Neutrinos & Origin of Elements

PHY 8850

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Neutrinos & Origin of Elements, Spring 2009

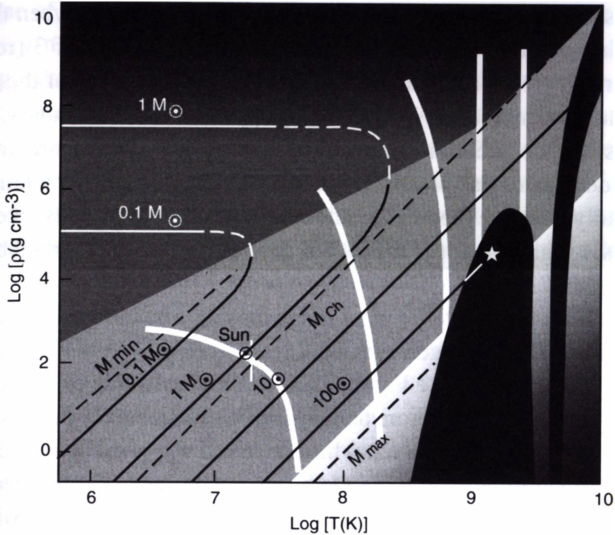
Agenda

1. Evolution of Stars
2. Evolution of Low-Mass Stars
3. supernovae

Overview

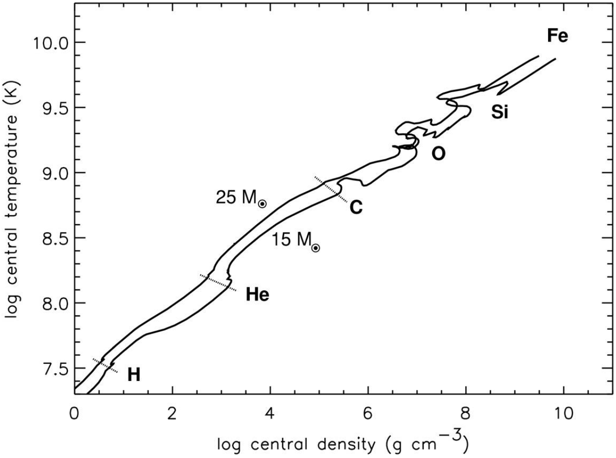
1. Evolution of Stars
2. Evolution of Low-Mass Stars
3. supernovae

Evolution Tracks



Evolution of Stars in the temperature-density diagram

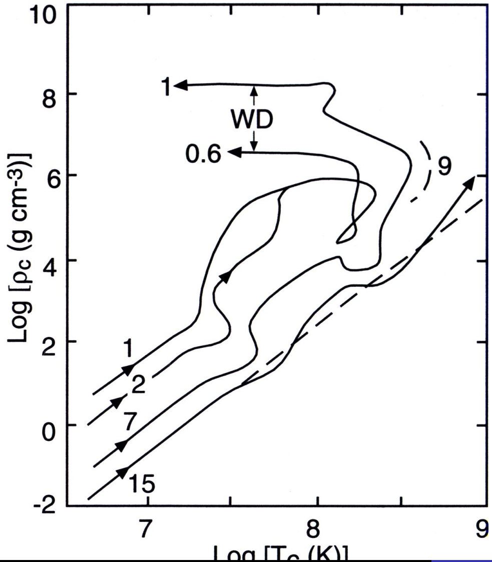
Evolution of Stars, 15 $M_\odot$ and 25 $M_\odot$



Evolution of central temperature and density for initial stellar masses of 15 $M_\odot$ and 25 $M_\odot$ in the density-temperature diagram

(note reversal of T and ρ)

Evolution of Stars, 1–15 $M_\odot$



Evolution of central temperature and density for initial stellar masses of 1 $M_\odot$ to 15 $M_\odot$ in the temperature-density diagram.

The Chandrasekhar Mass

- The limiting mass for degenerate stars is called the **Chandrasekhar Mass**

$$M_{\mathrm{Ch}} = \frac{M_3}{4\pi}\left(\frac{3}{2}\right)^{1/2}\left(\frac{hc}{Gu^{4/3}}\right)^{3/2}{\mu_{\mathrm{e}}}^{-2} = (5.836\,\mathrm{M}_\odot){\mu_{\mathrm{e}}}^{-2}$$

$$M_{\mathrm{Ch}} = 1.459\,\mathrm{M}_\odot\left(\frac{\mu_{\mathrm{e}}}{2}\right)^{-2}$$

  (Nobel Prize in Physics 1983)
- for an iron core with $\mu_{\mathrm{e}} = 2.15$ we obtain $M_{\mathrm{Ch}} = 1.26\,\mathrm{M}_\odot$
- for "hot" cores of massive stars partially degenerate relativistic equation of state has to be used
  $\Rightarrow M_{\mathrm{crit}} > M_{\mathrm{Ch}}$

$$M_{\mathrm{crit}} \approx M_{\mathrm{Ch}}\left[1 + \frac{\pi^2 k^2 T^2}{{\epsilon_{\mathrm{F}}}^2}\right], \quad \epsilon_{\mathrm{F}} = 1.11\left(\frac{\rho}{10^7\,\mathrm{g\,cm}^{-3}}Y_{\mathrm{e}}\right)^{1/3}\mathrm{MeV}$$

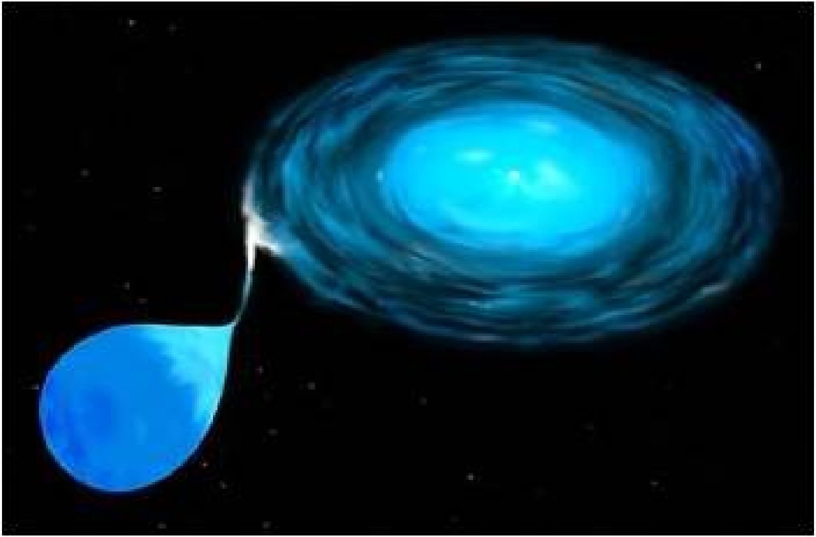
where ϵ_{F} is the Fermi energy for the relativistic and partially degenerate electrons, $Y_{\mathrm{e}} = 1/\mu_{\mathrm{e}}$.

