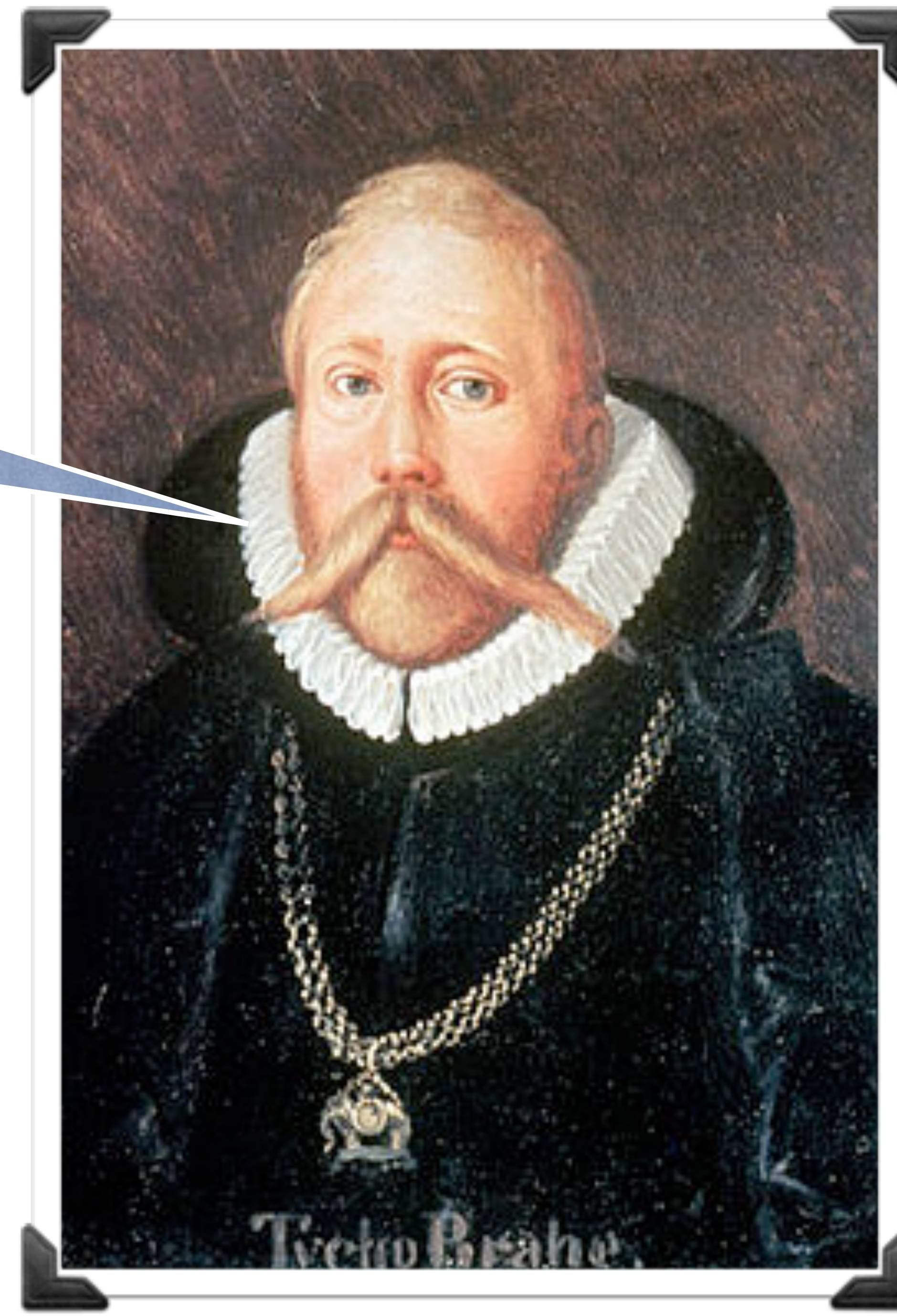
Principles of Astrophysics and Cosmology

Welcome Back to PHYS 3368



Tycho Brahe
December 14, 1546 - October 24, 1601

Announcements

- Reading Assignments: Chapter 4.4 - 4.6.
- Next lab is Monday, March 30th. You will have a take-home lab that day.
- Problem Set 8 is due in class on Monday, April 1st.
- Monday, April 13th: Special lecture about something awesome by Matt Stein
- Wednesday, April 15th in class lab. Be to report to FOSC 032 that day.
- Wednesday, April 15th your final paper is due (hard copy and electronic pdf). Be sure to review the paper guidelines.
- Dr. Cooley will be out of town April 14th - April 17th.
- The final exam in this course will be on Wednesday, May 6th from 6:30 - 8:00 pm. It will cover the second half of the course.
- Dr. Cooley will be on the NPR show Science Friday this Friday, March 27th from 2:20 - 2:50 pm.

Goals for Today's Class

- What is the fate of stars of ~8 solar masses or more?
- What is a neutron star and how does it form?
- How does a supernova form?
- What particles do supernova eject and how do we detect them?
- (time permitting) What are pulsars?

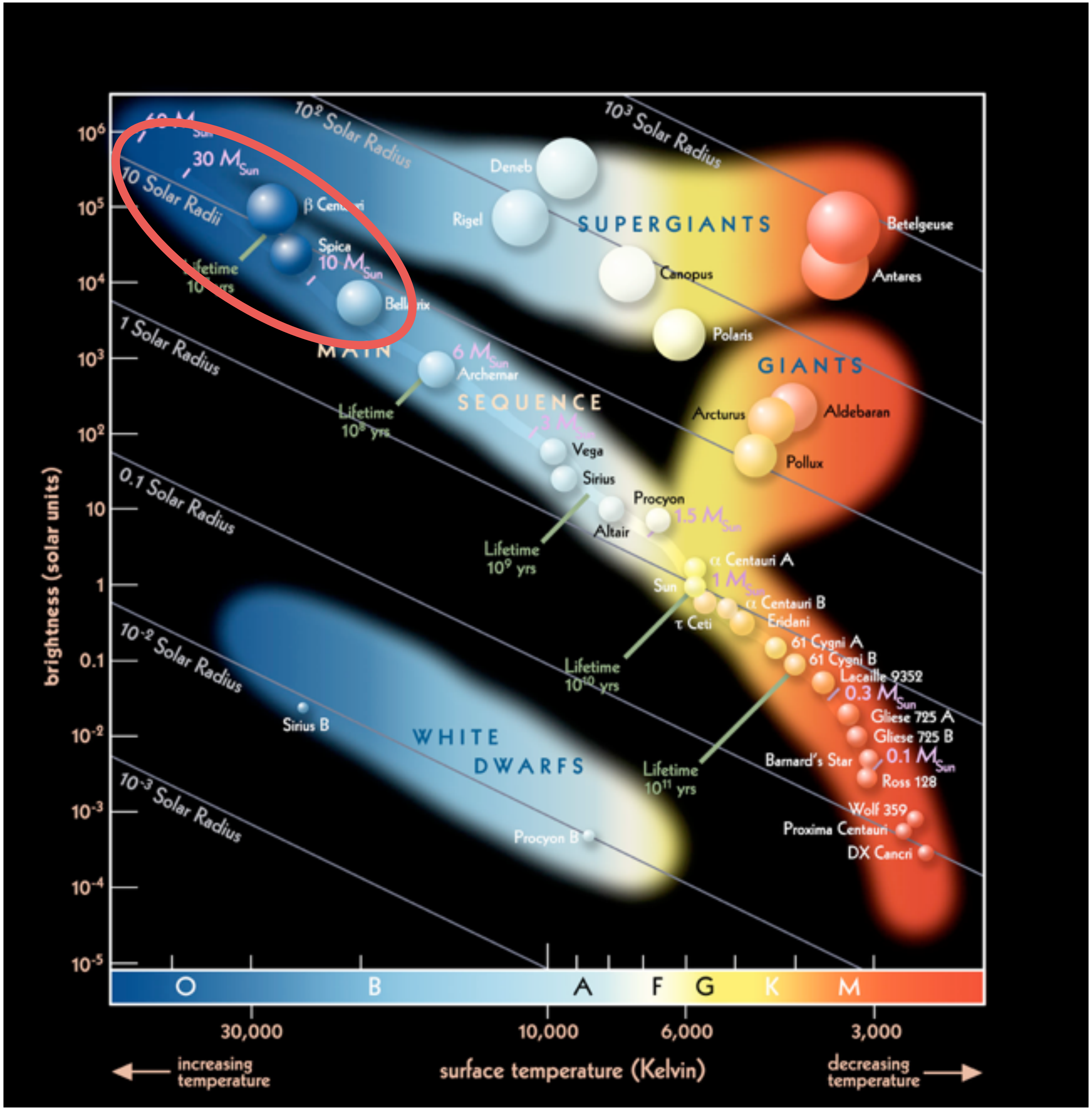
What is a Brown Dwarf?

