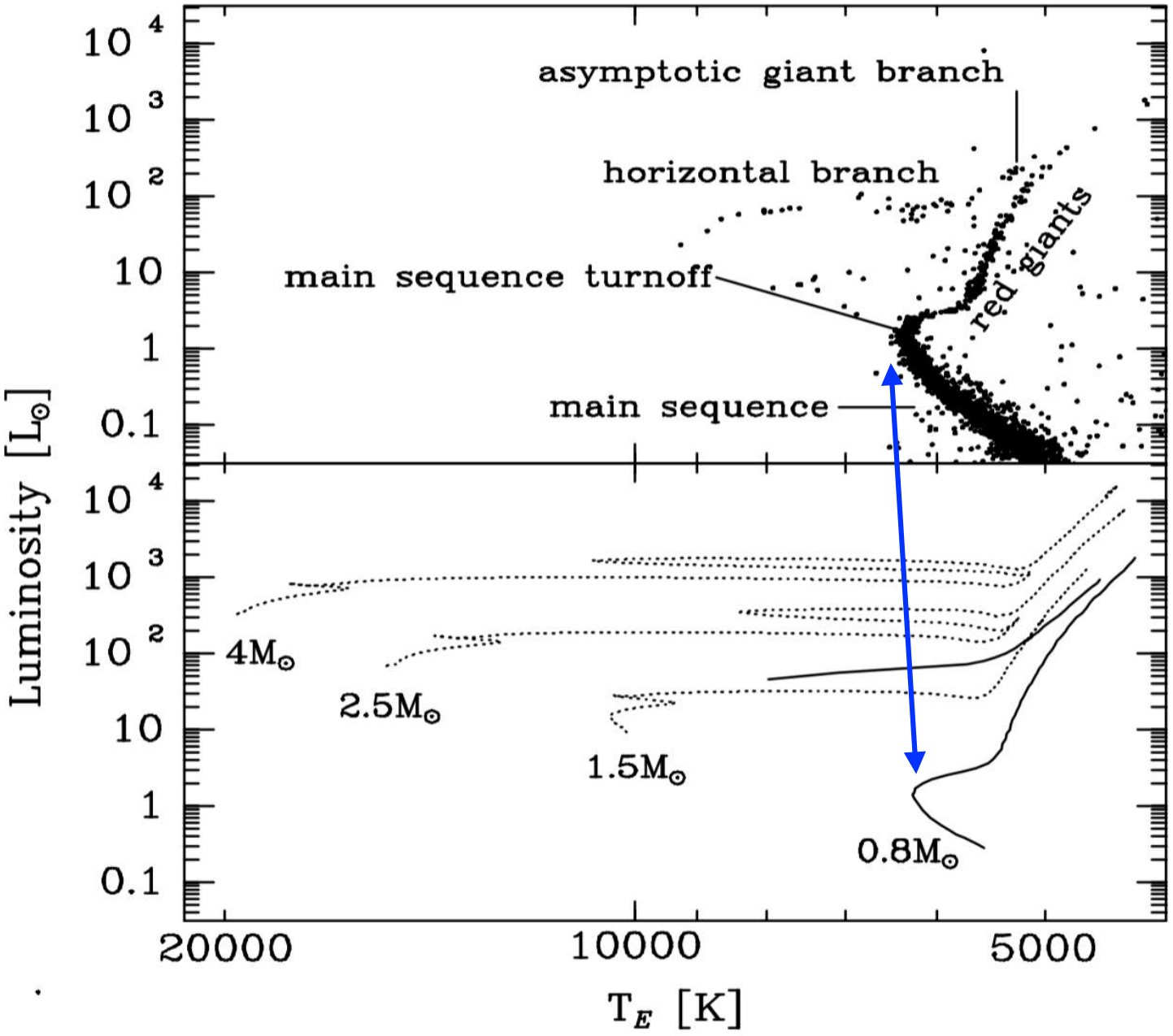


Observed H-R diagram for M3 globular cluster

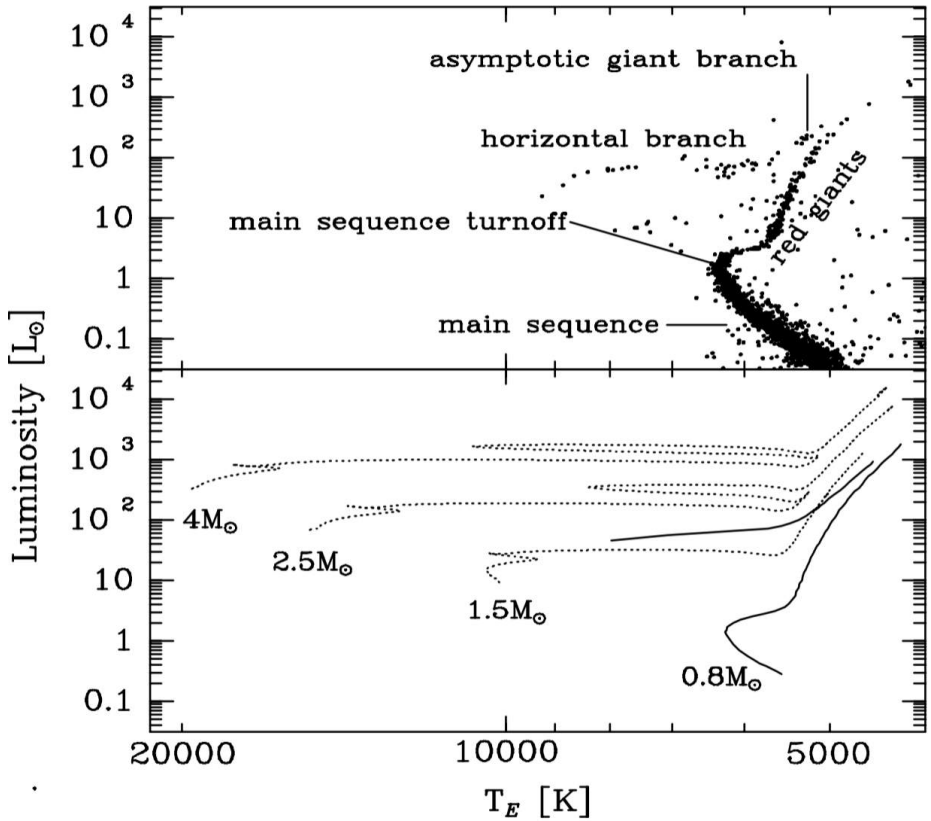
Theoretical stellar evolution tracks (HB, AGB only shown for 0.8 M_{sun})

