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lecture cource on

Astroparticle physics

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4 Supernovae and supernova neutrinos

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- 4.2 Supernova neutrinos
- 4.3 Supernova neutrino detection
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4.1 Supernova process

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 ($\sim 1.4 \cdot M_{sun}$)
  - "standard candle"
- Explosion caused by the core collapse of a massive star ($\sim 8 \cdot M_{sun}$)
  - 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

4.1 Supernova process

Core collapse – type II supernova – 1

- A heavy star ($\sim 8 \cdot M_{sun}$) evolves through all the stages of stellar fusion
  - ending up with an iron core by silicon burning at $T \sim 4 \times 10^9$ K
- Eventually, the core mass exceeds the Chandrasekhar limit
  - the core becomes unstable
- The core is driven into collapse by two triggering processes
  - the photo-disintegration of iron nuclei by thermal photons ($E_\gamma \approx 2.5$ MeV) speeds up the collapse by absorbing energy
  - the conversion of protons to neutrons by electrons via inverse beta decay: $e^- + p \longrightarrow n + \nu_e$
    ☞ neutronisation
  - at higher temperature: $e^- + {}^{56}\mathrm{Fe} \longrightarrow {}^{56}\mathrm{Mn} + \nu_e$
- At high densities, the form of pressure opposing the core collapse is called electron degeneracy pressure
  - relativistic electrons

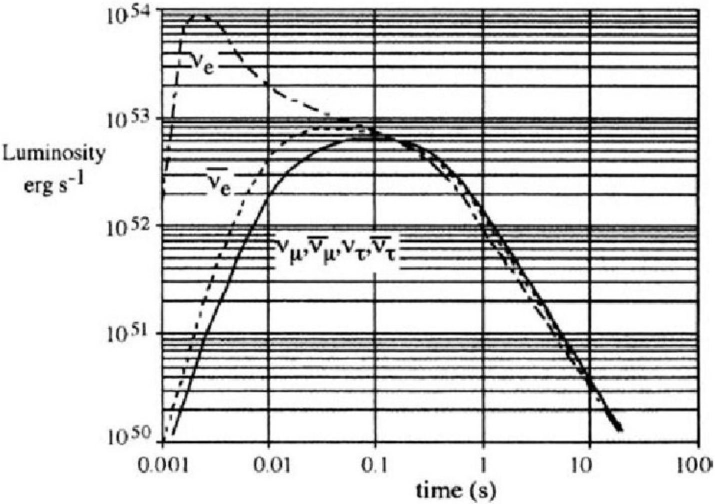
4.1 Supernova process

Core collapse – type II supernova – 2

- As more and more electrons are converted to neutrinos, the deneneracy pressure of electrons will steadily decrease and finally the collapse take place
- The collapse is halted in a fraction of second as the core reaches the nuclear density
  - further compression is resisted by nuclear force
- As soon as the core density exceeds the nuclear density by a factor of 2–3, the core material will "bounce"
  - outgoing supersonic shock wave
- At the initial core collapse the neutronisation produces an emission of neutrinos (ν_e)
  - the outgoing shock wave is accompanied by neutrino burst of 10^{56}–10^{57} ν_e's during a few milliseconds
  - neutrinos become trapped at nuclear densities
- In the cooling phase all neutrino flavours are emitted by approximately the same amount

4.1 Supernova process

Core collapse – type II supernova – neutrino luminosity



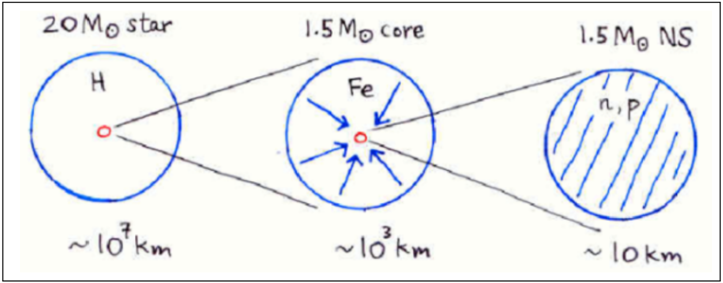
4.1 Supernova process

Core collapse – type II supernova – role of neutrinos

- It has been discussed that the shock wave would not be strong enough to "explode" the supernova
  - the shock front would attenuate when passing the different layers of the star
- It has been proposed that the neutrino pulse could "restart" the shock wave

