Lezione Fermi 11

Luciano Maiani, AA 14-15

Morte di una stella: Novae e Supernovae. Stelle di prima, seconda e terza generazione

Sommario

Molte informazioni e figure, di questa e di altre lezioni, sono prese da: **Universe**, di Roger Freedman e William J. Kaufmann (2007)

1. Fusione nucleare e massa di una stella: da ZAM al destino finale
2. Stelle giganti e collasso del core: le Supernovae di tipo II
3. Supernova SN 1987A
4. Neutrino supernova astronomy?
5. Le stelle "quiete", come il Sole
6. Supernovae Ia: le nane bianche si risvegliano (talvolta)
7. Sintesi di elementi pesanti: dove? quando?
8. Metallicita' e Stelle di diverse generazioni (I, II, III?)

1. Fusione nucleare nelle stelle di grande massa (ZAM)

- La fusione nucleare e’ ostacolata dalla repulsione elettrostatica tra i nuclei, che cresce rapidamente al crescere del numero atomico
- quindi la fusione di elementi complessi (Carbonio, Ossigeno, Neon) richiede temperature di accensione sempre piu’ elevate, che si realizzano solo nelle stelle che partono con masse molto superiori ad 1 massa solare
- in queste stelle si arriva fino alla fusione del Silicio, in cui si arriva a produrre il Ferro, elemento al massimo della curva dell’energia di legame, dopo il quale la fusione non produce, ma piuttosto richiede, energia
- la sintetizzazione di elementi con numero atomico superiore avviene nelle fasi di collasso del nucleo o nei processi di coalescenza di due stelle di neutroni, casi in cui si forma un ambiente ricco di neutroni di alta energia.

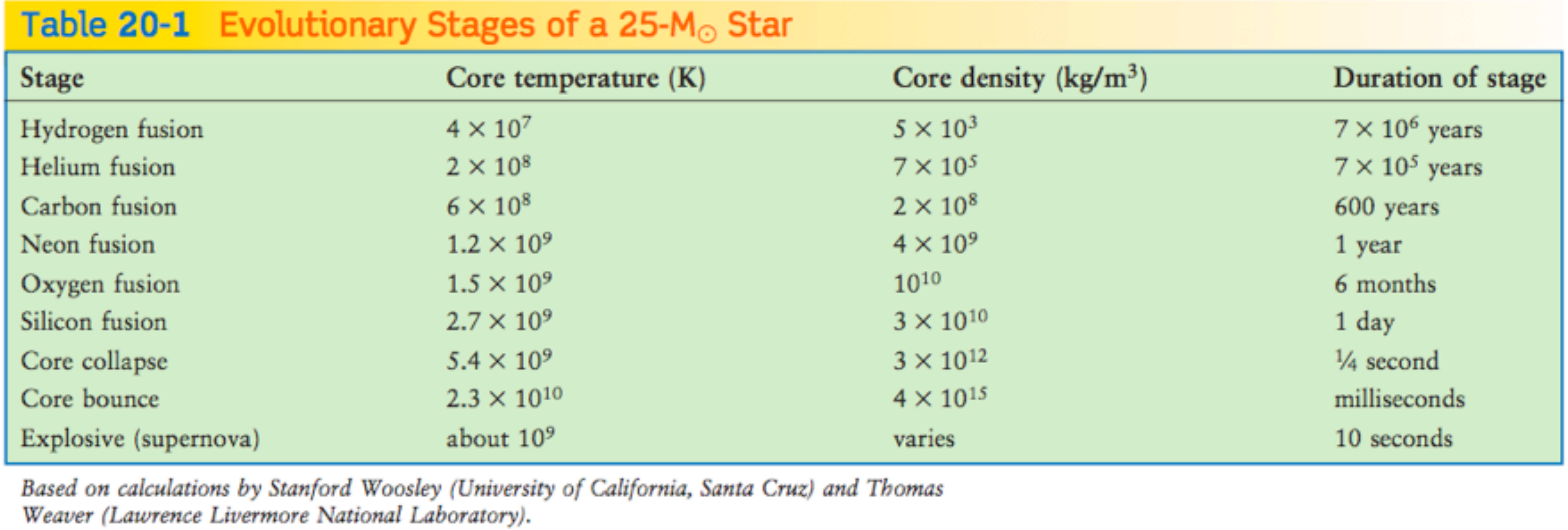


Table 20-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Based on calculations by Stanford Woosley (University of California, Santa Cruz) and Thomas Weaver (Lawrence Livermore National Laboratory).

il collasso del core

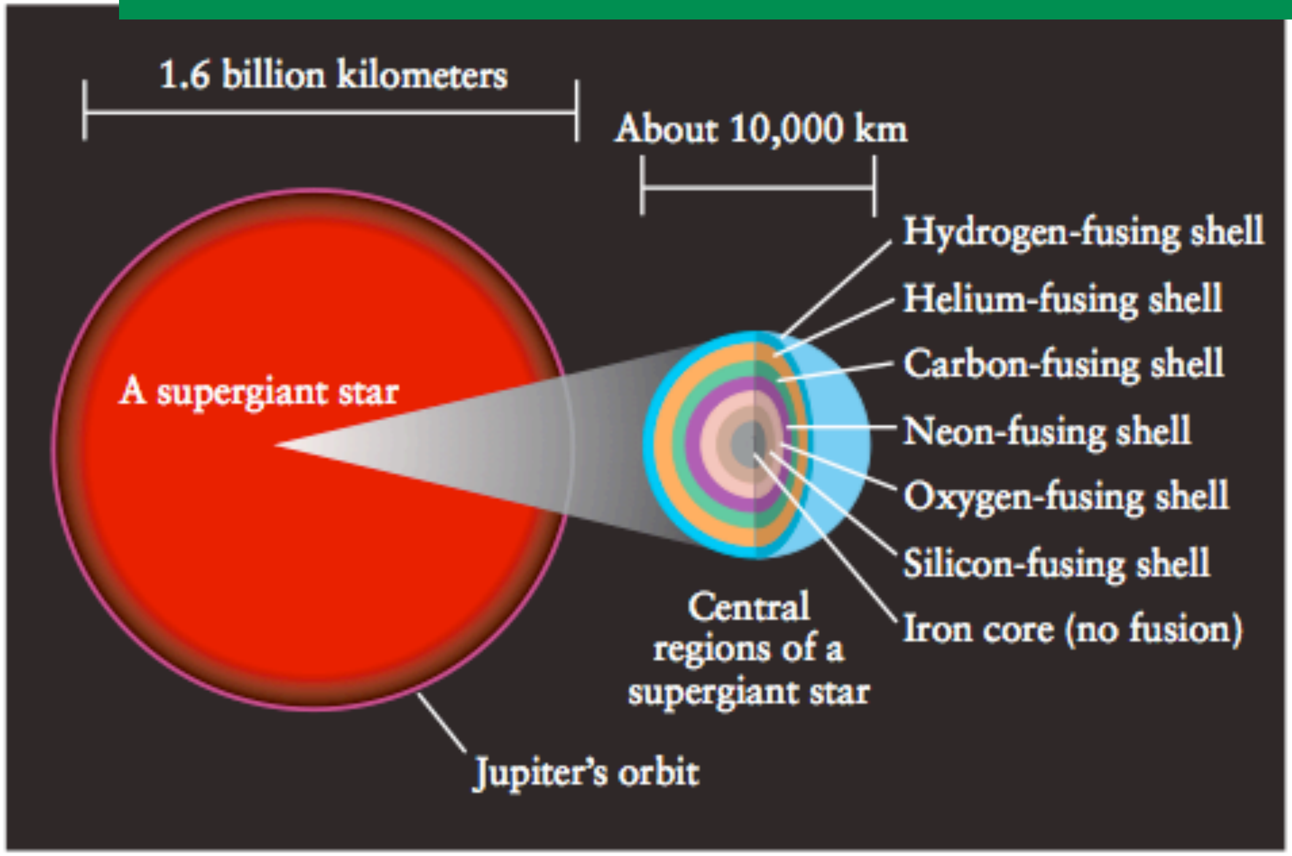


Figure 20-13

The Structure of an Old High-Mass Star Near the end of its life, a star with an initial mass greater than about 8 $M_\odot$ becomes a red supergiant. The star's overall size can be as large as Jupiter's orbit around the Sun. The stars energy comes from a series of concentric fusing shells, all combined within a volume roughly the same size as the Earth. Thermonuclear reactions do not occur within the iron core, because fusion reactions that involve iron absorb energy rather than release it.

