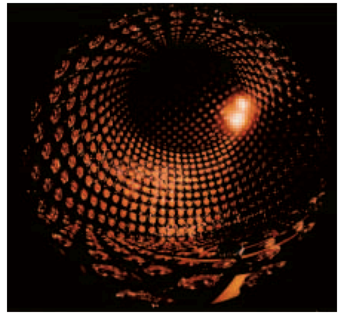
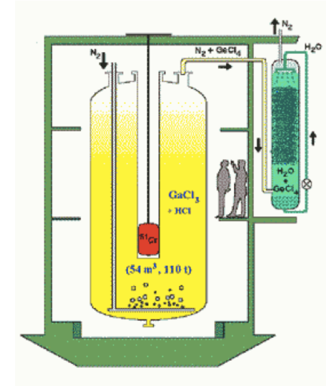
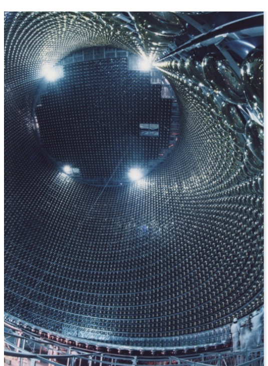
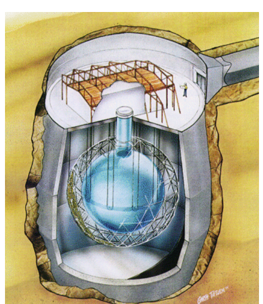
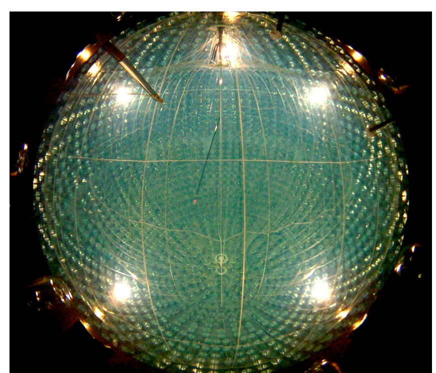
   

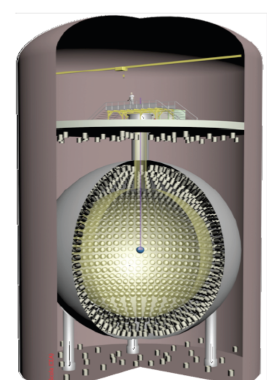
Neutrinos from the sun
and
from other sources

The IceCube Particle Astrophysics Symposium

May 13-15, 2013, University of Wisconsin - Madison

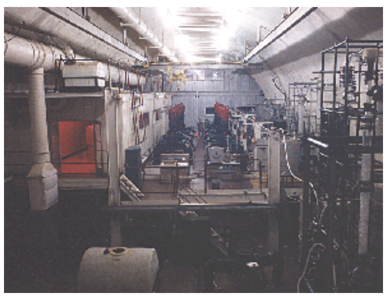
Stefan Schönert, Physik-Department, TU München

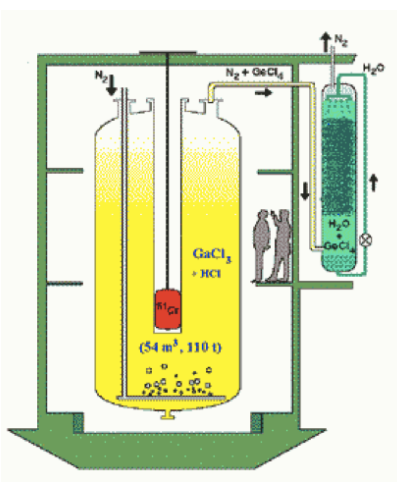
  

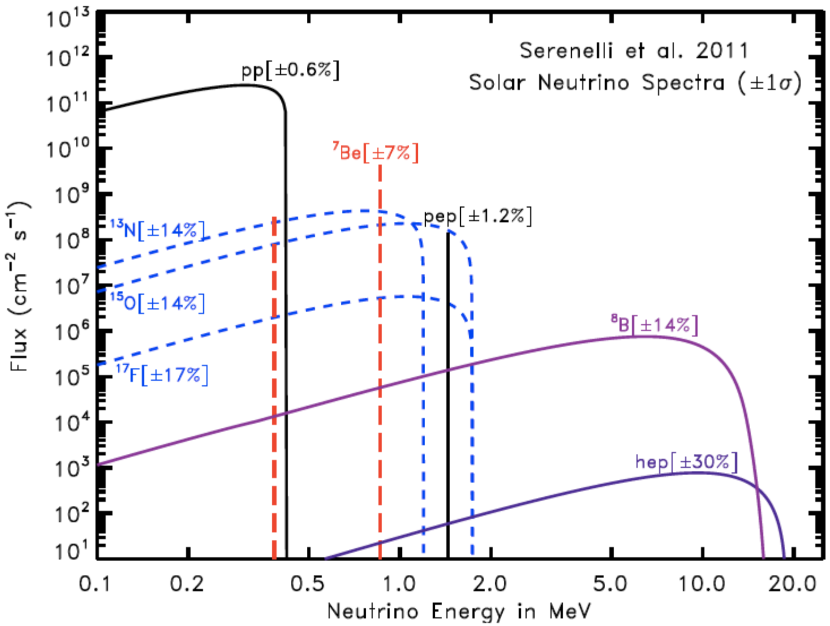
 

Solar neutrino data in the 90's:
astrophysical solution excluded

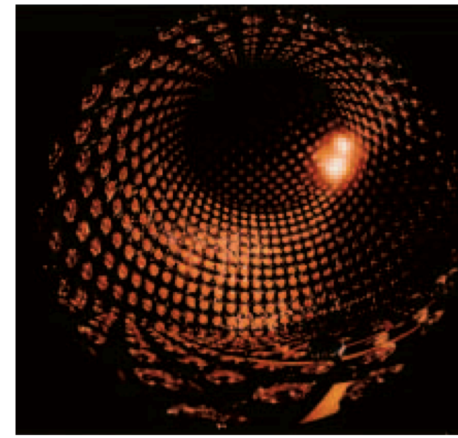
SAGE/GALLEX:
pp+^{7}Be+^{8}B







KamioKANDE: ^{8}B

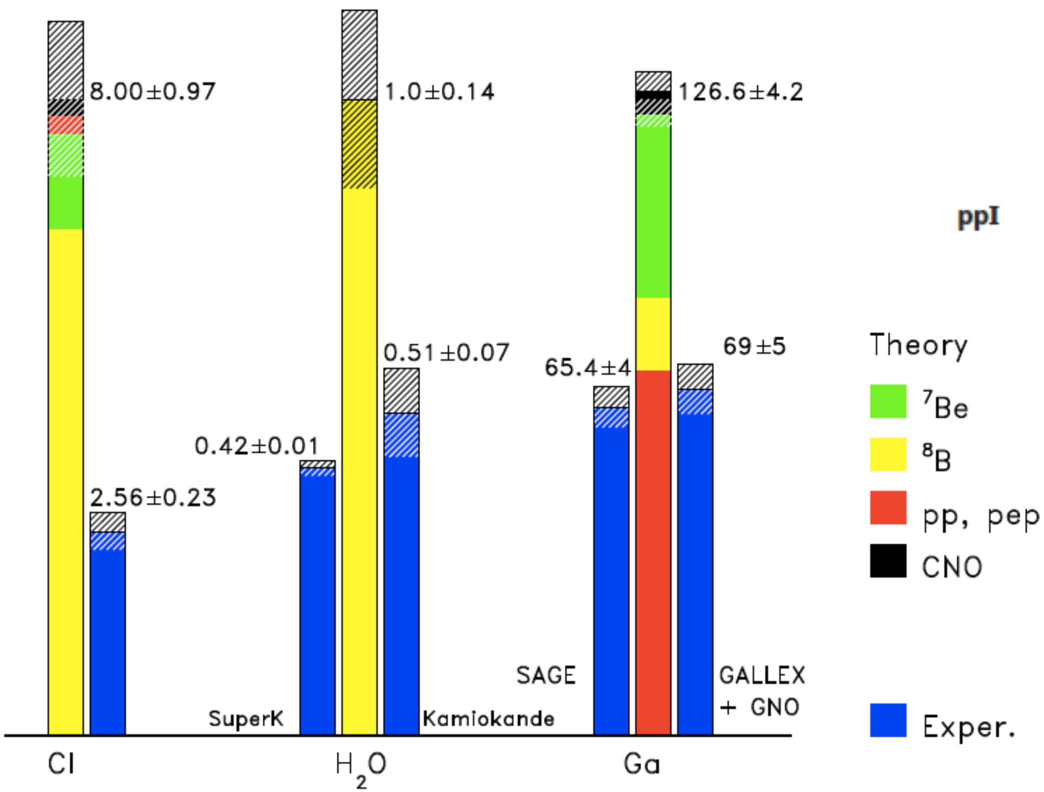


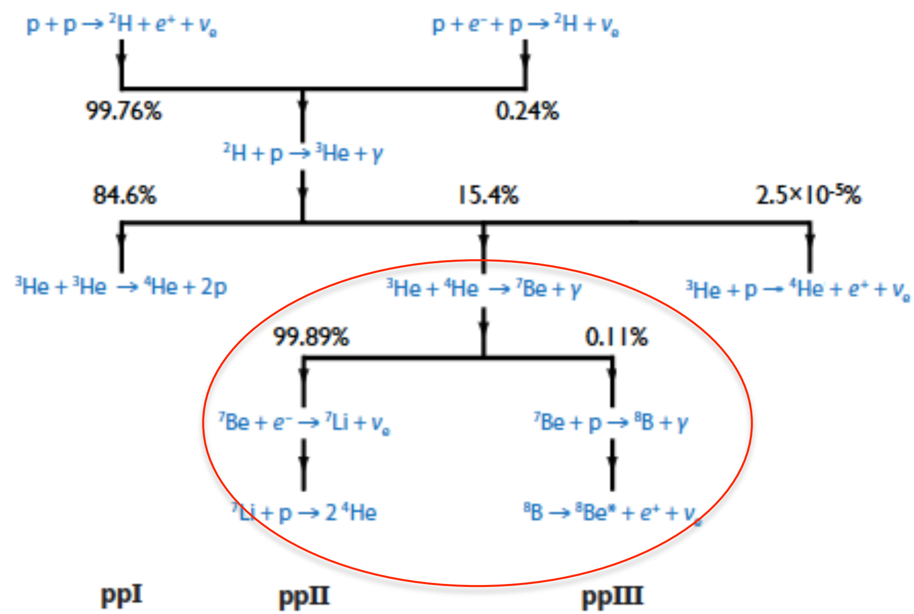
Homestake:(^{7}Be +) ^{8}B

No astrophysical solution to reconcile **combined** results ('missing ^{7}Be neutrinos'):

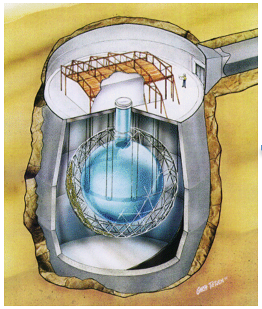
☑**Non-standard neutrino properties**

90's: The 'missing ^{7}Be problem'

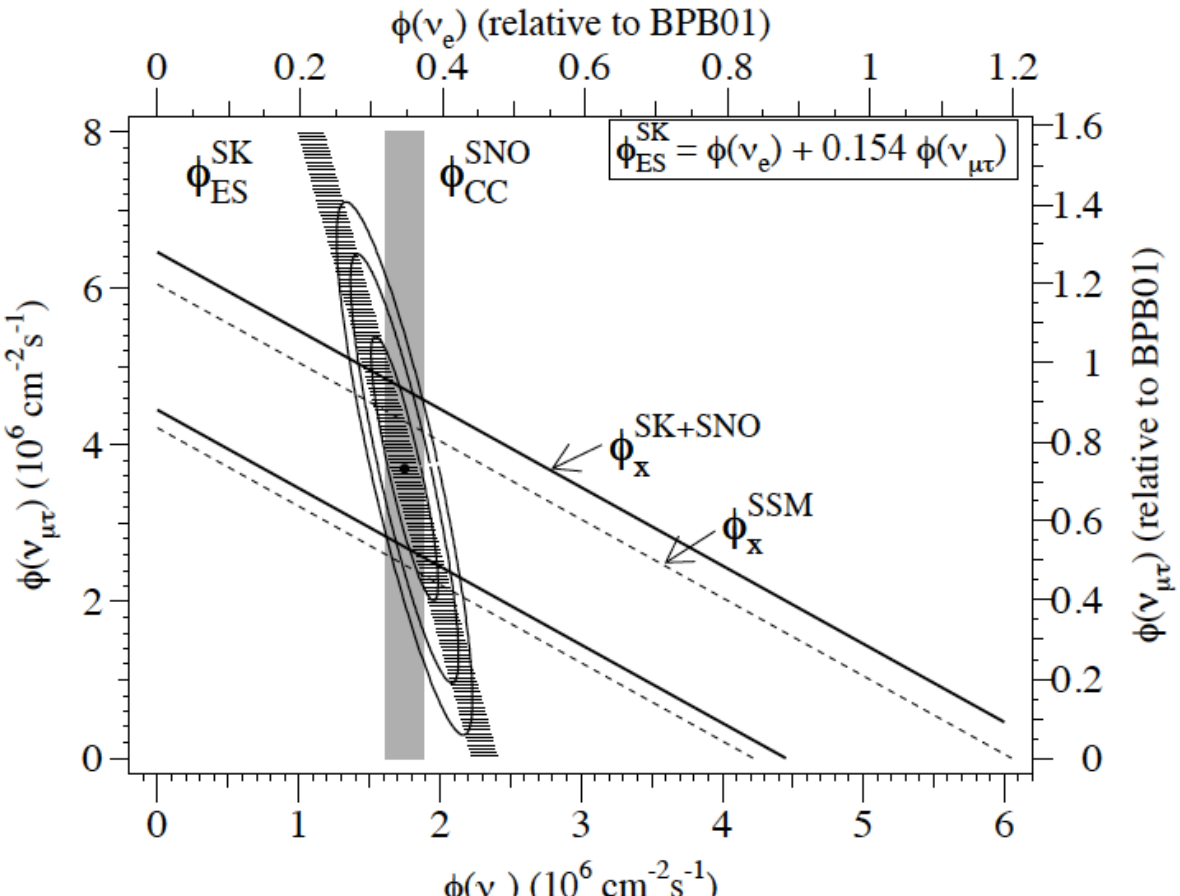




Smoking gun 2001:
SNO + SK: neutrino flavor conversion

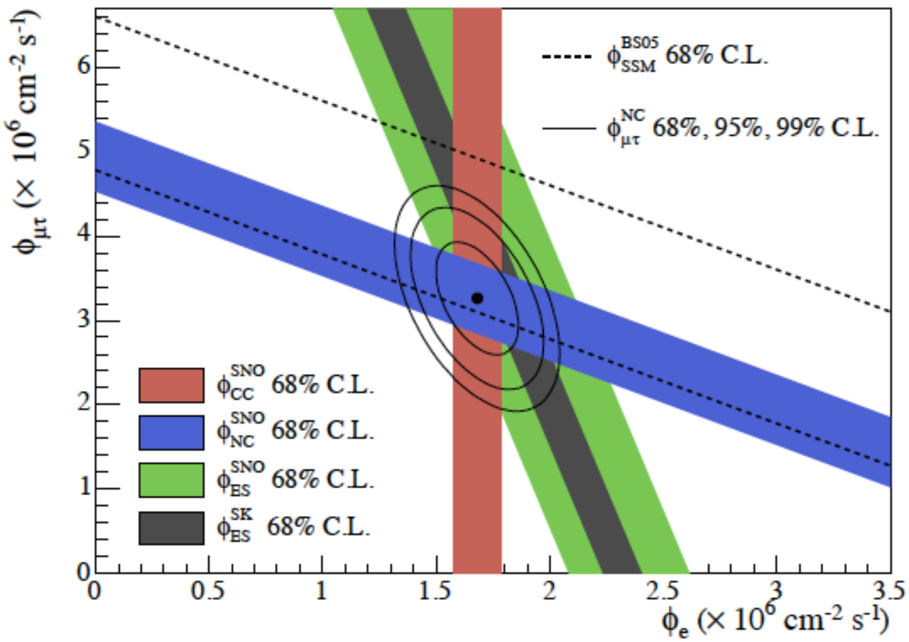


$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(CC)}$$
$$\nu_x + d \rightarrow p + n + \nu_x \qquad \text{(NC)}$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \text{(ES)}$$

