Taking a “ν” Look:

Studying Solar and Terrestrial Neutrinos with Borexino

IPP Tour 2012

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Princeton University

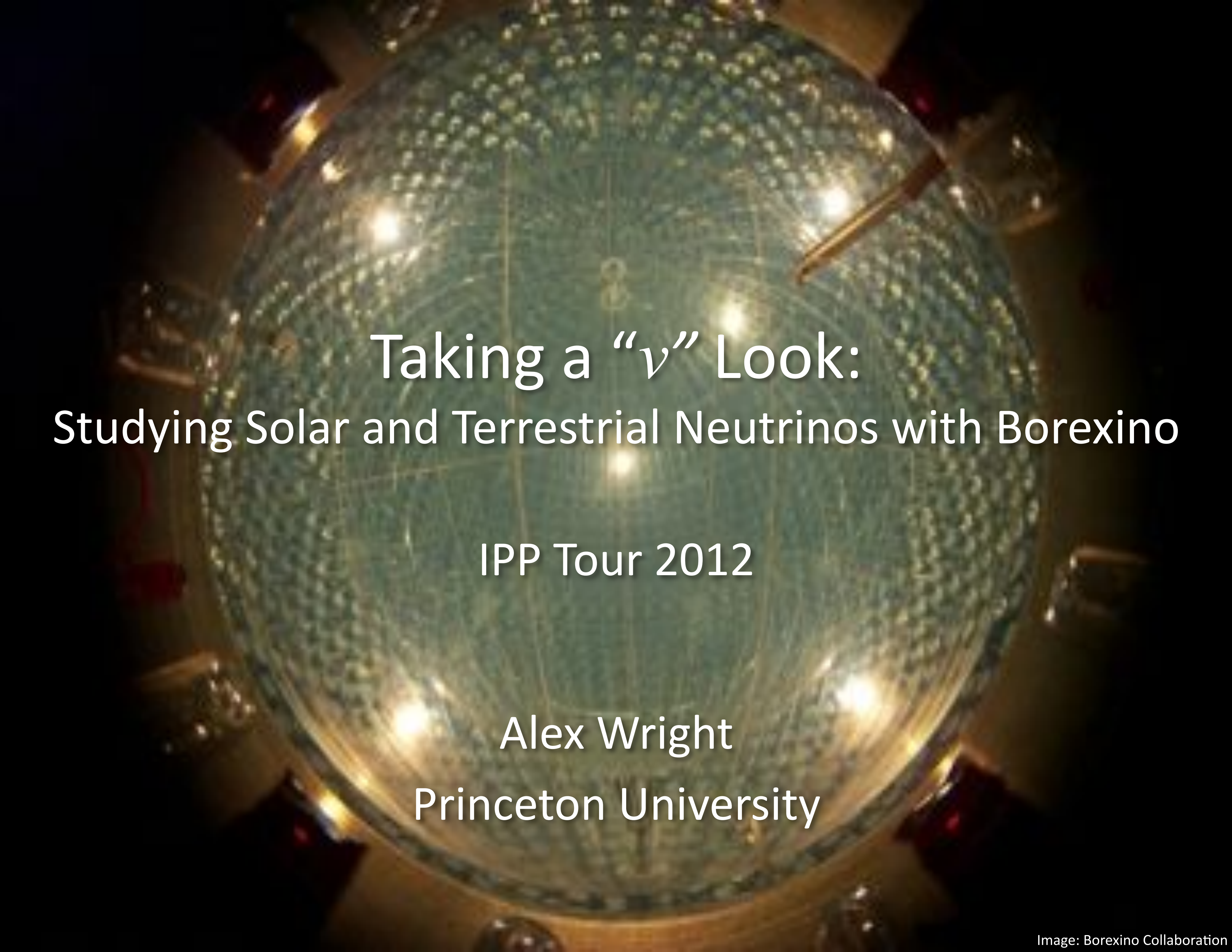


Image: Borexino Collaboration

Outline

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

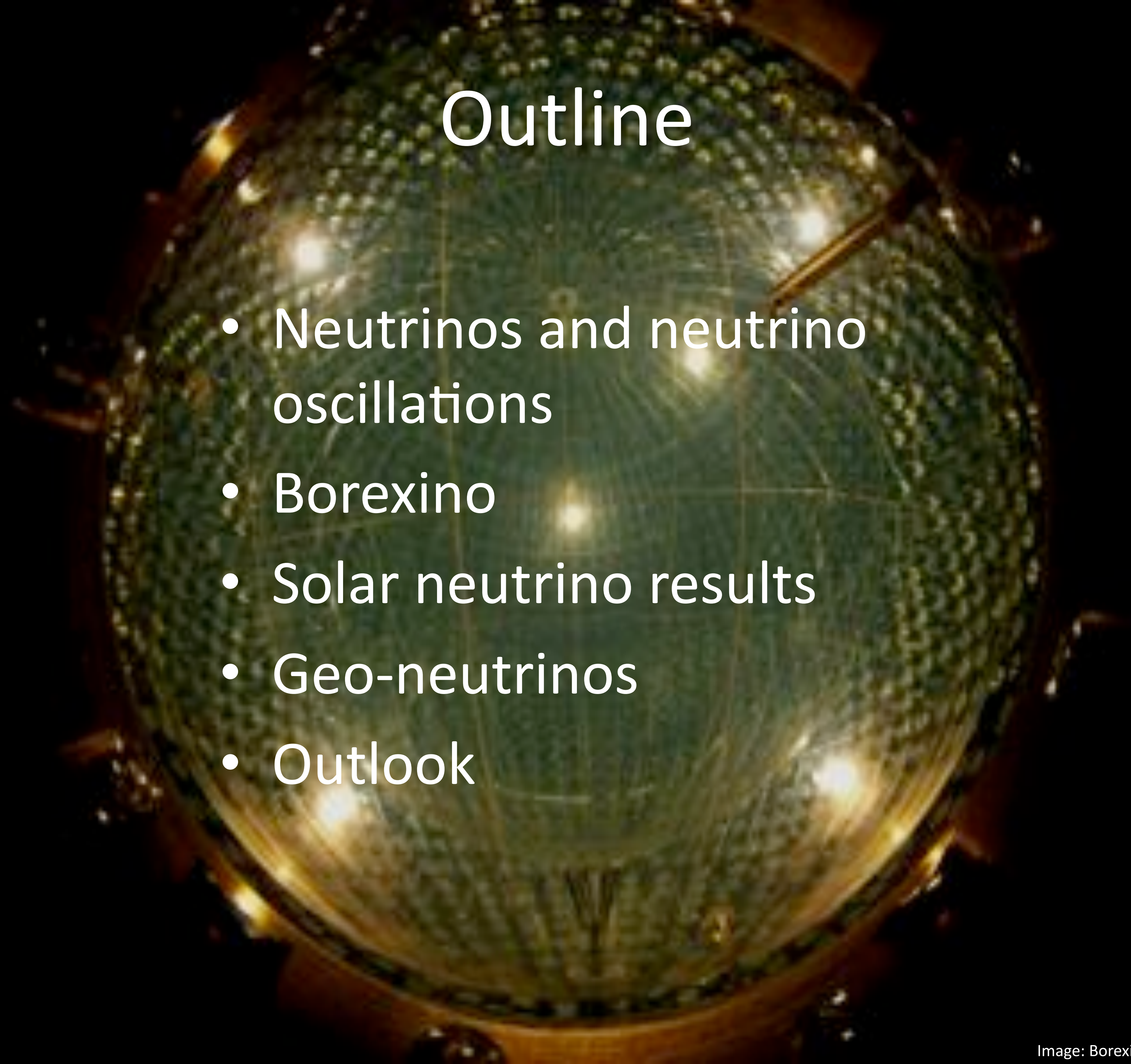
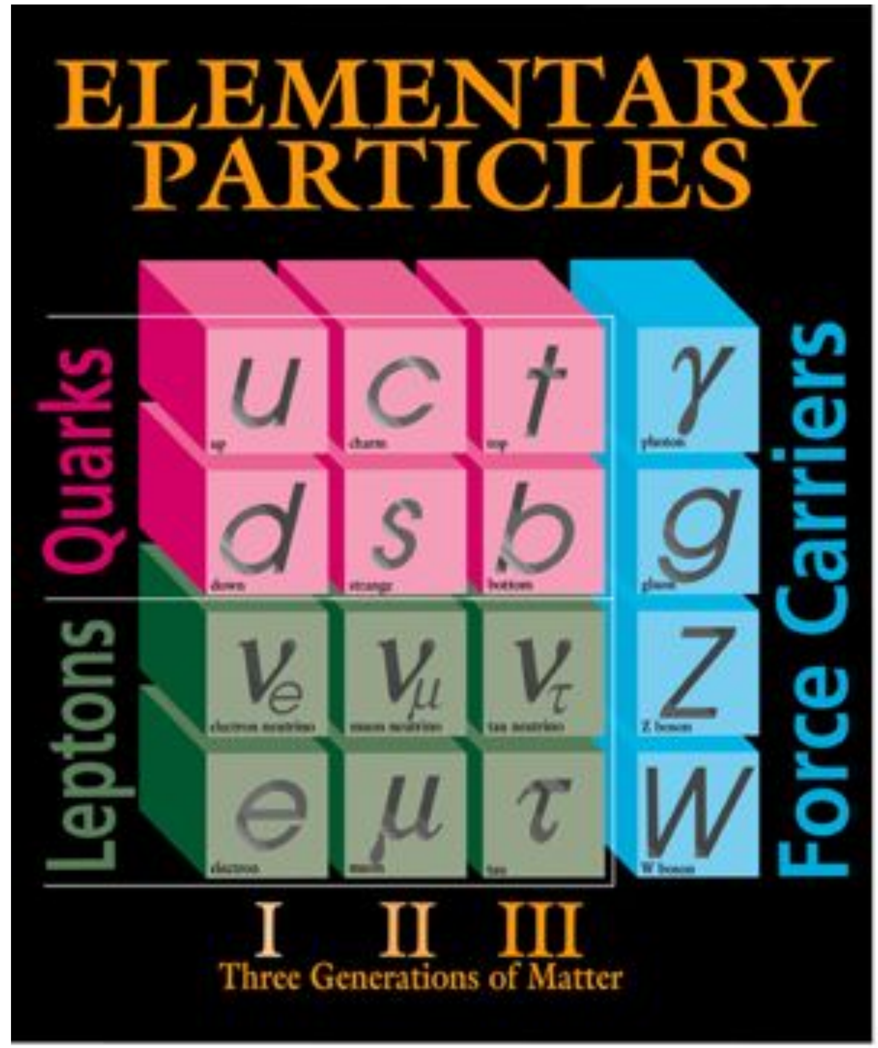


Image: Borexino Collaboration

Neutrinos

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



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

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

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

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

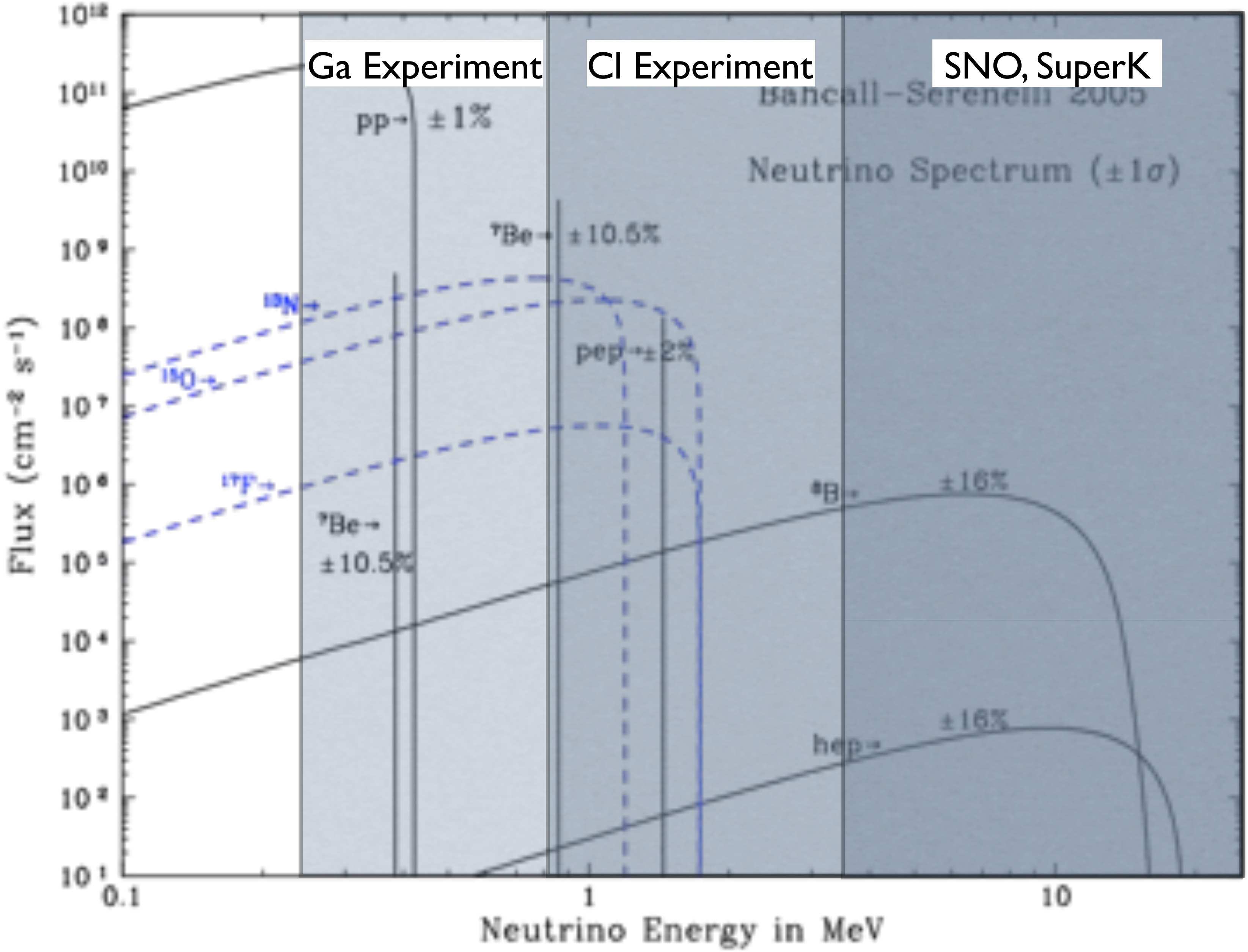
$${}^{14}N + p \rightarrow {}^{15}O + \gamma$$

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

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

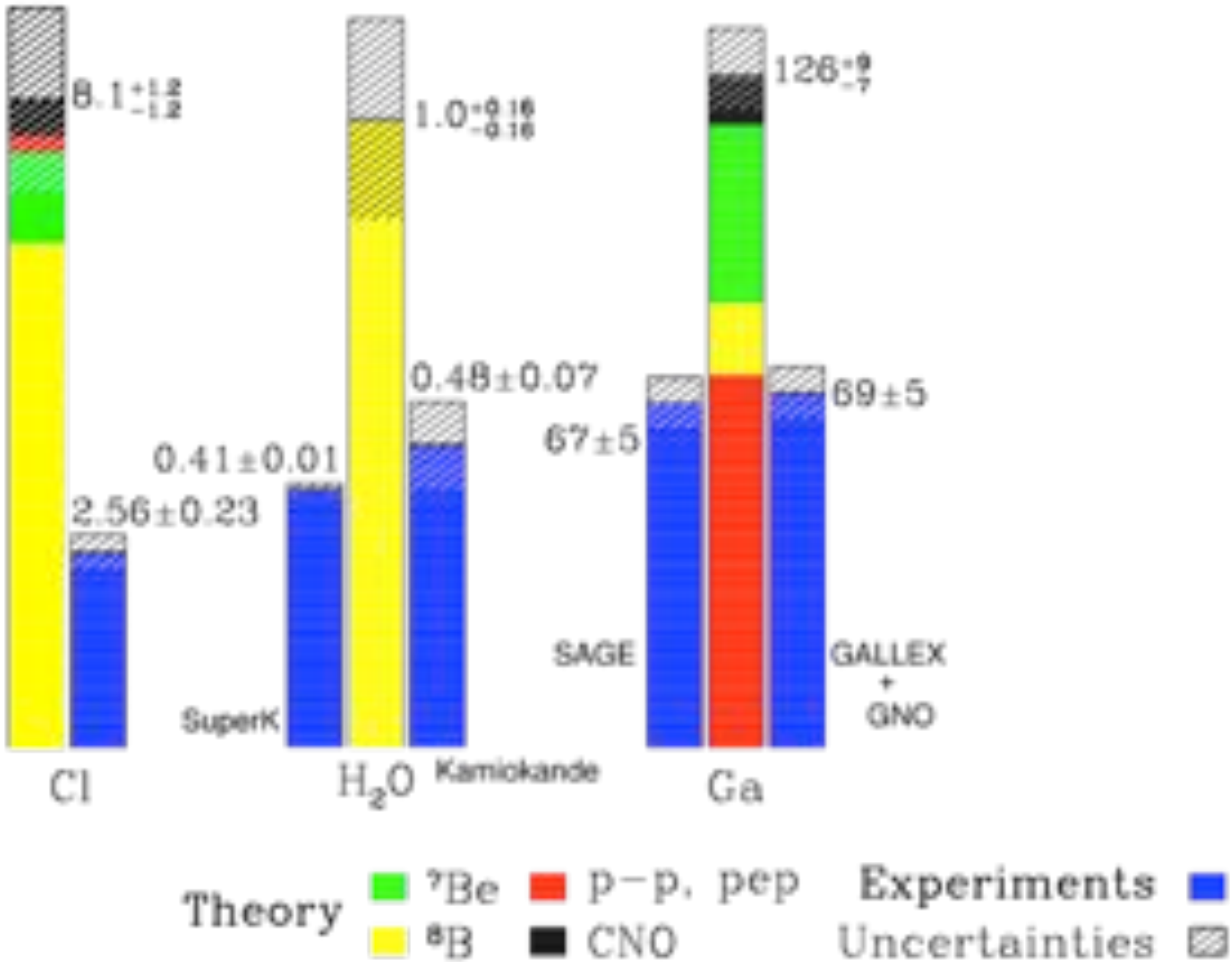
Image: bbc.co.uk

Neutrinos From the Sun



The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



The Solar Neutrino Problem

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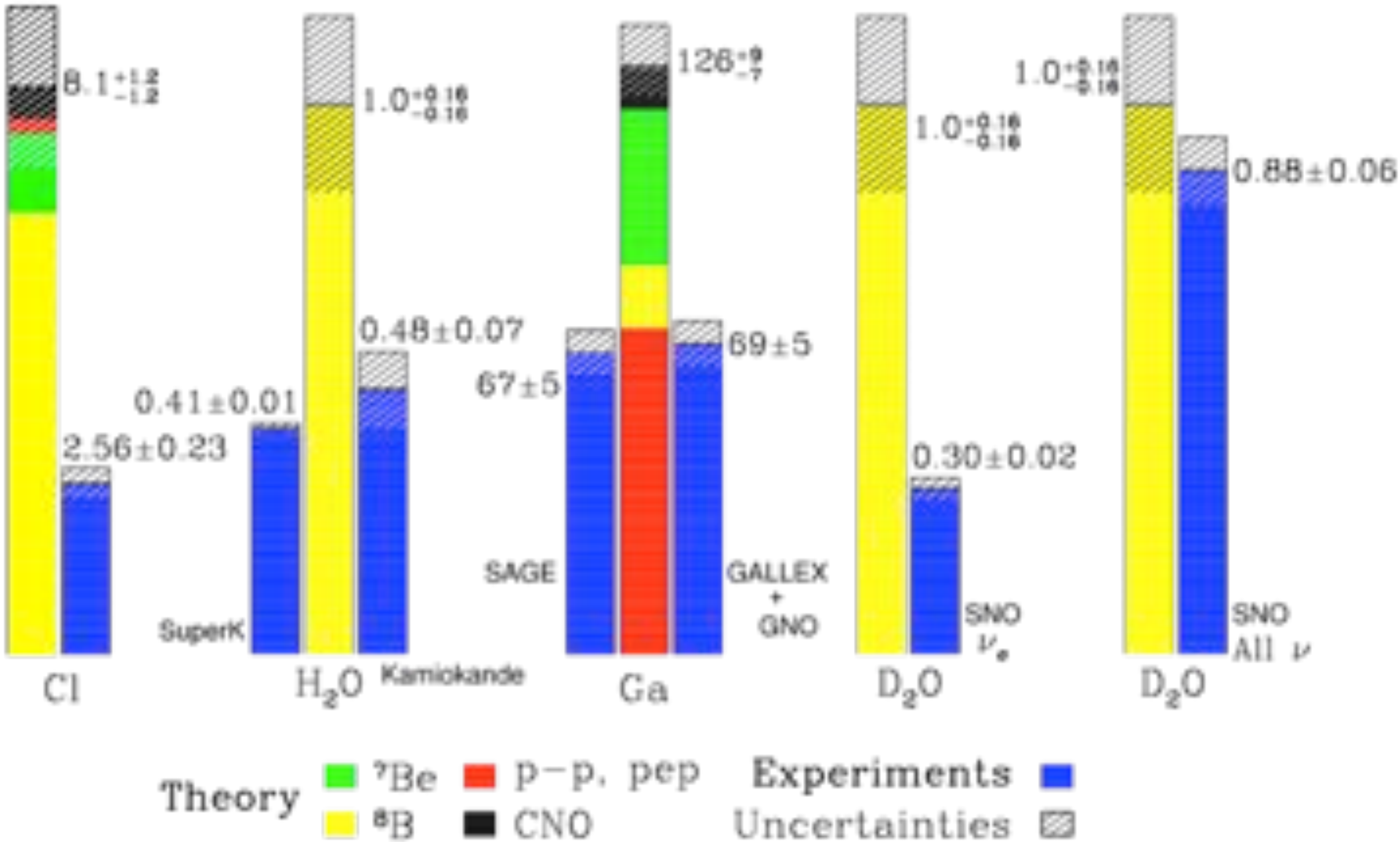
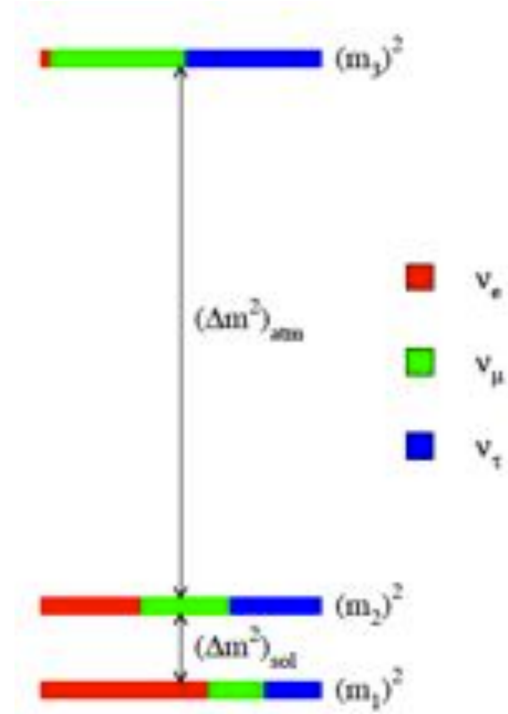


