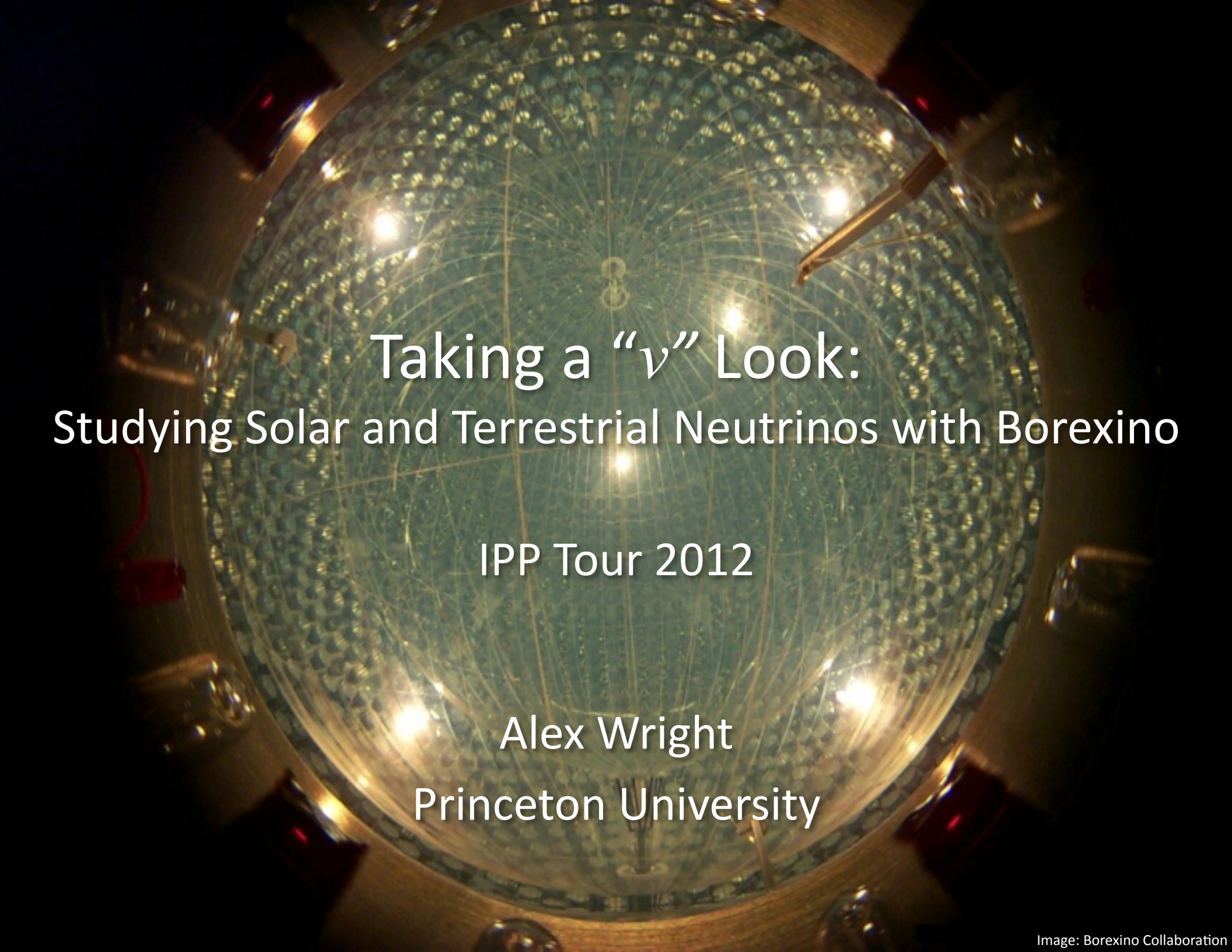


# Taking a "$\nu$" Look:

## Studying Solar and Terrestrial Neutrinos with Borexino

IPP Tour 2012

Alex Wright

Princeton University