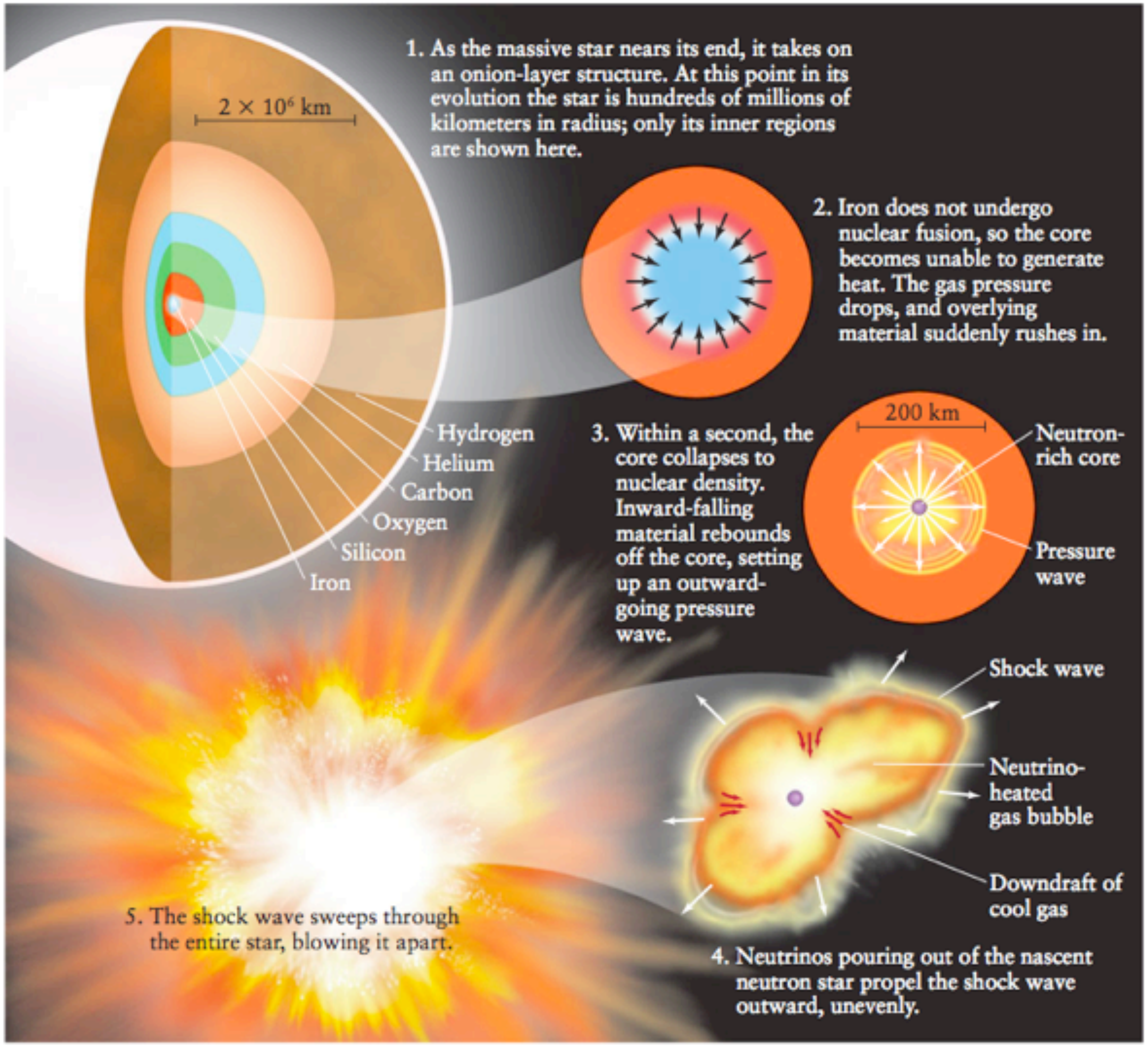
- Il ferro non e' fondibile
- finito il combustibile il core collassa per gravitazione
- nei primi momenti, elettroni e protoni "neutronizzano" e si forma una protostella di neutroni

$$e^- + p \to \nu_e + n$$

- questi neutrini riescono ad uscire con relativa facilita'
- ma la densita' del core aumenta rapidamente fino a non essere piu' trasparente ai neutrini
- alle alte temperature del core le coppie elettrone-positrone vanno all'equilibrio termico con neutrini e antineutrini di tutti i sapori
- le parti esterne del core in collasso "rimbalzano" sul core centrale e si crea un'onda in uscita

- l'onda e' sospinta dai neutrini "termici", che portano una frazione consistente dell'energia gravitazionale liberata
- si crea un'onda di shock, che spazza l'atmosfera esterna, fino ad arrivare all'esterno della stella
- una intensa radiazione di neutrini annuncia la supernova, la luce arrivera' qualche ora dopo

2. Stelle giganti e collasso del core: Supernova di tipo II



1. As the massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.

2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.

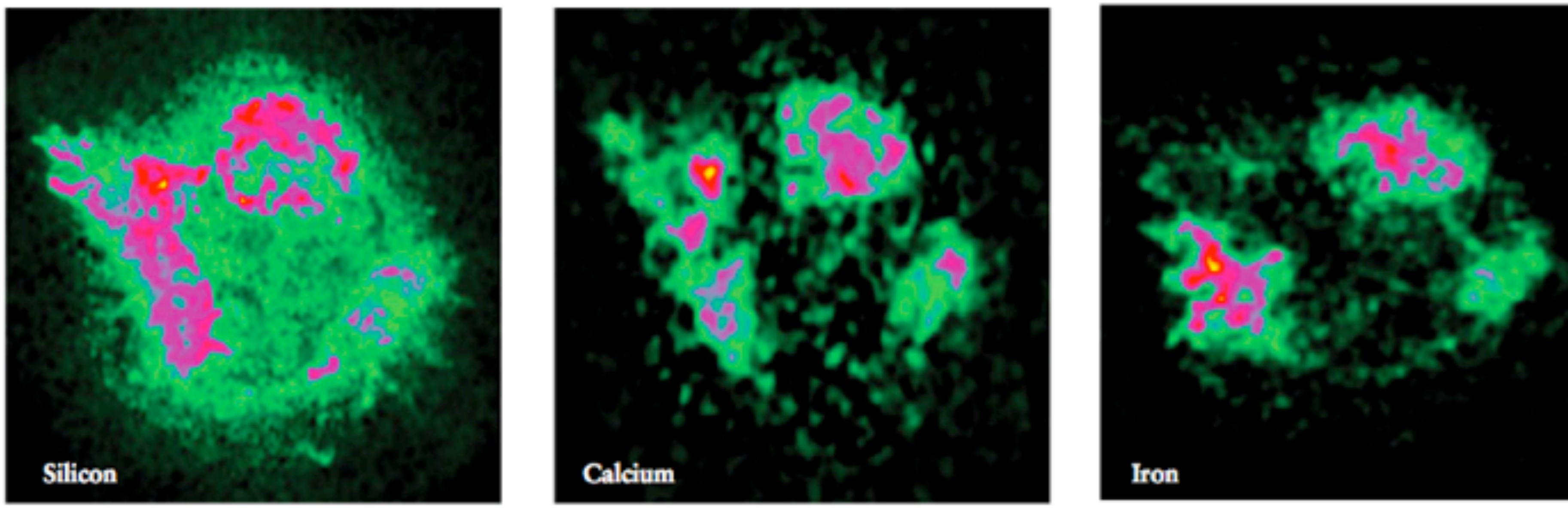
4. Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly.

5. The shock wave sweeps through the entire star, blowing it apart.

Figure 20-14

A Core-Collapse Supernova This series of illustrations depicts our understanding of the last day in the life of a star of more than about 8 $M_\odot$. (Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006)

Simulazione e realta’



(b) Material was ejected in “blobs” from the supernova that produced the Cassiopeia A supernova remnant R I V U X G

Figure 20-15

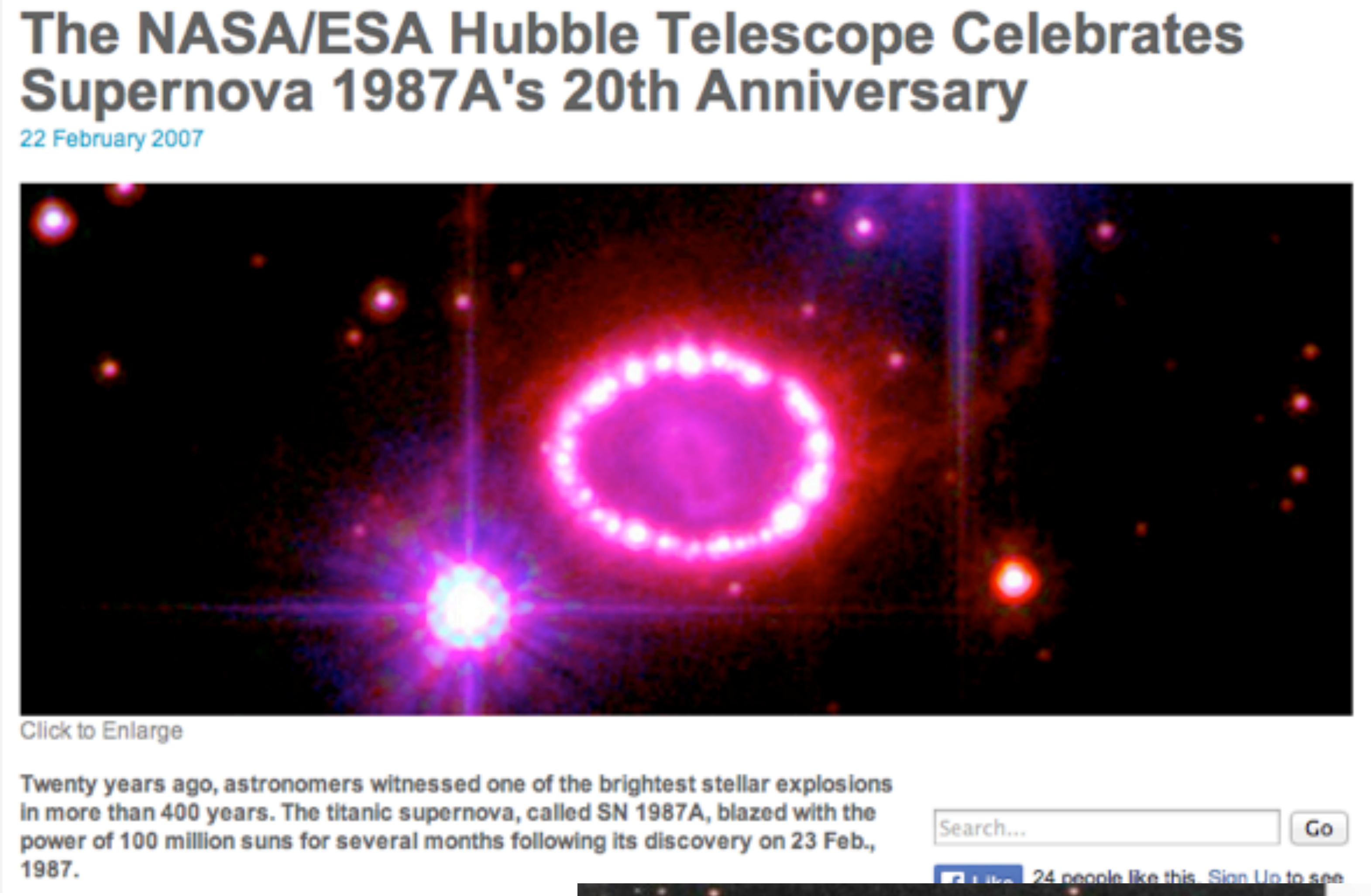
Turbulence in a Core-Collapse Supernova **(a)** This image from a supercomputer simulation show a cross section of a massive star several hours into the supernova explosion. The colors show the turbulent mixing of material from the star's inner regions (turquoise and blue) with hydrogen and helium from the outer layers (green and red). **(b)** Turbulence causes material to be ejected from the supernova in irregular “blobs,” as shown by the
of the supernova remnant Cassiopeia A. Each image was made
X-ray wavelength emitted by a particular element. (Figure 18-2
false-color image of Cassiopeia A made using visible, infrared,
wavelengths.) (a: Konstantinos Kifonidis, Max-Planck-Institut für A
b: U. Hwang et al., NASA/GSFC)

