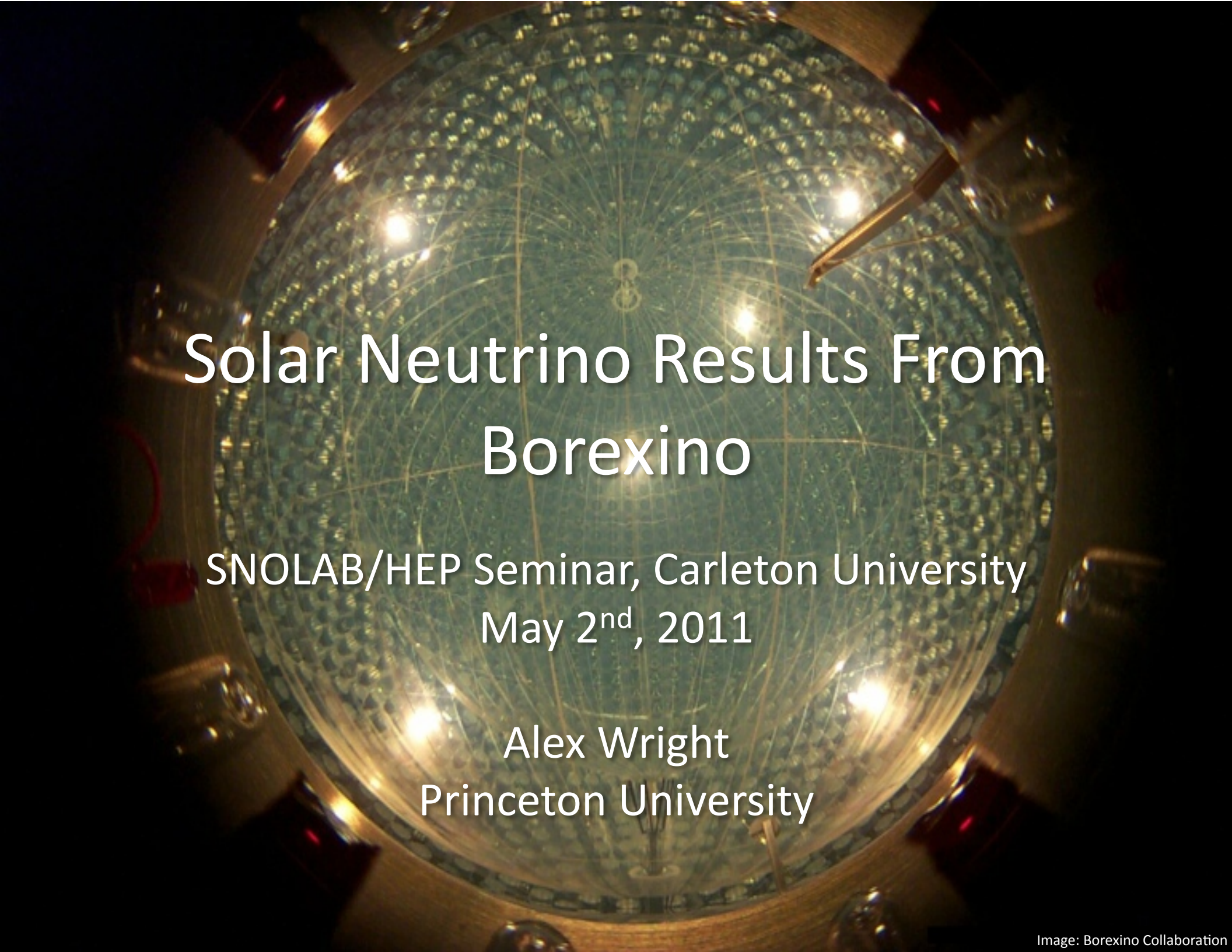




Solar Neutrino Results From Borexino

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

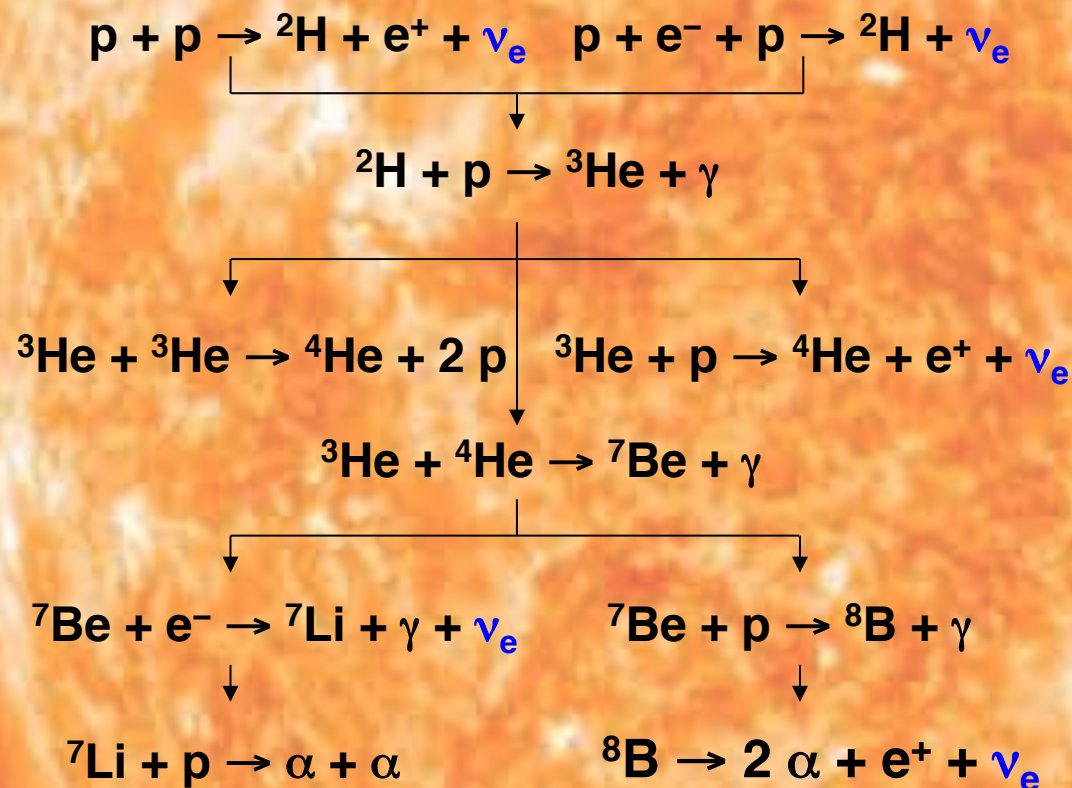
Alex Wright
Princeton University

Outline

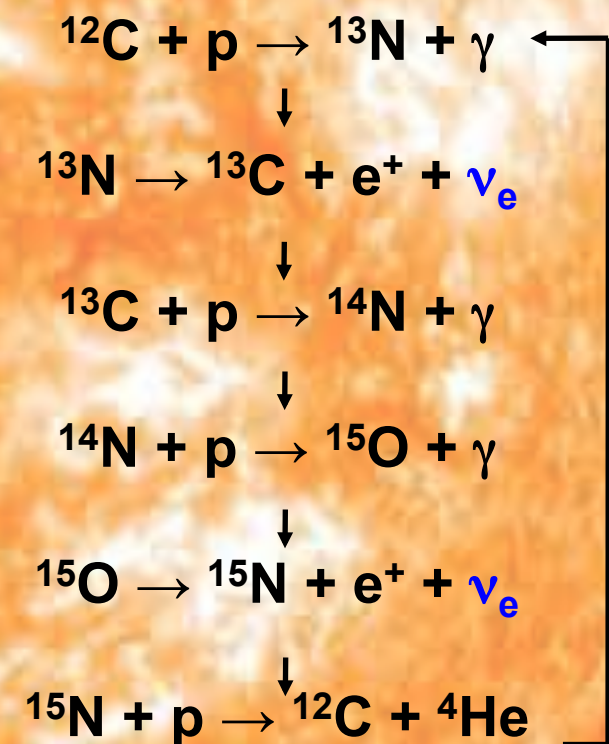
- Quick review of solar neutrinos and neutrino mixing
- Introduction to Borexino and previous results
- Source calibration campaign
- Recent results and implications
- Outlook

Solar Fusion Reactions

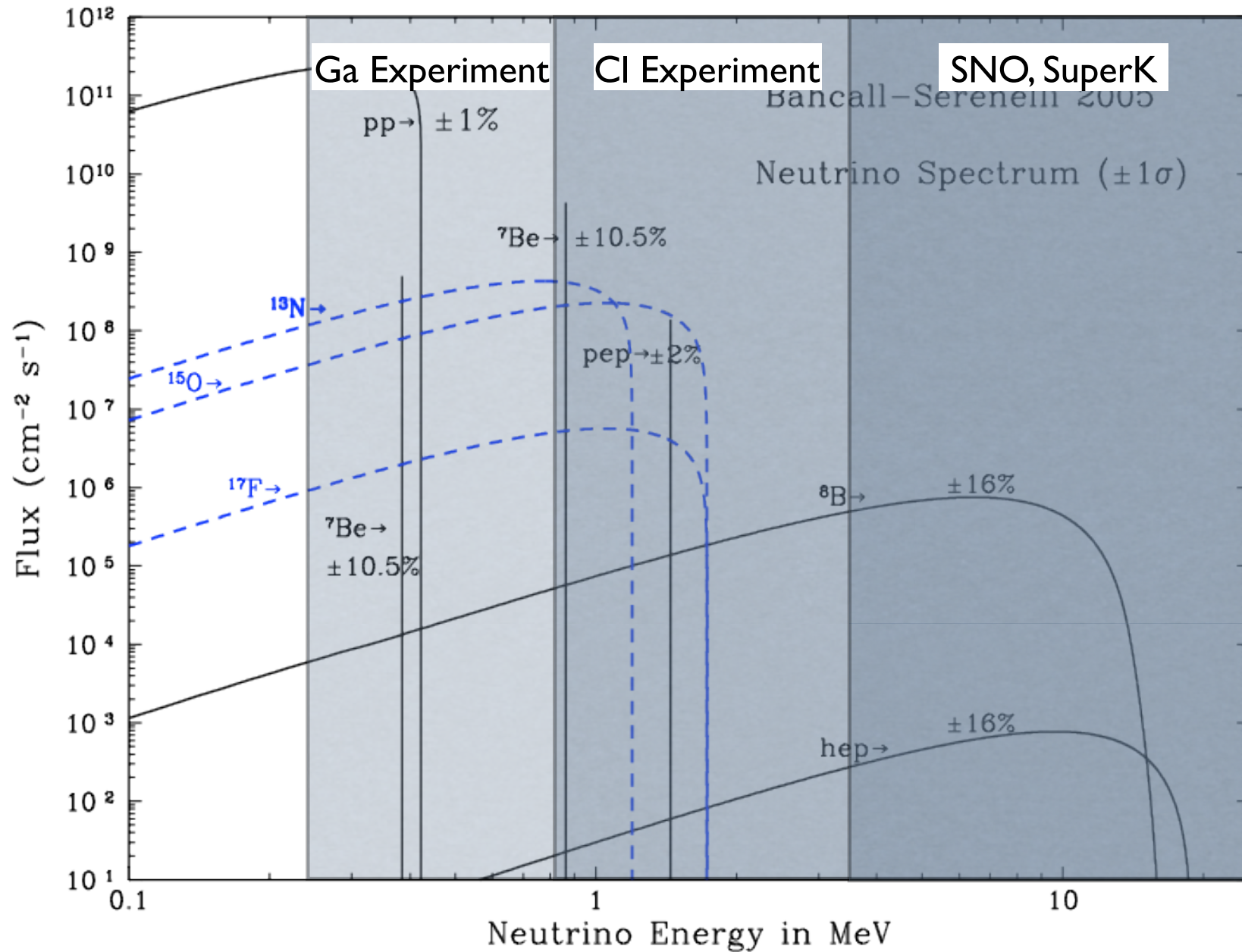
p-p Solar Fusion Chain



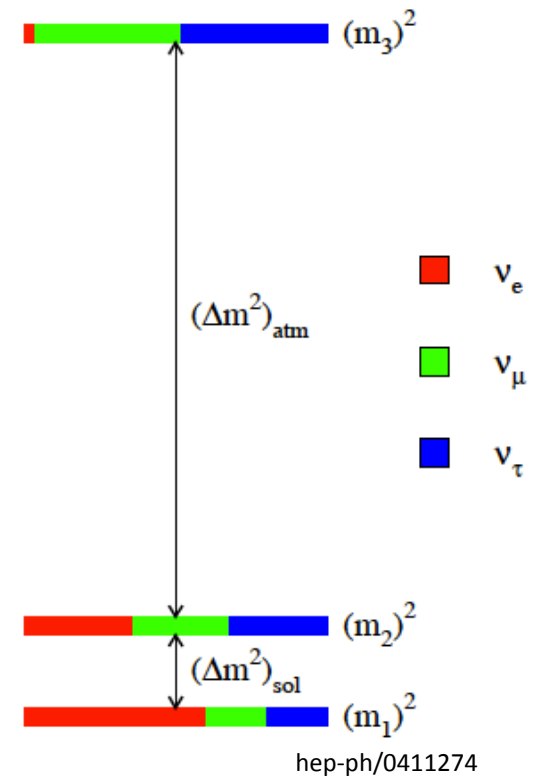
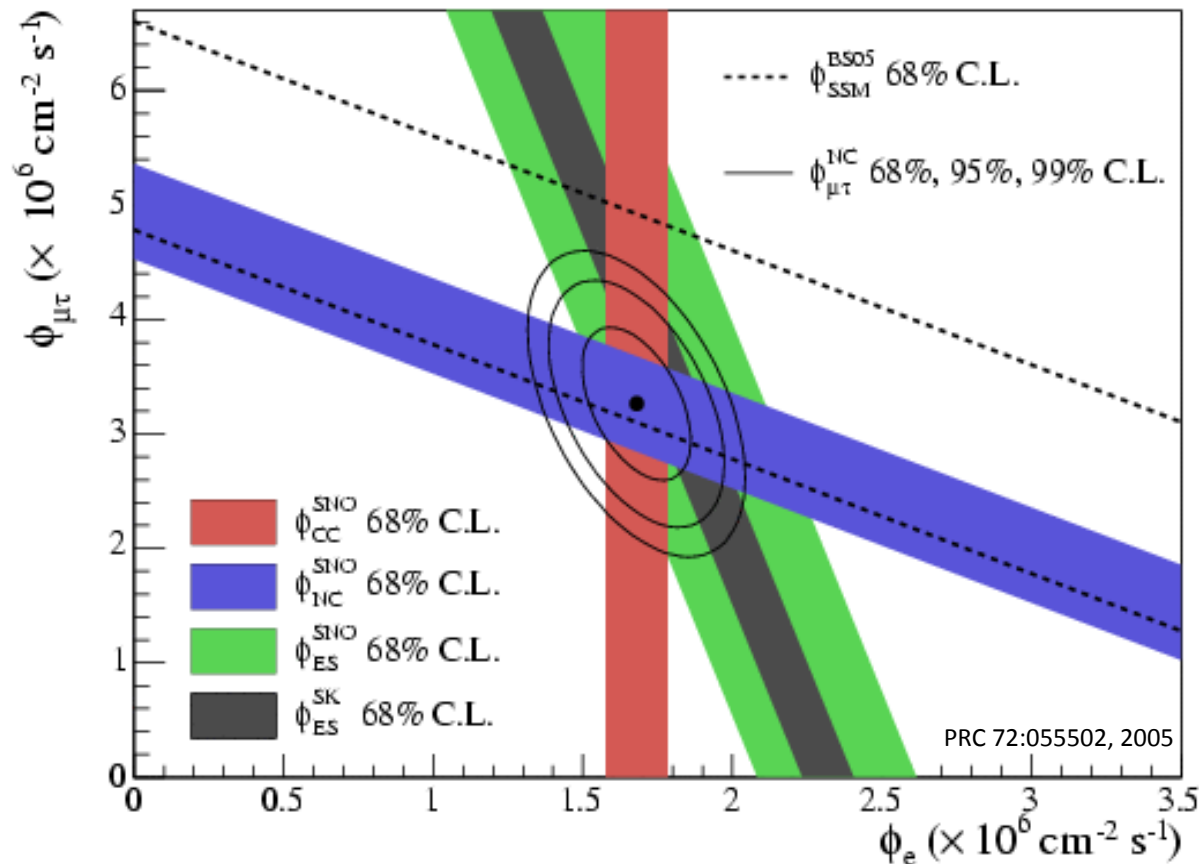
CNO Solar Fusion Cycle



Solar Neutrinos



SNO Results: Solar Neutrinos Oscillate



- 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

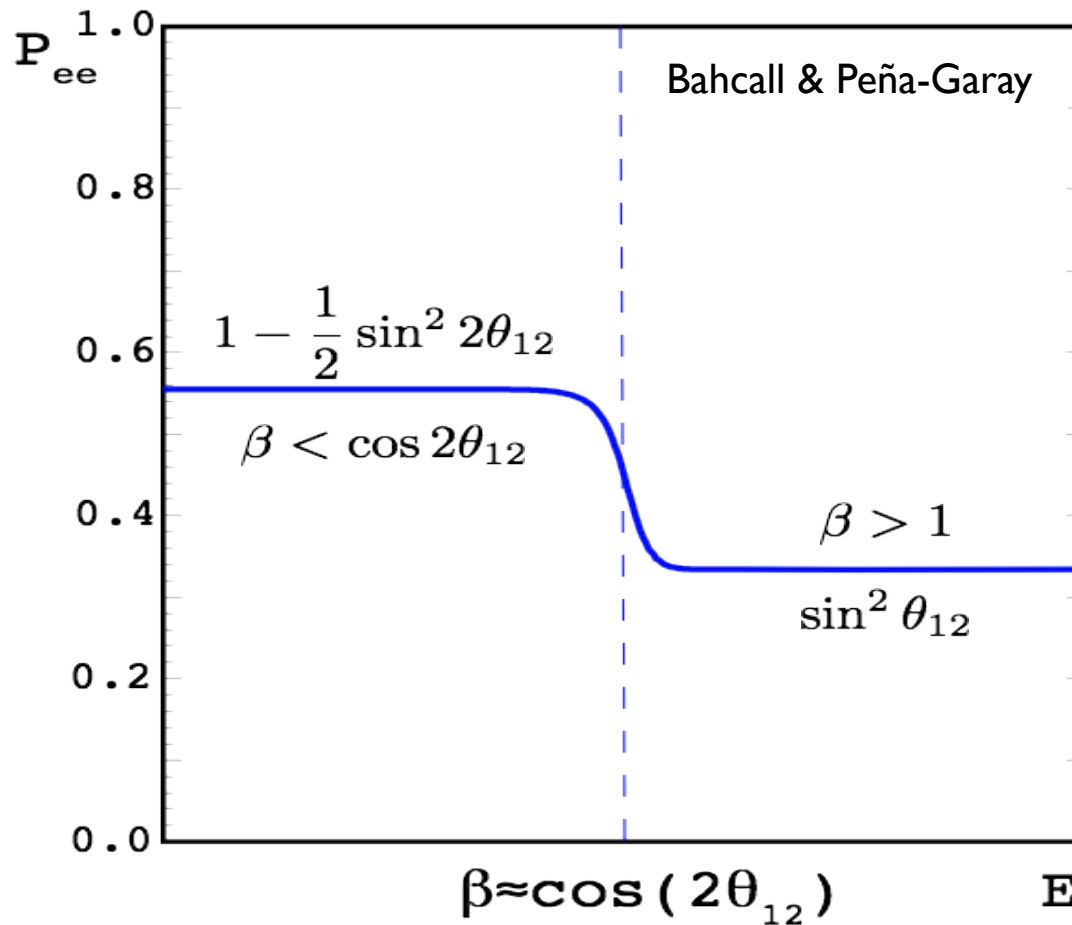
“MSW” Neutrino Oscillations

- 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:

$$\left(\begin{array}{cc} -\frac{\Delta m_{12}^2}{4E} \cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m_{12}^2}{4E} \sin 2\theta_{12} \\ \frac{\Delta m_{12}^2}{4E} \sin 2\theta_{12} & \frac{\Delta m_{12}^2}{4E} \cos 2\theta_{12} \end{array} \right)$$

- 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

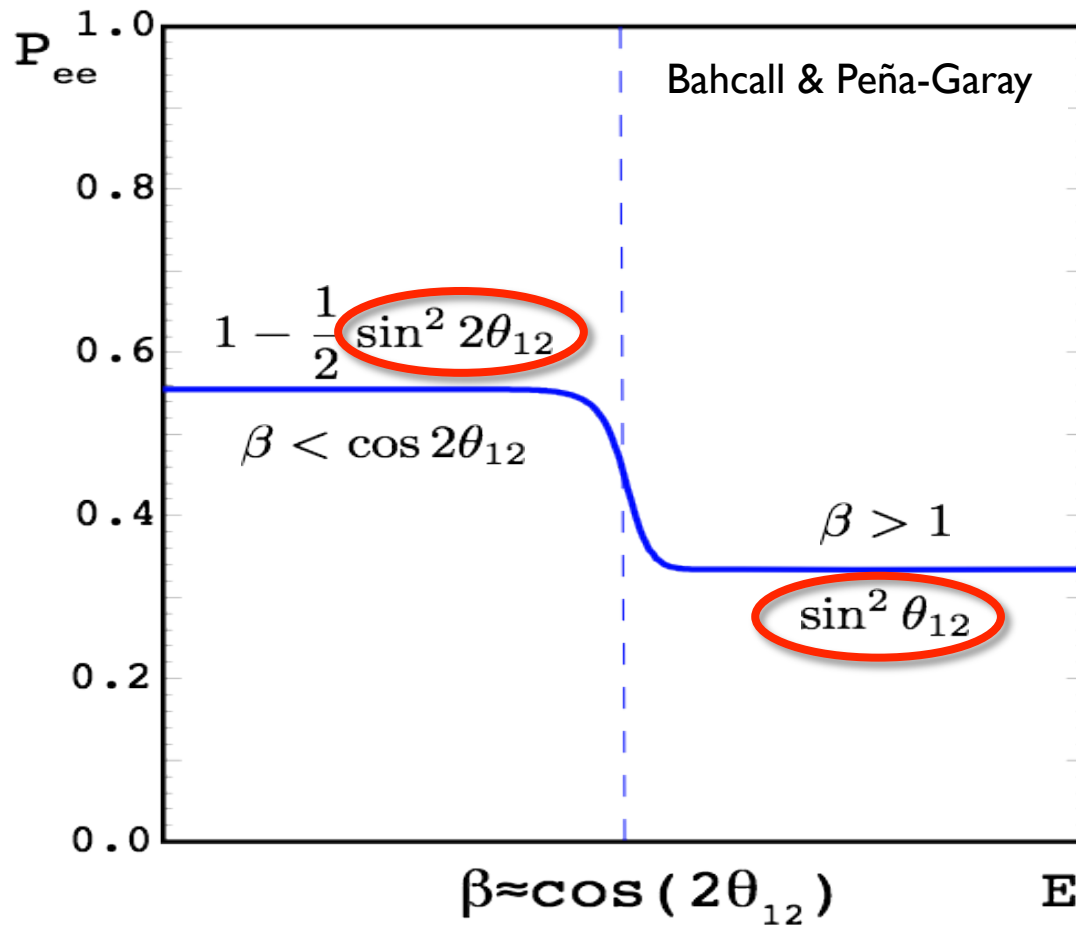


$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated “resonant conversion”

