# Studying Low Energy Neutrinos with Borexino and SNO+

LEPP Lunch Seminar, Cornell University

March 14th, 2012

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Princeton University

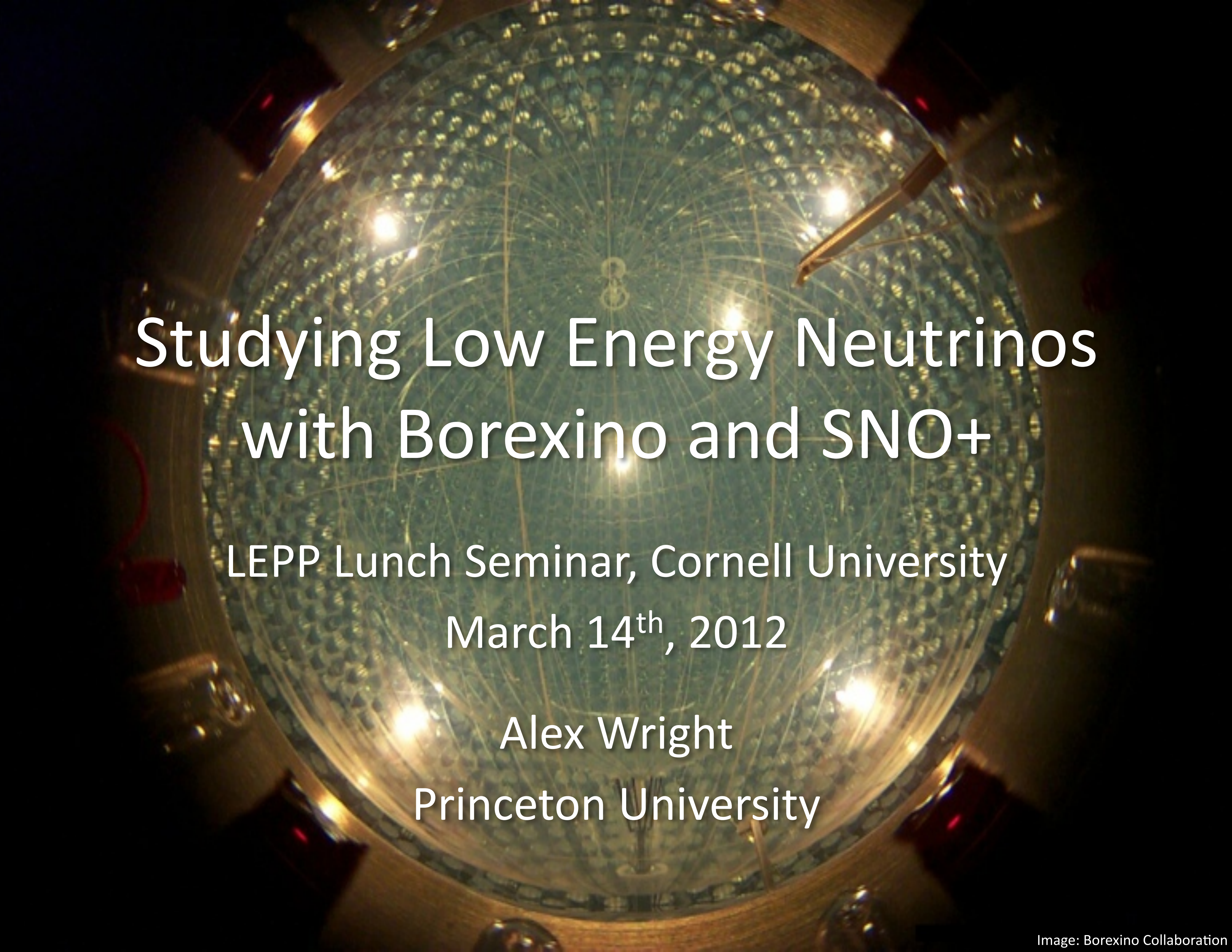


Image: Borexino Collaboration

# Outline

- Quick review of solar neutrinos and neutrino oscillations
- Introduction to Borexino
- Recent Borexino results
- Borexino future
- SNO+

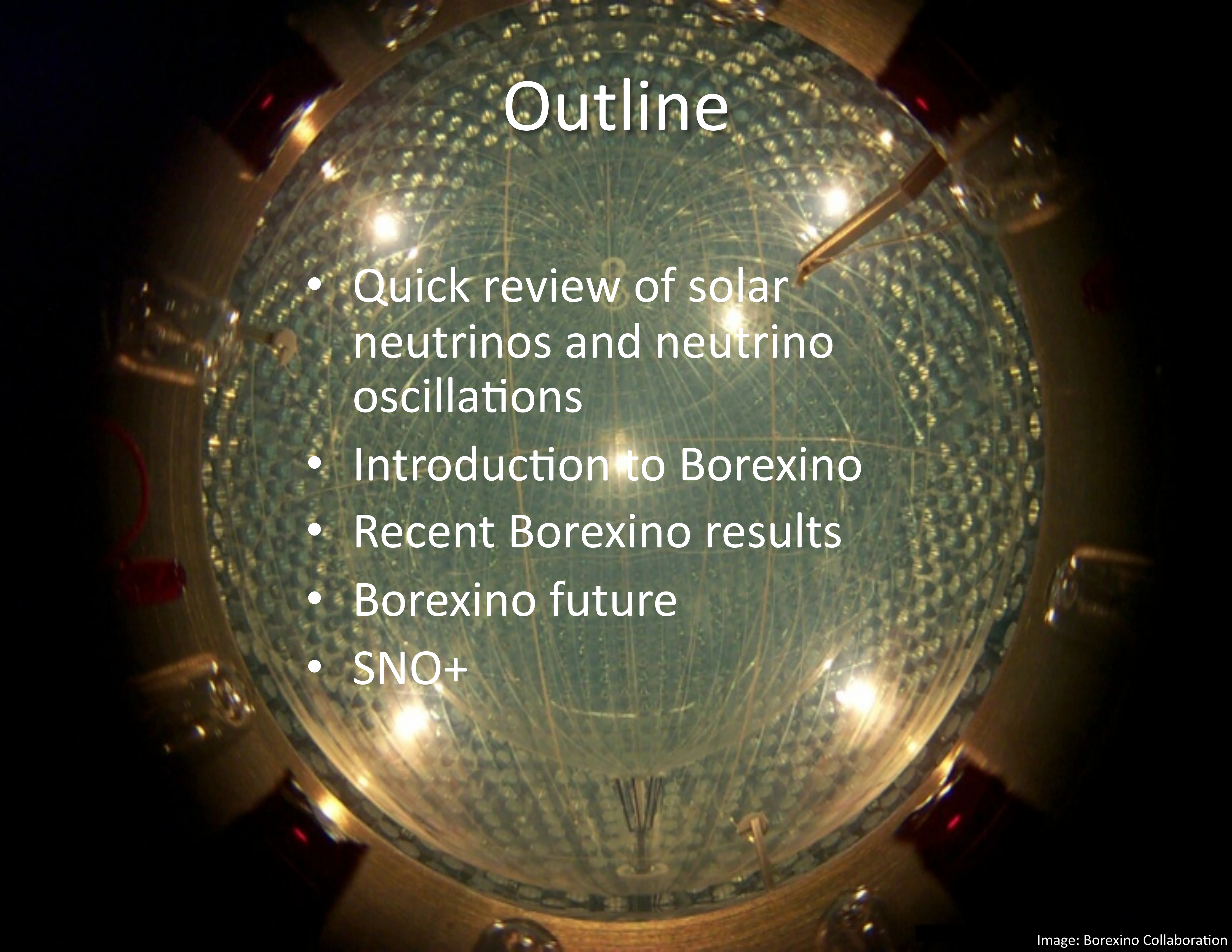


Image: Borexino Collaboration

# Neutrinos From the Sun

## p-p Solar Fusion Chain

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

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

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

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

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

$^{7}Li + p \rightarrow 2\,{}^{4}He$ $\quad$ $^{8}B \rightarrow 2\,{}^{4}He + e^{+} + \nu_e$

## CNO Solar Fusion Cycle

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

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

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

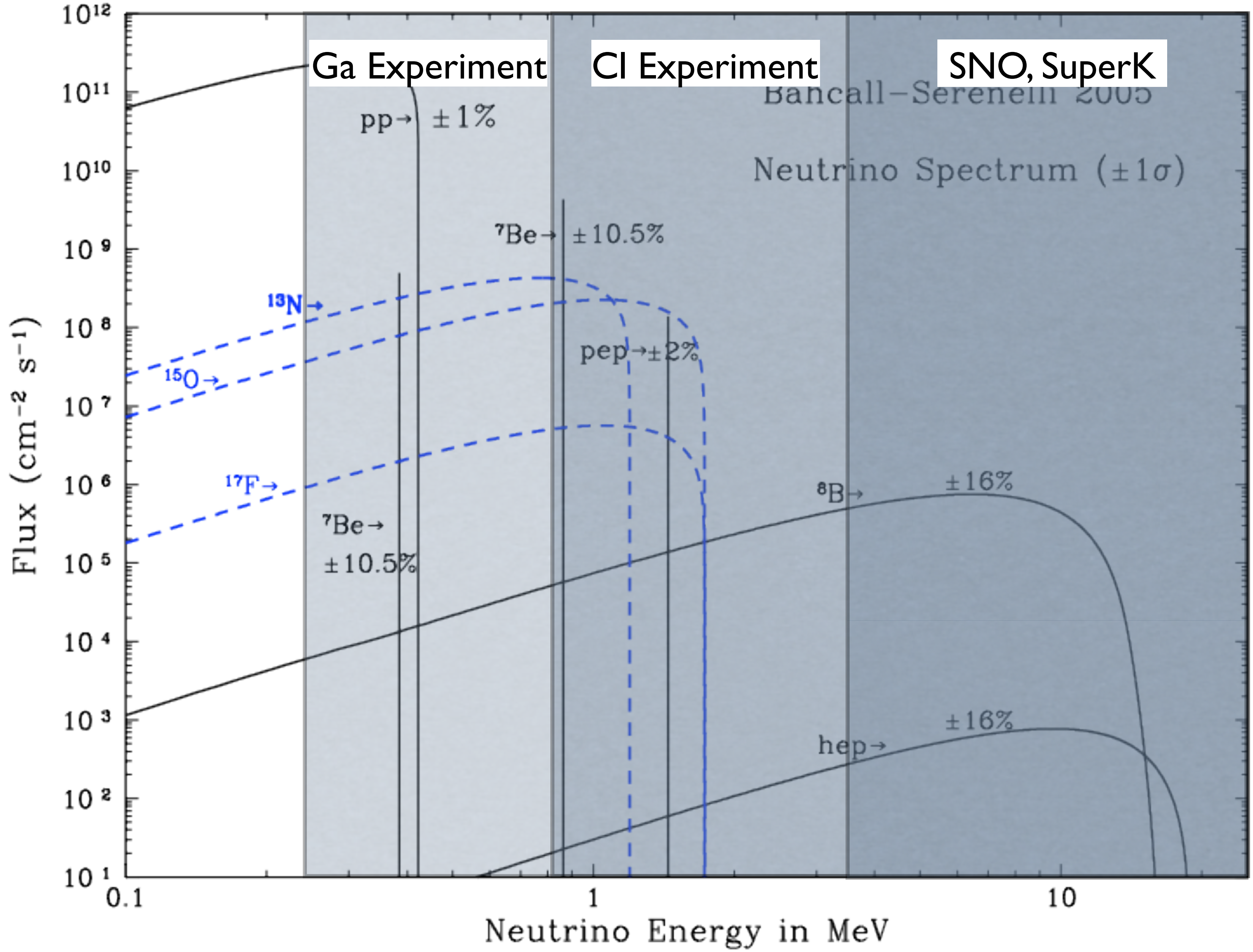
$^{14}N + p \rightarrow {}^{15}O + \gamma$

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

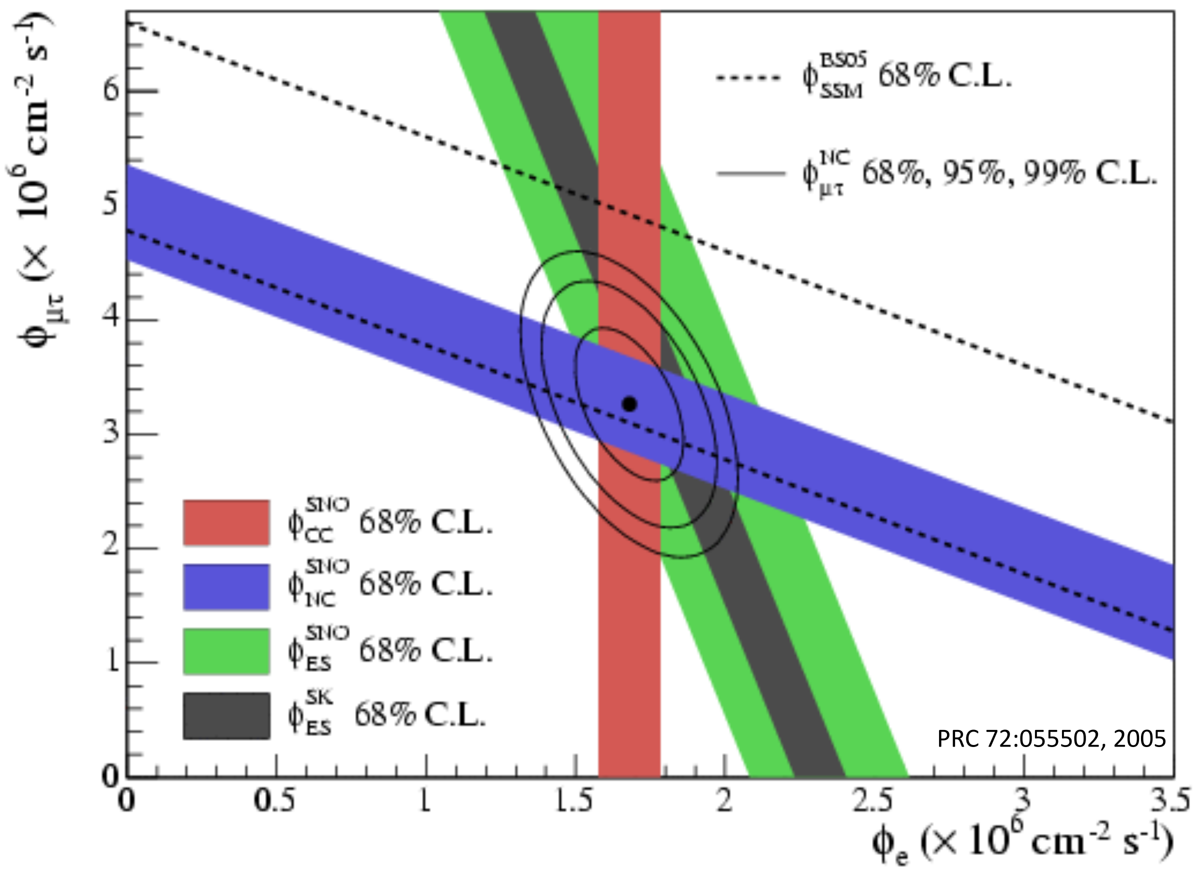
$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

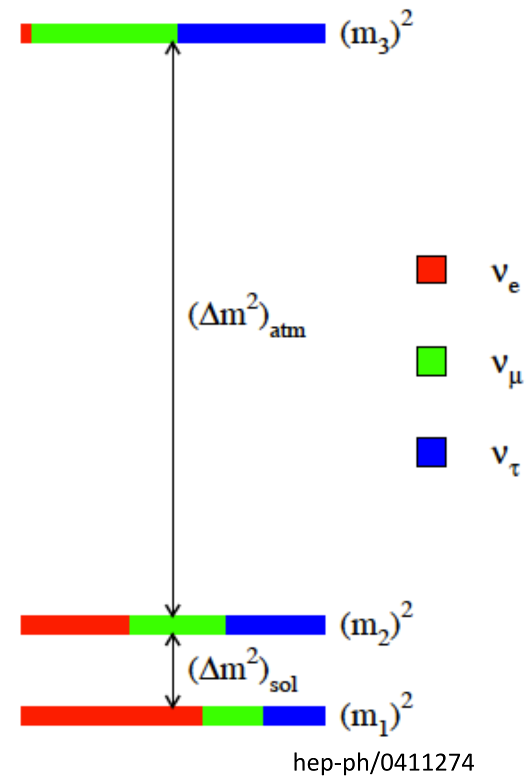
Image: bbc.co.uk

# Neutrinos From the Sun



# Solar Neutrino Oscillations




- 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

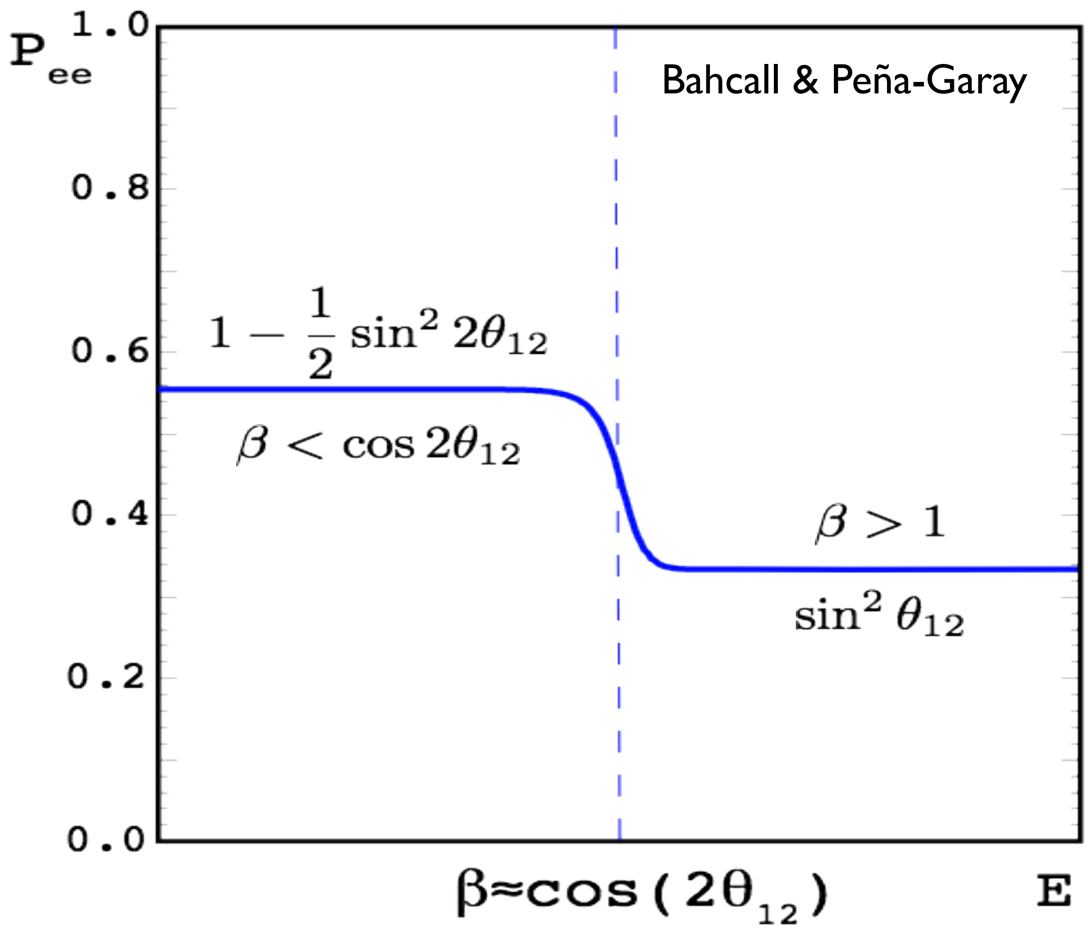
- When neutrinos propagate in matter, charged current interactions add an additional term to $\nu_e$ flavour in mass matrix:

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

- 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:

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

# MSW Oscillation Regimes

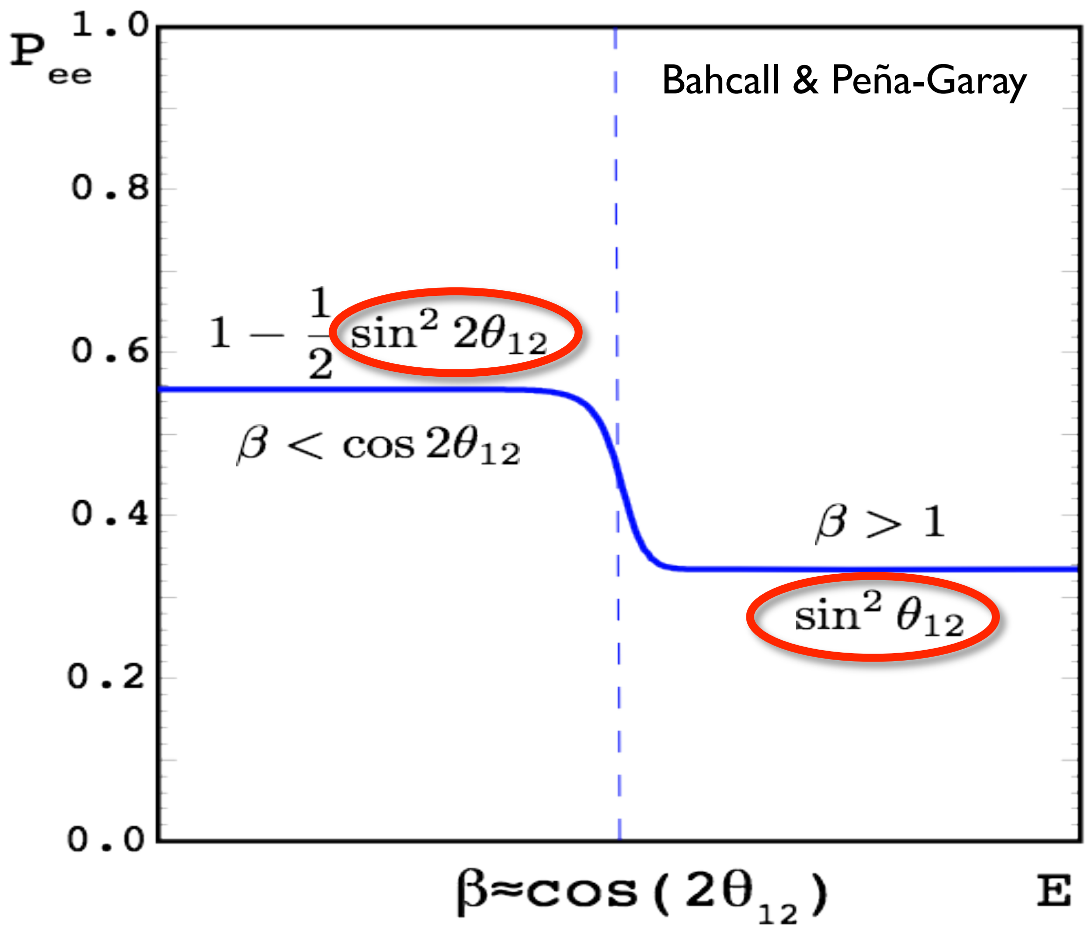



$$\beta = \frac{2^{3/2} G_F N_e}{\left(\frac{\Delta m^2}{E}\right)}$$

**Low energy:** Phase-averaged vacuum oscillations

**High energy:** Matter-dominated "resonant conversion"

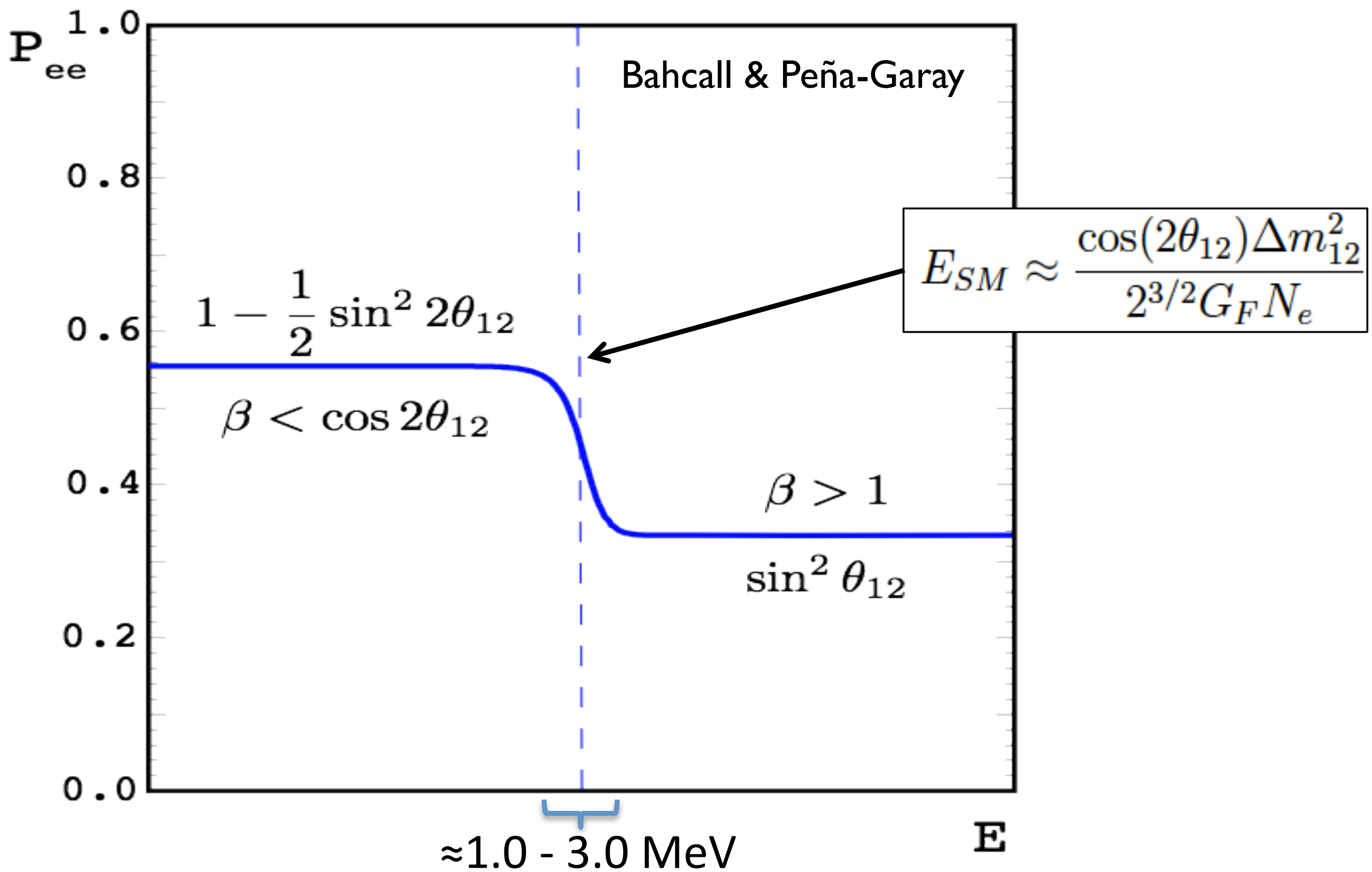
# MSW Oscillation Regimes




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

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

# MSW Oscillation Regimes

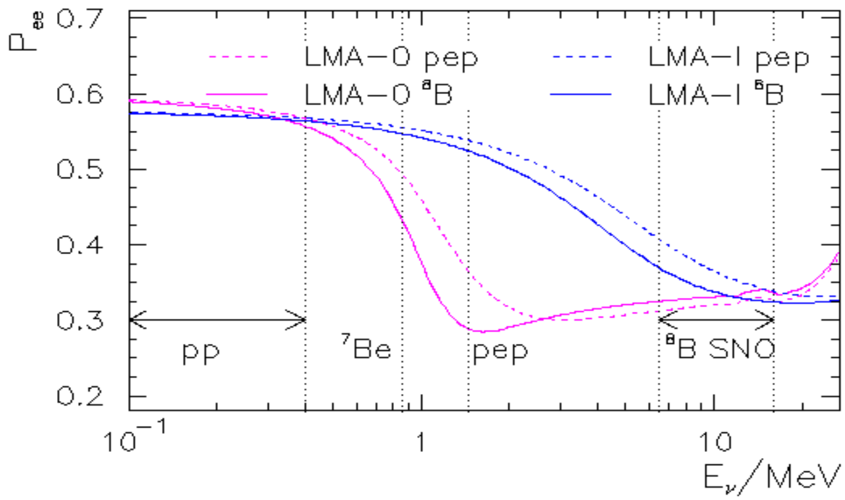



***Look in "transition region" to confirm MSW and that we know what is going on!***

# Possible New Physics in Transition Region

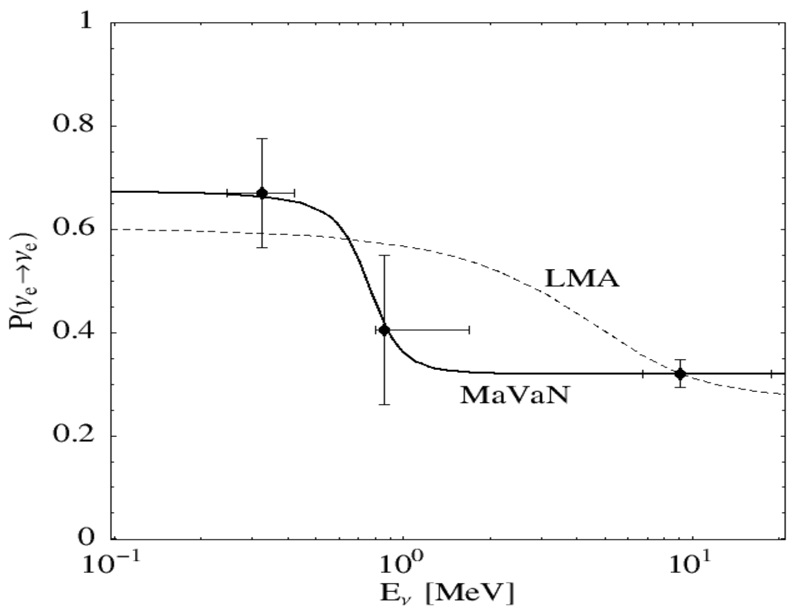
## Non-Standard Interactions

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



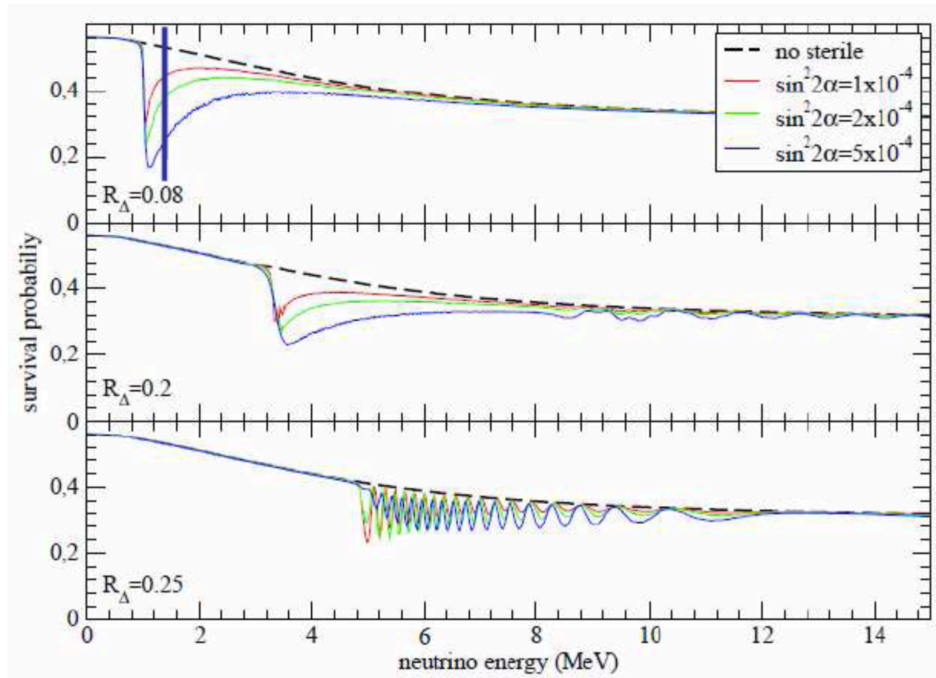

## Mass Varying Neutrinos

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

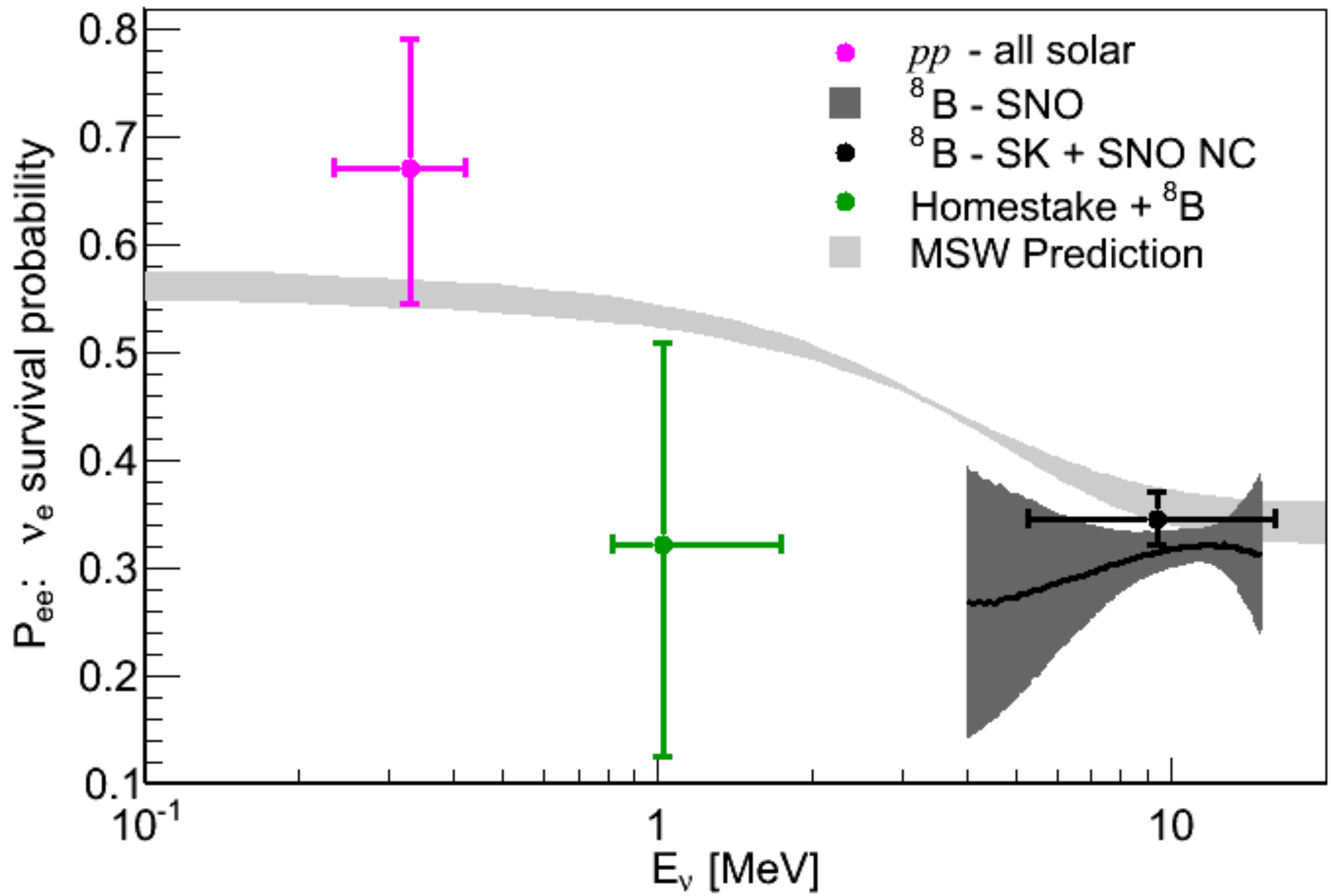



## Sterile Neutrinos

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

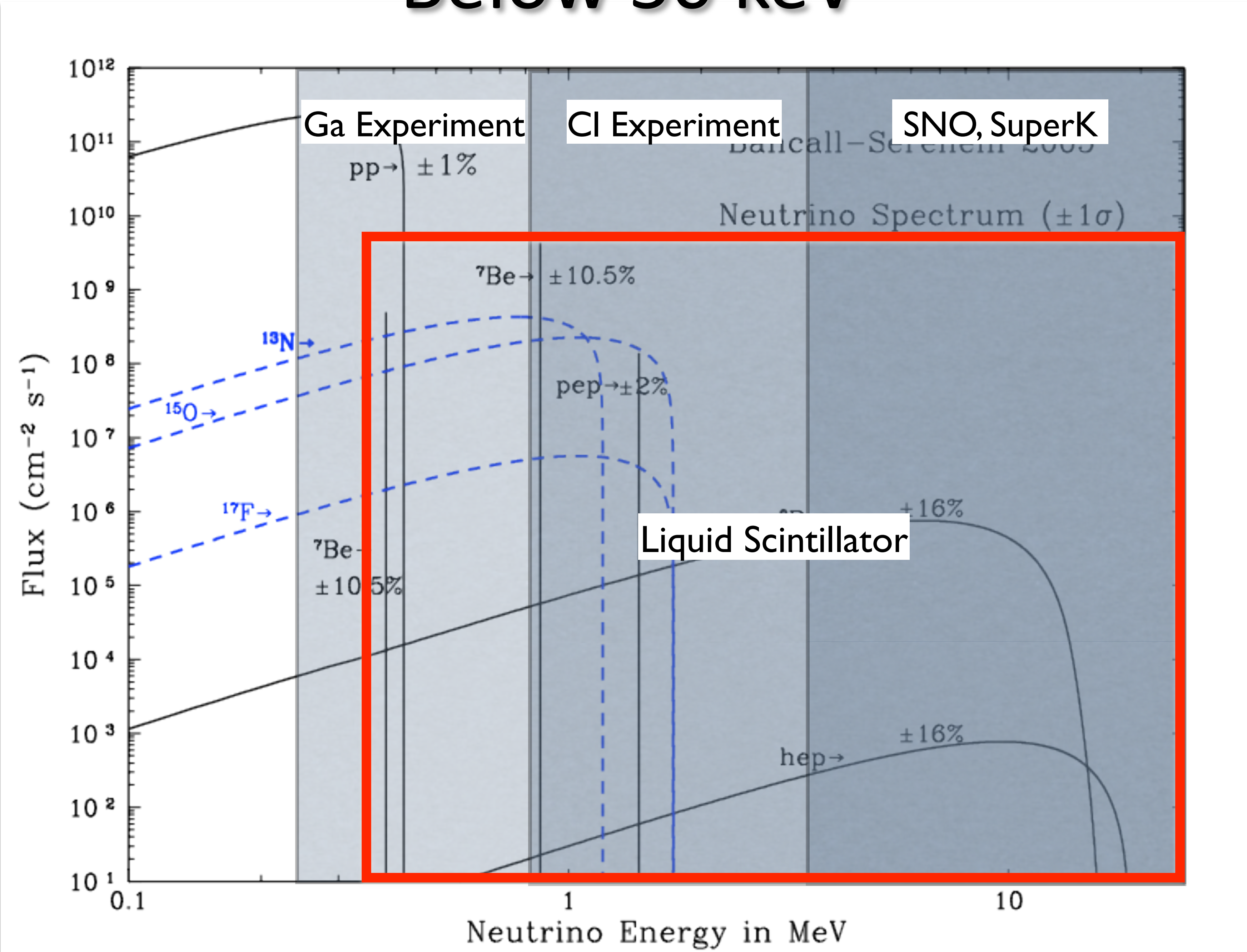


# Constraints on Transition Region Without Borexino

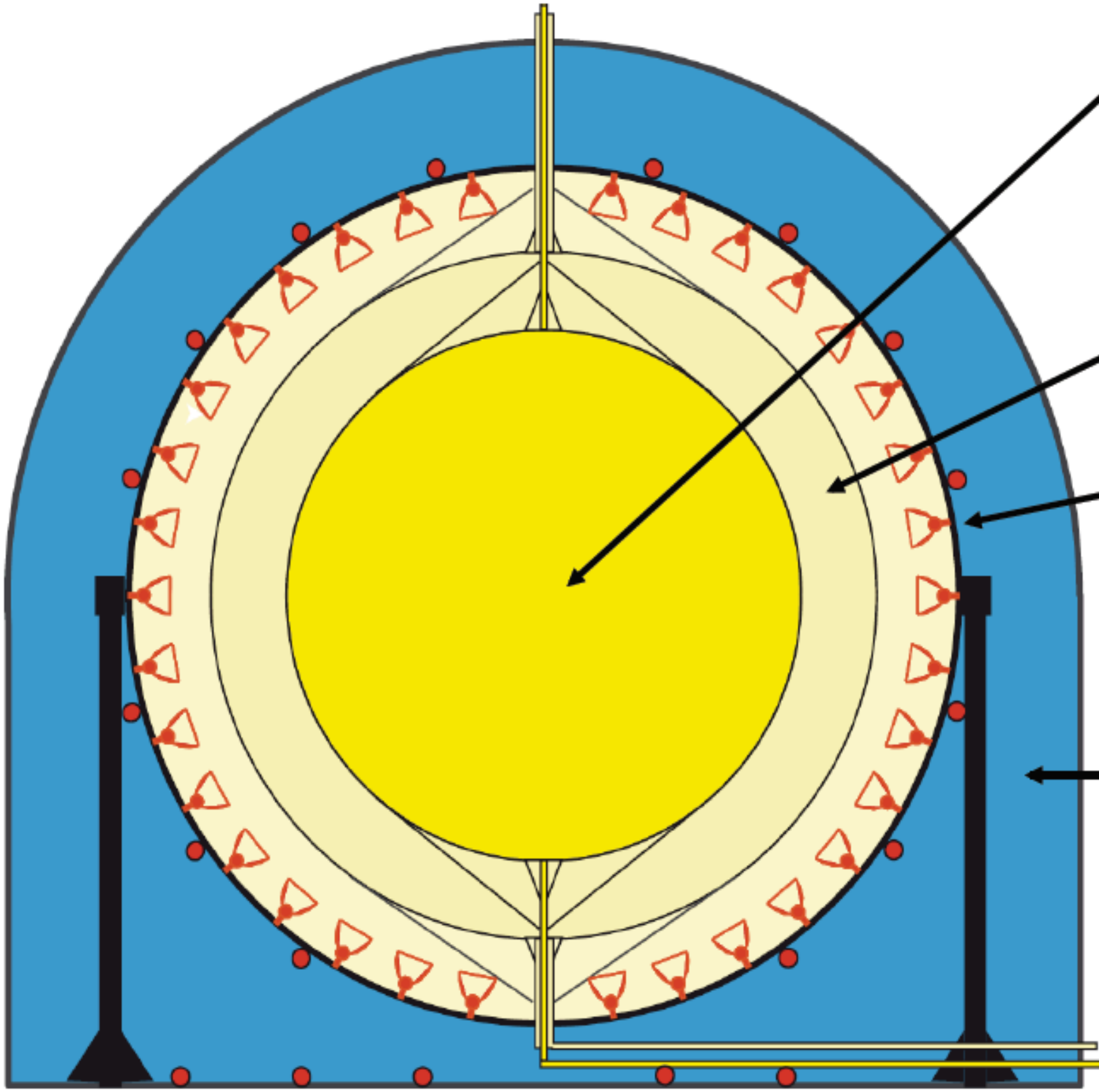



**Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated.** ***Real-time measurements needed in the transition region.***

# 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

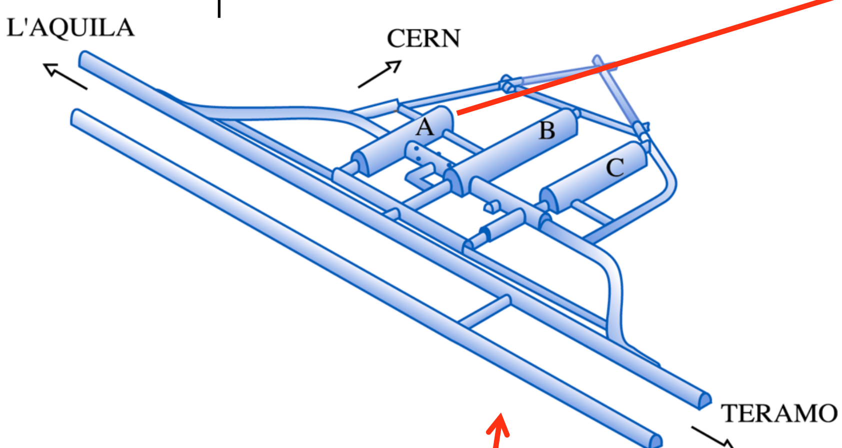
**non-scintillating buffer**

**stainless steel sphere**
6.85 m in radius
2212 inward-facing PMTs

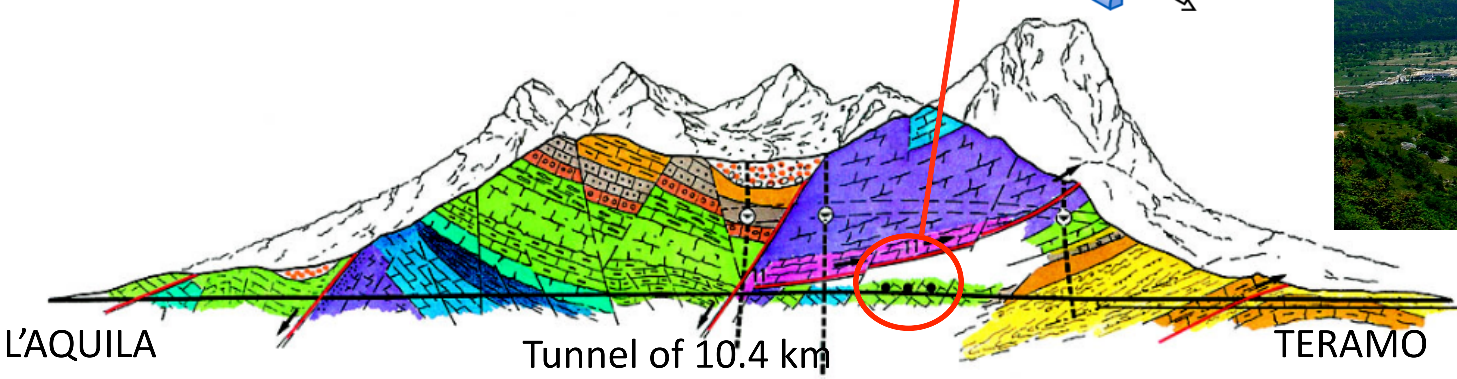
**outer water tank**
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

# 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

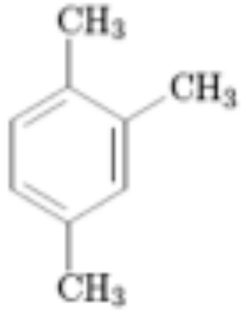
PRINCETON UNIVERSITY – PRINCETON, NJ, USA

ST. PETERSBURG NUCLEAR PHYSICS INSTITUTE – GATCHINA, RUSSIA

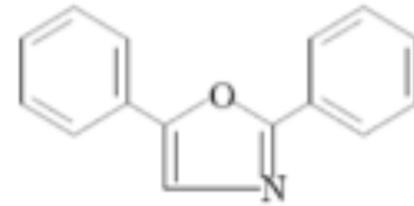
TECHNISCHE UNIVERSITÄT – MUENCHEN, GERMANY

UNIVERSITY OF MASSACHUSETTS AT AMHERST, MA, USA

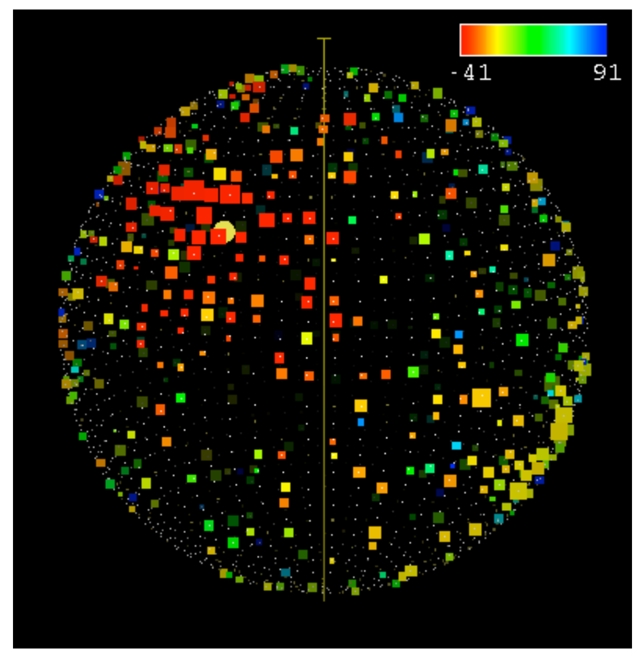
VIRGINIA POLYTECHNIC INSTITUTE – BLACKSBURG, VA, USA




# Detection Principle

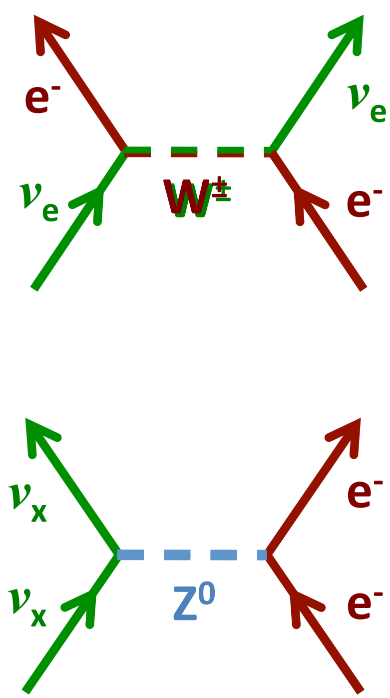


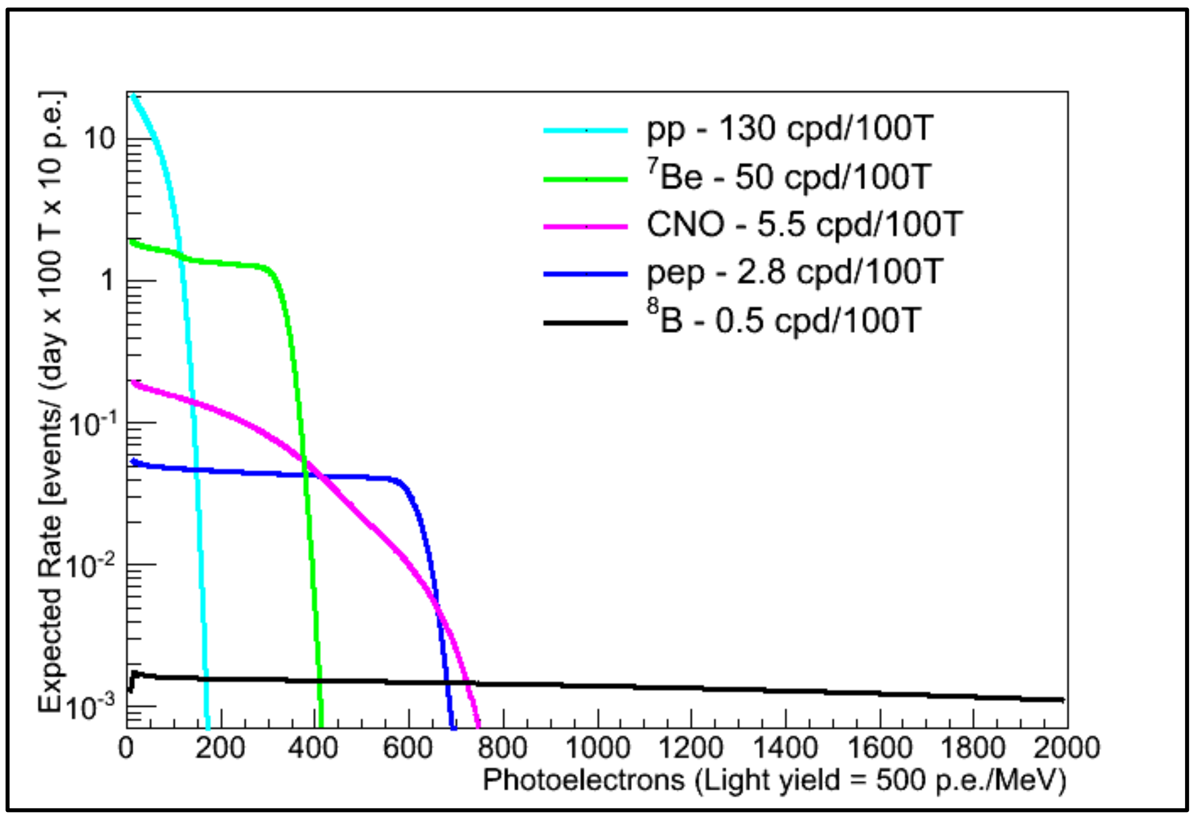

- Organic scintillator (pseudocumene + PPO) produces light when excited by charged particles
- ~12,000 photons/MeV, of which ~500 photons/MeV are detected by the photomultiplier tubes
  - Can detect events depositing < 50 keV
- Calorimetric measurement + pulse shape
  - Event energy from number of photons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



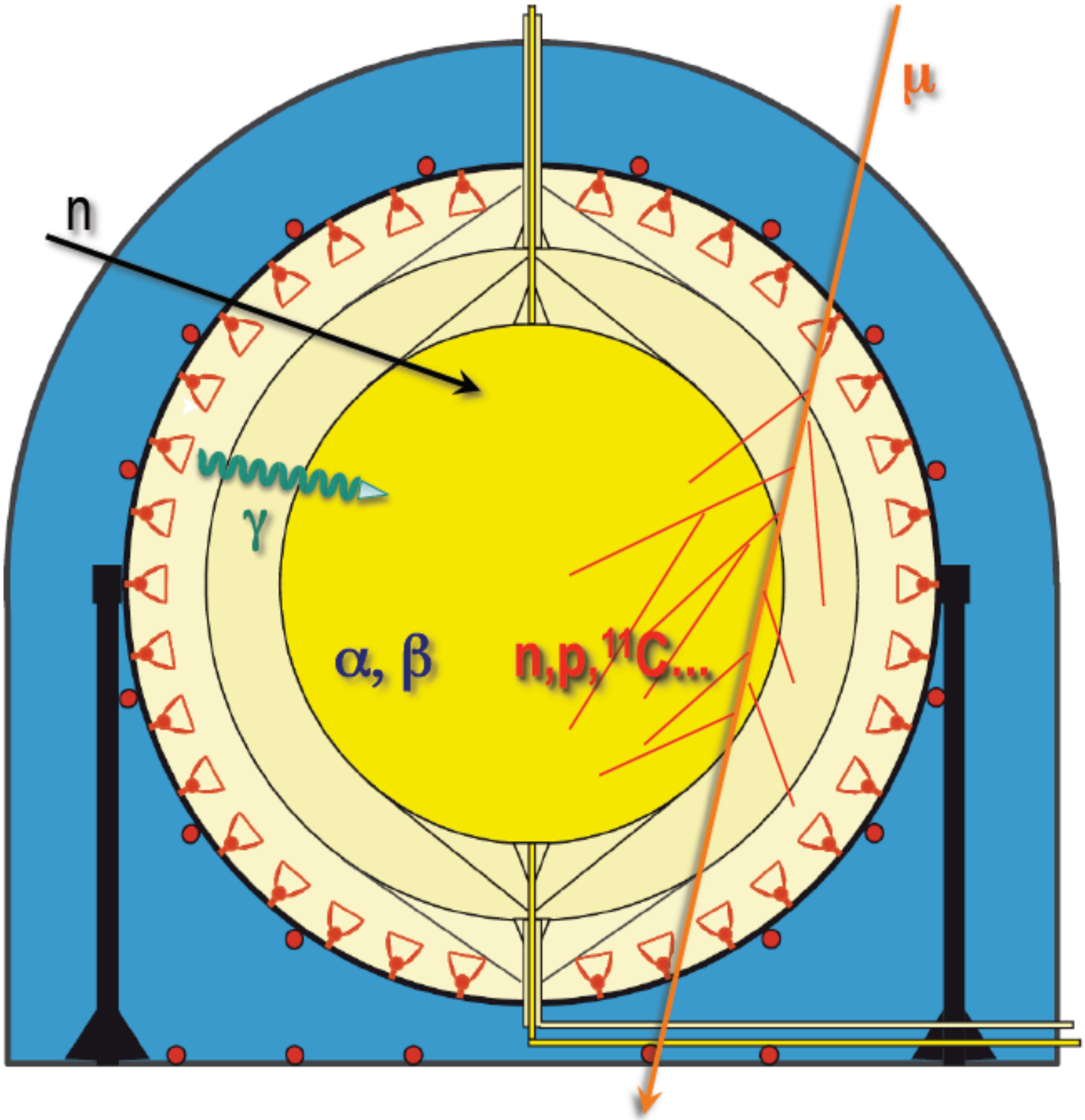
# Neutrino Detection

- Neutrinos interact via elastic scattering with electrons
  - Sensitive to all neutrino species, but cross section is 4-7 times larger for $\nu_e$ 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 ...)