Image: Borexino Collaboration

# Outline

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

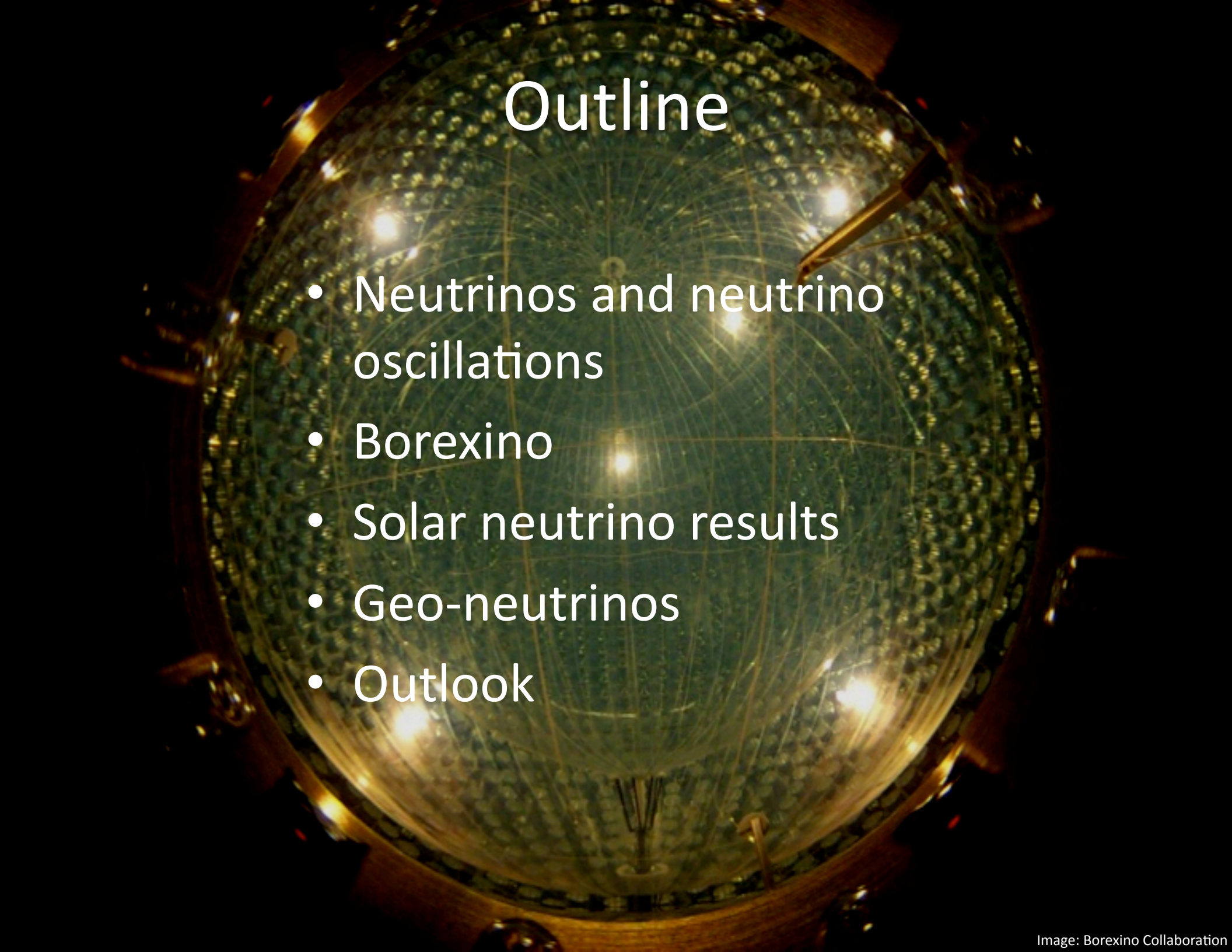
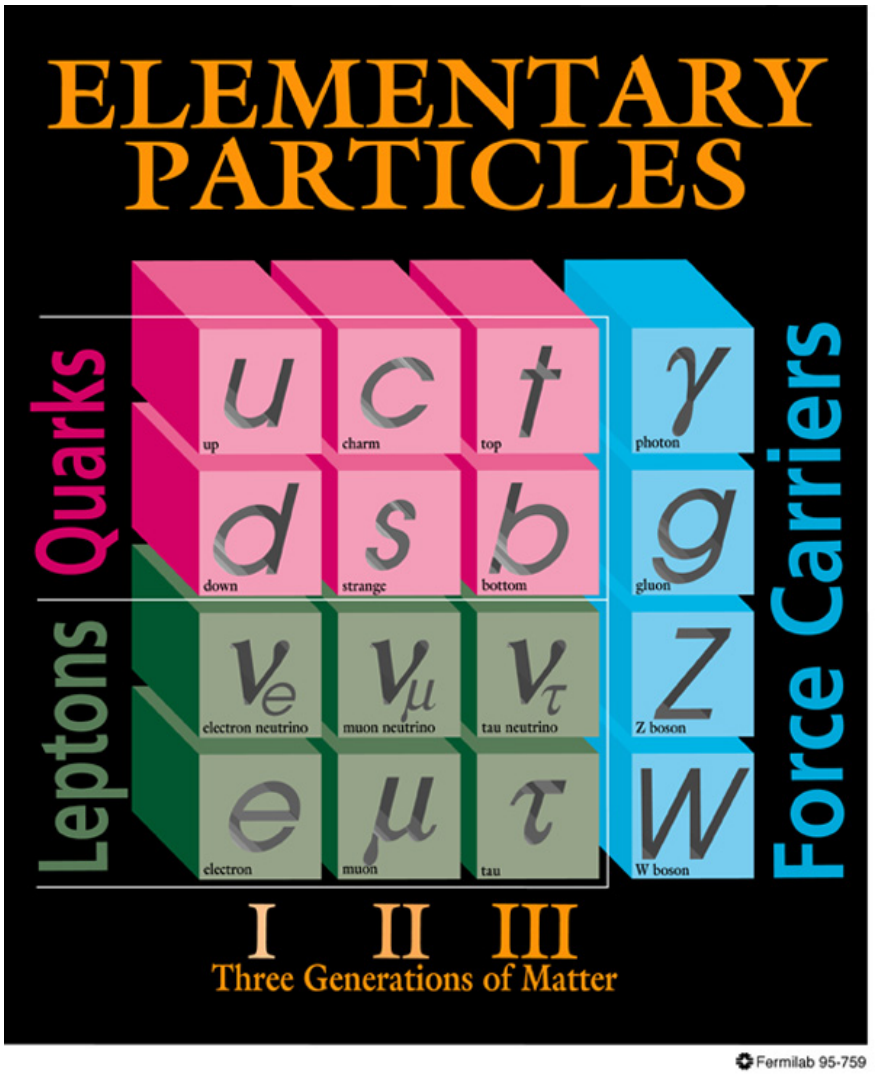


