Solar Neutrino Results From Borexino

SNOLAB/HEP Seminar, Carleton University
May 2nd, 2011

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Image: Borexino Collaboration

Outline

- Quick review of solar neutrinos and neutrino mixing
- Introduction to Borexino and previous results
- Source calibration campaign
- Recent results and implications
- Outlook

Image: Borexino Collaboration

Solar Fusion Reactions

p-p Solar Fusion Chain

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

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

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

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

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

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

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

$^{7}Li + p \rightarrow \alpha + \alpha$

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

$^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$

CNO Solar Fusion Cycle

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

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

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

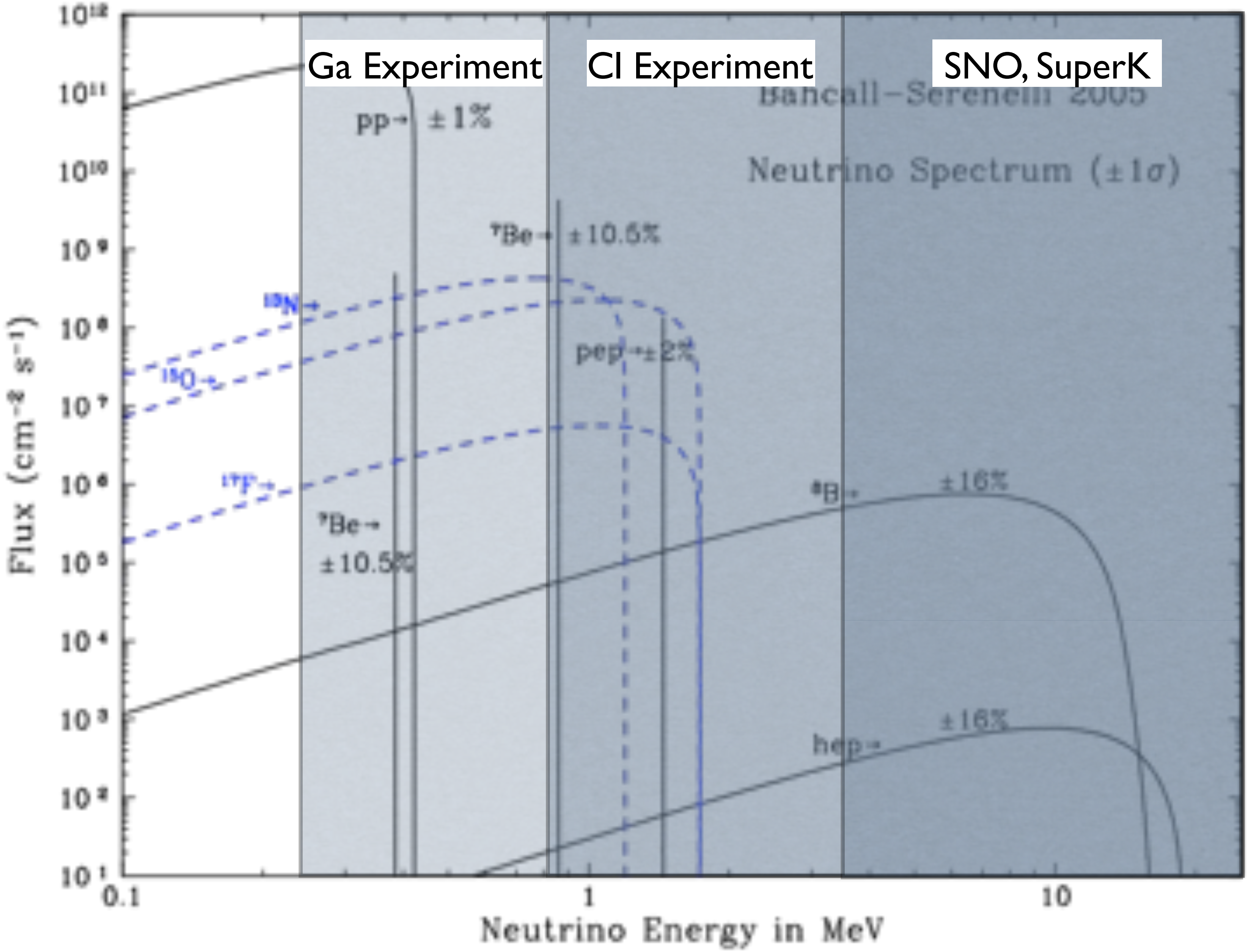
$^{14}N + p \rightarrow {}^{15}O + \gamma$

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

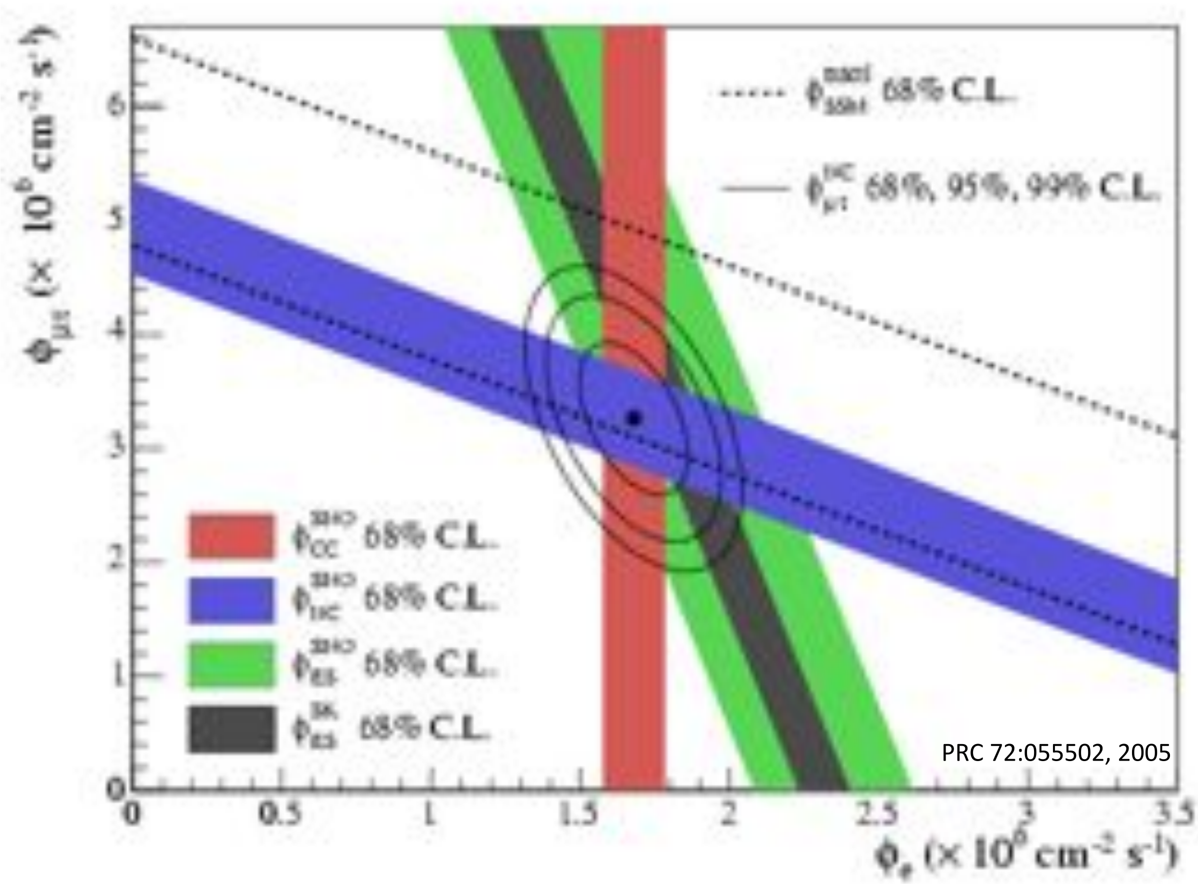
$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

Image: bbc.co.uk

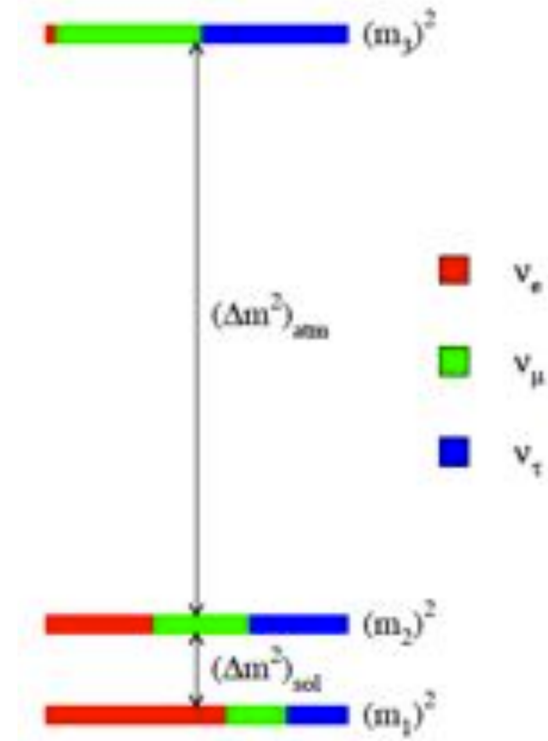
Solar Neutrinos



SNO Results: Solar Neutrinos Oscillate



PRC 72:055502, 2005



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

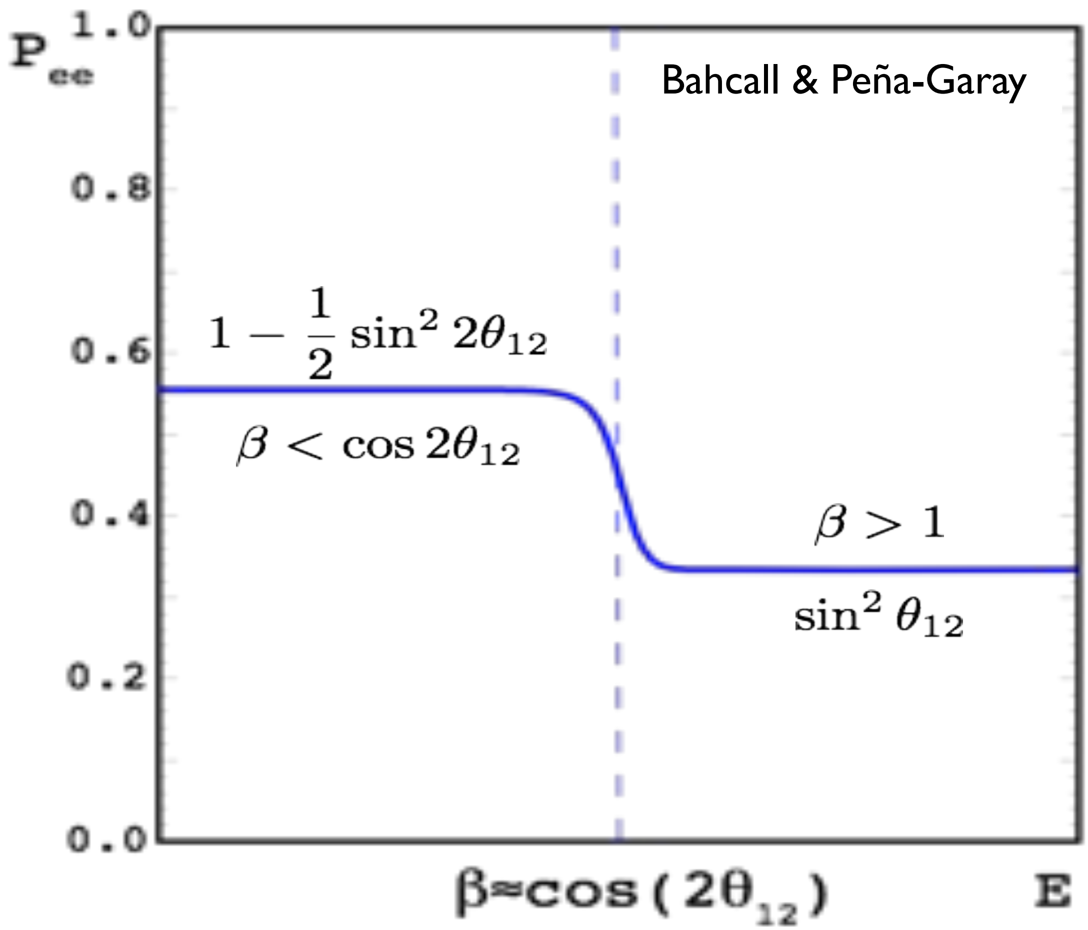
“MSW” Neutrino Oscillations

- 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:

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

  - 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

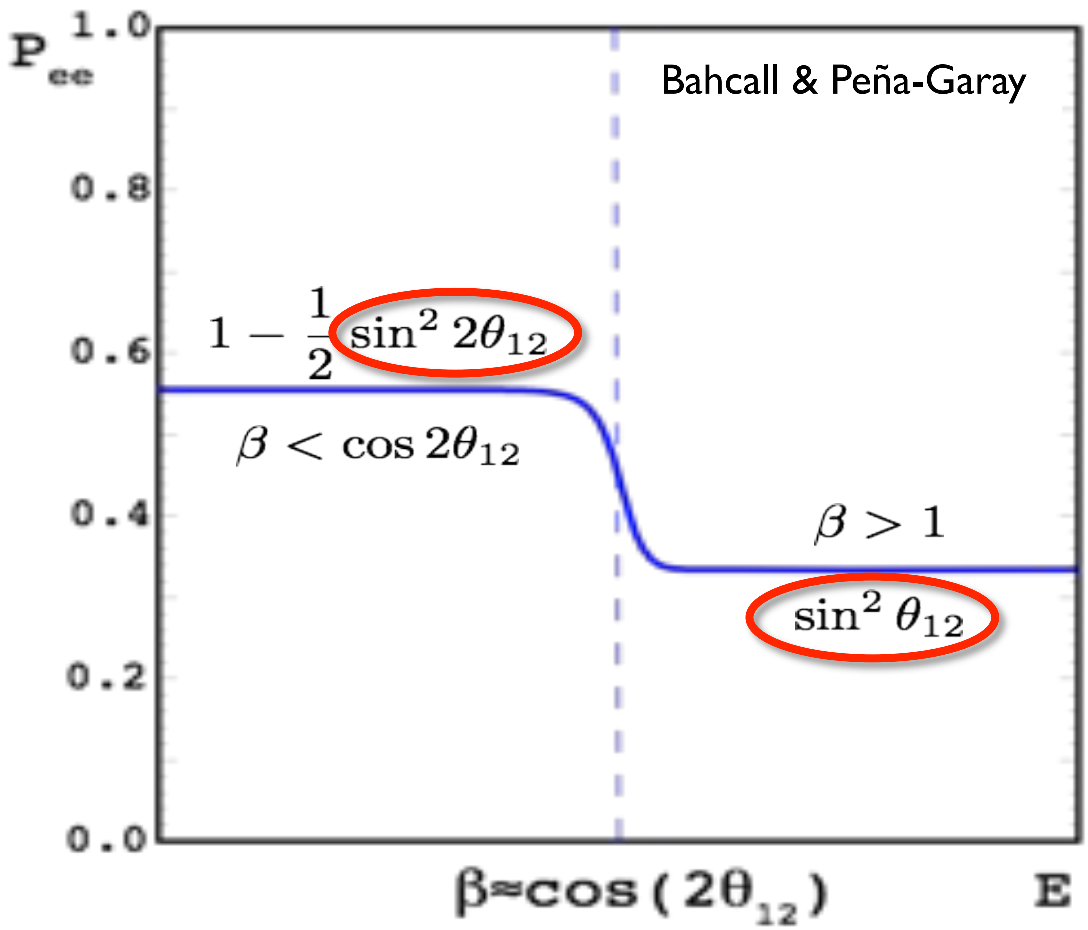


$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated "resonant conversion"

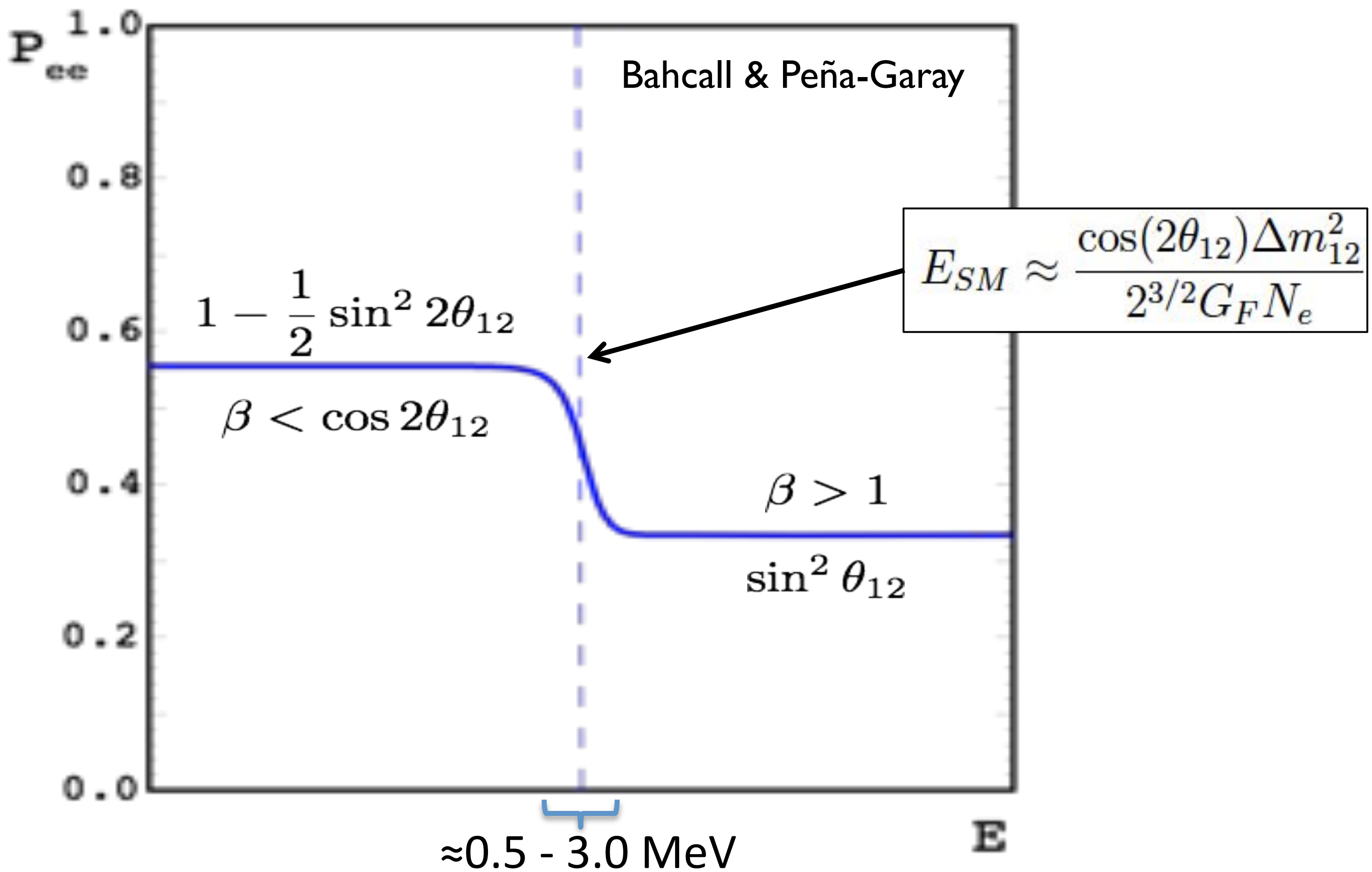
MSW Oscillation Regimes



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

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

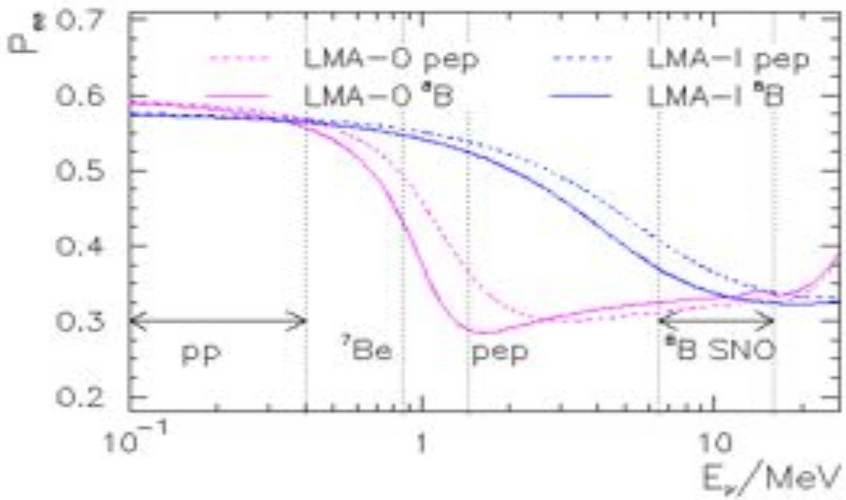
MSW Oscillation Regimes



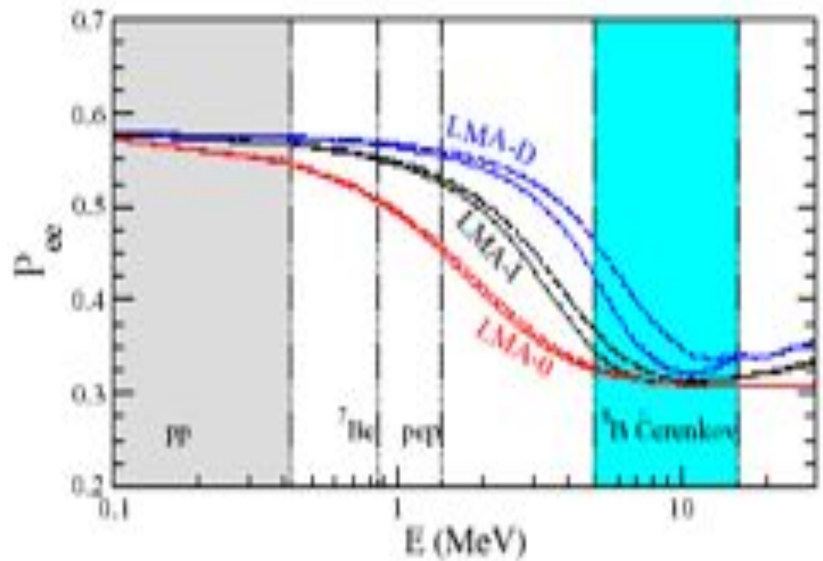
Look in "transition region" to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

