Evolving R Corona Borealis Stars with the *MESA* code

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MESA

Modules for Experiments in Stellar Astrophysics

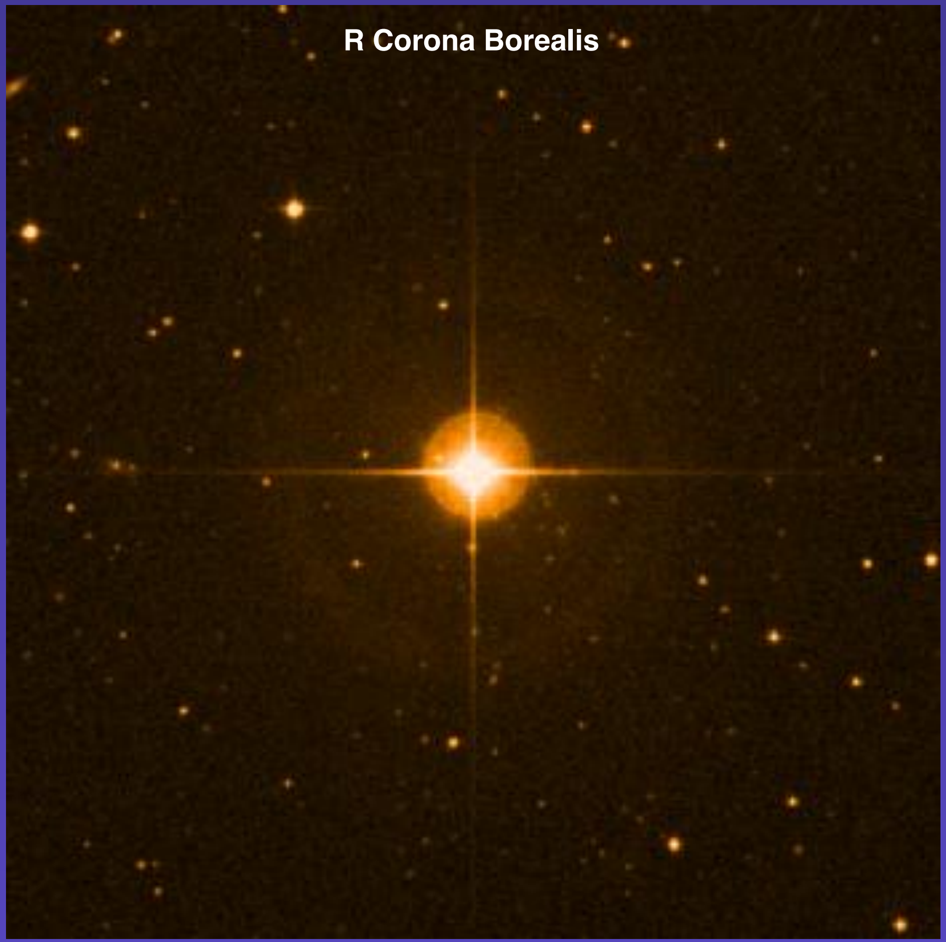
The STE||AR Group

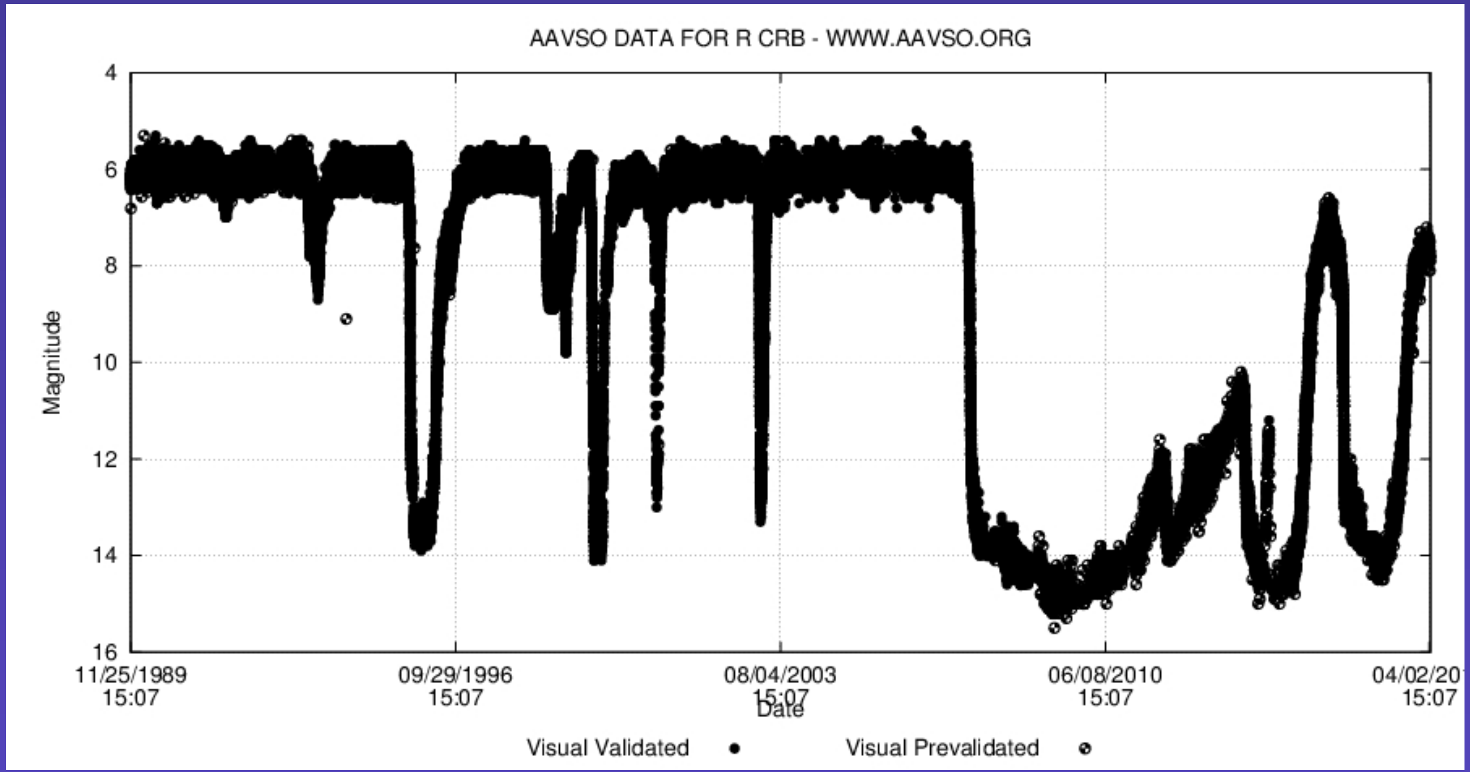

LSU Center for Computation and Technology (CCT) QueenBee Supercomputer

R Corona Borealis (RCB) stars

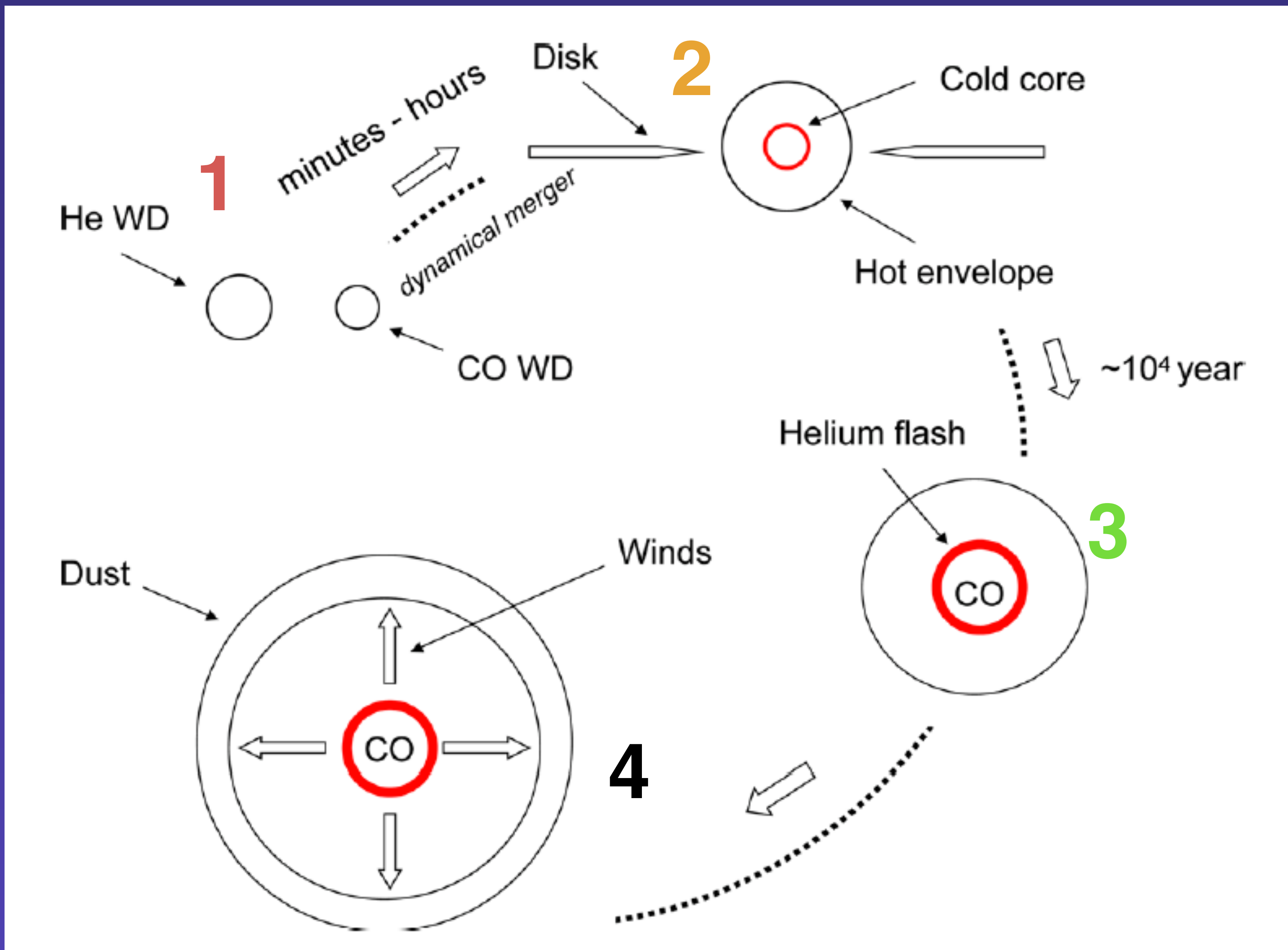
- ✳ Hydrogen-deficient supergiant stars (Clayton 2012)
- ✳ Very rare (~120 known in the galaxy!)
- ✳ Sudden declines in brightness by up to ~8 mag due to clouds of carbon dust
- ✳ $\log(L/L_\odot)$: 3.6 - 4.0 || $\log(T_{eff}$ [K]): 3.6 - 3.9

- ✳ Uncharacteristic abundances: low $^{16}O/^{18}O$, high $^{12}C/^{13}C$ ratios, sometimes enhanced Li
- ✳ Uncharacteristic abundances: enhanced s-process elements
- ✳ Consistent with partial He-burning (Clayton et al. 2017)
- ✳ Two models: Final Helium Flash (FF) and **double-degenerate (DD) merger**





