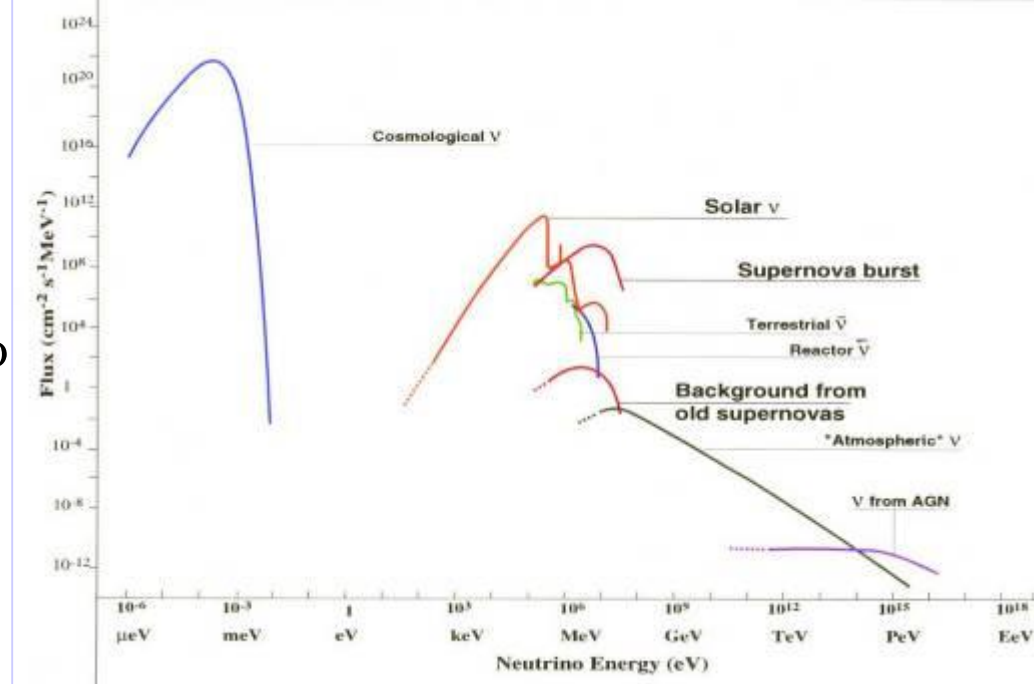


# Rivelazione di neutrini astrofisici

- Negli ultimi venti anni i neutrini sono diventati una sonda per l'astrofisica
- Si sono osservati, e in alcuni casi misurati in grande dettaglio:
  - Antineutrini dalla Terra
  - Neutrini dal sole:
    - Alta energia (boro)
    - Energia intermedia (Berillio)
    - Bassa energia (pp)
  - Antineutrini da supernova
- Per la comprensione dei risultati, cioè la calibrazione dei telescopi con neutrini, è essenziale la conoscenza del fenomeno delle oscillazioni dei neutrini, discusso nel capitolo precedente



- Scopo di questo capitolo è di passare in rassegna i risultati attuali, discutere le loro implicazioni e dare un quadro delle prospettive future

# 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  $^{40}\text{K}$ ) to terrestrial heat production?

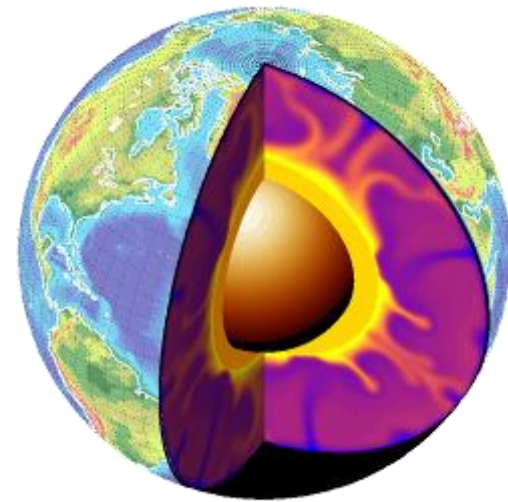
• 2 - How much U and Th in the crust?

• 3 - How much U and Th in the mantle?

• 4 - What is hidden in the Earth's core?

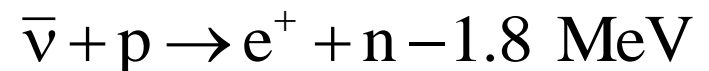
(geo-reactor,  $^{40}\text{K}$ , ...)

• 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  $^{40}\text{K}$ ) bring to surface information on the abundances of these elements in the Earth's interior

• Geo-neutrinos from Uranium and Thorium (not from Potassium) are above threshold for inverse beta on free protons

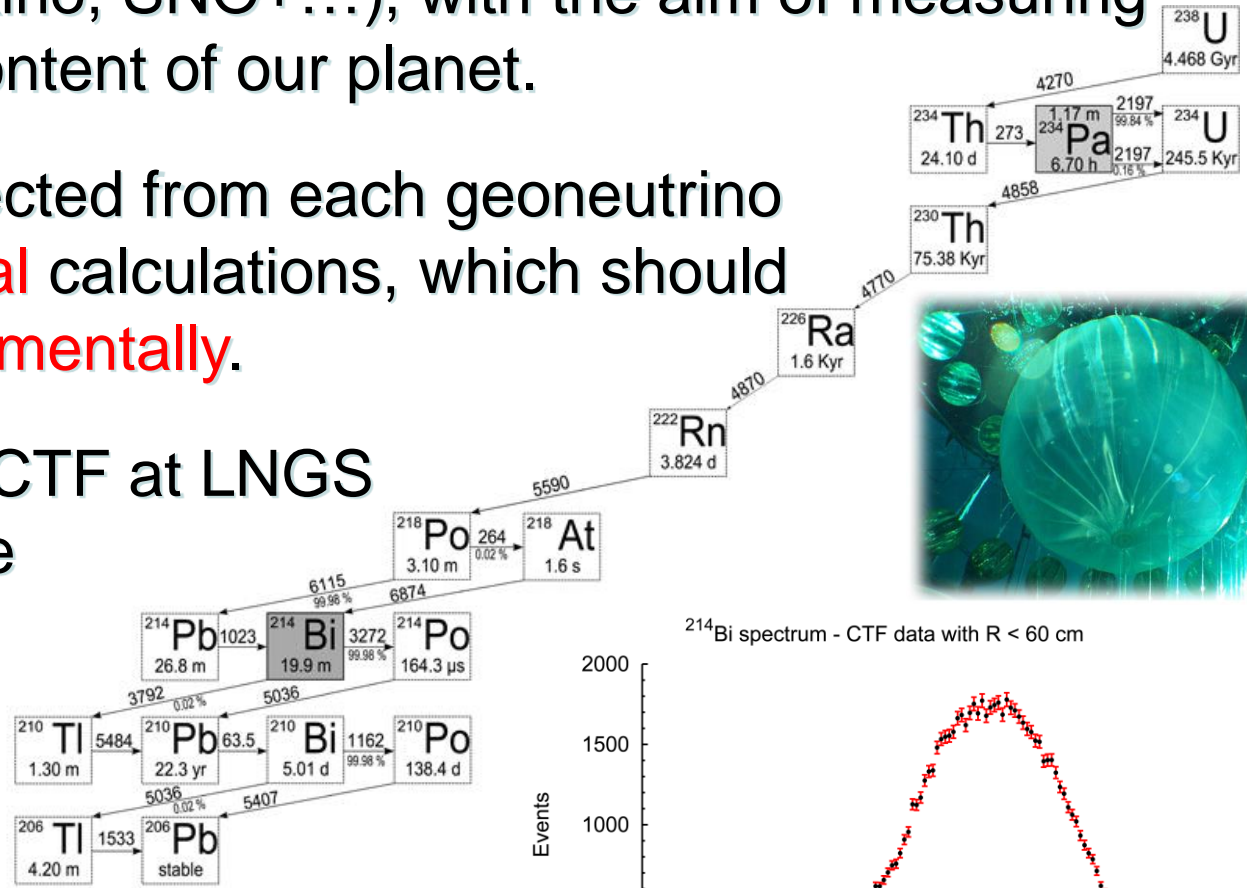


# Nuclear physics inputs needed for geo-neutrino studies

✓ Geo-neutrino detection is the goal of several experiments (KamLAND, Borexino, SNO+...), with the aim of measuring the radioactivity content of our planet.

✓ The signal expected from each geoneutrino relies on **theoretical** calculations, which should be checked **experimentally**.

✓ In this respect, CTF at LNGS provides an unique opportunity, which we are presently exploring.



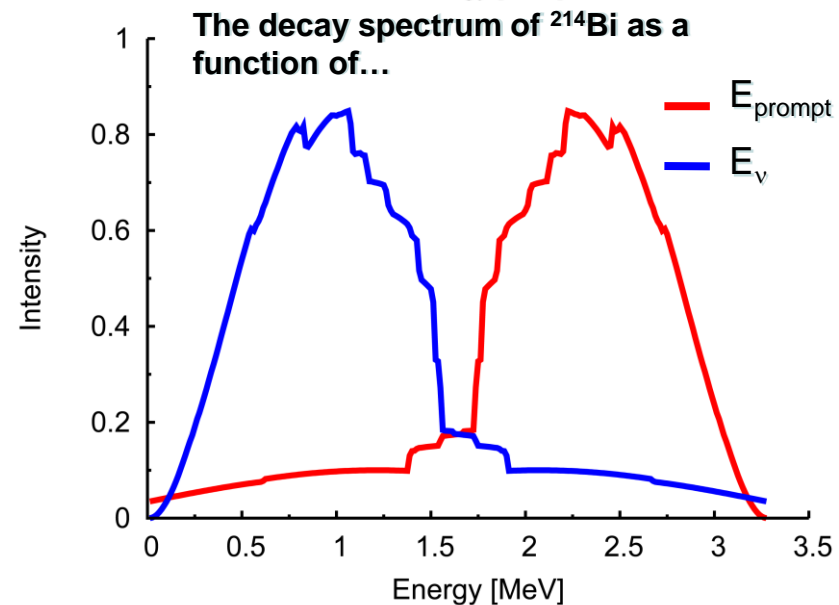
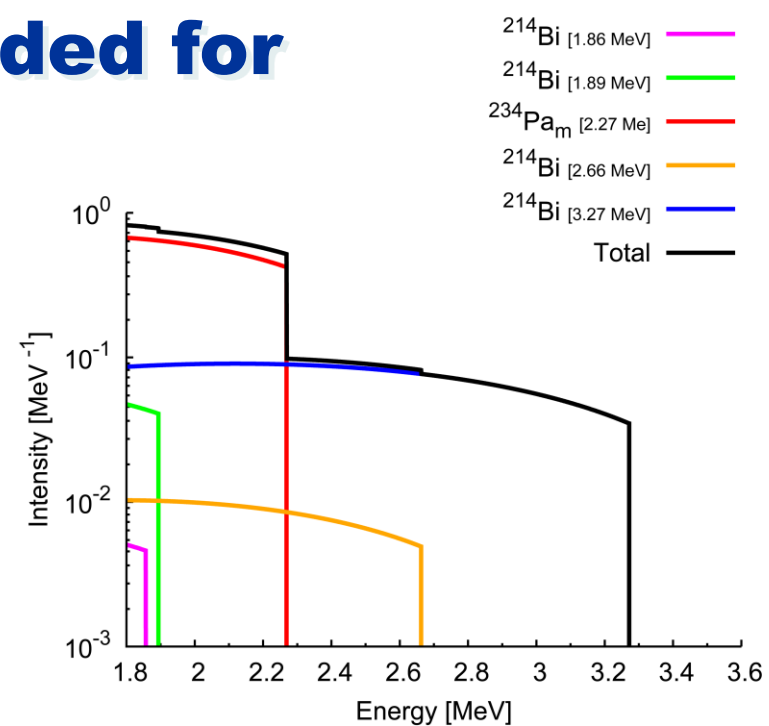
# Nuclear physics inputs needed for geo-neutrino studies\*

✓ Neutrino spectra are necessary for calculating the geo-neutrino signal. So far, they are derived from theoretical calculations. We propose to measure them directly.

✓ For each nuclear decay, the neutrino energy  $E_\nu$  and the “prompt energy”  $E_{\text{prompt}} = T_e + E_\gamma$  are fixed by energy conservation:  $Q = E_\nu + E_{\text{prompt}}$

✓ Measure  $E_{\text{prompt}}$  and will get  $E_\nu$

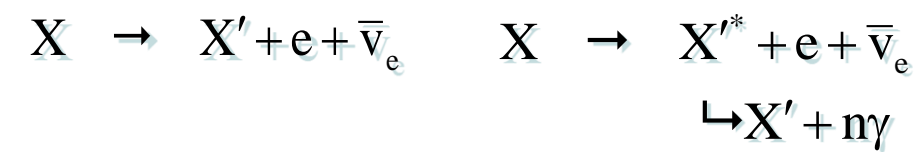
✓ With CTF @ LNGS a method for experimental determination of geo-neutrino spectra has been developed measuring the “prompt energy” of  $^{214}\text{Bi}$  decay



\* G. Bellini, G. Fiorentini, A. Ianni, M. Lissia, F. Mantovani and O. Smirnov

# Study of $^{214}\text{Bi}$ decay with CTF @ LNGS

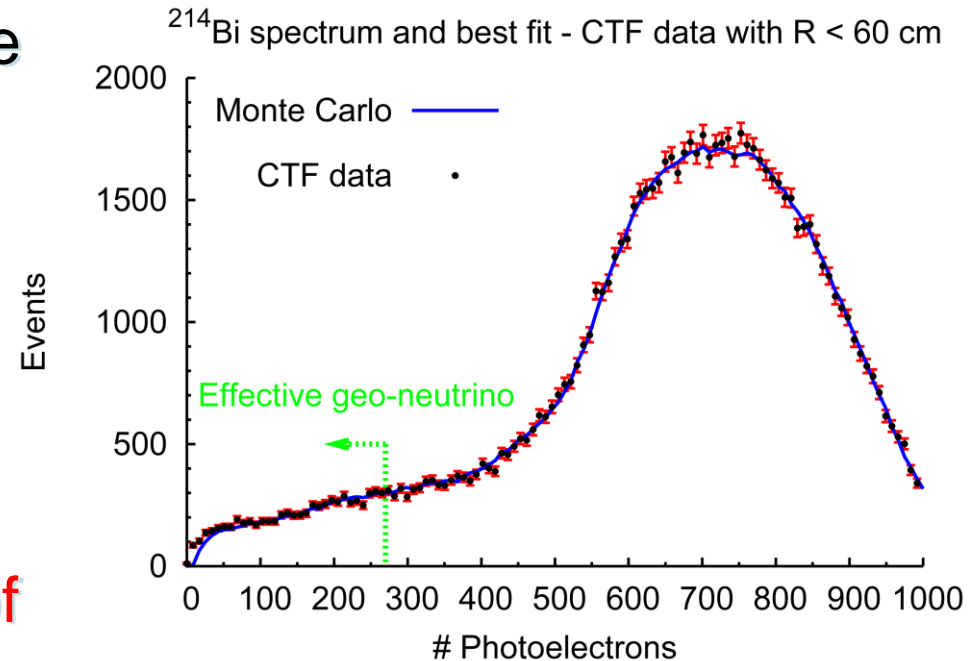
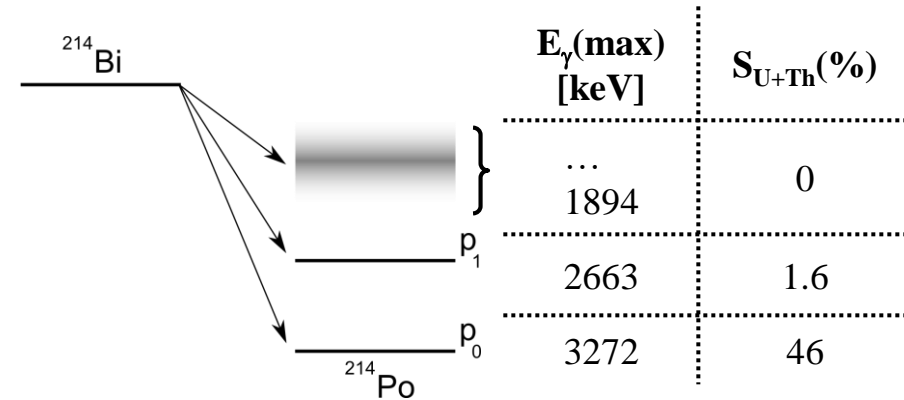
✓ Geo-neutrinos are produced through  $\beta$  and  $\beta\text{-}\gamma$  transitions:



✓ For geo-neutrino studies only the ground and first excited state are relevant.

✓ By using data from a  $^{222}\text{Rn}$  contamination of CTF, we measured the feeding probabilities  $p_0$  and  $p_1$  of these states.

