

Astrophysics I: Stars and Stellar Evolution

AST 4001

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Los Alamos National Laboratory

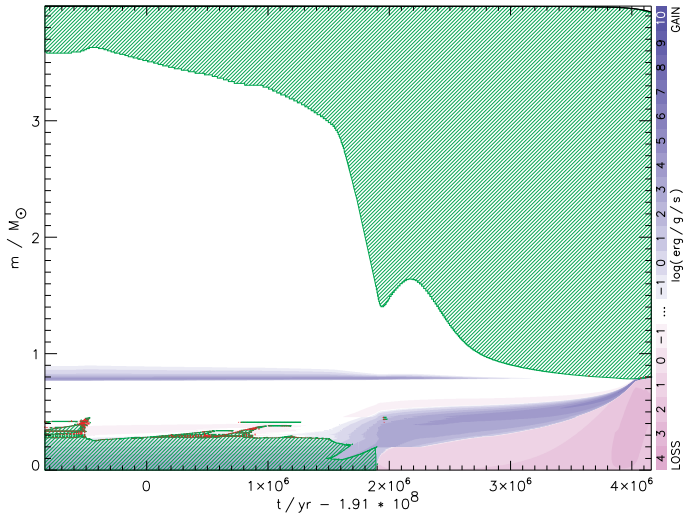
³Department of Astronomy and Astrophysics
University of California at Santa Cruz

Stars and Stellar Evolution, Fall 2008

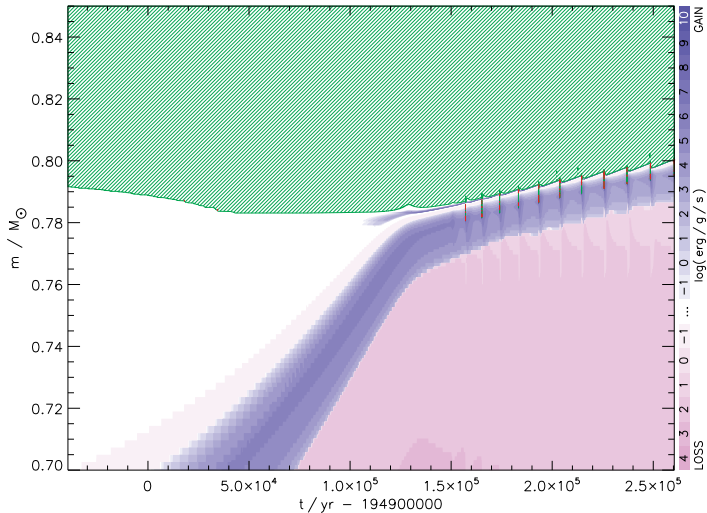
Overview

- 1 Recap
 - AGB Stars
- 2 Planetary Nebula Formation
 - AGB Lifetime
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- 3 Low-Mass Stars
 - Degenerate Helium Core Ignition
 - Evolution in the HRD
 - Internal Evolution of the Sun

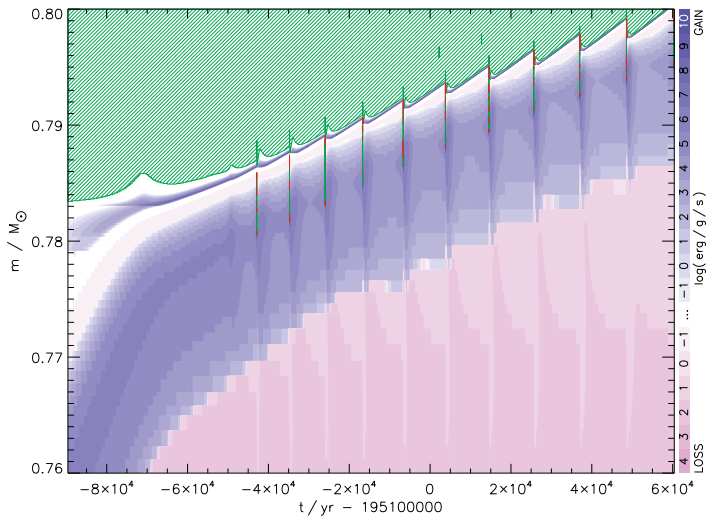
Kippenhahn Diagram, $4 M_{\odot}$ Star, He Depletion



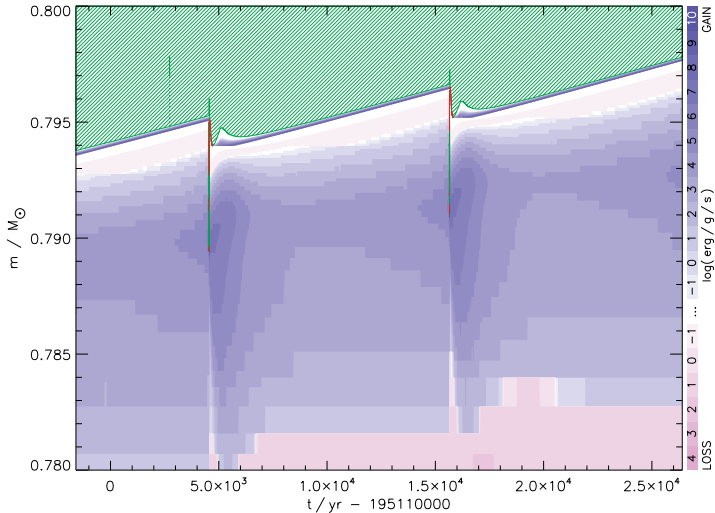
Kippenhahn Diagram, $4 M_{\odot}$ Star, Post-Core He burning



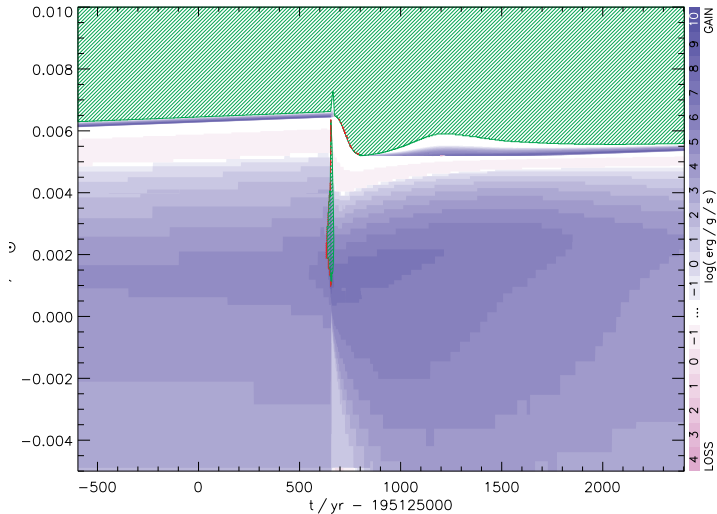
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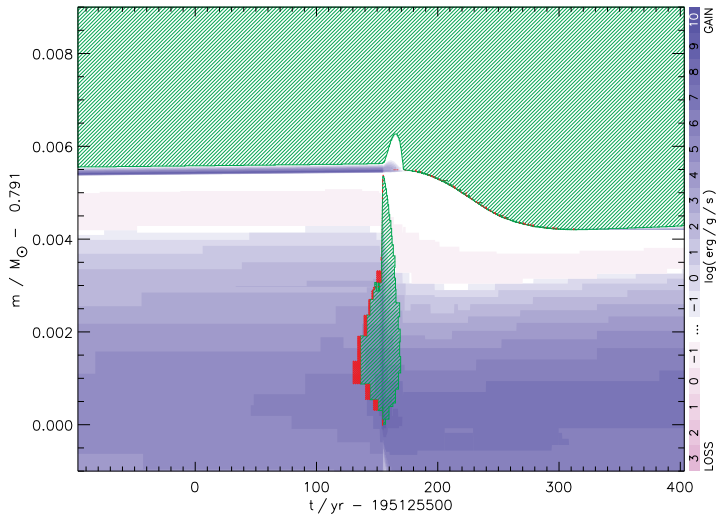
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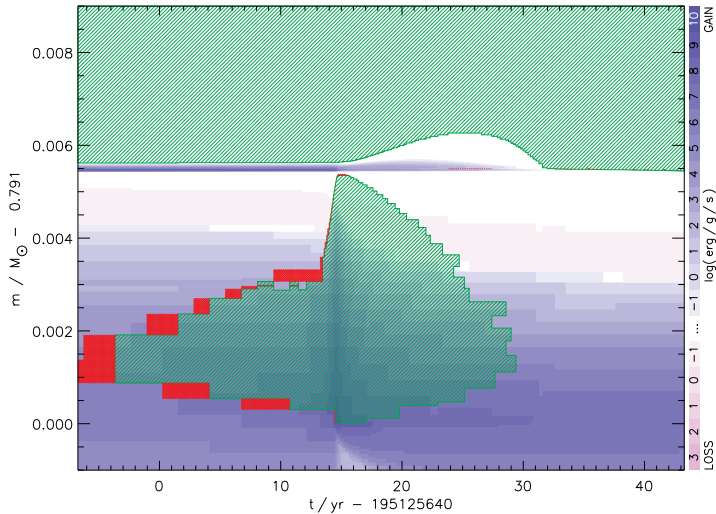
Kippenhahn Diagram, 4 M_⊙ Star, Post-Core He burning



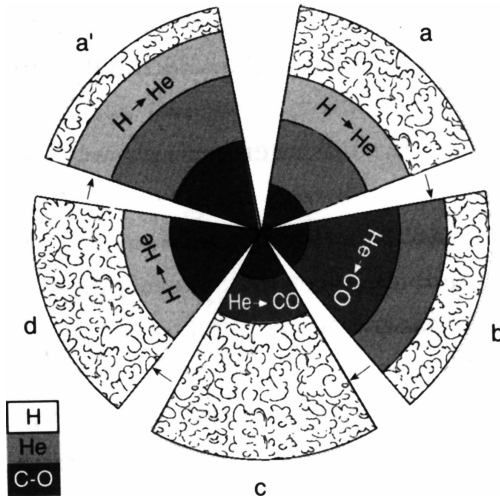
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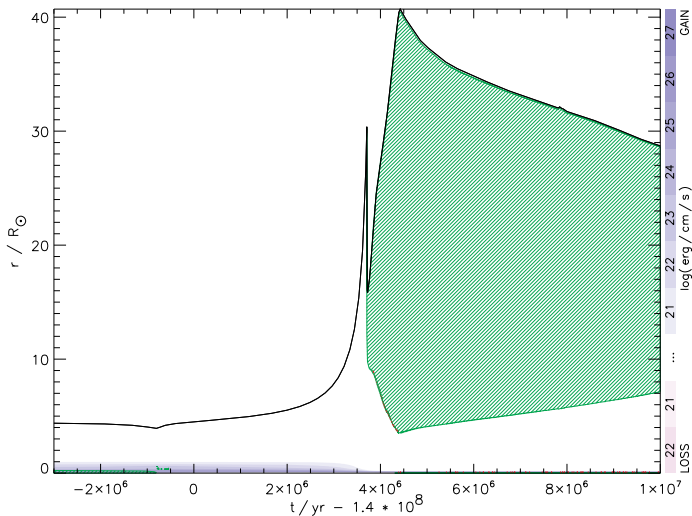
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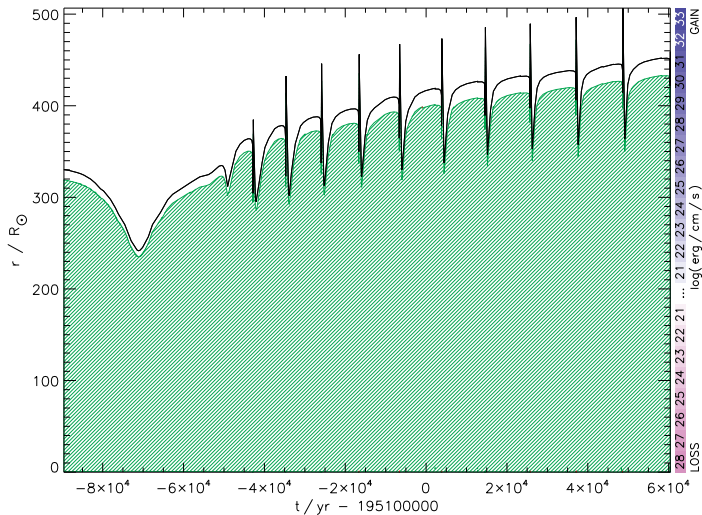
Change of Structure During AGB Cycle



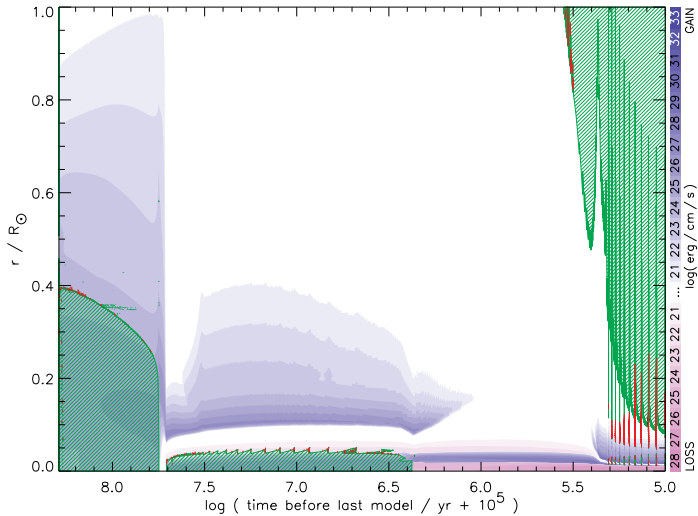
Kippenhahn-Radius Diagram, $4 M_{\odot}$ Star, Helium Ignition



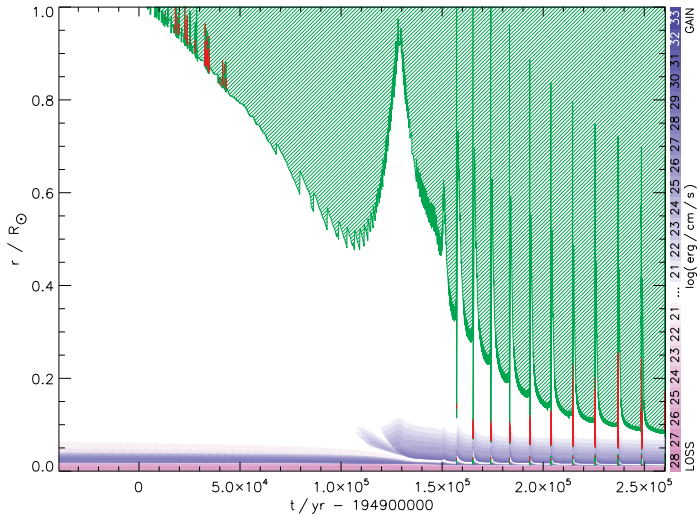
Kippenhahn-Radius Diagram, $4 M_{\odot}$ Star, Start of AGB



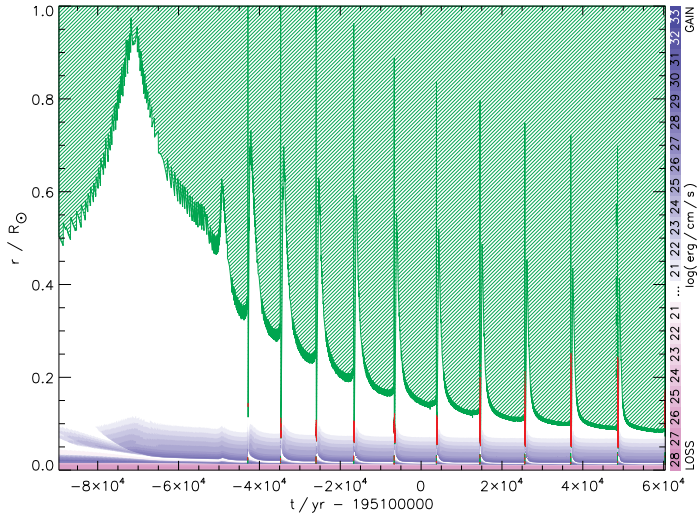
Kippenhahn-Radius Diagram, $4 M_{\odot}$ Star



