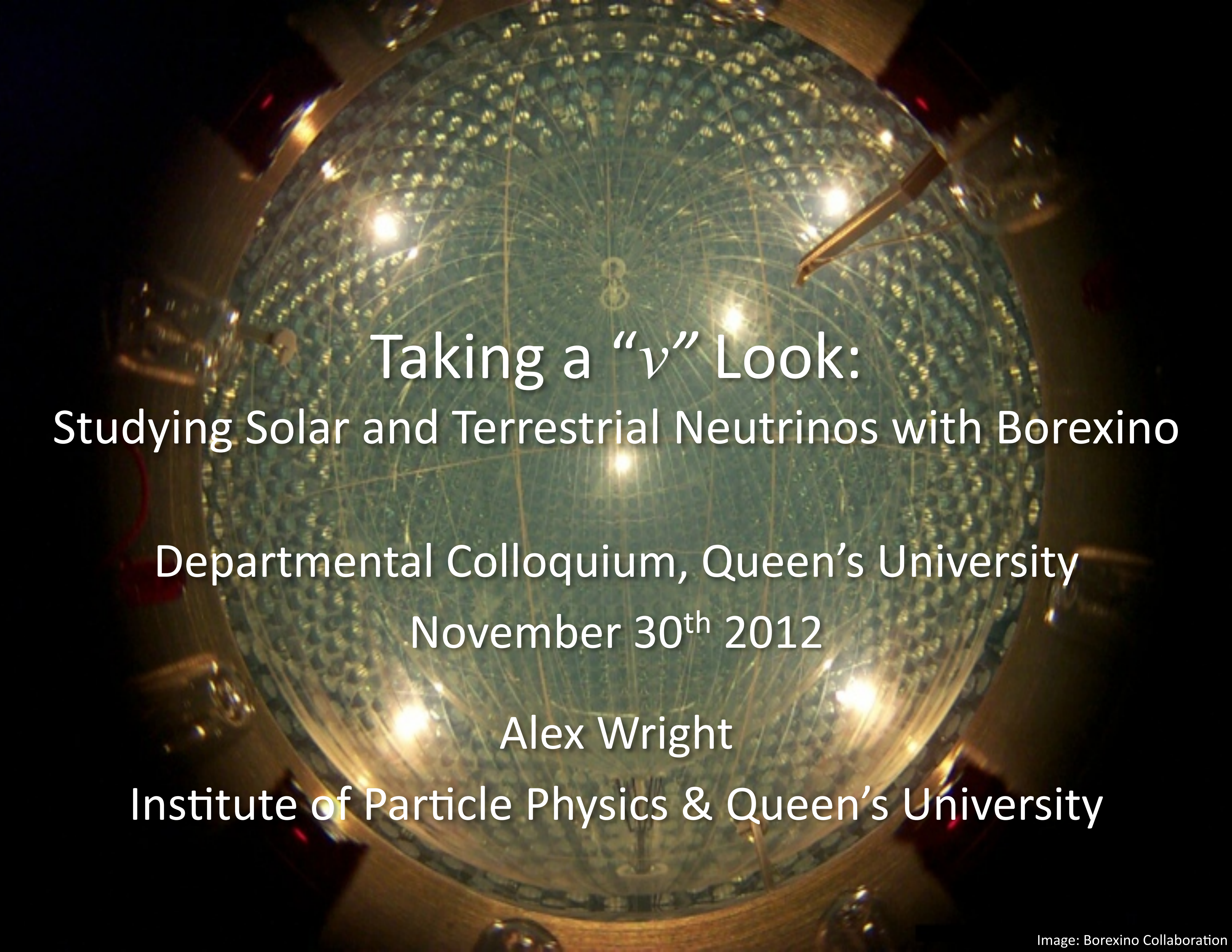


Taking a “ν” Look:

Studying Solar and Terrestrial Neutrinos with Borexino

Departmental Colloquium, Queen’s University

November 30th 2012

Alex Wright

Institute of Particle Physics & Queen’s University

Image: Borexino Collaboration

Outline

- Neutrinos and neutrino oscillations
- Borexino
- Solar neutrino results
- Geo-neutrinos
- Outlook

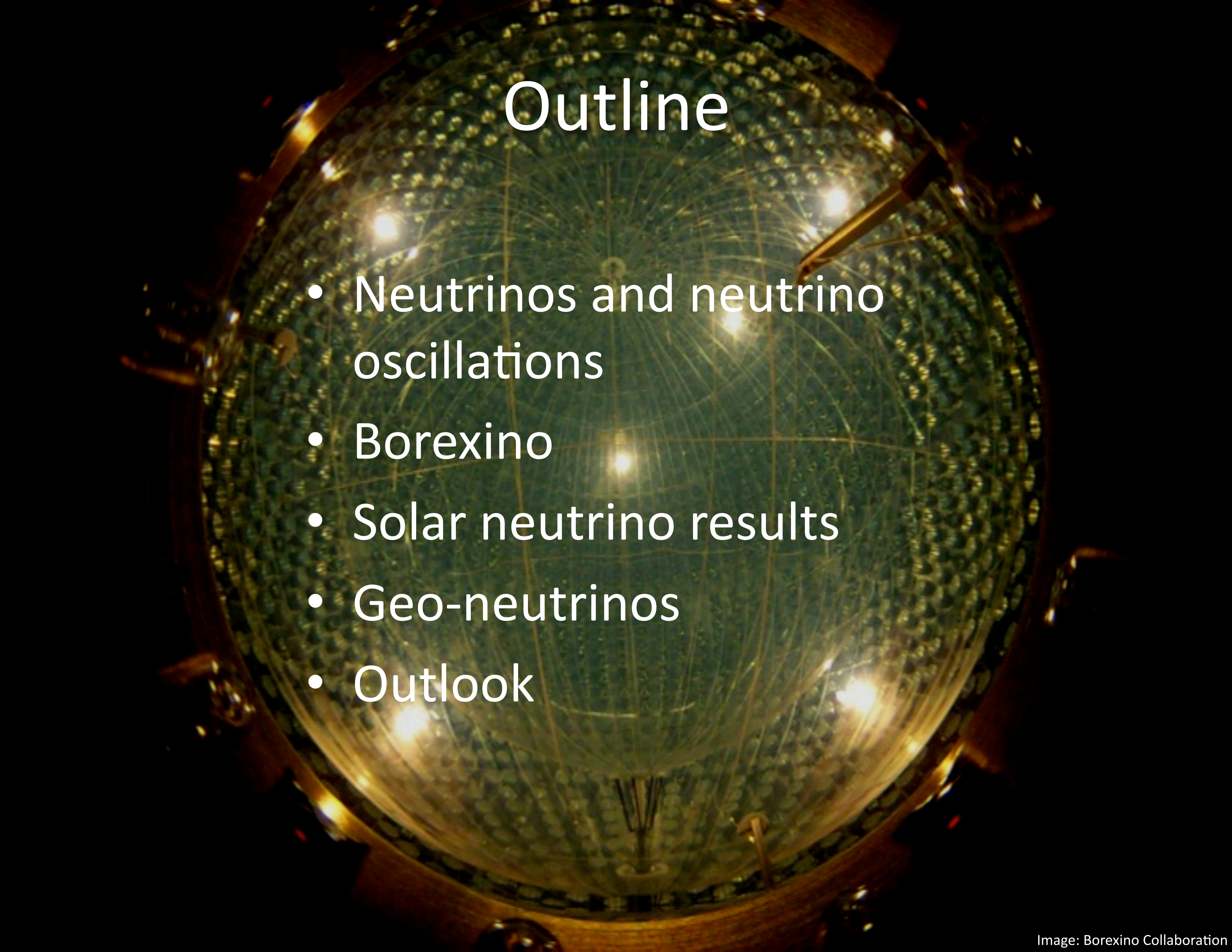
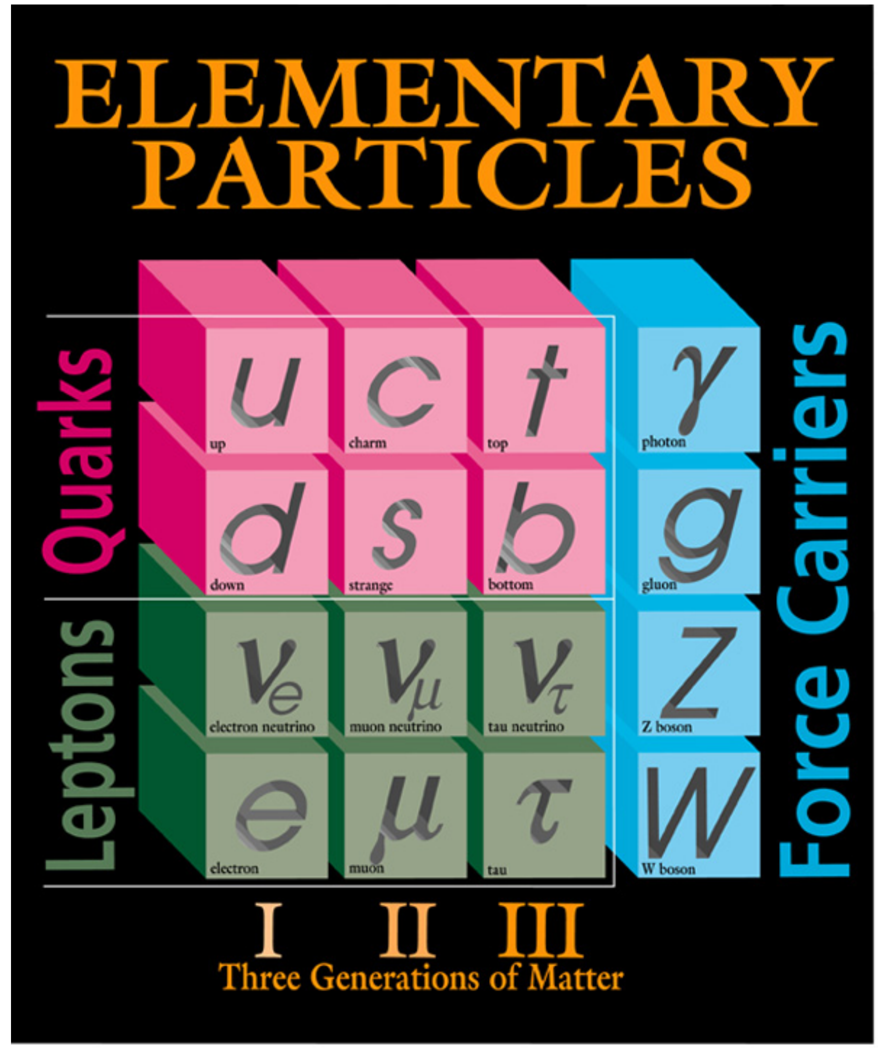


Image: Borexino Collaboration

Neutrinos

- Neutral fundamental fermions
- Weakly interacting
  - Typical cross sections of order $10^{-45}cm^2$
- Three neutrino "flavours"
  - Defined by interactions with charged leptons



Fermilab 95-759

Neutrinos From the Sun

p-p Solar Fusion Chain

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

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

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

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

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

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

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

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

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

$^{8}B \rightarrow 2\,{}^{4}He + e^{+} + \nu_e$

CNO Solar Fusion Cycle

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

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

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

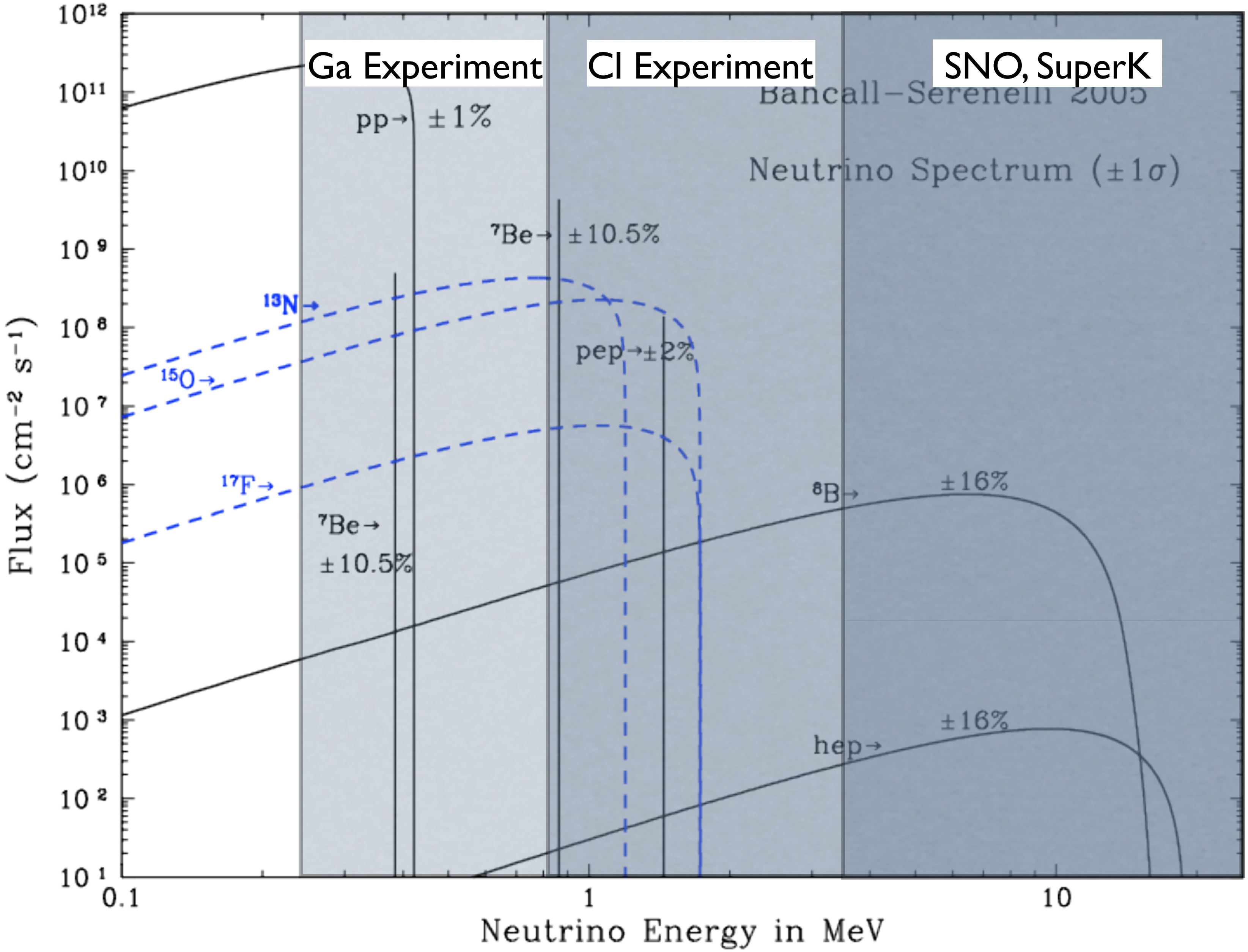
$^{14}N + p \rightarrow {}^{15}O + \gamma$

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

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

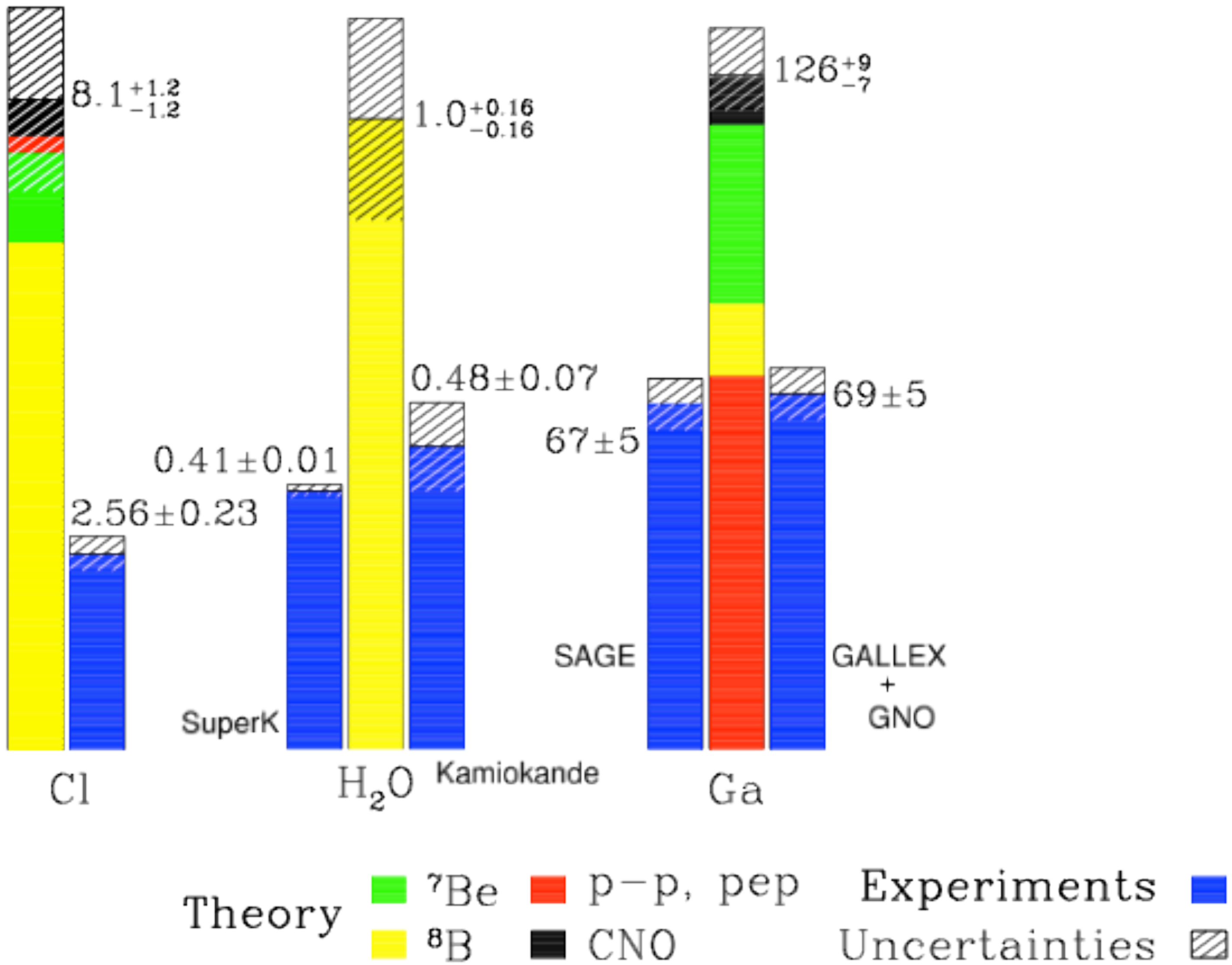
Image: bbc.co.uk

Neutrinos From the Sun



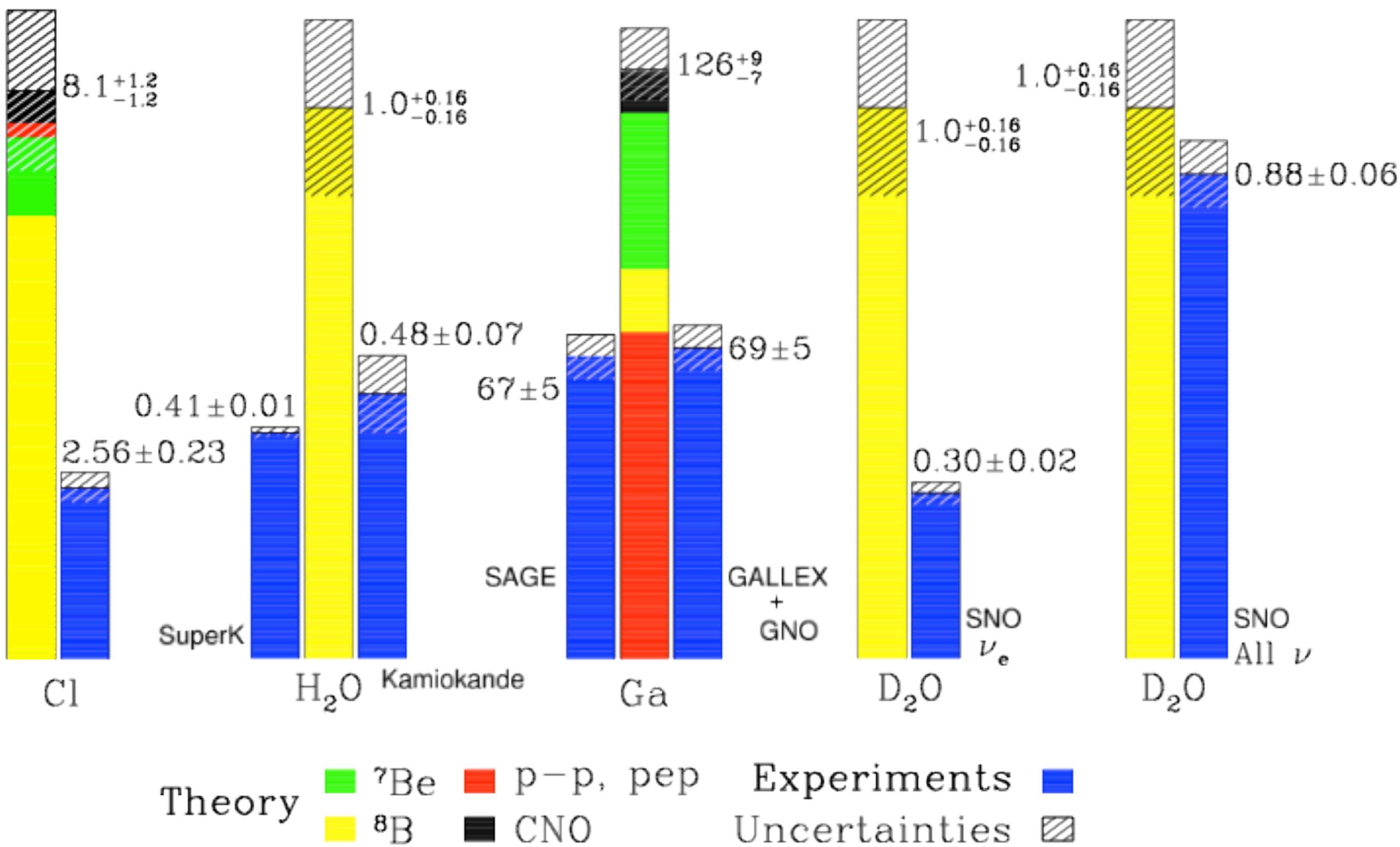
The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



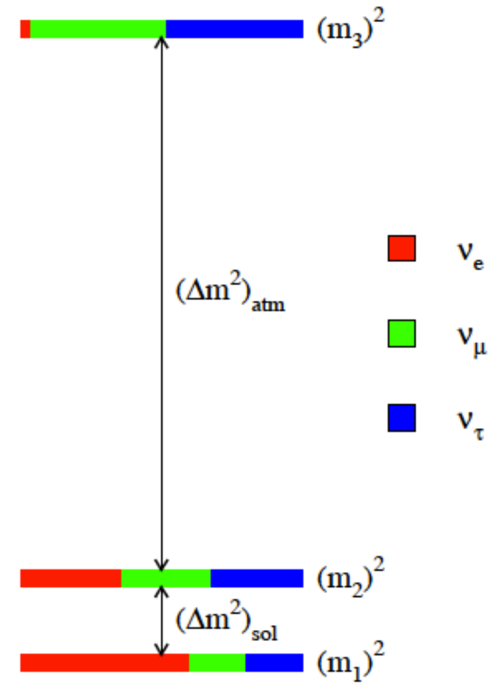
The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



Neutrino Oscillations

- Neutrino flavour and mass eigenstates "misaligned"
- Related by the PMNS matrix
  - Unitary mapping with 3 mixing angles (θ_{12}, θ_{13}, θ_{23}), perhaps two Majorana phases (α_1, α_2), and one CP violating phase (δ)



hep-ph/0411274

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$-s_{23}$ = -sin(θ_{23})

c_{13} = cos(θ_{13})

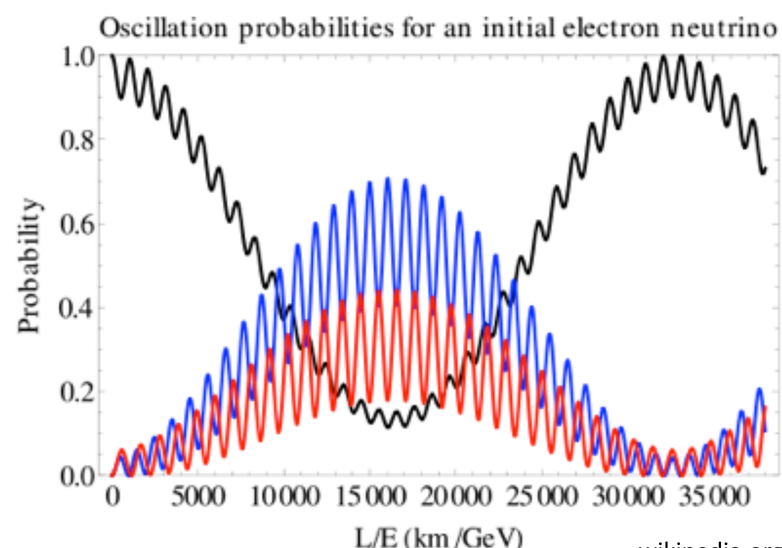
wikipedia.org

Neutrino Oscillations

- Producing a neutrino in a flavour eigenstate produces a superposition of mass eigenstates
- Phase differences acquired in mass eigenstate propagation change apparent flavour content:

$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m_{21}^2}{4\overline{p}}L\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{31}^2}{4\overline{p}}L\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{32}^2}{4\overline{p}}L\right)$$

Symmetry Magazine



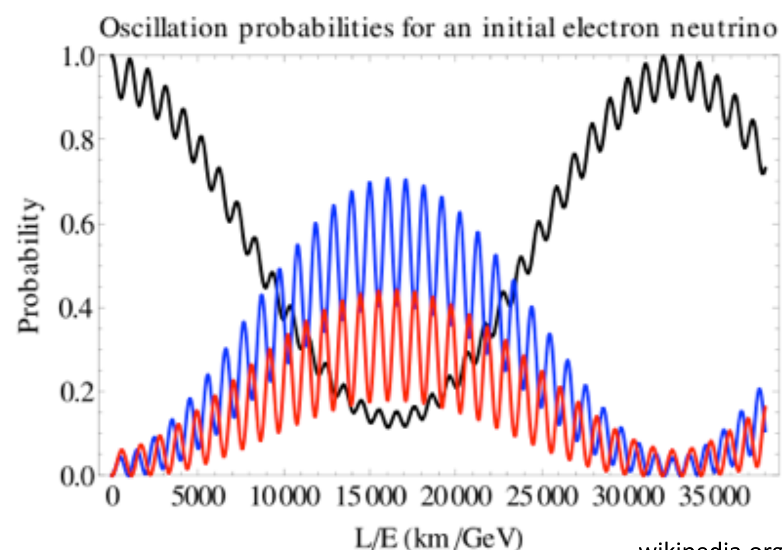
wikipedia.org

Neutrino Oscillations

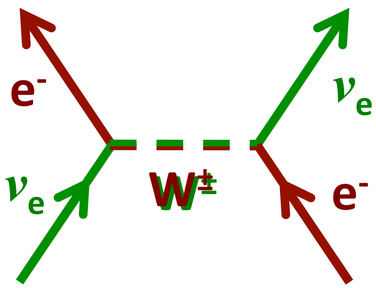
- Producing a neutrino in a flavour eigenstate produces a superposition of mass eigenstates
- Phase differences acquired in mass eigenstate propagation change apparent flavour content
- In solar neutrinos we see a phase averaged survival probability:

$$P_{ee} = \cos^4(\theta_{13}) \left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right)$$
$$+ \sin^4(\theta_{13})$$
$$\sim 1 - \frac{1}{2}\sin^2(2\theta_{12}) \qquad (\theta_{13} = 0)$$

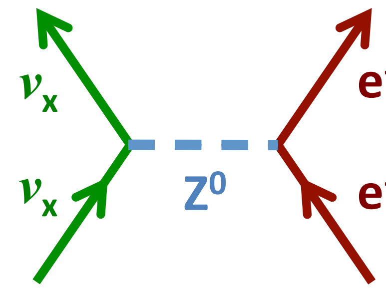
Symmetry Magazine



wikipedia.org



The Matter of Matter

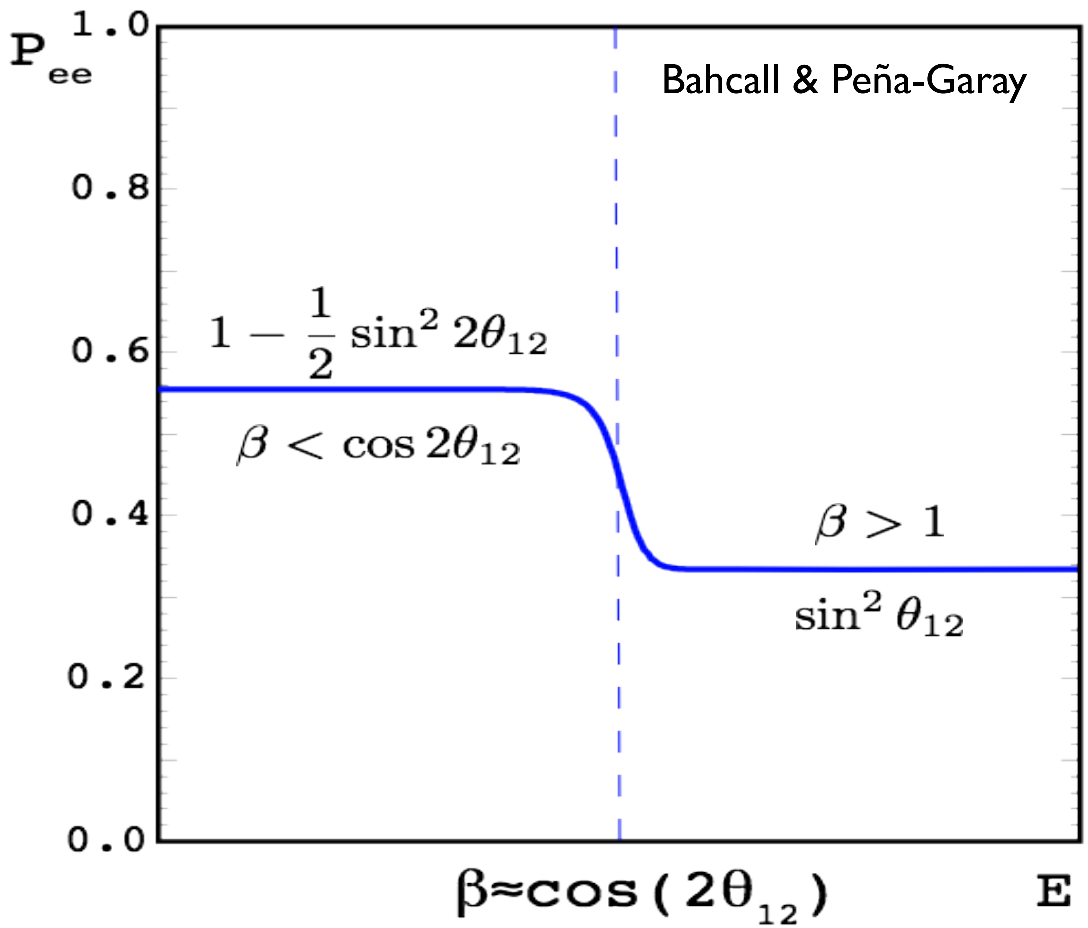


- When neutrinos propagate in matter, charged current interactions add an additional term to ν_e flavour in Hamiltonian mass matrix:

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

- Mikheyev-Smirnov-Wolfenstein effect: as neutrinos propagate out of the sun, the matter effect can lead to a resonant enhancement of the transition probability

MSW Oscillation Regimes

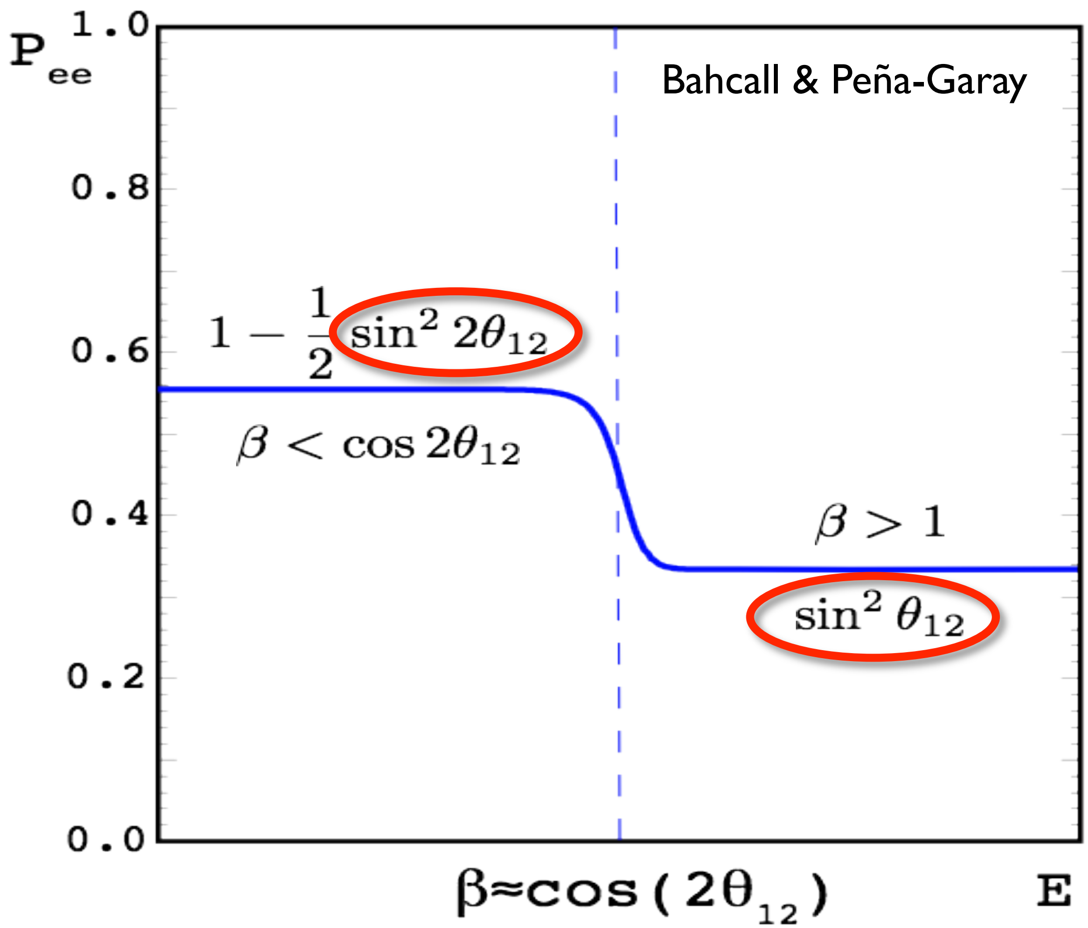


$$\beta = \frac{2^{3/2} G_F N_e}{\left(\frac{\Delta m^2}{E}\right)}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated "resonant conversion"

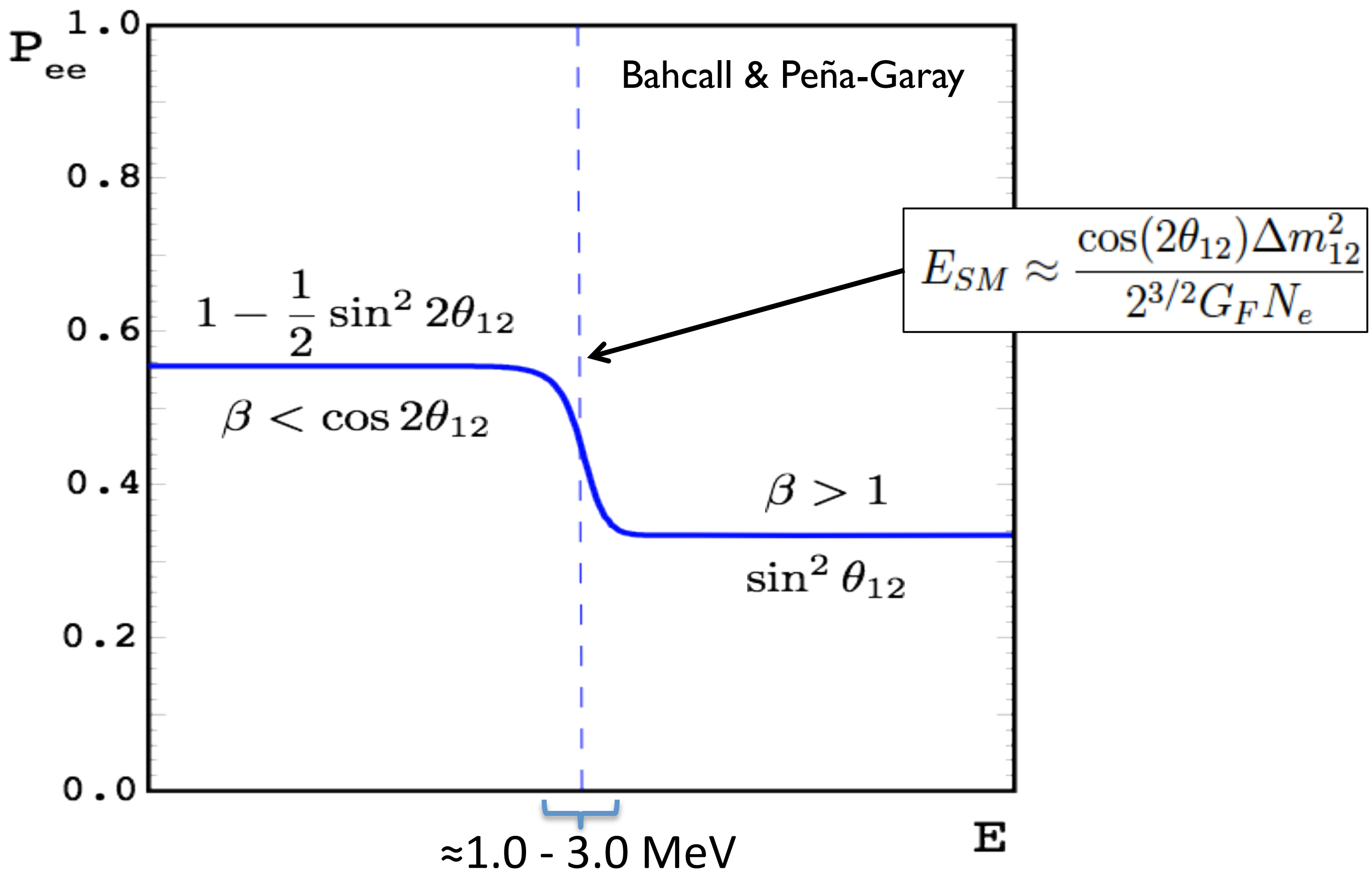
MSW Oscillation Regimes



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

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

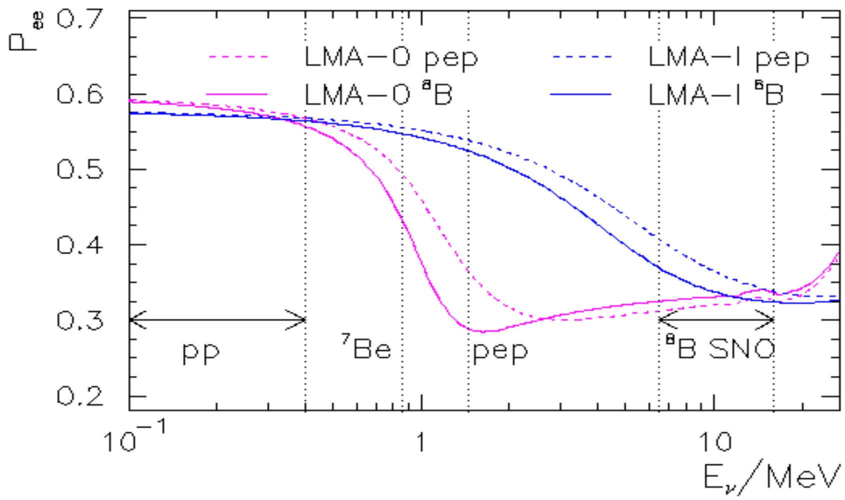


Look in "transition region" to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

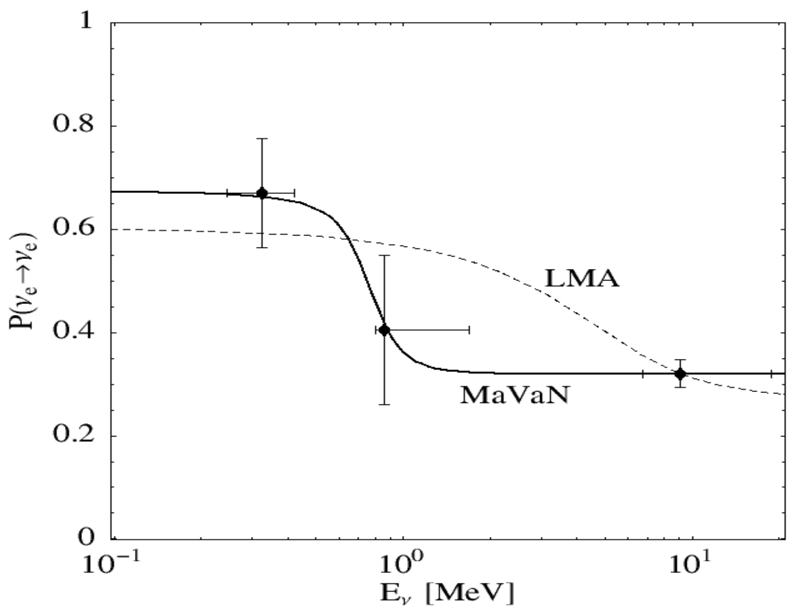
Non-Standard Interactions

Friedland *et al.*, PLB **594**:347 (2004)



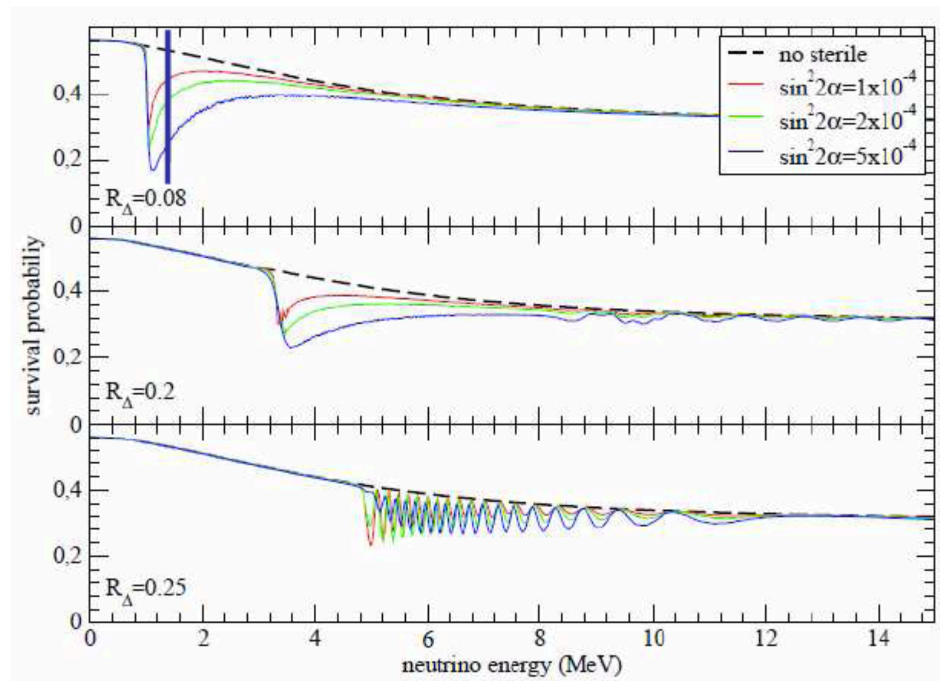
Mass Varying Neutrinos

Barger *et al*. PRL **95**:211802 (2005)

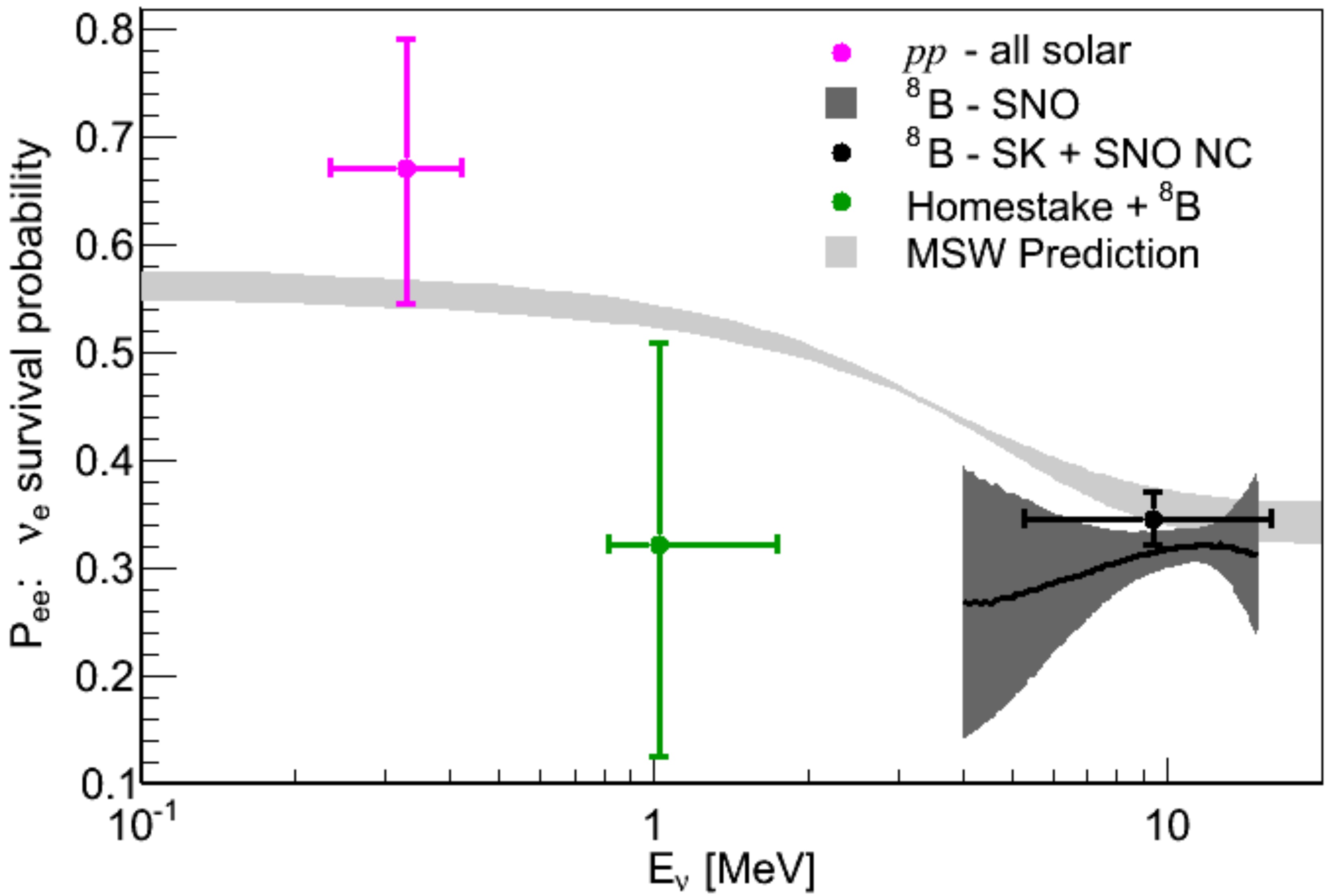


Sterile Neutrinos

de Holanda and Smirnov, PRD **83**:113011 (2011)