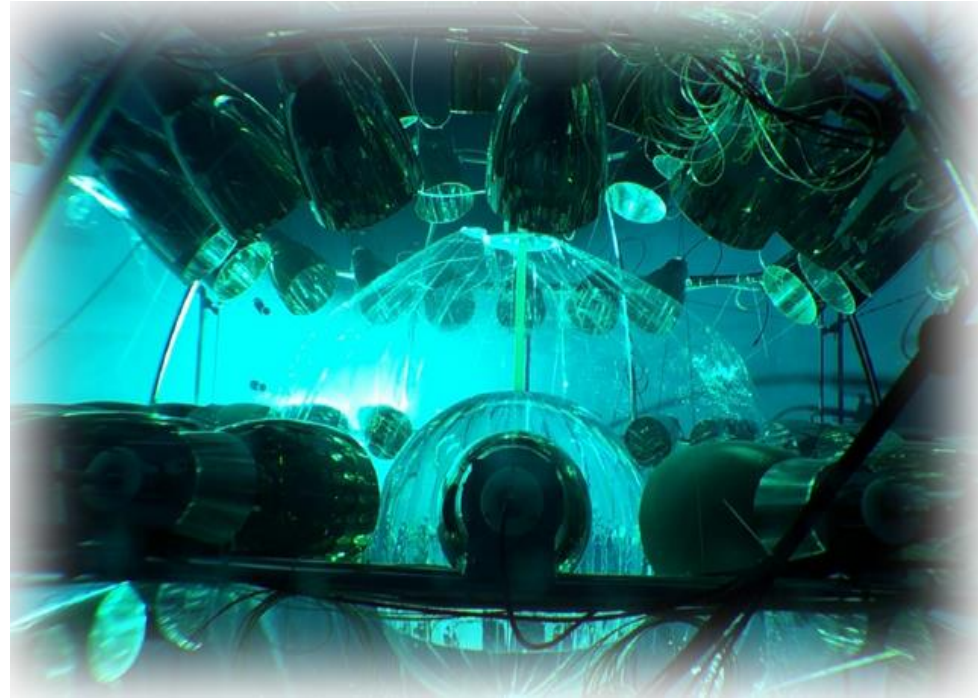
✓ The result is **consistent and of comparable accuracy** with that found in Table of Isotopes (derived from indirect measurements of  $\gamma$  line intensities and theoretical assumptions)



	CTF	TOI
$p_0$	$0.174 \pm 0.004$	$0.182 \pm 0.006$
$p_1$	$0.021 \pm 0.005$	$0.017 \pm 0.006$

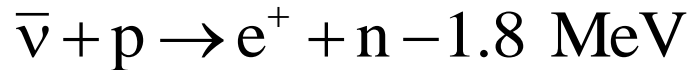
# Conclusions and perspectives

- ✓ Decay spectra of heavy nuclei are generally the fruit of **theoretical calculations**.
- ✓ A method for **experimental determination** of geo-neutrino spectra has been developed.
- ✓ We have exploited it for the study of  $^{214}\text{Bi}$  decay, which provides the most important contribution to geo-neutrino signal.
- ✓ We have started an experimental study of  $^{212}\text{Bi}$  and  $^{234}\text{Pa}$  decays using sources dissolved in a vial placed inside CTF.
- ✓ Our approach can be extended beyond geo-neutrinos, for experimental studies of other nuclear decays.



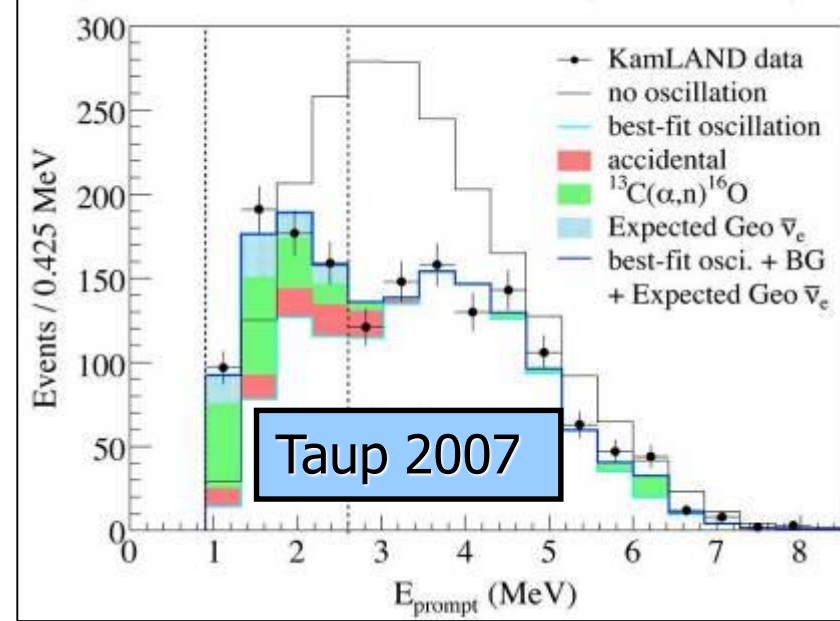
# KamLAND 2002-2007 results on geo-neutrino

- KamLAND, the 1000 ton scintillator detector in Japan, can measure the energy deposited by positrons ( $E_{\text{prompt}}$ ) and thus the antineutrino energy



- Above 2.8 MeV, the signal only comes from reactors. The interval 1 MeV-2.8 MeV is the geoneutrino energy range.
- In five years data ~ 630 counts in the geo-n energy range:
- ~ **340** reactors antineutrinos.

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



- ~ **160** fake geo-n, from  $^{13}\text{C}(\alpha, n)$
- Some contamination from polonium is still there. Alpha particles produce fast neutrons, which first scatter on protons (which provide ionization and scintillation 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

# Implications of KamLAND result

- Note that the geoneutrino counts obtained by subtraction are affected by statistical fluctuations of the total counts  $D = \sqrt{630} \sim 25$

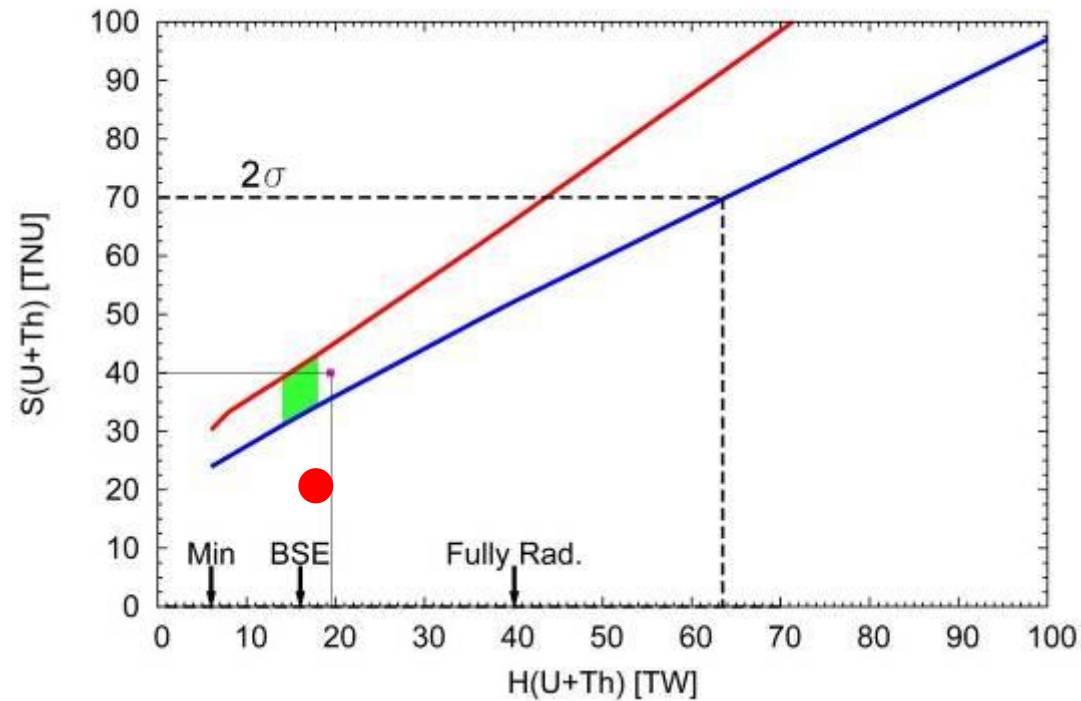
- The analysis of the experimental results gives

$$N(U+Th) = 75 \pm 27$$

- Note that event rate is about one per month

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

- It is consistent within 1s 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 geoneutrinos is now available!!!



# Observation of geo-neutrinos

## Borexino Collaboration

### Abstract

Geo-neutrinos, electron anti-neutrinos produced in  $\beta$  decays of naturally occurring radioactive isotopes in the Earth, are a unique direct probe of our planet's interior. We report the first observation of geo-neutrinos, performed with the Borexino detector at Laboratori Nazionali del Gran Sasso. Anti-neutrinos are detected through the neutron inverse  $\beta$  decay reaction. With a 252.6 ton·yr fiducial exposure after all selection cuts, we detected  $9.9_{-3.4}^{+4.1}({}_{-8.2}^{+14.6})$  geo-neutrino events, with errors corresponding to a 68.3% (99.73%) C.L. From the  $\ln \mathcal{L}$  profile, the statistical significance of the Borexino geo-neutrino observation corresponds to a 99.997% C.L.

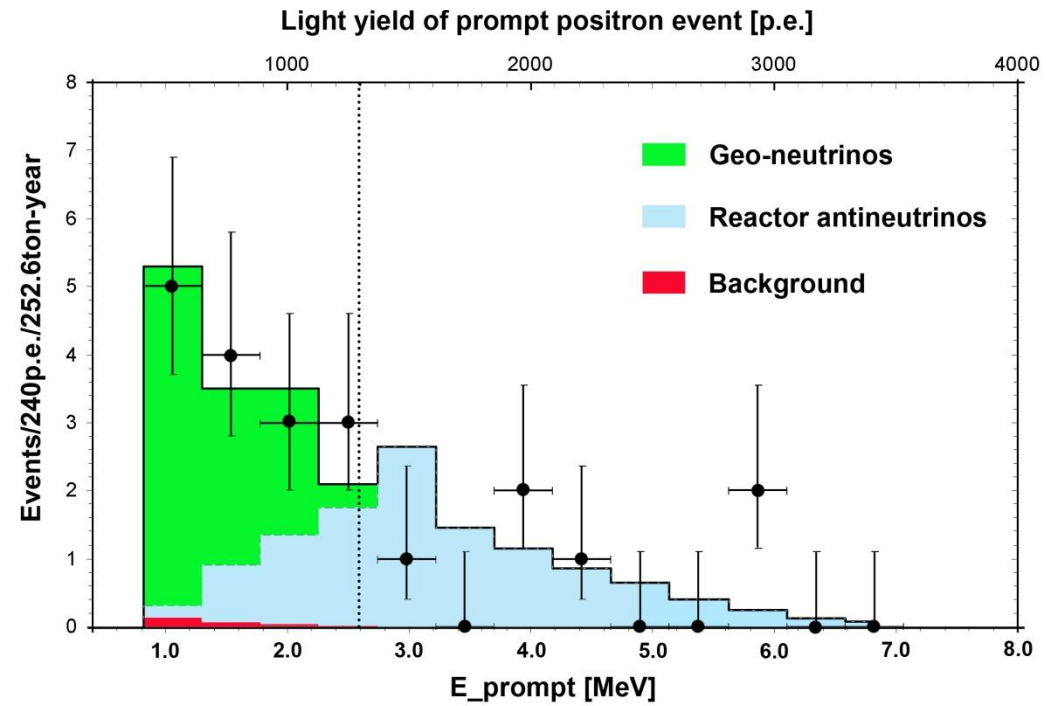
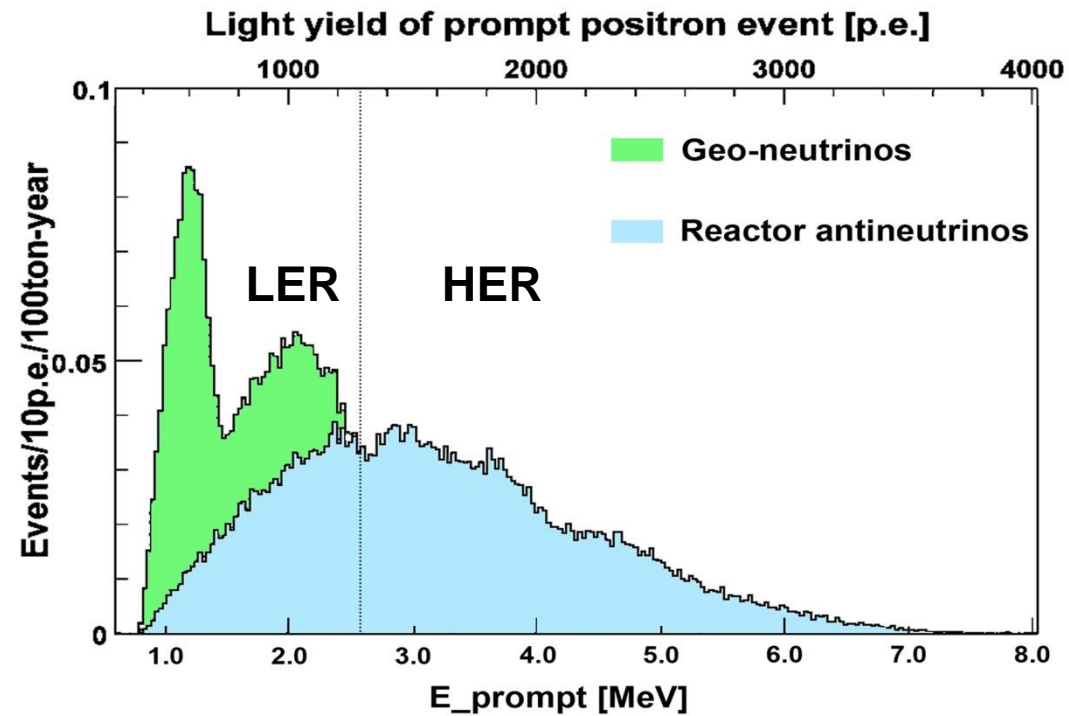
Our measurement of the geo-neutrinos rate is  $3.9_{-1.3}^{+1.6}({}_{-3.2}^{+5.8})$  events/(100 ton·yr).

The observed prompt positron spectrum above 2.6 MeV is compatible with that expected from european nuclear reactors (mean base line of approximately 1000 km). Our measurement of reactor anti-neutrinos excludes the non-oscillation hypothesis at 99.60% C.L.

This measurement rejects the hypothesis of an active geo-reactor in the Earth's core with a power above 3 TW at 95% C.L.

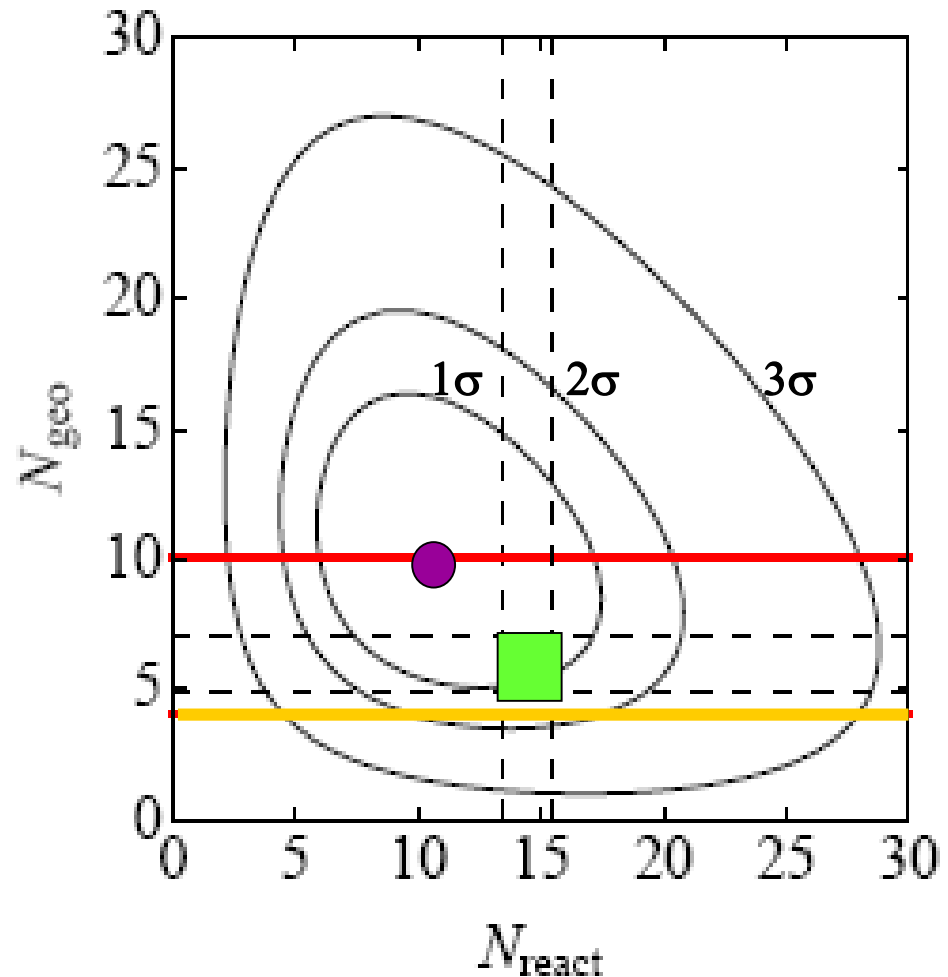
# Borexino: expectations and results

- Predict a total of 20.7 events in 24 months  
( $G=6.3$   $R=14$   $Bk=0.4$ )
- The HER can be used to test the experiment sensitivity to reactors
- In the LER one expects comparable number of geo-nu and reactor-nu
- Observe 21 events in 24 months, attributed to  
 $R=10.7_{-3.4}^{+4.3}$   
 $G=9.9_{-3.4}^{+4.1}$   
 $BK=0.4$
- One event per month experiment!



