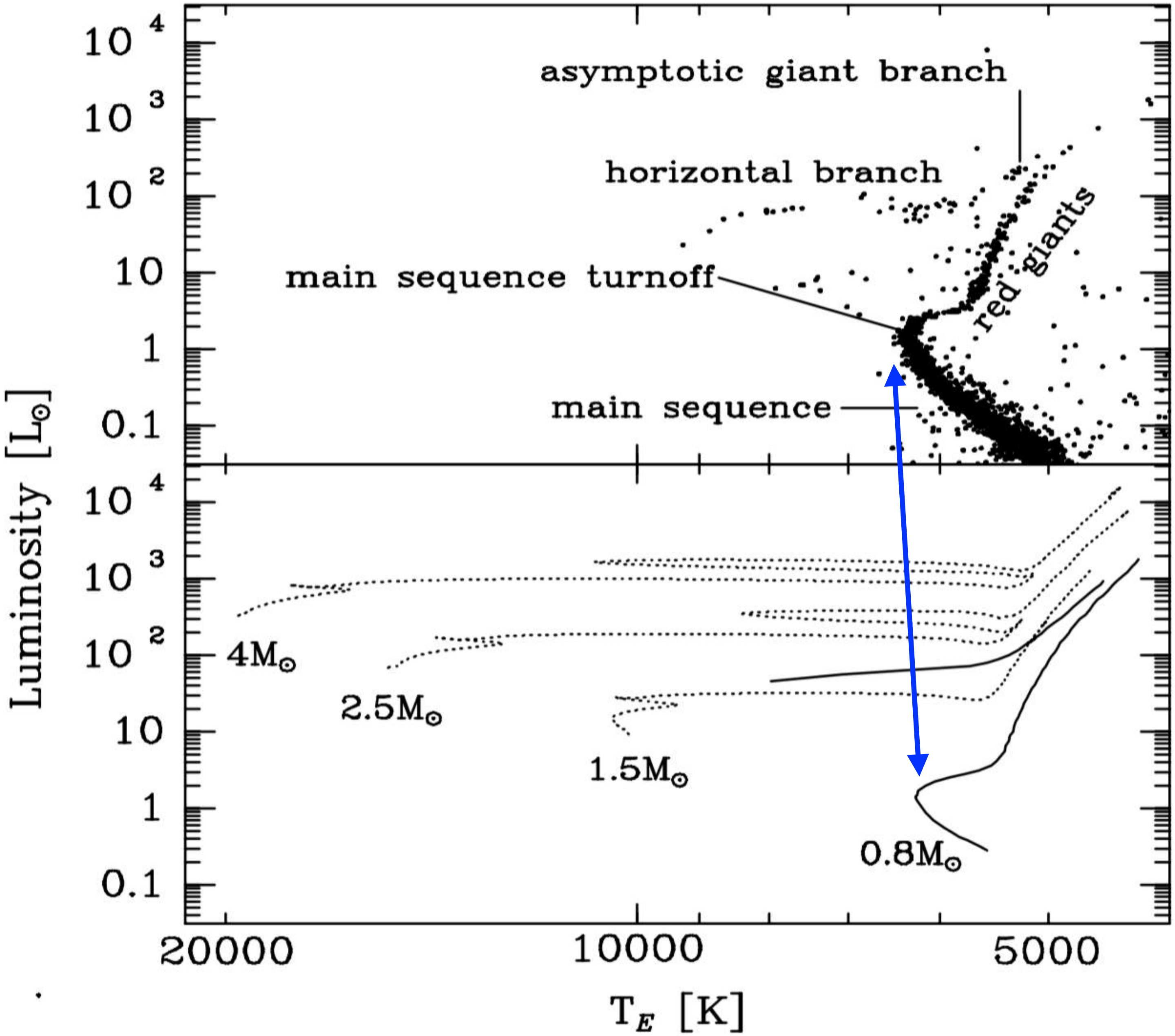
Globular cluster M3

~500,000 stars inside radius ~10 pc



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)

Maoz Fig. 4.1

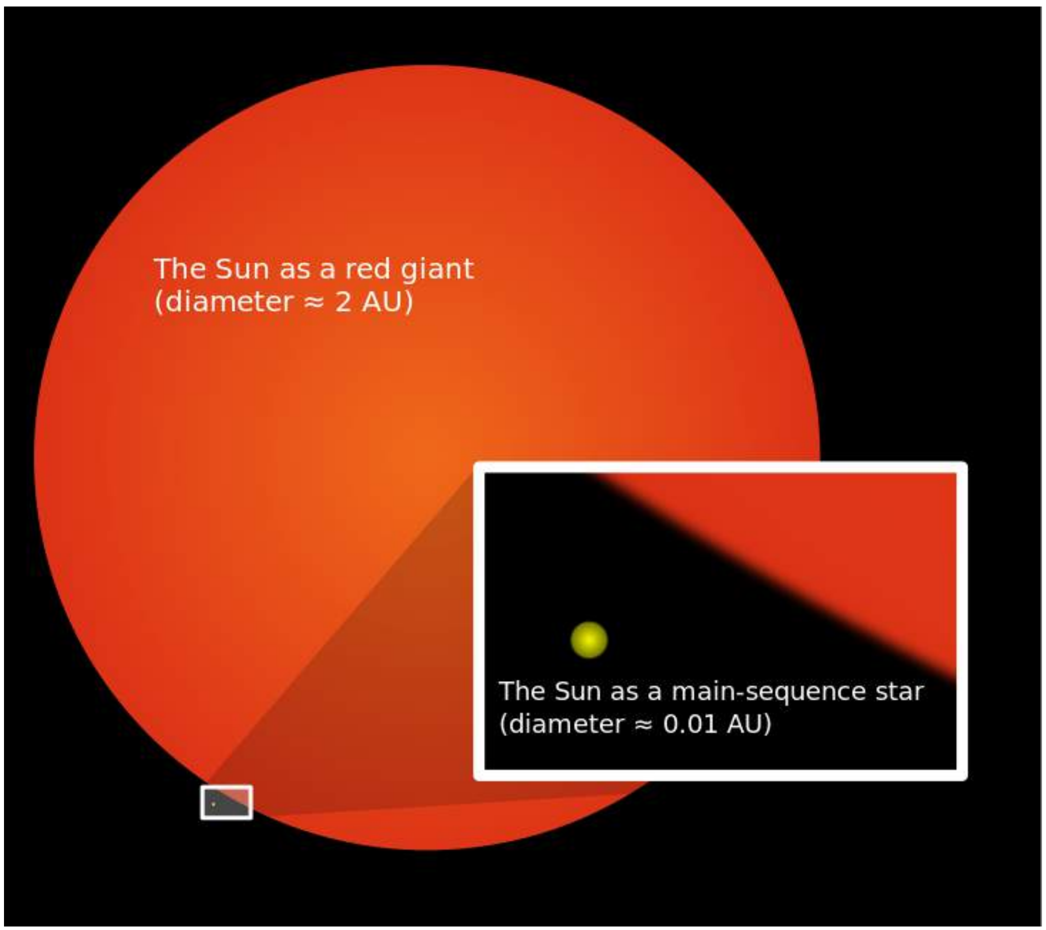
Which galaxy is older, and why?

