10. Supernovae, SN and diffuse SN neutrinos

Hydrogen and Helium burning
10. Supernovae, SN and diffuse SN neutrinos

Helium burning

- Burning of helium in the core takes place via reaction
  \[ ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} \]

- The Q-value of the reaction is
  \[ Q = m(^4\text{He}) + m(^4\text{He}) - m(^8\text{Be}) \approx -92 \text{ keV} \]
  - \( Q < 0 \) \( \Rightarrow \) endothermic reaction; needs energy to take place

- The effective mean energy for thermonuclear fusion reaction is (the Gamow peak)
  \[ E_0 = \left( \frac{bkT}{2} \right)^{2/3} \]
  - \( E_0 = 92 \text{ keV} \) \( \Rightarrow \) \( T = 1.2 \times 10^8 \text{ K} \)
  - \( T \) rather high (for hydrogen burning: \( T \approx 10-20 \times 10^6 \text{ K} \))

- \( \tau(^8\text{Be}) \approx 2.6 \times 10^{-16} \text{ s} \) \( \Rightarrow \) \( ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} \)
10. Supernovae, SN and diffuse SN neutrinos

Helium burning – producing $^{12}$C

- Reaction

$$3 \times ^4\text{He} \rightarrow ^{12}\text{C} \quad (Q \approx 7.3 \text{ MeV})$$

is energetically possible, but its probability is too low to account for the observed abundances of $^{12}$C

- Fred Hoyle (1950’s) proposed a two-step process:
  the probability of $^8\text{Be} + ^4\text{He}$ would be greatly enhanced if $^{12}$C had an energy level (a resonance state with high cross section) close to the $Q$-value of the reaction ($\sim 7.3$ MeV)

$\implies$ soon after the excited state ($E^* \approx 7.65$ MeV, $J^{\pi} = 0^+$) was found at Caltech

  - step 1: $^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be}$
  
  - step 2: $^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C}^*$

- Equilibrium concentration of $^{8}\text{Be}$ in $^4\text{He}$ environment

  - At $T \approx 100 \times 10^6$ K and $\rho \approx 10^5$ g·cm$^{-3}$: $N(^8\text{Be}) / N(^4\text{He}) \approx 10^{-9}$

  - Rate: $R_{3\alpha} = N_{^8\text{Be}} \cdot N_{^4\text{He}} \cdot \langle \sigma v \rangle_{^8\text{Be}^4\text{He}}$
10. Supernovae, SN and diffuse SN neutrinos

Helium burning – producing $^{16}$O

▶ Once $^{12}$C has been created, production of $^{16}$O may start, however

▶ reaction

$^{12}$C* → $^{8}$Be + $^{4}$He + $\gamma$

dominates over

$^{12}$C* → $^{12}$C + 2$\gamma$

$\Rightarrow$ $^{12}$C + $^{4}$He → $^{16}$O

▶ Finally, for heavy stars in less than million years, $^{4}$He in the core is consumed, and the core contains mostly $^{12}$C and $^{16}$O
10. Supernovae, SN and diffuse SN neutrinos

Carbon and Oxygen burning

- **Carbon burning:** $T > 5 \times 10^8$ K
- **Oxygen burning:** $T > 10^9$ K

- **Carbon burning reactions**
  
  $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^{4}\text{He}$
  
  $\rightarrow ^{23}\text{Na} + \text{p}$
  
  $\rightarrow \ldots$

- **Oxygen burning reactions**
  
  $^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + ^{4}\text{He}$
  
  $\rightarrow ^{31}\text{S} + \text{n}$
  
  $\rightarrow ^{31}\text{P} + \text{p}$
  
  $\rightarrow \ldots$

- Carbon and oxygen burning produces silicon in the core
10. Supernovae, SN and diffuse SN neutrinos

Silicon burning

- Complex sequence of reactions taking place in relative short time (≈ 1 day) under nearly equilibrium conditions

- The Coulomb barrier of reactions like $^{28}\text{Si} + ^{28}\text{Si} \rightarrow ^{56}\text{Ni}$ is too high for direct fusion (no time for barrier penetration)
  - higher $T$ would increase the photodisintegration rate (iron-group nuclei can resist photodisintegration up to $\sim 7 \times 10^9$ K)
  - "step-by-step process"

- At lower temperatures ($\sim 5 \times 10^9$ K) capture of $\alpha$-particle dominates
  - $^{28}_{14}\text{Si} + ^4\text{He} \rightarrow ^{32}_{16}\text{S} + \gamma$
  - $^{32}_{16}\text{S} + ^4\text{He} \rightarrow ^{36}_{18}\text{Ar} + \gamma$
  - ...
  - $^{48}_{22}\text{Ti} + ^4\text{He} \rightarrow ^{52}_{24}\text{Cr} + \gamma$
  - $^{52}_{24}\text{Cr} + ^4\text{He} \rightarrow ^{56}_{26}\text{Ni} + \gamma$

- The core is filled with iron-group nuclei and the fusion processes stops, as the binding energy do not release energy any more