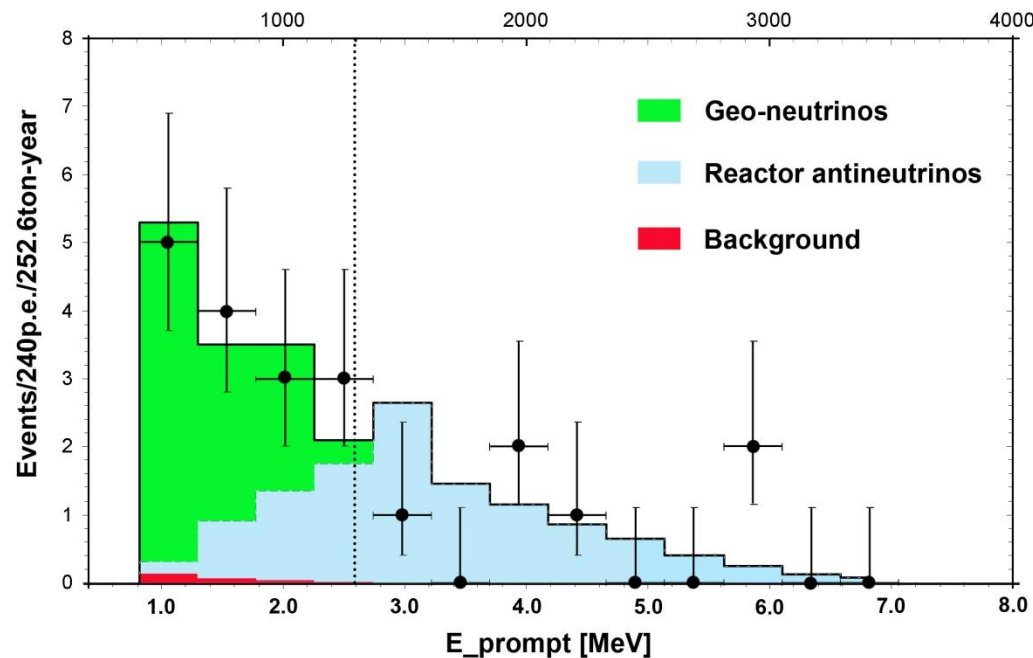
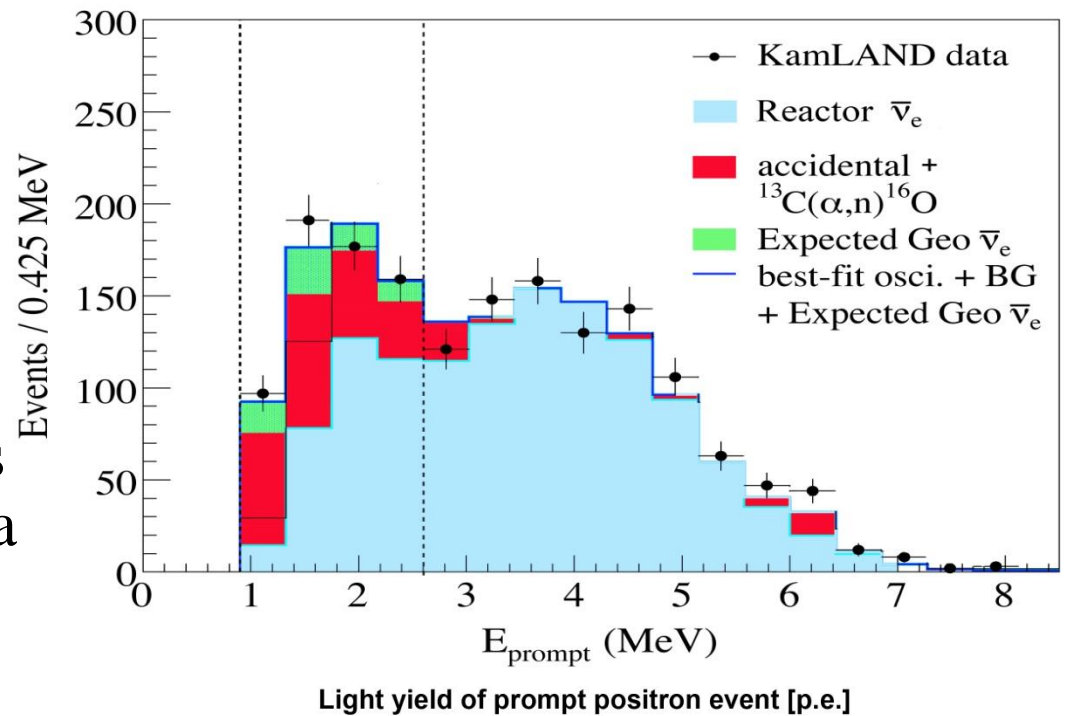
# The significance of the observation

- $G=0$  is excluded with CL of 99.997% CL (corresponding to  $4\sigma$ )
- The Best fit is :
  - within  $1\sigma$  from the BSE prediction;
  - close to the fully radiogenic model;
  - some  $2\sigma$  from the minimal radiogenic mode



# KamLAND vs Borexino

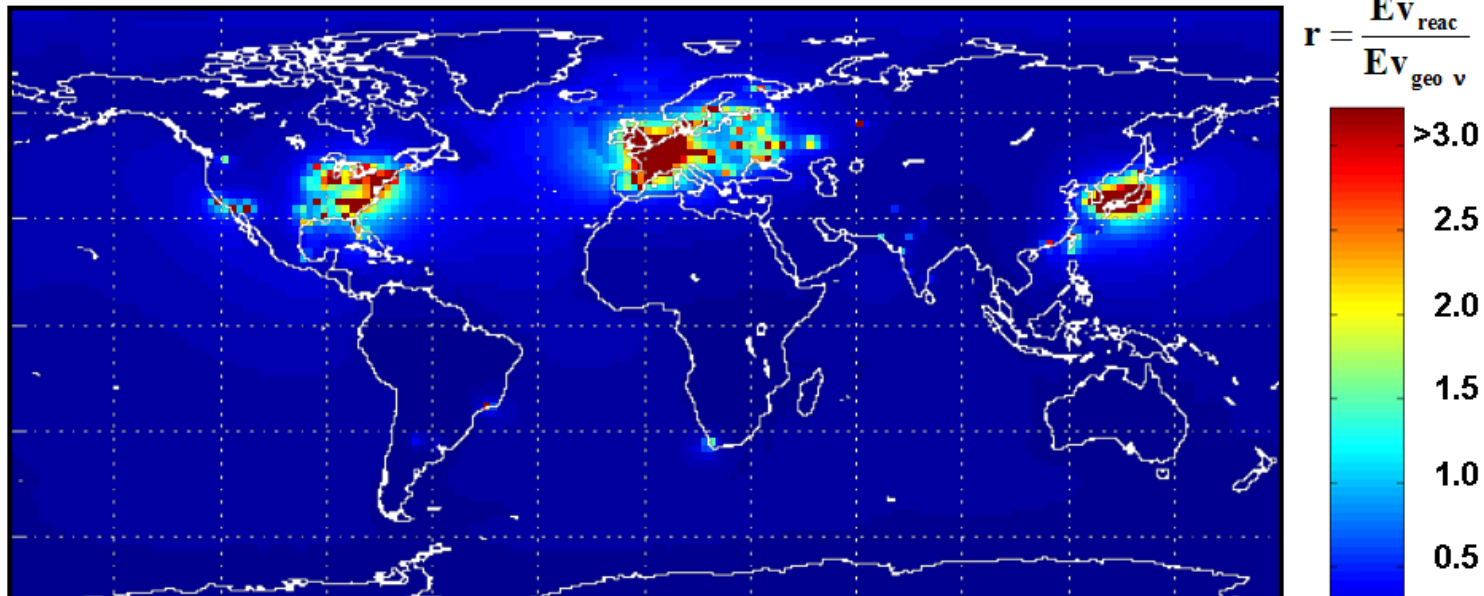
- KamLAND in 4 years collected 630 events in the LER.
- Most due to **Reactors** (340) and **Background** (220)
- After subtraction one remains with some 70 **geonu** events, a  $2.5\sigma$  evidence of geo- $\nu$ .
- Borexino has a smaller mass and exposure time
- It benefits from:
  - much higher purity
  - absence of nearby reactors
- **This is why B. can give better results even with smaller statistics**



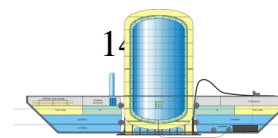
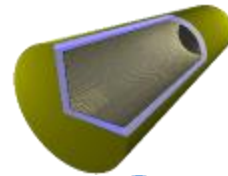
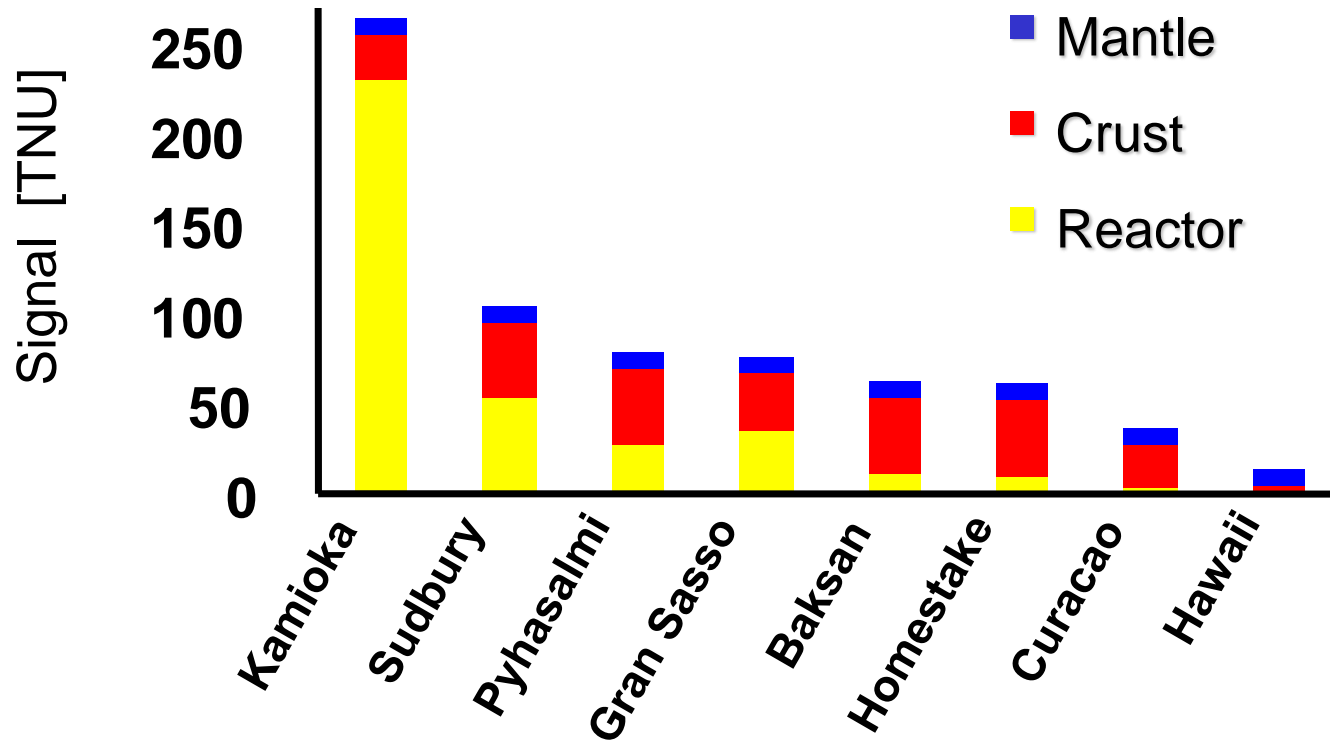
# Nuclear reactors: the enemy of geo-neutrinos

- KamLAND is 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  $r \approx 1$ , which makes this site much better than Kamioka

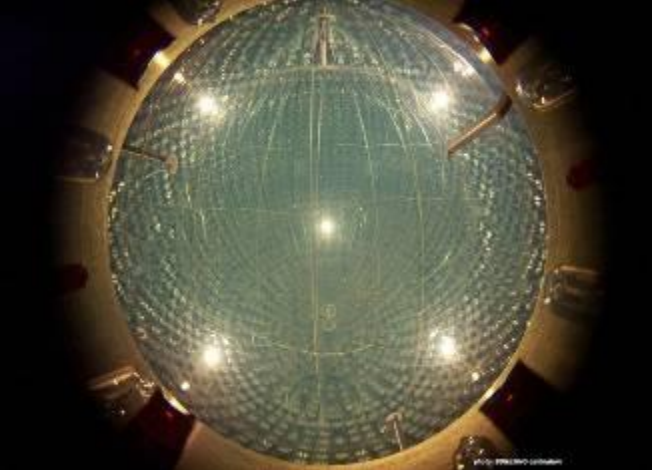
	$r$
Kamioka	6.7
Sudbury	1.1
Gran Sasso	0.9
Pyhasalmi	0.5
Baksan	0.2
Homestake	0.2
Hawaii	0.1
Curacao	0.1



# Running and planned experiments



- 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.

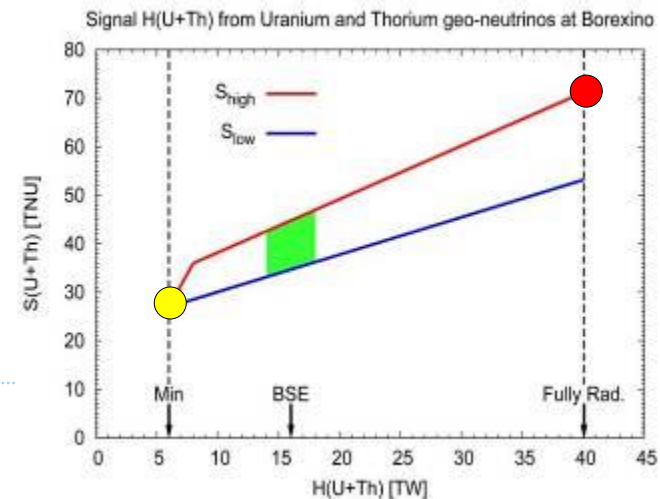
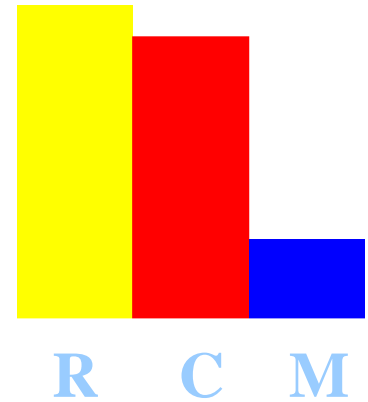


# Borexino at Gran Sasso



- A 300-ton liquid scintillator underground detector, running since may 2007.

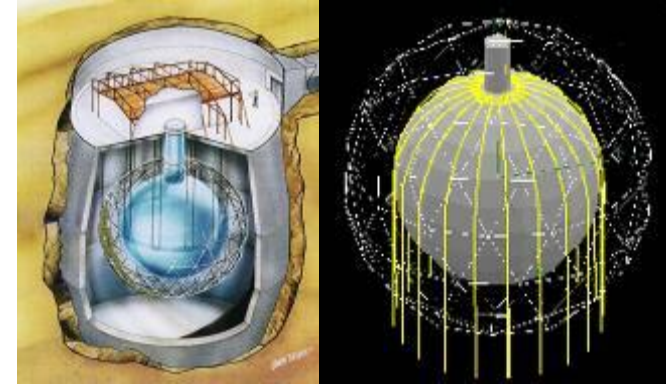
- Signal, mainly generated from the crust, is comparable to reactor background.
- From BSE expect 5 – 7 events/year\*
- In about two years should get 3s evidence of geoneutrinos.
- Results are expected soon, and should provide the first real proof of geoneutrinos



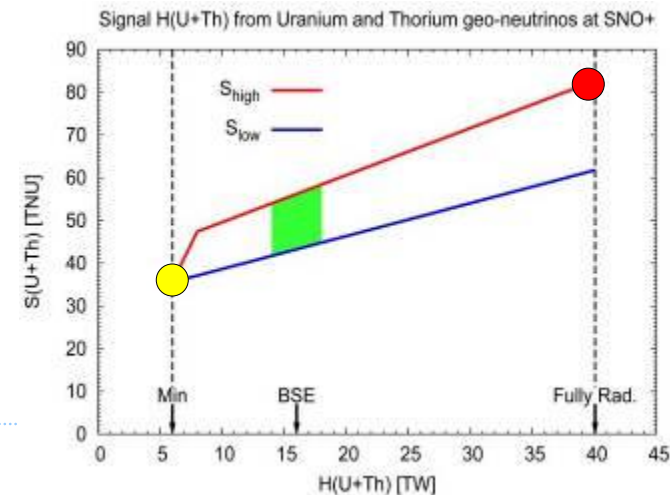
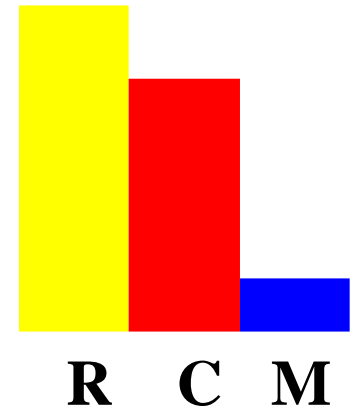
\* For 80% eff. and 300 tons  $C_9H_{12}$  fiducial mass



# 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 SNO collaboration has planned to fill the detector with LS in 2009-2010
- The size is similar to Kamioka, but the reactor background is much smaller
- 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.

