Neutrino 2008

太陽ニュートリノと原子炉(θ_{12})実験

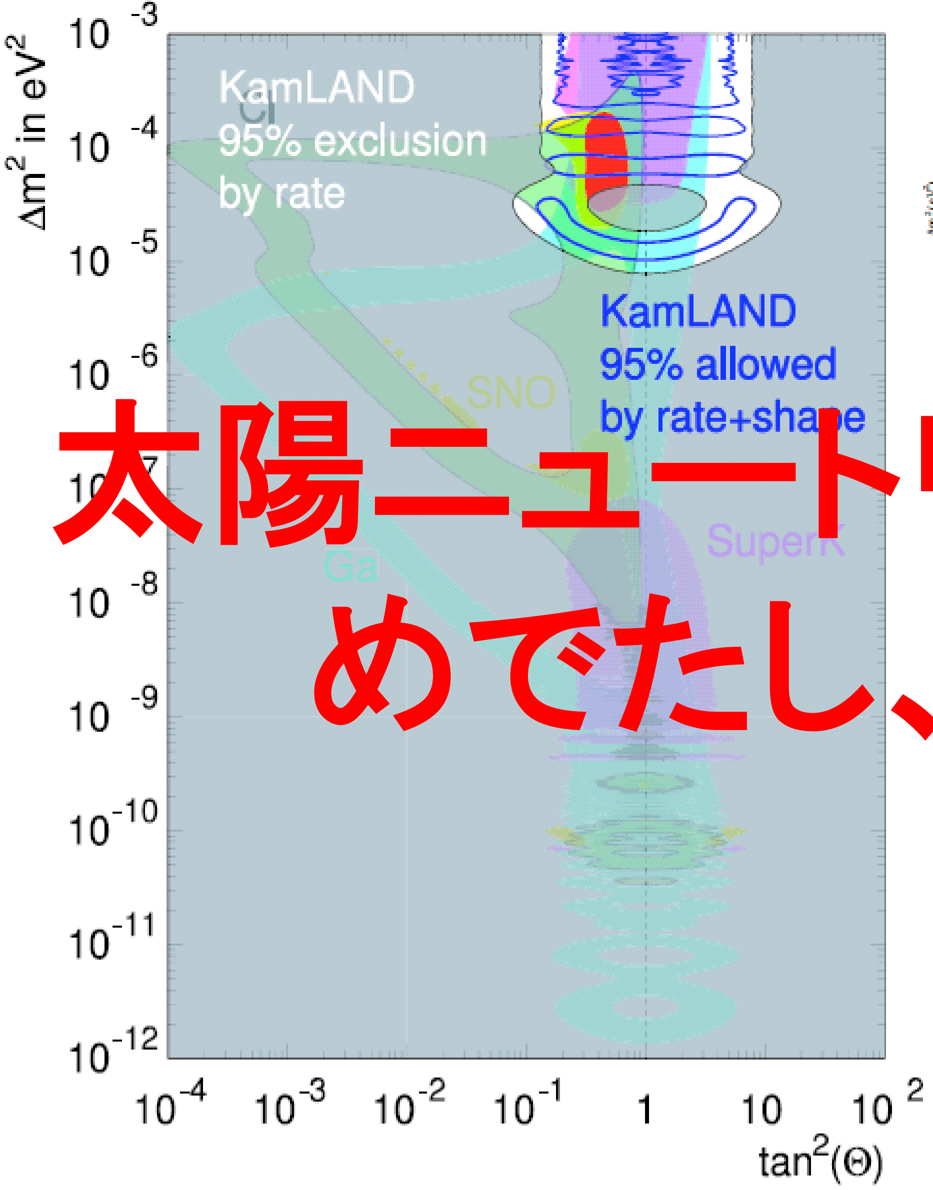
結果報告のまとめ

池田一得　（ICRR）

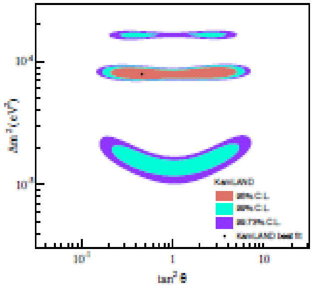
2008年6月27日

Precision Neutrino Measurements

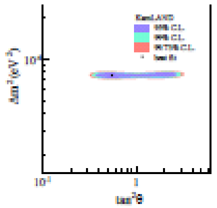
KL 2002



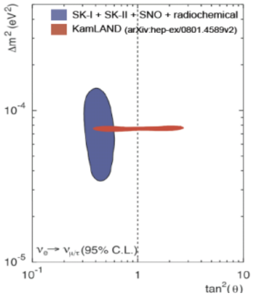
KL 2004



KL 2007



Solar+KL



太陽ニュートリノ実験（θ_{12}）
めでたし、めでたし

Neutrino Oscillation:
A precision measurement!

From Decowski

もくじ、

実験結果報告

＞　SK-I＋II

＞　SNO

＞　Borexino

＞　KamLAND

将来の展望

＞　太陽ニュートリノ観測の明日

＞　各実験の目標

まとめ

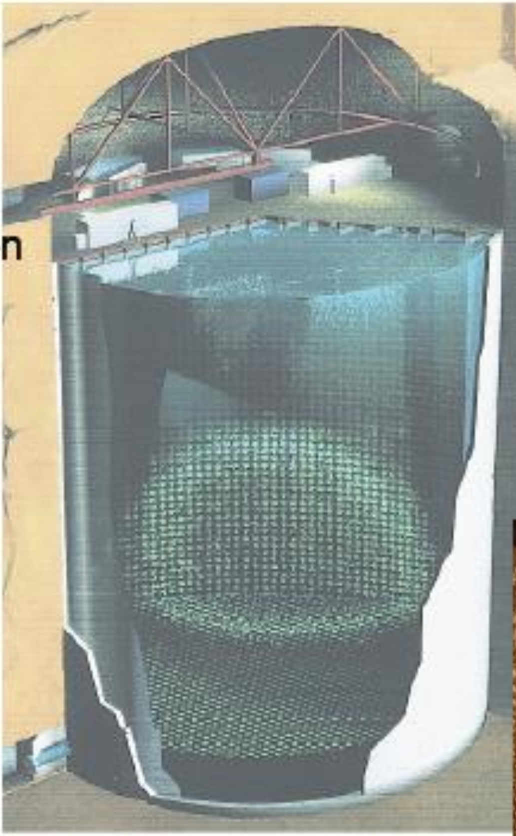
SK-I&SK-II Solar analysis

Super-Kamiokande

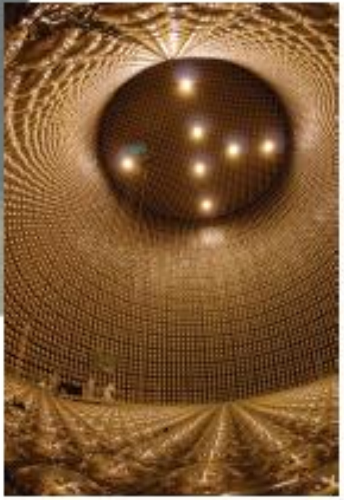
Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

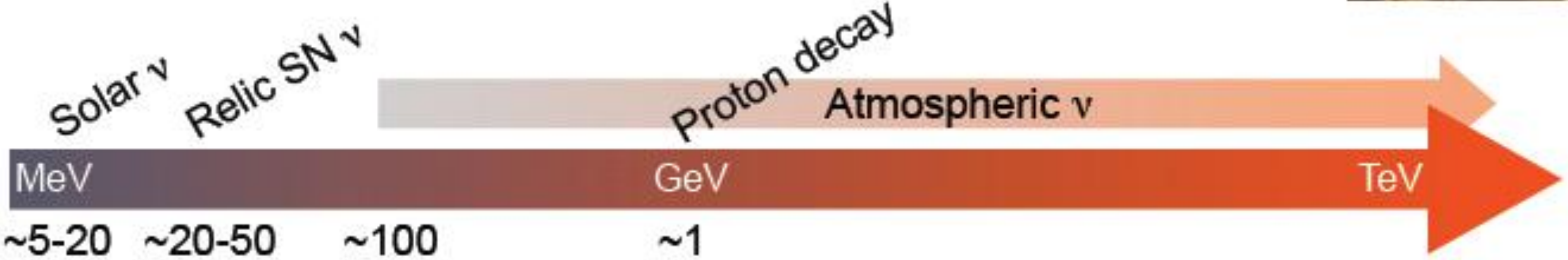
Water Čerenkov detector
  50 ktons (22.5 ktons fiducial)

Instrumented with
  50-cm PMTs in Inner Detector (ID)
  20-cm PMTs in Outer Detector (OD)



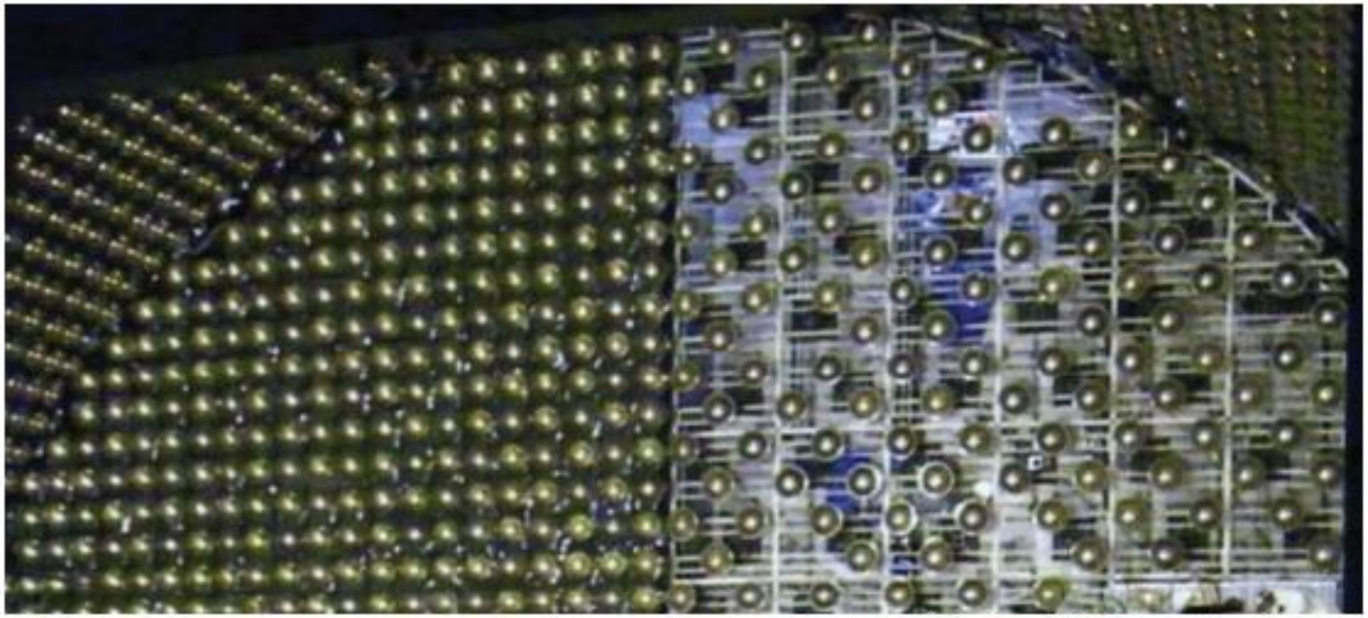
Goals of Super-K
- Solar neutrinos
- Supernova neutrinos (+ relic SN)
- Atmospheric neutrinos
- Proton decay




Solar ν
Relic SN ν
Proton decay
Atmospheric ν
MeV
GeV
TeV
~5-20
~20-50
~100
~1

From J Raaf

Timeline

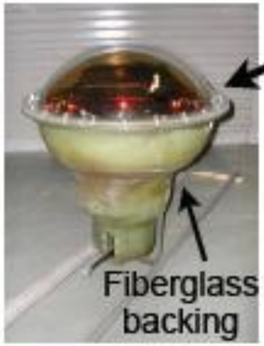


During SK-III construction

SK-I (1996-2001)
11,146 ID PMTs
(40% coverage)
1,885 OD PMTs

accident

SK-II (2003-2005)
5182 ID PMTs
(19% coverage)
Acrylic shields added



SK-III (2006-2008)
11,129 ID PMTs (40% cov.)
OD segmentation
(top/barrel/bottom)

Coming soon:
SK-IV (2008- ...)
Replace DAQ electronics

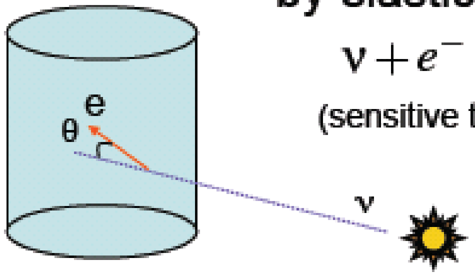
From J Raaf

Solar ν's at Super-K

^{8}B neutrino measurement
by elastic scattering:

$$\nu + e^- \rightarrow \nu + e^-$$

(sensitive to all ν flavors)

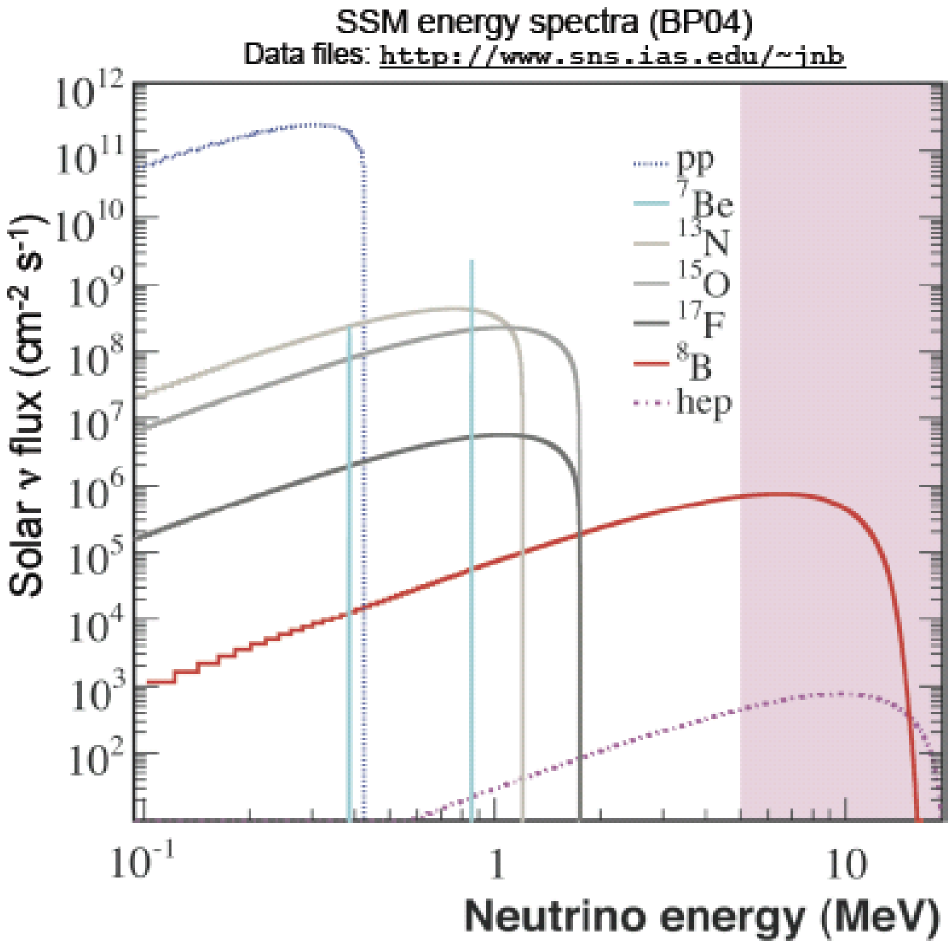


Reconstruct:

energy of recoil electron
direction relative to Sun

Measure/observe:

- Day/Night flux differences
- Seasonal flux variations
- Spectral distortion



Observed event rate in Super-K:
~15 evts/day with E_e > 5 MeV

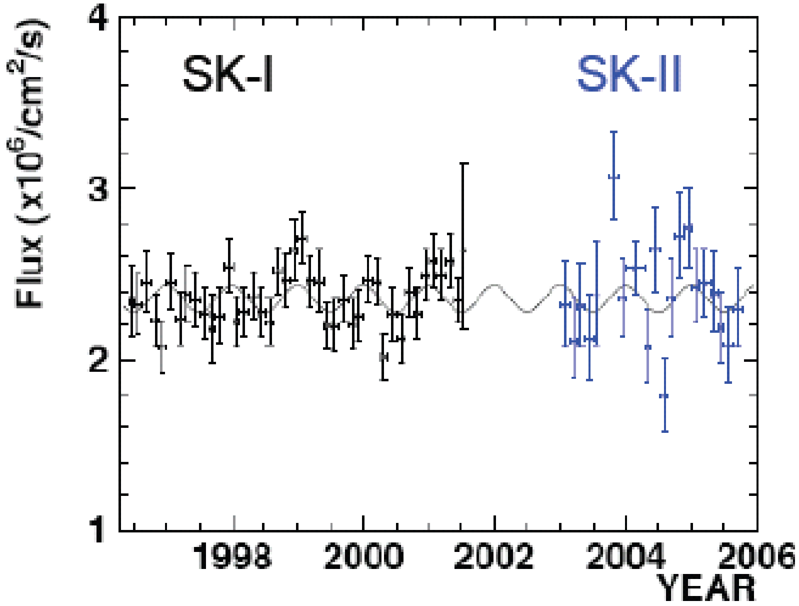
From J Raaf

SK-I + SK-II Solar ν Flux

	Livetime (days)	Energy range (MeV)	Number of signal events	Flux ($\times 10^6$ cm^{-2} sec^{-1})
SK-I	1496	5.0-20.0	$22404 \pm 226\ (\text{stat})\ ^{+784}_{-717}\ (\text{sys})$	$2.35 \pm 0.02\ (\text{stat}) \pm 0.08\ (\text{sys})$
SK-II	791	7.0-20.0	$7212.8\ ^{+152.9}_{-150.9}\ (\text{stat})\ ^{+483.3}_{-461.6}\ (\text{sys})$	$2.38 \pm 0.05\ (\text{stat})\ ^{+0.16}_{-0.15}\ (\text{sys})$

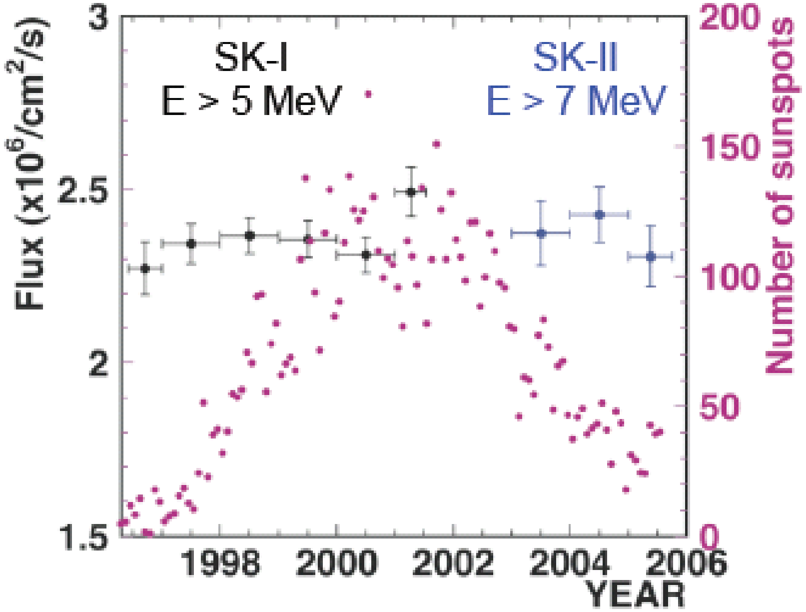
Time Variations of Flux

Seasonal Variation



Consistent with expected variations due to eccentricity of Earth's orbit

Correlation with Solar Activity

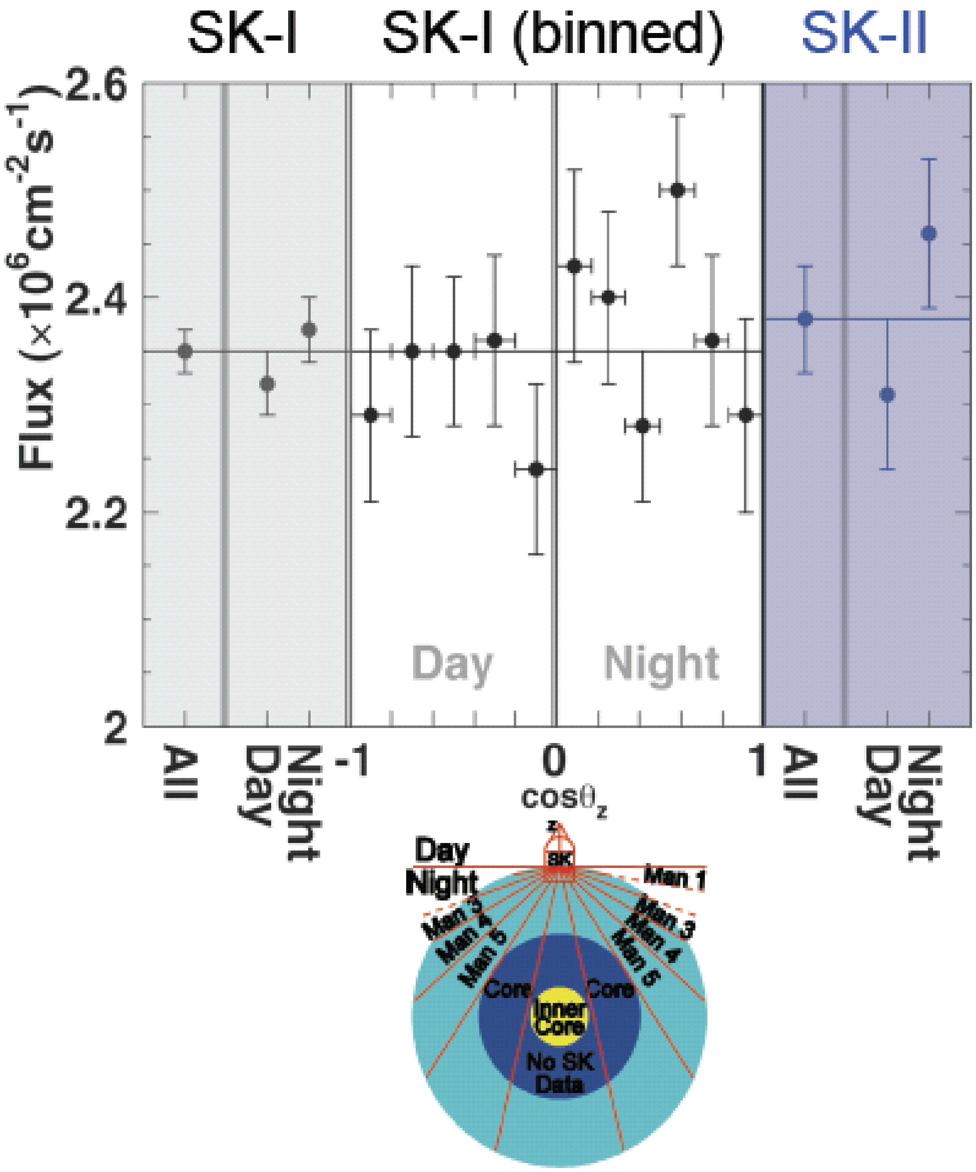


No correlation with solar cycle minima or maximum seen

From J Raaf

SK-I + SK-II Solar ν Flux

Day-Night Asymmetry



$$\mathcal{A} = \frac{\Phi_{day} - \Phi_{night}}{\frac{1}{2}(\Phi_{day} + \Phi_{night})}$$

SK-I day-night asymmetry:

$$-0.021 \pm 0.020\ (\mathrm{stat})^{+0.013}_{-0.012}\ (\mathrm{sys})$$

SK-II day-night asymmetry:

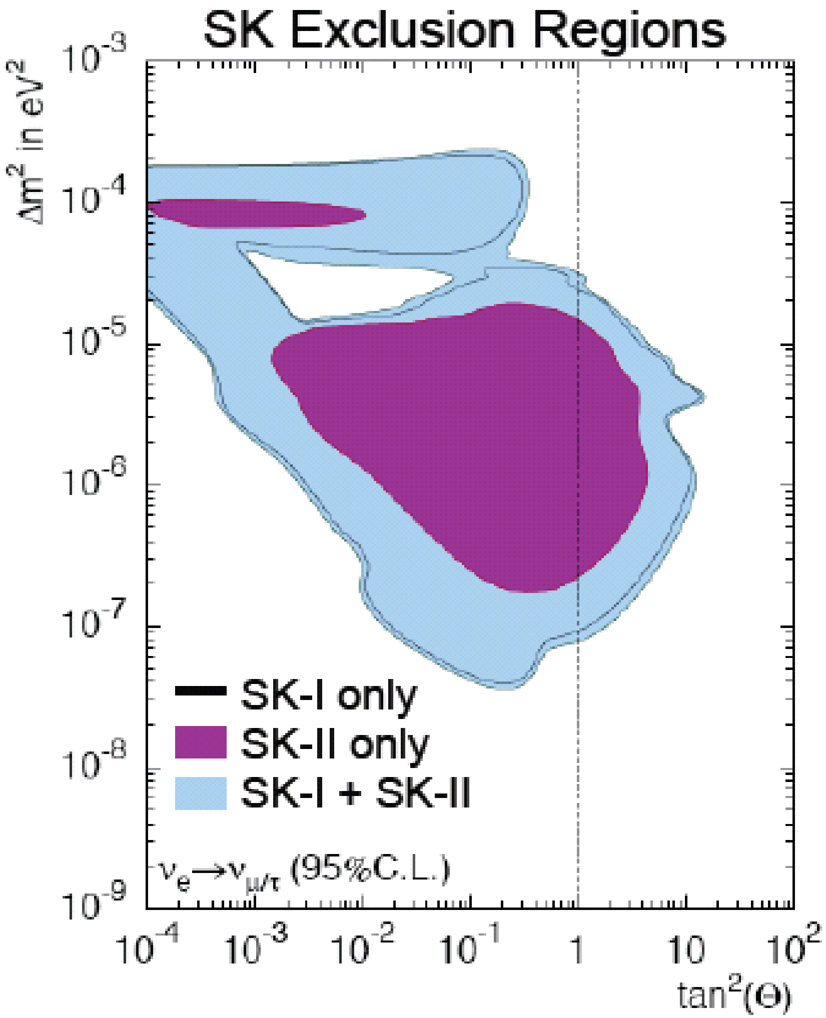
$$-0.063 \pm 0.042\ (\mathrm{stat}) \pm 0.037\ (\mathrm{sys})$$

Consistent with zero

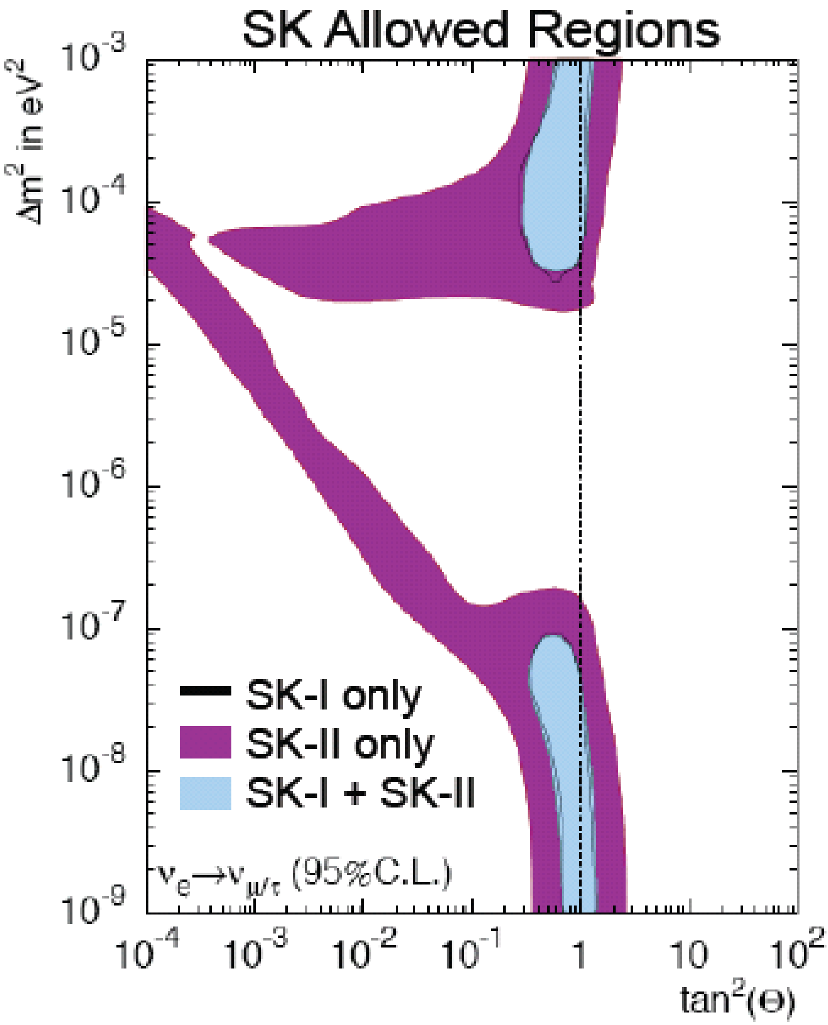
From J Raaf

Solar ν Oscillation Analysis (SK only)

arXiv:0803.4312



Based on SK energy spectrum shape, and time variations

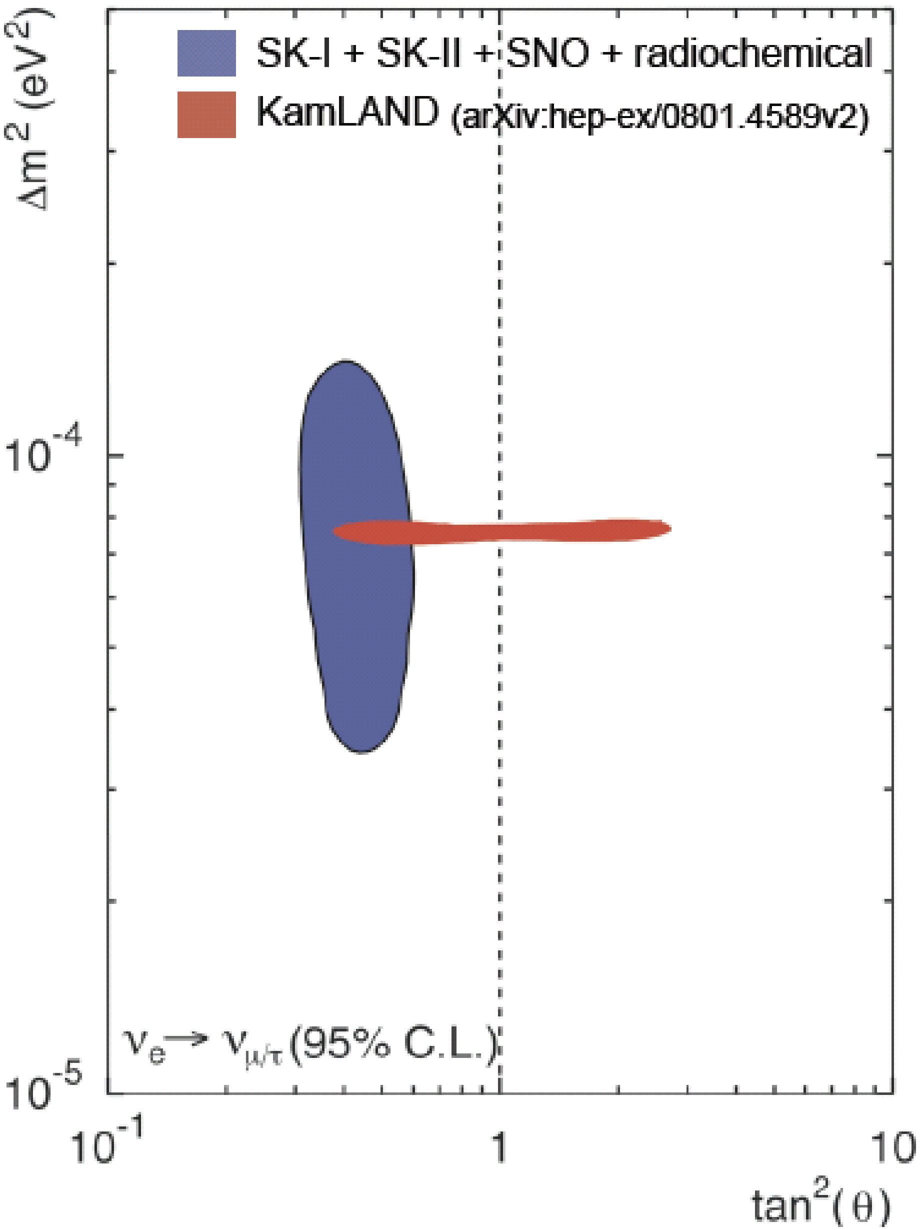


^{8}B flux constrained to SNO Salt Phase NC flux

S.N. Ahmed et al., PRL92 (2004) 181301

From J Raaf

Solar ν Oscillation (SK + other solar expts.)