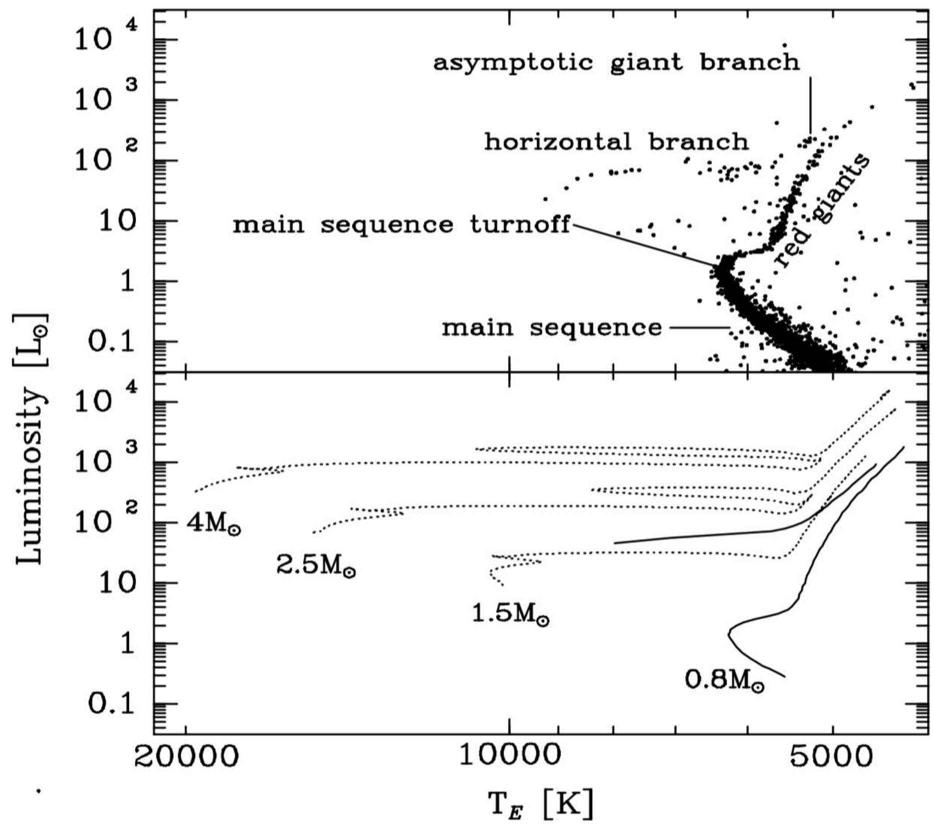
Blue stars formed in last <10-100 Myr

Red stars can stay on MS for longer than the age of the Universe — on average old

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



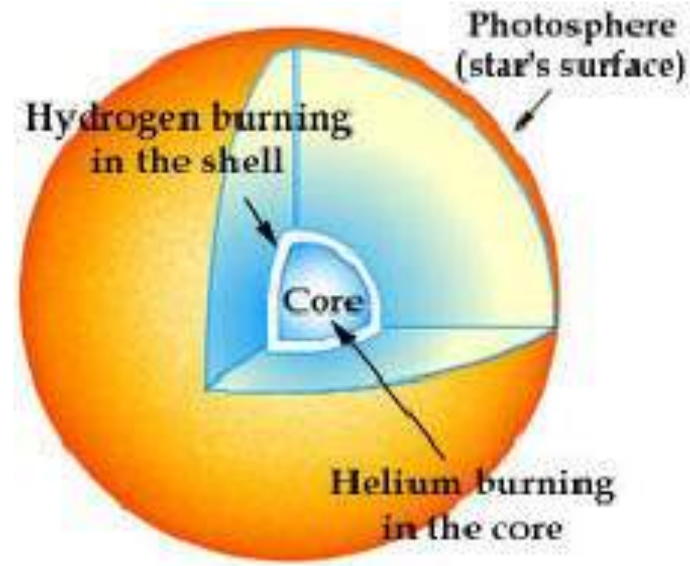


Horizontal branch (~1% of MS duration)

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

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

(no stable element with atomic mass #5 or 8, so can't just fuse He+H or He+He!)

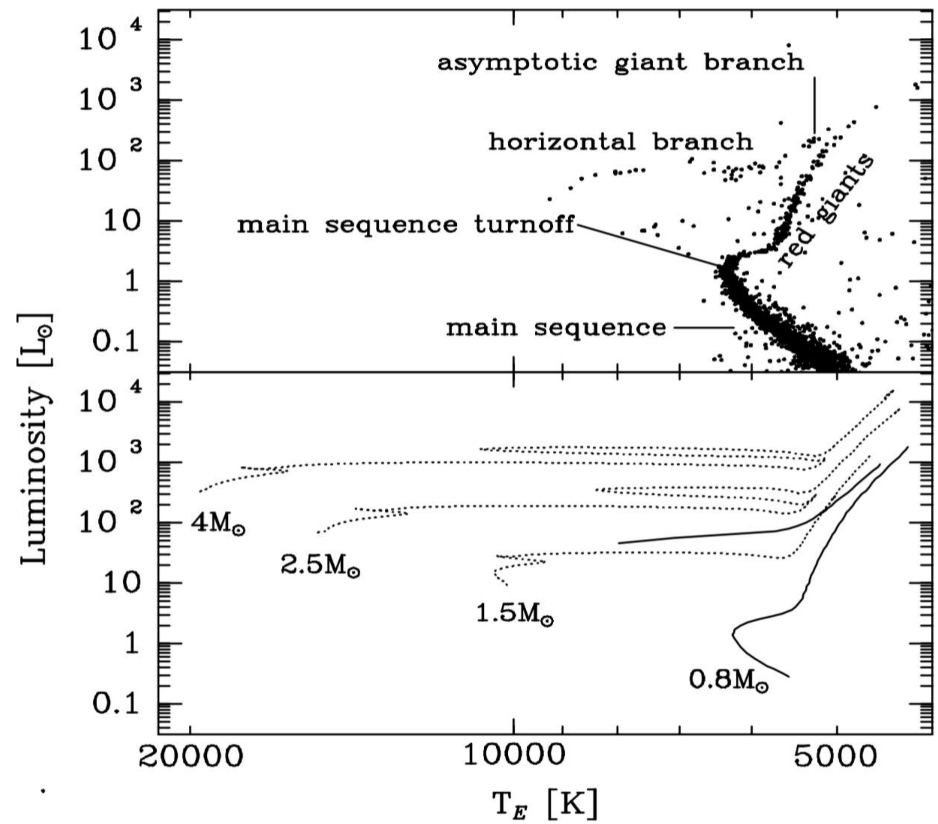


- some O & Ne also formed:

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

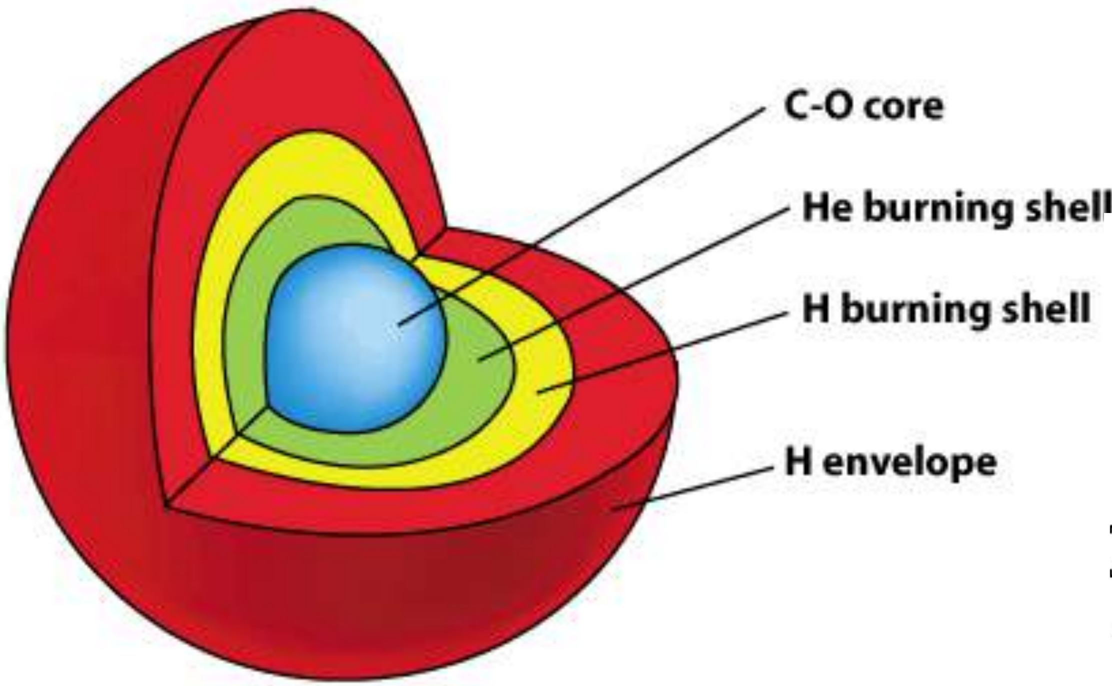
$$^{4}\mathrm{He} + {}^{16}\mathrm{O} \rightarrow {}^{20}\mathrm{Ne} + \gamma$$