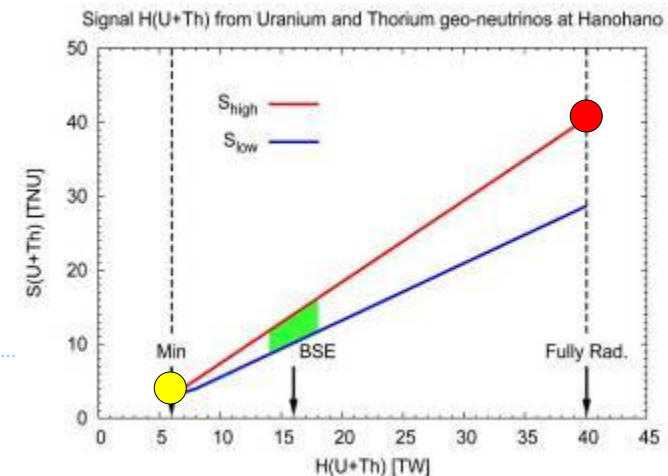
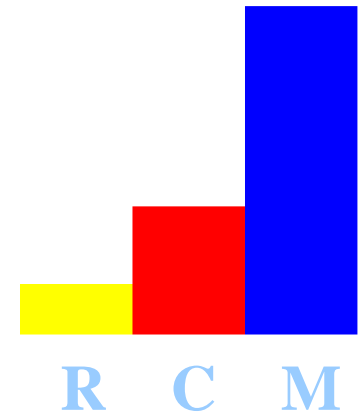
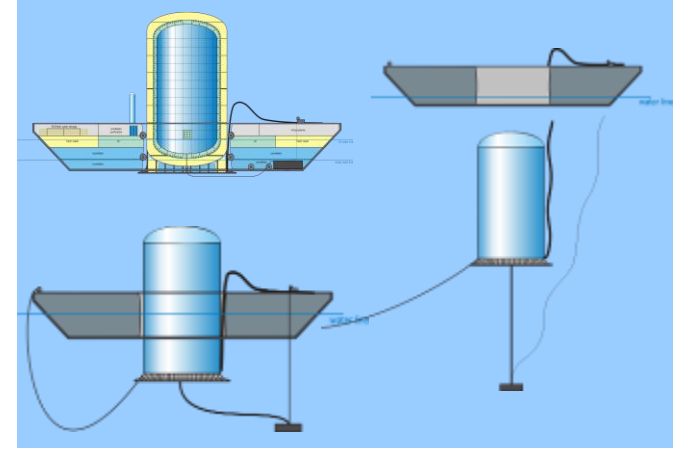


\* assuming 80% eff. and 1 kTon CH<sub>2</sub> fiducial mass



# 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<sub>2</sub> fiducial mass

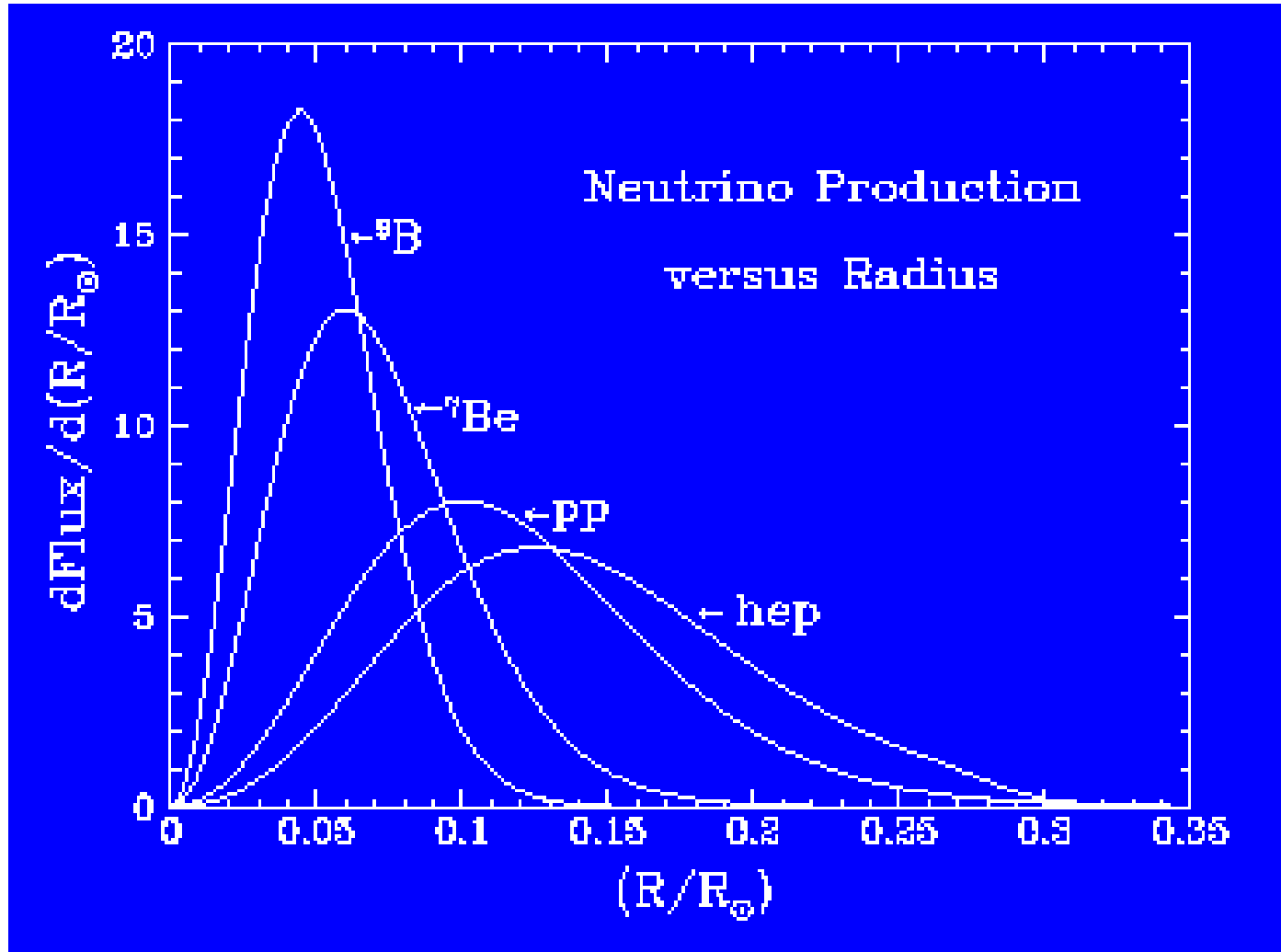
# Most studied solar neutrinos

Essentially one has three groups:

- low energy : the pp neutrinos, coming from ppI
- intermediate energy: the Be neutrinos, from ppII
- high energy: Boron neutrinos

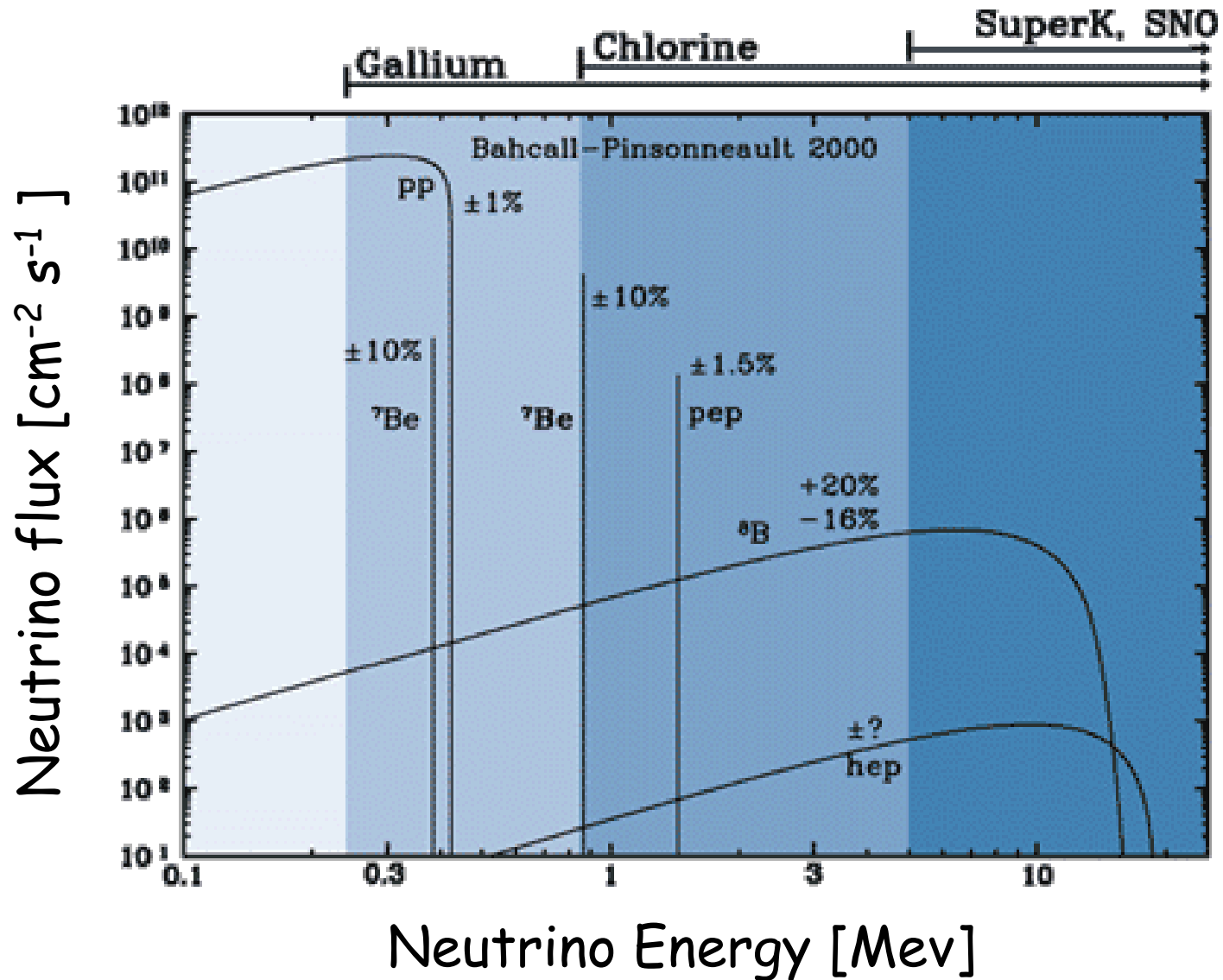
name:	pp	${}^7\text{Be}$	${}^8\text{B}$
reaction:	$p+p \rightarrow d+e^++\nu_e$	${}^7\text{Be}+e^- \rightarrow {}^7\text{Li}+\nu_e$	${}^8\text{B} \rightarrow {}^8\text{Be}+e^++\nu_e$
energy: [MeV]	$\leq 0.42$	0.861 (90%) 0.383 (10%)	$\leq 15$
abundance: [cm <sup>-2</sup> s <sup>-1</sup> ]	$5.96 \cdot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

# A group photo : production region



The fraction of neutrino produced inside the sun within  $dR$ <sup>19</sup>

# A group photo: energy space



# Solar $\nu$ experiments, completed or in data taking

Experiment/ Location/ Data taking	Target/ $\nu$ interaction/ Threshold	Technique	Sensitivity (SSM)				
			pp	${}^7\text{Be}$	CNO	pep	${}^8\text{B}$
<b>Chlorine/ Homestake (USA) 1970-1995</b>	<b>615 tons of <math>\text{C}_2\text{Cl}_4</math> <math>{}^{37}\text{Cl} (\nu_e, e) {}^{37}\text{Ar}</math> 814 keV</b>	<b>Radiochemical counting <math>{}^{37}\text{Ar}</math> atoms by gas proportional counters</b>	-	<b>15</b>	<b>6</b>	<b>3</b>	<b>77</b>
<b>Kamiokande/ Kamioka (Japan) 1987-1995</b>	<b>4500 tons of <math>\text{H}_2\text{O}</math> <math>e + \nu_x \rightarrow e + \nu_x</math> (CC+NC) 7 Mev on recoil electron</b>	Detection of Cerenkov light emitted by the e- Direction of e- Energy spectrum of e-	-	-	-	-	<b>100</b>
<b>SNO Subury (Canada) 2000-2007</b>	<b>1000 tons of <math>\text{D}_2\text{O}</math> Separate detection of CC and NC</b>	Detection of Cerenkov light emitted by the e- And neutron detection	-	-	-	-	<b>100</b>
<b>Borexino LNGS (Italy) 2007-ongoing</b>	<b>300 tons of <math>\text{C}_n\text{H}_{2n}</math> <math>e + \nu_x \rightarrow e + \nu_x</math> (CC+NC)</b>	Scintillation light emitted by the e-	-	<b>100</b>	?	?	<b>SI</b>
<b>Gallex/GNO LNGS (Italy) 1991-2005</b>	<b>101 tons of <math>\text{GaCl}_3</math> solut. <math>{}^{71}\text{Ga} (\nu_e, e) {}^{71}\text{Ge}</math> 233 keV</b>	<b>Radiochemical counting <math>{}^{71}\text{Ge}</math> atoms by gas proportional counters</b>	<b>54</b>	<b>27</b>	<b>7</b>	<b>2</b>	<b>10</b>
<b>SAGE Baksan (Caucasus) 1991-2005</b>	<b>60 tons of met. Ga <math>{}^{71}\text{Ga} (\nu_e, e) {}^{71}\text{Ge}</math> 233 keV</b>	<b>Radiochemical counting <math>{}^{71}\text{Ge}</math> atoms by gas proportional counters</b>	<b>54</b>	<b>27</b>	<b>7</b>	<b>2<sup>21</sup></b>	<b>10</b>

# Boron $\nu$ 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  $\nu_e$  since  $\sigma(\nu_e) / \sigma(\nu_\mu) \approx 6$

•Results

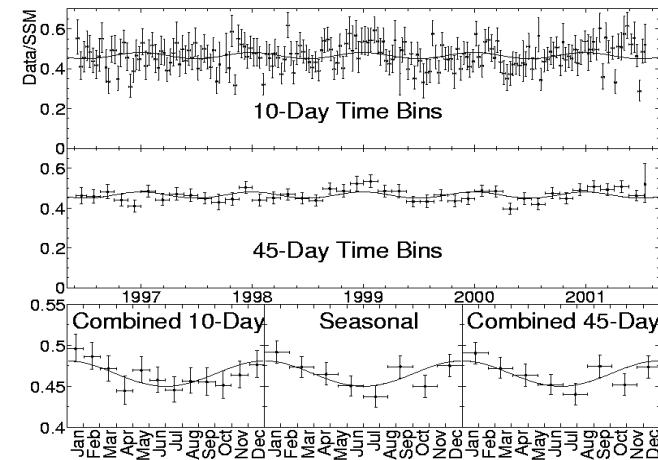
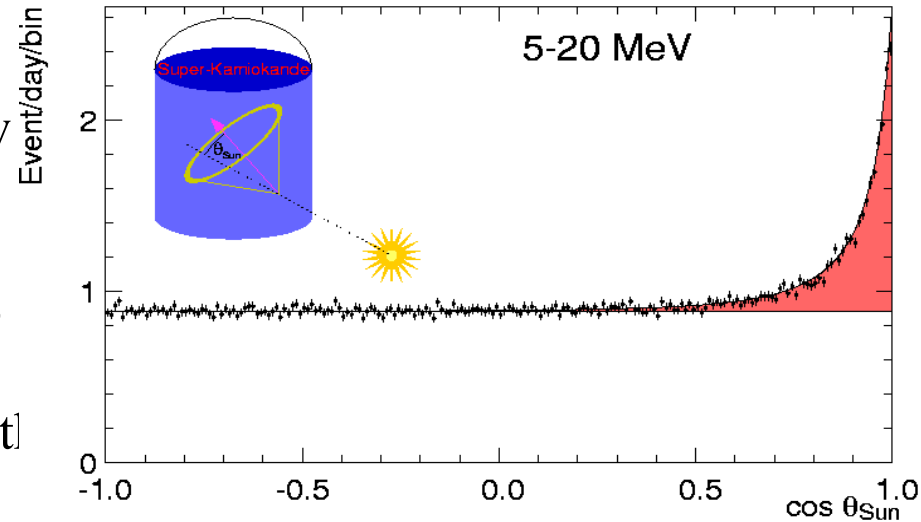
- It provides a clear “image” of the Sun with neutrinos.
- First real time experiment with solar neutrinos
- Observes seasonal variation of the flux, due to varying sun Earth oscillation
- Performs a precision test of the  $^8\text{B}$   $\nu$  energy spectrum

22000  $\nu$  events observed in 1496 days

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

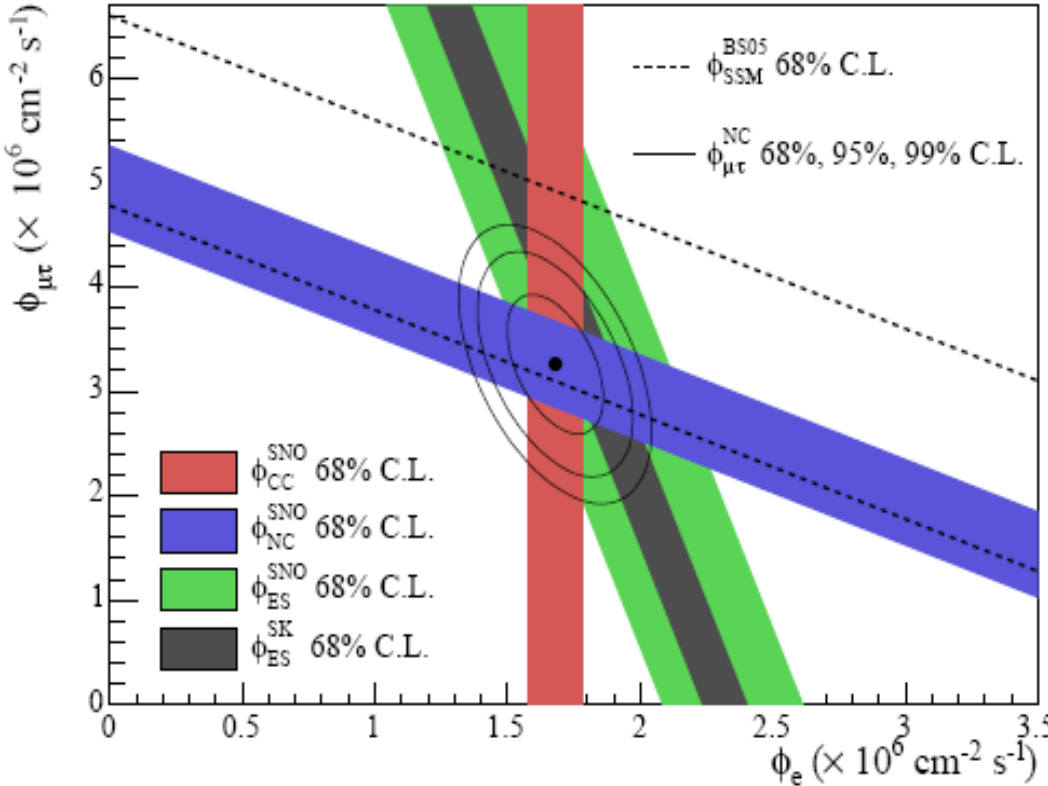
$$R (\text{exp/SSM}) = 0.465 \pm 0.005 \pm 0.013$$

•It observed half of the signal predicted by Standard Solar Model



# Boron neutrinos: the impact of SNO

- The results of SK can be plotted on a  $(\Phi_e, \Phi_{\mu\tau})$  as a narrow (gray) band, close to the vertical, due to the small sensitivity to neutrinos different from electron type
- The situation changes 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 (blue) interactions.
- This has provided a clear proof of neutrino oscillation, and a measurement of the total Boron flux



# Summary of Main SNO Solar $\nu$ Results

- direct measurement of the averaged survival probability of  $^8\text{B}$  solar  $\nu$

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

- total active flux of  $^8\text{B}$  solar  $\nu$  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

$$\Delta m^2 = (7.7 \pm 0.2) 10^{-5} \text{ eV}^2$$
$$\tan^2 \theta = 0.46^{+0.04}_{-0.05}$$



# The central solar temperature

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

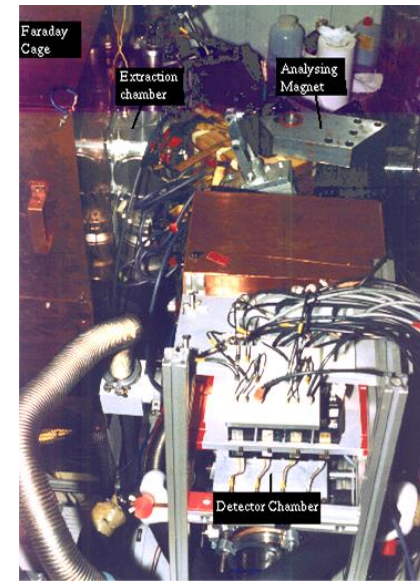
$$\Phi_B = \Phi_B^{(SSM)} [T / T_{(SSM)}]^{20} \cdot S_{33}^{-0.43} S_{34}^{0.84} S_{17} S_{e7}^{-1}$$

- The last terms are astrophysical factors, for the relevant reactions in the Sun (e.g.  $S_{33} = S(^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p)$ )
- The boron flux is measured with an accuracy of 4%. From the measured Boron flux, if nuclear cross sections are known perfectly, one would deduce deduces measured in the lab one deduces 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 at Gran Sasso experiment, so that presently nuclear uncertainties and Boron fluxes uncertainties are comparable.