4.1 Supernova process

Core collapse – Energy release – 1



The total gravitational energy released in the collapse to a neutron star

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

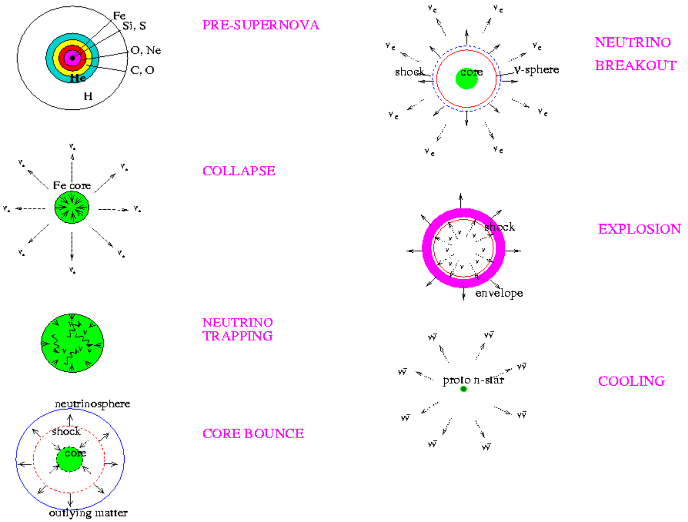
4.1 Supernova process

Core collapse – Energy release – 2

- Total energy release $E_{grav} \approx 3 \times 10^{59}$ MeV $\approx 3 \times 10^{46}$ J
- Kinetic energy of explosion $\approx 10^{-2} \cdot E_{grav}$
- EM radiation (incl. optically visible part) $\approx 10^{-4} \cdot \Delta E_B$
- Rest, ∼99%, of the energy is taken away by neutrinos
  - ∼1% of ν_e from an initial breakout burst
  - ∼99% are $\nu\bar{\nu}$ **pairs of all flavors** from the cooling phase
- Number of emitted neutrinos: $\sim 10^{58}$ of all types
- Number of expected supernova explosions in our Galaxy: ∼(3±1) per century
  - the two last (observed) supernovae: 1604 and ∼1680

4.1 Supernova process

Core collapse – schematic picture



4.2 Supernova neutrinos

Neutrino emission

The Energy of emitted neutrinos can be described by Boltzmann distribution

Different flavours are created at different temperatures

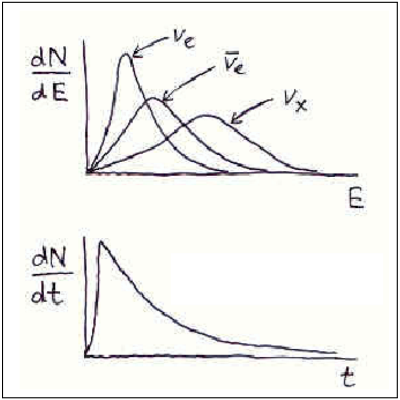
- $\langle E_{\nu_e} \rangle \approx 11$ MeV
- $\langle E_{\bar{\nu}_e} \rangle \approx 16$ MeV
- $\langle E_{\nu_{\mu\tau}} \rangle \approx 25$ MeV

Neutrinopulse is quite short

- duration $\sim 10 - 20$ s

Luminosities

- $L_{\nu_e}(t) \approx L_{\bar{\nu}_e}(t) \approx L_{\nu_{\mu\tau}}(t)$



4.3 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.
- Thus, the detectors have primary purpose other than supernova neutrino detection, for example, proton decay or 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 Cherenkov Detectors (AMANDA)
  - High-Z Detectors (ONMIS, LAND)
  - Liquid Argon (ICARUS, LANNDD, GLACIER)

4.3 Supernova neutrino detection

Scintillation detectors

- Usually liquid scintillators
  - material $C_x H_y$
  - surrounded by large amounts of PMTs
- Reactions
  - ν–e scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$
  - inverse β-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - CC-capture of $\bar{\nu}_e$: $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$
  - CC-capture of ν_e: $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$
  - NC-excitation of ${}^{12}C$:
    $\nu_x + {}^{12}C \rightarrow {}^{12}C^* + \nu_x'$
- Detectors
  - KamLAND in Kamioka
  - BOREXINO in Gran Sasso
  - SNO+, LENA
- Very little pointing and weak flavor capability

L. Cadonati et al. / Astroparticle Physics 16 (2002) 361–372

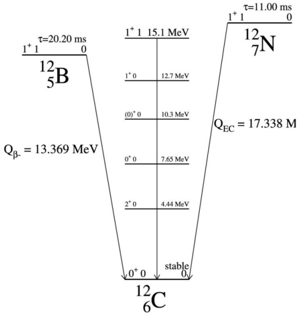


Fig. 1. Level diagram for the ${}^{12}C$, ${}^{12}N$, ${}^{12}B$ triad.