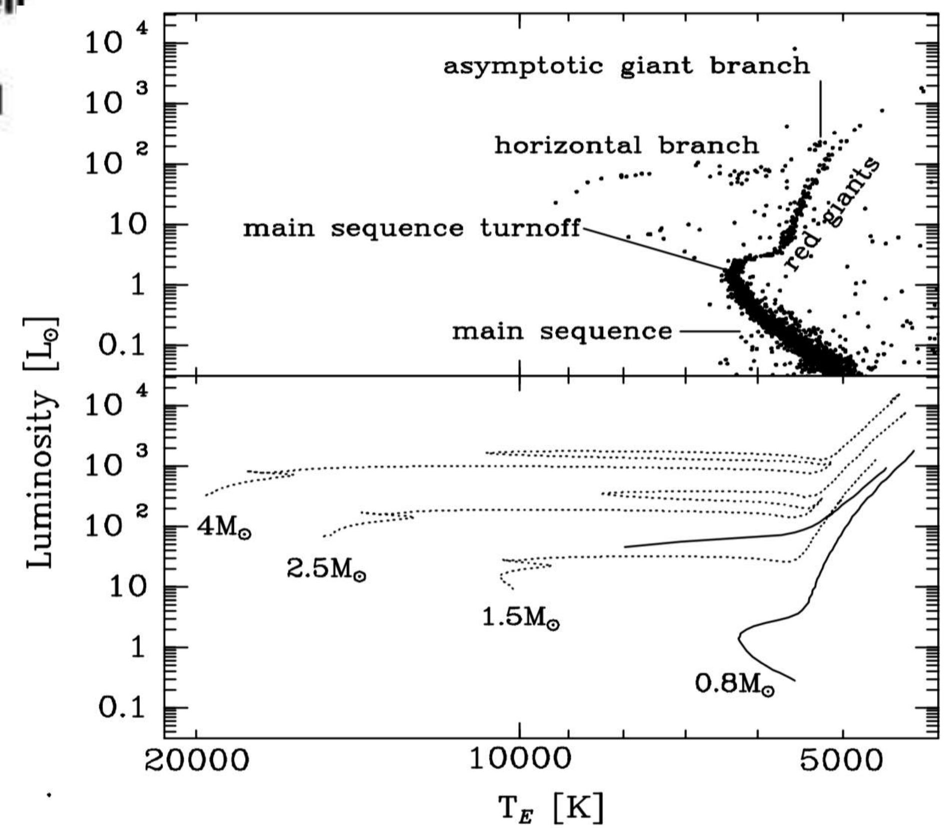
- H continues to burn in shell
- quickly moves to higher T_E (left of H-R), then more slowly to right



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

- <u>$M_0 \lesssim 8\ M_{sun}$:</u>
  - 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

- <u>$M_0 \gtrsim 8\ M_{sun}$:</u>
  - 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

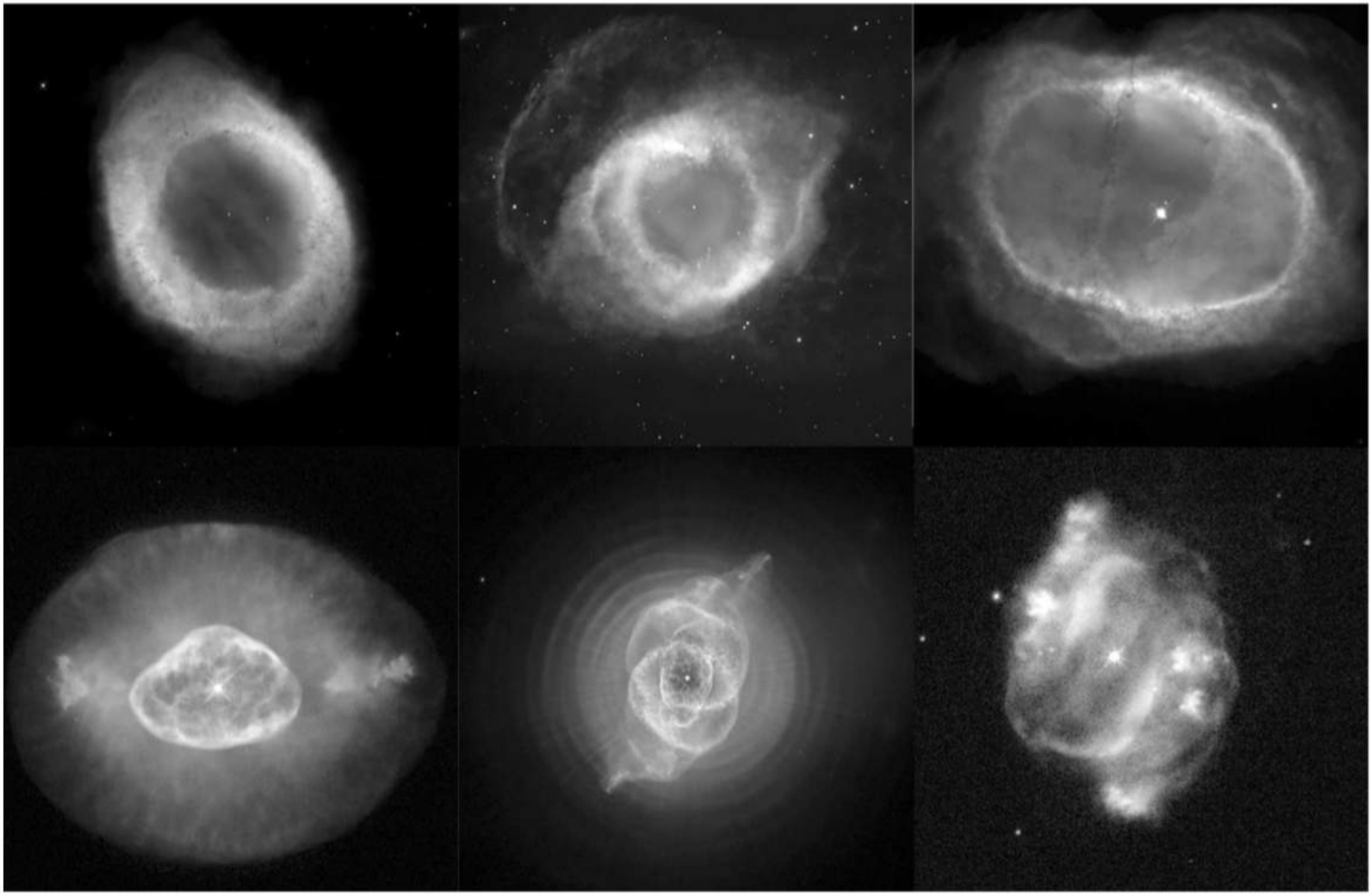
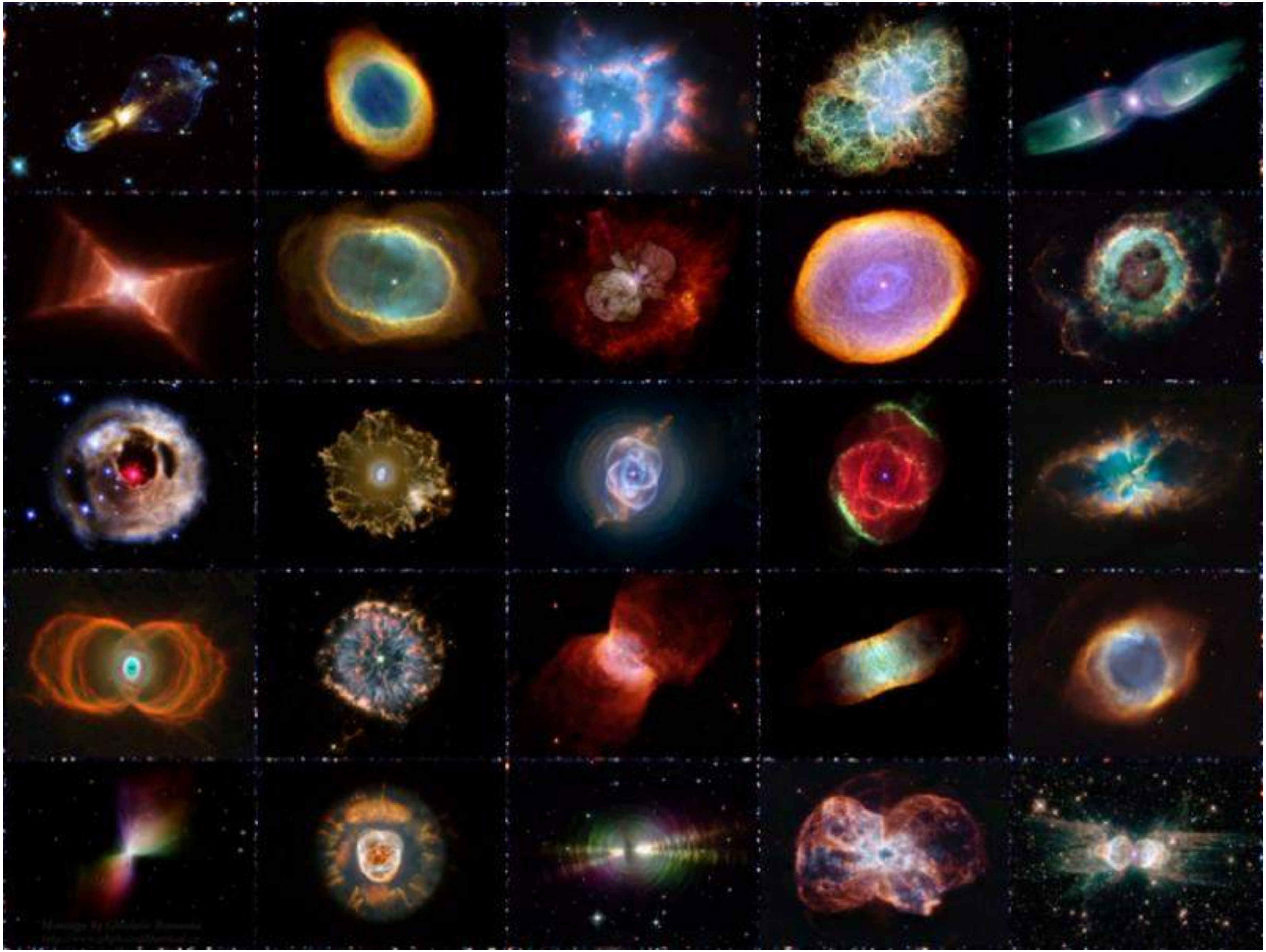