Figure 18-24 R I V U X G

A Supernova Remnant This composite image shows Cassiopeia A, the remnant of a supernova that occurred about 3000 pc (10,000 ly) from Earth. In the roughly 300 years since the supernova explosion, a shock wave has expanded about 3 pc (10 ly) outward in all directions from the explosion site. The shock wave has warmed interstellar dust to a temperature of about 300 K (Spitzer Space Telescope infrared image in red), and has heated interstellar gases to temperatures that range from 10^4 K (Hubble Space Telescope visible-light image in yellow) to 10^7 K (Chandra X-ray Observatory X-ray image in green and blue). (NASA; JPL-Caltech; and O. Krause, Steward Observatory)

3. La Supernova SN 1987A (Nube di Magellano)

- SN 1987A was discovered by Ian Shelton and Oscar Duhalde at the Las Campanas Observatory in Chile on February 24, 1987, and within the same 24 hours independently by Albert Jones in New Zealand.[4] On March 4–12, 1987, it was observed from space by Astron, the largest ultraviolet space telescope of that time.[7]
- Approximately two to three hours before the visible light from SN 1987A reached Earth, a burst of neutrinos was observed at three separate neutrino observatories. This is likely due to neutrino emission, which occurs simultaneously with core collapse, but preceding the emission of visible light. Transmission of visible light is a slower process that occurs only after the shock wave reaches the stellar surface.[13] At 07:35 UT, Kamiokande II detected 11 antineutrinos; IMB, 8 antineutrinos; and Baksan, 5 antineutrinos; in a burst lasting less than 13 seconds.
- Approximately three hours earlier, the Mont Blanc liquid scintillator detected a five-neutrino burst, but this is generally not believed to be associated with SN 1987A.[10]
- Although the actual neutrino count was only 24, it was a significant rise from the previously observed background level. This was the first time neutrinos known to be emitted from a supernova had been observed directly, which marked the beginning of neutrino astronomy. The observations were consistent with theoretical supernova models in which 99% of the energy of the collapse is radiated away in the form of neutrinos. The observations are also consistent with the models' estimates of a total neutrino count of 10^{58} with a total energy of 10^{46} joules.[14]
- The neutrino measurements allowed upper bounds on neutrino mass and charge, as well as the number of flavors of neutrinos and other properties.[10] For example, the data show that within 5% confidence, the rest mass of the electron neutrino is at most 16 eV, 30-millionths the mass of an electron. The data suggests that the total number of neutrino flavors is at most 8 but other observations and experiments give tighter estimates. Many of these results have since been confirmed or tightened by other neutrino experiments such as more careful analysis of solar neutrinos and atmospheric neutrinos as well as experiments with artificial neutrino sources.



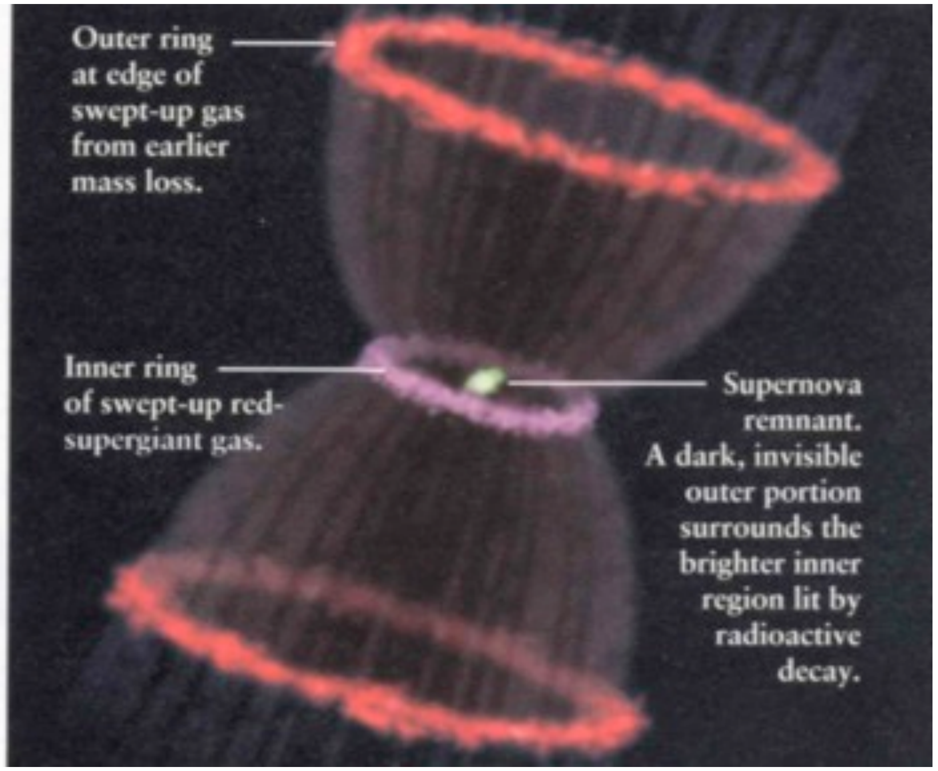
The NASA/ESA Hubble Telescope Celebrates Supernova 1987A's 20th Anniversary

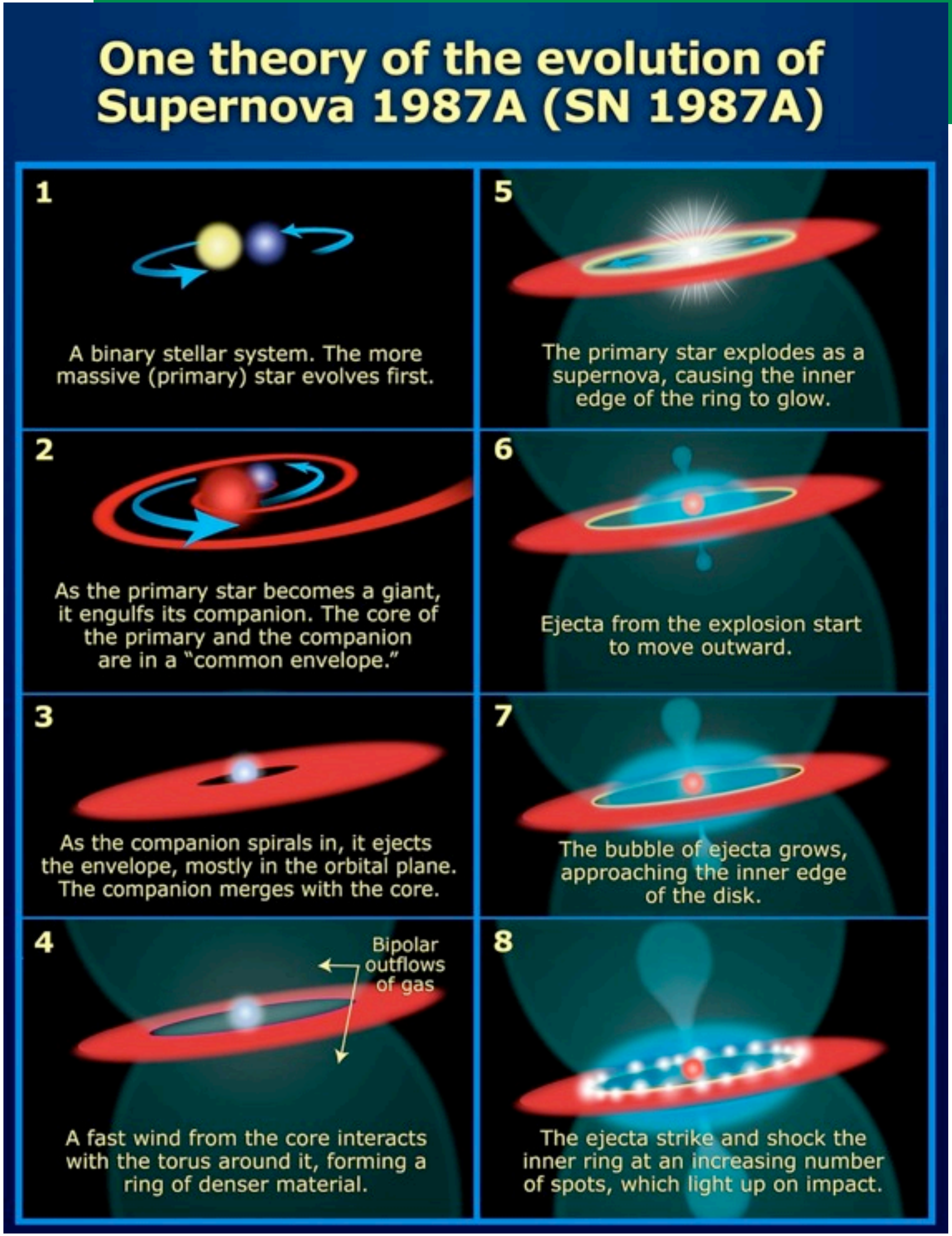
22 February 2007

Click to Enlarge

Twenty years ago, astronomers witnessed one of the brightest stellar explosions in more than 400 years. The titanic supernova, called SN 1987A, blazed with the power of 100 million suns for several months following its discovery on 23 Feb., 1987.

