Low energy neutrino physics

(tens of MeV or subMeV)

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Lepton Photon 2013

Outline of the talk

- Solar neutrinos: in progress
  short review of the results
  perspectives

- Geo neutrinos: in progress
  results

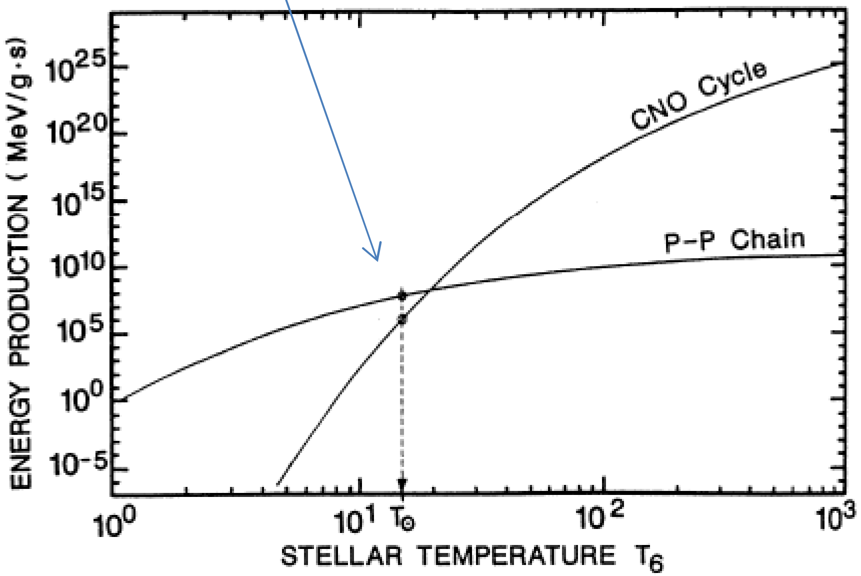
- Supernova neutrinos: in the dreams
  perspectives

- Source experiments to search for sterile neutrinos: project started
  perspectives

Fusion reactions in the Sun : the pp chain

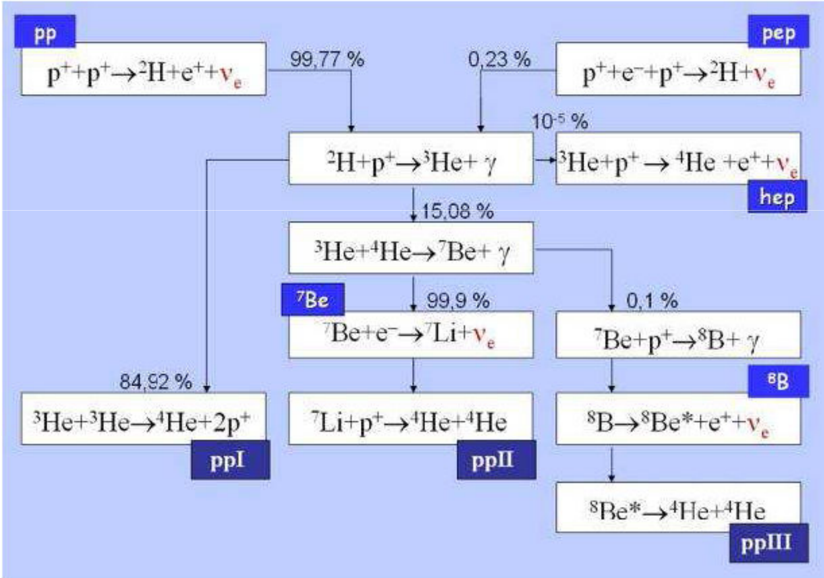
- Solar ν studies began to prove that Sun shines by nuclear fusion reaction
- Sun is a source of pure ν_e
- Baseline 10^8 Km allows sensitivities to Δm^2 up to 10^{-10} eV^2

$$T_{Sun} \approx 15\ 10^6 K$$



Rolfs C E and Rodney W S 1988 *Cauldrons in the Cosmos* (Chicago, IL: University of Chicago Press)

pp fusion chain: about 98% of the Sun energy



Fusion reaction in the Sun : the CNO chain

Very important for stars with mass higher than the SUN

Main CNO cycle

$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

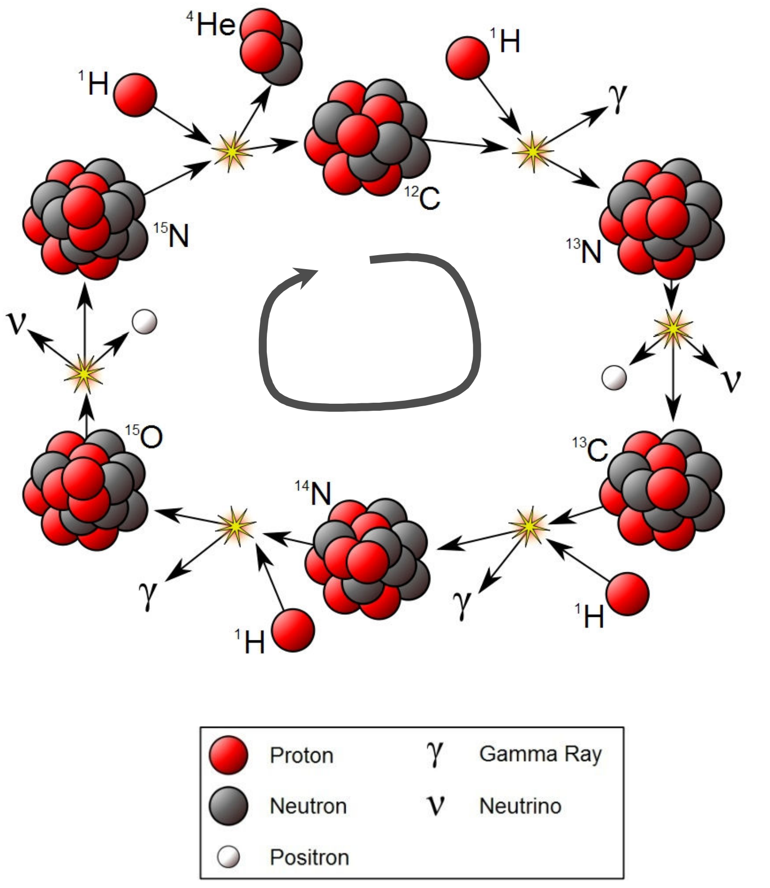
$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

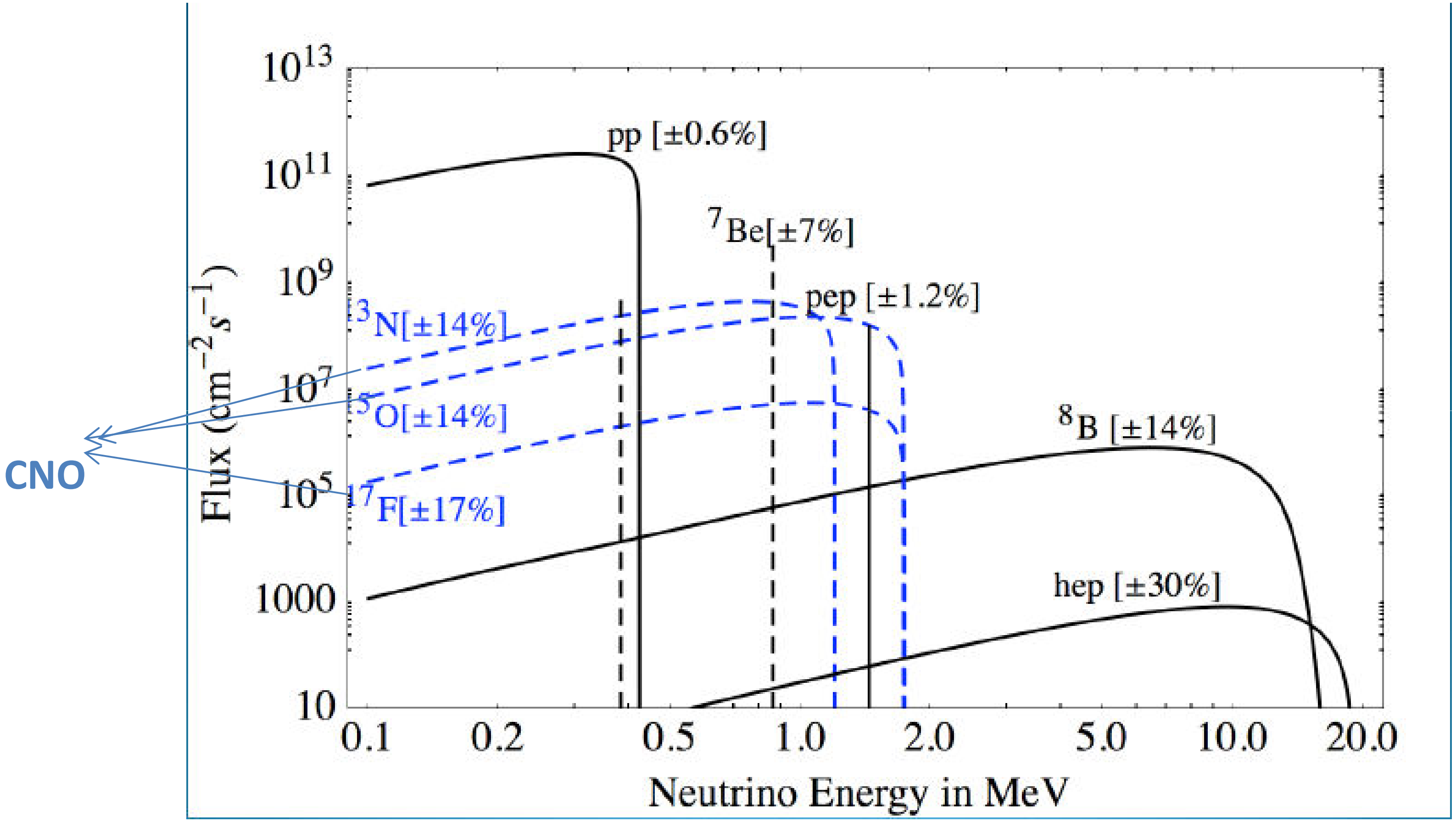
ν_N

ν_O

^{12}C : catalyst



Solar Neutrino energy spectrum at Earth



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

Solar Neutrinos flux predictions

Present predictions | Past predictions

Source	Flux $[cm^{-2}s^{-1}]$ SSM-GS98	Flux $[cm^{-2}s^{-1}]$ SSM-AGSS09	Flux $[cm^{-2}s^{-1}]$ SSM-GS98-2004
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$5.94(1\pm0.01)\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.40(1\pm0.02)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.86(1\pm0.12)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.79(1\pm0.23)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	$5.71(1\pm0.36)\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$5.03(1\pm0.41)\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$5.91(1\pm0.44)\times10^{6}$
Total CNO:	5.24×10^{8}	3.76×10^{8}	10.8×10^{8}
	High metallicity	Low metallicity	

CNO (^{13}N, ^{15}O, ^{17}F)

Present predictions:
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

Developments since 2004

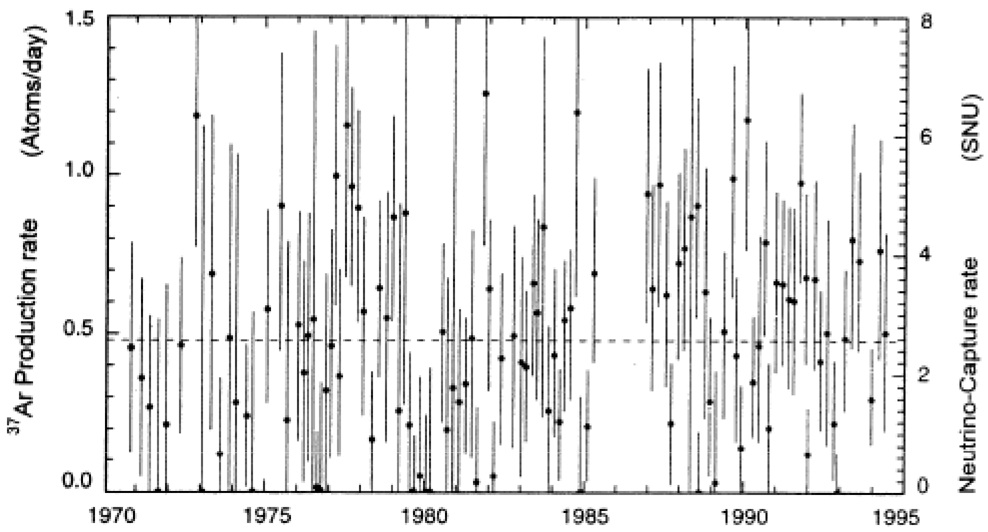
- Reduction of CNO due to new values of cross section ^{14}N(p,g)$^{15°}$
- Better accuracy of ^{3}He(^{4}He,γ)^{7}Be cross section
- New opacity calculations
- New surface elements abundance based on 3D models

Aldo M. Serenelli *et al.* 2011 *ApJ* **743** 24

The history began a long time ago.....

- The chlorine experiment: 1970.....
- Radiochemical experiment
- No spectral information
- Goal: prove that Sun shines thanks to fusion processes

B.T.Cleveland et al., Ap. J. 496 (1998) 505



Homestake mine (South Dakota)

600 tons of C_2Cl_4

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

$\quad \hookrightarrow {}^{37}Cl \; (T_{1/2}=35 \text{ d})$

814 KeV: no pp detection

About 1/3 of the expected rate was measured

The solar neutrino problem and its solution

exp	years	reaction	thresh old	Solar sensitivity	method	result
Chlorine	1968 - 1994	$\nu_e + ^{37}Cl = e- + ^{37}Ar$	0.814 MeV	8B , pep, 7Be	radiochemical 615 tons	R(exp/SSM)=0.34±0.03
Gallex-GN0	1991- 2003	$\nu_e + ^{71}Ga = e^- + ^{71}Ge$	0.233	8B , pep, 7Be,pp	radiochemical 30.3 t	R(exp/SSM)= 0.58±0.05
SAGE	1990-	$\nu_e + ^{71}Ga = e^- + ^{71}Ge$	0.233	8B , pep, 7Be,pp	radiochemical 50 t	0.59±0.06
Kamiokande (SuperKamiokande still running)	1987- 1995	$\nu_x + e- = \nu_x + e-$	7.5 … 3.5	8B	Cerenkov light 2.14 Kt water (22.4 Kt)	0.46±0.02
SNO	1999 2006 (moving to SNO+)	$\nu_e + d = e^- + p + p$ (CC) $\nu_e + d = \nu_x + p + n$ (NC) $\nu_e + e^- = \nu_x + e-$ (ES)	5 3.5	8B	1Kt $D_2 0$ Cerenkov	8B flux consistent with SSM!! Solar neutrino problem solved
Kamland (reactor antinu)	2002 -	Anti–ν_e+p= n+e-			Liquid scintillator	Reactor antinu L/E sensitive to solar region
Borexino	2007-	$\nu_x + e- = \nu_x + e-$	0.2	8B , pep, 7Be,pp	Liquid scintillator	7Be,pp,8B

Now we know that ν oscillate: move the focus to low energy solar ν spectroscopy

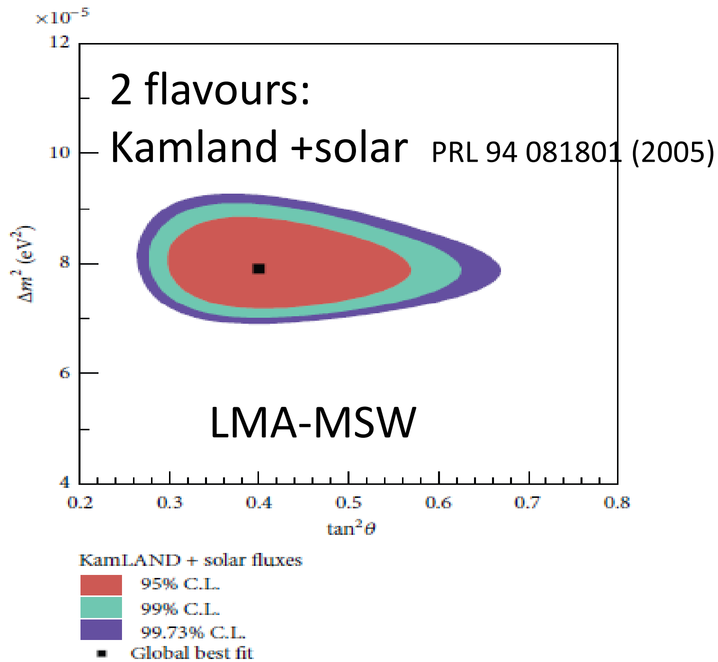
- Evidence of n oscillations and massive neutrinos
- Interaction of neutrinos with matter complicate the oscillation scenario
- Important for solar (and supernova) neutrinos MSW
- Year 2002: SNO results with NC
- Nobel Prize for R. Davis (chlorine exp.) and Koshiba
- Kamland results