A merger scenario for RCB stars

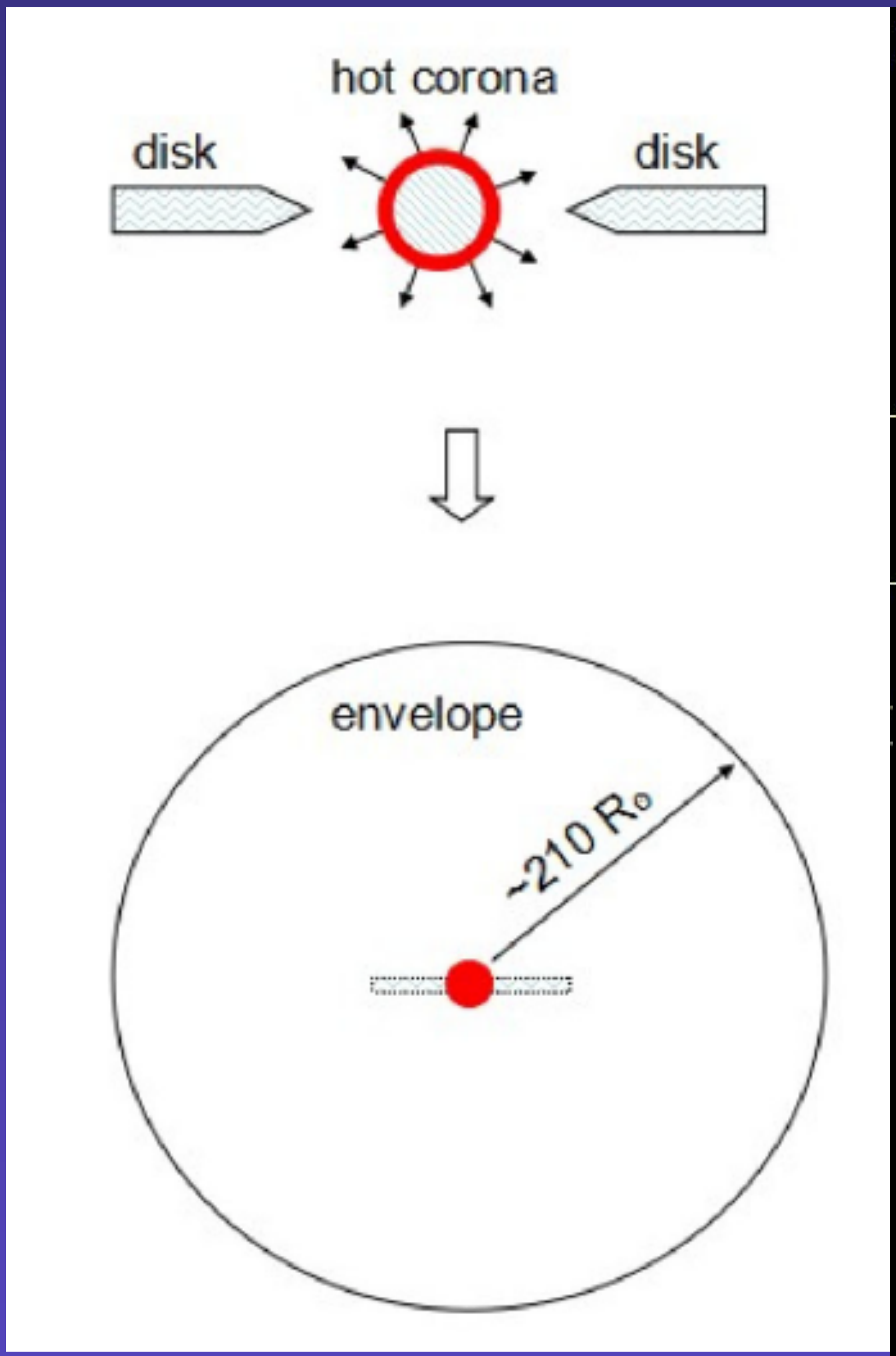


Zhang et al. 2014

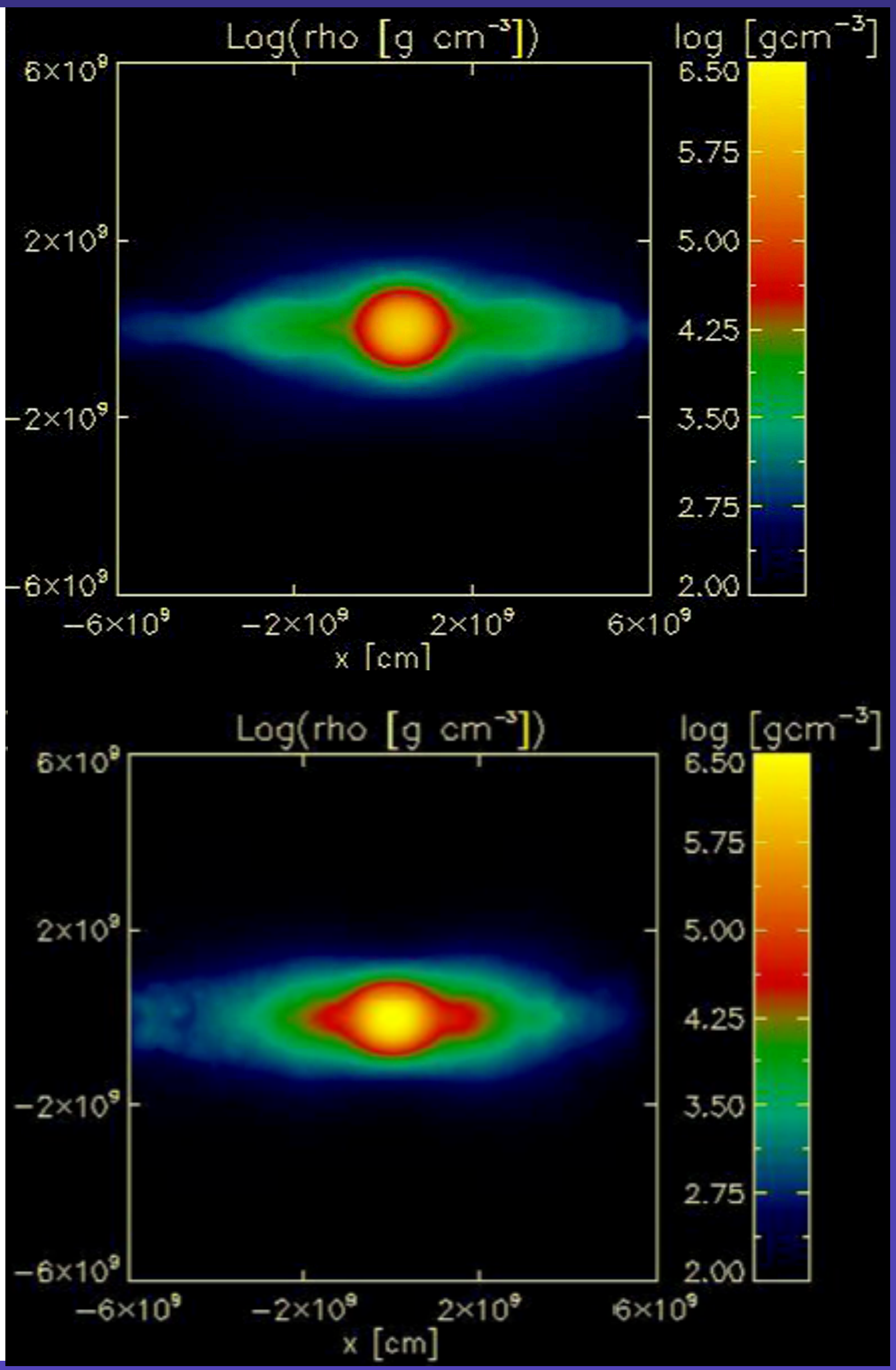
1. **A less-massive He-WD and a a more massive CO-WD coalesce and merge.**
2. **He-WD disrupted. Forms He-rich hot envelope ("corona") around cold, compact CO-WD and a disk.**
3. **He-burning starts in hot "shell" at the base of the corona.**
4. **Mixing transports s-process elements to surface; strong wind eject C-rich dust-forming shells.**

He /CO WD post-merger structure

- 3D AMR and SPH simulations show an elongated-shape that resembles the compact core - hot corona - disk - envelope configuration.
- Shape of the post-merger becomes spherical within a thermal time-scale of a few years.



