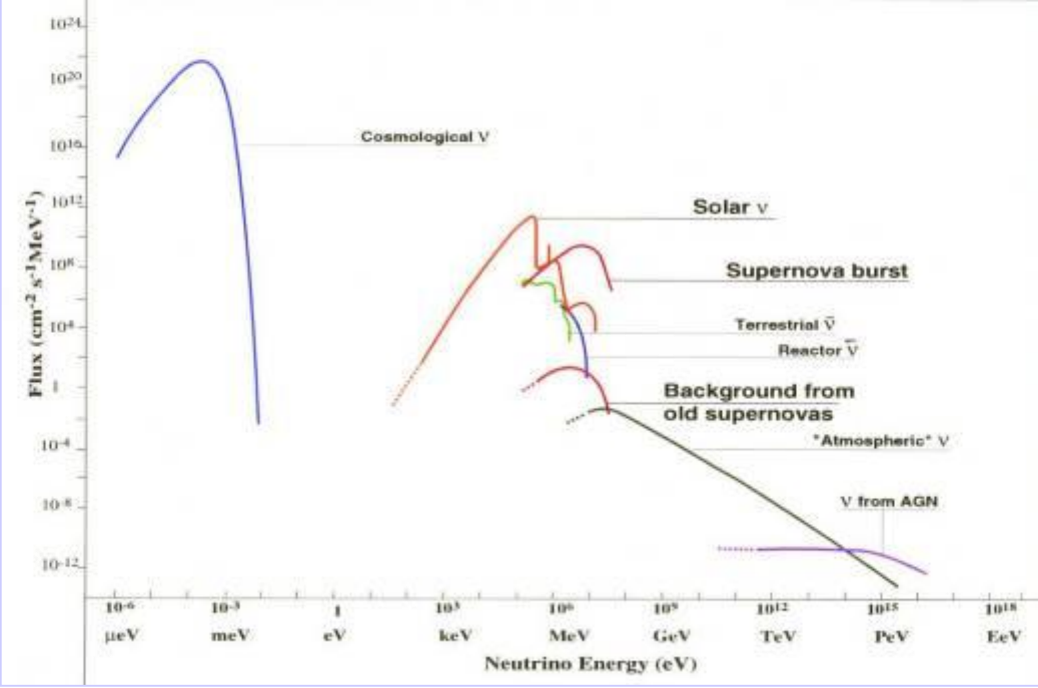
Astrophysical neutrino detection



•In the last thirty years neutrinos have become a probe for astrophysics.

•We had observations and in some case very detailed measurements of:

-Antineutrinos from the Earth

-Solar neutrinos:

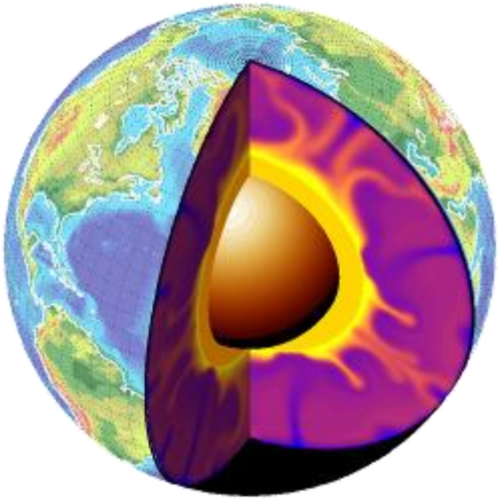
High energy (Boron)
Intermediate energy (Beryllium)
Low energy (pp)

-Supernova neutrinos

•For understanding the results, i.e. for the calibration of neutrino telescope, it is essential to know the phenomenon of neutrino oscillations , which was discussed in the previous chapter. precedente

•The goal of this chapter is to review available results, discuss their implications and provide a picture of future perspectives.

Open questions about natural radioactivity in the Earth and the role of geoneutrinos



- The basic questions are:

1 - What is the radiogenic contribution (from U, Th and ^{40}K) to terrestrial heat production?

- 2 - How much U and Th in the crust?
- 3 - How much U and Th in the mantle?
- 4 - What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)
- 5 - Is the standard geochemical model (BSE) consistent with geo-neutrino data?

- Geo-neutrinos, the antineutrinos from decay chain of long lived radioactive elements (U, Th and ^{40}K) bring to surface information on the abundances of these elements in the Earth's interior
- Remind that geo-neutrinos from Uranium and Thorium (not from Potassium) are above threshold for inverse beta on free protons

$$\bar{\nu} + p \rightarrow e^{+} + n - 1.8\ \text{MeV}$$

KamLAND 2002-2007 results on geo-neutrino

• KamLAND, the 1000 ton scintillator detector in Japan, can measure the energy deposited by positrons (E_{prompt}) and thus the anti-neutrino energy

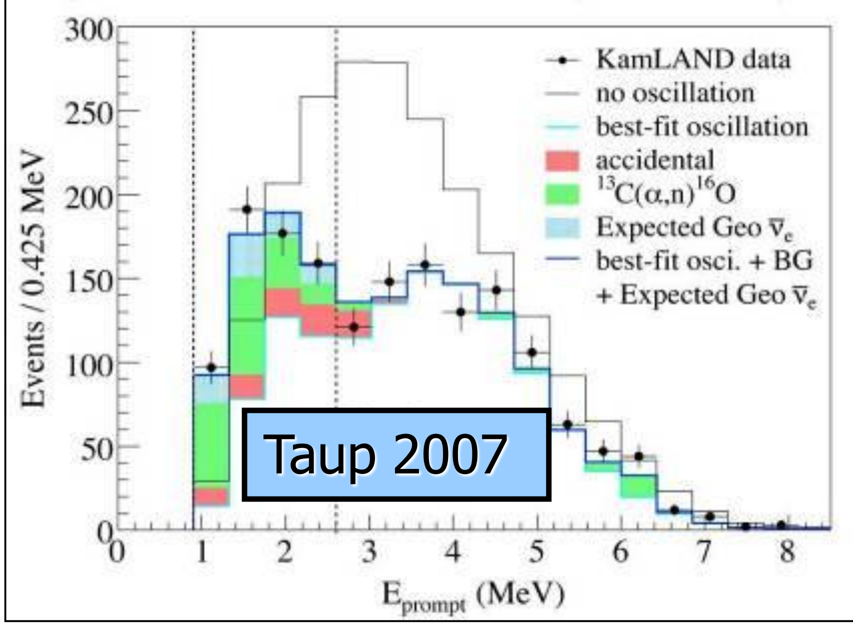
$$\bar{\nu} + p \rightarrow e^{+} + n - 1.8 \text{ MeV}$$

•Above 2.8 MeV, the signal only comes from reactors. The interval 1MeV-2.8 MeV is the geoneutrino energy window.

•In five years data ~ 630 counts in the geo-ν energy range:

• ~ **340** from reactor antineutrinos.

This is estimated by extrapolating the reactor data in the higher energy window.



• ~ **160** fake geo-ν, from $^{13}C(\alpha,n)$

•Some contamination from Polonium is still there. Alpha particles produce fast neutrons, which first scatter on protons (which provide ionization and scinitillation energy) and then are captured by p. In this way the antineutrino signal is mimicked

• ~ **60** random coincidences

• ~ **70 geo-neutrino events are obtained from subtraction (630-340-160-60=70)**

Implications of KamLAND result

•Note that the geoneutrino counts obtained by subtraction are affected by statistical fluctuations of the total counts D =√(630) ~25

•The analysis of the experimental results gives thus:

N (U+Th)=70±25

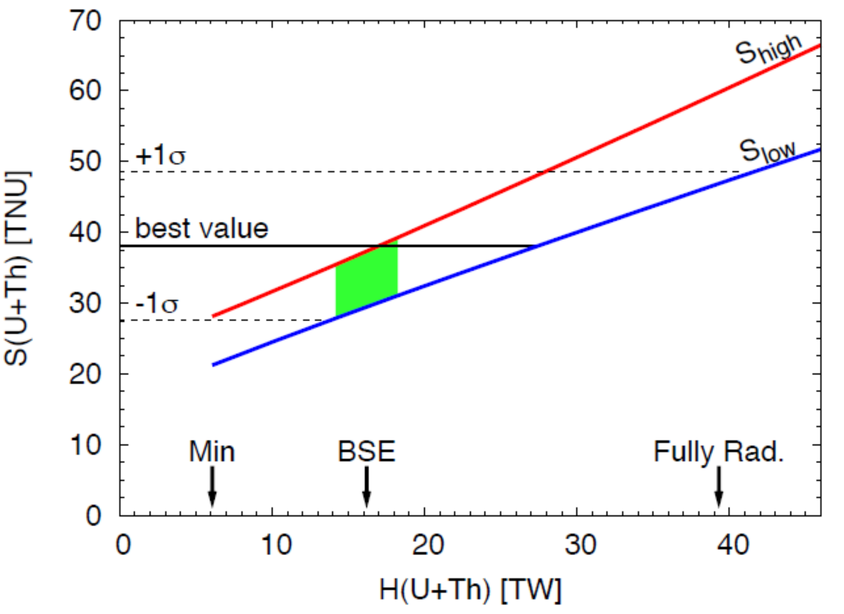
•Note that event rate is about one per month

•The KamLAND signal is in perfect agreement with BSE prediction.

•It is consistent within 1σ with:

-Minimal model (no radioactivity in the mantle)

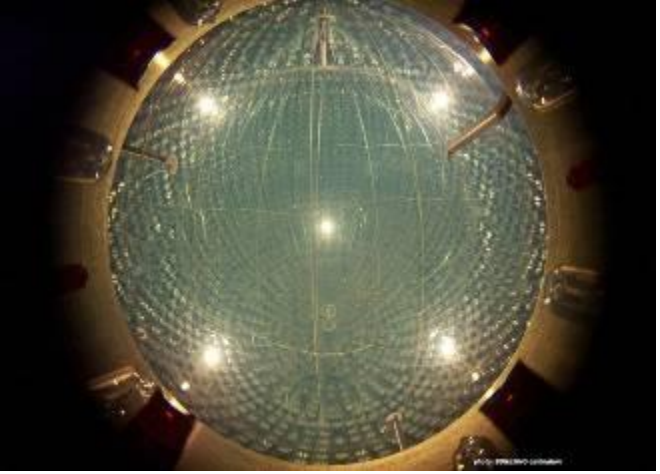
-Fully radiogenic model (i.e U and Th produce 45 TW)



•Concerning radiogenic heat, the 95% CL upper bound on geo-signal translates into* H(U+Th)<65 TW

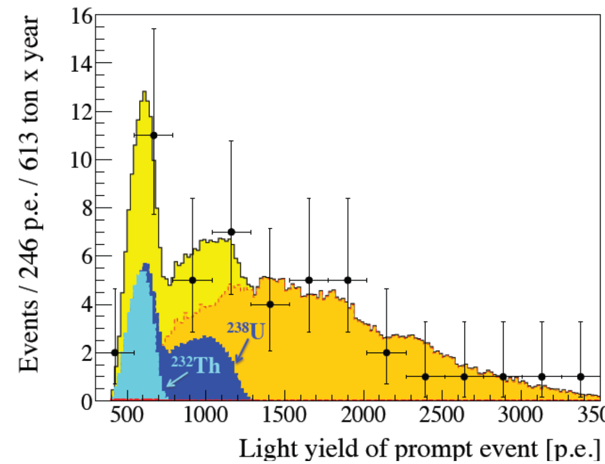
•This pioneering experiment has shown that the technique for identifying geo-neutrinos is now available!!!

* G. Fiorentini et al. - Phys.Lett. B 629 – 2005 - hep-ph/0508048

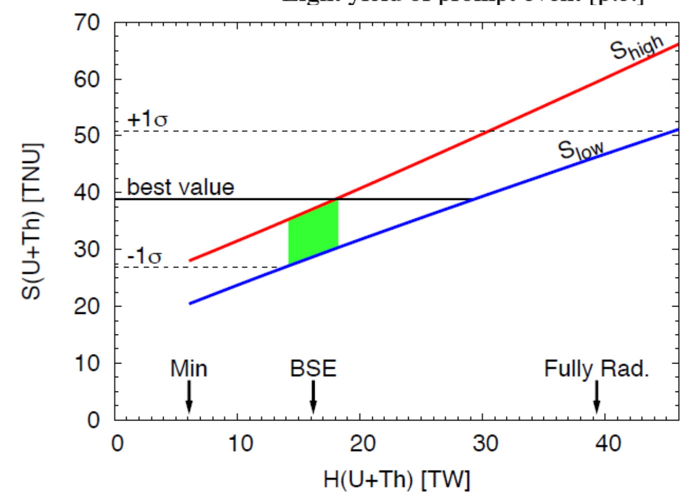


Borexino at Gran Sasso

- A 300-ton liquid scintillator underground detector, running since may 2007.
- Signal, mainly generated from the crust, is comparable to reactor background.