- Vista con il Telescopio Hubble, sette anni dopo, SN1987A ha svilppato una struttura ad anelli
- ricostruiti nello spazio, gli anelli disegnano una forma a clessidra, che incanala i gas residui della supernova
- al centro, i gas emettono luce a causa del decadimento dei radioisotopi prodotti durante il bounce





One theory of the evolution of Supernova 1987A (SN 1987A)

1 A binary stellar system. The more massive (primary) star evolves first.

2 As the primary star becomes a giant, it engulfs its companion. The core of the primary and the companion are in a "common envelope."

3 As the companion spirals in, it ejects the envelope, mostly in the orbital plane. The companion merges with the core.

4 A fast wind from the core interacts with the torus around it, forming a ring of denser material.

5 The primary star explodes as a supernova, causing the inner edge of the ring to glow.

6 Ejecta from the explosion start to move outward.

7 The bubble of ejecta grows, approaching the inner edge of the disk.

8 The ejecta strike and shock the inner ring at an increasing number of spots, which light up on impact.

4. Radiografia della Supernova con i Neutrini?

- Eventi di anti-ν_e registrati il 23 febbraio 1987 ai rivelatori Kamiokande, IMB e Baksan

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

rivelazione

- ***Non*** sono collegati ai neutrini che, nei primi microsecondi, segnalano la neutronizzazione del core attraverso il processo di decadimento beta inverso:

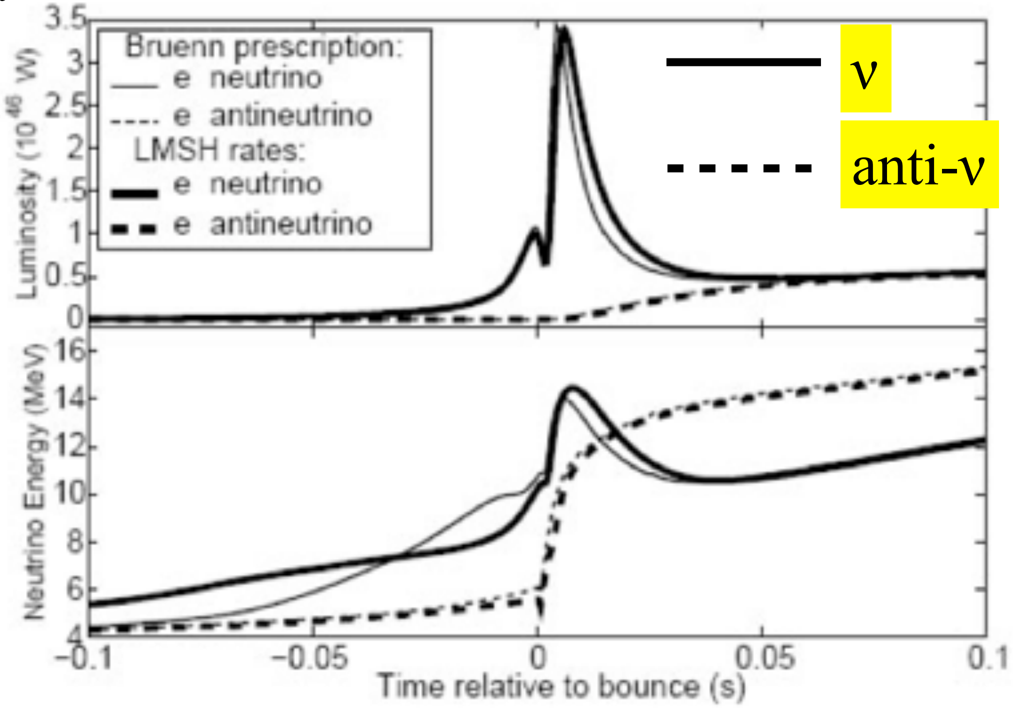
$$e^- + p \rightarrow \nu_e + n$$

neutronizzazione

- ma sono dovuti agli antineutrini emessi dopo il collasso del core, quando la protostella di neutroni si e' termalizzata

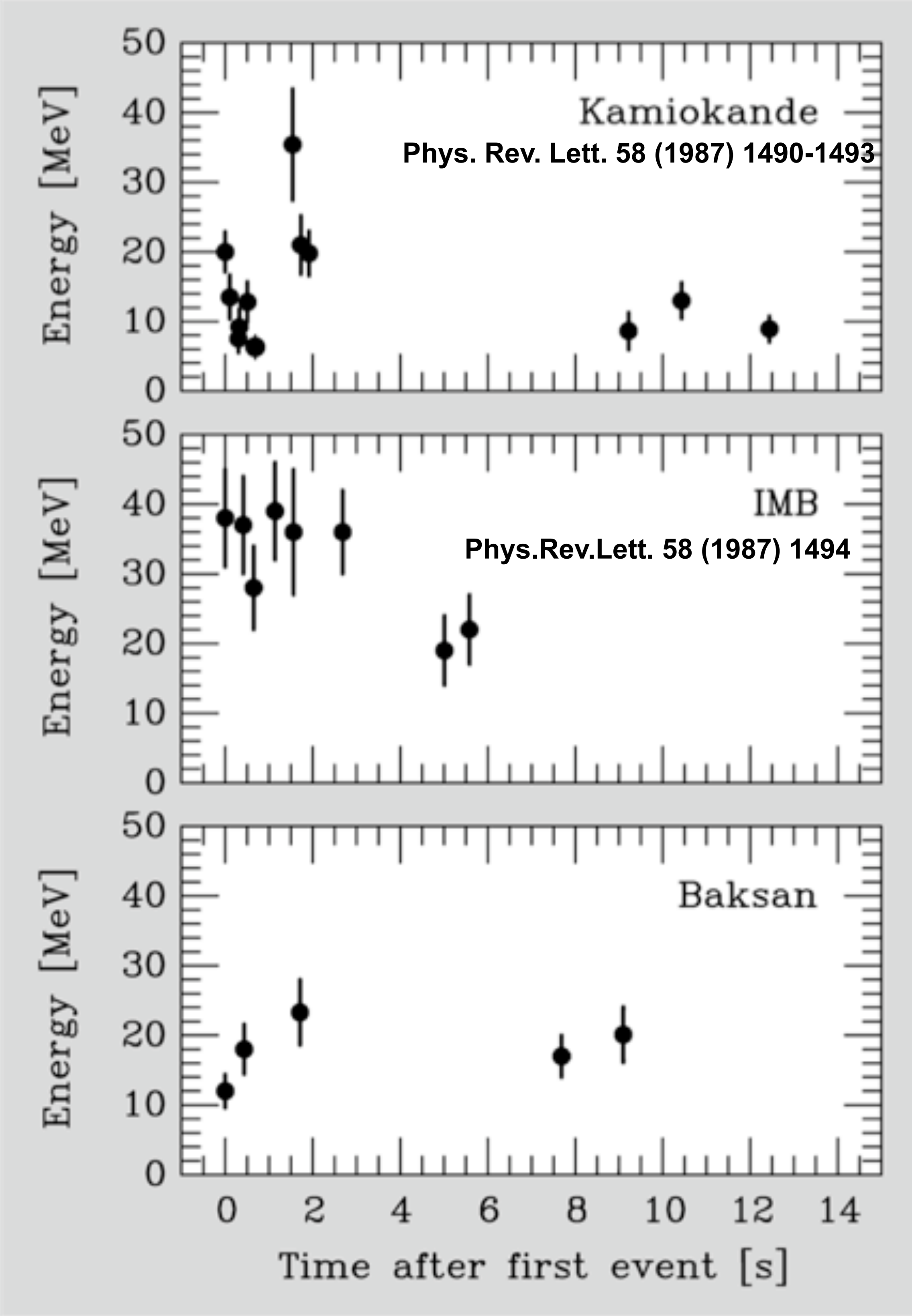
Luminosita'

Energia



(PRL **91 201102**)