Figure 4.2 Several examples of planetary nebulae, newly formed white dwarfs that irradiate the shells of gas that were previously shed in the final stages of stellar evolution. The shells have diameters of $\approx 0.2 - 1$ pc. Photo credits: M. Meixner, T.A. Rector, B. Balick et al., H. Bond, R. Ciardullo,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

Examples of post-MS mass loss



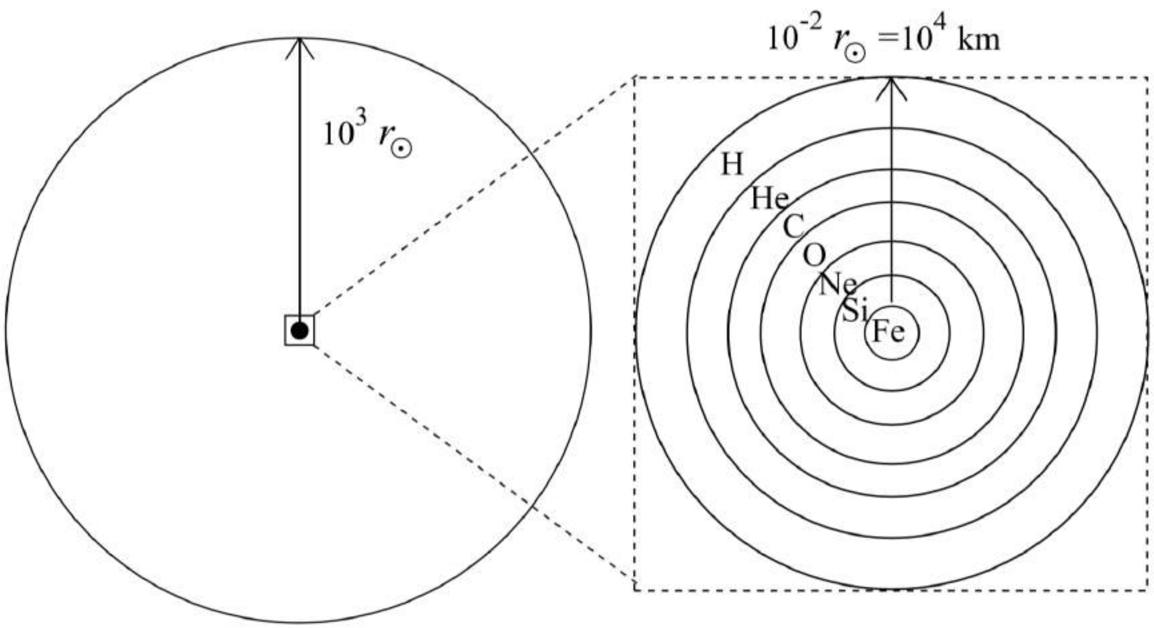
Onion-skin evolution of massive stars on giant branch