Image: Borexino Collaboration

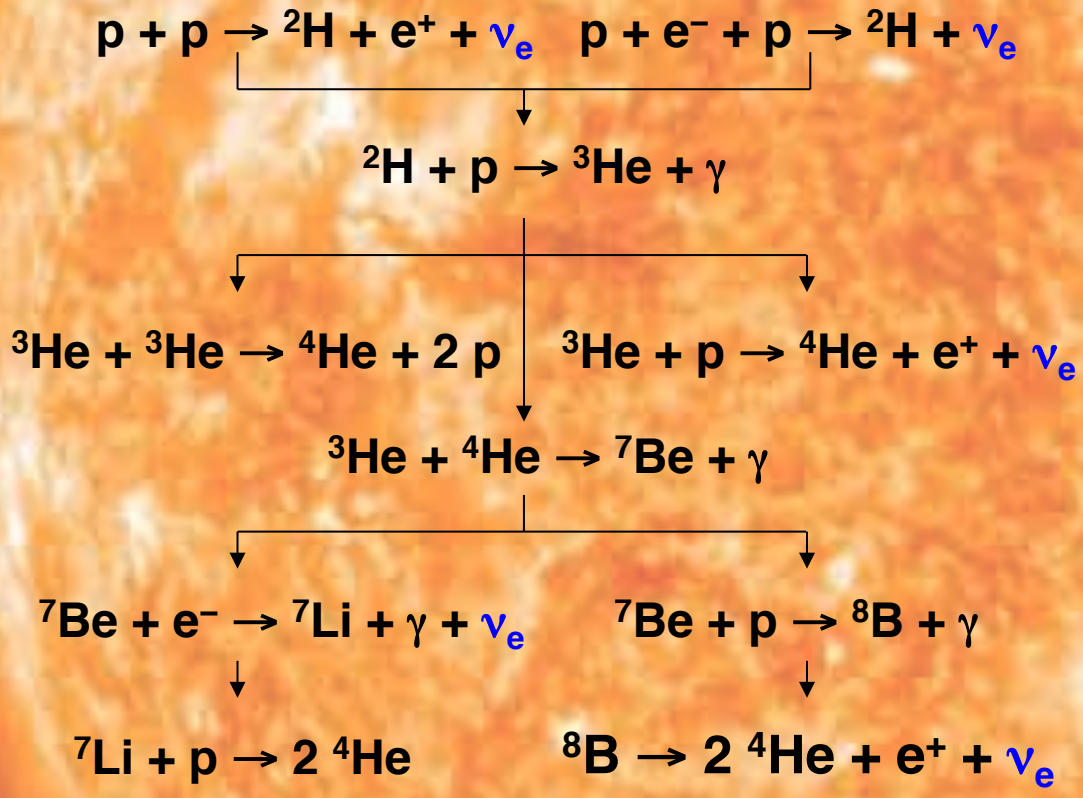
# Neutrinos

- 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




## CNO Solar Fusion Cycle

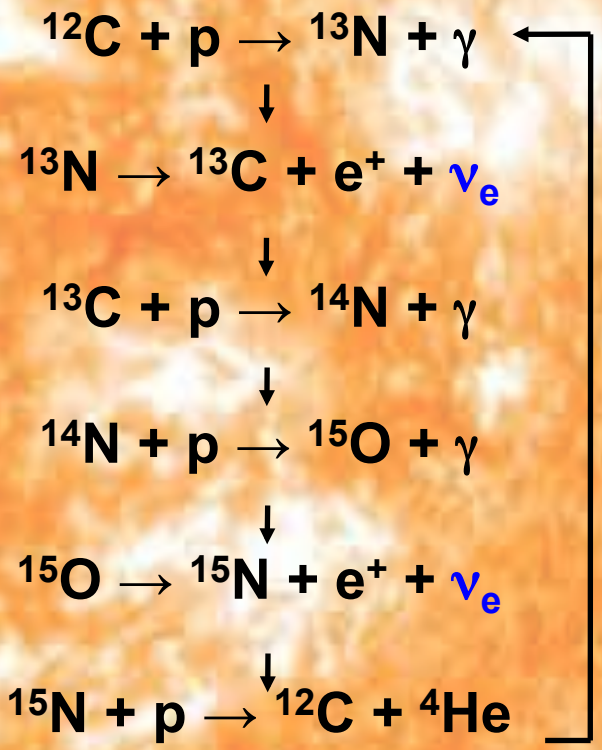
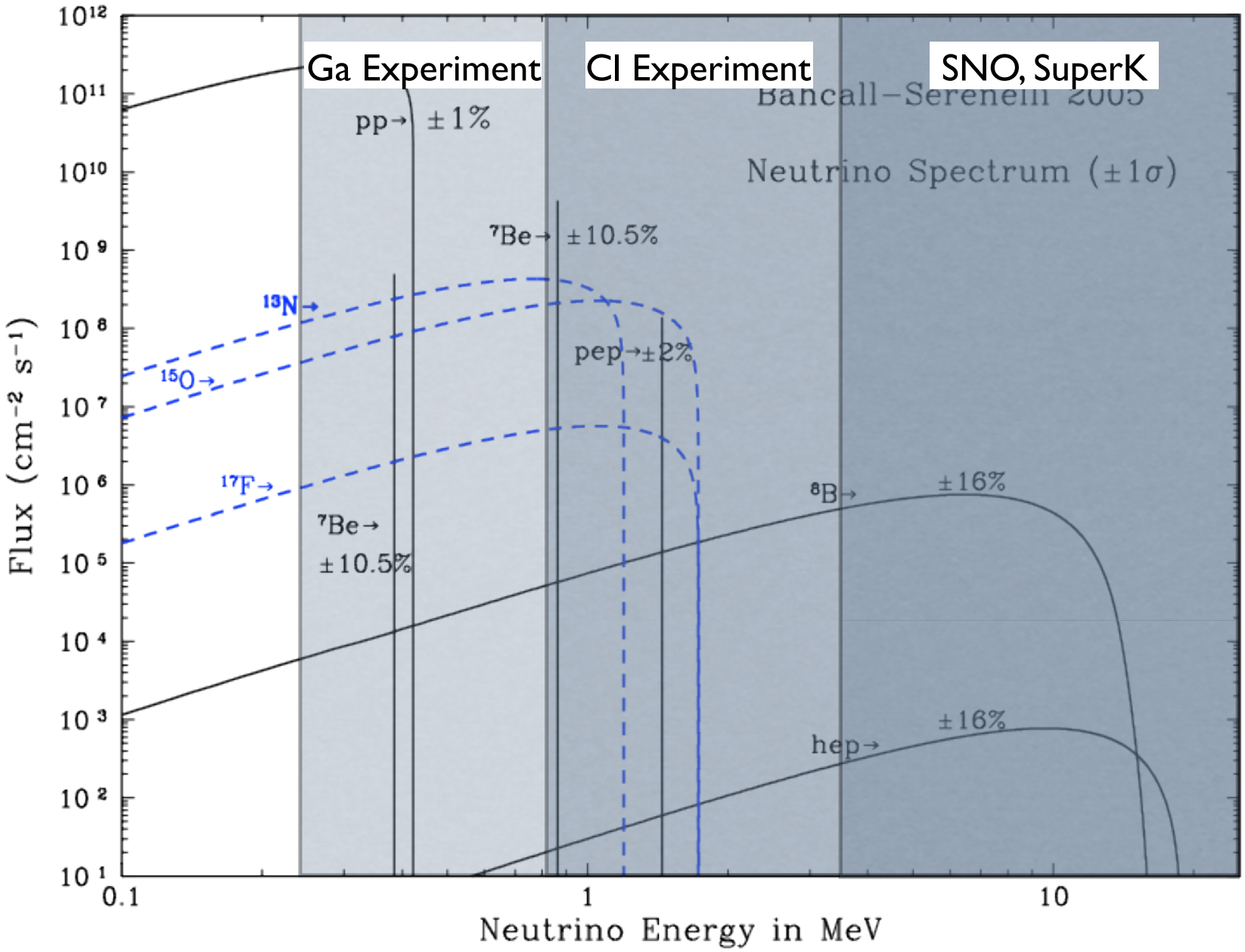


