Solar Neutrino Results From Borexino

HEP Seminar, University of Pennsylvania
November 8th, 2011

Alex Wright
Princeton University
for the Borexino Collaboration

Image: Borexino Collaboration

Outline

- Quick review of solar neutrinos and neutrino oscillations
- Introduction to Borexino
- Recent results and implications
- Outlook

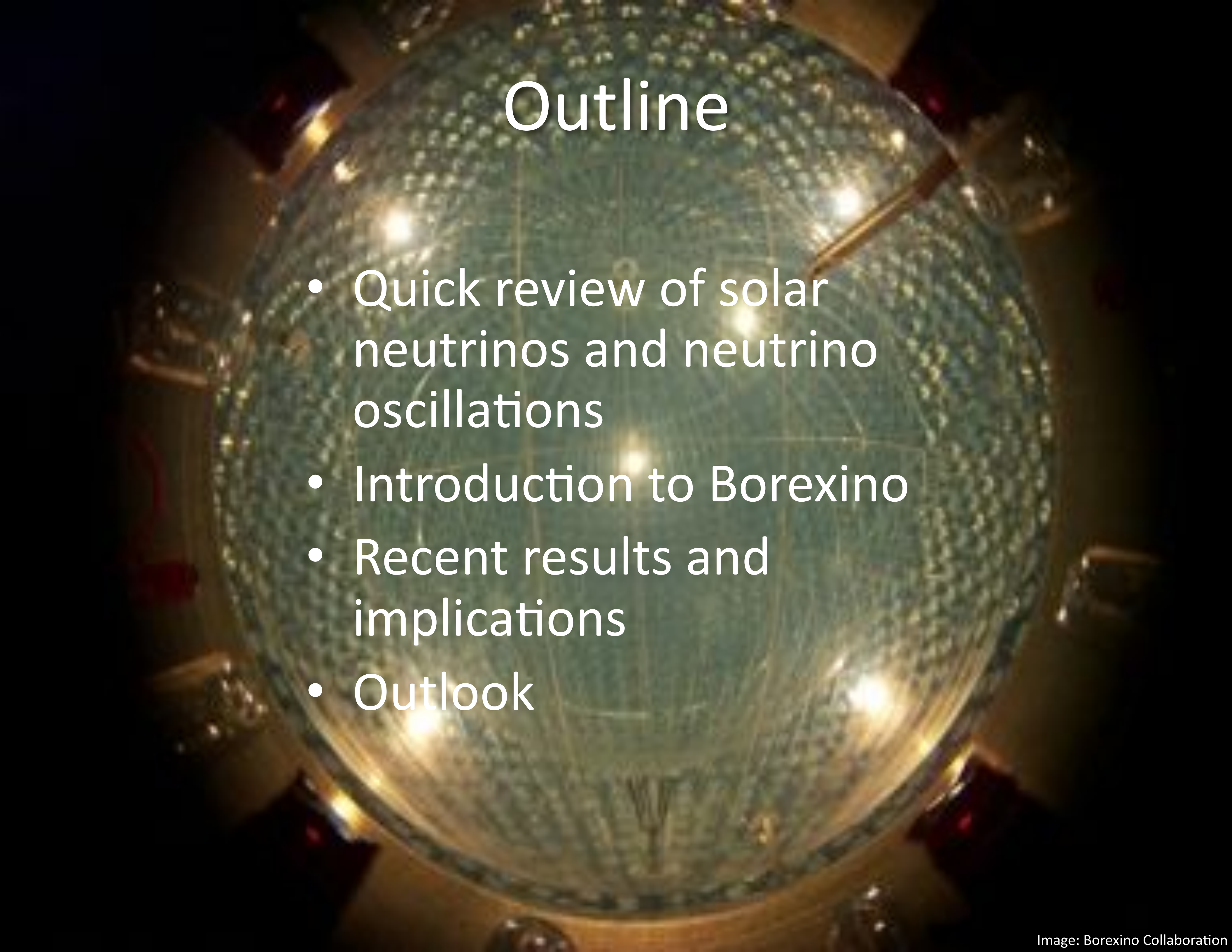


Image: Borexino Collaboration

Solar Fusion Reactions

p-p Solar Fusion Chain

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

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

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

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

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

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

CNO Solar Fusion Cycle

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

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

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

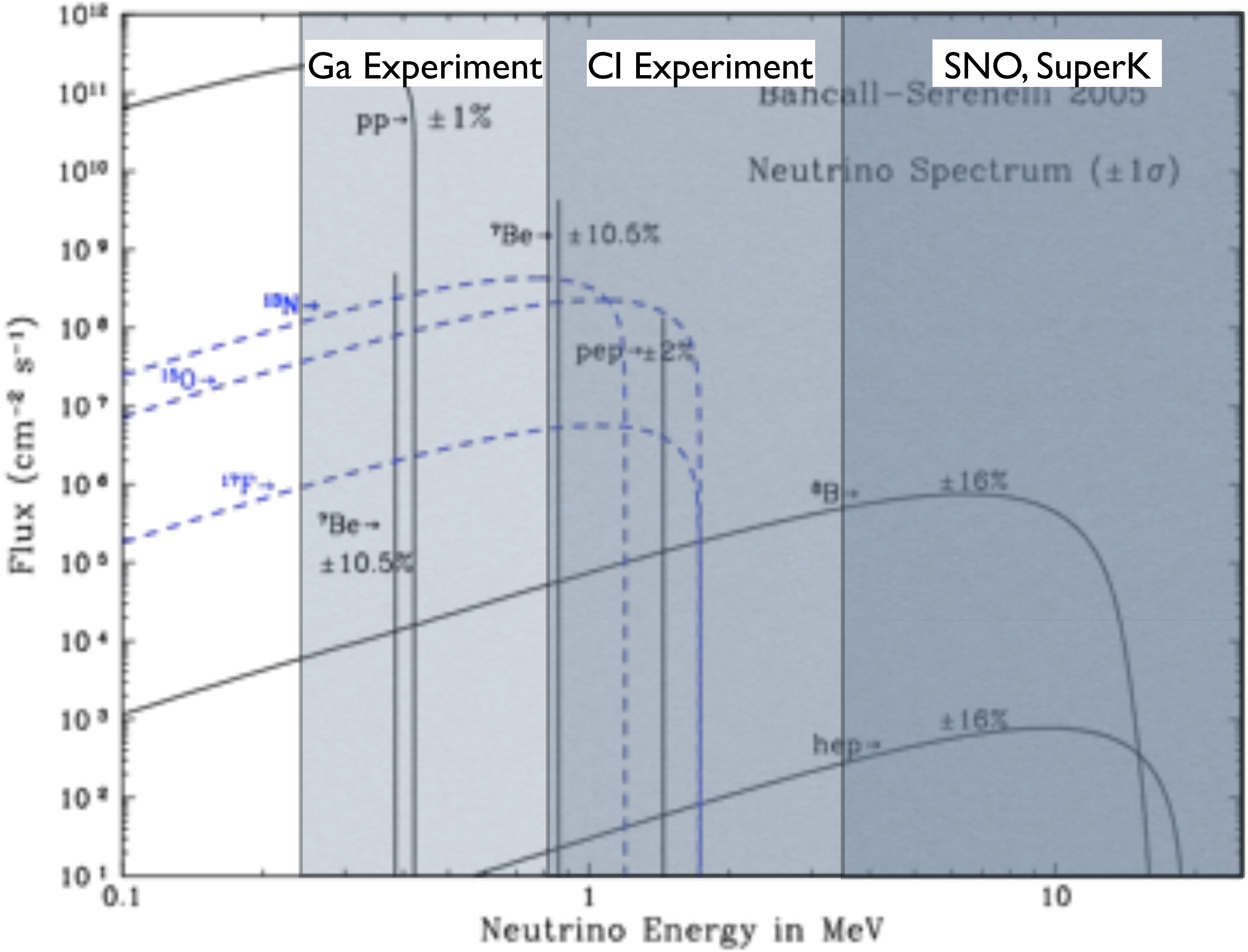
$^{14}N + p \rightarrow {}^{15}O + \gamma$

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

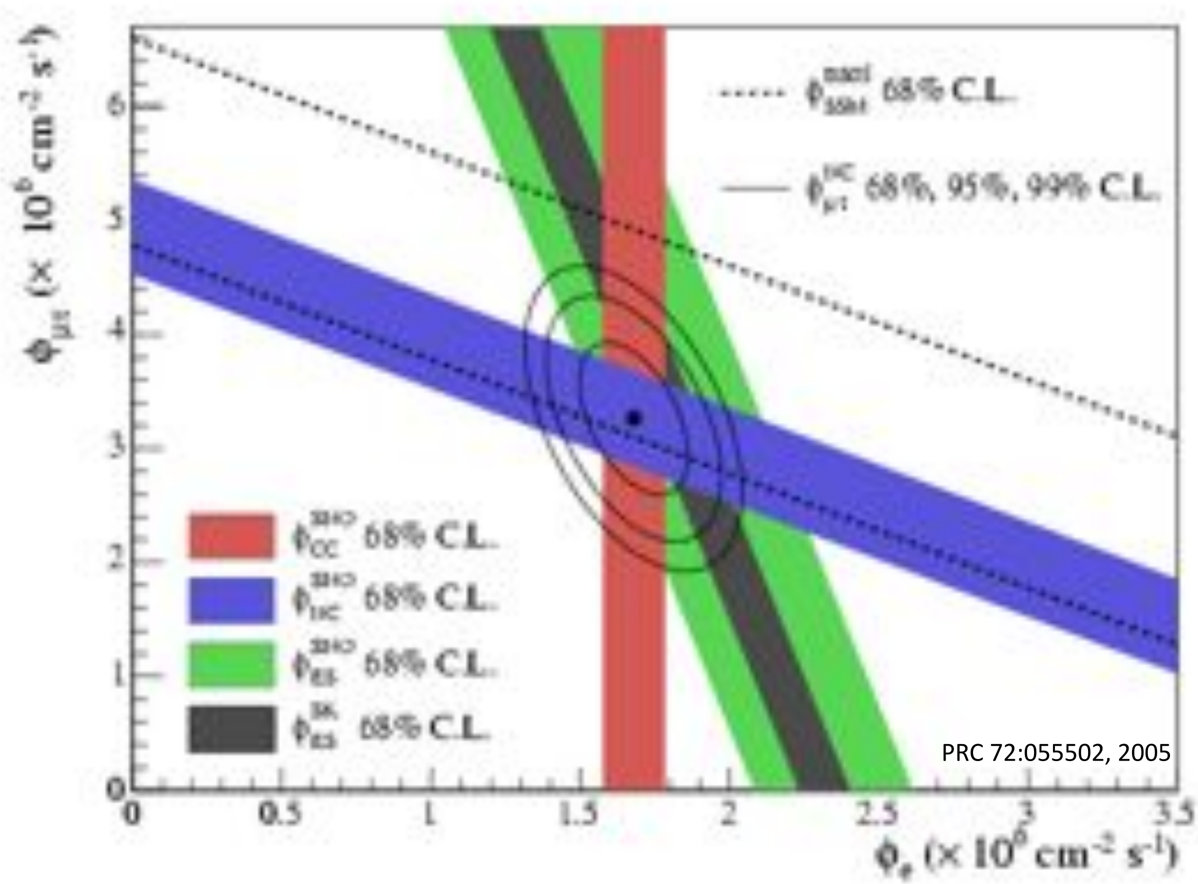
$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

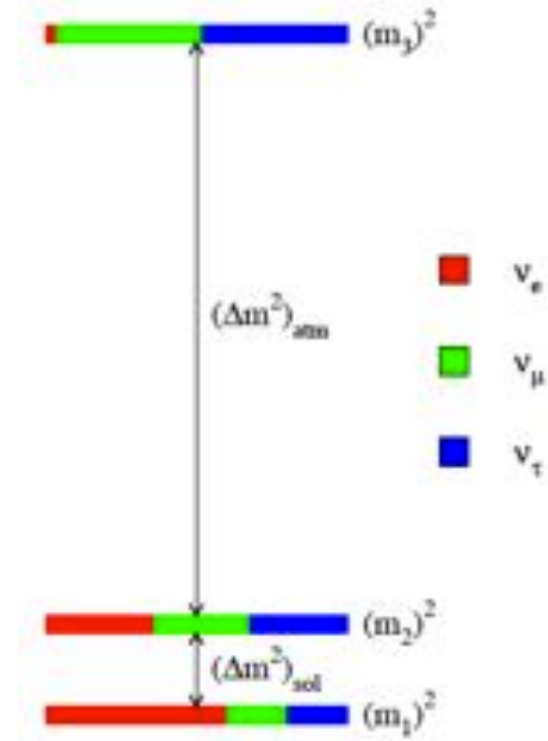
Image: bbc.co.uk

Solar Neutrinos



Solar Neutrino Oscillations





hep-ph/0411274

- Neutrinos are produced and detected in flavour eigenstates, but propagate in a superposition of mass eigenstates (CKM matrix ⟶ PMNS matrix)
- Phase differences acquired in mass eigenstate propagation change apparent flavour content

“MSW” Neutrino Oscillations

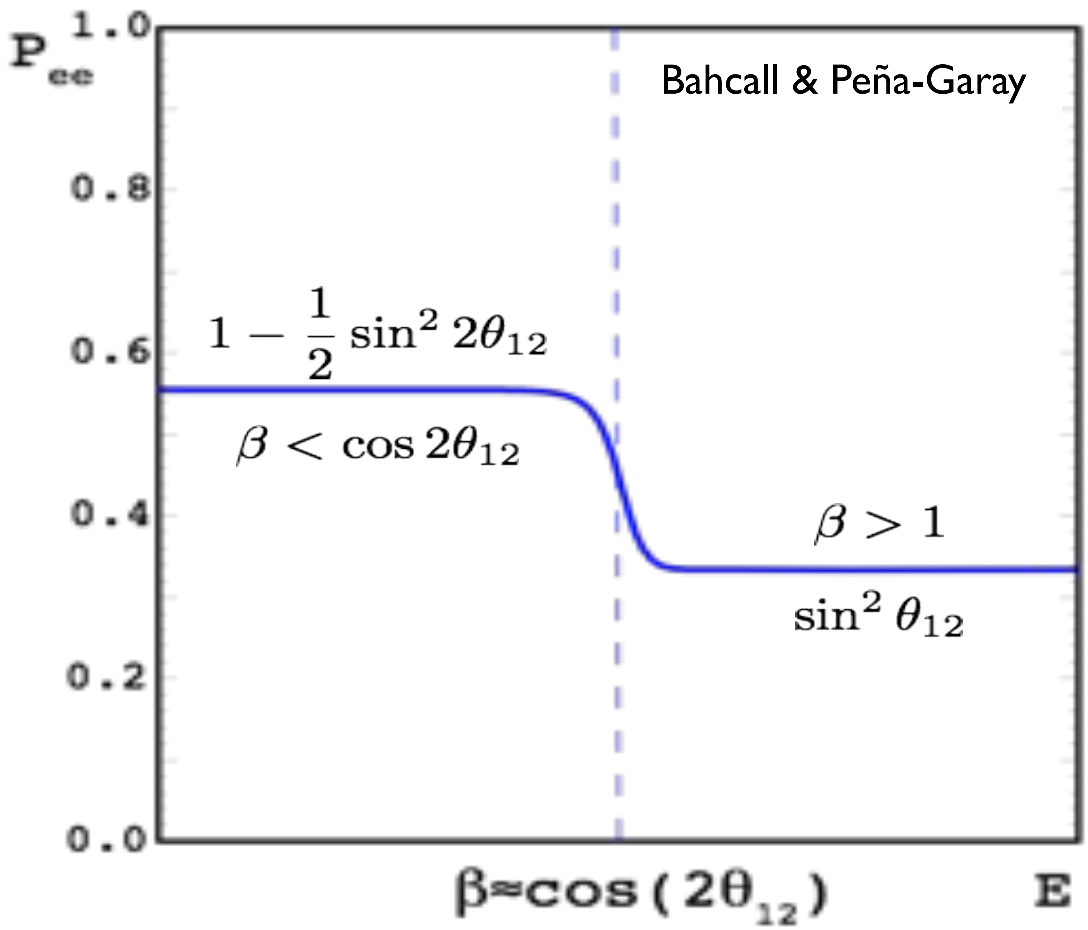
- When neutrinos propagate in matter, charged current interactions add an additional term to ν_e flavour in mass matrix:

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

- As neutrinos propagate out of the sun, the matter effect can lead to a resonant enhancement of the transition probability
  - “Strength” of the effect is energy dependant:

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

MSW Oscillation Regimes

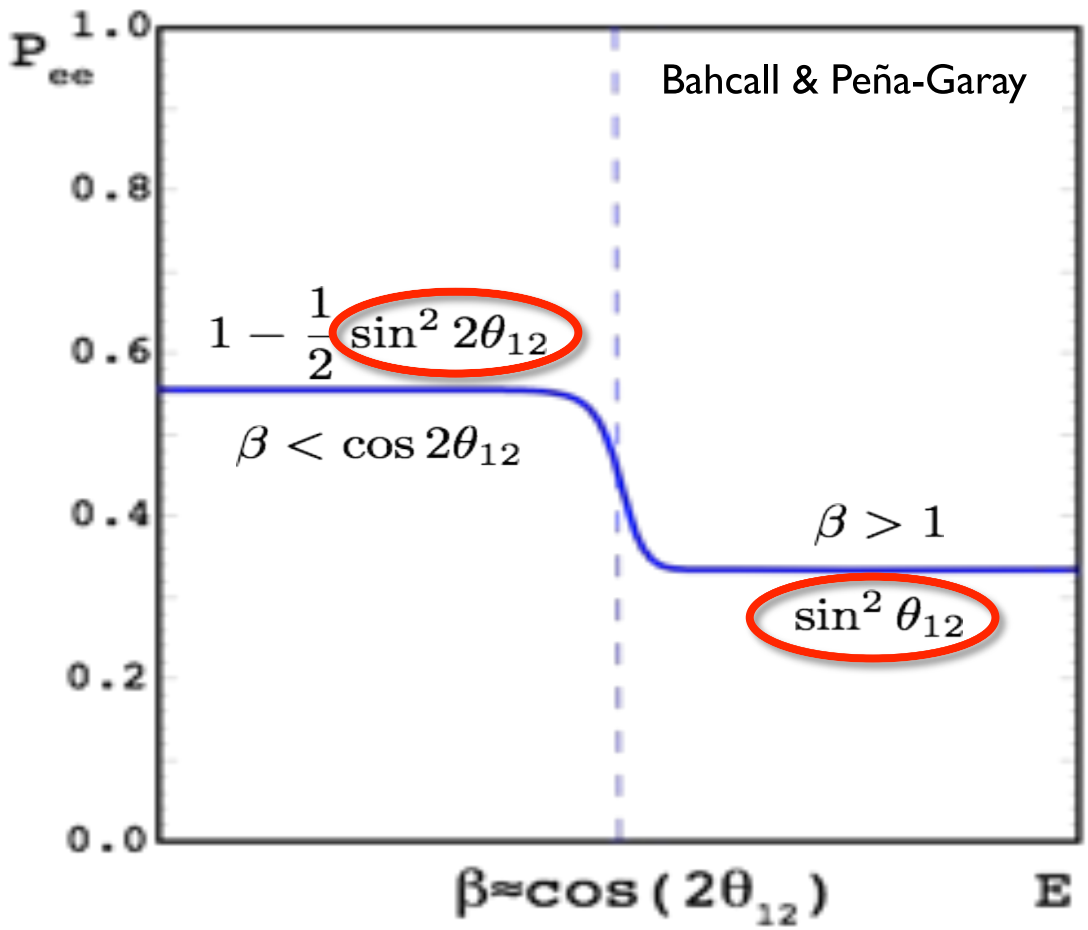


$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated "resonant conversion"

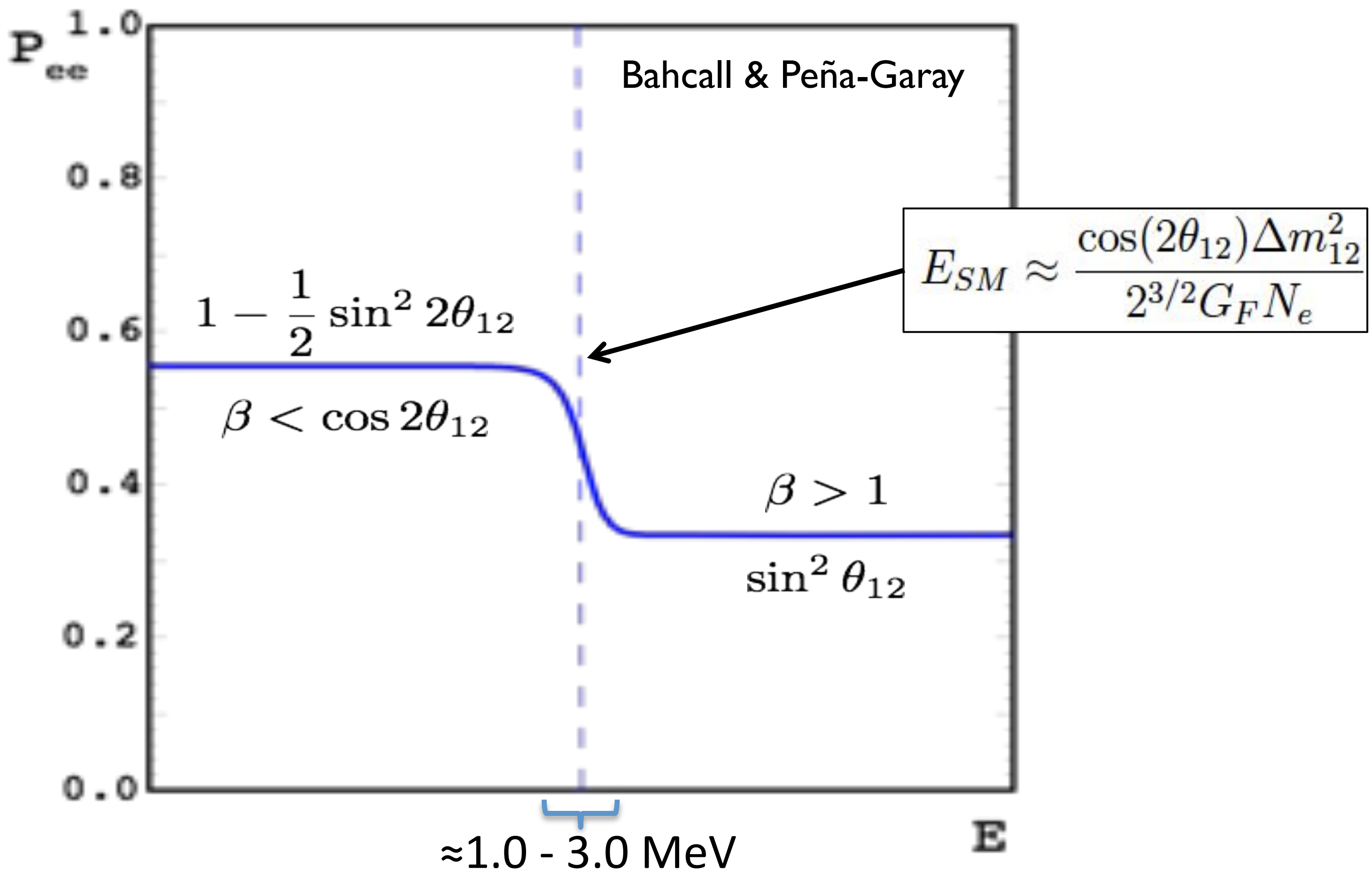
MSW Oscillation Regimes



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

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

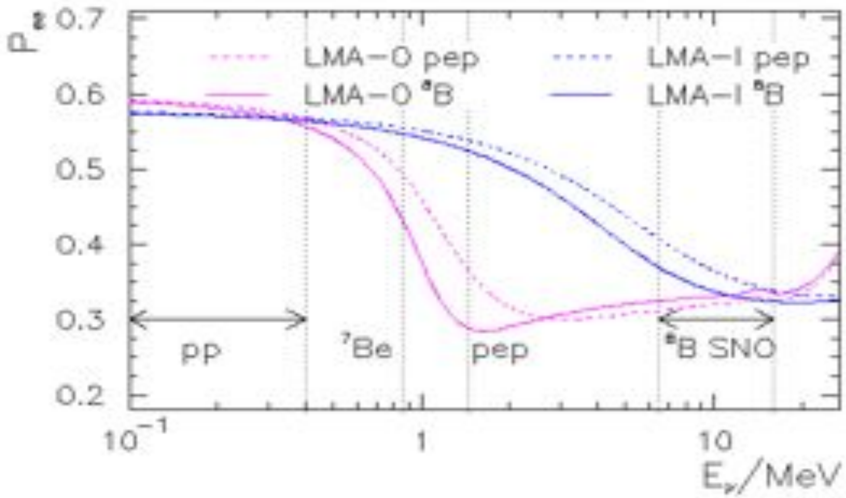


Look in "transition region" to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