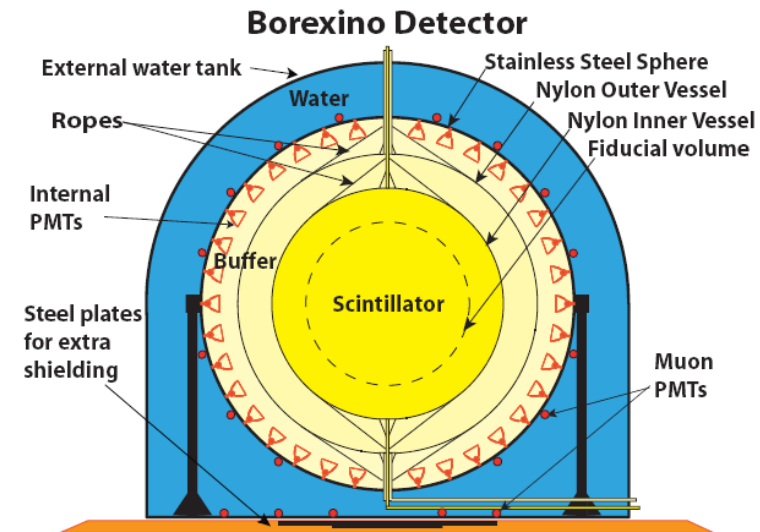
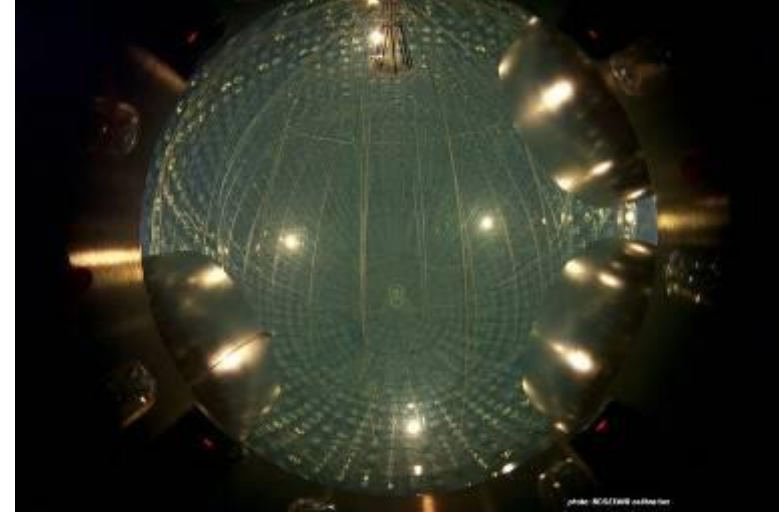
- The result is

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



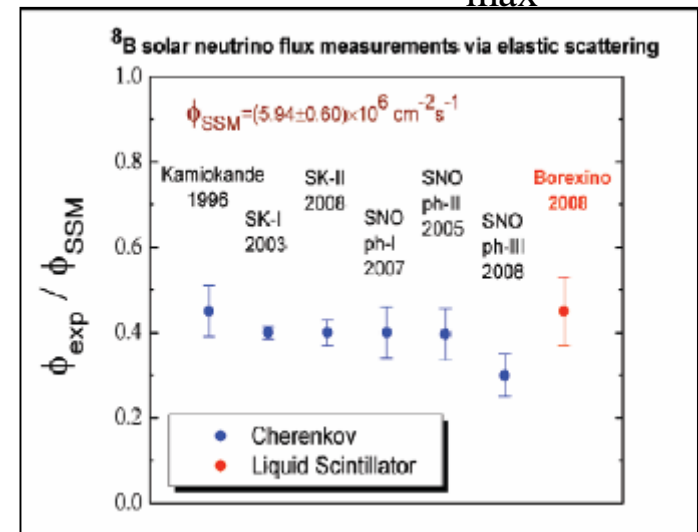
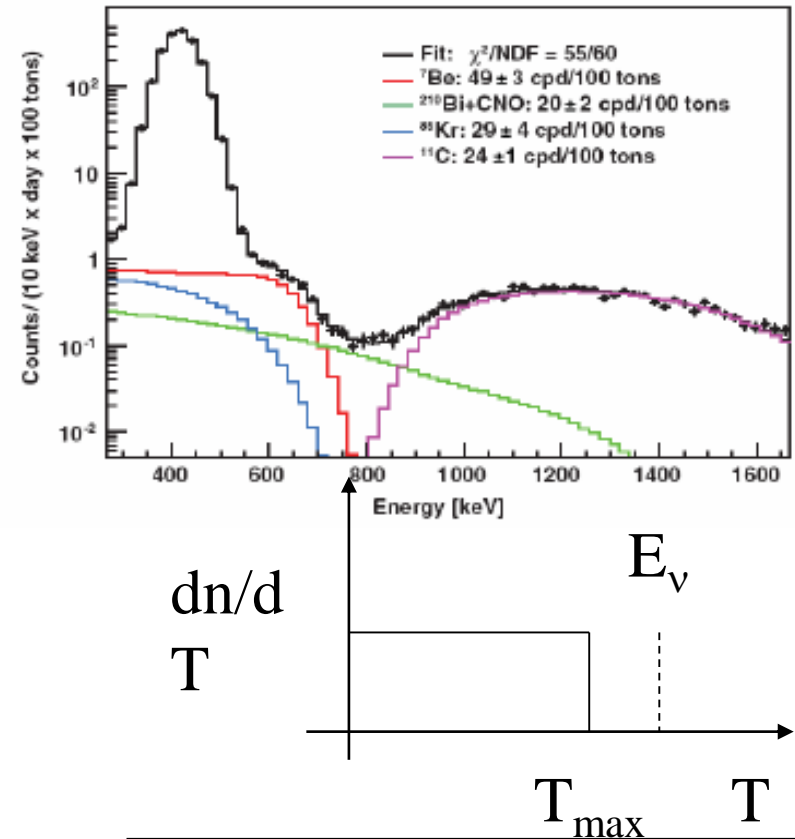
# Berillium neutrinos: Borexino at LNGS

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



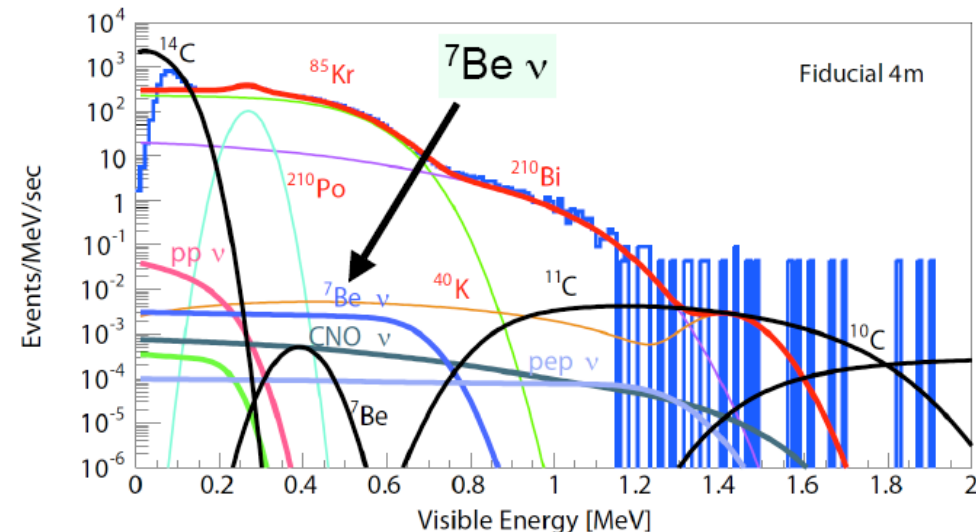
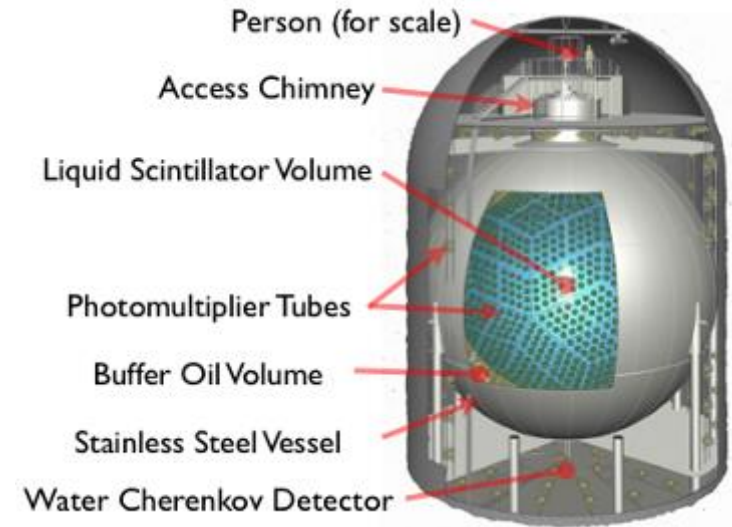
# Physics results on ${}^7\text{Be}$ by Borexino at LNGS

- Borexino has observed  ${}^7\text{Be}$  neutrino signal:  
 $49 \pm 3_{\text{stat}} \pm 4_{\text{syst}}$  (cpd/100 t)
- The expected signal for nonoscillated solar neutrino is  $74 \pm 4$  cpd/100 t, corresponding to a flux  ${}^7\text{Be}$ .
- The hypothesis of no oscillation for  ${}^7\text{Be}$  solar neutrinos is inconsistent with Borexino measurement at the  $4 \sigma$  C.L.
- The survival probability of the 0.862 MeV  ${}^7\text{Be}$  neutrinos is  $0.56 \pm 0.10$ .
- Note that this is close to the Vacuum oscillation result of KamLAND
- This is different for the case of  ${}^8\text{B}$  neutrinos, as confirmed by Borexino itself



# Experiment in progress for ${}^7\text{Be}$ : KamLAND

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



# Low energy $\nu$ experiments : the results of Gallex/GNO and Sage

## Experiment

## Results

**Gallex/GNO**

1991-2003

**69.3  $\pm$  4.1 (stat)  $\pm$  3.6 (sys)**

**SNU**

**R (exp/SSM) = 0.53  $\pm$  0.05 (exp)  $\pm$  0.03**

**SAGE**

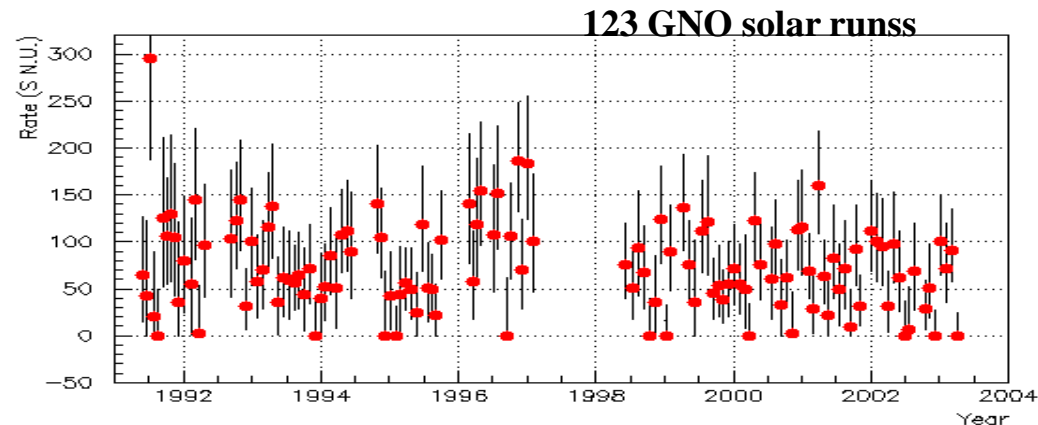
1991-ongoing

**(theo)  $\pm$  4.6  $\nu$  captured/day  $\pm$  3.5 (sys)**

**SNU**

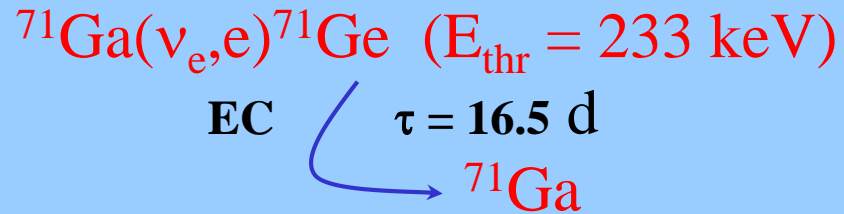
**R (exp/SSM) = 0.53  $\pm$  0.05 (exp)  $\pm$  0.03 (theo)**

- **First detection of pp solar neutrinos**
- **Evidence of suppression of sub-MeV  $\nu$  flux**
- **Monitoring of the low energy  $\nu$  flux over a complete solar cycle**



# Lo schema logico degli esperimento con Gallio

La reazione



La composizione del segnale:  
(BP00 SSM)

pp + pep	73 SNU	(55 %)
${}^7\text{Be}$	35 SNU	(27 %)
CNO	8 SNU	( 8 %)
${}^8\text{B}$	13 SNU	(10 %)
Tot	129 SNU	${}^{+9}_{-7} 1\sigma$

Il segnale atteso  
(SSM)

1.2  $\nu$  int. per day, but due to decay during exposure + ineff., 9  ${}^{71}\text{Ge}$  decay detected per extraction

Ora che abbiamo misurato il contributo degli altri neutrini (a parte CNO) possiamo estrarne il ruolo dei pp e dunque comprendere l'energetica solare

## Estrazione

$\text{GeCl}_4$  volatile in soluzione acida  
da 100 t of  $\text{Ga}_3\text{Cl}$  in sol. Flusso di azoto  
 $N = N_0 \exp(-f V_{\text{gas}}/V_{\text{sol}})$