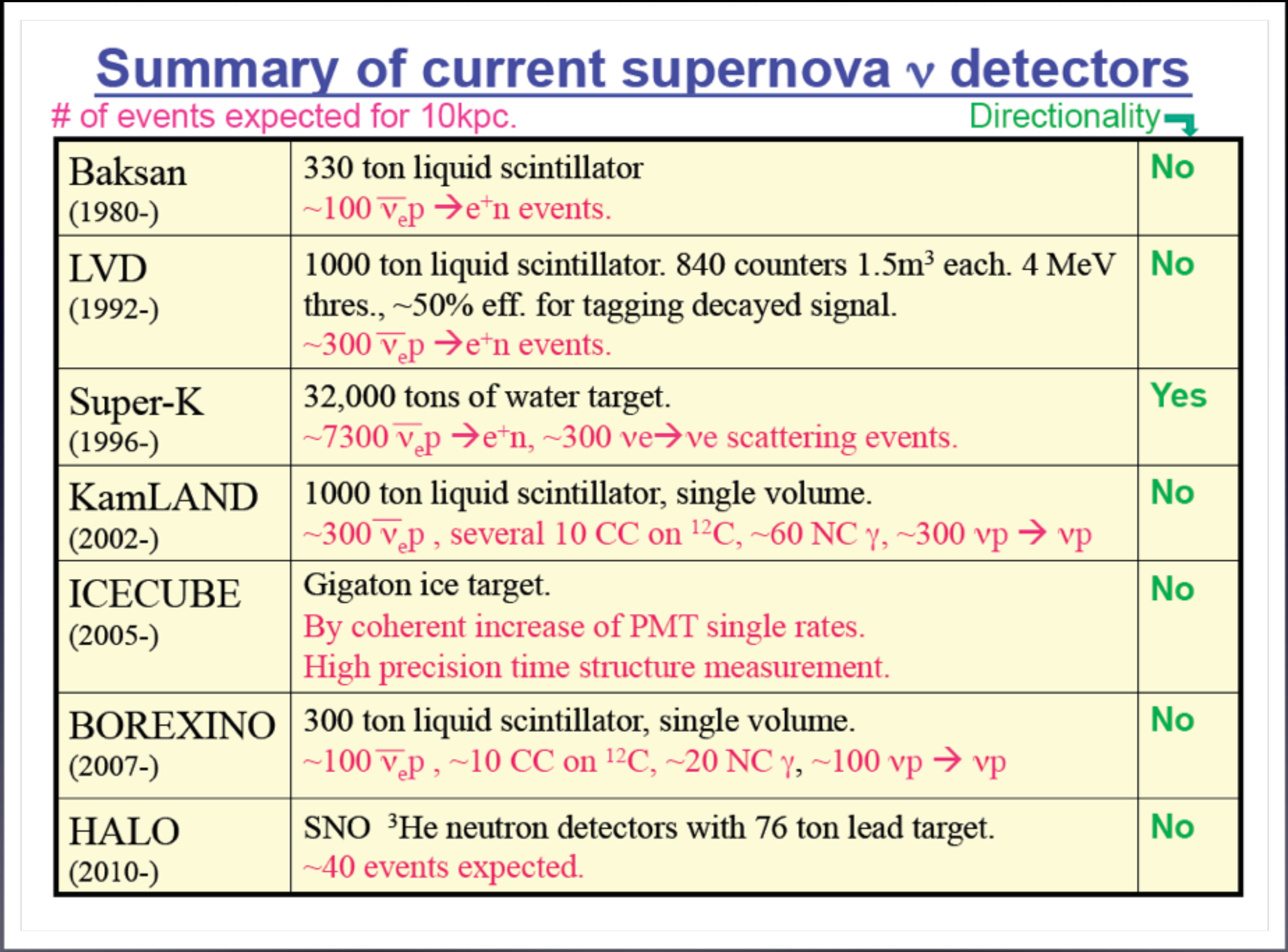
Luminosity and energy of the neutronization pulse. Note the smooth increase for $\bar{\nu}_e$ and the peak structure for ν_e.



Phys. Rev. Lett. 58 (1987) 1490-1493

Phys.Rev.Lett. 58 (1987) 1494

Fabio Cavanna, Yale e INFN L'Aquila, 2014



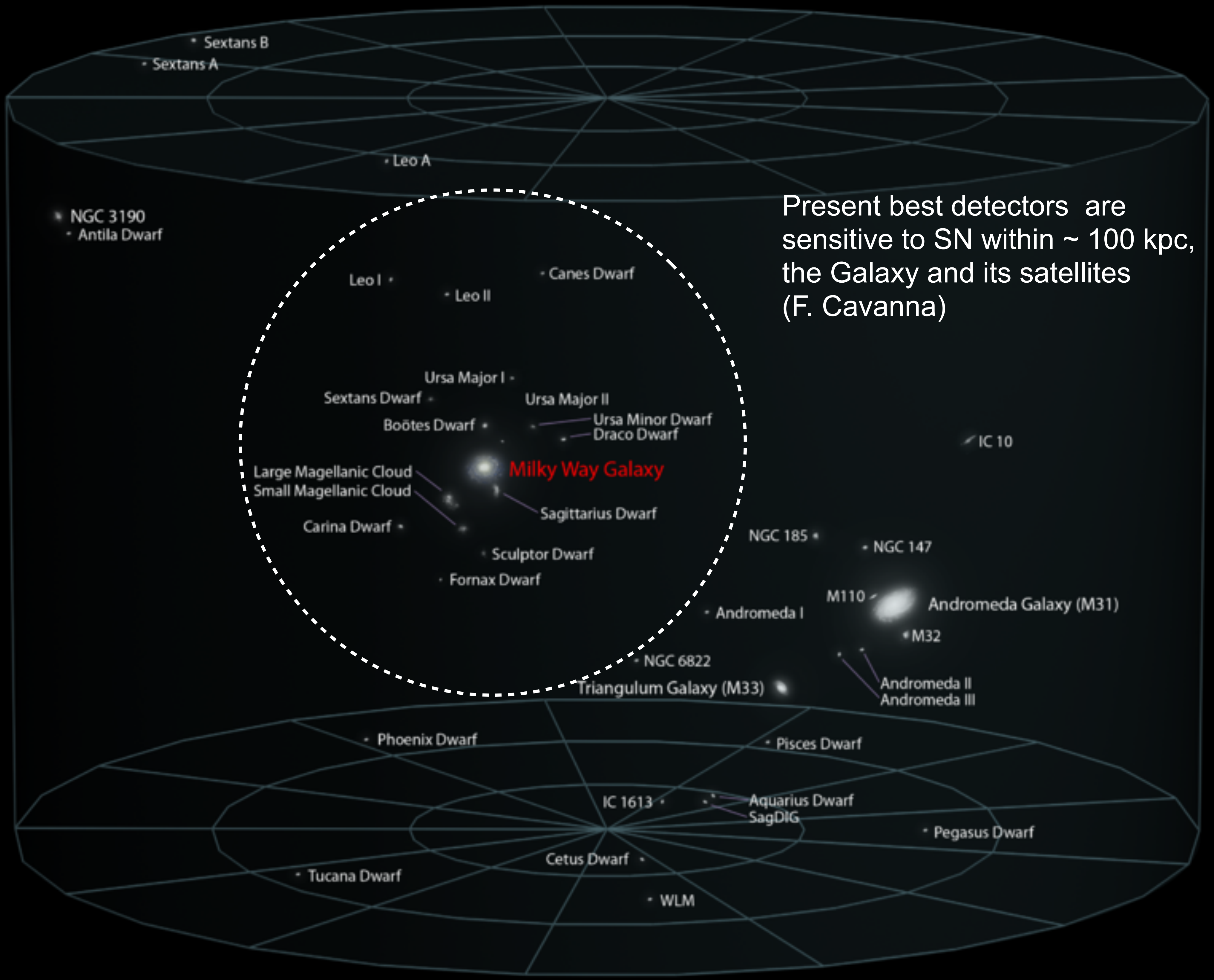
Summary of current supernova ν detectors

of events expected for 10kpc.

Directionality

Baksan (1980-)	330 ton liquid scintillator ~100 $\overline{\nu}_e p \to e^+ n$ events.	No
LVD (1992-)	1000 ton liquid scintillator. 840 counters 1.5m^3 each. 4 MeV thres., ~50% eff. for tagging decayed signal. ~300 $\overline{\nu}_e p \to e^+ n$ events.	No
Super-K (1996-)	32,000 tons of water target. ~7300 $\overline{\nu}_e p \to e^+ n$, ~300 $\nu e \to \nu e$ scattering events.	Yes
KamLAND (2002-)	1000 ton liquid scintillator, single volume. ~300 $\overline{\nu}_e p$, several 10 CC on ^{12}C, ~60 NC γ, ~300 $\nu p \to \nu p$	No
ICECUBE (2005-)	Gigaton ice target. By coherent increase of PMT single rates. High precision time structure measurement.	No
BOREXINO (2007-)	300 ton liquid scintillator, single volume. ~100 $\overline{\nu}_e p$, ~10 CC on ^{12}C, ~20 NC γ, ~100 $\nu p \to \nu p$	No
HALO (2010-)	SNO ^{3}He neutron detectors with 76 ton lead target. ~40 events expected.	No

Local Galactic Group



Present best detectors are sensitive to SN within ~ 100 kpc, the Galaxy and its satellites (F. Cavanna)