Non-Standard Interactions

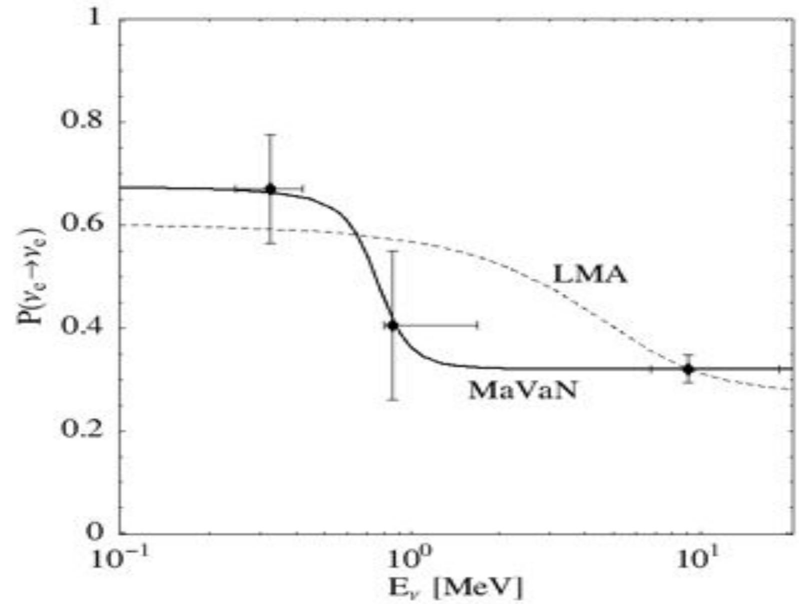


Friedland *et al*., PLB 594 (2004)



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

Mass Varying Neutrinos

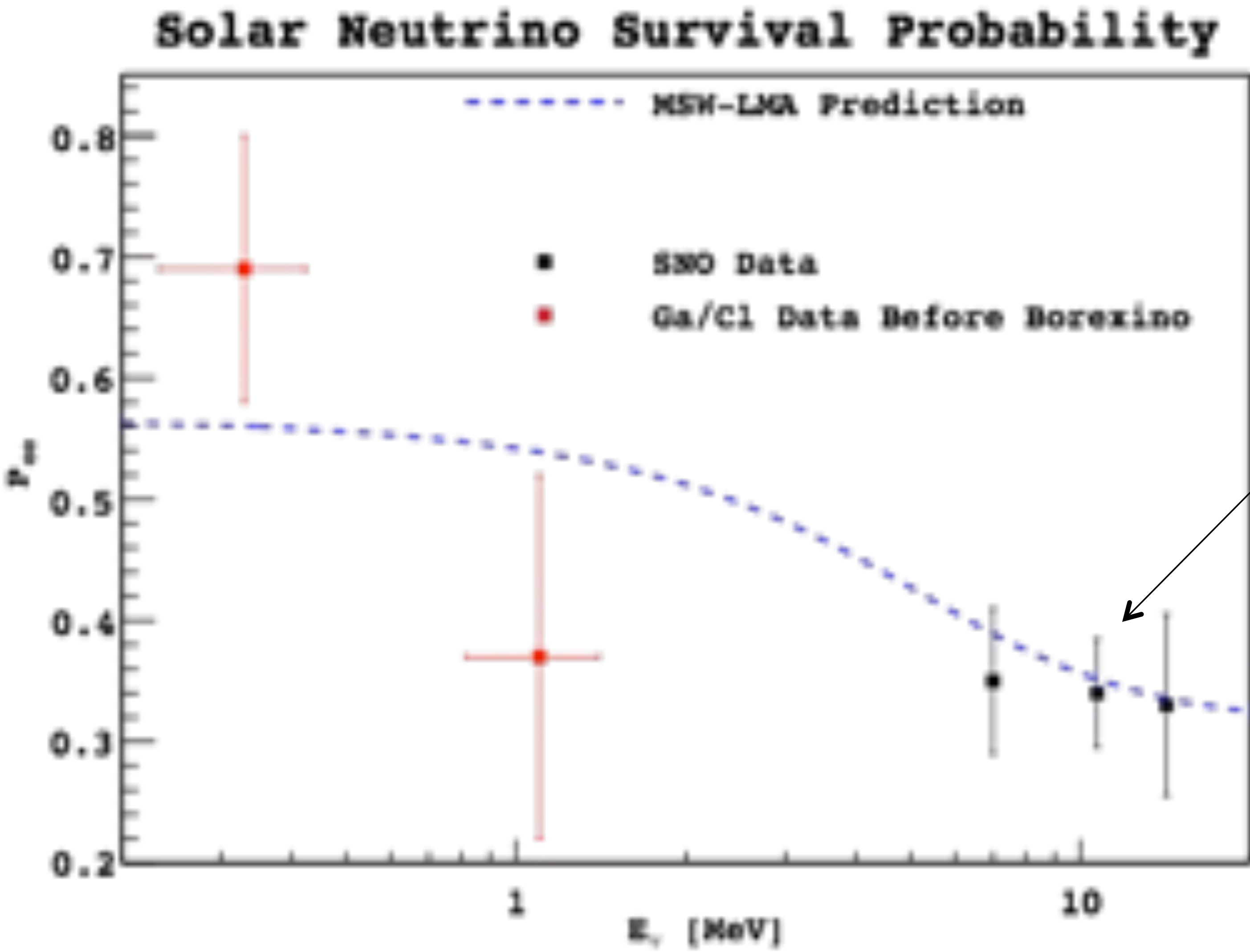


Barger *et al*. PRL 95 (2005)

Other Possibilities:

- CPT violations
- Sterile neutrino admixture

(Old) Experimental Constraints on Transition Region

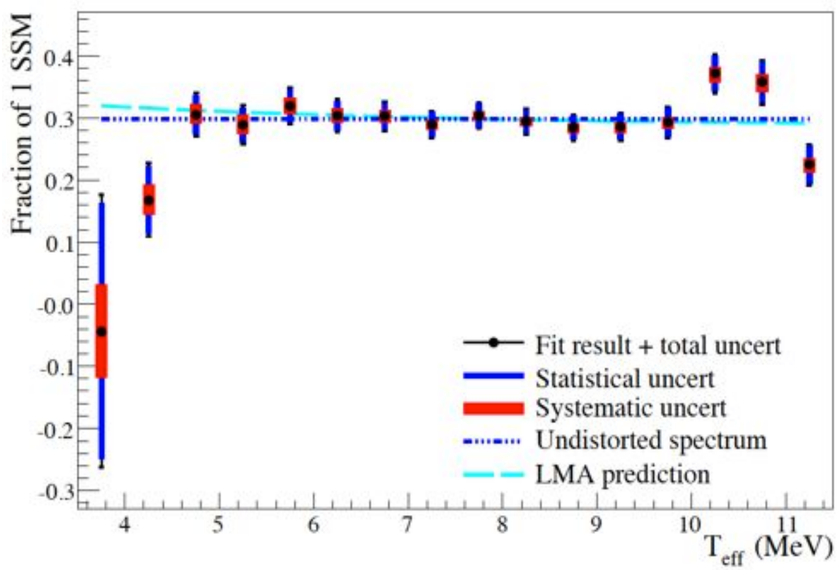


Confirmed by Kamiokande and SuperK

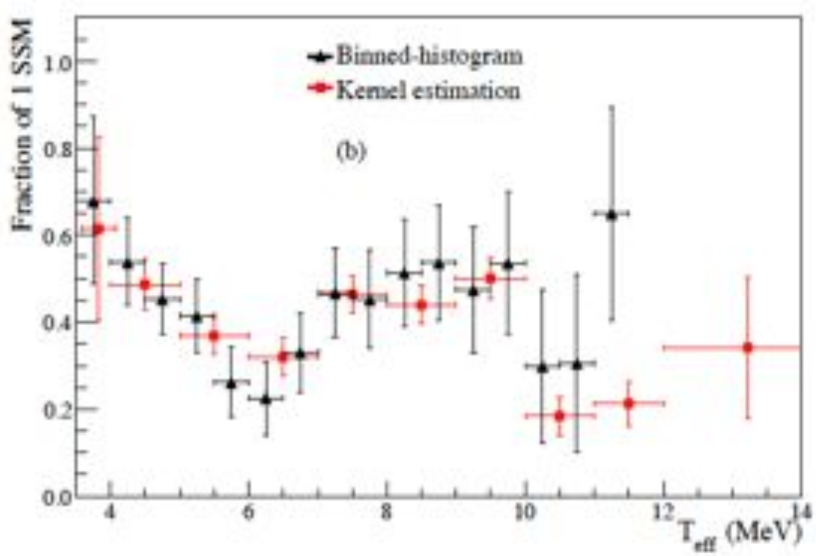
Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. ***Real-time measurements needed in the transition region.***

SNO Low Energy Threshold Analysis

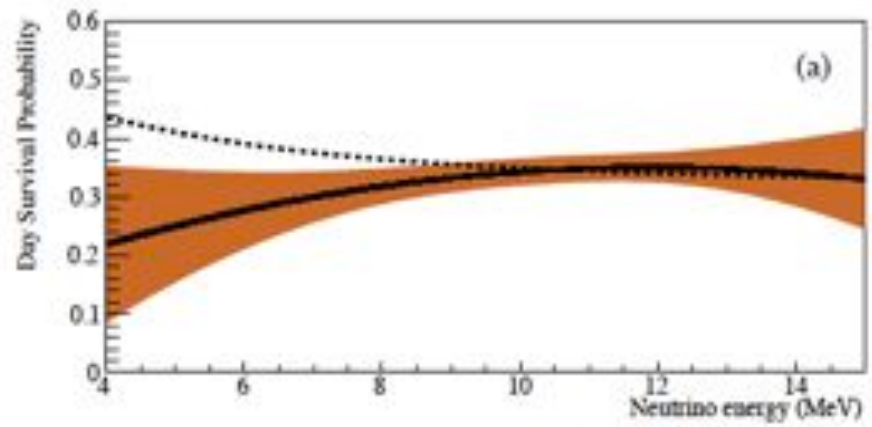
Charged Current: $T_{eff} = E_\nu - 1.44$ MeV

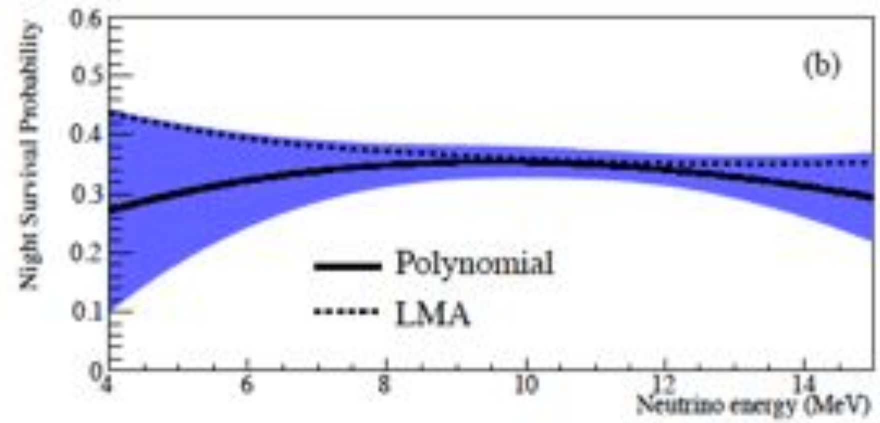


Elastic Scattering: $0 \leq T_{eff} \lesssim E_\nu - 0.24$ MeV



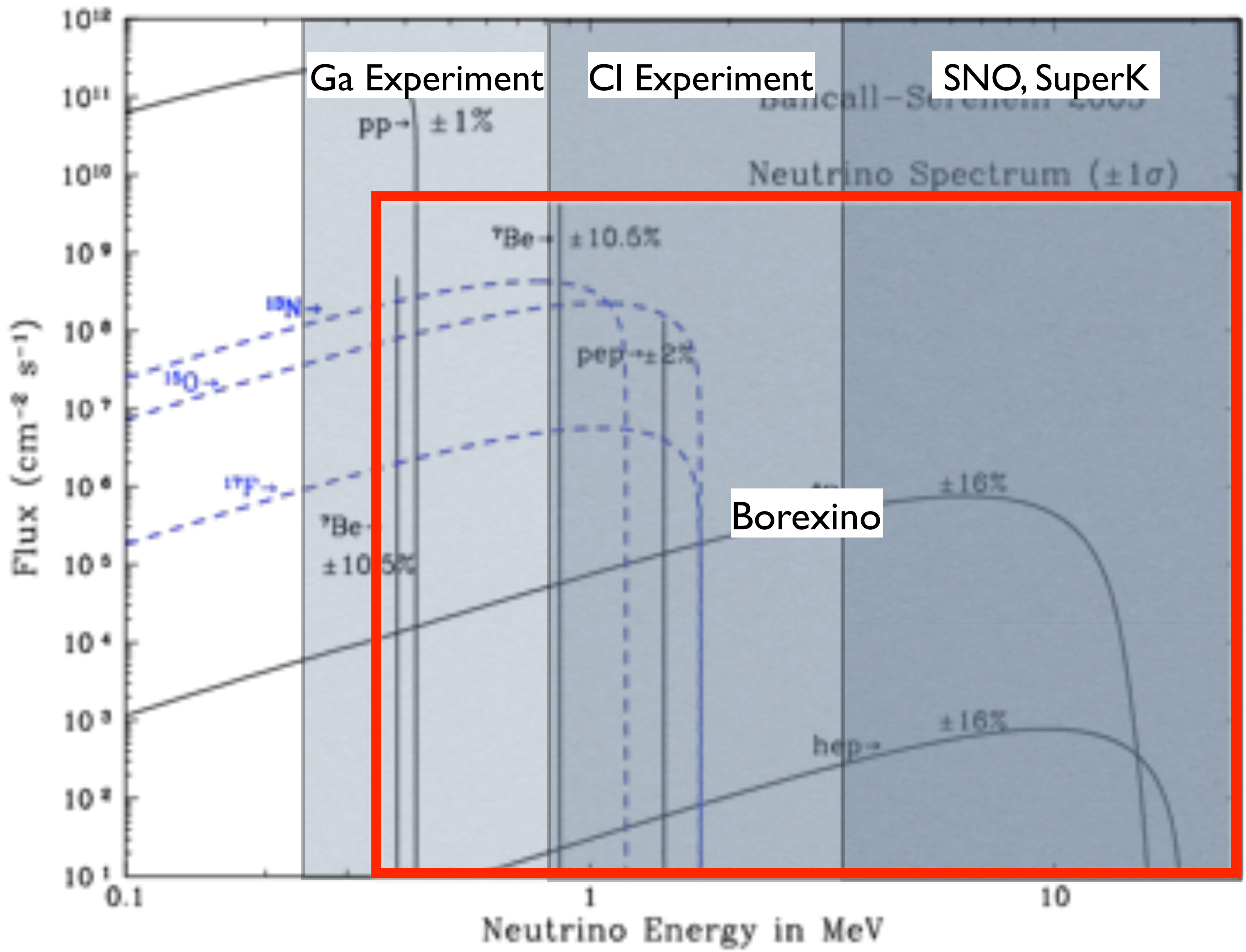
Quadratic Fits to P_{ee}



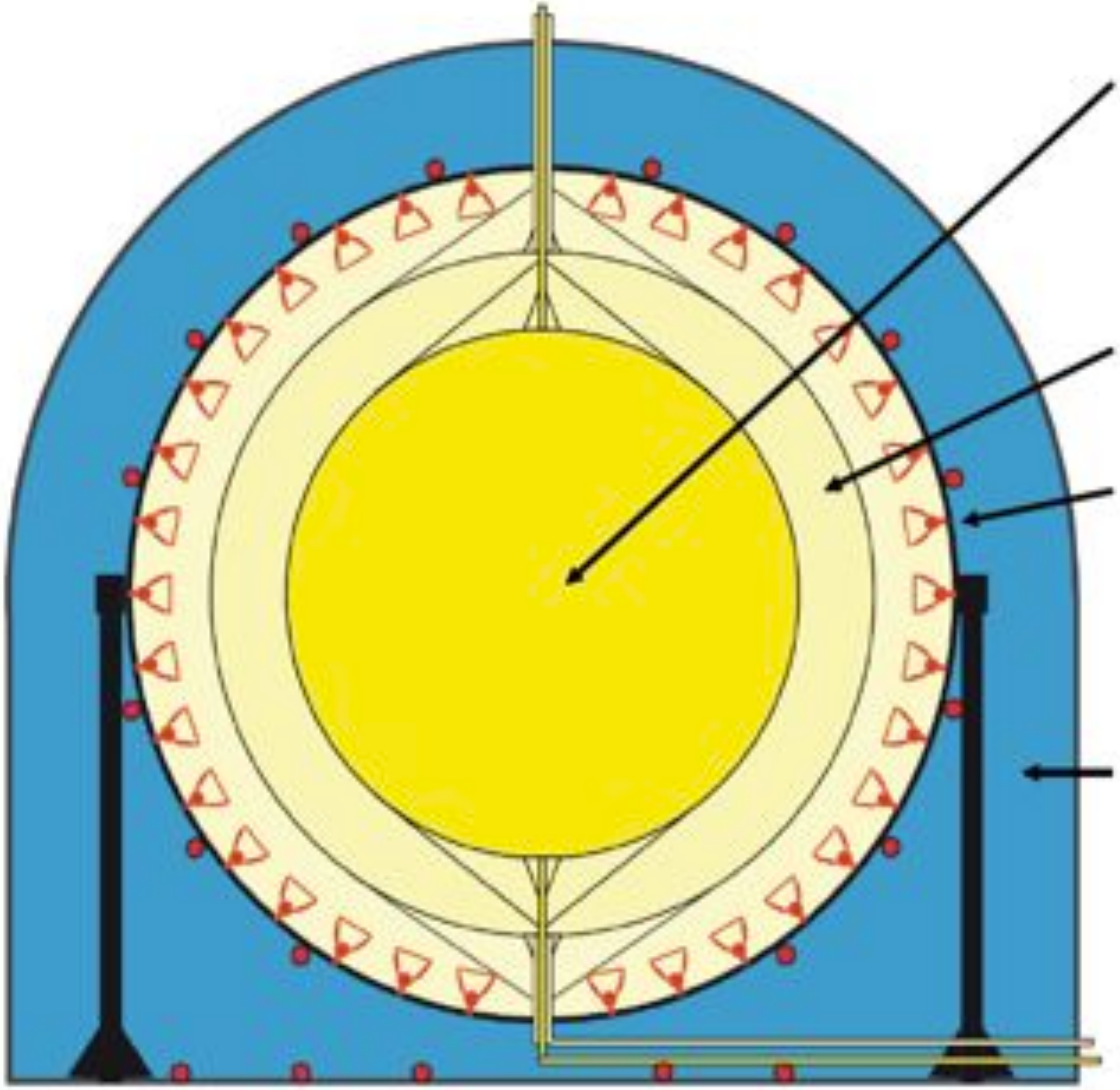


(Phys. Rev. C 81 (2010) 055504)