- The Borexino result is S_{geo} = (38.8+-12.0) TNU
- Also this value is in agreement with the BSEprediction
- In conclusion, both Borexino and Kamland are in agreement with the standard BSE model, predicting about 20 TW as radiogenic contribution

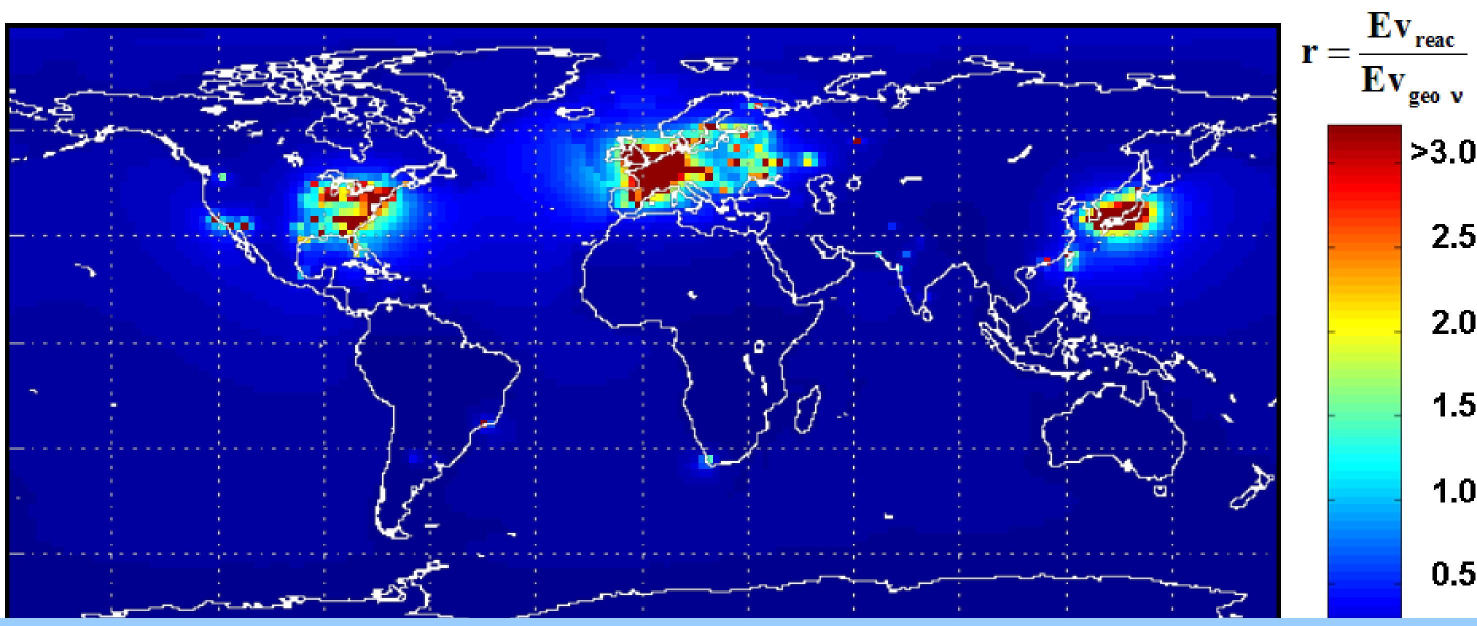


Borexino collaboration –Phys. Lett. B 2013

Nuclear reactors: the enemy of geo-neutrinos

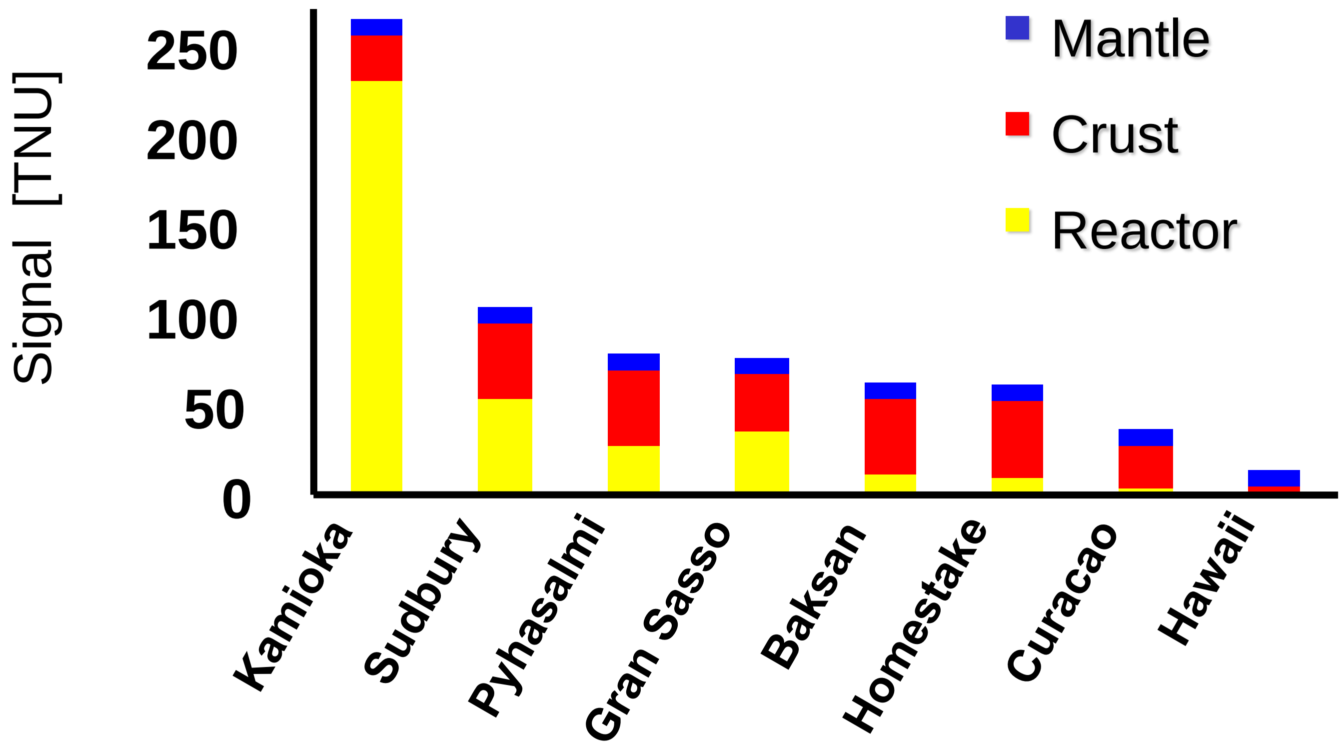
•KamLANDis plagued with events from reactors.
•A figure of merit for any location is the ratio **r** between reactor events and geoneutrino events in the geoneutrino energy window.
•Note that at Gran Sasso r ≈1, which makes this site much better than Kamioka

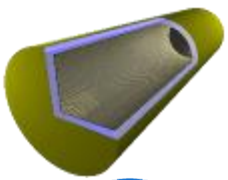
	r
Kamioka	6.7
Sudbury	1.1
Gran Sasso	0.9
Pyhasalmi	0.5
Baksan	0.2
Homestake	0.2
Hawaii	0.1
Curacao	0.1

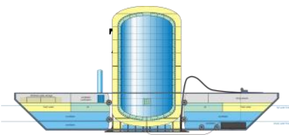


Fiorentini et al - Earth Moon Planets - 2006

Running and planned experiments

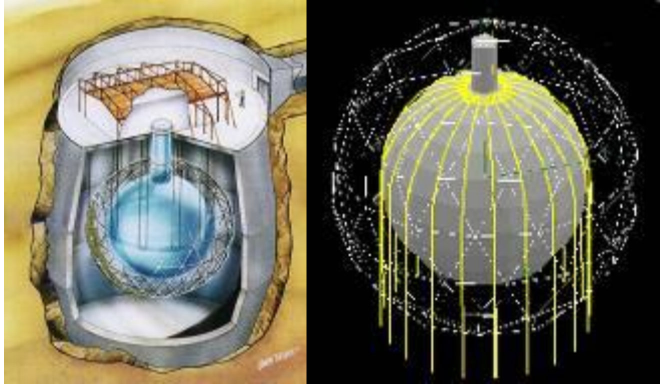






- So far only Kamland and Borexino have given experimental results for geo-neutrinos.
- Several experiments, either running or under construction or planned, have geo-ν among their goals.
- Figure shows the sensitivity to geo-neutrinos from crust and mantle together with reactor background.

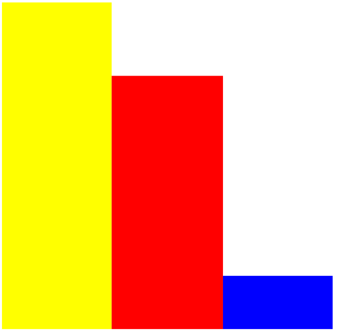
SNO+ at Sudbury



• SNO has been used so far filled with heavy water. The next stage is to change water with liquid scintillator.

•In this way one shall have 1000-ton liquid scintillator underground detector

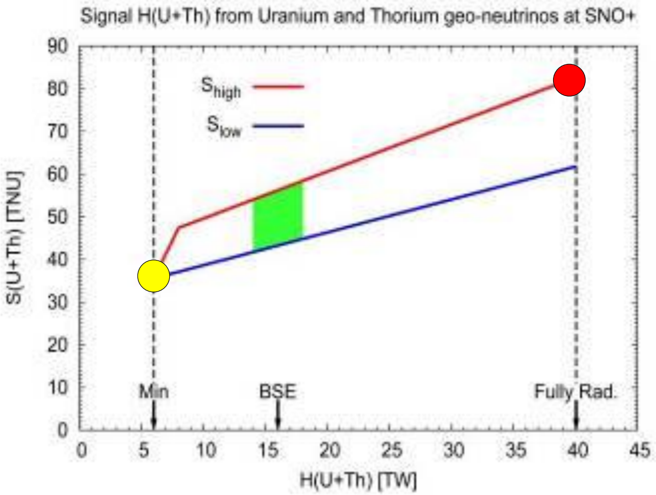
•The size is similar to Kamioka, but the reactor background is much smaller



• Some 80% of the signal is expected to come from the continental crust.

• From BSE expect 28 – 38 events/year*

• It should be capable of measuring U+Th content of the crust.

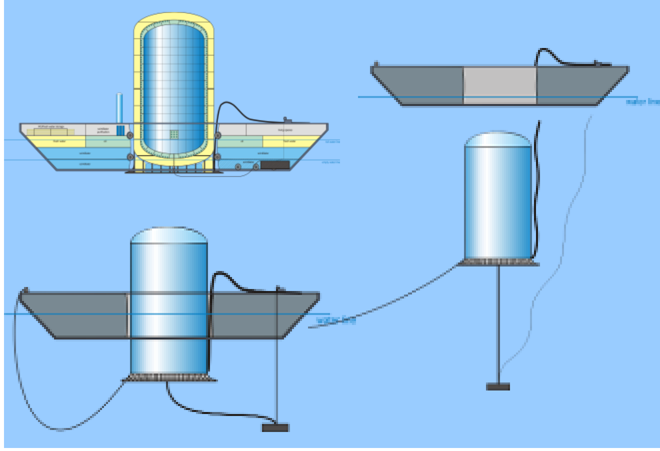


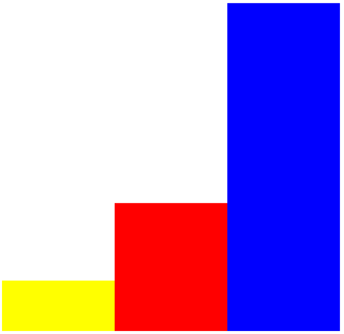
* assuming 80% eff. and 1 kTon CH_2 fiducial mass

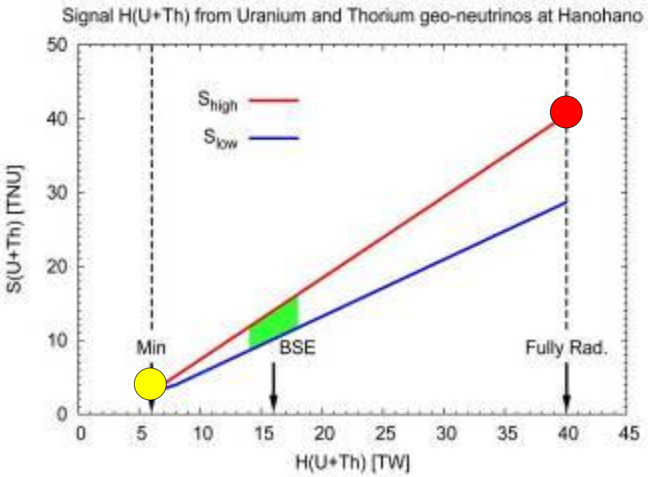
Chen, M. C., 2006, Earth Moon Planets 99, 221.

Hanohano at Hawaii

- Project of a 10 kiloton movable deep-ocean LS detector
- ~ 70% of the signal comes from the mantle
- From BSE expect 60 – 100 events/year*
- Excellent signal to background ratio, due to the absence of reactors.
- It should be capable of measuring U+Th content of the mantle







* *assuming 80% eff. and 10 kTon CH_2 fiducial mass*

Most studied solar neutrinos

Essentially one has three groups:

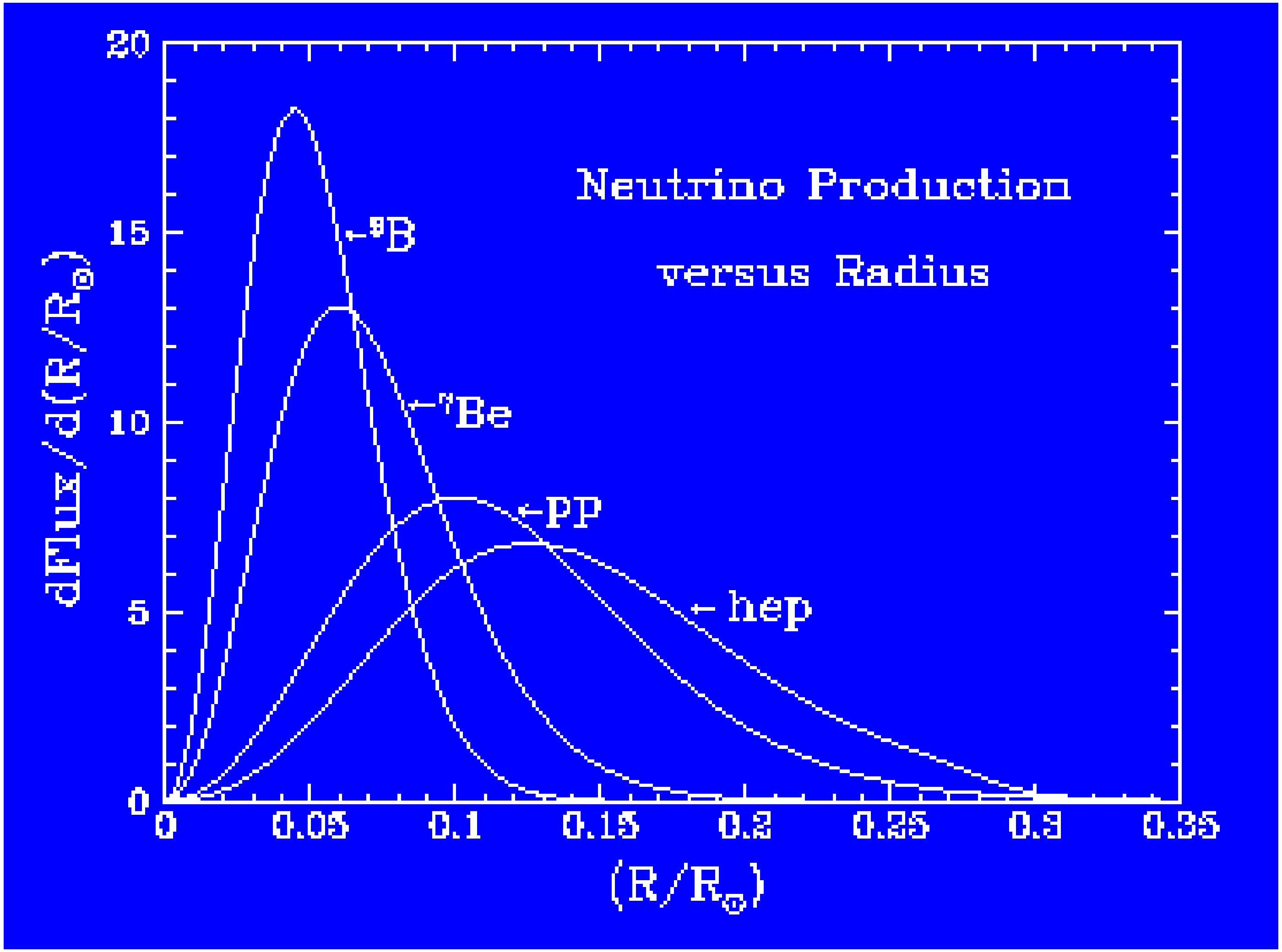
-low energy : the pp neutrinos, coming from ppI