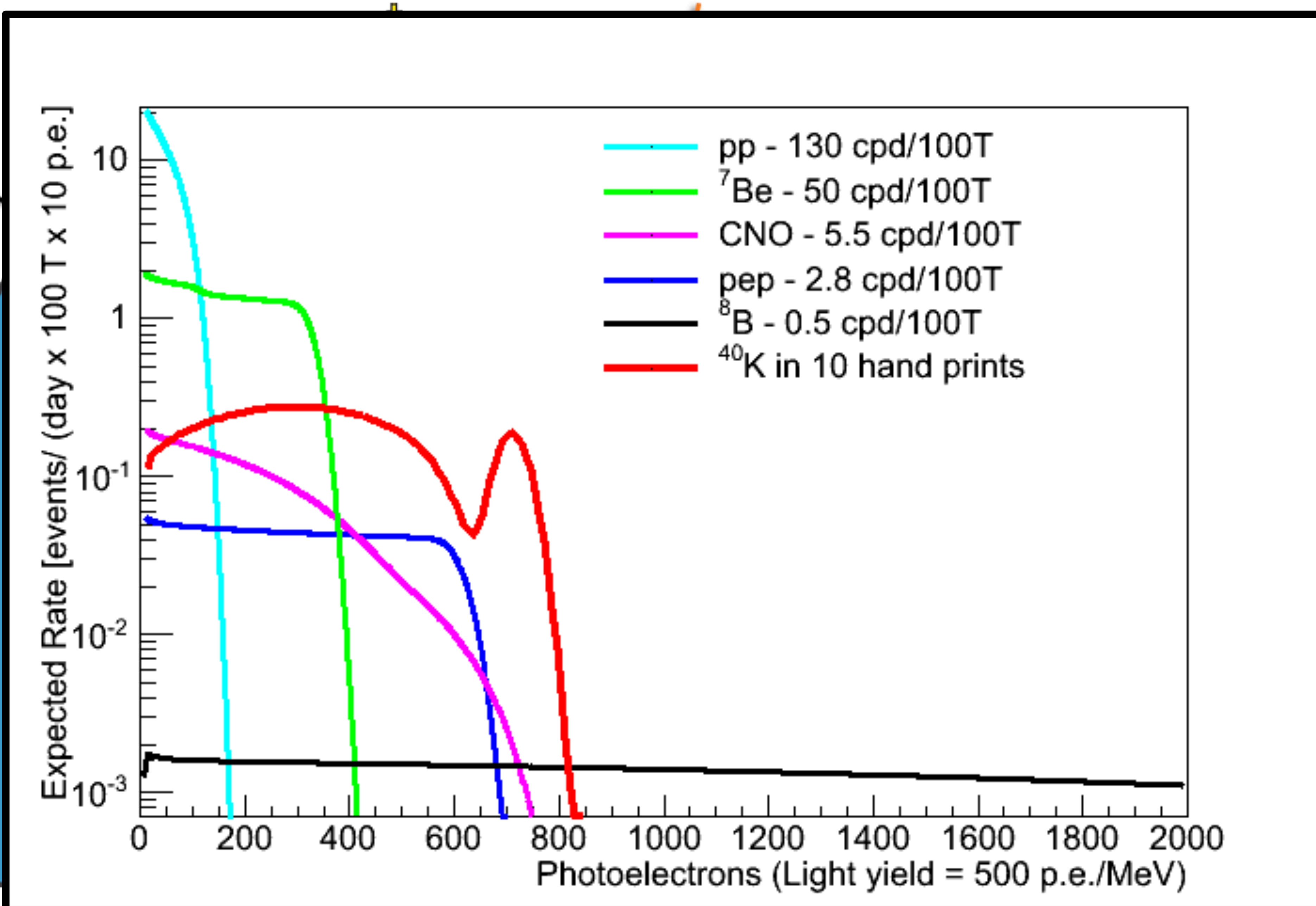
**Cosmic Muons**

**Cosmogenics**
neutrons and radionuclides from muon-spallation and hadronic showers

**Fast Neutrons**
from external muons

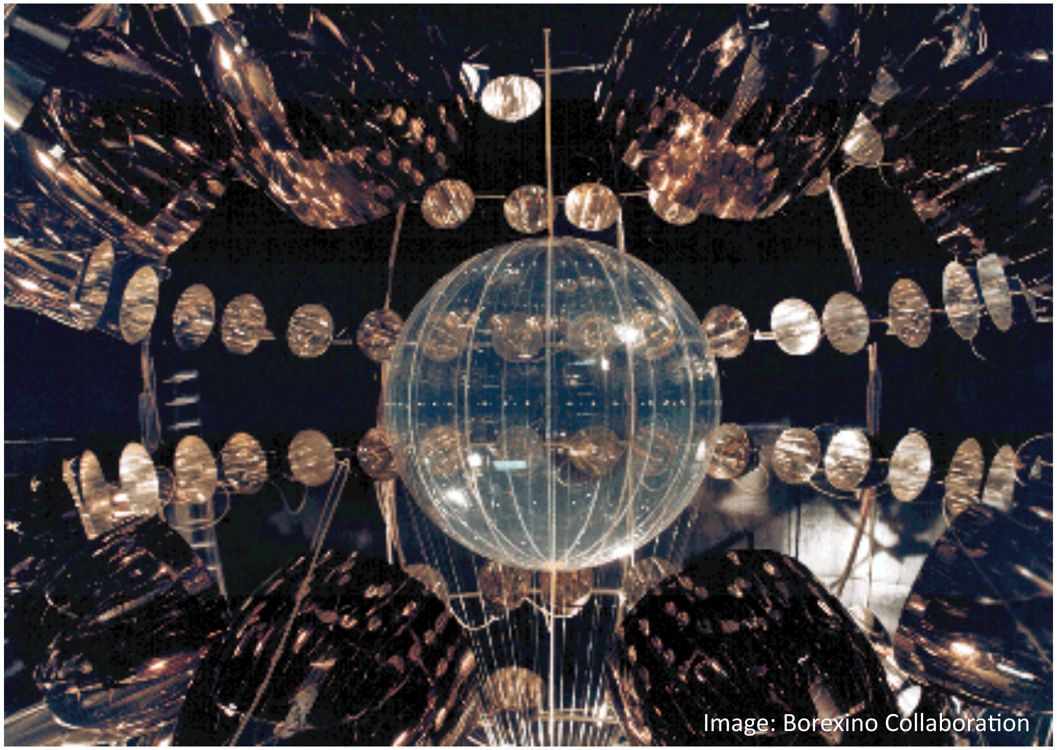
Slide: M. Wurm

# Central Challenge: Background Reduction




Slide: M. Wurm

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



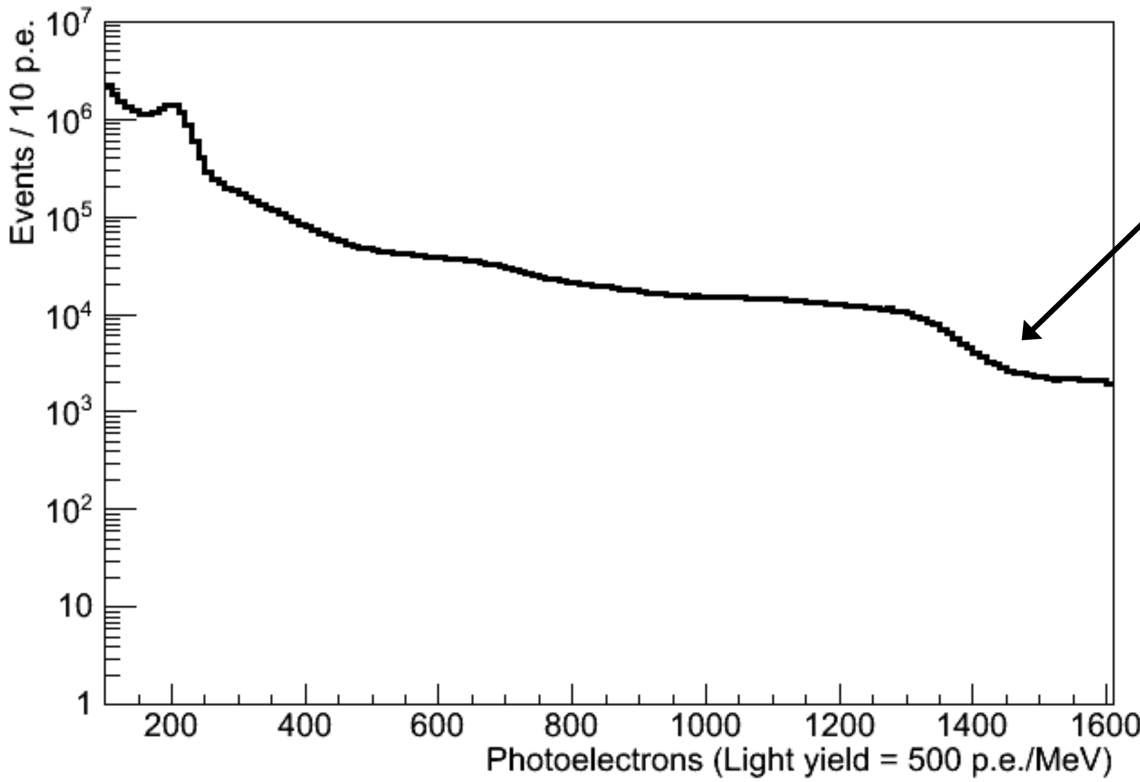

The Counting Test Facility III

| 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 | ~$5 \times 10^{-18}$ g/g | Purification |
| $^{232}Th$ | Dust | $10^{-6}$ g/g | ~$4 \times 10^{-18}$ g/g | Purification |
| $^{85}Kr$ | Air | 1 $Bq/m^3$ | ~$2 \times 10^{-3}$ $Bq/m^3$ | LAKN |
| $^{222}Rn$ | Air | 20-100 $Bq/m^3$ | $<10^{-6}$ $Bq/m^3$ | Air exclusion |
| $K_{nat}$ | Dust | ~$10^{-3}$ g/g | $<2 \times 10^{-15}$ g/g | Purification |
| μ | Cosmic | 200 $s^{-1}m^{-2}$ | $10^{-10}$ $s^{-1}m^{-2}$ | Underground, active veto |

# Borexino Neutrino Results

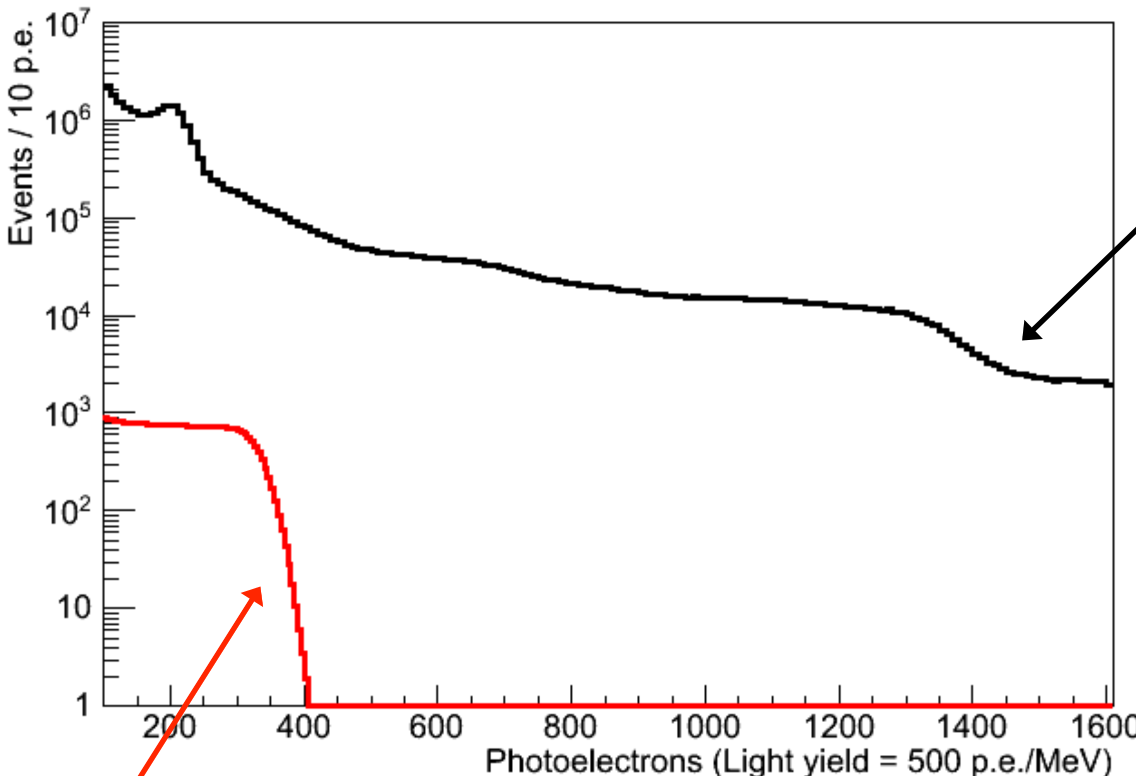
- $^{7}$Be Flux
  - (±30%) – Phys. Lett. B **658**:101 (2008).
  - (±10%) – Phys. Rev. Lett. **101**:091302 (2008).
  - (±5%) – Phys. Rev. Lett. **107**:141302 (2011).
- $^{7}$Be Day-Night Asymmetry
  - Phys. Lett. B **707**:22 (2012).
- $^{8}$B Flux + Spectrum ($T_{eff}$ > 3.0 MeV)
  - Phys. Rev. D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

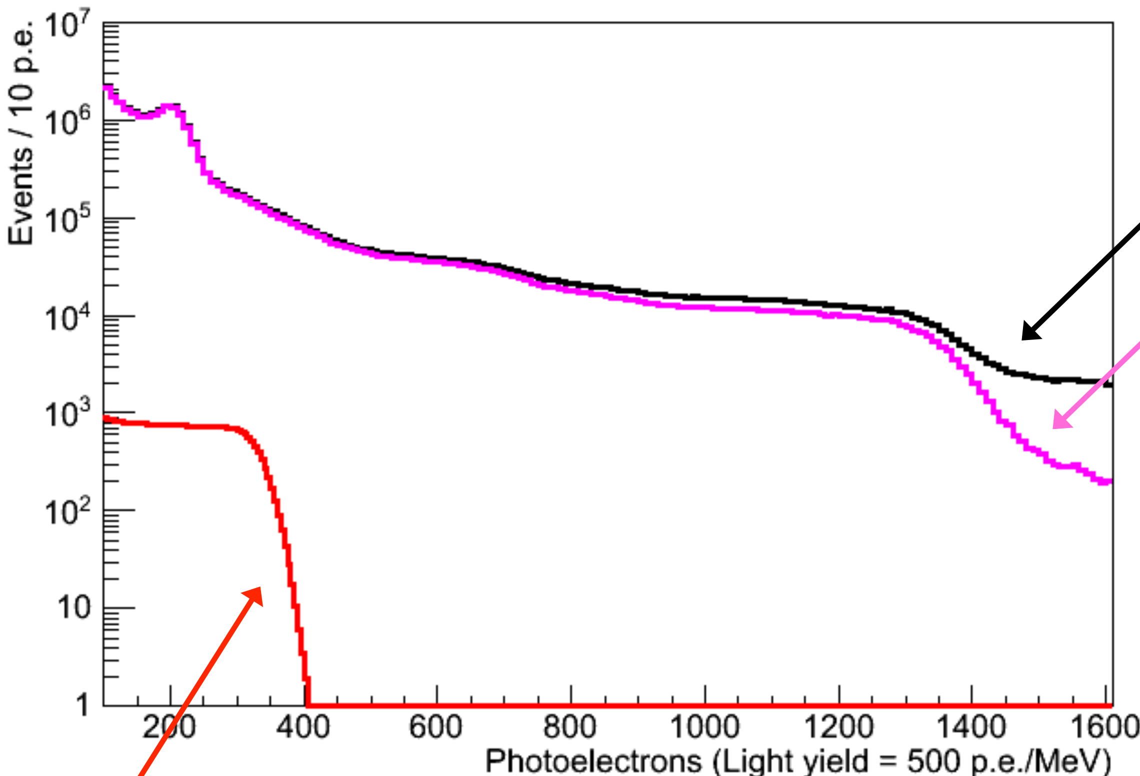
# Borexino Data




All data: 740 live days

Expected $^7$Be signal

# Borexino Data

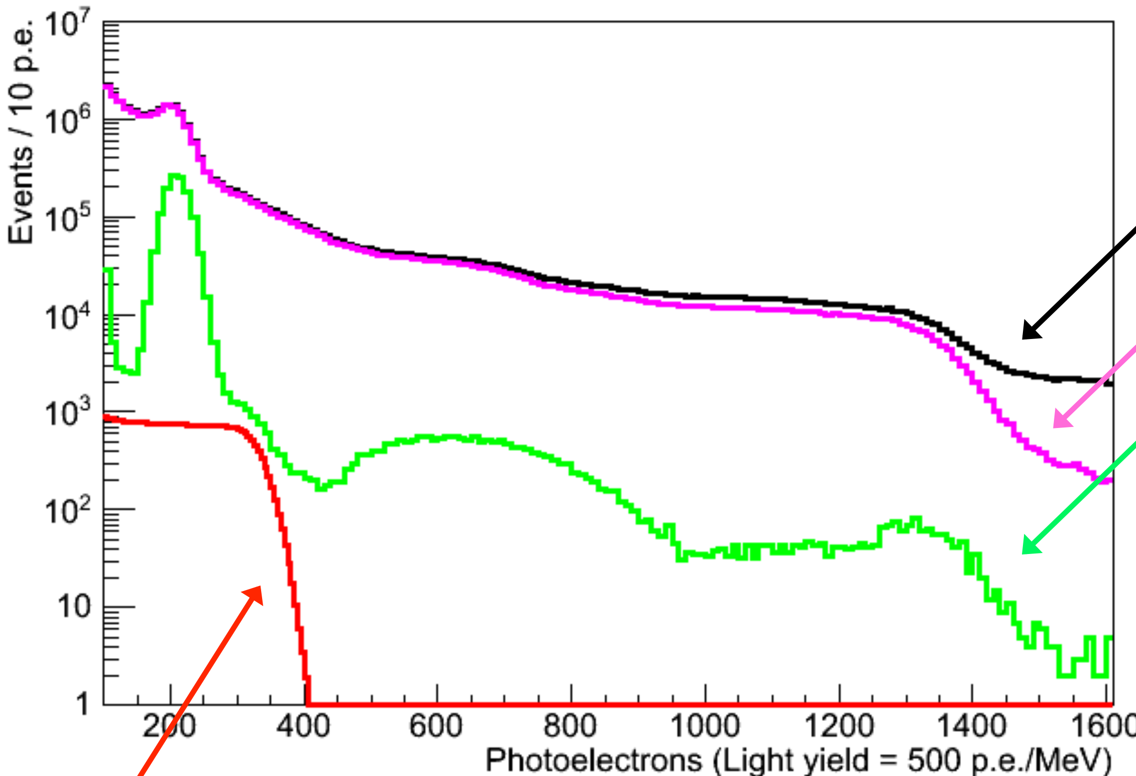



All data: 740 live days

Remove muons + muon followers (2 ms)

Expected $^7$Be signal

# Borexino Data




All data: 740 live days

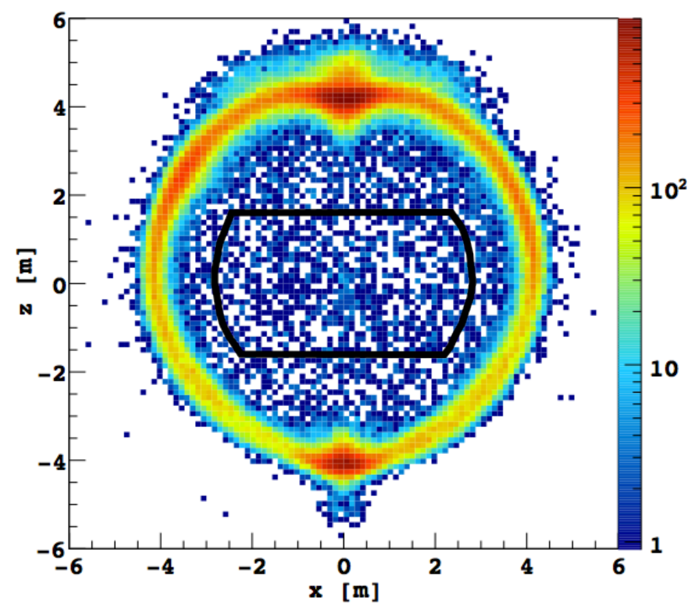
Remove muons + followers

Fiducial Volume + high level

Expected $^7$Be signal

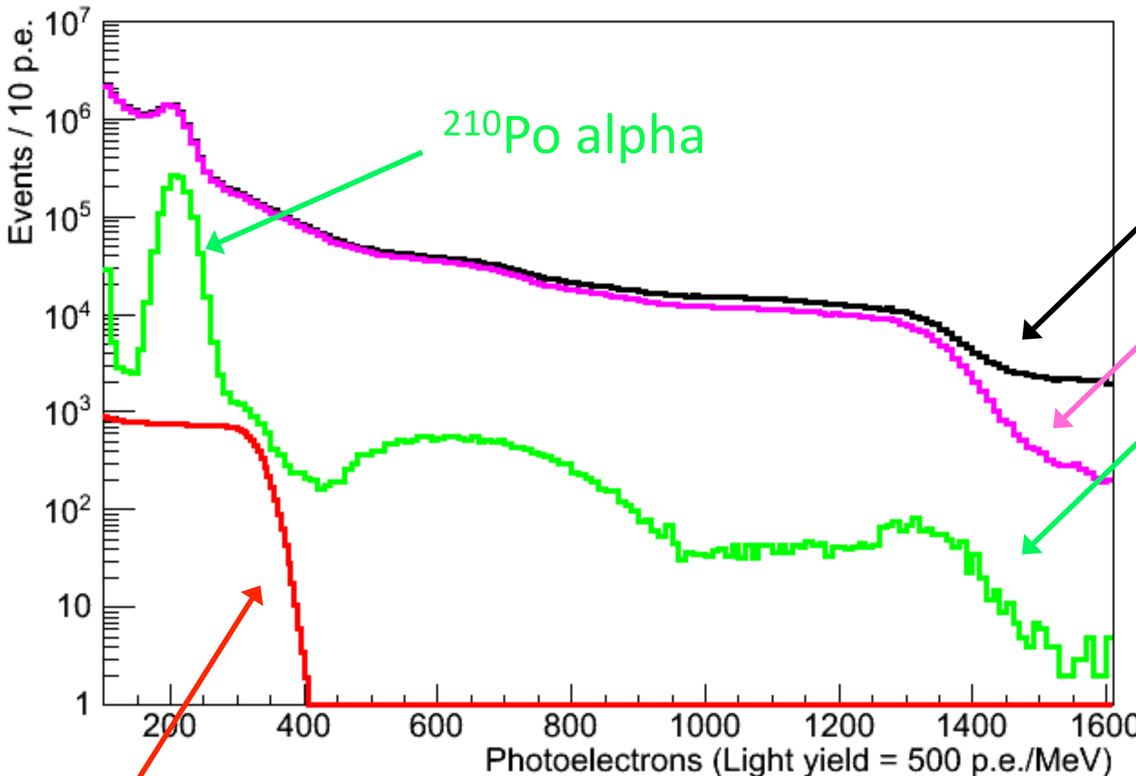
R < 3.02m

|z| < 1.67m




Fiducial mass = 75.6 tonnes

# Borexino Data




$^{210}$Po alpha

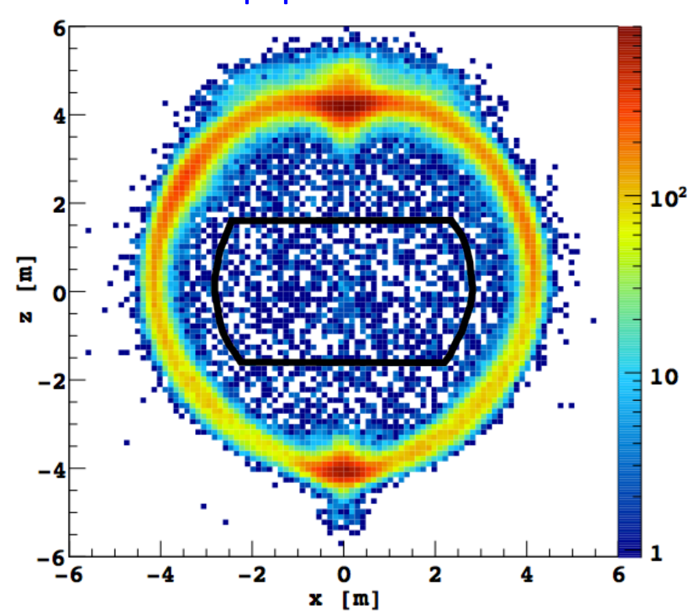
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