Borexino: Real-time Detection Below 100 keV



The Borexino Detector



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

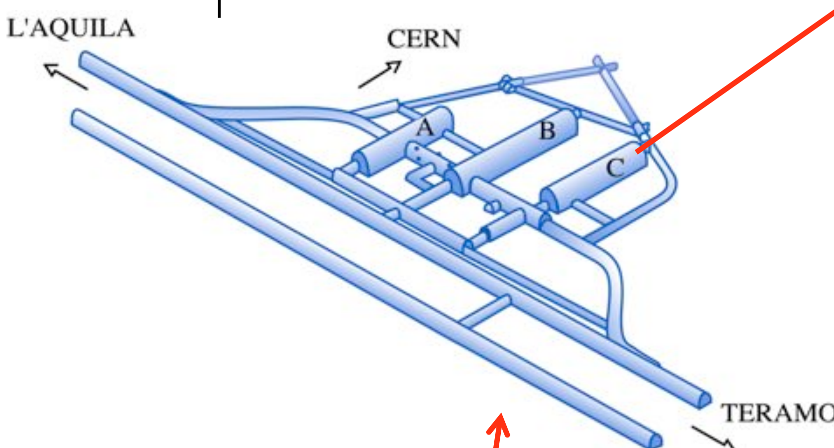
non-scintillating buffer

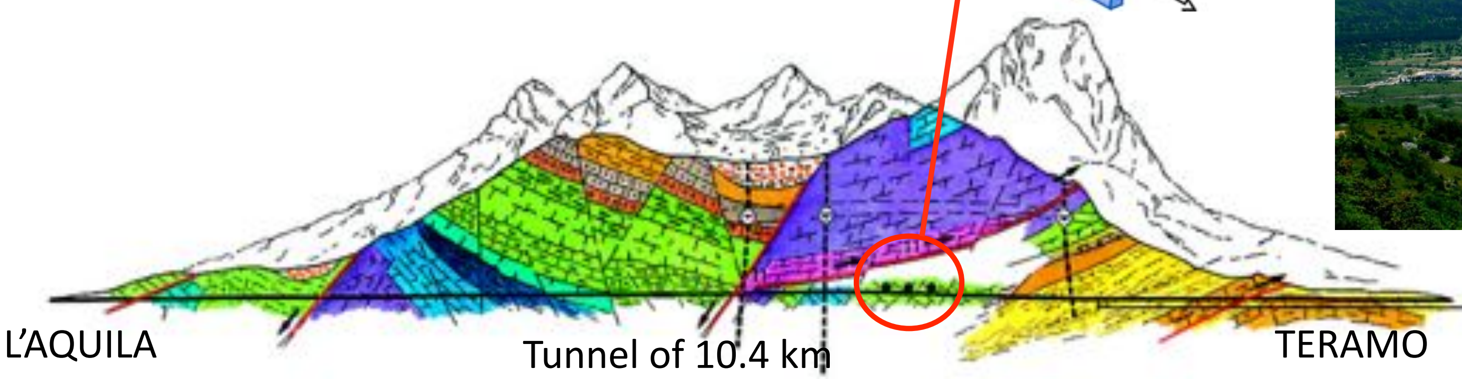
stainless steel sphere
6.85 m in radius
2212 inward-facing PMTs

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

Neutrino Detection With Liquid Scintillator

- Neut… …ron elasti…
- Detec… …ctron
  - Go… …time-of-…
  - Lov…
  - Go…
- Calor… …tional sensi…
  - Can't distinguish neutrino events from β/γ backgrounds

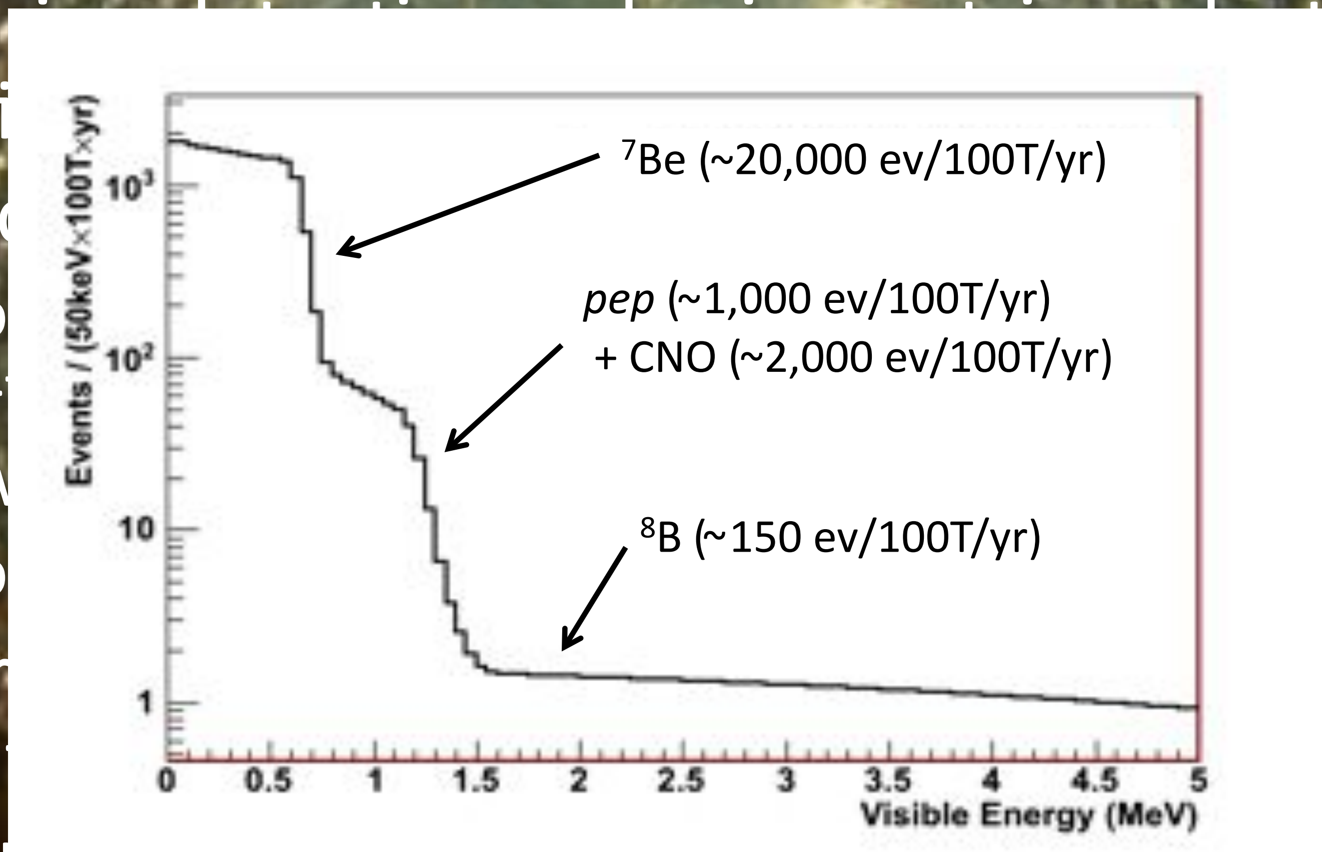
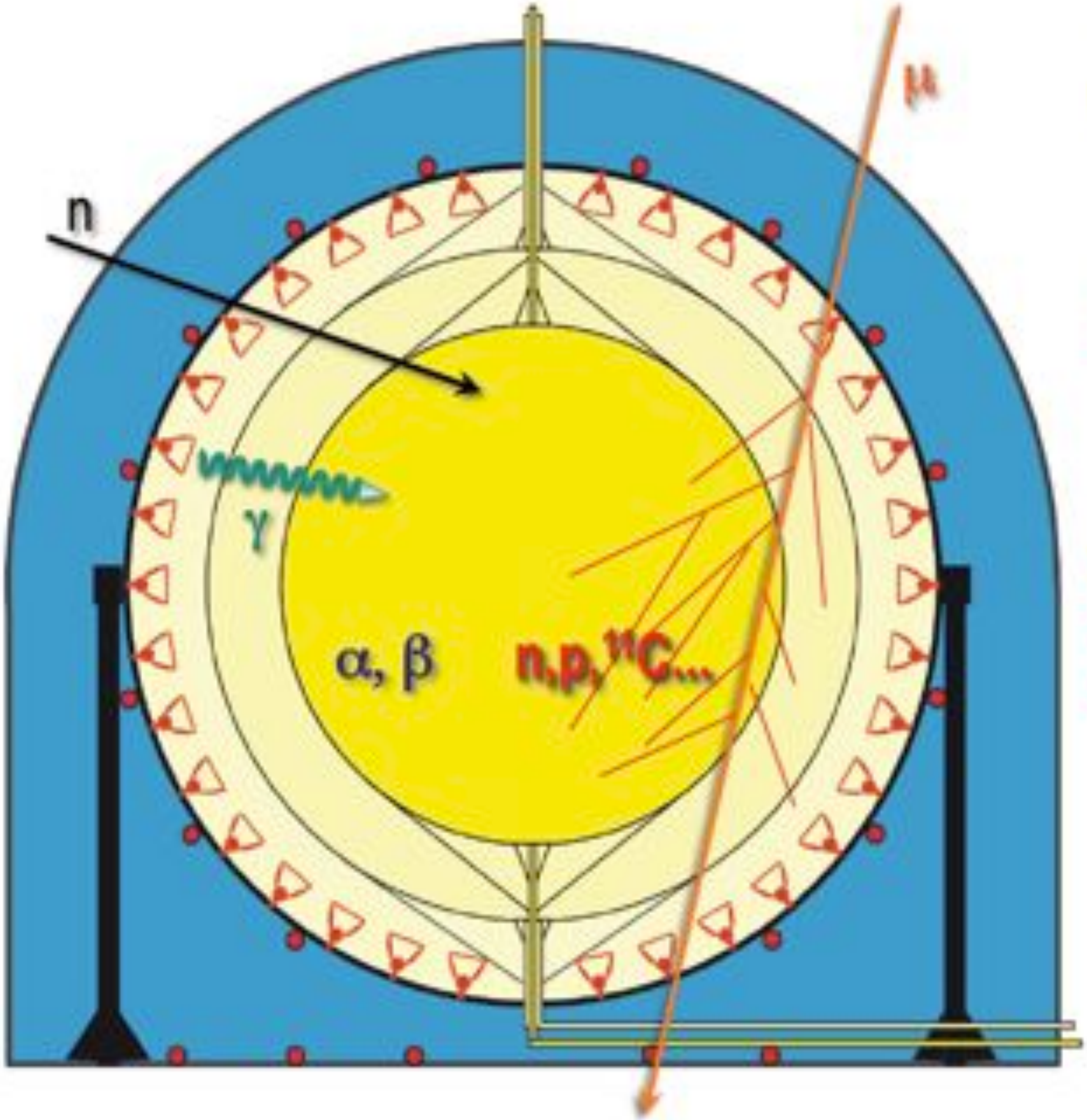


Image: Borexino Collaboration

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 ...)

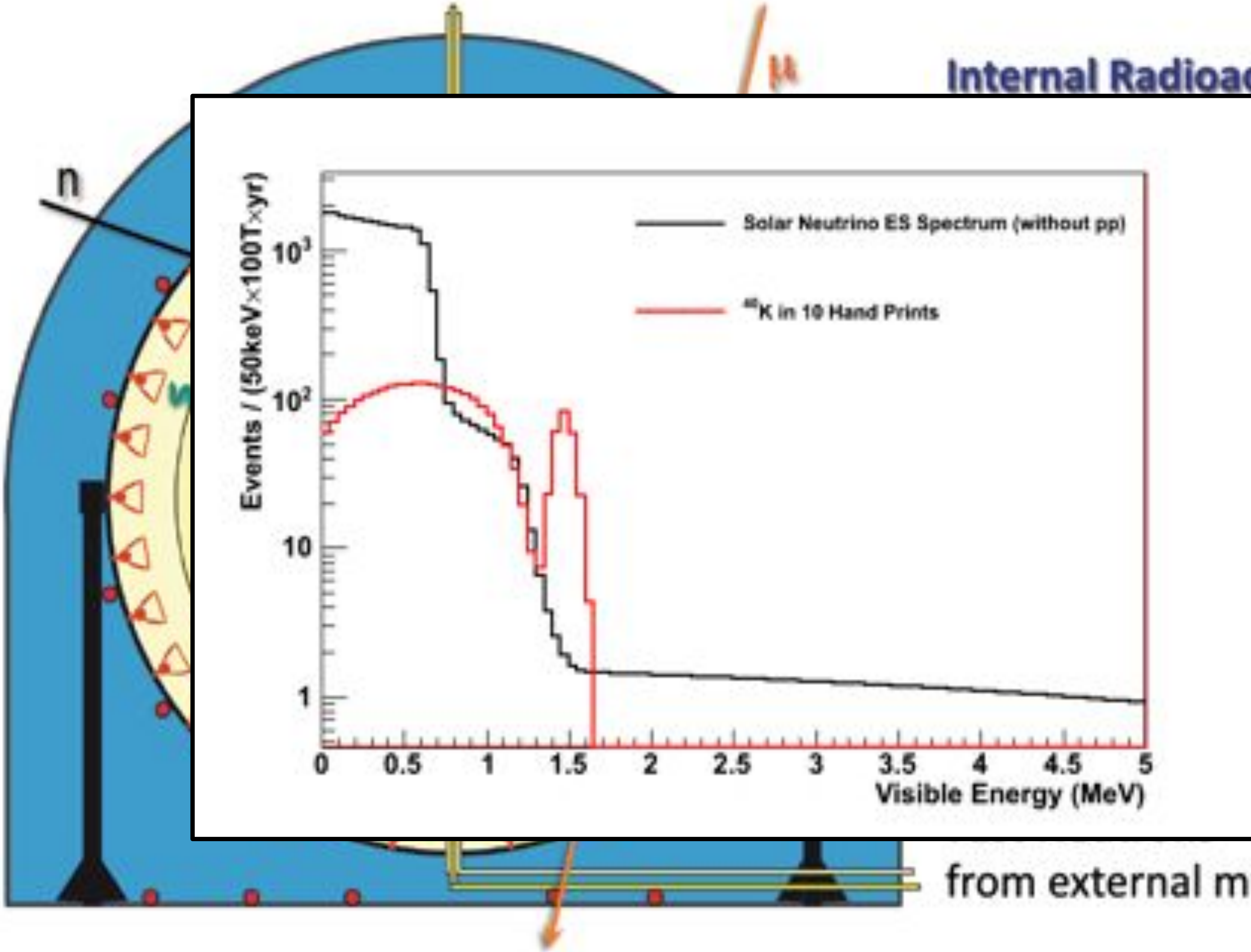
Cosmic Muons

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)

a-Rays

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

dionuclides
ation and
rs

from external muons

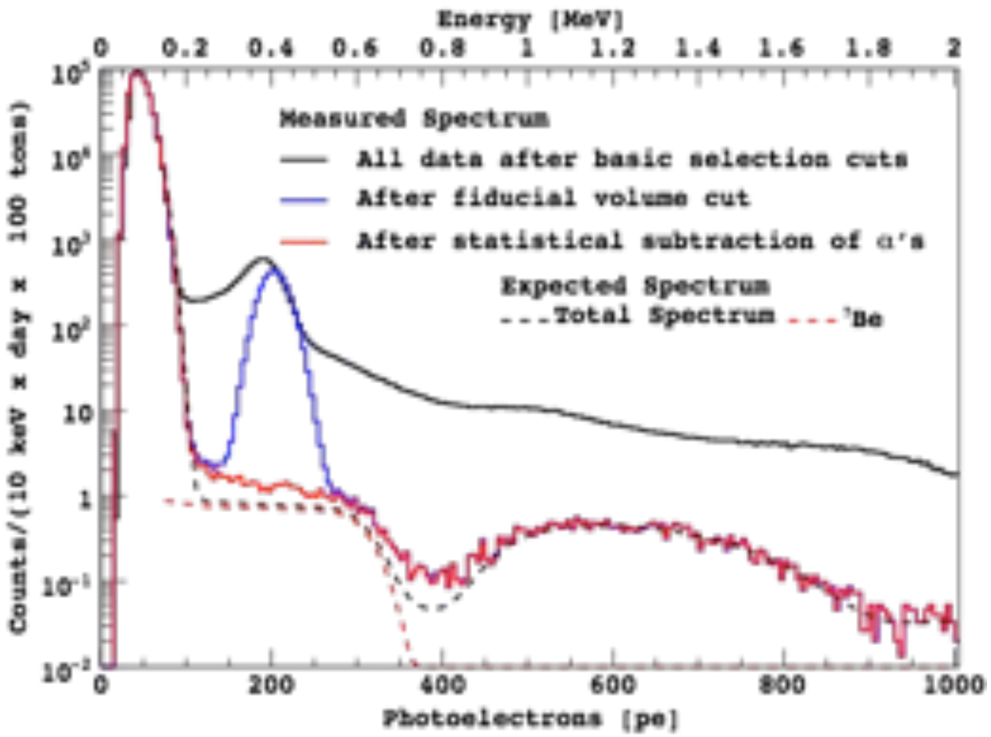
Borexino achieved unprecedented low levels of internal background.

The Counting Test Facility III

Contaminant	Source	Normal Conc.	Borexino Achieved	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Old oil
^{238}U	Dust	10^{-6} g/g	$<10^{-17}$ g/g	Purification
^{232}Th	Dust	10^{-6} g/g	$<10^{-18}$ g/g	Purification
^{85}Kr	Air	1 Bq/m^3	~$2x10^{-3}$ Bq/m^3	LAKN
^{222}Rn	Air	20-100 Bq/m^3	$<10^{-6}$ Bq/m^3	Air exclusion
K_{nat}	Dust	~10^{-3} g/g	$<3x10^{-14}$ g/g	Purification
μ	Cosmic	200 $s^{-1}m^{-2}$	10^{-10} $s^{-1}m^{-2}$	Underground, active veto

Borexino 192-day ^{7}Be Result

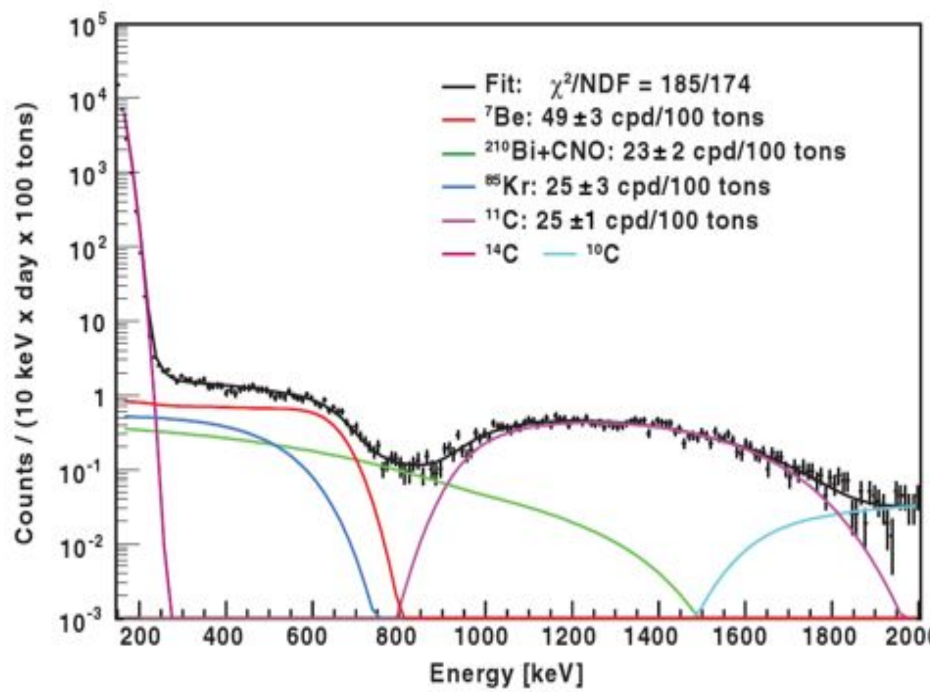
(PRL 101 9 (2008))