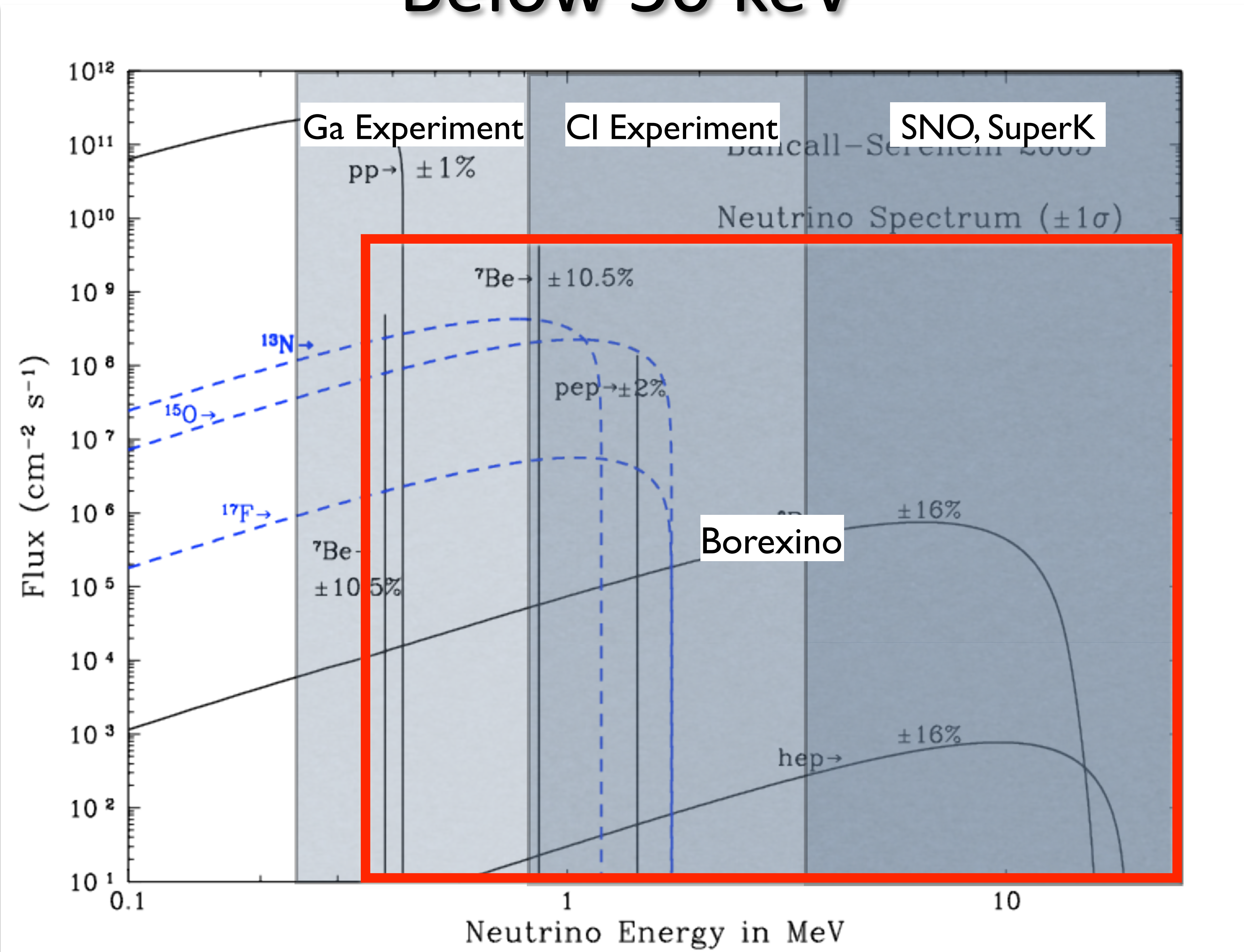


Constraints on Transition Region Without Borexino

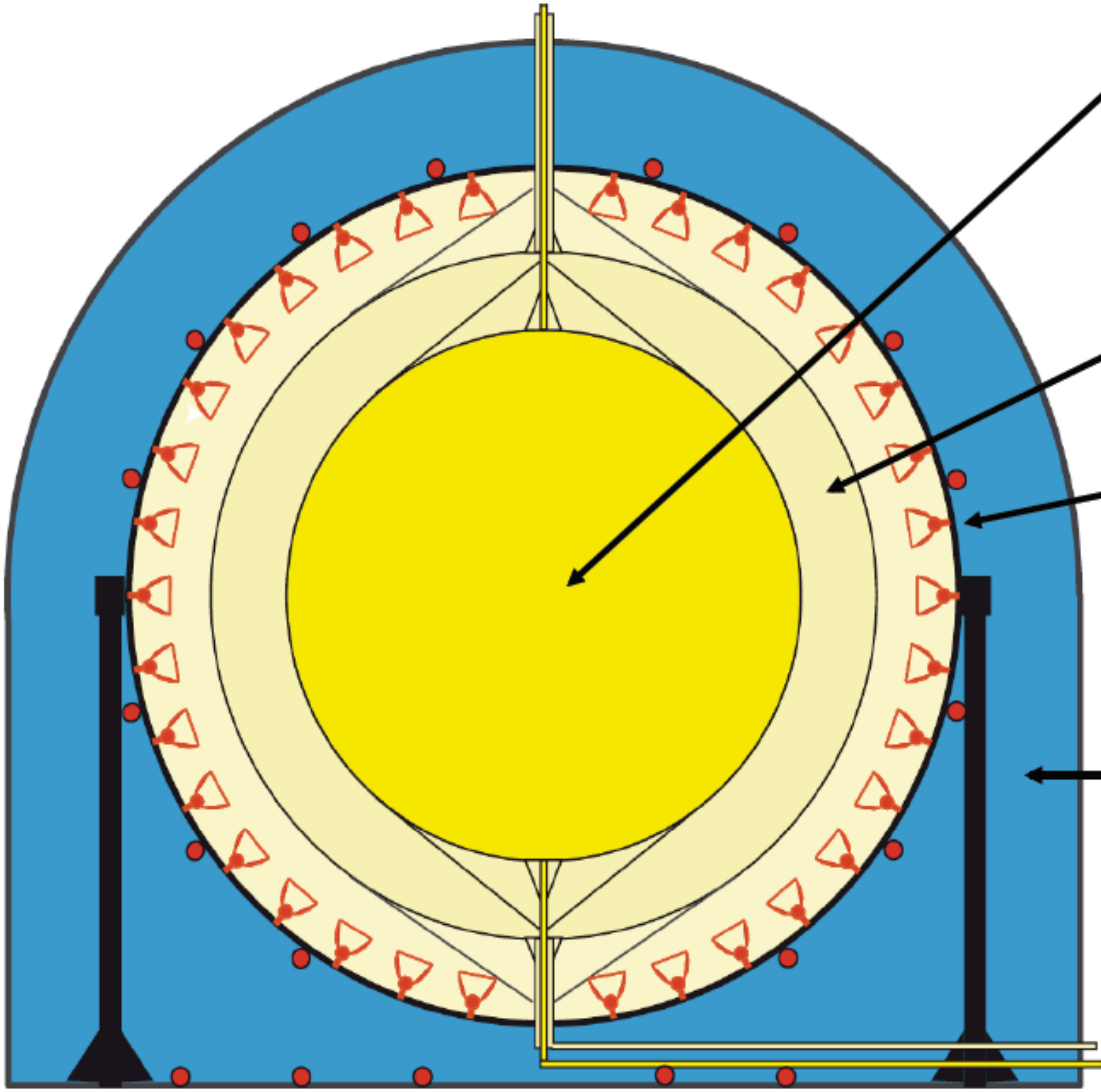


Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. ***Real-time measurements needed in the transition region.***

Borexino: Real-time Detection Below 50 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

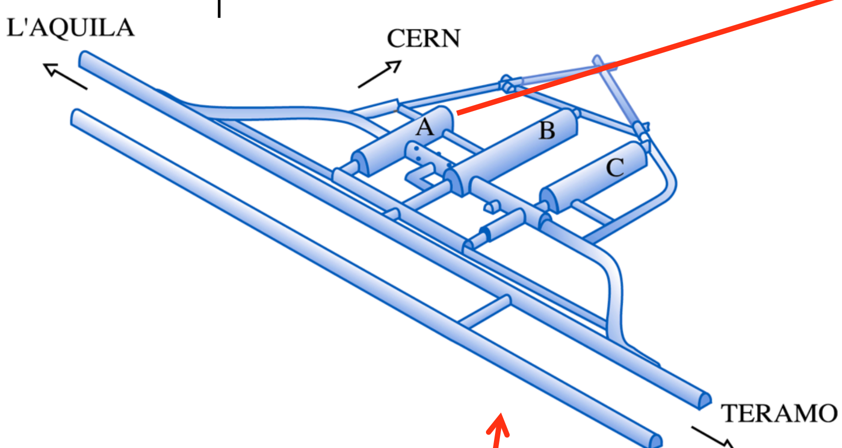
outer water tank
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

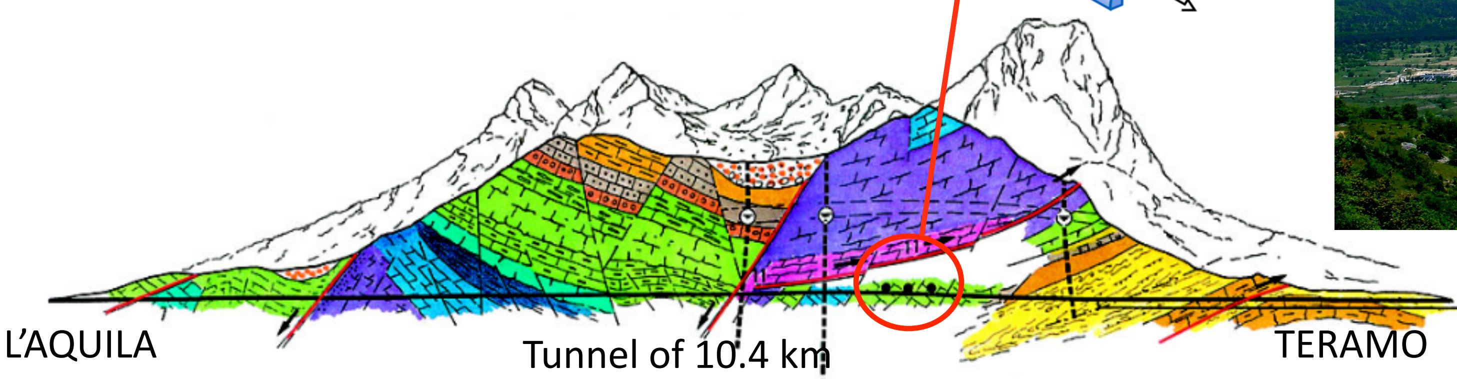
Laboratori Nazionali del Gran Sasso

4600' to surface

3500 m.w.e.

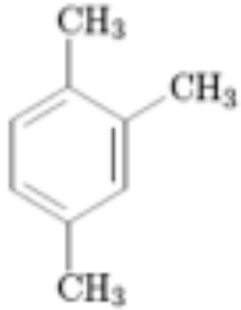
muon flux $1/m^2/hr$



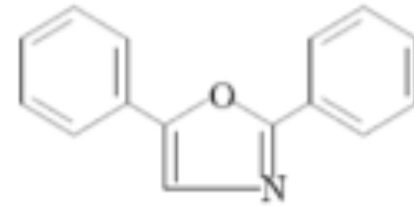


Borexino Collaboration

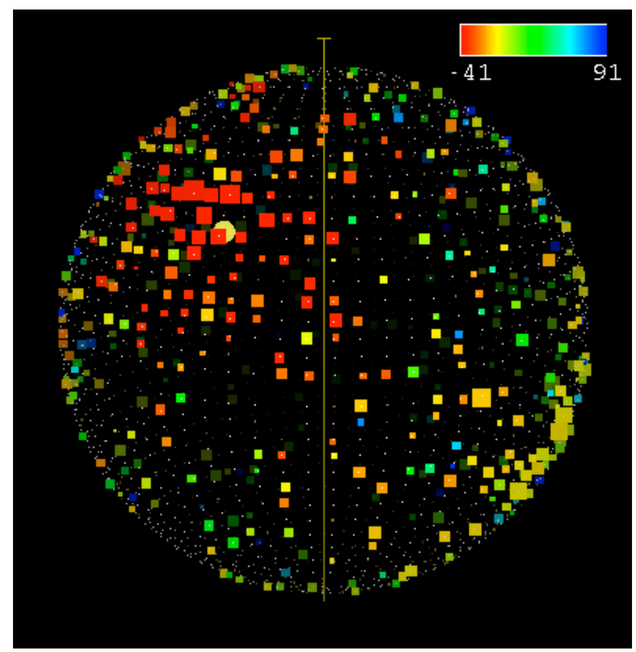
Astroparticle and Cosmology Laboratory – Paris, France
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN e Dipartimento di Fisica dell'Università – Genova, Italy
INFN e Dipartimento di Fisica dell'Università– Milano, Italy
INFN e Dipartimento di Chimica dell'Università – Perugia, Italy
Institut fur Experimentalphysik – Hamburg, Germany
Institute of Physics, Jagellonian University – Kracow, Poland
Instito de Fisica Corpuscular – Valencia, Spain
Joint Institute for Nuclear Research – Dubna, Russia
Kiev Institute for Nuclear Research – Kiev, Ukraine
NRC Kurchatov Institute – Moscow, Russia
Max-Planck Institute fuer Kernphysik – Heidelberg, Germany
Princeton University – Princeton, NJ, USA
St. Petersburg Nuclear Physics Institute – Gatchina, Russia
Technische Universität – Muenchen, Germany
University of Massachusetts at Amherst, MA, USA
Virginia Polytechnic Institute – Blacksburg, VA, USA



Detection Principle

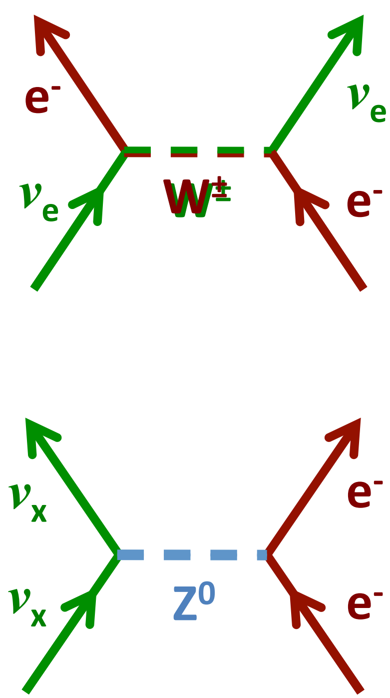


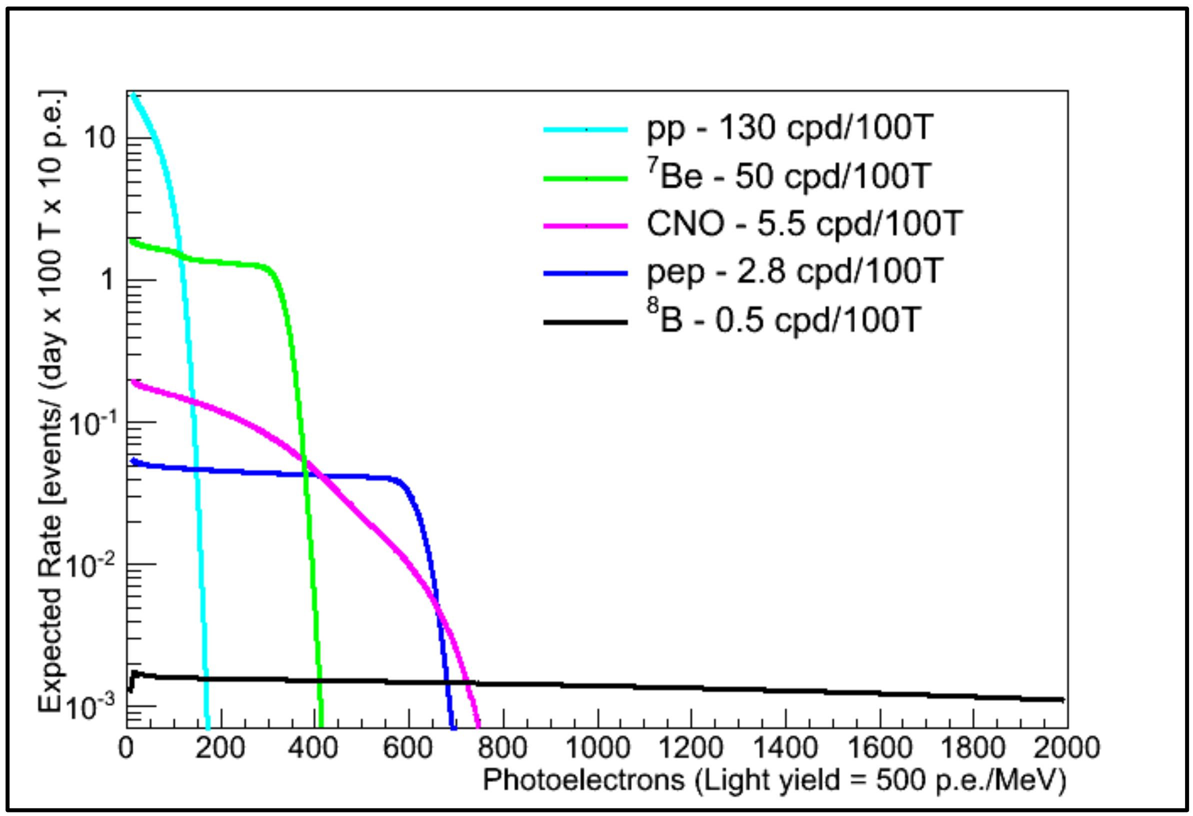
- Organic scintillator (pseudocumene + PPO) produces light when excited by charged particles
- ~12,000 photons/MeV, of which ~500 photons/MeV are detected by the photomultiplier tubes
  - Can detect events depositing < 50 keV
- Calorimetric measurement + pulse shape
  - Event energy from number of photons
  - Event position from photon time-of-flight



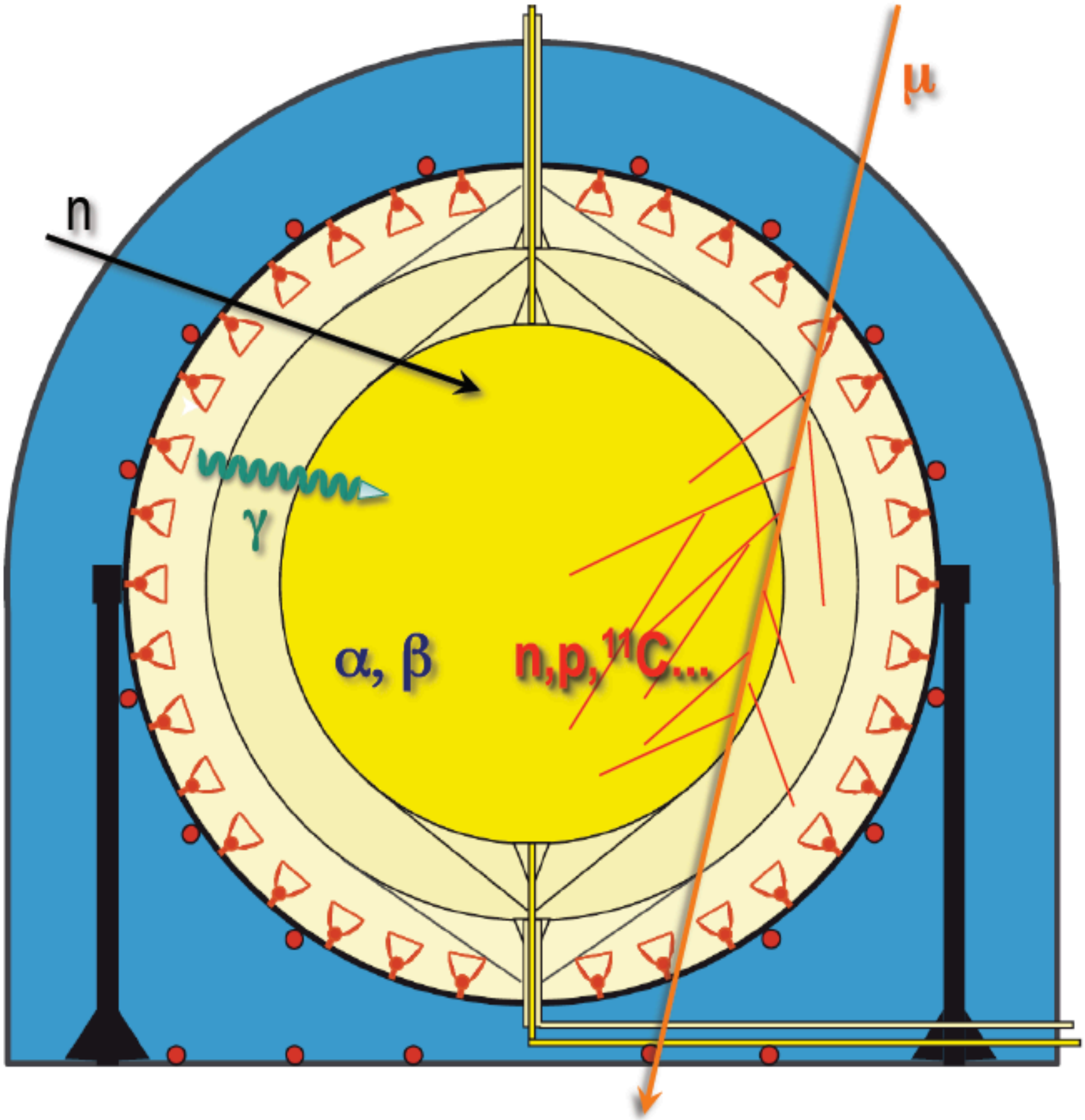
Neutrino Detection

- Neutrinos interact via elastic scattering with electrons
  - Sensitive to all neutrino species, but cross section is 4-7 times larger for ν_e than $\nu_{\mu,\tau}$
  - Detect scintillation from the recoiling electron





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 ...)

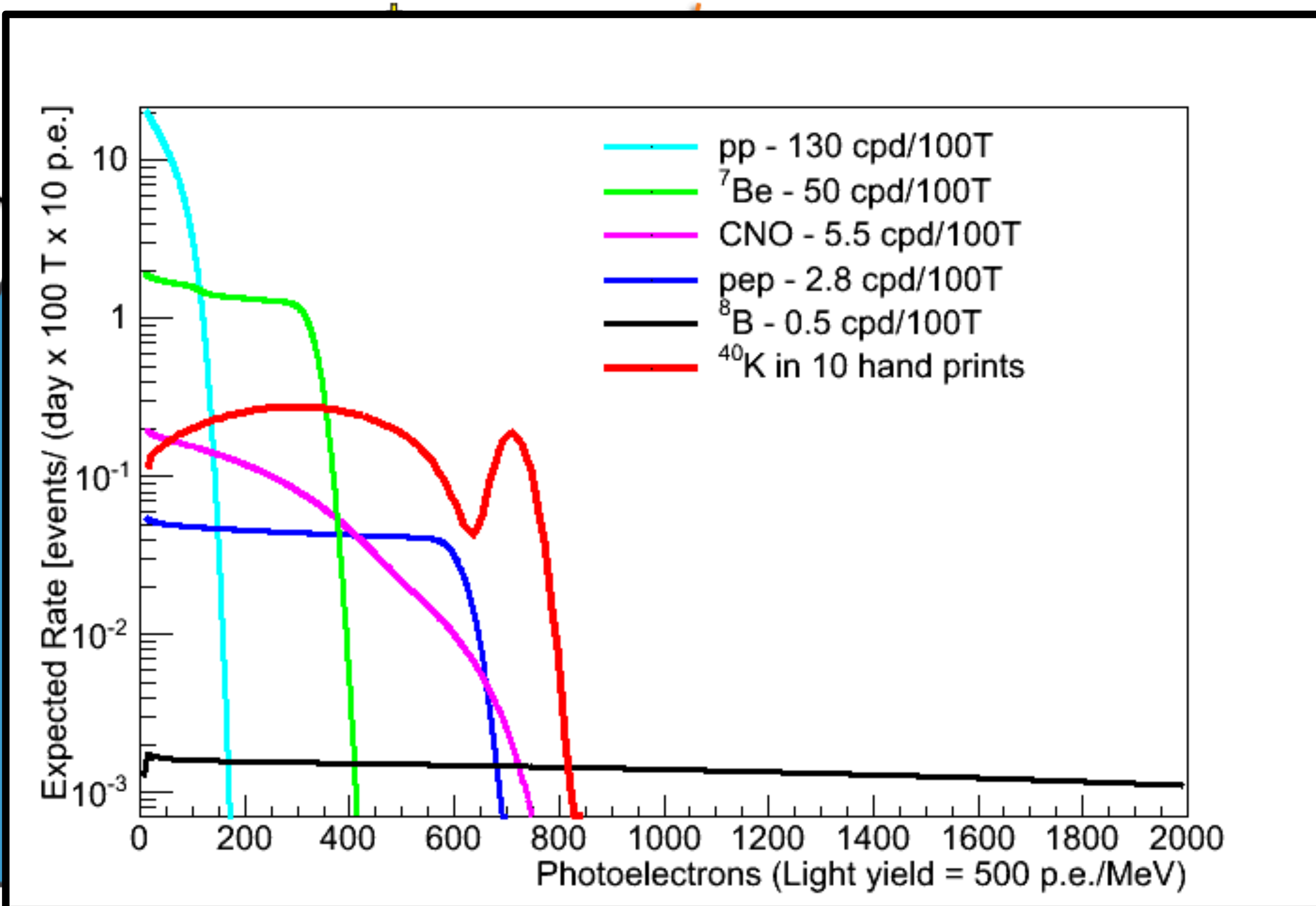
Cosmic Muons

Cosmogenics
neutrons and radionuclides from muon-spallation and hadronic showers

Fast Neutrons
from external muons

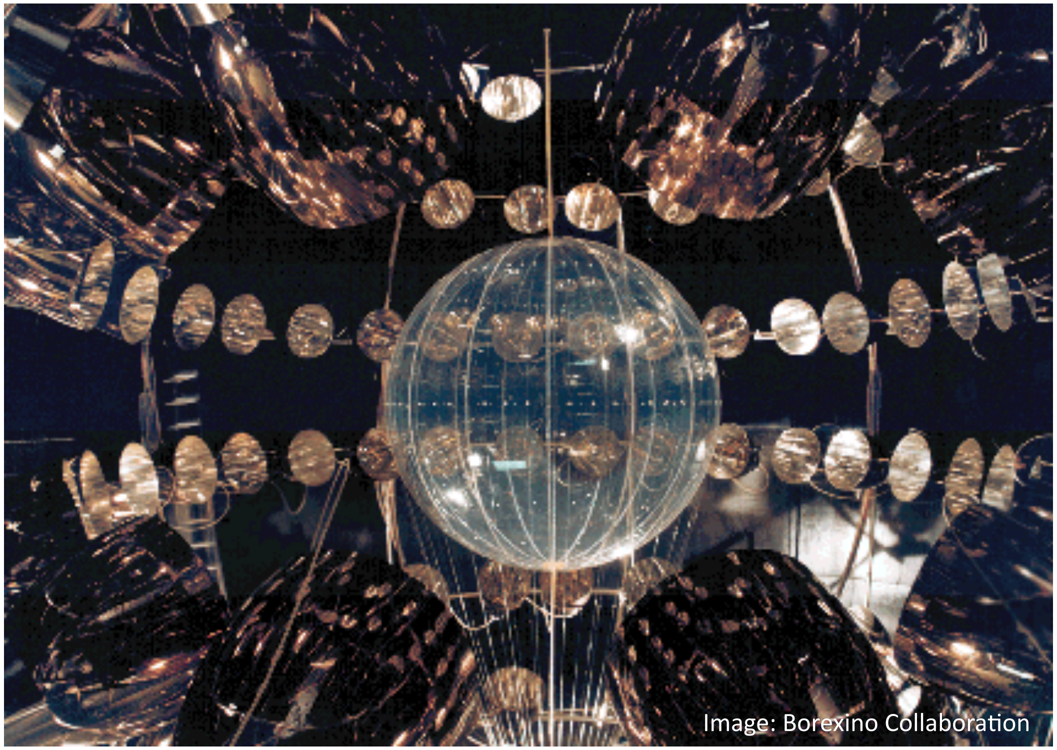
Slide: M. Wurm

Central Challenge: Background Reduction



Slide: M. Wurm

Borexino achieved unprecedented low levels of internal background.