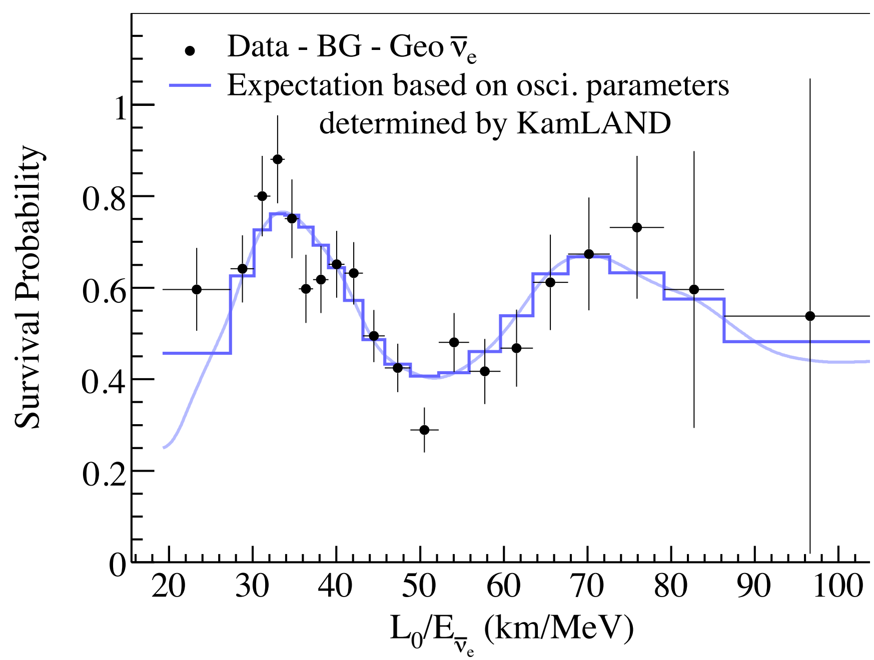


SNO NC-result (salt phase) 2005:

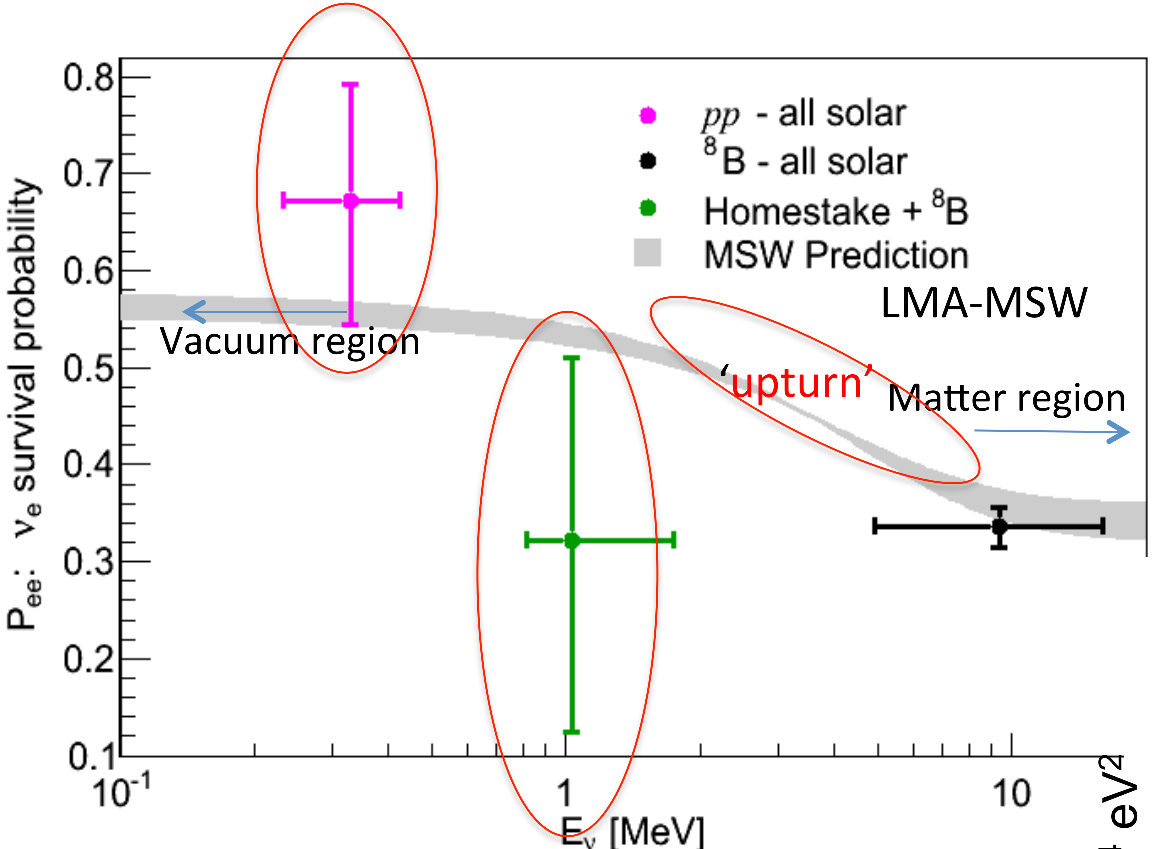
Flavor conversion induced by ν-matter interaction inside the sun



KamLAND: mixing parameters confirmed with vacuum oscillations

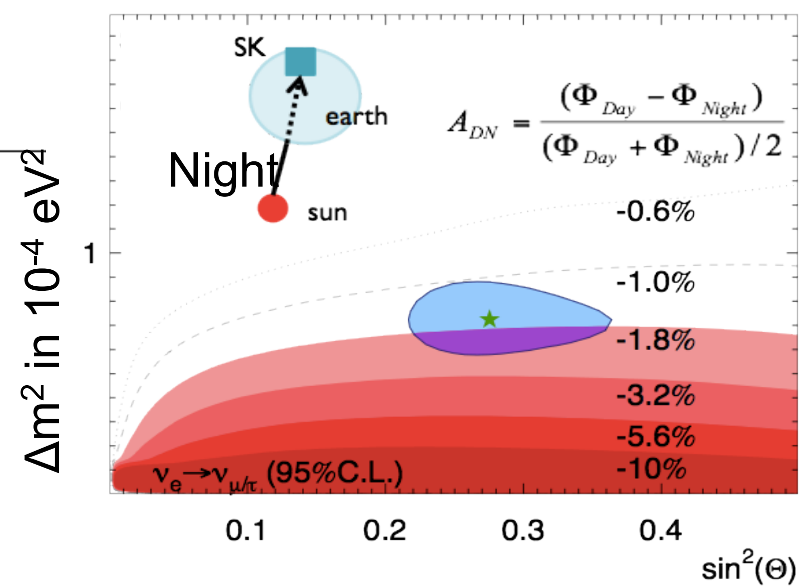


LMA-MSW expectation:



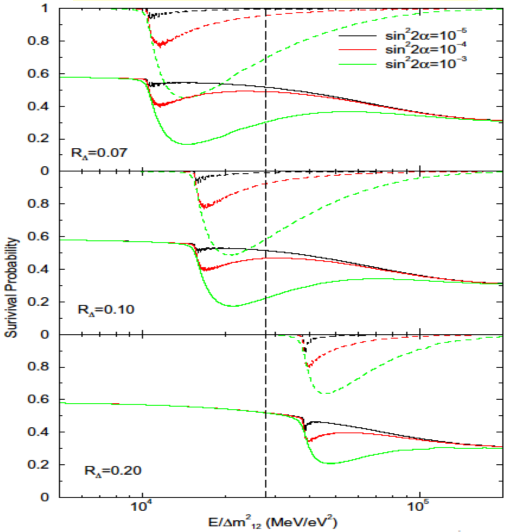
Matter effects observables:

- Upturn
- Day/night effect (^8B-ν's)



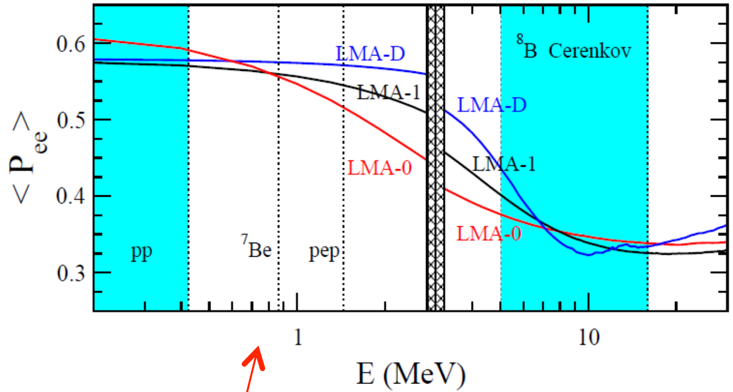
Models which predict non-upturn

Sterile neutrino



$$R_\Delta \equiv \frac{\Delta m^2_{01}}{\Delta m^2_{21}}$$

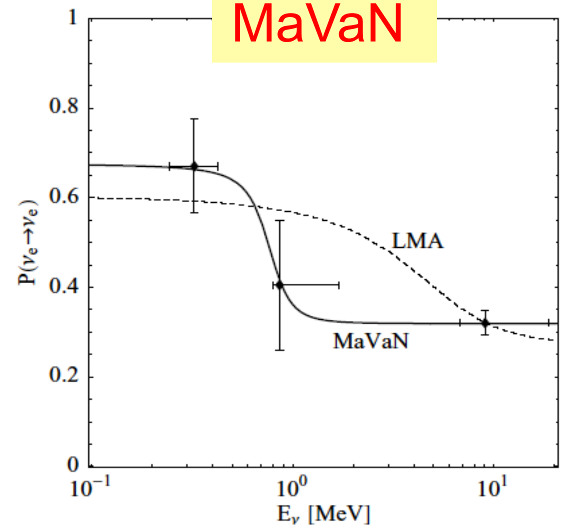
Holanda and Smirnov, Phys.Rev.D69(2004)113002. (hep-ph/0307266)



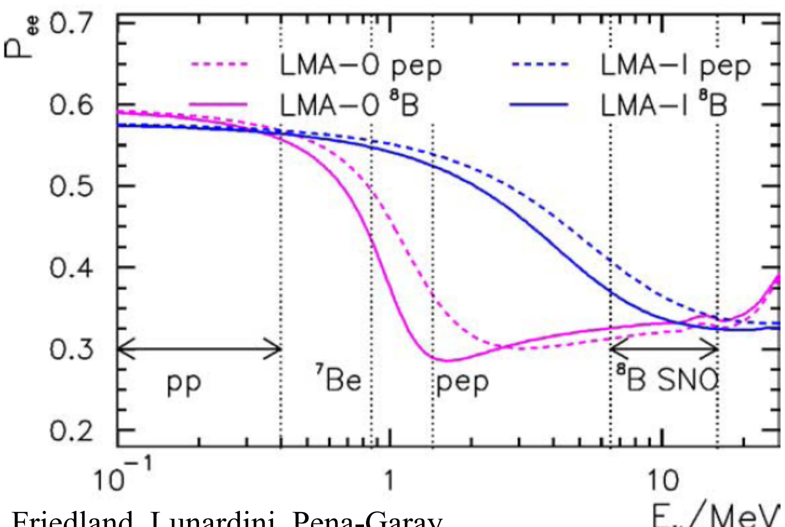
Miranda, Tortola and Valle, JHEP 0610:008,2006. (hep-ph/0406280)

Non standard Interaction

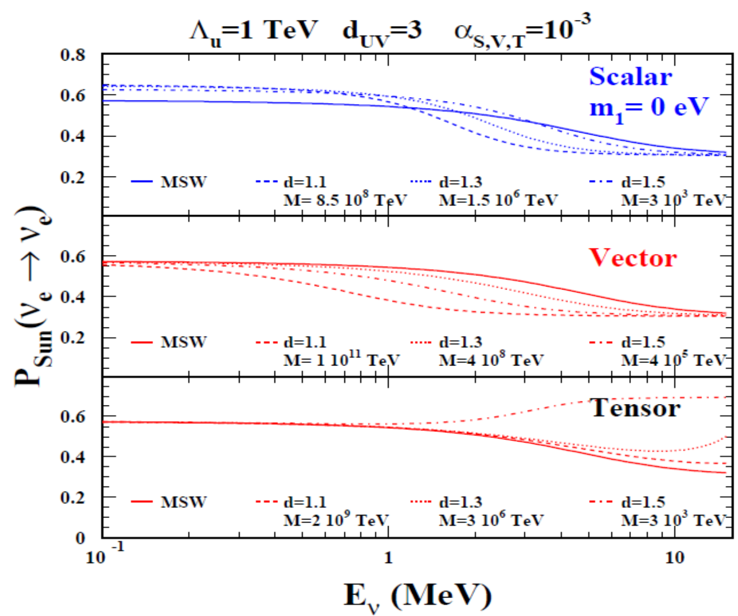
MaVaN



Barger, Huber and Marfatia, Phys.Rev.Lett.95:211802,2005 (hep-ph/0502196)



