



NEUTRINO MIXING OF ^7Be AND LOW-ENERGY ^8B SOLAR NEUTRINOS

DNP Meeting, Sante Fe
November 4th, 2010

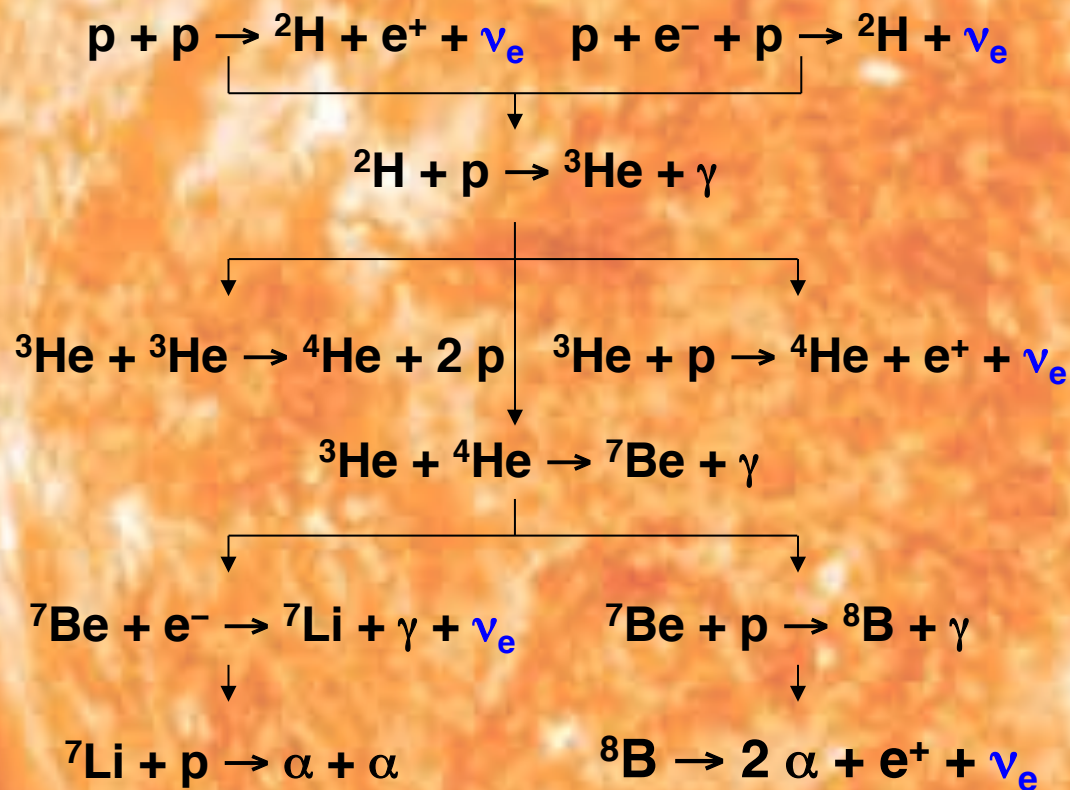
Alex Wright
Princeton University

Outline

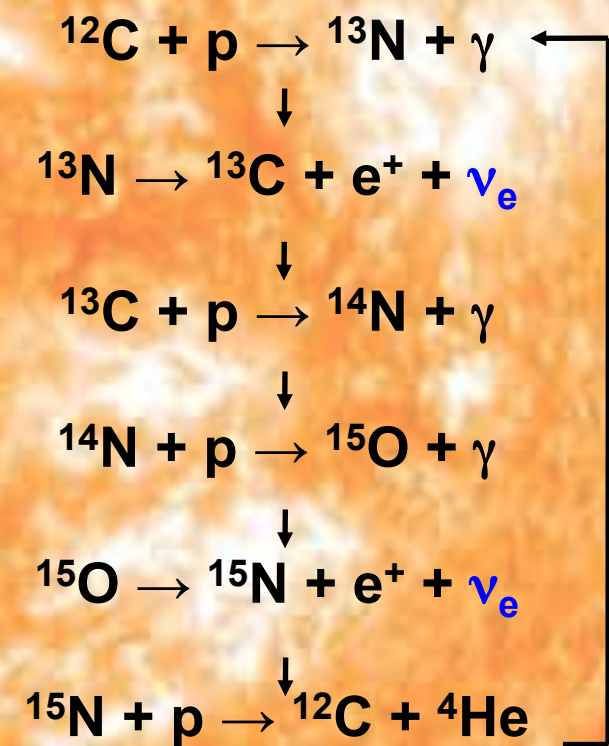
- Quick review of solar neutrinos and neutrino mixing
- Current low energy solar neutrino results
 - SNO
 - Borexino
- Outlook

Solar Fusion Reactions

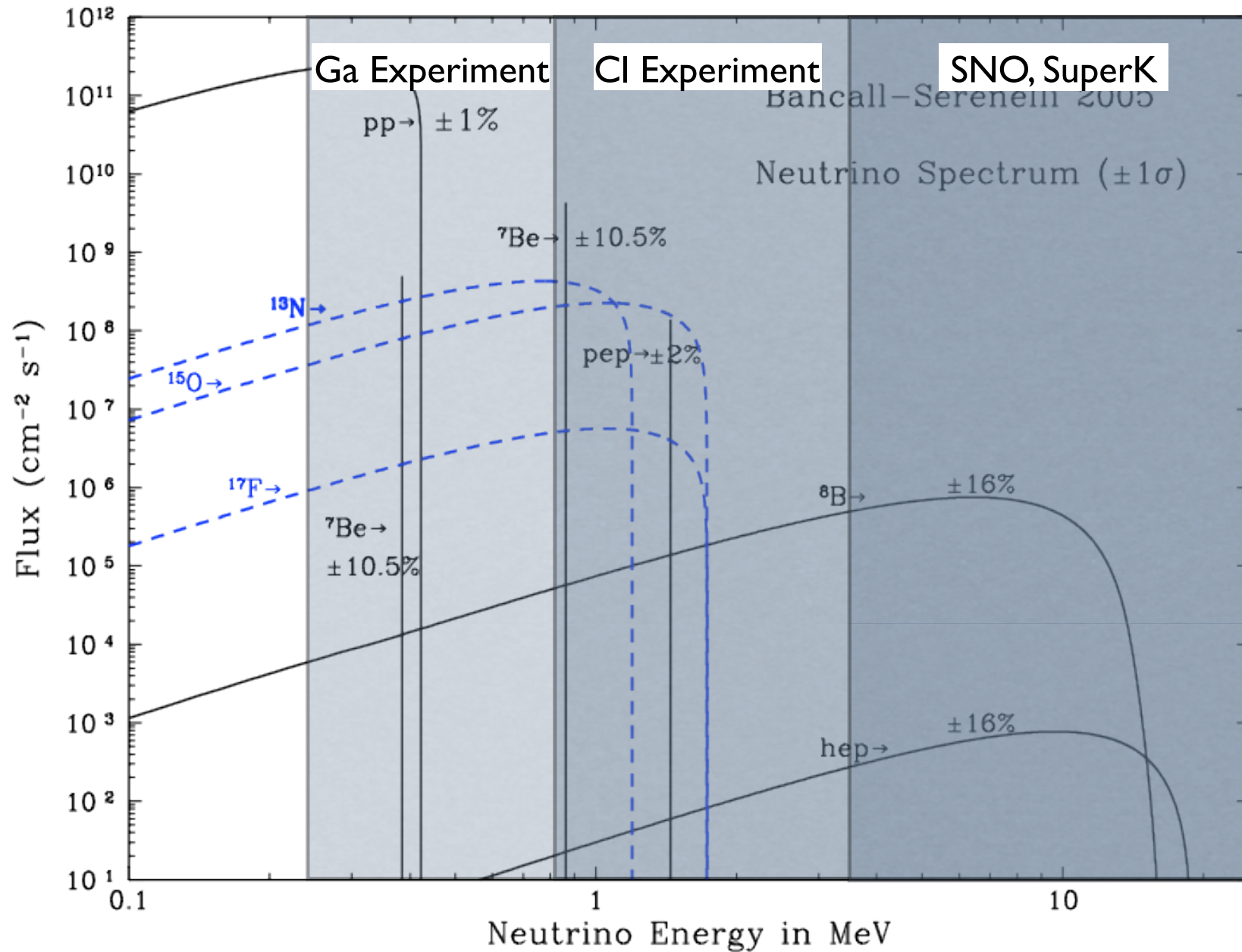
p-p Solar Fusion Chain



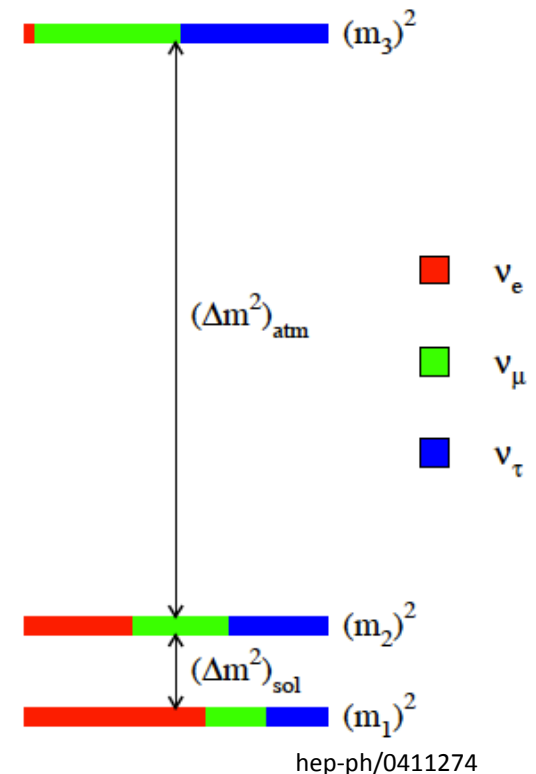
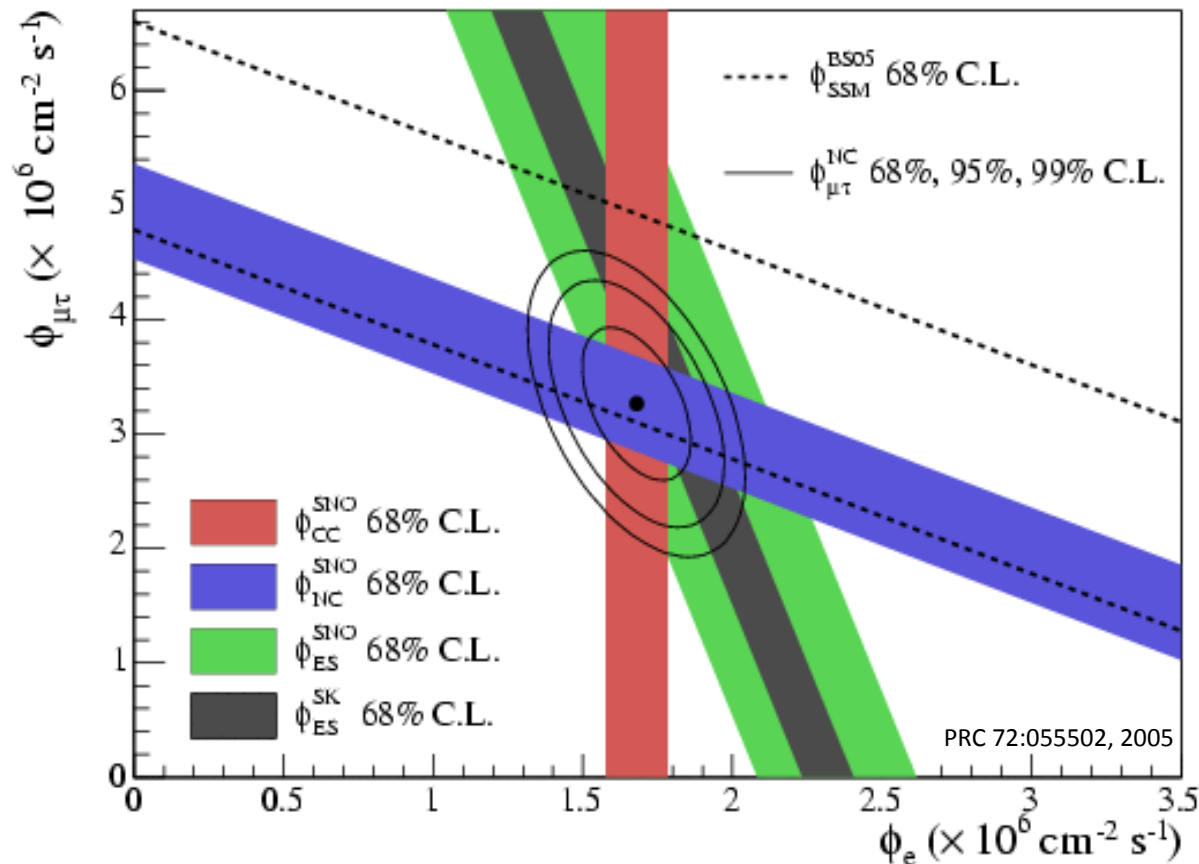
CNO Solar Fusion Cycle