5. Le stelle “quiete”, come il Sole

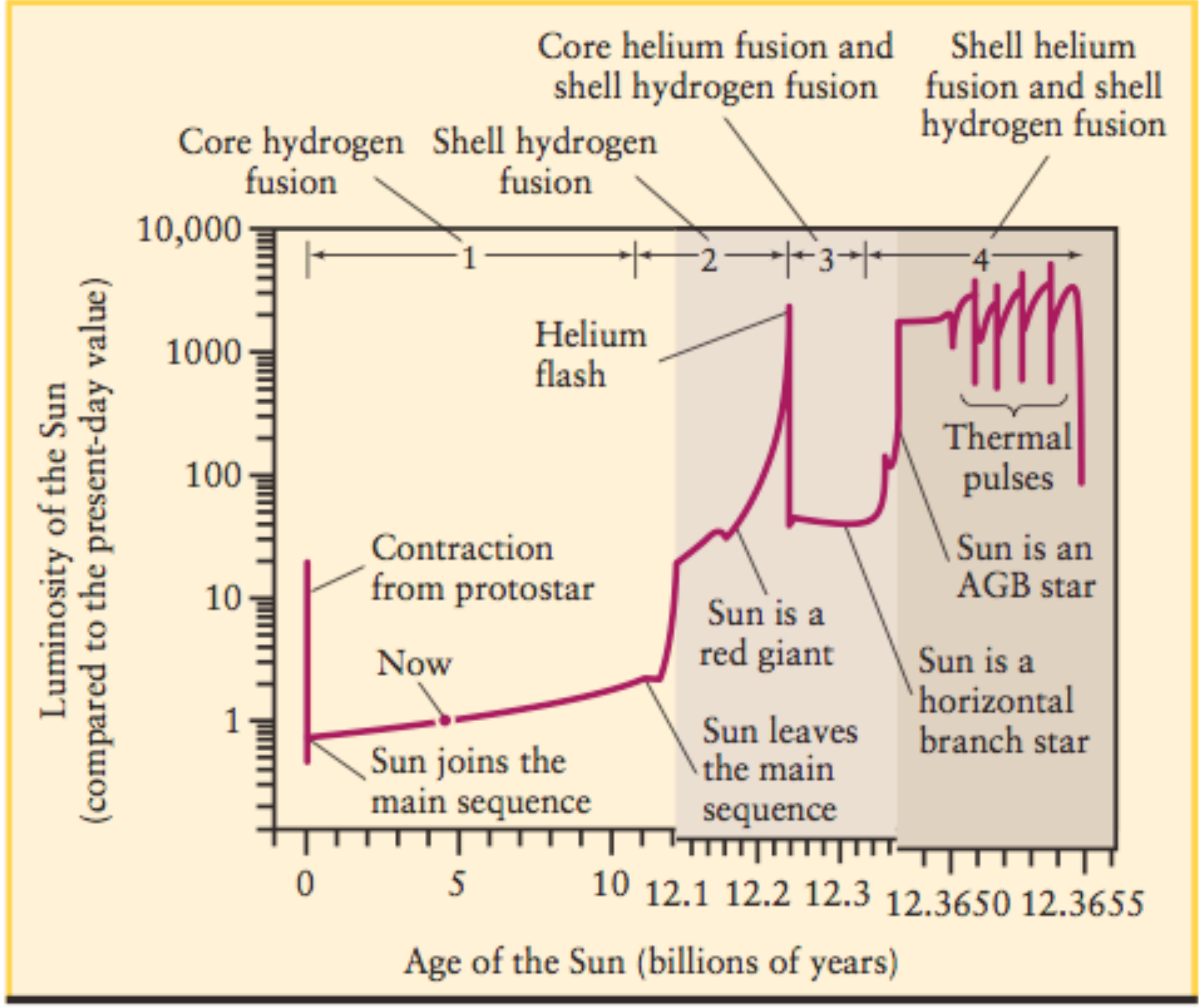
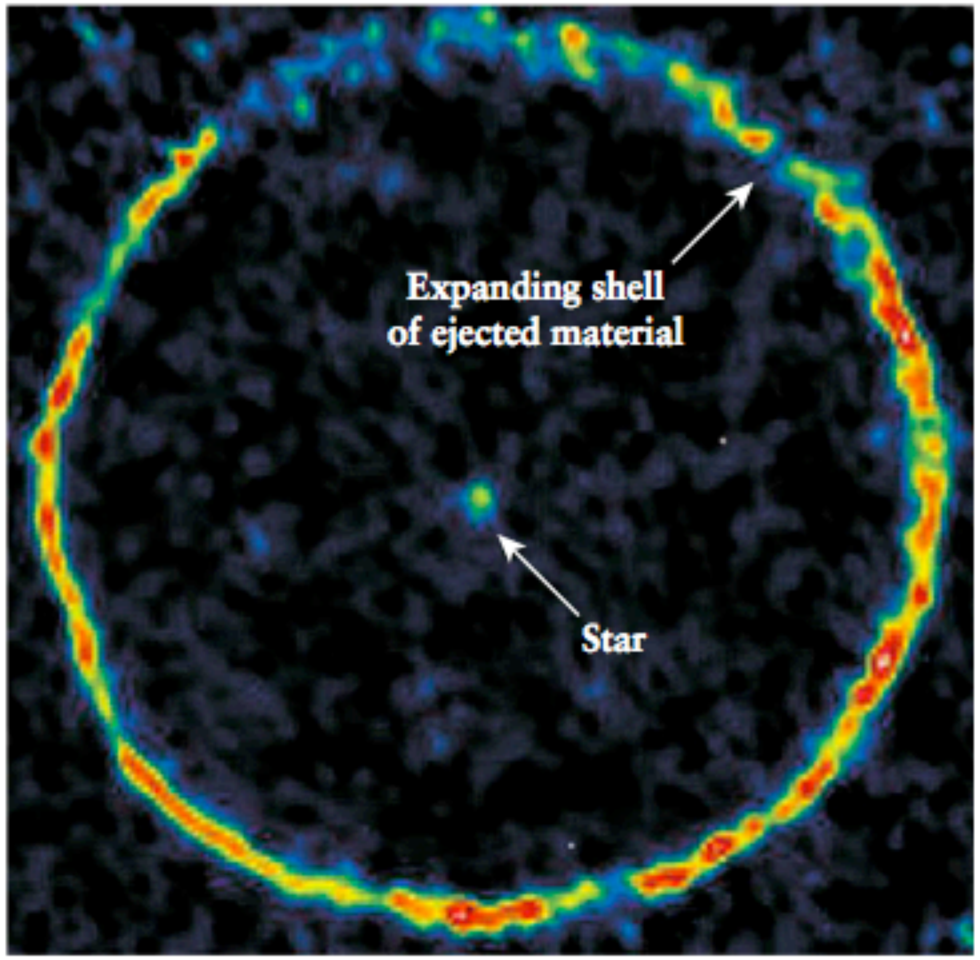


Figure 20-5

Further Stages in the Evolution of the Sun This diagram, which shows how the luminosity of the Sun (a 1-$M_\odot$ star) changes over time, is an extension of Figure 19-8. We use different scales for the final stages because the evolution is so rapid. During the AGB stage there are brief periods of runaway helium fusion, causing spikes in luminosity called thermal pulses. (Adapted from Mark A. Garlick, based on calculations by I.-Juliana Sackmann and Kathleen E. Kramer)