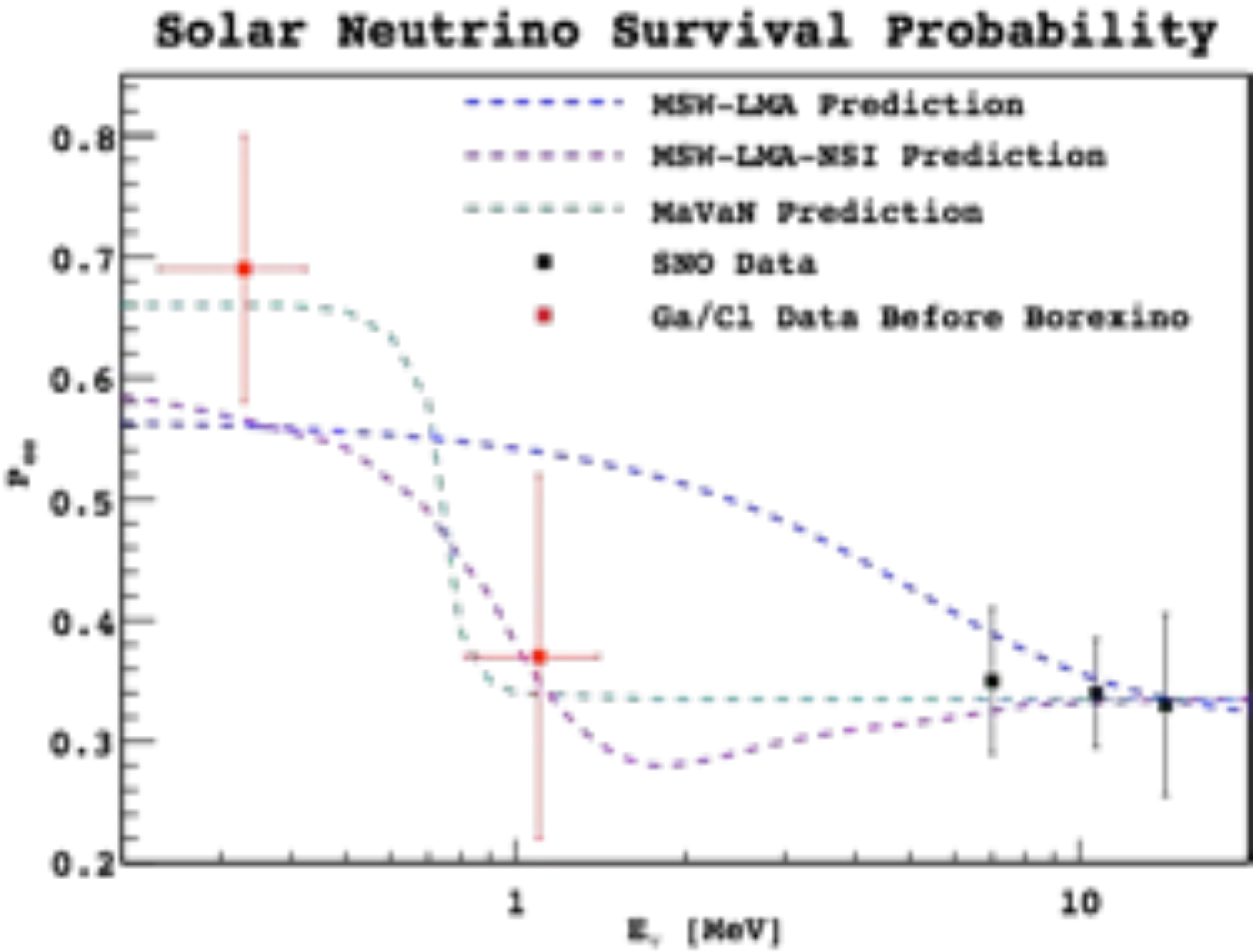


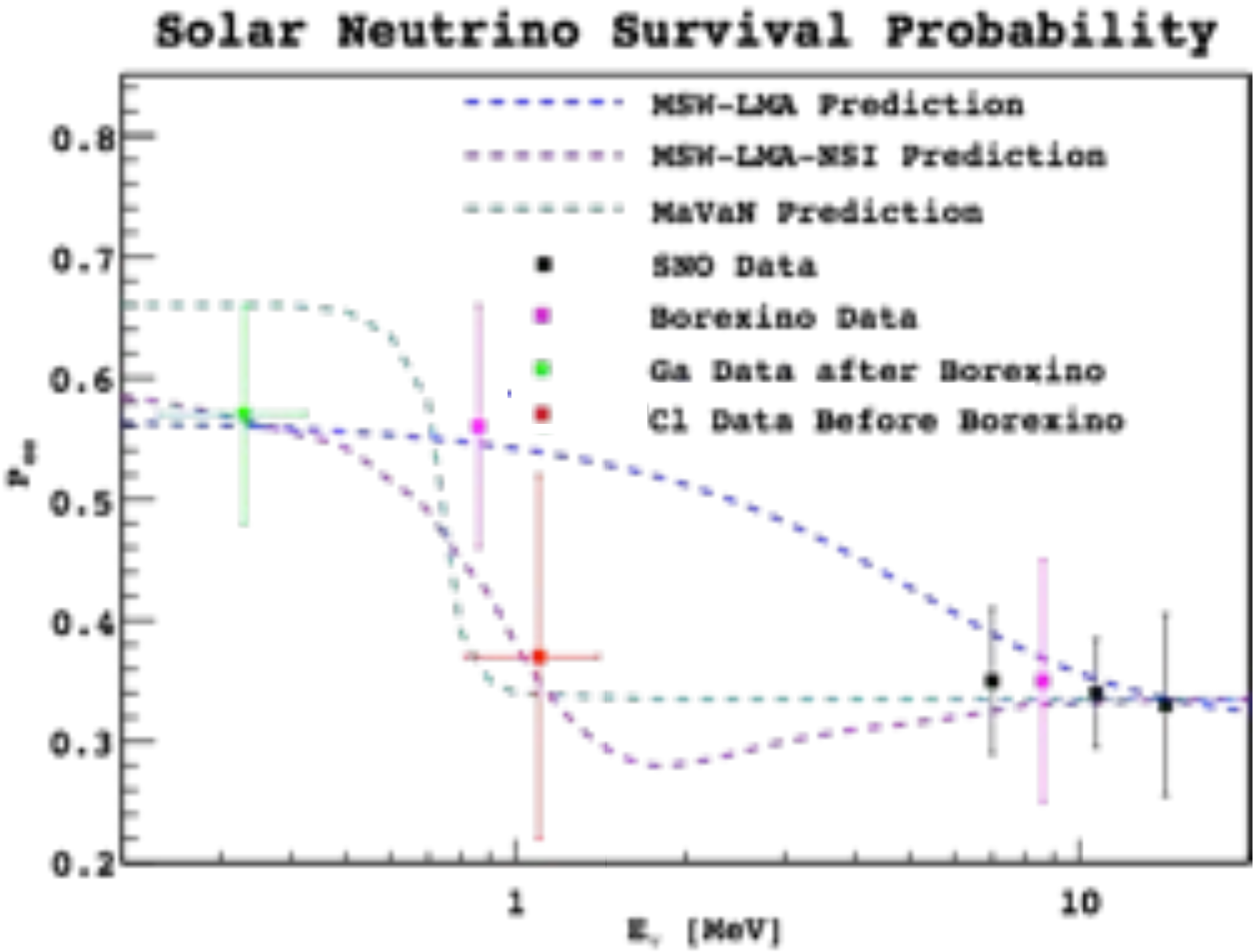
0.862 MeV ^{7}Be Result:

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

Systematics	
Scintillator Density	0.2%
Livetime	0.1%
Cut Sacrifice	0.3%
Fiducial Mass	6.0%
Detector Response	6.0%
Total	**8.5%**



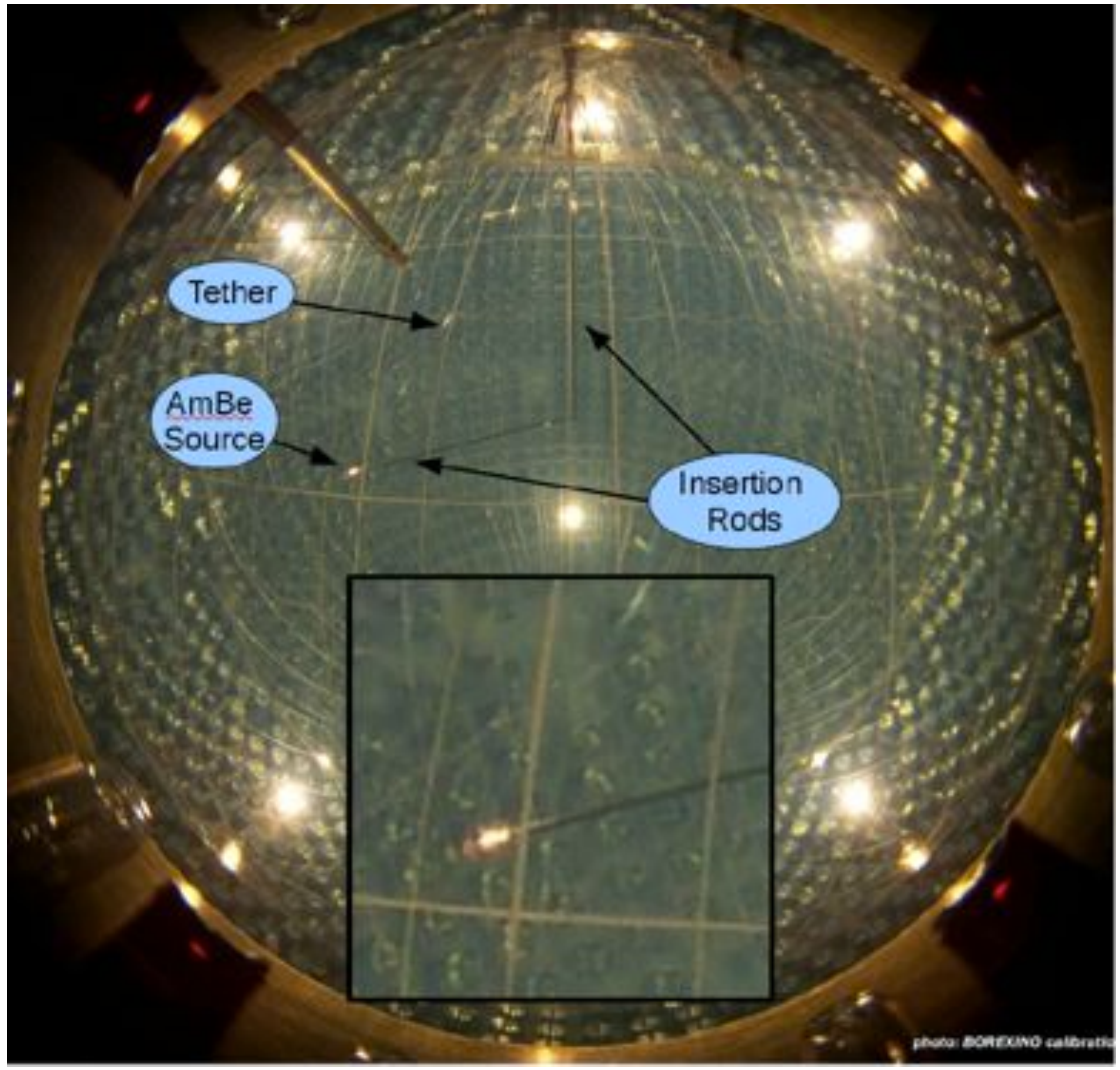

Solar Neutrino Survival Probability
MSW-LMA Prediction
MSW-LMA-NSI Prediction
MaVaN Prediction
SNO Data
Ga/Cl Data Before Borexino
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
10
E [MeV]



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 Internal Calibrations

- Study detector position and energy response by deploying radioactive and laser sources in the detector
- 3D source deployment system developed at Virginia Tech



Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

Source Deployment System

- Neutrally buoyant 1m long stainless steel rods connected together in a glovebox within a class 100 clean room
- One section has a pivot, allowing the source to be placed “off-axis”
- Umbilical containing fiber optic used to “raise” the pivot

Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

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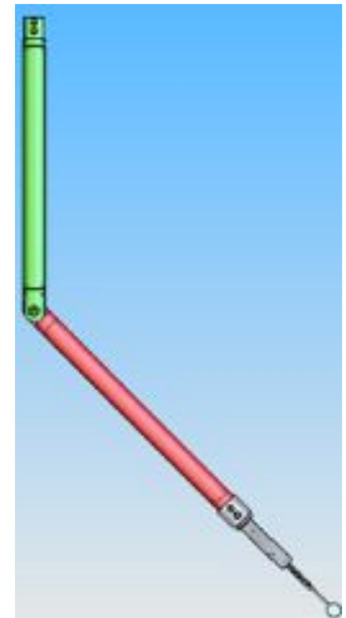
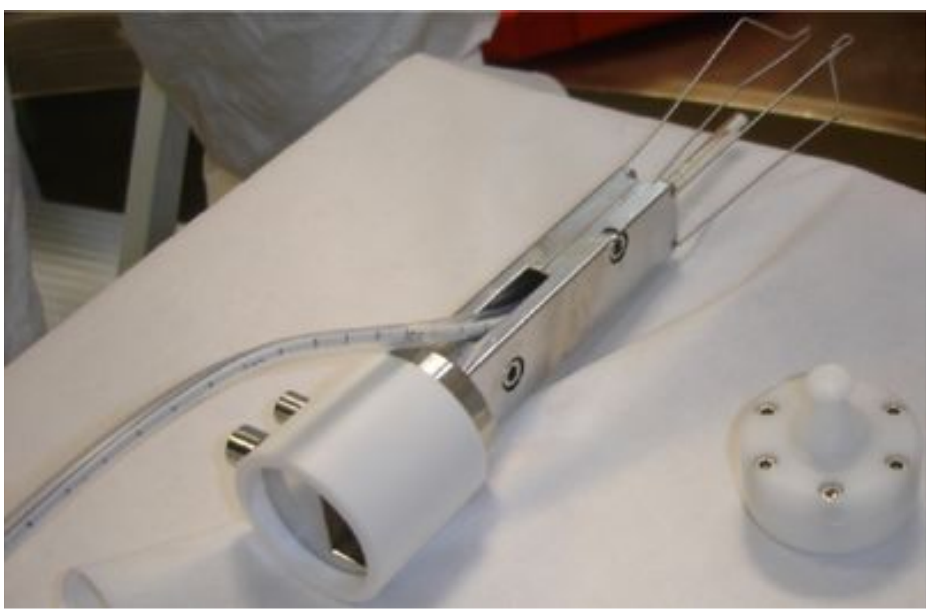
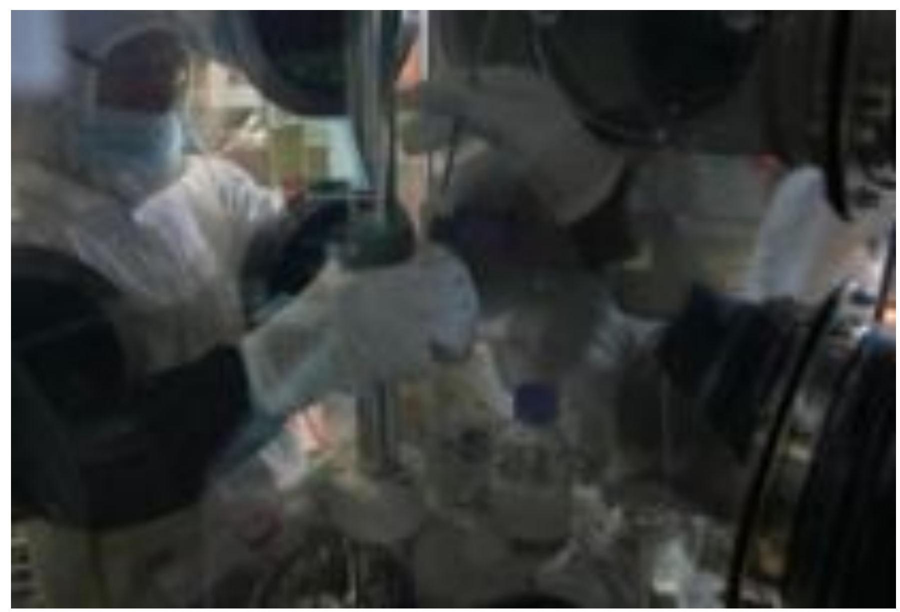


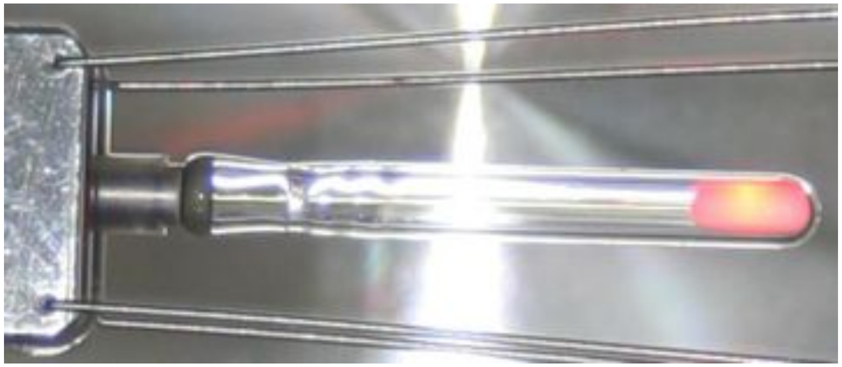


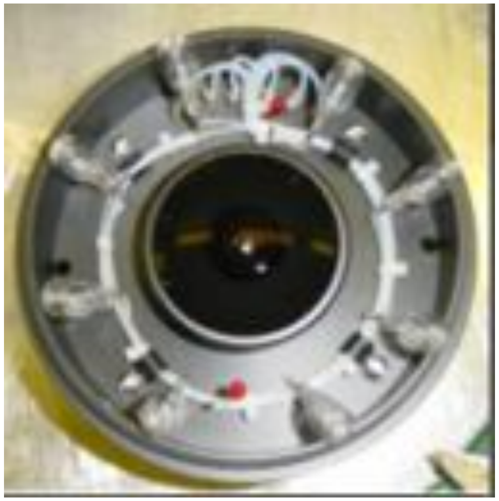


Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

Determining Source Location

- Red light from a diffuser on the source mount recorded by 7 CCD cameras
- Designed to measure source position to 2 cm



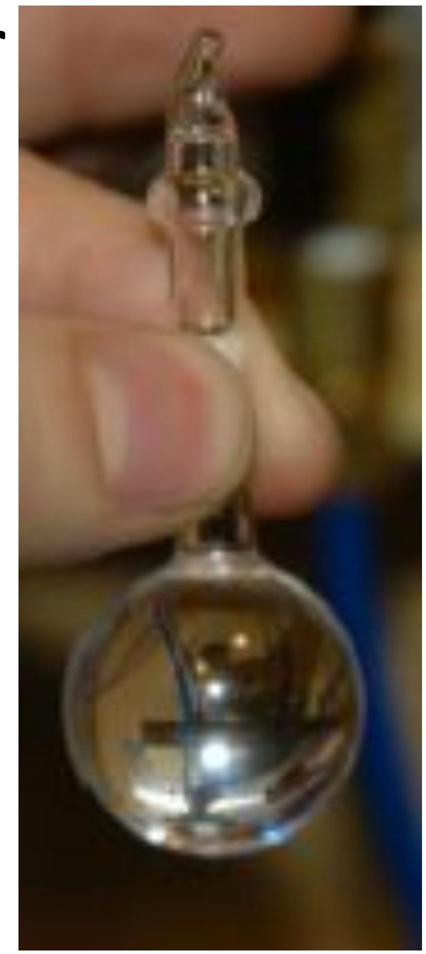


Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

Sources

- Aqueous γ-sources in flame-sealed quartz vials
- α and β sources in vials of scintillator
- Encapsulated AmBe

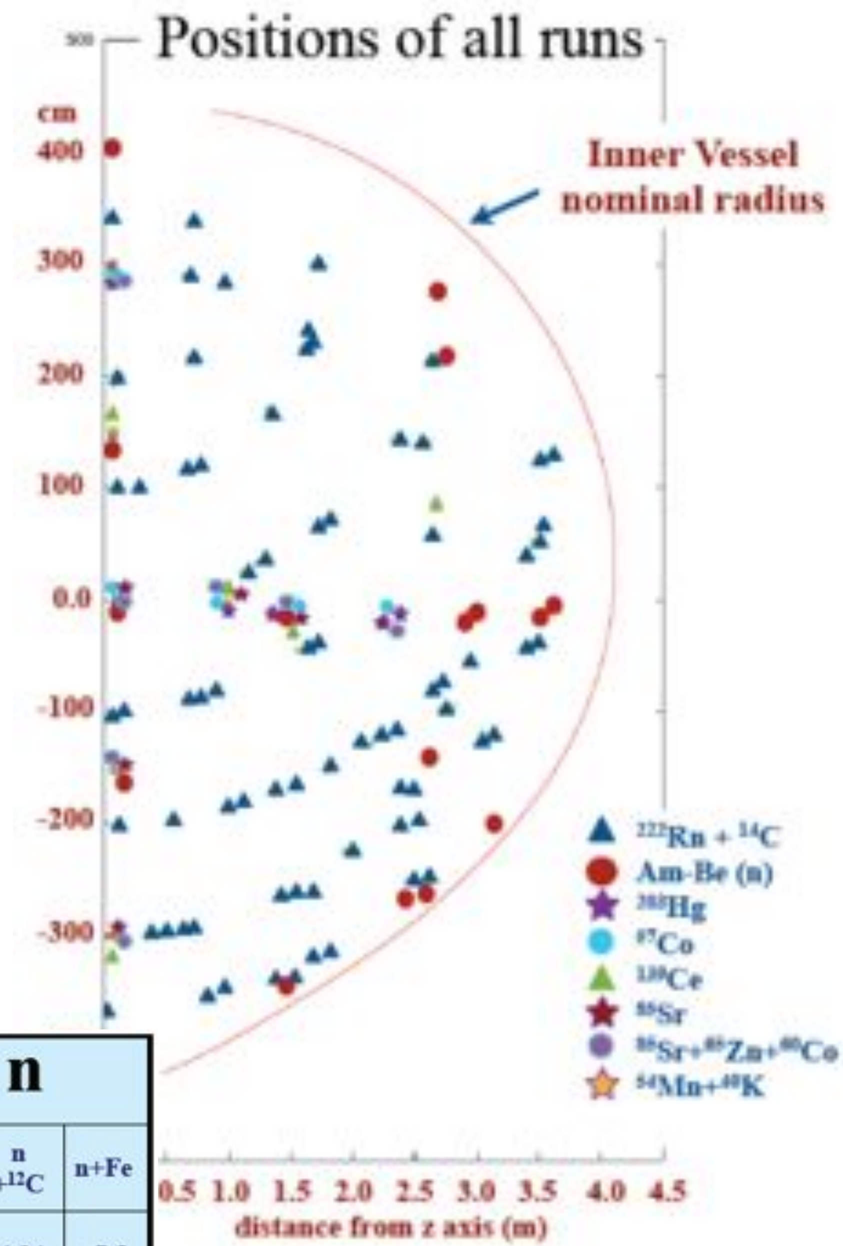




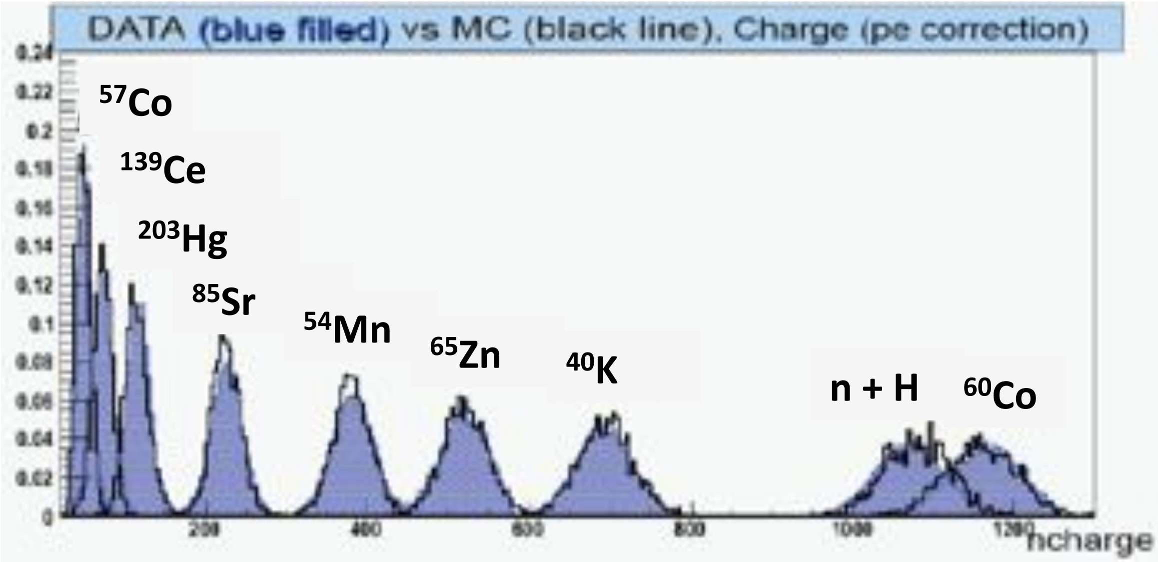
Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