SNO data:

371-day salt phase (CC & NC fluxes)
306-day pure D_2O phase (A_{D-N})

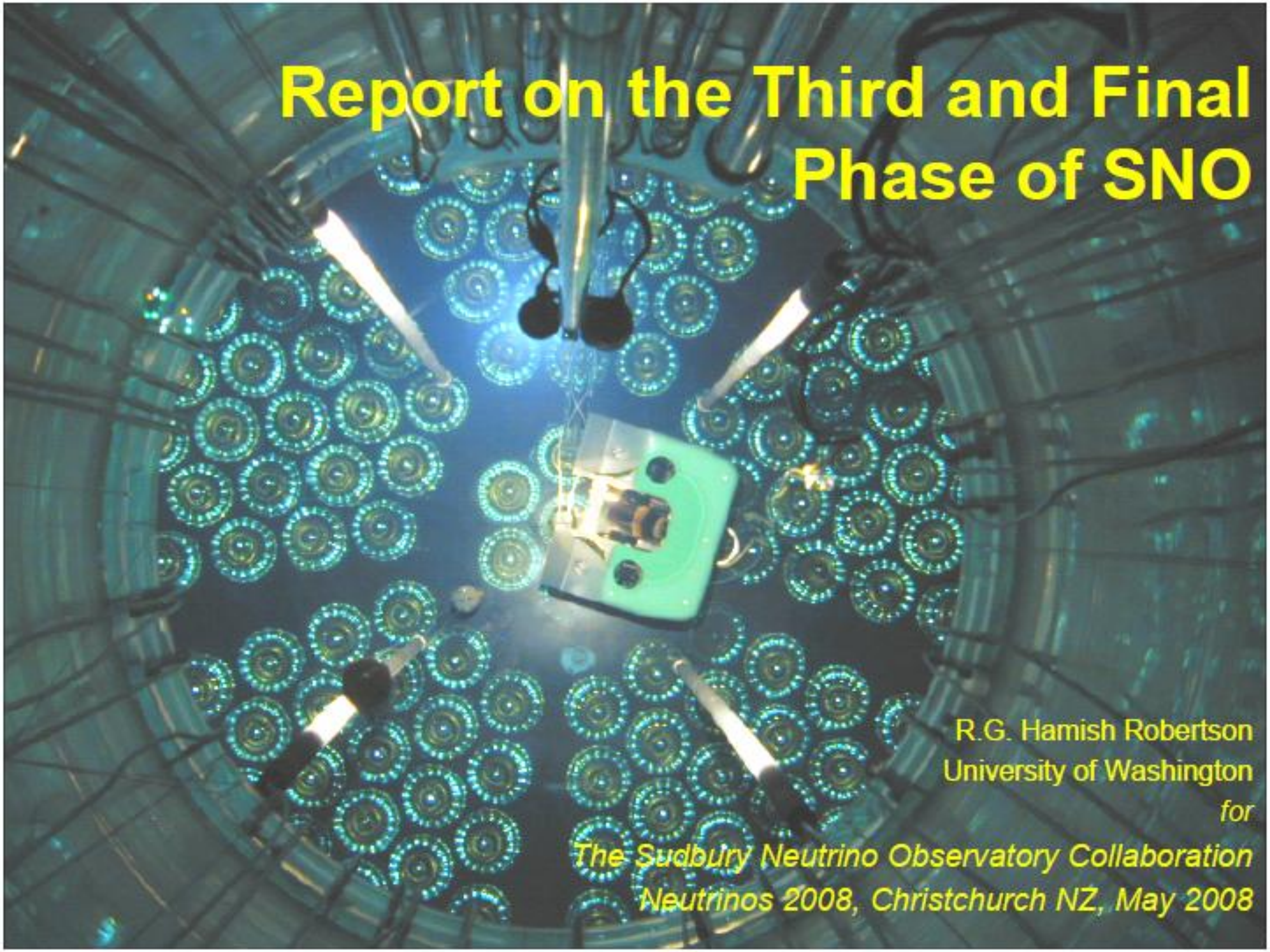
Radiochemical data:

Homestake
SAGE
GALLEX

Combined experimental data allow us to measure the oscillation parameters in this framework...

...but we would still like to observe predicted upturn at low energy

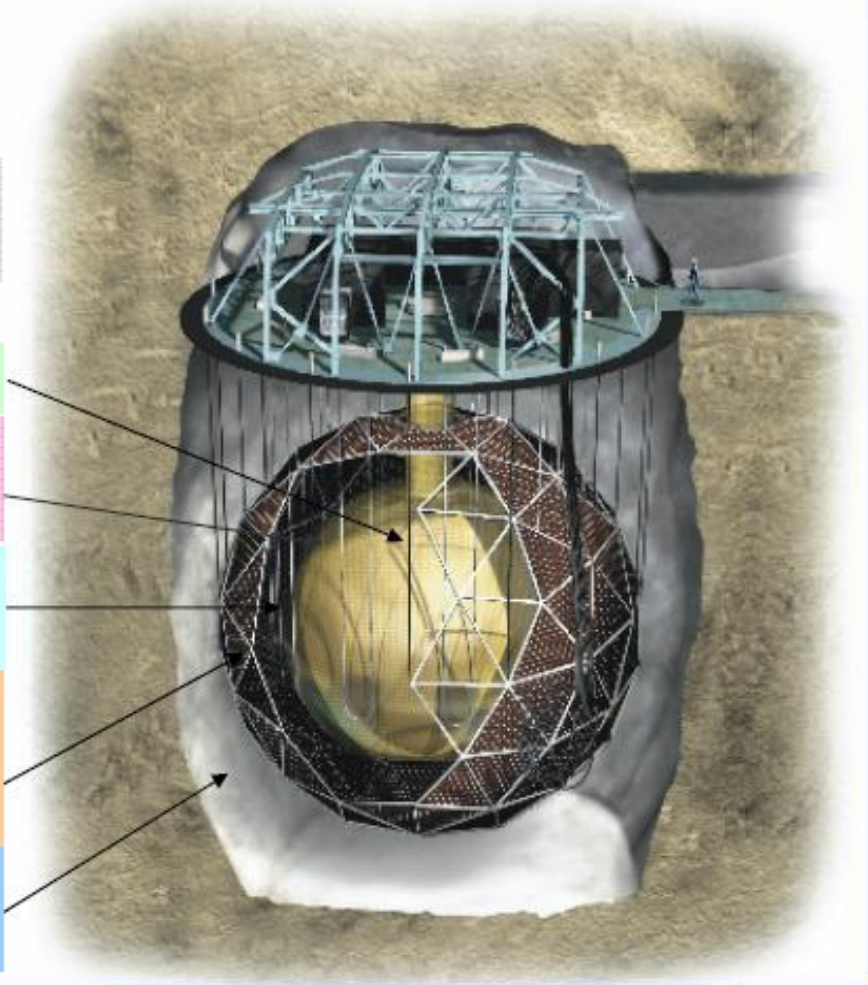
From J Raaf



Report on the Third and Final Phase of SNO

R.G. Hamish Robertson
University of Washington
for
The Sudbury Neutrino Observatory Collaboration
Neutrinos 2008, Christchurch NZ, May 2008

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:

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{ES}$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{NC}$$

3 neutron detection methods:

$$n + d \rightarrow t + \gamma + 6.25 \text{ MeV}$$

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

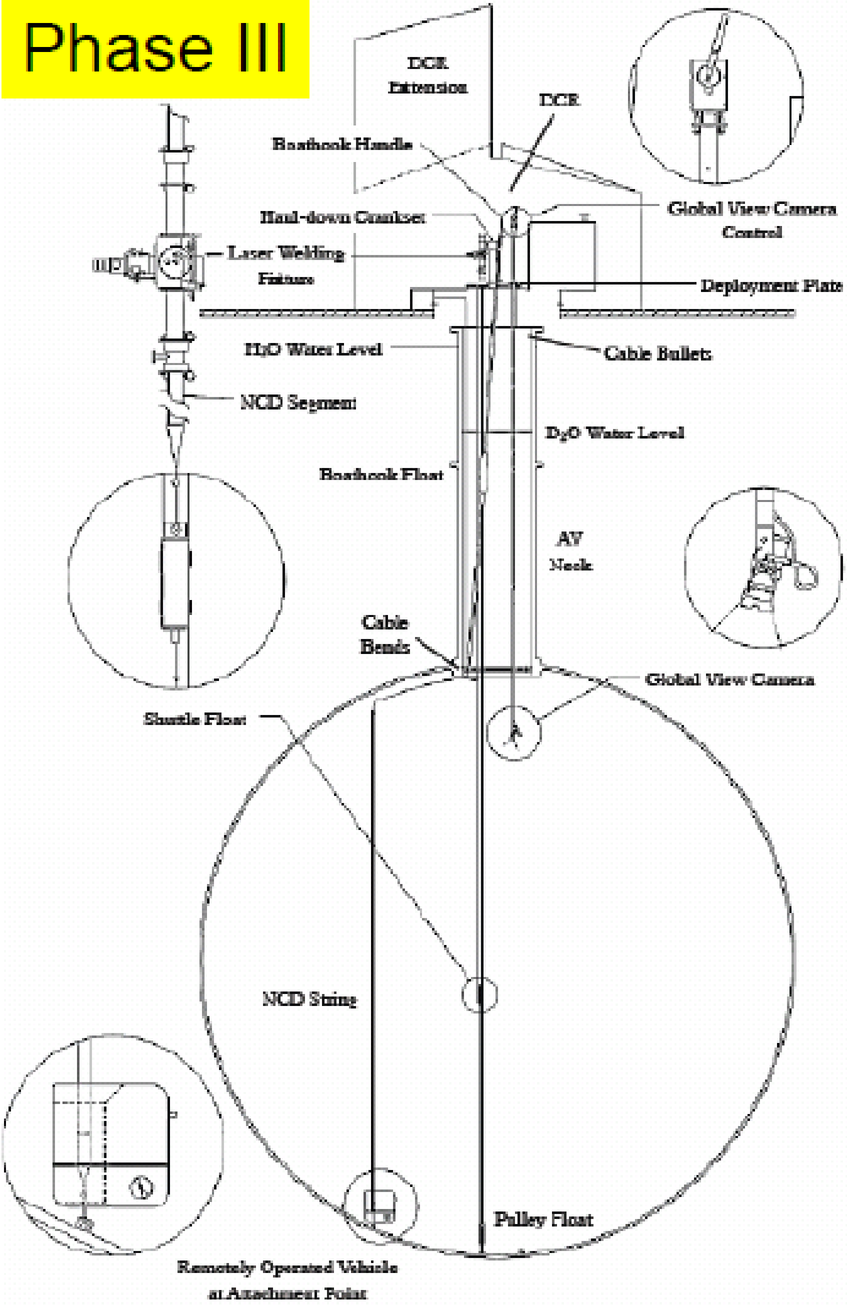
$$\boxed{n + {}^{3}He \rightarrow p + t + 0.76 \text{ MeV}}$$

3 Phases:

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

From Robertson

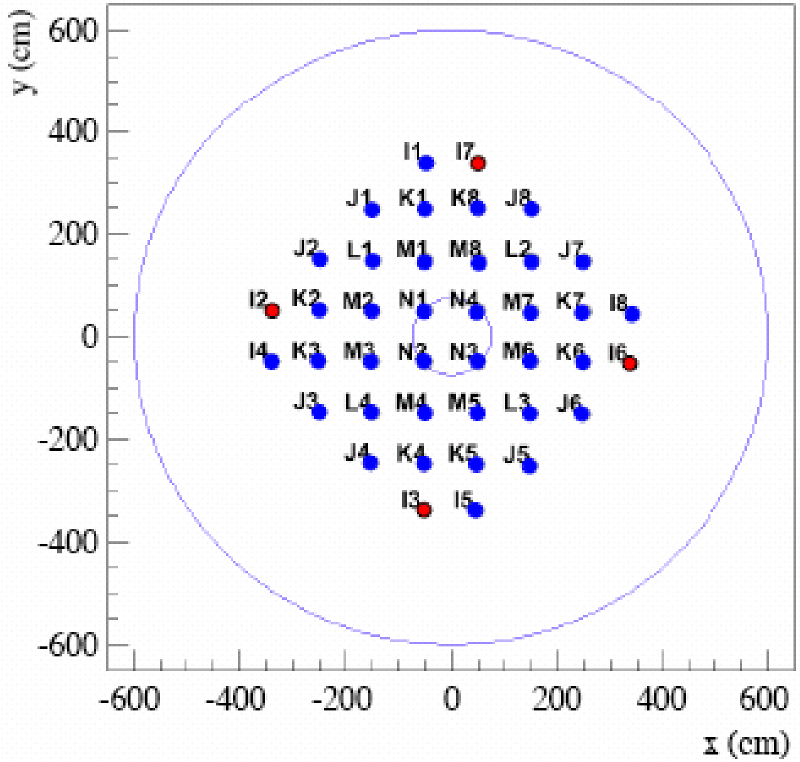
Phase III



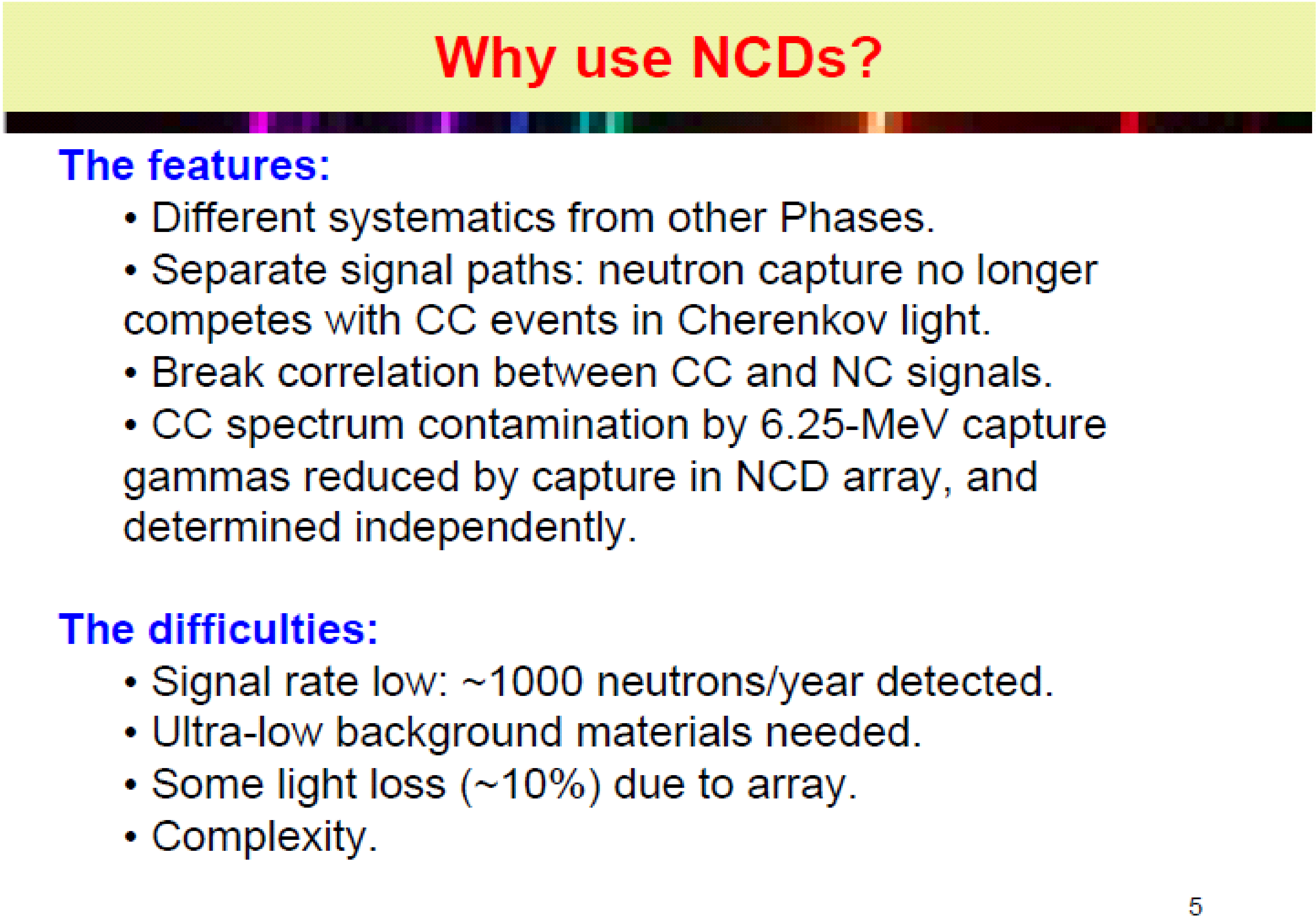
Counters 2 - 3m long laser-welded together and deployed by a submersible vehicle.

36 strings of ^{3}He, 4 strings of ^{4}He on a 1 x 1 m grid.

Total length 398 m



From Robertson



Why use NCDs?

The features:

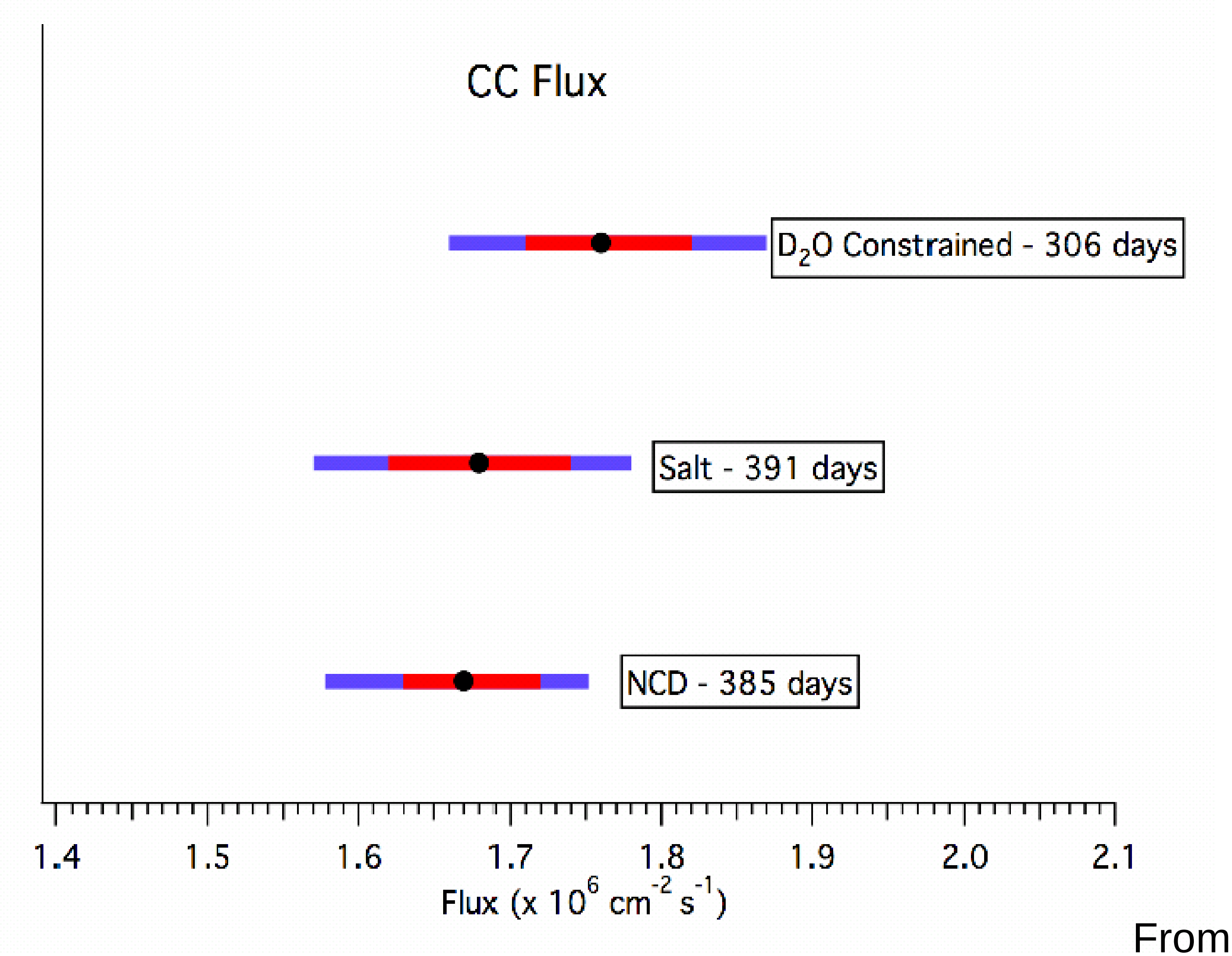
- Different systematics from other Phases.
- Separate signal paths: neutron capture no longer competes with CC events in Cherenkov light.
- Break correlation between CC and NC signals.
- CC spectrum contamination by 6.25-MeV capture gammas reduced by capture in NCD array, and determined independently.

The difficulties:

- Signal rate low: ~1000 neutrons/year detected.
- Ultra-low background materials needed.
- Some light loss (~10%) due to array.
- Complexity.

From Robertson

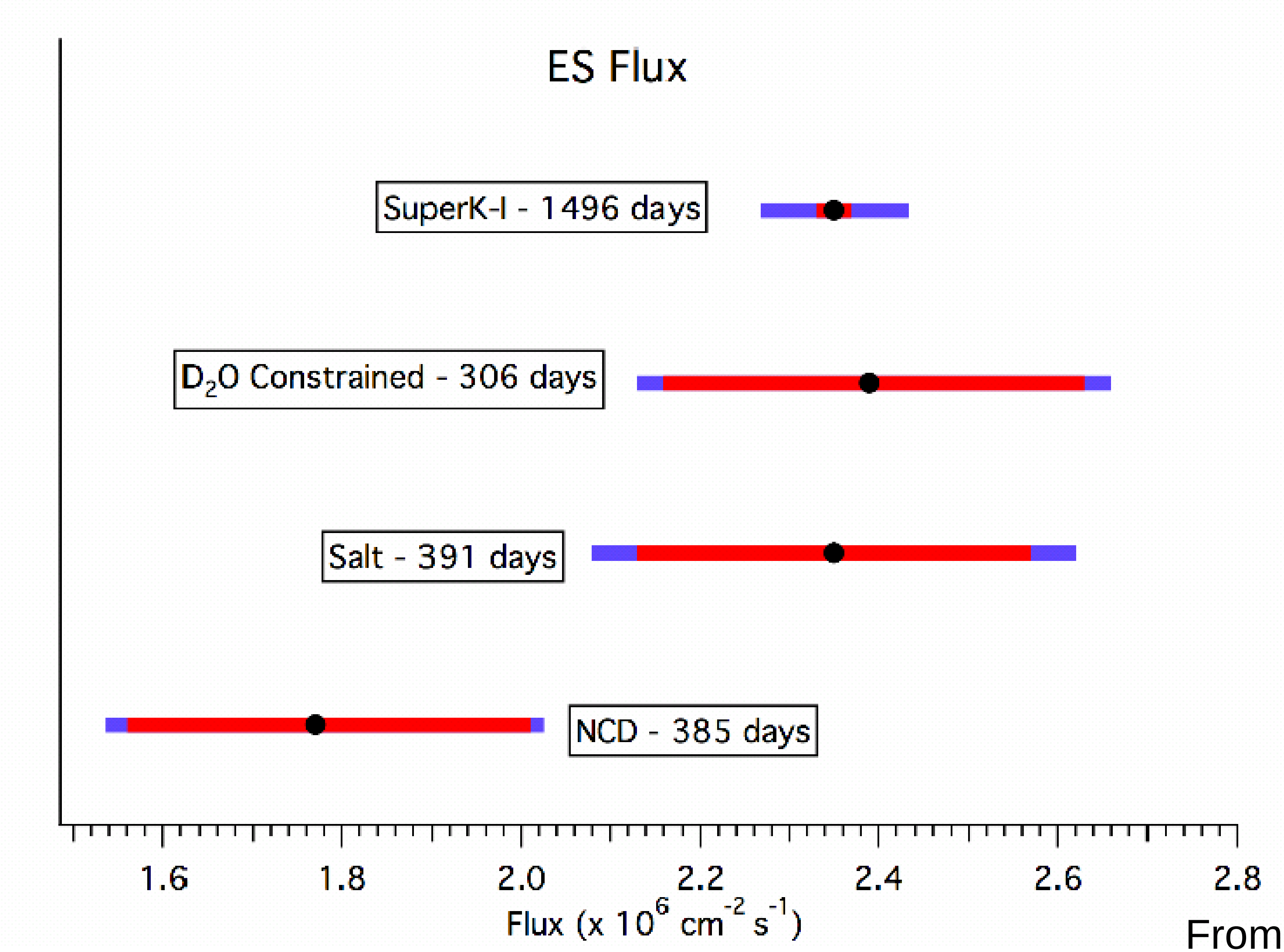
SNO CC Flux: 3 Phases



From Robertson

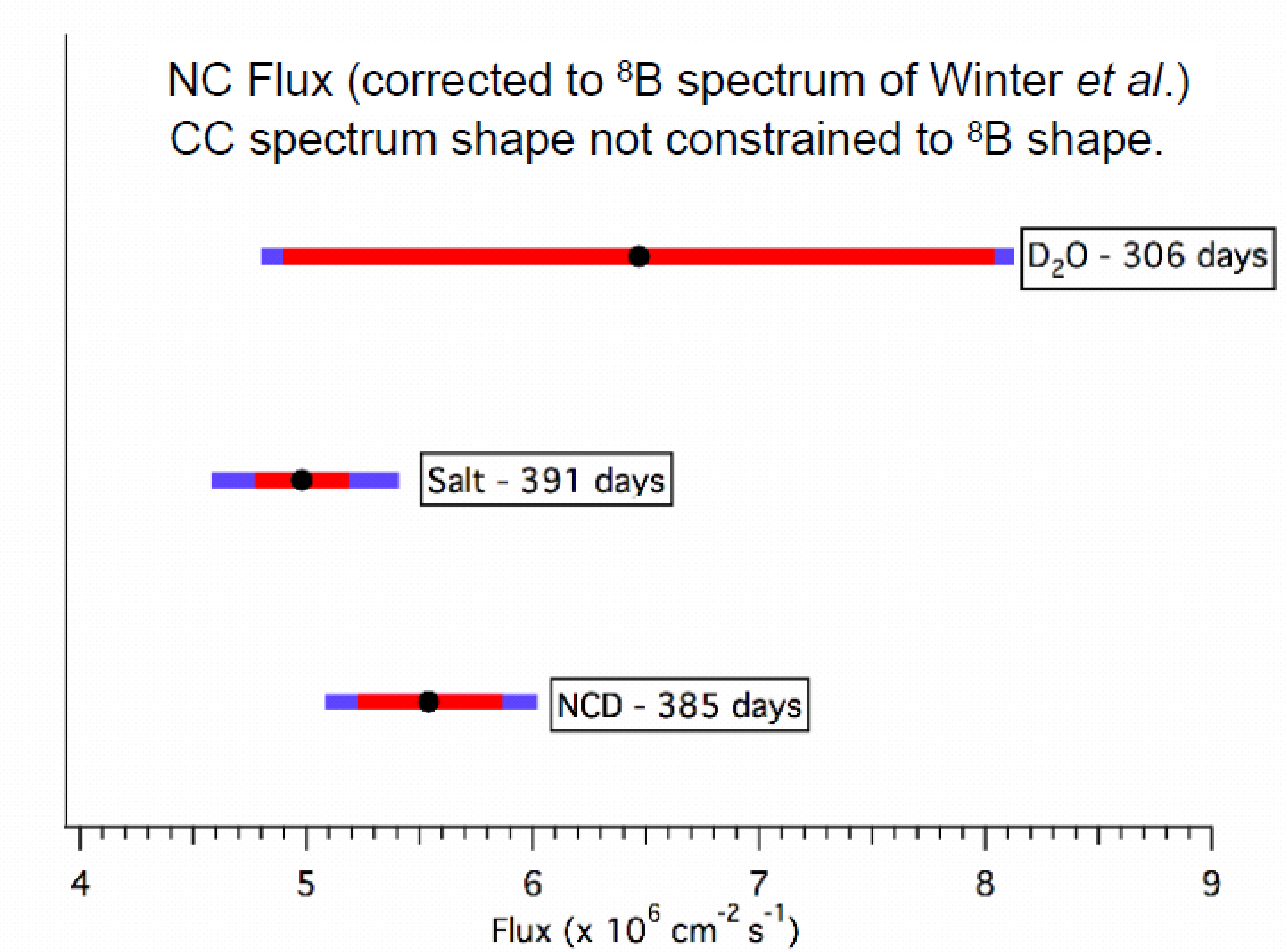
SNO, S-K ES Flux

p-value for consistency of NC/CC/ES in the salt & NCD phases + D_2O NC(unconstr) is 32.8%