Neutrino Oscillations

- 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

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

$-s_{23}$ = $-\sin(\theta_{23})$

c_{13} = $\cos(\theta_{13})$

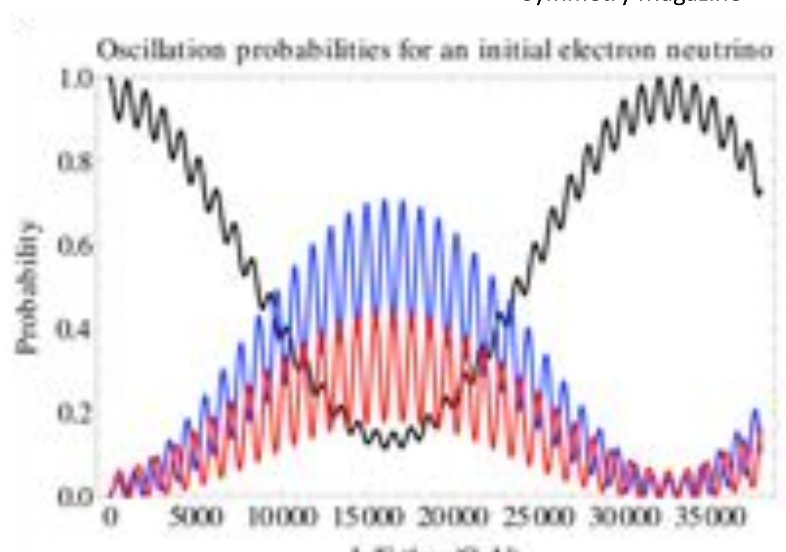
wikipedia.org

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:

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


Symmetry Magazine



wikipedia.org

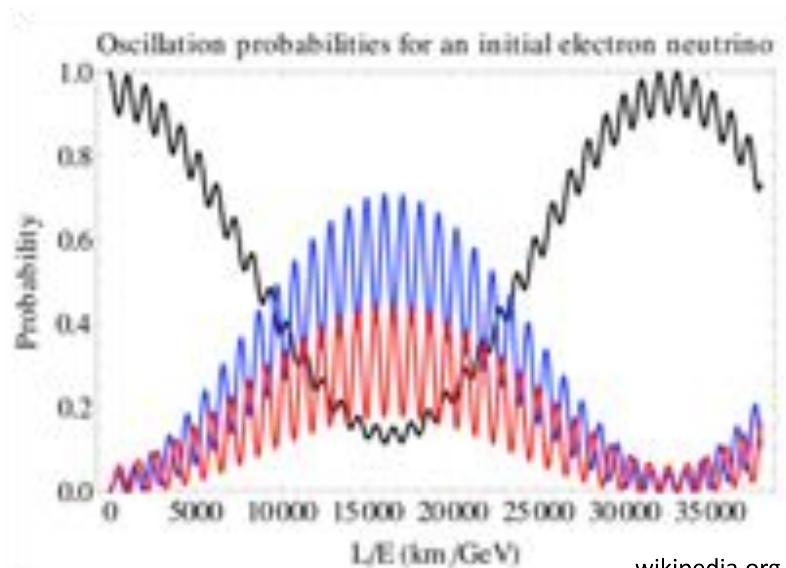
Neutrino Oscillations

- 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:

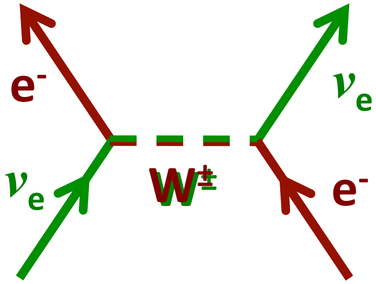
$$P_{ee} = \cos^4(\theta_{13})\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right) + \sin^4(\theta_{13})$$

$$\sim 1 - \frac{1}{2}\sin^2(2\theta_{12}) \qquad (\theta_{13} = 0)$$

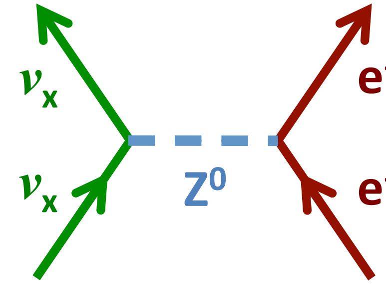
Symmetry Magazine



wikipedia.org



The Matter of Matter

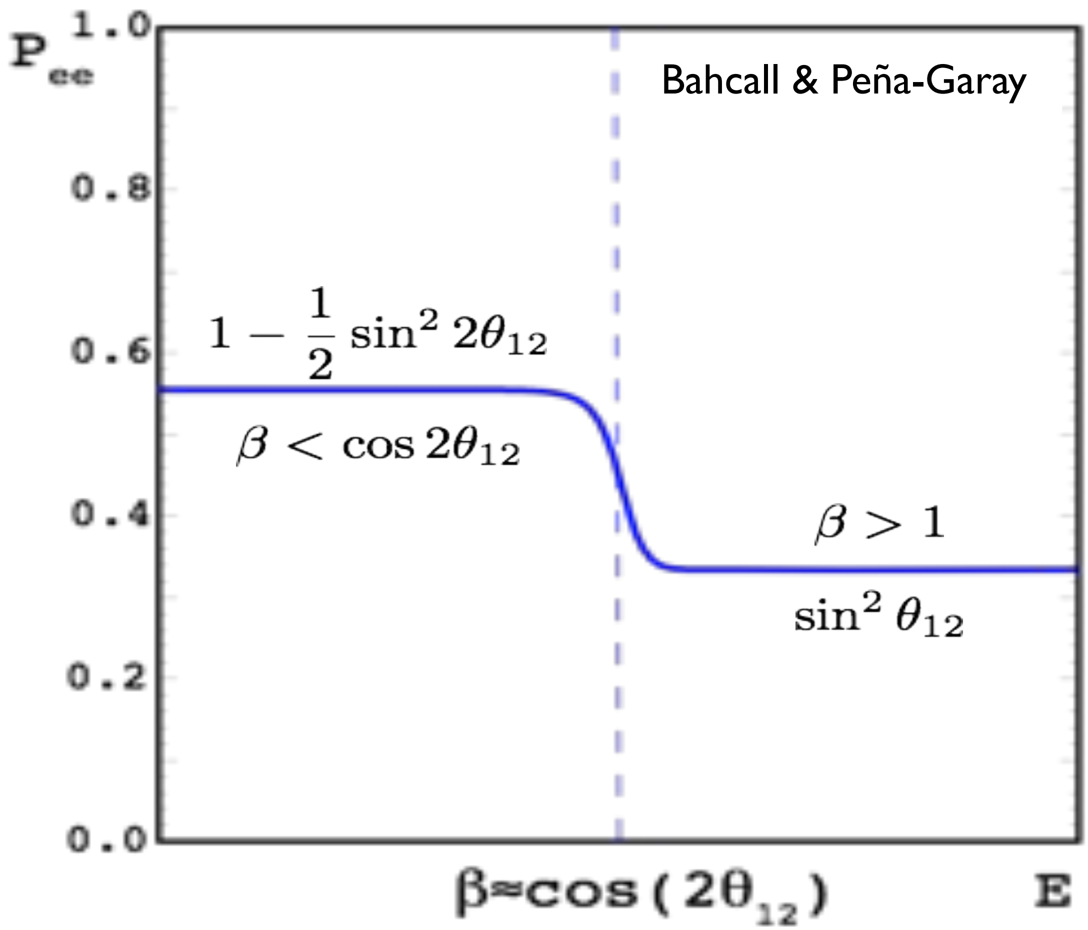


- When neutrinos propagate in matter, charged current interactions add an additional term to ν_e flavour in Hamiltonian mass matrix:

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

- 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

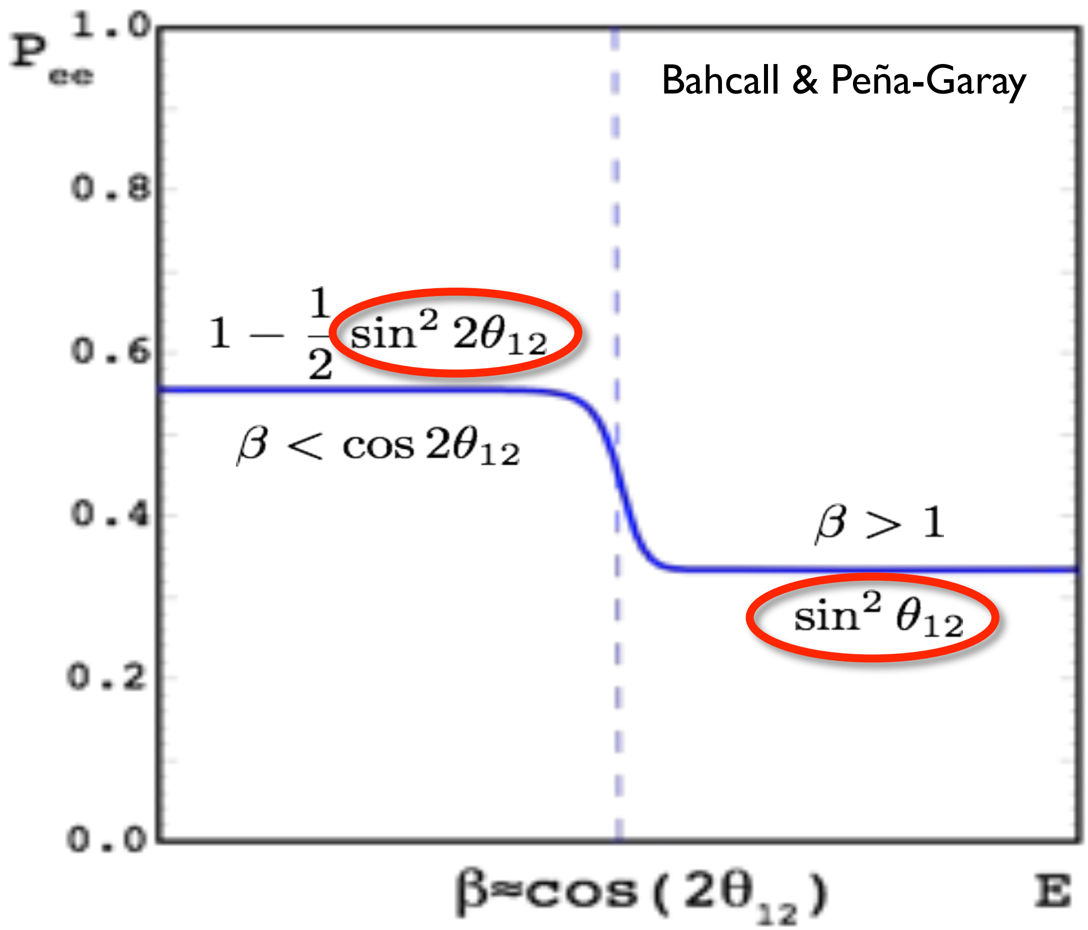


$$\beta = \frac{2^{3/2} G_F N_e}{\left(\frac{\Delta m^2}{E}\right)}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated “resonant conversion”

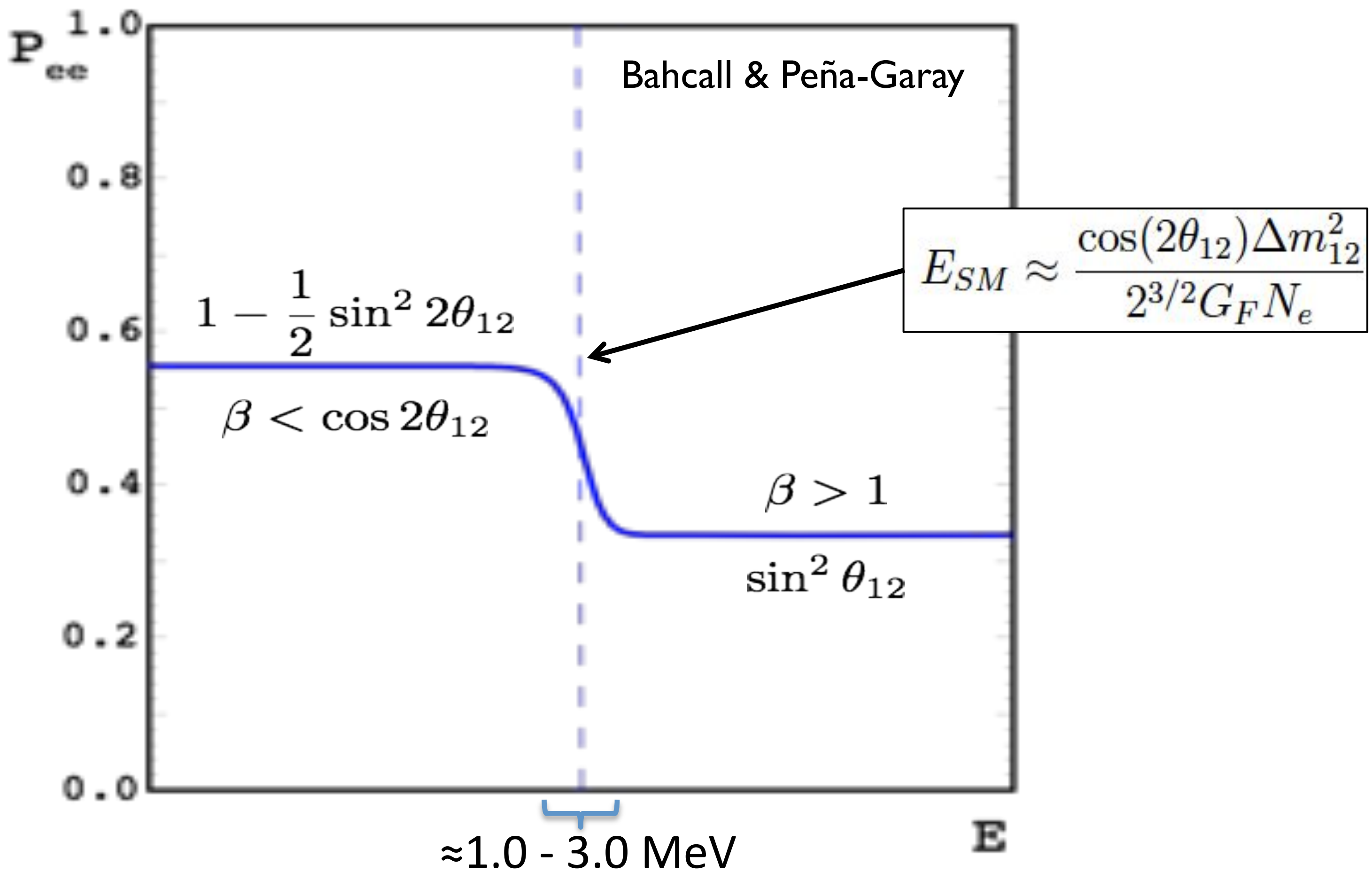
MSW Oscillation Regimes



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

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

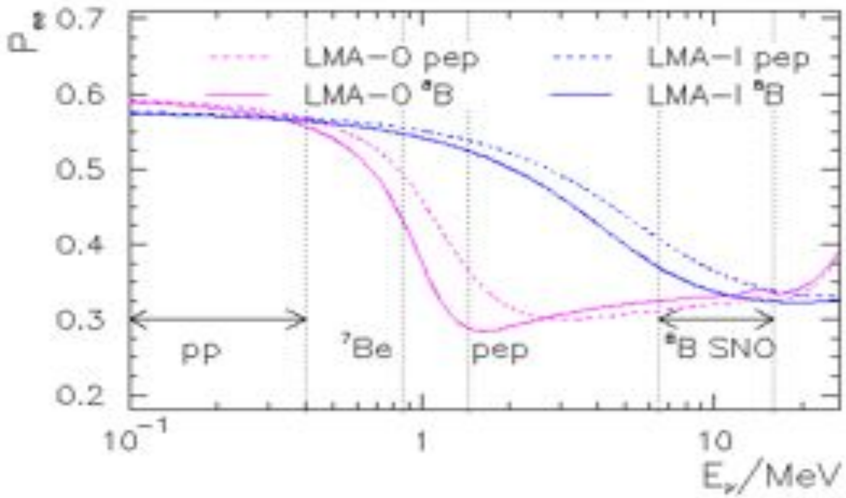


Look in "transition region" to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