Implications and Applications

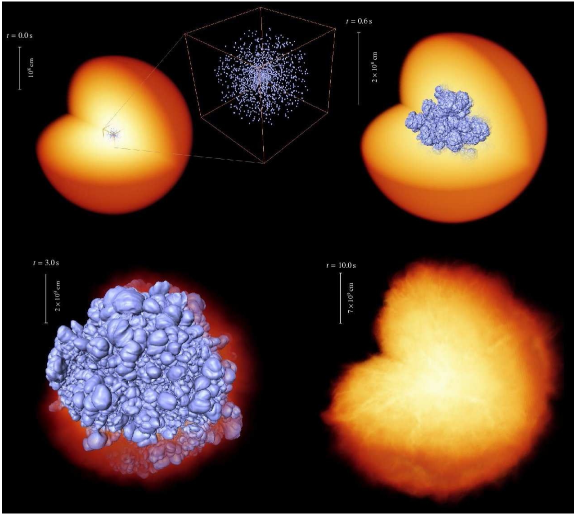
What happens when the Chandrasekhar Mass is reached?

- for massive stars (take into account corrections for μ_e and T): core collapses to form neutron star or black hole
- usually a supernova results, but, especially in case a black hole is formed (big core), much of the inner part of the star may be swallowed;
- in this case, at rare occasions, powerful gamma-ray bursts may result.
- for white dwarfs, it depends on the composition:
  - for white dwarfs made of Ne, Mg, and O:
    resulting from heavier progenitor stars,
    it will collapse to a neutron star (“electron capture supernova”)
  - for white dwarfs made of carbon and oxygen:
    it will ignite burning of carbon in the center and explode as a thermonuclear **Type Ia supernova**

Type Ia Supernova Progenitor



Type Ia Supernova Explosion

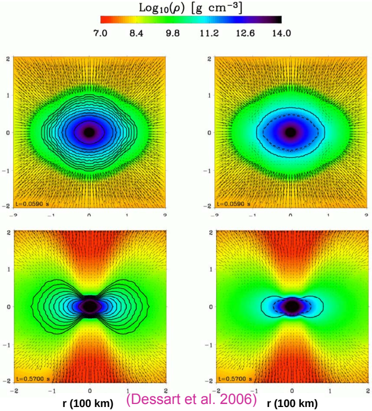


simulation of a Type Ia supernova explosion

(by Fritz Röpke)

Accretion Induced Collapse

Accretion Induced Collapse



(Dessart et al. 2006)

- NeMgO WD accretes from companion star
- When Chandrasekhar mass is approached, electron captures reduce electron degeneracy pressure support

◀ Rapid collapse and bounce (faint SN)

Fate of Stars

- stars with masses below $0.7\,\mathrm{M}_\odot$ have not yet evolved off the MS even if as old as the universe!
  These are red dwarf stars. All ever formed are still around.
- stars with initial masses $M \lesssim 2\,\mathrm{M}_\odot$ ignite helium burning under degenerate conditions in their core. They are usually referred to as low-mass stars.
- stars with initial mass $2\mathrm{M}_\odot \lesssim 9\mathrm{M}_\odot$ are called intermediate mass stars. They ignite helium burning non-degenerate. We can distinguish stars that later ignite carbon burning in the center ($M \gtrsim 7.5\,\mathrm{M}_\odot$) and those that don't.
- Stars with masses $M \gtrsim 9\,\mathrm{M}_\odot$ form iron codes that collapse to make core collapse supernovae

Overview

1. Evolution of Stars
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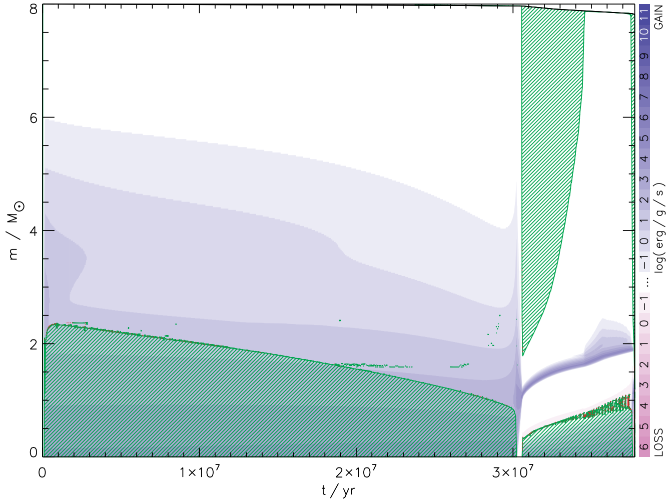
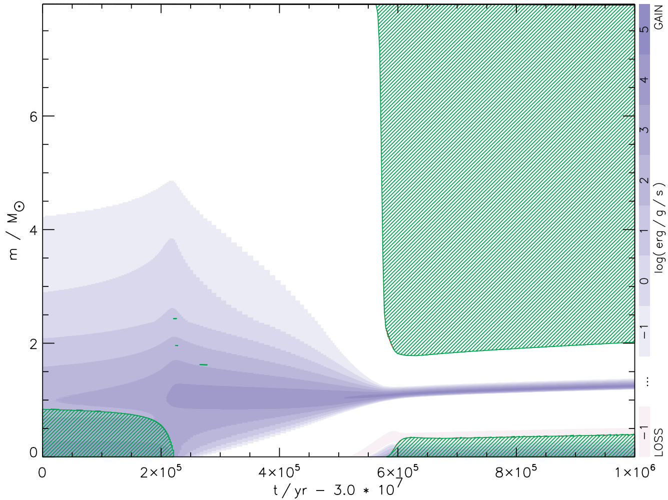
The Schönberg-Chandrasekhar Limit

- Low mass stars have a radiative core.
- hydrogen first depletes in the center, then increasingly further out
- this leads to the gradual build-up of a non-degenerate helium core of increasing mass.
- a critical limit exists above which this core no longer can sustain the pressure against the overlaying envelope layers, the The Schönberg-Chandrasekhar Limit.

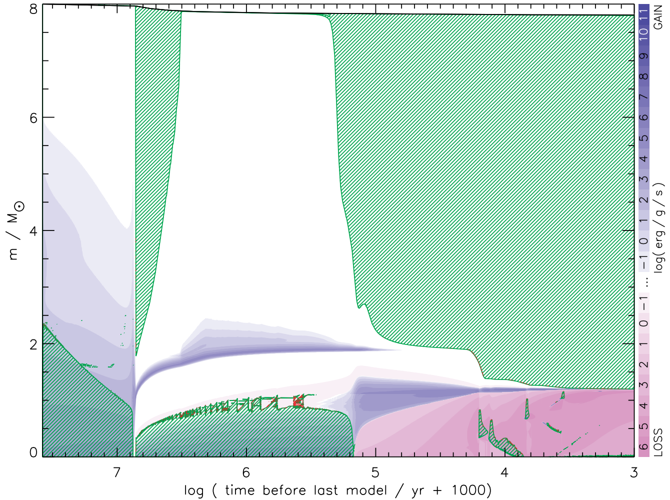
Kippenhahn Diagram, 8 $M_\odot$ Star



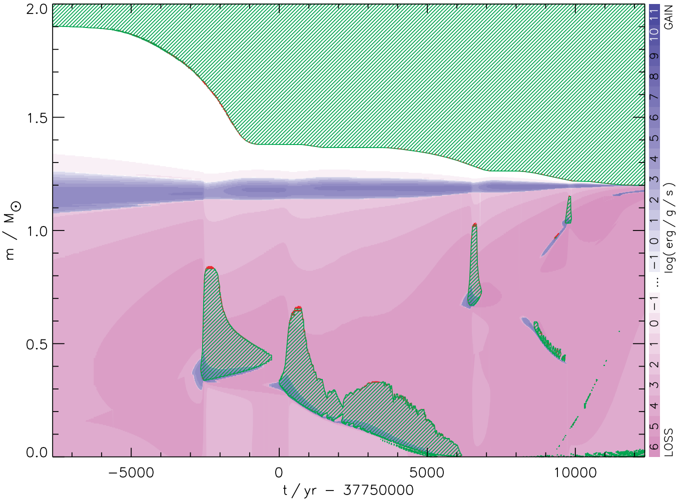
Kippenhahn Diagram, 8 $M_\odot$ Star, He Ignition



