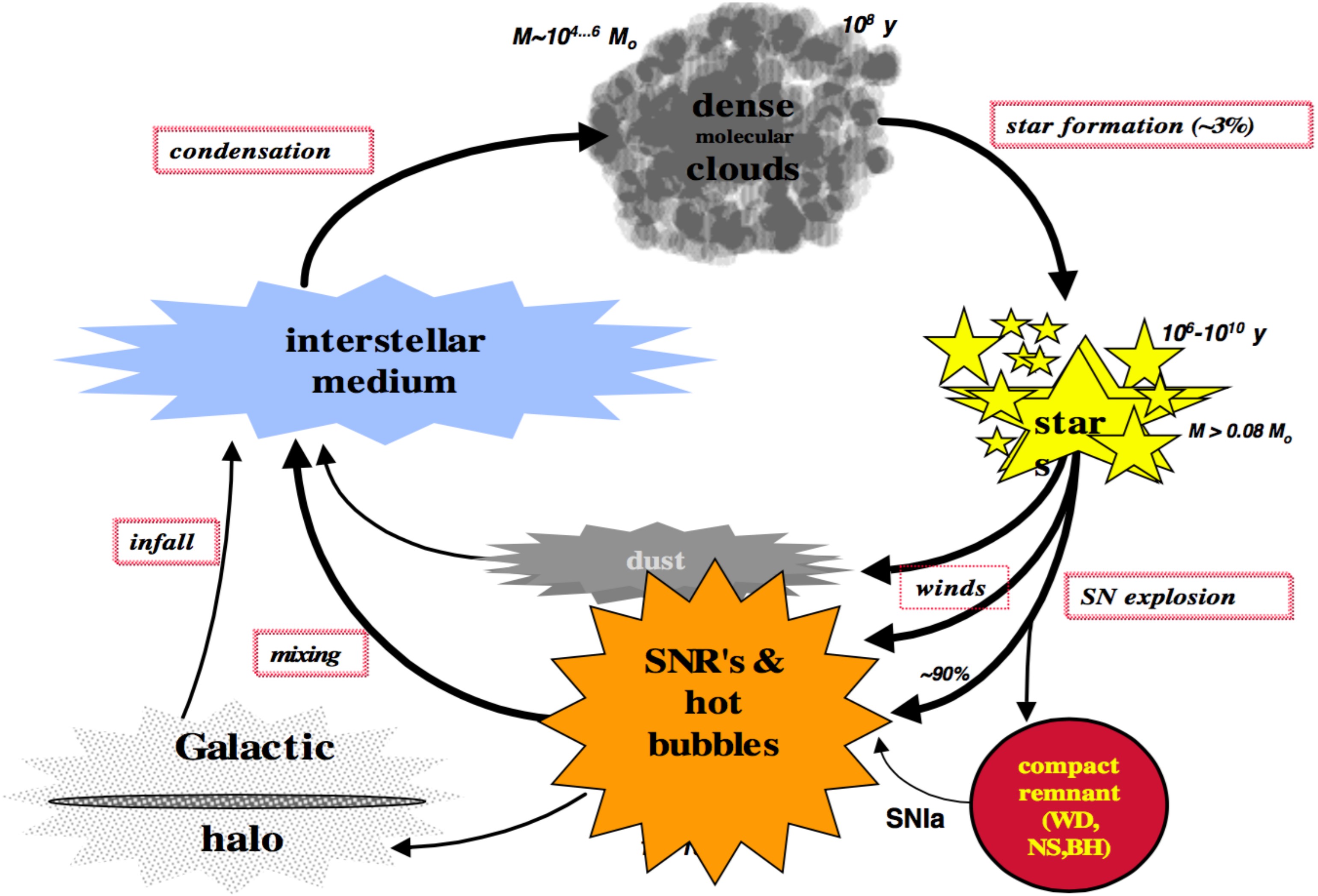
Astrofisica Nucleare e Subnucleare

Neutrino Astrophysics

Cosmic Cycle



$M{\sim}10^{4\ldots6}\ M_o$

10^8 y

dense molecular clouds

star formation (~3%)

condensation

interstellar medium

10^6-10^{10} y

stars

$M > 0.08\ M_o$

infall

dust

winds

SN explosion

mixing

~90%

SNR's & hot bubbles

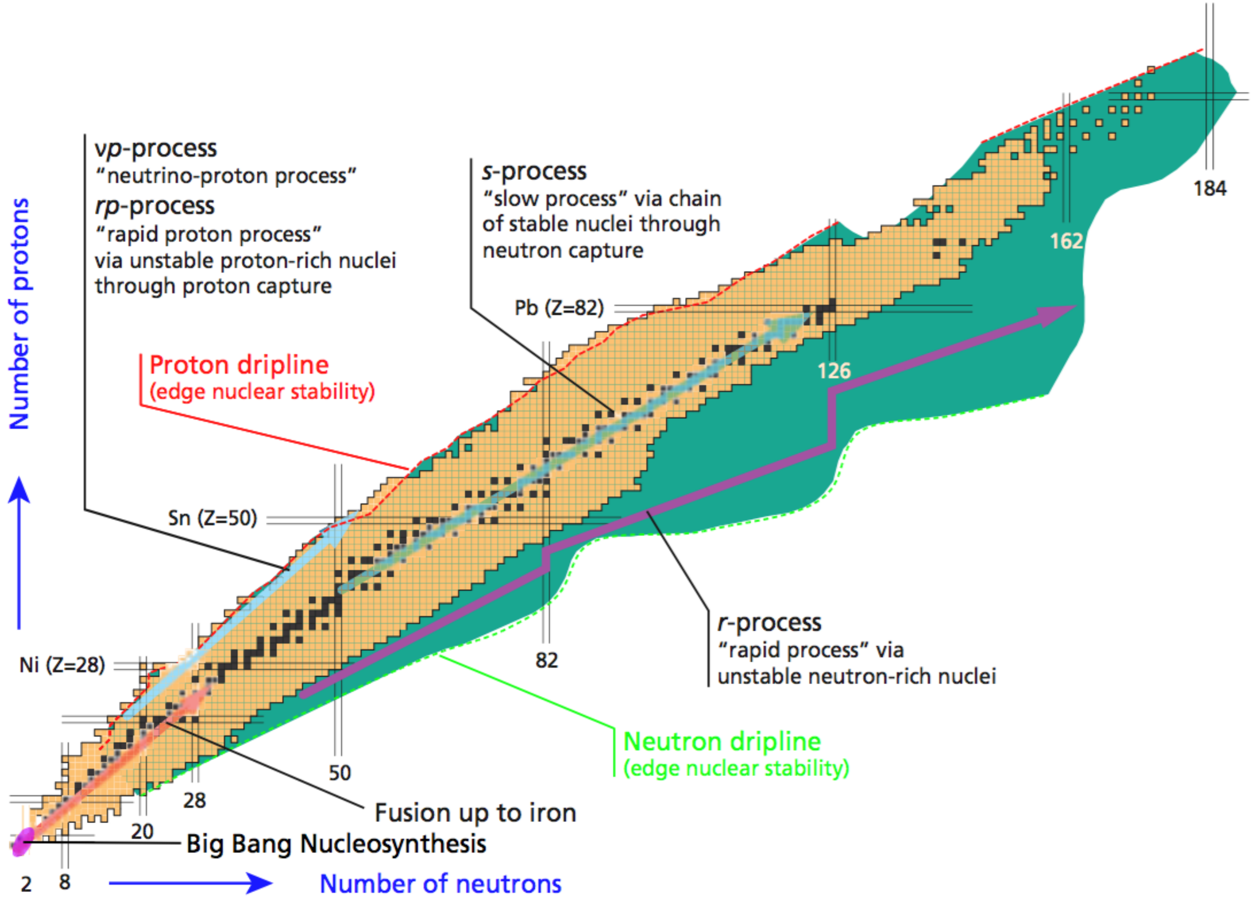
Galactic halo

SNIa

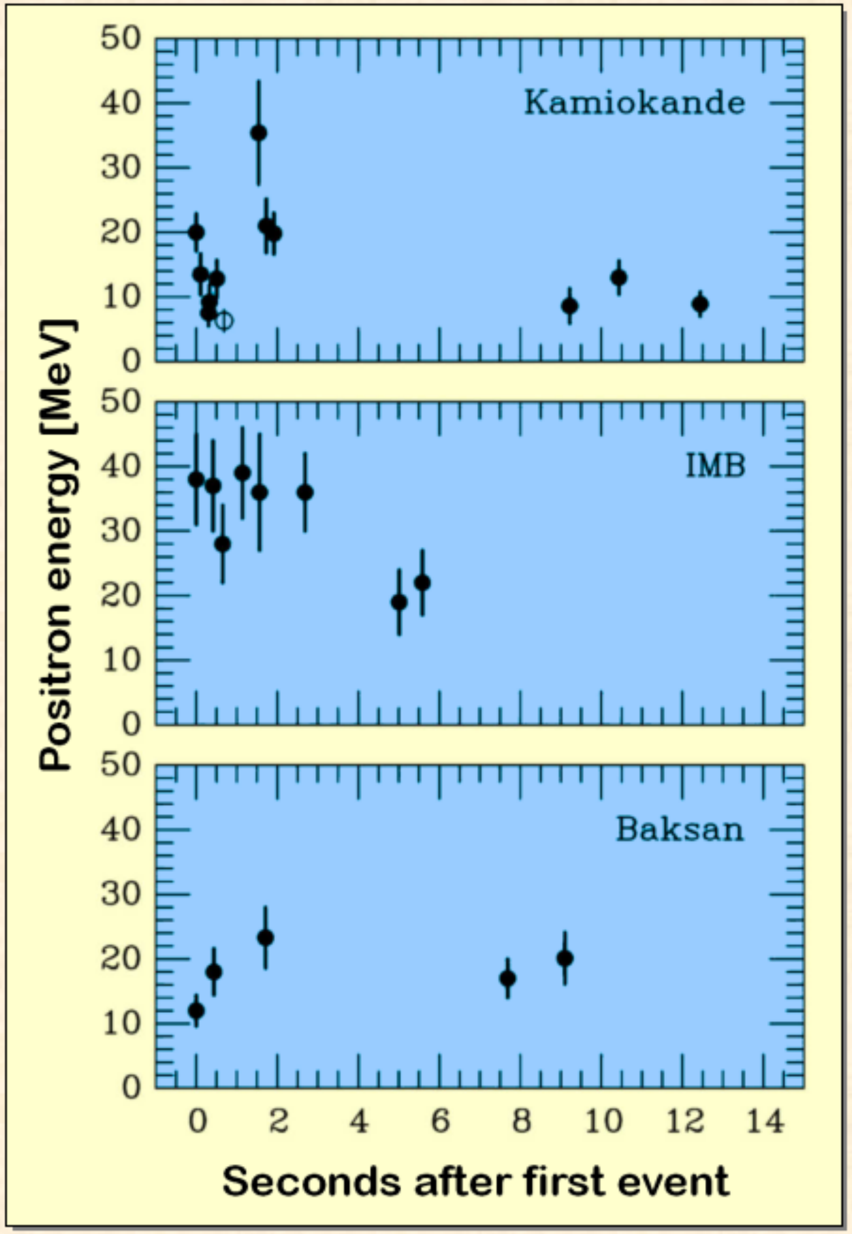
compact remnant (WD, NS,BH)

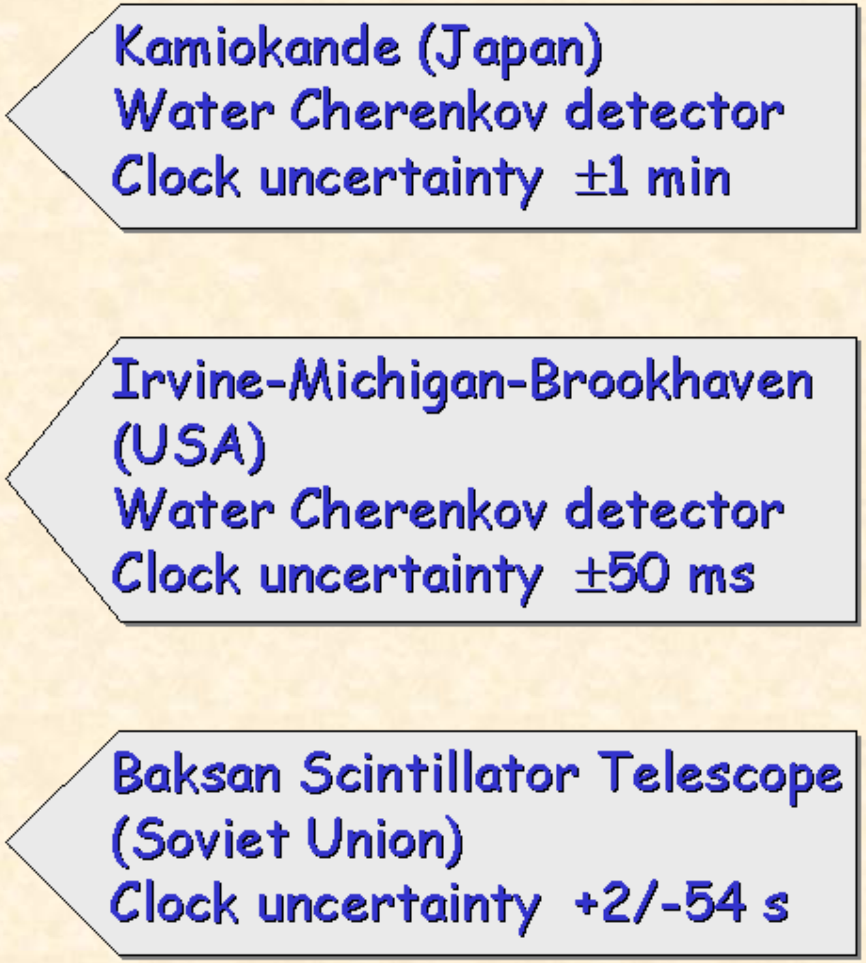
Nucleosynthesis processes

In 1957 Burbidge, Burbidge, Fowler and Hoyle and independently Cameron, suggested several nucleosynthesis processes to explain the origin of the elements.



Neutrino Signal of Supernova 1987A





Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

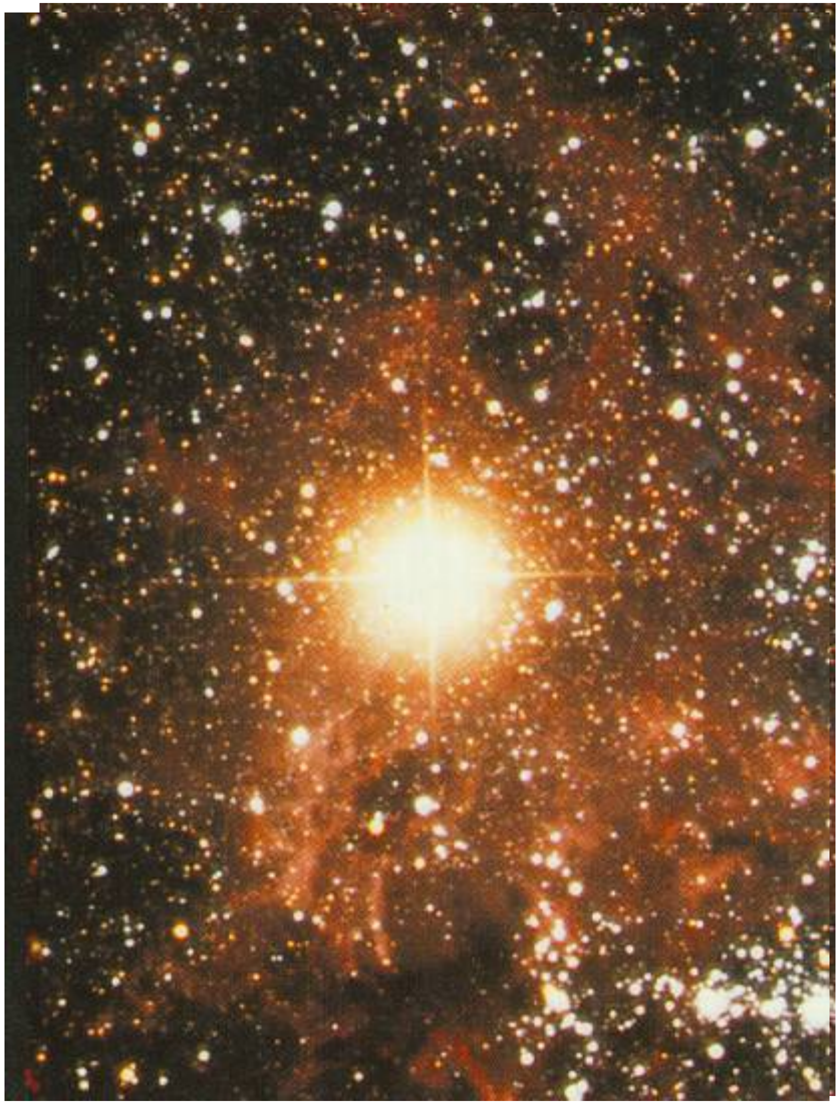
Within clock uncertainties, signals are contemporaneous

Georg Raffelt, Max-Planck-Institut für Physik (München)

Astrofisica Nucleare e Subnucleare

Supernovae Neutrinos

Supernovae



Anglo-Australian Telescope

The field of the supernova SN1987A after 23 February 1987.

This picture shows a small area of sky in the **Large Magellanic Cloud**, the nearby dwarf companion galaxy to our own Galaxy.

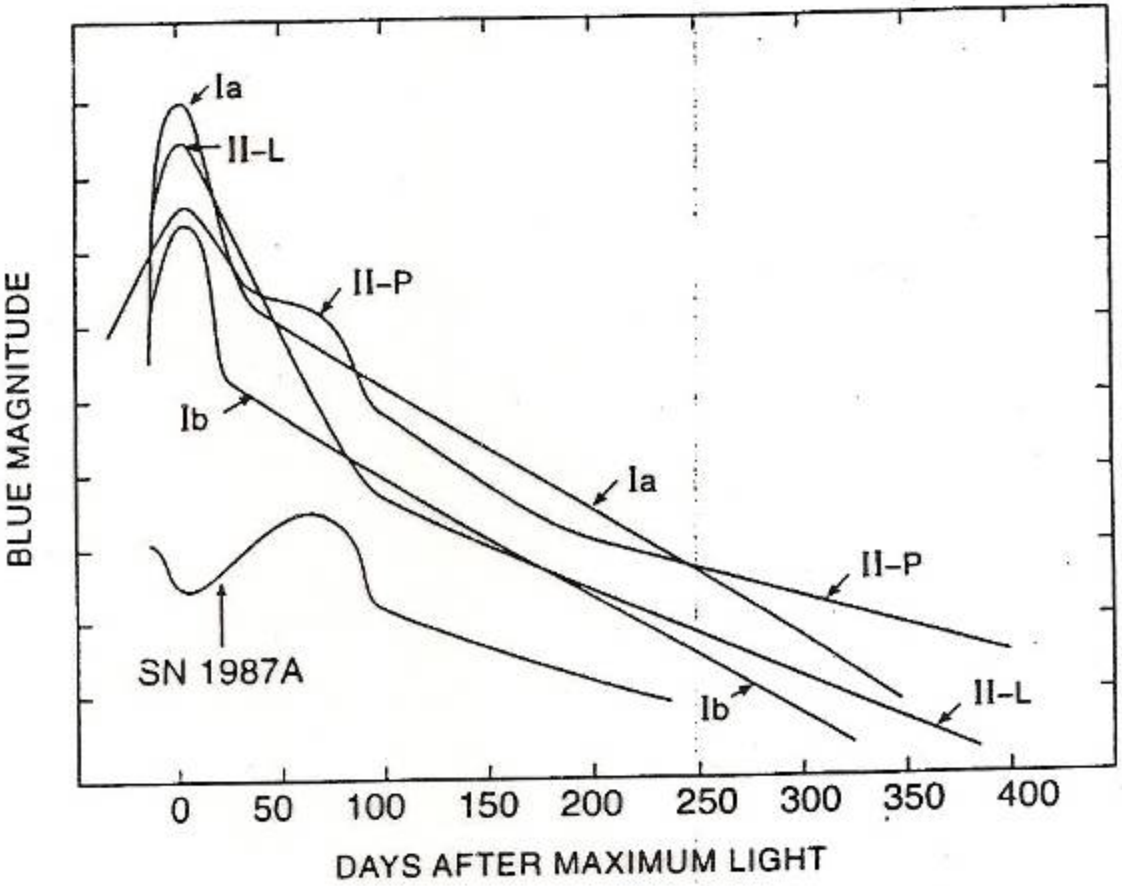
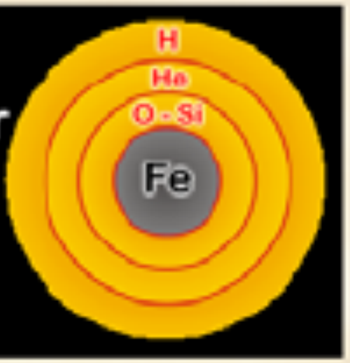


Figure 13.3. Brightness in the B-band for different supernova types. The deviation of supernova 1987a from the standard schemes can clearly be seen. Type II supernovae which have an almost linear decline after the maximum (II-L) are distinguished from those which remain almost constant over a longer time and display a form of plateau (II-P). SN 1987a appears from its characteristics to be a new form (from [Whe90]).

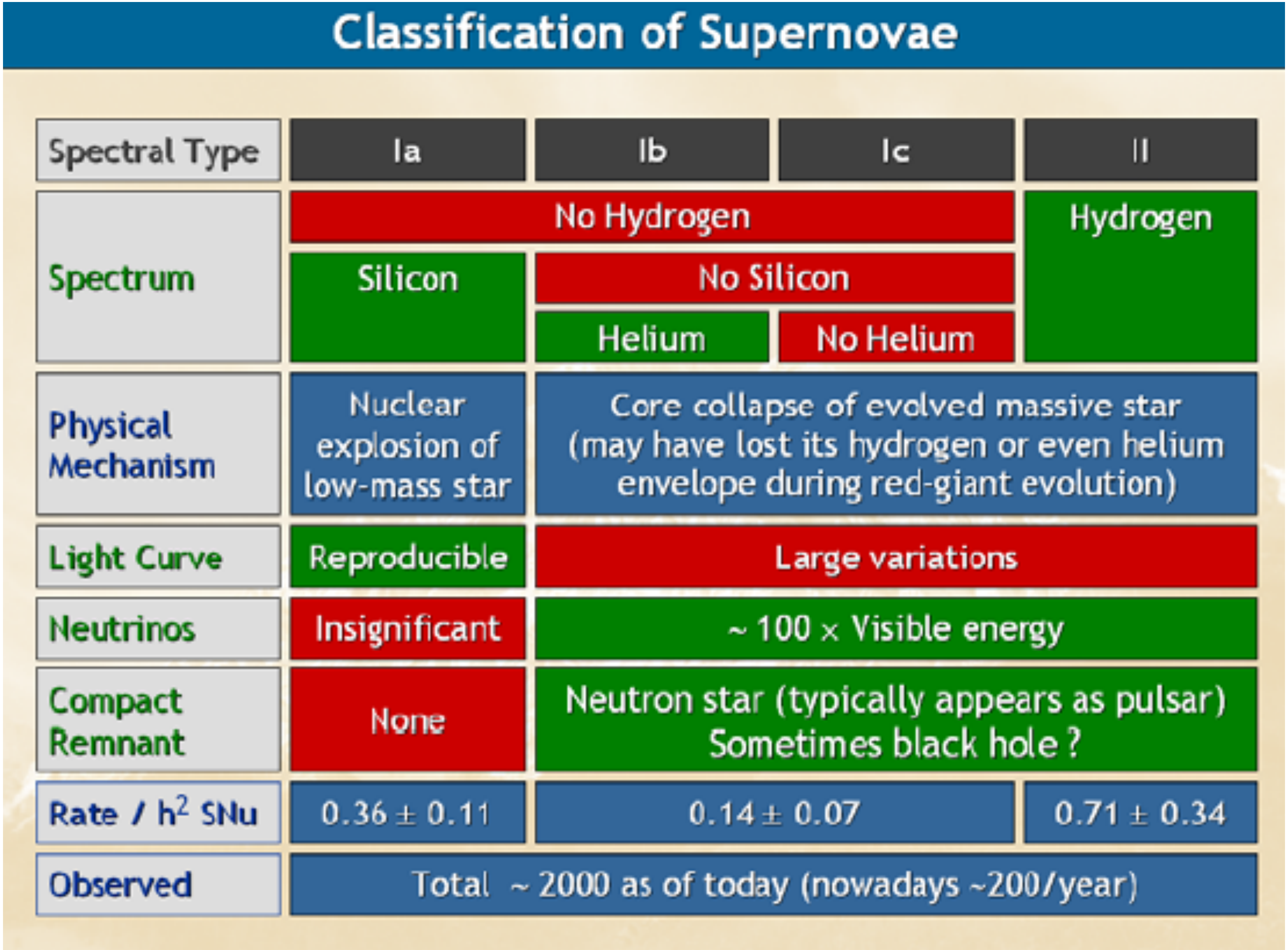
Type Ia vs. Core-Collapse Supernovae

Type Ia	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion 	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface 

Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

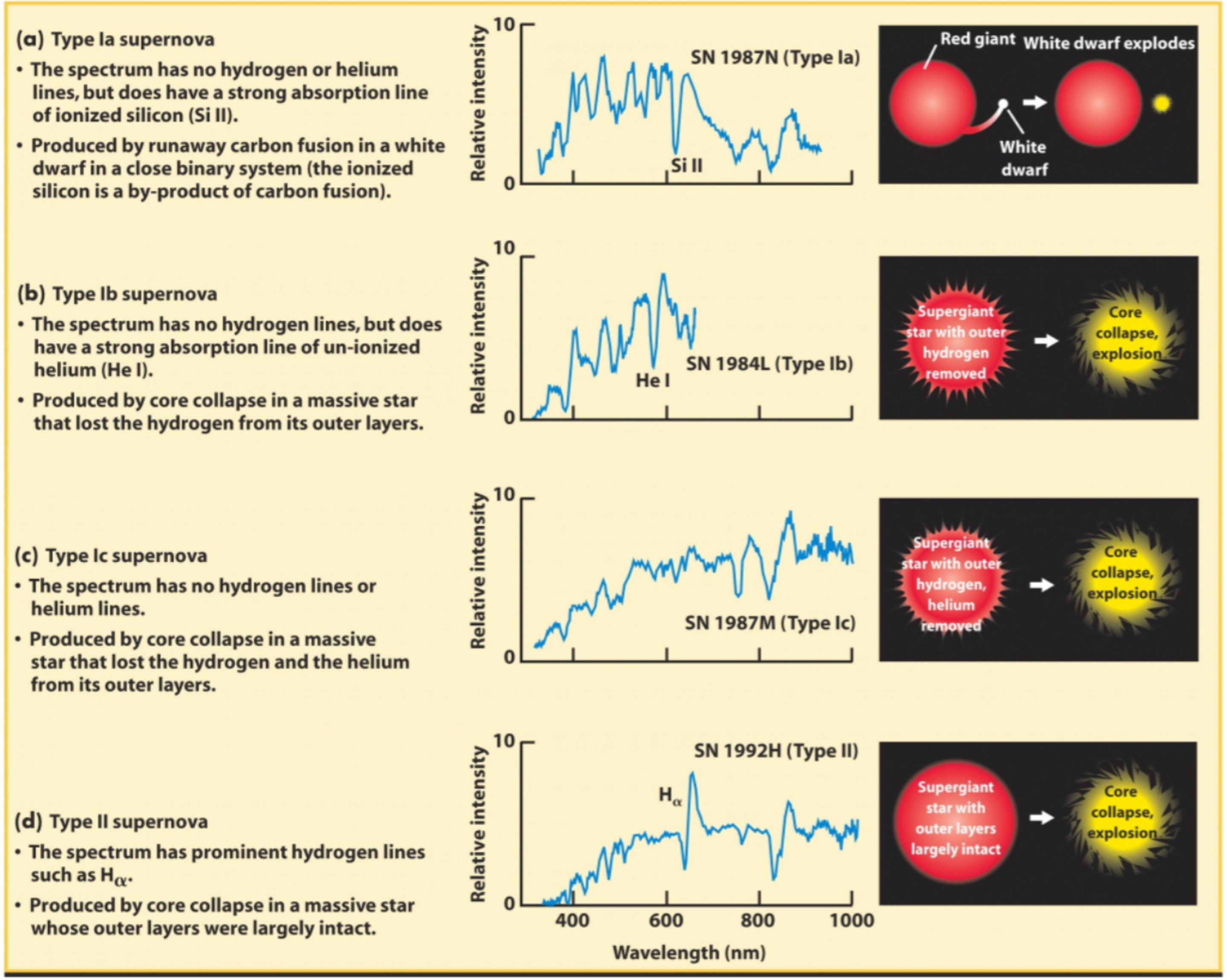
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos



Classification of Supernovae

<table>
<tr><th>Spectral Type</th><th>Ia</th><th>Ib</th><th>Ic</th><th>II</th></tr>
<tr><td rowspan="3">Spectrum</td><td colspan="3">No Hydrogen</td><td rowspan="3">Hydrogen</td></tr>
<tr><td rowspan="2">Silicon</td><td colspan="2">No Silicon</td></tr>
<tr><td>Helium</td><td>No Helium</td></tr>
<tr><td>Physical Mechanism</td><td>Nuclear explosion of low-mass star</td><td colspan="3">Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)</td></tr>
<tr><td>Light Curve</td><td>Reproducible</td><td colspan="3">Large variations</td></tr>
<tr><td>Neutrinos</td><td>Insignificant</td><td colspan="3">~ 100 × Visible energy</td></tr>
<tr><td>Compact Remnant</td><td>None</td><td colspan="3">Neutron star (typically appears as pulsar)
Sometimes black hole ?</td></tr>
<tr><td>Rate / h^2 SNu</td><td>0.36 ± 0.11</td><td colspan="2">0.14 ± 0.07</td><td>0.71 ± 0.34</td></tr>
<tr><td>Observed</td><td colspan="4">Total ~ 2000 as of today (nowadays ~200/year)</td></tr>
</table>

Supernova types



(a) Type Ia supernova

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).