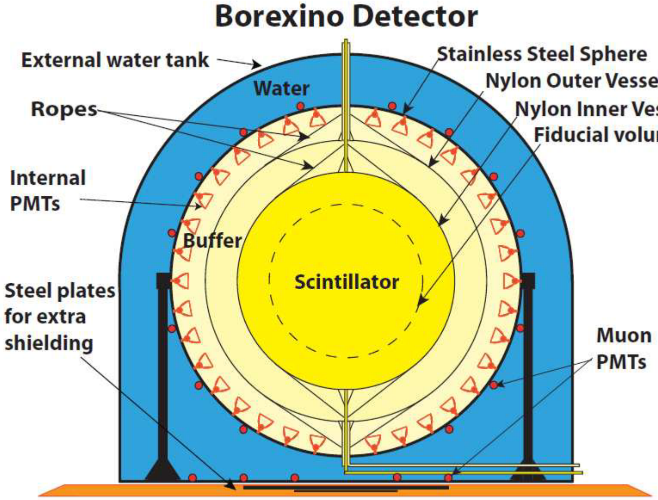
Friedland, Lunardini, Pena-Garay PLB594(2004)347(hep-ph/0402266)

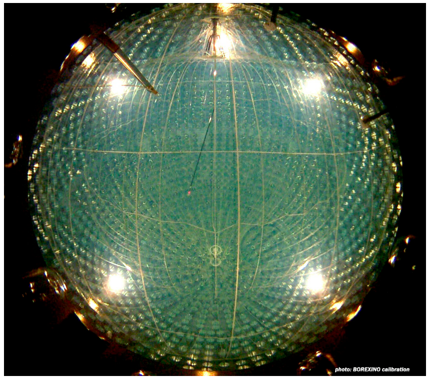


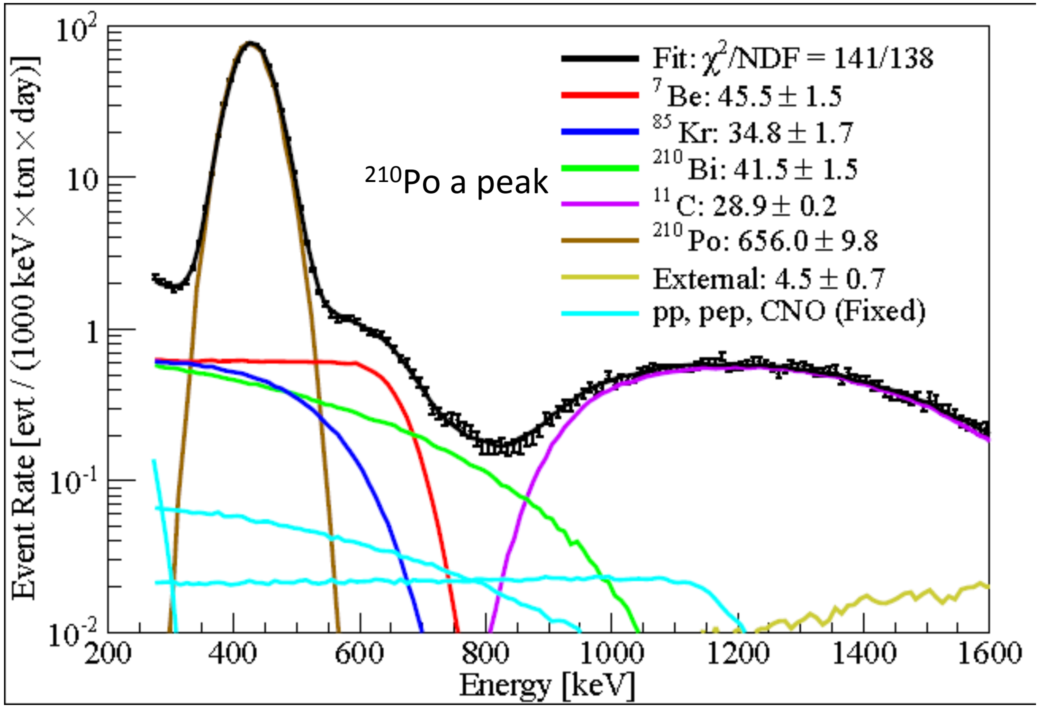
Gonzalez-Garcia,Holanda,Zukanovich ,Funchal, JCAP 0806:019,2008. (hep-ph/0803.1180)

Unparticle

Borexino: ^{7}Be ν's (0.862 MeV)





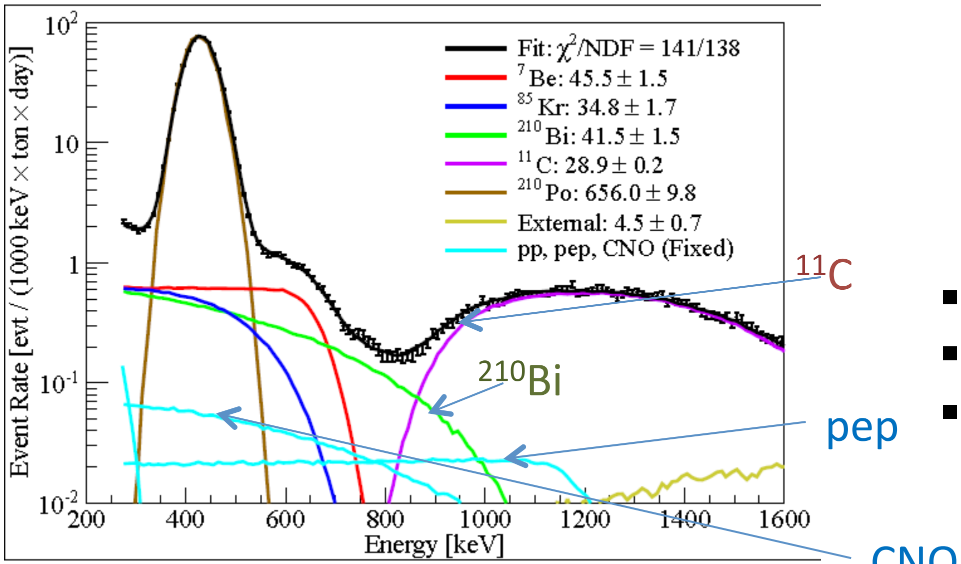


- **ν_e flux reduction** 0.62 +- 0.05
- **electron neutrino survival probability**
  0.51 +- 0.07 @0.862MeV

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

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

Borexino: pep-ν's



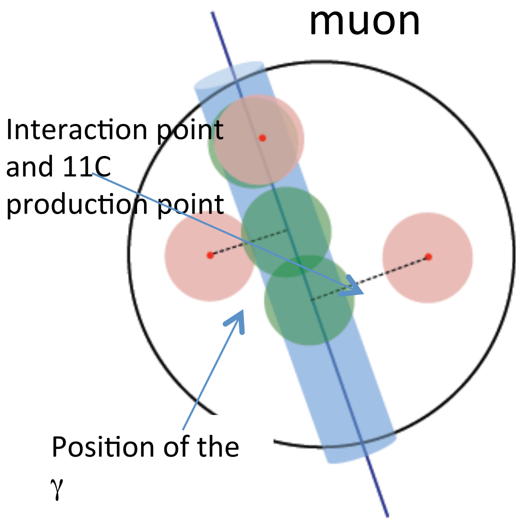
- Expected pep interaction rate: 2-3 cpd/100t
- Background: ^{11}C ^{210}Bi external γ
- ^{210}Bi and CNO spectra: very similar

- Three Fold Coincidence: ^{11}C reduction
- Novel pulse shape discrimination:

  e^+ from ^{11}C decay form positronium

  live time before annihilation in liquid: few ns delayed scintillation signal

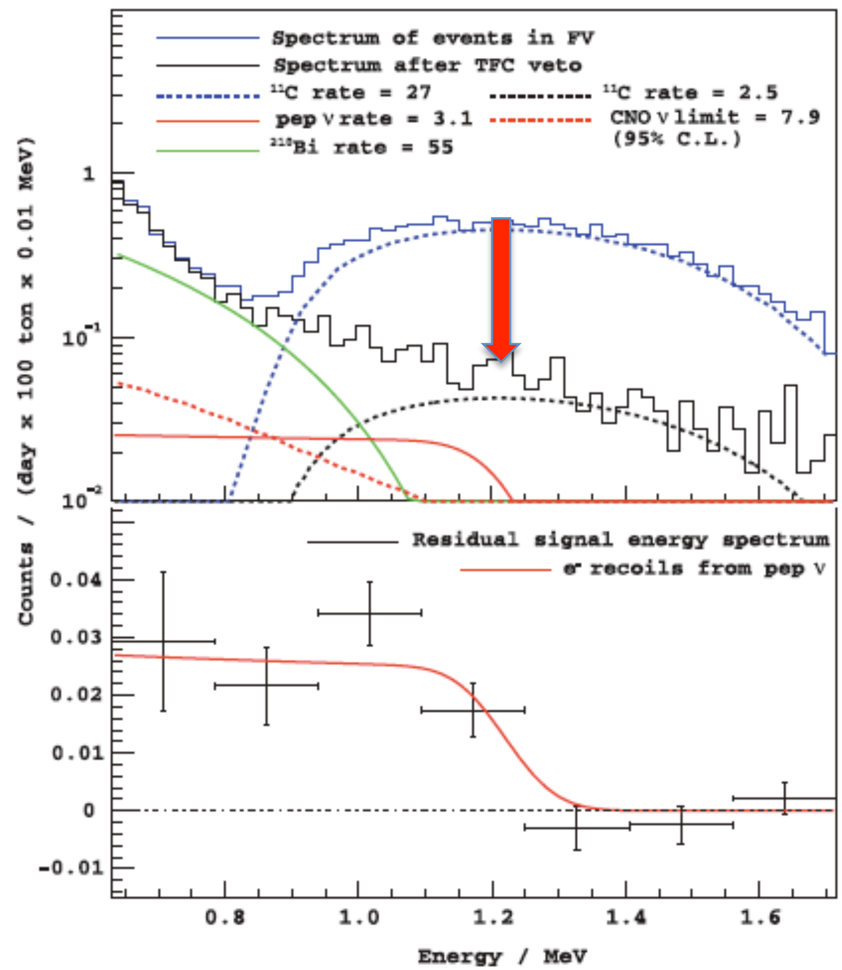
^{11}C reduction and pep-CNO results



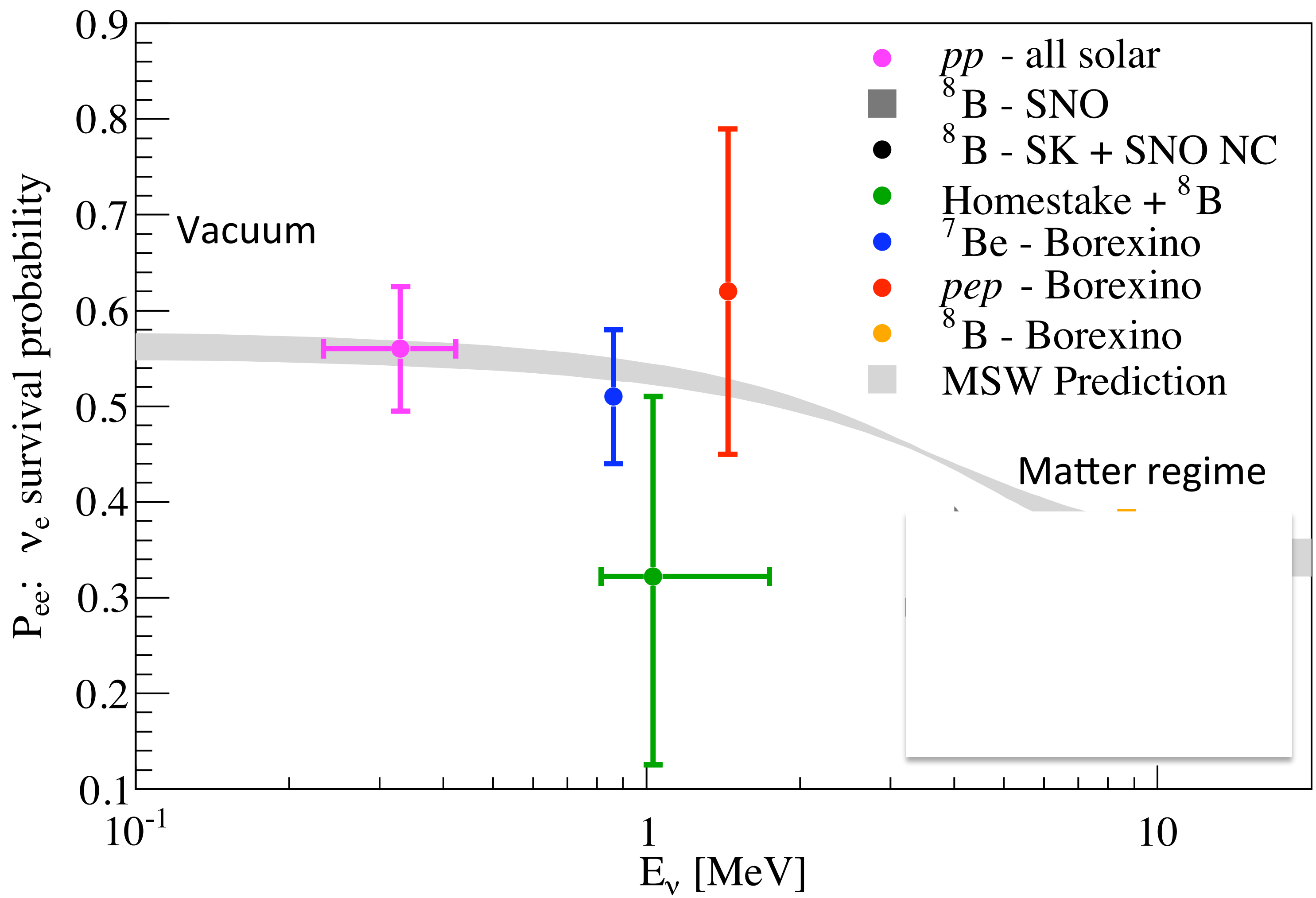
MVA:

- fit of the energy spectra
- fit the radial distribution of the events
- fit the pulse shape parameter

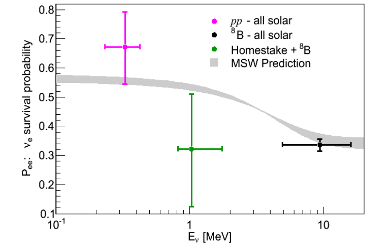
ν	Interaction rate [counts/(day·100 ton)]	Solar-ν flux $[10^8 cm^{-2} s^{-1}]$	Data/SSM ratio
pep	$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$	1.6 ± 0.3	1.1 ± 0.2
CNO	< 7.9 ($< 7.1_{stat\ only}$)	< 7.7	< 1.5