Solar ν mainly influenced by

$$\mathbf{U}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \theta_{12} \quad \Delta m^2_{1,2}$$

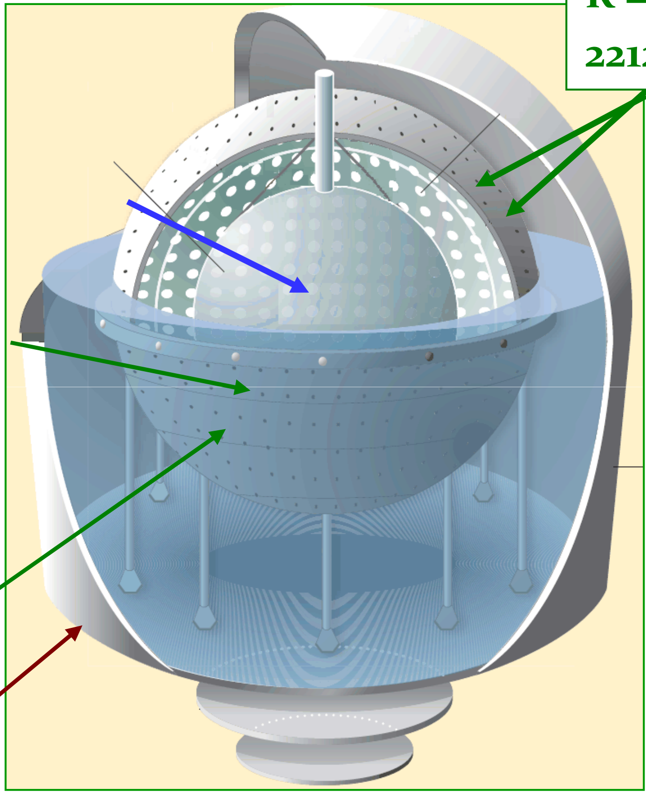
Data combination	Δm^2_{21}	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
KamLAND	$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$	$0.010^{+0.033}_{-0.034}$
KamLAND + solar	$7.53^{+0.19}_{-0.18}$	$0.437^{+0.029}_{-0.026}$	$0.023^{+0.015}_{-0.015}$
KamLAND + solar + θ_{13}	$7.53^{+0.18}_{-0.18}$	$0.436^{+0.029}_{-0.025}$	$0.023^{+0.002}_{-0.002}$

arxiv 1303.4667v1 (2013) Kamland Coll.



Solar neutrino measurements now:

- understand details of the oscillation model
- provide input for solar models
- Borexino : very low energy solar ν spectroscopy



Stainless Steel Sphere:
R = 6.75 m
2212 PMTs

Scintillator:
270 t PC+PPO (1.5 g/l)
in a 150 μm thick
inner nylon vessel (R = 4.25 m)

Buffer region:
PC+DMP quencher
4.25 m < R < 6.75 m

Outer nylon vessel:
R = 5.50 m
(^{222}Rn barrier)

Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water

ν detection:
elastic scattering on electrons

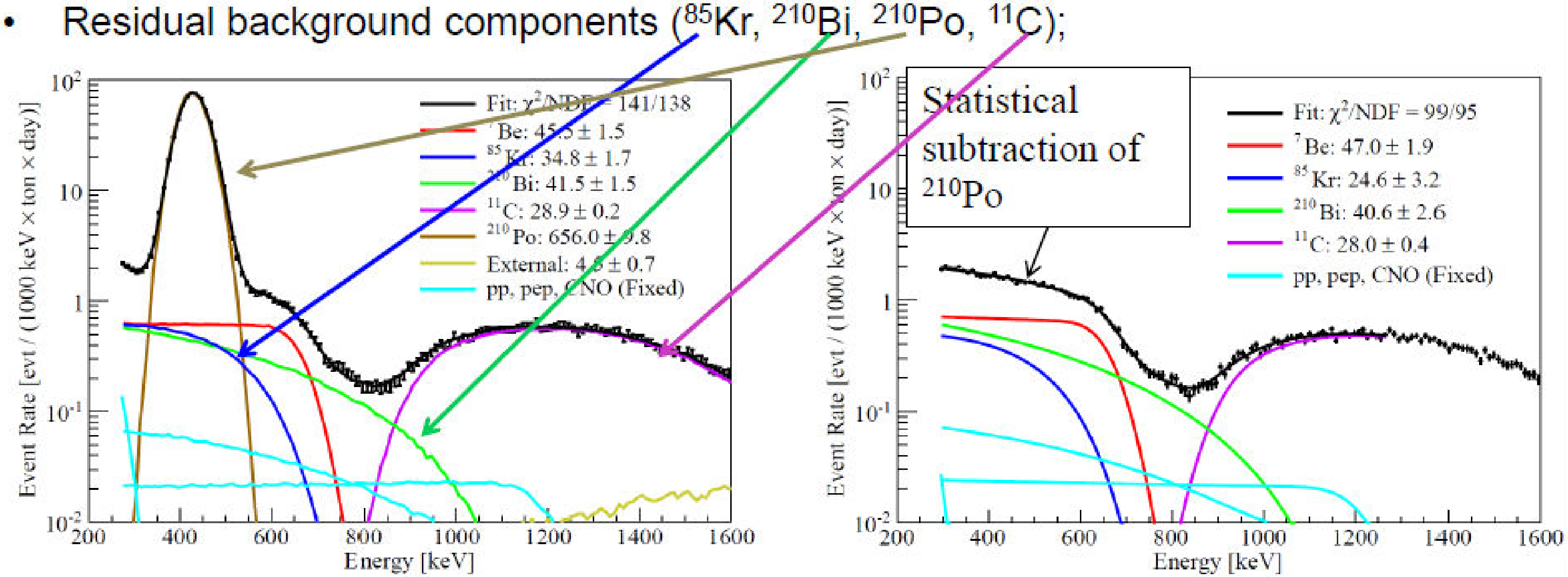
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- ≈500 phe/MeV (electron equivalent)
- Energy resolution 4.5%
- Space resolution 10 cm @1MeV
- "wall less" Fiducial Volume
- Pulse shape capability
- Calibration in situ with radioactive sources
- Accurate Monte Carlo modeling of the energy and time response function
- No signature except the spectral shape
- Needed extremely low background

The smallest radioactive background in the world:
9-10 orders of magnitude smaller than the every-day environment

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

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



$$R_{^7Be} = 46.0 \pm 1.5\ (stat)^{+1.5}_{-1.6}\ (syst)\quad cpd/100t$$

$$R_{no\ oscillation} = 74.0 \pm 5.2\quad cpd/100t$$

- ν_e flux reduction 0.62 +- 0.05
- 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)

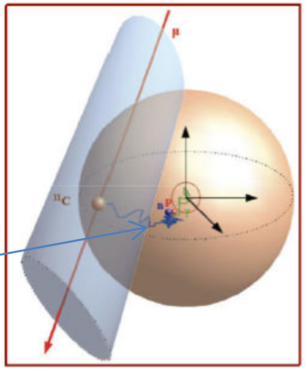
$$A_{DN} = \frac{N-D}{(N+D)/2} = 0.001 \pm 0.012\ (stat) \pm 0.007 (sys)$$

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

pep (1.44 MeV) solar flux measurement and CNO limits in Borexino

Interaction point and 11C production point

Position of the γ



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

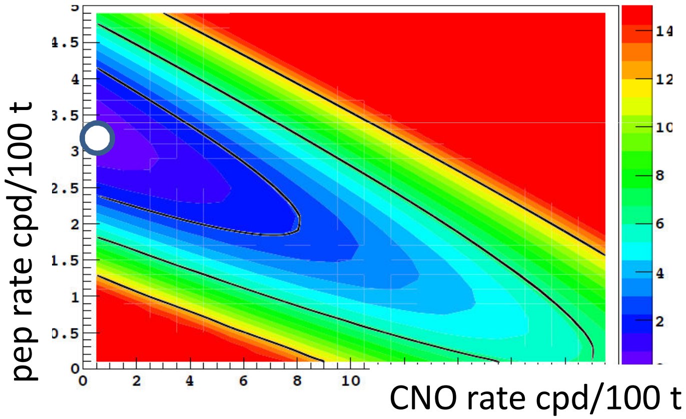
${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$ $\tau \sim 30$ min

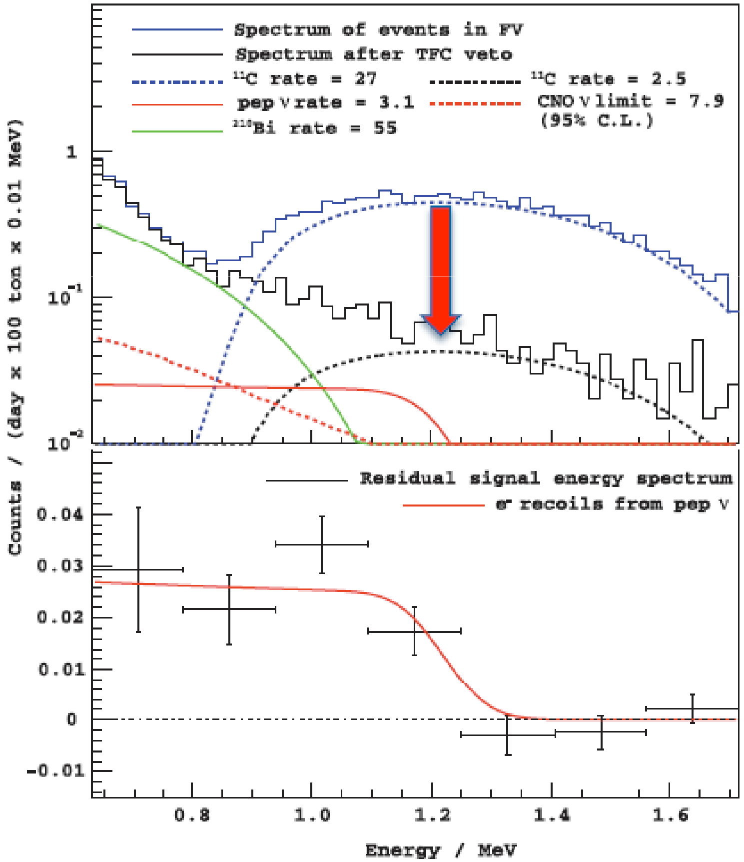
$n + p \rightarrow d + \gamma$ $\tau \sim 260\ \mu s$

- n capture on H: γ 2.2 MeV τ=246 μs
- Space and time Veto
- Residula exposure 48.5%

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

Δchi^2 profile for fixed pep and CNO rates

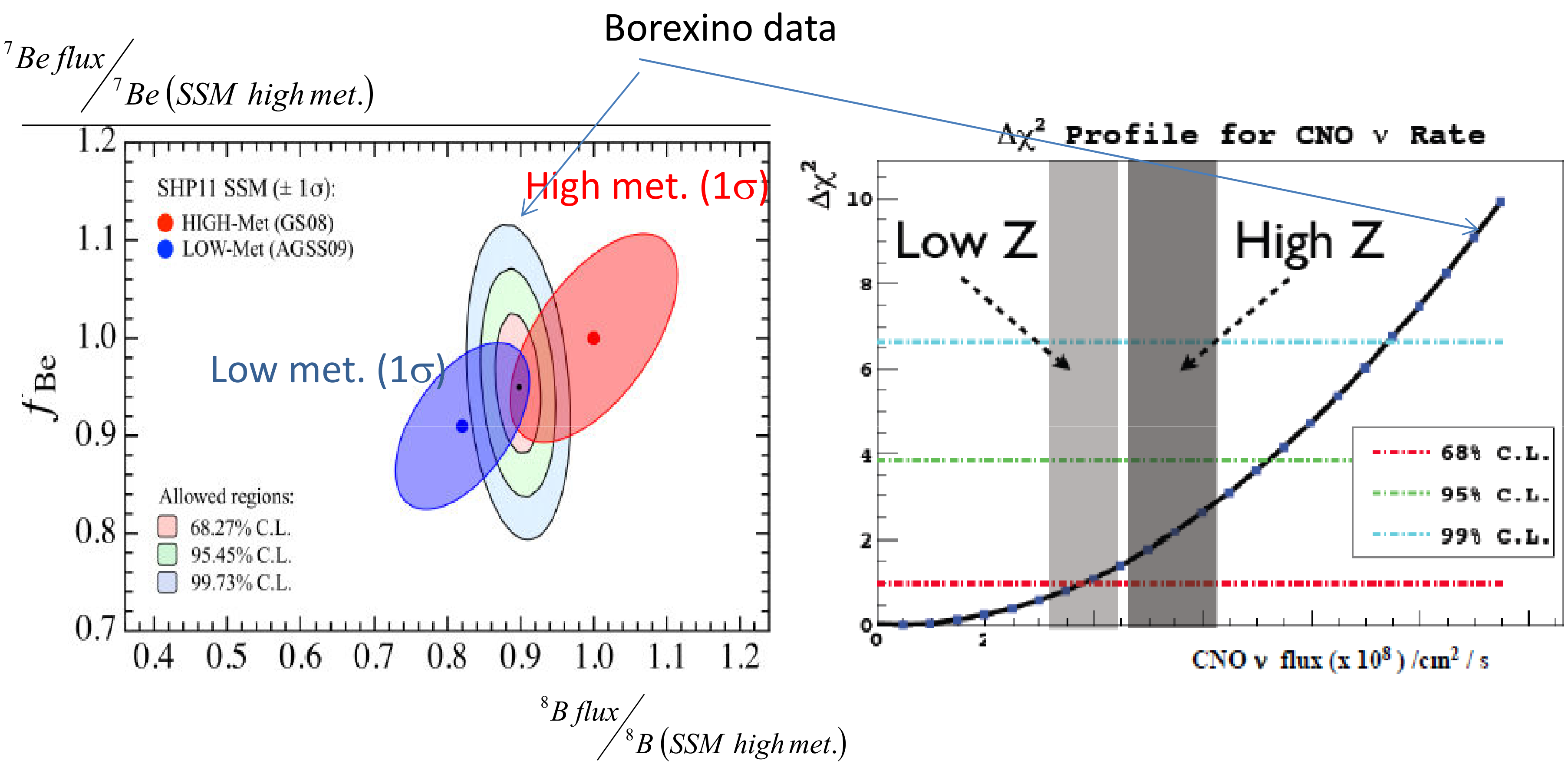




ν	Interaction Rate (cpd/100t)	DATA/SSM (high metallicity)
	Counts/(days 100 t)	ratio
pep	3.1±0.6 (stat) ± 0.3(sys)	1.1±0.2
CNO	<7.9	<1.5

Best limit on CNO- not yet enough to select solar models….

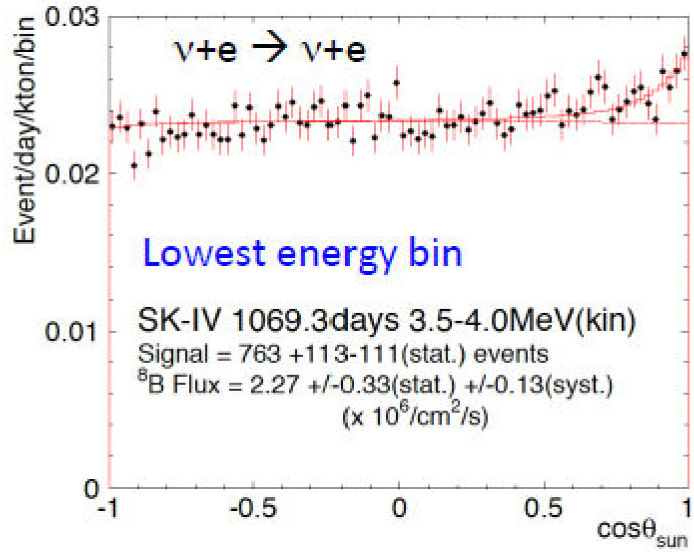
Can we discrimininate between solar models ??