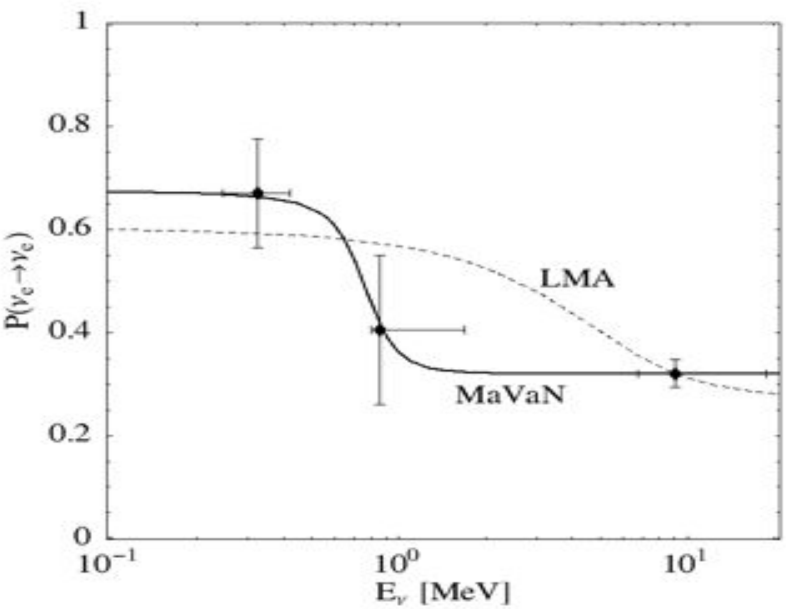
Non-Standard Interactions

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



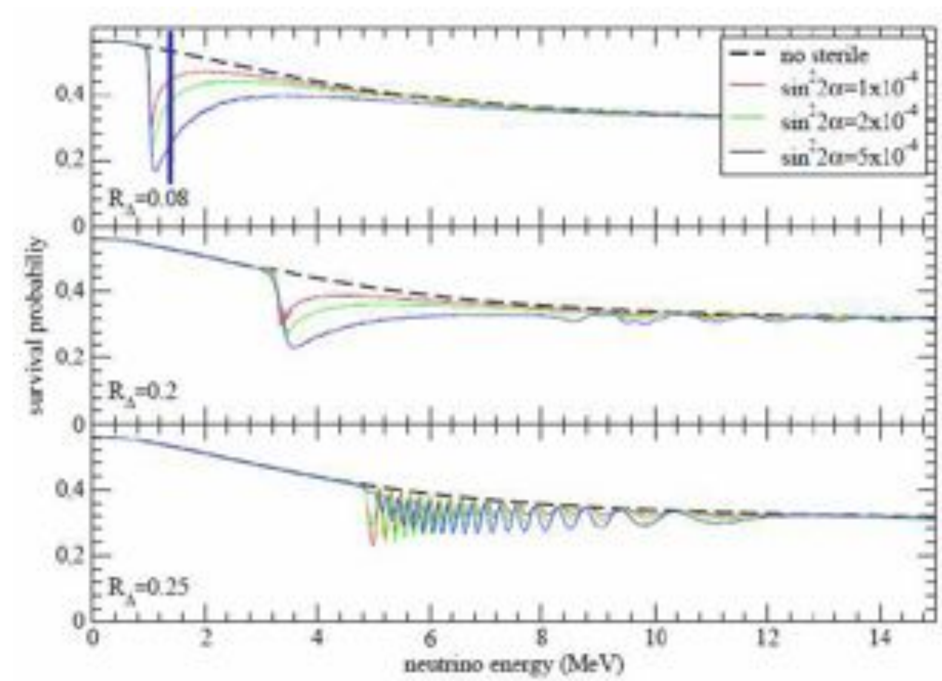
Mass Varying Neutrinos

Barger *et al*. PRL 95 (2005)

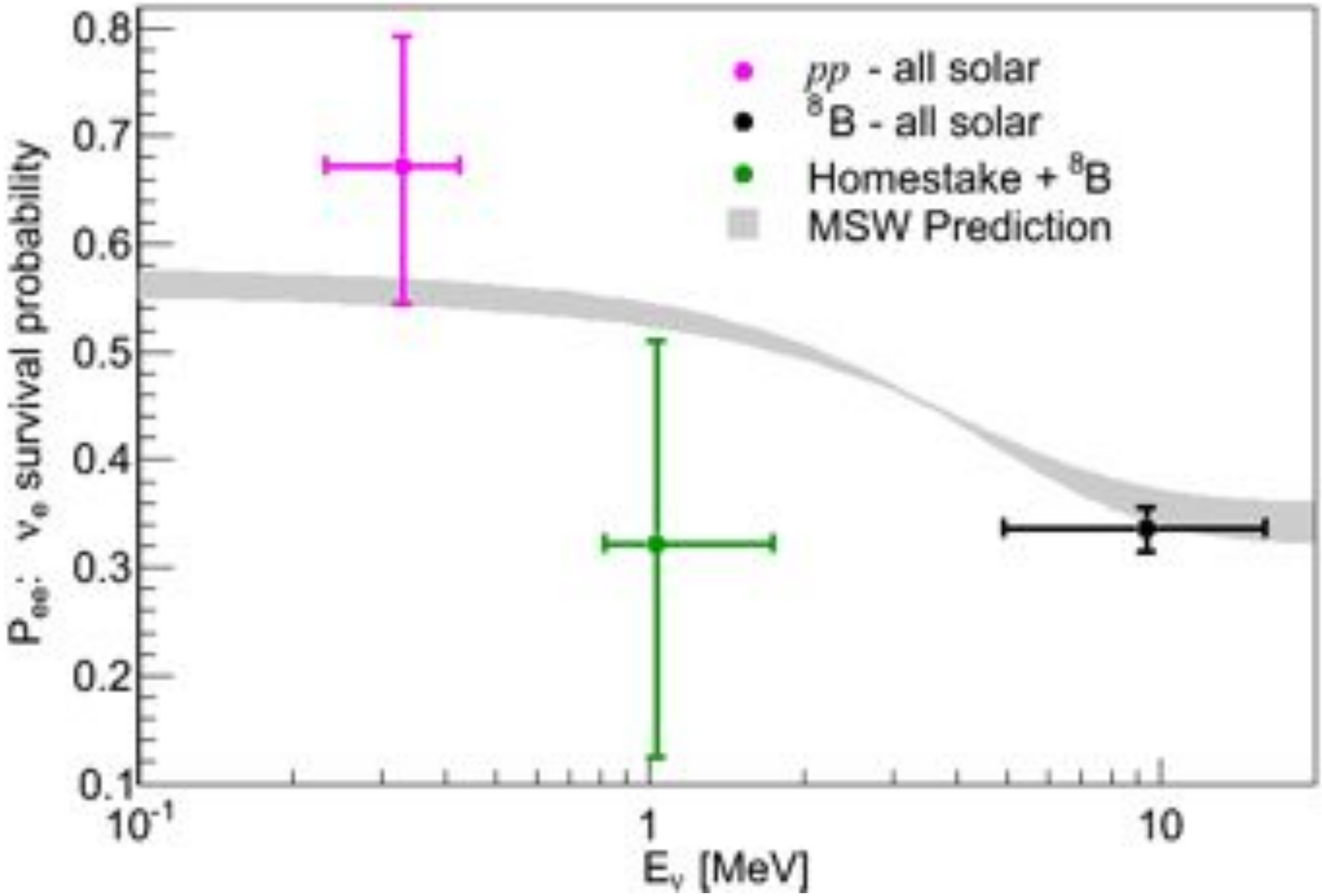


Sterile Neutrinos

Holanda and Smirnov, arXiv:1012:5627 (2010)

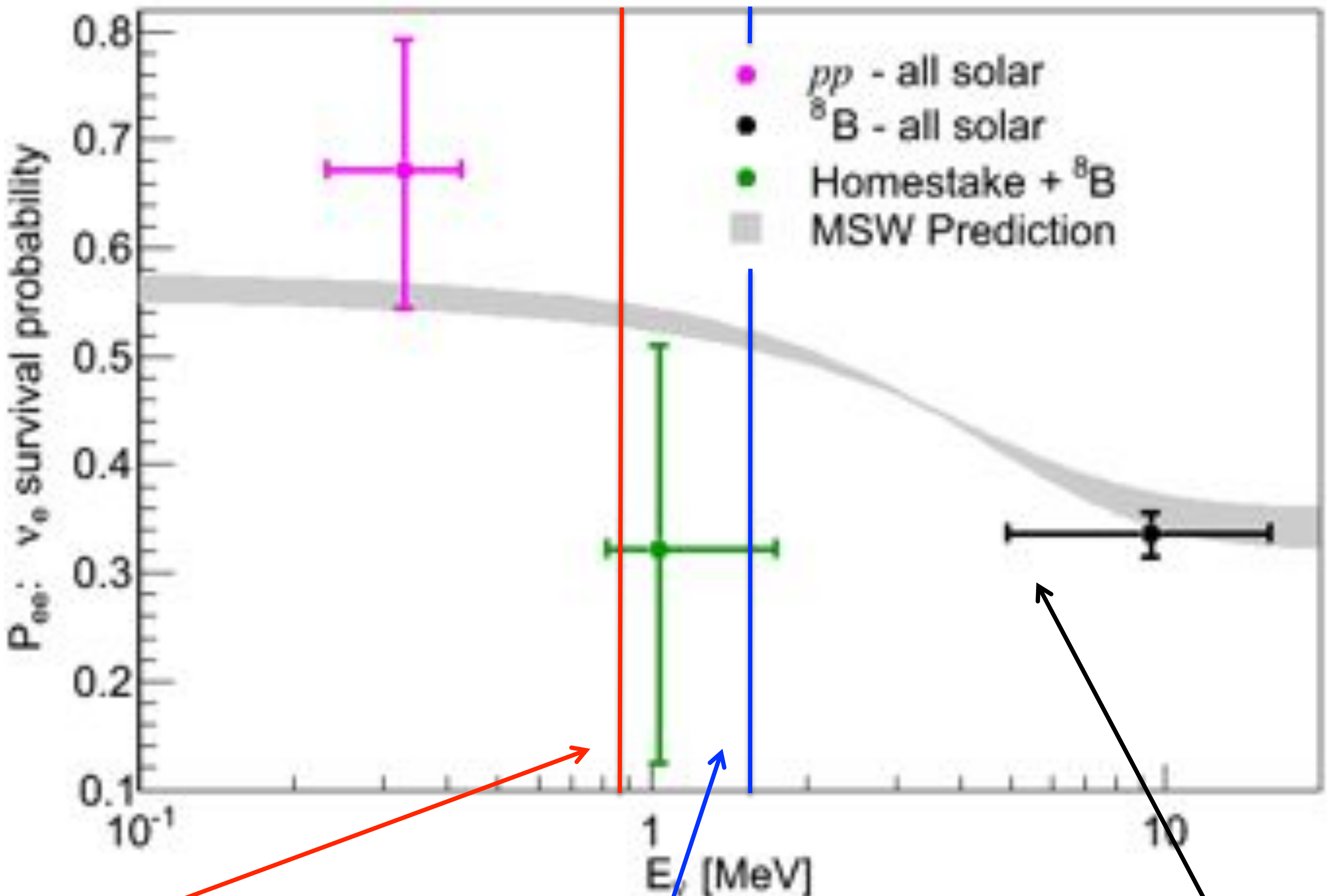


Pre-Borexino Constraints on Transition Region



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

Probing the Transition Region



862 keV ^{7}Be neutrinos:
High flux, monoenergetic,
Constrain T.R. from below.

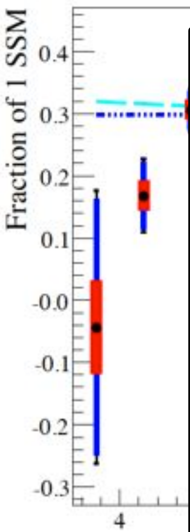
pep neutrinos:
Ideal energy for testing new physics,
precise SSM flux prediction.

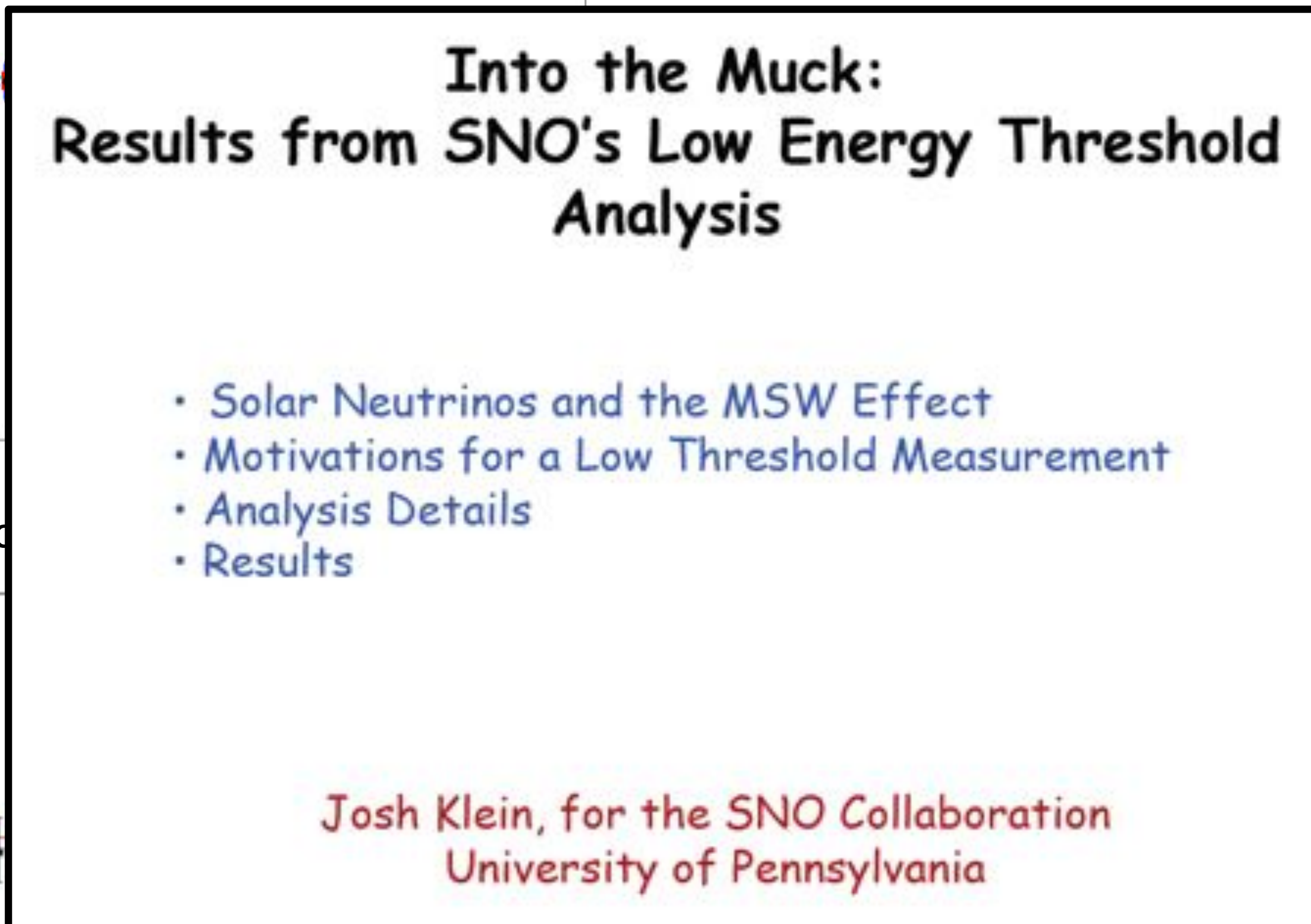
Low energy ^{8}B neutrinos:
Enter T.R. from above.

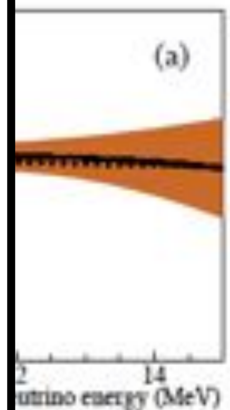
SNO Low Energy Threshold Analysis

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

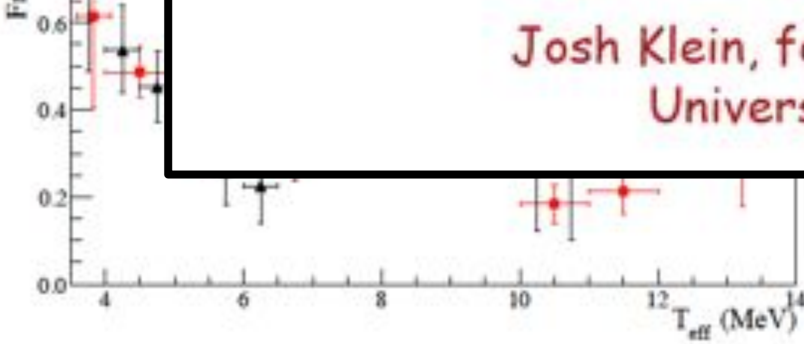
Quadratic Fits to P_{ee}

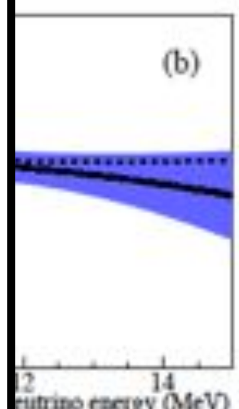






Elastic Sc

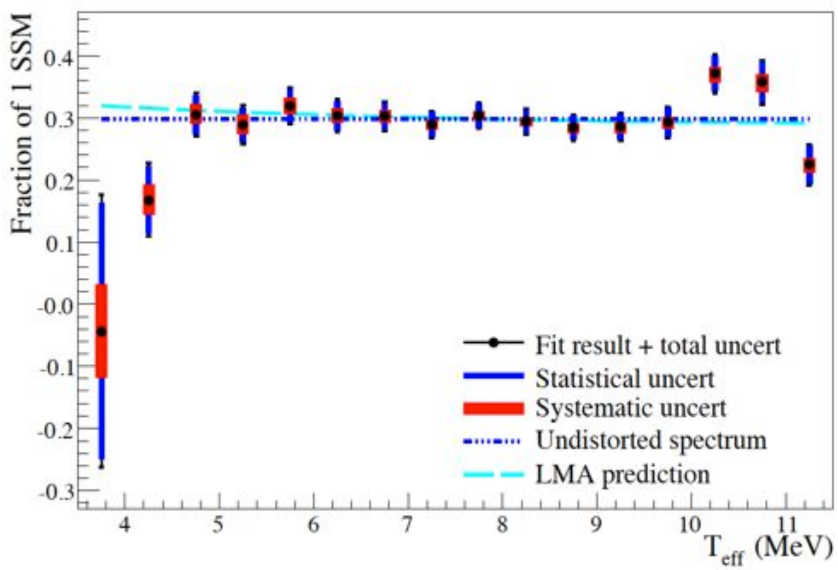




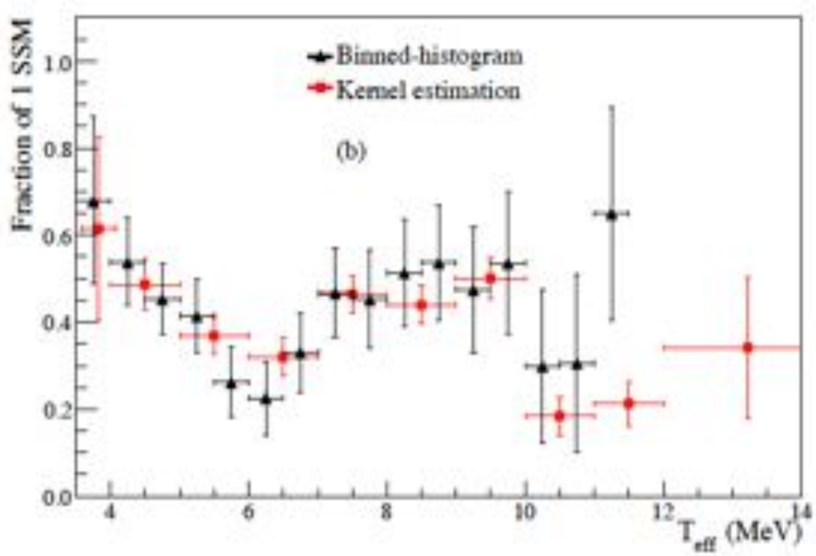
(Phys. Rev. C 81 (2010) 055504, arXiv:1109.0763)

SNO Low Energy Threshold Analysis

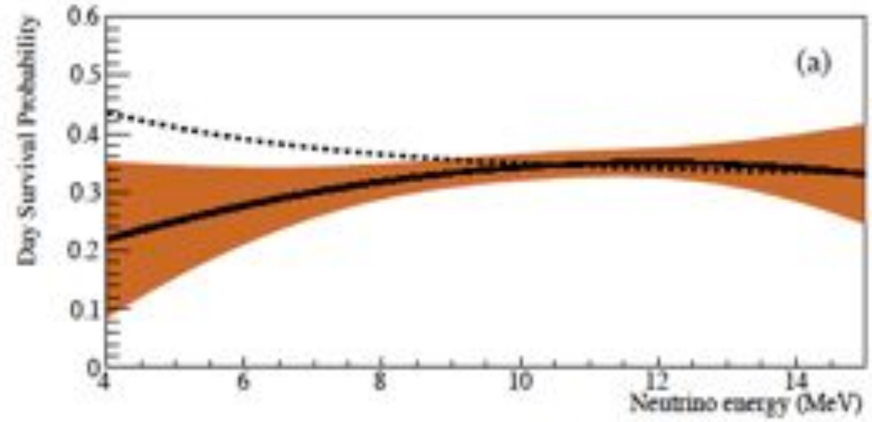
Charged Current: $T_{eff} = E_\nu - 1.44$ MeV

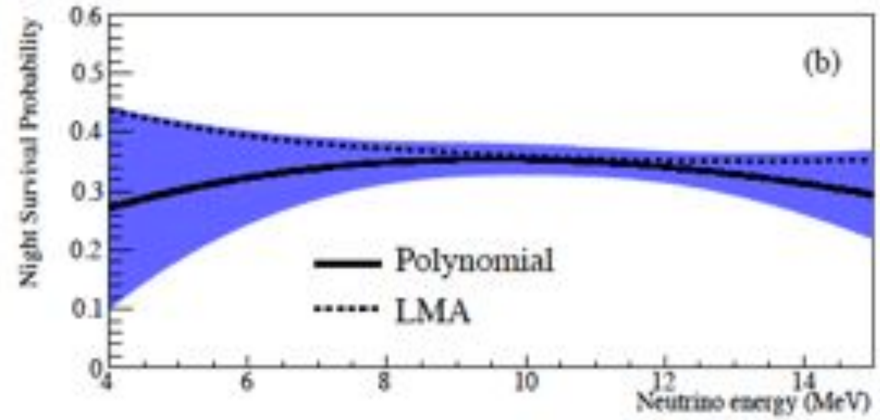


Elastic Scattering: $0 \leq T_{eff} \lesssim E_\nu - 0.24$ MeV



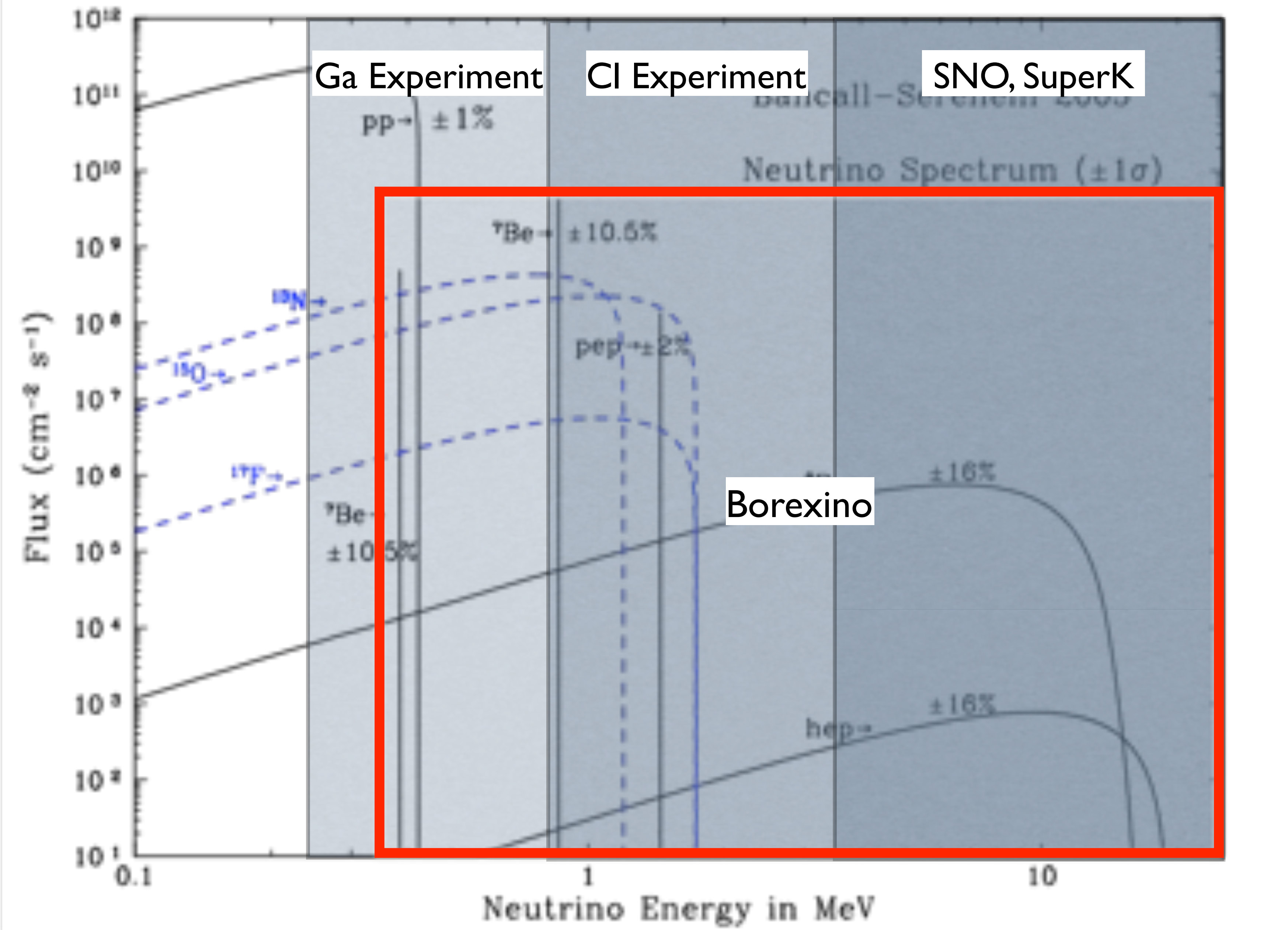
Quadratic Fits to P_{ee}





(Phys. Rev. C 81 (2010) 055504, arXiv:1109.0763)

