Nuclear Physics I: Nuclear Astrophysics

PHYS 8801

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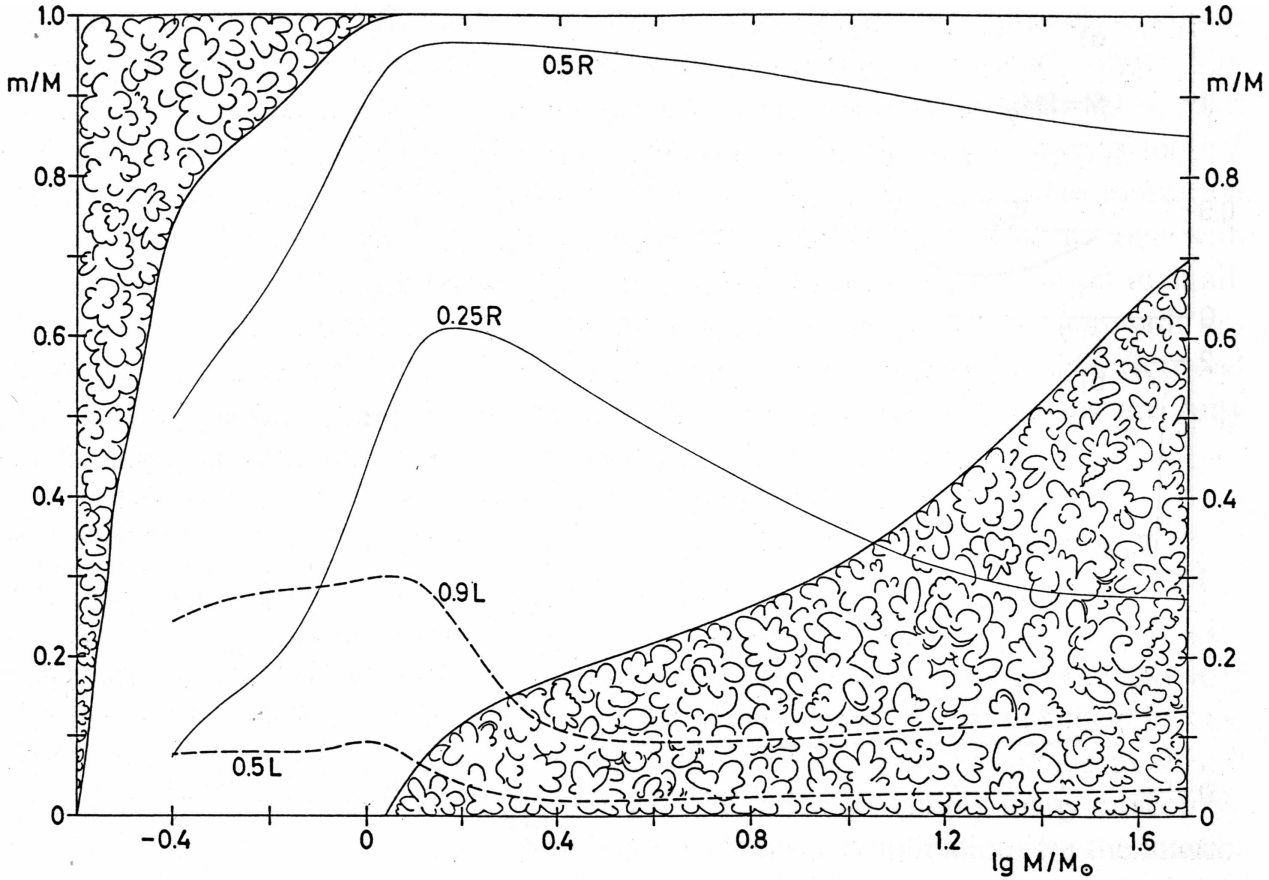
University of Minnesota

Nuclear Physics I: Nuclear Astrophysics, Spring 2012

Agenda

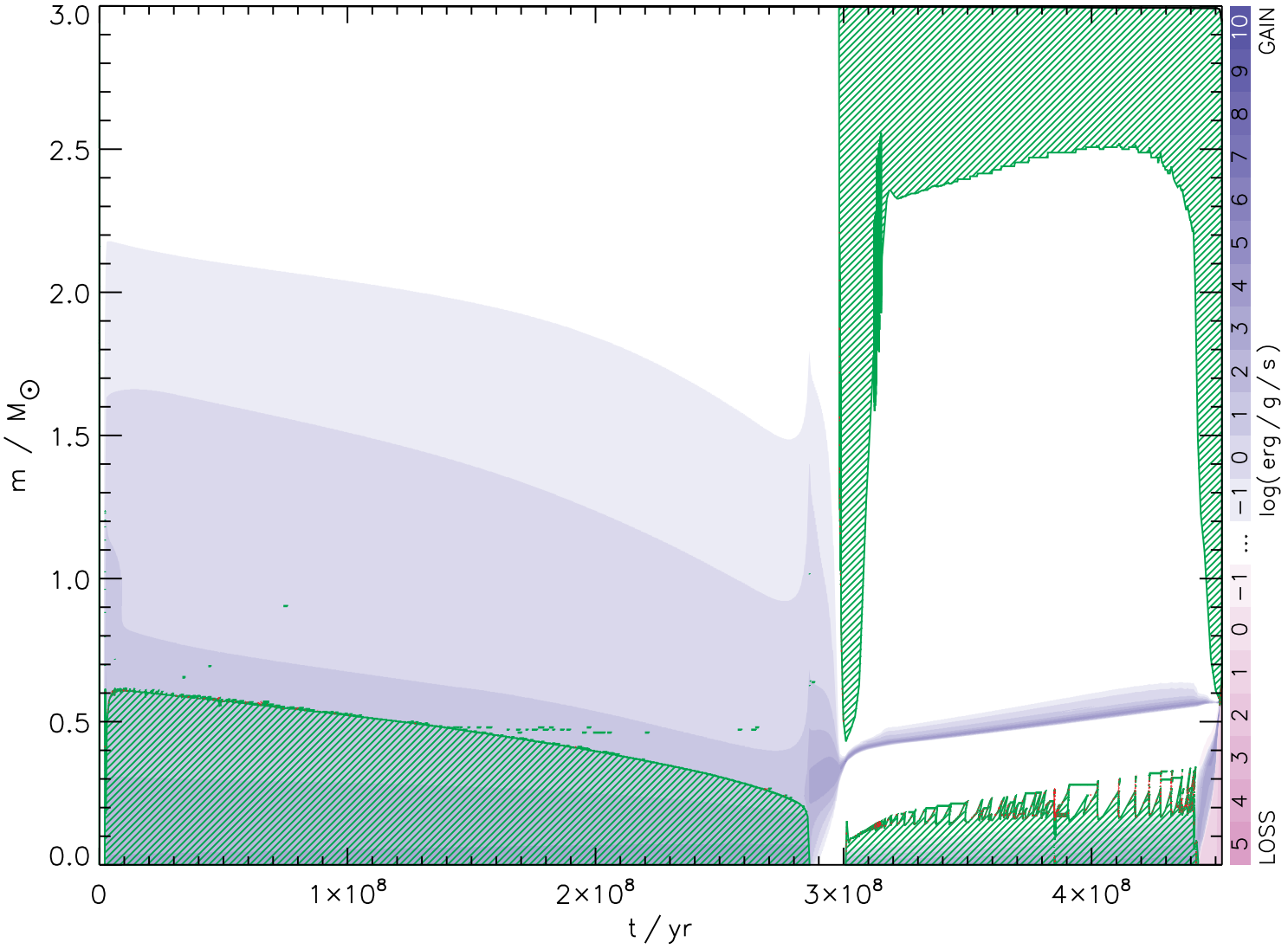
1. Low-Mass Stars
   - Main-Sequence Convection Zones
   - Degenerate Helium Core Ignition
   - Evolution in the HRD
2. The Sun
   - Internal Evolution of the Sun

Regimes of Convection (local [in]stability)

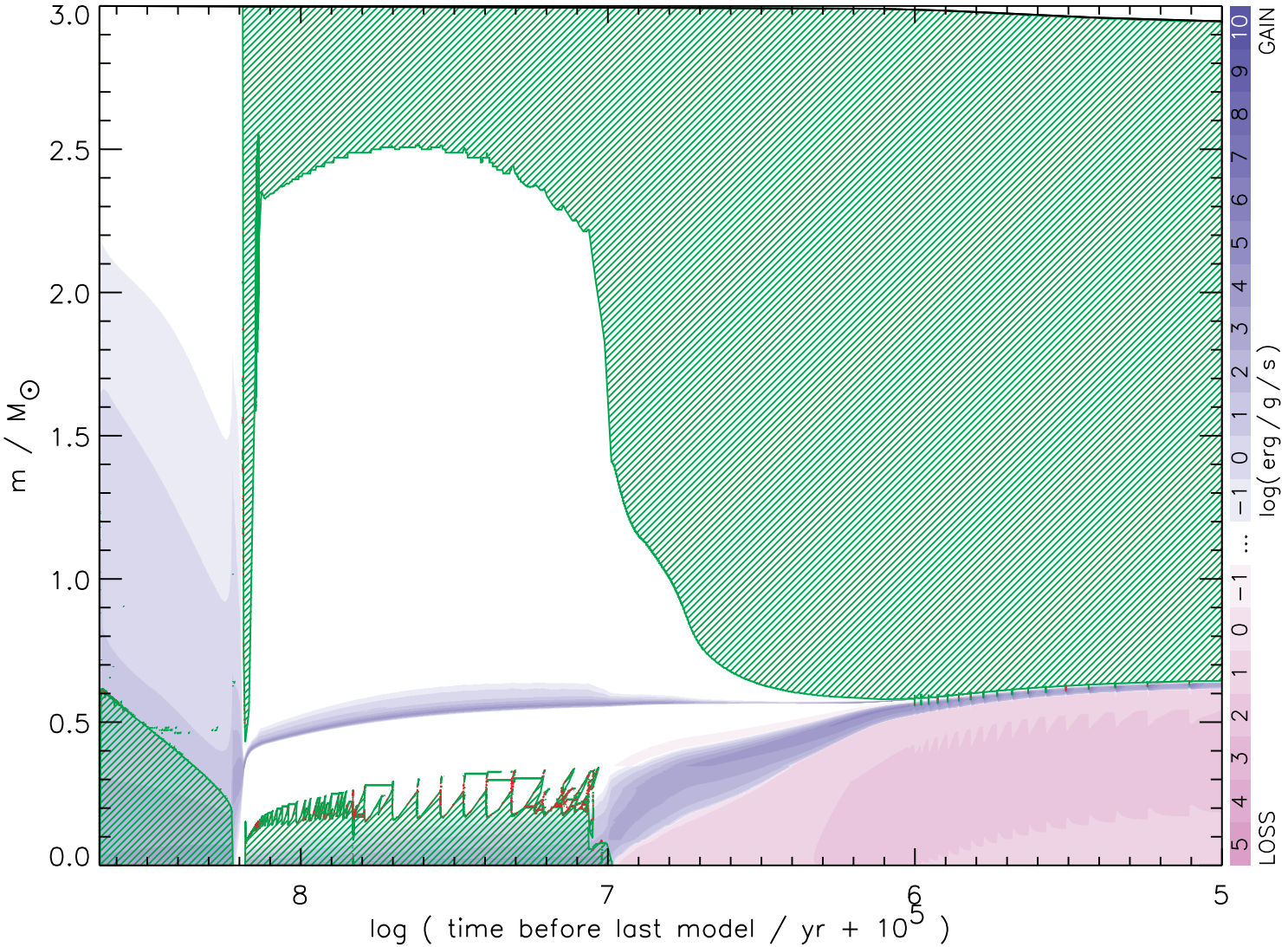


Regimes of convection as a function of mass (*x*-axis) and fractional stellar mass (*y*-axis) on the **Z**ero-**A**ge **M**ain **S**equence (ZAMS).

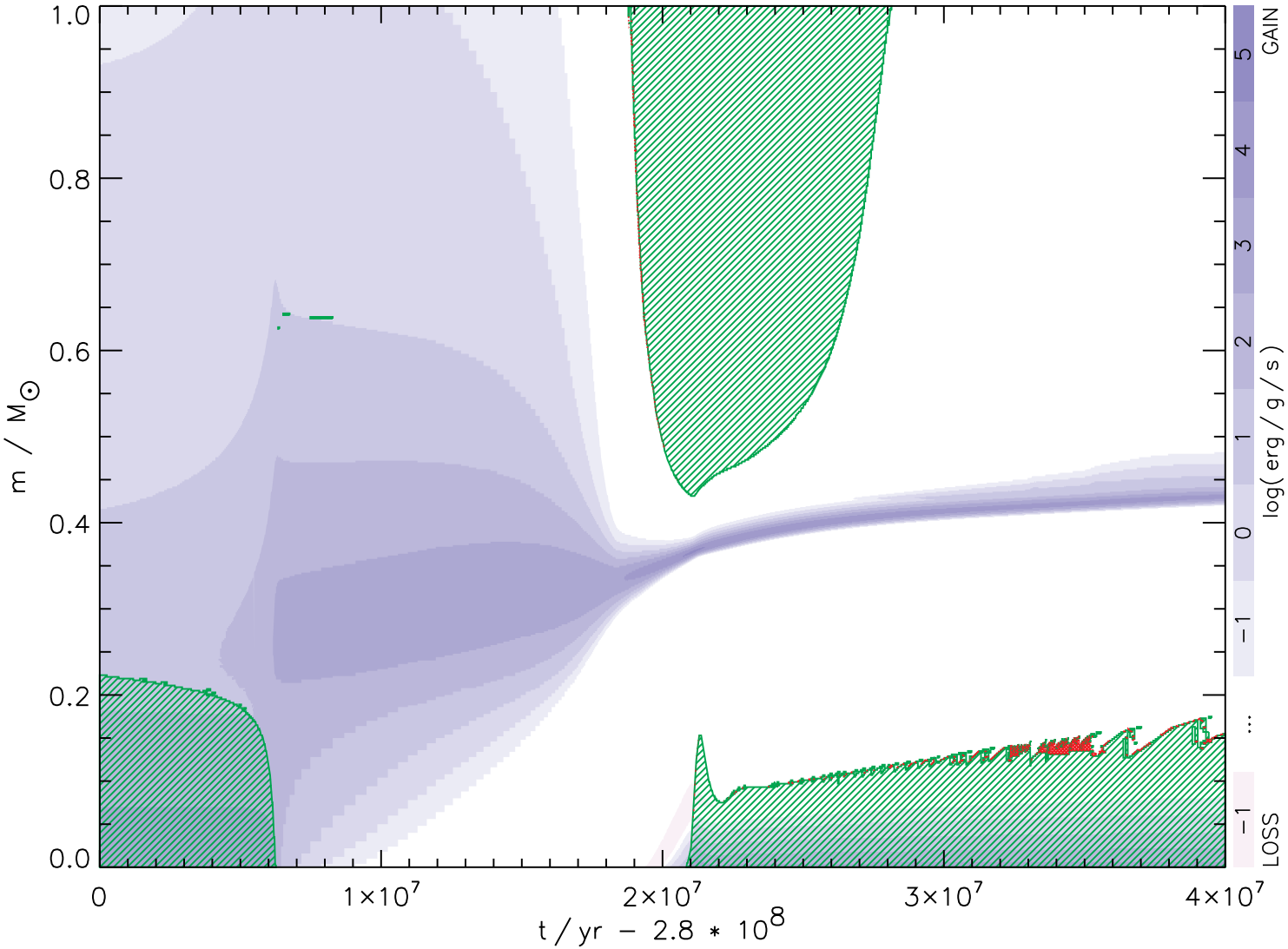
Kippenhahn Diagram, 3 $M_\odot$ Star



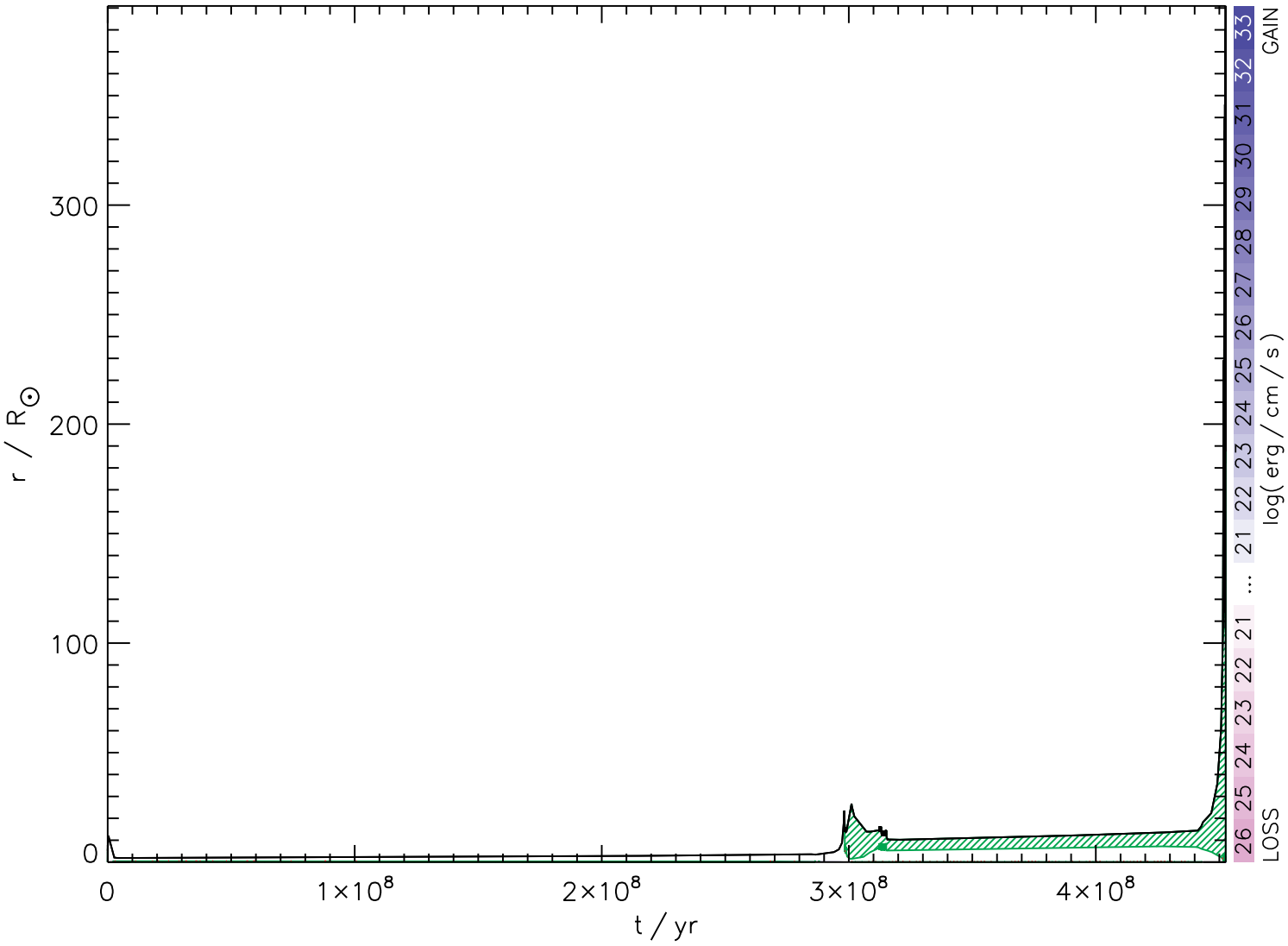
Kippenhahn Diagram, 3 $M_\odot$ Star



Kippenhahn Diagram, 3 $M_\odot$ Star, He Ignition



Kippenhahn-Radius Diagram, 3 $M_\odot$ Star



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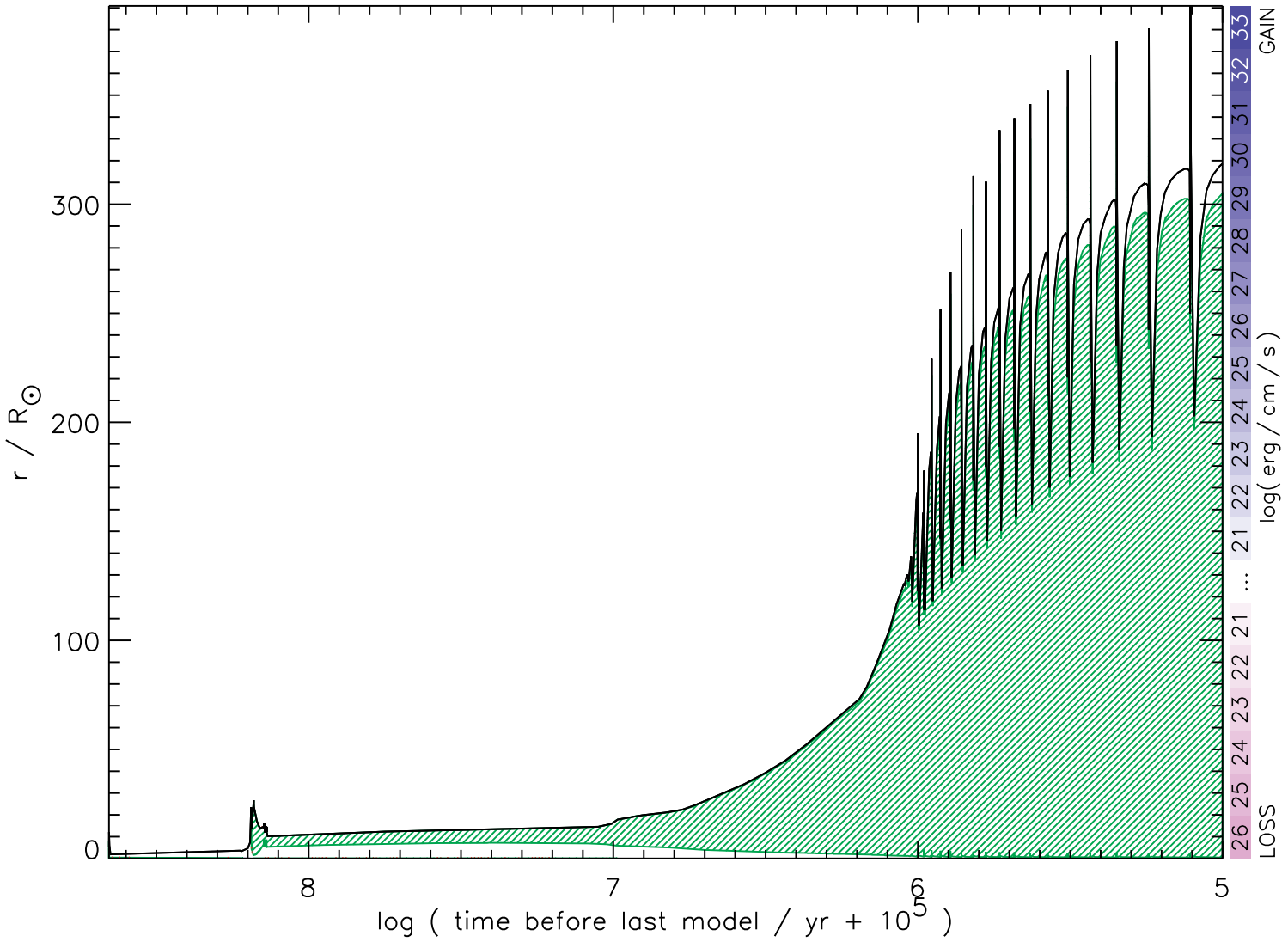
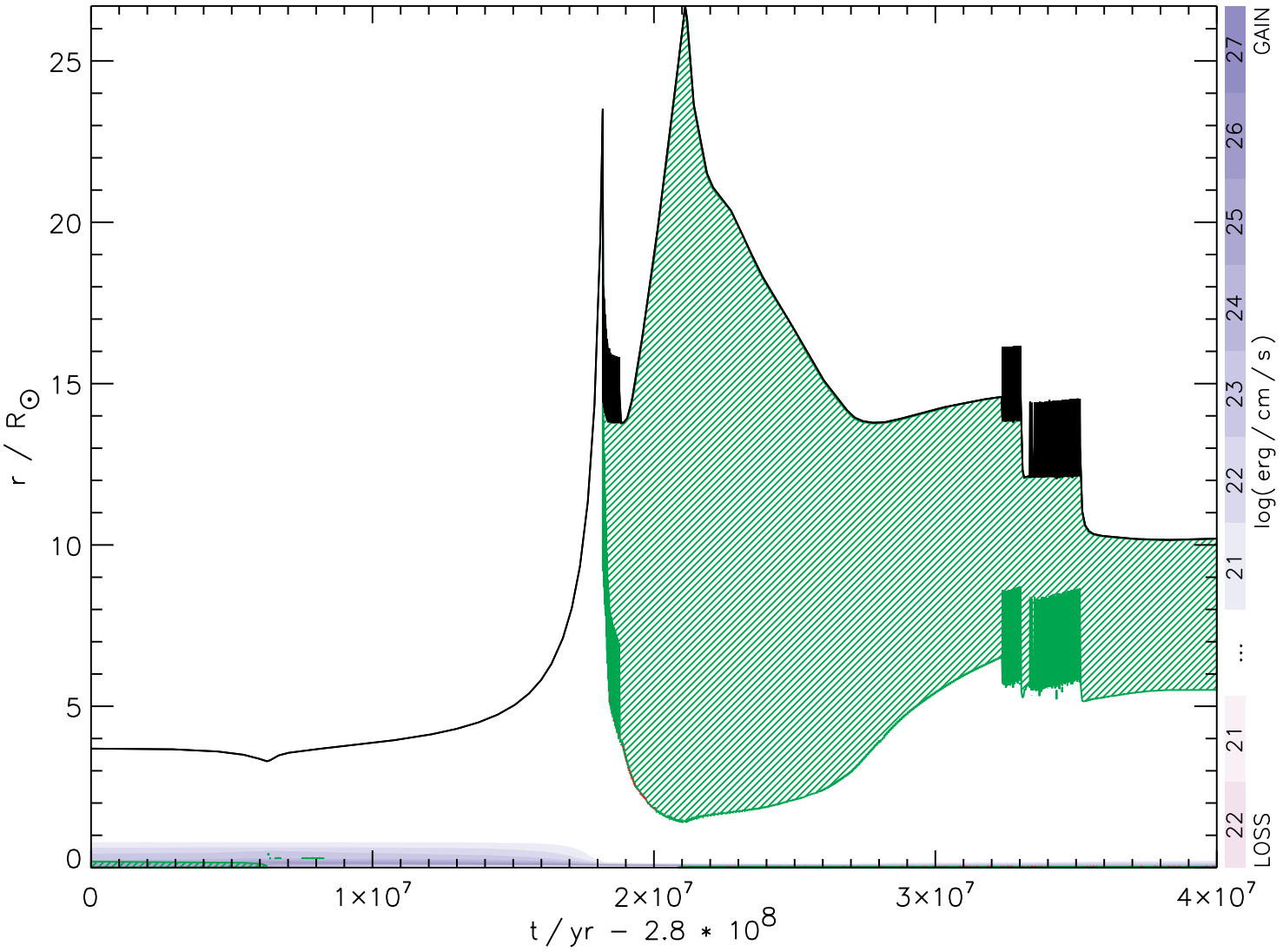
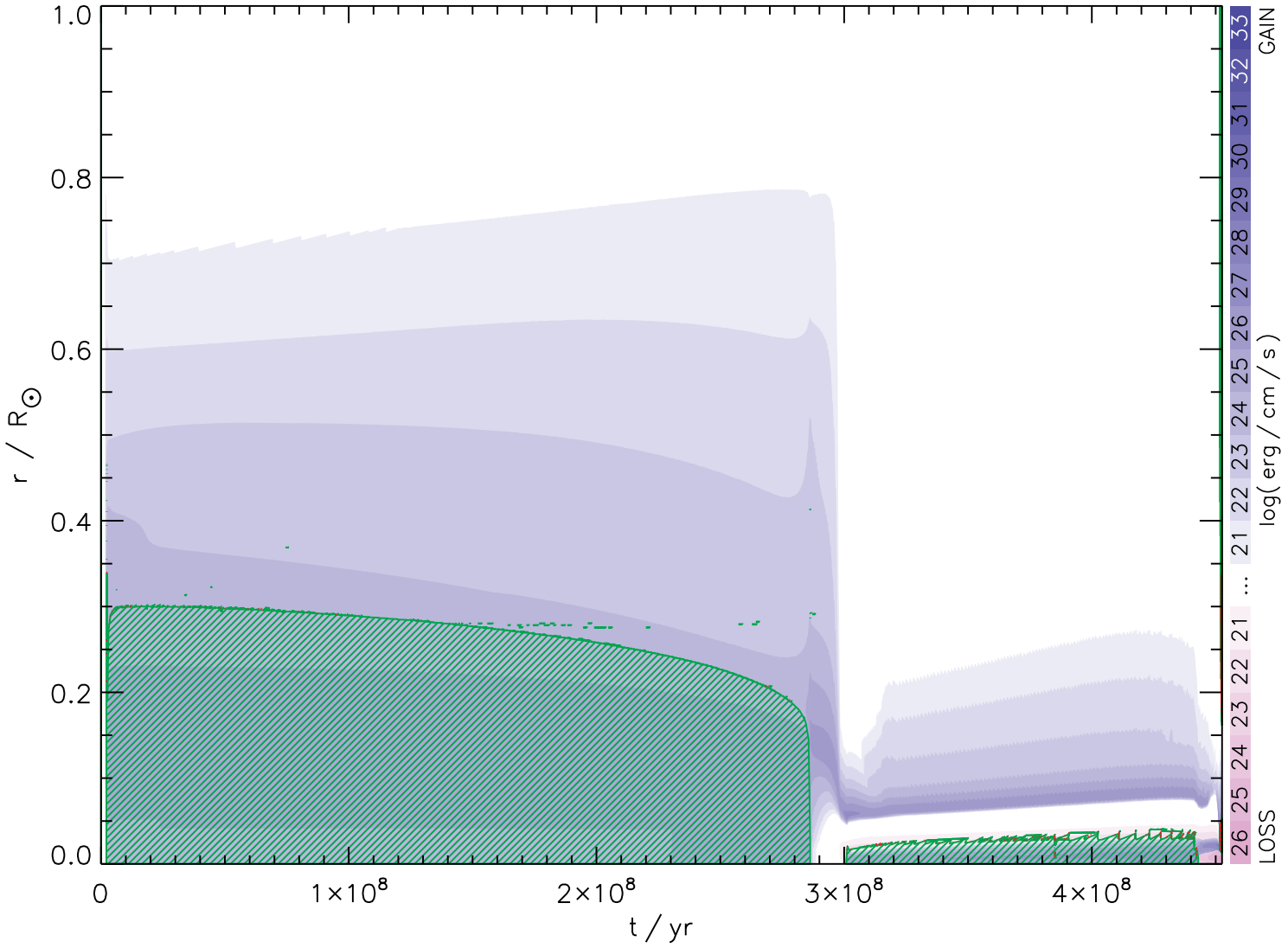


Kippenhahn-Radius Diagram, 3 $M_\odot$ Star, He Ignition



Kippenhahn-Radius Diagram, 3 $M_\odot$ Star



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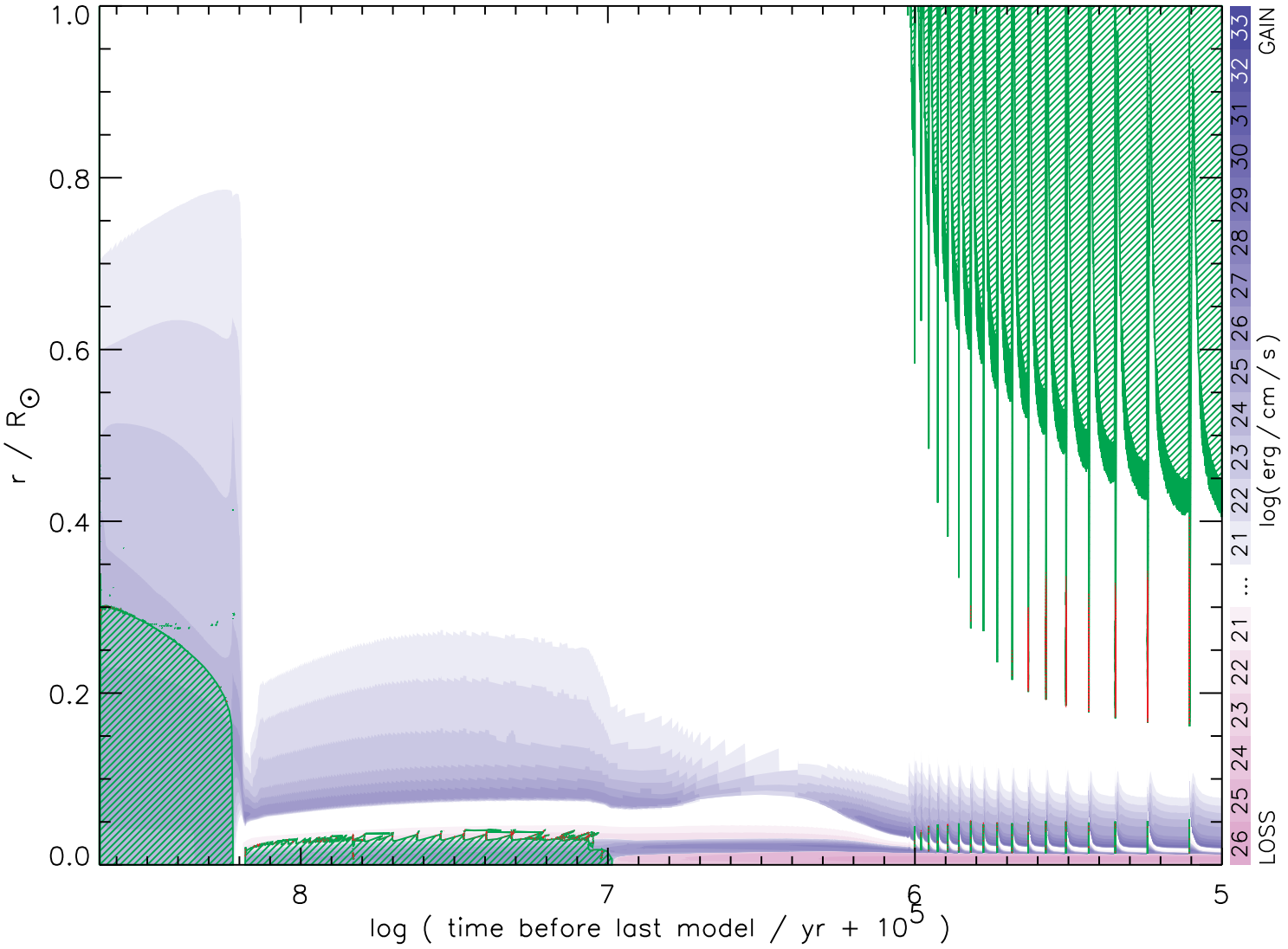
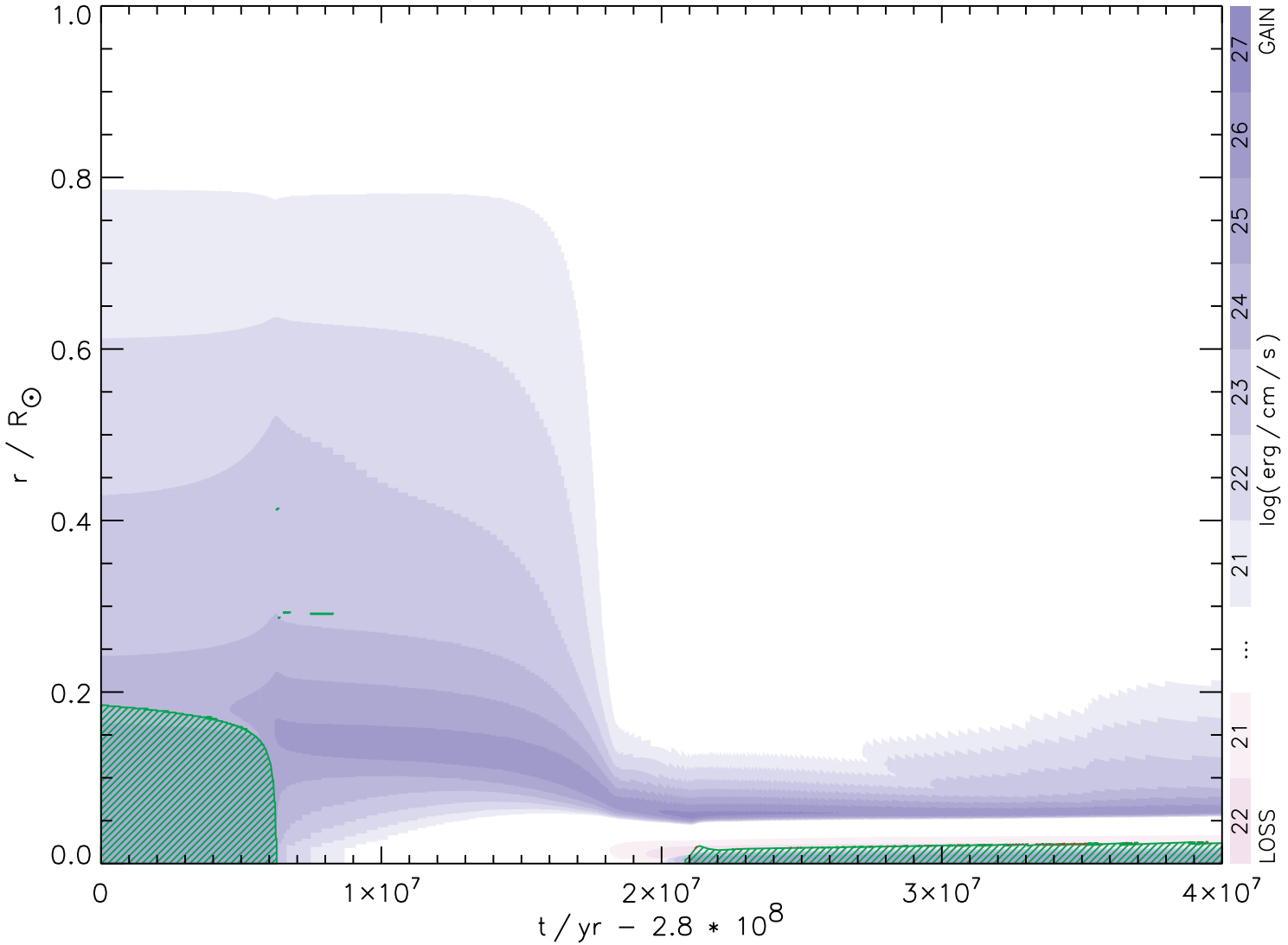
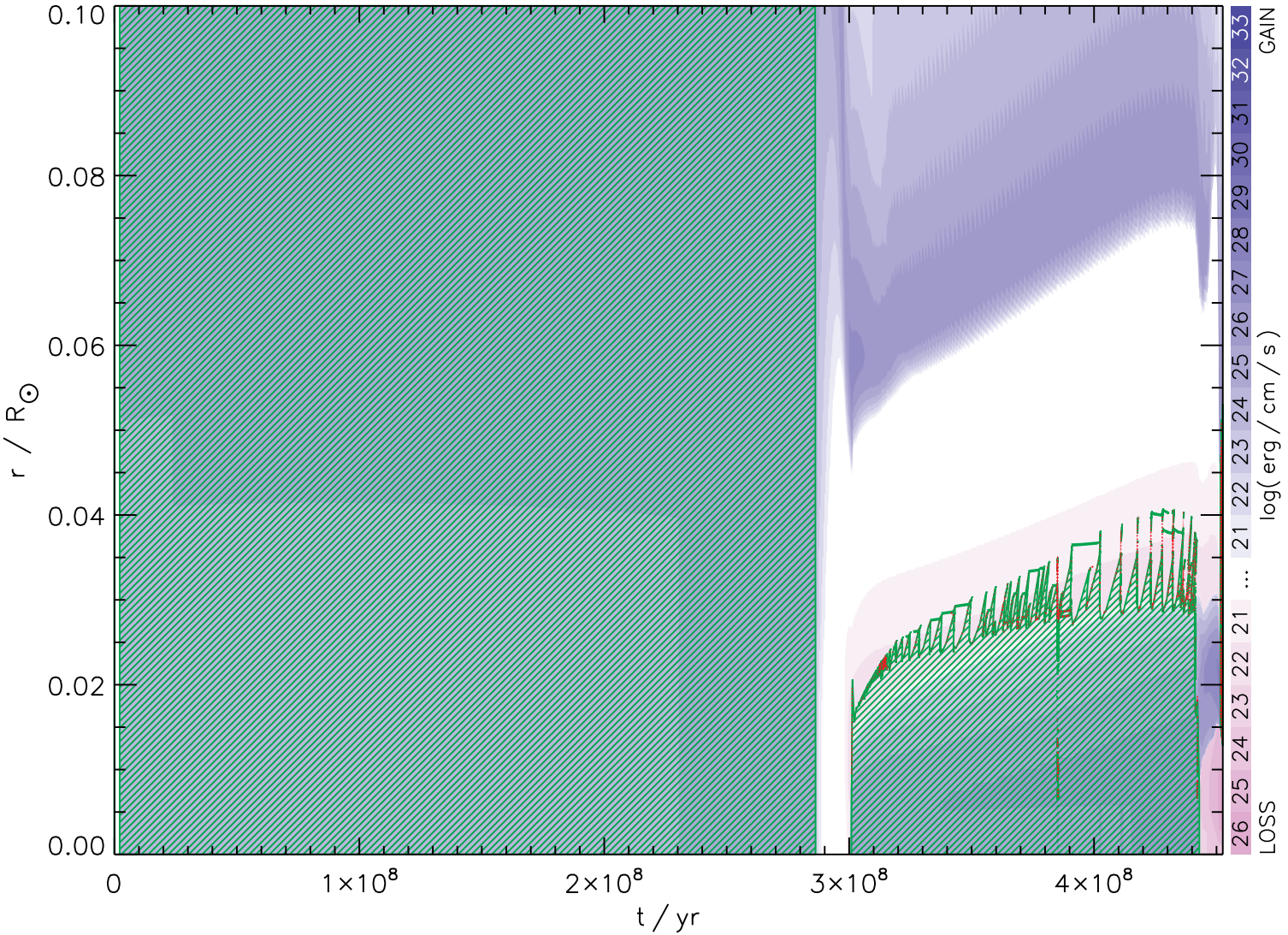