Zhang et al. 2014



Staff et al. (2018)

$q = M_{He}/M_{CO} \sim 0.45\text{-}0.75$

$M_{PM} \sim 0.8\text{-}1.1\ M_{\odot}$

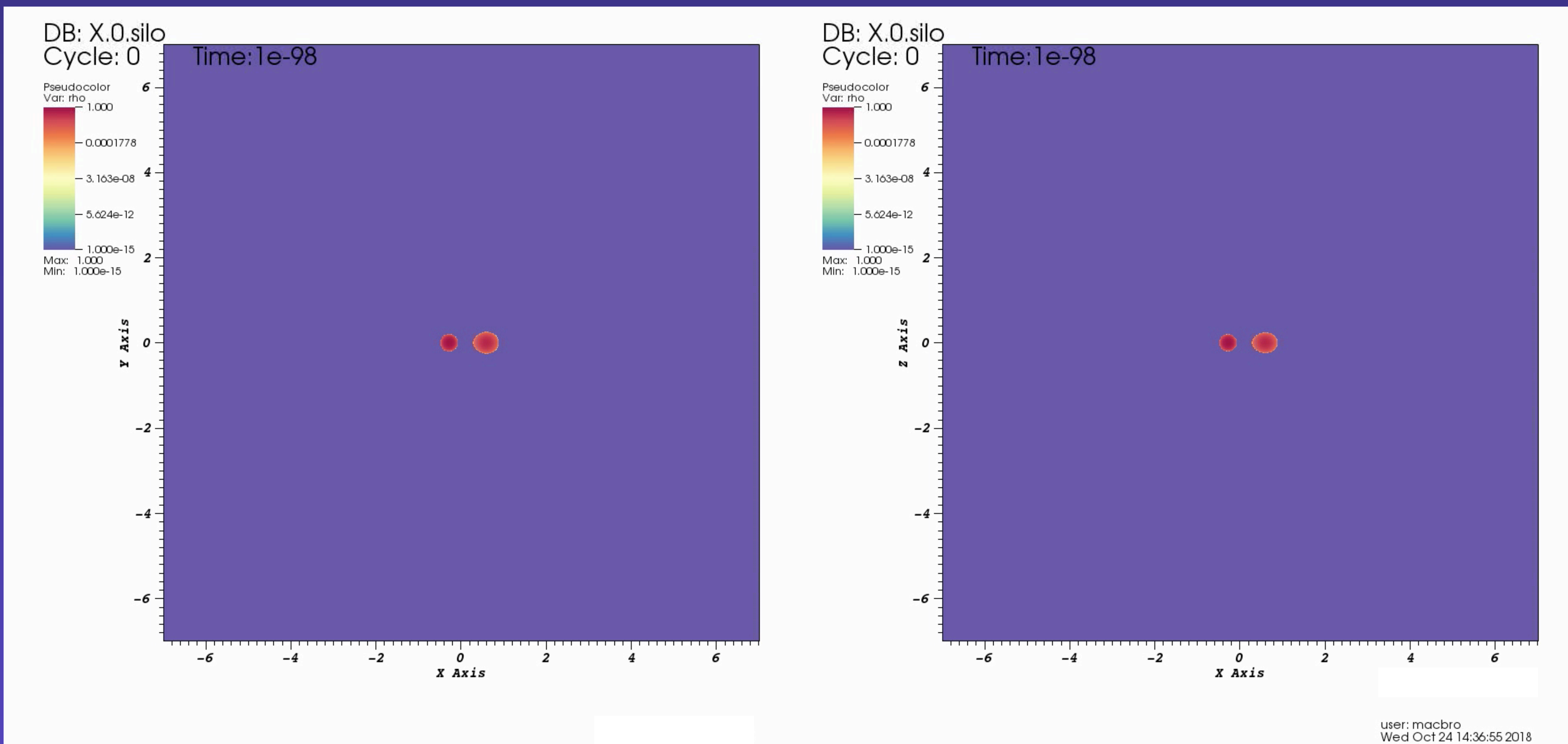
$R_{PM} \sim 0.1\ R_{\odot}$

$v/v_{crit} \sim 0.2$

$T_{He\text{-}shell} \sim 3 \times 10^8$ K

LSU OctoTiger 3D Merger Simulation of $0.6\,M_\odot$ (CO–WD) + $0.3\,M_\odot$ (He–WD)