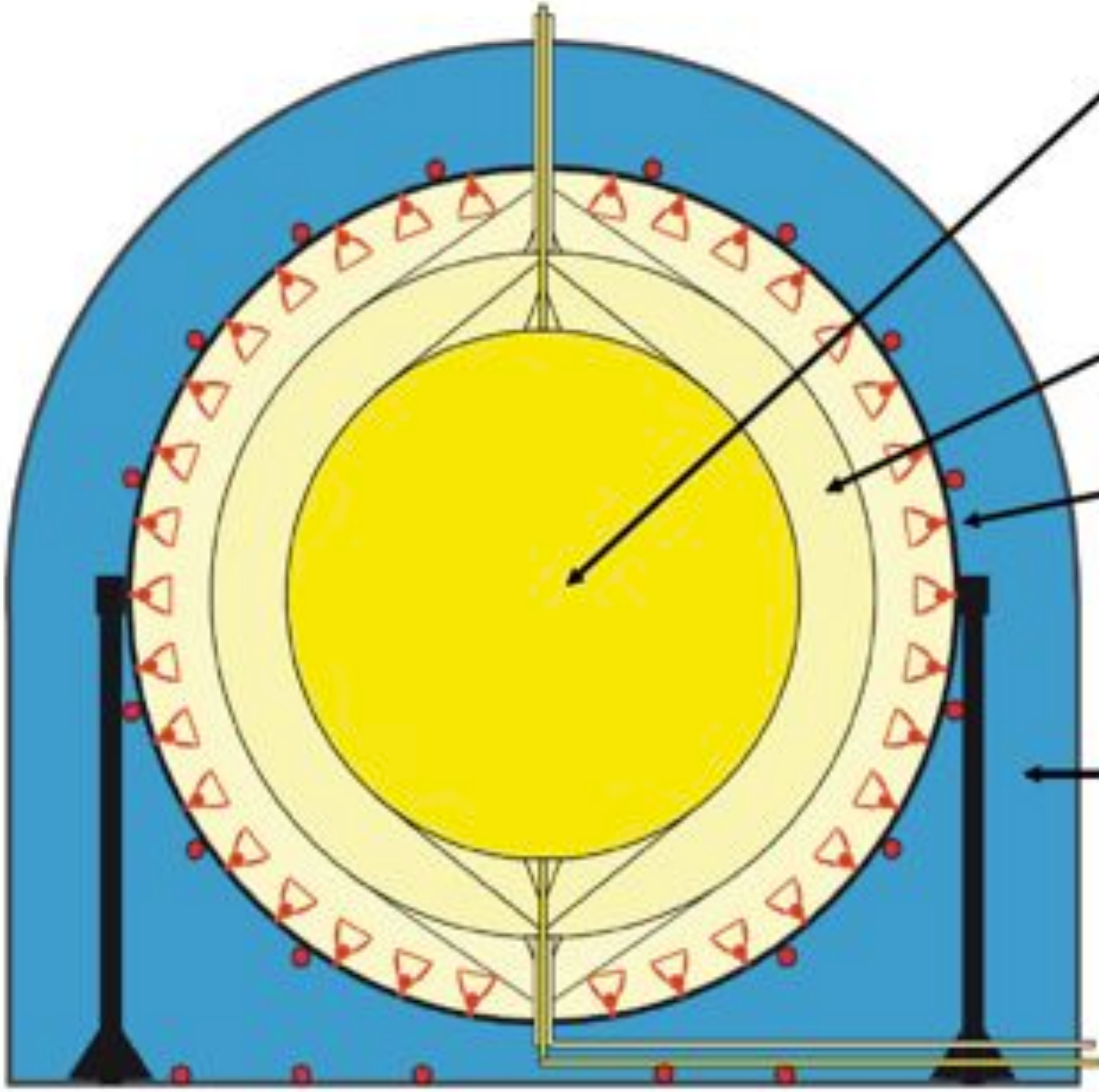
Borexino: Real-time Detection Below 100 keV



Borexino Solar 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
  - arXiv:1104.2150 (2011).
- ^{8}B Flux + Spectrum (T_{eff} > 3.0 MeV)
  - Phys. Rev. D **82**:033006 (2010).
- *pep* and CNO flux
  - arXiv:1110.3230 (2011).

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

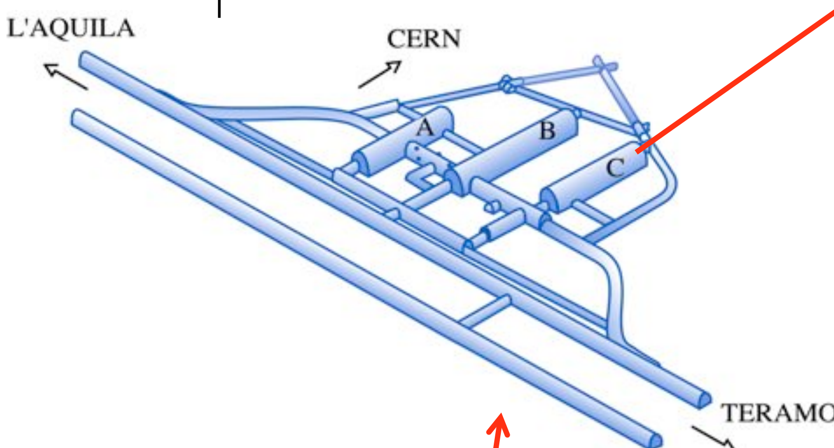
outer water tank
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

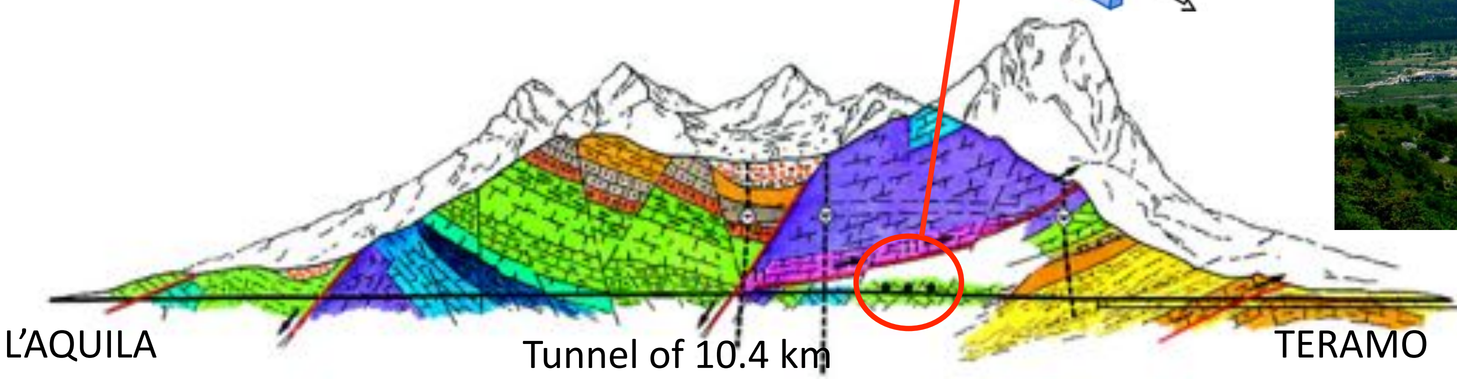
Laboratori Nazionali del Gran Sasso

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
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

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

- Ne… astic sc…
- De… ron
  - … ime-
  -
  -
- Ca… onal se…
  -

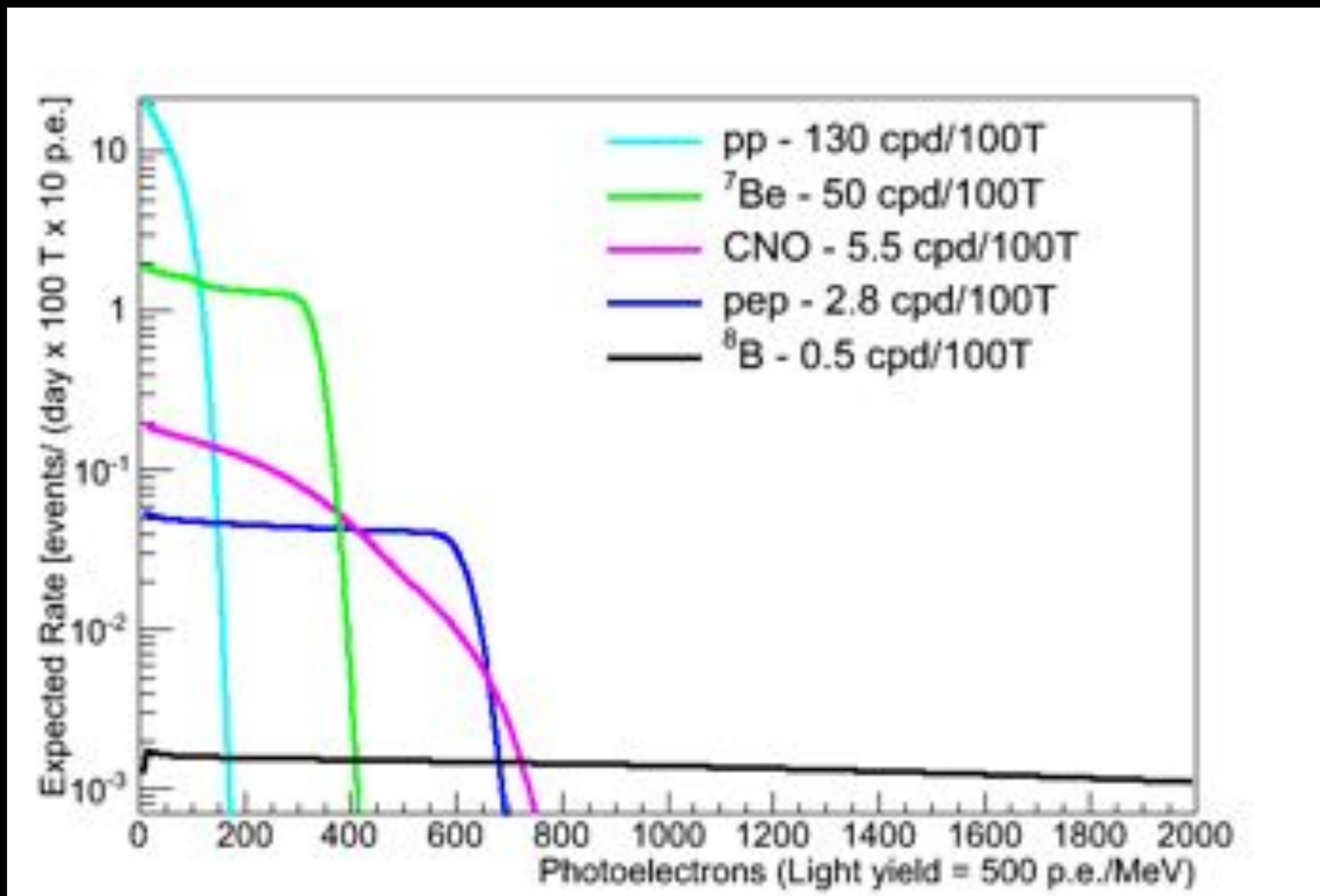
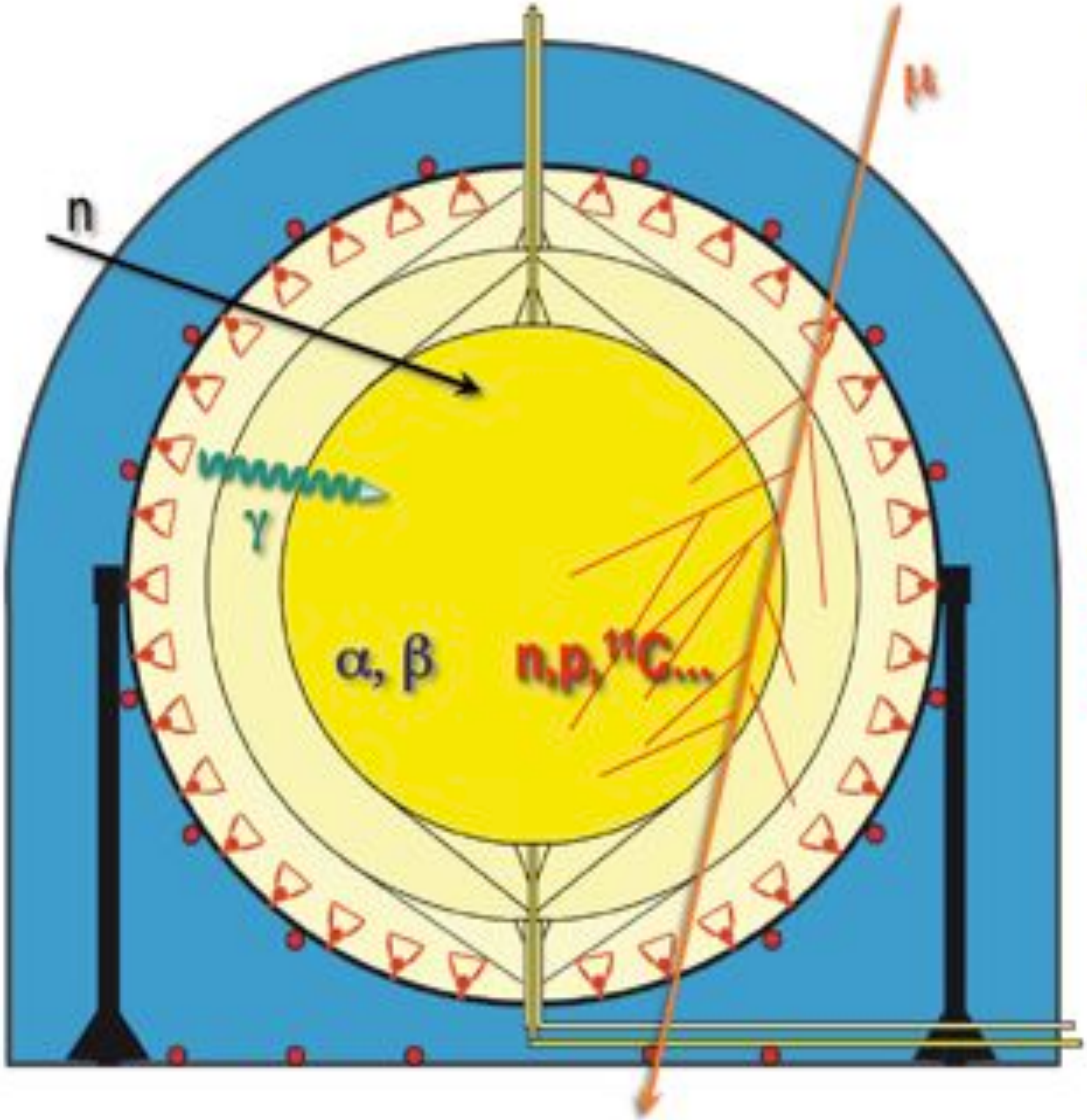


Image: Borexino Collaboration

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 ...)

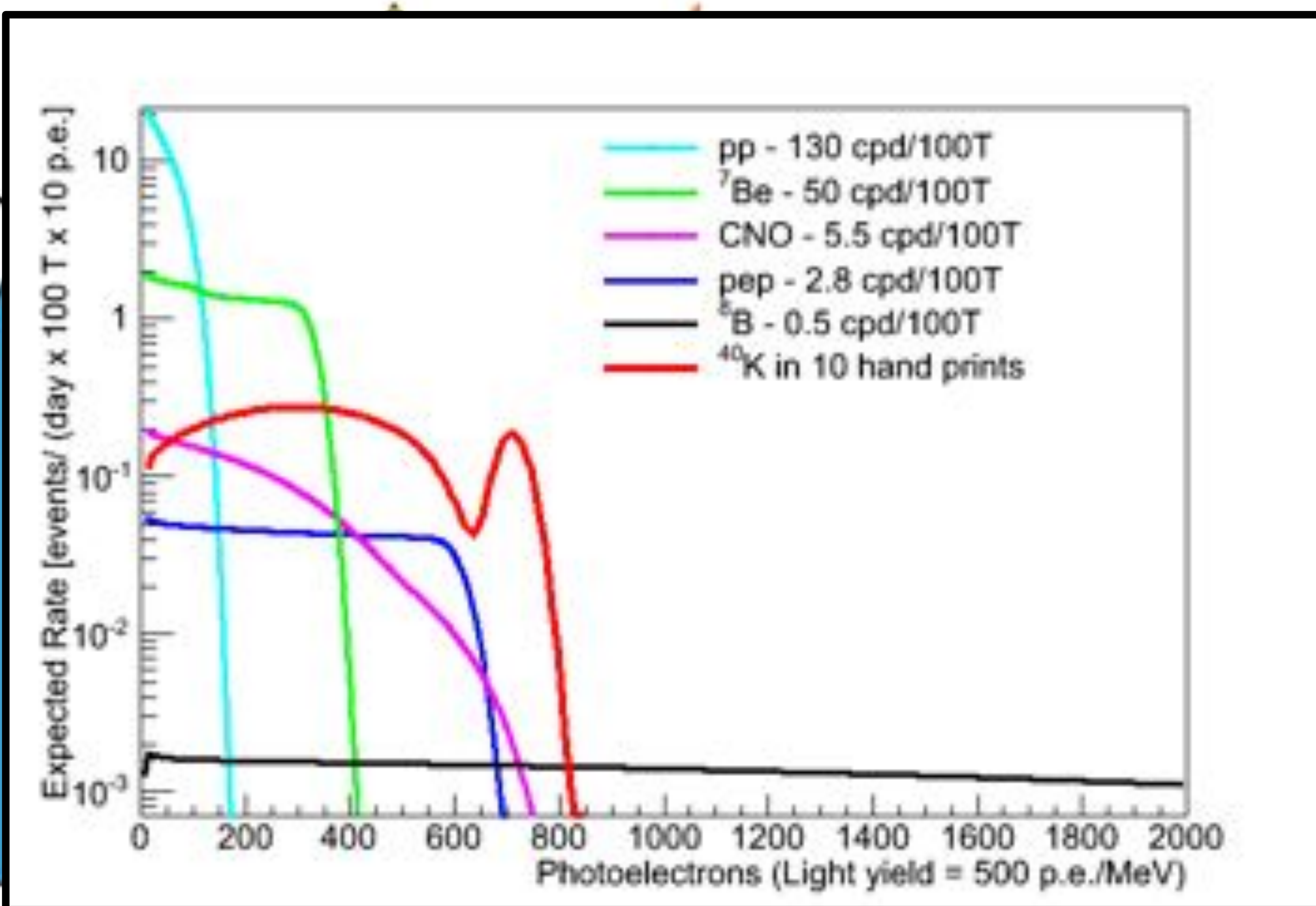
Cosmic Muons

Cosmogenics
neutrons and radionuclides from muon-spallation and hadronic showers

Fast Neutrons
from external muons

Slide: M. Wurm

Central Challenge: Background Reduction



Slide: M. Wurm

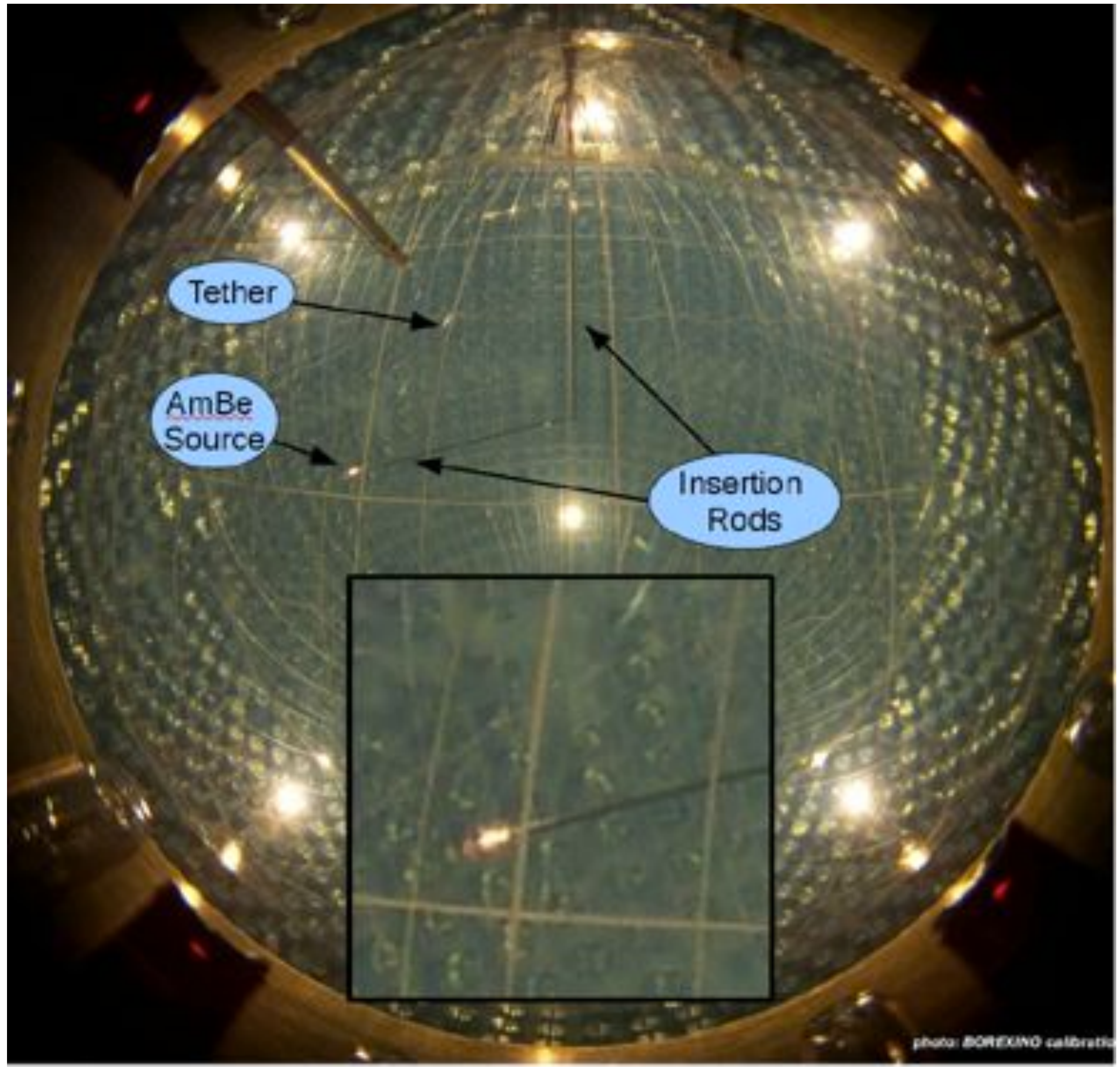
Borexino achieved unprecedented low levels of internal background.