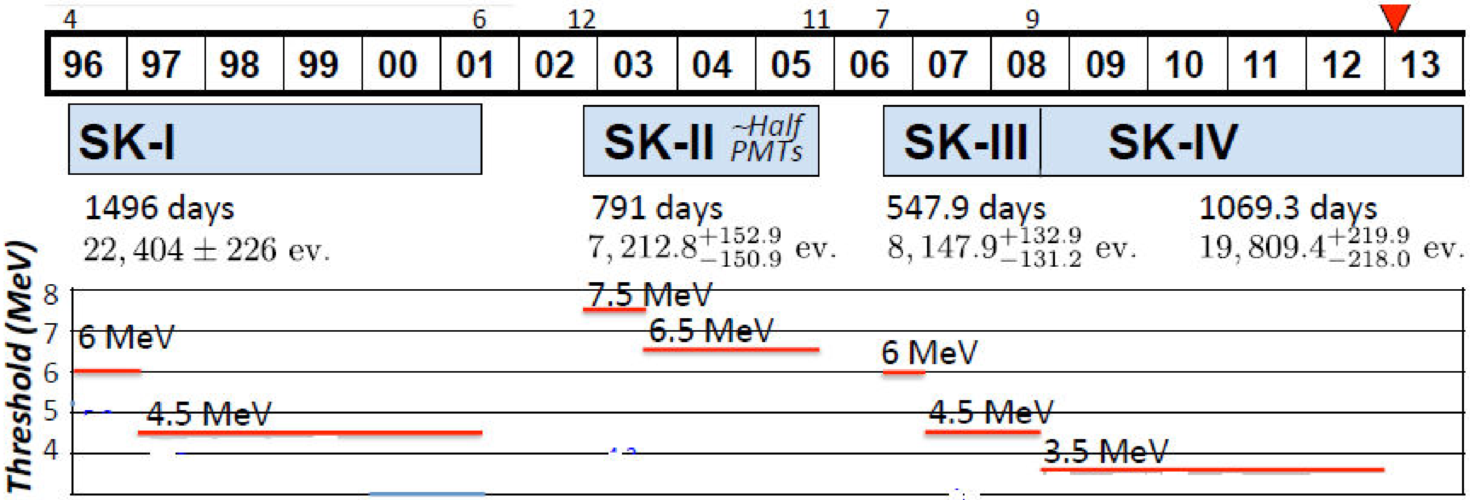


Solar ^{8}B: (Kamiokande) and SuperKamiokande

$$\nu_x + e^- \longrightarrow \nu_x + e^- .$$

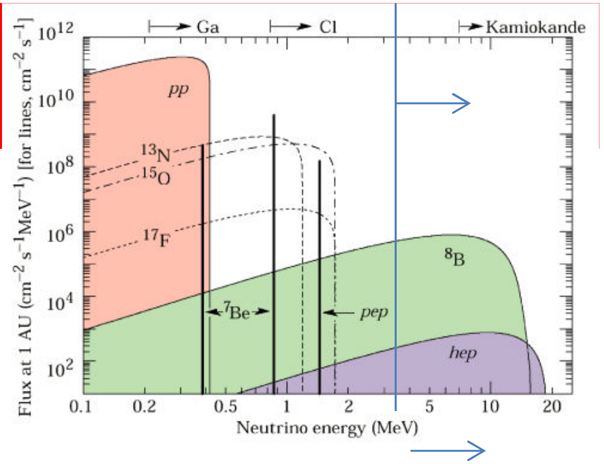
- Total 3904 days
  - 57,574.1 solar neutrino events
- Analysis threshold: down to 3.5 MeV
  - Possible to 3.0 MeV in near future
- Fiducial volume
  - 22.5 kt (> 5.0 MeV)
  - 13.3 kt (4.5-5.0 MeV)
  - 8.8 kt (3.5-4.5 MeV)

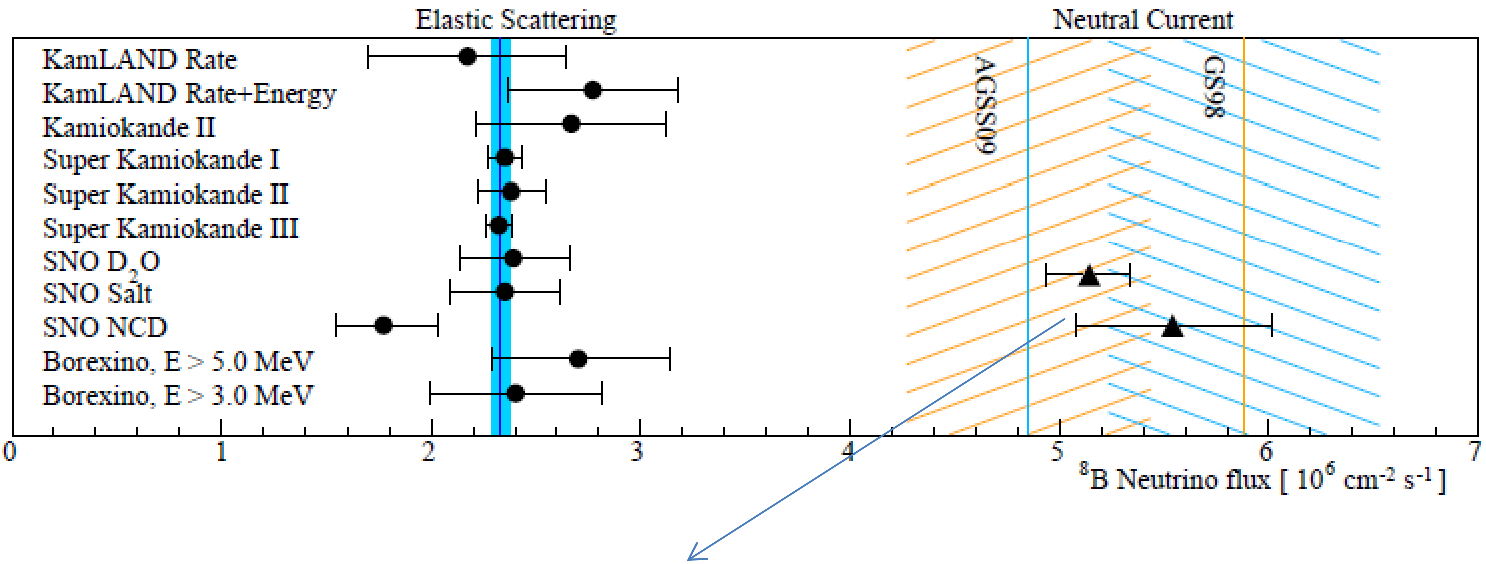




Adapted from Y. Suzuki Neutrino telescopes March 2013

^{8}B solar neutrinos



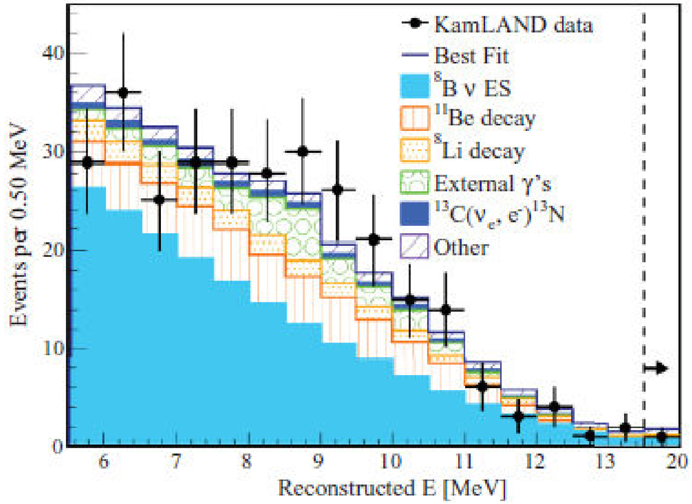


SNO has provided the absolute 8B flux

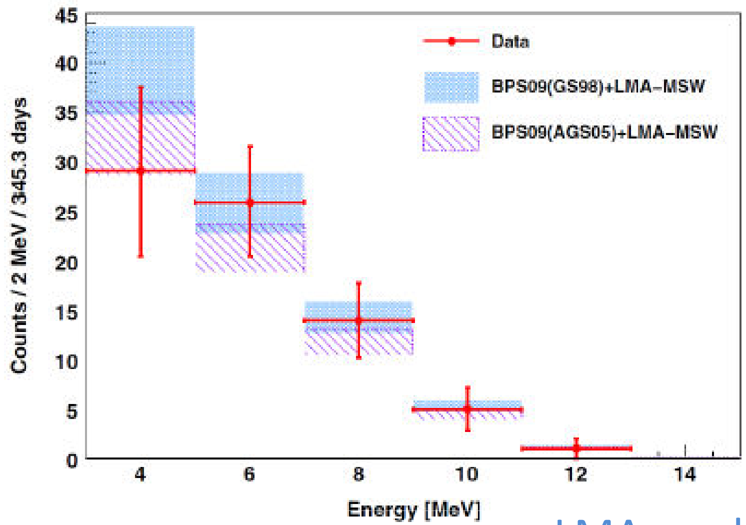
Figure from PRC 84, 035804 (2011)
Kamland coll.

^{8}B solar neutrinos

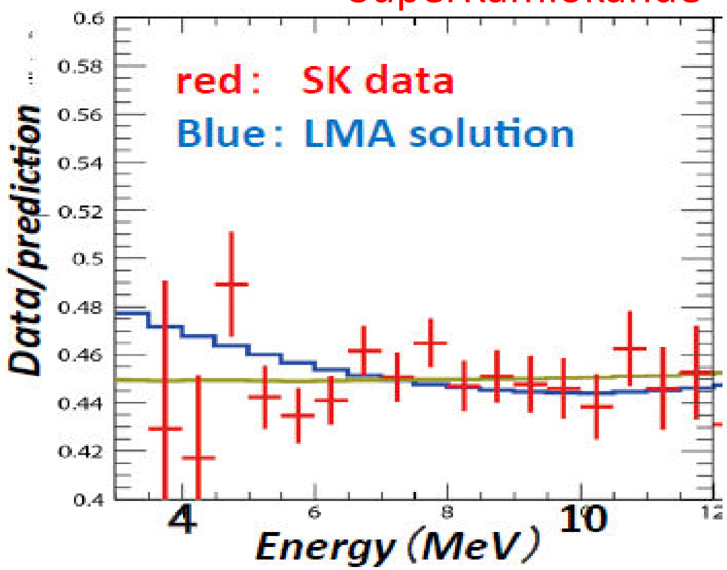
Kamland PRC 84, 035804 (2011)



Borexino (3MeV threshold) G. Bellini et al. PRD 82 033006 (2010)

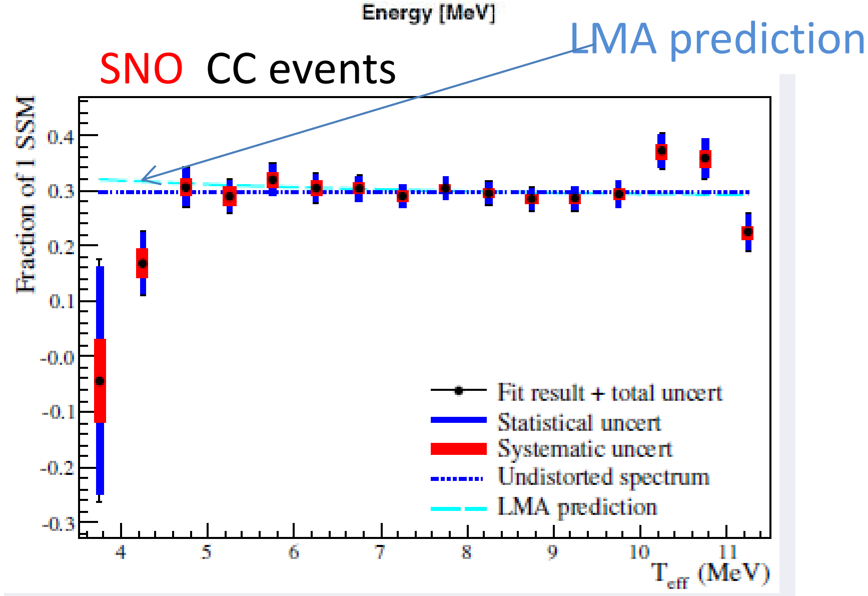


SuperKamiokande



Super K. Suzuki@Neutrino Telescopes Venice 2013

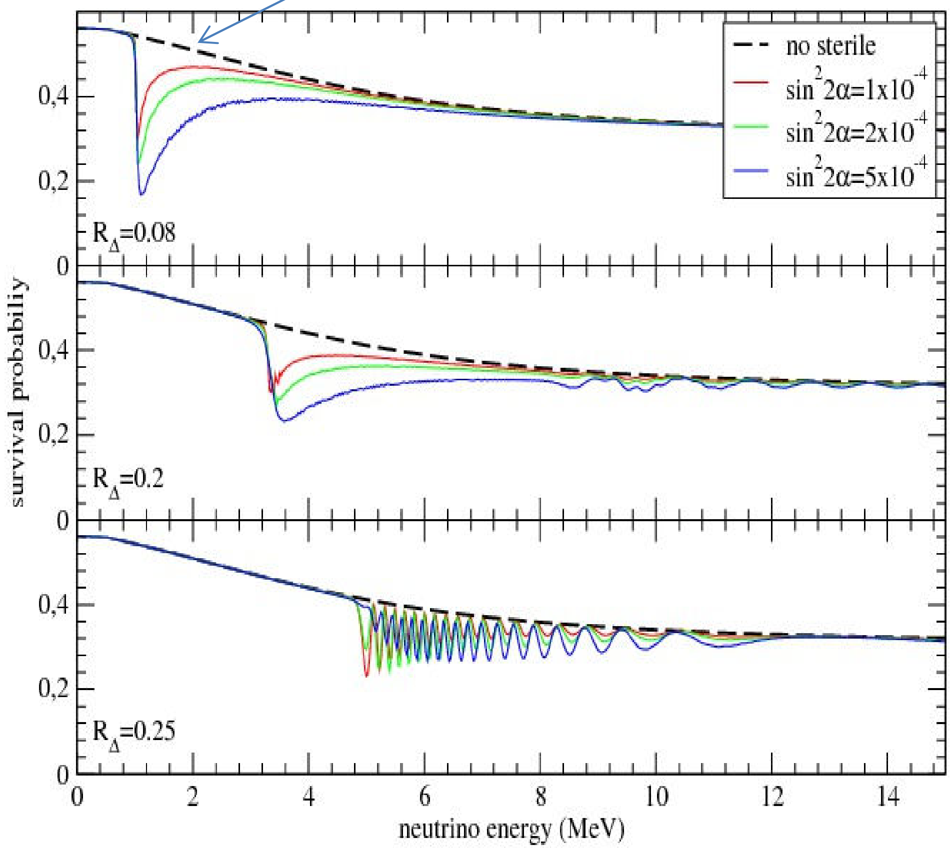
SNO CC events



arxiv 1109.0763 SNO LETA 3.5 MeV threshold

Solar ^8B : the Up-turn???