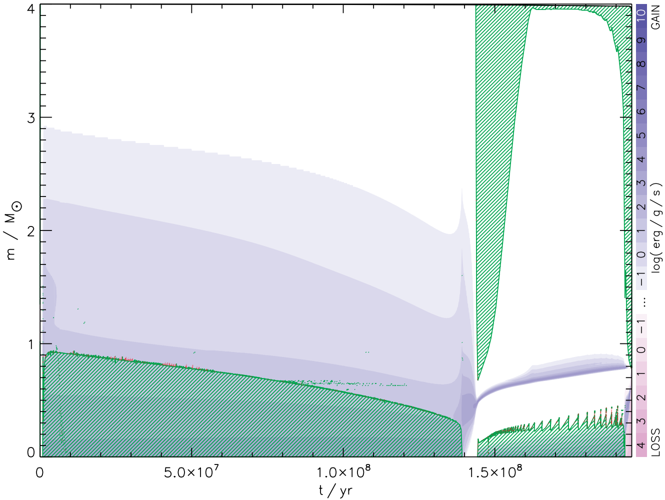
Kippenhahn Diagram, 8 $M_\odot$ Star



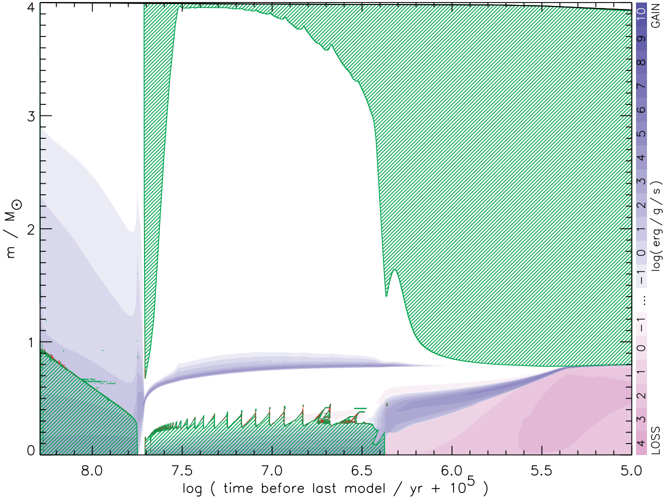
Kippenhahn Diagram, 8 $M_\odot$ Star, Off-Center C Ignition



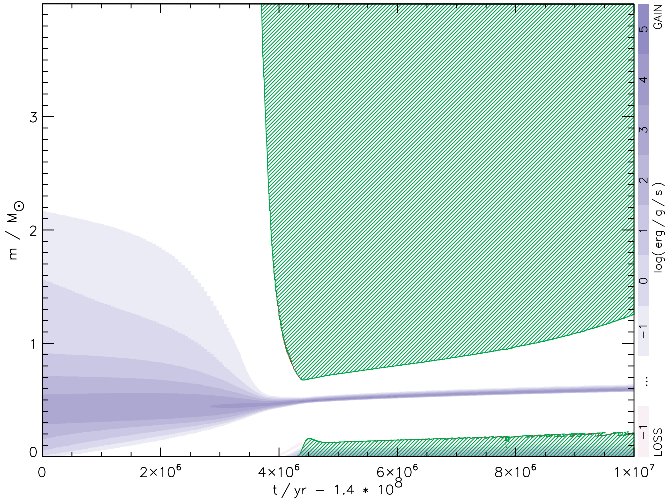
Kippenhahn Diagram, 4 $M_\odot$ Star



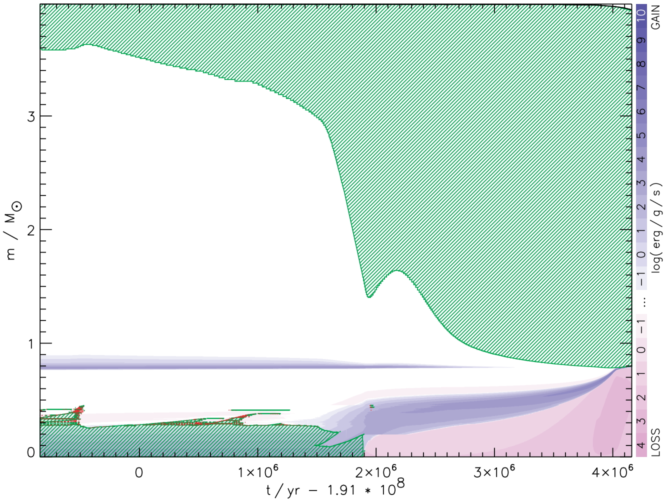
Kippenhahn Diagram, $4\,M_\odot$ Star



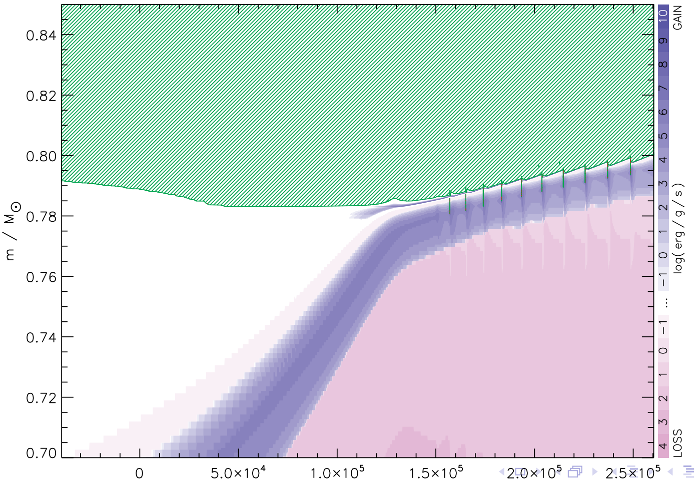
Kippenhahn Diagram, 4 $M_\odot$ Star, He Ignition



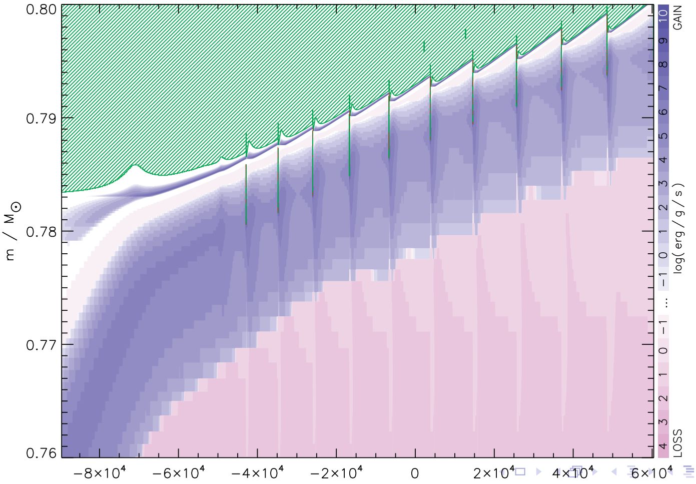
Kippenhahn Diagram, 4 $M_\odot$ Star, He Depletion



