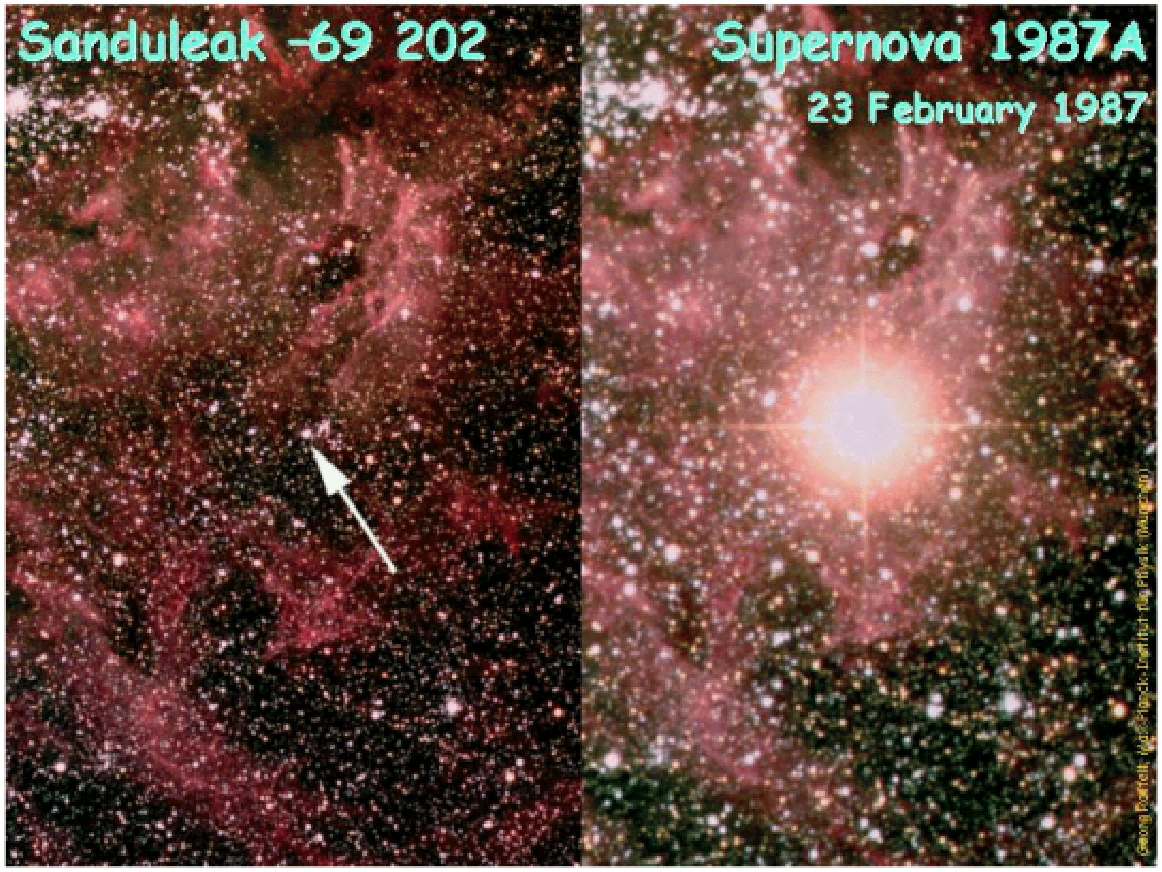
Neutrino AstroPhysics
Supernova Neutrino Detection



November 6, 2003

Content of the Lecture

Intro: Neutrino Properties

Supernova Properties (neutrino related)

(Supernova) Neutrino Detection

Underground Physics

Underground Laboratories

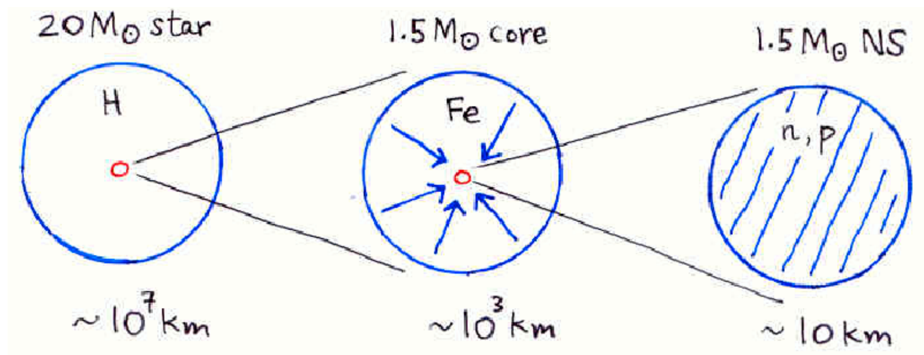
Supernova SN1987A

What will be learned ?

Introduction
Neutrino Properties

- three flavors (types): electron, muon and tau neutrinos, and their anti-neutrinos
- Recent data from the Sudbury Neutrino Observatory (SNO) and from the Super-Kamiokande (Super-K, SK) demonstrated that **neutrinos oscillate**
  ☞ **neutrinos have mass**
  - SK : atmospheric $\nu_\mu \longrightarrow \nu_\mathrm{x}$ (not ν_e)
    SNO : solar $\nu_\mathrm{e} \longrightarrow \nu_{\mu\tau}$
- Neutrino properties are still poorly known
- Interact extremely weakly with matter
  - can be used to investigate the supernova core collapse or the interior of the Sun
    (in the Sun: $\sim$2 sec for ν to get from centre to surface, gammas are captured)
  - very difficult to observe experimentally (needs huge-size detectors)
- Experimental observation of neutrinos gives information on neutrinos and/or on their source
- Neutrino sources
  - Sun (ν_e), Supernova (all)
  - Atmosphere ($\nu_{\mu\tau}$)
  - Nuclear reactors, Earth's crust (β-decay of fission fragments, $\bar{\nu}_\mathrm{e}$)
  - Accelerator (muon factory, $\nu_{\mu\tau}$)

Supernova Properties
(1) Energy release



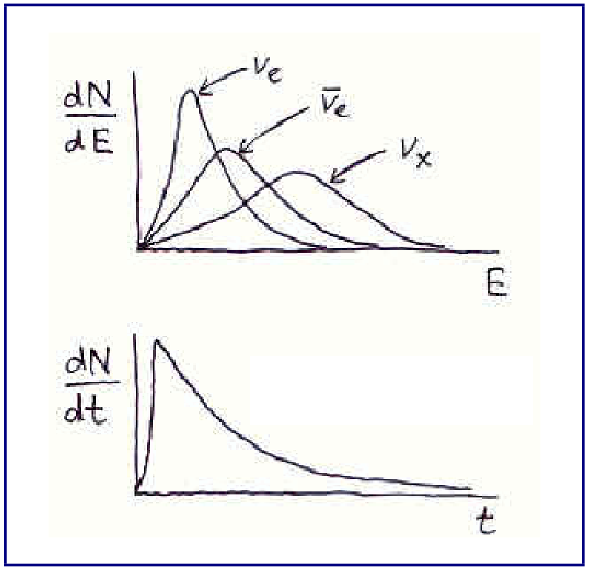
$$\Delta E_B \approx \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{GM_{core}^2}{R_{core}} \approx 3 \times 10^{59}\ \mathrm{MeV} \approx 3 \times 10^{46}\ \mathrm{J}$$

- Kinetic energy of explosion $\approx 10^{-2} \cdot \Delta E_B$
- 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