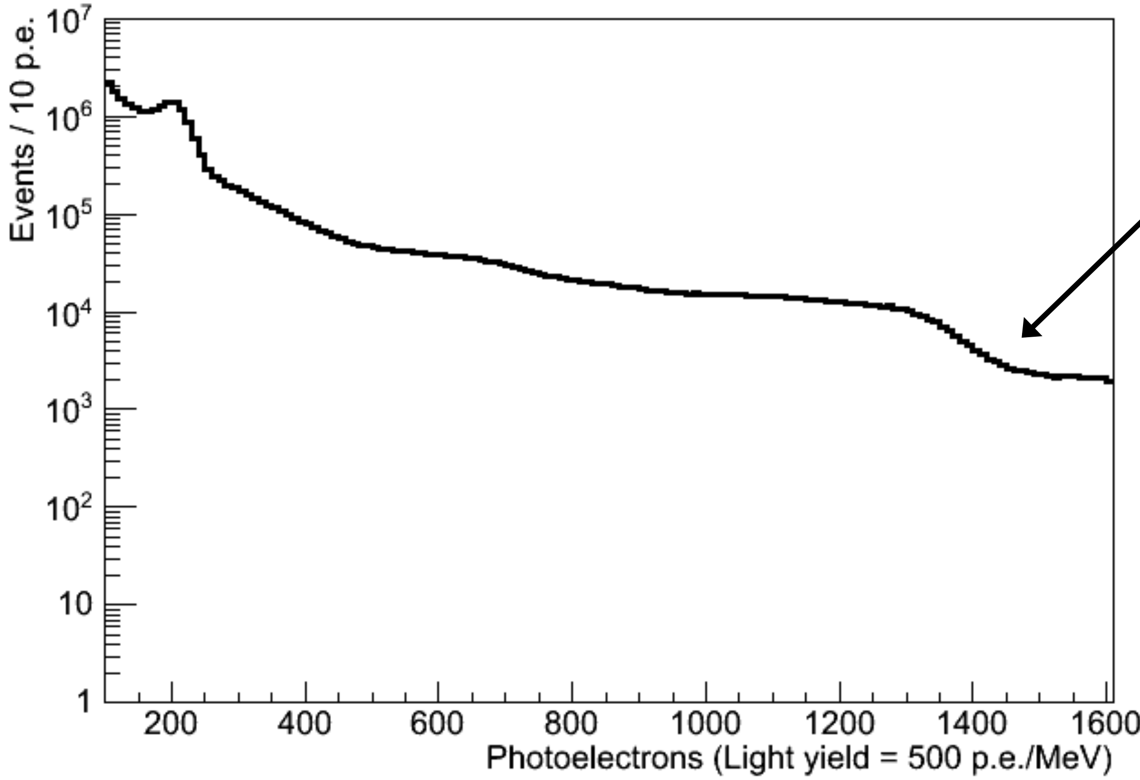
The Counting Test Facility III

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	~$5x10^{-18}$ g/g	Purification
^{232}Th	Dust	10^{-6} g/g	~$4x10^{-18}$ 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	<$2x10^{-15}$ g/g	Purification
μ	Cosmic	200 $s^{-1}m^{-2}$	10^{-10} $s^{-1}m^{-2}$	Underground, active veto

Borexino Neutrino Results

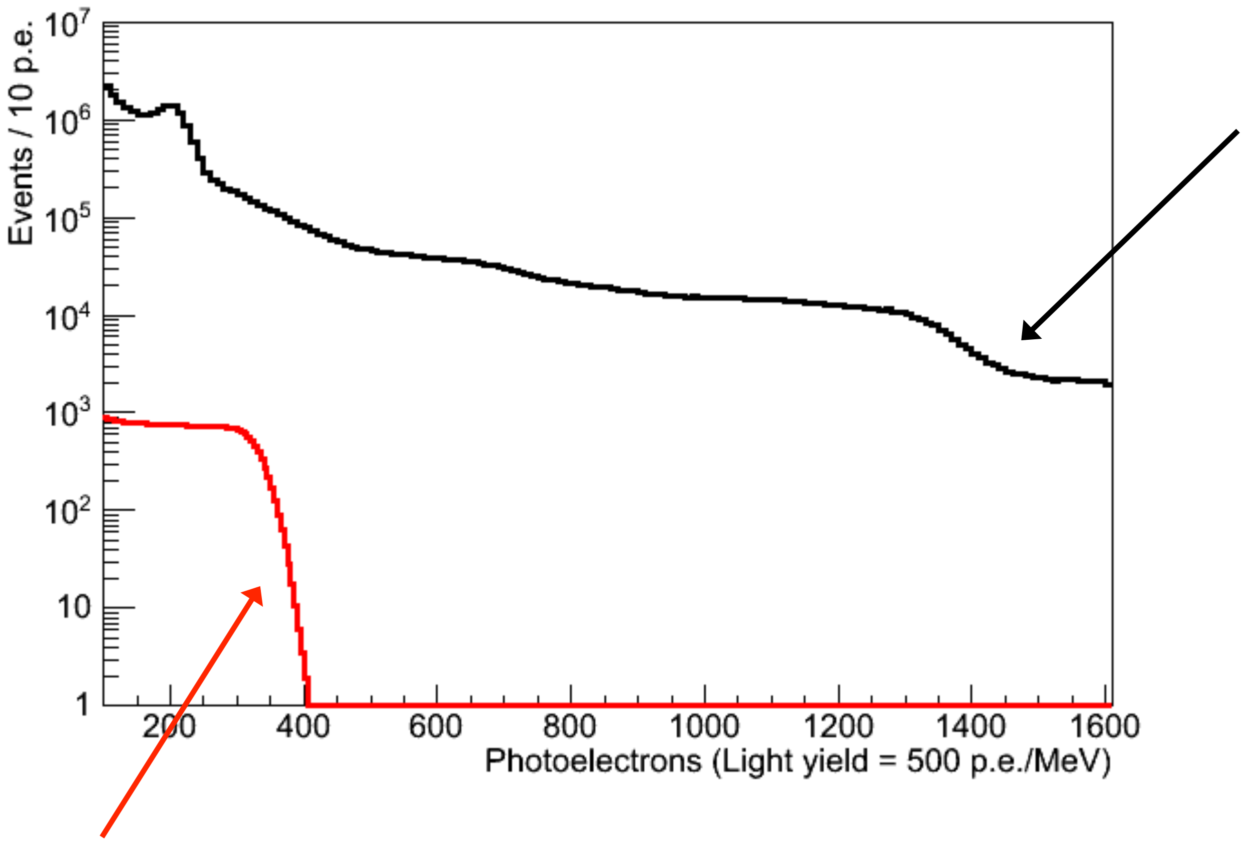
- ^{7}Be Flux
  - (±30%) – Phys. Lett. B **658**:101 (2008).
  - (±10%) – Phys. Rev. Lett. **101**:091302 (2008).
  - (±5%) – Phys. Rev. Lett. **107**:141302 (2011).
- ^{7}Be Day-Night Asymmetry
  - Phys. Lett. B **707**:22 (2012).
- ^{8}B Flux + Spectrum (T_{eff} > 3.0 MeV)
  - Phys. Rev. D **82**:033006 (2010).
- *pep* and CNO flux
  - Phys. Rev. Lett. **108**:051302 (2012).
- Geo-neutrinos
  - Phys. Lett. B **687**:299-304 (2010).
- Solar anti-neutrinos
  - Phys. Lett. B **696**:191-196 (2011).
- CNGS neutrino time-of-flight
  - Phys. Lett. B **716**:401 (2012)

Borexino Data



All data: 740 live days

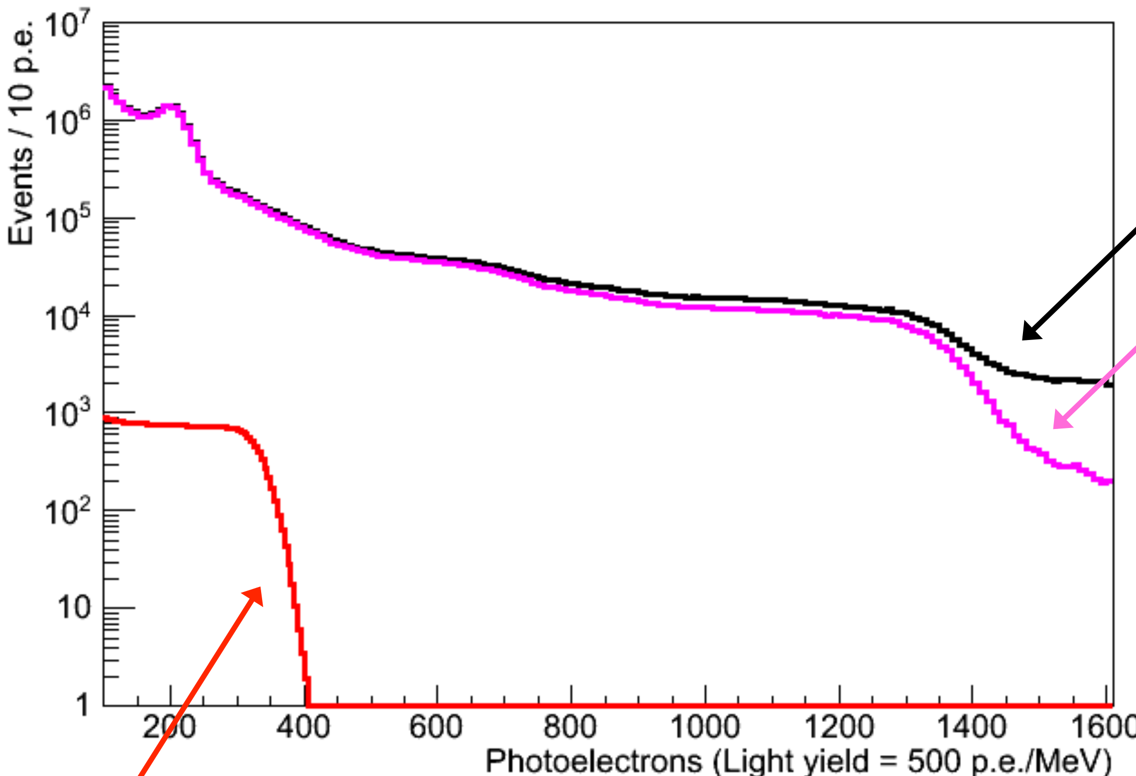
Borexino Data



All data: 740 live days

Expected ^7Be signal

Borexino Data

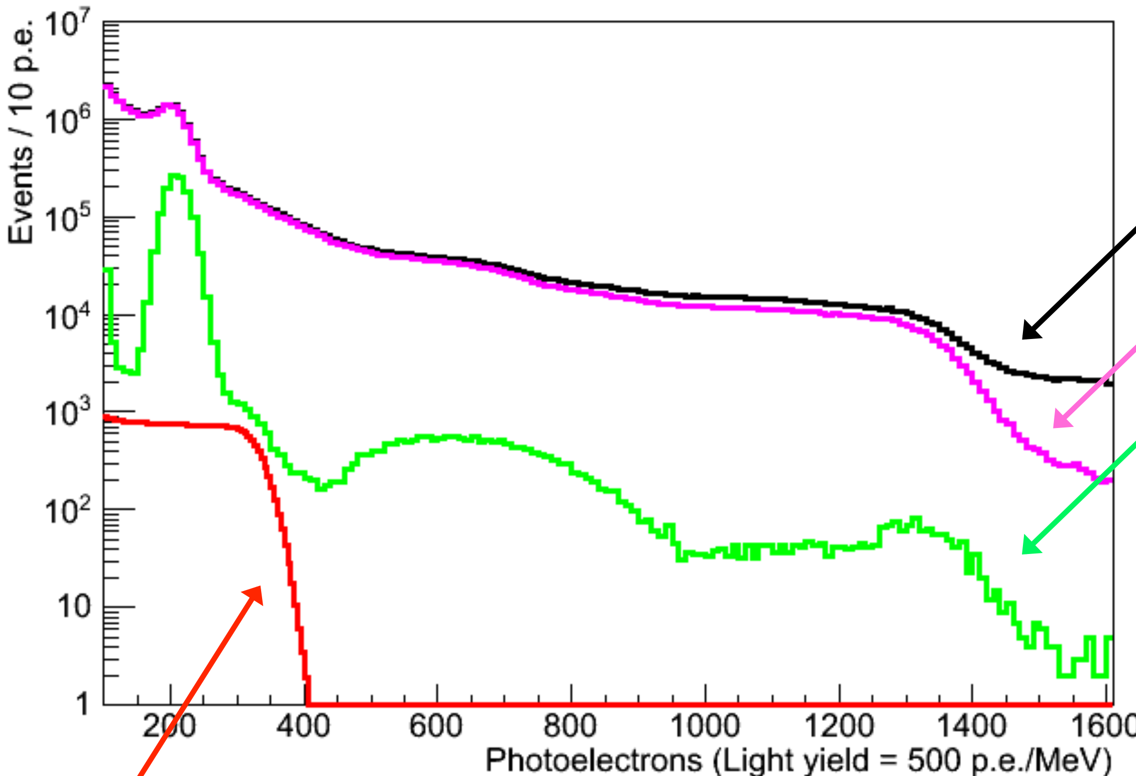


All data: 740 live days

Remove muons + muon followers (2 ms)

Expected ^{7}Be signal

Borexino Data



All data: 740 live days

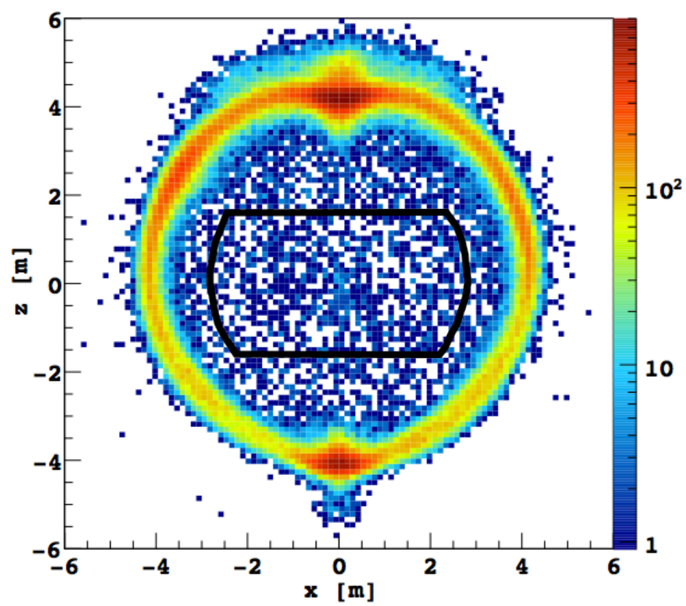
Remove muons + followers

Fiducial Volume + high level

Expected ^{7}Be signal

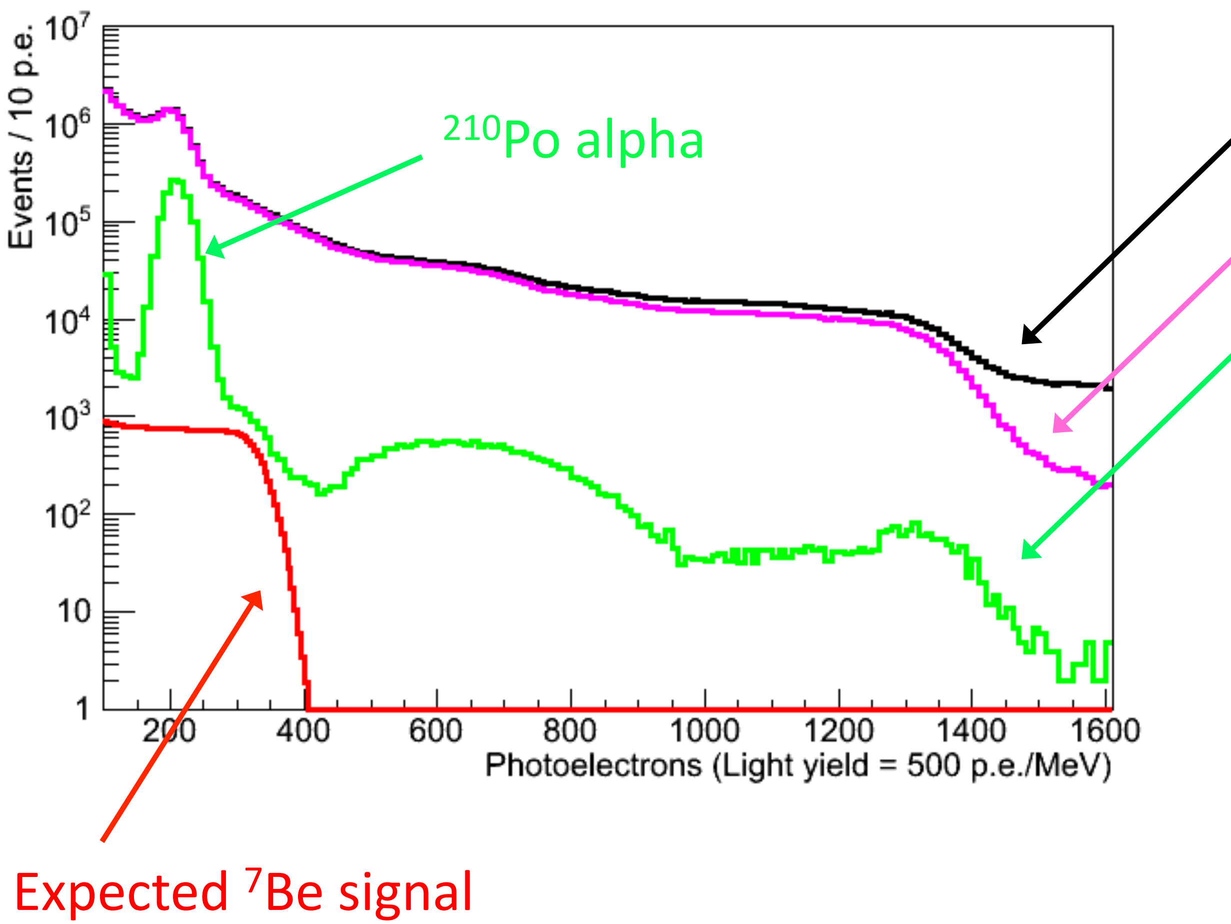
R < 3.02m

|z| < 1.67m

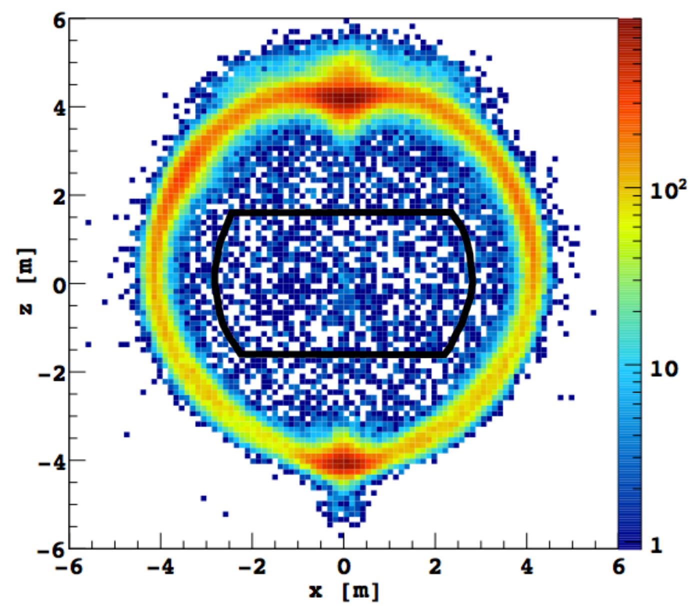


Fiducial mass = 75.6 tonnes

Borexino Data

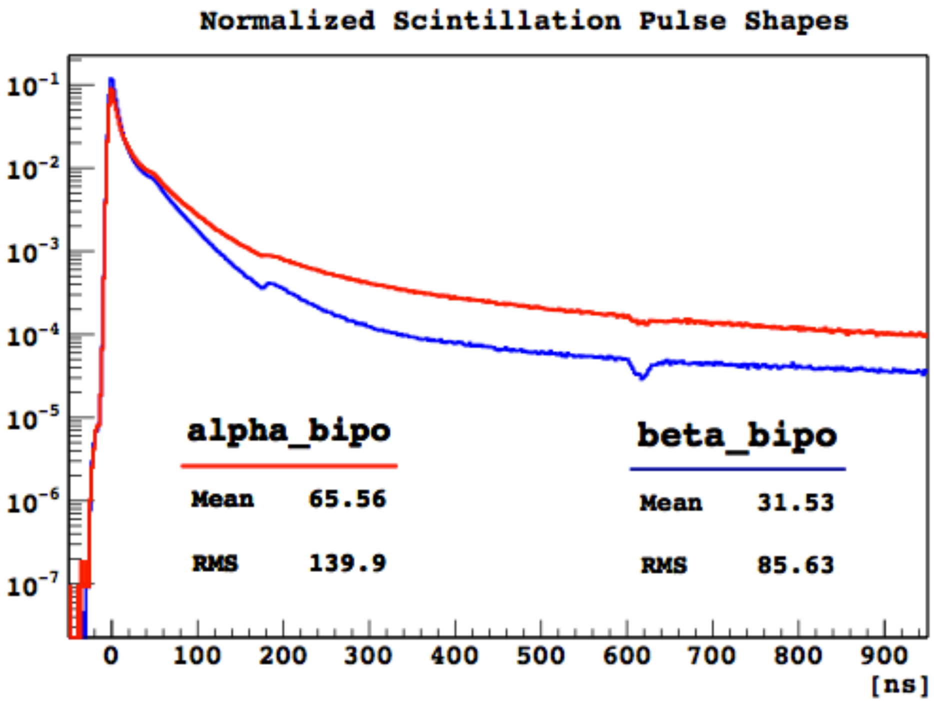


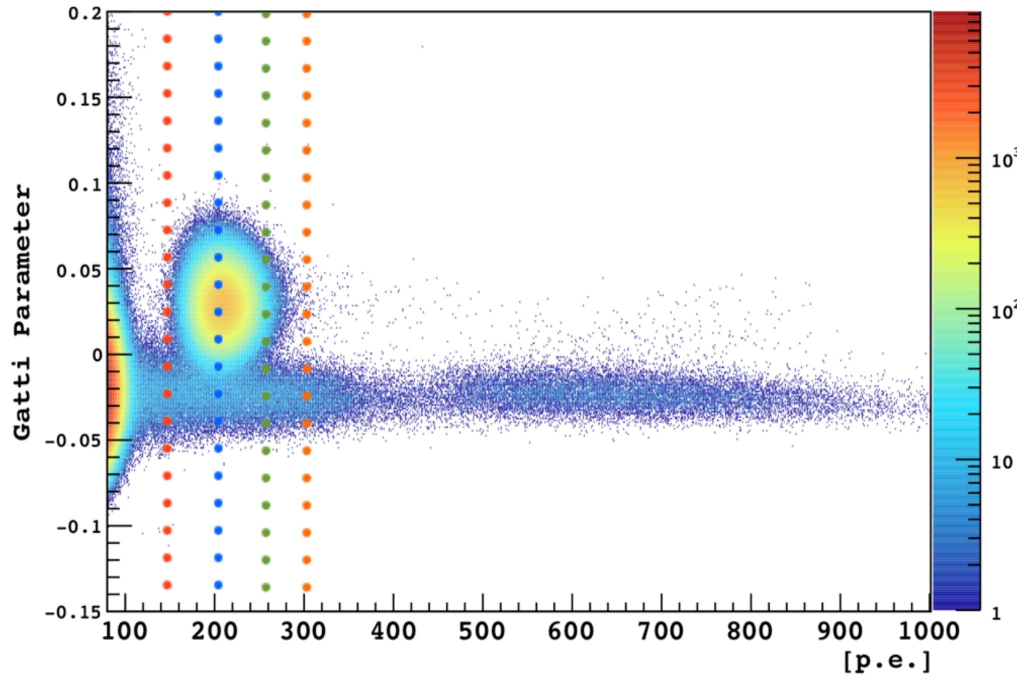
R < 3.02m
|z| < 1.67m



Fiducial mass = 75.6 tonnes

Alpha Pulse Shape Discrimination



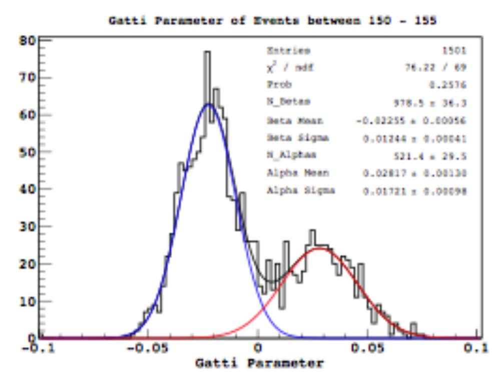


$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

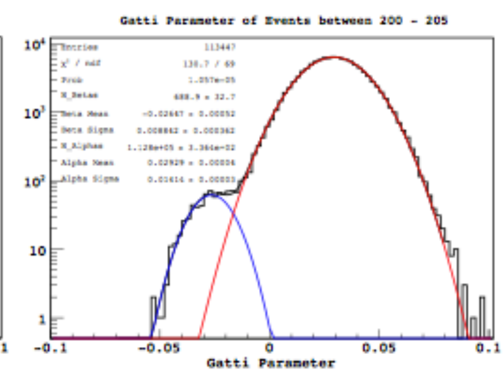
$$w[t] \equiv \frac{r_\alpha[t] - r_\beta[t]}{r_\alpha[t] + r_\beta[t]}$$

