Neutrino Mixing of ^{7}Be and Low-Energy ^{8}B Solar Neutrinos

DNP Meeting, Sante Fe
November 4th, 2010

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Image: Borexino Collaboration

Outline

- Quick review of solar neutrinos and neutrino mixing
- Current low energy solar neutrino results
  - SNO
  - Borexino
- Outlook

Image: SNO Collaboration

Solar Fusion Reactions

p-p Solar Fusion Chain

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

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

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$ $\quad$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

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

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$ $\quad$ ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$

CNO Solar Fusion Cycle

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

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

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

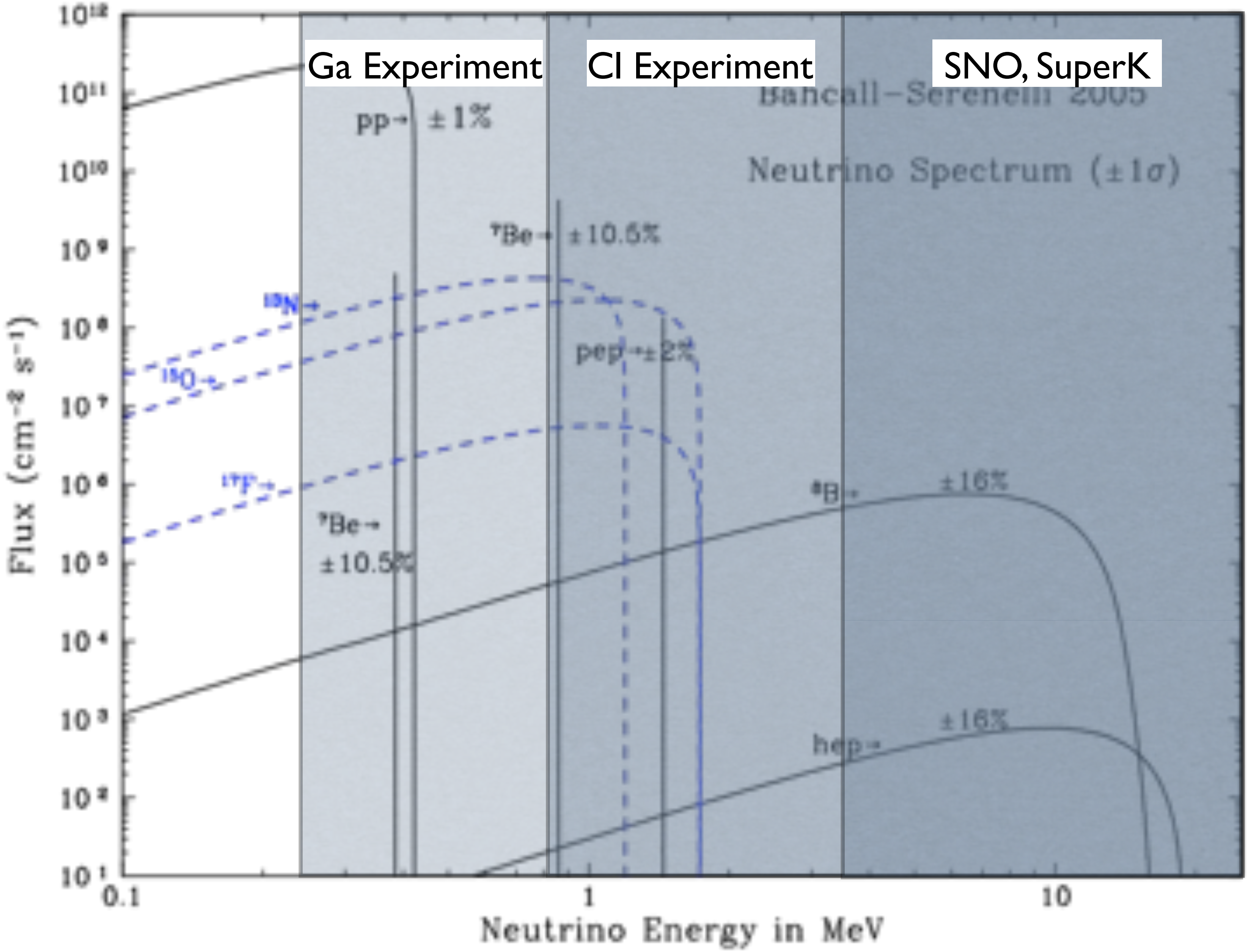
$${}^{14}N + p \rightarrow {}^{15}O + \gamma$$

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

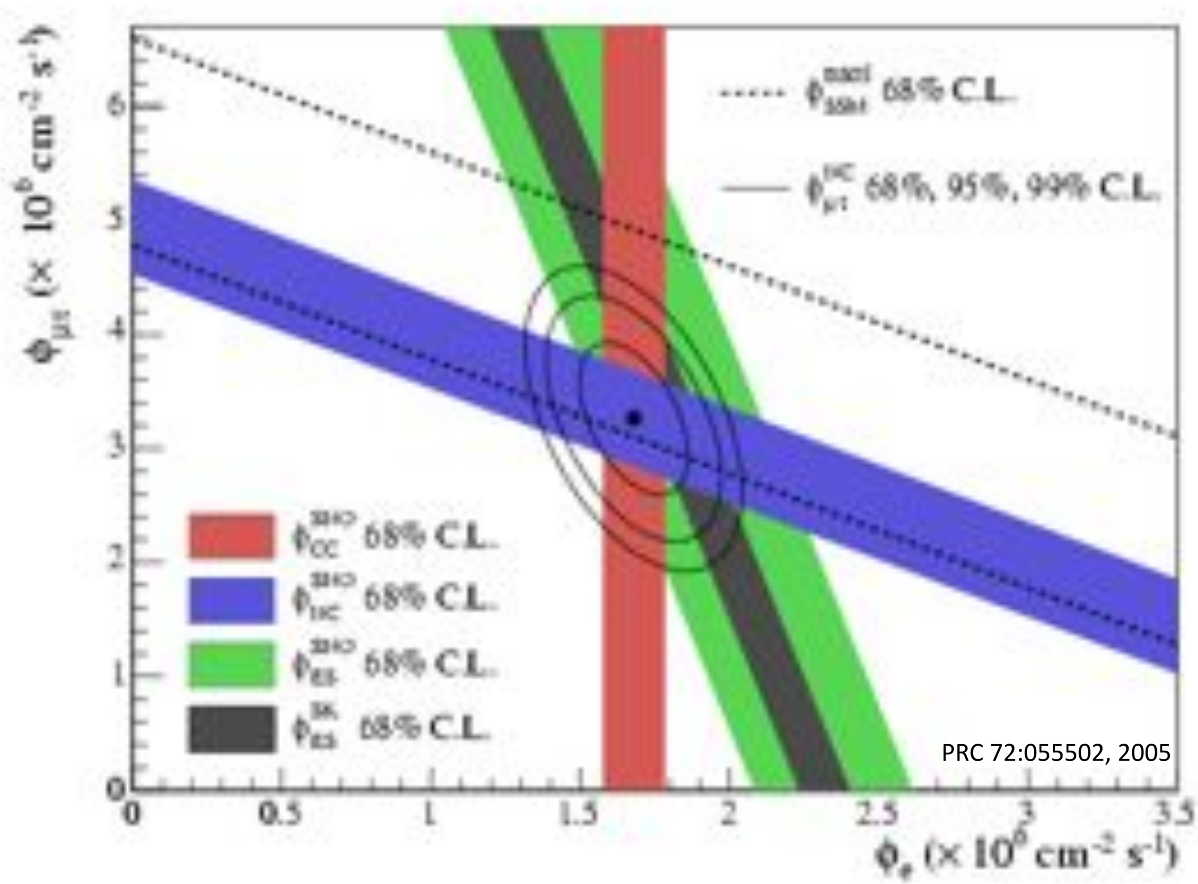
$${}^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$

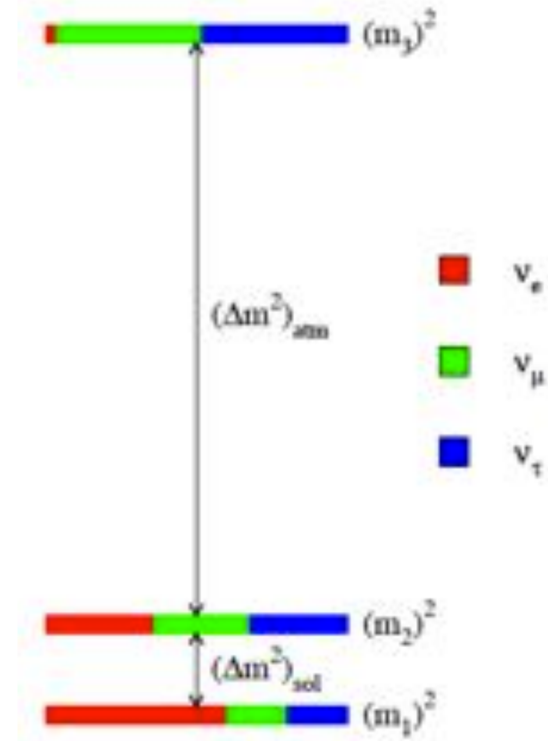
Image: bbc.co.uk

Solar Neutrinos



SNO Results: Solar Neutrinos Oscillate





hep-ph/0411274

- Neutrinos are produced and detected in flavour eigenstates, but propagate in a superposition of mass eigenstates
- Phase differences acquired in mass eigenstate propagation changes apparent flavour content

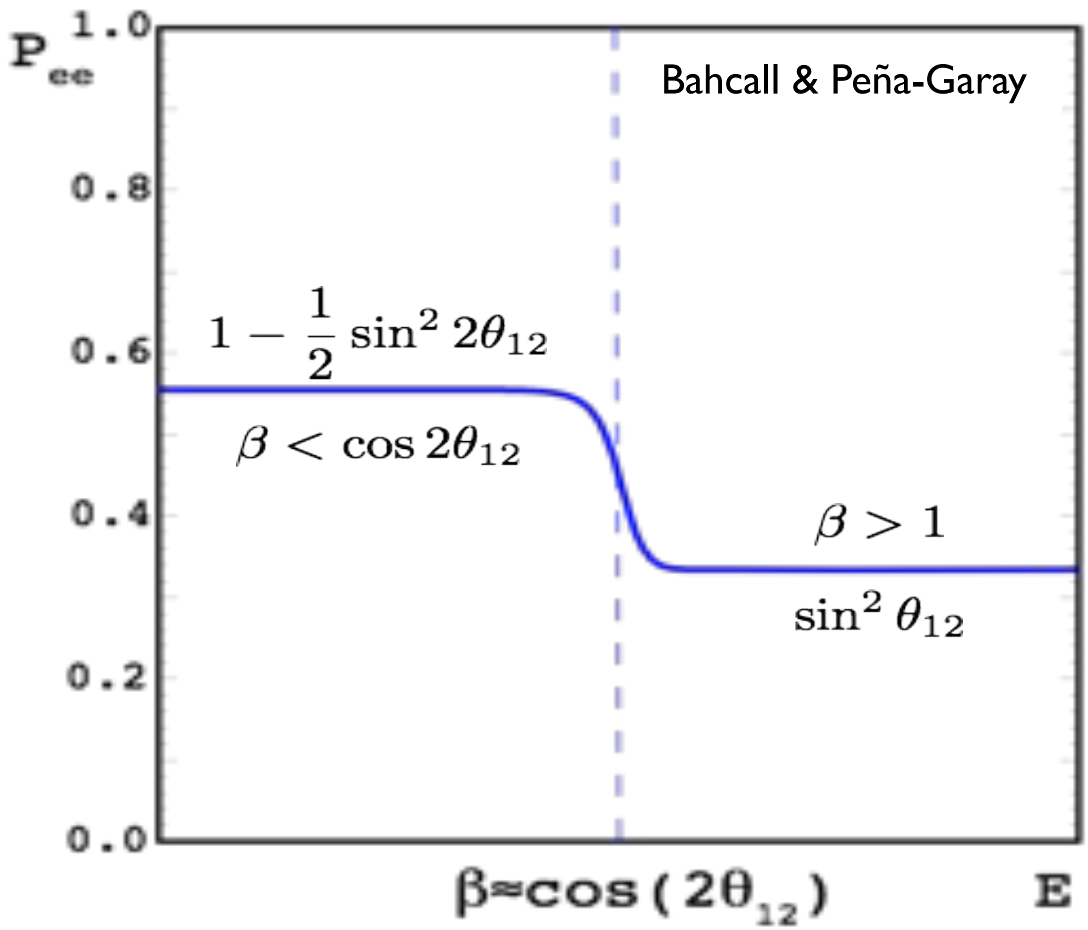
"MSW" Neutrino Oscillations

- The electron neutrino survival probabilities measured by the different neutrino experiments are well described by "matter enhanced" oscillations
- Similar to quark oscillations (CKM matrix ➔ PMNS matrix)
- Charged current interactions with matter add an additional term to ν_e flavour in mass matrix:

$$\begin{pmatrix} -\frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} \\ \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} & \frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} \end{pmatrix}$$

  - Note that, because θ_{13} is small and the mass splittings are quite different, solar neutrinos are well described by "two-flavour" oscillations

