LOW ENERGY NEUTRINOS

Gioacchino Ranucci - INFN Milano

PIC 2013

Beijing - 5 September, 2013

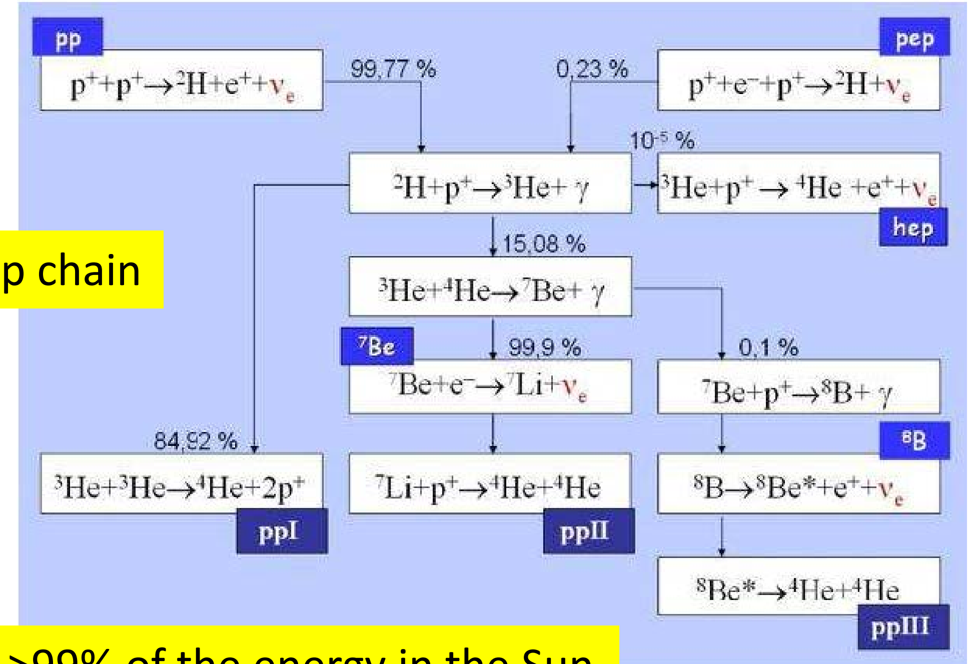
1-Solar neutrinos and the SSM

2-Geo-neutrino detection, status and perspectives

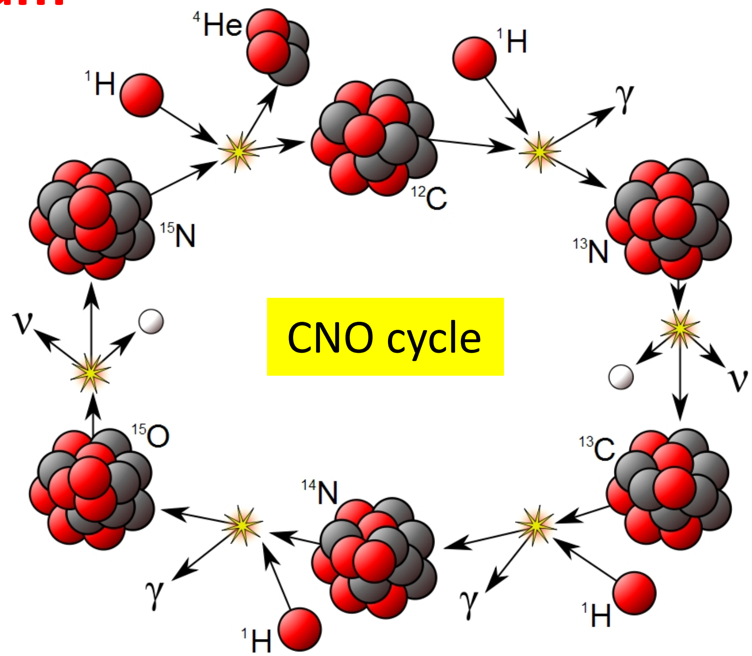
3-Supernova neutrinos

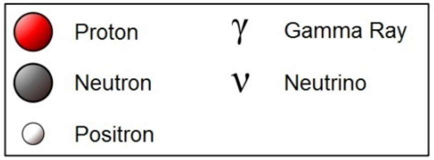
Solar neutrinos production and spectrum

pp chain



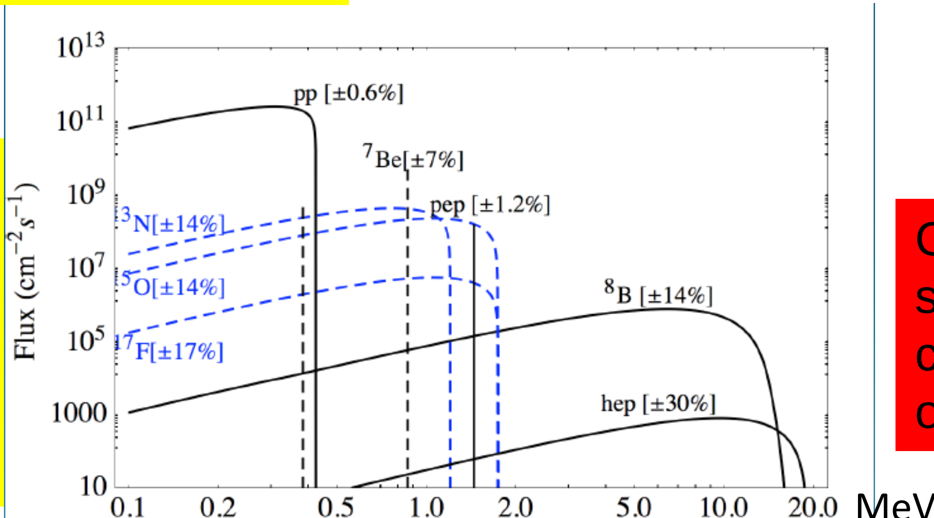
>99% of the energy in the Sun





SSM prediction

A. Serenelli et al., Astroph. J. 7432 2011



Controversy about the surface metallicity composition of the Sun still open: High Z vs Low Z

Solar neutrino experiments: an almost five decade long saga

Radiochemical experiments:

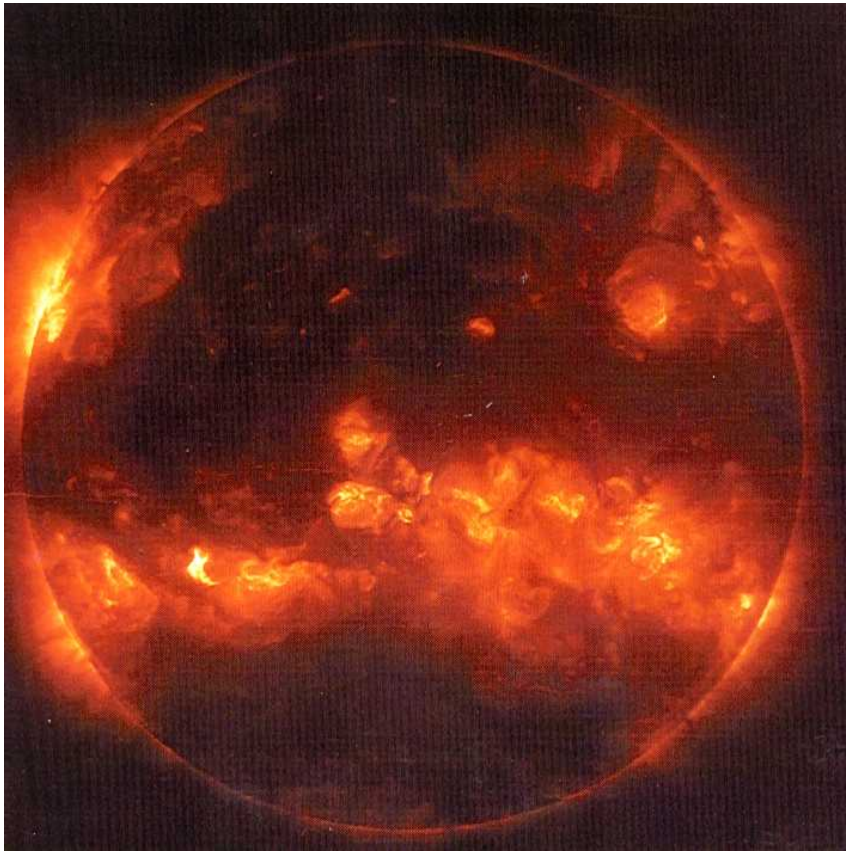
- Homestake (Cl)
- Gallex/GNO (Ga)
- Sage (Ga)