$e[t]$: Event Time Profile

$r_{\alpha/\beta}[t]$: Reference time profile

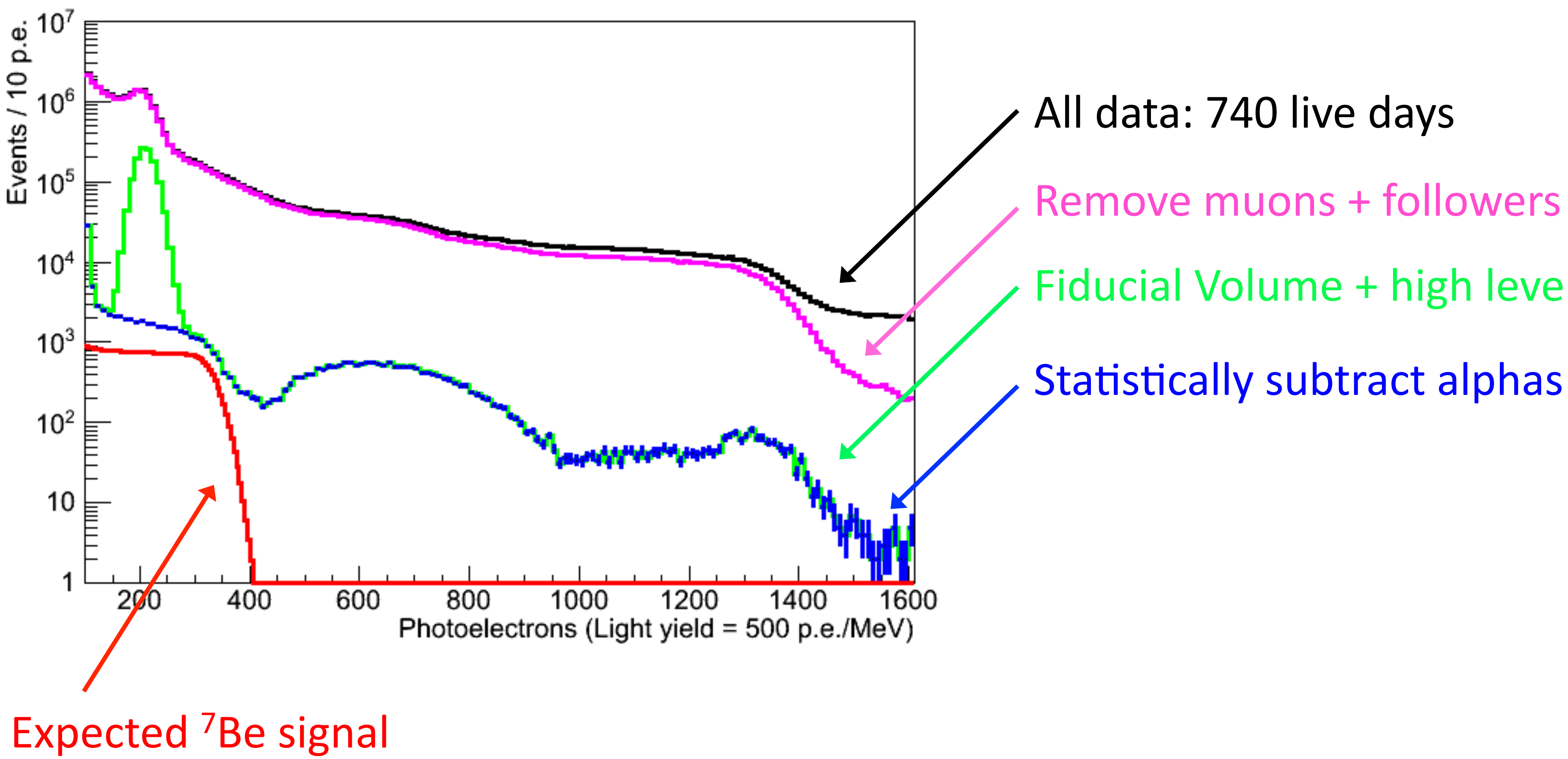


150 p.e.



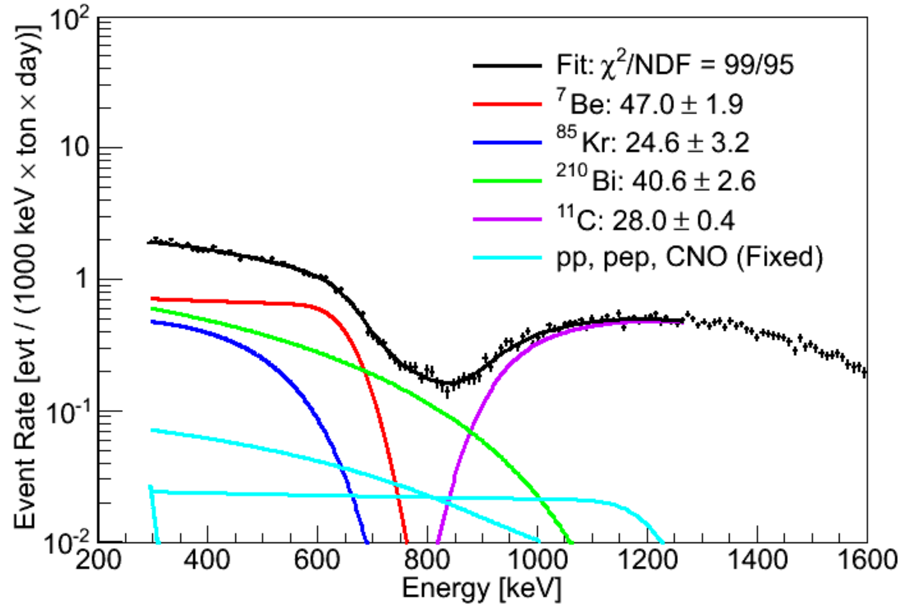
200 p.e.

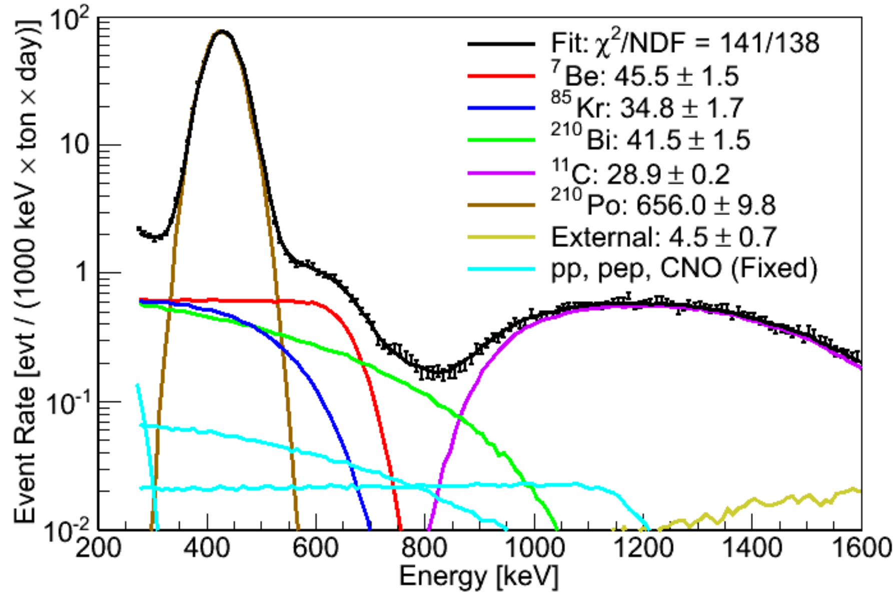
Borexino Data



^{7}Be Signal Extraction

- Fit the observed energy spectrum with the expected signal and background shapes to determine the ^{7}Be flux
- Different fit configurations used to estimate uncertainties



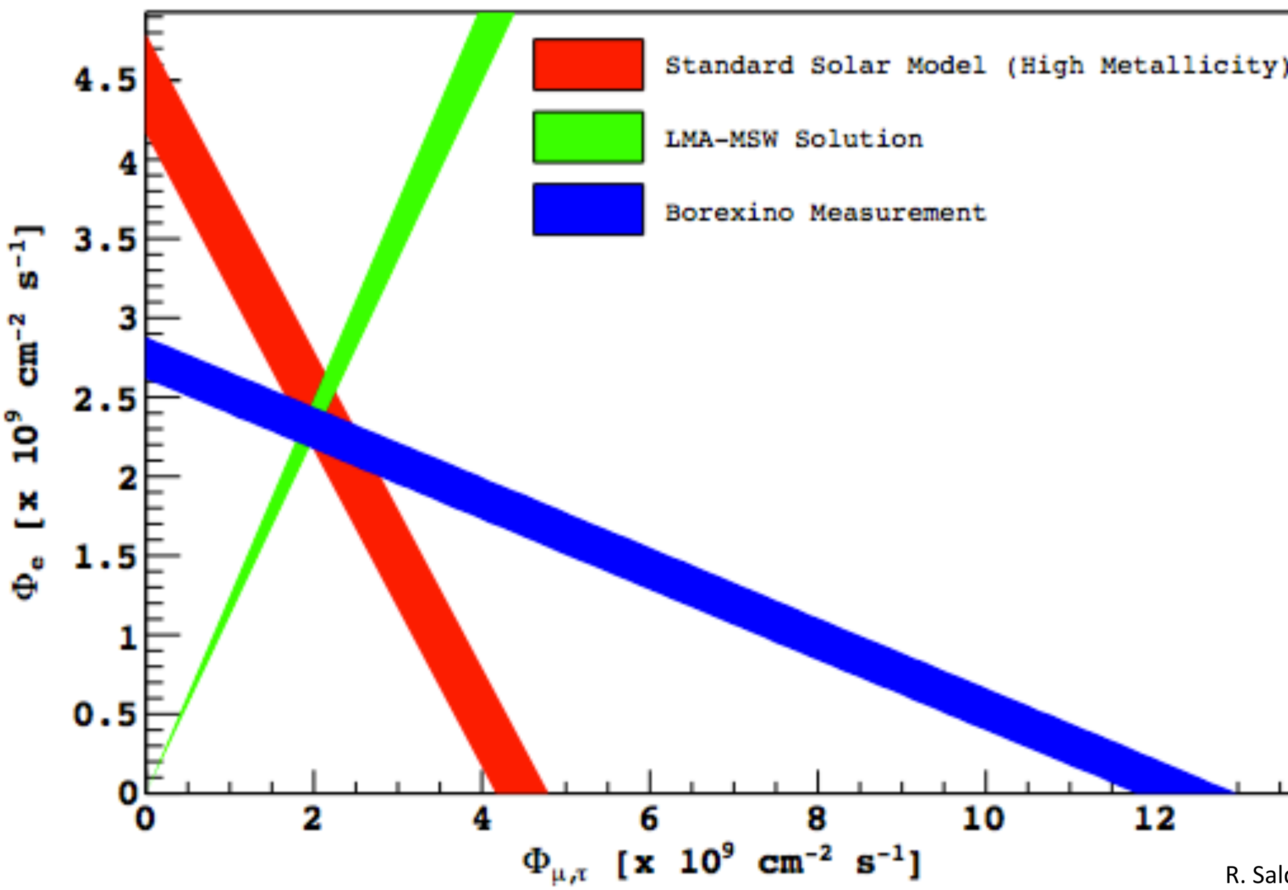


Precision ^{7}Be Flux Result

(Phys. Rev. Lett. **107**:141302 (2011))

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

➡ $\Phi_{7Be} = (4.84 \pm 0.24) \times 10^9\ cm^{-2}s^{-1}$ ➡ $P_{ee}(862\ keV) = 0.51 \pm 0.07$



R. Saldanha, Ph.D. Thesis, Princeton (2011)

Precision ^{7}Be Flux Result

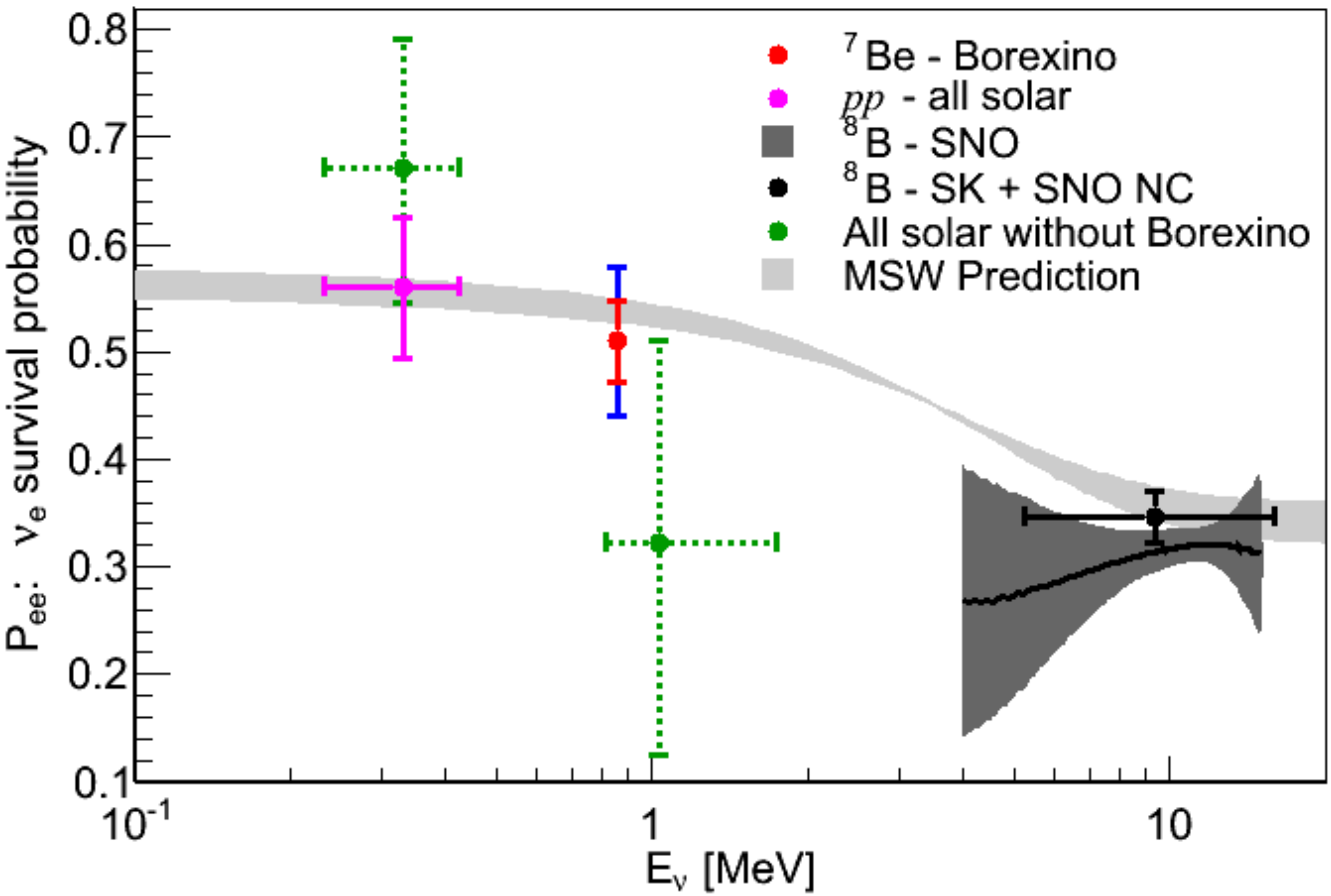
(Phys. Rev. Lett. **107**:141302 (2011))

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

→ $\Phi_{7Be} = (4.84 \pm 0.24) \times 10^9\ cm^{-2}s^{-1}$ → $P_{ee}(862\ keV) = 0.51 \pm 0.07$

Systematic Uncertainties	
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 Methods	2.0%
Total	**$^{+3.4}_{-3.6}$%**

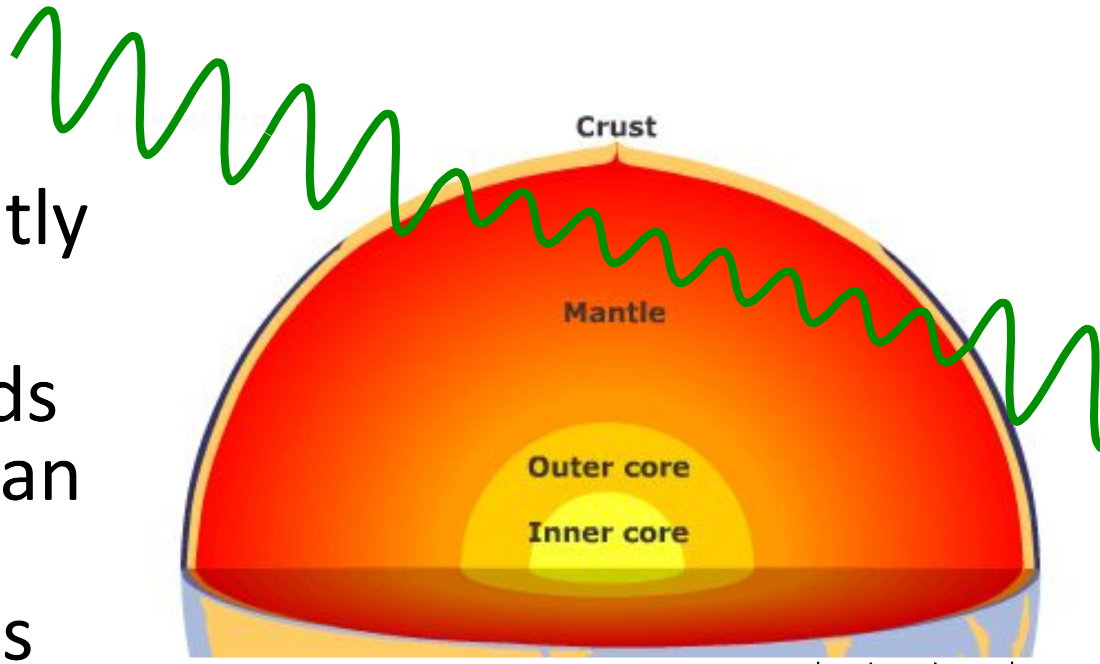
Precision ^{7}Be Flux Result



Significantly improved constraint on low energy P_{ee}.

^{7}Be 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



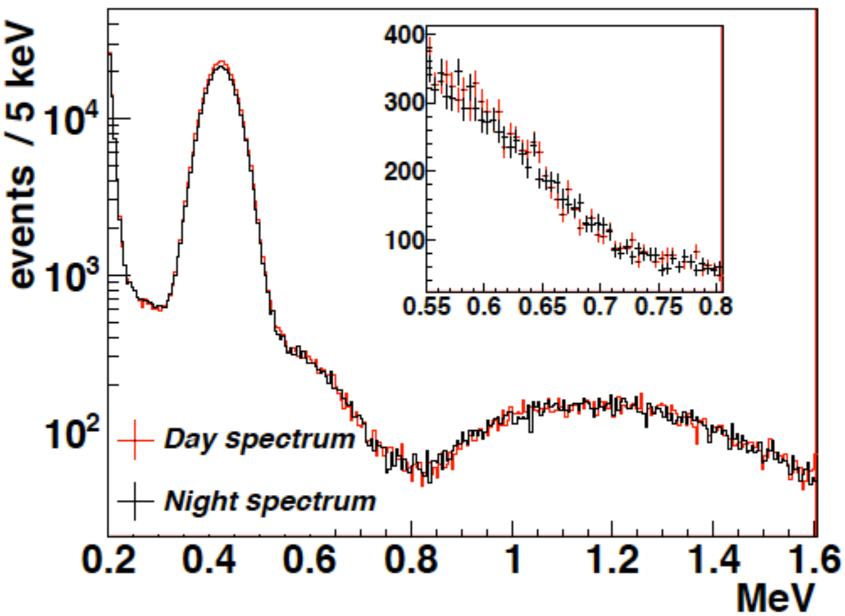
www.education.ezinemark.com

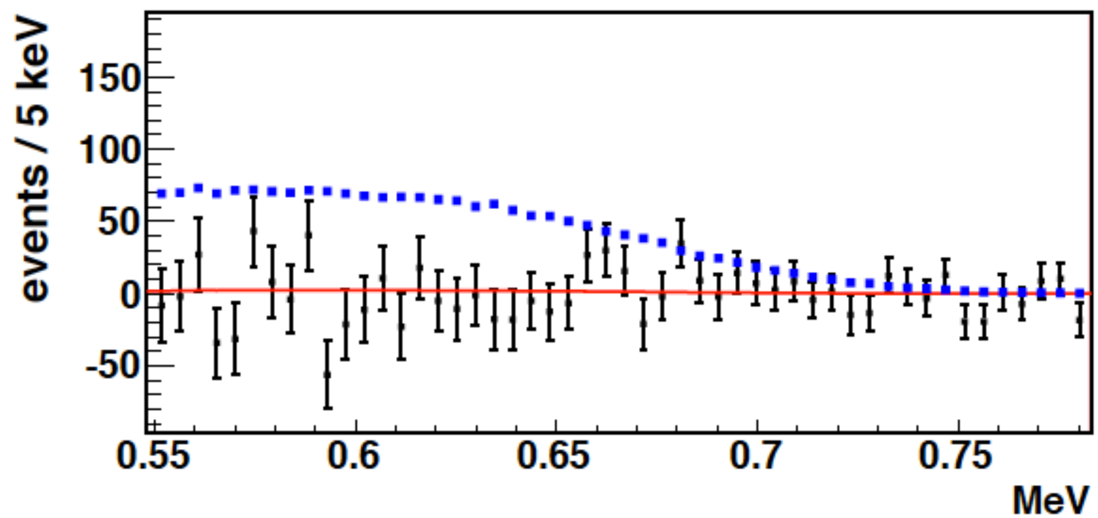
Model	Predicted A_{nd} (862 keV)
LMA	<0.001
LOW	0.11 - 0.80
MaVaN	~0.20

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

^{7}Be Day-Night Asymmetry Search

(Phys. Lett. B **707**:22 (2012))





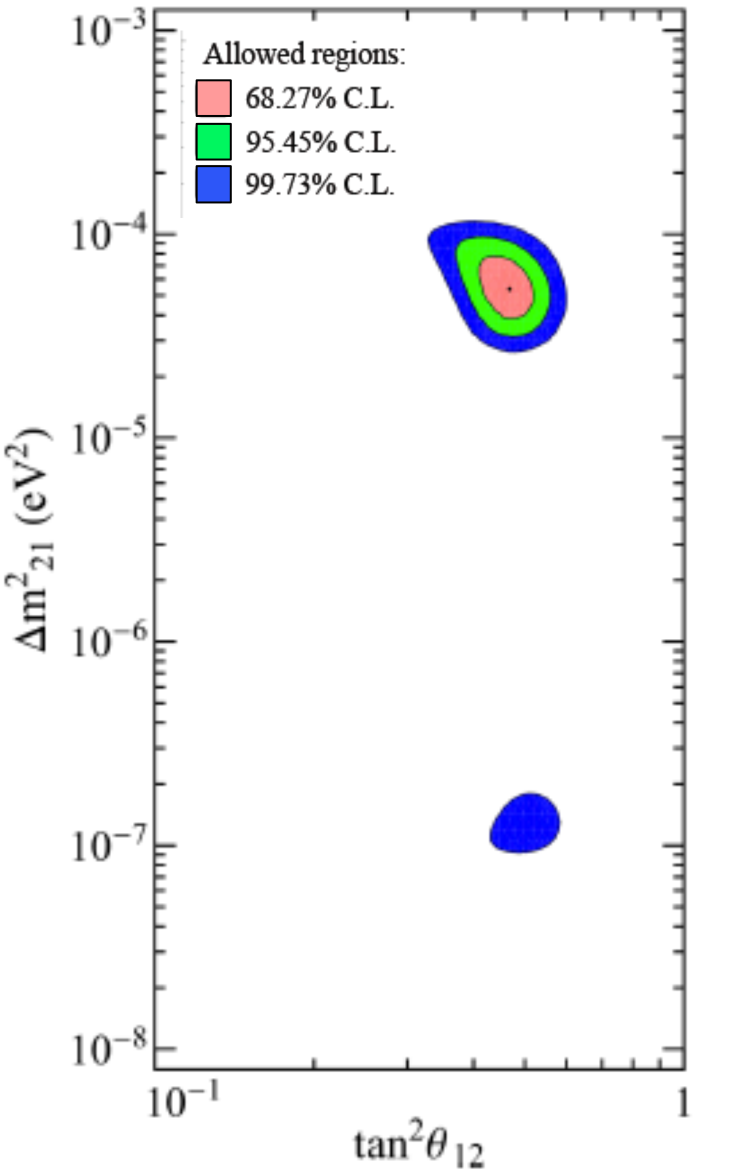
A_{dn}(862 keV): $0.001 \pm 0.012_{stat} \pm 0.007_{sys}$

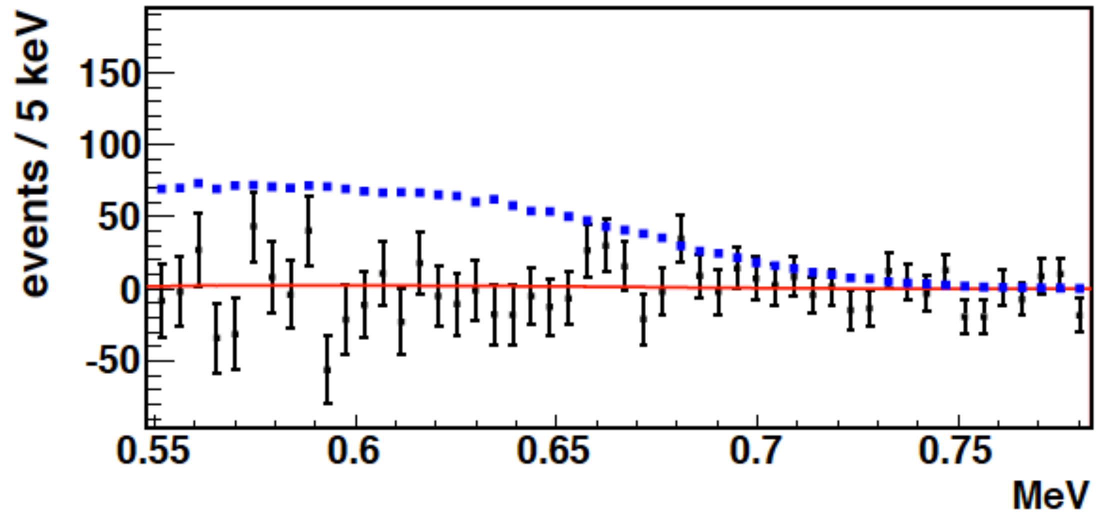
Fit for ^{7}Be in the difference between the day and night spectra to obtain the most stringent limit.