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

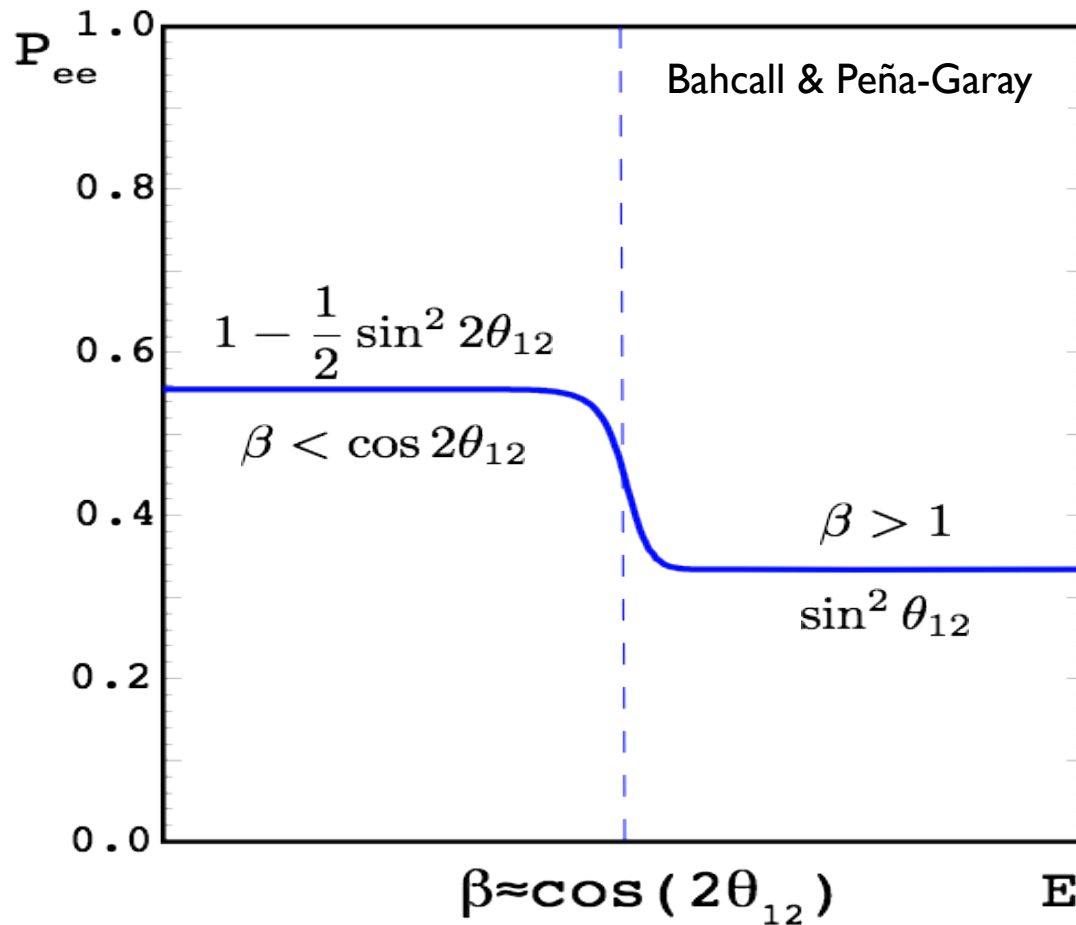
“MSW” Neutrino Oscillations

- 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

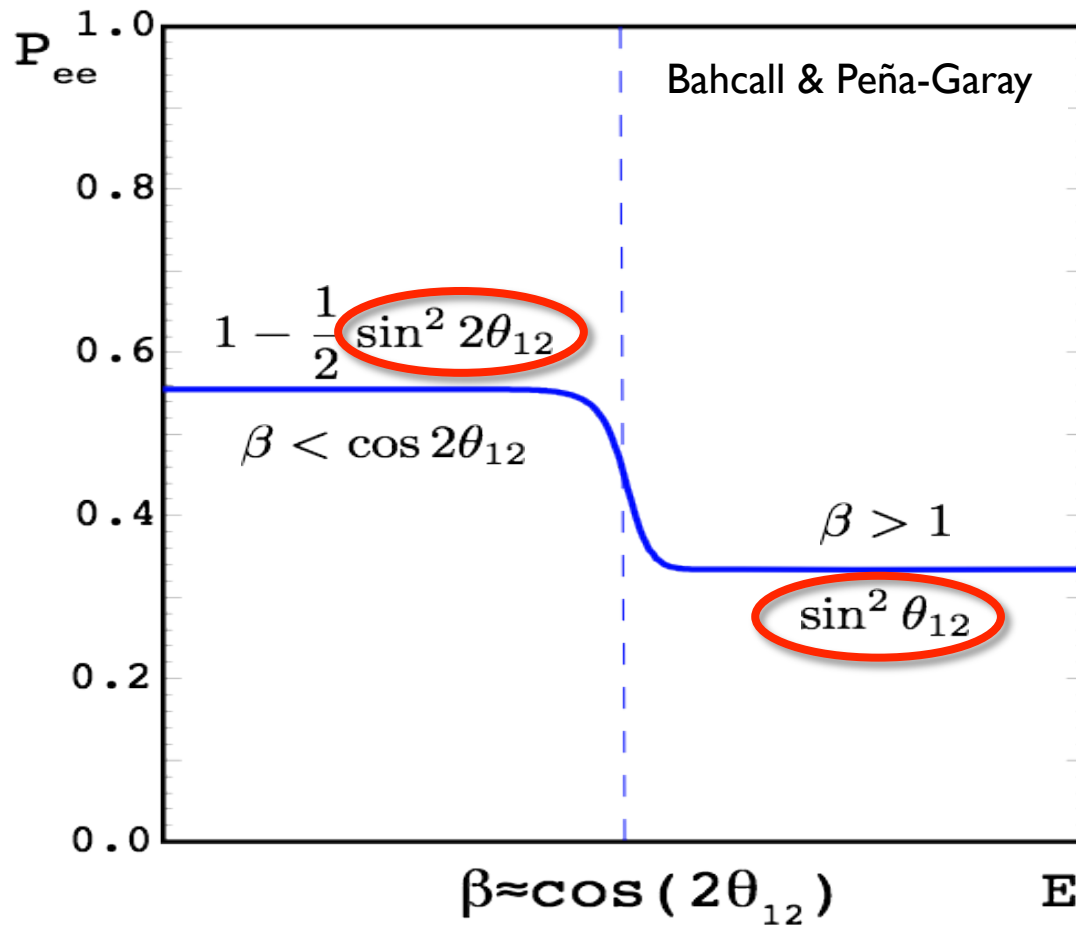


$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated “resonant conversion”

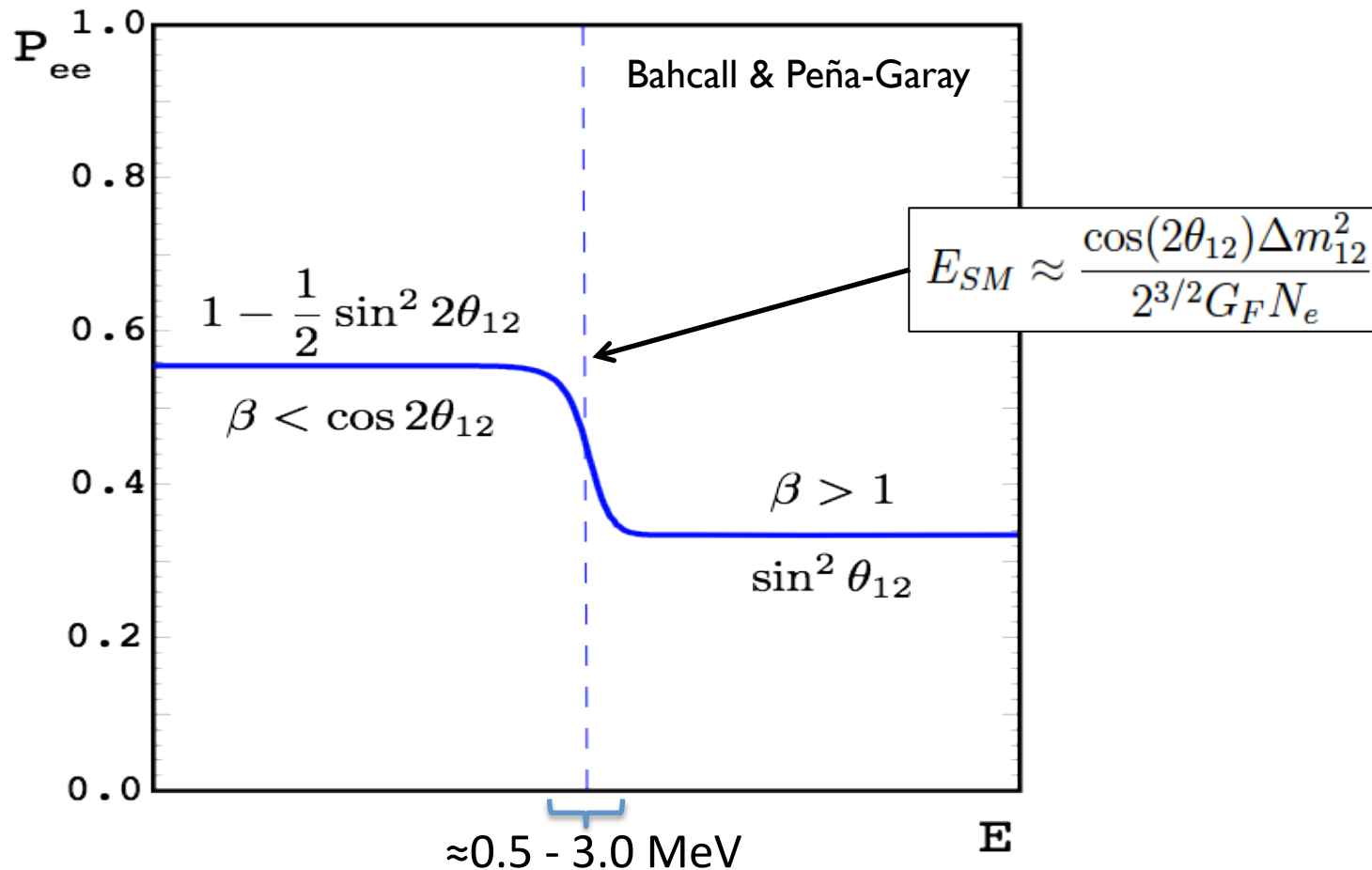
MSW Oscillation Regimes



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

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

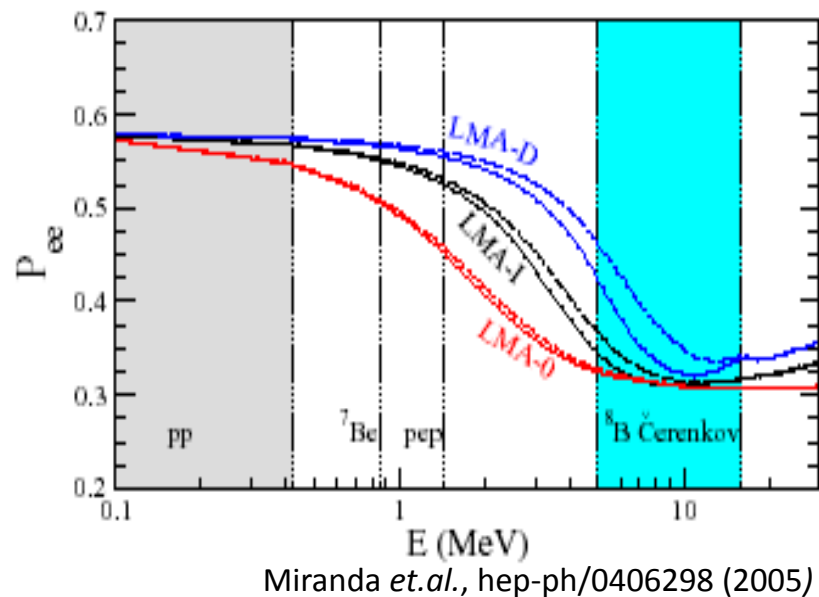
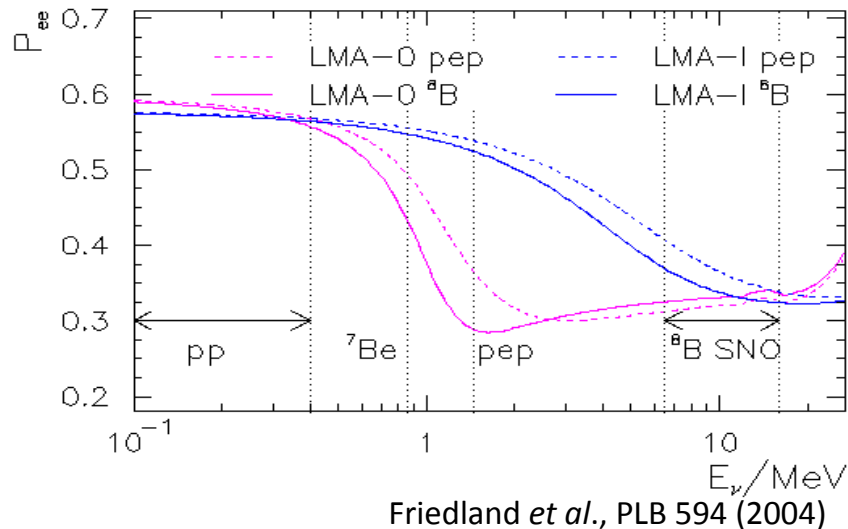
MSW Oscillation Regimes



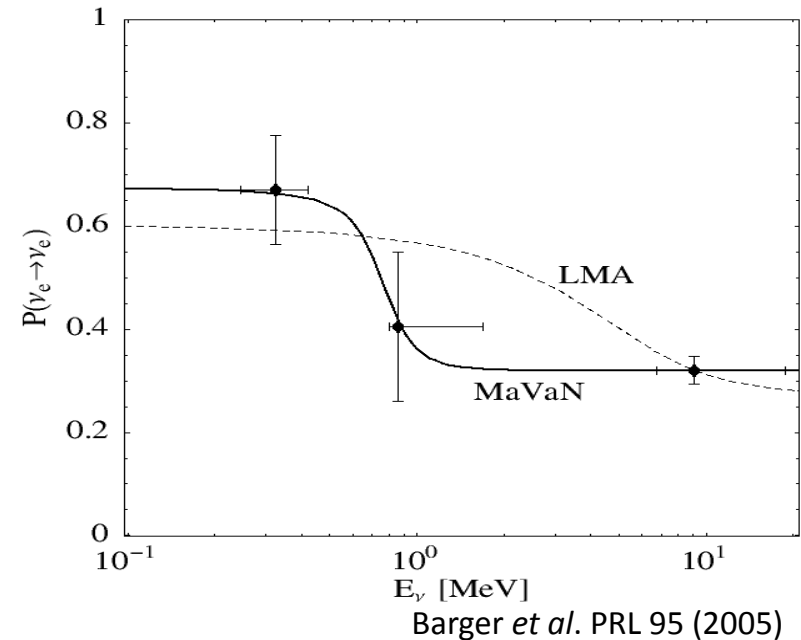
Look in “transition region” to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