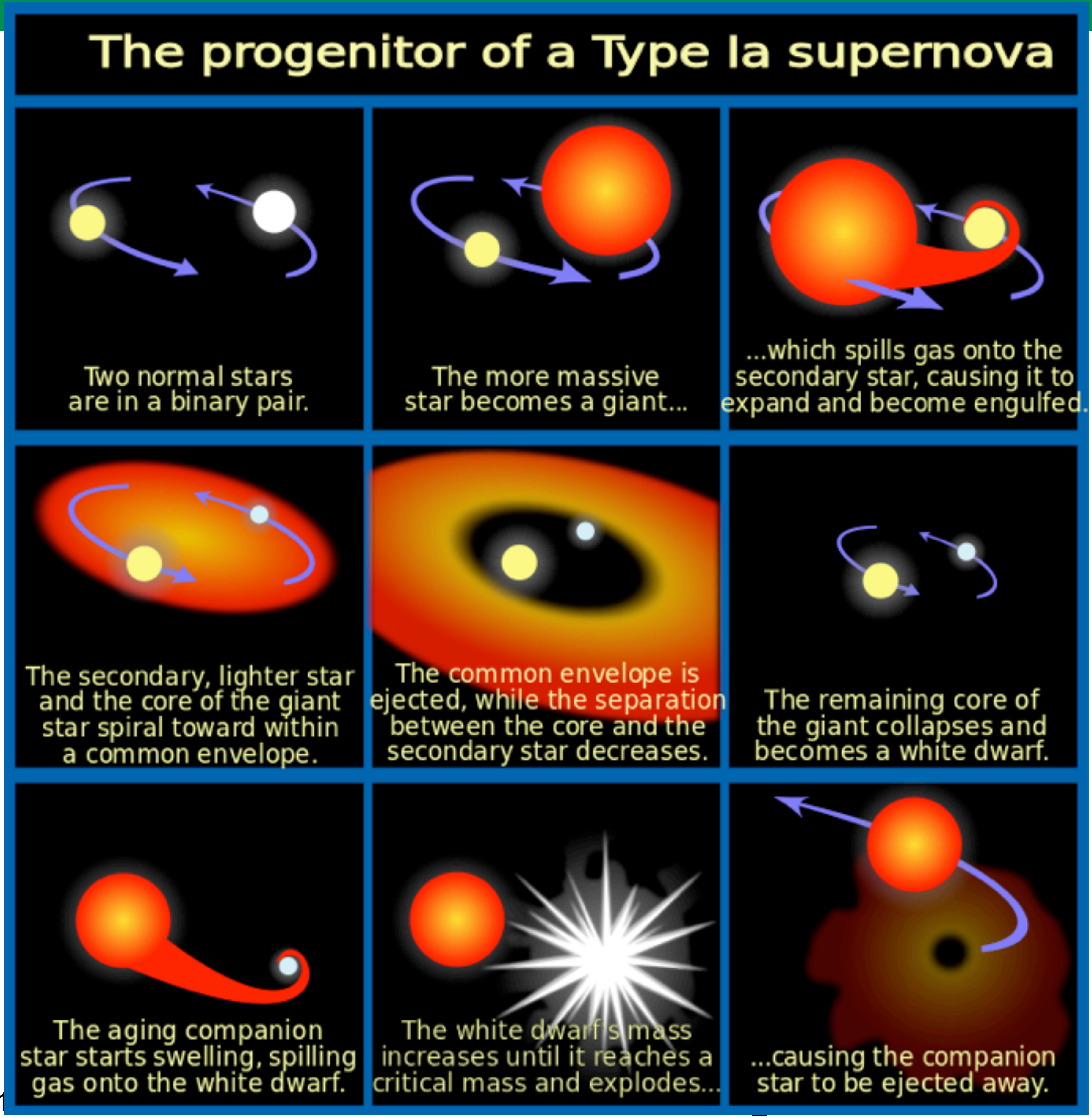
WEB LINK 20.3

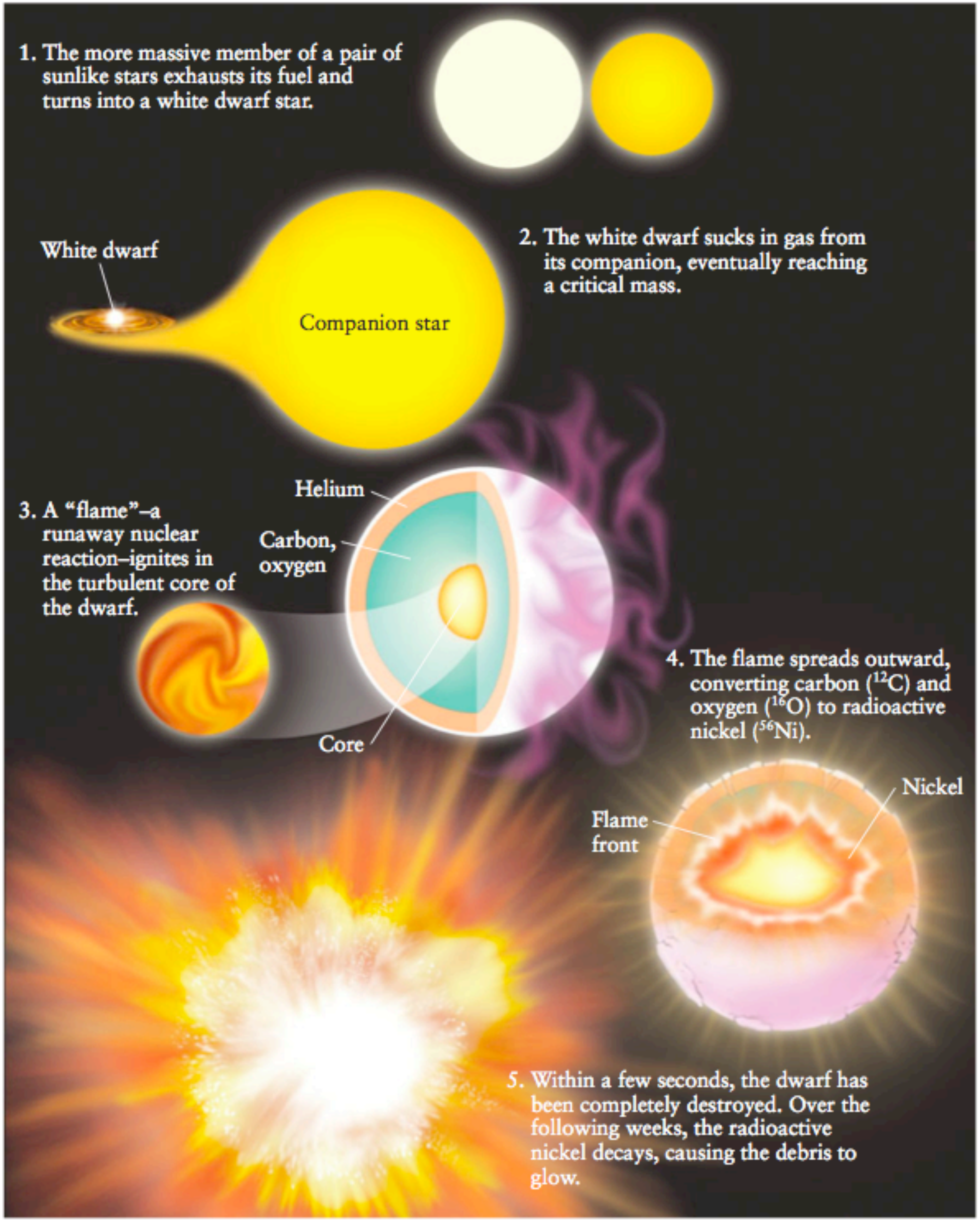
Figure 20-4 R I V U X G

A Carbon Star TT Cygni is an AGB star in the constellation Cygnus that ejects some of its carbon-rich outer layers into space. Some of the ejected carbon combines with oxygen to form molecules of carbon monoxide (CO), whose emissions can be detected with a radio telescope. This radio image shows the CO emissions from a shell of material that TT Cygni ejected some 7000 years ago. Over that time, the shell has expanded to a diameter of about $\frac{1}{2}$ light-year. (H. Olofsson, Stockholm Observatory, et al./NASA)

- gli strati esterni della stella sono sospinti gentilmente nello spazio
- il core, finito il combustibile, e’ sostenuto dalla pressione degli elettroni: una nana bianca

6. Supernova Ia: le nane bianche si risvegliano (talvolta)

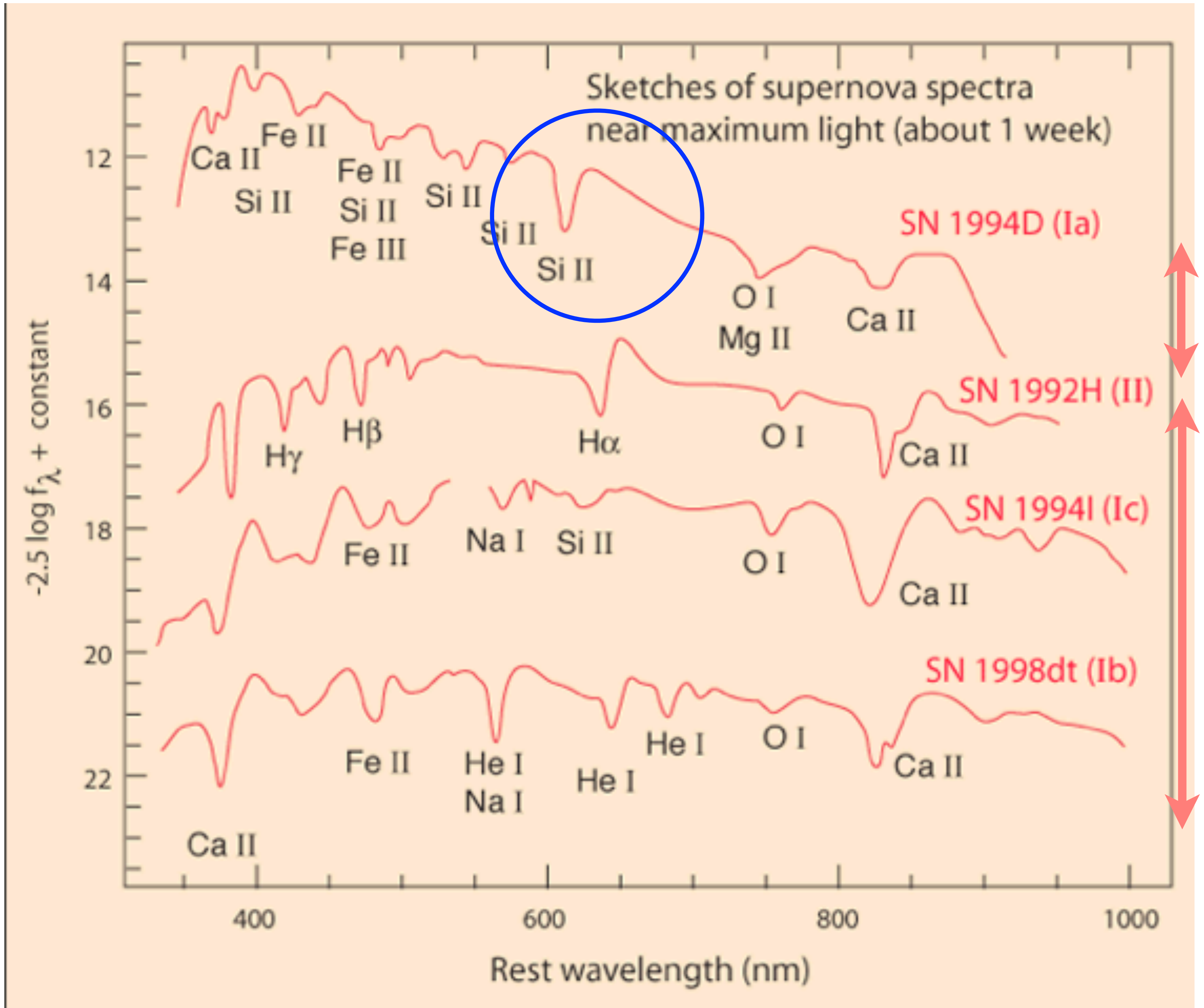




1. The more massive member of a pair of sunlike stars exhausts its fuel and turns into a white dwarf star.
2. The white dwarf sucks in gas from its companion, eventually reaching a critical mass.
3. A “flame”–a runaway nuclear reaction–ignites in the turbulent core of the dwarf.
4. The flame spreads outward, converting carbon (^{12}C) and oxygen (^{16}O) to radioactive nickel (^{56}Ni).
5. Within a few seconds, the dwarf has been completely destroyed. Over the following weeks, the radioactive nickel decays, causing the debris to glow.