Face-on view *Edge-on view*



MESA post-merger structure relaxation

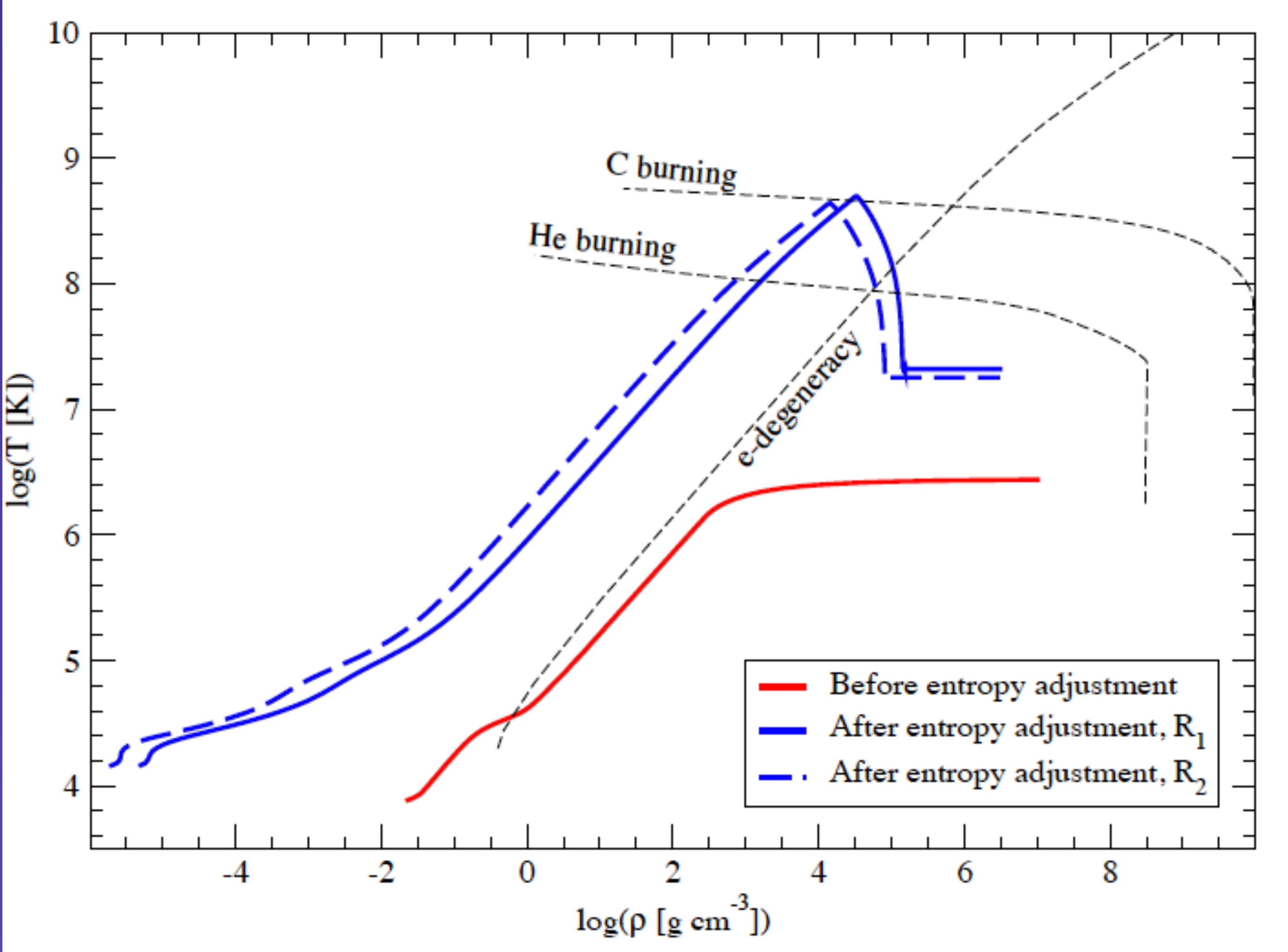
A. We evolve a 1.5 $M_\odot$ and a 6 $M_\odot$ star to a He- and CO-WD phase accordingly with MESA and a large nuclear reaction network (76 isotopes - from n to ^{60}Zn)

B. We use numerical relaxation algorithms ***with physics turned-off*** to create a model with mass equal to the mass of the desired post-merger object.

C. Mass interior to the mass of the CO-WD is relaxed to a degenerate state

D. The composition of the core is relaxed to the computed composition of a CO WD and the composition of the envelope to a mass-averaged (mixed) composition of a He WD (both WD mixtures computed in step "A").

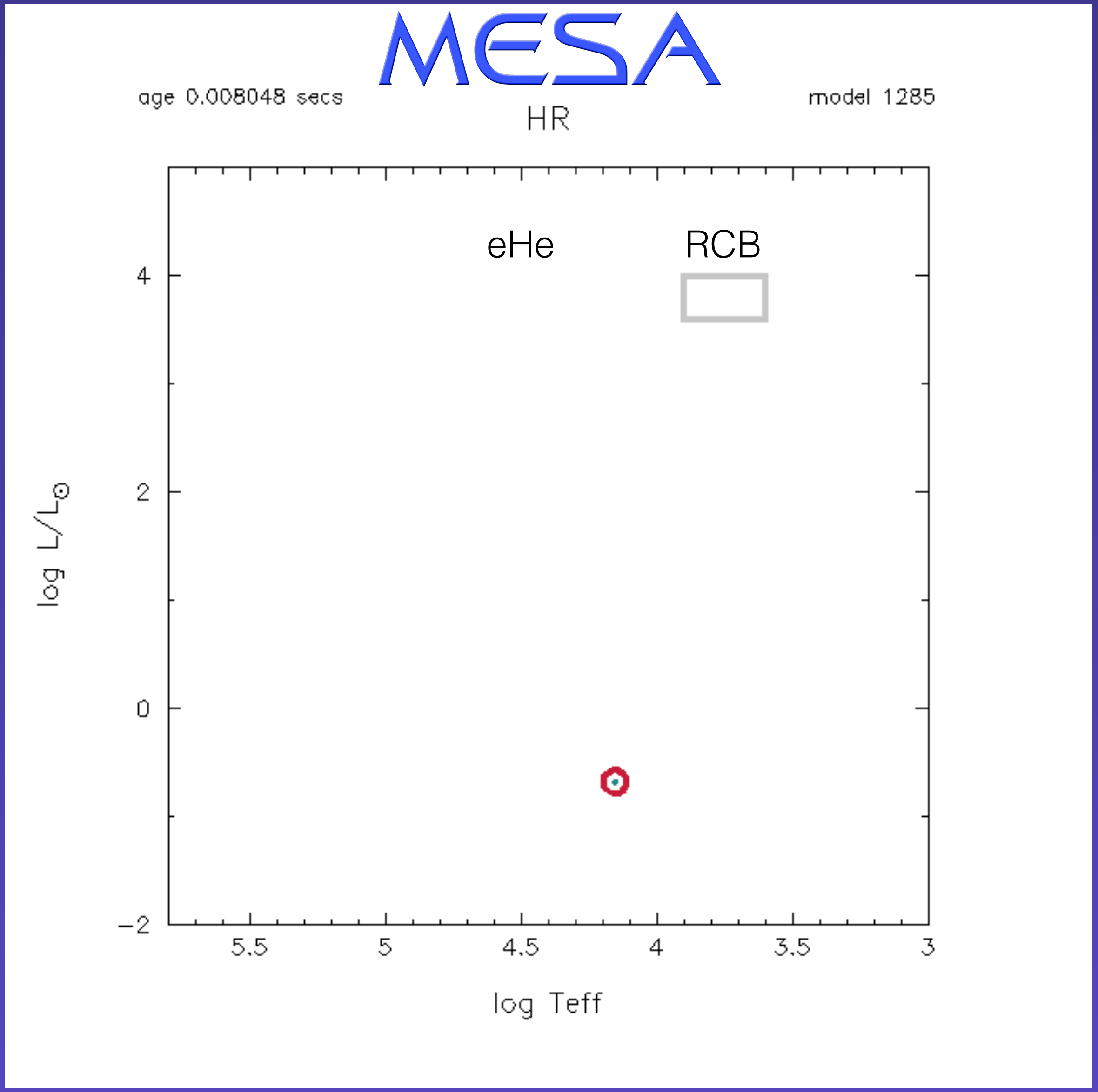
E. A user-defined amount of entropy is injected in the He envelope so that it expands mimicking the desired final core/hot corona/envelope structure.