Non-Standard Interactions



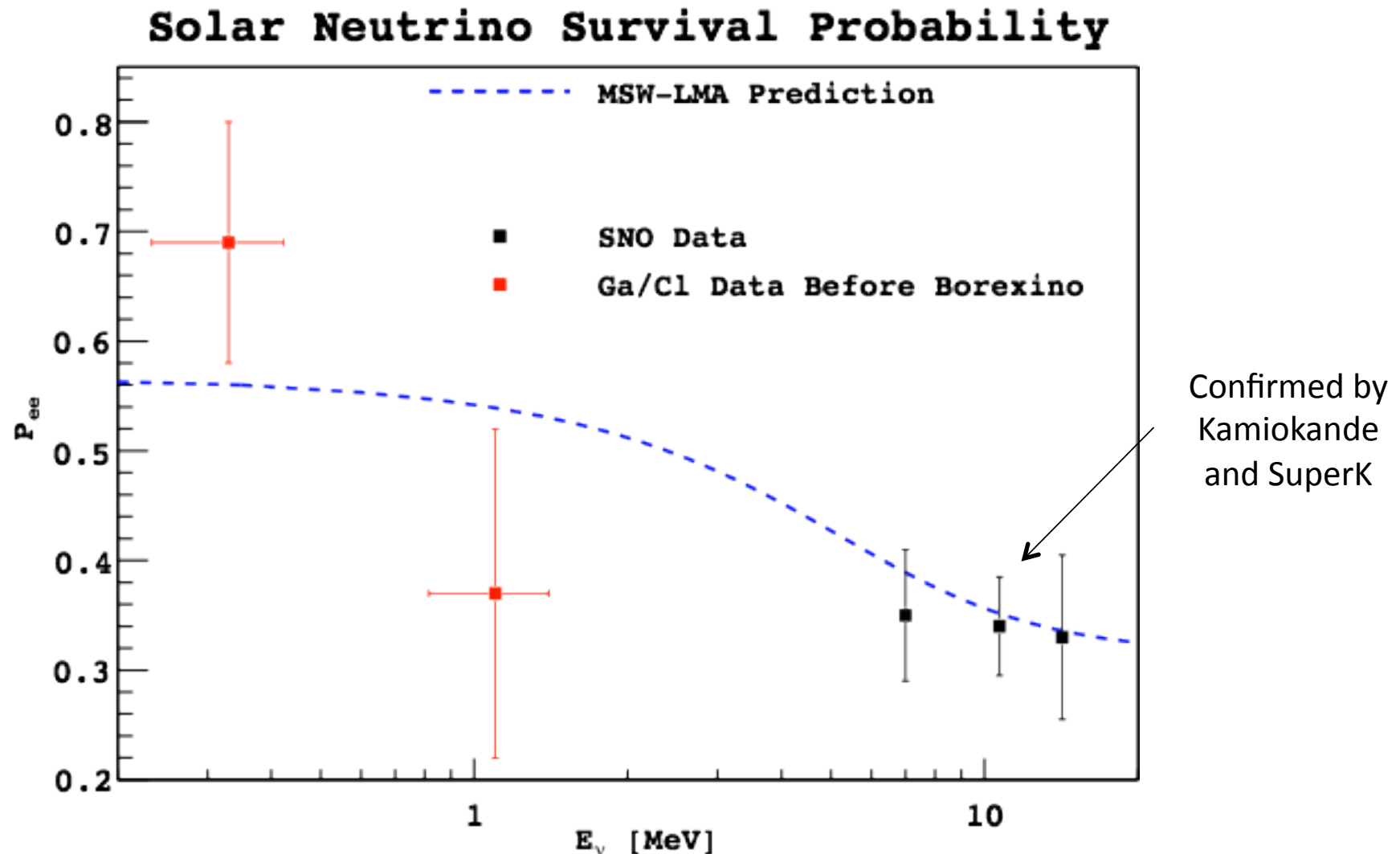
Mass Varying Neutrinos



Other Possibilities:

- CPT violations
- Sterile neutrino admixture

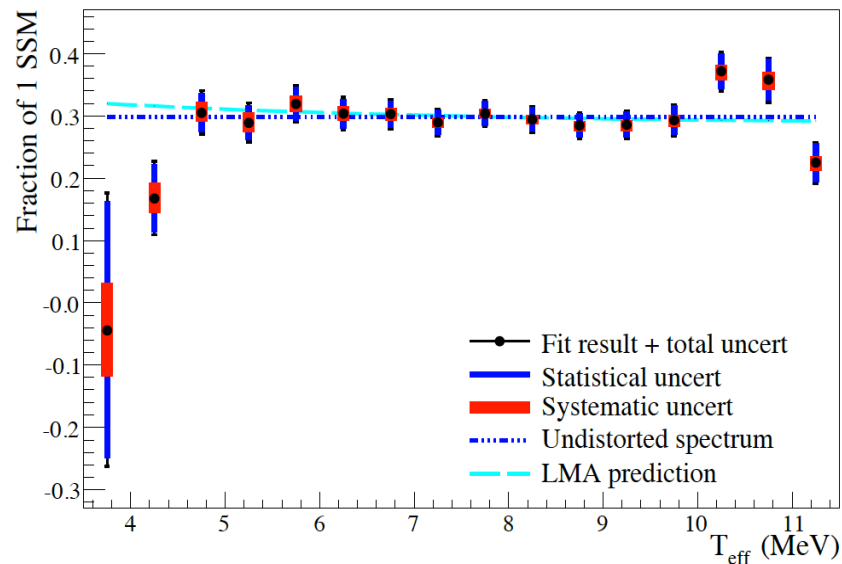
(Old) Experimental Constraints on Transition Region



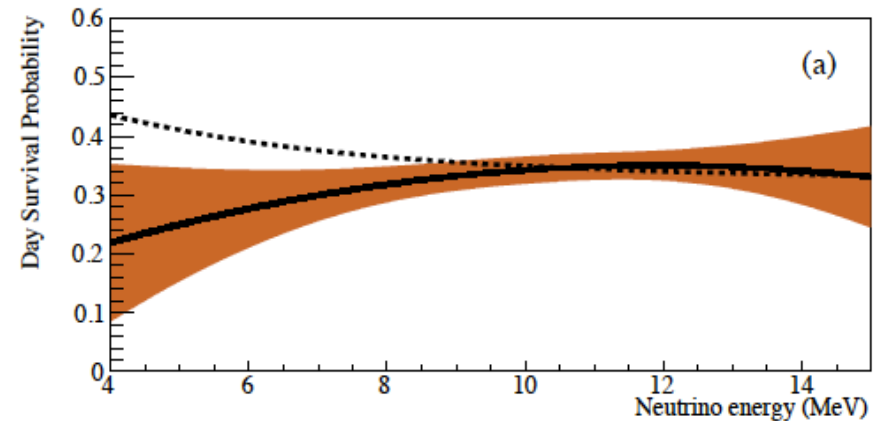
Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. *Real-time measurements needed in the transition region.*

SNO Low Energy Threshold Analysis

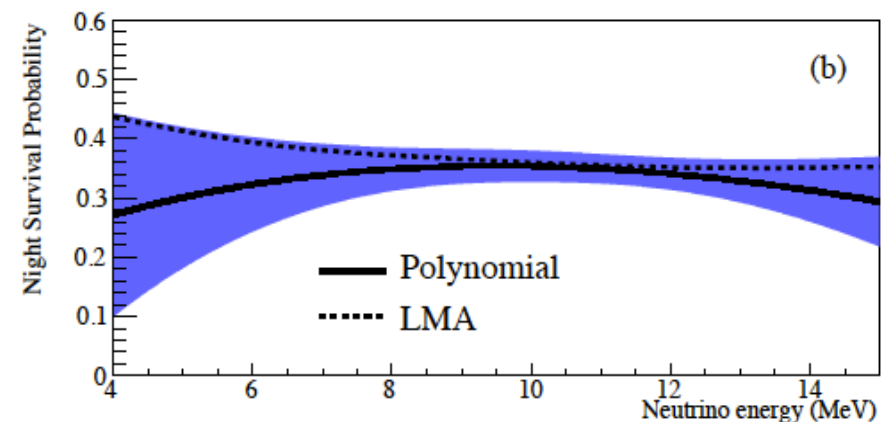
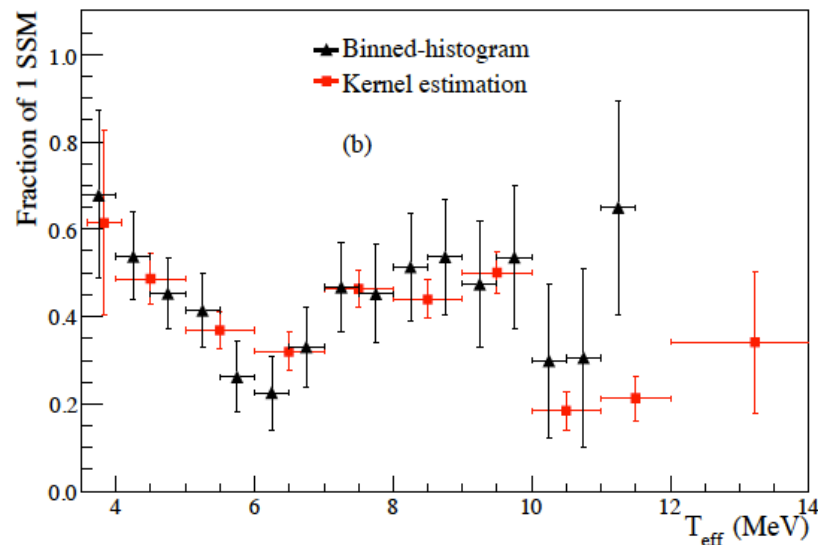
Charged Current: $T_{\text{eff}} = E_\nu - 1.44 \text{ MeV}$