Kippenhahn-Radius Diagram, 3 $M_\odot$ Star, He Ignition



Kippenhahn-Radius Diagram, 3 $M_\odot$ Star



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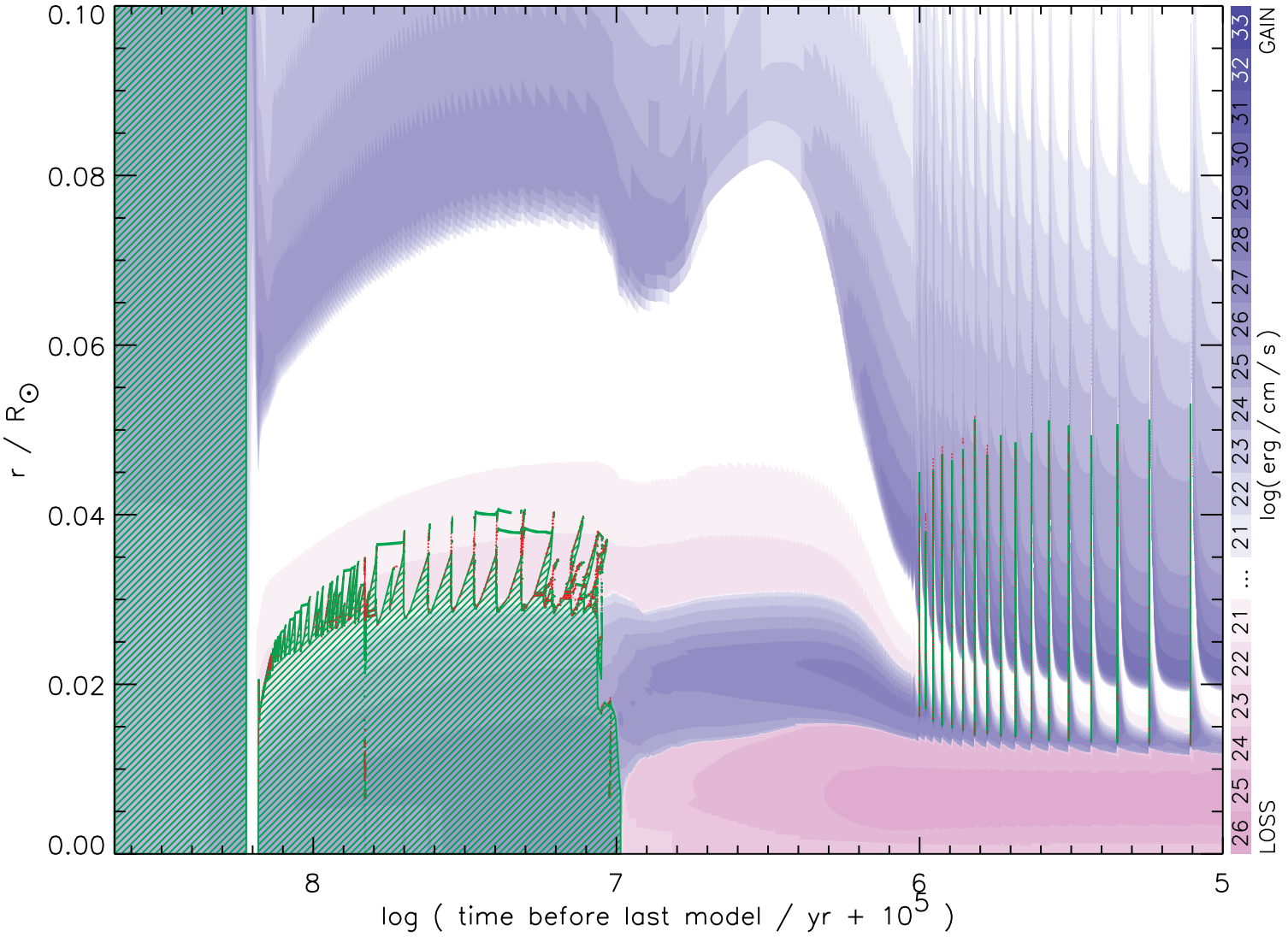
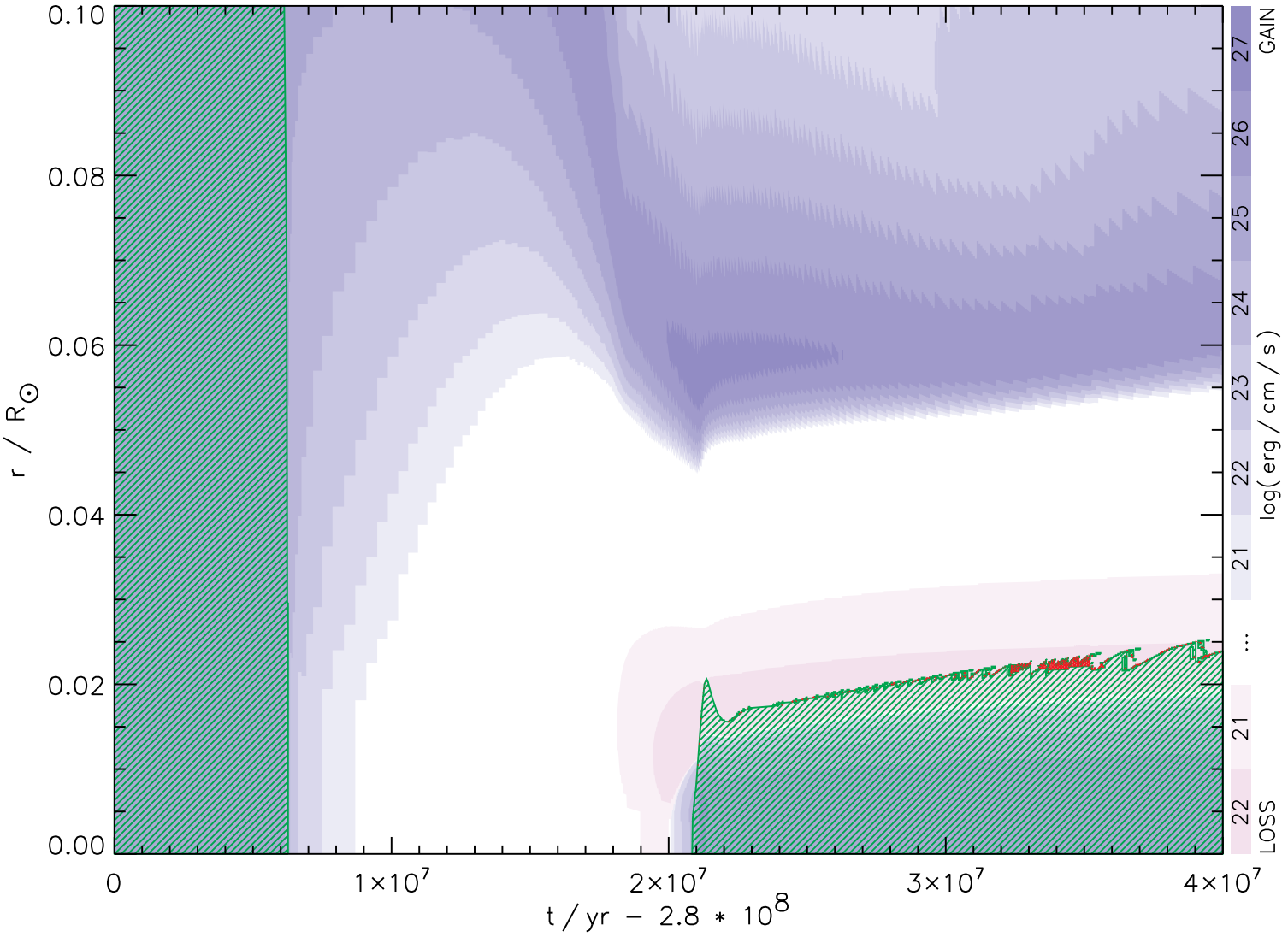


Kippenhahn-Radius Diagram, 3 $M_\odot$ Star, He Ignition



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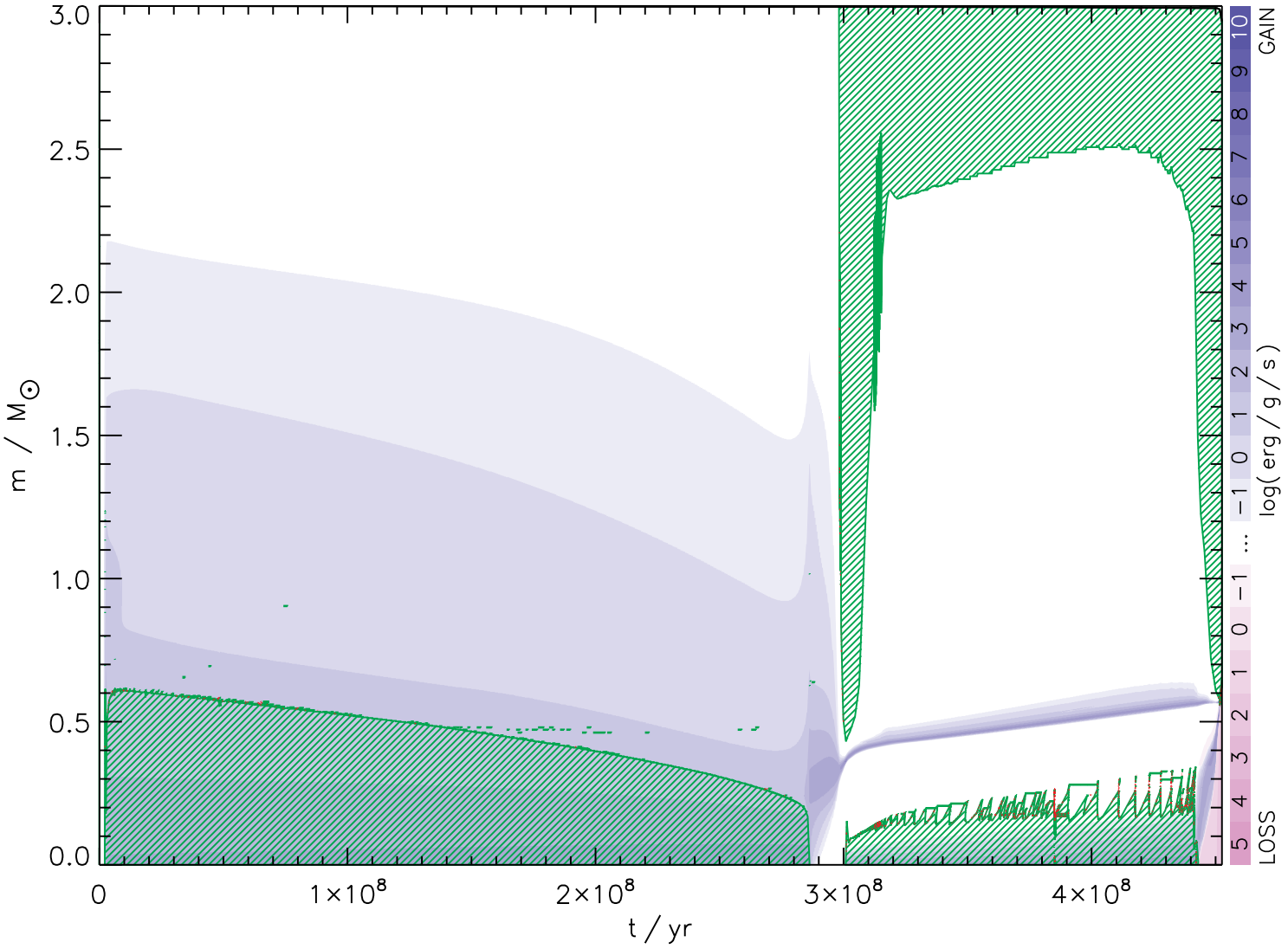

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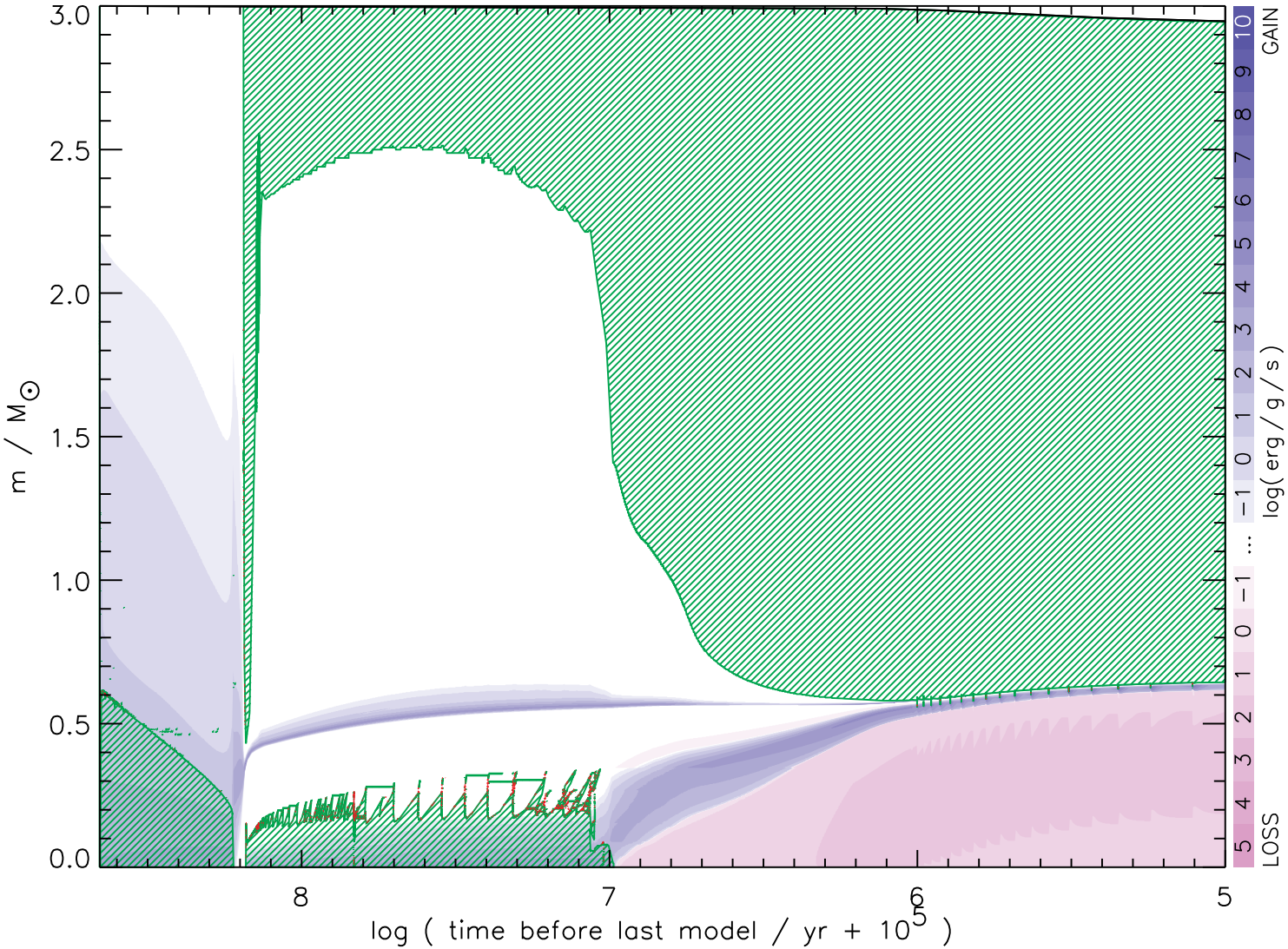
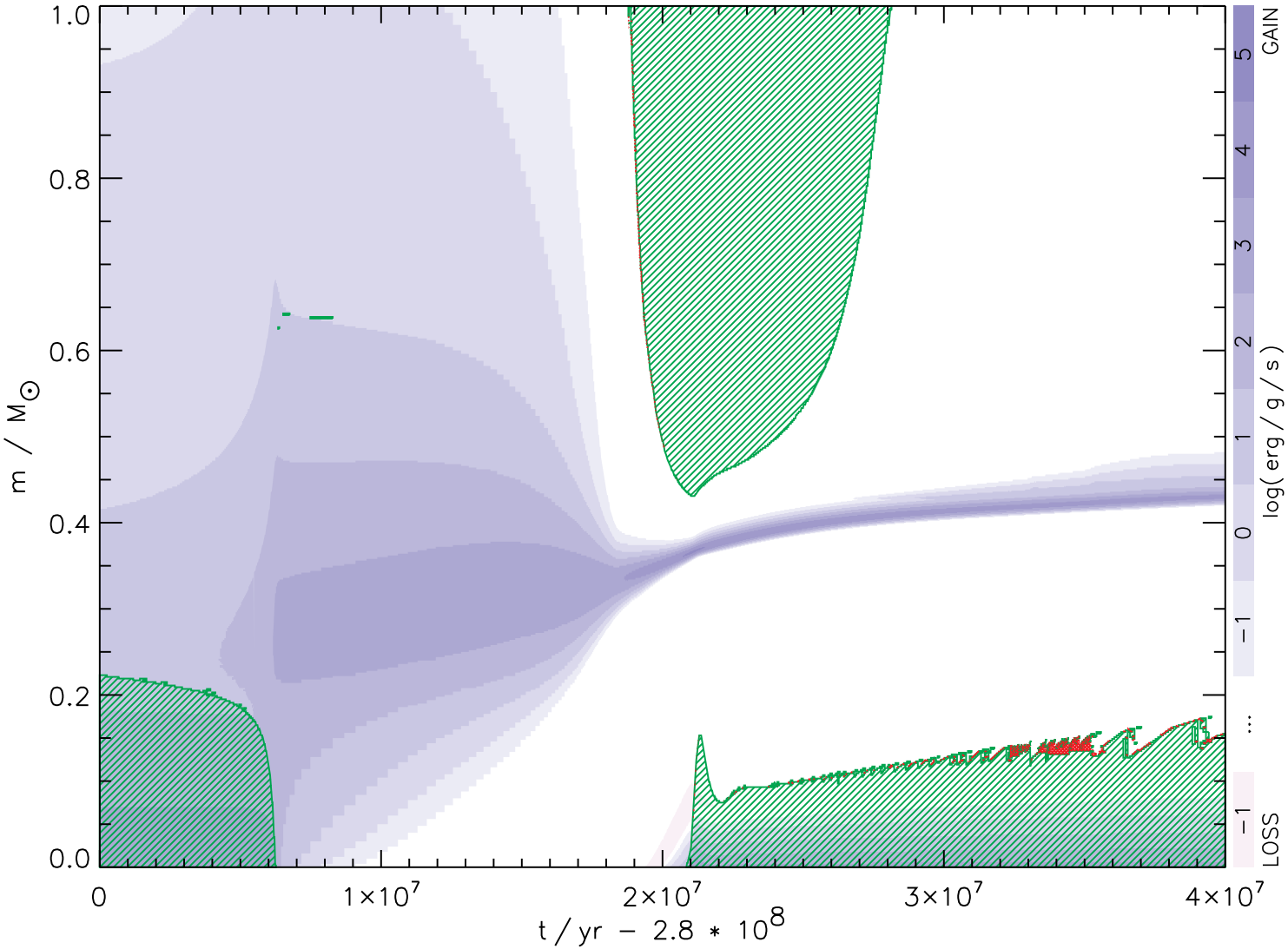
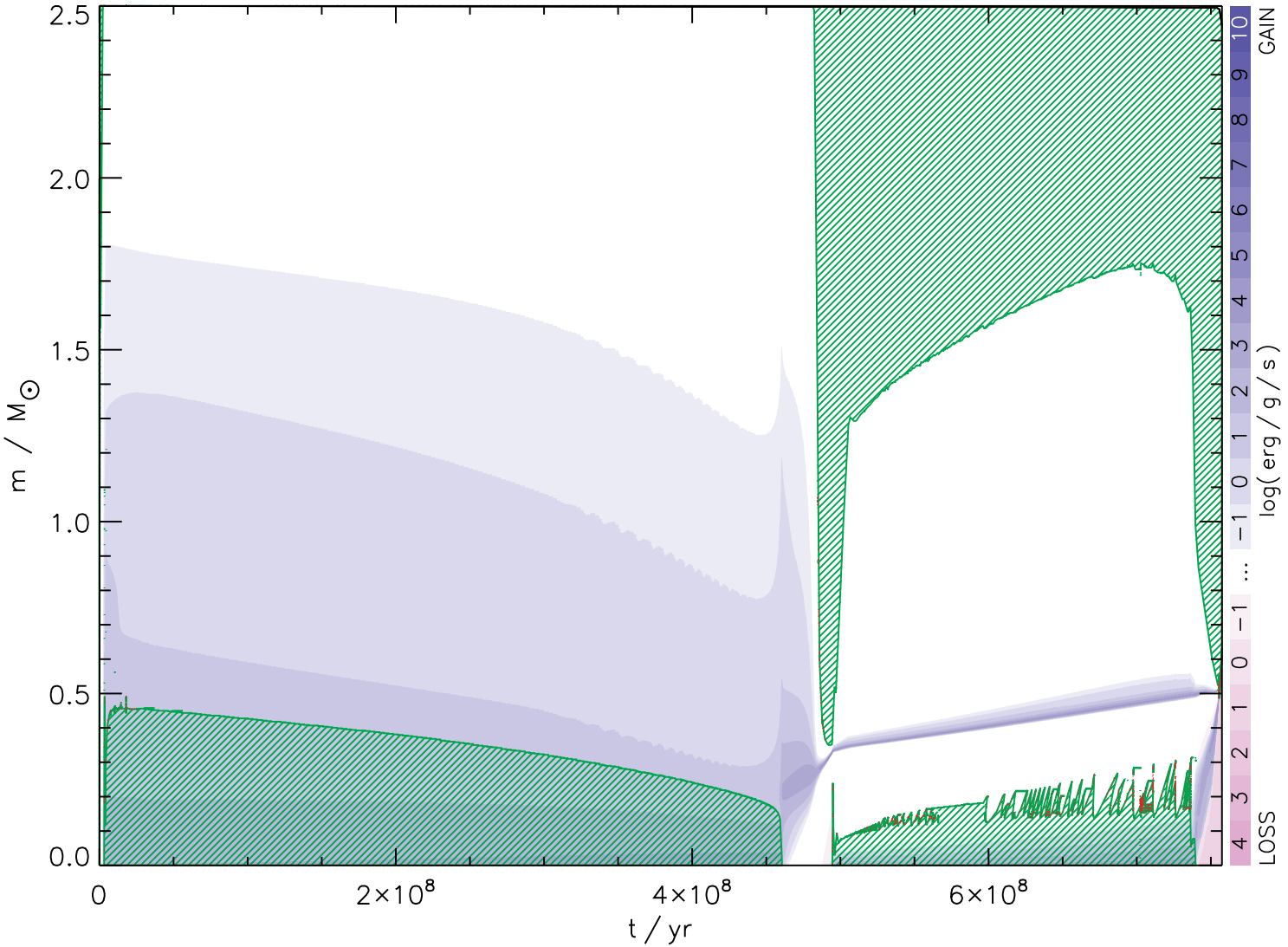


Kippenhahn Diagram, 3 $M_\odot$ Star, He Ignition



Kippenhahn Diagram, 2.5 $M_\odot$ Star



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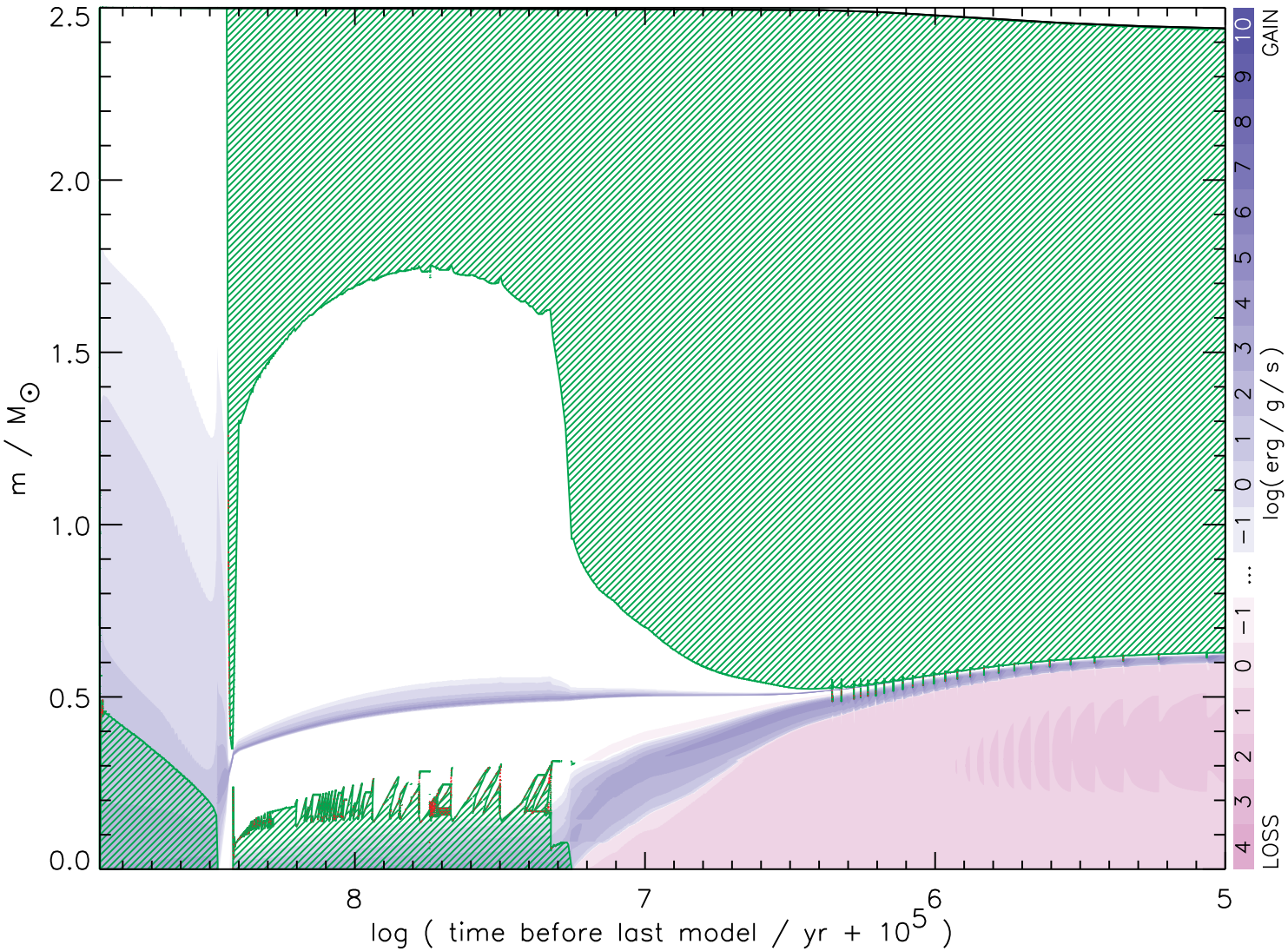
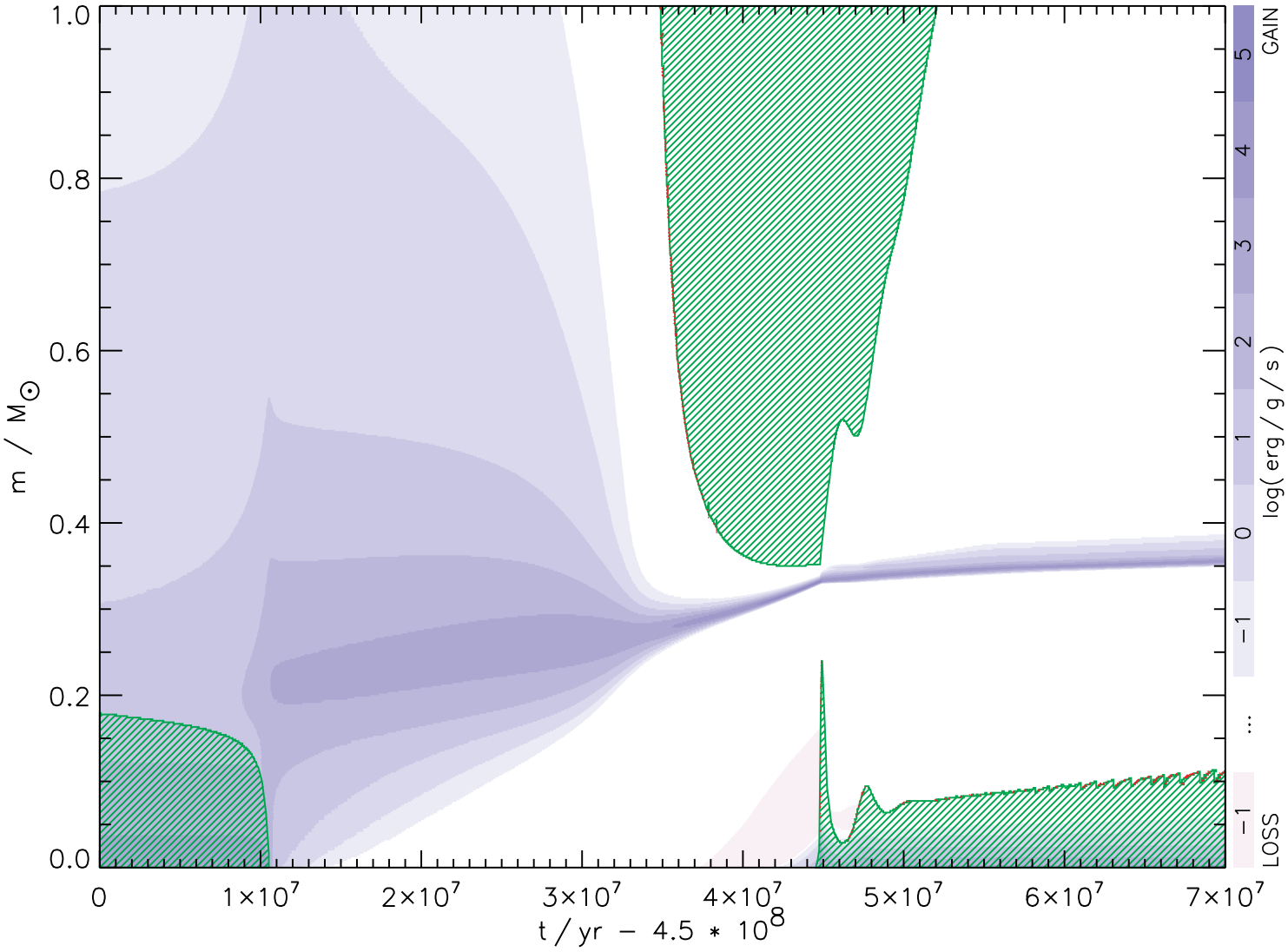
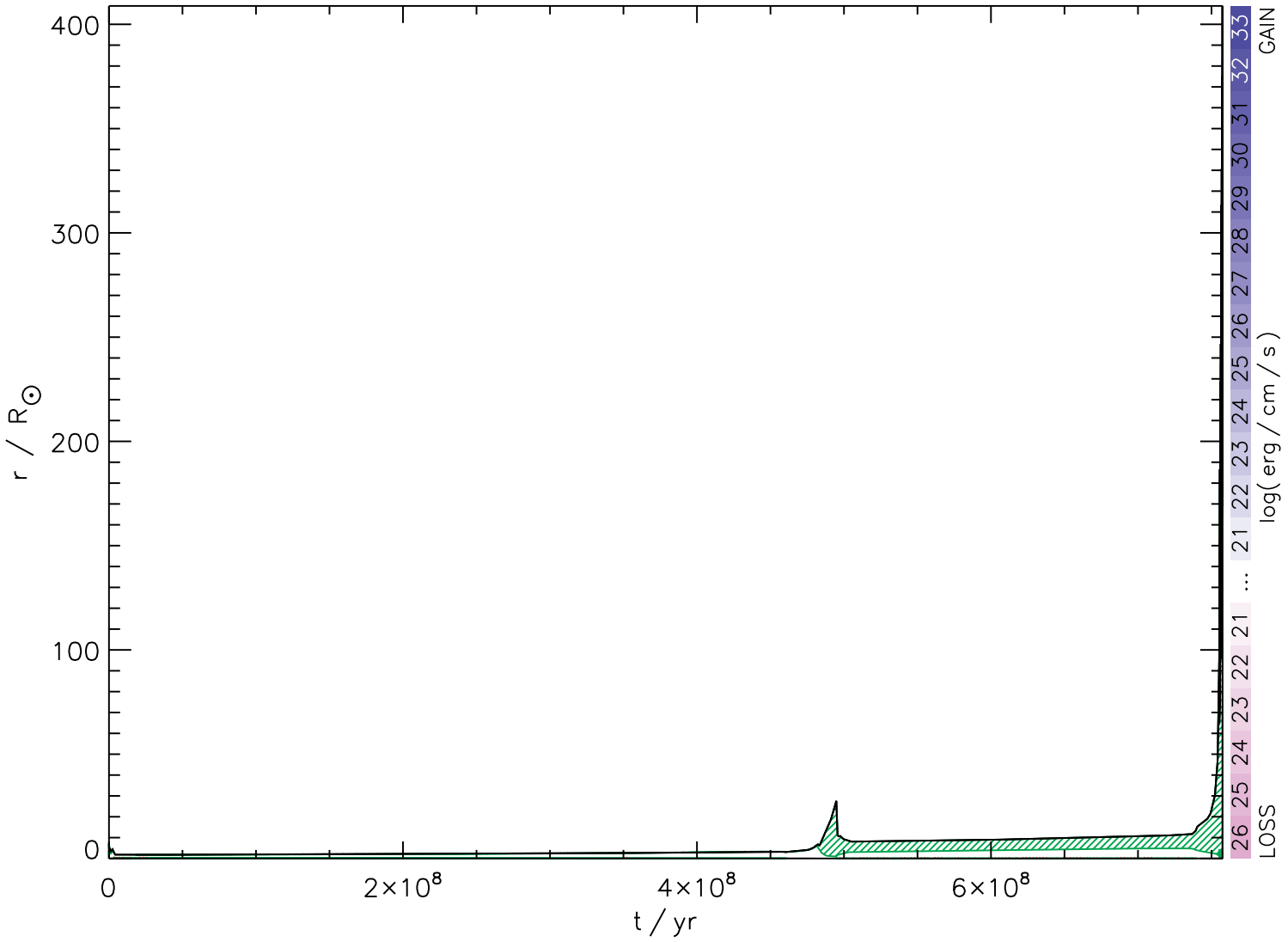