Supernova Properties
(2) Neutrino emission

- The Energy of emitted neutrinos can be described by Boltzmann distribution

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



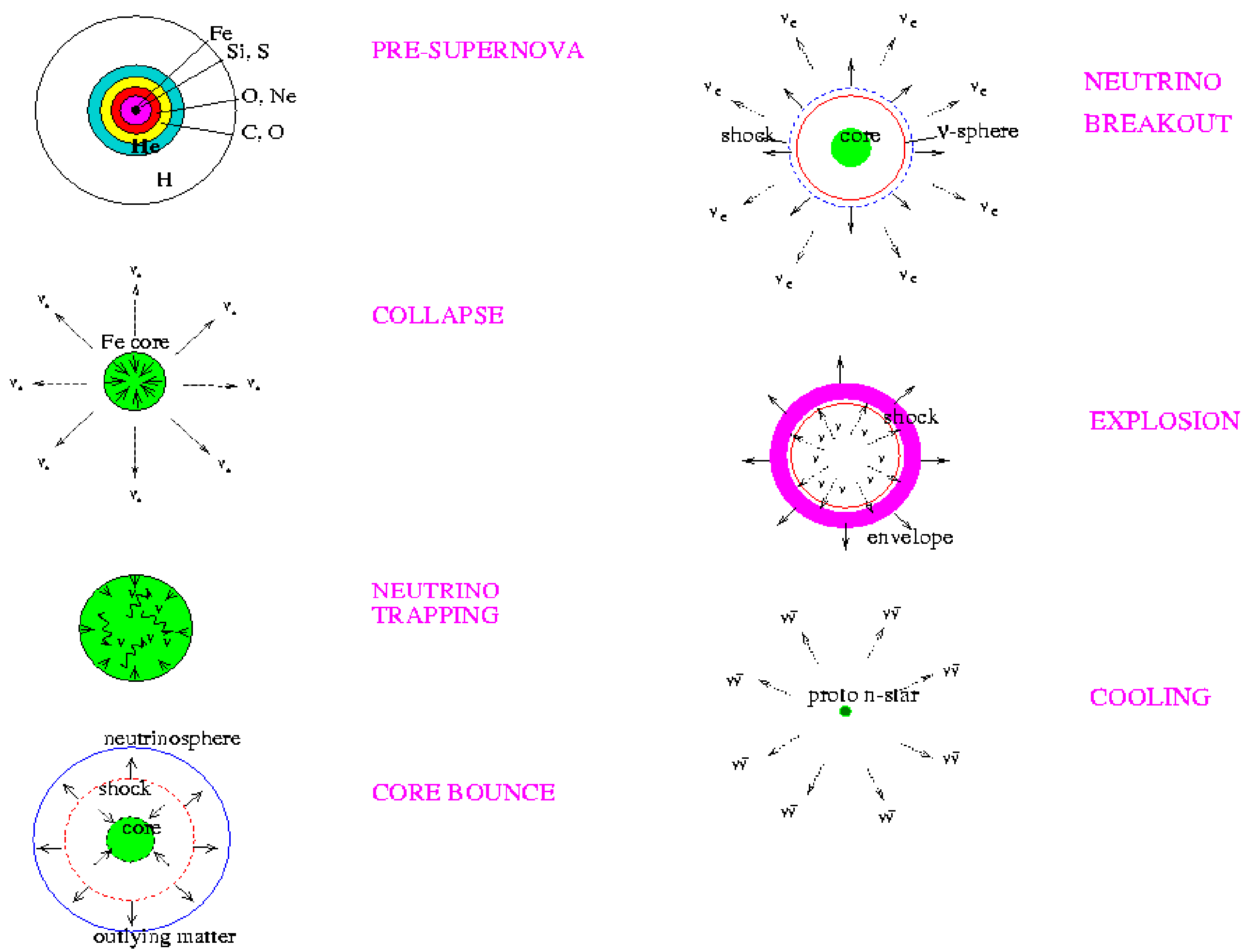
- Neutrinopulse is quite short
  ☞ duration $\sim 10 - 20$ s

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

- Number of emitted neutrinos: $\sim\mathbf{10}^{58}$ of all types

- Number of expected supernova explosions in our Galaxy: $\sim$ **3$\pm$ 1 per century**

Supernova Properties
(3) Core collapse



Supernova Neutrino Detection and Detectors

Supernova Neutrino Detection
(1) 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, most of the detectors described here have primary purpose other than supernova neutrino detection, for example, proton decay search, solar neutrino physics, or neutrino oscillation physics.

- Scintillation Detectors (MACRO, LVD, Borexino, KamLAND, Baksan, Mini-BooNE)
- Water Čerenkov Detectors (SK, SNO, UNO, Hyper-K)
- Heavy Water Čerenkov Detectors (SNO)
- Long String Water Čerenkov Detectors (AMANDA)
- High-Z Detectors (ONMIS, LAND)
- Liquid Argon (ICANOE (or ICARUS), LANNDD)

Supernova Neutrino Detection
(3) Scintillation Detectors : General

- Usually liquid scintillators
  - ☞ material C_xH_y : C_9H_{12} pseudocumene (PC)
    C_9H_{10} phenyl-o-xylylethane (PXE)
  - ☞ surrounded by PMTs
- Reactions
  - ν–e scattering: $\nu_x + e^- \longrightarrow \nu_x + e^-$
  - inverse β-decay: $\bar{\nu}_e + p \longrightarrow e^+ + n$
  - CC-capture of $\bar{\nu}_e$: $\bar{\nu}_e + {}^{12}C \longrightarrow {}^{12}B + e^+$
  - CC-capture of ν_e: $\nu_e + {}^{12}C \longrightarrow {}^{12}N + e^-$
  - NC-excitation of ${}^{12}C$: $\nu_x + {}^{12}C \longrightarrow {}^{12}C^* + \nu_x'$
- Detectors
  - KamLAND in Kamioka
  - BOREXINO in Gran Sasso
    (ready, but not yet running due to a leak)
- Very little pointing and weak flavor capability

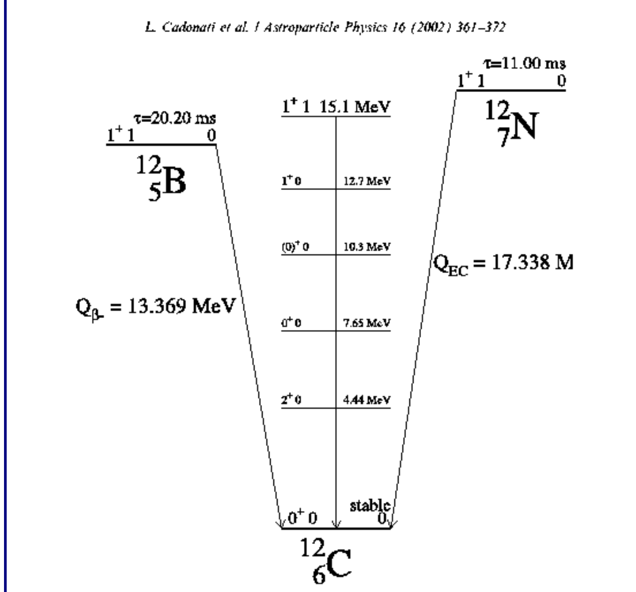


Fig. 1. Level diagram for the ${}^{12}C$, ${}^{12}N$, ${}^{12}B$ triad.

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Supernova Neutrino Detection

(3.1) Scintillation Detectors : BOREXINO

Consists of 300 tons of pseudocumene (PC, C_9H_{12})

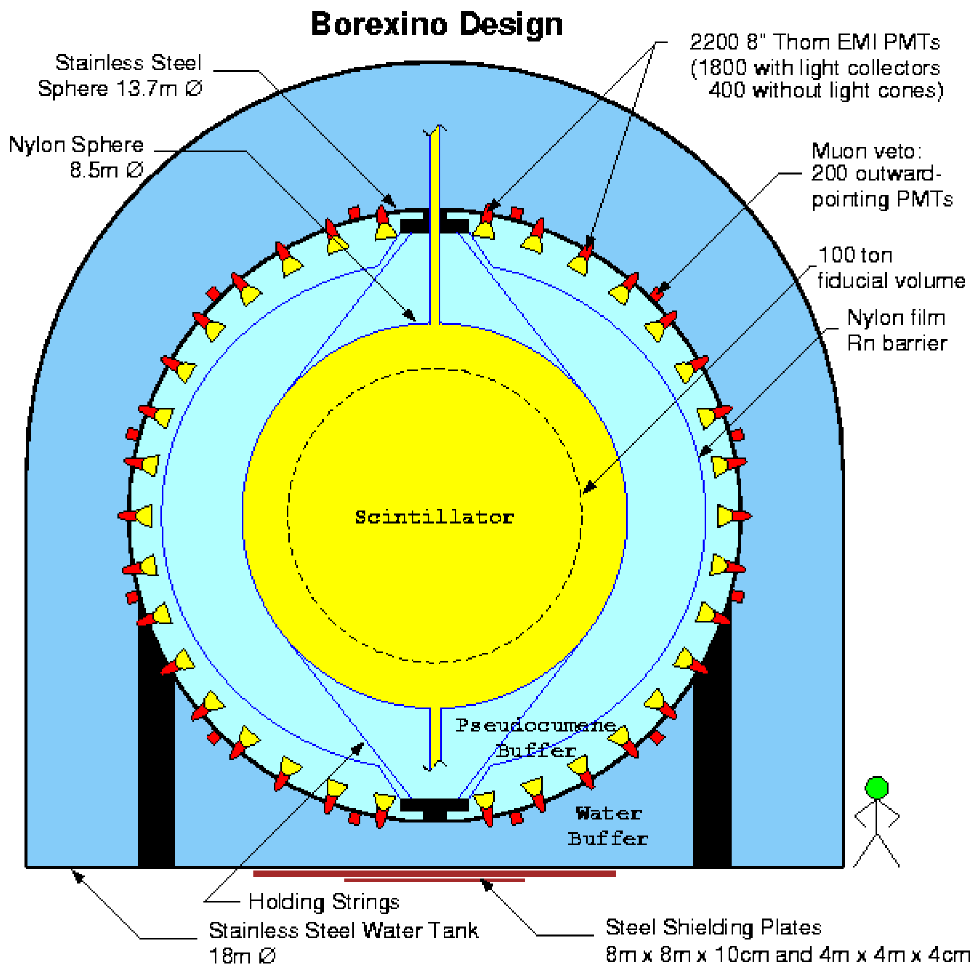

Table 3
Supernova neutrino events in Borexino from a supernova at 10 kpc, with $\varepsilon_B = 3 \times 10^{53}$ ergs binding energy release

