

Detection of Supernova Neutrinos

Neutrino signal: $\langle E_\nu \rangle \sim 10 \text{ MeV}$, $\Phi_\nu \sim 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$ "Standard SN" (10 kpc)

<u>Phases</u>	<u>Energy</u>	<u>Luminosity</u>	<u>Duration</u>
• Neutronization burst from $p + e^- \rightarrow n + \nu_e$	$\langle E_{\nu_e} \rangle \sim 15 \text{ MeV}$	$4 \times 10^{53} \text{ erg/s}$	$\mathcal{O}(10 \text{ ms})$
• Accretion phase still mostly ν_e	$\langle E \rangle \sim 10 - 20 \text{ MeV}$	$3 \times 10^{52} \text{ erg/s}$	$\mathcal{O}(100 \text{ ms})$
• Cooling phase $\bar{\nu}\nu$ pair production → all flavors	$\langle E \rangle \sim 10 \text{ MeV}$	10^{52} erg/s	$\mathcal{O}(10 \text{ s})$

In general: $\langle E_{\nu_\mu} \rangle > \langle E_{\nu_\tau} \rangle > \langle E_{\nu_e} \rangle$

→ due to different depths of last scattering surface
(less pronounced in recent models)

Oscillations: • strong matter effects during accretion
• collective oscillations during cooling

Observation goals:

Astrophysics: • confirm phases of SN explosion model
• spectral energies & fluxes in time-dependence
→ separate ν flavors
• observe black hole formation → sudden stop of ν emission

Neutrino physics:

• Mass hierarchy by matter effects
— in the Sun: resonant conversion of ν_e neutronization peak → $N_{\mu\tau}$
(inversion of $\nu_e \leftrightarrow \nu_{\mu\tau}$ energy ordering)
rise-time of SN signal ($\bar{\nu}_e$ rise faster than $\bar{\nu}_{\mu\tau}$)
→ spectral conversion inverts this trend)
— in the Earth: regeneration of $\nu_e / \bar{\nu}_e$ depending on hierarchy
→ spectral wiggles

- observation of collective oscillations (e.g. by spectral swap)
- neutrino mass from TOF measurements (blurring of fast time structures)
 - typical accuracies: $m_\nu \lesssim 1\text{eV}$
- search for non-standard effects (sterile ν 's, ν magnetic moment)

Detector types

- Water-Cherenkov detectors (WCDs)
- Liquid-scintillator detectors (LSDs)
- LAr-TPCs
- Composite detectors: Lead + ^3He counters

Interaction types

Spectral energy range: $0 \sim 50\text{MeV}$

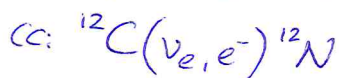
→ Inverse beta decay (WCDs, LSDs)

$$\bar{\nu}_e + p \rightarrow n + e^+, Q = 1.8\text{MeV}$$

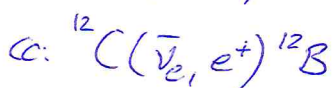
- excellent energy resolution: $E_\nu = E_{e^+} - Q$
 - large cross-section → majority of events
 - good signal ID in LSDs
 - some pointing capability in LSDs
- ⇒ detailed information on $\bar{\nu}_e$ signal

→ Reactions on nuclei

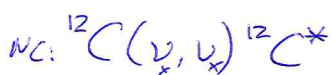
□ Liquid Scintillator: $^{12}\text{C}, (^{13}\text{C})$



• Q-values $\sim 15\text{MeV}$



• final state lepton of CC → energy information
• re-decay of $^{12}\text{N}, ^{12}\text{B}$ for event tagging



• γ -emission from $^{12}\text{C}^* \rightarrow ^{12}\text{C}, \sim 15\text{MeV}$
• integral flux information of all flavors

→ spectral information on ν_e , flux information for ν_x

→ distinguishable from other reaction channels

□ Water Cherenkov: ^{16}O

• as above: CC $\nu_e, \bar{\nu}_e$, NC ν_x

• low threshold (5MeV), but cannot be separated from other channels

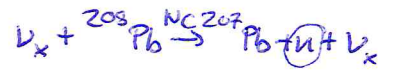
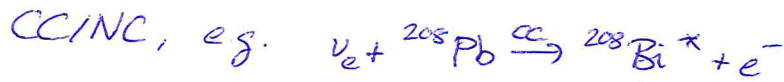
□ Liquid Argon: ^{40}Ar

• CC $\nu_e \rightarrow Q$ -value: 6 MeV

\rightarrow large cross-section + energy information

• CC $\bar{\nu}_e \rightarrow Q$: 11 MeV

□ Lead detectors: ^{208}Pb



\rightarrow integral measurement of neutrino signal by neutron tagging

\rightarrow Elastic scattering

on electrons:



• no intrinsic threshold

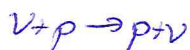
• energy information from recoil electrons

• directionality

• dominated by ν_e because of larger cross-section

\rightarrow accessible in LS (event separation), H_2O , LAr

on protons:



• no intrinsic threshold

• very-low energy transfer: $E_\nu \ll m_p$

• cross-section identical for all flavors \rightarrow mainly $\bar{\nu}_\mu, \bar{\nu}_\tau$

\rightarrow only visible in LS (quenching!)

SN 1987A

• progenitor star: blue giant ($20 M_\odot$) in Great Magellanic Cloud, $d \approx 50 \text{ kpc}$

• neutrinos observed in three (+1) experiments:

- mostly $\bar{\nu}_e$ because of high IBD cross-section

- Water Cherenkov detectors:

Kamiokande: 11 ν in 2100 t

IMB: 8 ν in 5000 t

- Liquid Scintillator detectors:

Baksan: 5 ν in 200 t

[Modane: 5 ν] too early (several hours)

Supernova physics

• confirmation of core-collapse theory

• total energy released based on neutrino signal: $(2 \pm 1) \cdot 10^{53} \text{ erg}$

• Signal duration: $\sim 10 \text{ sec}$

Neutrino properties

- upper limits on neutrino mass, electric charge, magnetic moment
(TOF) (B-fixed)

- limit for neutrino velocity compared to the speed of light
from time difference Δt between neutrino and photon arrival time:

$$t_\gamma = \frac{D}{c} = \frac{50 \text{ kpc}}{3 \cdot 10^5 \text{ km/s}} = 5 \cdot 10^{12} \text{ s}$$

$$\Delta t_{\text{at earth}} = t_\gamma - t_\nu = 3\mu \approx 10^9 \text{ s}$$

photons cannot be emitted before core collapse, neutrinos in the collapse
→ it is conservative to assume simultaneous emission

$$\rightarrow \frac{\Delta t}{t_\gamma} < 2 \cdot 10^{-9}$$

Supernova signal in current detectors

SN rate within the Milky Way: 1-3 per century

for "standard" SN: $8 M_\odot$ @ 10 kpc

- Super-Kamiokande: $\sim 10^4 \bar{\nu}_e$ mostly IBDs $\rightarrow \bar{\nu}_e$ flux + spectrum

- Borexino, KamLAND: $\sim 10^2 \bar{\nu}_e$ IBD
LVD $\sim 10 \nu_e$ $^{12}\text{C}(\nu_e, e^-)^{12}\text{N}$
 $\sim 10^2 \nu_x$ $\nu + p \rightarrow p + \nu$

- IceCube

$\sim 10^6 \nu$ in spheres of $\sim 5\text{m}$ around each PMT
→ no individual signals, but increase in noise level
→ very precise flux measurement (as function of energy)

- HALO

$\sim 20-200 \nu$ in 70t of lead