(b) Type Ib supernova

- The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).
- Produced by core collapse in a massive star that lost the hydrogen from its outer layers.

(c) Type Ic supernova

- The spectrum has no hydrogen lines or helium lines.
- Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.

(d) Type II supernova

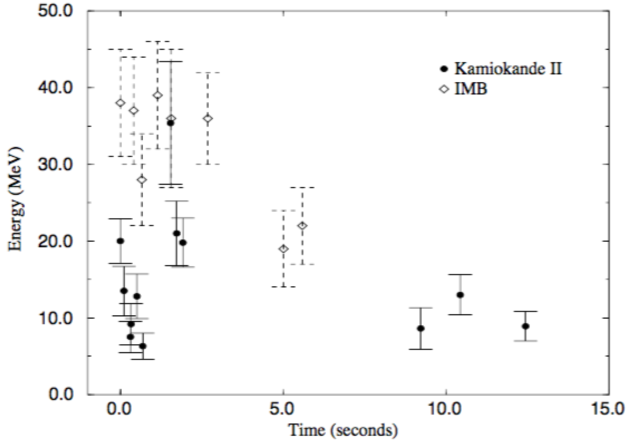
- The spectrum has prominent hydrogen lines such as H_α.
- Produced by core collapse in a massive star whose outer layers were largely intact.

SN1987A

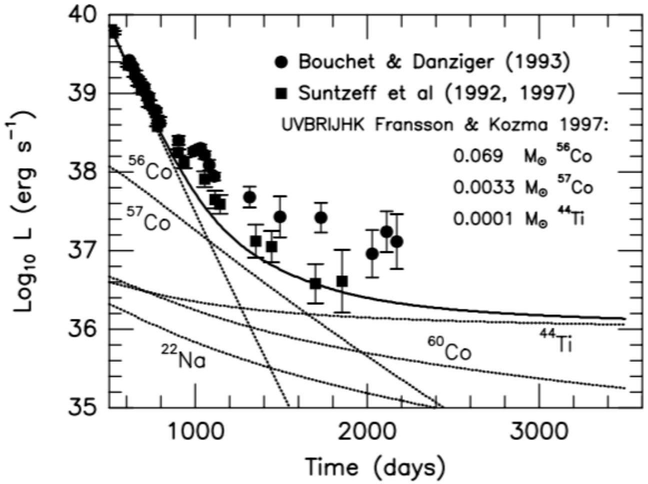
Type II supernova in LMC
(~ 55 kpc)

- $E_{\text{grav}} \approx 10^{53}$ erg
- $E_{\text{rad}} \approx 8 \times 10^{49}$ erg
- $E_{\text{kin}} \approx 10^{51}$ erg = 1 Bethe

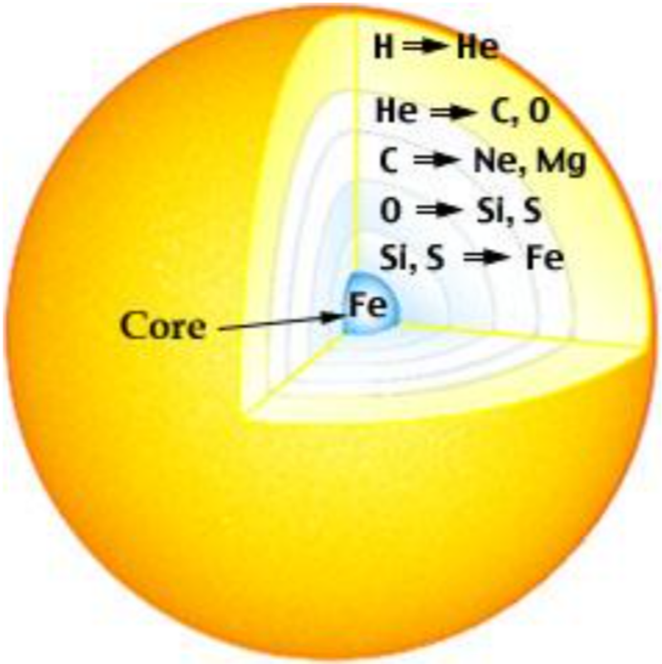
neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



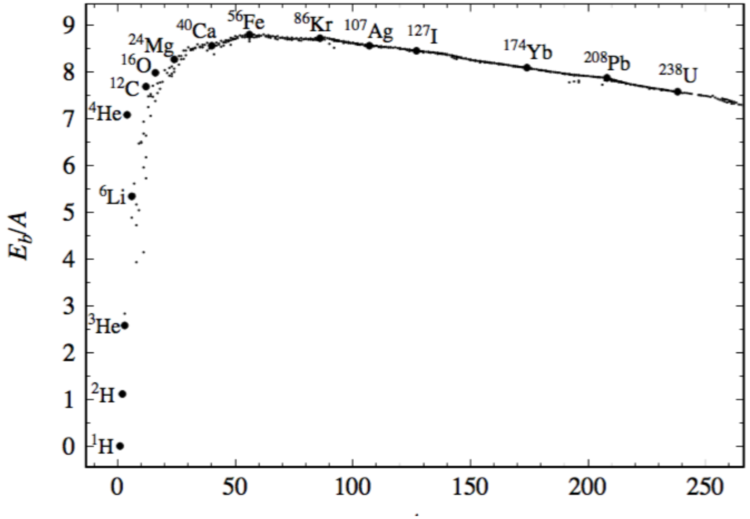
light curve



Presupernova Star



- Star has an onion like structure.
- Iron is the final product of the different burning processes.
- As the mass of the iron core grows it becomes unstable and collapses when it reaches around 1.4 $M_{\odot}$.

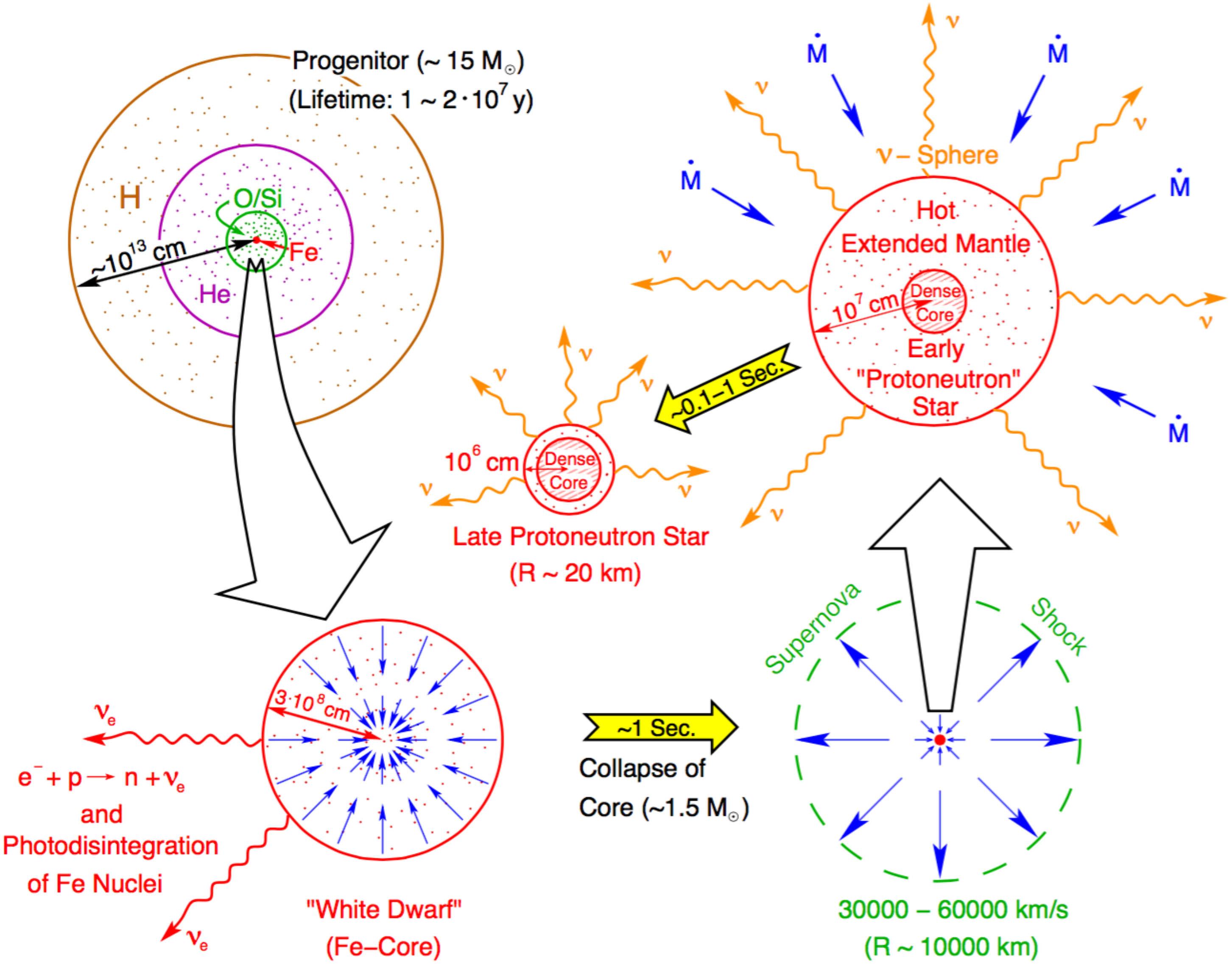


Early iron core

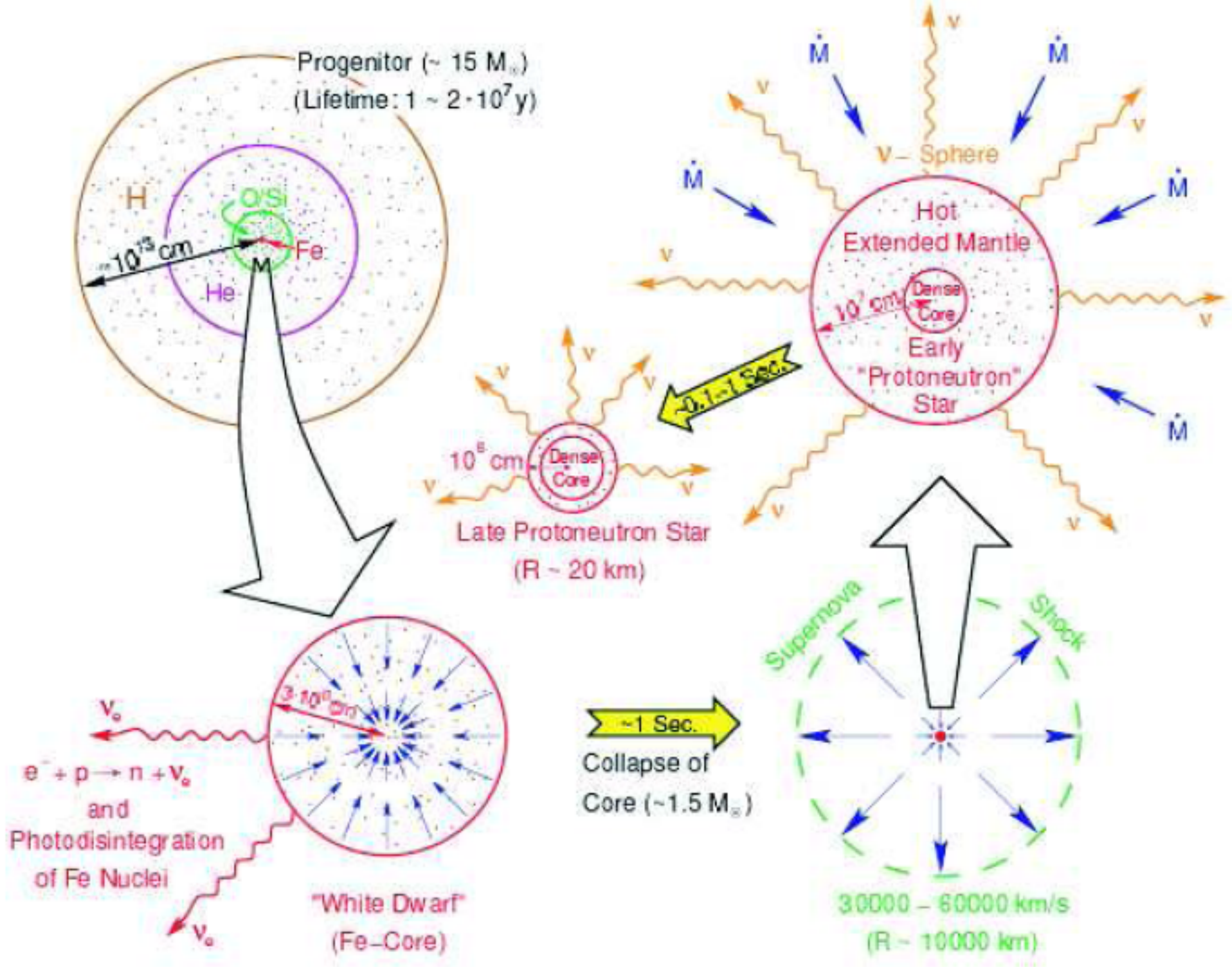
- The core is made of heavy nuclei (iron-mass range $A = 45$–65) and electrons. Composition given by Nuclear Statistical Equilibrium. There are Y_e electrons per nucleon.
- The mass of the core M_c is determined by the nucleons.
- There is no nuclear energy generation which adds to the pressure. Thus, the pressure is mainly due to the degenerate electrons, with a small correction from the electrostatic interaction between electrons and nuclei.
- As long as $M_c < M_{\text{ch}} = 1.44(2Y_e)^2 M_\odot$ (plus slight corrections for finite temperature), the core can be stabilized by the degeneracy pressure of the electrons.

- Stars with masses above eight solar masses undergo ***gravitational collapse***.
- Once the core of the star becomes constituted primarily of iron, further compression of the core does not ignite nuclear fusion and the star is unable to thermodynamically support its outer envelope.
- As the surrounding matter falls inward under gravity, the temperature of the core rises and iron dissociates into α particles and nucleons.
- Electron capture on protons becomes heavily favored and electron neutrinos are produced as the core gets neutronized (a process known as ***neutronization***).
- When the core reaches densities above 10^{12} g/cm^3, neutrinos become trapped (in the so-called neutrinosphere).
- The collapse continues until 3 − 4 times nuclear density is reached, after which the inner core rebounds, sending a shock-wave across the outer core and into the mantle.
- This shock-wave loses energy as it heats the matter it traverses and incites further electron-capture on the free protons left in the wake of the shock.
- During the few milliseconds in which the shock-wave travels from the inner core to the neutrinosphere, electron neutrinos are released in a pulse. This neutronization burst carries away approximately **10^{51} ergs of energy**.

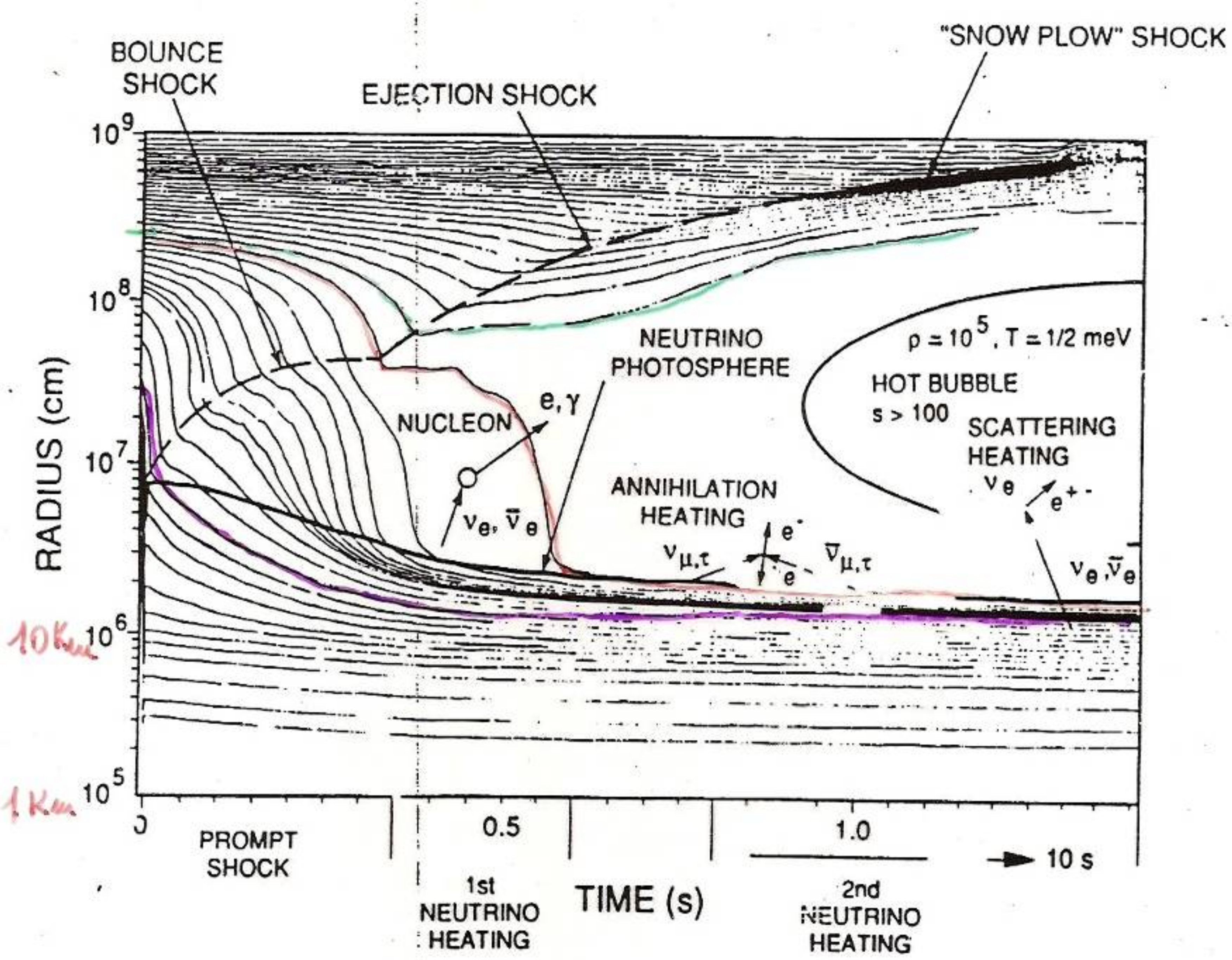
Schematical Evolution



- 99% of the binding energy E_b, of the protoneutron star is released in the following ~ 10 seconds primarily via β-decay (providing a source of electron antineutrinos), v_e, anti-v_e and e+e− annihilation and nucleon bremsstrahlung (sources for all flavors of neutrinos including v_μ, anti-v_μ, v_t and anti-v_t), in addition to electron capture.



Schematic illustration of a SN explosion. The dense Fe core collapses in a fraction of a second and gets neutronized (lower-left). The inner core rebounds and gives rise to a shock-wave (lower-right). The protoneutron star cools by the emission of neutrinos.


"SNOW PLOW" SHOCK
BOUNCE SHOCK
EJECTION SHOCK
10⁹
10⁸
10⁷
10⁶
10⁵
10Km
1Km
RADIUS (cm)
NEUTRINO PHOTOSPHERE
ρ = 10⁵, T = 1/2 meV
HOT BUBBLE
s > 100
NUCLEON
e, γ
νe, ν̄e
ANNIHILATION HEATING
SCATTERING HEATING
νe
e+-
e-
νμ,τ
ν̄μ,τ
e
νe, ν̄e
0
0.5
1.0
→ 10 s
PROMPT SHOCK
1st NEUTRINO HEATING
TIME (s)
2nd NEUTRINO HEATING

Onset of collapse

There are two processes that make the situation unstable:

1. Silicon burning is continuing in a shell around the iron core. This adds mass to the iron core increasing M_c.
2. Electrons can be captured by protons (free or in nuclei):

$$e^- + A(Z,N) \rightarrow A(Z-1,N+1) + \nu_e.$$

This reduces the pressure and keep the core cold, as the neutrinos leave. The net effect is a reduction of Y_e and consequently of the Chandrasekhar mass (M_{ch})

Initial conditions

The dominant contribution to the pressure comes from the electrons. They are degenerate and relativistic:

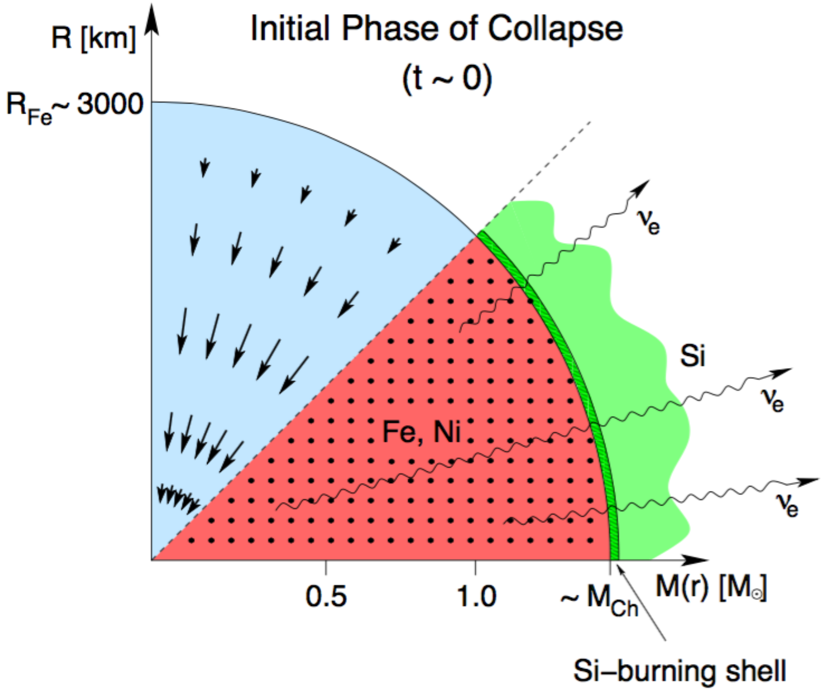
$$P \approx n_e \mu_e = n_e \varepsilon_F$$

μ_e is the chemical potential, fermi energy, of the electrons:

$$\mu_e \approx 1.11(\rho_7 Y_e)^{1/3}\ \mathrm{MeV}, \quad \frac{\rho Y_e}{m_u} = n_e$$

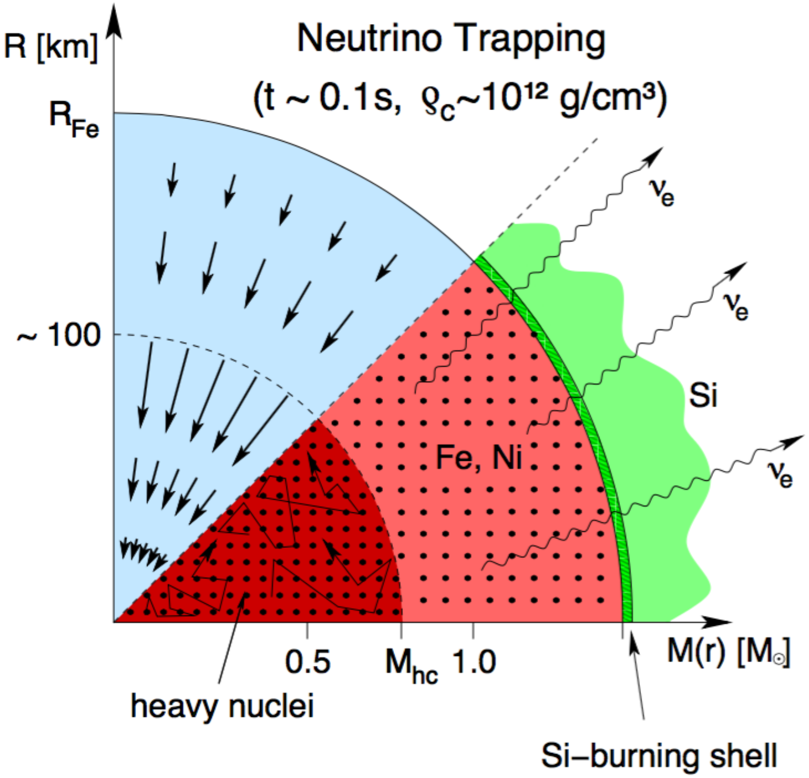
For $\rho_7 = 1$ ($\rho = 10^7$ g cm^{-3}) the chemical potential is 1 MeV, reaching the nuclear energy scale. At this point is energetically favorable to capture electrons by nuclei.