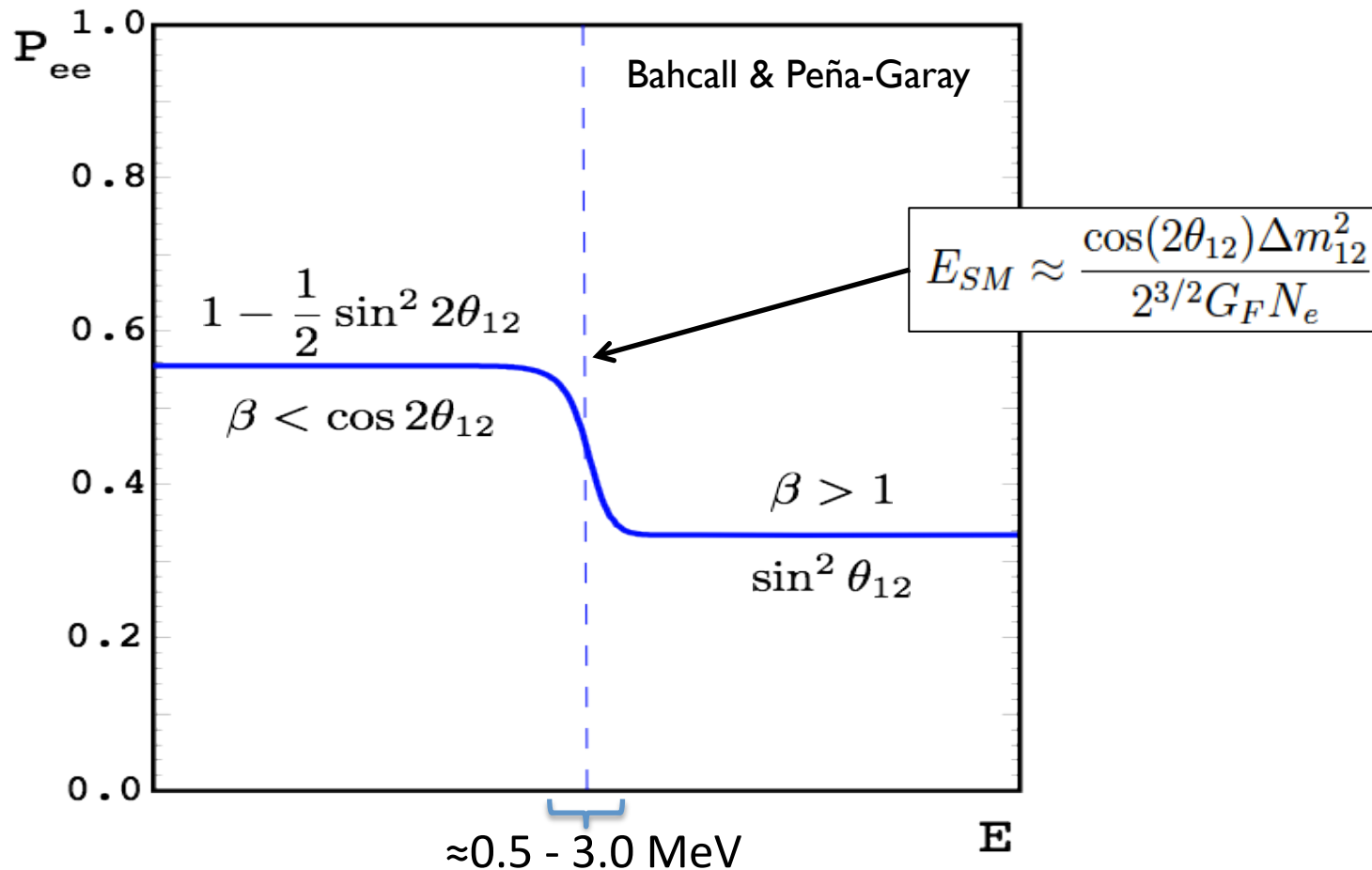
MSW Oscillation Regimes



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

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

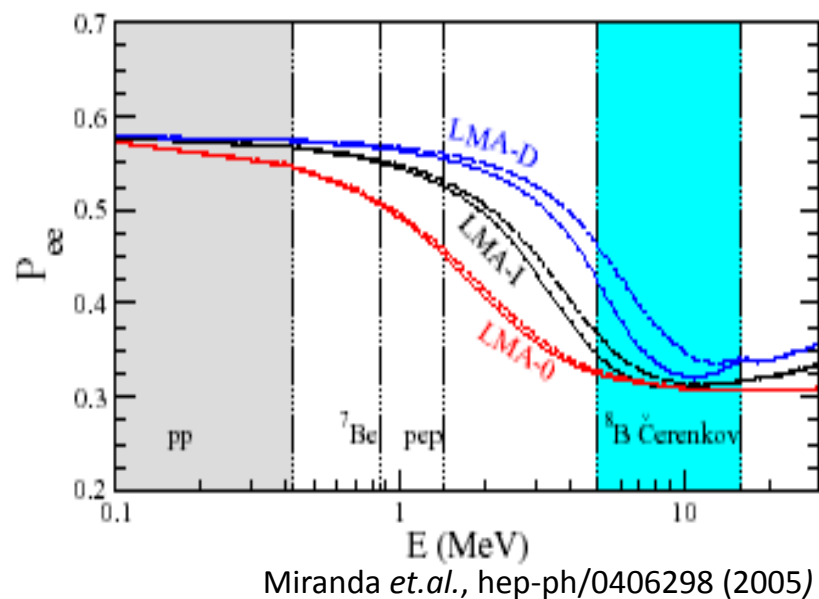
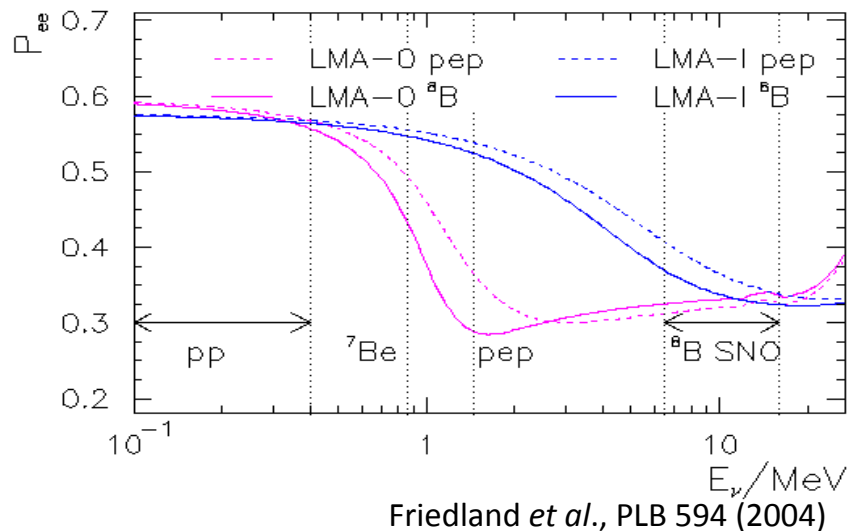
MSW Oscillation Regimes



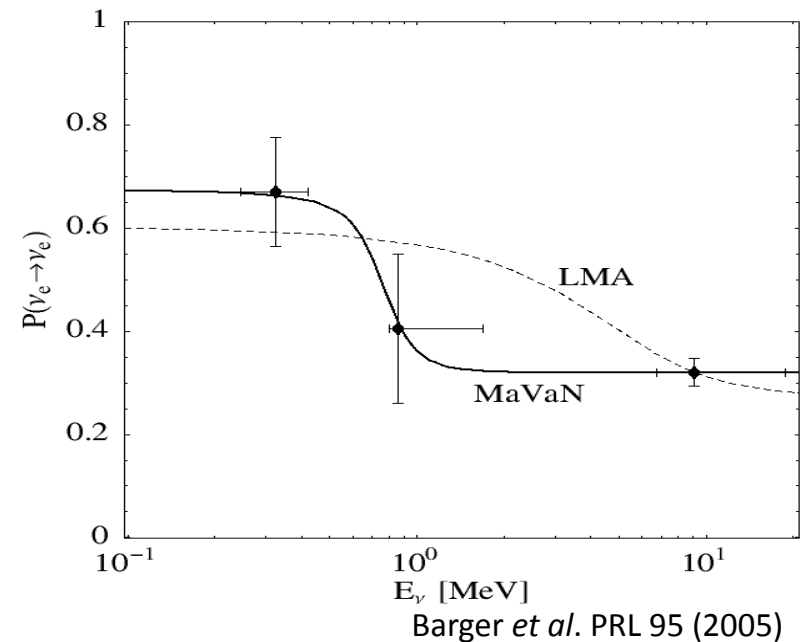
Look in “transition region” to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

Non-Standard Interactions



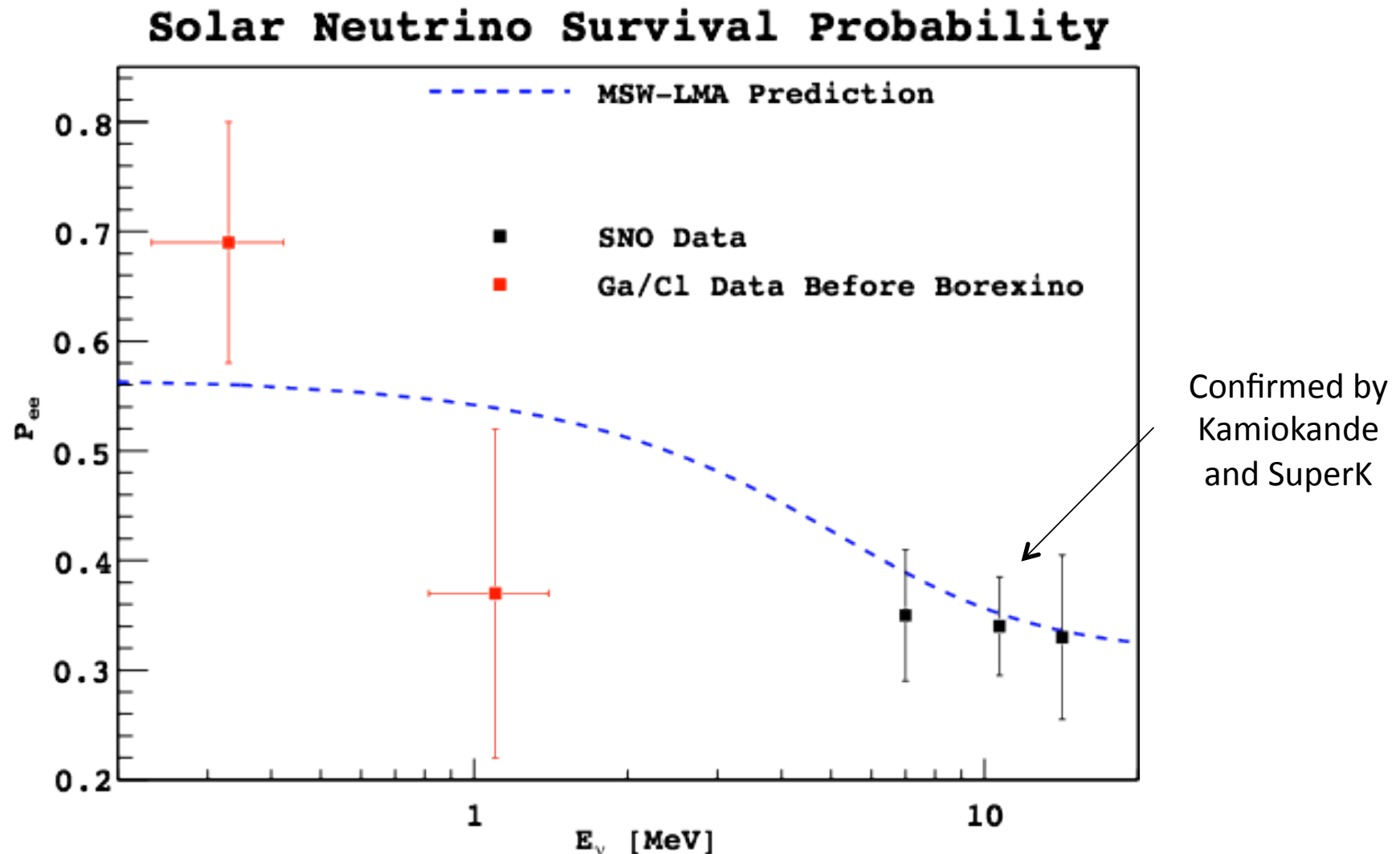
Mass Varying Neutrinos



Other Possibilities:

- CPT violations
- Sterile neutrino admixture

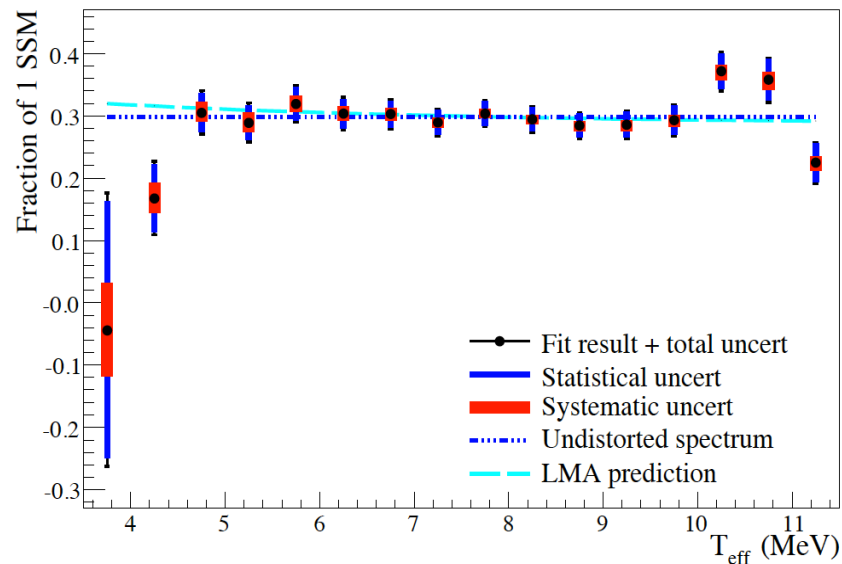
(Old) Experimental Constraints on Transition Region



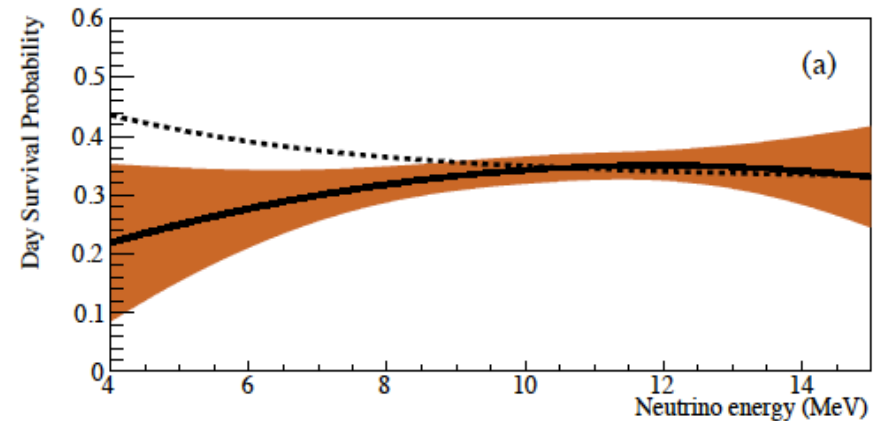
Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. *Real-time measurements needed in the transition region.*

SNO Low Energy Threshold Analysis

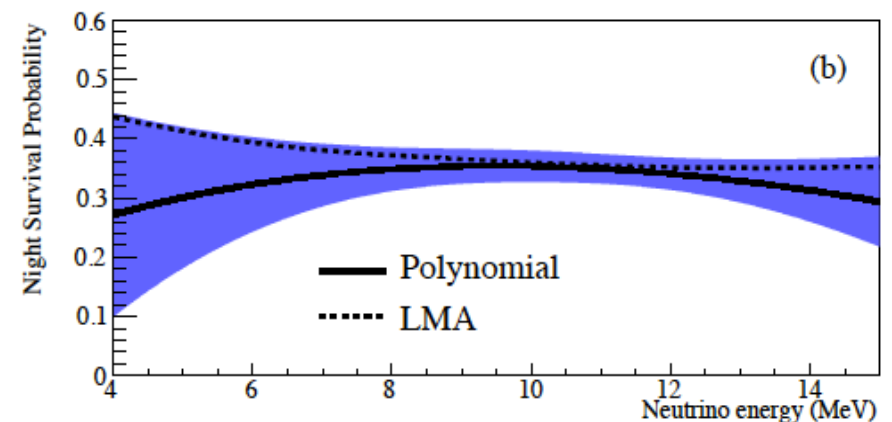
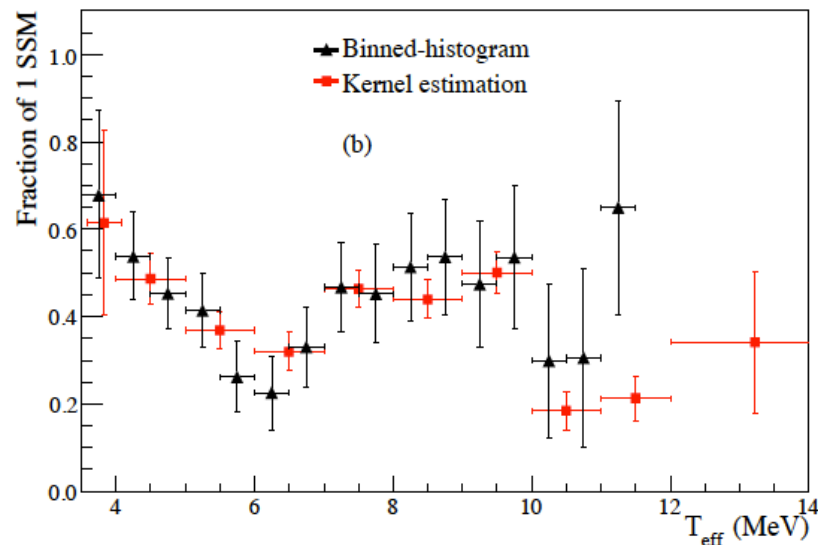
Charged Current: $T_{\text{eff}} = E_\nu - 1.44 \text{ MeV}$