Real time Cherenkov experiments

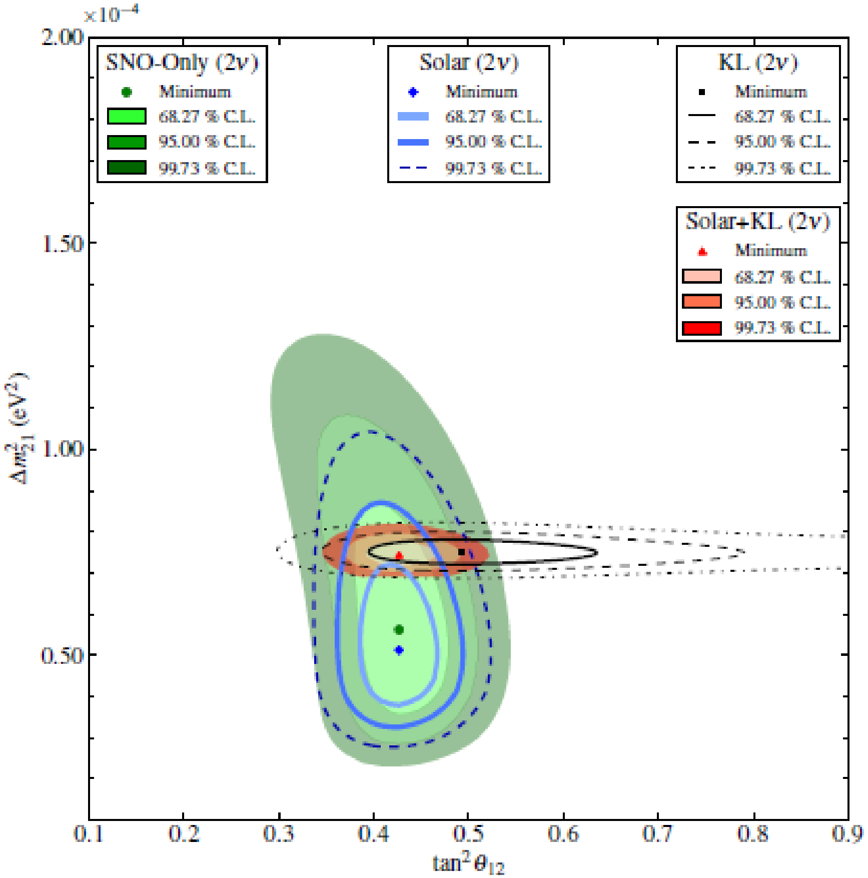
- Kamiokande/Super-Kamiokande
- SNO

Scintillator experiments

- Borexino



Long standing discrepancy between measured and predicted fluxes: Solar Neutrino Problem
Culminated in a crystal clear proof that neutrino oscillates



SOLAR PLUS

KAMLAND (Reactor anti-ν's)

Neutrino oscillations !

$$\Delta m^2_{21} = 7.46^{+0.20}_{-0.19} \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.427^{+0.027}_{-0.024}$$

arXiv:1109.0763

MSW (Mikheyev-Smirnov-Wolfenstein) matter enhanced flavor conversion - LMA (Large Mixing Angle) solution

Main achievements of solar neutrino investigation

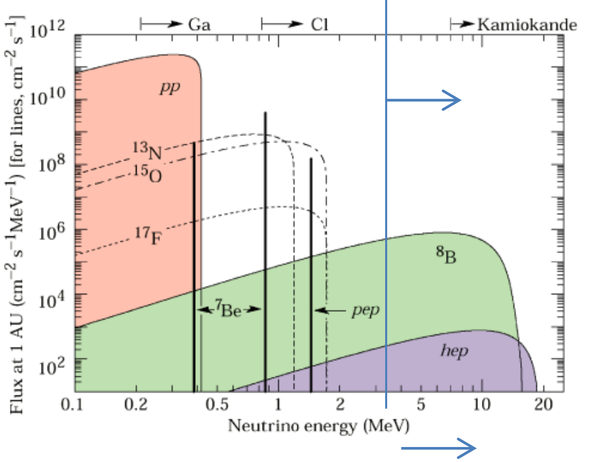
Neutrino physics

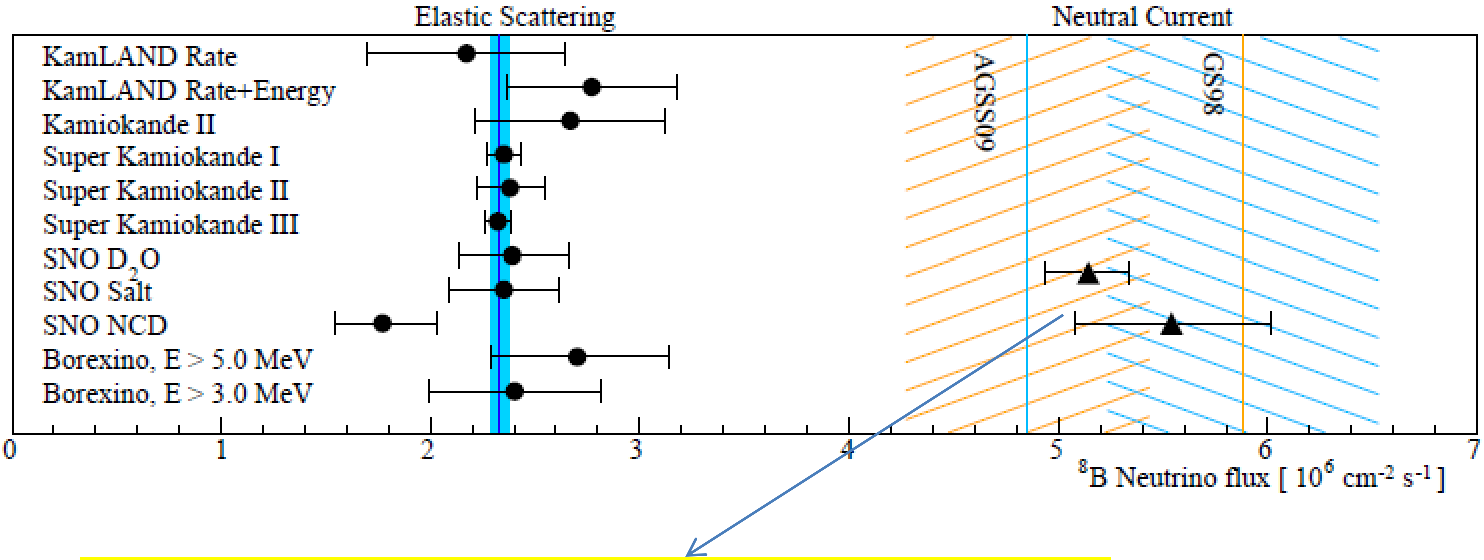
- ✓ Proof of neutrino oscillation MSW-LMA solution and determination of the relevant mixing parameters (**the crown jewel**! Motivated the 2002 Nobel prize)
- ✓ P_{ee} survival probability at various energies, check of the matter to vacuum transition e.g. check of the MSW-LMA solution in the sub-MeV regime

Astrophysics

- ✓ Experimental proof of the nuclear mechanism powering the stars
  - Main outcome of the integral radiochemical experiments
- ✓ Determination of the individual neutrino fluxes from the core of the Sun
  - "Oscillated" ^{8}B flux (through elastic scattering) : SK , SNO, Borexino, KamLAND
  - Absolute ^{8}B flux (CC and NC current) SNO
  - "Oscillated" ^{7}Be and pep fluxes (through ES) Borexino

^{8}B neutrinos





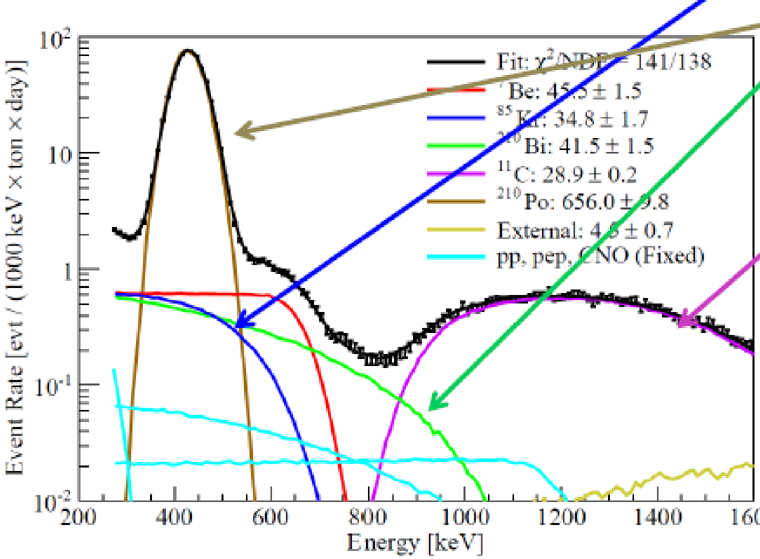
SNO has provided the absolute ^{8}B flux

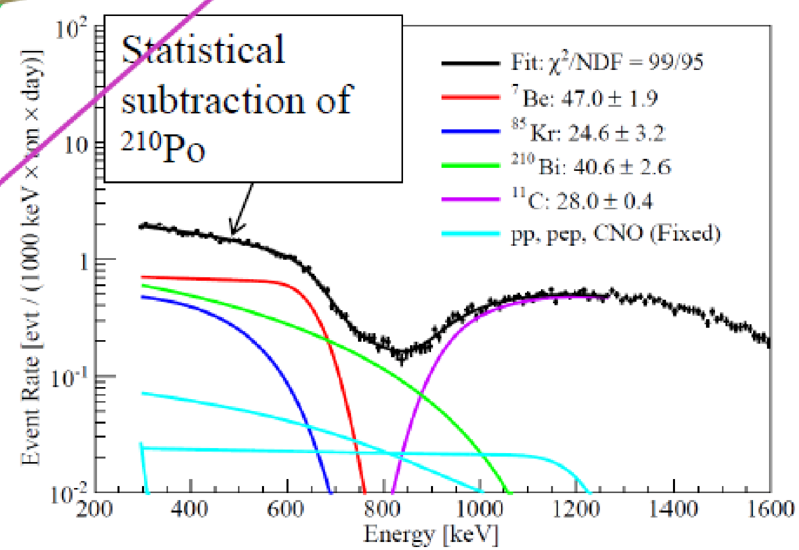
Threshold progressively lowered along the years: from 7 MeV of Kamiokande to 3 MeV of Borexino

Figure from PRC 84, 035804 (2011) Kamland coll.