Kippenhahn Diagram, 2.5 $M_\odot$ Star, He Ignition



Kippenhahn-Radius Diagram, 2.5 $M_\odot$ Star



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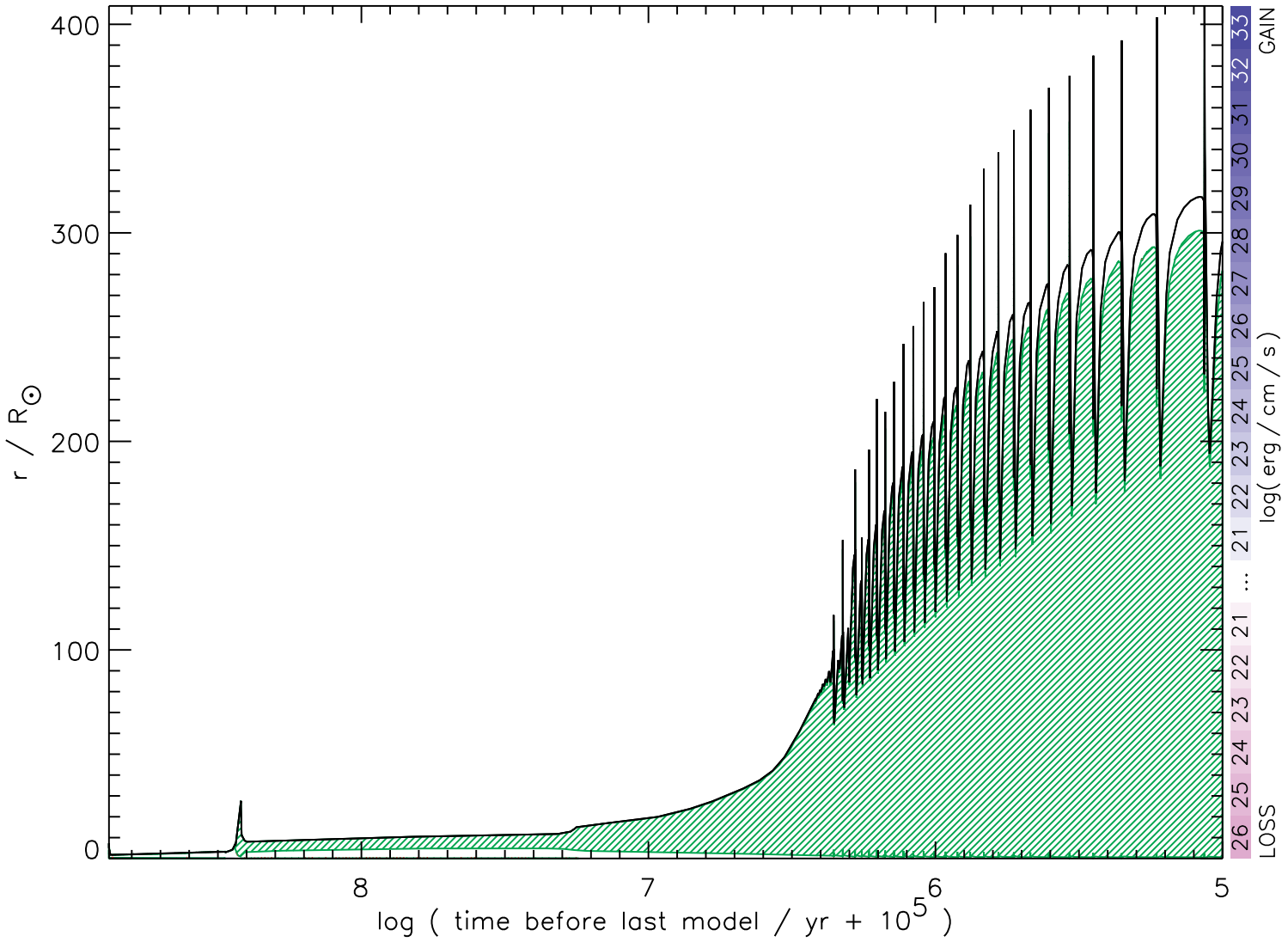
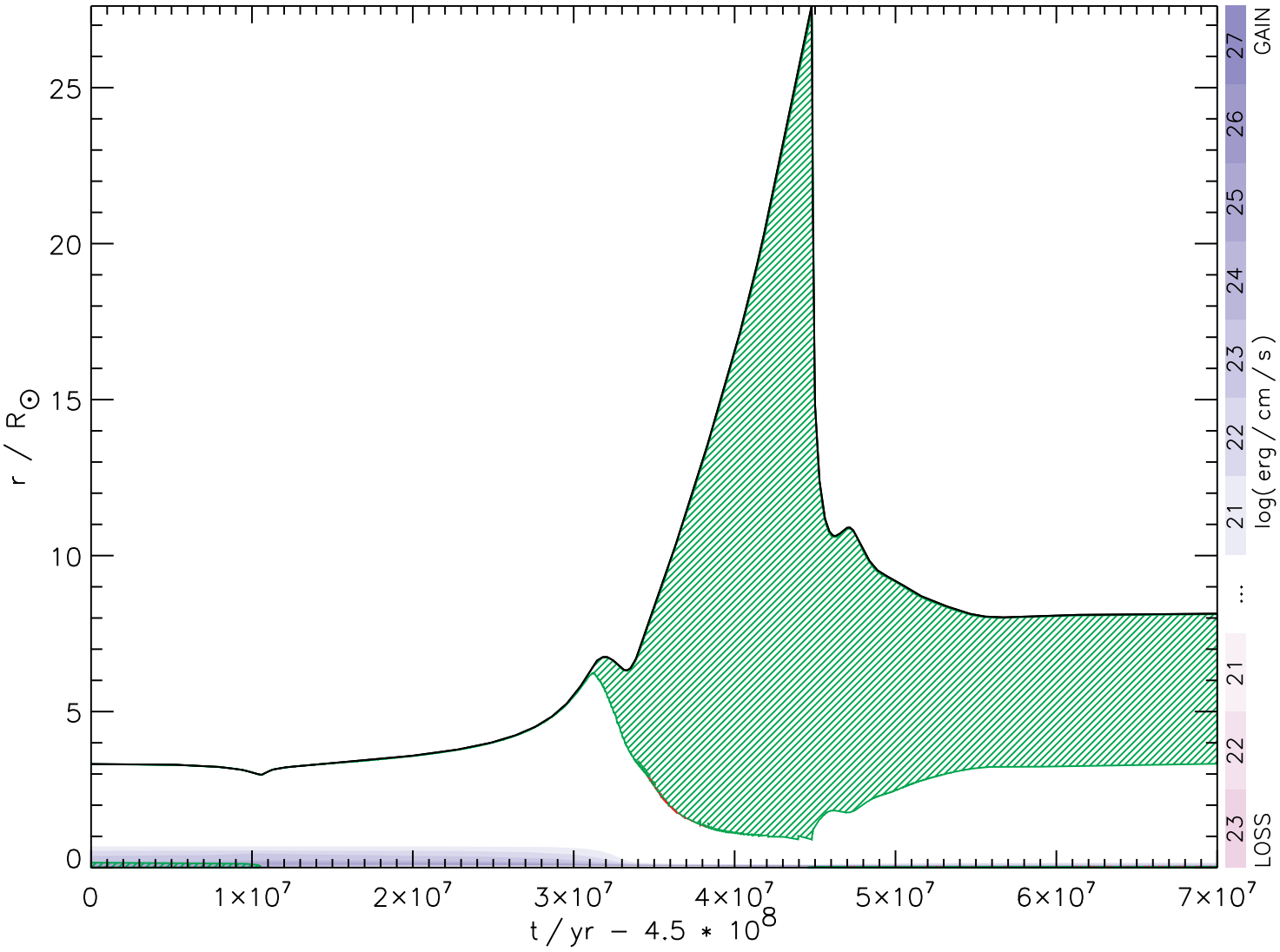


Kippenhahn-Radius Diagram, 2.5 $M_\odot$ Star, He Ignition



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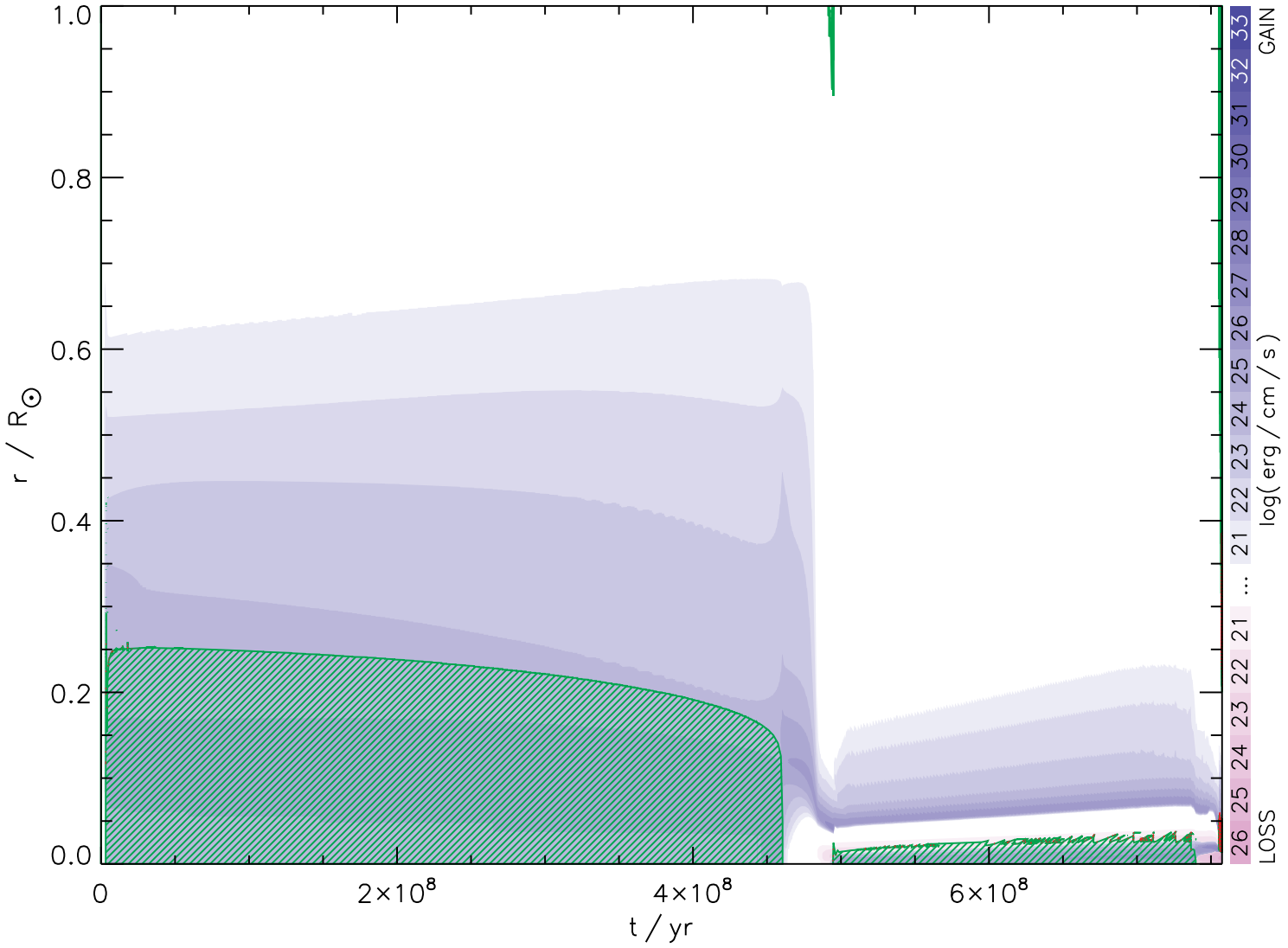

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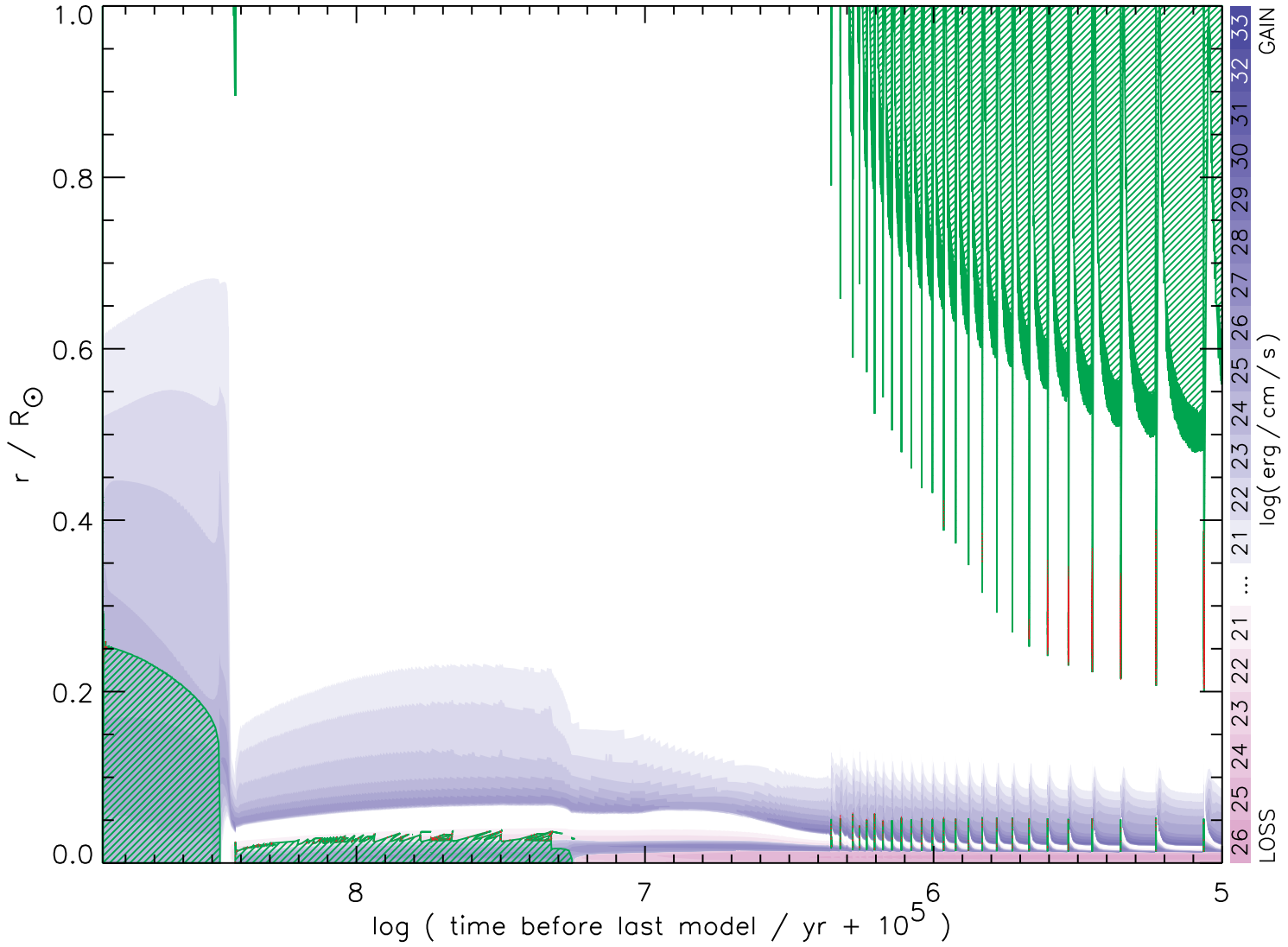
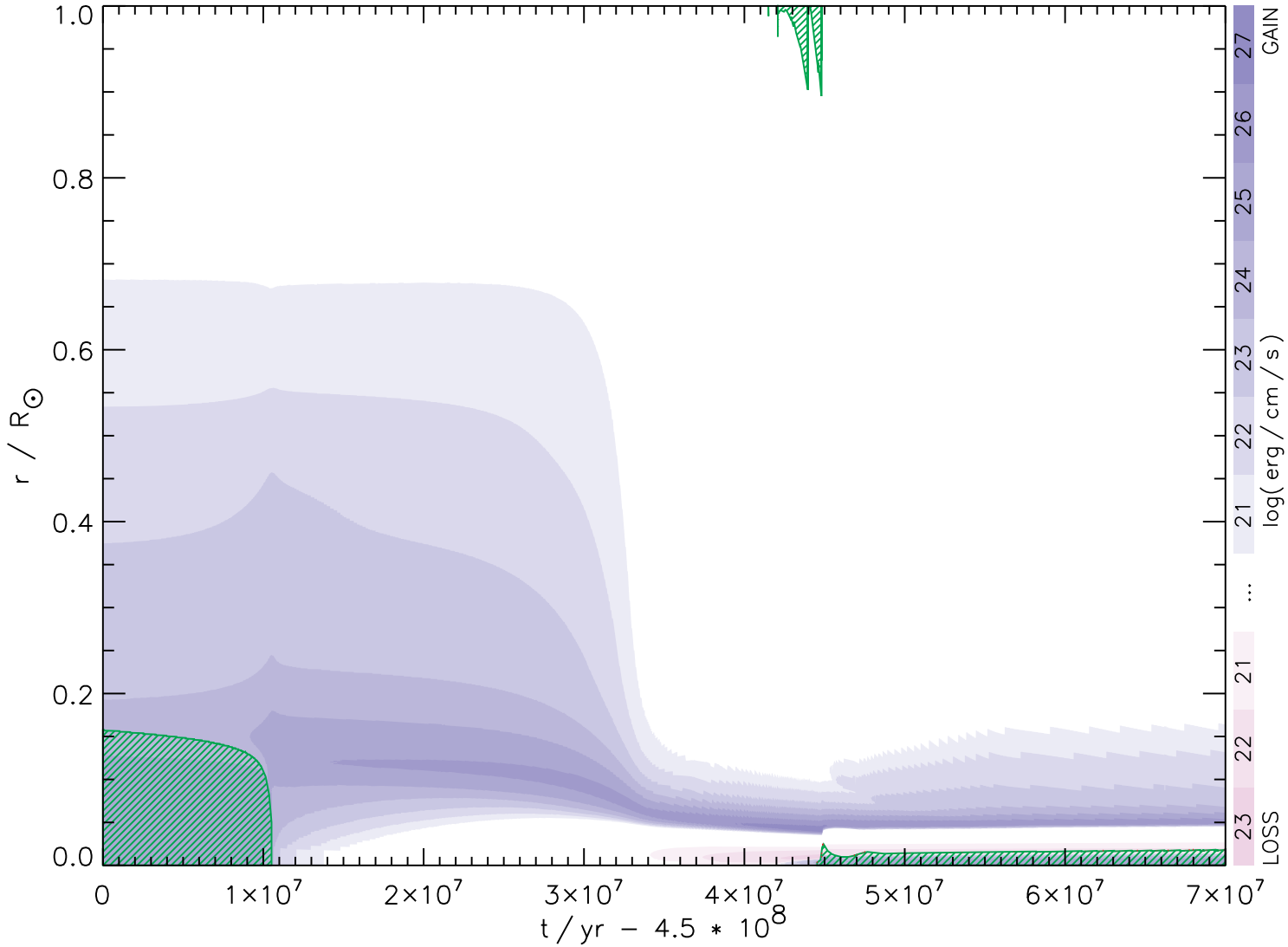


Kippenhahn-Radius Diagram, 2.5 $M_\odot$ Star, He Ignition



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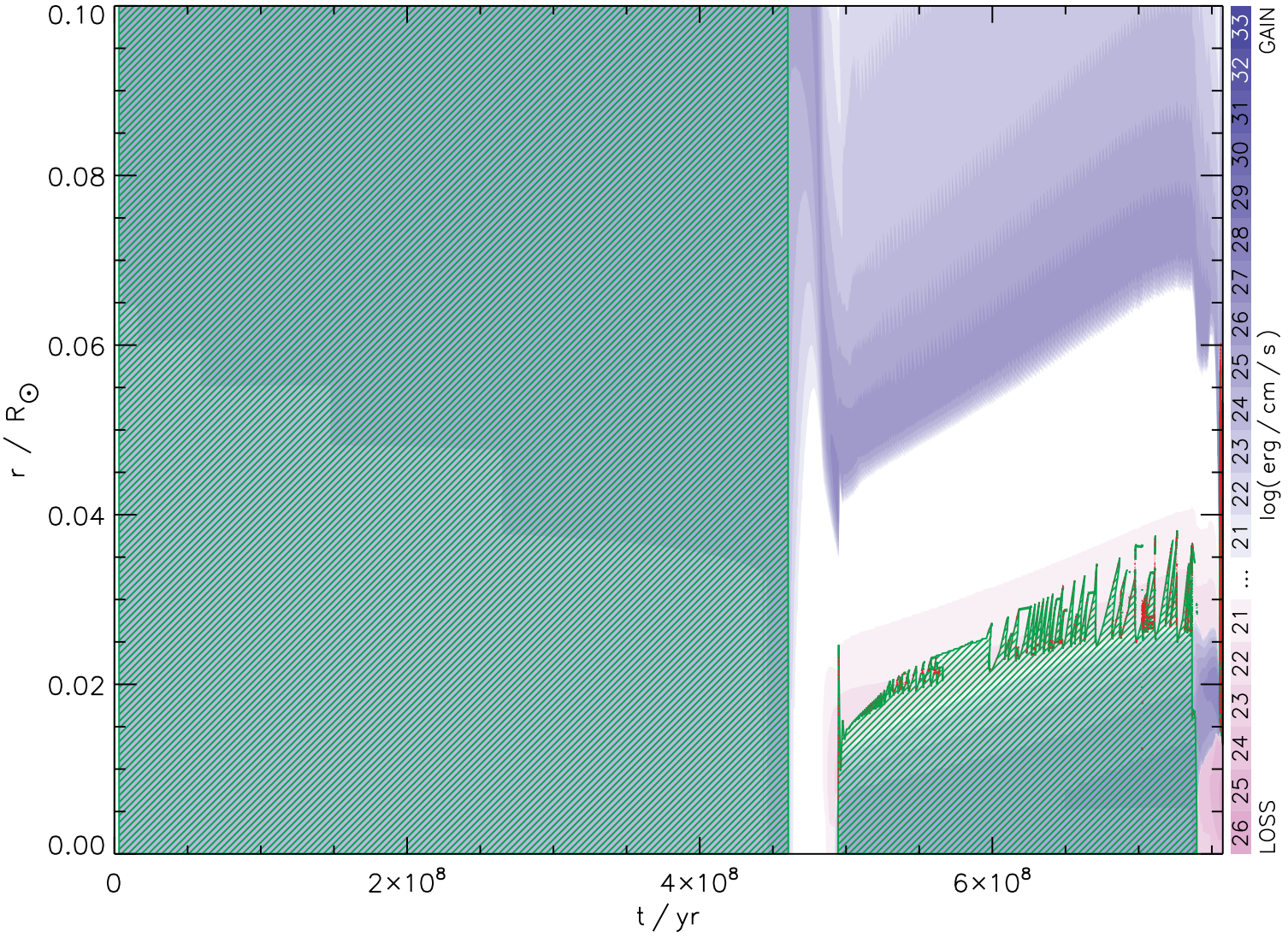
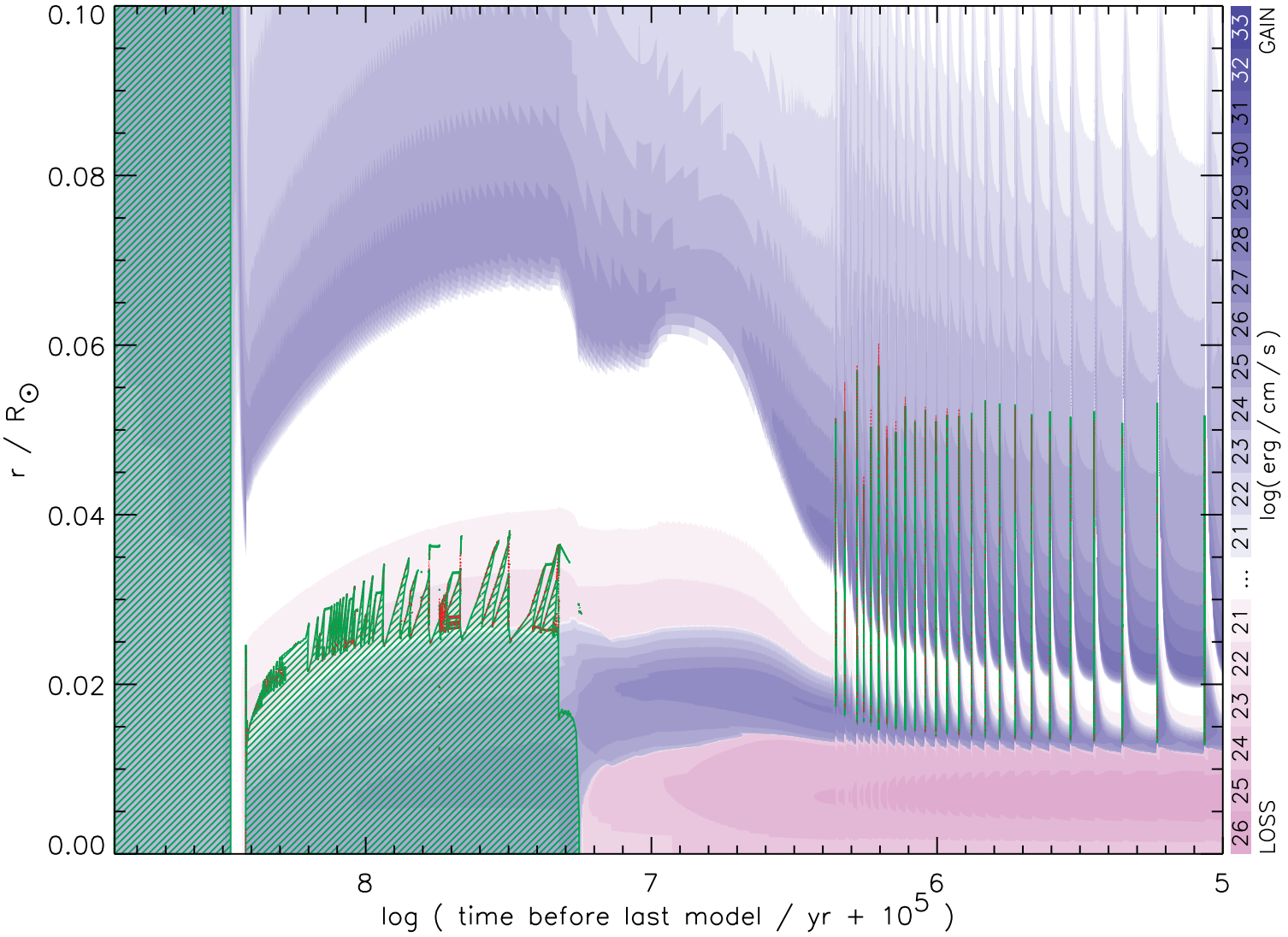
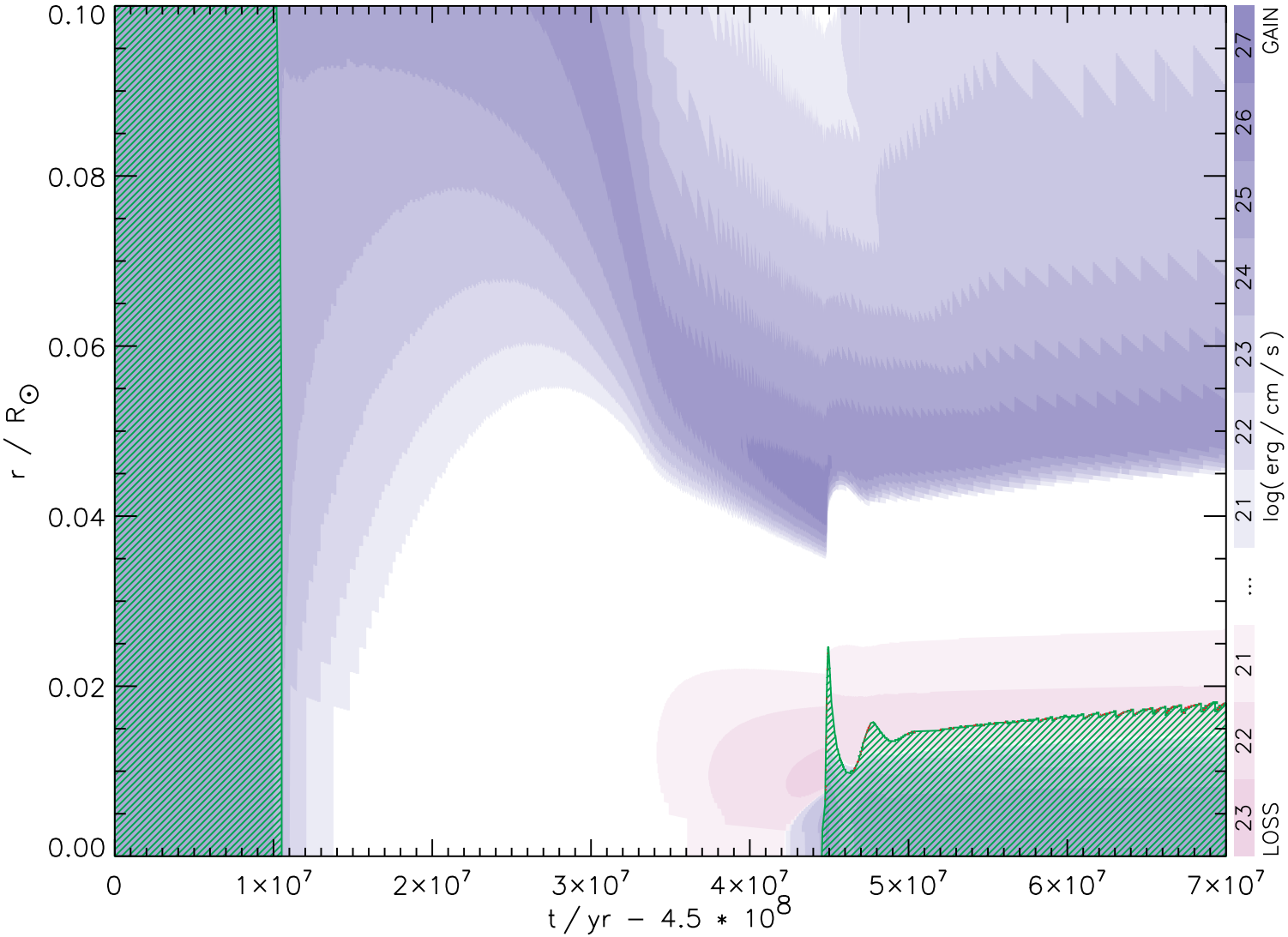


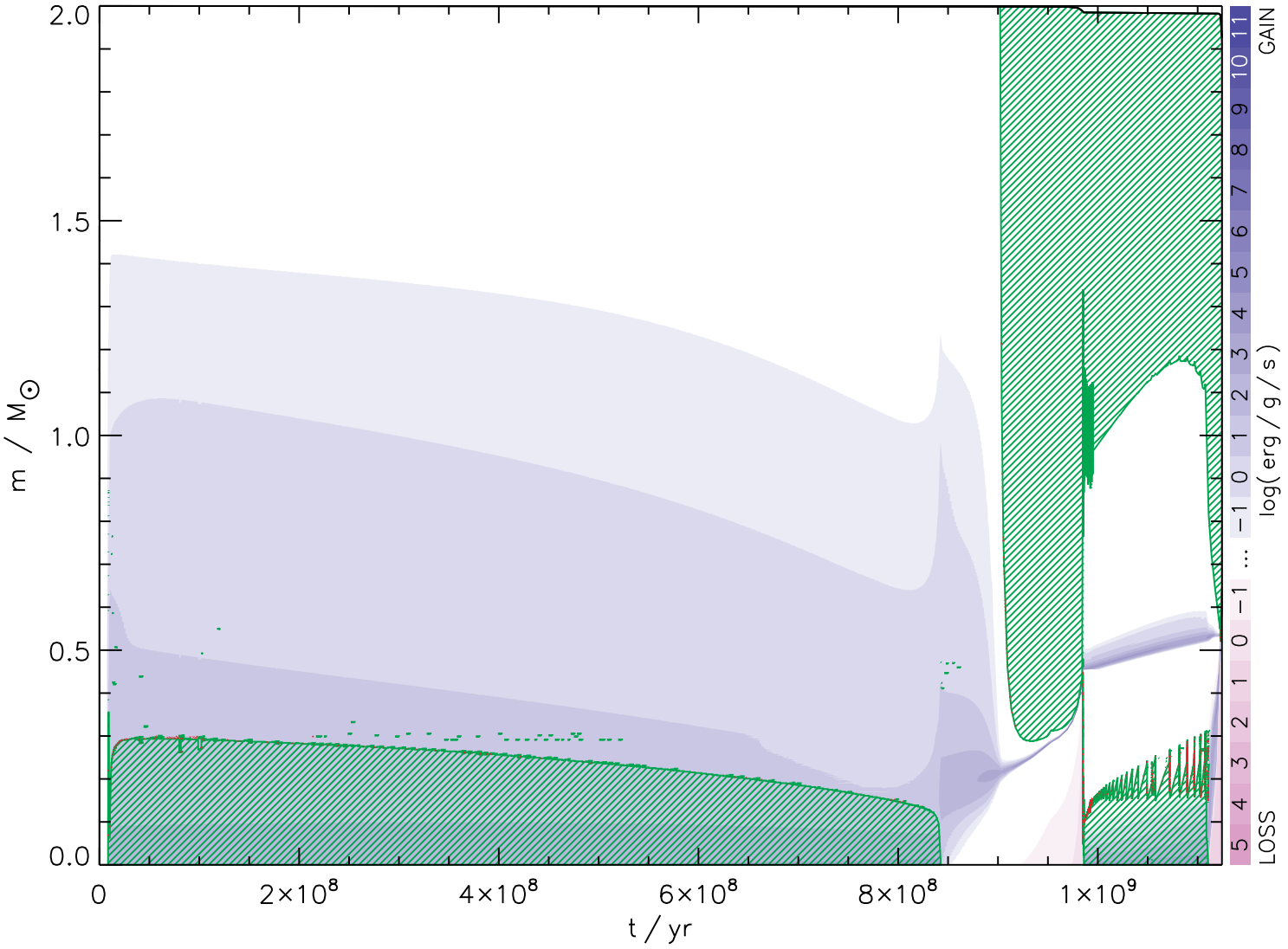
Kippenhahn-Radius Diagram, 2.5 $M_\odot$ Star



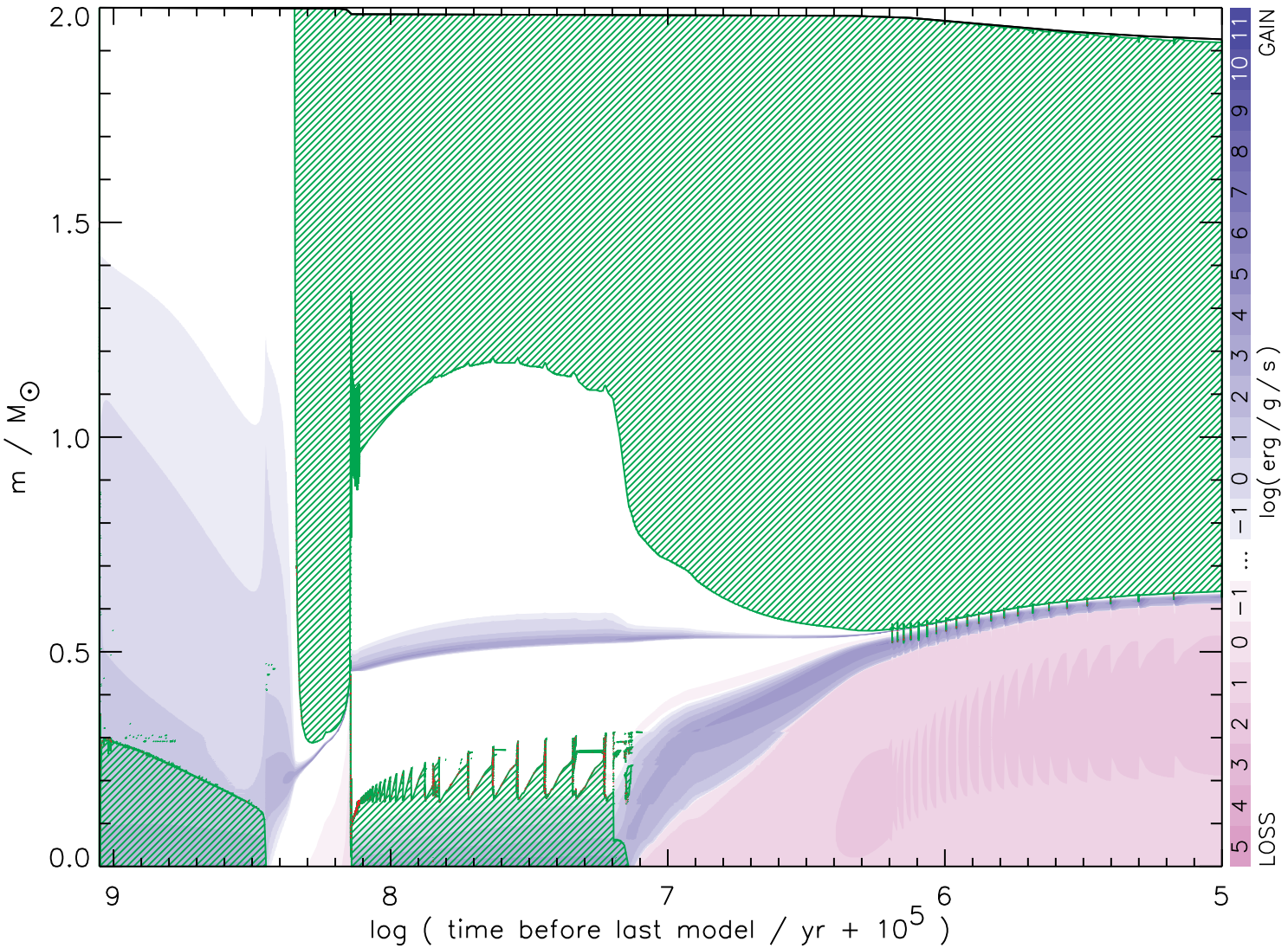
Kippenhahn-Radius Diagram, 2.5 $M_\odot$ Star, He Ignition