Presupernova evolution



- $T = 0.1$–0.8 MeV, $\rho = 10^7$–10^{10} g cm^{-3}. Composition of iron group nuclei.
- Important processes:
    - electron capture: $e^- + (N,Z) \rightarrow (N+1, Z-1) + \nu_e$
    - β^- decay: $(N,Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu}_e$
- Dominated by allowed transitions (Fermi and Gamow-Teller)
- Evolution decreases number of electrons (Y_e) and Chandrasekar mass ($M_{\mathrm{ch}} \approx 1.4(2Y_e)^2 M_\odot$)

Collapse phase



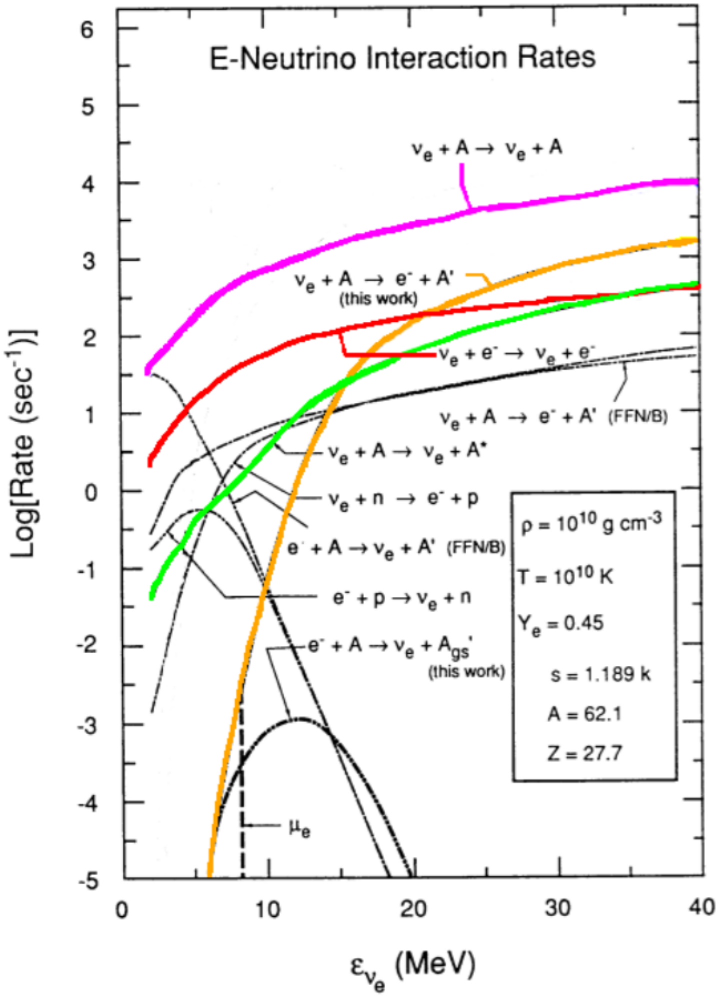
Important processes:

- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$

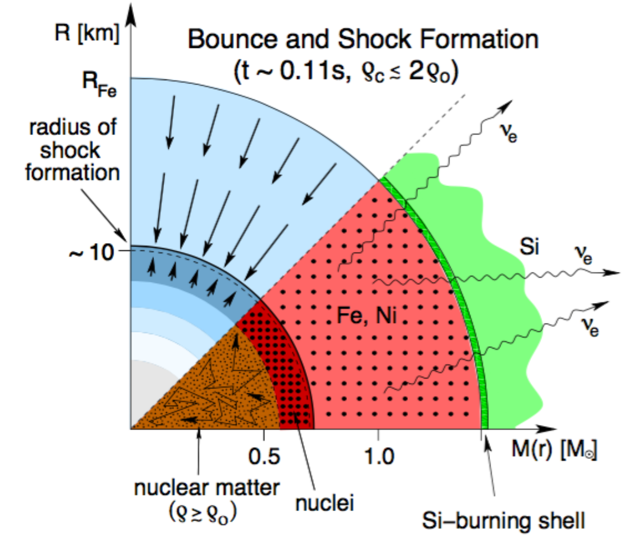
Neutrino interactions in the collapse

Bruenn and Haxton (1991)
Based on results for ^{56}Fe

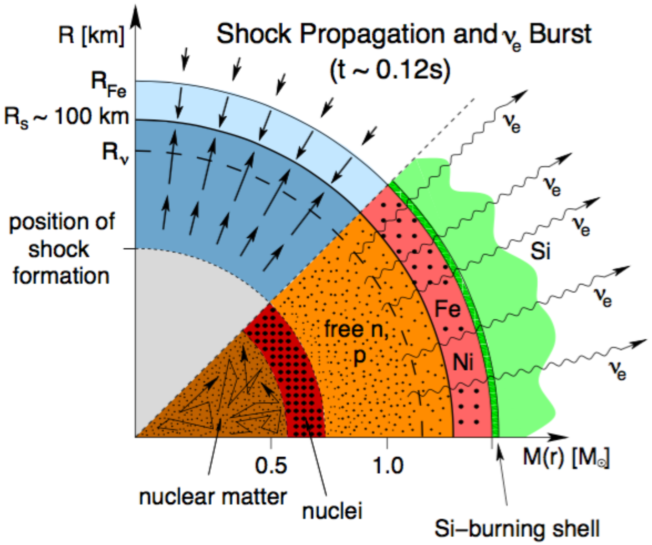


- Elastic scattering:
  $\nu + A \rightleftarrows \nu + A$ (trapping)
- Absorption:
  $\nu_e + (N,Z) \rightleftarrows e^- + (N-1, Z+1)$
- ν-e scattering:
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)
- Inelastic ν-nuclei scattering:
  $\nu + A \rightleftarrows \nu + A^*$

Bounce and ν_e burst



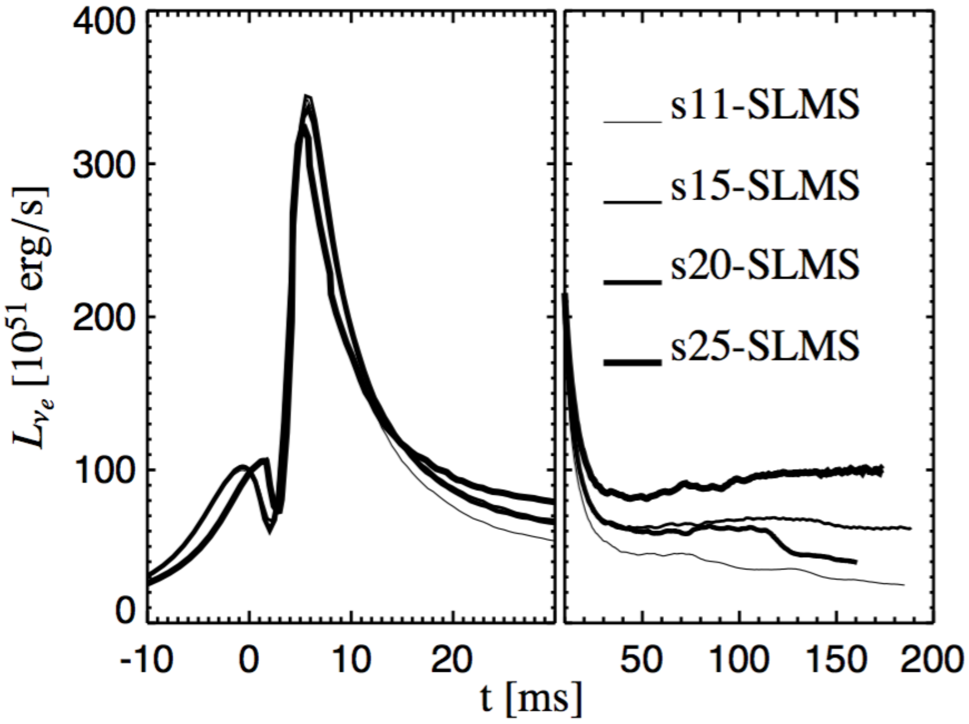
Bounce and Shock Formation
($t \sim 0.11$s, $\varrho_c \leq 2\varrho_0$)



Shock Propagation and ν_e Burst
($t \sim 0.12$s)

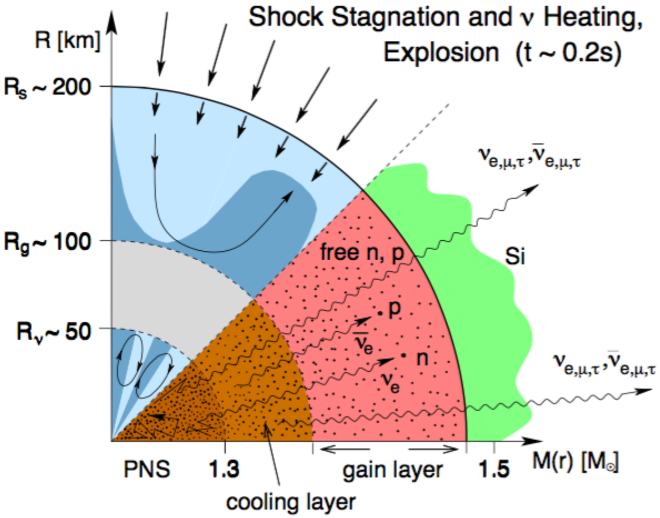
- Collapse continues until central density becomes around twice nuclear matter density.
- Sudden increase in nuclear pressure stops the collapse and a shock wave is launched at the sonic point. The energy of the shock depends on the Equation of State.
- The passage of the shock dissociates nuclei into free nucleons which costs ~ 8 MeV/nucleon. Additional energy is lost by neutrino emission produced by electron capture (ν_e burst).
- Shock stalls at a distance of around 100 km.

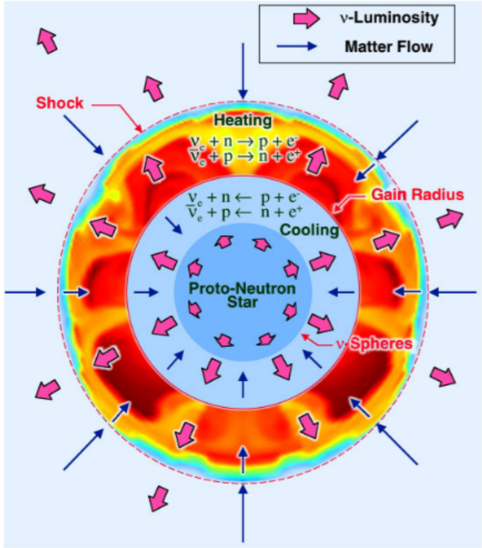
Neutrino burst



- Burst is produced when shock wave reaches regions with densities low enough to be transparent to neutrinos
- Burst structure does not depend on the progenitor star.
- Future observation by a supernova neutrino detector. Standard neutrino candles.

Delayed explosion mechanism: neutrino heating





Main processes:

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

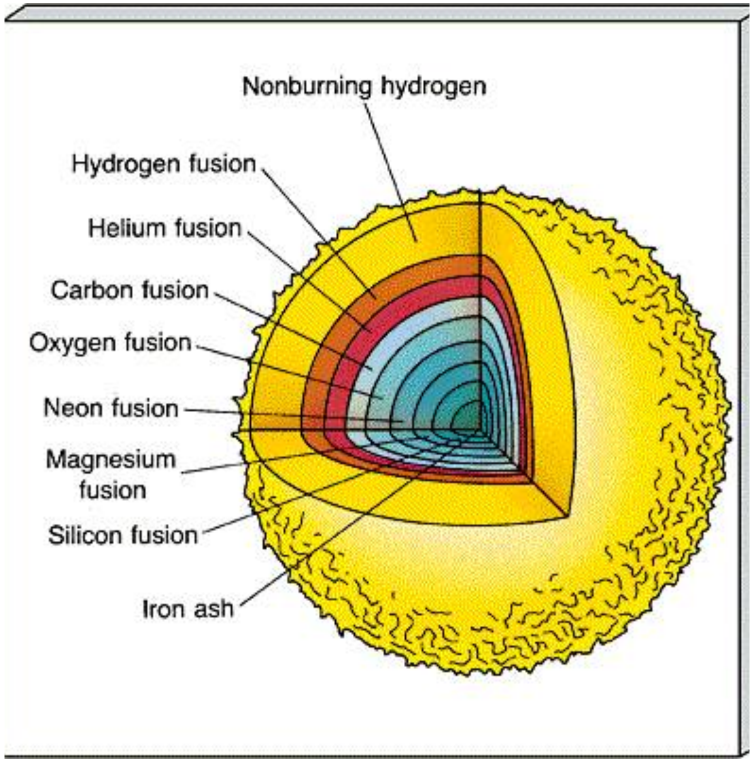
Concept of gain radius due to Bethe.
Corresponds to the region where cooling (electron positron capture) and heating (neutrino antineutrino absorption) are equal.

$$\text{Cooling: } 143\left(\frac{kT}{2\,\text{MeV}}\right)^6 \text{MeV/s}$$

$$\text{Heating: } 110\left(\frac{L_{\nu_e,52}\epsilon_{\nu_e}^2}{r_7^2} Y_n + \frac{L_{\bar{\nu}_e,52}\epsilon_{\bar{\nu}_e}^2}{r_7^2} Y_p\right) \text{MeV/s}$$

Gravitational energy of a nucleon at 100 km: 14 MeV
Energy transfer induces convection and requires multidimensional simulations.

Pre supernovae



Evolutionary stages of a 25 MSUN star:

Stage	Temperature (K)	Duration of stage
Hydrogen burning	4×10^7	7×10^6 years
Helium burning	2×10^8	5×10^5years
Carbon burning	6×10^8	600 years
Neon burning	1.2×10^9	1 year
Oxygen burning	1.5×10^9	6 months
Silicon burning	2.7×10^9	1 day
Core collapse	5.4×10^9	1/4 second

Naked eye Supernovae

Recorded explosions visible to naked eye:

Year (A.D.)	Where observed	Brightness
185	Chinese	Brighter than Venus
369	Chinese	Brighter than Mars or Jupiter
1006	China, Japan, Korea, Europe, Arabia	Brighter than Venus
1054	China, SW India, Arabia	Brighter than Venus
1572	Tycho	Nearly as bright as Venus
1604	Kepler	Brighter than Jupiter
1987	Ian Shelton (Chile)	

Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}c^2$

This shows up as

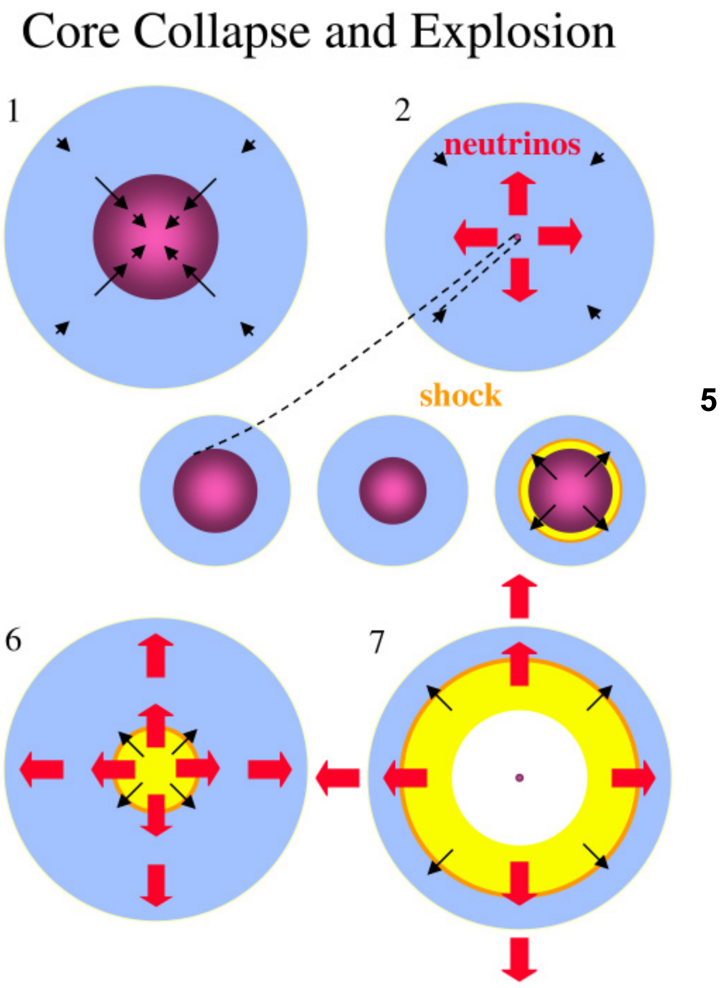
99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons (outshine host galaxy)

Neutrino luminosity

$L_\nu \approx 3\times10^{53}$ erg / 3 sec $\approx 3\times10^{19}\ L_{SUN}$

While it lasts, outshines the photon luminosity of the entire visible universe!

Explosion

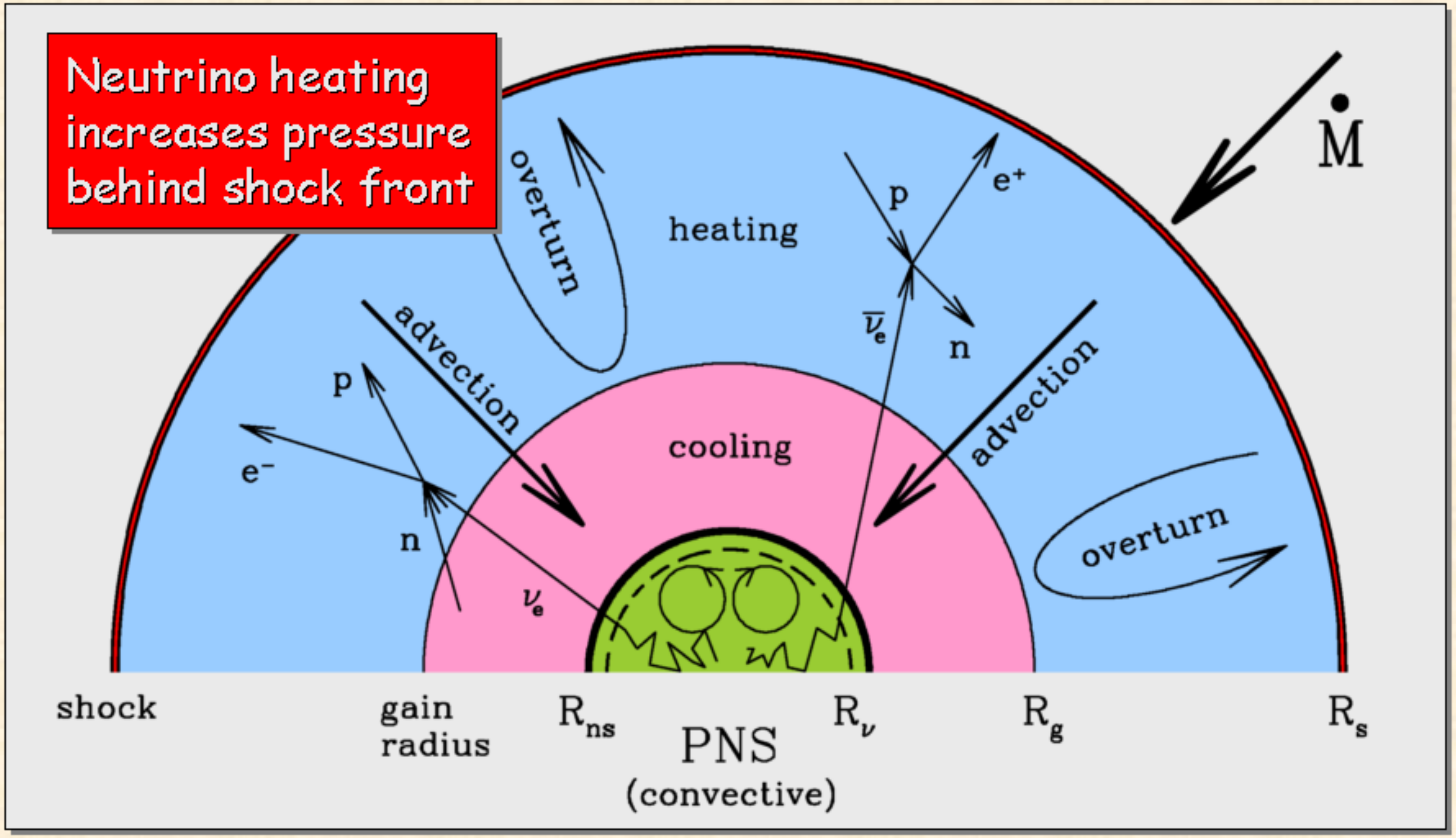


- Collapse and re-bound(1-4) creates a shock wave(5) propagating outward from center of core(6) , meeting in falling outer core material
- Shock stalls due to neutrino escape & nuclear dissociation
- Deleptonisation of the core creates intensive neutrino flux (99% of energy)
- Neutrino interactions behind the shock reheat the shock and drive it outwards(7)
- Measuring ^{56}Fe(ν_e ,e$^-$) ^{56}Co provides valuable data to guide shock formation models.
- Other cross sections, ^{28}Si, should also play an important role.