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
$\bar{\nu}_e + p \to e^+ + n$	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

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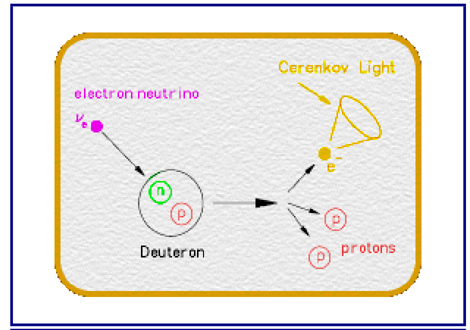
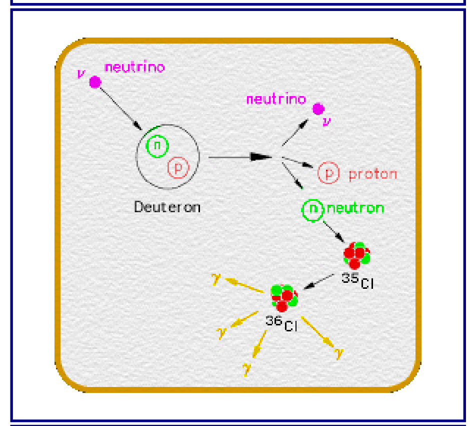
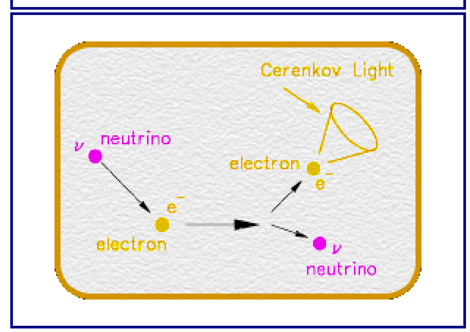
Supernova Neutrino Detection

(4) (Heavy) Water Čerenkov Detectors : General

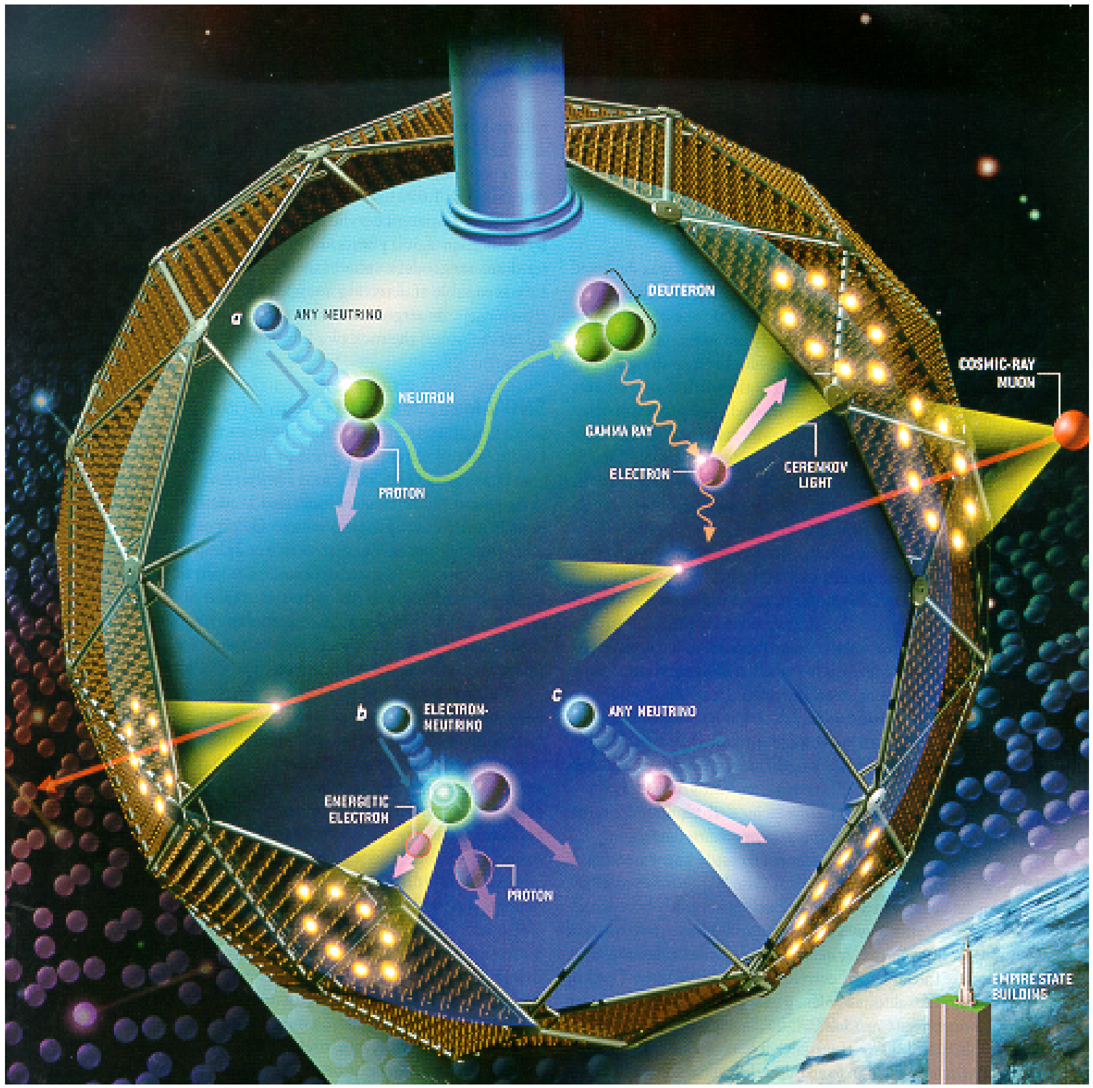
- Volume of clear water (H_2O) or heavy water (D_2O), vieved by PMTs
- Reactions in H_2O
  - inverse β-decay: $\bar{\nu}_e + p \longrightarrow e^+ + n$
  - CC-capture of $\bar{\nu}_e$: $\bar{\nu}_e + {}^{16}O \longrightarrow {}^{16}N + e^+$
  - CC-capture of ν_e: $\nu_e + {}^{16,18}O \longrightarrow {}^{16,18}F + e^-$
  - NC-excitation of ${}^{16}O$: $\nu_x + {}^{16}O \longrightarrow {}^{16}O^* + \nu'_x$
- Reactions in D_2O
  - CC-breakup : $\nu_e + d \longrightarrow p + p + e^-$
  - NC-breakup : $\nu_x + d \longrightarrow p + n + \nu_x$
  - Elastic scattering (ES): $\nu_x + e^- \longrightarrow \nu_x + e^-$
- Detectors
  - SNO in Sudbury (H_2O, D_2O)
  - Kamiokande II, Super-Kamiokande in Kamioka
  - IMB in Fairport (Ohio) (not in use)
- H_2O : Some pointing and flavor capability
  D_2O : Very good flavor sensitivity, some pointing