Age dating star clusters using MS turn off (13 Gyr)

Fig. 4.1

Red giant (~10% of MS duration)

- most core converted into He → core contracts, *T* rises
- H starts burning in *shell* surrounding core
- factor ~100 expansion in radius: *L* increases, T_E (surface) decreases



Horizontal branch (~1% of MS duration)

- when T~10^8 K, ρ~10^4 g cm^{-3}, core He burns via "triple α":

$$^4\mathrm{He} + {}^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma(7.275\ \mathrm{MeV})$$

(no stable element with atomic mass #5 or 8)

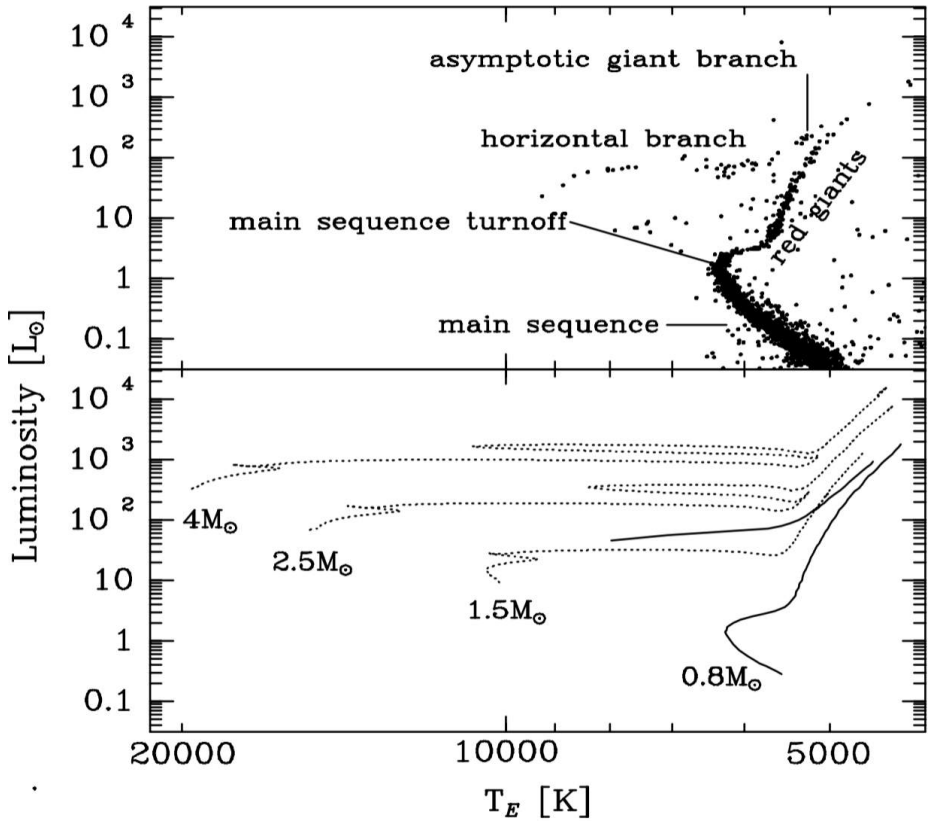
- some O & Ne also formed:

