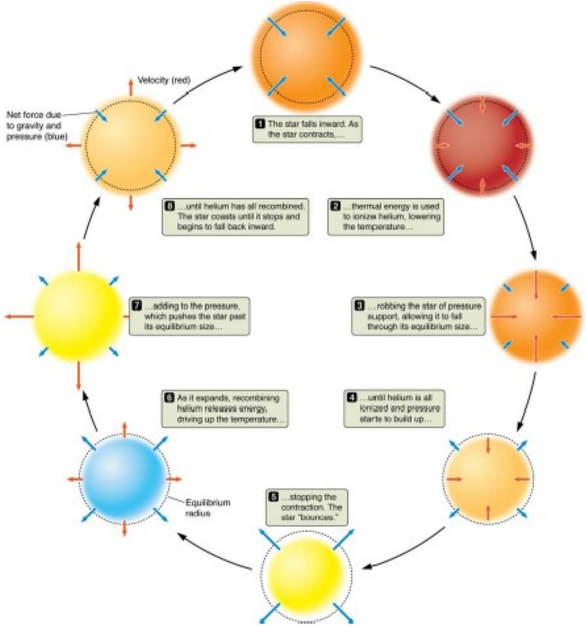
Astrophysics and Nuclear Astrophysics

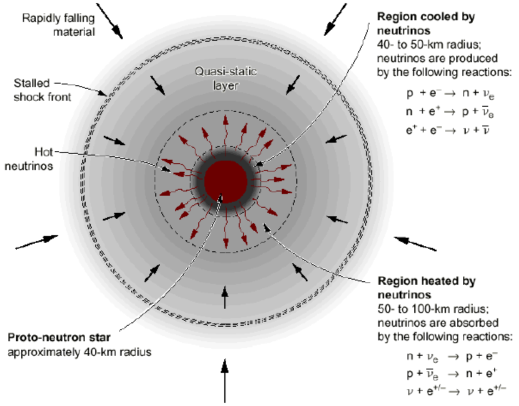
(LPHY2263)

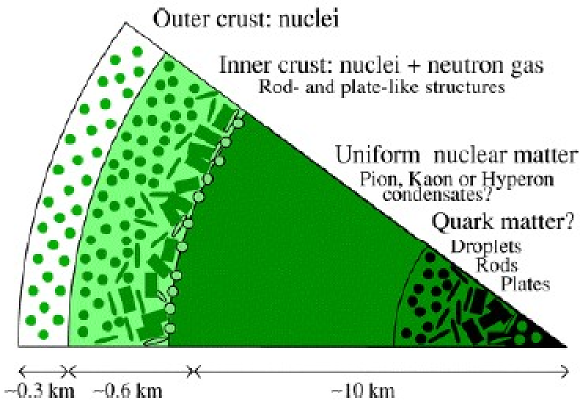
Andrea Giammanco, UCL

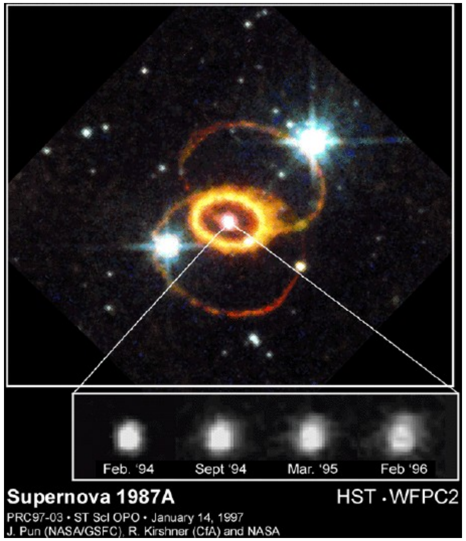
Chapter #5

- Death of a massive star
  - Exiting from the Main Sequence
  - Cepheids
  - Supernovae
  - Neutron stars
  - Black holes
  - The neutrino burst of 1987







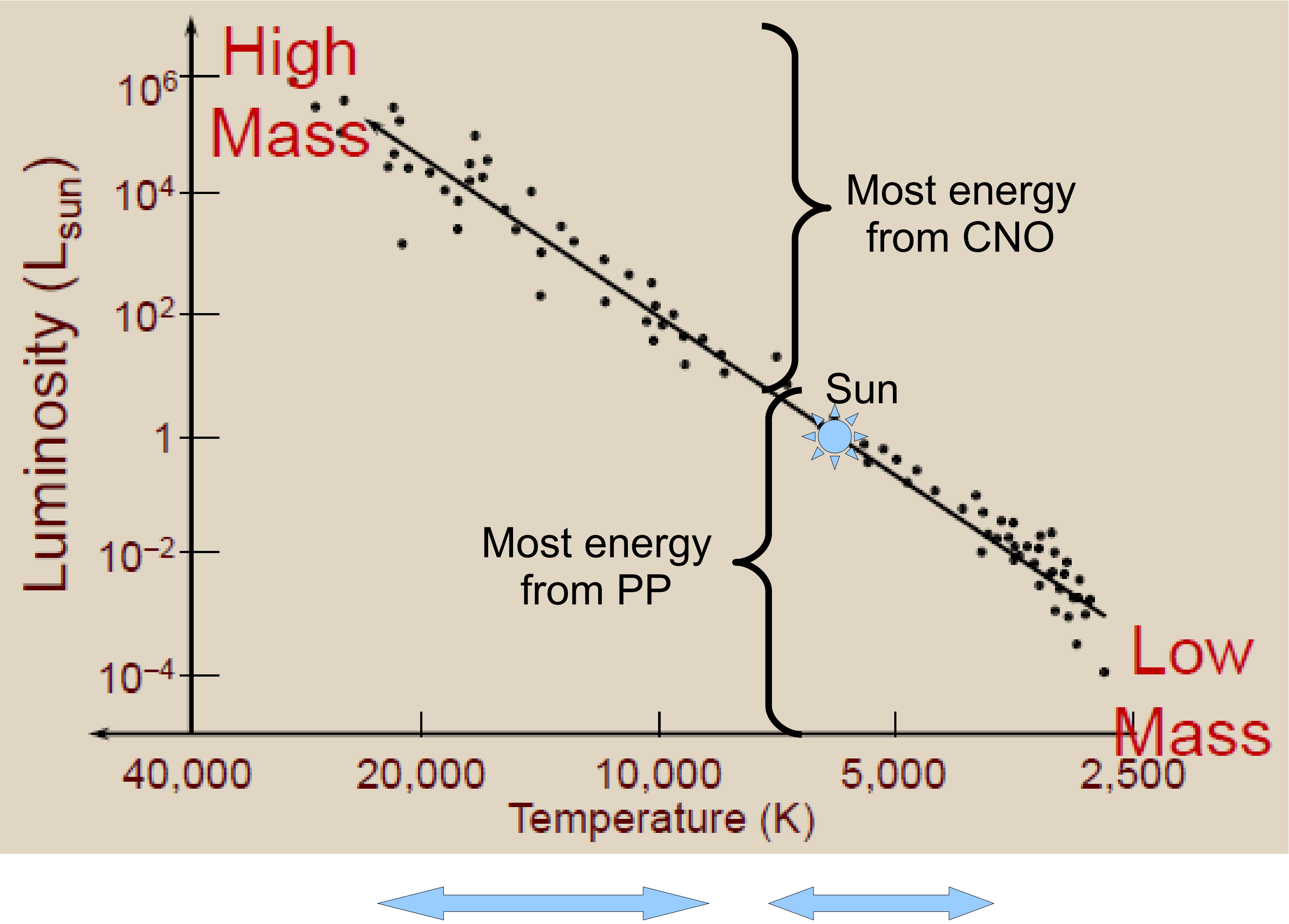


Supernova 1987A HST · WFPC2

PRC97-03 • ST ScI OPO • January 14, 1997

J. Pun (NASA/GSFC), R. Kirshner (CfA) and NASA

Main Sequence in the H-R diagram



Most energy from CNO

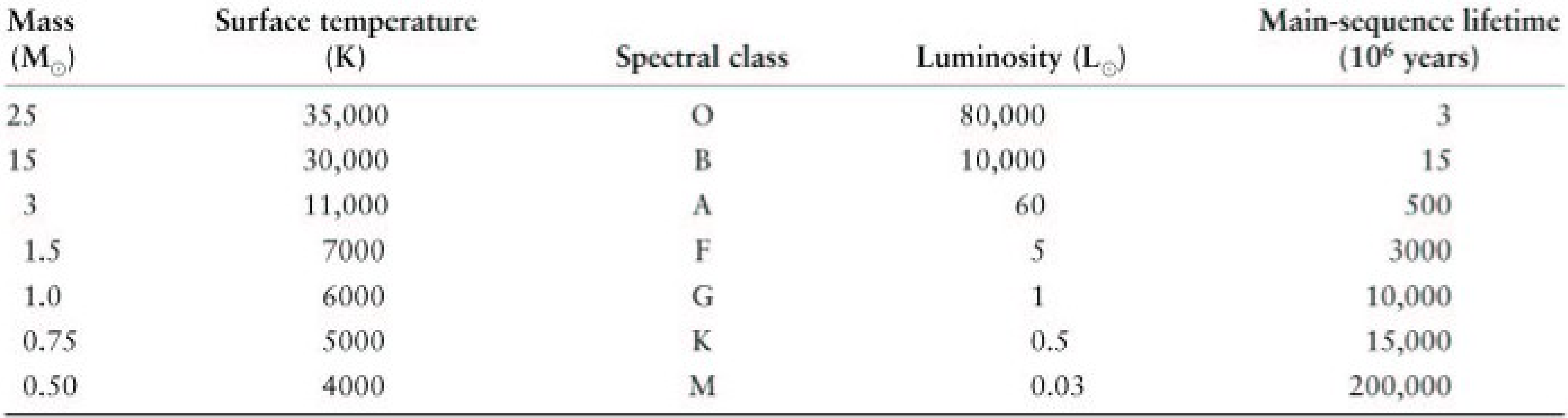
Most energy from PP

This lesson

Previous lesson

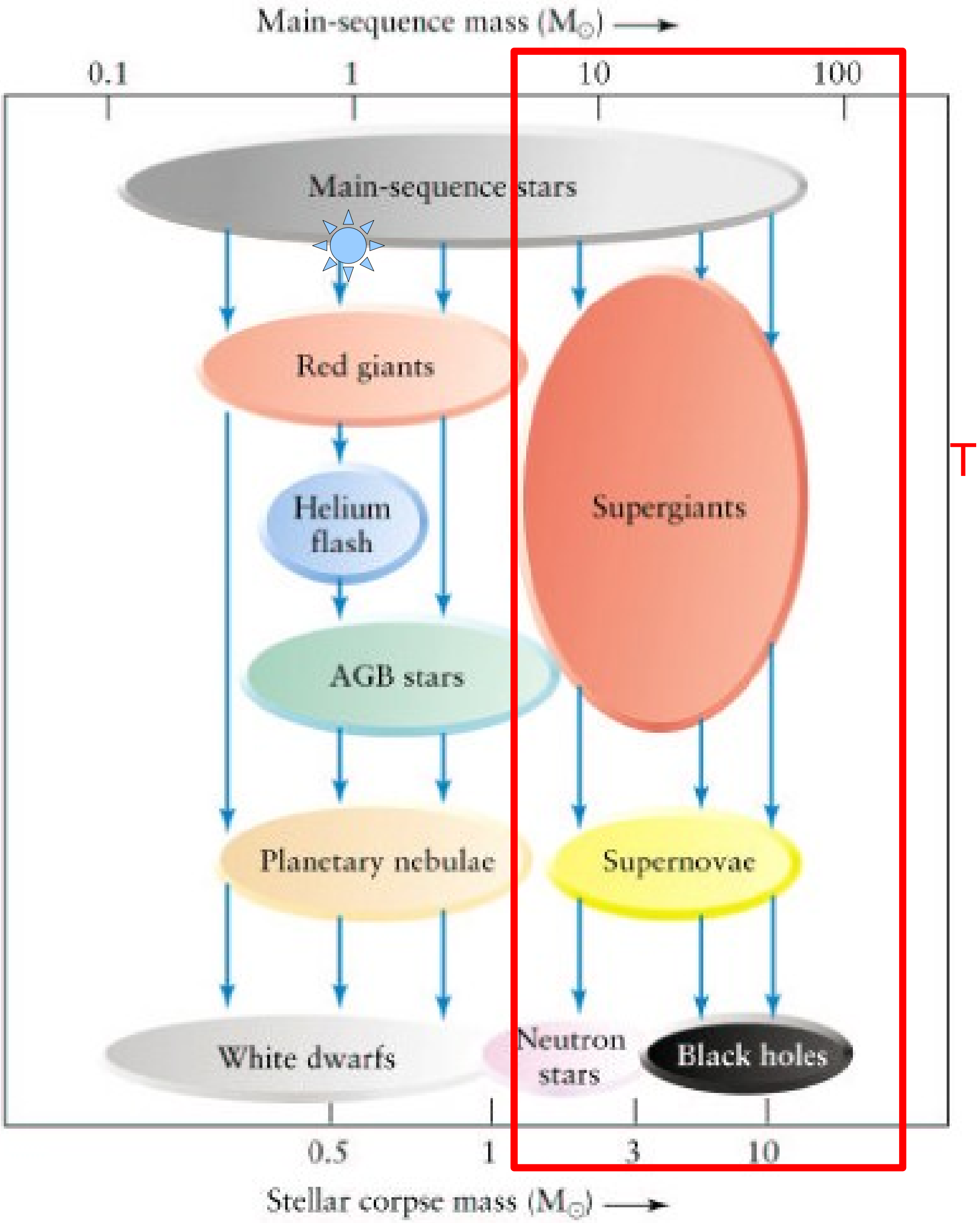
Lifetime-mass relationship in the Main Sequence