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

  - sequence of contraction & heating of inner regions

  - burning & synthesis of heavier elements

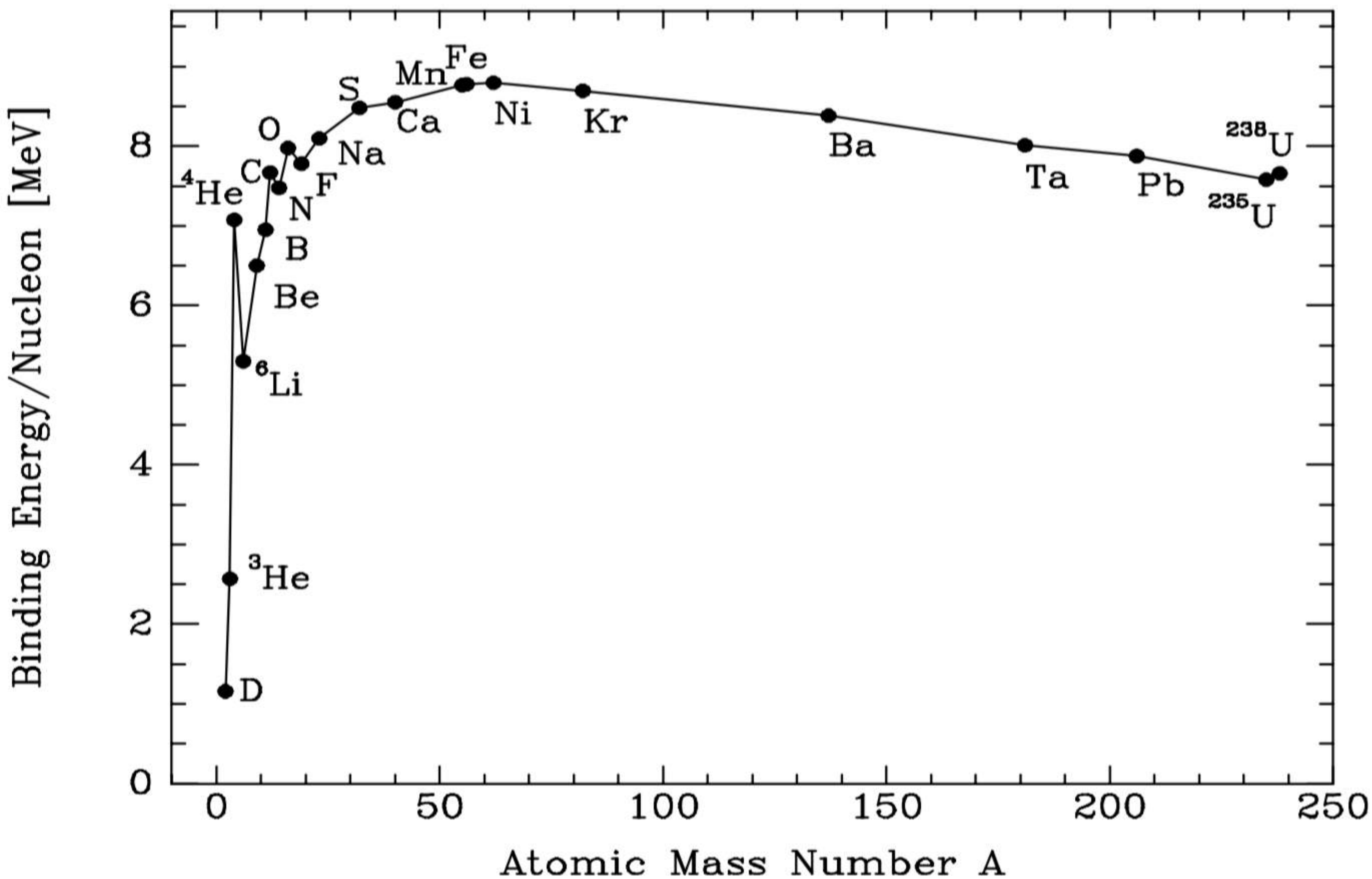
  - progressively faster, e.g. M_0=25 M_{sun}



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 Chandrasekhar mass ~1.4 M_{sun}, 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, ν_e's, depleting core of e^-'s and removing e^- degeneracy P

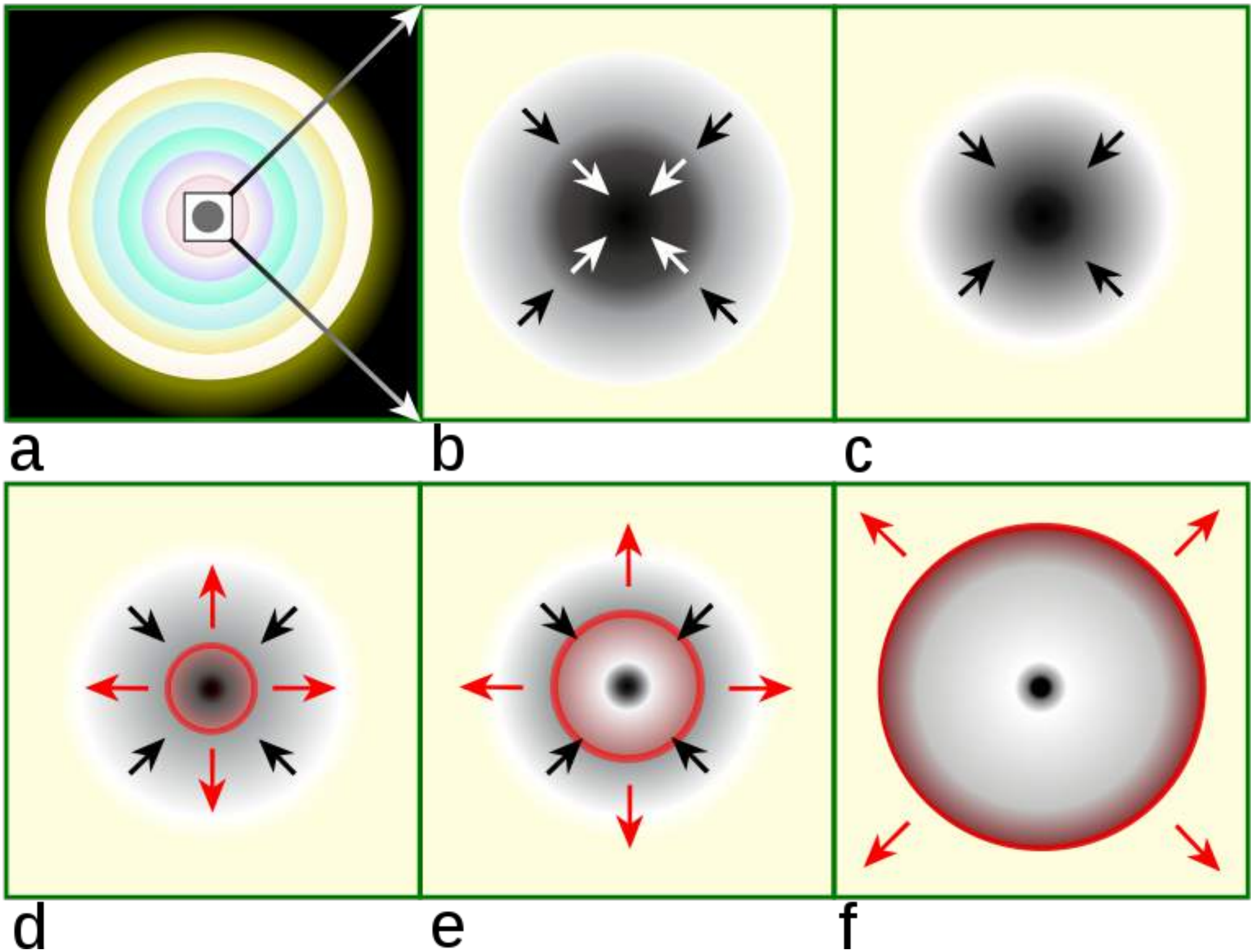
$$\mathrm{e}^- \;+ \mathrm{p} \rightarrow \; \mathrm{n} \;+\; \nu_\mathrm{e}$$

