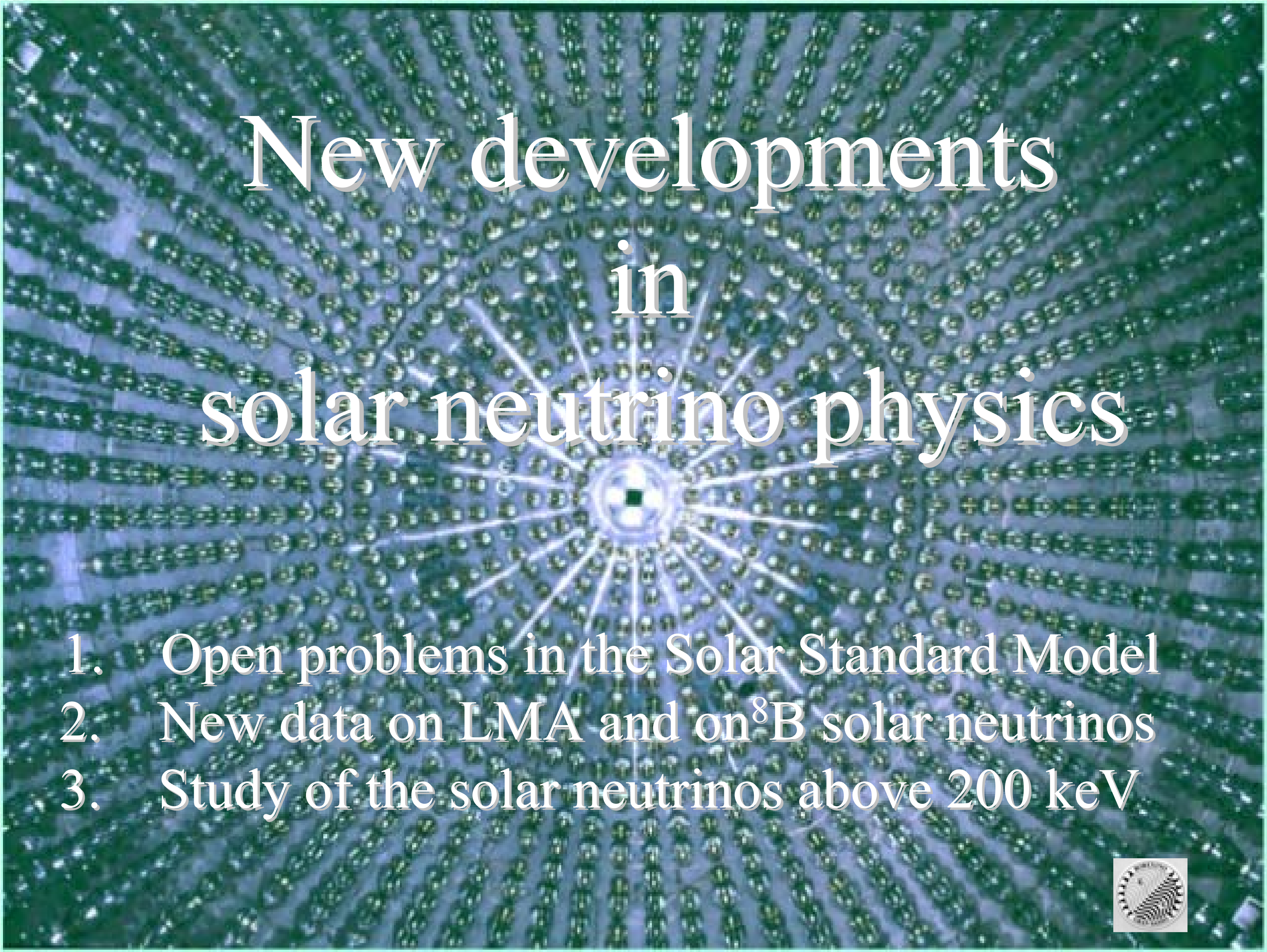
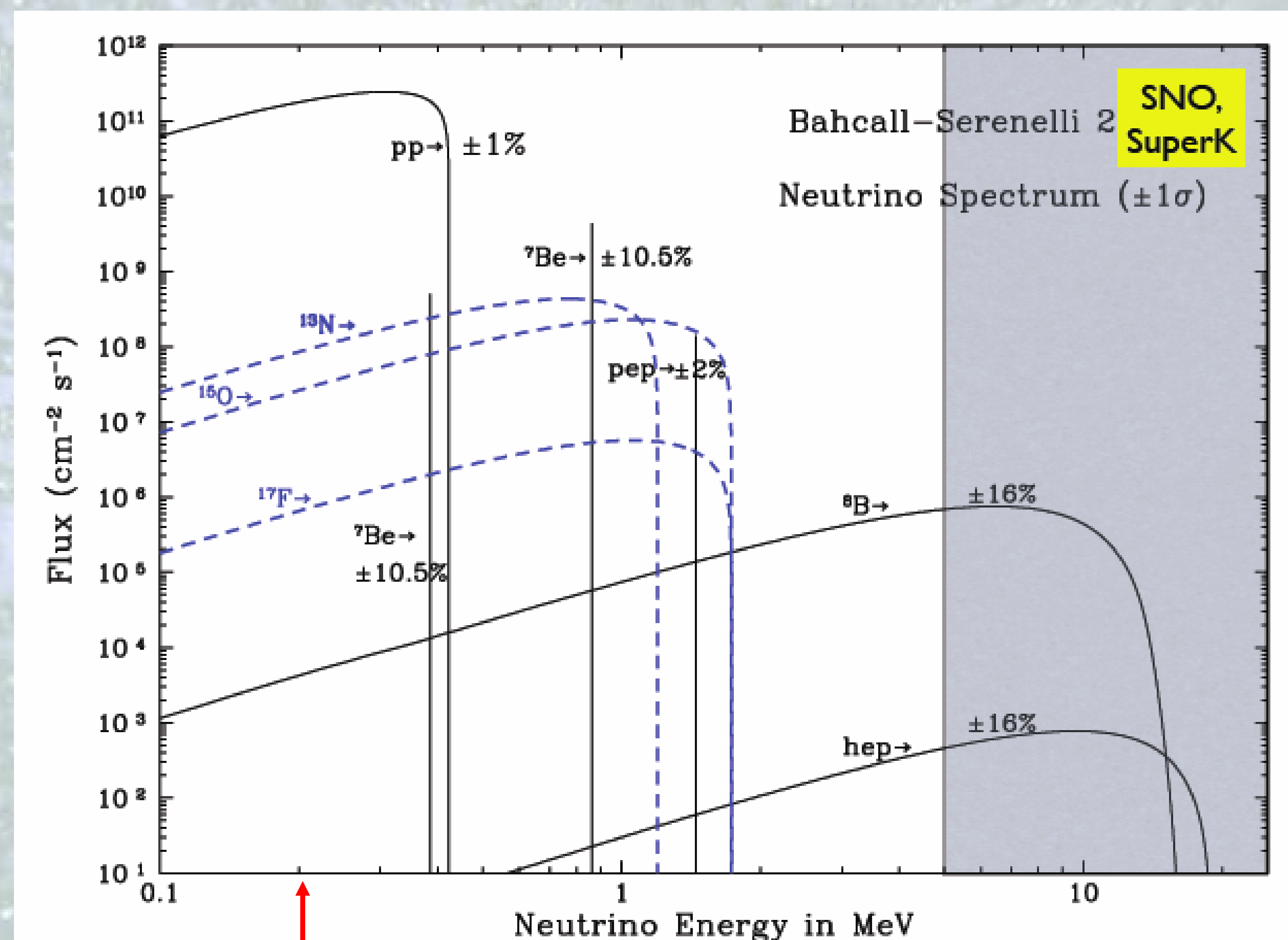


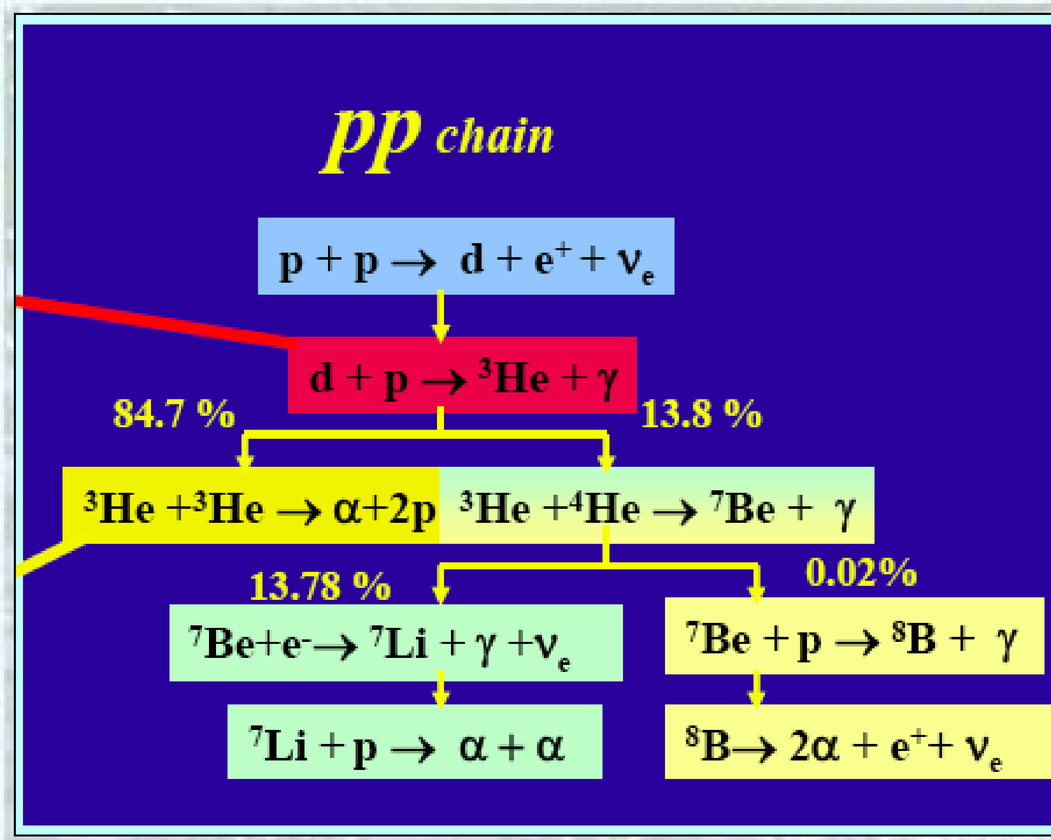
New developments in solar neutrino physics

1. Open problems in the Solar Standard Model
2. New data on LMA and on ^8B solar neutrinos
3. Study of the solar neutrinos above 200 keV

SNO and Superkamiokande studied the solar ν above 4.5 (5)MeV (about 1/10000)



LUNA



S_{34}

errors on ^{8}B and ^{7}Be fluxes are reduced

$^{14}N(p,\gamma)^{15}O$

Slowest process in CNO chain ($S_{1,14}$)

CNO flux reduced of ≈ 50%

Solar surface abundances are determined from analyses of photospheric atomic and molecular spectral lines.

The associated solar atmosphere modeling has been done in one dimension in a time-independent hydrostatic analysis that incorporates convection (GS98)

A much improved 3D model of the solar atmosphere has been developed, which better reproduces line profiles and brings the Solar abundances into better agreement with other stars in the neighborhood (AGS05)

Due to this improved analysis the solar surface contains 30-40% less carbon, nitrogen, oxygen, neon and argon than previously believed. .