## Apparato ed operazioni in

See f.i. PL B490(2000)16  
PL B314(1993)445

Extract  
 $\text{GeCl}_4$   
12 h

Add 1 mg  
of carrier

$\text{GeCl}_4$

10 h

In tank

$\text{GeH}_4 + \text{Xe}$   
in counter  $V = 1\text{cc}$

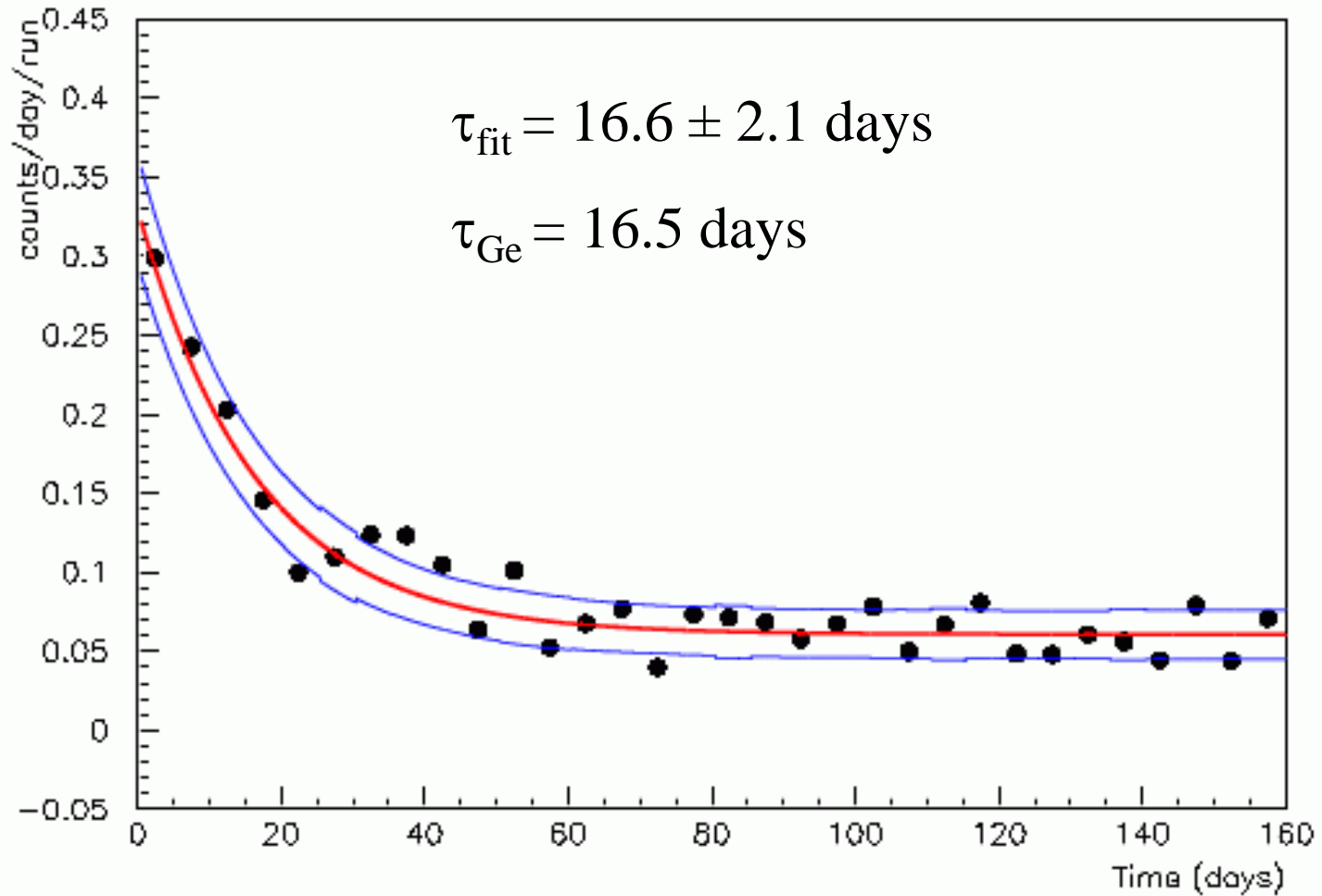
Wait  
21-28 d for SR  
1 d for blanks

Counter in  
shielding

6 months

Stop counting  
Remove counter

## Time distribution

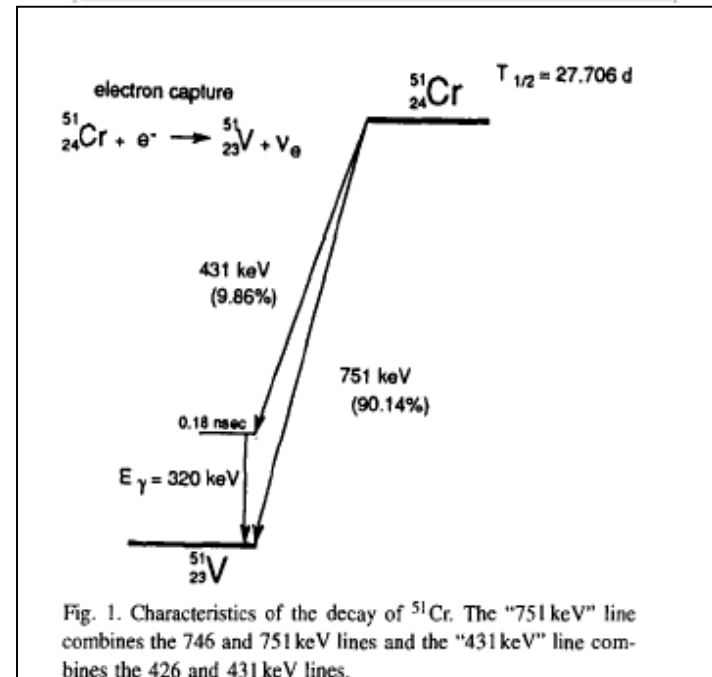




# La calibrazione con la sorgente di $^{51}\text{Cr}$

- The GALLEX experiment, has performed an investigation with an intense man-made  $^{51}\text{Cr}$  neutrino source ( $61.9 + 1.2 \text{ PBq}$ ).
- The source, produced via neutron irradiation of  $\sim 36 \text{ kg}$  of chromium enriched in  $^{50}\text{Cr}$ , primarily emits  $746 \text{ keV}$  neutrinos. It was placed for a period of 3.5 months in the reentrant tube in the GALLEX tank, to expose the gallium chloride target to a known neutrino flux.
- These xperiment provides the ratio,  $R$ , of the production rate of Cr-produced  $^{71}\text{Ge}$  measured in these source exposures to the rate expected from the know 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
$^{50}\text{Cr}$	4.345%	$> 1.8 \times 10^{17} \text{ y}$	$\epsilon\epsilon$	-	$^{50}\text{Ti}$
$^{51}\text{Cr}$	syn	27.7025 d	$\epsilon$ $\gamma$	- 0.320	$^{51}\text{V}$ -
$^{52}\text{Cr}$	83.789%	$^{52}\text{Cr}$ is stable with 28 neutrons			
$^{53}\text{Cr}$	9.501%	$^{53}\text{Cr}$ is stable with 29 neutrons			
$^{54}\text{Cr}$	2.365%	$^{54}\text{Cr}$ is stable with 30 neutrons			



<b>Strength</b>	<b>63.4 PBq</b>	<b>69.1 PBq</b>
<b>R</b> <b>(meas/expt)</b>	<b>1.01</b> <b><math>\pm 11.5\%</math></b>	<b>0.84</b> <b><math>\pm 11.5\%</math></b> <sup>33</sup>

## GALLEX + GNO

Circa 12 anni di presa dati in cui sono stati analizzati 123 run solari, corrispondenti a 3281 giorni, ossia 9 anni. Il risultato finale è

$$\text{Rate} = 69.3 \pm 4.1 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

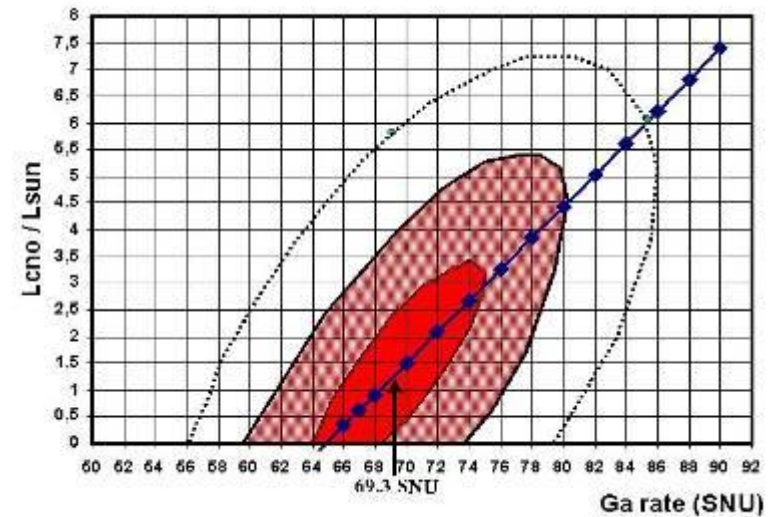
Da confrontarsi con le previsioni del modello solare se i neutrini non avessero oscillato

$$R \text{ (exp/SSM)} = 0.53 \pm 0.05 \text{ (exp)} \pm 0.03$$

Da notare che, come nel caso del Berillio, domina il meccanismo delle oscillazioni di vuoto

1SNU = 1 Solar Neutrino Unit =  $10^{-36}$  interazioni per atomo bersaglio

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



- Are there additional energy sources beyond 4H
- 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)  $K_{\text{nuc}} = \Phi_{\text{tot}} Q/2$ , and compare it with the observed photon luminosity  $K$ :

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

- This means that - to within 35% - the Sun is actually powered by 4H->He fusion, via the pp chain
- A more precise conclusion requires measuring the CNO contribution (wait for Borexino and/or SNO+)

# La soluzione del Solar Neutrino Puzzle (inquadramento)

- In 30 anni, tutti gli esperimenti di neutrini solari hanno rilevato un deficit di  $\nu_e$  rispetto alle predizioni. Nel 2001 SNO, un esperimento con neutrini solari sensibile sia ai  $\nu_e$  che a tutti gli altri tipi di neutrini, ha dimostrato che  $\Phi(\nu_e) = 1/3 \Phi(\nu_e + \nu_\mu + \nu_\tau)$ , cioè 2/3 dei  $\nu_e$  si trasformano per strada.
- I parametri dell'oscillazione che riproducono i dati sperimentali di tutti gli esperimenti con i neutrini solari sono:

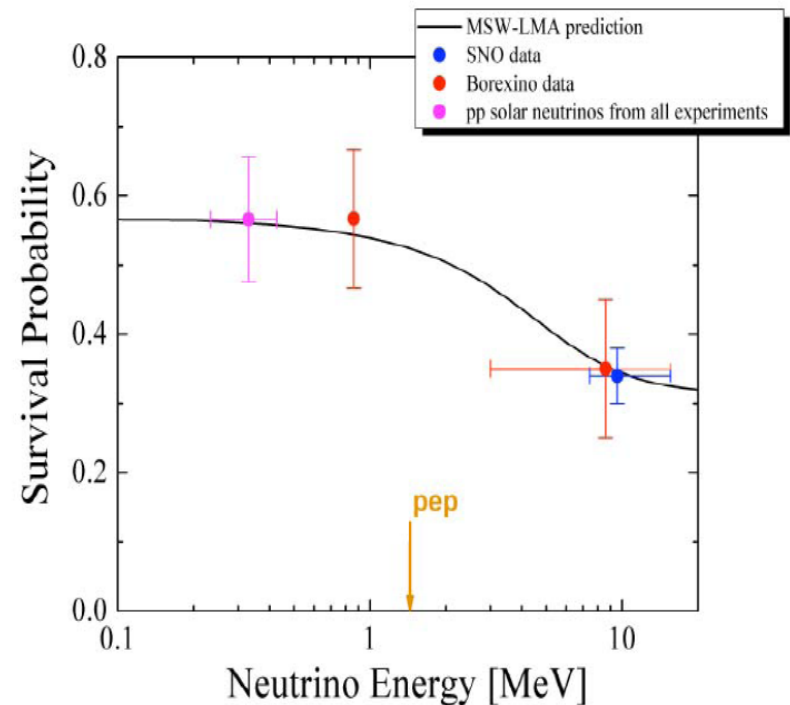
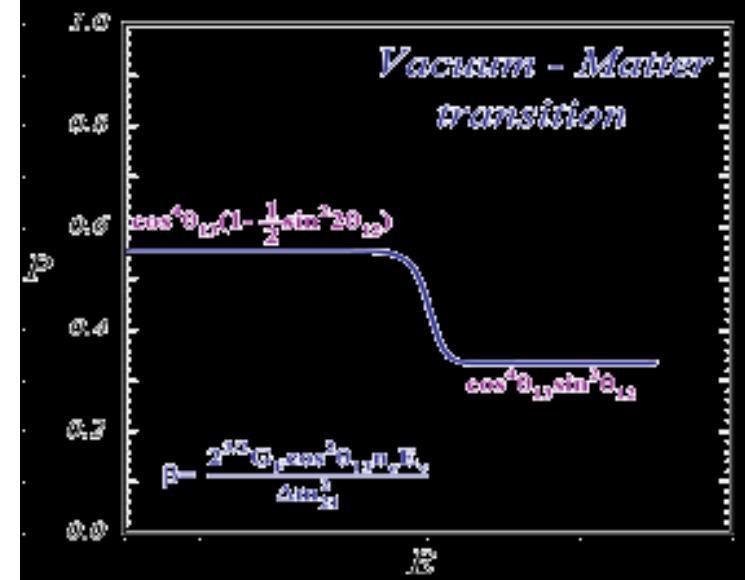
$$\Delta m^2 = 7.7 \cdot 10^{-5} \text{ eV}^2$$

$$\text{tg}^2\theta = 0.46$$

- Per il boro, siamo nella regione dei parametri per i quali vale l'espressione della probabilità di sopravvivenza dominata dall'effetto di materia
- I neutrini solari con energia  $\approx 10 \text{ MeV}$  hanno una  $P_{ee} \approx 30\%$  (domina l'effetto di materia).
- Quelli ad energie inferiori o dell'ordine di  $1 \text{ MeV}$  hanno  $P_{ee} \approx 60\%$  (domina l'effetto di vuoto o massa)
- In altri termini, è soppressa maggiormente la componente più energetica dello spettro dei neutrini solari
- I valori per i parametri di oscillazione per i neutrini solari sopra scritti sono in ottimo accordo con quanto trovato dall'esperimento KamLAND

# $\nu_e$ survival probability as a function of energy, from solar data

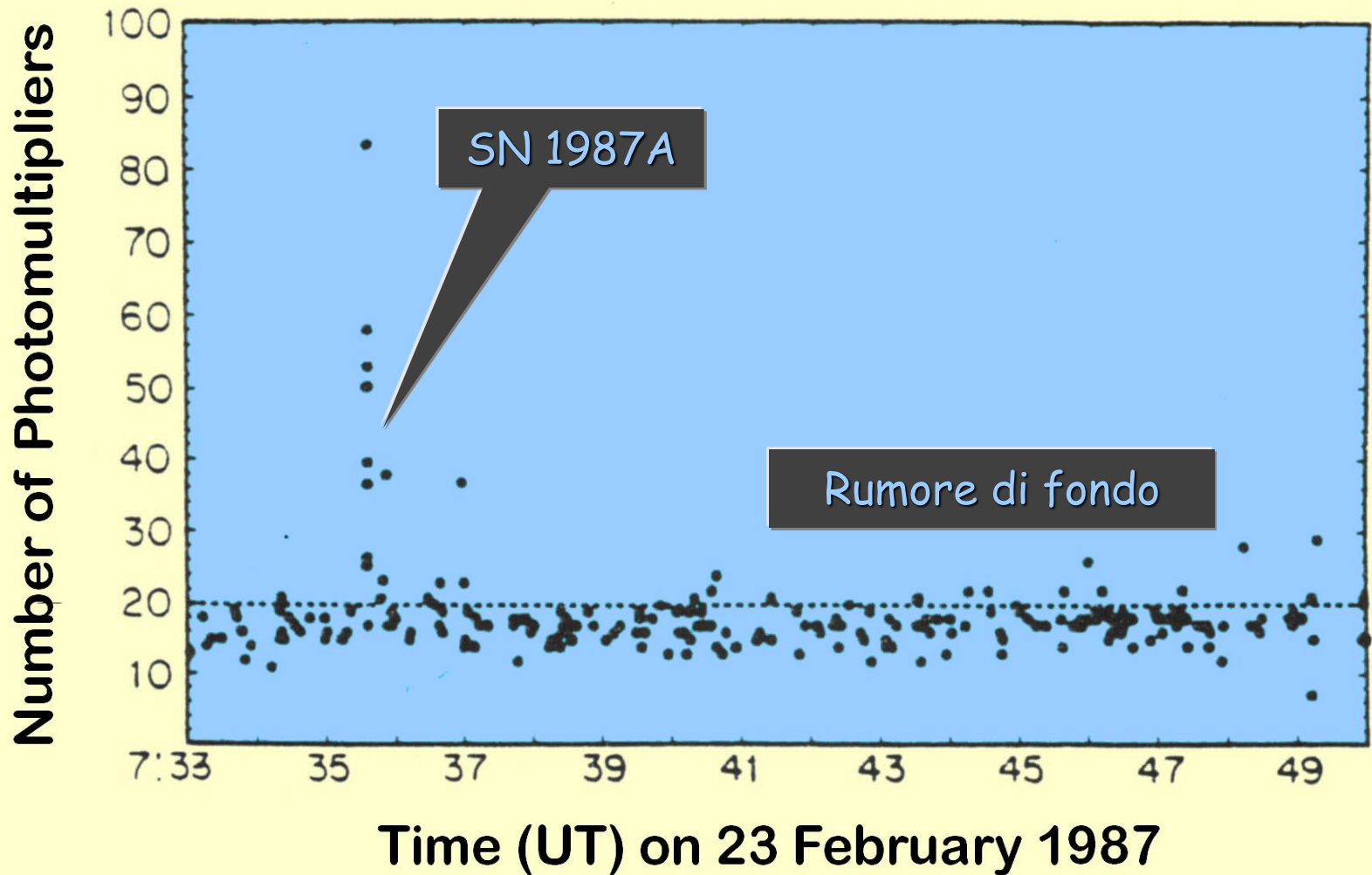
- The theoretical curve for the survival probability is shown on the top.
- It includes the possibility of oscillation into 3 neutrinos, however at present there is no sign of  $\theta_{13} \neq 0$
- On the bottom, the values of the survival probability as measured from different experiments, in different 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



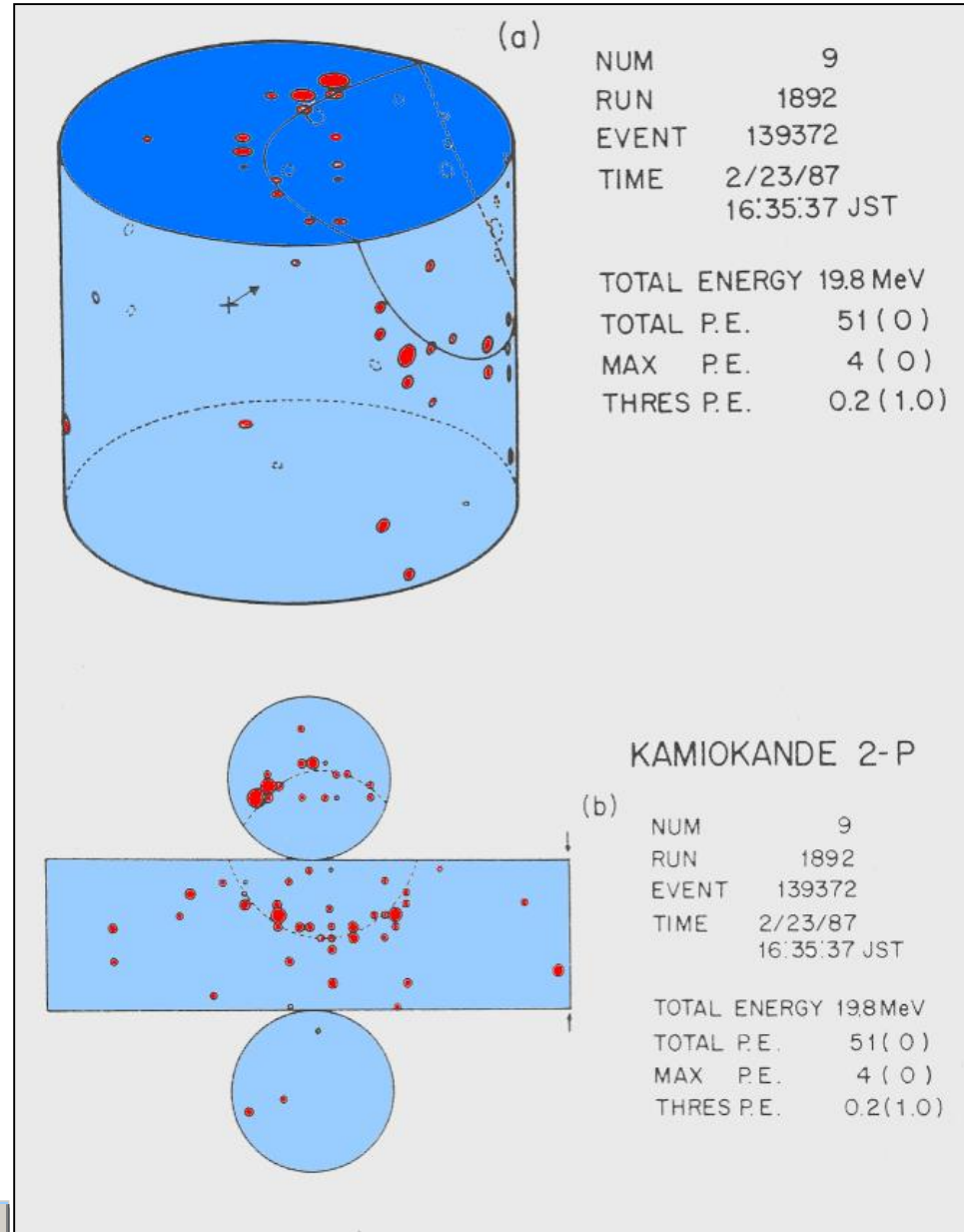
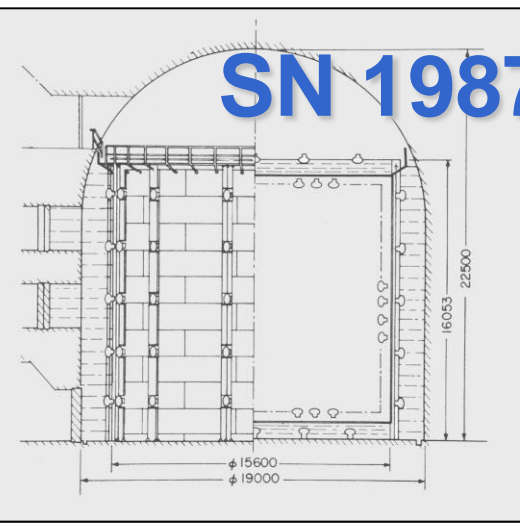
# Supernova 1987A