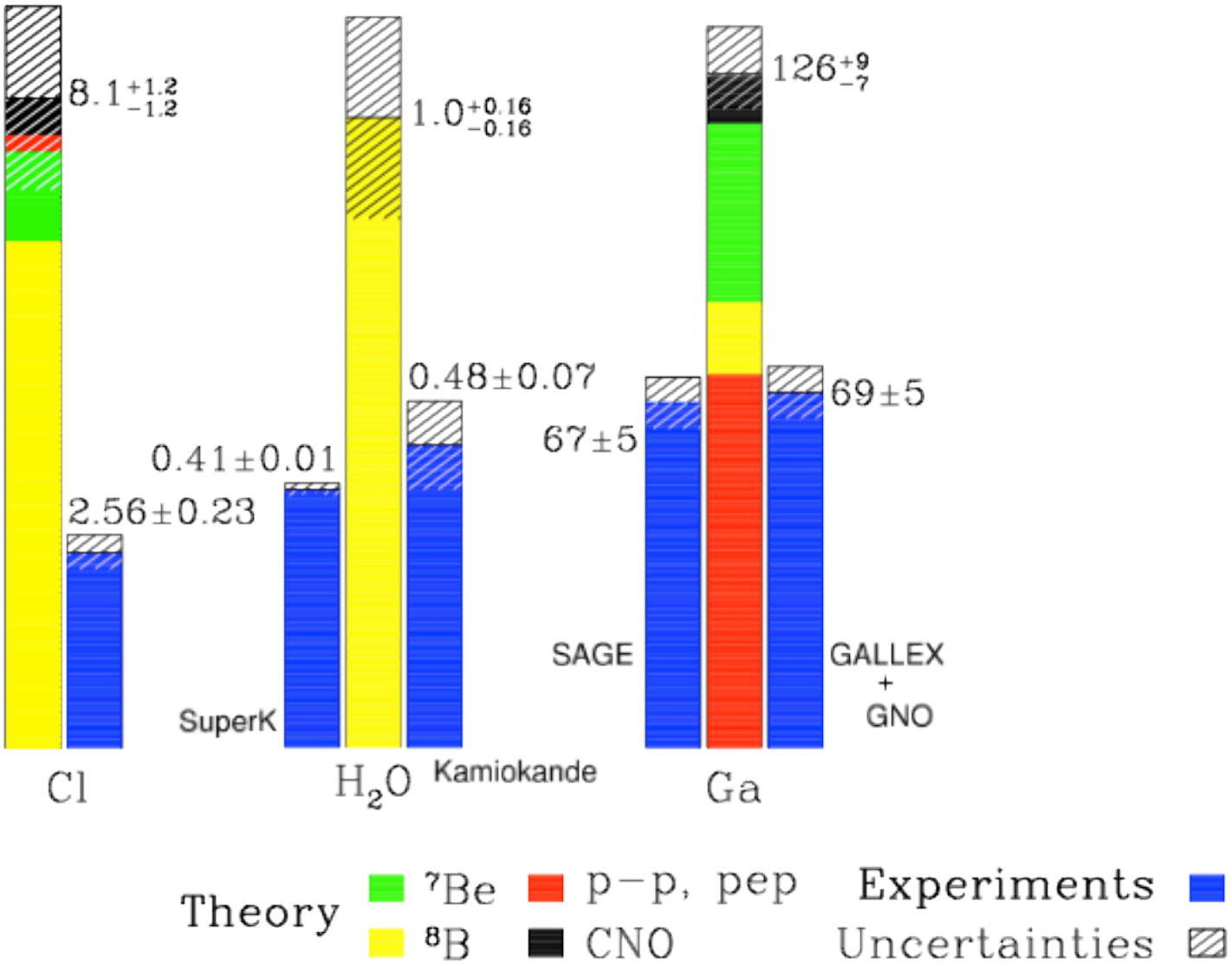

Image: bbc.co.uk

# Neutrinos From the Sun



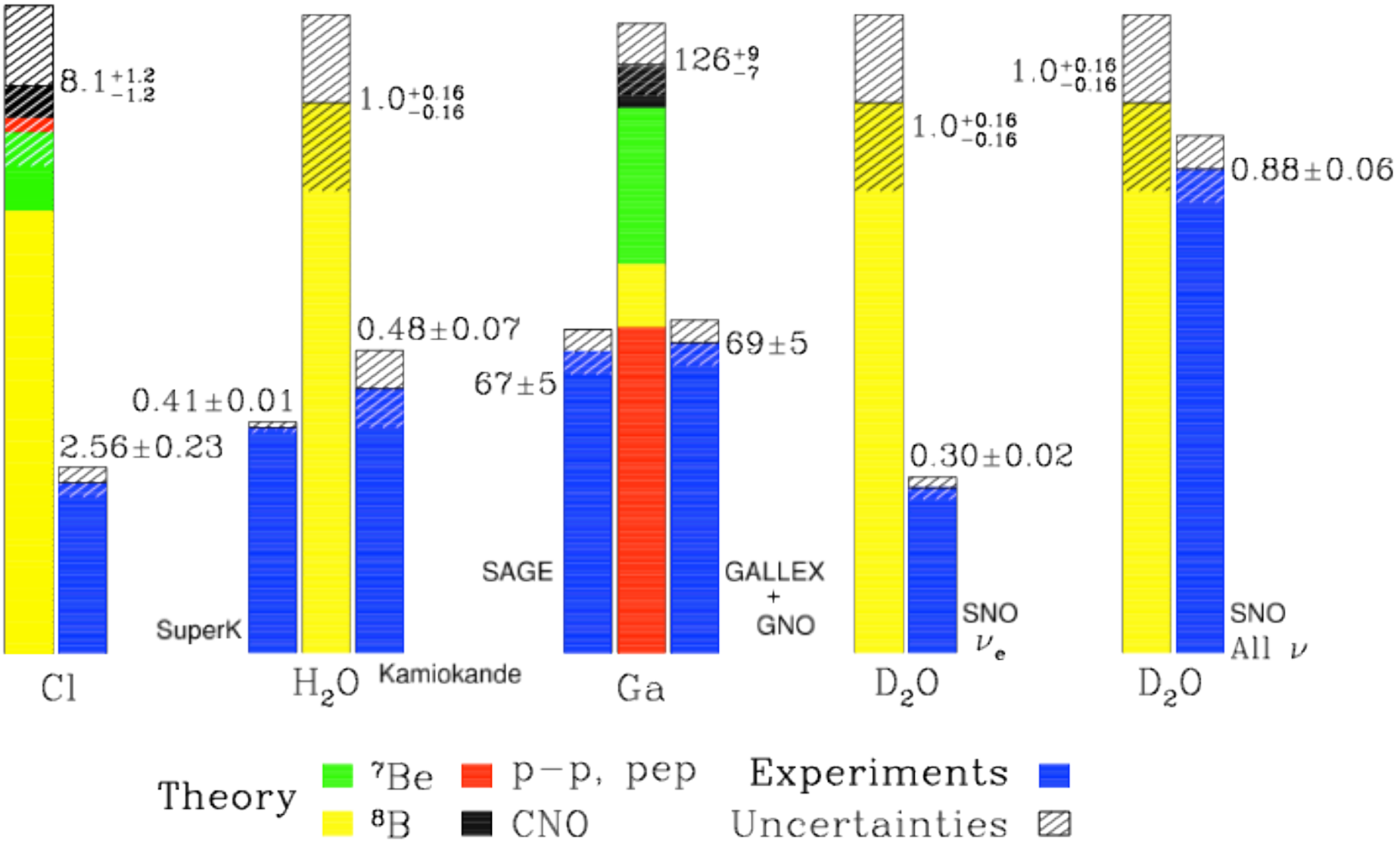
# The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



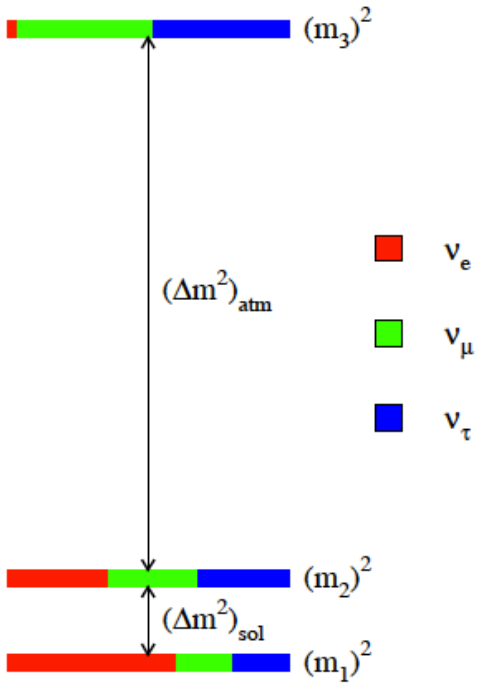
# The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