From Robertson

SNO NC Flux: 3 Phases



🟥 stat 🟦 stat + syst

From Robertson

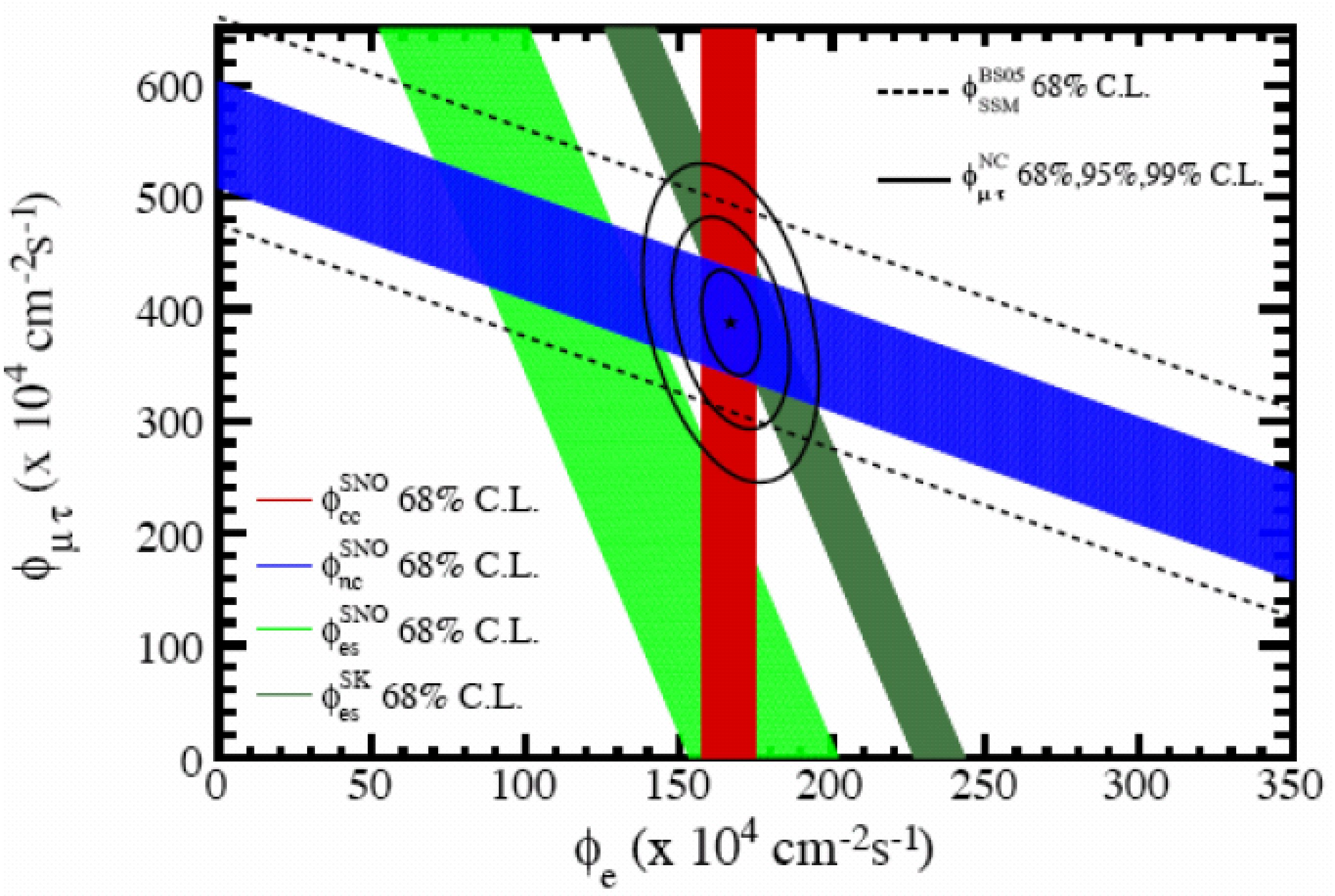
Results from SNO NCD Phase & Super-K

Preliminary

Fluxes

(10^4 cm^{-2} s^{-1})

ν_e:	167(9)
ν_{ES}:	177(26)
ν_{total}:	554(48)
ν_{SSM}:	569(91)



ϕ_{SSM} = 569(1±0.16) x 10^4 cm^{-2} s^{-1} (BSB05-OP: Bahcall, Serenelli, Basu Ap. J. 621, L85, 2005).

Super-K: PRD 73, 112001, 2006

From Robertson

391- day salt results

$$\phi_{CC} = 1.68 \ {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \ {}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

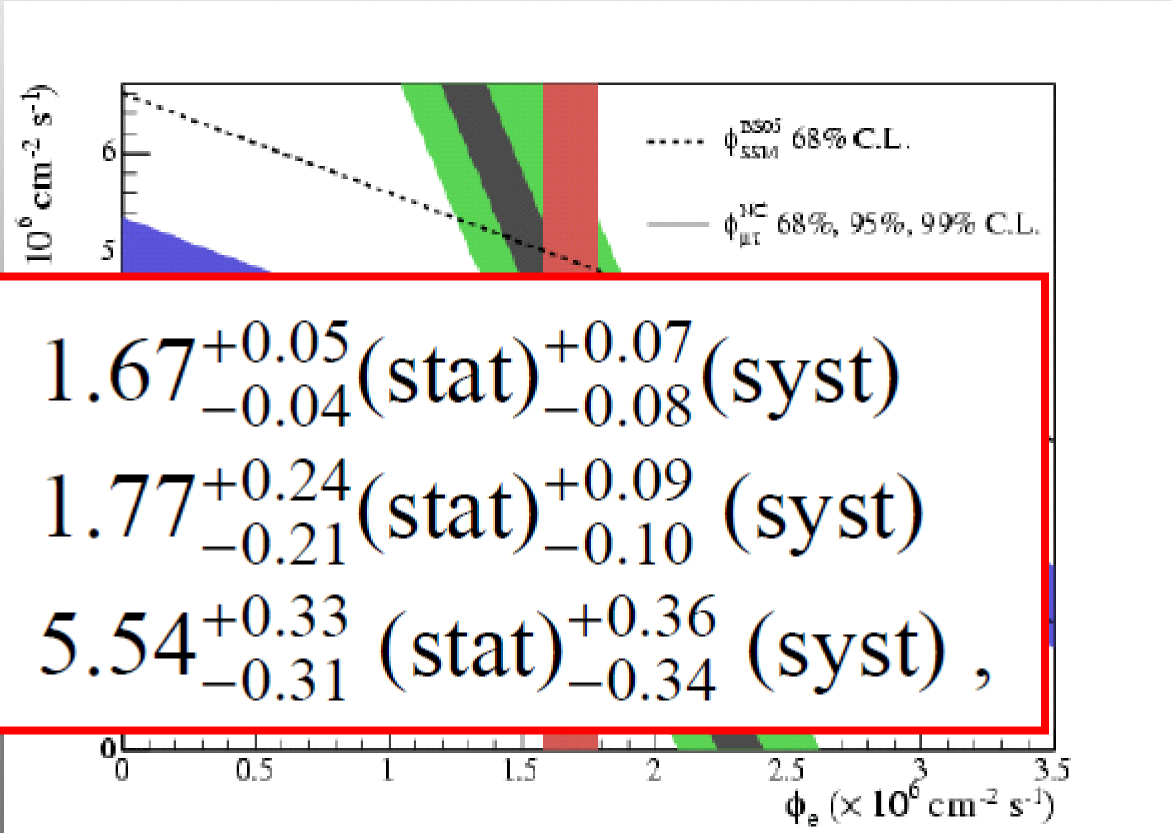
$$\phi_{ES} = 2.35 \ {}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

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

In units of 10^{-6} cm^{-2} s^{-1}

$$\Delta m^2 = 8.0^{+0.4}_{-0.3} \times 10^{-5} \ \text{eV}^2$$

$$\theta = 33.9^{+1.6}_{-1.6} \quad \text{deg}$$



$$\phi^{SNO}_{CC} = 1.67^{+0.05}_{-0.04}(\text{stat})^{+0.07}_{-0.08}(\text{syst})$$

$$\phi^{SNO}_{ES} = 1.77^{+0.24}_{-0.21}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$$

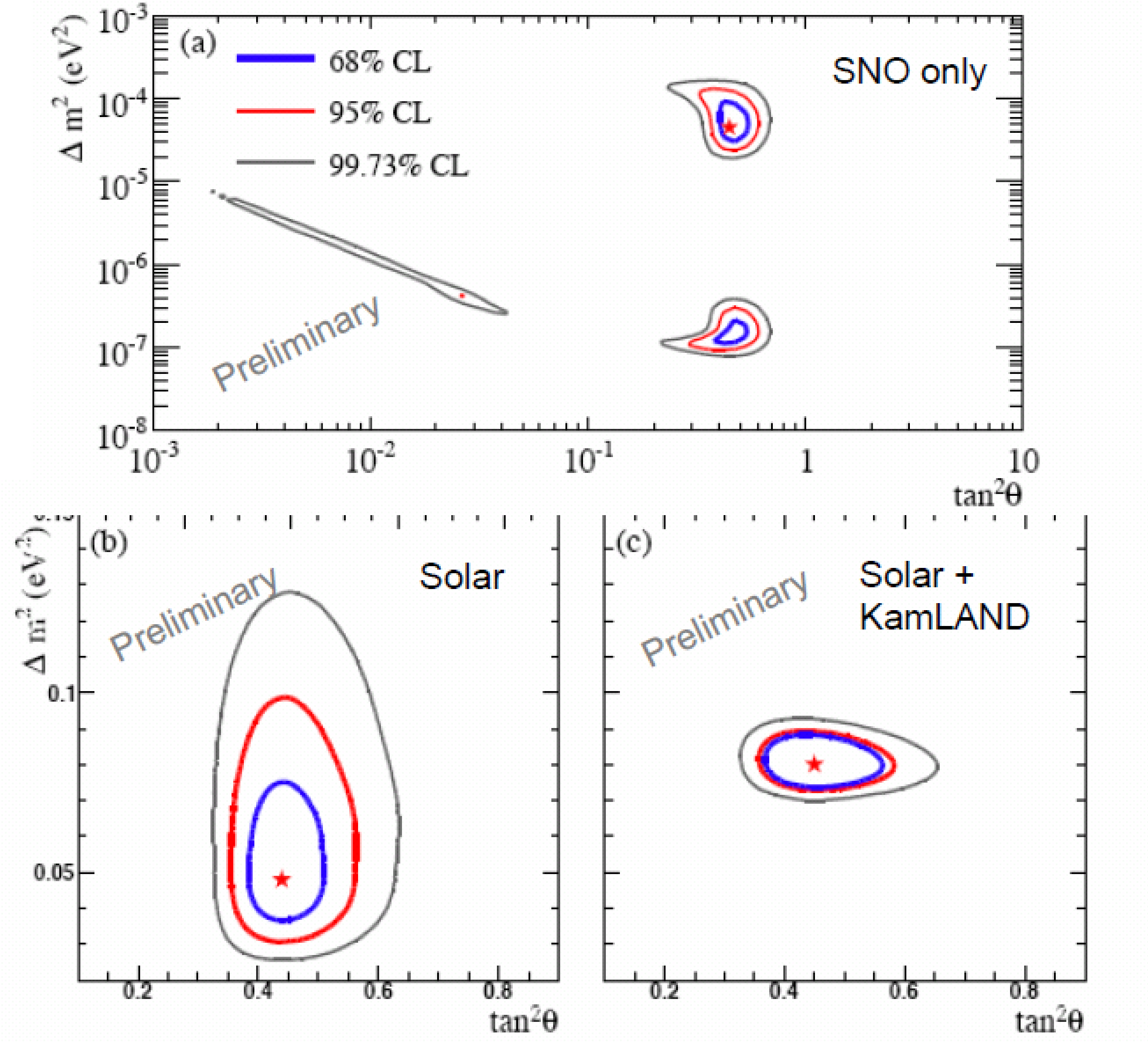
$$\phi^{SNO}_{NC} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst}),$$

PRC **72**, 055502 (2005)

From Robertson

2-Neutrino Oscillation Contours

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033 \text{ (total).}$$



Cl-Ar
Super-K
SAGE
Gallex
GNO
SNO
Borexino

766 t-y KamLAND

From Robertson

Solar + KamLAND fit results (preliminary)

$$\Delta m^2 = 7.94^{+0.42}_{-0.26} \times 10^{-5} \text{ eV}^2$$

$$\tan^2\theta = 0.447^{+0.047}_{-0.043}$$

$$\theta = 33.8^{+1.4}_{-1.3} \quad \text{degrees}$$

$$\phi_{8B} = 0.873(1 \pm x)\phi_{8B(BSB05-OP)}$$

2-neutrino mixing model.
Marginalized 1-σ uncertainties.
All SNO phases.
KamLAND: PRL 94, 081801 (2005).
x to be published later.

This work:

- NCD results agree well with previous SNO phases. Minimal correlation with CC. Different systematics.
- New precision on θ

Future work:

- 3-phase analysis
- 3-neutrino analysis
- LETA (Low Energy Threshold Analysis)
- *hep* flux
- Day-night, other variations
- Muons, atmospheric ν

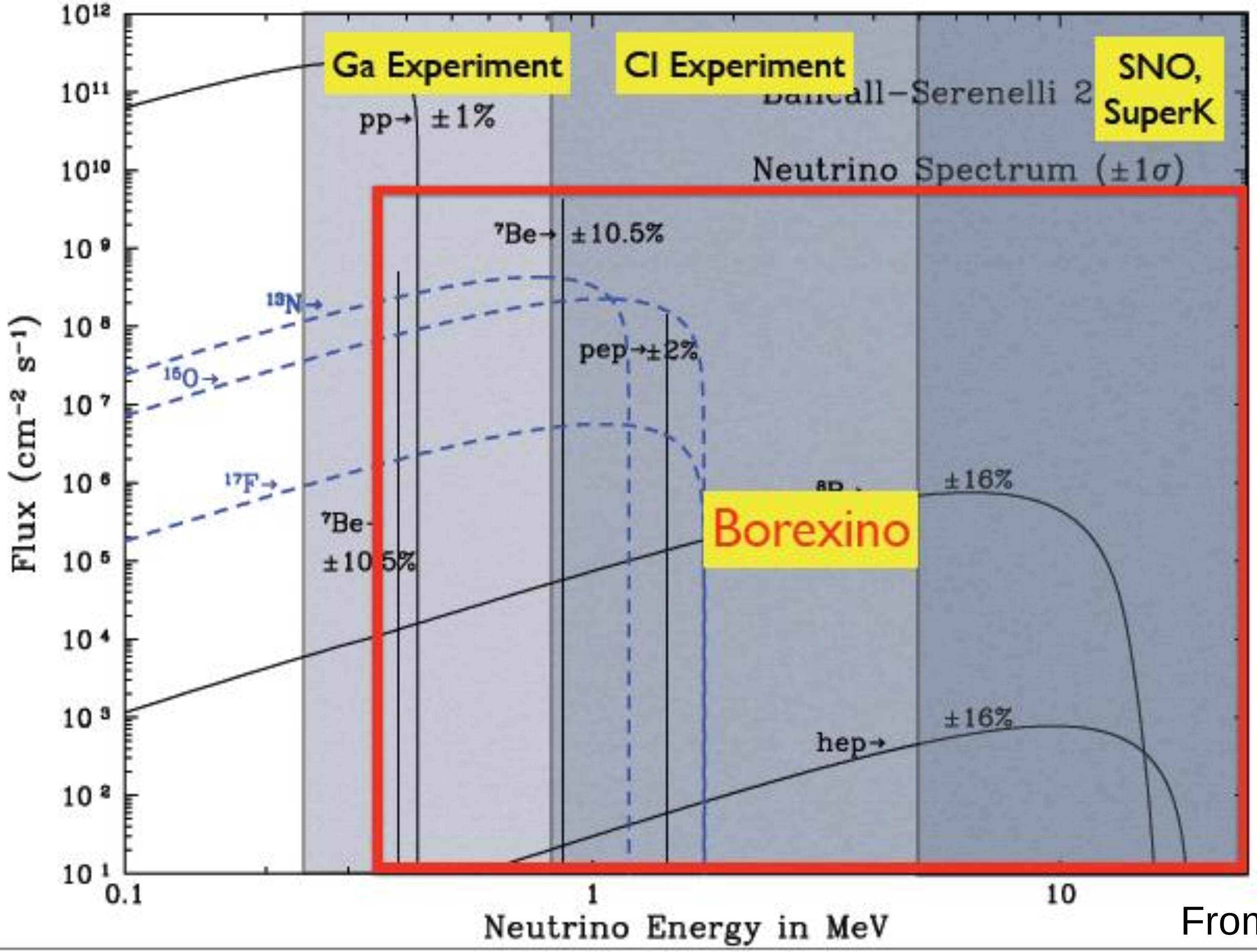
From Robertson

192 days of Borexino

Neutrino 2008
Christchurch, New Zeland
May 26, 2008

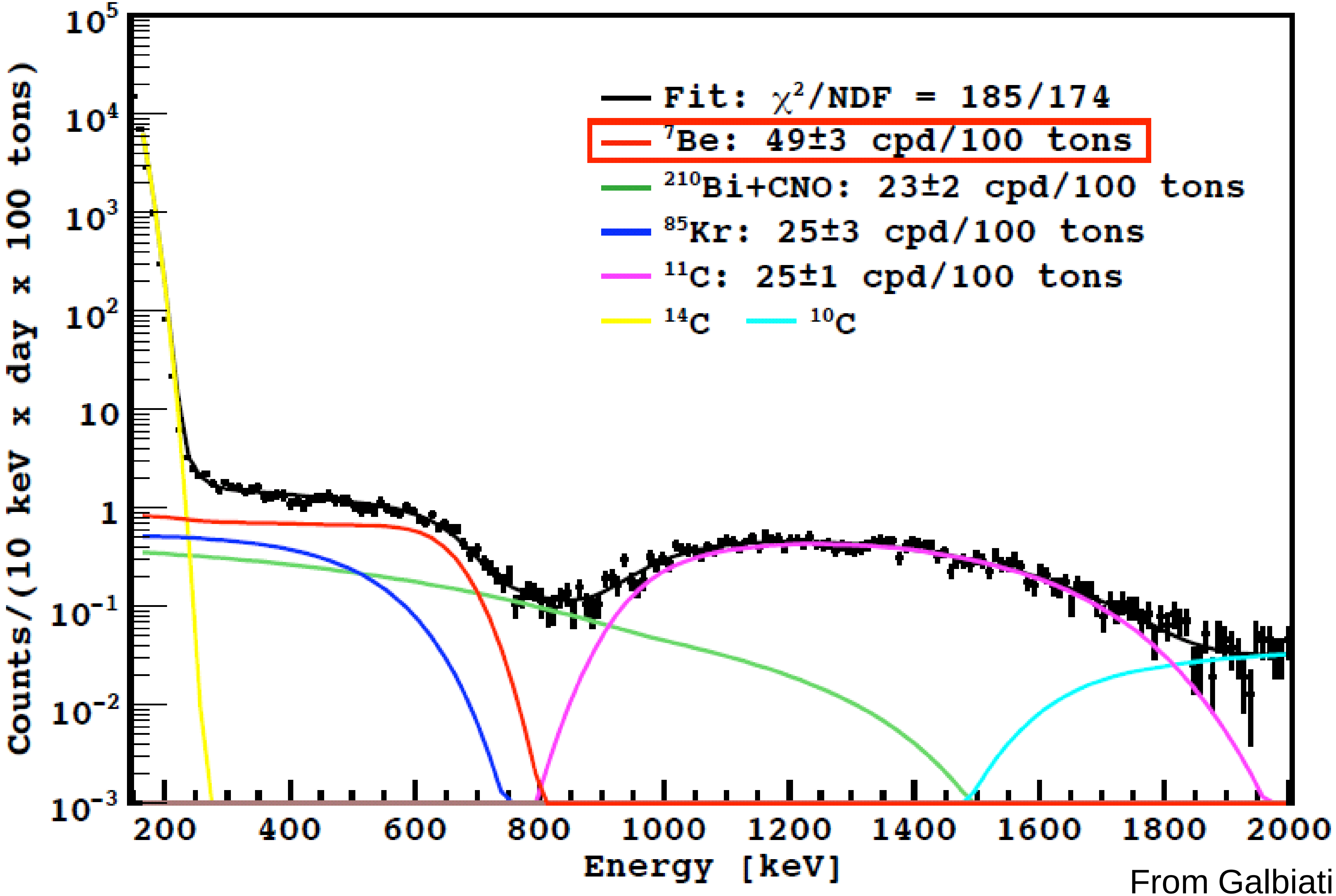
Cristiano Galbiati
on behalf of
Borexino Collaboration

Solar Neutrinos Spectrum



From Galbiati

New Results: 192 Days



From Galbiati

Systematic & Measurement

Expected interaction rate in absence of oscillations:

75±4 cpd/100 tons

for LMA-MSW oscillations:

48±4 cpd/100 tons

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

^{7}Be Rate:

$49 \pm 3_{stat} \pm 4_{syst}$ cpd/100 tons

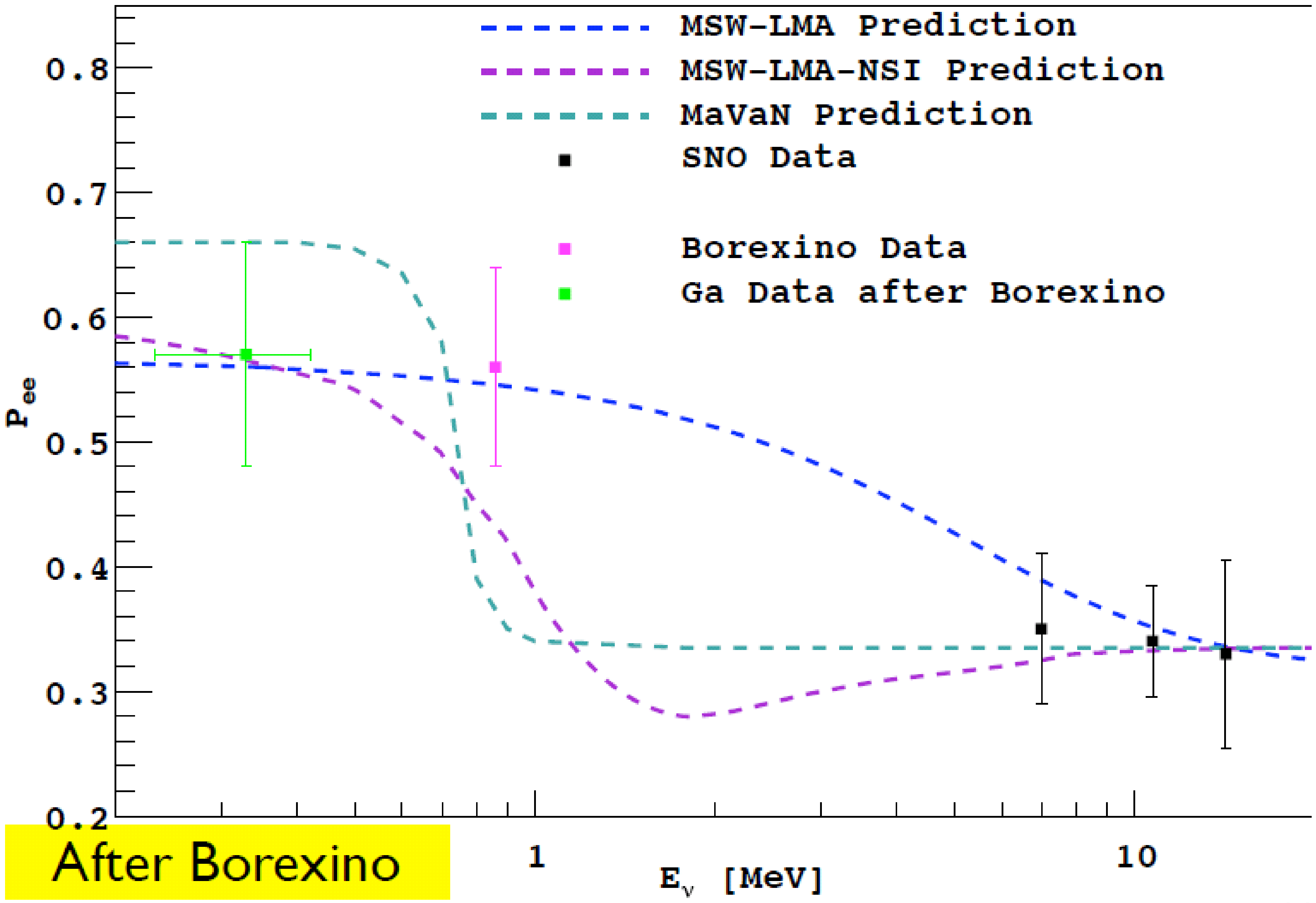
From Galbiati

ν_e Survival Probability Global Analysis

- We determine the survival probability for ^{7}Be and *pp* electron neutrinos ν_e under the assumption of the high-Z BPS07 SSM and using input from all solar experiments (cfr. Barger et al., PRL 88, 011302 (2002))
  - $P_{ee}\left({}^7\mathrm{Be}\right) = 0.56 \pm 0.08$
  - $P_{ee}\left(pp\right) = 0.57 \pm 0.09$

From Galbiati

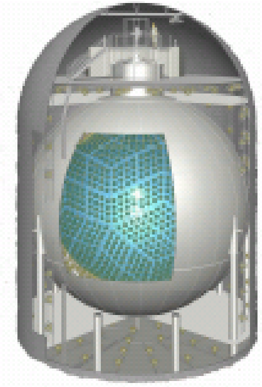
Solar Neutrino Survival Probability



After Borexino

From Galbiati

KamLAND Neutrino Oscillation Results and Solar Future

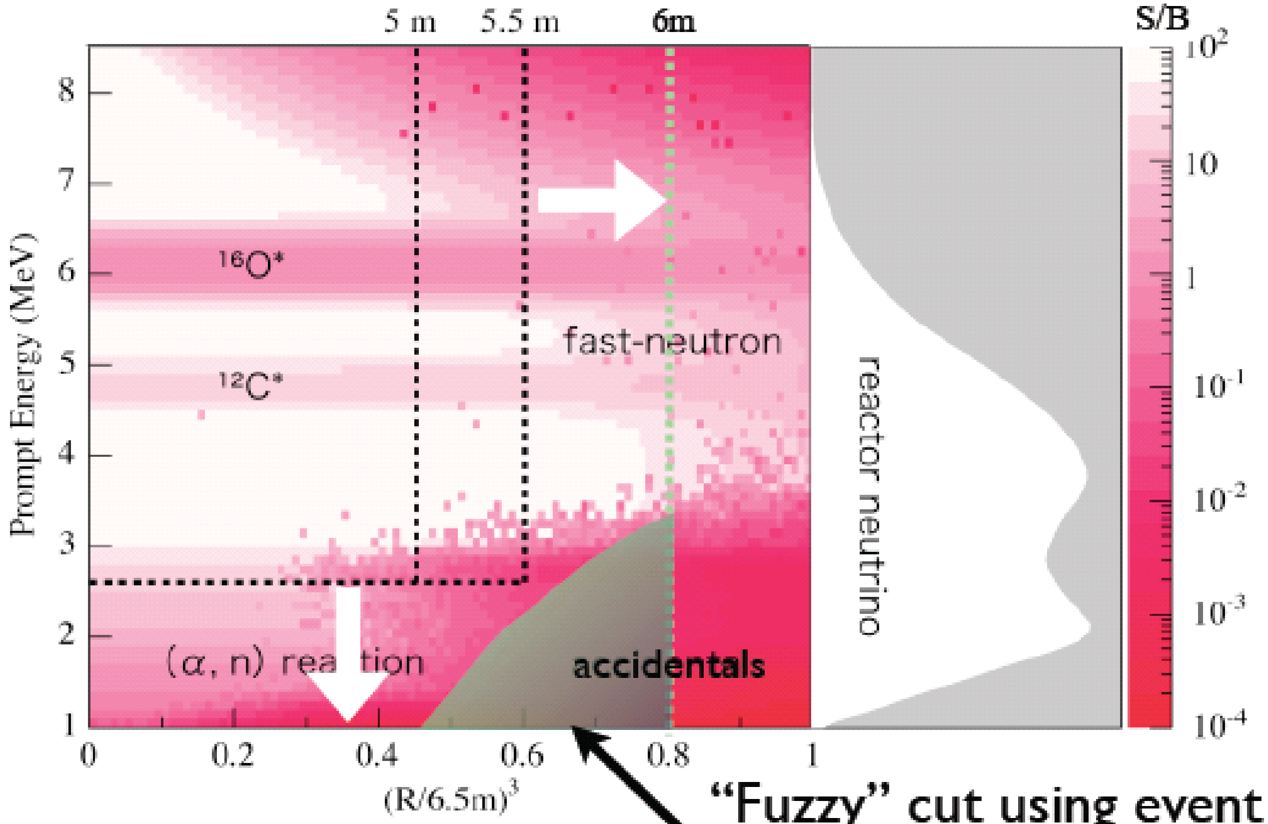


Patrick Decowski (UC Berkeley)
for the
KamLAND Collaboration

Neutrino 2008, Christchurch, NZ

Analysis Improvements

	Max Radius(m)	Lifetime(days)	Exposure(ton-yr)	Exposure Increase
KL2002	5	145	162	1x
KL2004	5.5	515	766	4.7x
Latest	6	1491	2881	17.8x