-intermediate energy: the Be neutrinos, from ppII

-high energy: Boron neutrinos

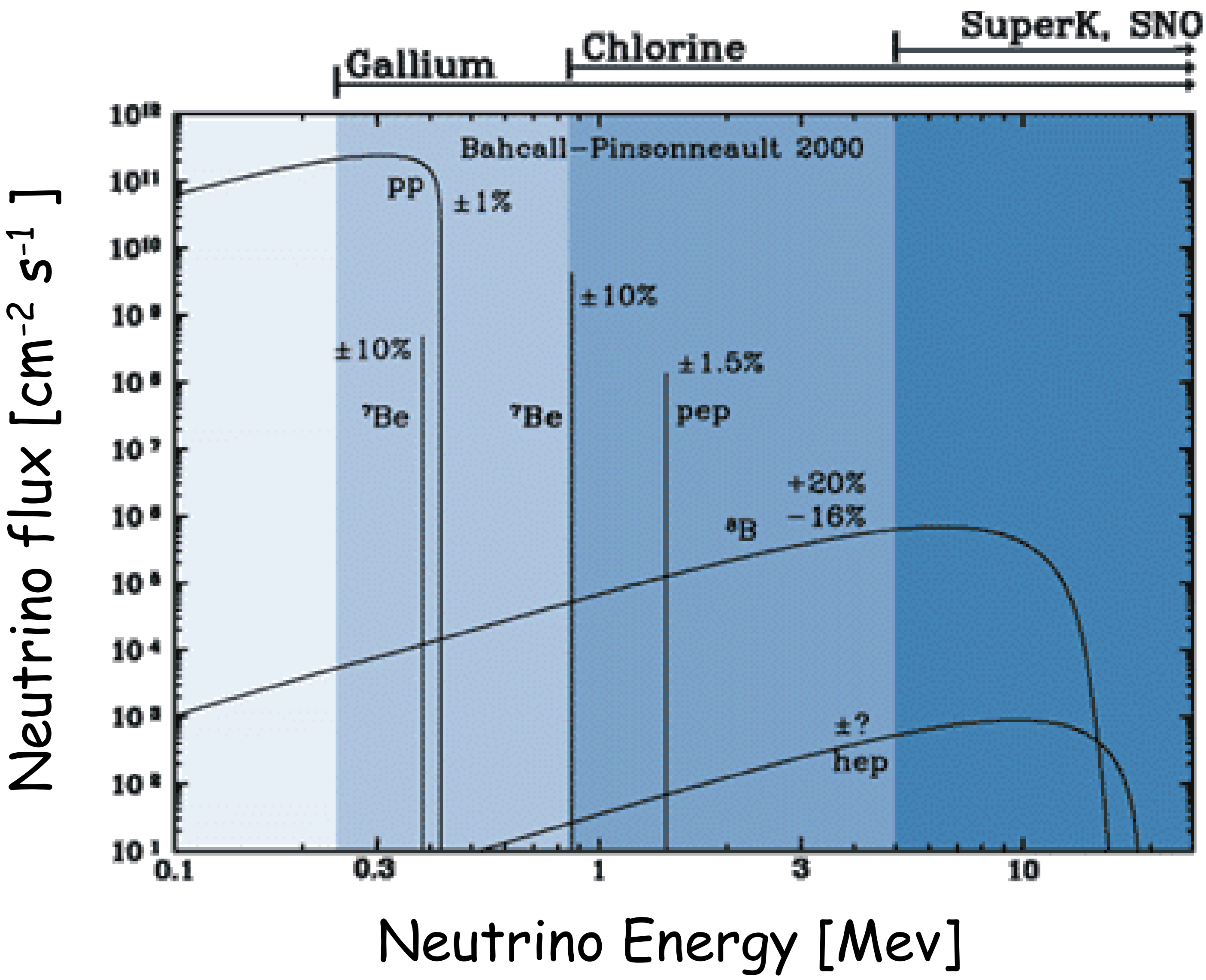
name:	pp	^{7}Be	^{8}B
reaction:	$p+p \rightarrow d+e^{+}+\nu_e$	$^7Be+e^{-} \rightarrow {}^7Li+\nu_e$	$^8B \rightarrow {}^8Be+e^{+}+\nu_e$
energy: [MeV]	≤ 0.42	0.861 (90%) 0.383 (10%)	≤ 15
abundance: [cm $^{-2}$ s^{-1}]	$5.96 \cdot 10^{10}$	$4.82 \cdot 10^{9}$	$5.15 \cdot 10^{6}$
uncertainty: (1σ)	1%	10%	18%
Production zone:	0.1 R_o	0.06 R_o	0.05 R_o^{10}

A group photo : production region



The fraction of neutrino produced inside the sun within dR

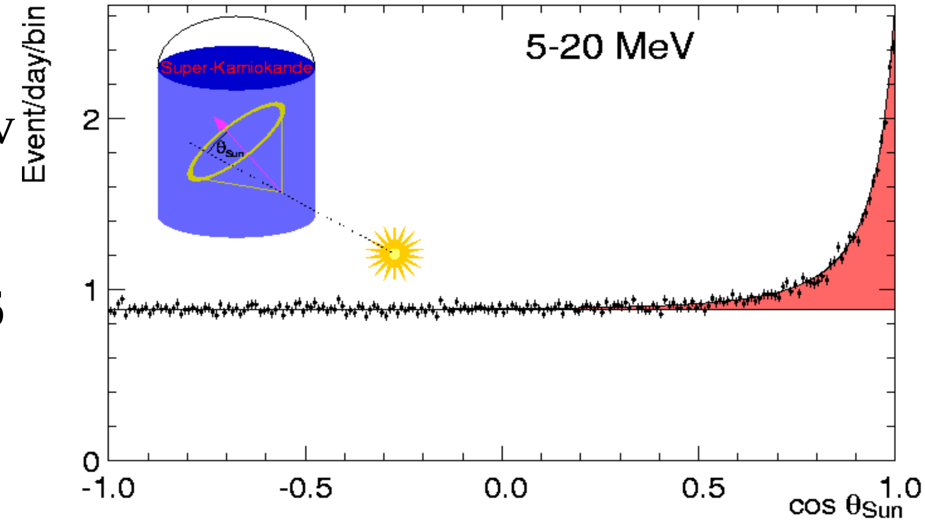
A group photo: energy space



Solar ν experiments, completed or in data taking

Experiment/ Location/ Data taking	Target/ ν interaction/ Threshold	Technique	Sensitivity (SSM) pp	^{7}Be	CNO	pep	^{8}B
Chlorine/ Homestake (USA) 1970-1995	**615 tons of C_2Cl_4** **$^{37}Cl\ (\nu_e, e)\ ^{37}Ar$** **814 keV**	**Radiochemical** counting ^{37}Ar atoms by gas proportional counters	-	15	6	3	77
Kamiokande/ Kamioka (Japan) 1987-1995	**4500 tons of H_2O** **$e + \nu_x \rightarrow e + \nu_x$ (CC+NC)** **7 Mev on recoil electron**	Detection of Cerenkov light emitted by the e- Direction of e- Energy spectrum of e-	-	-	-	-	100
SNO Subury (Canada) 2000-2007	**1000 tons of D_2O** **Separate detection of CC and NC**	Detection of Cerenkov light emitted by the e- And neutron detection	- -	- -	- -	- -	100 100
Borexino LNGS (Italy) 2007-ongoing	**300 tons of C_nH_{2n}** **$e + \nu_x \rightarrow e + \nu_x$ (CC+NC)**	Scintillation light emitted by the e-	-	100	?	YES	YES
Gallex/GNO LNGS (Italy) 1991-2005	**101 tons of $GaCl_3$ solut.** **$^{71}Ga\ (\nu_e, e)\ ^{71}Ge$** **233 keV**	**Radiochemical** counting ^{71}Ge atoms by gas proportional counters	54	27	7	2	10
SAGE Baksan (Caucasus) 1991-2005	**60 tons of met. Ga** **$^{71}Ga\ (\nu_e, e)\ ^{71}Ge$** **233 keV**	**Radiochemical** counting ^{71}Ge atoms by gas proportional counters	54	27	7	2	10

Boron ν experiments : the results of Kamiokande and Superkamiokande



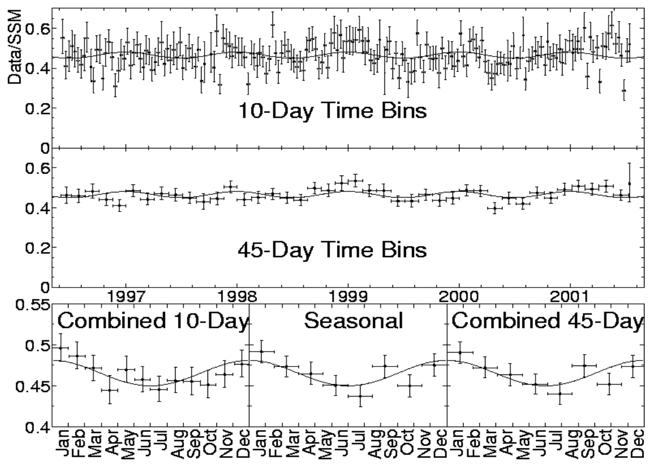
•Method: measure the directional Cerenkov radiation emitted by electrons from

$$e + \nu \rightarrow e + \nu$$

Most sensitive to ν_e since $\sigma(\nu_e) / \sigma(\nu_\mu) \approx 6$

•Results:

- It provides a clear "image" of the Sun with neutrinos.
- First real time experiment with solar neutrinos
- Observes seasonal variation of the flux, due to varying sun Earth oscillation
- Performs a precision test of the ^{8}B ν energy spectrum



22000 ν events observed in 1496 days

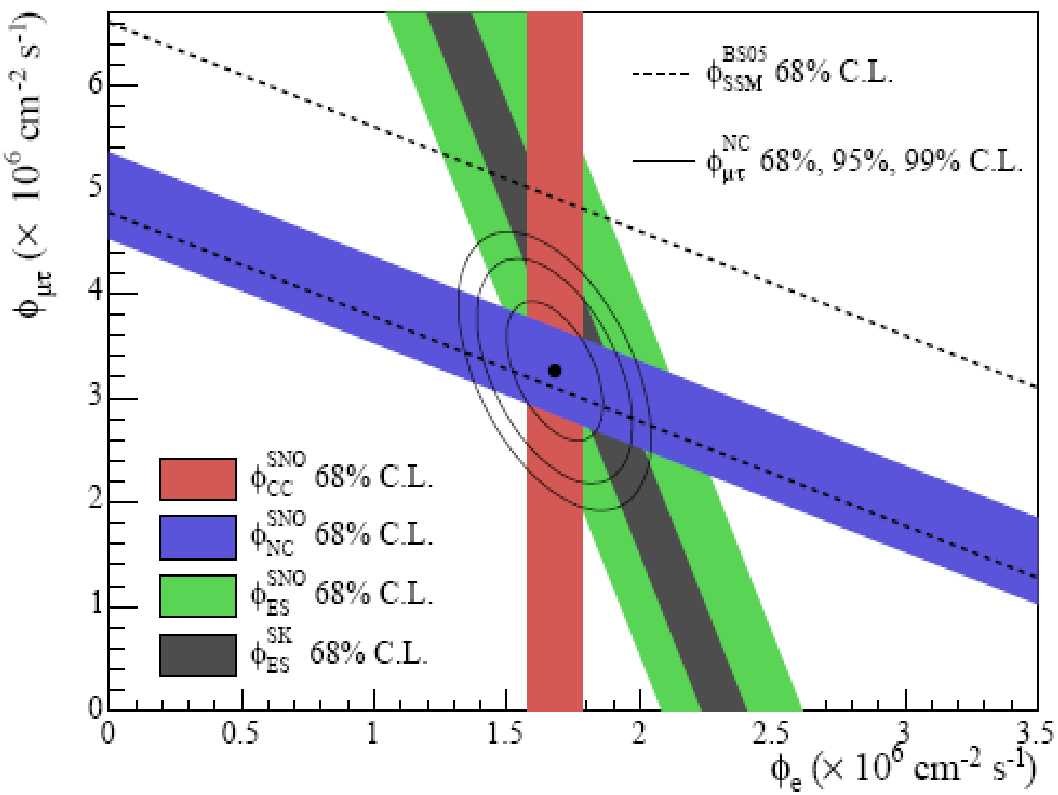
$\Phi(^8B) = 2.35 \text{ +- } 0.025 \text{ +- } 0.065 \ \ 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

R (exp/SSM) = 0.465 +/- 0.005 +/- 0.013

•The experimental resul is half of the signal predicted by Standard Solar Model

Boron neutrinos: the impact of SNO

- The results ok SuperKamiokande, plotted on a (Φ_e, $\Phi_{\mu\tau}$) plane,are a narrow (gray) band, close to the vertical, due to the small sensitivity to neutrinos different from electron type
- The situation changed markedly with the impact of SNO, which was able to detect electron scattering (green), but also and most important, to distinguish CC (red) from NC (bleu) interactions.
- This has provided a clear proof of neutrino oscillation, and a measurement of the total Boron flux



Summary of Main SNO Solar ν Results

- direct measurement of the averaged survival probability of ^{8}B solar ν

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

- total active flux of ^{8}B solar ν agrees with solar model calculations

$$\phi_{NC} = \left(4.94 \pm 0.21(\text{stat.})^{+0.38}_{-0.34}\right) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

- global fit of oscillation parameters, including KamLAND and all solar neutrino data, gives…

$\Delta m^2 = (7.7 \pm 0.2) 10^{-5}\ \text{eV}^2$

$tg^2\theta = 0.46 + 0.04\ -0.05$

The central solar temperature

- Boron neutrinos are excellent solar thermometers due to their high (≈20) power dependence on the central solar temperature.