# Neutrino Oscillations

- Neutrino flavour and mass eigenstates “misaligned”
- Related by the PMNS matrix
  - Unitary mapping with 3 mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$), perhaps two Majorana phases ($\alpha_1$, $\alpha_2$), and one CP violating phase ($\delta$)




hep-ph/0411274

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

$-s_{23} = -\sin(\theta_{23})$ $\quad$ $c_{13} = \cos(\theta_{13})$

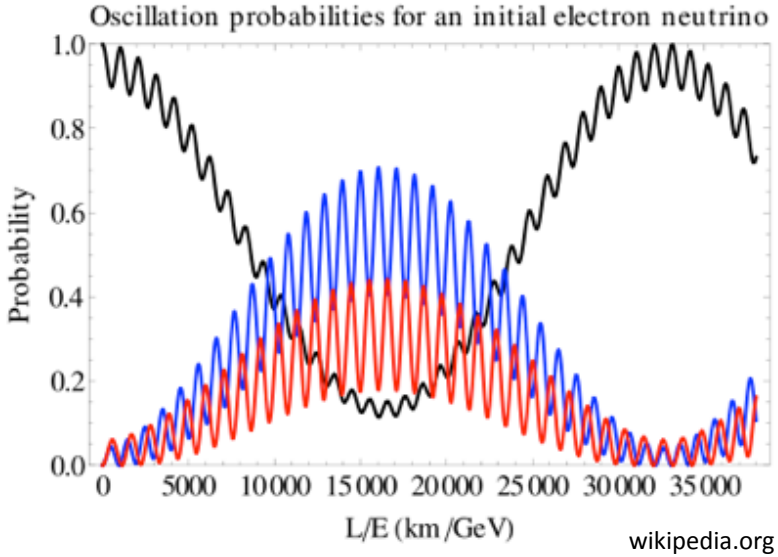
wikipedia.org

# 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:

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

Symmetry Magazine



wikipedia.org

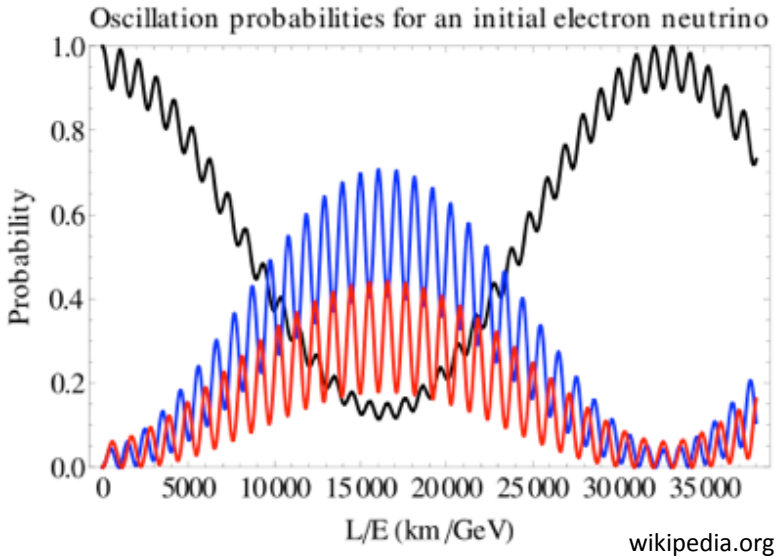
# Neutrino Oscillations

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

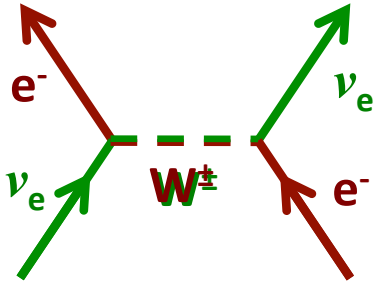
$$P_{ee} = \cos^4(\theta_{13}) \left(1 - \frac{1}{2}\sin^2(2\theta_{12})\right) + \sin^4(\theta_{13})$$