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	~5×10^{-18} g/g	Purification
^{232}Th	Dust	10^{-6} g/g	~4×10^{-18} g/g	Purification
^{85}Kr	Air	1 Bq/m^3	~2×10^{-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	<2×10^{-19} g/g	Purification
μ	Cosmic	200 $s^{-1}m^{-2}$	10^{-10} $s^{-1}m^{-2}$	Underground, active veto

Borexino Internal Calibrations

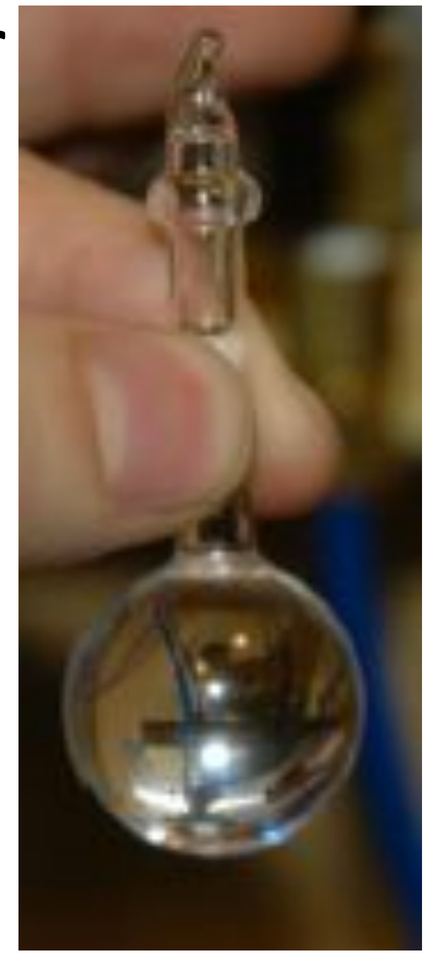
- Study detector position and energy response by deploying radioactive and laser sources in the detector
- 3D source deployment system developed at Virginia Tech



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

Sources

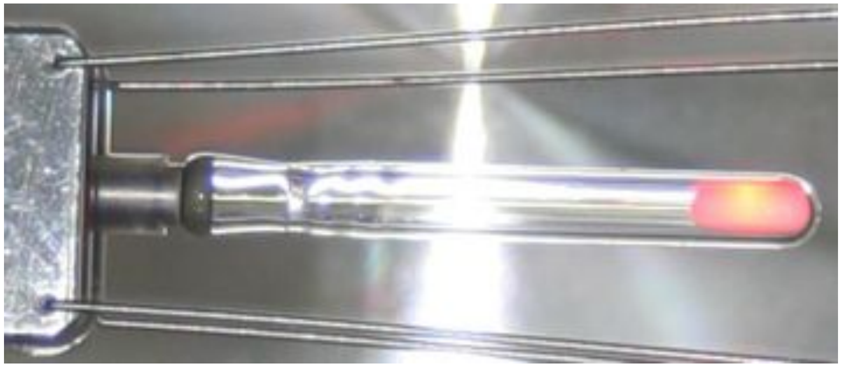
- Aqueous γ-sources in flame-sealed quartz vials
- α and β sources in vials of scintillator
- Encapsulated AmBe

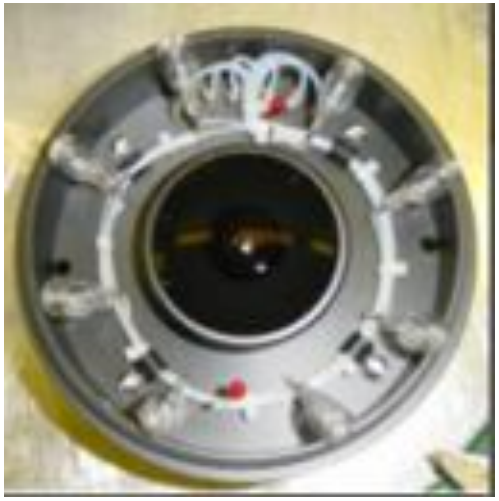


Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

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

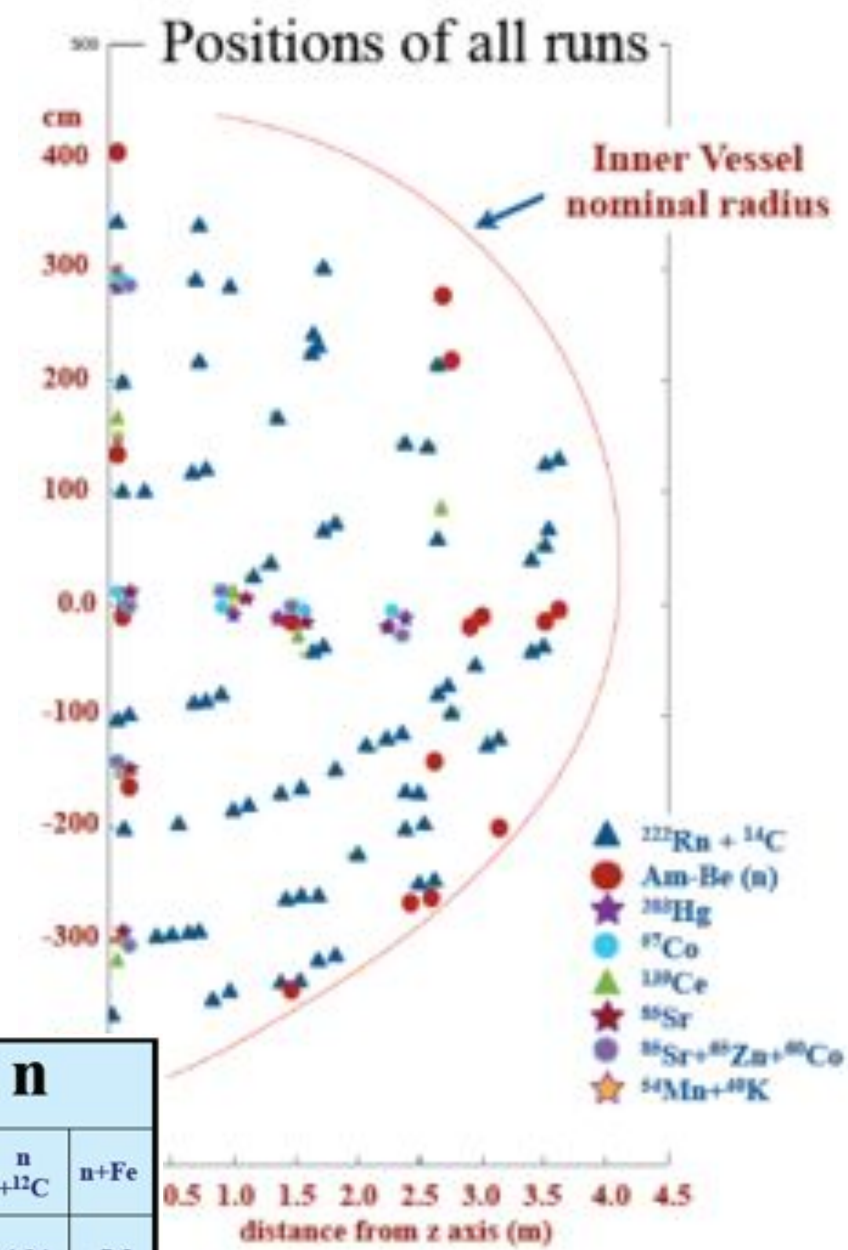




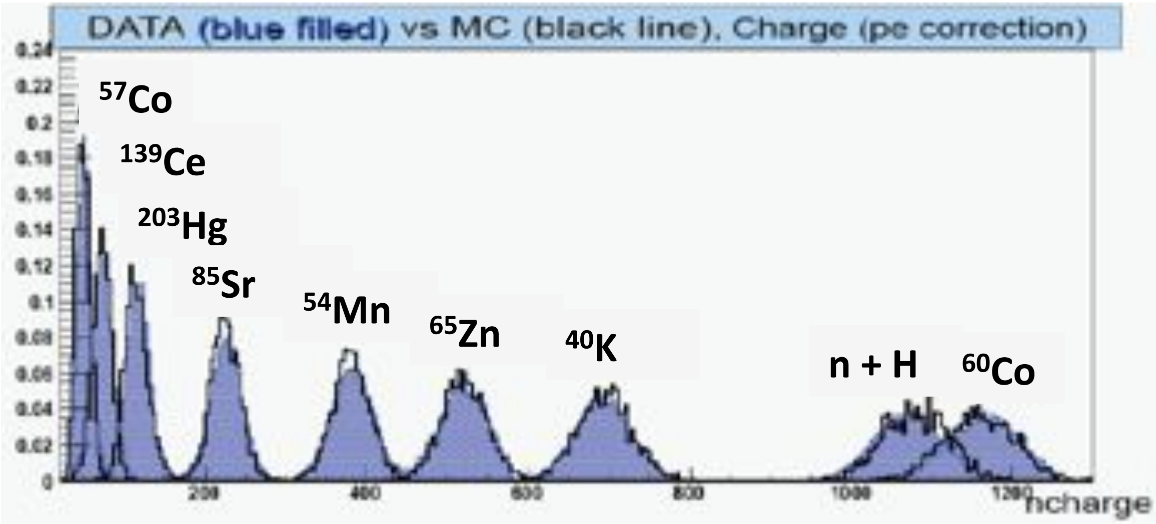
Images: Steve Hardy, PhD Thesis, Virginia Tech, 2010

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



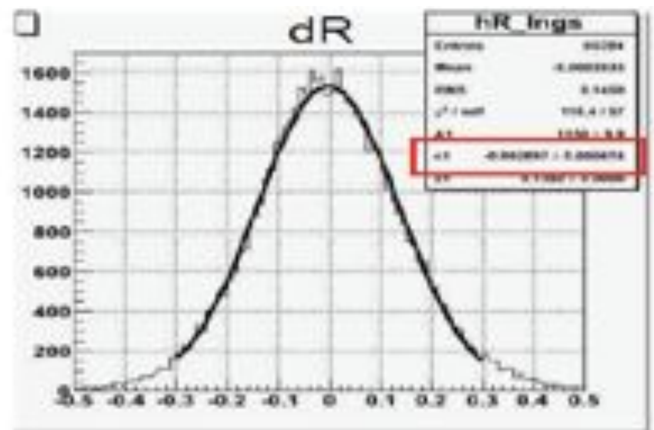
Study light yield, quenching, position variation.

Data-MC mean light yields agree to 1% in F.V.

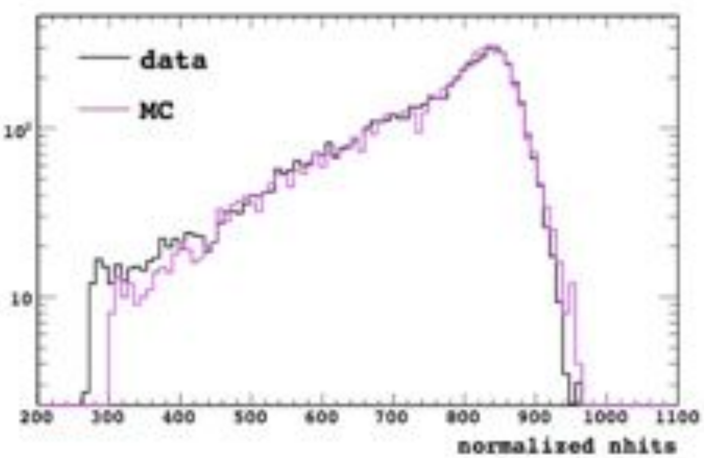
Measure position resolution: 10 – 12 cm

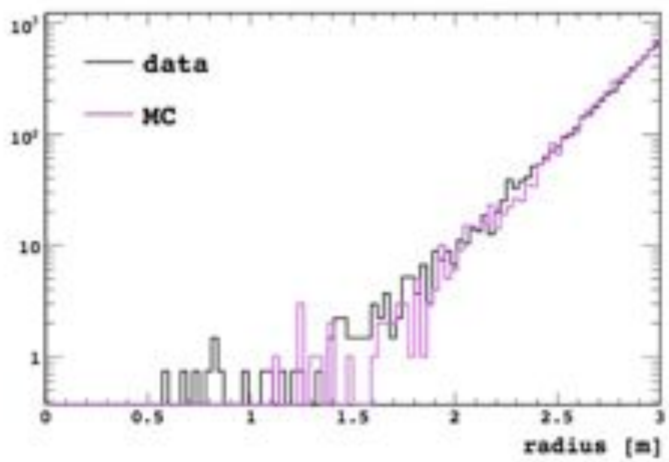
Fiducial Volume: $1.0^{+0.005}_{-0.013}$

$Z_{rec} - Z_{ccd}$ (m)



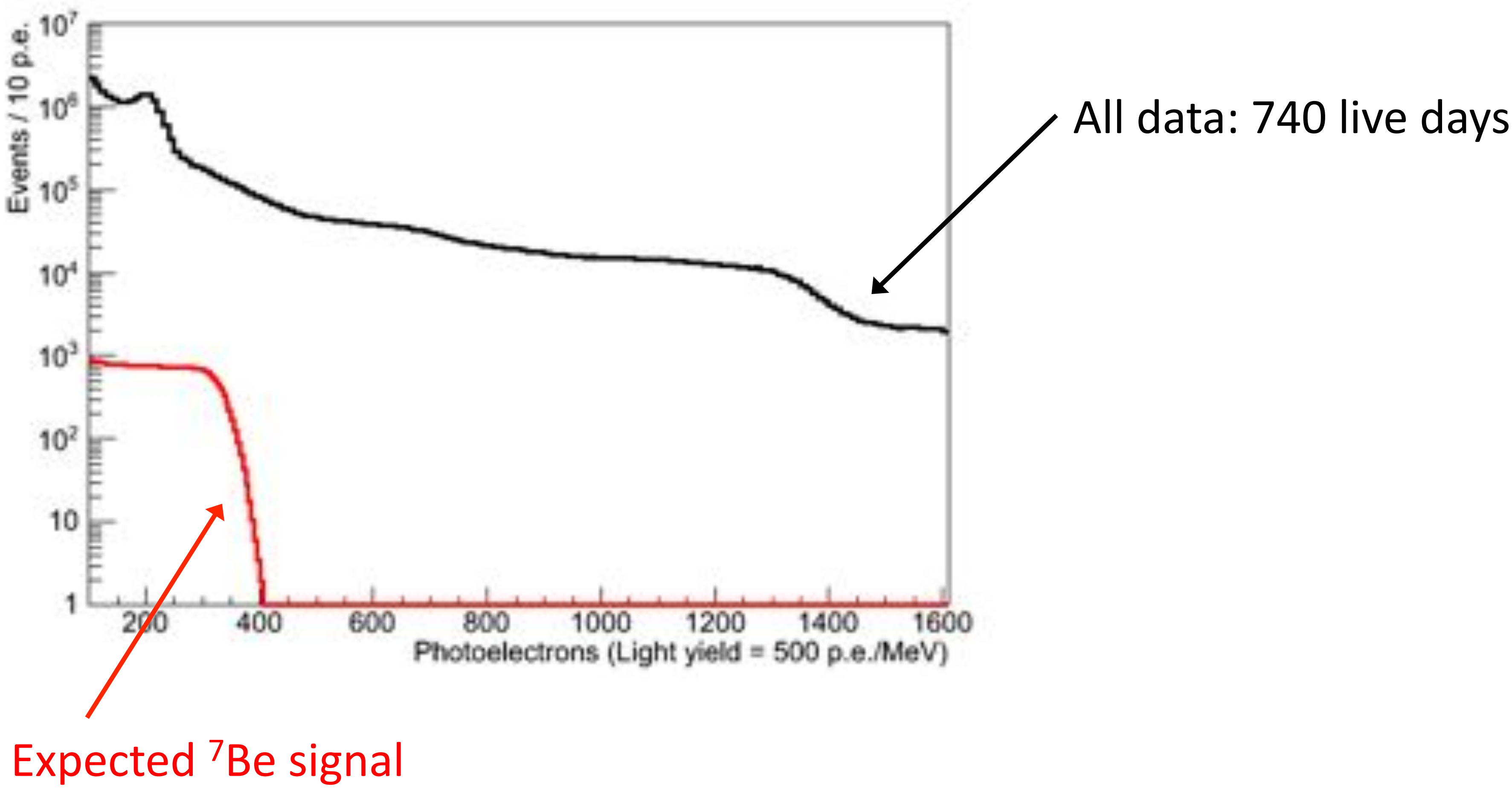
$R_{rec} - R_{ccd}$ (m)



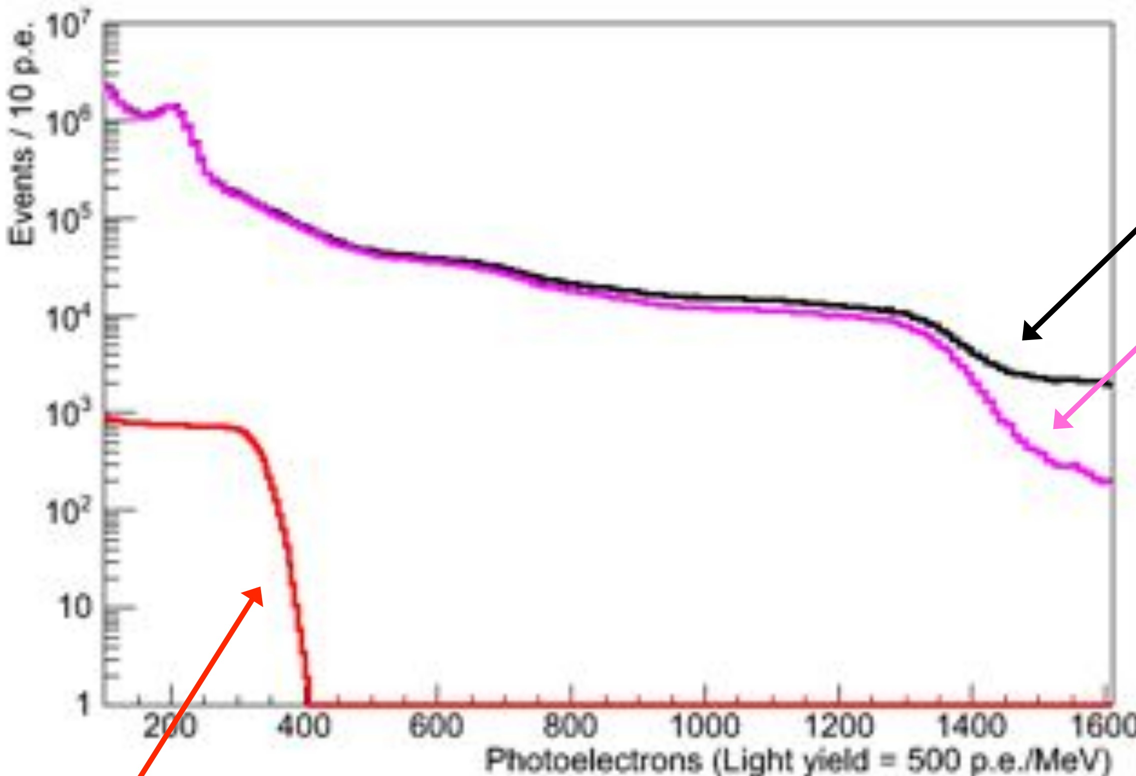


Confirm energy/radial PDF for external background.

Borexino Data



Borexino Data

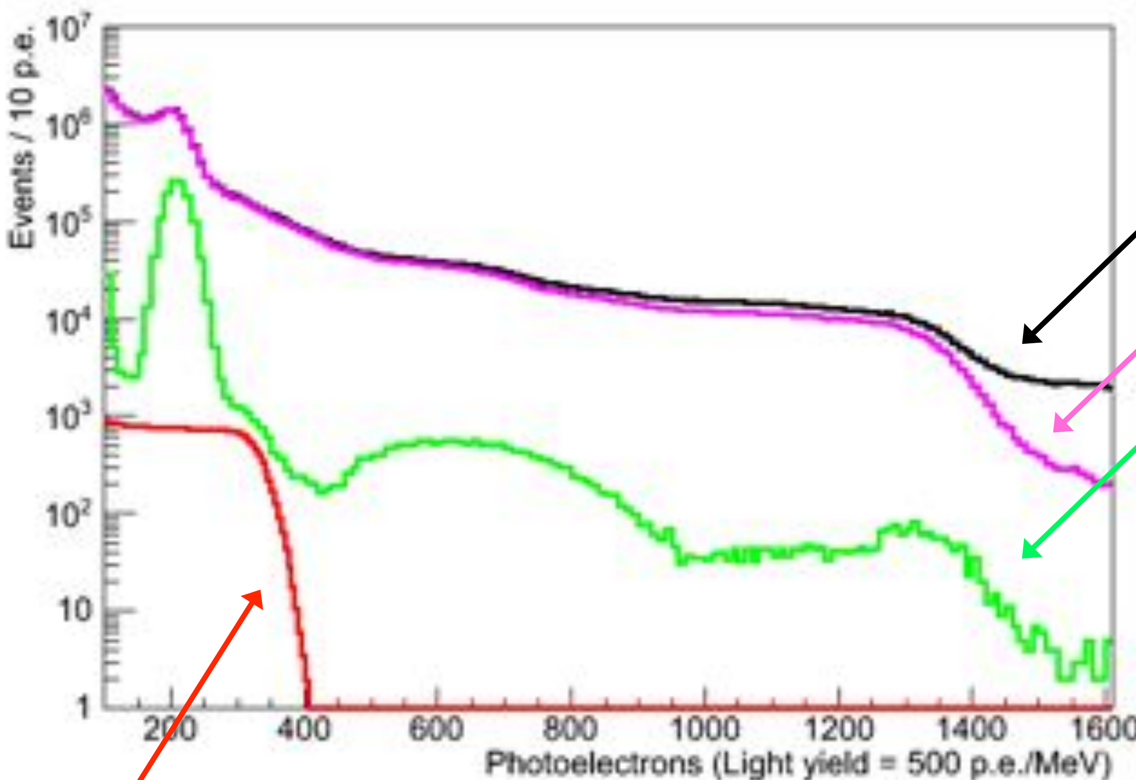


All data: 740 live days

Remove muons + muon followers (2 ms)

Expected ^{7}Be signal

Borexino Data



All data: 740 live days

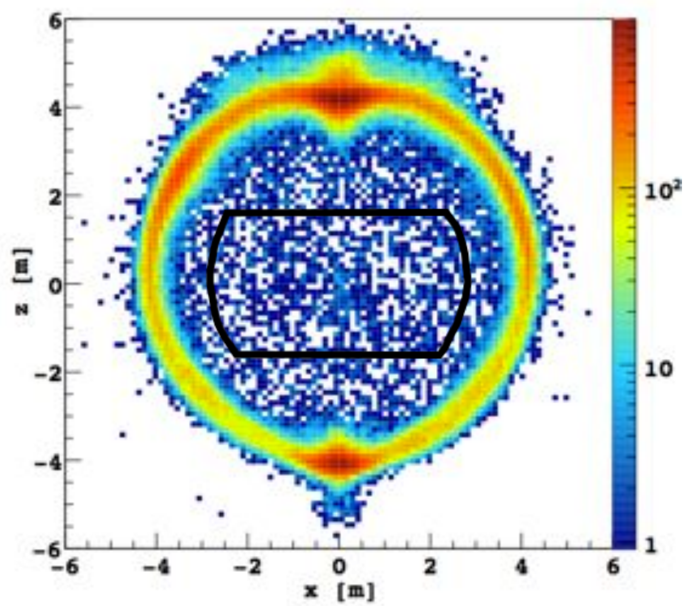
Remove muons + followers

Fiducial Volume + high level

Expected ^{7}Be signal

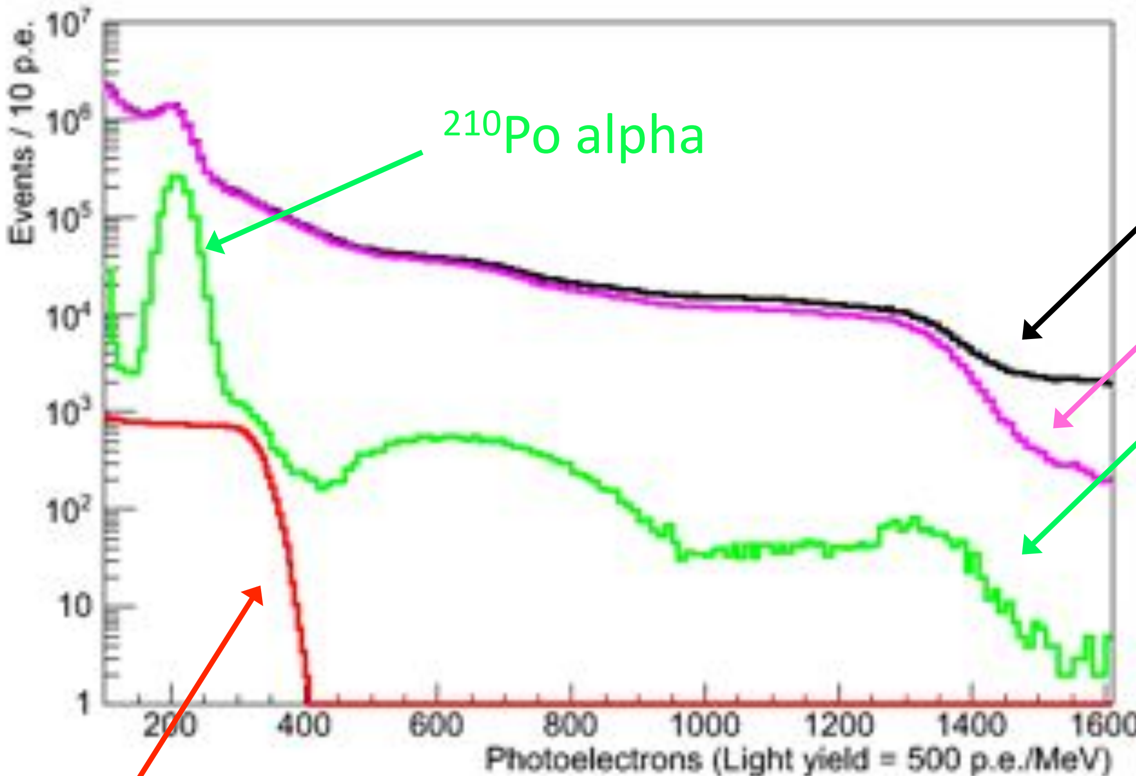
R < 3.02m

|z| < 1.67m



Fiducial mass = 75.6 tonnes

Borexino Data



^{210}Po alpha

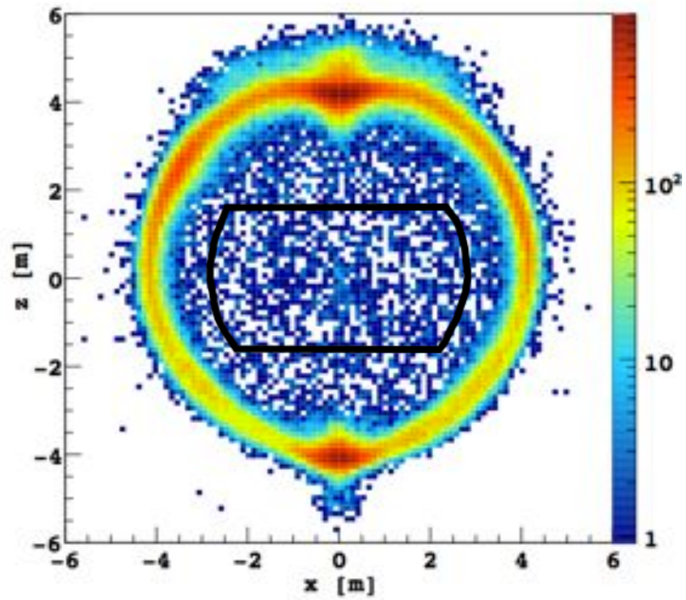
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