LMA survival probability



- lower the thereshold as much as possible
- Hints for new physics??
- Background issues
- Statistics
- SuperKamiokande can see the effect

arxiv 1012.5627v2 (2011)

Solar Neutrino fluxes: observations vs predictions

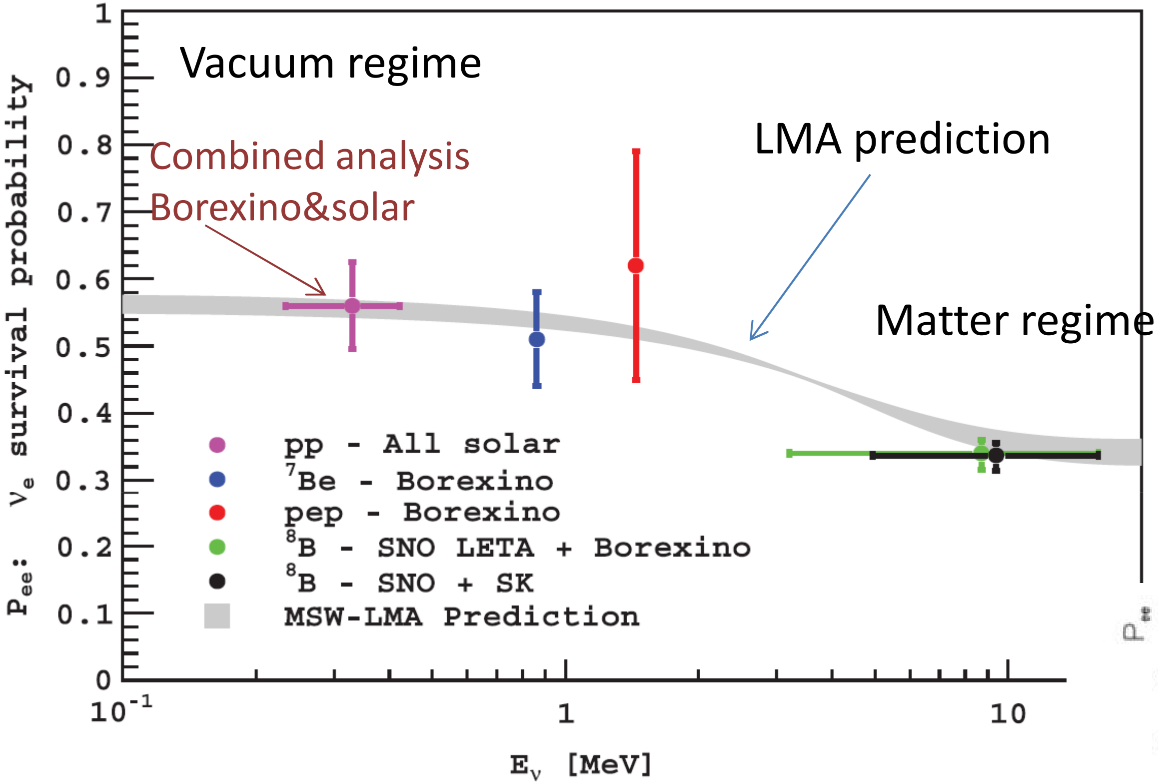
Assuming the luminosity constraint

Source	Flux [$cm^{-2}s^{-1}$] SSM-GS98	Flux [$cm^{-2}s^{-1}$] SSM-AGSS09	Flux [$cm^{-2}s^{-1}$] Data
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$6.06(1^{+0.003}_{-0.01})\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.60(1\pm0.19)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.84(1\pm0.05)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.046^{+0.159}_{-0.152}(stat)^{+0.107}_{-0.123}(syst)$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$3.76(1\pm0.15)\times10^{8}$	$<6.7\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$<3.2\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$<59\times10^{6}$
CNO	5.24×10^{8}	3.76×10^{8}	**$<7.7\times10^{8}$ (2σ)**

Without the luminosity constraint: ϕ_{pp} determined with 15% uncertainty

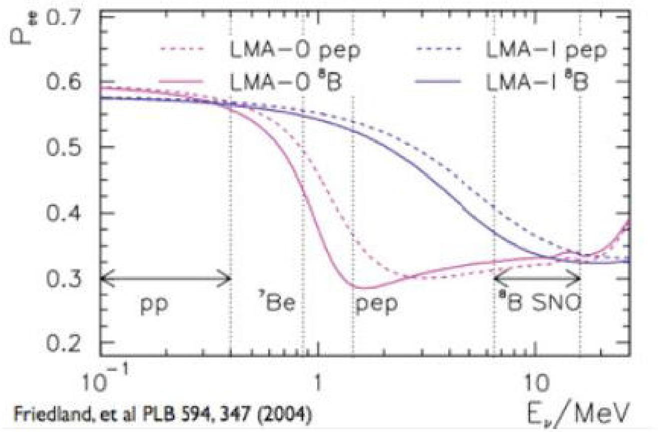
upper limit smaller than 2004 prediction!

Electron neutrinos survival probablity



Pee as expected from ν oscillation
+Matter effect (LMA-MSW)

Not standard ν interactions

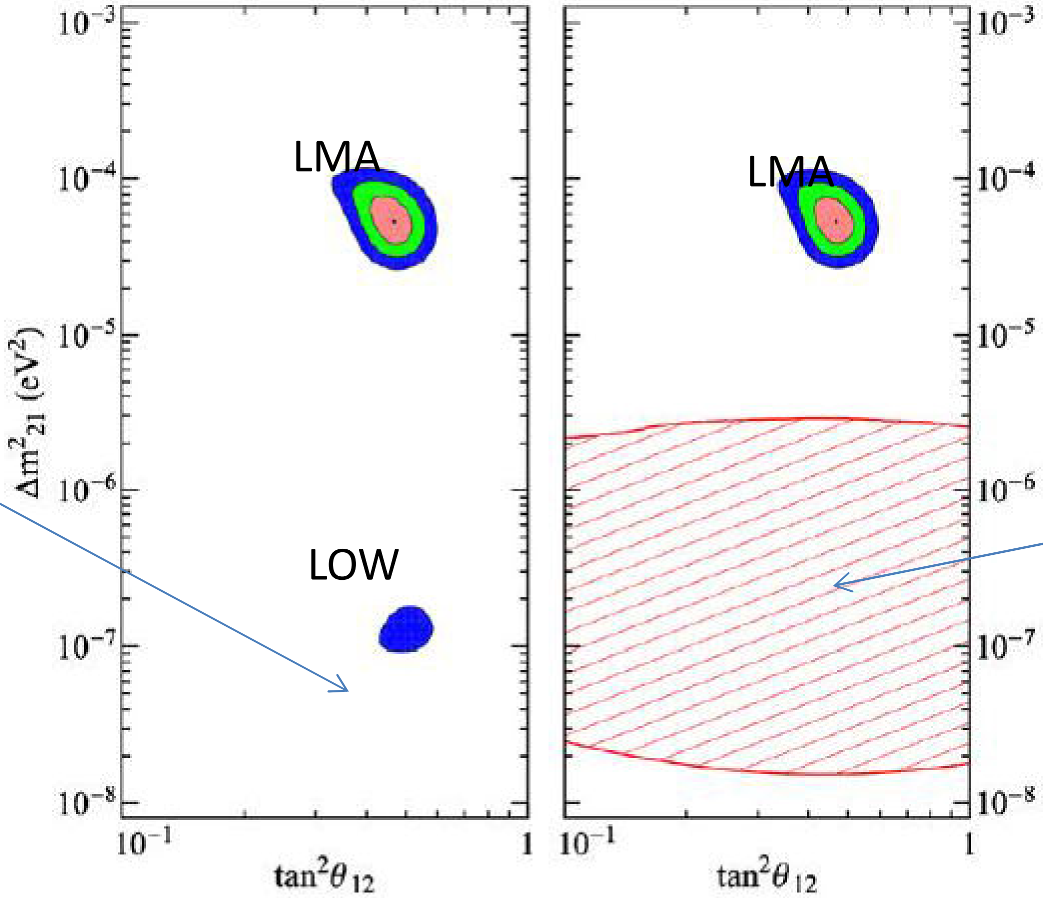


Solar ν alone (without the reactor antiν of Kamland) select LMA

- All solar exp.
- without Borexino
- without Kamland

All solar exp.
including Borexino

A small portion
of the "LOW"
region
is not excluded



The ADN of
Borexino allows to
exclude the LOW
region

Strong confirmation of the LMA solution
without using anti-ν data (and without assuming CPT)

G. Bellini et al., Borexino Coll. +C Pena Garay, Phys. Lett. B707 (2012) 22.

What next on solar neutrinos???

- Direct measurement of pp neutrino spectrum: test Sun luminosity
- High precision pep: Non Standard Interactions (NSI), test LMA with accuracy
- Measure CNO : solar and stellar models
- ^{8}B up-turn: reduce the threshold (non standard interactions, sterile neutrinos…)
- Improve ^{7}Be measurement (and calculation) (solar models)

What next ? Borexino Phase II

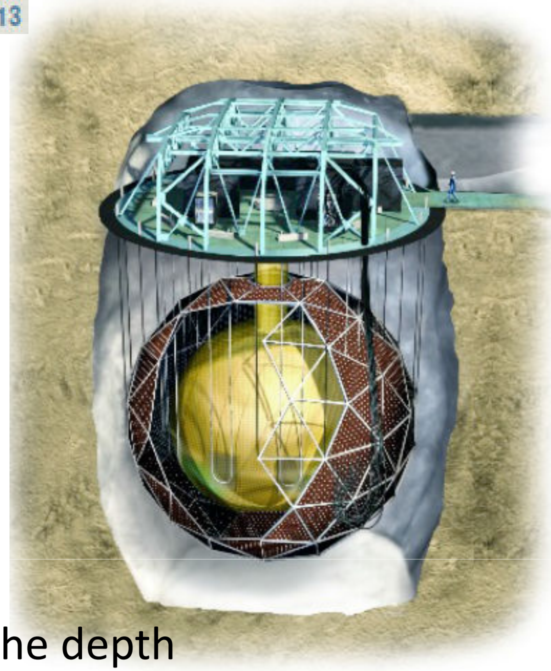
After the purification of the scintillator

1) Krypton: strongly reduced: consistent with zero cpd/100t from spectral fit
2) ^{210}Bi : from ~70 cpd/100tons to 20 cpd/100tons) ;
3) ^{238}U (from ^{214}Bi-Po tagging) < 9.7 10^{-19} g/g at 95% C.L.
4) ^{232}Th < 2.9 10^{-18} g/g at 95% C.L.
5) ^{210}Po
6) It may be possible to estimate the ^{210}Bi content from ^{210}Po evolution in time;

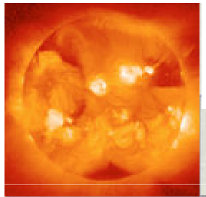
7) pp, higher precision pep and 7Be, toward CNO: are in the wish list of Borexino

What next ? SNO+

SJM PEETERS, RENO50, JUNE 2013



- Fill SNO with liquid scintillator
- 780 tonnes LAB+PPO
- 9000 PMTS
- Water shield by Ultra Pure Water
- Wide physics program



Assuming the Borexino background level

	1 year	2 yrs
pep	9.1%	6.5%
^{8}B	7.5%	5.4%
^{7}Be	4%	2.8%
pp	a few %?	
CNO	15%?	

Reduced ^{11}C background due to the depth
10^4 μ/day@Borexino
70 μ/day@SNO+
.....The worse enemy is ^{210}Bi

- Begin scintillator filling: early 2014
- Check Background
- Priority is $\beta\beta$ decay (add ^{130}Te to scintillator)

What next ? LENS Indium based liquid scintillator

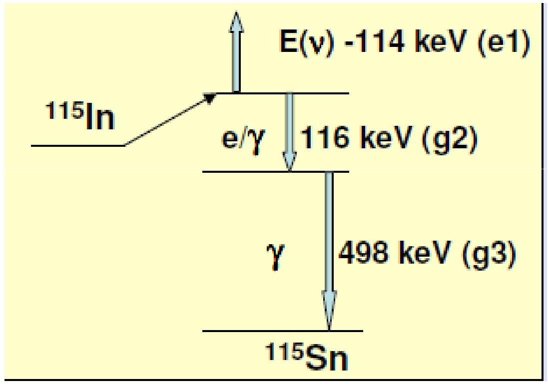
R. Raghavan, Phys.. Rev. Lett. 37, 259 (1976)

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$ prompt

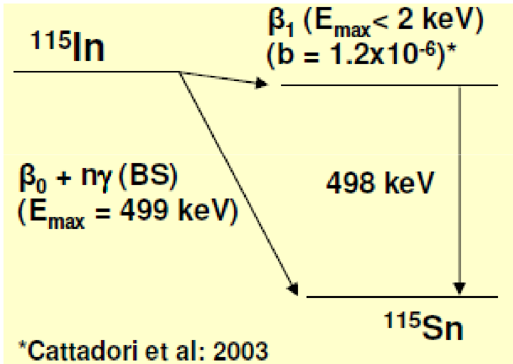
$${}^{115}Sn^* \rightarrow {}^{115}Sn + \gamma\,(116\ keV) + \gamma\,(497\ keV)$$ Delayed τ=4.6 μs

Clean signature of νe events
(In pure LS the spectral shape is the only signature)

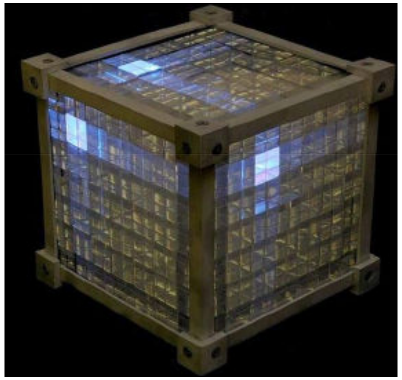
Q= 114 keV sensitivity to pp , ^{7}Be, pep, CNO, 8B
Clean spectral measurement: $E_\nu = e^- - 114$keV



Signal



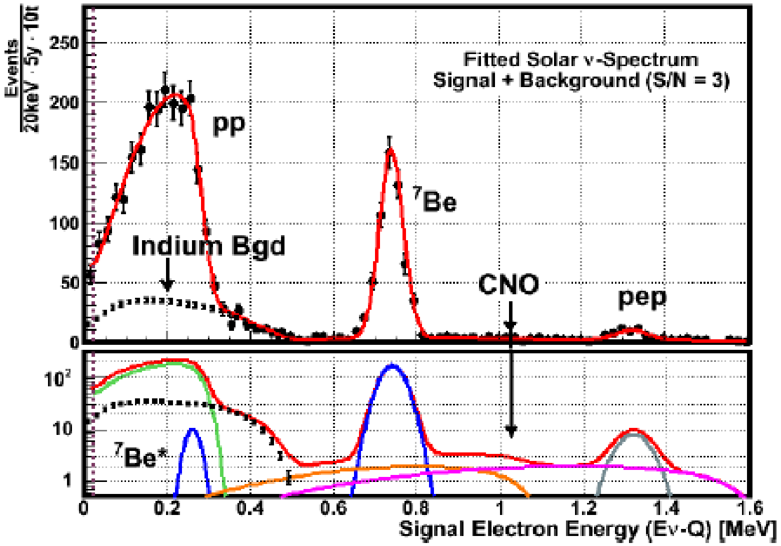
Background



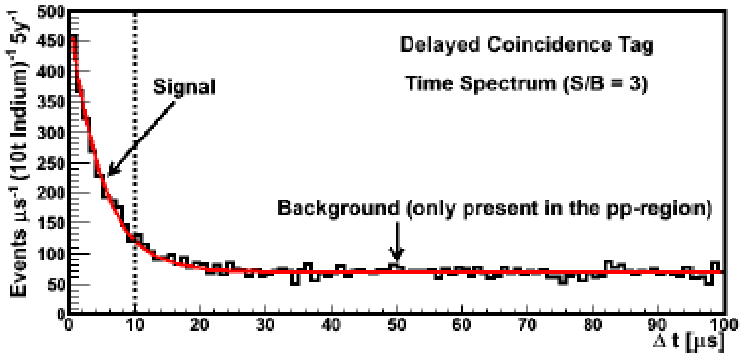
Random coincidences of β decay of ^{115}In (In activity ≈0.25 Bq/g)
Important only for pp
10 t In: 400 pp/year
8 1013 decays/year

3D segmentation of the detector: Lattice with teflon reflectors, PMTS at the end
Space and time cuts

What next ? LENS   Indium based liquid scintillator



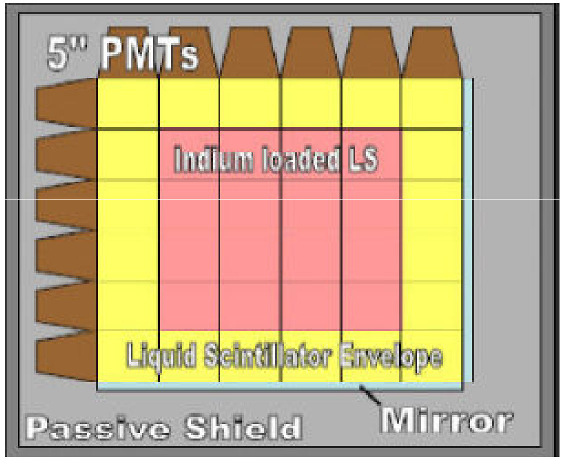
Simulated spectrum; 5 years,
10 tons of Indium loading in LS



C. Grieb et al.,PhysRevD 75 0903006 (2007)

8% In can be loaded in LS
9000 g/MeV (about 75 % of clean LS)
Att . Lengh 8m
Time stability > year