SSM using GS98 (BS05) in excellent agreement with helioseismology

The revised abundance (AGS05) gives wrong predictions for the speed of sound and density at various locations inside the Sun - discrepancies below the convective zone: associated properties of the SSM in conflict with helioseismology

Is the SSM assumption of a homogeneous zero age Sun correct?-The convective zone could be depleted in metals relative to the radiative core.
Solar metal differentiation connected to the formation of the gaseous giant planets(H.S.08)

Neutrino experiments may help to resolve the problem

PS08

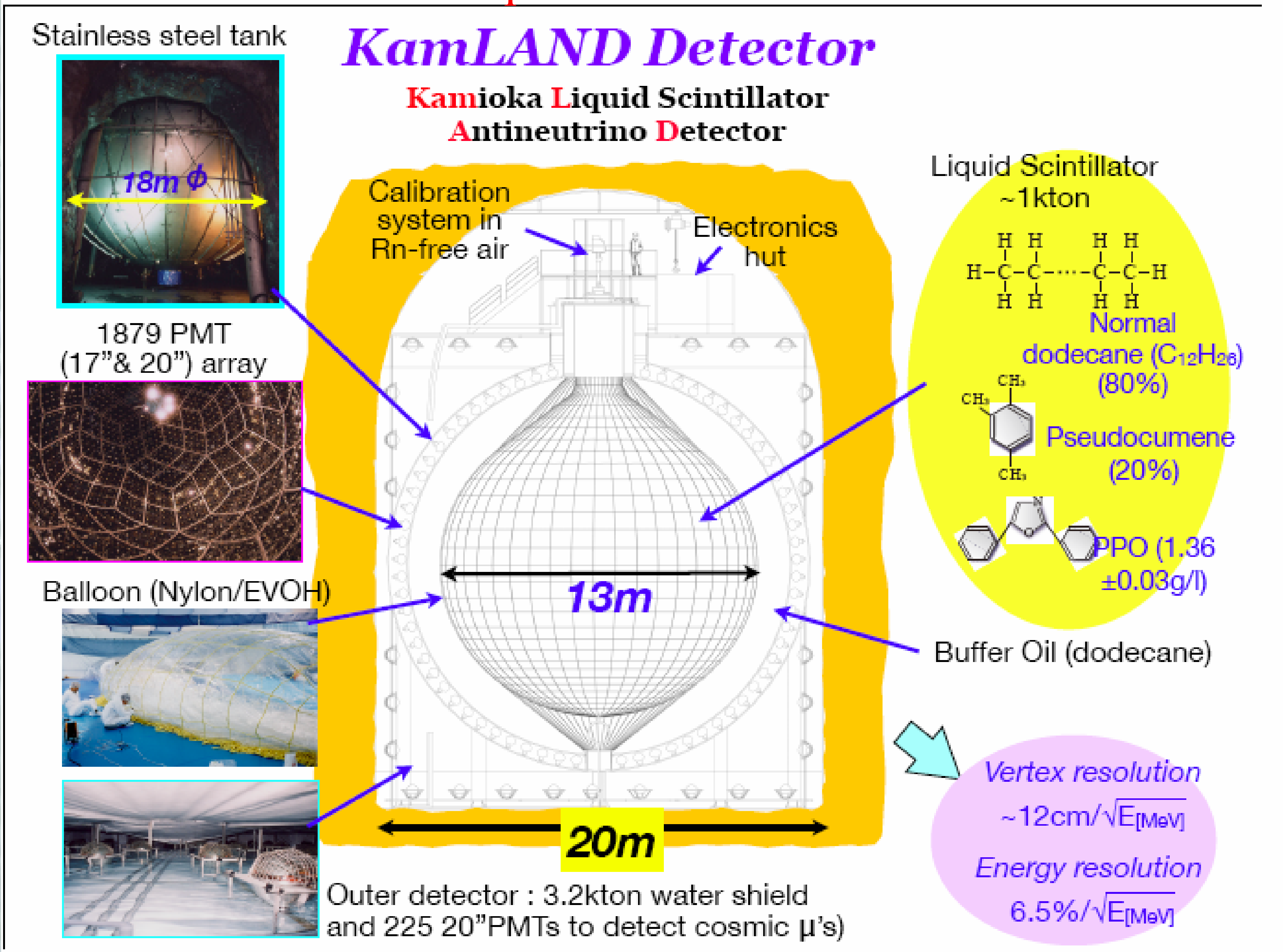
	GS98	AGS05	Δ_{TH}	Exp. results
^{8}B	5.95 $10^6/cm^2s$	4.72 $10^6/cm^2s$	±0.54-0.85	$5.54^{+0.33+0.36}_{-0.31-0.34}$ $10^6 cm^{-2}s^{-1}$
^{7}Be	5.08 $10^9/cm^2s$	4.55 $10^9/cm^2s$	±0.24	5.12 ± 0.51 $10^9 cm^{-2}s^{-1}$
N	2.93 $10^8/cm^2s$	1.93 $10^8/cm^2s$	+0.91 -0.82	
O	2.20 $10^8/cm^2s$	1.37 $10^8/cm^2s$	+0.73 -0.63	
F	5.82 $10^6/cm^2s$	3.24 $10^6/cm^2s$	±3.04	

Improve the parameter errors of the Solar Model with the Solar neutrino measurements: use measured neutrino fluxes + the oscillation model to determine the Opacity, Diffusion, S-factors (when not measured with high precision in Lab.), in addition to Z/X.

Good extrapolation from Luna. S_{34}, from 93 keV of the beam energy to 20 keV; $S_{1.14}$, from 80 keV to $\leq$ 35 keV.
Brown at al. measure S_{34}(2007) at 330 keV lowest energy.
S_{34} accepted range: 0.53-0.61 keV b

Compare the photon Luminosity to the ν Luminosity (which corresponds to ≈2% of the total energy)-measurements of pp (or pep), ^{7}Be fluxes are needed
[neutrinos take ≈ 8’ to reach the Earth; the photons, ≈ 4 10^4 years]

New results con LMA parameters from Kamland



(Shirai at NOVE08)

@ Reactor antineutrinos at a <d>≈180 km

@ data: from 515.1±0.3 ⟶ 1490.8±0.5 days
F.V.:from R=5.5m ⟶ 6. m

@ $\overline{\nu} + p \rightarrow e^{+} + n$ $E_{\overline{\nu}} \geq 1.8\,MeV$

2γ(>1.02MeV)

$E_{prompt} = T_{e+} + 2m_e = E_{\overline{\nu}} - 0.8\,MeV$

≈200μs

+p ⟶ d+γ(2.2 MeV)
+^{12}C ⟶ C+ γ(4.9 MeV)

@E_{prompt} from 2.6-8.5 MeV ⟶ 0.9-8.5 MeV
$E_{delayed}$: 1.8-2.6 MeV (n capt. For p); 4.0-5.8 MeV(n capt. For ^{12}C)

@Off-axis calibration Vtx resolution ≈ $12cm/\sqrt{E(MeV)}$
En. resolution≈ $6.5\%/\sqrt{E(MeV)}$

Estimated backgrounds

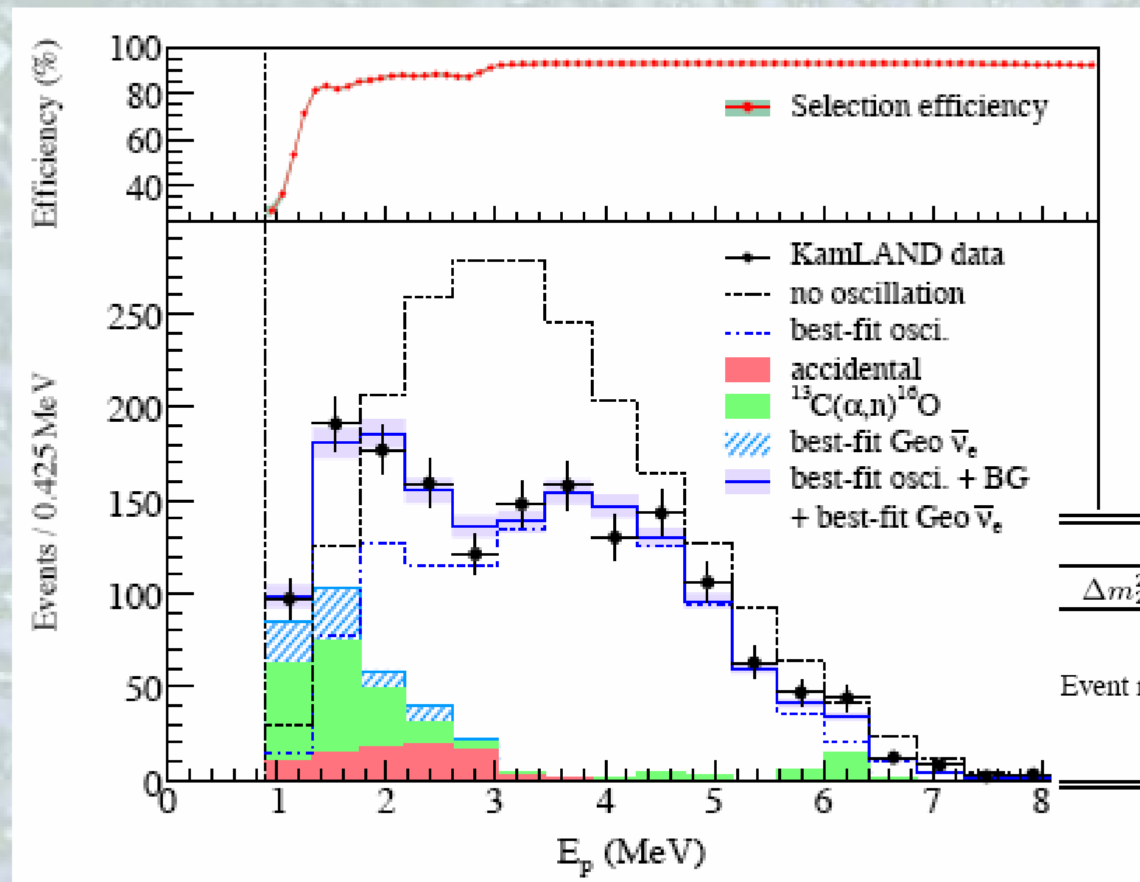
Background	Contribution
Accidentals	80.5 ± 0.1
$^{9}Li/^{8}He$	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
$^{13}C(\alpha,n)^{16}O$ G.S.	157.2 ± 17.3
$^{13}C(\alpha,n)^{16}O\ ^{12}C(n,n\gamma)^{12}C$ (4.4 MeV γ)	6.1 ± 0.7
$^{13}C(\alpha,n)^{16}O$ 1st exc. state (6.05 MeV $e^{+}e^{-}$)	15.2 ± 3.5
$^{13}C(\alpha,n)^{16}O$ 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total	276.1 ± 23.5

- Accidental background-increasing with the F.V
- Major background ^{210}Po α decays ($\approx 5.5\ 10^{9}$). $\alpha + {}^{13}C \rightarrow {}^{16}O^{*} + n$

$^{16}O^{*} \rightarrow$ (6.05 MeV $e^{+}e^{-}$)(6.13 MeV γ)

np scattering, termal.and capture

- $^{9}Li/^{8}He$ and spallation n cosmogenic ; rejected freezing the whole detector or part of it during a proper time (2 ms-2 s)



expected: 2179±89

observed: 1609

background: 276.1±23.5

systematic

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\overline{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

OLD

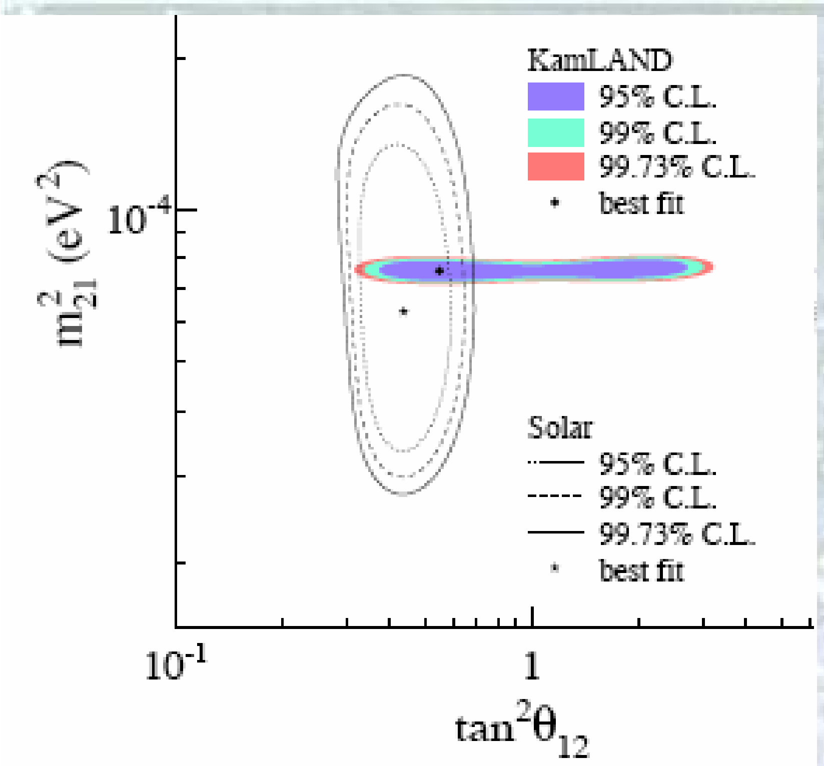
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \cdot 10^{-5}\, eV^2$$