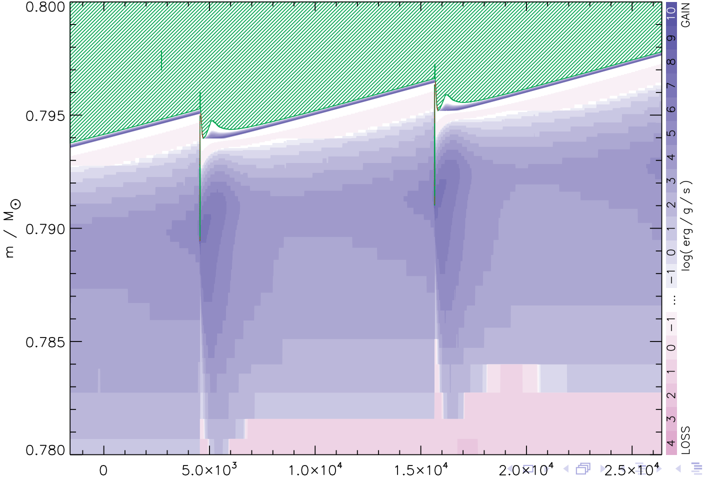
Kippenhahn Diagram, 4 $M_\odot$ Star, Post-Core He burning



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



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



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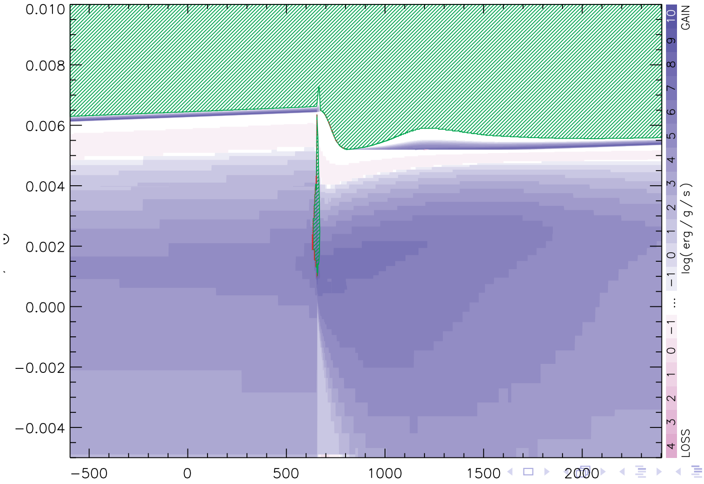

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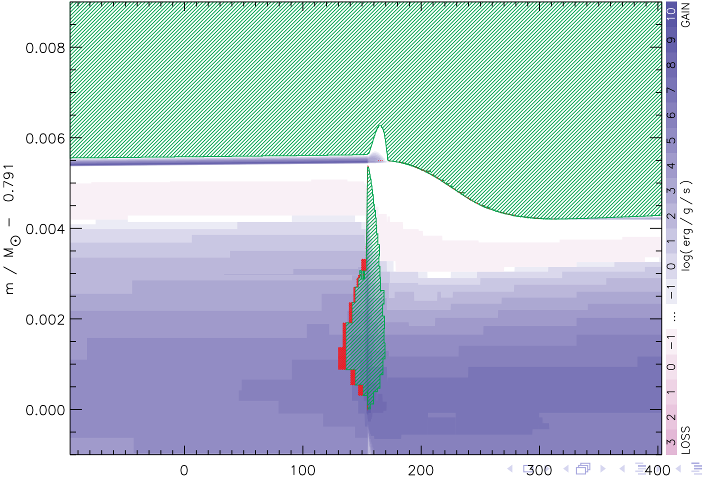

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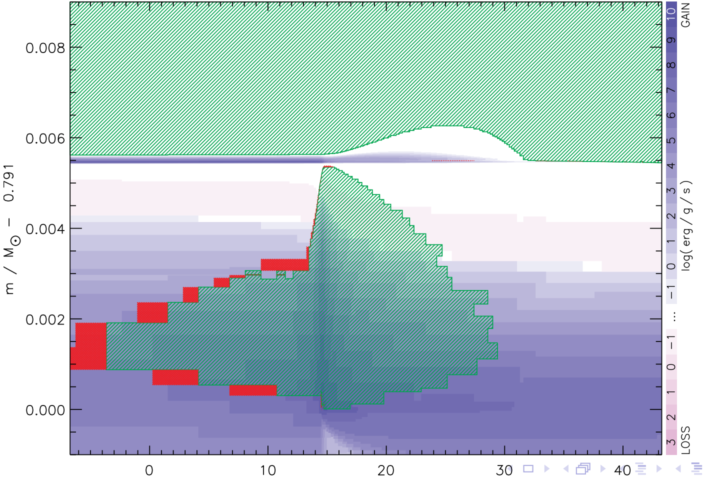


The Asymptotic Giant Branch (I)

asymptotic giant branch stars are characterized by

- two burning shells, hydrogen burning and helium burning, in an unstable configuration, leading to thermal pulses
- luminosity uniquely determined by core mass, not total mass
- strong stellar winds from the surface, driven by pulsations and radiation pressure on dust forming in the outer layers

The Asymptotic Giant Branch (II)

Eventually the entire envelope is blown away leaving behind a white dwarf star. Typical wind mass loss rates are of the order of $10^{-6}\,\mathrm{M}_\odot/\mathrm{yr}$

$$\dot{M} \sim 10^{-13}\mathrm{M}_\odot/\mathrm{yr}\,\frac{L}{\mathrm{L}_\odot}\frac{R}{\mathrm{R}_\odot}\frac{\mathrm{M}_\odot}{M}$$

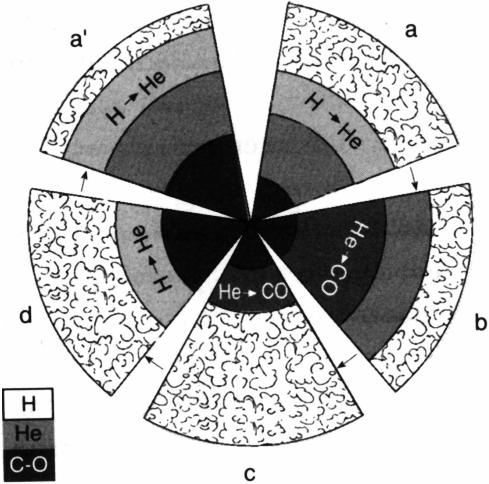
for $M > 0.5\mathrm{M}_\odot$ luminosity is given by

$$\frac{L}{\mathrm{L}_\odot} = 6\times10^4\left(\frac{M}{\mathrm{M}_\odot} - 0.5\right)$$

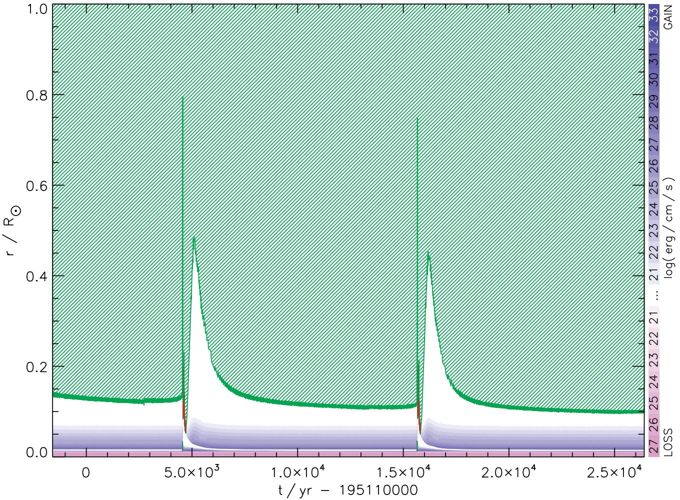
The Asymptotic Giant Branch (III)

