Detection of Supernova Neutrinos

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

Phases

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

In general: $\langle E_{\nu_{\tau,\mu}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$

→ 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 → NH
    (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: $m_\nu \lesssim 1\,\mathrm{eV}$
- 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 + ^{3}He counters

Interaction types

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

→ Inverse beta decay (WCDs, LSDs)

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

- 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}C, (^{13}C)

CC: $^{12}C(\nu_e, e^-)^{12}N$

CC: $^{12}C(\bar{\nu}_e, e^+)^{12}B$

- Q-values $\sim 15\,\mathrm{MeV}$
- final state lepton of CC → energy information
- re-decay of ^{12}N, ^{12}B for event tagging

NC: $^{12}C(\nu_x, \nu_x)^{12}C^*$

- γ-emission from $^{12}C^* \rightarrow {}^{12}C$, $\sim 15\,\mathrm{MeV}$
- 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 (5 MeV), but cannot be separated from other channels

□ Liquid Argon: ^{40}Ar

- CC ν_e → Q-value: 6MeV
  - → large cross-section + energy information
- CC $\bar{\nu}_e$ → Q: 11MeV

□ Lead detectors: ^{208}Pb

CC/NC, e.g. $\nu_e + {}^{208}Pb \xrightarrow{CC} {}^{208}Bi^* + e^-$ $\nu_x + {}^{208}Pb \xrightarrow{NC} {}^{207}Pb + \textcircled{n} + \nu_x$

$\hookrightarrow {}^{207}Bi + \gamma + \textcircled{n}$

→ integral measurement of neutrino signal by neutron tagging

→ Elastic scattering

on electrons:
$\nu + e \rightarrow e + \nu$

- no intrinsic threshold
- energy information from recoil electrons
- directionality
- dominated by ν_e because of larger cross-section

→ accessible in LS (event separation), H_2O, LAr

on protons:
$\nu + p \rightarrow p + \nu$

- no intrinsic threshold
- very-low energy transfer: $E_\nu \ll m_p$
- cross-section identical for all flavors → mainly $\overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_\tau$

→ only visible in LS (quenching!)

SN 1987A

- progenitor star: blue giant ($20M_\odot$) in Great Magellanic Cloud, $d = 50kpc$
- neutrinos observed in three (+1) experiments:

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

- Water Cherenkov detectors: Kamiokande : 11 ν in 2140t
  IMB : 8 ν in 5000t
- Liquid Scintillator detectors: Baksan : 5 ν in 200t
  [Modane : 5 ν] too early (several hours)

Supernova physics

- confirmation of core-collapse theory
- total energy released based on neutrino signal: $(2 \pm 1) \cdot 10^{53}$ erg
- Signal duration: ~10sec

Neutrino properties

- upper limits on neutrino mass, electric charge, magnetic moment
  (TOF) (B-field)
- limit for neutrino velocity compared to the speed of light from time difference Δt between neutrino and photon arrival time:

$$t_\gamma = D/c = \frac{50\,\mathrm{kpc}}{3\cdot 10^8\,\mathrm{m/s}} = 5\cdot 10^{12}\,\mathrm{s}$$

$$\Delta t_{\text{at earth}} = t_\gamma - t_\nu = 3\,\mathrm{h} \approx 10^4\,\mathrm{s}$$

photons cannot be emitted before core collapse, neutrinos in the collapse
→ it is conservative to assume simultaeneous 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: $8M_\odot$ @ 10kpc

- Super-Kamiokande:	$\sim 10^4\,\bar{\nu}_e$	mostly IBDs → $\bar{\nu}_e$ flux + spectrum
- Borexino, KamLAND: LVD	$\sim 10^2\,\bar{\nu}_e$	IBD
	$\sim 10\,\nu_e$	$^{12}C(\nu_e, e^-)^{12}N$
	$\sim 10^2\,\nu_x$	$\nu + p \rightarrow p + \nu$
- IceCube	$\sim 10^6\,\nu$	in spheres of ~5m around each PMT → no individual signals, but increase in noise level → very precise flux measurement (as function of energy)
- HALO	$\sim 20\text{-}200\,\nu$	in 70t of lead