Quadratic Fits to P_{ee}

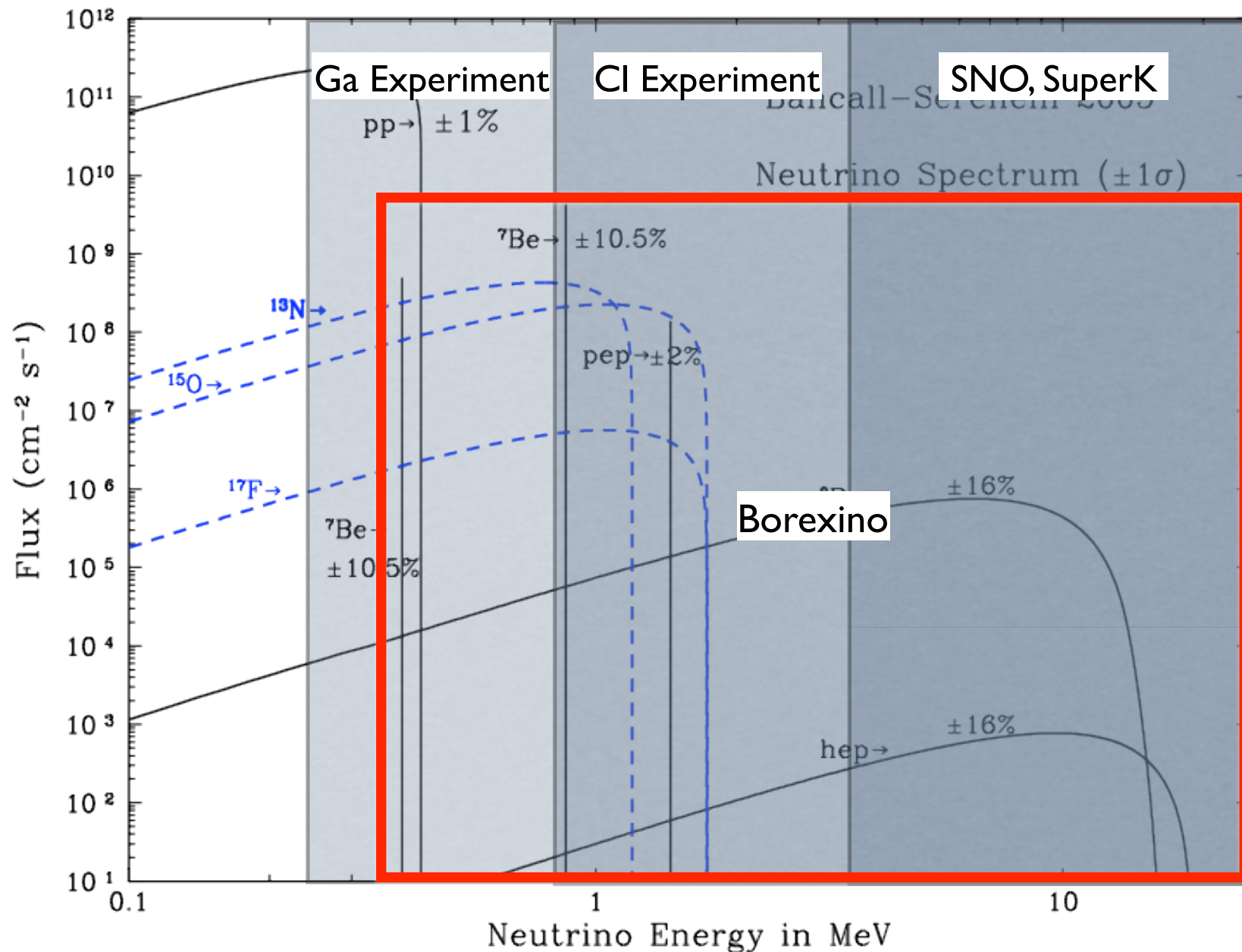


Elastic Scattering: $0 \leq T_{\text{eff}} \lesssim E_\nu - 0.24 \text{ MeV}$

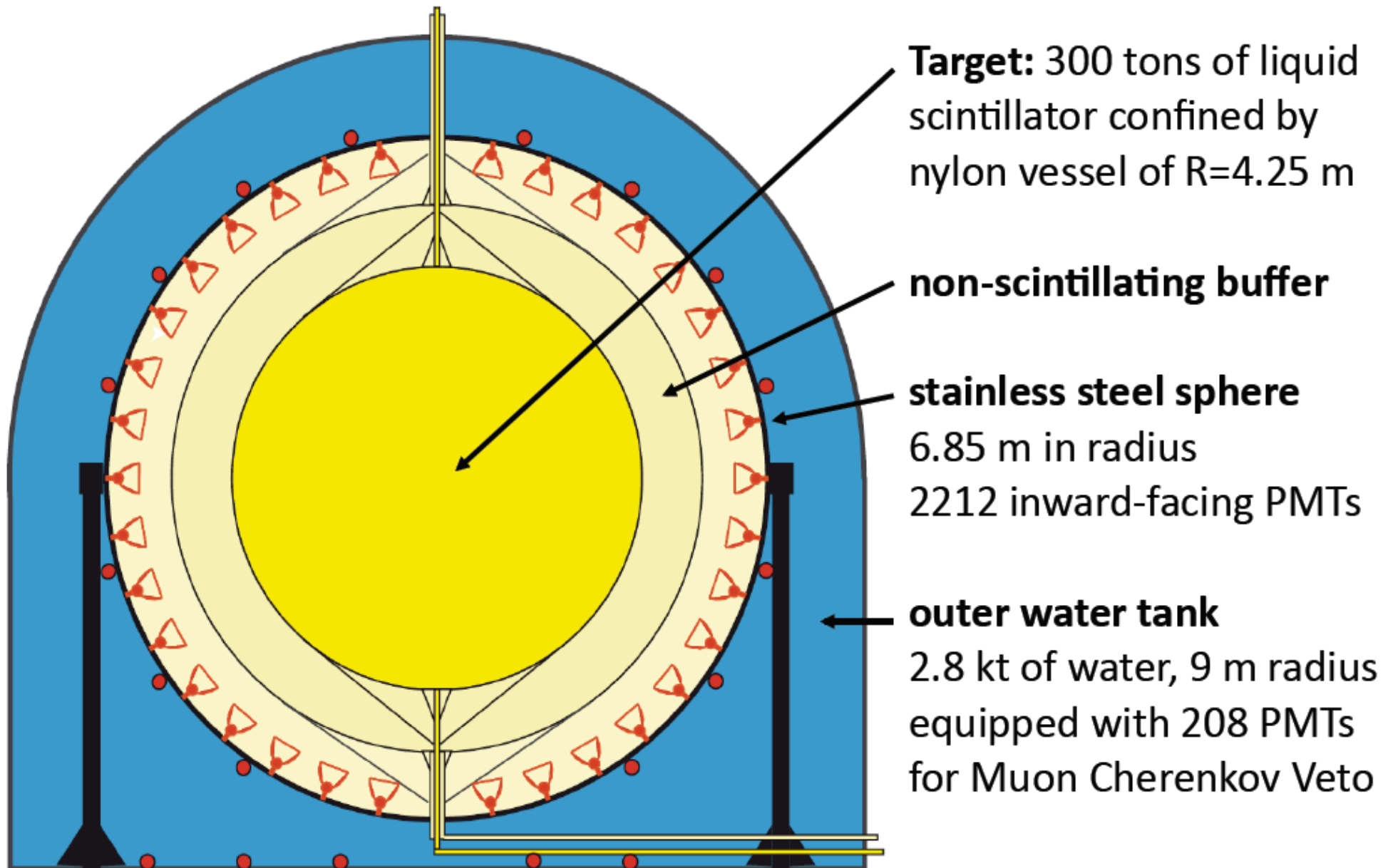


(Phys. Rev. C 81 (2010) 055504)

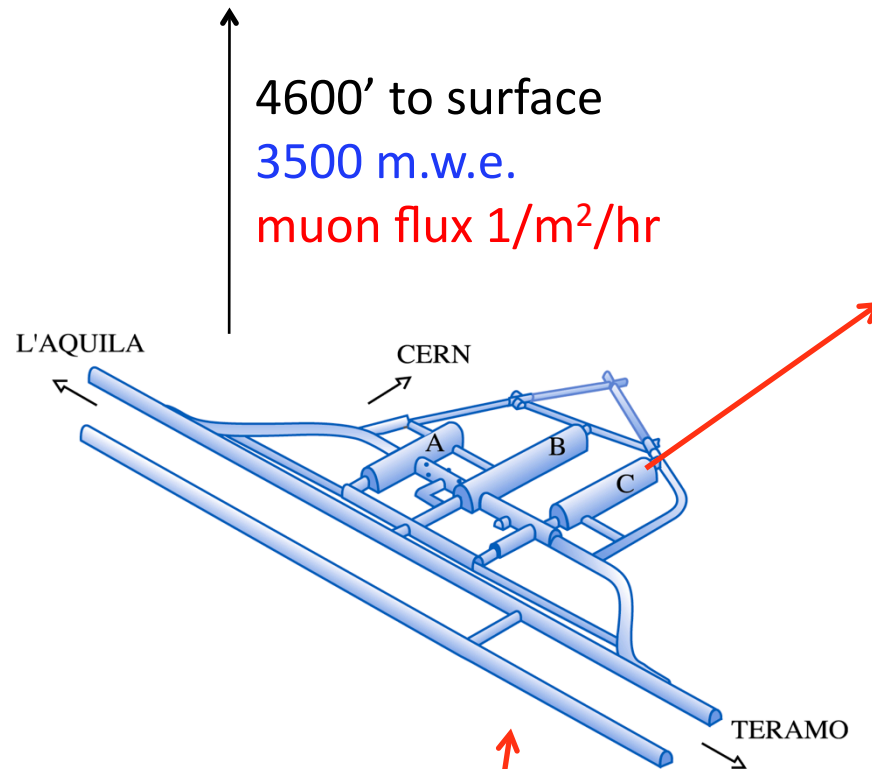
Borexino: Real-time Detection Below 100 keV



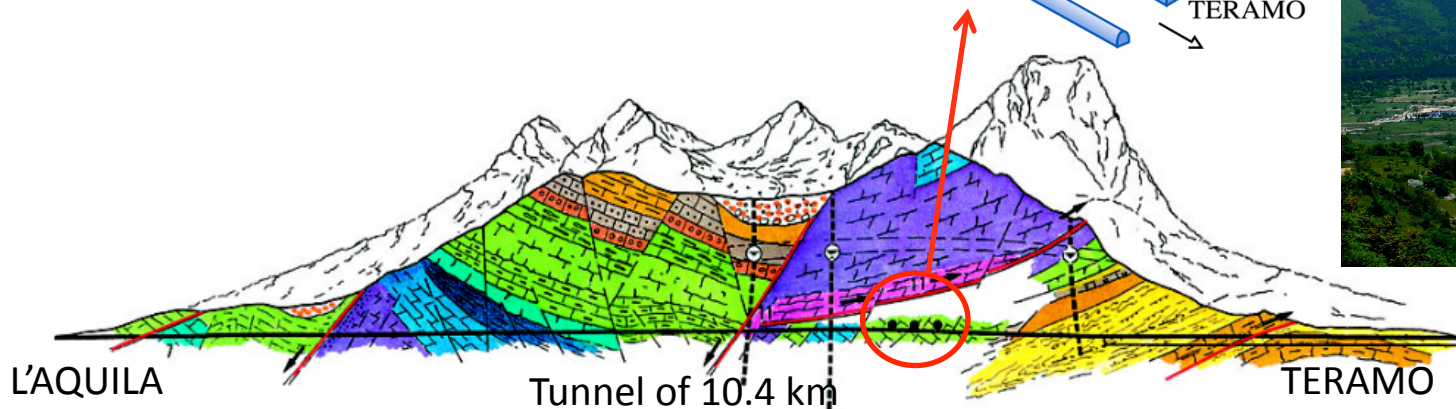
The Borexino Detector



Laboratori Nazionali del Gran Sasso



4600' to surface
3500 m.w.e.
muon flux $1/\text{m}^2/\text{hr}$

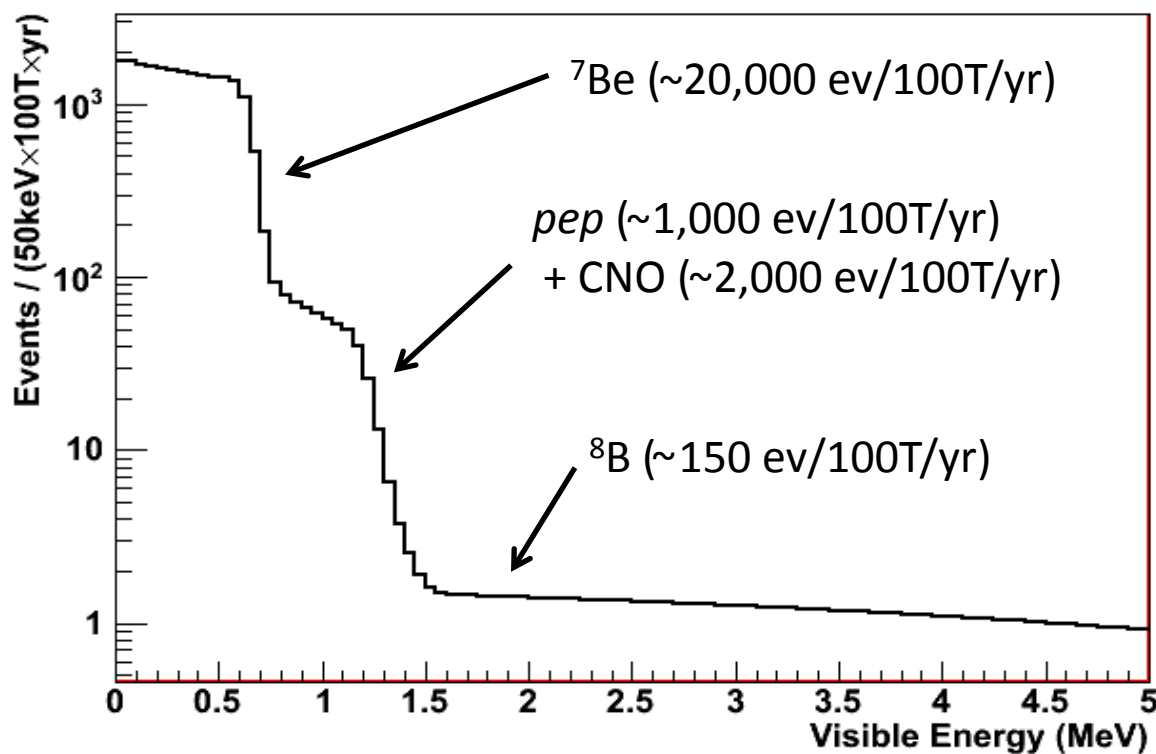


Neutrino Detection With Liquid Scintillator

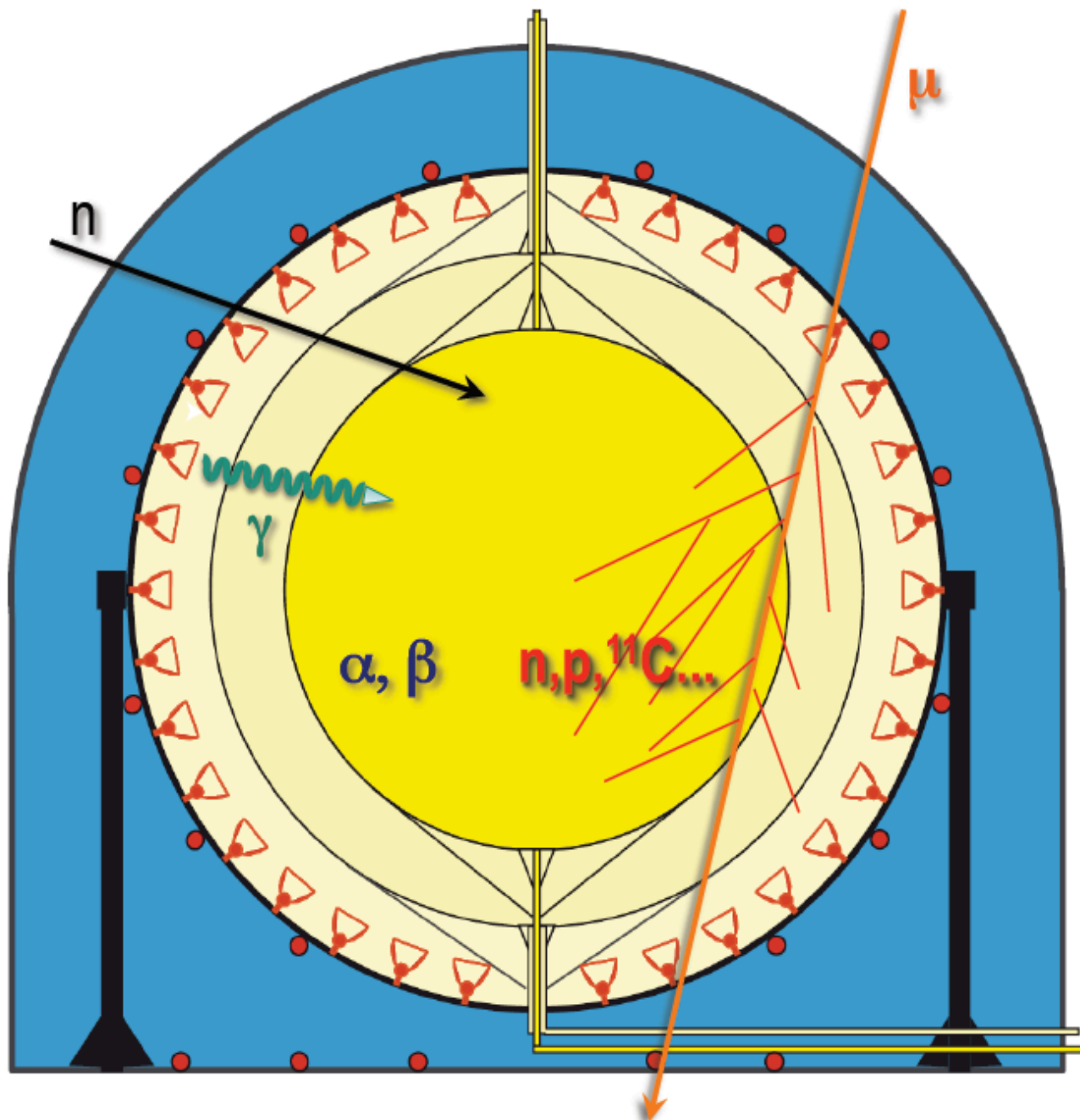
- Neutrino detection via neutrino-electron elastic scattering
- Detect scintillation light from recoiling electron
 - Good position reconstruction (10-15cm) from time-of-flight
 - Low energy threshold ($\sim 60\text{keV}$)
 - Good energy resolution ($\sim 500\text{p.e./MeV}$)
- Calorimetric measurements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

Neutrino Detection With Liquid Scintillator

- Neutrino detection with liquid scintillator
- Neutrino elastic scattering
- Detection of neutrinos
 - Good energy resolution
 - Low background
 - Good timing
- Calorimetric detection
 - Can't distinguish neutrino events from p/γ backgrounds



Central Challenge: Background Reduction



Internal Radioactivity

traces of radioisotopes in the scintillator (U/Th, ${}^{40}\text{K}$)

External Gamma-Rays

from buffer, steel sphere, PMT glass (${}^{40}\text{K}$, ${}^{208}\text{Tl}$...)

Cosmic Muons

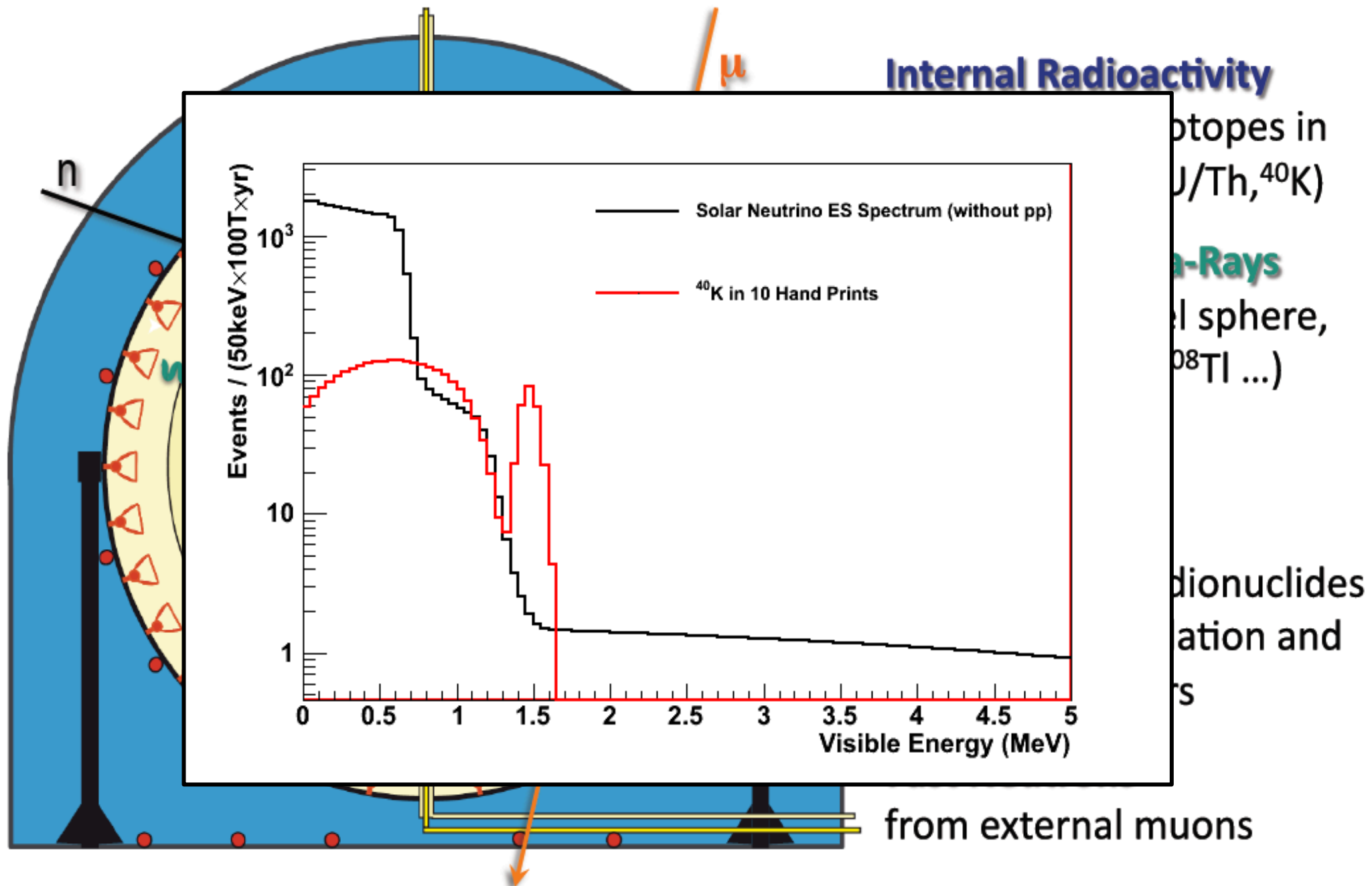
Cosmogenics

neutrons and radionuclides from muon-spallation and hadronic showers

Fast Neutrons

from external muons

Central Challenge: Background Reduction



***Borexino achieved
unprecedented low levels of
internal background.***

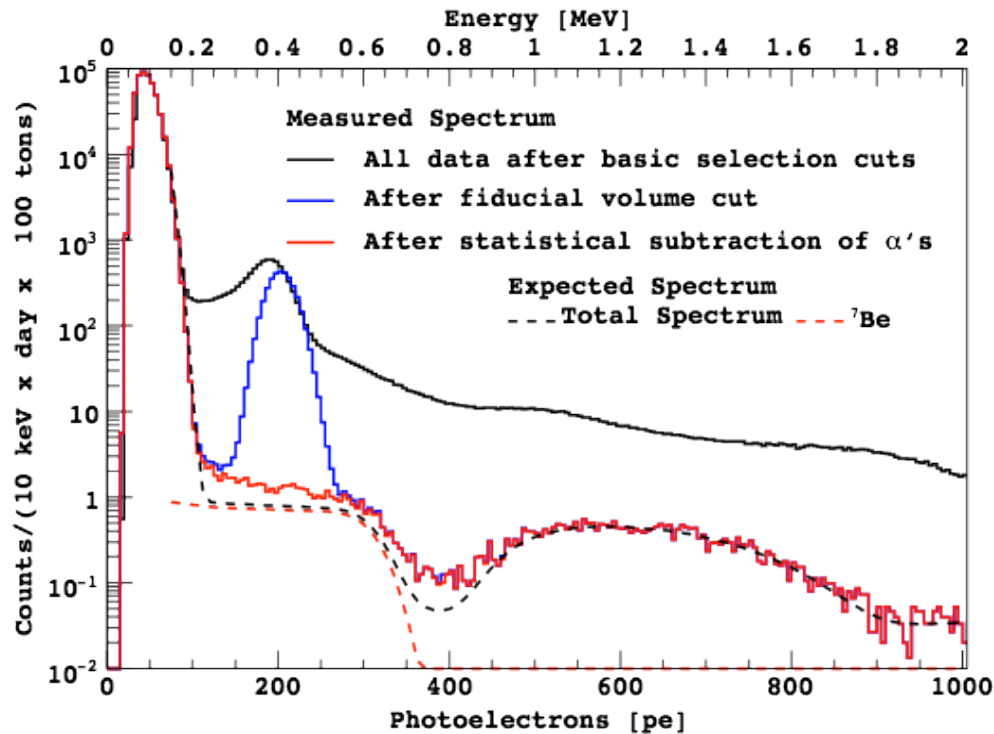


The Counting Test Facility III

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	$<10^{-17} \text{ g/g}$	Purification
^{232}Th	Dust	10^{-6} g/g	$<10^{-18} \text{ g/g}$	Purification
^{85}Kr	Air	1 Bq/m^3	$\sim 2 \times 10^{-3} \text{ Bq/m}^3$	LAKN
^{222}Rn	Air	$20\text{-}100 \text{ Bq/m}^3$	$<10^{-6} \text{ Bq/m}^3$	Air exclusion
K_{nat}	Dust	$\sim 10^{-3} \text{ g/g}$	$<3 \times 10^{-14} \text{ g/g}$	Purification
μ	Cosmic	$200 \text{ s}^{-1}\text{m}^{-2}$	$10^{-10} \text{ s}^{-1}\text{m}^{-2}$	Underground, active veto