Borexino Calibration Campaigns

- 4 major calibration campaigns (Oct ’08, Jan ‘09, June ’09, July ’09)
- 35 livedays of calibration data with sources in 295 positions



	γ								β		α	n		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2	7.8	2.226	4.94	~7.5



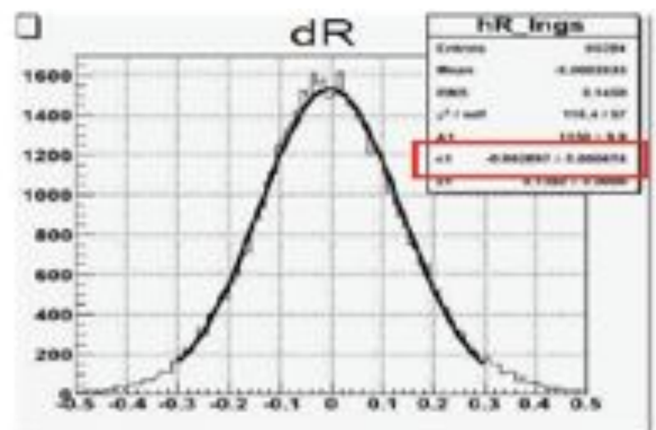
Study light yield, quenching, position variation.

➡ *Reduced energy uncertainties by more than a factor of two.*

Position Resolution:
10 – 12 cm
Fiducial Volume:
$1.0^{+0.013}_{-0.005}$

➡ *Reduced fiducial volume uncertainty by roughly a factor of five.*

$Z_{rec} – Z_{ccd}$ (m)

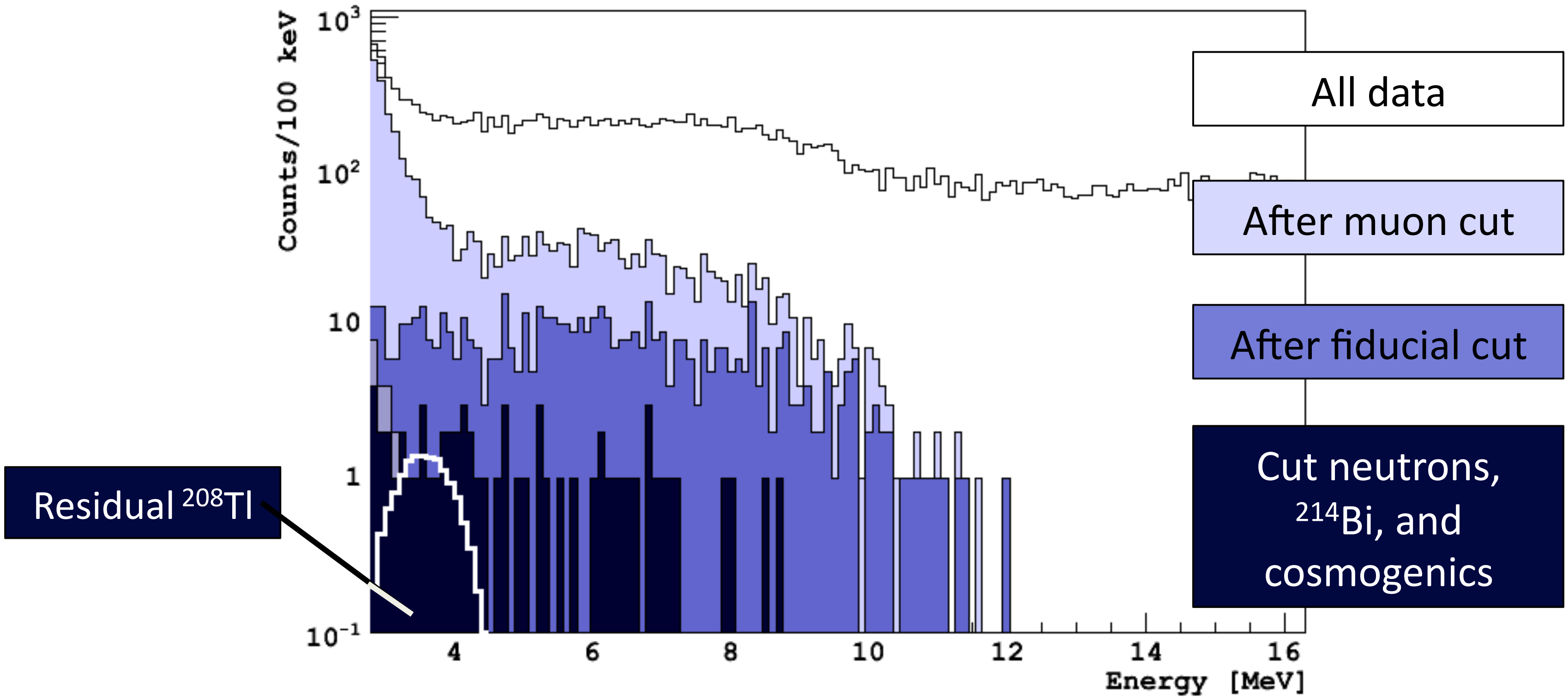


$R_{rec} – R_{ccd}$ (m)

Calibration paper in preparation!

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

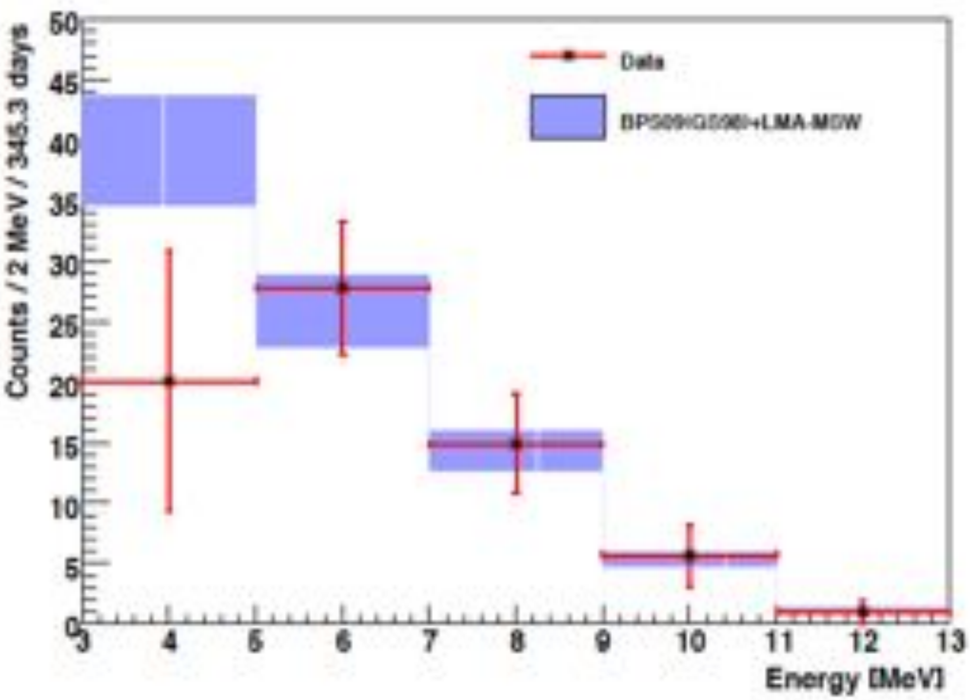
Sum Residuals

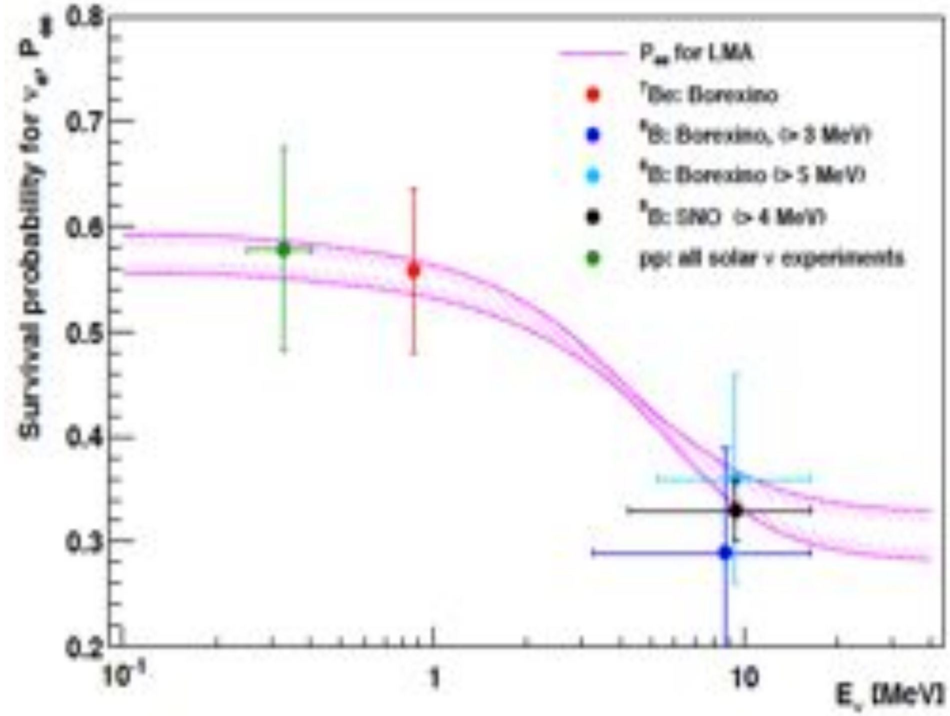
^{8}B Counting Rate (245 live days):

>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

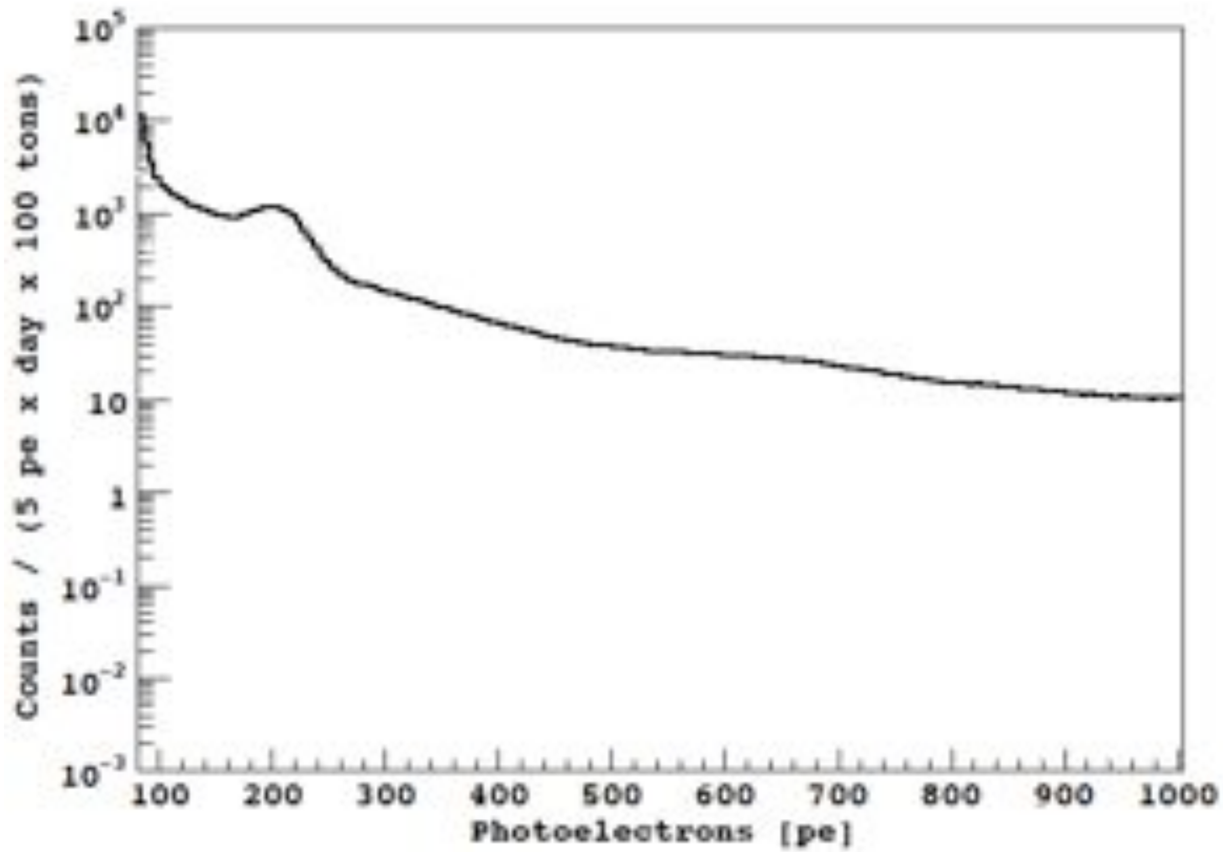




Beginning to test MSW with a single experiment:
Borexino ^{7}Be and ^{8}B P_{ee}'s differ by 1.9σ

Borexino 741-day ^{7}Be Result

(arXiv:1104.1816v1 and arXiv:1104.2150v1)



All data after data cleaning cuts (2.3% total deadtime) removing:

1. Muons and followers with 300ms (ID) or 2ms (OD)
2. Multi-cluster events
3. Co-incident events within 1.5m and 2ms
4. Events that differ significantly from single-site scintillation events (hit time and spatial distribution, hits/charge)

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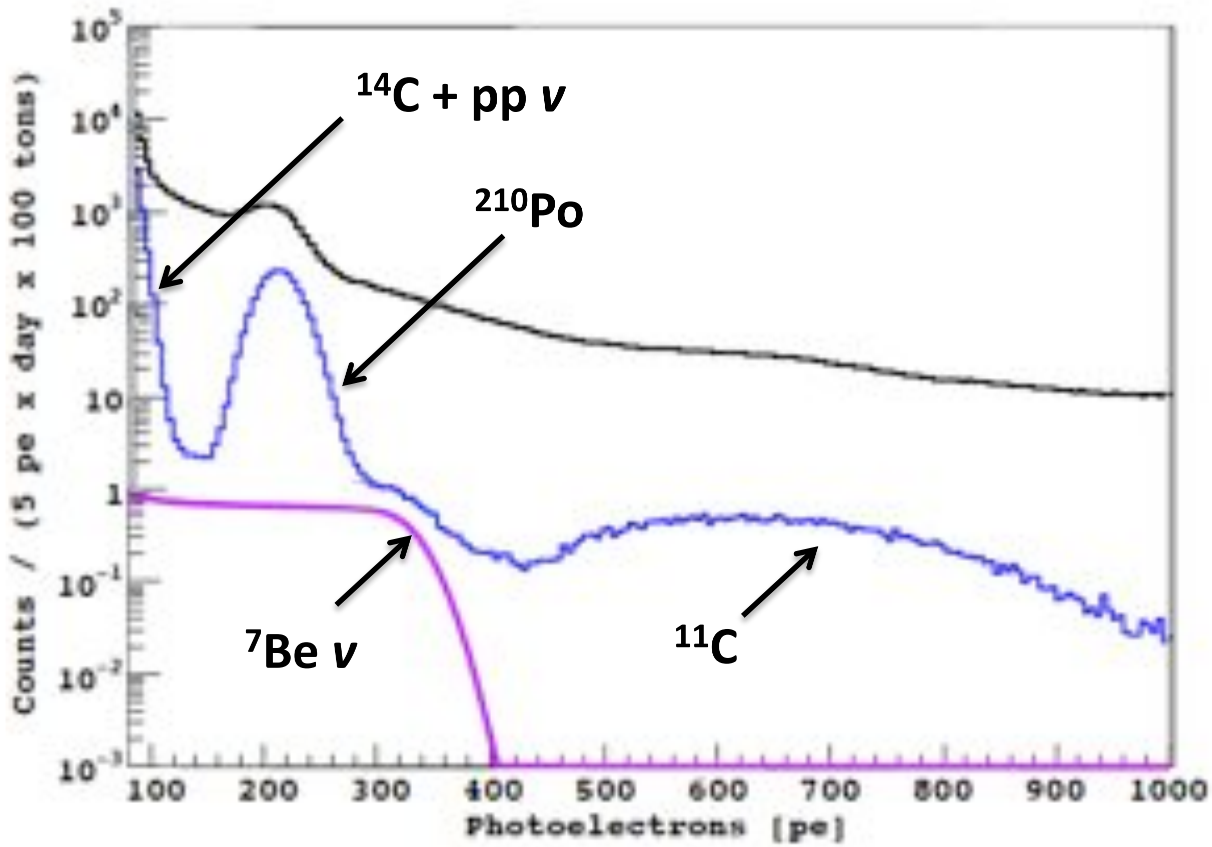
(arXiv:1104.1816v1 and arXiv:1104.2150v1)



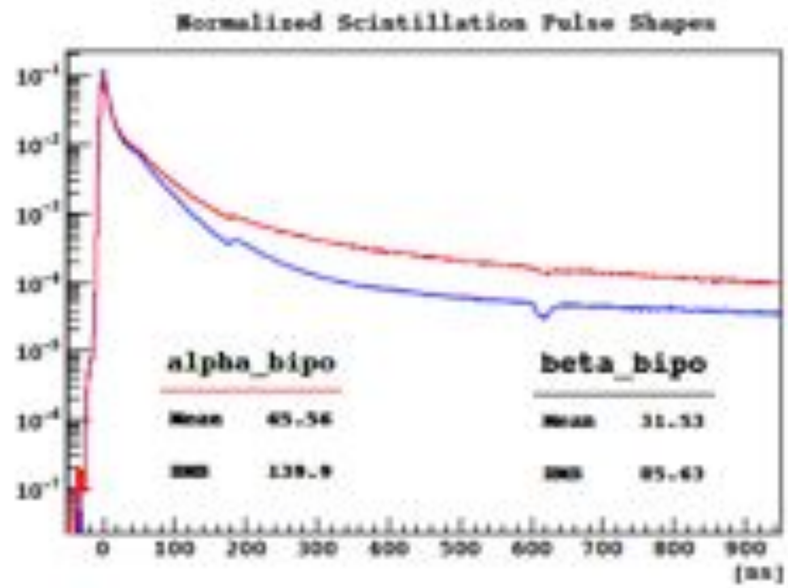
After fiducial volume cut:

1. R < 3.02m
2. |z| < 1.67m

Fiducial mass = 75.7 tonnes

α-β Separation by PSA

- In organic scintillator, particles with higher ionization density produce more “slow” light
- Separation based on “Gatti Parameter”
  - Weight signal, S, in time bin i by difference ratio of average α and β pulse shapes in bin i
- Either cut on Gatti, or, in each energy bin, fit the number of alphas in “Gatti space” and subtract



$$G = \sum_i P_i S_i$$

$$P_i = \frac{(\overline{\alpha_i} - \overline{\beta}_i)}{(\overline{\alpha_i} + \overline{\beta}_i)}$$