Expected ^{7}Be signal

R < 3.02m
|z| < 1.67m



Fiducial mass = 75.6 tonnes

Pulse Shape Discrimination

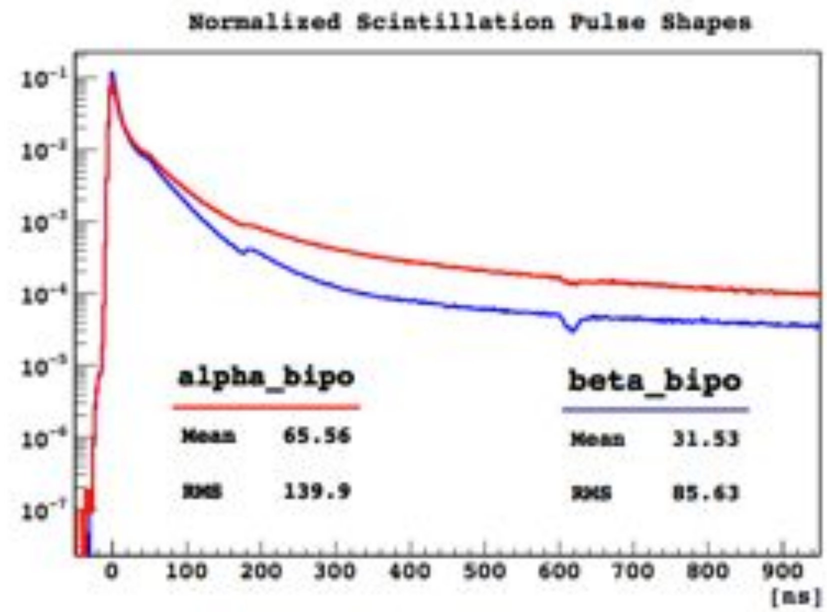
- Particles with higher ionization density produce more slow light
- Separate by comparing to reference α and β events using the "Gatti Parameter"

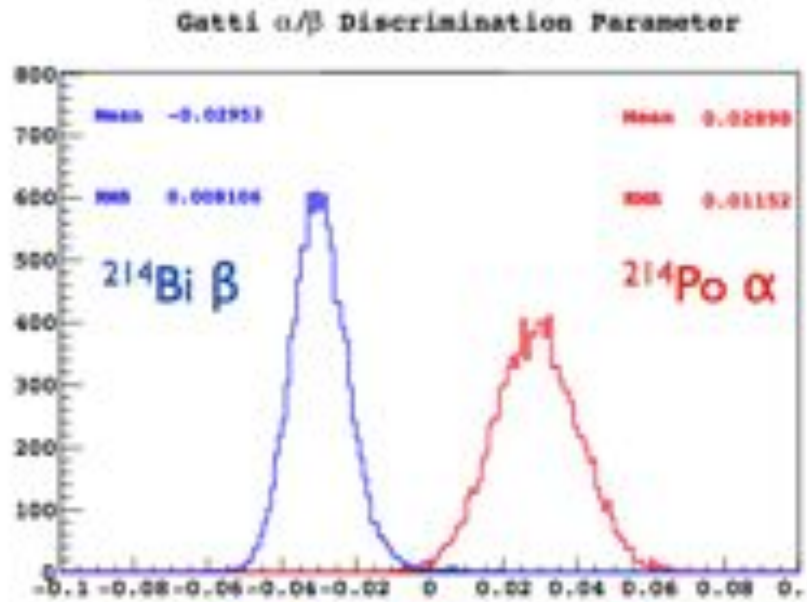
$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

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

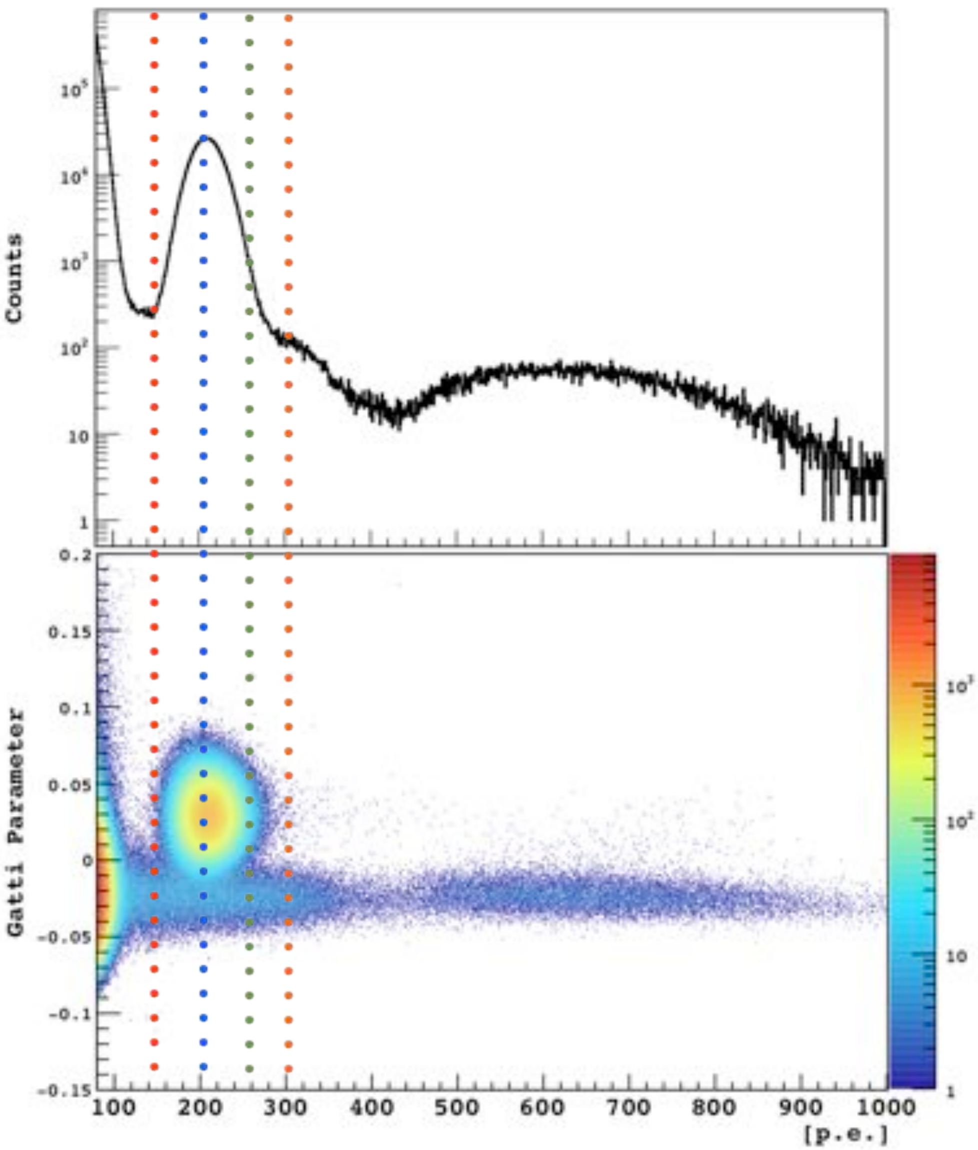
$e[t]$: Event Time Profile

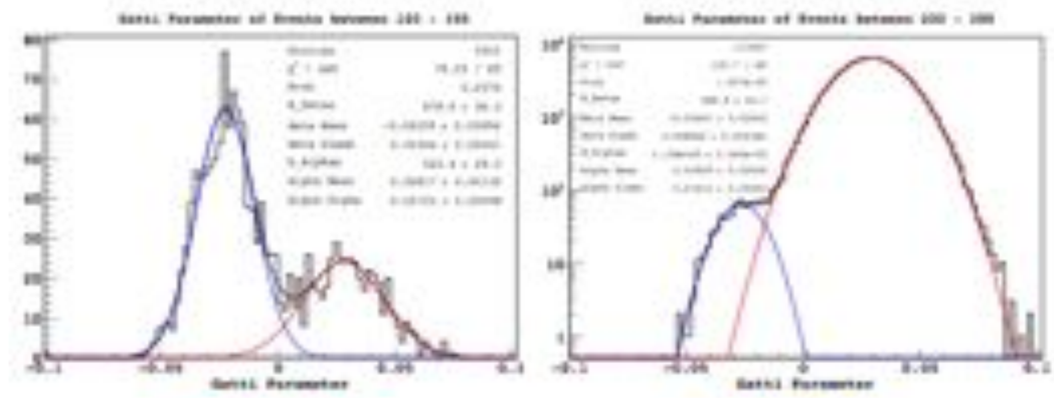
$r_{\alpha/\beta}[t]$: Reference time profile





Alpha Statistical Subtraction





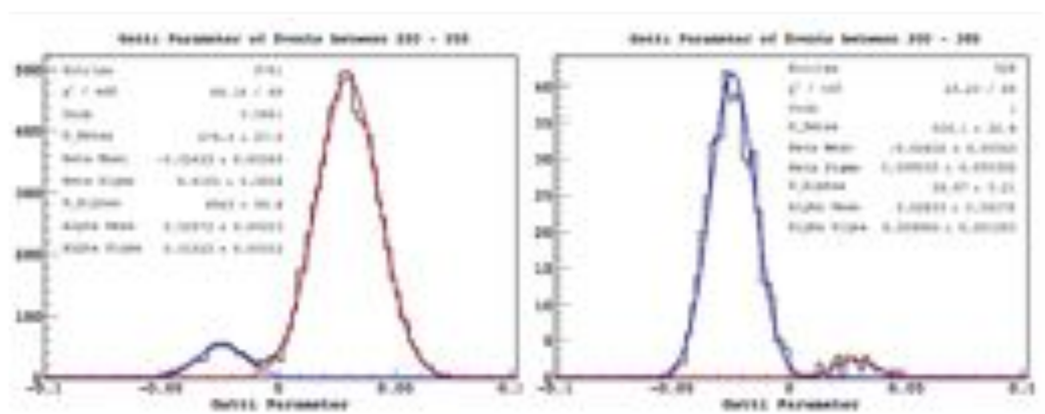
150 p.e.

200 p.e.

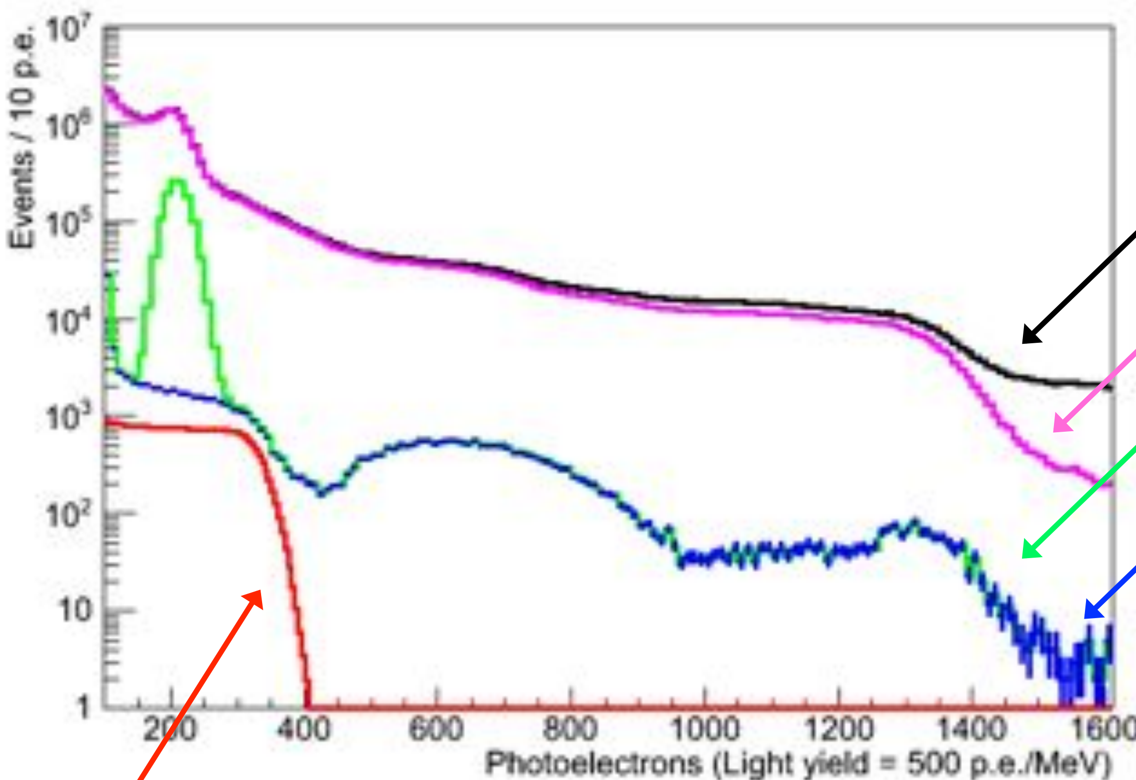
Fit each energy bin with the sum of two Gaussians

250 p.e.

300 p.e.



Borexino Data



All data: 740 live days

Remove muons + followers

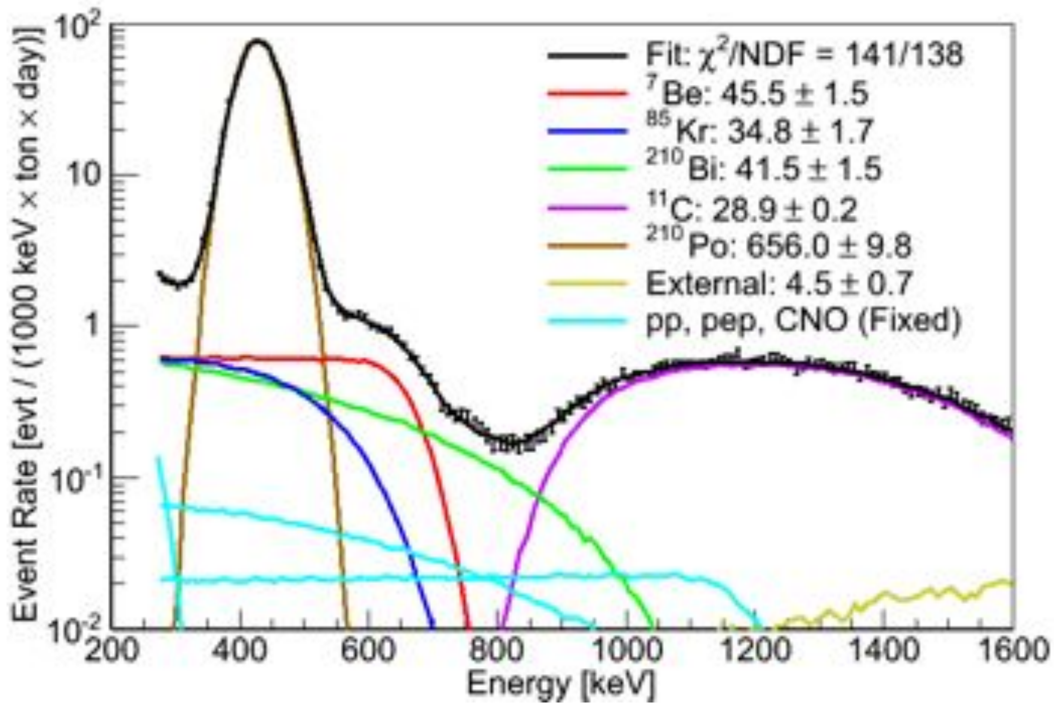
Fiducial Volume + high level

Statistically subtract alphas

Expected ^{7}Be signal

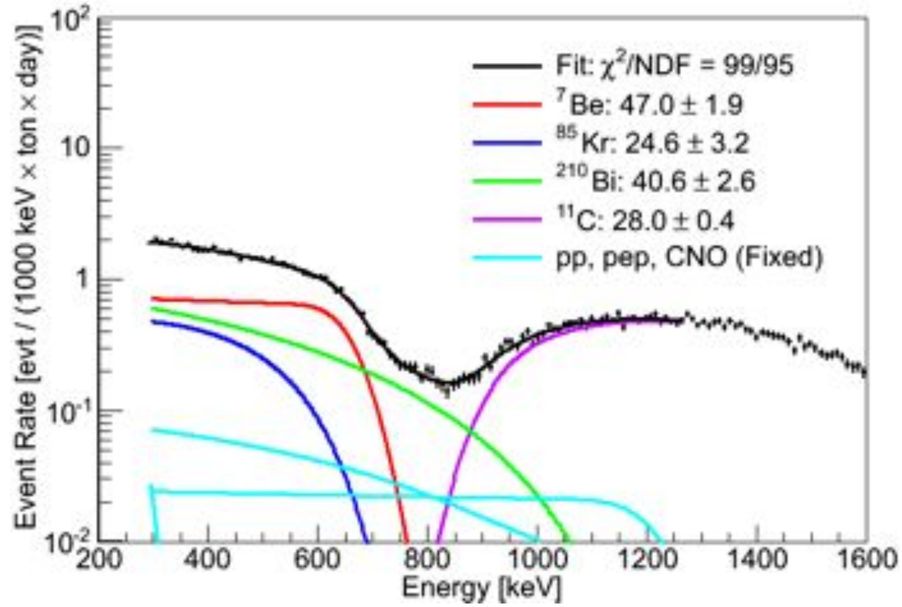
^{7}Be Signal Extraction

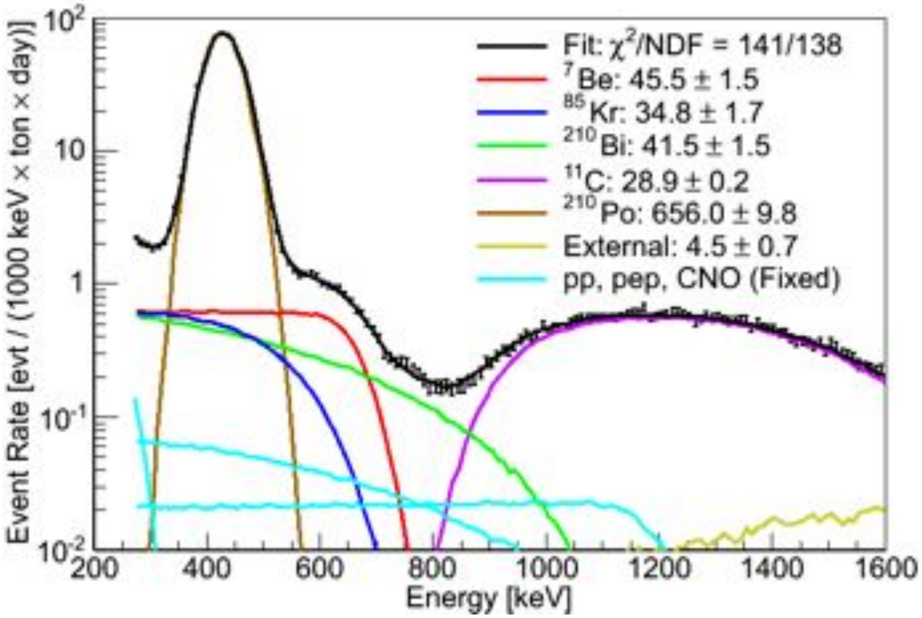
- 1-D binned likelihood fits in energy
- ^{7}Be, ^{210}Po, ^{85}Kr, ^{11}C, ^{210}Bi weights floated
- *pp, pep*, ^{8}B, and CNO fixed to SSM fluxes + LMA
- ^{222}Rn, ^{218}Po, and ^{214}Pb weights constrained by ^{214}Bi-^{214}Po co-incidence



^{7}Be 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

Precision ^{7}Be Flux Result

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

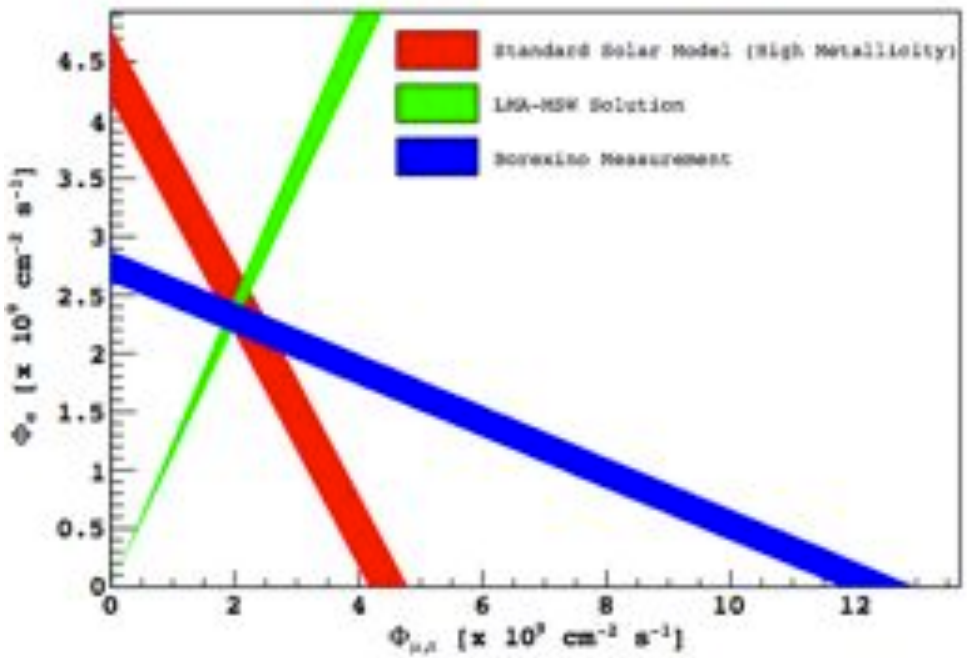
→ $\Phi_{7Be} = (4.84 \pm 0.24) \times 10^9\ cm^{-2}s^{-1}$ → $P_{ee}(862\ keV) = 0.51 \pm 0.07$

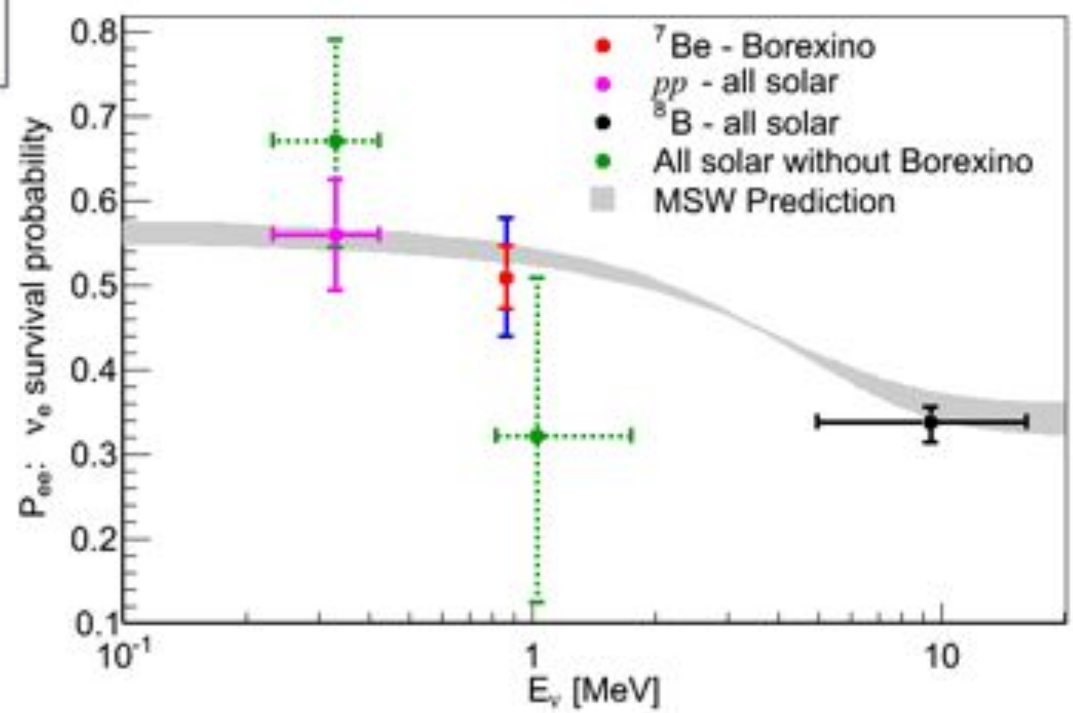
Systematics	
Trigger Efficiency	0.1%
Scintillator Density	0.05%
Livetime	0.04%
Cut Sacrifice	0.1%
Fiducial Mass	$^{+0.5}_{-1.3}$%
Energy Scale	2.7%
Fit Methods	2.0%
Total	**$^{+3.4}_{-3.6}$%**

Previously:

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

Precision ^{7}Be Flux Result





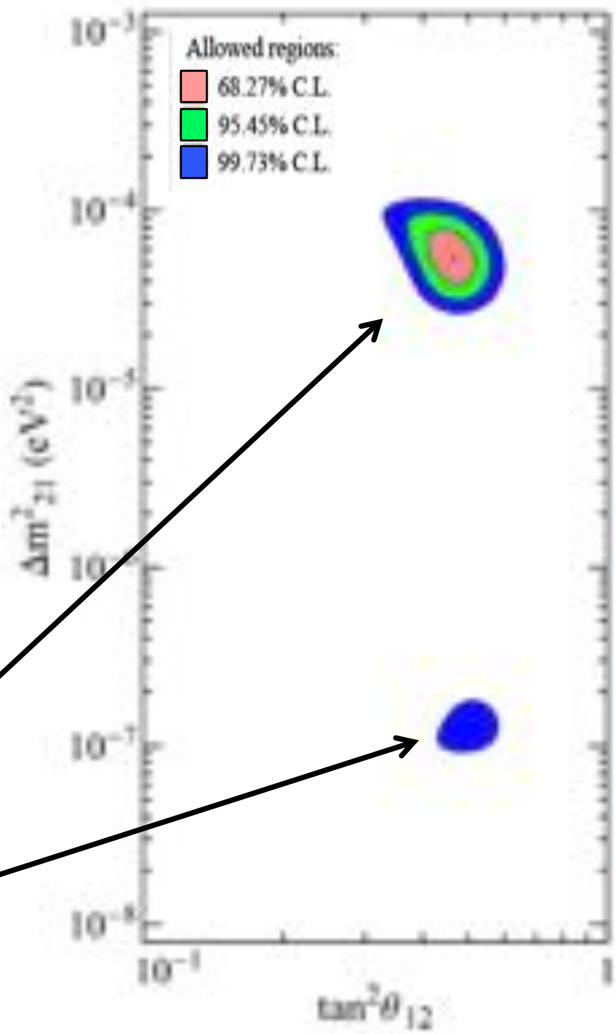
^{7}Be Day-Night Effect

- 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

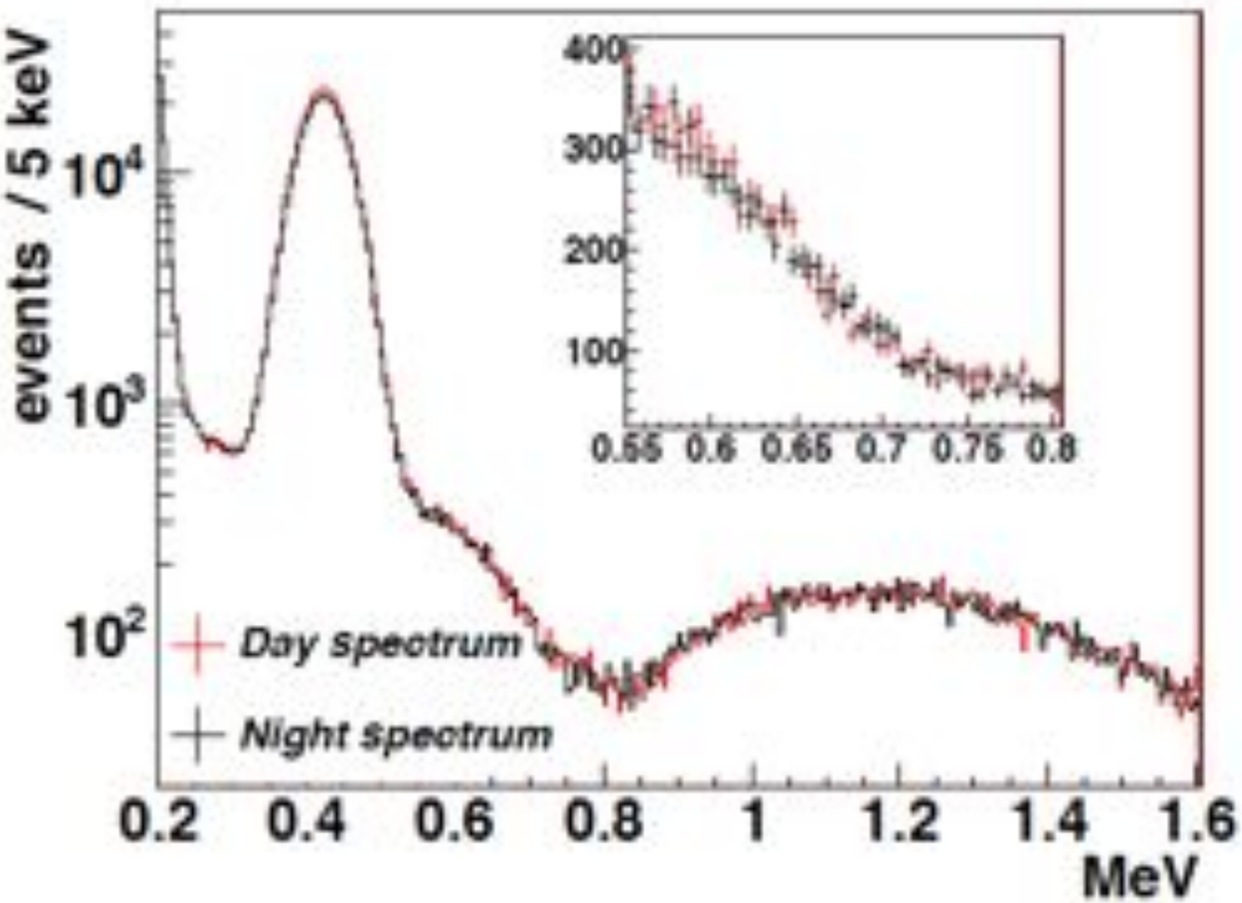
$$A_{dn} = 2\frac{R_n^{^7Be} - R_d^{^7Be}}{R_n^{^7Be} + R_d^{^7Be}} = \frac{R_{diff}}{R}$$

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

Global Solar without Borexino



^{7}Be Day-Night Asymmetry Search I

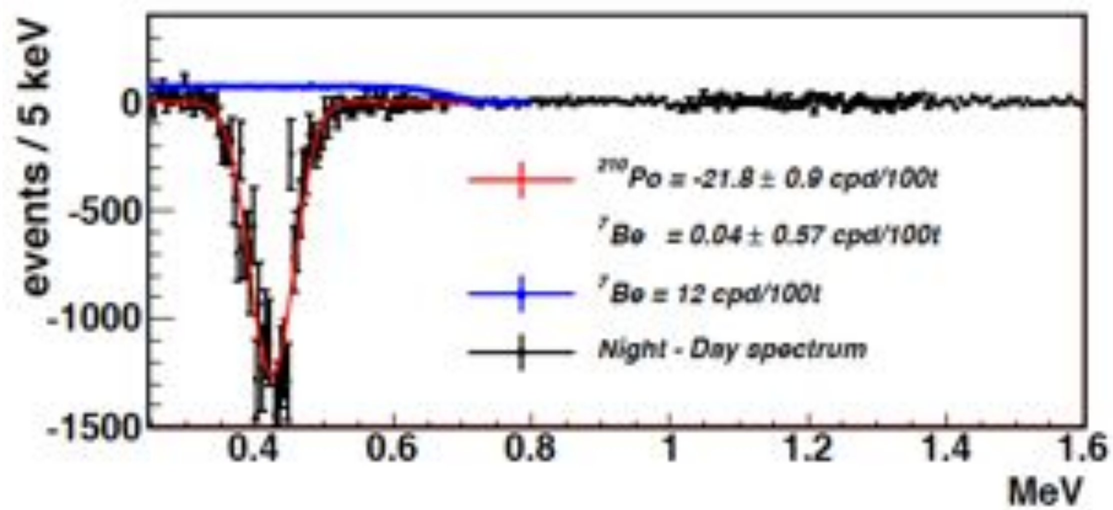


- Fit the day and night spectra separately

→ **A_{dn}(862 keV): 0.007 ± 0.073**

^{7}Be Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
- 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

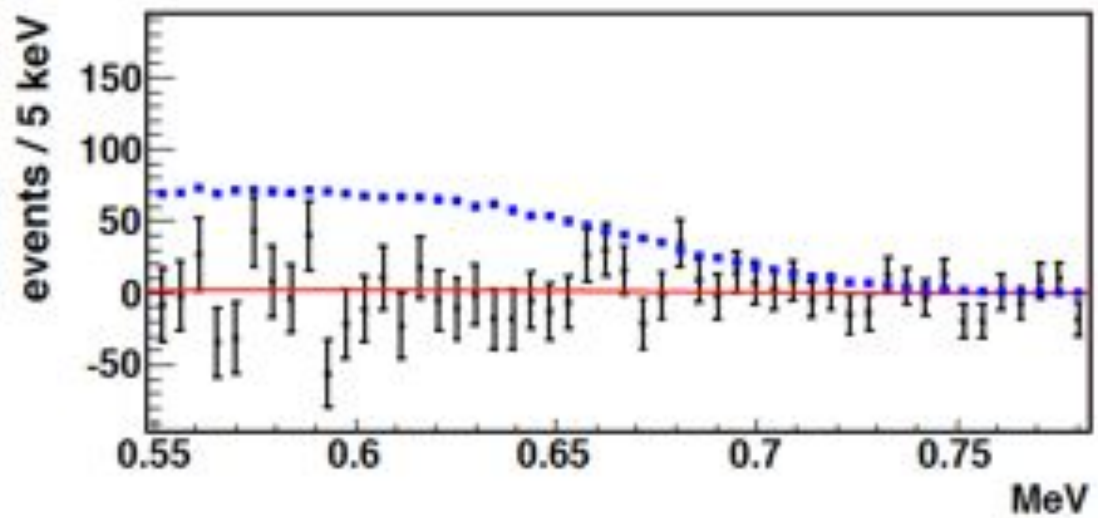


A_{dn}(862 keV): $0.001 \pm 0.012_{stat} \pm 0.007_{sys}$

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	$\pm$ 0.005
Total systematic error	0.007

^{7}Be Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
- 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



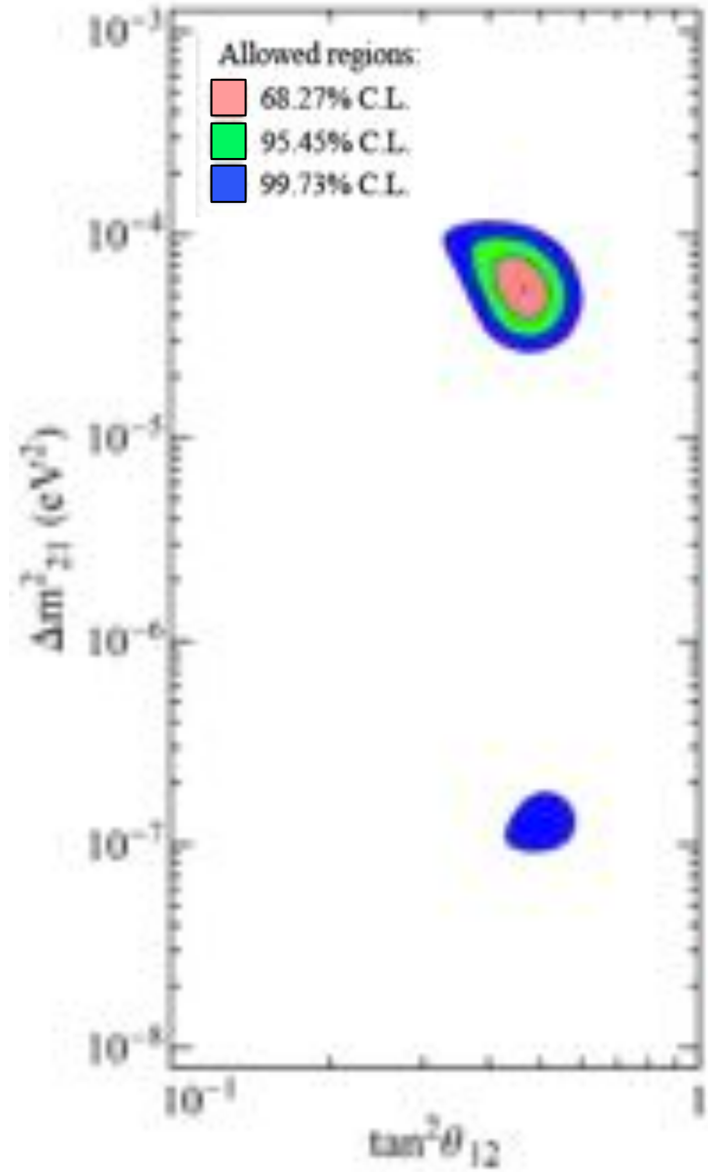
A_{dn}(862 keV): $0.001 \pm 0.012_{stat} \pm 0.007_{sys}$

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	$\pm$ 0.005
Total systematic error	0.007

^{7}Be Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
- 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

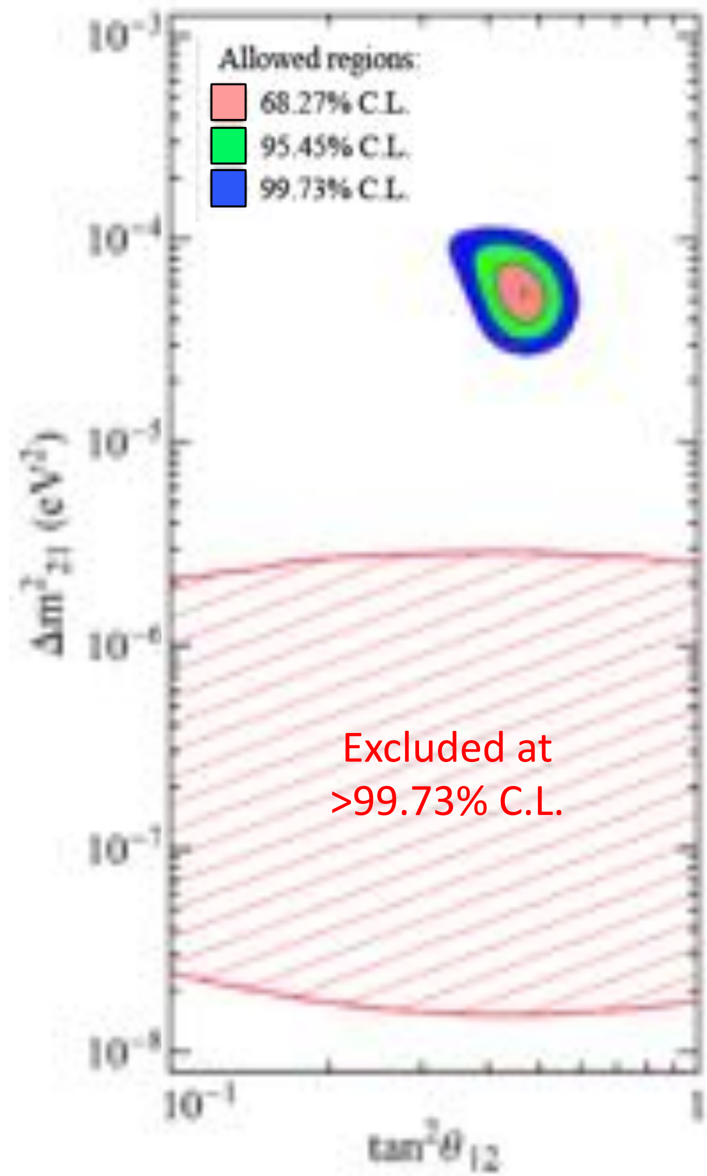
Global Solar, without Borexino



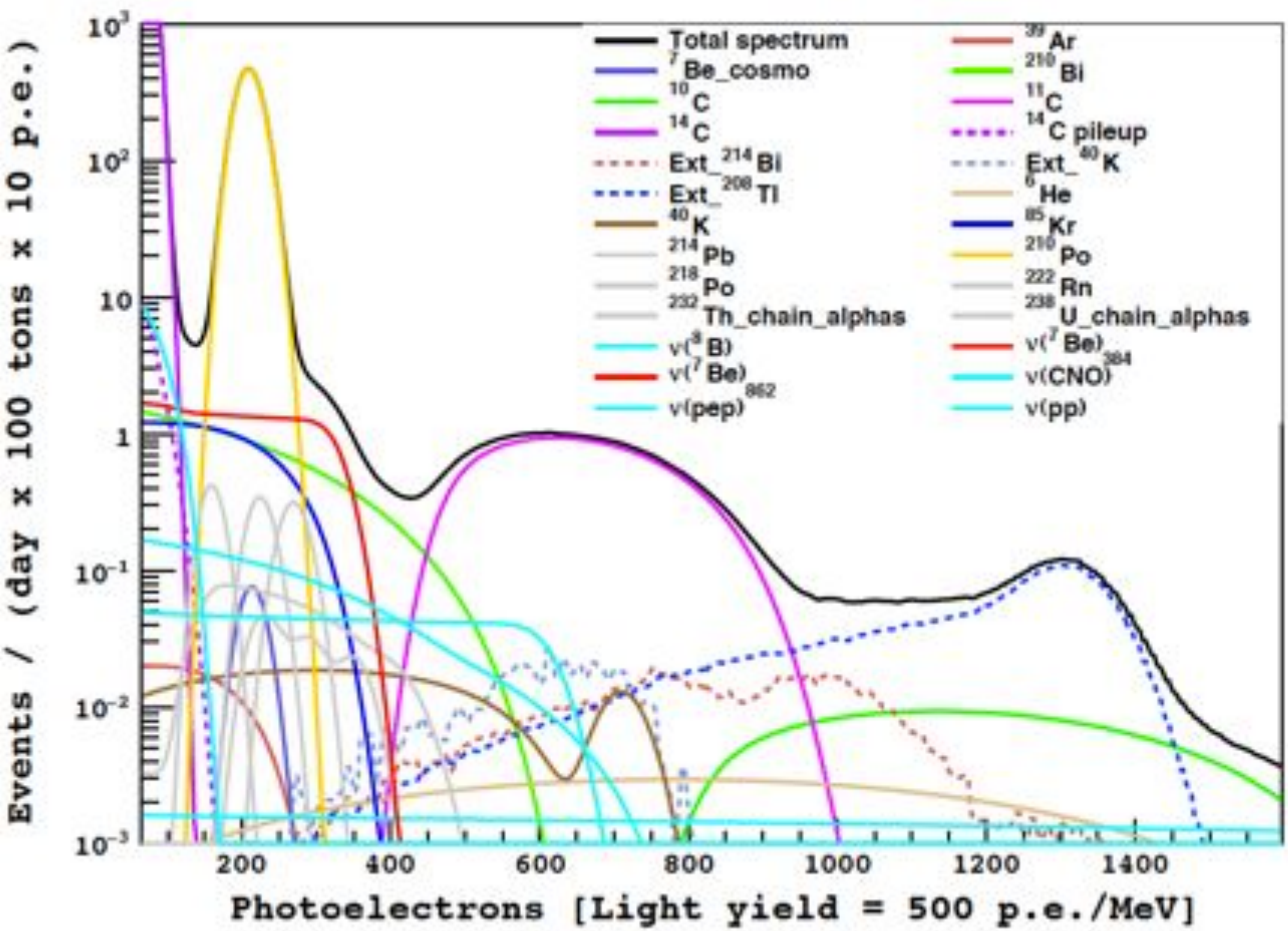
^{7}Be Day-Night Asymmetry Search II

- Normalize the day and night spectra to the day livetime
- 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

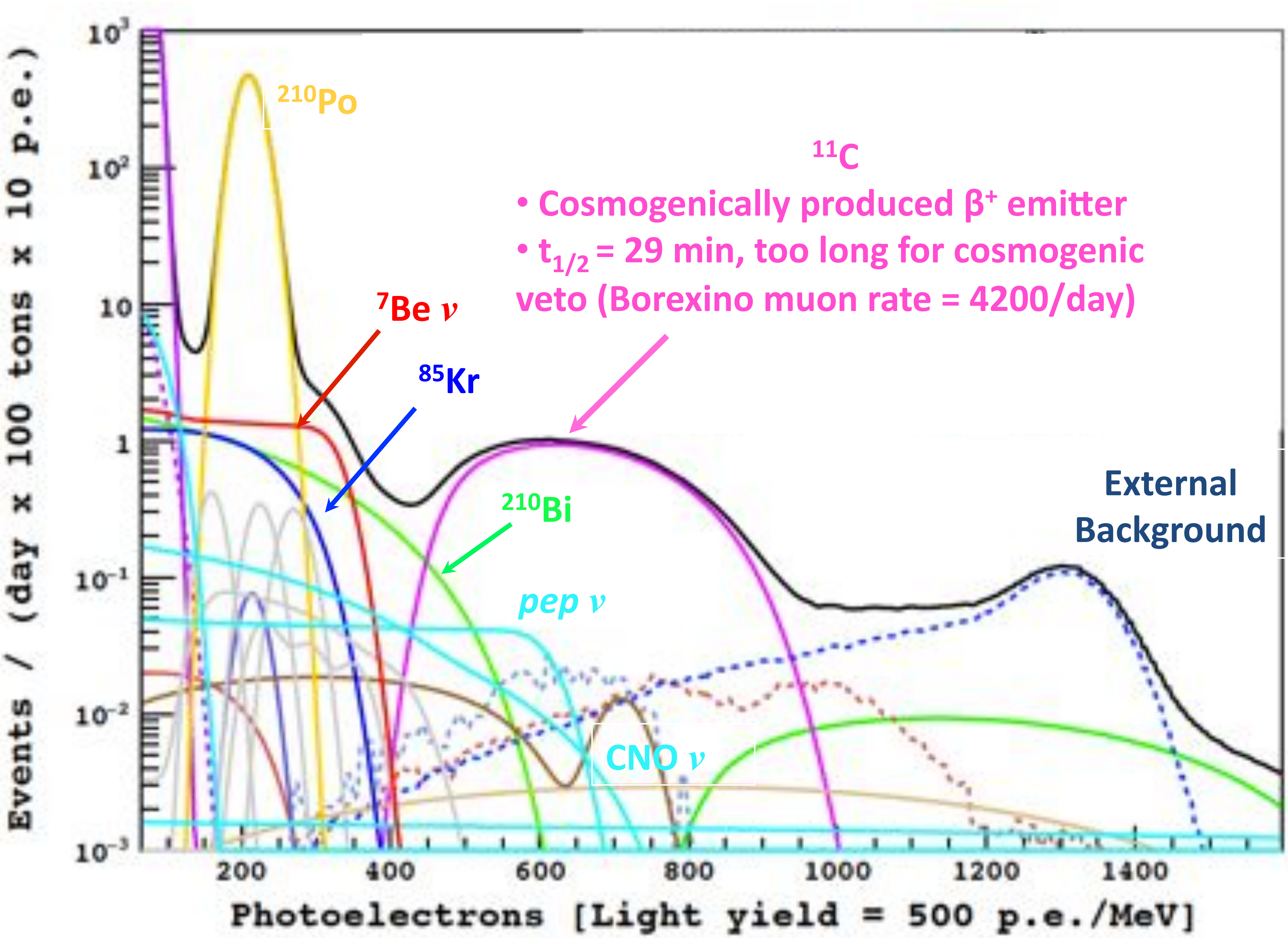
Global Solar, with Borexino



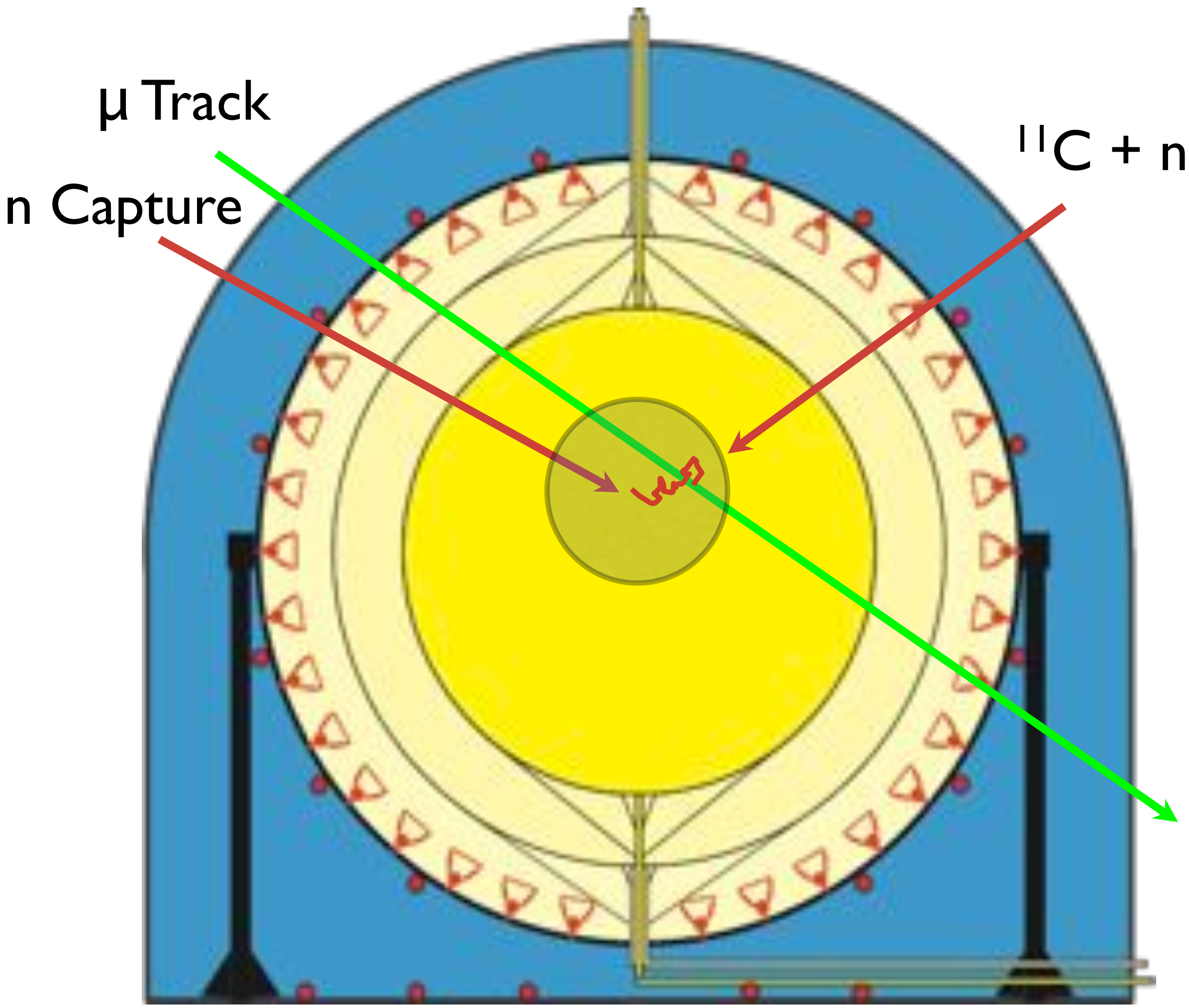
"Into the Muck": *pep* and CNO Neutrinos