^{7}Be (0.862 MeV) solar flux from Borexino

- Residual background components (^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C);





Experimental spectrum fit to the model to extract the ^{7}Be flux

$$R_{^7Be} = 46 \pm 1.5\ (stat)^{+1.5}_{-1.6}\ (syst)\quad cpd/100t$$

$$R_{no\ oscillation} = 74 \pm 5.2\quad cpd/100t$$

- Unprecedented 5% precision
- Estimate of the total flux $(4.84\pm0.24)\times10^{9}$ cm^{-2}s^{-1}
- ν_e survival probability 0.51 +- 0.07 @0.862MeV

- Search for a day night effect:
- not expected for ^{7}Be in the LMA-MSW model
- Large effect expected in the “LOW” solution (excluded by solar exp+Kamland)

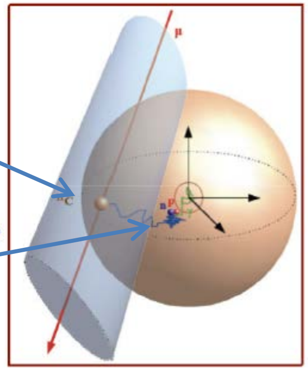
$$\boxed{A_{DN} = \frac{N-D}{(N+D)/2} = 0.001 \pm 0.012\ (stat) \pm 0.007 (sys)}$$

G. Bellini et al., Borexino Collaboration, Phys. Lett. B707 (2012) 22.
G. Bellini et al., Borexino Collaboration, Phys. Rev. Lett. 107 (2011) 141362.

pep (1.44 MeV) flux measurement and CNO limit in Borexino

Interaction point and ^{11}C production point

Position of the γ



$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

${}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$

t~30min

$n + p \rightarrow d + \gamma$

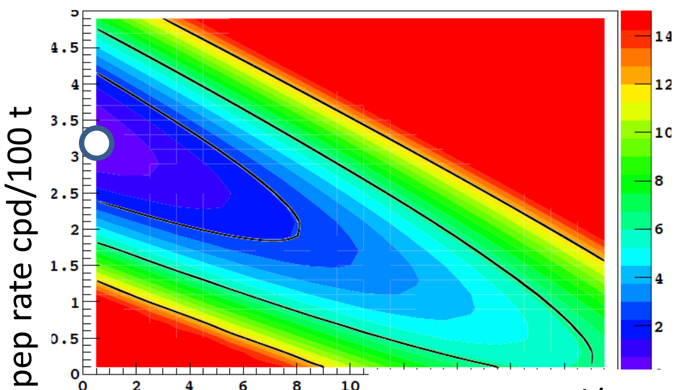
τ~260μs

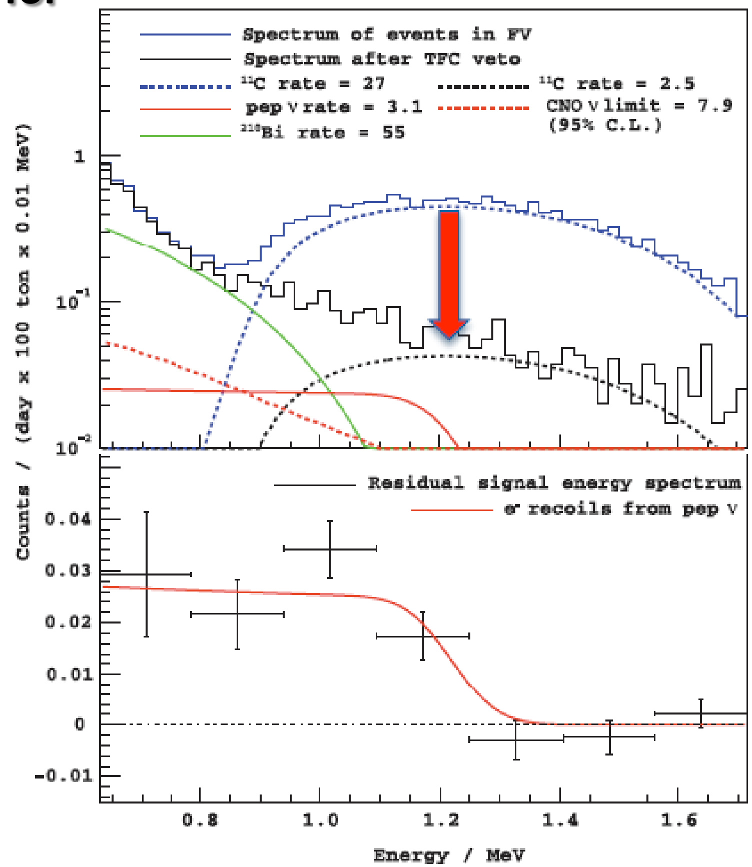
- n capture on H: γ 2.2 MeV τ=260 μs
- Space and time Veto
- Residual exposure 48.5%

Threefold coincidence for ^{11}C rejection

G. Bellini et al., Borexino Coll., Phys. Rev. Lett. 108 (2012) 051302

Δchi^2 profile for fixed pep and CNO rates

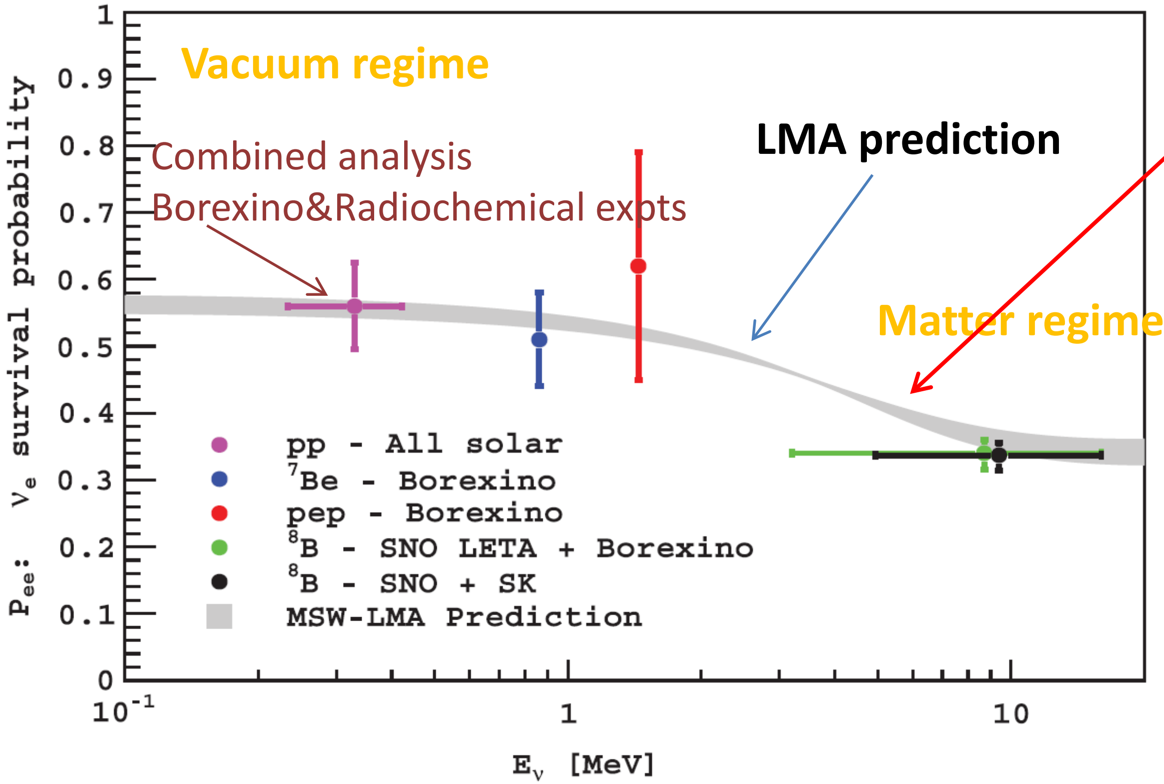




ν	Interaction Rate (cpd/100t)	DATA/SSM (high metallicity)
	Counts/(days 100 t)	ratio
pep	3.1±0.6 (stat) ± 0.3(sys)	1.1±0.2
CNO	<7.9	<1.5 (95% C.L.)