- an extended phase of steady hydrogen shell burning builds up an increasingly thicker degenerate helium layer for some hundred years
- thermonuclear runaway in helium shell, $L \sim 10^8\,\mathrm{L}_\odot$
- “third” dredge-up after after helium shell flash
- nucleosynthesis of the strong component of the *s*-process in the helium shell making heavy elements up to lead starting from iron
- dredge-up brings freshly synthesized material into the envelope where winds blow it away.
- growth of the core is due to competition (“race”) of dredge-up after helium shell flash and mass loss

Change of Structure During AGB Cycle



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



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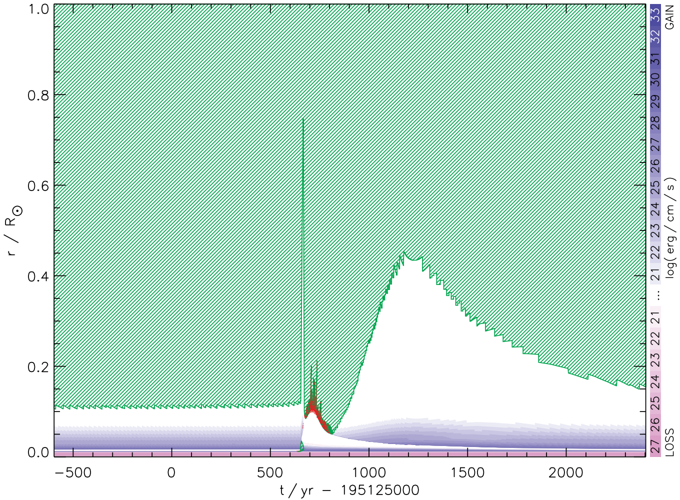

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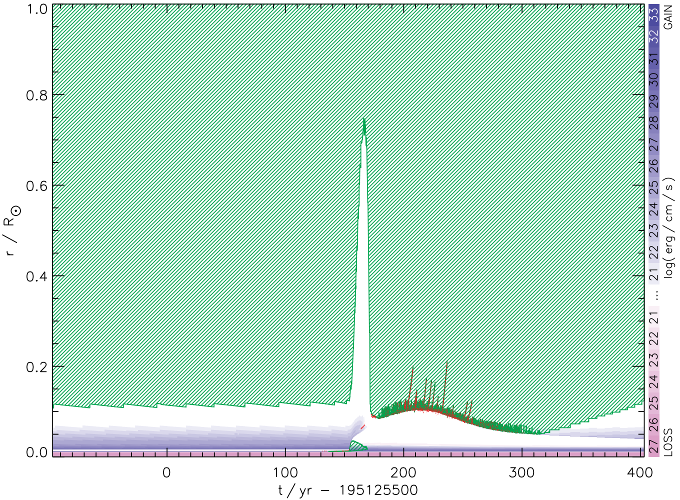

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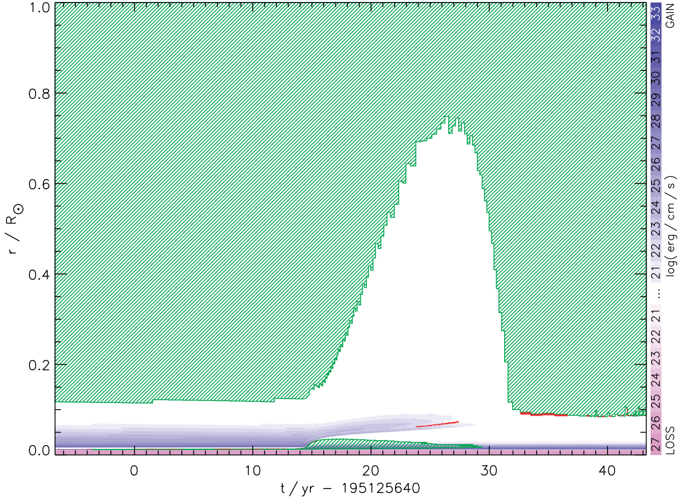


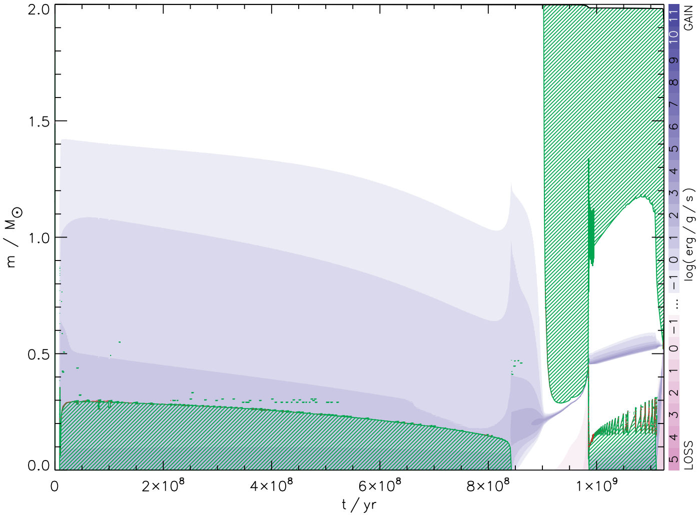
Core Contraction and Degeneracy

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

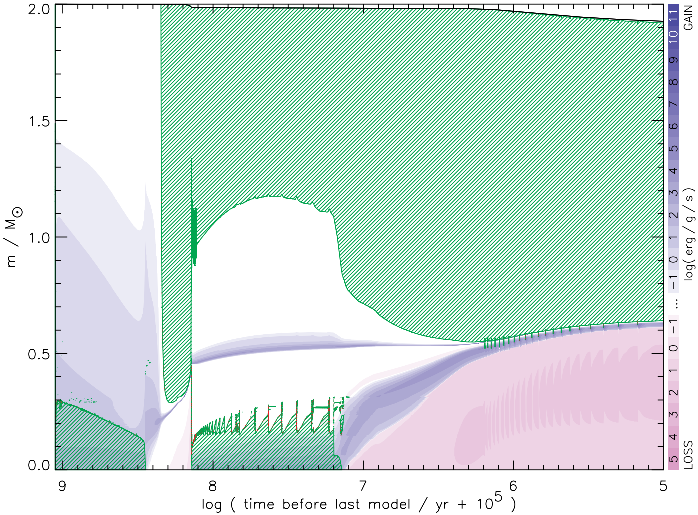
$$P_{\mathrm{s,max}} \lesssim \mathrm{K}_1 \left(\frac{3 M_{\mathrm{c}}}{4\pi {R_{\mathrm{c}}}^3} \right)^{5/3}$$

- occurs for stars below about $2\,\mathrm{M}_\odot$
- 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 $10^{11}\,\mathrm{L}_\odot$ - the luminosity of an entire galaxy or a supernova, but invisibly inside the star