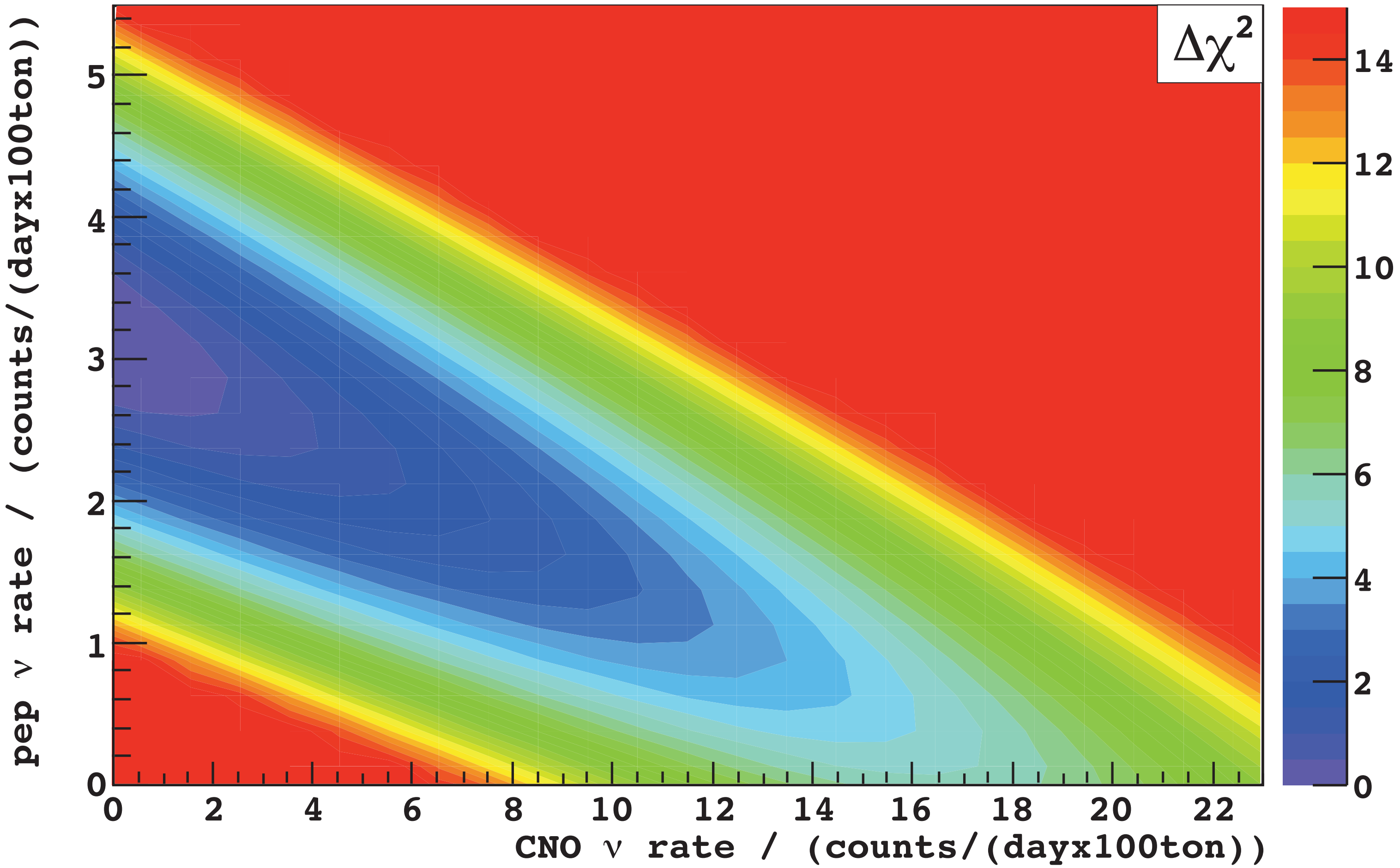
Impact of Be-7 and pep measurements



Before:



pep vs CNO rates in Borexino

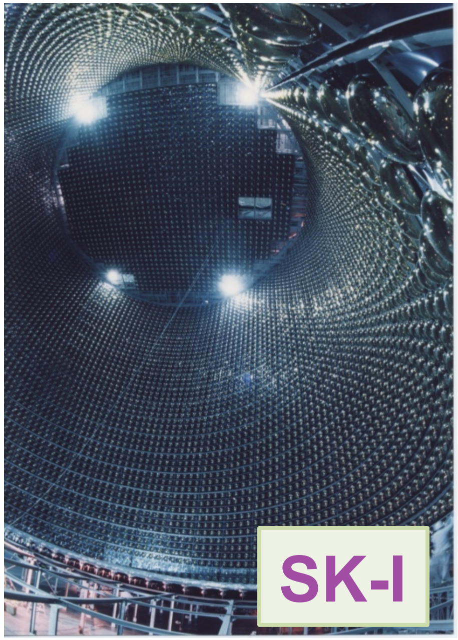


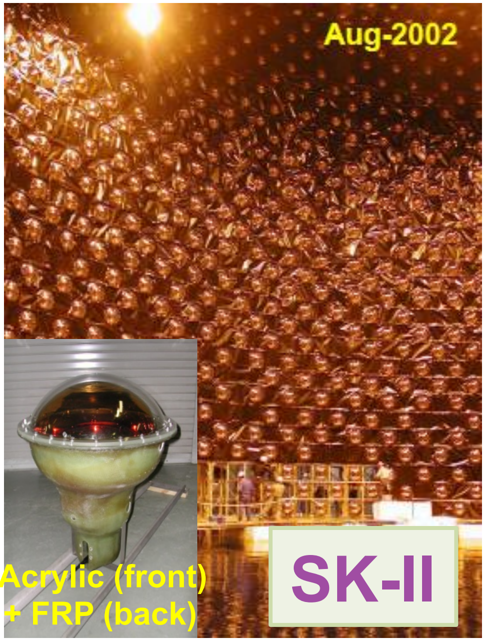
Phases of Super-Kamiokande

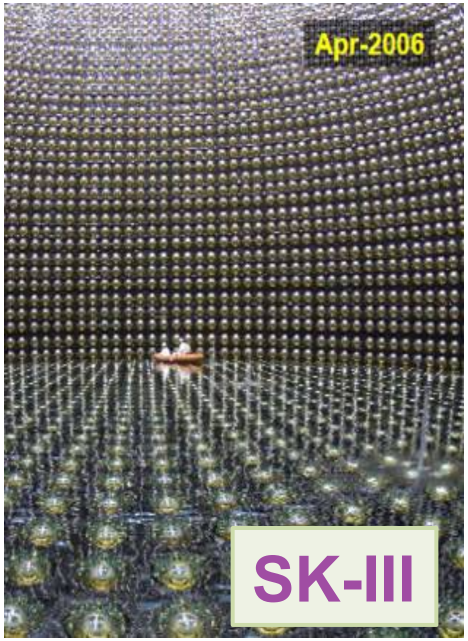
Courtesy Nakahata

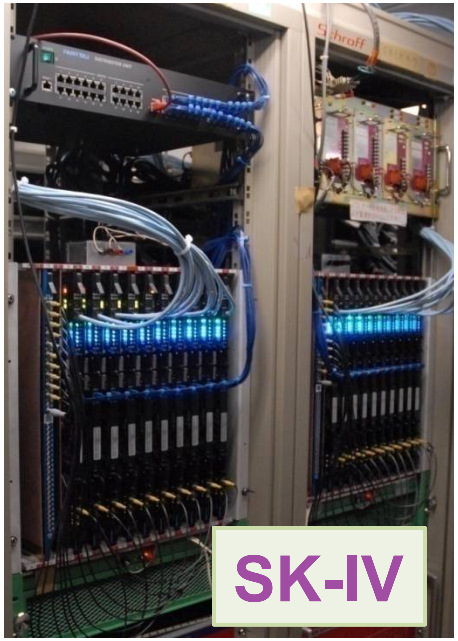
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12

SK-I | SK-II | SK-III | SK-IV





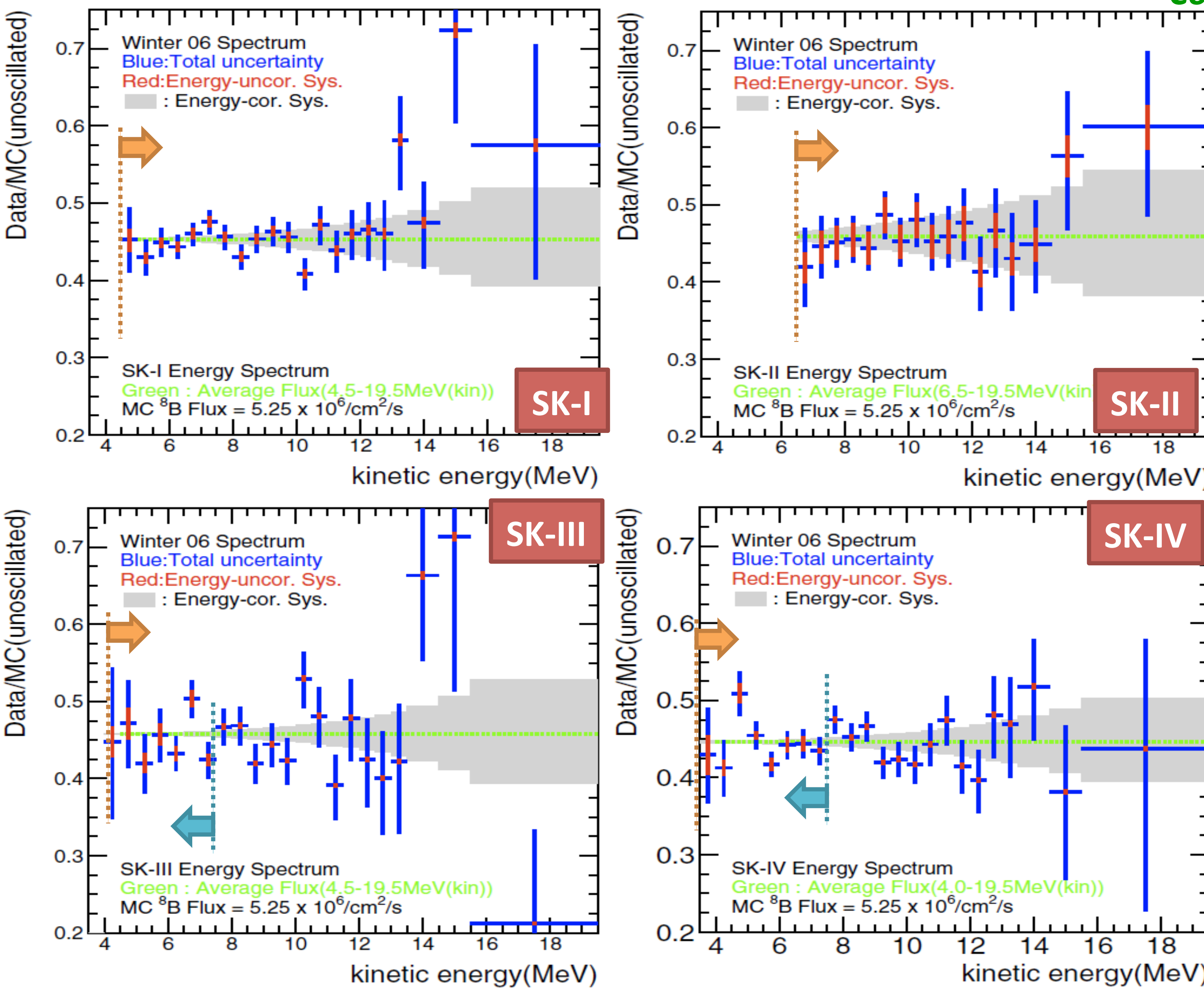




	SK-I	SK-II	SK-III	SK-IV (Current)	SK-IV (Target)
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
Energy Threshold (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV

SK ^{8}B energy spectrum: reducing analysis threshold

Courtesy Nakahata



vertical scale:
$\phi_{8B} = 5.25 \times 10^6$ [/cm^2/s]

^{8}B energy spectrum (SK combined)

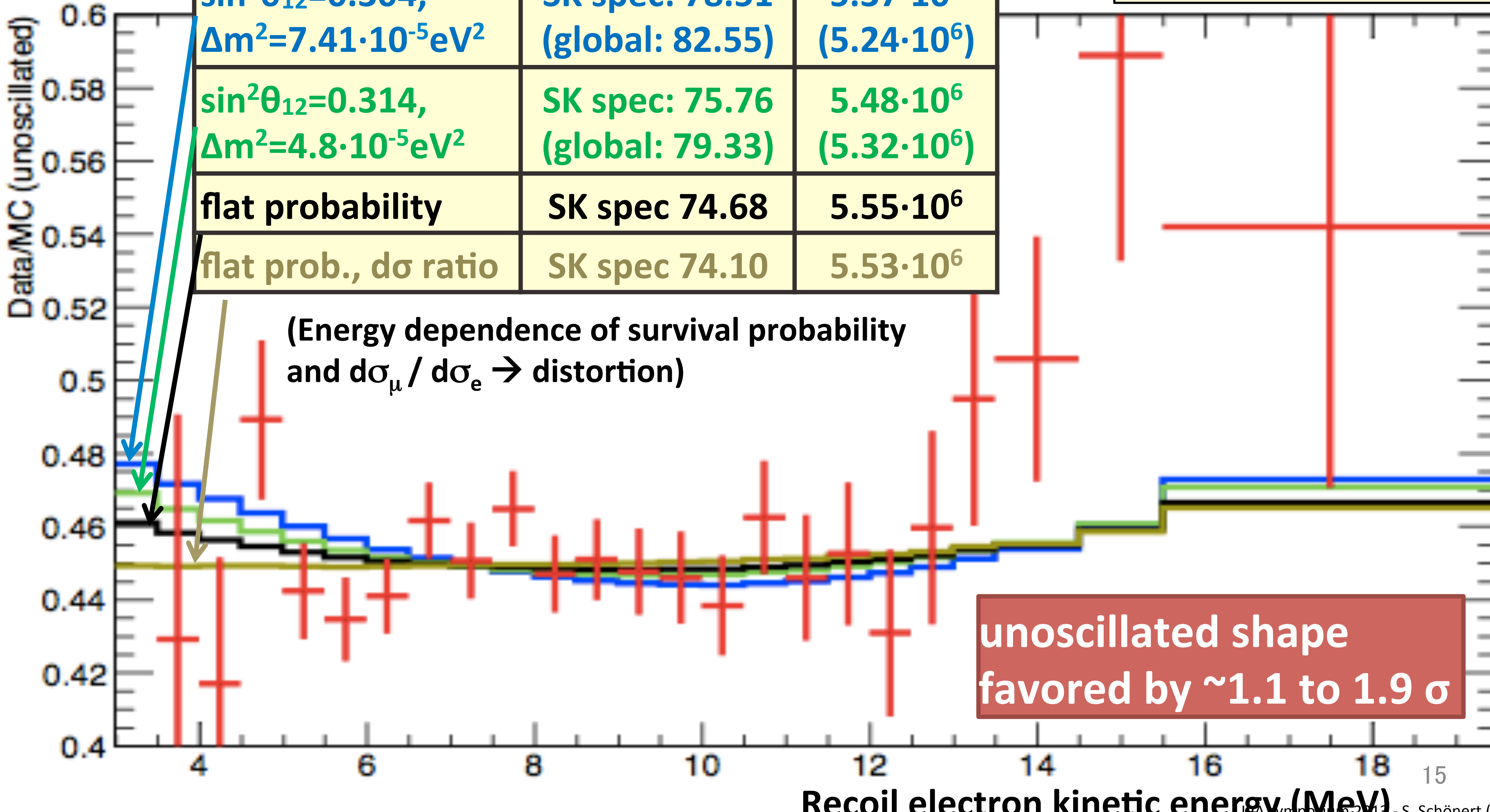
Courtesy Nakahata

- $\sin^2\theta_{13}$ is fixed at 0.025
- *hep* flux is constrained to 7.88 (1+/-0.16) [×10^3 /cm^2/s]