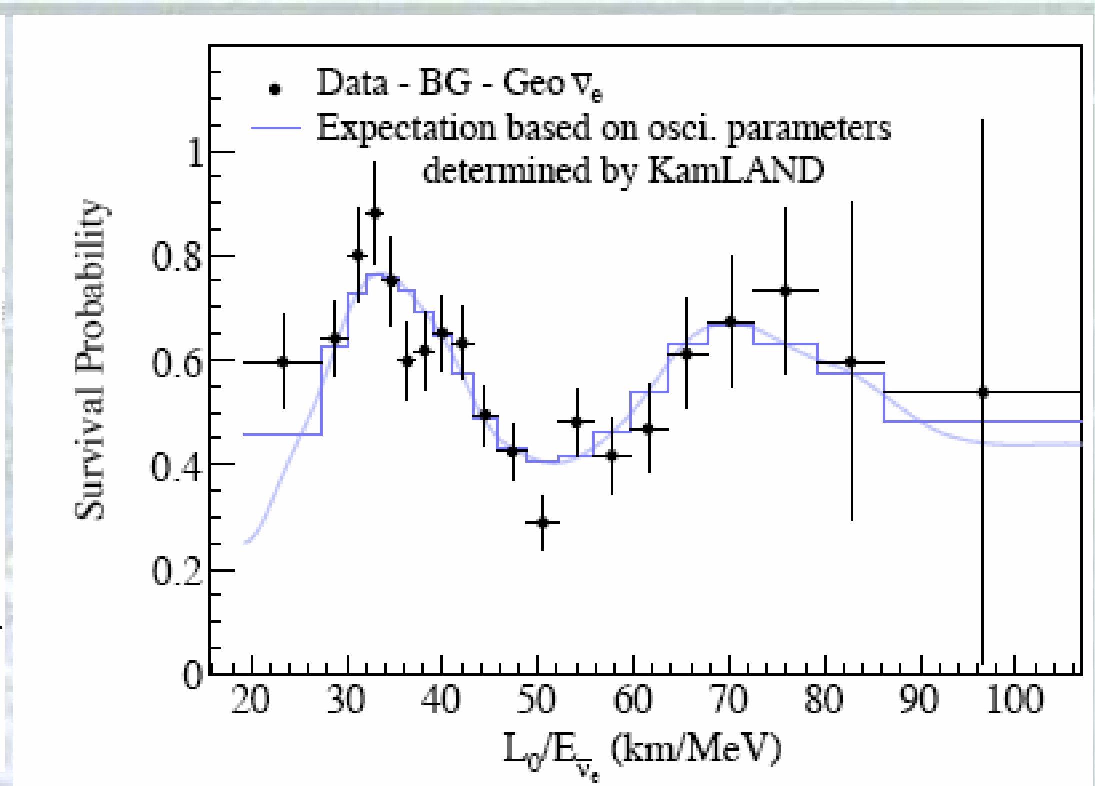
$$\tan^2\theta = 0.4^{+0.10}_{-0.07}$$

NEW

$$\Delta m^2 = 7.58^{+0.14}_{-0.13}(stat) \pm 0.15(syst) \cdot 10^{-5}\, eV^2$$

$$\tan^2\theta = 0.56^{+0.10}_{-0.07}(stat)^{0.10}_{-0.06}(syst)$$





Two ν analysis (θ_{13}=0) ⇨

$$\Delta m^2 = 7.59 \pm 0.21 \cdot 10^{-5}\, eV^2$$

$$\tan^2\theta = 0.47^{+0.06}_{-0.05}$$

New results on ^{8}B from SNO phase III

SNO

6000 mwe overburden

1000 tonnes D_2O

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shield H_2O

Support Structure for 9500 PMTs, 60% coverage

5300 tonnes Outer Shield H_2O

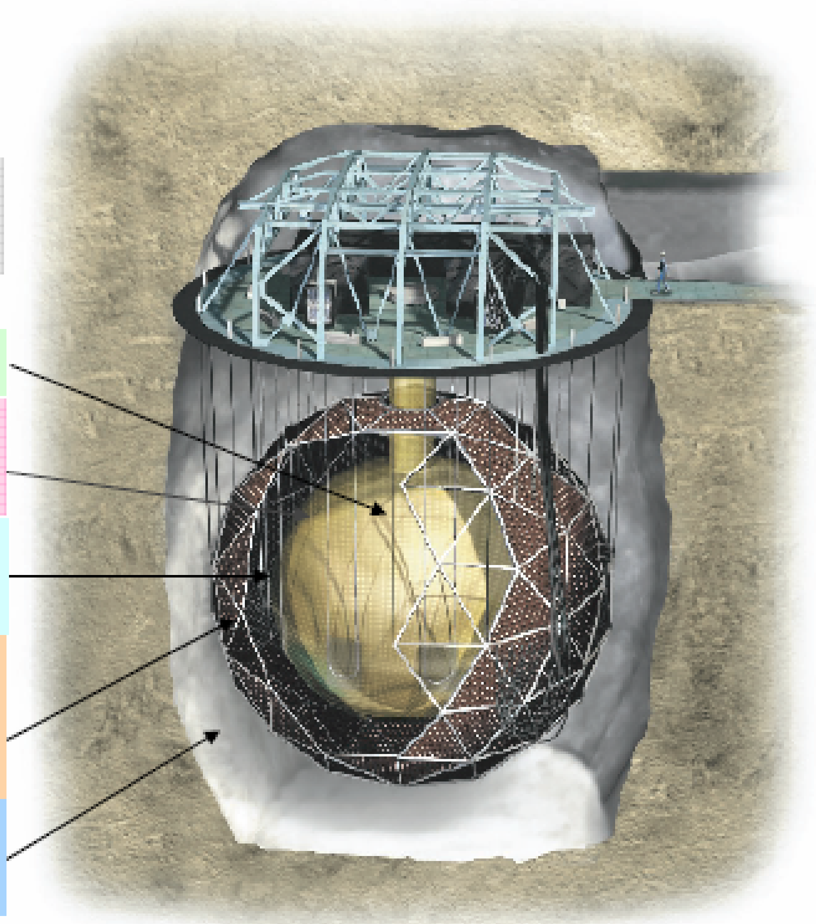


Image courtesy National Geographic

3 Reactions:

$\nu_x + e^- \to \nu_x + e^-$ ES

$\nu_e + d \to p + p + e^-$ CC

$\nu_x + d \to p + n + \nu_x$ NC

3 neutron detection methods:

$n + d \to t + \gamma + 6.25$ MeV

$n + {}^{35}Cl \to {}^{36}Cl + \gamma + 8.6$ MeV

$n + {}^{3}He \to p + t + 0.76$ MeV

3 Phases:

- Just D_2O
- D_2O + 2 tonnes NaCl
- D_2O + ^{3}He Proportional Counters (“NCDs”)

(Robertson at Neutrino 08)

Phase III>> 36 ^{3}He proportional counters (-6)-NCD

4 ^{4}He p.c. insensitive to the neutrons, to study the background

>>385.17 live days of data taking

@neutrons produced in the NC reactions are captured by the ^{3}He, producing a proton-triton pair-e.max:764 keV but part of it can be absorbed by the counter walls-

@detection efficiencies determined by n calibration source (^{252}Cf,^{241}AmBe) or n γ produced by activated ^{24}NaCl.

@background →

main sources: NCD radioact,,

n from acrylic vessel and H_2O,

n produced in the atmosphere,

D_2O radioact,, etc.

Source	PMT Events	NCD Events
D_2O radioactivity	7.6 ± 1.2	28.7 ± 4.7
NCD bulk/^{17}O,^{18}O	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
Atmospheric ν/^{16}N	24.7 ± 4.6	13.6 ± 2.7
"Other backgrounds"	0.7 ± 0.1	2.3 ± 0.3
NCD "hotspots"	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
Total internal neutron background	$56.4^{+5.6}_{-5.4}$	$144.6^{+13.8}_{-14.8}$
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6
Cherenkov events from β–γ decays	$5.8^{+9.7}_{-2.9}$	–
IAVB	< 0.3 (68% CL)	–

>Simultaneous fit on: NC from NCD,
NC,CC,ES from PMTs
α background, n background

>PMT events reconstructed in energy, $\cos\theta_{Sun}$,radial position

systematics

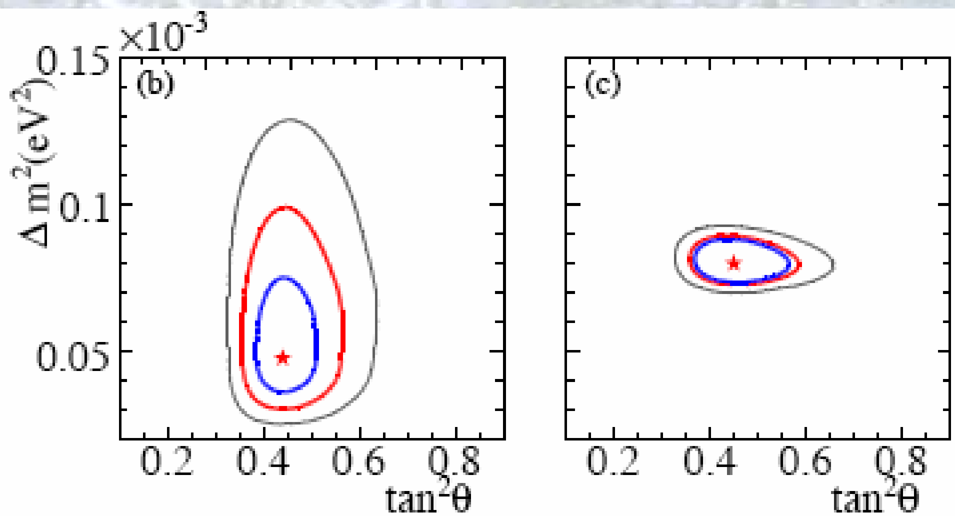
Nuisance Parameter	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
PMT energy scale	±0.6	±2.7	±3.6
PMT energy resolution	±0.1	±0.1	±0.3
PMT radial scaling	±0.1	±2.7	±2.7
PMT angular resolution	±0.0	±0.2	±2.2
PMT radial energy dep.	±0.0	±0.9	±0.9
Background neutrons	±2.3	±0.6	±0.7
Neutron capture	±3.3	±0.4	±0.5
Cherenkov/AV backgrounds	±0.0	±0.3	±0.3
NCD instrumentals	±1.6	±0.2	±0.2
NCD energy scale	±0.5	±0.1	±0.1
NCD energy resolution	±2.7	±0.3	±0.3
NCD alpha systematics	±2.7	±0.3	±0.4
PMT data cleaning	±0.0	±0.3	±0.3
Total experimental uncertainty	±6.5	±4.0	±4.9
Cross section [16]	±1.1	±1.2	±0.5