What is the difference between a star and a planet?

Planets shine by reflected light; stars shine by producing their own light.

Stars from from a cloud of contracting gas, temperature in the center rises to the point hydrogen begins to fuse; planets from from small particles of dust left over from star formation, particles collide and stick together.

Brown dwarfs are objects that have the size of a giant planet (think Jupiter) and a small star. The object can not sustain fusion of hydrogen. Thus, they are dubbed "**failed stars**".


30 M_{Sun}
10 Solar Radii
10^2 Solar Radius
10^3 Solar Radius
β Centauri
Spica
10 M_{Sun}
Bellatrix
Deneb
Rigel
SUPERGIANTS
Canopus
Betelgeuse
Antares
Polaris
MAIN
SEQUENCE
6 M_{Sun}
Archernar
GIANTS
Arcturus
Aldebaran
Pollux
1 Solar Radius
Lifetime 10^8 yrs
Vega
Sirius
Procyon
1.5 M_{Sun}
Altair
Lifetime 10^9 yrs
α Centauri A
Sun
1 M_{Sun}
α Centauri B
τ Ceti
Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
0.3 M_{Sun}
Gliese 725 A
Gliese 725 B
Barnard's Star
0.1 M_{Sun}
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Sirius B
WHITE DWARFS
Procyon B
brightness (solar units)
10^6 10^5 10^4 10^3 10^2 10 1 0.1 10^{-2} 10^{-3} 10^{-4} 10^{-5}
O B A F G K M
30,000 10,000 6,000 3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Core Collapse in Massive Stars

High core temperatures + high density = nuclear burning past CNO.

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

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

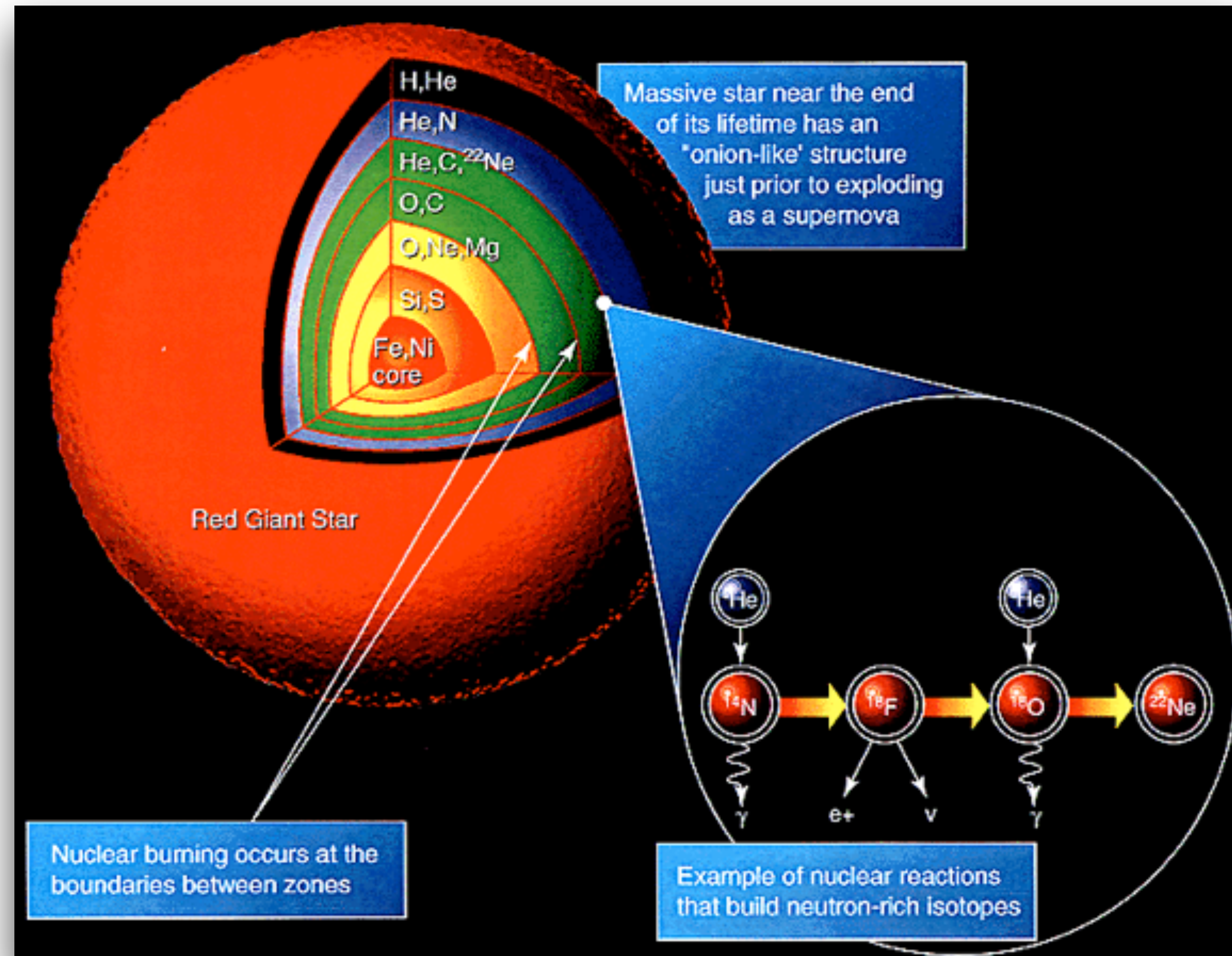
$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{20}\mathrm{Ne} + ^{4}\mathrm{He} + \gamma$$