4.3 Supernova neutrino detection

Scintillation detectors: Borexino – 300 tons of pseudocumene (PC, C_9H_{12})

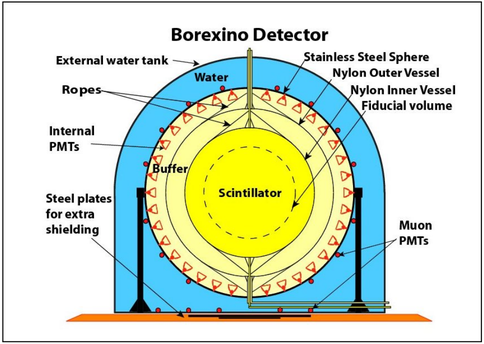


Table 3
Supernova neutrino events in Borexino from a supernova at 10 kpc, with $\varepsilon_B = 3 \times 10^{53}$ ergs binding energy release

Reaction channel	$\langle E_\nu \rangle$ (MeV)	$\langle \sigma \rangle$ (cm^2)	N_{events}
ν_e–e	11	1.02×10^{-43}	2.37
$\bar{\nu}_e$–e	16	6.03×10^{-44}	0.97
ν_x–e	25	3.96×10^{-44}	0.81
$\bar{\nu}_x$–e	25	3.25×10^{-44}	0.67
Total ν–e			4.82
$\bar{\nu}_e + p \rightarrow e^+ + n$	16	2.70×10^{-41}	79
$^{12}C(\nu_e, e^-)^{12}N$	11	1.85×10^{-43}	0.65
$^{12}C(\bar{\nu}_e, e^+)^{12}B$	16	1.87×10^{-42}	3.8
Neutral-current excitation			
$\nu_e + {}^{12}C$	11	1.33×10^{-43}	0.4
$\bar{\nu}_e + {}^{12}C$	16	6.88×10^{-43}	1.5
$\nu_x + {}^{12}C$	25	3.73×10^{-42}	20.6
Total $^{12}C(\nu, \nu')^{12}C^*$			22.5

4.3 Supernova neutrino detection

Scintillation detectors: LENA – 50 ktons of PXE (C_9H_{10})

- Assuming a star of $8\times M_{sun}$ (3×10^{53} erg) at $D = 10$ kpc (standard supernova)
- In LENA detector ∼15000 events
  - $\bar{\nu}_e + p \to n + e^+$; $n + p \to d + \gamma$ ∼7500 – 13800
  - $\bar{\nu}_e + {}^{12}C \to {}^{12}B + e^+$; ${}^{12}B \to {}^{12}C + e^- + \bar{\nu}_e$ ∼150 – 610
  - $\nu_e + {}^{12}C \to {}^{12}N + e^-$; ${}^{12}N \to {}^{12}C + e^+ + \nu_e$ ∼200 – 690
  - $\nu_x + {}^{12}C \to {}^{12}C^* + \nu_x$; ${}^{12}C^* \to {}^{12}C + \gamma$ ∼680 – 2070
  - $\nu_x + e^- \to \nu_x + e^-$ (elastic scattering) ∼680
  - $\nu_x + p \to \nu_x + p$ (elastic scattering) ∼1500 – 5700
- Accurate and detailed analysis possible

4.3 Supernova neutrino detection

Water Cherenkov detectors: General – heavy and normal water

- Volume of clear water (H_2O) or heavy water (D_2O), vieved by PMTs
- Reactions in H_2O
  - inverse β-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - CC-capture of $\bar{\nu}_e$: $\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$
  - CC-capture of ν_e: $\nu_e + {}^{16,18}O \rightarrow {}^{16,18}F + e^-$
  - NC-excitation of ^{16}O: $\nu_x + {}^{16}O \rightarrow {}^{16}O^* + \nu_x'$
- Reactions in D_2O
  - 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
  - Proposed: UNO, Hyper-K, MEMPHYS
- H_2O : Some pointing and flavor capability
  D_2O : Very good flavor sensitivity, some pointing