- A star can stay in the Main Sequence if:
  - It is in hydrostatic equilibrium
  - It burns H into He
- How long can it burn H into He? Depends on:
  - Amount of H available → mass of the star
  - How fast fusion occurs → luminosity
  - ⇒ Lifetime ~ mass/luminosity
- Remember: luminosity ~ mass$^{3.5}$
  - ⇒ Lifetime ~ mass$^{-2.5}$
  - Massive (hot) stars live less than light (cold) ones

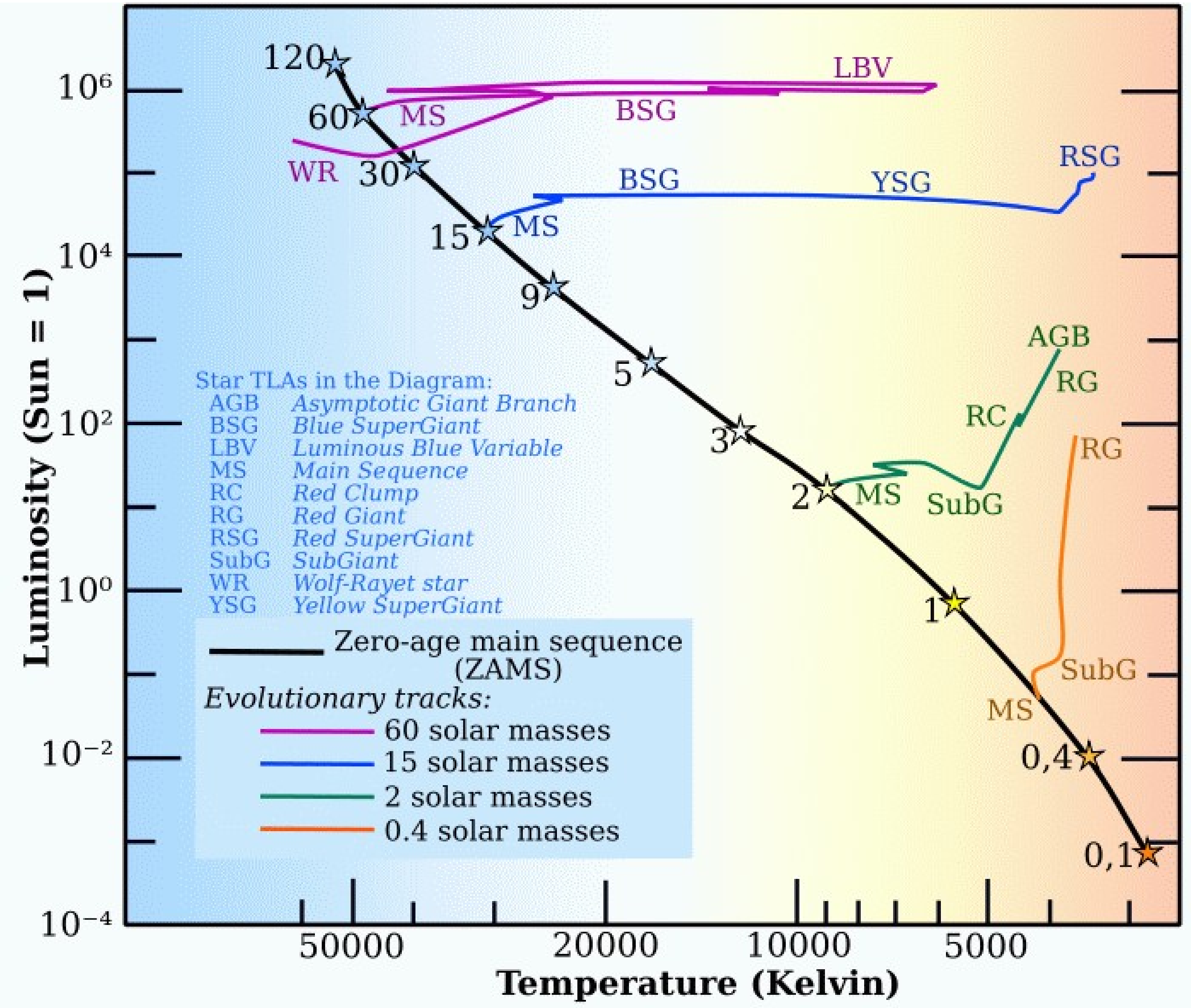


This lesson

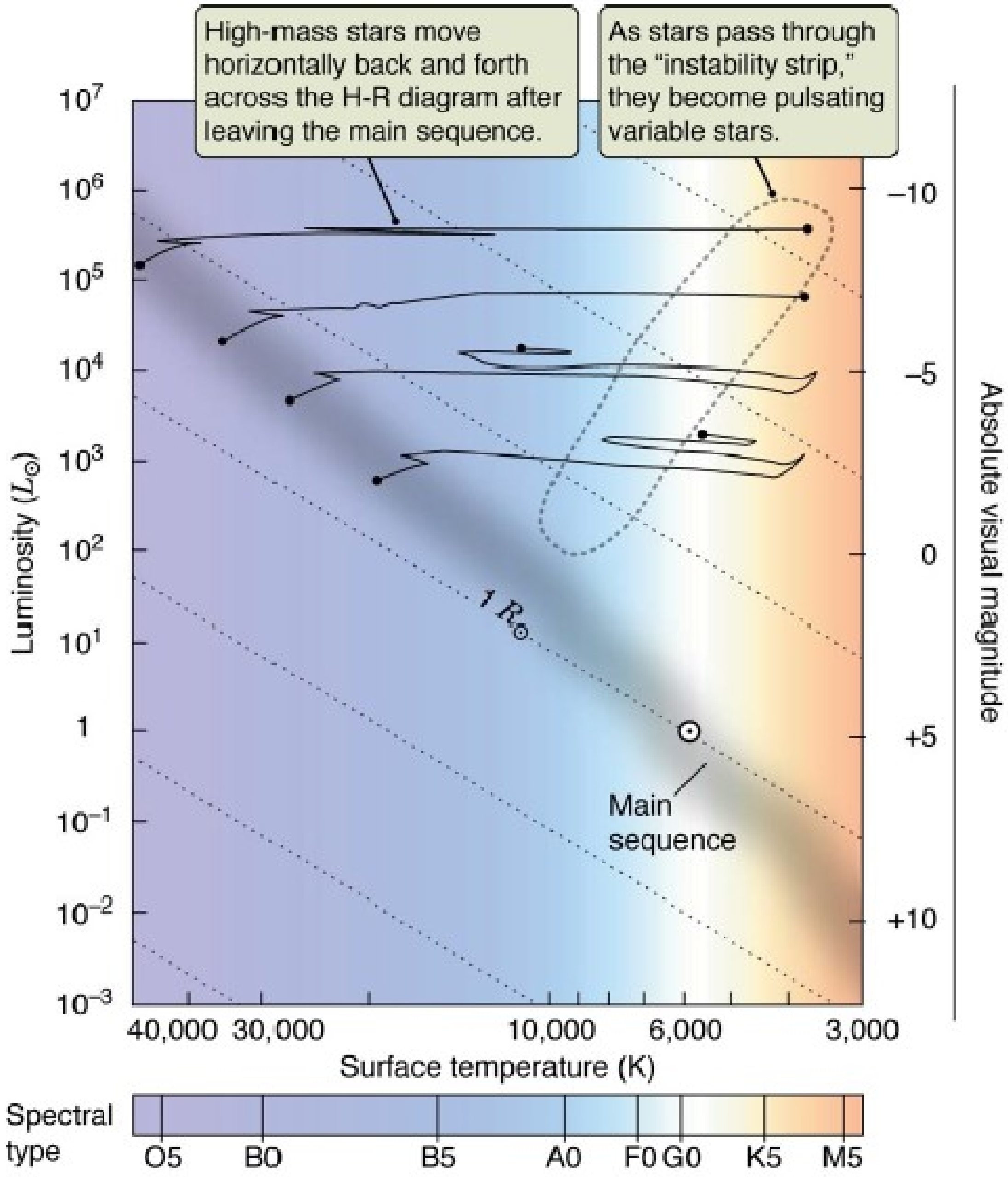
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	3
15	30,000	B	10,000	15
3	11,000	A	60	500
1.5	7000	F	5	3000
1.0	6000	G	1	10,000
0.75	5000	K	0.5	15,000
0.50	4000	M	0.03	200,000


Main-sequence mass ($M_\odot$) →
0.1
1
10
100
Main-sequence stars
Red giants
Helium flash
AGB stars
Planetary nebulae
Supergiants
Supernovae
White dwarfs
Neutron stars
Black holes
0.5
1
3
10
Stellar corpse mass ($M_\odot$) →

This lesson


Luminosity (Sun = 1)
10⁶
10⁴
10²
10⁰
10⁻²
10⁻⁴
Temperature (Kelvin)
50000
20000
10000
5000
120
60
30
15
9
5
3
2
1
0,4
0,1
LBV
BSG
MS
WR
RSG
BSG
YSG
MS
AGB
RG
RC
MS
SubG
RG
SubG
MS
Star TLAs in the Diagram:
AGB Asymptotic Giant Branch
BSG Blue SuperGiant
LBV Luminous Blue Variable
MS Main Sequence
RC Red Clump
RG Red Giant
RSG Red SuperGiant
SubG SubGiant
WR Wolf-Rayet star
YSG Yellow SuperGiant
Zero-age main sequence (ZAMS)
Evolutionary tracks:
60 solar masses
15 solar masses
2 solar masses
0.4 solar masses

Evolution of massive stars


High-mass stars move horizontally back and forth across the H-R diagram after leaving the main sequence.

As stars pass through the "instability strip," they become pulsating variable stars.