Quadratic Fits to P_{ee}

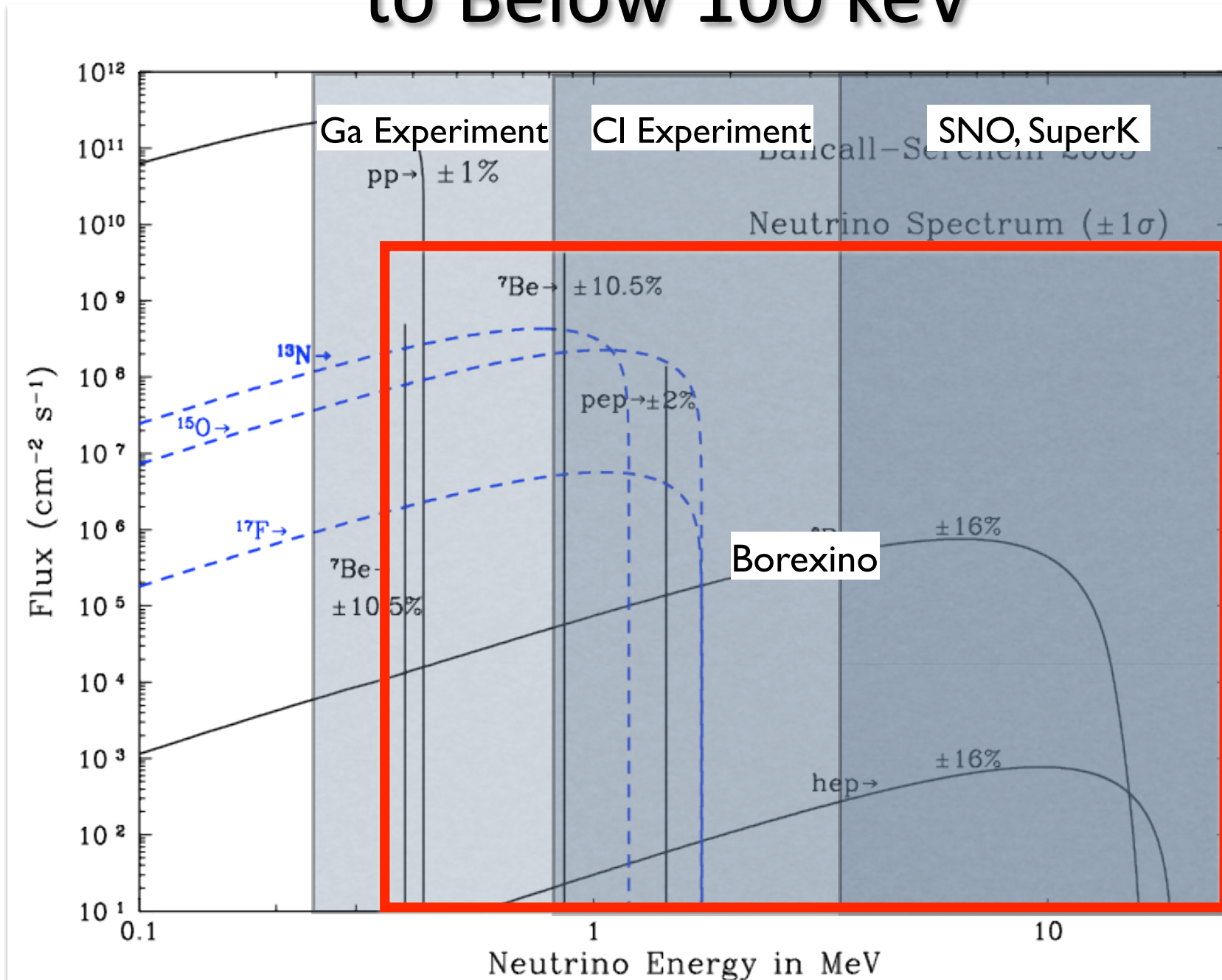


Elastic Scattering: $0 \leq T_{\text{eff}} \lesssim E_\nu - 0.24 \text{ MeV}$

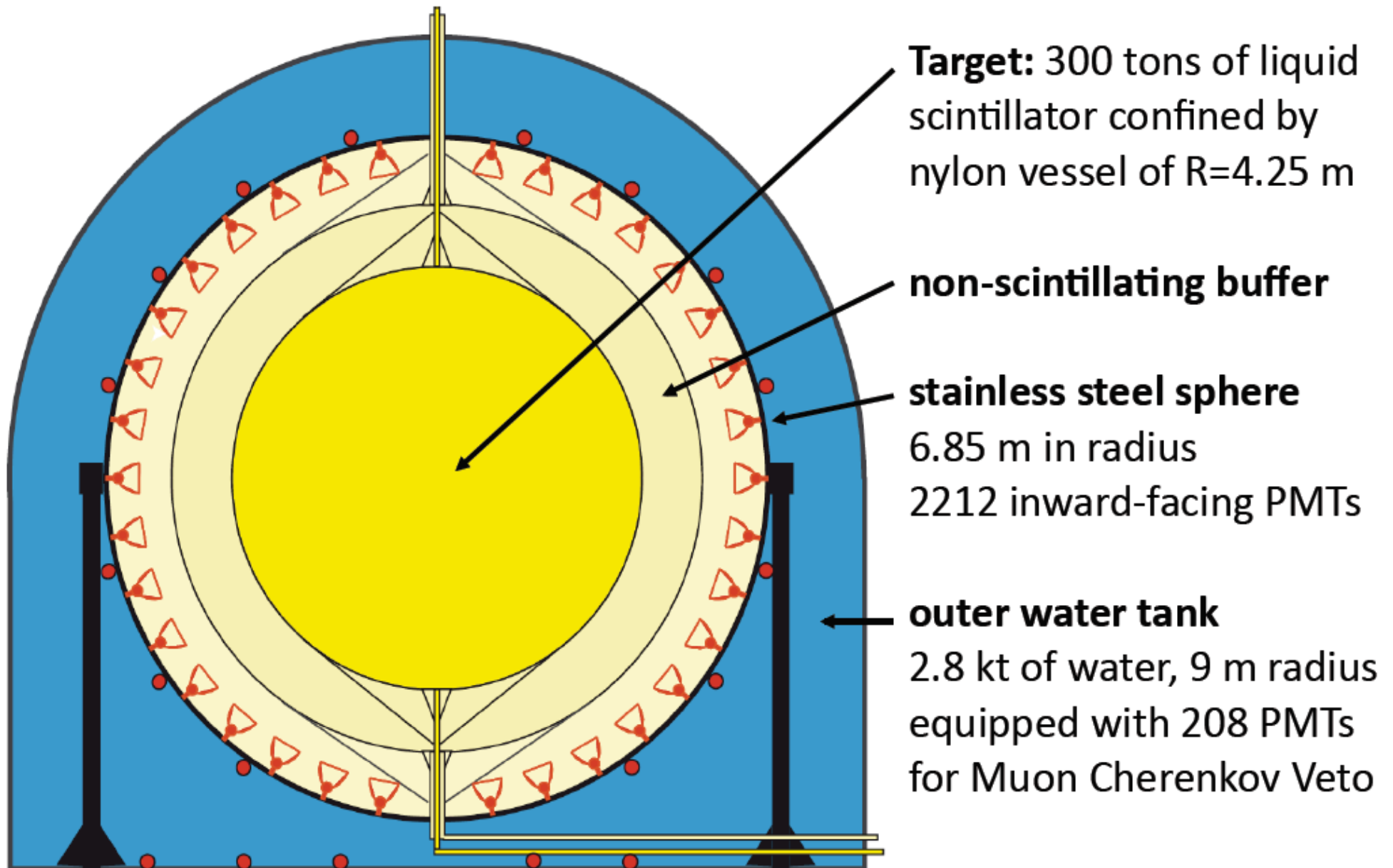


(Phys. Rev. C 81 (2010) 055504)

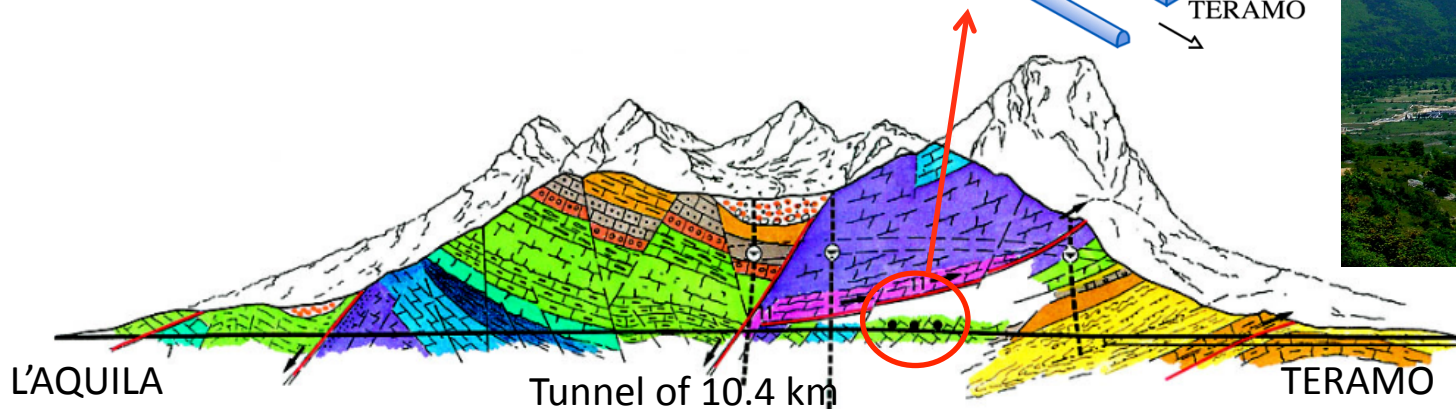
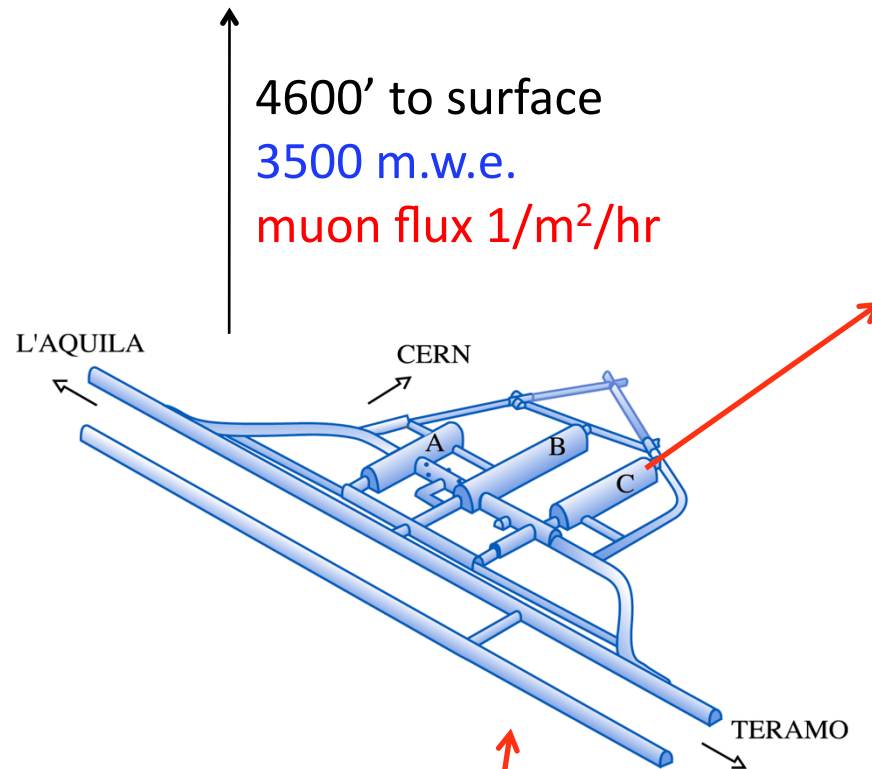
Liquid Scintillator: Real-time Detection to Below 100 keV