$\Rightarrow$ core collapse SN
## 10. Supernovae, SN and diffuse SN neutrinos

### Major nuclear burning processes

<table>
<thead>
<tr>
<th>Burning stage and nuclear fuel</th>
<th>Process</th>
<th>$T_{\text{thr.}}$ [10⁶ K]</th>
<th>Products</th>
<th>Time</th>
<th>$T$ [10⁹ K]</th>
<th>$\rho$ [g cm⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen burning</td>
<td>pp</td>
<td>4</td>
<td>He</td>
<td>7x10⁶ y</td>
<td>0.06</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>CNO</td>
<td>15</td>
<td>He, N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium</td>
<td>3α</td>
<td>100</td>
<td>C, O</td>
<td>5x10⁵ y</td>
<td>0.23</td>
<td>7x10²</td>
</tr>
<tr>
<td>Carbon</td>
<td>C + C</td>
<td>600</td>
<td>O,Ne,Ma,Mg</td>
<td>600 y</td>
<td>0.93</td>
<td>2x10⁵</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O + O</td>
<td>1000</td>
<td>Mg,S,P,Si</td>
<td>0.5 y</td>
<td>2.3</td>
<td>1x10⁷</td>
</tr>
<tr>
<td>Silicon</td>
<td>Equilib.</td>
<td>3000</td>
<td>Cr, Fe, Ni</td>
<td>1 day</td>
<td>4.1</td>
<td>3x10⁷</td>
</tr>
<tr>
<td>Core collapse</td>
<td></td>
<td></td>
<td></td>
<td>seconds</td>
<td>8.1</td>
<td>3x10⁹</td>
</tr>
<tr>
<td>Core bounce</td>
<td></td>
<td></td>
<td></td>
<td>millisecs</td>
<td>75</td>
<td>3x10¹⁴</td>
</tr>
<tr>
<td>Explosive burning</td>
<td></td>
<td></td>
<td></td>
<td>0.1–10 s</td>
<td>1.2–7</td>
<td>varies</td>
</tr>
</tbody>
</table>
10. Supernovae, SN and diffuse SN neutrinos

Supernova types – Classification

- Supernovae arises from two different final stages of stars
  - Thermonuclear explosion of a white dwarf in a binary system
    + critical limit called the Chandrasekhar mass ($\sim 1.4 \cdot M_{\text{SUN}}$)
    + standard candle
  - Explosion caused by the core collapse of a massive star ($\sim 8 \cdot M_{\text{sun}}$)
    + no more fuel to produce energy in the core of a star
- Supernovae are classified spectroscopically by the appearance of hydrogen in their spectrum
  - Type I – no sign of hydrogen in the spectrum
    + subdivided into type Ia (white dwarf, no neutrinos produces), Ib and Ic (core collapse SN)
  - Type II – contain hydrogen in the spectrum
- The whole supernova process is more complex than suggested by the simple classification scheme
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – The basic picture – 1/4

- Stars of mass more than $\sim 10 \cdot M_{\text{SUN}}$ can ignite silicon-burning phase
  - producing iron-group elements in the core

- The stability of the iron core against the gravitation is mainly guaranteed by the pressure of degenerate electrons
  - no more radiation pressure generated

- At very large densities the Pauli exclusion principle come into the play
  - each cell in phase space of size $h^3$ can occupy in maximum two $e^-$
  - pressure determined by the Fermi momentum (or energy): $p = f(n_e)$
    $\rightarrow$ it has no dependency on the temperature

- The stability condition of the core is given by the Chandrasekhar limit

$$M_{\text{Ch}} = 5.7 \cdot Y_e^2 \cdot M_{\text{SUN}}$$

where $Y_e$ is the number of electrons per nucleus

- when the iron core exceeds this limit, the electron pressure can not compete with the gravitation, and the core-collapse process may start
- for stars of $\sim 15 \cdot M_{\text{SUN}}$ the limit is $M_{\text{Ch}} \sim 1.5 \cdot M_{\text{SUN}}$
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – The basic picture – 2/4

- The cause of exceeding the Chandrasekhar limit is the photo-disintegration of (iron-group) nuclei and electron capture by free protons and heavy nuclei:

\[ e^- + p \rightarrow n + \nu_e \]

\[ \Rightarrow \text{the number of electrons is strongly reduced} \]
\[ \Rightarrow \text{the pressure decreases} \]
\[ \Rightarrow \text{the core collapses quickly} \]

- The core collapses in two parts:
  - the inner part (\(\sim 0.6 \cdot M_{\odot}\)) collapses homologously (i.e., the density profile is kept) at a speed of \(\sim 0.5 \text{ cm/ns}\)
  - the outer part collapses at supersonic speed (\(\sim 1-3 \text{ cm/ns}\))

- The outer layers of the star do not notice the collapse of the iron core.
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – The basic picture – 3/4

- More and more electron-capture processes are taking place and the core is becoming more dense
  - further decrease in the electron density, and
  - more neutrinos produced ($\nu_e$)
- The emitted neutrinos can now leave the core zone unhindered
- At density around $10^{12}$ g·cm$^{-3}$ neutrinos become trapped and they move with the collapsing material
  - neutrino trapping
- The collapsing core finally reaches the nuclear density ($\sim 3 \times 10^{14}$ g·cm$^{-3}$)
  - nuclear force strongly repulsive
  - matter becomes incompressible
  $\implies$ back bounce – strong outward-directed shock wave is generated
- The shock wave should blow up the star as a supernova
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – The basic picture – 4/4