Best limit on CNO so far….

The global oscillation picture: survival probability of the electron neutrinos



The rise of the P_{ee} toward the low energy range should reflect in an "upturn" of the ^{8}B experimental spectrum not yet observed in the data

P_{ee} curve (grey band) as expected from ν oscillation+Matter effect (LMA-MSW)

Solar neutrinos : open issues

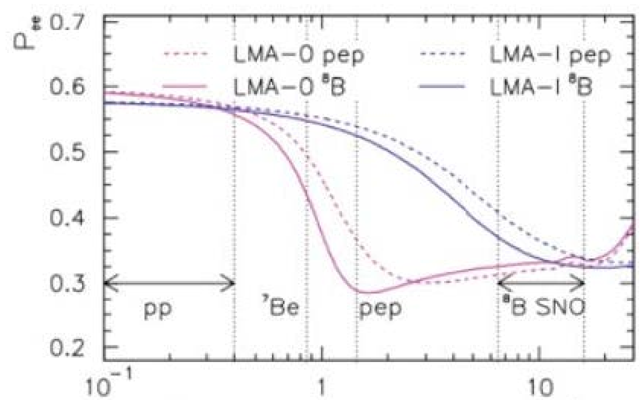
(Yet) Unresolved puzzles

SSM

- high vs. low metallicity of the surface of the Sun

Experimental data

- Missing upturn (predicted by MSW-LMA solution) in the ^{8}B spectrum (SNO and SK) - will more data unveil the mystery?



Friedland, et al PLB 594, 347 (2004)

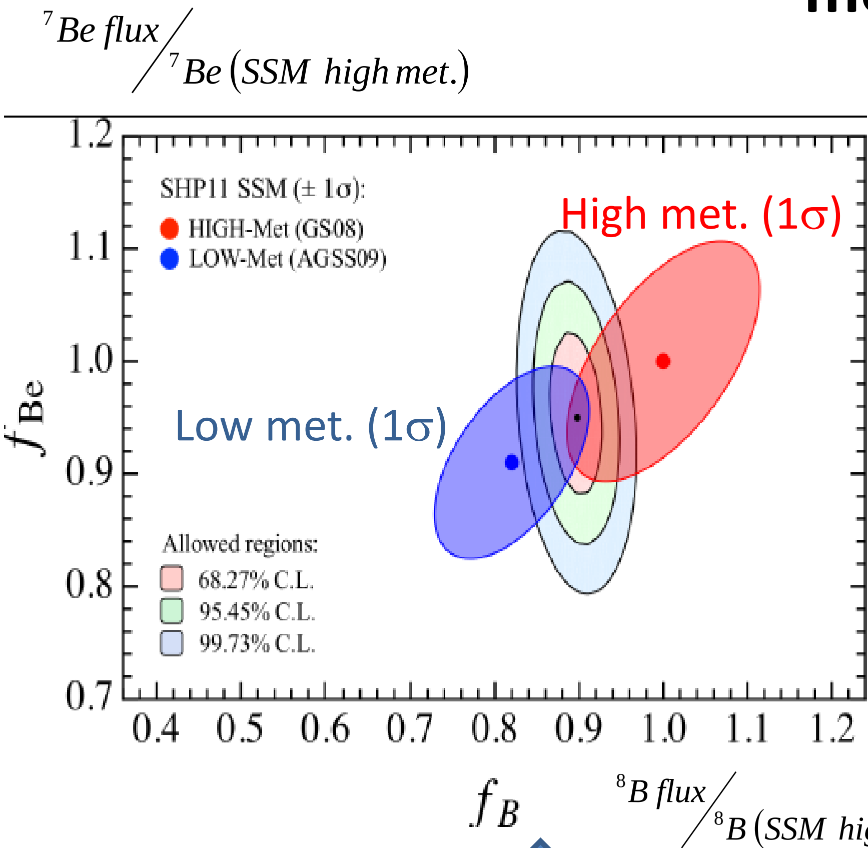
The P_{ee} is altered by beyond SM physics

Further "Desiderata"

- Full spectroscopy : still missing pp and CNO fluxes
- Improved precision on ^{7}Be, pep and ^{8}B

Precise experimental constrain on the Pee → is there room for beyond standard model effects ? **NSI** , **Mass Varying Neutrinos**, **Long range Leptonic forces**, **ultra-light sterile neutrinos** (arXiv:1305.5835 and Phys. Rev. D83 (2011) 113011)

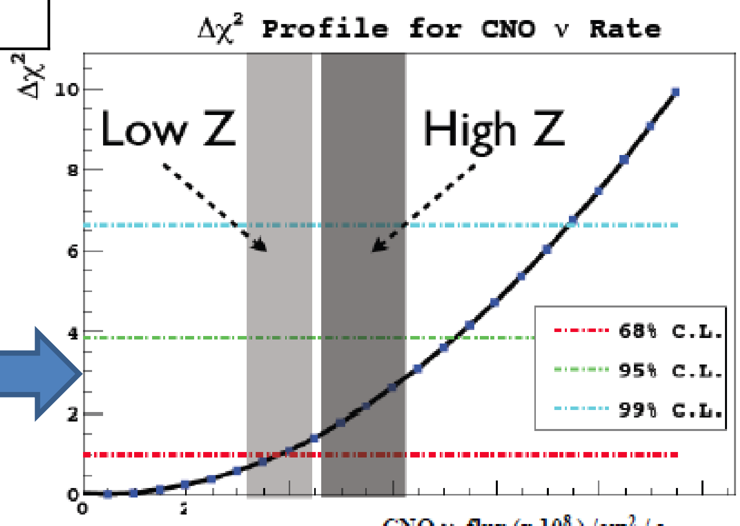
Can the current data discriminininate between high and low metallicity ?



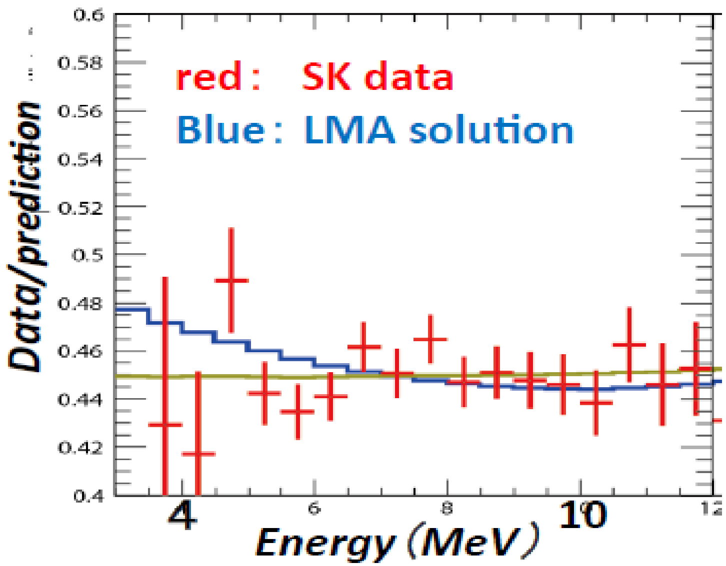
ν	Diff. %
pp	0.8
pep	2.1
^{7}Be	8.8
^{8}B	17.7
^{13}N	26.7
^{15}O	30.0
^{17}F	38.4

The major predicted difference is in the CNO flux

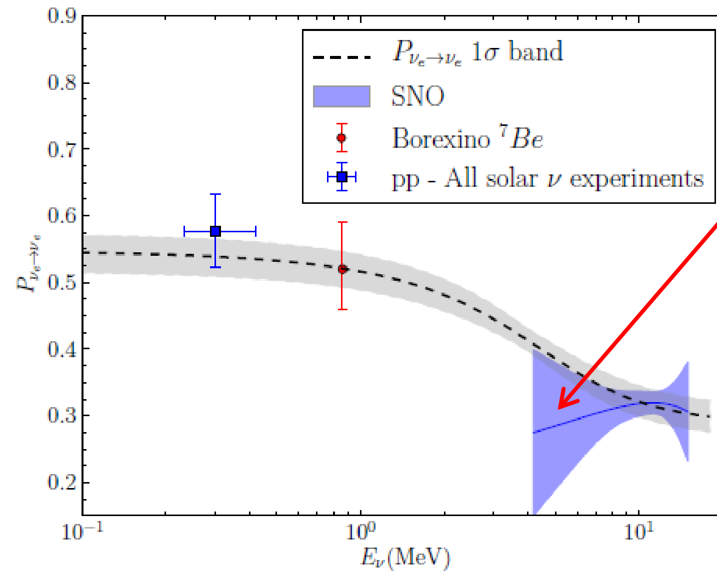
The Borexino data cannot disentangle between the two models
Similar situation with the ^{8}B flux from SNO