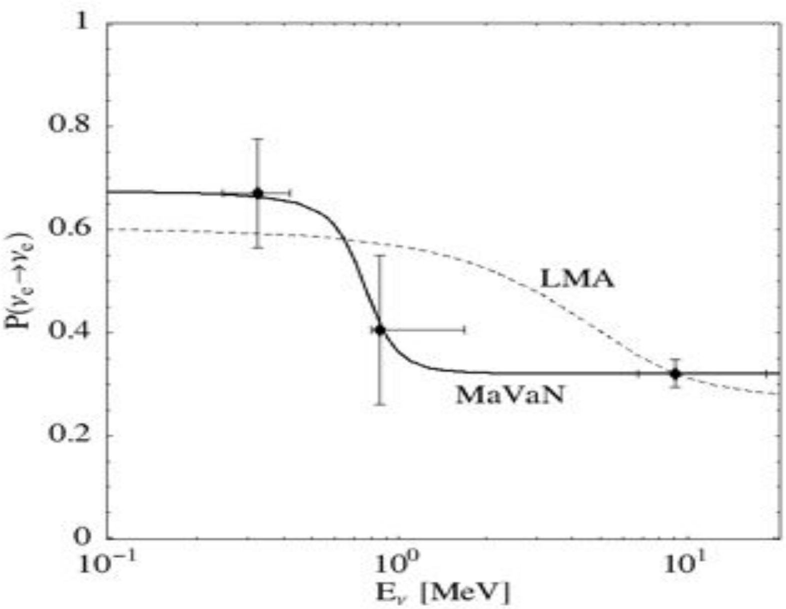
Non-Standard Interactions

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



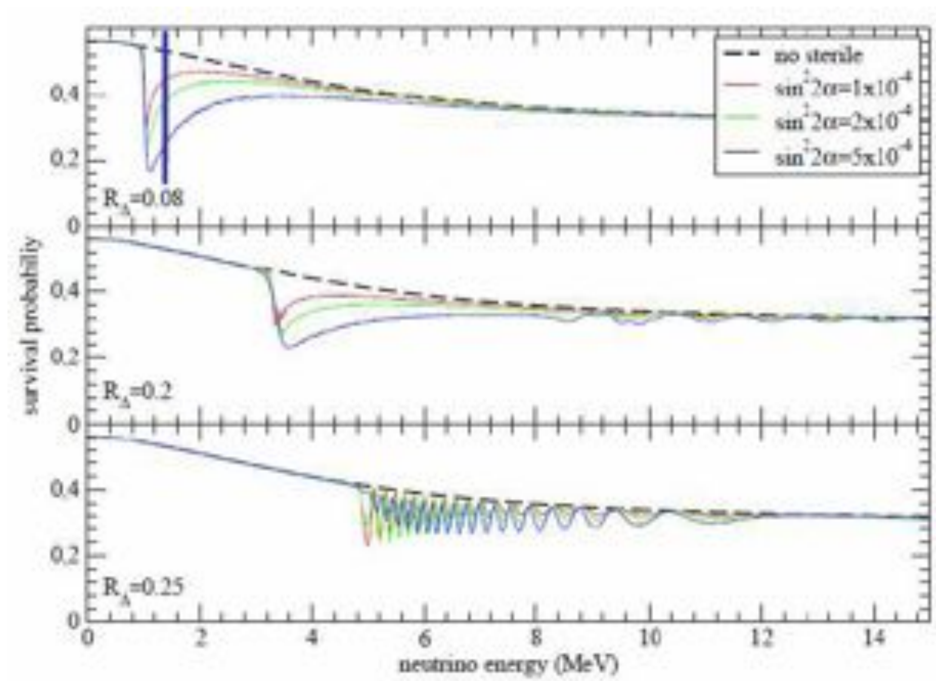
Mass Varying Neutrinos

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

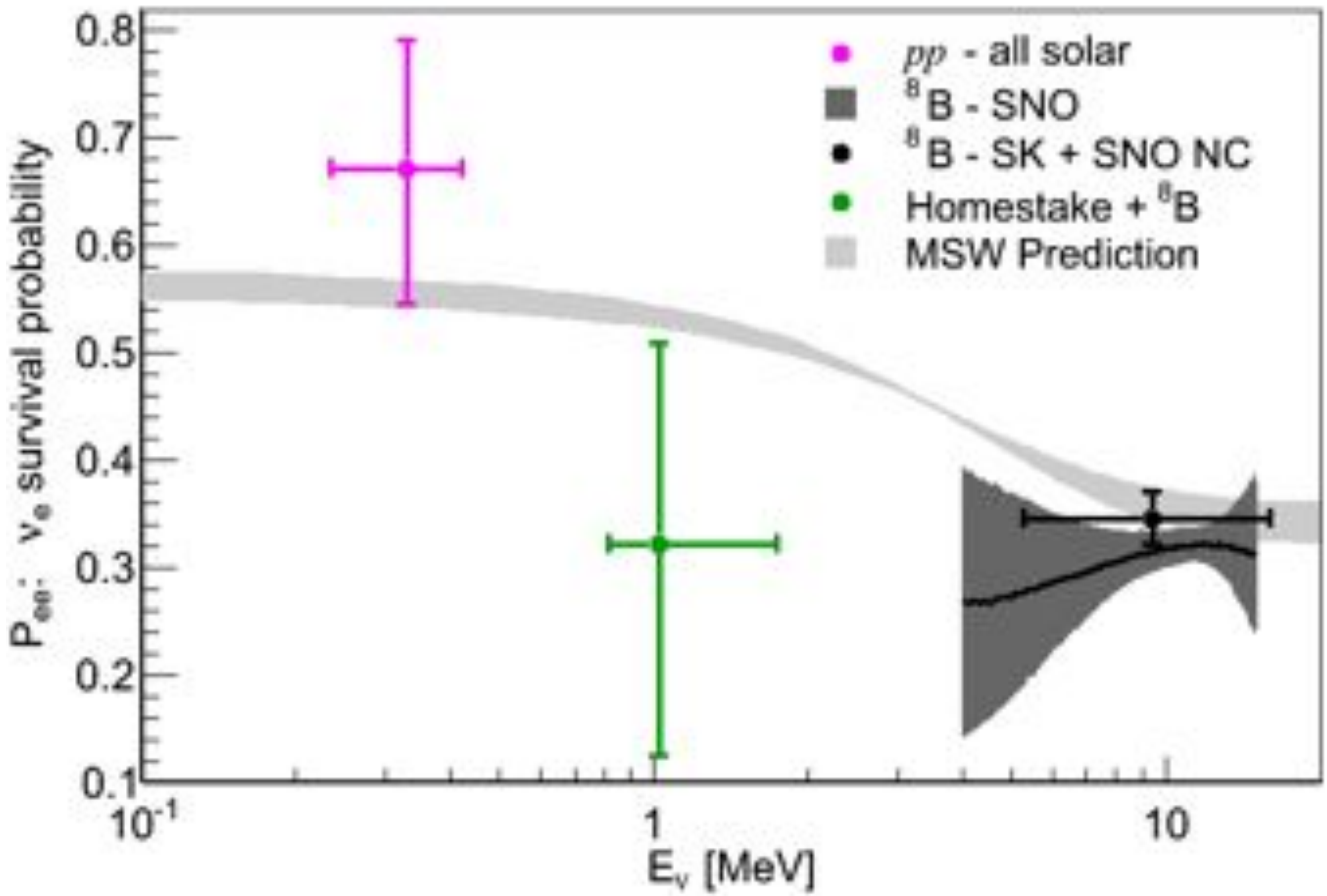


Sterile Neutrinos

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

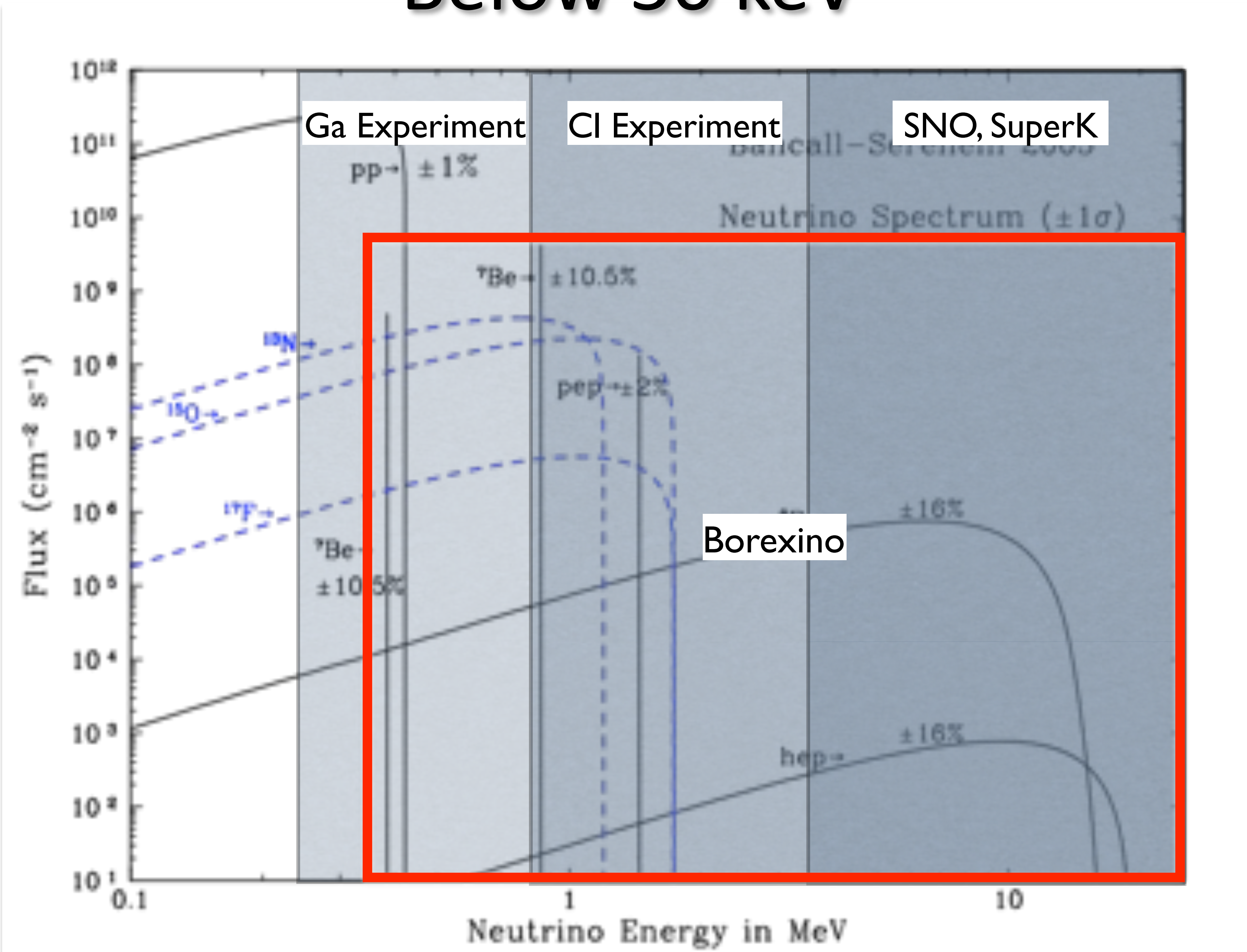


Constraints on Transition Region Without Borexino

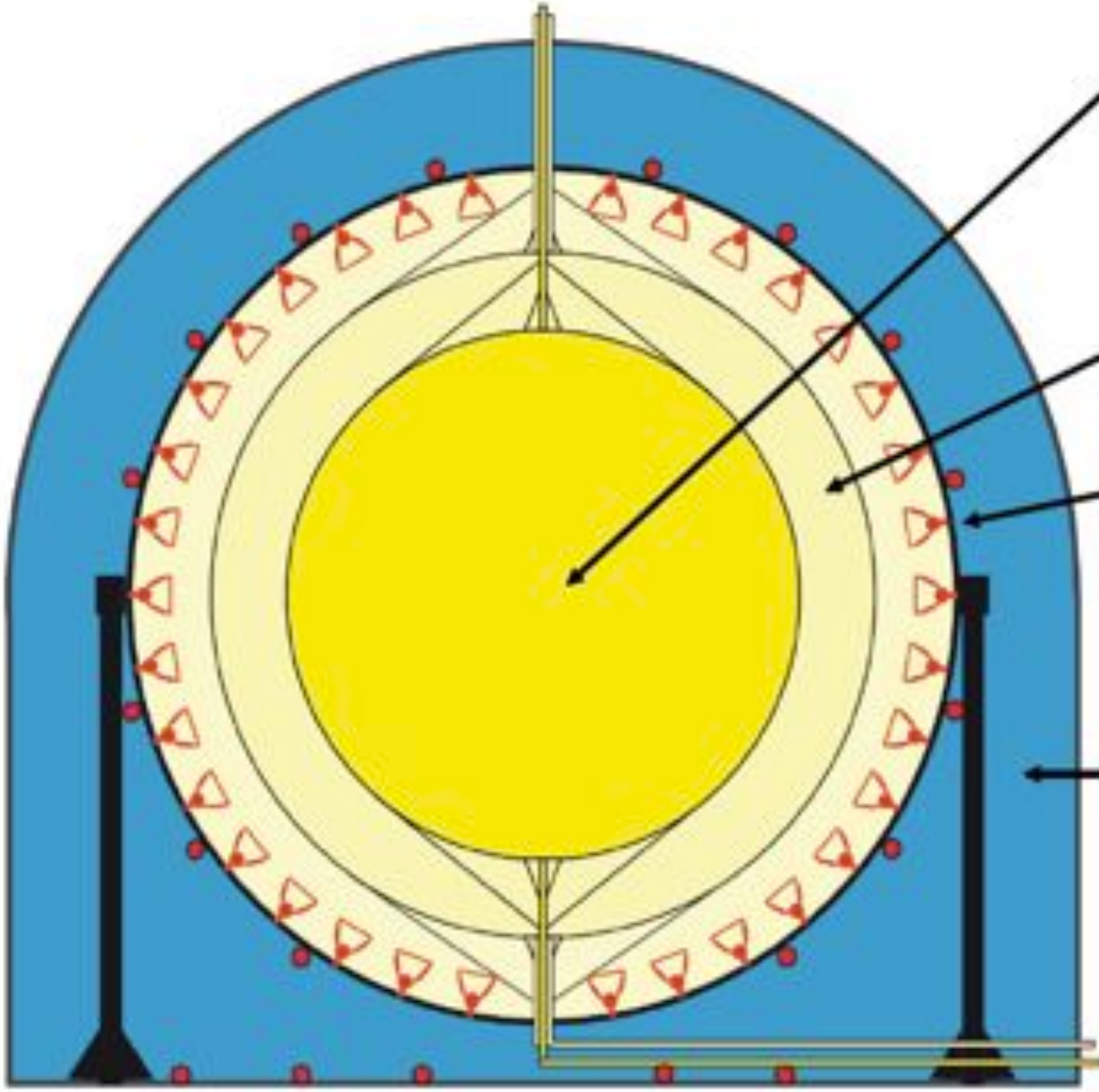


Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. ***Real-time measurements needed in the transition region.***

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

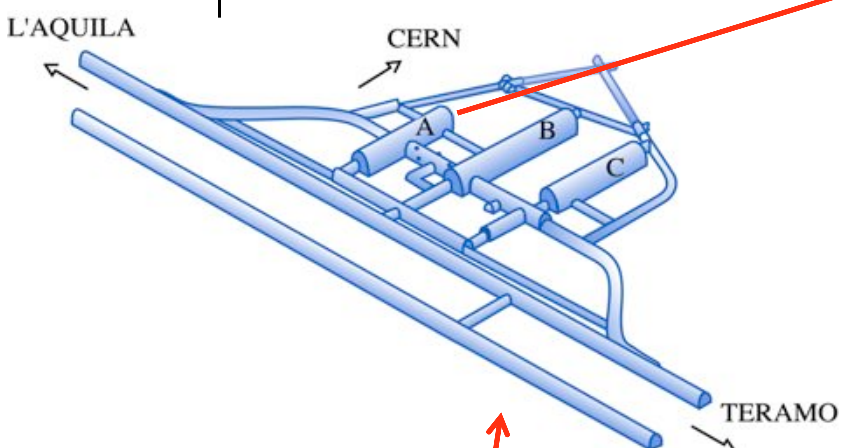
outer water tank
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

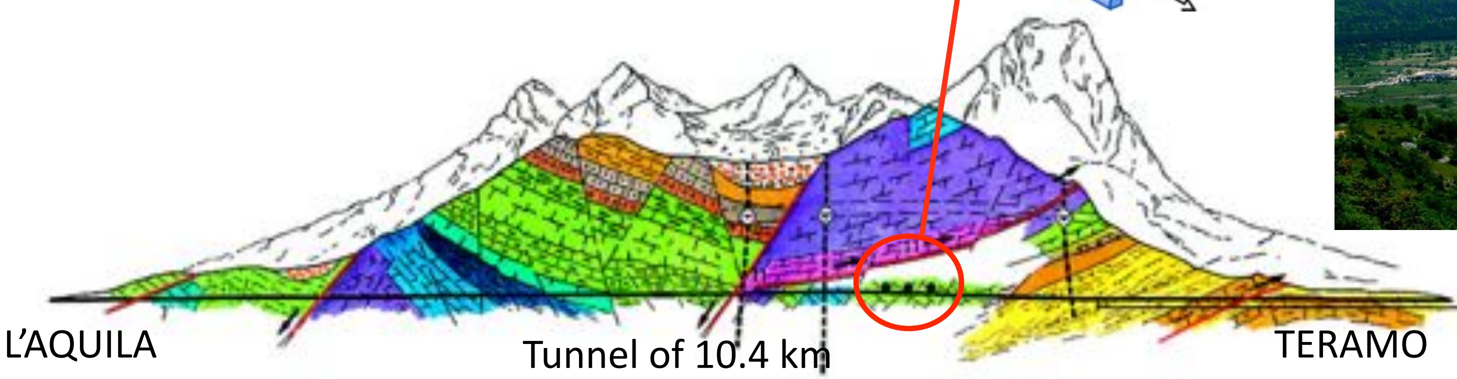
Laboratori Nazionali del Gran Sasso

4600’ to surface

3500 m.w.e.

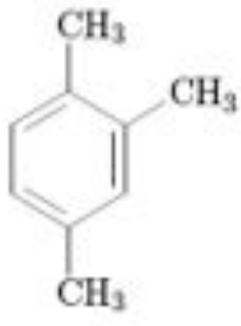
muon flux $1/m^2/hr$



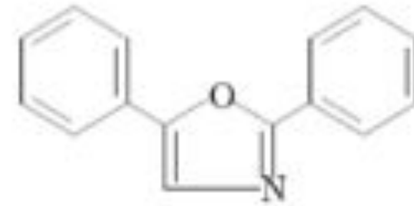


Borexino Collaboration

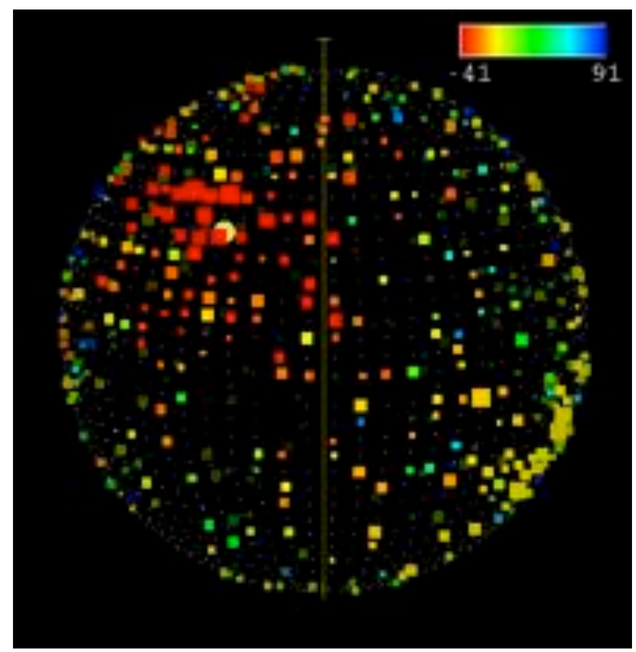
Astroparticle and Cosmology Laboratory – Paris, France
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN e Dipartimento di Fisica dell'Università – Genova, Italy
INFN e Dipartimento di Fisica dell'Università– Milano, Italy
INFN e Dipartimento di Chimica dell'Università – Perugia, Italy
Institut 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

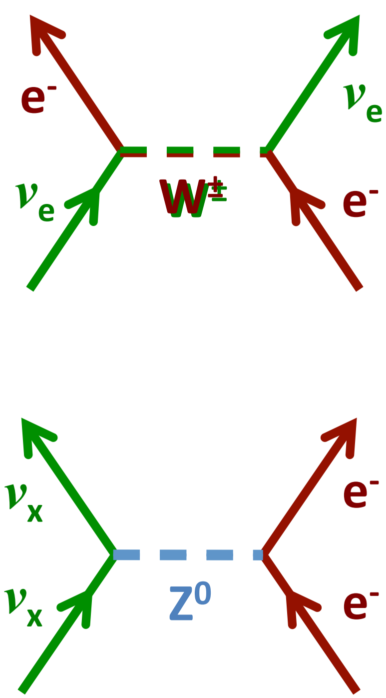


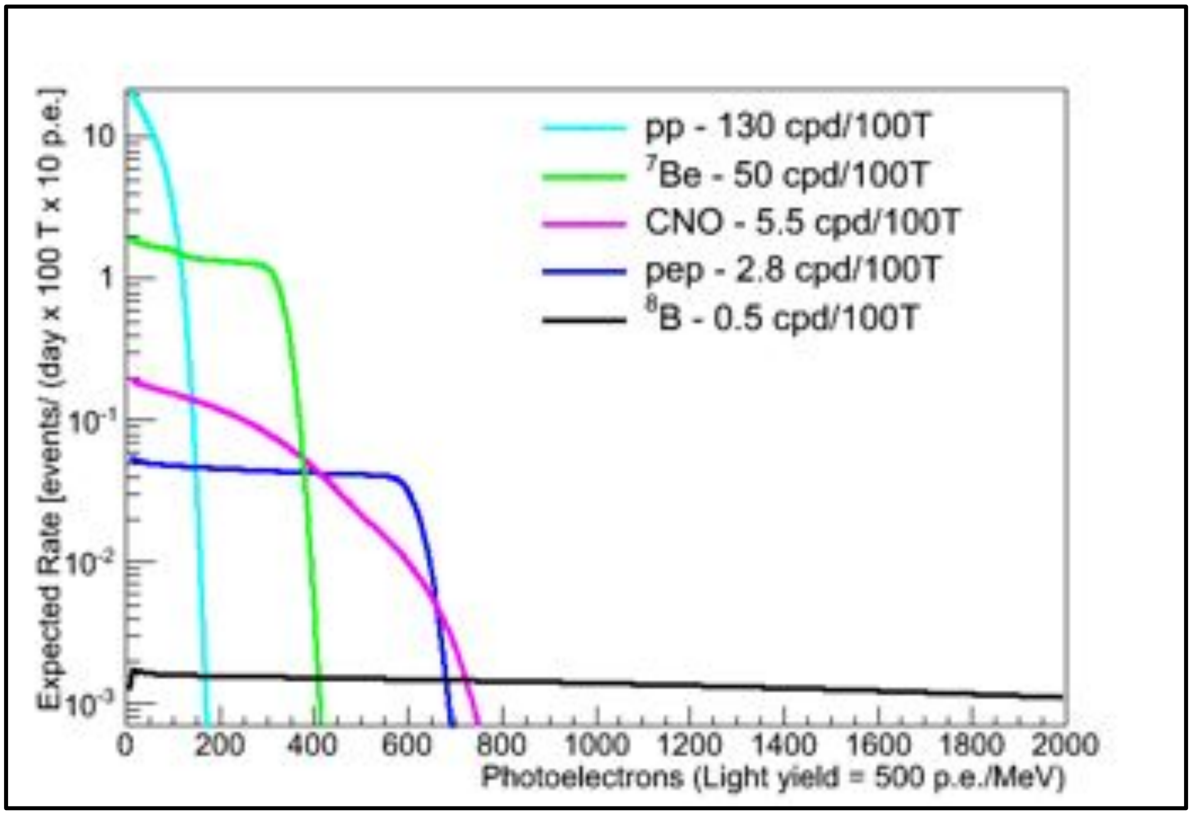
- Organic scintillator (pseudocumene + PPO) produces light when excited by charged particles
- ~12,000 photons/MeV, of which ~500 photons/MeV are detected by the photomultiplier tubes
  - Can detect events depositing < 50 keV
- Calorimetric measurement + pulse shape
  - Event energy from number of photons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



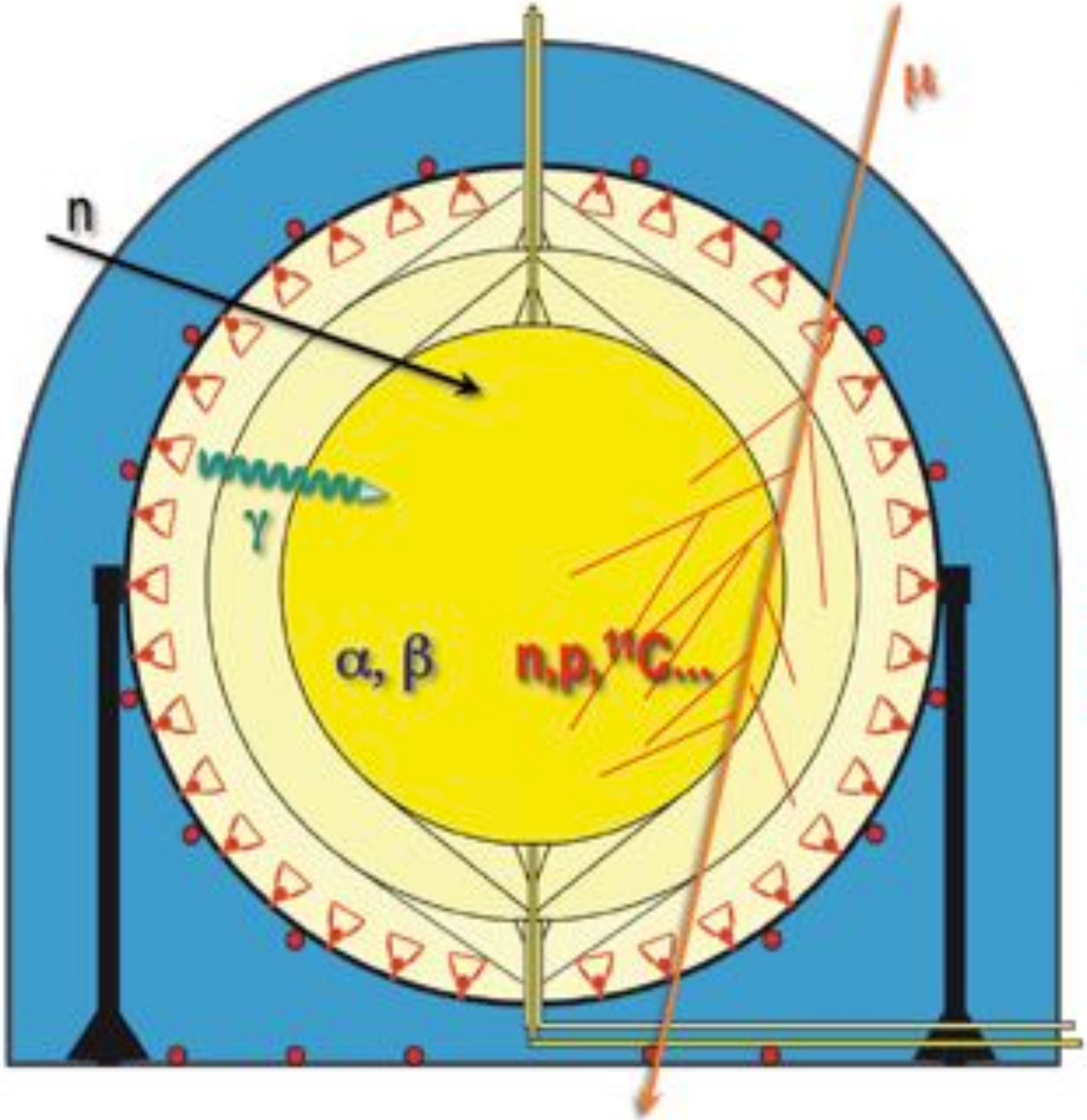
Neutrino Detection

- 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 ...)