Neutrinos to the Rescue

Adapted from Janka, astro-ph/0008432

Neutrino heating increases pressure behind shock front



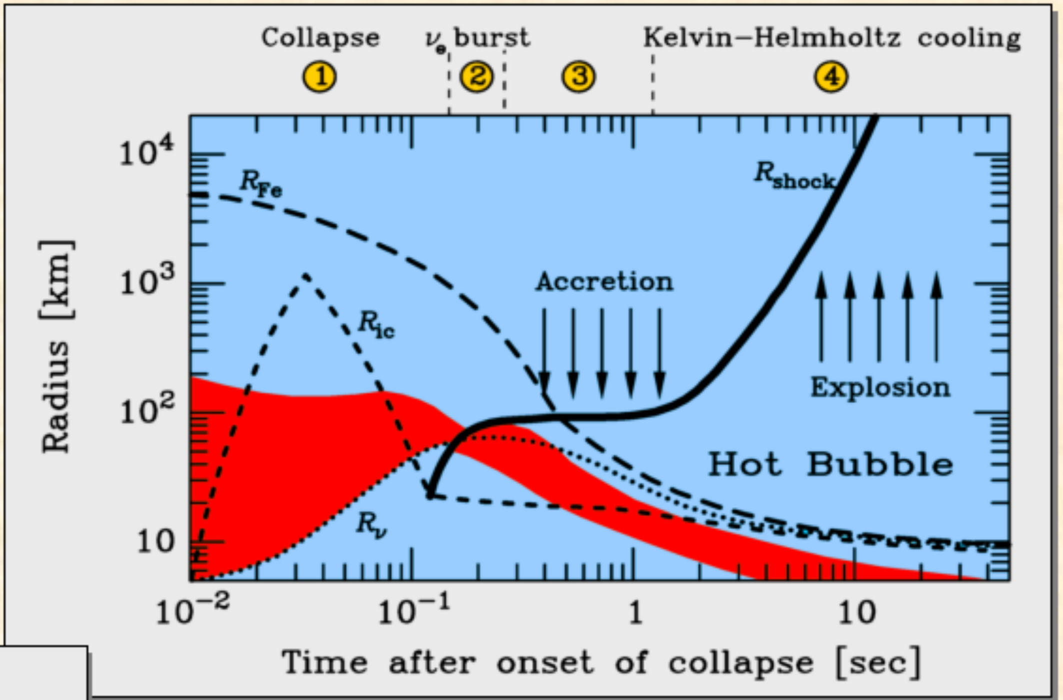
Heating mostly by β processes ($\nu_e + n \to p + e^-$ and $\bar{\nu}_e + p \to n + e^+$)
Pair annihilation ($\nu + \bar{\nu} \to e^- + e^+$) negligible

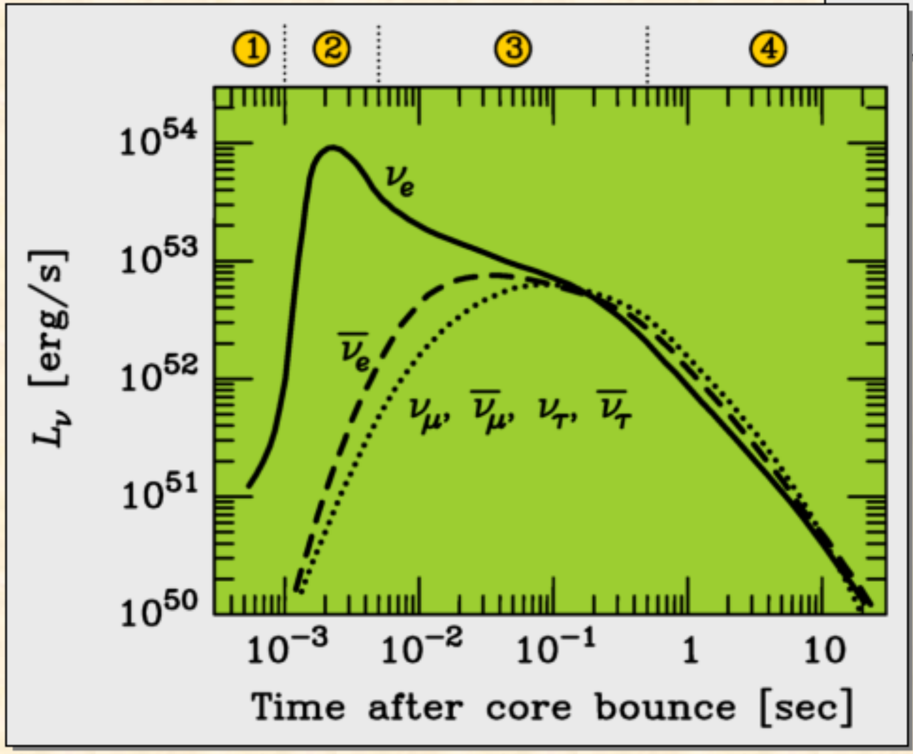
Mu- and tau-neutrino fluxes and spectra not crucial for explosion

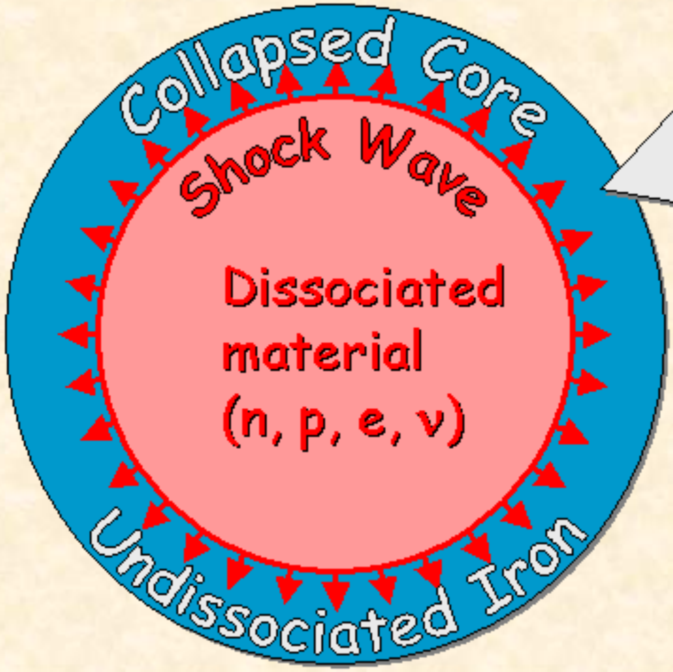
Georg Raffelt, Max-Planck-Institut für Physik (München)

Supernova Neutrino Signal

1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling



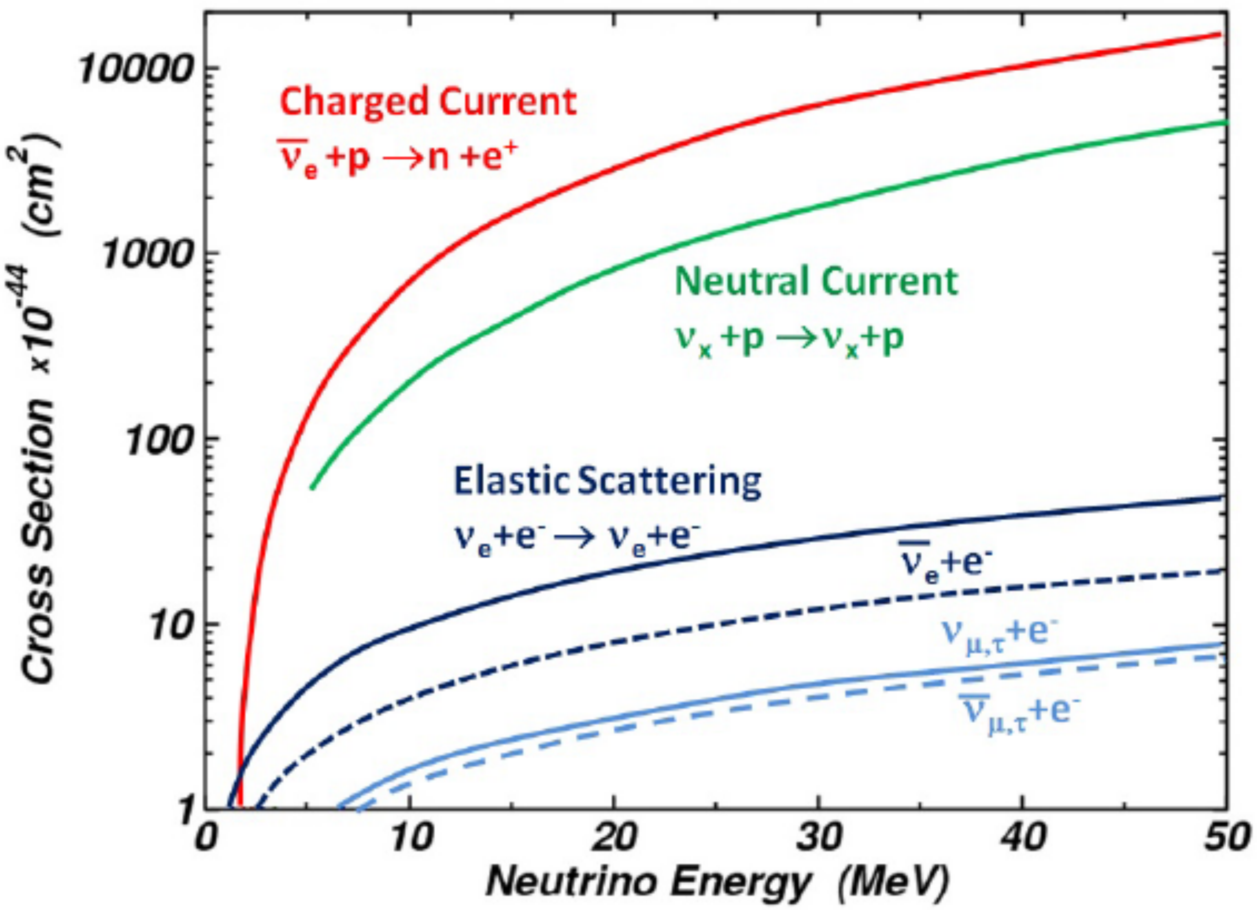




Traps neutrinos and lepton number of outer core layers

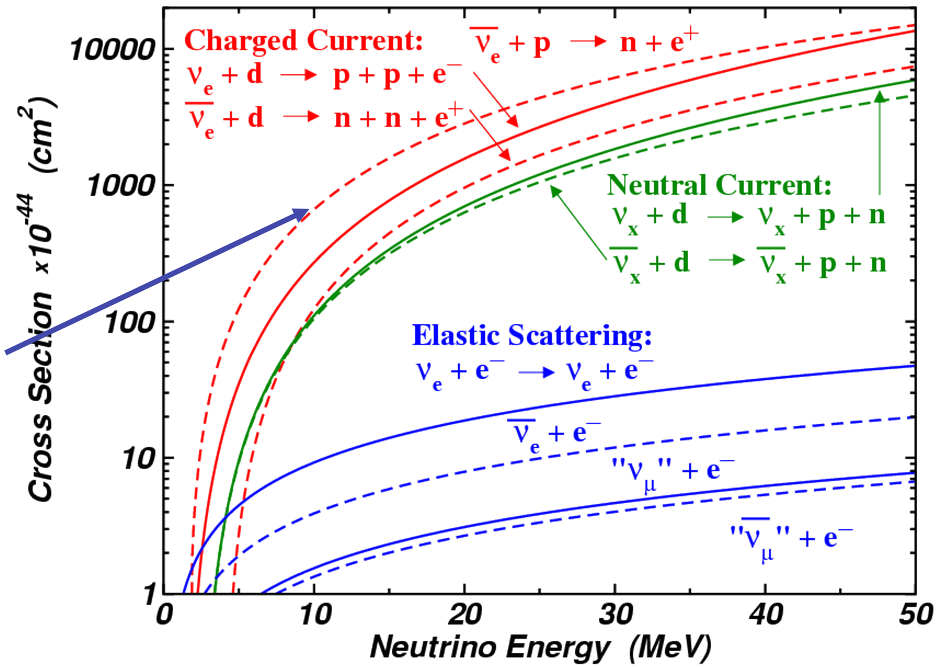
Georg Raffelt, Max-Planck-Institut für Physik (München)

The SN neutrino signal



8.6 The SN1987A

Neutrino cross sections:



Distance: 52 kpc (LMC)

Introduction: Core collapse of type-II SN

- *Neutronization*, ~10 ms
- 10^{51} erg, ν_e only

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

→ t=0

- *Thermalization:* ~10 s
- 3×10^{53} erg
- $L_{\nu_e}(t) \approx L_{anti\text{-}\nu_e}(t) \approx L_{\nu_x}(t)$

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

Detection: mainly through $\boxed{\bar{\nu}_e + p \rightarrow n + e^+}$

~300 events/kt (@GC)

Supernovae explode in Nature, but non in computers (J. Beacom, ν2002)

The SN1987A: how many events?

1- Energy released $2.5\ 10^{53}$ erg
2- Average ν_e energy $\approx$ 16 MeV = $2.5\ 10^{-5}$ erg
3- $N_{source} = (1/6) \times 2.5\ 10^{53} / (2.5\ 10^{-5}) = 1.7\ 10^{57}\ \nu_e$

4- LMC Distance : D=52 kpc = $1.6\ 10^{23}$ cm
5- Fluency at Earth: $F = N_{Source}/4\pi D^2 = 0.5\ 10^{10}\ \text{cm}^{-2}$
6- Targets in 1 Kt water: $\mathbf{N_t = 0.7\ 10^{32}}$ protons
7- cross section: $\sigma(\text{anti}\nu_e\text{+p}) \sim \mathbf{2\text{x}10^{-41}\ cm^2}$

8- $N_{e^+} = F\ (\text{cm}^{-2}) \times \sigma\ (\text{cm}^2) \times N_t\ (\text{kt}^{-1}) = 0.5\ 10^{10} \times 2\text{x}10^{-41} \times 0.7\ 10^{32}$
= 7 positrons/kt
9 – M(Kam II) = 2.1 kt, efficiency $\varepsilon \sim 80\%$
10 – Events in Kam II = 7 x 2.1 x $\varepsilon \sim$ **12 events**

For a SN @ Galactic Center (8.5 kpc) :
$N_{events} = 7\text{x}(52/8.5)^2 = 260\ e^+/\text{kt}$

The Detectors

- Water Cherenkov detectors
  - Kamiokande (Japan)
  - IMB (Ohio)
- Liquid scintillation telescopes
  - Baksan – USSR Academy of Sciences, in North Caucasus Mountains, Russia
  - Mont Blanc – Italian Soviet collaboration, in Mont Blanc Laboratory, France

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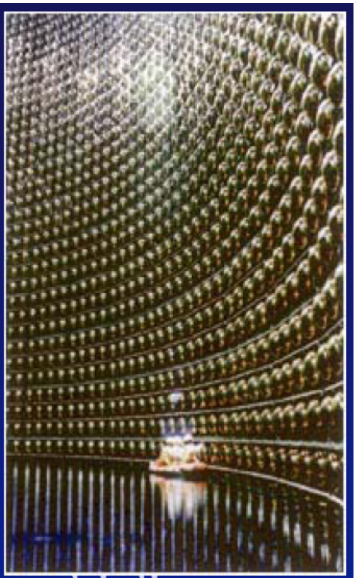
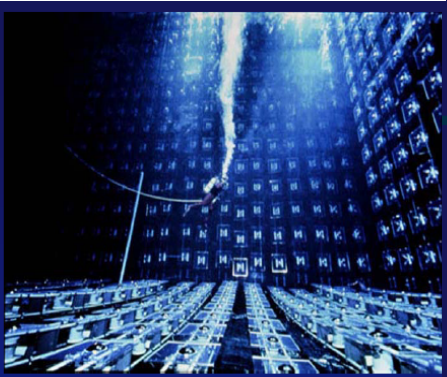
Kamiokande II



- Located in the Kamioka mine in Japan
- 1000m underground
- Cylindrical tank
  - d = 15.6m, h = 16m
- Large (D = 20 inches) photomultipliers
- Volume of water weighs 3000 metric tons

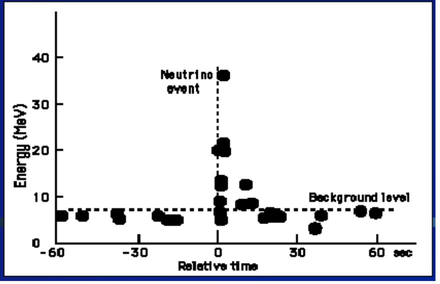
IMB



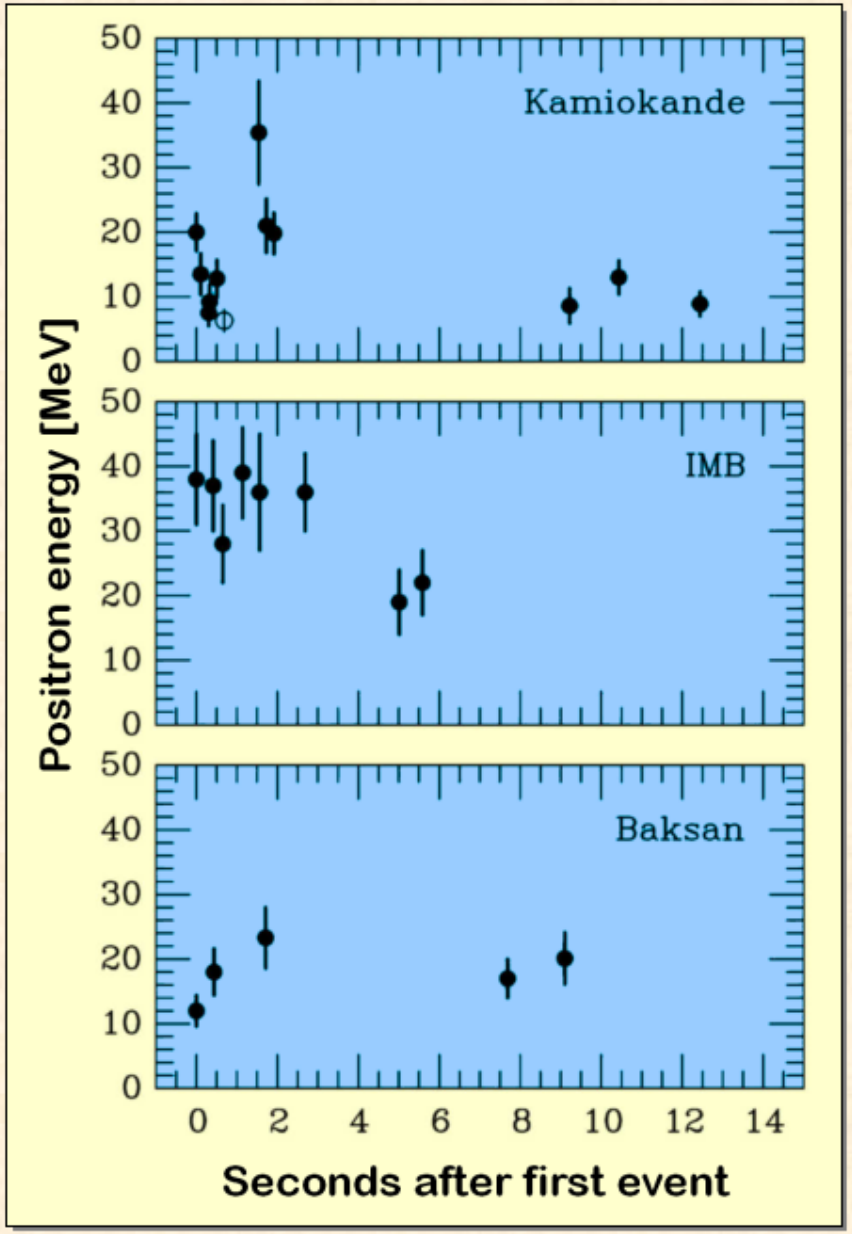
- Located in the Morton Thiokol mine in Ohio
- 580m underground
- Rectangular tank
  - 18 by 17 by 23 m
- 2048 8” photomultipliers
- 2.5 million gallons of water
- Compared to Kamiokande II: Larger volume, but not as deep

Results

- Feb 23, 7:36 UT:
  - K II records 9 neutrinos within 2 sec, 3 more neutrinos 9-13 seconds later
  - IMB records 8 neutrinos within 6 seconds
  - Baksan records 5 neutrinos within 5 seconds
- 25 neutrinos detected!



Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

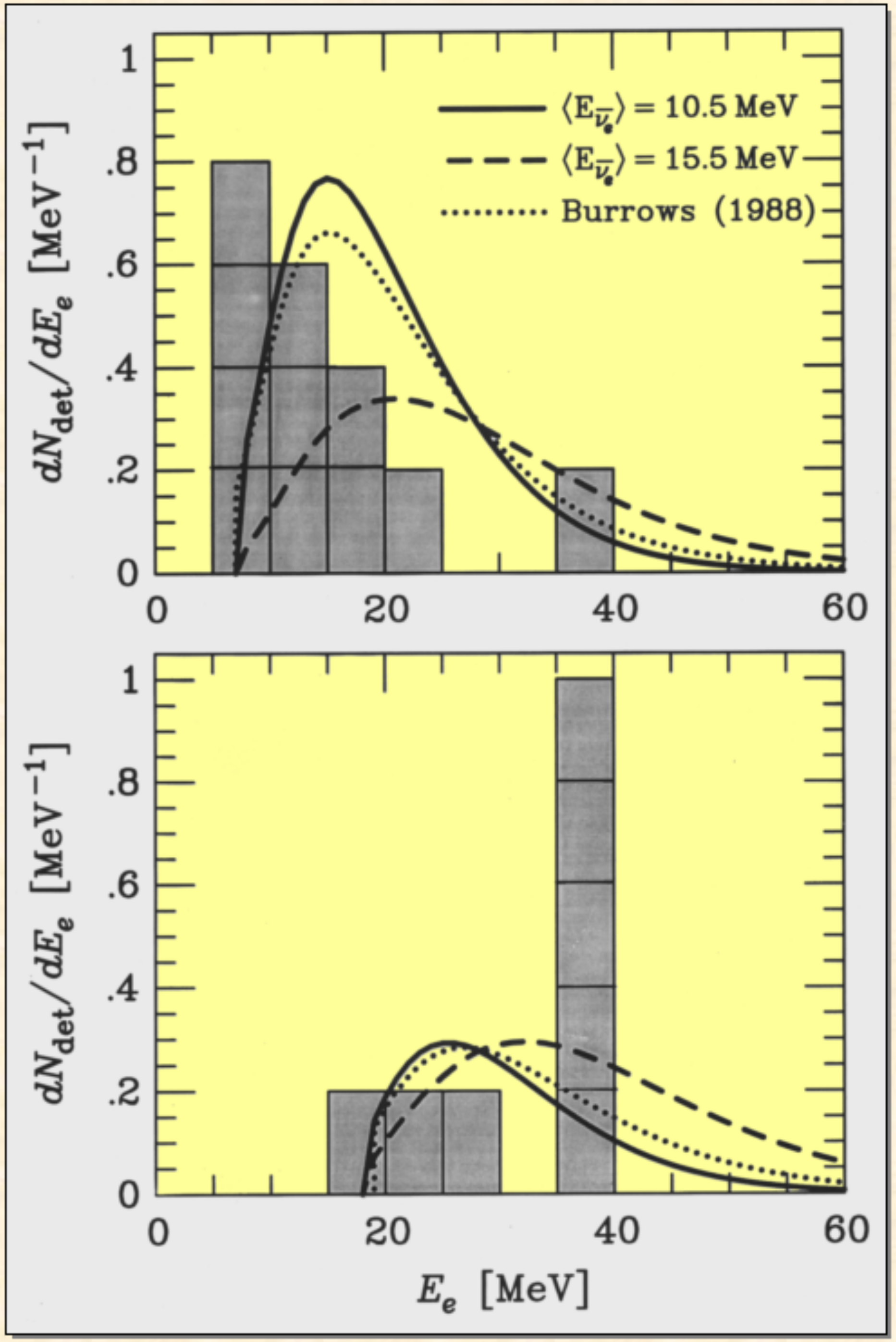
Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Georg Raffelt, Max-Planck-Institut für Physik (München)

Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino mass from SN

- The observation of supernova neutrinos should bring a better understanding of the core collapse mechanism from the feature of the time and energy spectra, and constraints the supernova models.
- Moreover, an estimation of the neutrino masses could be done in the following manner. The velocity of a particle of energy *E* and mass *m*, with *E* >> *m*, is given by (with c = 1):

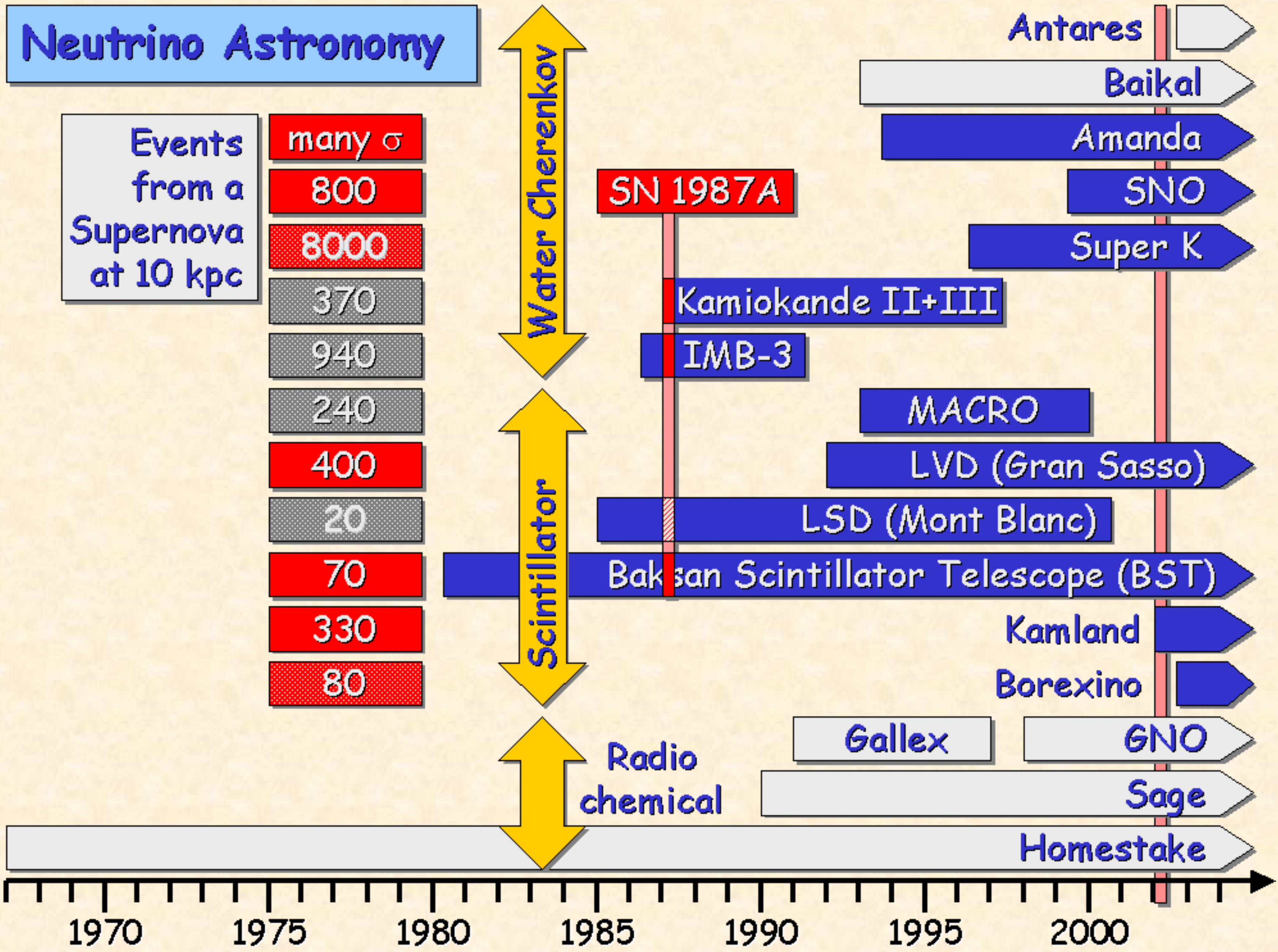
$$v = \frac{p}{E} = \frac{(E^2 - m^2)^{½}}{E} \approx 1 - \frac{m^2}{2E} \quad .$$

- Thus, for a supernova at distance *d*, the delay of a neutrino due to its mass is, expressed in the proper units:

$$\Delta t_{[\mathrm{s}]} \approx 0.05 \, \frac{m_{[\mathrm{eV}]}^{\;2}}{E_{[\mathrm{MeV}]}} \, d_{[\mathrm{kpc}]} \quad .$$

- Therefore, neutrinos of different energies released at the same instant should show a spread in their arrival time.