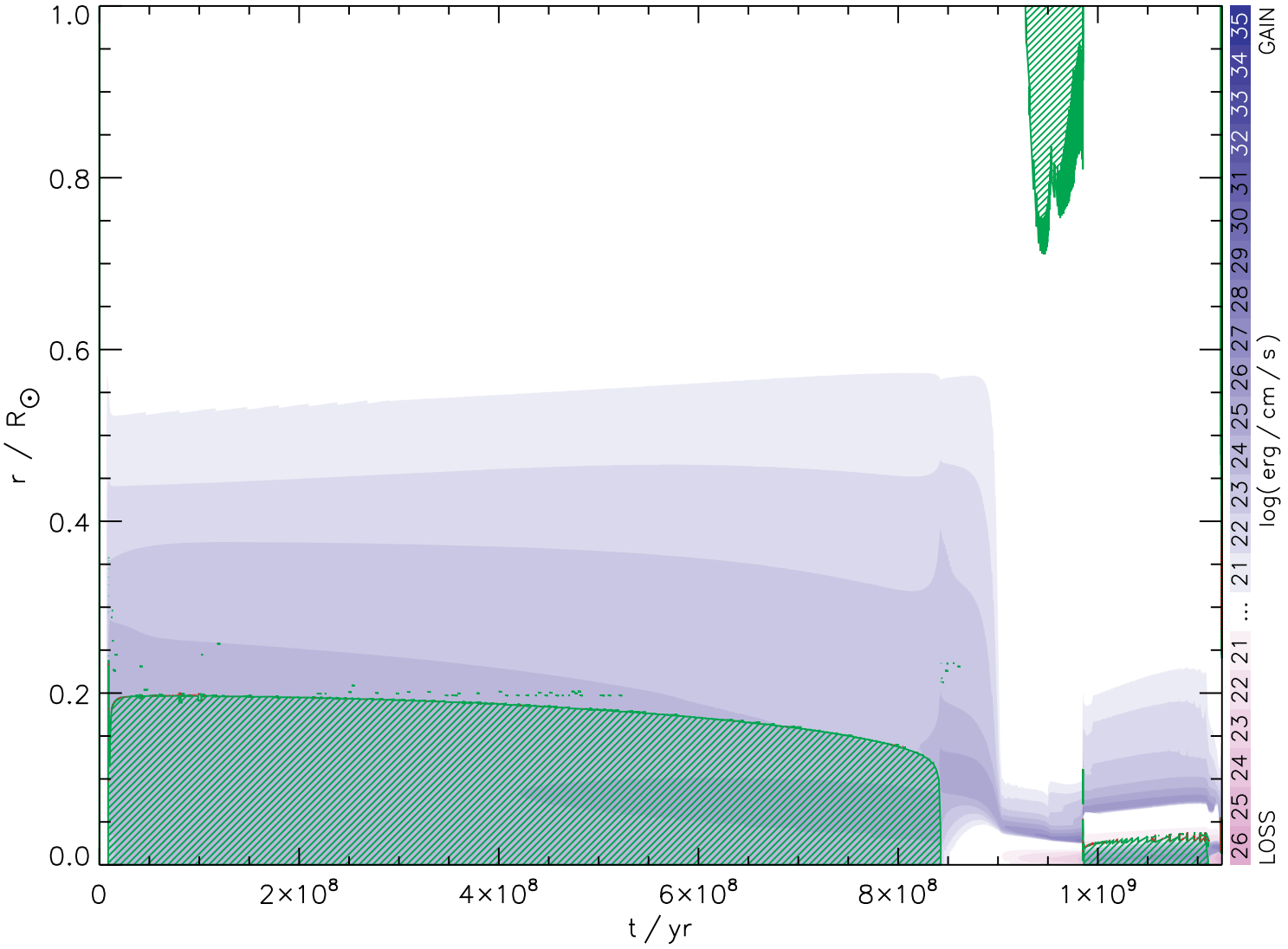
Kippenhahn Diagram, $2M_\odot$ Star



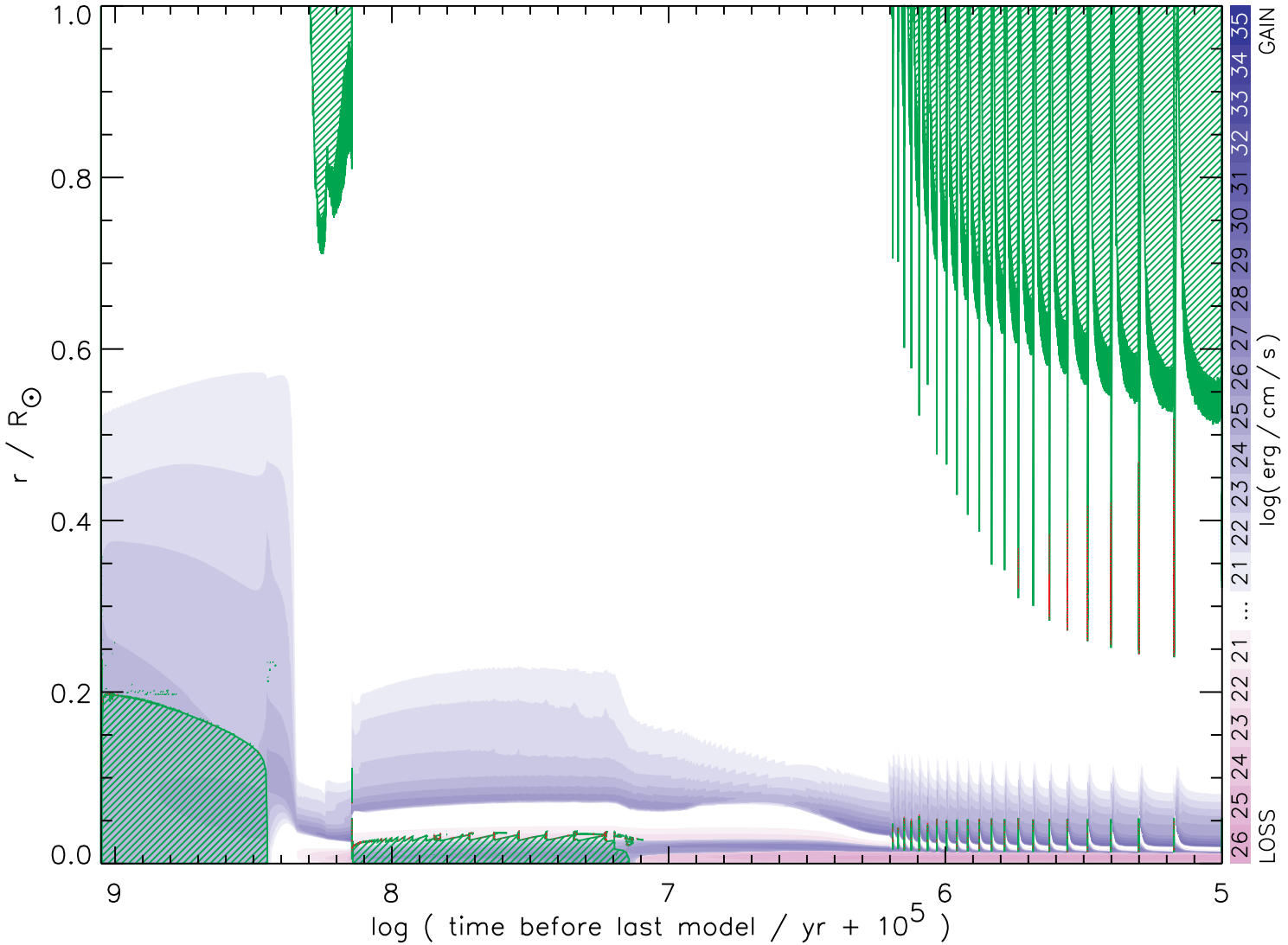
Kippenhahn Diagram, $2M_\odot$ Star



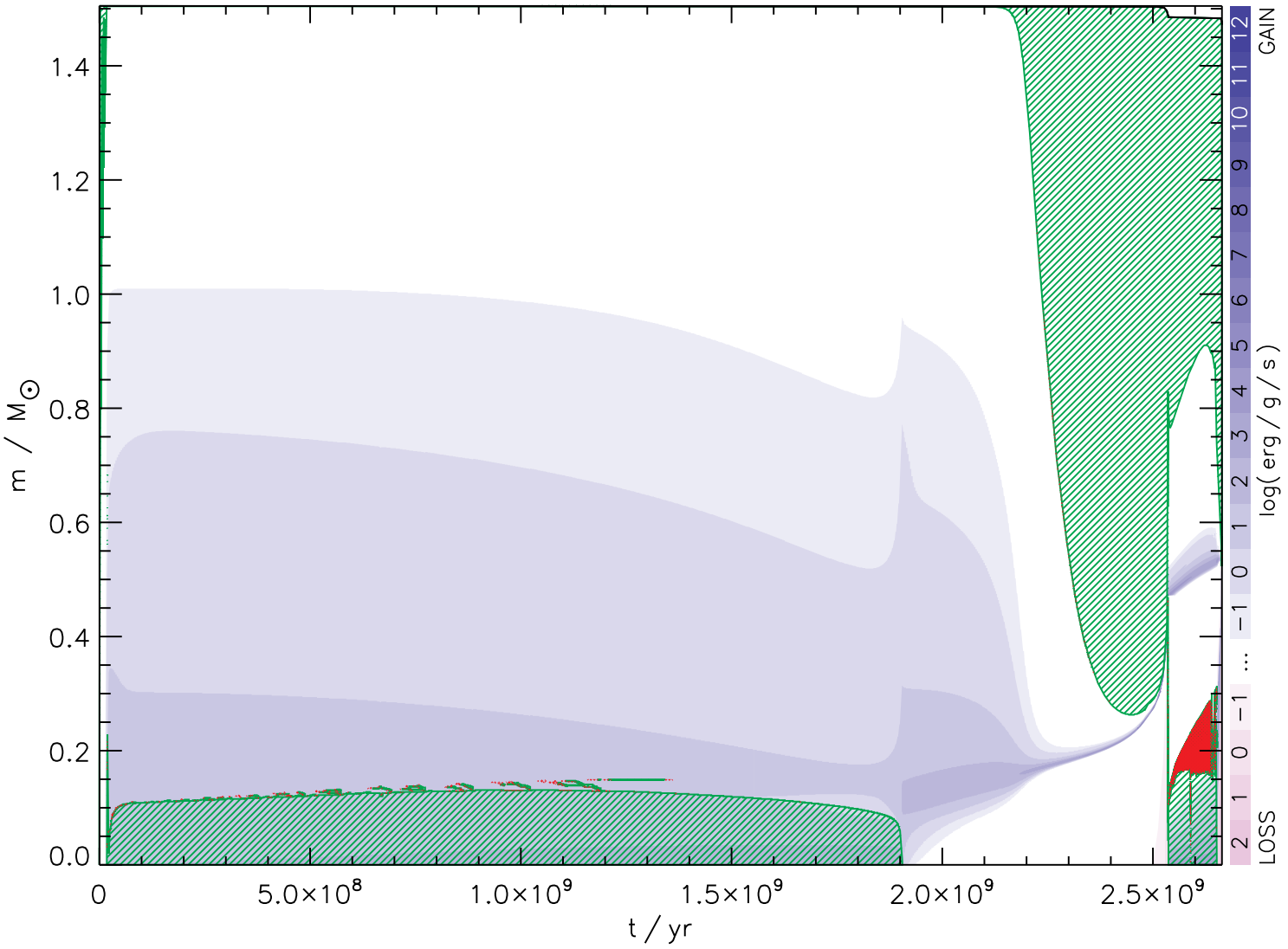
Kippenhahn-Radius Diagram, $2M_\odot$ Star



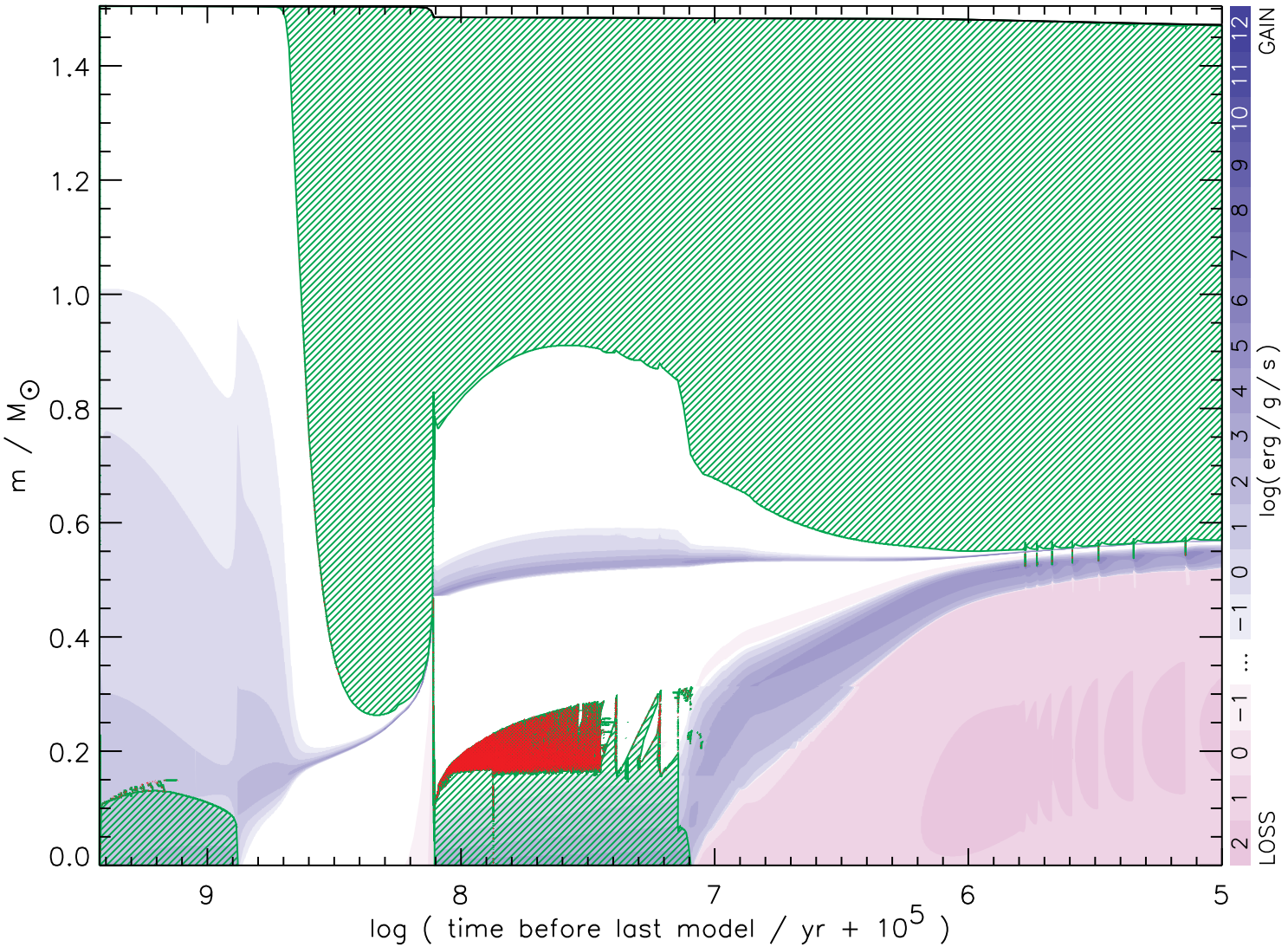
Kippenhahn-Radius Diagram, $2M_\odot$ Star



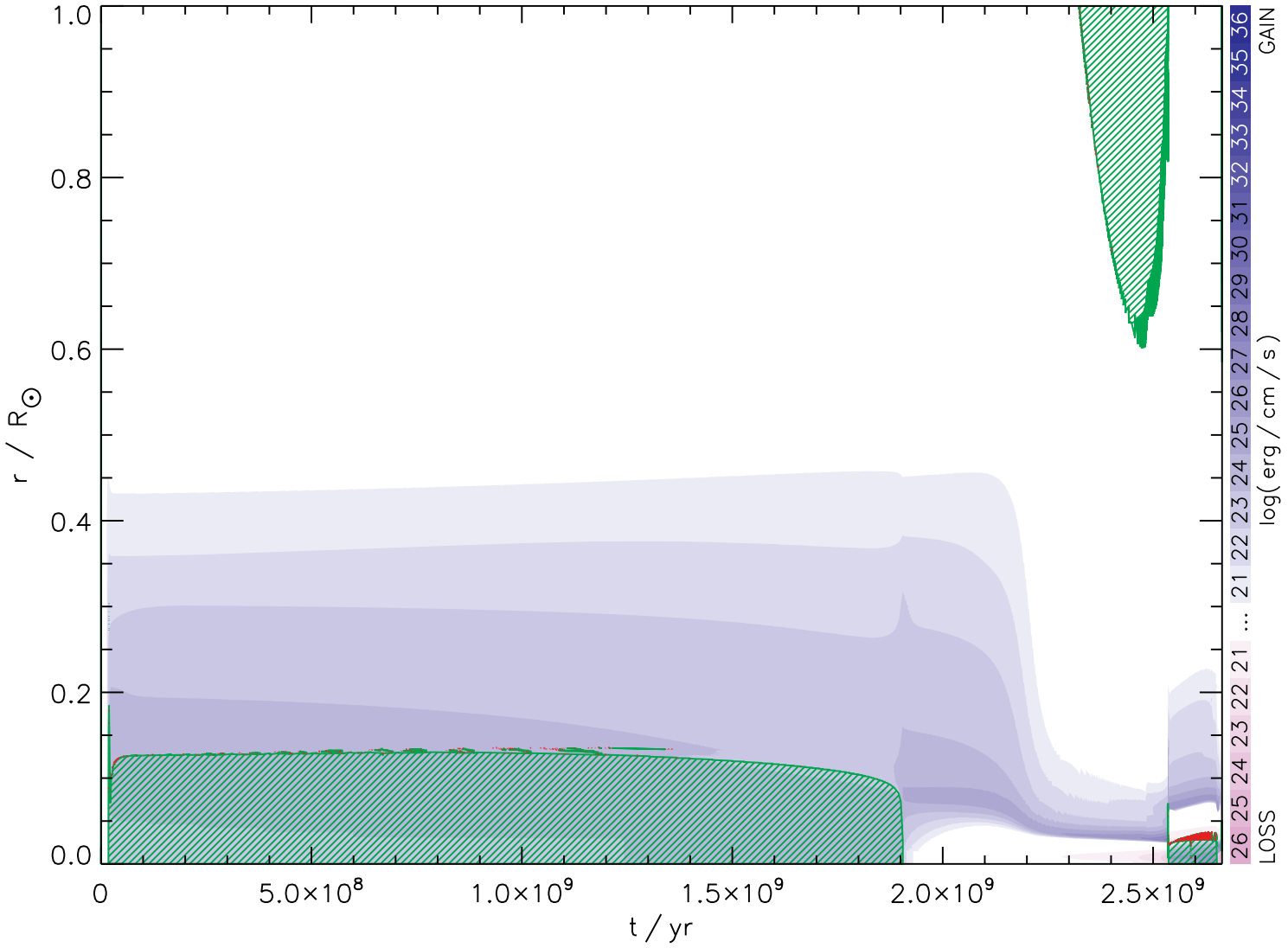
Kippenhahn Diagram, 1.5$M_\odot$ Star



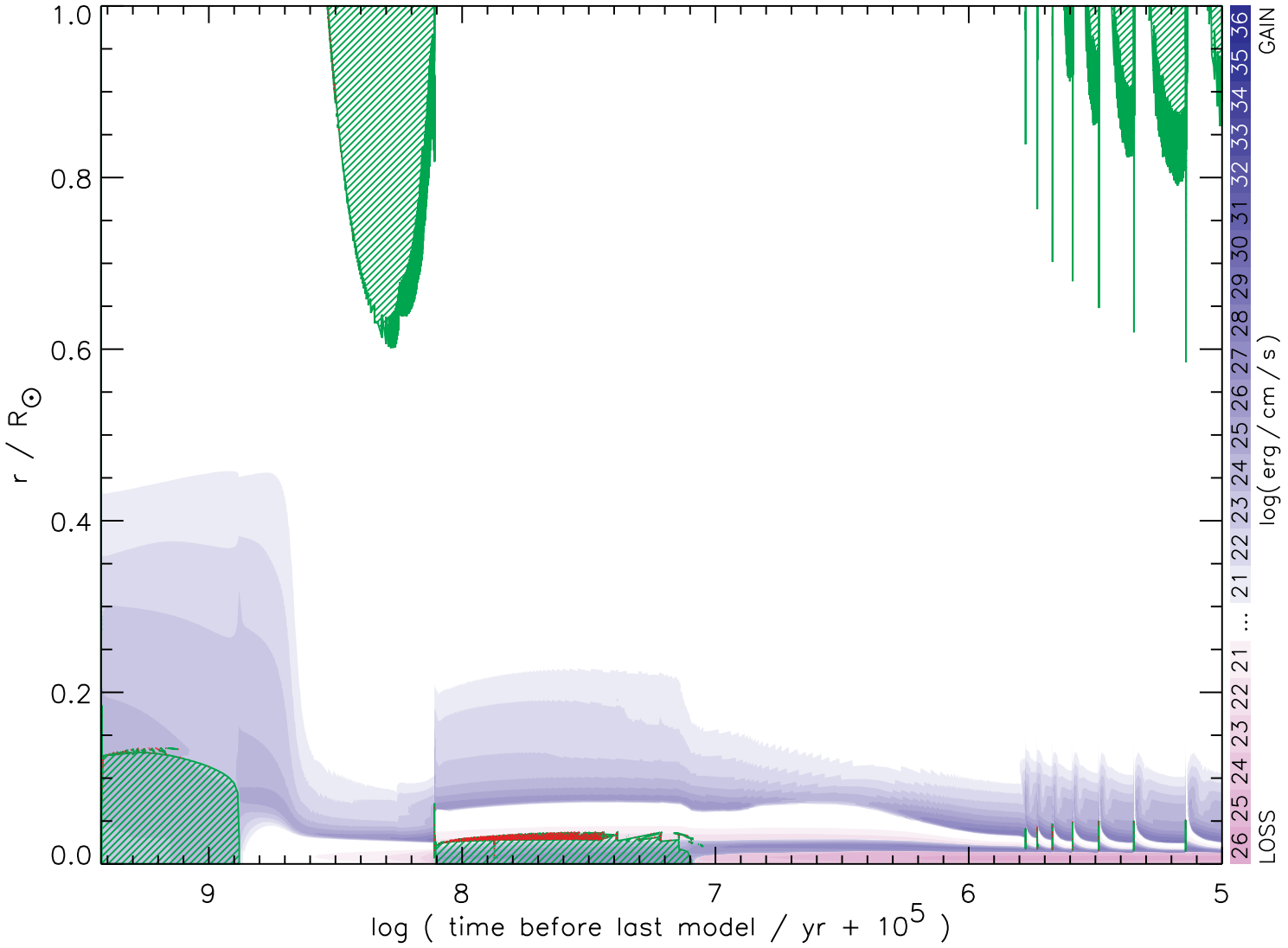
Kippenhahn Diagram, 1.5$M_\odot$ Star



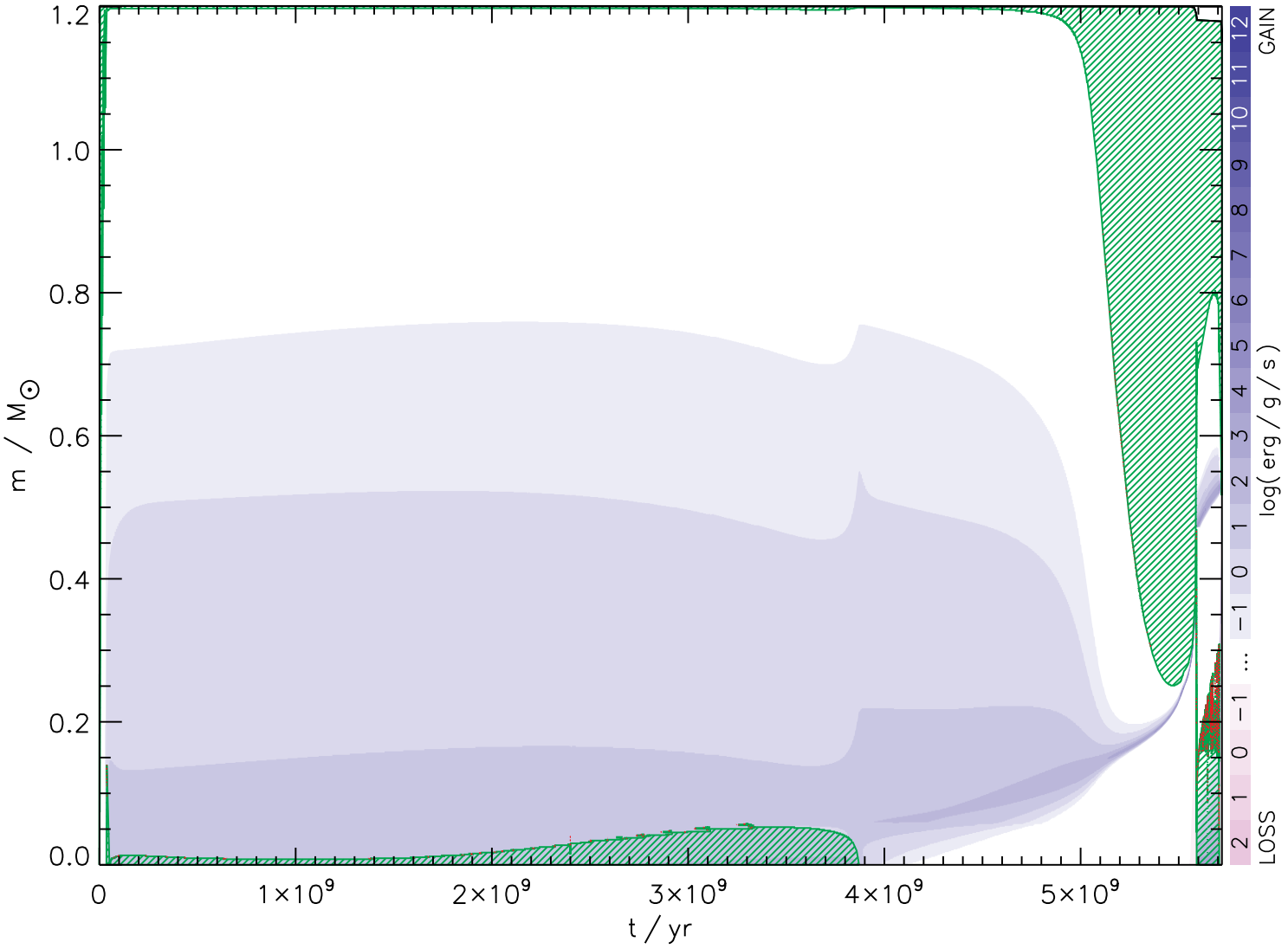
Kippenhahn-Radius Diagram, 1.5$M_\odot$ Star



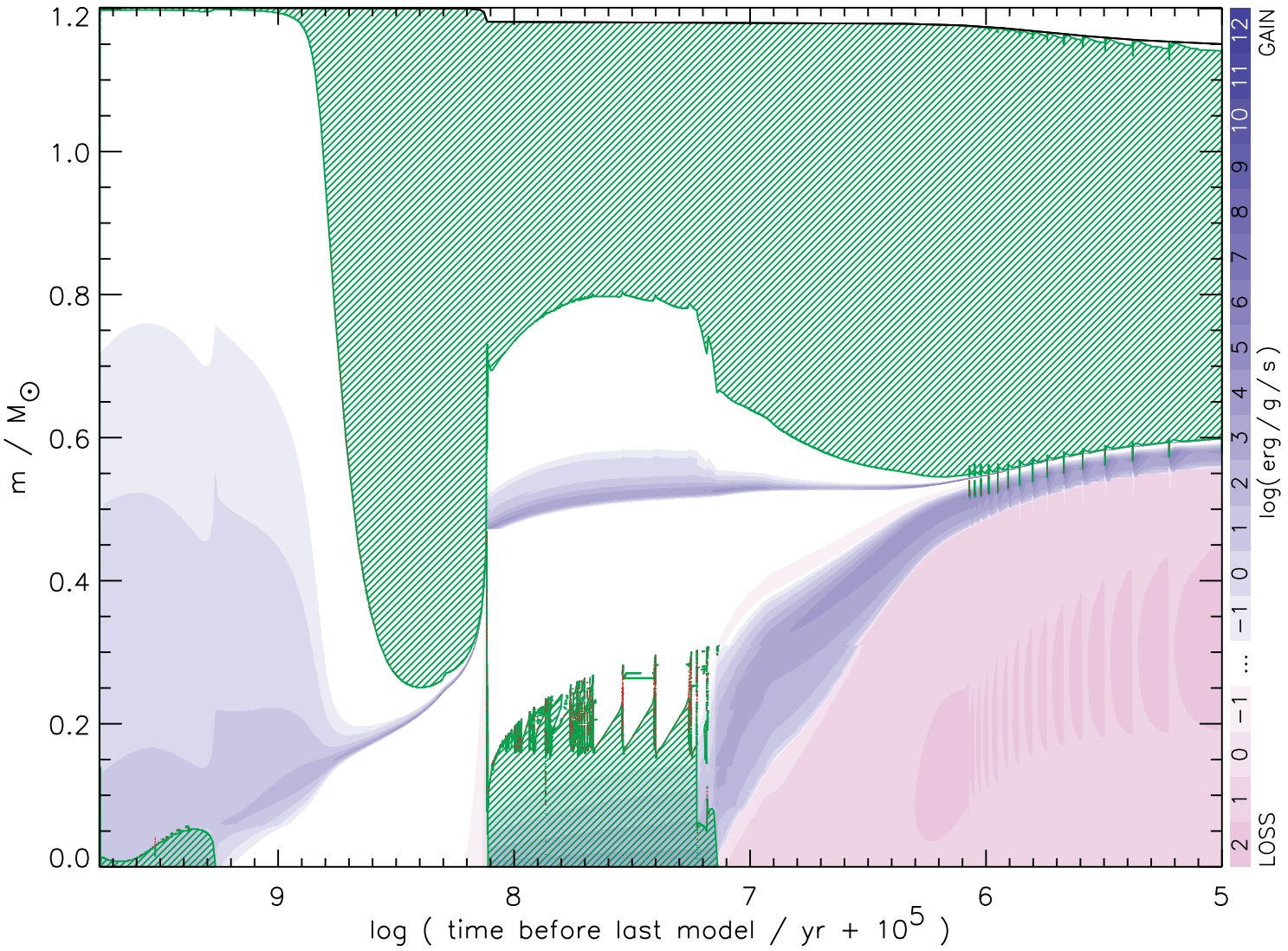
Kippenhahn-Radius Diagram, 1.5$M_\odot$ Star



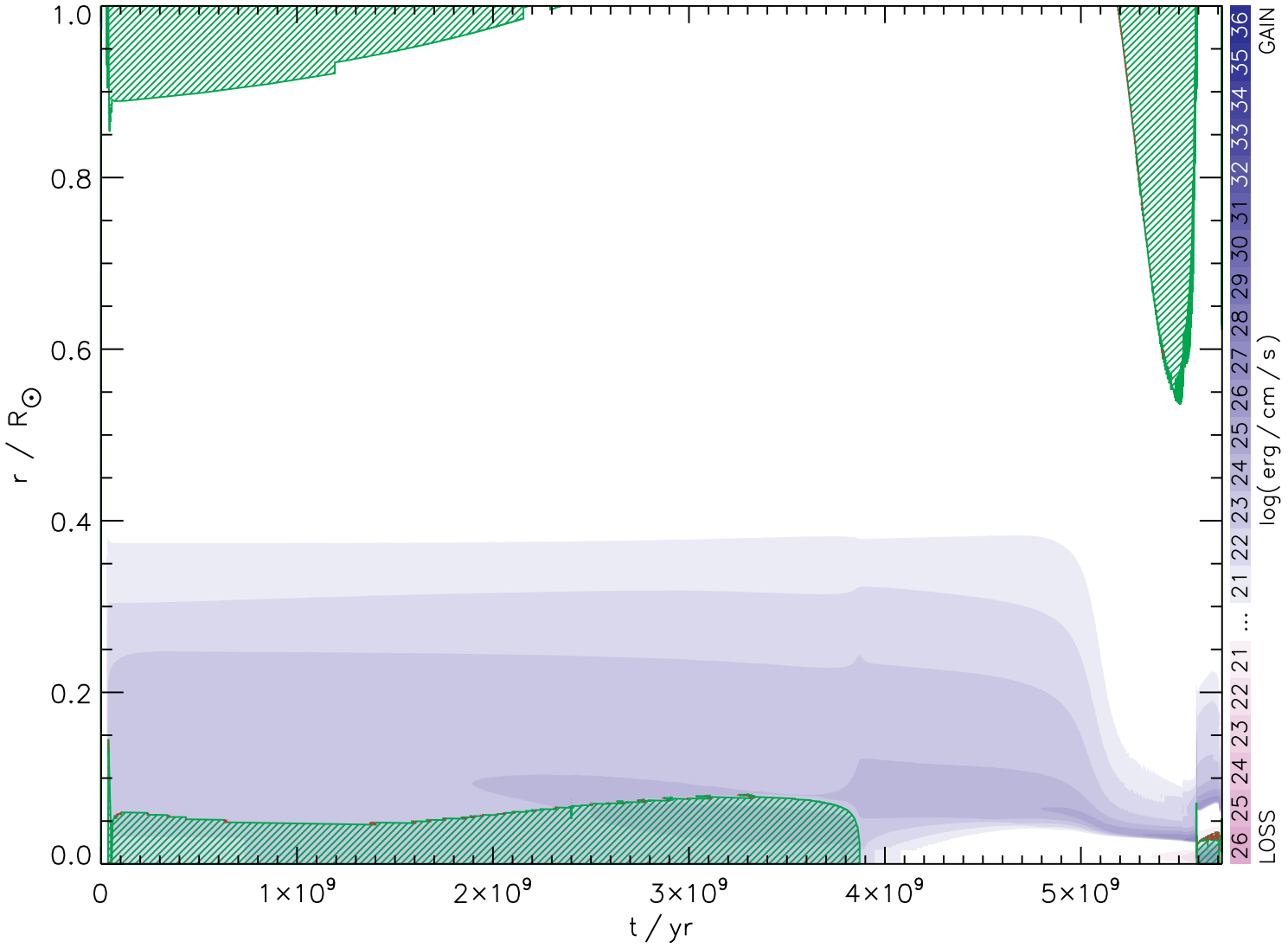
Kippenhahn Diagram, 1.2 $M_\odot$ Star



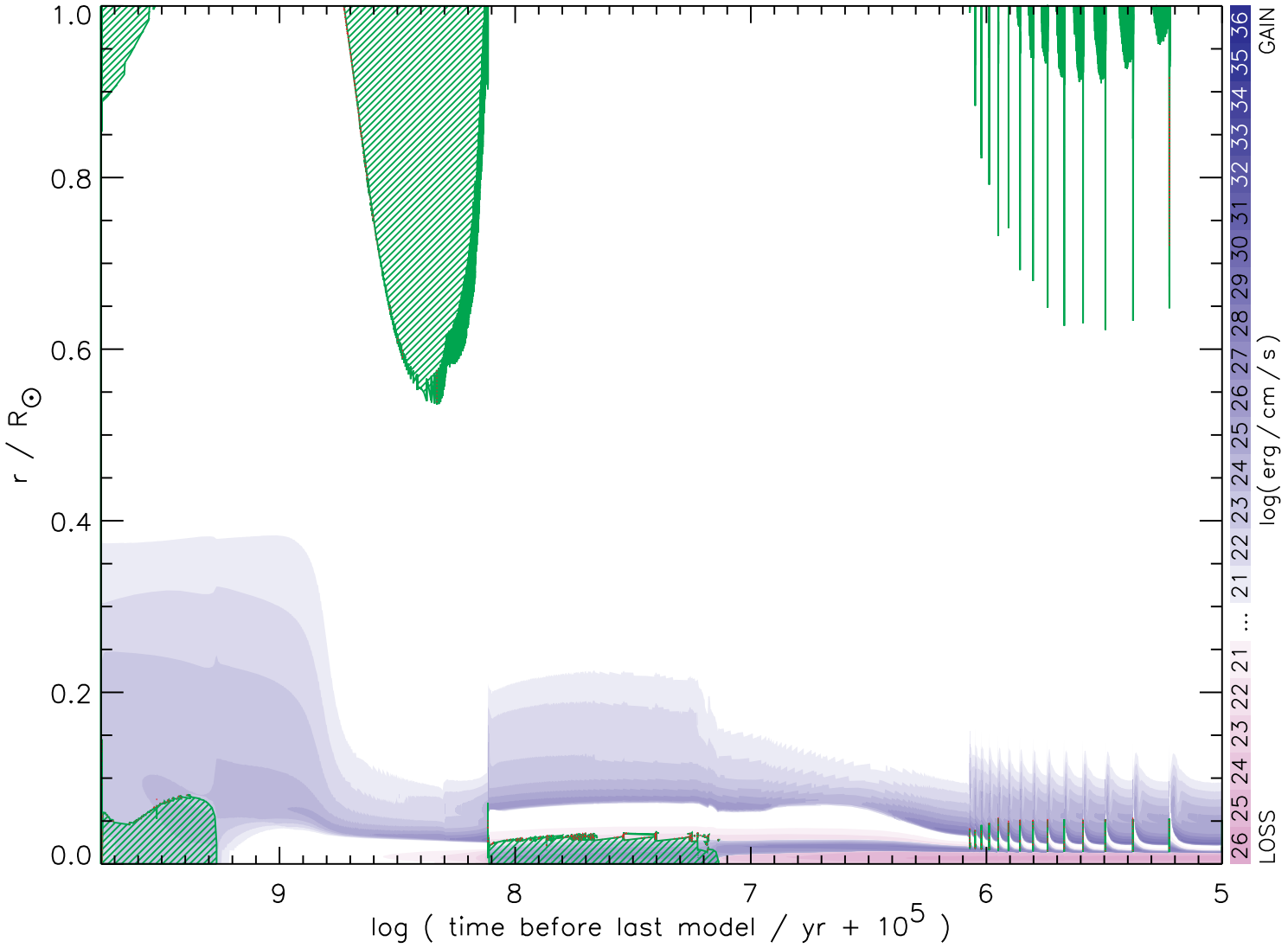
Kippenhahn Diagram, 1.2 $M_\odot$ Star



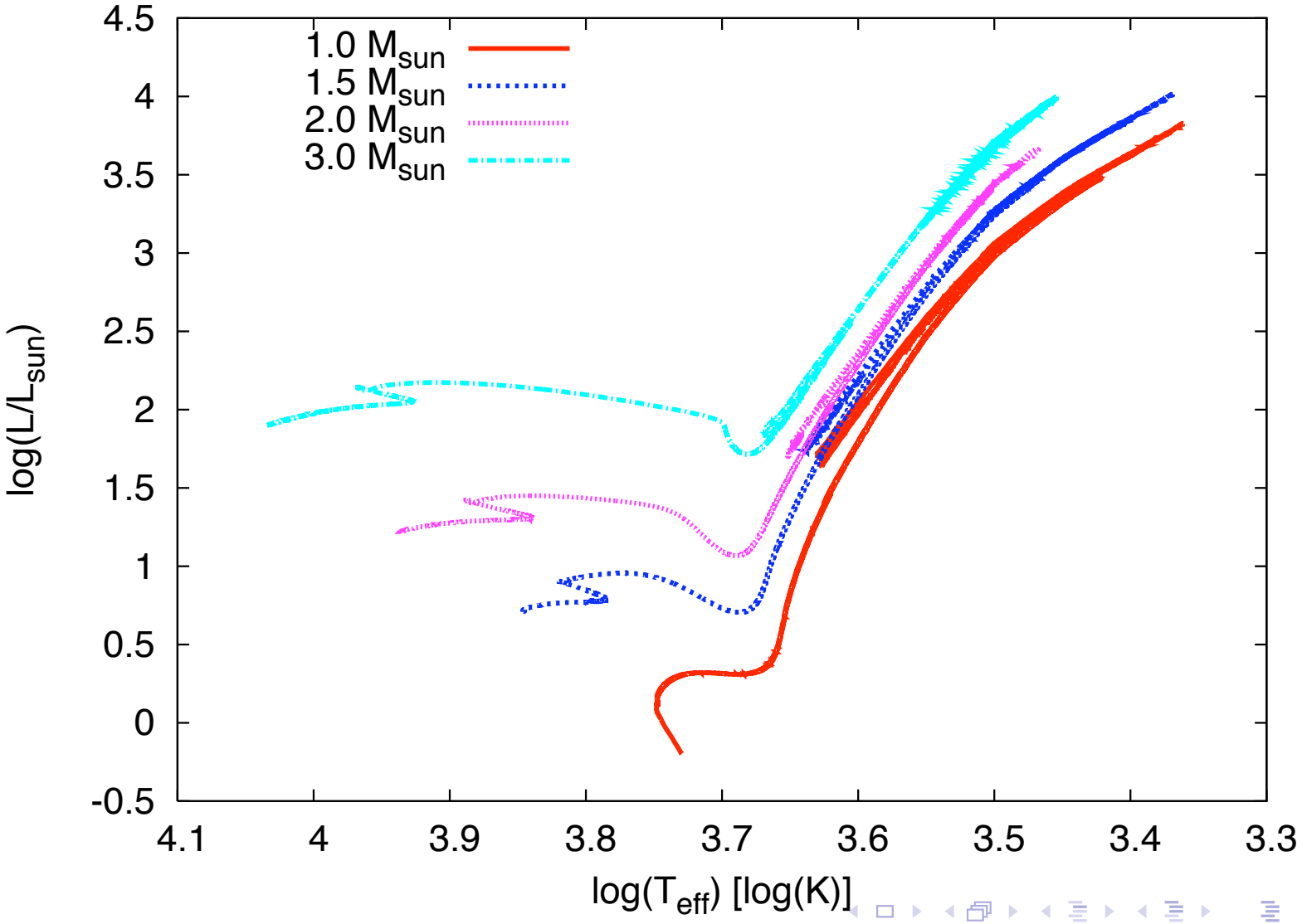
Kippenhahn-Radius Diagram, 1.2 $M_\odot$ Star