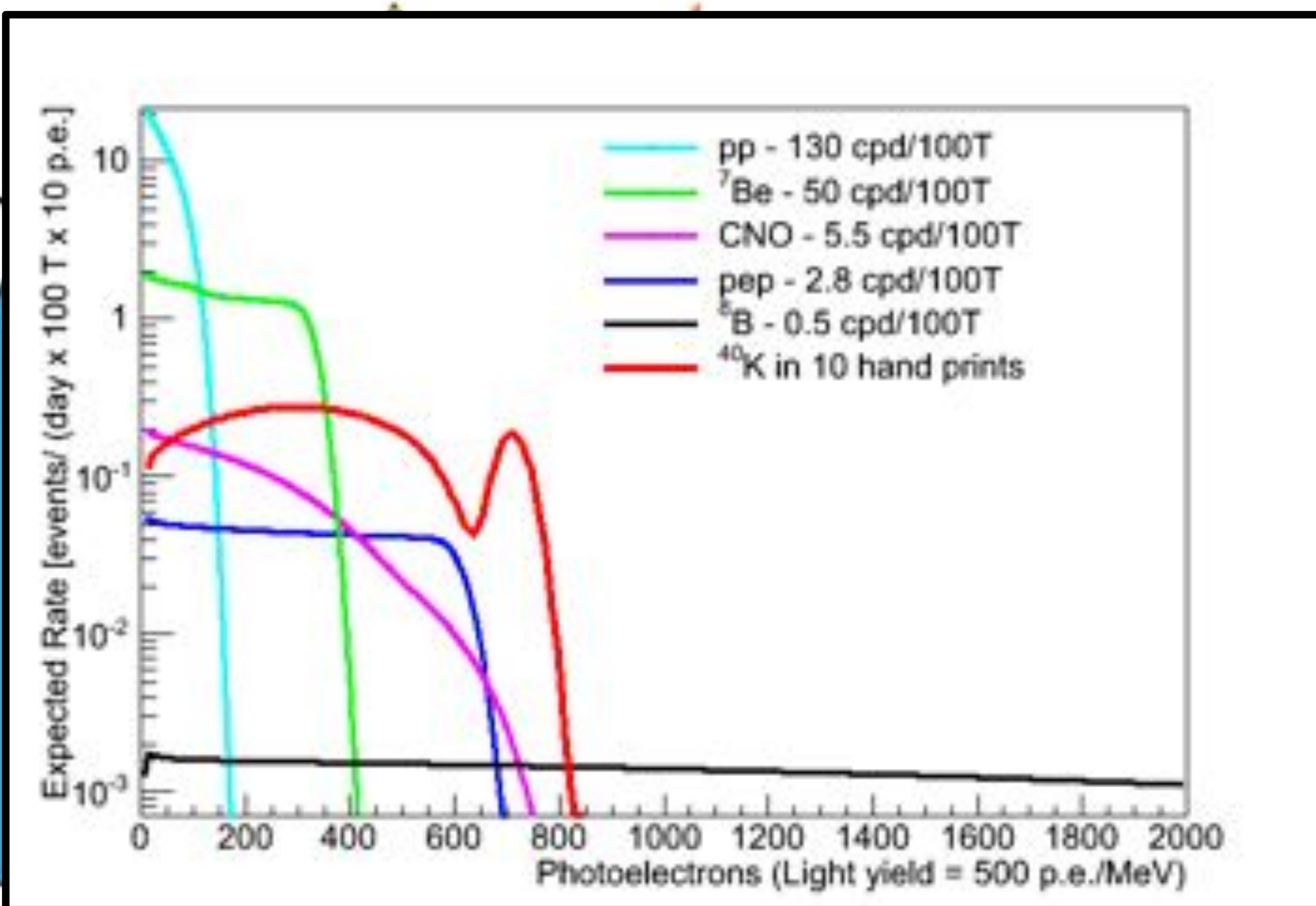
Cosmic Muons

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.

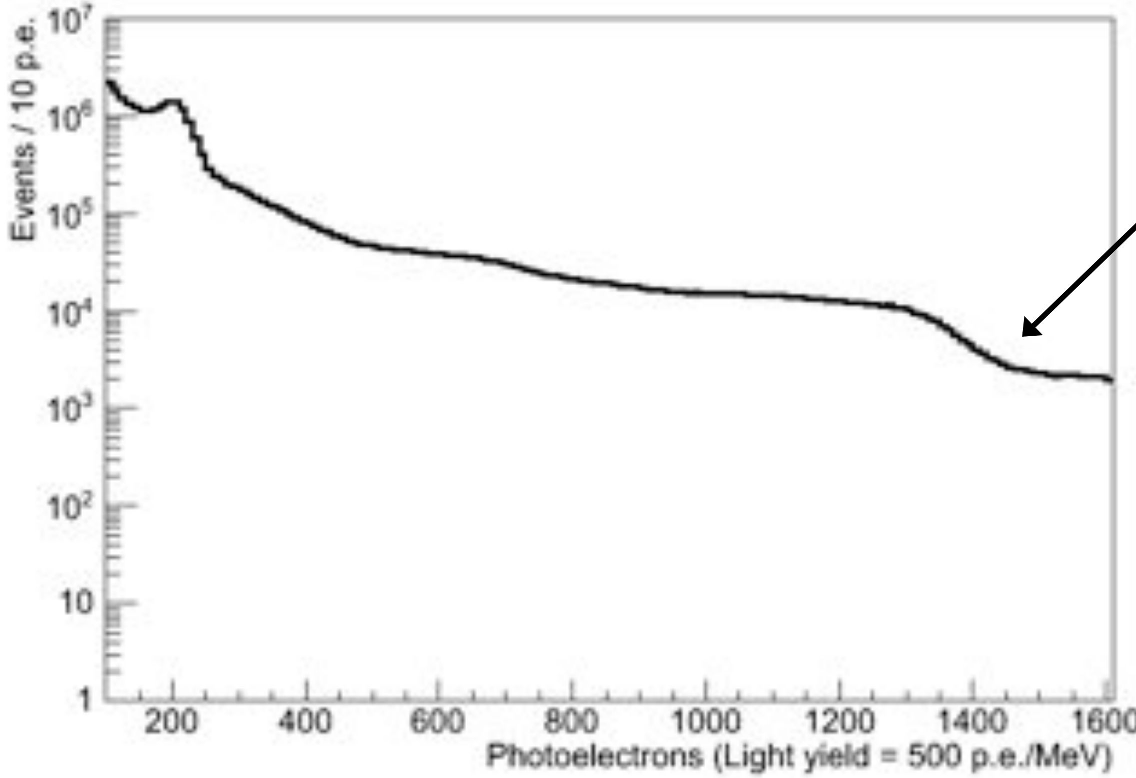
The Counting Test Facility III

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	~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^{-15} g/g	Purification
μ	Cosmic	200 $s^{-1}m^{-2}$	10^{-10} $s^{-1}m^{-2}$	Underground, active veto

Borexino Neutrino Results

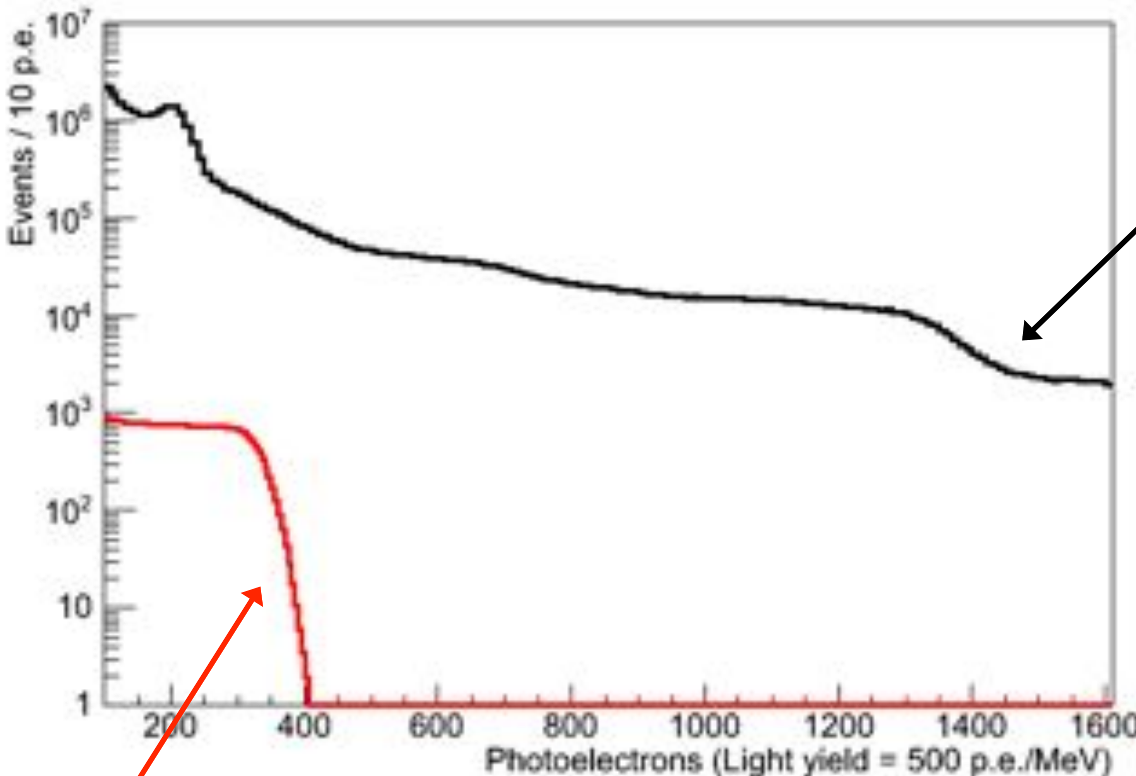
- ^{7}Be Flux
  - (±30%) – Phys. Lett. B **658**:101 (2008).
  - (±10%) – Phys. Rev. Lett. **101**:091302 (2008).
  - (±5%) – Phys. Rev. Lett. **107**:141302 (2011).
- ^{7}Be Day-Night Asymmetry
  - Phys. Lett. B **707**:22 (2012).
- ^{8}B Flux + Spectrum (T_{eff} > 3.0 MeV)
  - Phys. Rev. D **82**:033006 (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).

Borexino Data



All data: 740 live days

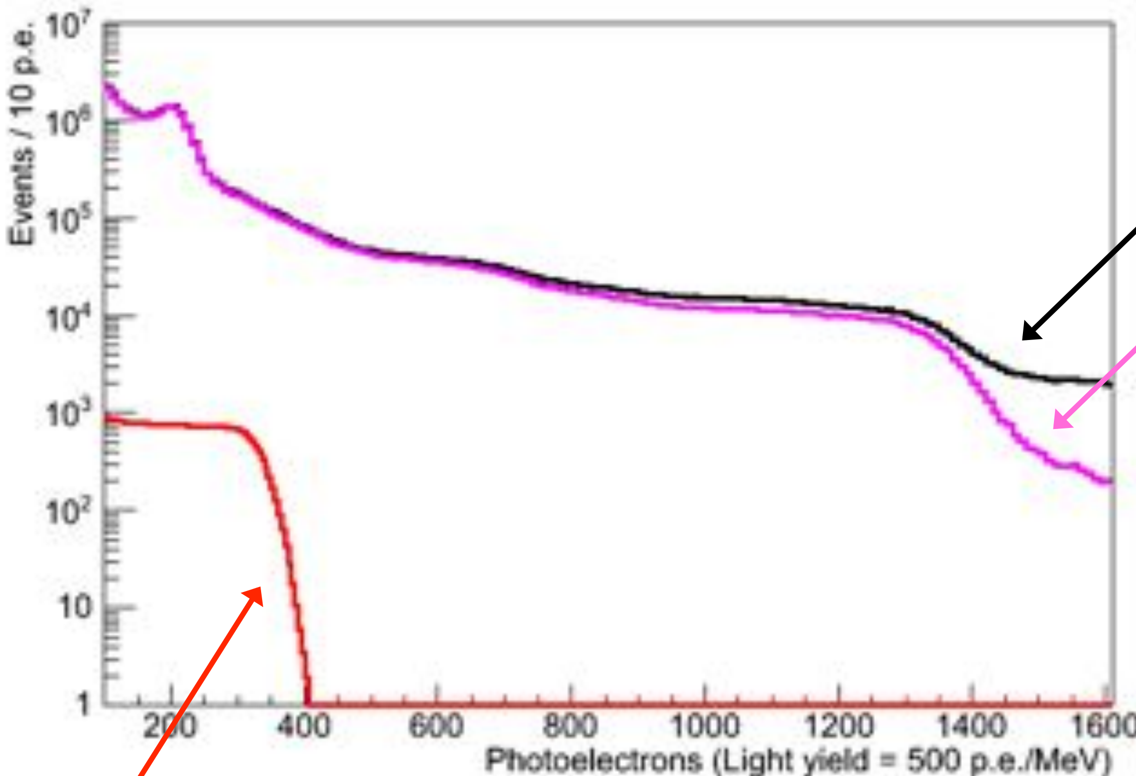
Borexino Data



All data: 740 live days

Expected ^{7}Be signal

Borexino Data

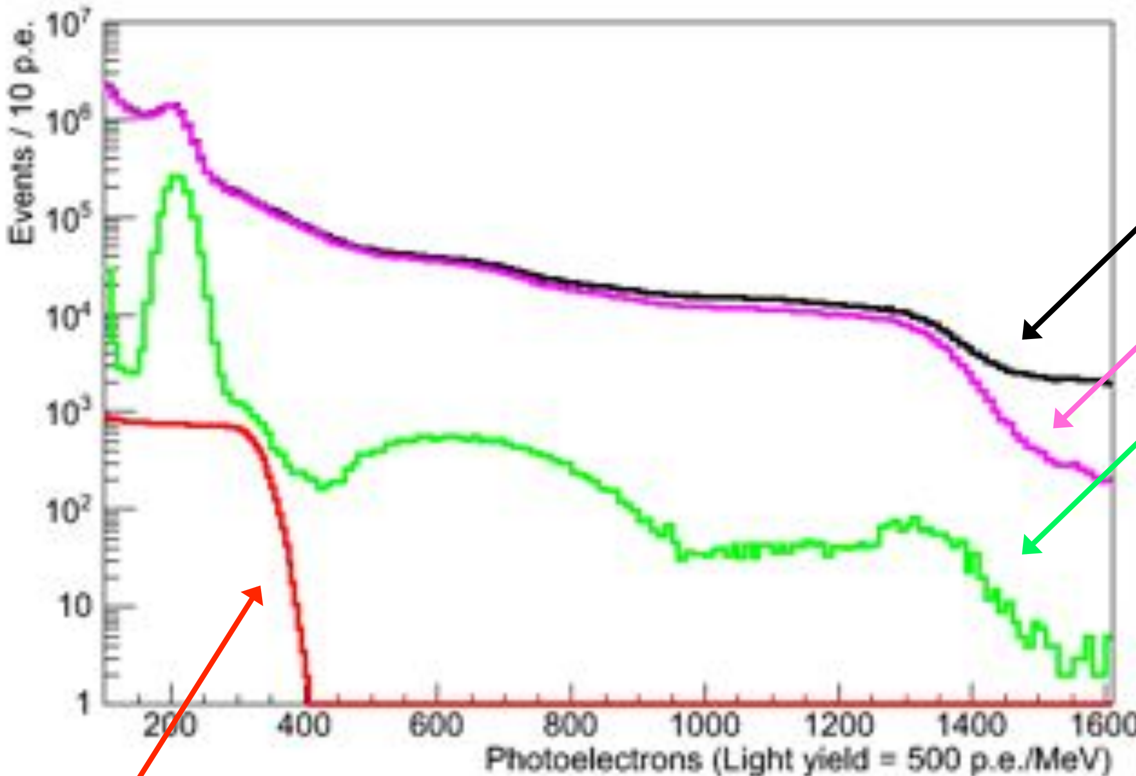


All data: 740 live days

Remove muons + muon followers (2 ms)

Expected ^{7}Be signal

Borexino Data



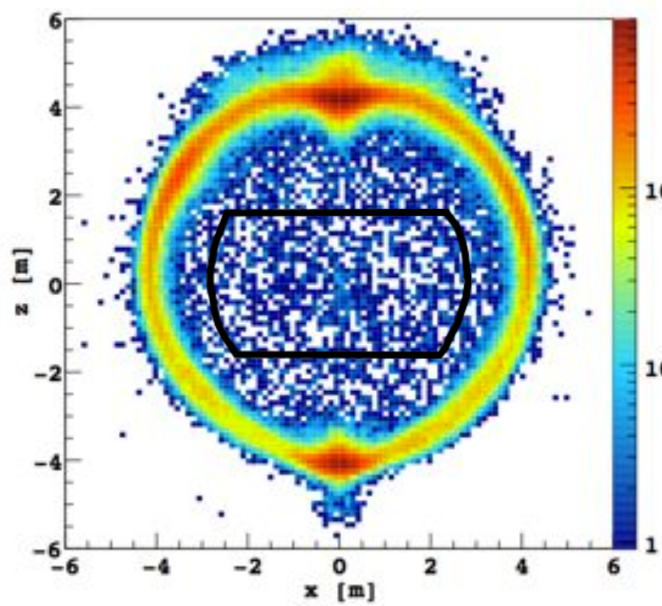
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

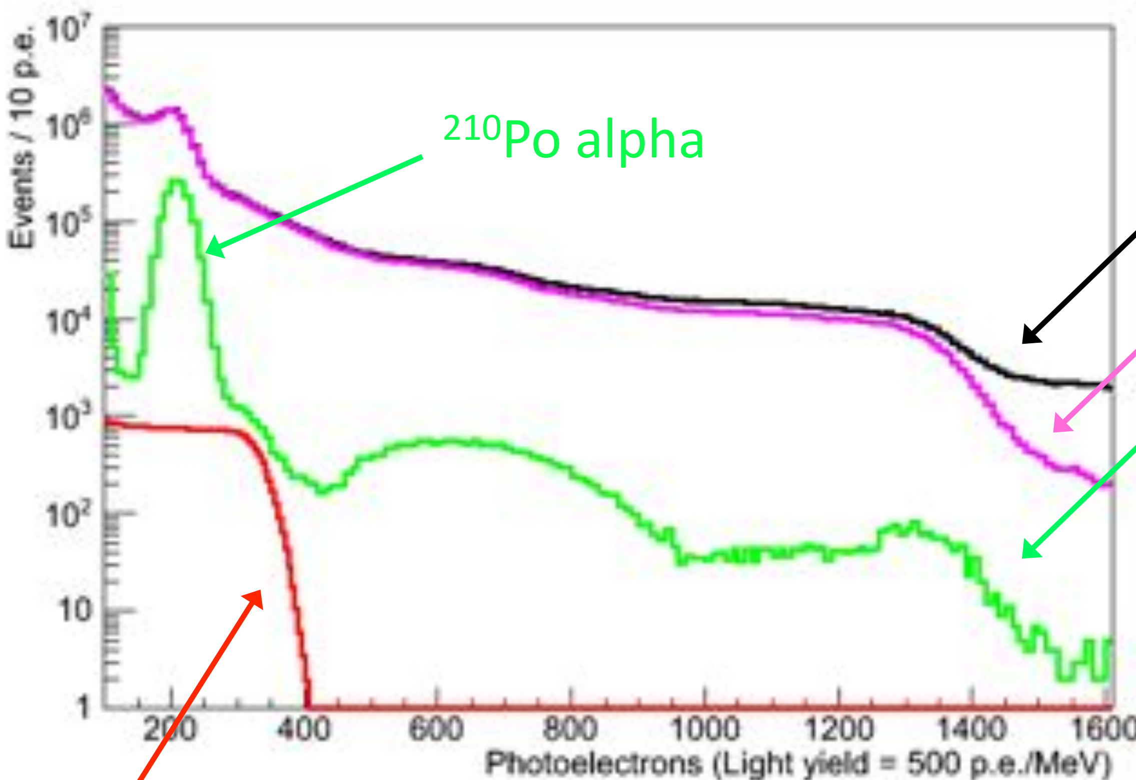
Expected ^{7}Be signal

R < 3.02m
|z| < 1.67m



Fiducial mass = 75.6 tonnes

Borexino Data



^{210}Po alpha

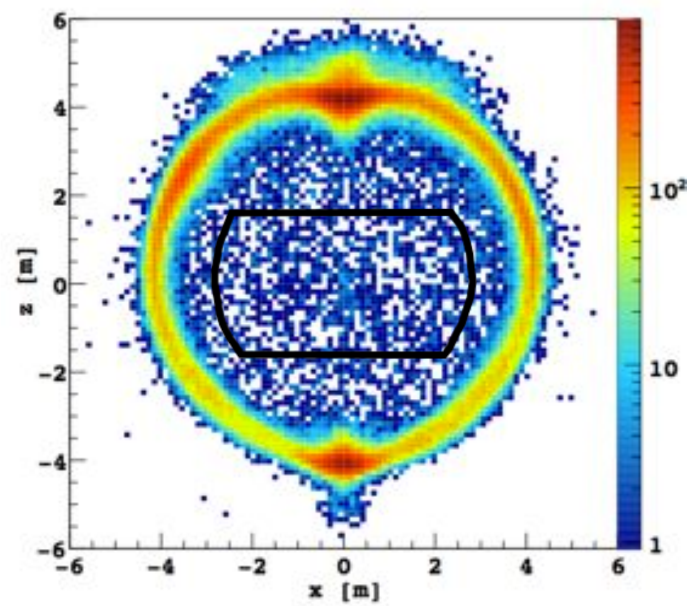
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