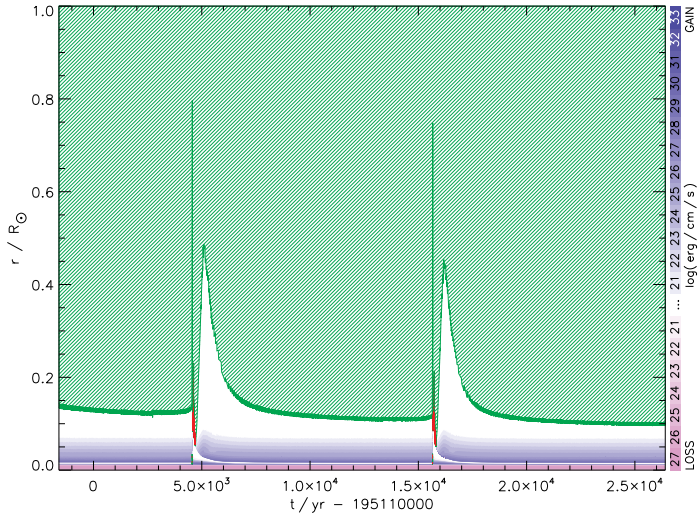
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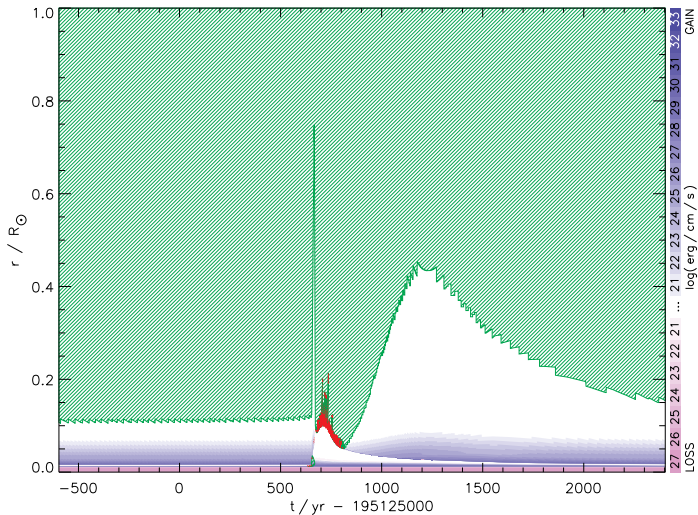
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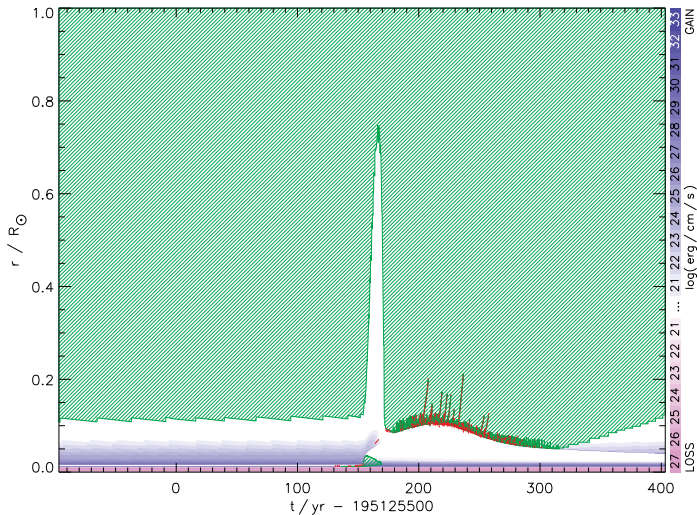
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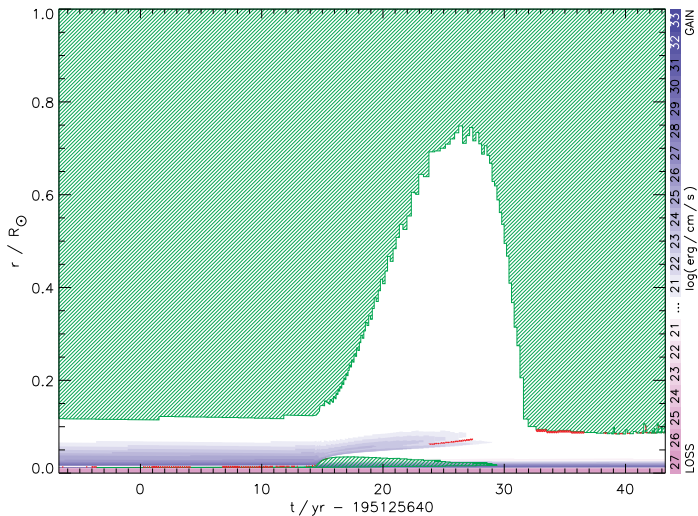
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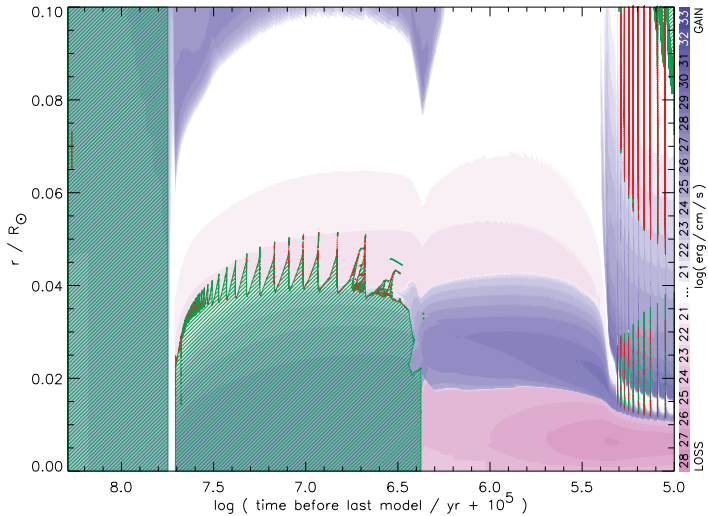
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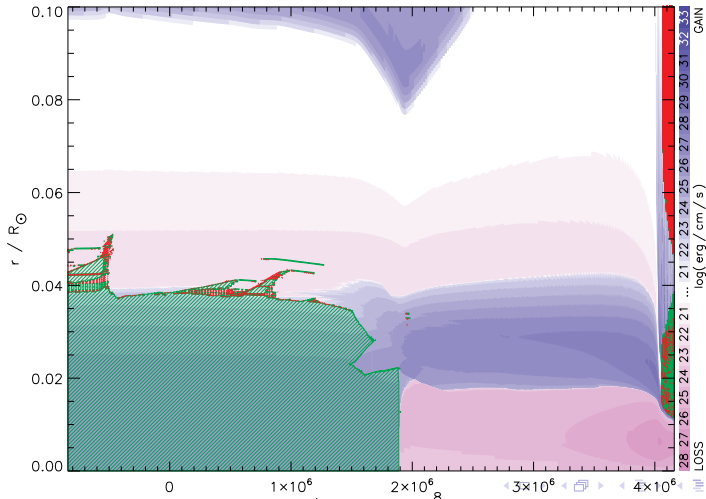
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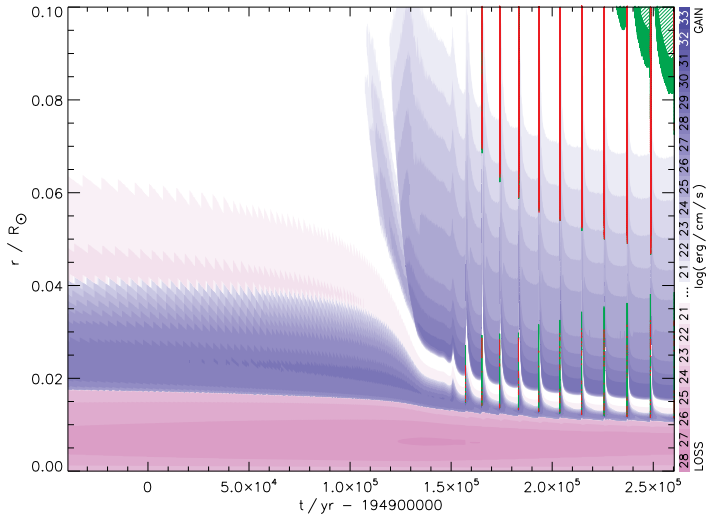
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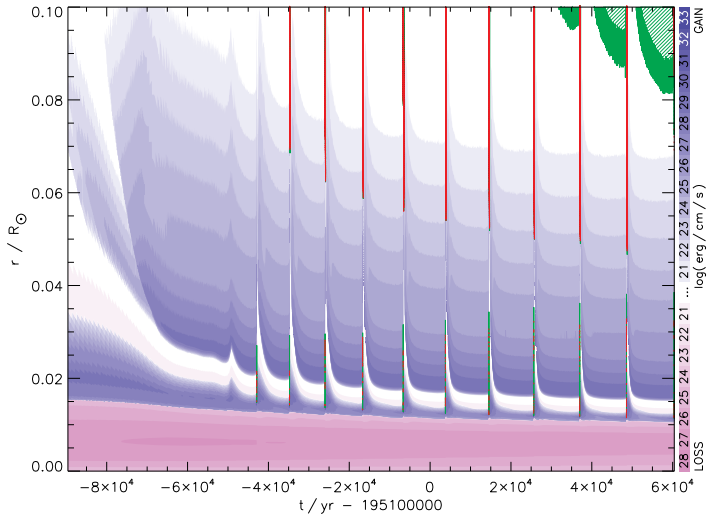
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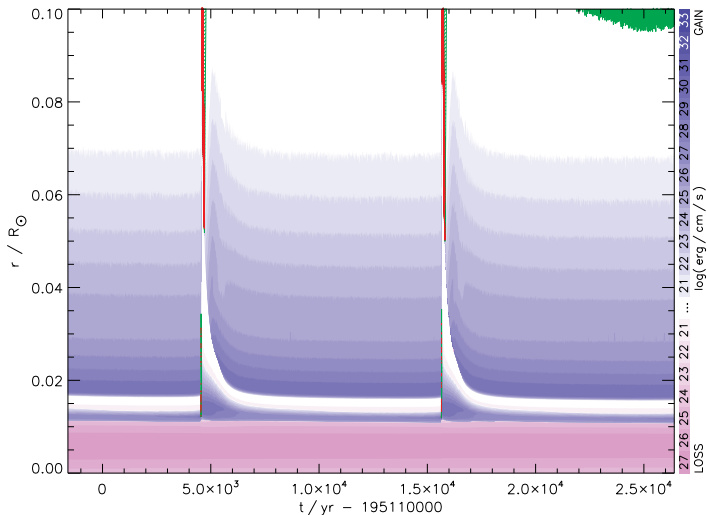
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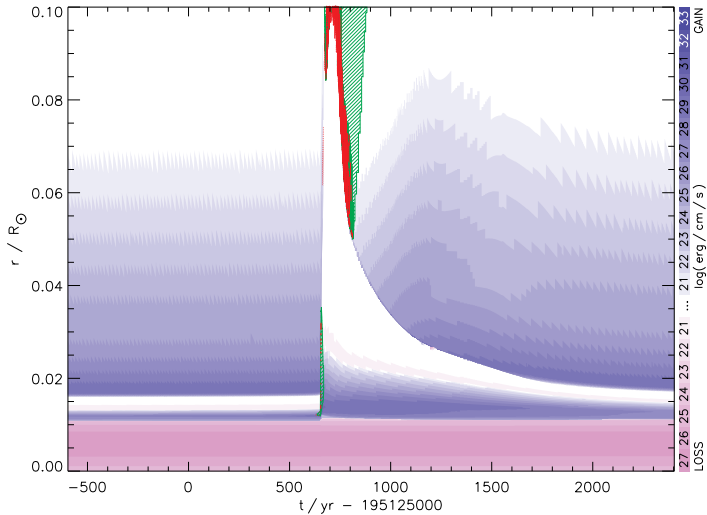
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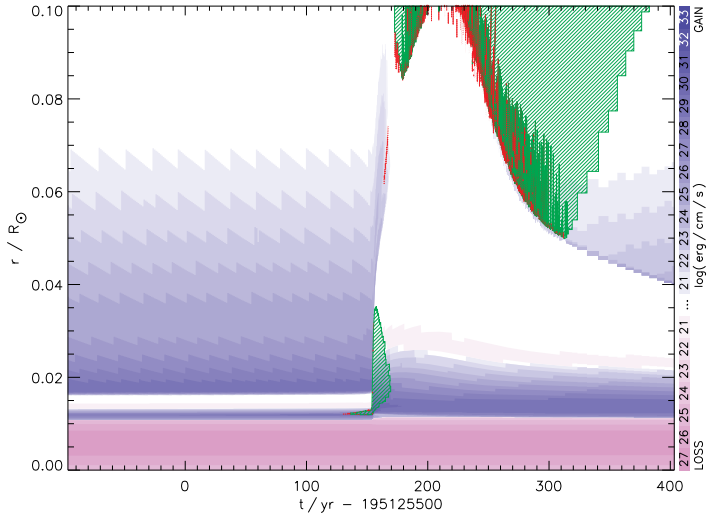
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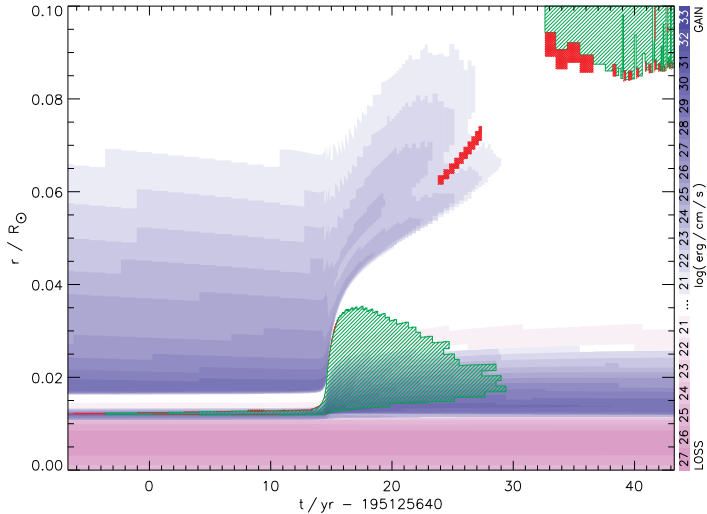
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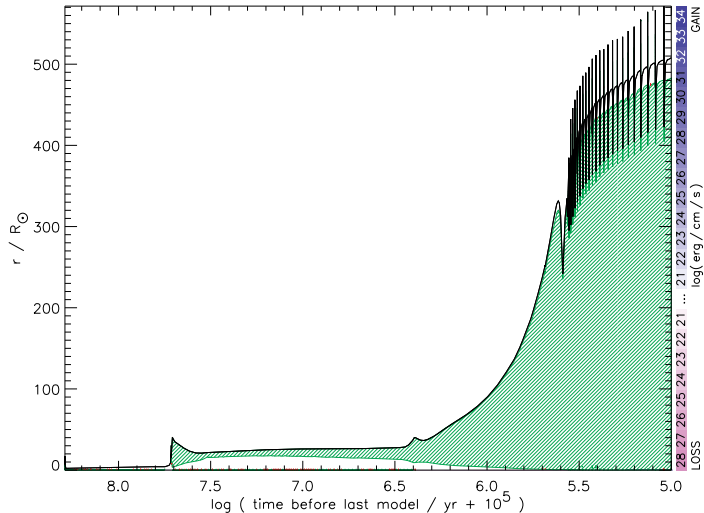
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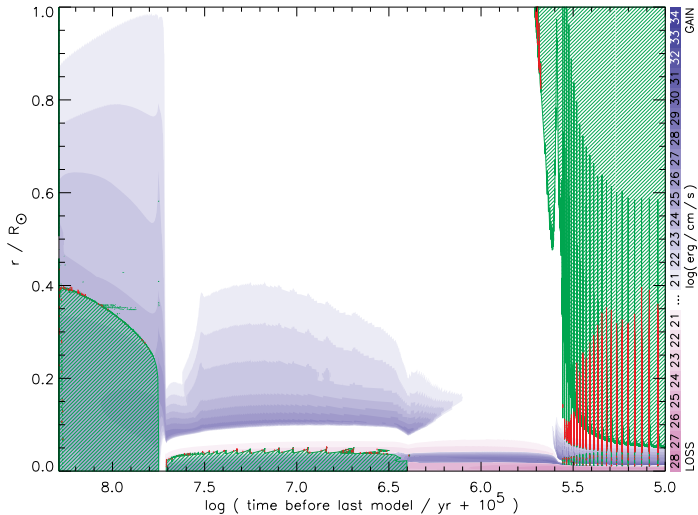
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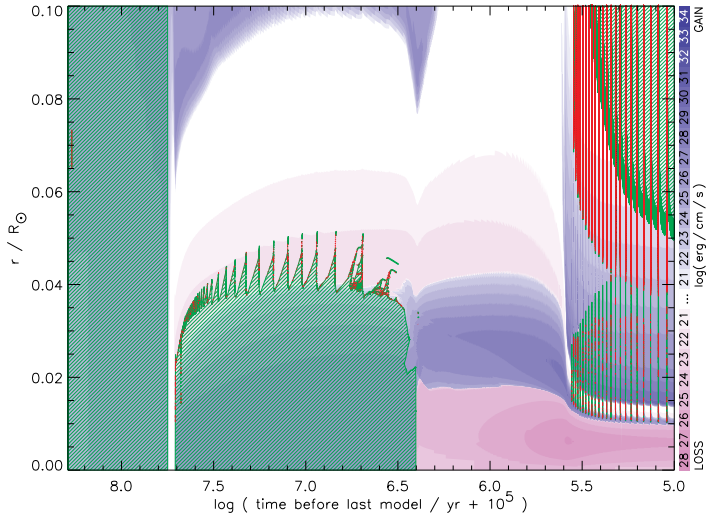
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AGB Lifetime

- AGB stars turn H into He to build up an He layer, and He into C at the base of the He layer
- energy release per unit mass $5 \times 10^{18} \text{ erg g}^{-1}$
- thermal equilibrium

$$\dot{M}_c = \frac{L}{Q} \approx 1.2 \times 10^{-11} \frac{L}{L_\odot} M_\odot/\text{yr}$$

- we obtain a core growth rate of

$$\frac{dM_c}{M_c - 0.5 M_\odot} = 7.2 \times 10^{-7} \text{ yr}^{-1} dt$$

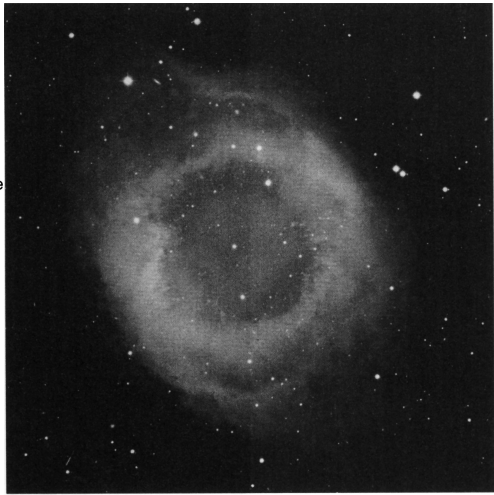
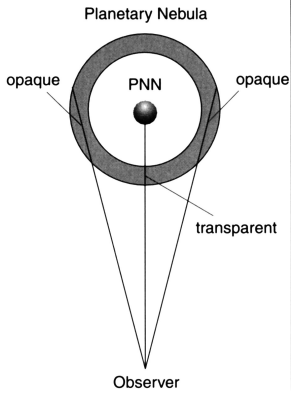
- assuming a starting mass of $M_{c,0}$ and a maximum final mass of the Chandrasekhar mass M_{Ch} we obtain

$$\tau_{\text{AGB}} < 1.4 \times 10^6 \text{ yr} \times \ln \left(\frac{M_{\text{Ch}} - 0.5 M_\odot}{M_{c,0} - 0.5 M_\odot} \right)$$