Phase III results →

$$\phi_{CC}^{SNO} = 1.67^{+0.05}_{-0.04}(\text{stat})^{+0.07}_{-0.08}(\text{syst})$$
$$\phi_{ES}^{SNO} = 1.77^{+0.24}_{-0.21}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$$
$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst}),$$

$$\frac{\Phi_{cc}}{\Phi_{nc}} = 0.301 \pm 0.033(\textit{total})$$

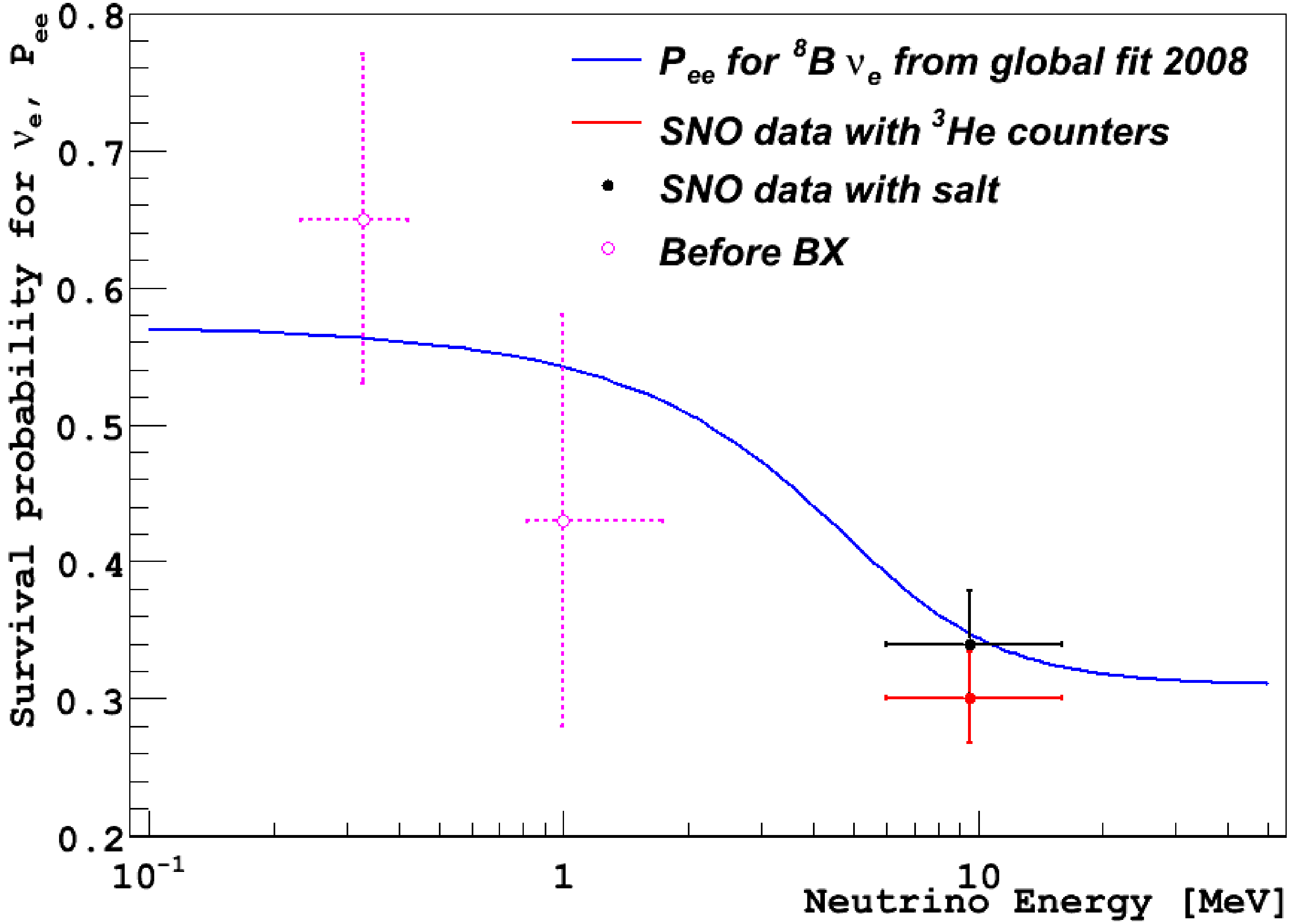
NC and CC
in good agreement with the phases I and II
ES within 1.5 σ



all solar all solar + Kamland

	$\Delta m^2 (eV^2) \cdot 10^{-5}$	$\tan^2 \theta$
previous	7.92±71	$0.458^{+0.08}_{-0.07}$
Kamland 08	$7.58^{+0.14}_{-0.13} \pm 0.15$	$0.56^{+0.10+0.10}_{-0.07-0.06}$
SNO total 08	4.57	0.447
Solar 05+ Kamland	7.59 ± 0.21	$0.47^{+0.06}_{-0.05}$
Cl-Ar, SK, Sage,Gallex, SNO 08, Borex,Kamland	$7.94^{+0.42}_{-0.26}$	$0.448^{+0.05}_{-0.04}$

Best LMA parameters from the total fit 2008 (SNO coll. 08)



•Borexino is located under the Gran Sasso mountain which provides a shield against cosmic rays (4000 m water equivalent);

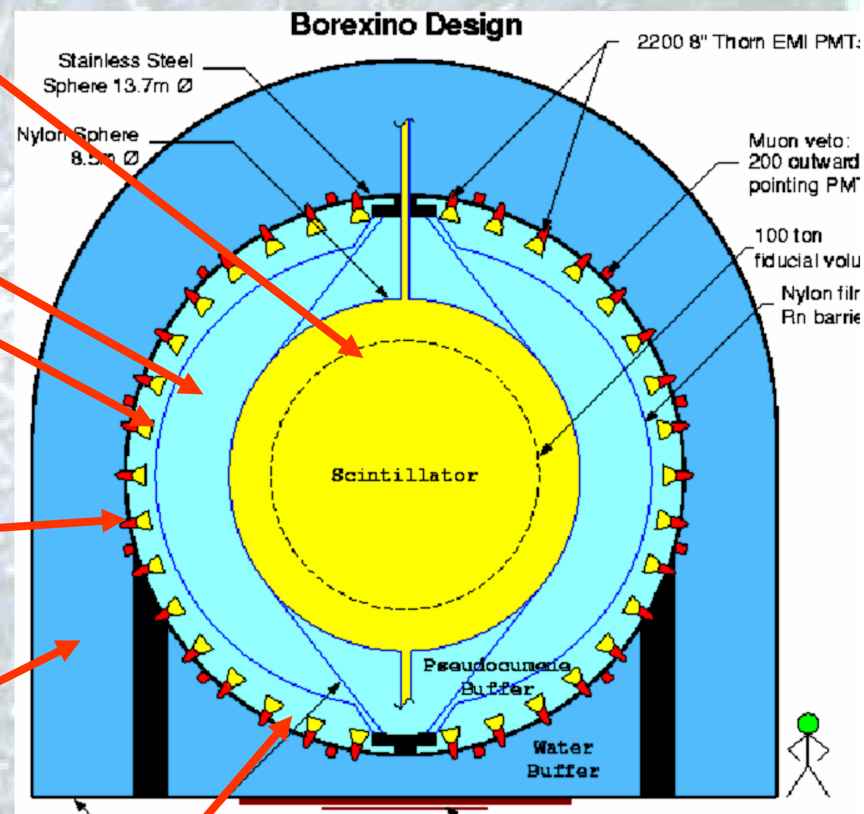
Core of the detector: 278 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

1st shield: 890 tons of ultra-pure buffer liquid (PC+quencher) contained in a stainless steel sphere of 6.75 m radius;

External nylon vessel; it is a barrier against Rn emitted by PMT and s.steel

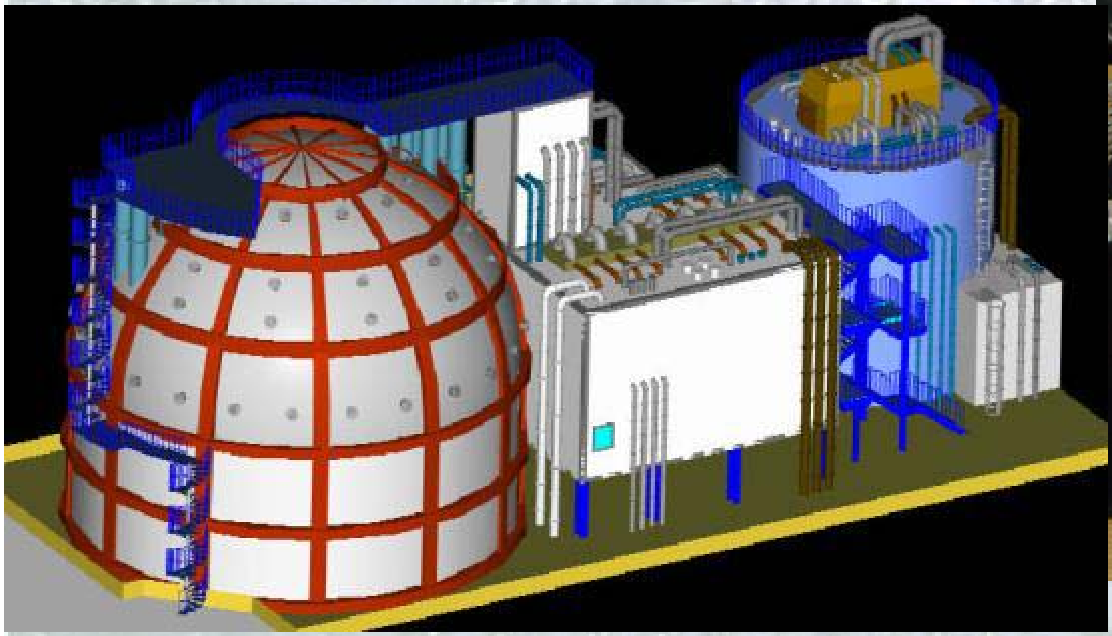
2214 photomultipliers pointing towards the center to view the light emitted by the scintillator (1843 with opt. concentr.)

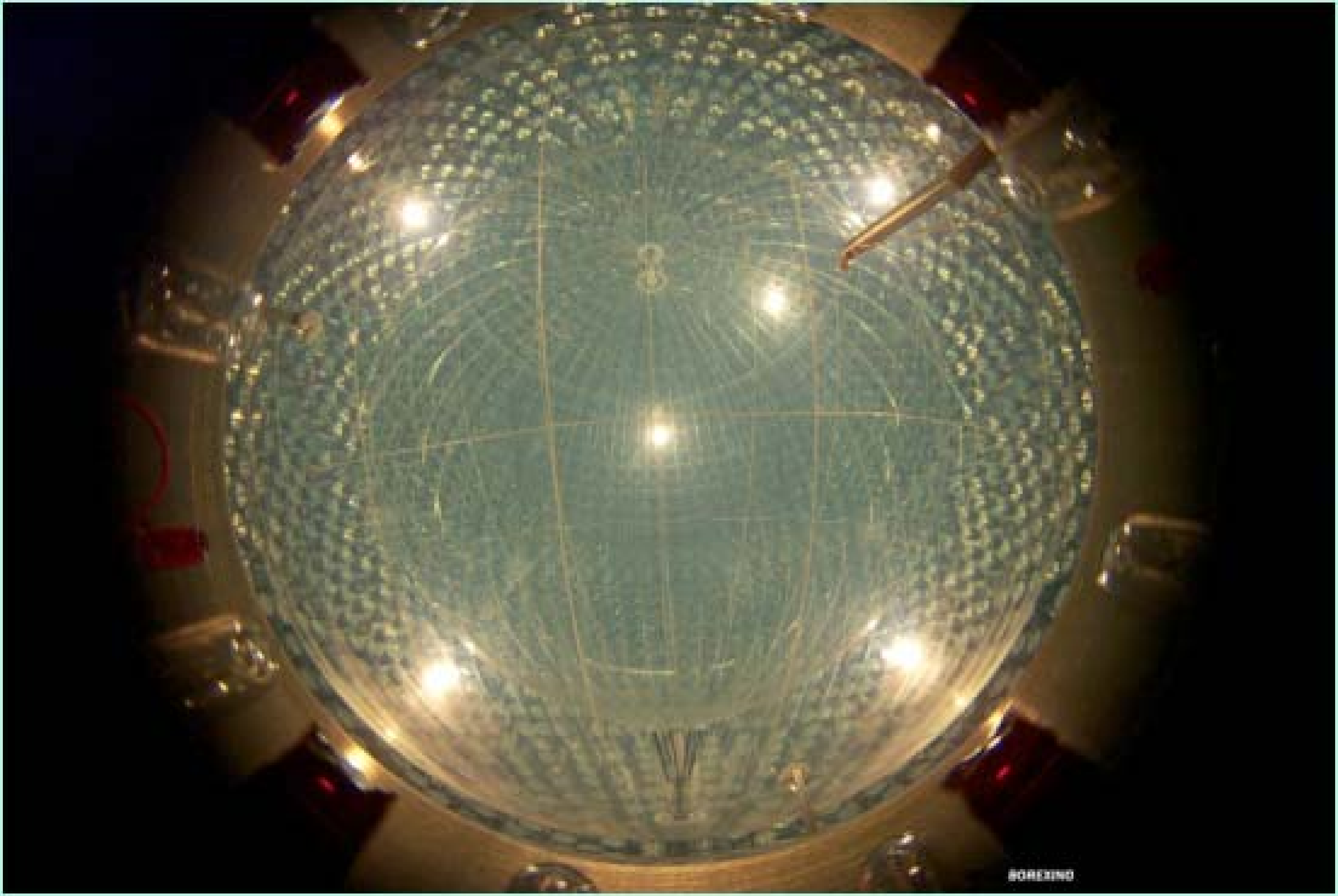
2nd shield: 2100 tons of ultra-pure water contained in a cylindrical dome;