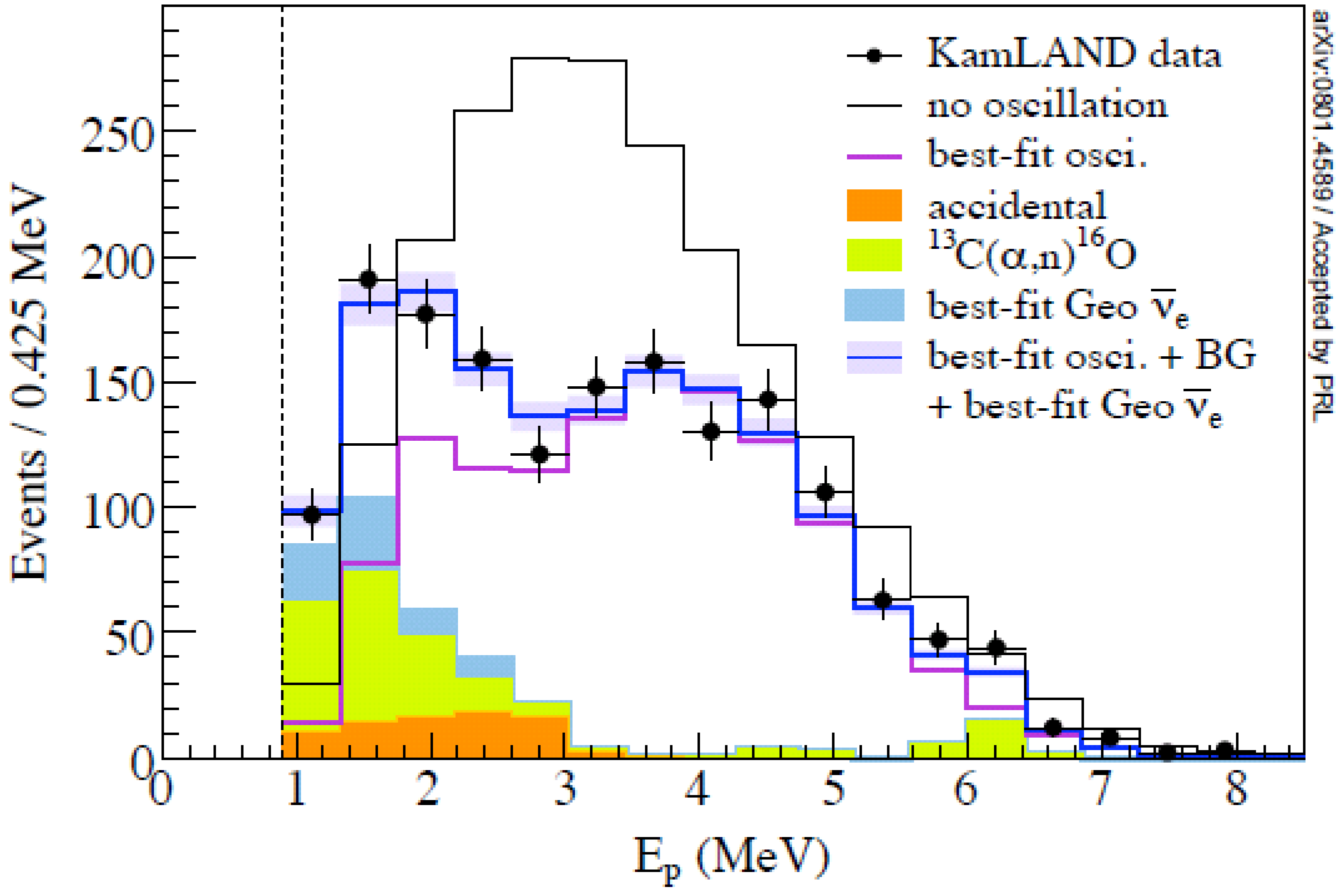


Energy threshold from 2.6MeV → 1.0MeV (Inverse Beta Decay threshold)

“Fuzzy” cut using event characteristics to distinguish signal from accidentals

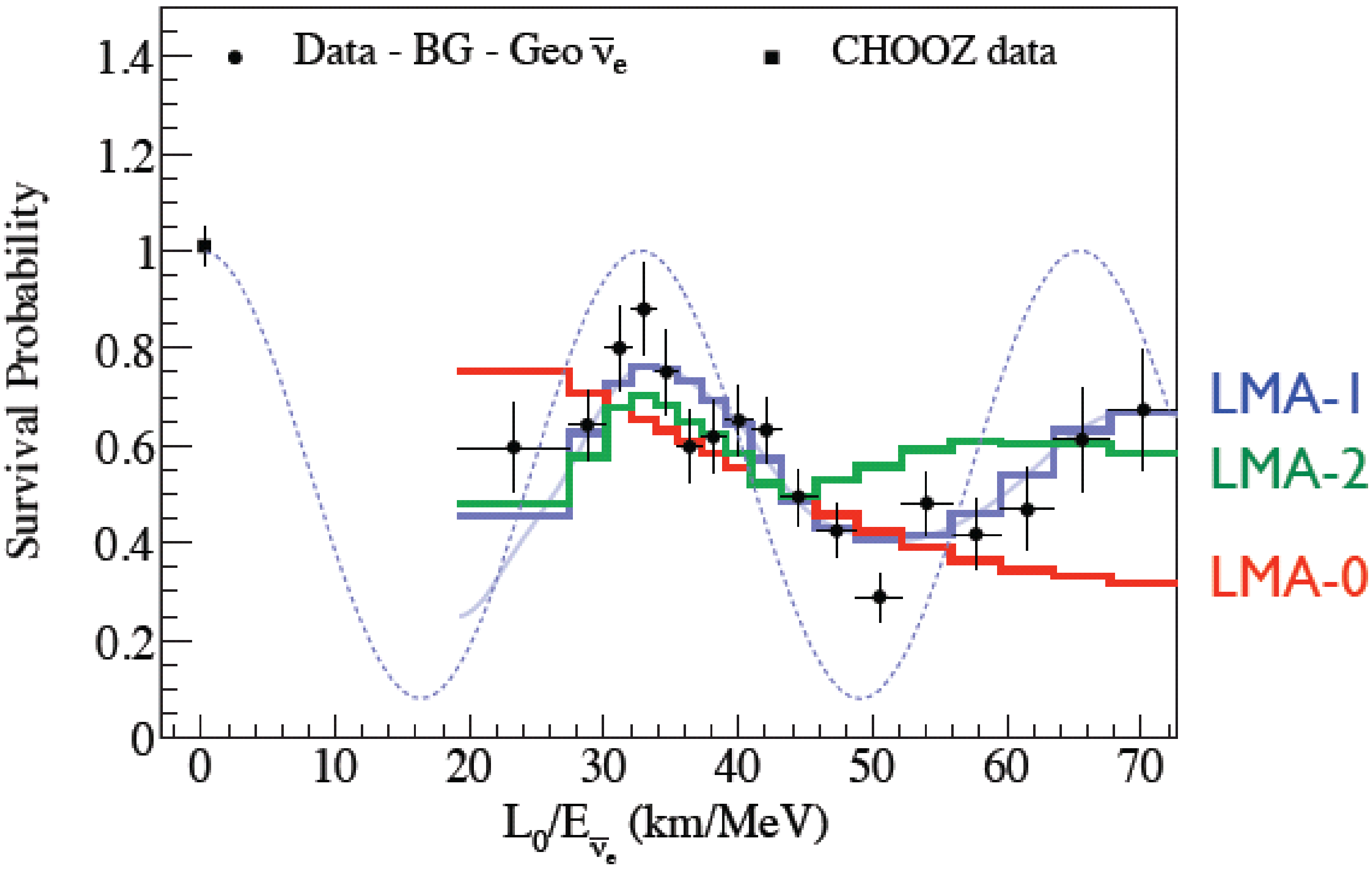
Energy Spectrum

From Mar 9, 2002 to May 12, 2007
1491 live days, 2881 ton-year exposure (3.8x KL2004)



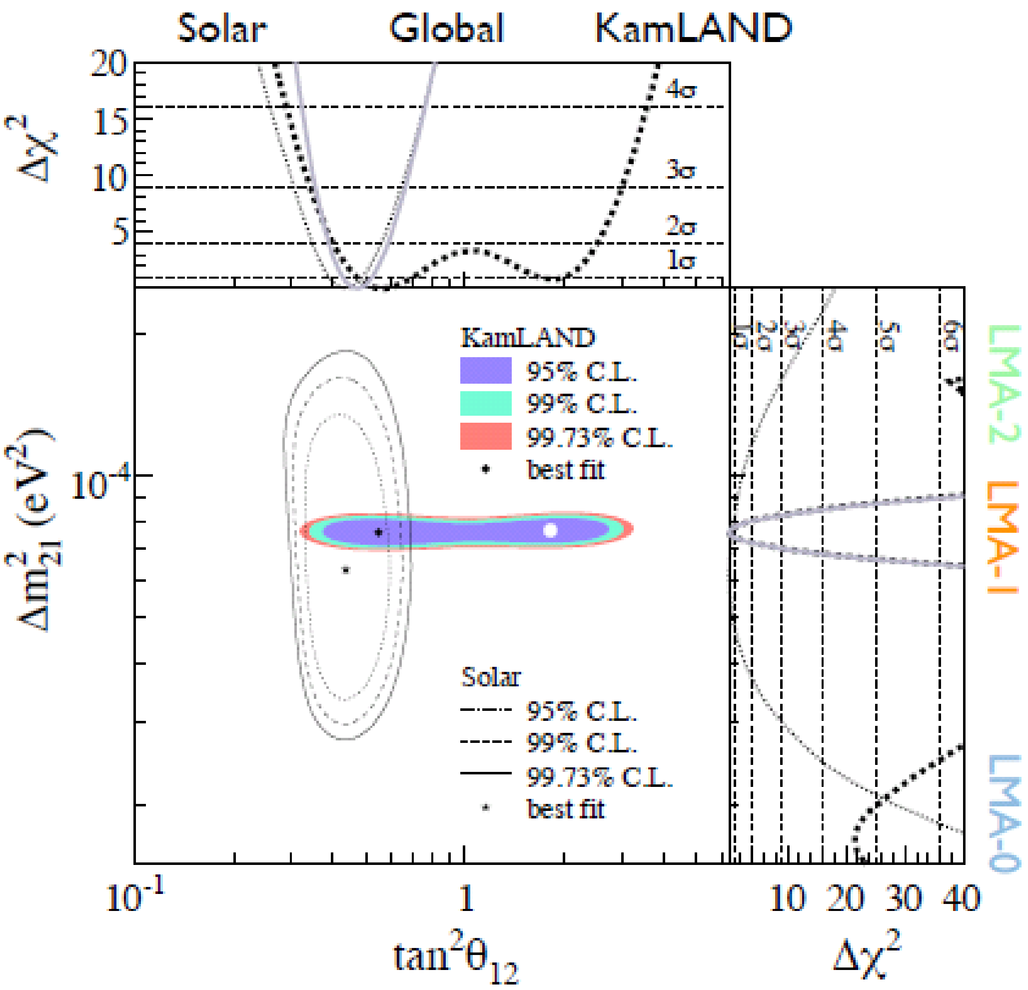
Fit to scaled no-oscillation spectrum excluded at 5.1σ

L/E Plot



$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$

Neutrino Oscillation Parameters



Best-fit light side:

$$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

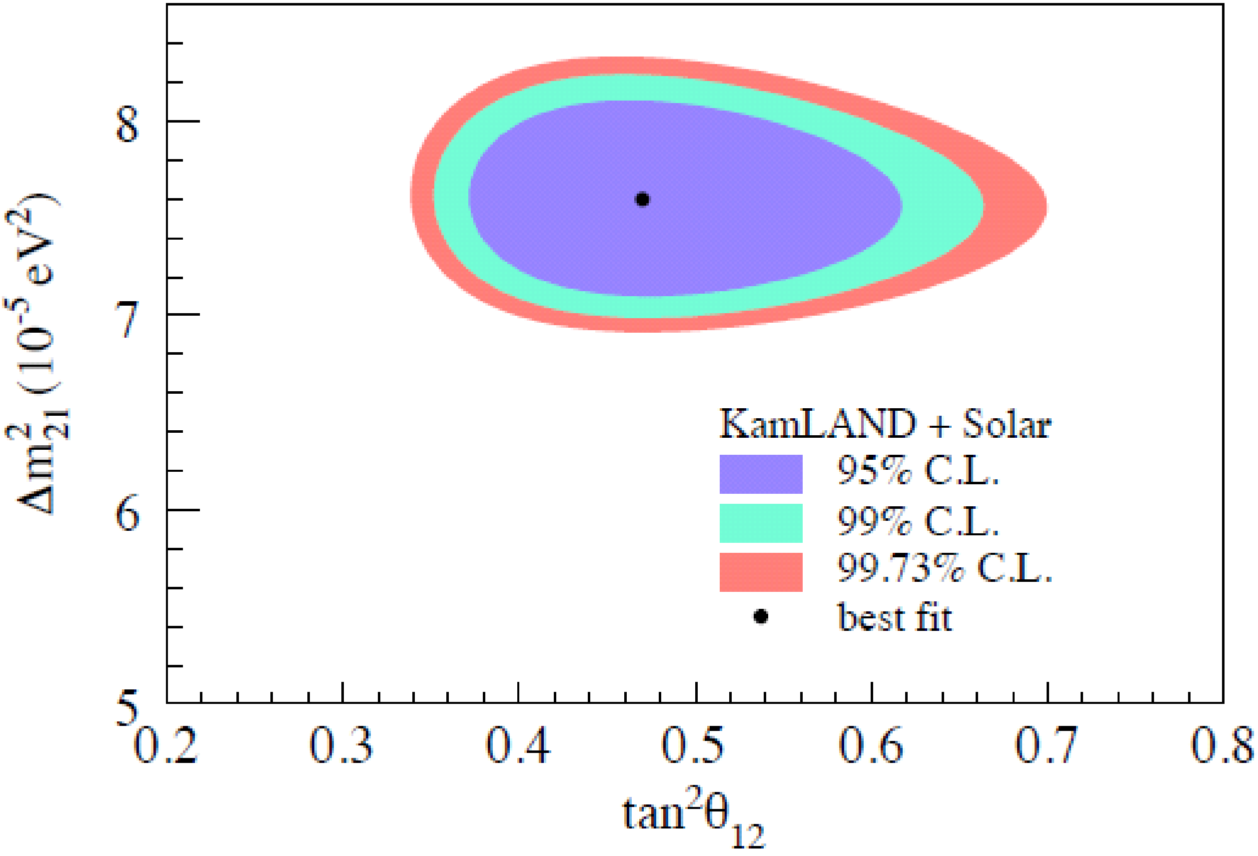
$$\tan^2\theta = 0.56^{+0.14}_{-0.09}$$

Best-fit dark side:

$$\Delta m^2 = 7.64 \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta = 1.84$$

Global Analysis



Solar Experiments + KamLAND:

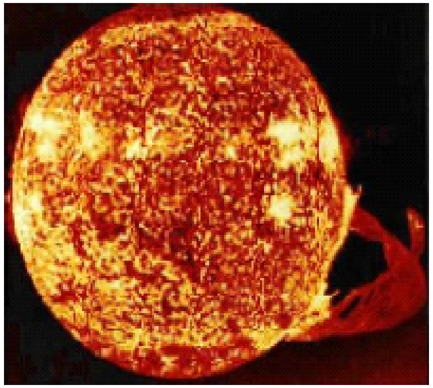
$$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$$

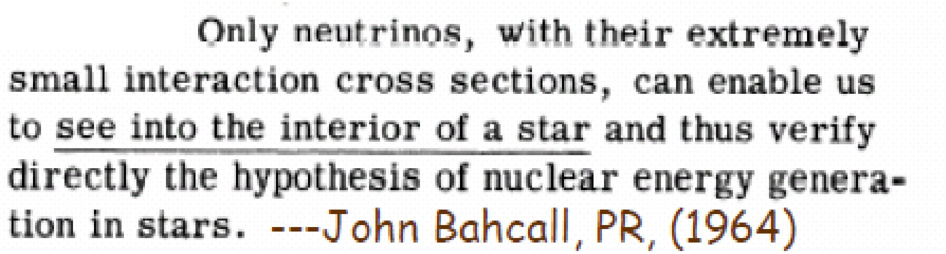
$$\tan^2\theta = 0.47^{+0.06}_{-0.05}$$

太陽ν観測の将来

Goals of the Future Solar ν Program

- Use neutrinos to understand the Sun (and other stars)





Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. ---John Bahcall, PR, (1964)

Example: The solar `metallicity problem':

- Helioseismology convinced `everyone' that SSM was correct
- Modern measurements of surface metallicity are lower than before
- Which makes SSM helioseismologic predictions wrong

But! CNO neutrinos tell us metallicity of solar core

→ Flux may differ by factor of 2 between old/new metallicity

(Maybe Jupiter and Saturn `stole' metals from solar photosphere?
---Haxton and Serenelli, astro-ph:0805.2013v1)

From Klein

Goals of the Future Solar ν Program

- Use neutrinos to understand the Sun (and other stars)

Measurements now precise enough to constrain SSM

(Bandyopadhyaya, Choubey, Srubabati Goswami, and Petcov, hep-ph/0608323v1)

With luminosity constraint:

Exp. Uncs. Theory Uncs.

$$\begin{aligned}
\phi(\mathrm{pp})_{\mathrm{measured}} &= (1.02 \pm 0.02 \pm 0.01)\phi(\mathrm{pp})_{\mathrm{theory}} \\
\phi(^{8}\mathrm{B})_{\mathrm{measured}} &= (0.88 \pm 0.04 \pm 0.23)\phi(^{8}\mathrm{B})_{\mathrm{theory}} \\
\phi(^{7}\mathrm{Be})_{\mathrm{measured}} &= (0.91^{+0.24}_{-0.62} \pm 0.11)\phi(^{7}\mathrm{Be})_{\mathrm{theory}}
\end{aligned}$$

Bahcall and Pinsonneault

But without constraint: $L_{\nu}/L_{¤}$ known only to 20-40%

→ `Unitarity' test that integrates over a lot of new physics

(most sensitive to pp flux)

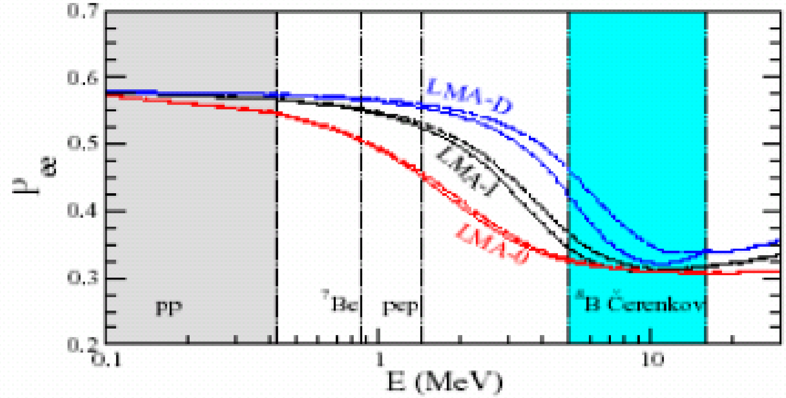
From Klein

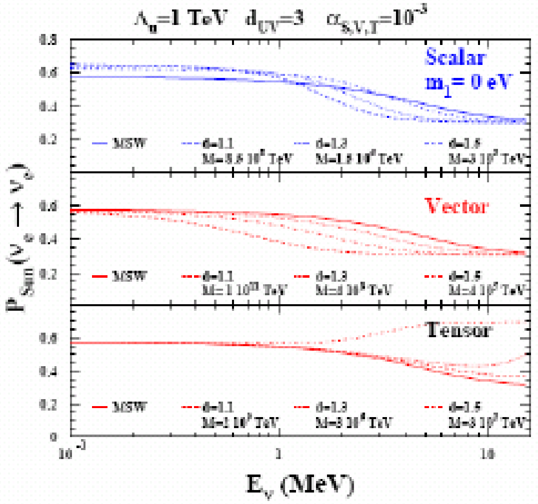
Goals of the Future Solar ν Program

- Can we observe MSW-specific signatures?

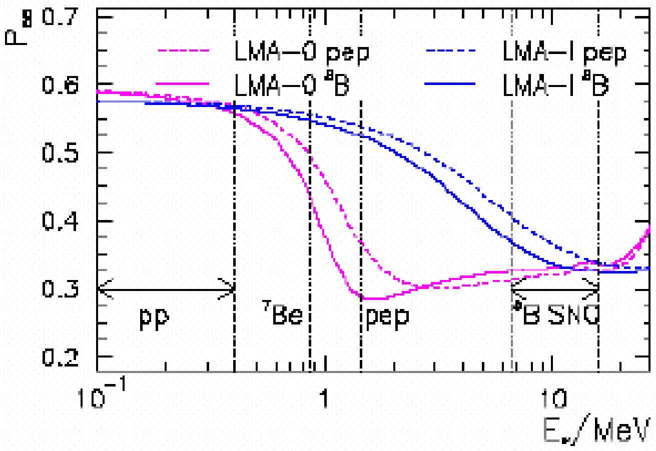
Nonstandard effects can be enhanced by MSW-like resonance

Miranda, Tortola, Valle, hep-ph/0406289 (2005)

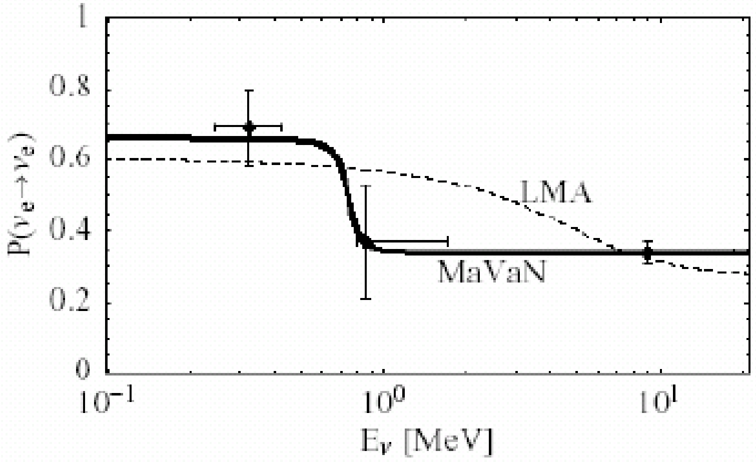




M. C. Gonzalez-Garcia, P. C. de Holanda,
E. Masso and
R. Zukanovich Funchalc,
hep-ph/0803.1180



Friedland, Lunardini, Peña-Garay, PLB 594, (2004)



Barger, Huber, Marfatia, PRL95, (2005)

From Klein

Unparticle effects

Effects in solar neutrinos

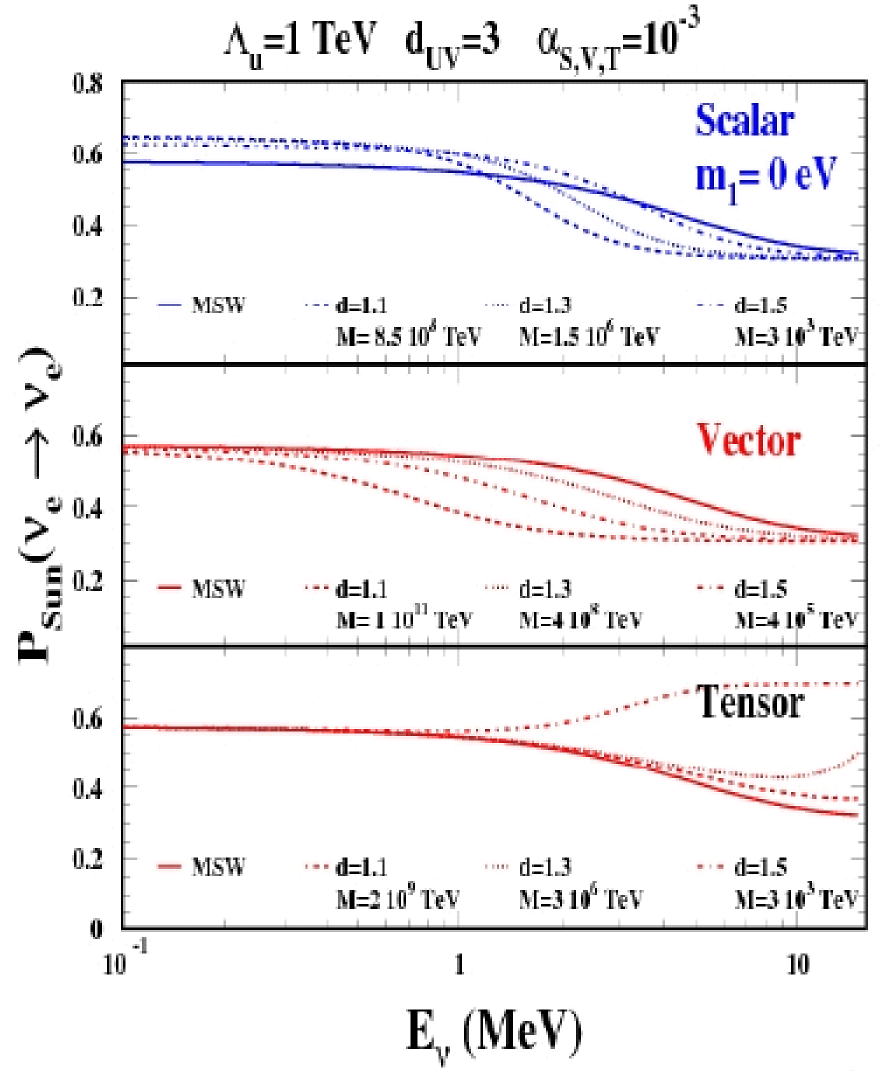
Neutrino decay: $\nu_i \rightarrow \nu_j$ U

L. Anchordoqui, H. Goldberg

Unparticle exchange:
modify mater potential
and effective neutrino mass
→ modify survival probability

M.C. Gonzalez-Garcia,
P.C. de Holanda,
R. Zukanovich-Funchal

M - mass of messenger
d_H - dimension of operator in hidden sector,
d - dimension of unparticle operator
Λ_U - infrared fixed point

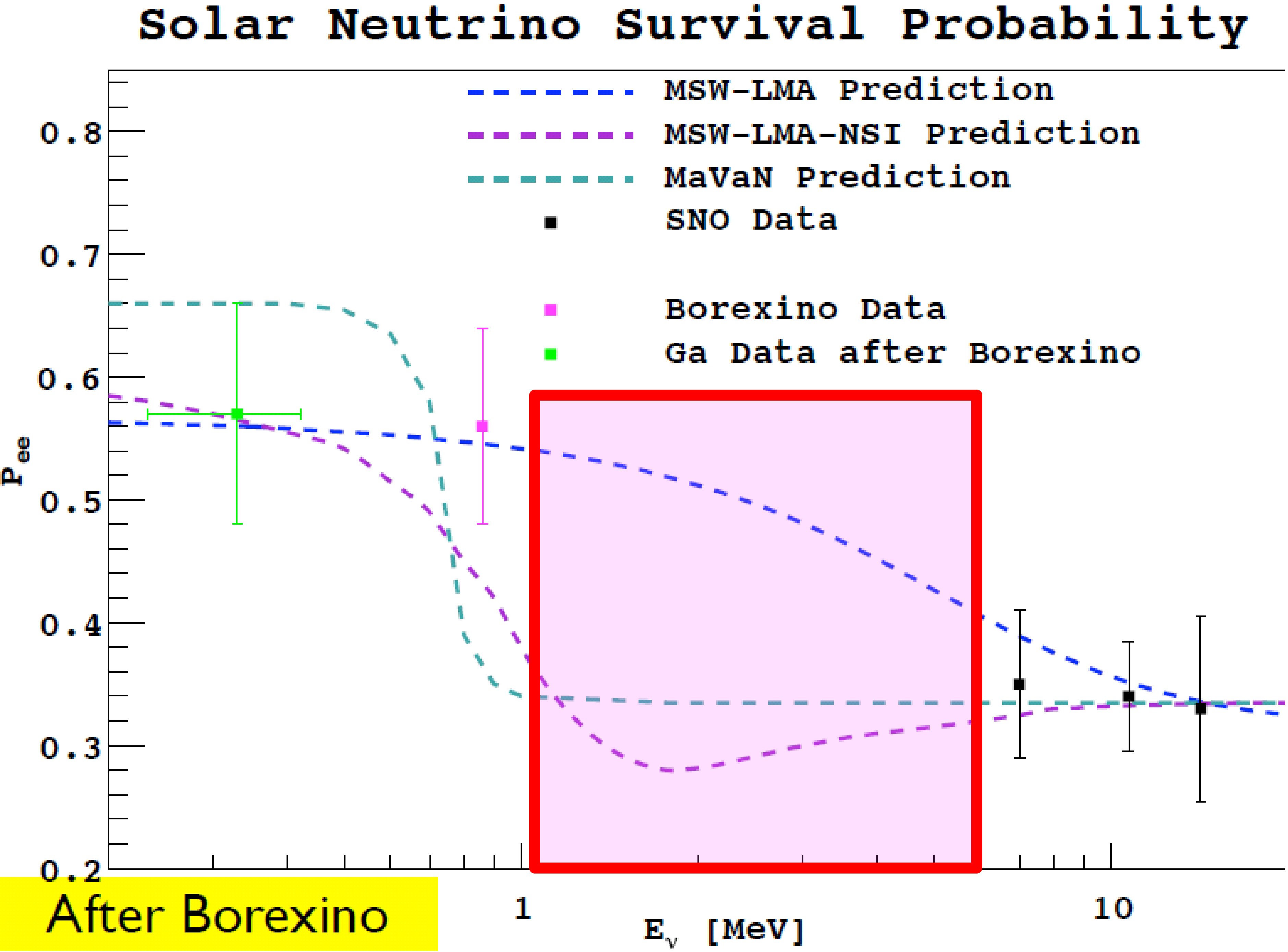


From Smirnov

Experiment	Detection Reaction	Targeted Solar νs	Technology	Other Physics	Status
KamLAND	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	^{7}Be,CNO, pep	Liq. scintillator	Reactor νs, geo-νs	Purification underway
SNO+	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pep, CNO	Liq. scintillator	0νββ, geo-νs	Engineering, purification
LENS	$\nu_e + {}^{115}In \rightarrow e^- + 2\gamma + {}^{115}Sn$	pp, ^{7}Be, pep	In-doped liq. scintillator	----------	Prototype bkd studies
XMASS	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic Xe	dark matter, 0νββ	800 kg stage in design
CLEAN	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic Ne	dark matter (DEAP/CLEAN)	0.1 and 1 ton engineering
MOON	$\nu_e + {}^{100}Mo \rightarrow e^- + {}^{100}Tc$	pp, ^{7}Be, pep	Scintillator/ Fiber sandwich	0νββ	Prototype for 0νββ
MUNU/TPC	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp, ^{7}Be, pep, CNO	CF4 TPC	μ_ν (reactor)	μ_ν results, recon studies
HERON	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic He	----------	R&D complete Proposal ended
XAX	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryo. Xe+Ar	dark matter, 0νββ	Design and simulation
Mega-H_2O	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	^{8}B, hep	H_2O Cerenkov	P-dk, LBL νs	Design, sim.