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



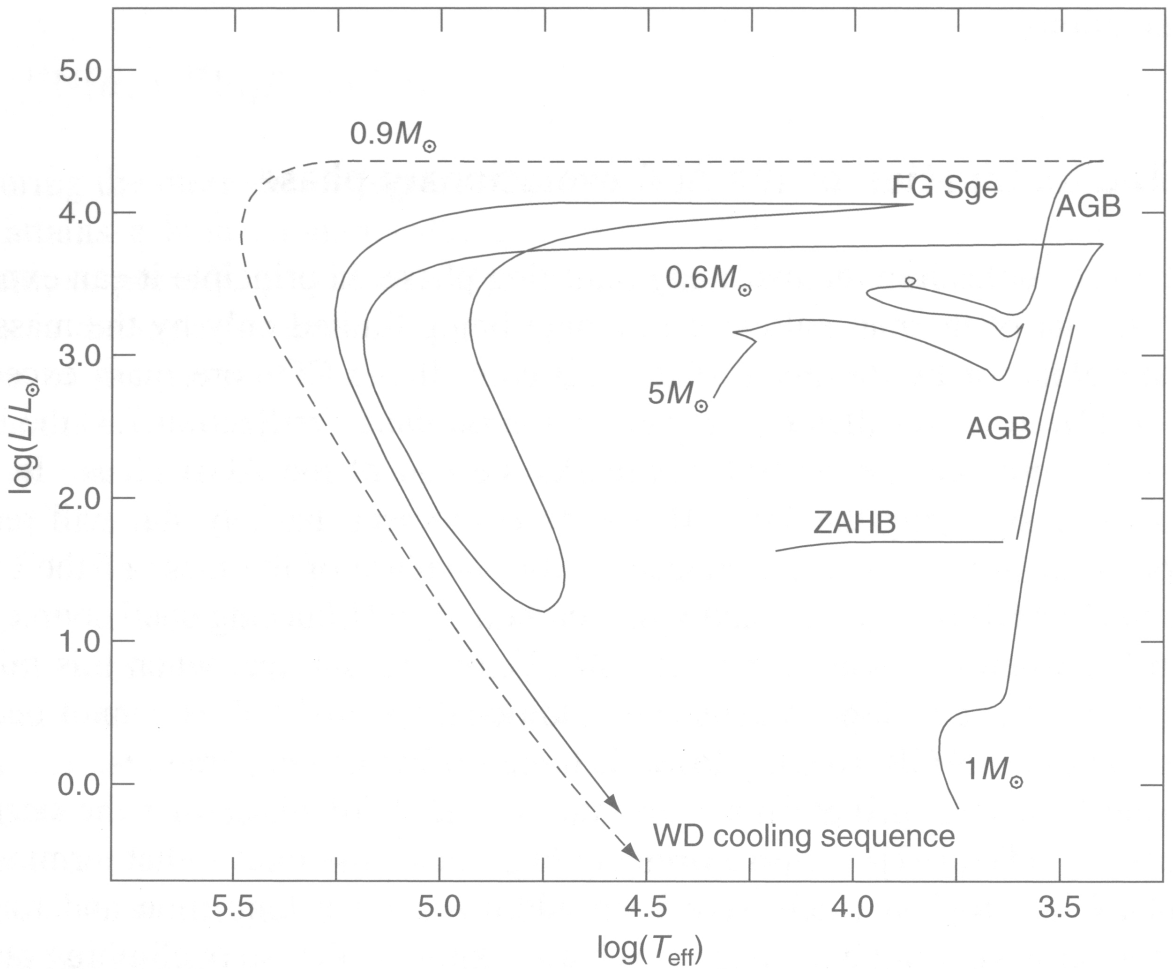
Evolution Through Core Contraction



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

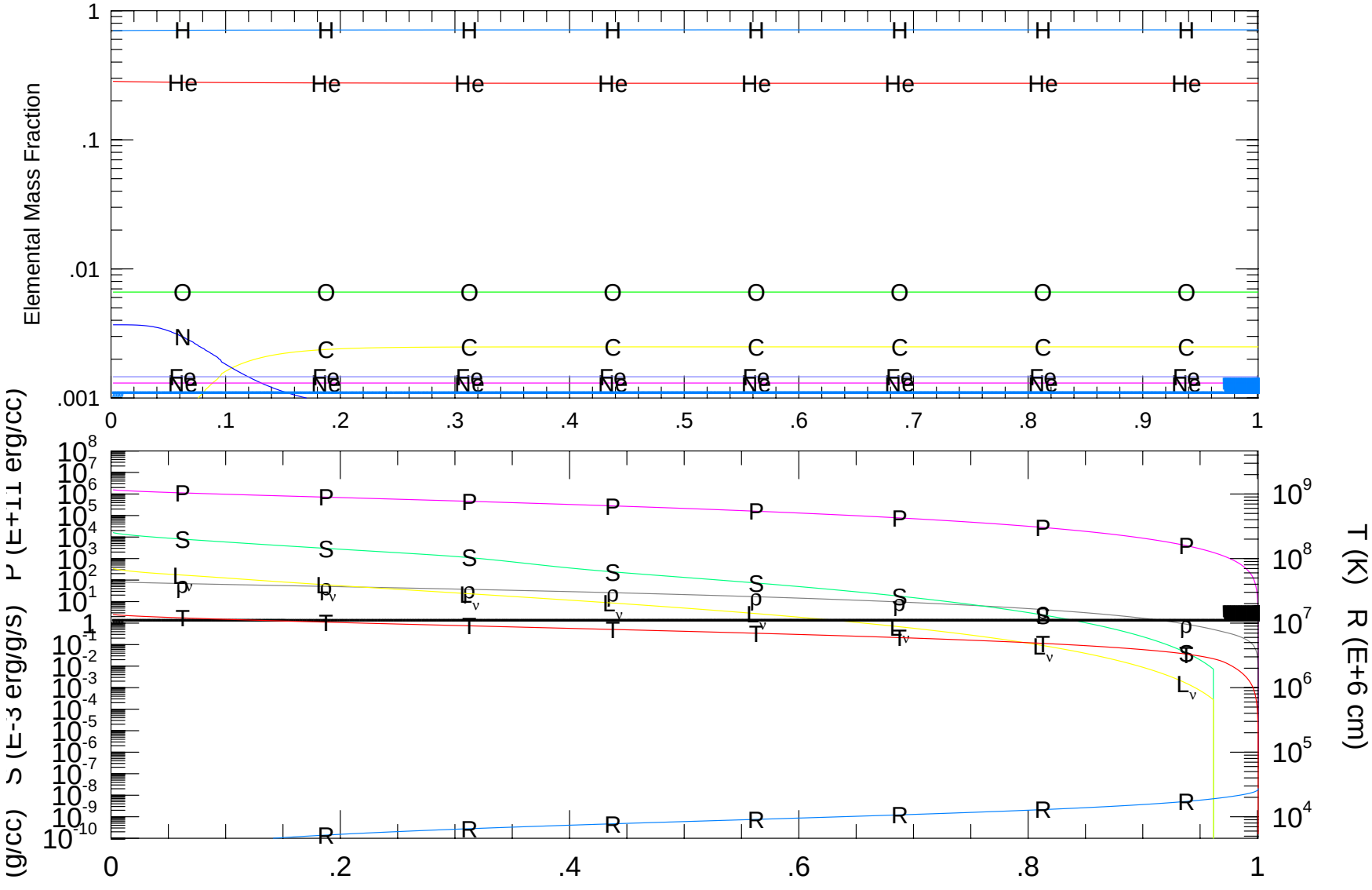


ZAHB = Zero-Age Horizontal Branch

1 $M_\odot$ Star

Evoluition of a 1 $M_\odot$ Star like the sun.

1 $M_\odot$ Star


Elemental Mass Fraction
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N
Ne
Fe
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0
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10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{9}
T (K) R (E+6 cm)
(g/cc) S (E-3 erg/g/s) P (E+11 erg/cc)
0
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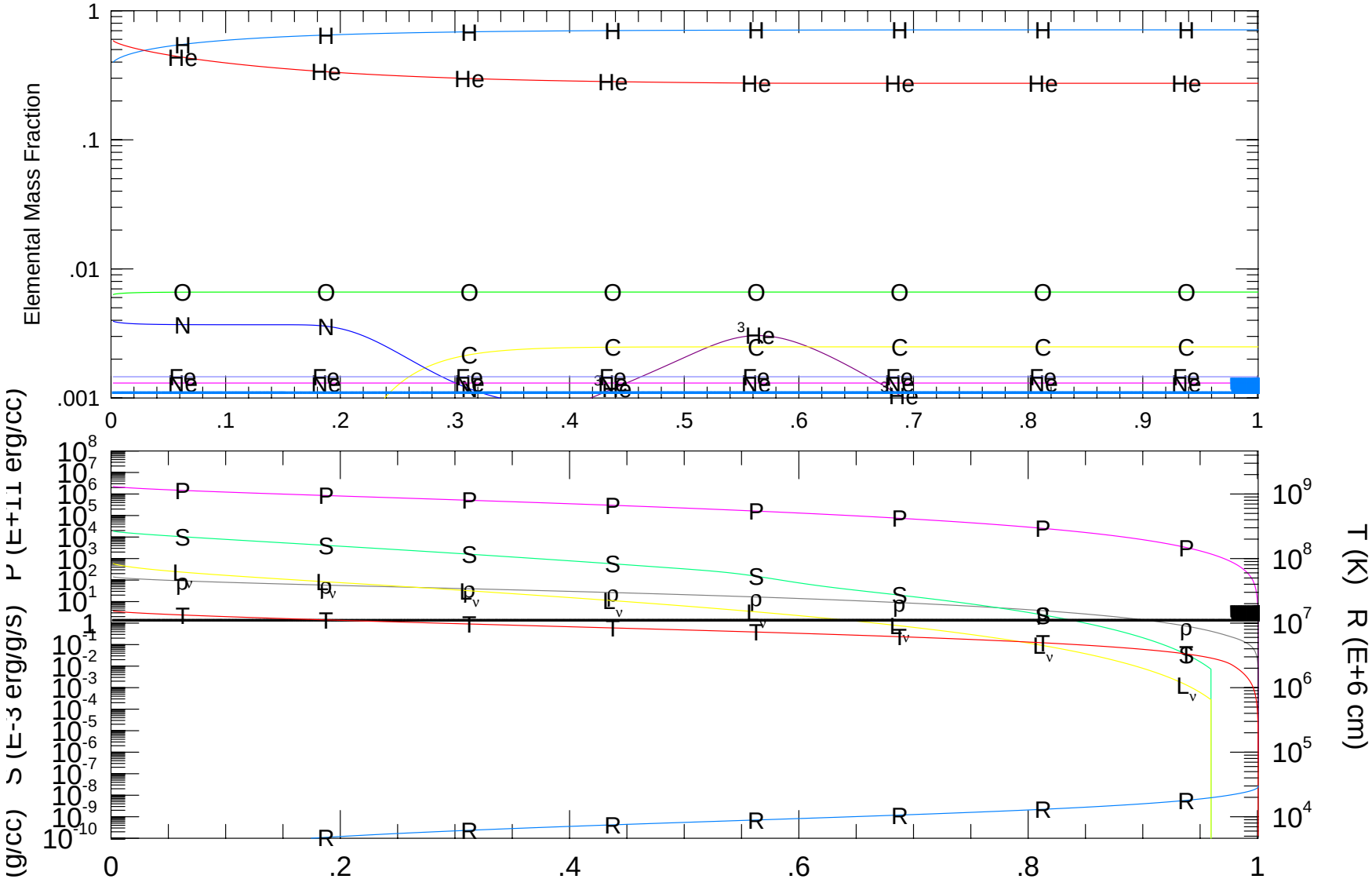
.6
.8
1

1 $M_\odot$ Star


Elemental Mass Fraction
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O
N
C
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Fe
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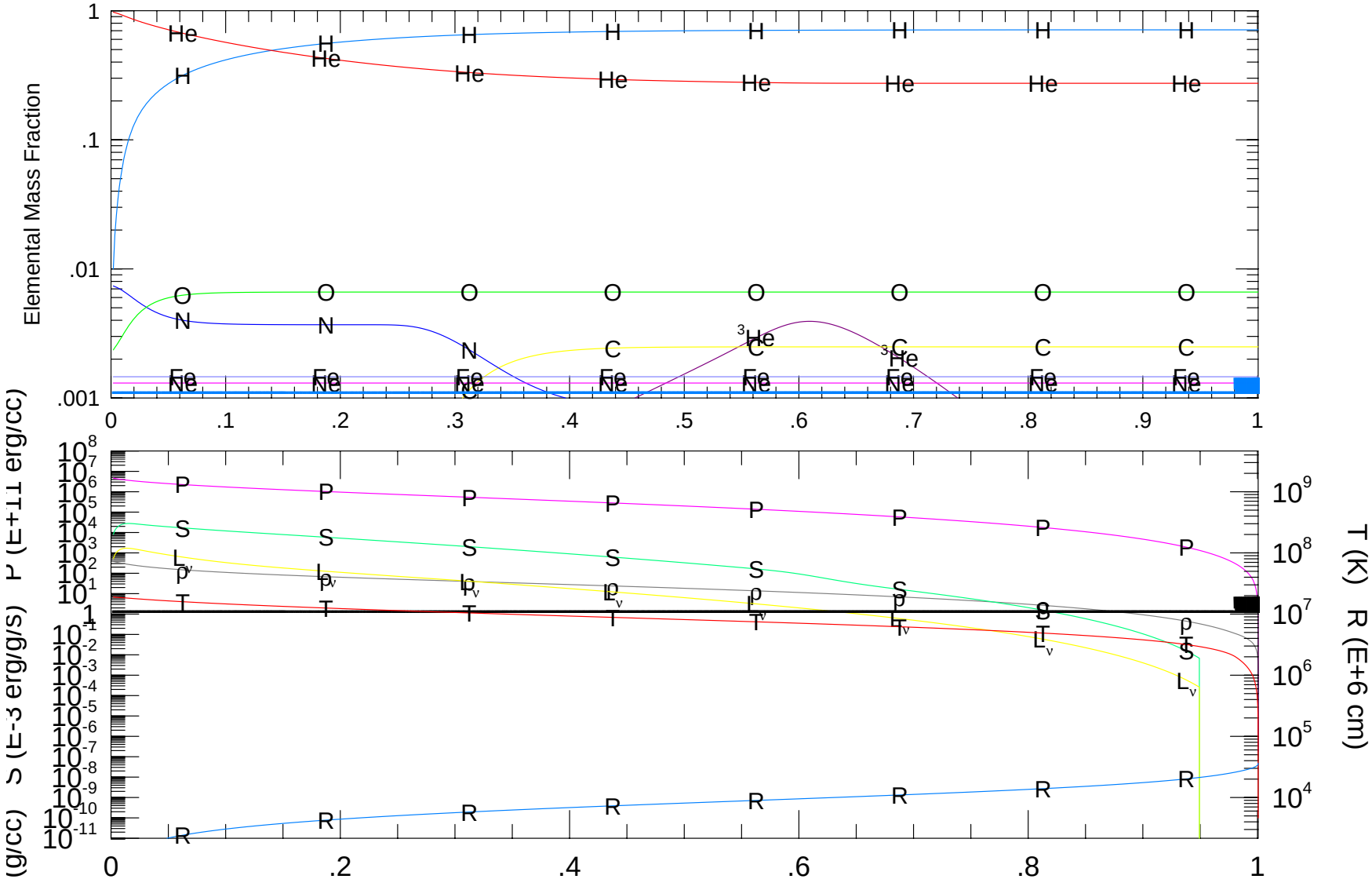
1
T (K) R (E+6 cm)

1 $M_\odot$ Star


Elemental Mass Fraction
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^{3}He
(g/cc) S (E-3 erg/g/s) P (E+11 erg/cc)
T (K) R (E+6 cm)
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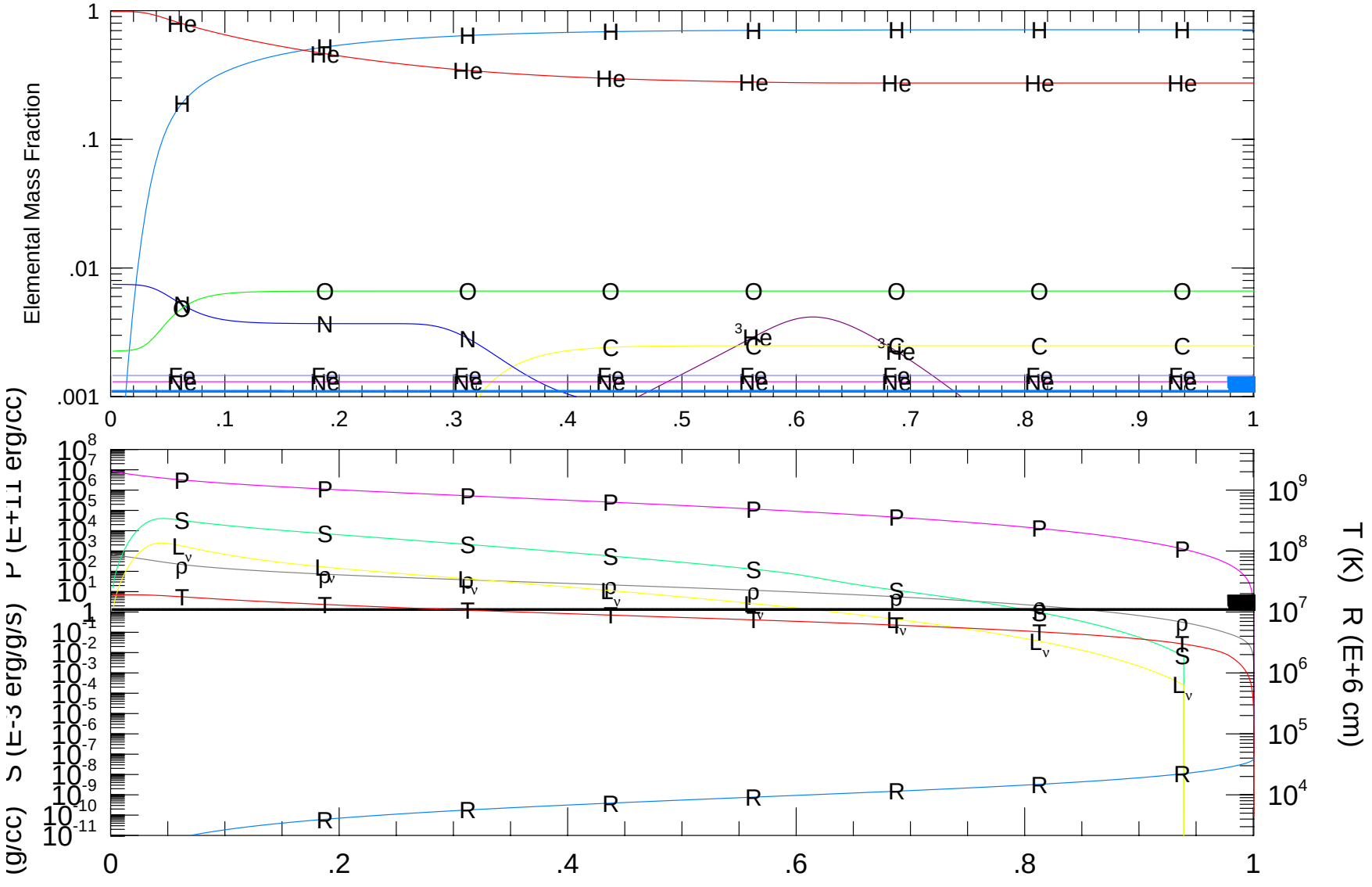
1

1 $M_\odot$ Star


Elemental Mass Fraction
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.001
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.3
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.6
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He
H
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N
C
Fe
Ne
^{3}He
(g/cc) ρ (E-3 erg/g/s) ε P (E+11 erg/cc)
T (K) R (E+6 cm)
P
S
L_ν
ρ
T
R
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10^6
10^5
10^4
10^9
10^{-11}
.2
.4
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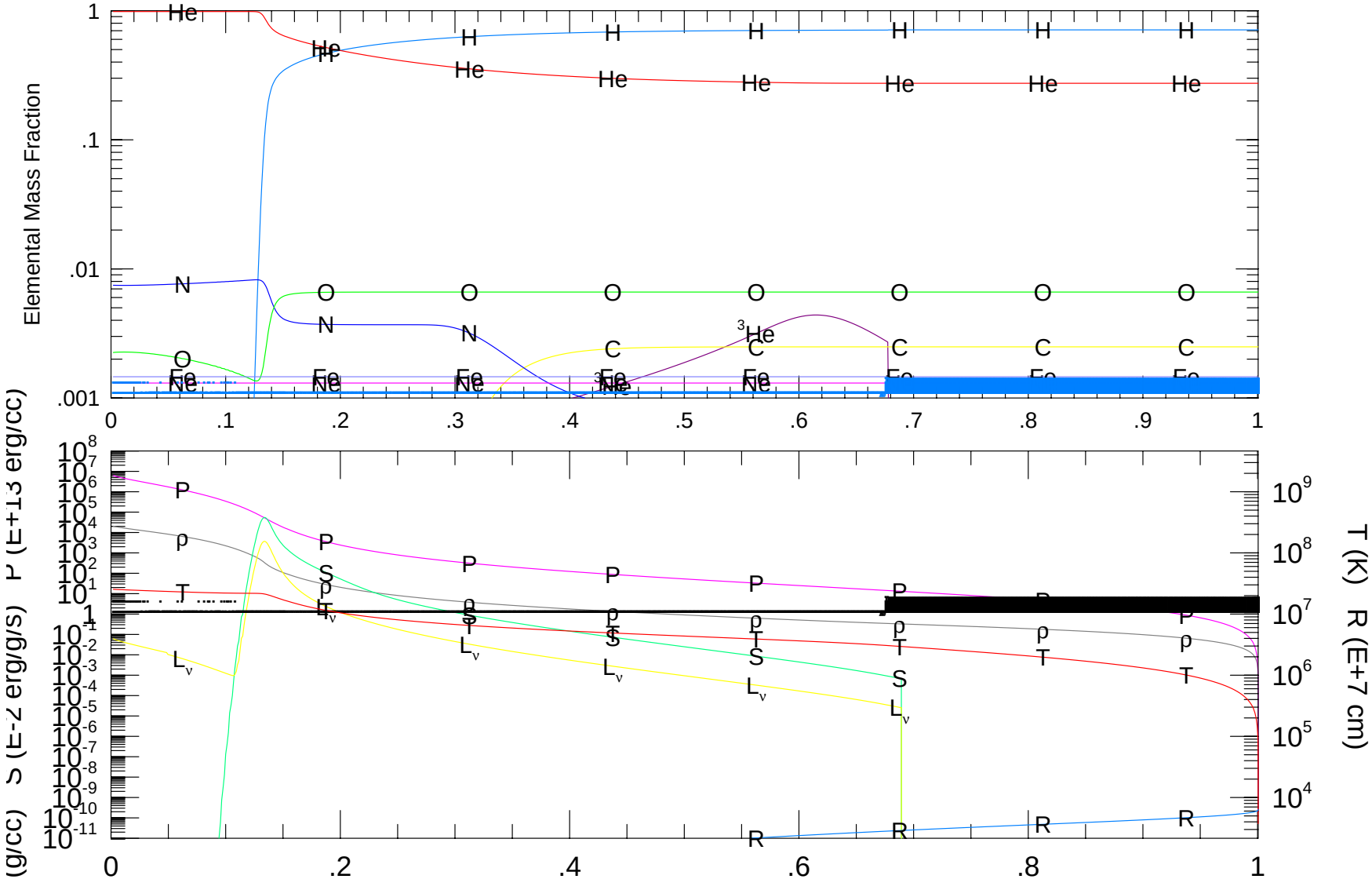
1 $M_\odot$ Star


Elemental Mass Fraction
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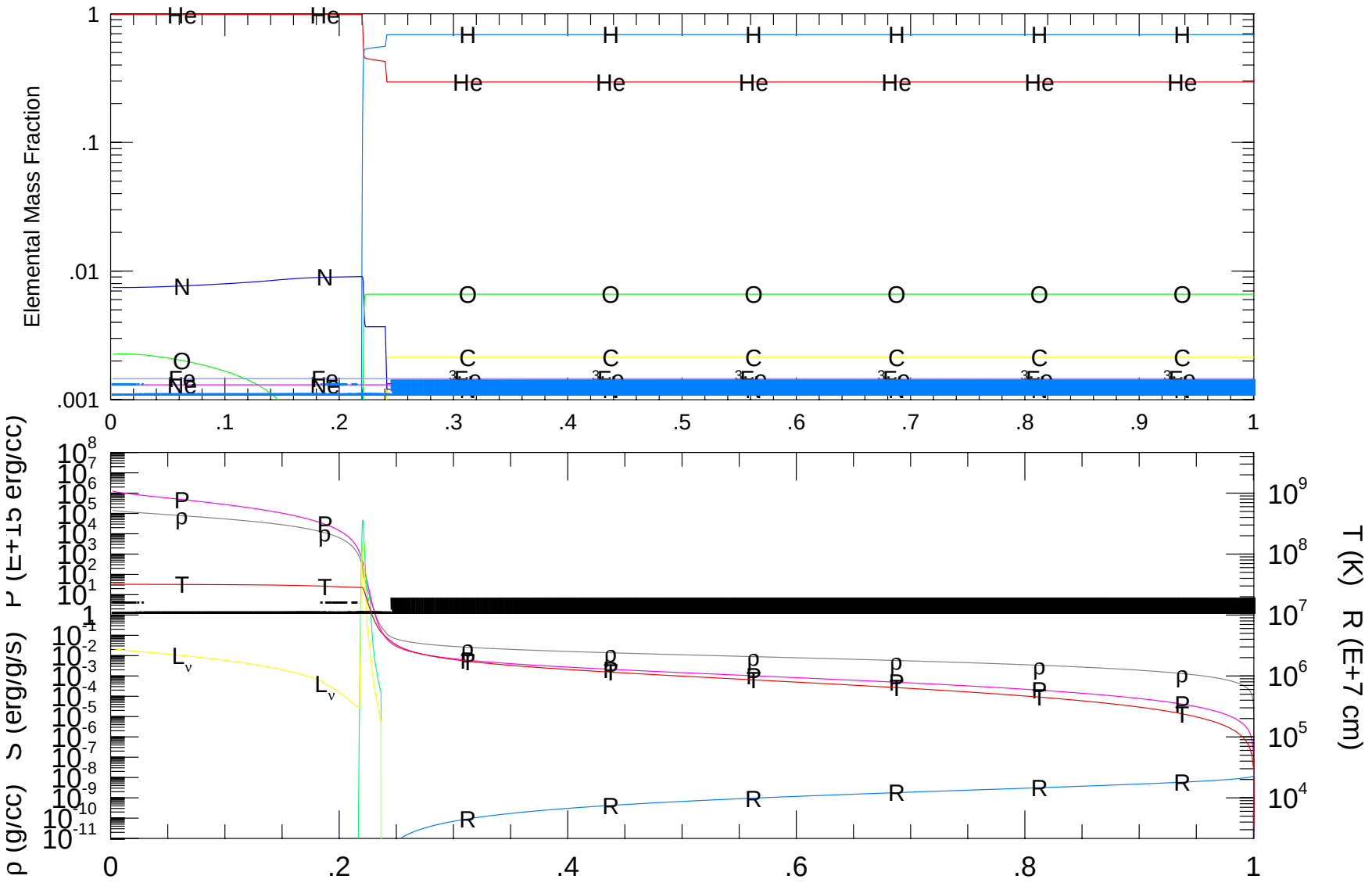
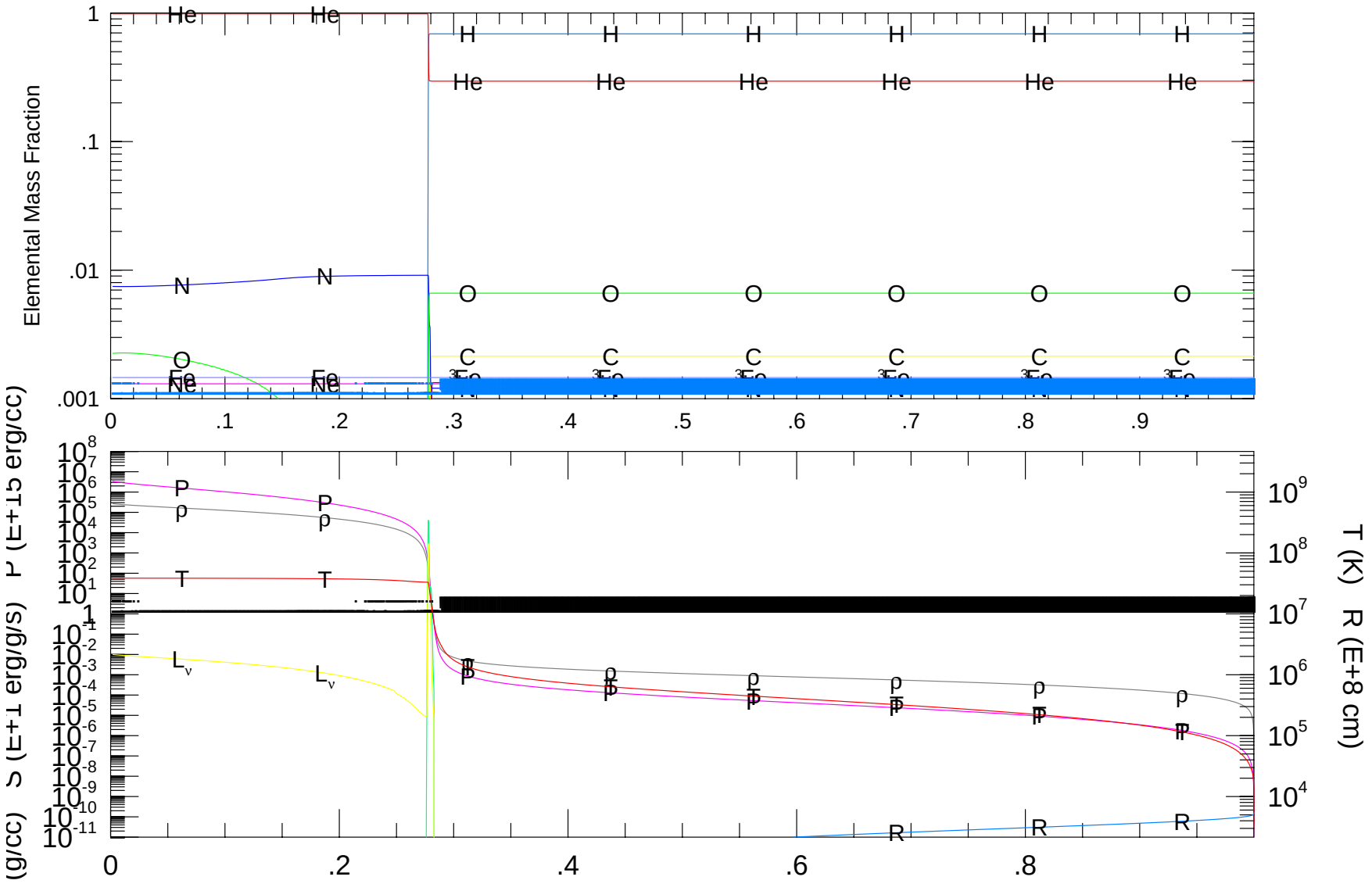
.1
.01
.001
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
He
H
N
O
C
Ne
Fe
^{3}He
(g/cc) S (E+2 erg/g/s) P (E+13 erg/cc)
T (K) R (E+7 cm)
P
ρ
T
S
L_ν
R
0
.2
.4
.6
.8
1

1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
He
H
N
O
C
Fe
Ne
ρ (g/cc)
P (E+15 erg/cc)
S (erg/g/s)
T (K)
R (E+7 cm)
P
ρ
T
L_ν
R

1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
0
.1
.2
.3
.4
.5
.6
.7
.8
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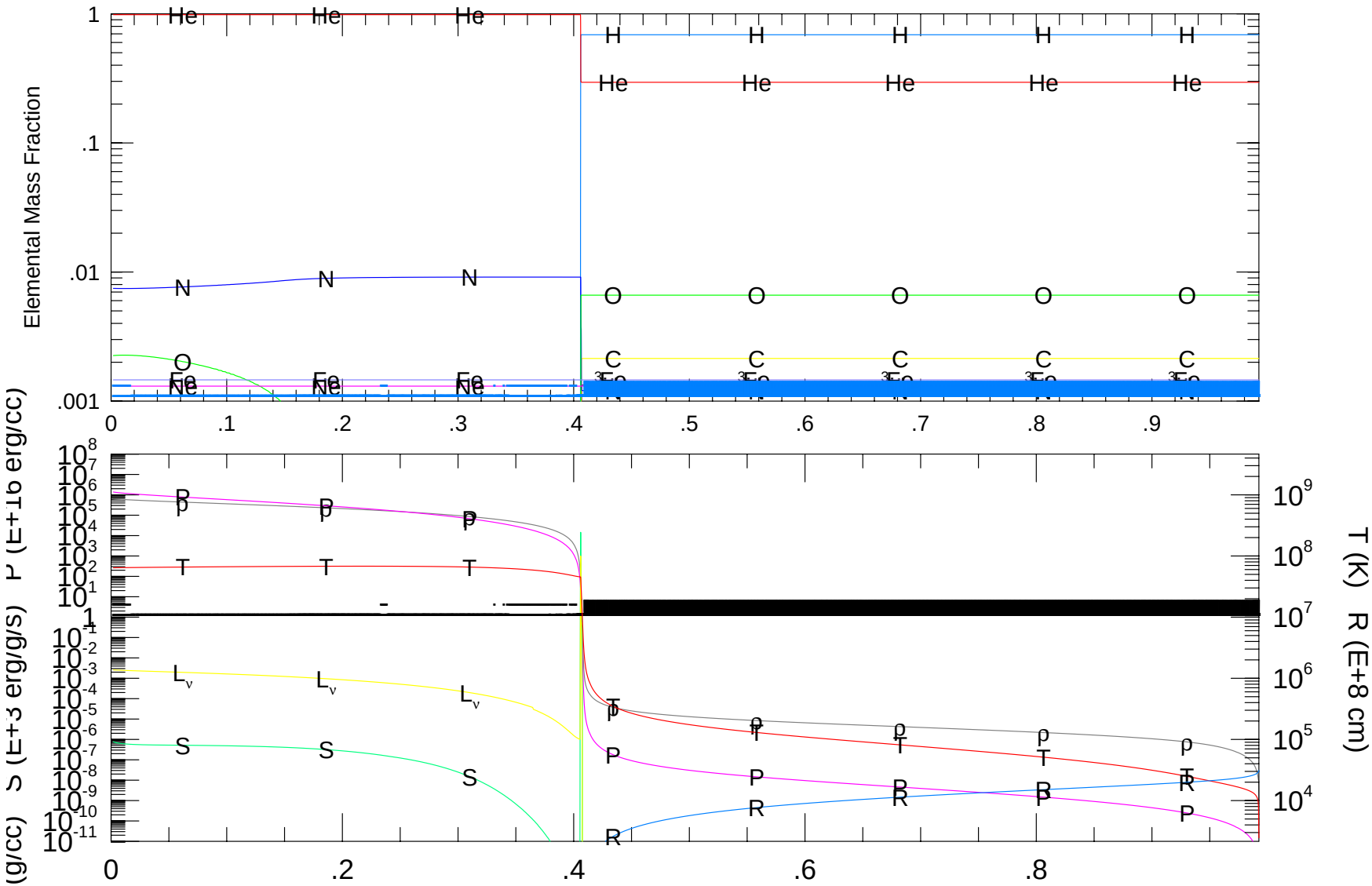
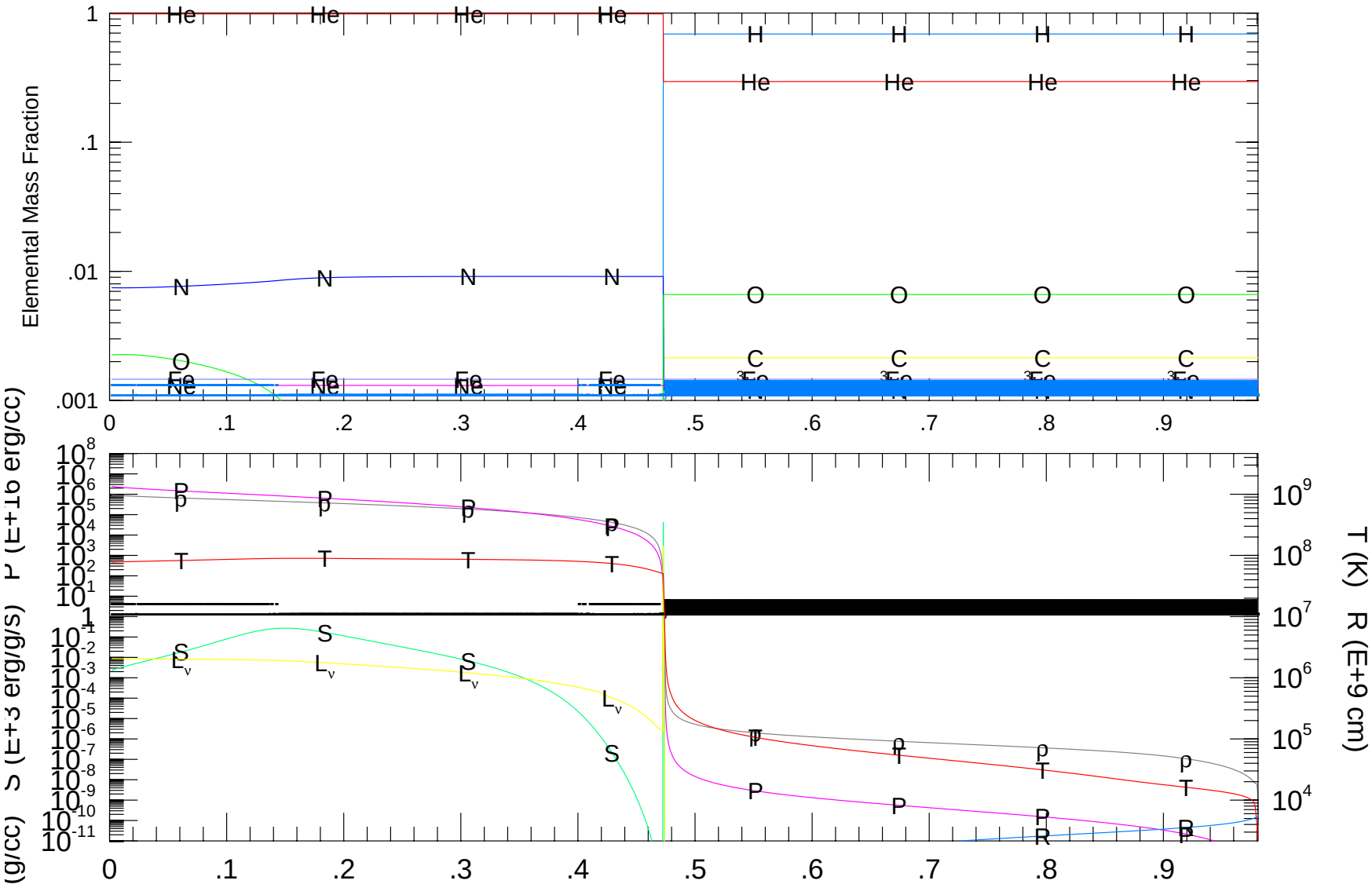
He
H
N
O
C
Ne
Fe
P
ρ
T
L_ν
R
(g/cc) ρ (E+1 erg/g/s) L_ν P (E+15 erg/cc)
T (K) R (E+8 cm)