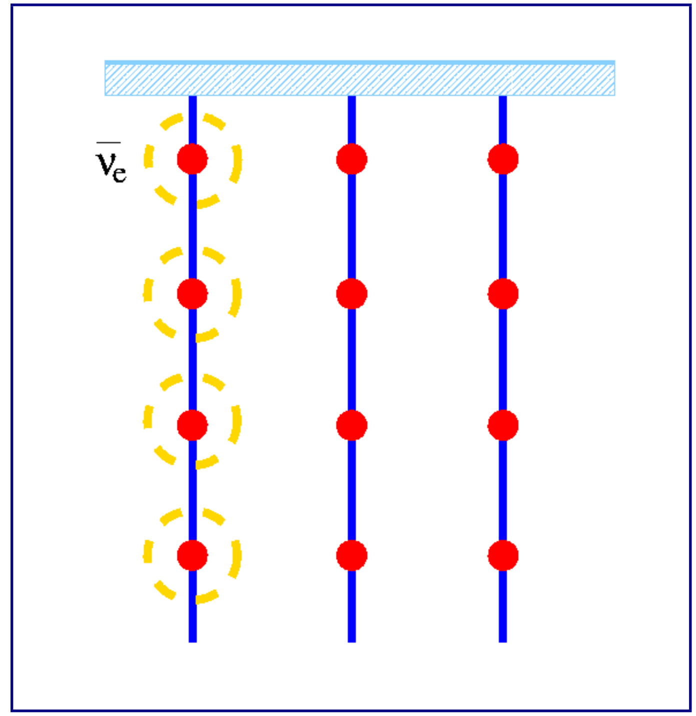


Supernova Neutrino Detection
(4.1) Heavy Water Čerenkov Detectors : SNO



Supernova Neutrino Detection
(5) Long String Water Čerenkov Detectors

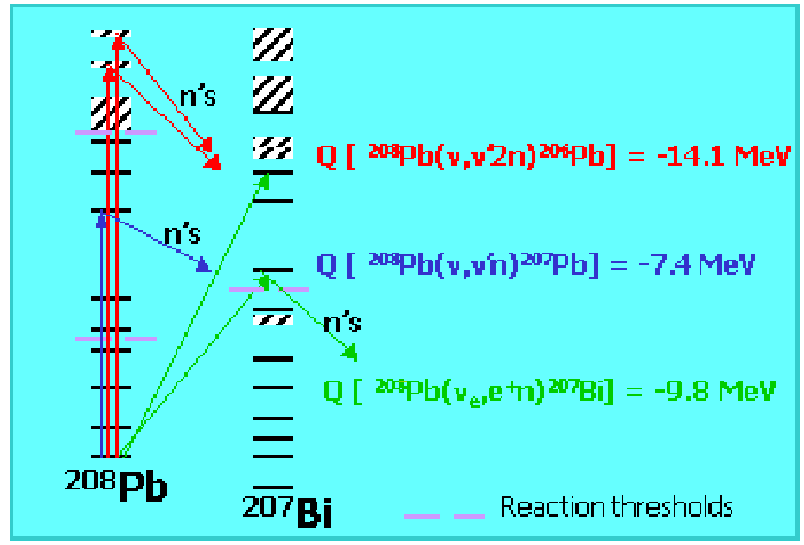
- $\sim$1 km long strings of PMTs in very clean water or ice
- Reactions similar to water Čerenkov (mainly $\bar{\nu}_e$)
- Detectors
  - AMANDA in the Antarctic ice
  - Antares in the Mediterranean
  - Baikal in the Lake Baikal
  - NESTOR in the Mediterranean



Supernova Neutrino Detection

(6) High-Z Detectors : General

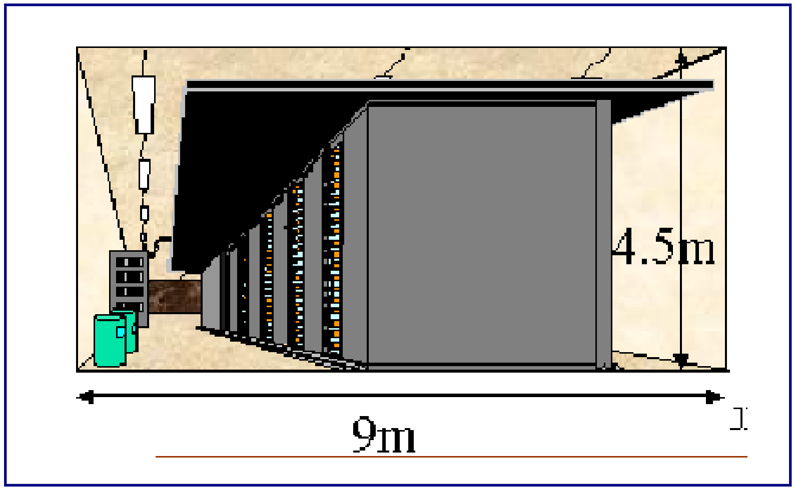
- Large quantity of Pb, $Pb(ClO_4)_2$, or Fe (few to tens of kT)
- Pb, Fe ☞ scintillator (neutron counter)
  $Pb(ClO_4)_2$ ☞ Čerenkov
- Advantages
  - Pb (and Fe) has relatively high cross section, and it is low-cost material
  - Pb has small neutron capture cross section



- 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
  - OMNIS, LAND (only proposed) (these would be dedicated SN neutrino detectors)
- Good flavor capability, no pointing

Supernova Neutrino Detection
(6.1) High-Z Detectors : OMNIS

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



Comparison of 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 detected neutron events versus supernova distance (16 0.5 kT Pb modules)

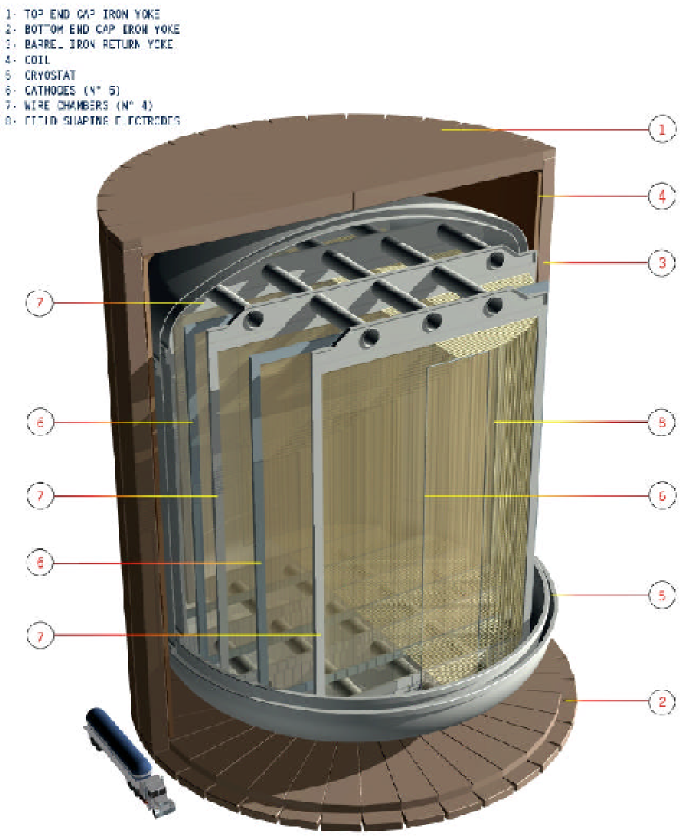
Distance	0.20 kpc	0.50 kpc	1.0 kpc	2.0 kpc	4.0 kpc	8.0 kpc	16 kpc
Counts	3×10^6	0.5×10^6	112000	27500	6860	1740	440

Supernova Neutrino Detection

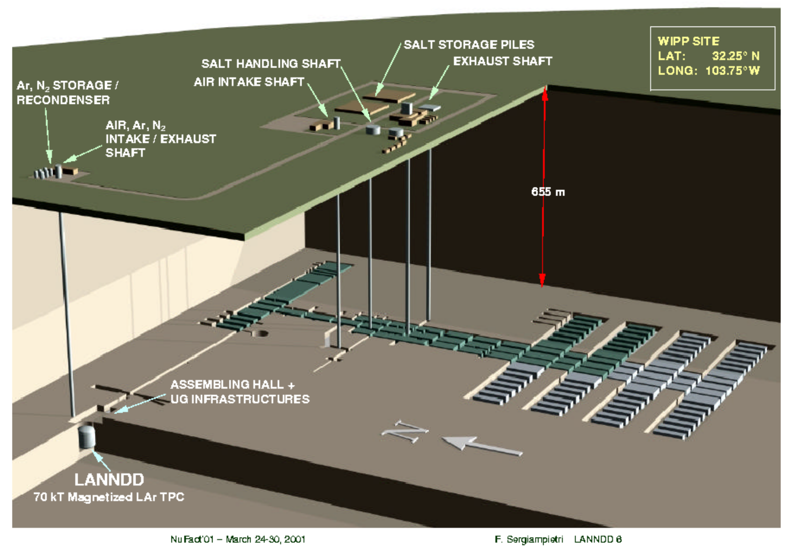
(7) LANNDD, 70 kton TPC at WIPP

Liquid Argon Neutrino and Nucleon Deacy Detector in magnetic field

The full detector



LANNDD at the WIPP site at Carlsbad (NM)