Main differences with Sun:

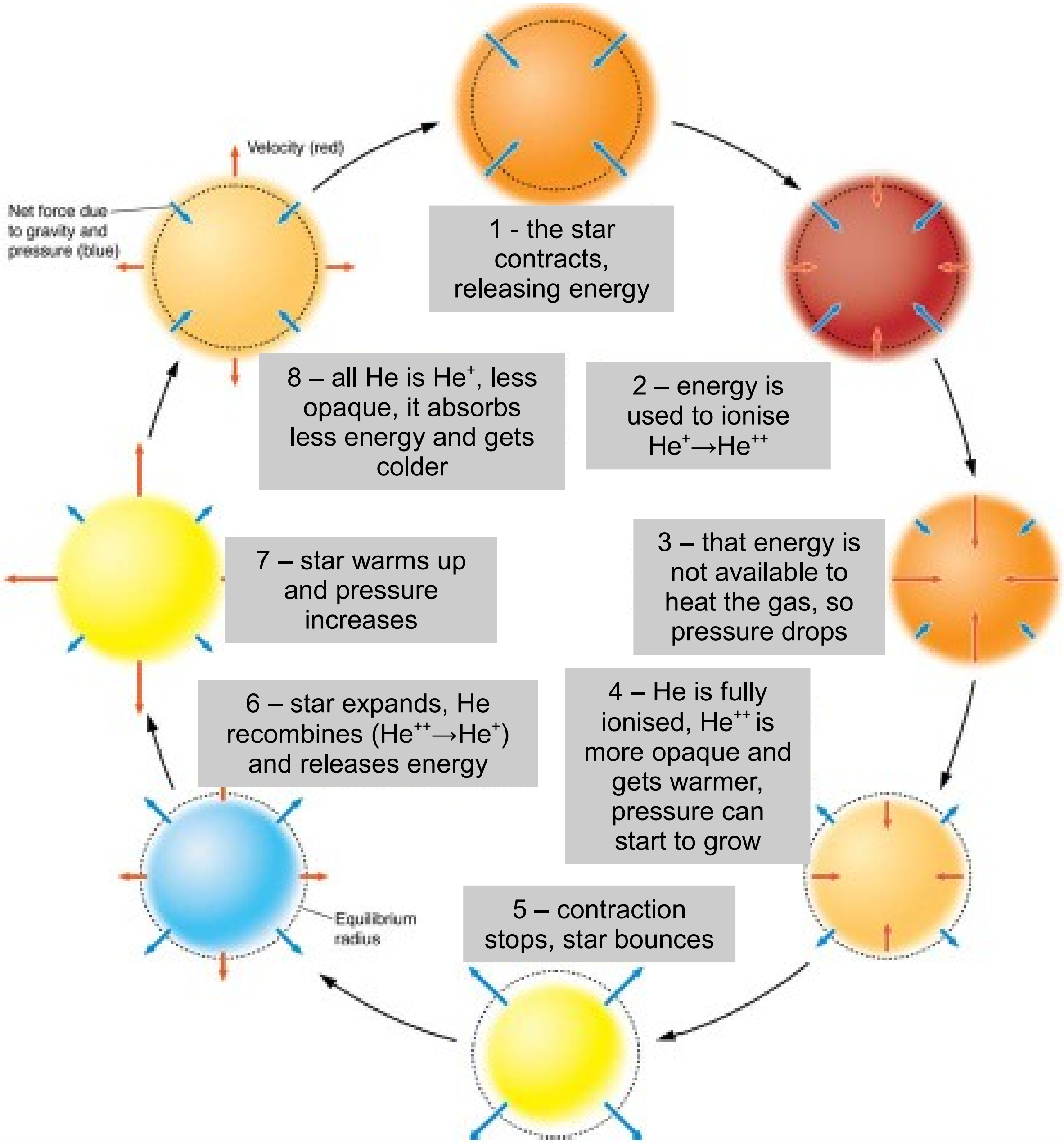
- Core temperature is high enough that He fusion starts before electrons become degenerate; this happens only when the core is made of Fe

- Mass loss is important at all stages of evolution

- Luminosity doesn't change much during evolution

- There is a phase of pulsation

Cepheids



1 - the star contracts, releasing energy

2 – energy is used to ionise $He^+ \rightarrow He^{++}$

3 – that energy is not available to heat the gas, so pressure drops

4 – He is fully ionised, He^{++} is more opaque and gets warmer, pressure can start to grow

5 – contraction stops, star bounces

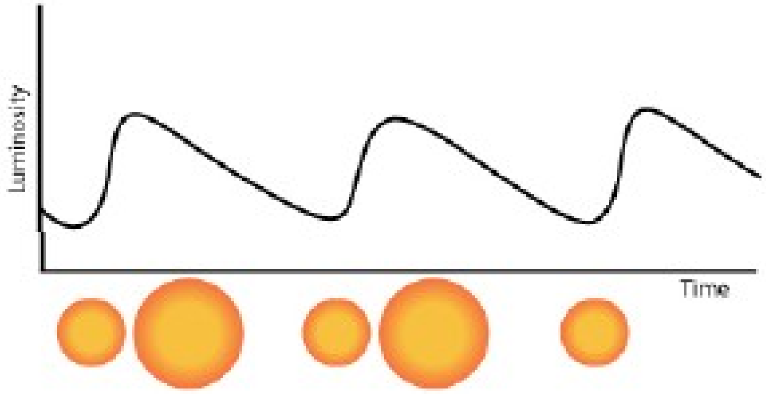
6 – star expands, He recombines ($He^{++} \rightarrow He^+$) and releases energy

7 – star warms up and pressure increases

8 – all He is He^+, less opaque, it absorbs less energy and gets colder

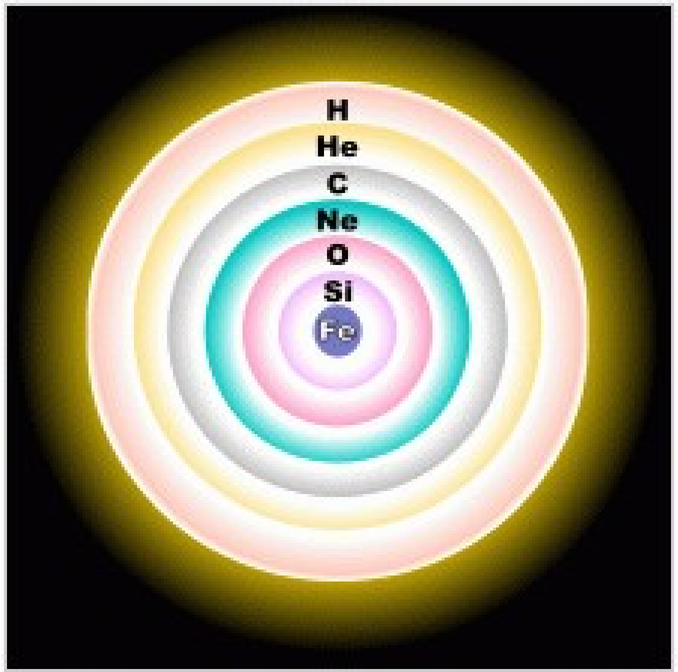
Variable stars:

- Periodicity in star luminosity
- Explained by oscillation between He^+ and He^{++}
- He^{++} is more opaque than He^+ *(Why?)* so it absorbs more energy
- Linear luminosity-time relationship; Cepheids are used for distance calibration



Aging of a massive star

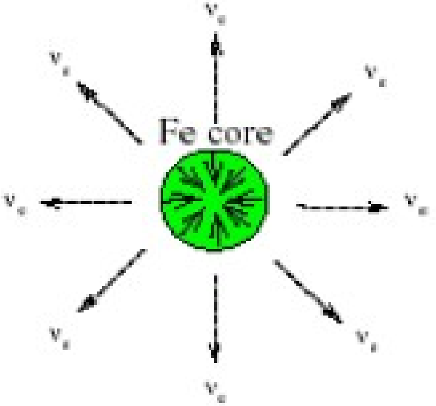
- It burns a succession of nuclear fuels:
  - Hydrogen: O(100 million) years
  - Helium: O(1 million) years
  - Carbon: O(1000) years
  - Neon: O(10) years
  - Oxygen: O(1) year
  - Silicon: O(1) day



- It builds up an inert Fe core
  - Iron cannot be used to produce energy: it is the most stable element, its fusion *absorbs* energy

Iron core collapse

- When the mass of the iron core is 1.2-2 M_{sun}:
  - Collapses by gravity and begins to heat up
  - Reaches $T > 10^{10}$ K
- At that T, two energy-consuming processes begin:
  - Nuclear photodisintegrations: $\gamma + X \rightarrow$ free p, n, α
  - Inverse β-decay: $e^- + p \rightarrow \nu_e + n$ (the ν_e escapes)
  - Both take energy away $\Rightarrow$ collapse accelerates
- In ~1 second:
  - Radius: 6000 km ($\sim R_{earth}$) $\rightarrow$ ~50 km
  - Density: 10^8 g/cm^3 $\rightarrow 10^{14}$ g/cm^3



Becoming nuclear matter

- Because of inverse β-decay, the core suddenly becomes mostly made of neutrons
  - This "neutronization" creates a 10 ms burst of ν_e
  - Normal β-decay ($n \rightarrow p e^- \bar{\nu}_e$) is stopped: electron states are filled up to a Fermi energy that is larger than ΔE of the decay
- When density reaches 2.4×10^{14} g/cm^3, i.e. the density of atomic nuclei (R~30 Km), nuclear forces dominate
- At that point, neutron degeneracy (see last lesson) enters the game, and degeneration pressure stops the collapse
  - The core collapse, suddenly halted, rebounds
  - This creates a *shock wave* that induces more nuclear reactions as it passes

Neutrino burst

- This neutron core has an initial temperature of 10^{11} K
- ~10% of the entire star's rest mass is converted into a ten-second burst of neutrinos which is the main output of the event
    - Only 1% of the energy output is converted into kinetic energy and photons (by neutrinos that interact in the large gas density of the envelope), the rest is emitted around as neutrino energy
    - Sufficient to give a luminosity of ~10 billions L_{sun} for some minutes (more than an entire galaxy)

"Prompt" and "thermal" neutrinos

- Prompt neutrinos are those from inverse β decay:

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

- The temperature is so high that some photons can produce e^+e^- pairs in the EM field of the nuclei (*question: why not in vacuum?*), and that e^+ and e^- are so energetic that they can produce Z bosons (m_Z=91 GeV – *question: what is the minimum energy needed for e^+ and e^-?*)

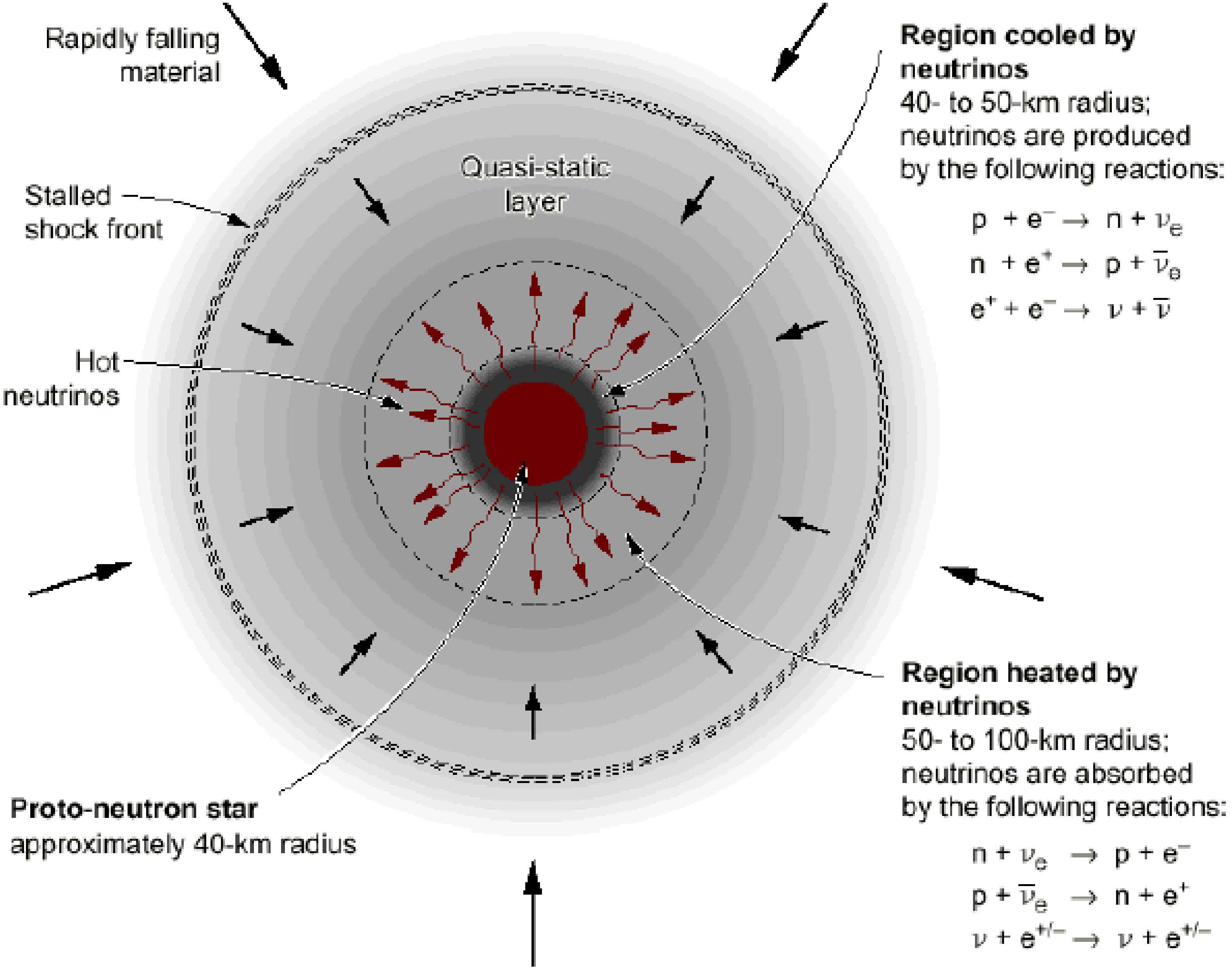
- In 20% of the cases, $Z\rightarrow\nu\bar{\nu}$; it doesn't care about flavour

$$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_e + \bar{\nu}_e$$

$$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_\mu + \bar{\nu}_\mu$$

$$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_\tau + \bar{\nu}_\tau$$

Shock wave



Rapidly falling material

Stalled shock front

Hot neutrinos

Proto-neutron star
approximately 40-km radius

Region cooled by neutrinos
40- to 50-km radius;
neutrinos are produced
by the following reactions:

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

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

$e^+ + e^- \rightarrow \nu + \overline{\nu}$

Region heated by neutrinos
50- to 100-km radius;
neutrinos are absorbed
by the following reactions:

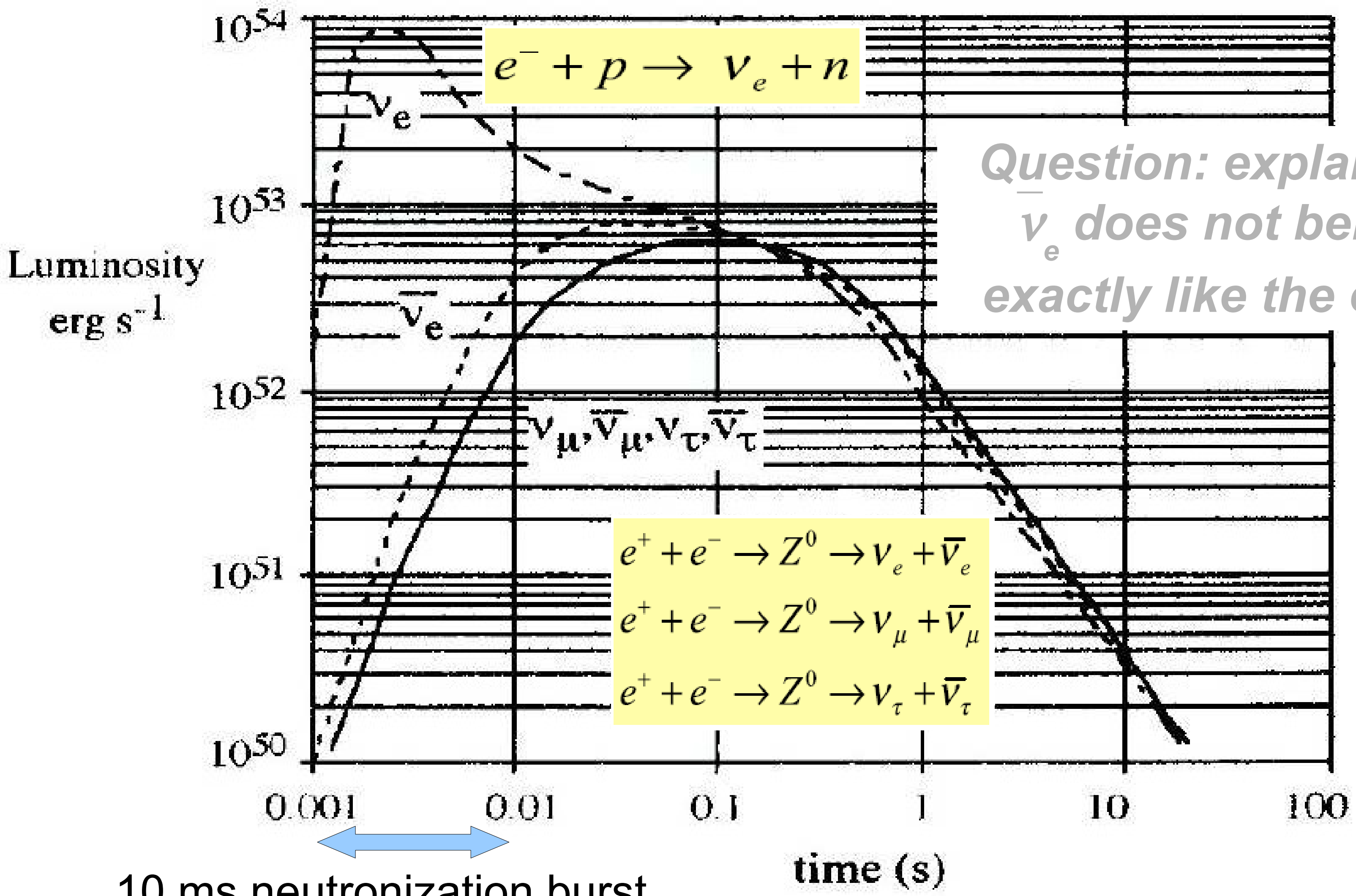
$n + \nu_e \rightarrow p + e^-$

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

$\nu + e^{+/-} \rightarrow \nu + e^{+/-}$

Neutrino luminosity versus time

Generic form from theory prediction. Source



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

$$e^+ + e^- \to Z^0 \to \nu_e + \bar{\nu}_e$$

$$e^+ + e^- \to Z^0 \to \nu_\mu + \bar{\nu}_\mu$$

$$e^+ + e^- \to Z^0 \to \nu_\tau + \bar{\nu}_\tau$$

Question: explain why $\bar{\nu}_e$ does not behave exactly like the others

10 ms neutronization burst

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

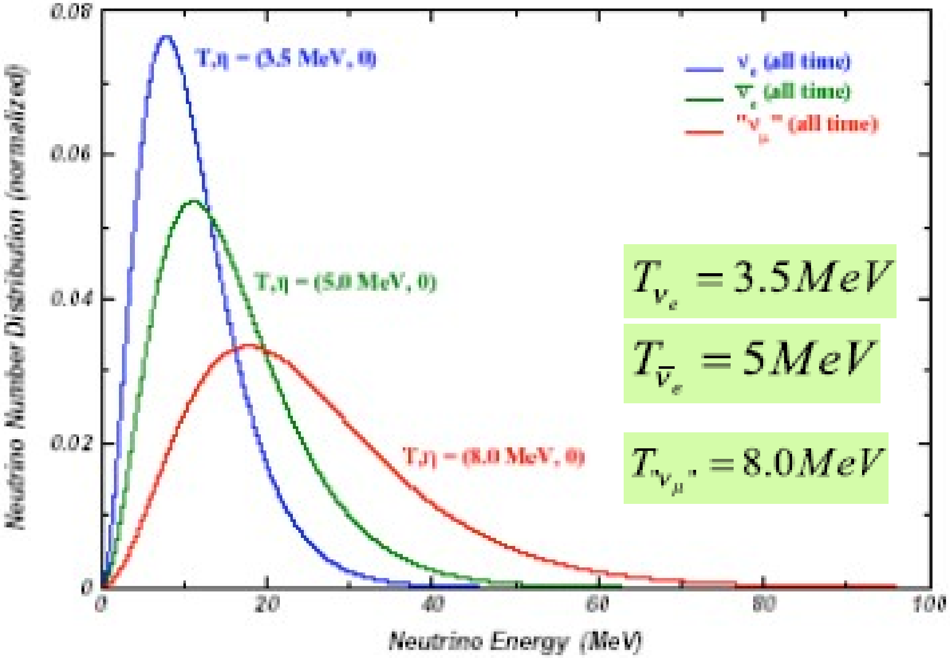
Integrated luminosity of a supernova

- Potential energy of a sphere of mass M and radius R is:

$$\frac{3}{5}\frac{GM^2}{R}$$

- Assume that all gravitational energy converts into neutrino energy during collapse from r~O(1000) km to R~O(10) km
- From this formula, for a neutron core with M_{core}~1.4M_{sun}, we get a total emitted neutrino energy of order 10^{53} erg
- 1% of this goes into pushing/heating the envelope, and 1% of this is then re-emitted as light
- So we get 10^{49} erg emitted as light in total → if all re-emitted in 10 seconds, 10^{48} erg/s; compare with ~ 10^{33} erg/s from the Sun
- → $L_{SN} \sim 10^{15} L_{sun}$ during 10 seconds!

Neutrino energy spectra



$T_{\nu_e} = 3.5MeV$

$T_{\bar{\nu}_e} = 5MeV$

$T_{\nu_\mu'} = 8.0MeV$

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E} = 4\pi R^2 \frac{g\pi c}{(2\pi\hbar c)^3} \frac{E^2}{\exp[(E-\mu)/kT]+1} \frac{1}{4\pi D^2}$$

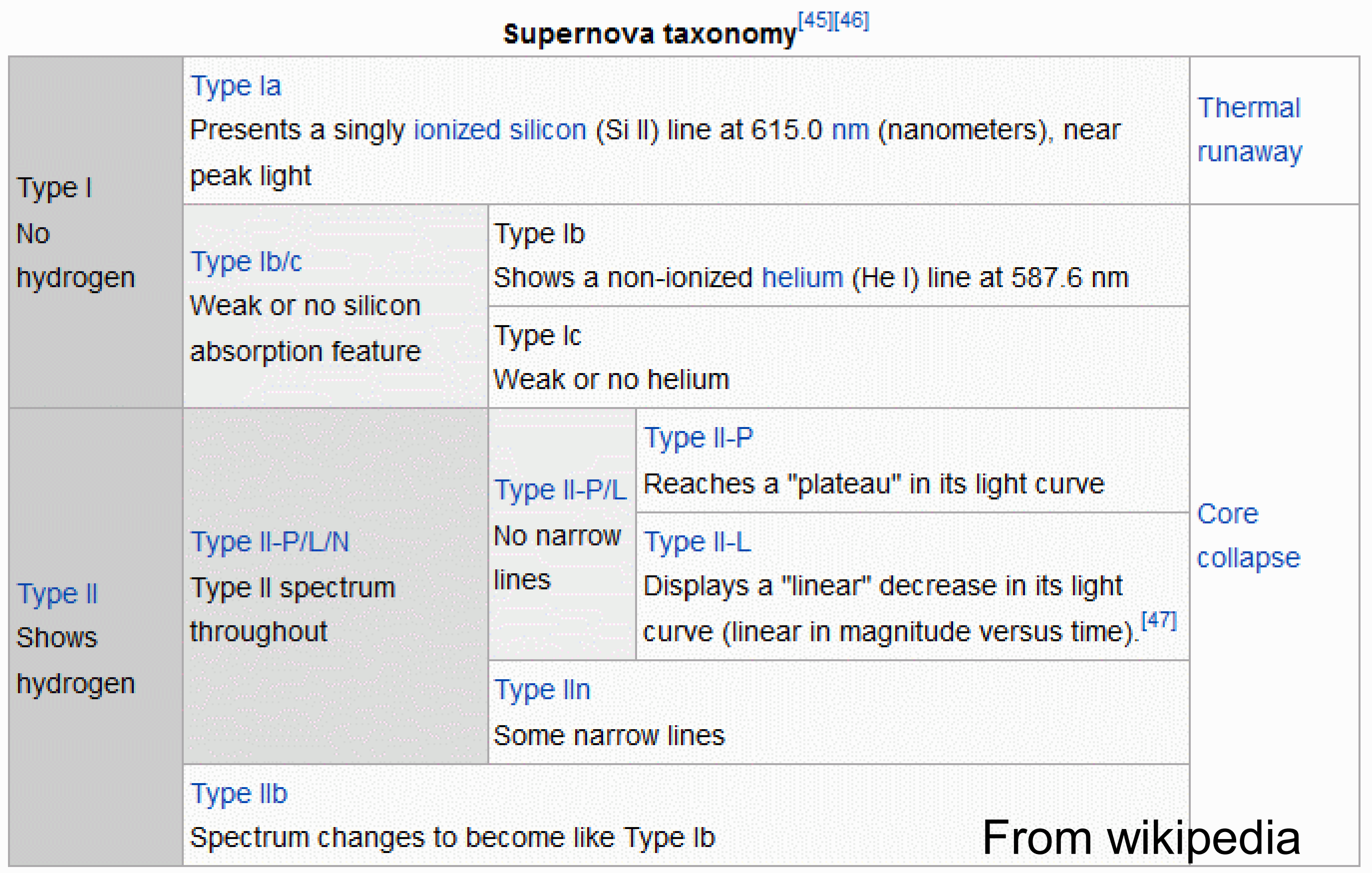
R: radius of neutrinosphere
D: distance from us
Take g=1, μ=0, R~50 km