Lauer, Chatzopoulos et al. 2018

MESA post-merger evolution

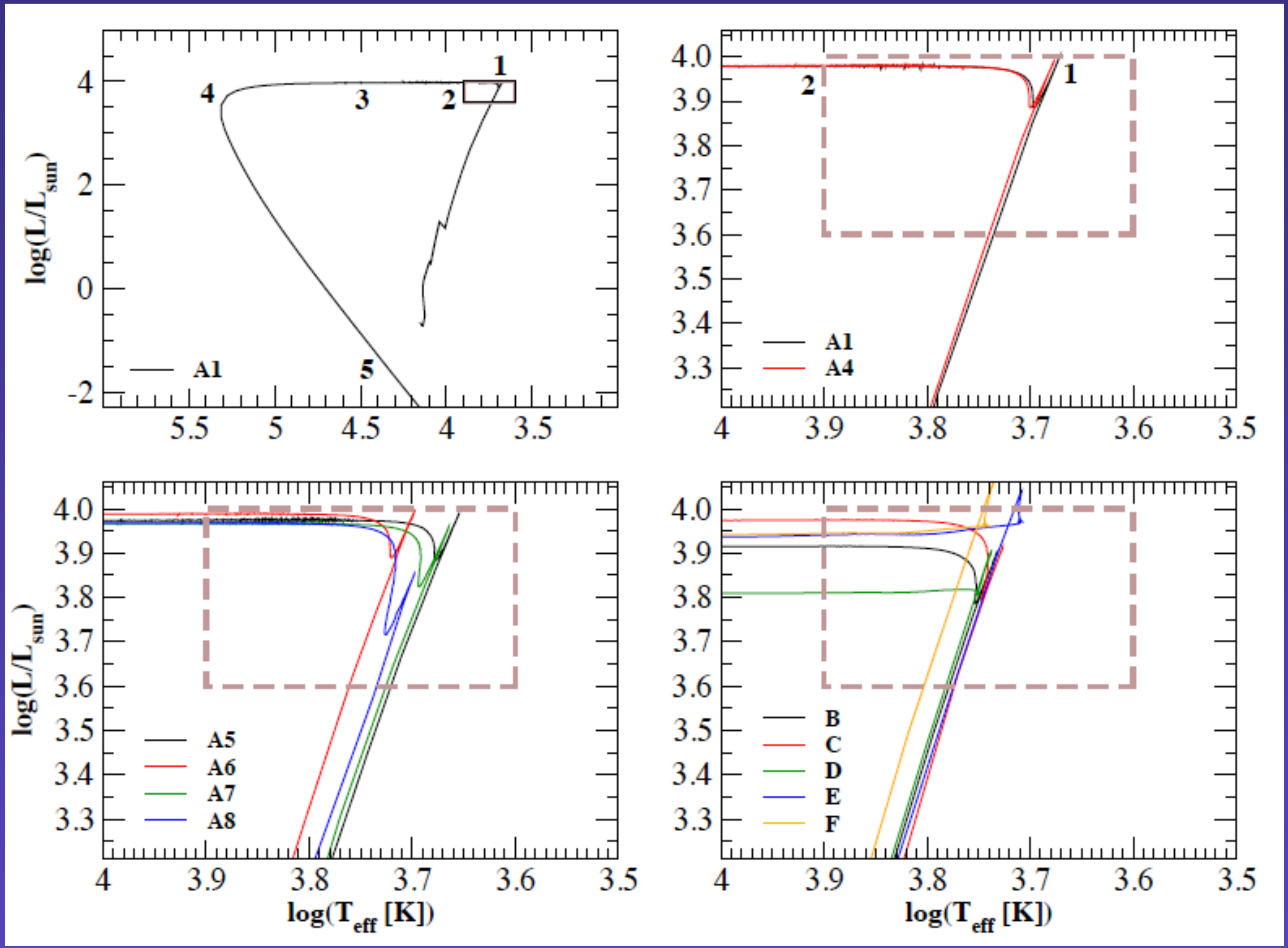
- Physics modules (nuclear burning, energy transport, rotational mixing etc) now turned-on.
- Evolution followed for ~1 billion years.
- Models of the Hertzsprung—Russell (HR) diagram tracks through the RCB phase and beyond!
- Surface abundances during RCB phase computed
- Relevant time-scales computed.
- All for models spanning the relevant parameter space in terms of He/CO WD initial masses, initial rotation, initial hydrogen abundances etc.
- Lauer, Chatzopoulos et al. 2019