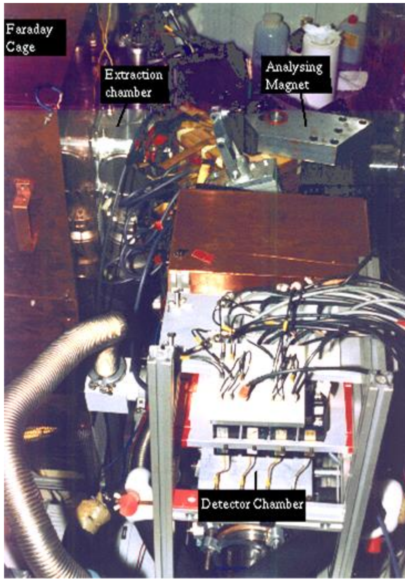
$$\Phi_B = \Phi_B^{(SSM)} [T / T_{(SSM)}]^{20} \cdot S_{33}^{-0.43} S_{34}^{0.84} S_{17} S_{e7}^{-1}$$

- The last terms are astrophysical factors, for the relevant reactions in the Sun (e.g. $S_{33} = S(^3He + ^3He \rightarrow {}^4He + 2p)$
- The boron flux is measured with an accuracy of 4%. From the measured Boron flux, if nuclear cross sections measured in the lab were known perfectly, one would deduce T with accuracy of 0.2%

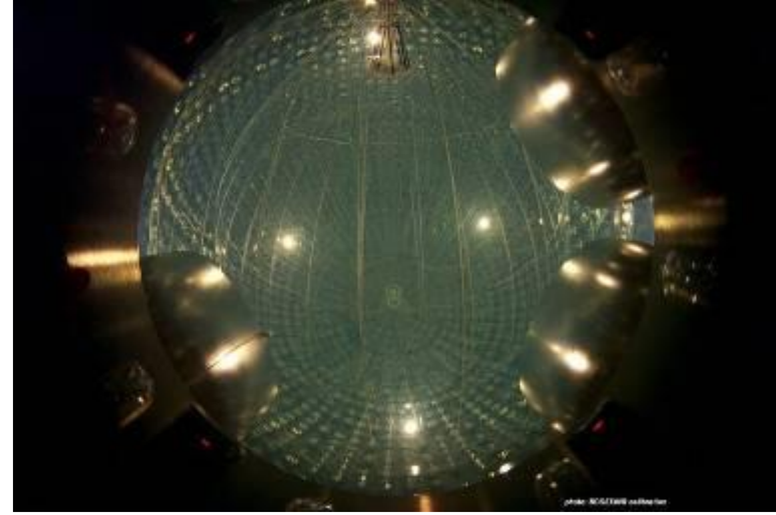
•In fact, in the last few years there have been several new, more accurate measurements of the astrophysical S-factors, mainly by the Luna experiment at Gran Sasso, so that presently nuclear uncertainties and Boron fluxes uncertainties are comparable.

•The result is

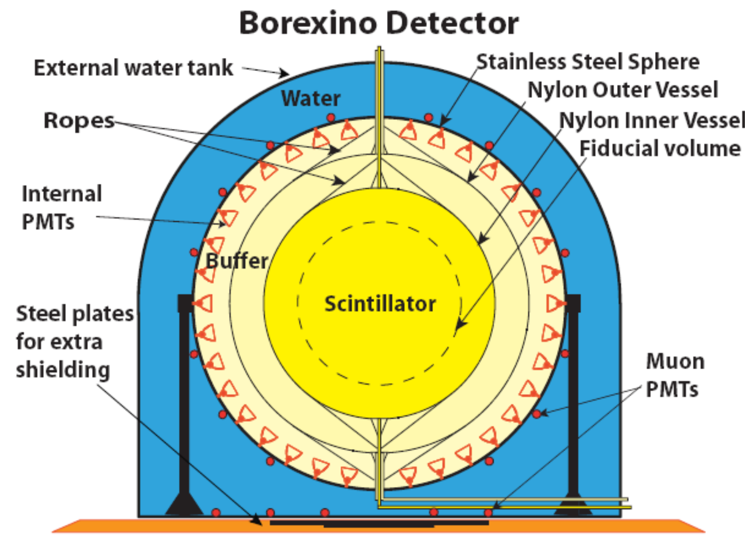
$$T = 15.7(1 \pm 0.3\%)\ 10^6\ K$$



Berillium neutrinos: Borexino at LNGS



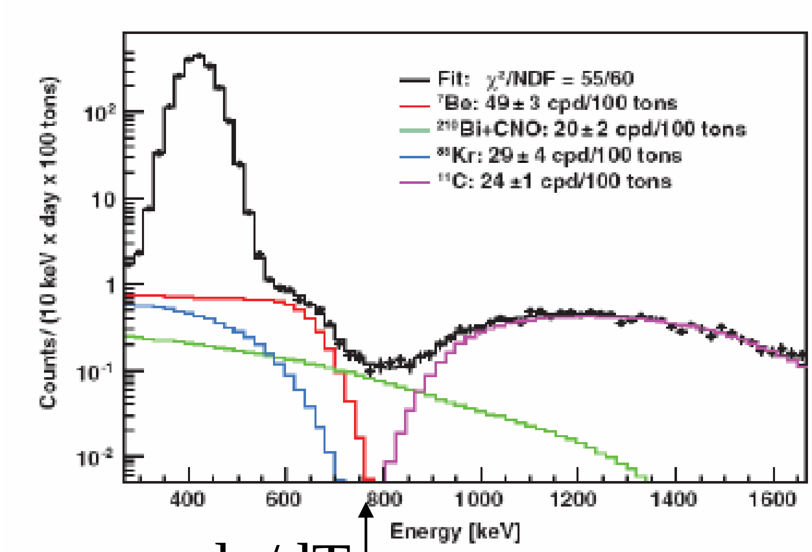
- 300 tons of pseudocumene-based scintillator, of which 100 ton are fiducial volume
- Main goal: measurement of ^{7}Be solar neutrinos by means of ν-e scattering
- 2212 8” PMTs, with light yield ~500 p.e./MeV
- detector was filled on May 15, 2007; first result August 16, 2007, presently running.

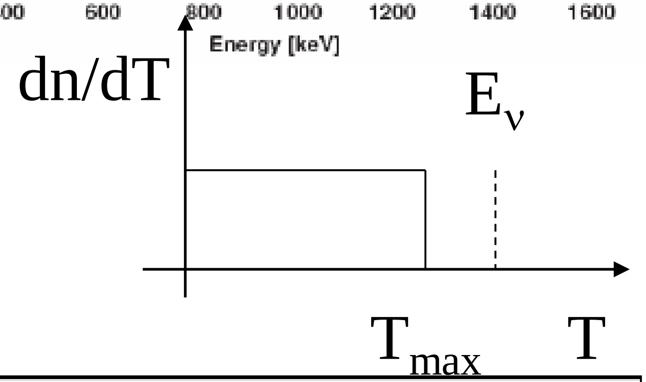


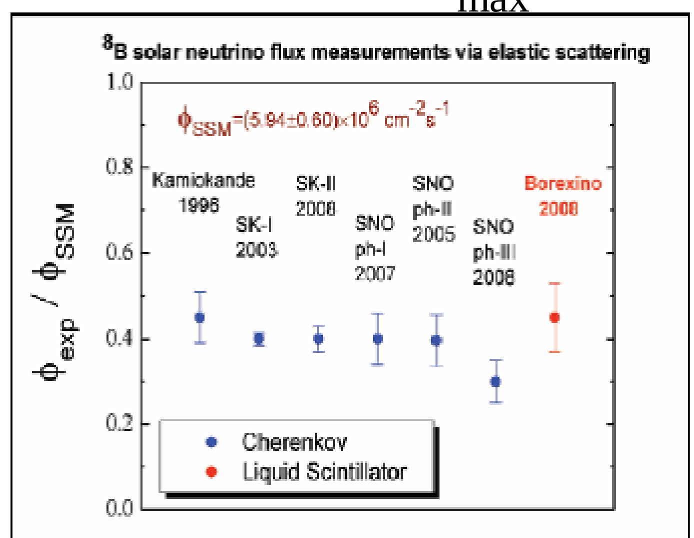
Physics results on ^{7}Be by Borexino at LNGS

- Borexino has observed 7Be neutrino signal:

  49±3stat±4syst (cpd/100 t)
- The expected signal for non oscillated solar neutrino would be is 74±4 cpd/100 t
- The hypothesis of no oscillation for ^{7}Be solar neutrinos is inconsistent with Borexino measurement at the 4 σ C.L.
- The survival probability of the 0.862 MeV 7Be neutrinos is 0.56±0.10.
- Note that this is close to the Vacuum oscillation result of KamLAND
- This is different for the case of ^{8}B neutrinos, as confirmed by Borexino itself



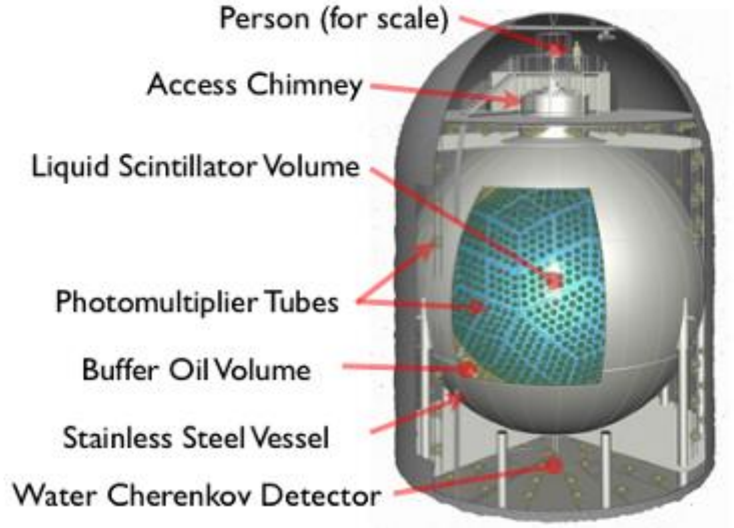


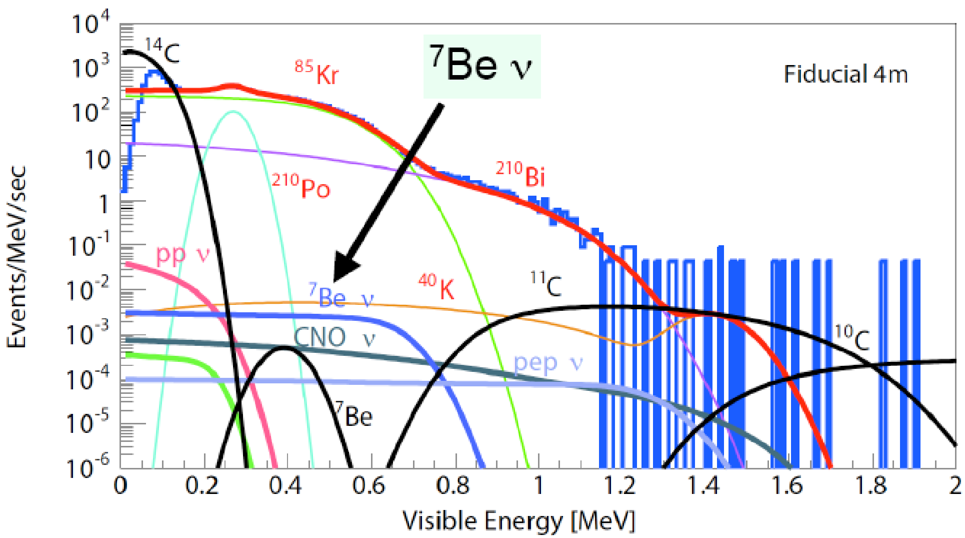


- DA AGGIORNARE….

Experiment in progress for ^{7}Be: KamLAND

- Same operation principle as Borexino
- 1000 tons (80% dodecane, 20% pseudocumene)
- 1880 PMTs (17" and 20")
  - 34% photocathode coverage
- Singles spectrum shows ^{210}Pb and ^{85}Kr and also ^{40}K contamination
- must purify liquid scintillator to achieve solar ν sensitivity
- goal: 10^5 to 10^6 reduction



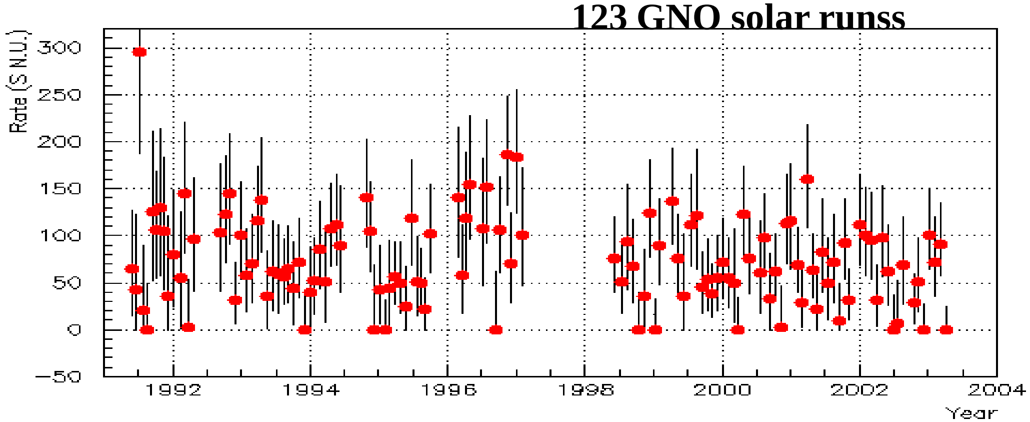


Low energy ν experiments : the results of Gallex/GNO and Sage

Experiment	Results
Gallex/GNO 1991-2003	**69.3 +- 4.1 (stat) +- 3.6 (sys) SNU** R (exp/SSM) = 0.53 +- 0.05 (exp) +- 0.03 (theo) 0.6 ν captured/day
SAGE 1991-ongoing	**69.9 +- 4.6 (stat) +- 3.5 (sys) SNU** R (exp/SSM) = 0.53 +- 0.05 (exp) +- 0.03 (theo)

- **First detection of pp solar neutrinos**
- **Evidence of suppression of sub-Mev ν flux**
- **Monitoring of the low energy ν flux over a complete solar cycle**

123 GNO solar runss



The calibration with the 51Cr source

- The GALLEX experiment, has performed an investigation with an intense man-made ^{51}Cr neutrino source (61.9 + 1.2 PBq).
- The source, produced via neutron irradiation of ~ 36 kg of chromium enriched in ^{50}Cr, primarily emits 746 keV neutrinos. It was placed for a period of 3.5months in the reentrant tube in the GALLEX tank, to expose the gallium chloride target to a known neutrino flux.
- This experiment provides the ratio, R, of the production rate of Cr-produced 71Ge measured in these source exposures to the rate expected from the known source activity
- The result not only was the first observation of low-energy neutrinos from a terrestrial source, but also (a) provides an overall check of GALLEX, indicating that there are no significant experimental artifacts or unknown errors at the 10% level

Most stable isotopes					
Main article: Isotopes of chromium					
iso	NA	half-life	DM	DE (MeV)	DP
^{50}Cr	4.345%	> 1.8×10^{17} y	εε	-	^{50}Ti
^{51}Cr	syn	27.7025 d	ε	-	^{51}V
			γ	0.320	-
^{52}Cr	83.789%	^{52}Cr is stable with 28 neutrons			
^{53}Cr	9.501%	^{53}Cr is stable with 29 neutrons			
^{54}Cr	2.365%	^{54}Cr is stable with 30 neutrons			

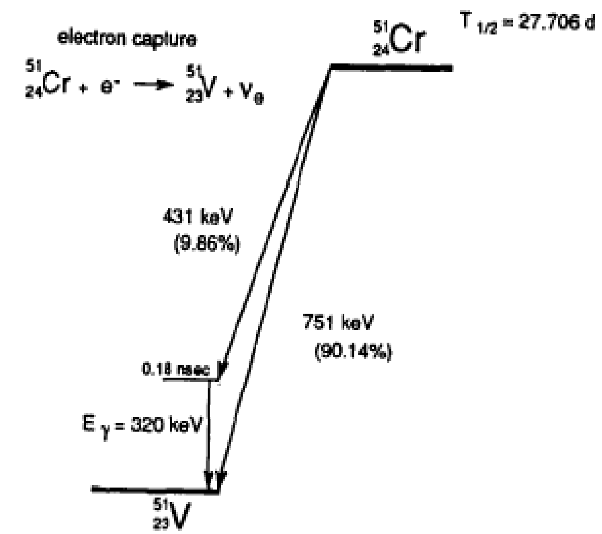


Fig. 1. Characteristics of the decay of ^{51}Cr. The "751 keV" line combines the 746 and 751 keV lines and the "431 keV" line combines the 426 and 431 keV lines.