Kippenhahn Diagram, $2M_\odot$ Star



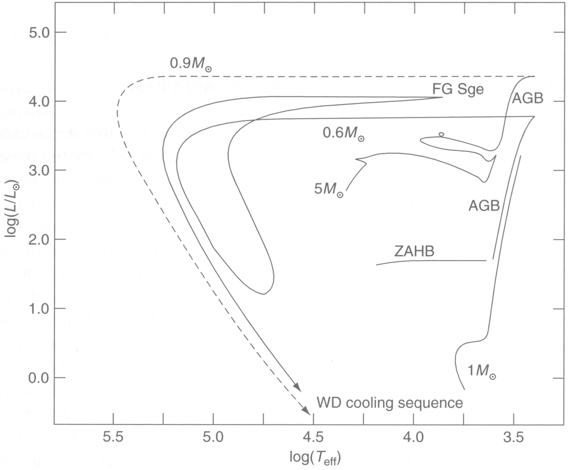
Kippenhahn Diagram, $2M_\odot$ Star



Low-Mass Stars and the Horizontal Branch

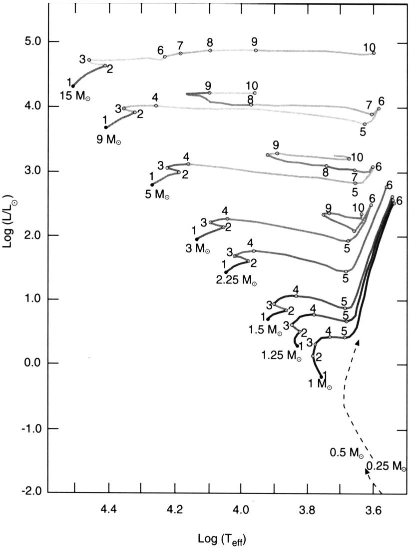
- *after core helium flash*, low-mass stars ($0.7 - 2\,\mathrm{M}_\odot$) undergo contraction and cooling of the envelope
- this is similar to contraction *from* the Hayashi line during star formation, only in *reverse*
- stars of different initial mass have comparable *core mass* at the time of helium flash, but different envelope mass
- formation of horizontal branch (HB) in the HRD, $L \sim 50 - 100\,\mathrm{L}_\odot$
- 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

Evolution tracks and lifetimes



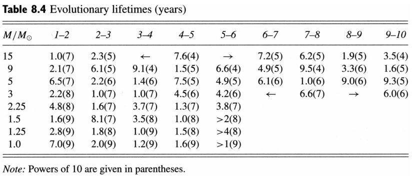
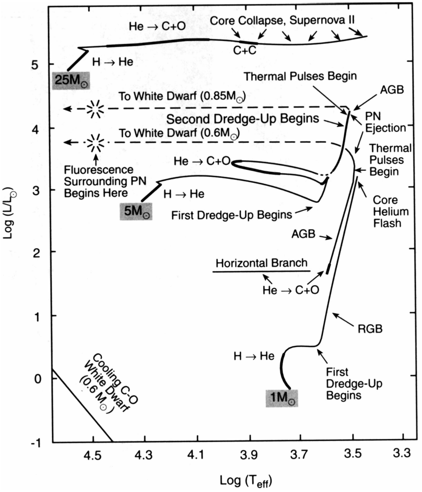


Table 8.4 Evolutionary lifetimes (years)

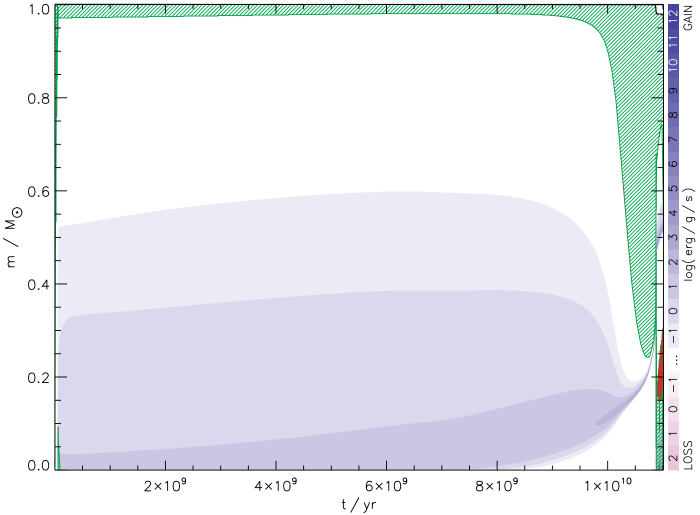
$M/M_\odot$	*1–2*	*2–3*	*3–4*	*4–5*	*5–6*	*6–7*	*7–8*	*8–9*	*9–10*
15	1.0(7)	2.3(5)	←	7.6(4)	→	7.2(5)	6.2(5)	1.9(5)	3.5(4)
9	2.1(7)	6.1(5)	9.1(4)	1.5(5)	6.6(4)	4.9(5)	9.5(4)	3.3(6)	1.6(5)
5	6.5(7)	2.2(6)	1.4(6)	7.5(5)	4.9(5)	6.1(6)	1.0(6)	9.0(6)	9.3(5)
3	2.2(8)	1.0(7)	1.0(7)	4.5(6)	4.2(6)	←	6.6(7)	→	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.