The Borexino Detector



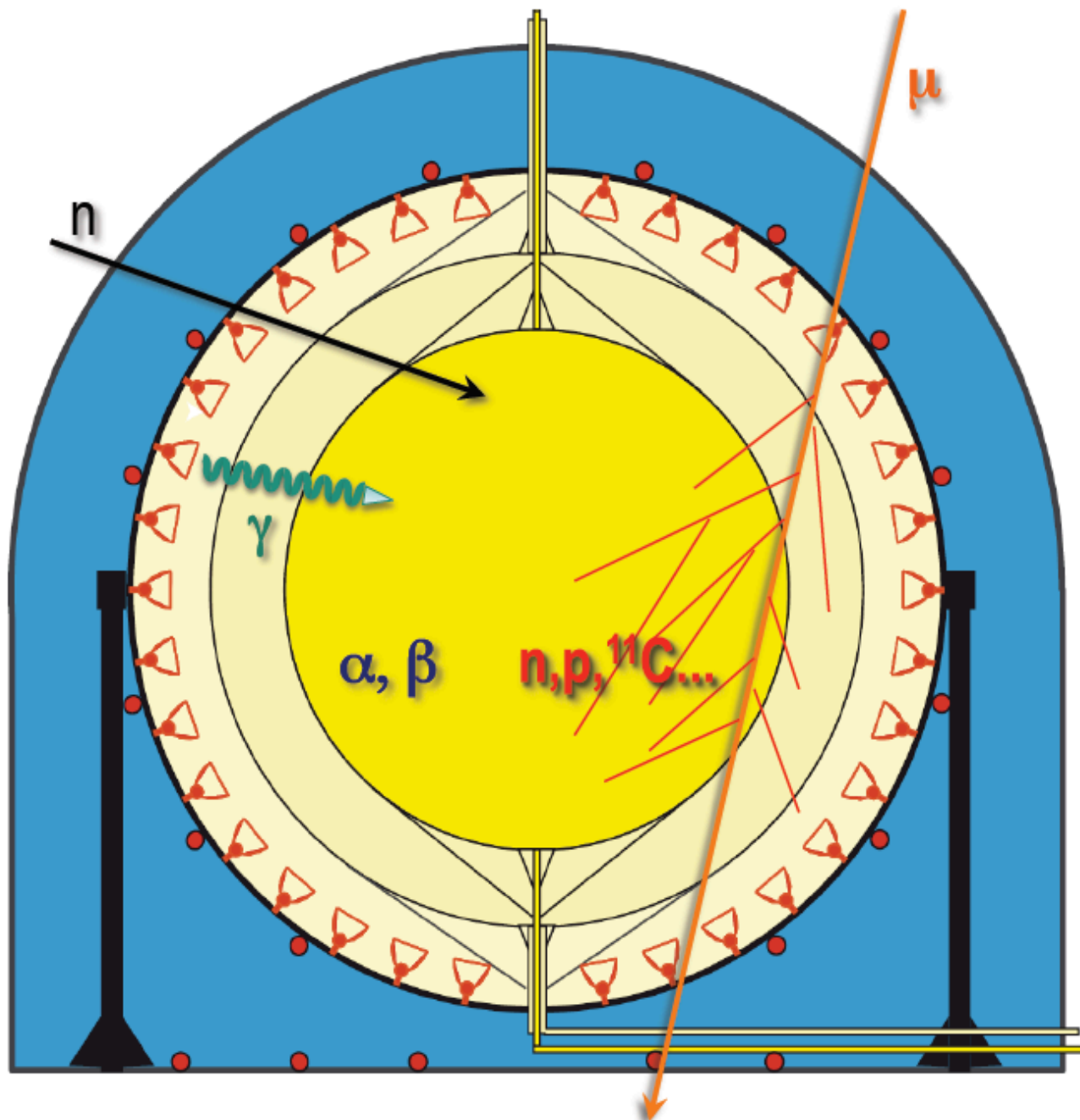
Laboratori Nazionali del Gran Sasso



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

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

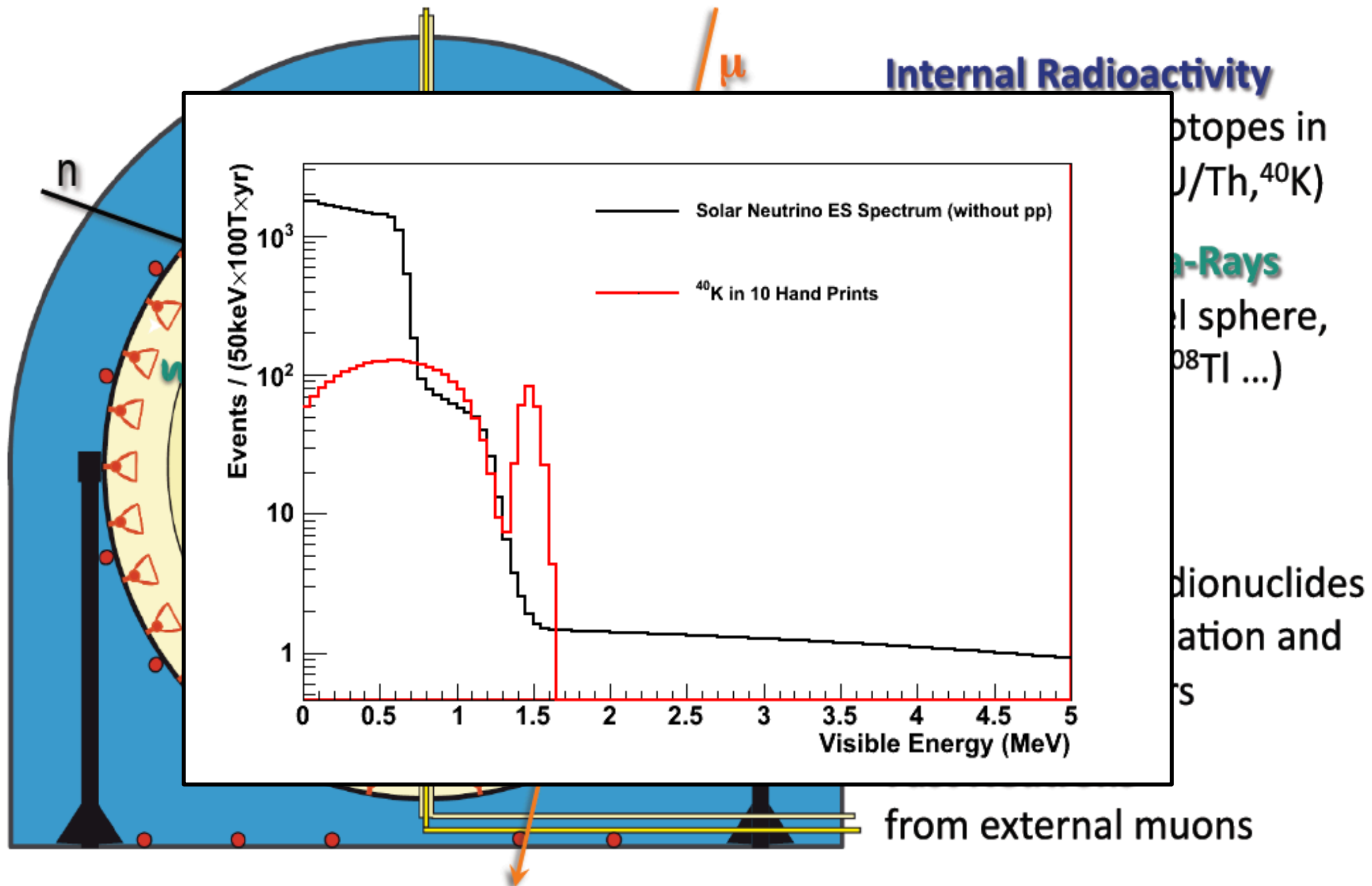
Cosmogenics

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.***



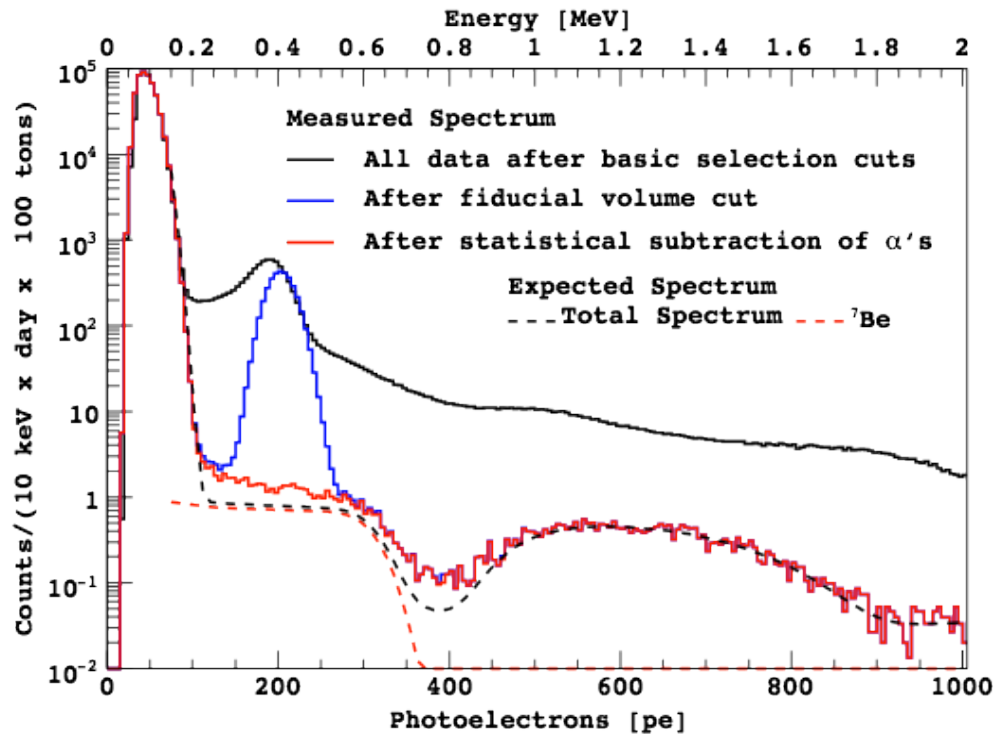
Image: Borexino Collaboration

The Counting Test Facility III

Contaminant	Source	Normal Conc.	Borex Req.	Reduction Method	Borex Achieved
μ	Cosmic	200/(s·m ²)	10 ⁻¹⁰ / (s·m ²)	Underground, active veto	<10 ⁻¹⁰ /(s·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 ^7Be Result

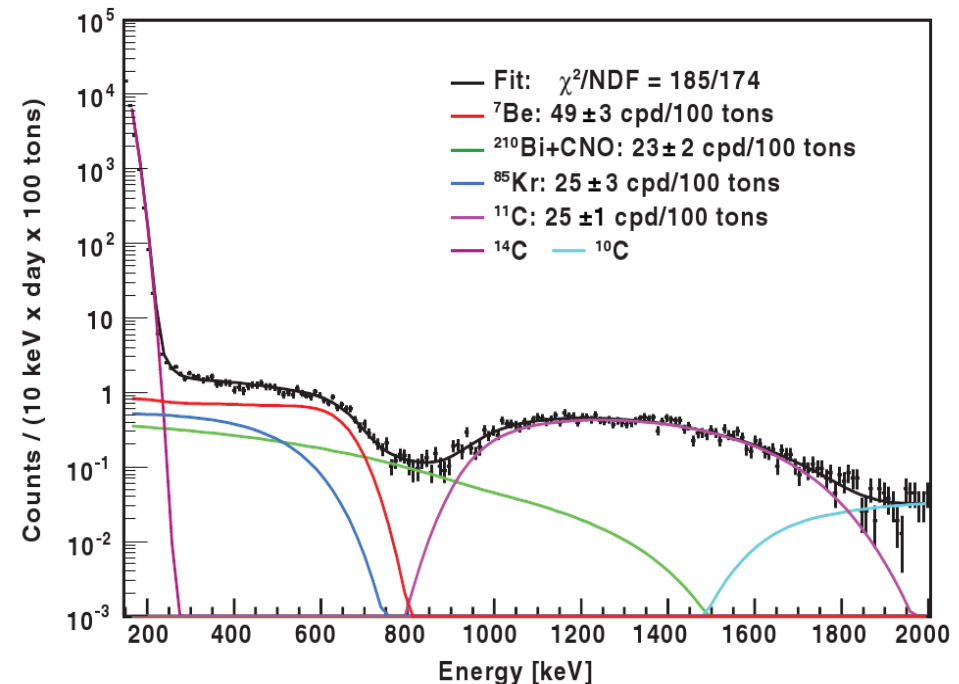
(PRL 101 9 (2008))



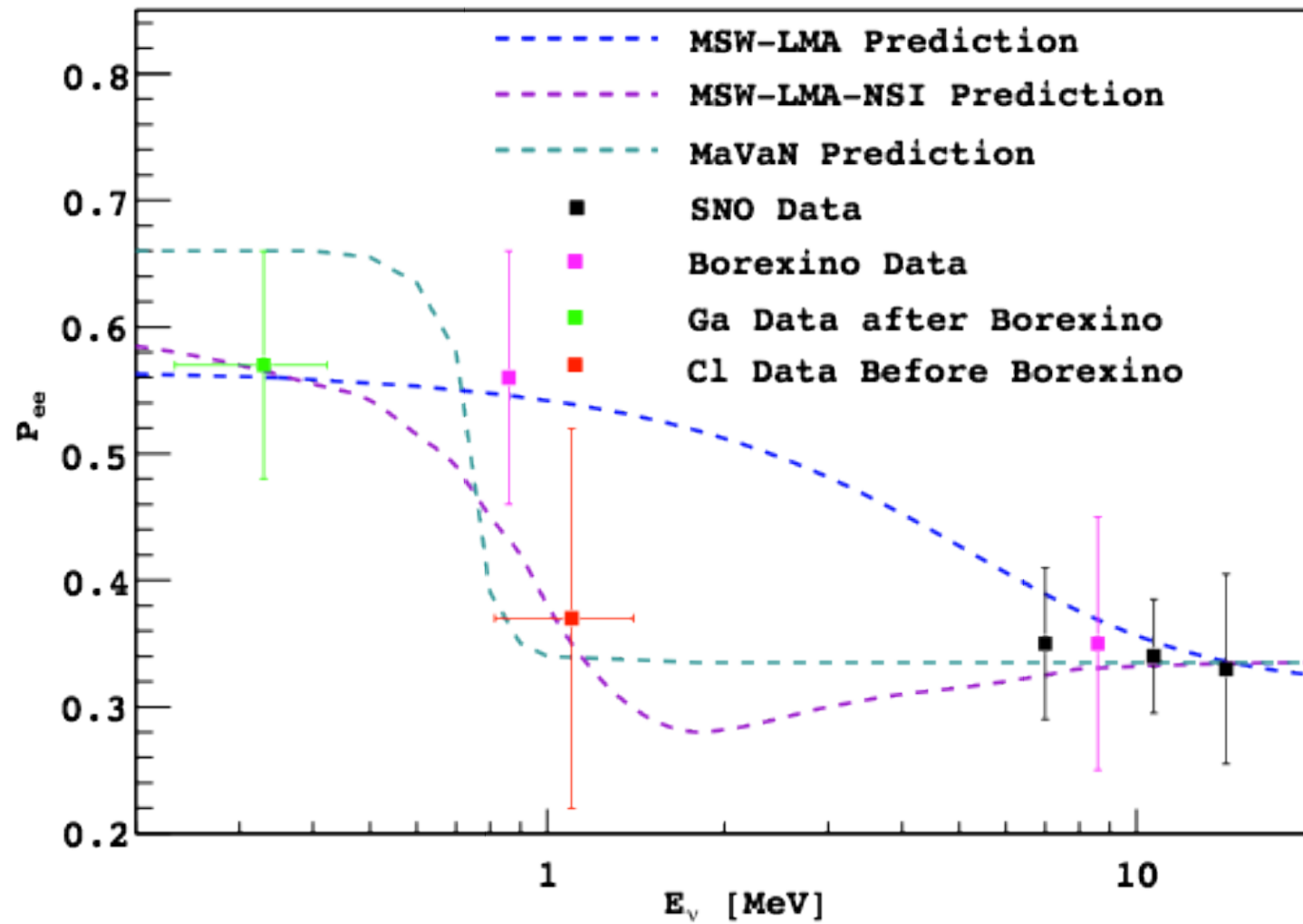
0.862 MeV ^7Be Result:
 $49 \pm 3_{\text{stat}} \pm 4_{\text{sys}}$ cpd/100T

Compare with SSM
(BS06, High Metallicity):