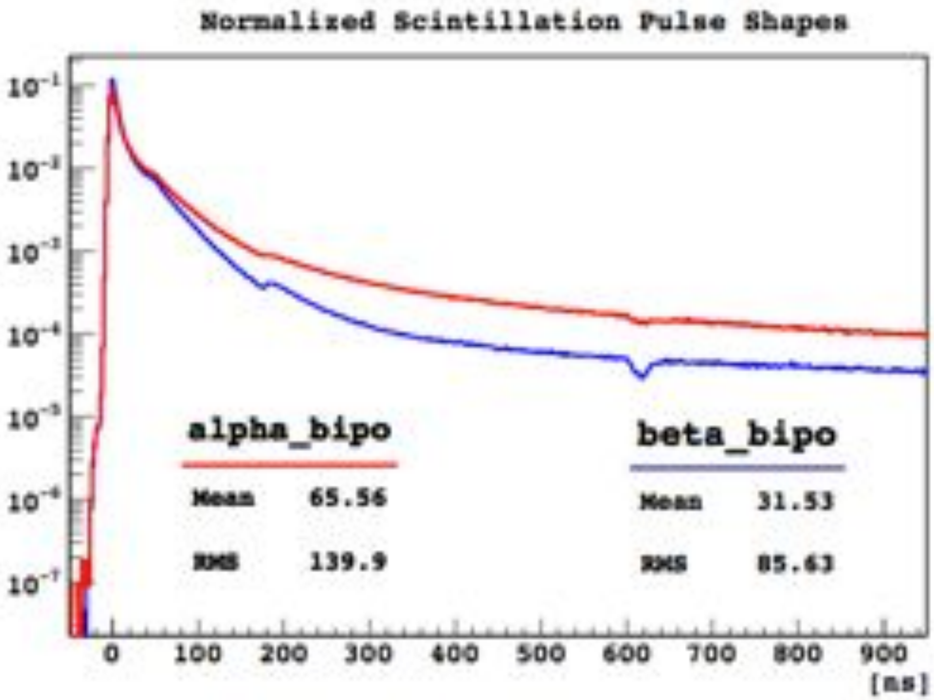
Expected ^{7}Be signal

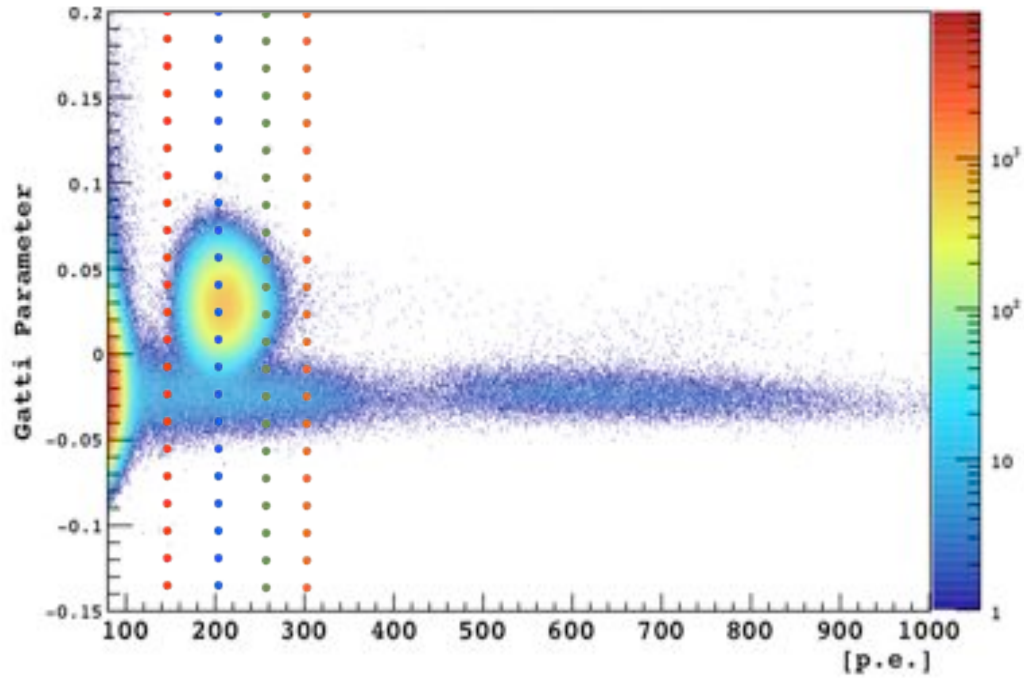
R < 3.02m
|z| < 1.67m



Fiducial mass = 75.6 tonnes

Alpha Pulse Shape Discrimination



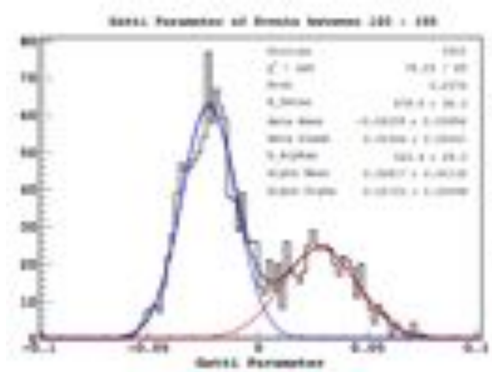


$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

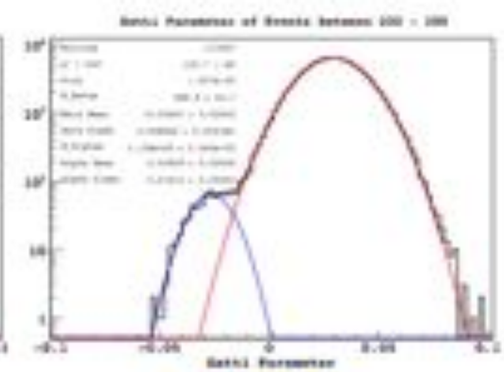
$$w[t] \equiv \frac{r_\alpha[t] - r_\beta[t]}{r_\alpha[t] + r_\beta[t]}$$

$e[t]$: Event Time Profile

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

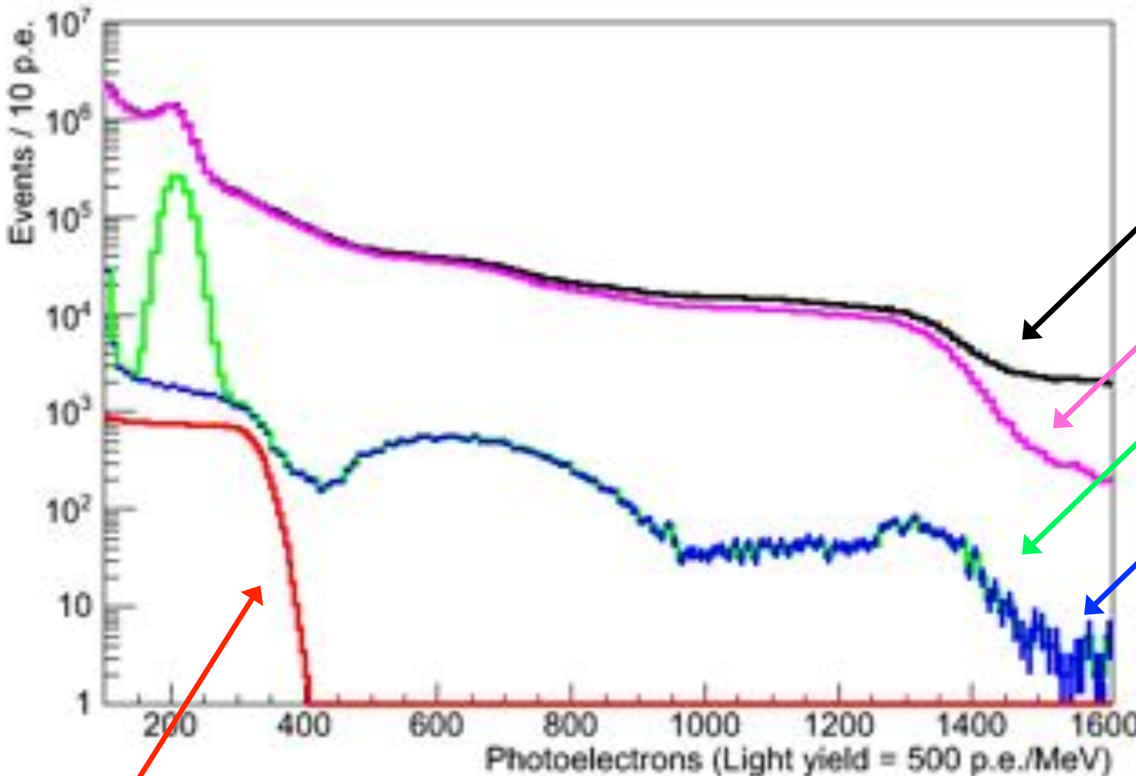


150 p.e.



200 p.e.

Borexino Data



All data: 740 live days

Remove muons + followers

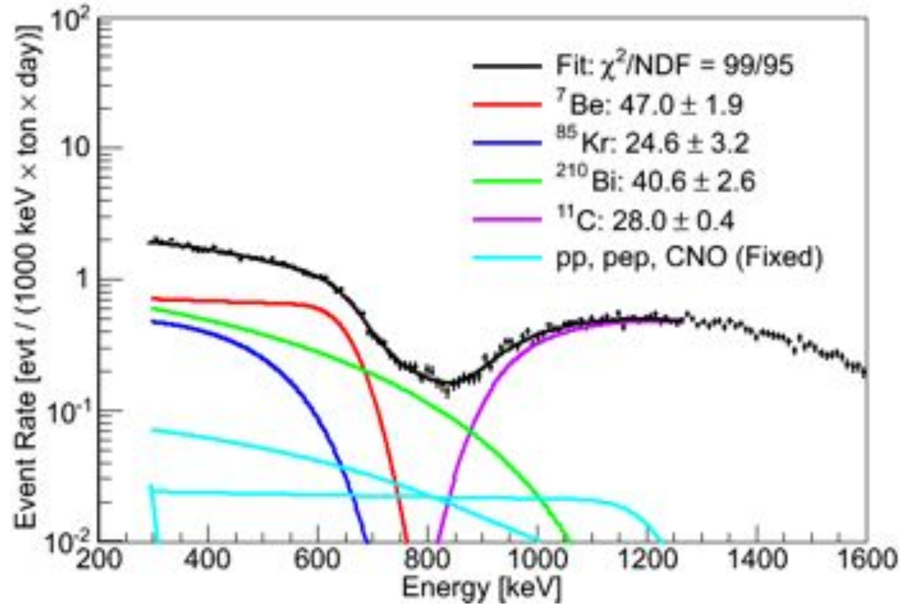
Fiducial Volume + high level

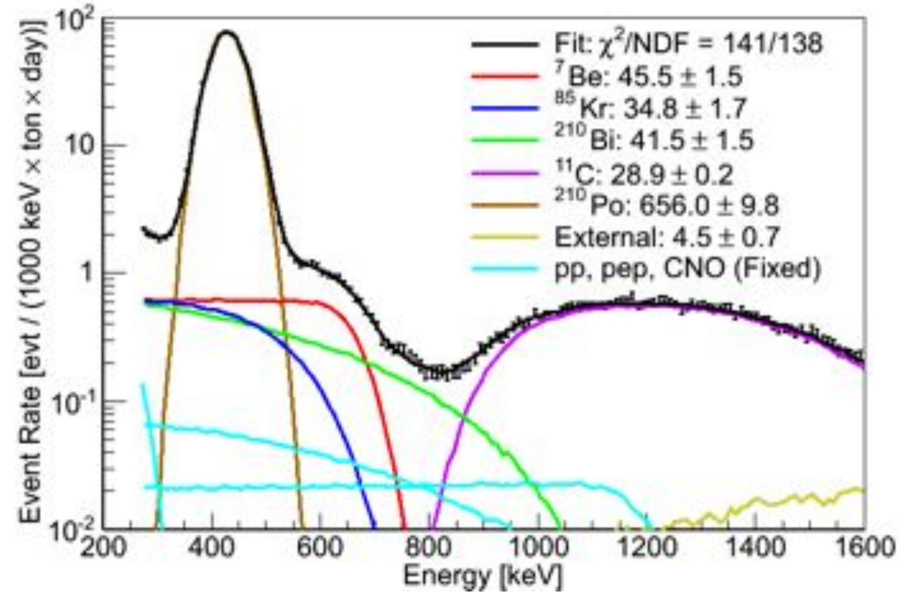
Statistically subtract alphas

Expected ^{7}Be signal

^{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)

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

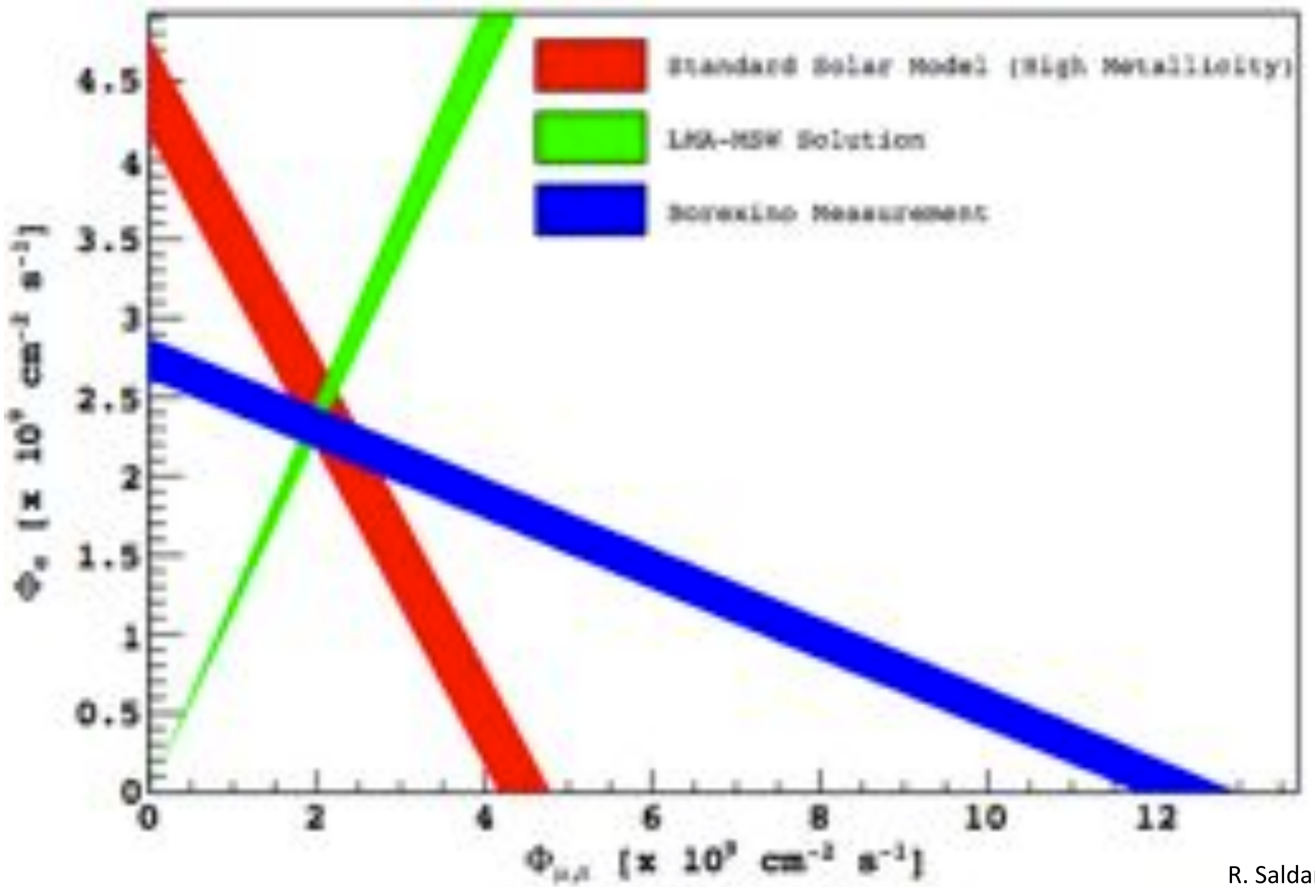
Systematic Uncertainties	
Trigger Efficiency	0.1%
Scintillator Density	0.05%
Livetime	0.04%
Cut Sacrifice	0.1%
Fiducial Mass	$^{+0.5}_{-1.3}$%
Energy Scale	2.7%
Fit Methods	2.0%
Total	**$^{+3.4}_{-3.6}$%**

Precision ^{7}Be Flux Result

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

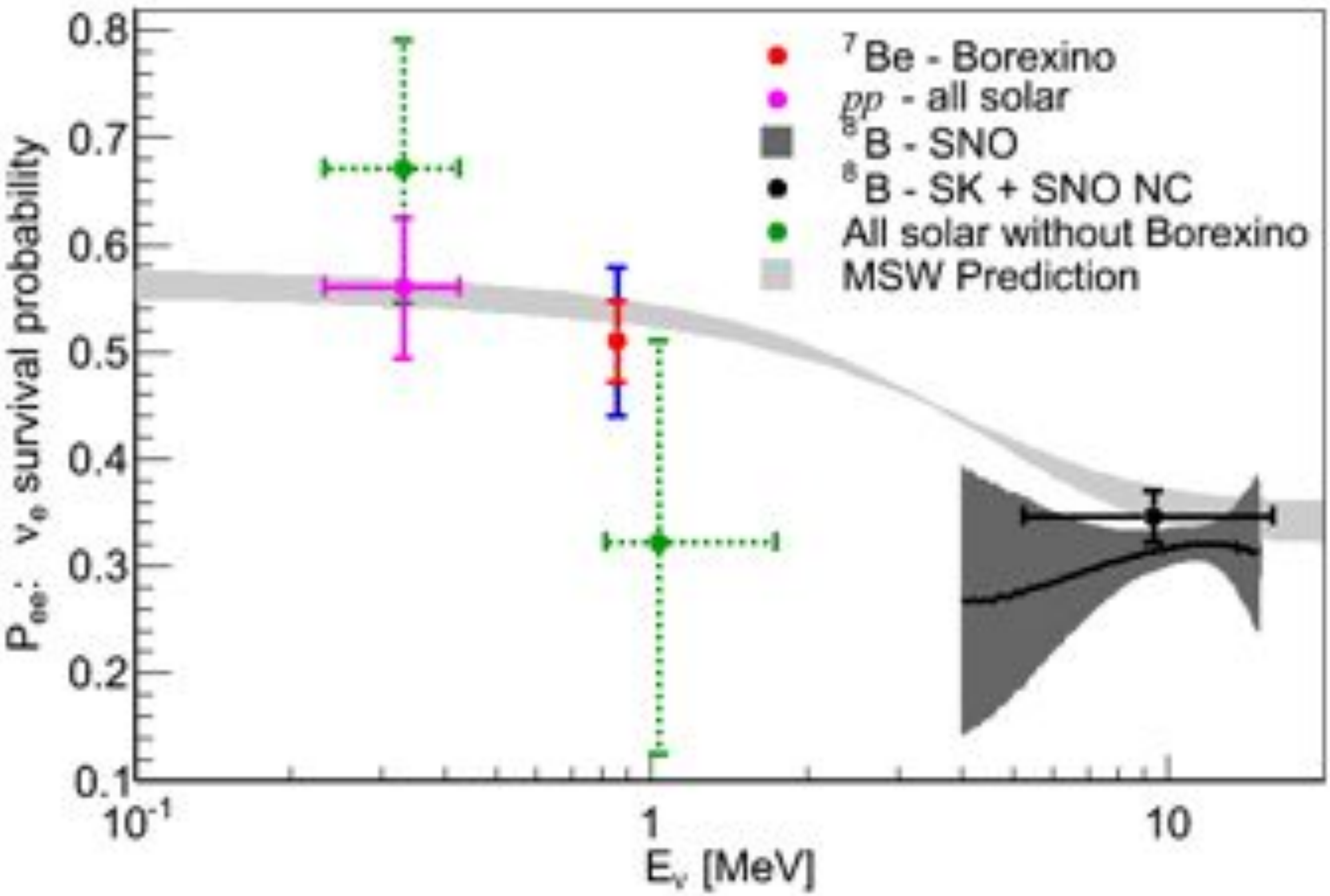
Borexino 862 keV ^{7}Be counting rate: $46.0 \pm 1.5_{stat}\,{}^{+1.5}_{-1.6}{}_{sys}$ /(d 100T)

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



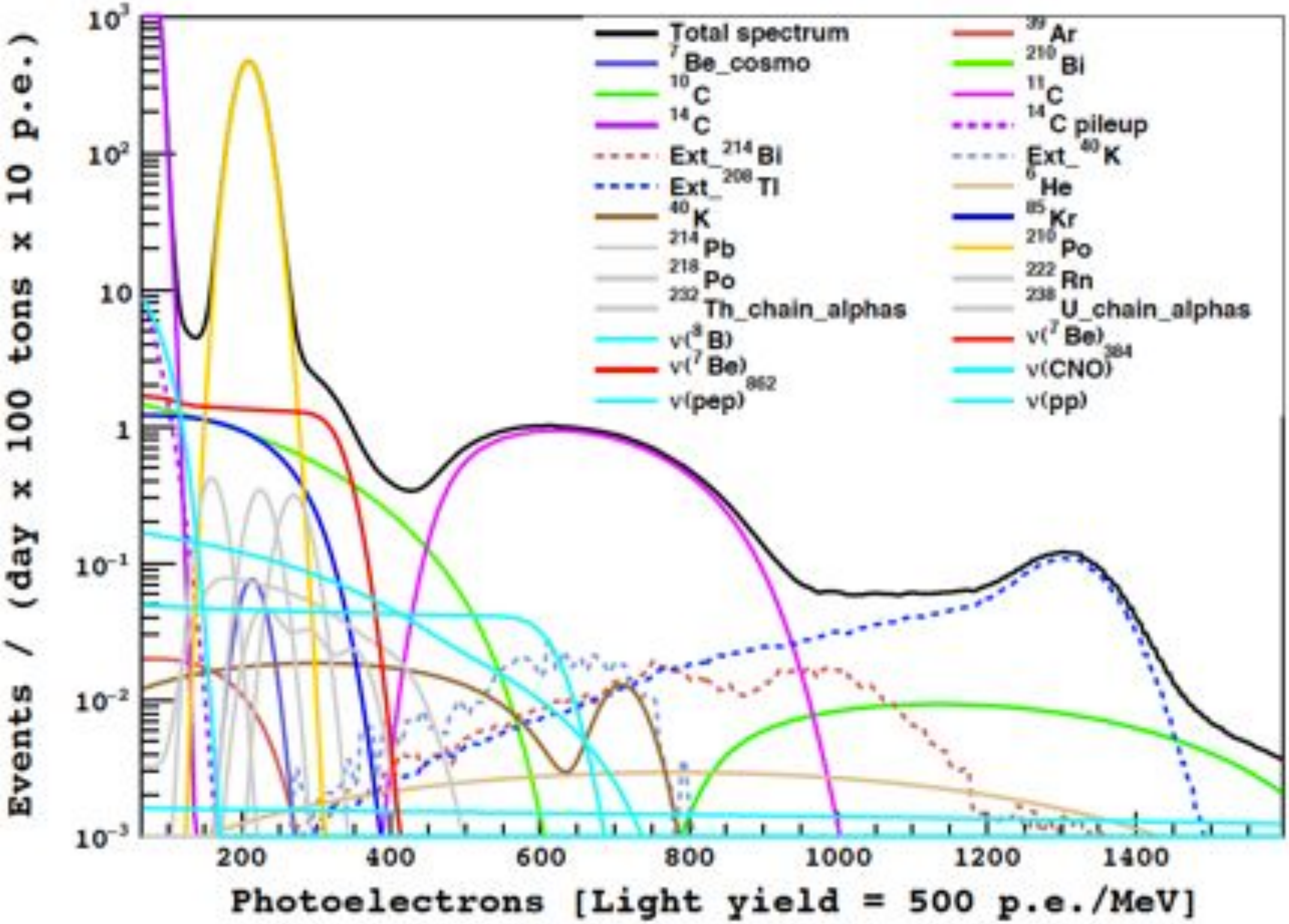
R. Saldanha, Ph.D. Thesis, Princeton (2011)