MSW Oscillation Regimes

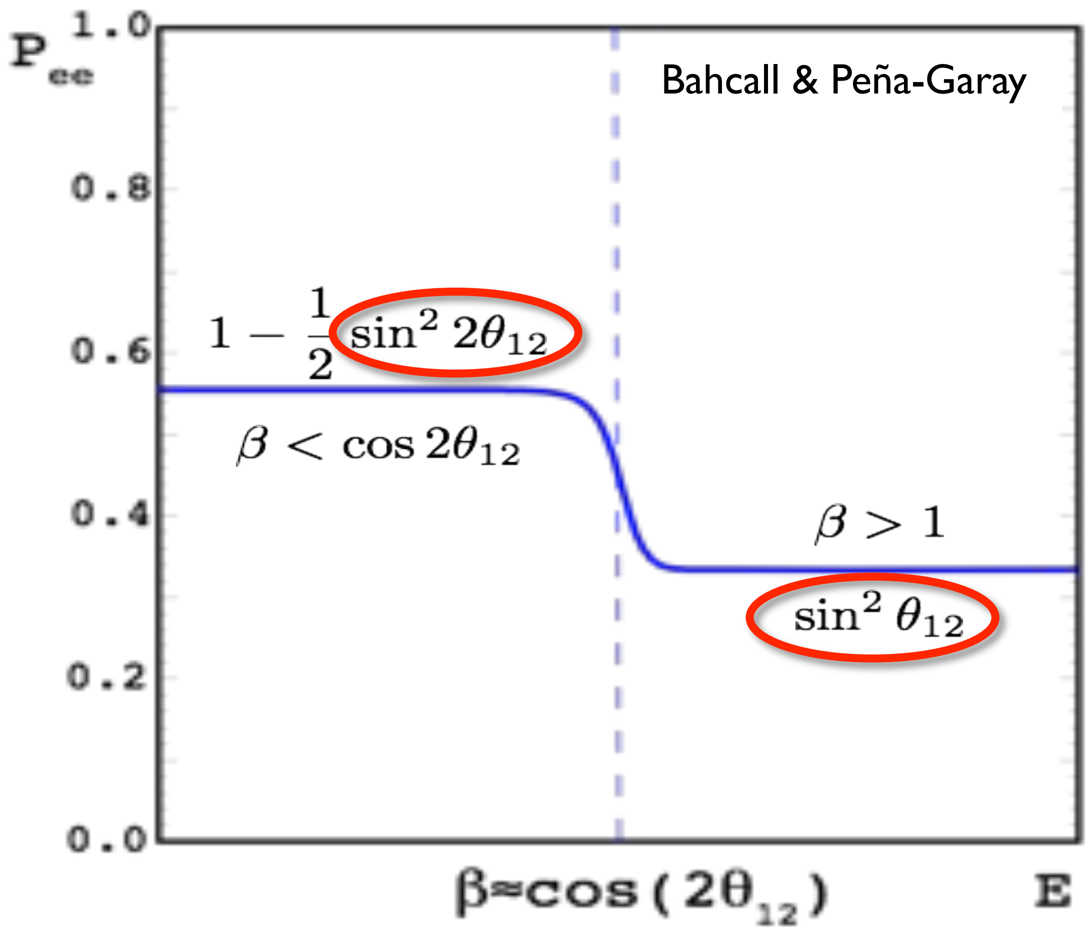


$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated "resonant conversion"

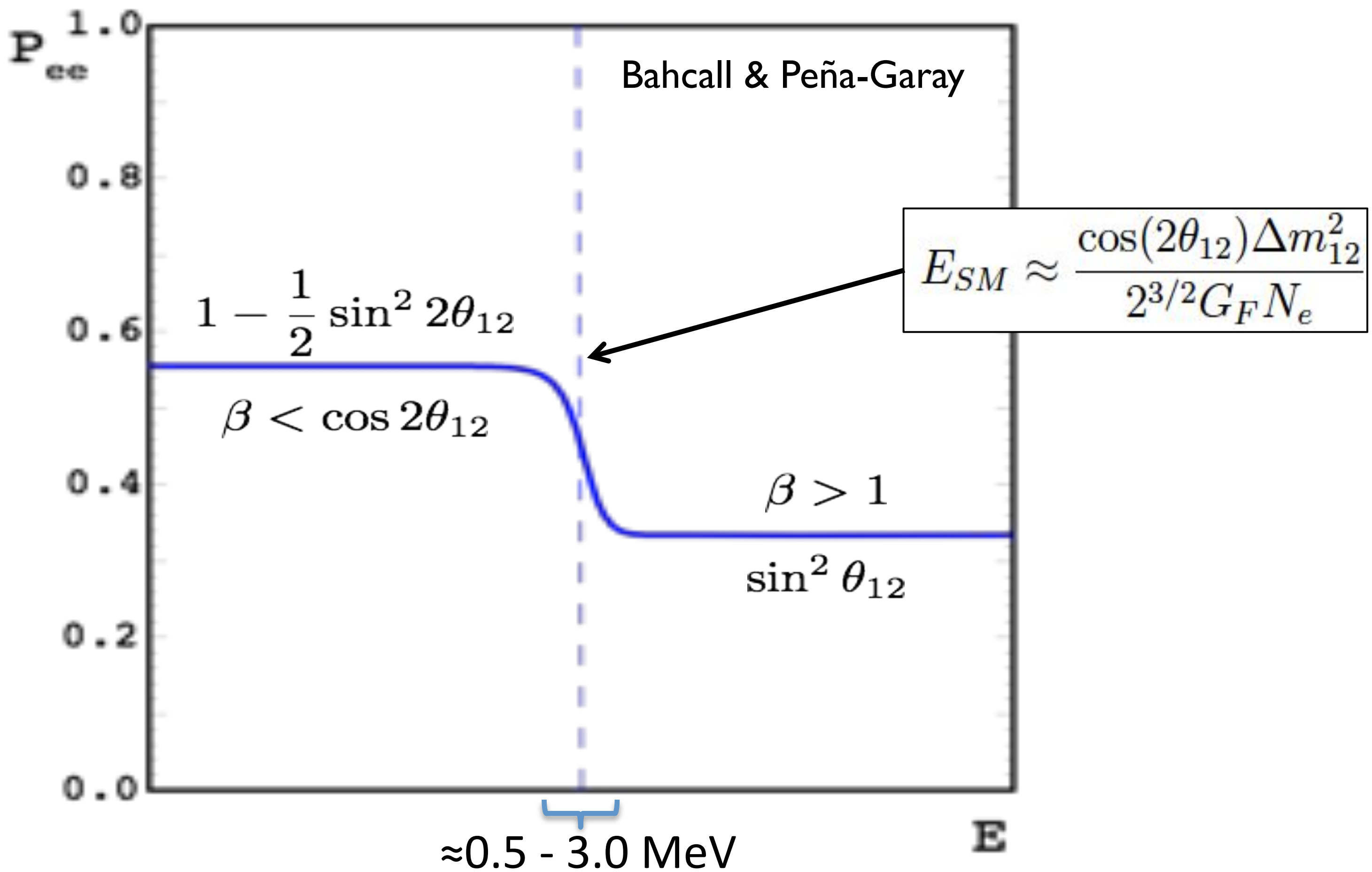
MSW Oscillation Regimes



$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

In these regimes, P_{ee} depends only on Θ_{12}, not on the mass splitting or the details of the neutrino-matter interaction

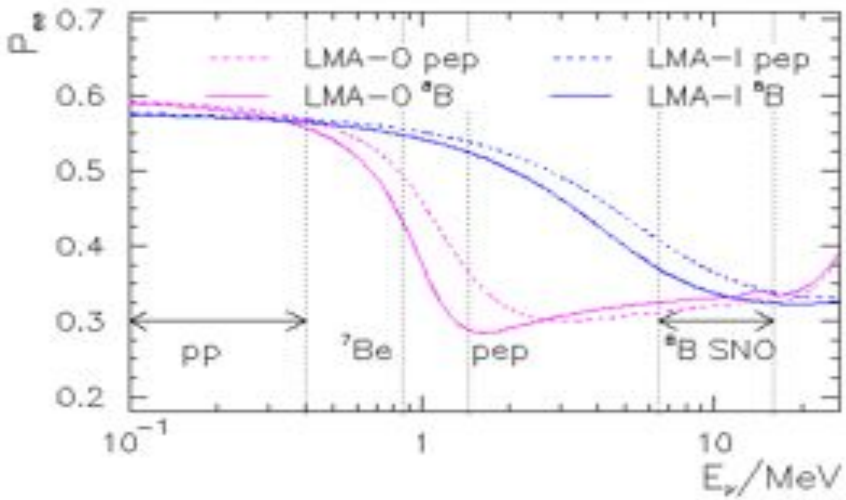
MSW Oscillation Regimes



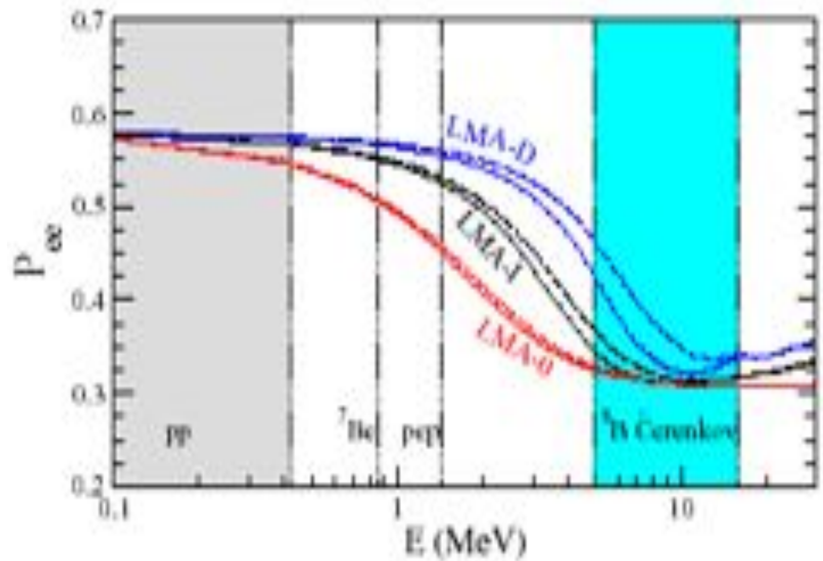
Look in "transition region" to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

Non-Standard Interactions

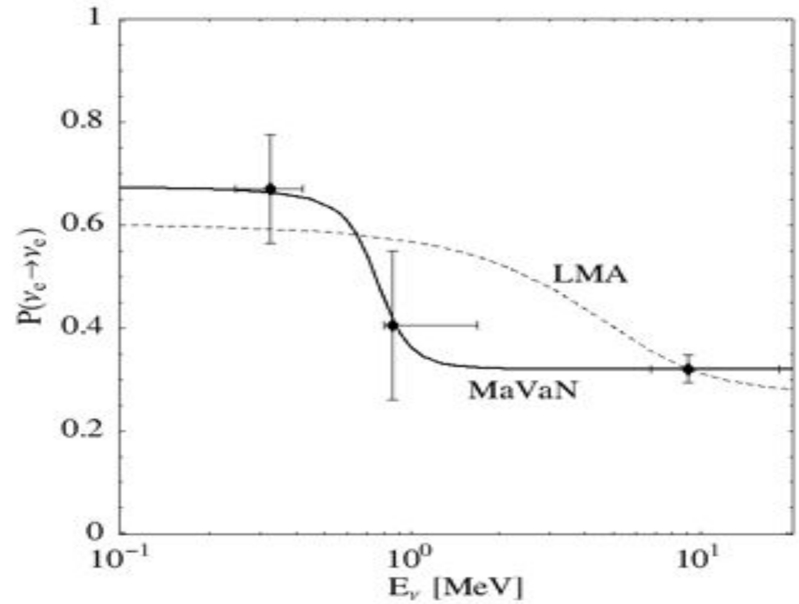


Friedland *et al*., PLB 594 (2004)



Miranda *et.al.*, hep-ph/0406298 (2005)