$$^4\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma$$

$$^4\mathrm{He} + {}^{16}\mathrm{O} \rightarrow {}^{20}\mathrm{Ne} + \gamma$$

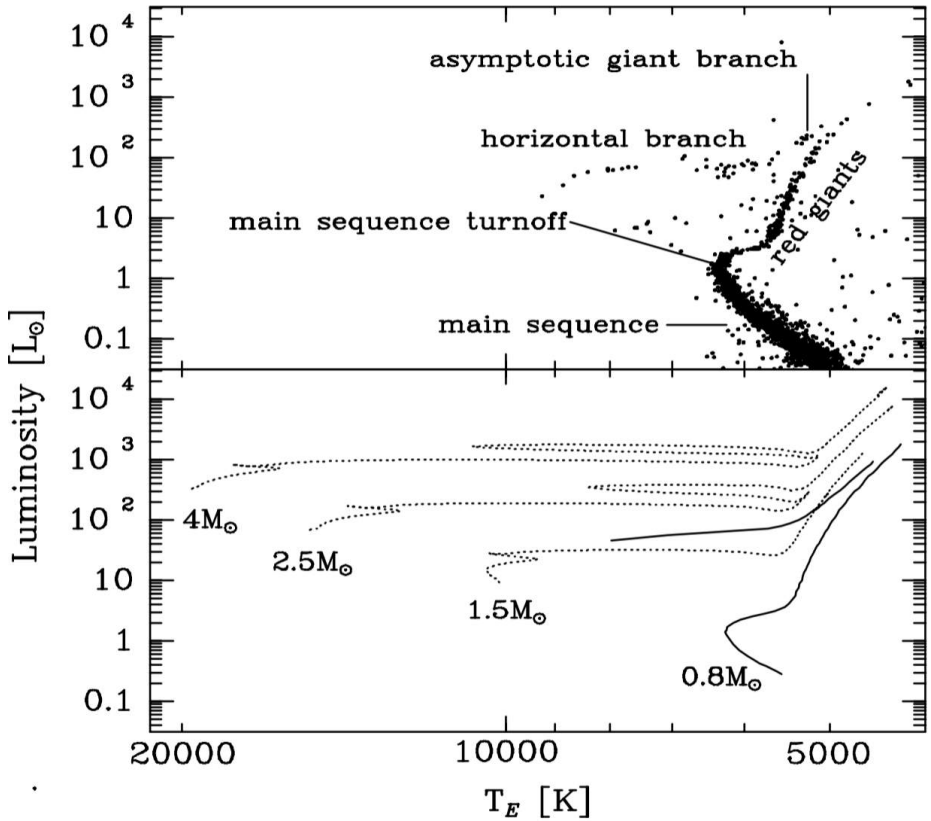
- H continues to burn in shell

- quickly moves to higher T_E (left of H-R), then more slowly to right



Asymptotic giant branch

- repeat of RG evolution but with He+H shell burning around inert C+O core



What happens next depends on initial mass

- $M_0 \lesssim 8\ M_{sun}$:
  - He/C/O core becomes supported by e^- degeneracy P — no more nuclear burning
  - remaining envelope blown off → planetary nebula (lasts ~10^4 yr)
  - exposed degenerate core → WD

- $M_0 \gtrsim 8\ M_{sun}$:
  - continue sequence of core contraction and synthesis of heavier elements
  - until Fe core, when nuclear burning can no longer produce energy → core collapse supernova
  - leaves NS or BH