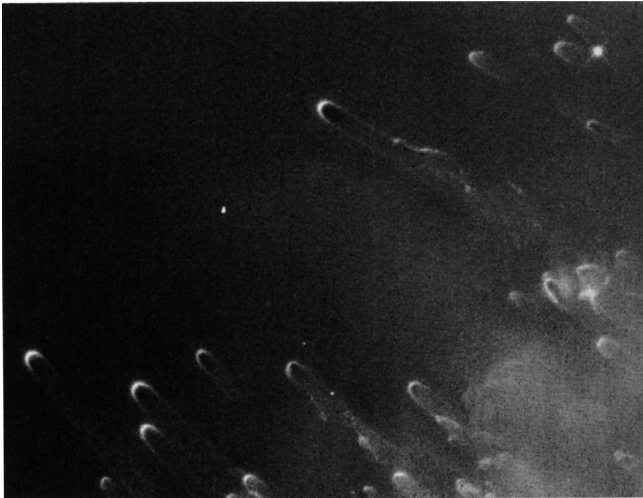
Planetary Nebula (PN) Formation

- eventually all extended red giant envelope is lost by stellar winds
- star gets very hot (30,000 K)
- blows a fast hot **superwind** that evacuates bubble around it
- formation of “ring”-shaped **“planetary” nebula**
- eventually burning in shell stops when mass of shell drops below $10^{-3} \dots 10^{-4} M_{\odot}$
- lower mass stars make lower mass WDs
- more lower mass stars, therefore more lower-mass remnants

Planetary Nebula Ring



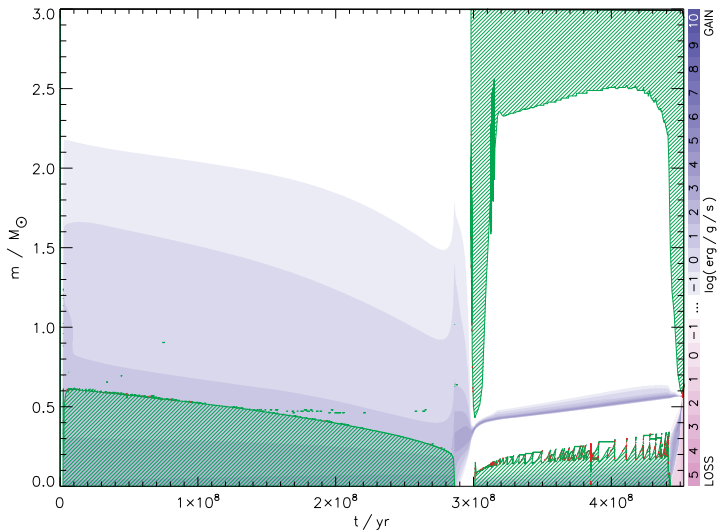
Helix Nebula Details



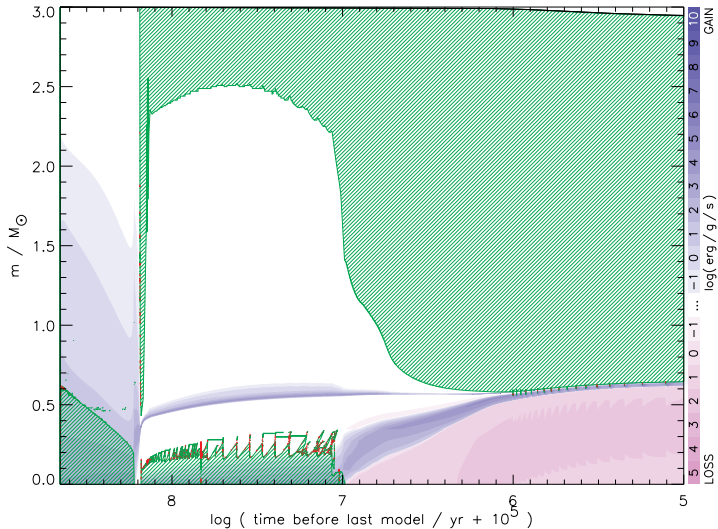
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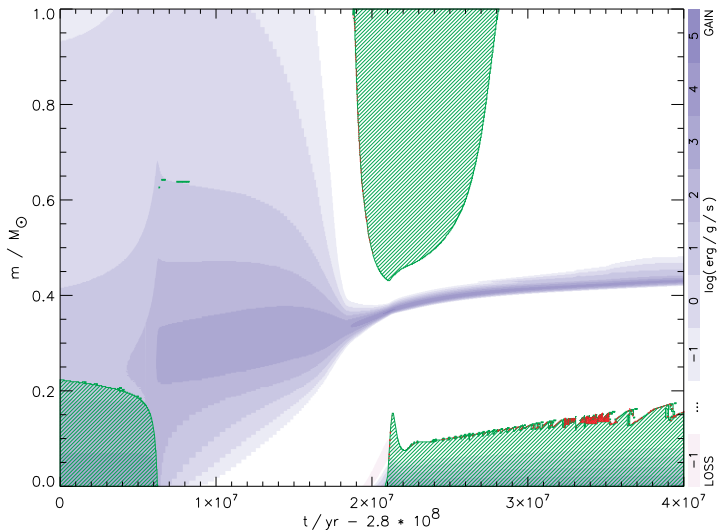
Kippenhahn Diagram, $3 M_{\odot}$ Star



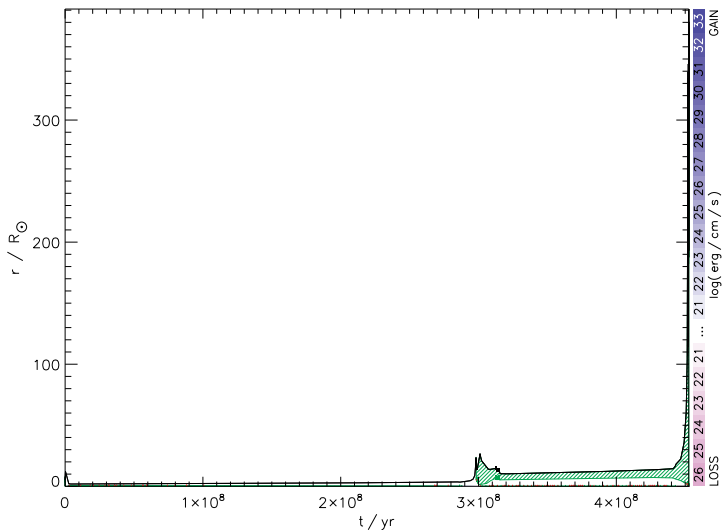
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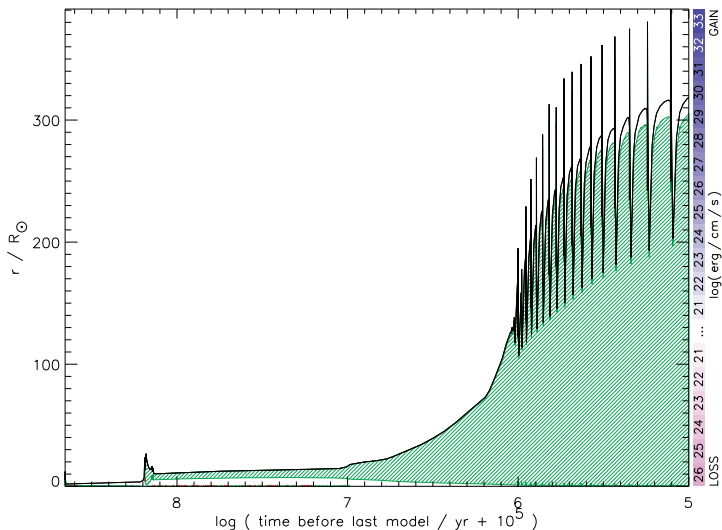
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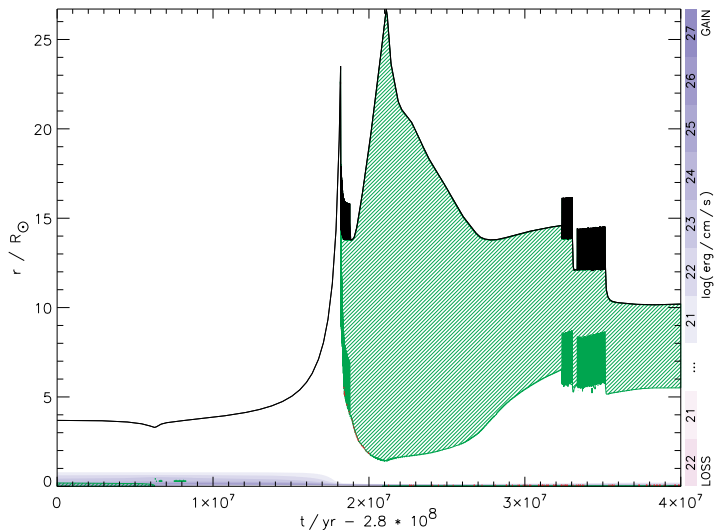
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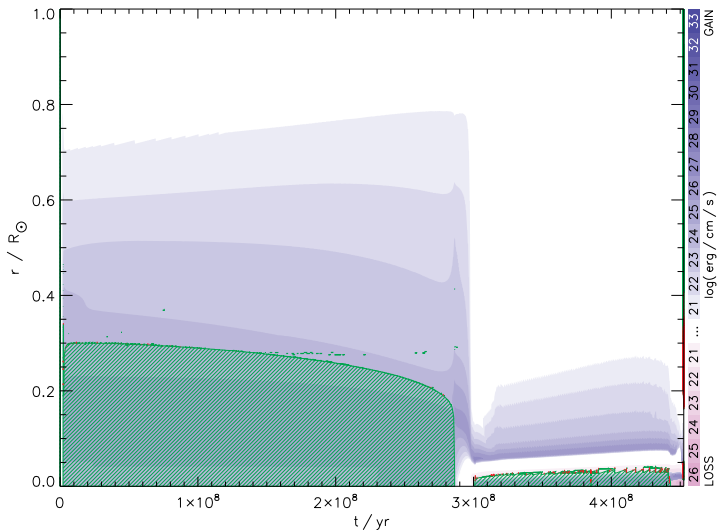
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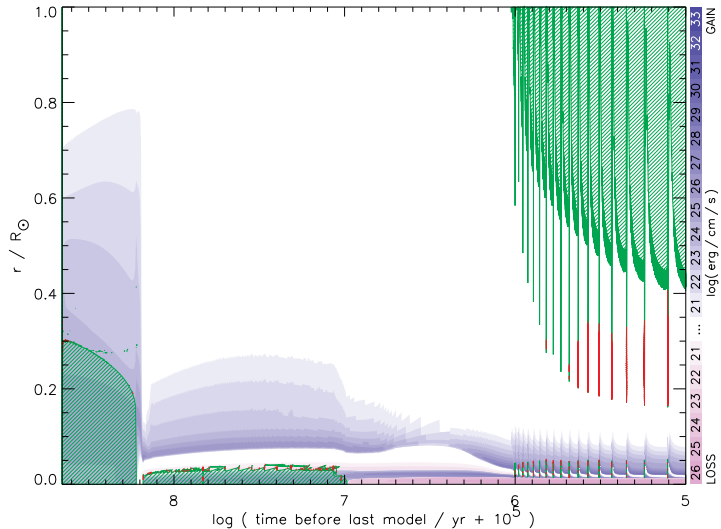
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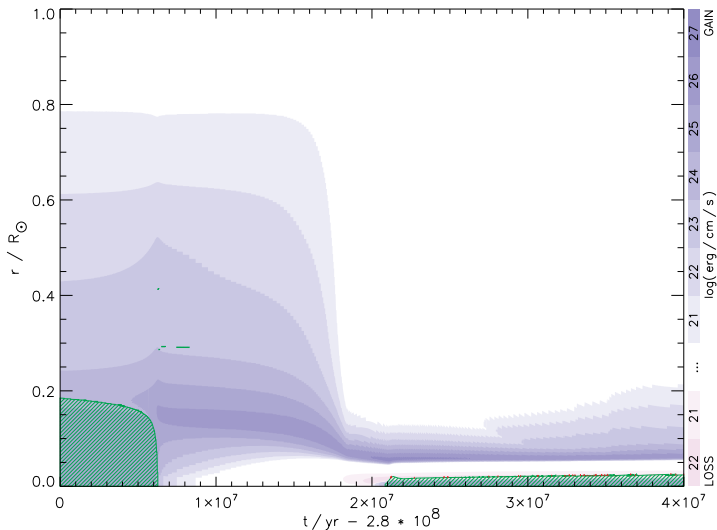
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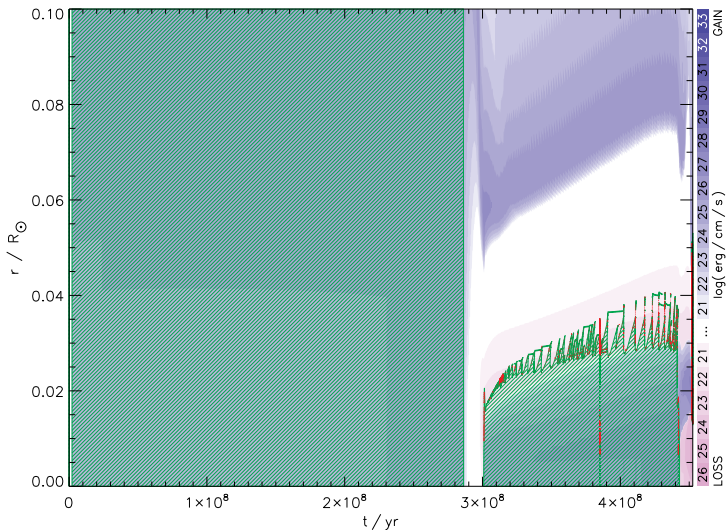
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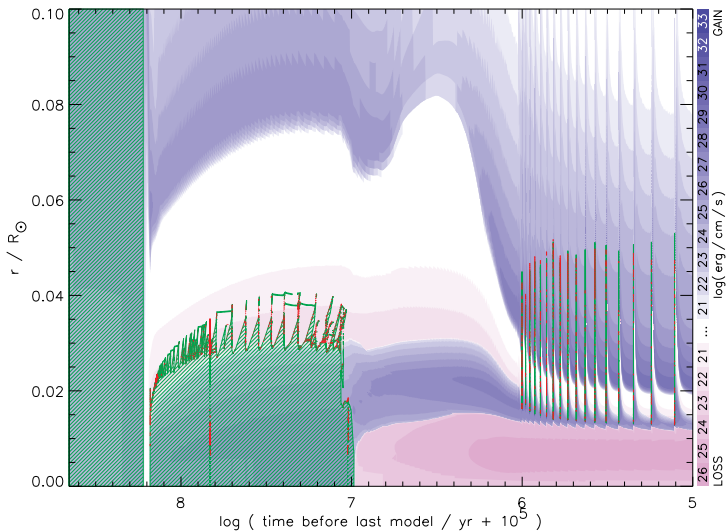
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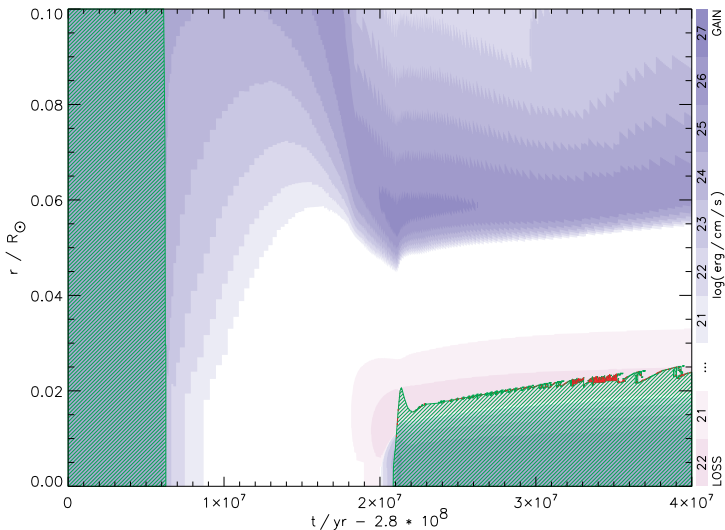
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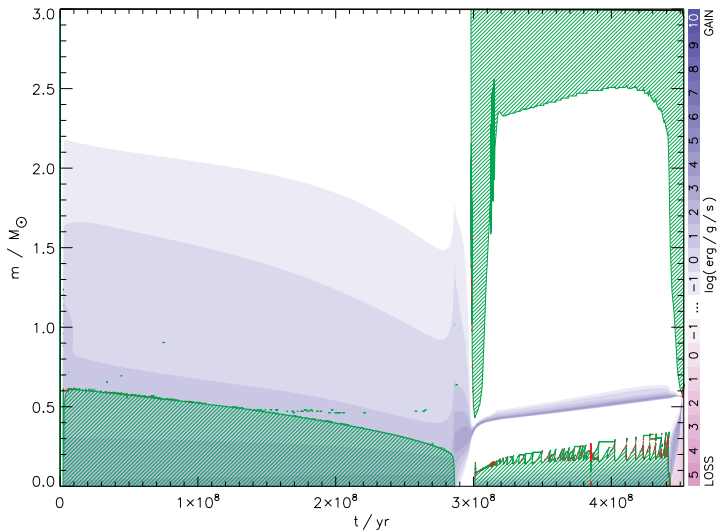
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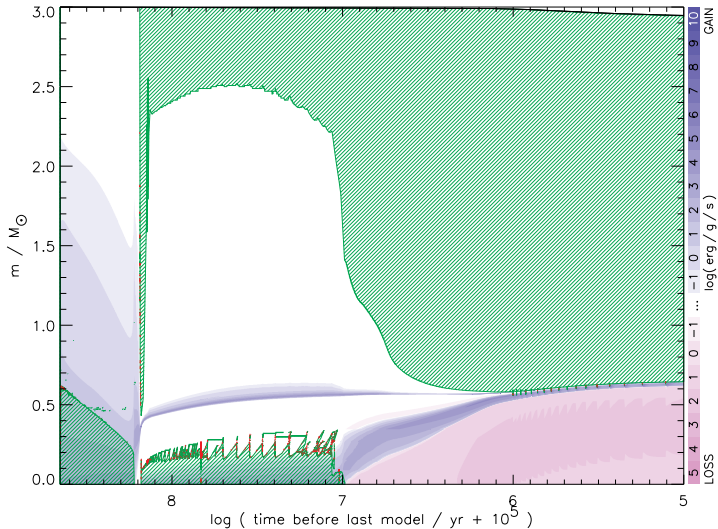
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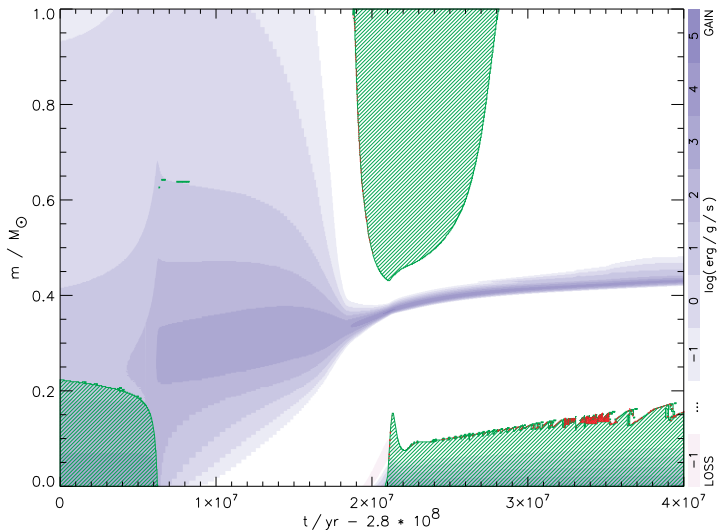
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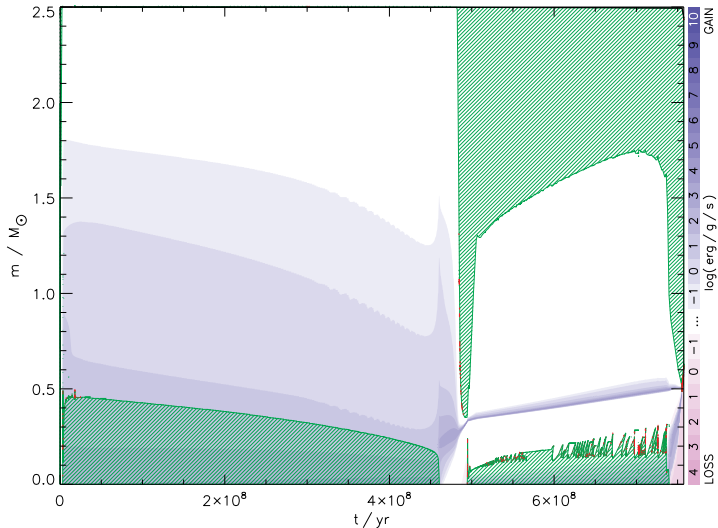
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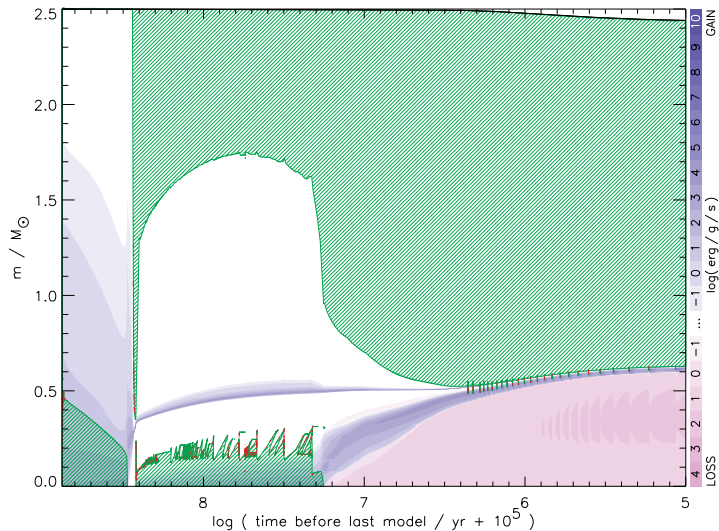
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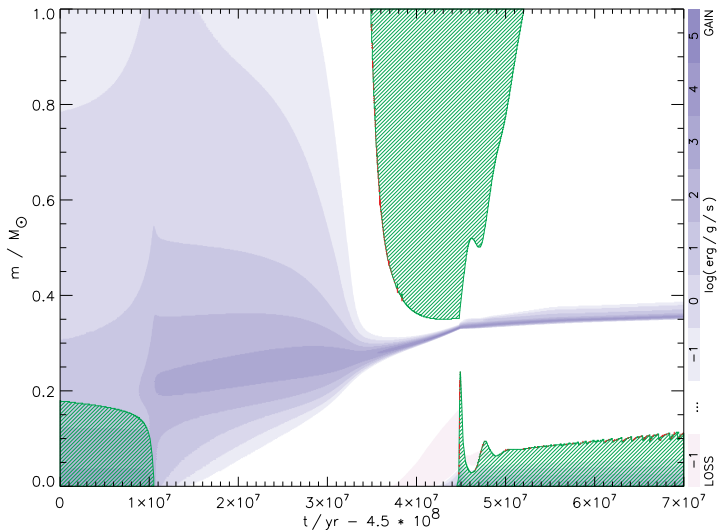
Kippenhahn Diagram, $2.5 M_{\odot}$ Star