- The current spherical SN computer simulation models suggests that the core bounce and the shock wave formation are not sufficient to explain a supernova explosion
  - the shock wave loses energy and is stalled at the distance of 100–150 km and no explosion is generated
  - something is missing: the role of neutrinos?
- The stalled shock wave may be revised by neutrino heating
  - in some 1D models
- Also the dissociation leads to a pressure increase in the core
  - these may ignite the delayed explosion
- The prompt explosion
  - the shock wave is not stalled
- The object behind the shock wave becomes first a proto-neutron star and finally a neutron star
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – Schematically

PRE-SUPEROVA

COLLAPSE

NEUTRINO BREAKOUT

EXPLOSION

NEUTRINO TRAPPING

COOLING

CORE BOUNCE
The total (gravitational potential) energy available in the collapse to a neutron star

\[ E_{\text{grav}} \approx \frac{3}{5} \frac{GM_{\text{NS}}^2}{R_{\text{NS}}} \approx 3 \times 10^{59} \text{ MeV} \approx 5 \times 10^{46} \text{ J} \]

\[ \approx 5 \times 10^{53} \text{ erg} \]
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – Energy release – 2

- The total energy release
  \[ E_{\text{grav}} \approx 3 \times 10^{59} \text{ MeV} \approx 5 \times 10^{46} \text{ J} \approx 5 \times 10^{53} \text{ erg} \]

- The energy absorbed in Fe photo-disintegration
  \[ \approx 0.07 \cdot E_{\text{grav}} \]

- The kinetic energy of the envelope
  \[ \approx 0.03 \cdot E_{\text{grav}} \]

- The sum of "observable" energy
  \[ E_{\text{obs}} \approx 5 \times 10^{52} \text{ erg} \]

- EM radiation (incl. optically visible part) takes
  \[ E_{\gamma} \approx 0.01 \cdot E_{\text{obs}} \]

- Rest, \( \sim 99\% \), of the energy is taken away by neutrinos
  - \( \sim 1\% \) of \( \nu_e \) from an initial breakout burst (duration \( \sim 10 \text{ ms} \))
  - \( \sim 99\% \) are \( \nu \bar{\nu} \) pairs of all flavors from the cooling phase (duration \( \sim 10 \text{ s} \))

- Number of emitted neutrinos: \( \sim 10^{58} \) of all types
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – Neutrino luminosity

- Luminosity
  \[ L_\nu = \frac{1}{4\pi D^2} \frac{W_\nu}{<E_\nu>} \]

- Different flavours are created at different temperatures
  - \( <E_{\nu e}> \approx 11 \text{ MeV} \)
  - \( <E_{\bar{\nu} e} > \approx 16 \text{ MeV} \)
  - \( <E_{\nu \mu\tau} > \approx 25 \text{ MeV} \)

- Luminosities
  - \( L_{\nu e}(t) \approx L_{\bar{\nu} e}(t) \approx L_{\nu \mu\tau}(t) \)

- Neutrino pulse is quite short
  - \( D \sim 10 - 20 \text{ s} \)
10. Supernovae, SN and diffuse SN neutrinos

Core collapse supernova – Neutrino energy spectrum

- The flux can be expressed as

\[
f_\nu(E_\nu) = \frac{1}{T_\nu^3 F_2(0)} \times \frac{E_\nu^2}{e^{E_\nu/T_\nu} + 1}
\]

with \( T_\nu = 4, 5, \) and 8 MeV for \( \nu_e, \bar{\nu}_e, \) and \( \nu_x (x = \mu, \tau) \)

- Normalization

\[
W_\nu = 2 \times 10^{59} \text{ MeV}
\]

\[
< E_\nu > = T_\nu \cdot F_3(0)/F_2(0)
\]

F is a Fermi integral
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – General

▶ Several kinds of detectors are capable of detecting supernova neutrino burst
▶ Detectors dedicated to the supernova neutrino detection don’t still exist, even thought some of them are proposed
  ▶ problem is the rare explosion rate
▶ The detectors have then primary purpose other than supernova neutrino detection, for example
  ▶ proton decay studies
  ▶ solar neutrino studies
▶ Detector types for supernova neutrino detection
  ▶ Scintillation Detectors (Borexino, KamLAND, SNO+, LENA)
  ▶ Water Cherenkov Detectors (SK, UNO, Hyper-K, MEMPHYS)
  ▶ Heavy Water Cherenkov Detectors
  ▶ Long String Water/Ice Cherenkov Detectors (AMANDA, IceCube)
  ▶ High-Z Detectors (ONMIS, LAND)
  ▶ Liquid Argon (ICARUS, LANNDD, GLACIER)
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – Scintillation detectors

- Usually liquid scintillators
  - surrounded by large amounts of PMTs
  - material CₓHᵧ