Borexino 192-day ^7Be Result

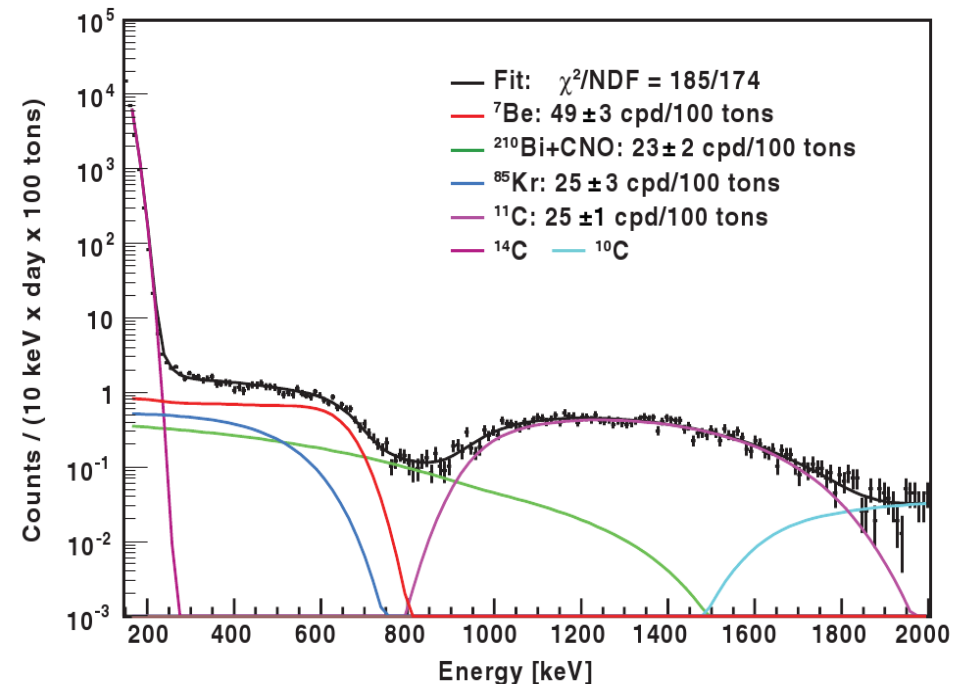
(PRL 101 9 (2008))



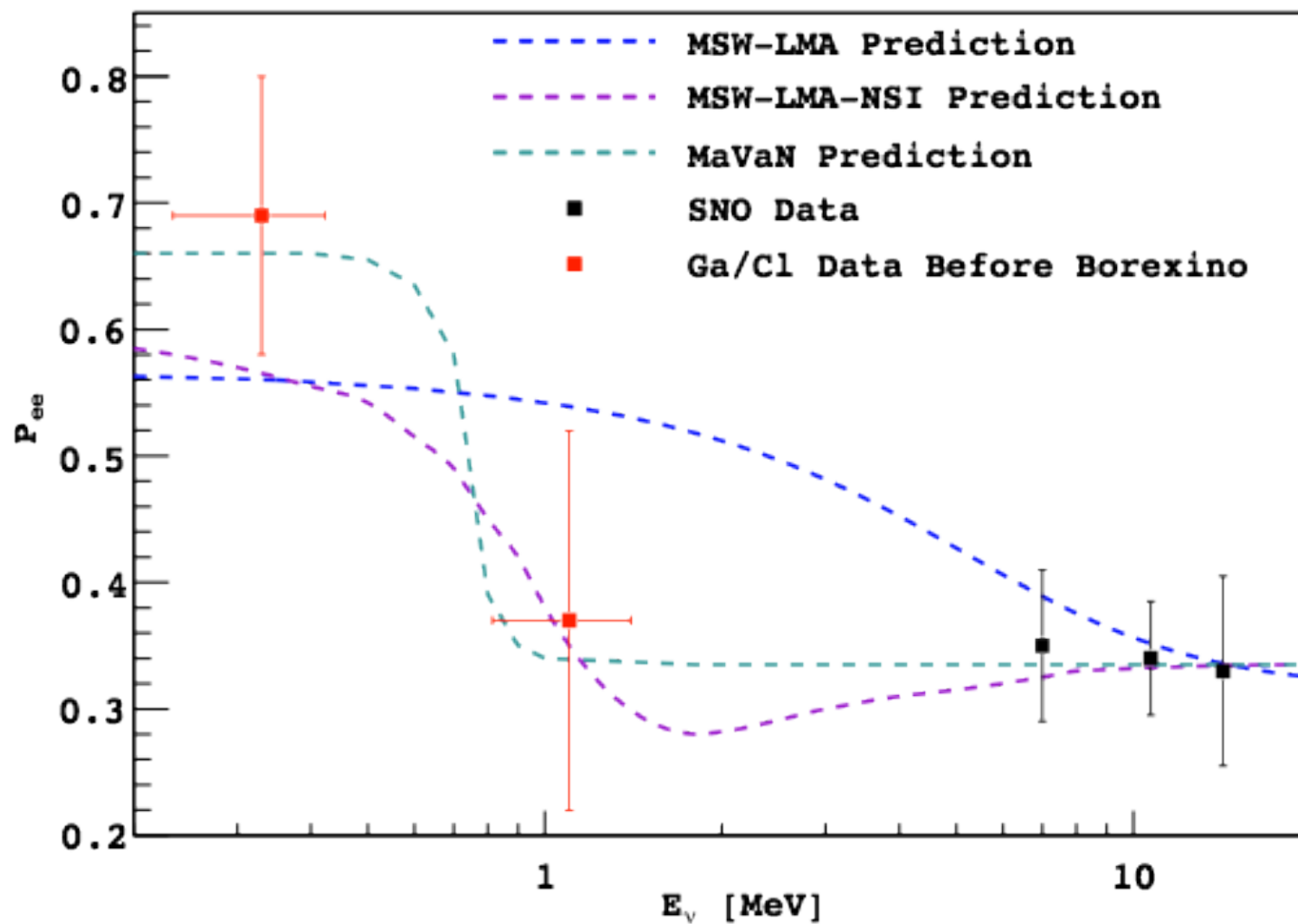
0.862 MeV ^7Be Result:
 $49 \pm 3_{\text{stat}} \pm 4_{\text{sys}}$ cpd/100T

Systematics

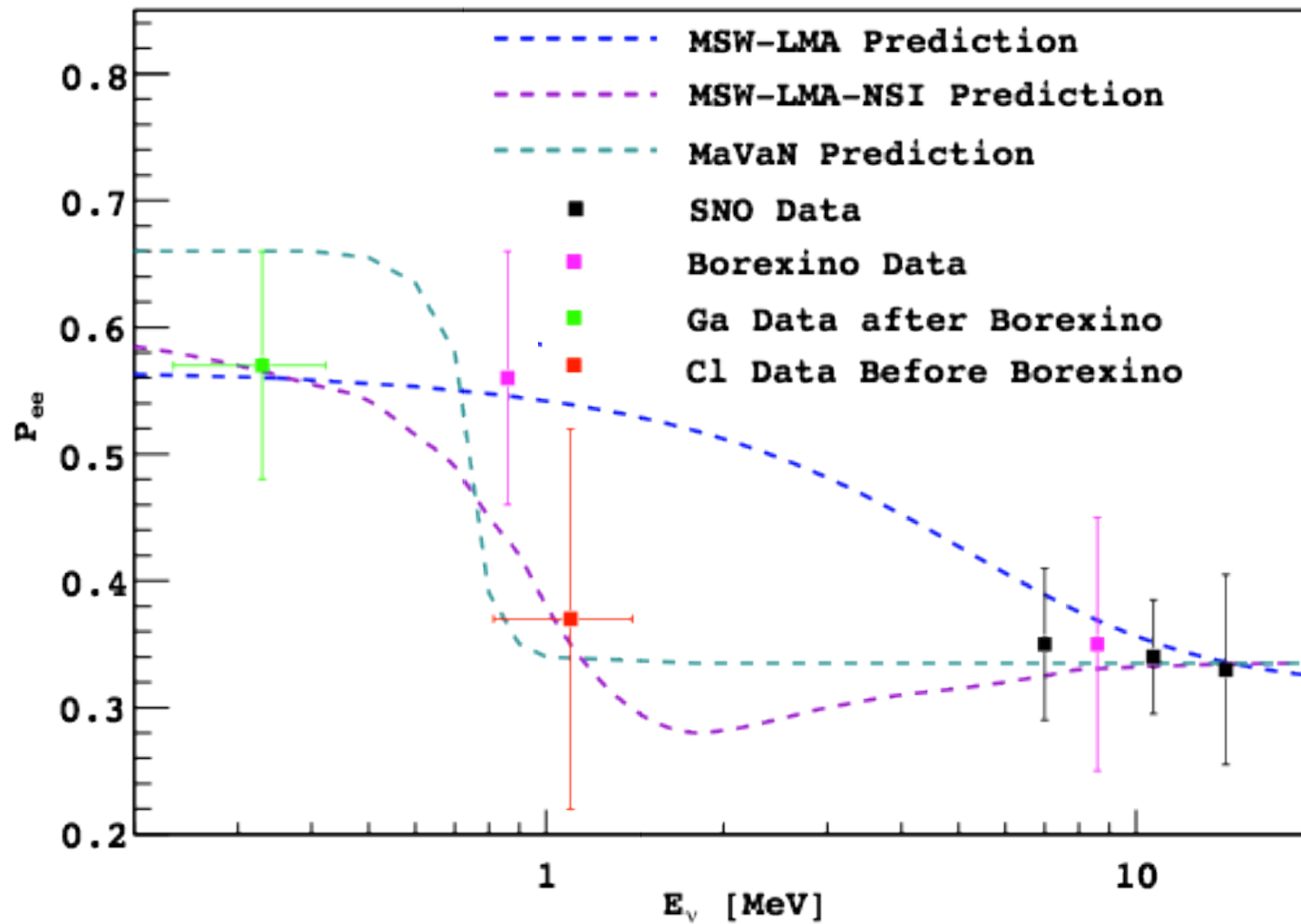
Scintillator Density	0.2%
Livetime	0.1%
Cut Sacrifice	0.3%
Fiducial Mass	6.0%
Detector Response	6.0%
Total	8.5%



Solar Neutrino Survival Probability

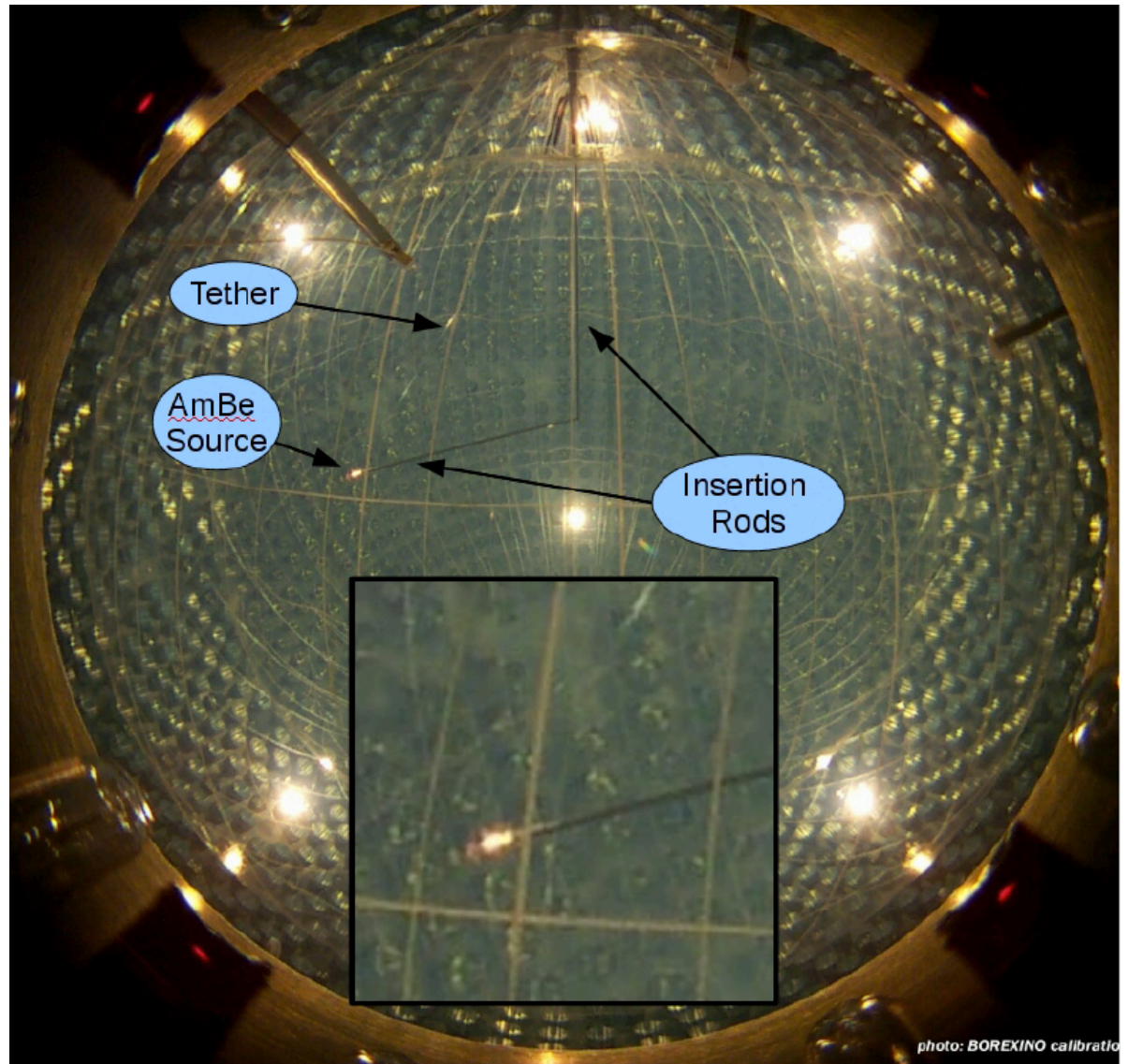


Solar Neutrino Survival Probability



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



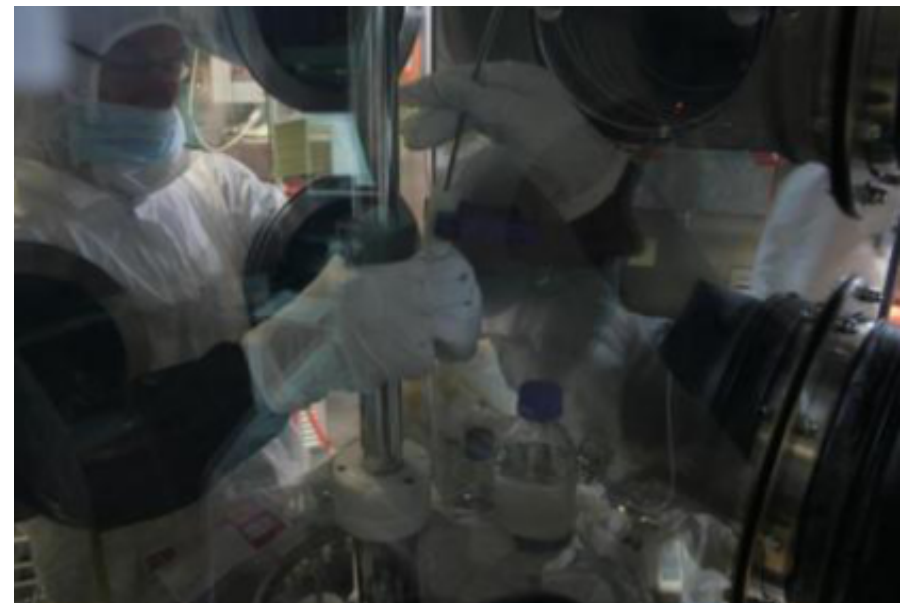
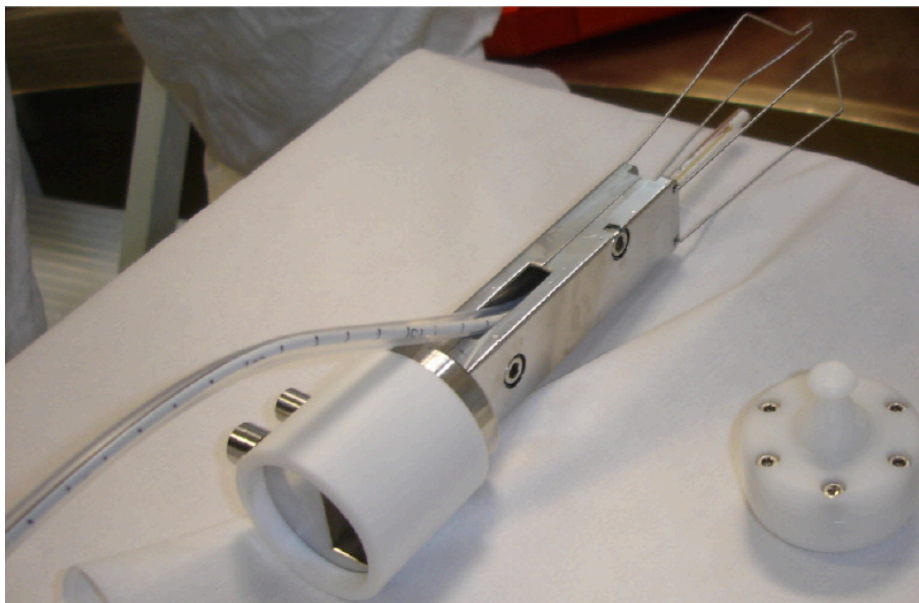
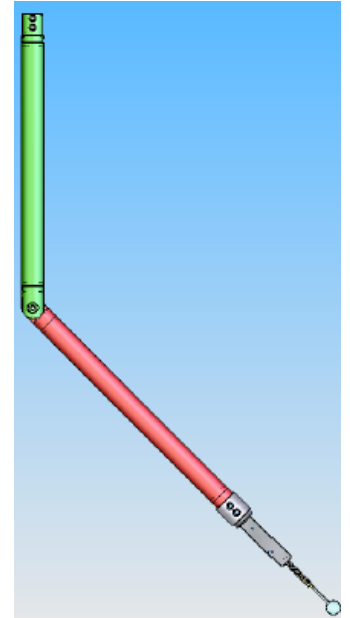
Source Deployment System