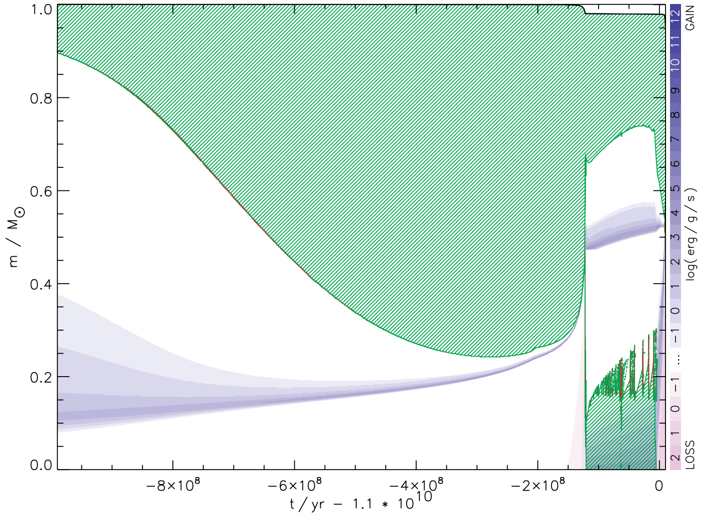
Stellar evolution in the HRD



Kippenhahn Diagram, 1$M_\odot$ Star



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



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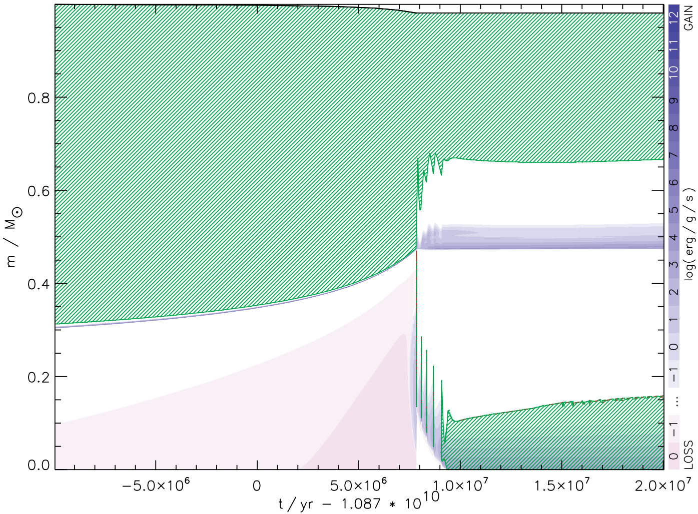
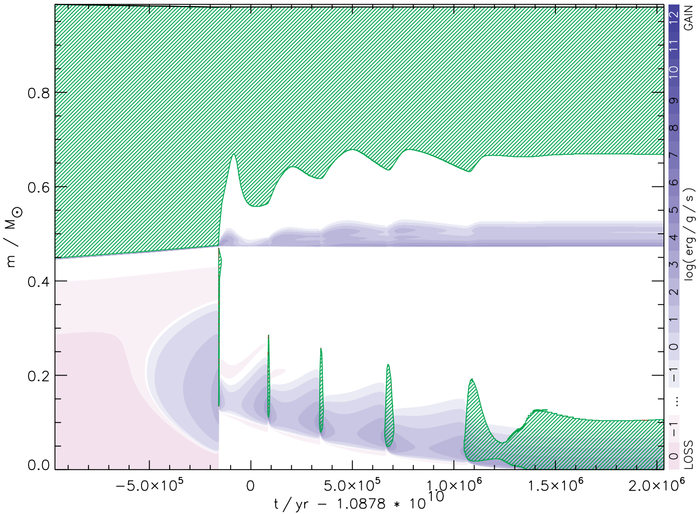
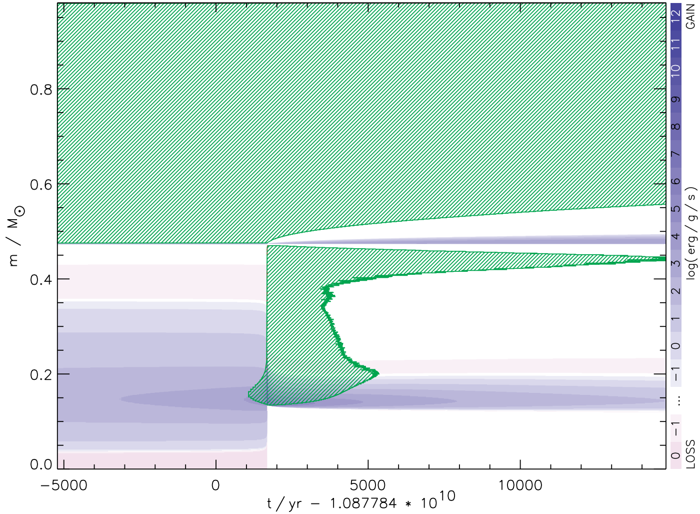


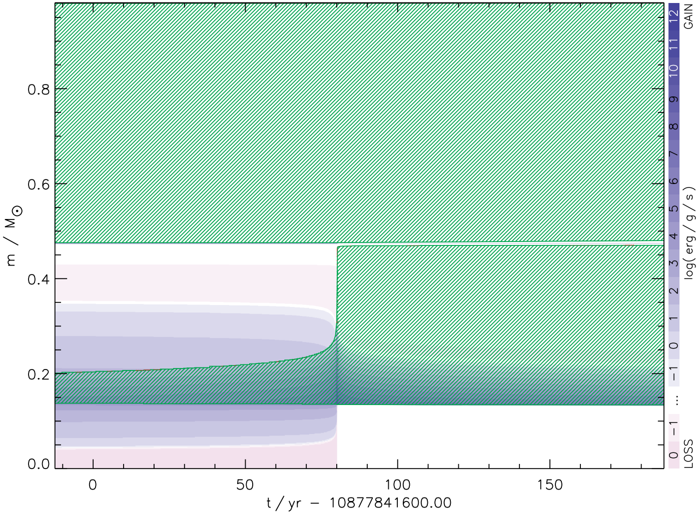
Kippenhahn Diagram, $1M_\odot$ Star, Helium Ignition



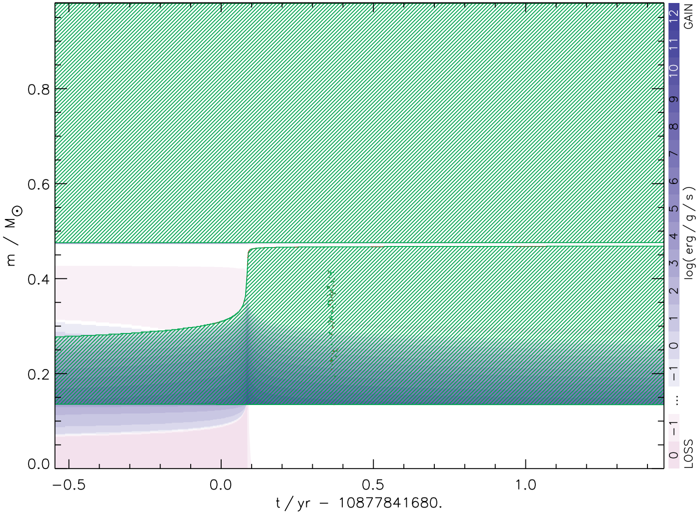
Kippenhahn Diagram, $1M_\odot$ Star, Helium Ignition



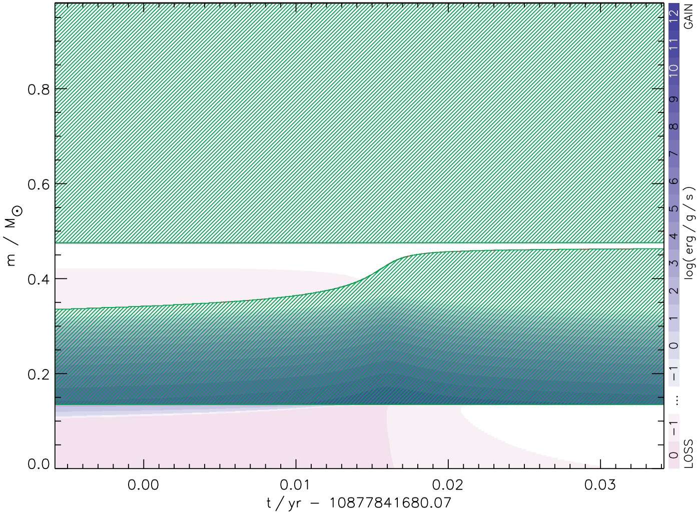
Kippenhahn Diagram, $1M_\odot$ Star, Helium Ignition



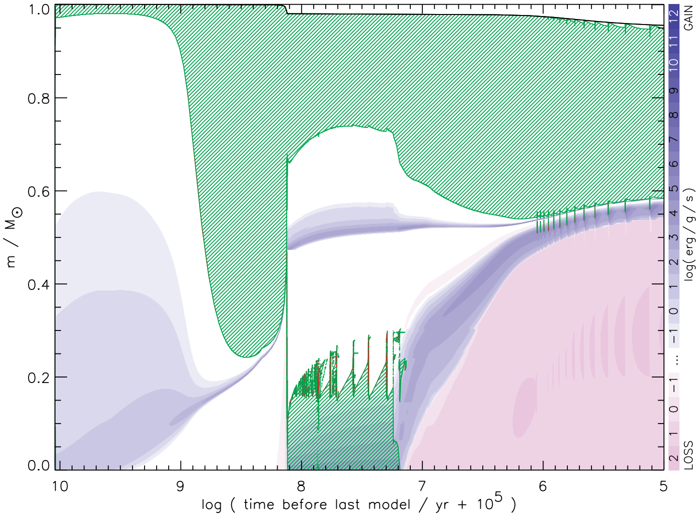
Kippenhahn Diagram, $1M_\odot$ Star, Helium Ignition