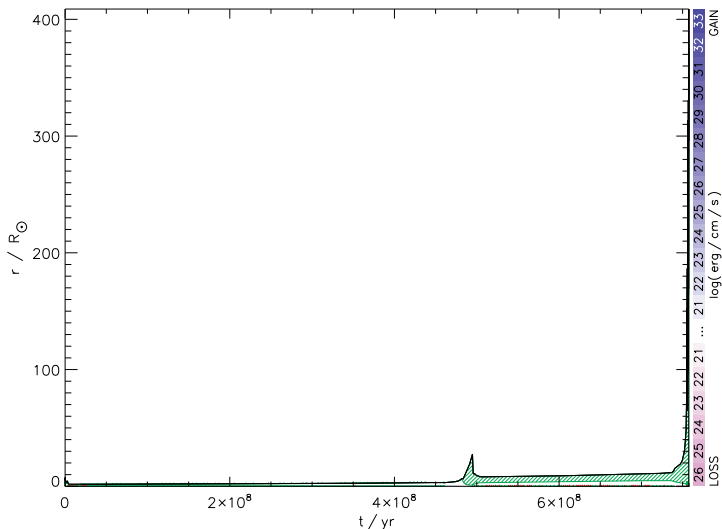
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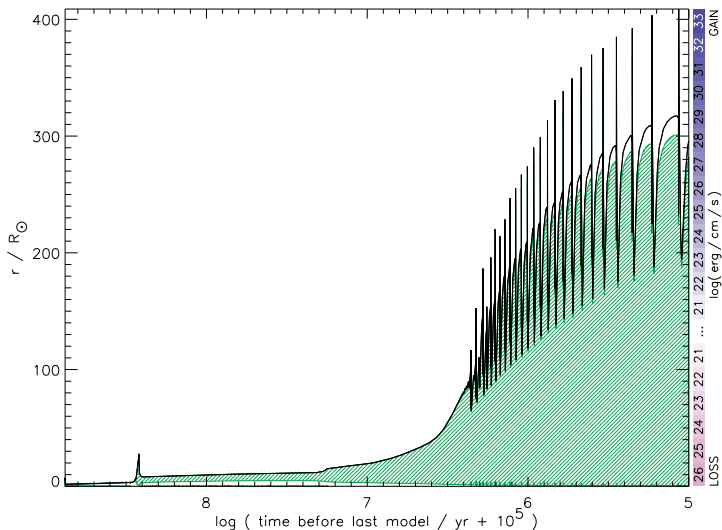
Kippenhahn Diagram, $2.5 M_{\odot}$ Star, Helium Ignition



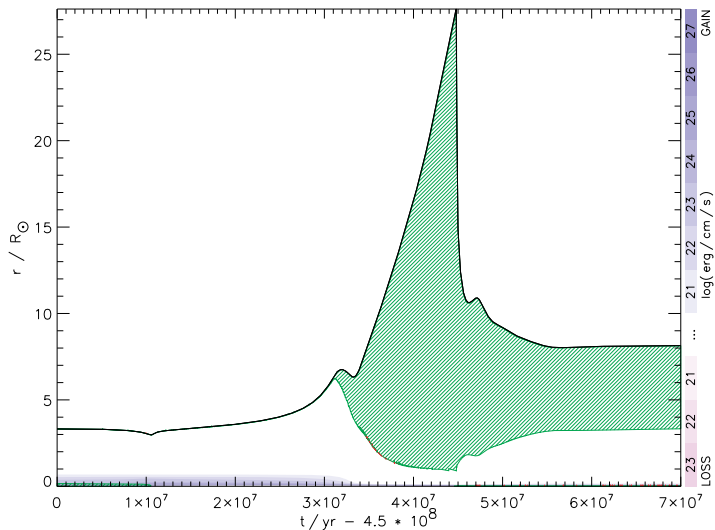
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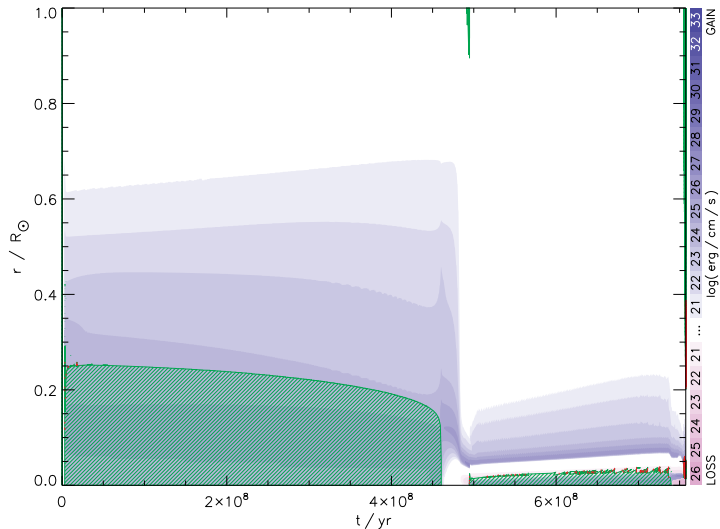
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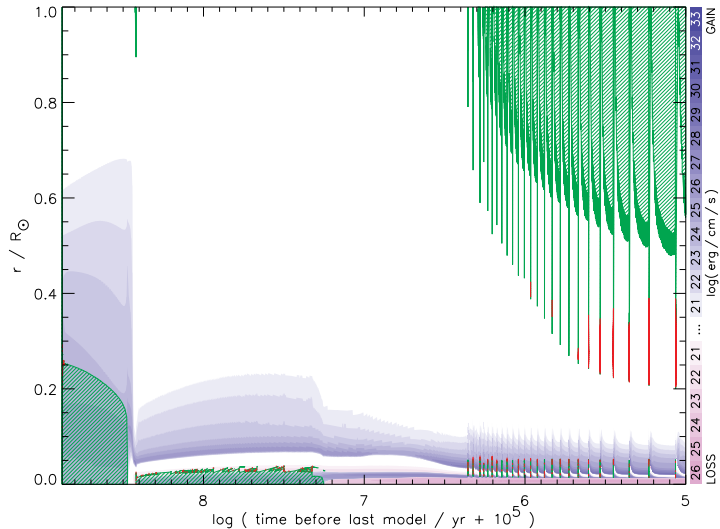
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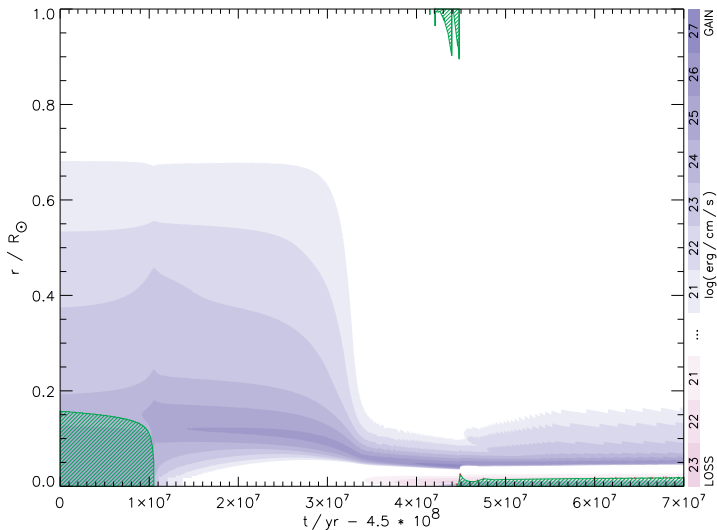
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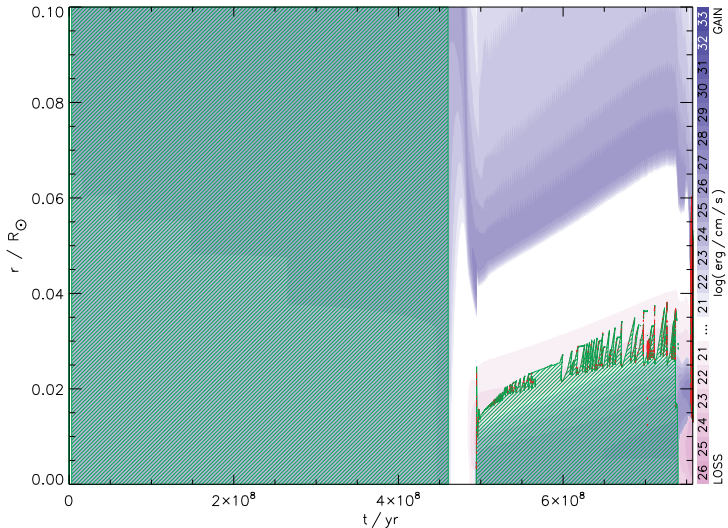
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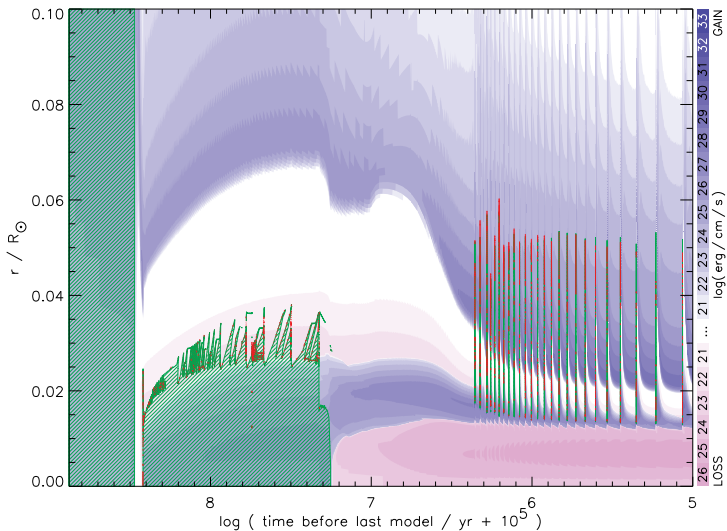
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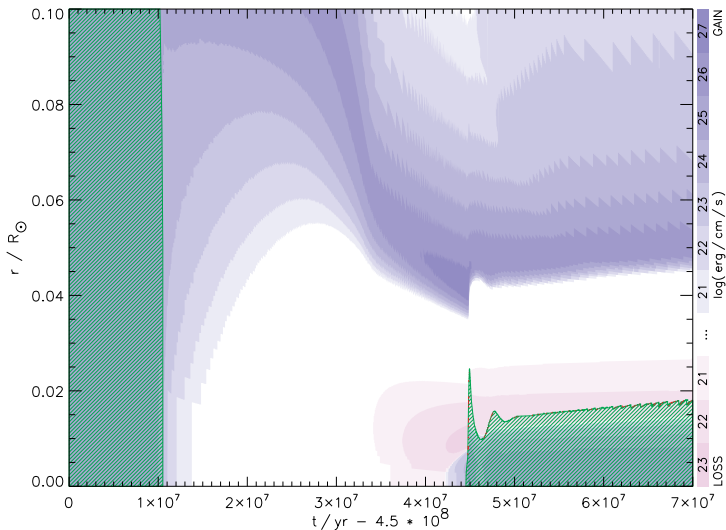
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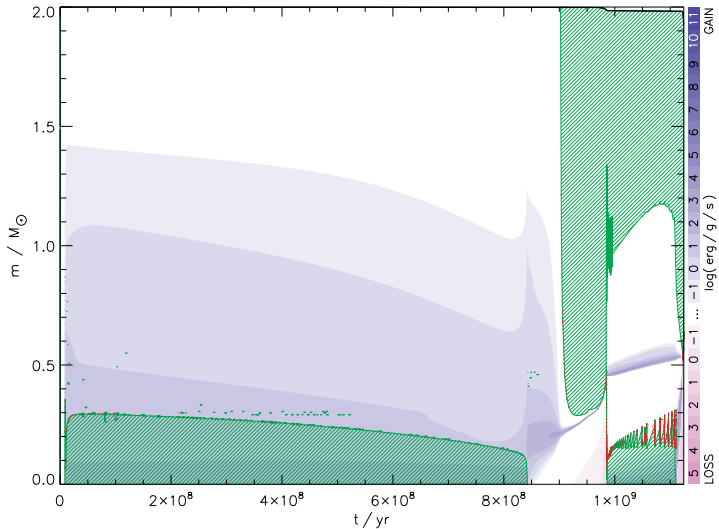
Core Contraction and Degeneracy