Results: HR evolution

✓ **Evolution to RCB "box" within a few hundred years for all models**

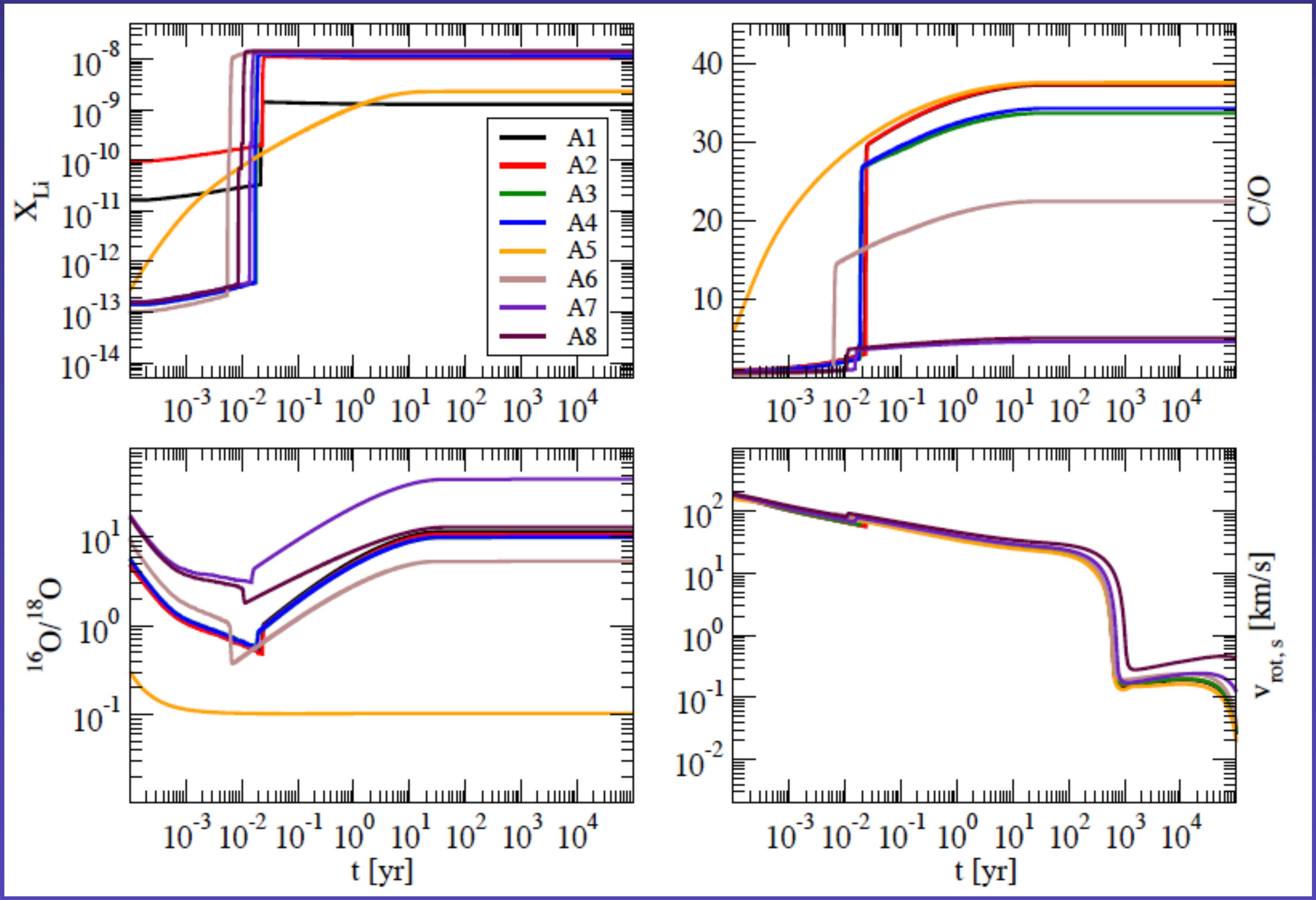
✓ **Consistent final RCB masses (~0.8-1.2 $M_{\odot}$) and surface rotational velocities (~0.1 km/s)**



Lauer, Chatzopoulos et al. 2018

Results: Nucleosynthesis

- ✓ **Enhanced Li surface abundances (2.4 - 3.5; R Cor Bor = 2.8)**
- ✓ **Consistent $^{16}O/^{18}O$ ratios (1-13; R Cor Bor = 1)**
- ✓ **Consistent C/O ratios (1-40; R Cor Bor = 1.6)**