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

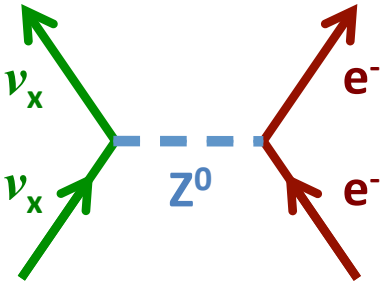
Symmetry Magazine




wikipedia.org




# The Matter of Matter

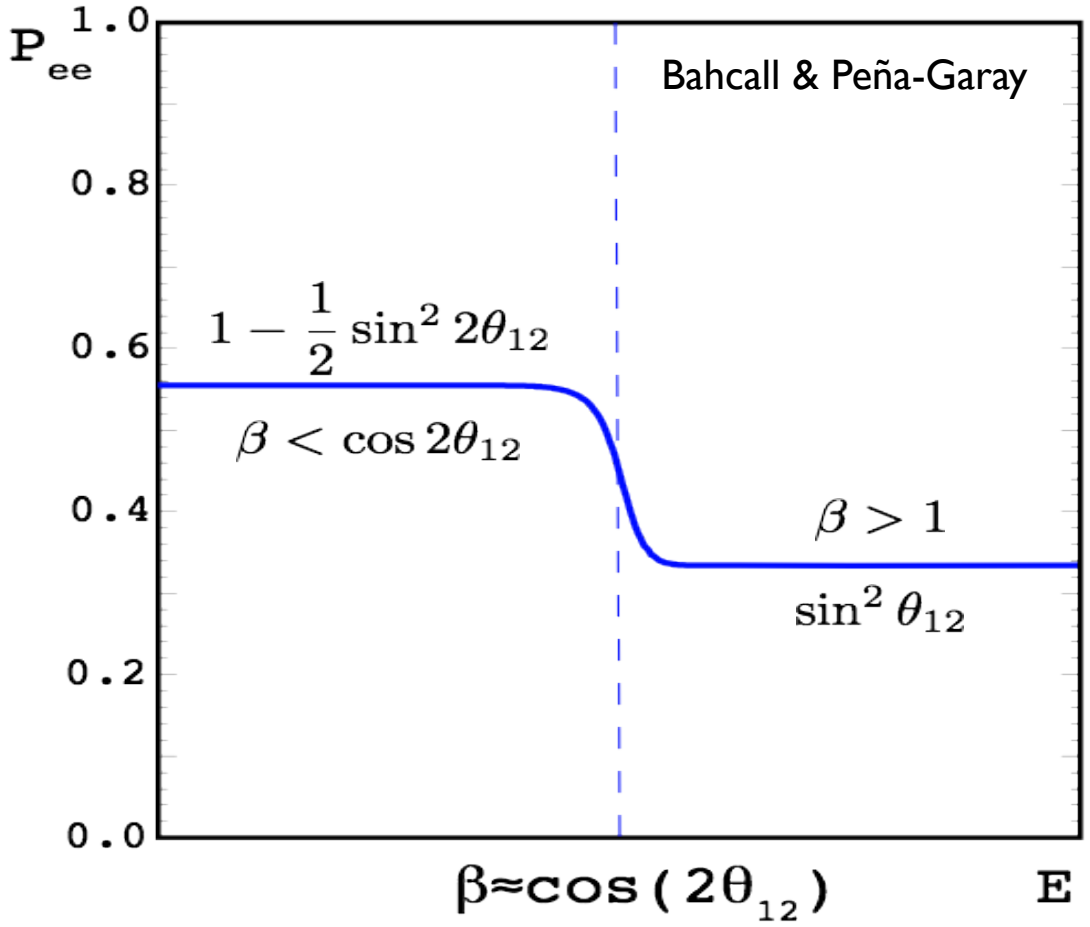



- When neutrinos propagate in matter, charged current interactions add an additional term to $\nu_e$ flavour in Hamiltonian mass matrix:

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

- 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

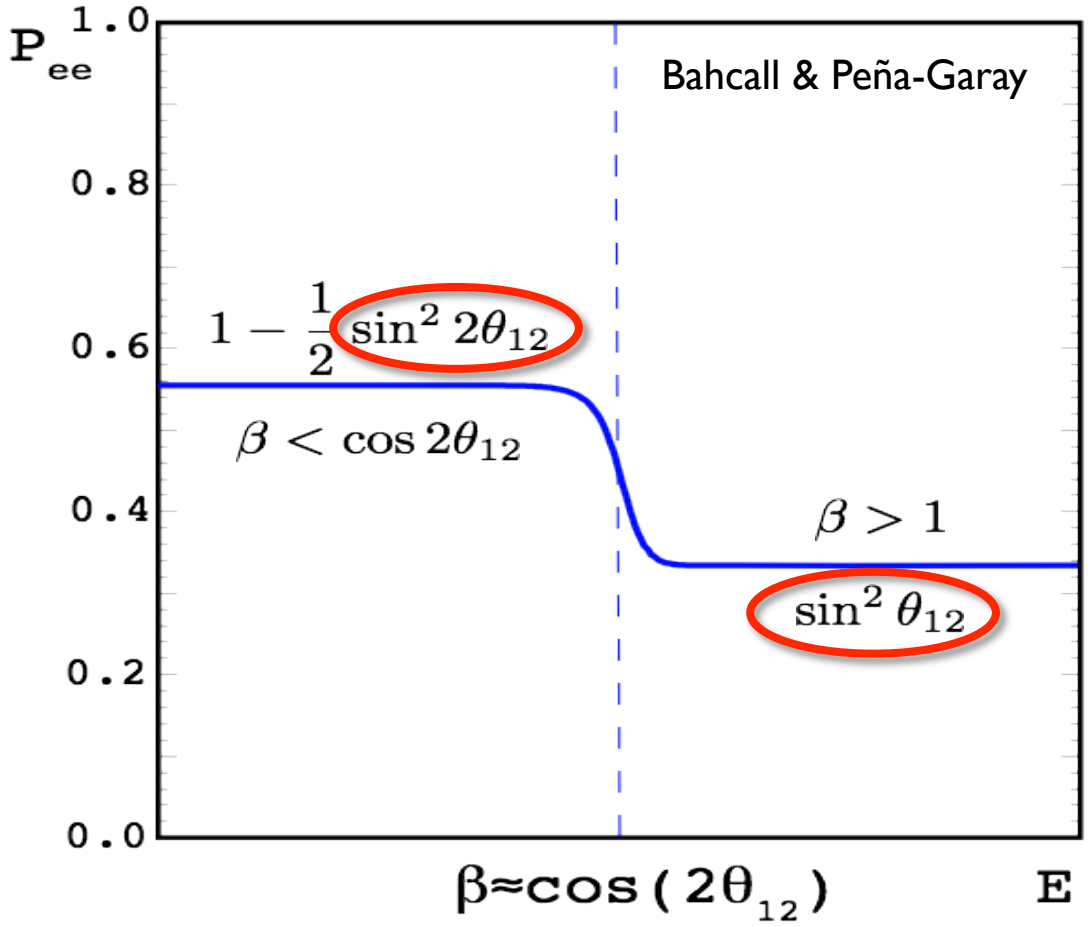



$$\beta = \frac{2^{3/2} G_F N_e}{\left(\frac{\Delta m^2}{E}\right)}$$

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

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

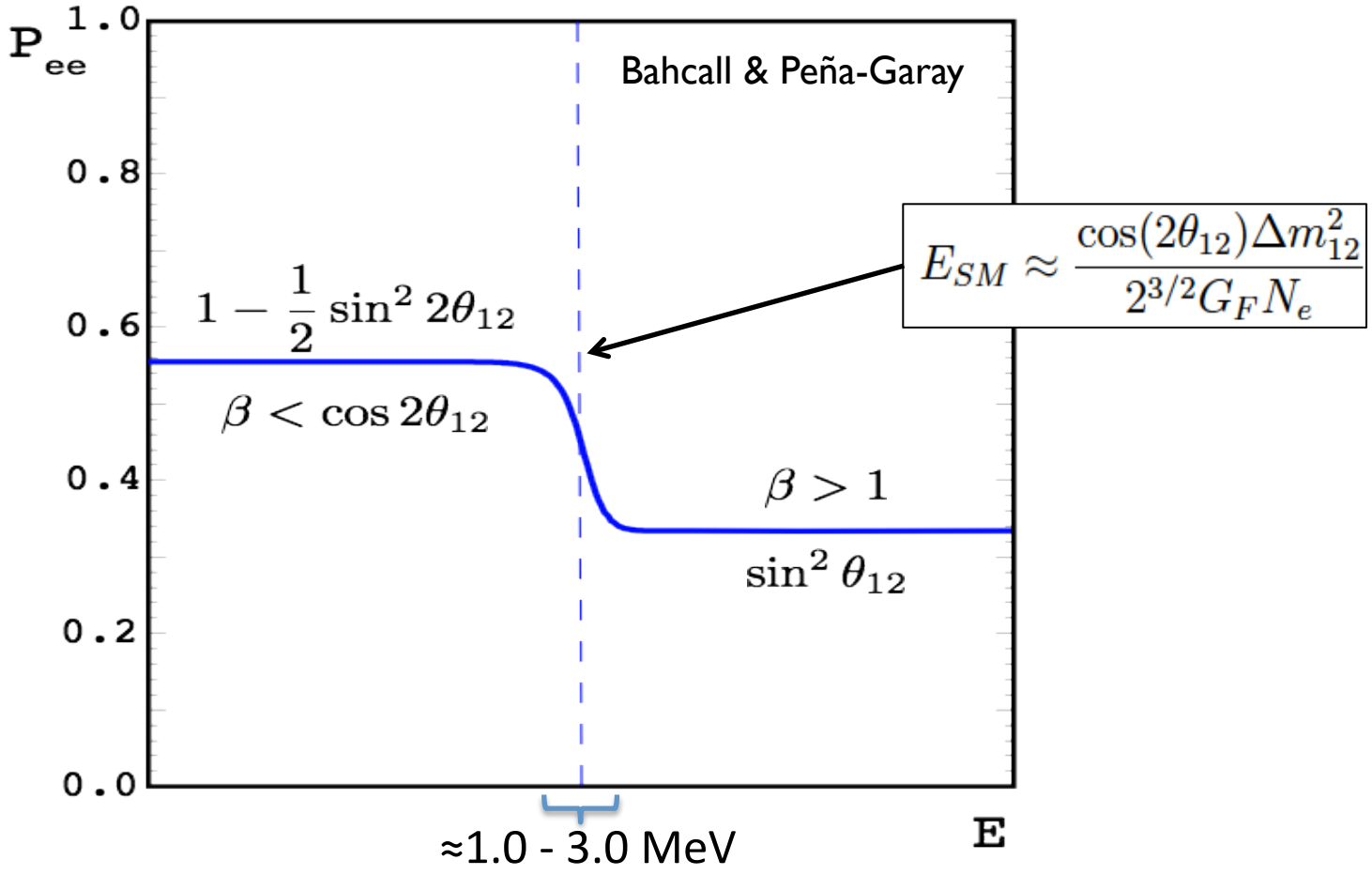