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

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

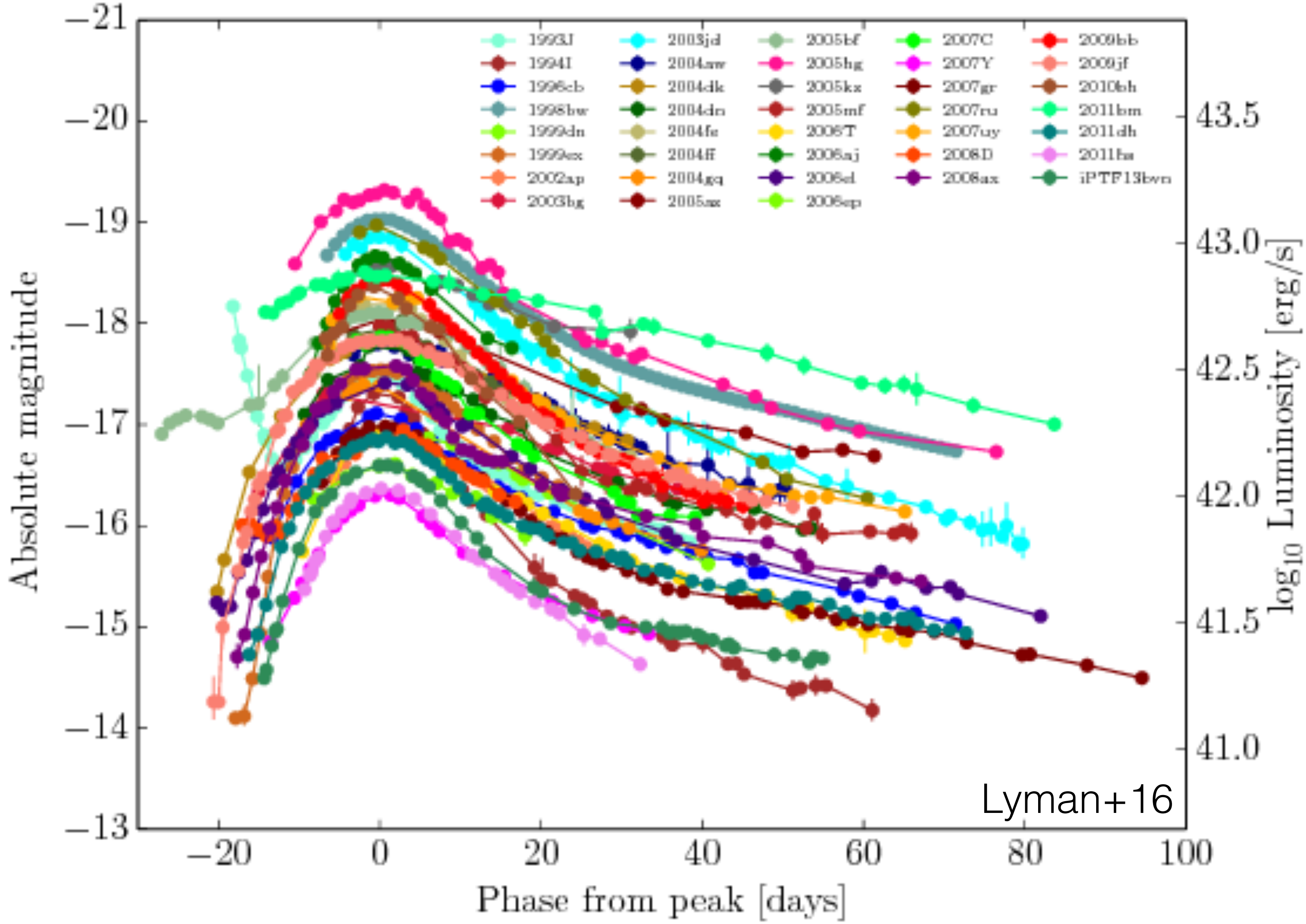
➜ NS formation in few s, ν burst, Type II SN (H lines from envelope in spectrum)

Core collapse-powered supernova



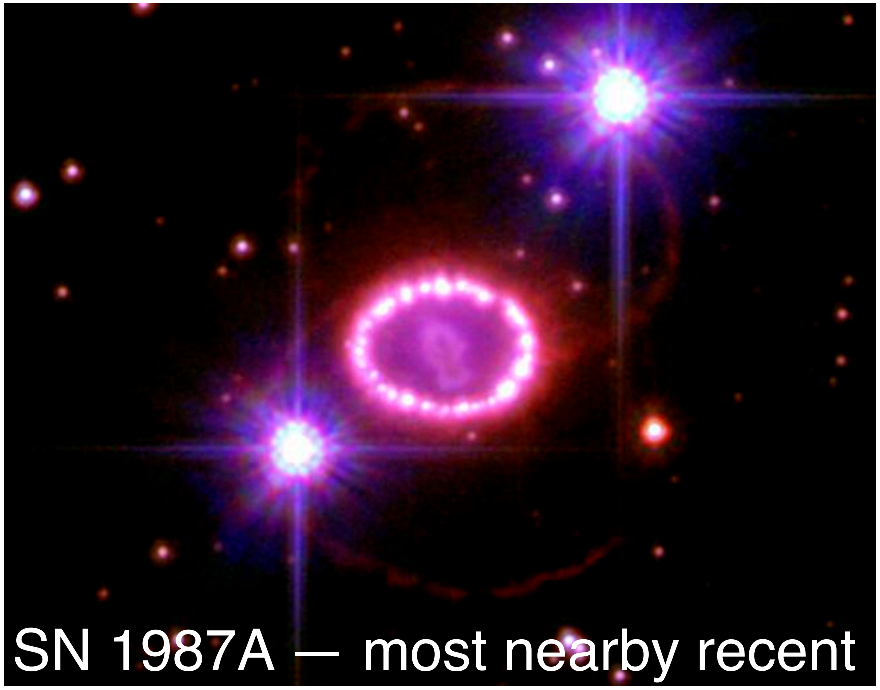
Exactly how the collapse energy powers the supernova explosion is still an active research problem. The latest simulations suggest neutrinos interacting with matter on their way out (the “neutrino mechanism”) can do it.

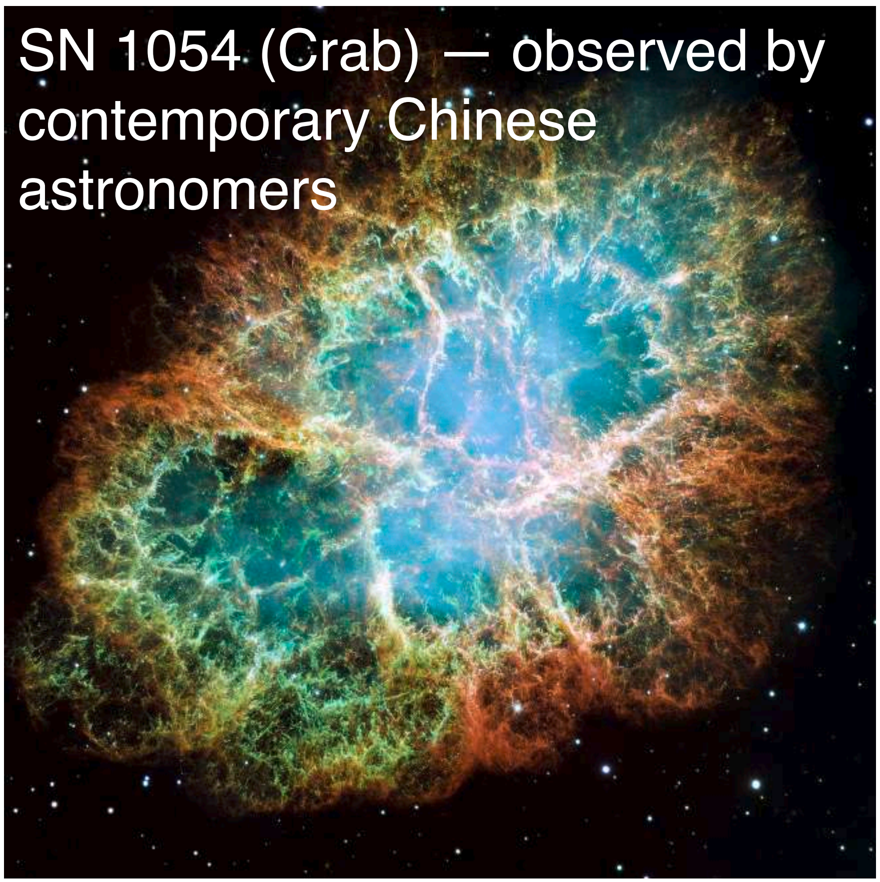
Core collapse SN light curves



Powered by the decay of radioactive elements synthesized when the iron peak is reached. $^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe}$ with half-life 77.7 days.