- Reactions
  - ν–e scat.: \( \nu_x + e^- \rightarrow \nu_x + e^- \)
  - inv. \( \beta \)-decay: \( \bar{\nu}_e + p \rightarrow e^+ + n \) (*)
  - CC-capture of \( \bar{\nu}_e \):
    \( \bar{\nu}_e + ^{12}\text{C} \rightarrow ^{12}\text{B} + e^+ \)
  - CC-capture of \( \nu_e \):
    \( \nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N} + e^- \)
  - NC-excitation of \( ^{12}\text{C} \):
    \( \nu_x + ^{12}\text{C} \rightarrow ^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma \)

- Detectors
  - KamLAND, BOREXINO
  - SNO+, LENA

- Good energy resolution and low threshold, very little pointing

Fig. 1. Level diagram for the \(^{12}\text{C}, ^{12}\text{N}, ^{12}\text{B}\) triad.
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – Scintillation detectors – Number of events

- **Borexino**
  - 300 tons
- **KamLAND**
  - 1 kton
- **SNO+**
  - 1 kton

<table>
<thead>
<tr>
<th>Reaction channel</th>
<th>$\langle E_v \rangle$ (MeV)</th>
<th>$\langle \sigma \rangle$ (cm$^2$)</th>
<th>$N_{\text{events}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_e - e$</td>
<td>11</td>
<td>$1.02 \times 10^{-43}$</td>
<td>2.37</td>
</tr>
<tr>
<td>$\bar{v}_e - e$</td>
<td>16</td>
<td>$6.03 \times 10^{-44}$</td>
<td>0.97</td>
</tr>
<tr>
<td>$v_x - e$</td>
<td>25</td>
<td>$3.96 \times 10^{-44}$</td>
<td>0.81</td>
</tr>
<tr>
<td>$\bar{v}_x - e$</td>
<td>25</td>
<td>$3.25 \times 10^{-44}$</td>
<td>0.67</td>
</tr>
<tr>
<td>Total $v - e$</td>
<td></td>
<td></td>
<td>4.82</td>
</tr>
<tr>
<td>$\bar{v}_e + p \rightarrow e^+ + n$</td>
<td>16</td>
<td>$2.70 \times 10^{-41}$</td>
<td>79</td>
</tr>
<tr>
<td>$^{12}\text{C}(v_e, e^-)^{12}\text{N}$</td>
<td>11</td>
<td>$1.85 \times 10^{-43}$</td>
<td>0.65</td>
</tr>
<tr>
<td>$^{12}\text{C}(\bar{v}_e, e^+)^{12}\text{B}$</td>
<td>16</td>
<td>$1.87 \times 10^{-42}$</td>
<td>3.8</td>
</tr>
</tbody>
</table>

**Neutral-current excitation**

<table>
<thead>
<tr>
<th>Reaction channel</th>
<th>$\langle E_v \rangle$ (MeV)</th>
<th>$\langle \sigma \rangle$ (cm$^2$)</th>
<th>$N_{\text{events}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_e + ^{12}\text{C}$</td>
<td>11</td>
<td>$1.33 \times 10^{-43}$</td>
<td>0.4</td>
</tr>
<tr>
<td>$\bar{v}_e + ^{12}\text{C}$</td>
<td>16</td>
<td>$6.88 \times 10^{-43}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$v_x + ^{12}\text{C}$</td>
<td>25</td>
<td>$3.73 \times 10^{-42}$</td>
<td>20.6</td>
</tr>
<tr>
<td>Total $^{12}\text{C}(v, v')^{12}\text{C}^*$</td>
<td></td>
<td></td>
<td>22.5</td>
</tr>
</tbody>
</table>
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – Scintillation detectors – Number of events in LENA

- LENA would be 50 kton liquid scintillation detector

- Assuming a star of $8 \times M_{\text{sun}} \ (3 \times 10^{53} \text{ erg})$ at $D = 10 \text{ kpc}$ (standard supernova)

- In LENA detector $\sim 15000$ events
  - $\bar{\nu}_e + p \rightarrow n + e^+; \ n + p \rightarrow d + \gamma \quad \sim 7500 - 13800$
  - $\bar{\nu}_e + ^{12}\text{C} \rightarrow ^{12}\text{B} + e^+; \ ^{12}\text{B} \rightarrow ^{12}\text{C} + e^- + \bar{\nu}_e \quad \sim 150 - 610$
  - $\nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N} + e^-; \ ^{12}\text{N} \rightarrow ^{12}\text{C} + e^+ + \nu_e \quad \sim 200 - 690$
  - $\nu_x + ^{12}\text{C} \rightarrow ^{12}\text{C}^* + \nu_x; \ ^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma \quad \sim 680 - 2070$
  - $\nu_x + e^- \rightarrow \nu_x + e^- \ (\text{elastic scattering}) \quad \sim 680$
  - $\nu_x + p \rightarrow \nu_x + p \ (\text{elastic scattering}) \quad \sim 1500 - 5700$

- Accurate and detailed analysis possible
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – Water Cherenkov detectors