- Schönberg-Chandrasekhar limit only valid for ideal gas
- for degenerate gas instead we need to use

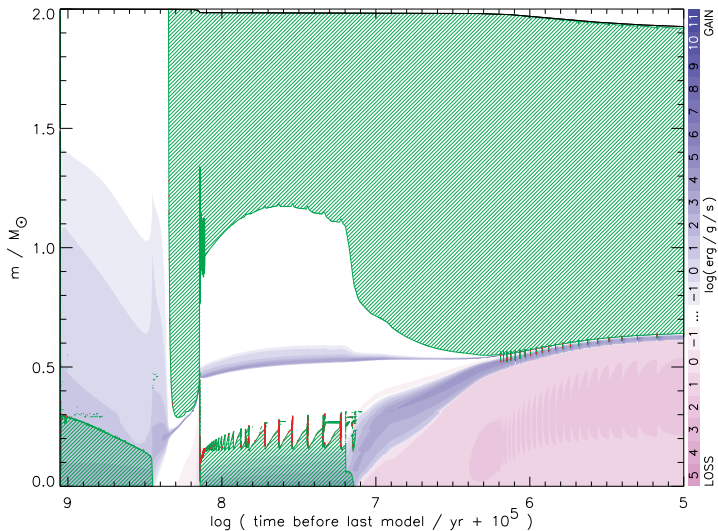
$$P_{s,\max} \lesssim K_1 \left(\frac{3M_c}{4\pi R_c^3} \right)^{5/3}$$

- occurs for stars below about $2 M_\odot$
- gradual appearance of the red giant
- hydrogen shell forms and burns outward
- quiet evolution at first
- eventually ignition of helium under degenerate conditions
- thermonuclear runaway: **helium flash**
- nuclear power of $10^{11} L_\odot$ - the luminosity of an entire galaxy or a supernova, but invisibly inside the star

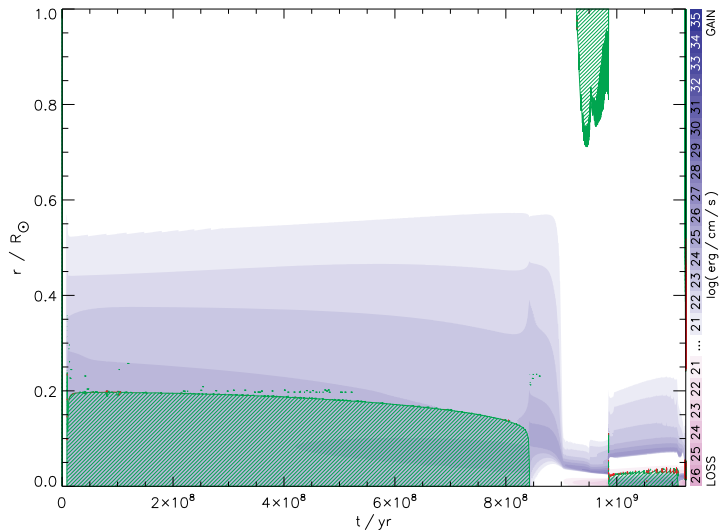
Kippenhahn Diagram, $2M_{\odot}$ Star



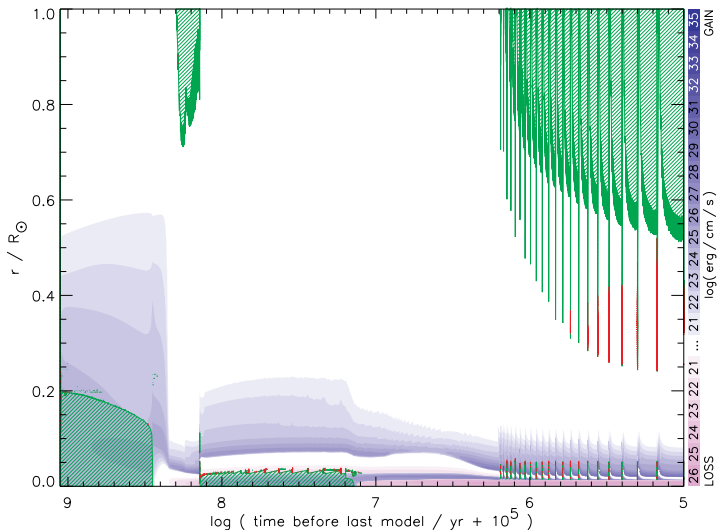
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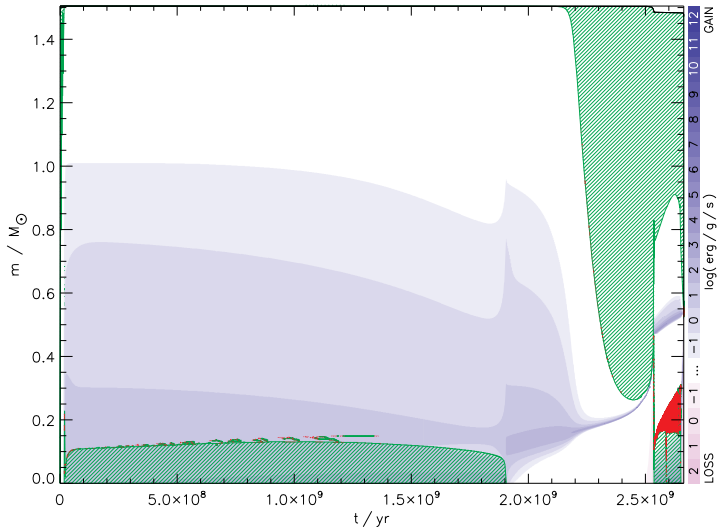
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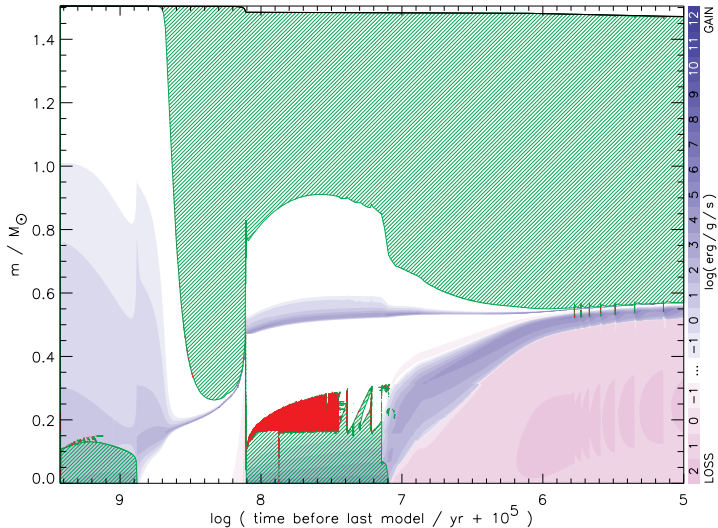
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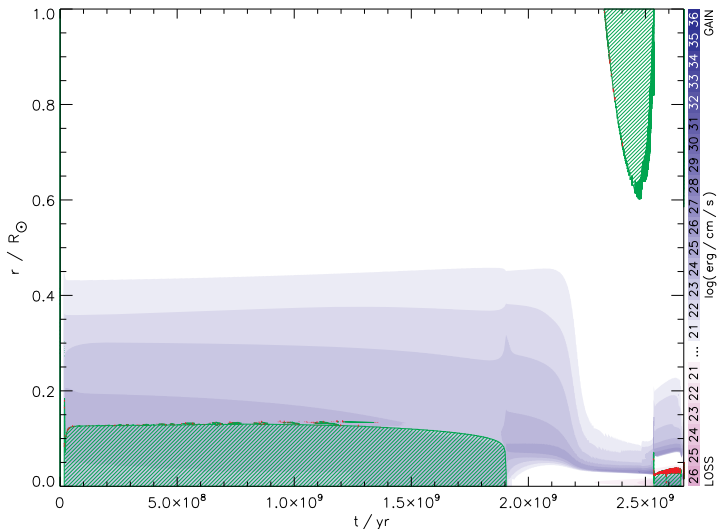
Kippenhahn Diagram, $1.5M_{\odot}$ Star



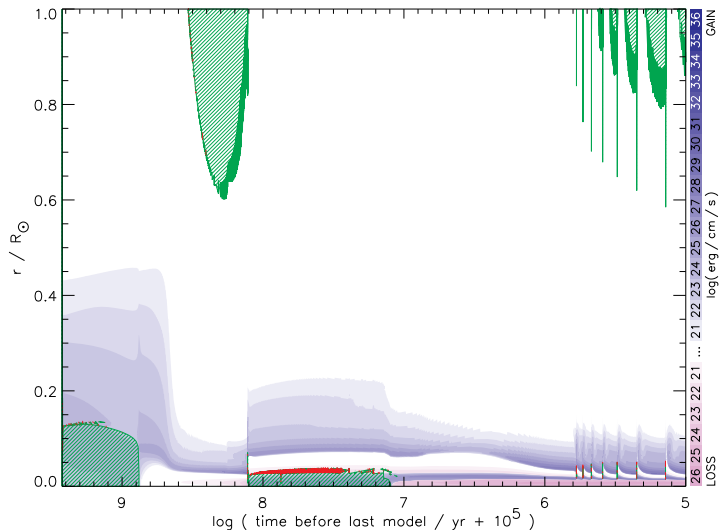
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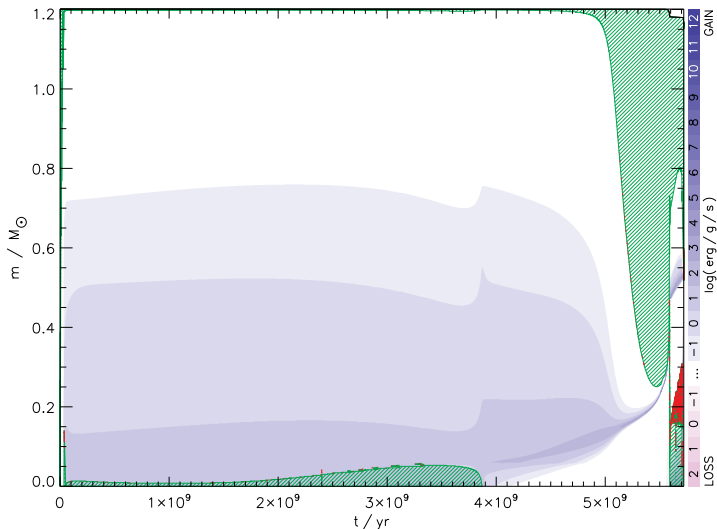
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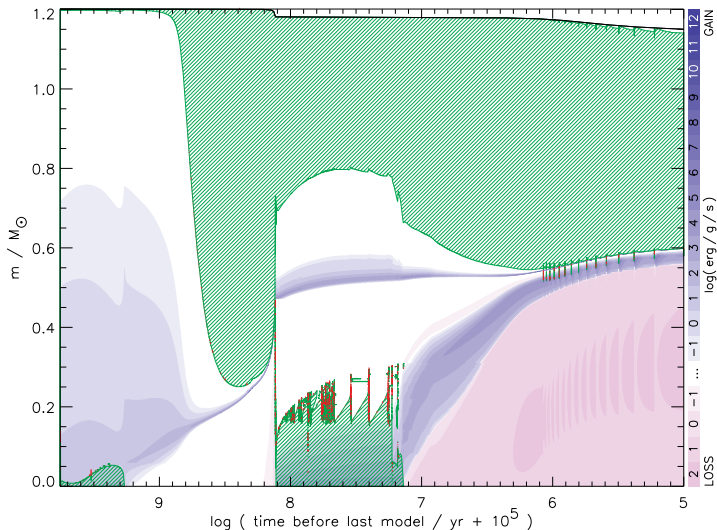
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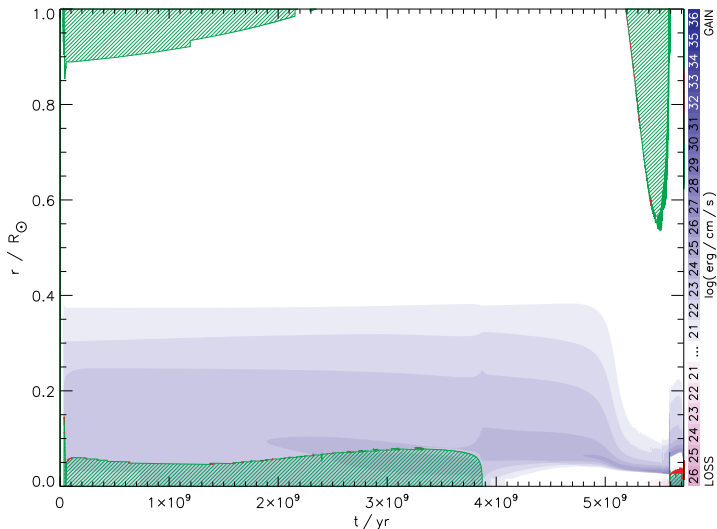
Kippenhahn Diagram, $1.2 M_{\odot}$ Star



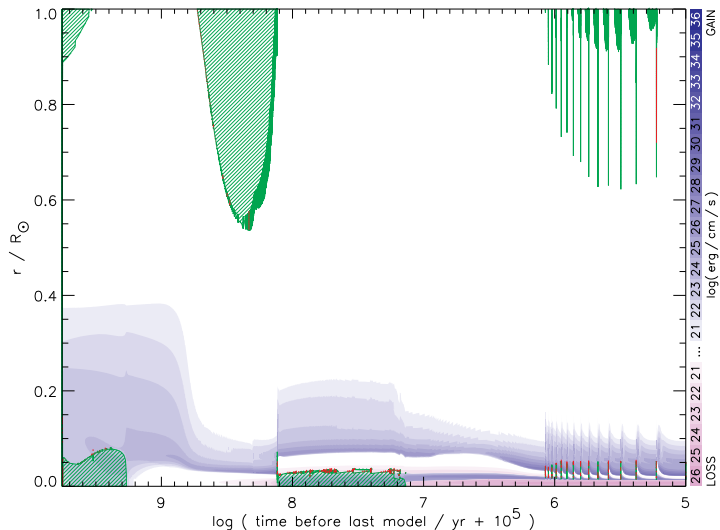
Kippenhahn Diagram, $1.2 M_{\odot}$ Star



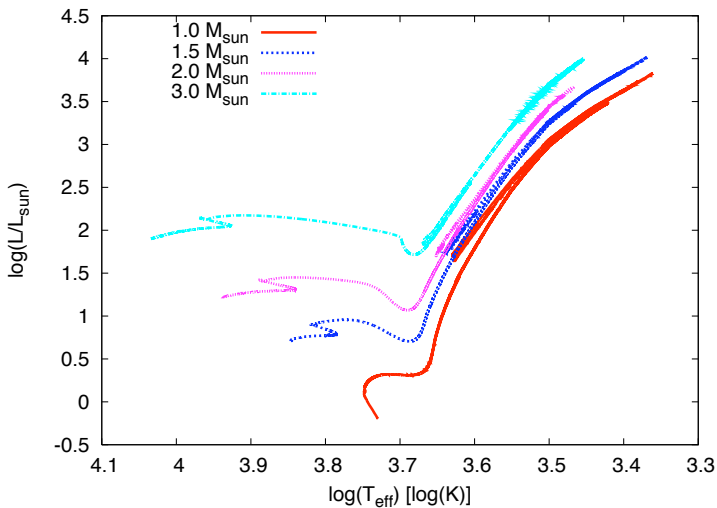
Kippenhahn-Radius Diagram, $1.2 M_{\odot}$ Star



Kippenhahn-Radius Diagram, $1.2 M_{\odot}$ Star



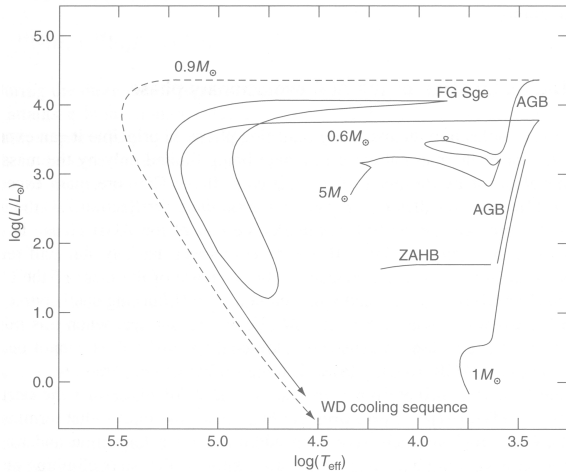
Evolution Through Core Contraction



Low-Mass Stars and the Horizontal Branch

- *after core helium flash*, low-mass stars ($0.7 - 2 M_{\odot}$) undergo contraction and cooling of the envelope
- this is similar to contraction *from* the Hayashi line during star formation, only in *reverse*
- stars of different initial mass have comparable *core mass* at the time of helium flash, but different envelope mass
- formation of **horizontal branch (HB)** in the HRD,
 $L \sim 50 - 100 L_{\odot}$
- highest envelope masses are to the right, are red
- lifetime on HB is about 10^8 yr
- mass loss of star on the HB \Rightarrow mass in the H envelope drops
 \Rightarrow change of position on HB

Low-Mass Stars and the Horizontal Branch



ZAHB = Zero-Age
Horizontal Branch

RR Lyrae Stars

- stars on the blue side of the HB have mostly radiative envelopes
- they are pulsationally unstable with periods of a few hours
- they form the class of the **RR Lyrae** variable stars

Evolution tracks and lifetimes

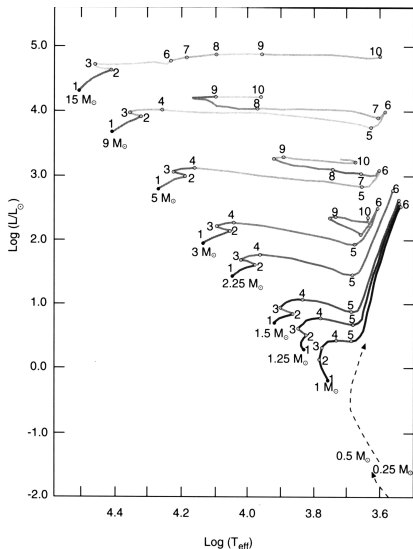
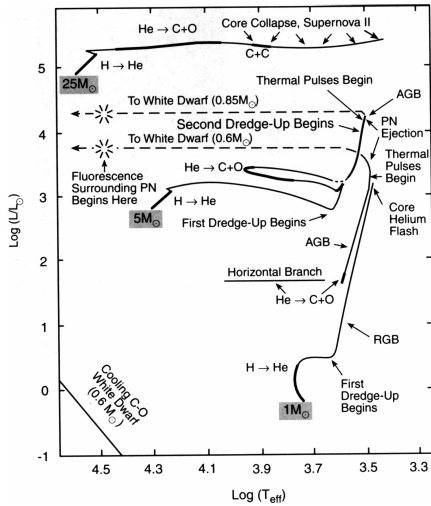


Table 8.4 Evolutionary lifetimes (years)

M/M_{\odot}	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
15	1.0(7)	2.3(5)	←	7.6(4)	→	7.2(5)	6.2(5)	1.9(5)	3.5(4)
9	2.1(7)	6.1(5)	9.1(4)	1.5(5)	6.6(4)	4.9(5)	9.5(4)	3.3(6)	1.6(5)
5	6.5(7)	2.2(6)	1.4(6)	7.5(5)	4.9(5)	6.1(6)	1.0(6)	9.0(6)	9.3(5)
3	2.2(8)	1.0(7)	1.0(7)	4.5(6)	4.2(6)	←	6.6(7)	→	6.0(6)
2.25	4.8(8)	1.6(7)	3.7(7)	1.3(7)	3.8(7)				
1.5	1.6(9)	8.1(7)	3.5(8)	1.0(8)	>2(8)				
1.25	2.8(9)	1.8(8)	1.0(9)	1.5(8)	>4(8)				
1.0	7.0(9)	2.0(9)	1.2(9)	1.6(9)	>1(9)				

Note: Powers of 10 are given in parentheses.