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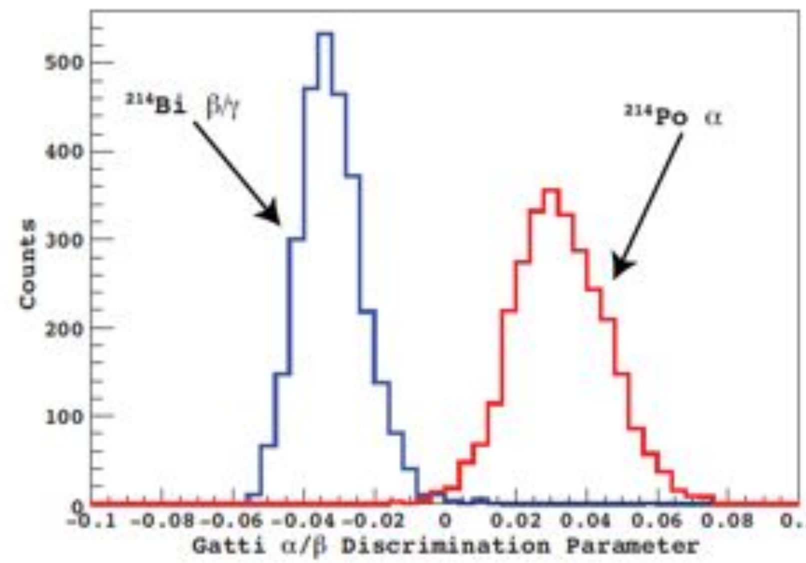
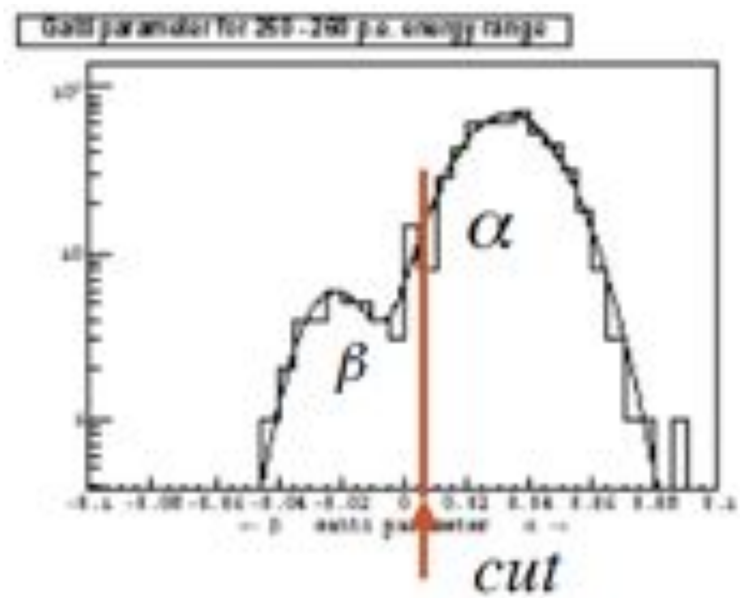
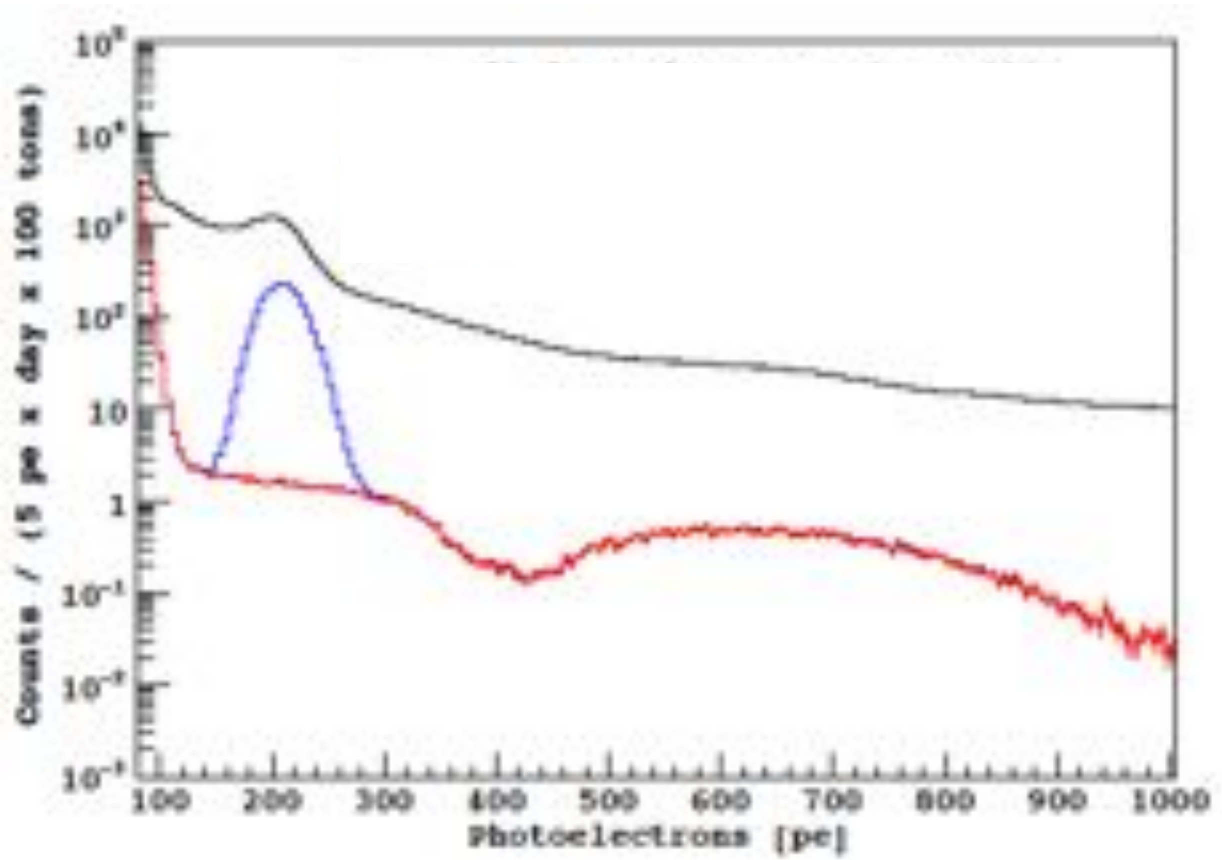
  - Weight signal, S, in time bin i by difference ratio of average α and β pulse shapes in bin i
- Either cut on Gatti, or, in each energy bin, fit the number of alphas in "Gatti space" and subtract





Borexino 741-day ^{7}Be Result

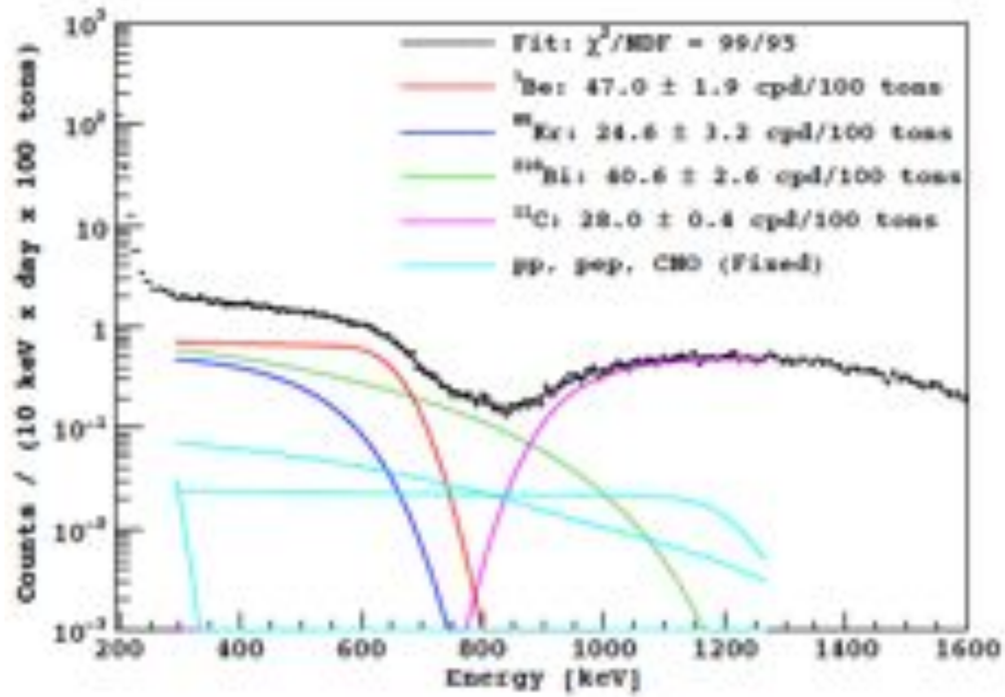
(arXiv:1104.1816v1 and arXiv:1104.2150v1)



After α statistical subtraction

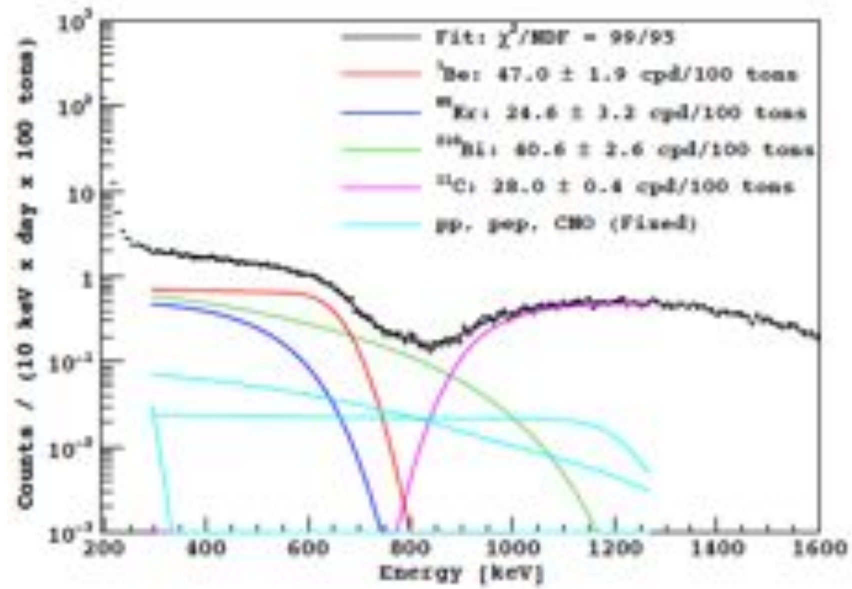
Signal Extraction

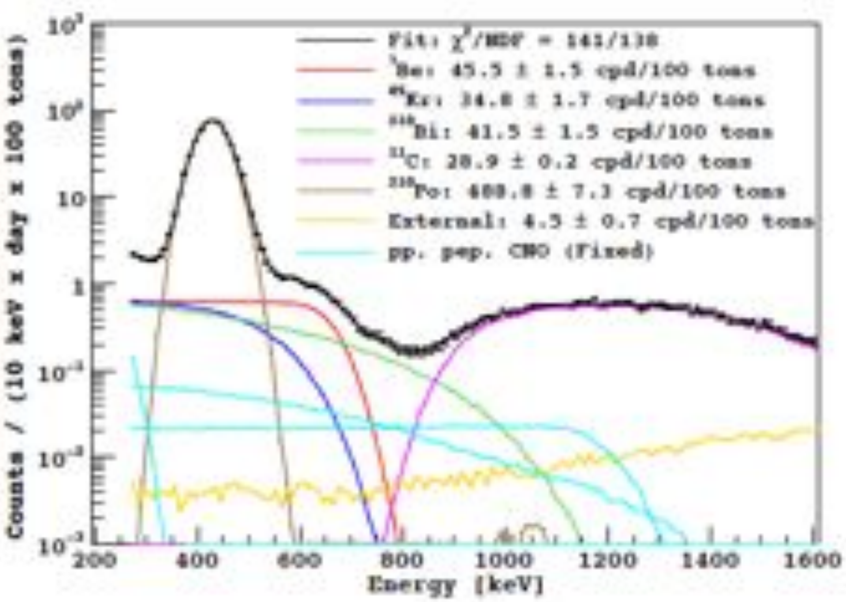
- 1-D binned likelihood fits in energy
- ^{7}Be, ^{210}Po, ^{85}Kr, ^{11}C, ^{210}Bi weights floated
- *pp, pep*, ^{8}B, and CNO fixed to SSM fluxes + LMA
- ^{222}Rn, ^{218}Po, and ^{214}Pb weights constrained by ^{214}Bi-^{214}Po co-incidence



Signal Extraction

- Analytical fits
  - Analytic description of detector response based on calibration data
  - Float energy scale, resolution in fit





- Monte Carlo fits
  - Tune MC detector response on calibration data
  - Energy scale, resolution fixed in fit
  - Include external backgrounds, increase fit range

Average Result

Borexino 862 keV ^{7}Be counting rate: $46.0 \pm 1.5_{stat}\ ^{+1.6}_{-1.5}{}_{sys}$ /(d 100T)

➡ $P_{ee}(862\ \text{keV}) = 0.52^{+0.07}_{-0.06}$

Systematics	
Trigger Efficiency	0.1%
Scintillator Density	0.05%
Livetime	0.04%
Cut Sacrifice	0.1%
Fiducial Mass	$^{+1.3}_{-0.5}$%
Energy Scale	2.7%
Fit Stability	1.7%
Fit Methods	1.0%
Total	$^{+3.6}_{-3.4}$**%**

Recall previously:

Systematics	
Scintillator Density	0.2%
Livetime	0.1%
Cut Sacrifice	0.3%
Fiducial Mass	6.0%
Detector Response	6.0%
Total	**8.5%**

Average Result

Borexino 862 keV ^{7}Be counting rate: $46.0 \pm 1.5_{stat} \, ^{+1.6}_{-1.5}{}_{sys}$ /(d 100T)

➡ $P_{ee}(862\ \text{keV}) = 0.52\ ^{+0.07}_{-0.06}$

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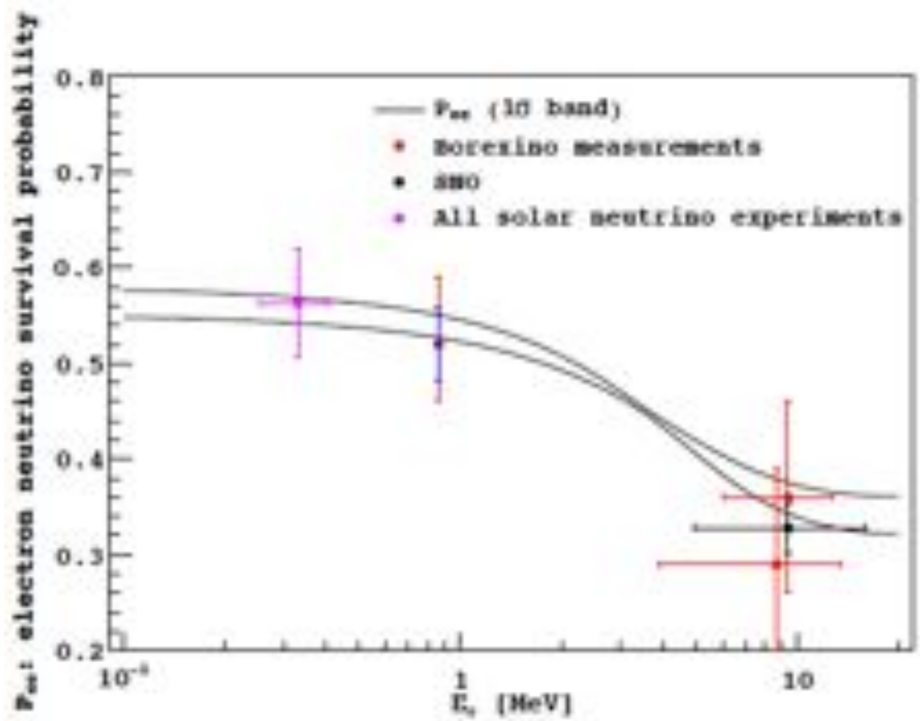


Day-Night Effect

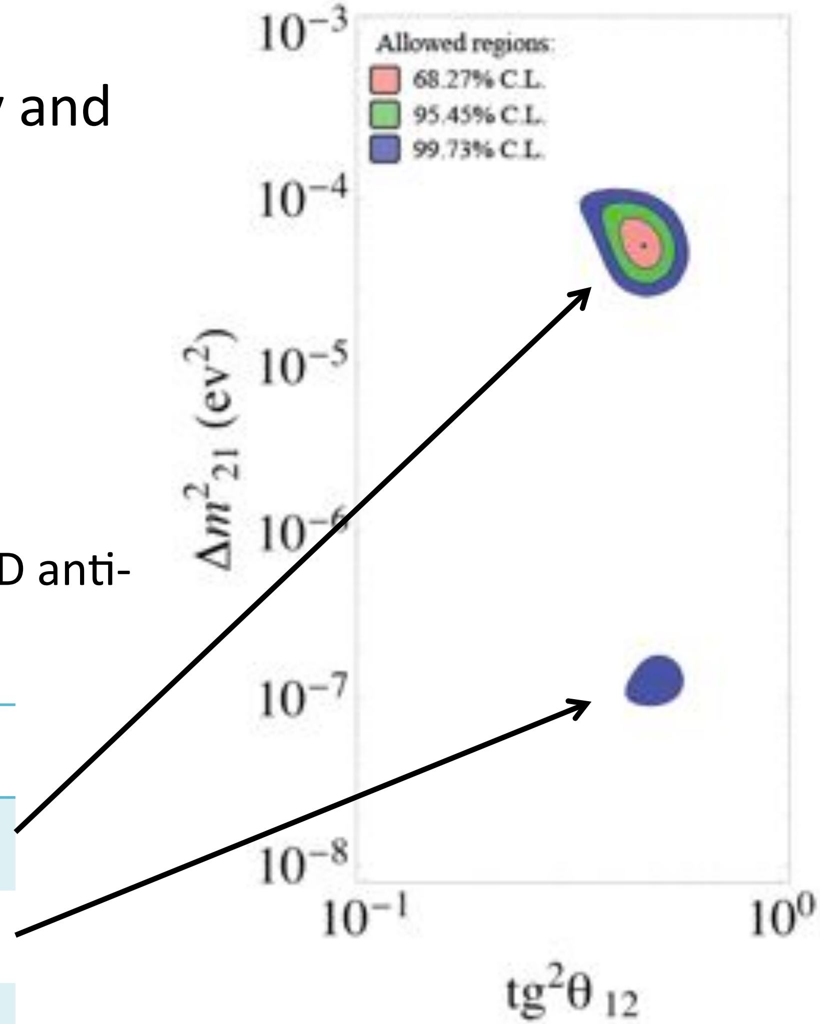
- As solar neutrinos (diabatically) enter the earth, ν_e can be coherently regenerated
- Size of the effect depends on mixing parameters, can cause the effective day and night neutrino fluxes to be different

$$A_{dn} = 2\frac{R_n^{^7Be} - R_d^{^7Be}}{R_n^{^7Be} + R_d^{^7Be}} = \frac{R_{diff}}{R}$$

- Gives Borexino a powerful tool to discriminate between LMA and LOW oscillations
  - Otherwise, LOW is excluded using KamLAND anti-neutrino data

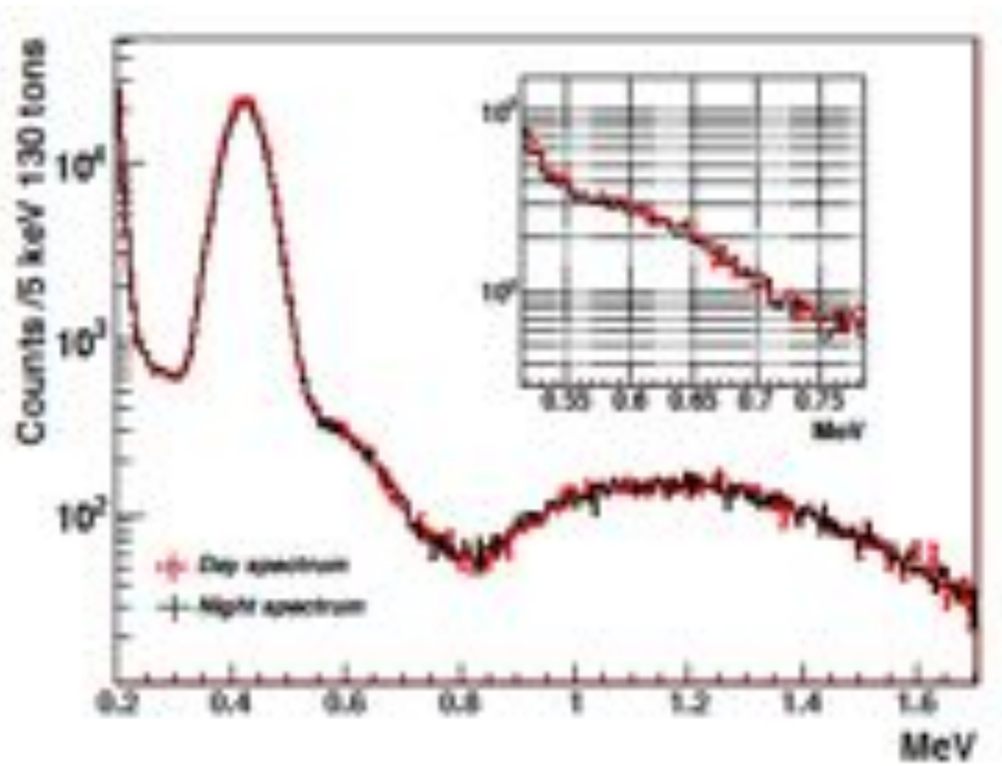
Model	Predicted A_{nd} (862 keV)
LMA	<0.001
LOW	0.11 - 0.80
MaVaN	~0.20