200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Low energy solar ν:Borexino




BOREXINO

Borexino Science goals

- To make the first ever observations of sub-MeV ν in real time, testing the SSM, the LMA solution of the Solar Neutrino Problem and the oscillation model in the vacuum and in the transition regions
- To provide a strong constraint on the ^{7}Be rate, at or below 5%, such as to provide an essential input to check the balance between photon and neutrino luminosity of the Sun
- To confirm the solar origin of the 7Be ν, by checking the expected 7% seasonal variation of the signal due to the Earth's orbital eccentricity

taking into account the radiopurity levels much better that the design prescriptions

⇒ detect the CNO ν, never directly observed (very important also in the massive stars, where is the dominant reaction)

⇒ study the pep ν (indirect constraint on pp ν flux), possibly the tail end of the pp ν flux and the ^{8}B from a 3 MeV threshold

Very high radiopurity- special methods and tools developed

>Cleaning scintillator : PC: water extraction,distillation (80 mbar,90-95 ^{0}C),
nitrogen stripping, ultrafine filtration

>Ultrapure N_2 for stripping: ultrapure Nitrogen: $Rn < 0.1\ \mu Bq/m^3$
LAK Nitrogen: 0.01 ppm Ar, 0.03 ppt Kr

>Special care in the PC procurement: old layers crude oil, special loading station directly connected to the production plant, special shipping vessels, special unloading station, rapid transport to the underground lab to avoid cosmogenic production of radioactive nuclides (^{7}Be)

>Extreme precaution in the fabrication and assembly of the Nylon Vessels: selection and extrusion of the materials in controlled area, construction in clean room with Rn control,special bags for shipping

>All surfaces electropolished: detector components, lines, fittings,valves

>Special developments and selection of the components (as the PMTs),

>Any operation in clean room or in N_2, Ar atmosphere

Radiopurity levels checked with a high sensitivity detector, installed on purpose: the Counting Test Facility → $5\ 10^{-16}$ g/g of sensitivity
The various batches of PC tested in CTF for ^{14}C at the level of $10^{-18}\ ^{14}C/^{12}C$.

ν-e scattering

•The time and the total charge are measured, and the position is reconstructed for each event . Absolute time is also provided(GPS)

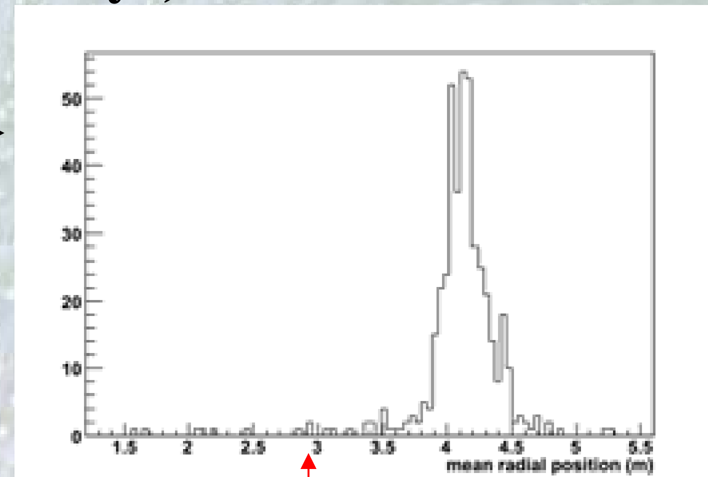
LY≈500 p.e./MeV

(taking into account the β quenching factor)

Spatial resolution: 16 cm at 500 keV
(scaling as $N_{p.e.}^{1/2}$)
Energy resolution: 10% at 200 keV
8% at 400 keV
6% at 1 MeV

Background (240 days)

^{232}Th: (6.8±1.5) 10^{-18} g/g
from ^{212}Bi-^{212}Po



^{238}U: (1.6±0. 1) 10^{-17} g/g
from^{214}Bi-^{214}Po

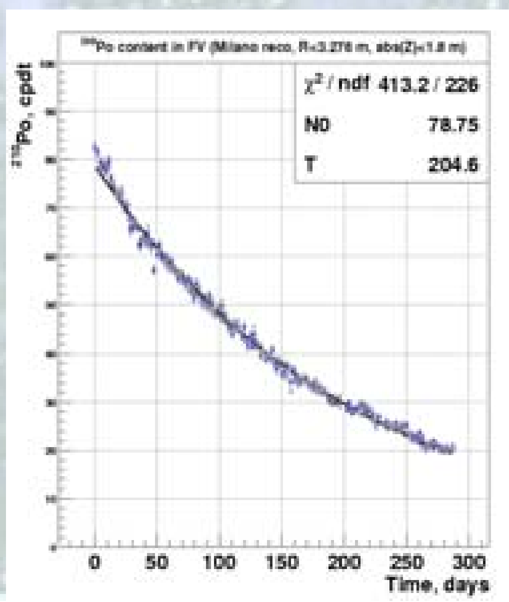
^{85}Kr β decay- 687 keV

8 events → 29±14 c/d

^{85}Kr $\xrightarrow{\beta}$ ^{85m}Rb $\xrightarrow{\gamma}$ ^{85}Rb

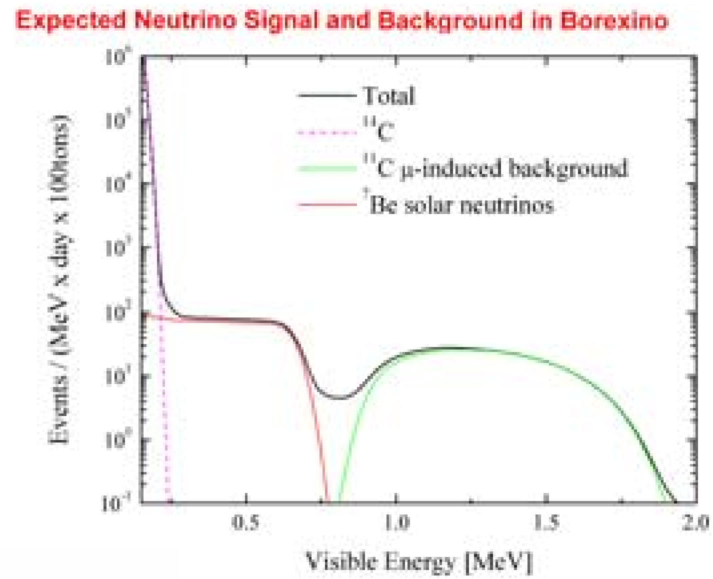
173 keV   514 keV

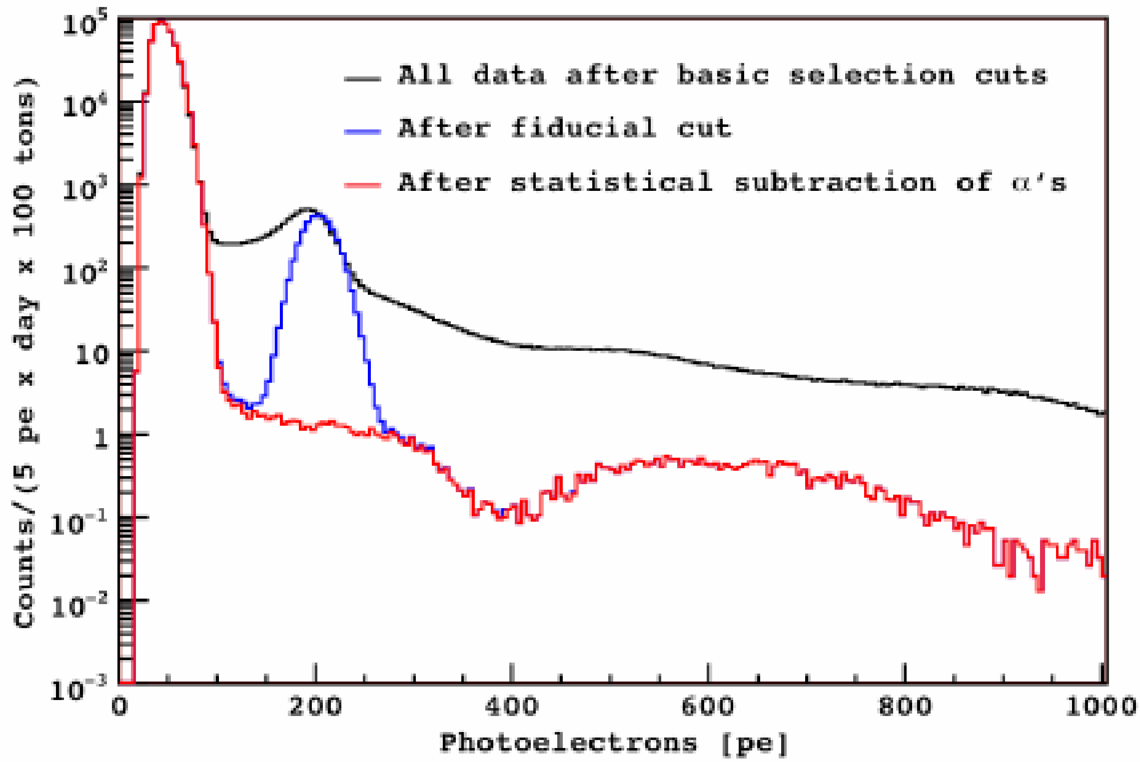
τ= 1.46 μs - BR: 0.43%



^{210}Po- α, Q=5.41 Mev quenched by ≈13-
no evidence of ^{210}Bi

Spectral fit in ≈ 192 days





Once vetoed or subtracted:

> muons and all events within 2 ms after a muon

>^{222}Rn daughters subtracted

α/β discrimination- Gatti parameter

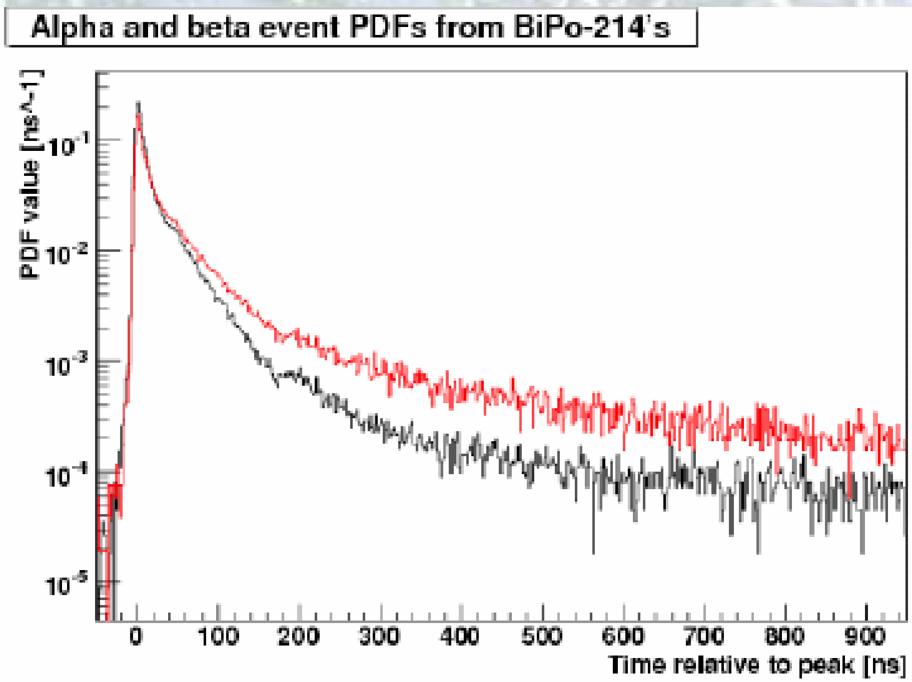
#Borex.Coll.N.I.M.A,584(2008)98

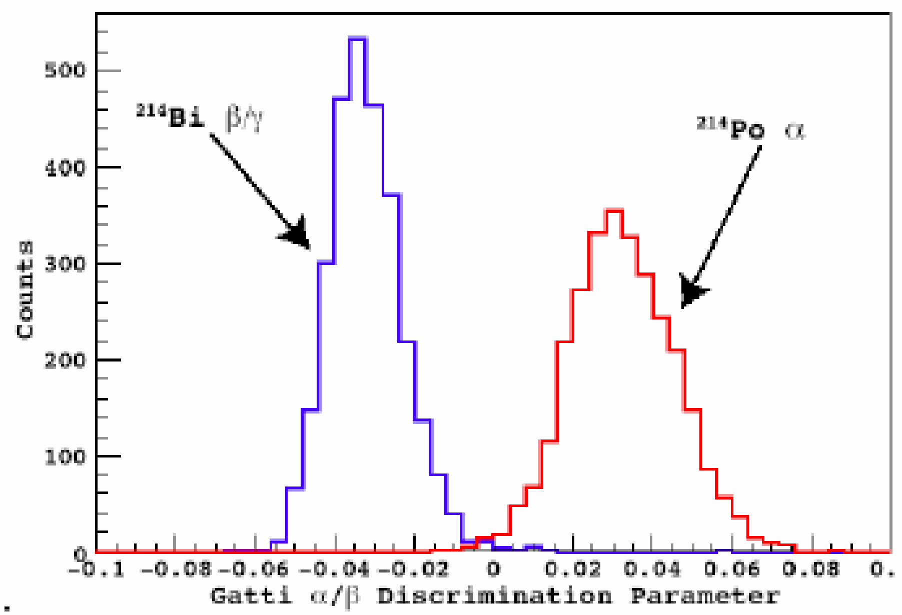
$G_\alpha = \sum_i P_i \beta_i$ α_i, β_i –>n. p.e. for the indiv. shape within a given Δt (2 ns)

$G_\beta = \sum_i P_i \alpha_i$

$$P_i = \frac{(\bar{\alpha}_i - \bar{\beta}_i)}{(\bar{\alpha}_i + \bar{\beta}_i)}$$

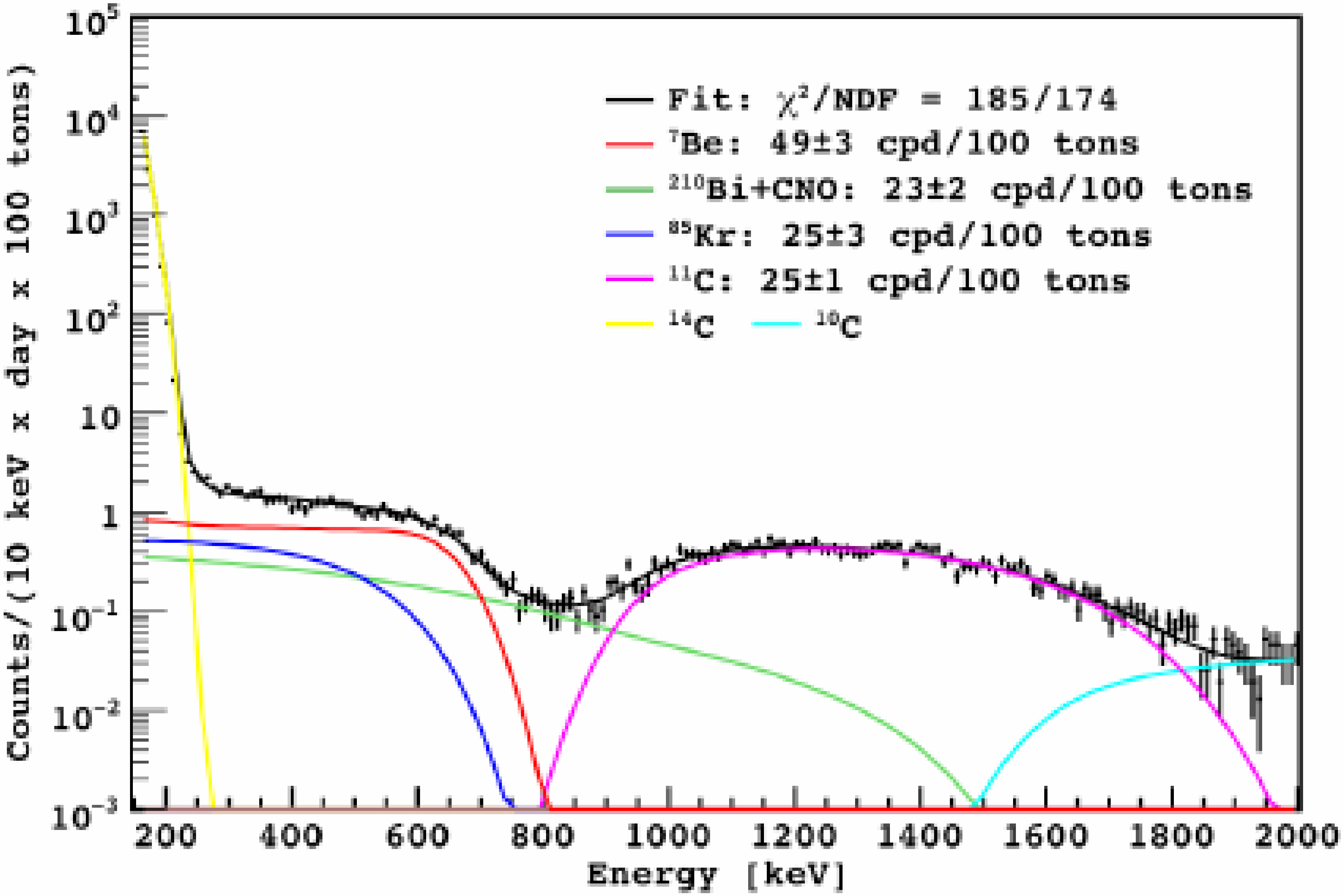
$\bar{\alpha}_i, \bar{\beta}_i$ –>av. shape of current pulses (pdf)



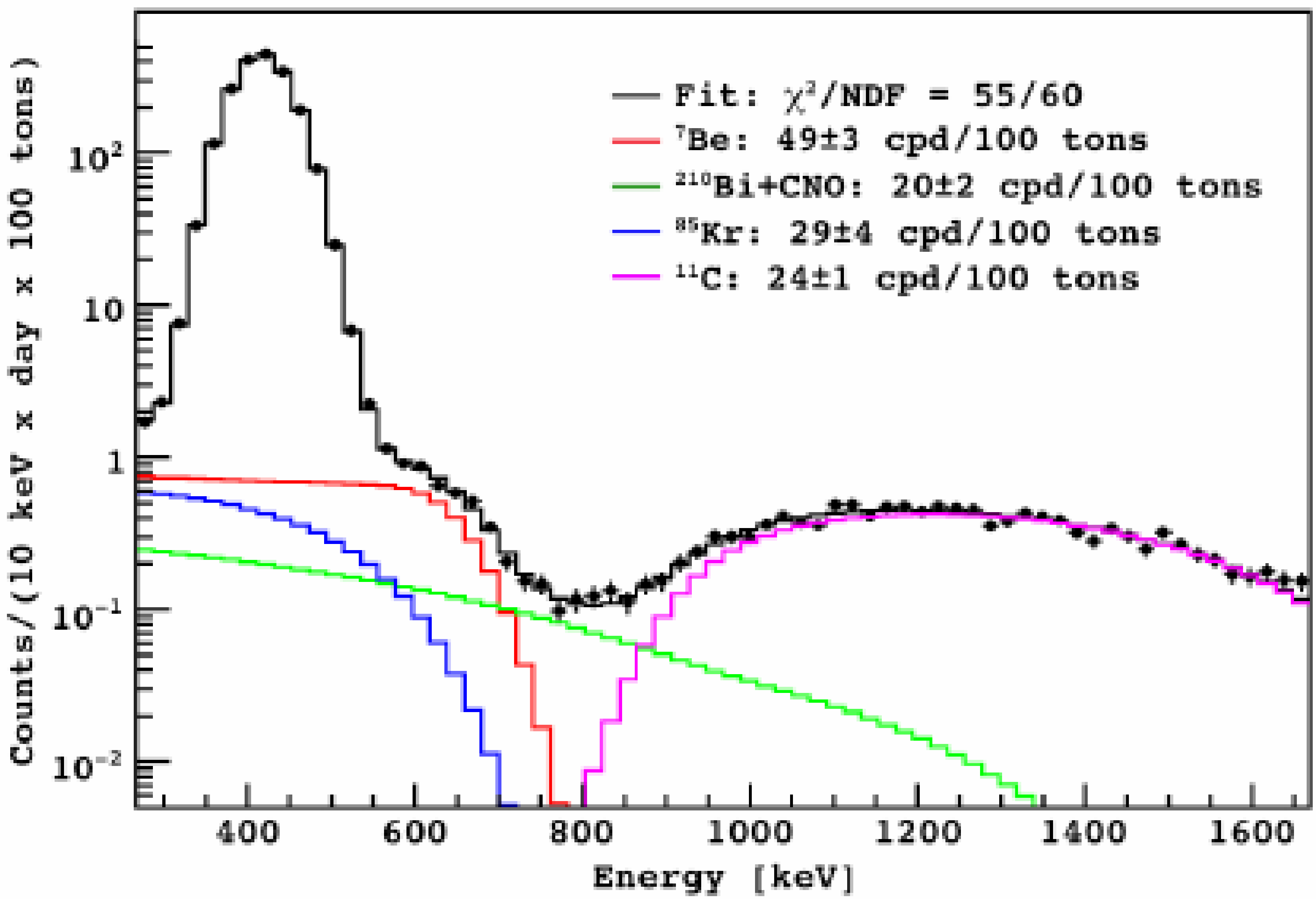


This analysis for the reference curves has been done during the filling period, when ^{222}Rn was present

BOREXINO: 192 days-free parameters: ^{7}Be, ^{14}C, CNO, ^{11}C, ^{83}Kr;
-fixed at the SSM values: pp, pep



BOREXINO: 192 days



Systematic

- F.V. definition from the IV: uniform background sources(^{14}C,^{222}Rn, capture of cosmogenic n), ^{229}Rn decay emitted by nylon, diffuser balls on the IV surface,laser activated.

- Detector response function

Estimated 1σ Systematic Uncertainties* [%]

Total Scintillator Mass	0.2
Fiducial Mass Ratio	6.0
Live Time	0.1
Detector Resp. Function	6.0
Cuts Efficiency	0.3
Total	8.5