Mass Varying Neutrinos

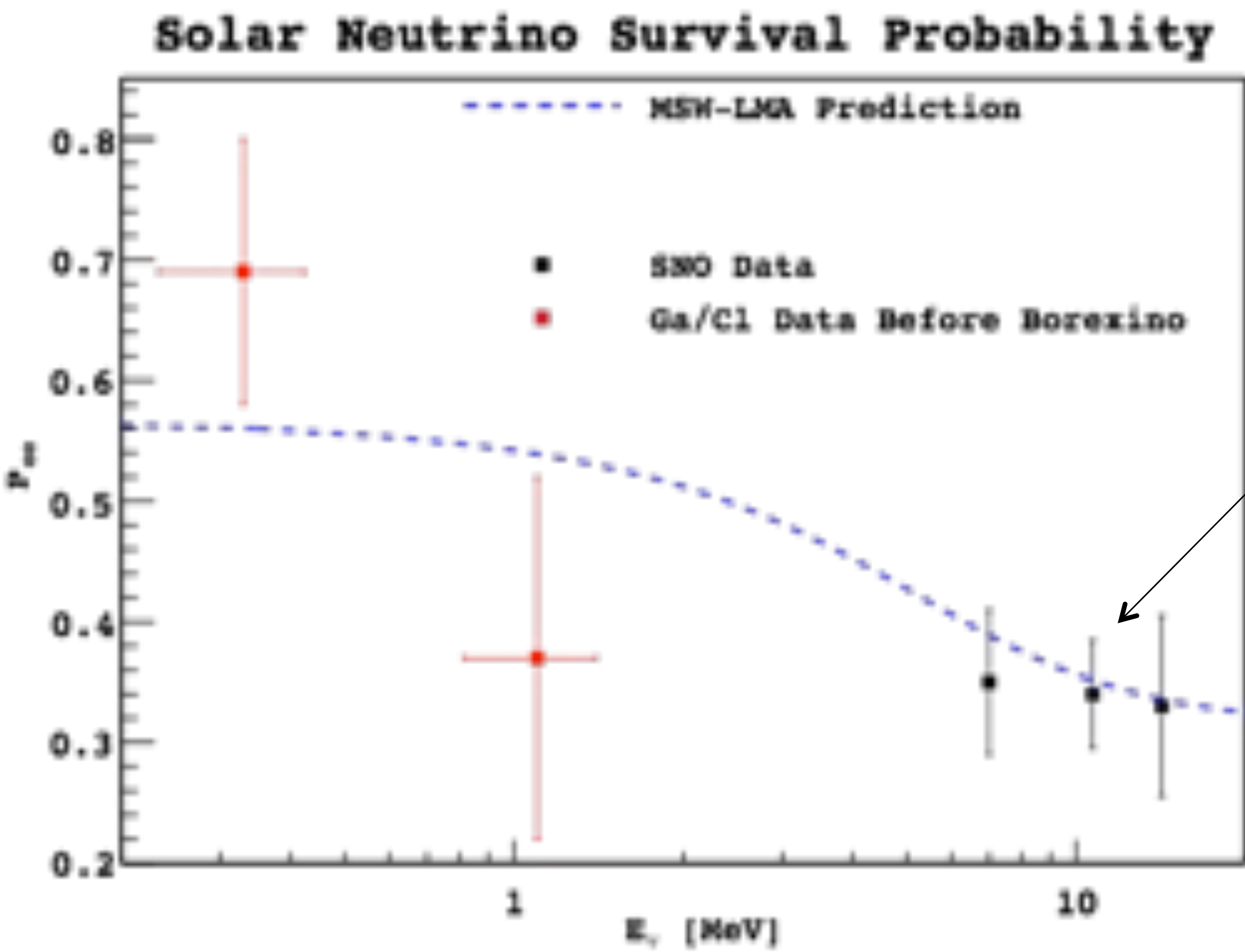


Barger *et al*. PRL 95 (2005)

Other Possibilities:

- CPT violations
- Sterile neutrino admixture

(Old) Experimental Constraints on Transition Region

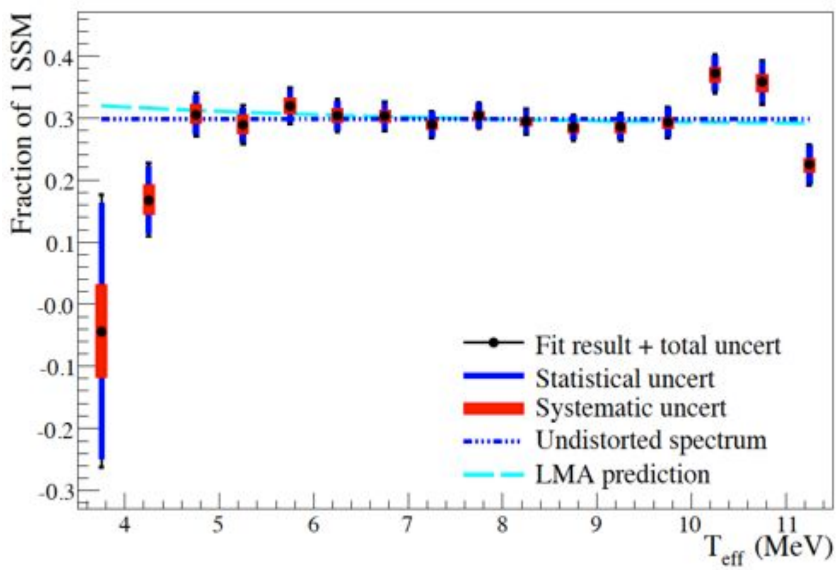


Confirmed by Kamiokande and SuperK

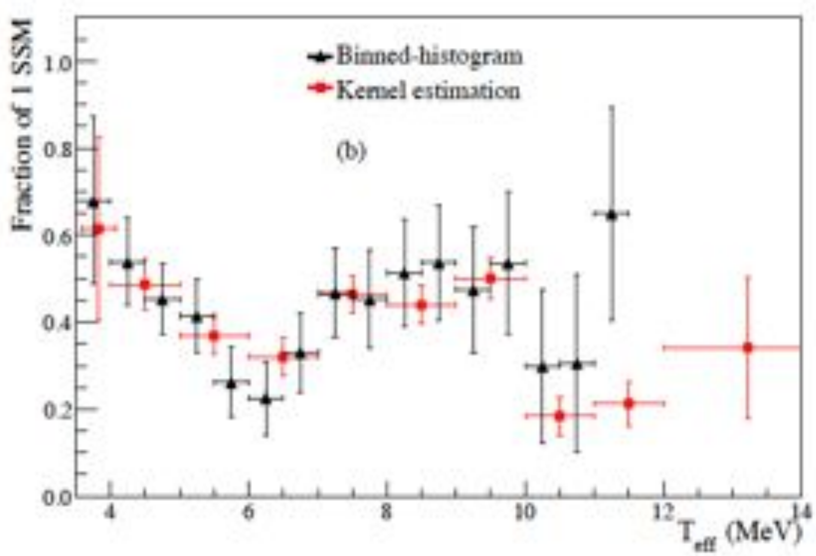
Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. ***Real-time measurements needed in the transition region.***

SNO Low Energy Threshold Analysis

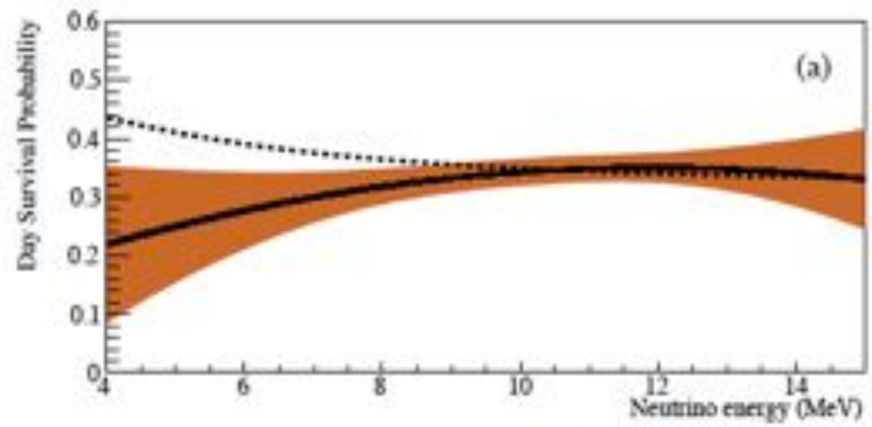
Charged Current: $T_{eff} = E_\nu - 1.44$ MeV