The spectra are not the same:

- Probability of interaction during the escape is larger for neutrinos than for anti-neutrinos *(Why?)*
- And larger for electronic neutrinos than for muonic/tauonic (equal for muonic and tauonic) *(Why?)*
- Larger interaction probability → the ones that we see had their last interaction in an outer (colder) part

Supernovae

- There are several types of supernovae, coming from different evolutions of a star – what we have described here is one of the known paths towards a Type II supernova
  - *The general subject of supernovae can be chosen as a dissertation*



Supernova taxonomy[45][46]

<table>
<tr><td rowspan="3">Type I
No hydrogen</td><td colspan="3">Type Ia
Presents a singly ionized silicon (Si II) line at 615.0 nm (nanometers), near peak light</td><td>Thermal runaway</td></tr>
<tr><td rowspan="2">Type Ib/c
Weak or no silicon absorption feature</td><td colspan="2">Type Ib
Shows a non-ionized helium (He I) line at 587.6 nm</td><td rowspan="6">Core collapse</td></tr>
<tr><td colspan="2">Type Ic
Weak or no helium</td></tr>
<tr><td rowspan="4">Type II
Shows hydrogen</td><td rowspan="3">Type II-P/L/N
Type II spectrum throughout</td><td rowspan="2">Type II-P/L
No narrow lines</td><td>Type II-P
Reaches a "plateau" in its light curve</td></tr>
<tr><td>Type II-L
Displays a "linear" decrease in its light curve (linear in magnitude versus time).[47]</td></tr>
<tr><td colspan="2">Type IIn
Some narrow lines</td></tr>
<tr><td colspan="3">Type IIb
Spectrum changes to become like Type Ib</td></tr>
</table>

From wikipedia

Supernova nucleosynthesis

- Elements heavier than Iron, and up to Plutonium, are created in the r-process
  - ("r" is for "rapid", as opposed to "s" for "slow")
- After "neutronization", core is rich in free neutrons that cannot decay (because β-decay is stopped)
- Large neutron flux and high temperature: neutron capture reactions become dominant
  - Highly-unstable neutron-rich nuclei are created
- Process stops when nuclei become so large that they can undergo spontaneous fission
  - Their fragments then have β-decay when T is lower

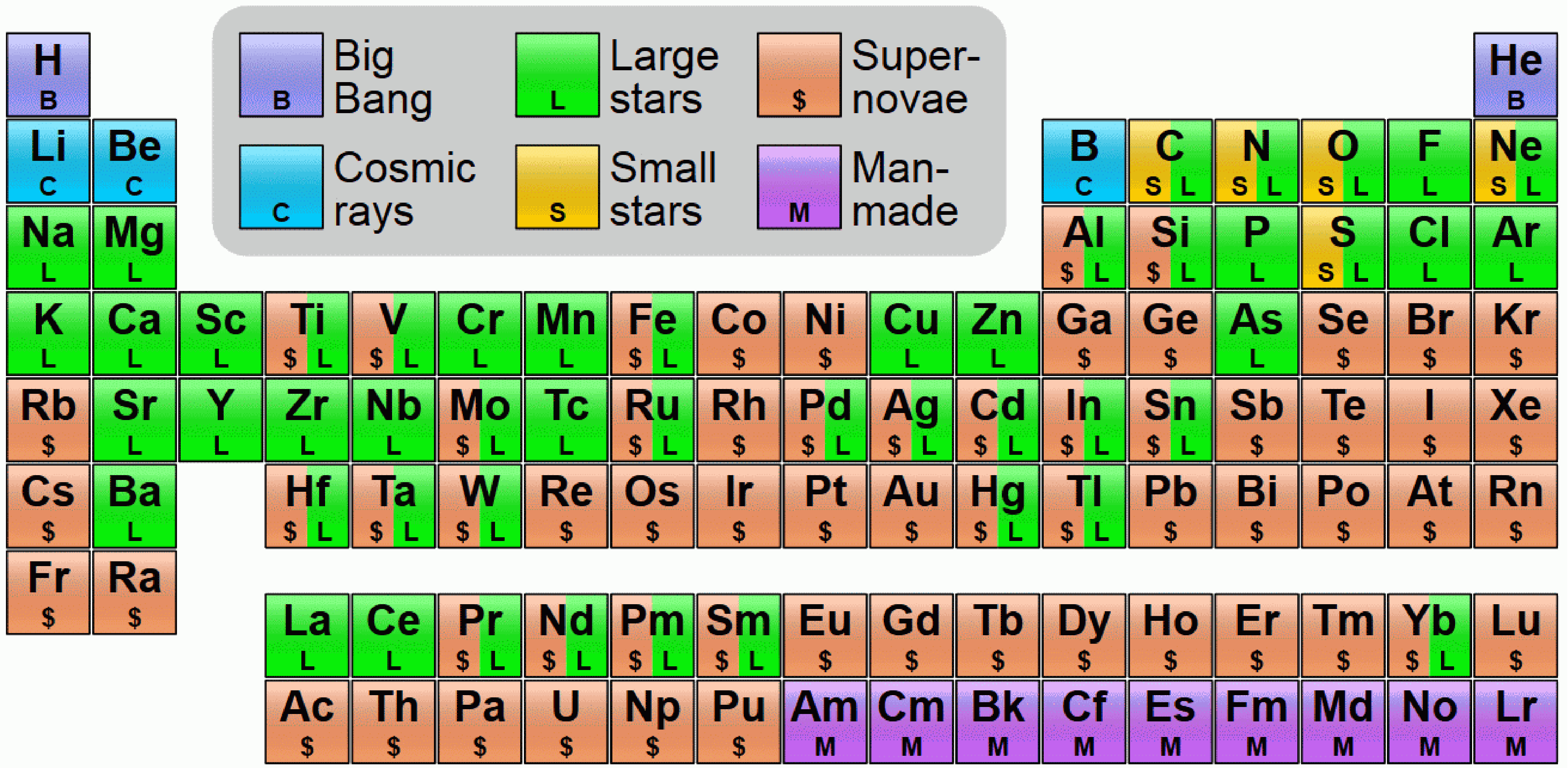
Recapitulation on nucleosynthesis

- Main Sequence stars produce Helium
- Aging stars produce elements up to Iron (Fe)
- AGBs (from light stars) produce elements up to Lead (Pb)
- Supernovas (from heavy stars) produce elements up to Plutonium (Pu)
- We are surrounded by almost all the elements of the Mendeleev table because the Sun is a second generation star, born from the debris of dead first generation stars

But something is missing

- We know that ~25% of the Universe is made of He
- We have seen that all stars produce He, but even all the stars existing and existed in the Universe are not sufficient to have produced so much
- In a future lesson we will study "Big Bang nucleosynthesis"

Main producer of each element



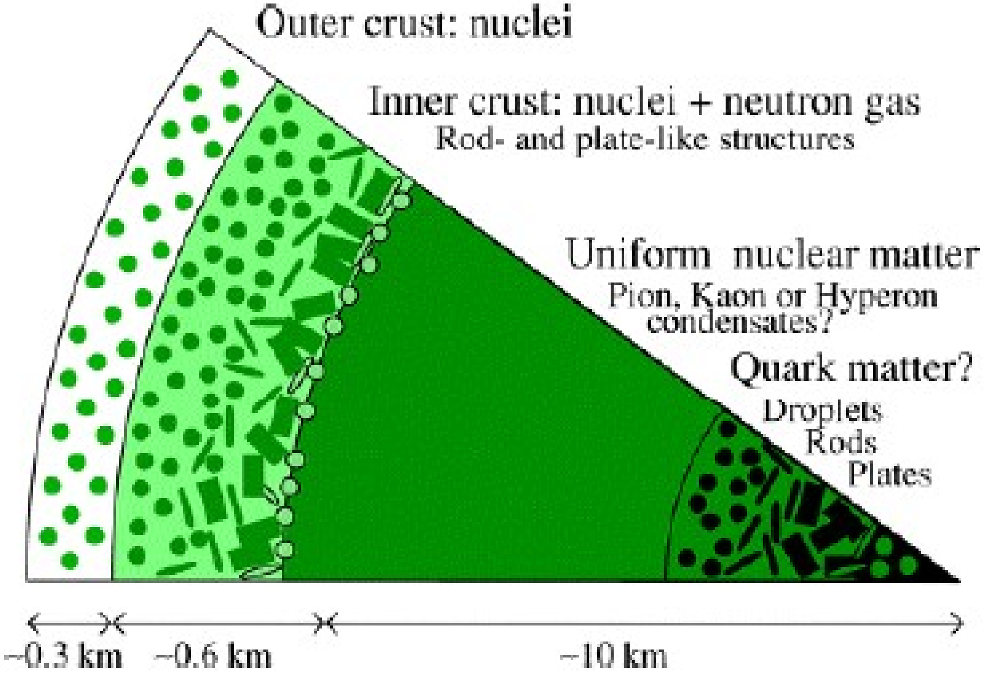
B Big Bang
L Large stars
$ Super-novae
C Cosmic rays
S Small stars
M Man-made

H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al $ L	Si $ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti $ L	V $ L	Cr L	Mn L	Fe $ L	Co $	Ni $	Cu L	Zn L	Ga $	Ge $	As L	Se $	Br $	Kr $
Rb $	Sr L	Y L	Zr L	Nb L	Mo $ L	Tc L	Ru $ L	Rh $	Pd $ L	Ag $ L	Cd $ L	In $ L	Sn $ L	Sb $	Te $	I $	Xe $
Cs $	Ba L		Hf $ L	Ta $ L	W $ L	Re $	Os $	Ir $	Pt $	Au $	Hg $ L	Tl $ L	Pb $	Bi $	Po $	At $	Rn $
Fr $	Ra $																
			La L	Ce L	Pr $ L	Nd $ L	Pm $ L	Sm $ L	Eu $	Gd $	Tb $	Dy $	Ho $	Er $	Tm $	Yb $ L	Lu $
			Ac $	Th $	Pa $	U $	Np $	Pu $	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

Picture taken from wikipedia.
Big Bang nucleosynthesis and Cosmic Rays will be the subject of future lessons.