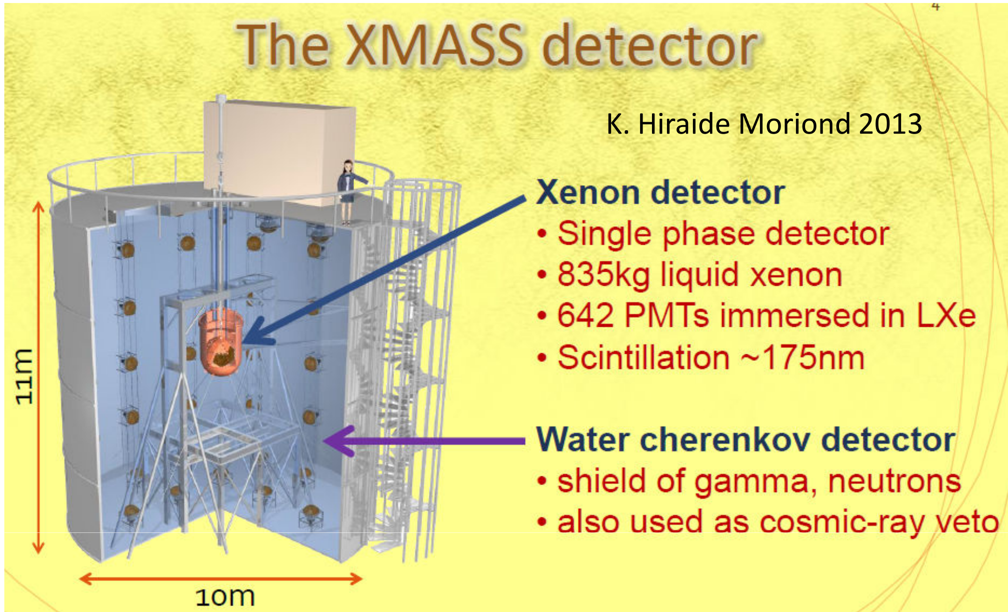
Detector prototype under test in the Kimbalton mine (Virginia):
6X6X6 lattice
130 liters LS   (microLens)



LENS expected performances

Cell Size mm	Cube size m	Pe yield /MeV	Det Eff %	pp-ν /t In/y	Bgd /t In/y	S/N	M (In)* ton	M (InLS) ton	PMT
75	4	1000	64%	40	13	3	10	125	13300 (3")
125	5	950	40%	26	9	2.9	15.3	190	6250 (5")

What next? Cryogenic Xenon, Neon (noble liquid) scintillators for low en. solar spectroscopy

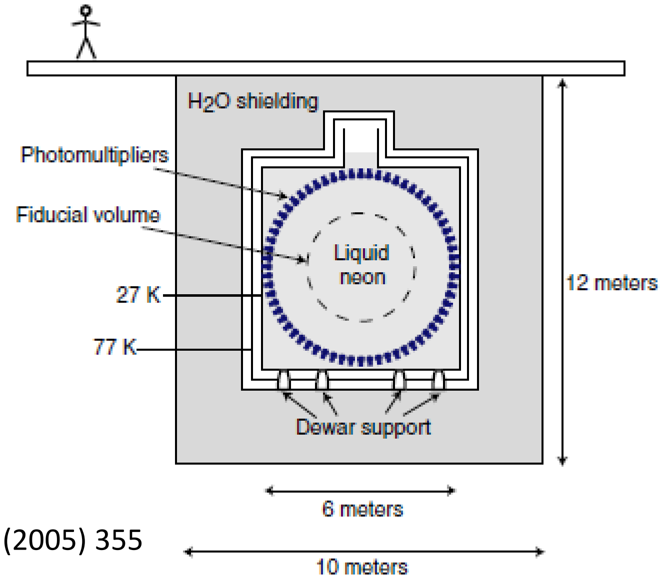


- First run performed
- Detector upgrading
- Resume data taking in summer 2013
- Current focus: Dark matter
- Long term goal: solar neutrinos

arxiv 1301.2815v1 (2013)

CLEAN
conceptual design
100t liquid neon

Small prototype running at SNOLAB
arxiv 1111:3260v2 (2012)



Astroparticle Physics 22 (2005) 355
M. Kinsey et al.,

What next? LENA

Liquid scintillator and PMT: scaling up (X 150) Borexino keeping its performances (or doing even better)

Egg shaped cavern

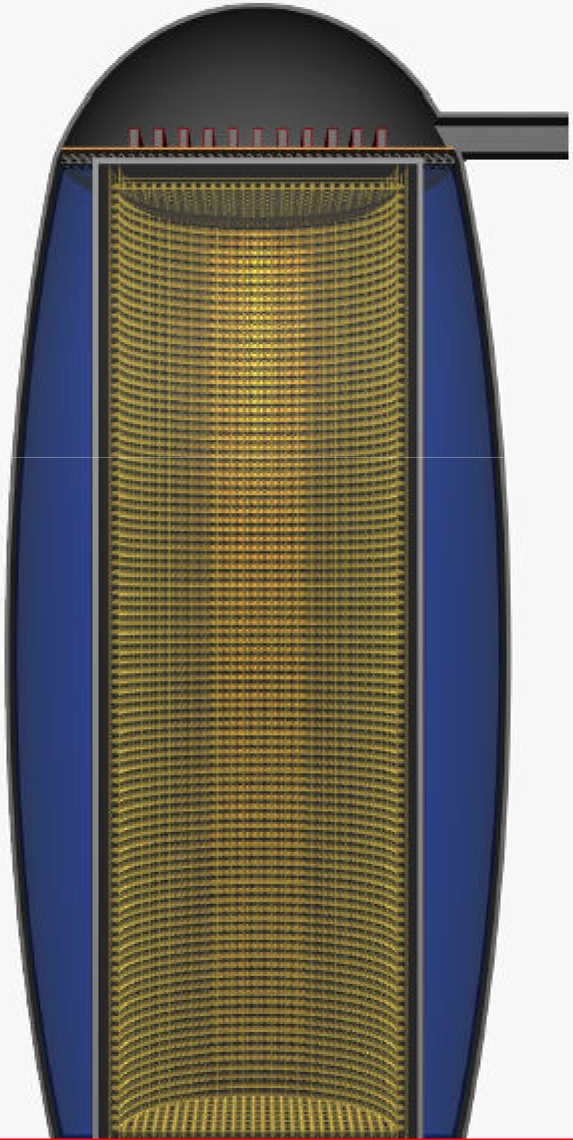
- $\updownarrow$ 115 m
- $\varnothing > 36$ m

Detector Tank

- concrete wall
- cylindrical – $\updownarrow = 100$ m, $\varnothing = 32$ m
- 29600 12" PMTs

Target

- 50 kt scintillator



Electronics hall

- 15 m high
- top muon veto

Water-filled cavern

- 4000 8" PMTs
- veto for inclined muon tracks
- shielding for fast neutrons

Antineutrinos from the Earth: geoν

•Detected by Kamland and Borexino

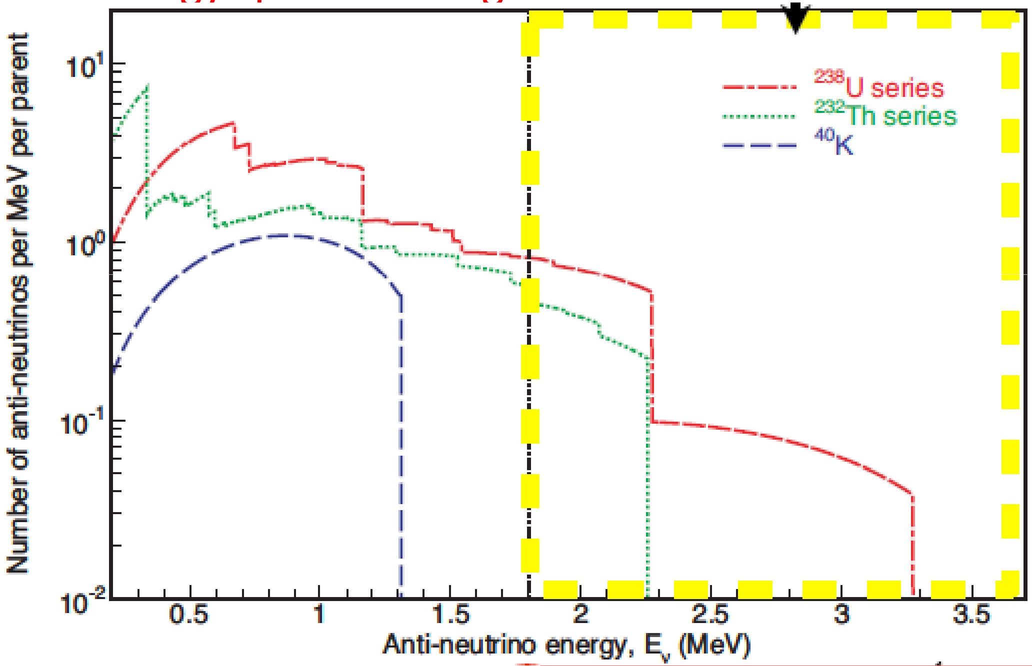
G. Bellini et al., (Borexino Coll.) Phys. Lett. B 687 (2010) 299; Phys Lett B 722 4 (2013) 295 Borexino Coll.

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 Neutrino Geoscience (Takayama) 2013

Energy spectrum of geoν :



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

•"prompt signal"

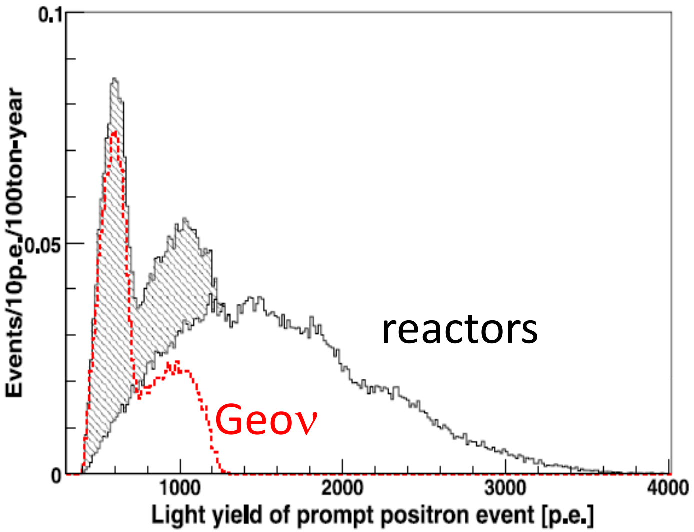
e+: energy loss + annihilation (2 γ 511 KeV each)

•"delayed signal"

n capture after thermalization 2.2 γ

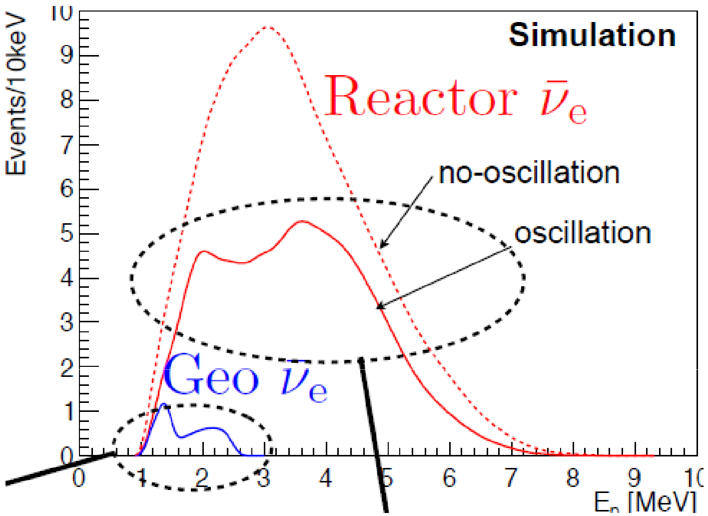
- Low flux: 3 order of magnitude less than ^{7}Be solar ν!
- Geoν: they probe the U,Th content of the Earth (no K)
- Multidisciplinary research: particle physics&geophysics

Simulation for Borexino



1MeV≈ 500 p.e.

Simulation for Kamland



- Reactors antiν are a source of background
- Lower effect in Borexino (there are not near reactors)
- Borexino has also lower background (accidental, αn…) $^{13}C\ (^{210}Po\ \alpha, n)^{16}O$
- But larger target mass in Kamland 300t/1000t before the FV cuts

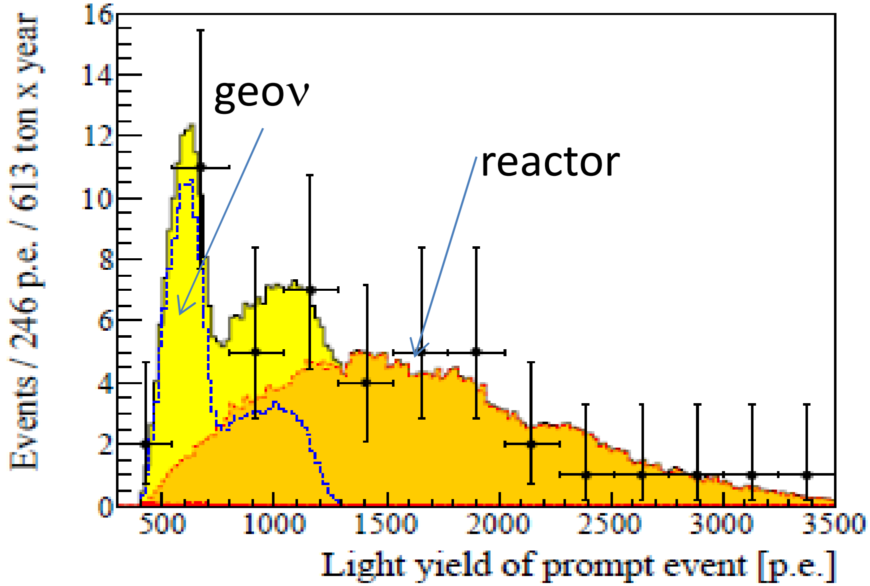
Borexino geoν results

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

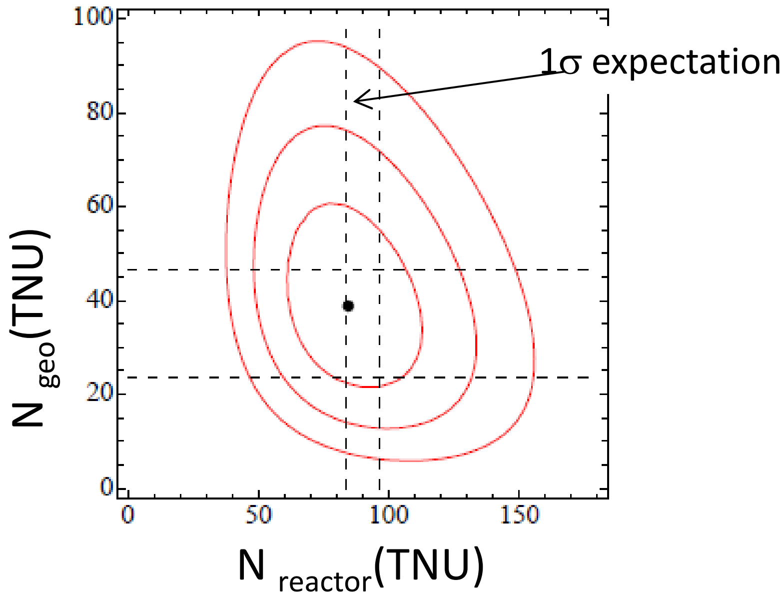
TNU=1ev/ (y 10^{32} protons)

$N_{reactor}$ 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

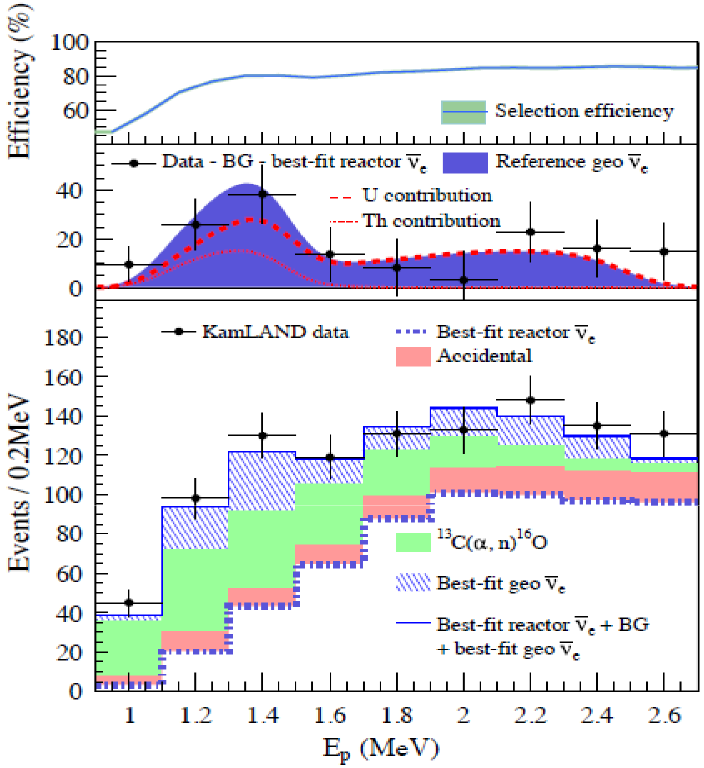


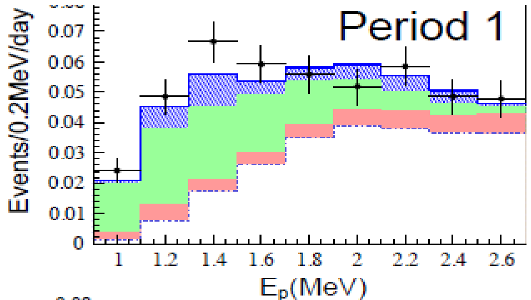
No geoν signal: rejected at 4.5 σ C.L.