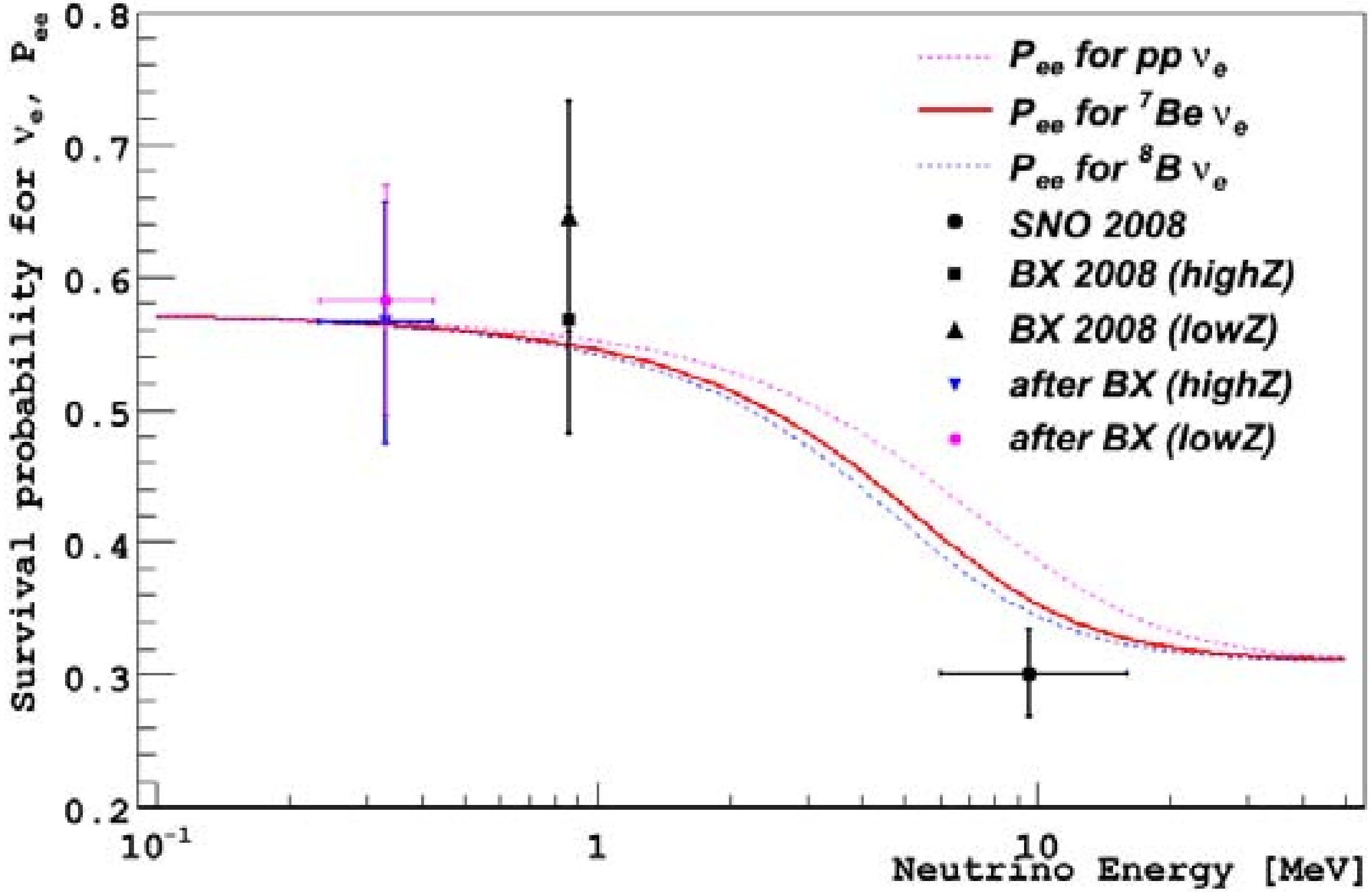
*Prior to Calibration

$49 \pm 3_{stat} \pm 4_{syst}$ cpd/100tons for 862 keV ^{7}Be solar ν

$\Phi(^7Be) = (5.12 \pm 0.51) \times 10^9 cm^{-2}s^{-1}$ SSM; H.M.$(5.08 \pm 0.56) \times 10^9 cm^{-2}s^{-1}$

L.M.$(4.55 \pm 0.5) \times 10^9 cm^{-2}s^{-1}$

Using LMA with: $\delta m_{12}^2 = 7.94 \cdot 10^{-5}$ eV^2 $\tan^2\theta_{12} = 0.447$ (global fit from SNO08)



Goal: 5% Total error

$$R_l\ [\mathrm{SNU}] = \sum_i R_{l,i} f_i P_{ee}^{l,i}$$

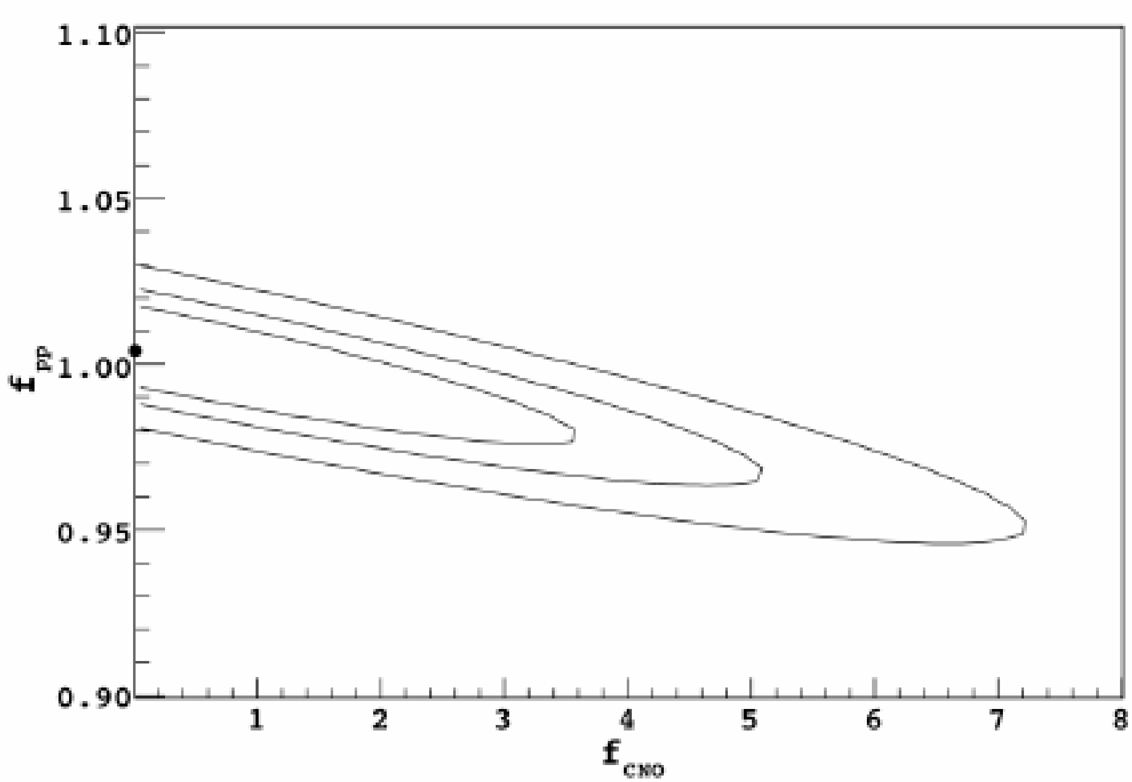
$l = \{\mathrm{Ga}, \mathrm{Cl}\}$

$i = \{pp, pep, \mathrm{CNO}, {}^7\mathrm{Be}, {}^8\mathrm{B}\}$

f_i Ratio between measured and predicted flux

$P_{ee}^{l,i}$ Survival Probability Averaged over Threshold

$f_{^8B}$ and $f_{^7Be}$ from exp.
pep constrained by pp
pp constrained by L_s



F_{pp} vs f_{cno}: 1σ 2σ 3σ

Neutrino Magnetic Moment

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

EM current affects cross section σ

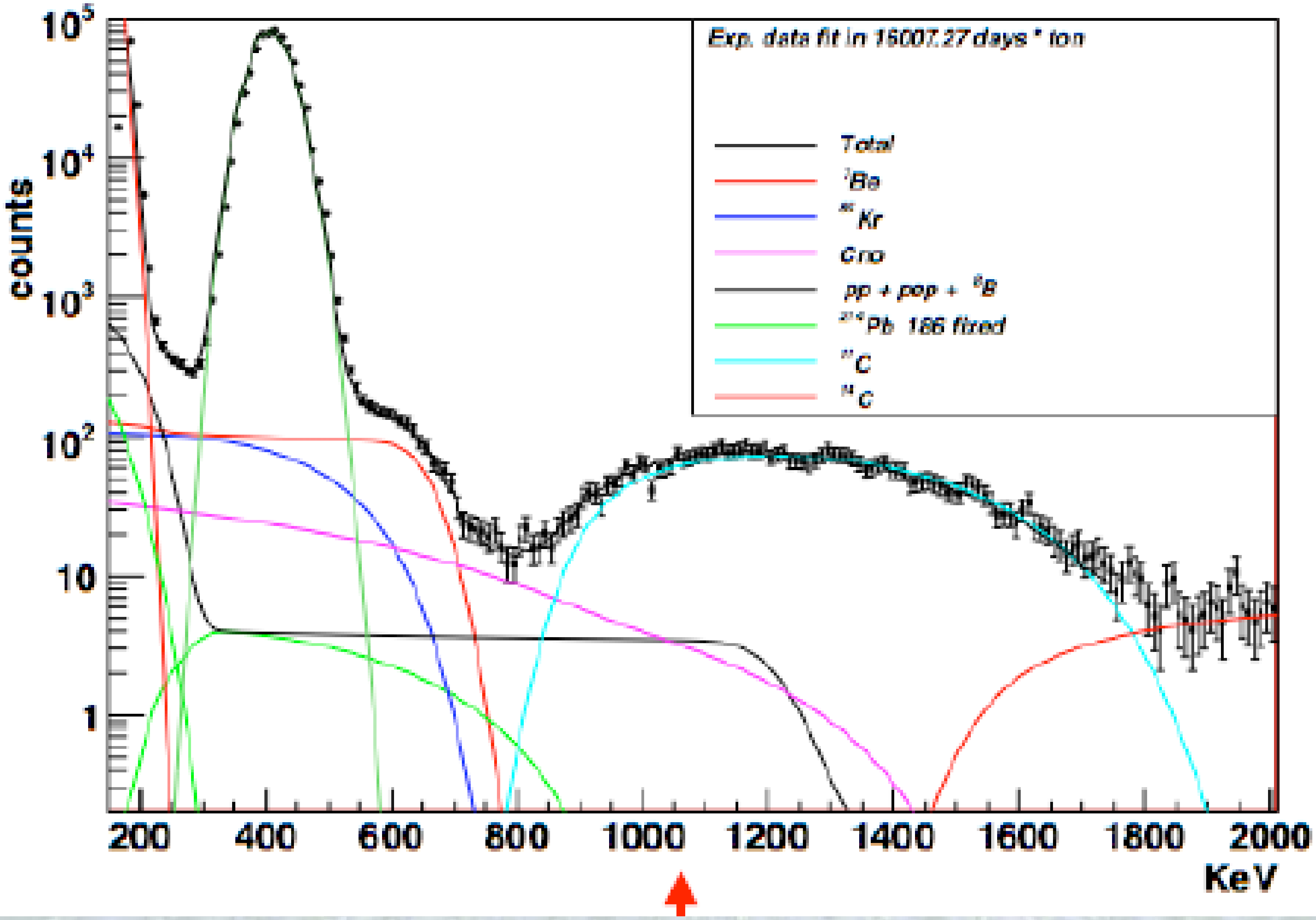
Spectral shape sensitive to μ_ν

Sensitivity enhanced at low energies ($\sigma \approx 1/T$)

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi \alpha_{em}^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

Estimate	Method	90% C.L. 10^{-11} μ_B
SuperK	^{8}B	<11
Montanino et al.	^{7}Be	<8.4
GEMMA	Reactor	<5.8
Borexino	^{7}Be	<5.4

Study of pep and CNO fluxes



Best estimate for cosmogenic ^{11}C is 25 cpd/100 tons (1.1 μ $m^{-2}h^{-1}$, $\langle E_\mu \rangle$ 325 GeV)