Neutron stars

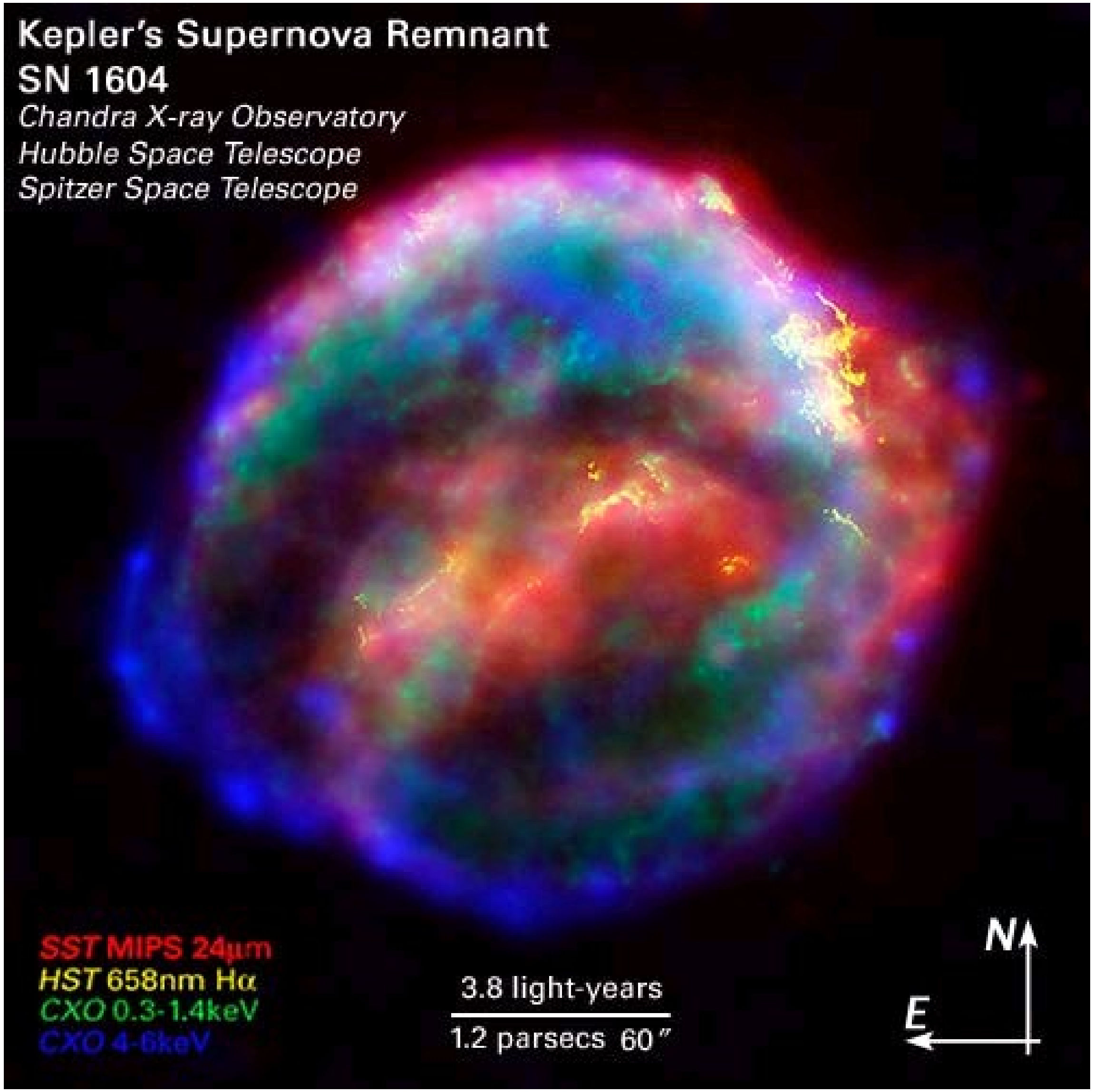
- They are the core, now naked, of stars whose initial mass was between 8 and 18 M_{sun}
- Neutron degeneracy pressure counterbalances gravity
- Very exotic behaviour: most of the neutron star can be modeled as a single giant nucleus



Black holes

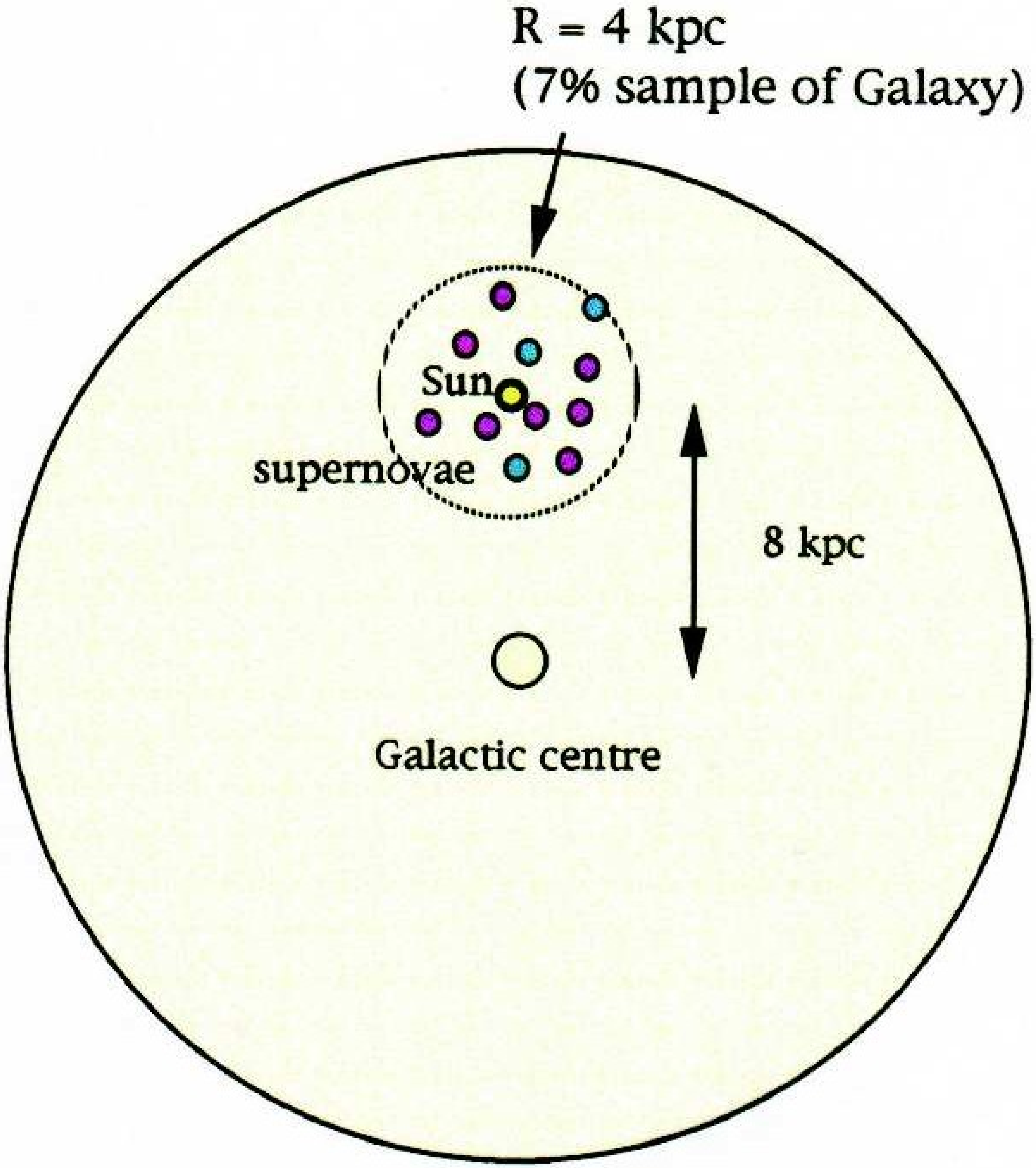
- If the initial star's mass is larger than ~18 M_{sun}, its post-supernova neutron core will be larger than 2-3 M_{sun}, and neutron degeneracy pressure will not be enough against gravity
- It collapses into a Black Hole, defined as an object that doesn't let photons escape (and therefore is "black")
- "Events horizon" is given by Schwarzschild's radius
  - $R_s=2GM/c^2$; can be derived in General Relativity
- Note: "classically" (and by General Relativity) the Black Hole is a "singularity" with 0 size and ∞ density
  - Quantum mechanics may solve the paradox of ∞ density, but we have no satisfactory quantum theory of gravity yet

Documented supernovae in the Milky Way

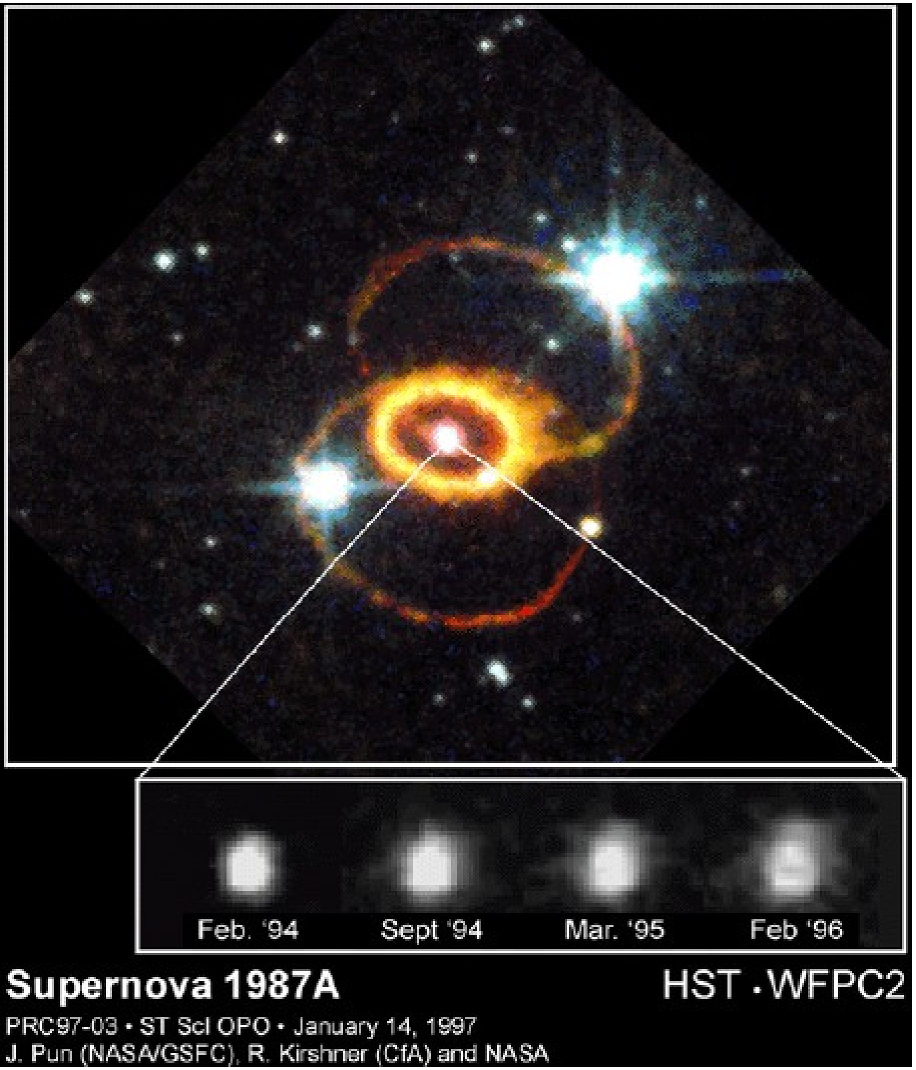


Only 8 supernovae recorded by humans in the Milky Way

- Chinese records: 185, 386, 392, 1006
- Later: 1054 (Crab Nebula), 1181, 1572 (observed by Tycho Brahe; gas still hot,10^7 K), 1604 (observed by Kepler, still with naked eye)
- No SN in Milky Way since invention of telescope


R = 4 kpc
(7% sample of Galaxy)
Sun
supernovae
8 kpc
Galactic centre

SN1987A



Supernova 1987A HST · WFPC2

PRC97-03 · ST ScI OPO · January 14, 1997
J. Pun (NASA/GSFC), R. Kirshner (CfA) and NASA

- January 1987: the nearest supernova since 1604
- A blue super-giant (15 M_{sun}) exploded in the Large Magellanic Cloud (one of the "satellites" of our galaxy)
- Very precious source of data to understand supernovae

Supernovae are still very luminous for years after explosion: part of their energy is kept by the ionized gas of their remnant nebulae

Neutrinos from SN1987A

- Supernova models predict that photons take ~3-4 hours before being able to escape the surrounding dense gas
- But neutrinos interact much less, and need much less time to escape
- Knowing when SN1987A appeared in the telescopes, the physicists running large neutrino detectors had a look at the data as a function of time
- They found a ν burst 3 hours before the photons arrived