<1MeV Solar ν観測が熱い

From Klein

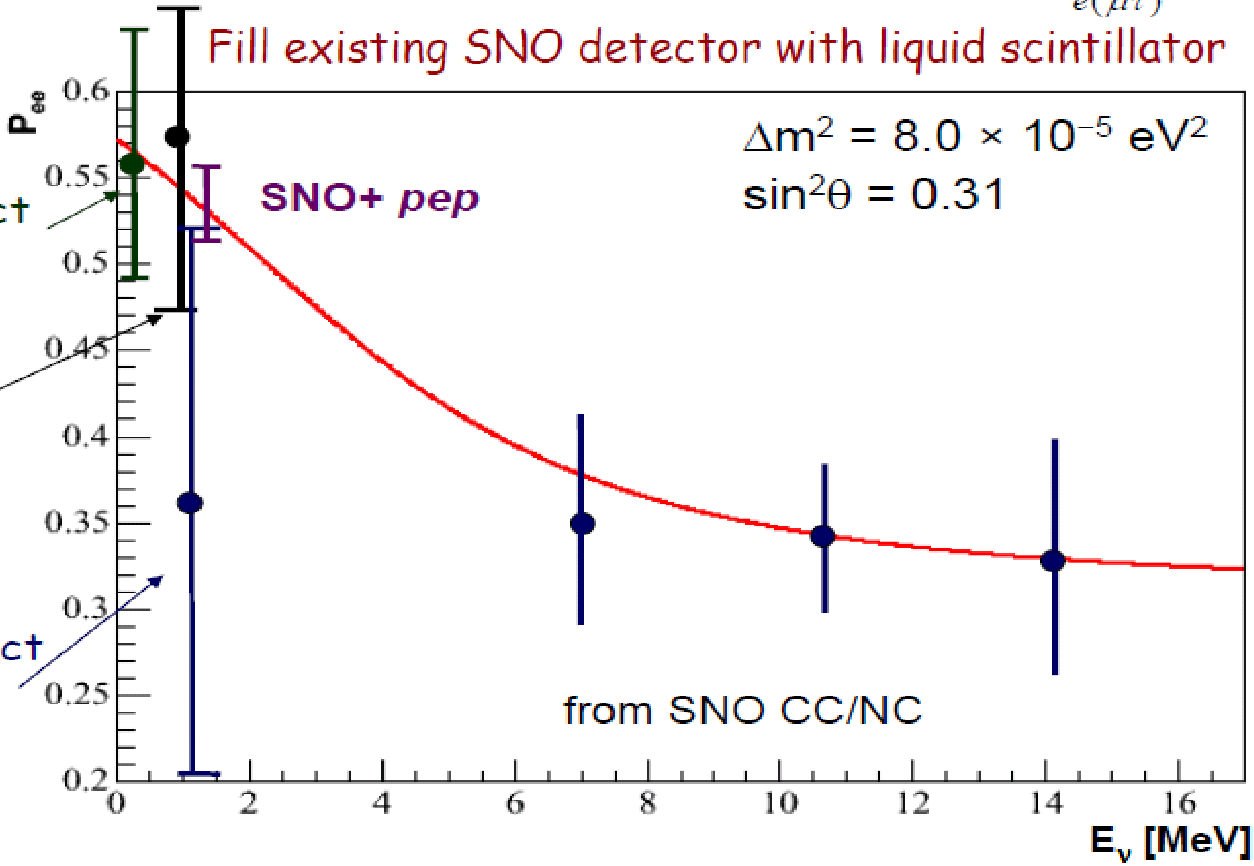


After Borexino

SNO+

$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$

Fill existing SNO detector with liquid scintillator



Ga subtract
^{7}Be and ^{8}B

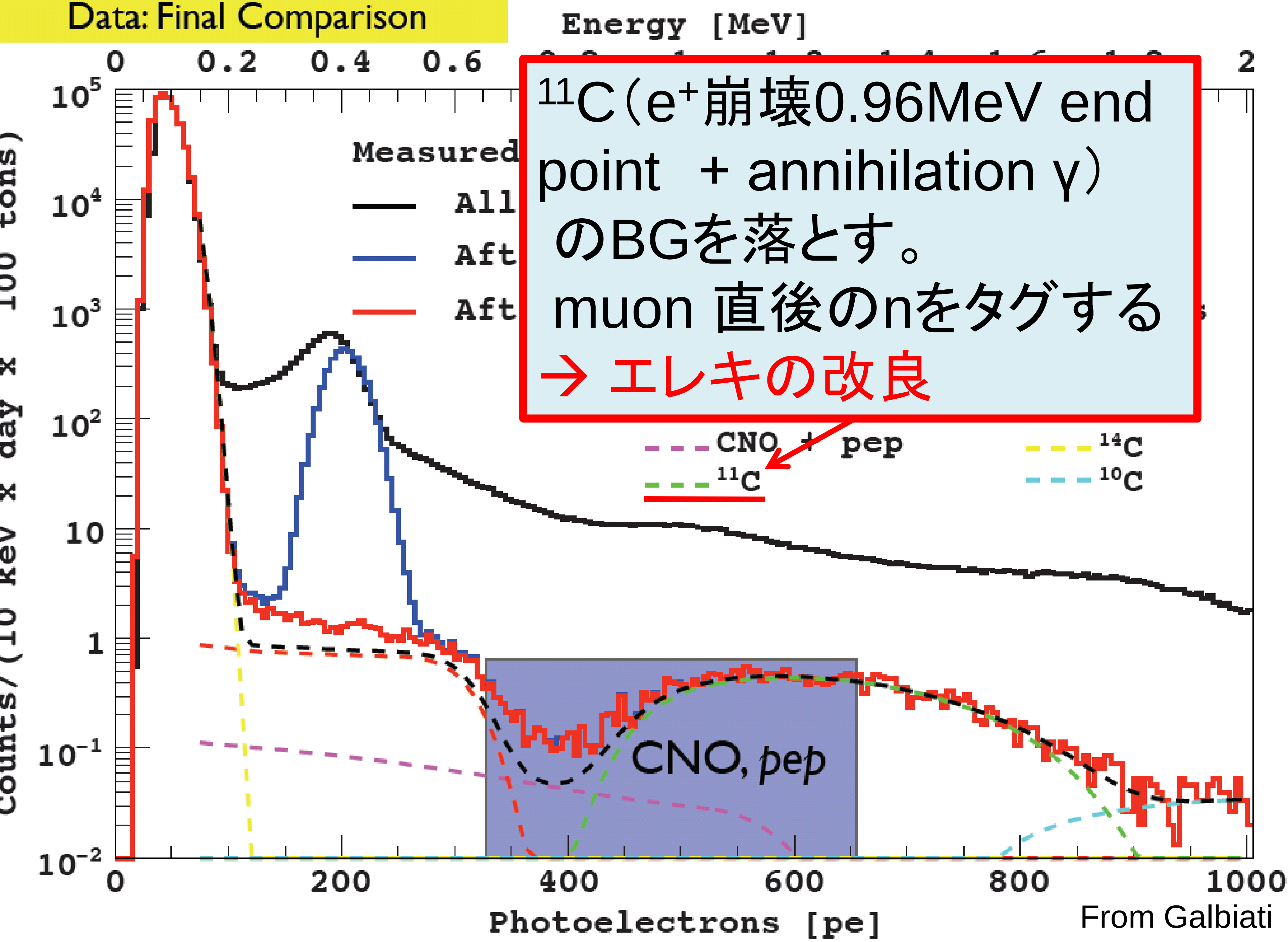
^{7}Be from
Borexino

Cl subtract
^{8}B using
SNO

Need background reductions similar to KamLAND, but
^{11}C not a problem because of low cosmic rate, and *pep* above ^{85}Kr/^{210}Po

From Klein

Data: Final Comparison



^{11}C（e$^+$崩壊0.96MeV end point + annihilation γ）のBGを落とす。

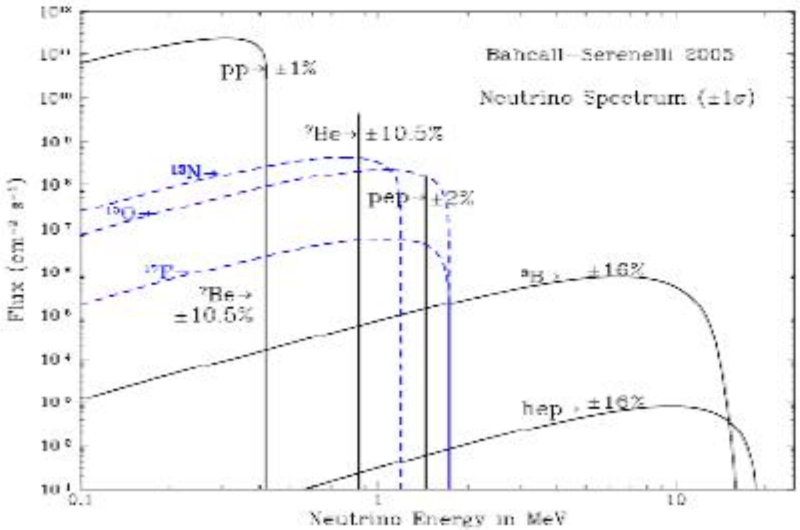
muon 直後のnをタグする

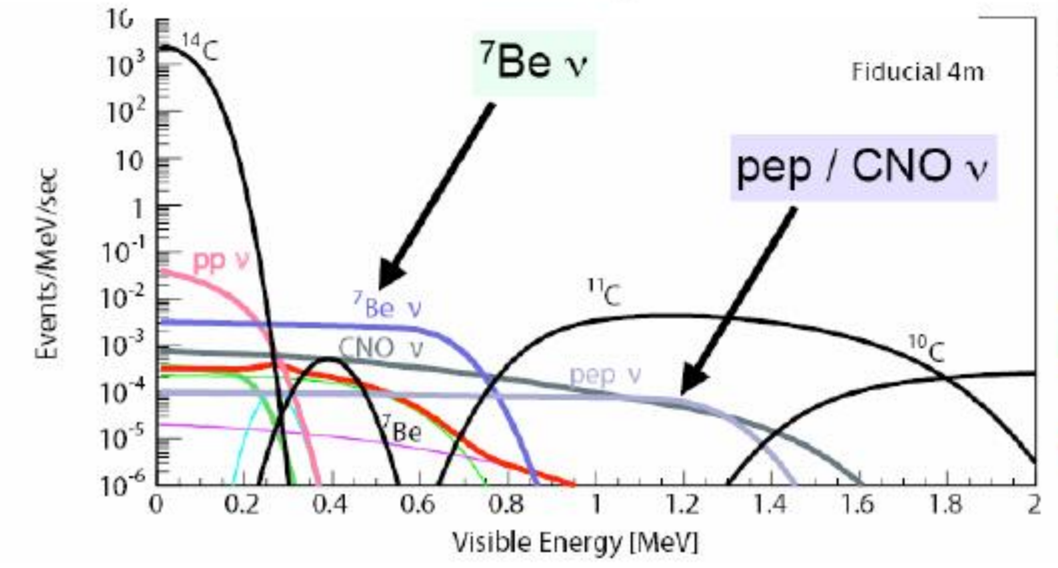
→ エレキの改良

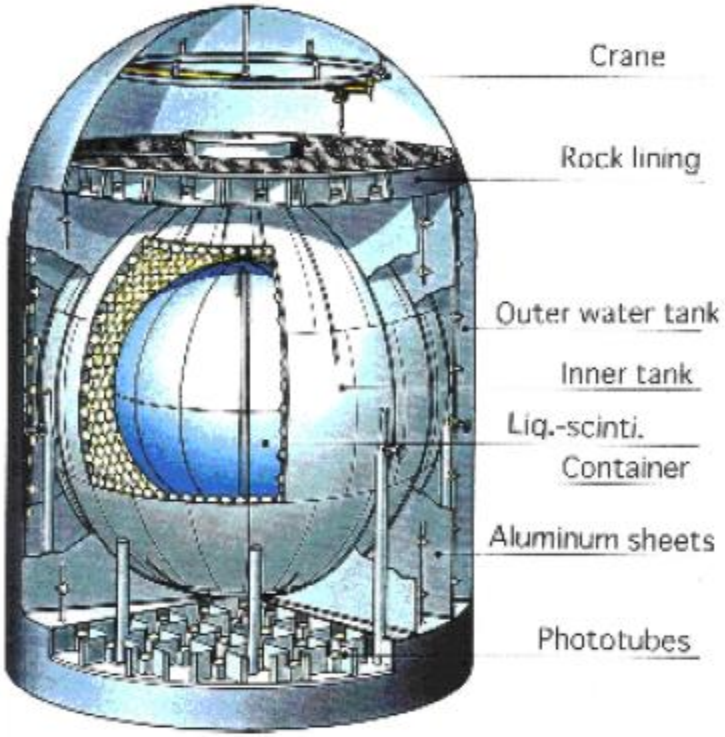
From Galbiati

KamLAND (Low BG)

$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$





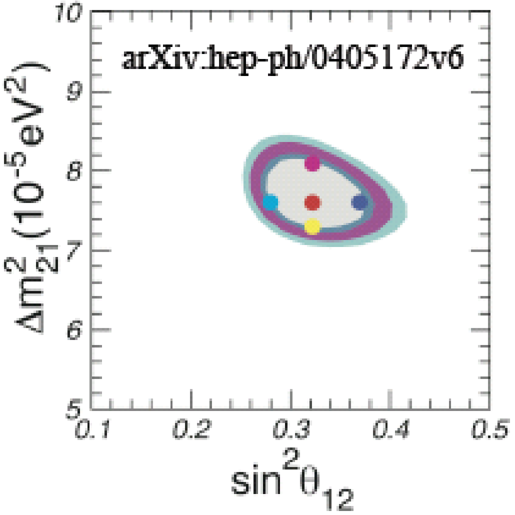


Need substantial reductions (10^{-4}-10^{-6}) in backgrounds---
e.g., ^{210}Pb and ^{85}Kr.

From Klein

SK-III solar analysisの現状

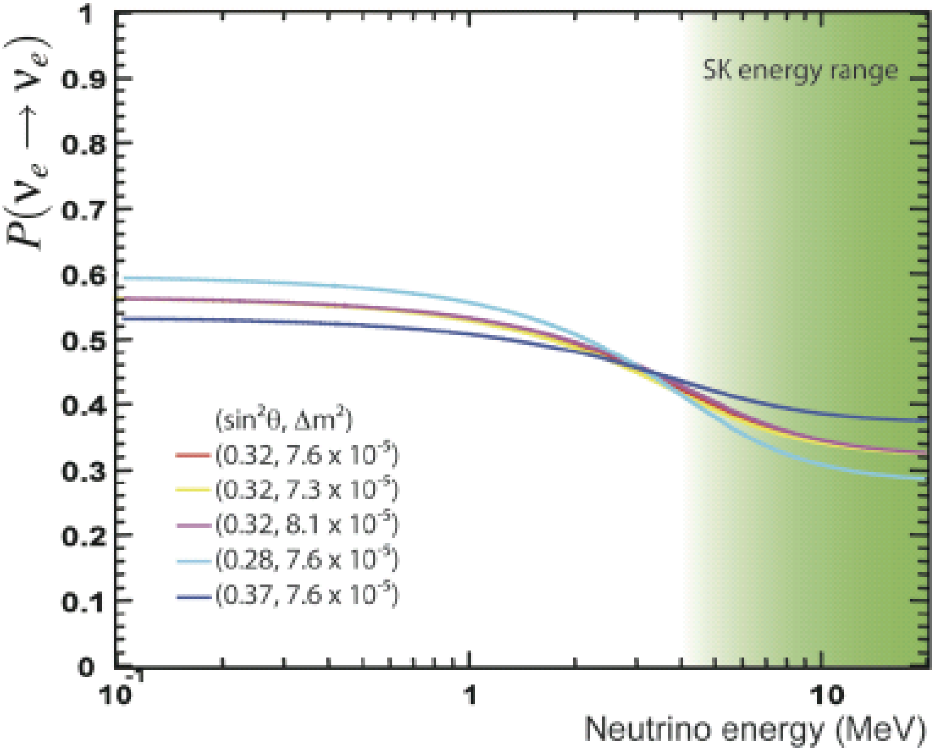
Future Prospects for SK Solar



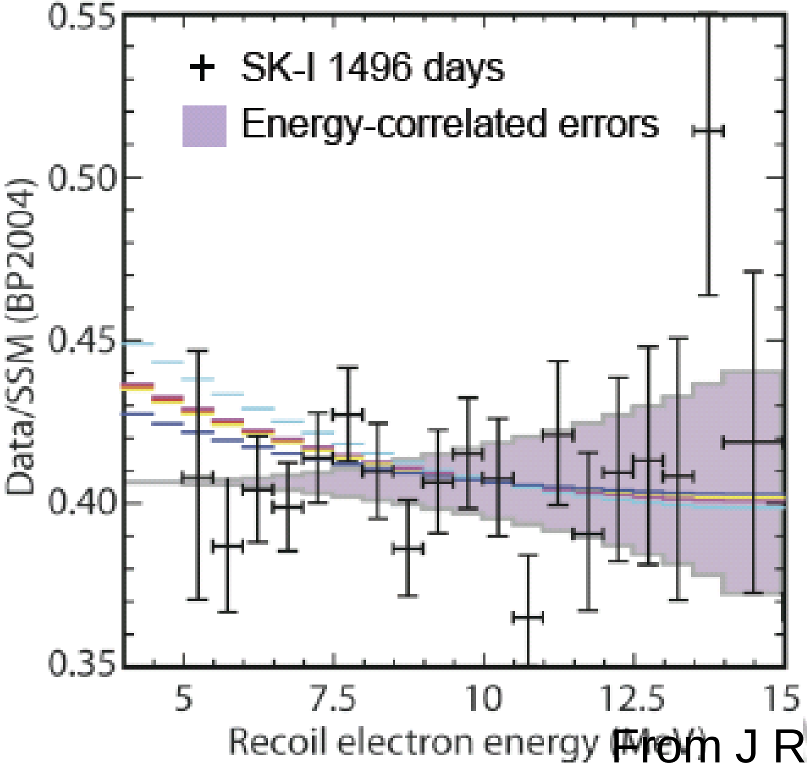
Low energy upturn ~10% effect in Super-K

In order to see it, we must:

- reduce statistical errors
- reduce energy-correlated sys errors (0.5 x SK-I)
- lower energy threshold



Work in progress...



From J Raaf

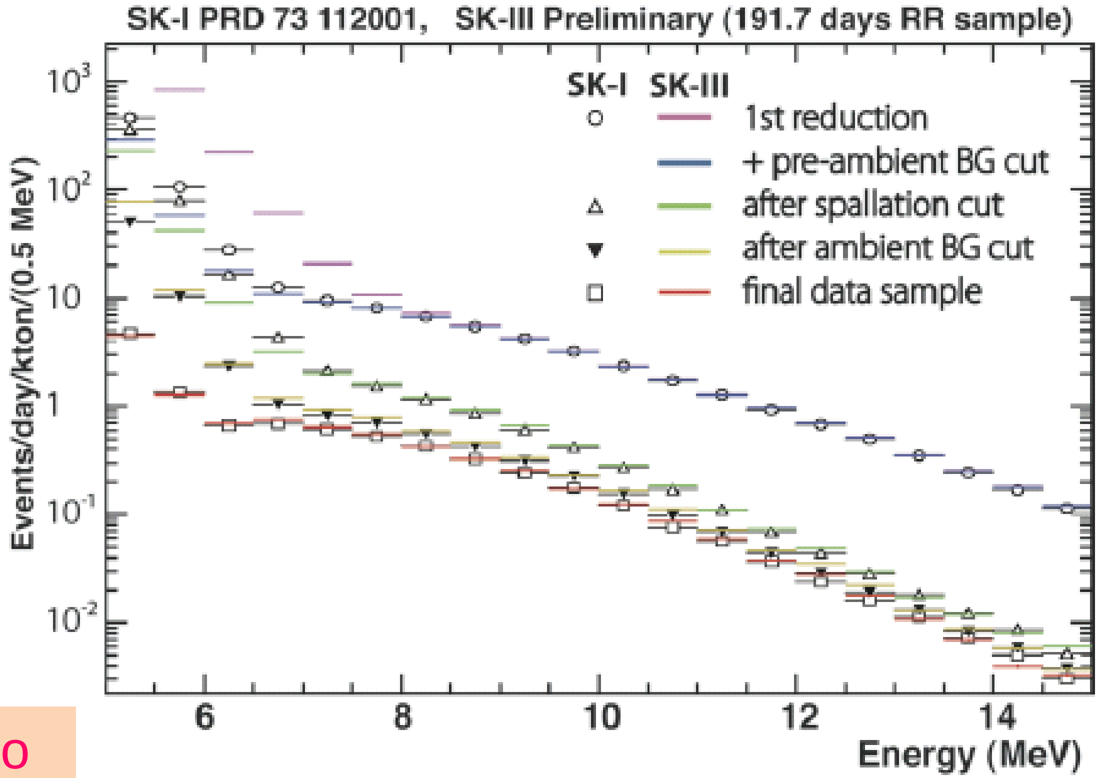
Solar neutrino data reduction: SK-III

Run period shown: Jan. 24, 2007 - Mar. 2, 2008

Datasets:

✤ Full Final (FF) sample
Livetime: 288.9 days
Energy > 6.5 MeV

✤ Radon Reduced (RR) sample
(shown)
→ periods of high radon activity removed
Livetime: 191.7 days
Energy > 5 MeV



SK-III has already reached to the similar signal to noise ratio as SK-I in 5-20 MeV

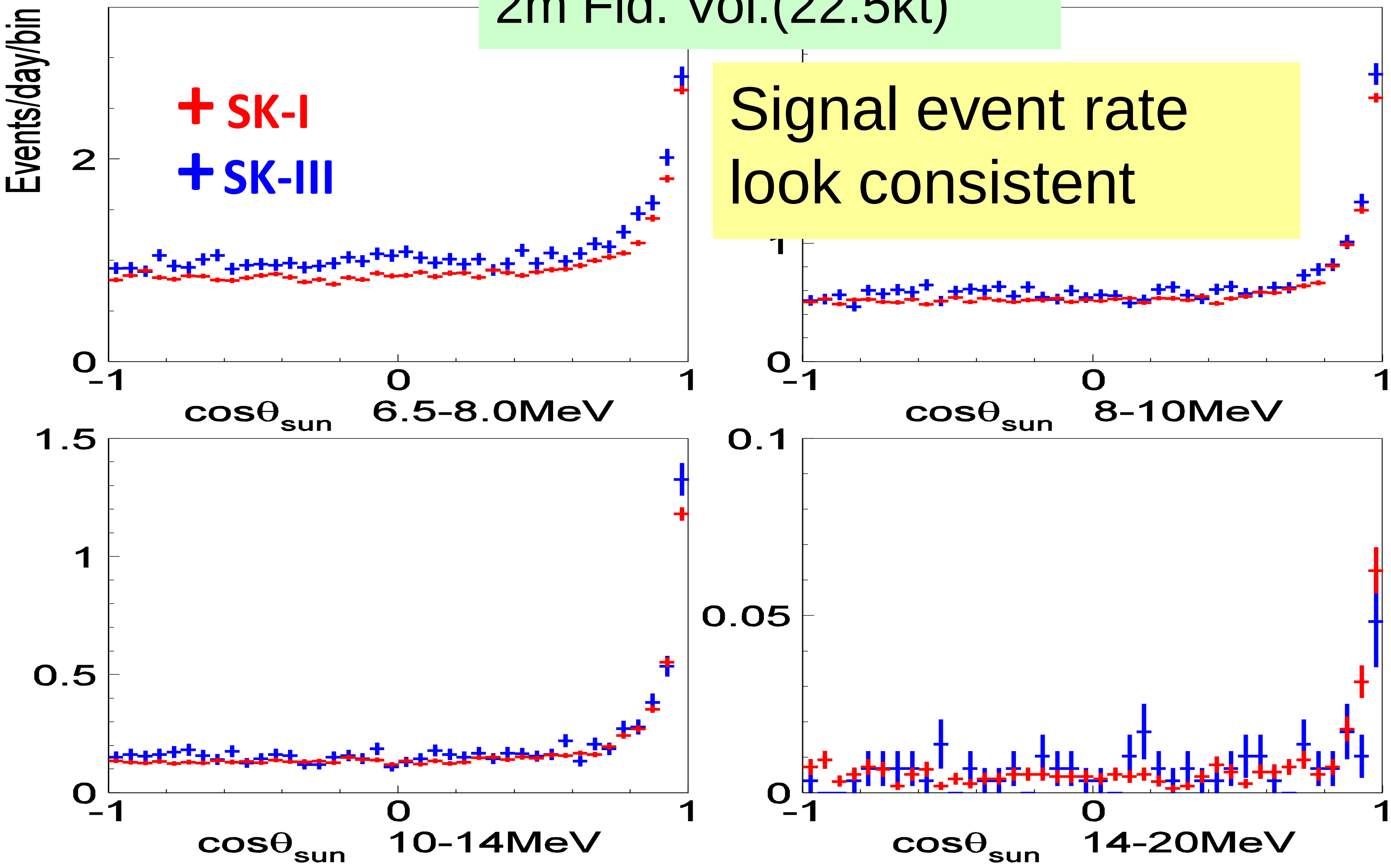
100% trigger efficiency at 5 MeV
Preliminary SK-III reduction tools