4.3 Supernova neutrino detection

High-Z detectors: General

- 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) has relatively high cross section, and it is low-cost material
  - Pb has small neutron capture cross section
- Reactions
  - NC : $\nu_x + {}^{208}Pb \longrightarrow {}^{208}Pb^* + \nu'_x \longrightarrow {}^{208-x}Pb + xn$
  - CC : $\nu_e + {}^{208}Pb \longrightarrow {}^{208}Bi^* + e^- \longrightarrow {}^{208-x}Bi + xn$
- Detectors
  - proposed: OMNIS, LAND
    (these would be dedicated SN neutrino detectors)
- Good flavor capability, no pointing

4.3 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

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

Material, event type	CC-ν_e	CC-$\bar{\nu}_e$	NC-ν_e	NC-$\bar{\nu}_e$	NC-ν_x	Total
Pb, single-n	59	0	8	37	677	781
Pb, double-n	26	0	0	1	20	47
Fe, single-n	4	5	2	6	146	163

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

Distance	0.50 kpc	1.0 kpc	2.0 kpc	4.0 kpc	8.0 kpc	16 kpc
Counts	0.5×10^6	112000	27500	6860	1740	440

4.3 Supernova neutrino detection

Summary of SNν detectors

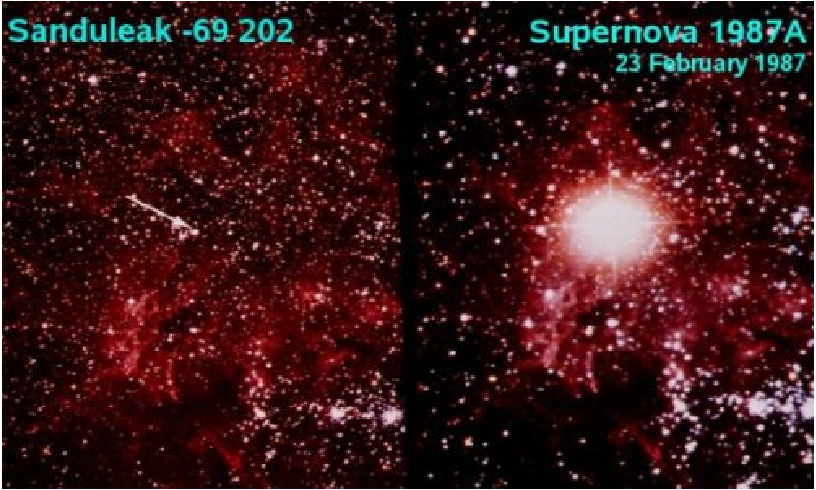
Detector	Type	Mass [kT]	Location	Events at 8 kpc	Status	Flavor
Super-K	Water-Čerenkov	32	Japan	7000	Running again for SN by Nov 02	$\bar{\nu}_e$
SNO	Light water	1.0	Canada	450	running	$\bar{\nu}_e$
	Heavy water	1.4		350		all
LVD	Scintillator	1	Italy	200	running	$\bar{\nu}_e$
KamLAND	Scintillator	1	Japan	300	running	$\bar{\nu}_e$
BOREXINO	Scintillator	0.3	Italy	100	ready 2003	$\bar{\nu}_e$
Baksan	Scintillator	0.33	Russia	5 0	running	$\bar{\nu}_e$
Mini-BooNe	Scintillator	0.7	USA	200	running	$\bar{\nu}_e$
AMANDA	Long String (water)	0.4/PMT	South Pole	N/A	running	$\bar{\nu}_e$
ICARUS	Liquid Argon	2.4	Italy	200	running (?)	ν_e
OMNISS	Pb	2 – 3	USA (?)	$>$1000	proposed	all
LANNDD	Liquid Argon	70	USA (?)	6000	proposed	ν_e
UNO	Water-Čerenkov	600	USA(?)	$>10^5$	proposed	$\bar{\nu}_e$
Hyper-K	Water-Čerenkov	1000	Japan	$>10^5$	proposed 2009	$\bar{\nu}_e$

4.4 Supernova neutrinos

What can be learned?