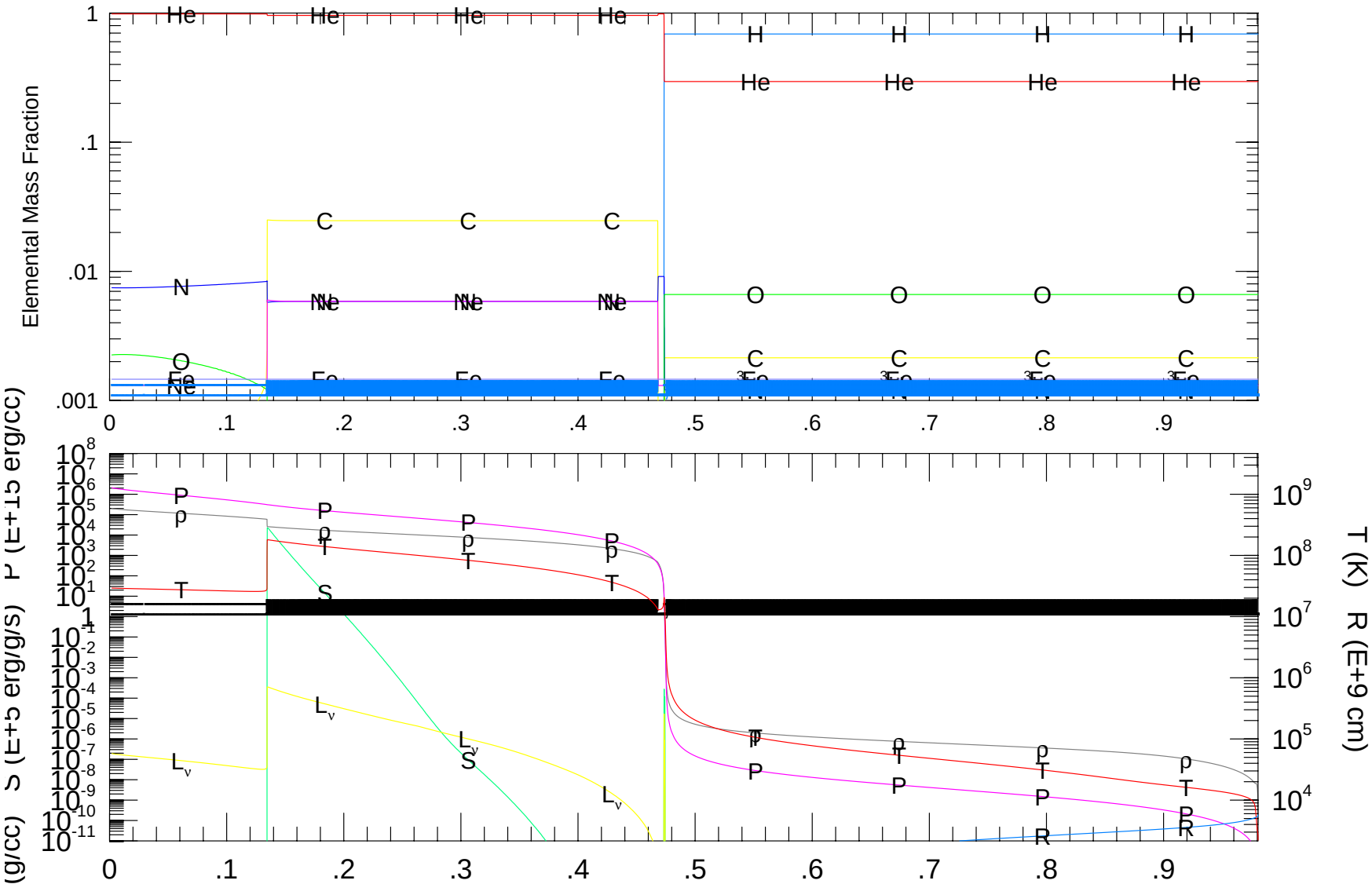
1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
He
H
N
O
C
Ne
Fe
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
ρ
T
P
R
L_ν
S
(g/cc) S (E+3 erg/g/s) P (E+16 erg/cc)
T (K) R (E+8 cm)
10^9
10^8
10^7
10^6
10^5
10^4
0
.2
.4
.6
.8

1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
He
H
N
O
C
Fe
Ne
P
T
S
L_ν
ρ
R
10^9
10^8
10^7
10^6
10^5
10^4
T (K) R (E+9 cm)
(g/cc) S (E+3 erg/g/s) P (E+16 erg/cc)

1 $M_\odot$ Star


Elemental Mass Fraction
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.1
.01
.001
0
.1
.2
.3
.4
.5
.6
.7
.8
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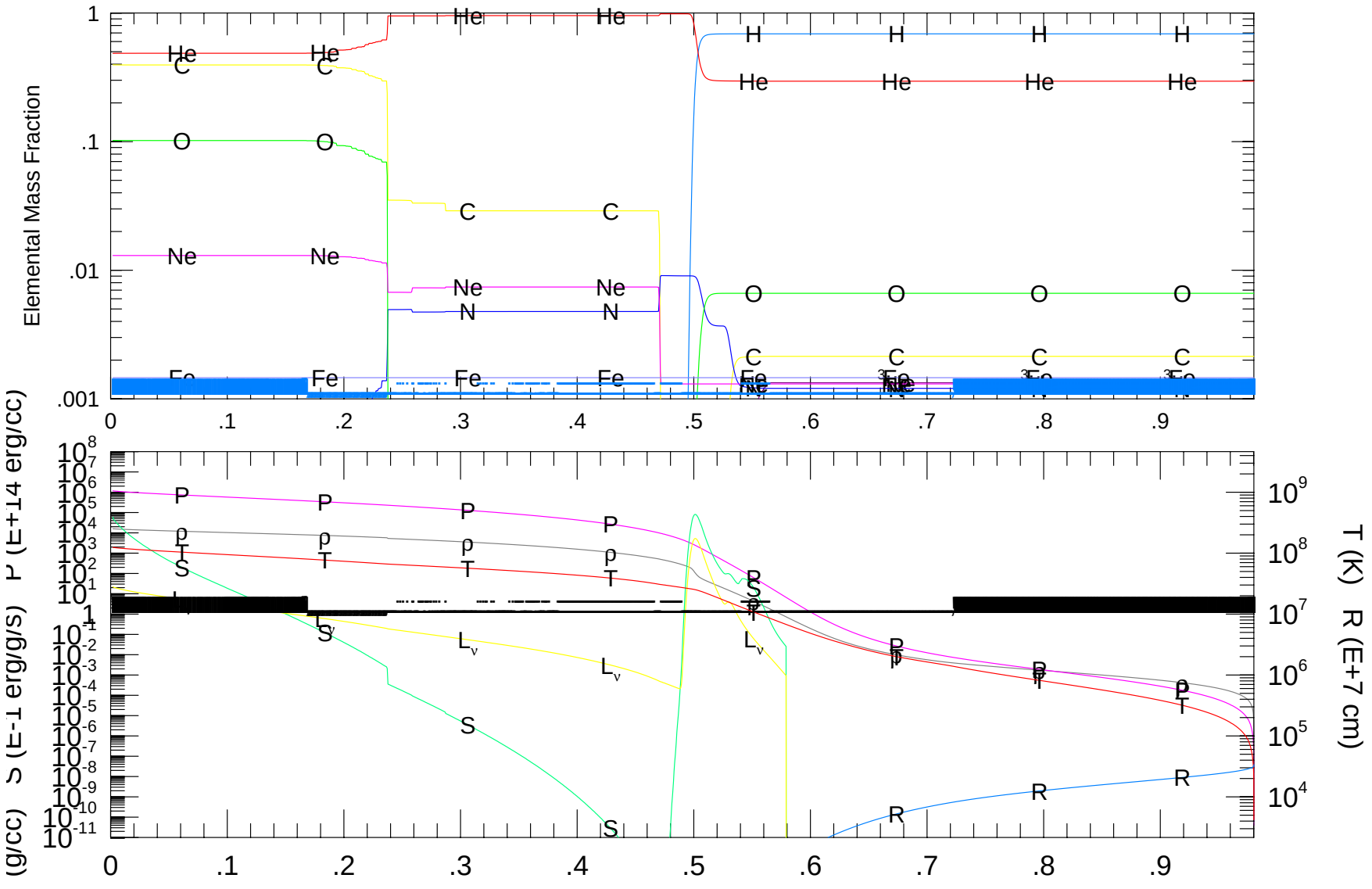
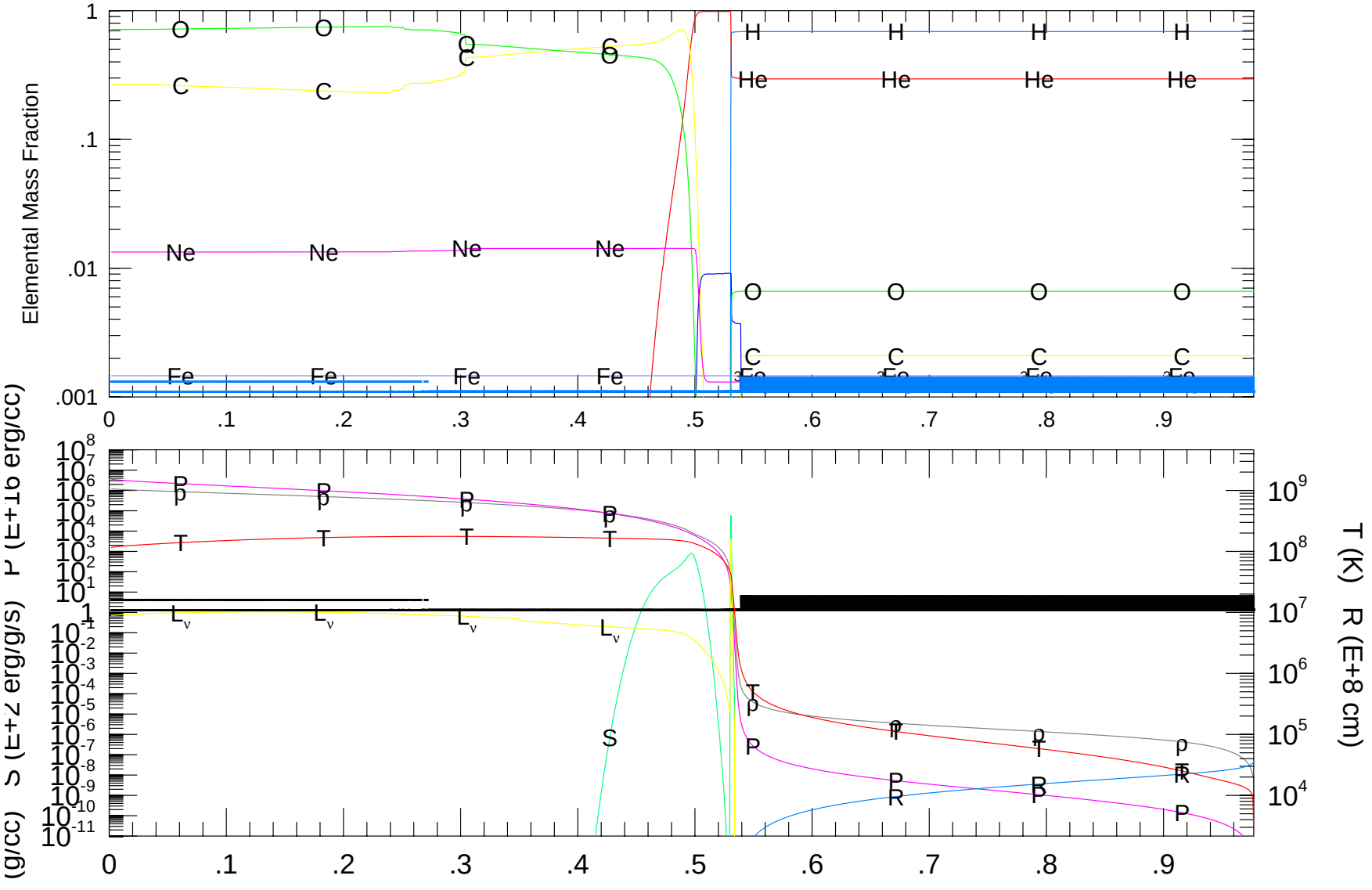
He
H
C
N
O
Ne
Fe
^{3}He
10^9
10^8
10^7
10^6
10^5
10^4
T (K) R (E+9 cm)
P
ρ
T
S
L_ν
R

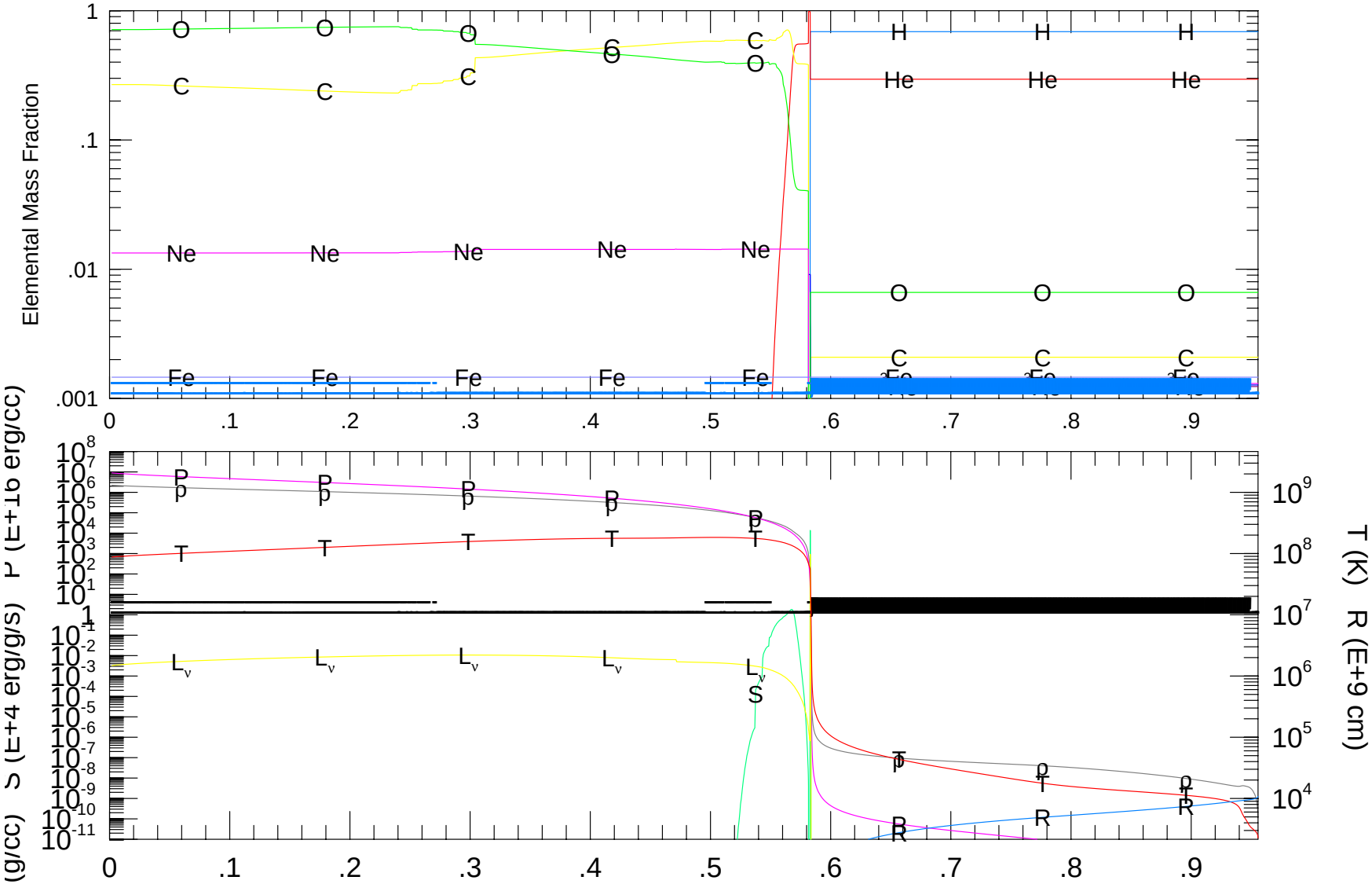
1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
He
C
O
Ne
N
Fe
H
P
ρ
T
S
L_ν
R
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{9}
T (K)
R (E+7 cm)
(g/cc)
P (E+14 erg/cc)
S (E-1 erg/g/s)

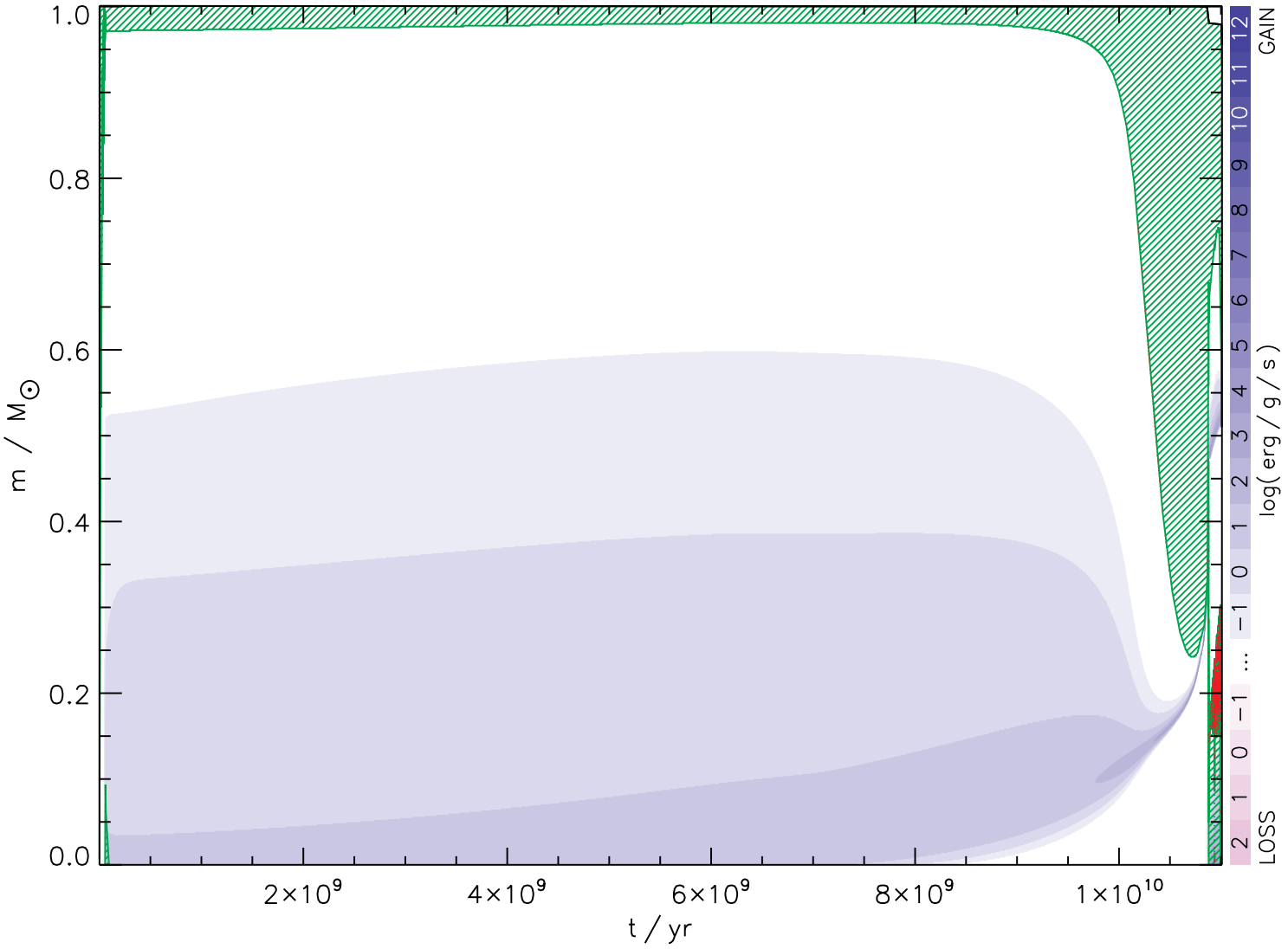
1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
O
C
Ne
Fe
H
He
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
(g/cc)
S (E+7 erg/g/s)
P (E+16 erg/cc)
T (K)
R (E+8 cm)
ρ
T
P
S
L_ν

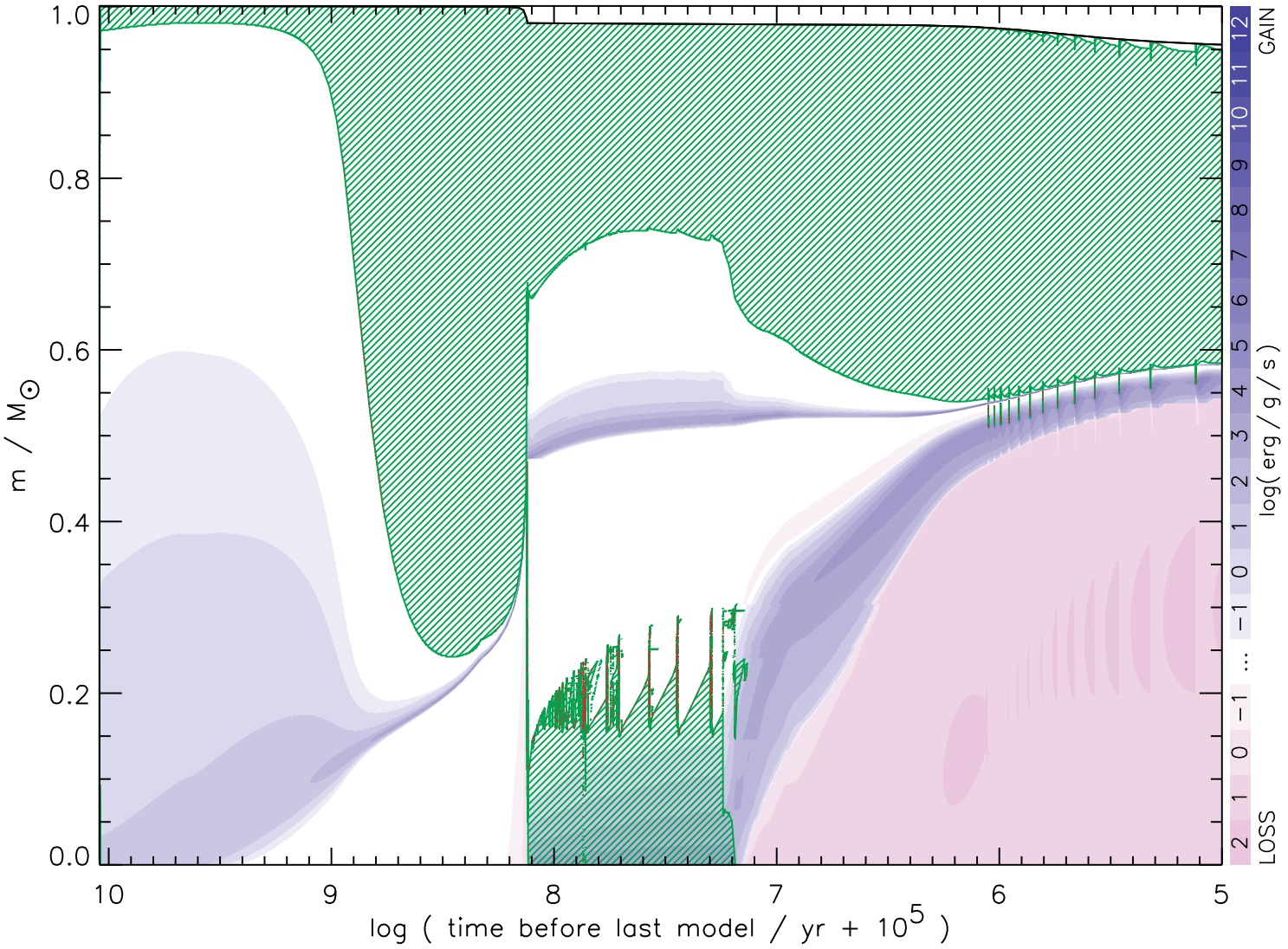
1 $M_\odot$ Star


Elemental Mass Fraction
1
.1
.01
.001
O
C
Ne
Fe
H
He
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
(g/cc) S (E+4 erg/g/s) P (E+16 erg/cc)
T (K) R (E+9 cm)
P
T
L_ν
S
ρ
R