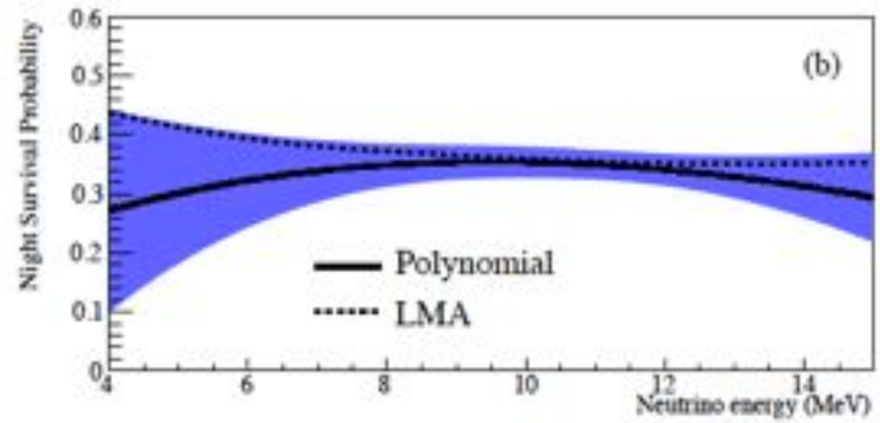


Elastic Scattering: $0 \leq T_{eff} \lesssim E_\nu - 0.24$ MeV



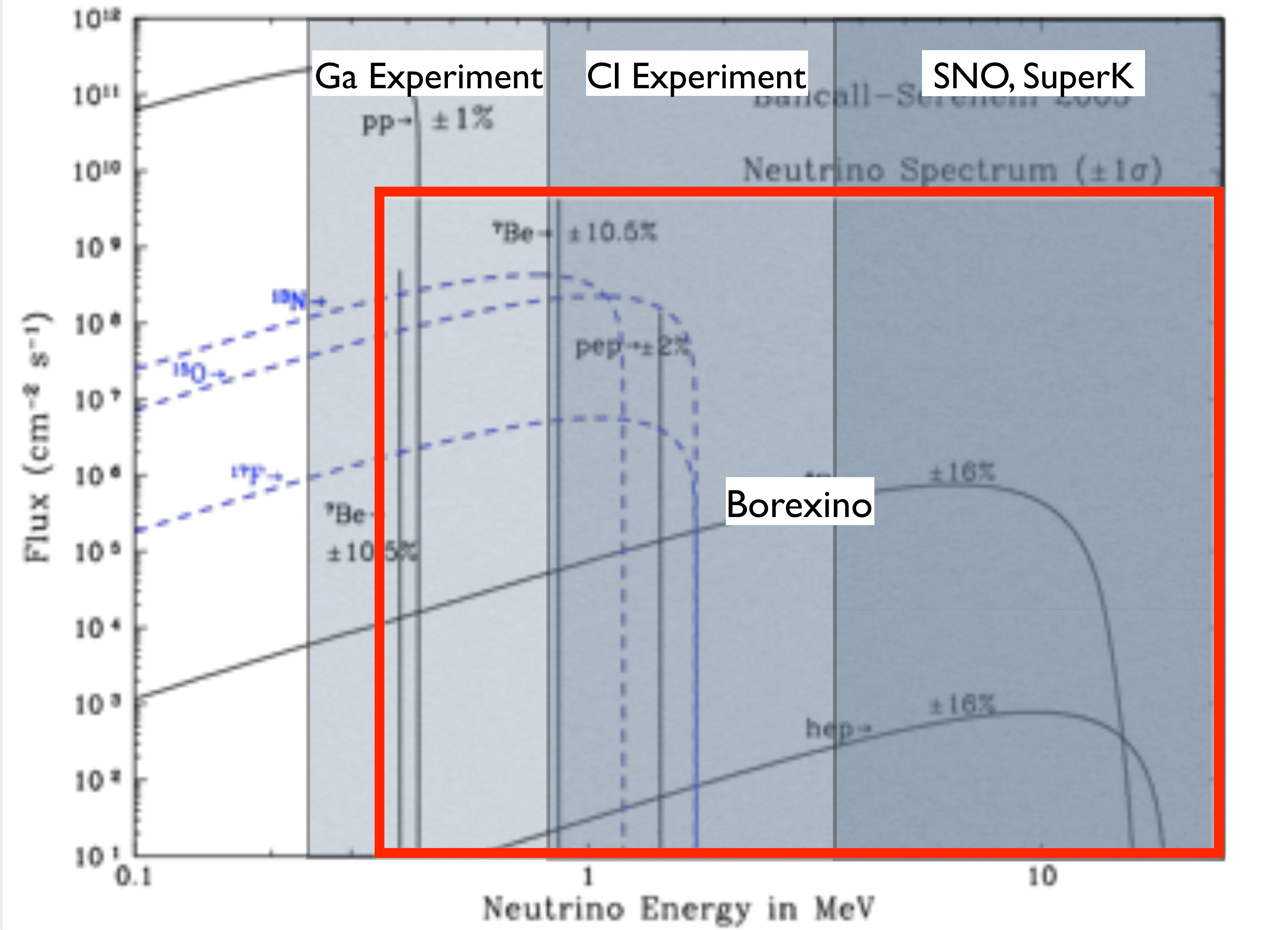
Quadratic Fits to P_{ee}



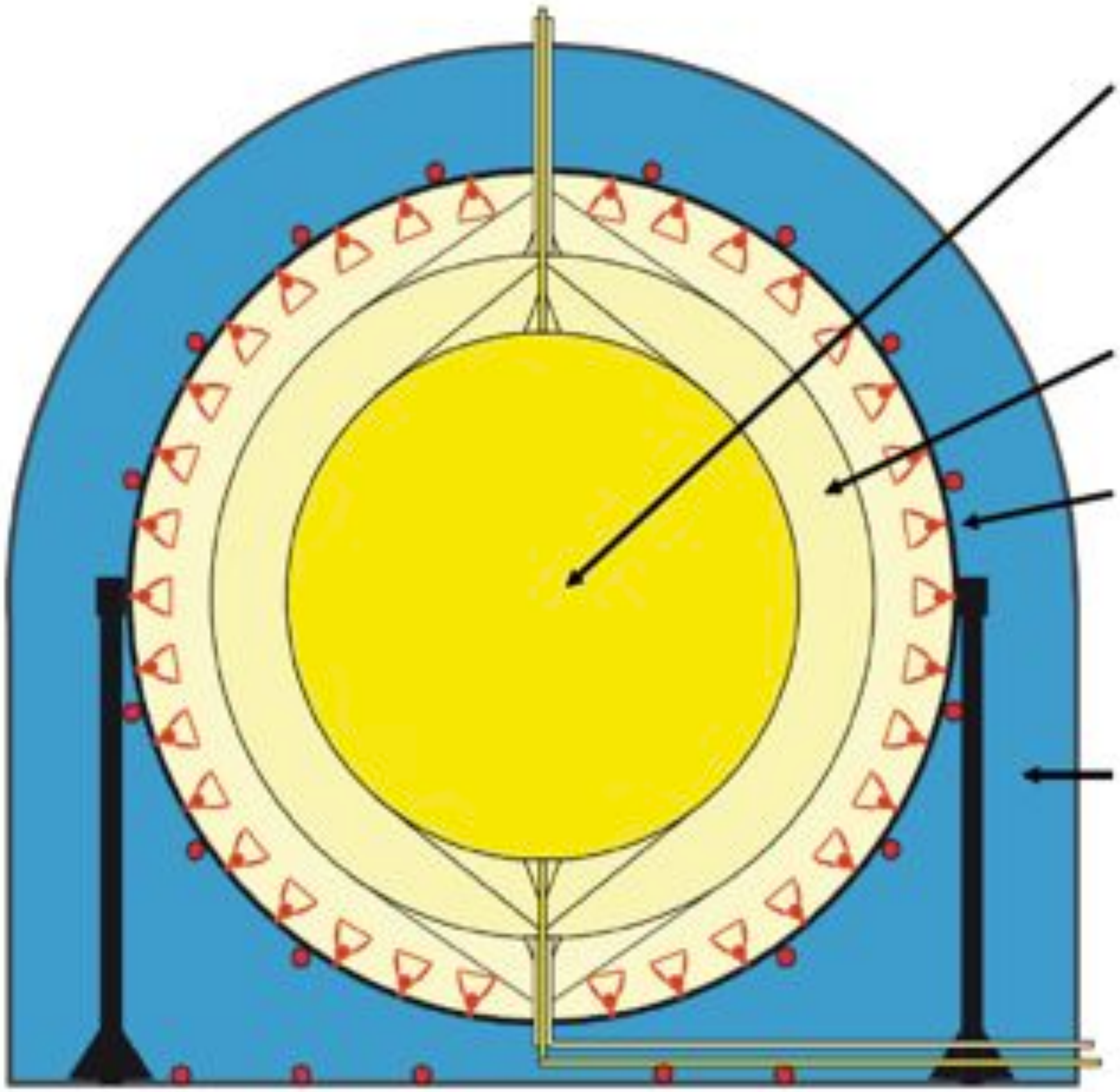


(Phys. Rev. C 81 (2010) 055504)

Liquid Scintillator: Real-time Detection to Below 100 keV



The Borexino Detector



Target: 300 tons of liquid scintillator confined by nylon vessel of R=4.25 m

non-scintillating buffer

stainless steel sphere
6.85 m in radius
2212 inward-facing PMTs

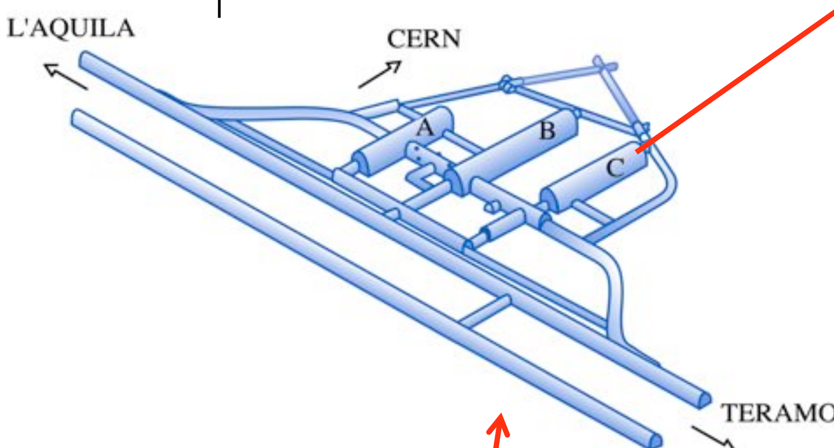
outer water tank
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

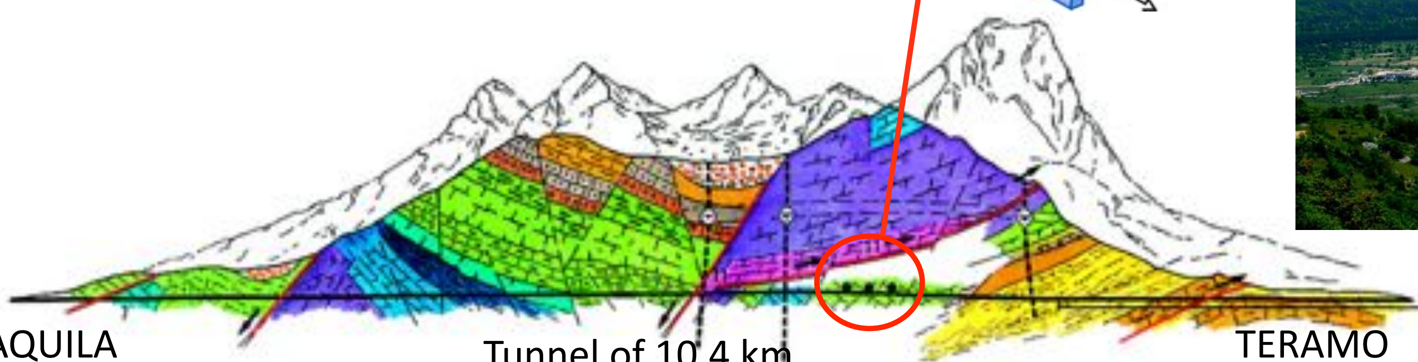
Laboratori Nazionali del Gran Sasso

4600’ to surface

3500 m.w.e.

muon flux 1/m^2/hr





Neutrino Detection With Liquid Scintillator

- Neutrino detection via neutrino-electron elastic scattering
- Detect scintillation light from recoiling electron
    - Good position reconstruction (10-15cm) from time-of-flight
    - Low energy threshold (~60keV)
    - Good energy resolution (~500p.e./MeV)
- Calorimetric measurements only, no directional sensitivity
    - Can't distinguish neutrino events from β/γ backgrounds

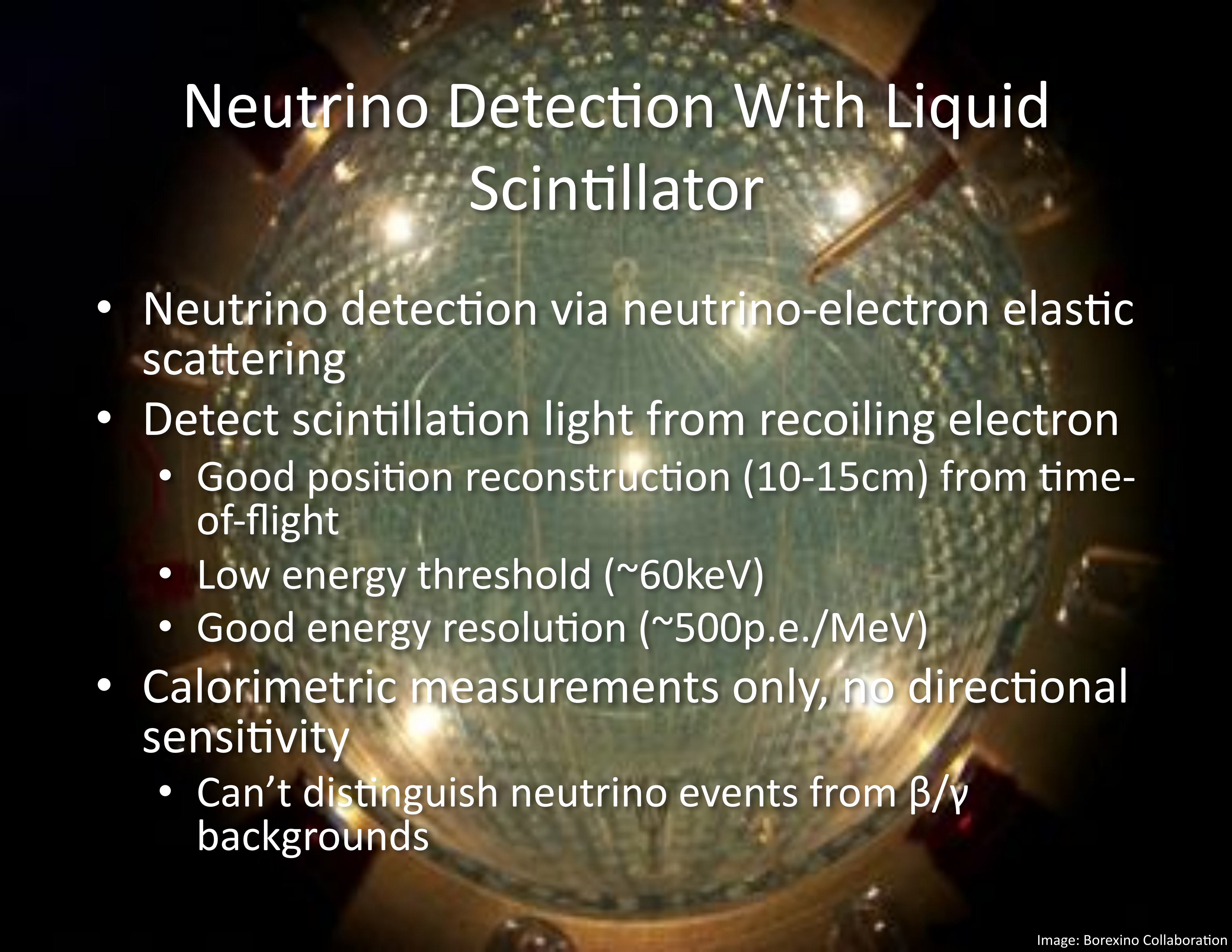
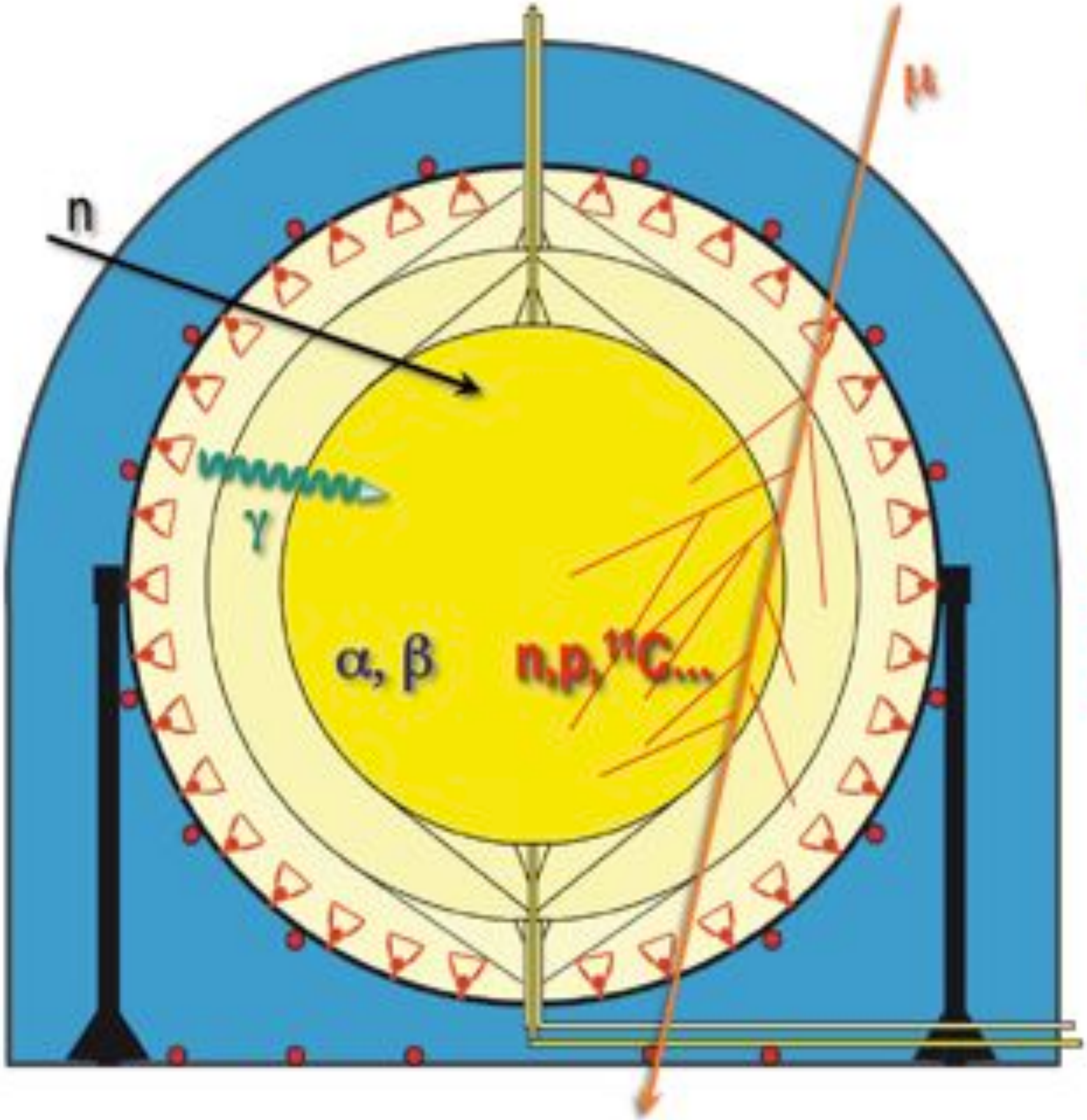


Image: Borexino Collaboration

Central Challenge: Background Reduction



Internal Radioactivity
traces of radioisotopes in the scintillator (U/Th,^{40}K)

External Gamma-Rays
from buffer, steel sphere, PMT glass (^{40}K, ^{208}Tl ...)