- Volume of clear water (H$_2$O) or heavy water (D$_2$O), viewed by PMTs
- Reactions in H$_2$O
  - inverse $\beta$-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - CC-capture of $\bar{\nu}_e$: $\bar{\nu}_e + {}^{16}\text{O} \rightarrow {}^{16}\text{N} + e^+$
  - CC-capture of $\nu_e$: $\nu_e + {}^{16,18}\text{O} \rightarrow {}^{16,18}\text{F} + e^-$
  - NC-excitation of $^{16}\text{O}$: $\nu_x + {}^{16}\text{O} \rightarrow {}^{16}\text{O}^* + \nu'_x \rightarrow {}^{16}\text{O} + \gamma$
- Reactions in D$_2$O
  - CC-breakup: $\nu_e + d \rightarrow p + p + e^-$
  - NC-breakup: $\nu_x + d \rightarrow p + n + \nu_x$
  - Elastic scattering (ES): $\nu_x + e^- \rightarrow \nu_x + e^-$
- Detectors
  - No heavy water detectors running (or proposed)
  - Super-K in Kamioka, Japan is running (50 ktons)
  - Proposed: UNO, Hyper-K, MEMPHYS
- H$_2$O: Some pointing and flavor capability
- D$_2$O: Very good flavor sensitivity, some pointing
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – Water Cherenkov detectors – MEMPHYS and Hyper-K

- MEMPHYS (~650 kton) proposed to Frejus
- Hyper-K (~650 kton per tank) proposed to Kamioka
  - 2 cylindrical tanks of 48 m × 54 m × 250 m, ~700 m underground
### 10. Supernovae, SN and diffuse SN neutrinos

**Supernova neutrino detection – Water Cherenkov detectors – Number of events**

- SK – 50 ktons
- MEMPHYS $\sim \times 10$
- Hyper-K $\sim \times 20$

Table 2: Expected number of events in SK (32 kton of fiducial volume) from a supernova at the Galactic Center.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Events</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p$</td>
<td>7349</td>
<td>95.9</td>
</tr>
<tr>
<td>$\nu_e + e$</td>
<td>107</td>
<td>1.4</td>
</tr>
<tr>
<td>$\bar{\nu}_e + e$</td>
<td>23</td>
<td>0.3</td>
</tr>
<tr>
<td>$\nu_x + e$</td>
<td>69</td>
<td>0.9</td>
</tr>
<tr>
<td>$\nu_e + O$</td>
<td>50</td>
<td>0.65</td>
</tr>
<tr>
<td>$\bar{\nu}_e + O$</td>
<td>63</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Total on e</strong></td>
<td>199</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Total on O</strong></td>
<td>113</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Total on p</strong></td>
<td>7349</td>
<td>95.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>7661</td>
<td>100</td>
</tr>
</tbody>
</table>
10. Supernovae, SN and diffuse SN neutrinos

 Supernova neutrino detection – High-Z detectors

- Large quantity of Pb, Pb(ClO$_4$)$_2$, or Fe (few to tens of kT)
- Pb, Fe
  - scintillator (neutron counter)
- Pb(ClO$_4$)$_2$
  - Cherenkov
- Advantages
  - Pb and Fe have relatively high cross section and are relatively low-cost material
  - Pb has small neutron capture cross section
- Reactions
  - NC : $\nu_x + ^{208}\text{Pb} \rightarrow ^{208}\text{Pb}^* + \nu'_x \rightarrow ^{208-\times}\text{Pb} + xn$
  - CC : $\nu_e + ^{208}\text{Pb} \rightarrow ^{208}\text{Bi}^* + e^- \rightarrow ^{208-\times}\text{Bi} + xn$
- Detectors (these would be dedicated SN neutrino detectors)
  - proposed: OMNIS, LAND
- Good flavor capability, no pointing
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – High-Z detectors – OMNIS

- Observatory for Multiflavor Neutrino Interactions from Supernova
- Pb as metal or as perchlorate (with or without Fe)
- Modular structure
- Dedicated supernova neutrino detector

Single- and double-neutron events, per kT of material, no oscillation

<table>
<thead>
<tr>
<th>Material, event type</th>
<th>CC-$\nu_e$</th>
<th>CC-$\bar{\nu}_e$</th>
<th>NC-$\nu_e$</th>
<th>NC-$\bar{\nu}_e$</th>
<th>NC-$\nu_x$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb, single-n</td>
<td>59</td>
<td>0</td>
<td>8</td>
<td>37</td>
<td>677</td>
<td>781</td>
</tr>
<tr>
<td>Pb, double-n</td>
<td>26</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>20</td>
<td>47</td>
</tr>
<tr>
<td>Fe, single-n</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>146</td>
<td>163</td>
</tr>
</tbody>
</table>

Number of events versus supernova distance (16 0.5-kT Pb modules)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 kpc</td>
<td>$0.5 \times 10^6$</td>
</tr>
<tr>
<td>1.0 kpc</td>
<td>112000</td>
</tr>
<tr>
<td>2.0 kpc</td>
<td>27500</td>
</tr>
<tr>
<td>4.0 kpc</td>
<td>6860</td>
</tr>
<tr>
<td>8.0 kpc</td>
<td>1740</td>
</tr>
<tr>
<td>16 kpc</td>
<td>440</td>
</tr>
</tbody>
</table>
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – TPC detector network