Good agreement of SK-III with SK-I final data sample

From J Raaf

Solar angle distribution

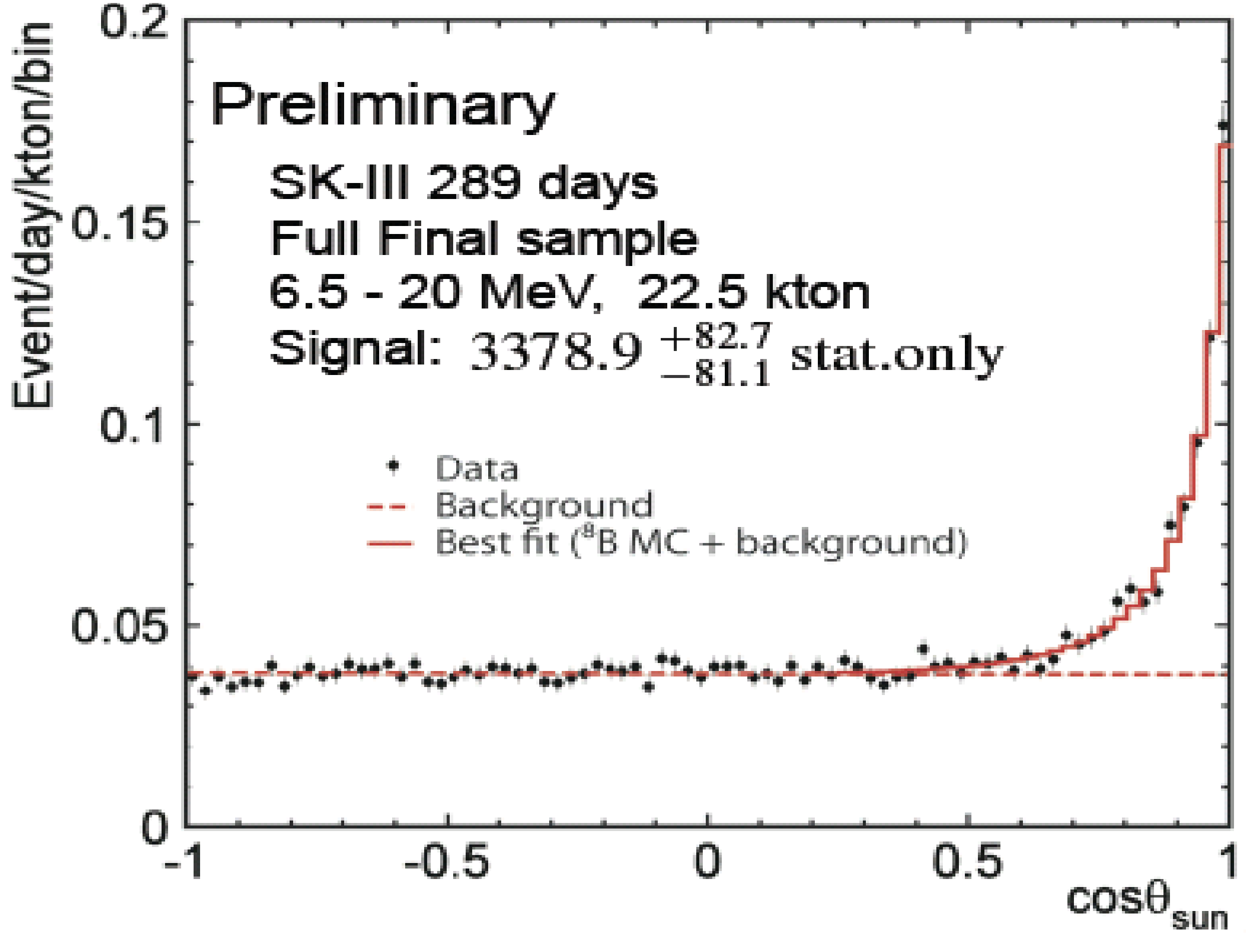
SK-I & SK-III FF 289 days



2m Fid. Vol.(22.5kt)

Signal event rate look consistent

Extract number of signal events by fit to signal + background shapes

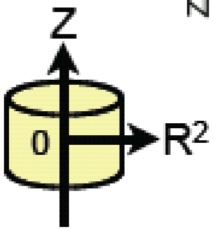


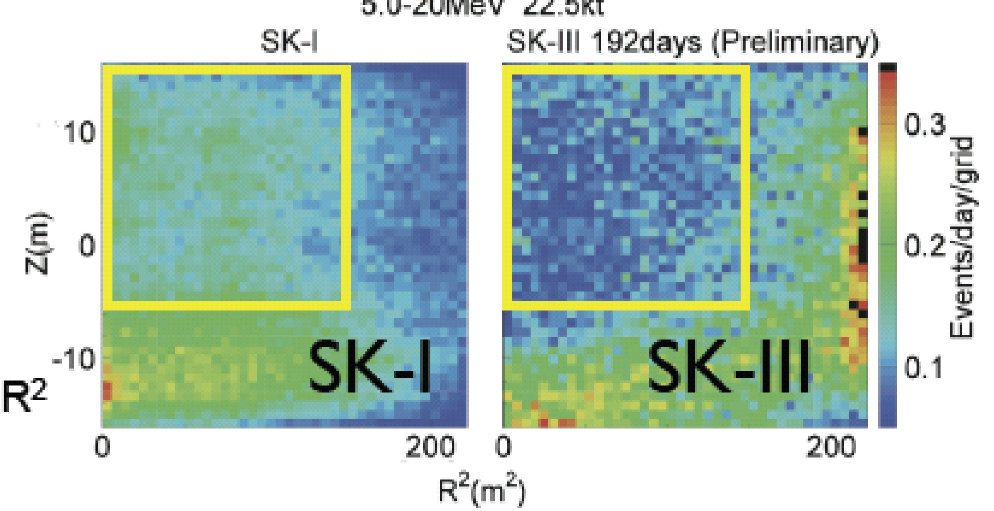
	Livetime (days)	Energy range (MeV)	Number of signal events	Flux ($\times 10^6$ cm^{-2} sec^{-1})
SK-III	289	6.5-20.0	$3378.9^{+82.7}_{-81.1}$(stat only)	In preparation

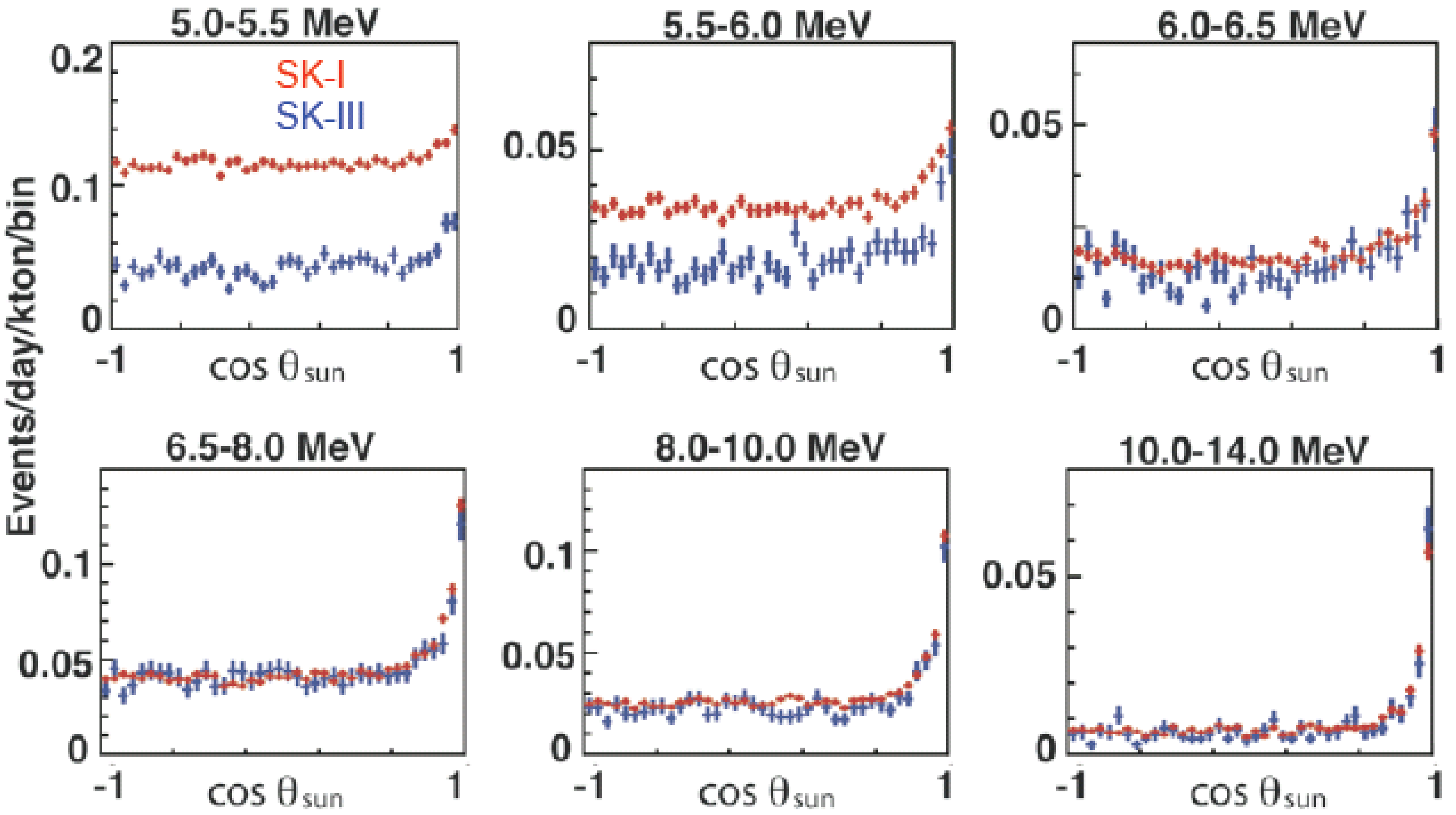
From J Raaf

SK-III: Background in the central region (RR sample)

SK-III background rate lower than SK-I in central region

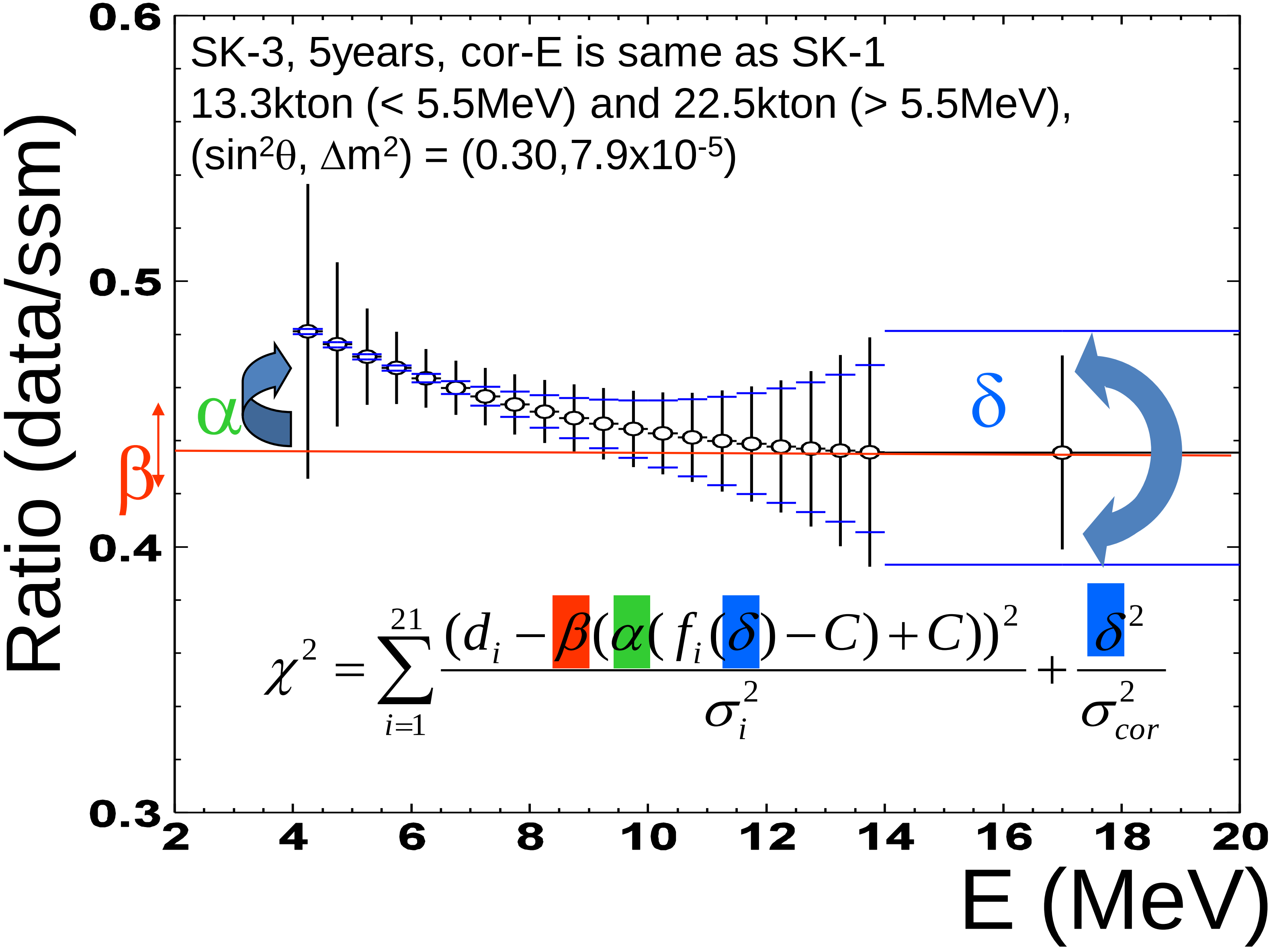






From J Raaf

Sensitivity calculation



SK-3, 5years, cor-E is same as SK-1

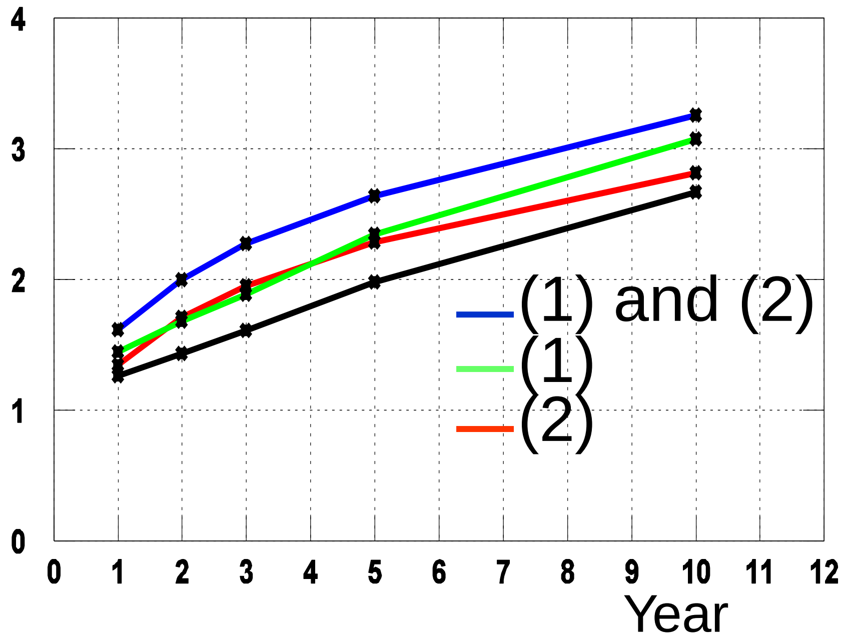
13.3kton (< 5.5MeV) and 22.5kton (> 5.5MeV),

$(\sin^2\theta, \Delta m^2) = (0.30, 7.9\times10^{-5})$

$$\chi^2 = \sum_{i=1}^{21} \frac{(d_i - \beta(\alpha(f_i(\delta) - C) + C))^2}{\sigma_i^2} + \frac{\delta^2}{\sigma_{cor}^2}$$

Sensitivity

In the case of $(\sin^2\theta, \Delta m^2) = (0.30, 7.9\times10^{-5})$



The black line shows the 13.3kton (4.0-5.5MeV), 22.5kton (5.5-20MeV) fiducial volume with the same energy correlated error as SK-I

(1) If fiducial volume for E<5.5MeV is enlarged to 22.5kton with low B.G.

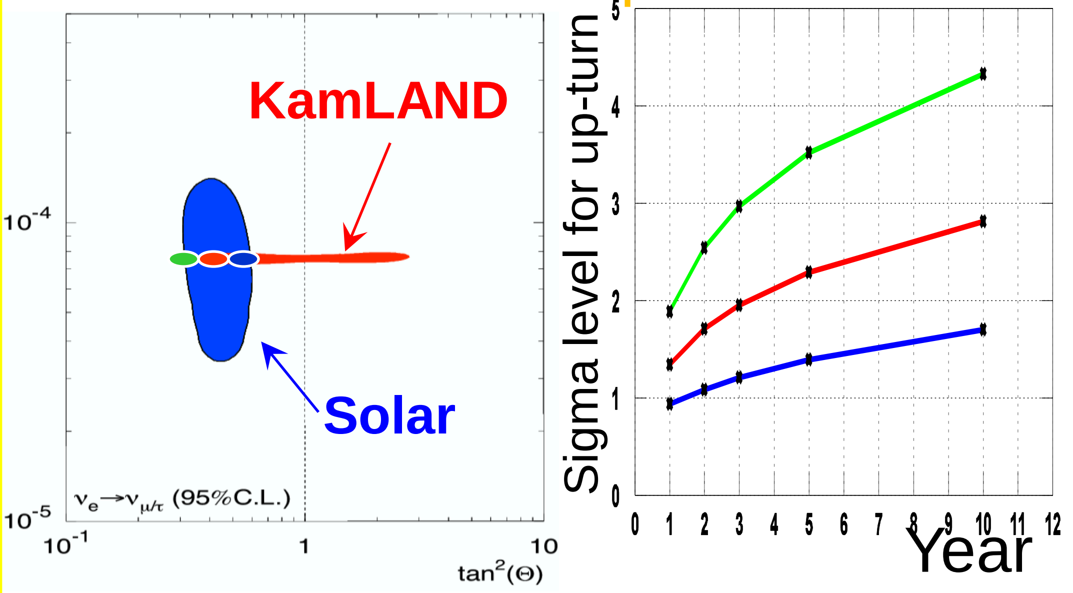
(2) If energy correlated systematic error is reduced by 50%.

First target : 2 σ level upturn discovery with 3 years observation.

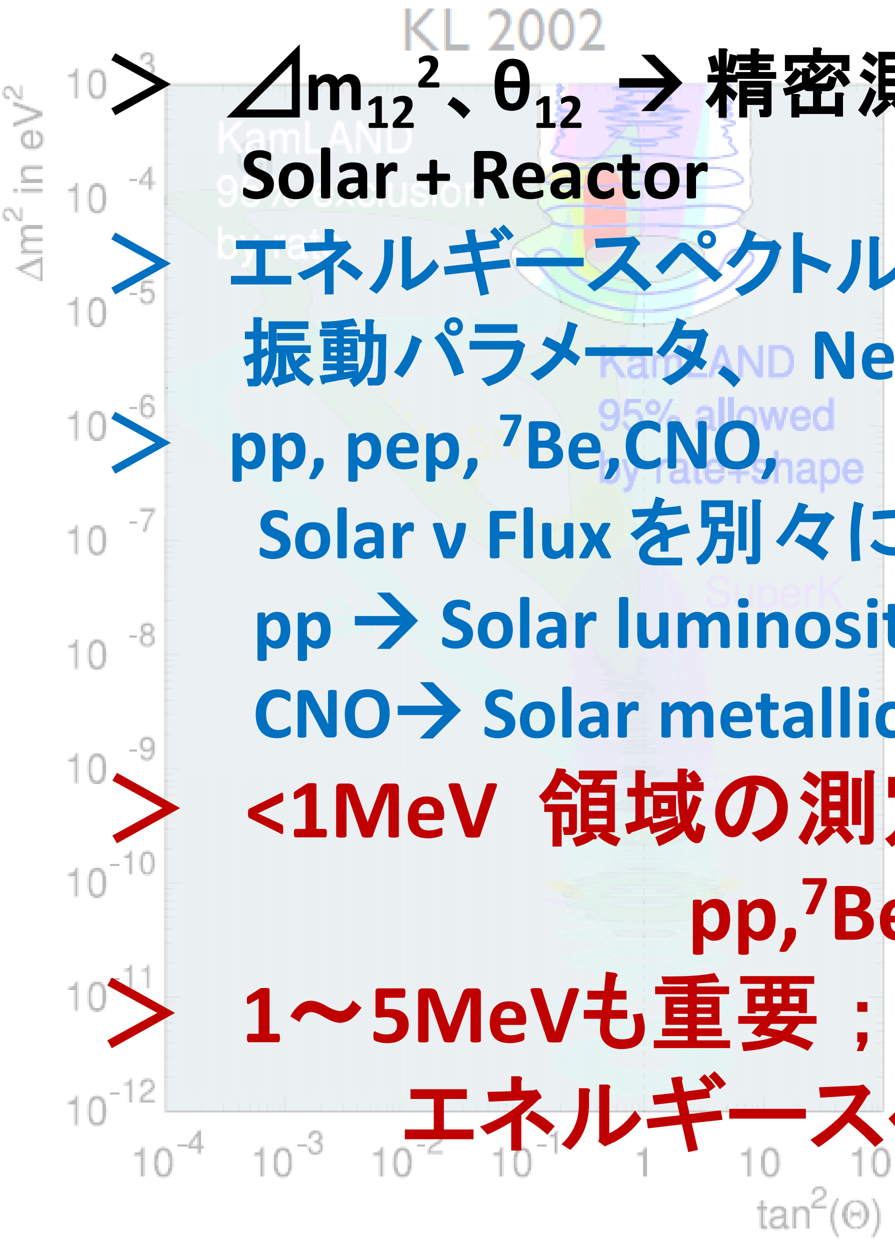
Need to enlarge fiducial volume with low BG as large as possible

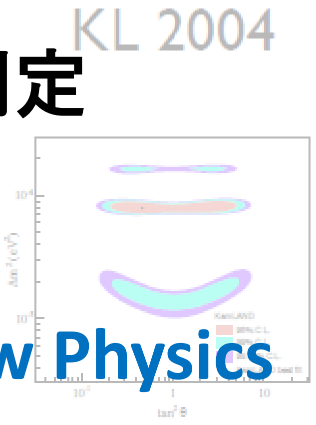
Also the reduction of the energy correlated systematic error is important.

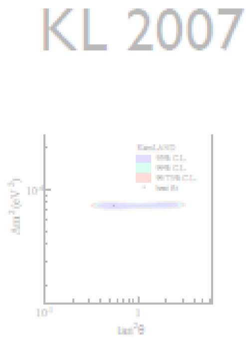
Parameter dependence

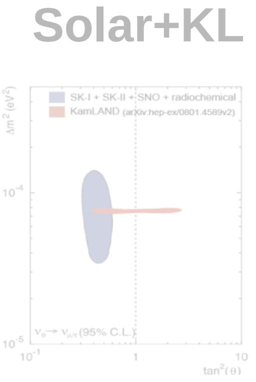


まとめ、









＞ Δm_{12}^2、θ_{12} → 精密測定

Solar + Reactor

＞ エネルギースペクトル

振動パラメータ、New Physics

＞ pp, pep, ^{7}Be,CNO,

Solar ν Flux を別々にきちんと測定。

pp → Solar luminosity

CNO→ Solar metallicity problem の鍵

＞ <1MeV 領域の測定

pp,^{7}Be,CNO,pep

＞ 1～5MeVも重要；

エネルギースペクトルの歪み

Neutrino Oscillation:
A precision measurement!

From Decowski

太陽ニュートリノ実験（θ_{12}）

めでたしめでたし

つづく、

補足スライド

SK-IV: DAQ Upgrade

- Simplified detector operations
  unified readout scheme for ID and OD

- Increased reliability/performance
  - fewer discrete components

  - improve energy resolution
    wider dynamic range

  - improve multiple-hit capability
    efficient ID of μ-decay electrons

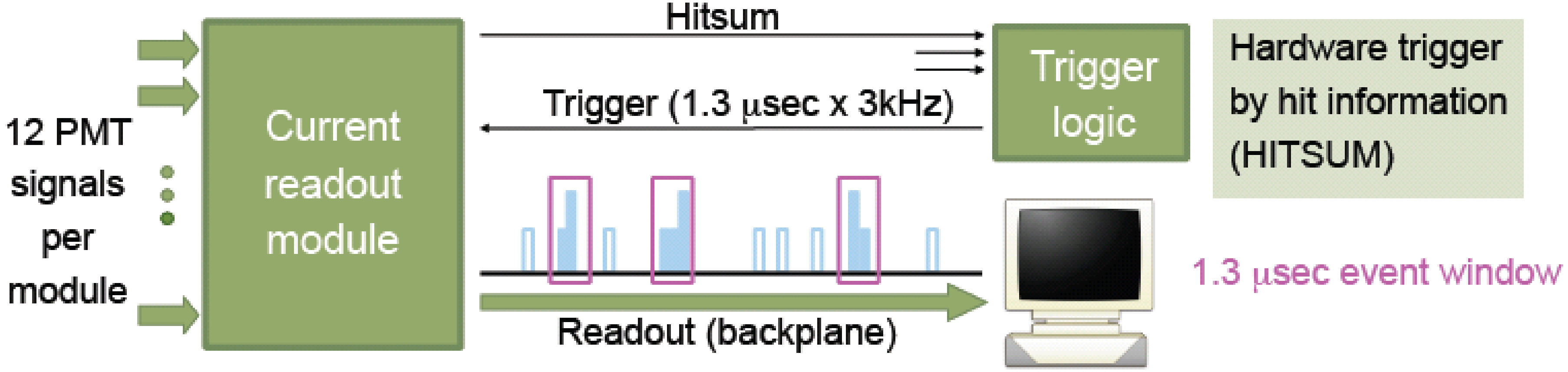
  - reduce SPE hit threshold
    low E solar ν's
    γ-tagging for proton decay

  - improve supernova burst capability

- Ethernet-based readout
  increased bandwidth and reduced dead time
  build DAQ system from commodity network devices!

New DAQ readout scheme

SK-I,II,III DAQ scheme:



12 PMT signals per module

Current readout module

Hitsum

Trigger (1.3 μsec x 3kHz)

Trigger logic

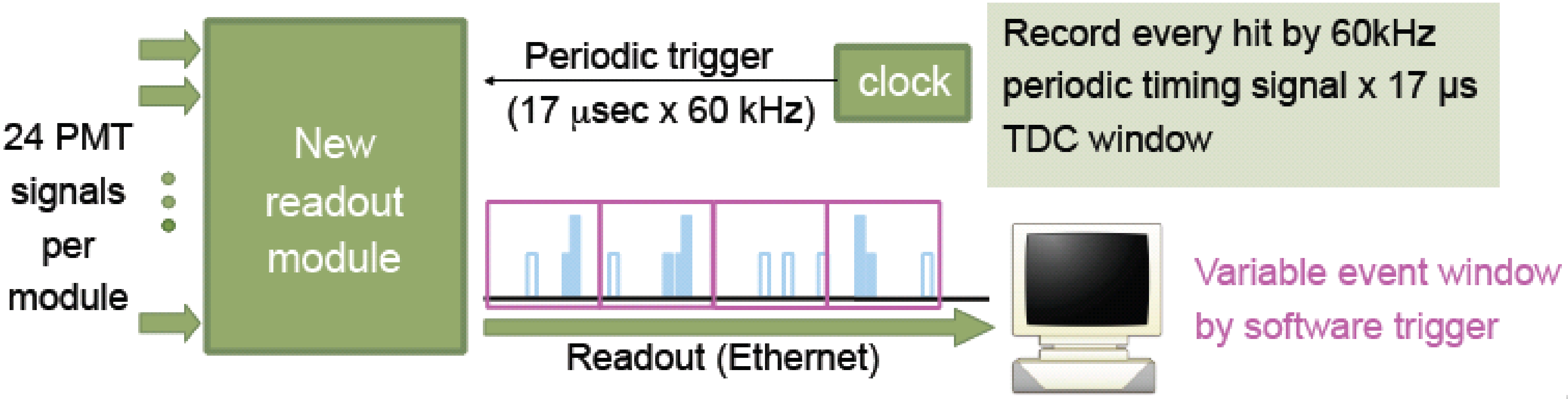
Readout (backplane)

Hardware trigger by hit information (HITSUM)

1.3 μsec event window

SK-IV DAQ scheme:

No hardware trigger. Instead record all hits and apply software triggers.