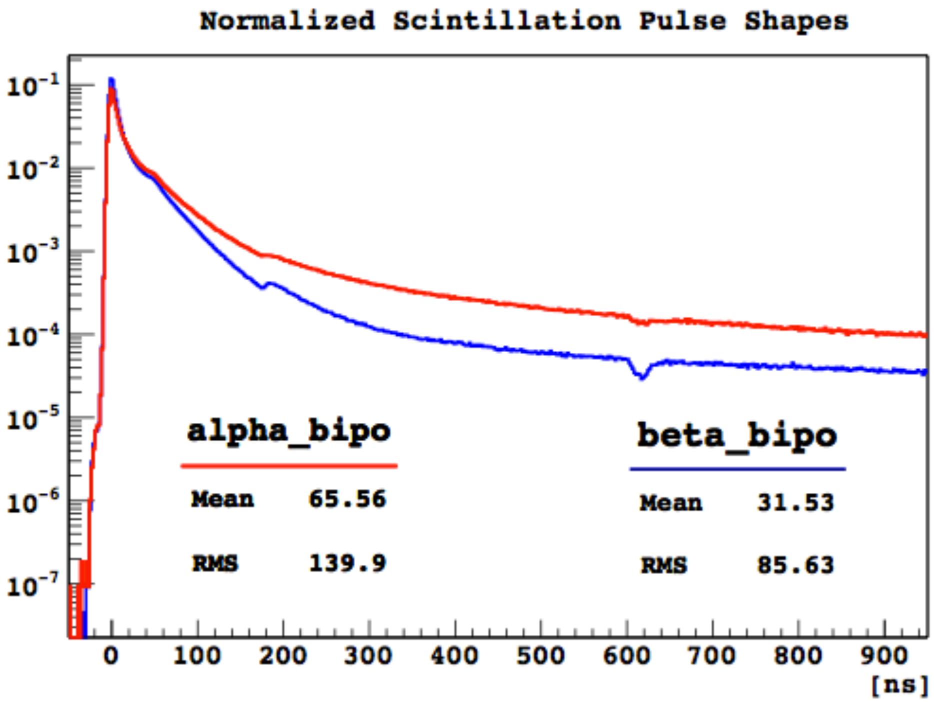
Expected $^{7}$Be signal

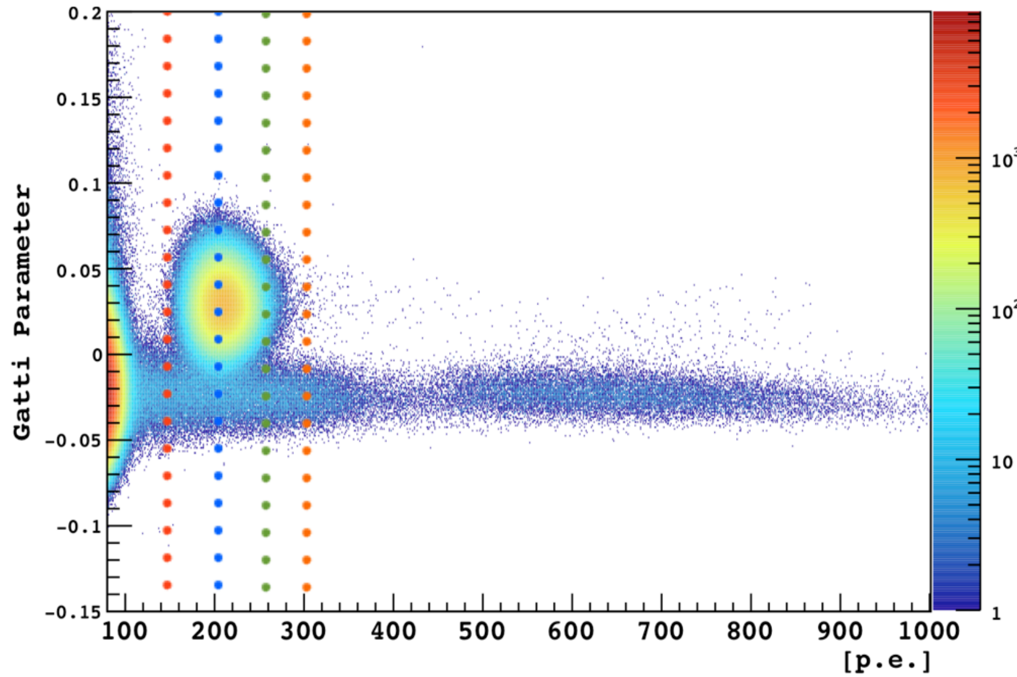
R < 3.02m
|z| < 1.67m




Fiducial mass = 75.6 tonnes

# Alpha Pulse Shape Discrimination



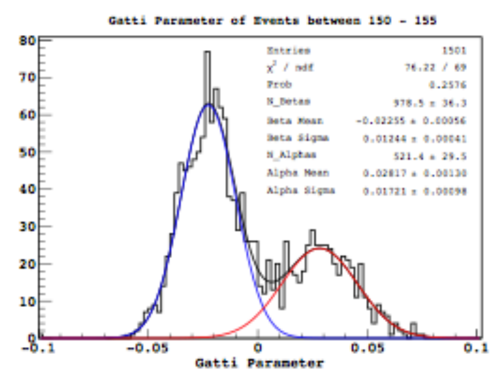




$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

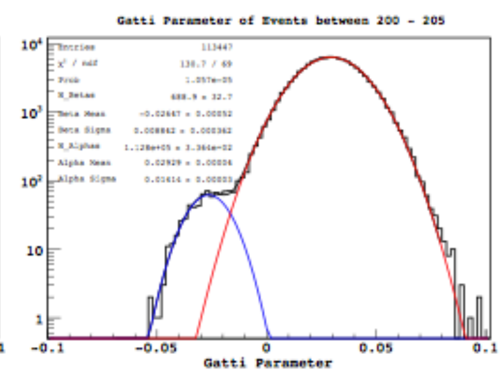
$$w[t] \equiv \frac{r_\alpha[t] - r_\beta[t]}{r_\alpha[t] + r_\beta[t]}$$

$e[t]$ : Event Time Profile

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

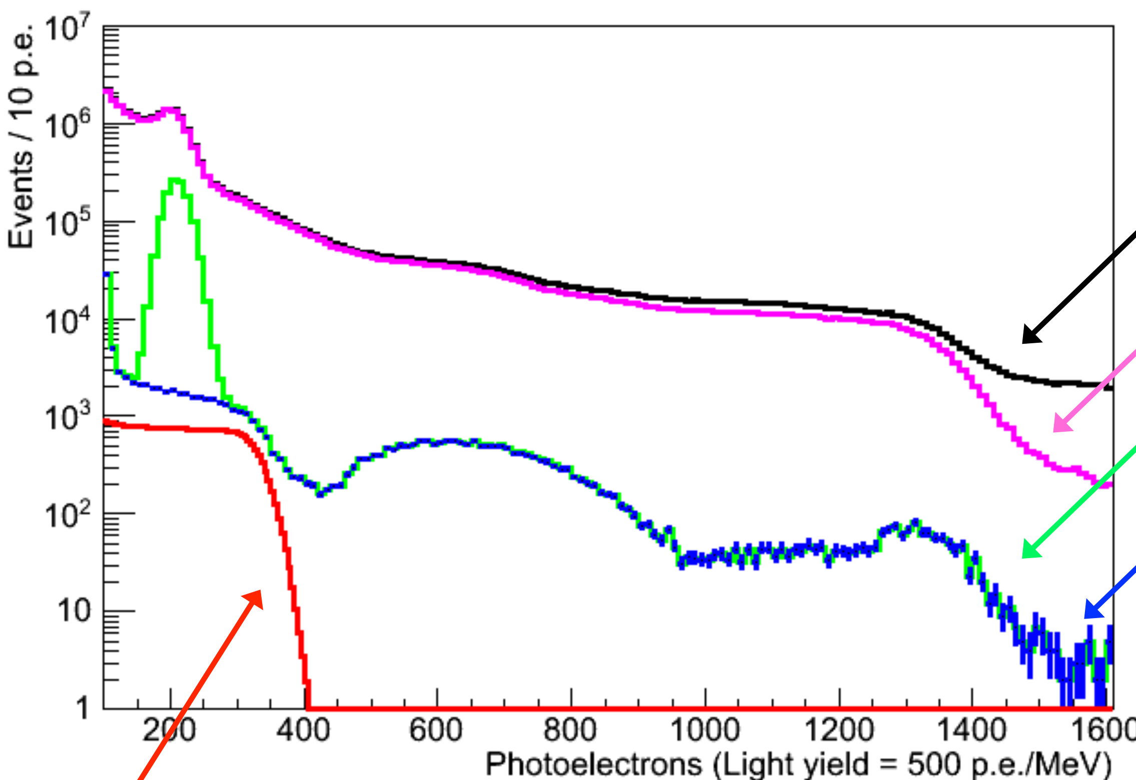



150 p.e.




200 p.e.

# Borexino Data




All data: 740 live days

Remove muons + followers

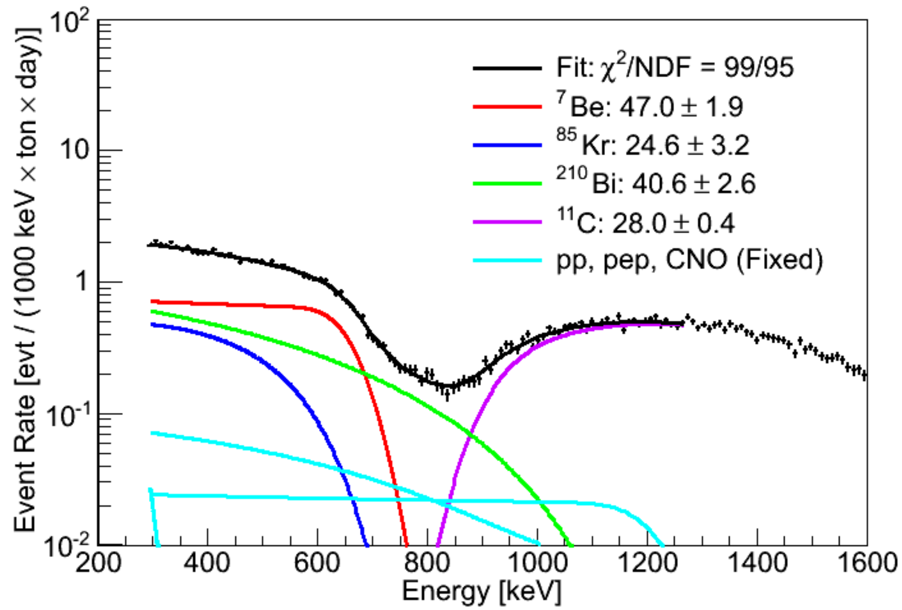
Fiducial Volume + high level

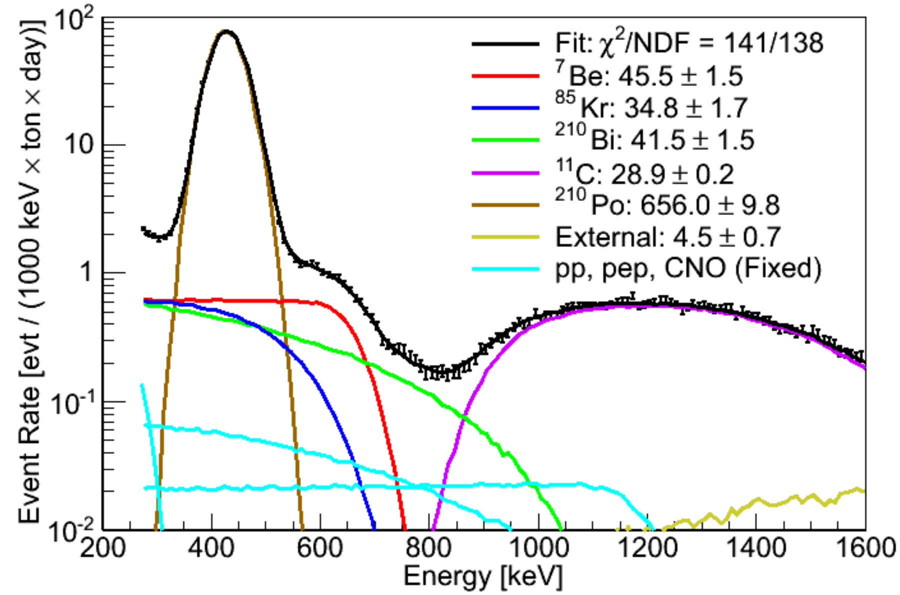
Statistically subtract alphas

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** | ${}^{+3.4}_{-3.6}\%$ |

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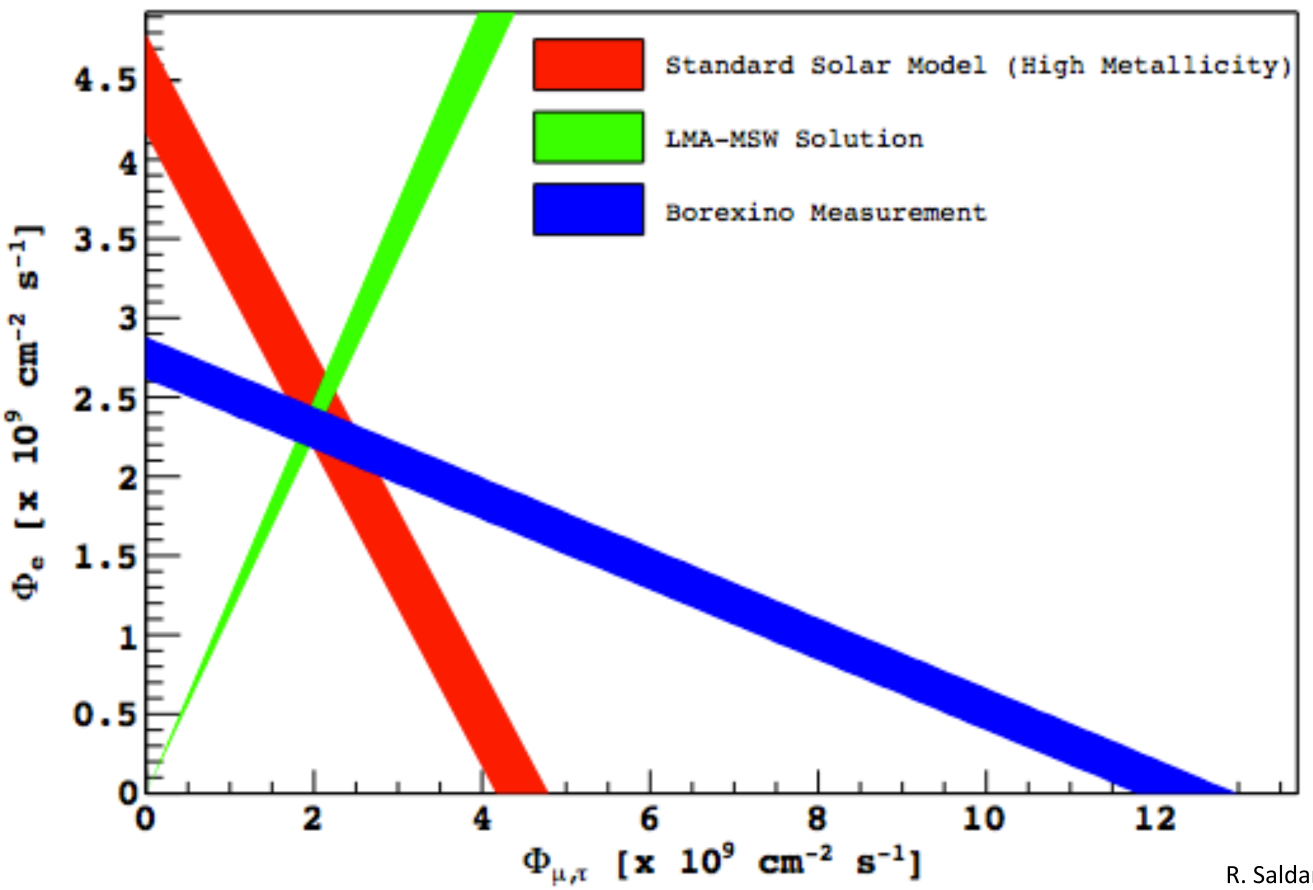
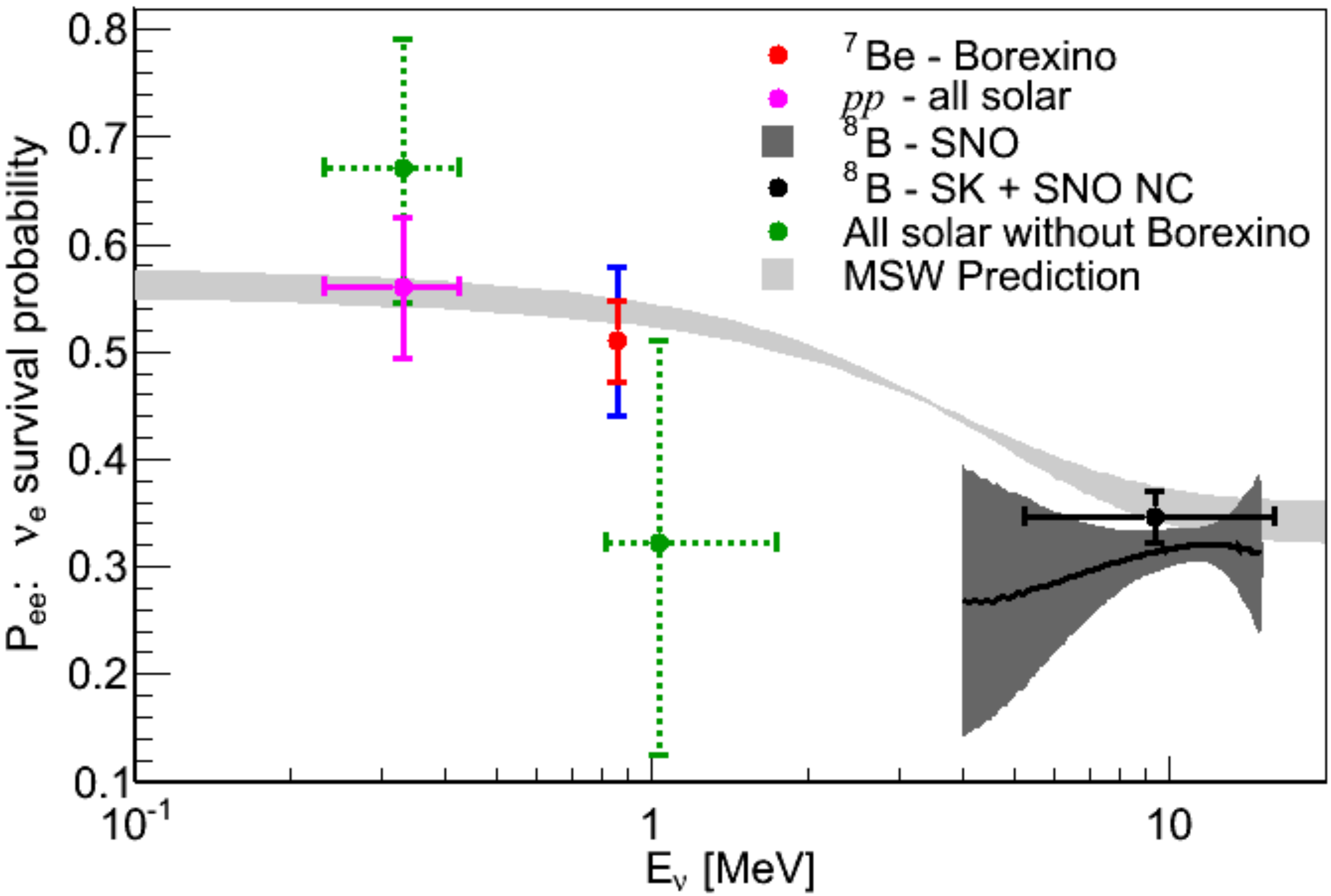