→ CNO: 5 cpd/100 tons

→ pep: 2 cpd/100 tons

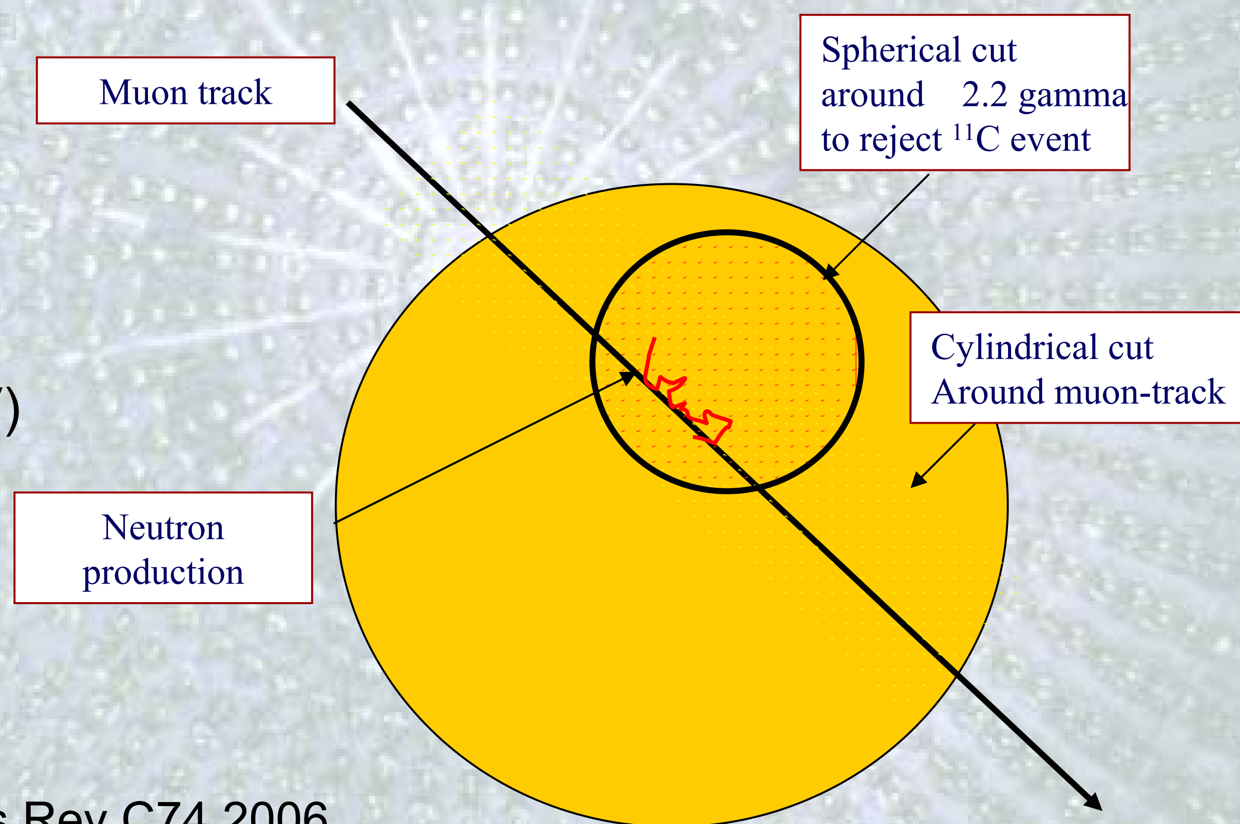
Expected from SSM

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

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

n capture

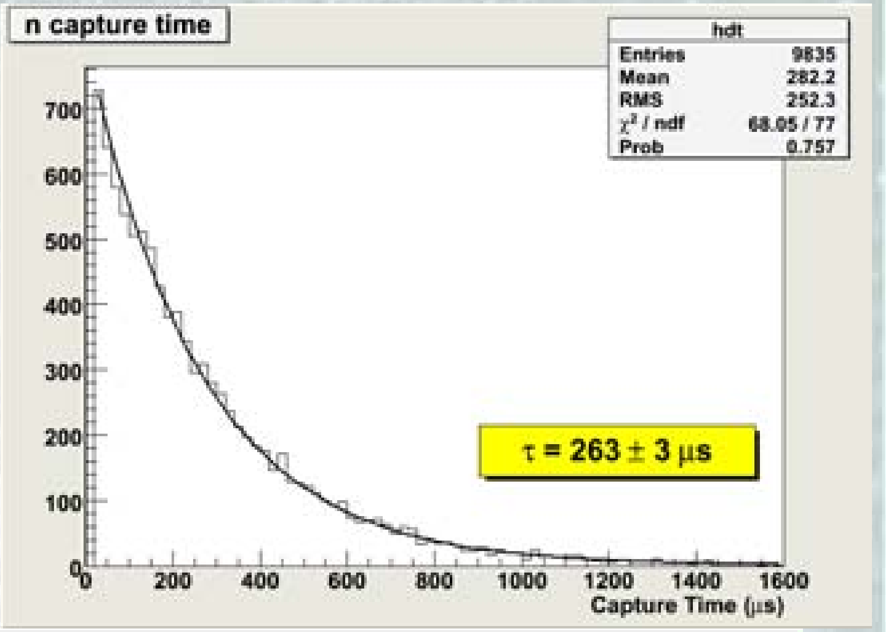
γ (2.2 MeV)



#Borex. Coll.Phys.Rev.C74,2006

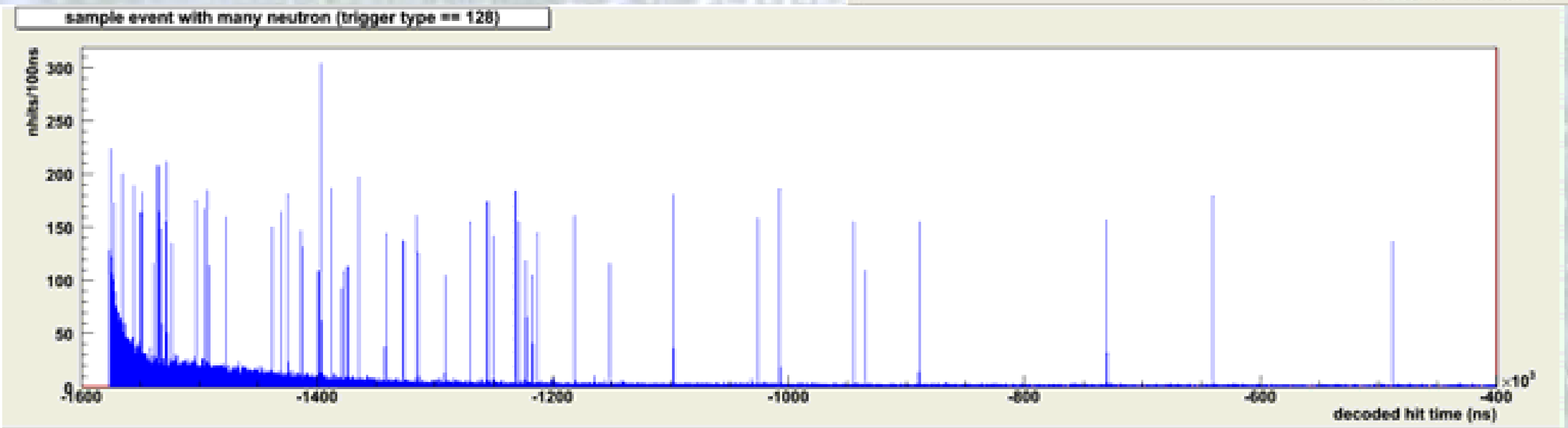
^{11}C and neutrons after muons

- electronics improvement to detect all the neutrons produced by a muon
  - Implementation of the main electronics
  - FADC in parallel to the main electronics



Now: 87% rejection

Still in progress

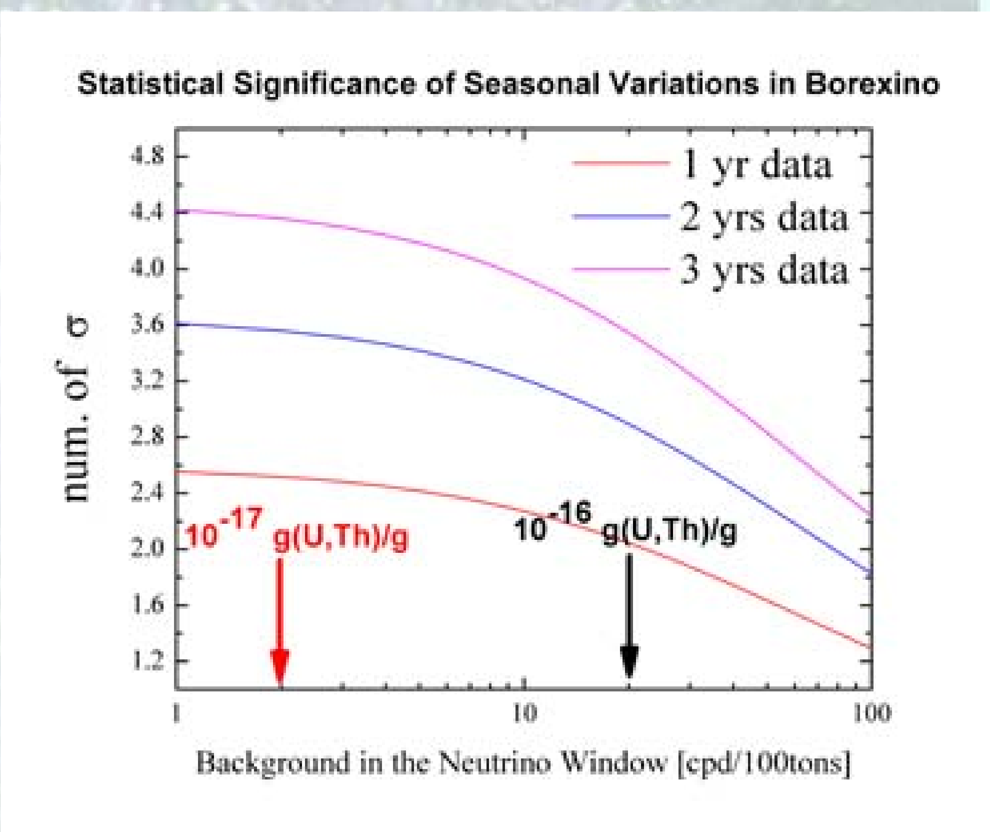


What next in Borexino

@ possibly p-p neutrinos (40 keV window; 190-230 keV)

@ seasonal variations of the solar ν flux due to the eccentricity of the Earth orbit

250-800 keV
En. window



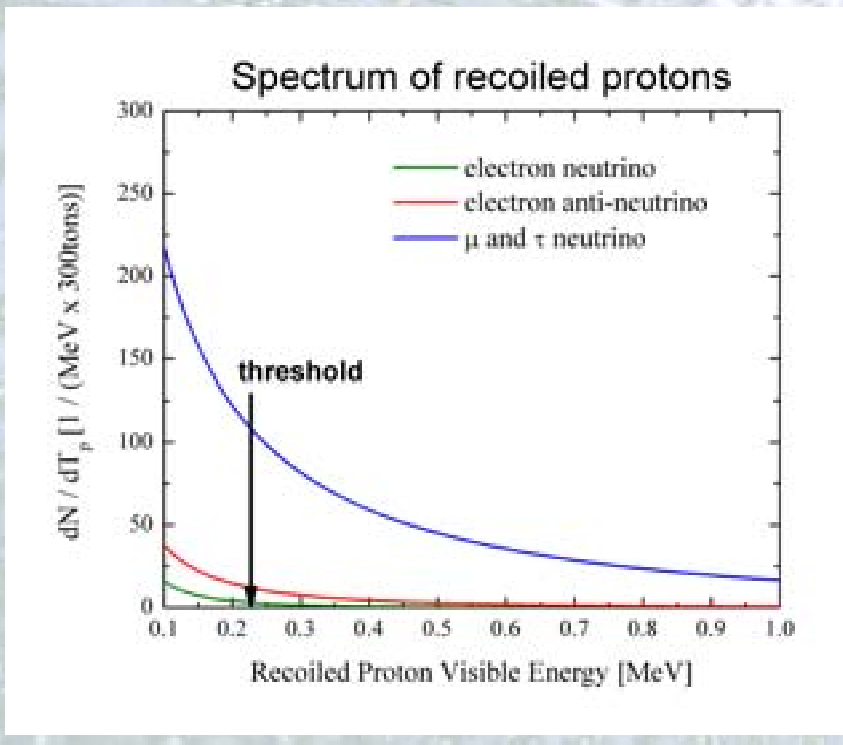
@Anti-neutrino from Earth: Spectrum

Main bckg: from reactors - very low at Gran Sasso

In 300 tons: 7- 17 ev/y - S/N=1.2

@ Supernova

Standard SN @ 10kpc



Detection channel	Any hierarchy
Inverse-Beta Decay (E_ν > 1.8 MeV)	79
ν-p ES (E_ν > 0.25 MeV)	55
$^{12}C(\nu,\nu)^{12}C^*$ ($E\gamma$ = 15.1 MeV)	17

Conclusions

- There are still open problems in the SSM. The experiments on Solar ν can help with precise measurements of the solar fluxes
- New results from SNO and Kamland on the LMA parameters are available, reinforcing the previous ones
- Due to the very high radiopurity Borexino has measured directly the ^{7}Be flux and it is working to measure the other solar ν fluxes: CNO, pep, ^{8}B from 2.5 MeV, and perhaps pp
- In this way it is possible to probe the ν oscillation model in the vacuum and in the transition region.
- The LNGS site is ideal to measure the geoneutrinos flux
- Kamland started in these days a second attempt to purify the scintillator

Borexino collaboration

Genova

Perugia

Milano

APC Paris

Princeton University

Virginia Tech. University

Dubna JINR (Russia)

Kurchatov Institute (Russia)

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