	χ^2	$\phi_{^8B}$ [/cm^2/s]
$\sin^2\theta_{12}$=0.304, Δm^2=7.41·10^{-5}eV^2	SK spec: 78.51 (global: 82.55)	5.37·10^6 (5.24·10^6)
$\sin^2\theta_{12}$=0.314, Δm^2=4.8·10^{-5}eV^2	SK spec: 75.76 (global: 79.33)	5.48·10^6 (5.32·10^6)
flat probability	SK spec 74.68	5.55·10^6
flat prob., dσ ratio	SK spec 74.10	5.53·10^6

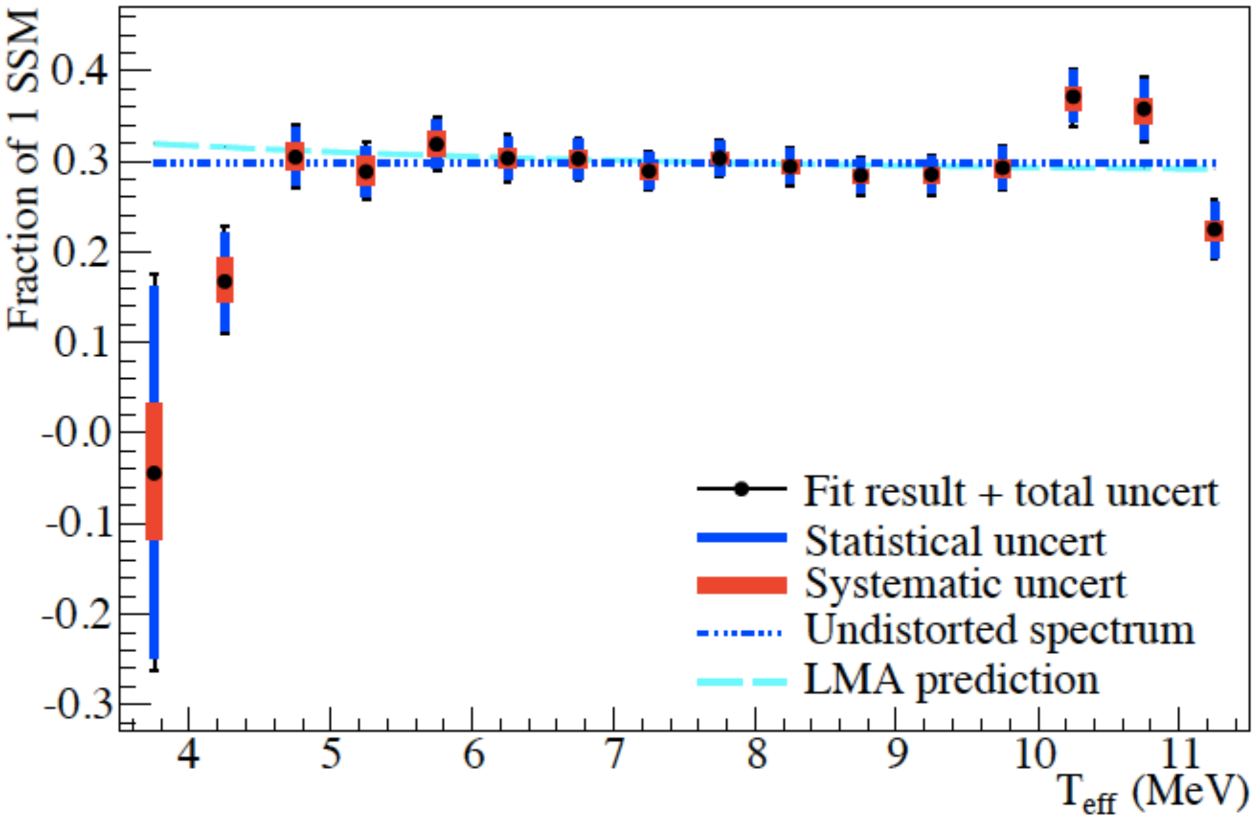
For vertical scale:
ϕ_{8B}=5.25×10^6
ϕ_{hep}=7.88×10^3 [/cm^2/s]

(Energy dependence of survival probability and $d\sigma_\mu / d\sigma_e$ → distortion)

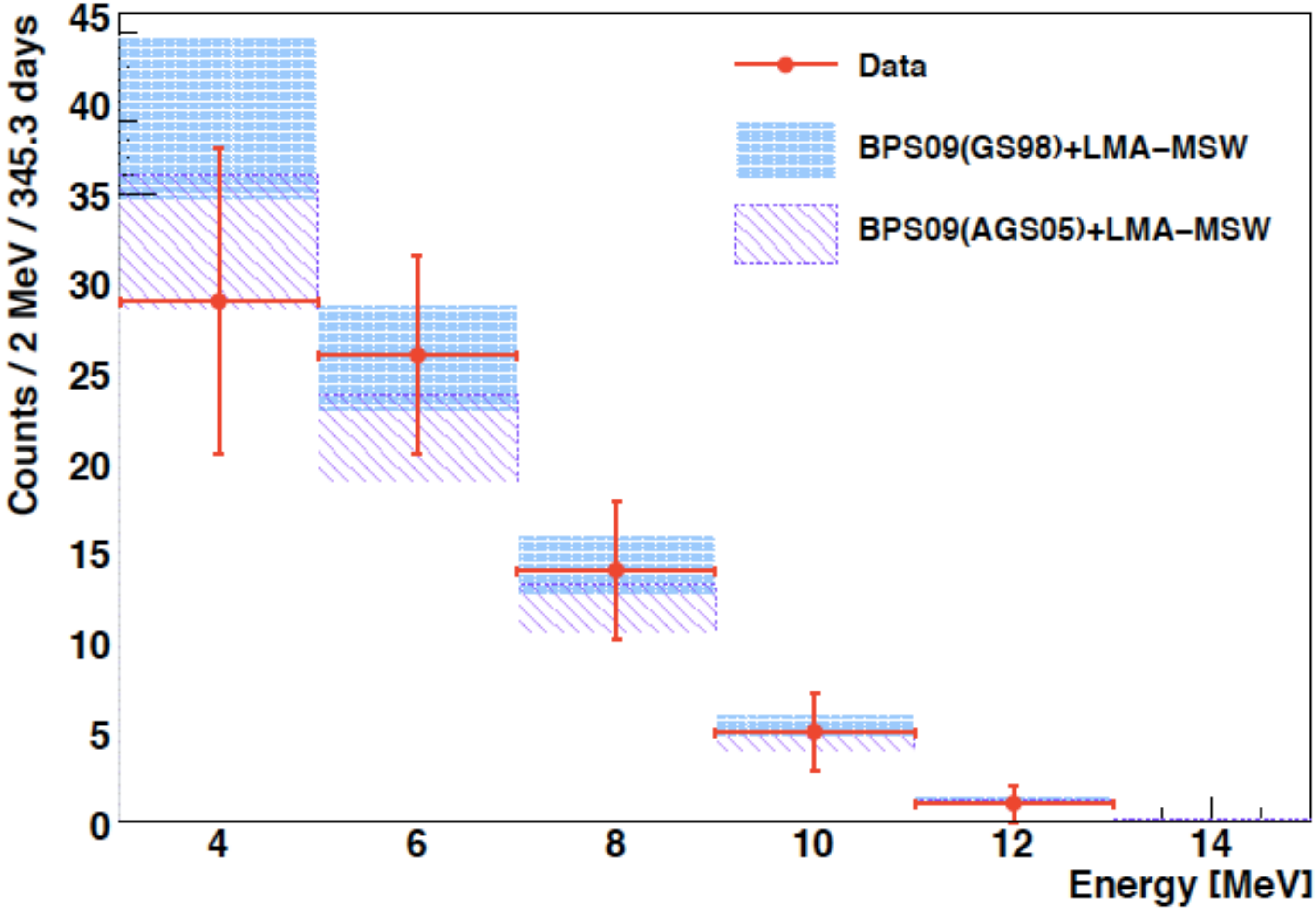


unoscillated shape favored by ~1.1 to 1.9 σ

SNO ^8B low-energy threshold analysis (3.5 MeV)

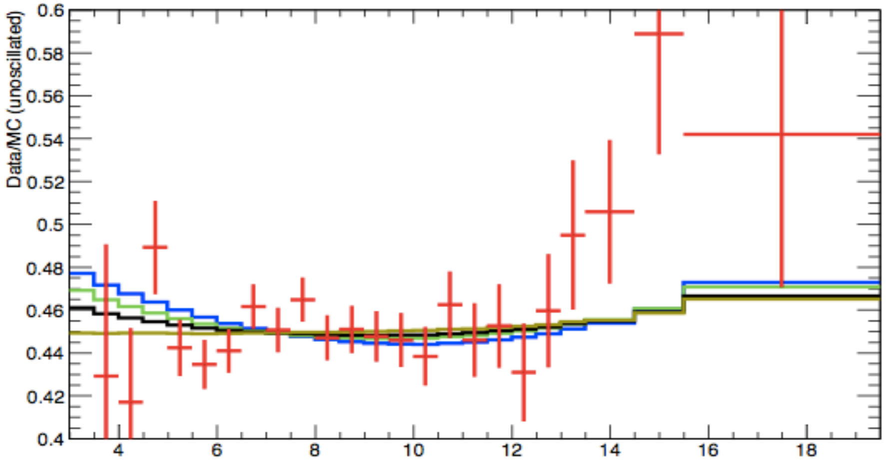


Borexino: low-threshold (3 MeV) ^{8}B analysis

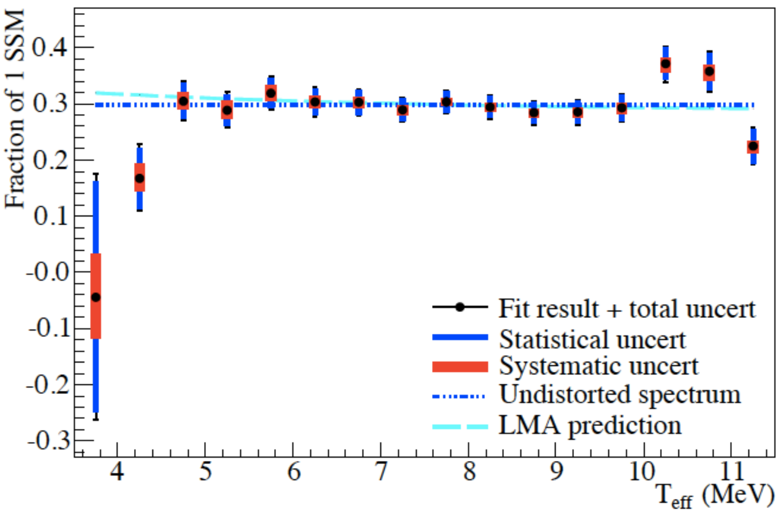


Status MSW upturn

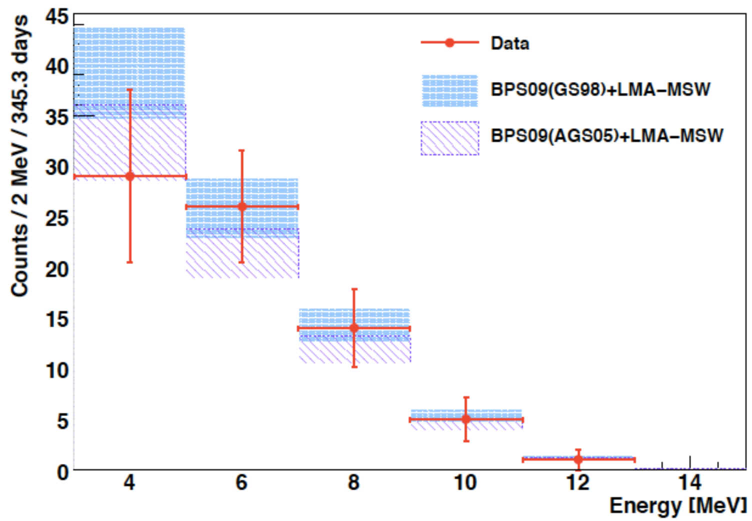
SK



SNO



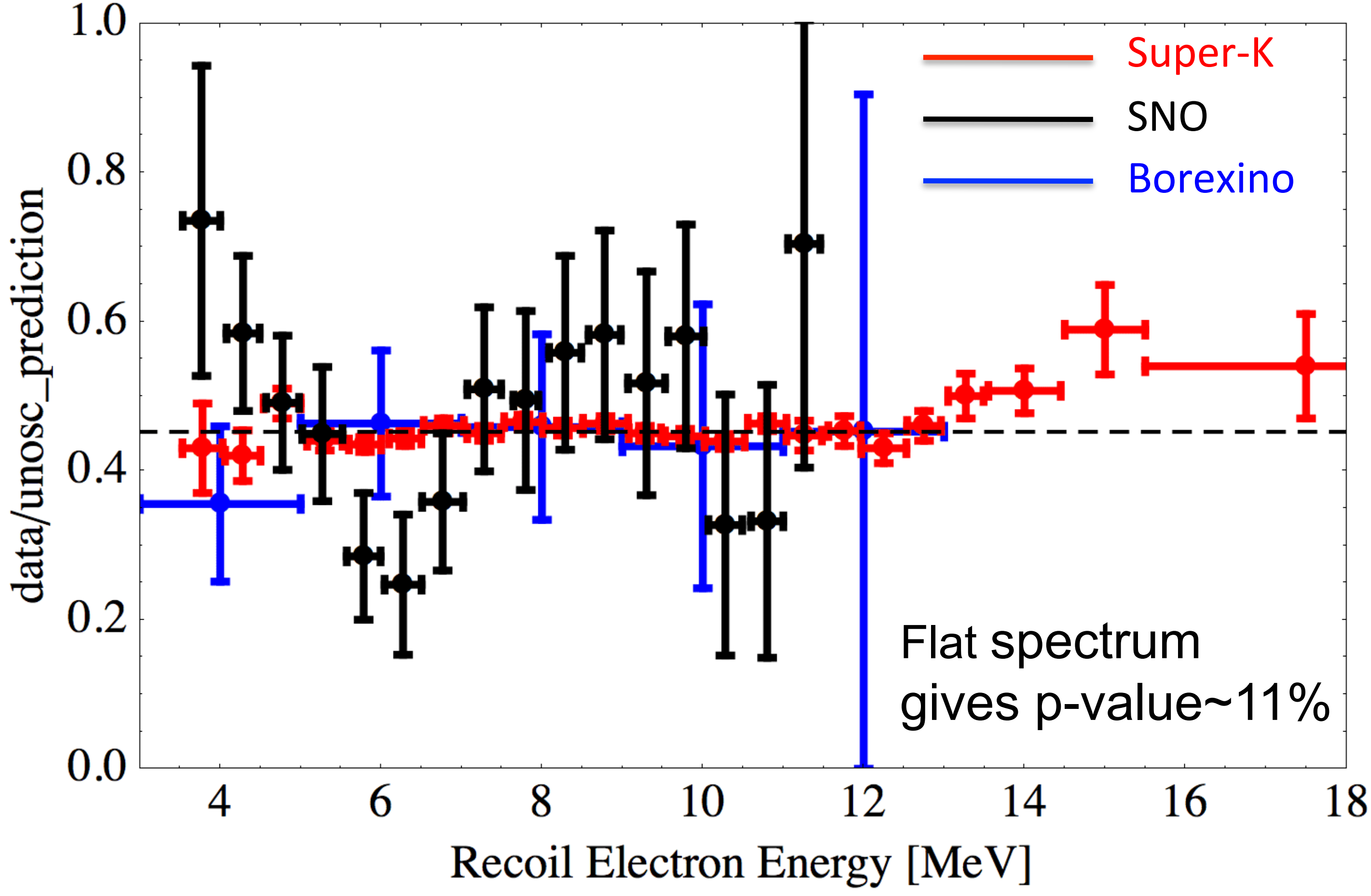
Borexino



Statistics (yet) too poor to refute null hypothesis (ie. MSW-upturn);