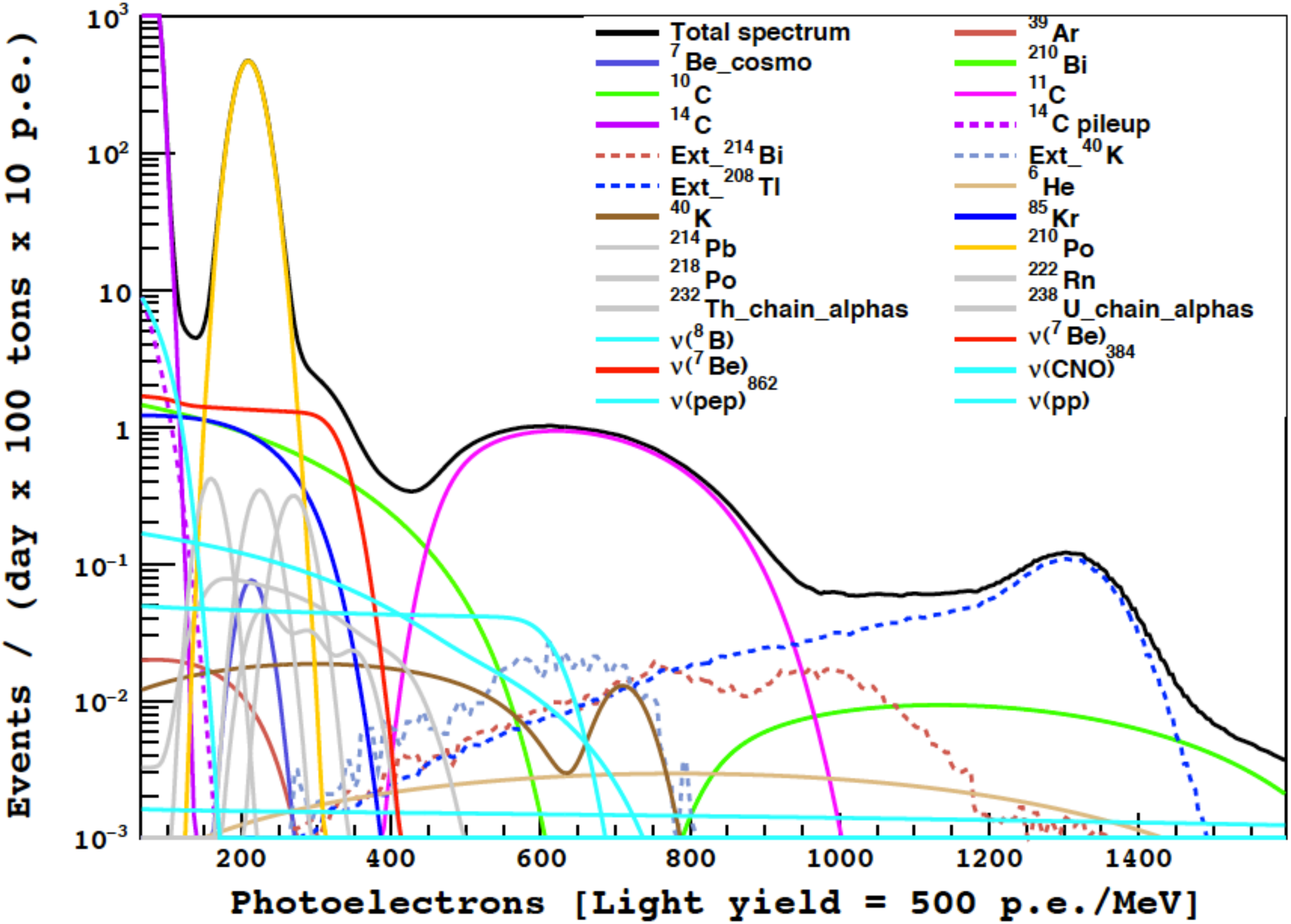

R. Saldanha, Ph.D. Thesis, Princeton (2011)

# Precision $^7$Be Flux Result

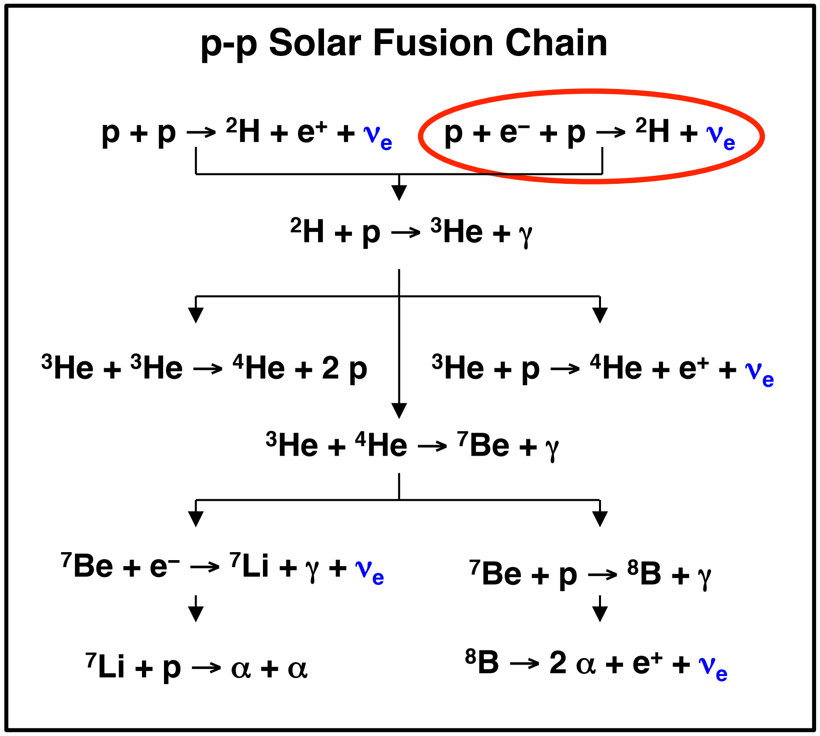


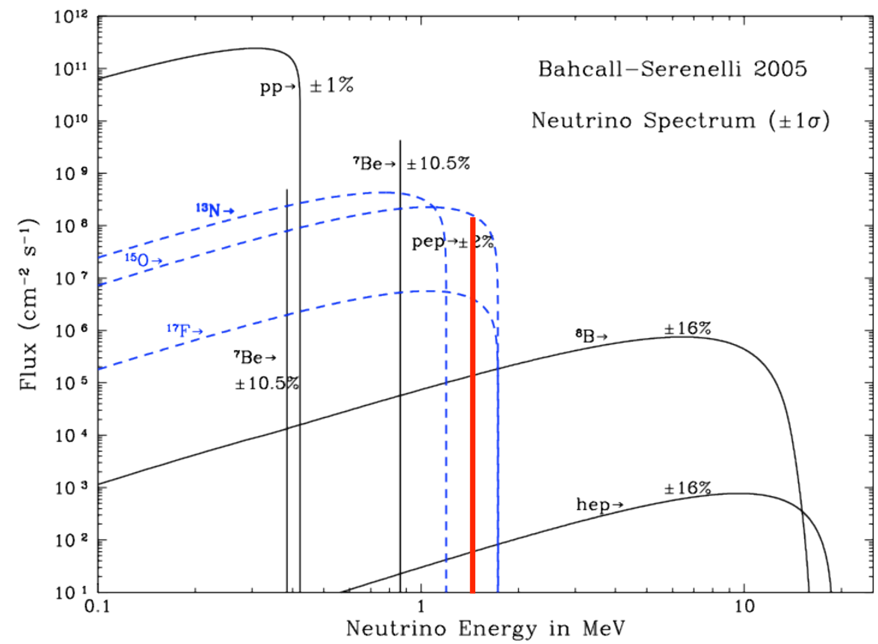

*Significantly improved constraint on low energy $P_{ee}$*

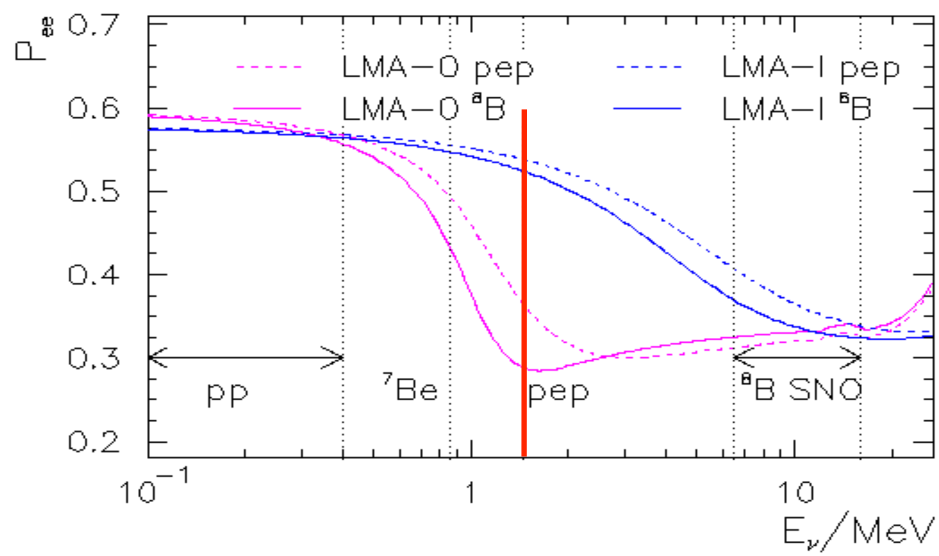
# "Into the Muck": *pep* and CNO Neutrinos



# *pep* Neutrinos



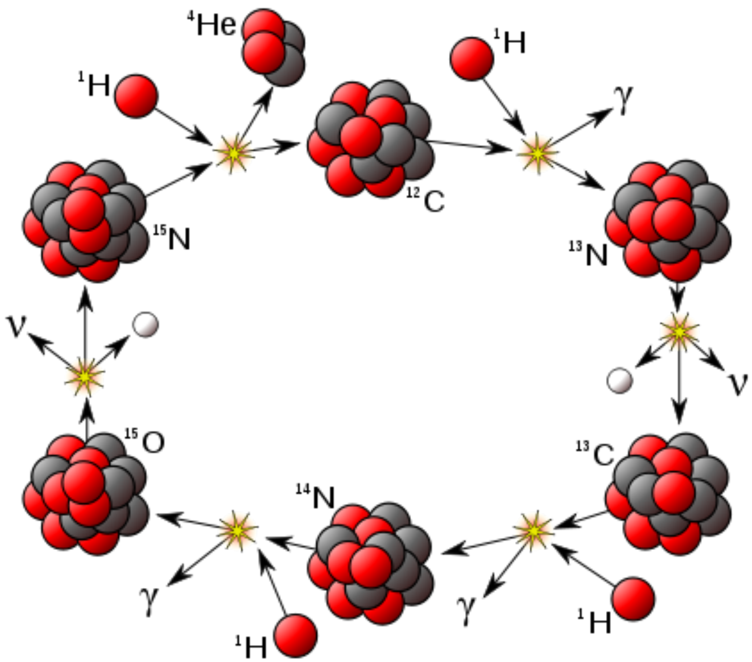




*First direct look at solar p-p fusion.*

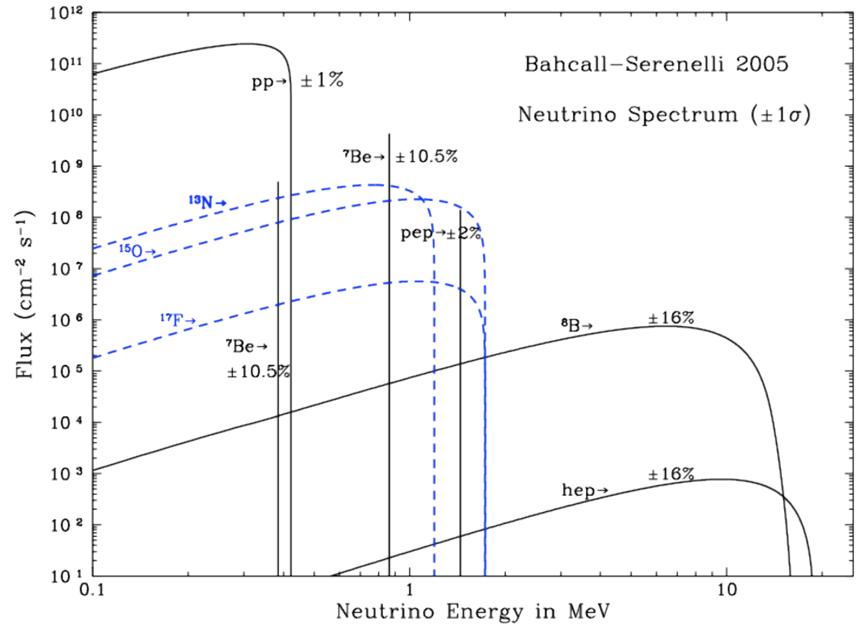
*Precision test of Standard Solar Model and oscillations.*

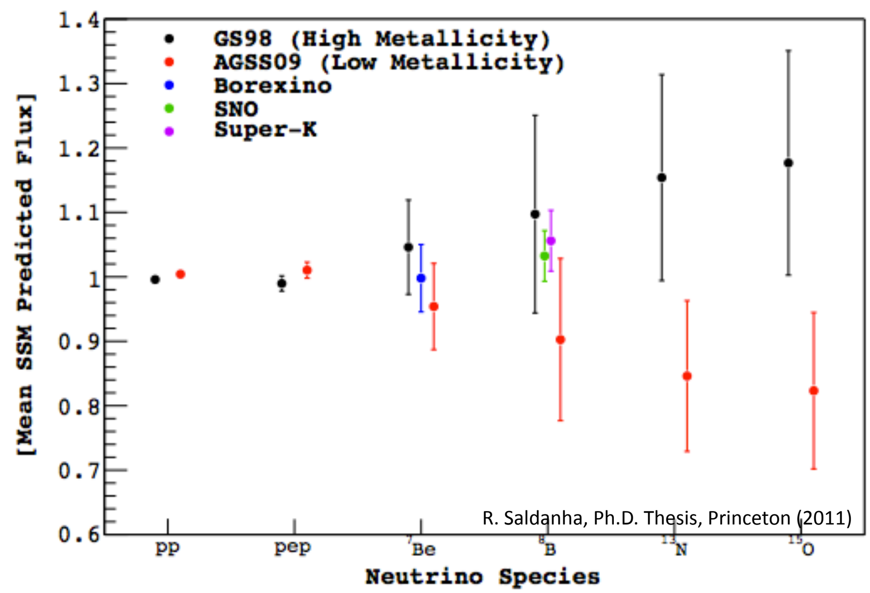
*Ideal energy to probe transition region.*

# CNO Neutrinos




Wikimedia.org



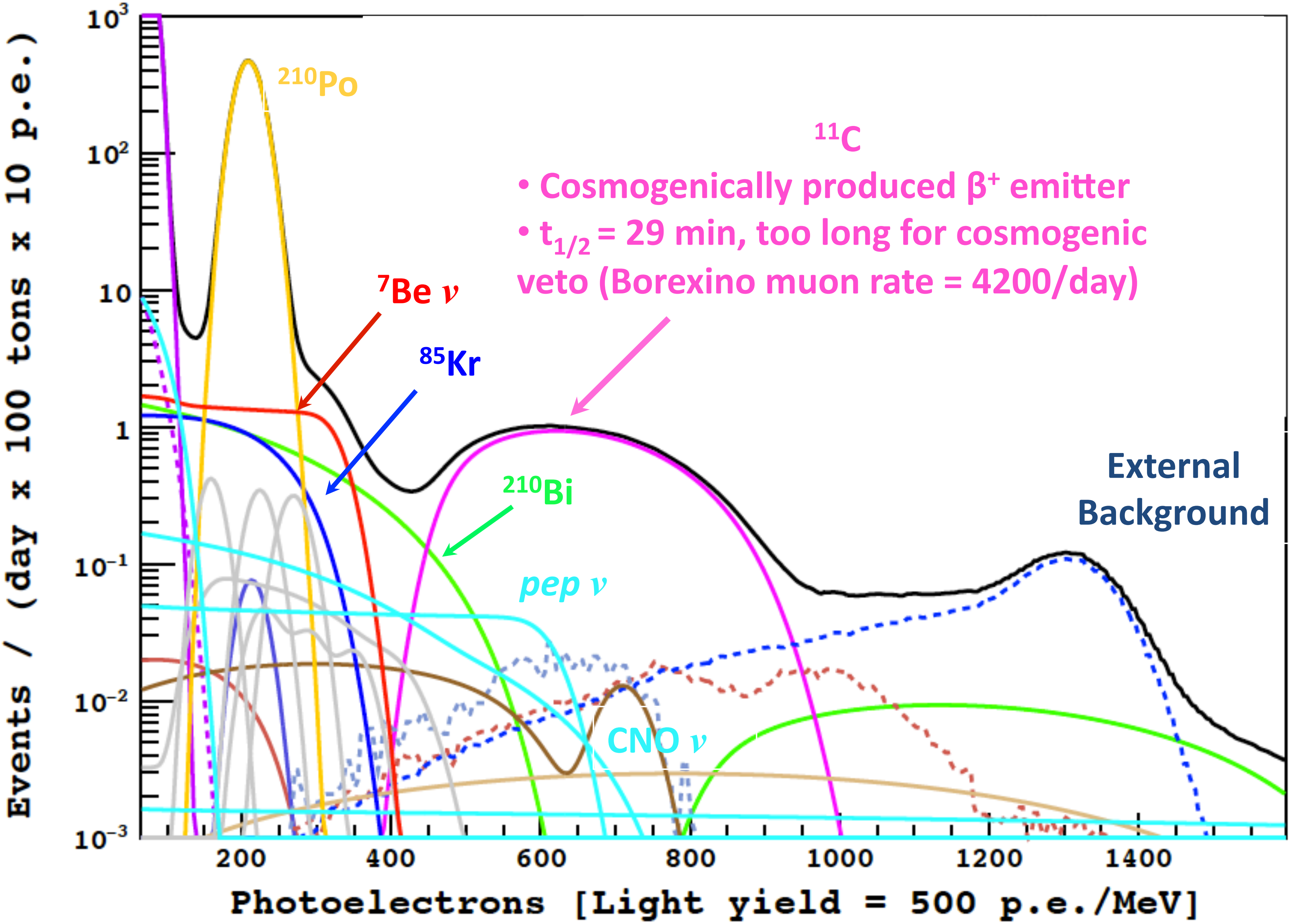




R. Saldanha, Ph.D. Thesis, Princeton (2011)

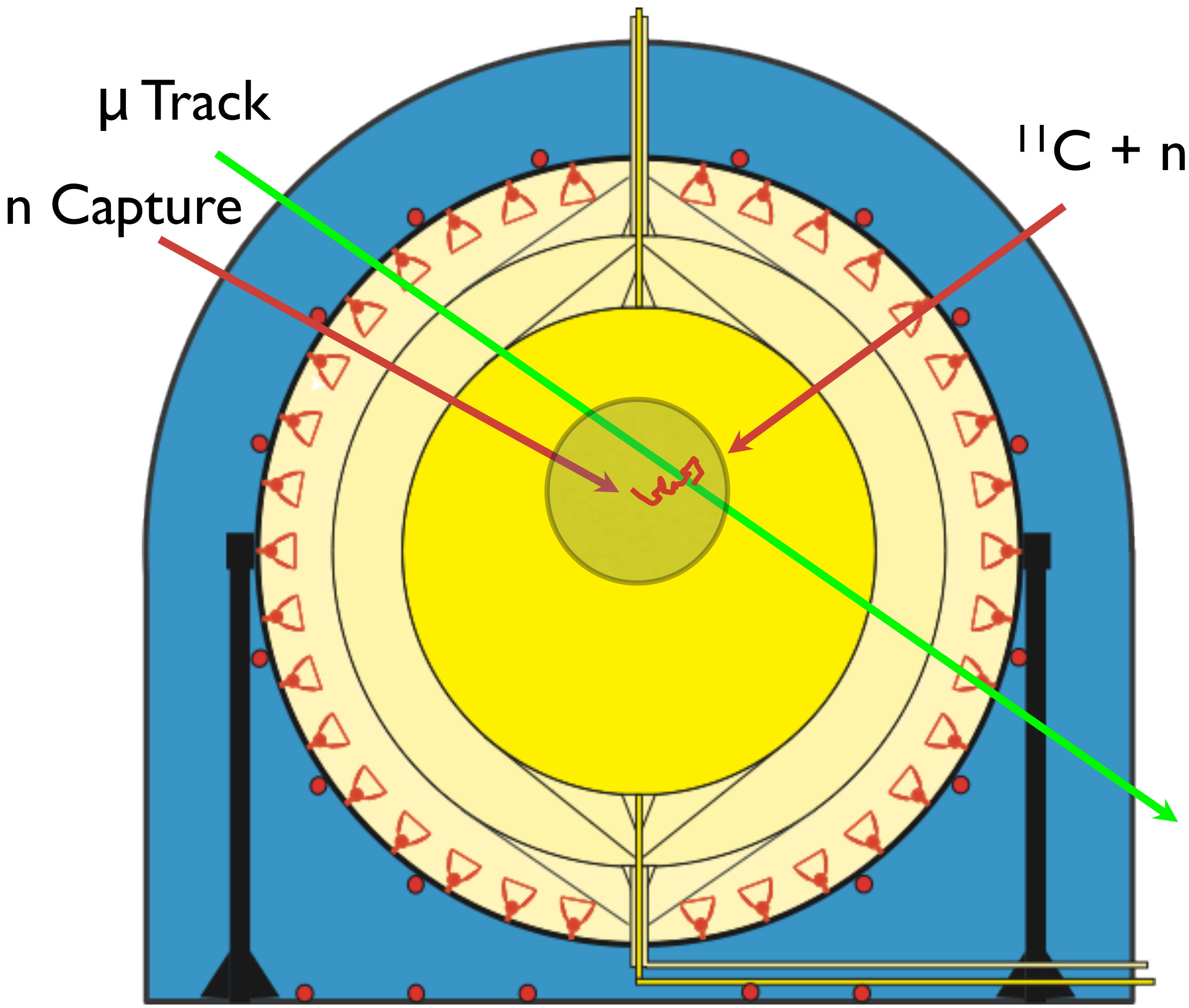
*First direct evidence for CNO cycle.*

*Measure solar metallicity.*

# $^{11}C$ Suppression



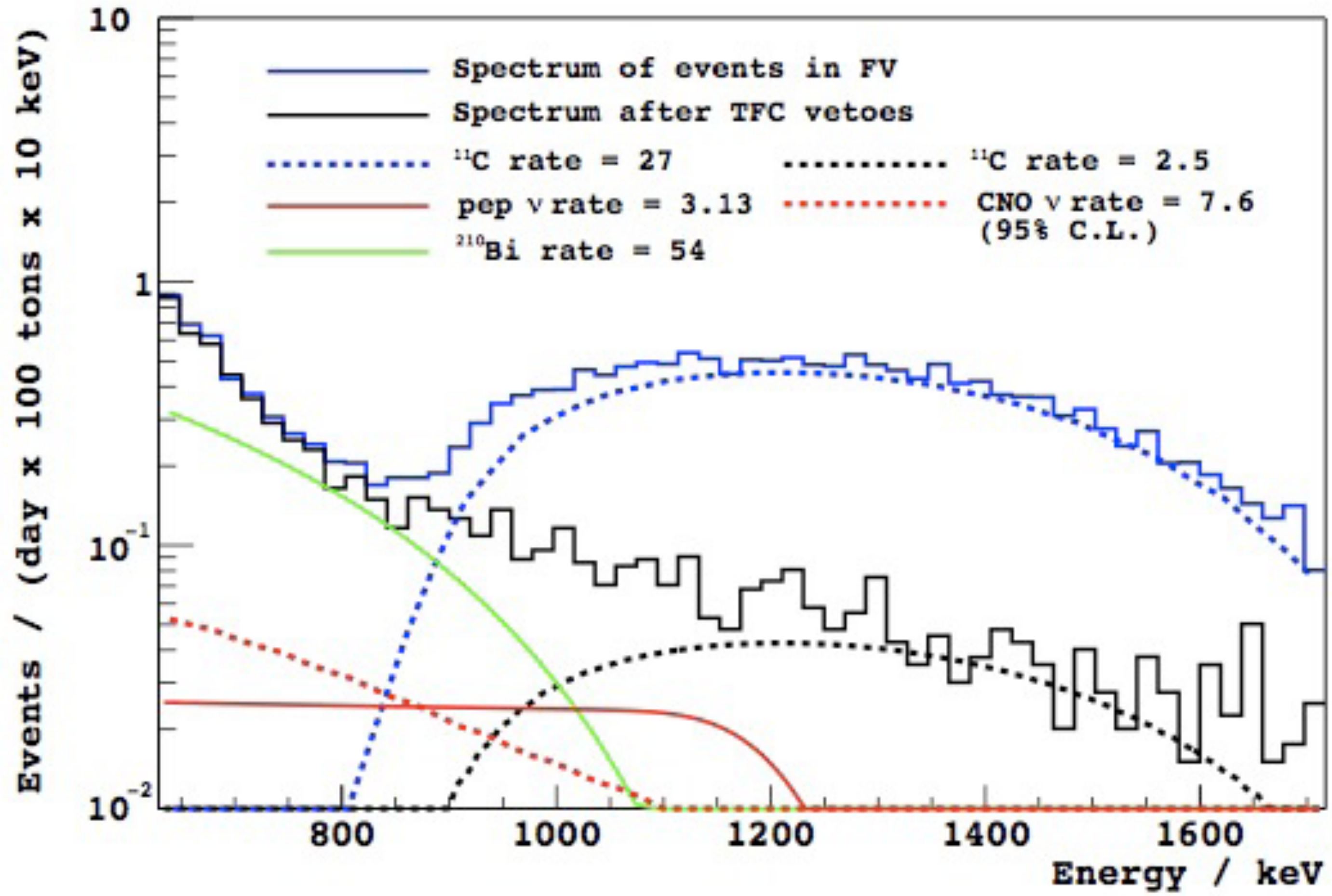
# Three-Fold Coincidence




- 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.***

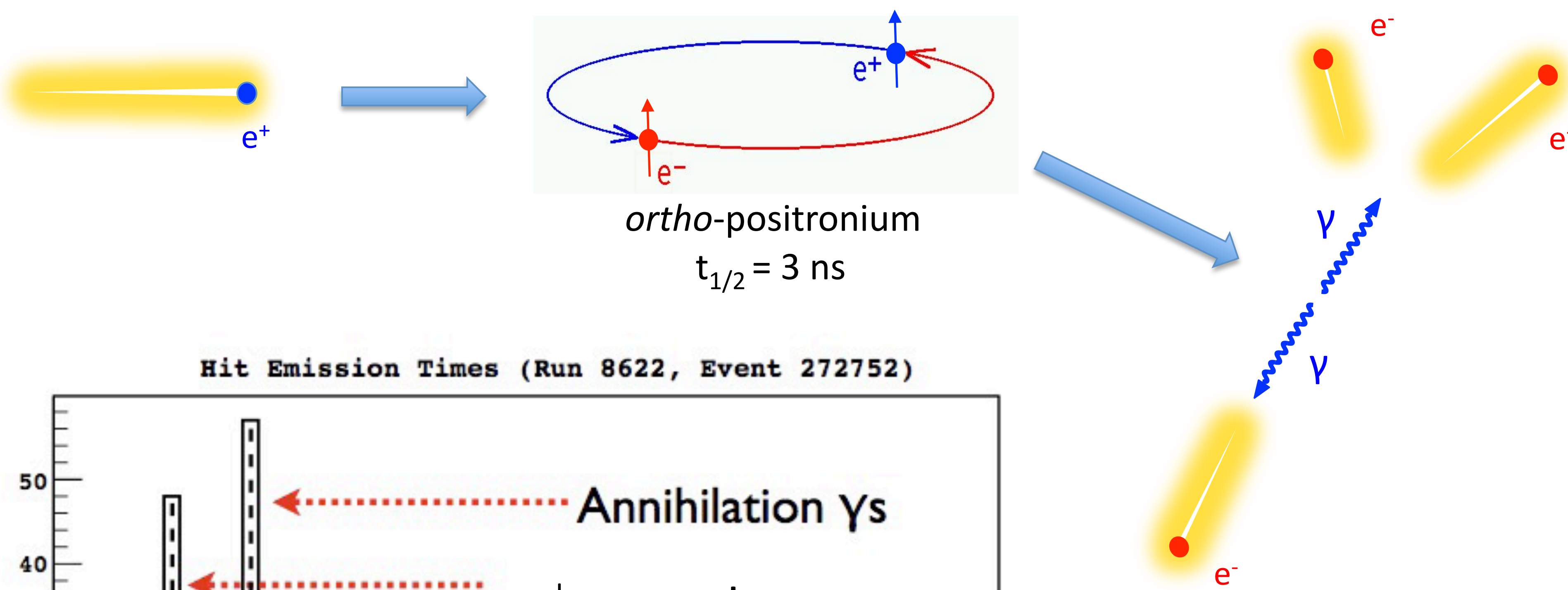
# Three-Fold Coincidence

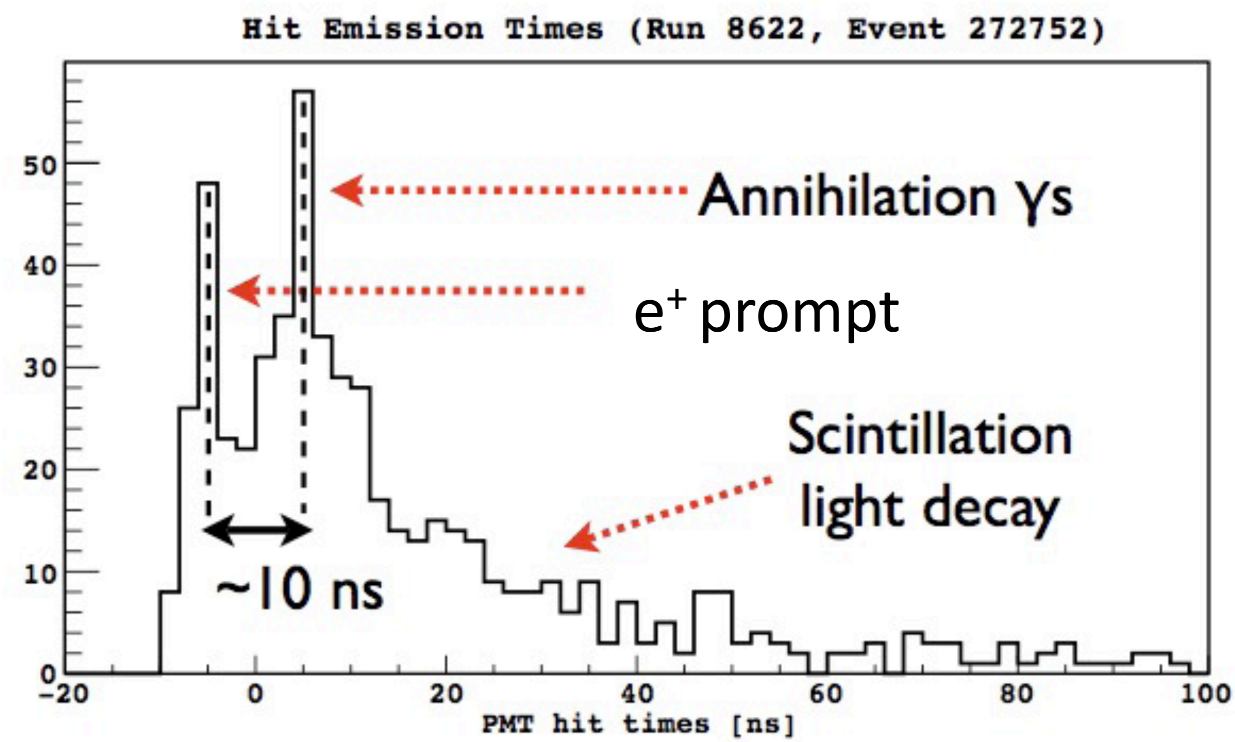



Remove 91% of $^{11}C$ and 51.5% of livetime.

