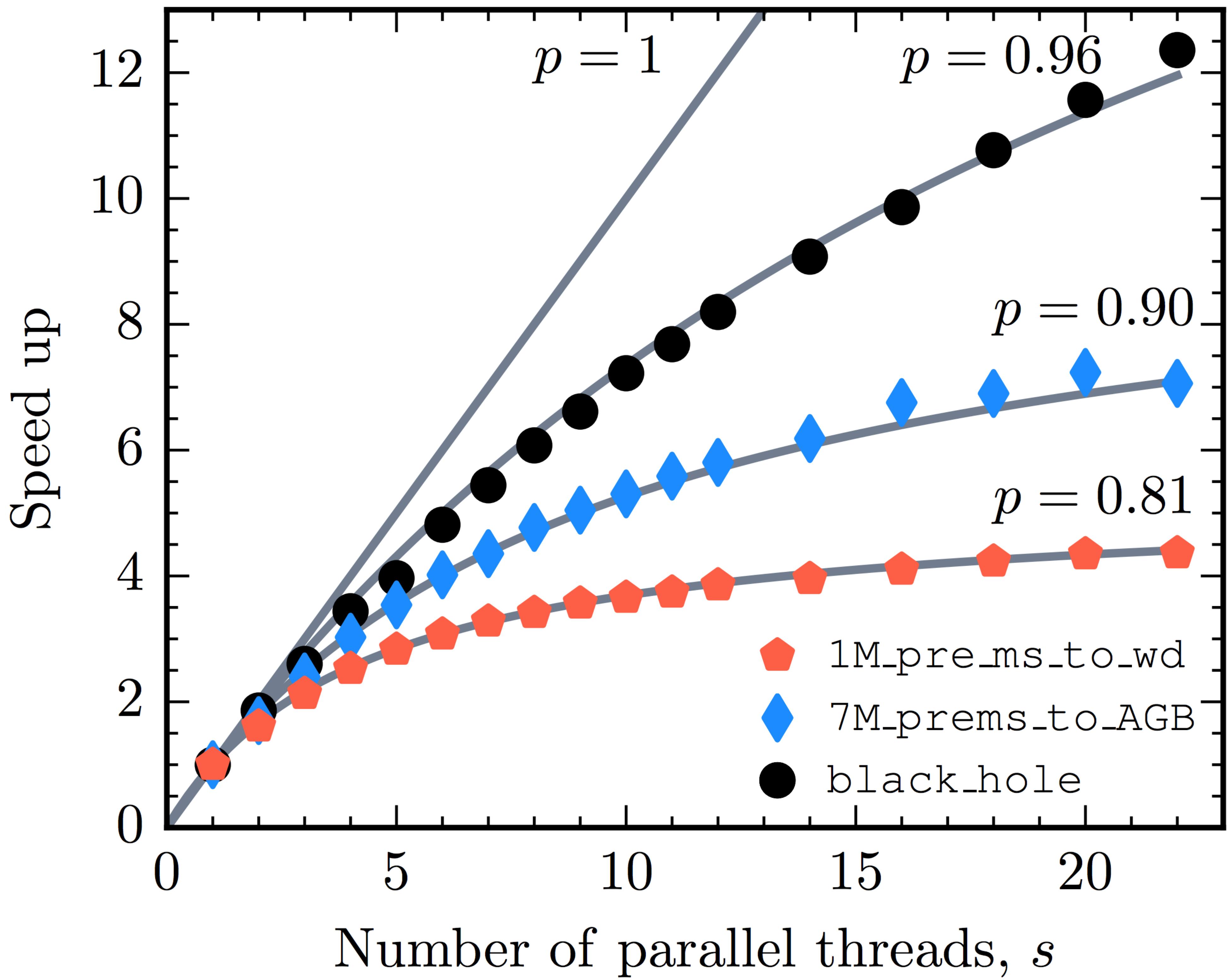


Figure 8. Evolution of convective luminosity L_c/L for the models shown in Figure 7. Cell number on the y-axis serves as a spatial coordinate, with cell 0 marking the stellar surface. The radiative interior of each model is not shown.

(Paxton+ 2019)

MESA Parallelism



(Paxton+ 2019)

Test Suites and TESTHUB

Development of the MESA source code is a collaborative process with multiple commits each day from developers working on separate parts of the codebase. In addition to serving as starting templates for science projects, the test cases in MESAstar and MESAbinary exist to detect when changes to the codebase cause unintended deviations from expected behavior (i.e., bugs). The number of test cases grows with time and is currently more than 100. MESA is committed to supporting reproducibility by giving bit-for-bit identical results on a variety of different hardware and software platforms, the test suite must be checked on a representative sample of host systems.

We have developed the MESA Testhub (testhub.mesastar.org). The Testhub is a web application that collects and organizes the results of test suite submissions. Every day, submissions from multiple computers and clusters with diverse hardware, operating systems, and compilers check out the most recent revision of MESA, run the test suite, and upload their results to the Testhub. Each day, a summary e-mail is sent to developers detailing which, if any, revisions had failing test cases submitted in the previous 24 hours.

(Paxton+ 2015, 2019)