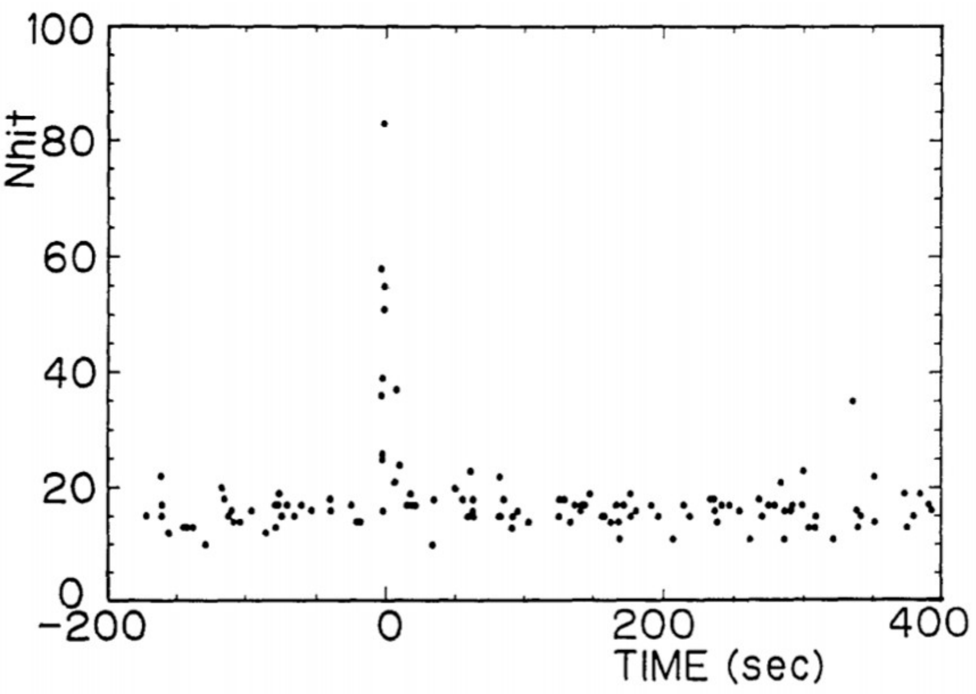
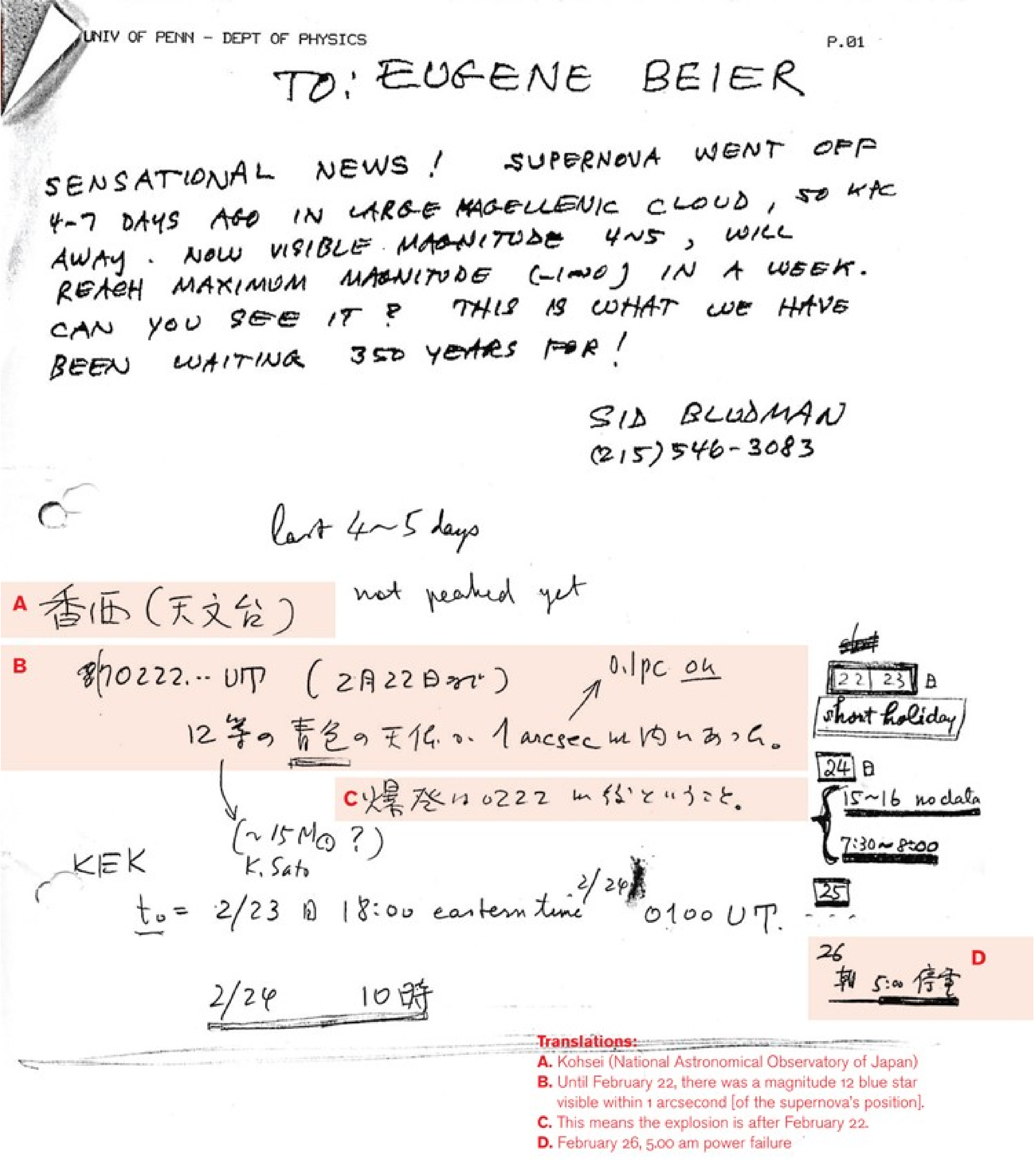


Fig. 2a : The supernova signal of the KAMIOKANDE-II experiment. It is a part of the laser printer output of the low energy raw data.Nhit is the number of hit photomultipliers.



UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL REACH MAXIMUM MAGNITUDE (-1~0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

last 4~5 days

A 香西（天文台）

not peaked yet

B 約0222… UT （2月22日まで）

12等の青色の天体が 1 arcsec 以内にあった。

0.1pc on

(~15M☉?)
K. Sato

C 爆発は0222 以後ということ。

KEK

t_0 = 2/23 日 18:00 eastern time 2/24 0100 UT.

2/24 10時

~~short~~

22 23 日
short holiday

24 日
15~16 no data
7:30~8:00

25

26
朝 5:00 停電 D

Translations:

A. Kohsei (National Astronomical Observatory of Japan)

B. Until February 22, there was a magnitude 12 blue star visible within 1 arcsecond [of the supernova's position].

C. This means the explosion is after February 22.

D. February 26, 5.00 am power failure

From here.

Next time might be the opposite: ν experiments and astronomical observatories are in much better communication and the former tell the latter where to point the telescopes

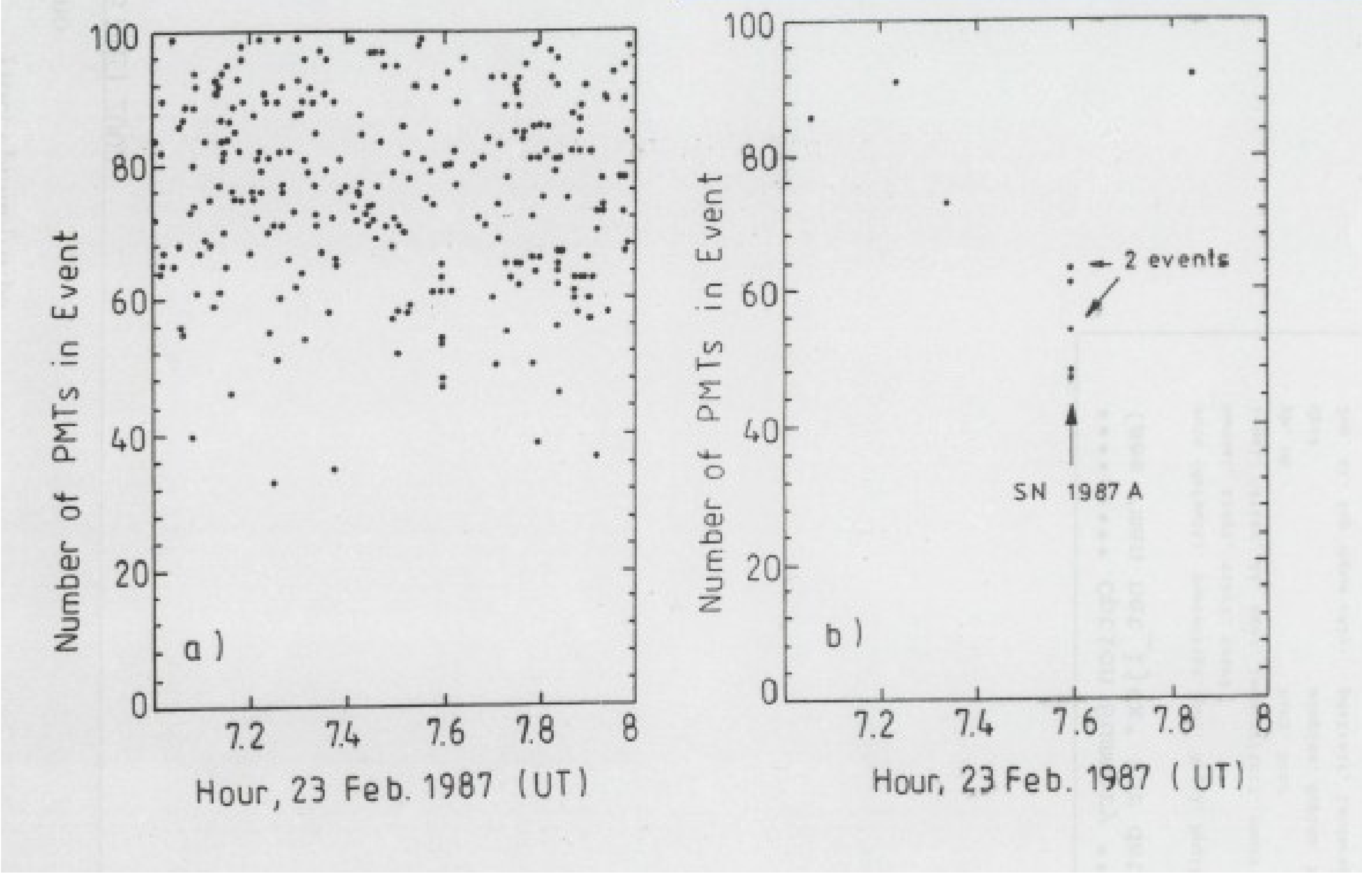
Confirmations from other experiments

Observations of SN1987A

IMB (Irvine-Michigan-Brookhaven)