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{23}\mathrm{Na} + p$$

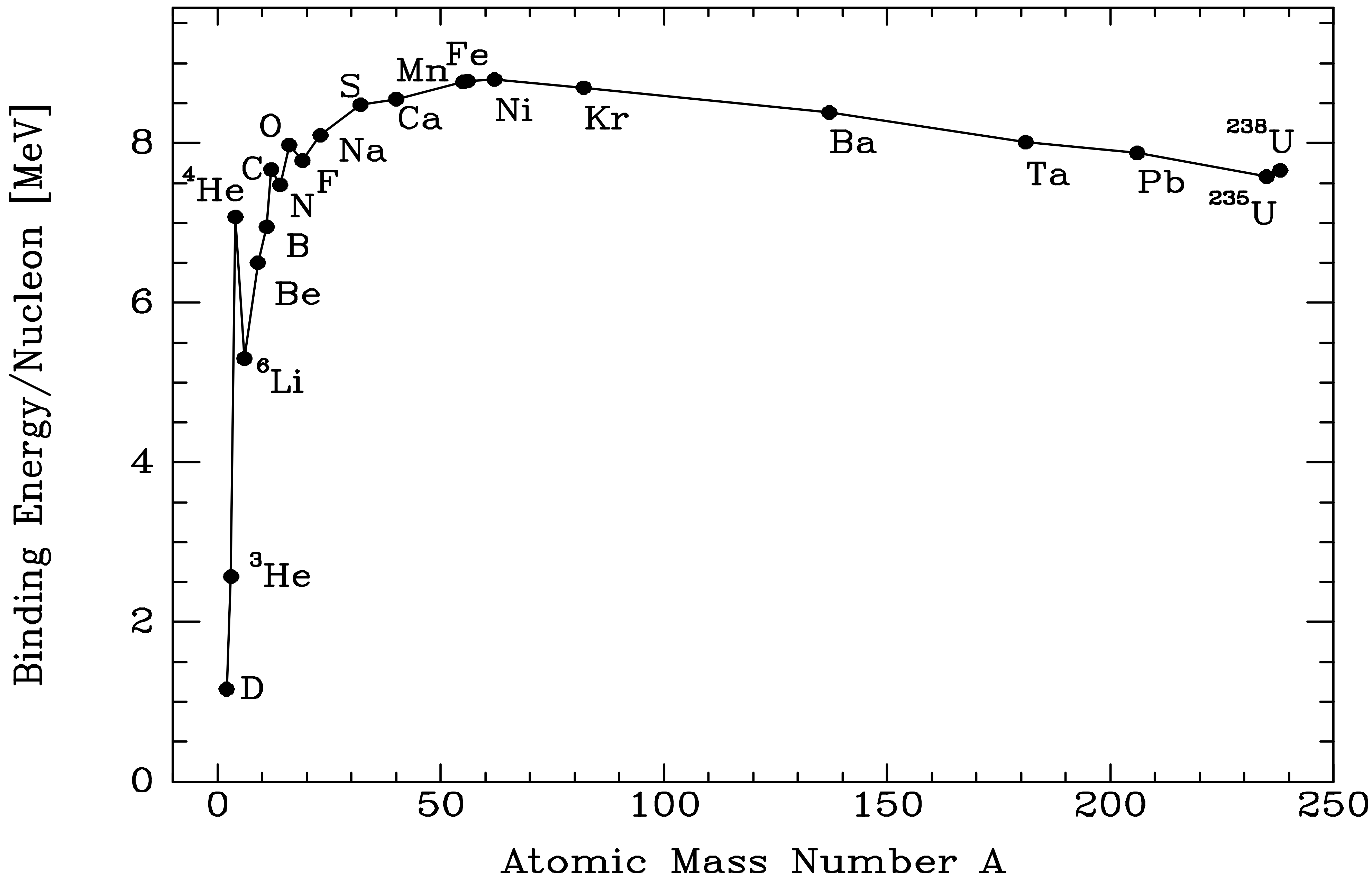
$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{23}\mathrm{Mg} + n$$

C burning, followed by Ne, O, and Si. This burning is very fast at end stages.

C $\sim$ 500 yr   Si $\sim$ 1 day



Burning leads to shell structure.



Fusion stops with iron. Why?

Energy is gained by fusing or fissioning elements with low binding energy per nucleon to those with high binding energy per nucleon. Fe is tightly bound and thus are a dead end in nuclear energy production. It consumes thermal energy rather than releasing it.

Review

In the final stages, core can no longer produce energy via fusion.

Core electrons are degenerate and relativistic.

What happens next?

Core Collapse

- Core can no longer support itself by nuclear burning.
- Core collapses — new energy source is the gravitational contraction.
- High temperature and density lead to two new processes.

Nuclear Photodisintegration:

Photons become abundant at high energies and are absorbed in an endothermic nuclear reaction.

$$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\,{}^{4}\mathrm{He} + 4n$$ energy consumption = 124 MeV

$$\gamma + {}^{4}\mathrm{He} \rightarrow 2p + 2n$$ energy consumption = 28.3 MeV

Neutronization:

Protons and electrons are forced together to make neutrons.

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

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

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

Implications

Fe He

- Photodisintegration:
  - Energy loss of star ~ (124 + 13 x 28.6)/56 ~ 8.8 MeV/nucleon = 1.4 x 10^{-5} erg.
  - There are 10^{57} protons in a Chandrasekhar mass, releases ~10^{52} erg (sun luminosity ~ 10^{33} erg).
- Neutronization:
  - Depletes core of electrons, degeneracy pressure and energy.
  - Energy is carried off by neutrinos.
- Combined:
  - Almost total loss of thermal pressure support
  - Unrestrained collapse of the core

Core collapses on a free-fall time scale:

Core density at end of Si burning, $\rho = 10^9$ g/cm^3.

Timescale for collapse (from stellar evolution models).

$$\tau_{\rm ff} = \left(\frac{3\pi}{32G\bar{\rho}}\right)^{1/2} \sim 0.1 \text{ s}$$

Core is not transparent to neutrinos, density at core is very high

Collapse is slowed by outgoing neutrino flux to a few seconds.

Most nucleons are converted to neutrons.

Density increases and temperature increases as core collapses. This leads to the reaction

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

Thus, a **neutron star** is formed.

Neutron Stars

Similar to white dwarfs - basic physics is degenerate fermion gas. However, we have neutrons, not electrons. Replace m_e with m_p.

$$r_{\rm ns} \approx 2.3 \times 10^9 \text{ cm} \, \frac{m_e}{m_n} \left(\frac{\mathcal{Z}}{A}\right)^{5/3} \left(\frac{M}{M_\odot}\right)^{-1/3} \approx 14 \text{ km} \left(\frac{M}{1.4 M_\odot}\right)^{-1/3}$$

Note: the Z/A factor is one, since almost all nucleons are neutrons.

Important Effects (we neglected):

1. Nuclear interactions play an important role in the EOS. The EOS is poorly known due to our poor understanding of details of the strong interaction.
2. The star is so compact that the effects of GR must be taken into account.

Compare gravitational and rest mass energies of a test particle of mass m.