Supernova Neutrino Detection

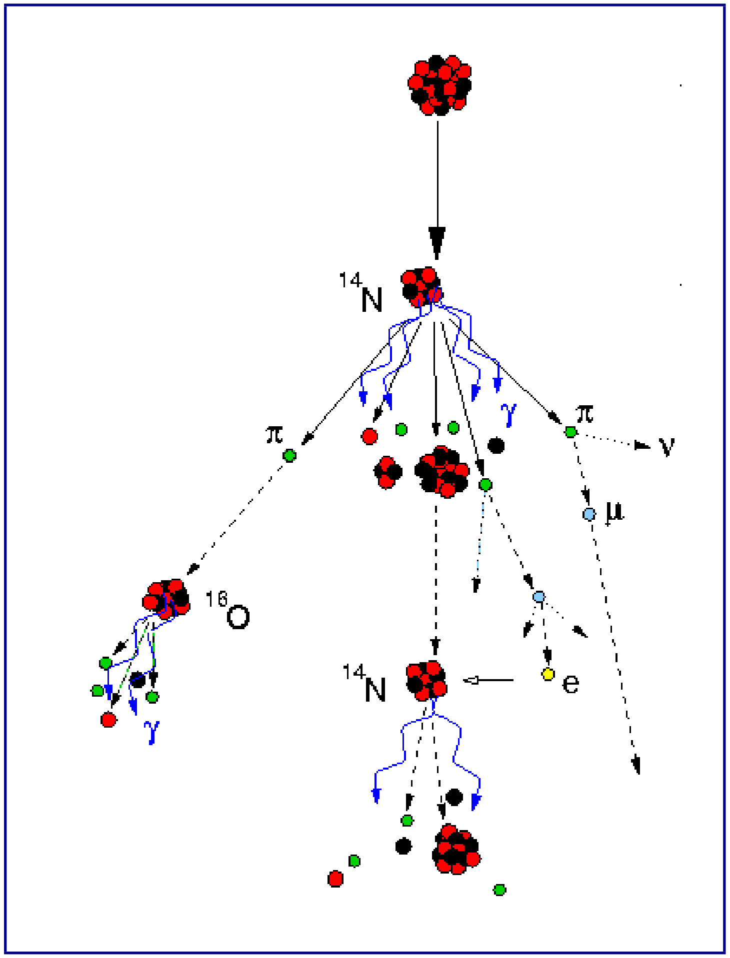
(8) Summary of SN Neutrino Detectors

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	$\bar{\nu}_e$

Underground Physics
and
Underground Laboratories

What Drives Physics Underground (i) ?

- High-energy cosmic rays (CR)
  - ☞ mostly protons (80%), up to iron (∼1%)
  - ☞ energy interval 10^6 eV – 10^{20} eV
  - ☞ origin and composition not fully known
  - ☞ collide with atmosphere atoms at 10 – 20 km
- In the atmosphere CR produce an Extensive Air Shower (EAS)
  - ☞ may contain millions of particles
  - ☞ hadrons (pions, kaons), electrons, positrons, fotons, **muons**
- CR flux at the sea level $\sim\mathbf{5 \times 10^9\ m^{-2}y^{-1}}$

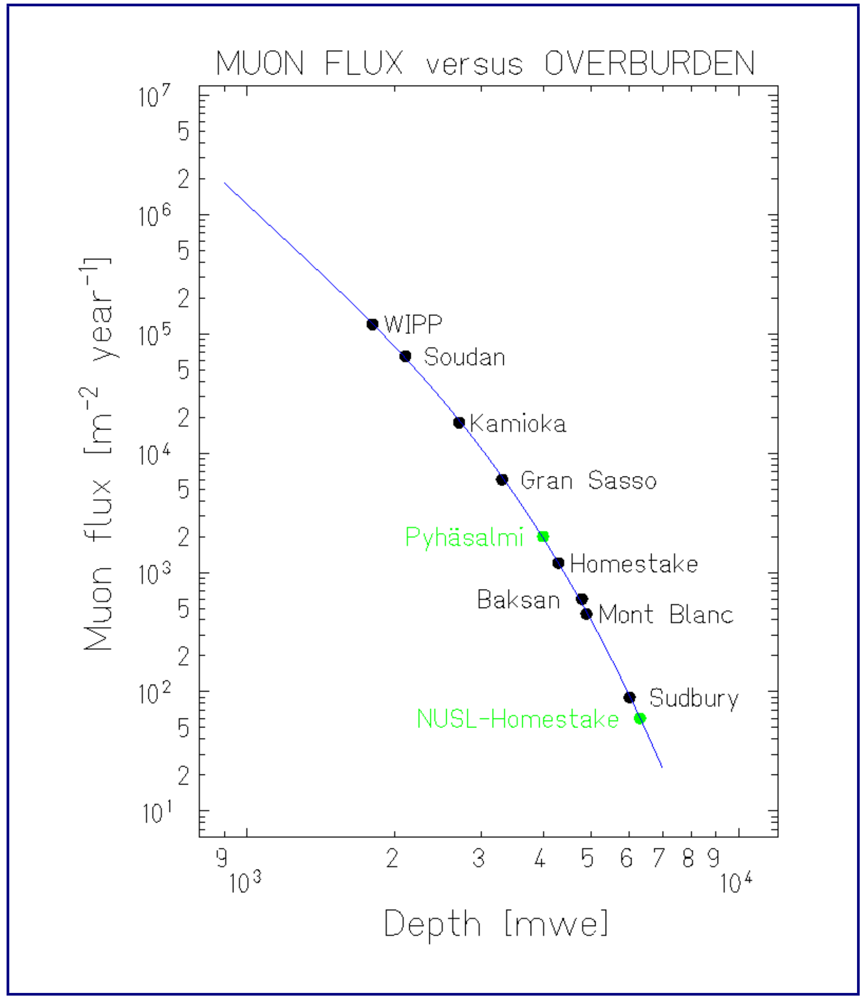


air_shower_i.tex

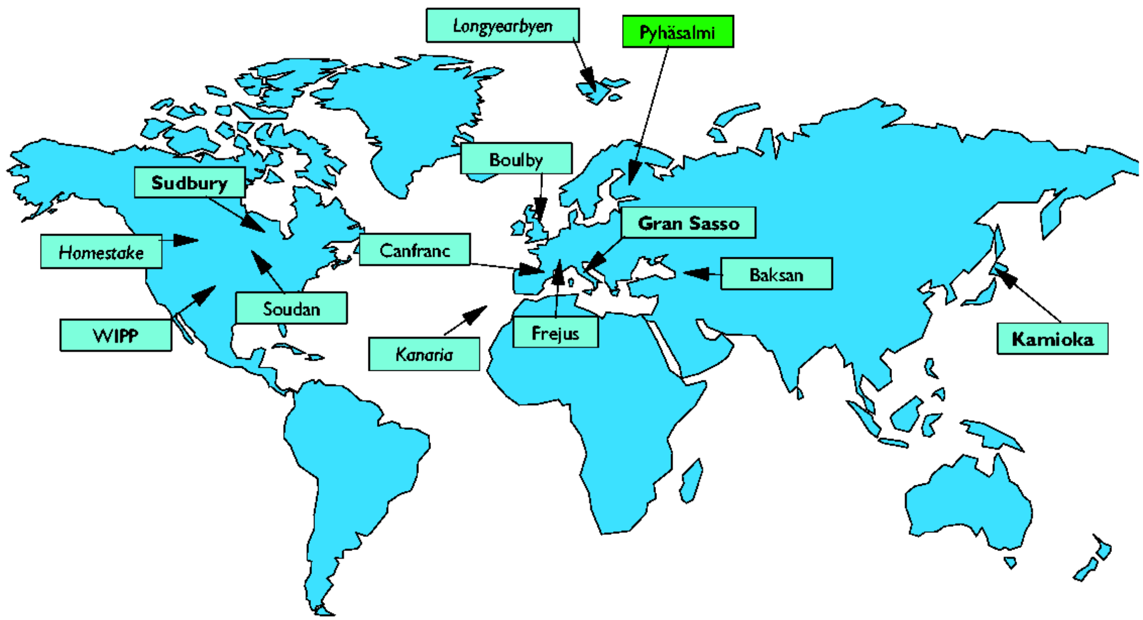
What Drives Physics Underground (ii) ?