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	$\pm$ 0.005
Total systematic error	0.007

^{7}Be Day-Night Asymmetry Search

Global Solar, without Borexino





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^{7}Be Day-Night Asymmetry Search

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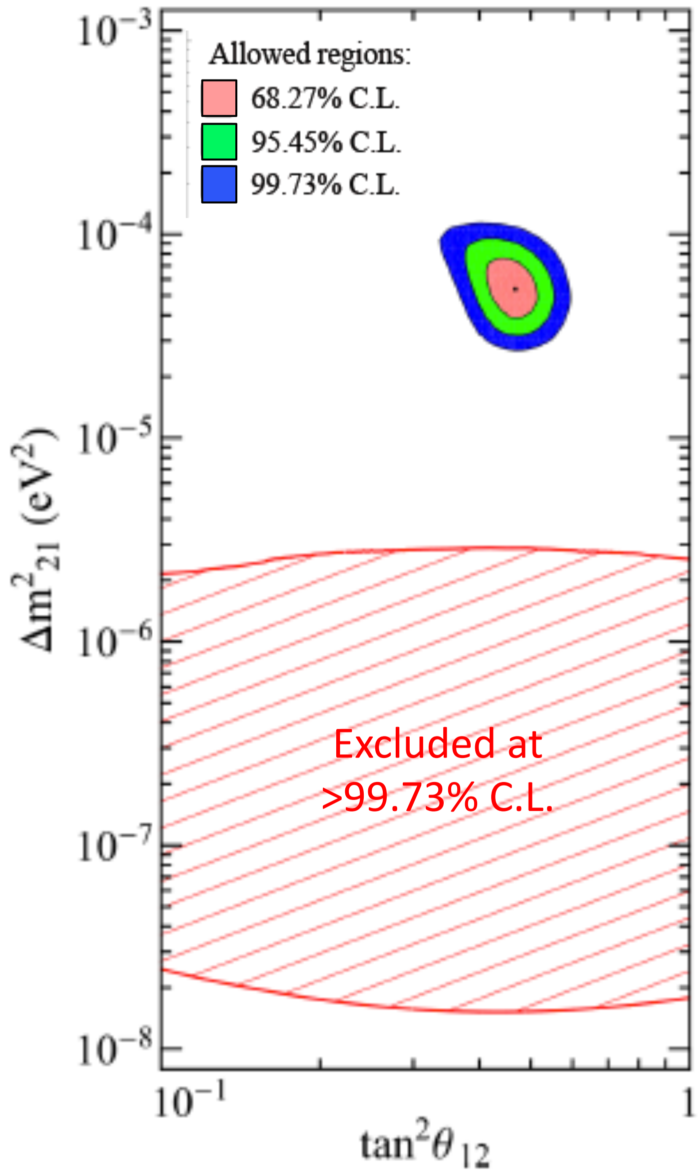

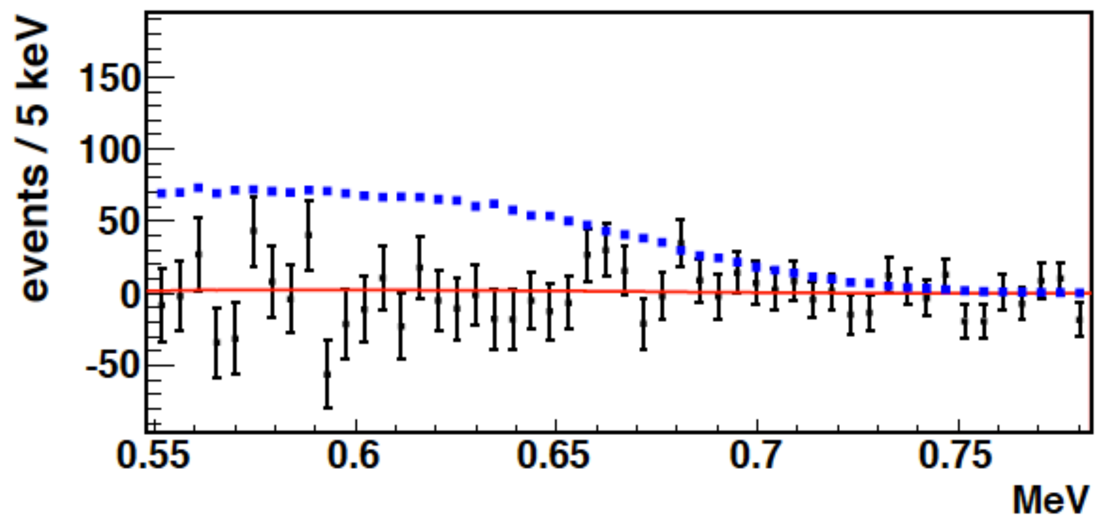

A_{dn}(862 keV): 0.001 ± 0.012$_{stat}$ ±0.007$_{sys}$

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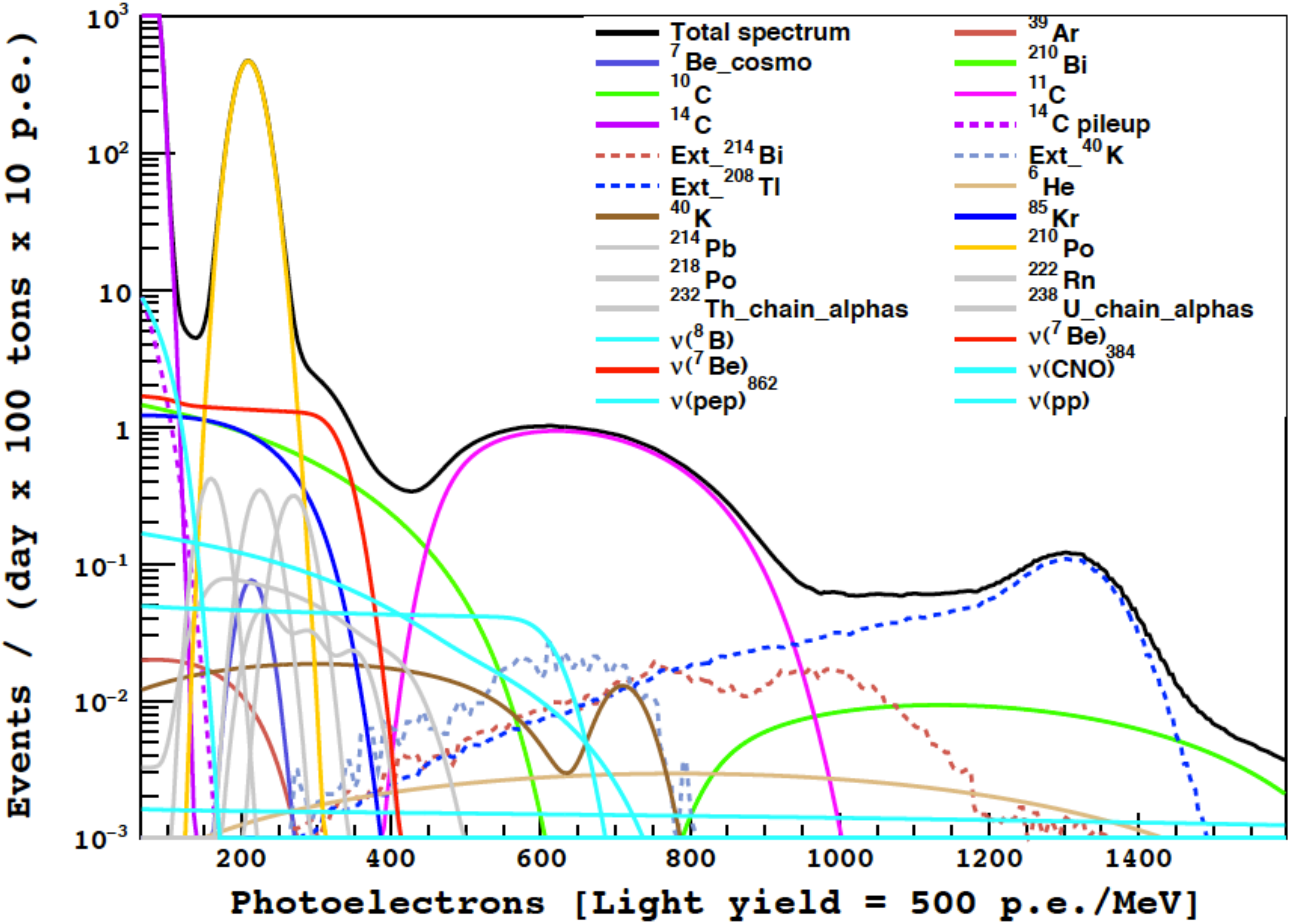
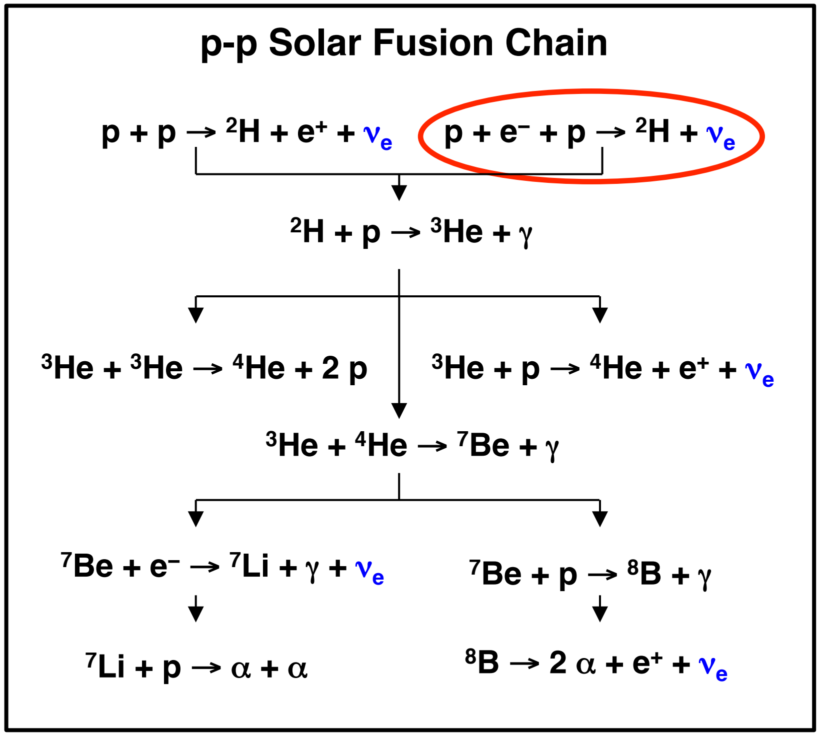
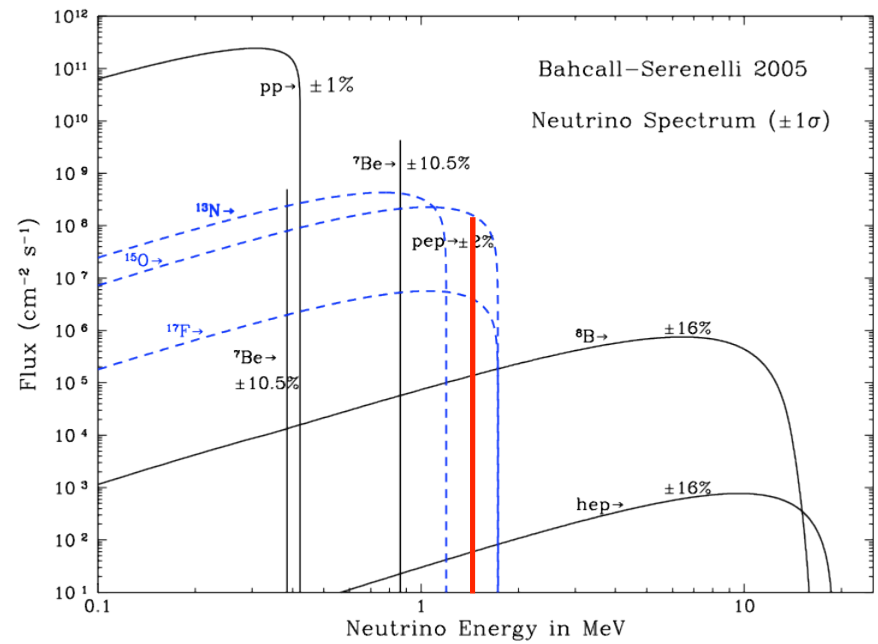
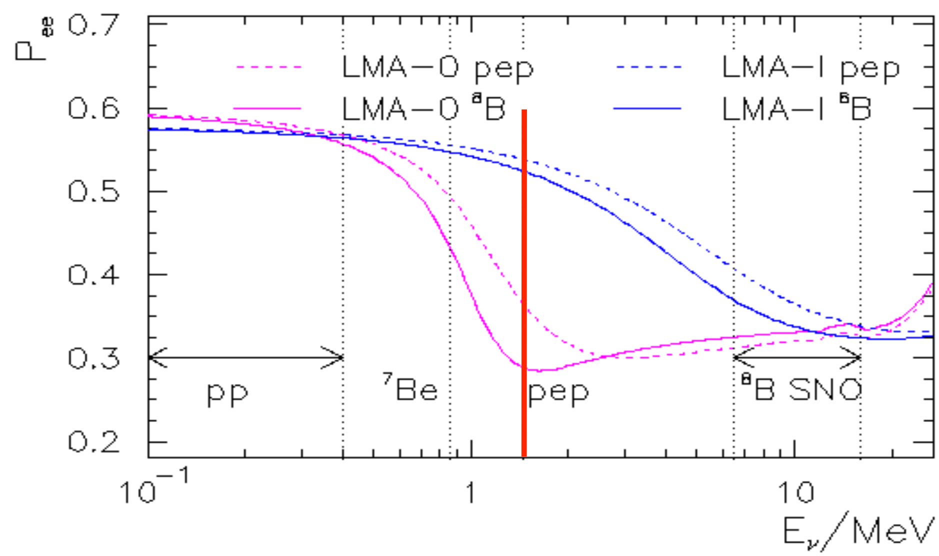
“Into the Muck”: *pep* and CNO Neutrinos



pep Neutrinos





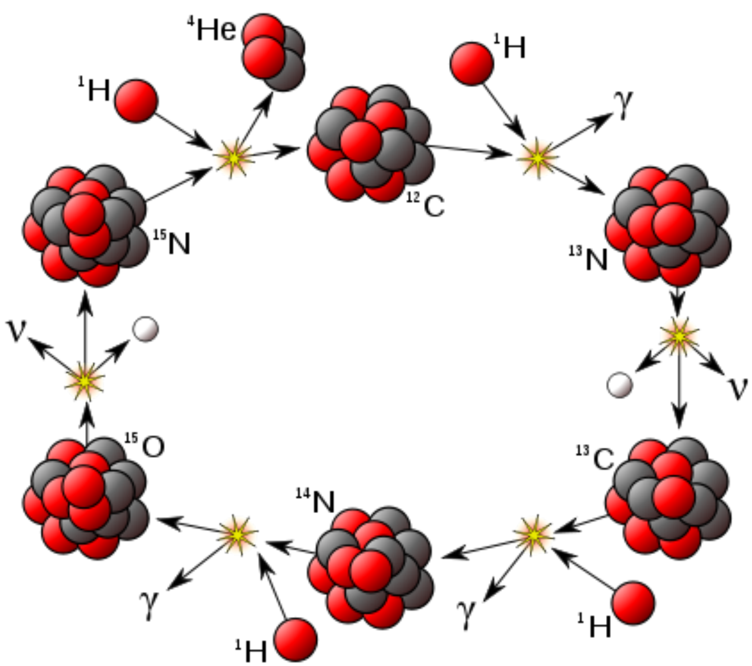


First direct look at solar p-p fusion.

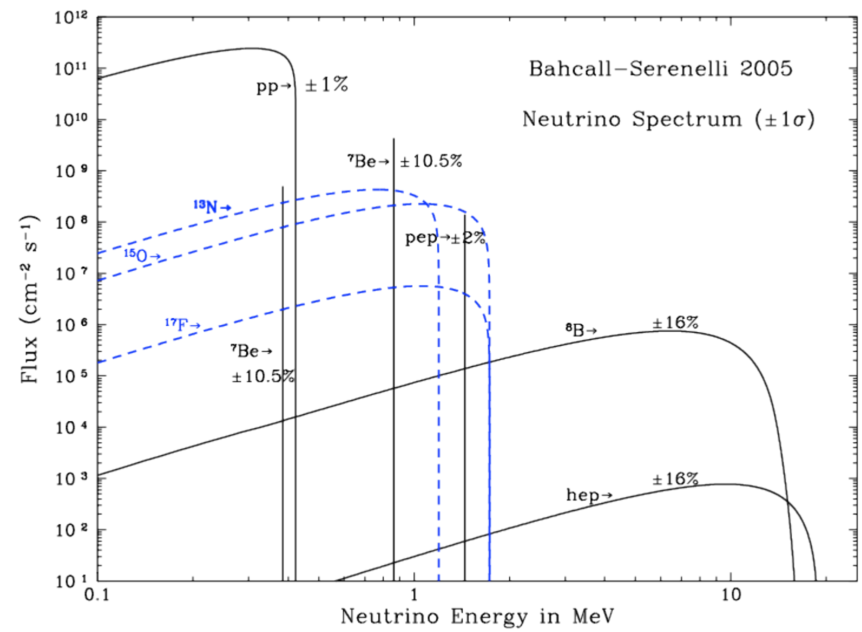
Precision test of Standard Solar Model and oscillations.

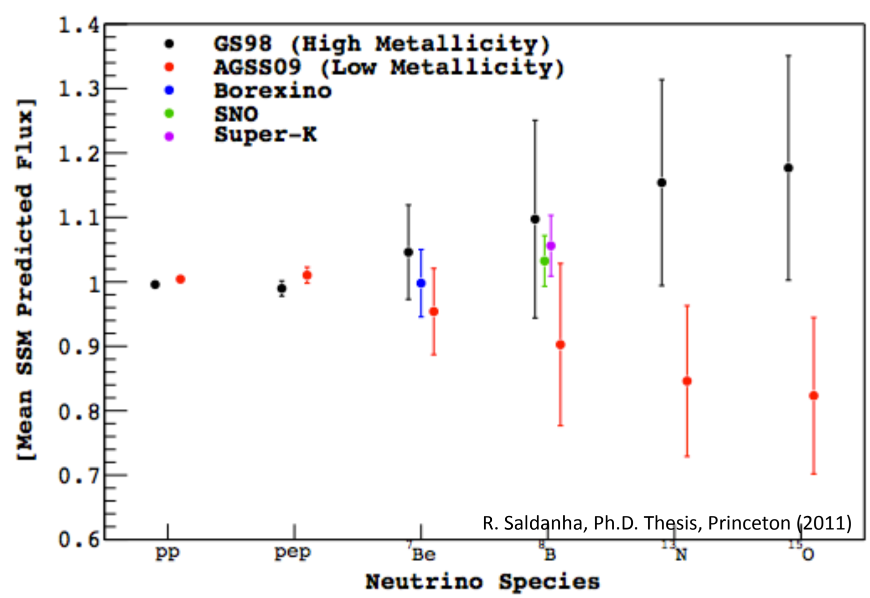
Ideal energy to probe transition region.

CNO Neutrinos



Wikimedia.org

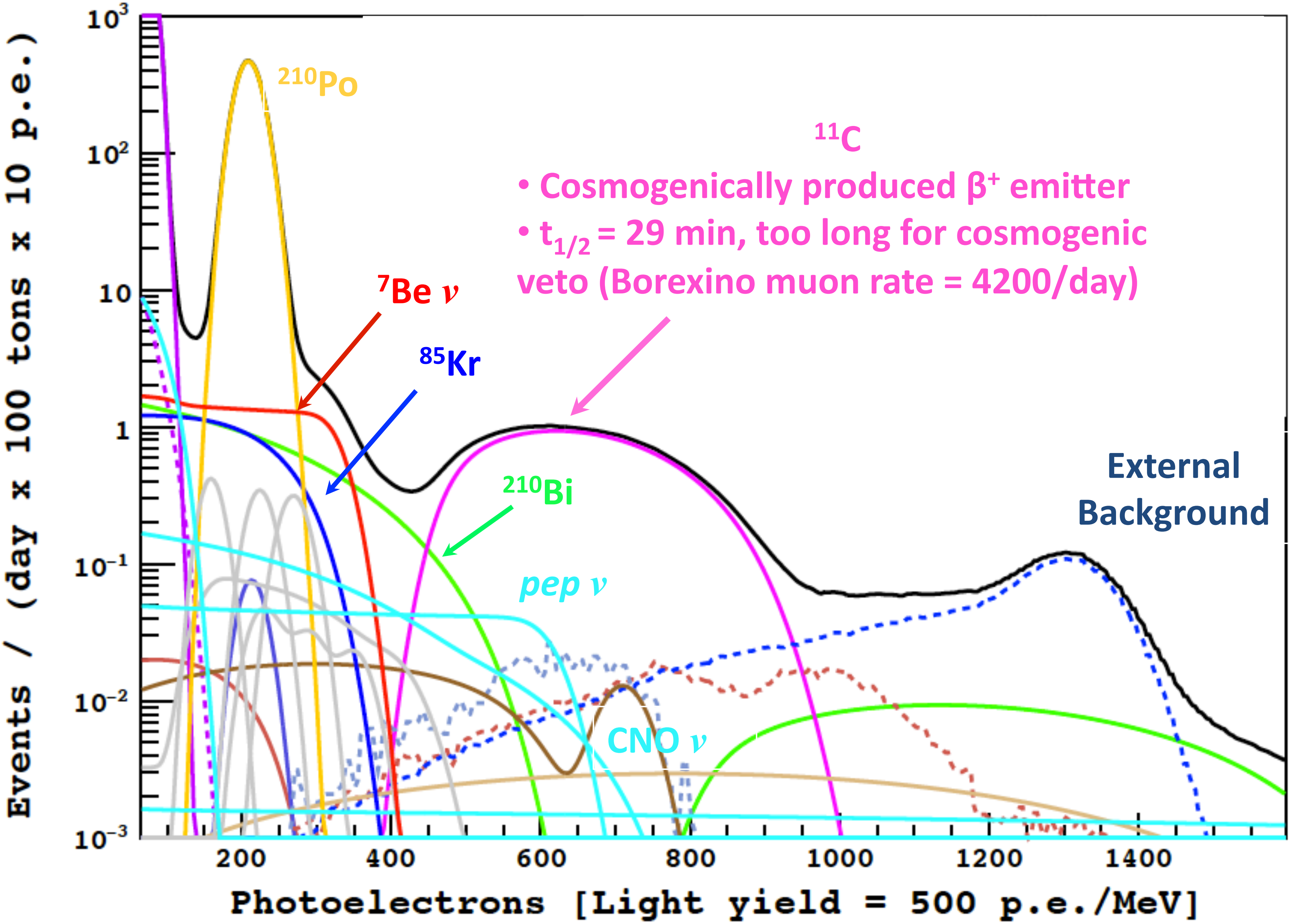




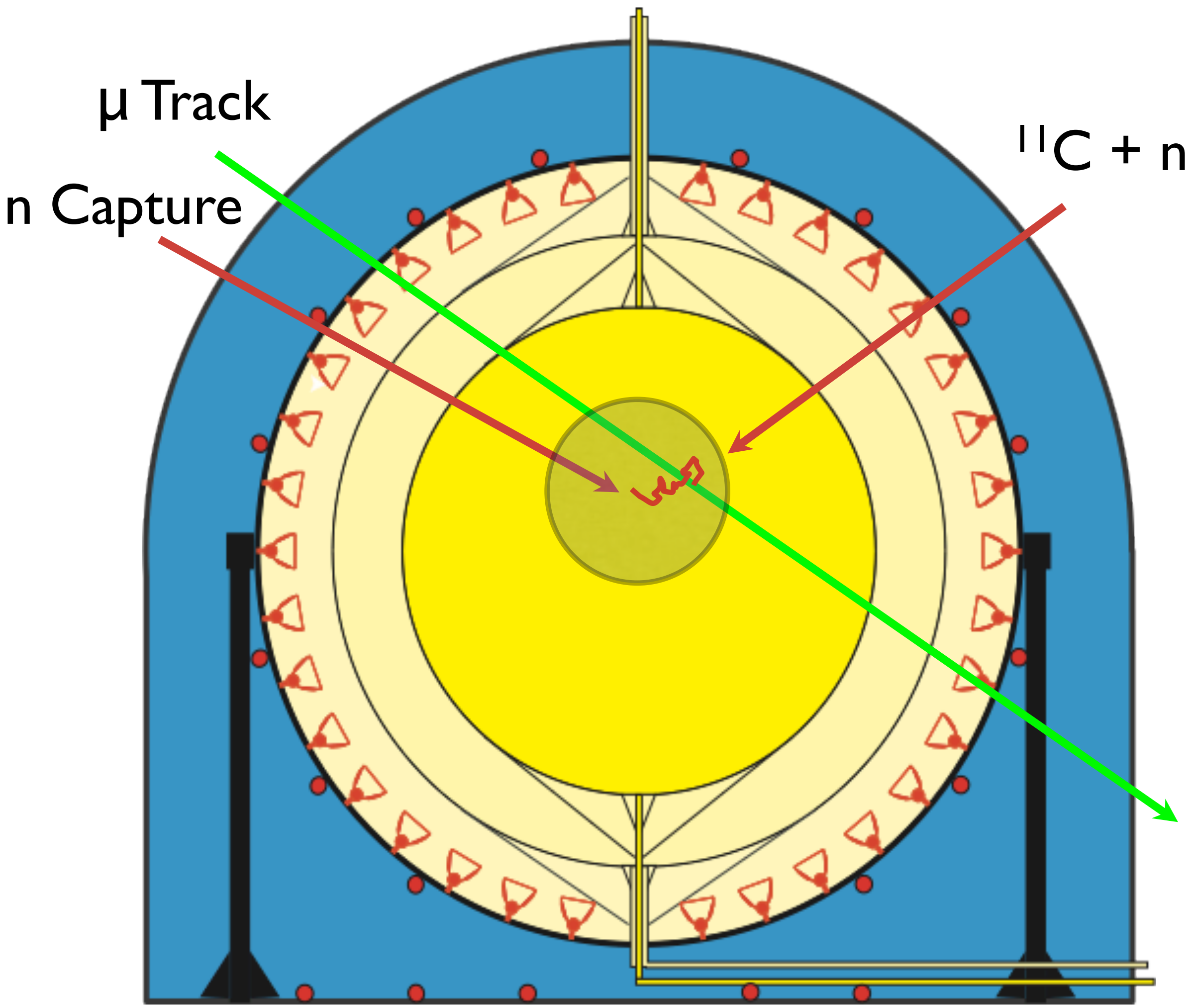
First direct evidence for CNO cycle.