$$E_{gr} = \frac{GMm}{2r} \qquad \text{and} \qquad E = mc^2$$

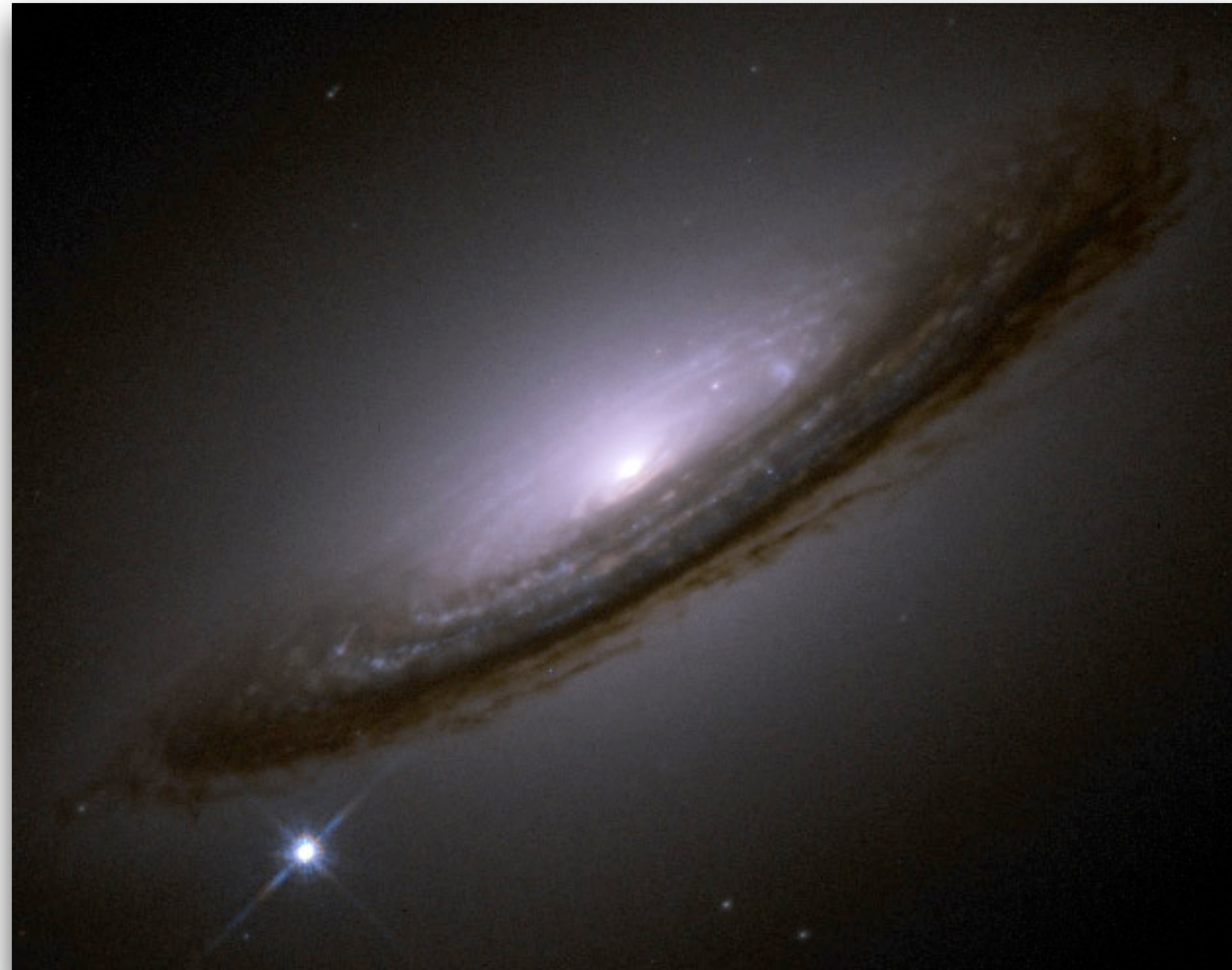
$$\frac{E_{\rm gr}}{mc^2} = \frac{GM}{rc^2} \approx \frac{6.7 \times 10^{-8}\ \mathrm{cgs} \times 1.4 \times 2 \times 10^{33}\ \mathrm{g}}{10 \times 10^5\ \mathrm{cm}\ (3 \times 10^{10}\ \mathrm{cm\ s^{-1}})^2} \approx 20\%$$

Matter falling onto a neutron star loses 20% of its rest mass and the mass of the star as measured via Kepler's law is 20% smaller than the total mass that composed it!

Detailed calculations that take into account GR and nuclear interactions give a radius of 10 km for a neutron star of $1.4M_{sun}$.

Limiting mass of a neutron star is not accurately known. The value is between $2M_{sun}$ and $3.2M_{sun}$.

Supernova Explosions



SN1994D

Properties

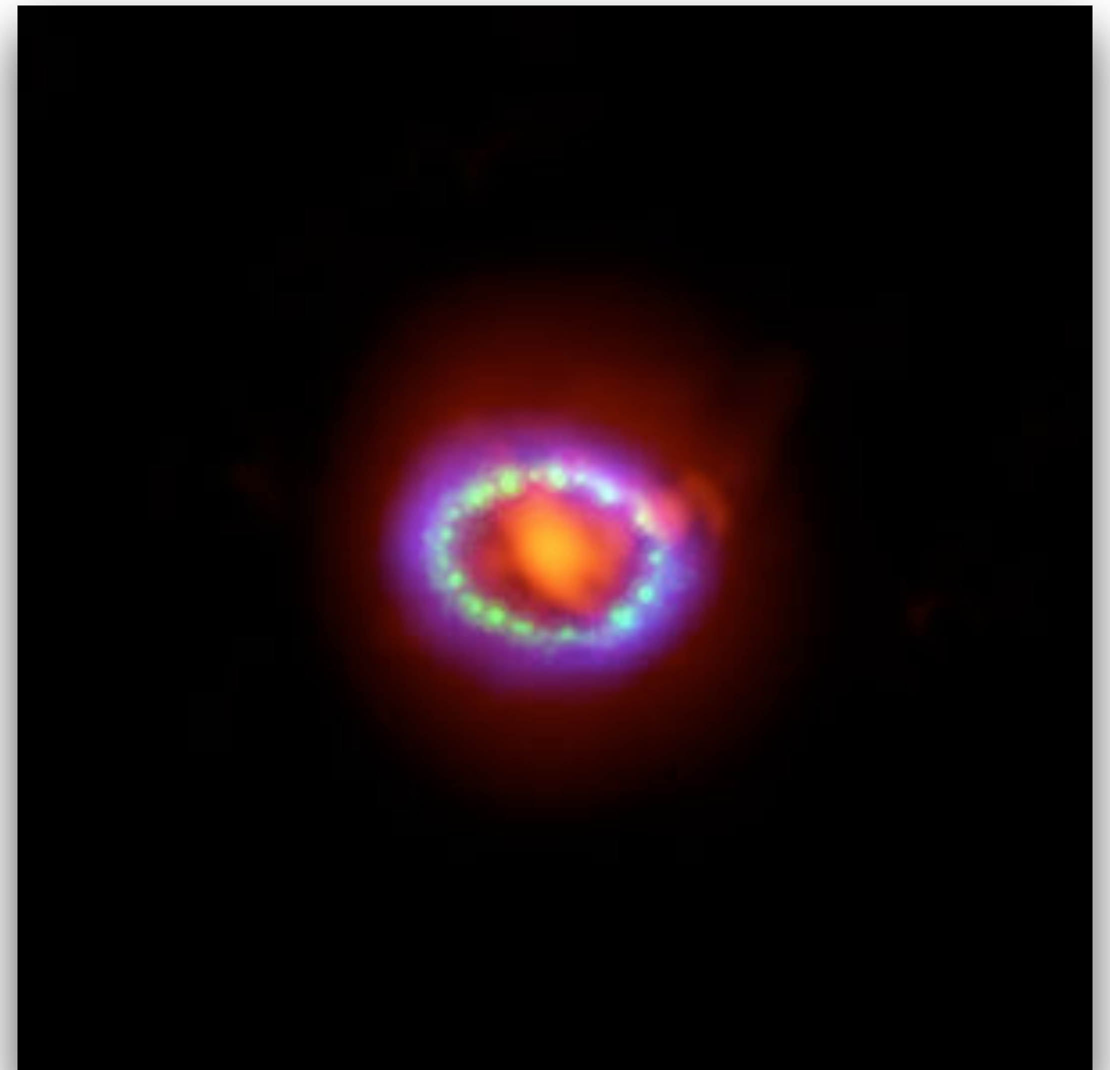
- The energy imparted by material flying out is about 3 x 10^{51} erg.
- Luminous energy of ~ 3 x 10^{49} erg can be observed for ~ 1 month after the explosion. This is driven by the decay of radioactive elements synthesized just before, during collapse & during explosion.
- The mean luminosity is

$$L_{SN} \sim 10^{43}\, erg\, s^{-1} = 3 \times 10^{9} L_{sun}$$

- The bulk of the energy released in SN is carried away by neutrino-antineutrino pairs.
- The density is so high, that photons can not emerge from the star. (Too many photon-photon collisions).

$$\gamma + \gamma \rightarrow e^{+} + e^{-} \rightarrow \nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau$$

Supernova 1987A



SN 1987A in the Large Magellanic Cloud.
Distance 50 kpc from Earth.
Nearest SN since 1604.