Figure 20-21

A Type Ia Supernova This series of illustrations depicts our understanding of how a white dwarf in a close binary system can undergo a sudden nuclear detonation that destroys it completely. Such a cataclysmic event is called a Type Ia supernova or thermonuclear supernova. (Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, “How to Blow Up a Star,” *Scientific American*, October 2006)



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Supernova Ia

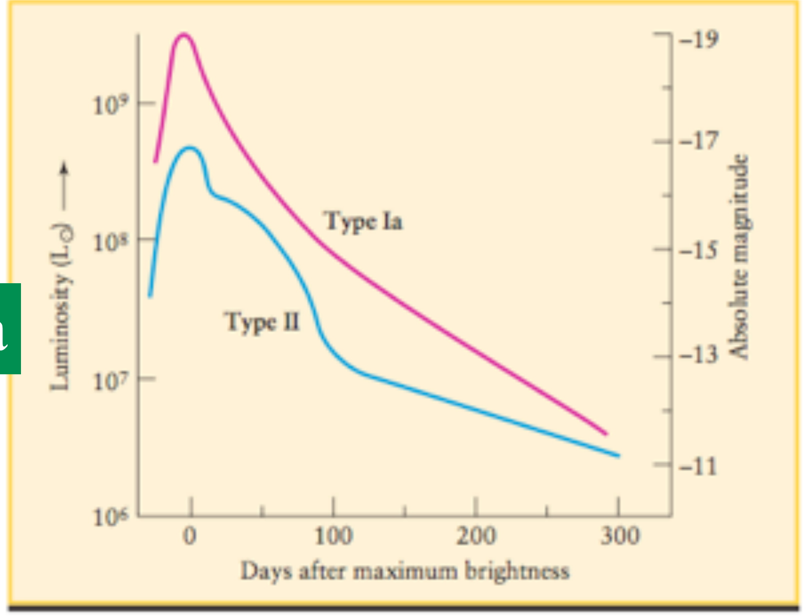


Figure 20-22

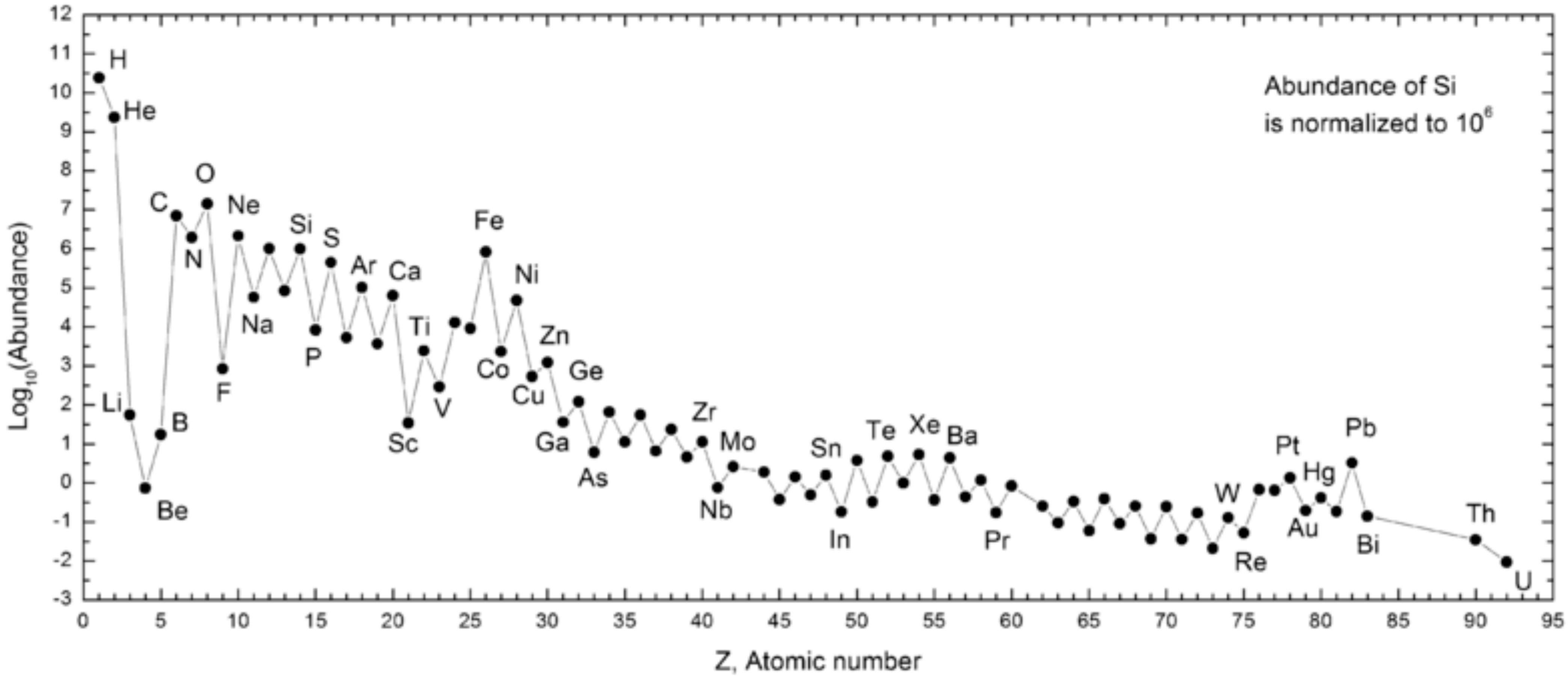
Supernova Light Curves A Type Ia supernova reaches maximum brightness in about a day, followed by a gradual decline in brightness. A Type II supernova reaches a maximum brightness only about one-fourth
f steep

Core-collapse Supernovae di vario tipo

- in una SN Ia, la stella si disintegra a seguito della reazione termonucleare di fusione del Carbonio
- per questo, le SN Ia sono anche indicate come ***SN termonucleari***

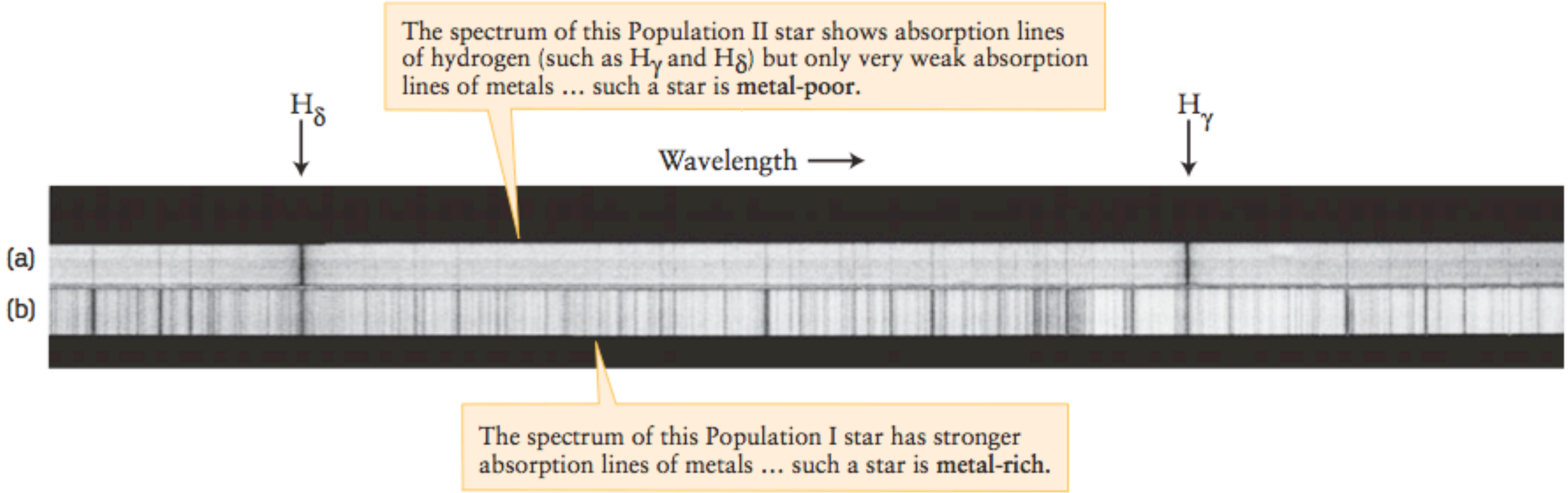
- La massa e quindi luminosita' assoluta di una SN Ia non varia molto e comunque L si puo' calibrare dalla forma della curva della luce
- Le SN Ia sono visibili anche nelle Galassie piu' lontane e forniscono una "candela standard" per la calibrazione delle distanze oltre 1 Mpc, fino a 1000 Mpc !

7. Sintesi di elementi pesanti: dove? quando?



- elementi fino al Fe: sintetizzati nella vita delle stelle
- elementi piu' pesanti sintetizzati nel flusso di neutroni della fase finale delle supernove o nella coalescenza di due stelle di neutroni
- dispersi nell'esplosione delle supernovae e disponibili per nuove stelle
- In effetti vediamo stelle con metallicita' assai diverse

8. Stelle di Popolazione I, II...e III?



The spectrum of this Population II star shows absorption lines of hydrogen (such as H_γ and H_δ) but only very weak absorption lines of metals … such a star is **metal-poor.**

The spectrum of this Population I star has stronger absorption lines of metals … such a star is **metal-rich.**

Figure 19-15 R I **V** U X G

Spectra of a Metal-Poor Star and a Metal-Rich Star The abundance of metals (elements heavier than hydrogen and helium) in a star can be inferred from its spectrum. These spectra compare **(a)** a metal-poor, Population II star and **(b)** a metal-rich, Population I star (the Sun) of the same surface temperature. We described the hydrogen absorption lines H_γ (wavelength 434 nm) and H_δ (wavelength 410 nm) in Section 5-8. (Lick Observatory)

- la differenza e’ interpretata in termini di due popolazioni di stelle:
- Pop. I: le piu’ recenti, come il Sole
- Pop.II: la generazione precedente, dalle cui ceneri sono nate le stelle di Pop. I: il Sole, il sistema solare...noi
- ma anche la Pop II e’ fatta di stelle che riciclano material creato da una precedente generazione: le prime stelle dopo il Big Bang, ipotizzate ma non (ancora?) osservate: Pop. III