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



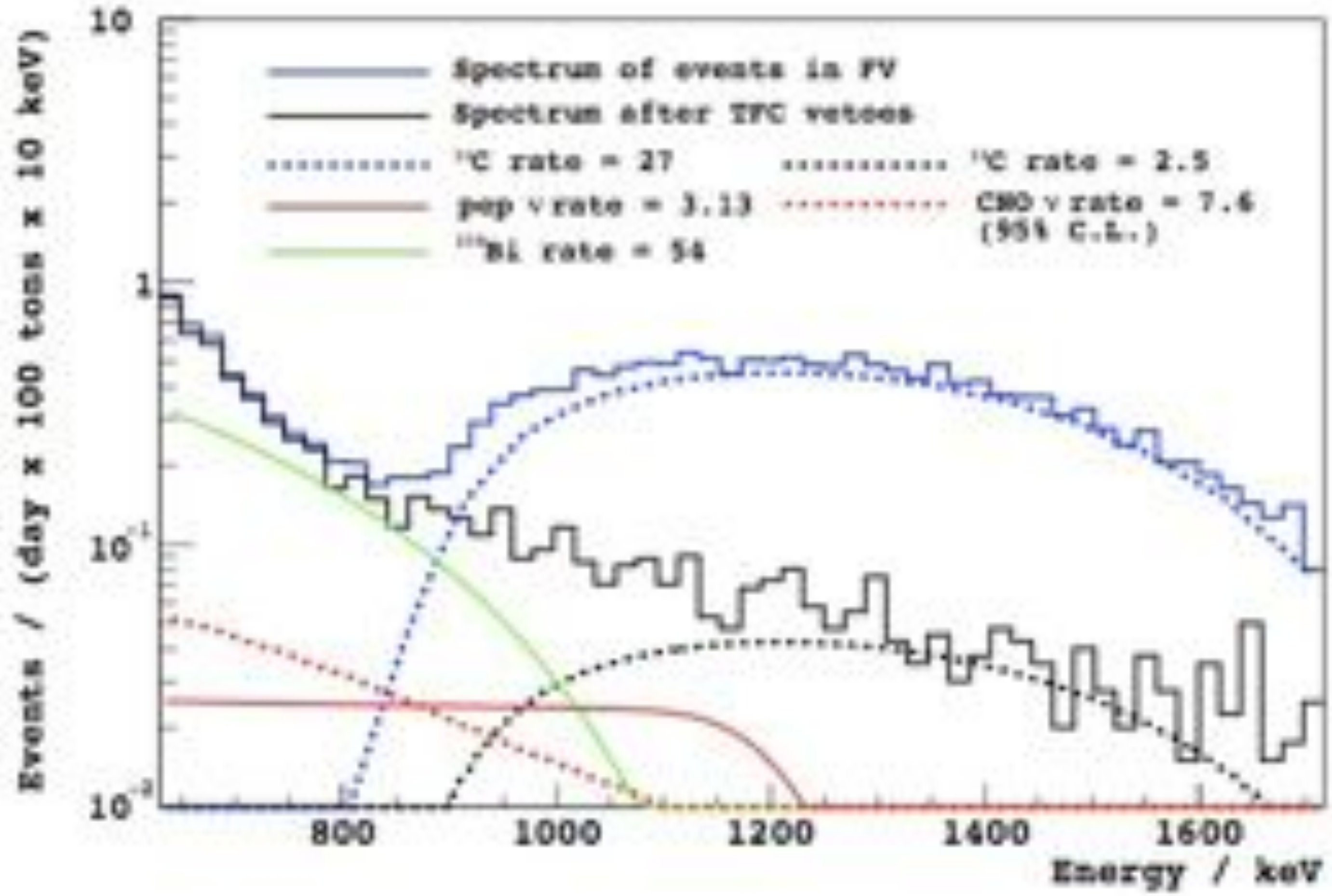
Three-Fold Coincidence



- 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

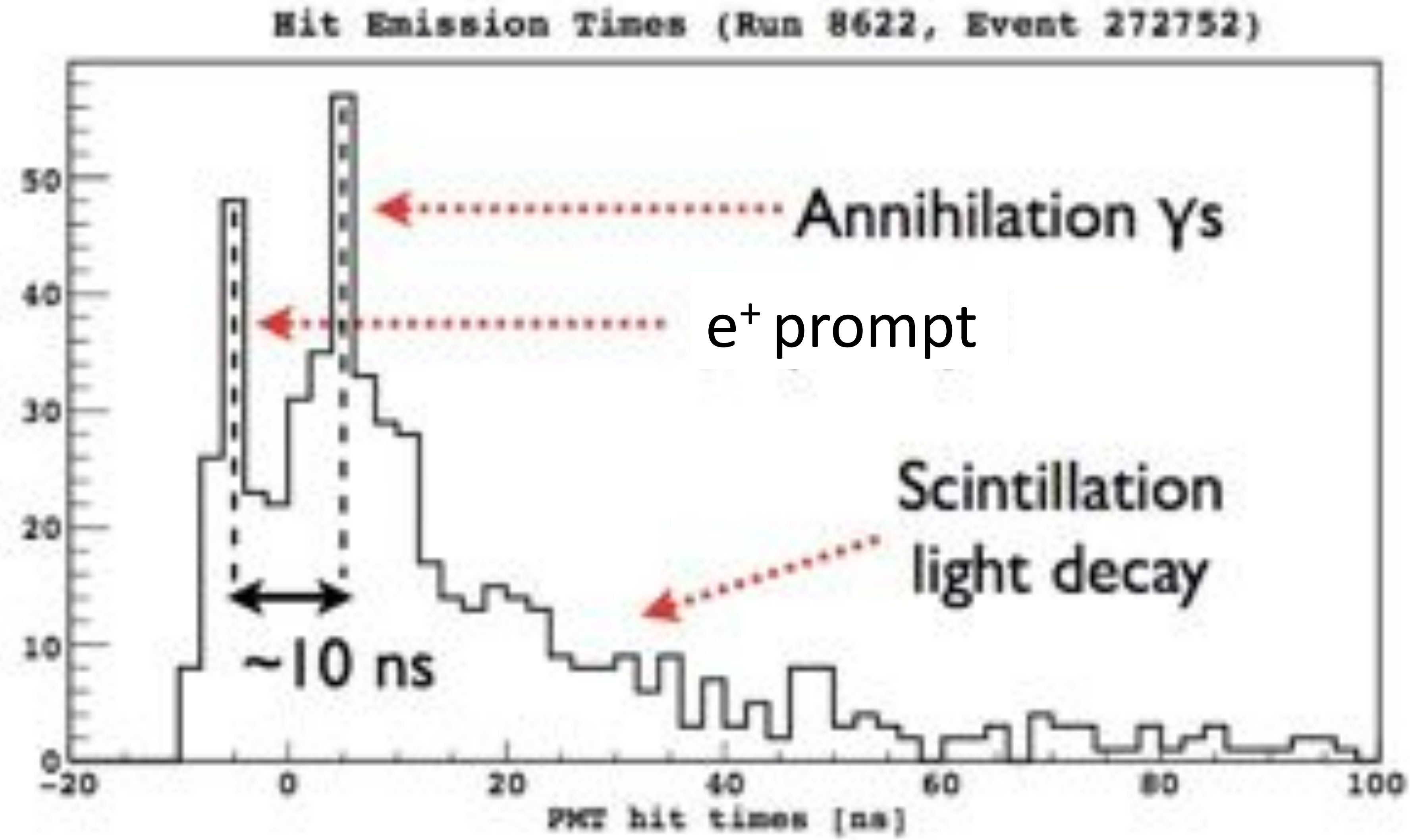
The ~125 muon-neutron coincidences/day can be vetoed without excessive loss of live time.

Three-Fold Coincidence



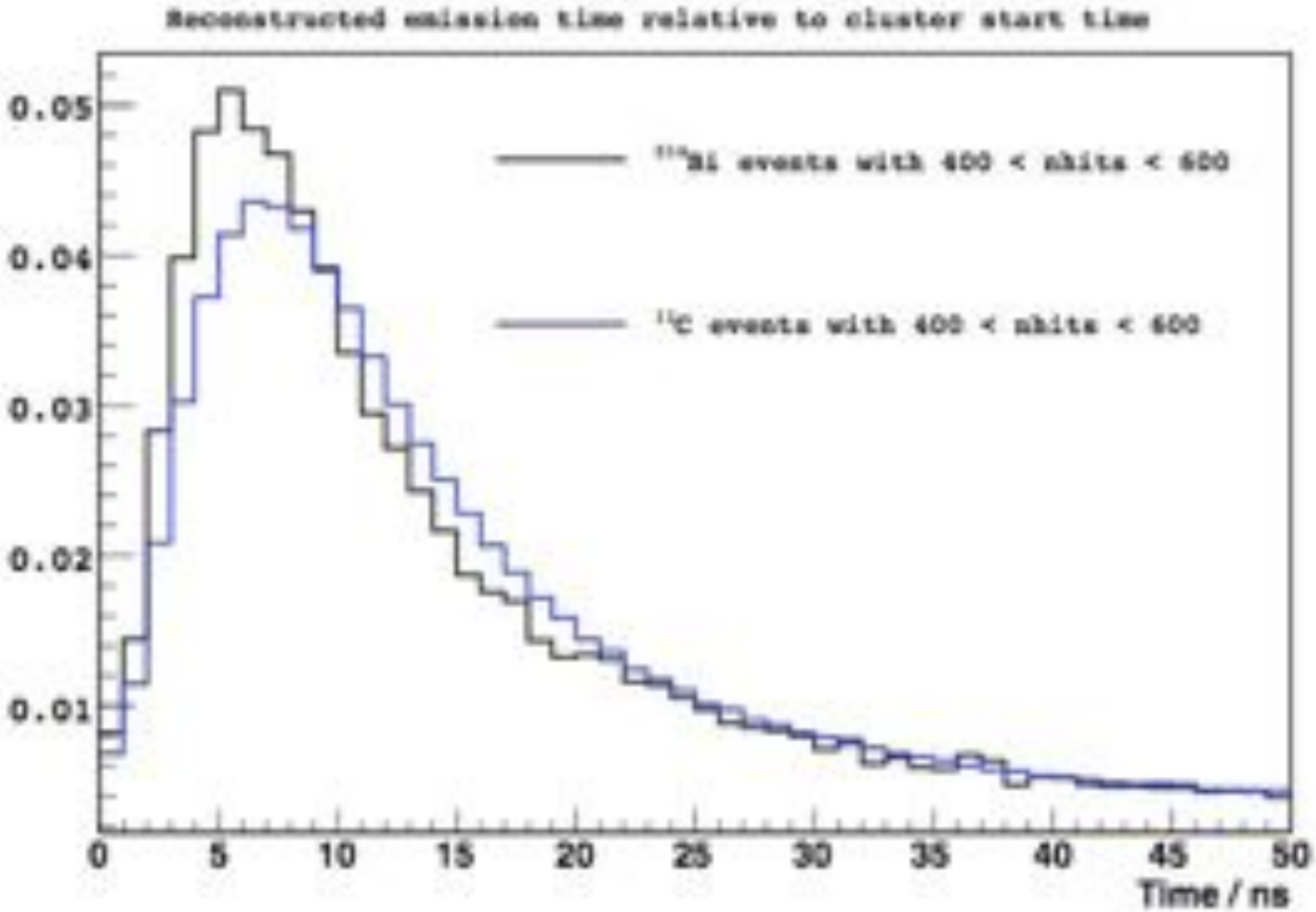
Remove 91% of ^{11}C with a livetime sacrifice of 51.5%.

e^+/e^- Pulse Shape Discrimination



- 50% of β^+ decays give *ortho*-positronium ($t_{1/2}$ = 3 ns).
- Gammas give multi-site topology.

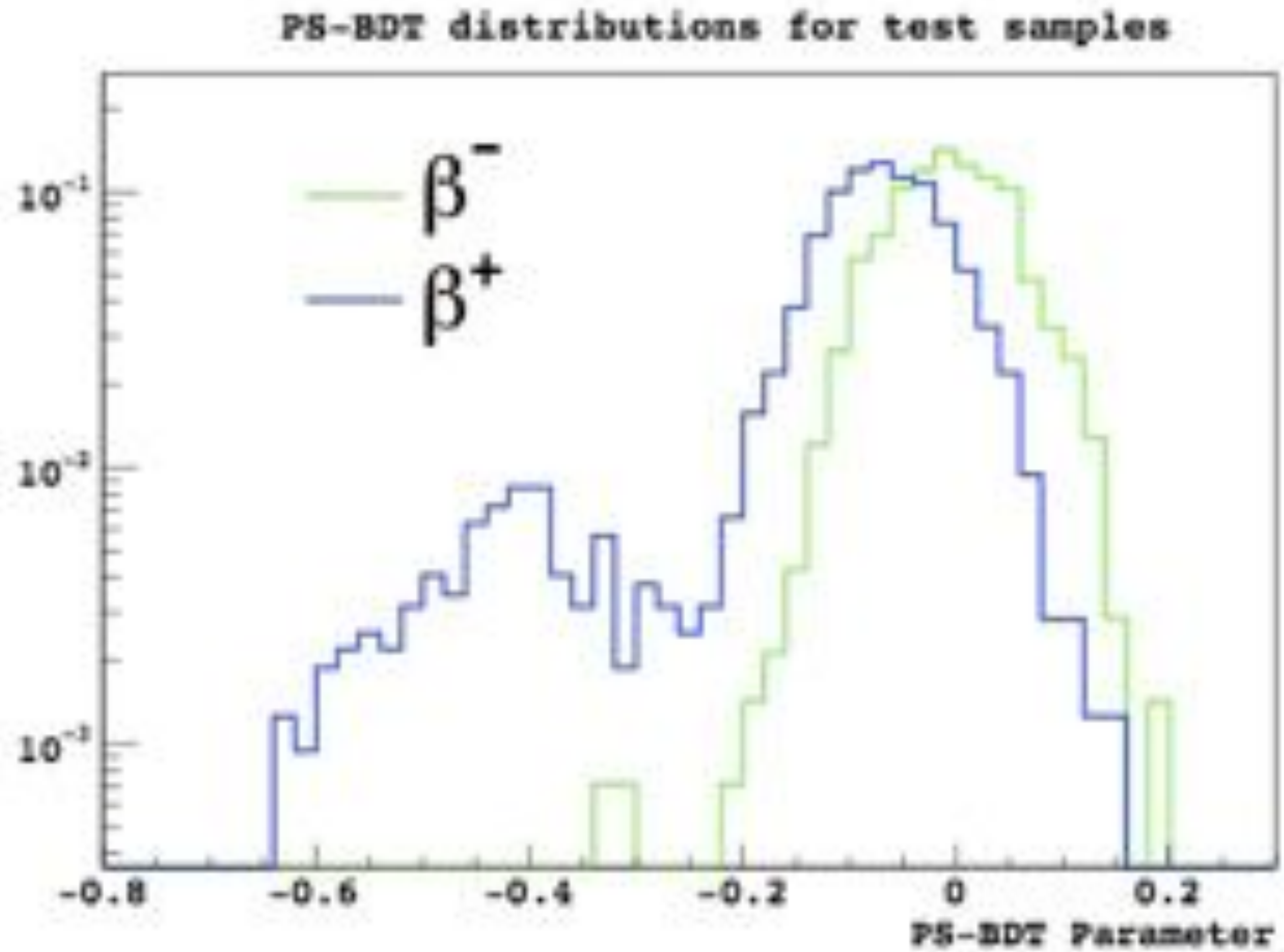
e^+/e^- Pulse Shape Discrimination



- 50% of β^+ decays give *ortho*-positronium ($t_{1/2}$ = 3 ns).
- Gammas give multi-site topology.

Phys. Rev. C **83**:015544 (2011)

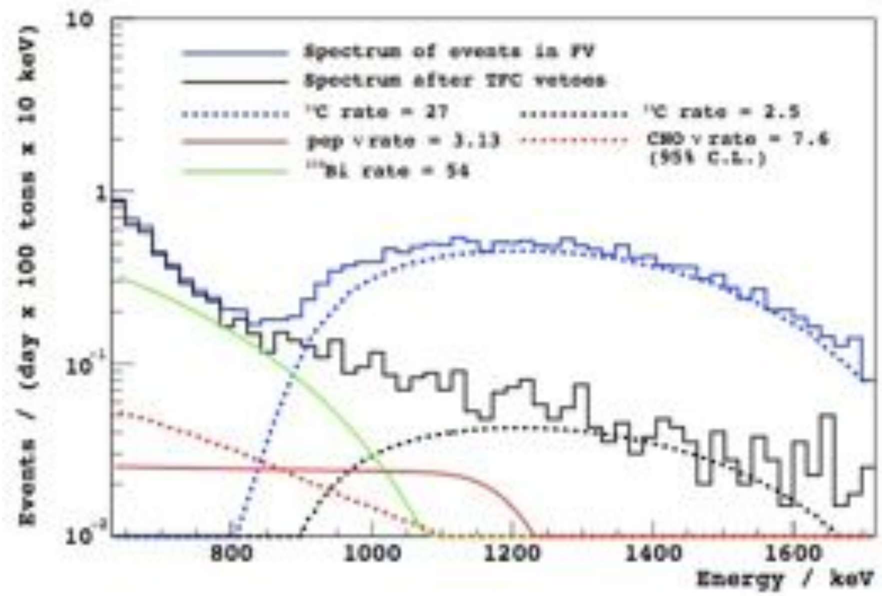
e^+/e^- Pulse Shape Discrimination

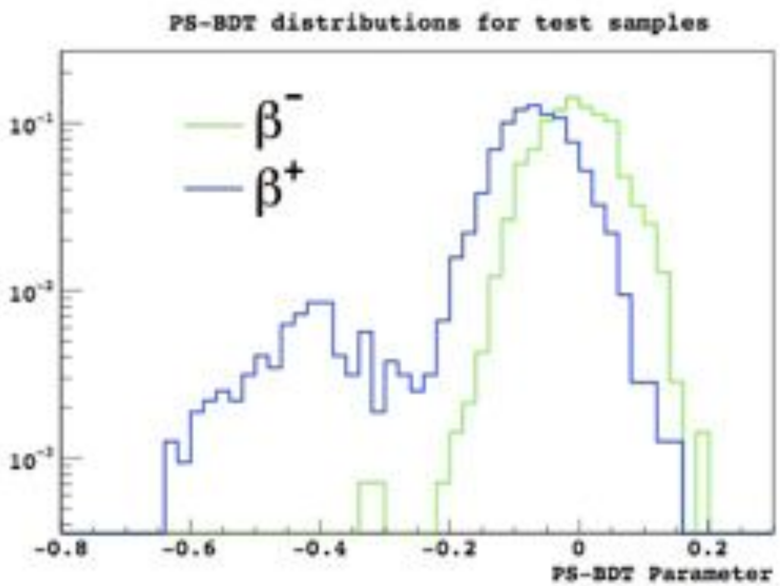


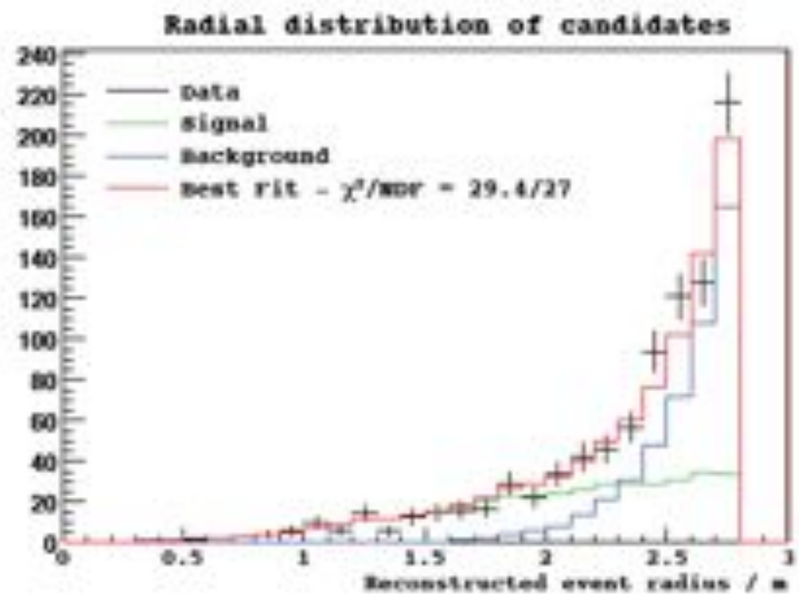
- Use boosted decision tree to optimize discrimination.
- Train, test, and build PDF with events cut by TFC.
- Include BDT variable in signal extraction.

Multi-Dimensional Fit

• Binned likelihood fits in energy, radius, and BDT
• 2D energy-radius and energy-BDT PDFs
• Simultaneous fits to TFC accepted and rejected spectra (double background statistics).







Multi-Dimensional Fit

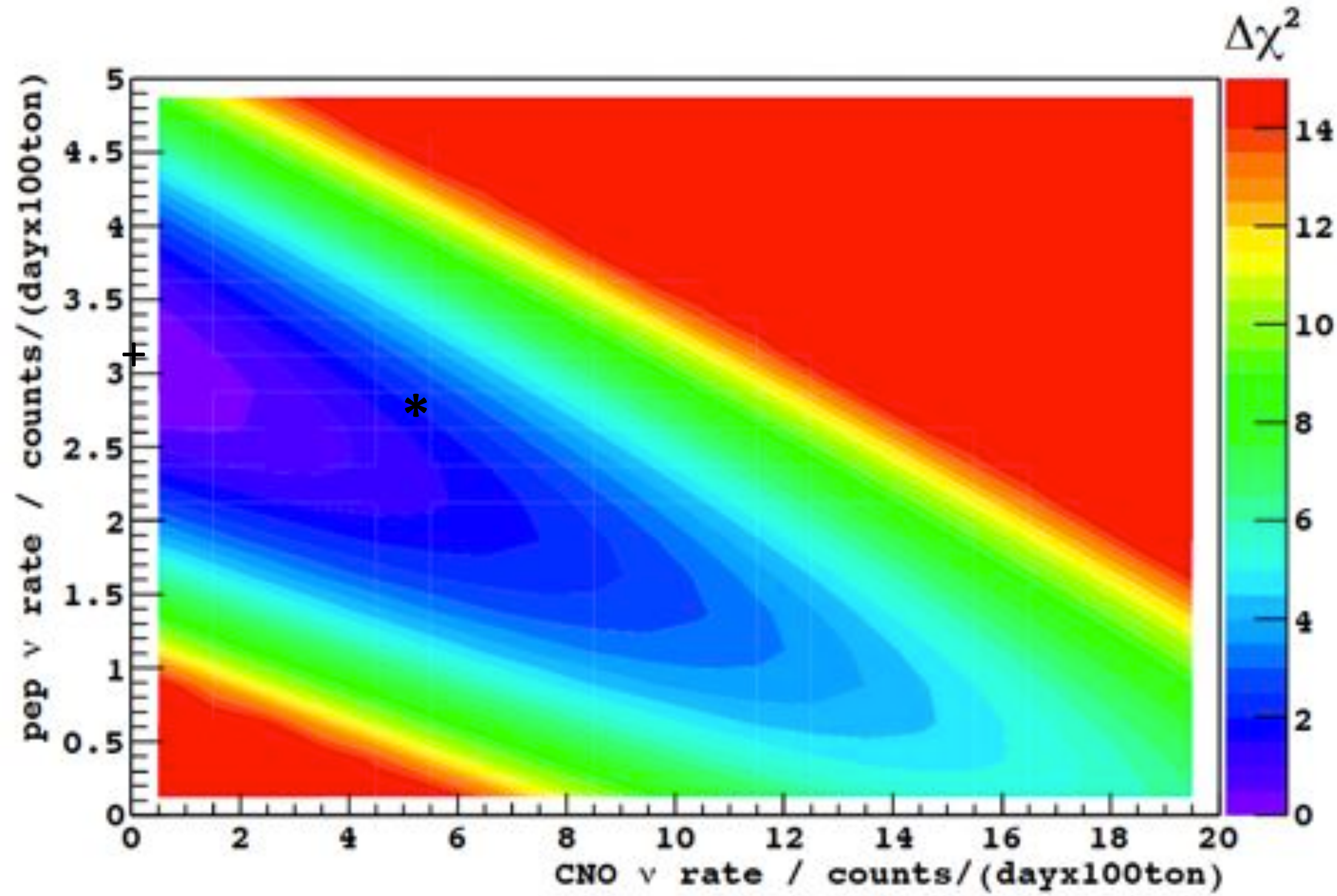
Species	Rate free or fixed	Common to both spectra	In PS-BDT fit	In radial dist. fit
pep ν	free	Yes	β^-	Bulk
CNO νs	free	Yes	β^-	Bulk*
^{7}Be ν	free	Yes	$\beta^{-}*$	Bulk*
pp ν	fixed to 133 cpd/100t	Yes	$\beta^{-}*$	Bulk*
^{8}B ν	fixed to 0.46 cpd/100t	Yes	β^-	Bulk
^{214}Pb	fixed to 1.95 cpd/100t	Yes	β^-	Bulk*
^{210}Bi	free	Yes	β^-	Bulk*
^{10}C	free	No	β^+	Bulk
^{11}C	free	No	β^+	Bulk
Ext. ^{214}Bi	free	Yes	β^-	External
Ext. ^{40}K	free	Yes	β^-	External
Ext. ^{208}Tl	free	Yes	β^-	External
^{6}He	free	No	β^-	Bulk
^{40}K	free	Yes	β^-	Bulk
^{85}Kr	free	Yes	$\beta^{-}*$	Bulk*
^{234m}Pa	free	Yes	β^-	Bulk