- 20 antineutrinos were discovered in a span of a few seconds by two different underground experiments (Kamiokande II and IMB).
- First time neutrinos were detected. The neutrinos were detector prior to the emission of visible light.
- The experiments were originally designed to detect proton decay.
- Neutrinos are detected via the process

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

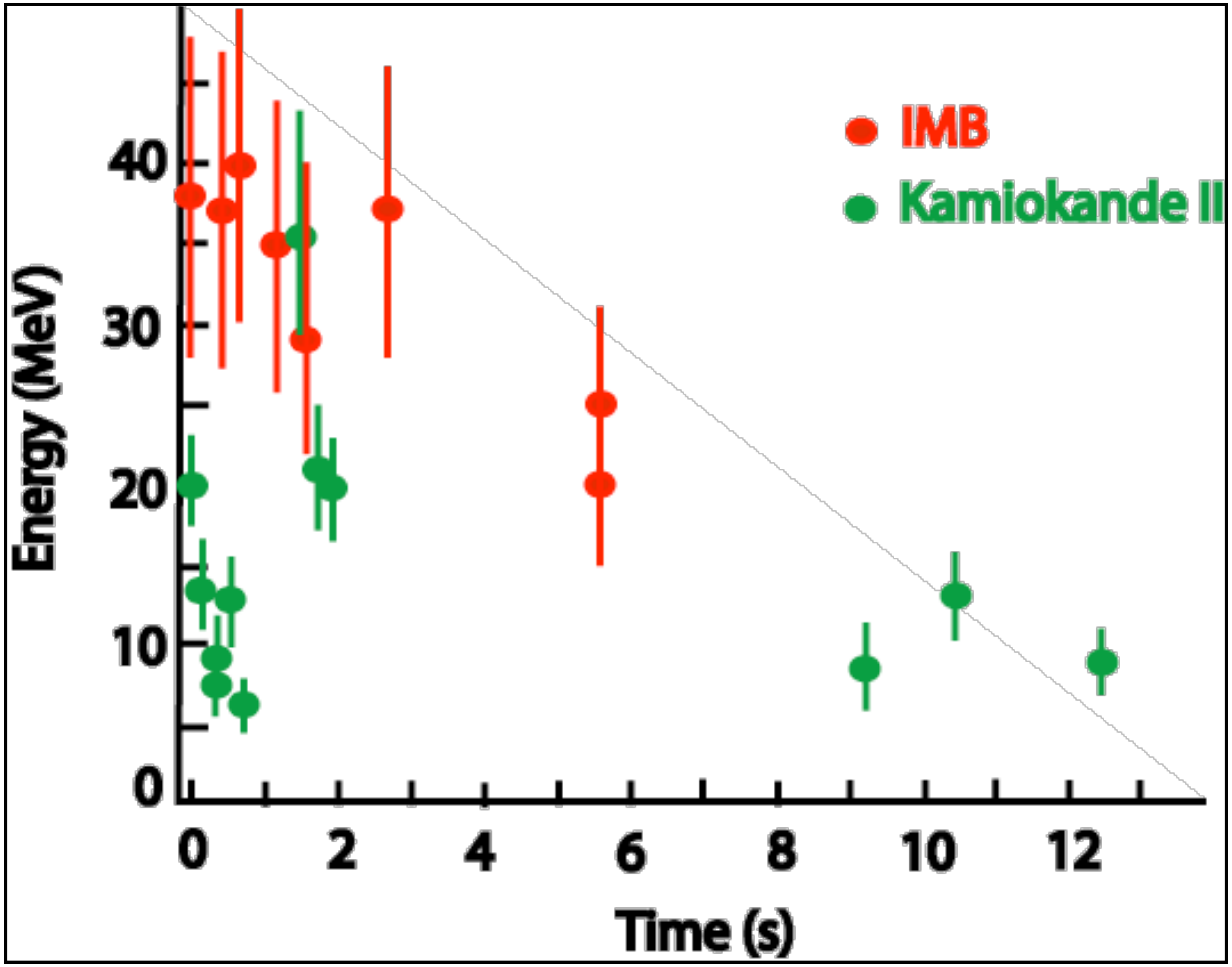
Nuclear Physics B (Proc. Suppl.) 3 (1988) 441–452
North-Holland, Amsterdam

2002 Nobel Prize in Physics for the first real time observation of supernova neutrinos. (This prize was shared with Ray Davis.)

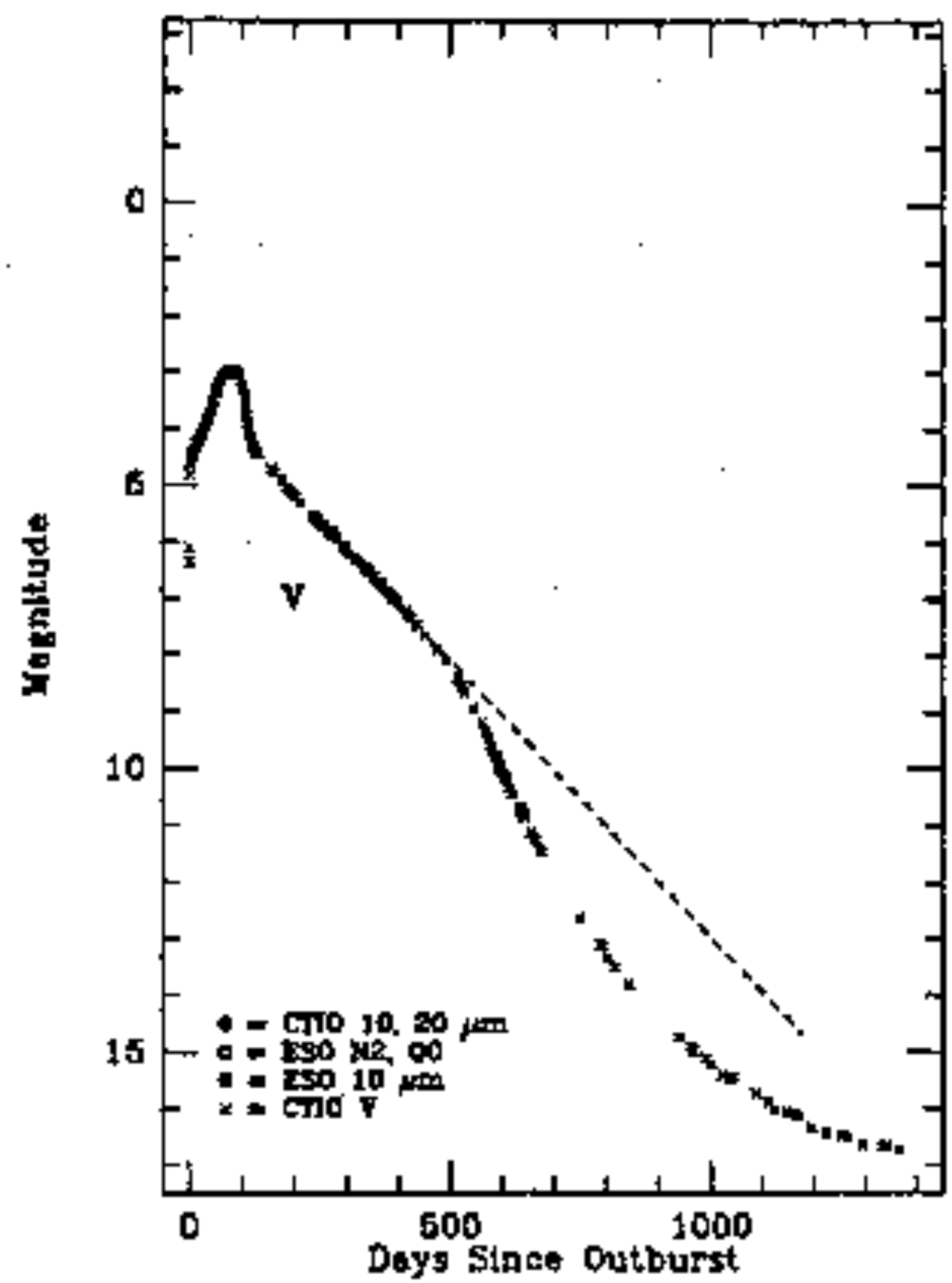
SUPERNOVA NEUTRINO SIGNAL AND KAMIOKANDE-II