Neutrino Astronomy



Events from a Supernova at 10 kpc	
many σ	Amanda
800	SNO
8000	Super K
370	Kamiokande II+III
940	IMB-3
240	MACRO
400	LVD (Gran Sasso)
20	LSD (Mont Blanc)
70	Baksan Scintillator Telescope (BST)
330	Kamland
80	Borexino

Georg Raffelt, Max-Planck-Institut für Physik (München)

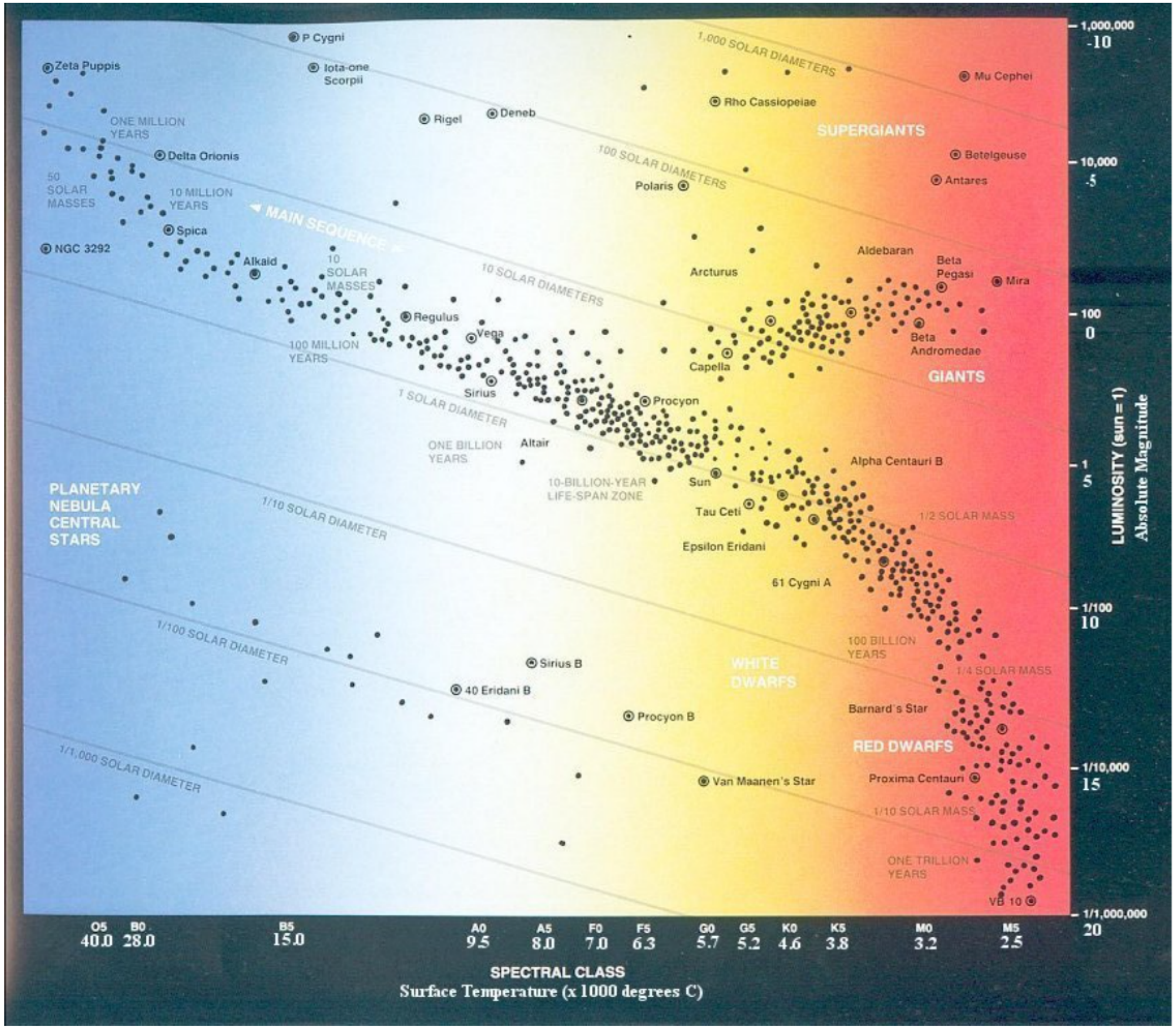
Neutrino Astrophysics

- The only SN seen with neutrino was SN1987a
- Small experiments, small statistics
- Qualitative agreement with the SN models
- Wait for the next near SN with the new larger experiments (SK, SNO, Borexino, LVD…)
- → neutrino properties (mass, livetime, magnetic moment) from astrophysics

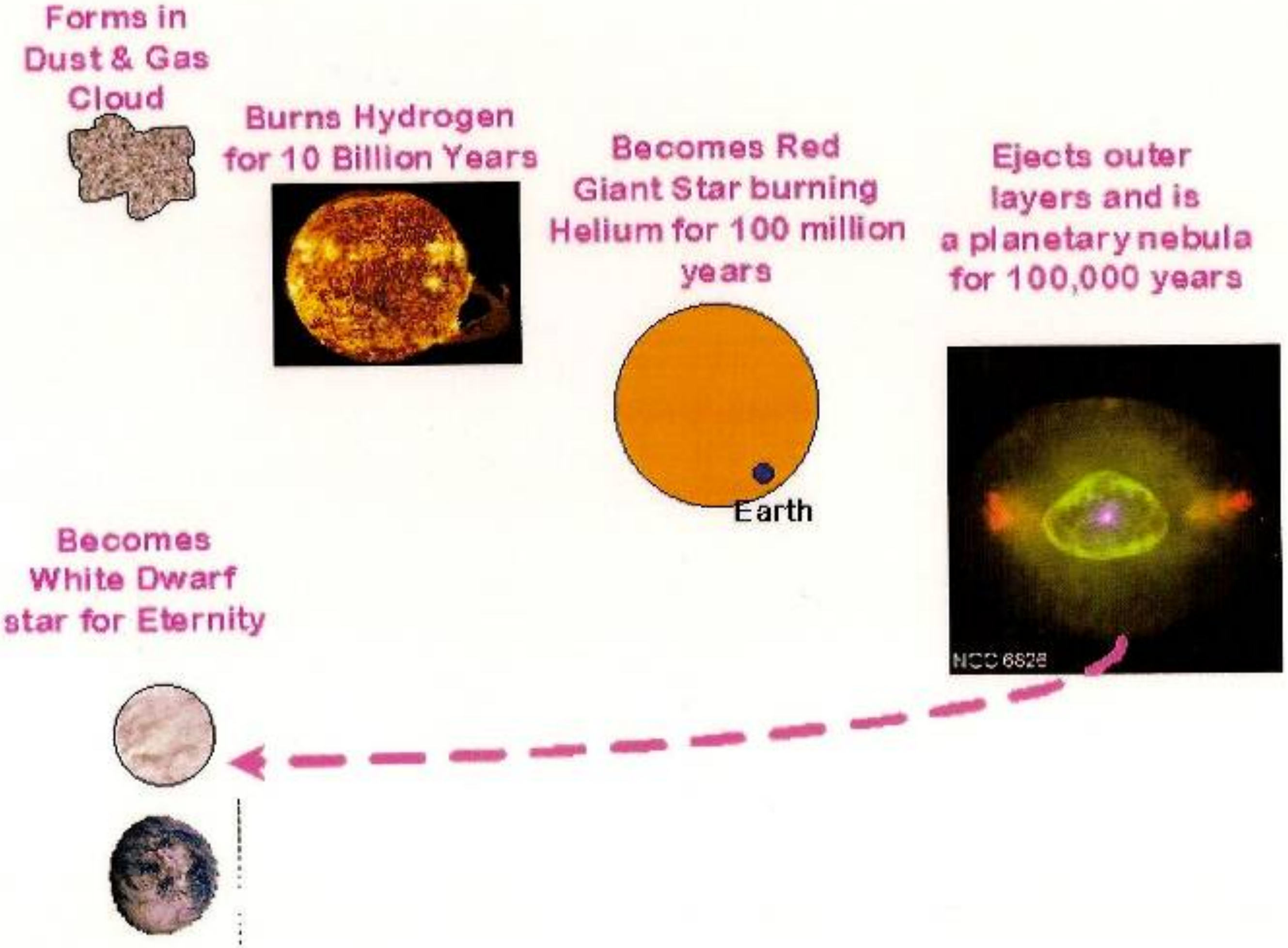
Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics - 1

Hertzspung-Russell diagram



Life of small star (< 1,4 $M_{\odot}$)



Forms in Dust & Gas Cloud

Burns Hydrogen for 10 Billion Years

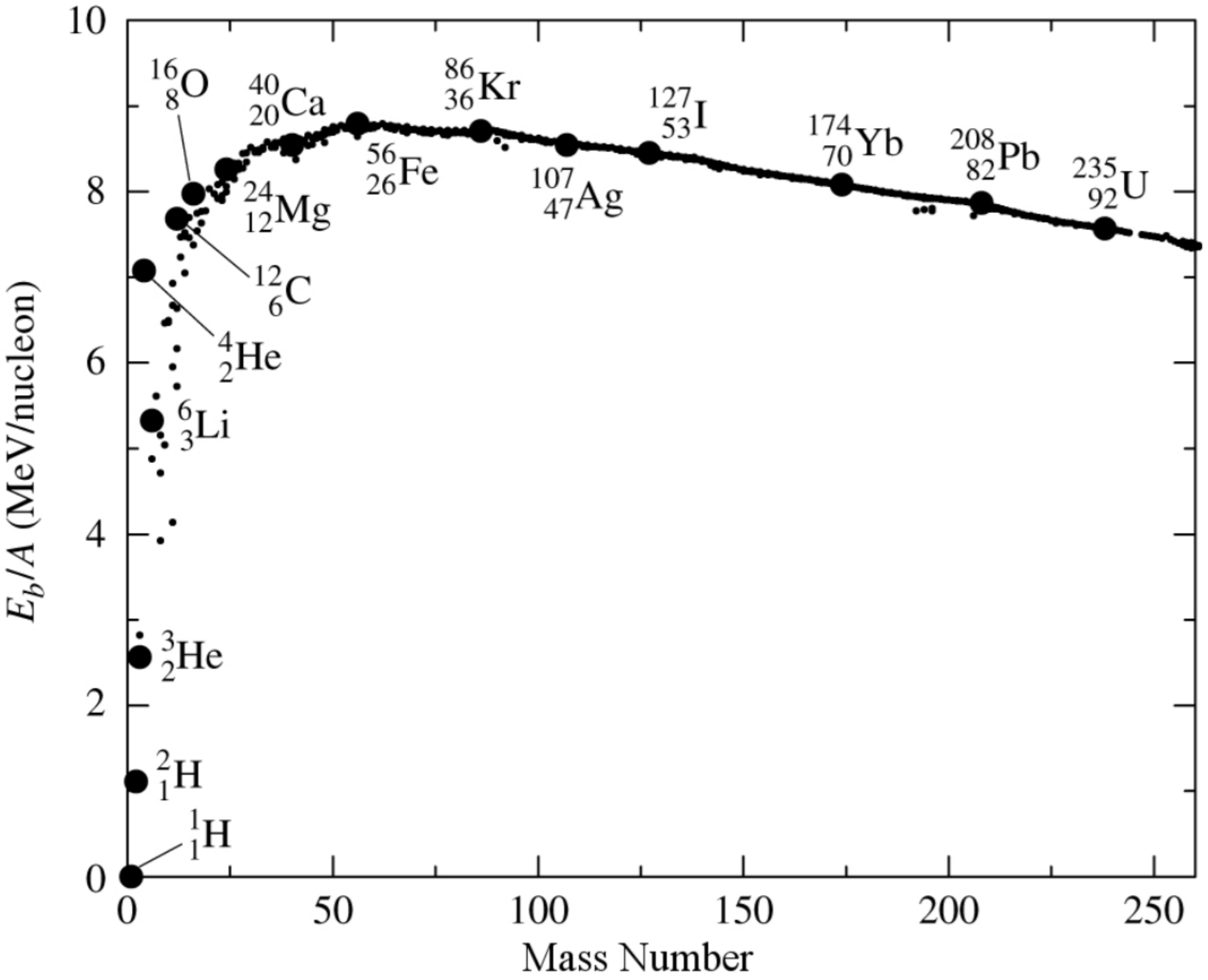
Becomes Red Giant Star burning Helium for 100 million years

Ejects outer layers and is a planetary nebula for 100,000 years

Becomes White Dwarf star for Eternity

Nuclear Binding Energy

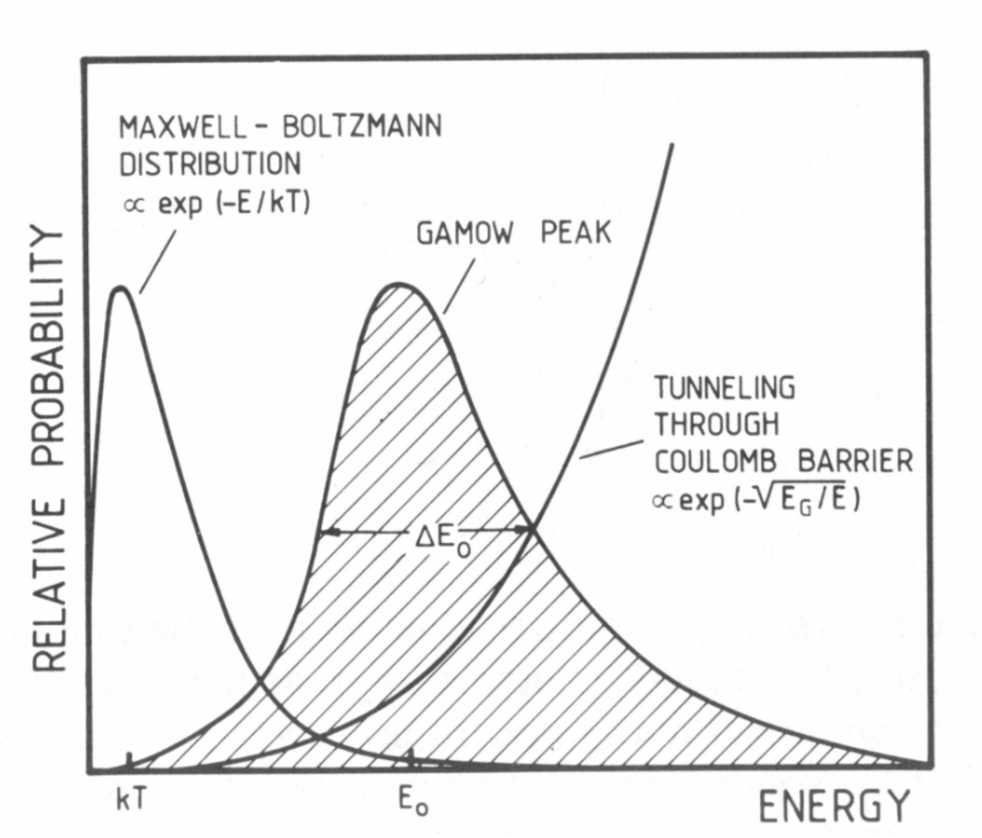
Liberated energy is due to the gain in nuclear binding energy.



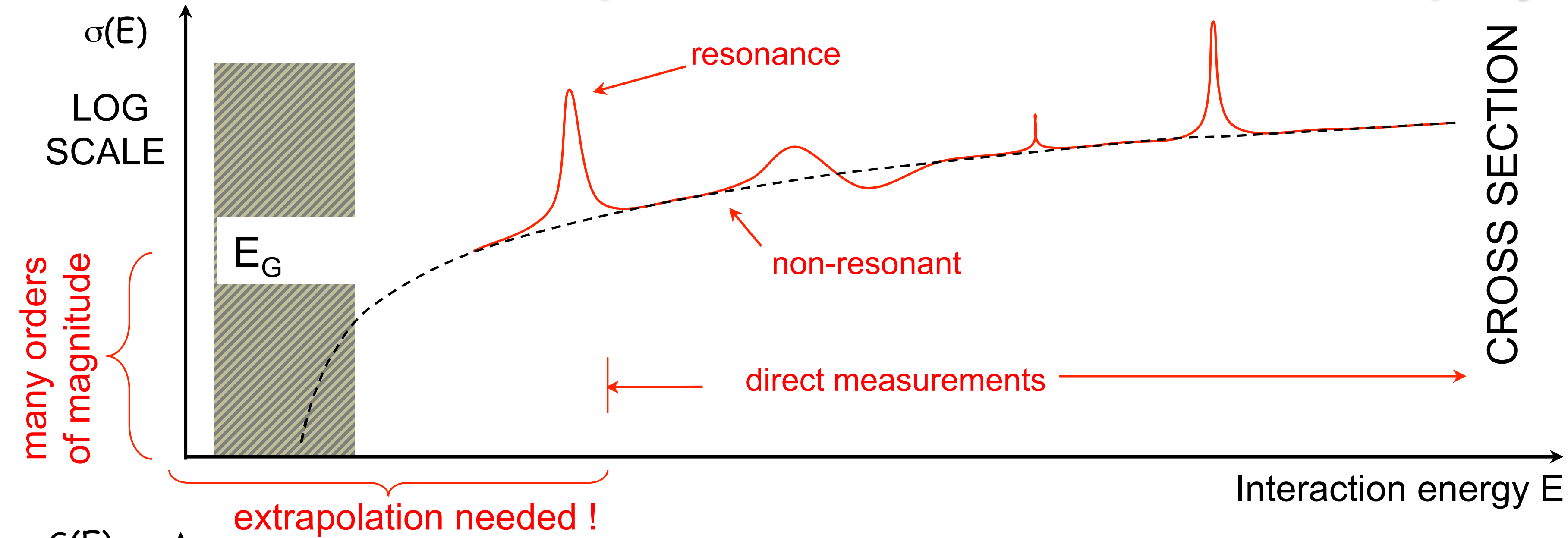
Gamow window

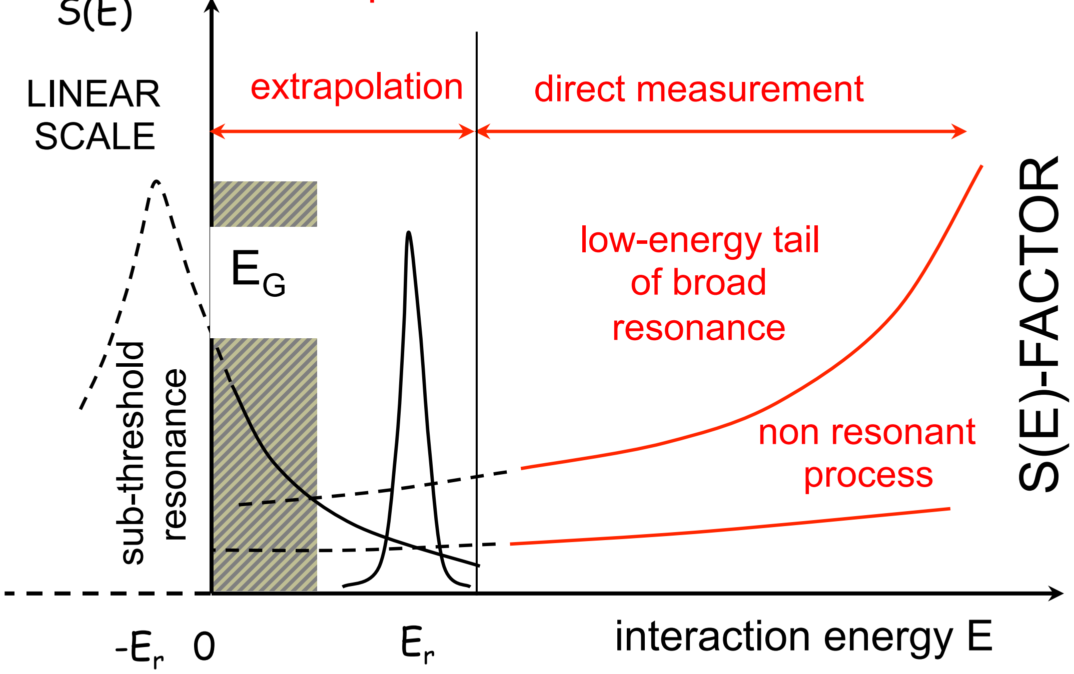
Using definition S factor:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi m} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}} \right] dE$$



Problem of extrapolation in nuclear astrophysi





Most of the reactions of astrophysical interest happen via radiative capture.

$^{14}N(p,\gamma)^{15}O$, $^{12}C(\alpha,\gamma)^{16}C$...

Hydrogen burning: ppI-chain

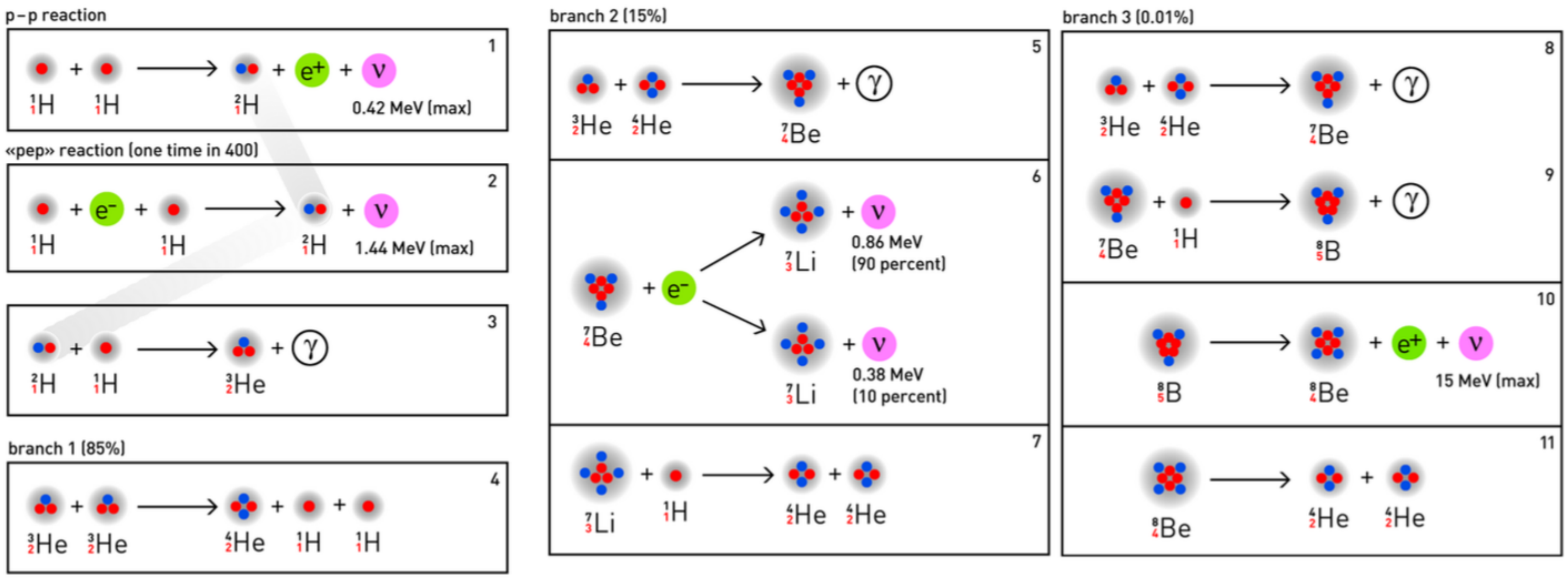
Step 1: $p + p \rightarrow {}^2\mathrm{He}$ (not possible)
$p + p \rightarrow d + e^+ + \nu_e$
Step 2: $d + p \rightarrow {}^3\mathrm{He}$
$d + d \rightarrow {}^4\mathrm{He}$ (d abundance too low)

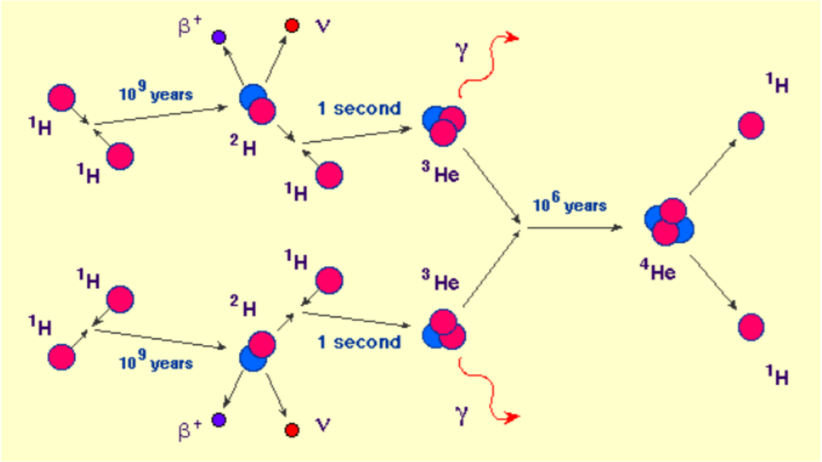
Step 3: ${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{Li}$ (^{4}Li is unbound)
${}^3\mathrm{He} + d \rightarrow {}^4\mathrm{He} + n$ (d abundance too low)
${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

$d + d$ not going because Y_d is small and $d + p$ leads to rapid destruction.
${}^3\mathrm{He} + {}^3\mathrm{He}$ goes because $Y_{3\mathrm{He}}$ gets large as nothing destroys it.

pp chains

Once ^{4}He is produced can act as catalyst initializing the ppII and ppIII chains.