$$P_{\text{ee}} = 0.56 \pm 0.1$$

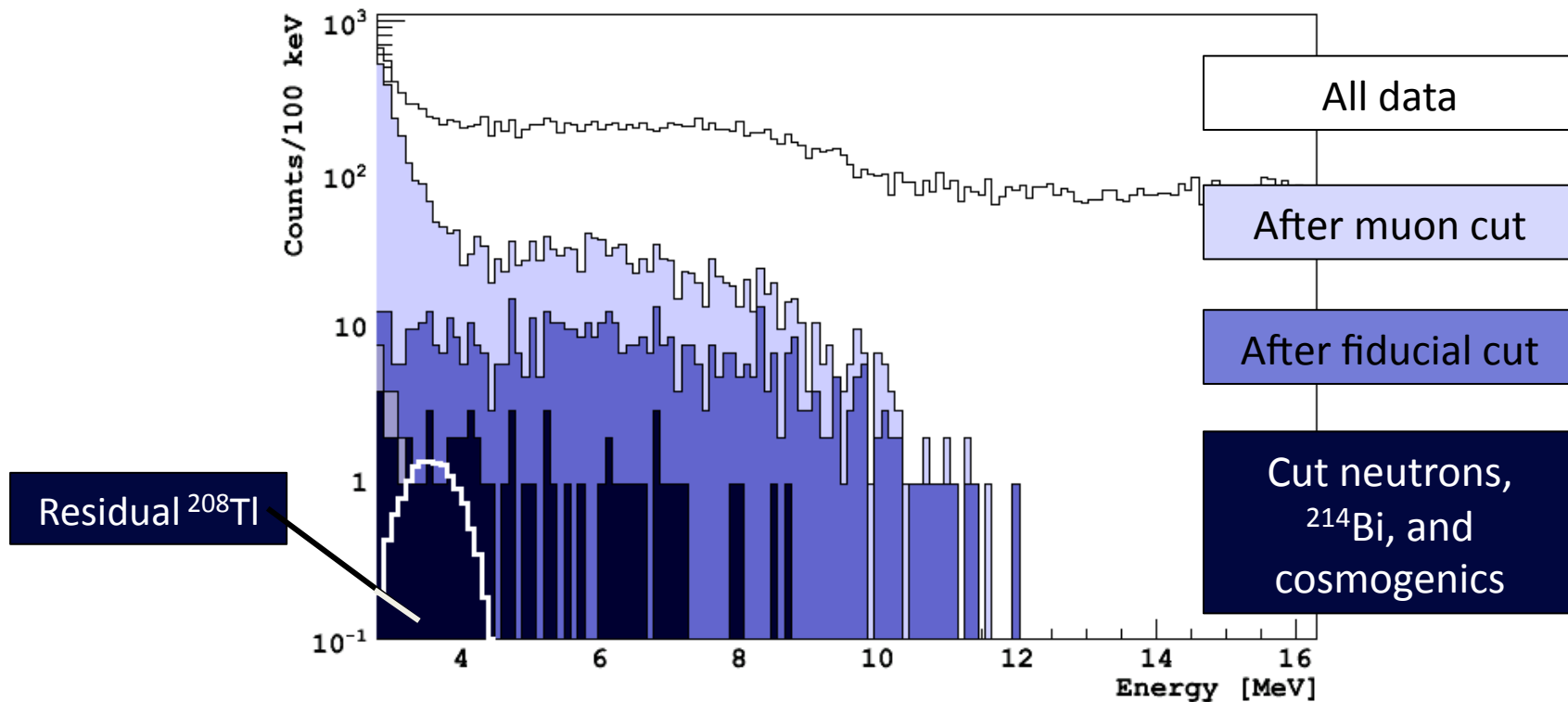


Solar Neutrino Survival Probability



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

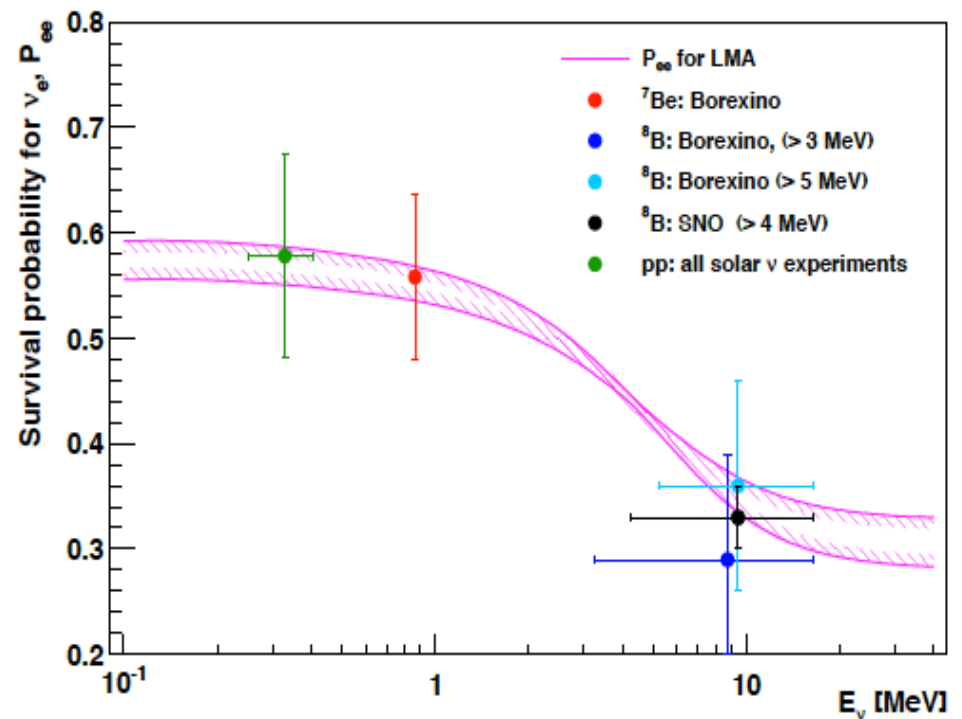
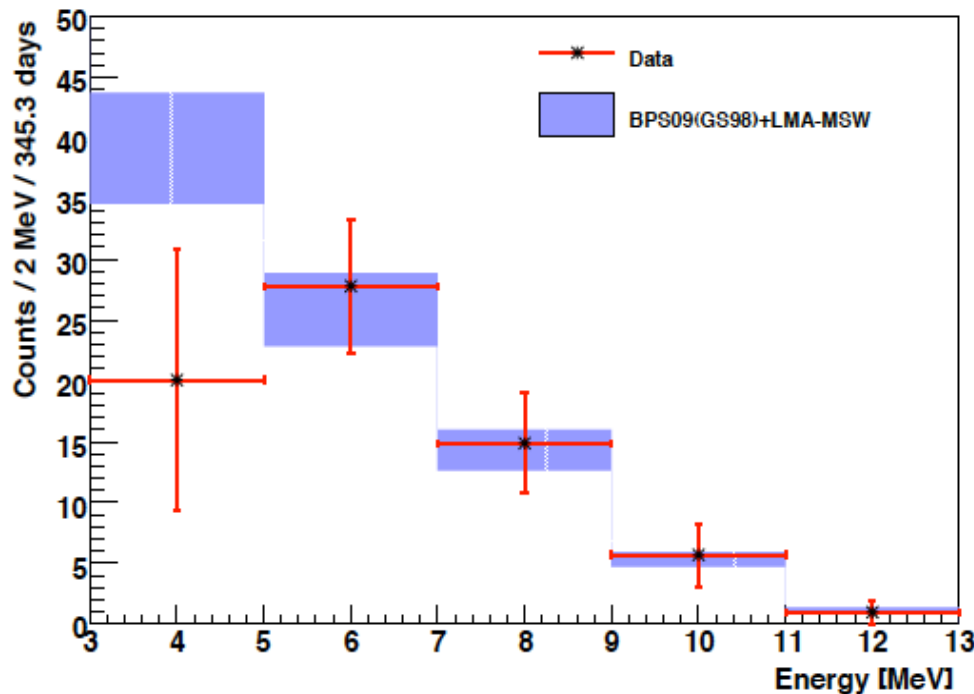
Sum Residuals

^8B Counting Rate (245 live days):

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

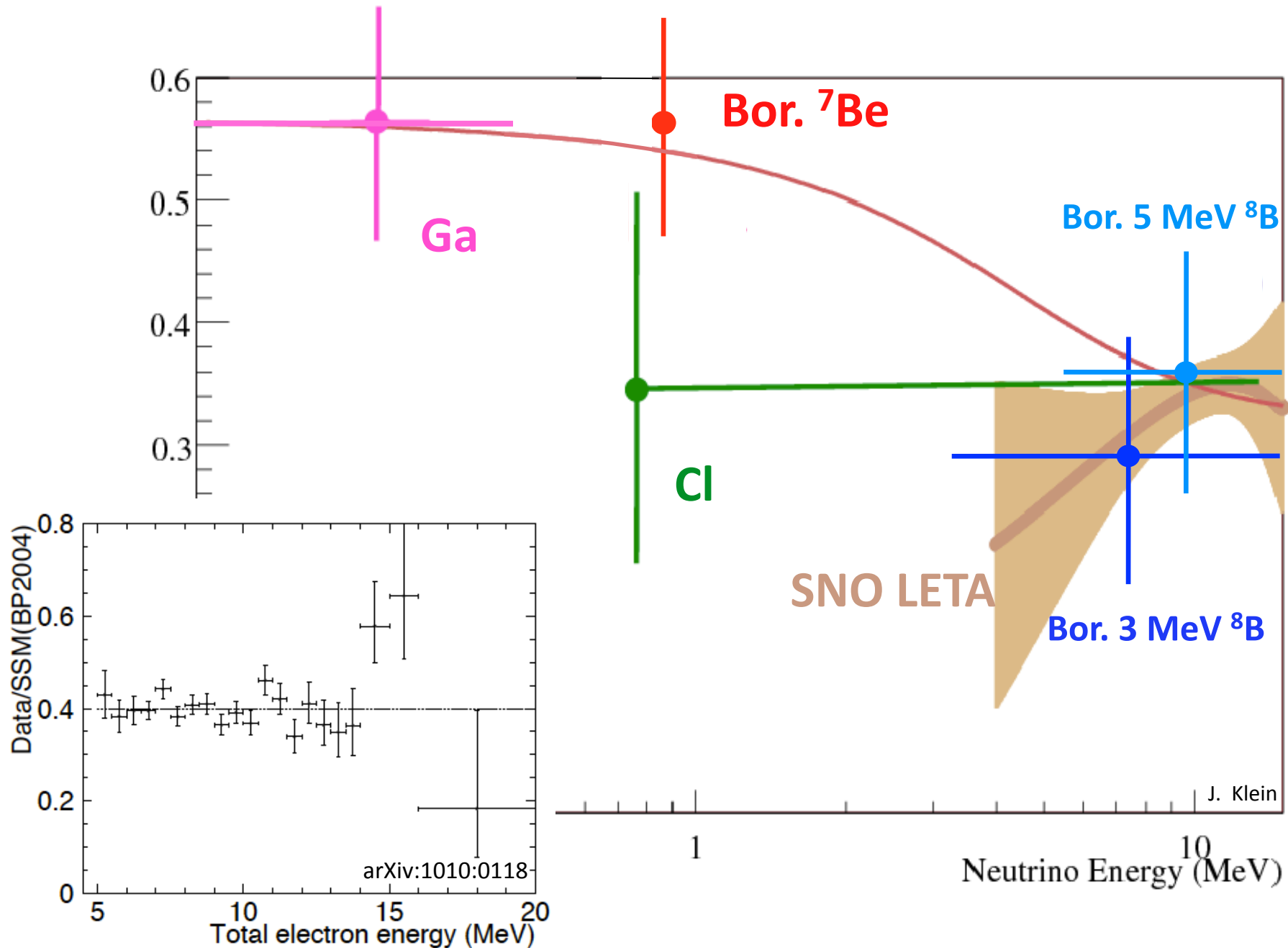
>5 MeV: $0.134 \pm 0.022(\text{stat})^{+0.008}_{-0.007}(\text{syst}) \text{ c/d/100 t}$

Borexino ES Spectrum



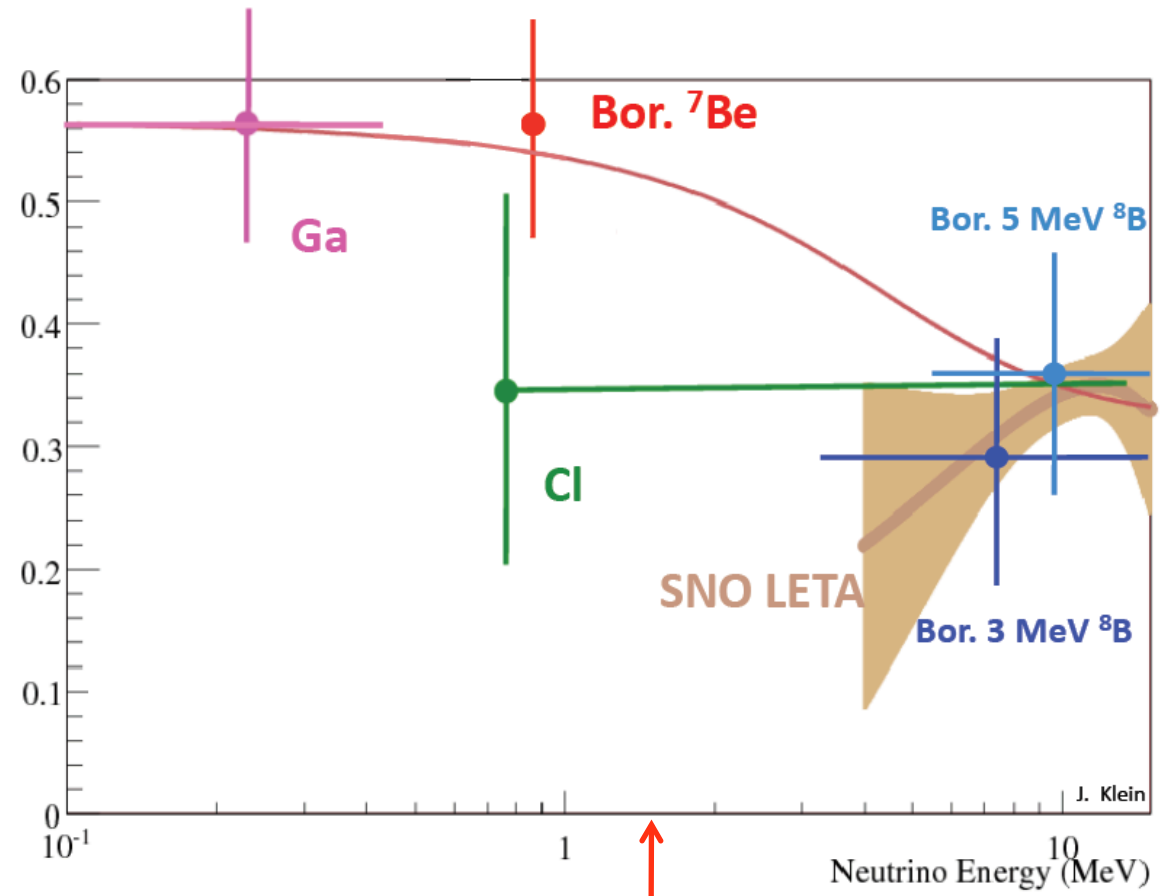
Beginning to test MSW with a single experiment:
Borexino ^7Be and ^8B P_{ee} 's differ by 1.9σ

Summary of Current Status



How to Proceed?

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



pep neutrinos:
 $\pm < 2\%$ SSM flux prediction

Experiment	Detection Reaction	Targeted Solar ν s	Technology	Other Physics	Status
KamLAND	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	${}^7\text{Be}$, CNO, pep	Liq. scintillator	Reactor ν s, geo- ν s	Purification underway
SNO+	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pep, CNO	Liq. scintillator	$0\nu\beta\beta$, geo- ν s	Engineering, purification
LENS	$\nu_e + {}^{115}\text{In} \rightarrow e^- + 2\gamma + {}^{115}\text{Sn}$	pp, ${}^7\text{Be}$, 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, $0\nu\beta\beta$	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	$\nu_e + {}^{100}\text{Mo} \rightarrow e^- + {}^{100}\text{Tc}$	pp, ${}^7\text{Be}$, pep	Scintillator/ Fiber sandwich	$0\nu\beta\beta$	Prototype for $0\nu\beta\beta$
MUNU/TPC	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp, ${}^7\text{Be}$, pep, CNO	CF ₄ 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, $0\nu\beta\beta$	Design and simulation
Mega-H₂O	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	${}^8\text{B}$, hep	H ₂ O Cerenkov	P-dk, LBL ν s	Design, sim.