Measure solar metallicity.

^{11}C Suppression



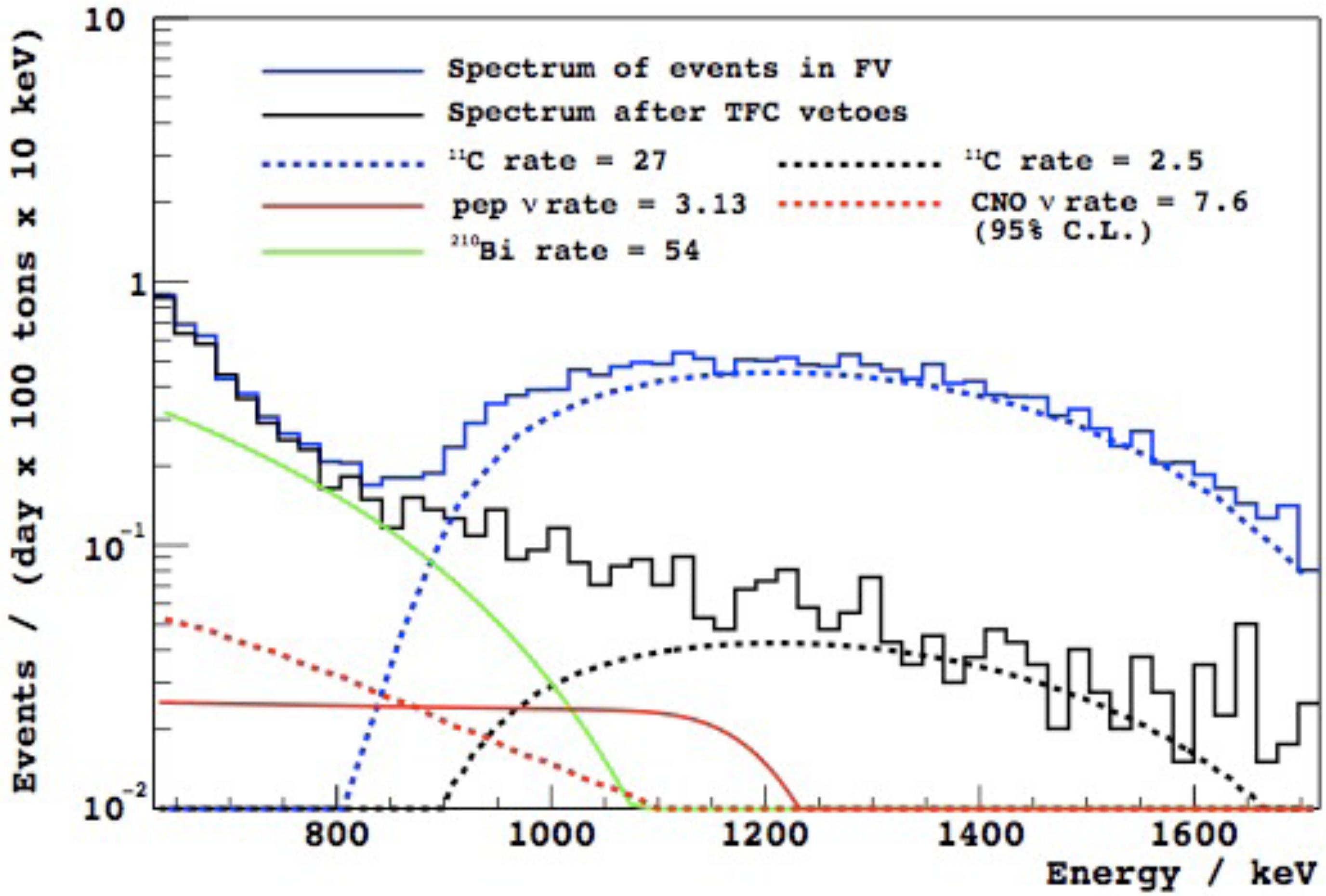
Three-Fold Coincidence



- Most ^{11}C produced via
  $^{12}C \rightarrow {}^{11}C + n$
- Delayed neutron capture signal identifies when and where ^{11}C was produced
- Special triggers and analogue DAQ system to identify muon + neutron

The ~125 muon-neutron coincidences/day can be vetoed without excessive loss of live time.

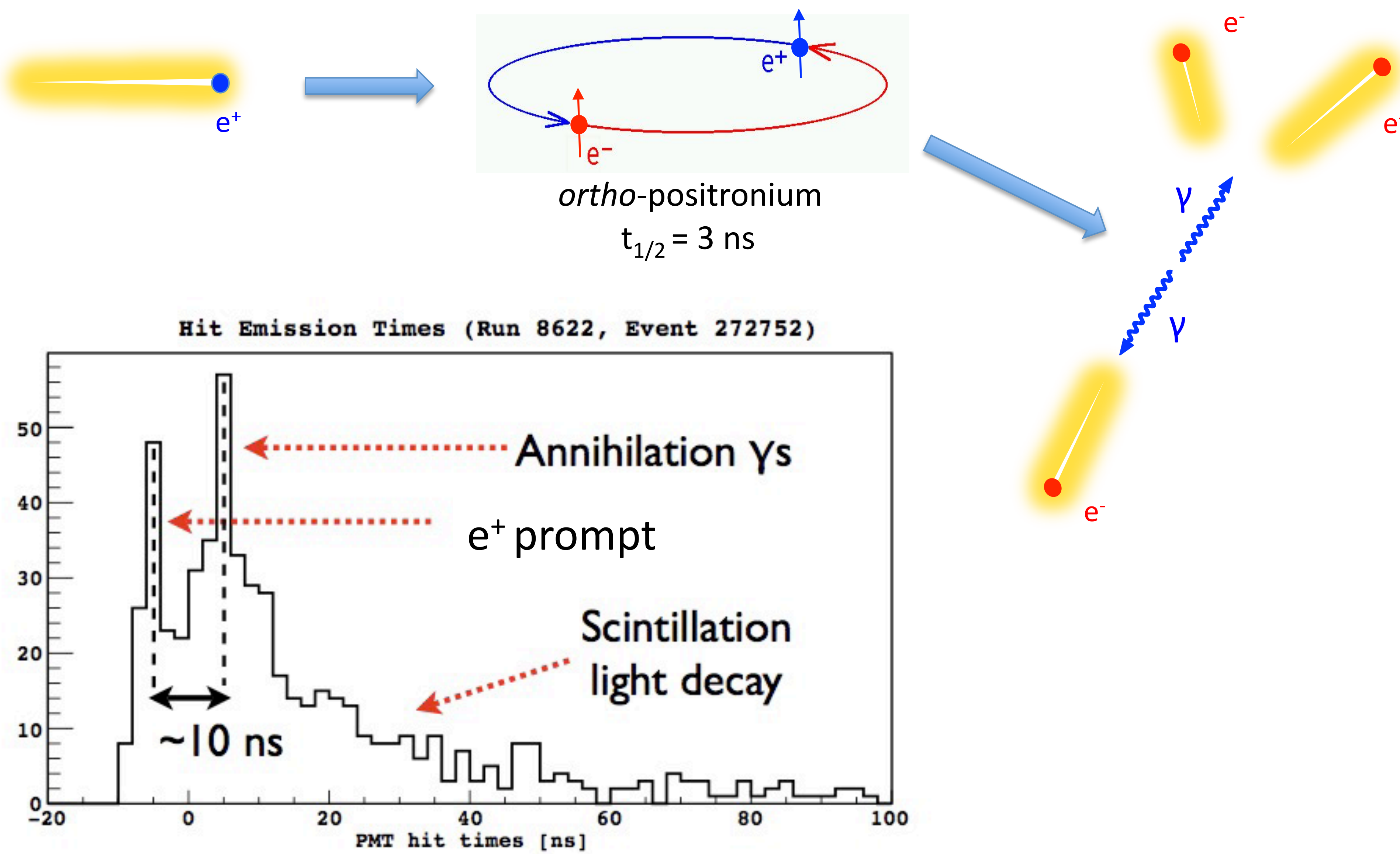
Three-Fold Coincidence



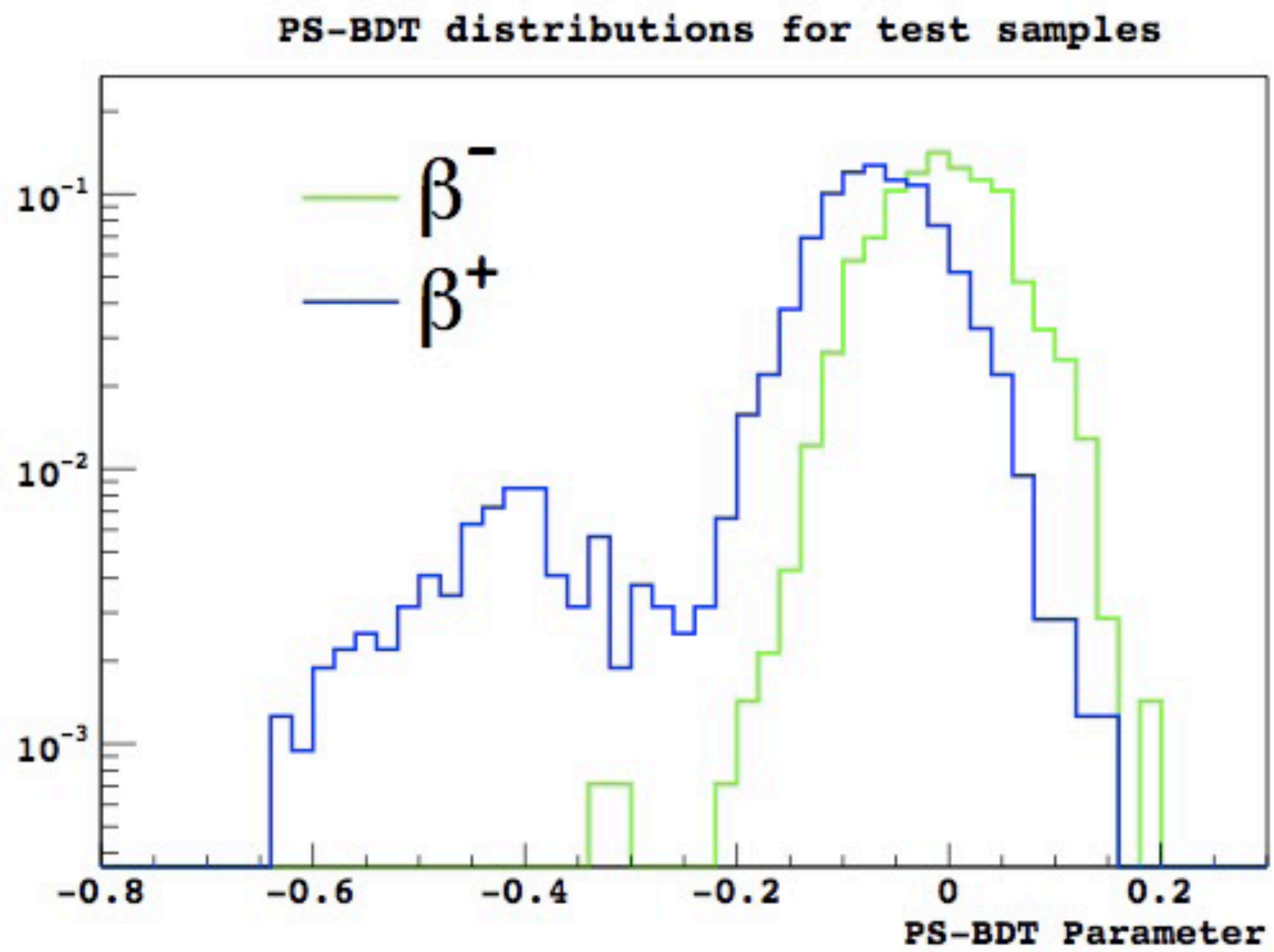
Remove 91% of ^{11}C and 51.5% of livetime.

e^+/e^- Pulse Shape Discrimination

(PRC 83:015522 (2011))



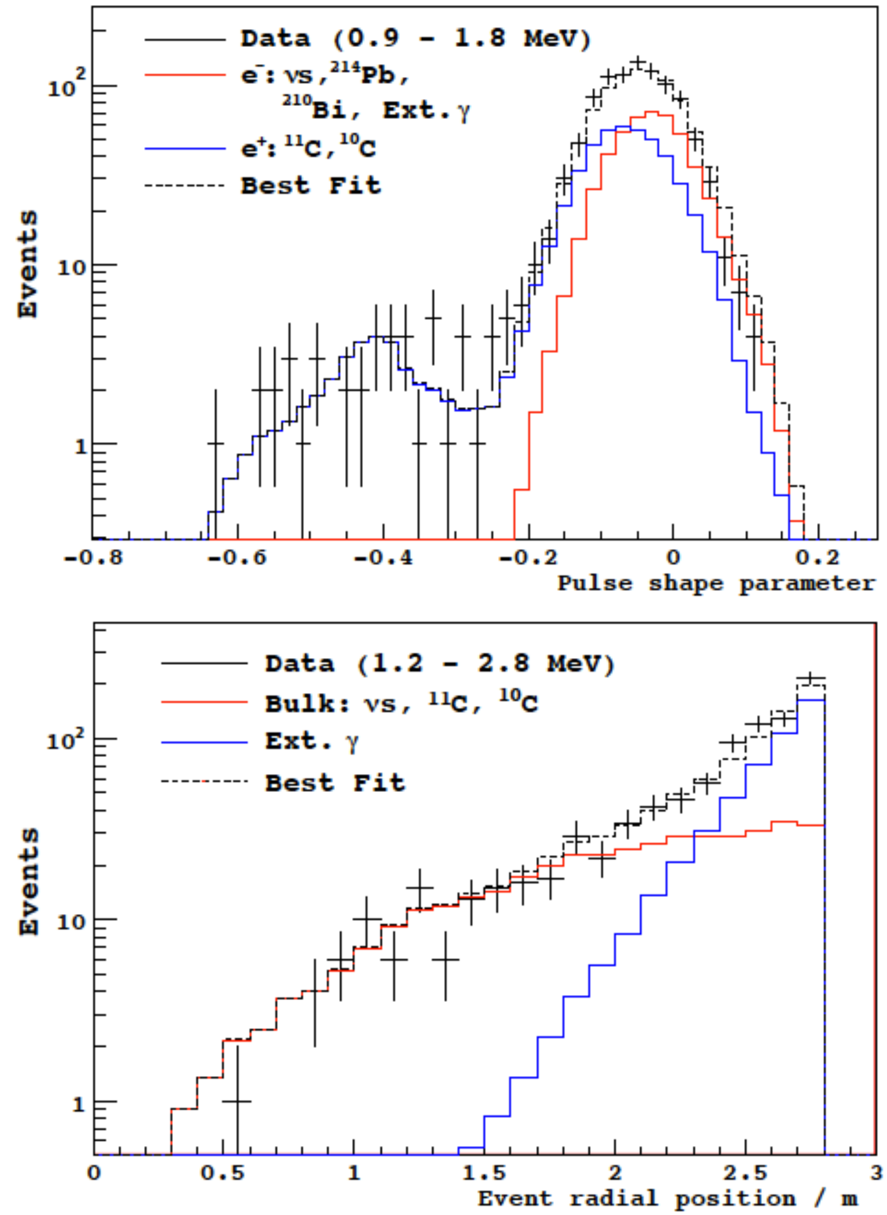
e^+/e^- Pulse Shape Discrimination



Boosted decision tree (BDT) discrimination parameter from pulse shape information.

pep/CNO Fit

- Fit in energy, radius, and BDT
- Radial and BDT distributions are energy dependent
- Simultaneously fit the TFC "signal-like" and "background-like" spectra
  - Double background statistics



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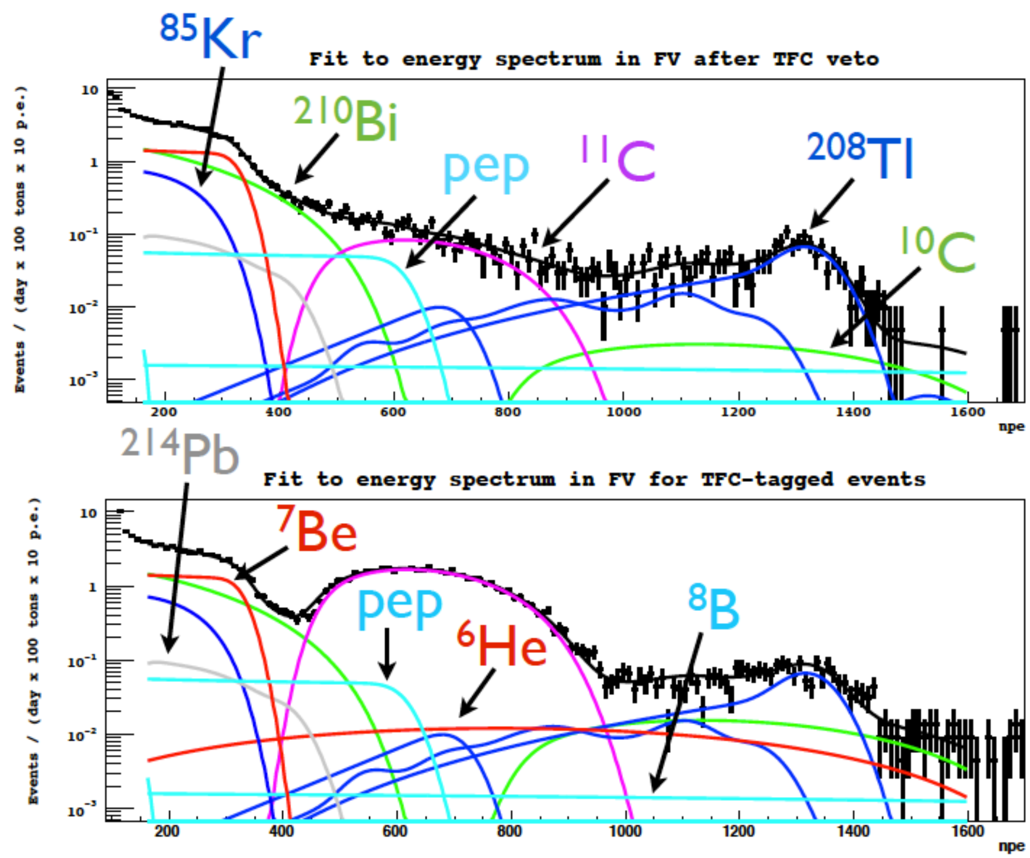
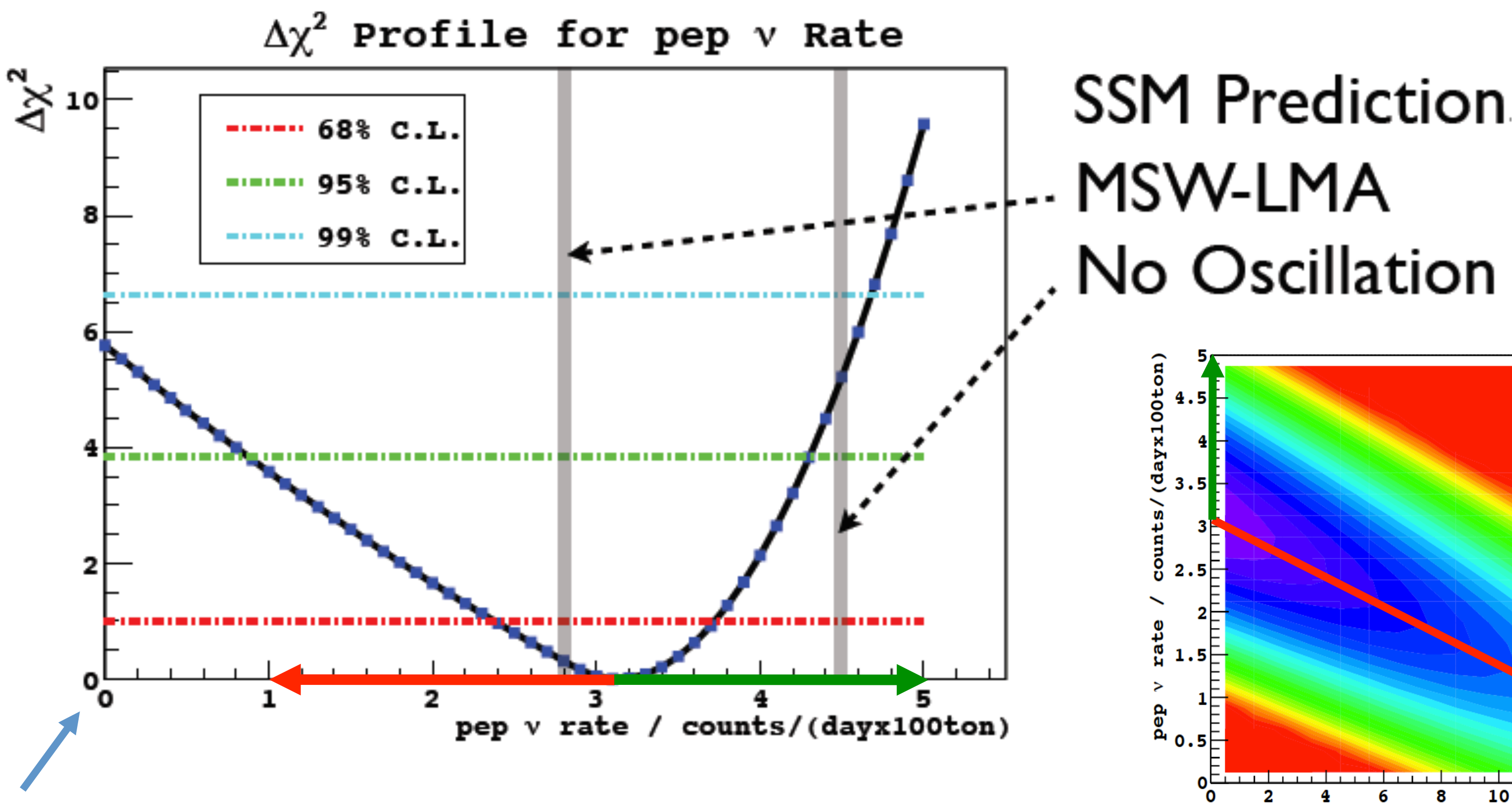


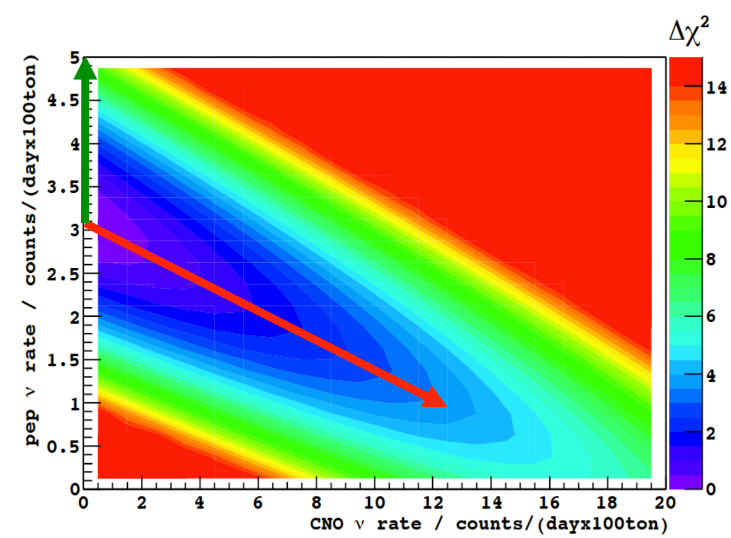
pep Result

(Phys. Rev. Lett. **108**:051302 (2012))