M. Koshiba
DESY and University of Tokyo

The collaborators of this experiment are:
K.Hirata, T.Kajita, M.Koshiba, M.Nakahata, Y.Ohyama, N.Sato, A.Suzuki, M.Takita and Y.Totsuka (Dept. of Physics and ICEPP, Univ. of Tokyo); T.Kifune and T.Suda (Inst. Cosmic Ray Research, Univ. of Tokyo); K.Takahashi and T.Tanimori (Nat. Lab. High Energy Physics (KEK)); K. Miyano and M.Yamada (Dept. of Physics, Univ. of Niigata); E.W.Beier, L.R.Feldsher, S.B.Kim, A.K.Mann, F.M.Newcomer, R.Van Berg and W.Zhang (Dept. of Physics, Univ. of Pennsylvania); B.G. Cortez (AT&T Bell Laboratories, Holmdel).

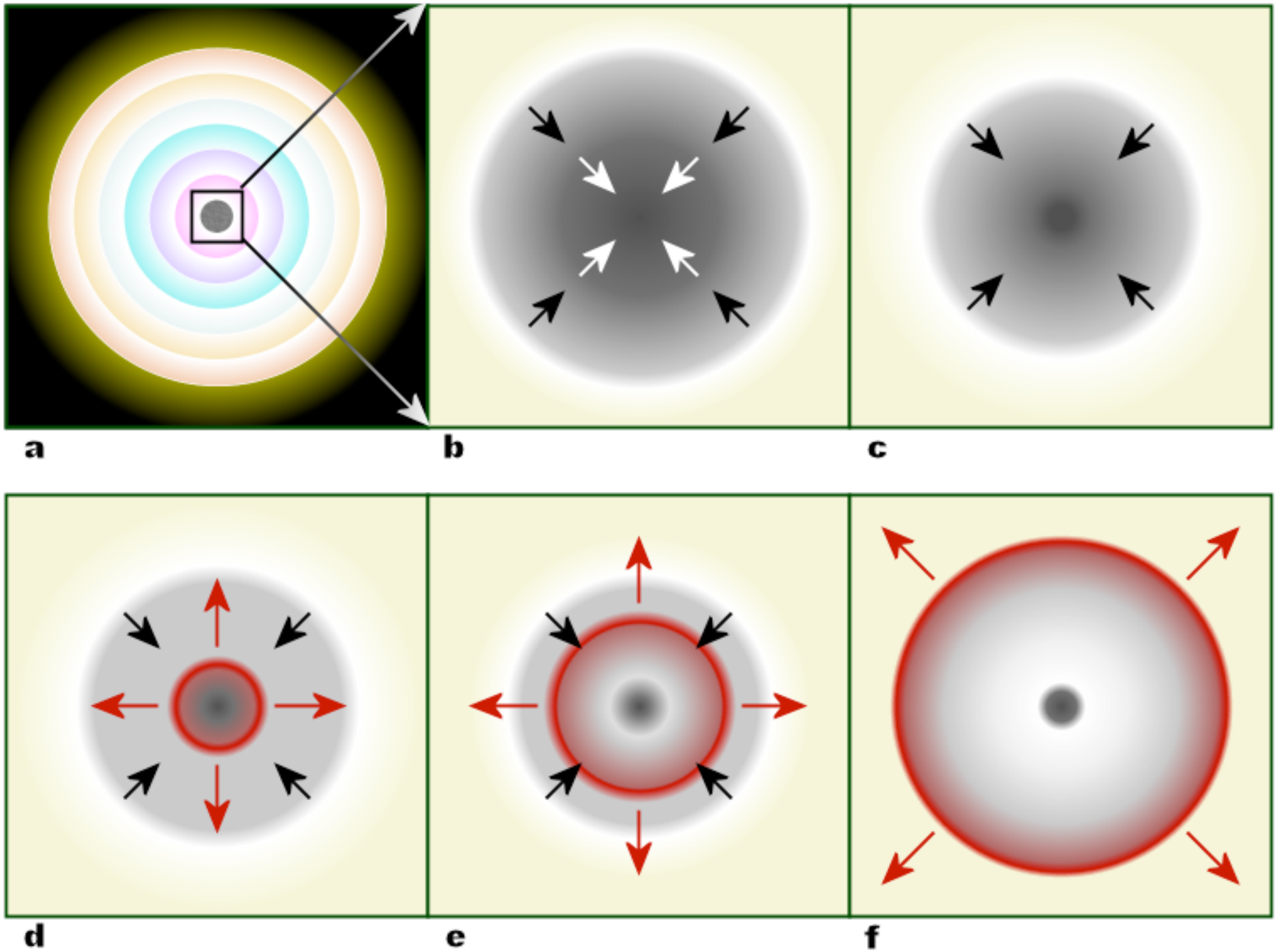


Neutrinos from SN1987A. The 8 neutrinos by the IBM experiment have greater energy than the 12 detected by the Kamiokande experiment because the IBM detector was not sensitive to low energy neutrinos.