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



Kippenhahn Diagram, $1 M_\odot$ Star



White Dwarf Star Masses

Stars with initial masses $\sim 7.5 - 9\,\mathrm{M}_\odot$

- exceed CO core mass of $\sim 1.1\,\mathrm{M}_\odot$
- ignite central carbon burning $\Rightarrow$ make ONeMg core
- do not ignite later burning stages
- lose envelope as AGB stars (+PN)
- $\Rightarrow$ ONeMg WDs with $M > 1.1\,\mathrm{M}_\odot$
- but due to IMF: few stars with $7.5\,\mathrm{M}_\odot < M < 9\,\mathrm{M}_\odot$

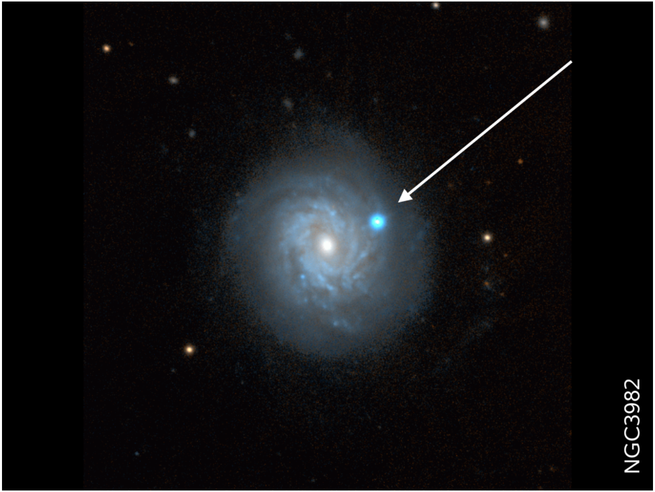
White Dwarf Star Masses

- stars with initial mass $2\,\mathrm{M}_\odot \lesssim M \lesssim 7.5\,\mathrm{M}_\odot$:
  - non-degenerate ignition of central He burning $\Rightarrow$ CO core
  - no ignition of carbon burning $\Rightarrow$ CO WD
  - make range of WD with mass below $\sim 1.1\,\mathrm{M}_\odot$
  - IMF $\Rightarrow$ more stars
- stars with initial mass $1\,\mathrm{M}_\odot \lesssim M \lesssim 2\,\mathrm{M}_\odot$:
  - formation degenerate He core, ignites when grown to $\sim 0.6\,\mathrm{M}_\odot$
  - $\Rightarrow$ CO Core
  - no ignition of carbon burning $\Rightarrow$ CO WD of about that mass
  - IMF $\Rightarrow$ many stars

White Dwarf Star Masses

- stars with initial mass $0.7\,\mathrm{M}_\odot \lesssim M \lesssim 1\,\mathrm{M}_\odot$
    - do not ignite carbon burning
    - $\Rightarrow$ He WD
    - typical masses: $\sim 0.2 - 0.4\,\mathrm{M}_\odot$
    - IMF $\Rightarrow$ many stars
- in binary star system
    - stellar core may be uncovered due to loss of envelope by interaction with companion star
    - $\Rightarrow$ typically occurs when star expands
    - $\Rightarrow$ at beginning RG or AGB phases
    - $\Rightarrow$ different mass distribution, typically lower masses

Supernovae



Overview

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2. Evolution of Low-Mass Stars
3. supernovae

Supernovae - Overview

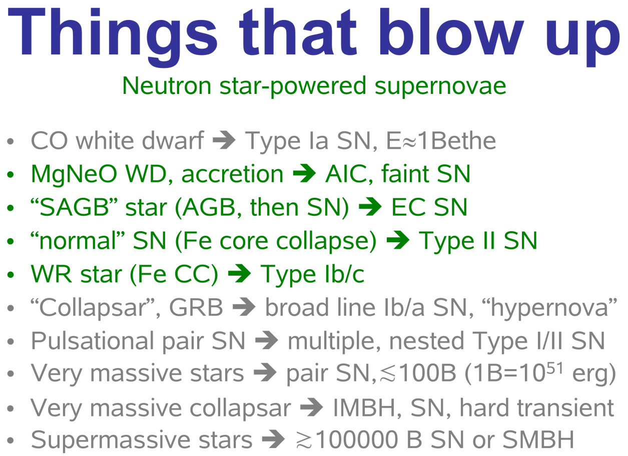
Things that blow up

supernovae from massive stars

1B=10^{51} erg

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

Supernovae

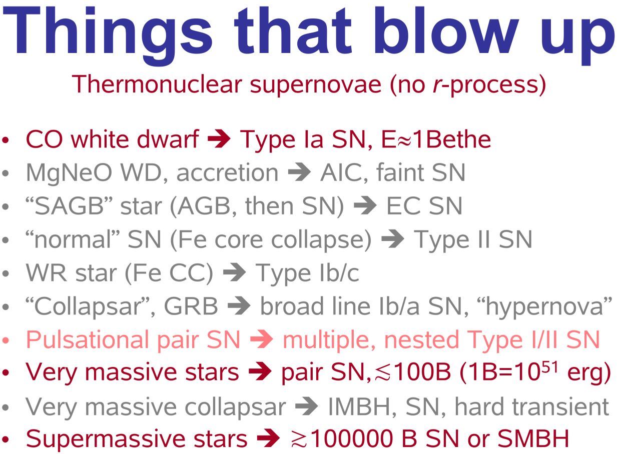


Things that blow up

Neutron star-powered supernovae

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

Supernovae



Things that blow up

Thermonuclear supernovae (no *r*-process)

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

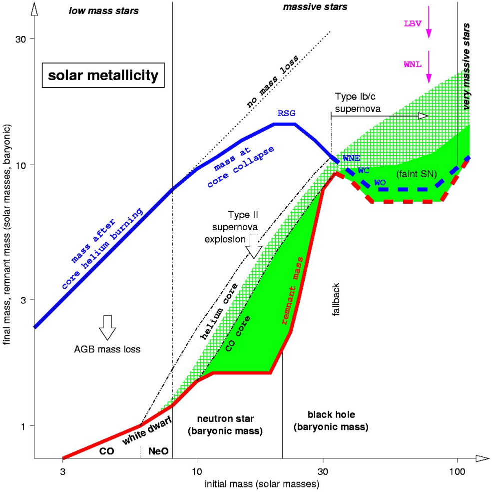
Supernovae

Things that blow up

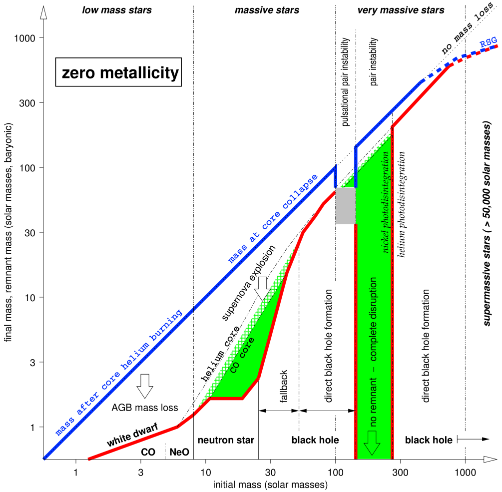
Black hole-powered supernovae (“Collapsars)

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

Stellar Mass Ranges - Solar Metallicity



Stellar Mass Ranges - Population III Stars



Remnants - Mass and Metallicity