J. Klein, Neutrino '08

Plus more from Borexino and SuperK....

Experiment	Detection Reaction	Targeted Solar ν s	Technology	Other Physics	Status
KamLAND	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	${}^7\text{Be}$, CNO, pep	Liq. scintillator	Reactor ν s, geo- ν s	Purification underway
SNO+	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pep, CNO	Liq. scintillator	$0\nu\beta\beta$, geo- ν s	Engineering, purification
LENS	$\nu_e + {}^{115}\text{In} \rightarrow e^- + 2\gamma + {}^{115}\text{Sn}$	pp, ${}^7\text{Be}$, 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, $0\nu\beta\beta$	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	$\nu_e + {}^{100}\text{Mo} \rightarrow e^- + {}^{100}\text{Tc}$	pp, ${}^7\text{Be}$, pep	Scintillator/ Fiber sandwich	$0\nu\beta\beta$	Prototype for $0\nu\beta\beta$
MUNU/TPC	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp, ${}^7\text{Be}$, pep, CNO	CF ₄ TPC	μ_ν (reactor)	μ_ν results, recon studies
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XAX	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryo. Xe+Ar	dark matter, $0\nu\beta\beta$	Design and simulation
Mega-H₂O	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	${}^8\text{B}$, hep	H ₂ O Cerenkov	P-dk, LBL ν s	Design, sim.

J. Klein, Neutrino '08

Plus more from **Borexino** and SuperK....

Improving the Borexino ^7Be Result

Current Result:

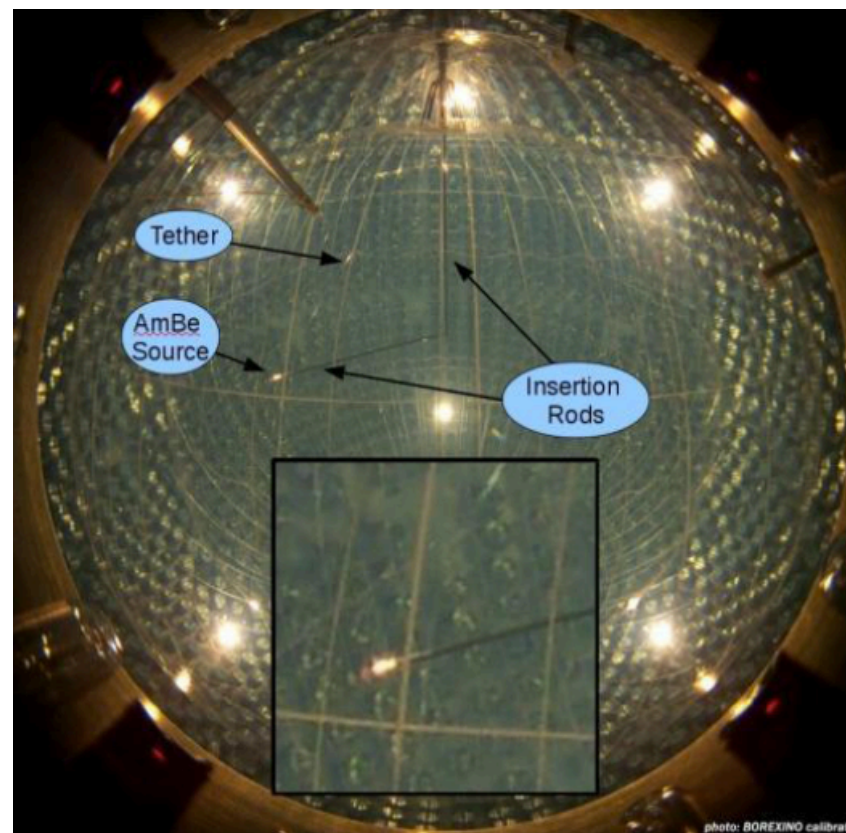
$$49 \pm 3_{\text{stat}} \pm 4_{\text{sys}} \text{ cpd/100T}$$

New Analysis: aim for 5% total uncertainty

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

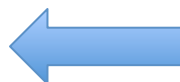
More than twice as much data

Source calibration campaigns

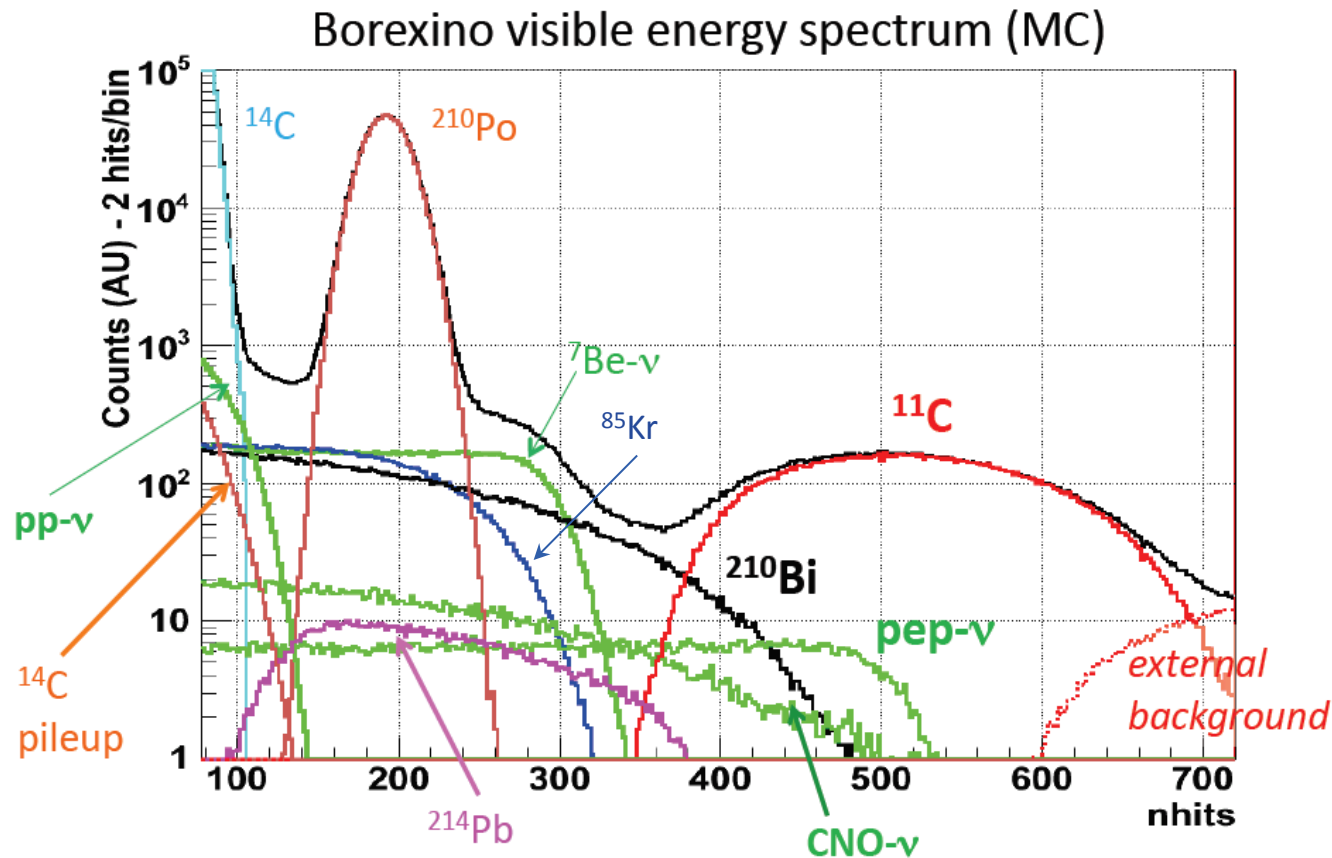


^8B result after calibrations:

Detector response	$\pm 3.5\%$
Fiducial volume	$\pm 3.8\%$



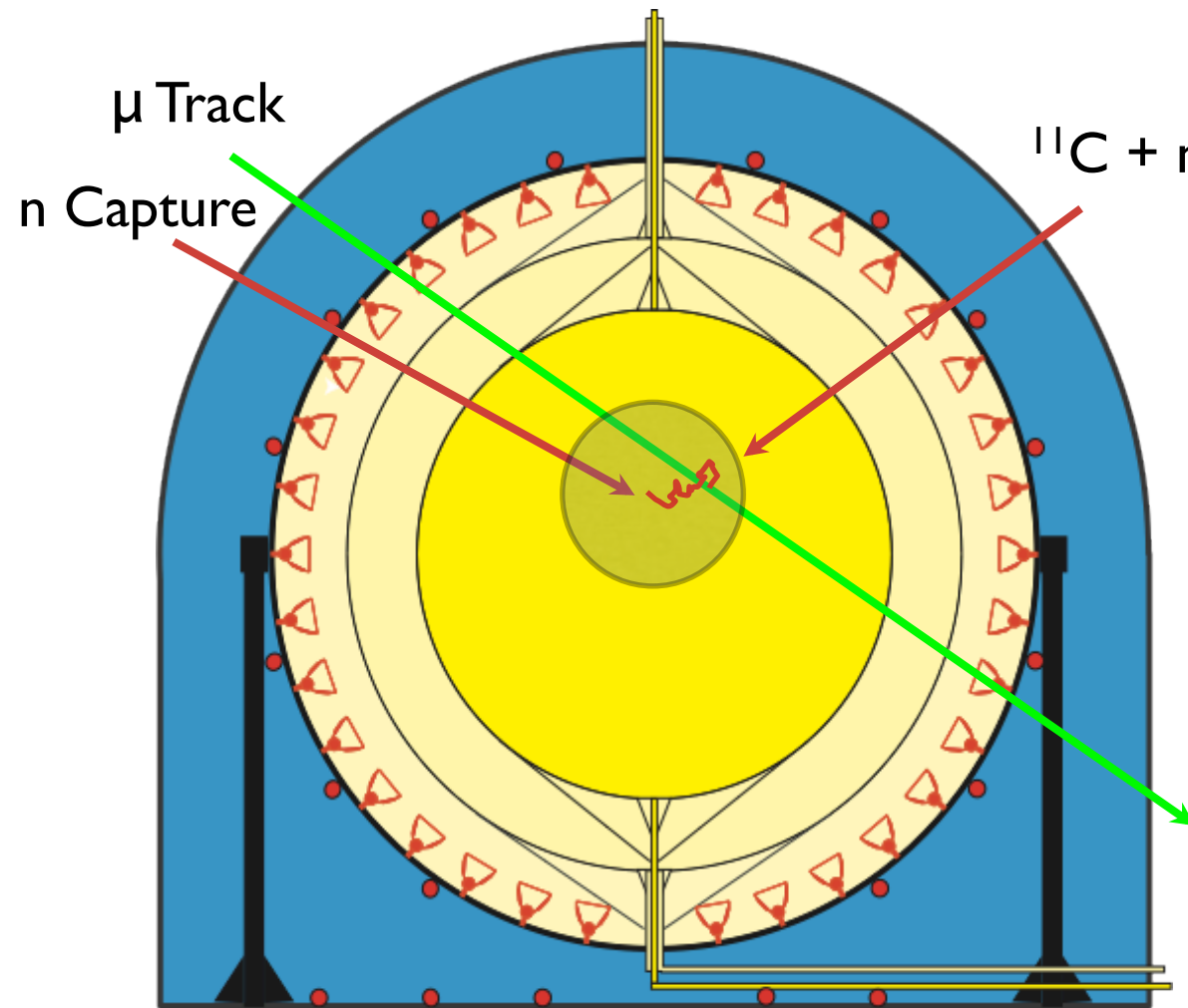
pep neutrinos in Borexino: ^{11}C Suppression



- ^{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!