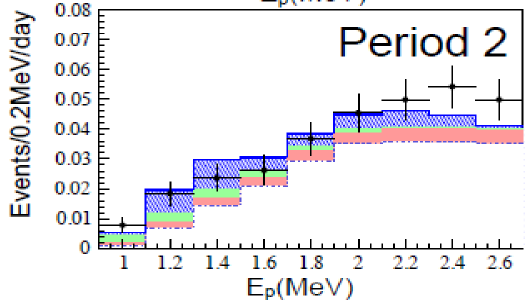
Kamland geoν results

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

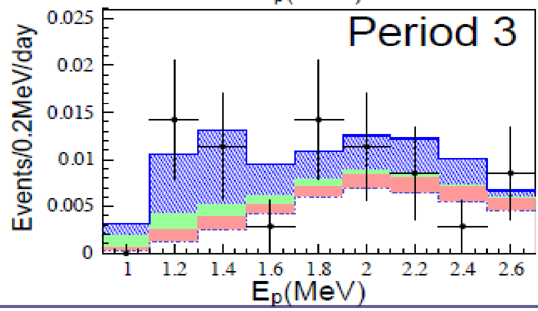




2002-2007



During and after scintillator purification
αn background reduced
Cross section measured



After the installation on the Xe ballon

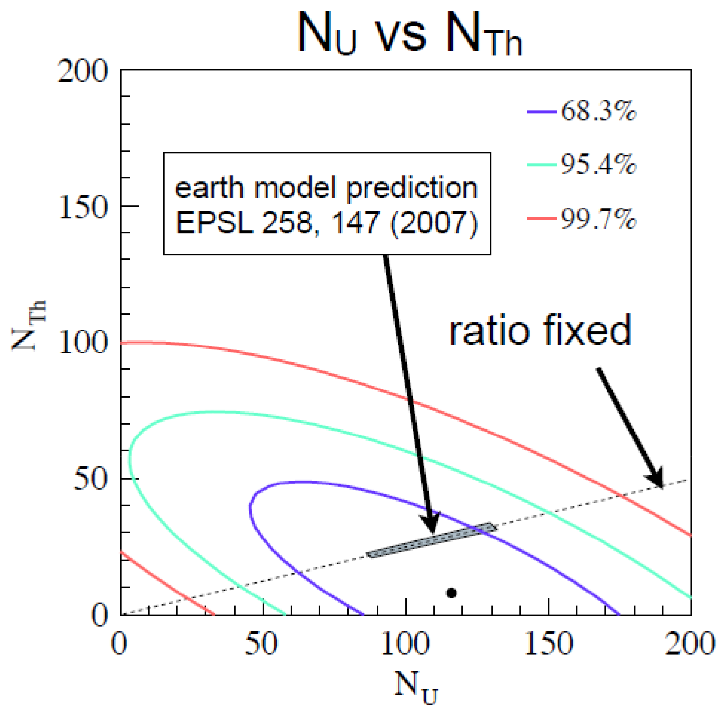
Background studied during the reactor off period after the Earthquake (from March 2011)

Best fit : N(U+Th) 116^{+28}_{-27} 31.1 ± 7.3 TNU

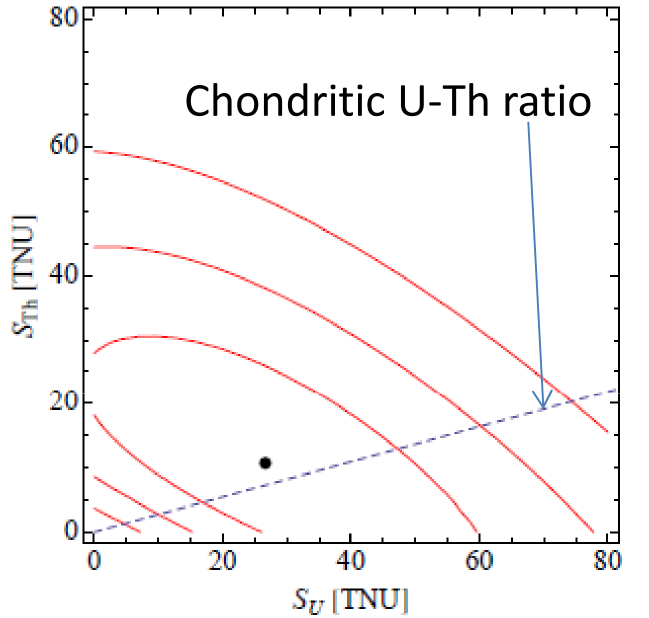
Flux : $3.4^{+0.8}_{-0.8}$ X 10^6 cm^{-2} s^{-1}

H. Watanabe Neutrino Geoscience 2013

Kamland



Borexino



Best fit

$S(^{238}U)$= 116 events

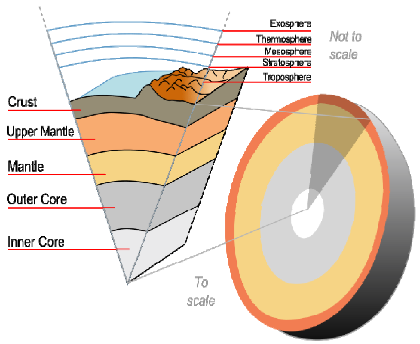
$S(^{232}Th)$ = 8 events

Best fit

$S(^{238}U)$ = 26.5 ± 19.5 TNU

$S(^{232}Th)$ = 10.6 ± 12.7 TNU

Geoν: implications about Earth models



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

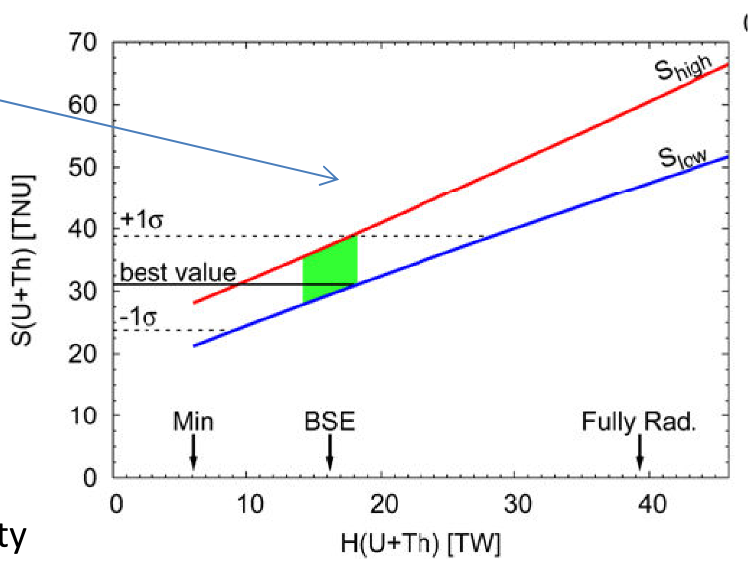
$$S_{Expected} = S_{LOCal} + S_{Rest\ Of\ Crust} + S_{Mantle}$$

$$S_{Mantle} = S_{Measured} - (S_{LOCal} + S_{Rest\ Of\ Crust})$$

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 plot)

	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



•Data not yet precise enough to select Earth models
•New multidisciplinary area, large interest from the geo- community

Adapted from F. Mantovani , Neutrino Geoscience 2013

Geoν: perspectives

SNO+ expected 28-38 events/year (Fiorentini et al,2005)
(50-67 TNU)

LENA about 10^3 events/year !!!

(Hano Hano: 10 Kt liquid scintillator movable and placed in the deep ocean
60-100 events/year)

SUPERNOVA neutrinos

- About 20 events from SN1987A detected by KamiokandeII, IMB (water Cerenkov)+ Baksan, LSD (scintillators)
- Supernova rate: few/100 years
- Not negligible probability now
- Present and planned neutrino detectors may see order of magnitudes more events than the SN1987A

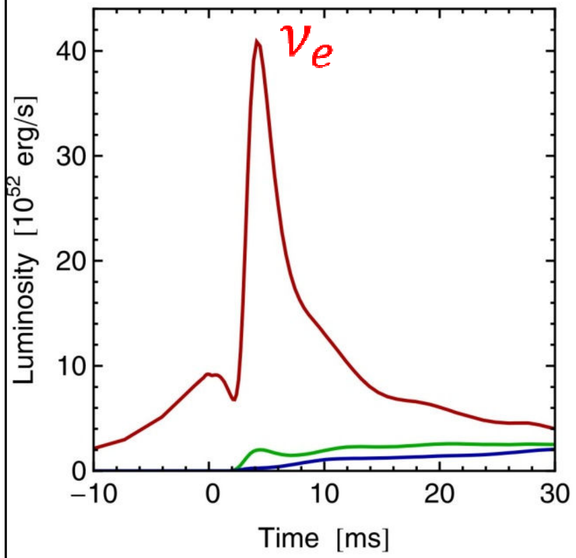
- Many models
- Stellar physics
- MSW
- Neutrino-neutrino interactions – collective flavour oscillations
- Special signature in the emitted neutrino spectra
- Complicated link between shape of the original ν flux and oscillations
- Signature in the shape of the spectra reaching the detectors
- Light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

}Effect sensitive to the mass hierarchy

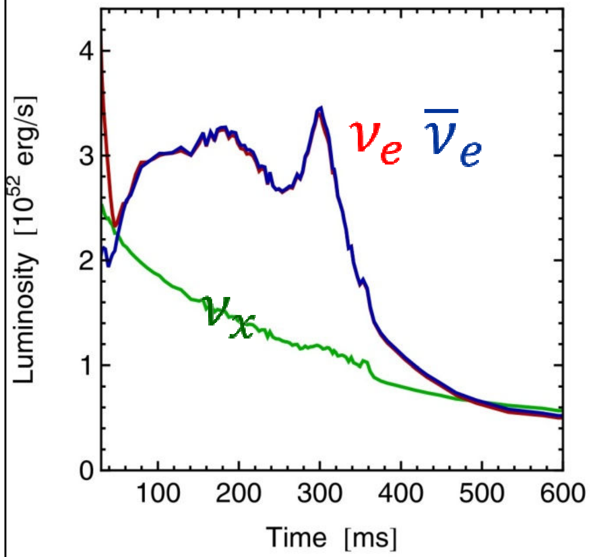
S. Choubey et al. arXiv:1008.0308 (2010) with many refences
Dighe, Smirov arXiv: 9907423v2 (1999)

SUPERNOVA neutrinos: example of time evolution of n luminosity

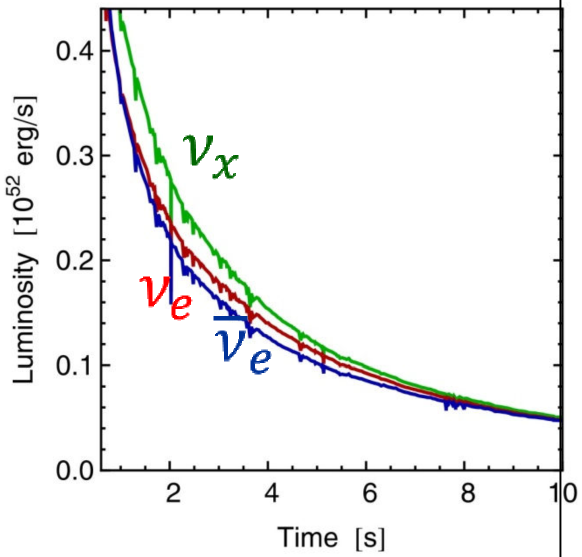
Prompt ν_e burst



Accretion



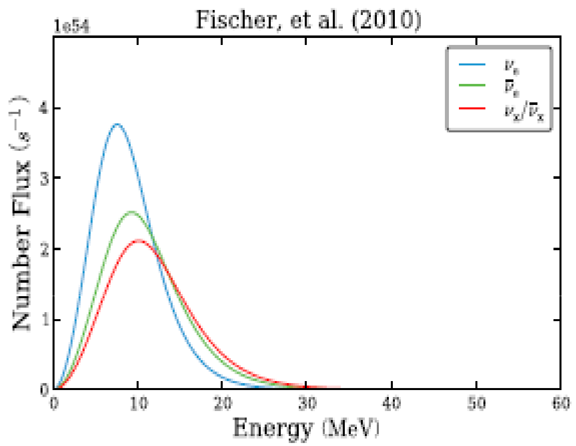
Cooling



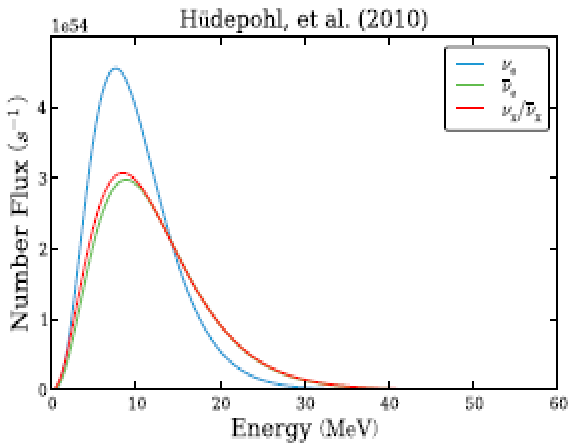
Fisher et al.,2010 [arxiv:0908.1871]

SUPERNOVA neutrinos: several differences in models

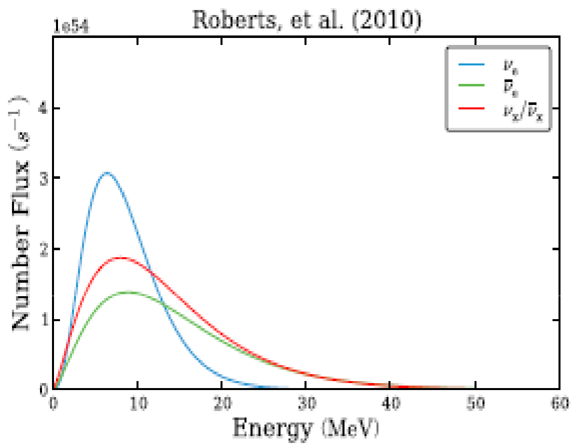
2s post core bounce



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

SUPERNOVA neutrinos: complicated dynamics due to collective effects

B. Dasgupta et al.
PRL 103 051105 (2009)

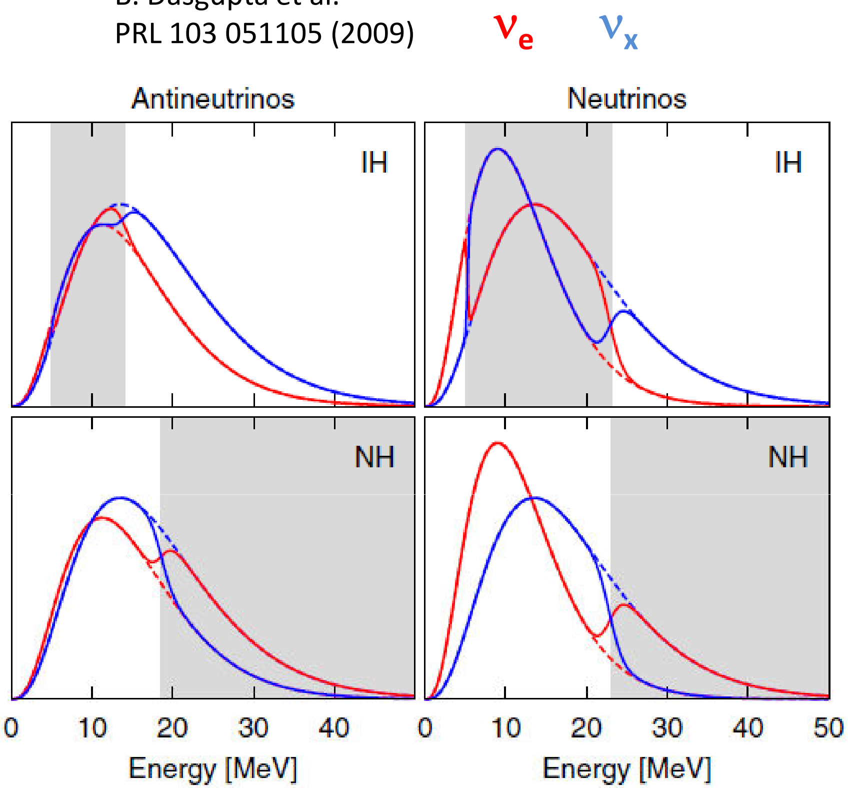


FIG. 1 (color online). SN neutrino spectra before (dashed lines) and after (solid lines) collective oscillations, but before possible Mikheyev-Smirnov-Wolfenstein conversions. The panels are for ν and $\bar{\nu}$, each time for IH and NH. Light gray (red) lines e flavor, dark gray (blue) x flavor. Shaded regions mark swap intervals.