New Borexino data under analysis

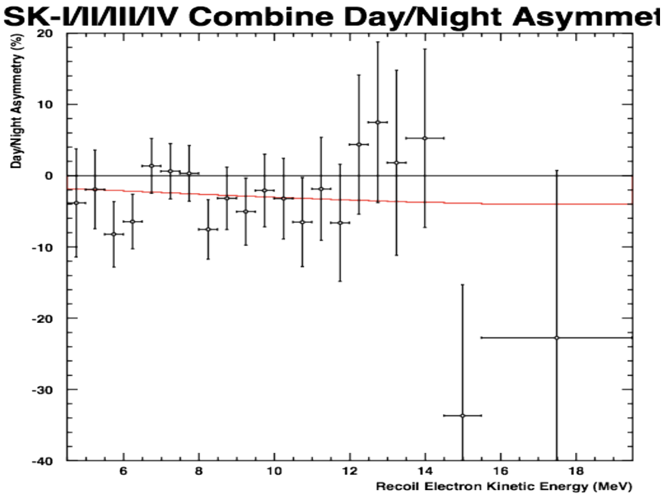
^8B Solar Neutrino Spectrum



neutrino-electron scattering

Matter driven day/night asymmetries:

SK:



$$A_{DN} = \frac{\text{Day flux} - \text{Night flux}}{0.5\,(\text{Day flux} + \text{Night flux})}$$

SK combined	-2.8±1.1±0.5 %

(consistent with expectation, at 2.6 sigma consistent with null hypothesis)

SNO:

$$A_{ee}(E_\nu) = 2\frac{P^{\mathrm{n}}_{ee}(E_\nu) - P^{\mathrm{d}}_{ee}(E_\nu)}{P^{\mathrm{n}}_{ee}(E_\nu) + P^{\mathrm{d}}_{ee}(E_\nu)},$$

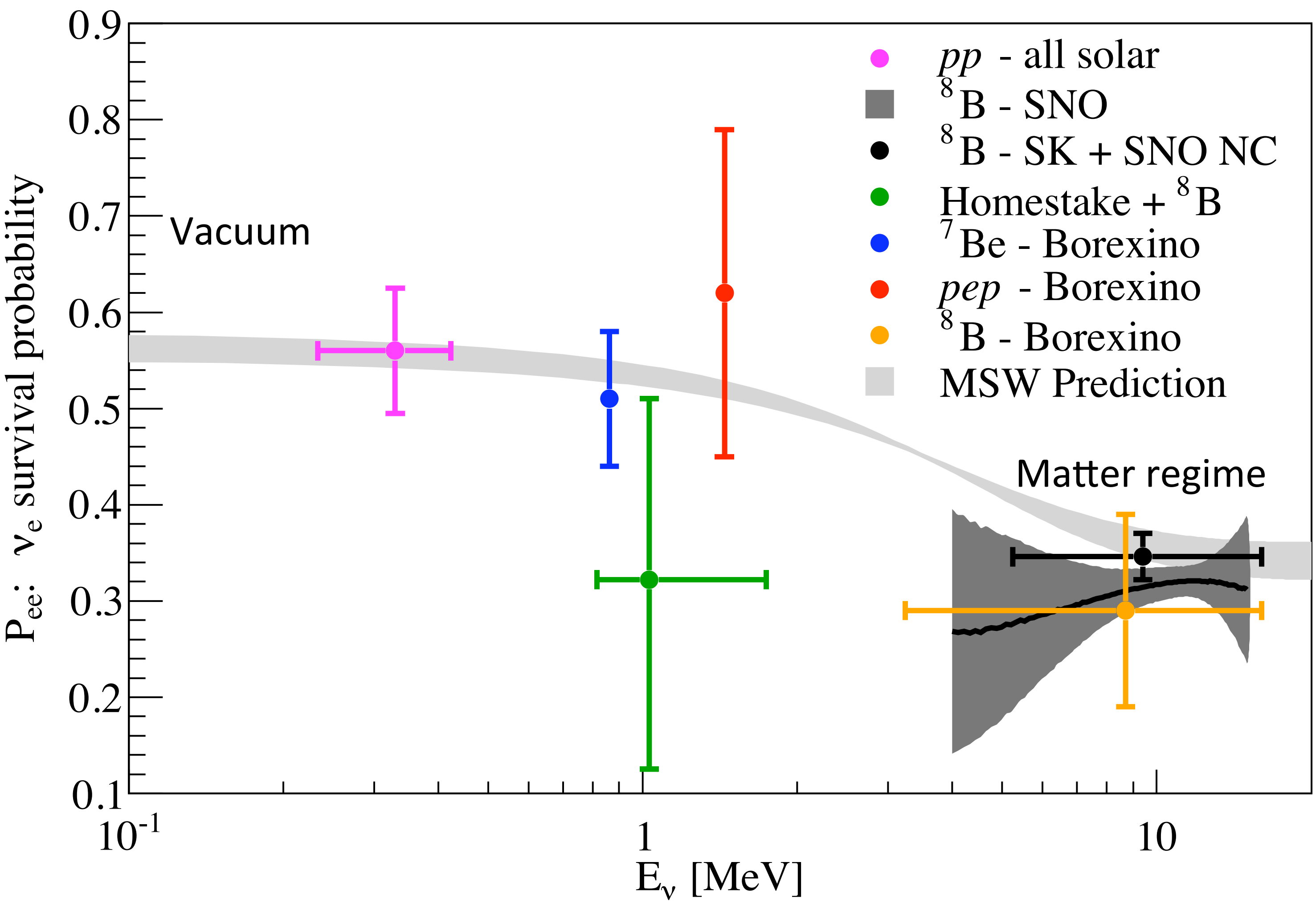
(61 % C.L. consistent with null hypothesis)

Borexino (0.86 MeV)

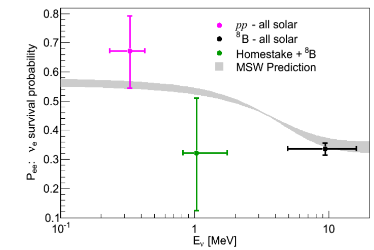
$$A_{DN} = \frac{N - D}{(N+D)/2} = 0.001 \pm 0.012\,(stat) \pm 0.007(sys)$$

(No assymetrie expected at 0.86 MeV)

Current status of survival probabilities



Before:

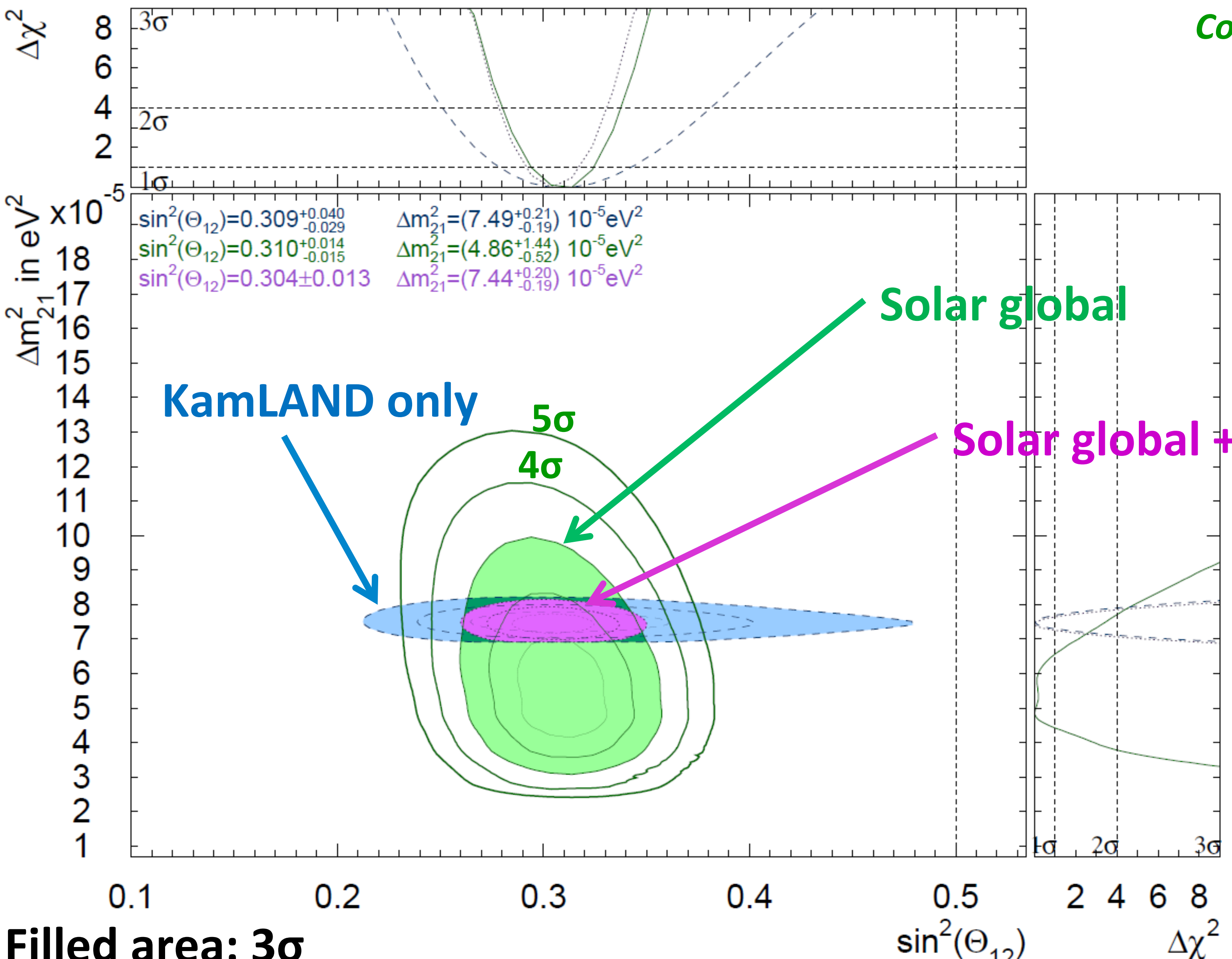


Solar global : θ_{12} - Δm_{21}^2

- **$\sin^2\theta_{13}$ is fixed at 0.025**

Filled area: 3σ

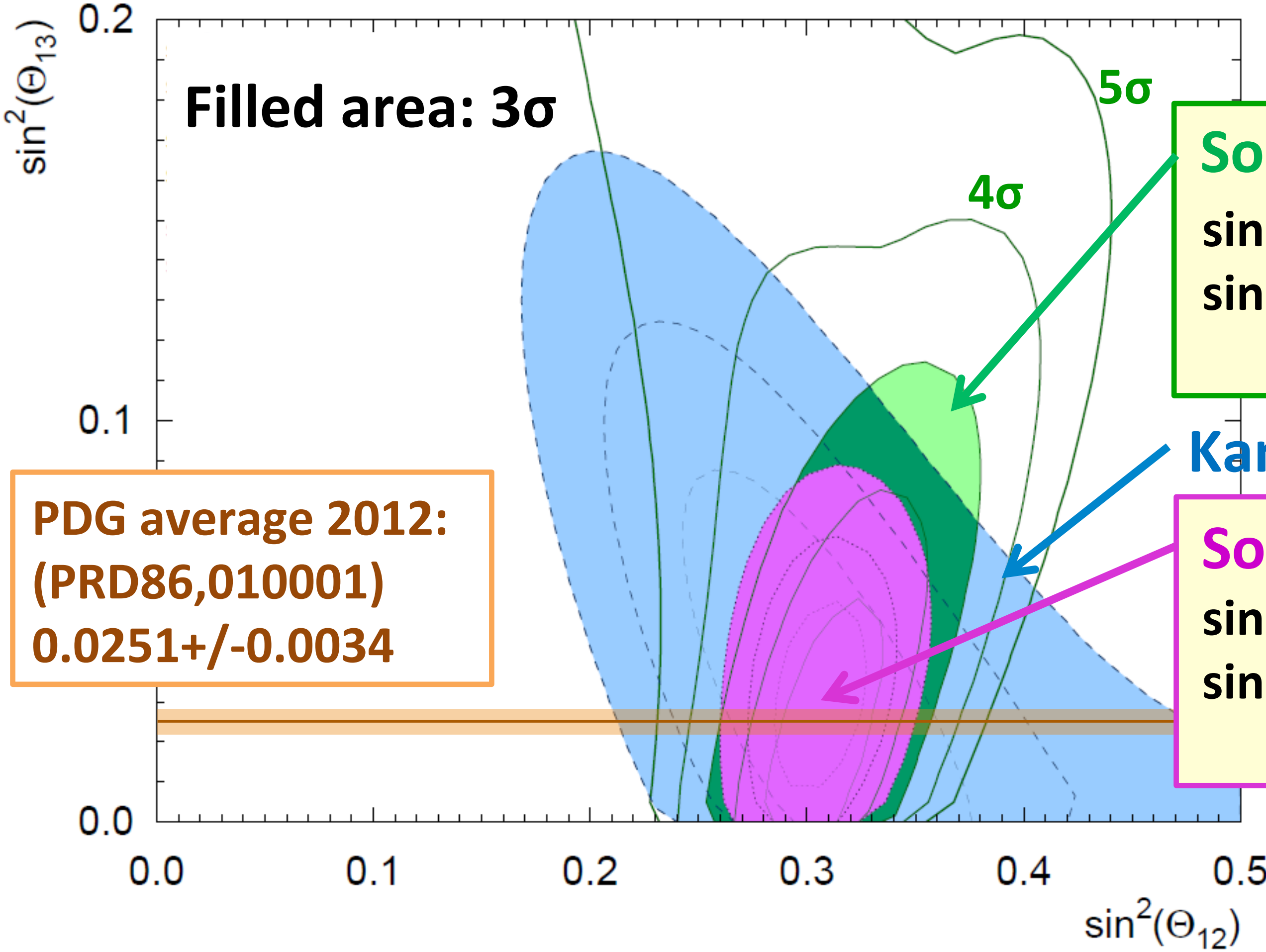
Courtesy Nakahata



Filled area: 3σ

Solar & KamLAND : θ_{12} - θ_{13}

Courtesy Nakahata



Solar global:

$\sin^2\theta_{12}$ = 0.305+0.021-0.016
$\sin^2\theta_{13}$ = 0.014+0.027-0.021
< 0.059 (95% C.L.)