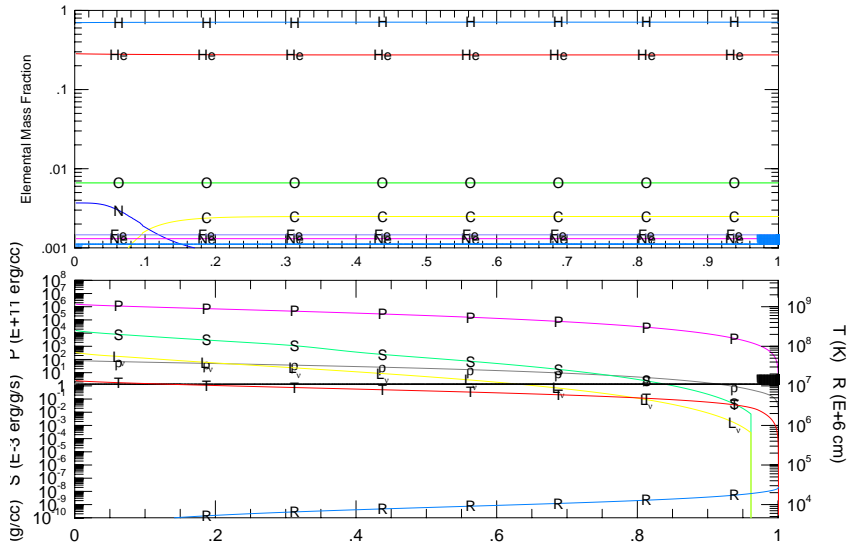
Stellar evolution in the HRD



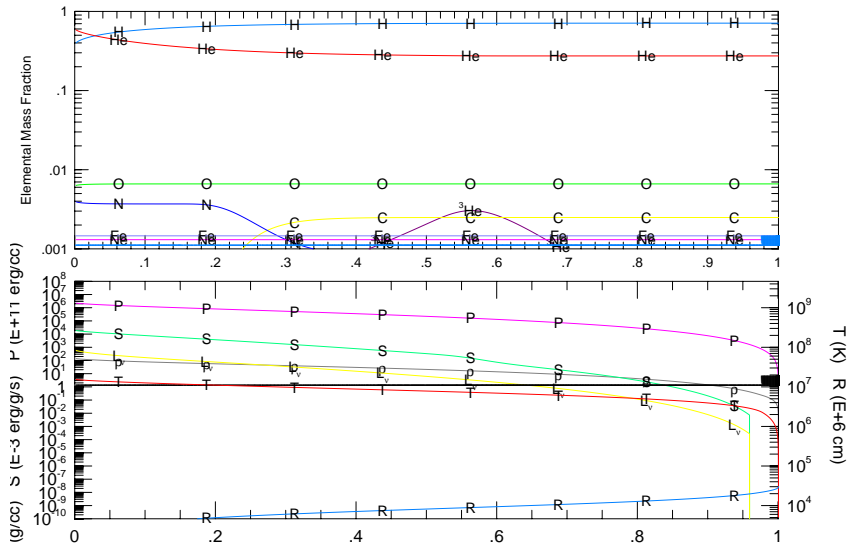
1 M_{\odot} Star

Evolution of a 1 M_{\odot} Star like the sun.

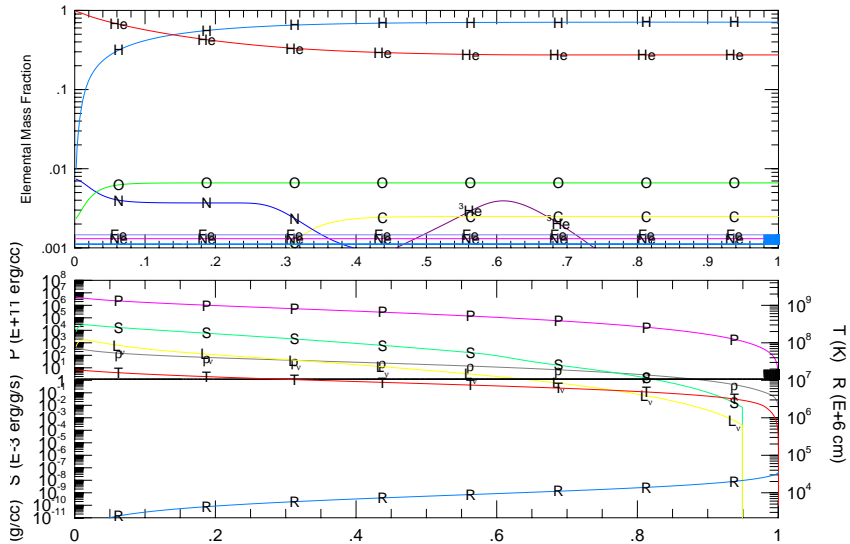
1 M_⊙ Star



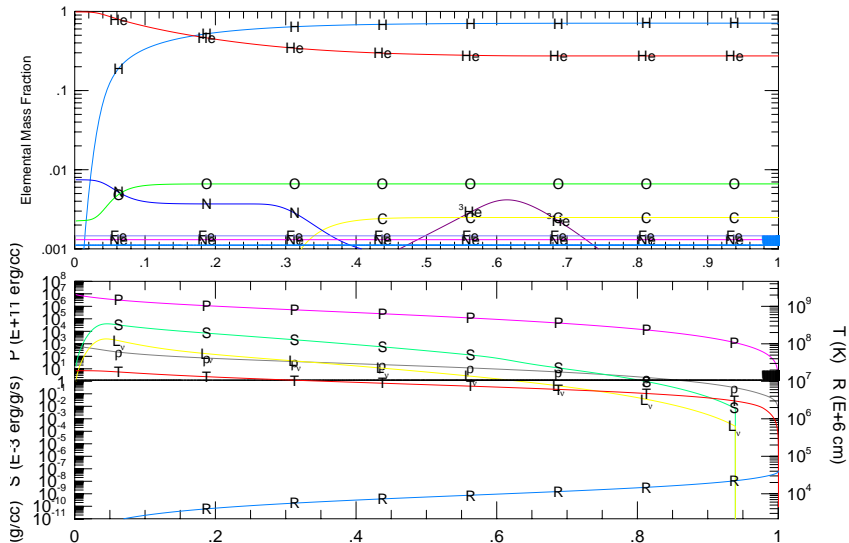
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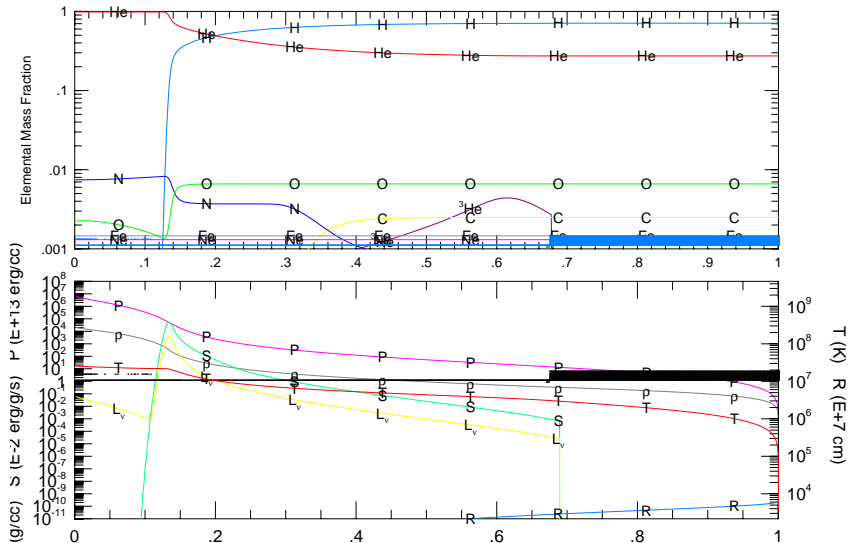
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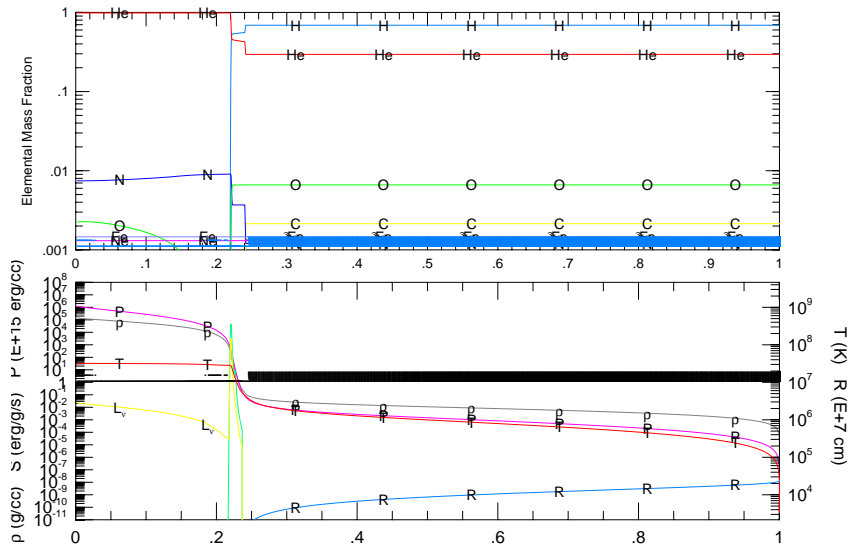
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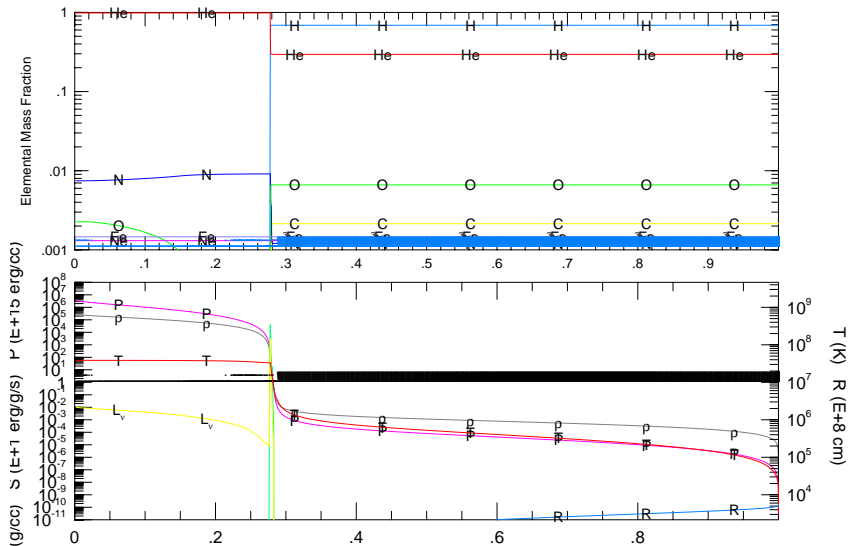
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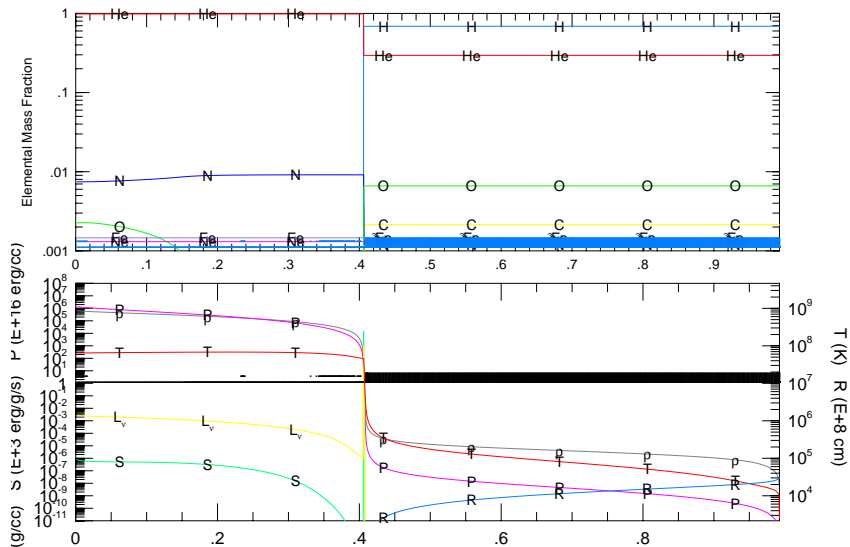
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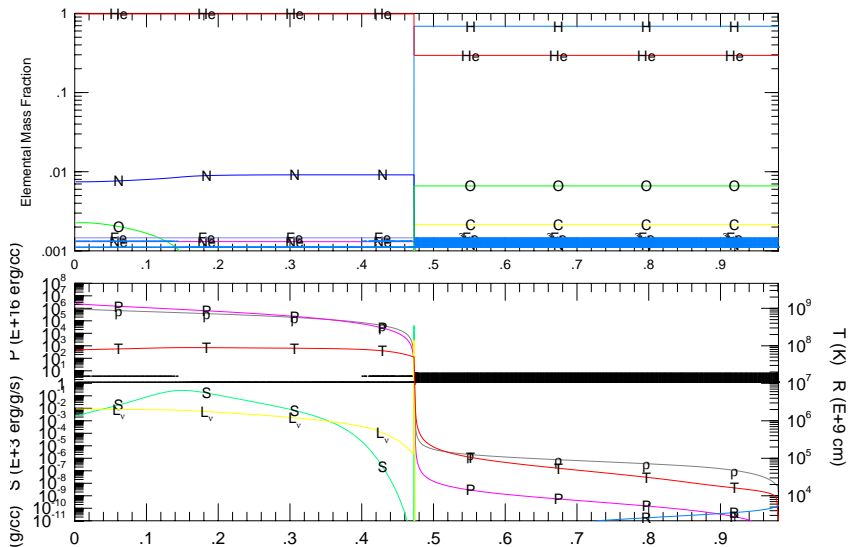
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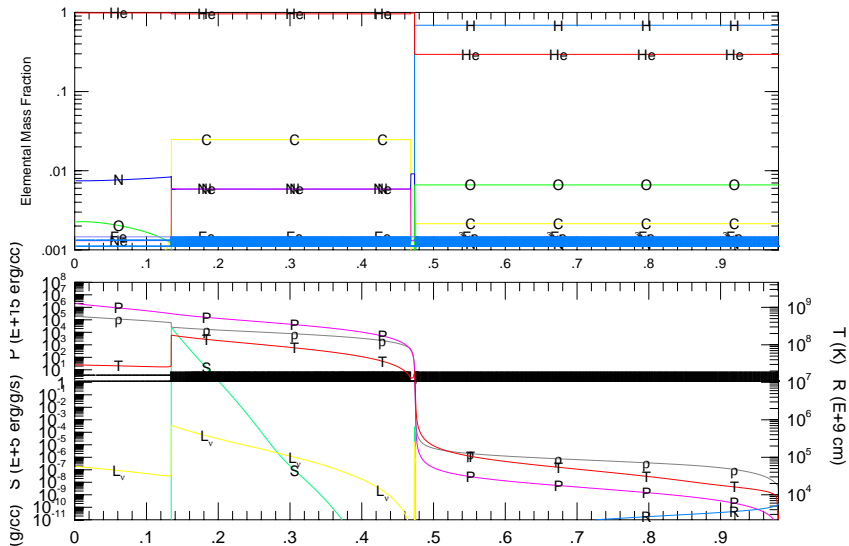
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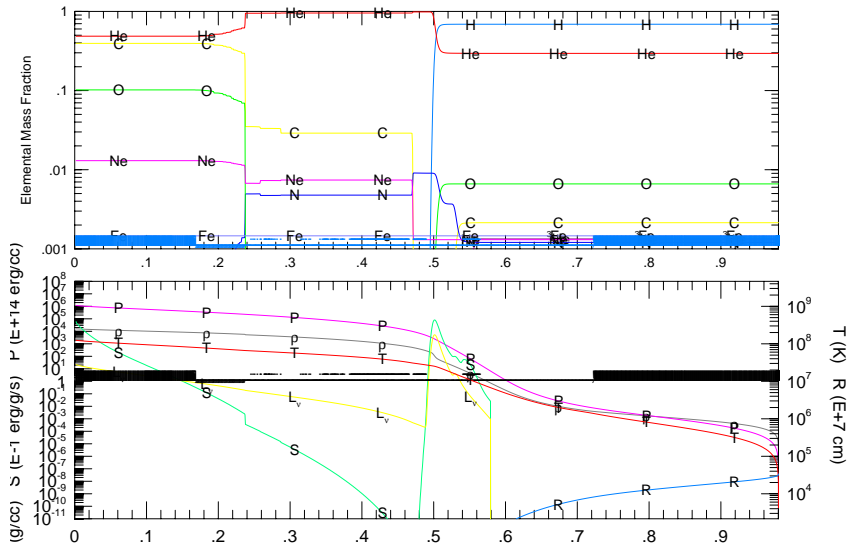
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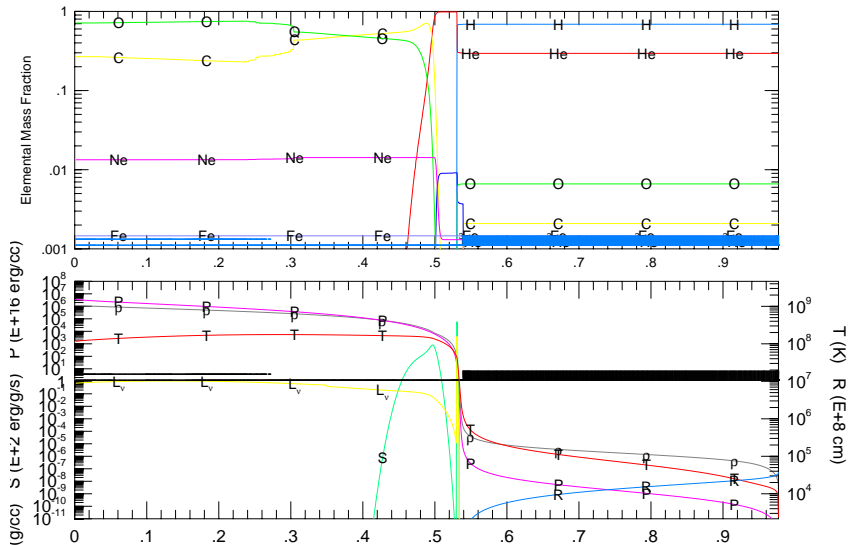
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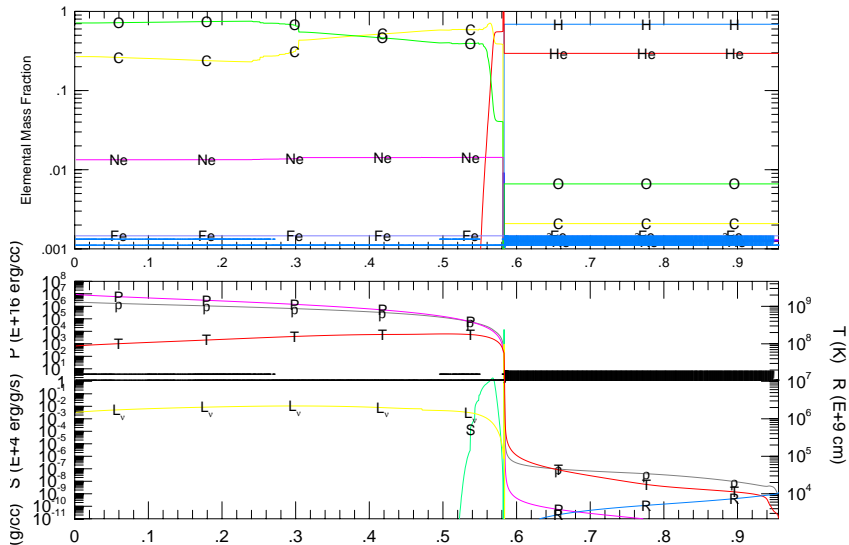
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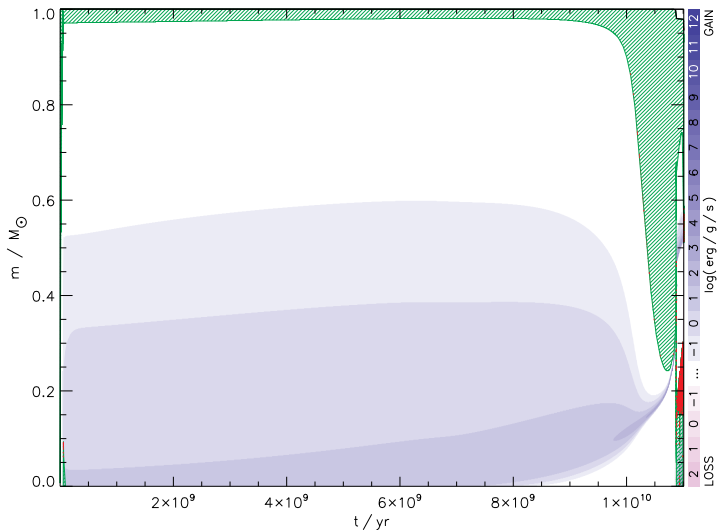
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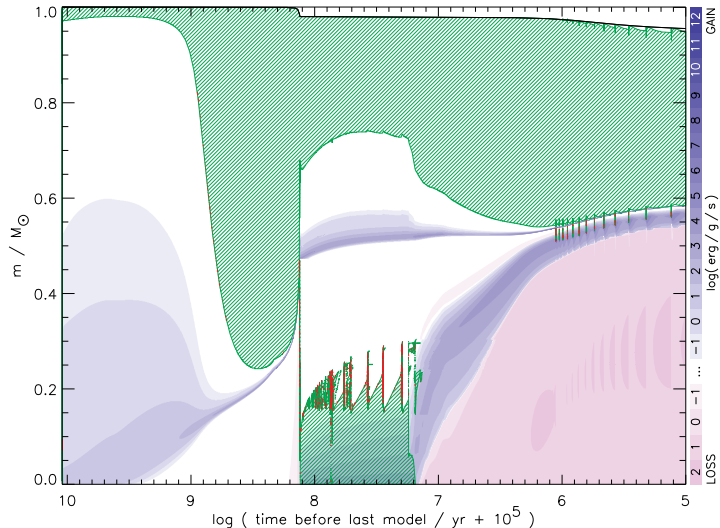
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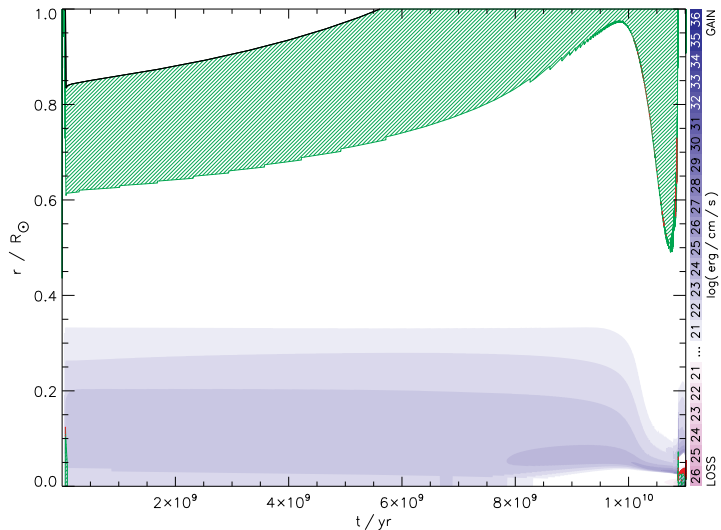
Kippenhahn Diagram, $1M_{\odot}$ Star