24 PMT signals per module

New readout module

Periodic trigger (17 μsec x 60 kHz)

clock

Readout (Ethernet)

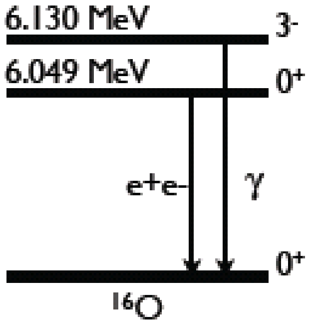
Record every hit by 60kHz periodic timing signal x 17 μs TDC window

Variable event window by software trigger

Dominant BG: $^{13}C(\alpha,n)^{16}O$

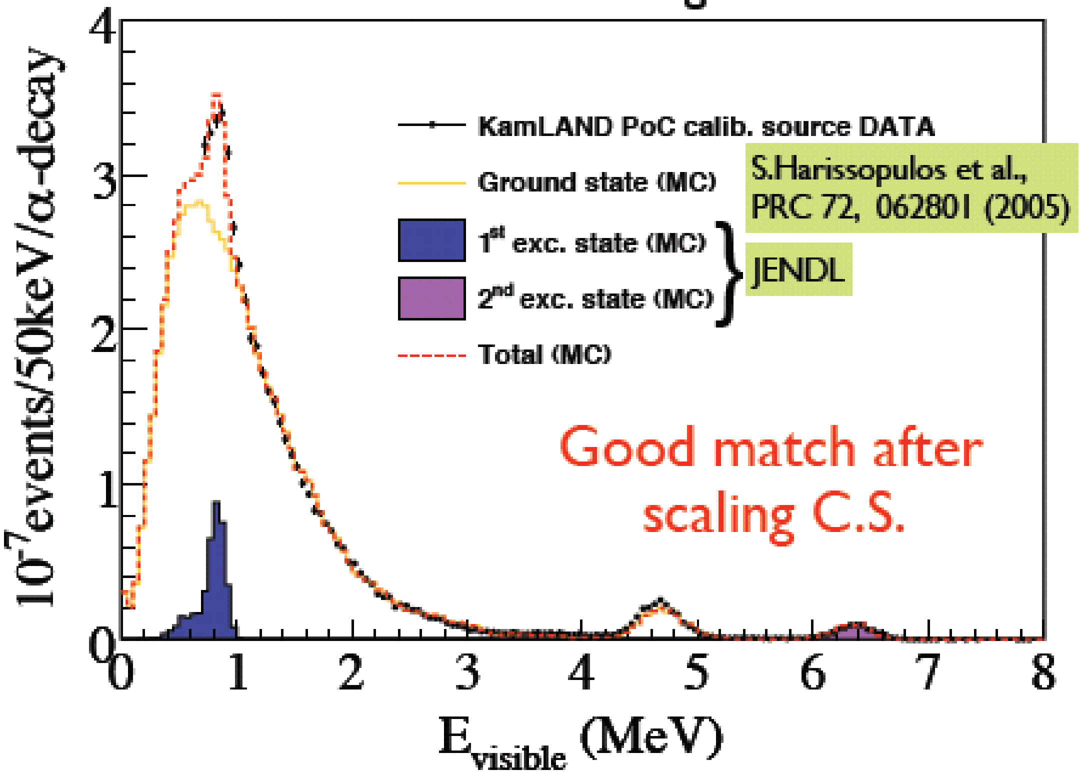
From ^{222}Rn chain: $^{210}Pb \xrightarrow{T_{1/2}=22yr} {}^{210}Bi \xrightarrow{5d} {}^{210}Po \xrightarrow{138d} {}^{206}Pb$

α, E=5.3MeV



1.1% abundance of ^{13}C in LS → $\mathbf{^{13}C(\alpha,n)^{16}O}$

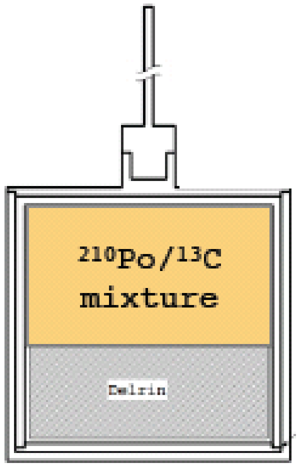
Cross sections tuned using detector MC



S.Harissopulos et al., PRC 72, 062801 (2005)

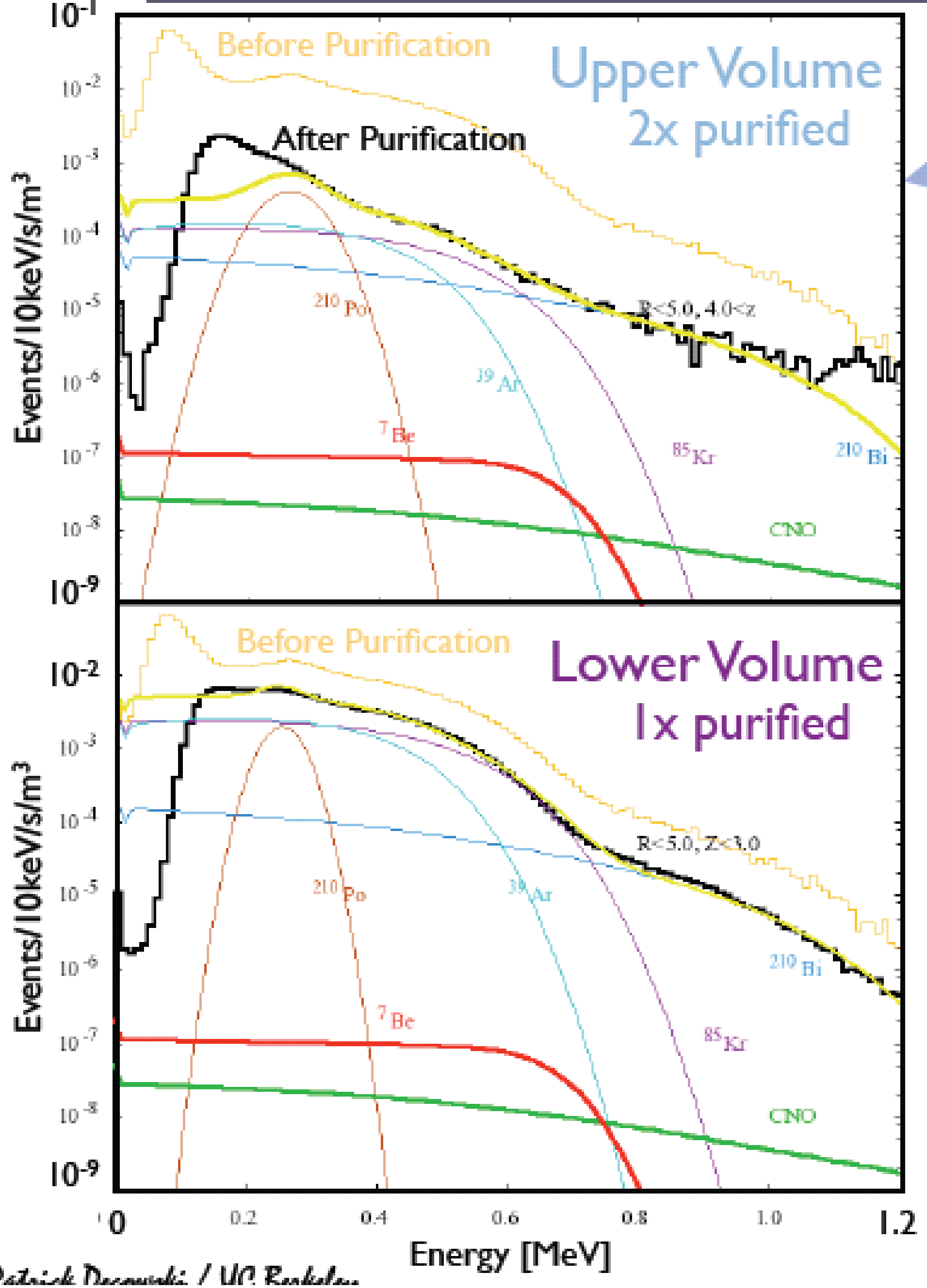
Good match after scaling C.S.

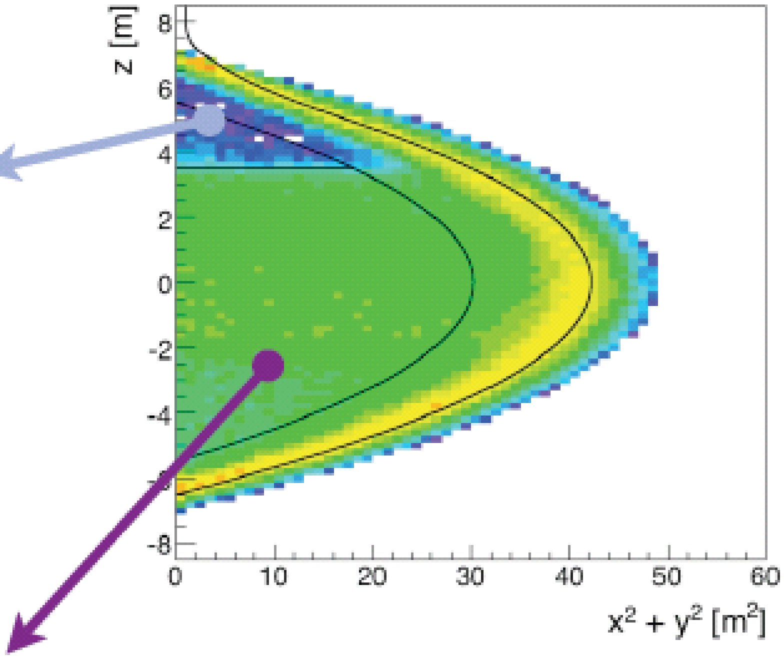
$^{210}Po^{13}C$ source deployed into the detector



D.McKee et al., NIM A527, 272 (2008)

1st Purification BG Levels



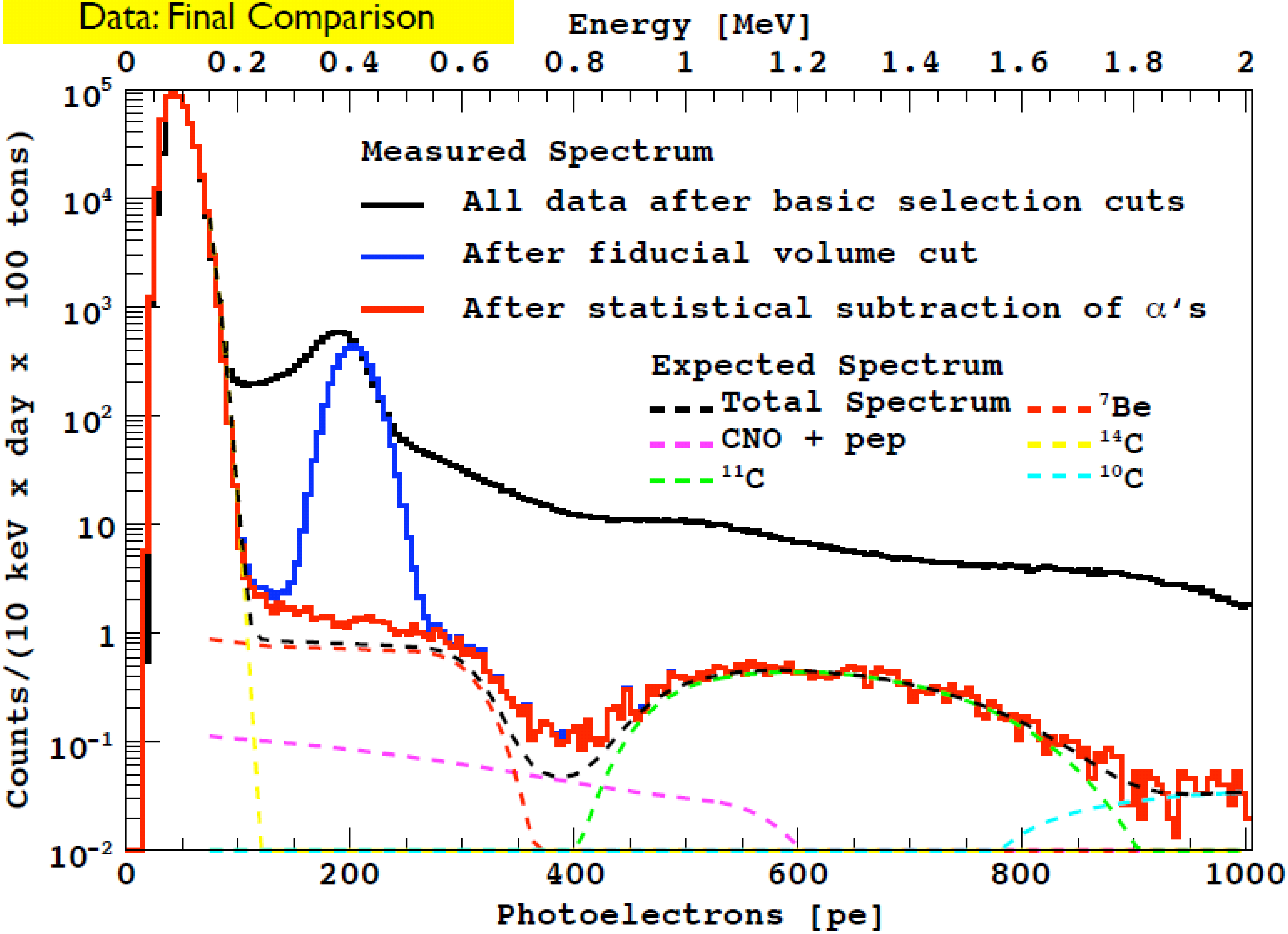


Background reduction fractions:

Background	Lower Volume	Upper Volume
^{40}K	0.29±0.03	0.29±0.03
^{85}Kr	0.36±0.02	$(2.8\pm0.8)\times10^{-2}$
^{210}Po	0.33±0.03	0.21±0.03
^{210}Bi	0.24±0.05	$(4.8\pm2.6)\times10^{-3}$

→ Main reactor & geo-neutrino BG $^{13}C(\alpha,n)^{16}O$ already down

Data: Final Comparison



Are solar neutrino oscillations robust?

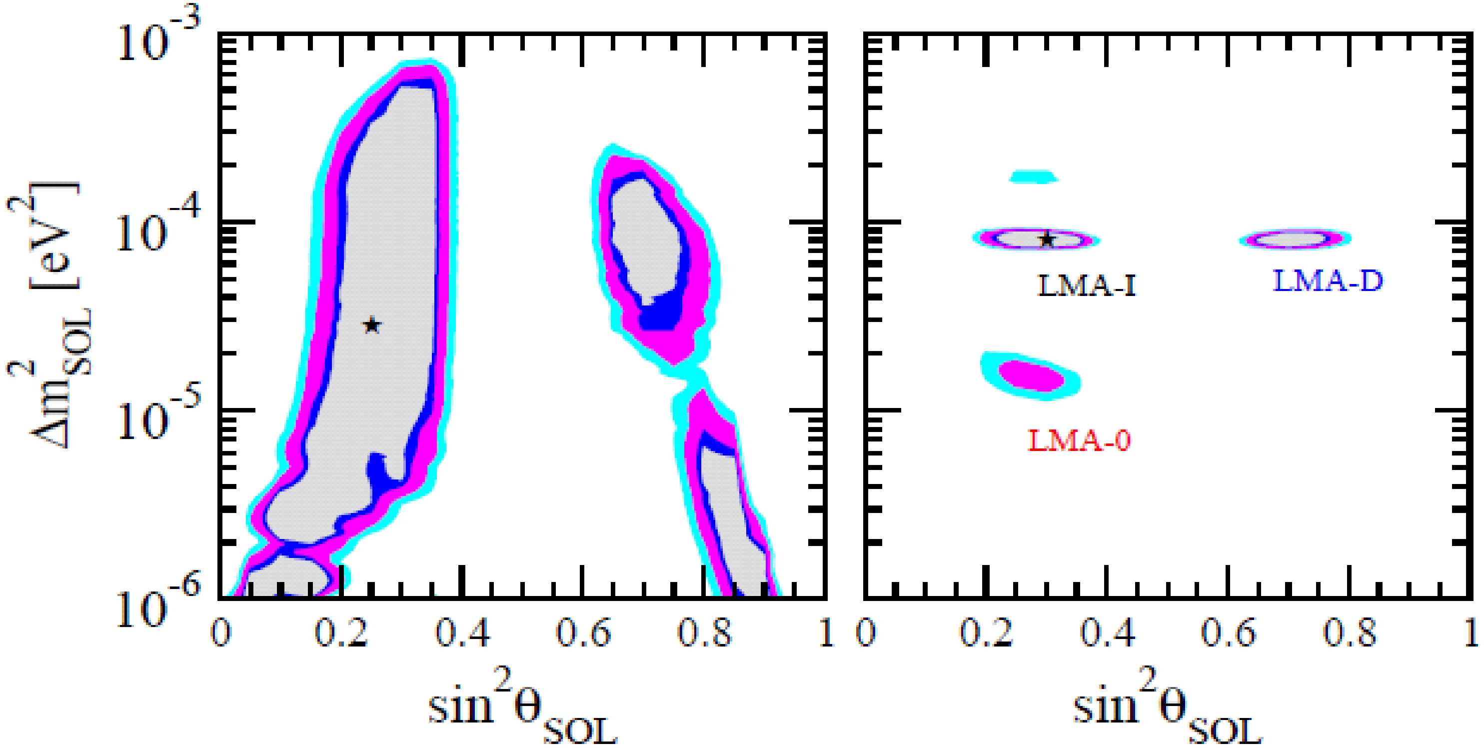
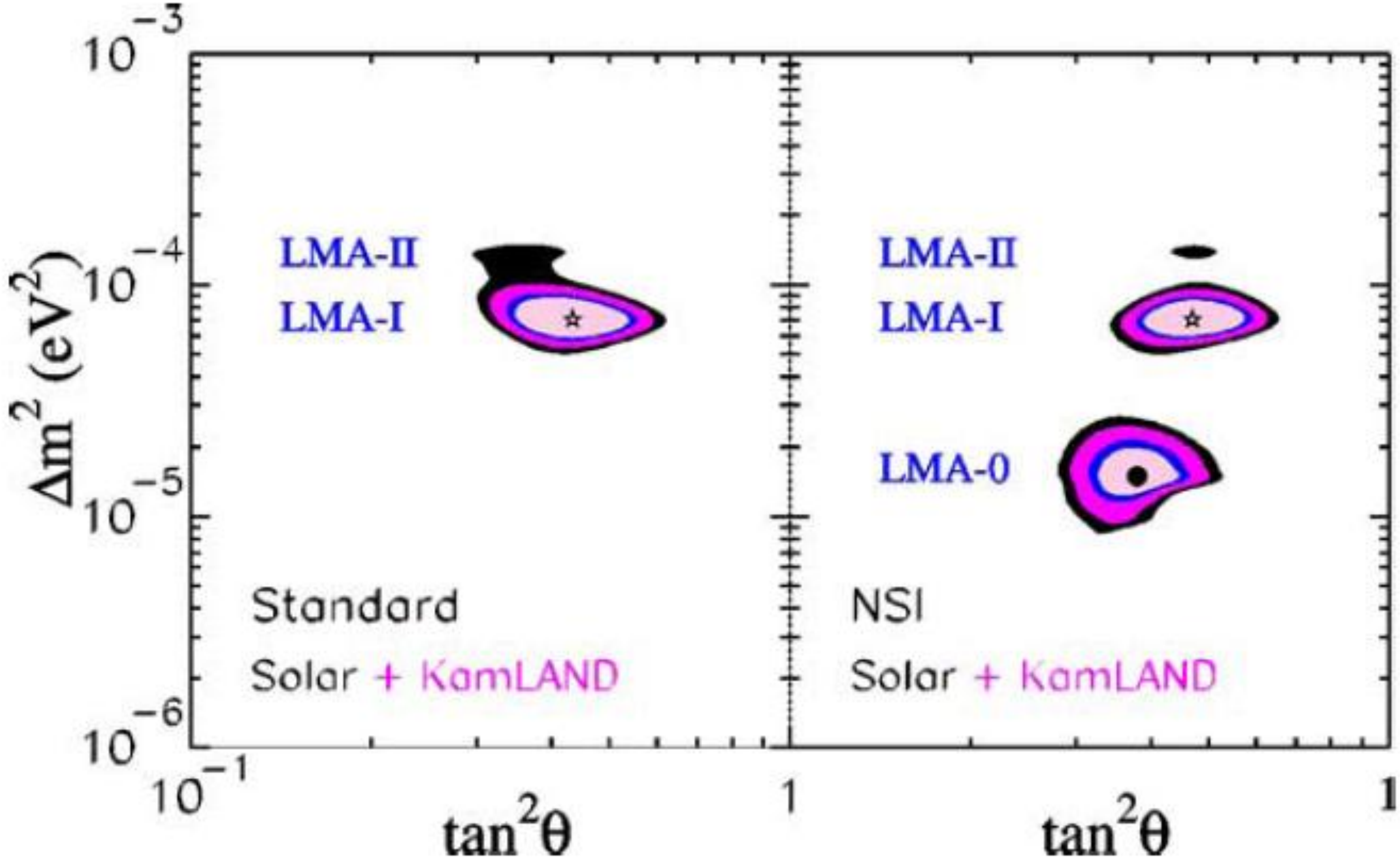


Figure 2: Allowed regions for the generalized OSC + NSI case, determined from the latest data: left panel corresponds to a solar only analysis, while the right panel corresponds to the combined solar+KamLAND analysis.

Solar neutrinos as probes of neutrino–matter interactions

Alexander Friedland[a], Cecilia Lunardini[b], Carlos Peña-Garay[b]



SK-I 、II　系統誤差

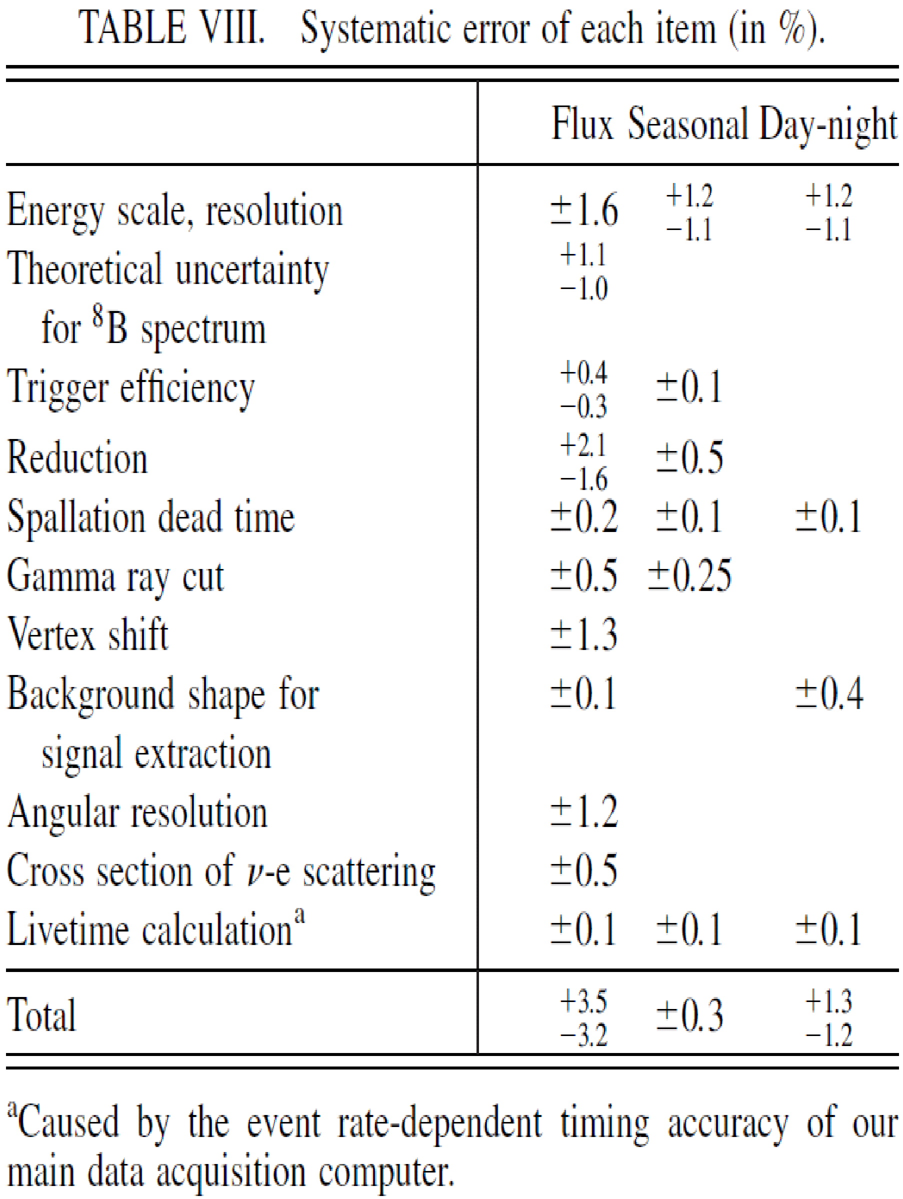
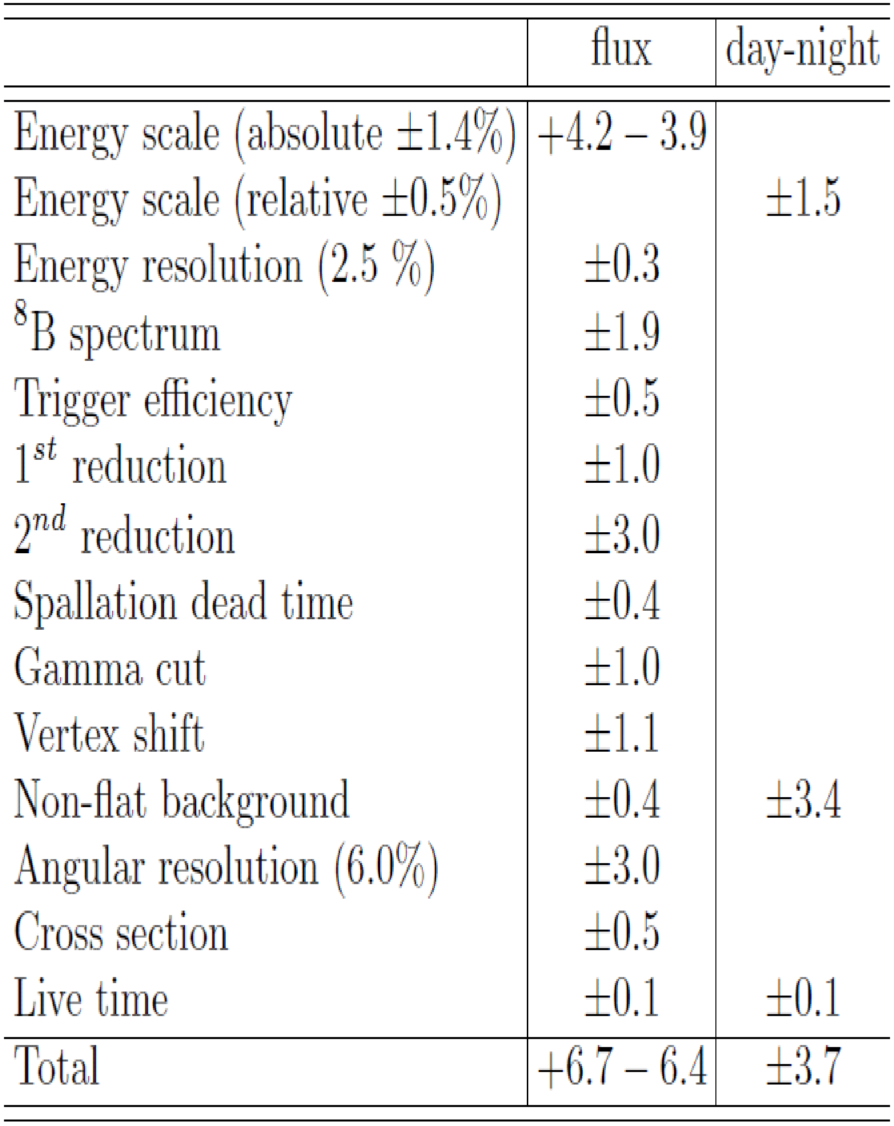


TABLE VIII. Systematic error of each item (in %).

	Flux	Seasonal	Day-night
Energy scale, resolution	±1.6	$^{+1.2}_{-1.1}$	$^{+1.2}_{-1.1}$
Theoretical uncertainty for ^{8}B spectrum	$^{+1.1}_{-1.0}$		
Trigger efficiency	$^{+0.4}_{-0.3}$	±0.1	
Reduction	$^{+2.1}_{-1.6}$	±0.5	
Spallation dead time	±0.2	±0.1	±0.1
Gamma ray cut	±0.5	±0.25	
Vertex shift	±1.3		
Background shape for signal extraction	±0.1		±0.4
Angular resolution	±1.2		
Cross section of ν-e scattering	±0.5		
Livetime calculation[a]	±0.1	±0.1	±0.1
Total	$^{+3.5}_{-3.2}$	±0.3	$^{+1.3}_{-1.2}$

[a] Caused by the event rate-dependent timing accuracy of our main data acquisition computer.