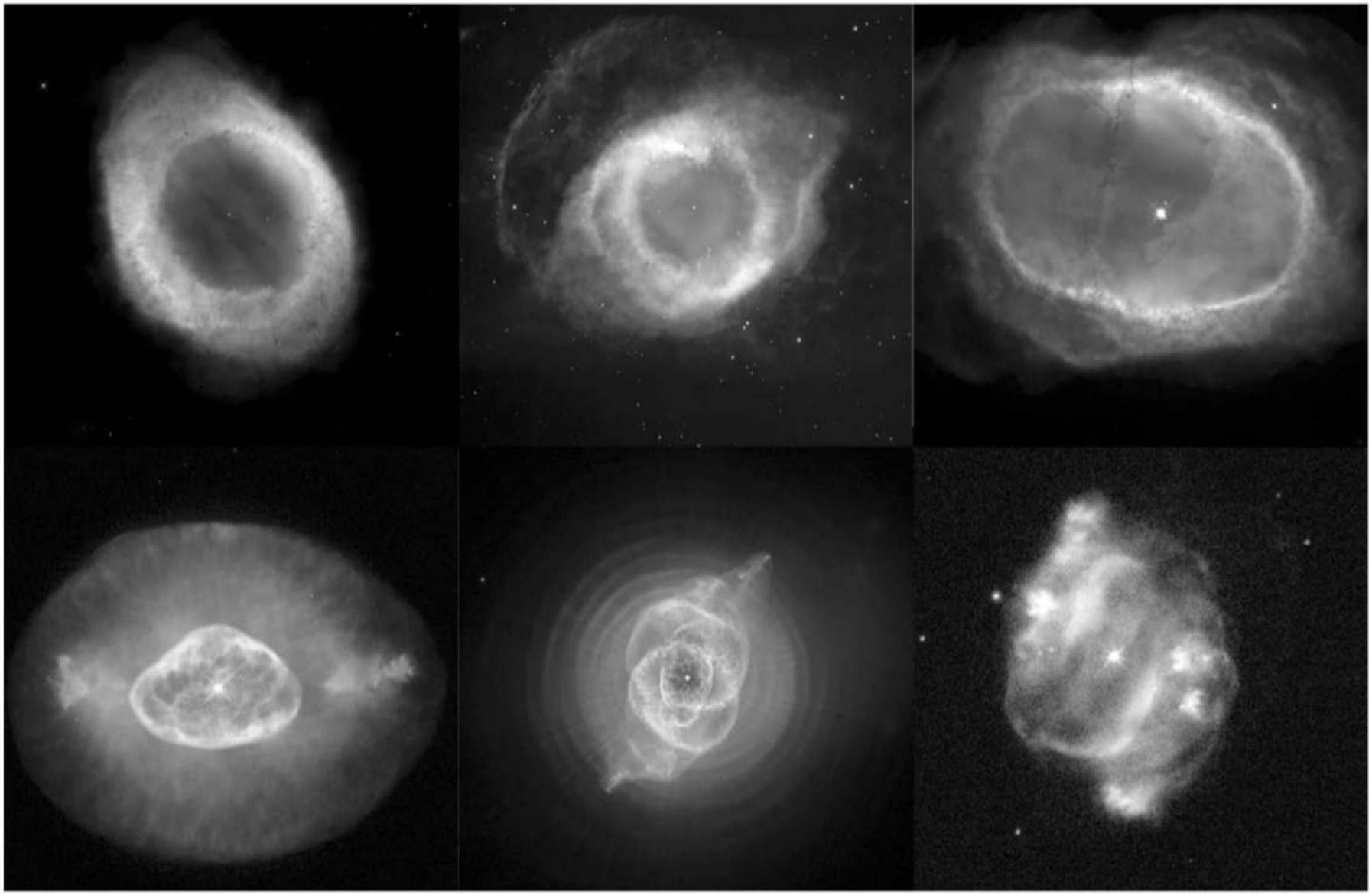
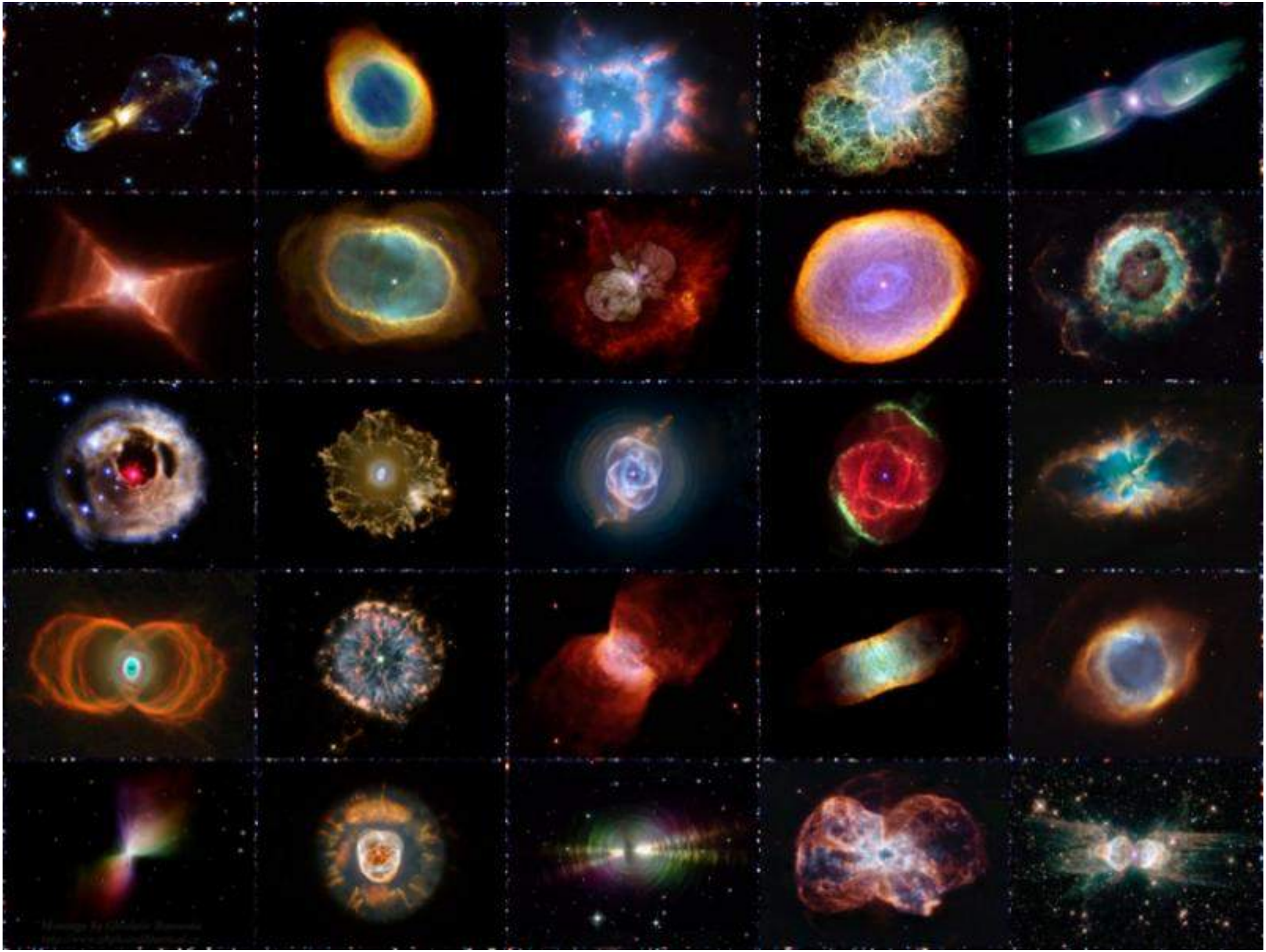