* Effectively excluded due to energy range

pp and ^{8}B neutrinos fixed to SSM values

^{214}Pb fixed to value from ^{214}BiPo coincidences

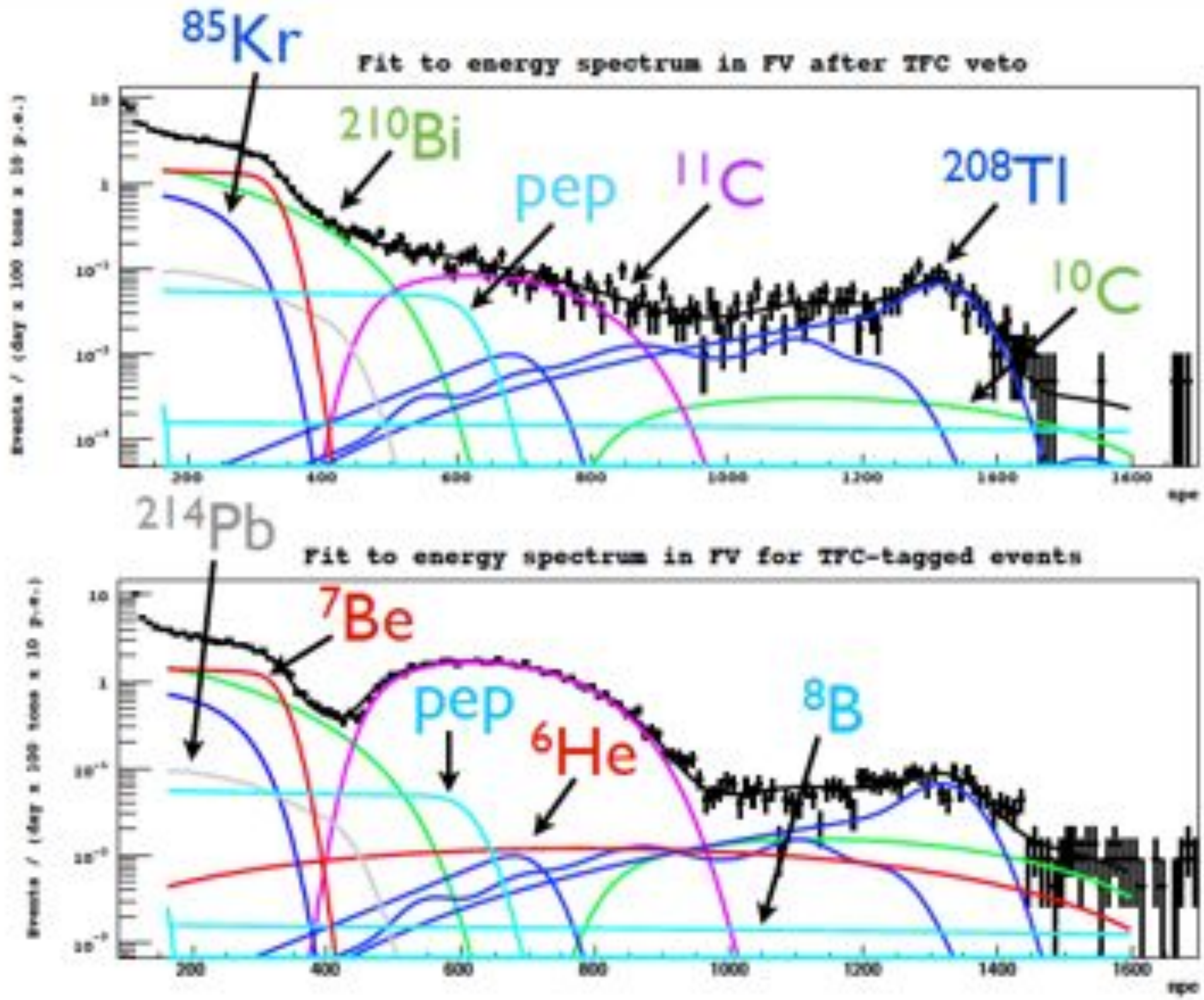
Fit Result



Best fit ('+'): (0, 3.13)

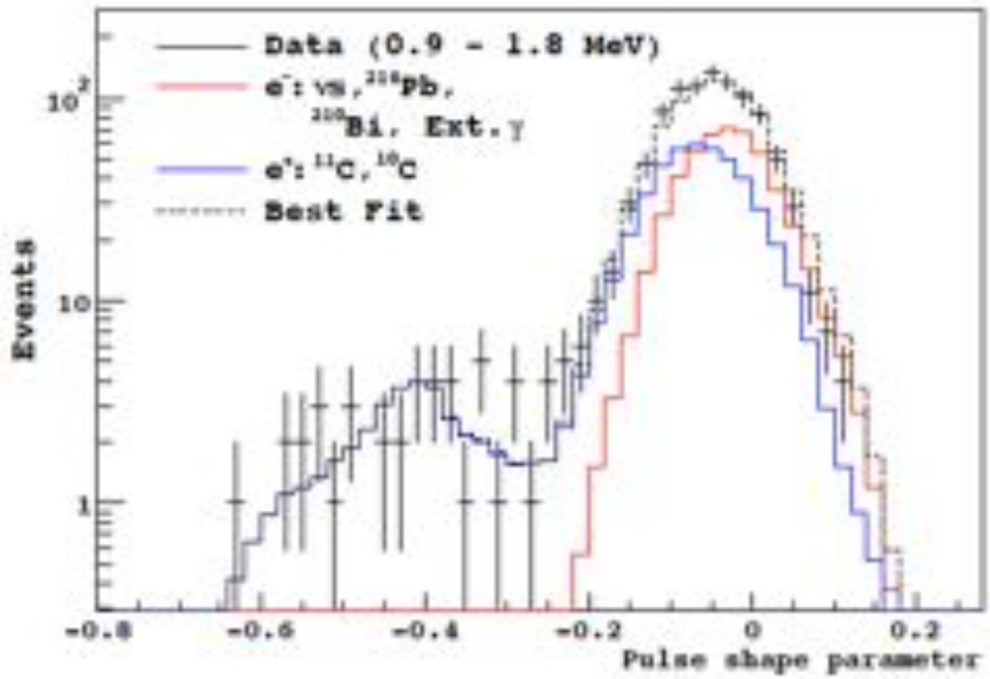
SSM + LMA prediction ('*'): (5.3, 2.8)

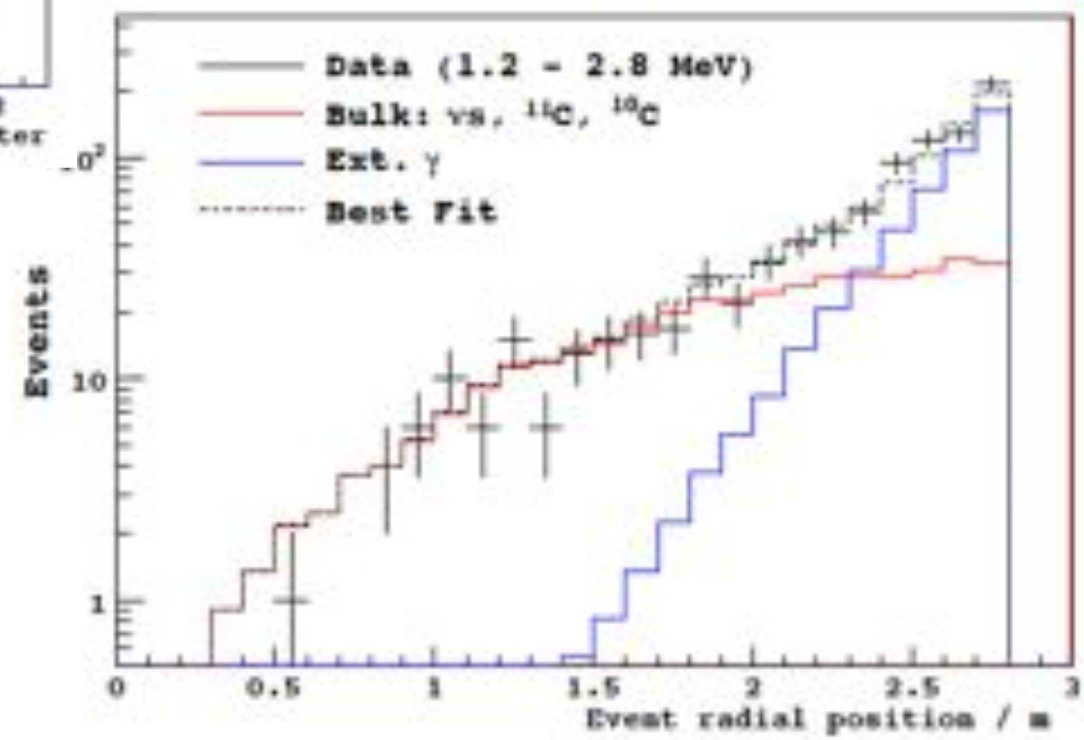
Fit Results



Fit p-value = 0.3 (from ensemble tests)

Fit Results

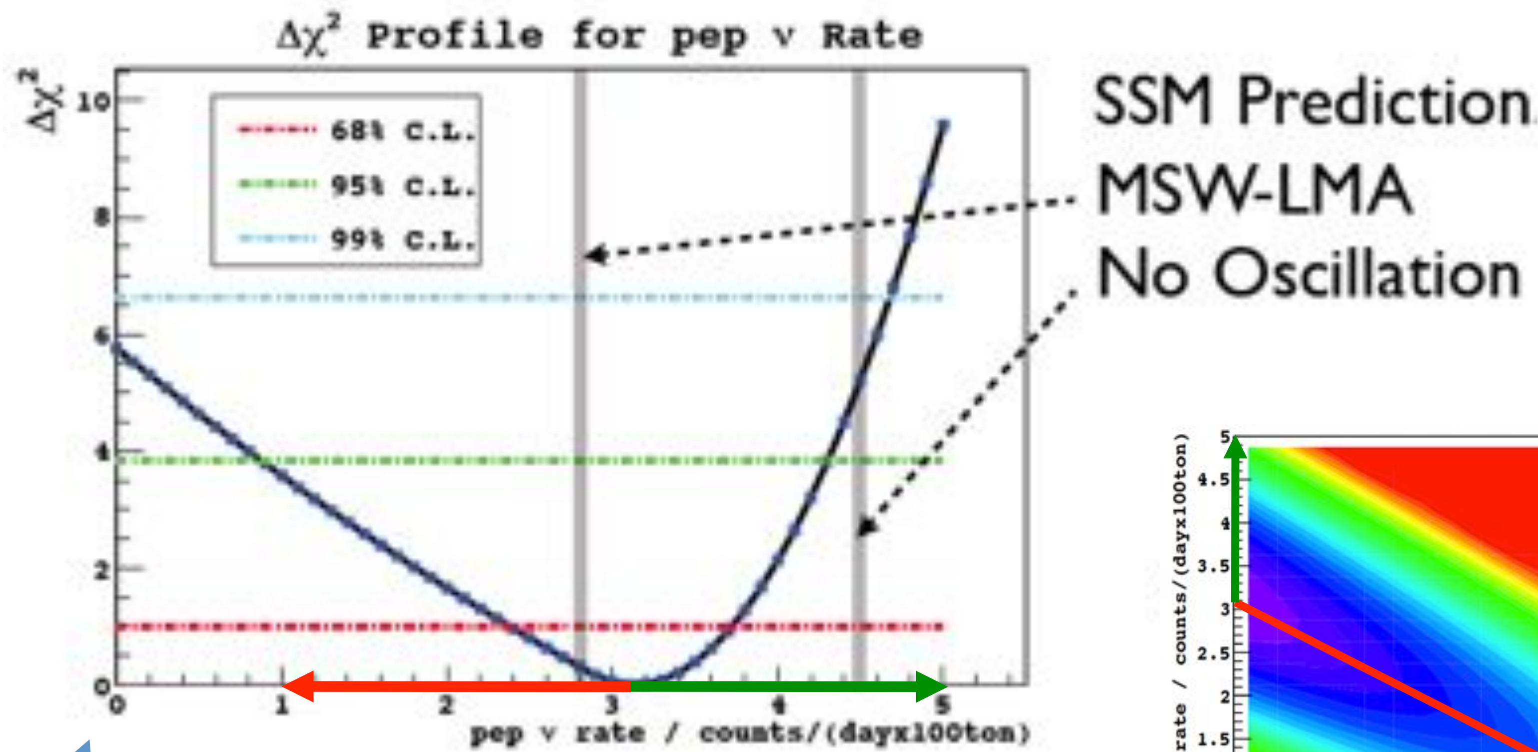

Data (0.9 - 1.8 MeV)
e⁻: νs, ²¹⁰Pb, ²¹⁰Bi, Ext. γ
e⁺: ¹¹C, ¹⁰C
Best Fit
Events
Pulse shape parameter

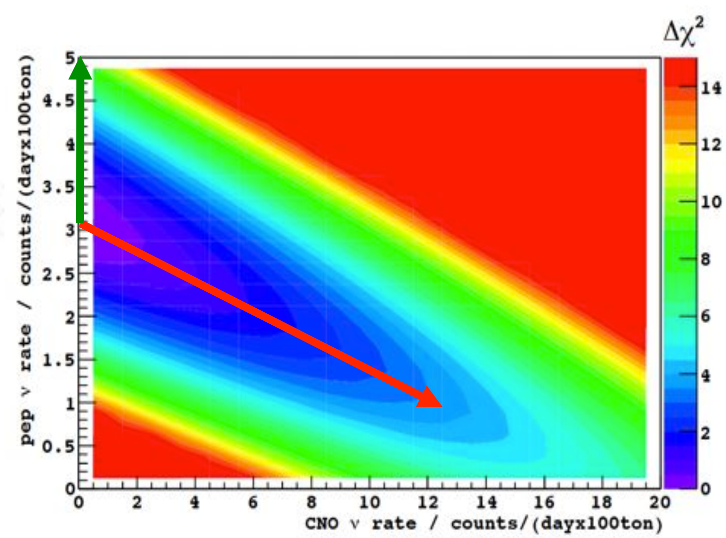

Data (1.2 - 2.8 MeV)
Bulk: νs, ¹¹C, ¹⁰C
Ext. γ
Best Fit
Events
Event radial position / m

pep Result

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

→ P_{ee}(1.44 MeV) = 0.62 ± 0.17



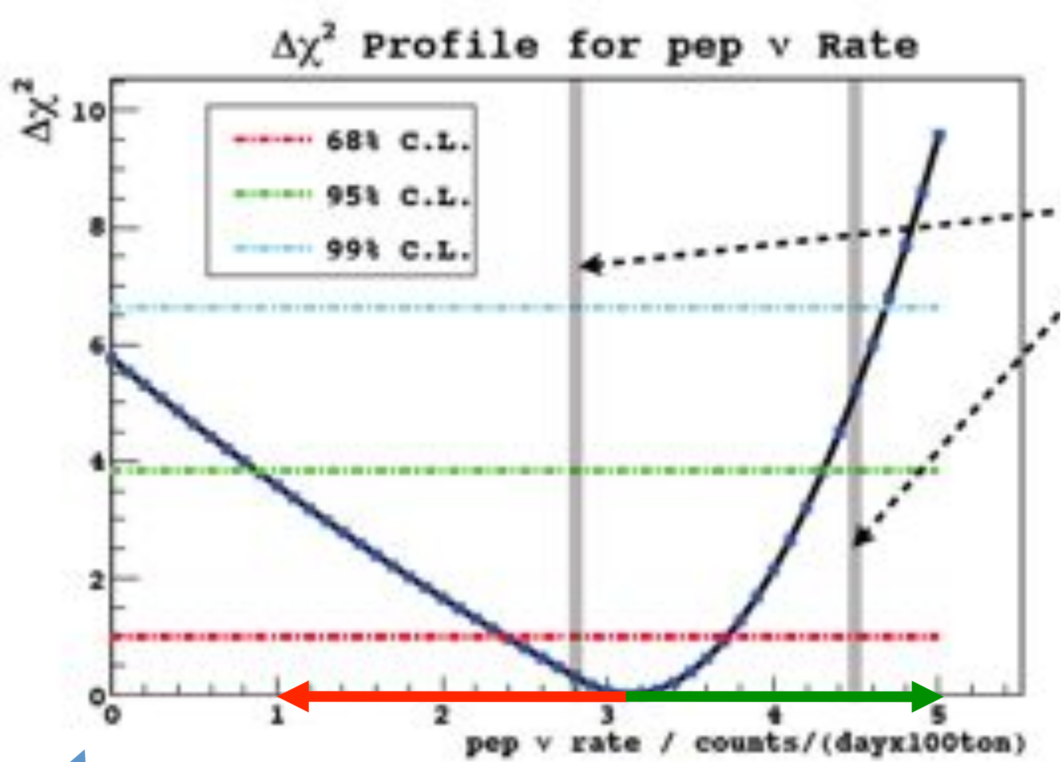


Φ_{pep} = 0 disfavoured at 98% C.L.

pep Result

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

→ P_{ee}(1.44 MeV) = 0.62 ± 0.17



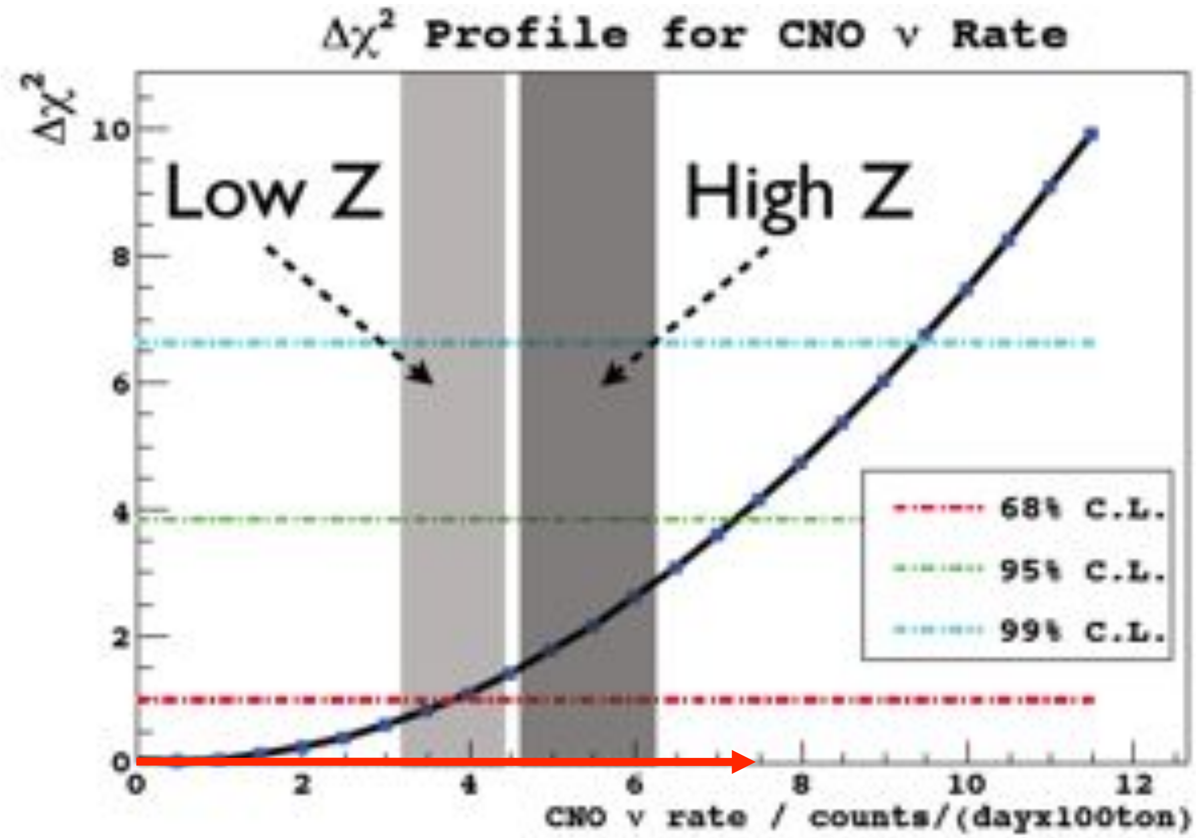
Systematics	
Fiducial Exposure	$^{+0.6}_{-1.1}$%
Energy Response	4.1%
^{210}Bi shape	$^{+1.0}_{-5.0}$%
Fit Methods	5.7%
^{85}Kr constraint	$^{+3.9}_{-0.0}$%
γ-rays in BDT	2.7%
BDT PDF statistics	5.0%
Total	**10%**

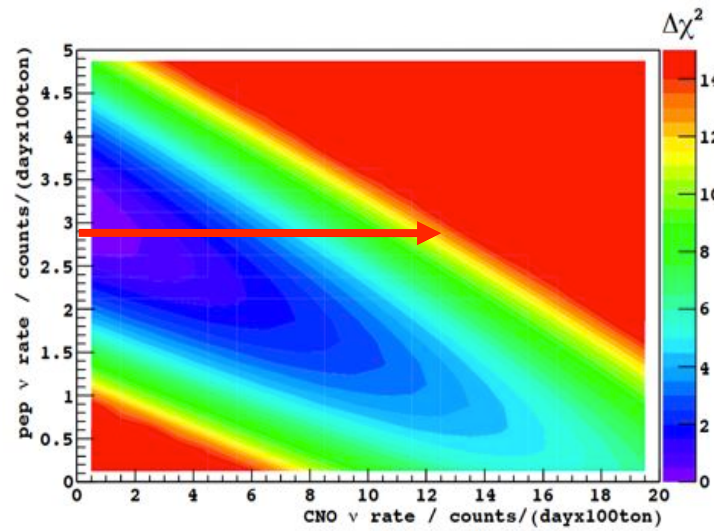
Φ_{pep} = 0 disfavoured at 98% C.L.

CNO Limit

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

→ (< 1.5 x high Z SSM)

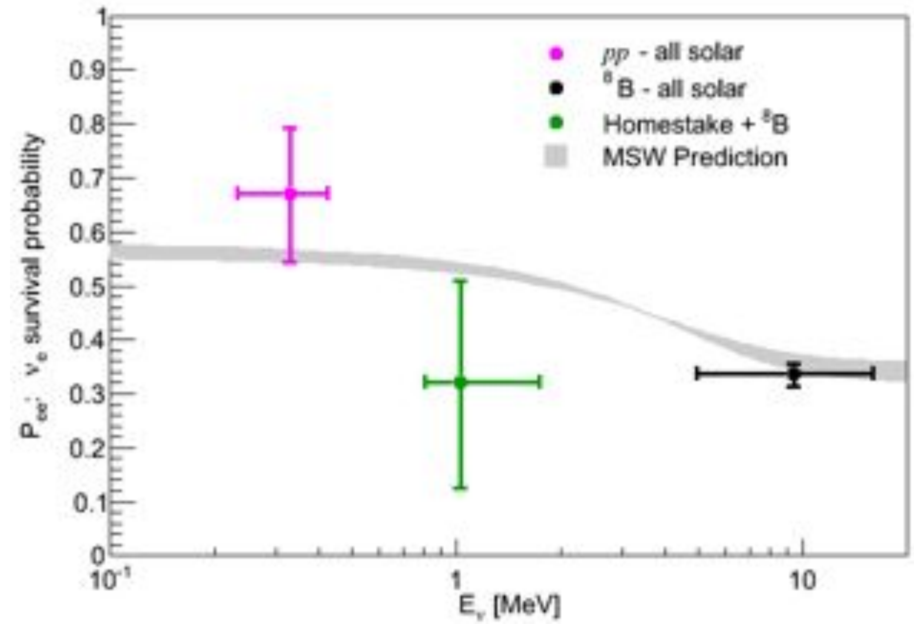


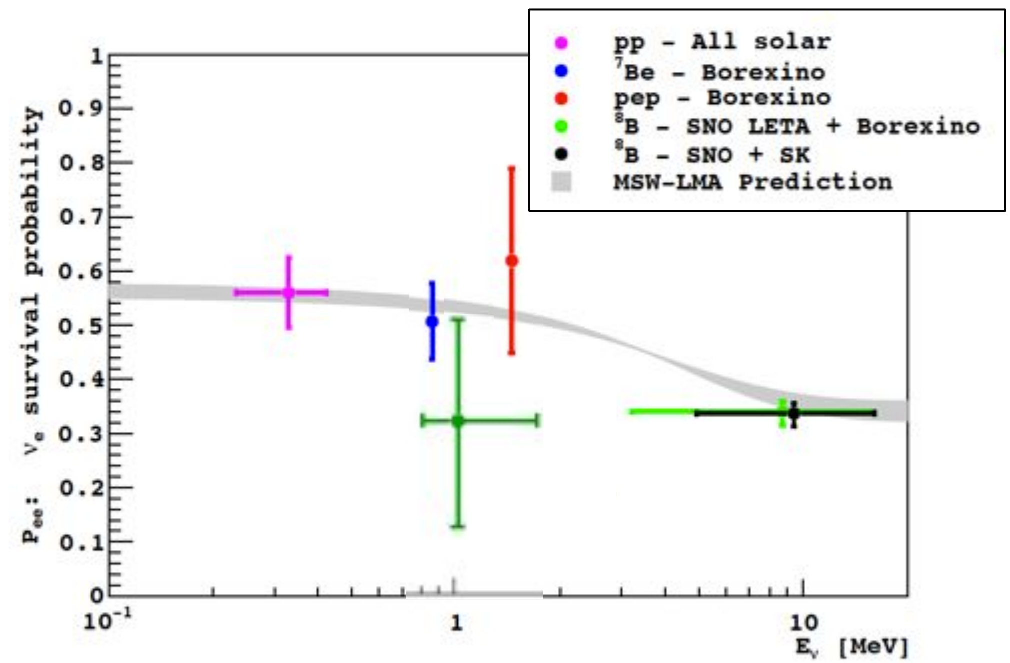


pep fixed at SSM prediction (2.8 ± 0.4) /(d 100T)

Summary

- Borexino has achieved unprecedented radiopurity and developed techniques to effectively suppress residual backgrounds
- ^{7}Be flux results significantly improve the experimental constraint on P_{ee} at low energy
- Day-night improves solar-only constraint on mixing parameters
- First direct study of the *pep* flux
- Most precise constraint on CNO flux





Borexino Future

- Procedures to (further!) purify the scintillator underway since July 2010
  - No sign of ^{85}Kr since January
  - Moderate reduction in ^{210}Bi
- Operations continue, with aim of further reducing ^{210}Bi, perhaps ^{210}Po
- Borexino will continue to take data for >3 more years
  - Improve measurements of low energy solar neutrinos, accrue further ^{8}B & geo-neutrino statistics