^8B solar neutrino and the upturn mystery in the SK and SNO results

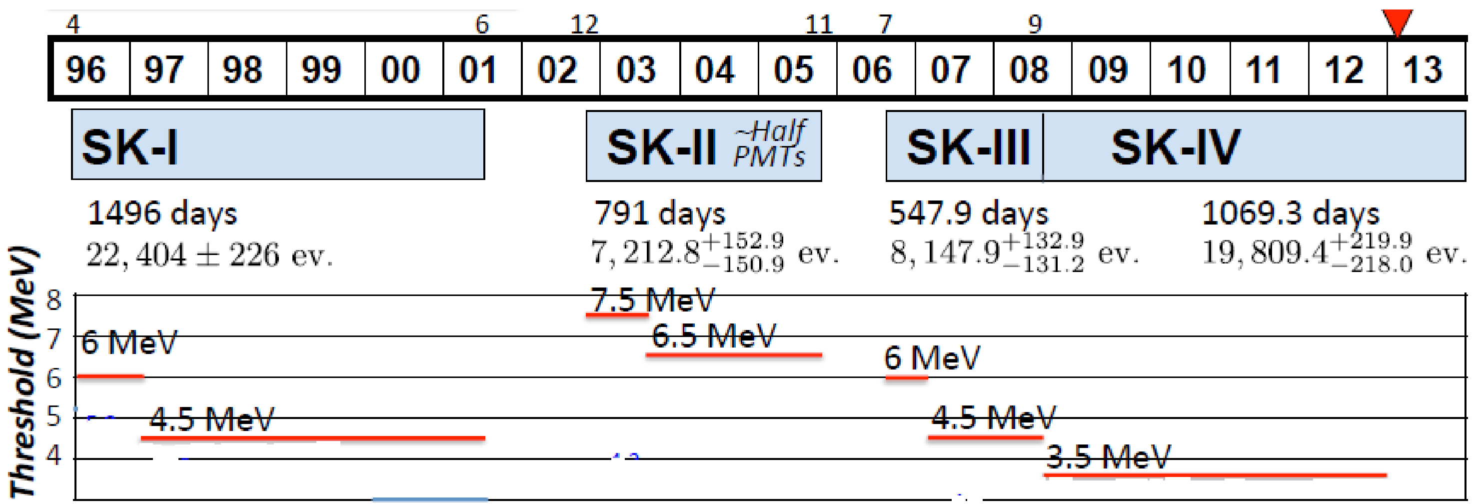


Super K. Suzuki@Neutrino Telescopes Venice March 2013



arxiv 1109.0763 SNO LETA 3.5 MeV threshold

Did SNO see even a downturn ?



Lowering the threshold in SK may help unveil the mystery Borexino already at 3 MeV but limited statistics

Adapted from Y. Suzuki Neutrino telescopes Venice March 2013

Outlook

Current experiments

- SK→ ^{8}B at low threshold
- Borexino → pp, CNO, improved precision on ^{7}Be, pep and ^{8}B

New experiments

- SNO+ (liquid scintillator) → perfectly suited for pep and CNO due to the depth of SNOLAB, in addition to ^{8}B - but priority given to double beta decay with ^{130}Te
- LENS (indium loaded liquid scintillator) → powerful tagging for precise pp, ^{7}Be and pep spectroscopy
- Massive Cryogenic detectors based on Xenon and Neon developed for Dark Matter search , if realized at the level of tens of tons would be ideal for pp measurement

Geo-neutrinos: anti-neutrinos from the Earth a new probe of Earth's interior

U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well fixed ratio:

Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [kg^{-1}s^{-1}]	ε_H [W/kg]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

Earth emits antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ whereas Sun shines in neutrinos.

A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons:

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

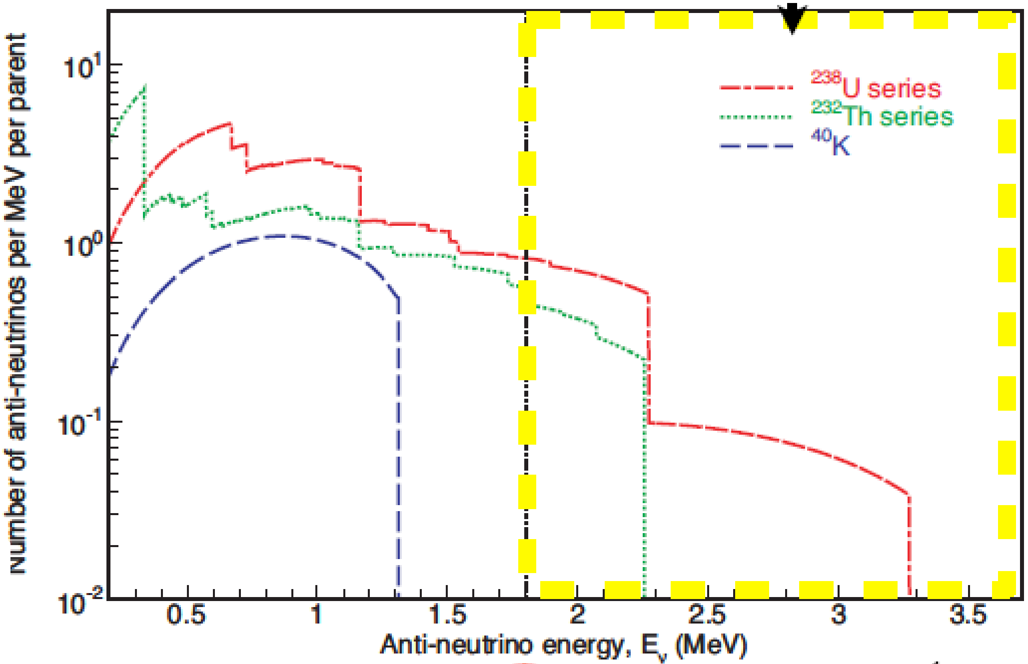
Classical antineutrino detection in liquid scintillation detectors

Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.

Detected so far by KamLAND and Borexino

- G. Bellini et al., (Borexino Coll.) Phys. Lett. B 687 (2010) 299; Phys Lett B 722 4 (2013) 295 Borexino Coll.
- T. Araki et al., (Kamland Coll.) Nature 436 (2005) 499; A. Gando et al. (Kamland Coll.) Nature Geoscience 4 (2011) 57 ; arxiv 1303.4667v1 (2013) Kamland Coll.

See Also Neutrino Geoscience (Takayama) 2013



$$\bar{\nu} + p \rightarrow n + e^{+}$$ E_ν>1.8 MeV

•"prompt signal"

e^+: energy loss + annihilation (2 γ 511 KeV each)

•"delayed signal"

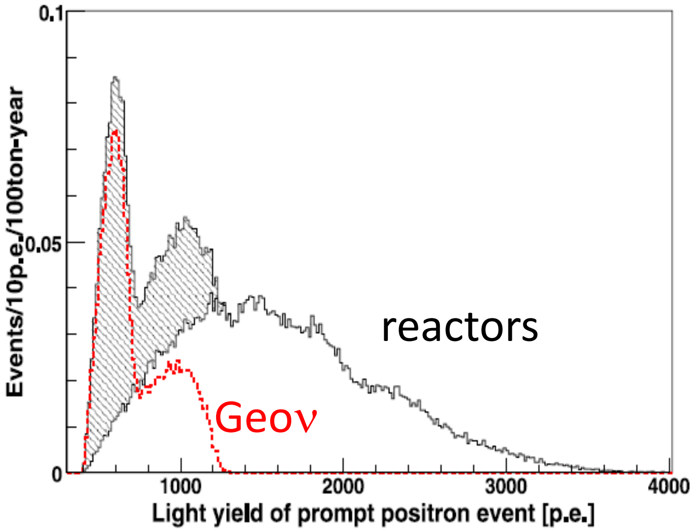
n capture after thermalization 2.2 γ

Predicted geo-antiν energy spectrum

- Flux in line with the Earth's model expectation
- Low flux: 3 order of magnitude less than ^{7}Be solar ν!
- Geo-ν probe the U,Th content of the Earth (not K)
- Multidisciplinary research: particle physics&geophysics

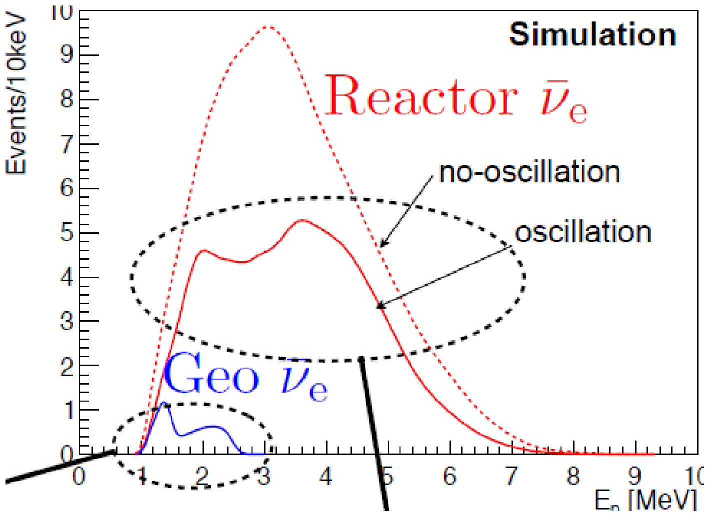
Geo-νs and reactor anti-νs : flux predictions

Prediction for Borexino



1MeV≈ 500 p.e.