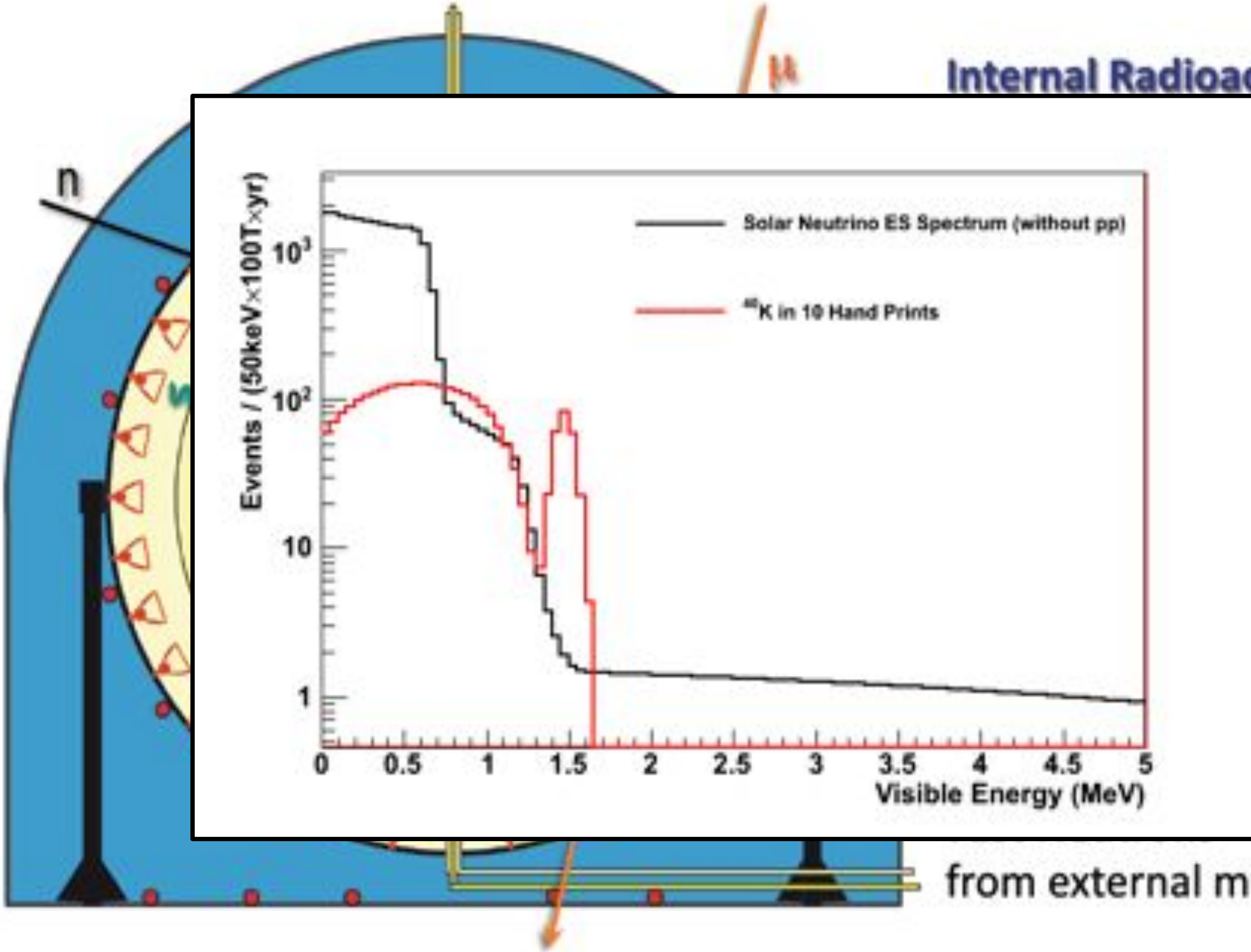
Cosmic Muons

Cosmogenics
neutrons and radionuclides from muon-spallation and hadronic showers

Fast Neutrons
from external muons

Slide: M. Wurm

Central Challenge: Background Reduction



Internal Radioactivity

otopes in
U/Th,^{40}K)

-Rays

l sphere,
^{08}Tl ...)

dionuclides
ation and
s
from external muons

Slide: M. Wurm

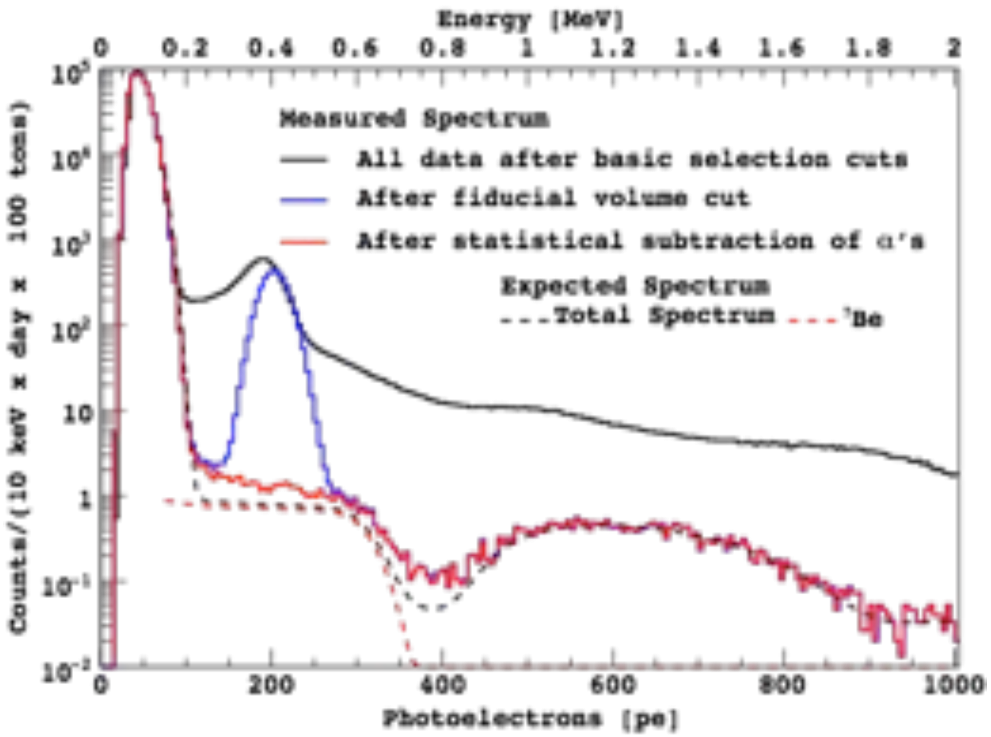
Borexino achieved unprecedented low levels of internal background.

The Counting Test Facility III

Contaminant	Source	Normal Conc.	Borex Req.	Reduction Method	Borex Achieved
μ	Cosmic	$200/(s \cdot m^2)$	$10^{-10}/(s \cdot m^2)$	Underground, active veto	$<10^{-10}/(s \cdot m^2)$
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Old oil	10^{-18}g/g
^{238}U	Dust	10^{-4} g/g	10^{-16} g/g	Purification	$<10^{-17}$g/g
^{232}Th	Dust	10^{-4}g/g	$<10^{-16}$ g/g	Purification	$<10^{-17}$g/g
^{85}Kr	Air	1 Bq/m^3	<0.01ppt	LAKN	<0.035 ppt
^{11}C	Cosmogenic	25 /day/100ton	~10/day	μ+n coincidence	3/day/100ton

Borexino 192-day ^{7}Be Result

(PRL 101 9 (2008))

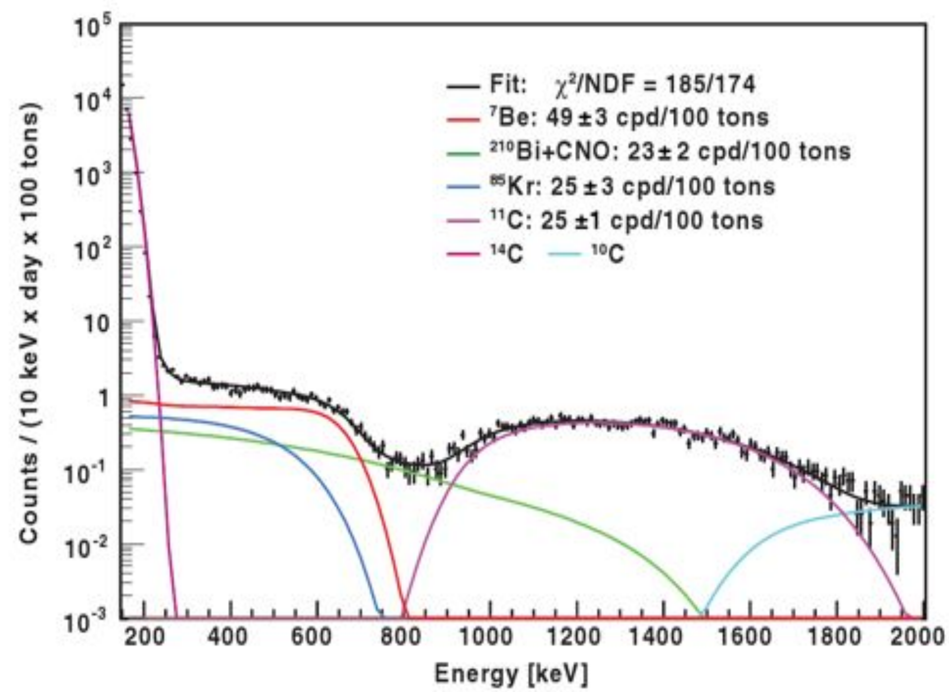


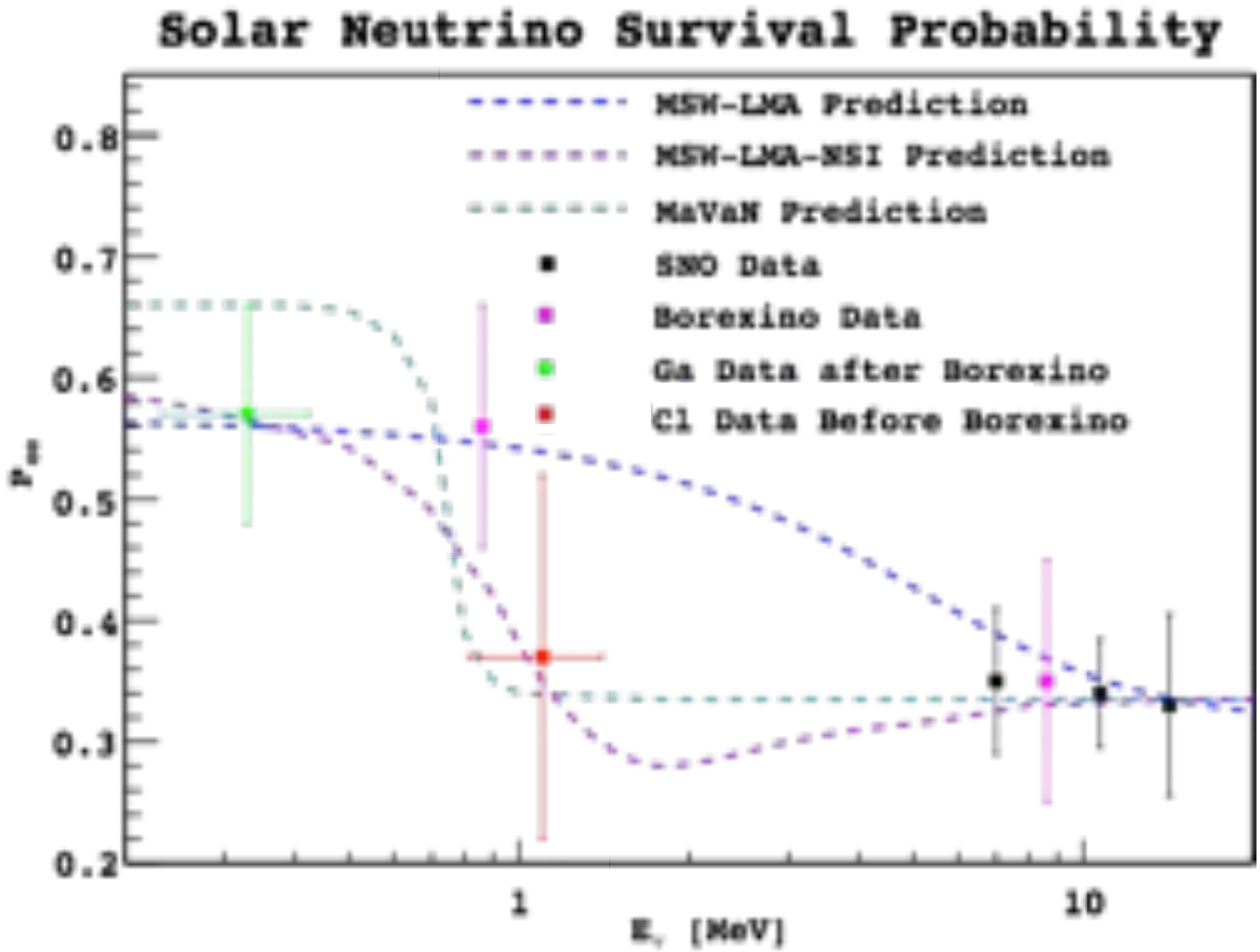
0.862 MeV ^{7}Be Result:

$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100T

Compare with SSM (BS06, High Metallicity):

$P_{ee} = 0.56 \pm 0.1$

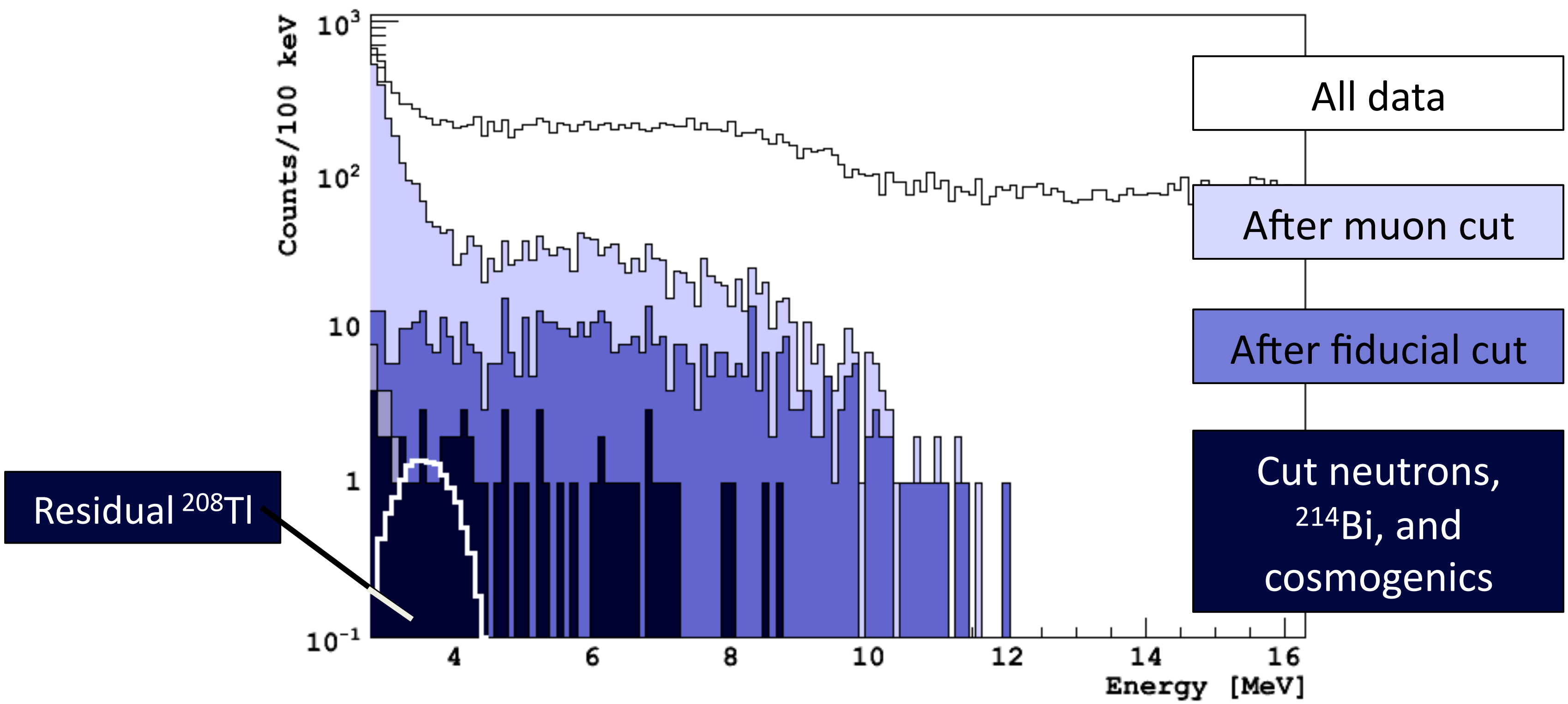




Solar Neutrino Survival Probability
MSW-LMA Prediction
MSW-LMA-NSI Prediction
MaVaN Prediction
SNO Data
Borexino Data
Ga Data after Borexino
Cl Data Before Borexino
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
10
E [MeV]

Borexino Low Energy ^{8}B Analysis

(PRD 82 (2010) 033006)



Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90±13	55±7
^{11}Be subtraction	79±13	47±8
Residual subtraction	75±13	46±8
Final sample	75±13	46±8

Background	Rate [10^{-4}cpd/100 t] >3 MeV	>5 MeV
Muons	4.5±0.9	3.5±0.8
Neutrons	0.86±0.01	0
External background	64±2	0.03±0.11
Fast cosmogenic	17±2	13±2
^{10}C	22±2	0
^{214}Bi	1.1±0.4	0

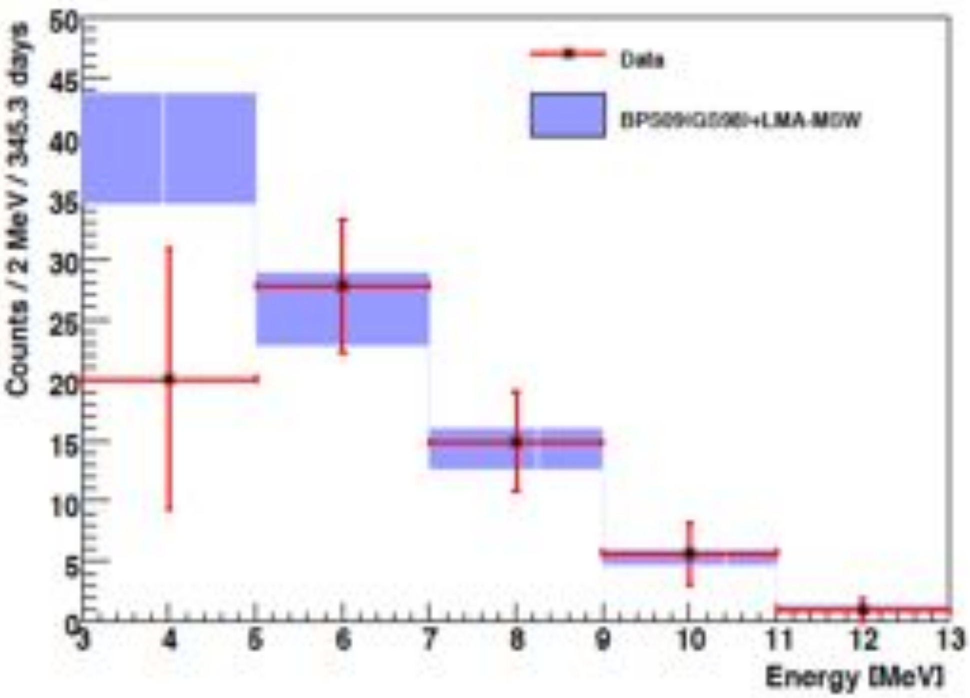
Sum Residuals

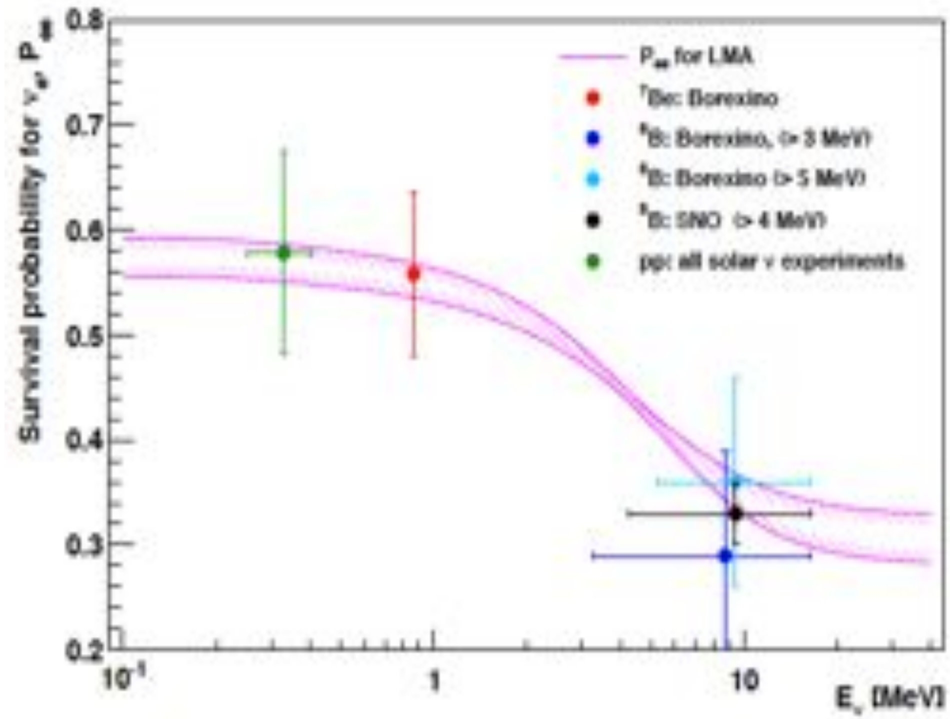
^{8}B Counting Rate (245 live days):