KamLAND only:

Solar global + KamLAND:

$\sin^2\theta_{12}$ = 0.305+0.015-0.014
$\sin^2\theta_{13}$ = 0.030+0.017-0.015
< 0.058 (95% C.L.)

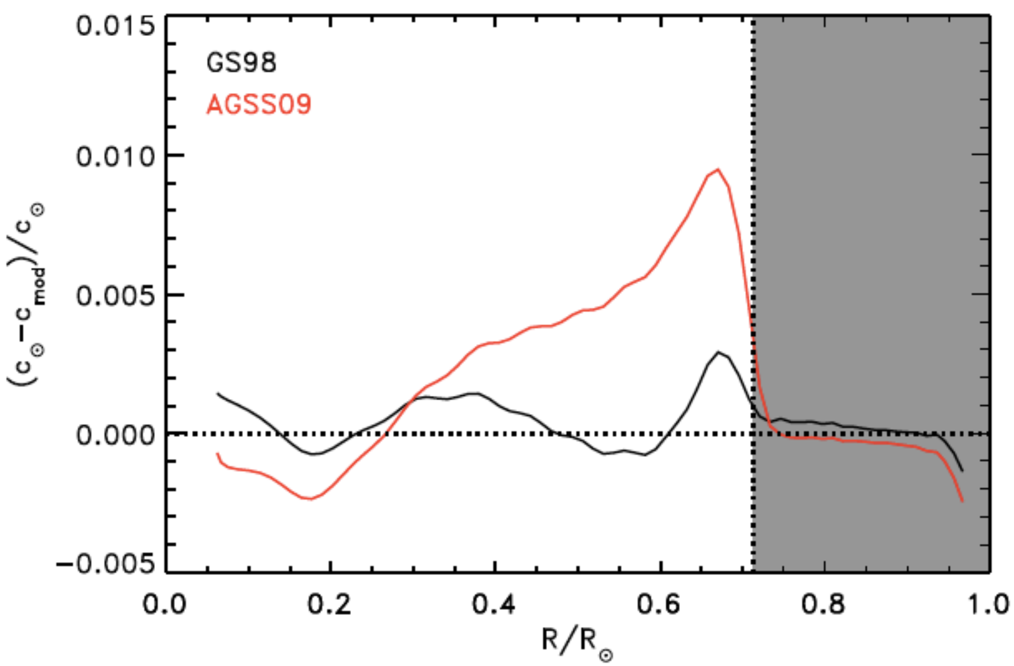
PDG average 2012:
(PRD86,010001)
0.0251+/-0.0034

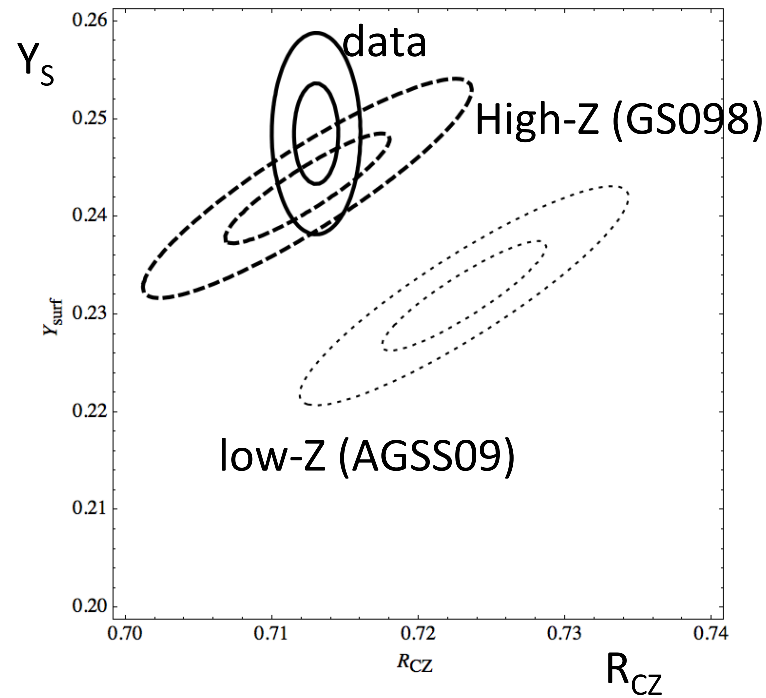
Consistent with θ_{13} Double Chooz, Daya Bay and Reno reactor experiments

The solar abundance problem

Improved determination of CNO surface abundance:

	$R_{CZ}/R_\odot$	Y_{surf}	$(Z/X)_{surf}$
SSM(GS98)	0.713	0.2423	0.0229
SSM(AGSS09)	0.724	0.2314	0.0178
Helioseismology	0.713 ± 0.001	0.2485 ± 0.0035	





Solar neutrino predictions for high/low-Z models

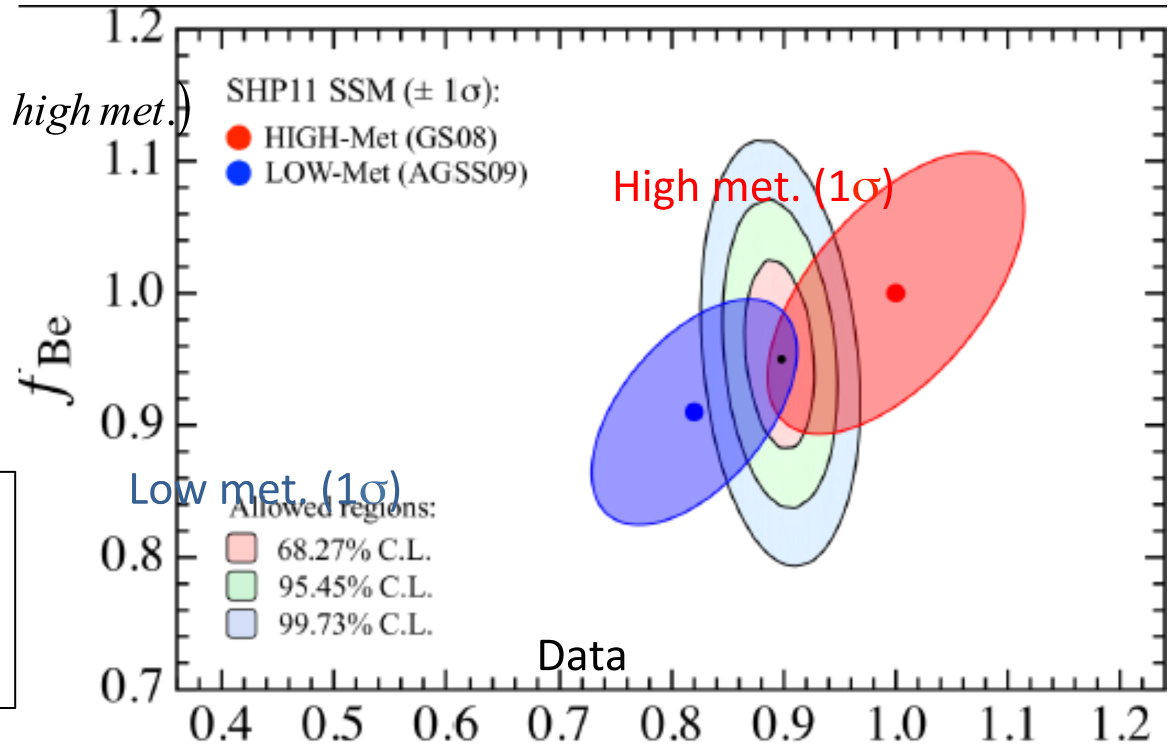
Source	Flux [$cm^{-2}s^{-1}$] SSM-GS98	Flux [$cm^{-2}s^{-1}$] SSM-AGSS09	Flux [$cm^{-2}s^{-1}$] SSM-GS98-2004
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$5.94(1\pm0.01)\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.40(1\pm0.02)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.86(1\pm0.12)\times10^{9}$
^{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}

CNO neutrinos key to solve solar abundance problem

^{7}Be vs ^{8}B ratios: high and low metallicity solar models

$$ {}^{7}Be\ flux \Big/ {}^{7}Be\,(SSM\ \ high\, met.) $$

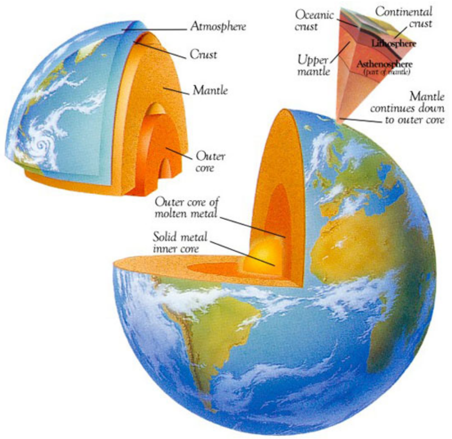


$$ {}^{8}B\ flux \Big/ {}^{8}B\,(SSM\ \ high\, met.) $$

- ~9% difference for ^{7}Be flux
- ~20% difference for ^{8}B
- Fit to the available solar neutrino data including BX and leaving free $f_{Be} = \Phi_{Be}/\Phi_{Be}(SSM)$ and $f_B=\Phi_B/\Phi_B(SSM)$

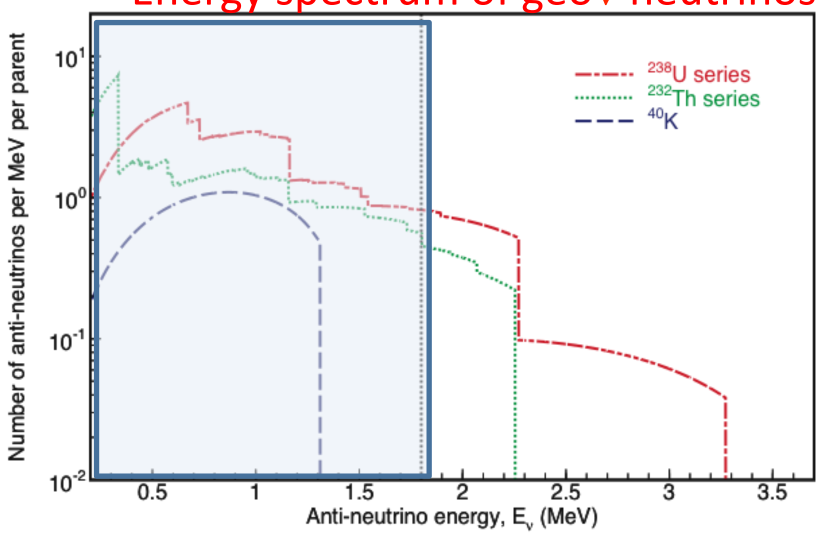
Need clean measurement of CNO neutrinos to discriminate

Geo-ν: new Borexino results



Previous Borexino result: G. Bellini et al., (Borexino Coll.) Phys. Lett. B 687 (2010) 299
Kamland: T. Araki et al., (Kamland Coll.) Nature 436 (2005) 499;
A. Gando et al. (Kamland Coll.) Nature Geoscience 4 (2011) 574
new Bx result: http://arxiv.org/abs/1303.2571

Energy spectrum of geoν neutrinos



$$\overline{\nu_e} + p \rightarrow n + e^+$$

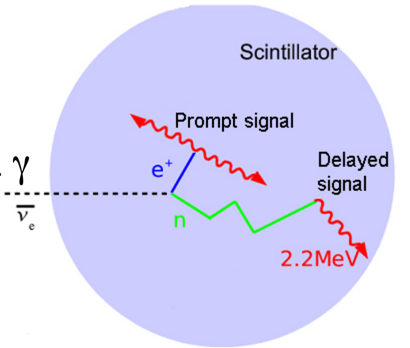
E_ν>1.8 MeV

- "prompt signal"

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

- "delayed signal"

n capture after thermalization 2.2 γ



Previous data Dec 2007-Dec2009 252.6 ton year
New data (2.4 X) Dec 2007-Aug2012 613.0 ton year
(3.69 ± 0.16) 10^{31} proton year