Figure 4.2 Several examples of planetary nebulae, newly formed white dwarfs that irradiate the shells of gas that were previously shed in the final stages of stellar evolution. The shells have diameters of $\approx 0.2 - 1$ pc. Photo credits: M. Meixner, T.A. Rector, B. Balick et al., H. Bond, R. Ciardullo, NASA, NOAO, ESA, and the Hubble Heritage Team



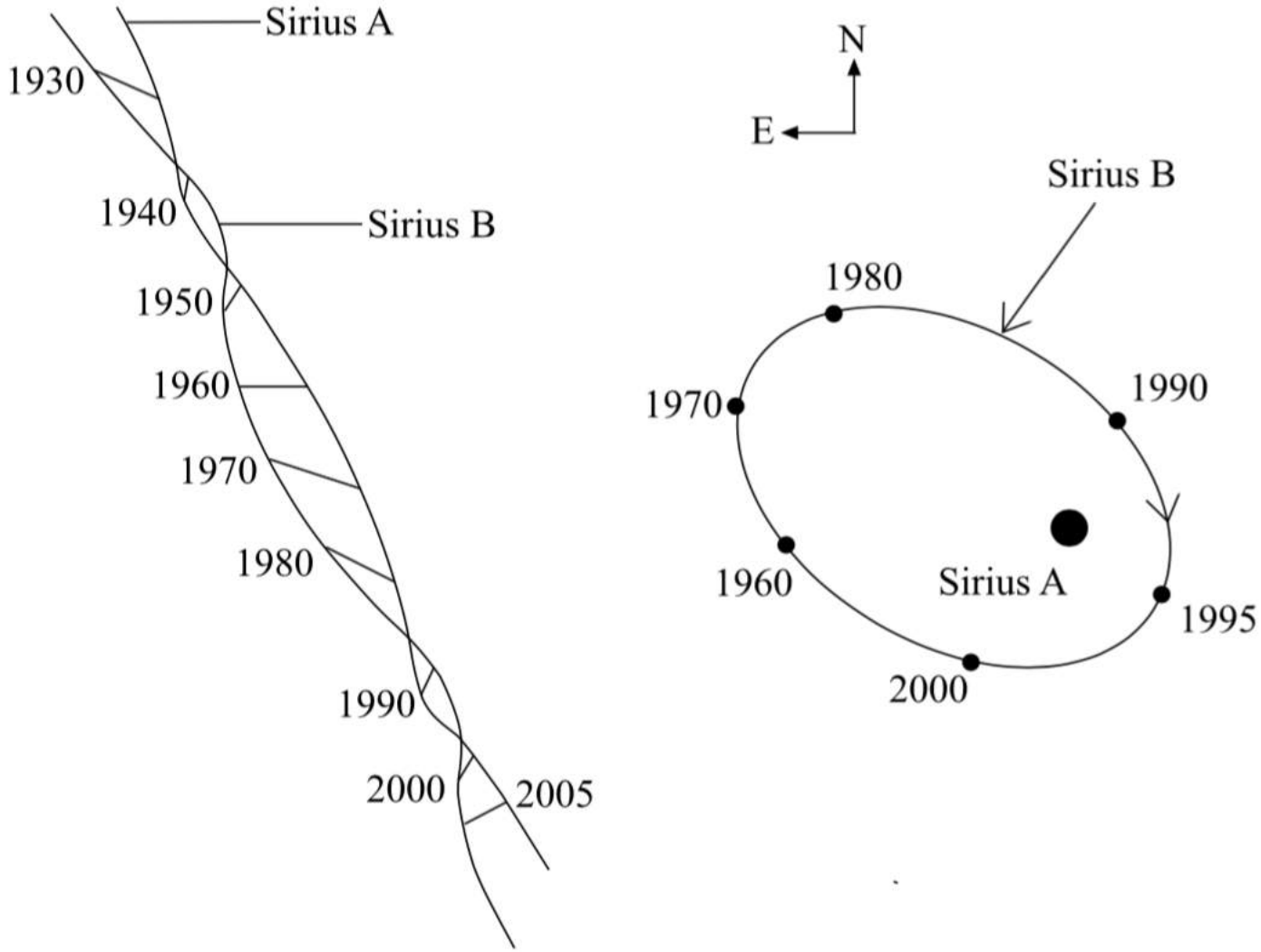


Figure 4.3 Observed motion on the sky, over the past century, of the visual binary consisting of Sirius A and its faint white dwarf companion, Sirius B. On the left are the observed positions due the orbital motions around the center of mass, combined with the proper motion of the system as a whole. On the right side, only the positions of Sirius B relative to Sirius A are shown. The maximum projected separation of the pair is 10 arcseconds. Using Kepler's Law, a mass close to $1M_{\odot}$ is derived for the white dwarf.