- Electrons, positrons, fotons and hadrons stop into the surface
- **Muons may penetrate extremely deep underground**
  - ☞ direct background from primary muons
  - ☞ secondary background from spallation reaction products (neutrons)
- Needs hundreds of metres of rock for shielding

☞ Underground Laboratories



World's Underground Laboratories
mines and tunnels



The three largest underground laboratories at the moment are

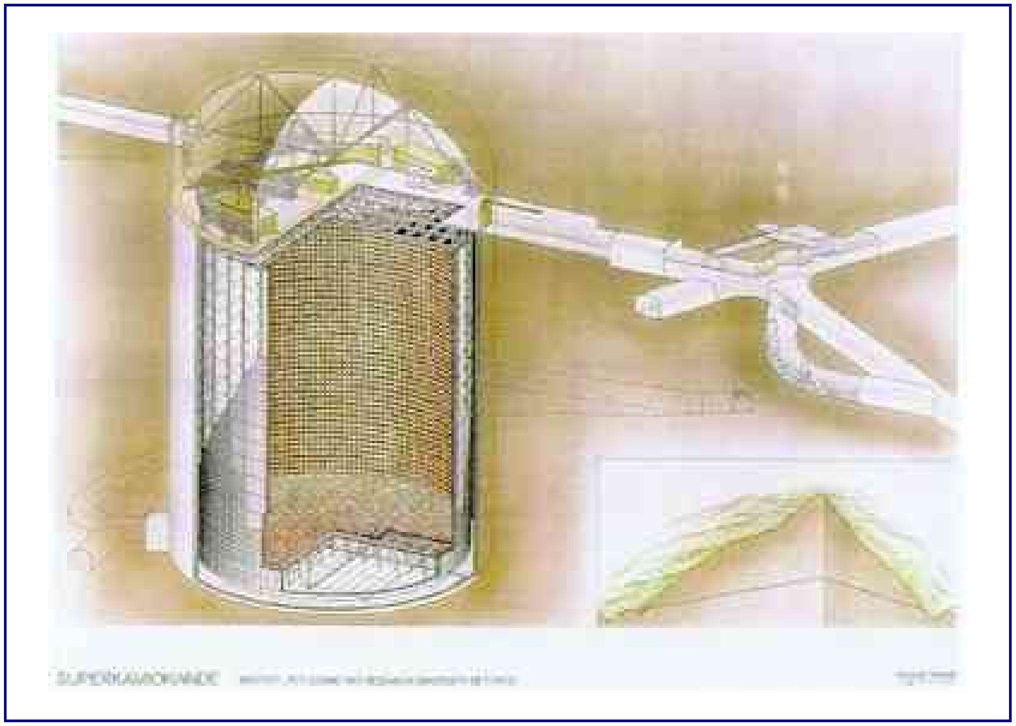
- Kamioka, Japan ☞ Measurement of atmospheric neutrinos
- SNO, Sudbury, Canada ☞ Measurement of solar neutrinos
- Gran Sasso, Italy

The Kamioka Observatory

- **Mozumi mine of the Kamioka Mining Company**
  ☞ mine not active
  ☞ laboratory started 1983

- **Experiments**
  - KamiokaNDE
  - Super-Kamiokande
  - KamLAND

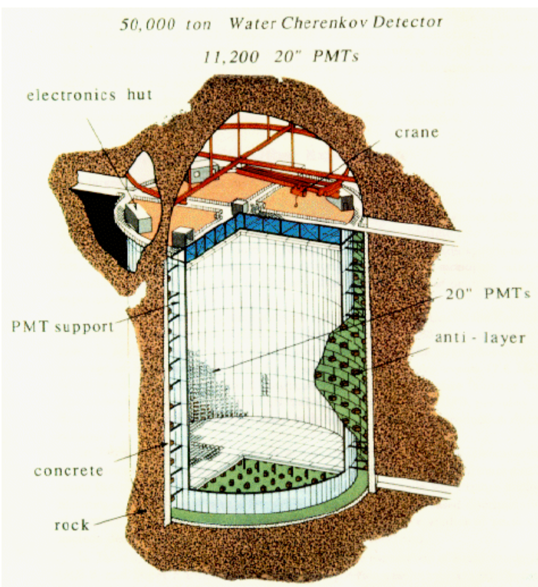
- **The Depth :**
  1000 m (2700 mwe)



KamiokaNDE and Super-Kamiokande Experiment

Kamioka Nucleon Decay Experiment

- to search for proton decay
- observed also Solar, atmospheric, and supernova neutrinos
- water Čerenkov detector $\sim$1.3 ktons of H_2O
- Solar and atmospheric neutrinos
- oscillation of accelerator-produced neutrinos : **K2K**
- Japan - USA collaboration



- water Čerenkov detector $\sim$22 ktons of H_2O
- uses elastic scattering of electrons (ES)
- PMTs : 11146 20-inch, 1885 8-inch
- the muon rate at SK: 1.88 Hz (reduced by $\sim 10^{-5}$)
- located 1000 m underground (2700 mwe)

Super-Kamiokande measurement of Solar ^{8}B and hep neutrinos

[S. Fukuda *et al.*, (SK-Collaboration), PRL**86**(2001)5651]

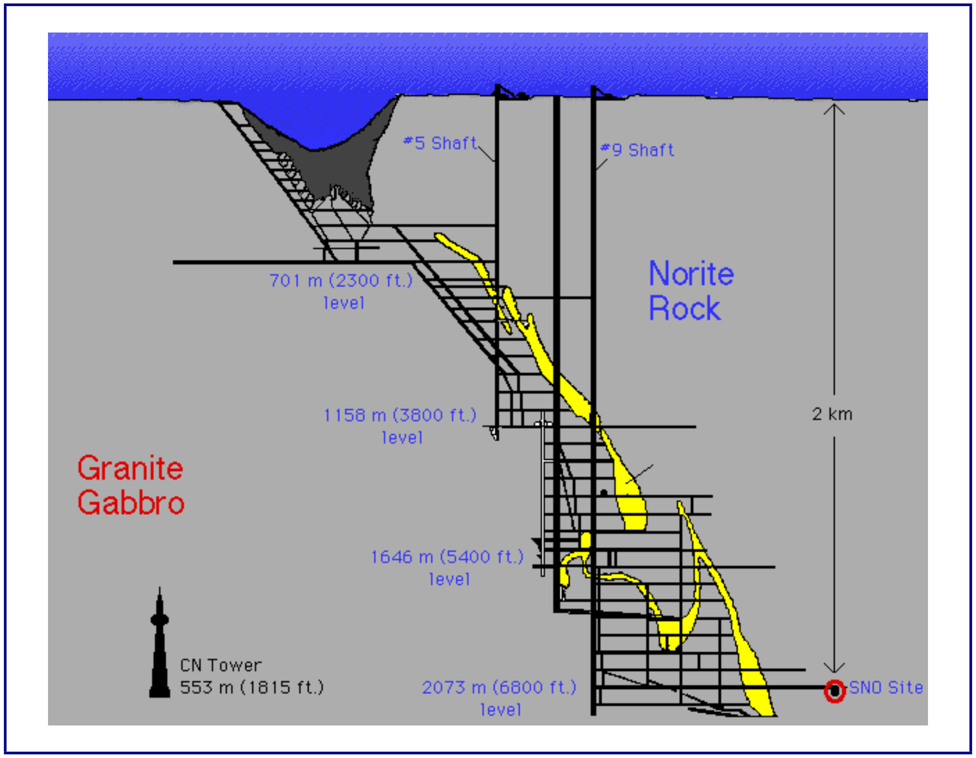
- SK-detector sensitive only electron neutrinos
- measurement time : 1258 days (May 1996 – Sept. 2000)
- analysis threshold 6.5 MeV (280 days) and 5.0 MeV (978 days)
  ☞ only high-energy solar neutrinos
- Solar neutrino events : $\mathbf{18464 \pm 204}$**(stat)** $^{+646}_{-556}$**(syst)**

  ☞ $\Phi_e = 2.32 \pm 0.03\text{(stat)}\ ^{+0.08}_{-0.07}\text{(syst)} \times 10^6 \quad \text{cm}^{-2} \cdot \text{s}^{-1}$
  $= \text{Flux at 1 AU}$

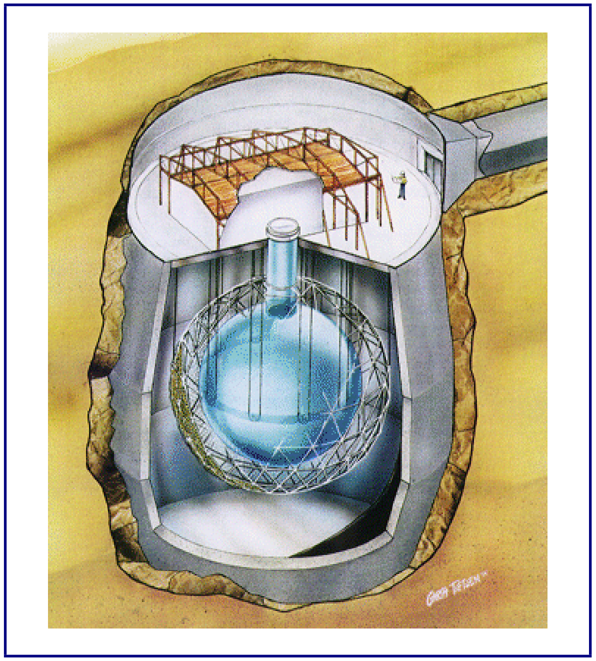
  ☞ $\mathbf{45.1 \pm 0.5}$**(stat)** $^{+1.6}_{-1.4}$**(syst) %** of the BP2000 SMM prediction
- measured also the hep-neutrino flux, the day-versus-night flux asymmetry, and the seasonal dependence of the flux