Geo-ν results: evidence of the signal

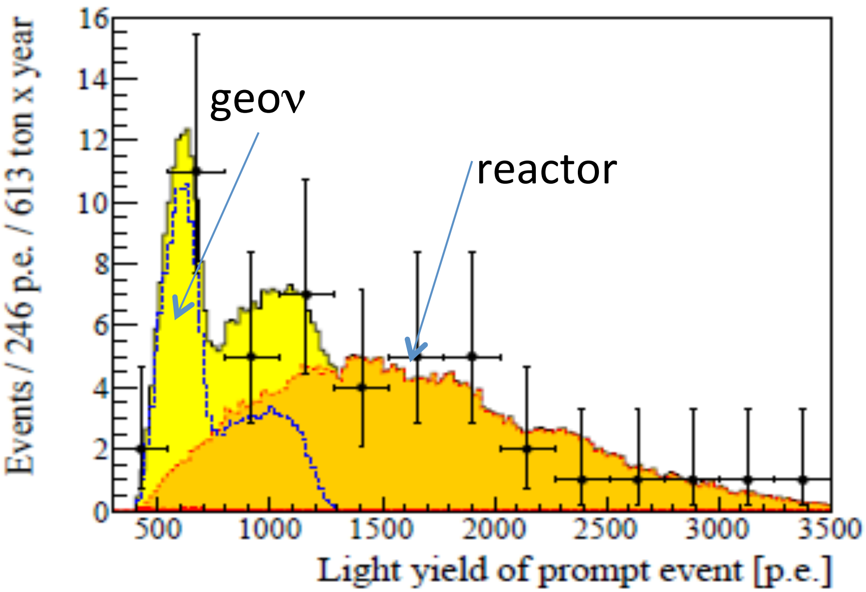
46 candidate events in 613±26 ton year

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

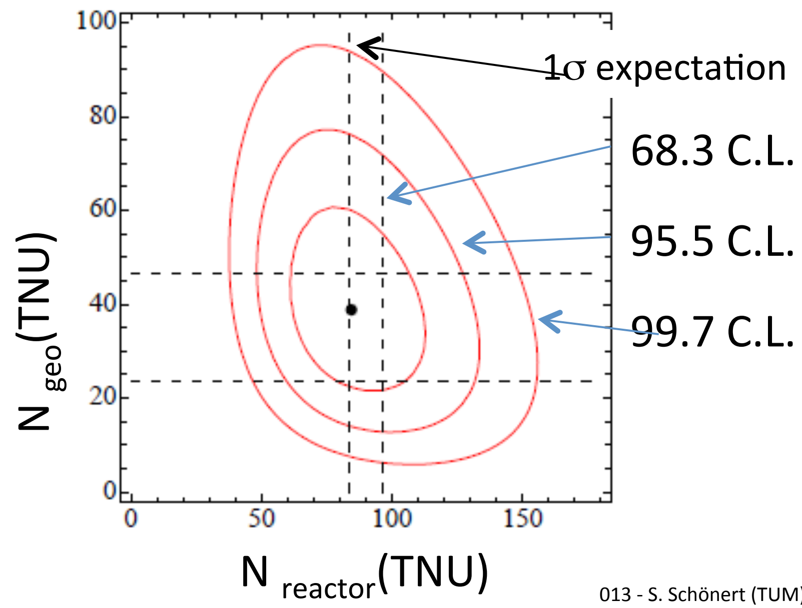
$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	Events	events	events	events	TNU	TNU
33.3±2.4	60.4±2.4	0.70±0.18	14.3±4.4 $9.9^{+4.1}_{-3.4}$	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$

Our previous result

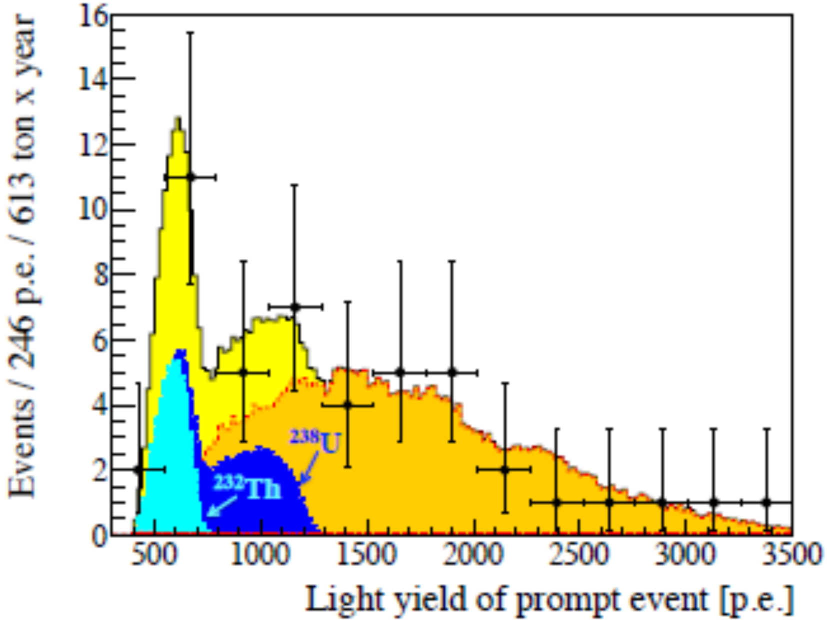
Unbinned likelihood fit



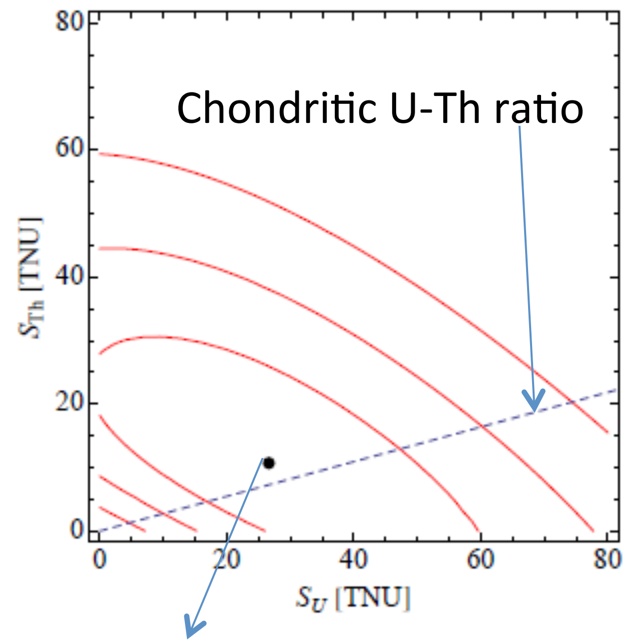
No geoν signal: rejected with prob. $6\ 10^{-6}$



Geo-ν results: U and Th separation



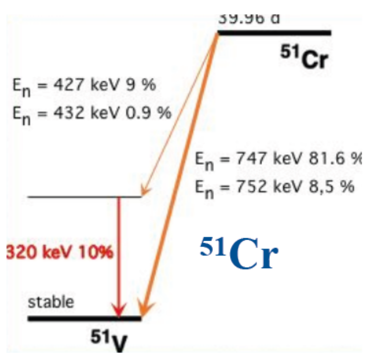
Fit with weight of ^{238}U and ^{232}Th spectra free

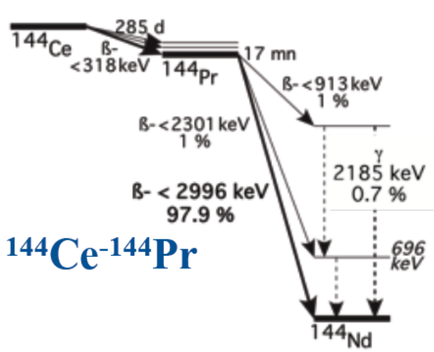


Best fit
S(^{238} U)= 26.5 ± 19.5 TNU
S(^{232} T) = 10.6 ± 12.7 TNU

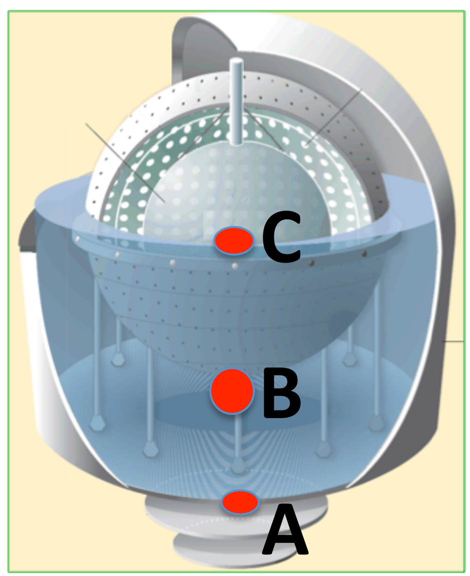
(anti-)ν_e's from artificial sources

Source	Production	τ (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



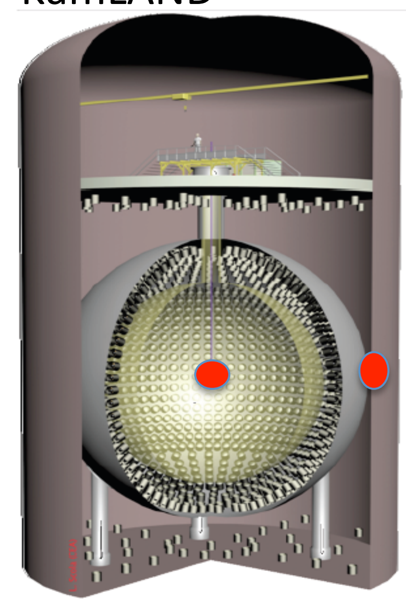


Borexino



A: ^{51}Cr (neutrino)
B/C ^{144}Ce – ^{144}Pr (anti-neutrino)

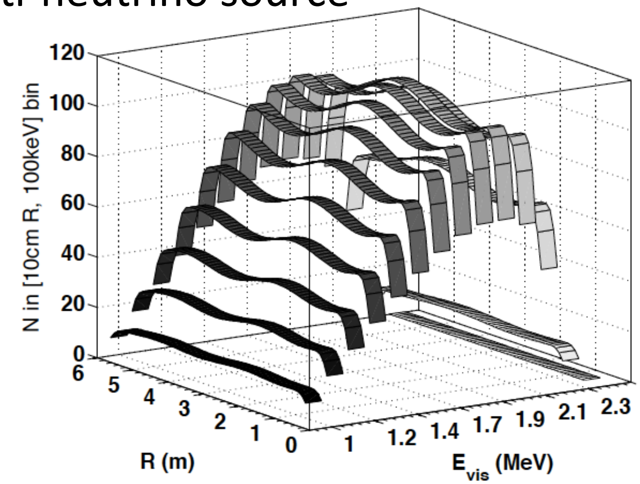
KamLAND



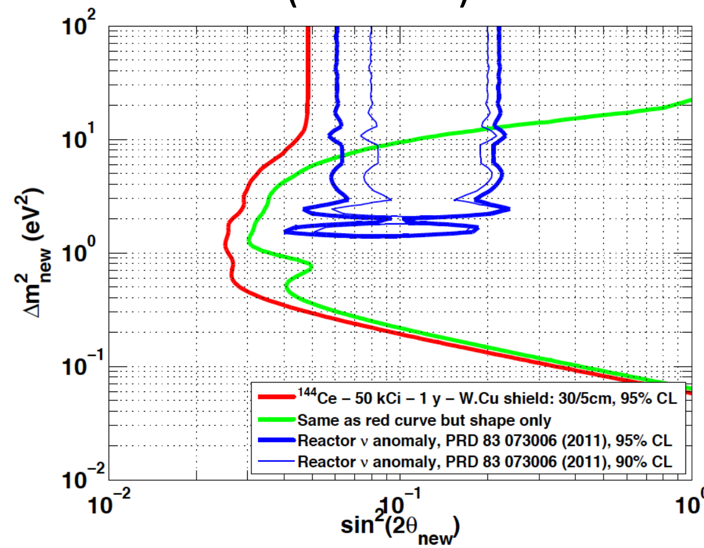
^{144}Ce – ^{144}Pr (anti-neutrino)

Kamland / Borexino: sensitivities

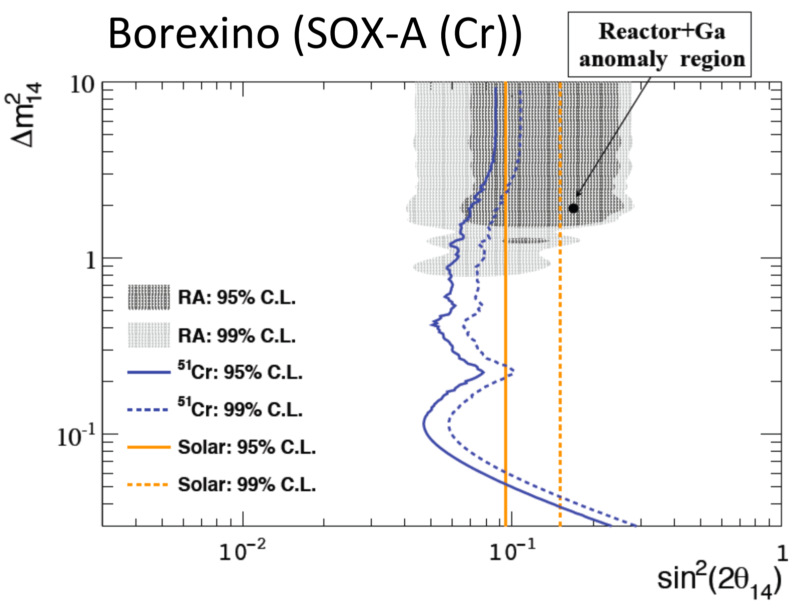
Space – energy oscillations with anti-neutrino source



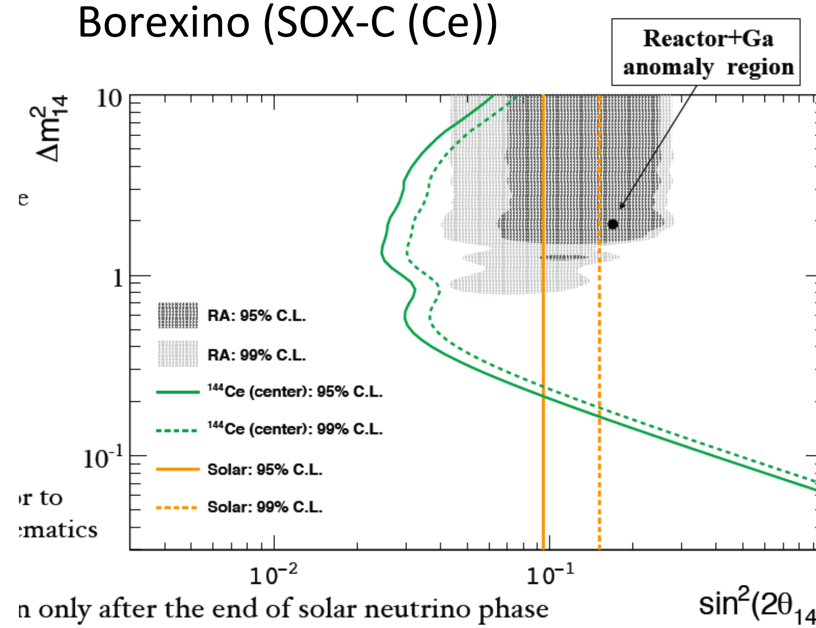
KamLAND (CeLAND)



Borexino (SOX-A (Cr))



Borexino (SOX-C (Ce))



Summary & short outlook

- Solar neutrino precision measurements:
  - Determination of oscillation parameters
  - Matter interactions (MSW): 'turnup'
  - Search for non-standard nu-properties
  - Solar physics: future CNO spectroscopy key to abundance problem (SNO+ / Borexino)
- Beyond solar and LB-reactor oscillations:
  - Geo-neutrino's
  - Future very-short-baseline oscillation measurements with sources funded: search for sterile neutrinos (also measurement of g_A and g_V)
- New large liquid scintillator projects under discussion: LENA, Daya-Bay II