Borexino *pep* counting rate: $3.1 \pm 0.6_{stat} \pm 0.3_{sys}$ /(d 100T)

➡ $\Phi_{pep} = (1.6 \pm 0.3) \times 10^8\ cm^{-2}s^{-1}$ ➡ $P_{ee}(1.44\ MeV) = 0.62 \pm 0.17$

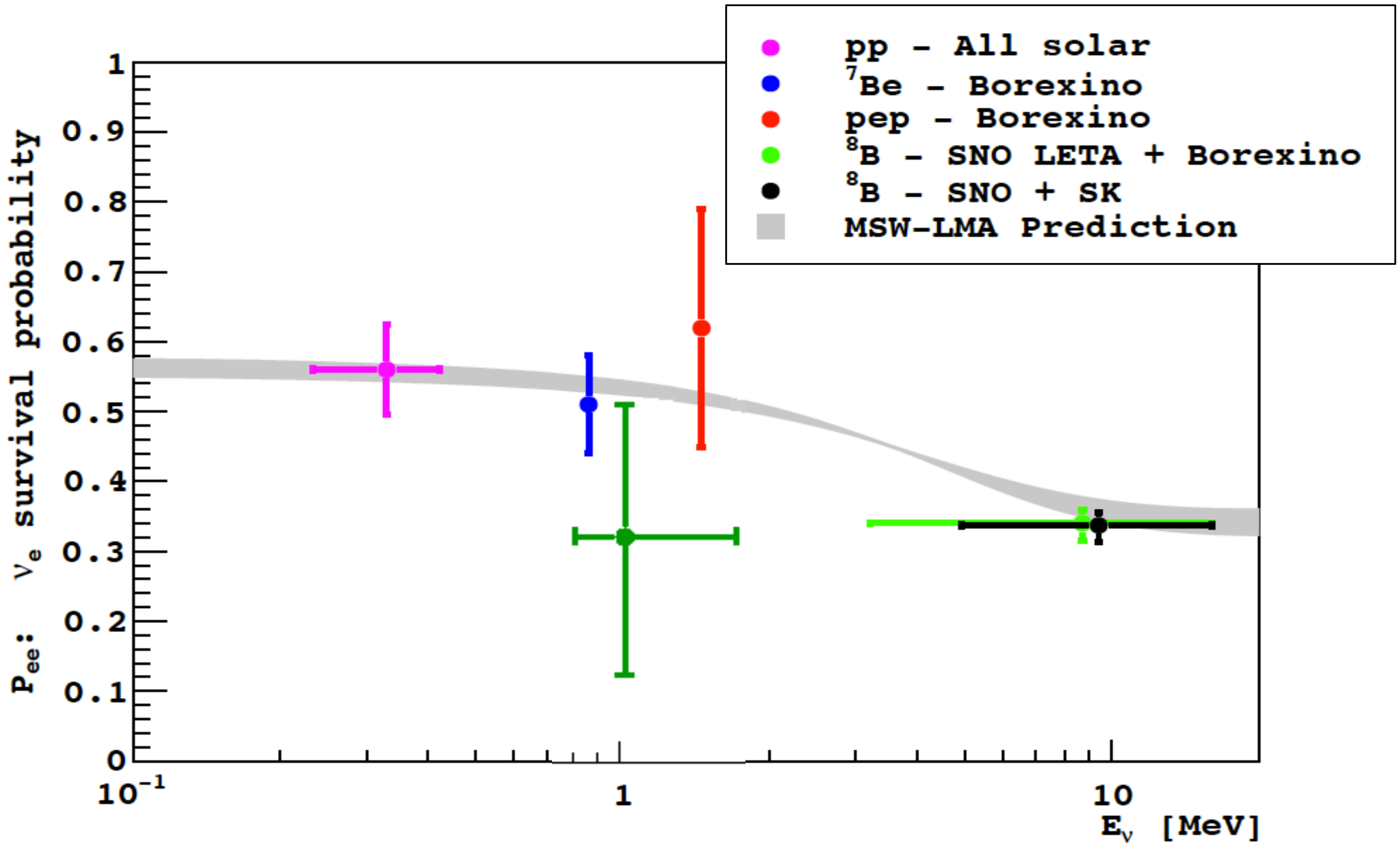




$\Phi_{pep} = 0$ disfavoured at 98% C.L.

pep Result

Borexino *pep* counting rate: 3.1 ± 0.6$_{stat}$ ± 0.3$_{sys}$ /(d 100T)



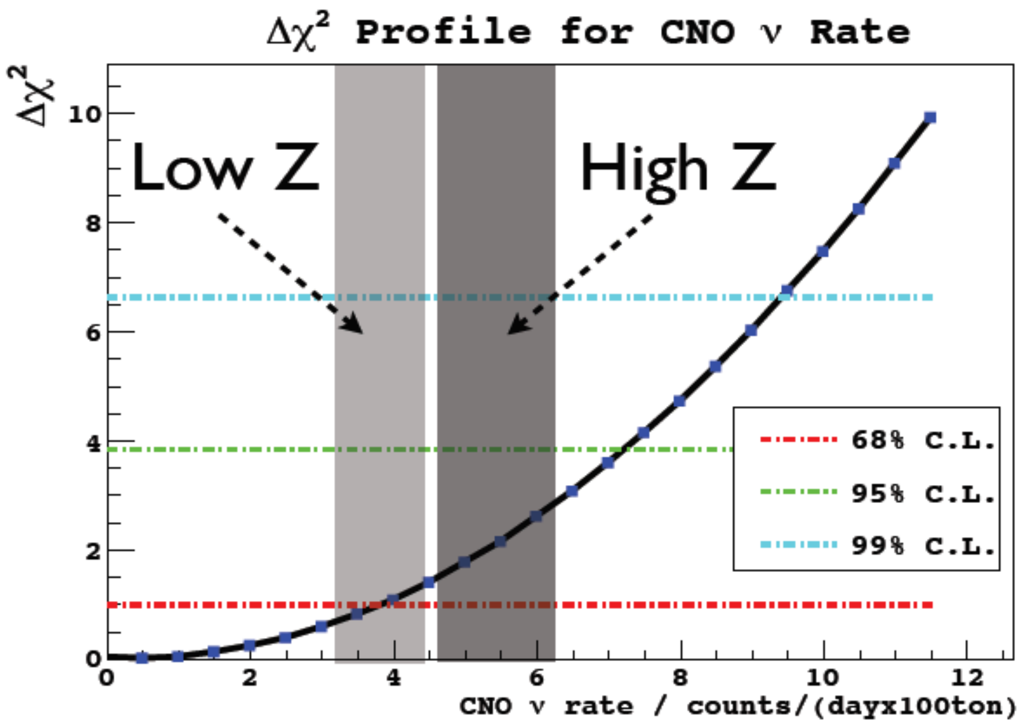
We have succeeded in extracting the pep signal from the background – more precise results possible in the future!

CNO Limit

(Phys. Rev. Lett. **108**:051302 (2012))

Borexino CNO counting rate: < 7.9 ($<7.1_{stat\ only}$) /(d 100T) (95% C.L)

→ **< 7.7 x 10^8 $cm^{-2}s^{-1}$ (< 1.5 x high Z SSM)**



pep rate fixed at SSM prediction:
(2.8 ± 0.4) /(d 100T)

Sensitivity approaching predicted rates: most stringent limit to date.

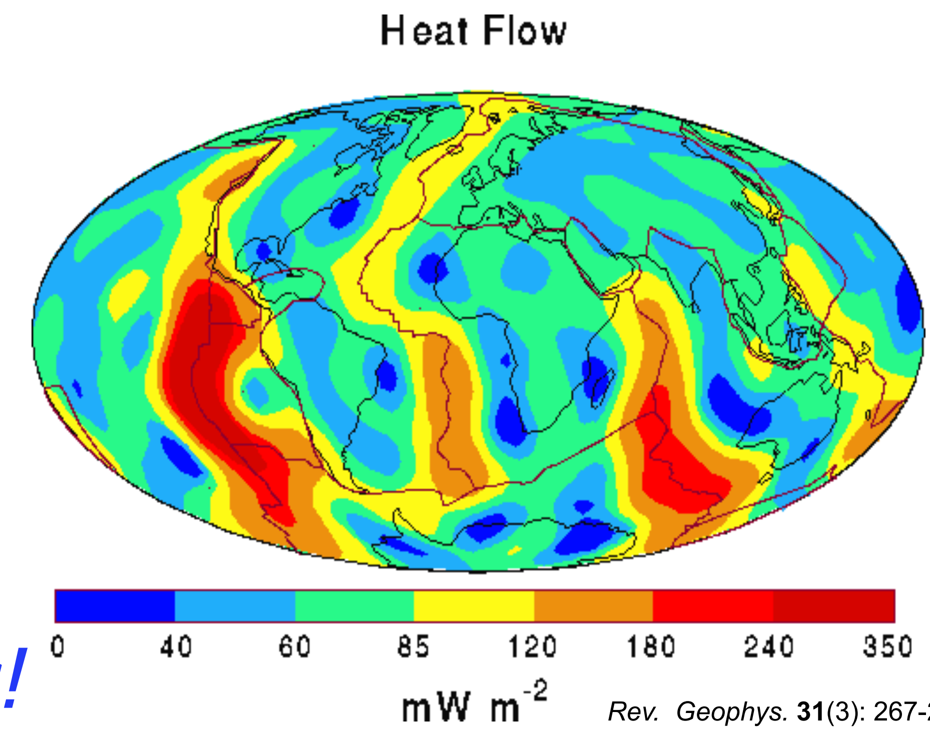
Result consistent with both high and low metallicity models.

Geo-Neutrinos

- Antineutrinos from β^- decay of K, U and Th in the earth's mantle and crust
- Models suggest that these decays are responsible for 40-100% of the earth's heat

Not well known!

- Use geoneutrinos to measure the earth's radiogenic heat and chemical composition

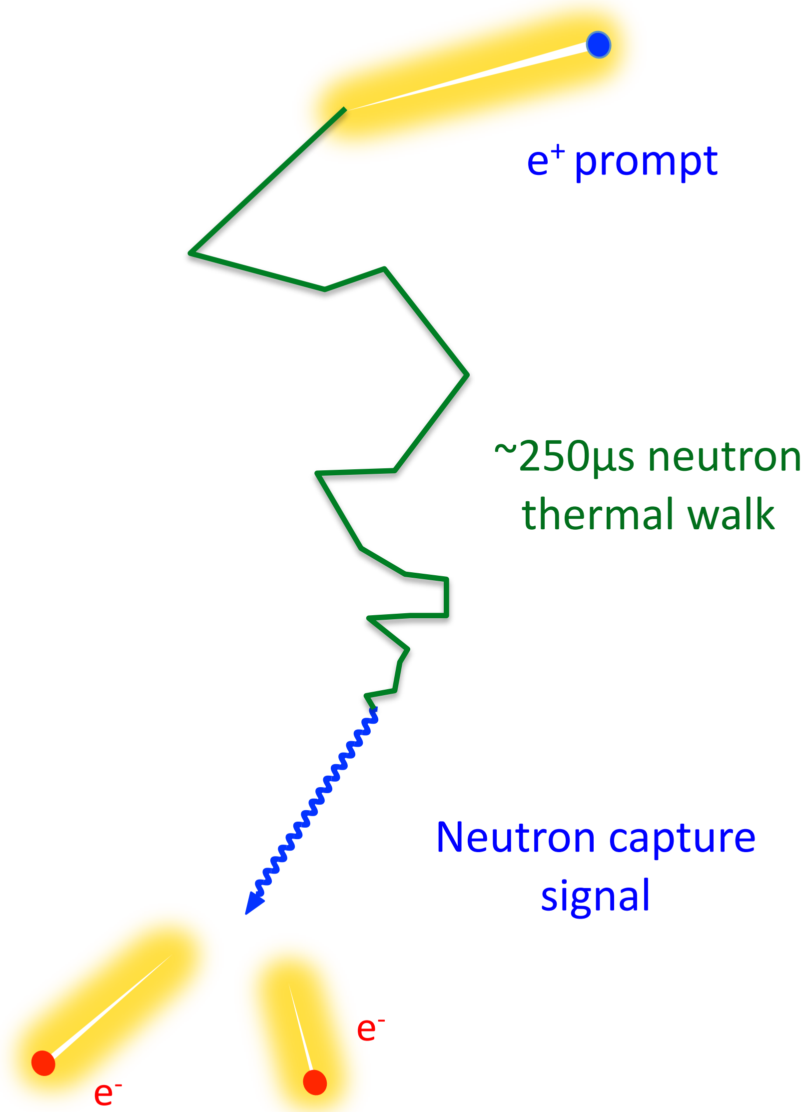


Rev. Geophys. **31**(3): 267-280 (1993)

Geophysics with neutrinos!

Detecting Geo-Neutrinos

- Expected rate in Borexino is tiny: <5/100T/yr
- Detection via $\bar{\nu}_e + p \rightarrow n + e^+$
  - Delayed co-incidence gives powerful background rejection
  - $E_{e+} = E_\nu - 0.782$ MeV
- Separate geo-neutrinos from reactor anti-neutrinos by energy spectrum



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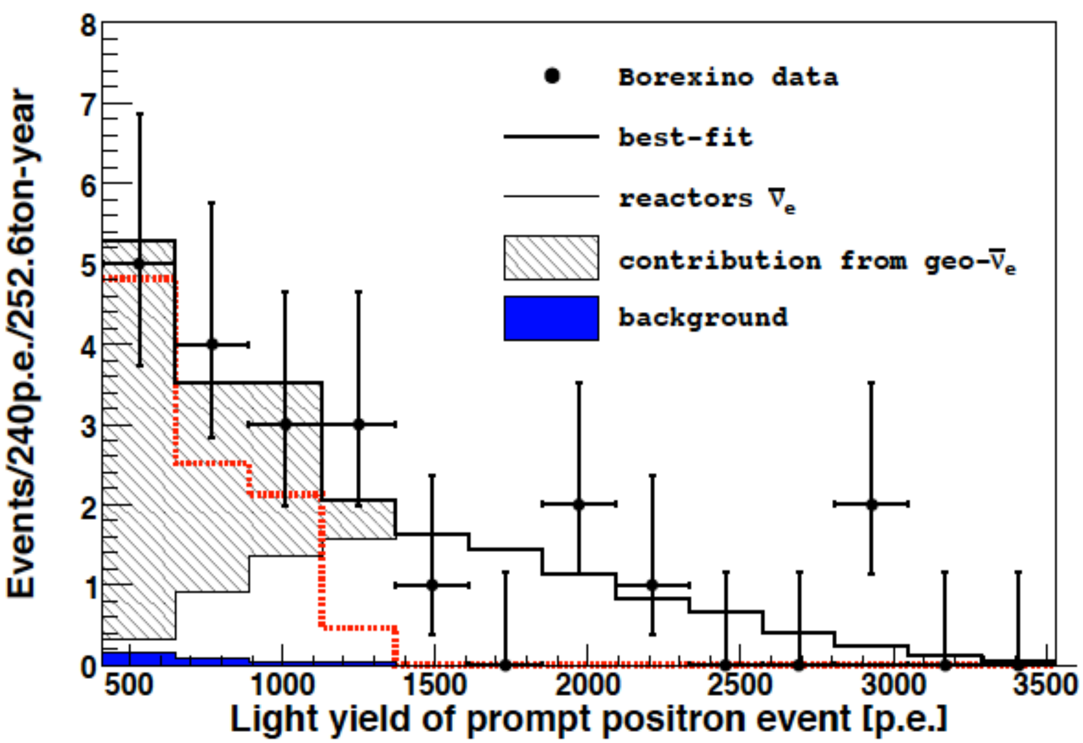
Geo-neutrinos in Borexino

(Phys. Lett. B **687**:299-304 (2010))

Borexino Geo-Neutrino Rate: $3.9^{+1.6}_{-1.3}$ ev/100T/yr



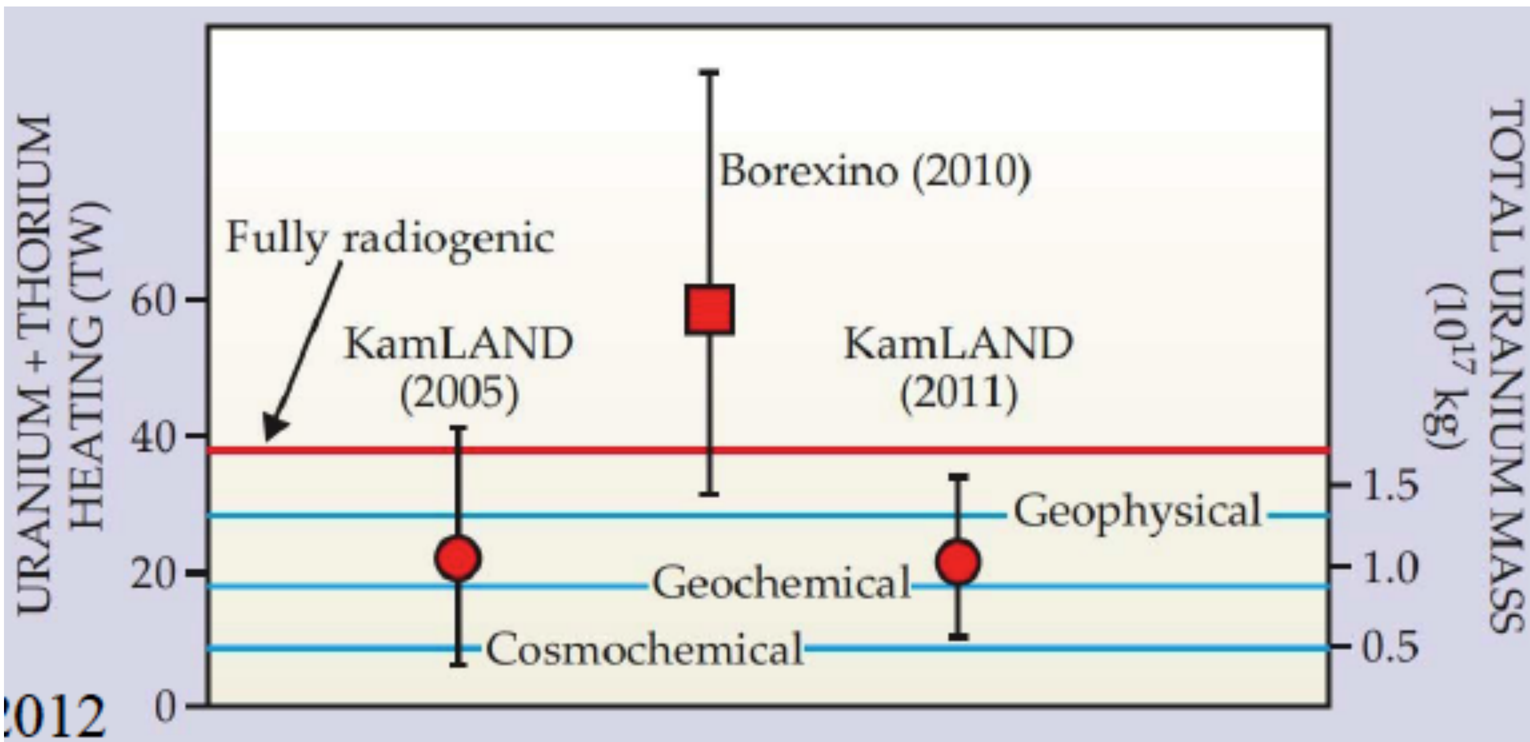
Delayed Co-incidence Backgrounds

Source	Background [events/(100 ton·yr)]
^{9}Li–^{8}He	0.03±0.02
Fast n's (μ's in WT)	<0.01
Fast n's (μ's in rock)	<0.04
Untagged muons	0.011±0.001
Accidental coincidences	0.080±0.001
Time corr. background	<0.026
(γ,n)	<0.003
Spontaneous fission in PMTs	0.0030±0.0003
(α,n) in scintillator	0.014±0.001
(α,n) in the buffer	<0.061
Total	0.14±0.02

Geo-neutrinos in Borexino

(Phys. Lett. B **687**:299-304 (2010))

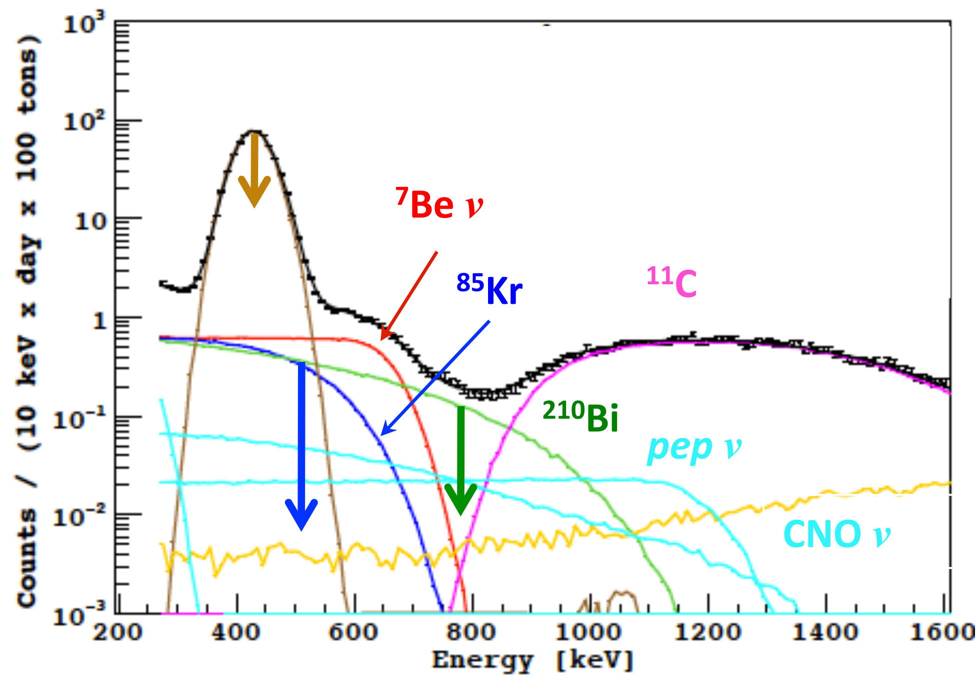
Borexino Geo-Neutrino Rate: $3.9^{+1.6}_{-1.3}$ ev/100T/yr



McDonough and Dye, SNOLAB workshop, May 2012

Borexino Future

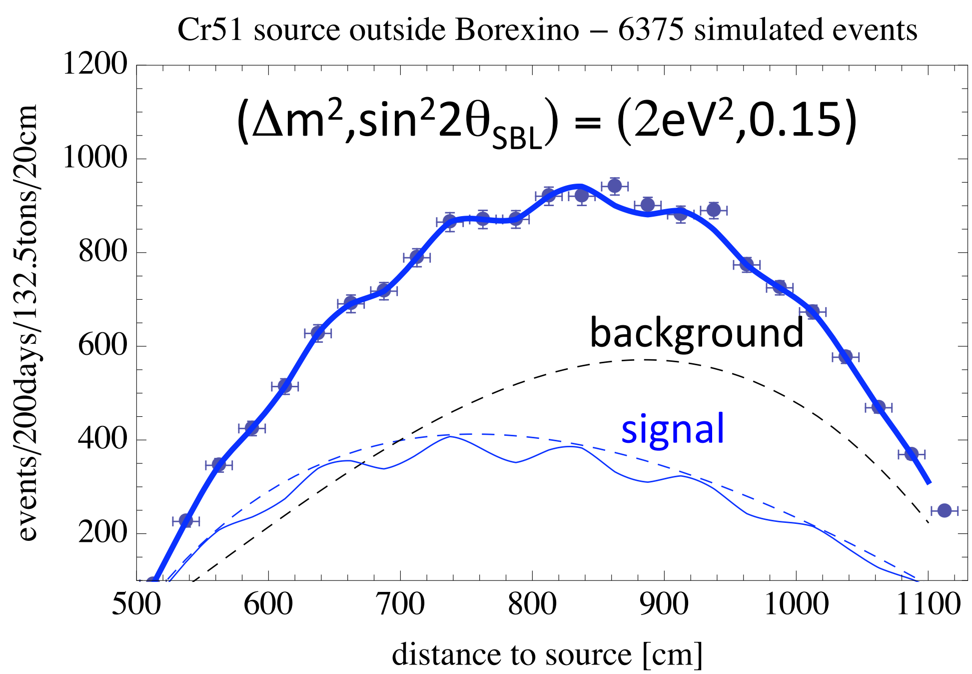
- Procedures to (further!) purify the scintillator underway since July 2010
  - No sign of ^{85}Kr since January 2011
  - Moderate reduction in ^{210}Bi
- Operations continue, with aim of further reducing ^{210}Bi, perhaps ^{210}Po
- Borexino will continue to take solar neutrino data for >3 more years



Increased statistics + lower backgrounds = improved measurements of the low energy solar neutrinos and geo-neutrinos.

Sterile Neutrino Search

- Several experiments (LSND, "reactor anti-neutrino anomaly," "gallium anomaly," CMB) give weak evidence for a 4th, sterile, neutrino
- Deploying a strong (10 MCi) electron capture neutrino source near Borexino would allow us to look for oscillations within the detector!



Summary

- Unprecedented radiopurity and new background suppression techniques give Borexino unique capability
  - Precision measurement of the ^{7}Be solar neutrino rate
  - First direct studies of the *pep* and CNO neutrino
  - First detection of geo-neutrinos
- Repurification and new opportunities promise even more exciting results in the future!