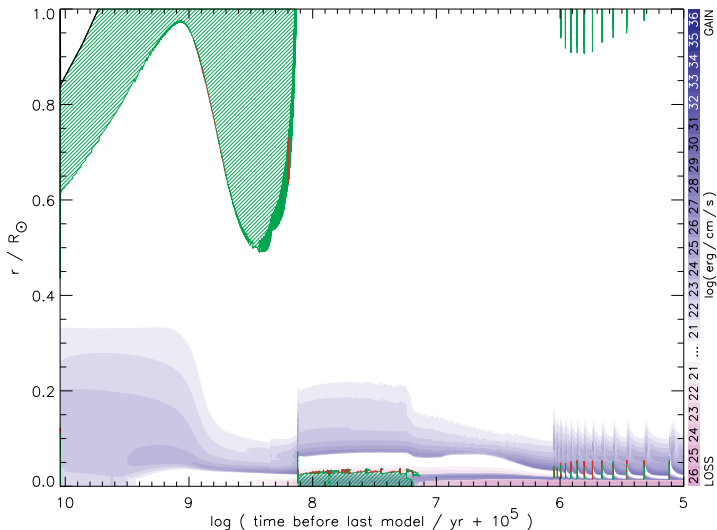
Kippenhahn Diagram, $1M_{\odot}$ Star



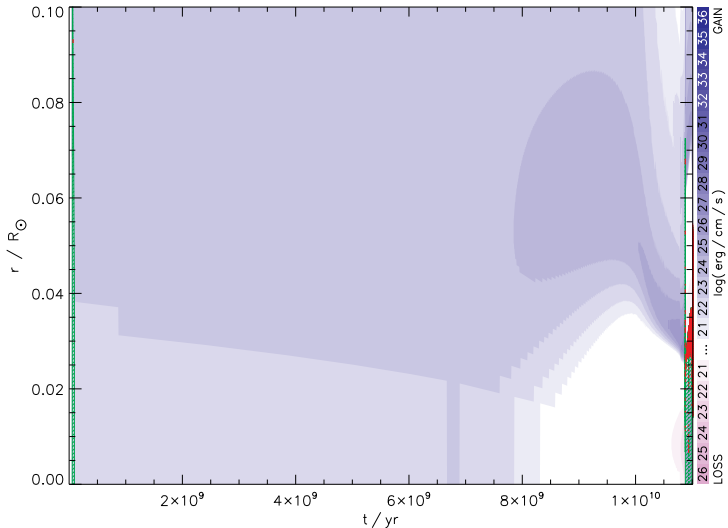
Kippenhahn Diagram, $1M_{\odot}$ Star



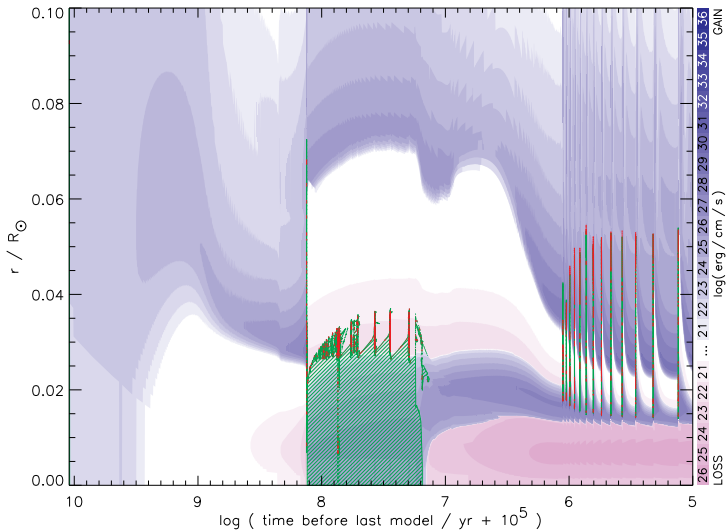
Kippenhahn Diagram, $1M_{\odot}$ Star



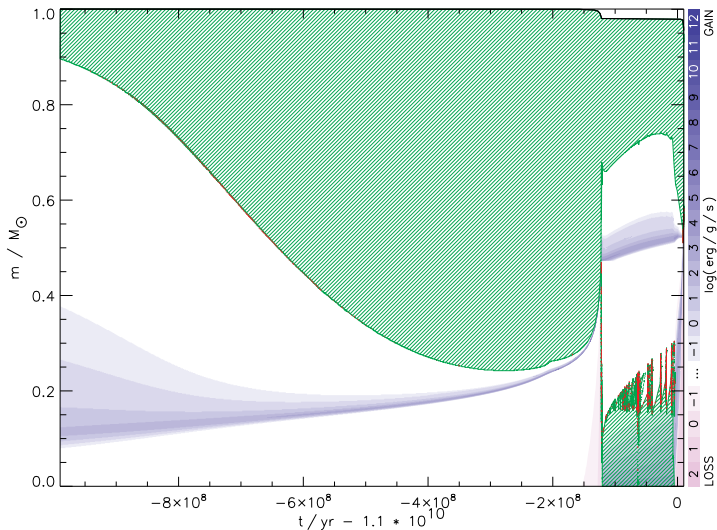
Kippenhahn Diagram, $1M_{\odot}$ Star



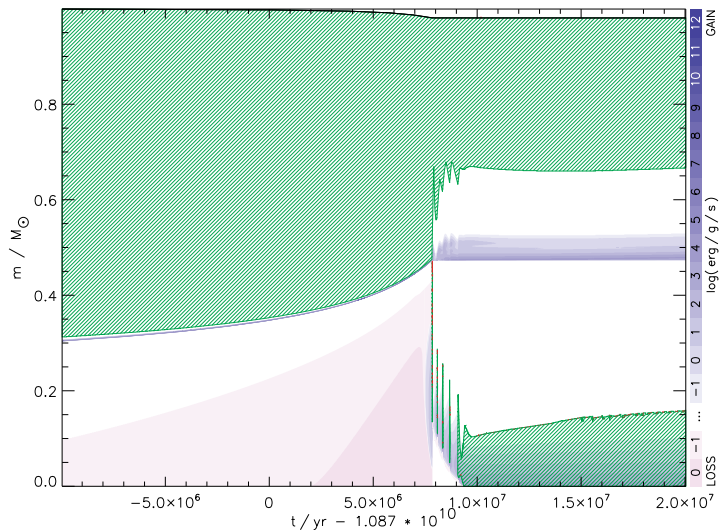
Kippenhahn Diagram, $1M_{\odot}$ Star



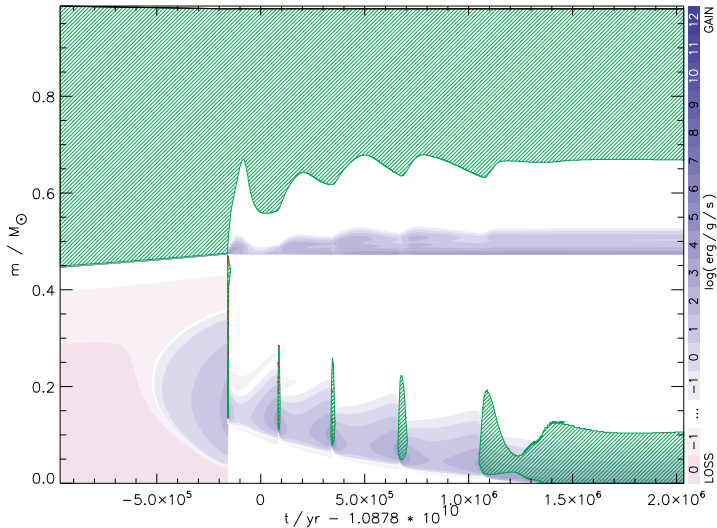
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



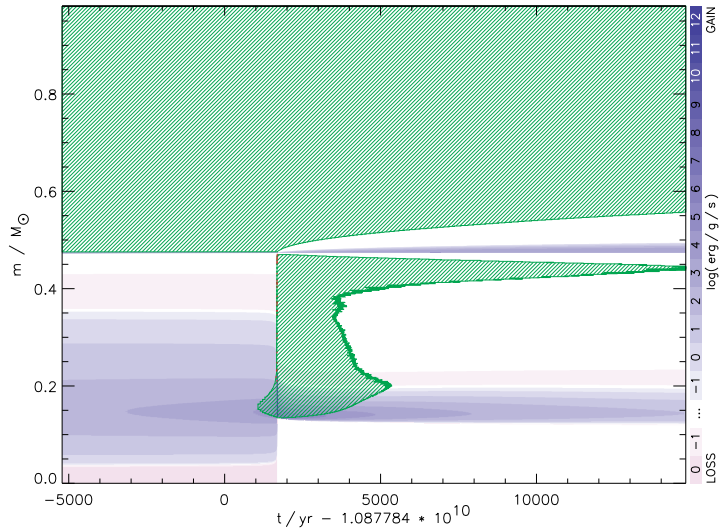
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



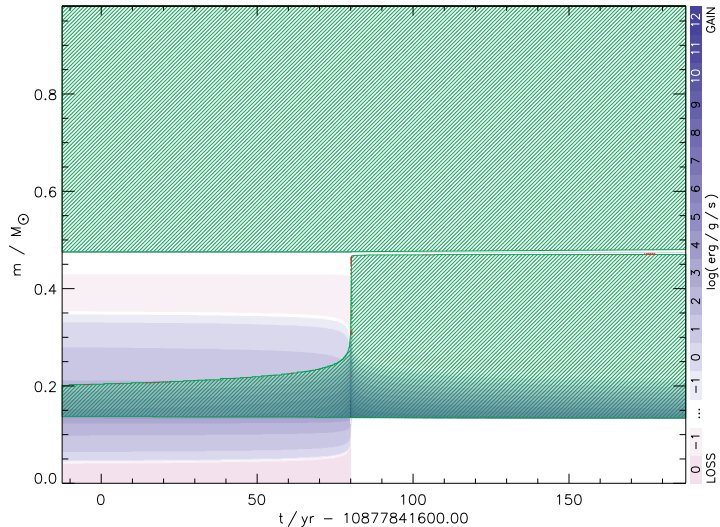
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