Reaction Network ppI-chain

$$\frac{dY_p}{dt} = -Y_p^2 \frac{\rho}{m_u} \langle \sigma v \rangle_{pp} - Y_d Y_p \frac{\rho}{m_u} \langle \sigma v \rangle_{pd} + Y_3^2 \frac{\rho}{m_u} \langle \sigma v \rangle_{33}$$

$$\frac{dY_d}{dt} = \frac{Y_p^2}{2} \frac{\rho}{m_u} \langle \sigma v \rangle_{pp} - Y_d Y_p \frac{\rho}{m_u} \langle \sigma v \rangle_{pd}$$

$$\frac{dY_3}{dt} = Y_d Y_p \frac{\rho}{m_u} \langle \sigma v \rangle_{pd} - Y_3^2 \frac{\rho}{m_u} \langle \sigma v \rangle_{33}$$

$$\frac{dY_4}{dt} = \frac{Y_3^2}{2} \frac{\rho}{m_u} \langle \sigma v \rangle_{33}$$

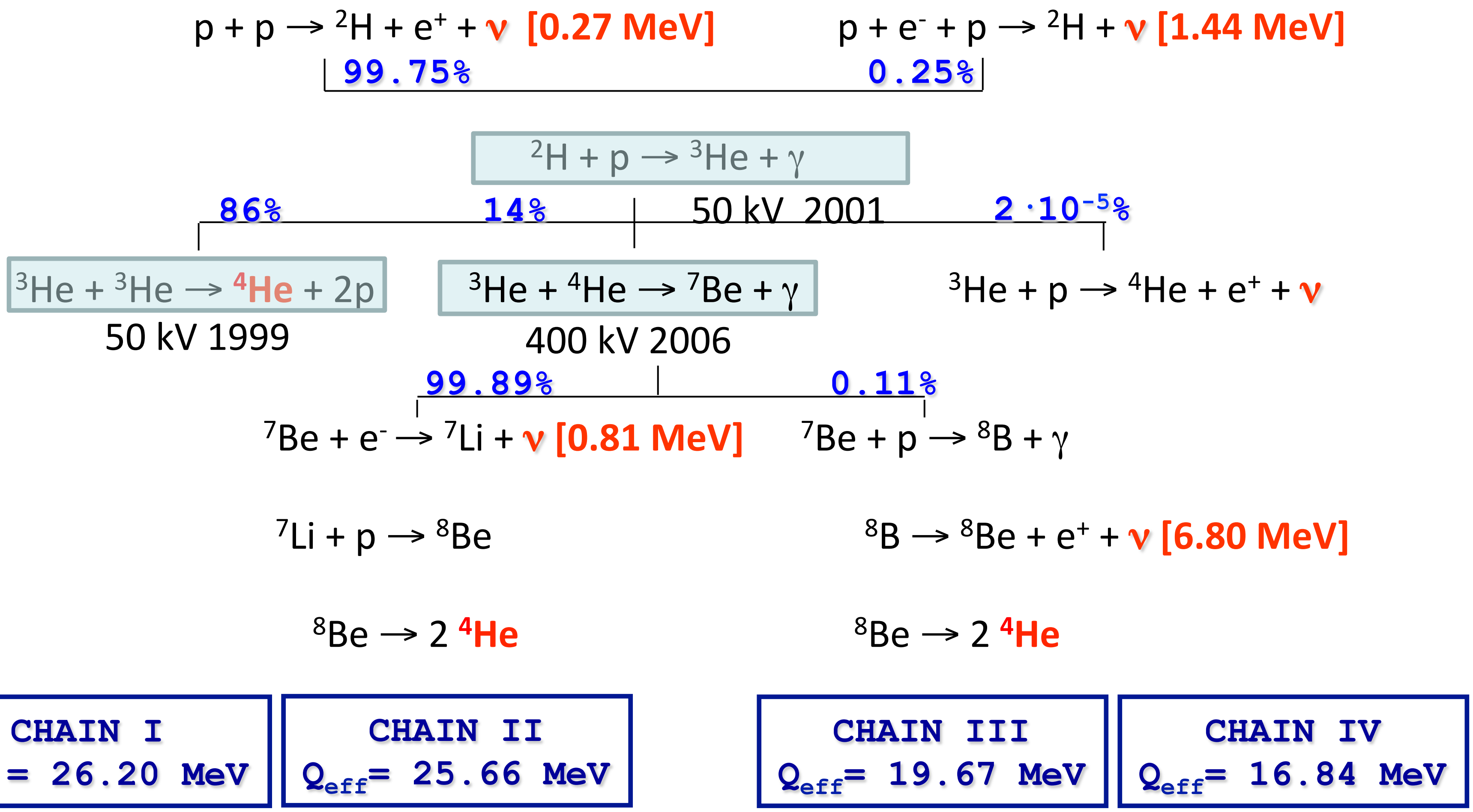
Stiff system of coupled differential equations.

The relevant S-factors

$p(p,e^+\nu_e)d$:	$S_{11}(0) = (4.00 \pm 0.05) \times 10^{25}$ MeV b calculated
$p(d,\gamma)^3$He:	$S_{12}(0) = 2.5 \times 10^{-7}$ MeV b measured at LUNA
^{3}He$(^3$He$, 2p)^4$He:	$S_{33}(0) = 5.4$ MeV b measured at LUNA

Laboratory Underground for Nuclear Astrophysics (Gran Sasso).

LUNA program: pp chain



$p + p \rightarrow {}^{2}H + e^{+} + \nu$ [0.27 MeV]

$p + e^{-} + p \rightarrow {}^{2}H + \nu$ [1.44 MeV]

99.75%

0.25%

$^{2}H + p \rightarrow {}^{3}He + \gamma$

50 kV 2001

86%

14%

$2 \cdot 10^{-5}\%$

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

50 kV 1999

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

400 kV 2006

$^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$

99.89%

0.11%

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$ [0.81 MeV]

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{7}Li + p \rightarrow {}^{8}Be$

$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ [6.80 MeV]

$^{8}Be \rightarrow 2\ {}^{4}He$

$^{8}Be \rightarrow 2\ {}^{4}He$

CHAIN I
$Q_{eff} = 26.20$ MeV

CHAIN II
$Q_{eff} = 25.66$ MeV

CHAIN III
$Q_{eff} = 19.67$ MeV

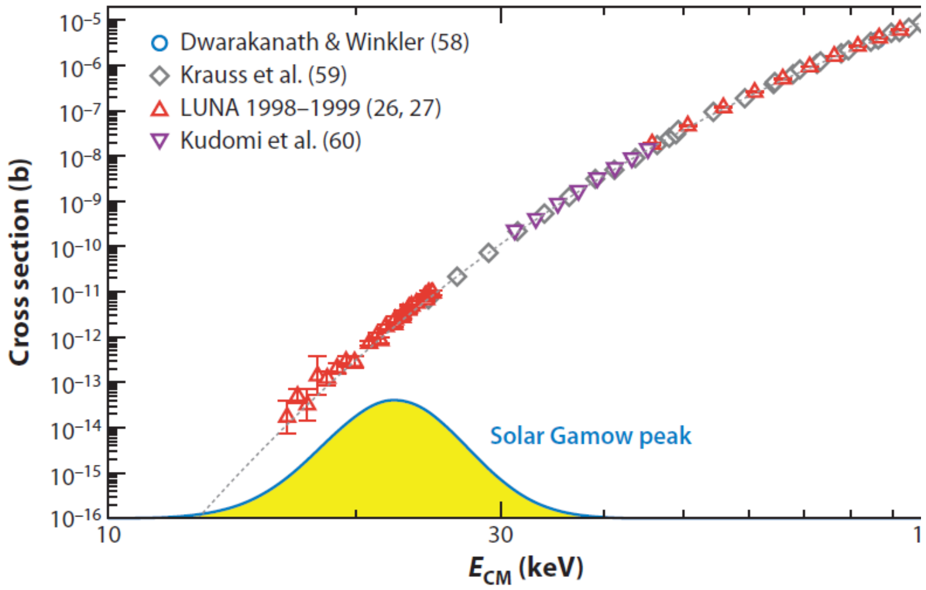
CHAIN IV
$Q_{eff} = 16.84$ MeV

LUNA (**L**aboratory **U**nderground for **N**uclear **A**strophysics)

50 kV accelerator @ Gran Sasso – Italy (1400 m rock -> 10^6 shielding factor)

$^3He(^3He,2p)^4He$

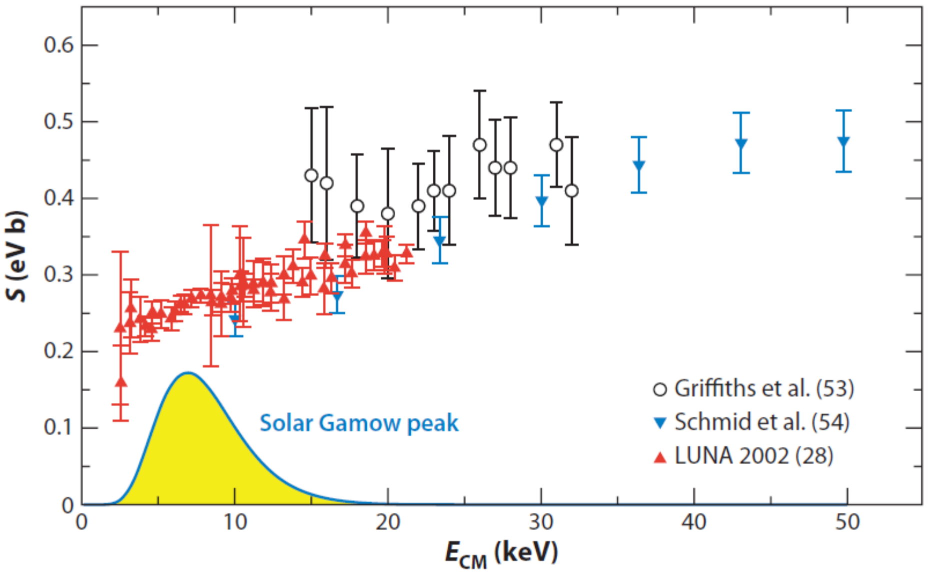
R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



At lowest energy: σ ~ 20 fb → 1 event/month

$d(p,\gamma)^3He$

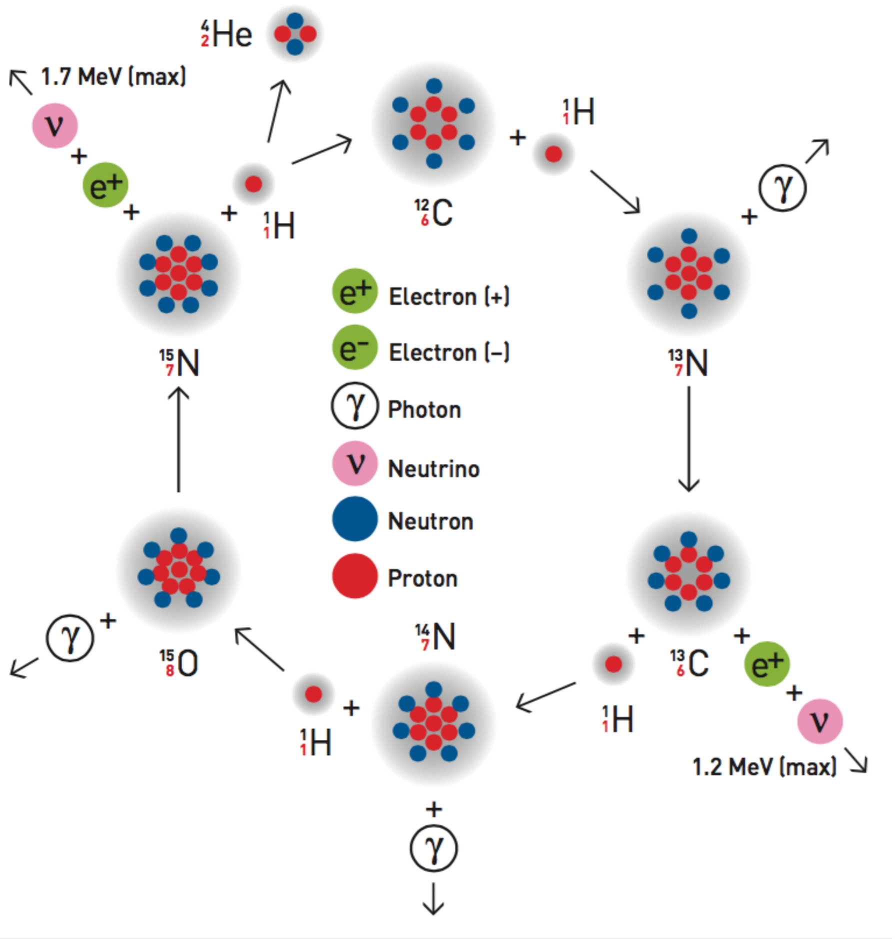
C. Casella et al.: Nucl. Phys. A706 (2002) 203-216



At lowest energy: σ ~ 9 pb → 50 counts/day

No *extrapolation* needed!

The other hydrogen burning: CNO cycle



requires presence of ^{12}C as catalyst.

The Carbon Cycle

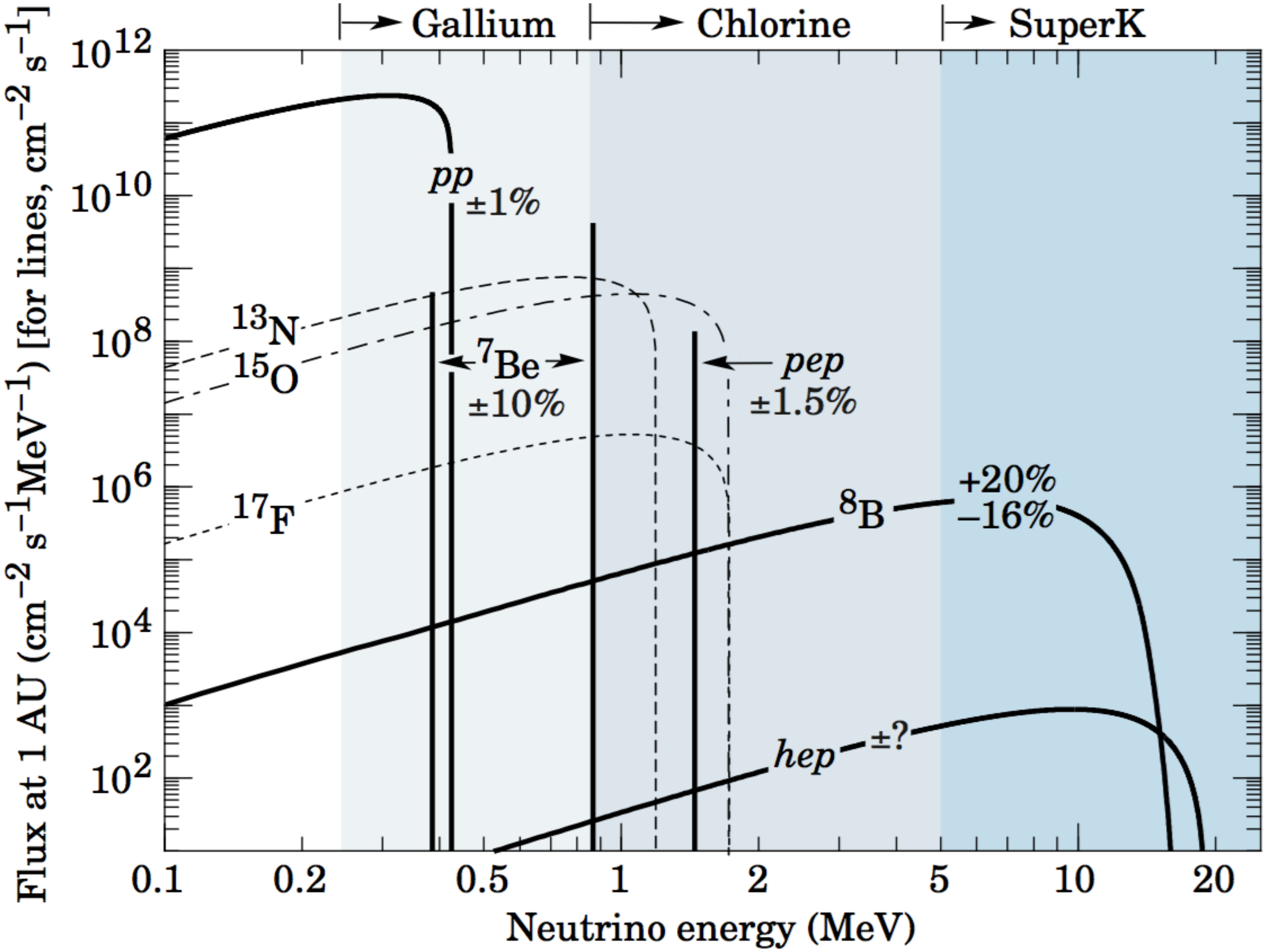
An alternative way of transmuting hydrogen into helium exists in the carbon cycle, which consists of the following six reactions

$$\begin{array}{llr} C^{12} + H^{1} \longrightarrow N^{13} + \gamma & + 1.95 \text{ Mev } (1.3 \times 10^{7} \text{ yrs}) & \\ N^{13} \longrightarrow C^{13} + e^{+} + \nu & + 2.22 \text{ Mev } (7 \text{ min}) & \\ C^{13} + H^{1} \longrightarrow N^{14} + \gamma & + 7.54 \text{ Mev } (2.7 \times 10^{6} \text{ yrs}) & \\ N^{14} + H^{1} \longrightarrow O^{15} + \gamma & + 7.35 \text{ Mev } (3.2 \times 10^{8} \text{ yrs}) & \\ O^{15} \longrightarrow N^{15} + e^{+} + \nu & + 2.71 \text{ Mev } (82 \text{ sec}) & \\ N^{15} + H^{1} \longrightarrow C^{12} + He^{4} & + 4.96 \text{ Mev } (1.1 \times 10^{5} \text{ yrs}) & \end{array} \qquad (10.3)$$

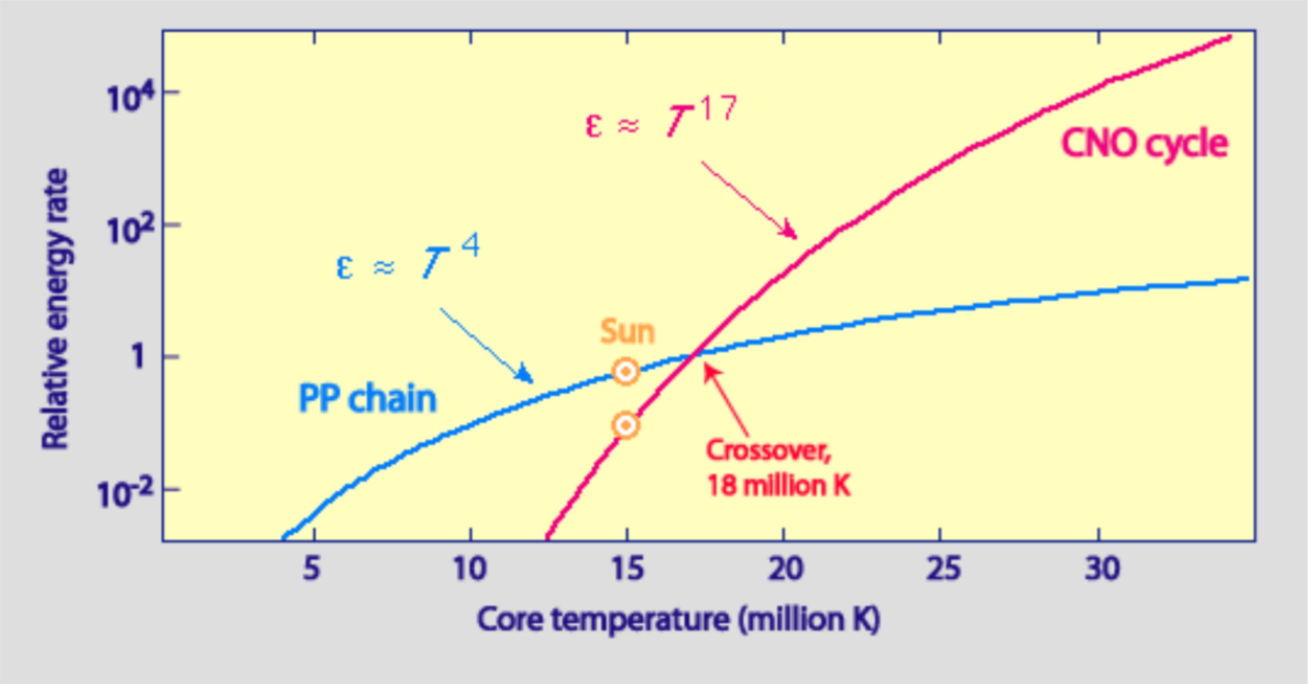
To start with, the collision of a proton with a common carbon nucleus produces a N^{13} particle with emission of a gamma ray. The N^{13} particle is not stable but decays—in seven minutes, on the average—into the heavy carbon isotope with the emission of a positron and a neutrino. Again, the positron disappears together with an electron and the neutrino leaves the star. The next build-up step is taken when a second proton collides with the heavy carbon isotope, forming a common nitrogen nucleus.

Neutrino spectrum (Sun)

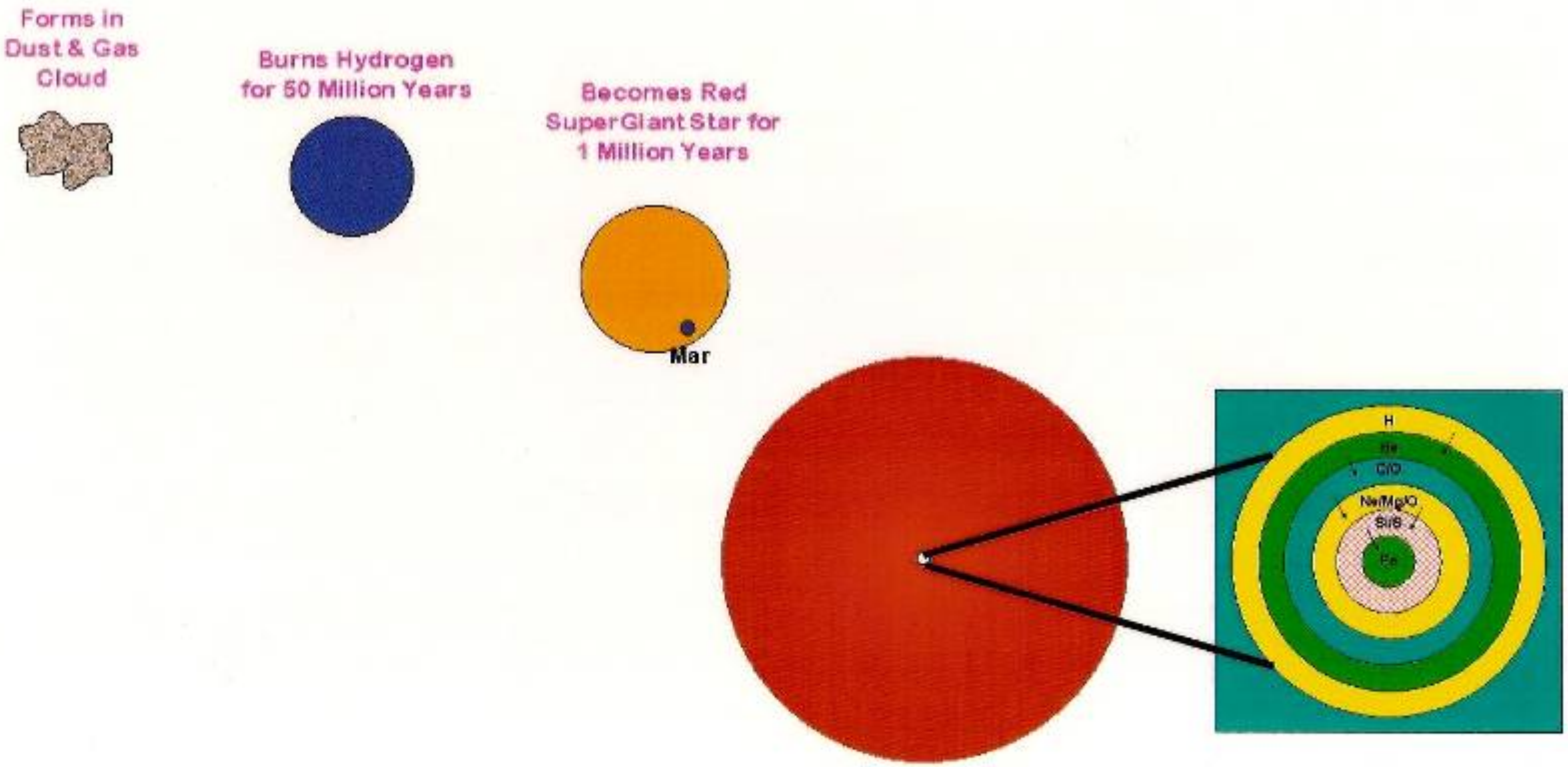
This is the predicted neutrino spectrum



Energy generation: CNO cycle vs pp-chains



Life of big star (> 1,4 $M_\odot$)



Forms in
Dust & Gas
Cloud

Burns Hydrogen
for 50 Million Years

Becomes Red
SuperGiant Star for
1 Million Years

End in Supernovae of type Ib, Ic et II

End of helium burning

Nucleosynthesis yields from stars may be divided into production by stars above and below 9 $\mathrm{M}_\odot$.

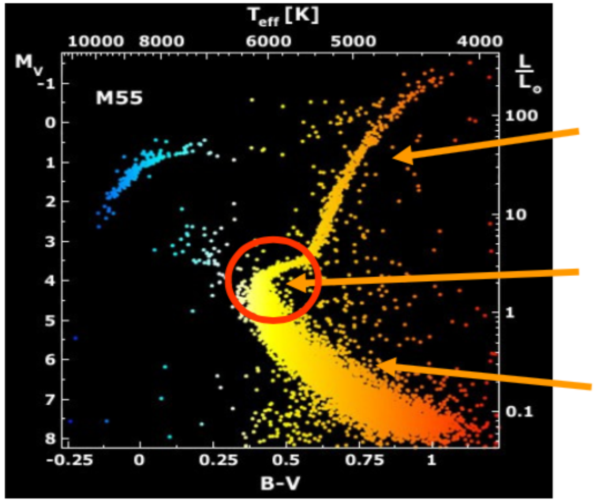
stars with $M \lesssim 9\,\mathrm{M}_\odot$ These stars eject their envelopes during helium shell burning producing planetary nebula and white dwarfs. Constitute the site for the s process.

stars with $M \gtrsim 9\,\mathrm{M}_\odot$ These stars will ignite carbon burning under non-degenerate conditions. The subsequent evolution proceeds in most cases to core collapse. These stars make the bulk of newly processed matter that is returned to the interstellar medium.