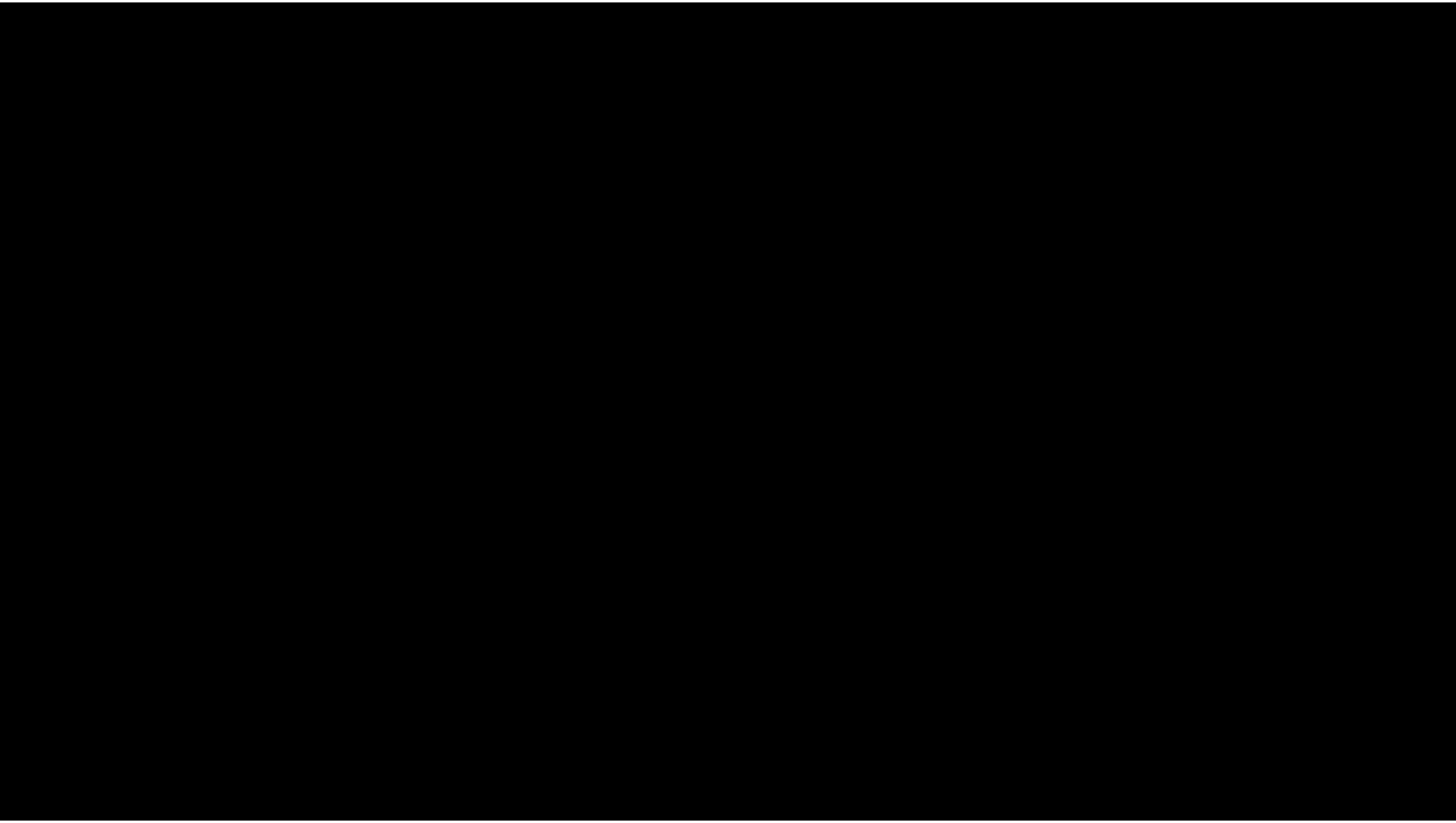
Core collapse SNe at different times and on different scales


SN 1987A — most nearby recent

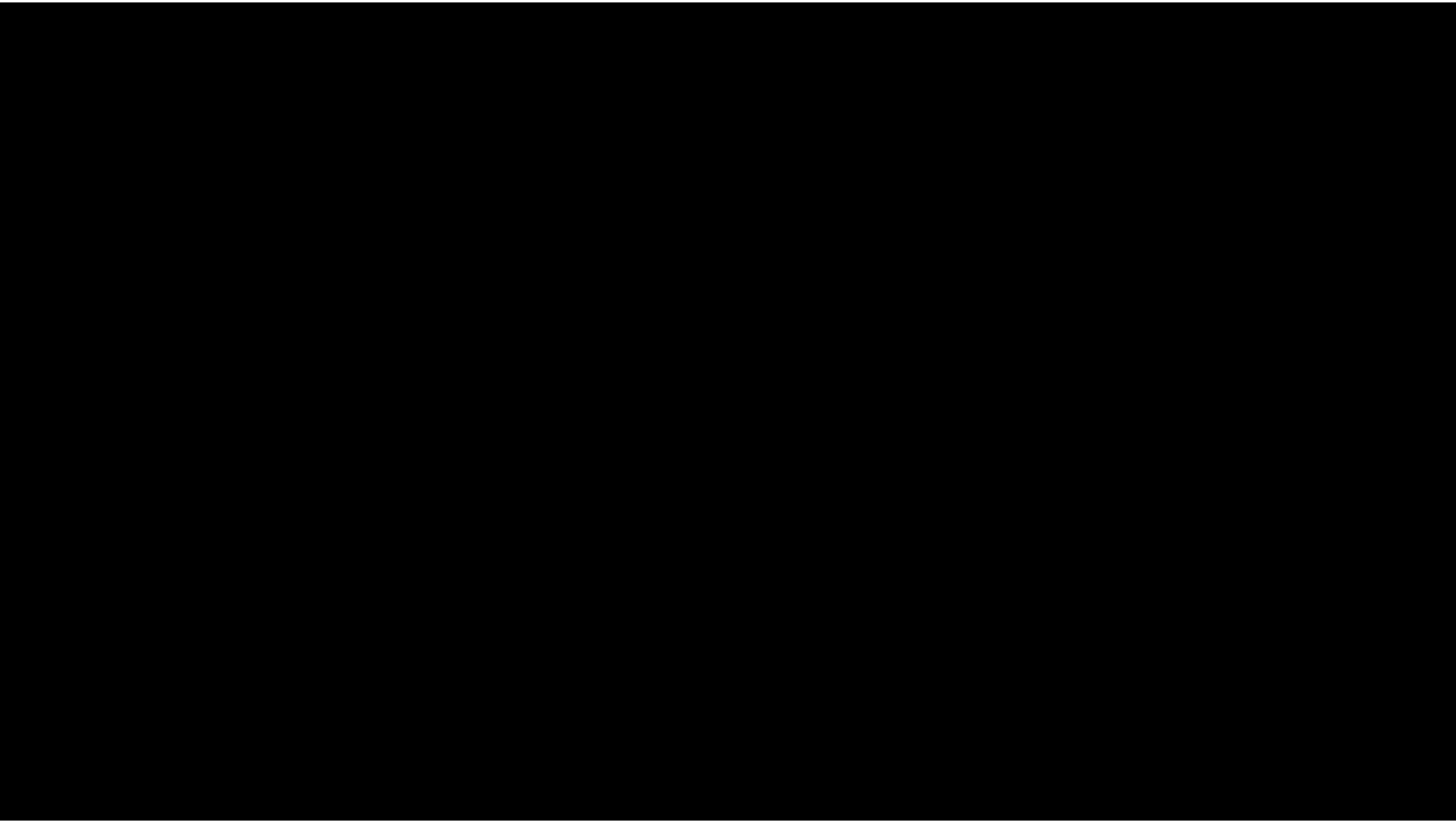

SN 1054 (Crab) — observed by contemporary Chinese astronomers


M82 starburst galaxy with SN-powered galactic wind (~10^6 K gas in blue)