- Neutrino Physics
  - neutrino absolute mass (with some accuracy)
  - neutrino oscillations
- Supernova Core Collapse Physics
  - explosion mechanism, supernova evolution in time
  - convection, hydrodynamics instabilities
  - proto neutron-star EoS
  - black hole formation mechanism
  - neutrino roles in r-process (in production of heavy elements)
- Signatures (by measuring flavour, energy and time structure of the neutrino burst)
  - pulse risetime and shape
  - breakout, luminosity cutoff (☞ black hole formation)
  - pulsation
  - cooling

4.5 Supernova SN1987A



4.5 Supernova SN1987A

General properties

- Astronomical Event of the Decade
- The Sanduleak star situated 167000 light years away, in the Large Magellanic Cloud (5 times further than the average distance expected for a Galactic supernova)
- Only stellar collapse, so far, from which neutrinos have been detected
- 20 neutrinos were detected by Kamiokande and IMB experiments (both used water Cherenkov detectors)
- In addition, some events were also registered by Baksan and Mont Blanc detectors (both were liquid scintillator), but these events are not accepted as SN1987A events

4.5 Supernova SN1987A

Kamiokande and IMB: The detectors

- See lecture notes 1.10 and 2.20 for more details
- Both detectors were designed to search for proton decay
- Water Cherenkov detectors, surrounded by PMTs
- Kamiokande II at 2700 mwe, IMB at 1570 mwe
- IMB had about 10 times larger mass
  - it was less sensitivity to low-energy events because of higher background rates
  - it also had lower efficiency in the collection of Cherenkov light
- Energy threshold in the IMB was about 20 MeV, and in Kamiokande II about 6 MeV

4.5 Supernova SN1987A

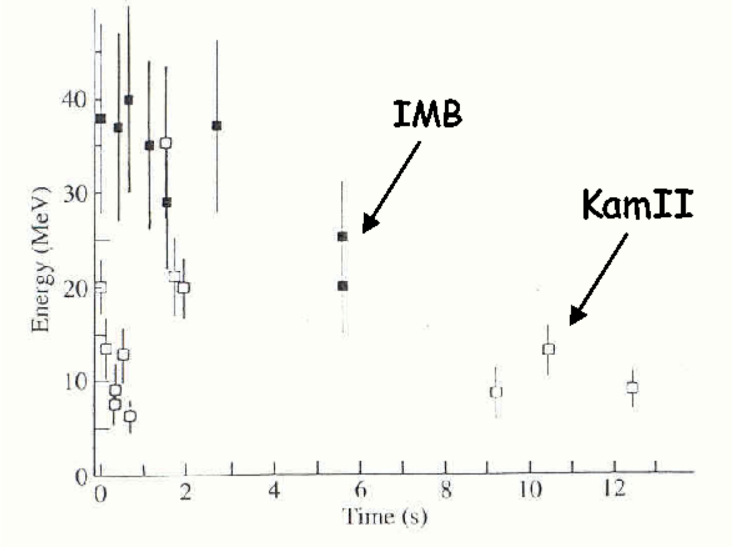
Kamiokande and IMB: Measured neutrino signals

Event no.	Time Feb. 23	Energy [MeV]	Angle [deg.]	Event no.	Time Feb. 23	Energy [MeV]	Angle [deg.]
K-1	35.00	20.0±2.9	18±18	IMB-1	41.37	38±7	80±10
K-2	35.11	13.5±3.2	40±27	IMB-2	41.79	37±7	44±15
K-3	35.20	7.5±2.0	108±32	IMB-3	42.02	28±6	56±20
K-4	35.32	9.2±2.7	70±30	IMB-4	42.52	39±7	65±20
K-5	35.51	12.8±2.9	135±23	IMB-5	42.92	36±9	33±15
K-6	35.69	6.3±1.7	68±77	IMB-6	44.06	36±6	51±10
K-7	36.54	35.4±8.0	32±16	IMB-7	46.38	19±5	42±20
K-8	36.73	21.0±4.2	30±18	IMB-8	46.96	22±5	104±20
K-9	36.92	19.8±3.2	38±22				
K-10	44.22	8.6±2.7	122±30				
K-11	45.43	13.0±2.6	49±26				
K-12	47.44	8.9±1.9	91±39				

Time is 07:35:xx.xx

4.5 Supernova SN1987A

Kamiokande and IMB: Measured energy spectrum



4.5 Supernova SN1987A

What were learned?

- About 600 scientific articles published (of all topics) by 2005
- Pre-existing calculations were in quite good agreement with the observed neutrino burst
- Quite low statistics, and only $\bar{\nu}_e$ were detected
  - important aspects of the theory could not be tested, for example, most of the energy is believed to be emitted in higher-temperature muon and tau neutrinos (and anti-neutrinos)
- New limits were obtained, for example, on the mass, charge, magnetic moment, decay rate, limiting velocity
  - $m(\bar{\nu}_e) \leq 15 \sim 30$ eV