The Sudbury Neutrino Observatory (SNO)

- **Laboratory works in the active mine**
  - ☞ large centre of mining operation
  - ☞ owned by INCO Ltd
- **The Depth : 2073 m (6010 mwe)**
- **Access by elevator and narrow tunnel**



The SNO Detector



- imaging water Čerenkov detector
- diameter 12 m
- 1000 tons of ultrapure D_20
- ultrapure H_20 shield
- 9450 20-cm PMTs
- $\sim$55% of the light produced 7 m of the centre of the detector will strike a PMT

SNO measurement of Solar ^{8}B neutrinos

[Q.R. Ahmad *et al.*, (SNO-Collaboration), PRL**87**(2001)071301-1,
Q.R. Ahmad *et al.*, (SNO-Collaboration), PRL**89**(2002)011301-2]

- SNO detected Solar ^{8}B neutrinos via three reaction
  - the CC reaction $\longrightarrow \nu_e$
  - the NC reaction $\longrightarrow \nu_x$ (x = e,μ,τ)
  - the ES of electrons $\longrightarrow \nu_x$ (x = e,μ,τ)

  ☞ i.e. SNO can measure all neutrino flavors
- measurement time : 306 days (Nov. 1999 – May 2001)
- Solar neutrino events : $\mathbf{1967.7}\ ^{+61.9}_{-60.9}$ for CC events

  $\mathbf{576.5}\ ^{+49.5}_{-48.9}$ for NC events

  $\mathbf{263.6}\ ^{+26.4}_{-25.6}$ for ES events
- ^{8}B Fluxes at 1 AU :

  ☞ $\Phi_e = 1.76 \pm 0.05(\text{stat}) \pm 0.09(\text{syst}) \times 10^{6} \quad \text{cm}^{-2}\cdot\text{s}^{-1}$

  ☞ $\Phi_{\mu\tau} = 3.41 \pm 0.45(\text{stat})\ ^{+0.48}_{-0.45}(\text{syst}) \times 10^{6} \quad \text{cm}^{-2}\cdot\text{s}^{-1}$
- agrees well with the SK data
- **The SNO measurement is the first direct evidence for neutrino flavor oscillations**

Gran Sasso

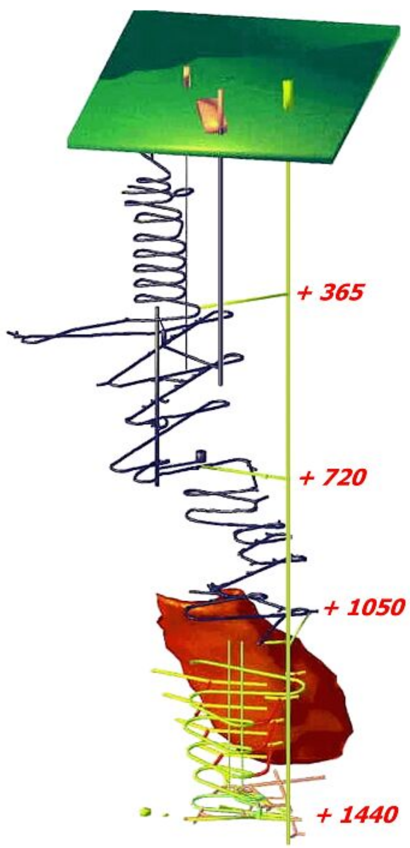
- the largest underground laboratory in the world
- locates beside the Gran Sasso tunnel (10.4 km long) on the highway connecting Terano and Rome
- three large experimental halls
- maximum depth is 1400 metres (3800 mwe)
- started 1980's
- expansion not possible

Gran Sasso Experiment

- Finished and running experiments
  - Solar neutrinos ☞ Gallex, GNO
  - supernova neutrinos ☞ LVD
  - atmospheric neutrinos ☞ MACRO
  - dark matter ☞ DAMA, CRESST, HDMS
  - $\beta\beta$ decay ☞ Heidelberg-Moscow
- Future experiments (under cosntruction or proposed)
  - GENIUS-TF : $\beta\beta$ decay, dark matter
  - CUORICINO : $\beta\beta$ decay
  - OPERA : neutrino oscillation
  - BOREXINO, LENS : Solar neutrinos
  - MONOLITH : atmospheric neutrinos

Pyhäsalmi mine

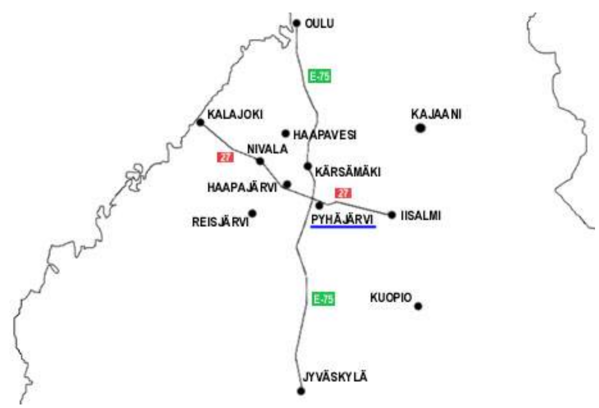
Advantages of the Pyhäsalmi mine



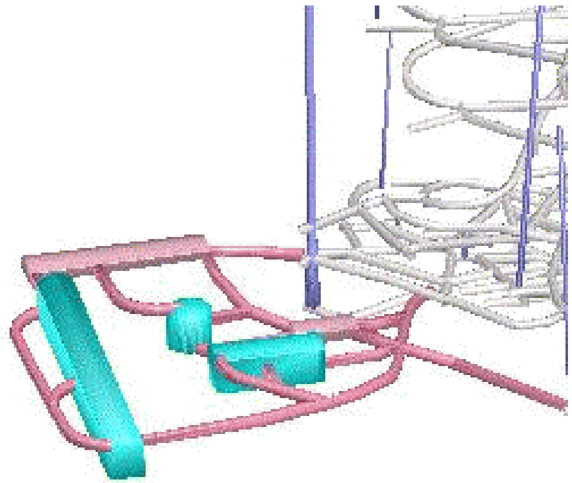
- DEEP
  The mine is the deepest operational base-metal mine in Euroopa
- DISTANCE
  A long way to CERN (2288 km)
- VOLUME
  New spaces and caverns can be excavated
- INFRASTRUCTURE
  Good traffic conditions around a year, modern infrastructure
- Very stable bedrock
- **Public local support**

Location & Distances

- in the middle of Finland along the highway 4 (E75)
- between Jyväskylä and Oulu
- the distances are: 165 km to Oulu, 180 km to Jyväskylä and 475 km to Helsinki.