Consequences

- Stars slightly heavier than the Sun burn hydrogen via CNO cycle.
- CNO cycle goes significantly faster. Such stars have much shorter lifetimes

Mass ($M_\odot$)	lifetime (yr)
0.8	1.4×10^{10}
1.0	1×10^{10}
1.7	2.7×10^{9}
3.0	2.2×10^{8}
5.0	6×10^{7}
9.0	2×10^{7}
16.0	1×10^{7}
25.0	7×10^{6}
40.0	1×10^{6}



High-mass stars evolved onto the giant branch

Turn-off point

Low-mass stars still on the main sequence

Helium Burning

- Once hydrogen is exhausted the stellar core is made mainly of helium. Hydrogen burning continues in a shell surrounding the core.
- $^4\mathrm{He} + p$ produces $^5\mathrm{Li}$ that decays in 10^{-22} s.
- Helium survives in the core till the temperature become large enough ($T \approx 10^8$ K) to overcome the coulomb barrier for $^4\mathrm{He} + {}^4\mathrm{He}$. The produced $^8\mathrm{Be}$ decays in 10^{-16}. However, the lifetime is large enough to allow the capture of another $^4\mathrm{He}$:

$$3\,{}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

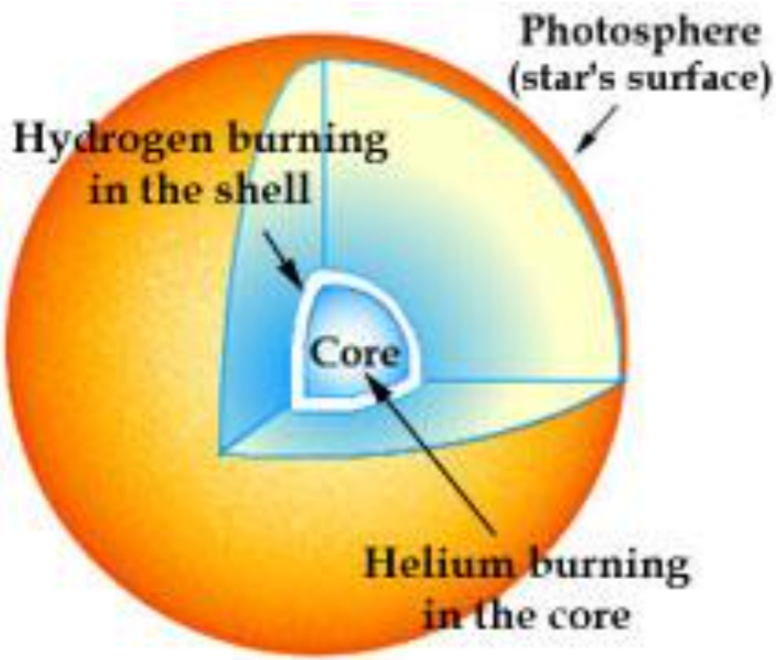
- Hoyle suggested that in order to account for the large abundance of Carbon and Oxygen, there should be a resonance in $^{12}\mathrm{C}$ that speeds up the production.
- $^{12}\mathrm{C}$ can react with another $^4\mathrm{He}$ producing $^{16}\mathrm{O}$

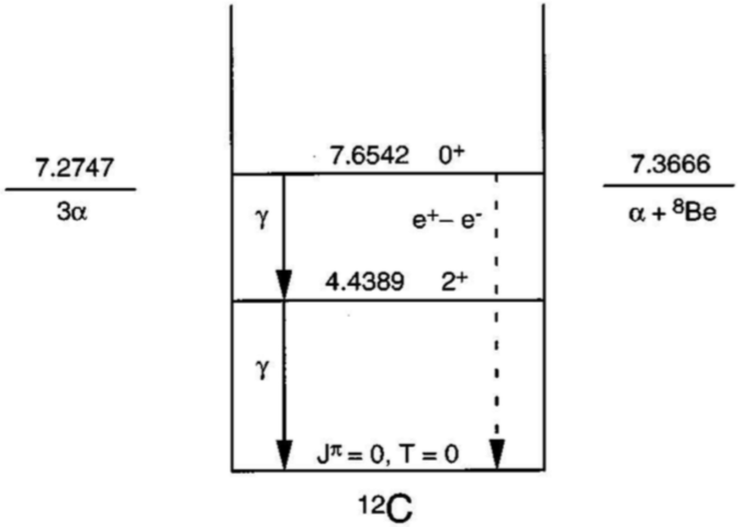
$$^{12}\mathrm{C} + \alpha \rightarrow {}^{16}\mathrm{O} + \gamma$$

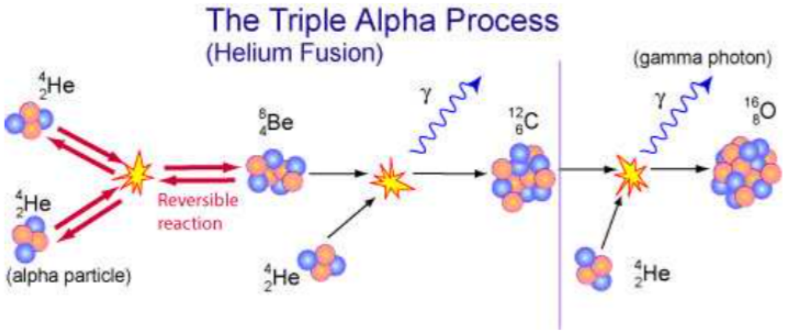
- These two reactions make up helium burning.

Hoyle State and tripple α reaction

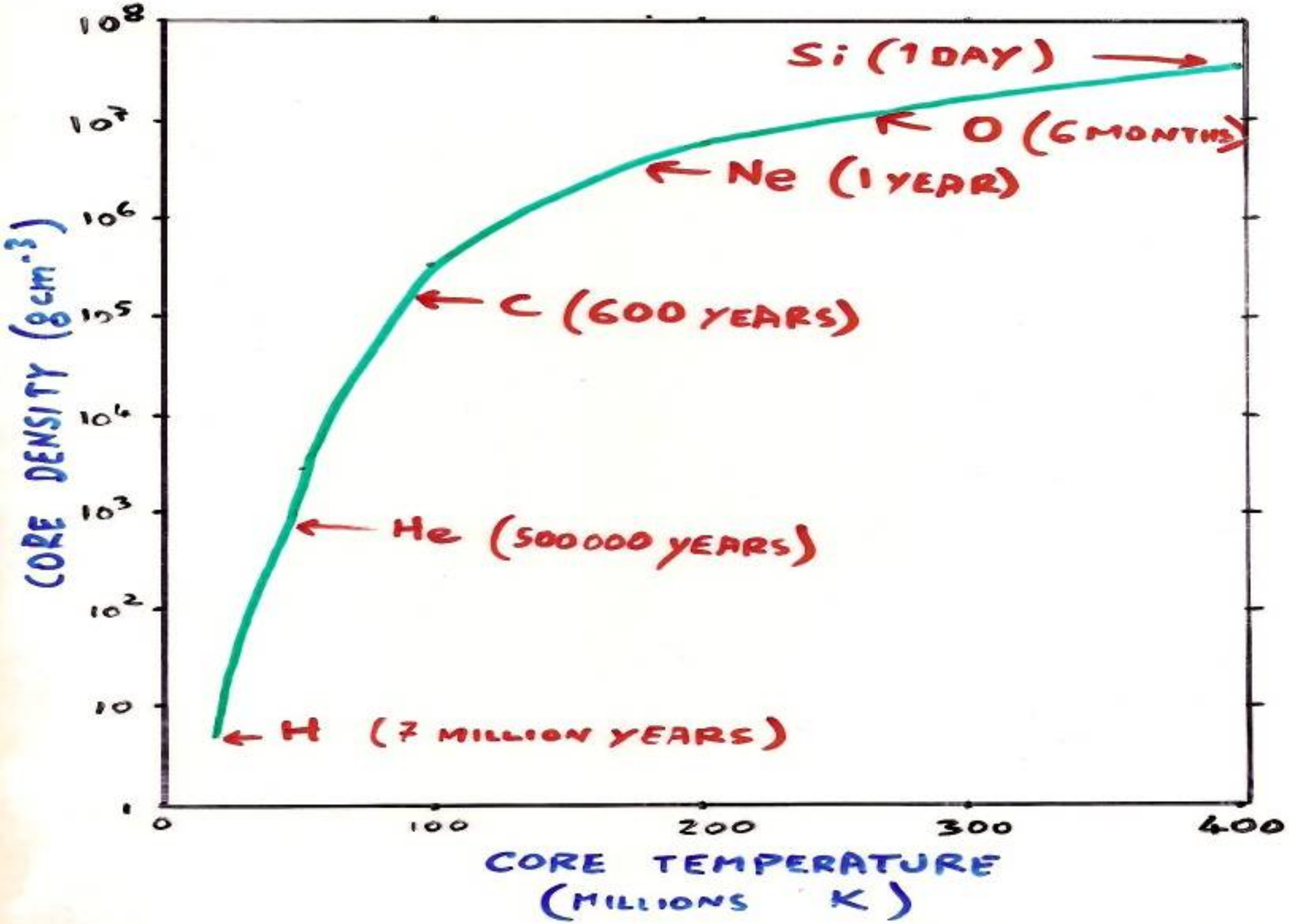
Red giant structure







MASSIVE STAR EVOLUTION : $M = 25 M_\odot$



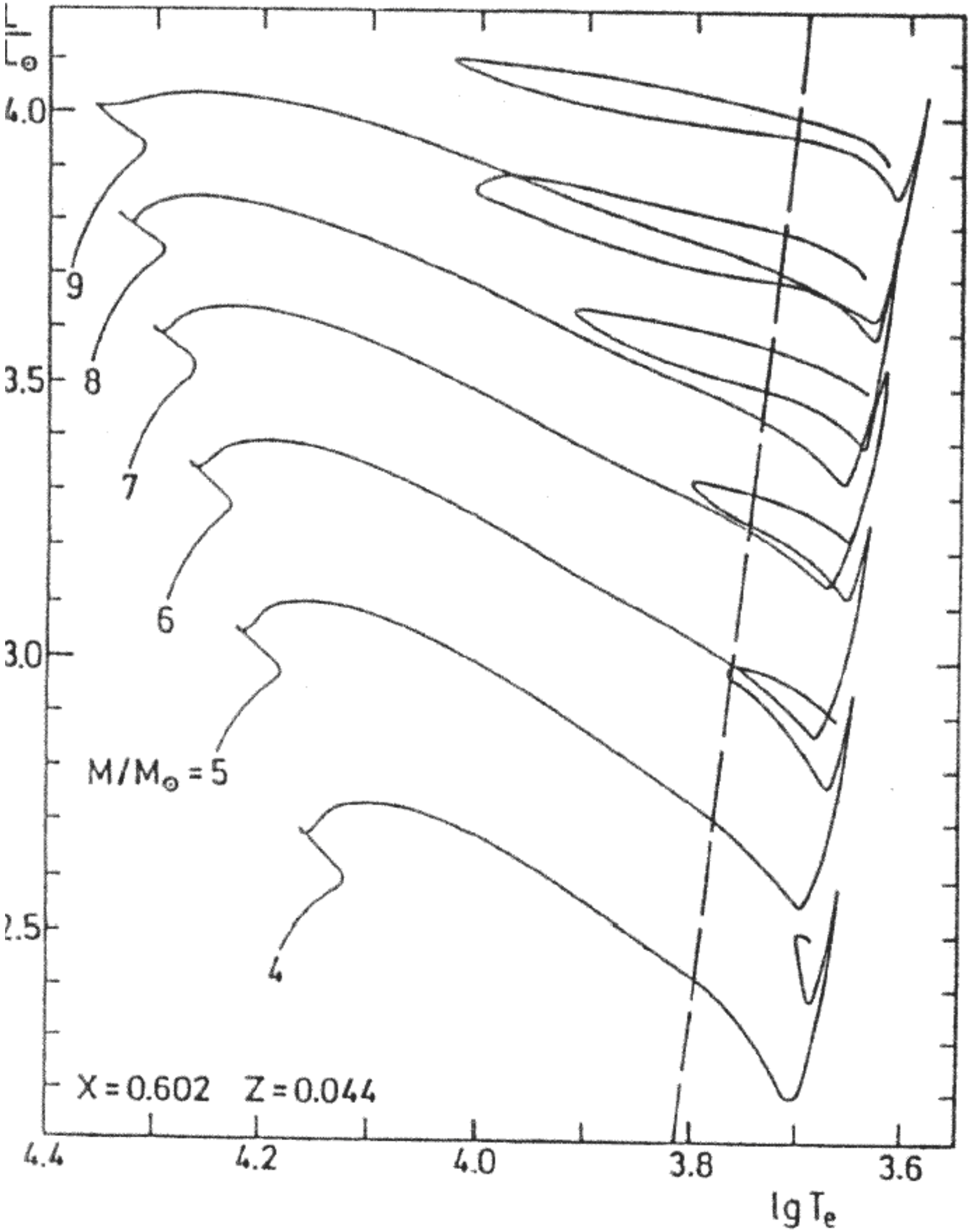
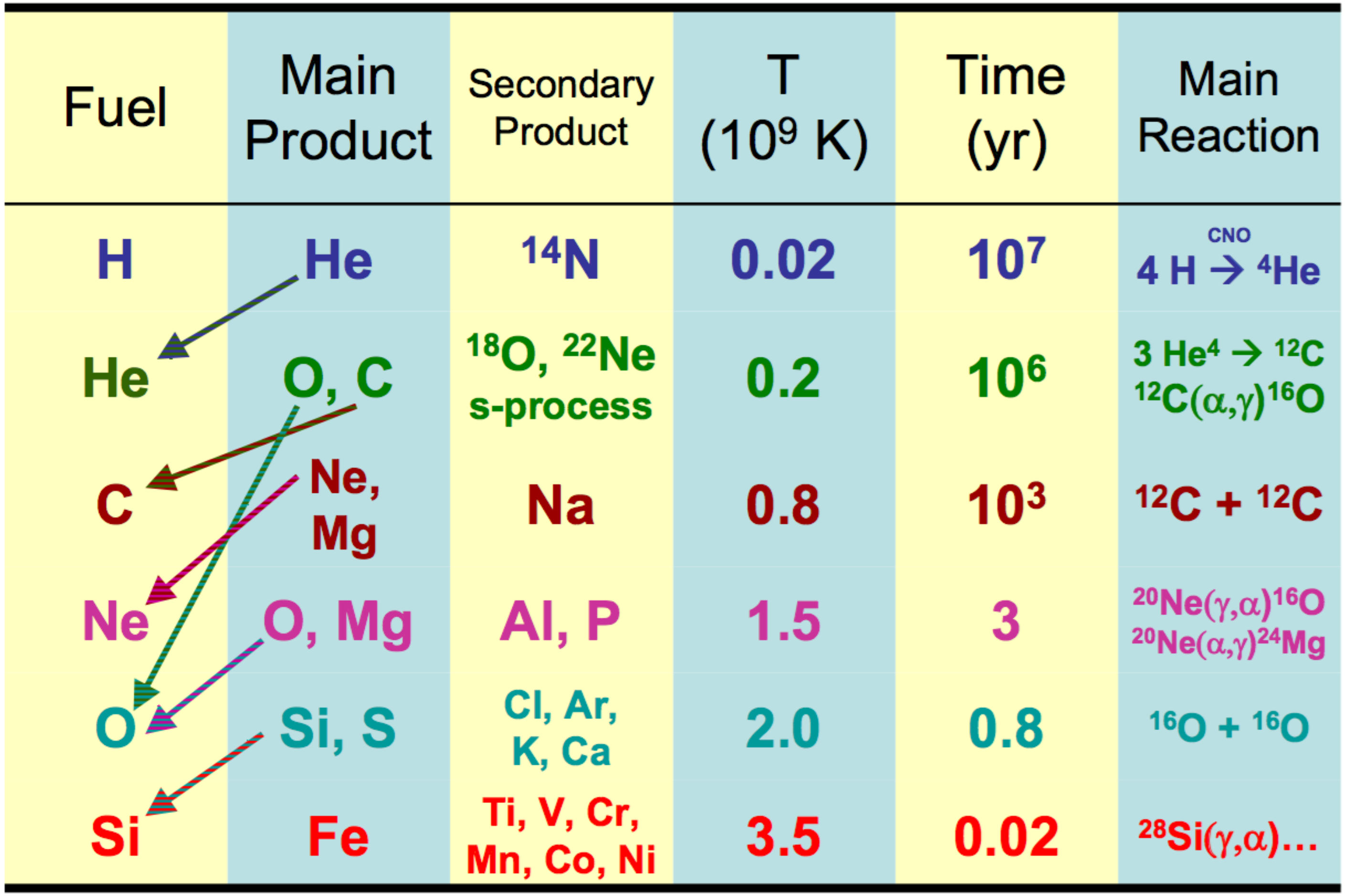


Fig. 31.6. Hertzsprung–Russell diagram with evolutionary tracks for stars in the mass range from $4M_\odot$ to $9M_\odot$ from the main sequence through helium burning (after MATRAKA et al., 1982). The broken line indicates the Cepheid strip

Stellar life

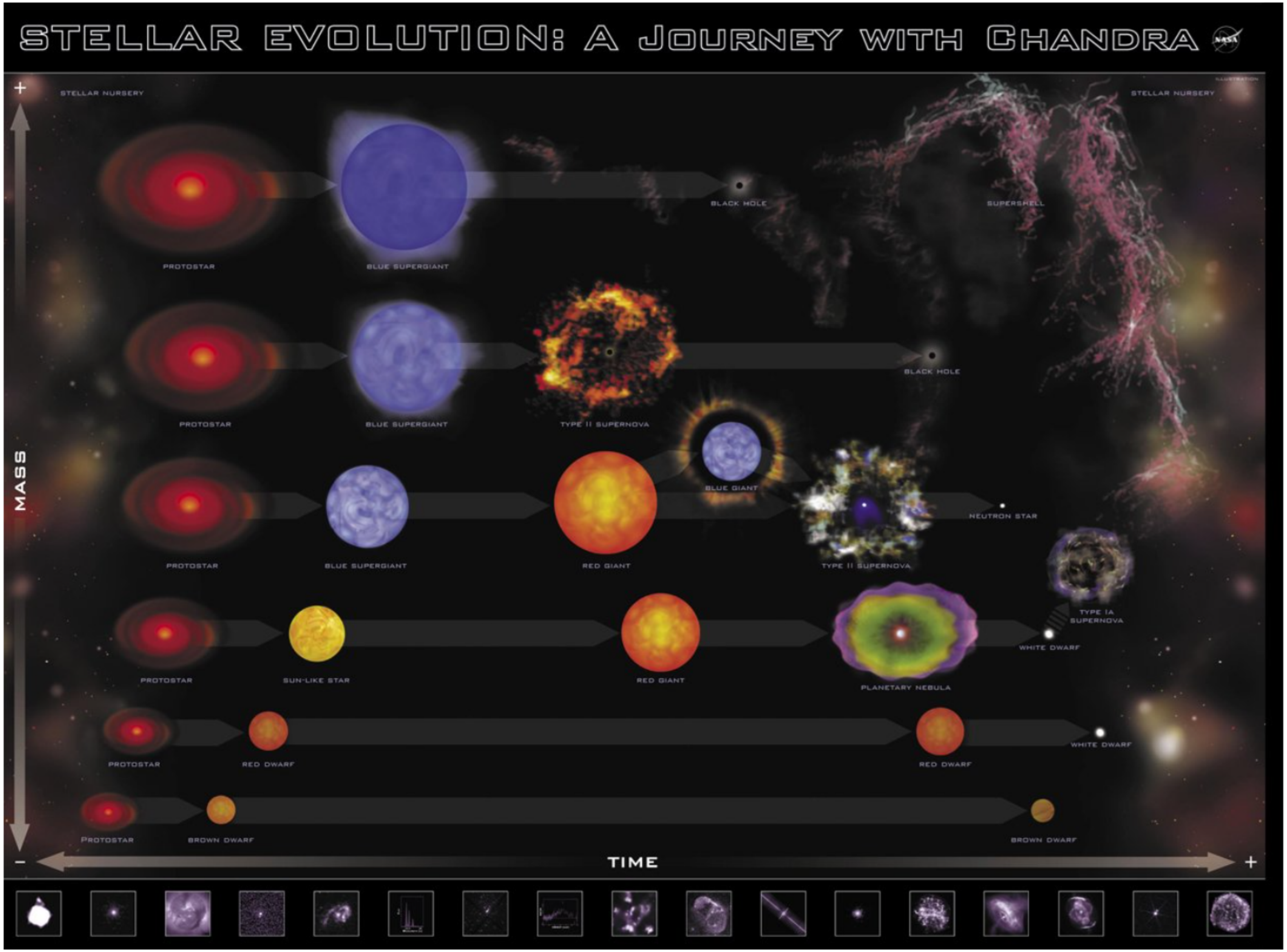
Nuclear burning stages

(e.g., 20 solar mass star)

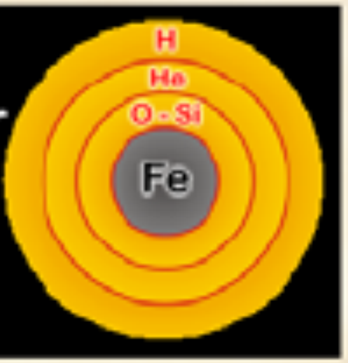


Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	**He**	**^{14}N**	**0.02**	**10^7**	**$4\,H \xrightarrow{CNO} {}^4He$**
He	**O, C**	**^{18}O, ^{22}Ne** **s-process**	**0.2**	**10^6**	**$3\,He^4 \rightarrow {}^{12}C$** **$^{12}C(\alpha,\gamma)^{16}O$**
C	**Ne, Mg**	**Na**	**0.8**	**10^3**	**$^{12}C + {}^{12}C$**
Ne	**O, Mg**	**Al, P**	**1.5**	**3**	**$^{20}Ne(\gamma,\alpha)^{16}O$** **$^{20}Ne(\alpha,\gamma)^{24}Mg$**
O	**Si, S**	**Cl, Ar, K, Ca**	**2.0**	**0.8**	**$^{16}O + {}^{16}O$**
Si	**Fe**	**Ti, V, Cr, Mn, Co, Ni**	**3.5**	**0.02**	**$^{28}Si(\gamma,\alpha)$…**

Stellar Evolution



Type Ia vs. Core-Collapse Supernovae

Type Ia	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion 	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface 

Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

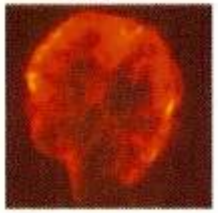
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