- 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



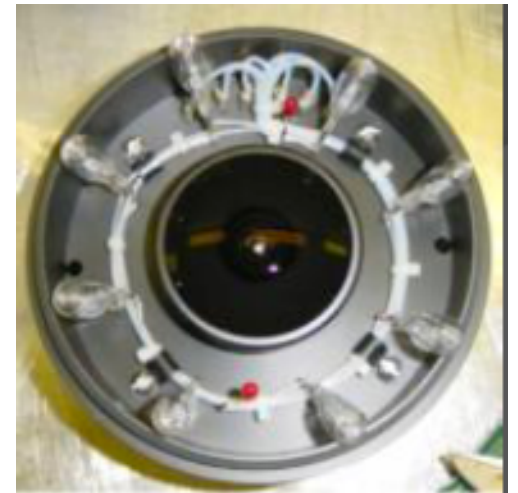
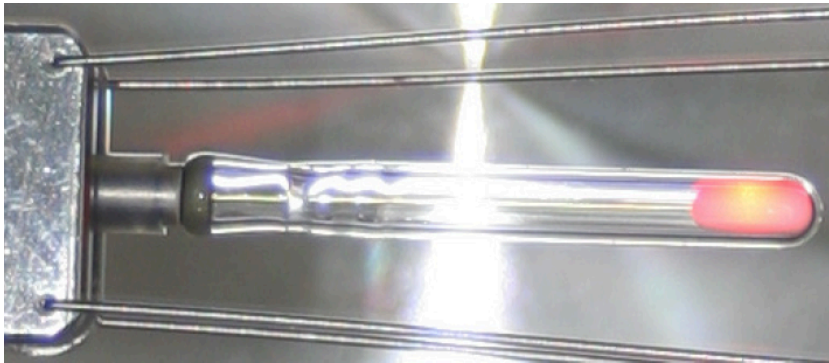
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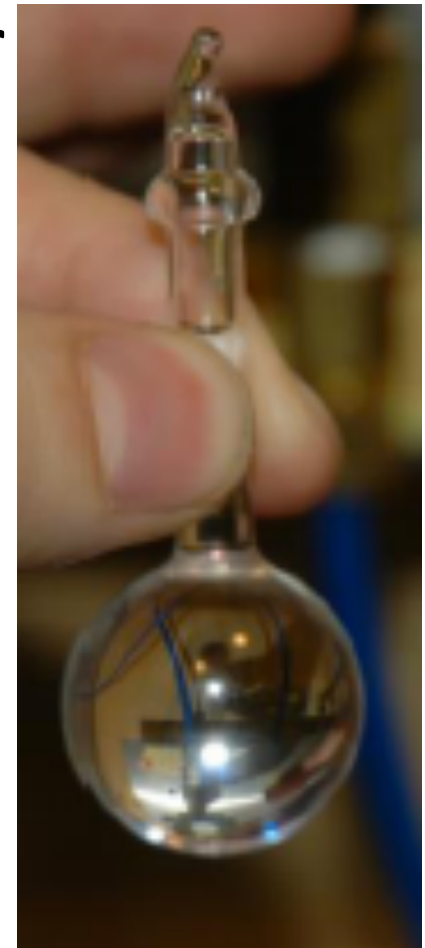
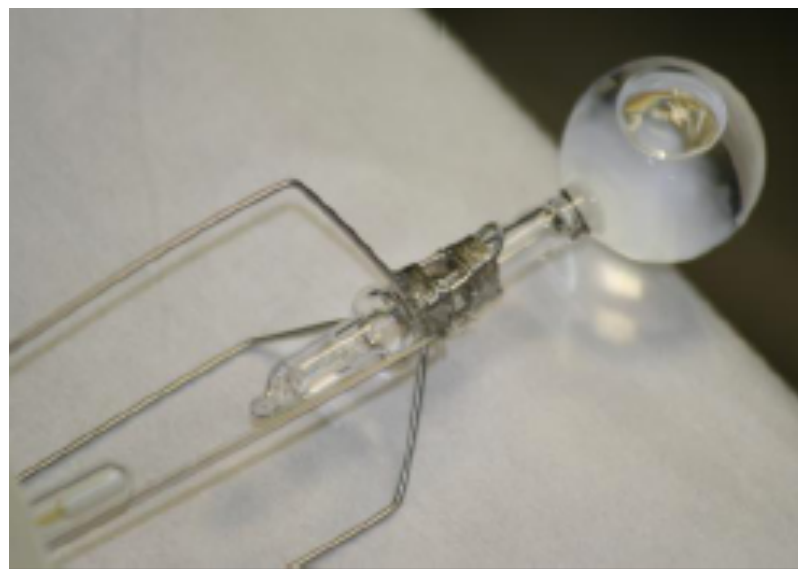
Determining Source Location

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



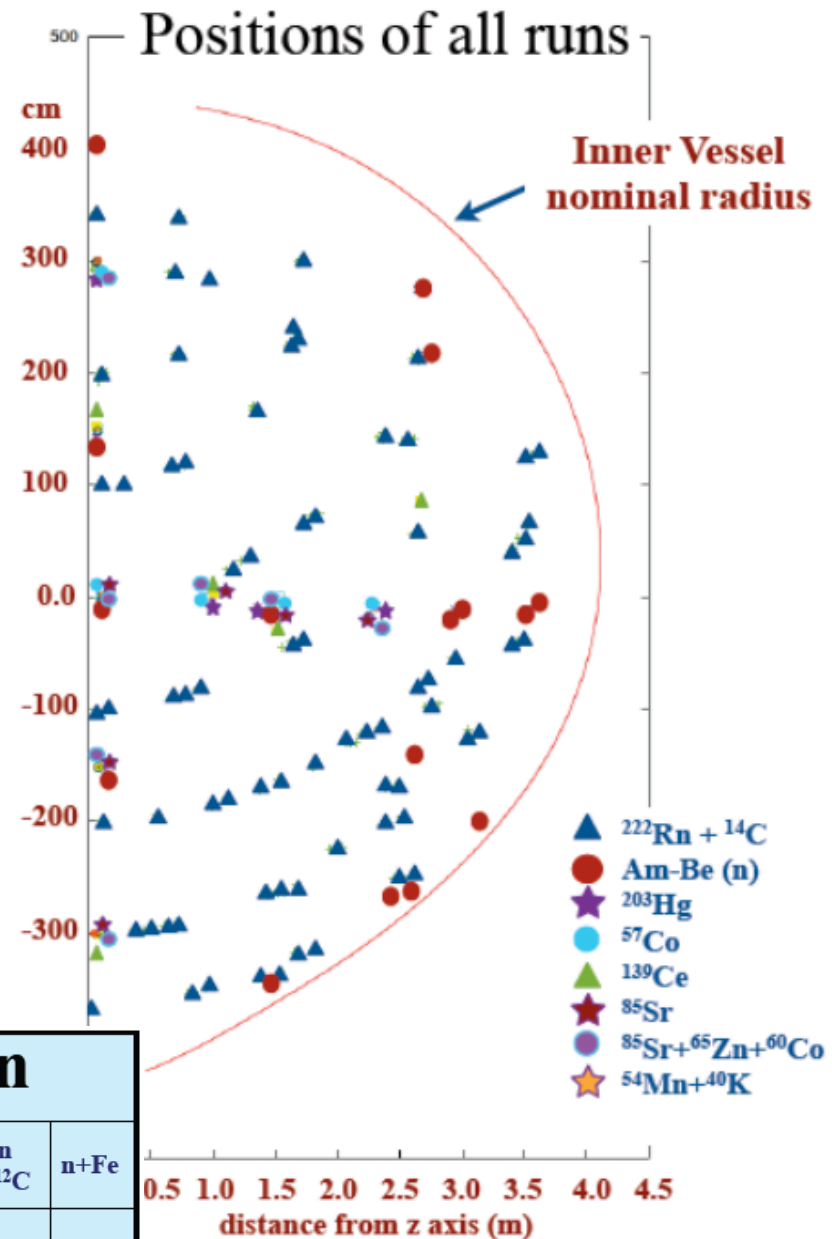
Sources

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

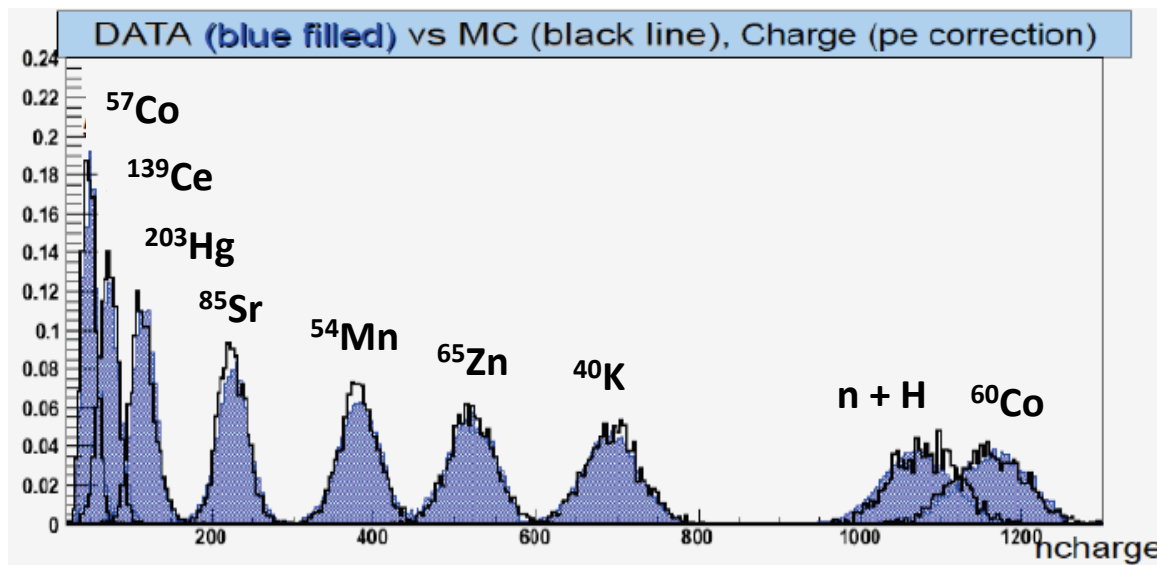


Borexino Calibration Campaigns

- 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	$\frac{n}{+^{12}\text{C}}$	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.*

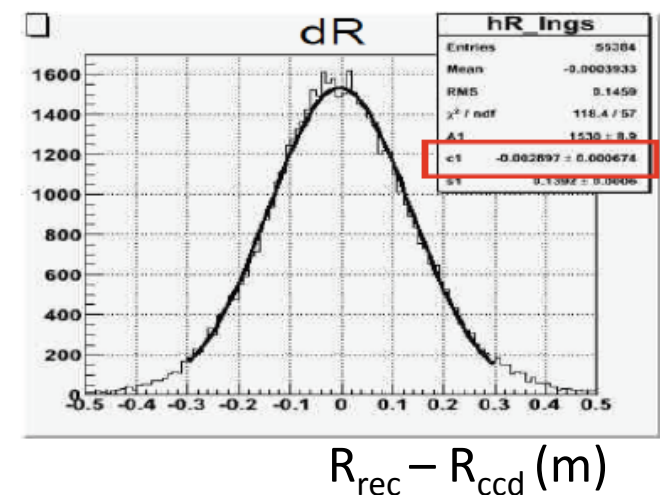
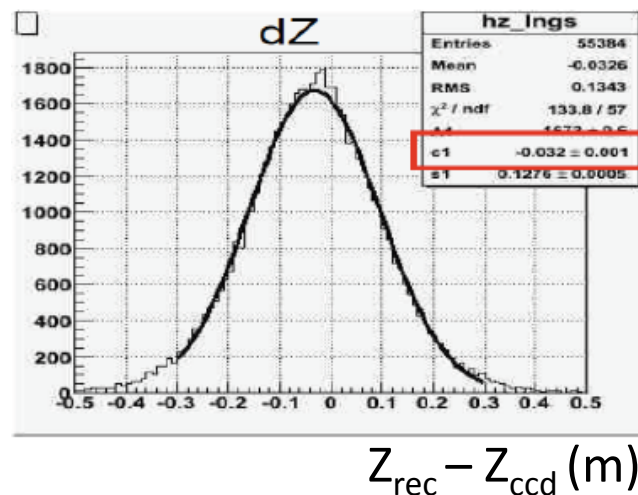
Position Resolution:

10 – 12 cm

Fiducial Volume:

$1.0^{+0.013}_{-0.005}$

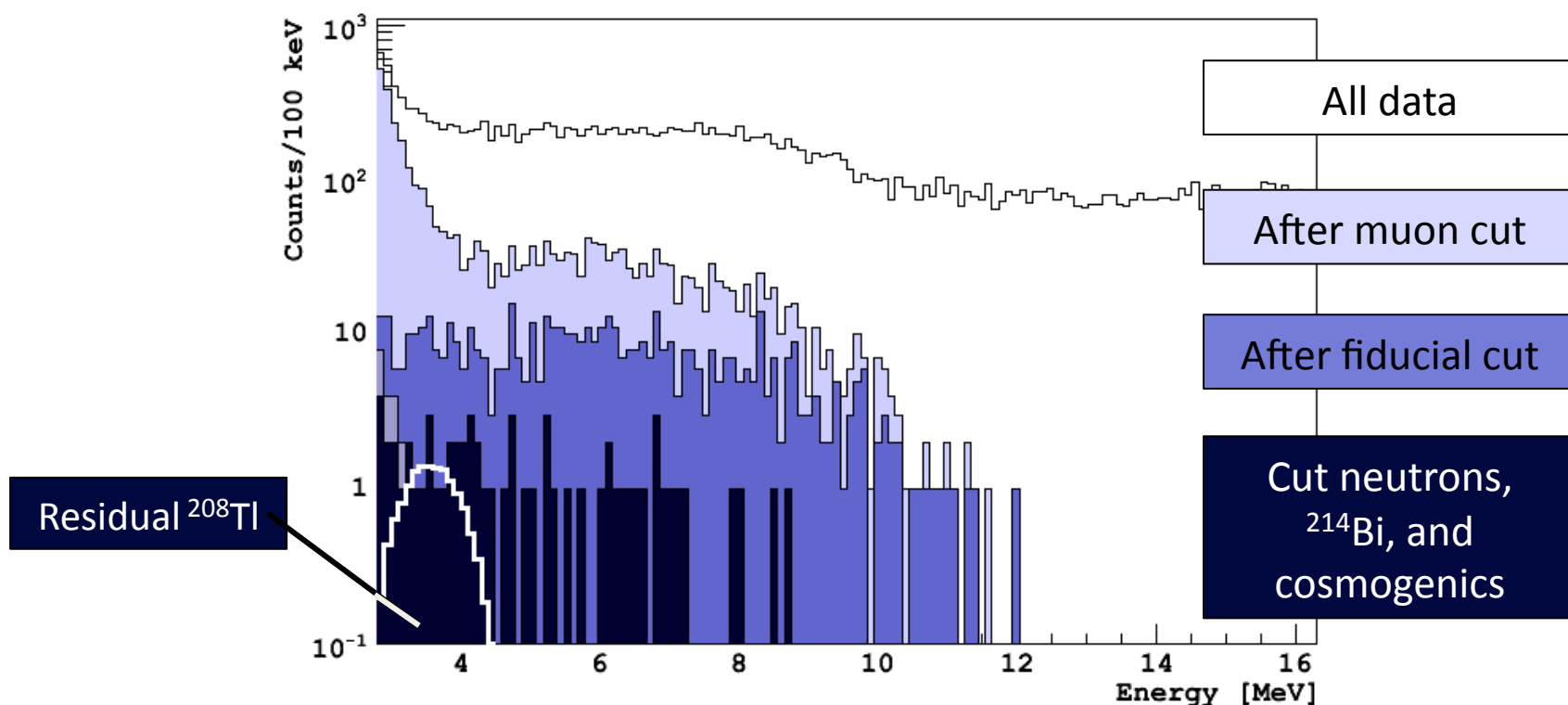
➔ *Reduced fiducial volume
uncertainty by roughly a
factor of five.*



Calibration paper in preparation!

Borexino Low Energy ^8B Analysis

(PRD 82 (2010) 033006)



Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
<i>Muon and neutron cuts</i>	6552	2679
<i>FV cut</i>	1329	970
<i>Cosmogenic cut</i>	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
<i>Muons</i>	4.5 ± 0.9	3.5 ± 0.8
<i>Neutrons</i>	0.86 ± 0.01	0
<i>External background</i>	64 ± 2	0.03 ± 0.11
<i>Fast cosmogenic</i>	17 ± 2	13 ± 2
^{10}C	22 ± 2	0
^{214}Bi	1.1 ± 0.4	0

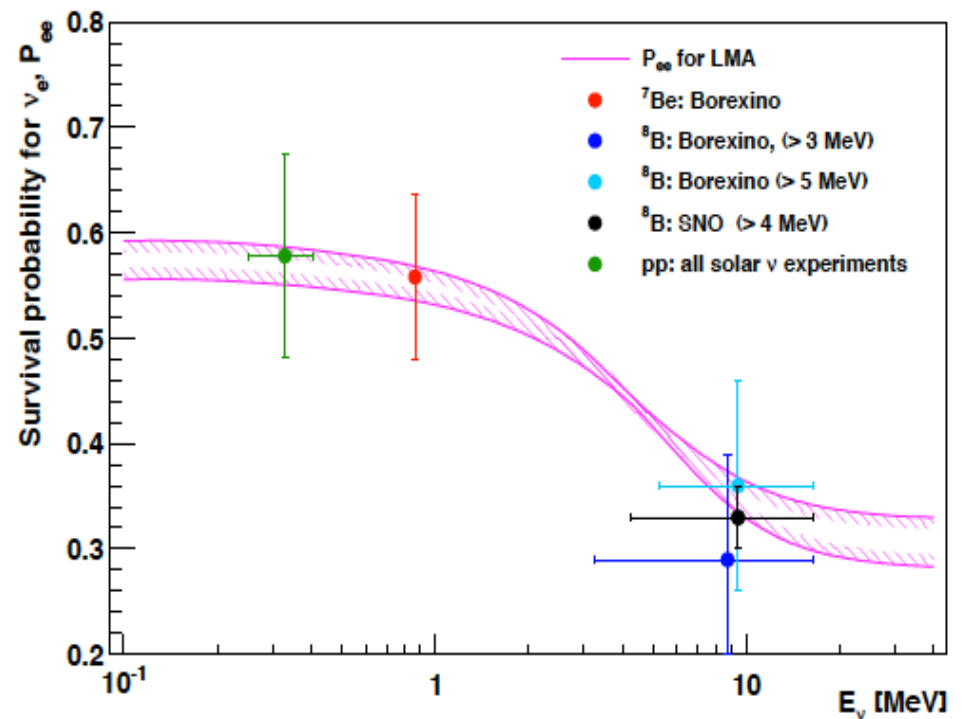
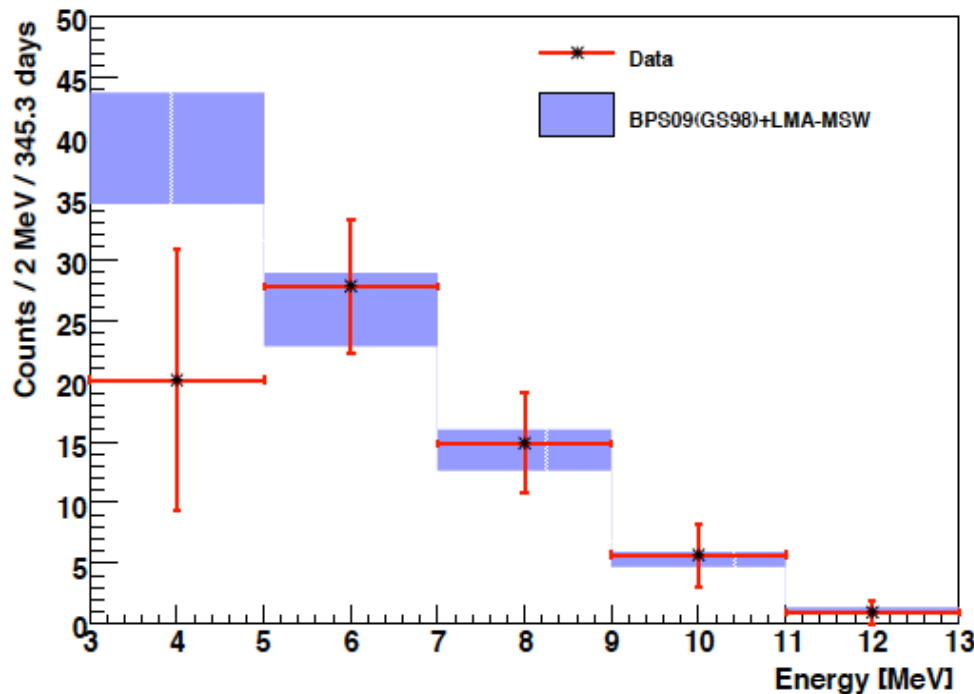
Sum Residuals

^8B Counting Rate (245 live days):

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

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

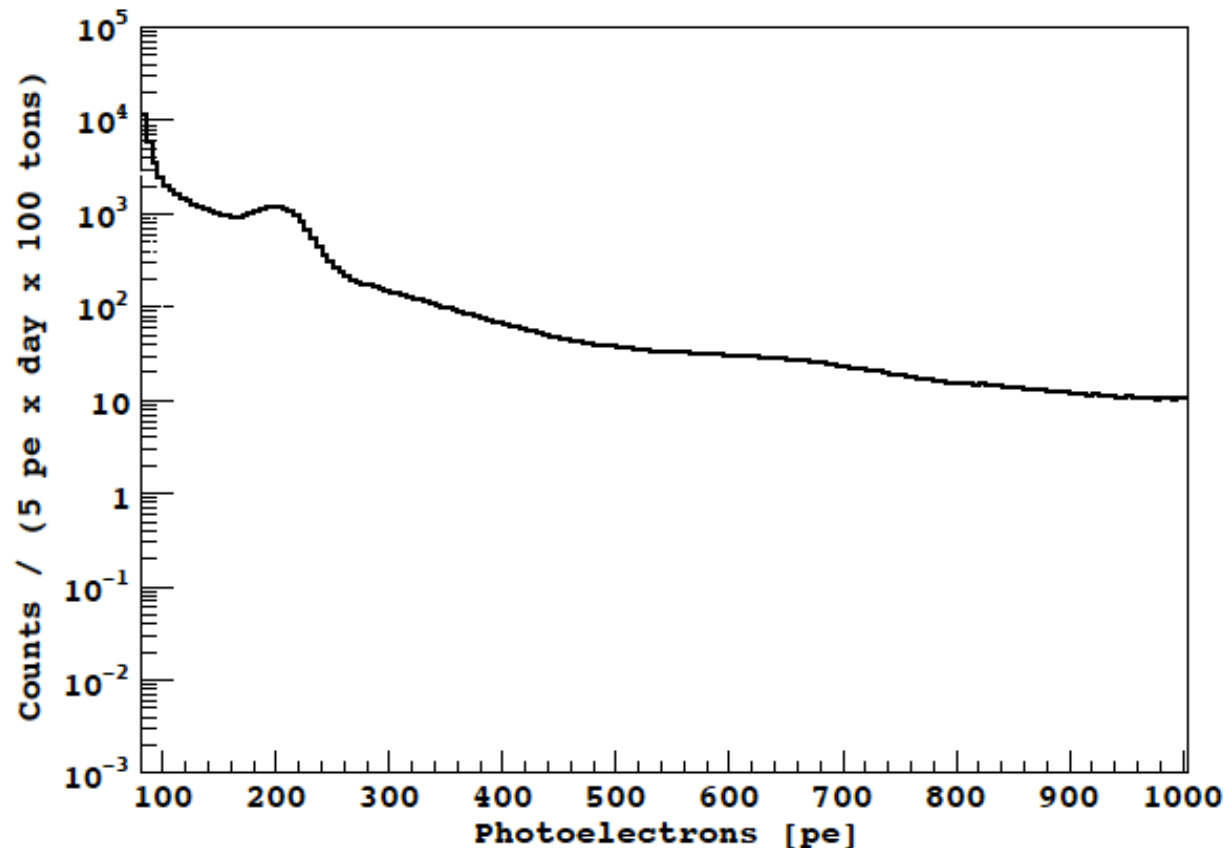
Borexino ES Spectrum



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

Borexino 741-day ^7Be Result

(arXiv:1104.1816v1 and arXiv:1104.2150v1)