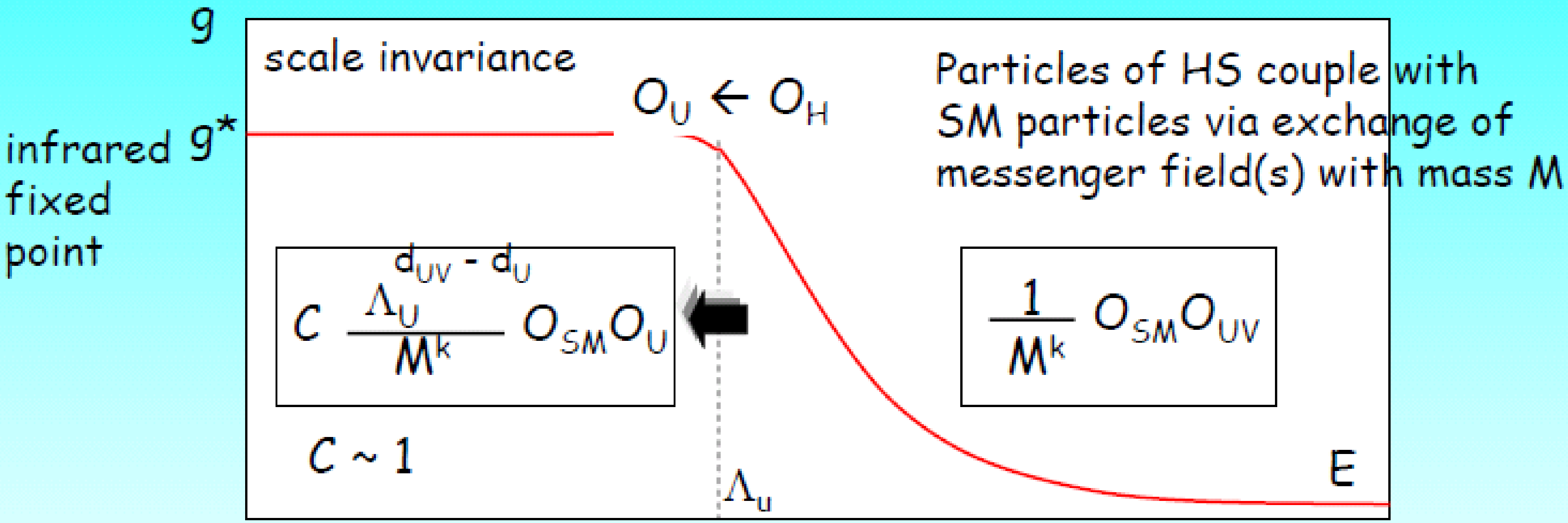


	flux	day-night
Energy scale (absolute ±1.4%)	+4.2 – 3.9	
Energy scale (relative ±0.5%)		±1.5
Energy resolution (2.5 %)	±0.3	
^{8}B spectrum	±1.9	
Trigger efficiency	±0.5	
1st reduction	±1.0	
2nd reduction	±3.0	
Spallation dead time	±0.4	
Gamma cut	±1.0	
Vertex shift	±1.1	
Non-flat background	±0.4	±3.4
Angular resolution (6.0%)	±3.0	
Cross section	±0.5	
Live time	±0.1	±0.1
Total	+6.7 – 6.4	±3.7

Unparticles

H. Georgi

Hidden sector (HS) e.g., gauge theory with fermions and coupling g



$O_U \leftarrow O_H$

Particles of HS couple with SM particles via exchange of messenger field(s) with mass M

$$C \frac{\Lambda_U^{d_{UV} - d_U}}{M^k} O_{SM} O_U \Leftarrow \frac{1}{M^k} O_{SM} O_{UV}$$

$C \sim 1$

If $g^* \gg 1$ → appearance of composite (confined) states of the HS particles (described by operators O_U)

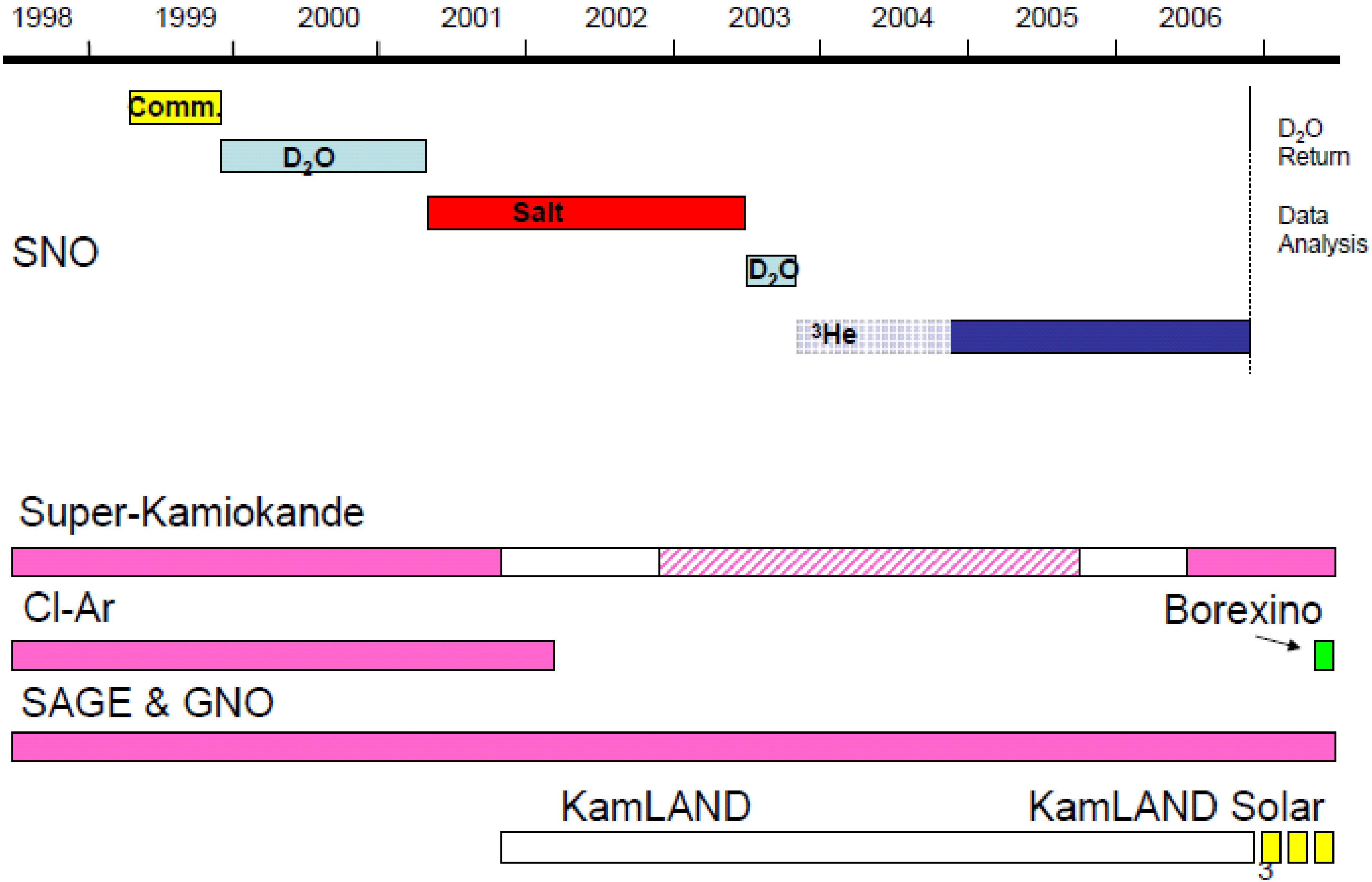
hadrons ← quarks

N. Krasnikov
M. A. Stepanov

Key difference: Scale invariance → continuous mass spectrum of confined states, Each has infinitesimal coupling with SM particles. Integral is finite

Individual (mass) modes: negligible effect

Solar Neutrino Program



Backgrounds

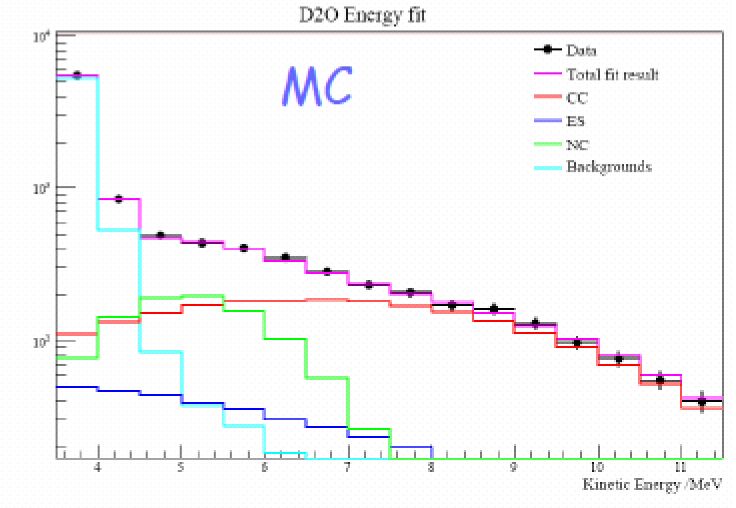
Source	PMT Events (neutrons)	NCD Events (neutrons)
D_2O Radioactivity	7.6 ± 1.2	28.7 ± 4.7
Atmospheric ν, ^{16}N	24.7 ± 4.6	13.6 ± 2.7
Other backgrounds	0.7 ± 0.1	2.3 ± 0.3
NCD Bulk PD, $^{17,18}O(\alpha,n)$	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
NCD hotspots	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6
TOTAL	77^{+12}_{-10}	185^{+25}_{-22}

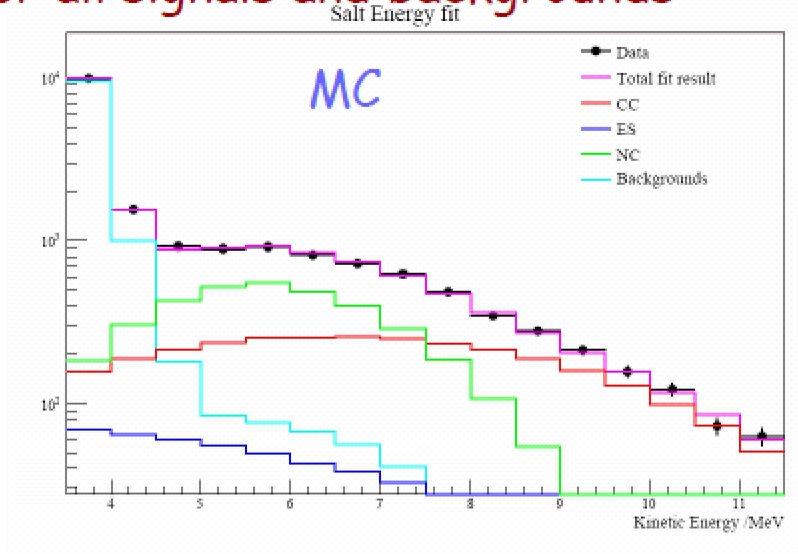
Nuisance Parameter	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
PMT energy scale	±0.6	±2.7	±3.6
PMT energy resolution	±0.1	±0.1	±0.3
PMT radial scaling	±0.1	±2.7	±2.7
PMT angular resolution	±0.0	±0.2	±2.2
PMT radial energy dep.	±0.0	±0.9	±0.9
Background neutrons	±2.3	±0.6	±0.7
Neutron capture	±3.3	±0.4	±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

Next Results

- SNO Low Energy Threshold Analysis

Joint phase 3D fit to MC for all signals and backgrounds





G. Orebi Gann

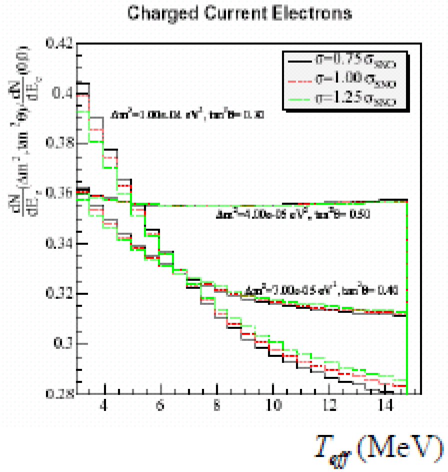
Increase in raw integral

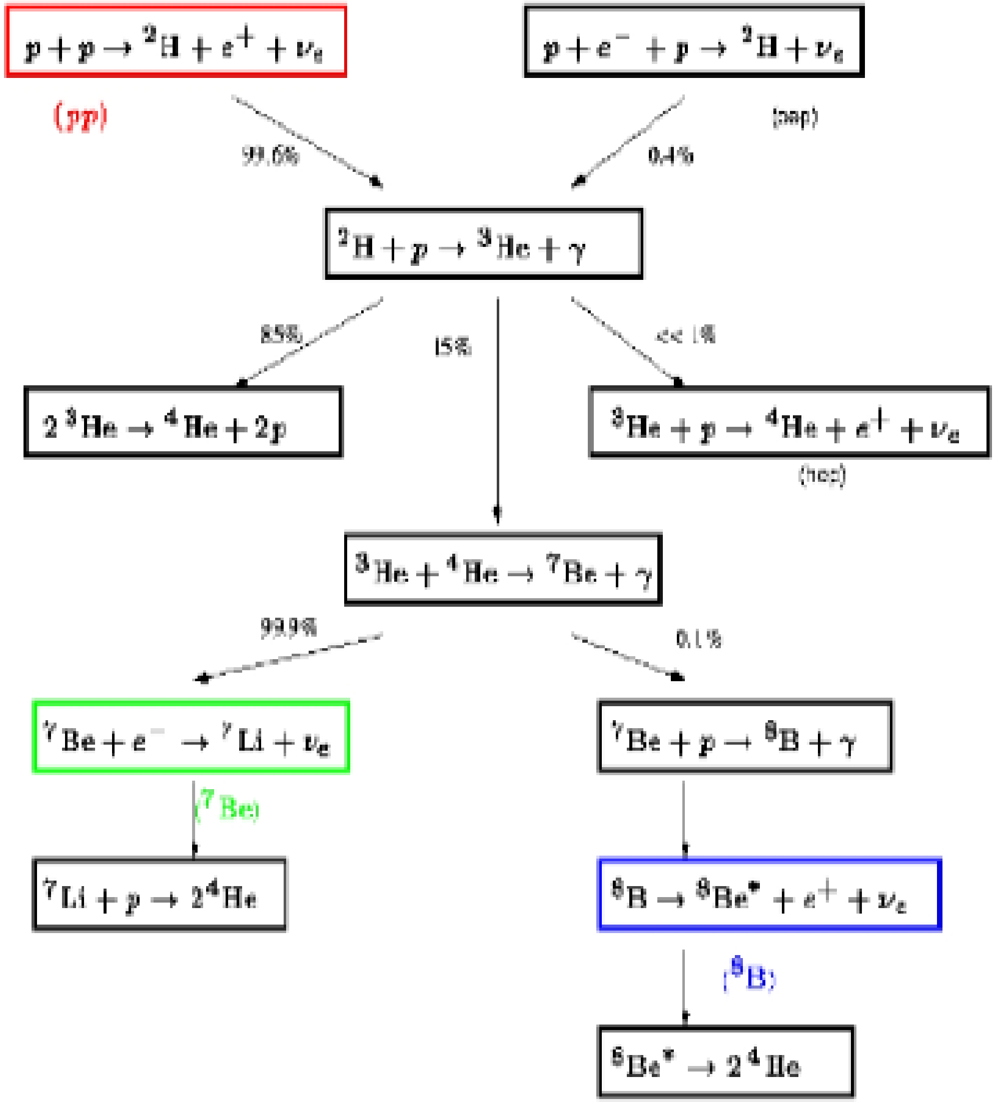
CC statistics ~30%

NC statistics ~70%

+ background rejection and many improvements in systematics

S. Seibert





$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

(*pp*)

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

(pep)

99.6%

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

15%

<< 1%

$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

(hep)

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.9%

0.1%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

(^{7}Be)

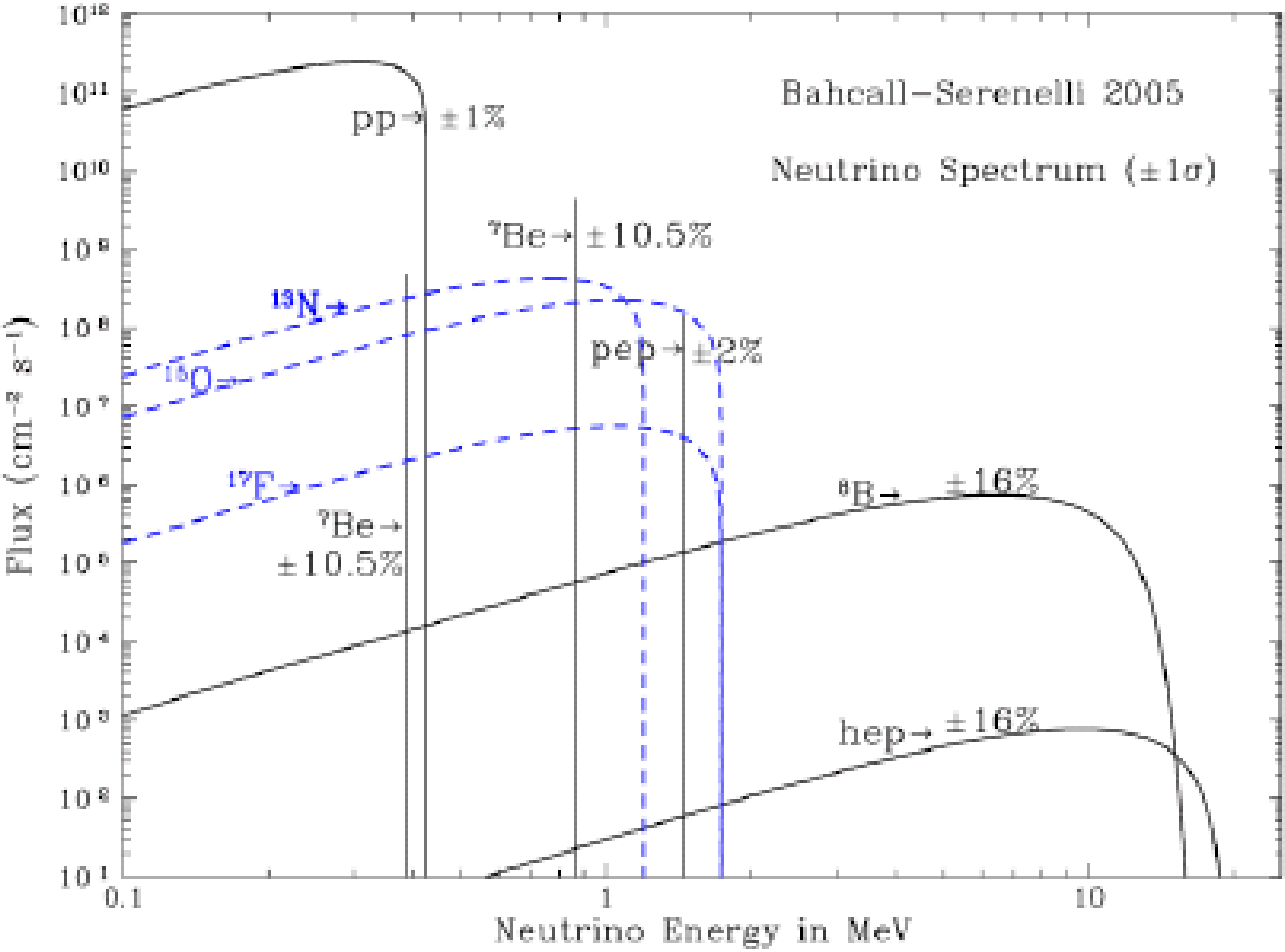
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

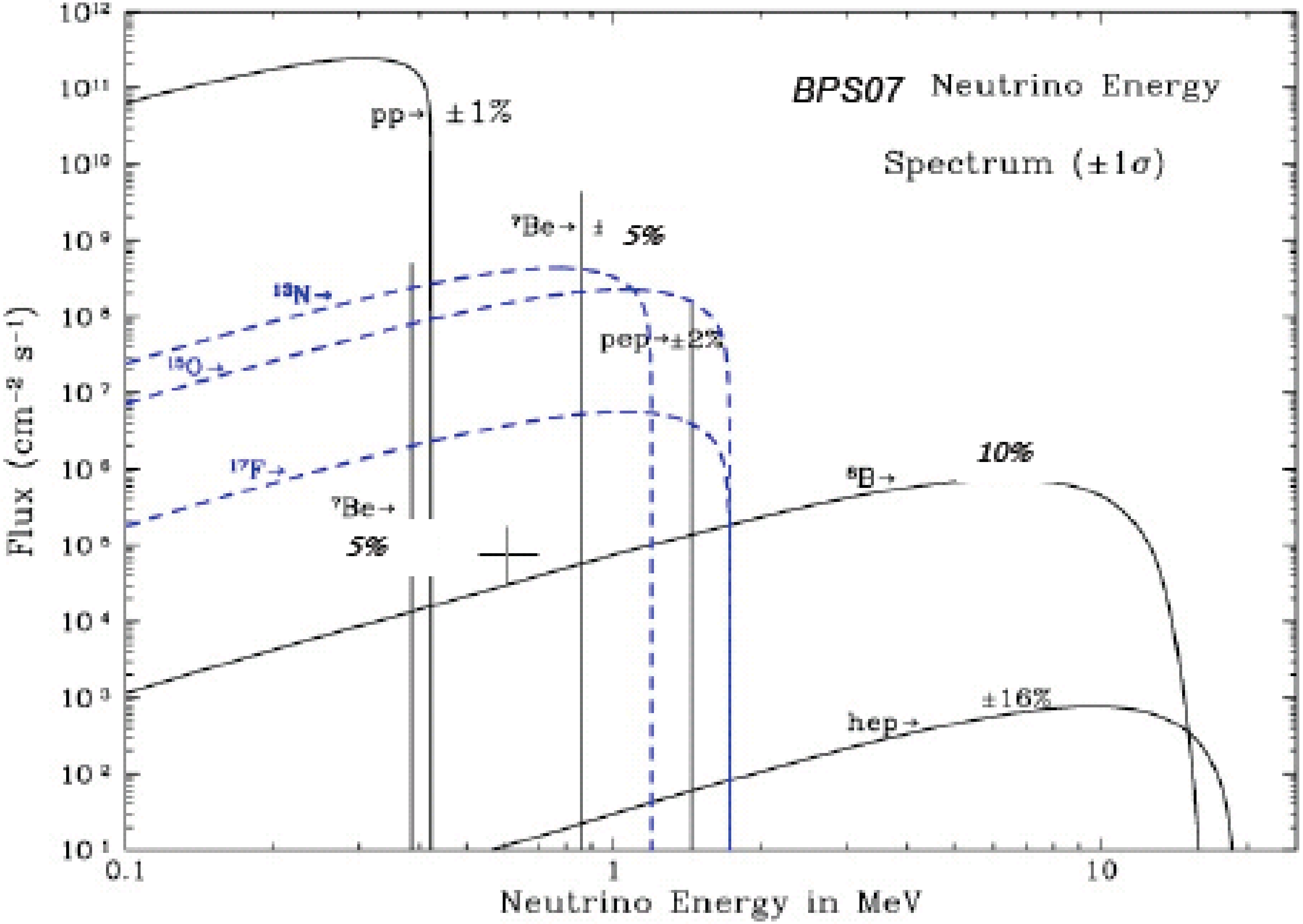
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

(^{8}B)

${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$


Bahcall-Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
pep→ ±2%
¹⁷F→
⁷Be→
±10.5%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10


BPS07 Neutrino Energy
Spectrum (±1σ)
pp→ ±1%
⁷Be→ ± 5%
¹³N→
¹⁵O→
¹⁷F→
pep→±2%
⁷Be→
5%
⁸B→
10%
hep→
±16%
Flux (cm⁻² s⁻¹)
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10
Neutrino Energy in MeV

BPS07 : High Z vs Low Z

	GS98	AGS05	δ_{TH} % (δ_Z)	EXP
pp	5.97	6.04	0.8 (0.3)	
pep	1.41	1.46	1.3 (0.6)	*
hep	7.90	8.22	15.4 (0.9)	
Be	5.08	4.55	5.0 (2.4)	***
B	5.94	4.72	10.1 (5.3)	4.94 (0.43)
N	2.93	1.93	+20-15 (11)	*
O	2.20	1.37	+23-16 (11)	*
F	5.82	3.24	25 (15)	

Neutrino fluxes can point out high/low Z model

Backgrounds

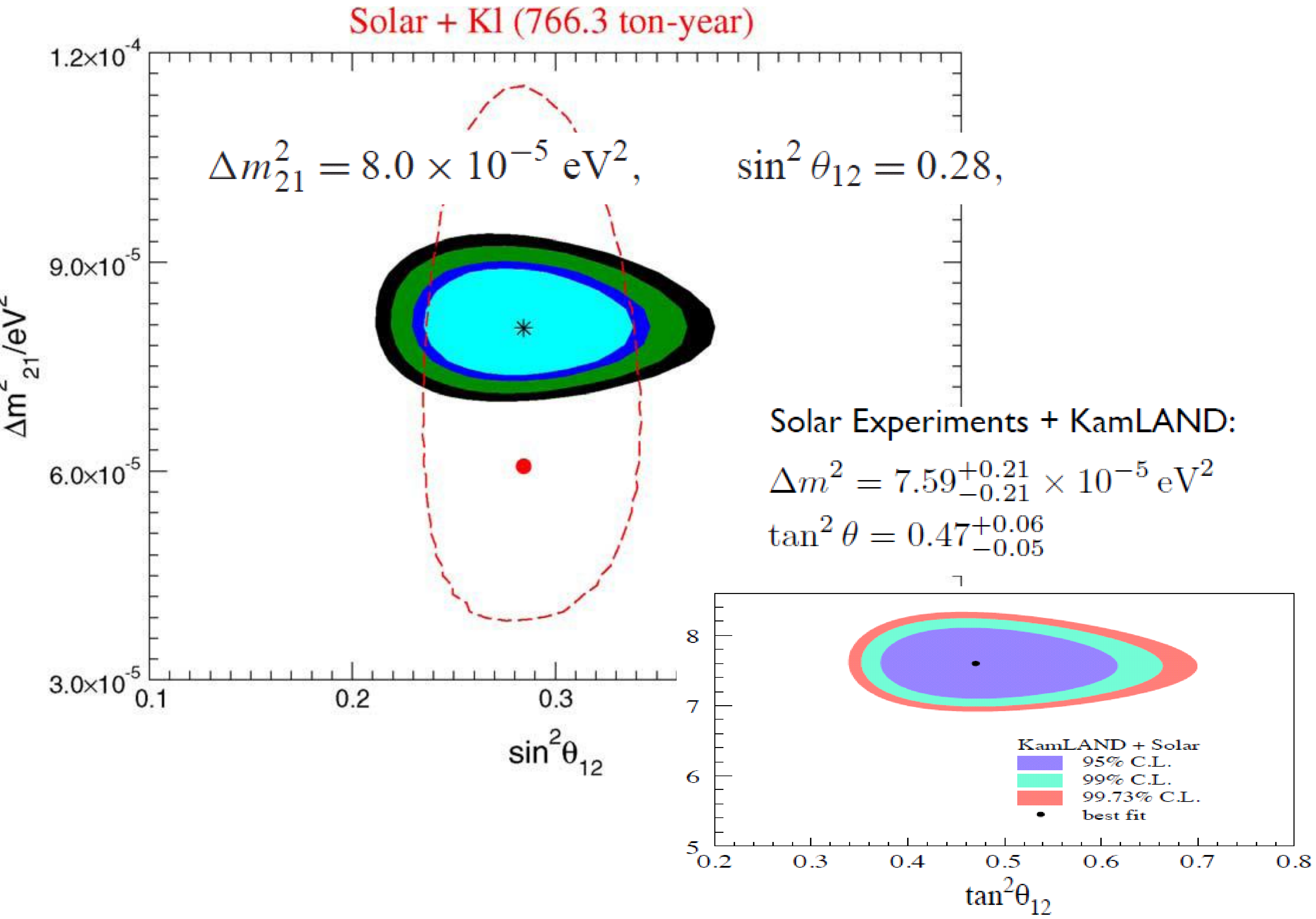
Background	Contribution	
Accidentals	80.5 ± 0.1	→ Accidental Coincidences
^{9}Li/^{8}He	13.6 ± 1.0	Cosmogenic
Fast neutron & Atmospheric ν	<9.0	
$^{13}C(\alpha,n)^{16}O_{gs}$, np → np	157.2 ± 17.3	Background from ^{222}Rn chain
$^{13}C(\alpha,n)^{16}O_{gs}$, $^{12}C(n,n')^{12}C^{*}$ (4.4 MeV γ)	6.1 ± 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 excluding geo-neutrino	276.1 ± 23.5	

Geo-neutrinos are a background to the neutrino oscillation measurement

→Talk by John Learned

Using one geological model, which assumes 16TW of radiogenic heat from U+Th geo-neutrinos, expect 69.7 events

However, analysis is done by simultaneously fitting geo- and reactor neutrinos !

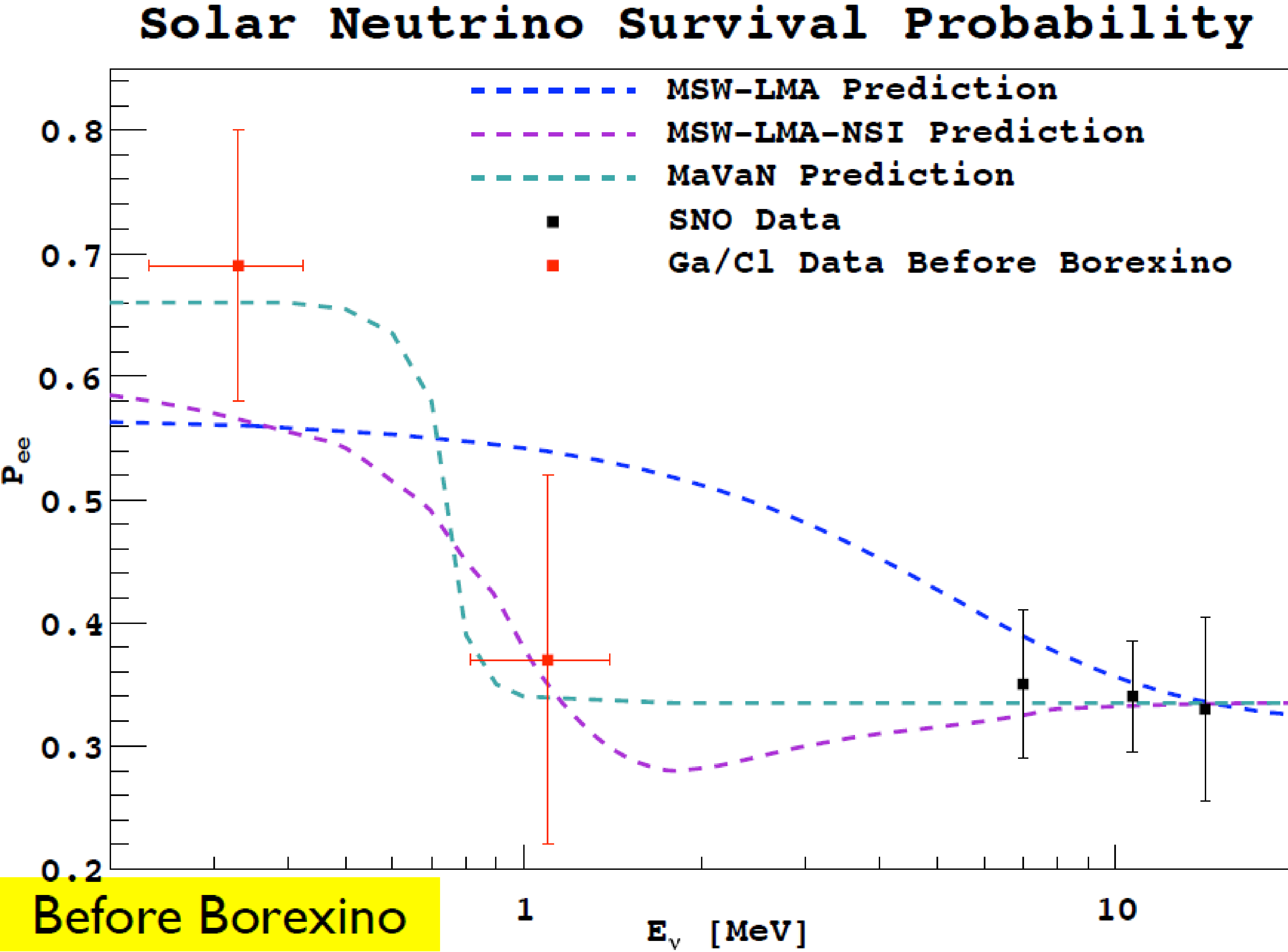


$$\Delta m^2_{21} = 8.0 \times 10^{-5}\ \mathrm{eV}^2, \qquad \sin^2\theta_{12} = 0.28,$$

Solar Experiments + KamLAND:

$$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$$

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



Before Borexino