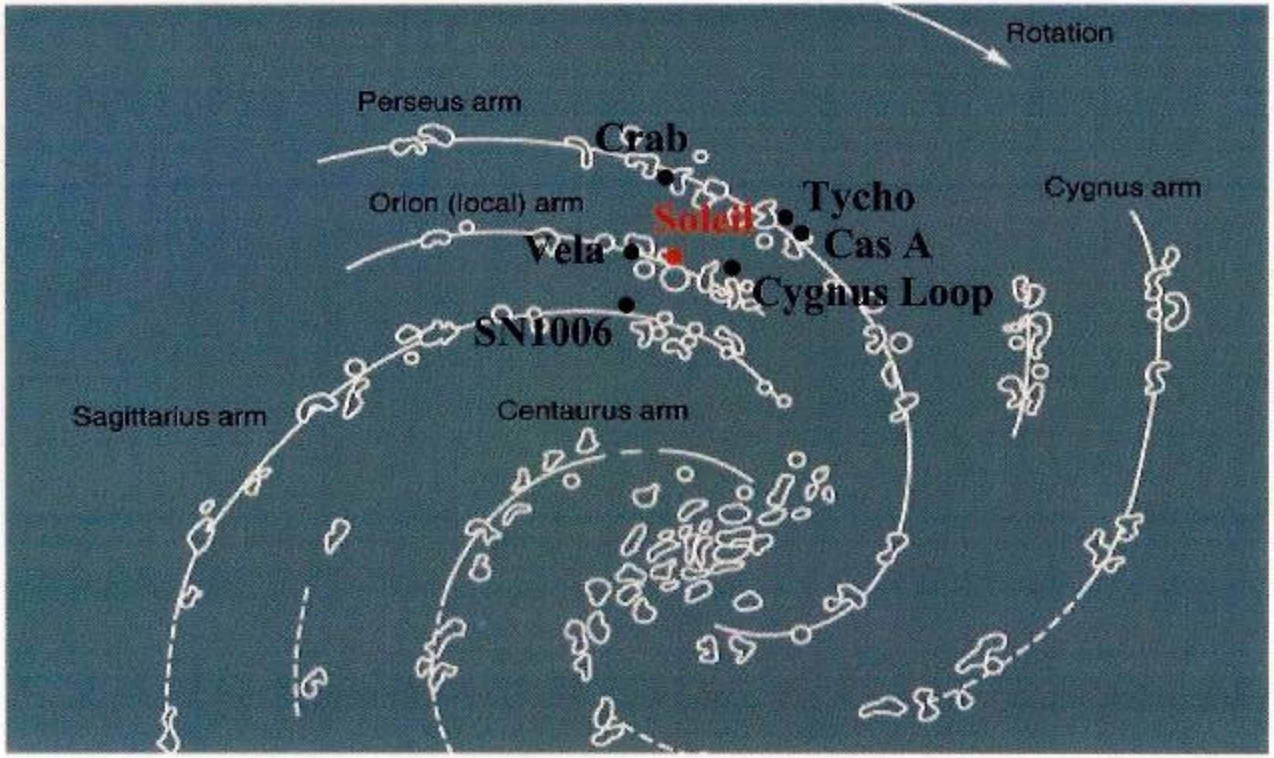
SuperNovae Remnants

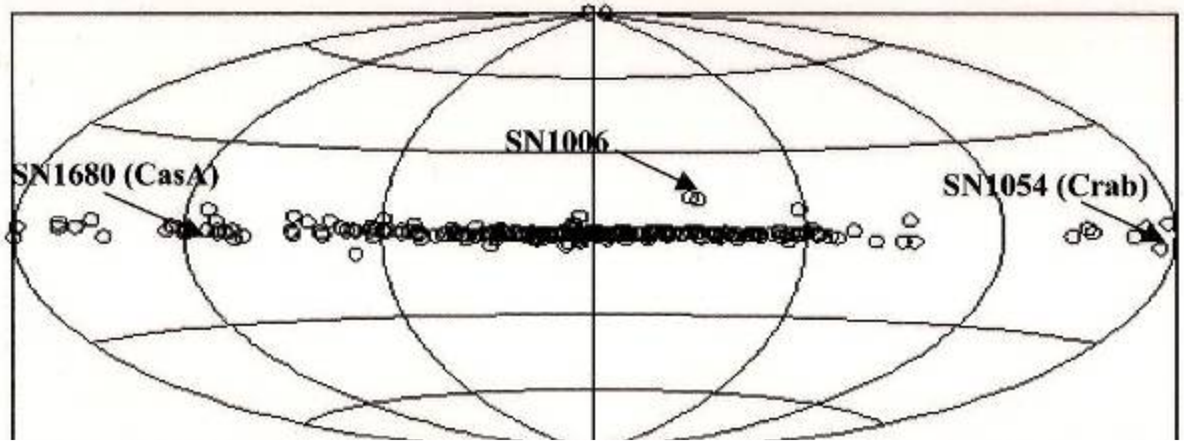
Vela

Tycho

Cygnus



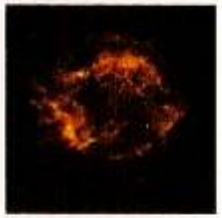




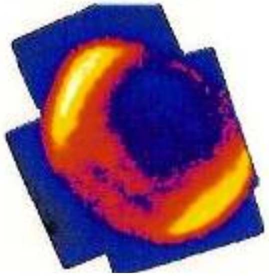
Crab

Kepler

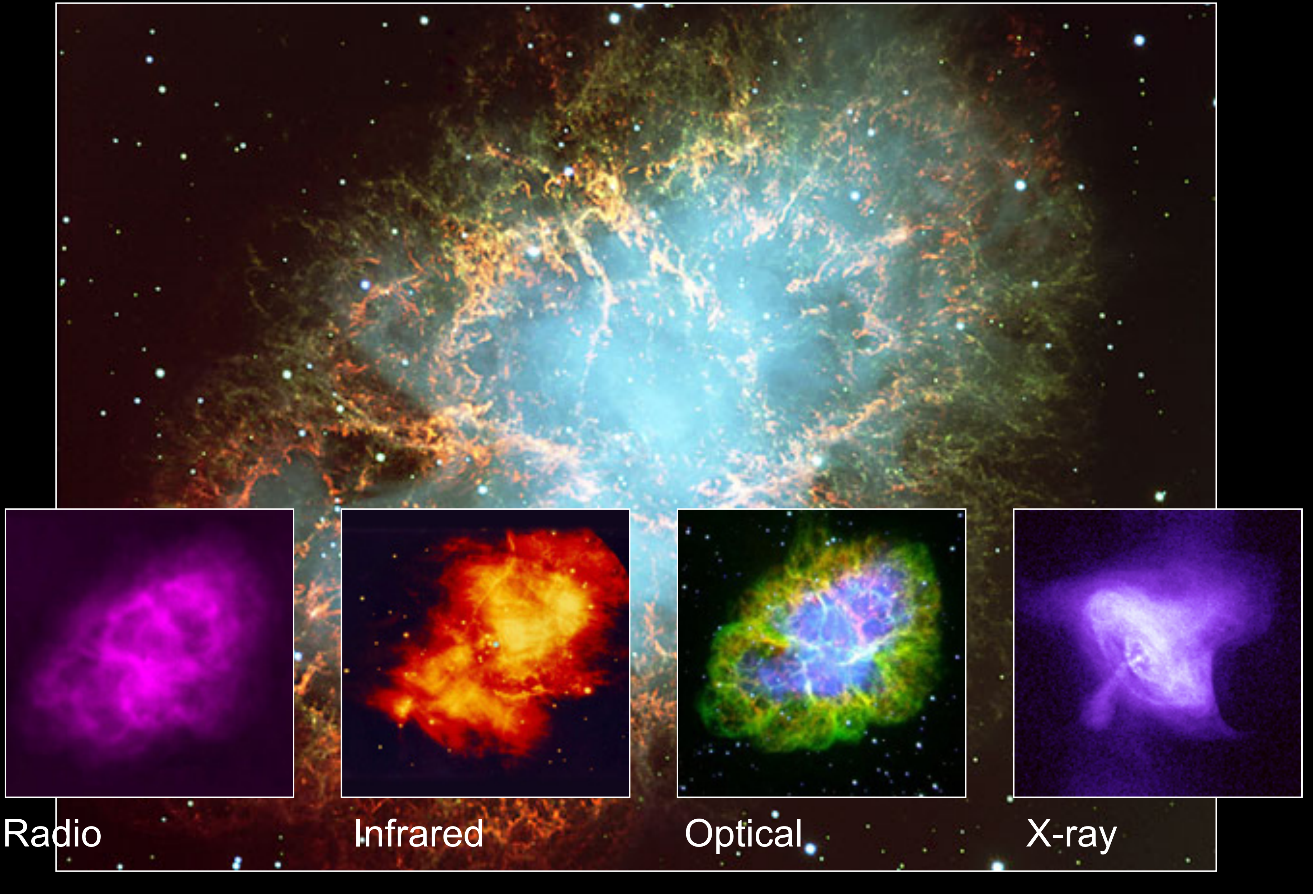
Cas A



SN1006



The Crab in Multi-Wavelengths Photons



Radio

Infrared

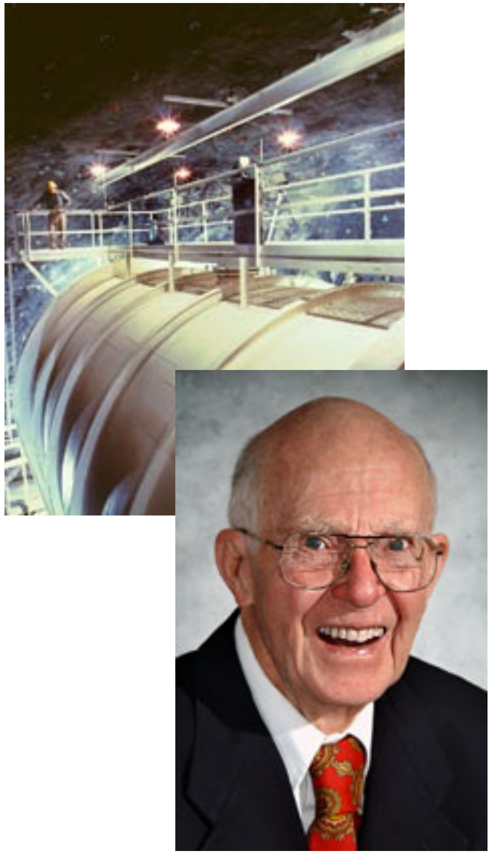
Optical

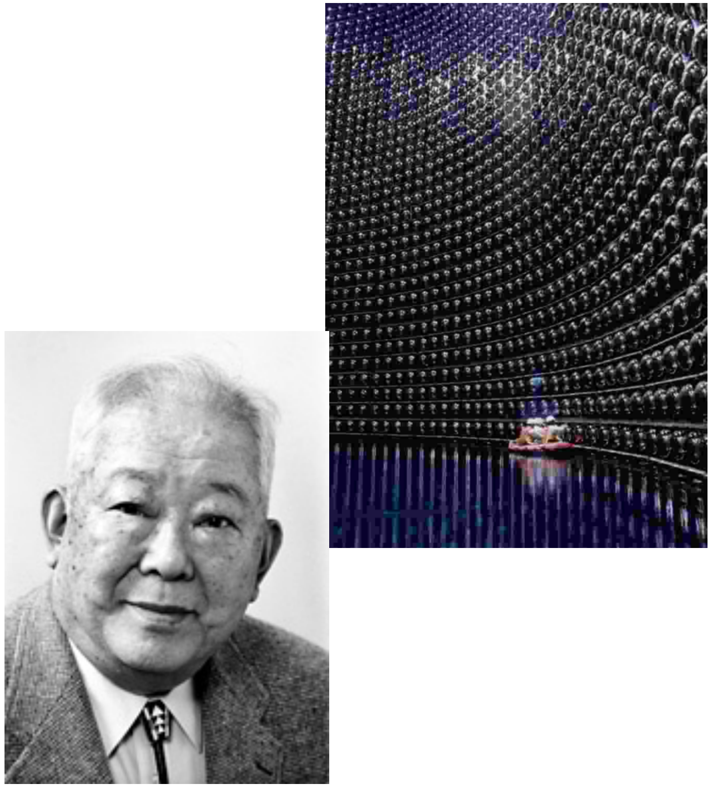
X-ray

Astrofisica Nucleare e Subnucleare

Solar Neutrinos

The 2002 Nobel Prize for the Solar Neutrino Physics

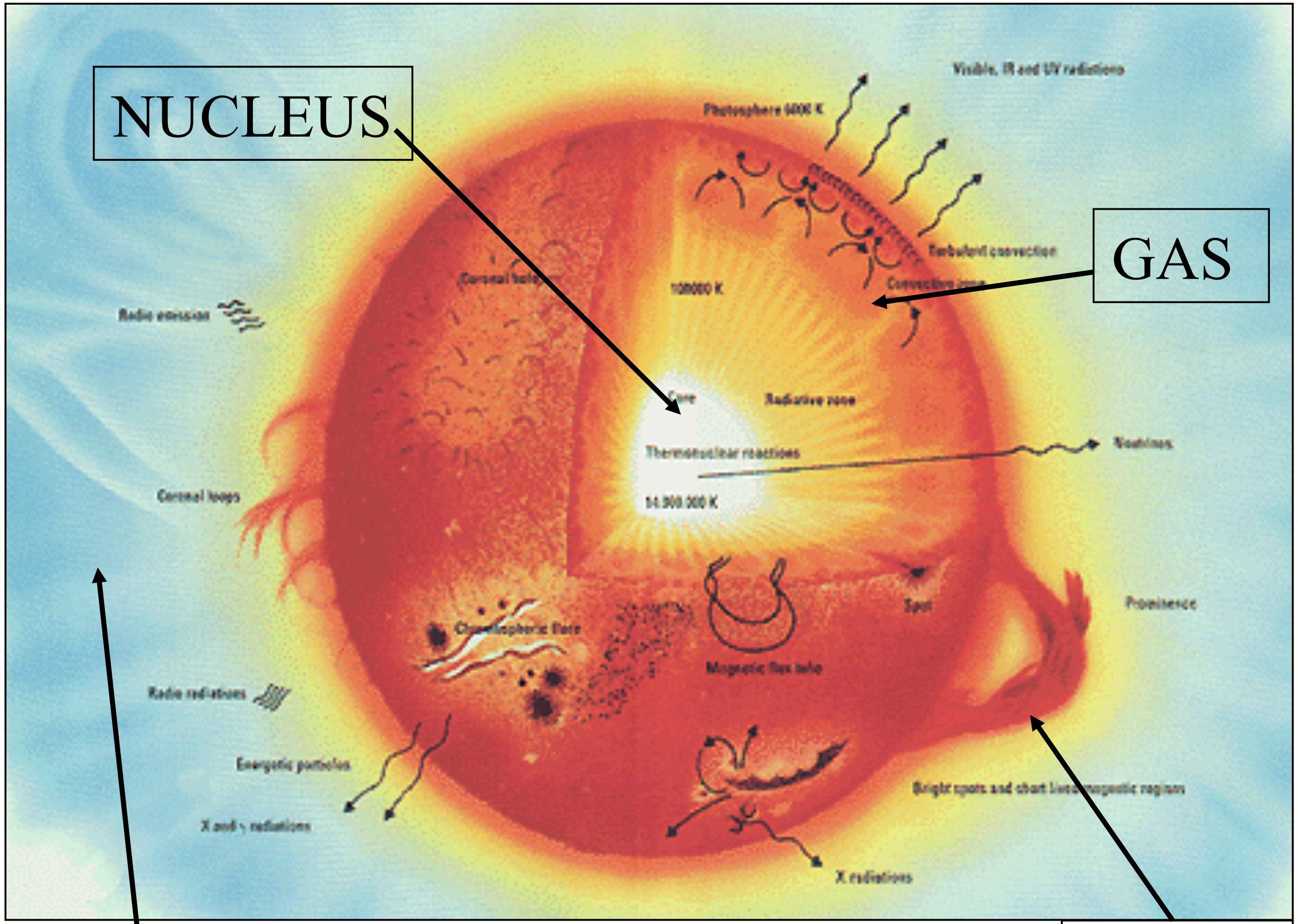




Masatoshi Koshiba
http://nobelprize.org/nobel_prizes/physics/laureates/2002/koshiba-lecture.pdf

Raymond Davis Jr.
http://nobelprize.org/nobel_prizes/physics/laureates/2002/davis-lecture.pdf

The Standard Solar Model



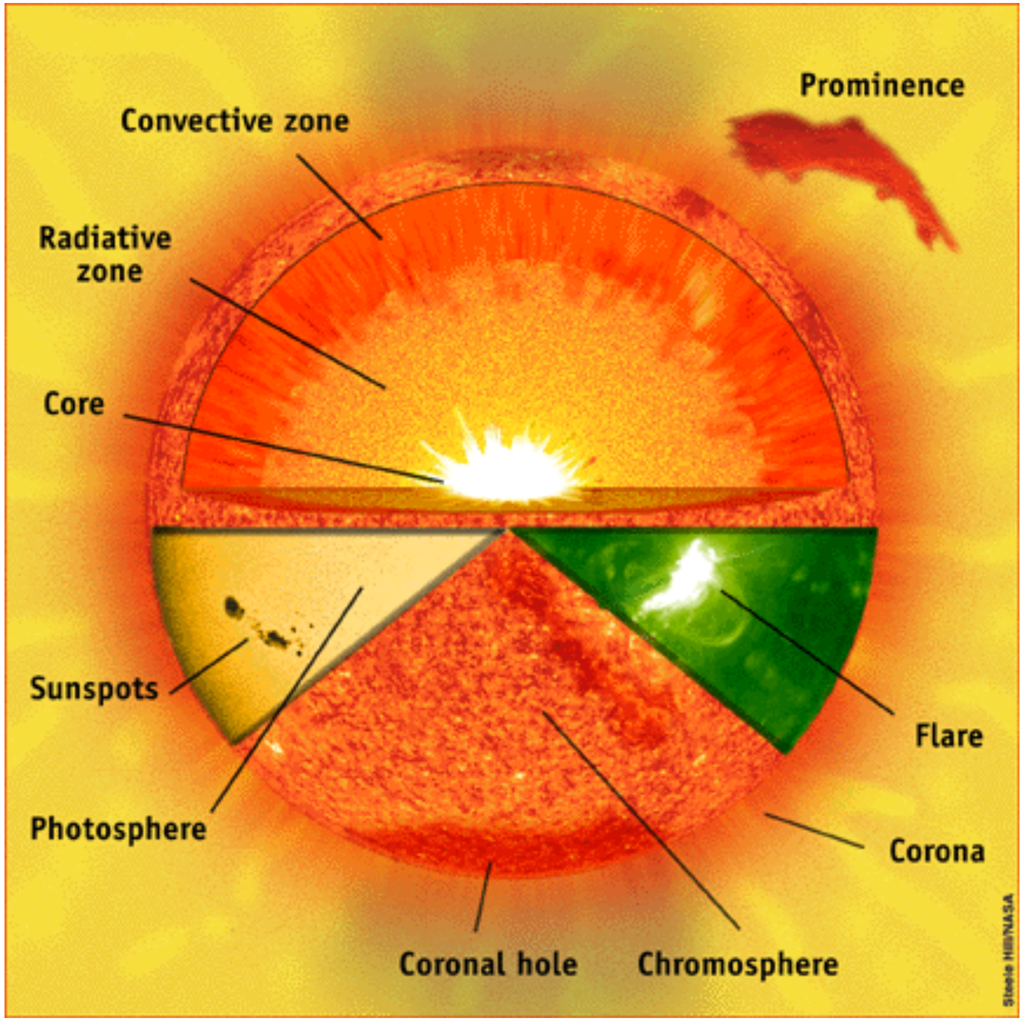
NUCLEUS

GAS

CORONA

FLARE

The Standard Solar Model



The Standard Solar Model

http://www.sns.ias.edu/~jnb/

- J. Bahcall: The main author of the SSM
- The standard solar model is derived from the conservation laws and energy transport equations of physics, applied to a spherically symmetric gas (plasma) sphere
- Constrained by the luminosity, radius, age and composition of the Sun

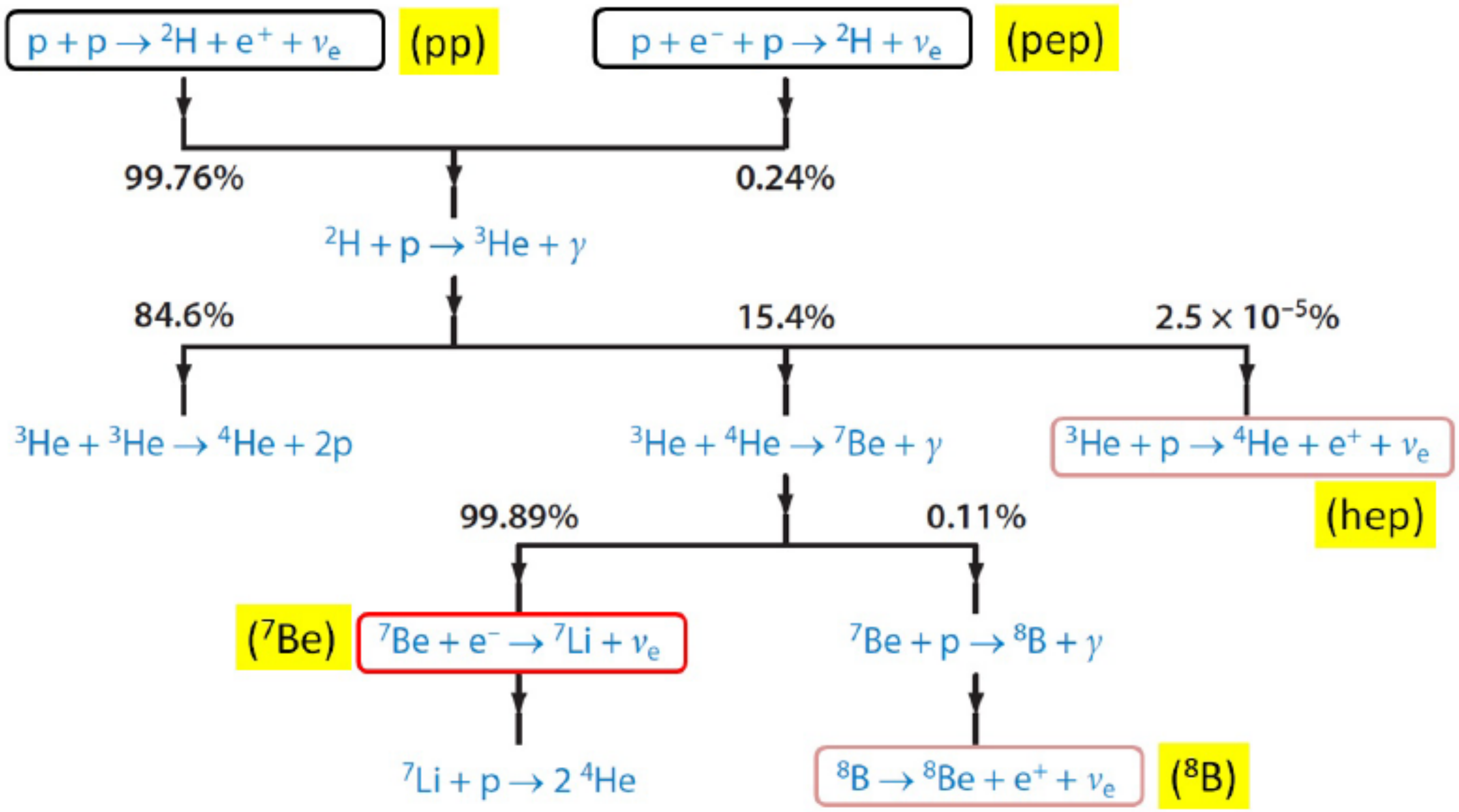
- Inputs for the Standard Solar Model
  - Mass
  - Age
  - Luminosity
  - Radius
- No free parameters
- Tested by helioseismology
- Fusion ⇒ neutrinos

Nota: Leggere l'articolo (tradotto anche in italiano)
http://www.sns.ias.edu/~jnb/Papers/Popular/Nobelmuseum/italianmystery.pdf

The predictions of the SSM

- Most of the neutrinos produced in the sun come from the first step of the pp chain.
- Their energy is so low (<0.425 MeV) → very difficult to detect.
- A rare side branch of the pp chain produces the "boron-8" neutrinos with a maximum energy of roughly 15 MeV
- These are the easiest neutrinos to observe, because the neutrino cross section increases with energy.
- A very rare interaction in the pp chain produces the "hep" neutrinos, the highest energy neutrinos produced in any detectable quantity by our sun.
- All of the interactions described above produce neutrinos with a spectrum of energies. The inverse beta decay of Be^7 produces mono-energetic neutrinos at either roughly 0.9 or 0.4 MeV.

ν from the Sun: the proton cycle



$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$ (pp)

$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$ (pep)

99.76%

0.24%

${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$

84.6%

15.4%

$2.5 \times 10^{-5}\%$

${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$

${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$

${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$ (hep)

99.89%

0.11%

(^{7}Be) ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$

${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$

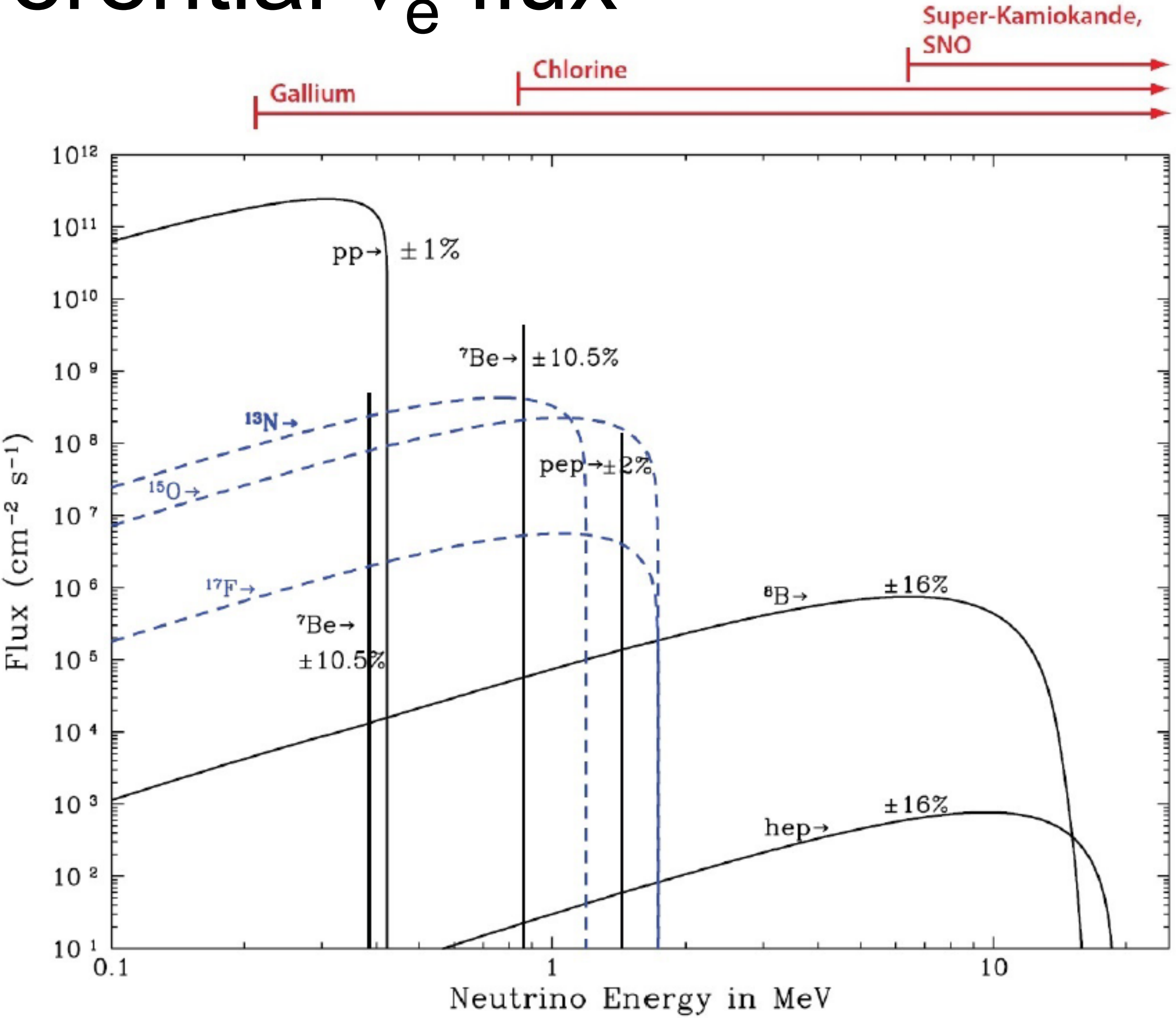
${}^7\text{Li} + p \rightarrow 2\,{}^4\text{He}$

${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$ (^{8}B)

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e \qquad Q = 26.73\ \text{MeV} \qquad \langle E_\nu \rangle \simeq 0.3\ \text{MeV}$$

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi D_\odot^2}\,\frac{2L_\odot}{(Q - \langle E_\nu \rangle)} = 6 \times 10^{10}\ \text{cm}^{-2}\text{s}^{-1}$$

Differential ν_e flux



Neutrino Emission

Source r	Reaction	Average Neutrino Energy $\langle E \rangle_r$ (MeV)	Maximum Neutrino Energy (MeV)
pp	$p + p \rightarrow d + e^+ + \nu_e$	0.2668	0.423 ± 0.03
pep	$p + e^- + p \rightarrow d + \nu_e$	1.445	1.445
^{7}Be	$e^- + {}^7\mathrm{Be} \rightarrow {}^7\mathrm{Li} + \nu_e$	0.3855 0.8631	0.3855 0.8631
^{8}B	$^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$	6.735 ± 0.036	~ 15
hep	$^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$	9.628	18.778
^{13}N	$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e$	0.7063	1.1982 ± 0.0003
^{15}O	$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^+ + \nu_e$	0.9964	1.7317 ± 0.0005
^{17}F	$^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^+ + \nu_e$	0.9977	1.7364 ± 0.0003

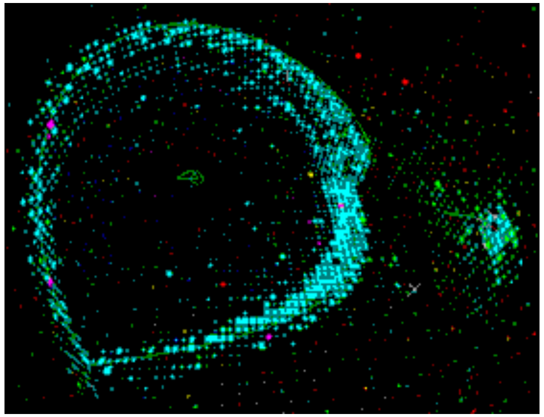
Experimental Techniques

Two detection techniques for the solar neutrinos:

1- elastic scattering

$$\nu_e + e \rightarrow \nu_e + e$$

SK



2- Neutron capture

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

No free neutrons in nature:

$$(Z,A) + \nu_e \rightarrow e + (Z+1,A)$$

Example: $^{71}Ga + \nu \rightarrow {}^{71}Ge + e$

3- The SNO way:

- $\nu_e + d \rightarrow e + p + p$
- $\nu_x + d \rightarrow \nu_x + n + p$

Solar Neutrino Detectors

- Neutrino Absorption Experiments
  - 37Cl
  - 71Ga
- Neutrino Scattering Experiments
  - SuperKamiokande
- Direct Counting experiments
  - SNO