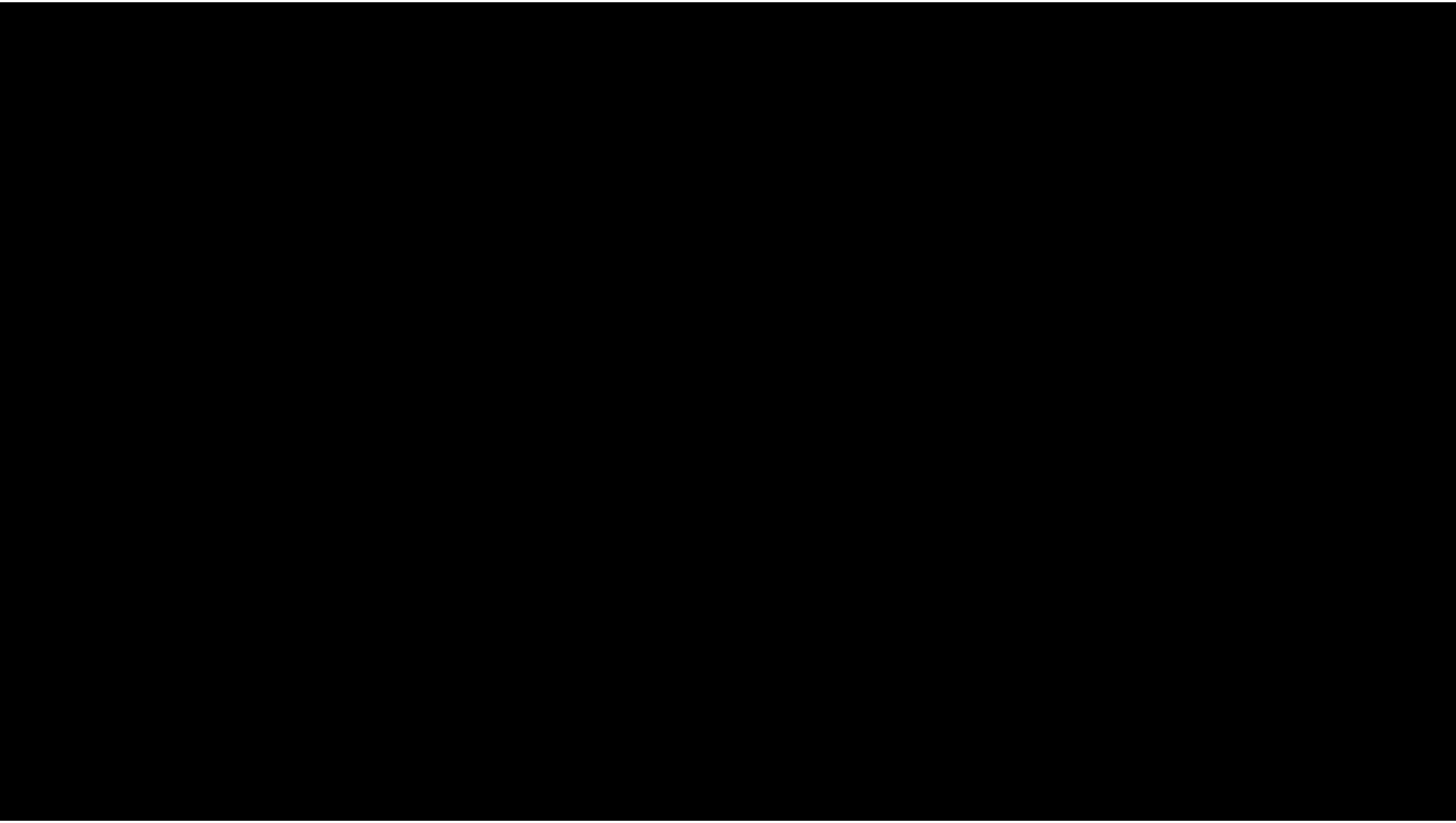
Evolution of single 1 M_{sun} star → WD



Evolution of single 10 M_{sun} star → pulsar



Evolution of single 20 M_{sun} star → BH



Sirius B white dwarf

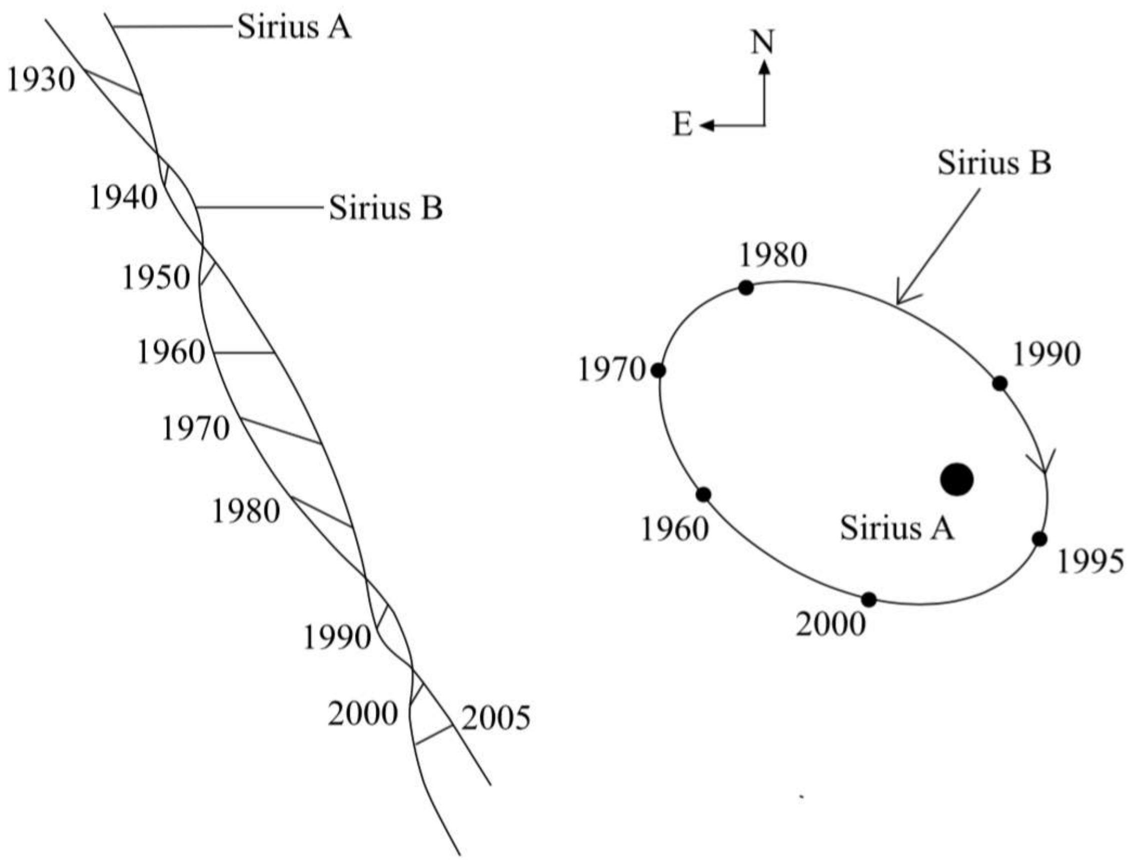


Figure 4.3 Observed motion on the sky, over the past century, of the visual binary consisting of Sirius A and its faint white dwarf companion, Sirius B. On the left are the observed positions due the orbital motions around the center of mass, combined with the proper motion of the system as a whole. 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.

Kepler's 3rd → M~1 M_{sun}

S-B (L, T_{eff}) → R~6,000 km

⇒ ρ ~ 10^6 g cm^{-3}

~1 ton cm^{-3}

Figure from Maoz