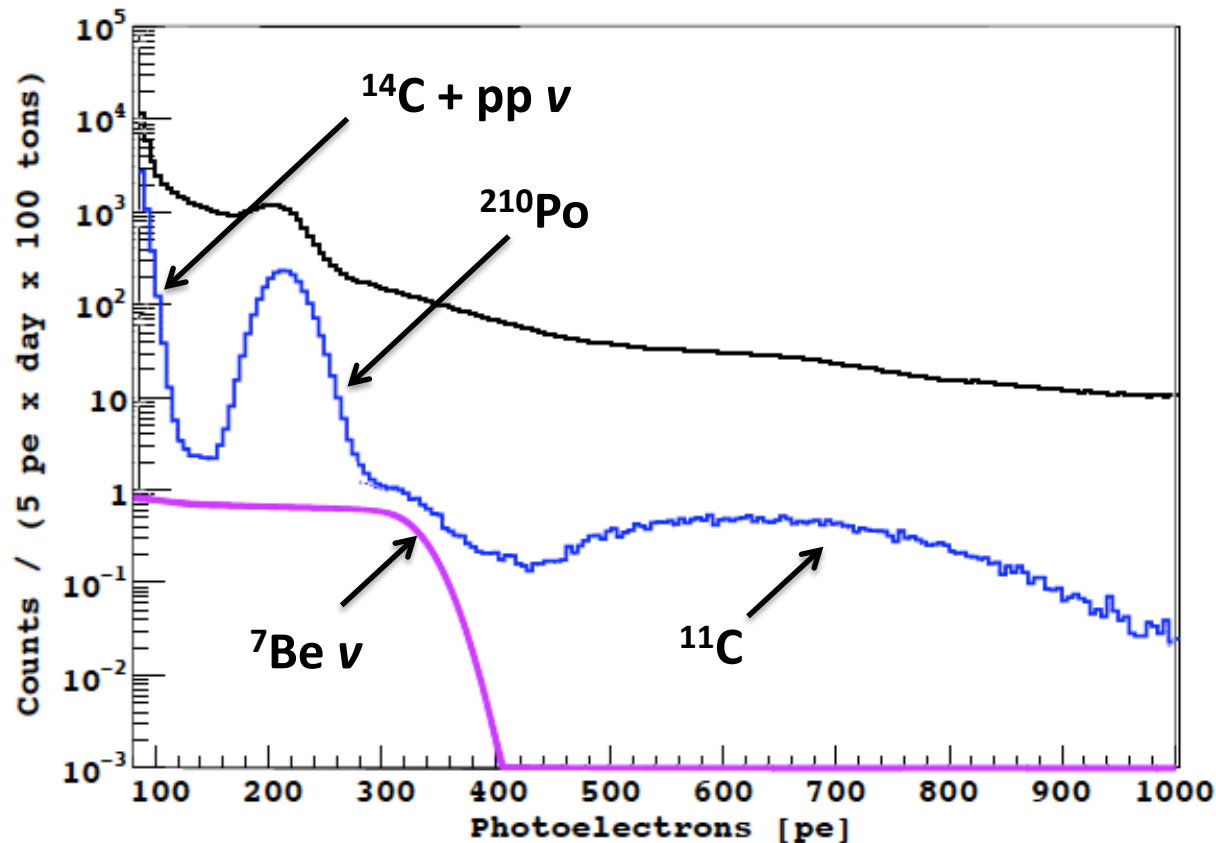


All data after data cleaning cuts (2.3% total deadtime) removing:

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)

Borexino 741-day ^7Be Result

(arXiv:1104.1816v1 and arXiv:1104.2150v1)



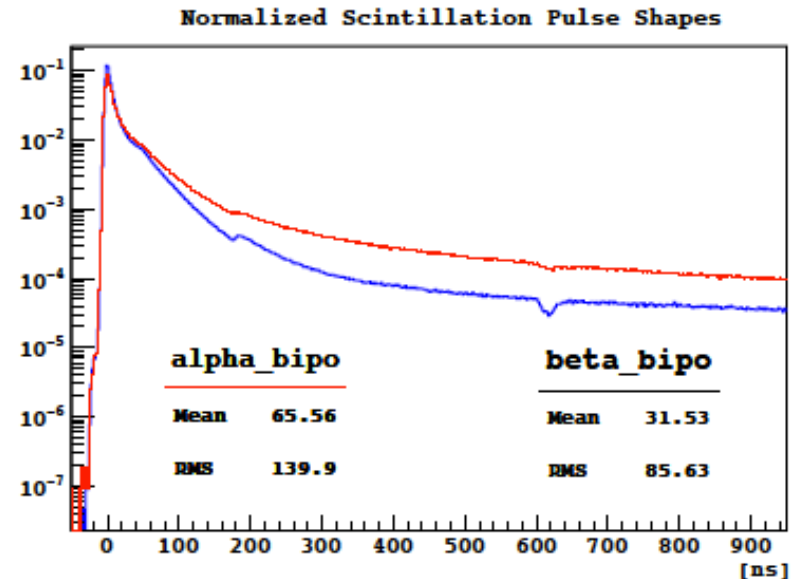
After fiducial volume cut:

1. $R < 3.02\text{m}$
2. $|z| < 1.67\text{m}$

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

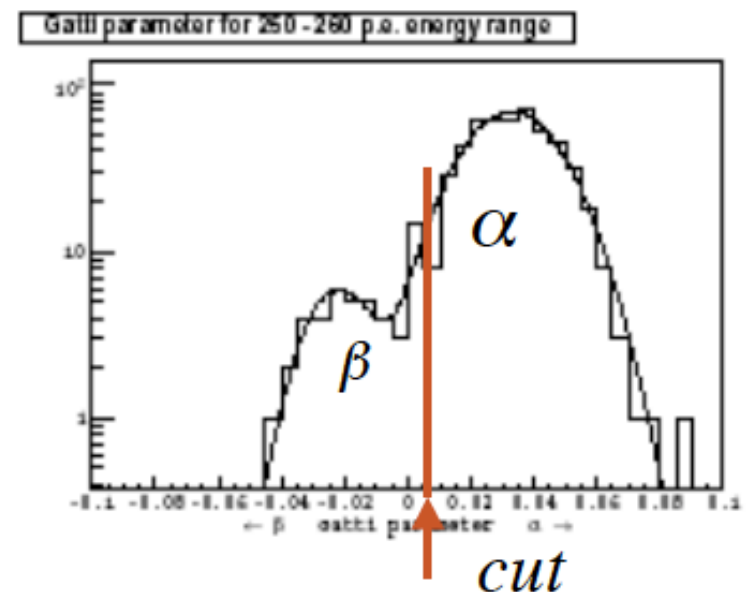
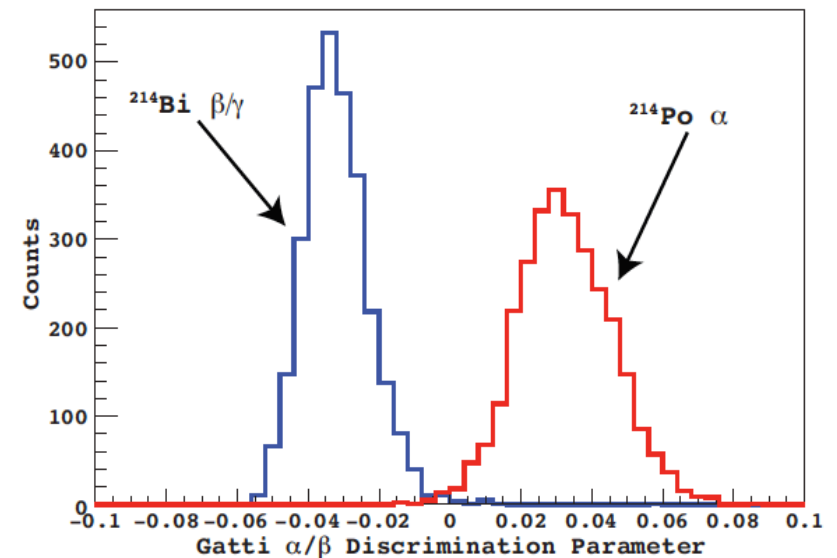


$$G = \sum_i P_i S_i$$

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

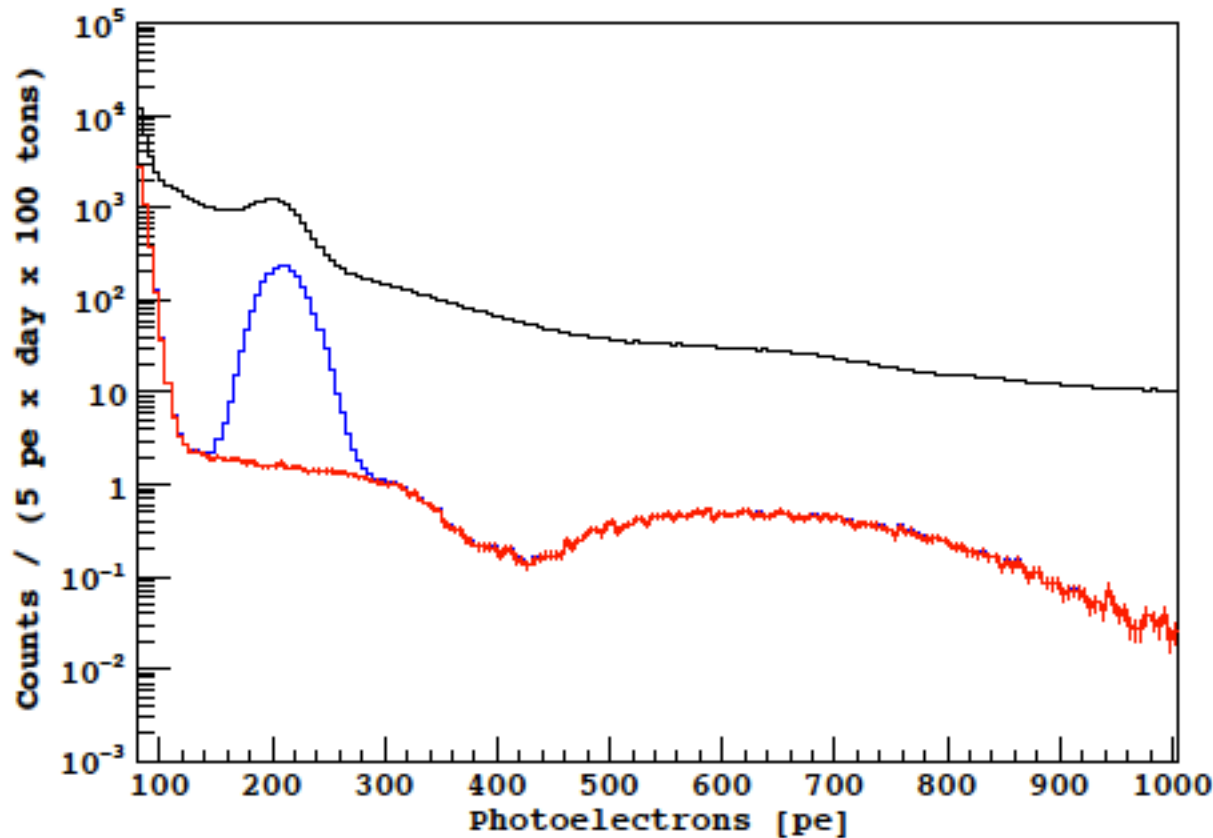
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Borexino 741-day ^7Be Result

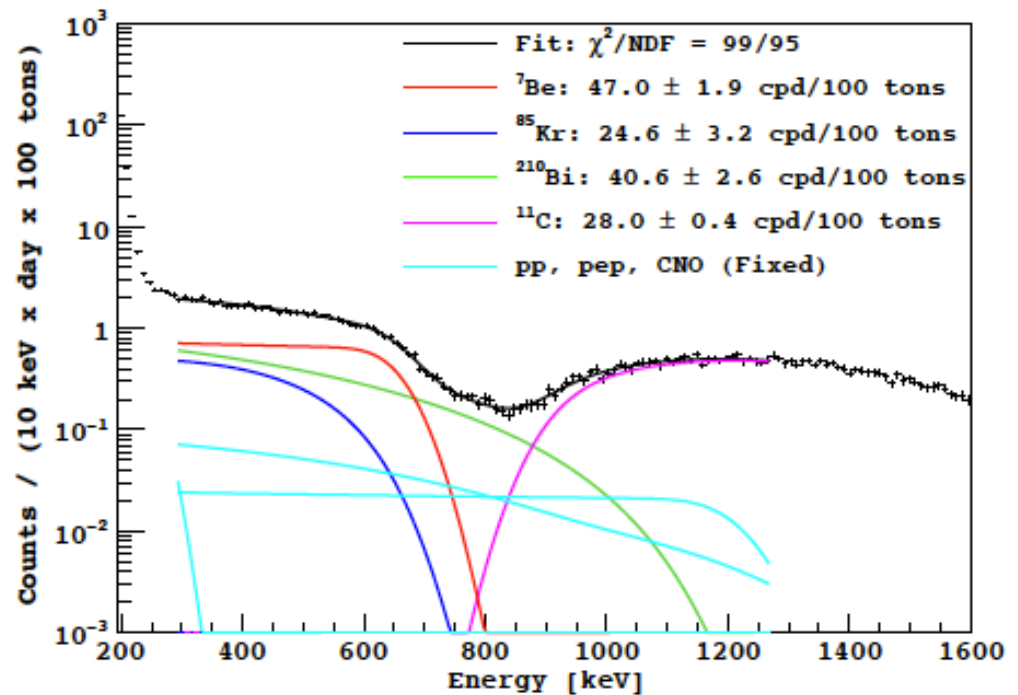
(arXiv:1104.1816v1 and arXiv:1104.2150v1)



After α statistical
subtraction

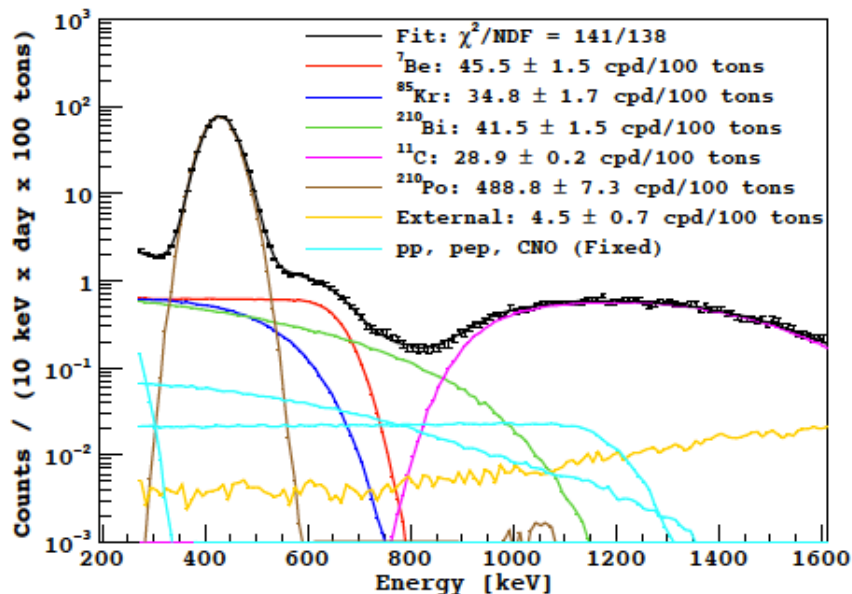
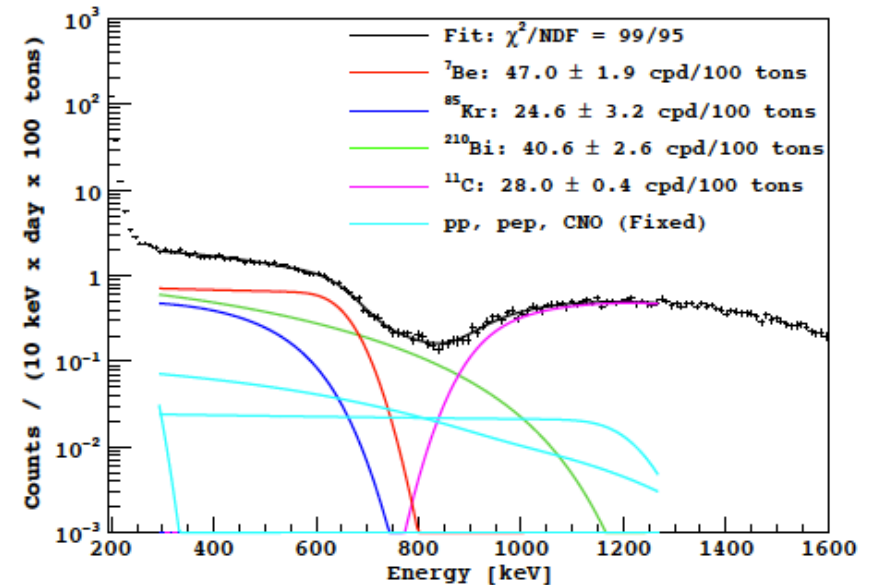
Signal Extraction

- 1-D binned likelihood fits in energy
- ${}^7\text{Be}$, ${}^{210}\text{Po}$, ${}^{85}\text{Kr}$, ${}^{11}\text{C}$, ${}^{210}\text{Bi}$ weights floated
- pp , pep , ${}^8\text{B}$, and CNO fixed to SSM fluxes + LMA
- ${}^{222}\text{Rn}$, ${}^{218}\text{Po}$, and ${}^{214}\text{Pb}$ weights constrained by ${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$ 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 ^7Be counting rate: $46.0 \pm 1.5_{\text{stat}} \pm 1.6_{\text{sys}} / (\text{d } 100\text{T})$

→ $P_{\text{ee}}(862 \text{ keV}) = 0.52 \pm 0.07$

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%

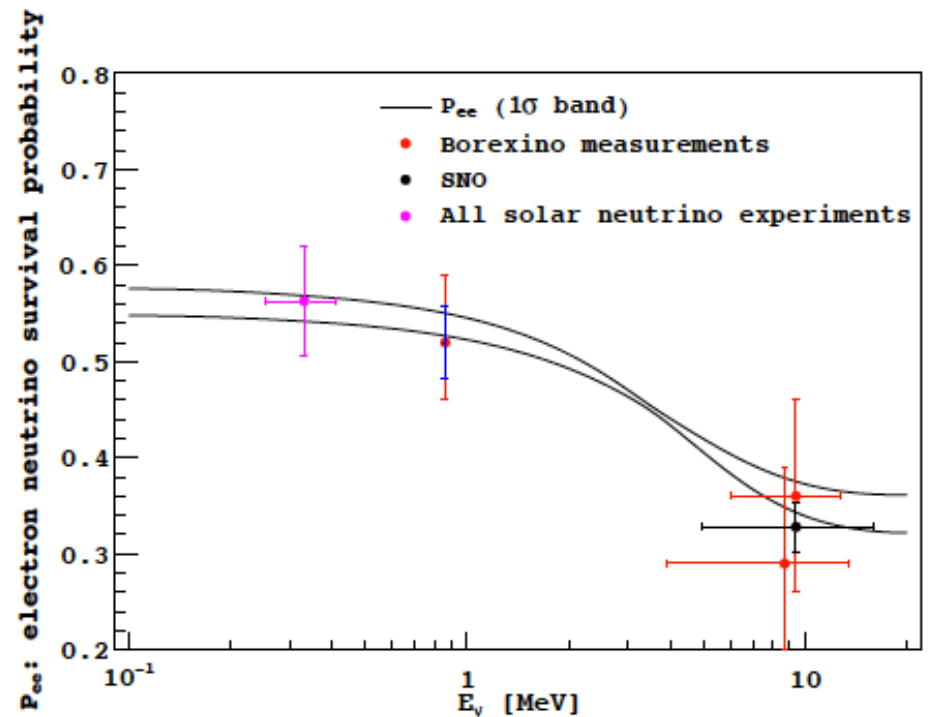
Average Result

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

→ $P_{ee}(862 \text{ keV}) = 0.52 \pm 0.07$

Systematics

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



Day-Night Effect

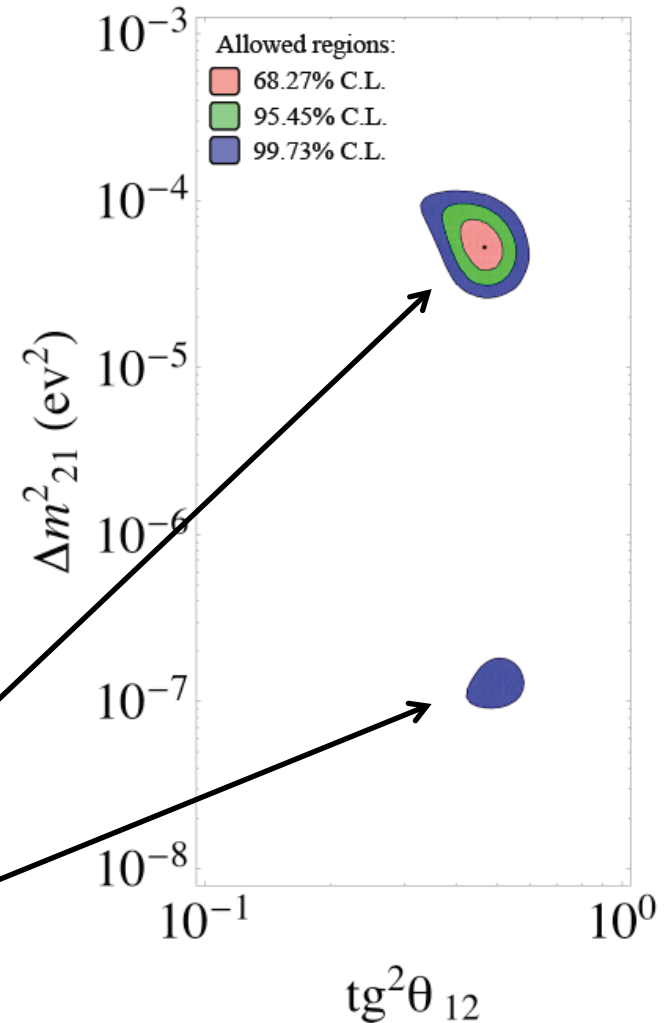
- As solar neutrinos (adiabatically) enter the earth, ν_e can be coherently regenerated
- Size of the effect depends on mixing parameters, can cause the effective day and night neutrino fluxes to be different