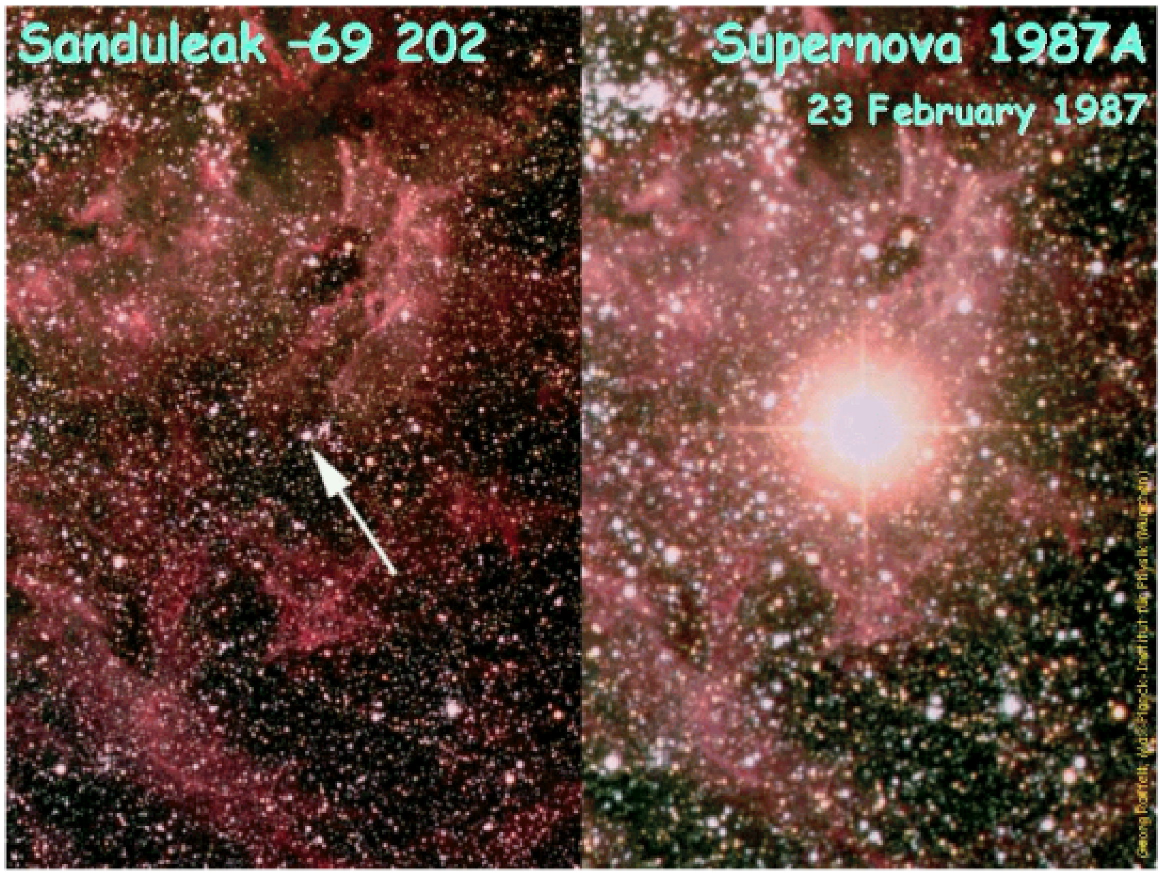


Deep Underground Laboratory



- New laboratory can be constructed at $\sim$ 1440 metres level
  (corresponding to $\sim$ 4000 mwe)
- Lot of space for new large-scale experiments
- Prefeasibility design and study completed
- Estimated cost-estimate $\sim$ 15 – 20 Meuros

Supernova 1987A



Supernova 1987A
(1) General Properties

- Astronomical Event of the Decade
- 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 (Irvine Michigan Brookhaven experiment) detectors (water Čerenkov)
- In addition, some events were also registered at Baksan and Mont Blanc detectors (liquid scintillator)

Supernova 1987A
(2) Kamiokande II and IMB Detectors

- Both detectors were designed to search for proton decay
- Water Čerenkov detectors, surrounded by PMTs
- Kamiokande 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 Čerenkov light
- Energy threshold in the IMB was about 20 MeV, and in Kamiokande II about 6 MeV

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(3) Measured Neutrino Signal

Event no.	Time(UT) on Feb. 23	Energy [MeV]	Angle [deg.]	Event no.	Time(UT) on Feb. 23	Energy [MeV]	Angle [deg.]
K-1	7:35:35.00	20.0±2.9	18±18	IMB-1	7:35:41.37	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				

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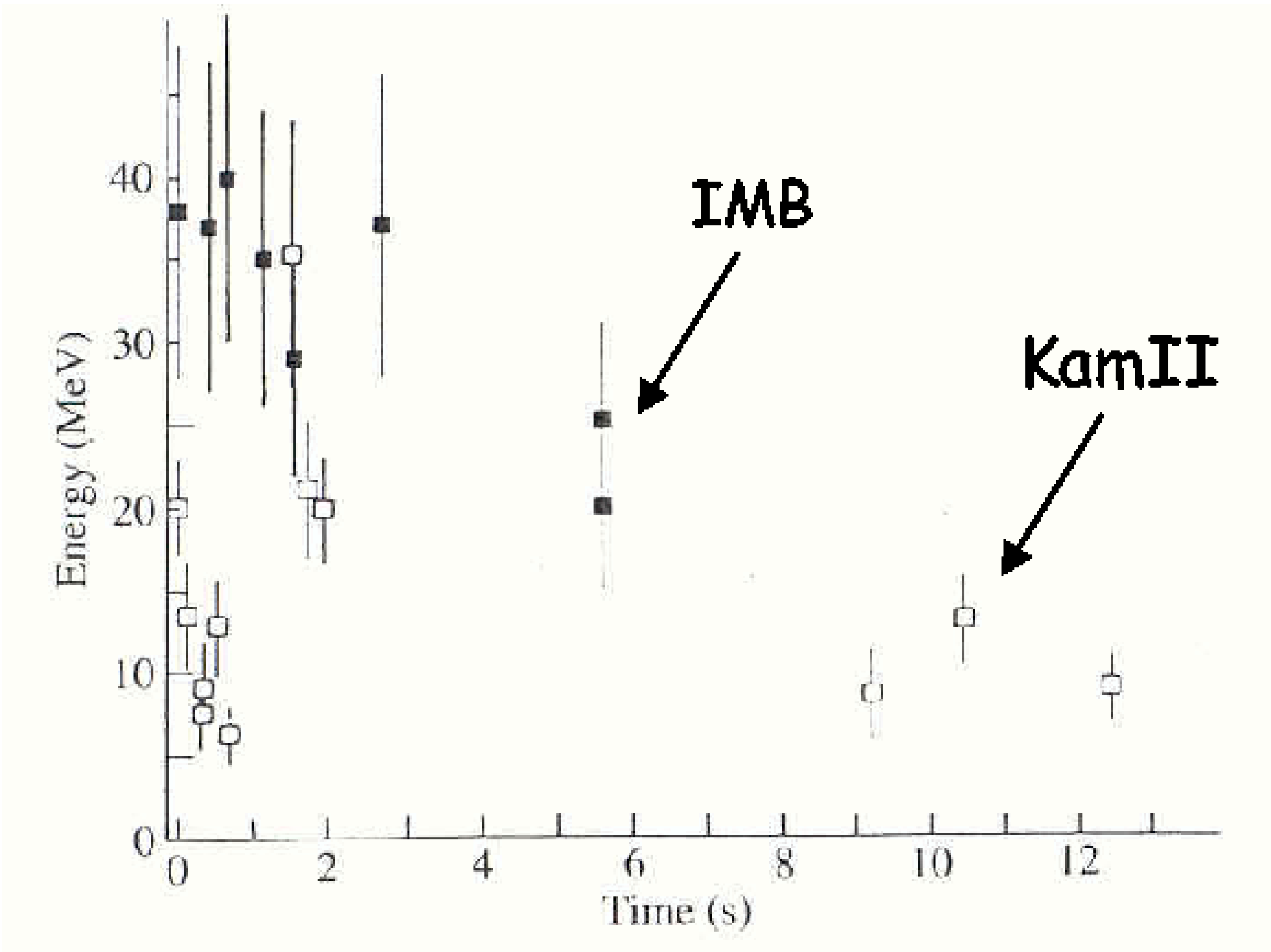
(4) Measured Energy Spectrum



Supernova 1987A
(5) What were learned ?

- Pre-existing calculations were in quite good agreement with the observed neutrino burst

- Quite low statistics, and only $\bar{\nu}_{\mathrm{e}}$ 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

  ☞ $\mathrm{m}(\bar{\nu}_{\mathrm{e}}) \leq 15 \sim 30$ eV

Physics

What can be Learned from a Galactic Supernova Neutrino Signal ?

Measurement of flavor, energy, and time spectra of supernova neutrino burst gives information on

- Neutrino Physics
- Supernova Mechanism (core collapse)

In addition,

- Early alert for astronomers

What will be Learned ?
(1) Neutrino Physics

- **Neutrino absolute mass**
  ☞ timo-of-flight delay in [s] compared to a zero-mass particle

$$\Delta t(E) = 0.0515(\frac{m_\nu}{E})^2 \cdot D$$

  m_ν is the mass of a neutrino flavor in [eV], E is the energy in [MeV], and D is the distance in [kpc]

  - look for: flavor-dependent delay
    energy-dependent time spread

- **Neutrino oscillation**
  ☞ flavor transformation inside the core (or in the Earth)
  - look for: spectral distortions (non-equal Luminosities)
    high-energy $\nu_e, \bar{\nu}_e$

- Always at least some core-collapse model dependence

What will be Learned ?
(2) Supernova Core Collapse Physics

- Information about
  - ☞ explosion mechanism, supernova evolution in time
  - ☞ convection, hydrodynamic instabilities
  - ☞ proto neutron-star EoS
  - ☞ black hole formation mechanism
  - ☞ neutrino roles in r-process (in production of heavy nuclei)
- Signatures
  - ☞ risetime
  - ☞ breakout, luminosity cutoff (☞ black hole formation)
  - ☞ pulsation
  - ☞ cooling

  by measuring flavor, energy, and time structure of the neutrino burst
- Requires knowledge on neutrino properties

What will be learned ?
(3) The Early Alert