Strength	63.4 PBq	69.1 PBq
R (meas/expt)	1.01 ±11.5%	0.84 ±11.5%

The final result of GALLEX + GNO

In total, there have been about 12 years of data taking . The final combine result was:

Rate = 69.3 ± 4.1 (stat.) ± 3.6 (syst.) SNU

This has to be compared with the prediction of the solar model in case that neutrino do not oscillate:

R (exp/SSM) = 0.53 +- 0.05 (exp) +- 0.03

Note that as in the case of Beryllium, vacuum oscillation mechanism dominates

1SNU =1 Solar Neutrino Unit= 10 -36 interactions per target atom

The significance of solar neutrino experiments

In summary have shown us that

-1) neutrino oscillate

-2) we can distinguish vacuum and matter oscillations

-3) the energetic of the Sun is fully accounted by hydrogen fusion and radiation energy losses, without need for other energy sources or losses.

The next trasparencies will elucidate these concepts.

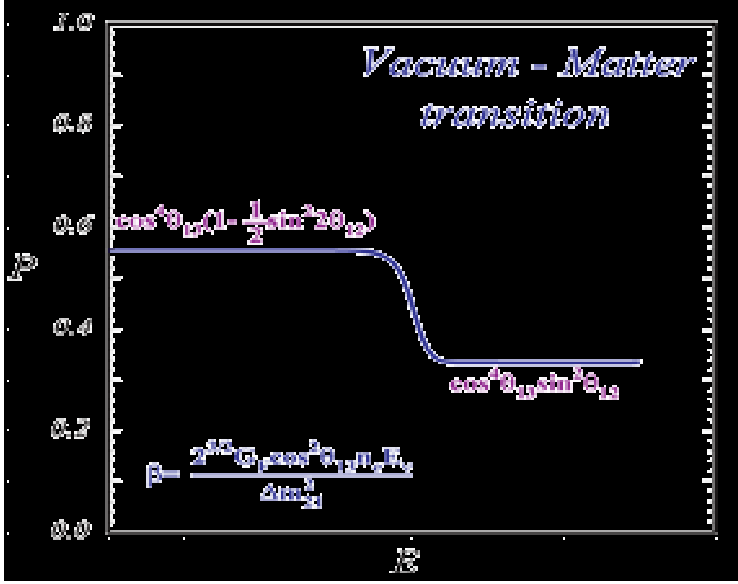
The solution of the Solar Neutrino Puzzle

- In 30 years, all solar neutrino experiments reported a deficit of ν_e with respect to predictions.
- In 2001 SNO, a solar neutrino experiment sensitive to all neutrino flavours, has shown that in the Boron energy region, $\Phi(\nu_e)=1/3\ \Phi(\nu_e+\nu_\mu+\nu_\tau)$,
  i.e. 2/3 of ν_e change flavour during their trip from sun to earth.
- The oscillation parameters which explain all solar neutrino experiments are:

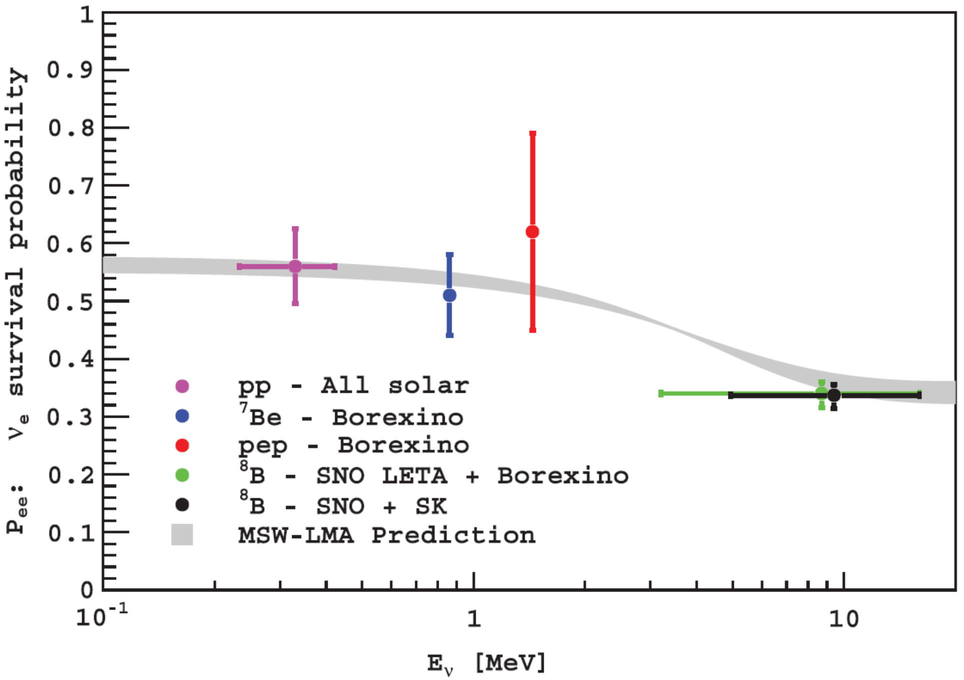
$$\Delta m^2=7.7\ 10^{-5}\ \text{eV}^2$$
$$tg^2\theta=0.46$$

- For Boron, matter effect dominates oscillation, and at energy of ≈ 10 MeV one has $P_{ee}\approx$ 30%.
- At energies smaller or of order 1MeV vacuum oscillation dominate and $P_{ee}\approx$ 60%
- The oscillation parameters deduced from solar neutrino experiments are in perfect agreement with what has been found by KamLAND for reactor antineutrinos.

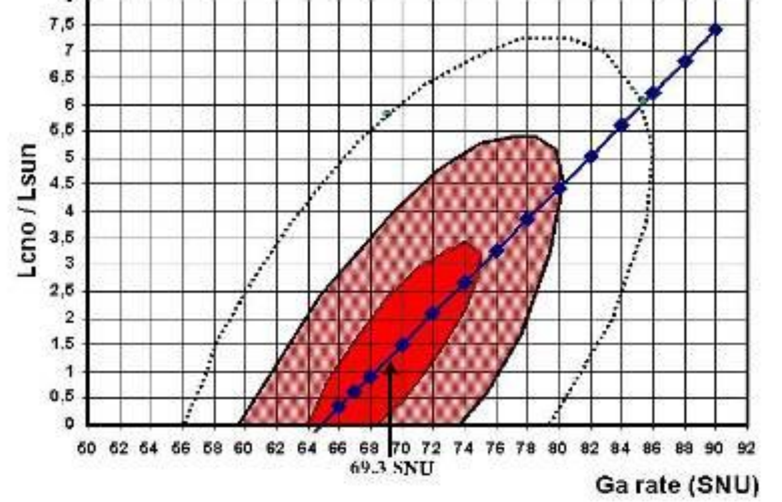
ν_e survival probability as a function of energy, from solar data



- The theoretical curve for the survival probability is shown on the top.
- It includes the possibility of oscillation into 3 neutrinos.
- On the bottom, the values of the survival probability as measured form different experiments, in different energy ranges
- Note that pp and Be neutrinos are in the range of vacuum oscillations, whereas boron neutrinos are dominated by matter effects.
- Not only neutrino oscillations have been established, but also matter effects have been detected



The ultimate answer of Gallium experiments: the Sun is fully powered by nuclear reactions



- Are there additional energy sources beyond 4H->He?:
- Are there additional energy losses, beyond photons and neutrinos?
- Remind that every 4H->He fusion gives 26.7 MeV and 2 neutrinos
- One can determine the "nuclear luminosity" from measured neutrino fluxes (S-Kam. SNO, Cl Ga) $K_{nuc} = \Phi_{tot} Q/2$, and compare it with the observed photon luminosity K:

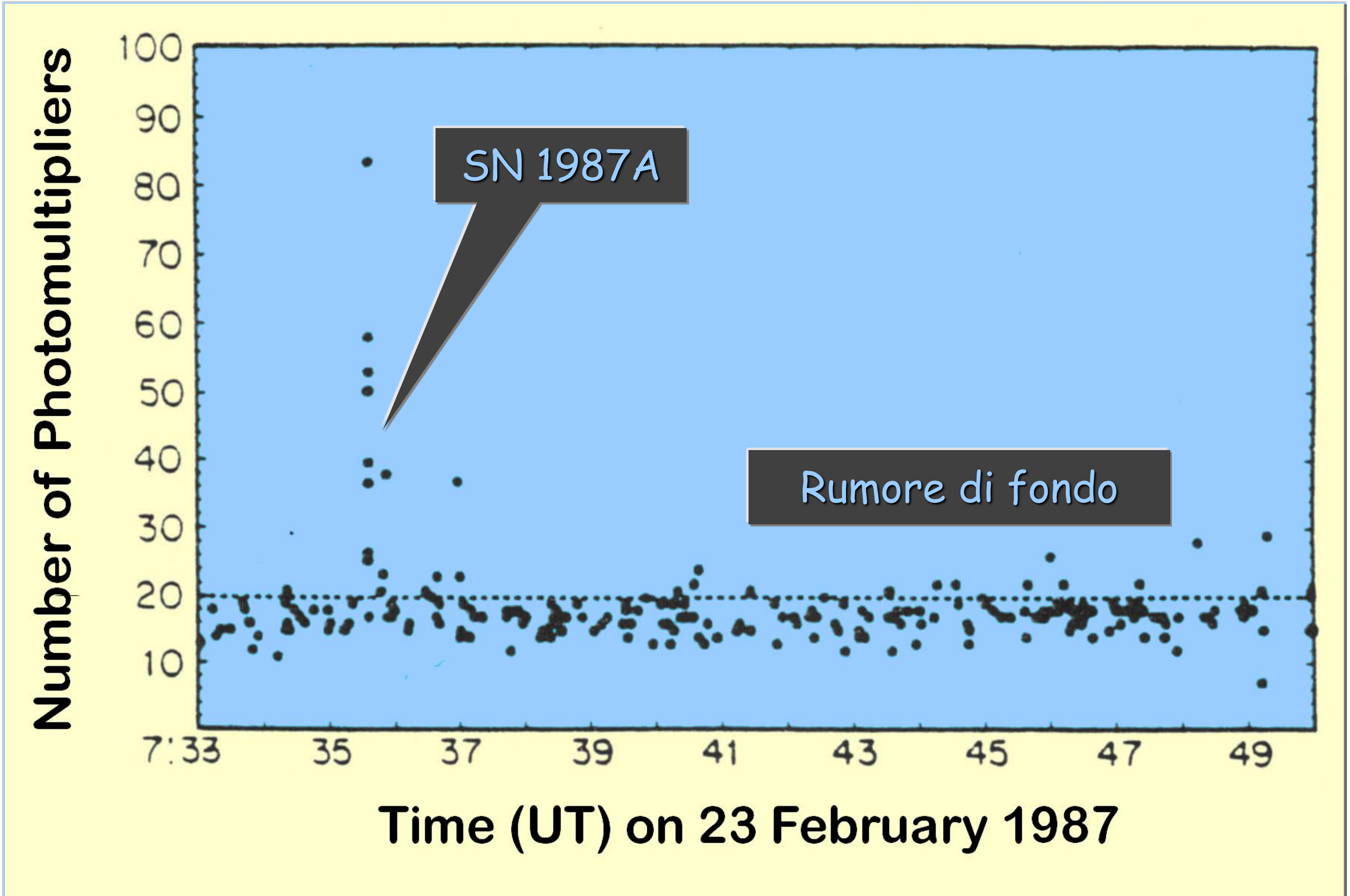
$$(K_{nuc}-K)/K = 0.40 \pm 0.35 \qquad (1\sigma)$$

- This means that - to within 35% - the Sun is actually powered by 4H->He fusion, via the pp chain
- A more precise conclusion will require measuring the CNO contribution .