Precision ^{7}Be Flux Result

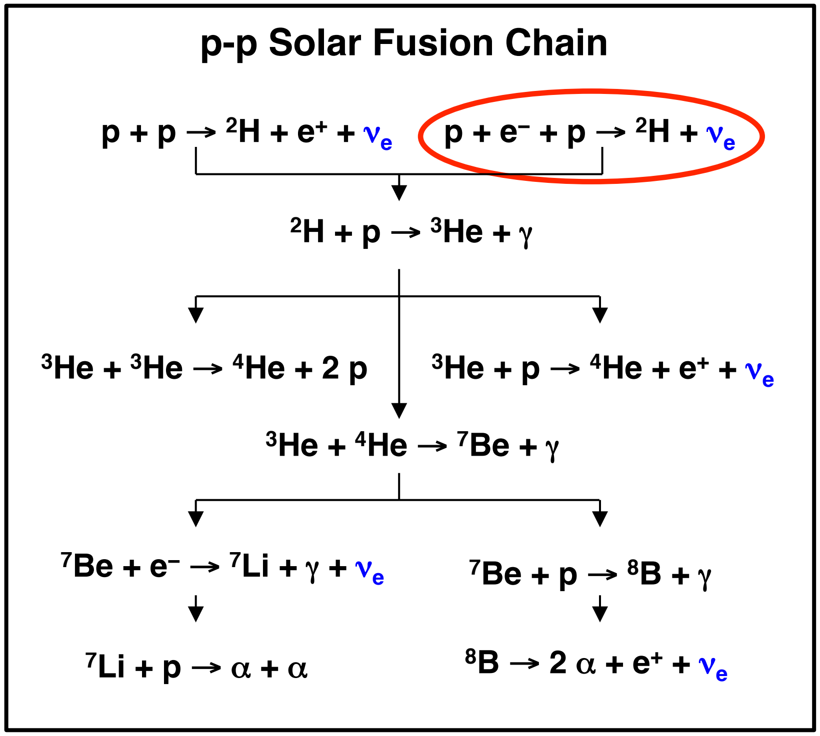


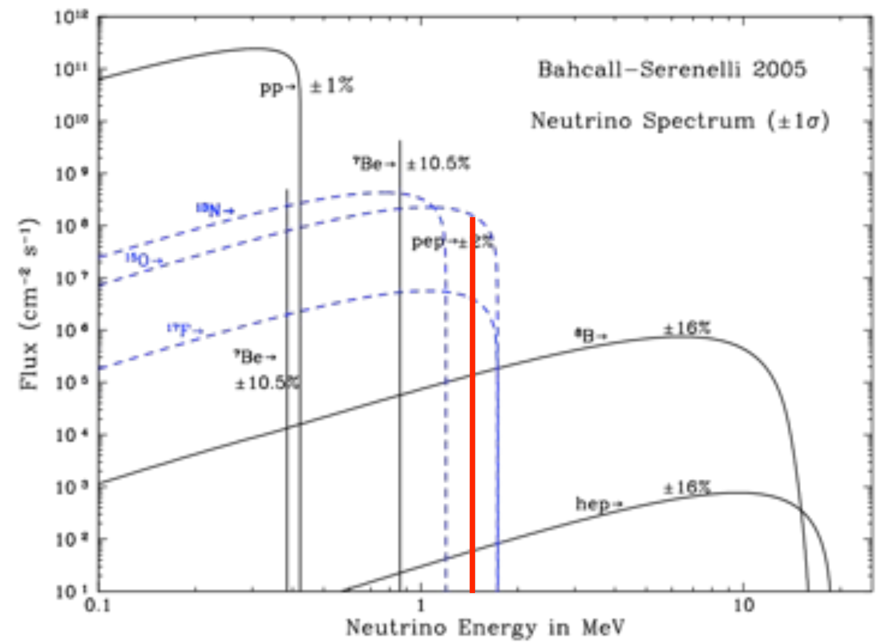
Significantly improved constraint on low energy P_{ee}.

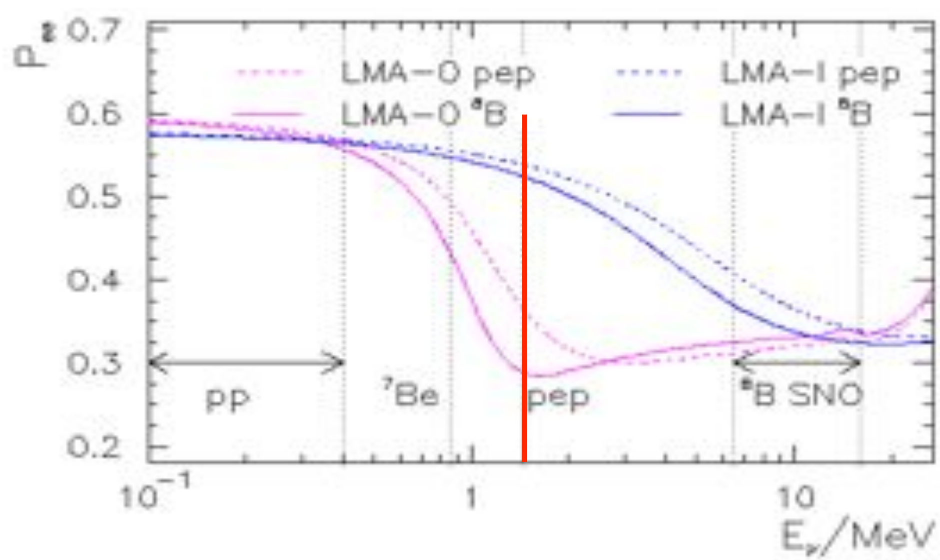
“Into the Muck”: *pep* and CNO Neutrinos



pep Neutrinos





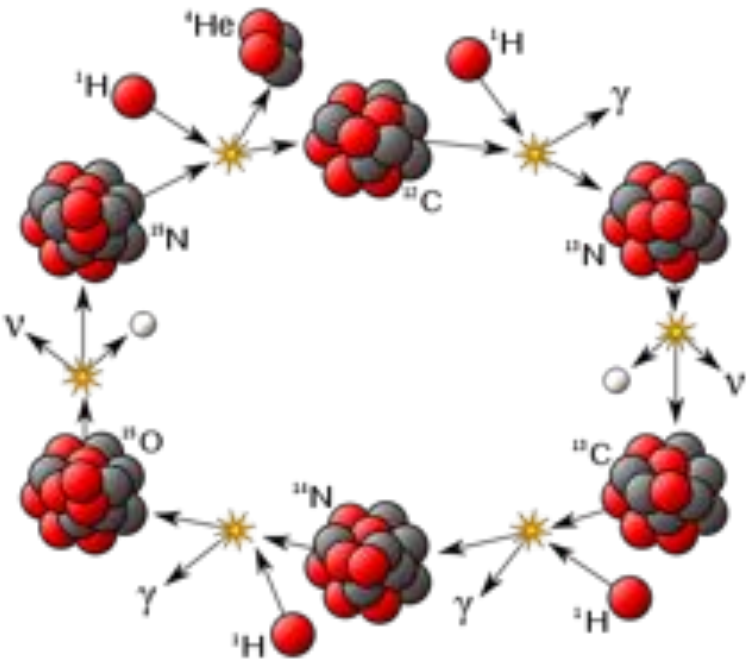


First direct look at solar p-p fusion.

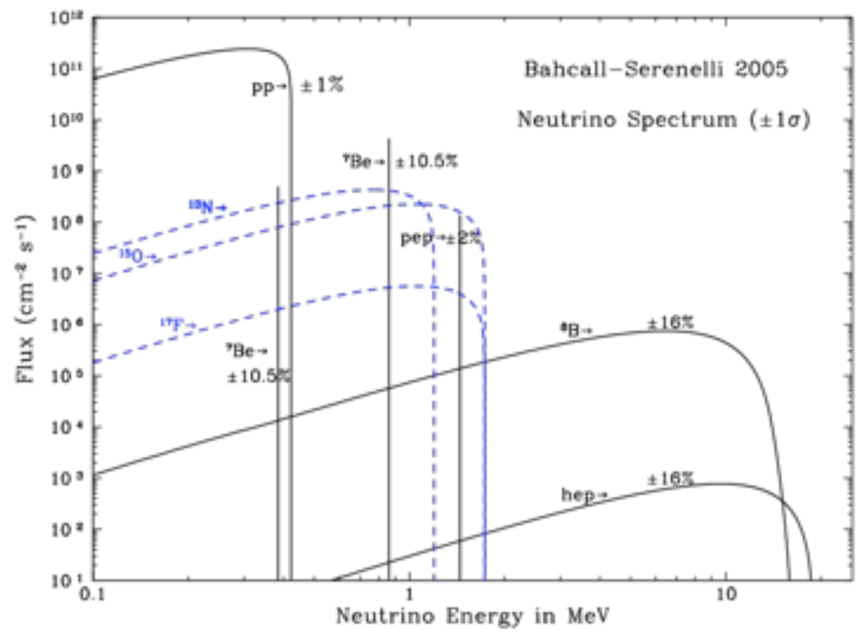
Precision test of Standard Solar Model and oscillations.

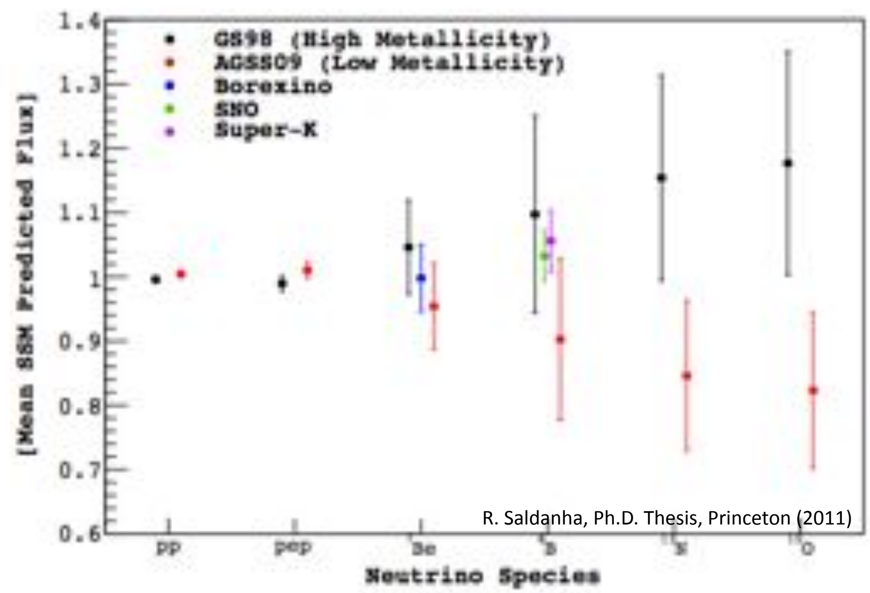
Ideal energy to probe transition region.

CNO Neutrinos



Wikimedia.org



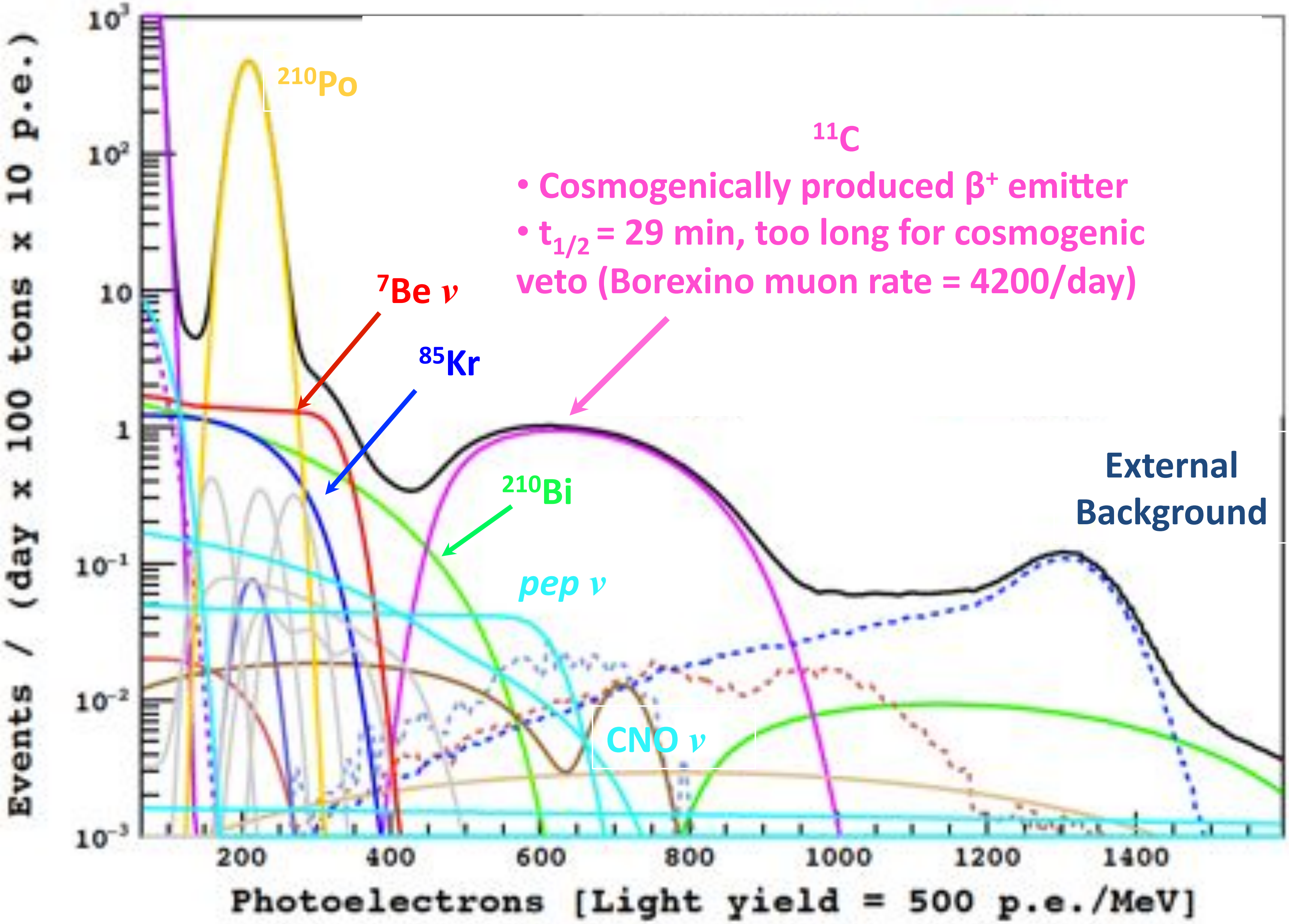


R. Saldanha, Ph.D. Thesis, Princeton (2011)

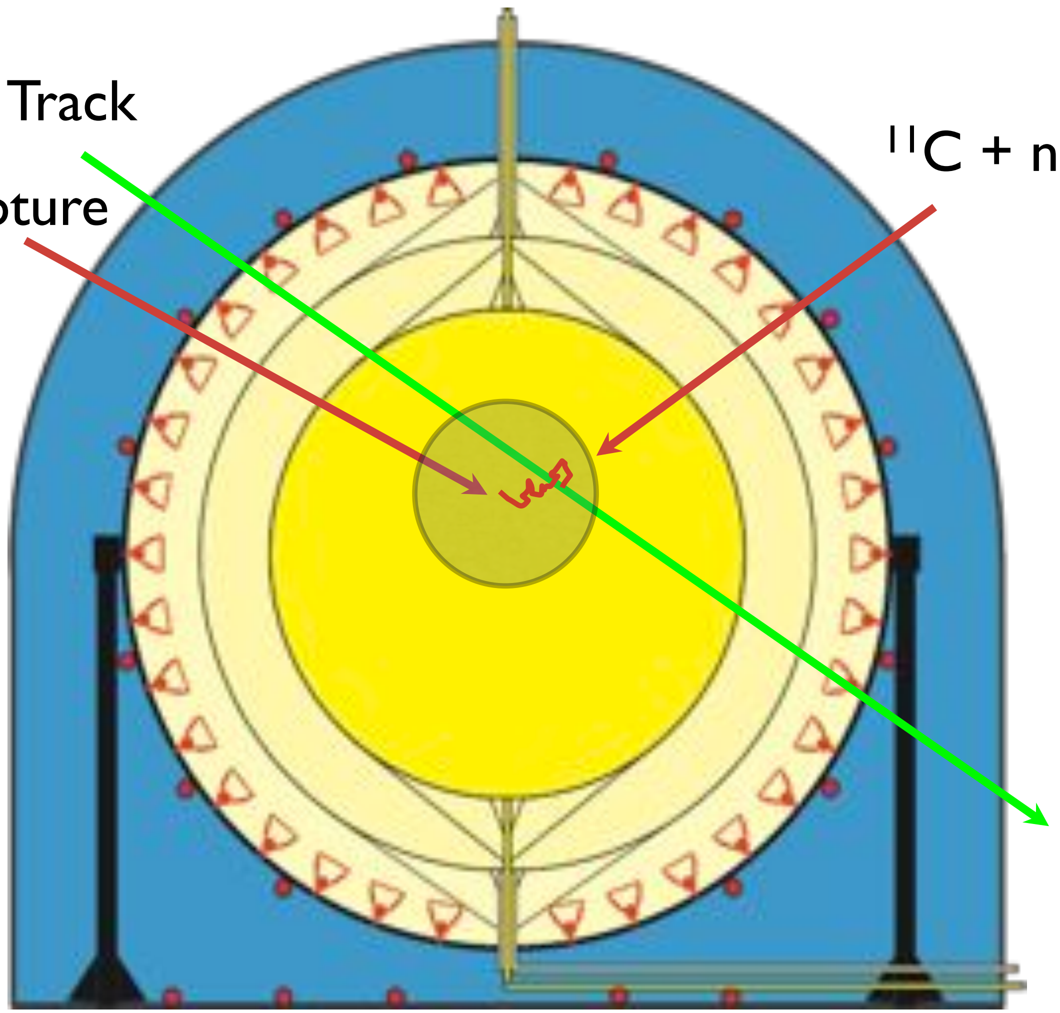
First direct evidence for CNO cycle.

Measure solar metallicity.

^{11}C Suppression



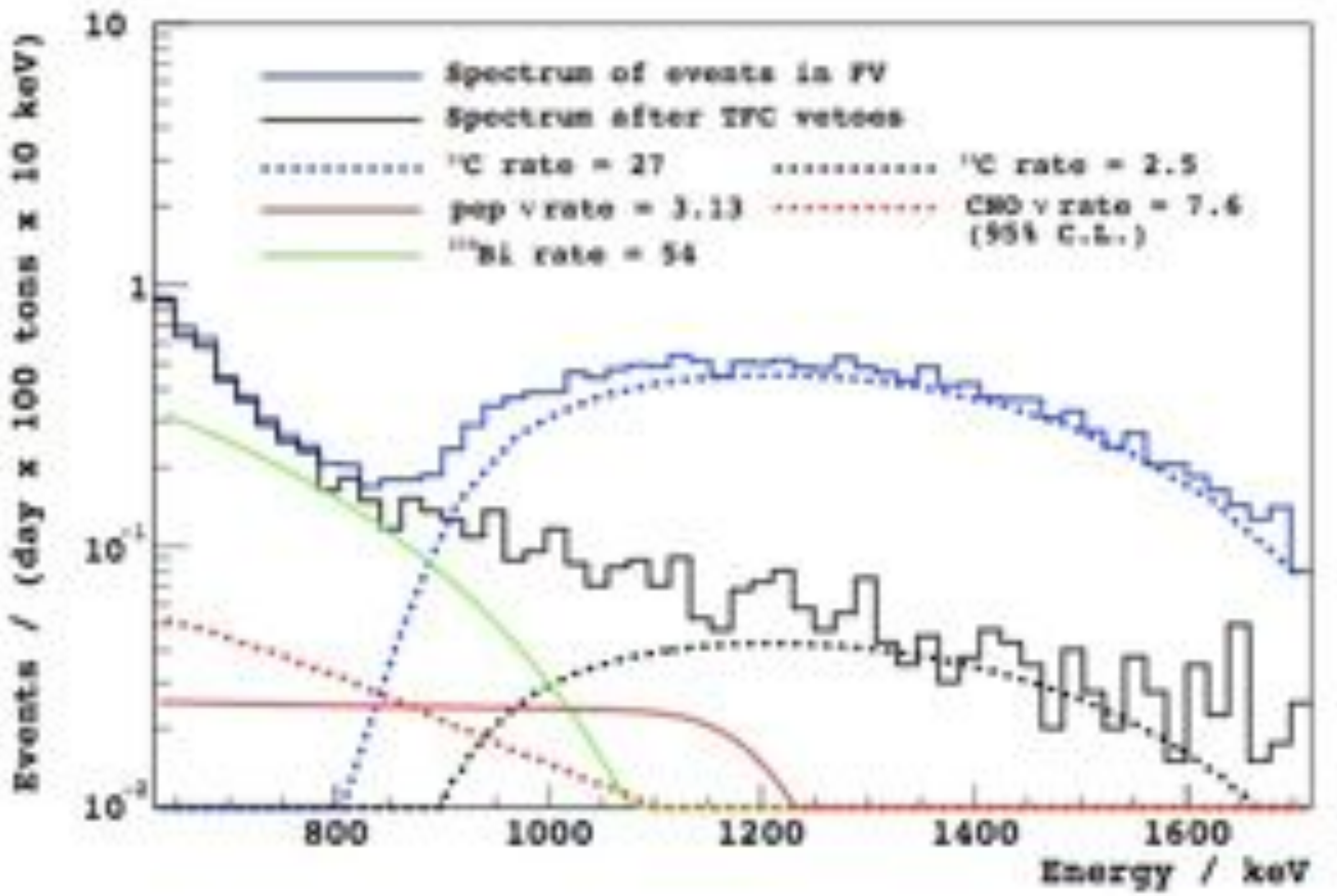
Three-Fold Coincidence



- 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.