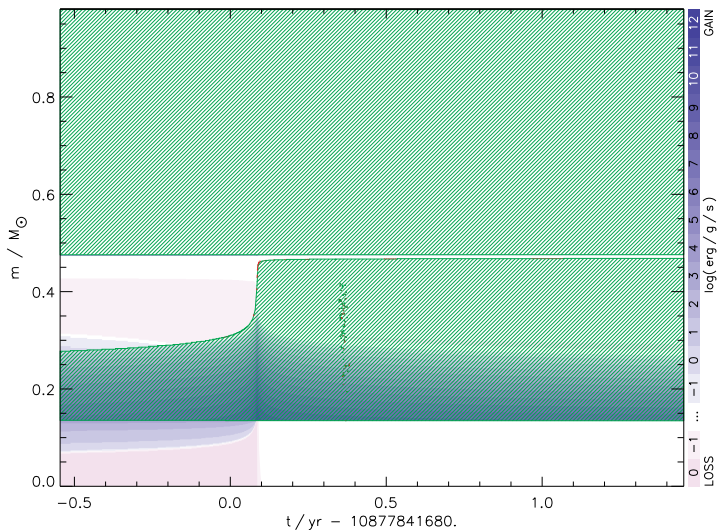
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



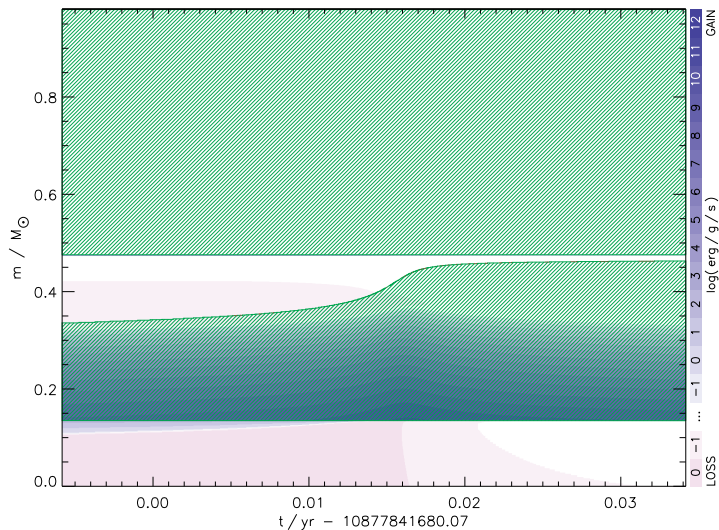
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



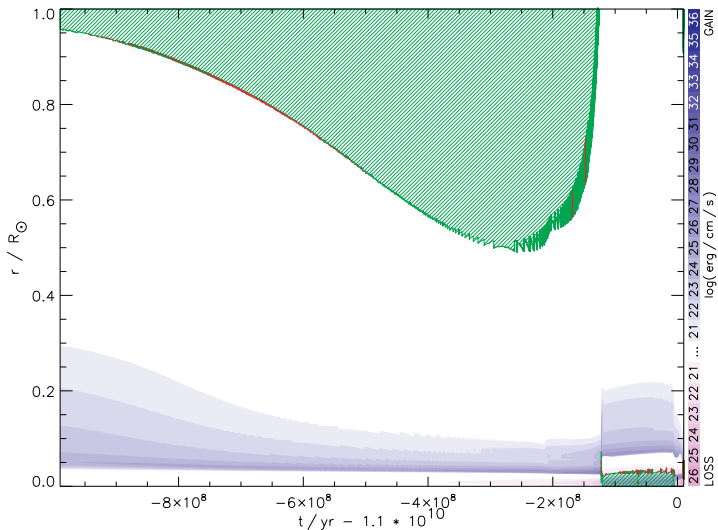
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



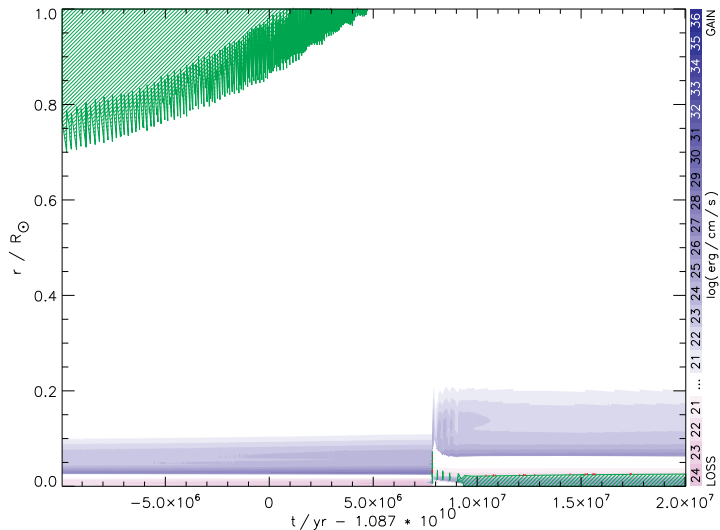
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



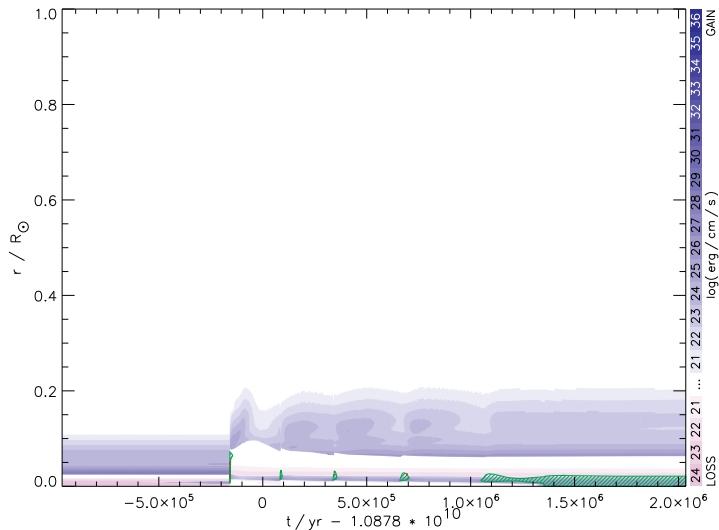
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



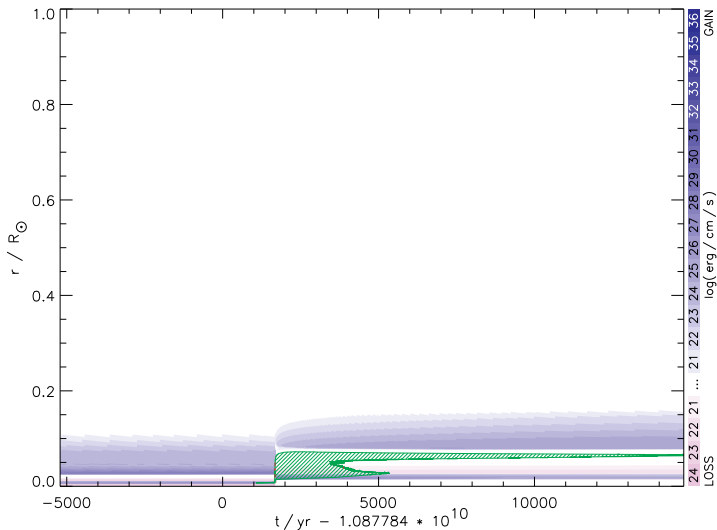
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



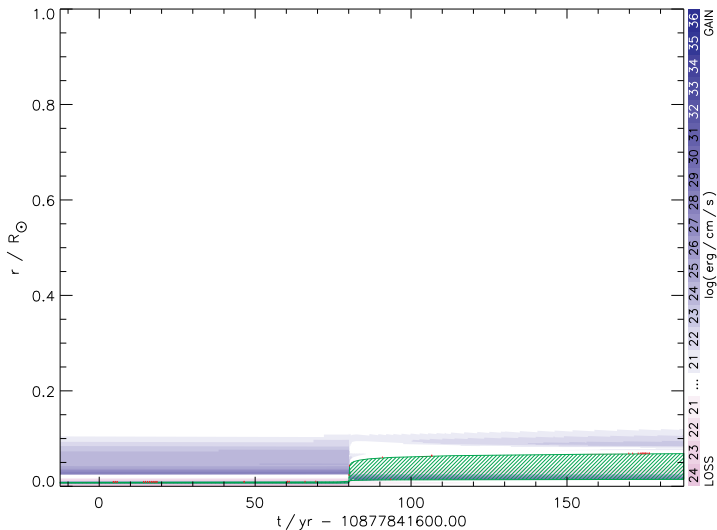
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



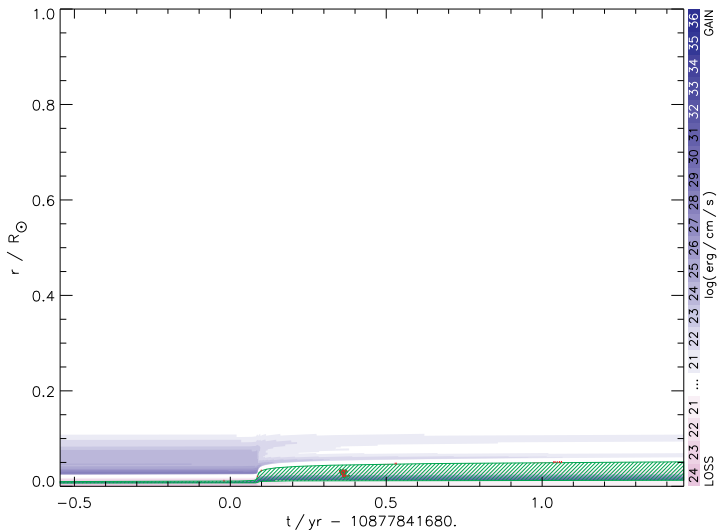
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



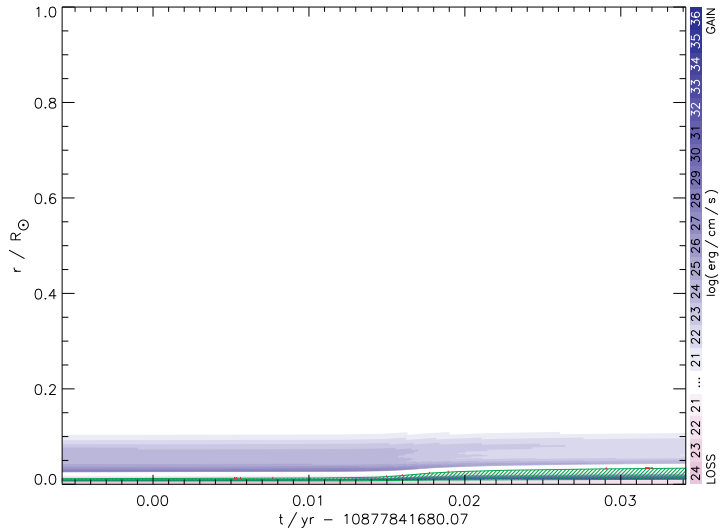
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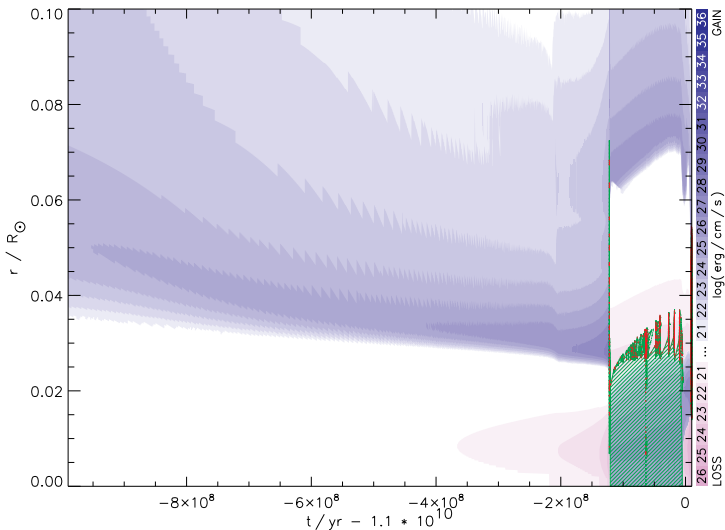
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



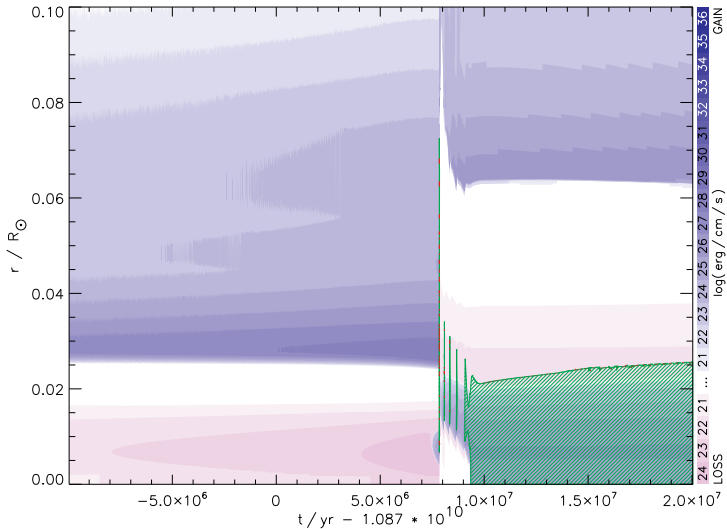
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



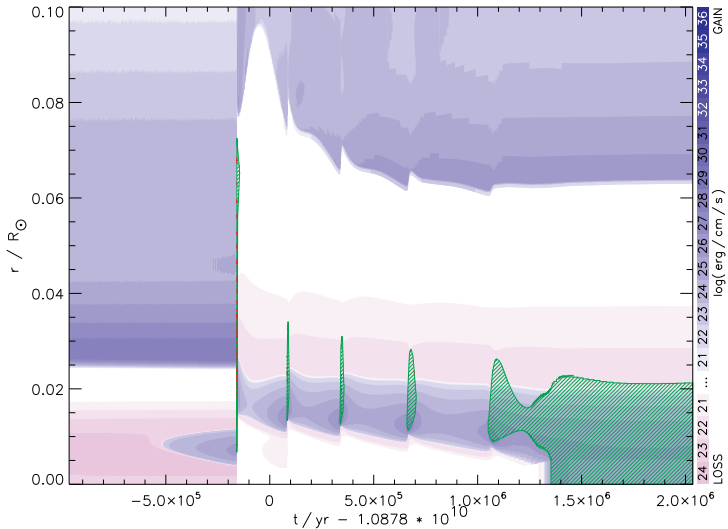
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



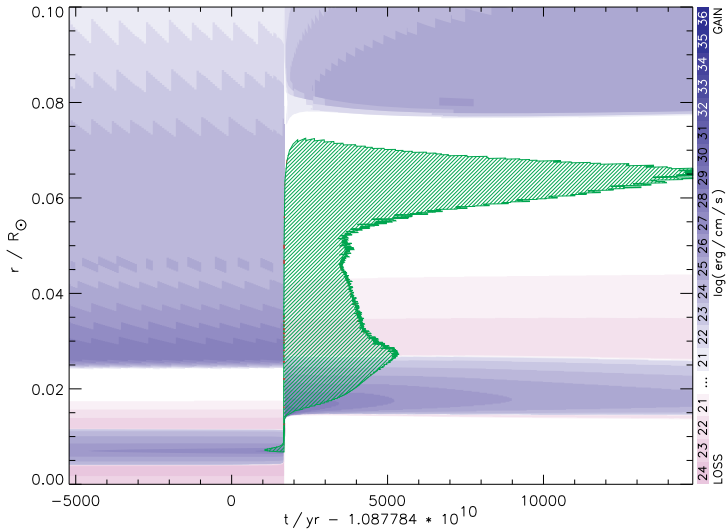
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



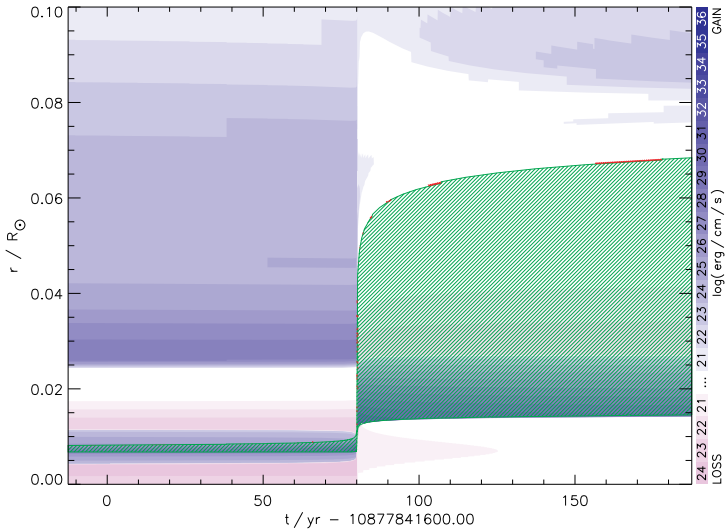
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



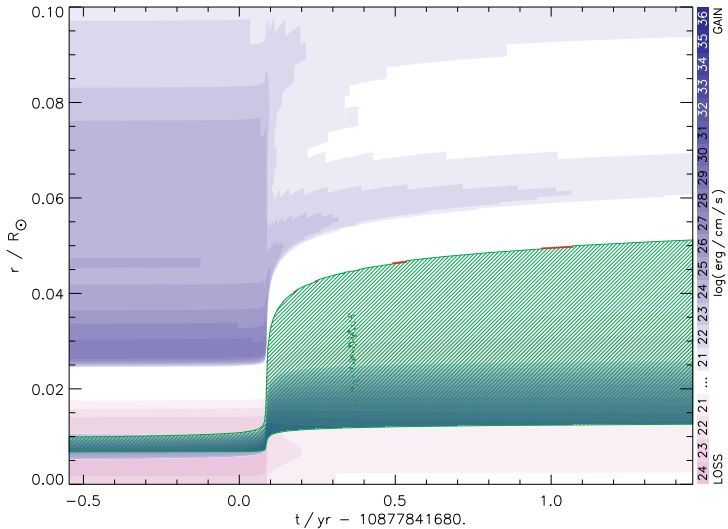
Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



Kippenhahn Diagram, $1M_{\odot}$ Star, Helium Ignition



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