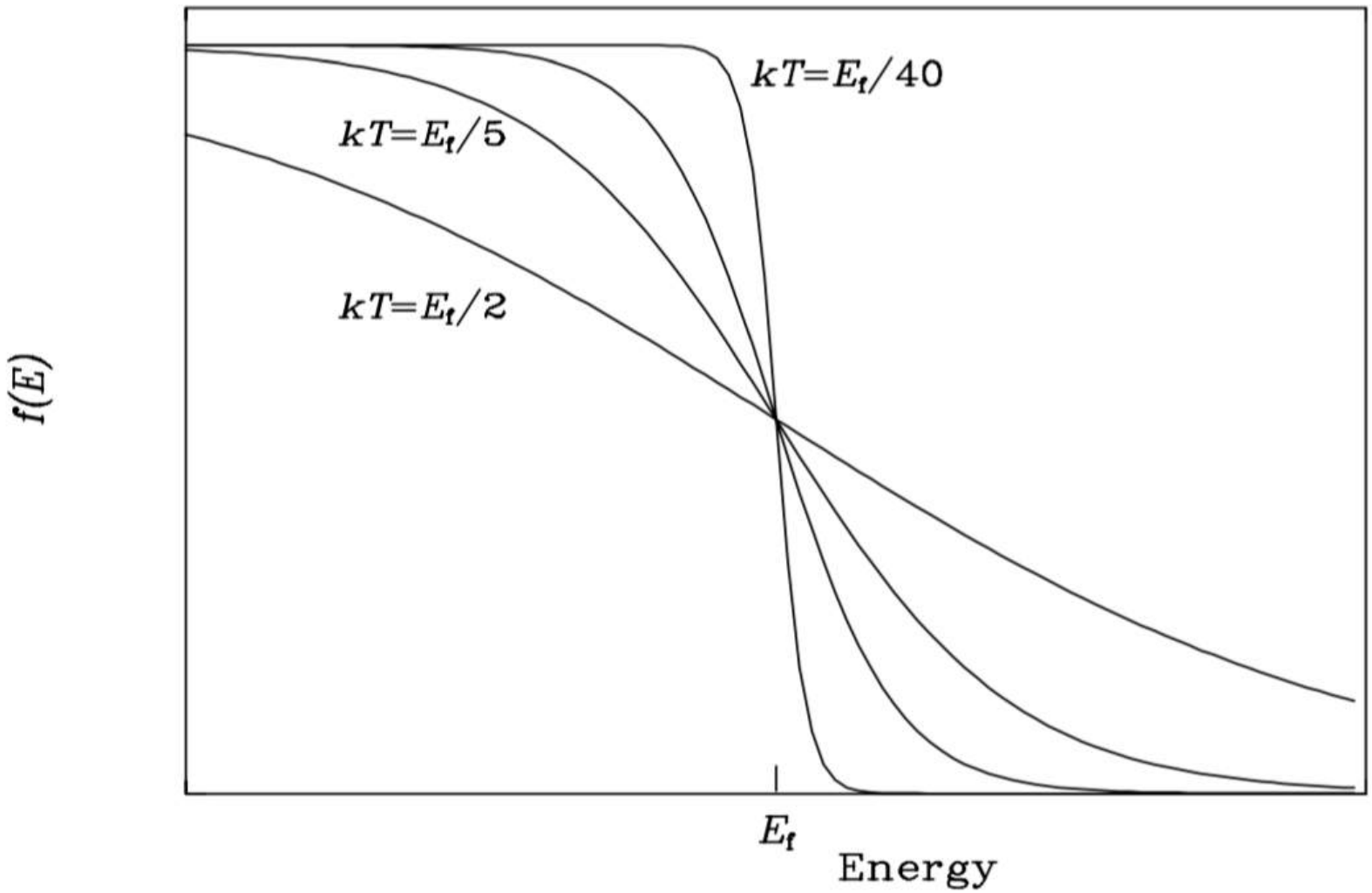


Figure 4.4 Approach to degeneracy of the Fermi-Dirac occupation fraction, $f(E)$, as $kT \rightarrow 0$, shown for $kT = E_f/2, E_f/5, E_f/10$, and $E_f/40$. At $kT \ll E_f$, all particles occupy the lowest energy state possible without violating the Pauli Exclusion Principle. The distribution then approaches a step function, with all energy states below E_f occupied, and all those above E_f empty.

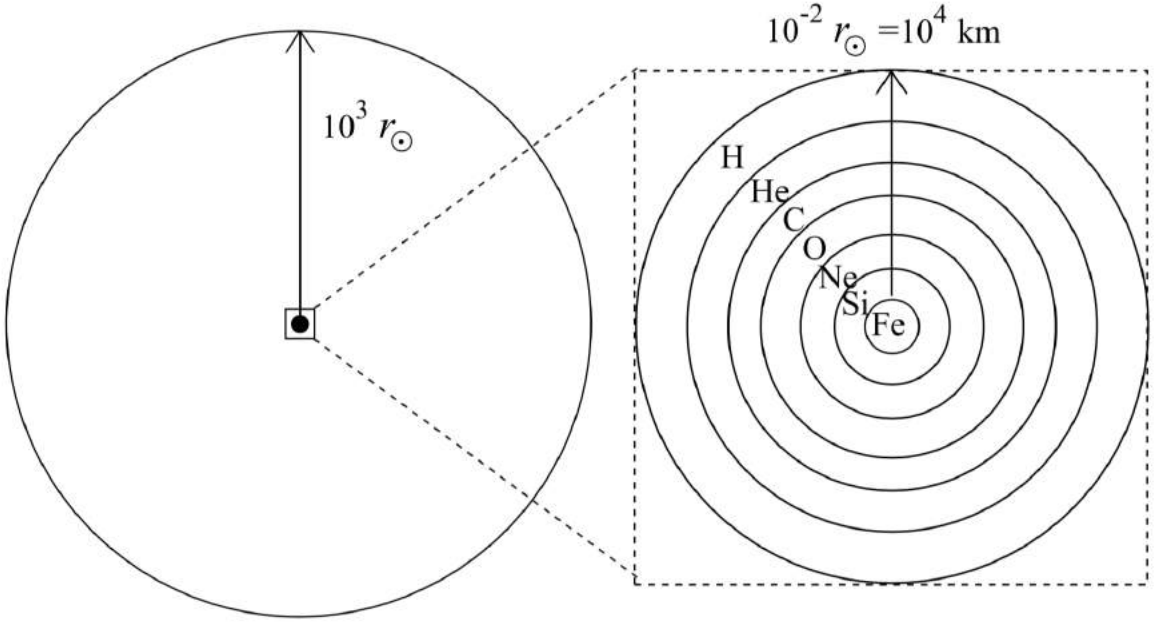
Onion-skin evolution of massive stars on giant branch