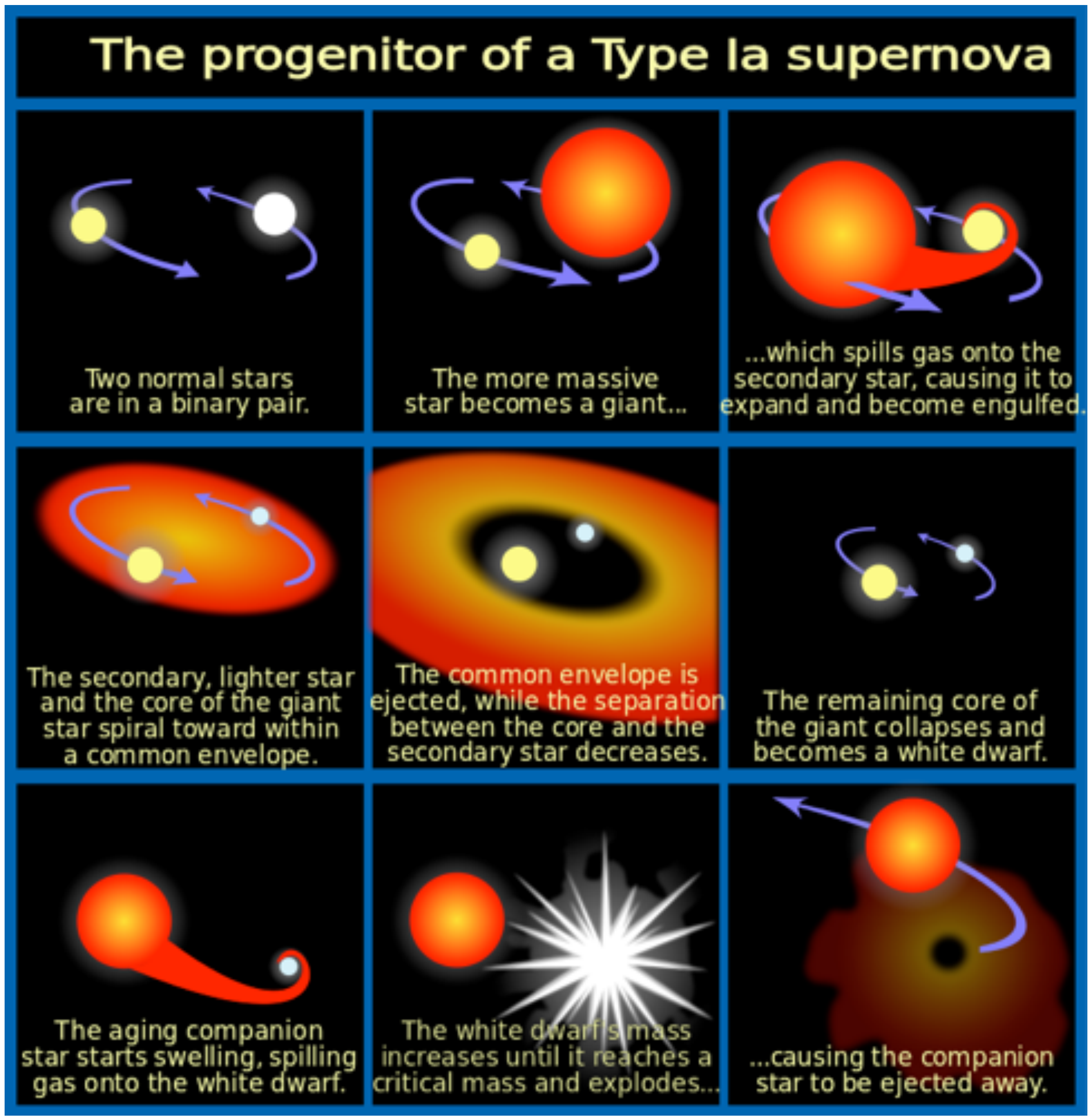


Optical light curve of SN1987A. Light faded at almost the same observed light at ^{66}Co (77 days).

Type II Supernova: Summary



Type Ia SN



- Mass transfer from companion onto WD happens until reach M_{ch}.
- At (or before) that stage, carbon core ignites. Temp rises, pressure increases. Classically, star should expand.
- Degenerate conditions prevent star from expanding, causes nuclear reaction rate to increase.
- Ends in a thermonuclear runaway — star explodes.

Supernova Summary

Type II SN

- Produced by core collapse of a massive star.
- Leaves behind a neutron star or black hole.

Type Ia SN

- Produced by the feeding of a white dwarf from a companion star.
- Leaves behind no stellar remnant.
- The kind of star the companion is unknown.
  - Merger of two WD?

Material expelled by both types of SN is essentially the only source of heavy elements in the universe. Lighter elements were formed in the early universe (more details later in the course).

Gamma Ray Bursts

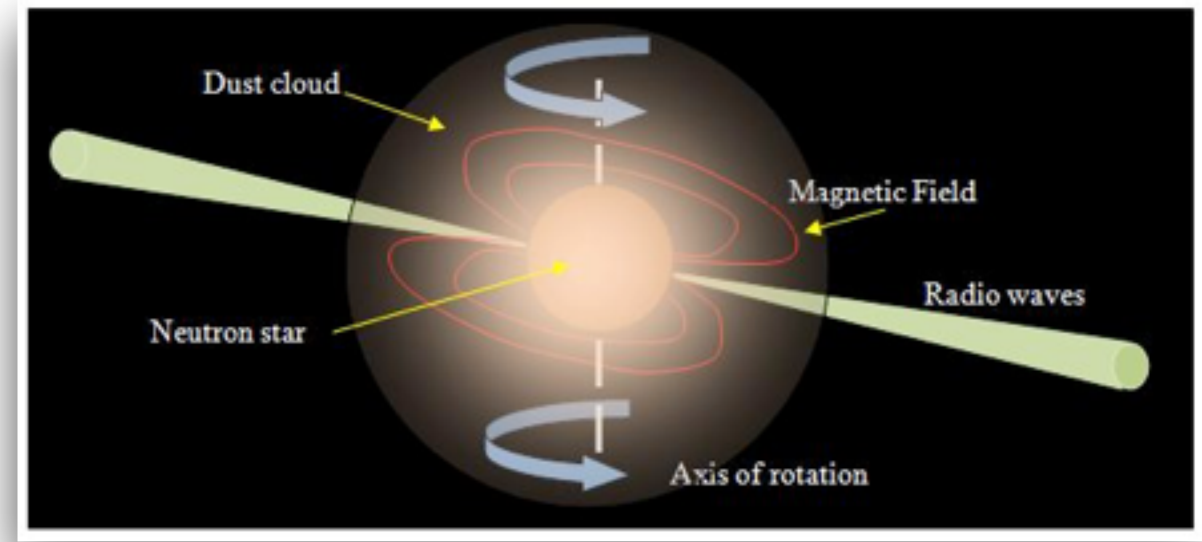
- Even more luminous than a SN explosion.
- Release 10^{51} erg over just a few seconds.
- Initially energy released at gamma frequencies, fading afterglows can be in x-rays (minutes), optical (days), and radio frequencies (weeks).
- Occurrence: Observe approximately 1 per day.
- Half of the explosions are in star forming galaxies.
- Nature and mechanism for GRBs is still widely debated.
    - Involved in formation of black holes?
    - Links to SN explosions?
    - Result from core collapse of massive stars?

Pulsars and Supernova Remnants

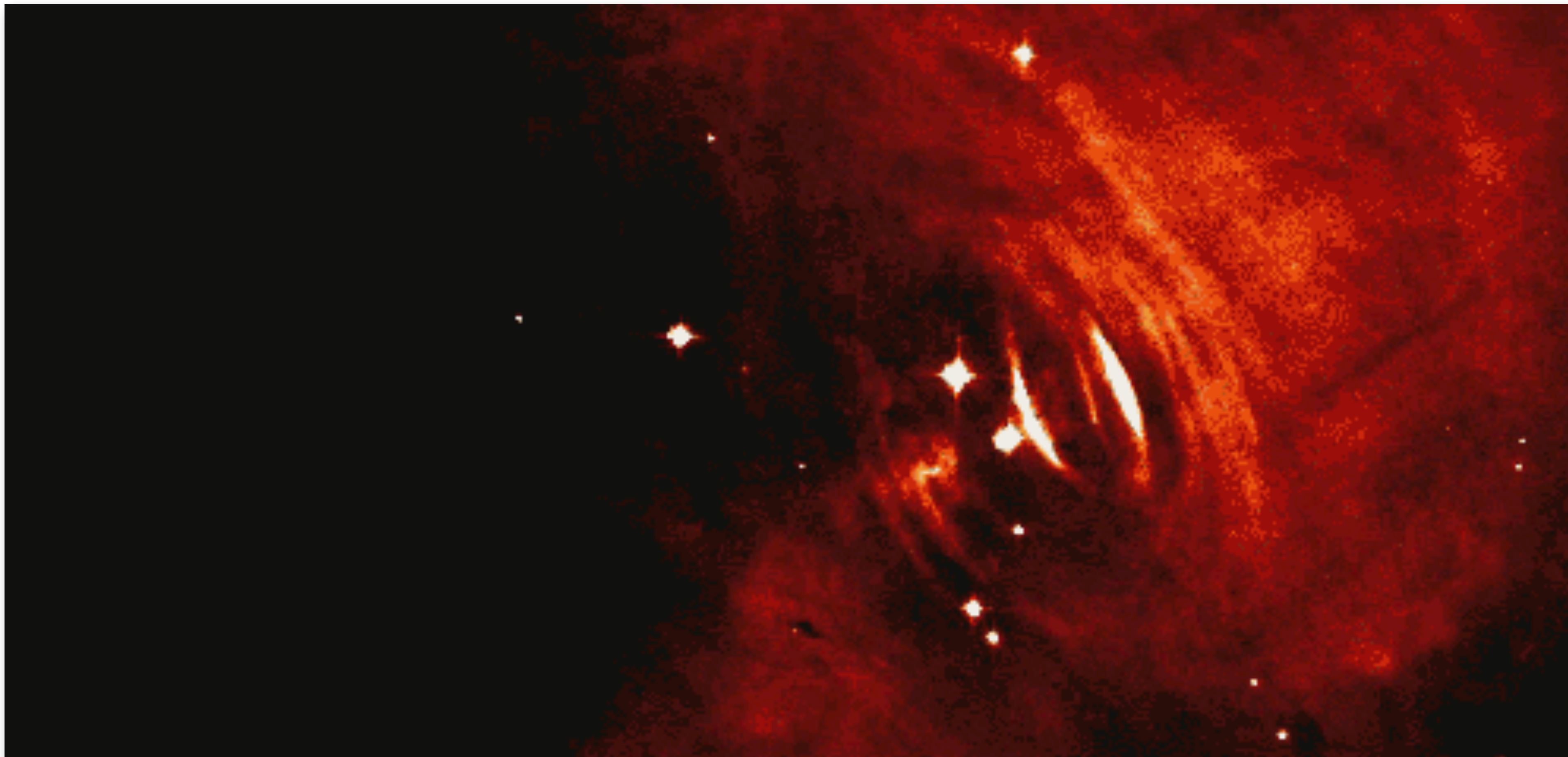
- The first pulsar was discovered in 1967. It had a pulse period of 1.33 s.
- It was named “LGM-1”. Any ideas what this stands for?