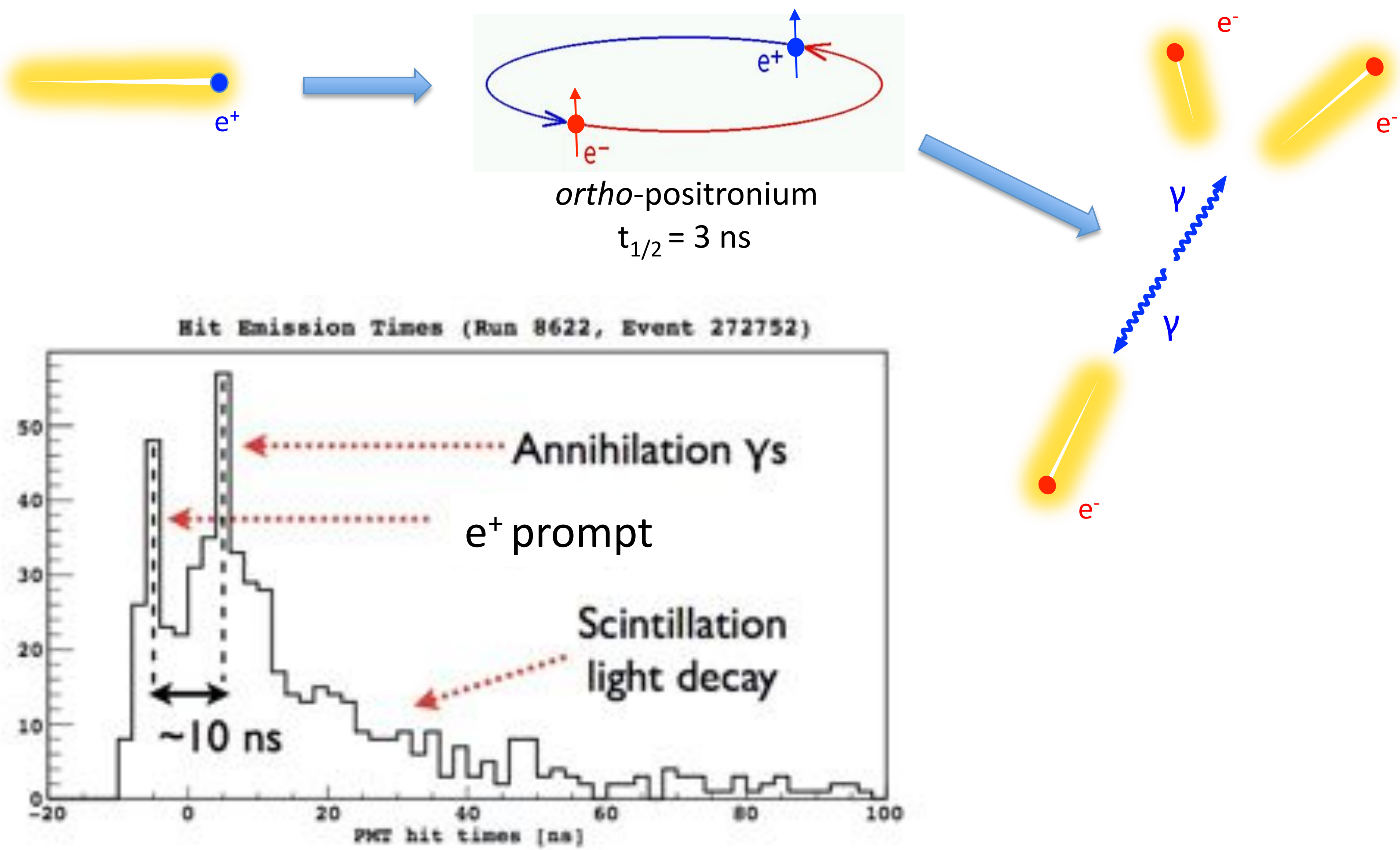
Three-Fold Coincidence



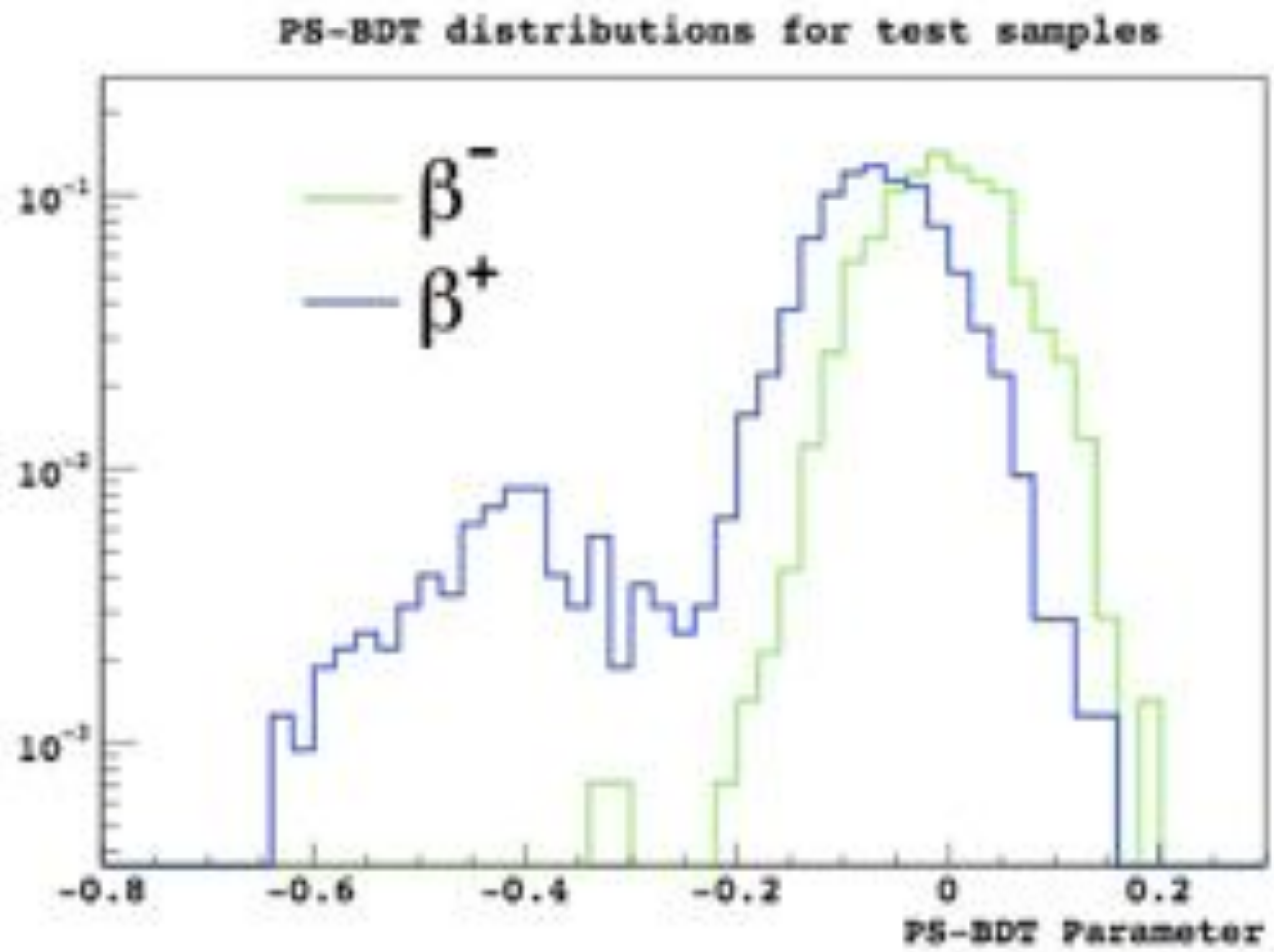
Remove 91% of ^{11}C and 51.5% of livetime.

e^+/e^- Pulse Shape Discrimination

(PRC 83:015522 (2011))



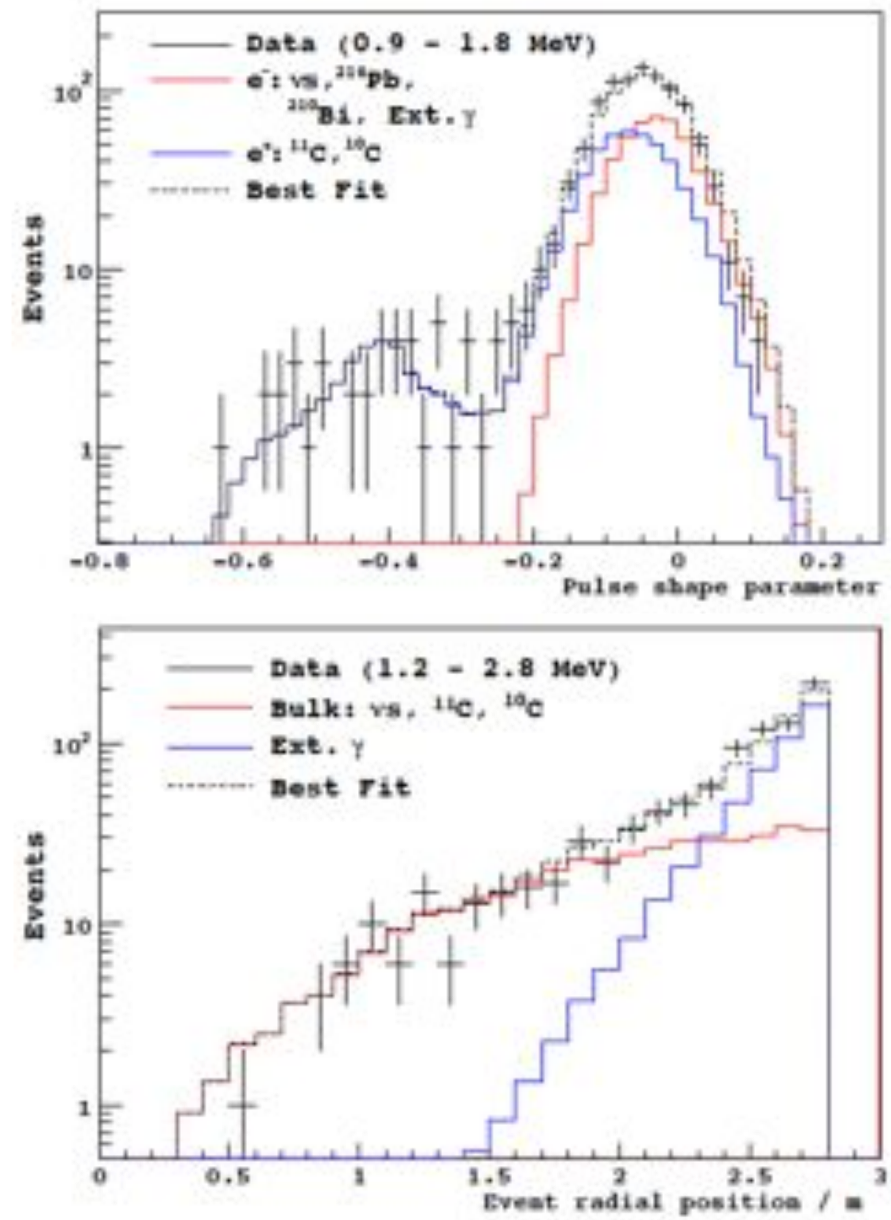
e^+/e^- Pulse Shape Discrimination



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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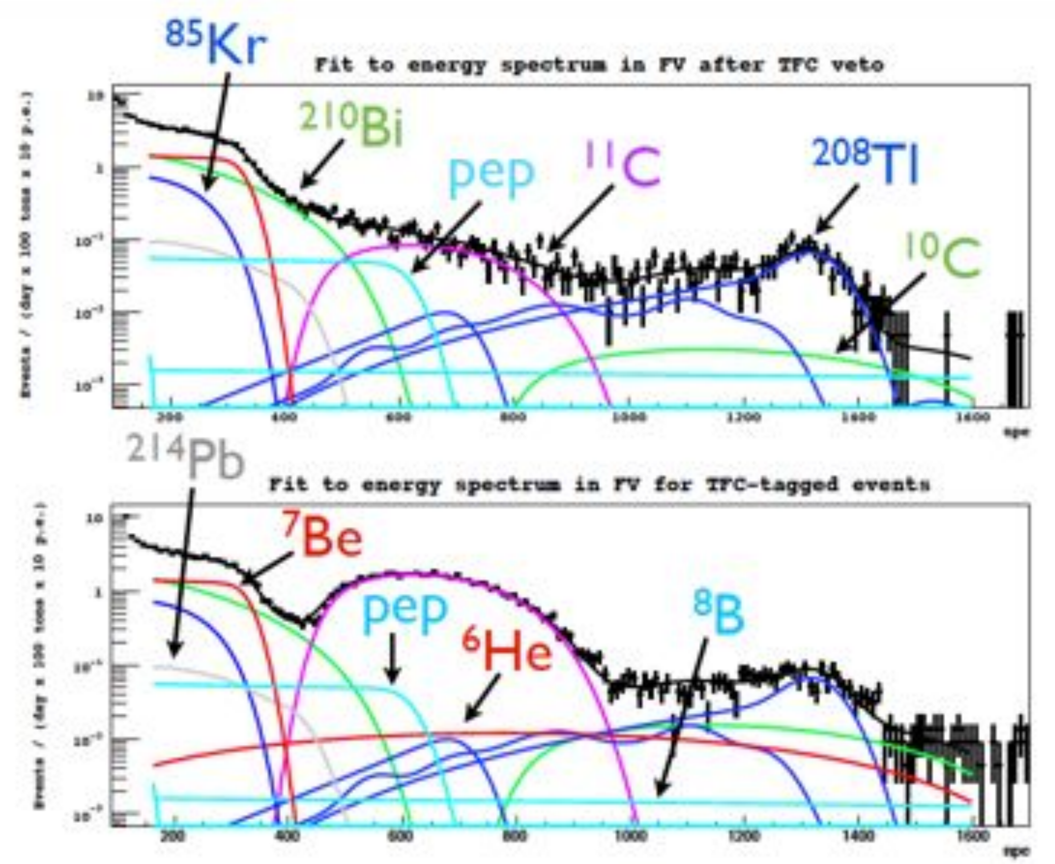
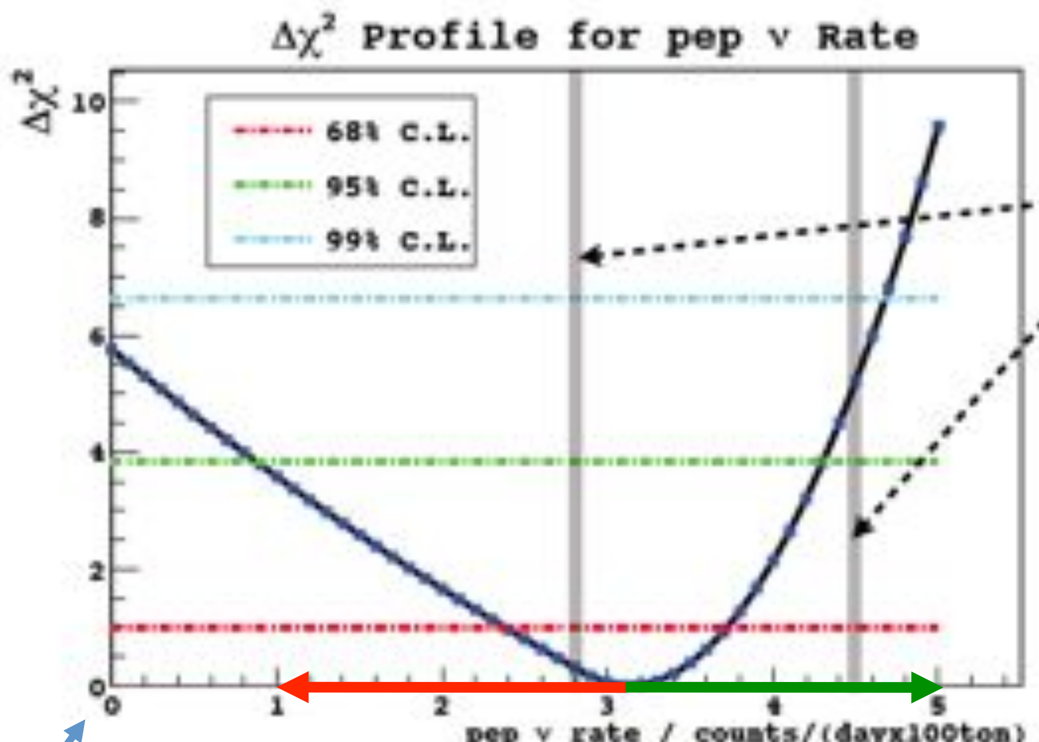


pep Result

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

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

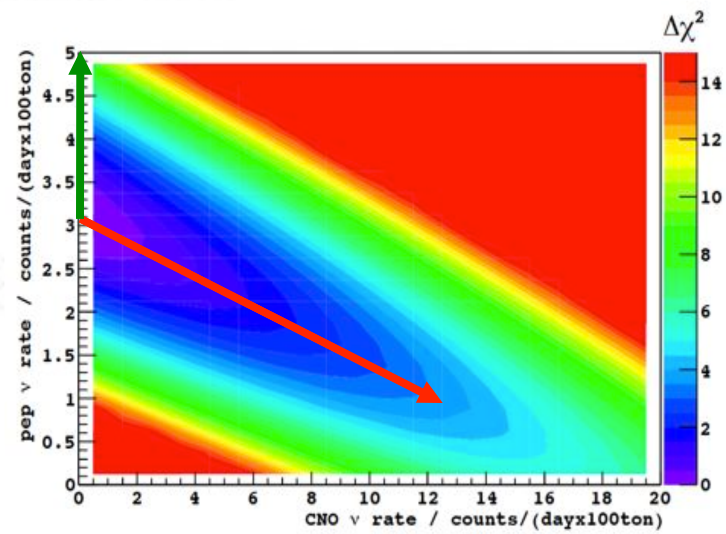
➡ $\Phi_{pep} = (1.6 \pm 0.3) \times 10^{8}\ cm^{-2}s^{-1}$ ➡ $P_{ee}(1.44\ MeV) = 0.62 \pm 0.17$



SSM Prediction

MSW-LMA

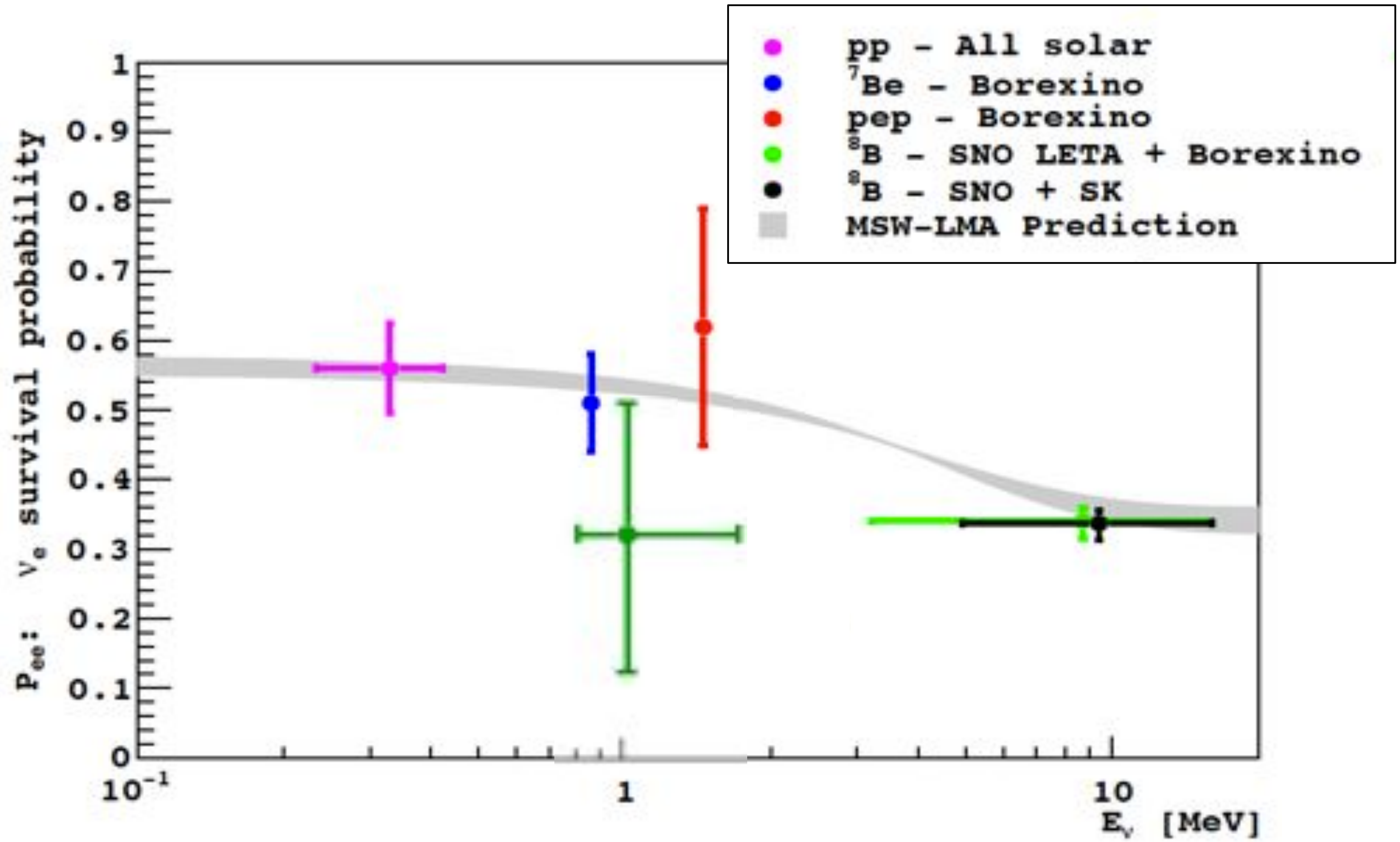
No Oscillation



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

pep Result

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



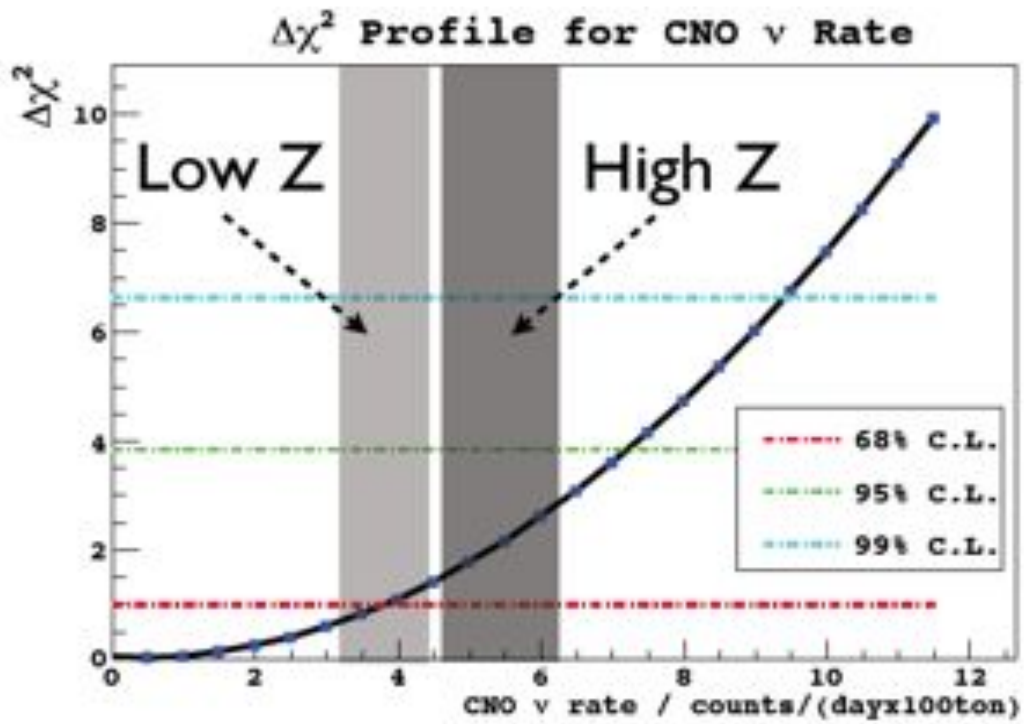
We have succeeded in extracting the pep signal from the background – more precise results possible in the future!