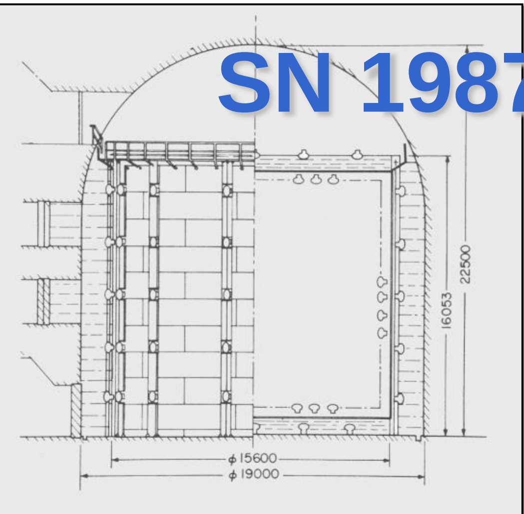
Supernova 1987A

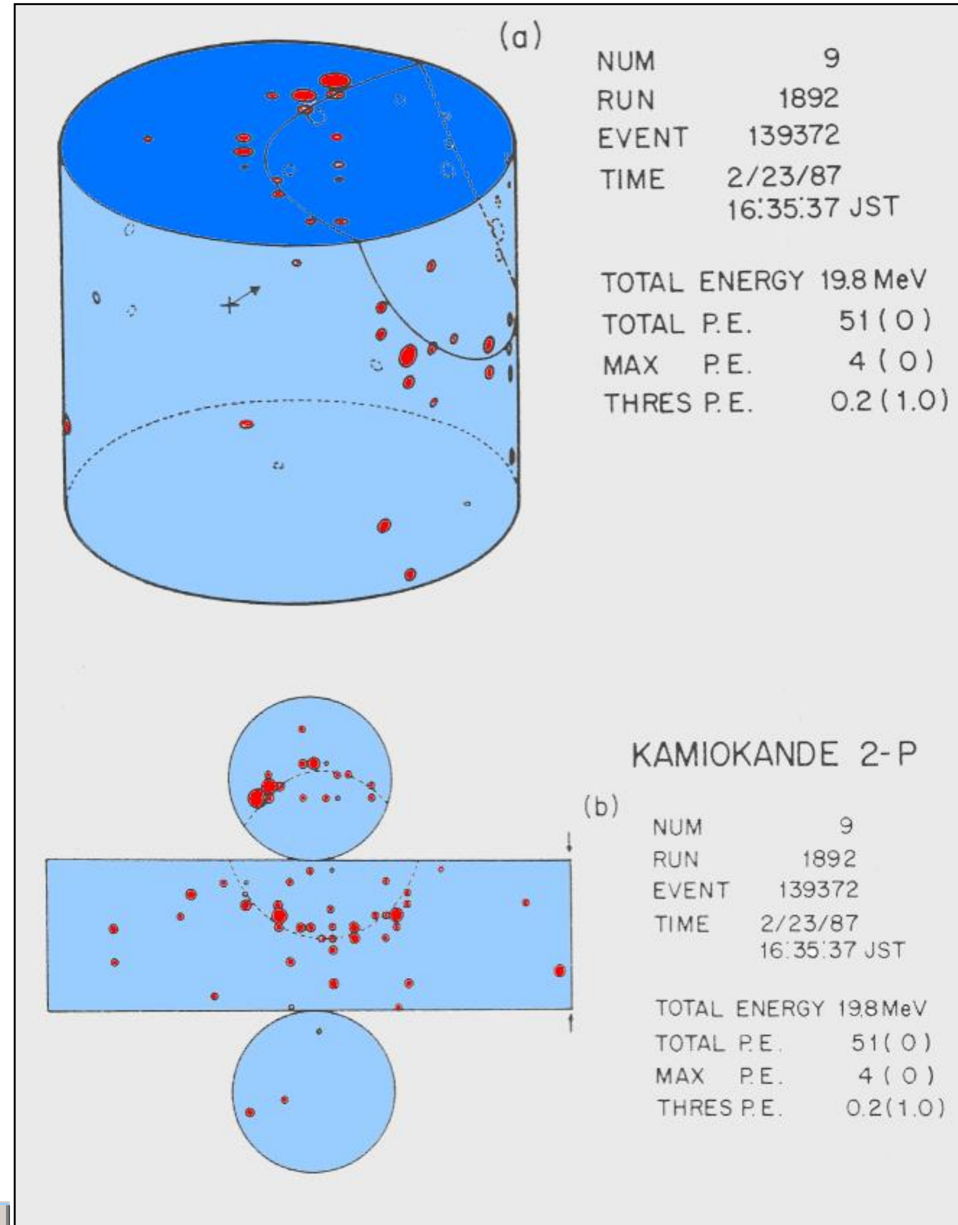
- Nebulosa di Magellano (LMC)
- 50 kpc

Segnale degli (anti)- Neutrini della SN 1987A in Kamiokande



SN 1987A Event No.9 in Kamiokande





- **The observed reaction is**

$$\text{Anti–}\nu_e + p \rightarrow n + e^+$$

- **Few MeV e^+ in water emit Cerenkov radiation, collected by fototubes in the walls**

Hirata et al., PRD 38 (1988) 448

Rilevatori

Le principali osservazioni dei neutrini della SN 1987A vengono da:

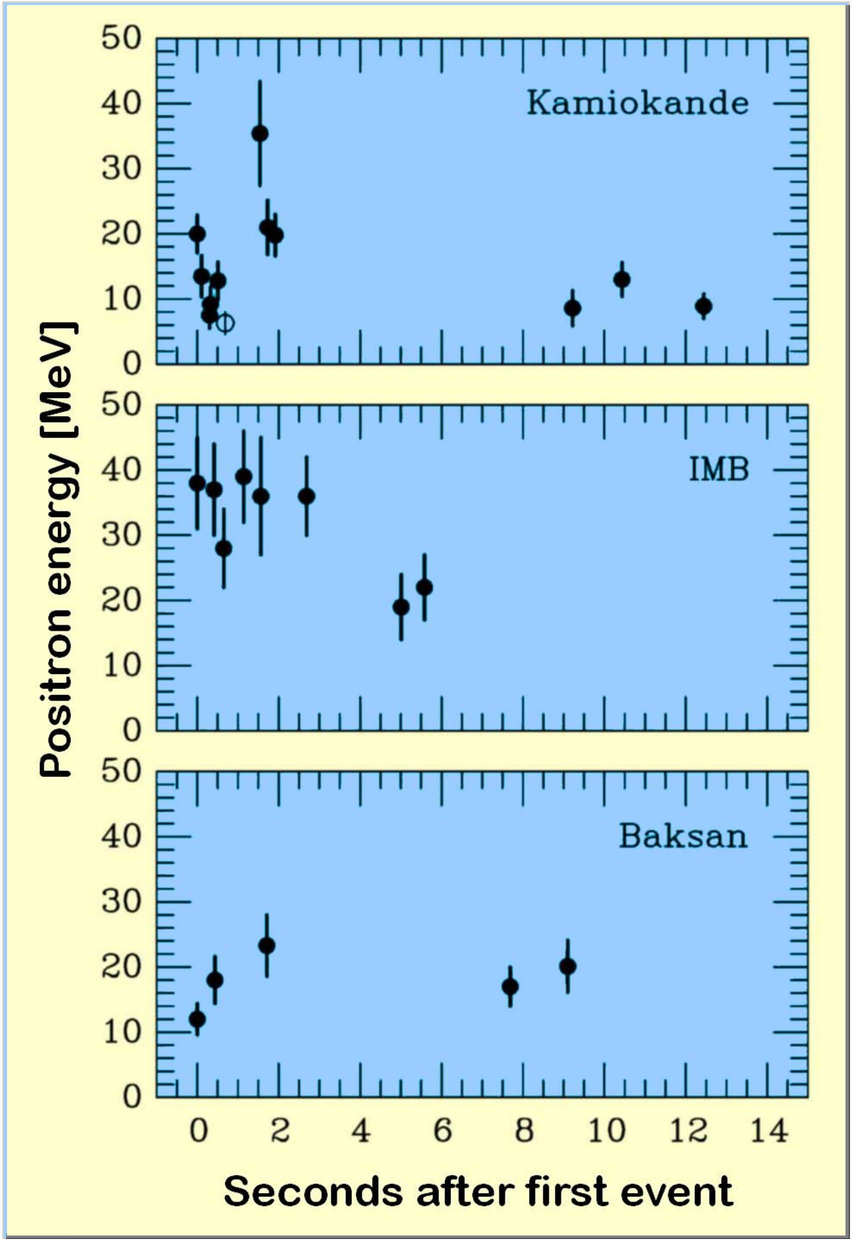
- KII (Kamiokande II)
- IMB (Irvine-Michigan-Brookhaven)

• Rilevatori Cherenkov ad acqua costruiti originariamente per cercare il decadimento del protone.
• I neutrini sono misurati dalla luce Cherenkov emessa da particelle secondarie cariche ($e^{\pm}$) di neutrini di bassa energia.

- BST (Baksan Scintillator Telescope)

• Misura la luce di scintillazione prodotta da particelle secondarie cariche.
• Ha dato una misura meno significativa degli altri.

Segnali dei neutrini dalla Supernova 1987A



Kamiokande (Giappone)
Rilevatore Cherenkov ad acqua
Incertezza temporale ±1 min

Irvine-Michigan-Brookhaven (US)
Rilevatore Cherenkov ad acqua
Incertezza temporale ±50 ms

Baksan Scintillator Telescope
(Unione Sovietica)
Incertezza temporale +2/-54 s

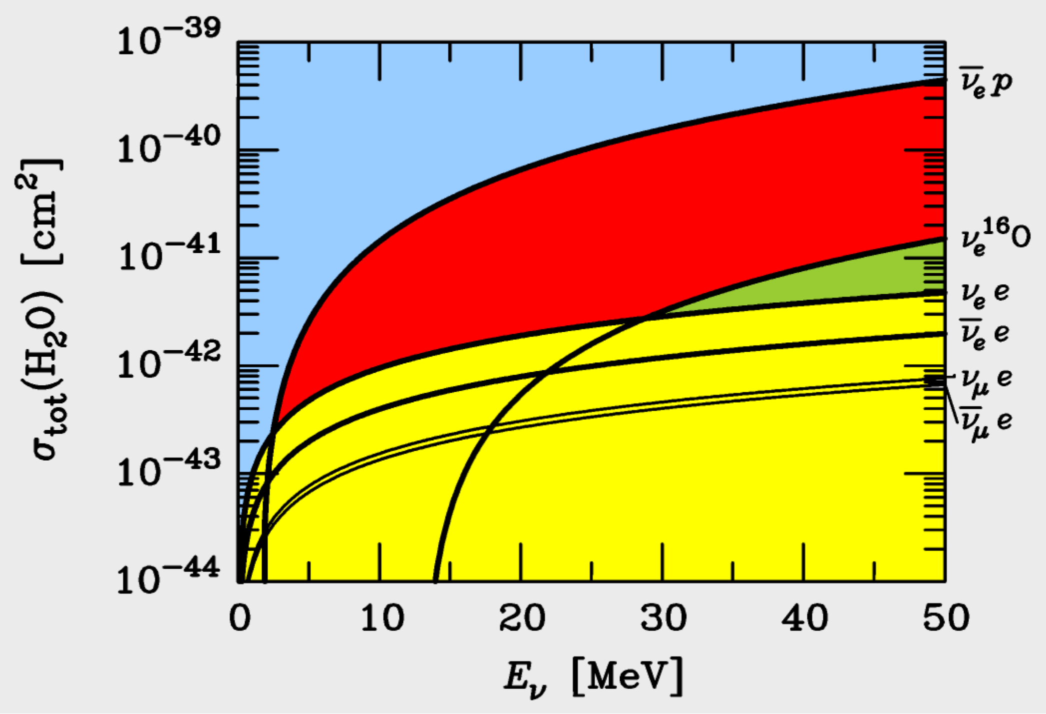
Entro le incertezza temporali,
i segnali sono contemporanei

Sezioni d'urto di neutrini e antineutrini in un bersaglio di acqua

•I processi principali per neutrini
•in acqua sono lo scattering su elettroni e l'interazione di corrente carica sui nuclei di ossigeno

•Per gli antineutrini, il processo beta inverso su protoni ha la sezione d'urto piu' grande.

•Questo e' il motivo per cui si ritiene che quelli che sono osservati nella SN sono gli antineutrini, di tipo elettronico ovviamente.

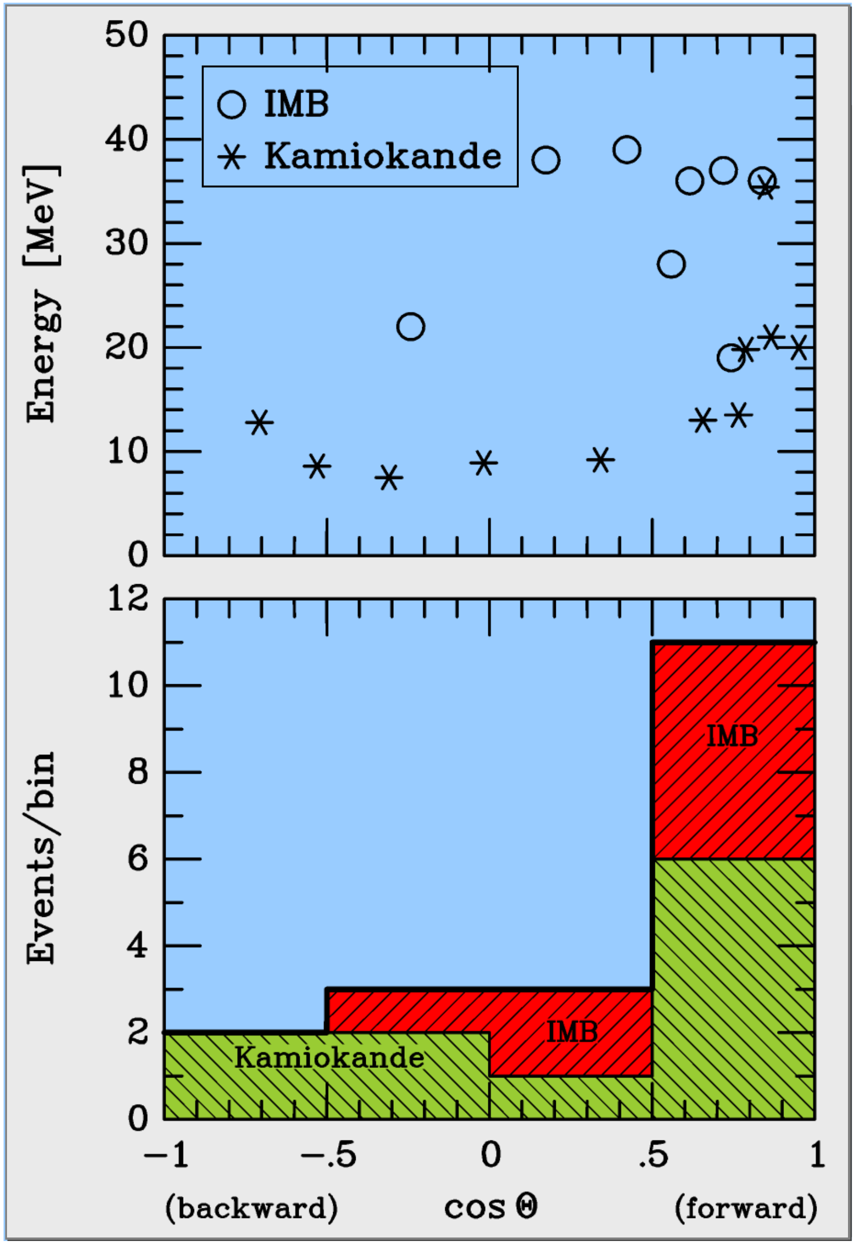


reazioni principali: $\bar{\nu}_e + p \rightarrow n + e^+$ dominante per le SN

$$\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$$

$\nu + e^- \rightarrow e^- + \nu$ dominante per il Sole

Distribuzione angolare dei neutrini da SN 1987A



- Ricordiamo che la reazione principale di rilevazione:

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

e' essenzialmente isotropa per le energie rilevanti.

- Ci si aspetta solo una frazione di eventi dalla reazione direzionale:

$$\nu + e^- \rightarrow e^- + \nu$$

- Il Segnale osservato e' compatibile con l'isotropia solo allo 0.1 % CL, ma non conosciamo alternative.