Prediction for Kamland



- Reactors anti-νs are the major source of background
- Lower contamination in Borexino (there are not near reactors)
- Borexino has also lower background (accidental, (α,n),….) ^{13}C (^{210}Po α, n)^{16}O
- But larger target mass in Kamland 300t/1000t before the FV cuts

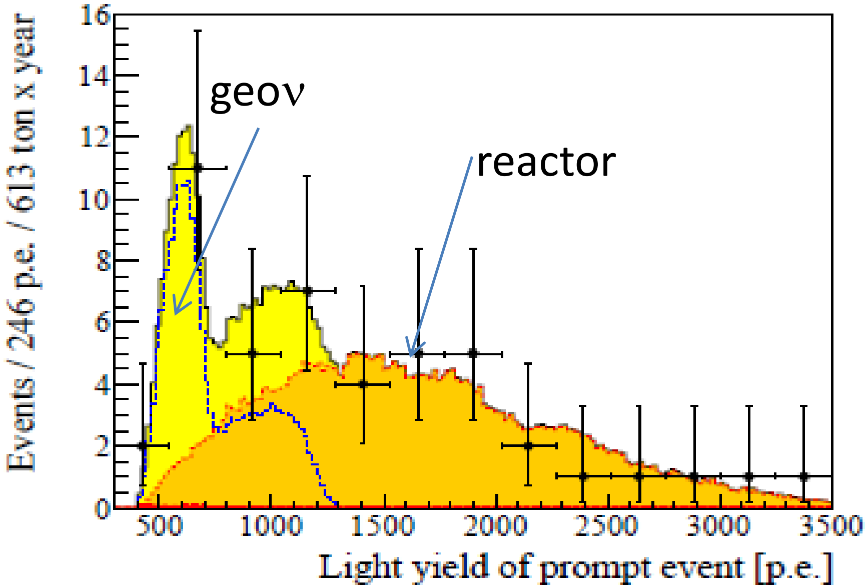
Borexino geo-ν results

Exposure: 613 ton year (3.69 10^{31} proton year)

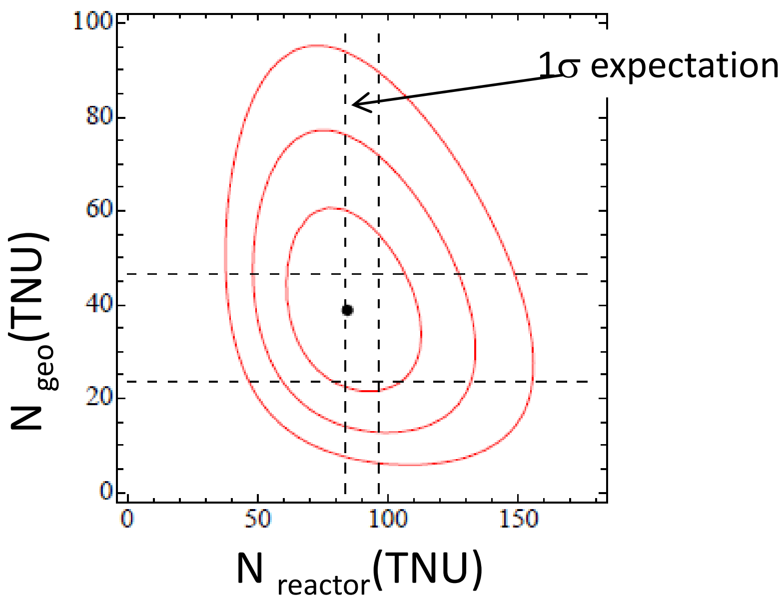
TNU=1ev/ (y 10^{32} protons)

$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	Events	events	events	events	TNU	TNU
33.3±2.4	60.4±2.4	0.70±0.18	14.3±4.4	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$

Unbinned likelihood fit

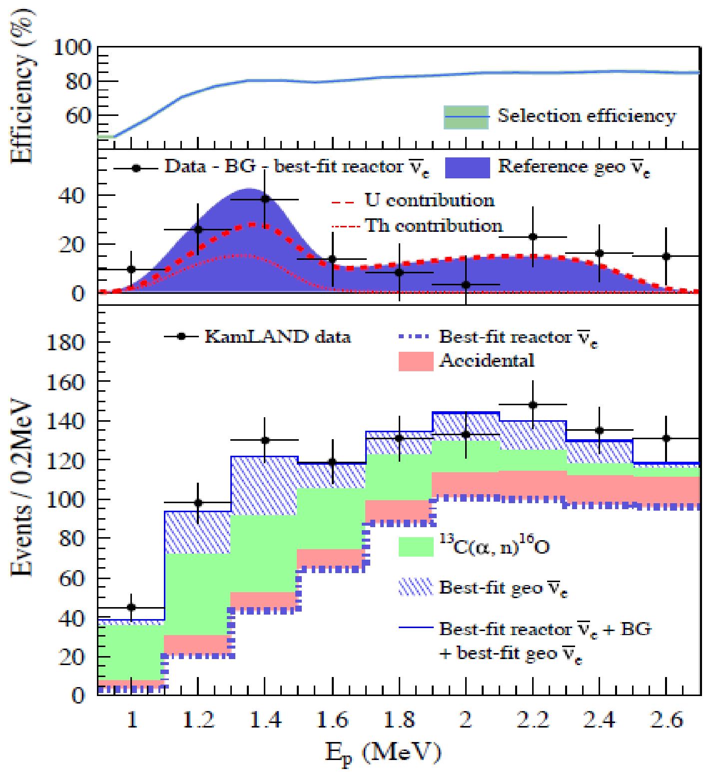


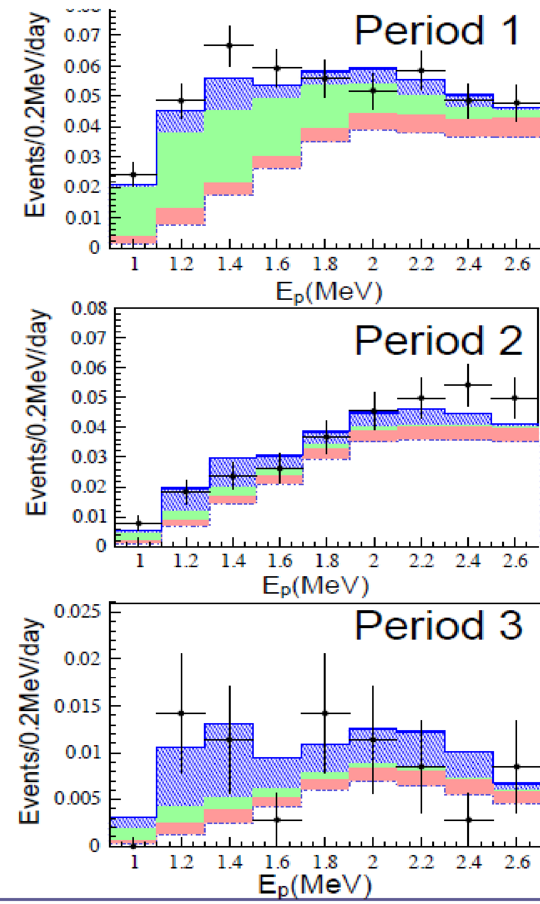
No geoν signal: rejected at 4.5 σ C.L.



Kamland geo-ν results

Exposure: (5.98 10^{31} proton year)





2002-2007

During and after scintillator purification
αn background reduced
Cross section measured

After the installation on the Xe ballon

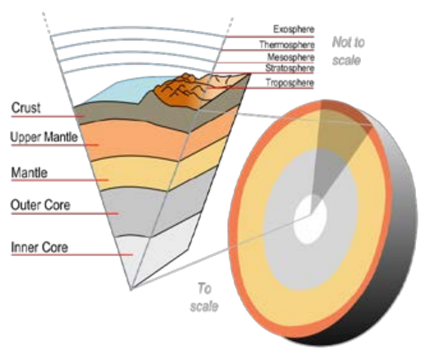
Background studied during the reactor off period after the Earthquake (from March 2011)

Best fit : N(U+Th) 116^{+28}_{-27} → 31.1±7.3 TNU (to be compared with 38.8±12.0 from Borexino)