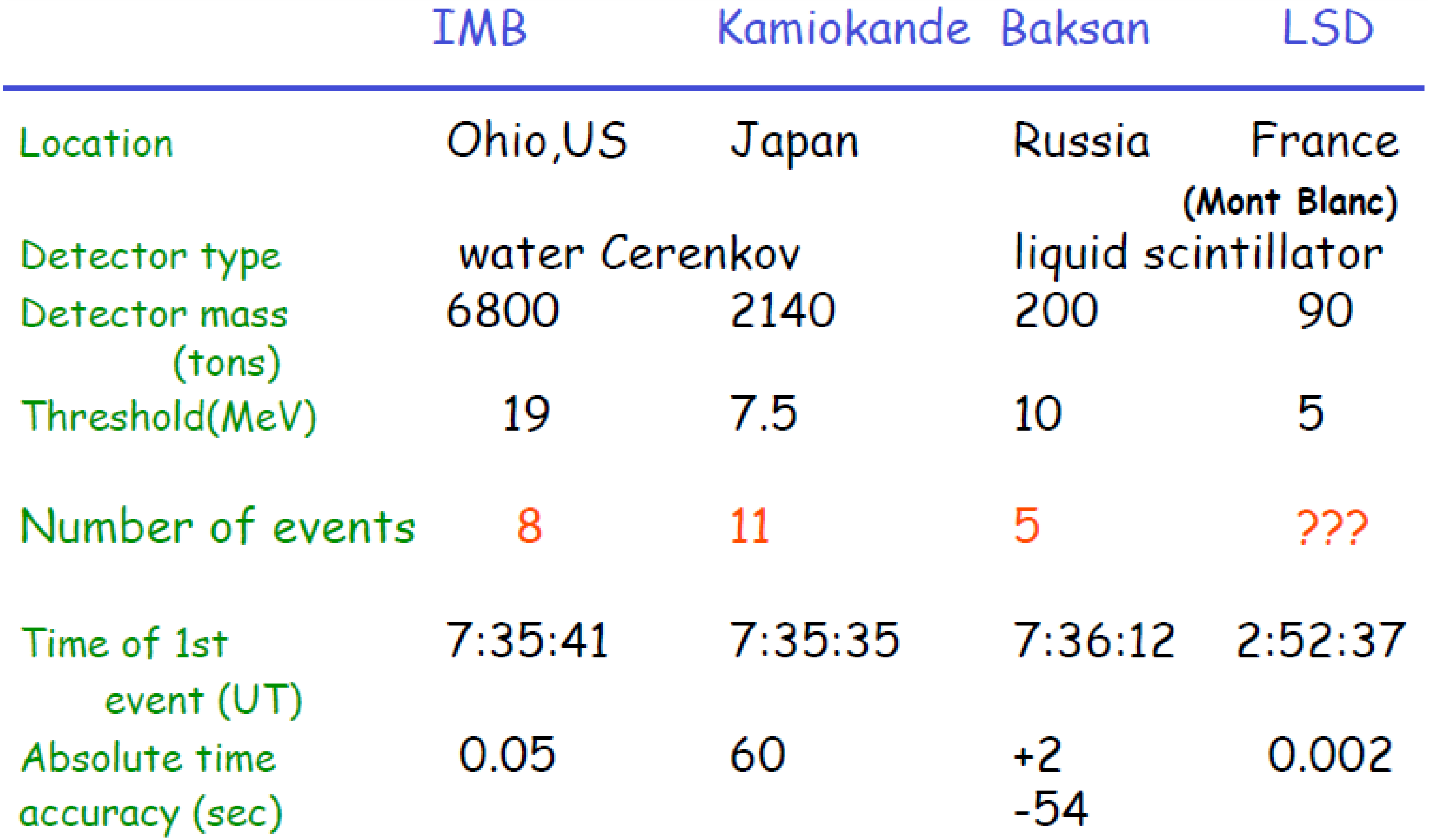
Raw data

After standard analysis rejecting atmospheric muons



Taken from here

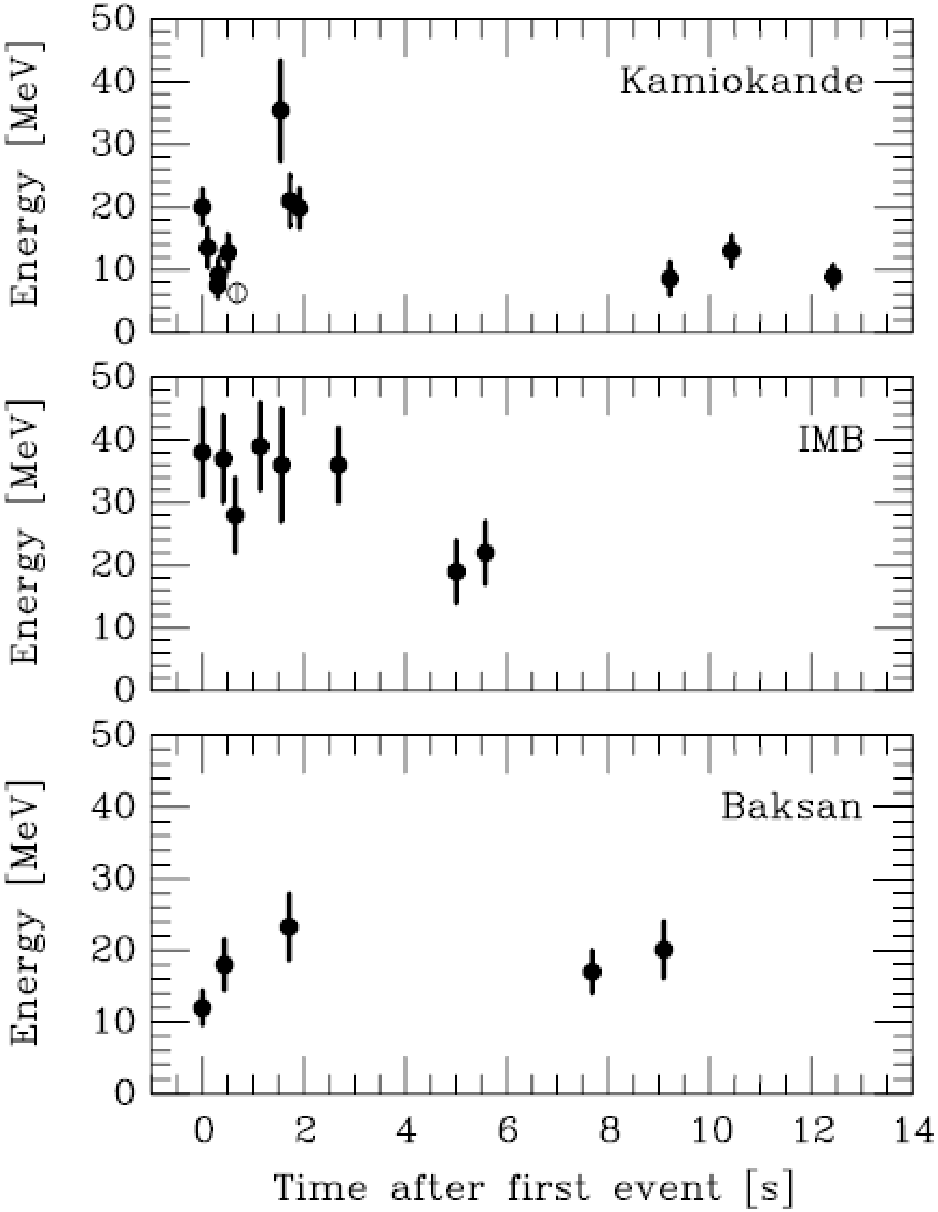
Confirmations from other experiments



	IMB	Kamiokande	Baksan	LSD
Location	Ohio,US	Japan	Russia	France (Mont Blanc)
Detector type	water Cerenkov		liquid scintillator	
Detector mass (tons)	6800	2140	200	90
Threshold(MeV)	19	7.5	10	5
Number of events	8	11	5	???
Time of 1st event (UT)	7:35:41	7:35:35	7:36:12	2:52:37
Absolute time accuracy (sec)	0.05	60	+2 -54	0.002

Table from here

What kind of neutrinos were seen?



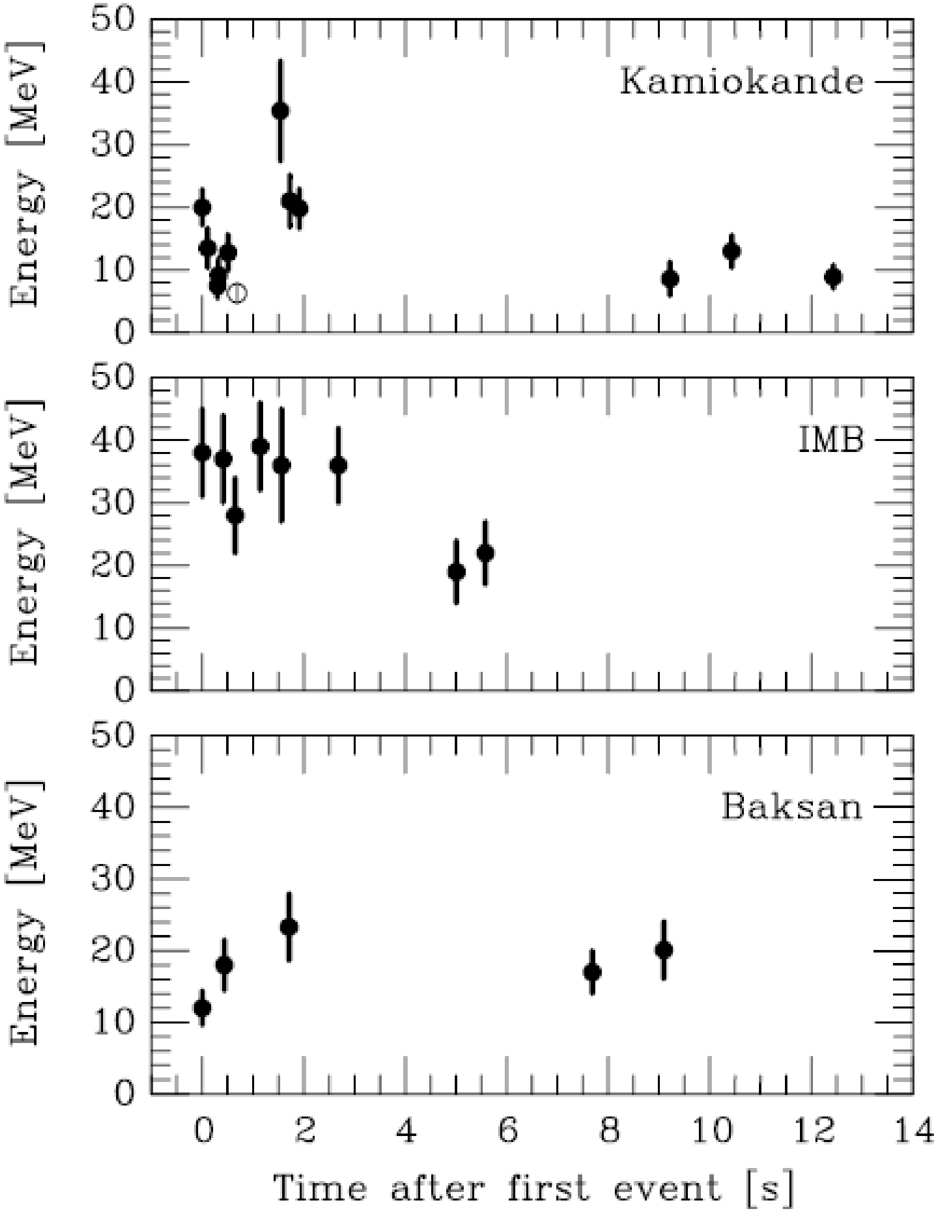
- Water detectors are sensitive to:

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

$$\nu_i + e^- \longrightarrow \nu_i + e^-$$

- But the cross section of the first reaction is almost 100 times larger than the second
- So these detectors were mostly recording electronic anti-neutrinos
- This explains why there is a broad ~10 s distribution and not a spike in the first ~0.01 s

SN1987A and neutrino mass



- The data from 3 neutrino detectors (left) show a spread of Δt_{obs}~10 s
- Supernova model: Δt_{SN}~10 s
- $\Rightarrow \nu$ speed is compatible with c $\Rightarrow \nu$ mass is compatible with 0
- <u>Exercise</u>: derive approximation

$$t = \frac{D}{c\sqrt{1-(m_\nu c^2/E_\nu)^2}}$$

- If this Δt_{obs} is only due to neutrino mass (Δt_{SN}~ 0), then the most energetic neutrinos should arrive before the less energetic

SN1987A and neutrino stability

- At that time, the "solar neutrino problem" had not been solved yet
  - Neutrino oscillations were one of the most popular explanations, but not the only one
  - Another option was that electron neutrinos are unstable and decay to a lighter neutrino that does not interact with our detectors
- <u>Exercise</u>: if the solar deficit (50% observed at Kamioka) is due to decay, how many events should have been observed by Kamioka instead of 11?
  - Earth-Sun distance: 150×10^6 km
  - SN1987A distance: 50 kpc

SN1987A and neutrino speed

- When the OPERA experiment at Gran Sasso recently made the claim (later retracted) that neutrinos travel at speed larger than c, one argument for skepticism was that neutrinos from SN1987A had arrived only 3 hours before light
- Exercise: if neutrino speed is a part in a million faster than light, how much earlier would have they arrived?

Recommended reading

- Two interesting articles, available online here:
  - Bahcall, Dar, Piran, letter to Nature
    - Written after the optical observation of SN1987A but before Kamiokande published these data; they suggested how to use it to study neutrino properties
    - Homework or dissertation: derive equations 2a-2c and deduce T of supernova from Kamiokande data
  - Bahcall, Glashow, Nature 326, 135–136; 476–477 (1987)
    - Written after Kamiokande reported the neutrinos
    - Derived upper limit on electron neutrino mass
    - Homework or dissertation: redo their analysis of the Kamiokande data