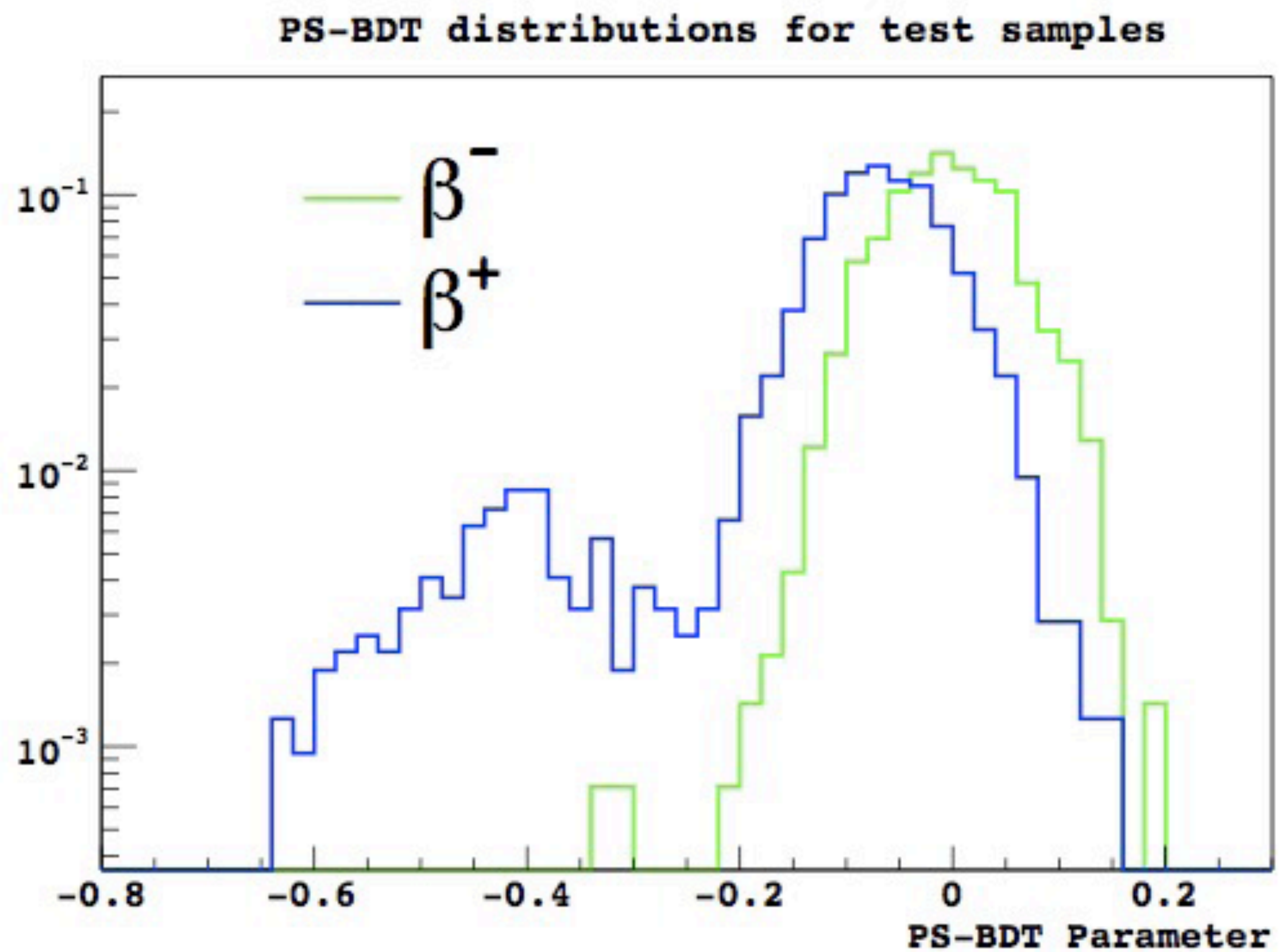
# $e^+/e^-$ Pulse Shape Discrimination

(PRC 83:015522 (2011))



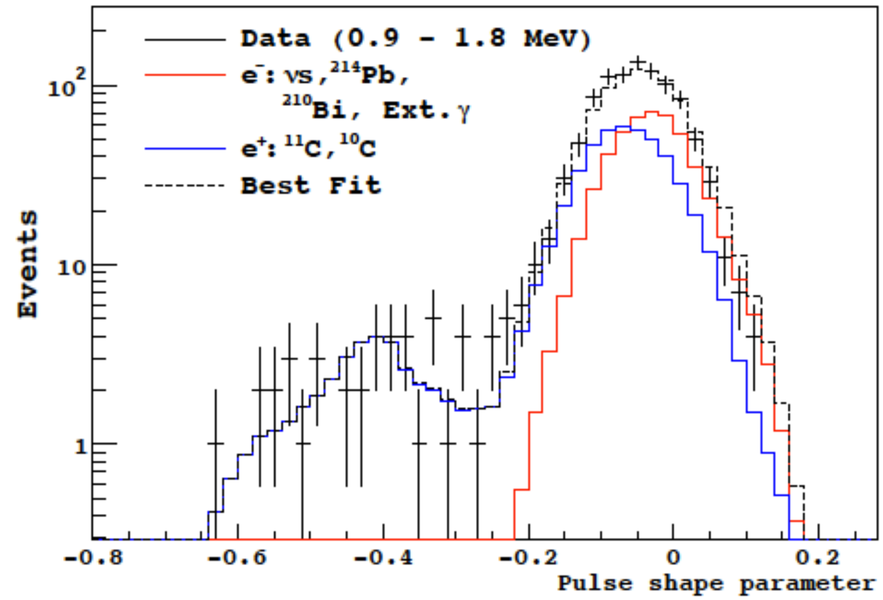
# $e^+/e^-$ Pulse Shape Discrimination

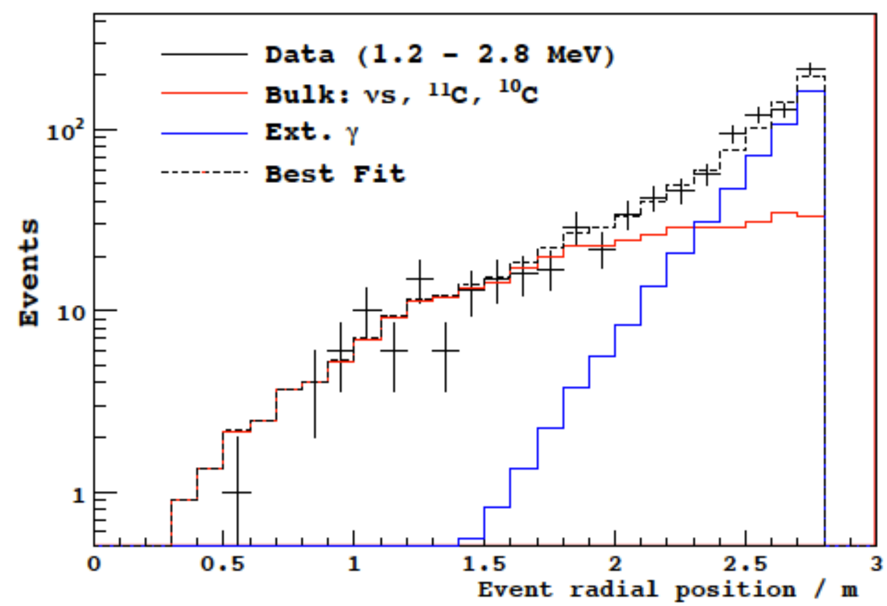



*Boosted decision tree (BDT) discrimination parameter from pulse shape information.*

# *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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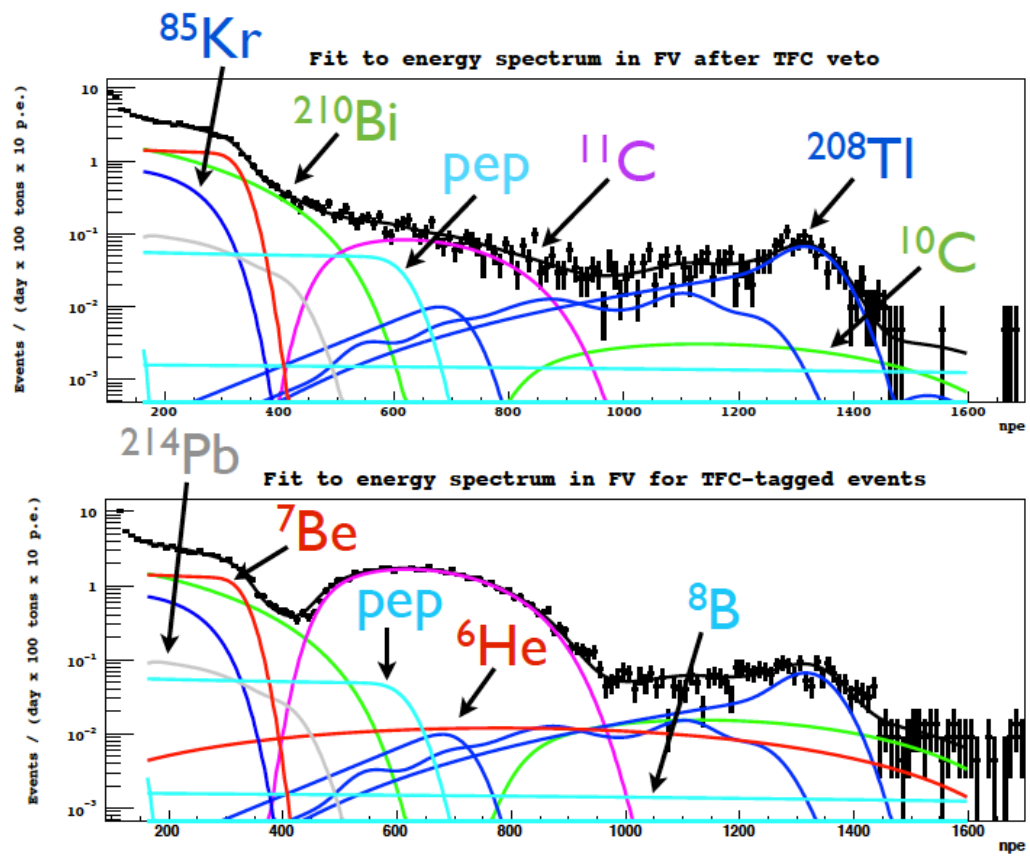
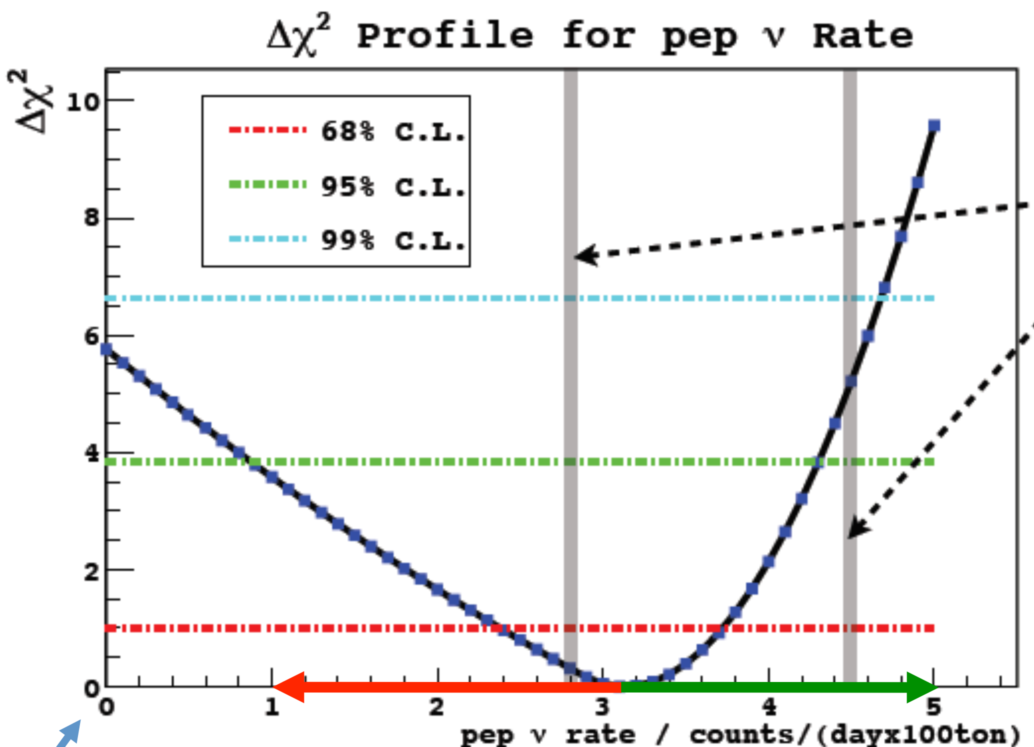


# *pep* Result

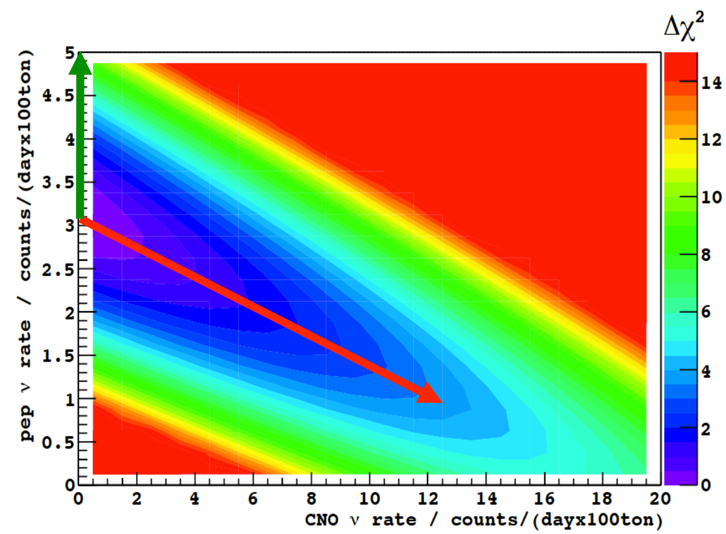
(Phys. Rev. Lett. **108**:051302 (2012))

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

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



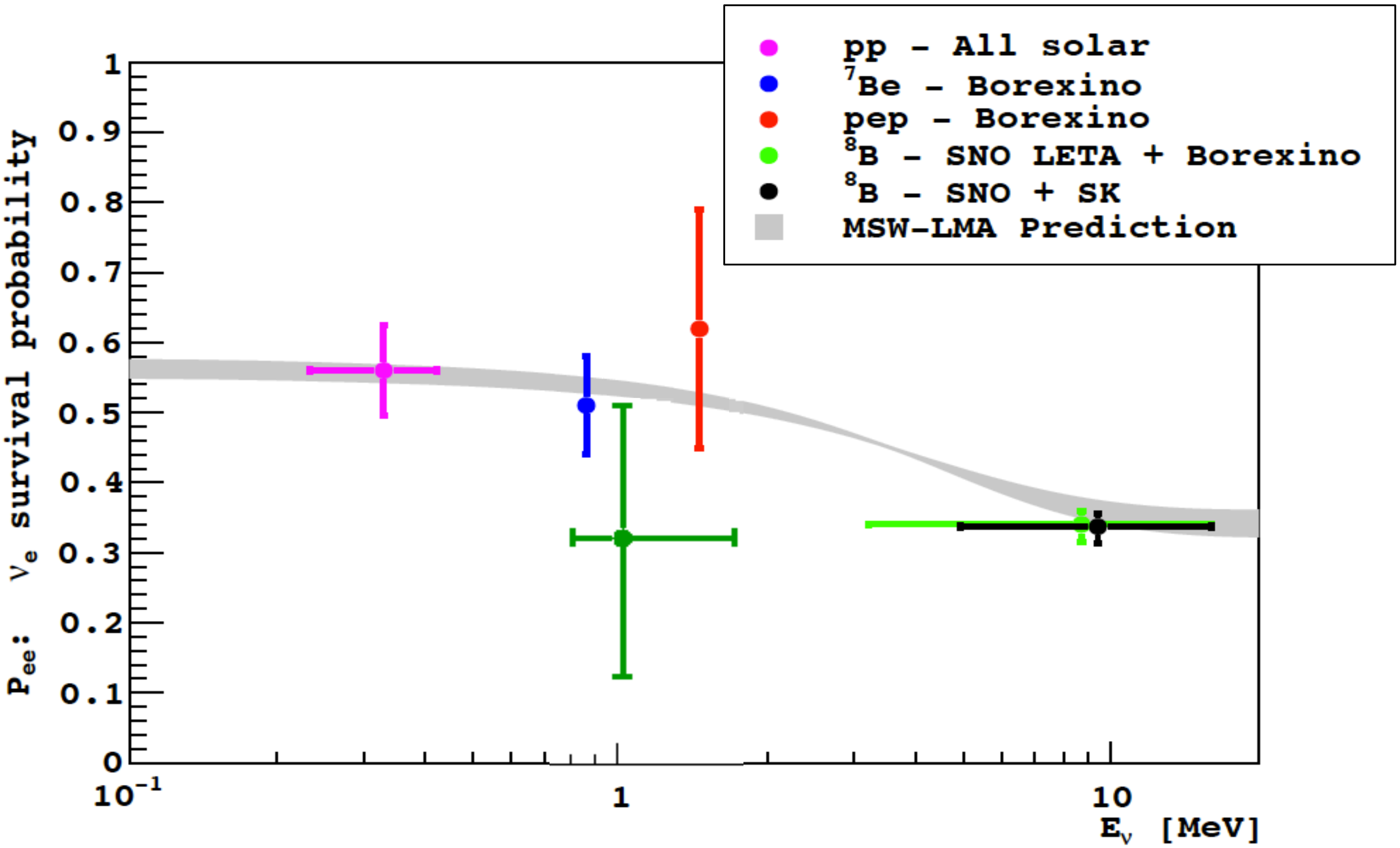

SSM Prediction
MSW-LMA
No Oscillation




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

# *pep* Result

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



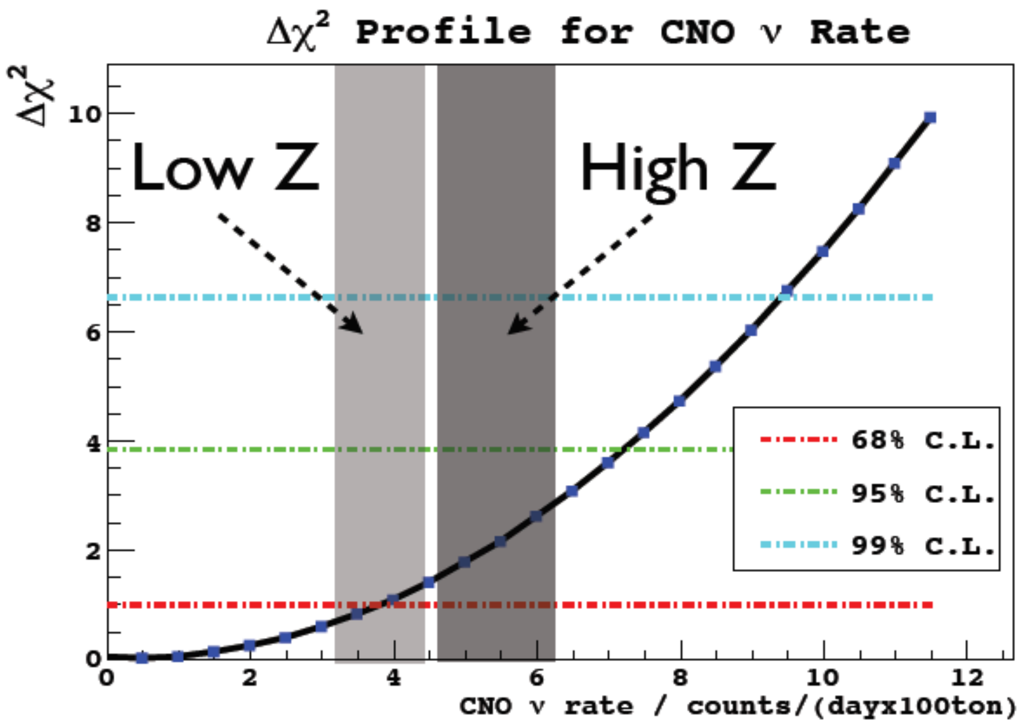

*We have succeeded in extracting the pep signal from the background – more precise results possible in the future!*

# CNO Limit

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

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

→ $< 7.7 \times 10^8$ $cm^{-2}s^{-1}$ (< 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.*

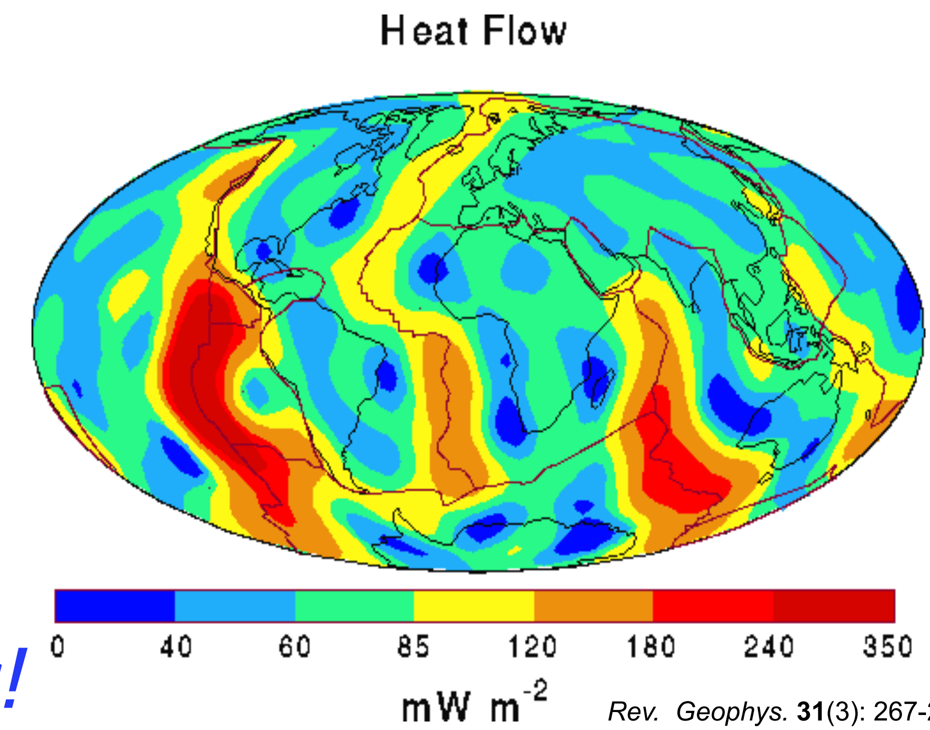
*Result consistent with both high and low metallicity models.*

# Geo-Neutrinos

- Antineutrinos from $\beta^-$ 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

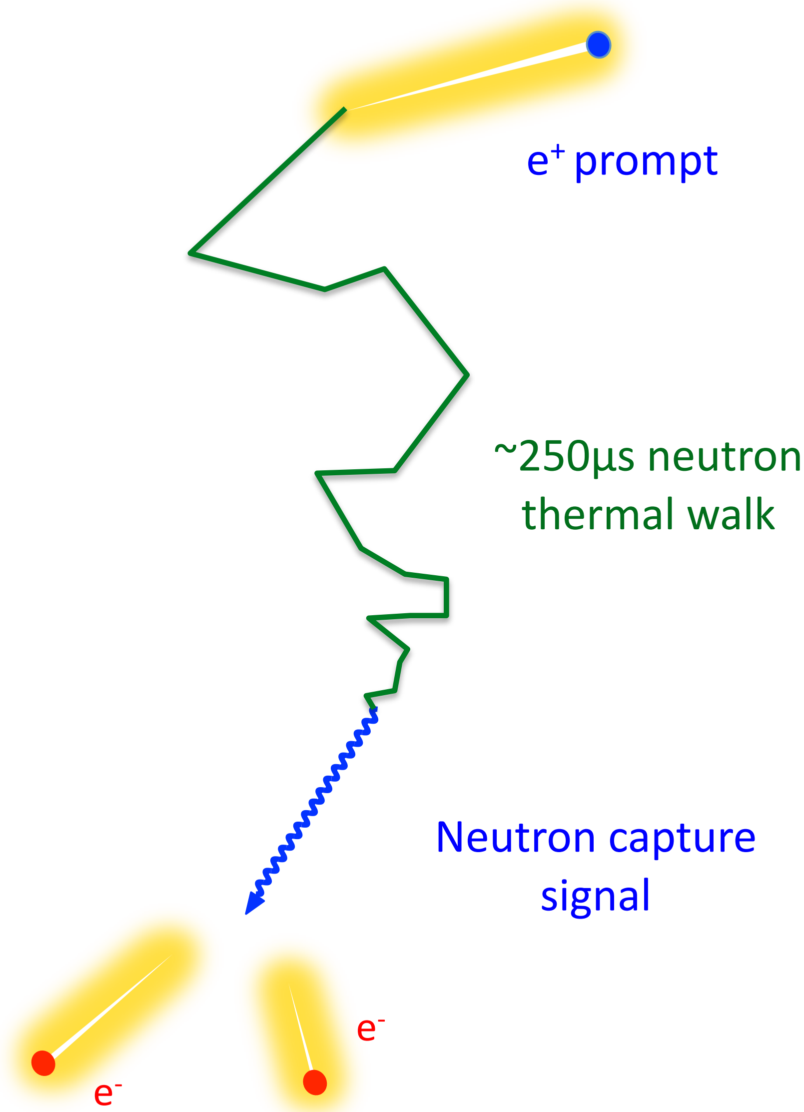



*Rev. Geophys.* **31**(3): 267-280 (1993)