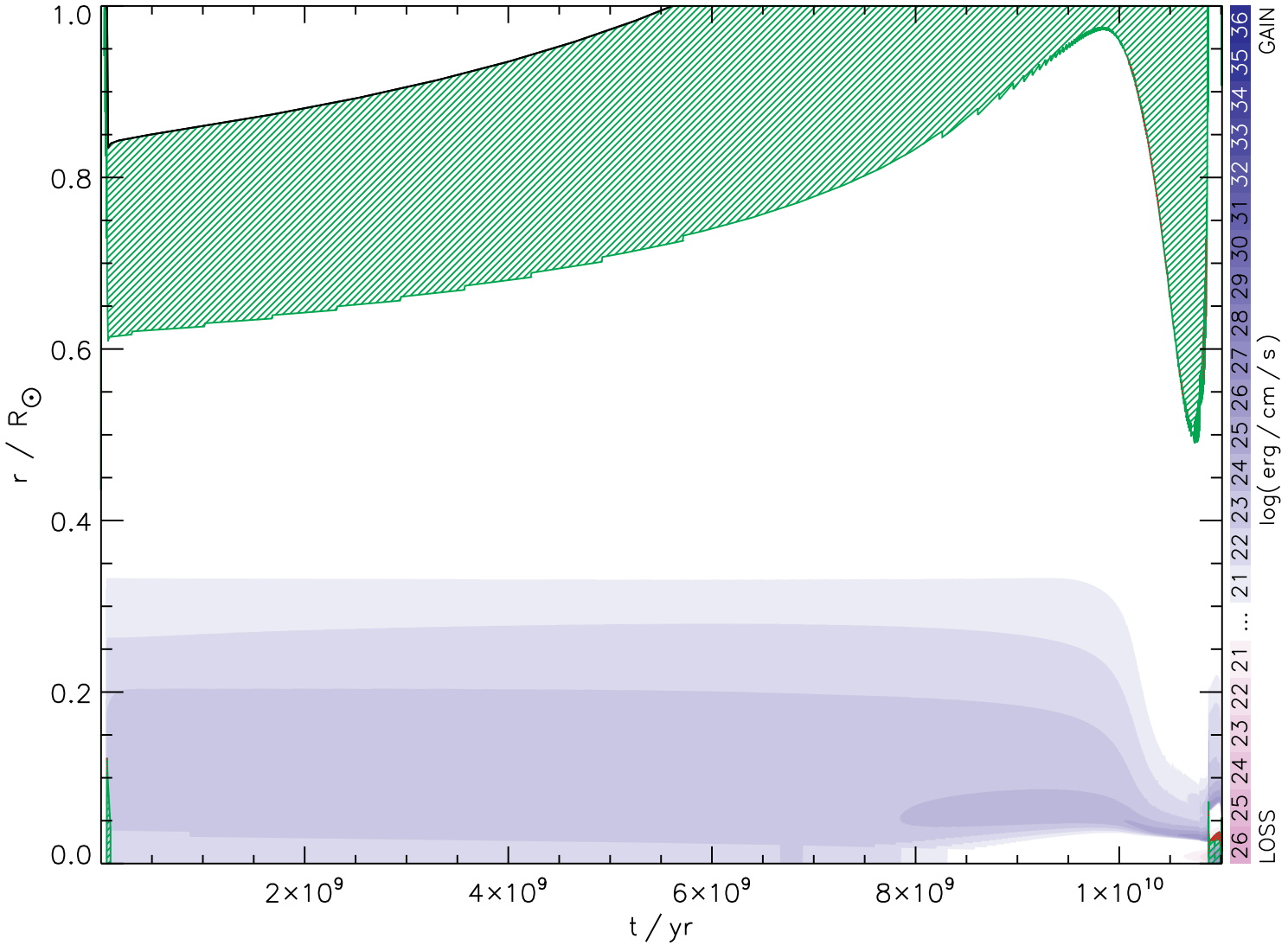
Kippenhahn Diagram, $1M_\odot$ Star



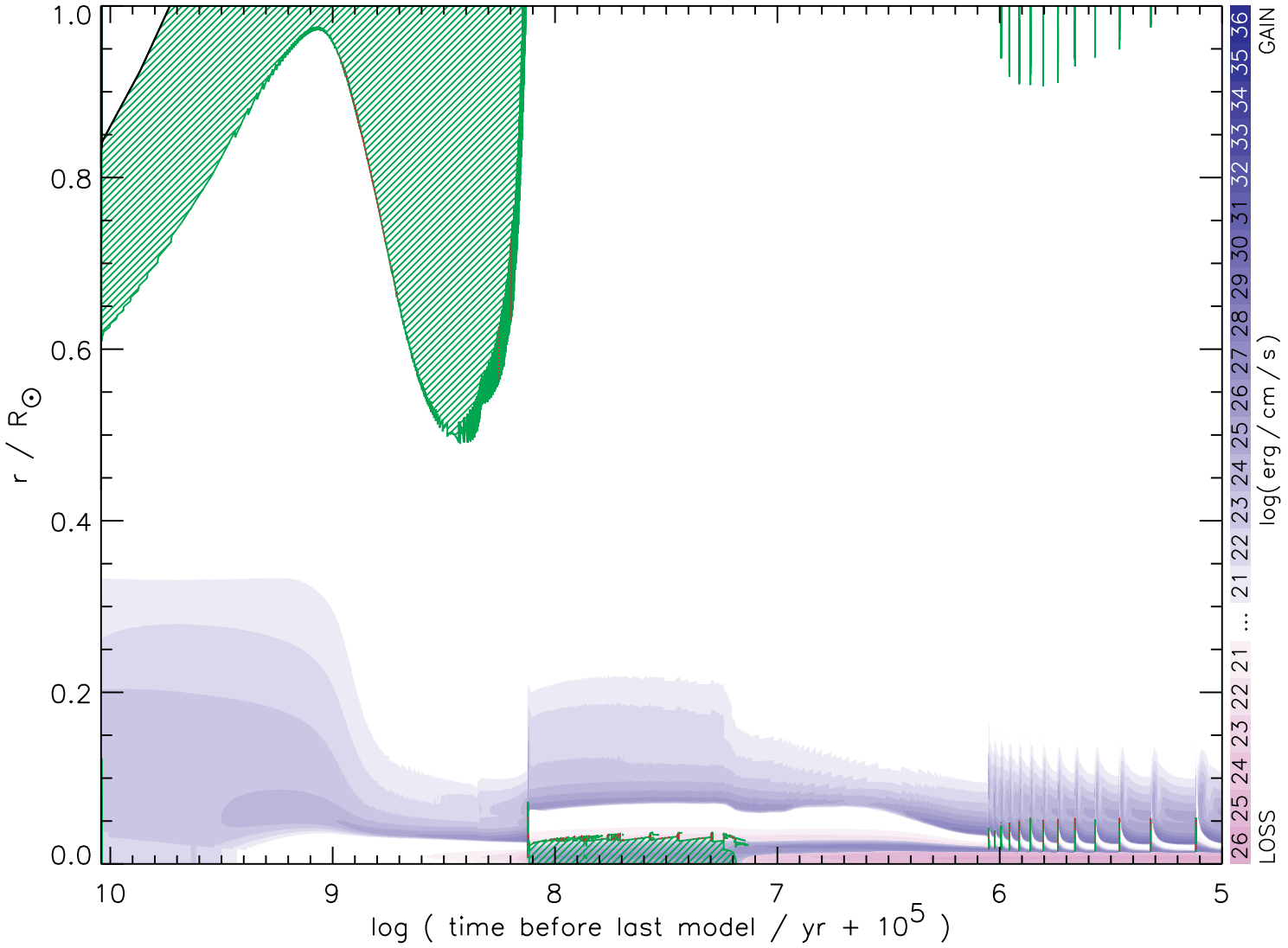
Kippenhahn Diagram, $1M_\odot$ Star



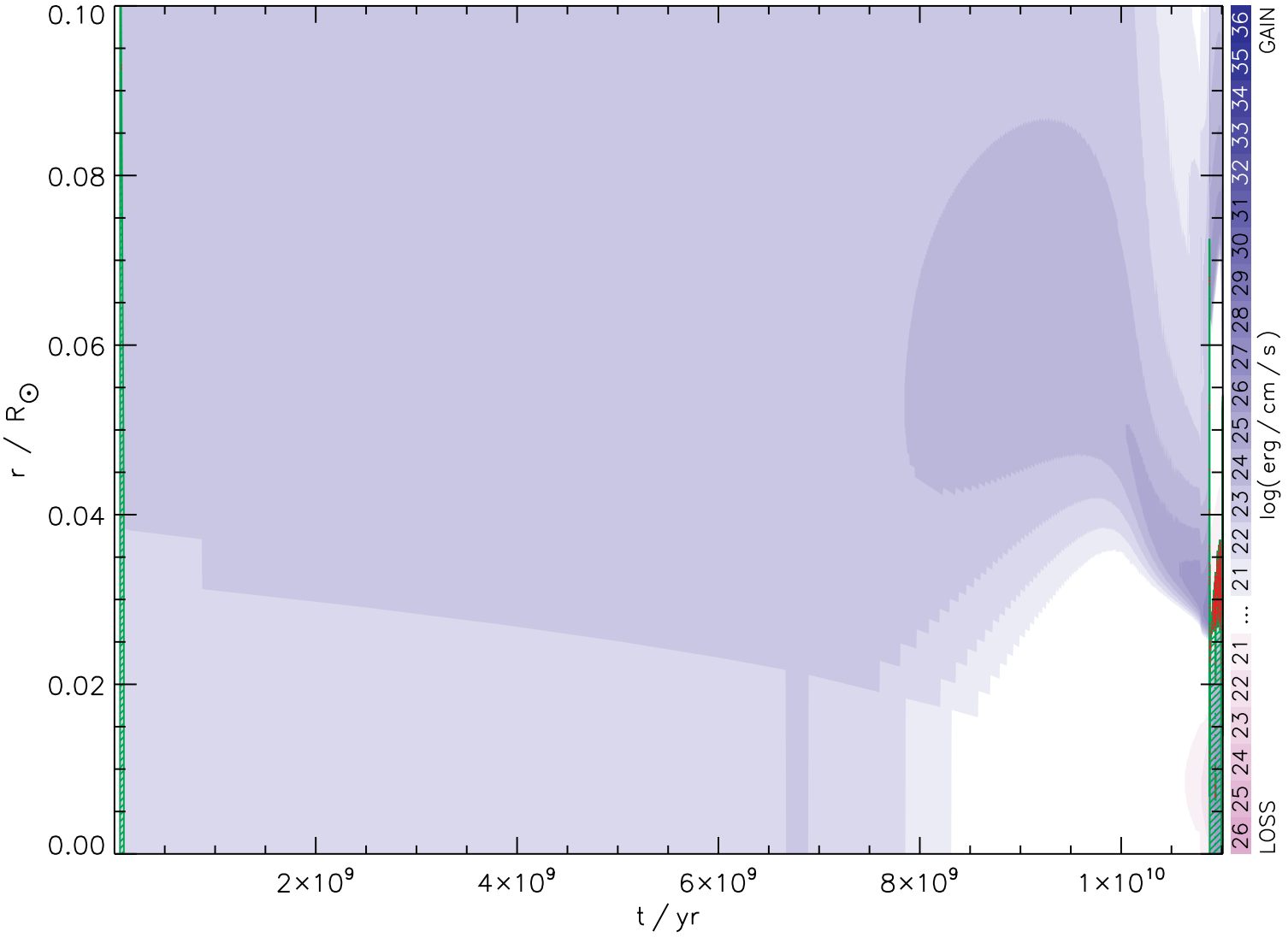
Kippenhahn Diagram, $1M_\odot$ Star



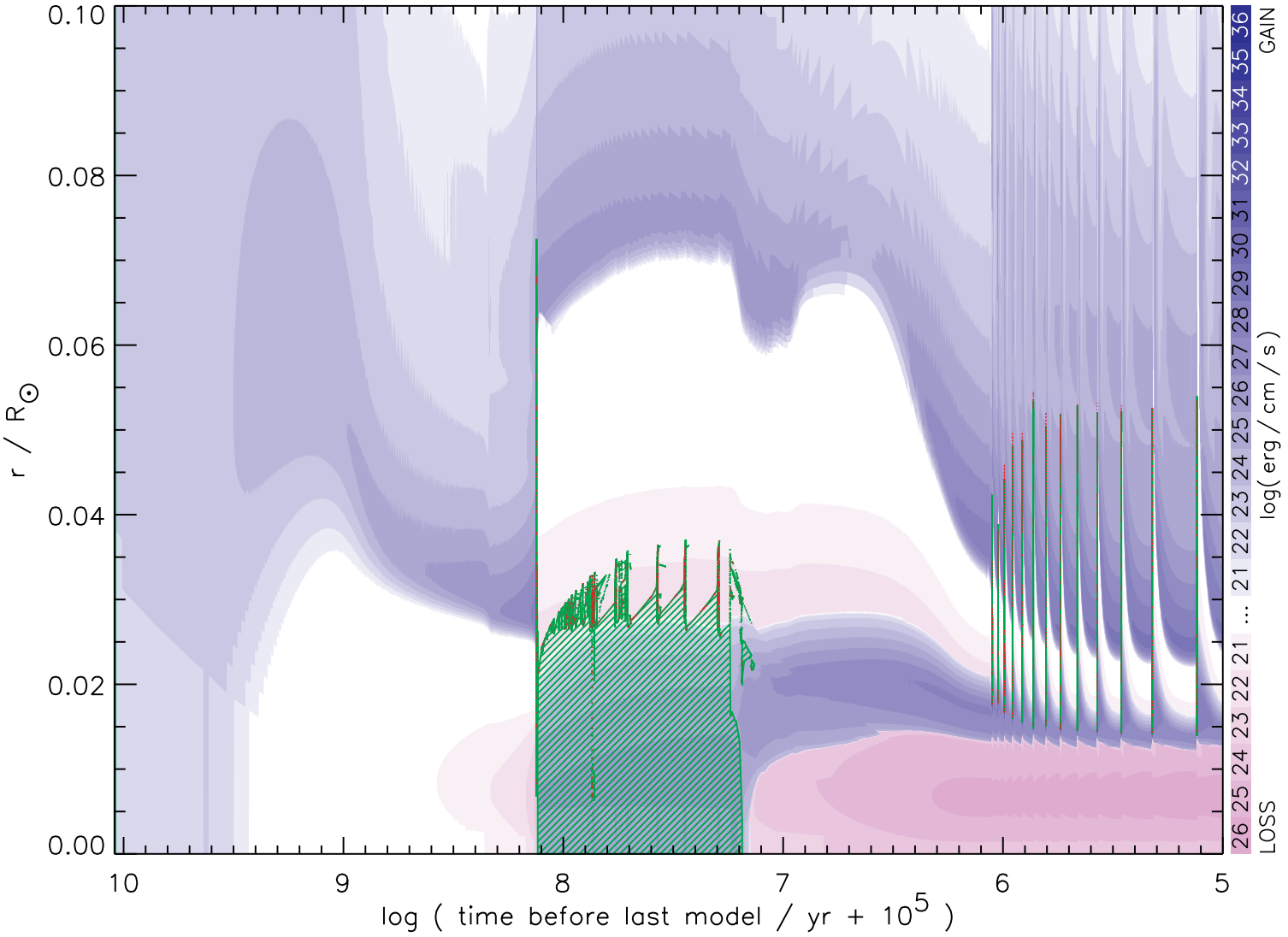
Kippenhahn Diagram, $1M_\odot$ Star



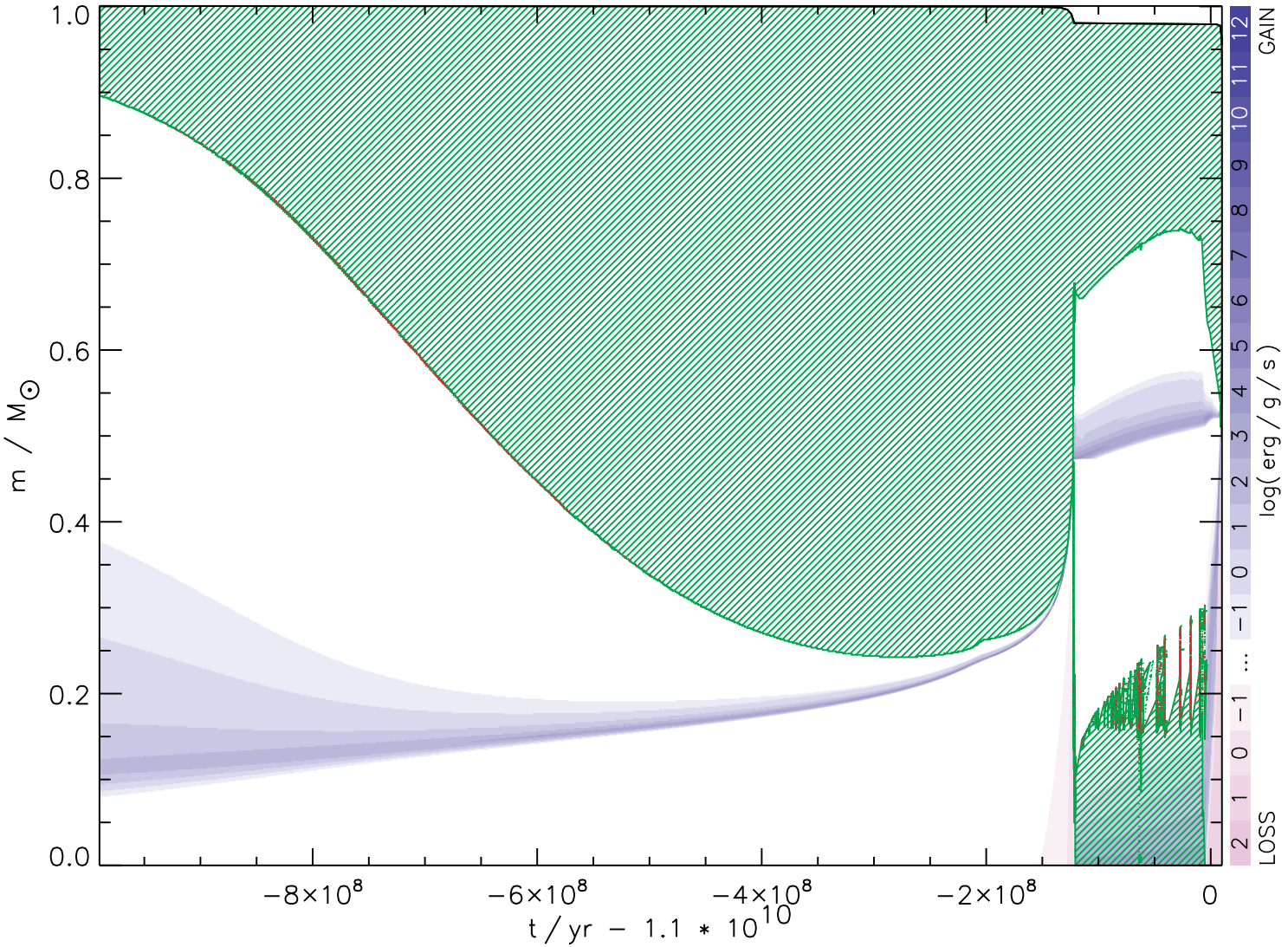
Kippenhahn Diagram, $1M_\odot$ Star



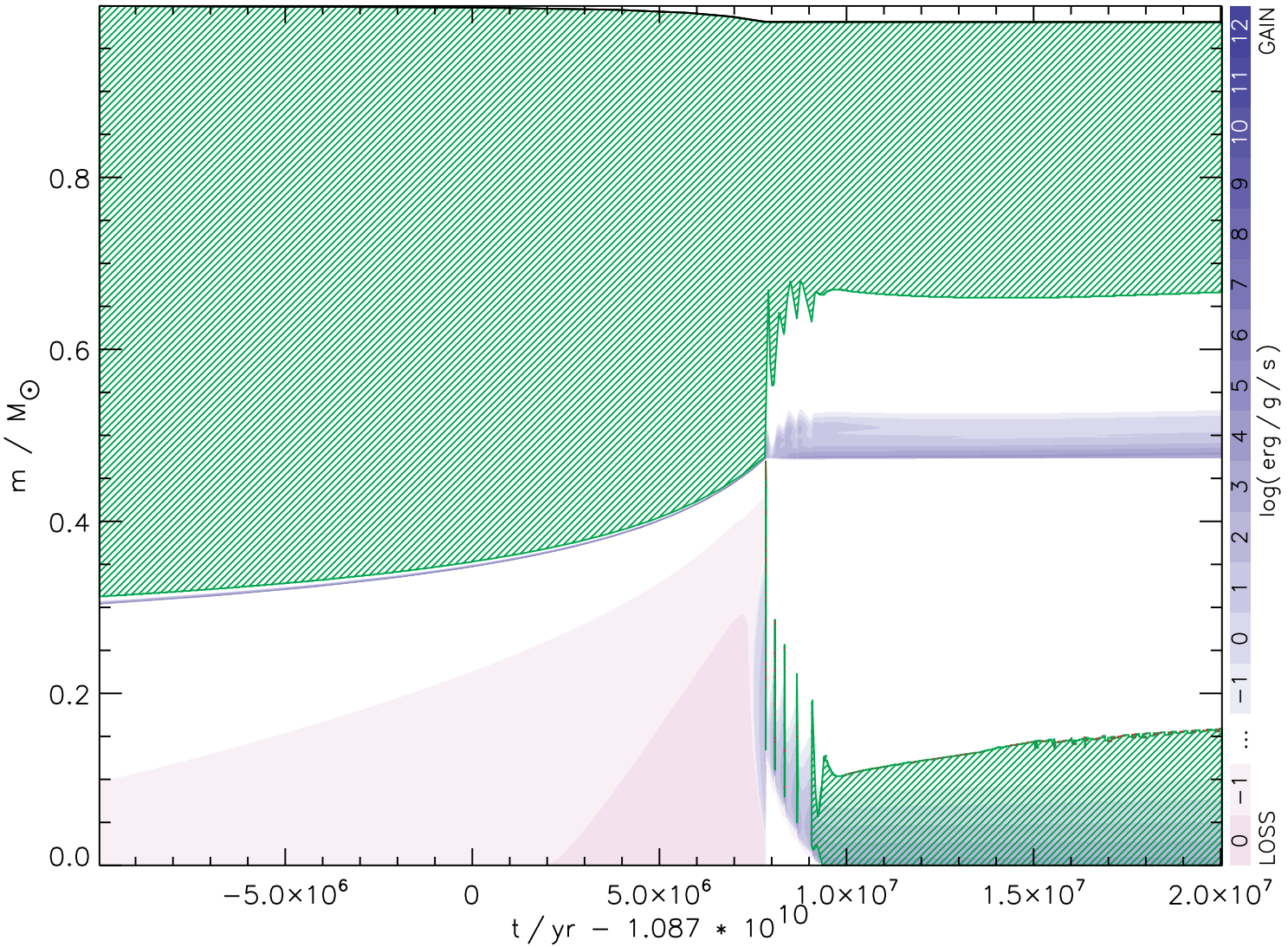
Kippenhahn Diagram, $1M_\odot$ Star



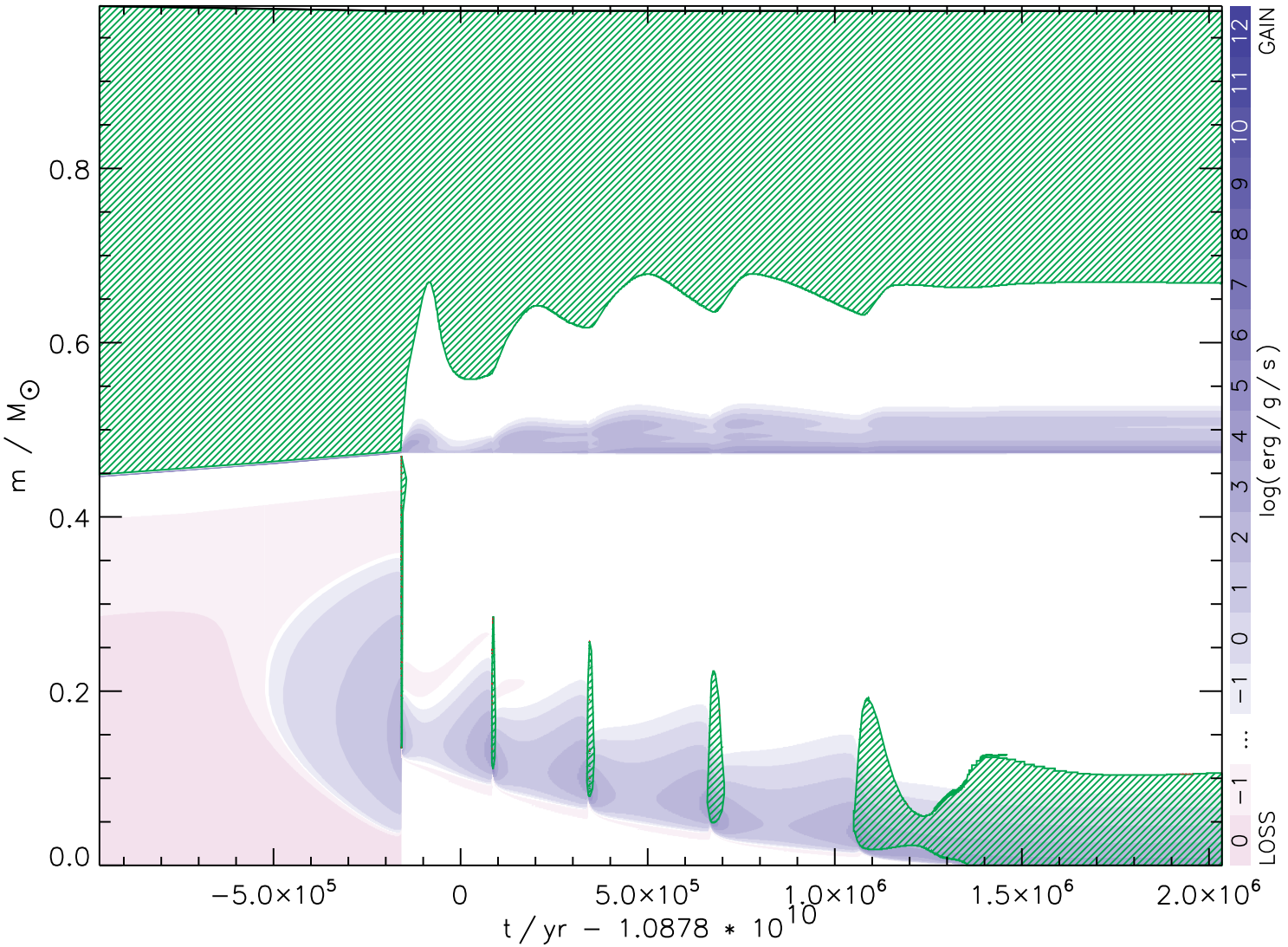
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



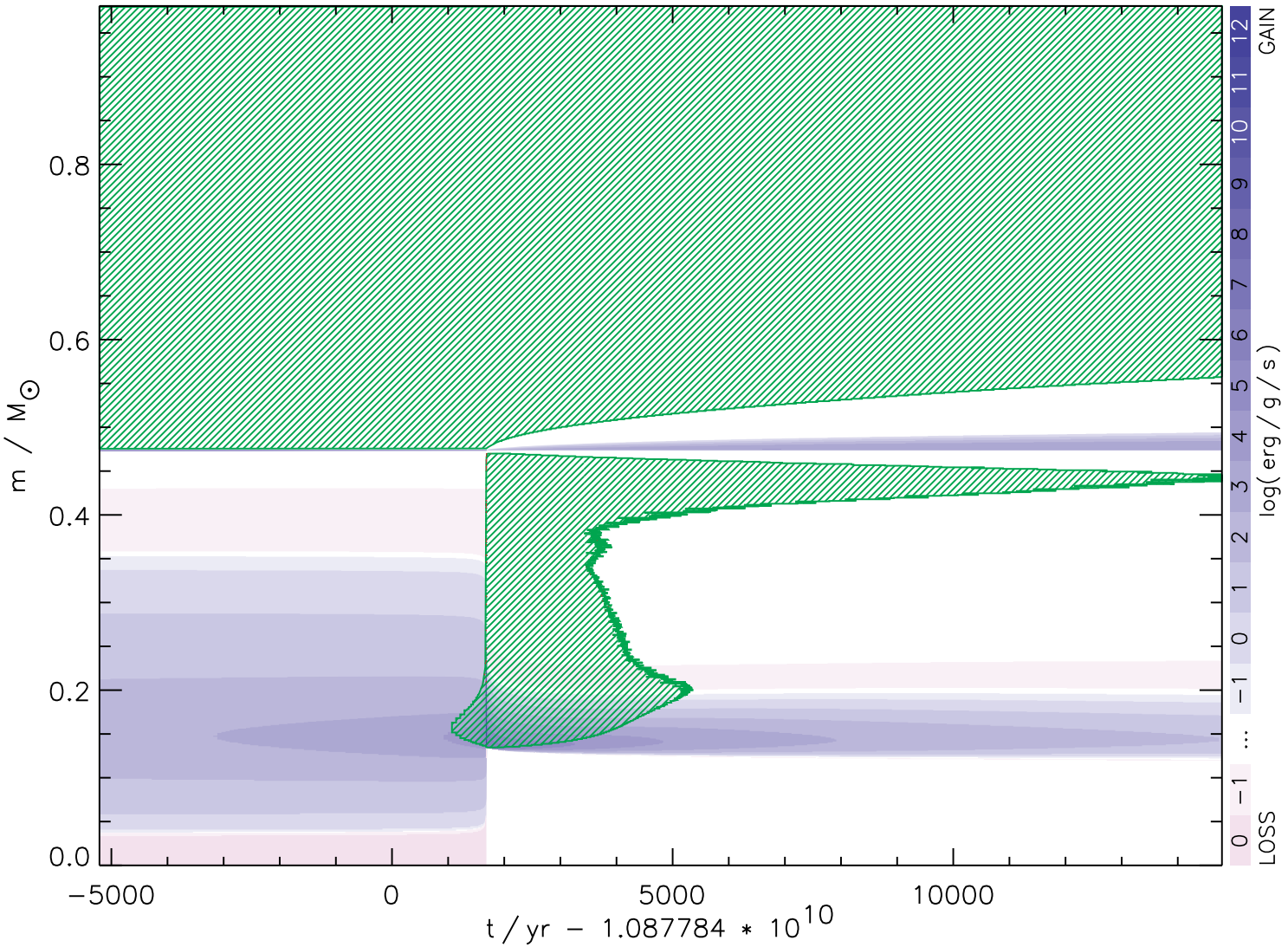
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



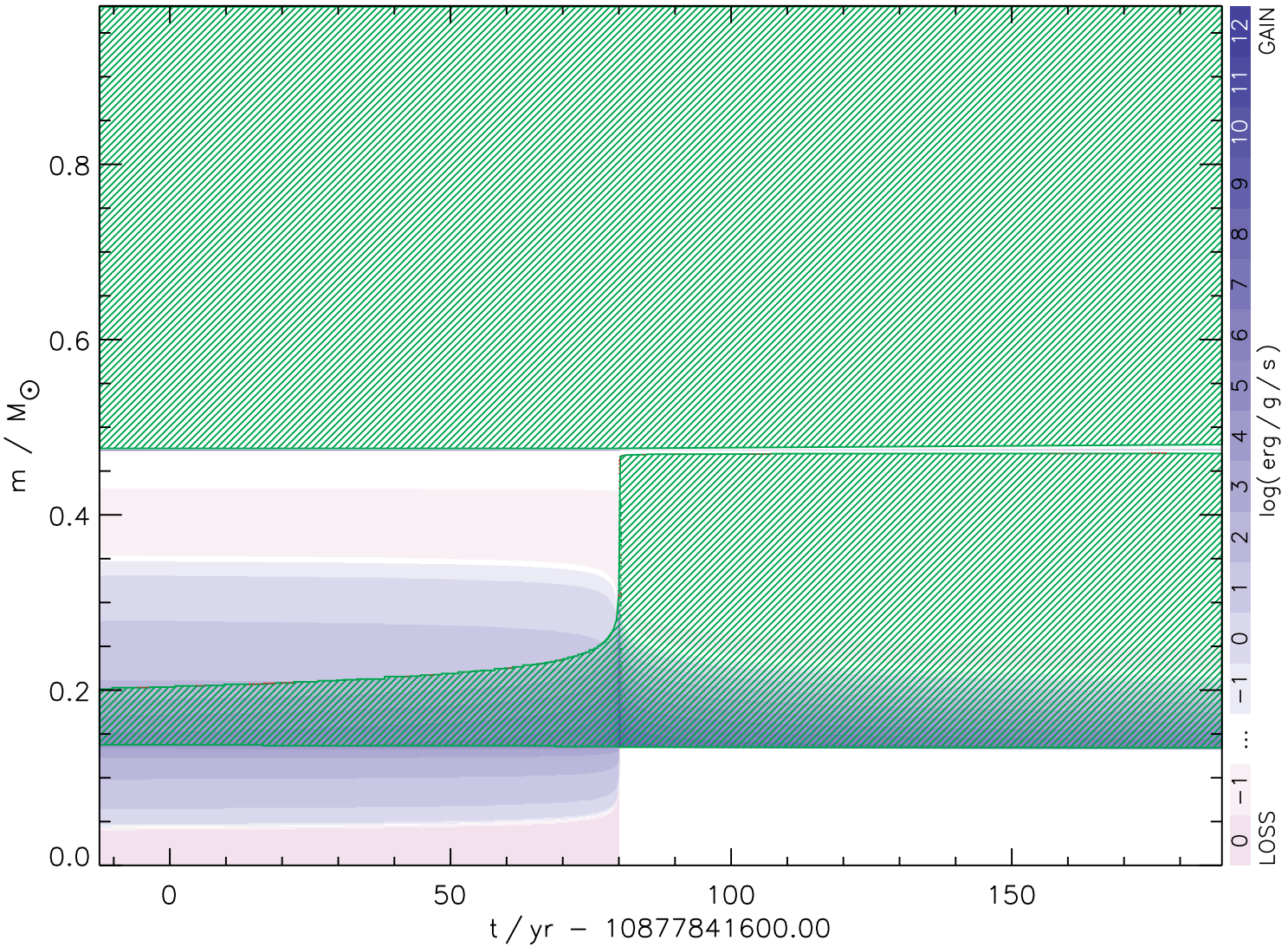
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



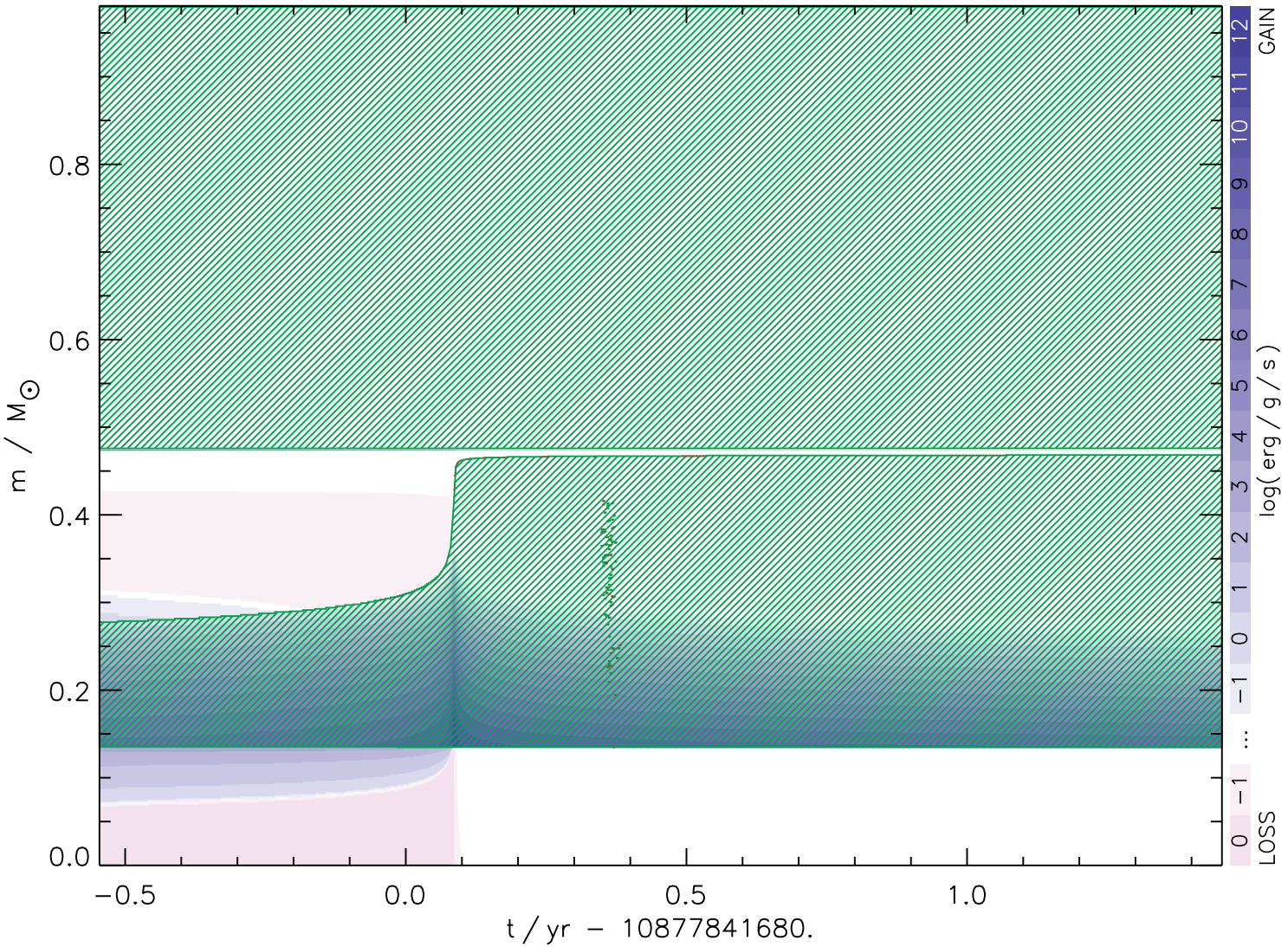
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



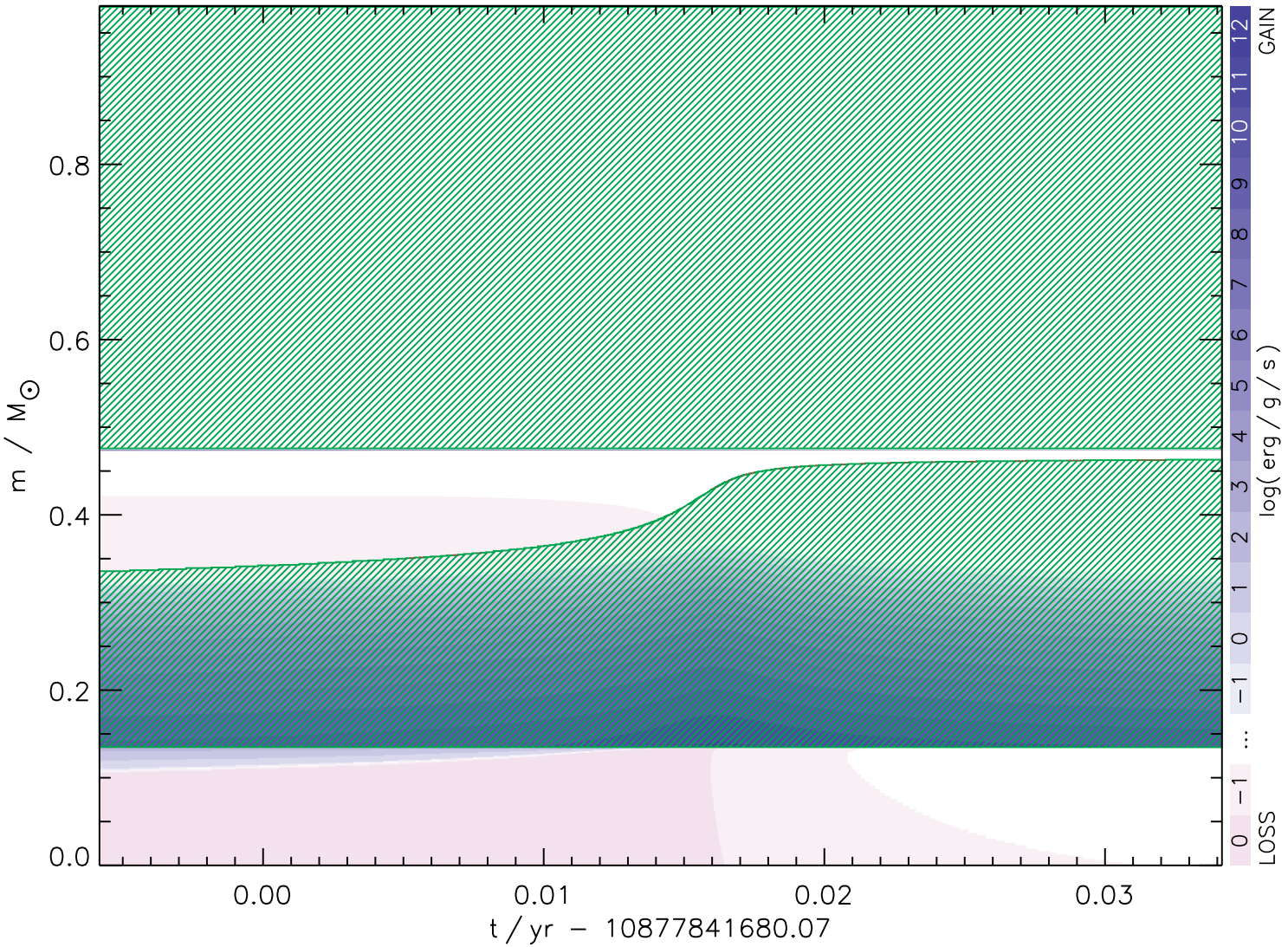
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



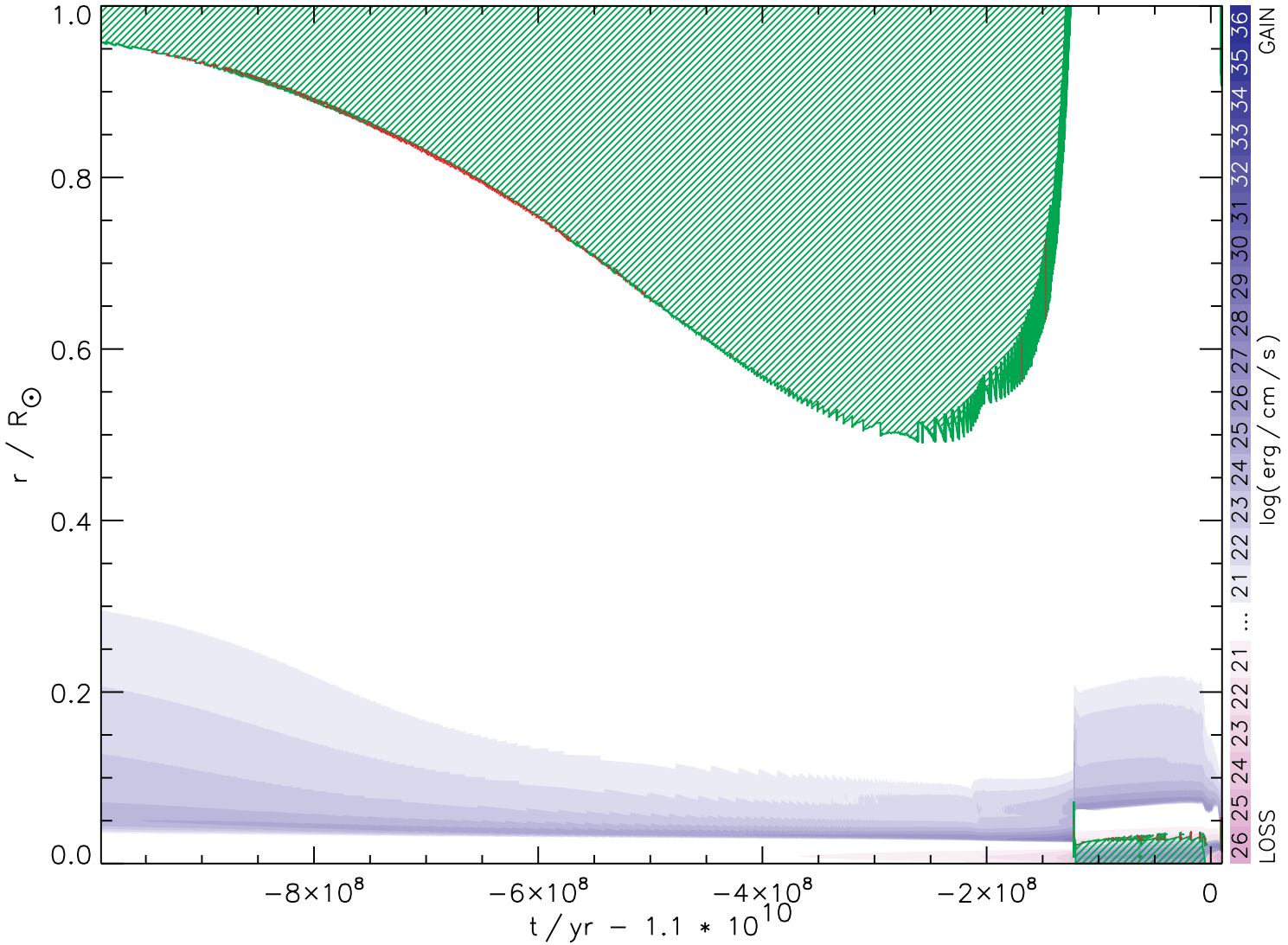
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



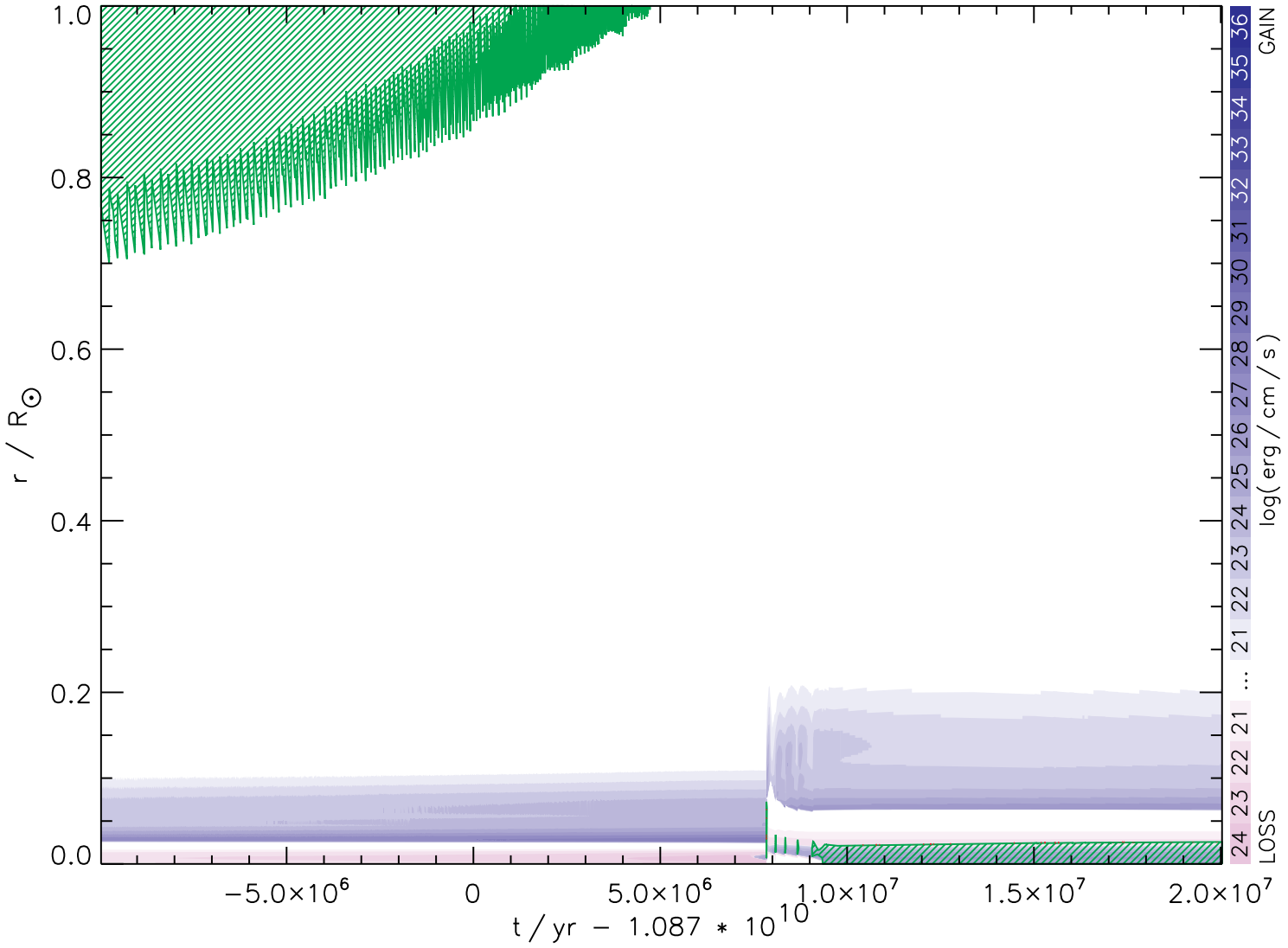
Kippenhahn Diagram, $1M_\odot$ Star, He Ignition



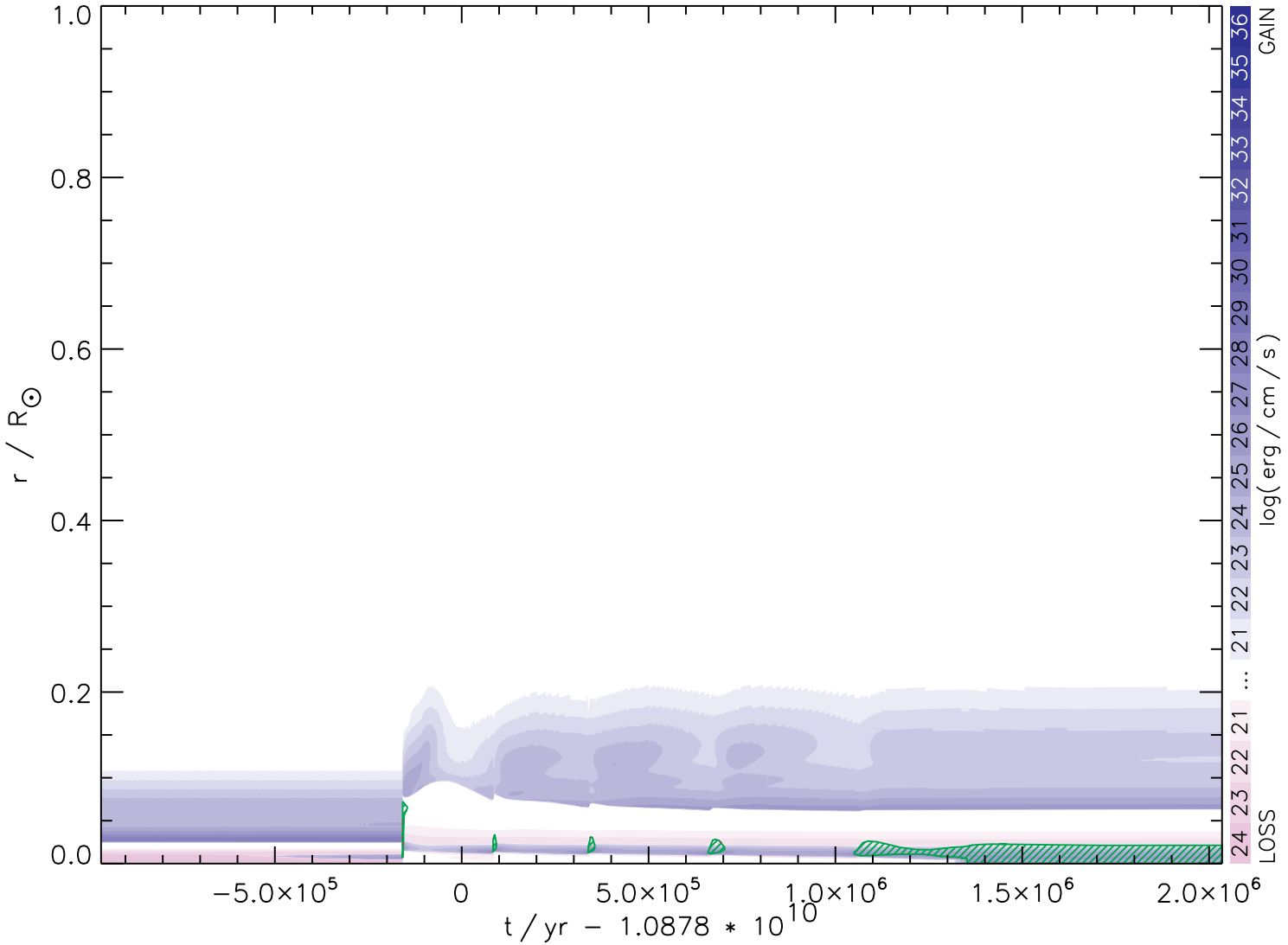
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