MSW complicates the picture
signatures in the final spectra
depend on model details
Neutrino physics + Astrophysics

S. Choubey et al. arXiv:1008.0308 (2010)

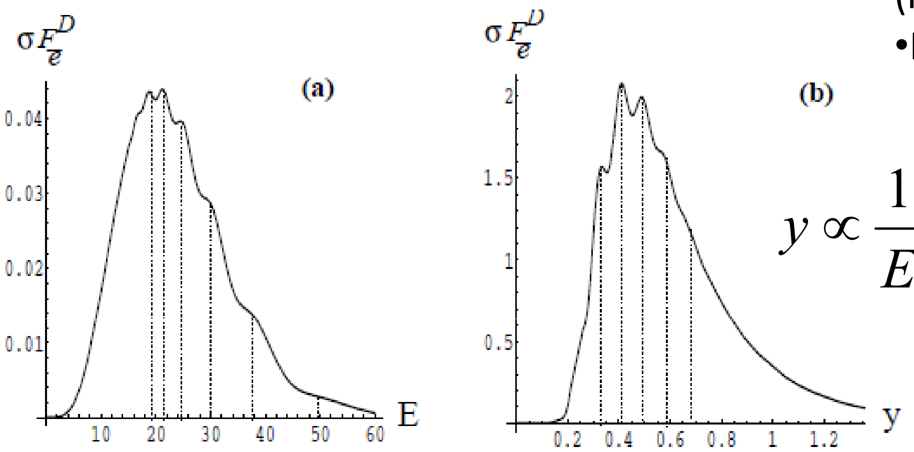
SUPERNOVA neutrinos: Earth matter effect and spectral modulation

A.S. Dighe et al. arXiv:0304 150 v2

- Peaks are equally spaced
- In the y variable
- Specific frequency

(not related to the original spectrum)

- Need high resolution (liquid scintillators)



$$y \propto \frac{1}{E}$$

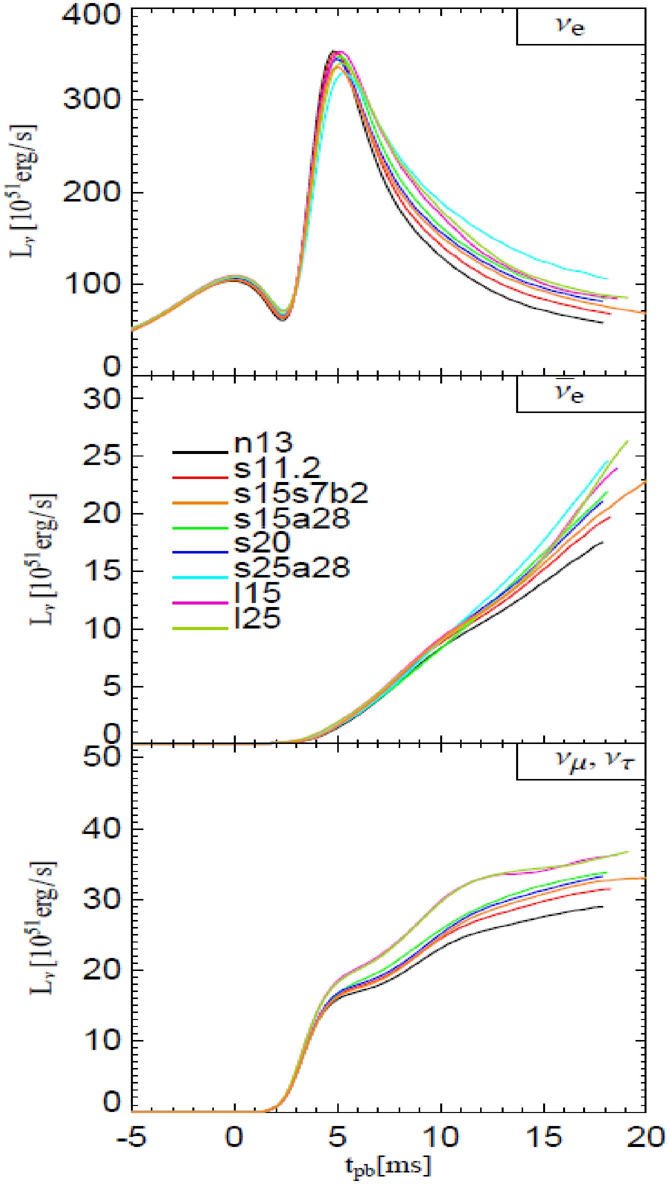
Figure 1. The energy spectrum (a) and the inverse-energy spectrum (b) of $\sigma F_{\bar{e}}^{D}$. The fluxes are normalized such that the area under each curve is unity. For all the examples in this paper, we use the primary neutrino flux parameters $\alpha_{\bar{\nu}_e} = \alpha_{\bar{\nu}_x} = 3.0$, $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV, $\langle E_{\bar{\nu}_x} \rangle = 18$ MeV, $\Phi^0_{\bar{\nu}_e}/\Phi^0_{\bar{\nu}_x} = 0.8$, which are realistic for the fluxes during the cooling phase. For the mixing parameters, we use $\Delta m^2_{\odot} = 6$ (in 10^{-5} eV^2) and $\sin^2(2\theta_{\odot}) = 0.9$. The distance travelled through the Earth is $L = 6$ (in 1000 km) unless otherwise specified.

Difficulties due to the low energy and degeneration of new models discussed in

E. Boriello et hep-ph 1207.5049v2

Modulation in the anti-neutrino spectrum means NH but collective effects complicates the picture

SUPERNOVA neutrinos: time structure of the first (20 ms) ne burst

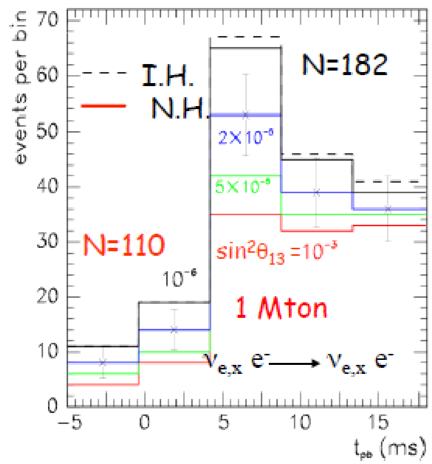


Non observation of the peak in the ν_e channel identifies NH

Presence of the peak not very sensitive to details of Stellar modeling

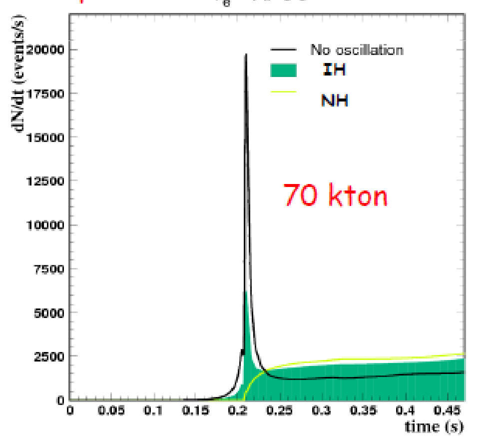
Possible detection in future detectors..

Water Cherencov



[M.Kachelriess & R. Tomas, hep-ph/0412082]

Liq Ar TPC ν_e ^{40}Ar CC



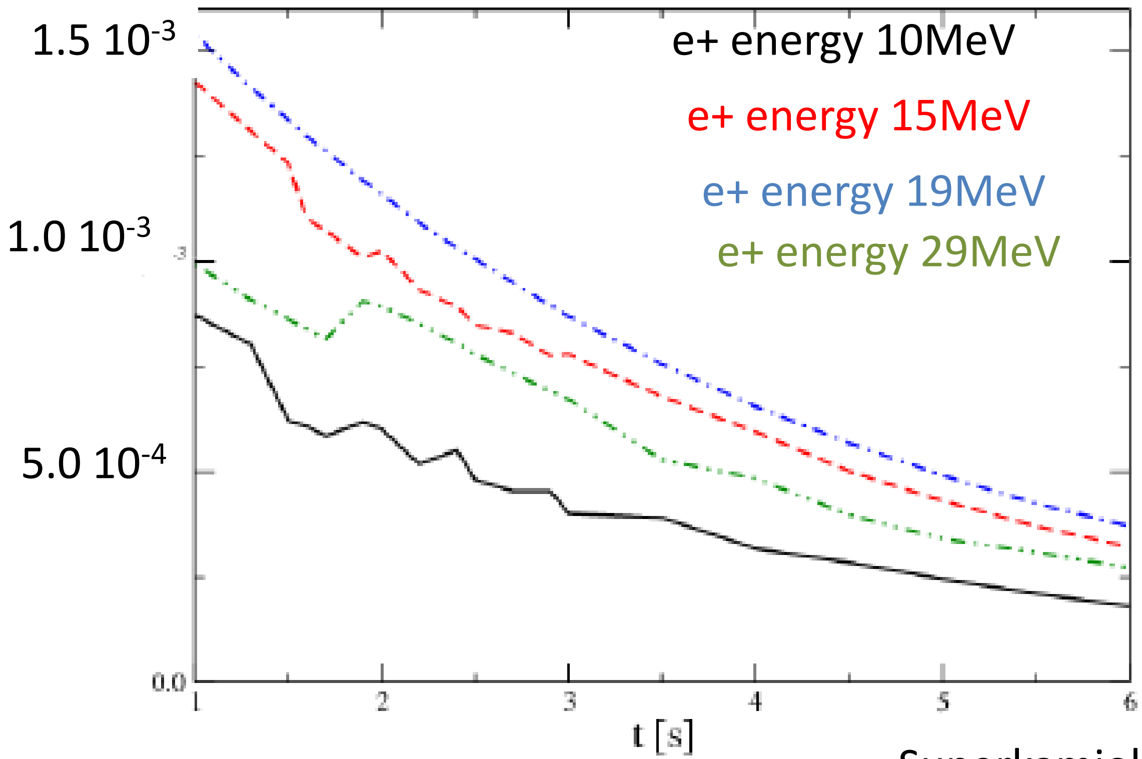
[I.Gil-Botella & A.Rubbia, hep-ph/0307244]

- The peak is not seen → The hierarchy is normal
- The peak is seen → The hierarchy is inverted

SUPERNOVA neutrinos: time structures at late times

- e+ events/(MeV s ton) vs time as detected in inverse beta decay $\overline{\upsilon_e} + p \rightarrow n + e^+$
- Neutrinos in the cooling phase including shock waves and νν interactions

J. Gava et al., PRL 103 (071101) (2009)



NH: exponential shape

IH : structures in the spectrum of anti-ν_e

Superkamiokande could see the effect

SUPERNOVA neutrinos: several 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 νx
ν Nucleus elastic scattering		Low recoil energy Possible in cryogenic noble liquid scintillators

SUPERNOVA neutrinos: expected number of events

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

K. Scholberg arxiv 1205.6003v1 (2012)

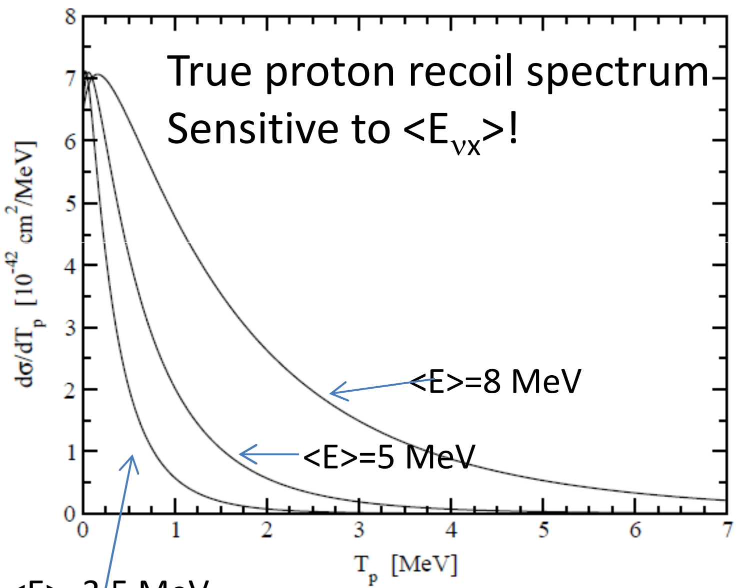
SuperK: mainly $\overline{\upsilon}_e + p \rightarrow n + e^+$
Addition of Gd in water:
project well advanced!!

SUPERNOVA neutrinos: νp elastic scattering in low background liquid scintillators

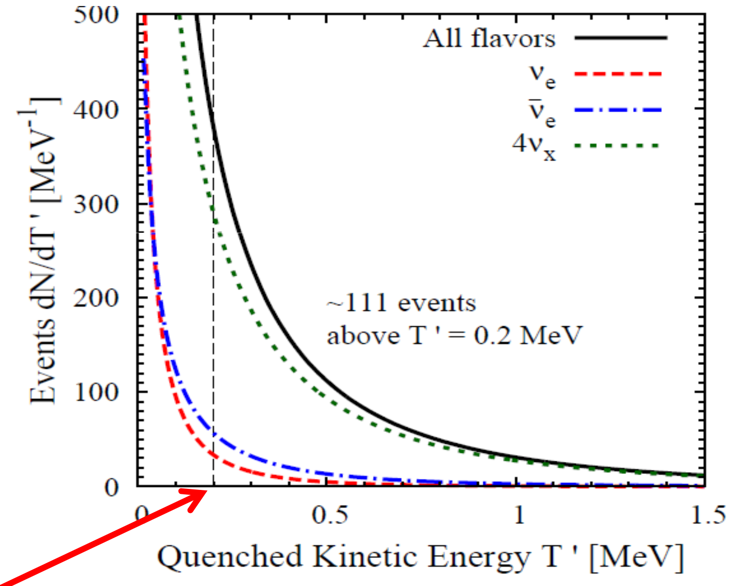
B. Dasgupta, J. Beacom arxiv 1103.2768 (2011)
J. Beacom et al., arxiv 0205220 (2002)

- Superkamiokande will mainly measure anti-ν_e
- ν_e : the best detector is probably liquid argon
- νp scattering important for measuring the spectrum of ν_μ ν_τ and antinu (all ν_x)

$$\frac{dN}{dT_p}(T_p) = C\int_{(E_\nu)_{min}}^{\infty} dE_\nu\, f(E_\nu)\,\frac{d\sigma}{dT_p}(E_\nu, T_p)$$



Expected recoil spectrum including quenching (SNO+ taken as example)



200 KeV energy threshold

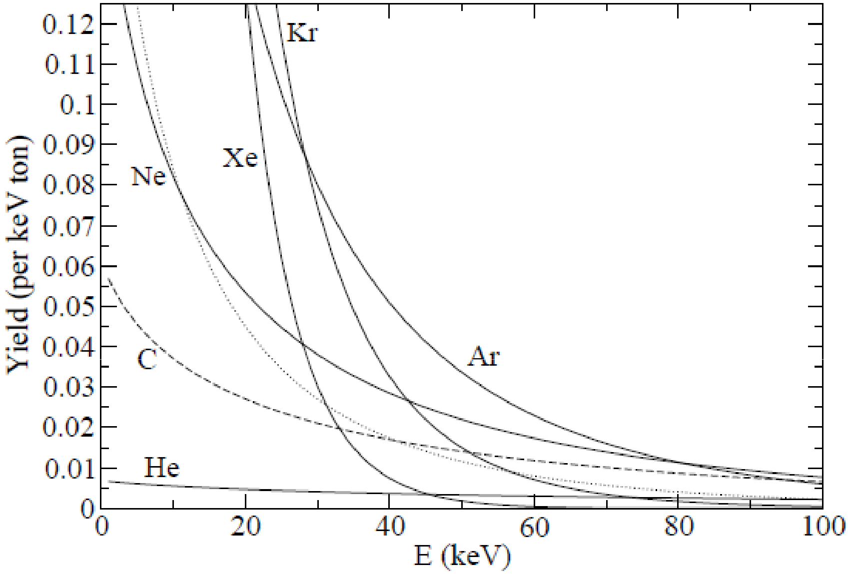
111 events @ SNO+
27 @ Borexino
66 @ Kamland
>10^3@LENA

Low backgroun technologies developed for solar ν make detectors powerful for Supernova ….