- 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



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

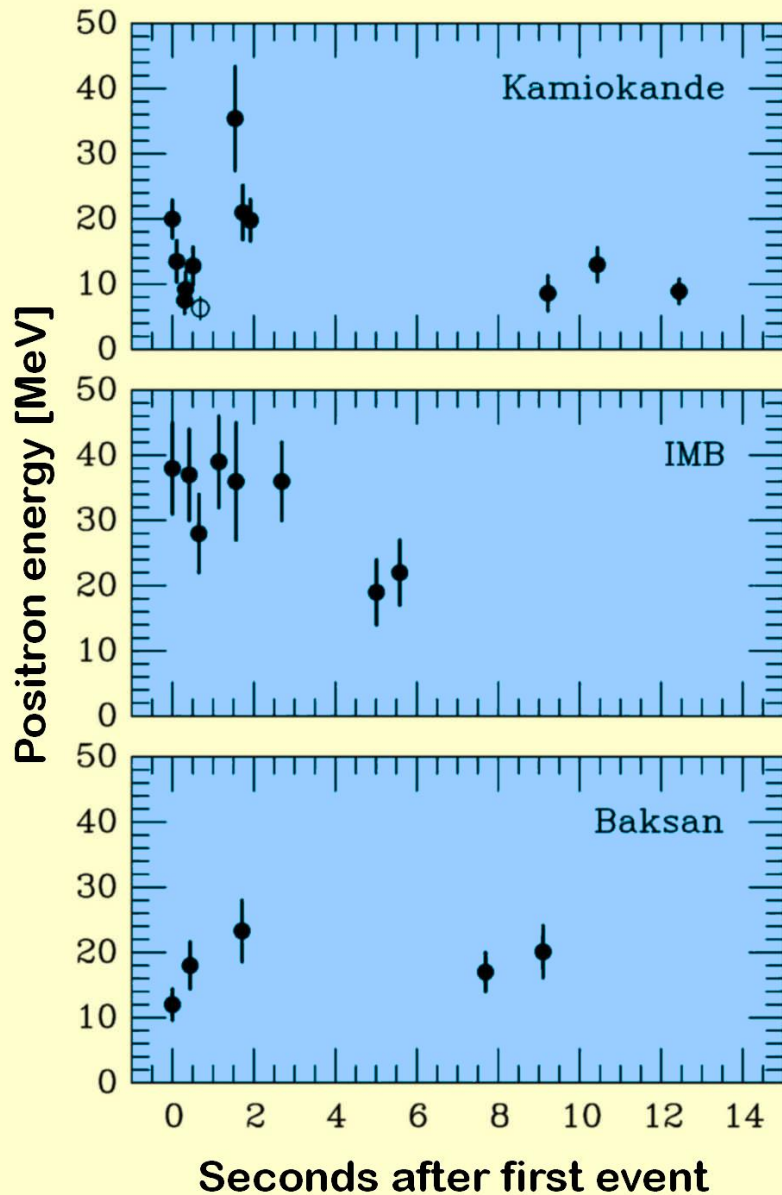


# Rilevatori

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  $\pm 1$  min

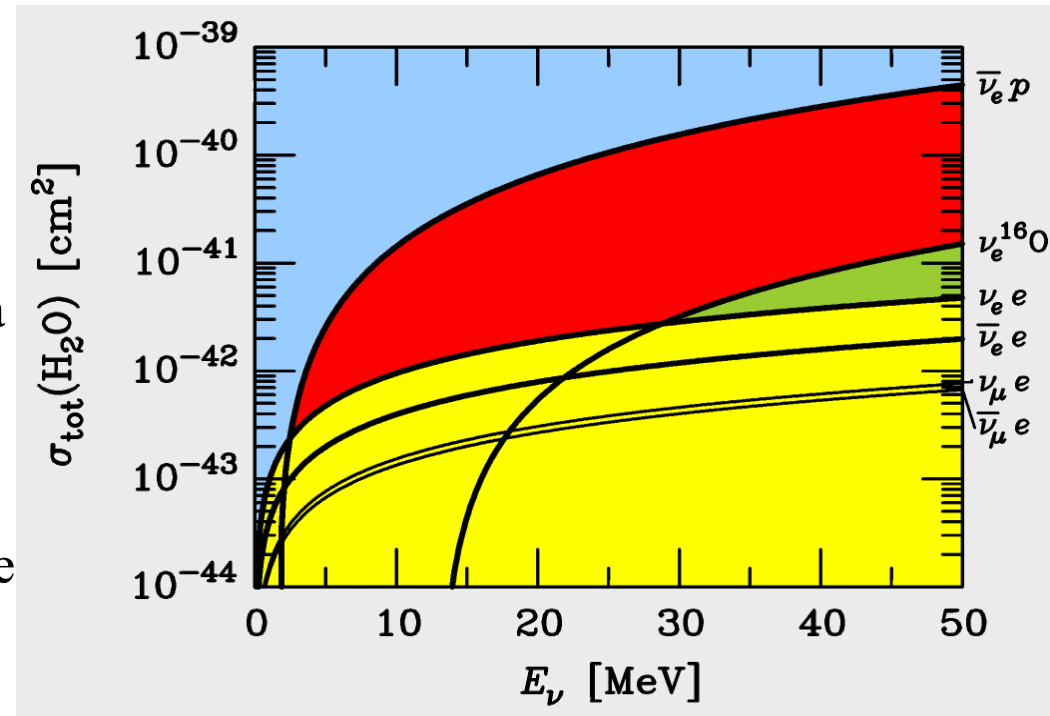
Irvine-Michigan-Brookhaven (US)  
Rilevatore Cherenkov ad acqua  
Incertezza temporale  $\pm 50$  ms

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

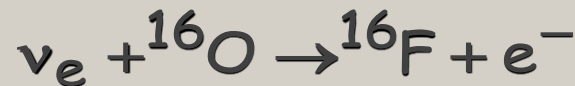
Entro le incertezza temporali,  
i segnali sono contemporanei

# 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.

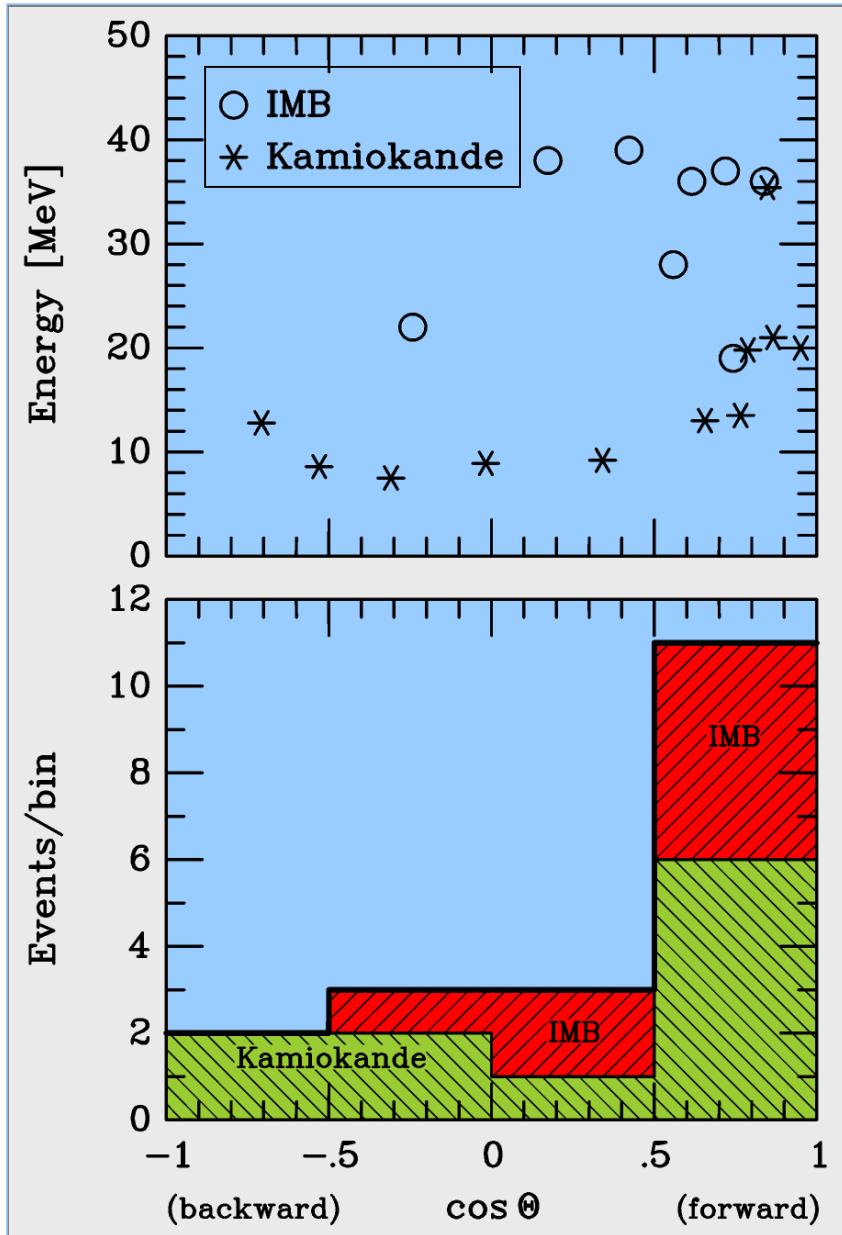


reazioni principali:  $\bar{\nu}_e + p \rightarrow n + e^+$  dominante per le SN

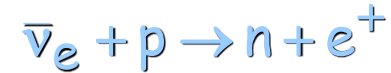


$\nu + e^- \rightarrow e^- + \nu$  dominante per il Sole

# Distribuzione angolare dei neutrini da SN 1987A



- Ricordiamo che la reazione principale di rilevazione:



e' essenzialmente isotropa per le energie rilevanti.

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



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

## Modello con raffreddamento esponenziale

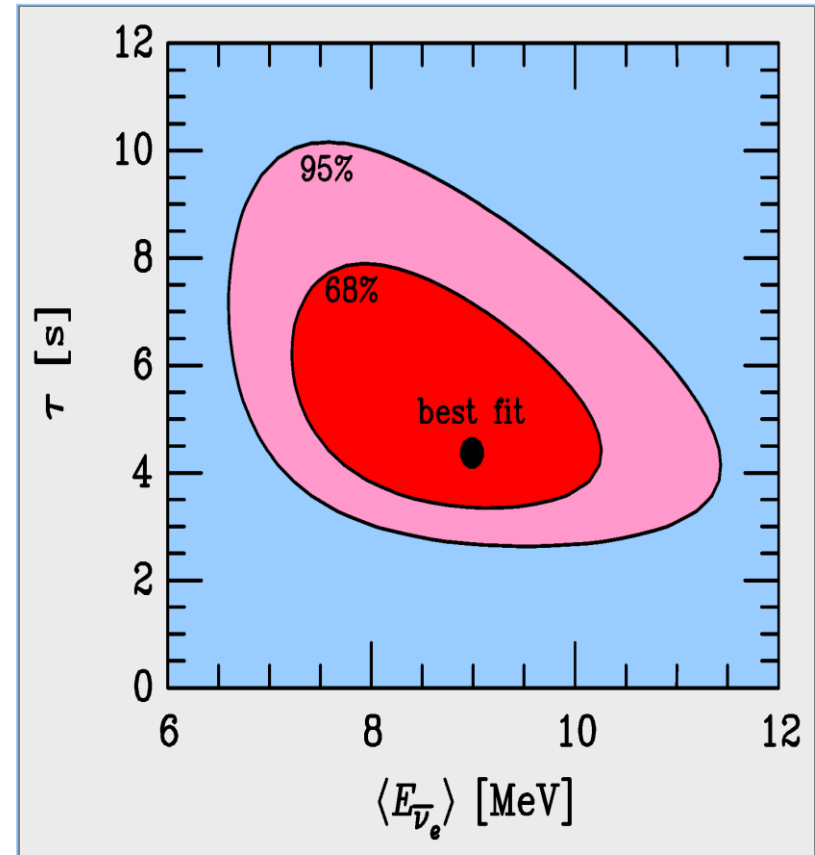
- I dati raccolti, una manciata di neutrini, sono in grado di confermare le caratteristiche principali del modello di supernova, ossia la luminosità, l'energia media dei neutrini, il tempo di raffreddamento
- Il modello più semplice è che i neutrini siano emessi termicamente da una sfera di raggio  $R$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

$$L=L_0 \exp (-t/\tau)$$

- Dove  $L_0$  è la luminosità iniziale in antineutrini di tipo elettronico e  $\tau$ , tempo di raffreddamento, sono parametri.
- Se determino questi, potrò anche determinare l'energia totale trasportata dagli antineutrini,  $U_B=6L_0 \tau$ , 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-Boltzmann avrò  $L= 4\pi R^2 \sigma T^4$
- Dunque anche la temperatura varia esponenzialmente [  $T=T_0 \exp (-t/ 4\tau)$  ]
- La temperatura è collegata all'energia media dei neutrini, secondo la distribuzione statistica,  $\langle E \rangle=3kT$ , e la luminosità è collegata al flusso misurato di neutrini, moltiplicato per la loro energia media.
- In breve, I parametri liberi sono tre,  $L_0$  (ovvero  $T_0$ ),  $\tau$  ed  $R$  da ricavarsi in termini dei dati dei neutrini

# I risultati principali sulla supernova

- L'analisi dei dati in questo semplice modello (Loredano & Lamb 95) da'
- $R = 40 \text{ Km}$
- $\tau = 4,4 \text{ s}$
- $kT_0 = 3,8 \text{ MeV}$
- L'energia liberata dalla supernova risulta di  $5 \cdot 10^{53} \text{ erg}$ , 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

# Informazioni sulle proprietà dei neutrini : limiti da SN 1987 A

Se i neutrini avessero massa  $\neq 0$  allora neutrini con diverse energie avrebbero diverse velocità ed arriverebbero sulla terra con tempi diversi.

Il ritardo tra due neutrini di diversa energia sarebbe:

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

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

Prendendo come energie:  $E_1 = 10 \text{ MeV}$  ed  $E_2 = 20 \text{ MeV}$

otteniamo facilmente:

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



## Stabilita' del neutrino

Per risolvere l'enigma dei neutrini solari Cabibbo et al. avevano proposto che i  $\nu_e$  potessero decadere durante il percorso sole-terra.

Questo implicherebbe che i neutrini avessero massa  $m \neq 0$  e vita media  $\tau$ :

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

Per  $E_{\nu\text{-sole}} = 10 \text{ MeV}$   
 $\dagger = 500 \text{ s}$   $\Rightarrow \tau \approx 5 \cdot 10^{-5} \text{ s} \frac{\mathbf{m}}{\text{eV}}$

L'aver osservato  $\nu_e$  dalla SN 1987 A implica:

$E_{\nu\text{-sn}} = 10 \text{ MeV}$   
 $\dagger = 150000 \text{ anni}$   $\Rightarrow \tau > 5 \cdot 10^5 \text{ s} \frac{\mathbf{m}}{\text{eV}}$

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  $\neq 0$  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

$$E = 10 \text{ MeV}$$

$$\Delta E = 10 \text{ MeV}$$

$$\Delta t \leq 10 \text{ s}$$

**CAMPO GALATTICO**

$$S \approx 10 \text{ kpc}$$

$$B \approx 10^{-6} \text{ G}$$

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

**CAMPO INTERGALATTICO**

$$S \approx 50 \text{ kpc}$$

$$B \approx 10^{-9} \text{ G}$$

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

I limiti di laboratorio danno:  
(scattering  $\nu$ -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:

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

Ne possiamo ricavare una stima della velocita' dei neutrini :