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

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

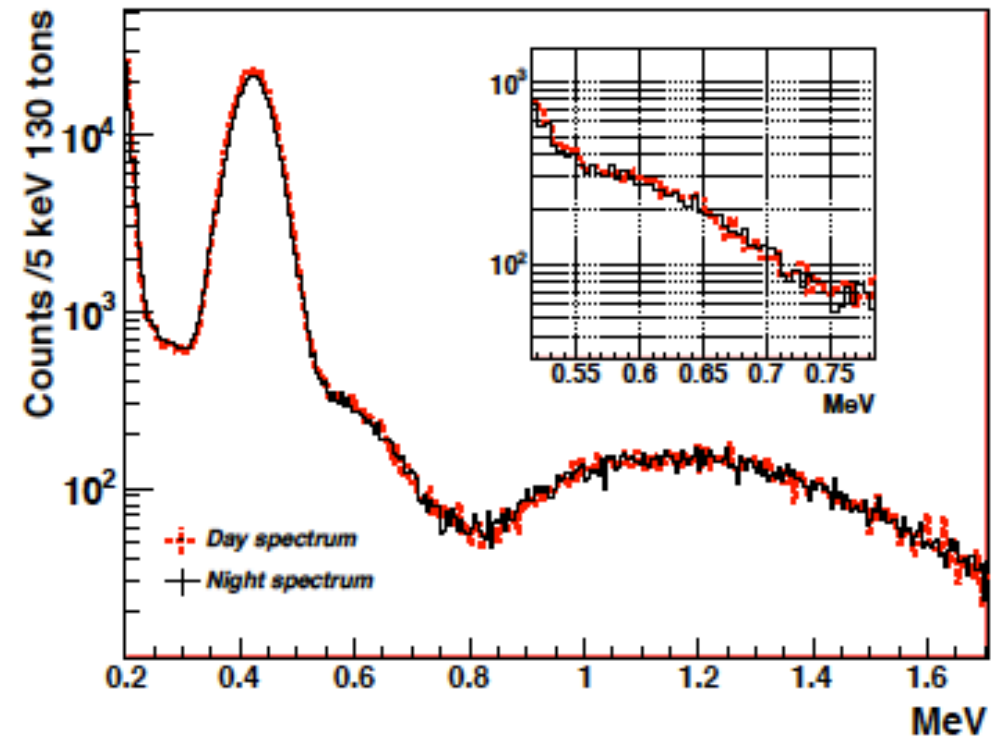
Model	Predicted A_{nd} (862 keV)
LMA	<0.001
LOW	0.11 - 0.80
MaVaN	~0.20

Global Solar without Borexino



Borexino Day-Night Asymmetry Search I

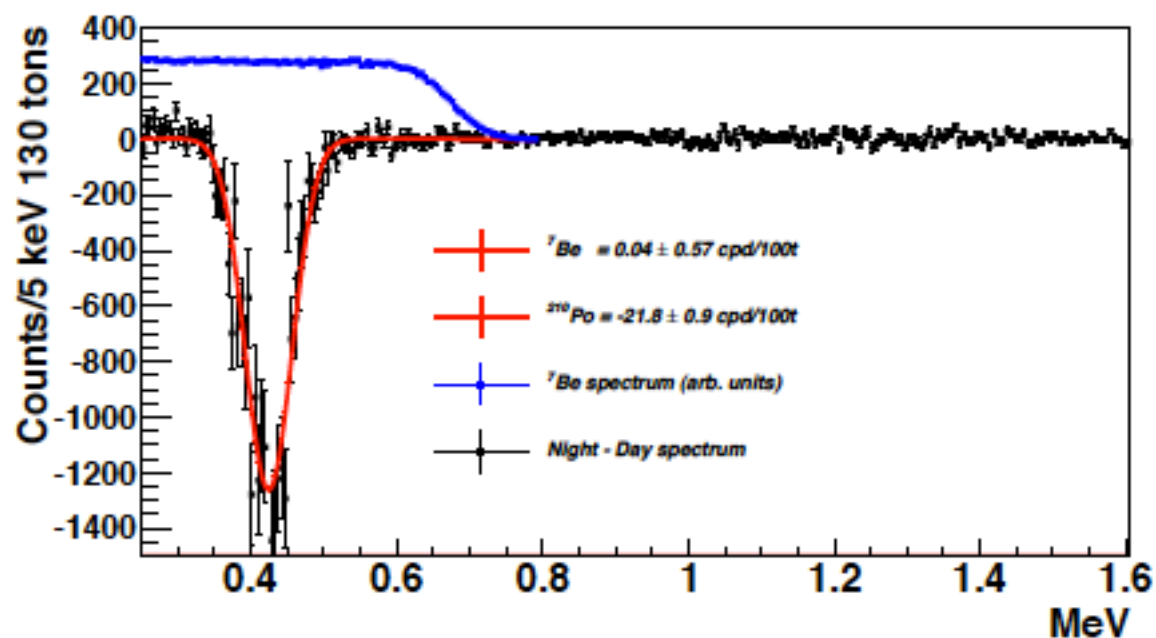
- Normalize the day and night spectra to the day livetime
 - Correct for earth's orbital eccentricity
- Fit the day and night spectra separately



→ $A_{\text{dn}}(862 \text{ keV}): 0.007 \pm 0.073$

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 ^7Be and ^{210}Po (decay maps to day-night effect)
- More precise result by assuming backgrounds are day-night invariant

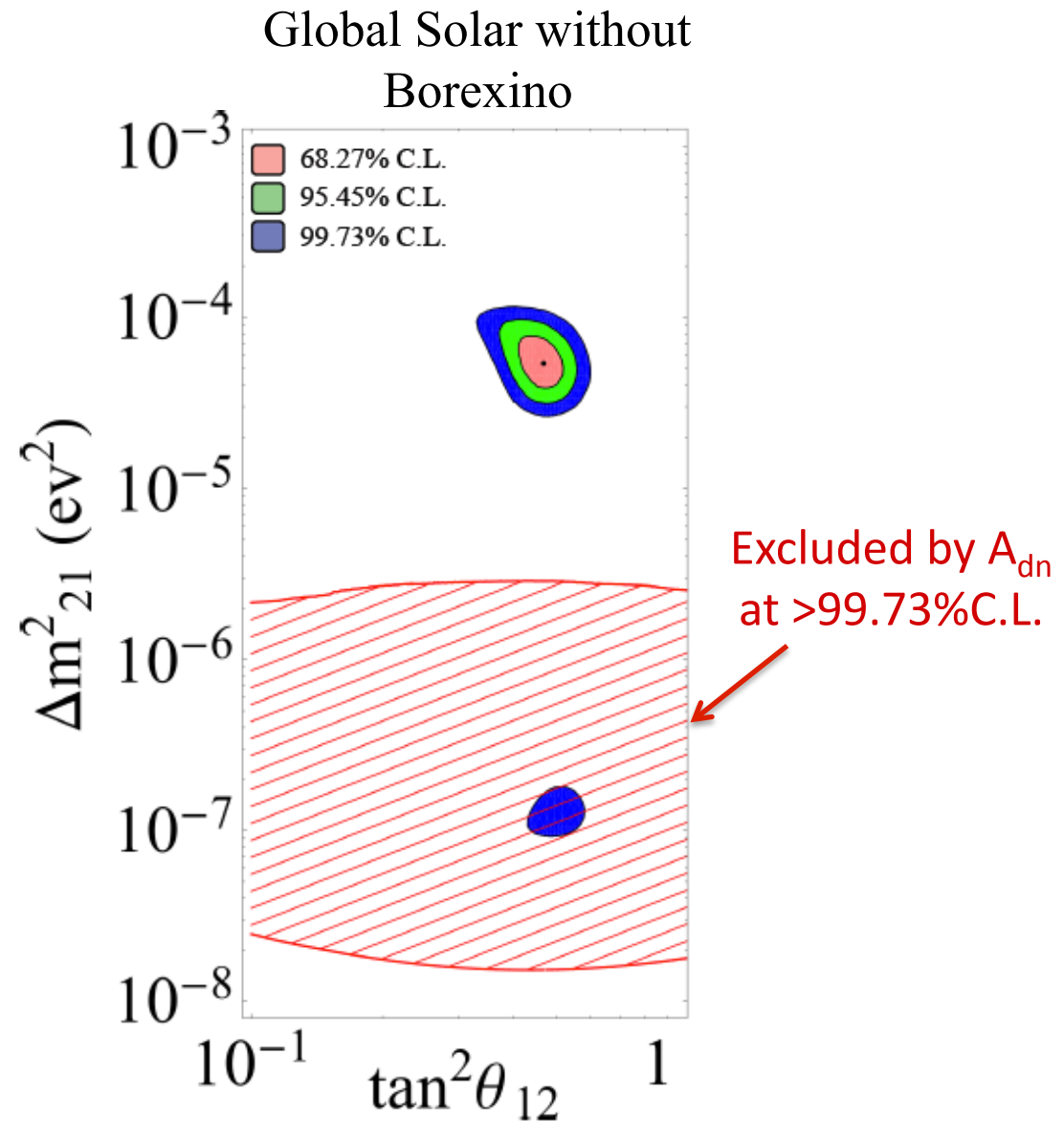


$$A_{dn}(862 \text{ keV}): 0.001 \pm 0.012_{\text{stat}} \pm 0.007_{\text{sys}}$$

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 ${}^7\text{Be}$ and ${}^{210}\text{Po}$ (decay maps to day-night effect)
- More precise result by assuming backgrounds are day-night invariant

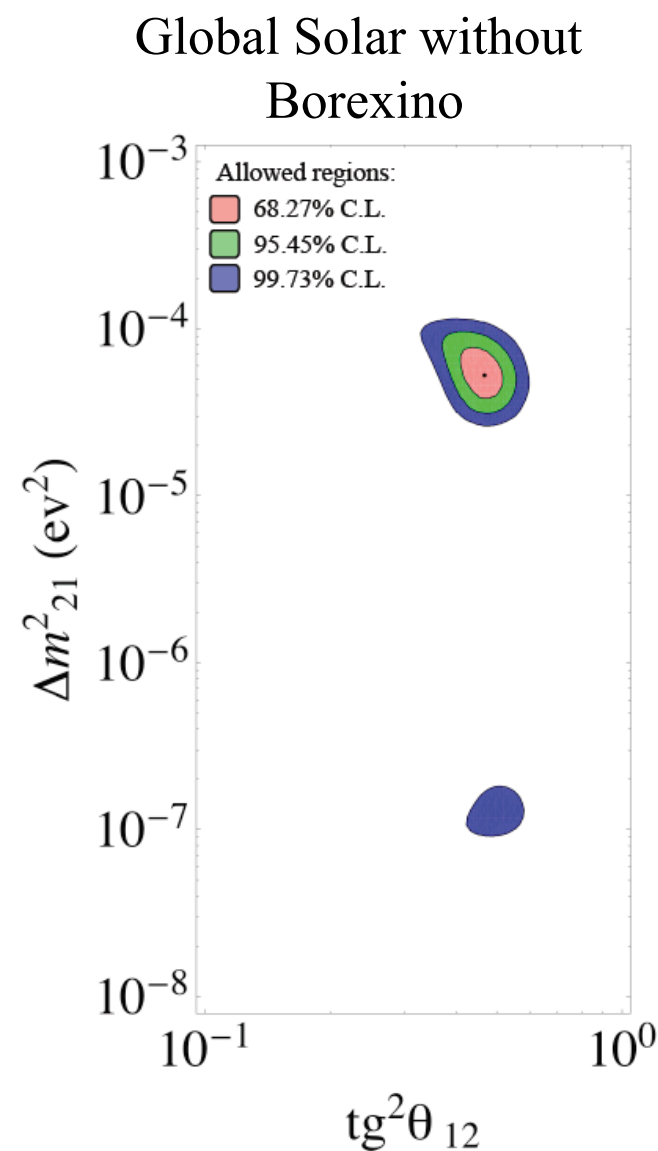


Borexino ^7Be Results

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

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

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

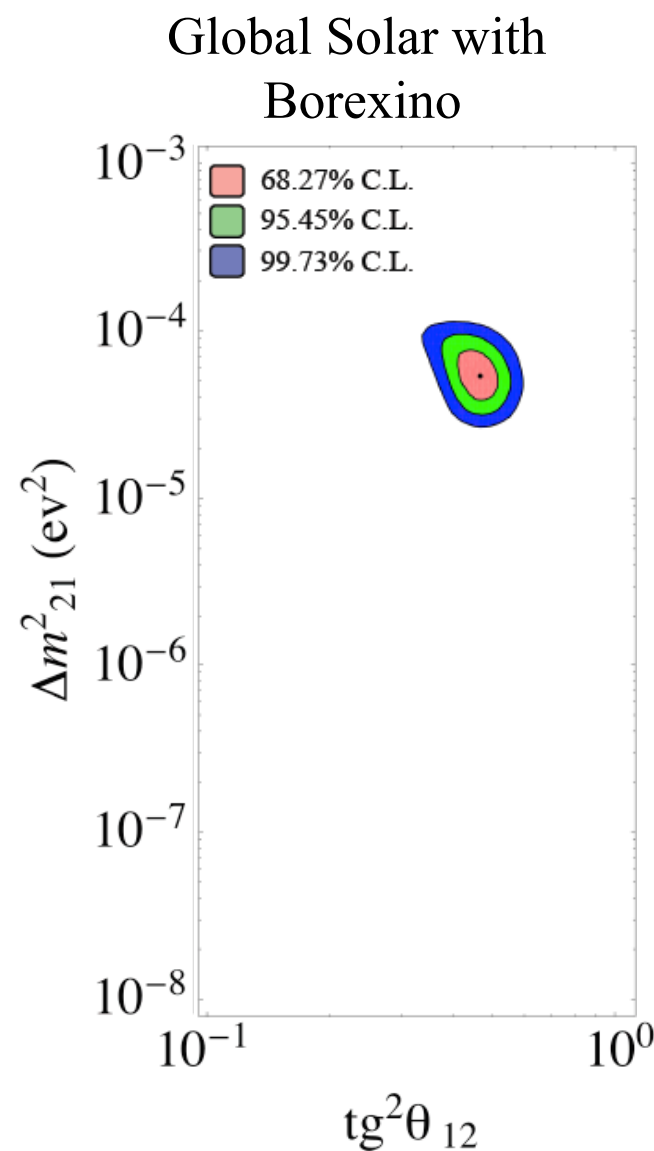


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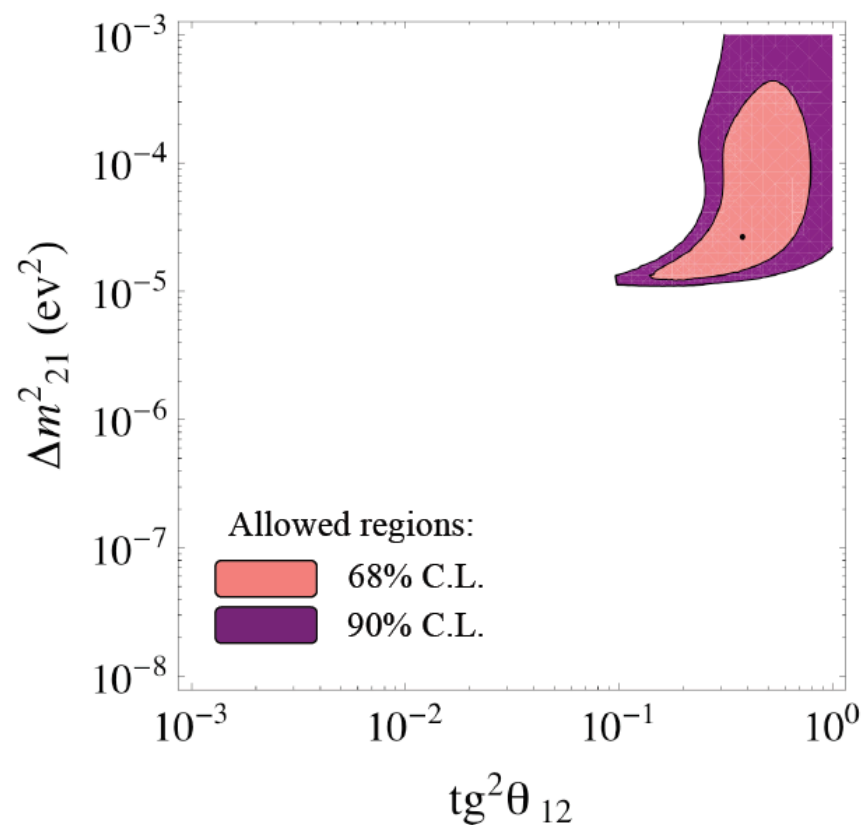
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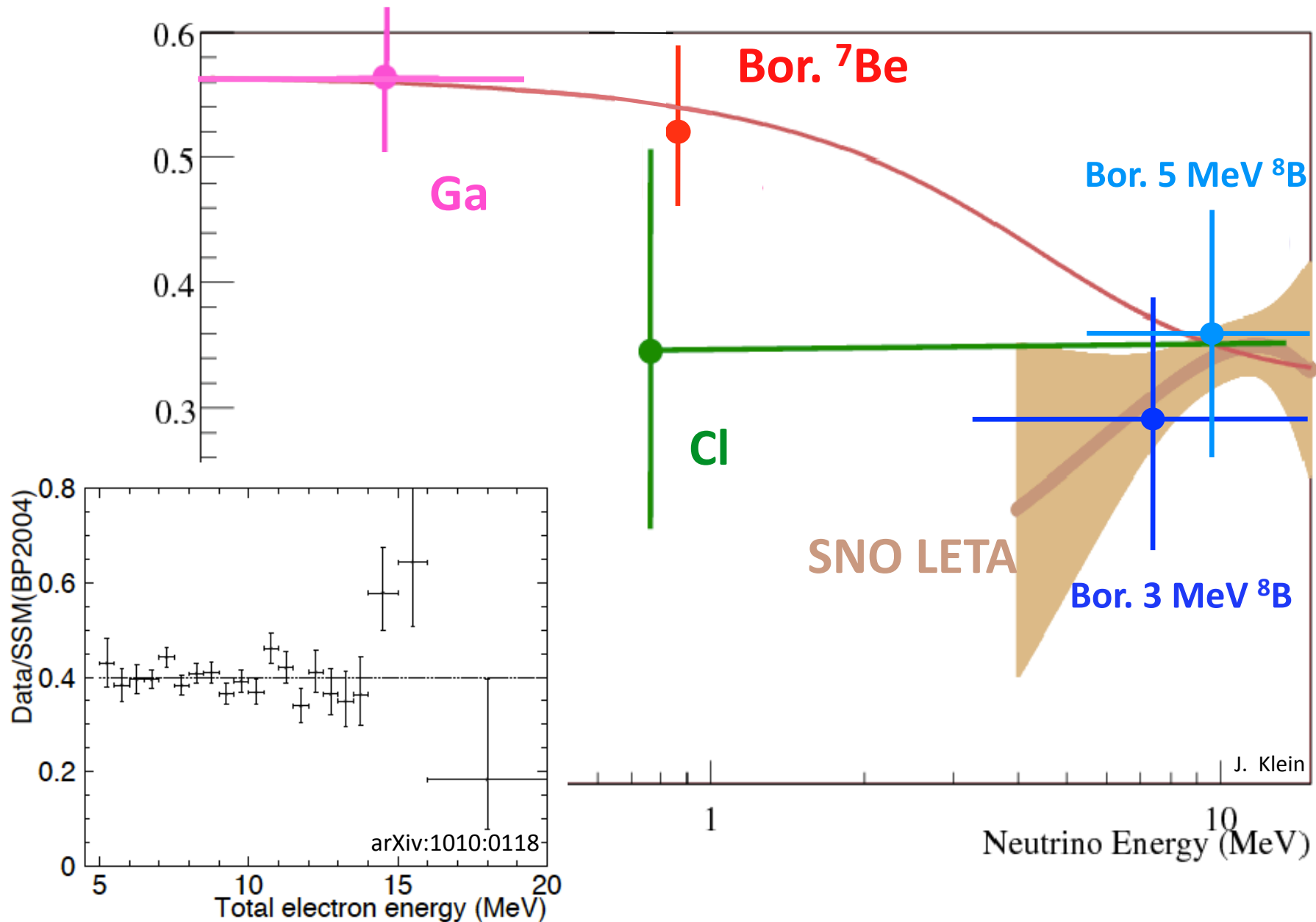
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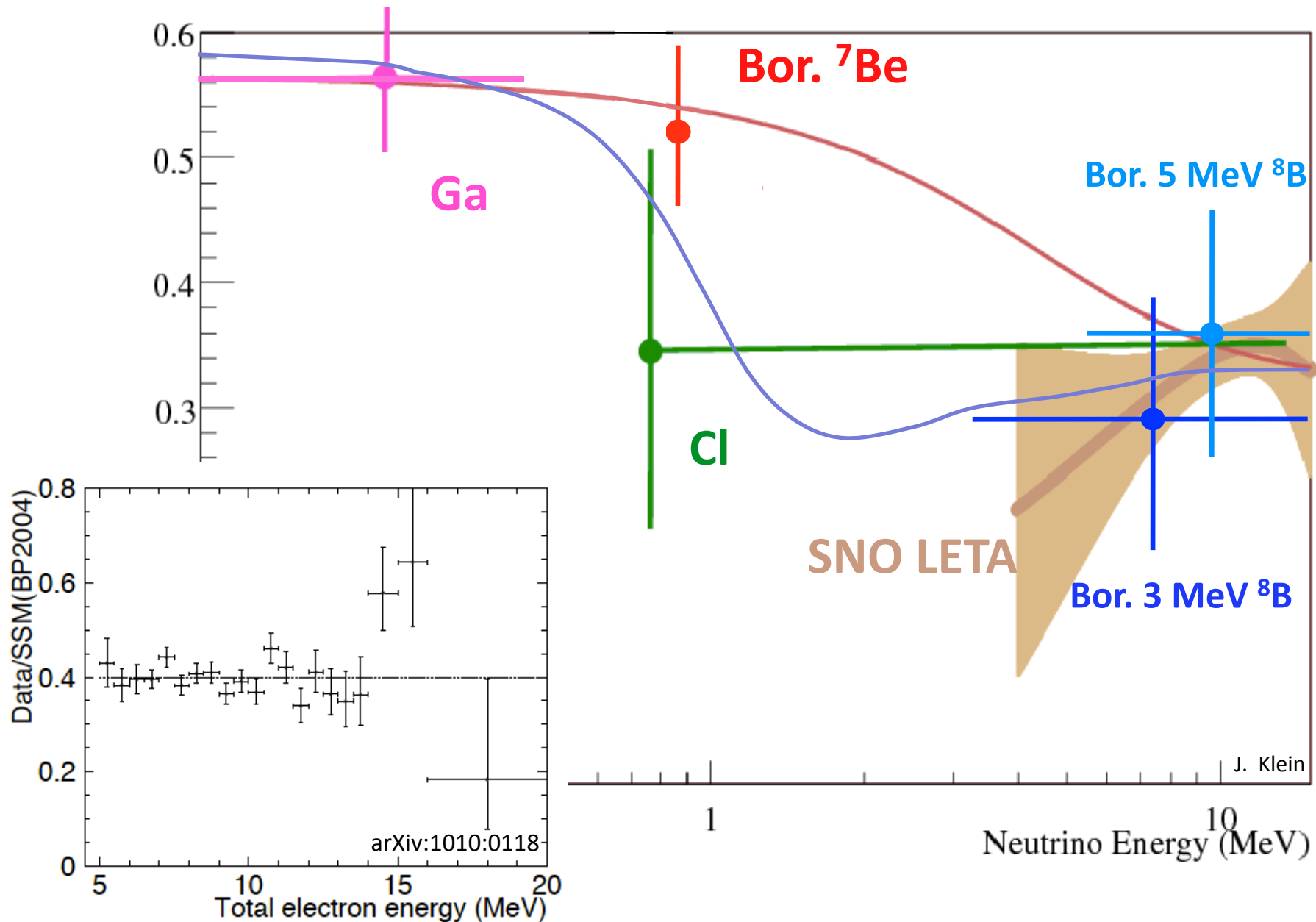
Borexino Alone