CNO Limit

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

Borexino CNO counting rate: < 7.9 (<$7.1_{\text{stat only}}$) /(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.

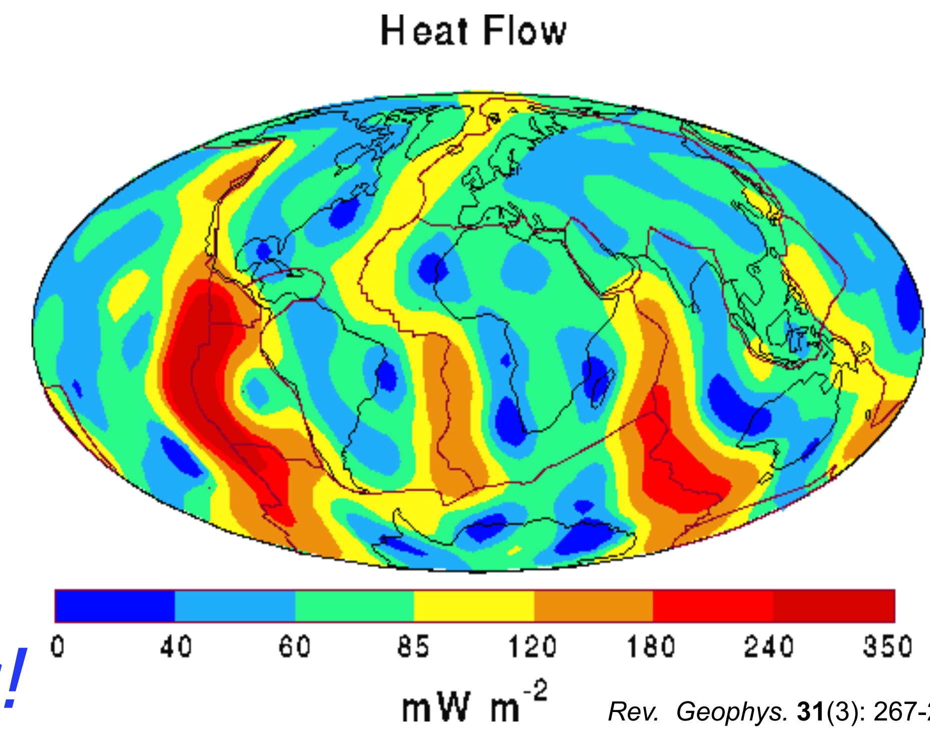
Result consistent with both high and low metallicity models.

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

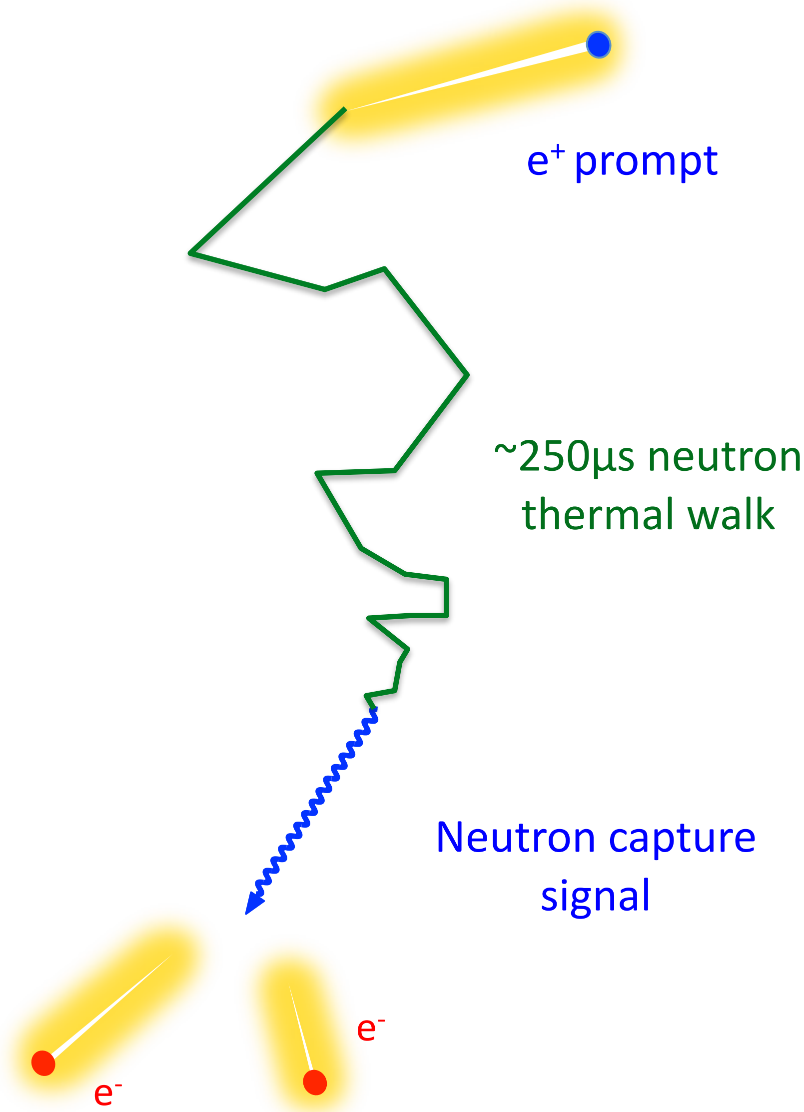


Rev. Geophys. **31**(3): 267-280 (1993)

Geophysics with neutrinos!

Detecting Geo-Neutrinos

- Expected rate in Borexino is tiny: <5/100T/yr
- Detection via $\overline{\nu}_e + p \rightarrow n + e^+$
  - 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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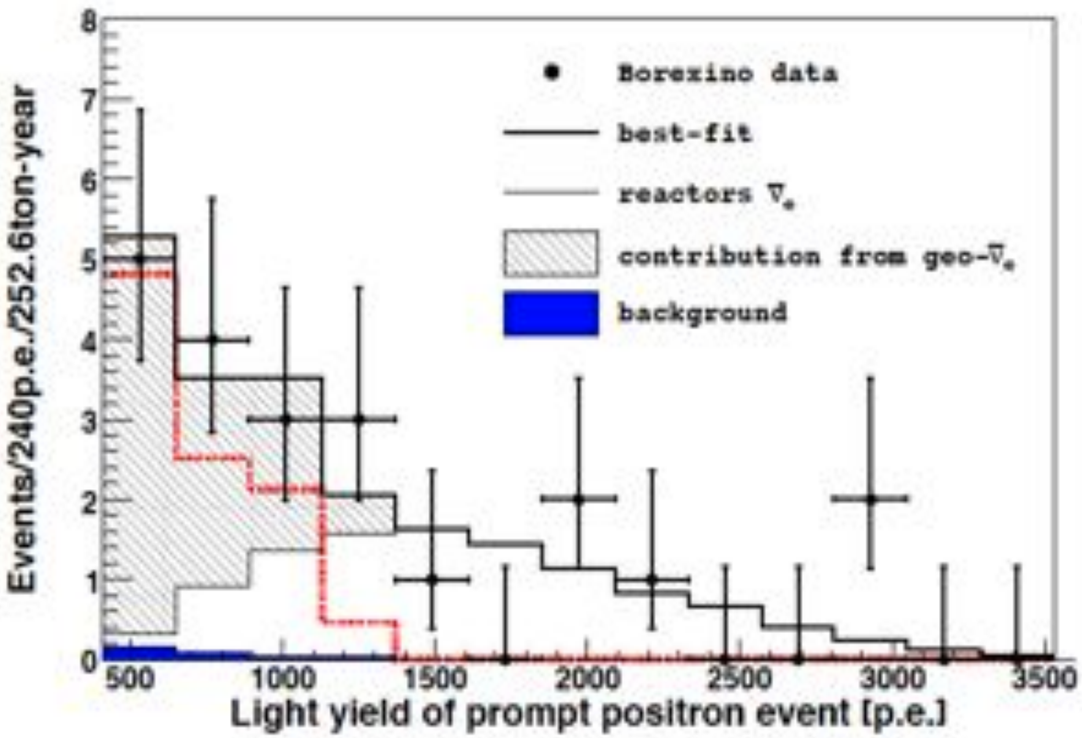
Geo-neutrinos in Borexino

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

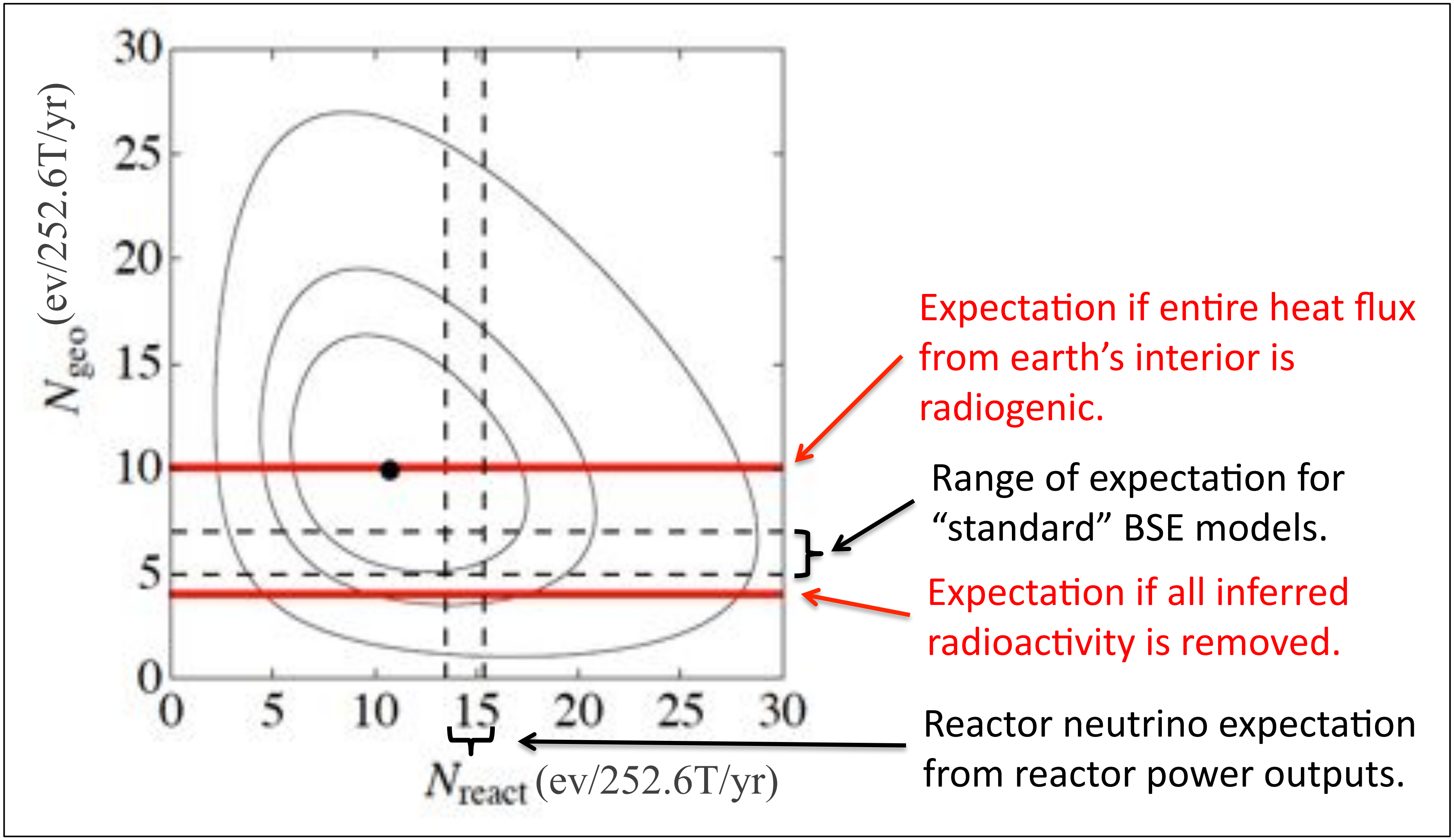
Borexino Geo-Neutrino Rate: $3.9^{+1.6}_{-1.3}$ ev/100T/yr



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

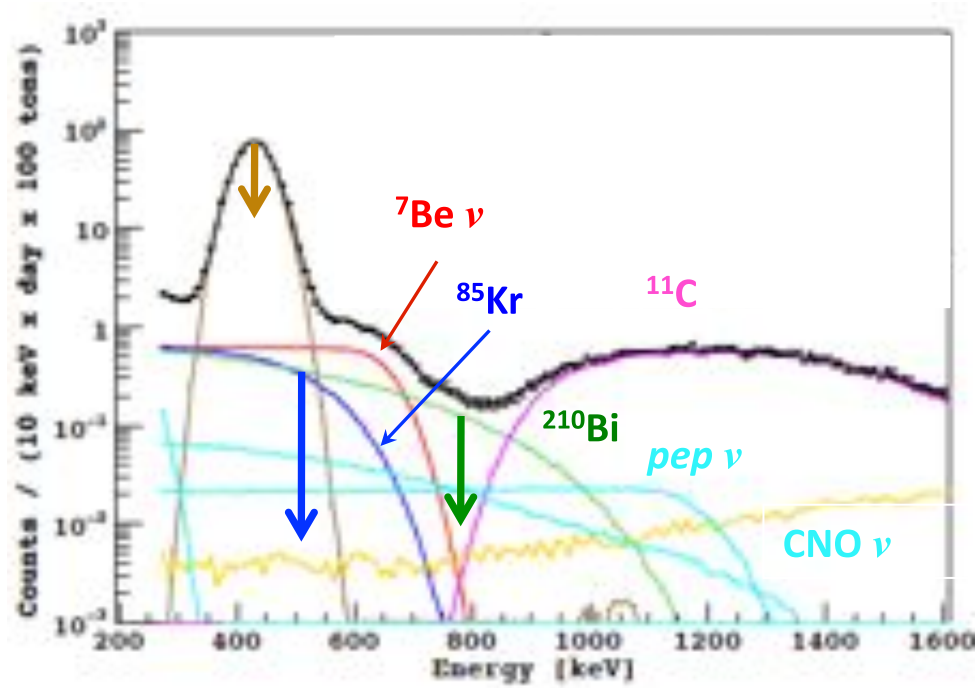
Geo-neutrinos in Borexino



Future, higher statistics, results from Borexino, KamLAND, and SNO+ should measure the U/Th ratio and hopefully separate the contributions from the mantle and the crust.

Borexino Future

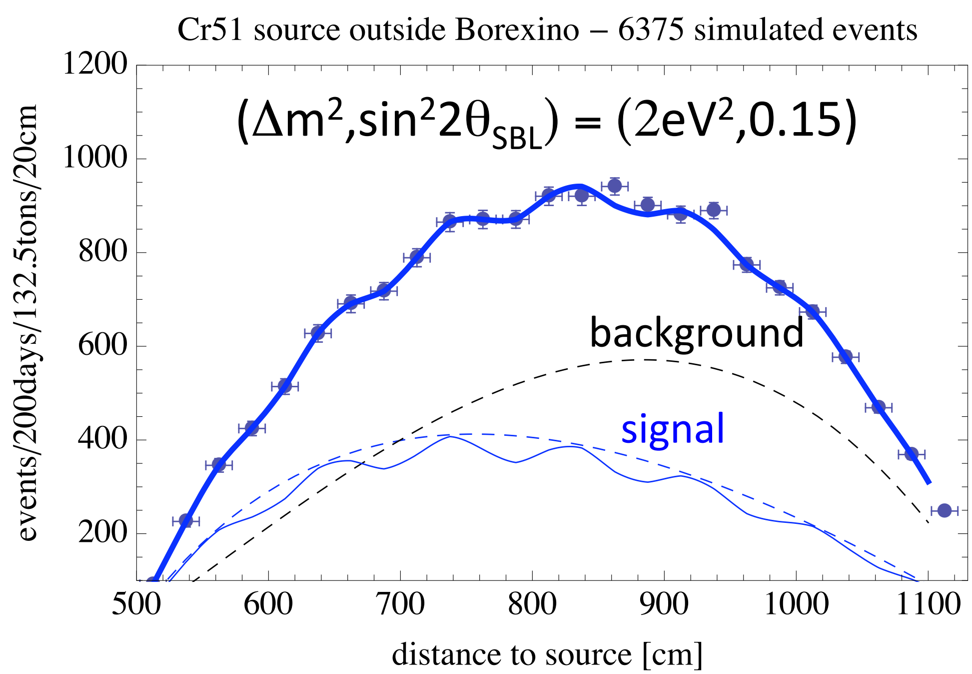
- Procedures to (further!) purify the scintillator underway since July 2010
  - No sign of ^{85}Kr since January 2011
  - Moderate reduction in ^{210}Bi
- Operations continue, with aim of further reducing ^{210}Bi, perhaps ^{210}Po
- Borexino will continue to take solar neutrino data for >3 more years



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

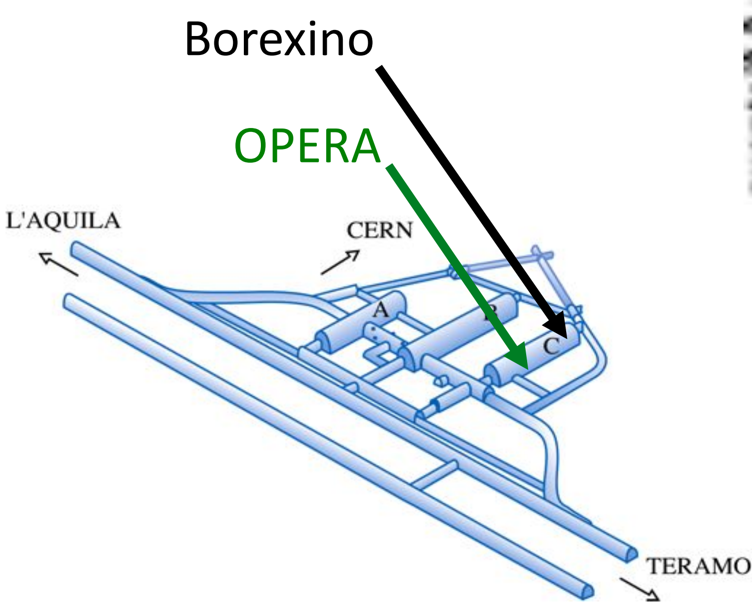
Sterile Neutrino Search

- 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!

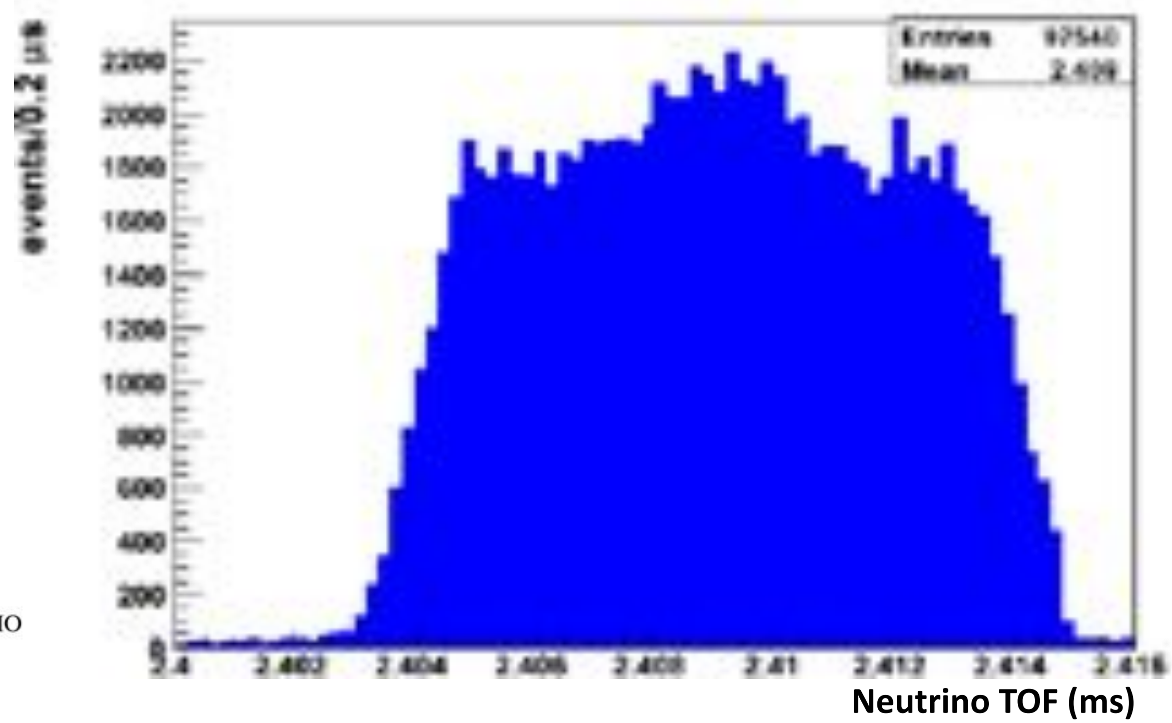


Neutrino Time-Of-Flight

- Borexino is located between OPERA and CERN
- We detect CNGS neutrinos too (JINST **6**:P05005 (2011))
- Timing system upgrades would allow Borexino to test the OPERA result (arXiv:1109.4897) - at least the detection part



Time Distribution of CNGS Neutrinos in Borexino



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!