Modello con raffreddamento esponenziale

- I dati raccolti, una manciata di neutrini, sono in grado di confermare le caratteristiche principali del modello di supernova, ossia la luminosita', l'energia media dei neutrini, il tempo di raffreddamento
- Il modello piu;' semplice e' che i neutrini siano emessi termicamente da una sfera di raggio R, con luminosita' che varia secondo una legge esponenziale:

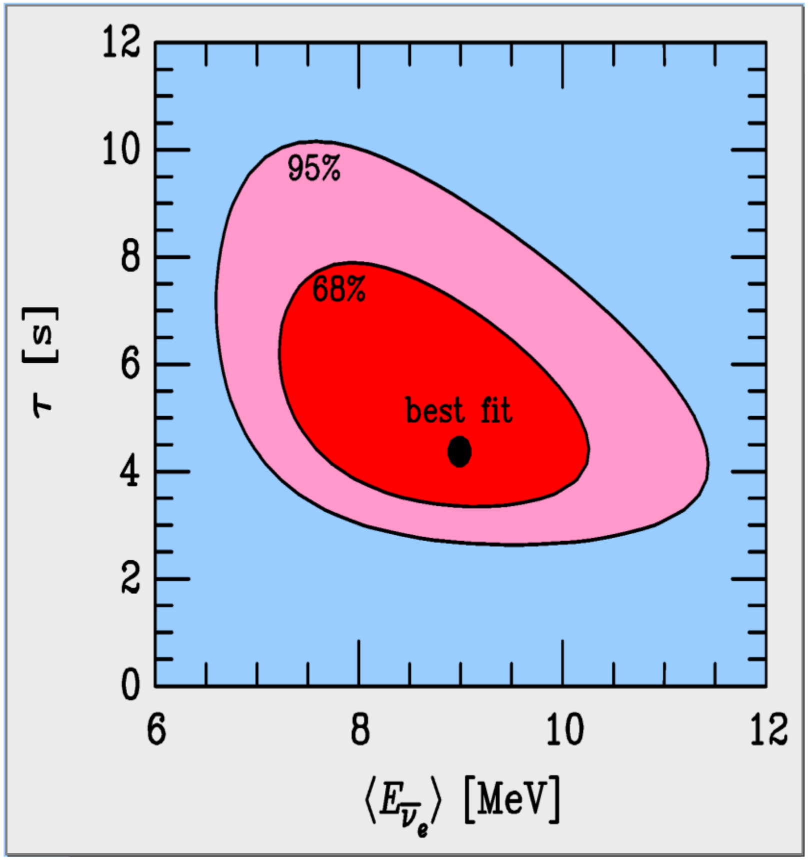
$$L=L_o \exp(-t/\tau)$$

- Dove L_o e' la luminosita' iniziale in antineutrini di tipo elettronico e τ, tempo di raffreddamento, sono parametri.
- Se determino questi, potro' anche determinare l'energia totale trasportata dagli antineutrini, $U_B=6L_o\,\tau$, ossia l'energia liberata dal collasso gravitazionale, se assumo che questo produca in egual misura neutrini e antineutrini, di ciascun tipo.
- Se l'emissione avviene termicamente da una sfera di raggio R, secondo la legge di Stefan-Boltzman avro' $L= 4\pi R^2 \sigma T^4$
- Dunque anche la temperatura varia esponenzialmente [$T=T_o \exp(-t/ 4\tau)$]
- La temperatura e' collegata all' energia media dei neutrini, secondo la distribuzione statistica, $\langle E\rangle=3kT$, e la luminosita' e' collegata al flusso misurato di neutrini, moltiplicato per la loro energia media.
- In breve, I parametri liberi sono tre, Lo (ovvero T_o) , τ ed R da ricavarsi in termini dei dati dei neutrini

I risultati principali sulla supernova

- L'analisi dei dati in questo semplice modello (Loredo & Lamb 95) da'
- R = 40 Km
- τ = 4,4 s
- kT_0 = 3,8 MeV

- L'energia liberata dalla supernova risulta di 5 10^{53} erg, in accordo coi modelli correnti
- Il raggio R della neutrino sfera e' anch;esso coerente con i modelli teorici
- Il quadro della formazione di una stella di neutroni, con emissione di energia in neutrini e' sostanzialmente confermato



Proprieta' dei neutrini

dalla SN 1987A

Infromazioni sulle proprieta' dei neutrini : limiti da SN 1987 A

Se i neutrini avessero massa ≠ 0 allora neutrini con diverse energie avrebbero diverse velocita' ed arriverebbero sulla terra con tempi diversi.

Il ritardo tra due neutrini di diversa energia sarebbe:

$$\Delta \mathbf{t} = \frac{\mathbf{L}}{2\mathbf{c}} \mathbf{m}^2 \mathbf{c}^4 \left(\frac{1}{\mathbf{E}_1^2} - \frac{1}{\mathbf{E}_2^2} \right)$$

Lo spread del tempo di arrivo dei neutrini elettronici non supera i 10 s.

Prendendo come energie: $E_1 = 10$ MeV ed $E_2 = 20$ MeV

otteniamo facilmente:

$$\mathbf{m}_{\nu_e} \mathbf{c}^2 \leq 20\,\mathbf{eV}$$

Stabilita' del neutrino

Per risolvere l'enigma dei neutrini solari Cabibbo et al. avevano proposto che i ν_e potessero decadere durante il percorso sole-terra.
Questo implicherebbe che i neutrini avessero massa m ≠ 0 e vita media τ:

$$\mathbf{t} = \gamma \cdot \tau = \frac{\mathbf{E}}{\mathbf{m}} \quad \Longrightarrow \quad \tau_{\nu_e} = \mathbf{t} \cdot \frac{\mathbf{m}_{\nu_e}}{\mathbf{E}_{\nu-\mathbf{sole}}}$$

Per $E_{\nu\text{-sole}} = 10$ MeV

t = 500 s

$$\Rightarrow \quad \tau \approx 5 \cdot 10^{-5} \mathbf{s} \, \frac{\mathbf{m}}{\mathbf{eV}}$$

L'aver osservato $\bar{\nu}_e$ dalla SN 1987 A implica:

$E_{\nu\text{-sn}} = 10$ MeV

t = 150000 anni

$$\Rightarrow \quad \tau > 5 \cdot 10^{5} \mathbf{s} \, \frac{\mathbf{m}}{\mathbf{eV}}$$

Possiamo dunque ricavare un limite diretto riguardo alla stabilita' del neutrino.

Carica elettrica del neutrino?

I neutrini, per arrivare fino a noi, devono attraversare un campo magnetico.
Se avessero carica ≠ 0 sarebbero deviati in maniera diversa a seconda della loro energia E.

$$\Delta t = \frac{1}{12} c S \frac{\Delta E}{E} \left(\frac{qBS}{E} \right)^2$$

Prendiamo $E = 10$ MeV
$\Delta E = 10$ MeV
$\Delta t \leq 10$ s

CAMPO GALATTICO

$S \approx 10$ kpc
$B \approx 10^{-6}$ G

$$q \leq 10^{-17} e$$

CAMPO INTERGALATTICO

$S \approx 50$ kpc
$B \approx 10^{-9}$ G

$$q \leq 10^{-15} e$$

I limiti di laboratorio danno:
(scattering ν-e)

$$q \leq 10^{-10} e$$

Verifica del principio di equivalenza

Principio di equivalenza: “tutti i corpi si muovono allo stesso modo in un campo gravitazionale”.

L’intervallo di tempo che intercorre tra il burst di neutrini e il segnale ottico e’ in accordo con quanto ci aspettiamo debba trascorrere tra il collasso gravitazionale del nucleo di Ferro e l’esplosione di Supernova.

I neutrini ed i fotoni sembrano quindi impiegare circa lo stesso tempo per raggiungere la terra, con un errore:

$$\mathbf{\Delta t}_{\nu-\gamma} \leq \mathbf{t}_{\nu-\gamma} \approx 3\,\mathbf{ore}$$

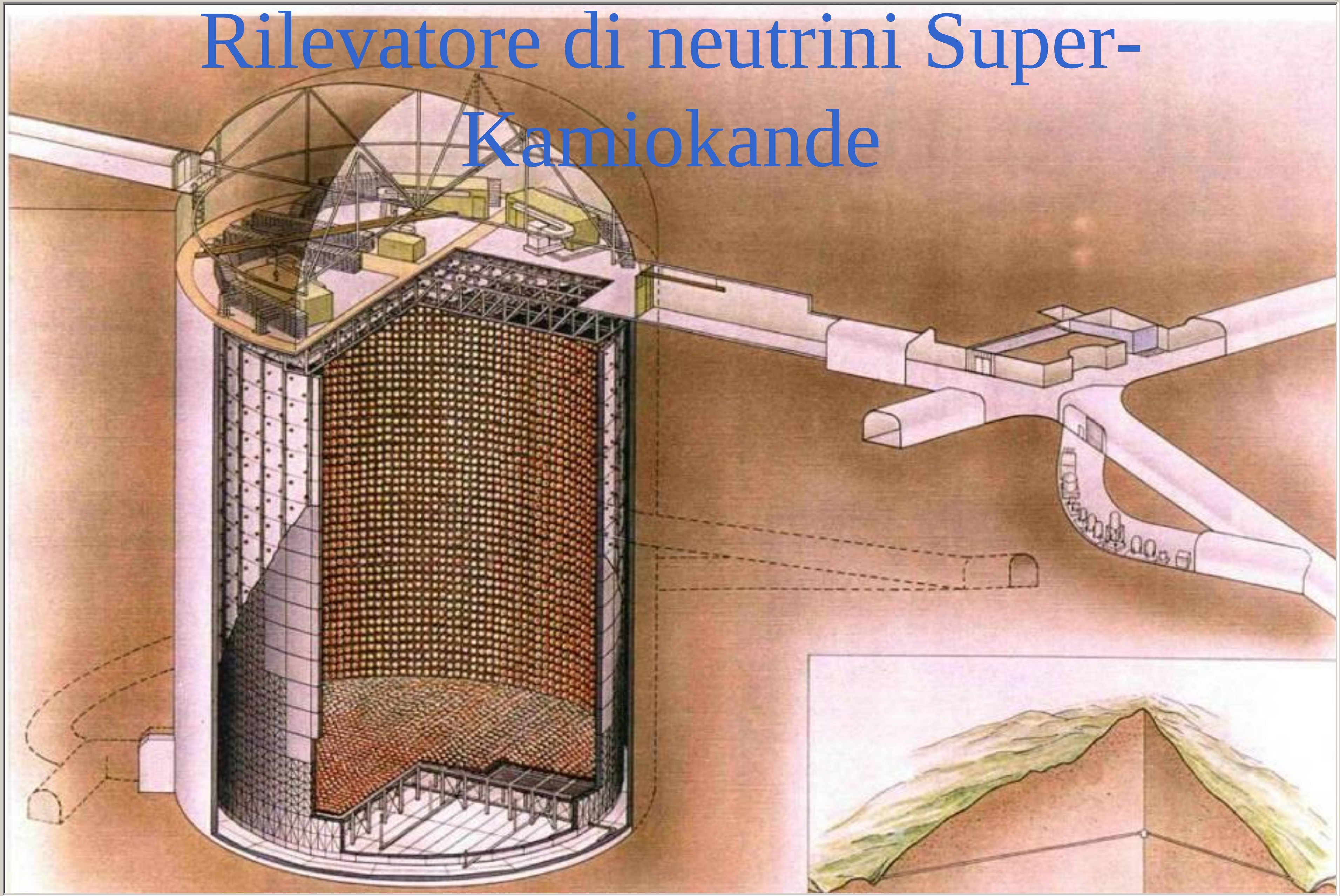
Ne possiamo ricavare una stima della velocita’ dei neutrini :

$$\mathbf{\Delta t}_{\nu-\gamma} = \mathbf{D}\left(\frac{1}{\mathbf{v}_\nu} - \frac{1}{\mathbf{c}}\right) \approx \frac{\mathbf{L}}{\mathbf{c}}\left(1 - \frac{\mathbf{v}_\nu}{\mathbf{c}}\right)$$

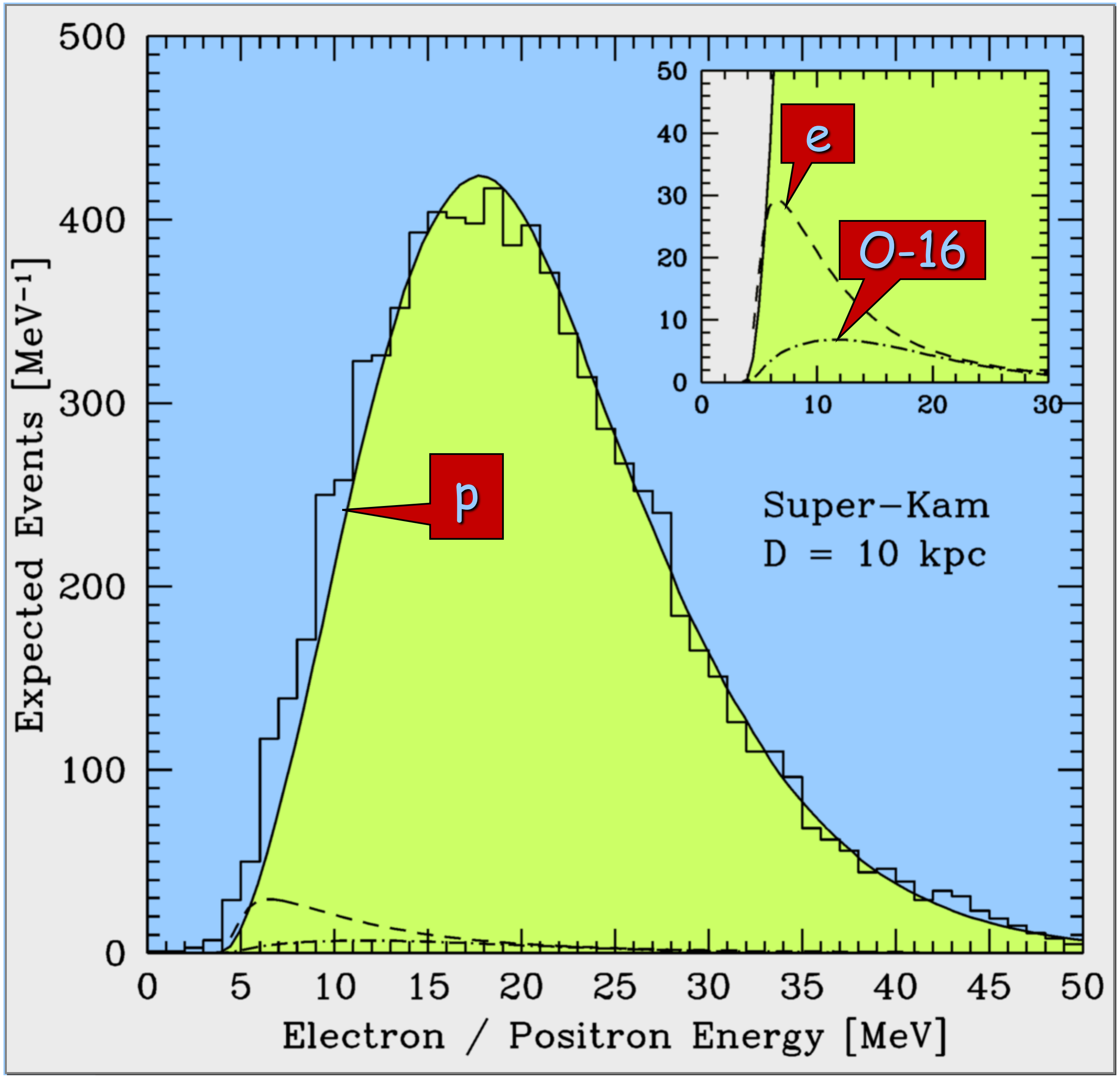
$$\boxed{\mathbf{v}_\nu = \mathbf{c}\left(1 \pm 10^{-9}\right)}$$