- Different approach to large-volume detectors
- A network of spherical TPC detectors for supernova neutrino observation
  - several "small" detectors in (European) underground laboratories
- arXiv:hep-ex/0503029: A network of neutral current spherical TPC’s for dedicated supernova detector
- High-pressure (10 bar Xe, 30–60 bar Ar) diameter 4–6 metres, Micromegas for readout
- Neutrino coherent scattering
  - large cross section: \( \sigma(E_\nu) \approx 10^{-38} \text{ cm}^2 \) at \( E_\nu = 20 \text{ MeV} \) for xenon
  - challenge to measure low-energy recoil (for Xe \( \sim 7 \text{ keV} \), in average)
- Number of events: \( N_{\nu_e} \sim 10, N_{\bar{\nu}_e} \sim 15, N_{\nu_x} \sim 70 \) (total \( \sim 95 \))
- A smaller prototype running in Frejus
## 10. Supernovae, SN and diffuse SN neutrinos

### Supernova neutrino detection – Summary of SNν detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass [kT]</th>
<th>Location</th>
<th>Events at 8 kpc</th>
<th>Status</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K</td>
<td>Water-Čerenkov</td>
<td>32</td>
<td>Japan</td>
<td>7000</td>
<td>Running again for SN by Nov 02</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>SNO</td>
<td>Light water</td>
<td>1.0</td>
<td>Canada</td>
<td>450</td>
<td>running</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td></td>
<td>Heavy water</td>
<td>1.4</td>
<td>Italy</td>
<td>350</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>LVD</td>
<td>Scintillator</td>
<td>1</td>
<td>Italy</td>
<td>200</td>
<td>running</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>KamLAND</td>
<td>Scintillator</td>
<td>1</td>
<td>Japan</td>
<td>300</td>
<td>running</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>BOREXINO</td>
<td>Scintillator</td>
<td>0.3</td>
<td>Italy</td>
<td>100</td>
<td>ready 2003</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>Baksan</td>
<td>Scintillator</td>
<td>0.33</td>
<td>Russia</td>
<td>50</td>
<td>running</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>Mini-BooNe</td>
<td>Scintillator</td>
<td>0.7</td>
<td>USA</td>
<td>200</td>
<td>running</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>AMANDA</td>
<td>Long String (water)</td>
<td>0.4/PMT</td>
<td>South Pole</td>
<td>N/A</td>
<td>running</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>ICARUS</td>
<td>Liquid Argon</td>
<td>2.4</td>
<td>Italy</td>
<td>200</td>
<td>running (?)</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>OMNISS</td>
<td>Pb</td>
<td>2 – 3</td>
<td>USA (?)</td>
<td>&gt;1000</td>
<td>proposed</td>
<td>all</td>
</tr>
<tr>
<td>LANNDD</td>
<td>Liquid Argon</td>
<td>70</td>
<td>USA (?)</td>
<td>6000</td>
<td>proposed</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>UNO</td>
<td>Water-Čerenkov</td>
<td>600</td>
<td>USA(?)</td>
<td>$&gt;10^5$</td>
<td>proposed</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>Water-Čerenkov</td>
<td>1000</td>
<td>Japan</td>
<td>$&gt;10^5$</td>
<td>proposed</td>
<td>$\bar{\nu}_e$</td>
</tr>
</tbody>
</table>

APP 2013 – UOulu – 10.28 –
10. Supernovae, SN and diffuse SN neutrinos

Supernova neutrino detection – What can be learned?

- Supernova Core Collapse Mechanism
  - driven by neutrinos?

- Supernova Core Collapse Physics
  - supernova evolution in time
  - convection, magnetic field, hydrodynamics instabilities
  - proto neutron-star EoS
  - black hole formation mechanism

- Neutrino Physics
  - neutrino absolute mass (with some accuracy)
  - neutrino oscillations

- Signatures (by measuring flavour, energy and time structure of the neutrino burst)
  - pulse risetime and shape
  - breakout, luminosity cutoff (→ black hole formation)
  - pulsation
  - cooling
10. Supernovae, SN and diffuse SN neutrinos

SN1987A
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – General

- SN1987A was discovered on Feb. 23, 1987 at a distance of \((50.1 \pm 3.1)\) kpc (or 150000 light years) in the Large Magellanic Cloud.
- It was Type-II (core collapse) SN as hydrogen lines were observed in the spectrum.
- It was the brightest SN since the Kepler SN in 1604:
  - the first time SN was observed at all wavelengths.
  - the first time \(\nu\)’s could be detector from SN.
- The progenitor Sanduleak -69\(^\circ\) 202 was a blue supergiant with a mass of \(\sim20\cdot M_{\odot}\):
  - until then it was assumed that only red giants could be exploded.
  - it was showed (in 1991) by simulations that also blue supergiant star can explode as SN.
  - it lived only \(\sim11\) million years.
- The total energy release (light, not neutrinos) of the explosion amounted to \((1.4 \pm 0.6) \times 10^{51}\) erg,
  - the explosion seemed to take place asymmetrically.
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – Amount of iron produced