Flux : $3.4^{+0.8}_{-0.8}$ X 10^6 cm^{-2} s^{-1}

H. Watanabe Neutrino Geoscience 2013

Geo-ν: implications for Earth models



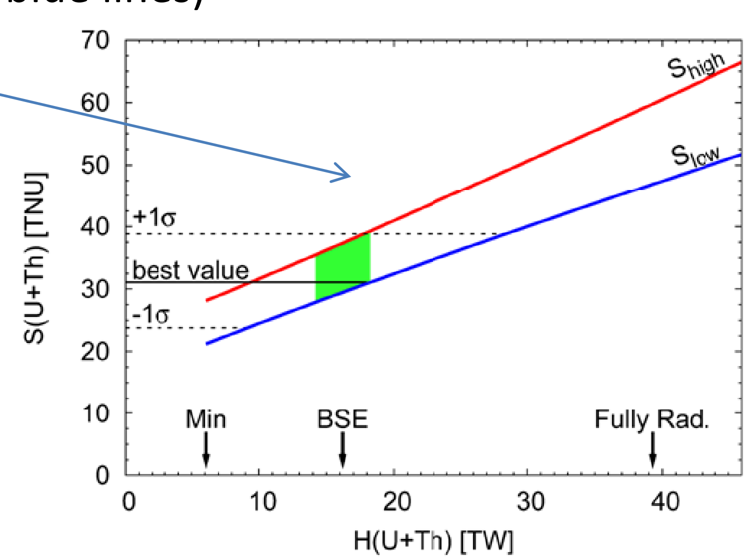
For each element (U,Th) the expected geo-ν signal S in one site on the Earth's surface is the sum of 3 contributions

$$S_{\text{Expected}} = S_{\text{LOCal}} + S_{\text{Rest Of Crust}} + S_{\text{Mantle}}$$

$$S_{\text{Mantle}} = S_{\text{Measured}} - \underbrace{(S_{\text{LOCal}} + S_{\text{Rest Of Crust}})}_{\text{It depends on local geology}}$$

We are interested in the Mantle contribution which is related to the U,Th mass (or radiogenic heat) in a model dependent way (red and blue lines)

	LOC (TNU)	ROC (TNU)	DATA (TNU)	MANTLE (TNU)	U+Th (TW)
Kamland	17.7±1.4	7.3±1.4	31.1±7.3	6.1±7.6	13±9
Borexino	9.7±1.3	13.7 ±2.5	38.8±12.0	15.4±12.3	23±14



Adapted from F. Mantovani , Neutrino Geoscience 2013

- Data not yet precise enough to select Earth models but well compatible with the Standard Earth Model (BSE)
- New multidisciplinary area, large interest from the geo- community

Geo-ν: perspectives

The next generation of large scintillation detectors will have automatically geo-neutrinos among their targets

SNO+ Imminent 28-38 events/year (expectation)

then JUNO (former Daya Bay II)

and later in the future LENA

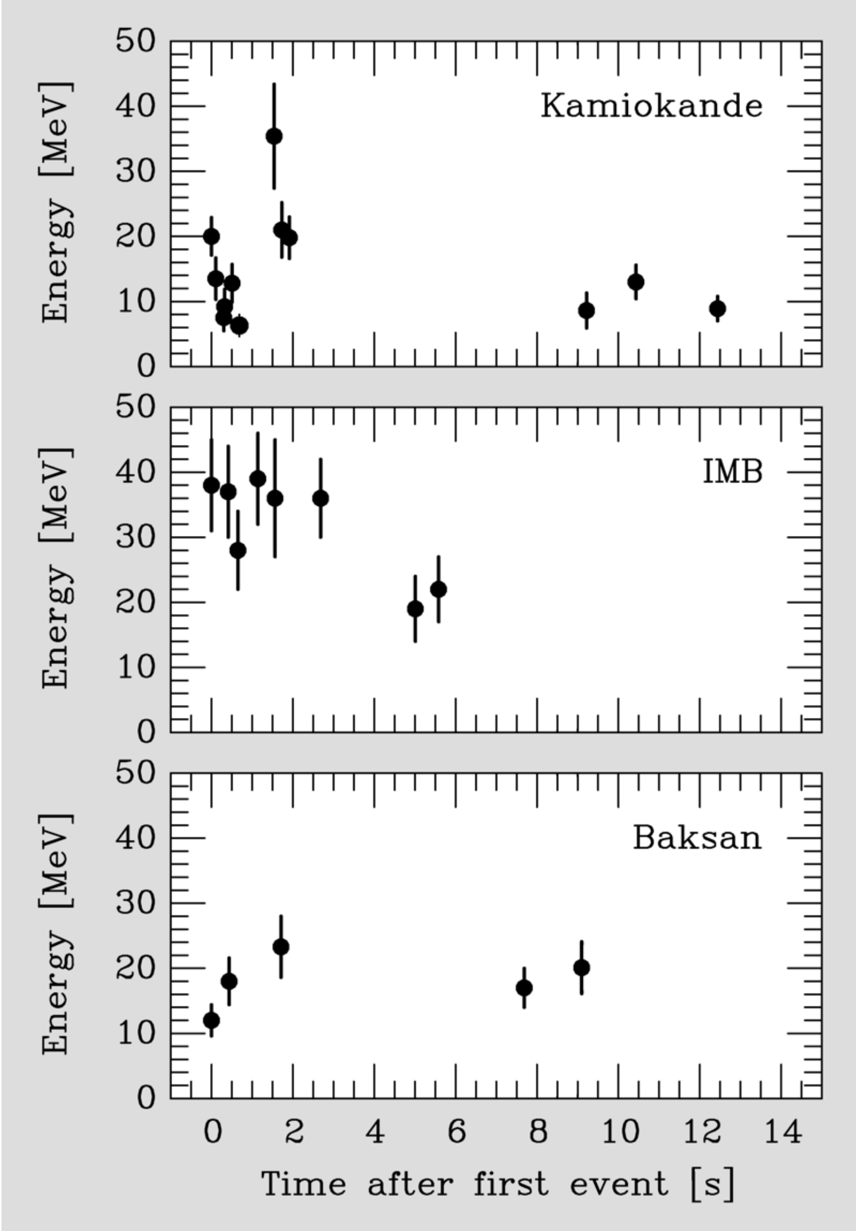
JUNO and LENA will have the capability of several hundreds events per year!

NEUTRINOS FROM SUPERNOVAe

•About 20 events from SN1987A detected by Kamiokande II & IMB (water Cerenkov) + Baksan (scintillator)
•Supernova rate in our galaxy: few/100 years
•Present and planned neutrino detectors may see order of magnitude more events than for SN1987A

•Many models
•Stellar physics
•MSW
•Neutrino-neutrino interactions – collective flavour oscillations
•Special signature in the emitted neutrino spectra
•Complicated link between shape of the original ν flux and oscillations
•Signature in the shape of the spectra reaching the detectors
•Light curves: time evolution of the detected neutrino signals
•Earth matter effect

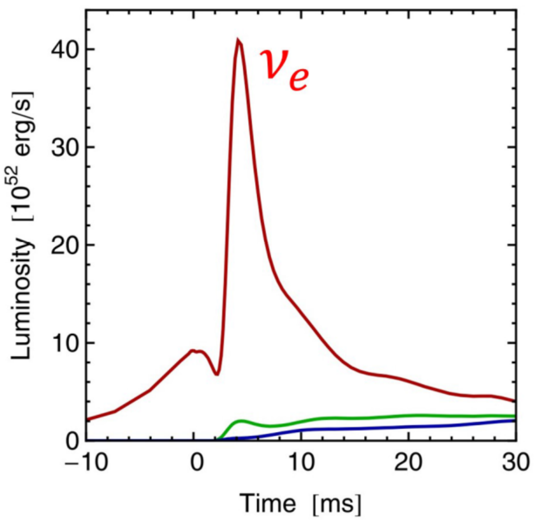
Effects sensitive to the mass hierarchy



S. Choubey et al. arXiv:1008.0308 (2010)
Dighe, Smirov arXiv: 9907423v2 (1999)

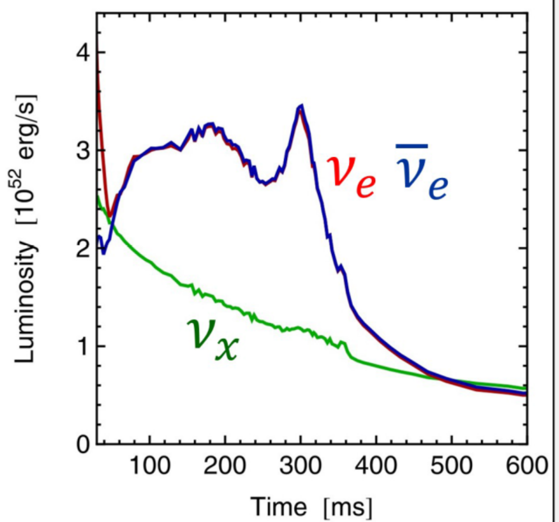
Model of the three phases of neutrino emission: timing

Prompt ν_e burst



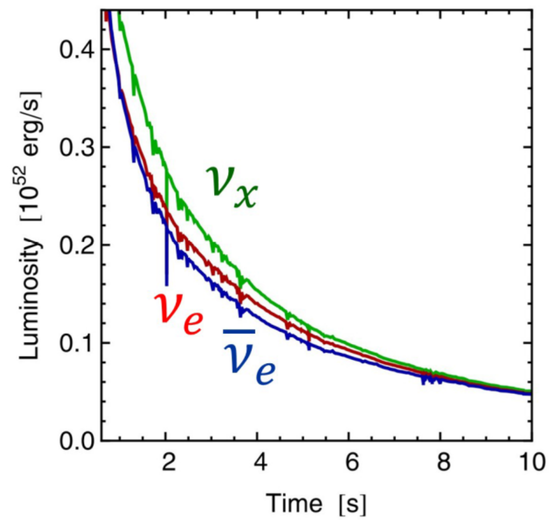
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling