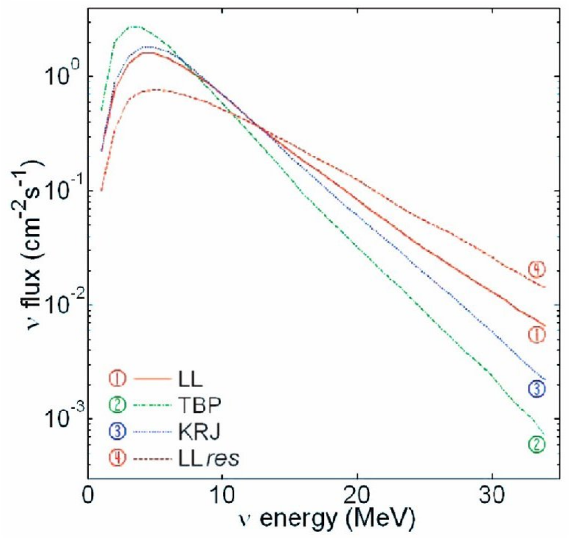
4.6 Diffuse supernova neutrinos

General

- The cosmic neutrino background
  - generated by core-collapse supernova explosions throughout the universe
  - know as supernova relic neutrinos or diffuse supernova neutrinos
- Diffuse supernova neutrinos are believed to provide a new source of information on
  - the core-collapse supernova explosion mechanism
  - the supernova rate
  - the star formation rate
- The detection of diffuse supernova neutrinos is demading
  - low integral flux $\sim 10^2\ \nu\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ (all flavours)
  - most probable detection channel: $\bar{\nu}_e + p \longrightarrow e^+ + n$ due to highest cross section ($\sigma = 6.8 \times 10^{-6}$ pb at 10 MeV)
- Background from nuclear reactor neutrinos (low-energy part) and from atmospheric neutrinos (high-energy part)

4.6 Diffuse supernova neutrinos

Neutrino energy spectrum



4.6 Diffuse supernova neutrinos

Experiments

- The best experimental limit on the diffuse supernova neutrino flux has been achieved by the Super–Kamiokande experiment (water Cherenkov)

$$\Phi(\bar{\nu}_e) < 1.2\ \mathrm{cm}^{-2} \cdot\ \mathrm{s}^{-1}, \qquad E(\bar{\nu}_e) > 19.3\ \mathrm{MeV}$$

- 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)

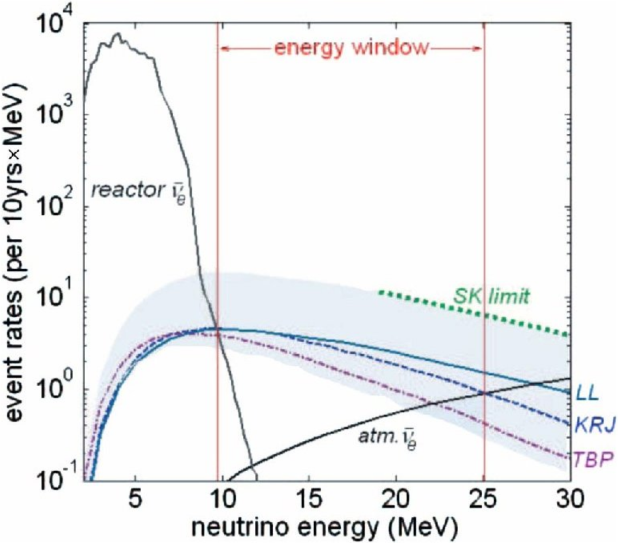
4.6 Diffuse supernova neutrinos

Experiments – LENA at Pyhäsalmi

- LENA is planned 50 kton liquid scintillation detector ∼1400 metres underground
- It can provide almost background-free energy window of 10–25 MeV for detecting diffuse supernova neutrinos
- LENA can detect ∼10 diffuse supernova neutrino events per year in Pyhäsalmi
- Within ten years of exposure
  - significant constraits on core-collapse supernova models
  - significant constraits 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
  - imptoving the limit given by the SK by a factor of 10

4.6 Diffuse supernova neutrinos

Event rate at Pyhäsalmi



4.7 Supernova neutrino detection

Dedicated setup: 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: $\sigma(E_\nu) \approx 10^{-38}$ cm^2 at $E_\nu = 20$ MeV for xenon
  - challence to measure low-energy recoil (for Xe ∼7 keV, in average)
- Number of events: $N_{\nu_e} \sim 10$, $N_{\bar{\nu}_e} \sim 15$, $N_{\nu_x} \sim 70$ (total ~ 95)

4.7 Supernova neutrino detection

Dedicated setup: TPC detector