- $M_0 \gtrsim 8\ M_{sun}$ (O-early B spectral types):

  - sequence of contraction & heating of inner regions

  - burning & synthesis of heavier elements

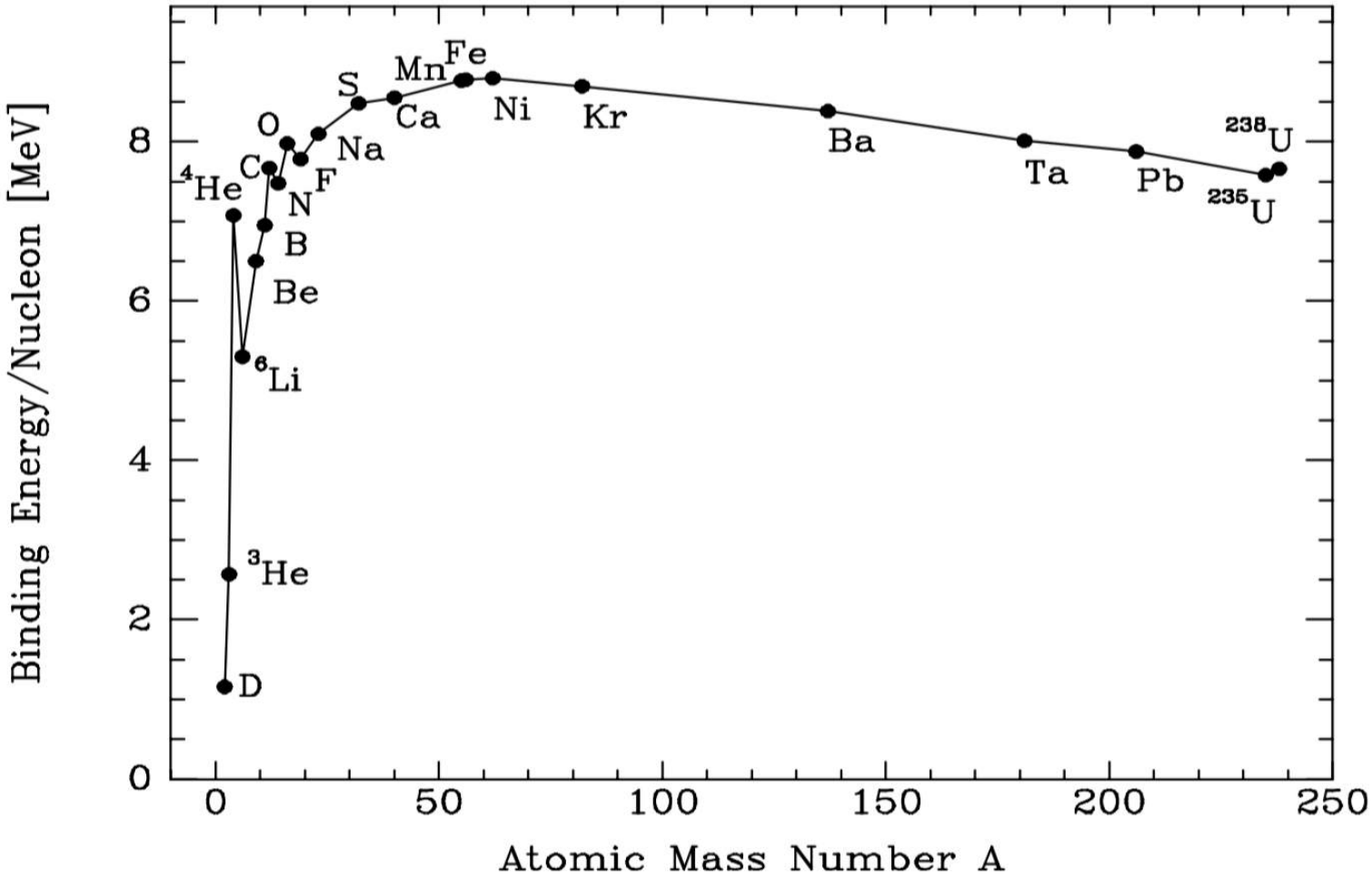
  - progressively faster, e.g. M_0=25 M_{sun}