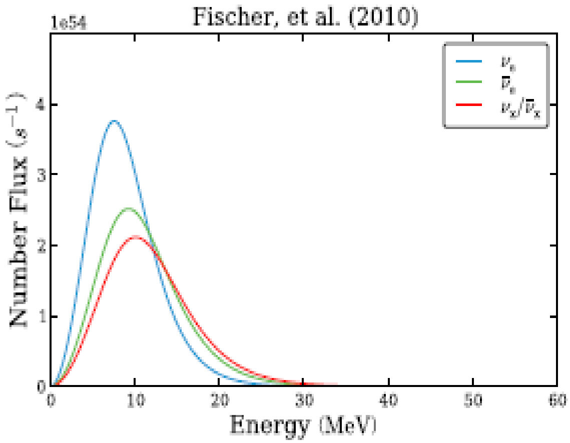


Cooling on neutrino diffusion time scale

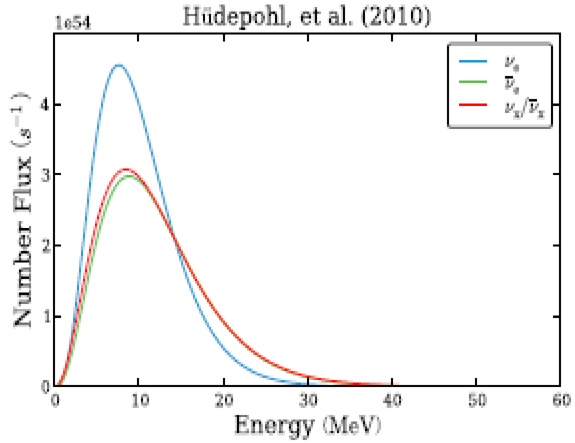
Fisher et al.,2010 [arxiv:0908.1871]

The prediction of the emitted neutrino spectrum depends upon the model

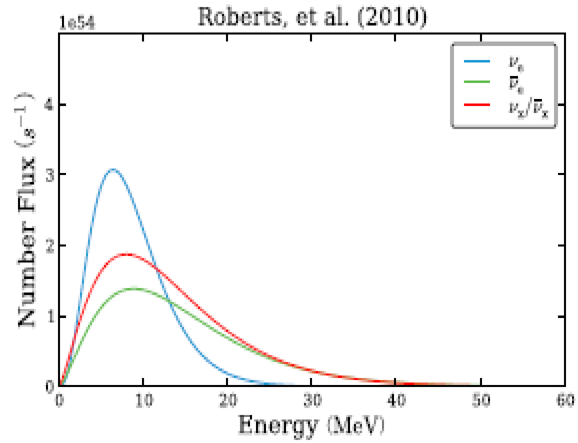
2s post core bounce



Fischer, et al. (2010)
Classic energy hierarchy
Symmetric late time spectra



Hudepohl, et al. (2010)
Anomalously hot $\bar{\nu}_e' s$.
Symmetric late time spectra



Roberts, et al. (2012)
Anomalously hot $\bar{\nu}_e' s$.
Asymmetric late time spectra

Adapted from H. Duan, JJ Cherry "Aspen Winter Workshop" Feb 2013

MSW complicates the picture
signatures in the final spectra
depend on model details
SN is potentially a rich «laboratory» for
thorough tests of diverse neutrino physics effects

Several detection channels in present and future detectors

Inverse beta decay $\overline{\upsilon_e} + p \rightarrow n + e^+$

1.8 MeV threshold, high cross section
Clean signature if n can be detected
(Liquid scint., Gd in water at Superk)

Elastic scatt. $\upsilon_x + e^- \rightarrow \upsilon_x + e^-$

All flavour, directionality, no energy threshold

CC reactions on nuclei

$$\upsilon_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$
$$\overline{\upsilon_e} + (N,Z) \rightarrow (N+1, Z-1) + e^+$$

E threshold,
signature (daughter in excited states)

νp elastic scattering $\nu + p \rightarrow \nu + p$

Low recoil energy
Ok for scintillators (many free protons)
Sensitive to ν_x

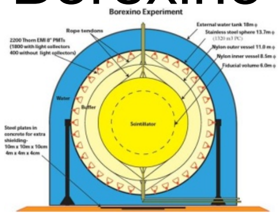
ν Nucleus elastic scattering

Low recoil energy
Possible in cryogenic noble liquid scintillators

Supernova detectors in the world

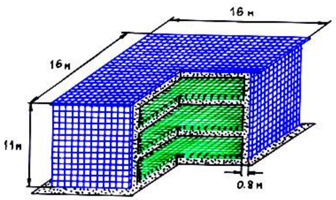
(running and near future experiments)

Borexino

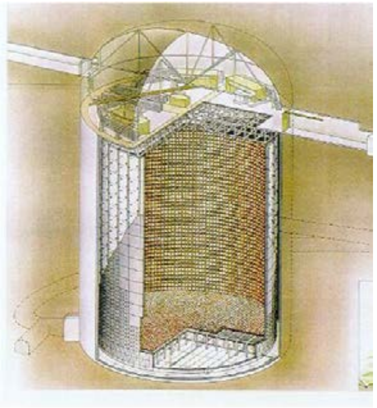


LVD

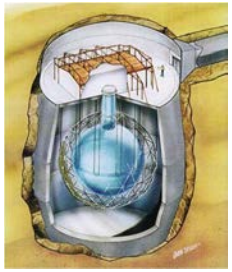
Baksan



Super-K

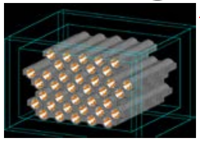


SNO+

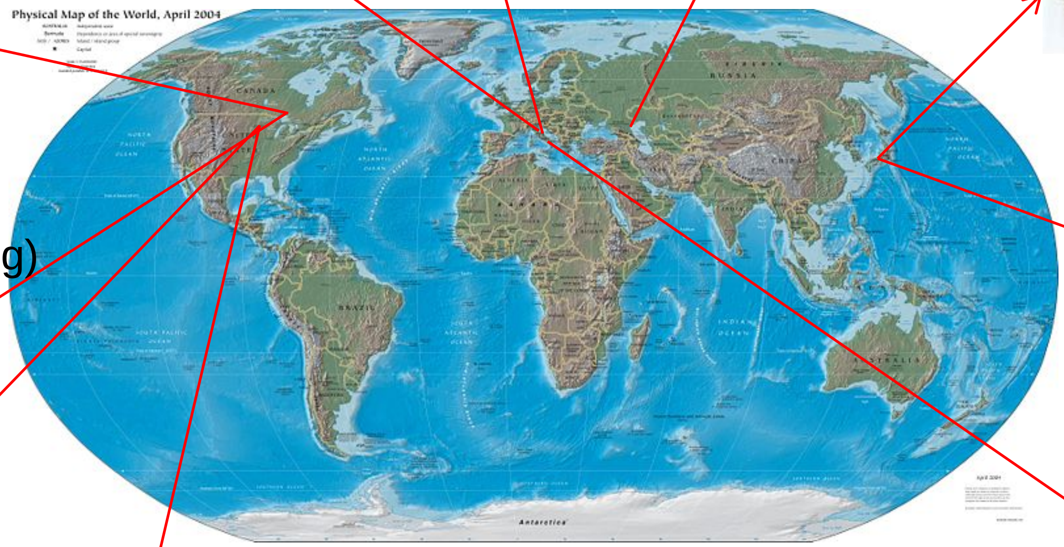


(under commissioning)

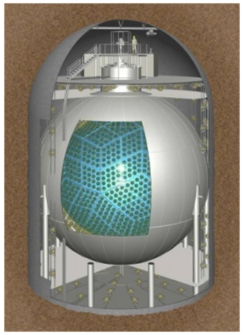
HALO



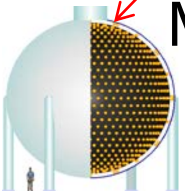
(proposed)



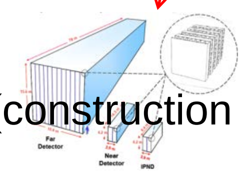
KamLAND



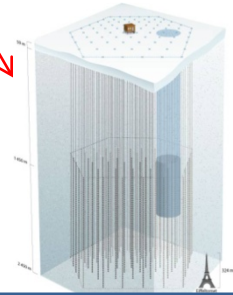
Mini-BOONE



NOνA



(construction almost completed)



IceCube

Icarus 600

Expected number of events for a Galaxy 10 Kpc Supernova

Take this as example:
many variations from model to model

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
Super-Kamiokande	H_2O	32	Japan	7,000	1996-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE*	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007-present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE*	Ar	0.17	USA	17	Near future
NOνA*	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

SuperK: mainly $\overline{\upsilon_e} + p \rightarrow n + e^+$
Addition of G_d in water: project well advanced!!

K. Scholberg arxiv 1205.6003 (2012)

Conclusions

Low energy neutrinos provided us with a number of very exciting outcomes

- mature and well established in the solar neutrino field →neutrino oscillation

- very interesting though preliminary and suggesting important future follow-ups in the realms of geo-neutrinos and supernova neutrinos