>3 MeV: $0.217 \pm 0.038(stat)^{+0.008}_{-0.008}(syst)\ c/d/100\,t$

>5 MeV: $0.134 \pm 0.022(stat)^{+0.008}_{-0.007}(syst)\ c/d/100\,t$

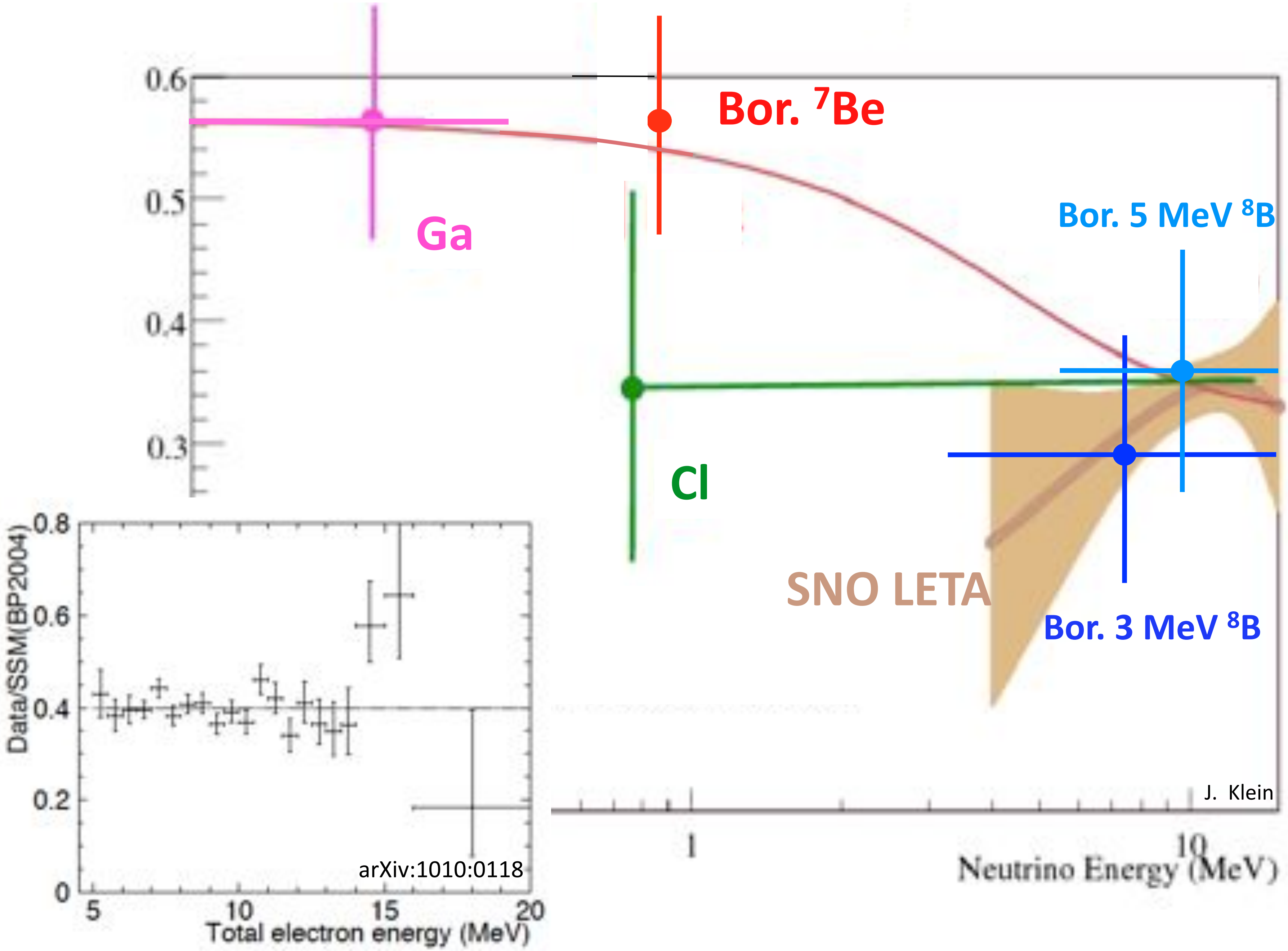
Borexino ES Spectrum





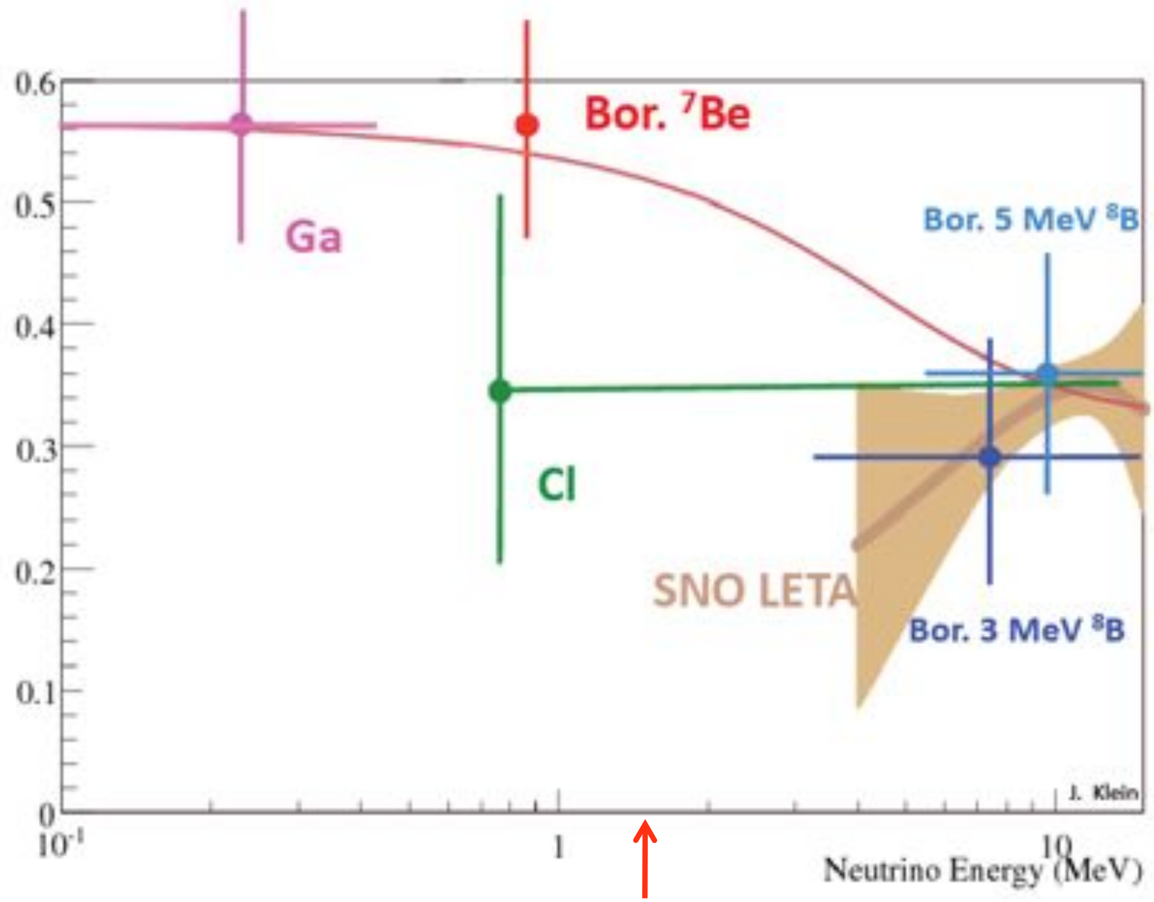
Beginning to test MSW with a single experiment: Borexino ^{7}Be and ^{8}B P_{ee}'s differ by 1.9σ

Summary of Current Status



How to Proceed?

- Improve the ^{7}Be measurement
- Lower the ^{8}B analysis threshold
- Measure the *pep* survival probability



pep neutrinos:
±<2% SSM flux prediction

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

J. Klein, Neutrino '08

Plus more from Borexino and SuperK….

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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.

J. Klein, Neutrino '08

Plus more from Borexino and SuperK....

Improving the Borexino ^{7}Be Result

Current Result:

$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100T

Contribution	Error
Statistics	± 6%
Total scintillator mass	± 0.2%
Efficiency of cuts	± 0.3%
Livetime	± 0.1%
Detector response	± 6%
Fiducial volume	± 6%
Total	**± 10.4%**

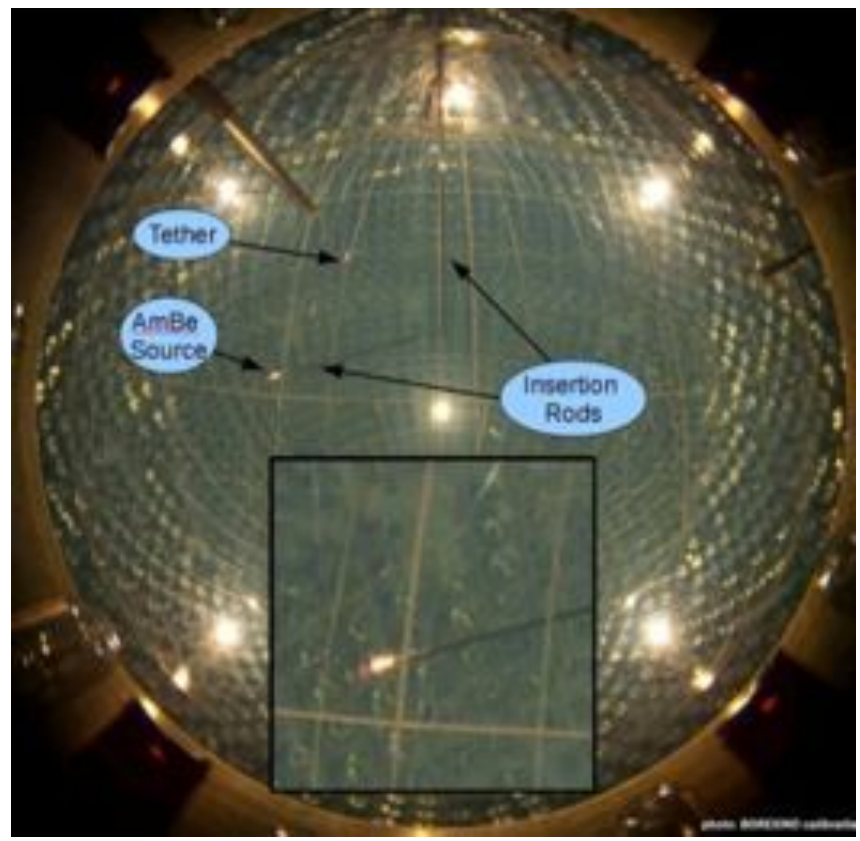
^{8}B result after calibrations:

Detector response	± 3.5%
Fiducial volume	± 3.8%

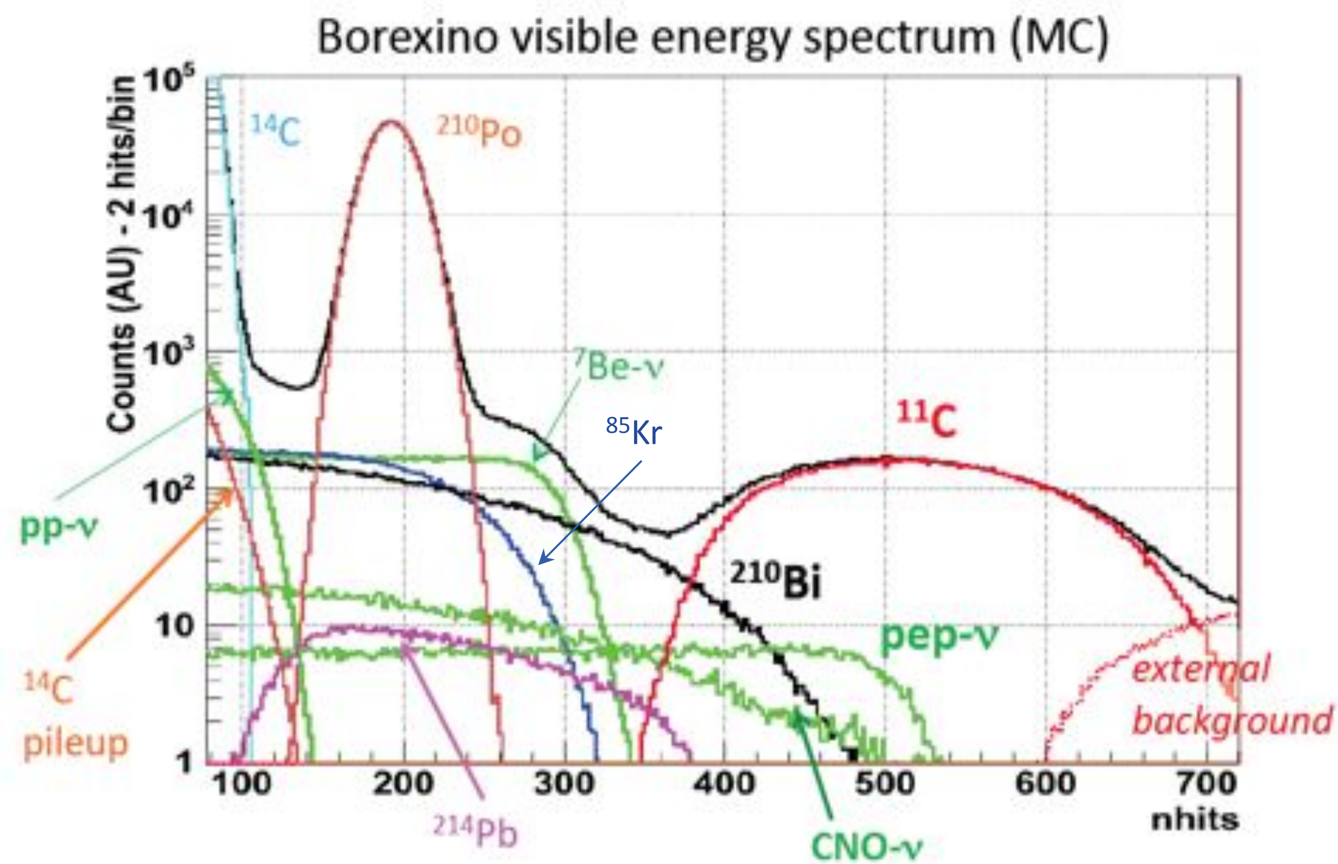
New Analysis: aim for 5% total uncertainty

More than twice as much data

Source calibration campaigns



pep neutrinos in Borexino: ^{11}C Suppression

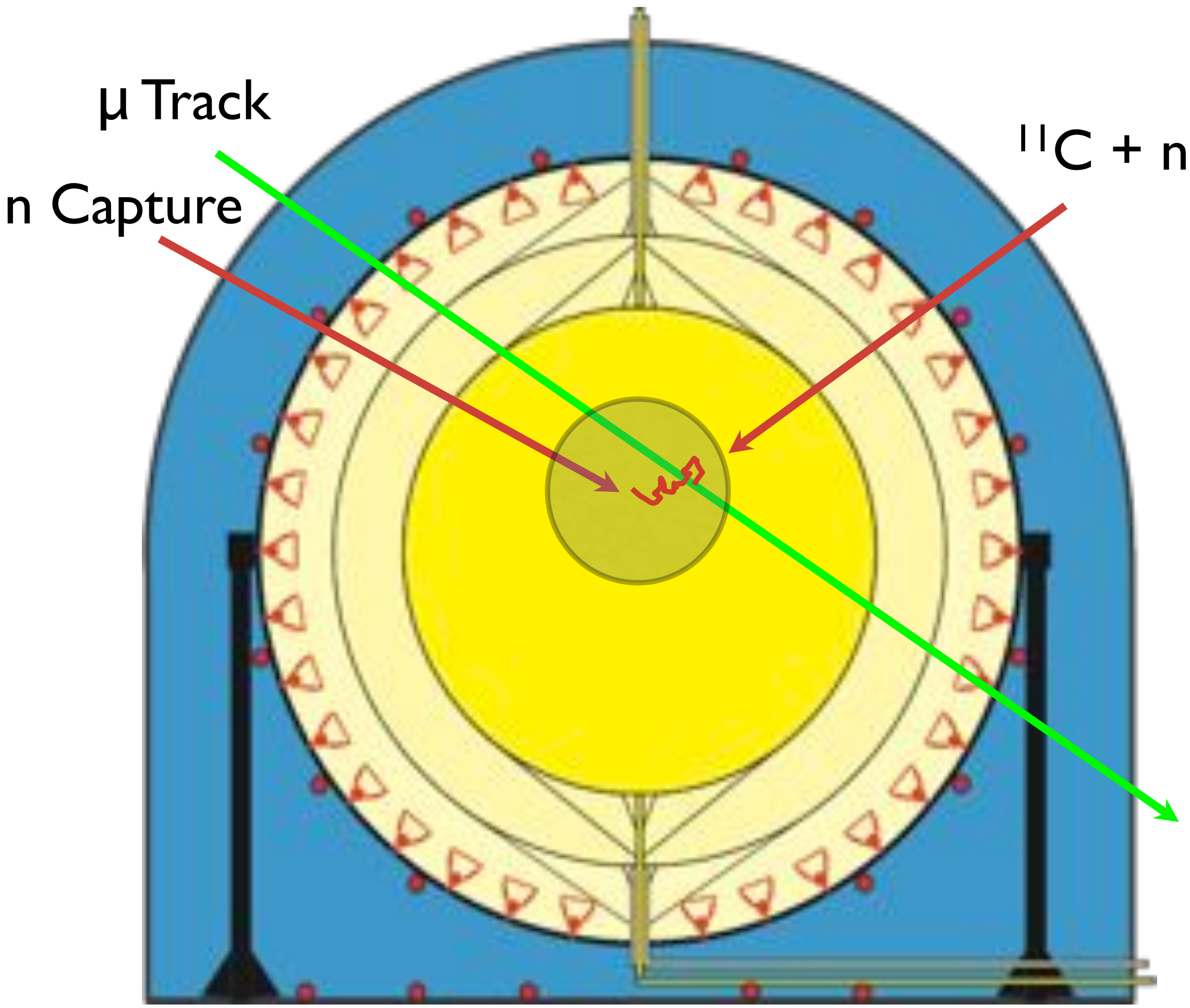


- ^{11}C is a cosmogenic radio-isotope with a half life of 20 minutes
- Borexino muon rate is 4300/day

Can't veto after every muon!