- The double-magic nucleus $^{56}\text{Ni}$ was mostly produced in the SN explosion, followed by the decay chain

$$^{56}\text{Ni} \ (EC/\beta^+, \ T_{1/2} = 6.1 \text{ d}) \rightarrow ^{56}\text{Co} \ (EC/\beta^+, \ T_{1/2} = 77.1 \text{ d}) \rightarrow$$

$$\rightarrow ^{56}\text{Fe}^\ast \rightarrow ^{56}\text{Fe}$$

- Characteristic $\gamma$-lines of the decay of $^{56}\text{Co} \ (E_\gamma = 847 \text{ keV} \text{ and } E_\gamma = 1238 \text{ keV})$ were detected by the SMM-satellite (at August 1987)

$$l'_\gamma s(^{56}\text{Co}) \implies M(^{56}\text{Fe}) \approx 0.075 \cdot M_{\text{SUN}}$$

- this equals to $M(^{56}\text{Fe}) \approx 25 \times 10^3$ times the mass of the Earth!

- $M(^{57}\text{Co}) \approx 0.009 \cdot M_{\text{SUN}}$

- $M(^{44}\text{Ti}) \approx 10^{-4} \cdot M_{\text{SUN}}$

- $M(^{22}\text{Na}) \approx 2 \times 10^{-6} \cdot M_{\text{SUN}}$
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – The light curve ($^{56}\text{Co}$)

$^{56}\text{Co}$ (EC/$\beta^+$, $T_{1/2}=77.1$ days) covered the light curve for the first $\sim 3$ years.
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – The light curve (full)

- $^{57}\text{Co}$ (EC, $T_{1/2} = 272$ days)
- $^{44}\text{Ti}$ (EC, $T_{1/2} = 66$ years)
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – What’s there now?

- It has been observed that the progenitor star Sanduleak -69° 202 really exploded.
- The mass of $\sim 20 \cdot M_{\text{SUN}}$ of the progenitor should have produced a neutron star.
- The Hubble Space Telescope has studied SN1987A regularly since August 1990.
- The (direct) search for a neutron star (i.e., pulsar, or anything else) at the known position of the Sanduleak has still been unsuccessful.
  - behind a dense dust cloud?
  - neutron star has accumulated more mass and collapsed to a black hole?
- The evidence for a pulsar in SN1987A by powering the light curve would be very interesting.
  - pulsar and SN has not yet been observed directly from the same event.
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – Neutrinos

- A total of four detectors (experiments) claimed to have seen neutrinos from SN1987A
  - two water Cerenkov detectors: Kamiokande II and IMB
  - two liquid scintillation detectors: Baksan and Mt Blanc

- Within a certain timing uncertainty, three of the experiments agree on the arrival time of the neutrino pulse, but not Mt Blanc experiment (∼4.5 h earlier)
  - it is generally assumed that Mt Blanc events were statistical fluctuations and are not related on SN1987A events
  - the absolute uncertainties of the event times of the three experiments were: Kamiokande II ±1 min, IMB ±50 ms, and Baksan -54 s, +2 s

- Neutrino signal arrived on the Earth 2–3 hours prior to the optical signal
  - SNEWS – SuperNova Early Warning System (Super-K, LVD, IceCube, Borexino)
10. Supernovae, SN and diffuse SN neutrinos

SN1987A – Neutrinos – Kamioka, IMB, and Baksan data

[Graph showing the energy vs. time for Kamiokande II, IMB, and Baksan data.]

[J.H. Bahcall: Neutrino Astrophysics, Table 15.4]
The basic picture of core-collapse SN is supported by the neutrino observation from SN1987A.

Only $\bar{\nu}_e$-induced events were detected (the first KII event perhaps $\nu_e$).

Average temperature $\langle T_\nu \rangle = (4.0 \pm 1.0)$ MeV and energy $\langle E_\nu \rangle = (12.5 \pm 3.0)$ MeV were obtained (by applying Fermi-Dirac distribution).

The total number of neutrinos (of all flavors) emitted by the SN1987A (from the distance of $1.5 \times 10^{18}$ km) was estimated as $N_{\text{tot}} \approx 8 \times 10^{57}$.

It corresponds to $E_{\text{tot}} = N_{\text{tot}} \cdot \langle E_\nu \rangle \approx (2 \pm 1) \times 10^{53}$ erg, being in good agreement with expectations.

The SN models investigated were in a strong favour of delayed explosion mechanism, proposing the radius of the resulting neutron star of approximately 10 km.

- neutron star not yet observed, however.