Global Solar without Borexino



Borexino Day-Night Asymmetry Search I

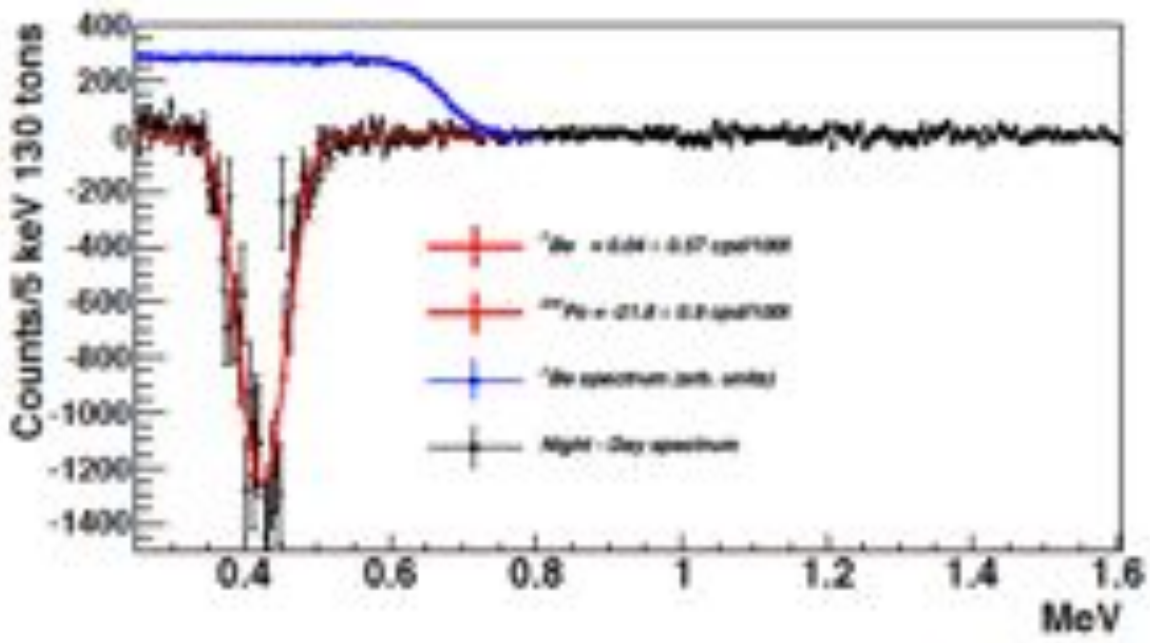
- Normalize the day and night spectra to the day livetime
  - Correct for earth's orbital eccentricity
- Fit the day and night spectra separately



→ **A_{dn}(862 keV): 0.007 ± 0.073**

Borexino Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
  - Correct for earth's orbital eccentricity
- Subtract them
- Fit the difference for ^{7}Be and ^{210}Po (decay maps to day-night effect)
- More precise result by assuming backgrounds are day-night invariant



A_{dn}(862 keV): $0.001 \pm 0.012_{stat} \pm 0.007_{sys}$

Source of error	Error on A_{dn}
Live–time	$< 5 \cdot 10^{-4}$
Cut efficiencies	0.001
Variation of ^{210}Bi with time	±0.005
Fit procedure	± 0.005
Total systematic error	0.007

Borexino Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
  - Correct for earth's orbital eccentricity
- Subtract them
- Fit the difference for ^7Be and ^{210}Po (decay maps to day-night effect)
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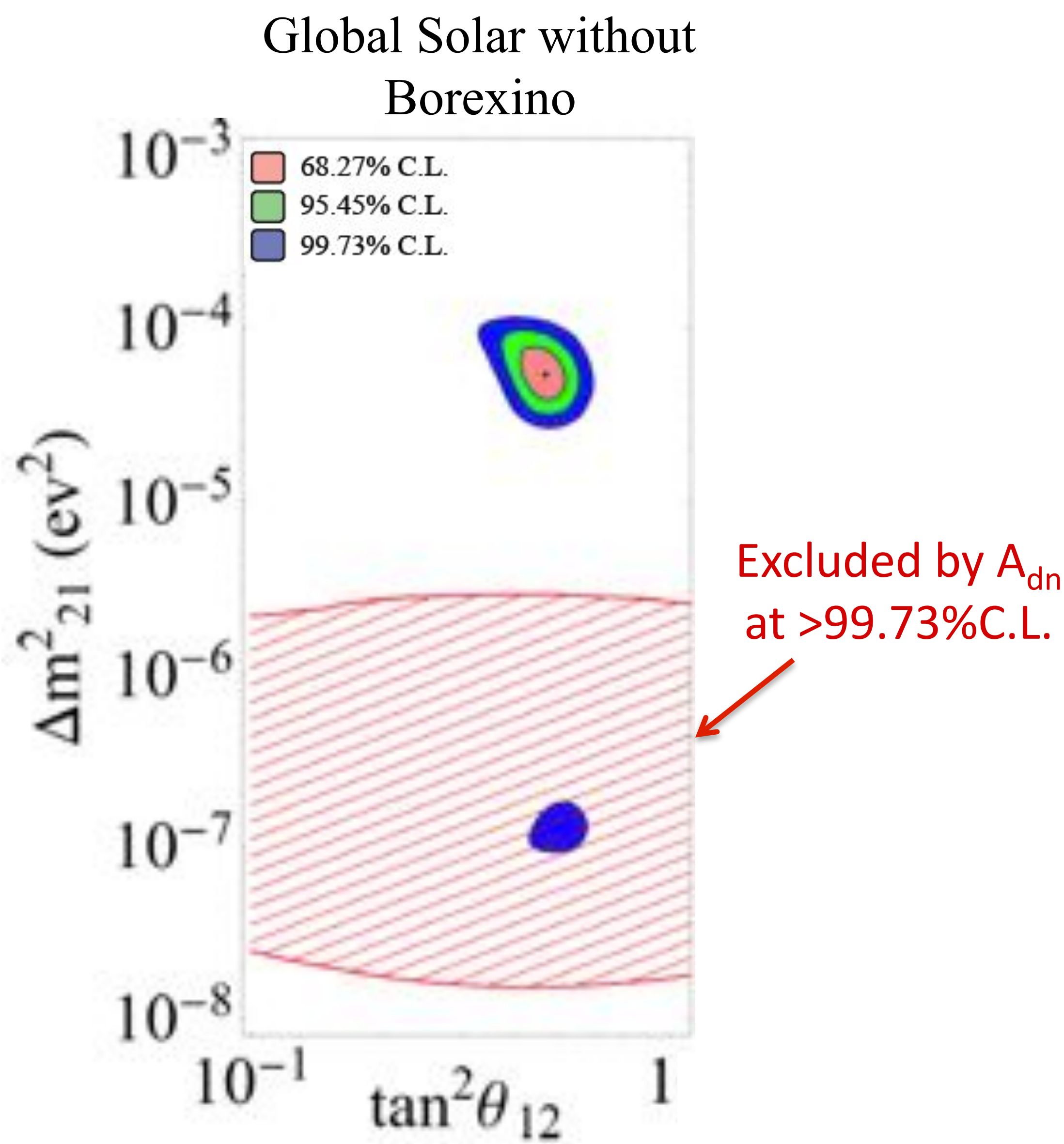


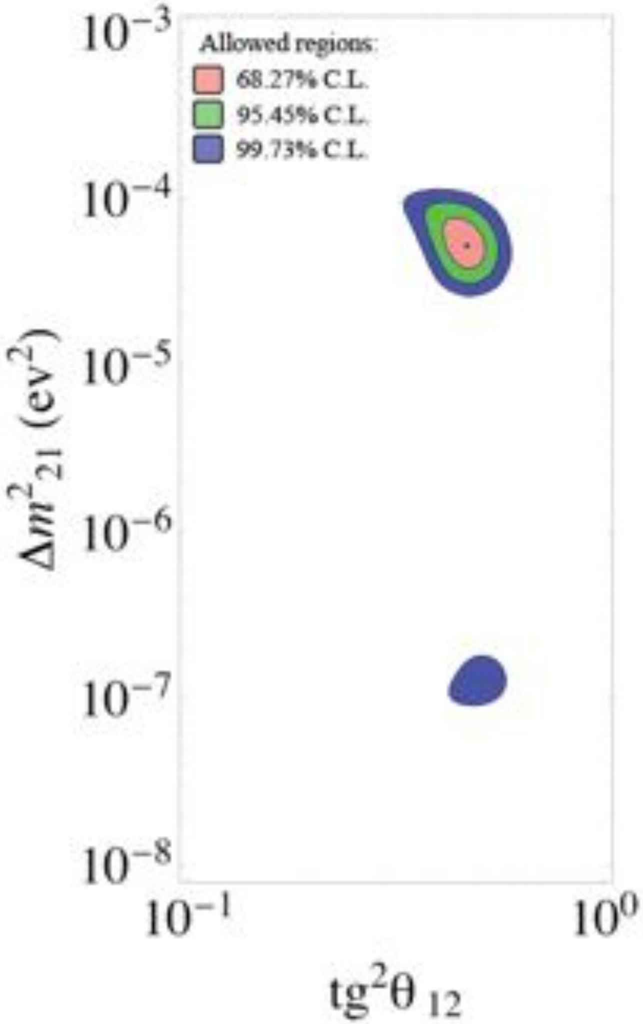
Borexino ^{7}Be Results

- P_{ee}**(862 keV) = 0.52** $^{+0.07}_{-0.06}$
  - Constrains low energy survival probability
- A_{dn} **= 0.001 ± 0.012 ± 0.007**
  - Rules out LOW at >8σ using solar only data
- Global best fit point (2 *ν* approximation)

$$\Delta m^2 = 5.3 \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.46$$

Global Solar without Borexino



Borexino ^{7}Be Results

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- $A_{dn} = 0.001 \pm 0.012 \pm 0.007$
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$$\Delta m^2 = 5.3\text{x}10^{-5} eV^2$$

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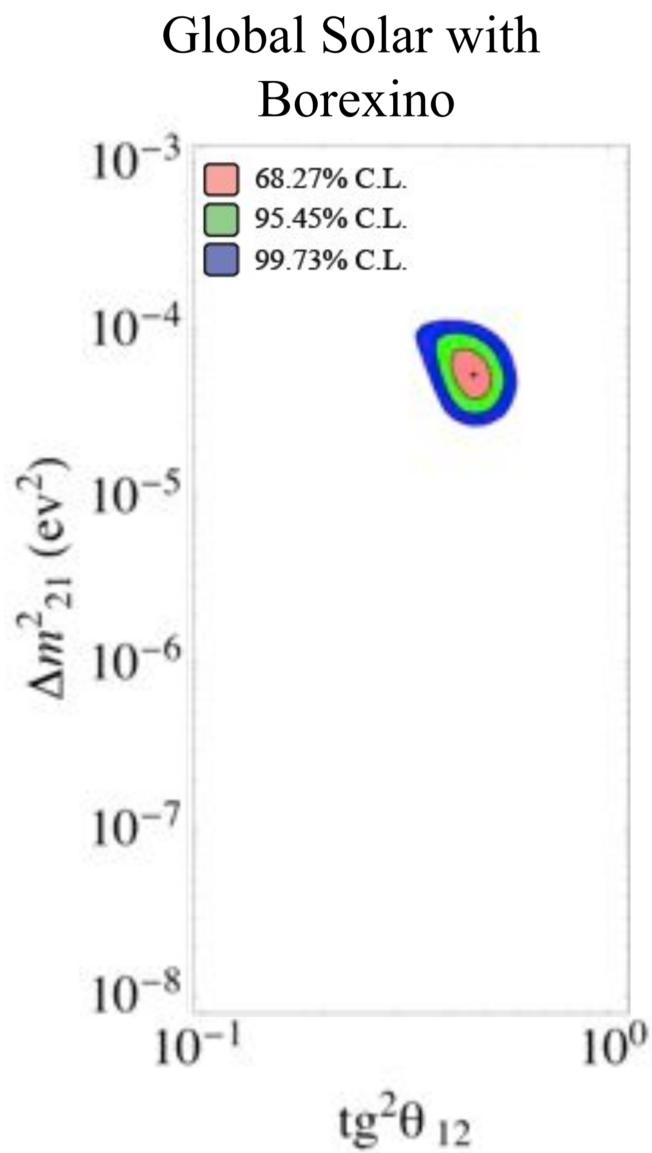

Borexino ^{7}Be Results

- $P_{ee}(862\ \text{keV}) = 0.52\ ^{+0.07}_{-0.06}$
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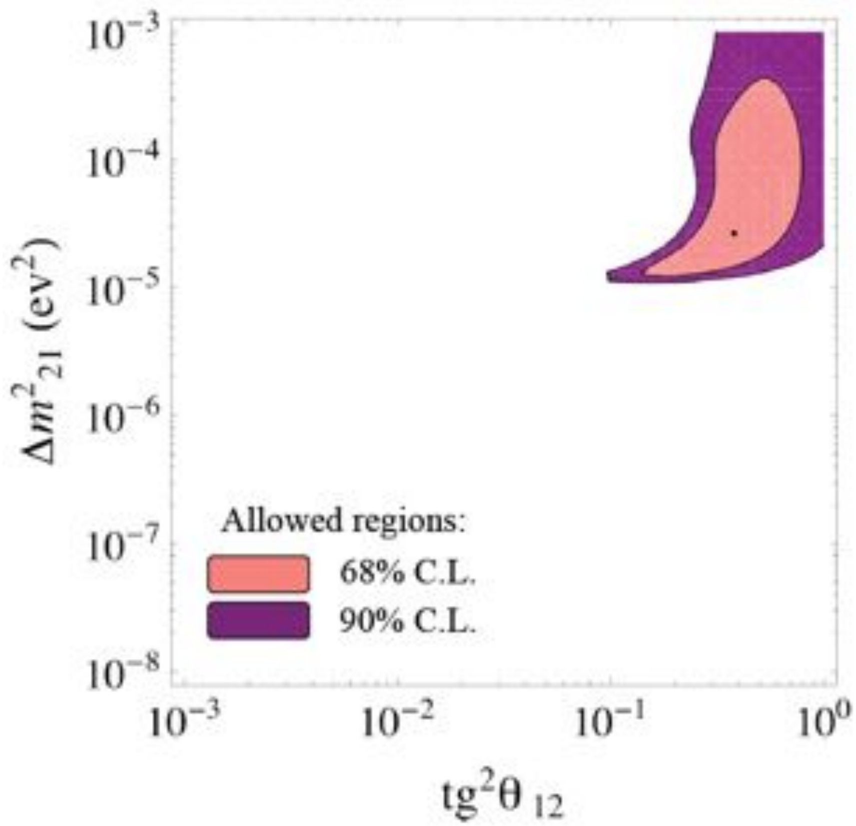
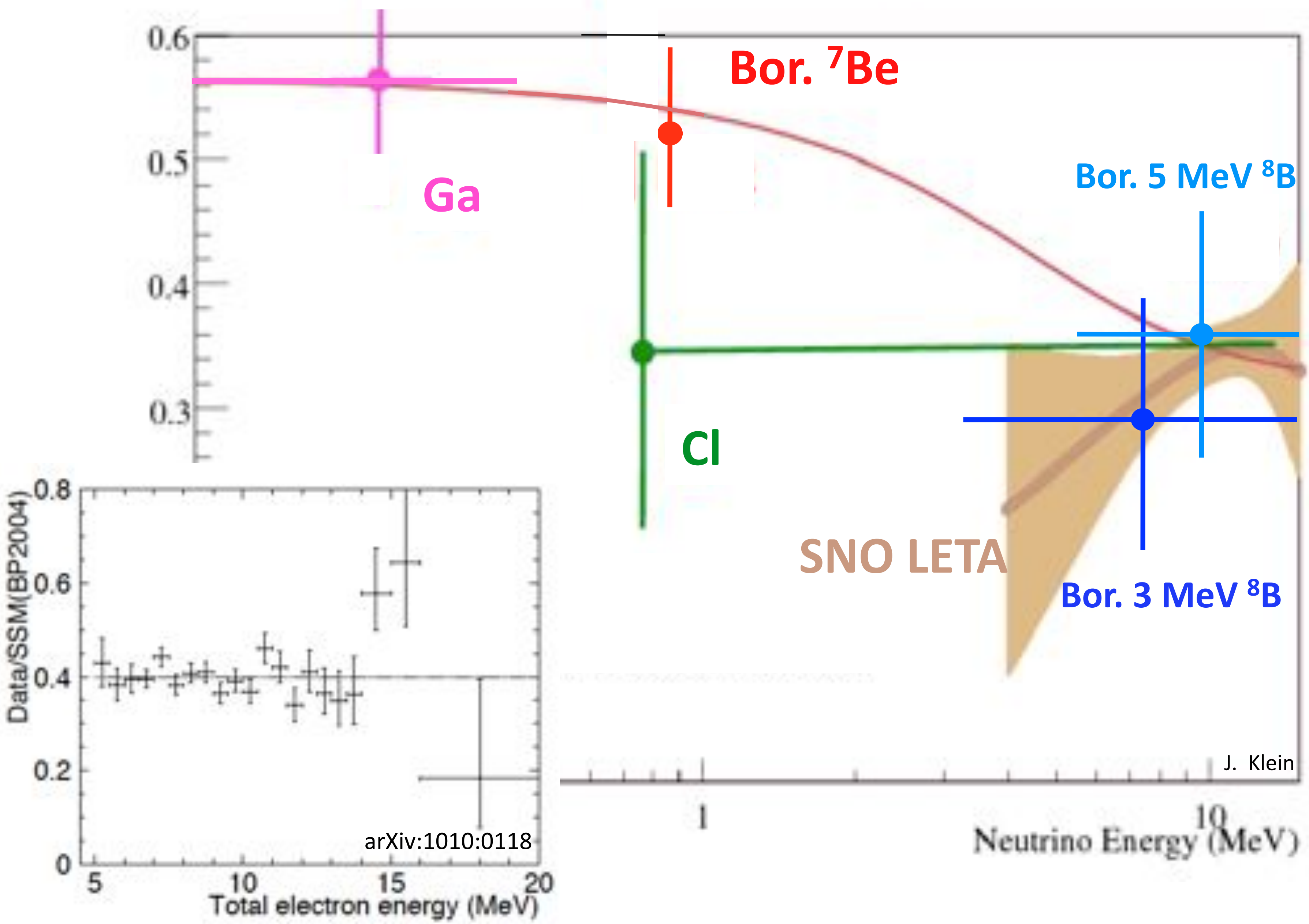
$$\Delta m^2 = 5.3\text{x}10^{-5}\text{eV}^2$$