Image credit: M. Wurm

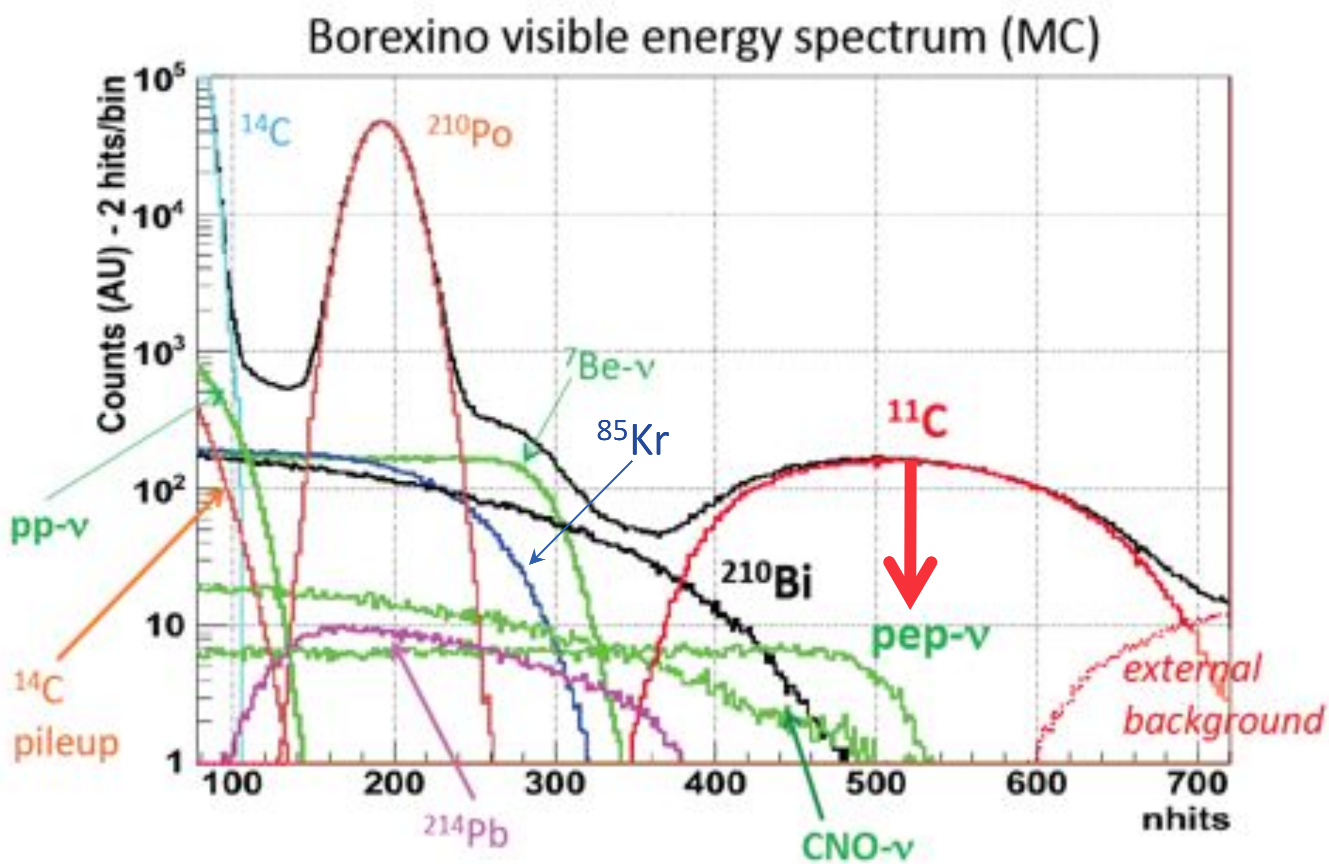
pep neutrinos in Borexino: ^{11}C Suppression



- Most ^{11}C production via $^{12}C \rightarrow {}^{11}C + n$
- Delayed neutron capture signal identifies when and where ^{11}C was produced

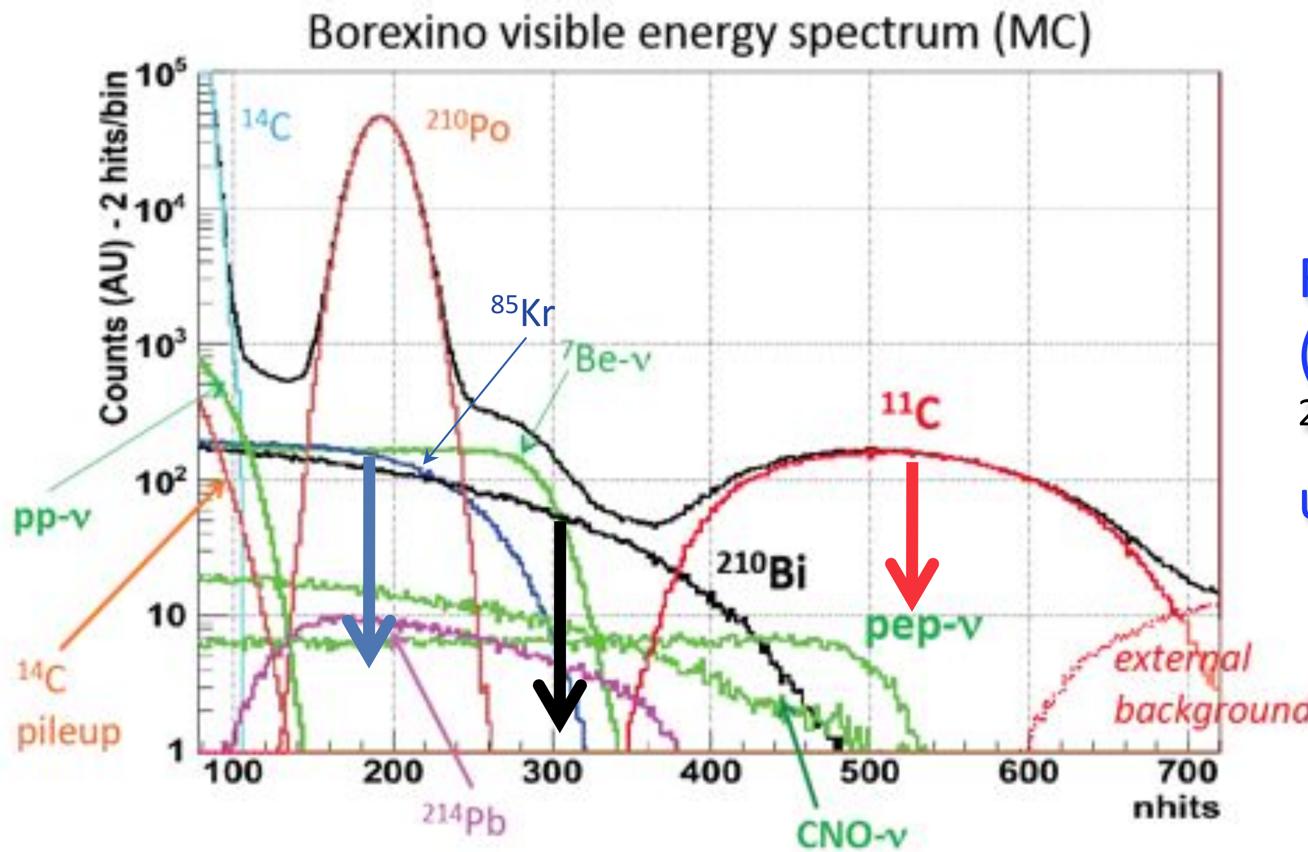
The ~125 muon-neutron coincidences/day (of which ~25 accompany ^{11}C production) can be vetoed without excessive loss of live time.

pep neutrinos in Borexino: ^{11}C Suppression



Believe that ^{11}C suppression will be sufficient to allow study of the pep: analysis in progress!

Borexino Future



Re-purification to (further!) reduce ^{210}Bi, ^{85}Kr, etc is underway

Run for at least three more years:

- **Improve ^{7}Be, ^{8}B measurements**
- **Study *pep*, and maybe CNO and *pp* neutrinos**

The best of Borexino is yet to come!

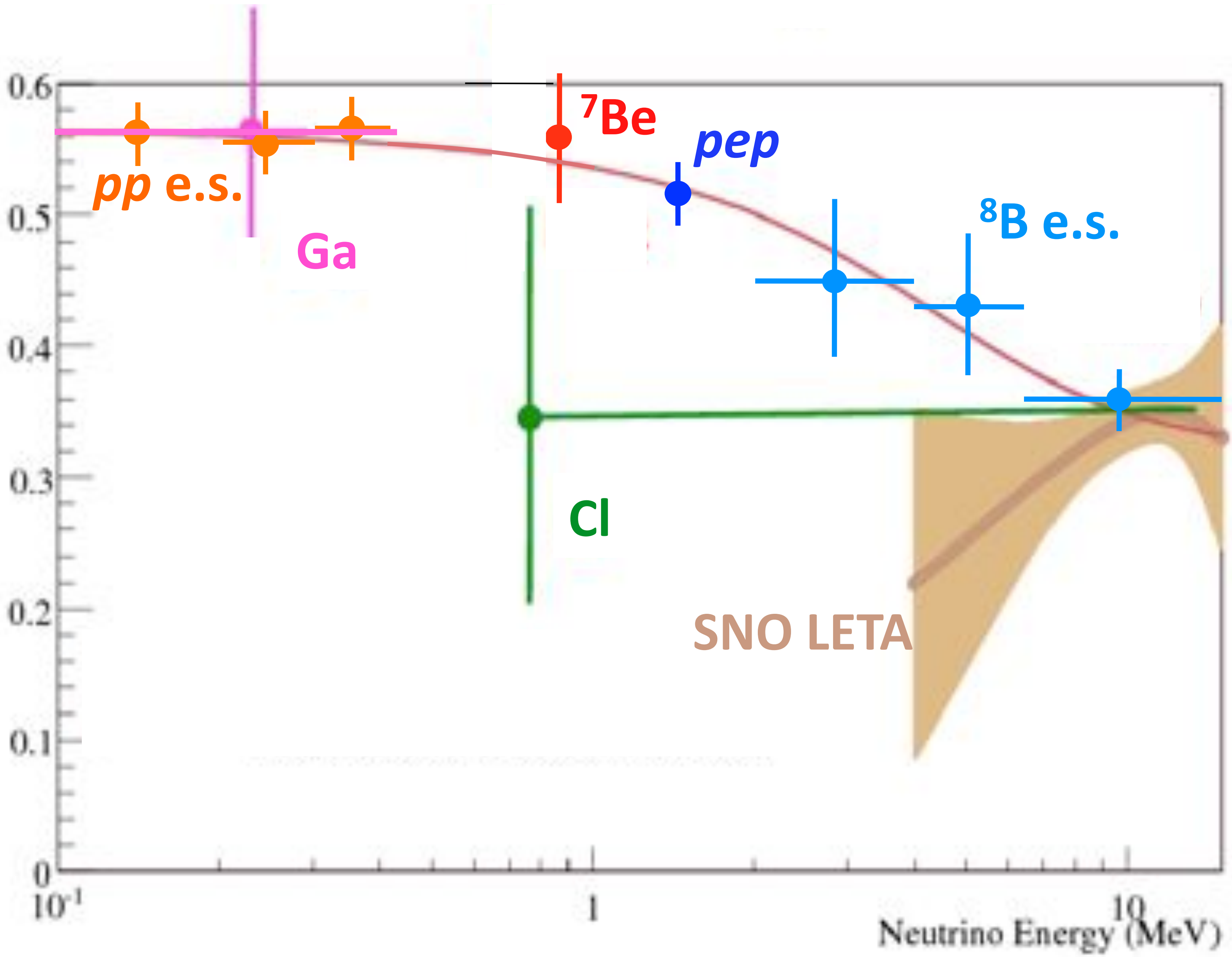
Beyond Borexino: SNO+

- Refill the SNO detector with liquid scintillator
  - 850T gives high statistics (~3 times Borexino)
- 6,000 m.w.e. gives much lower muon flux
  - ~ 55 ^{11}C events / 100T / yr
- SNO+ can measure the *pep* flux to high precision (<5%), along with CNO, ^{7}Be and low energy ^{8}B
- Data taking in 2012

Conclusions

- Measurements of P_{ee} in the transition region can test our understanding of neutrino oscillations
- SNO and Borexino have started to probe the transition region with real-time measurements
- More and better measurements are yet to come

Maybe One Day…



Maybe One Day…