Stage	Duration
H	7×10^6 yr
He	5×10^5 yr
C	600 yr
O	6 mo
Ne	1 yr
Si	1 day

Iron catastrophe

- Nuclear burning stops at Fe, when burning can no longer *produce* energy



- Fe core grows until it reaches its Chandrasekhar mass, then collapses

Core collapse

1. Nuclear photodisintegration:

Very high T → lots of γ's disintegrate core, absorbing energy

$$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\,{}^{4}\mathrm{He} + 4\mathrm{n} \quad \text{(costs 124 MeV)}$$

$$\gamma + {}^{4}\mathrm{He} \rightarrow 2\mathrm{p} + 2\mathrm{n} \quad \text{(costs 28.4 MeV)}$$

2. Neutronization:

Very high ρ → weak interactions produce n's, p's, ν_e's, depleting core of e^-'s and removing e^- degeneracy P

$$\mathrm{e}^- + \mathrm{p} \rightarrow \mathrm{n} + \nu_\mathrm{e}$$

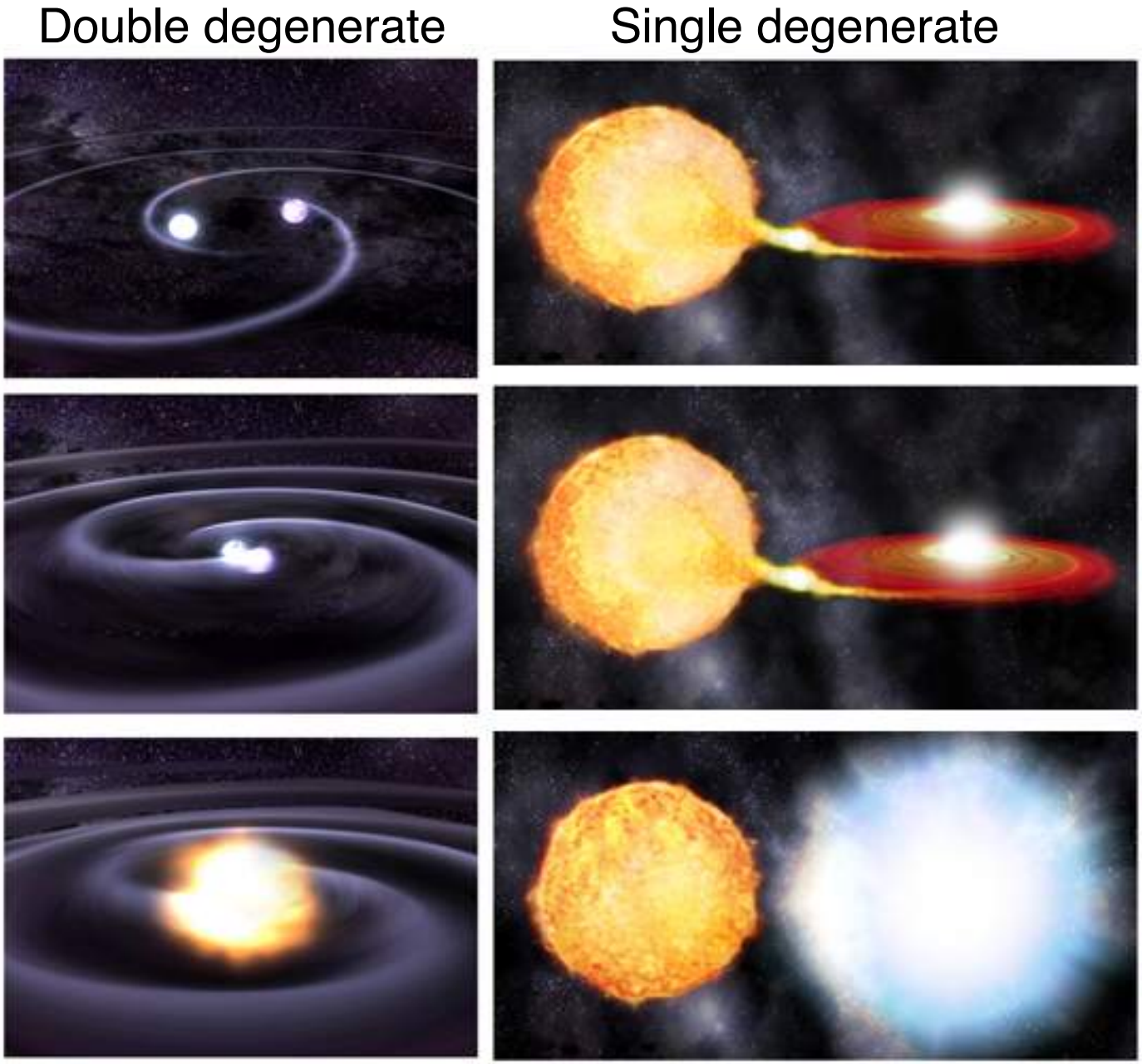
$$\mathrm{e}^- + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Mn} + \nu_\mathrm{e}$$

$$\mathrm{e}^- + {}^{56}\mathrm{Mn} \rightarrow {}^{56}\mathrm{Cr} + \nu_\mathrm{e}$$

➜ collapse to NS in few s, ν burst, Type II SN (H lines from envelope in spectrum)

Other type of SN: WDs gaining mass and exceeding M_{ch}

- Type Ia: no H in spectrum since no H in WDs



Type Ia SN nearby "Pinwheel" galaxy