$$\tan^2\theta_{12} = 0.46$$

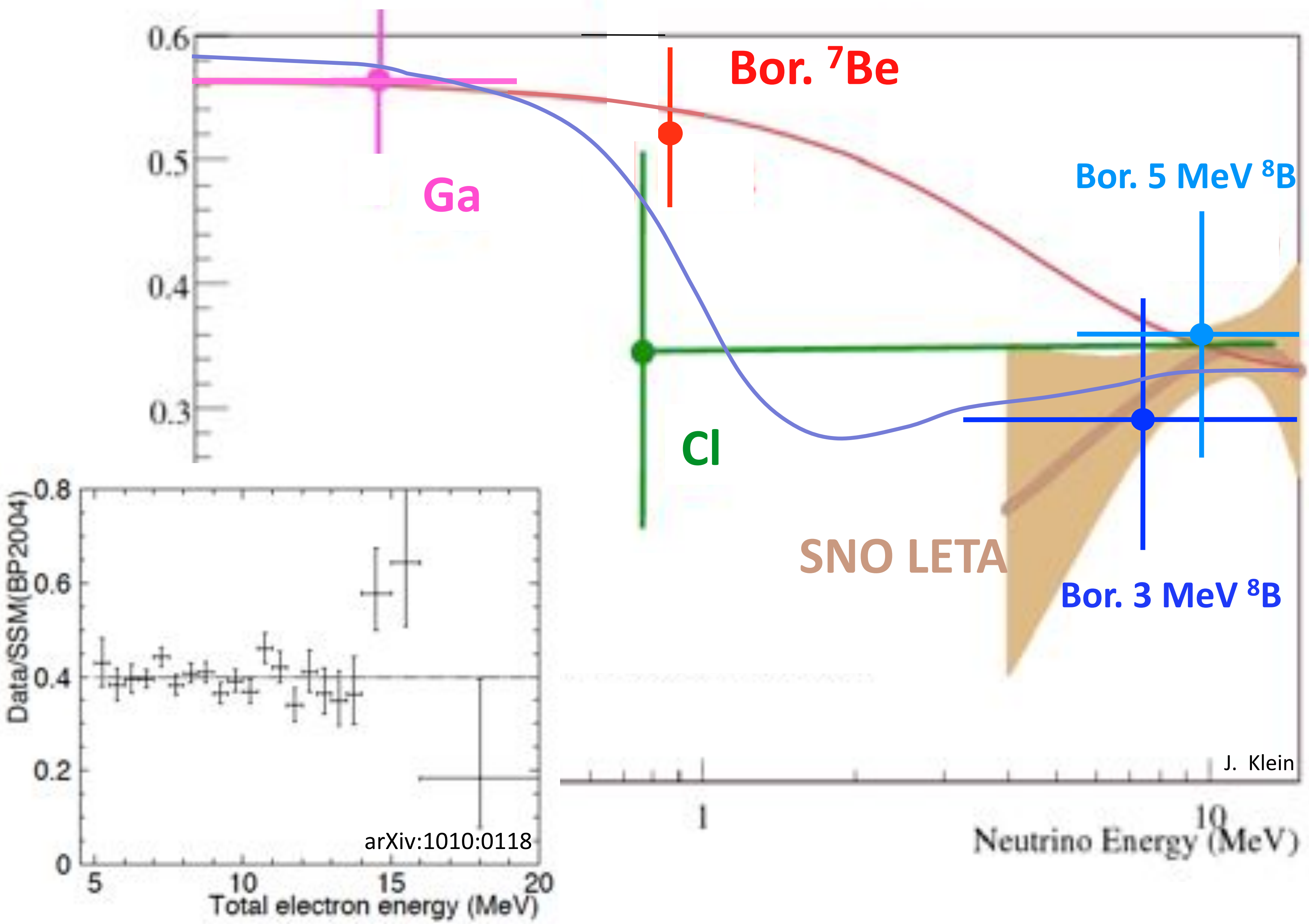
Borexino Alone



Summary of Current Status

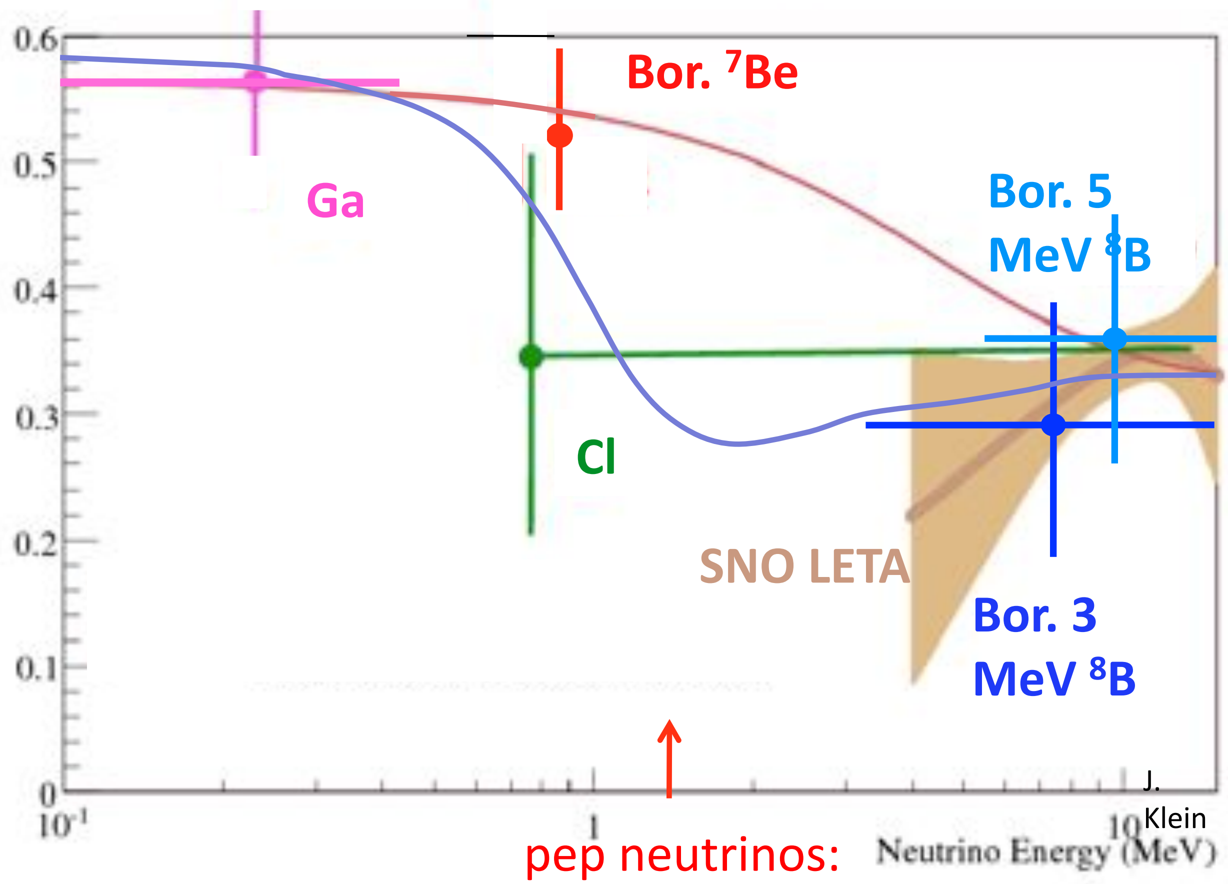


Summary of Current Status



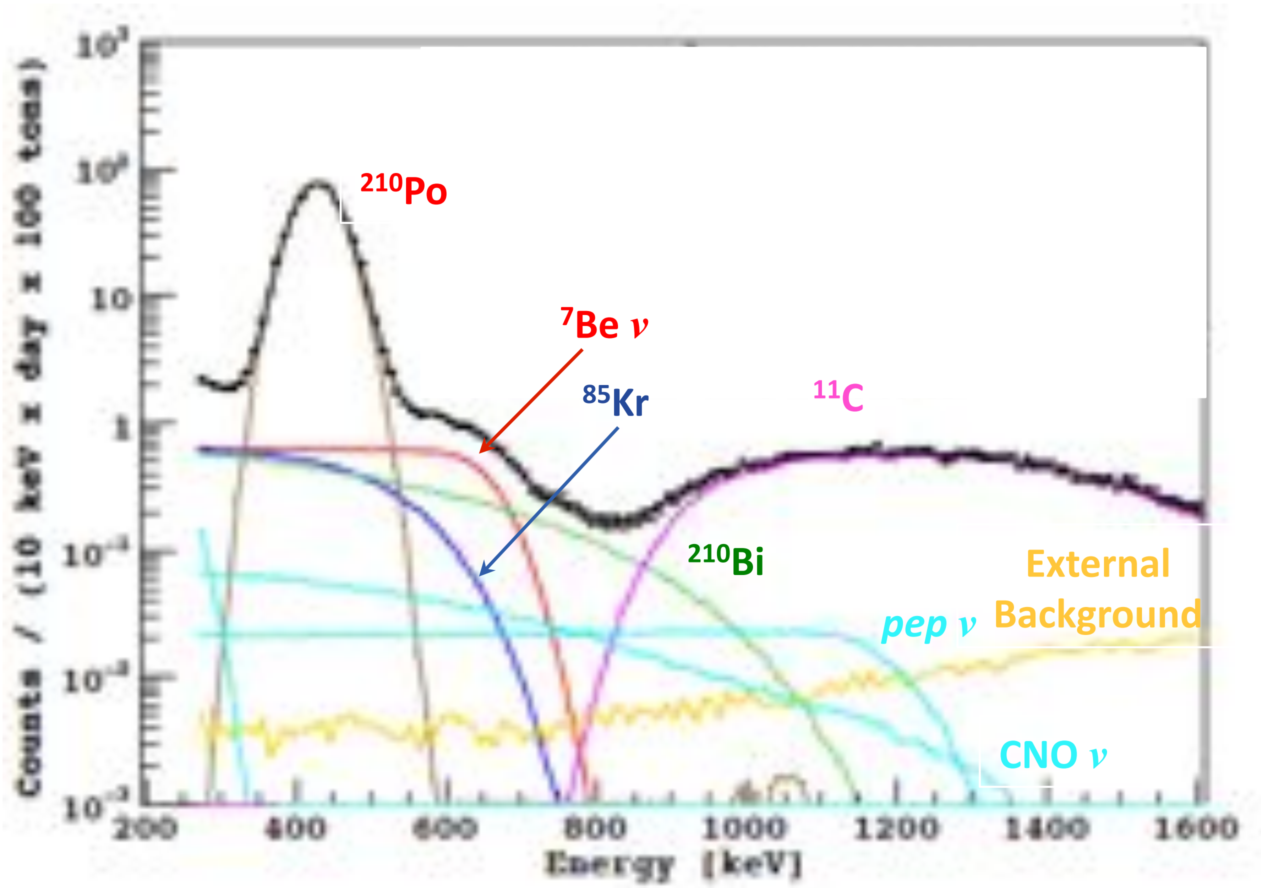
How to Proceed?

- Measure the *pep* survival probability



pep neutrinos:
±<2% SSM flux prediction

pep neutrinos in Borexino: ^{11}C Suppression

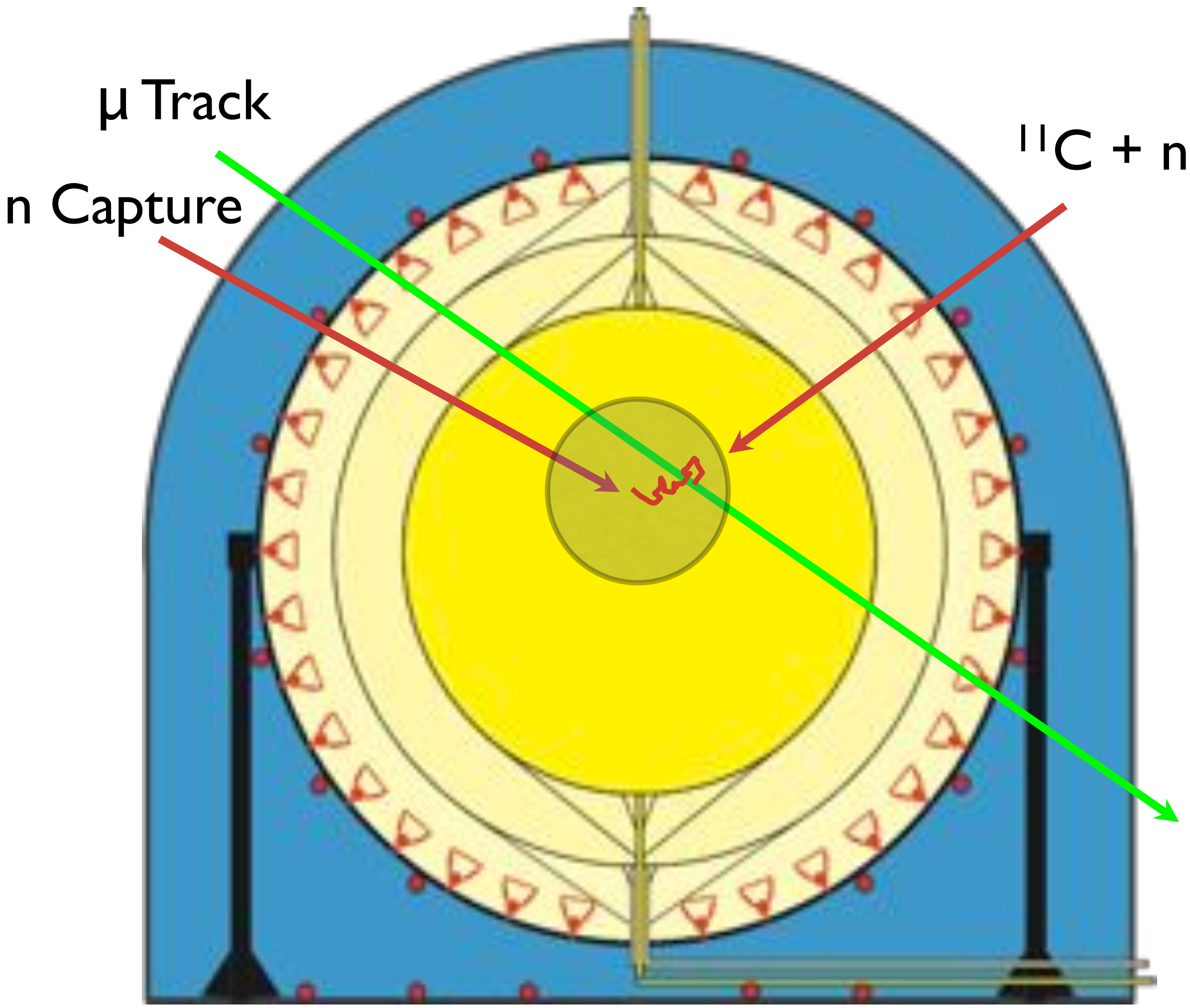


- ^{11}C is a cosmogenic radio-isotope with a half life of 20 minutes
- Borexino muon rate is 4300/day

Can't veto after every muon!

Image credit: M. Wurm

pep neutrinos in Borexino: ^{11}C Suppression

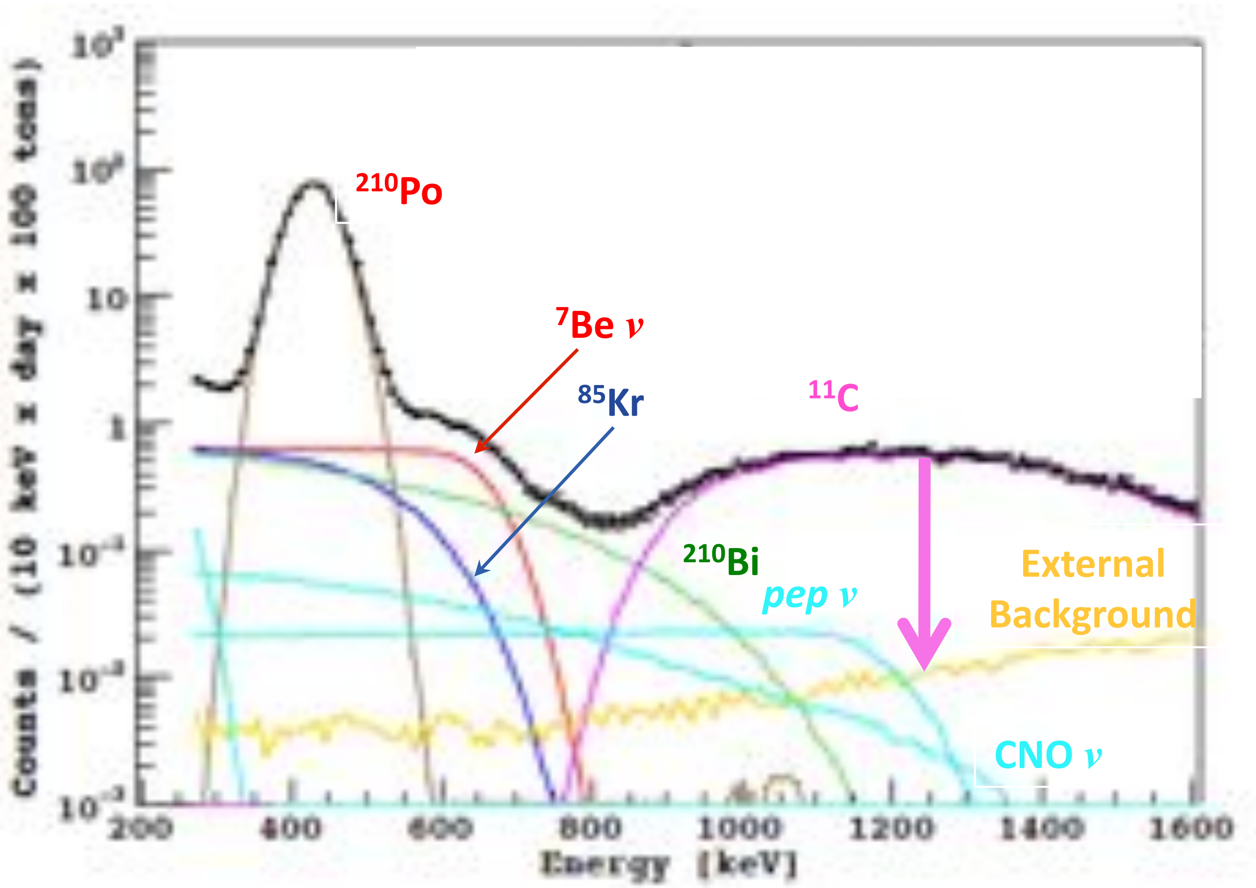


- Most ^{11}C production via $^{12}C \rightarrow {}^{11}C + n$
- Delayed neutron capture signal identifies when and where ^{11}C was produced
- Also looking into PSD based on ortho-positronium (~140ns)

PRC 83:015504 (2011)

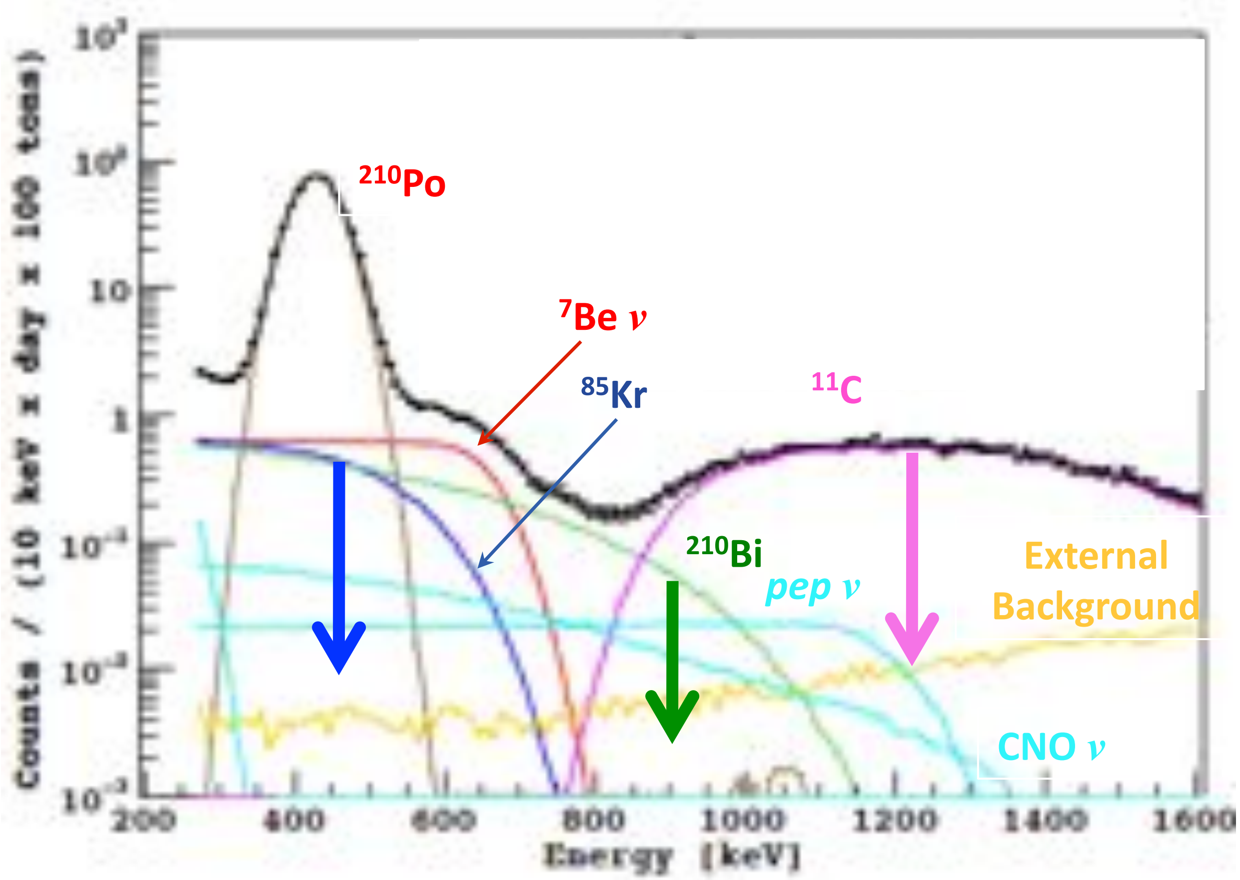
The ~125 muon-neutron coincidences/day (of which ~25 accompany ^{11}C production) can be vetoed without excessive loss of live time.

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!

Borexino Collaboration

Astroparticle and Cosmology Laboratory – Paris, France
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN e Dipartimento di Fisica dell'Università – Genova, Italy
INFN e Dipartimento di Fisica dell'Università– Milano, Italy
INFN e Dipartimento di Chimica dell'Università – Perugia, Italy
Institute for Nuclear Research – Gatchina, Russia
Institute of Physics, Jagellonian University – Cracow, Poland
Join Institute for Nuclear Research – Dubna, Russia
Kurchatov Institute – Moscow, Russia
Max-Planck Institute fuer Kernphysik – Heidelberg, Germany
Princeton University – Princeton, NJ, USA
Technische Universität – Muenchen, Germany
University of Massachusetts at Amherst, MA, USA
University of Moscow – Moscow, Russia
Virginia Tech – Blacksburg, VA, USA