*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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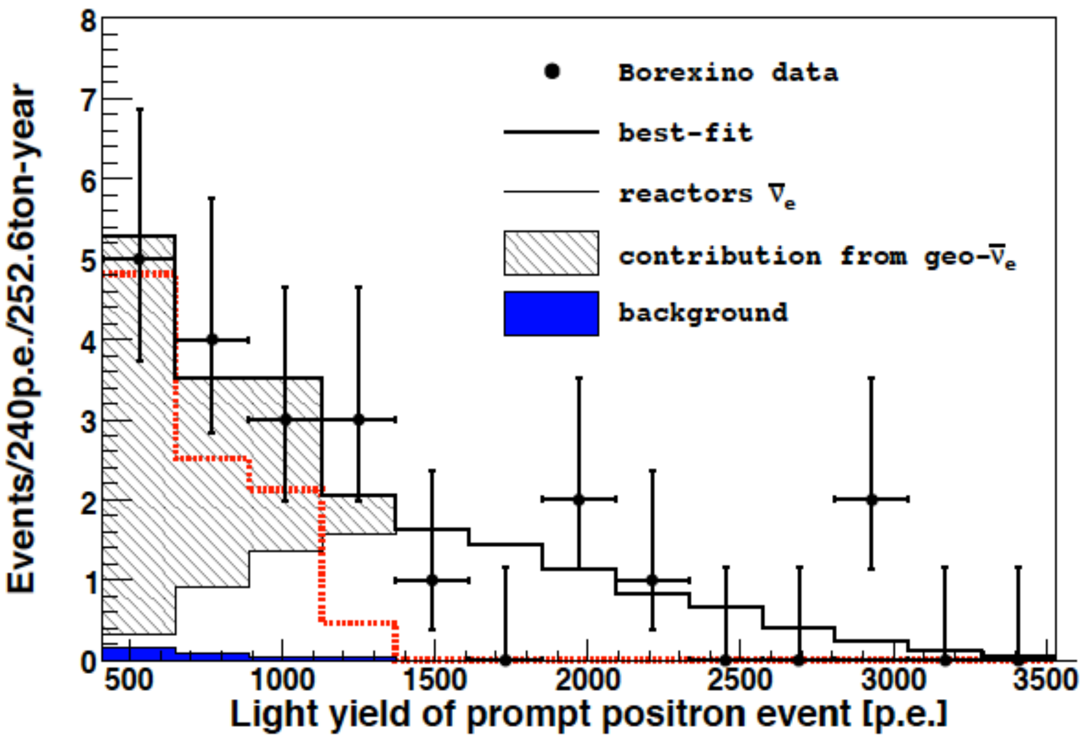
# Geo-neutrinos in Borexino

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

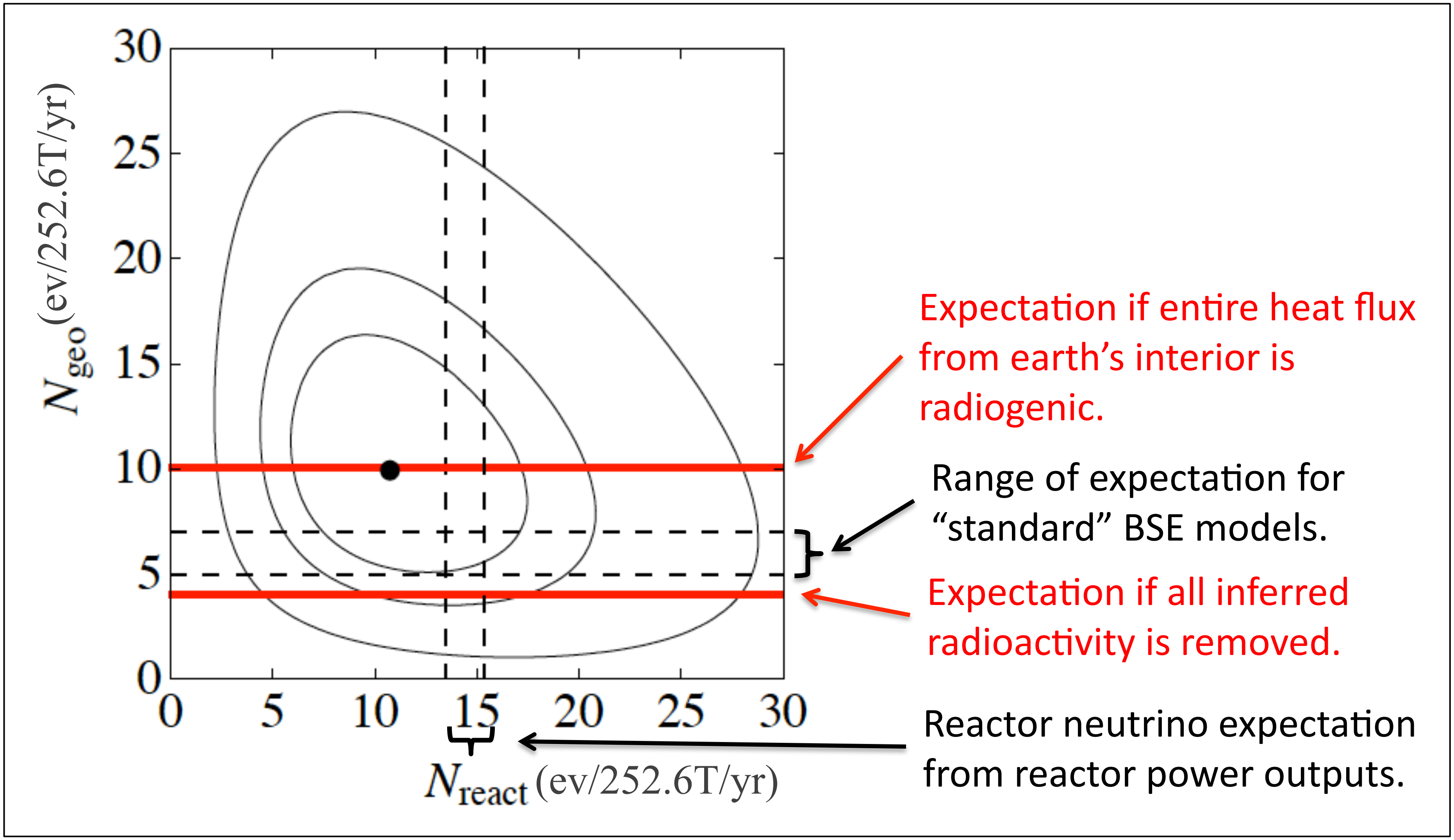
**Borexino Geo-Neutrino Rate: $3.9^{+1.6}_{-1.3}$ ev/100T/yr**




Delayed Co-incidence Backgrounds

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

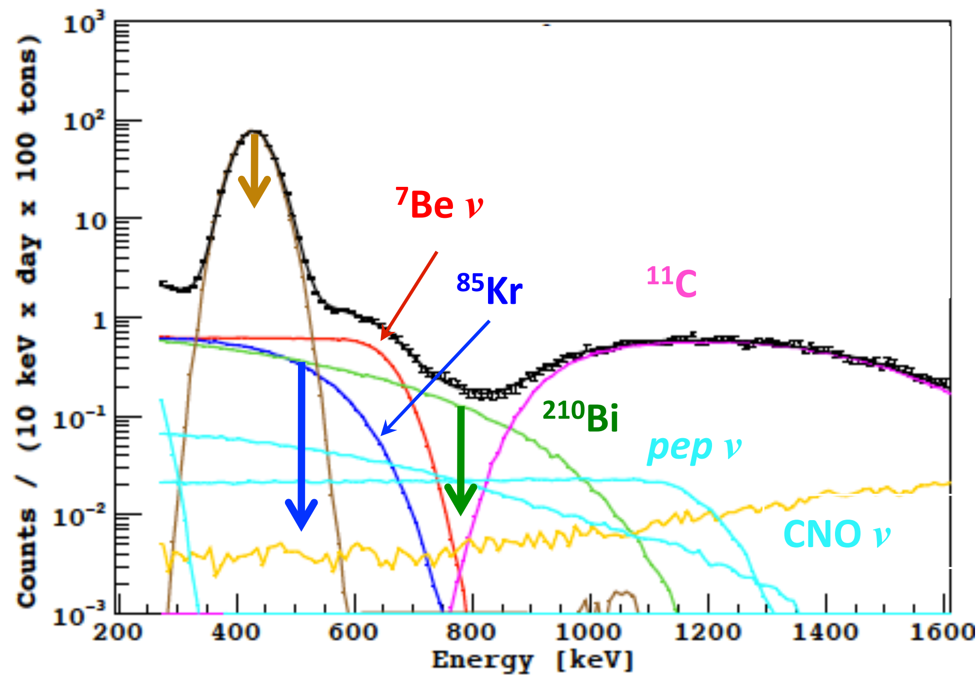
# Geo-neutrinos in Borexino




***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

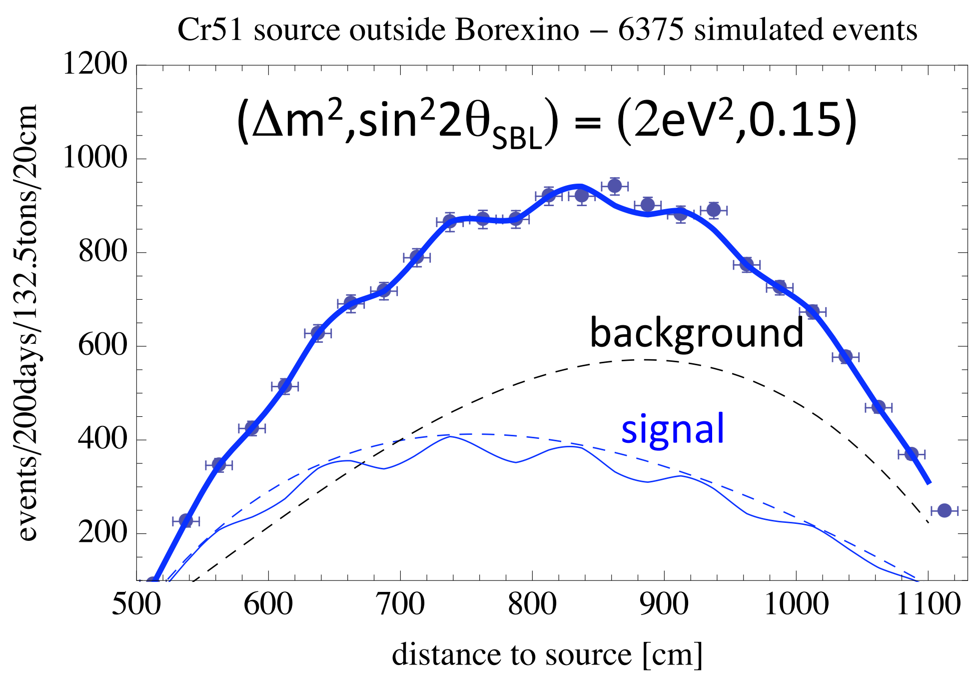
- Procedures to (further!) purify the scintillator underway since July 2010
  - No sign of $^{85}$Kr since January 2011
  - Moderate reduction in $^{210}$Bi
- Operations continue, with aim of further reducing $^{210}$Bi, perhaps $^{210}$Po
- Borexino will continue to take solar neutrino data for >3 more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




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

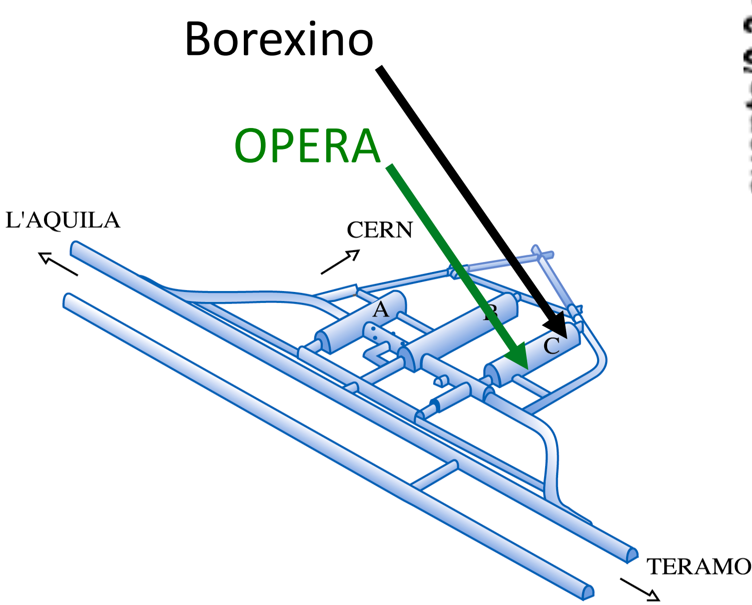
# Sterile Neutrino Search

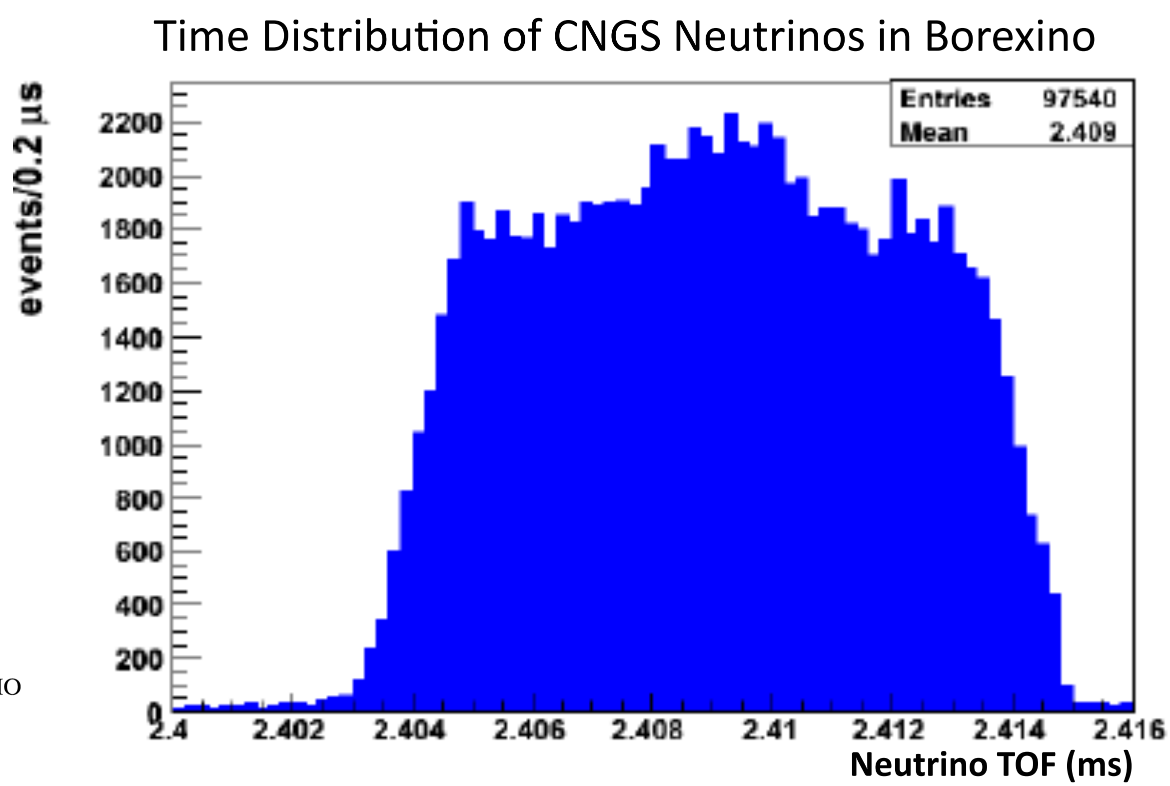
- Several experiments (LBNE, "reactor anti-neutrino anomaly," "gallium anomaly," CMB) give weak evidence for a 4th, sterile, neutrino
- Deploying a strong (10 MCi) electron capture neutrino source near Borexino would allow us to look for oscillations within the detector!



# Neutrino Time-Of-Flight

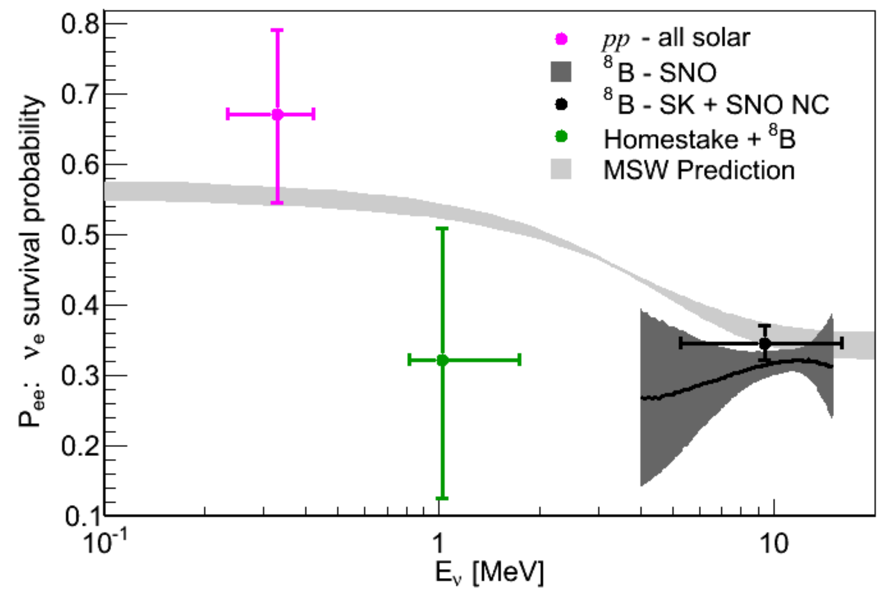
- Borexino is located between OPERA and CERN
- We detect CNGS neutrinos too (JINST **6**:P05005 (2011))
- Timing system upgrades would allow Borexino to test the OPERA result (arXiv:1109.4897) - at least the detection part

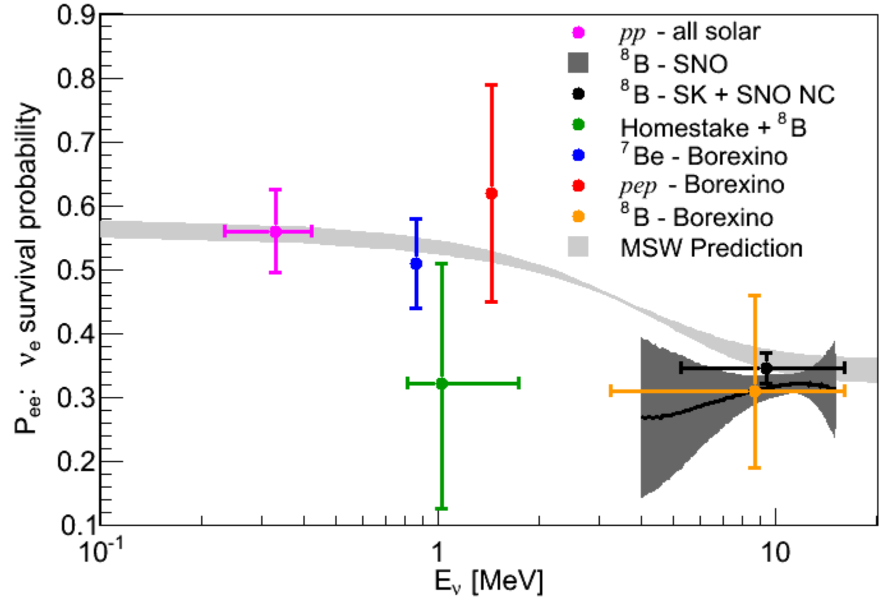


# Summary

- 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!



# SNO+

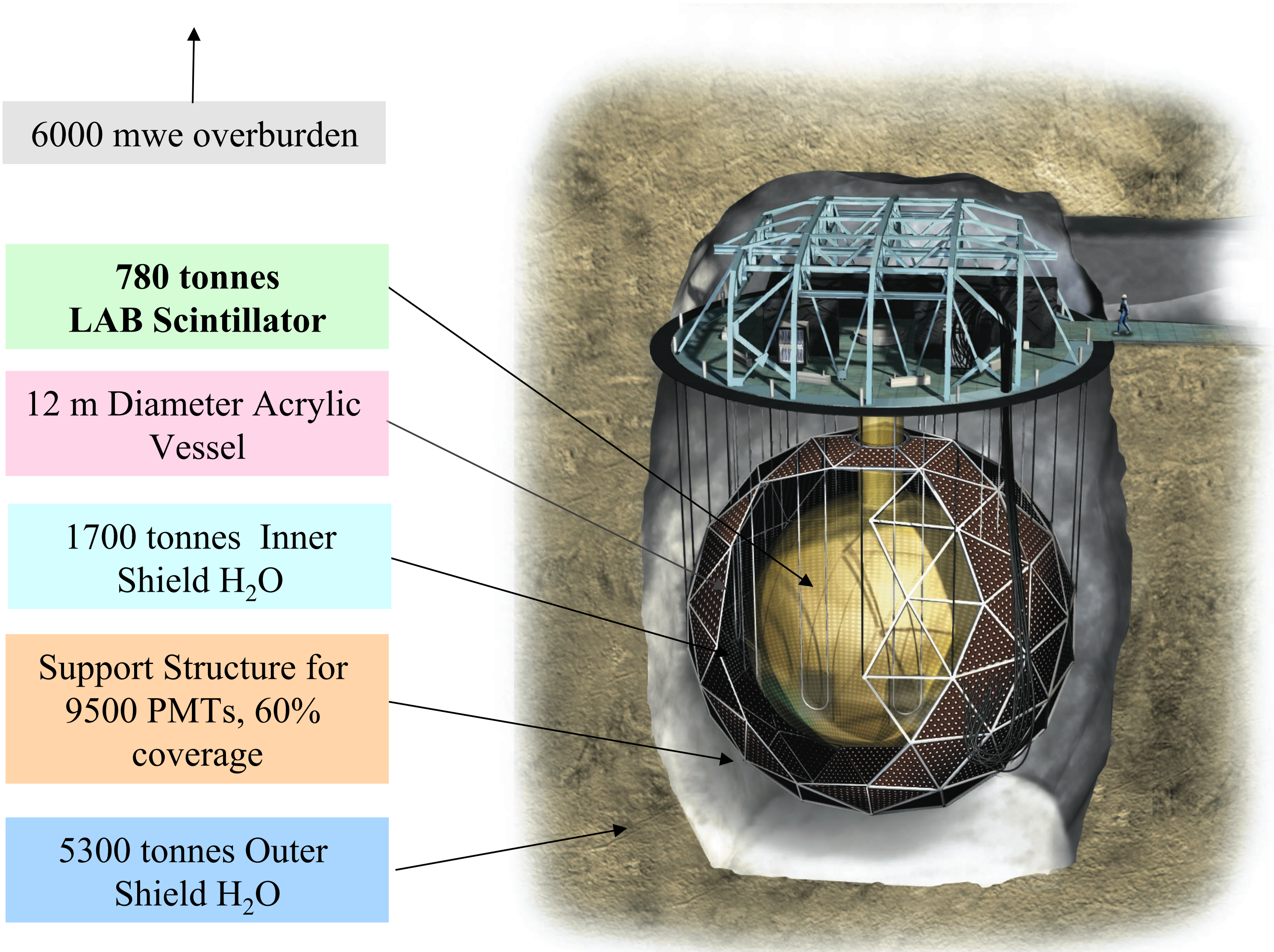
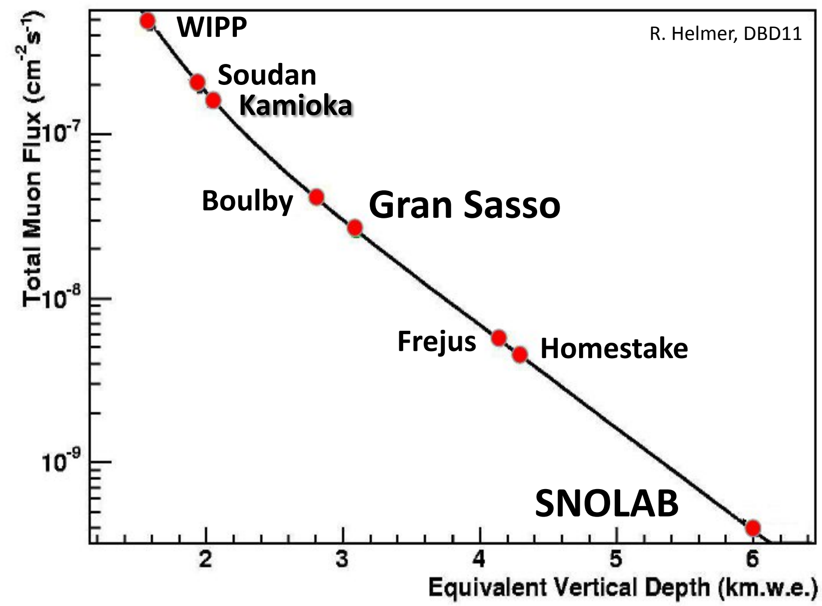


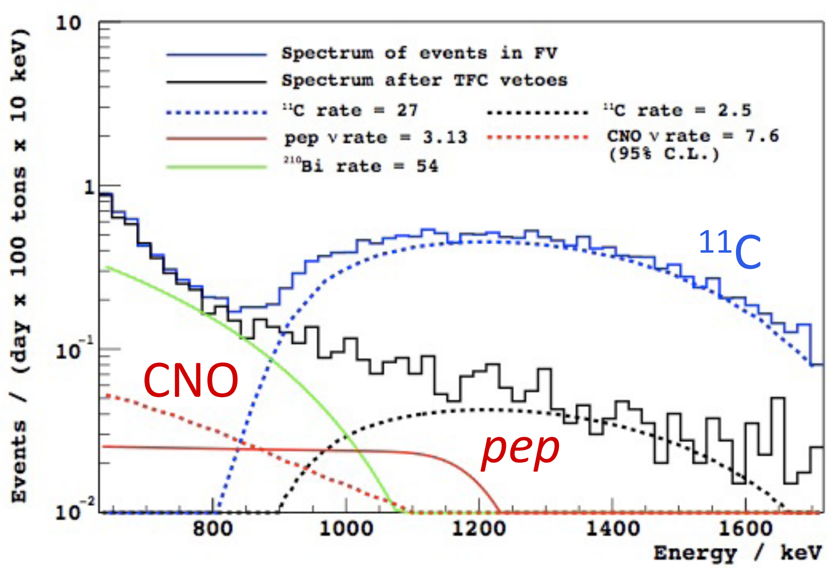

Image courtesy National Geographic

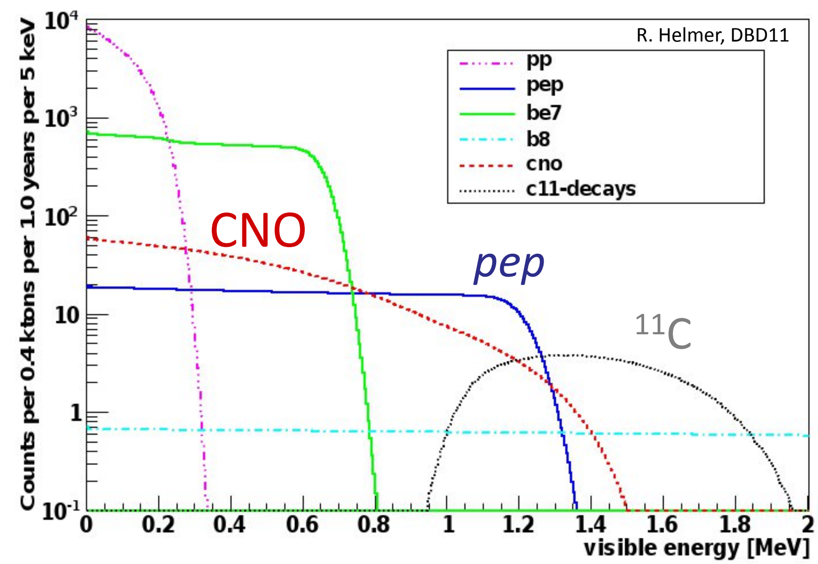
*Refilling the Sudbury Neutrino Observatory with organic scintillator to make (another) very capable neutrino detector!*