Il futuro

Rilevatore di neutrini Super-Kamiokande



Segnale di una SN Galattica in Super-Kamiokande

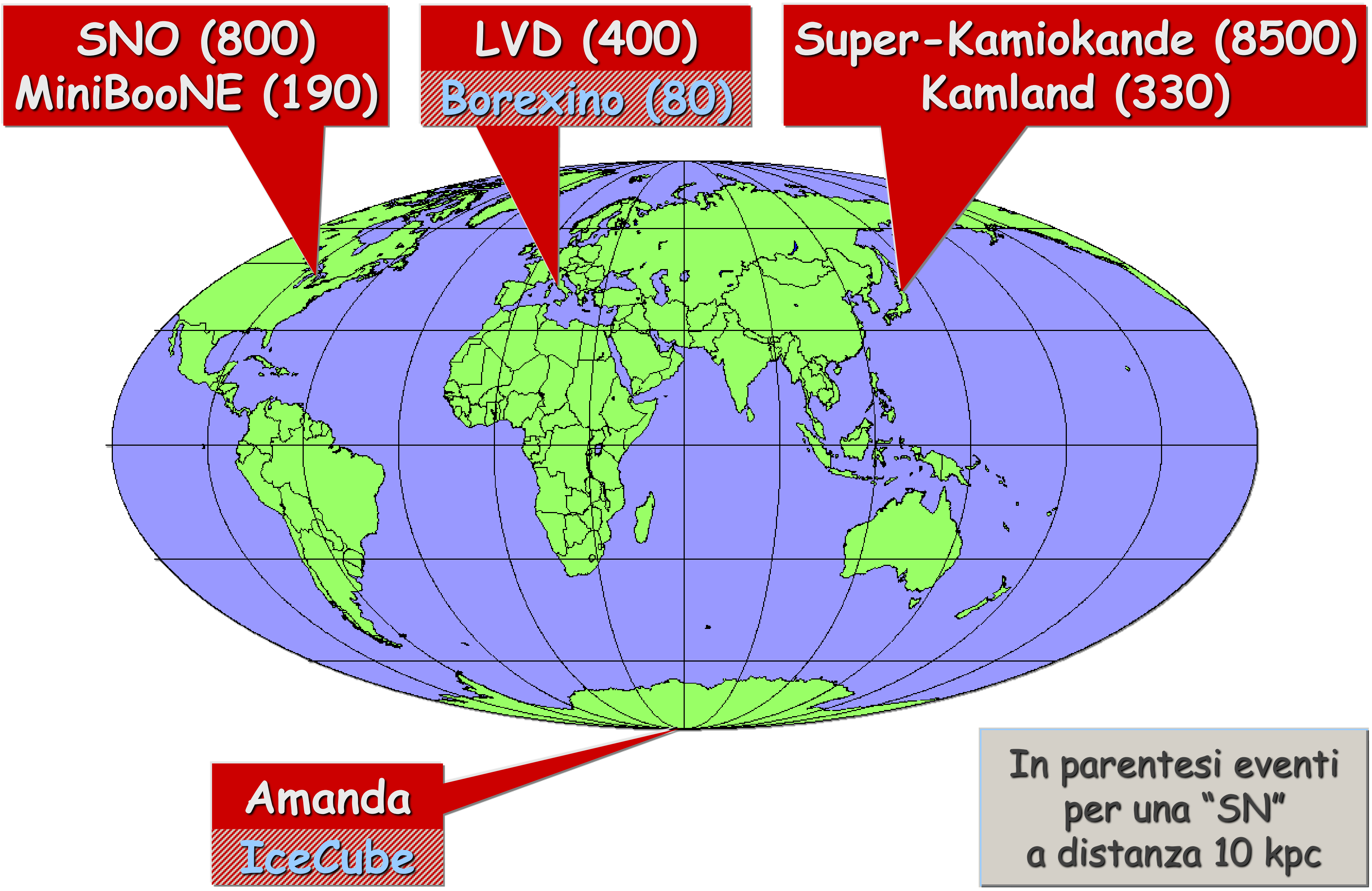


Simulazioni Monte-Carlo for Super-Kamiokande Segnale di SN a 10 kpc, basate su un modello numerico di Livermore

Totale of circa 8300 eventi per t < 18 s

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

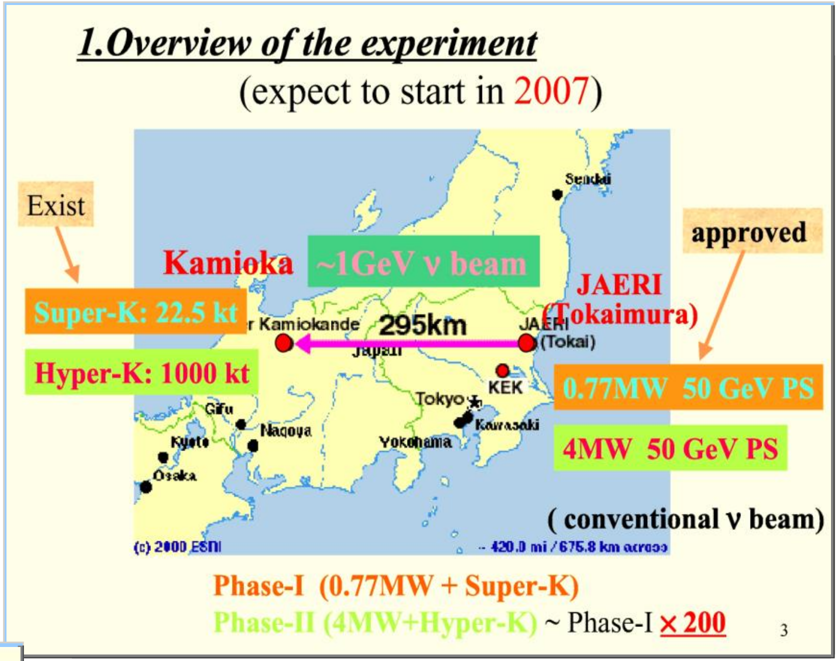
Grandi Rilevatori per Neutrini da SN

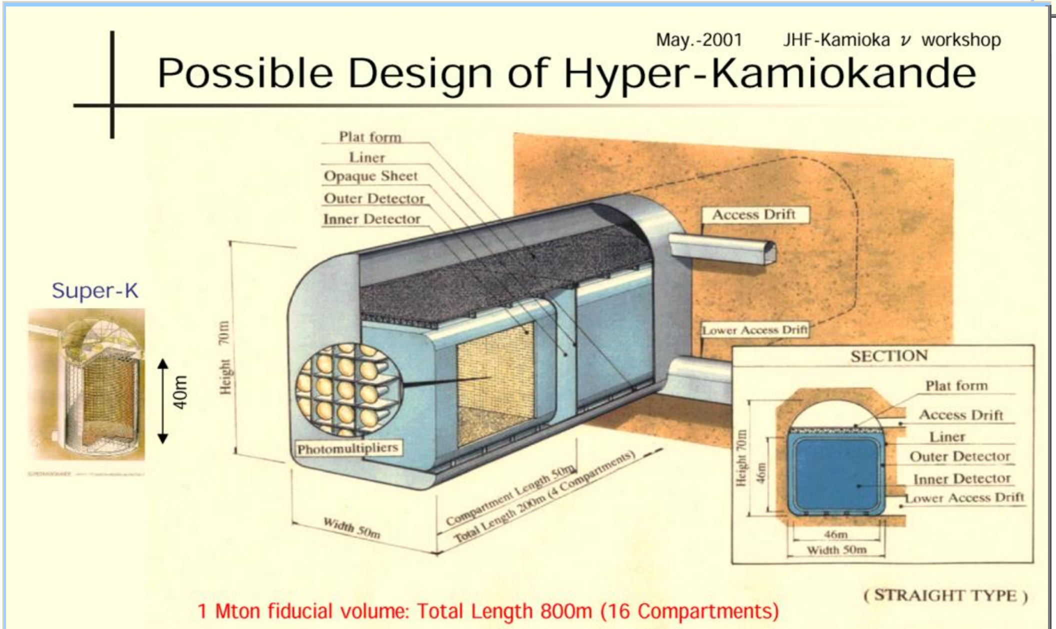


In parentesi eventi per una "SN" a distanza 10 kpc

The Future: A Megaton Detector?

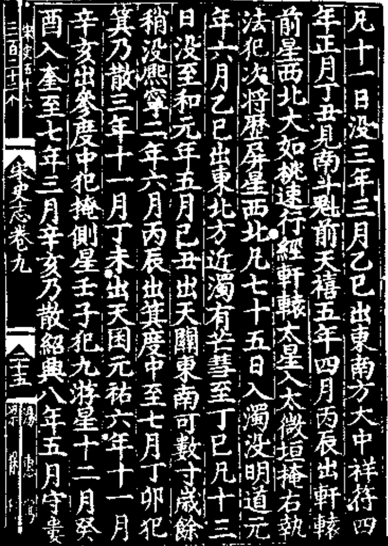
Megaton detector motivated by
- Long baseline neutrino osc.
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)





Similar discussions in
- USA (UNO project)
- Europe (Frejus Tunnel)

•Note however we are confined to the Galaxy

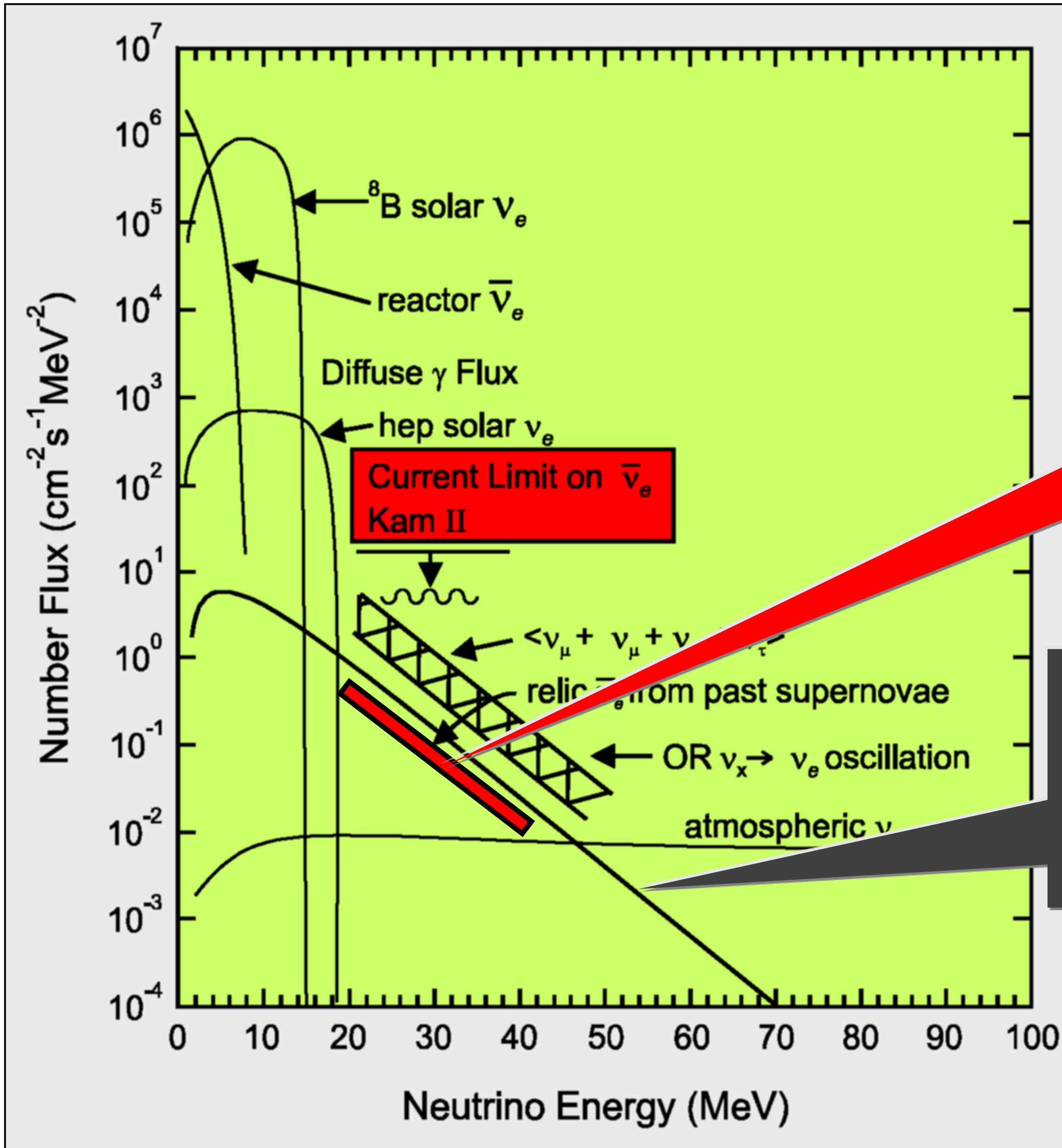

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

Relic neutrinos from past supernovae

- SN in our galaxy are rare and luck is needed to catch one
- However, we are exposed to the flux from past supernovae from other galaxies, integrated over the Hubble time
- This flux carries the history of the galactic evolution
- An observable window exist between Solar and atmospheric ν

Experimental Limits on Relic SN Neutrinos



Super-K upper limit
29 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

Upper-limit flux of
Kaplinghat et al.,
astro-ph/9912391
Integrated 54 cm^{-2} s^{-1}

Search for relic SN Nus at Super-Kamiokande

TABLE I: The SRN search results are presented for six theoretical models. The first column describes the method used to calculate the SRN flux. The second column shows the efficiency-corrected limit on the SRN event rate at SK. The third column is the flux limit set by SK, which can be compared with the theoretical predictions that are shown in the fourth column. The fifth column shows the flux predictions above a threshold of $E_\nu > 19.3$ MeV . Note that the heavy metal abundance calculation only sets a theoretical upper bound on the SRN flux [7].

Theoretical model	Event rate limit (90% C.L.)	SRN flux limit (90% C.L.)	Predicted flux	Predicted flux ($E_\nu > 19.3$ MeV)
Galaxy evolution [4]	< 3.2 events/year	$< 130\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$44\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.41\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Cosmic gas infall [5]	< 2.8 events/year	$< 32\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$5.4\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.20\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Cosmic chemical evolution [6]	< 3.3 events/year	$< 25\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$8.3\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.39\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Heavy metal abundance [7]	< 3.0 events/year	$< 29\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$< 54\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$< 2.2\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Constant supernova rate [4]	< 3.4 events/year	$< 20\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$52\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$3.1\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Large mixing angle osc. [8]	< 3.5 events/year	$< 31\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$11\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.43\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

hep-ex/0209028

Experimental sensitivity is approaching predictions