Little Green Men

- Today over 1000 pulsars are known. Some have periods as short as 0.03 s.



The Crab Pulsar



- First observed in 1054 by Chinese, Japanese and Korean Astronomers.
- Period $\tau = 33$ ms
- $L_{tot} \sim 5 \times 10^{38}$ erg s^{-1}
- $\omega = \frac{2\pi}{\tau} = 190 \text{ s}^{-1}$

Pulsars as Neutron Stars

What are possible mechanisms for producing the periodicity of the observed magnitude and regularity in these stars?

1. binaries
2. stellar pulsations
3. stellar rotation

Binaries:

Angular frequency, mass and separation are related by Kepler's law.

$$\omega^2 = \frac{G(M_1 + M_2)}{a^3}$$

$$a = \frac{[G(M_1 + M_2)]^{1/3}}{\omega^{2/3}} = 2 \times 10^7 \text{ cm} = 200 \text{ km}$$

where a is the separation and we assume object are of solar mass.

How does the separation distance compare to the radius of a normal star?

It is much smaller than a normal star or even a white dwarf. Only neutron stars could exist in such a binary.

BUT GR predicts orbiting masses as such a separation will lose energy (via gravitational waves), separation will shrink and orbital frequency will grow. Observed pulsar frequencies decrease with time.

Stellar Pulsations:

Stars are observed to pulsate regularly in various modes.

$$\tau \propto \rho^{-1/2}$$

Normal stars oscillate with periods between hours and months. WD oscillate with periods of 100 to 1000 s.

Neutron stars (10^8 x denser) should, therefore, pulsate with periods of 0.1s.

Pulsars commonly have a period of ~0.8 s. There is no class of stars that produce this pulsation period.

Stellar Rotation:

Assume anisotropic emission from a rotating star. What is the fastest a star can spin?

Angular frequency at which centrifugal forces do not break it apart.

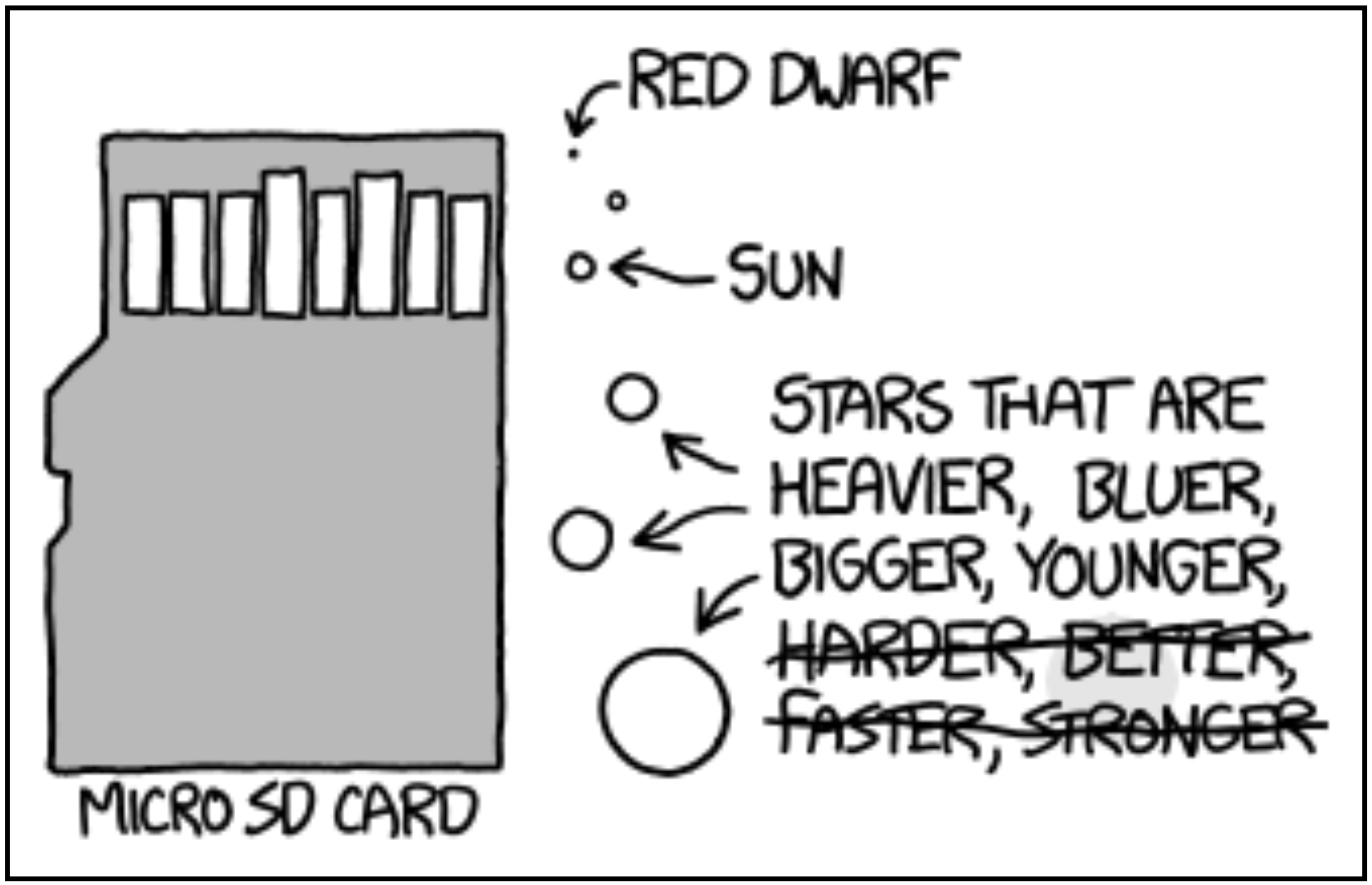
$$\frac{GMm}{r^2} > m\omega^2 r.$$

$$\frac{M}{r^3} > \frac{\omega^2}{G}$$

$$\bar{\rho} = \frac{3M}{4\pi r^3} > \frac{3\omega^2}{4\pi G} = 1.3 \times 10^{11}\ \mathrm{g\ cm^{-3}}$$

If the Crab is a spinning star and not flying apart, it's mean density must be 5x WD, but consistent with neutron star.

Stay Tuned!



https://what-if.xkcd.com/83/