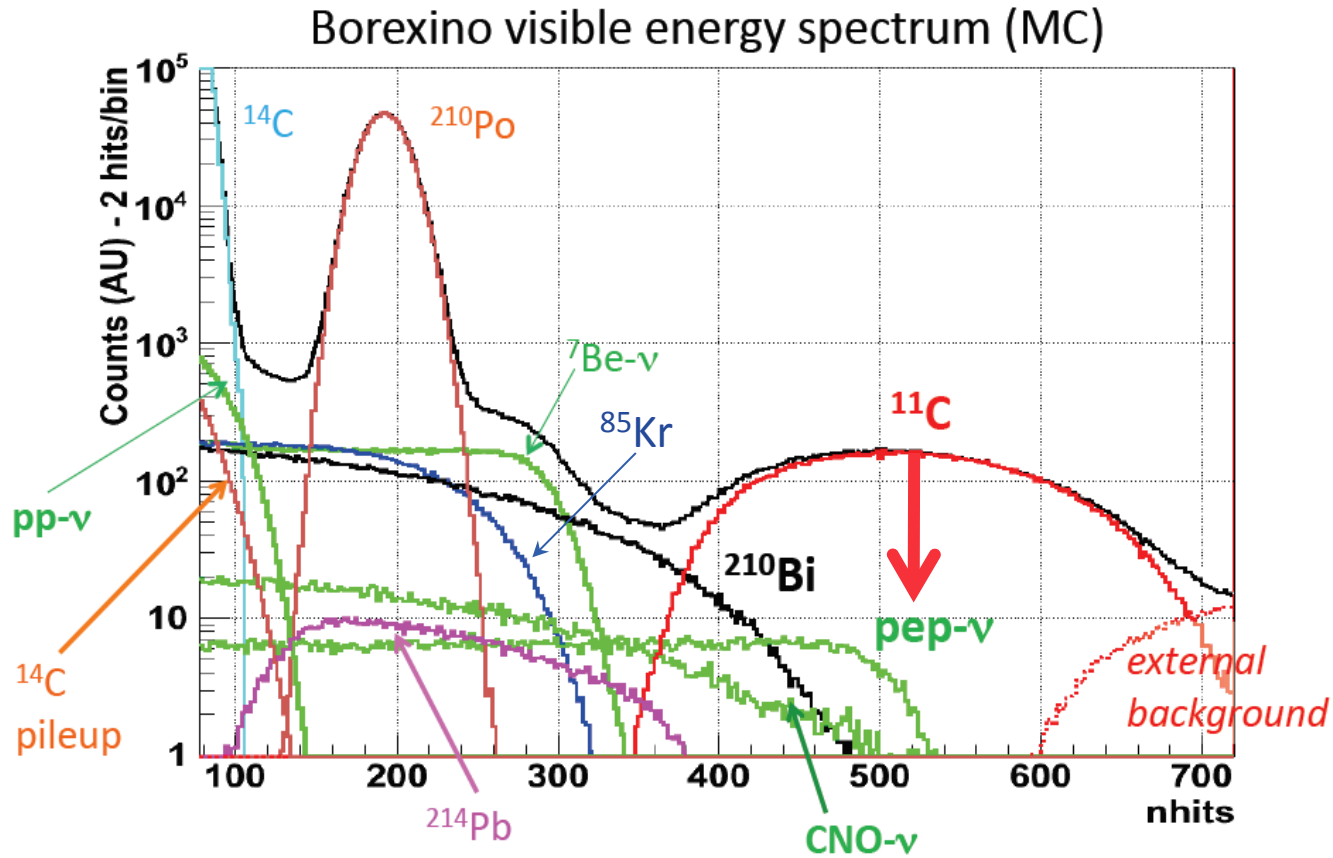
pep neutrinos in Borexino: ^{11}C Suppression



- 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

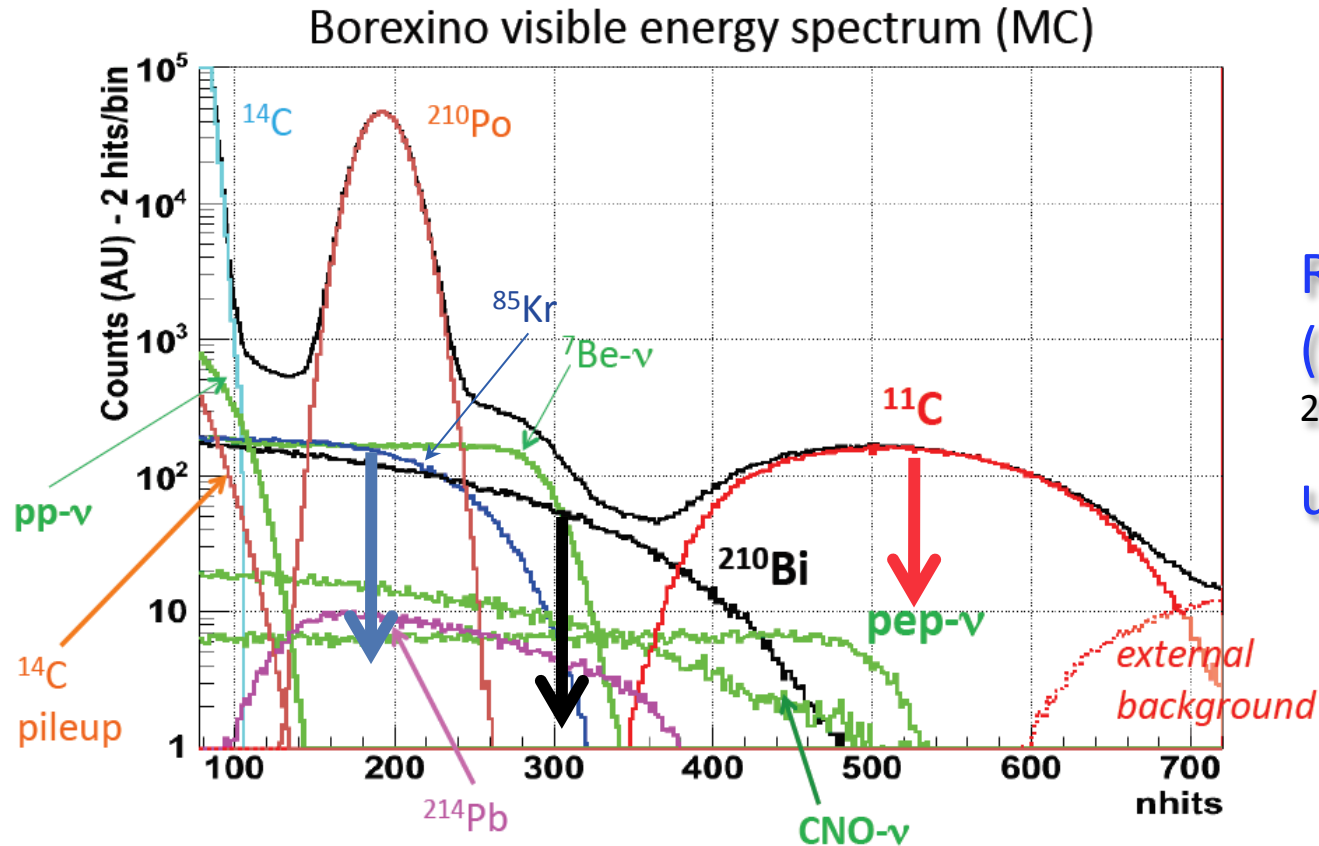
The ~ 125 muon-neutron coincidences/day (of which ~ 25 accompany ^{11}C production) can be vetoed without excessive loss of live time.

pep neutrinos in Borexino: ¹¹C Suppression



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

Borexino Future



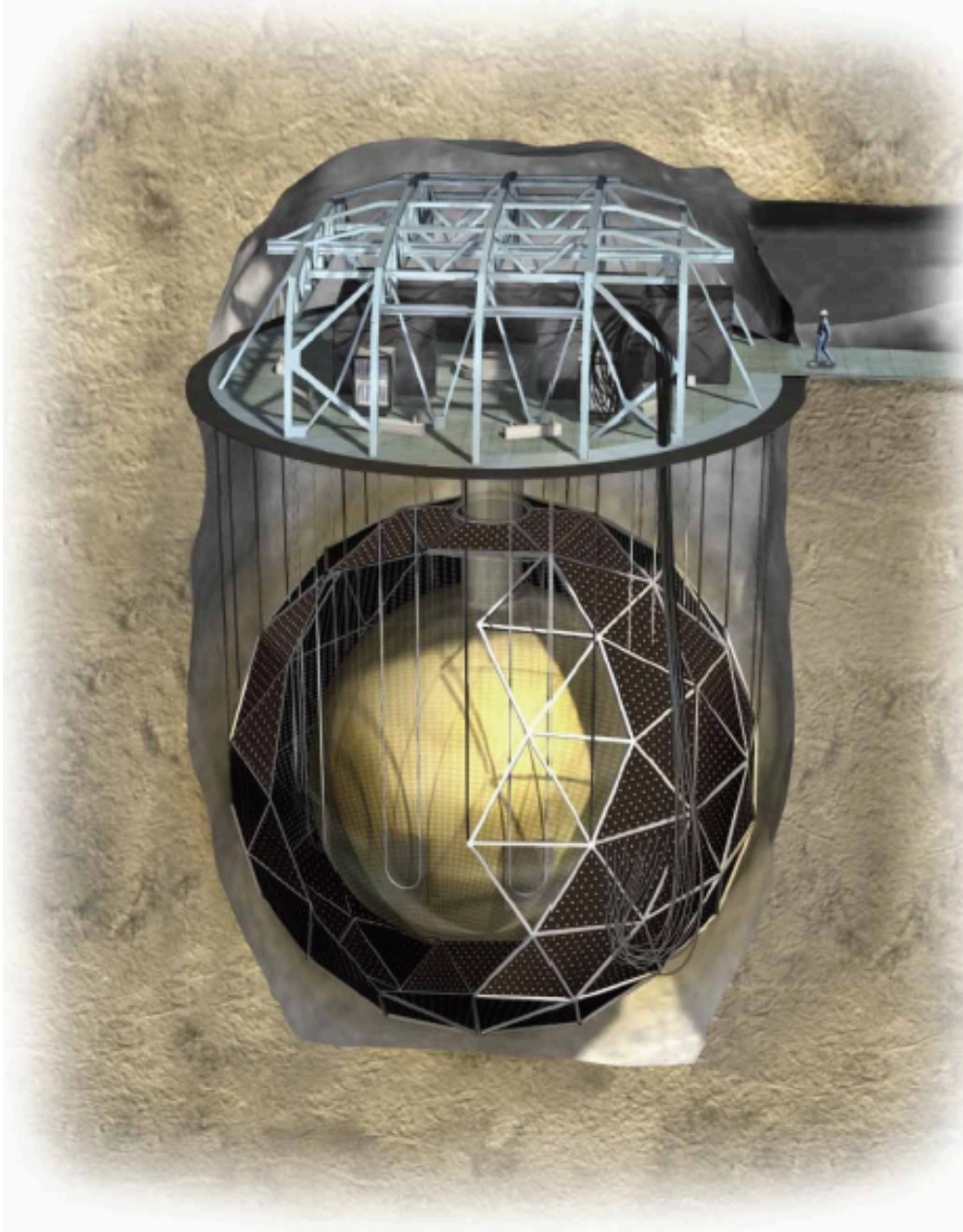
Re-purification to
(further!) reduce
²¹⁰Bi, ⁸⁵Kr, etc is
underway

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!

Beyond Borexino: SNO+

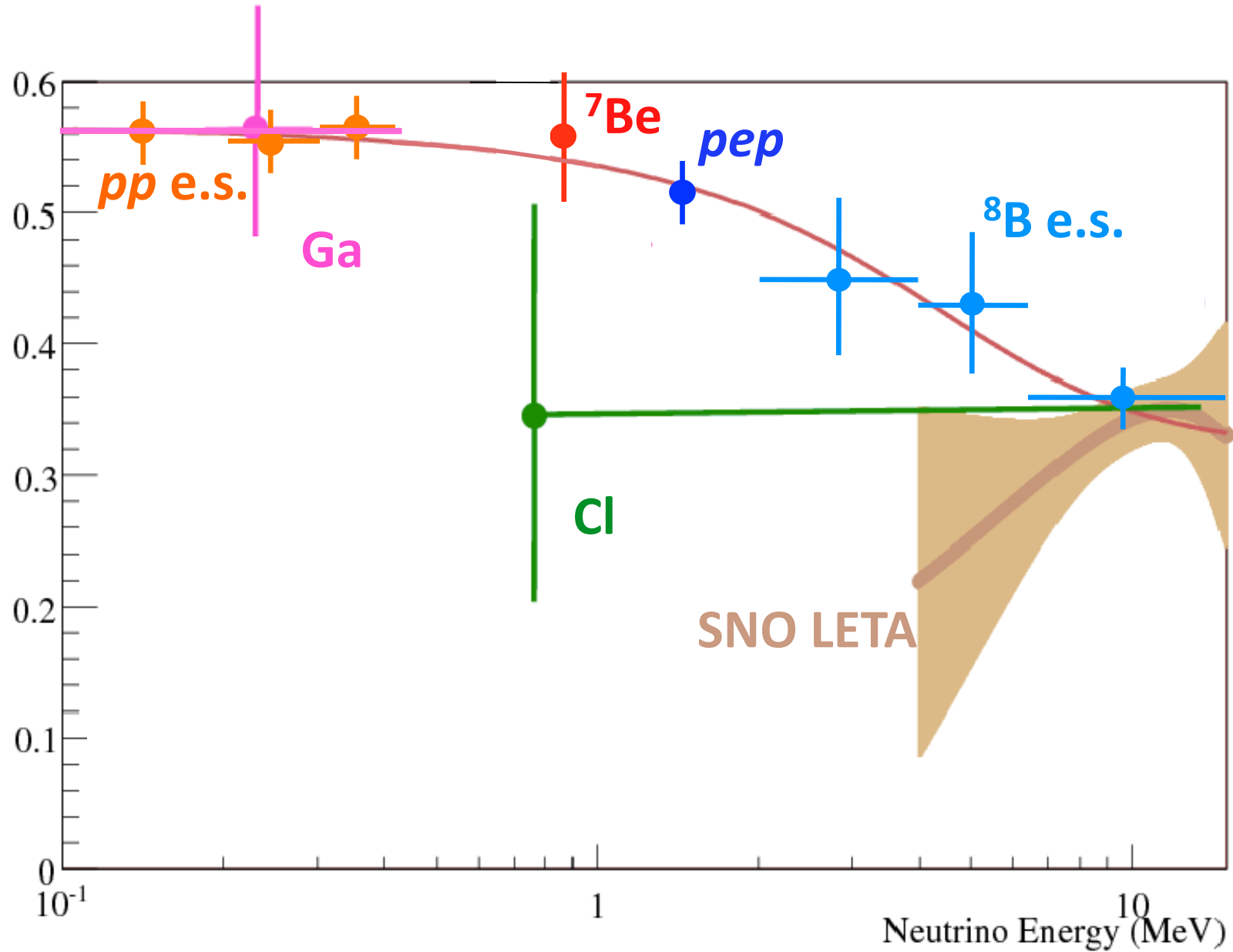


- Refill the SNO detector with liquid scintillator
 - 850T gives high statistics (~3 times Borexino)
- 6,000 m.w.e. gives much lower muon flux
 - ~ 55 ^{11}C events / 100T / yr
- SNO+ can measure the *pep* flux to high precision (<5%), along with CNO, ^7Be and low energy ^8B
- Data taking in 2012

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...