Summary of Current Status

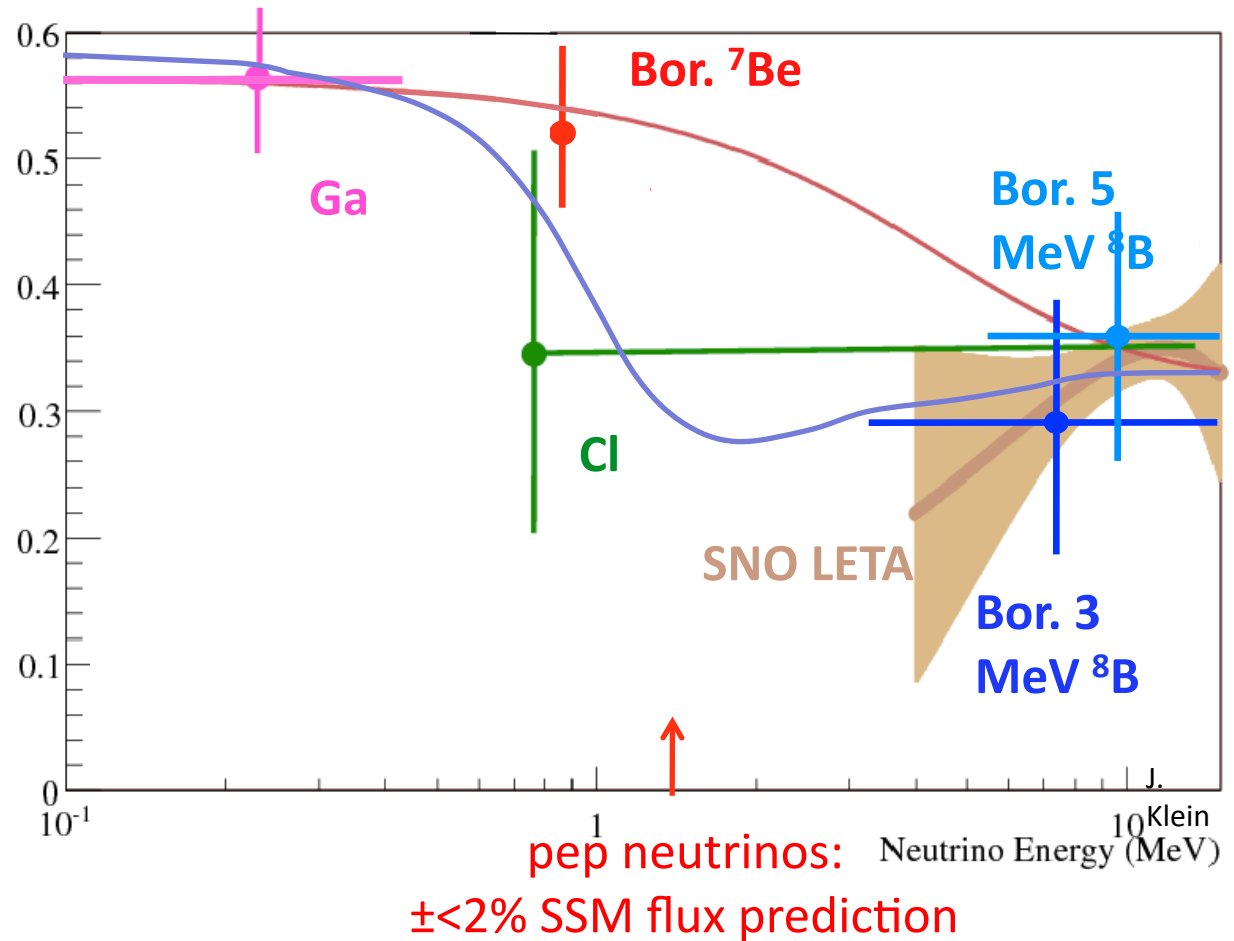


Summary of Current Status

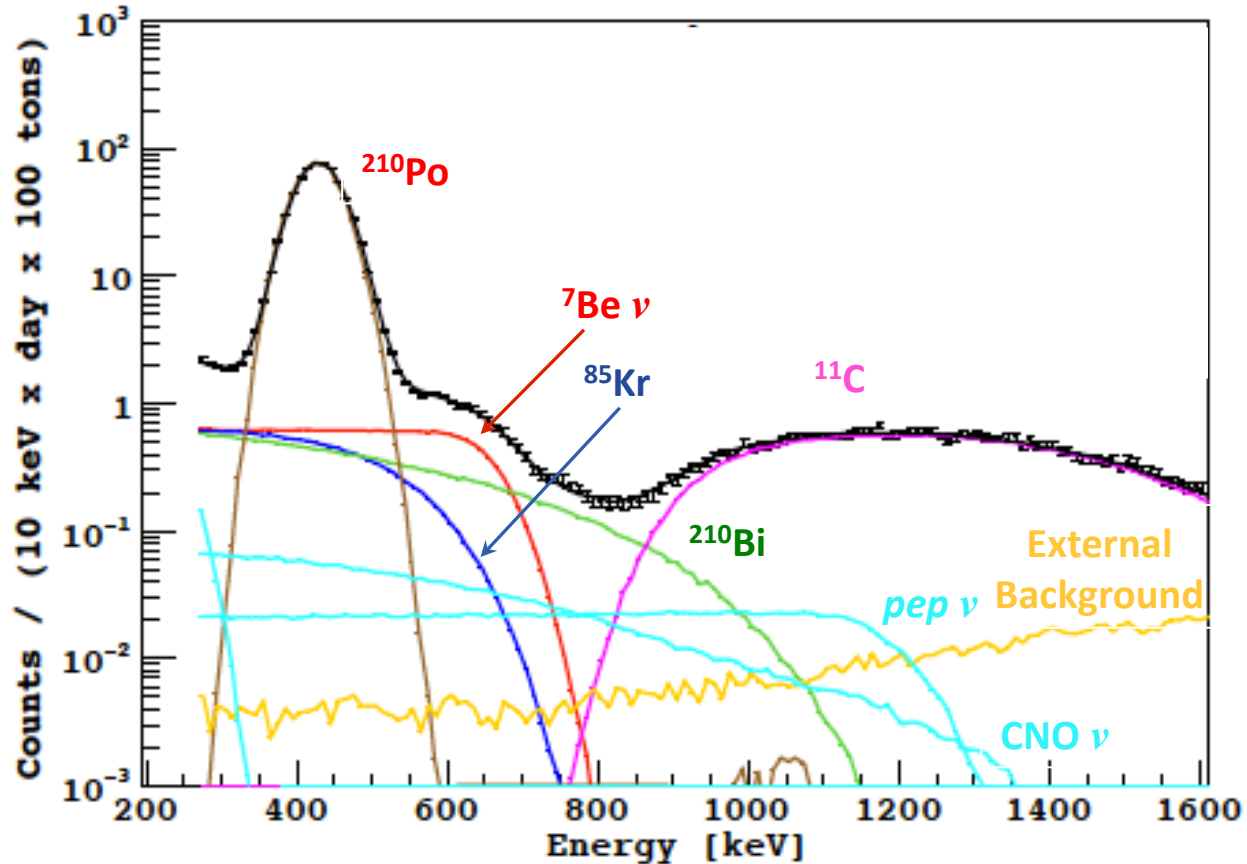


How to Proceed?

- Measure the *pep* survival probability



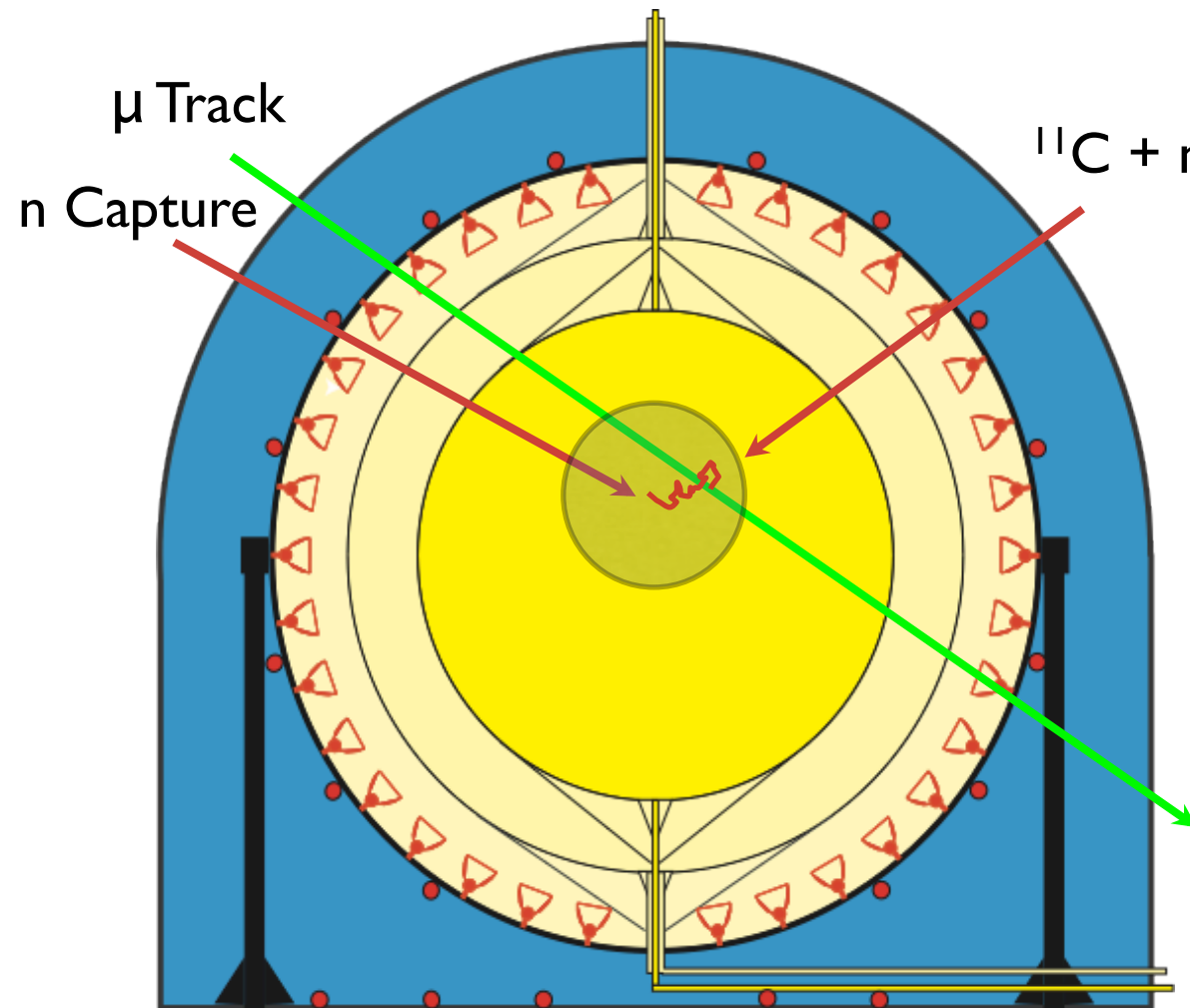
pep neutrinos in Borexino:
 ^{11}C Suppression



- ^{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!

pep neutrinos in Borexino: ^{11}C Suppression

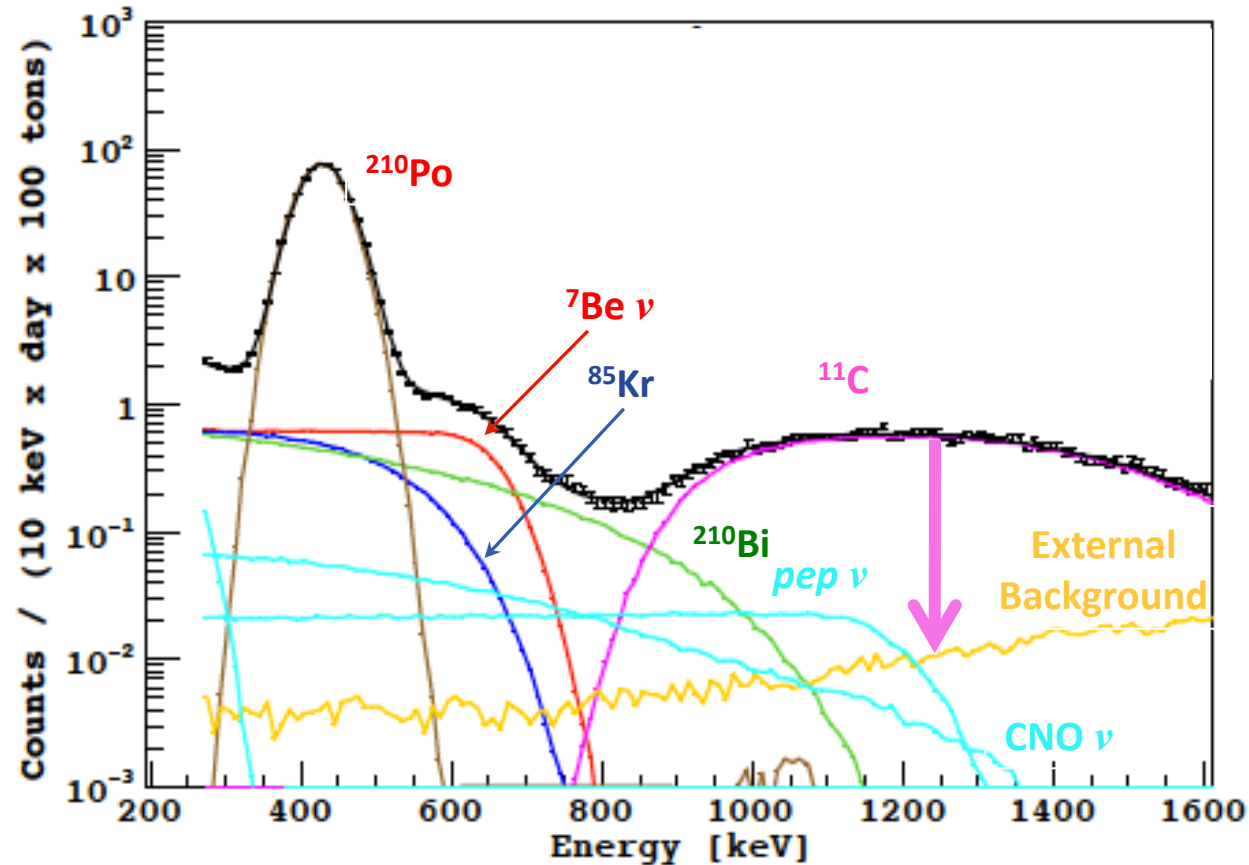


- Most ^{11}C production via $^{12}\text{C} \rightarrow ^{11}\text{C} + n$
- Delayed neutron capture signal identifies when and where ^{11}C was produced
- Also looking into PSD based on ortho-positronium ($\sim 140\text{ns}$)

PRC 83:015504 (2011)

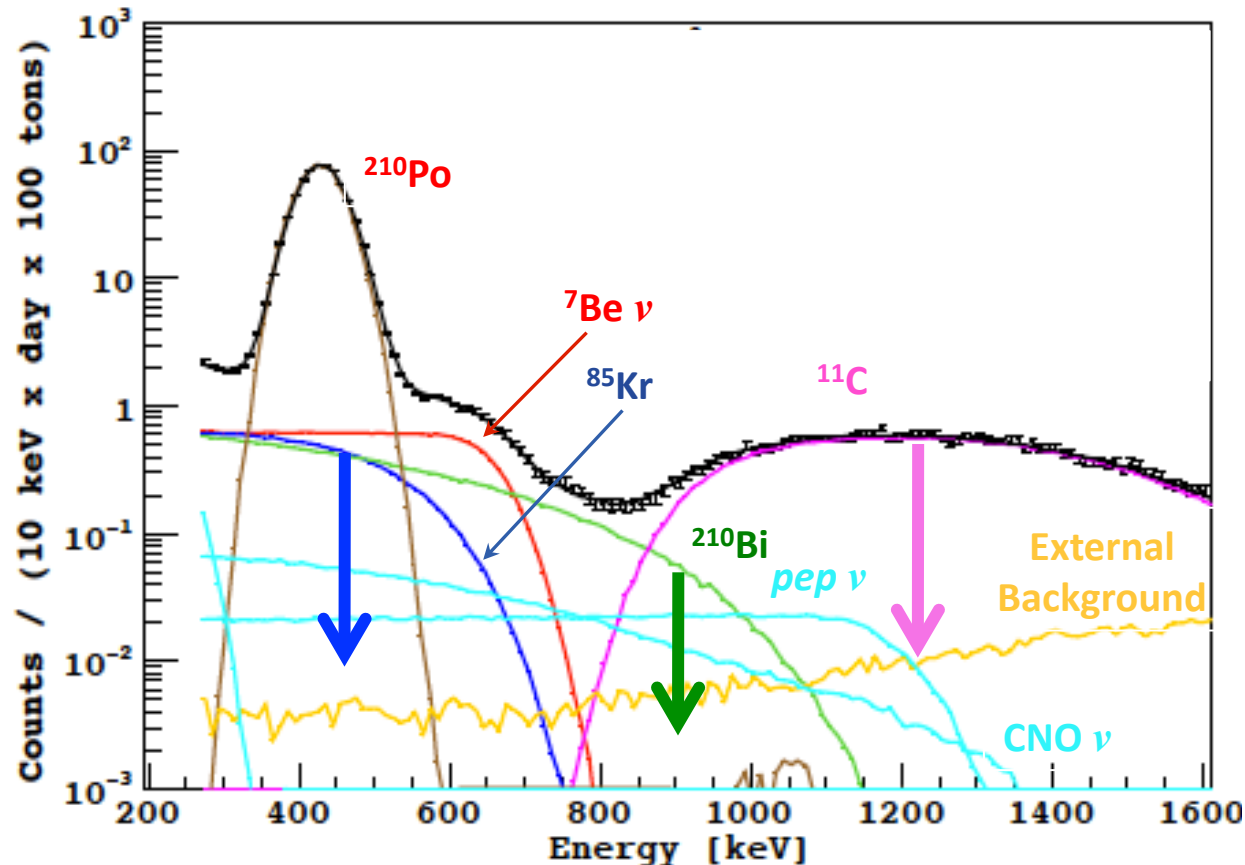
The ~ 125 muon-neutron coincidences/day (of which ~ 25 accompany ^{11}C production) can be vetoed without excessive loss of live time.

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

The best of Borexino is yet to come!

Borexino Collaboration

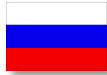
Astroparticle and Cosmology Laboratory – Paris, France 

INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy 

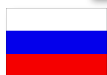
INFN e Dipartimento di Fisica dell'Università – Genova, Italy 

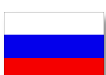
INFN e Dipartimento di Fisica dell'Università – Milano, Italy 

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 

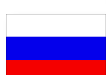
Kurchatov Institute – Moscow, Russia 

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 