SUPERNOVA neutrinos: ν nucleus elastic scattering

C.J.Horowitz et al, arxiv 03002071 (2003)

Recoil energy spectrum of some nucleus:
$<E_{\nu x}>=8$ MeV



Events/tons for a supernova at 10Kpc

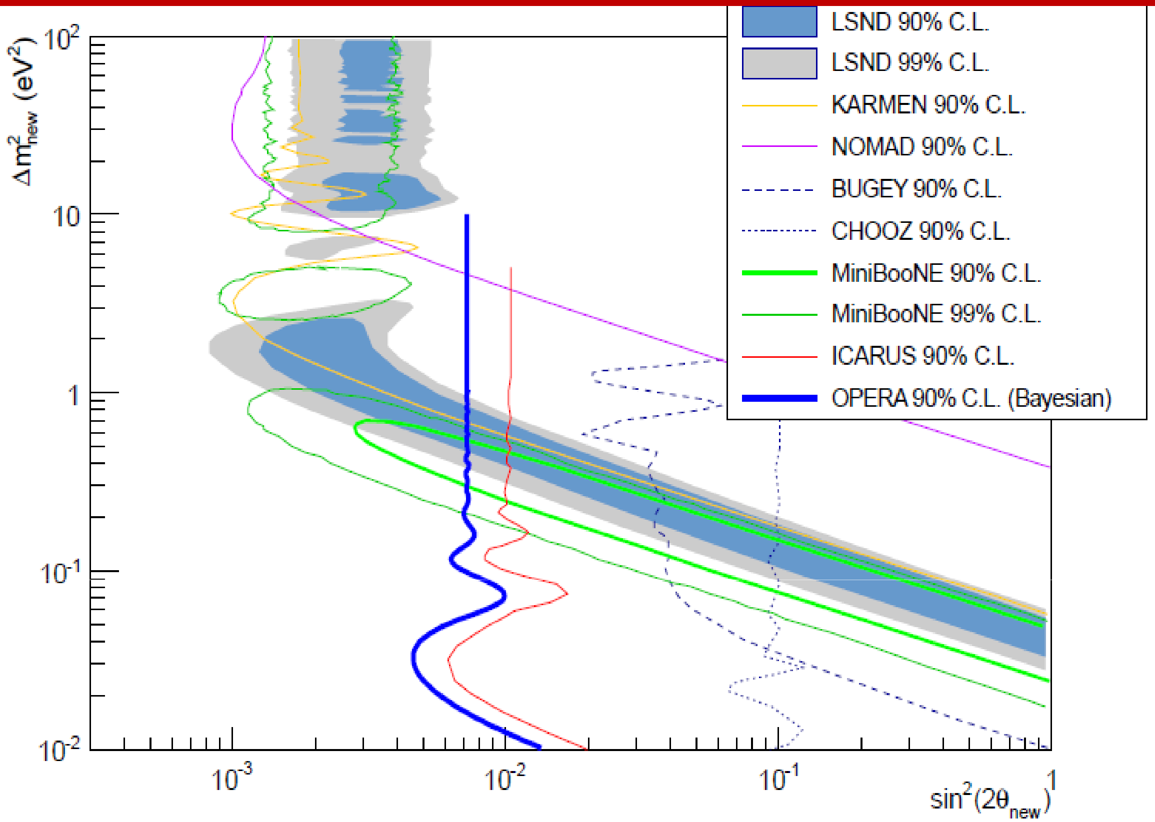
Table I: Yield.

Target	Y	Y > 5 keV	Y > 10 keV	Y > 25 keV	Y > 50 keV	< E > (keV)
^{4}He	0.85	0.82	0.79	0.72	0.62	240
^{12}C	2.5	2.2	2.0	1.6	1.1	83
^{20}Ne	4.0	3.3	2.9	2.0	1.2	46
^{28}Si	5.5	4.2	3.4	2.1	1.1	31
^{40}Ar	9.4	6.6	5.0	2.5	0.99	21
^{76}Ge	18.6	9.6	5.8	1.7	0.30	9.5
^{84}Kr	19.8	9.5	5.5	1.4	0.20	8.4
^{114}Cd	26.3	9.7	4.6	0.70	0.041	5.7
^{130}Te	31.8	10.1	4.3	0.47	0.014	4.8
^{132}Xe	31.1	9.8	4.1	0.43	0.012	4.8
^{208}Pb	47.5	7.3	1.7	0.022	0.001	2.6

Few hundreds events expected in CLEAN 100t

- Detection channel relevant for Cryogenic Detectors like Xmass and CLEAN
- WIMP (Ar, Xe…) detectors should have background low enough
- We need large mass

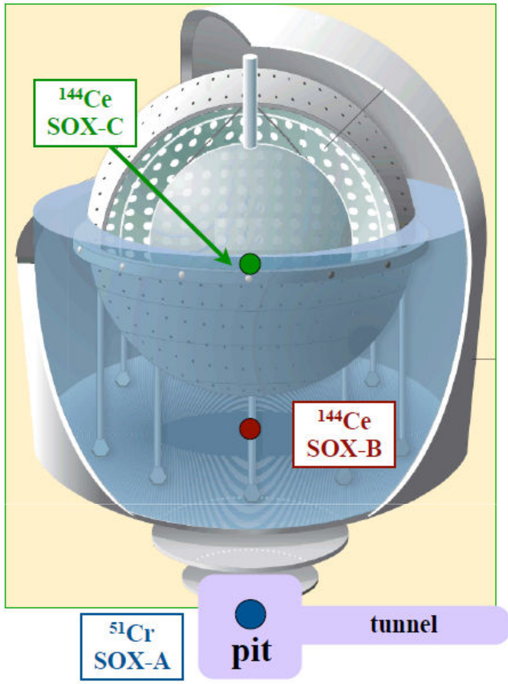
ν or anti ν sources in the low energy scintillator detectors to probe sterile neutrinos

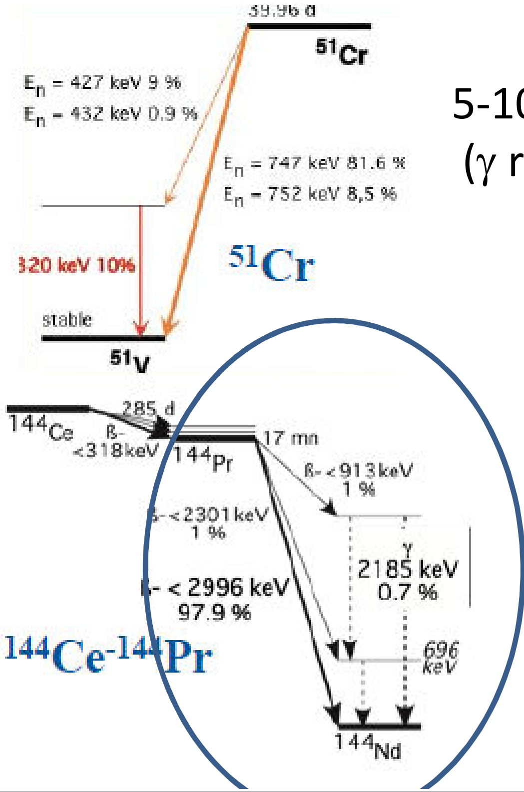


Plot taken from arxiv 1303.353 (2013) (Opera collaboration)

- LSND +MiniBoone
- Reactor anomaly
(flux measured at 100m too low)
- Gallium anomaly
(low rate measured by Gallium and Sage when exposed to v source low)

SOX (Source Oscillation Experiment) in Borexino





arxiv 1304.7721 (2013) Borexino Coll.
arxiv 1107.2335 (2011) M. Cribier et al.

5-10 MCi , external ν sources
(γ rays forbid to put it inside)

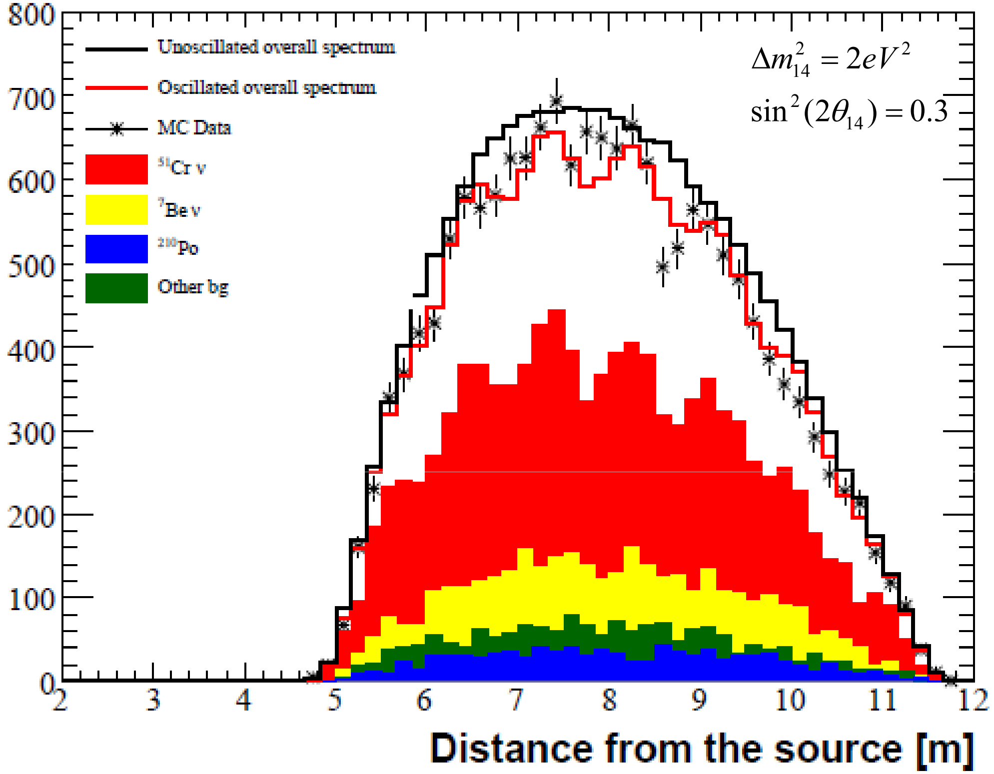
- Similar considerations apply for sources in Kamland or SNO+
- SOX is funded and it started

50-100 kCi
Internal, anti ν

Source	Production	T (days)	Decay mode	Energy [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr ν_e	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \gtrsim 5.\ 10^{14}$ cm^{-2} s^{-1}	40	EC γ 320 keV (10%)	0.746	0.011	0.19
^{144}Ce-^{144}Pr $\bar{\nu}_e$	Chemical extraction from spent nuclear fuel	411	β-	<2.9975	0.314	7.6

SOX (Source Oscillation Experiment) in Borexino

^{51}Cr external



$$P_{ee} = 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\Delta m^2_{41}(eV^2)L(m)}{E(MeV)}$$

$$\Delta m^2_{14} \approx eV^2$$

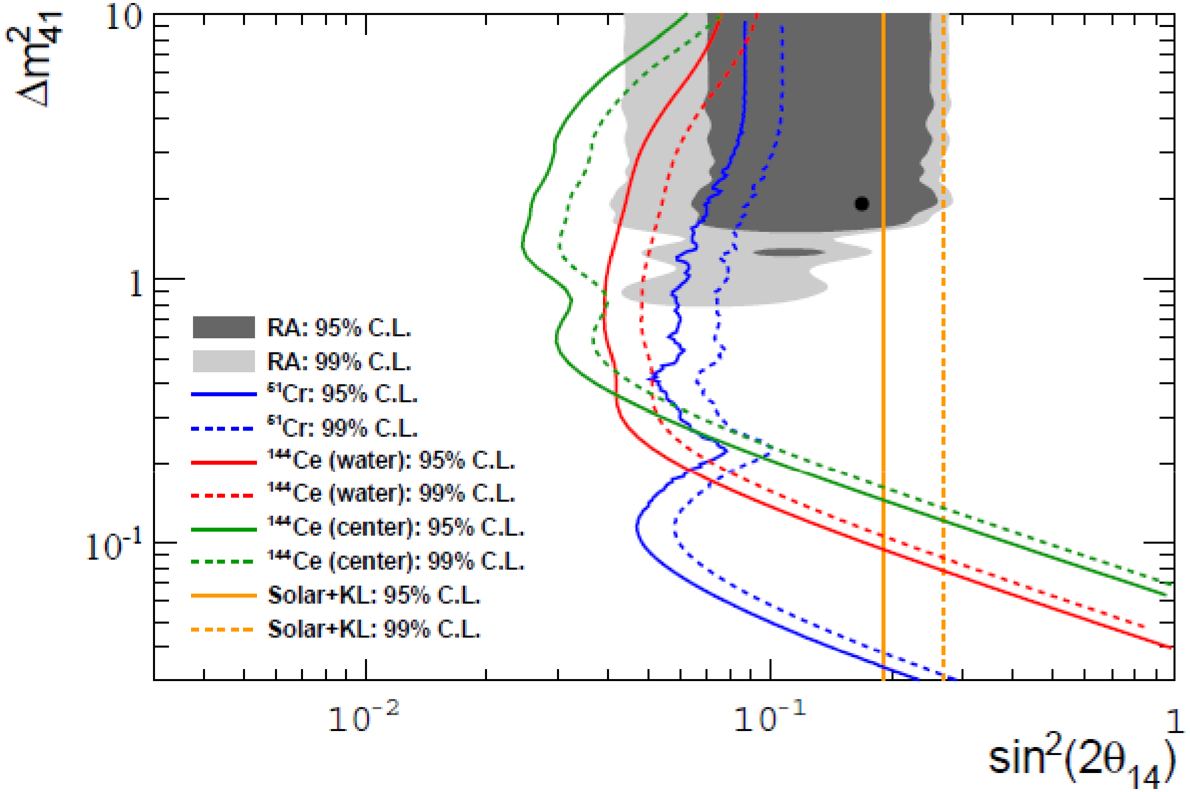
$$E \approx MeV$$

$$L \approx m$$

Space resolution 15cm
Source external

1) Disappearance
2) Oscillations: rate vs distance from the source

SOX (Source Oscillation Experiment) sensitivity



10 MCi (370 PBq) ^{51}Cr few months (the source decays)
75kCi (2.3 PBq) ^{144}Ce 1.5 years

Conclusions

- Solar neutrinos entered in the spectroscopy phase
- Interest for solar models (CNO)
- Verification of the oscillation physics (pep for Pee and NSI, Upturn of 8B)
- Direct pp measurement expected

- Geoneutrinos have been detected : more data are neceessary to constrain Earth models

- Low background detectors developed for solar physisc have great potential for Supernova
- Understanding details of supernova physics demands next generation detectors (high statistics)
- Supernova neutrinos are very rich of informations about astrophysics and neutrino properties

- ν or anti ν sources close or inside Borexino (or Kamland or similar detectors) can probe all the parameter space of the "Reactor anomaly" clarifying the issue of sterile neutrinos