# SNO+ Physics: Solar Neutrinos

- Precise measurement of the *pep* (~5% total uncertainty)
- Aim to measure the CNO
- Continue to push $^{8}B$ to lower energy



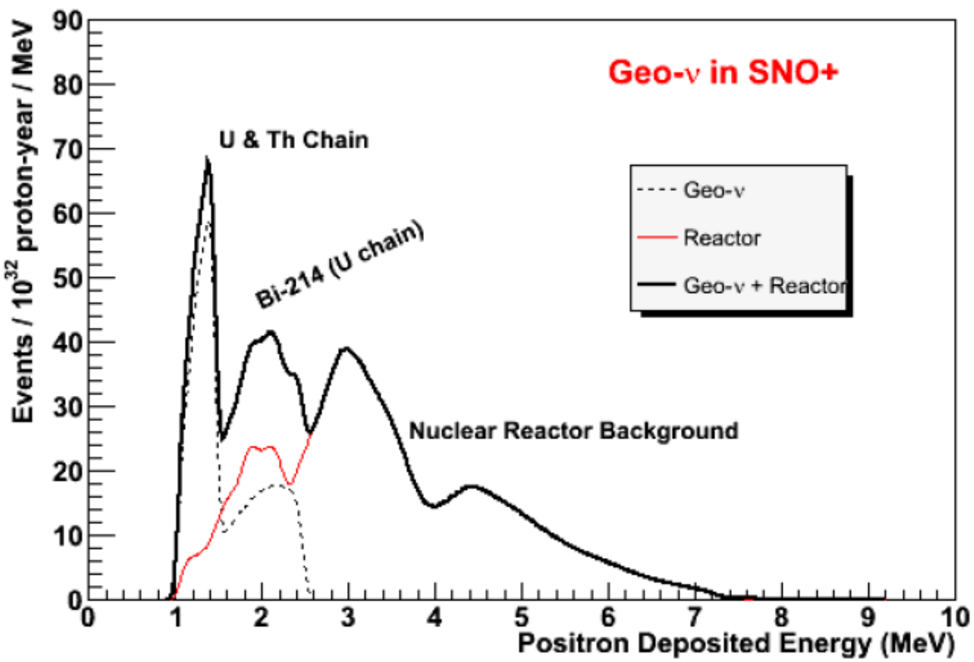



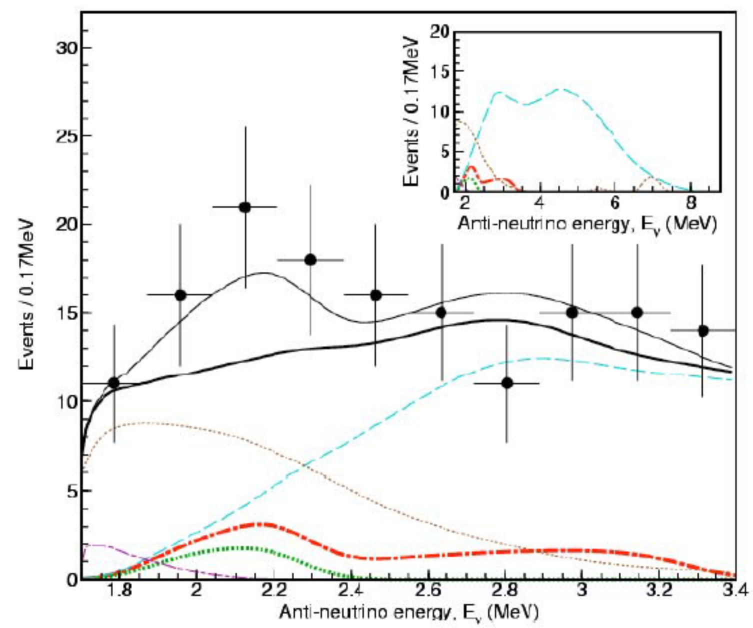




*Lower rate of cosmogenic backgrounds makes SNO+ pep measurement unique.*

# SNO+ Physics: Geo-Neutrinos

- Expect 29 geo-neutrino events per year on a background of 25 reactor antineutrinos
- Larger mass than Borexino and smaller reactor background than KamLAND
- Hopefully separate U/Th contributions
- Combined measurements in different locations can help separate crust and mantle contributions

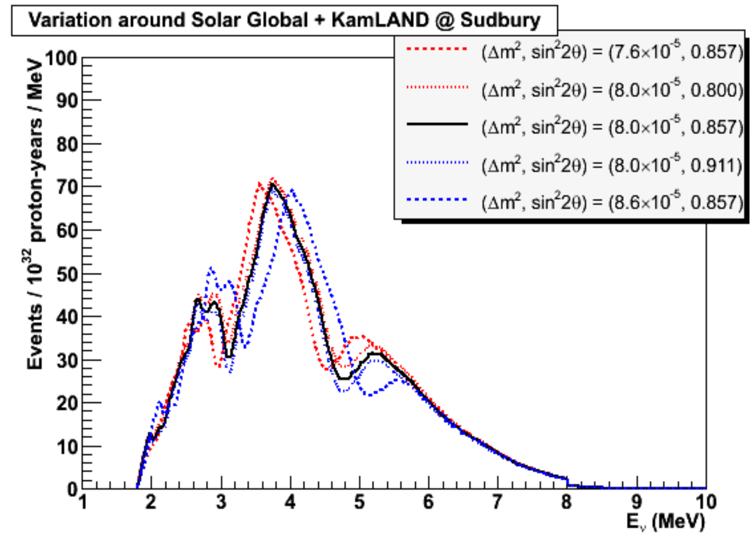


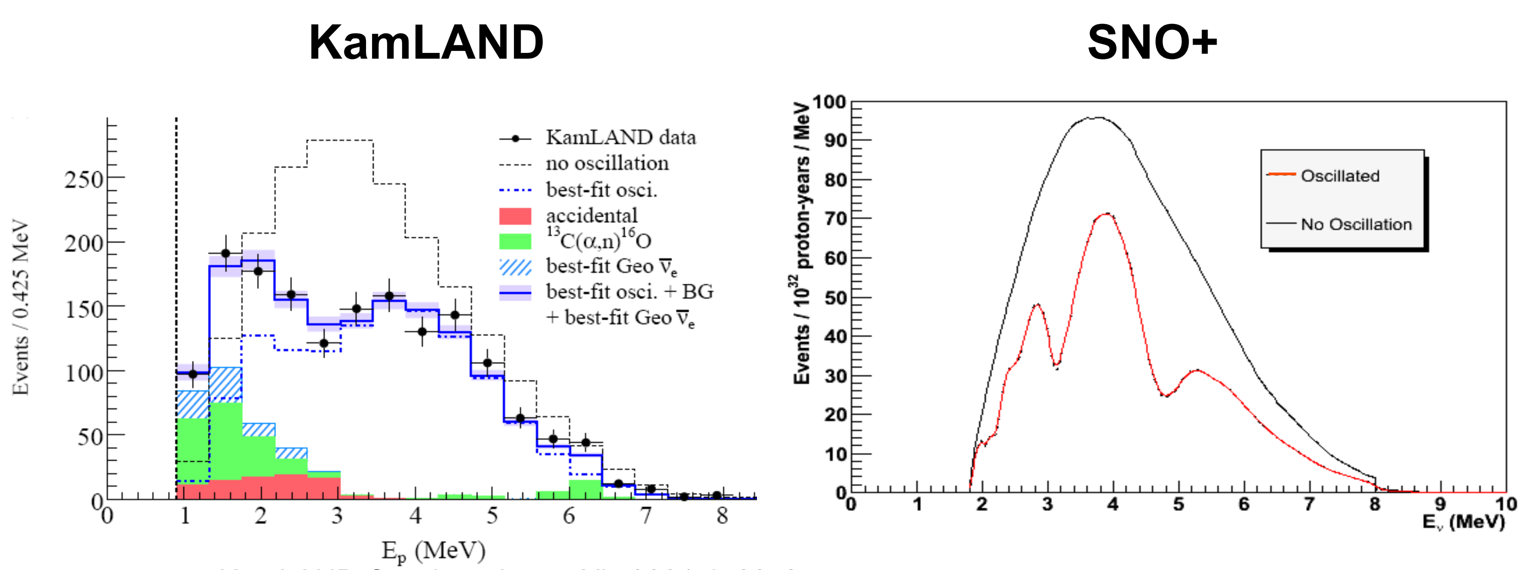




KamLAND - July 28, 2005 in Nature

# SNO+ Physics: Reactor Anti-Neutrinos

- Expect 90 events/yr, mainly from 3 reactors
- Confirm KamLAND result with high precision and longer baseline
  - Unique spectral features mean SNO+ can match KamLAND sensitivity



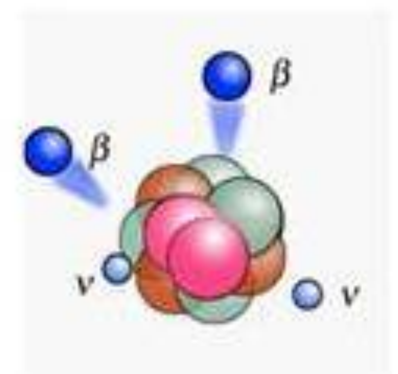



KamLAND Collaboration, arXiv:0801.4589v2

# SNO+ Physics: Neutrinoless Double Beta Decay

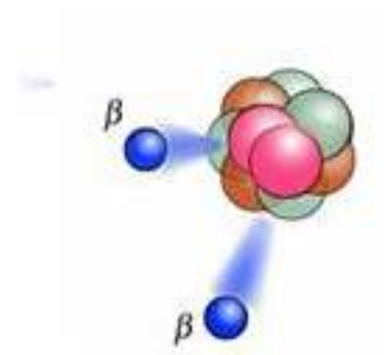
- Open question: are neutrinos Majorana or Dirac particles?
  - Are they their own anti-particles?
- In double beta decay, a nucleus releases two electrons and two antineutrinos:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$$




- If neutrinos are Majorana, sometimes neutrinoless double beta decay occurs:

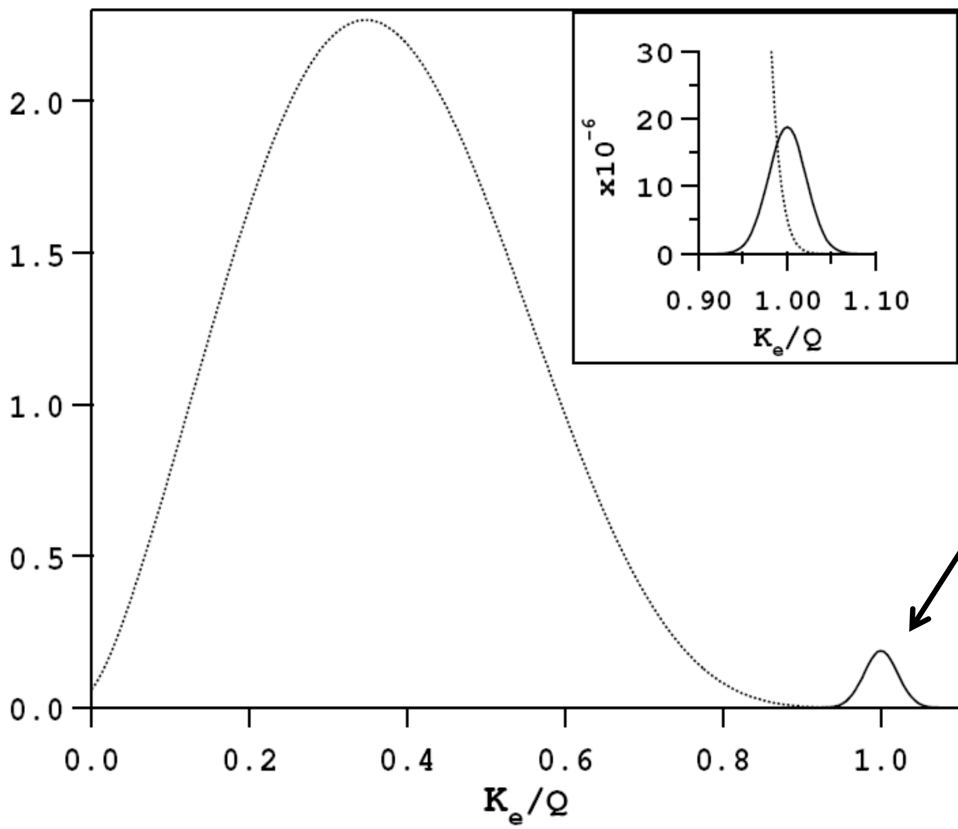
$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$




***Detection of neutrinoless D.B.D. proves that neutrinos are Majorana and proves information about the neutrino mass.***

# SNO+ Physics: Neutrinoless Double Beta Decay

***Searching for neutrinoless double beta decay involves looking for a tiny mono-energetic peak at the end of a large double beta decay***




Size of the peak is proportional to the square of the effective neutrino mass

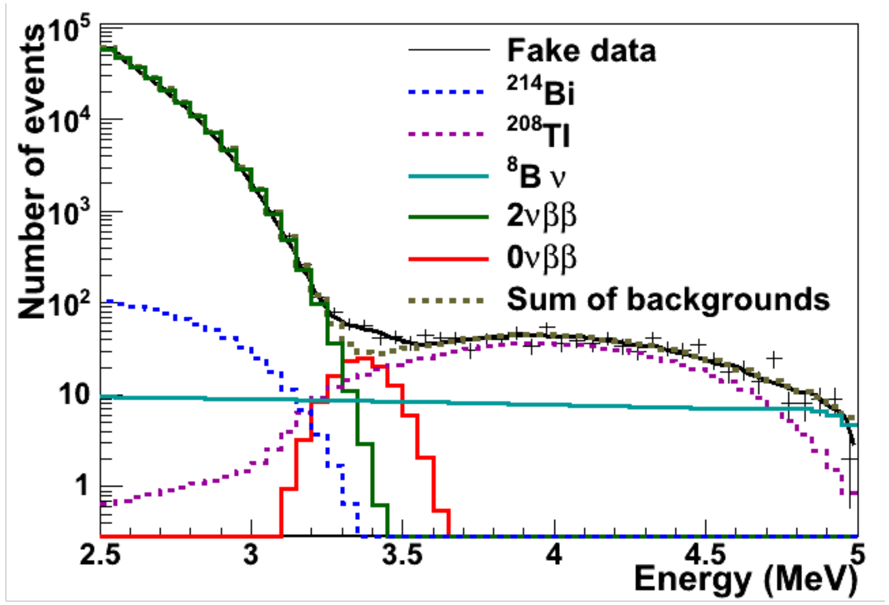
***D.B.D. experiments need good energy resolution, low backgrounds, and large amounts of isotope.***

Image: Elliott and Vogel, hep-ph/0202254

# SNO+ Physics: Neutrinoless Double Beta Decay

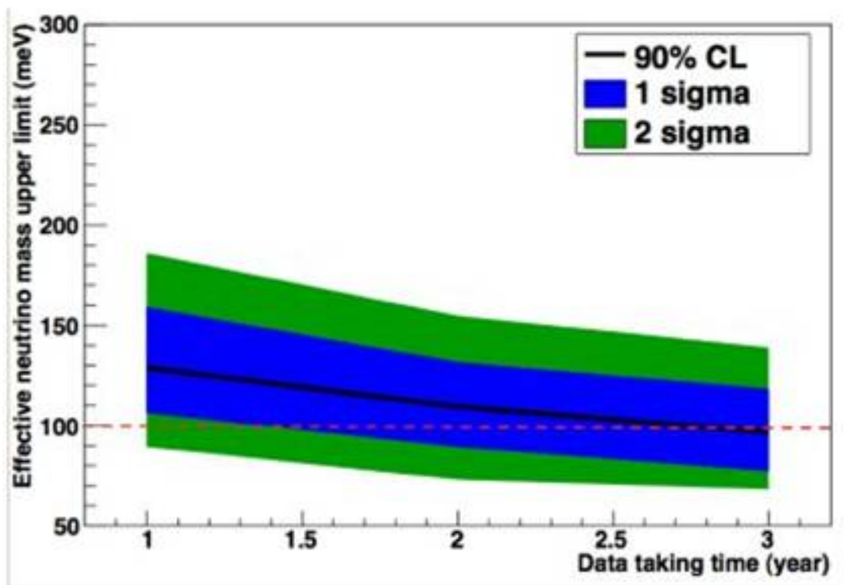
ββ-decay signal for 0.1% Nd loaded scintillator

- signal at the level of Klapdor (Phys. Lett. B 586 (2004) 198.)
- ~ 2 years live time




Neutrino mass sensitivity for 0.3% Nd loading:

- IBM-2 [Phys. Rev. C 79 (2009) 044301] nuclear m.e. values for Nd were used
- radioactivity backgrounds at the levels achieved by Borexino
- cosmogenic backgrounds included; pile-up can be rejected

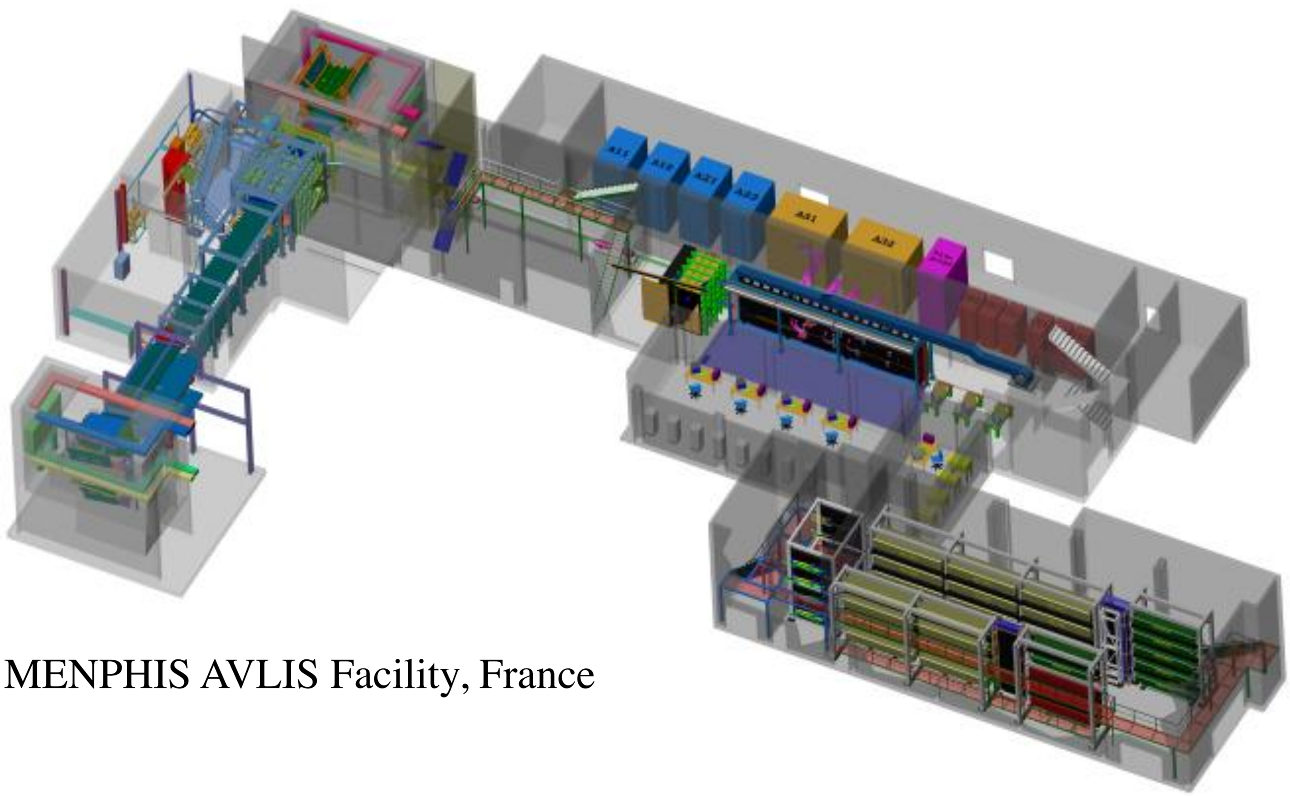



Slide from R. Helmer, DBD11

# SNO+ Physics: Neutrinoless Double Beta Decay

**Development of the laser isotope separation method (AVLIS) for obtaining weight amounts of highly enriched $^{150}$Nd isotope**

A.P. Babichev, I.S. Grigoriev, A.I. Grigoriev, A.P. Dorovskii, A.B. D'yachkov, S.K. Kovalevich, V.A. Kochetov, V.A. Kuznetsov, V.P. Labozin, A.V. Matrakhov, S.M. Mironov, S.A. Nikulin, A.V. Pesnya, N.I. Timofeev, V.A. Firsov, G.O. Tsvetkov, G.G. Shatalova

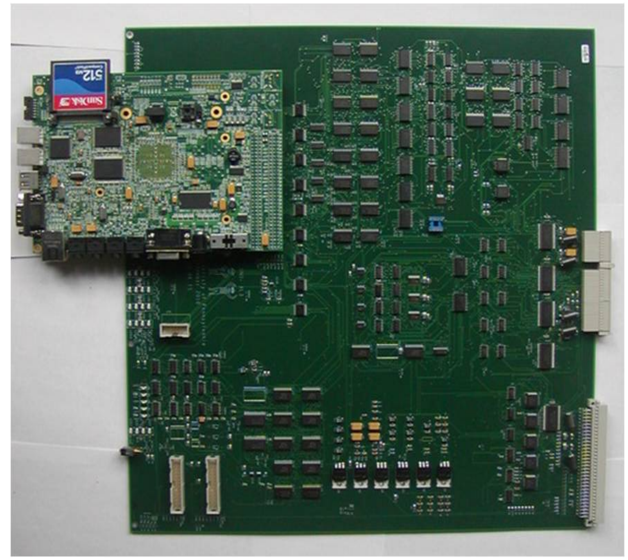


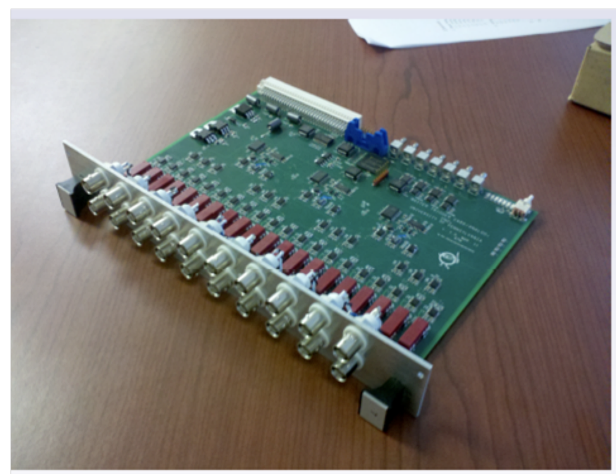
MENPHIS AVLIS Facility, France

*Neodymium enrichment being investigated: sensitivity could be extended to a few 10's of meV*

# SNO+ Status and Schedule

- 2011 - Electronics/DAQ upgrades installed
- 2012 - AV hold-down net installed
- Current - air fill data taking
- Spring 2012 – AV sanding
- Summer 2012 – water fill + water fill data taking
- Early 2013 – scintillator fill + data taking
- When ready – add DBD isotope





Images from R. Helmer, DBD11

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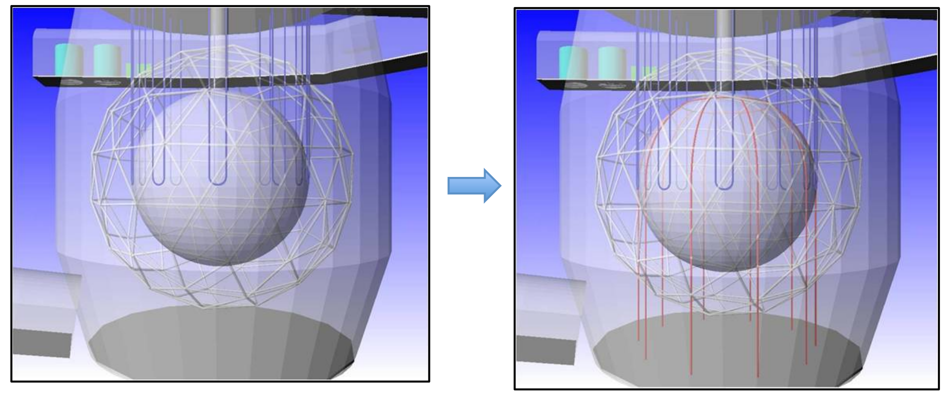

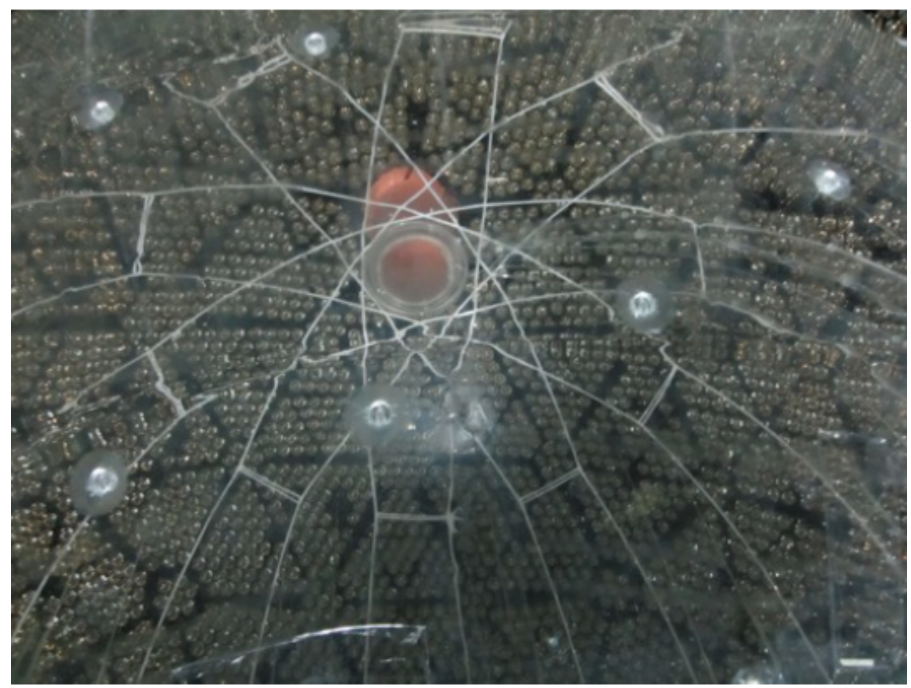

Photograph from Christine Kraus

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