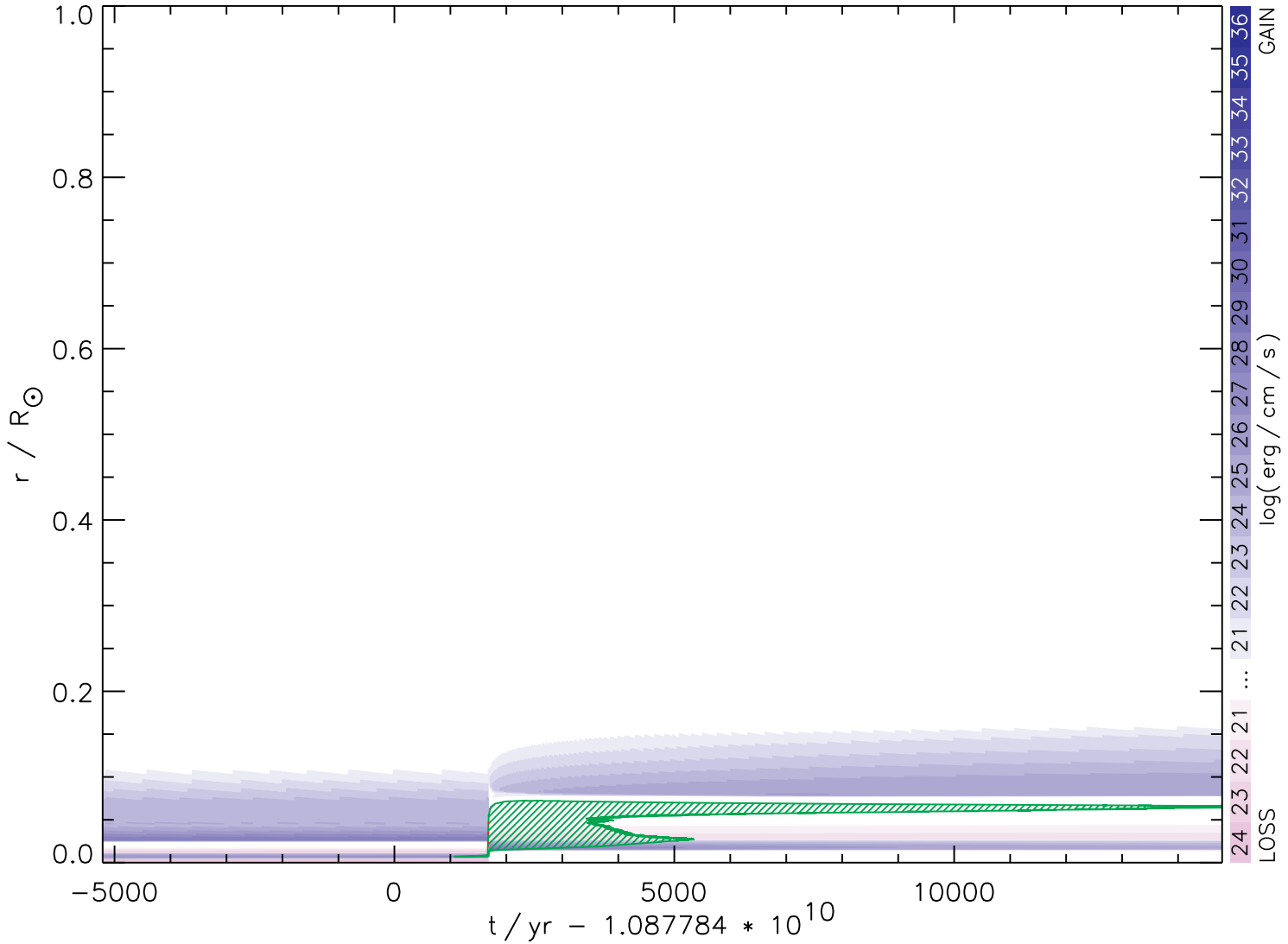
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



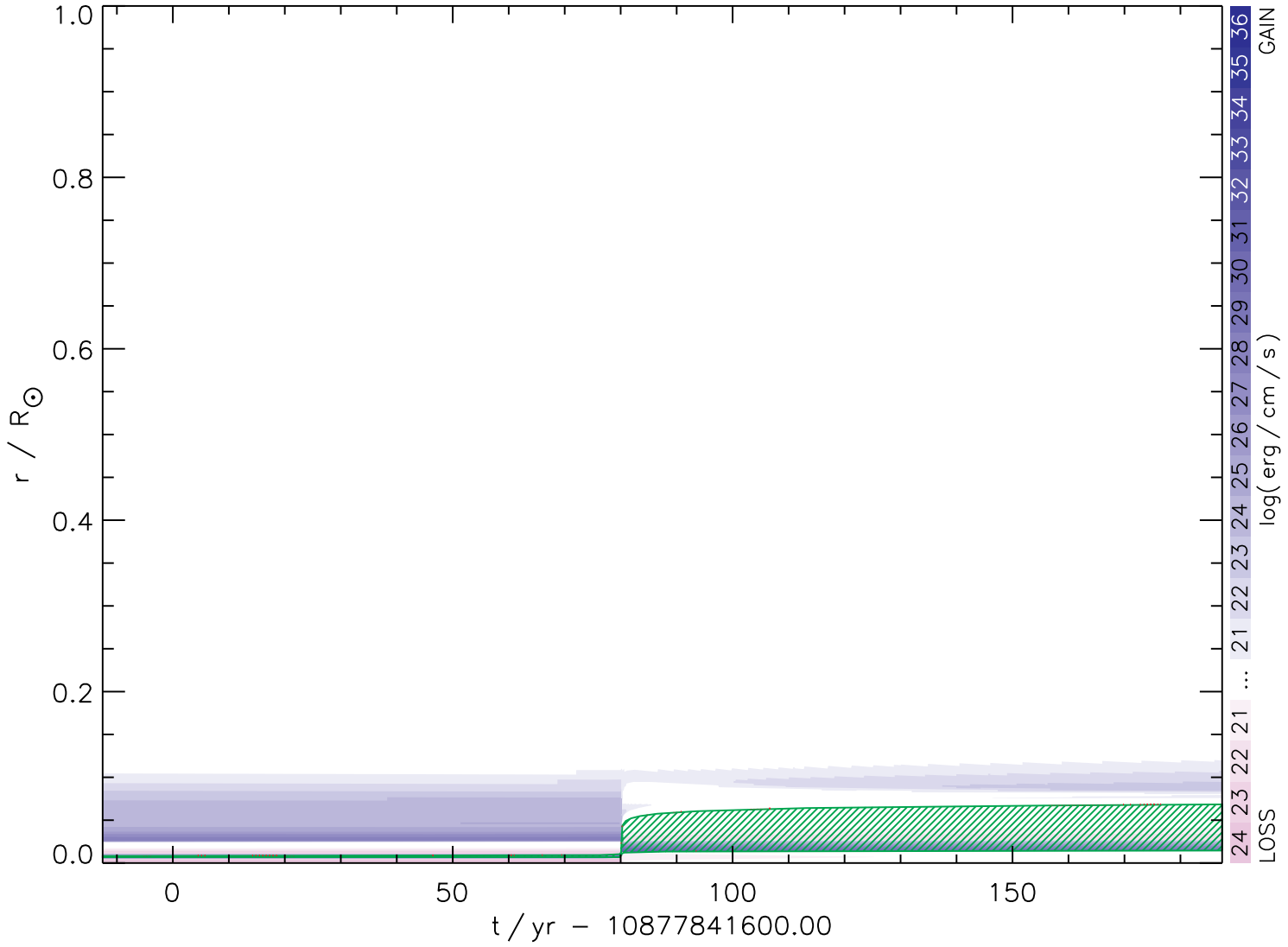
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



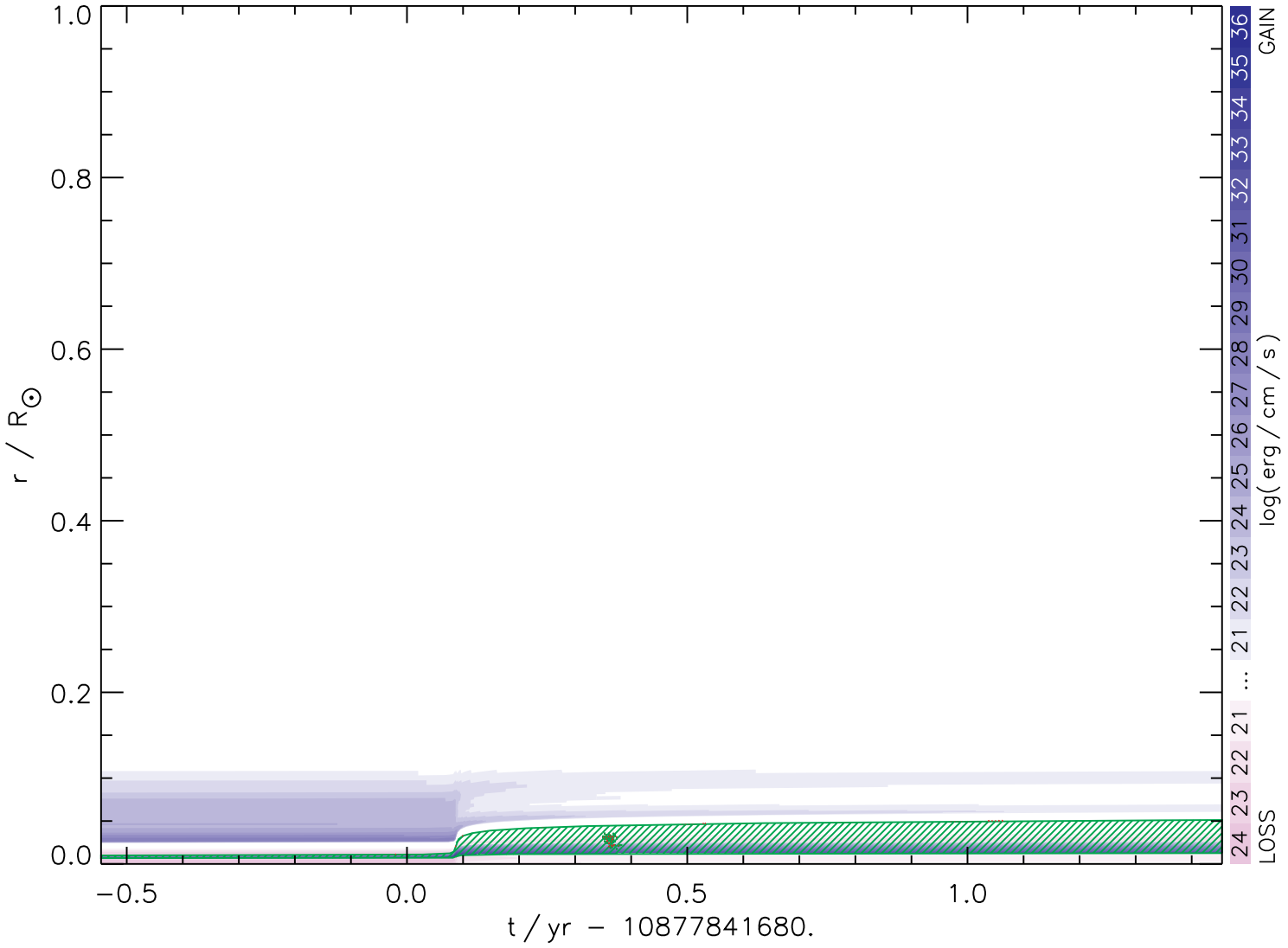
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



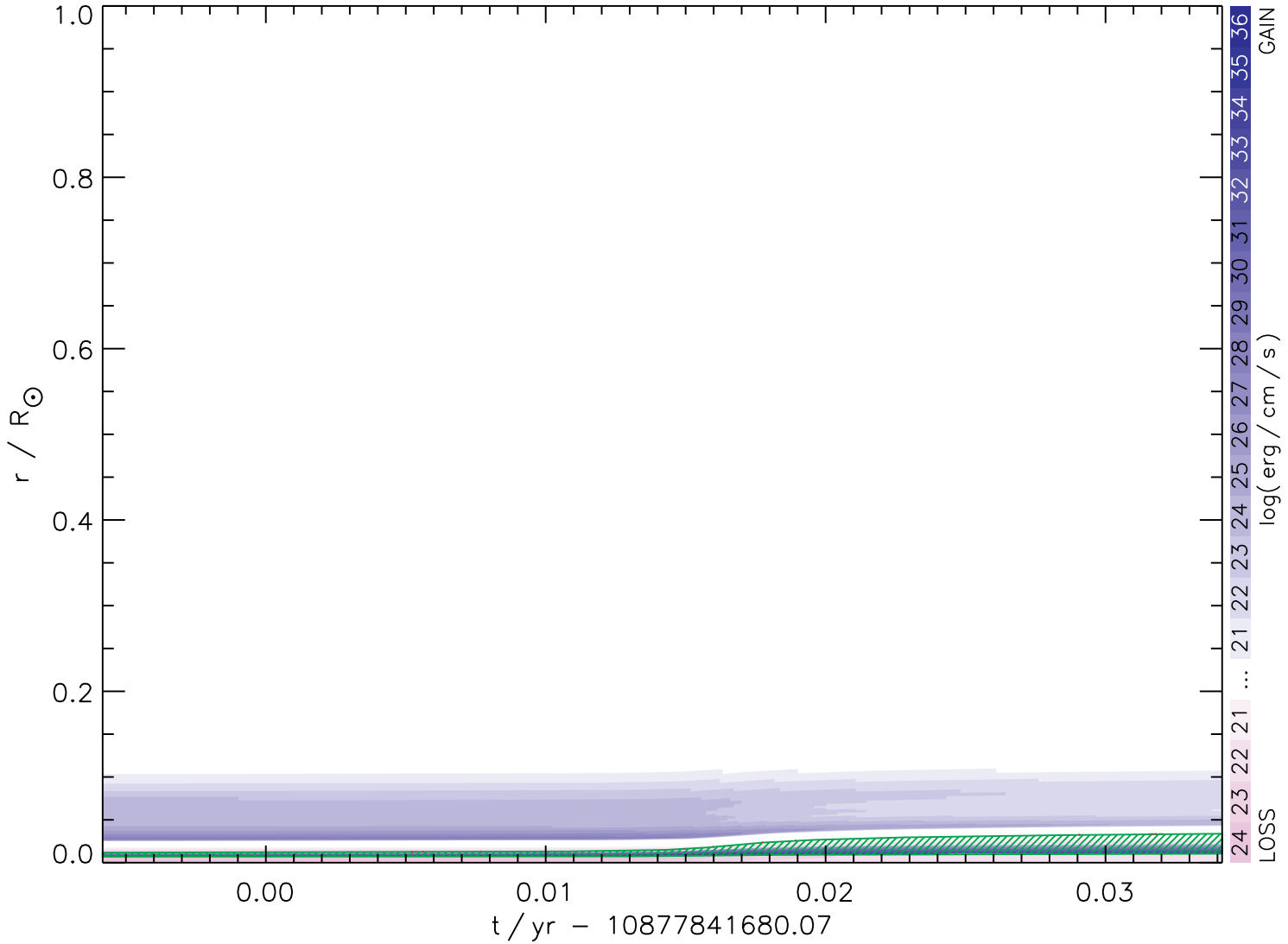
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



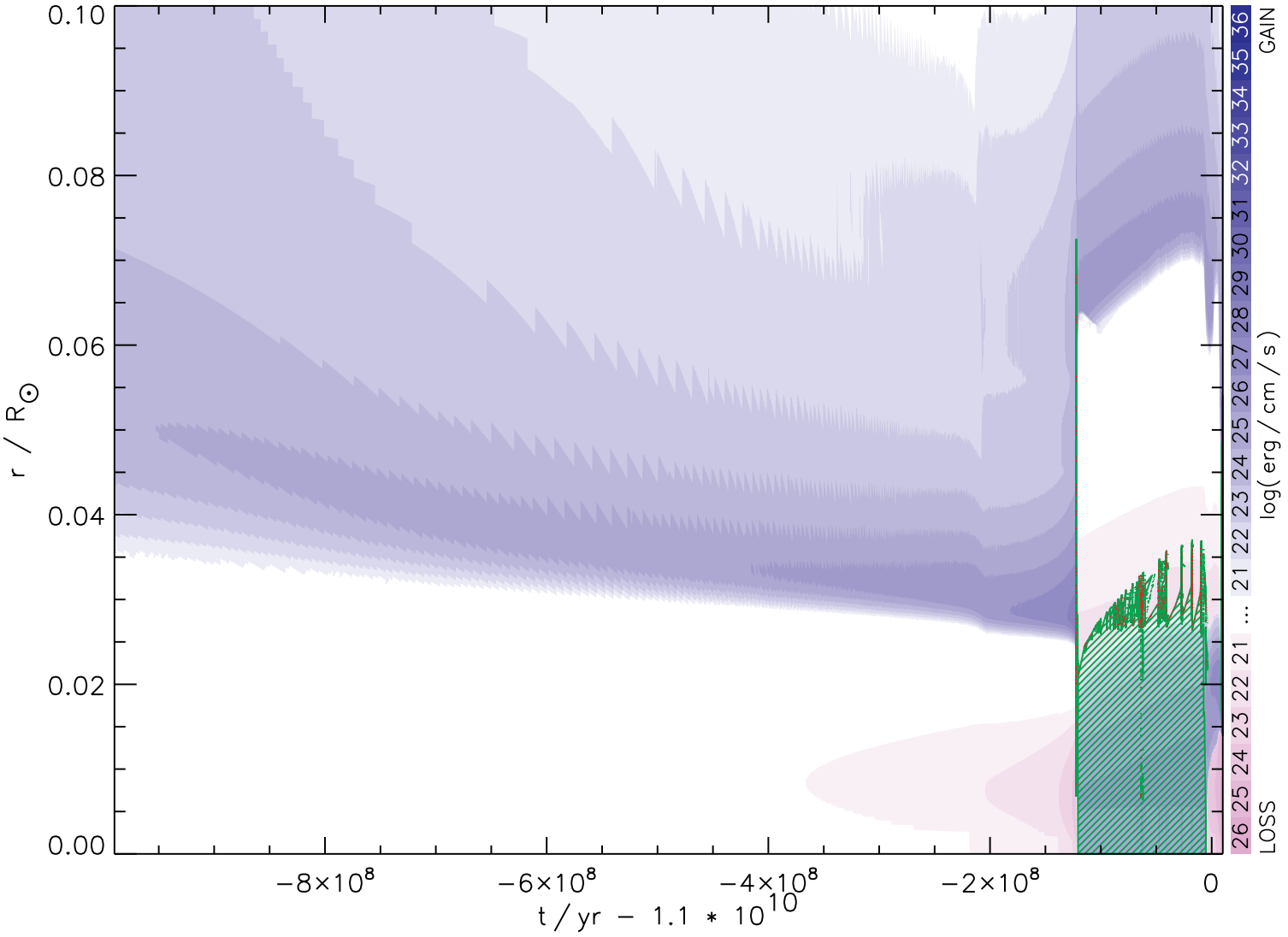
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



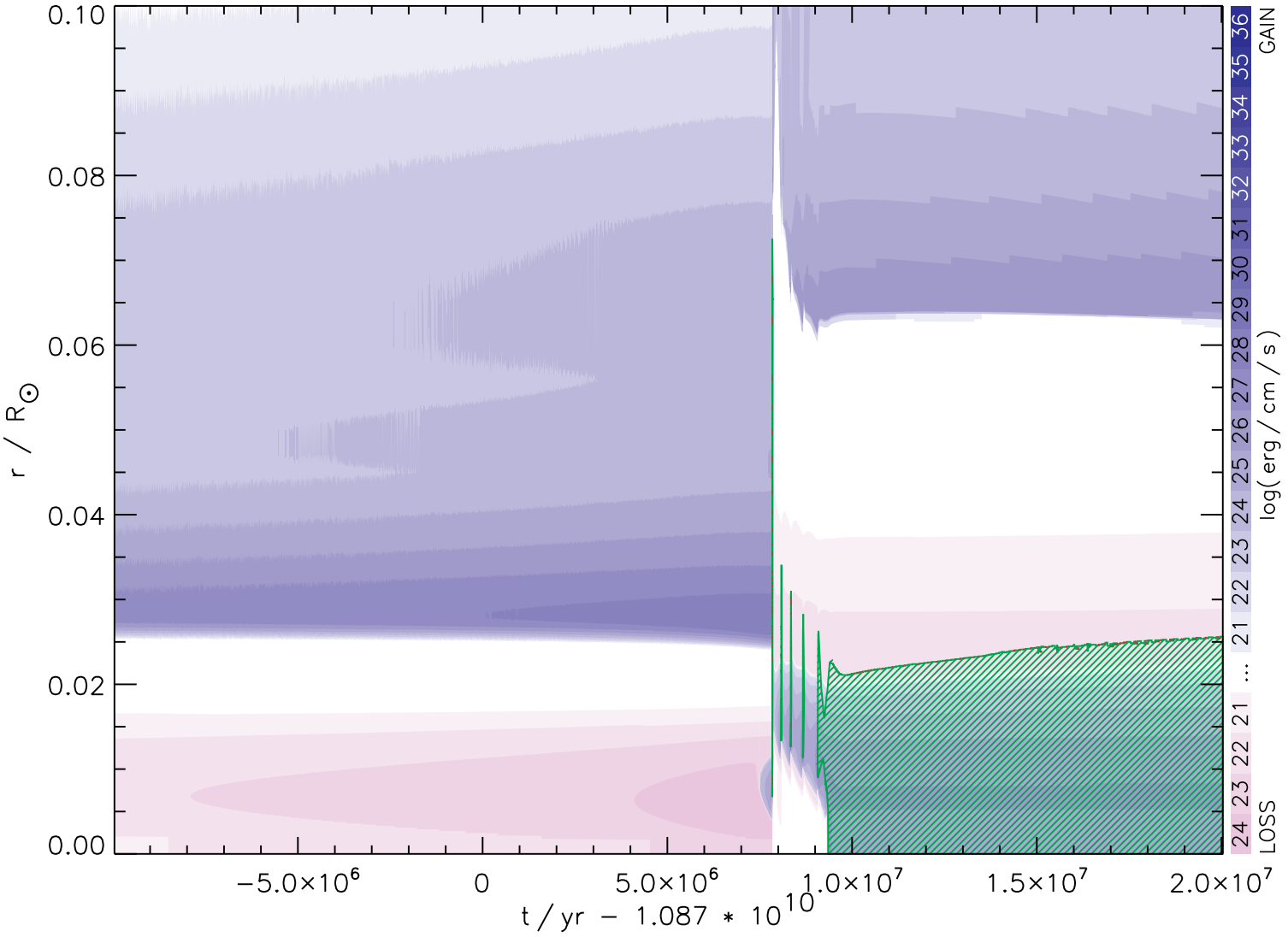
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



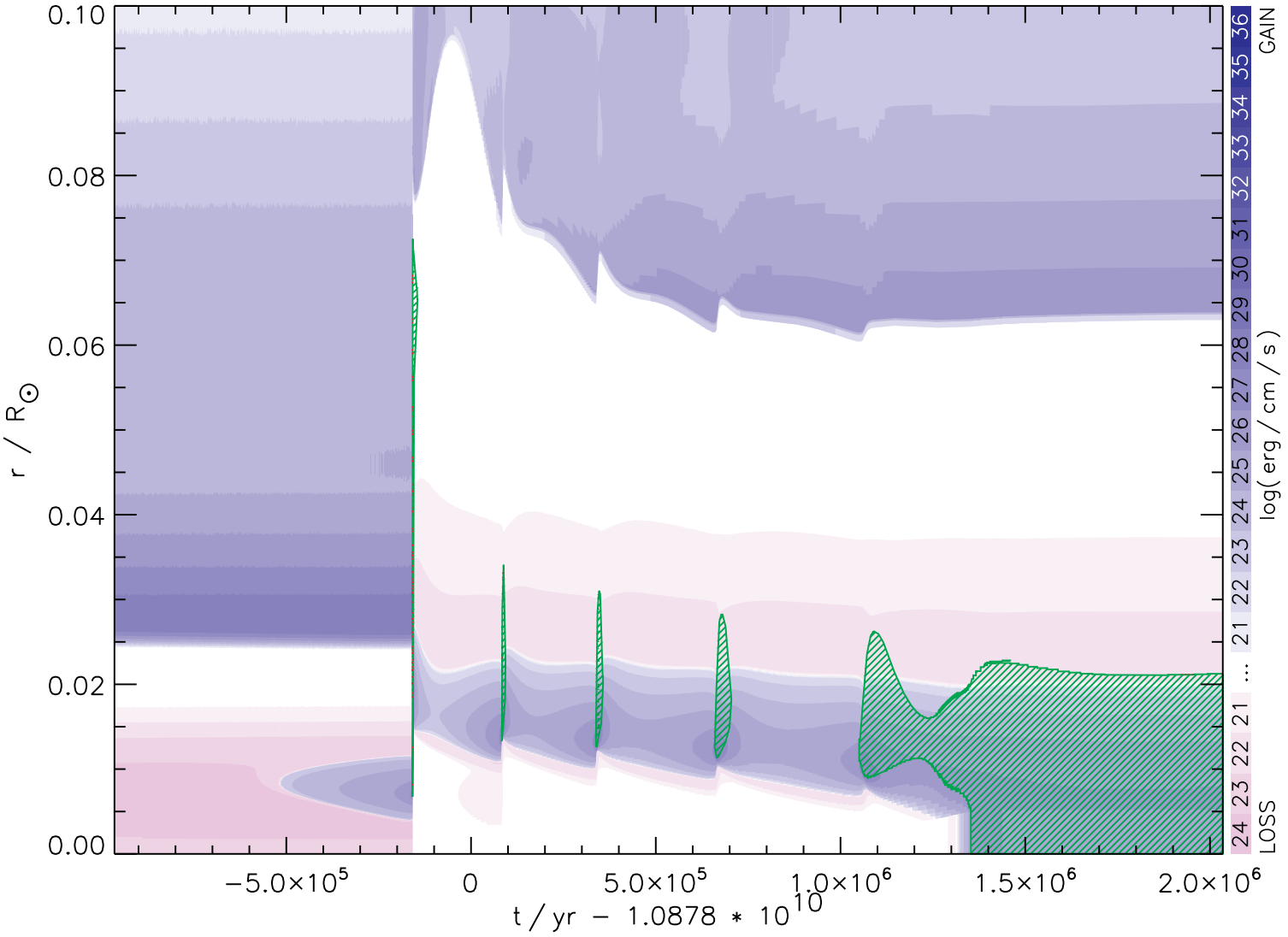
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



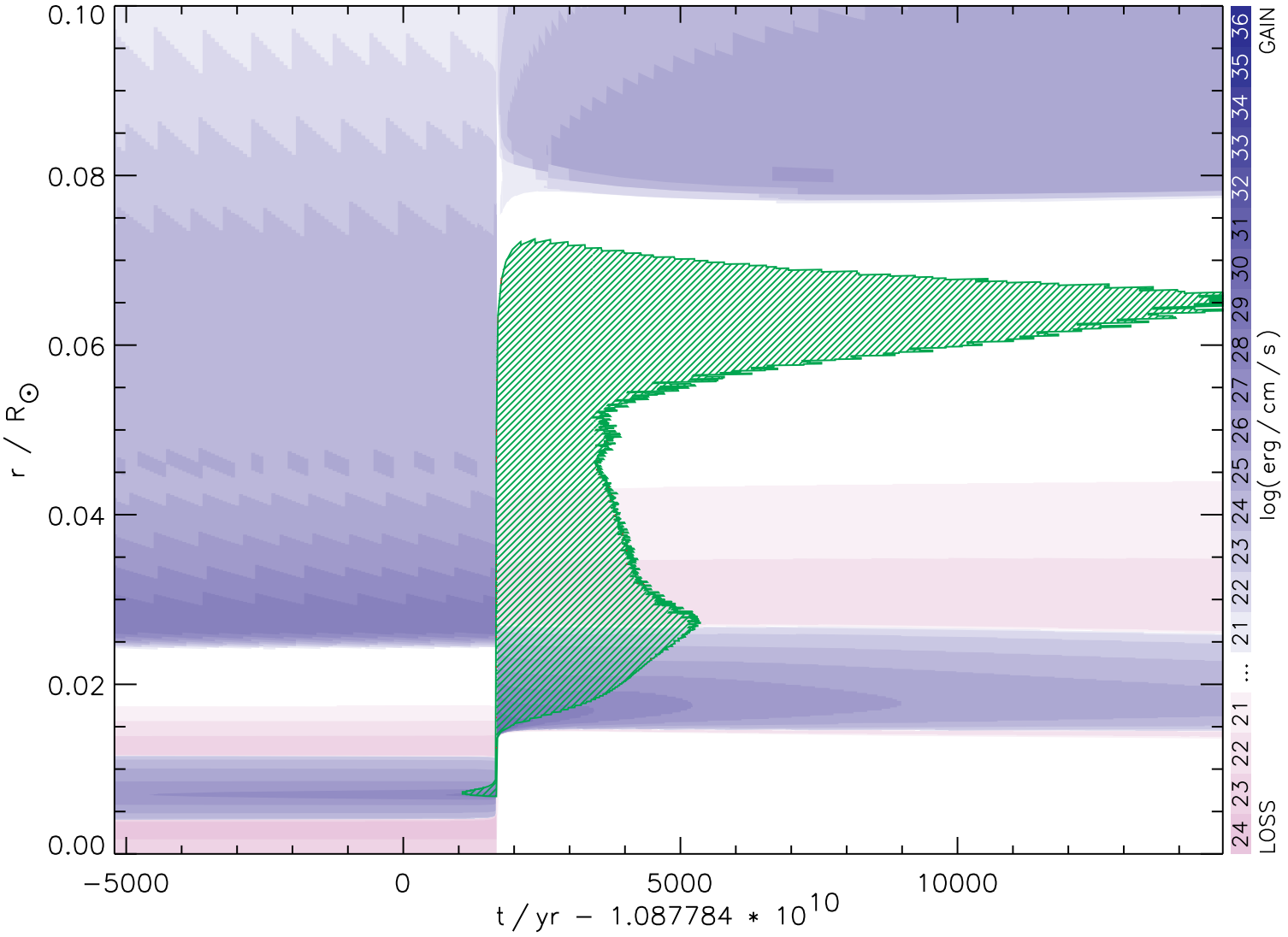
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



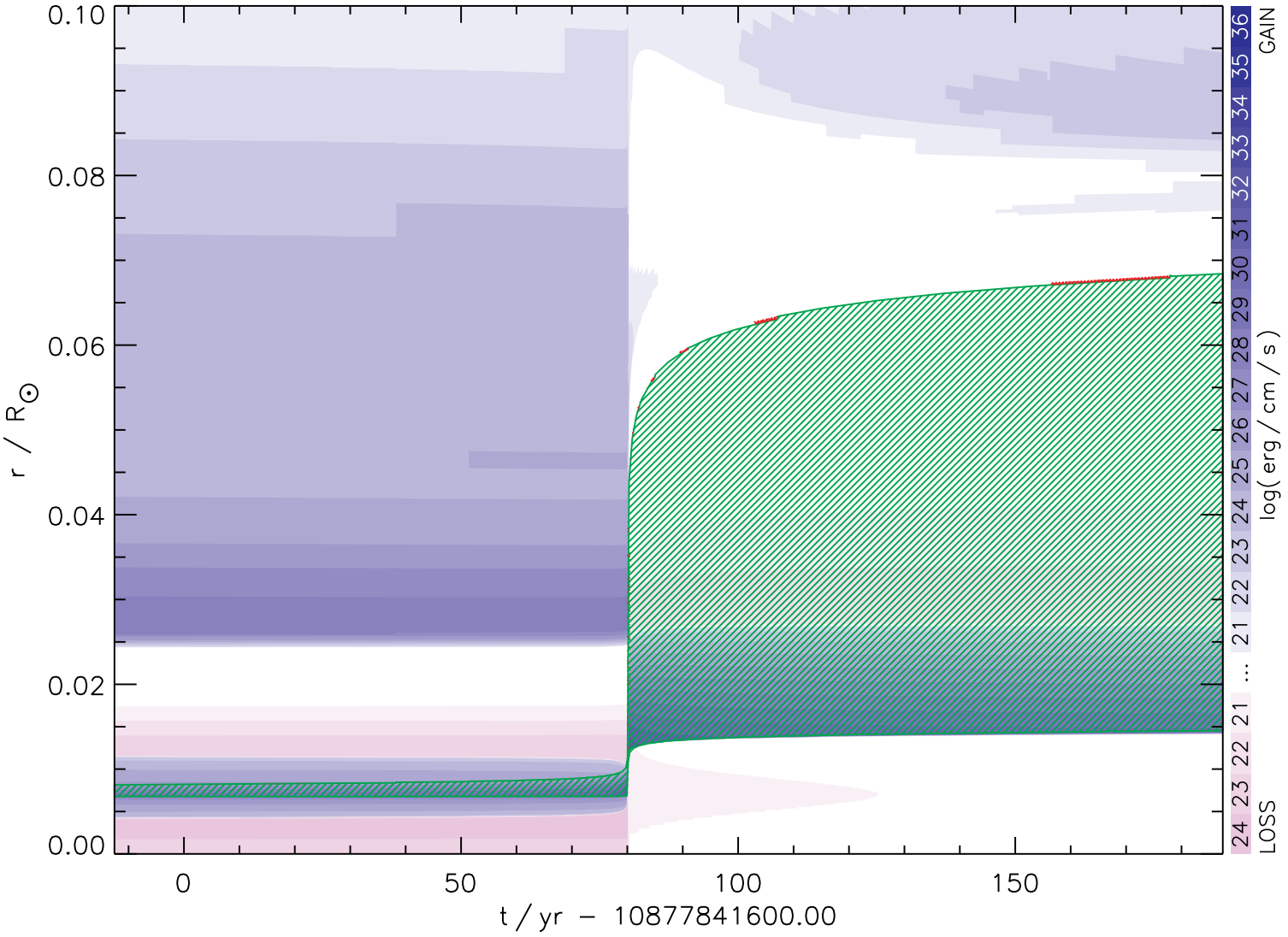
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



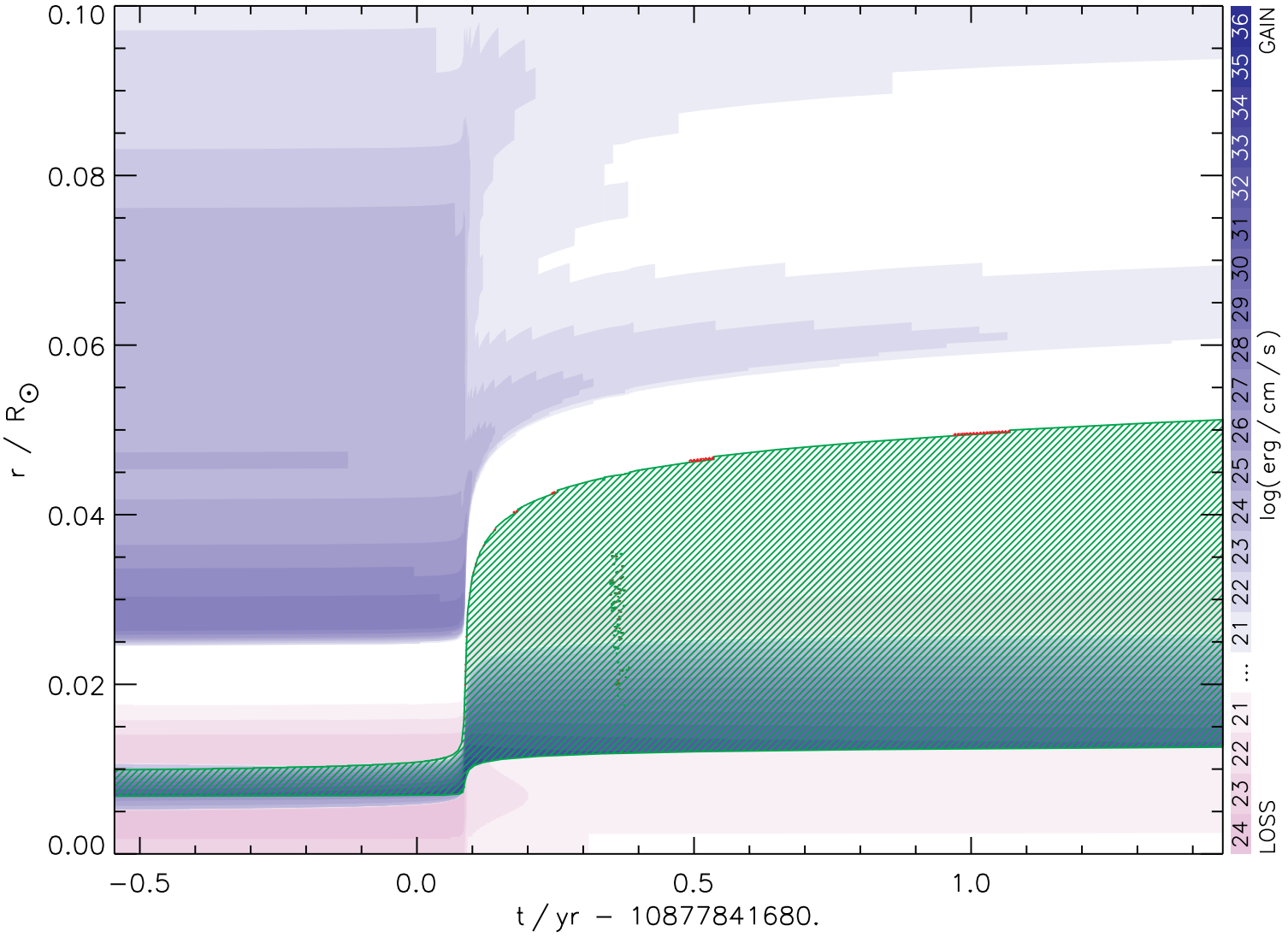
Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition



Kippenhahn Diagram, 1$M_\odot$ Star, He Ignition