The duration of the neutrino pulse was between 10 and 20 seconds.
10. Supernovae, SN and diffuse SN neutrinos

Supernova rate & two candidates for the next

- The last supernova in our galaxy was observed in 1604 (Kepler)
- The supernova rate (in our galaxy) is expected to be 1–6 per 100 years
  - many SN could not be observed optically behind the interstellar dust
  - Baksan Scintillator Telescope started on June 30, 1980 (still running)

- Two candidate stars in our galaxy expected to explode "soon" as SN
  - Rho Cassiopeiae
    - distance \(\sim 10000\) light years (\(\sim 3\) kpc), mass \(\sim 40\) M\(\text{SUN}\)
    - slowly pulsating, post-main sequence yellow supergiant
  - Eta Carinae
    - distance \(\sim 7500\) light years (\(\sim 2.3\) kpc), mass \(\sim 120\) M\(\text{SUN}\)
    - the closest so called hypernova candidate
      (\(\rightarrow\) direct collapse to black hole)

- Detecting SN neutrinos from Andromeda (M31) or Triangulum (M33) at the distance of \(\sim 750\) kpc requires megaton-class detectors
  - detectors like Hyper-K or MEMPHYS could see some events
10. Supernovae, SN and diffuse SN neutrinos

Diffuse supernova neutrinos – General

- All former core-collapse supernova explosions in the universe (one in every 10 seconds) should have produced a neutrino background, called diffuse supernova neutrino background (DSNB)
  - known also as supernova relic neutrinos
- Diffuse supernova neutrinos are believed to provide a new source of information, among others, on
  - the core-collapse supernova explosion mechanism
  - the supernova rate
  - the star formation rate
- The detection of diffuse supernova neutrinos is a challenge
  - continuous, but low flux of \( \sim 10^2 \, \nu \, \text{cm}^{-2} \cdot \text{s}^{-1} \)
  - due to the expansion of the universe, the energy of these neutrinos has decreased (red-shifted)
  - most probable detection channel: \( \bar{\nu}_e + p \rightarrow e^+ + n \) due to highest cross section (\( \sigma = 6.8 \times 10^{-6} \, \text{pb at 10 MeV} \))
10. Supernovae, SN and diffuse SN neutrinos

Diffuse supernova neutrinos – General

- The detection is also challenging due to the background from nuclear reactor neutrinos (low-energy part) and from atmospheric neutrinos (high-energy part).

- Diffuse supernova neutrino background has continuous but small flux
  - SN $\nu$-burst is observed 'easily' today or in the future and it provides a lot of information.

- If observed, the DSNB is (also) an excellent tool to study supernovae
  - we do not need to wait for tens of years for a SN $\nu$-burst
  - DSNB contains the average SN $\nu$-spectrum to test models, which is probably more important than observing a single SN $\nu$-burst (for SN models).
10. Supernovae, SN and diffuse SN neutrinos

Diffuse supernova neutrinos – Neutrino energy spectrum

- To determine the diffuse supernova neutrino flux three ingredients should be known
  - the cosmic core collapse supernova rate in the causal horizon
    (approximately 10 per second; known quite precisely)
  - the average supernova neutrino emission spectrum, combined with the neutrino oscillation within the supernovae (and in the Earth)
  - geometrical effects of the universe

- To measure it, detector properties need to be included
  - number of target atoms $\times$ the detection cross section

\[
\Phi(E_\nu) = \int_0^{z_{\text{max}}} R_{SN}(z) \times (1 + z) \cdot F_\nu(E_\nu(1 + z)) \times N_T \cdot \sigma(E_\nu) \times \\
\times \frac{c}{H_0} \cdot (1 + z)^{-1} \left[ \Omega_\Lambda + \Omega_m (1 + z)^3 \right]^{-1/2} \, dz
\]

$H_0 = 70 \, \text{km} \cdot \text{s}^{-1}$, $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$
10. Supernovae, SN and diffuse SN neutrinos

Diffuse supernova neutrinos – Neutrino energy spectrum

- Calculated fluxes at the Earth with four different models (detector properties not included)
- Integrated flux \( \approx 100 \, \nu \, \text{cm}^{-2} \cdot \text{s}^{-1} \)
10. Supernovae, SN and diffuse SN neutrinos

Diffuse supernova neutrinos – Experiments

- Diffuse supernova neutrinos have not yet been observed experimentally
- The best experimental limit on the diffuse supernova neutrino flux comes from the Super–Kamiokande experiment (water Cherenkov)
  - improved analysis and new data for 2853 live days (7.8 years)
- The upper limit (from SK) for the flux is
  \[ 2.8 < \Phi(\bar{\nu}_e) < 3.1 \text{ cm}^{-2} \cdot \text{s}^{-1}, \quad E(\bar{\nu}_e) > 17.3 \text{ MeV} \]

- Liquid scintillation detector provides better background rejection and allows lower energy threshold than water Cherenkov
  - KamLAND, BOREXINO and SNO+ are not massive to reach significant statistics
  - A large-volume (liquid scintillation) detector is required: LENA (50 kton)
LENA is planned 50 kton liquid scintillation detector $\sim 1400$ metres underground

- It can provide almost background-free energy window of 10–25 MeV for detecting diffuse supernova neutrinos

- LENA can detect 5–10 diffuse supernova neutrino events per year in Pyhäsalmi

- Within ten years of exposure
  - significant constraints on core-collapse supernova models
  - significant constraints on supernova rate in the near universe (up to the redshift $z = 2$)

- If no signal is detected (in ten years)
  - the new limits were significantly lower than all models predict
  - improving the limit given by the SK by a factor of $\sim 10$
DSNB-$\nu$ can be detected in the energy window between $\sim$10 MeV and $\sim$25 MeV

- the lower limit comes from nuclear reactor neutrinos
- the upper limit from cosmic-ray induces neutrinos