Lauer, Chatzopoulos et al. 2018

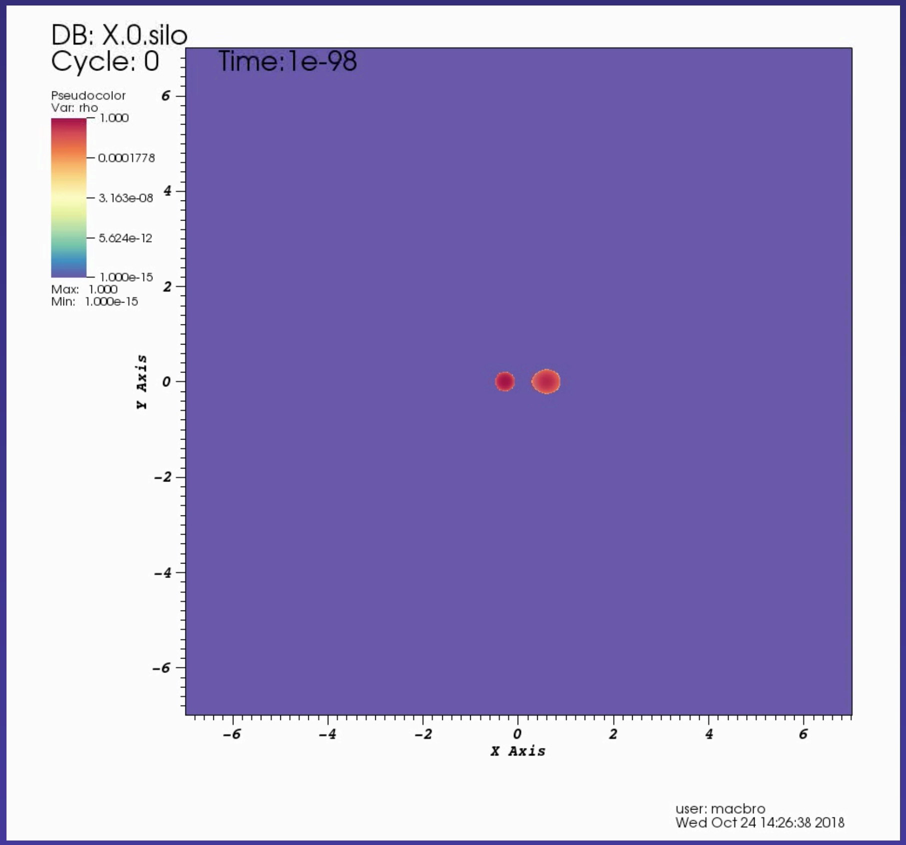
Results : RCB to EHe Star rates

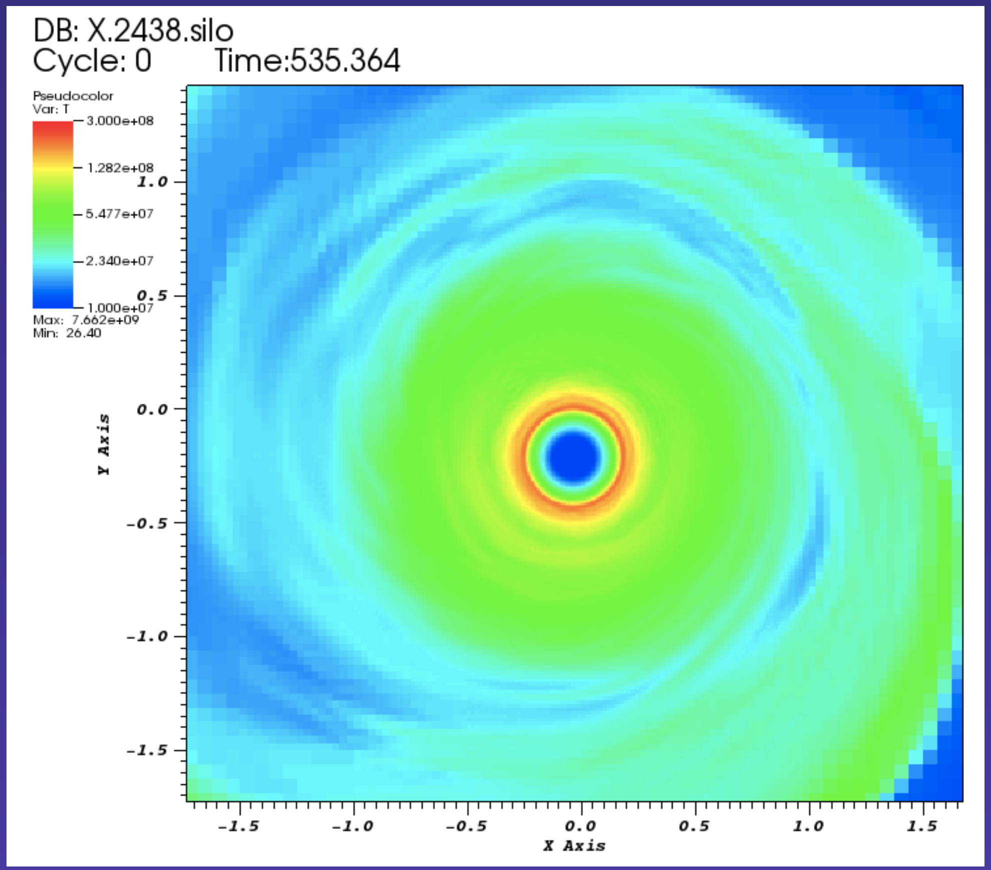
- ✓ **Good fit on the observed ratio of Extreme-He (EHe) stars and RCB stars in the Milky Way based on time-scales found in computed evolution.**

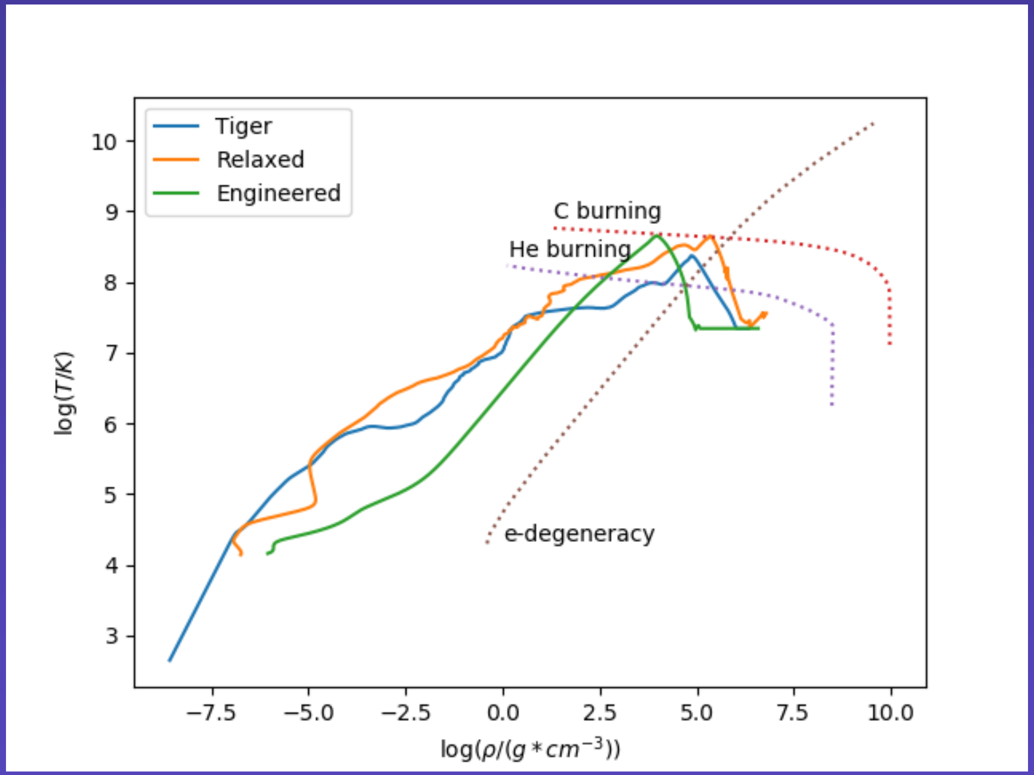
Model	t_B (10^5yr)	t_C (10^5yr)	t_C-t_B (10^5yr)	M_{RCB} at t_B ($M_\odot$)	$M_{RCB}{}^a$ ($M_\odot$)	# RCB[b]	# EHe[b]
A1	1.256	1.366	0.11	0.80	0.68	226	20
A2	1.284	1.395	0.11	0.80	0.68	231	20
A3	1.270	1.382	0.11	0.80	0.68	229	20
A4	1.265	1.377	0.11	0.80	0.68	228	20
A5	1.235	1.339	0.10	0.80	0.68	222	19
A6	1.282	1.400	0.12	0.80	0.68	231	21
A7	1.720	1.846	0.13	0.80	0.80	310	23
A8	2.759	2.922	0.16	0.80	0.70	497	29
B	1.706	1.845	0.14	0.85	0.64	307	25
C	2.038	2.137	0.10	0.90	0.66	367	18
D	0.742	0.862	0.12	0.95	0.61	134	22
E	0.163	0.187	0.02	0.99	0.61	29	4
F	0.331	0.371	0.04	1.05	0.63	60	7

Lauer, Chatzopoulos et al. 2018

A sneak peek to on-going work…







MESA
+
NUGRID

Summary & Future Work

- Merger scenario good fit to RCB observations, improvement on past work.
- Observed RCB to EHe star ratio in agreement with our predictions.
- Observed RCB nucleosynthesis in agreement with observations.

- **Future Work:** Map spherically-averaged post-merger structure from 3D Adaptive Mesh Refinement (AMR) simulation done with the LSU *OctoTiger* code into MESA.
- **Future Work:** Better nucleosynthesis using the *NuGrid* code in post-processing steps (hundreds of isotopes, including Y, Zr that are seen in RCB spectra).

THANK YOU!