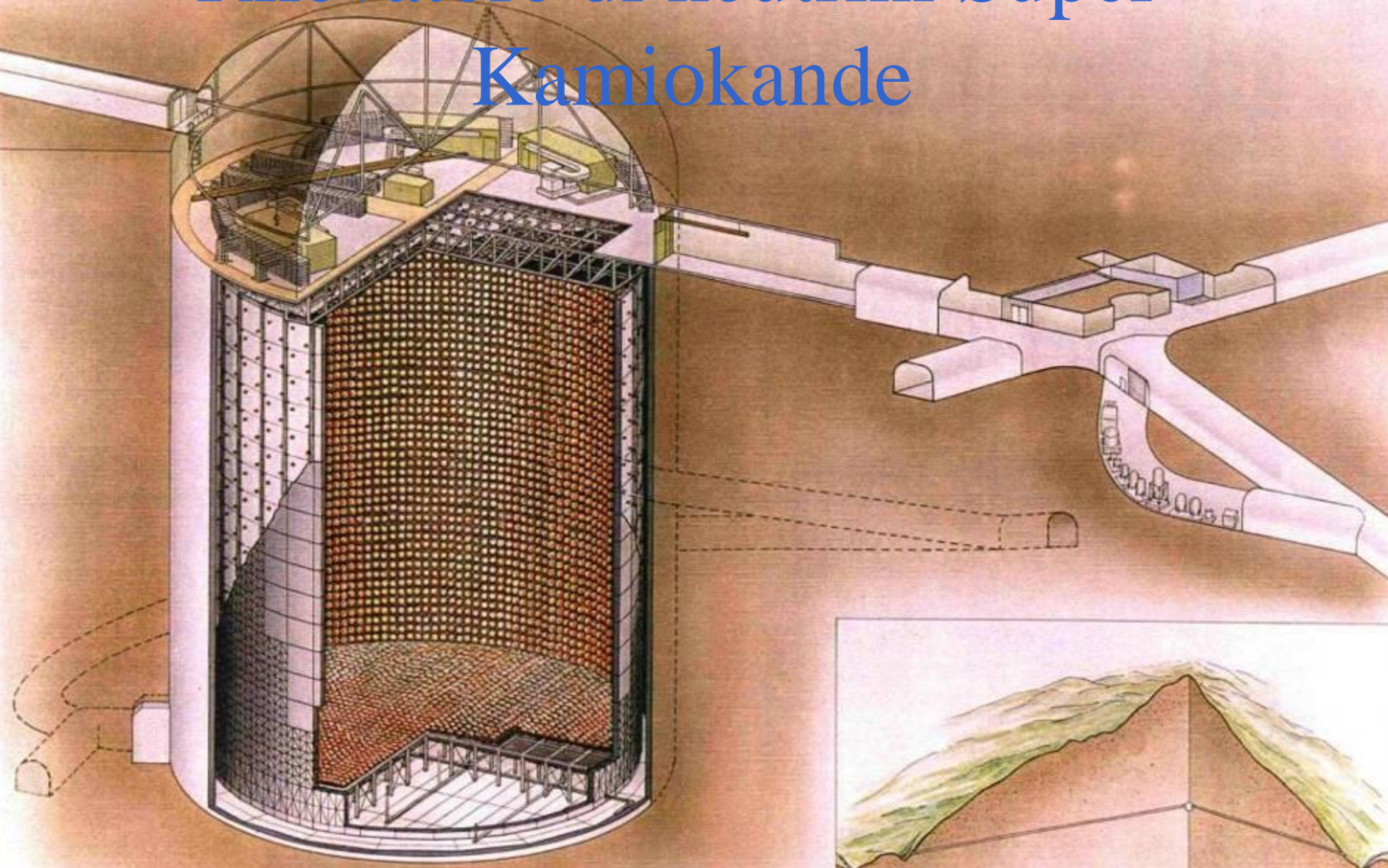
$$\Delta \mathbf{t}_{\nu-\gamma} = \mathbf{D} \left( \frac{1}{\mathbf{v}_{\nu}} - \frac{1}{\mathbf{c}} \right) \approx \frac{\mathbf{L}}{\mathbf{c}} \left( 1 - \frac{\mathbf{v}_{\nu}}{\mathbf{c}} \right)$$

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

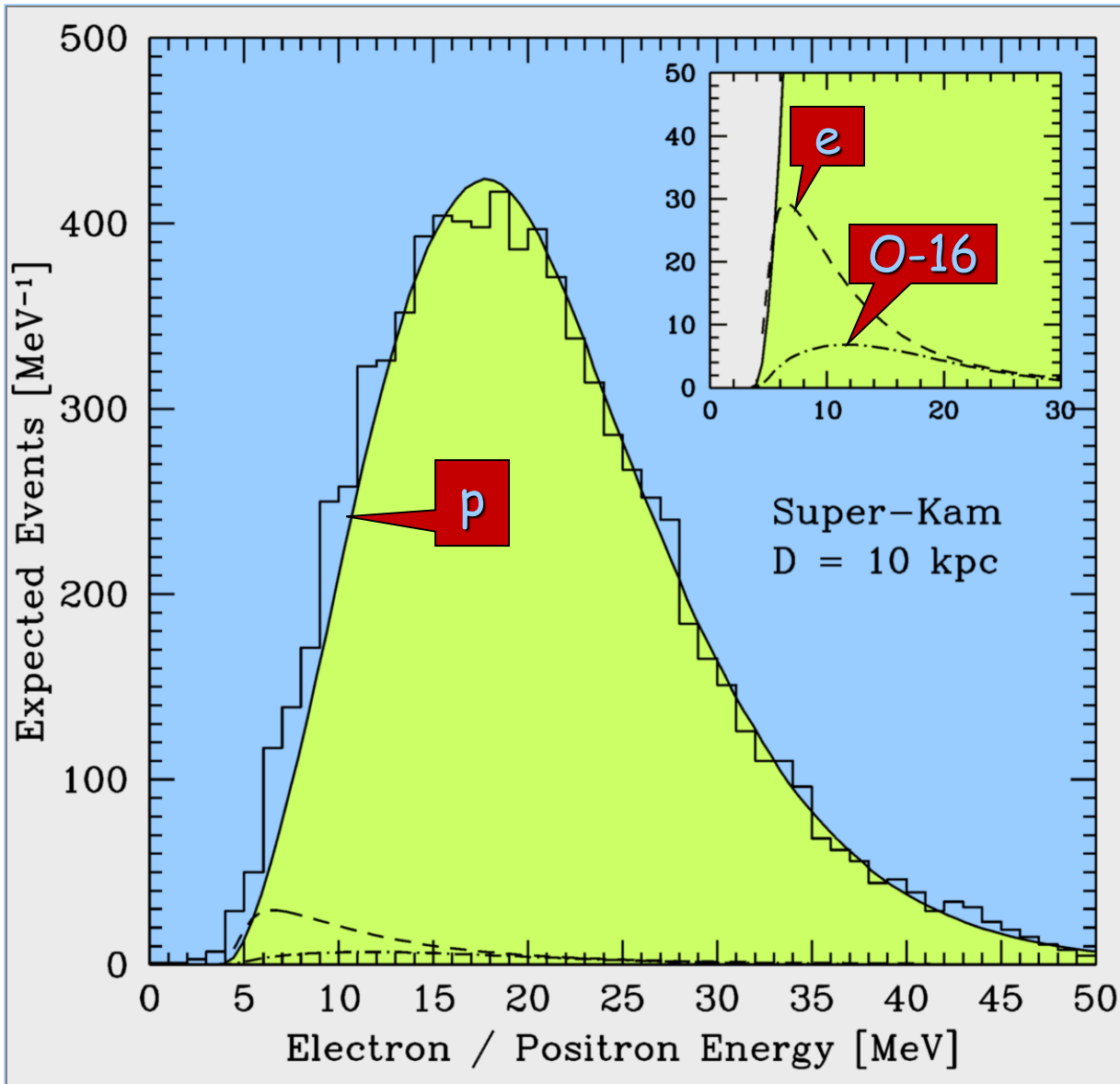


**Il futuro**

# 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 nu-  
merico di Livermore

Totale of circa 8300  
eventi per  $t < 18$  s

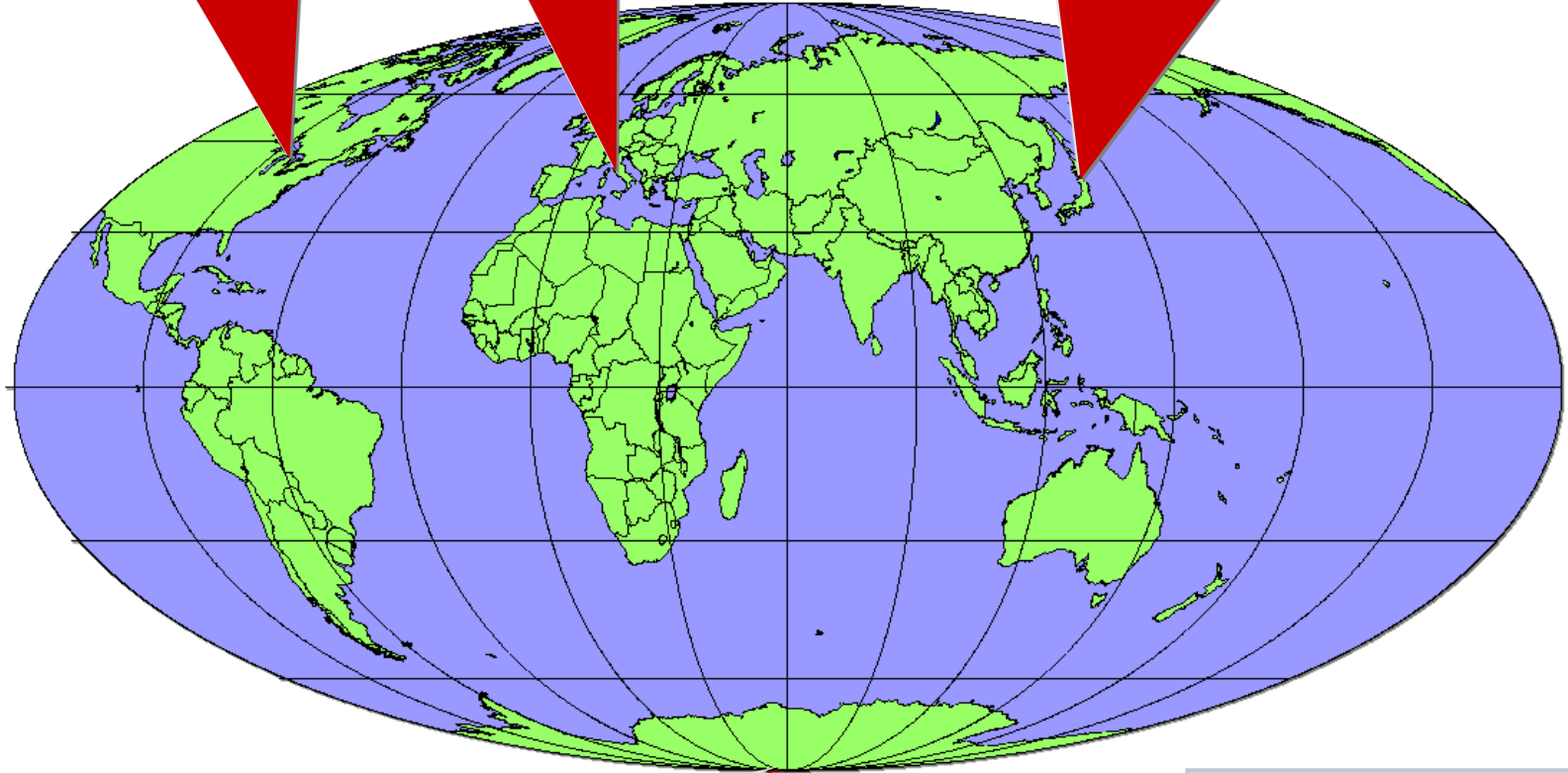
Totani, Sato, Dalhed  
& Wilson,  
ApJ 496 (1998) 216

# Grandi Rilevatori per Neutrini da SN

SNO (800)  
MiniBooNE (190)

LVD (400)  
Borexino (80)

Super-Kamiokande (8500)  
Kamland (330)



Amanda  
IceCube

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

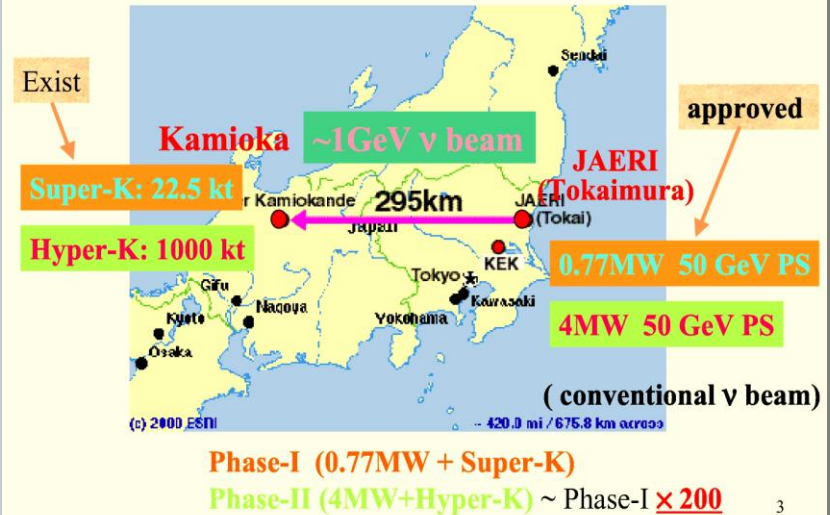
# The Future: A Megaton Detector?

Megaton detector motivated by

- Long baseline neutrino osc.
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos  
( $\sim 10^5$  events for SN at 10 kpc)

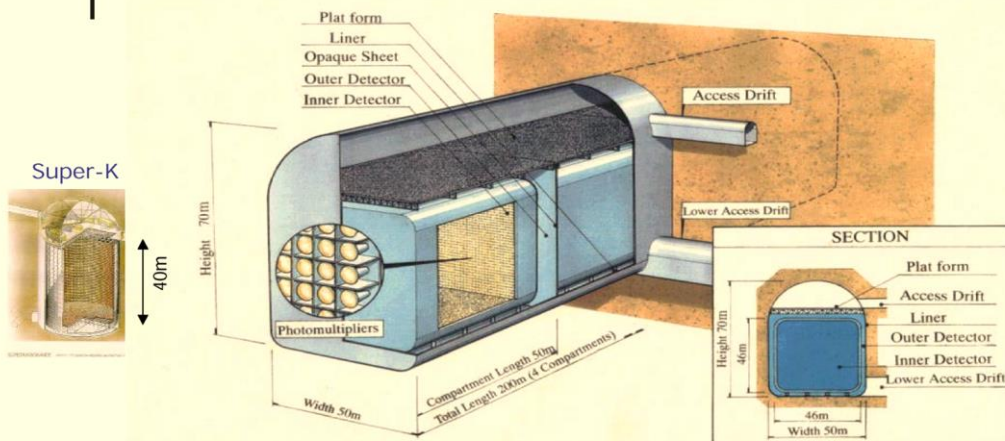
## 1. Overview of the experiment

(expect to start in 2007)



## Possible Design of Hyper-Kamiokande

May.-2001 JHF-Kamioka  $\nu$  workshop



1 Mton fiducial volume: Total Length 800m (16 Compartments)

(STRAIGHT TYPE)

Similar discussions in

- USA (UNO project)
- Europe (Frejus Tunnel)

• Note however we are confined to the Galaxy

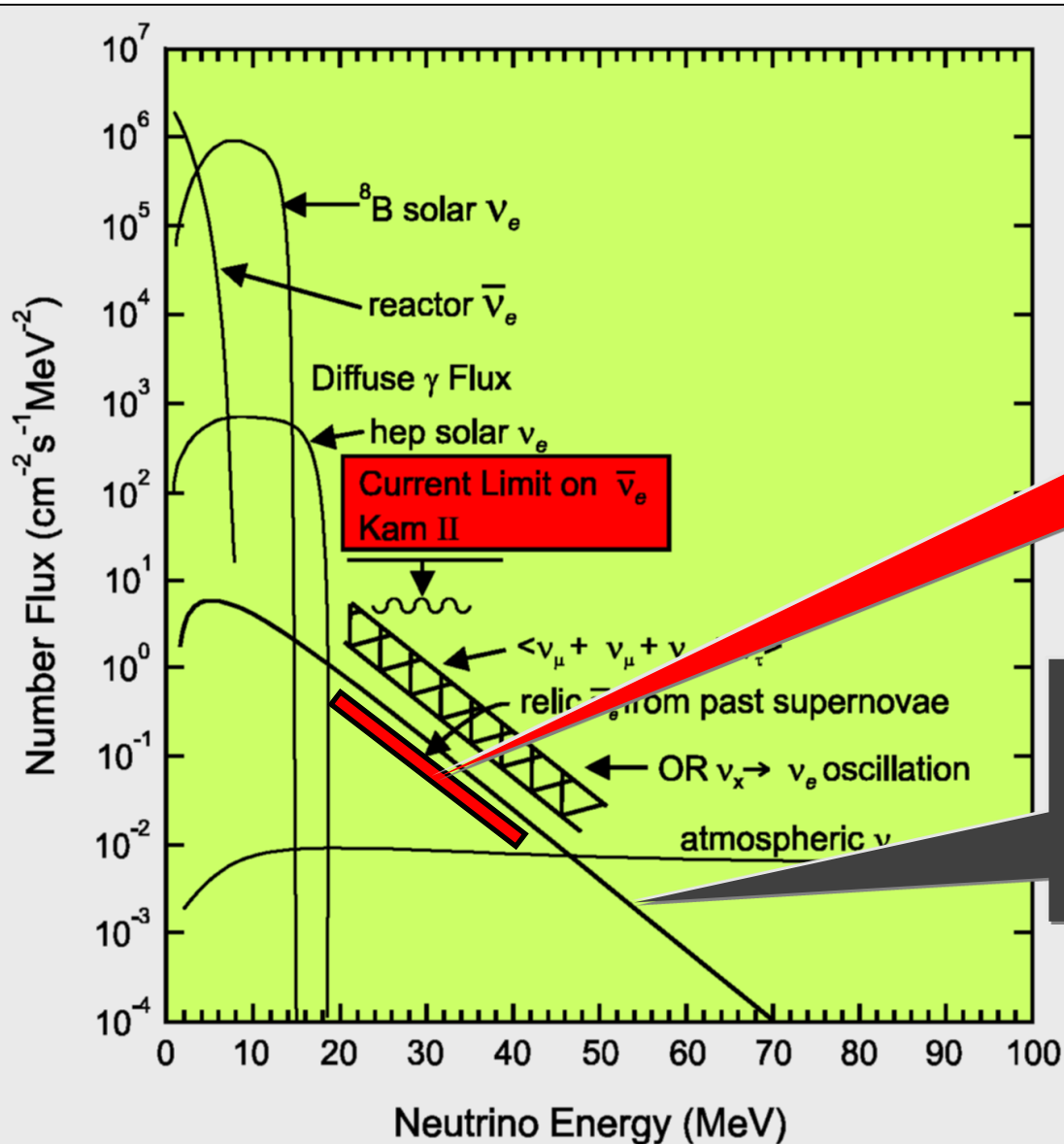


# Relic neutrinos from past supernovae

- 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  $\nu$

凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑月南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃連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没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没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因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

# Experimental Limits on Relic SN Neutrinos



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

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

# 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	$< 130 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$44 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.41 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Cosmic gas infall [5]	$< 2.8$ events/year	$< 32 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$5.4 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.20 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Cosmic chemical evolution [6]	$< 3.3$ events/year	$< 25 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$8.3 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.39 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Heavy metal abundance [7]	$< 3.0$ events/year	$< 29 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$< 54 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$< 2.2 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Constant supernova rate [4]	$< 3.4$ events/year	$< 20 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$52 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$3.1 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$
Large mixing angle osc. [8]	$< 3.5$ events/year	$< 31 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$11 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$	$0.43 \bar{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$

hep-ex/0209028

**Experimental sensitivity is approaching predictions**