# MSW Oscillation Regimes




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

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

# MSW Oscillation Regimes

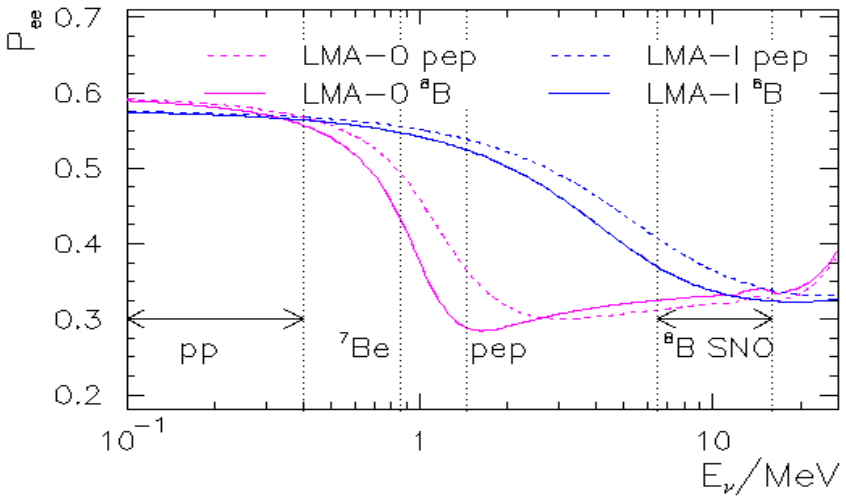



***Look in "transition region" to confirm MSW and that we know what is going on!***

# Possible New Physics in Transition Region

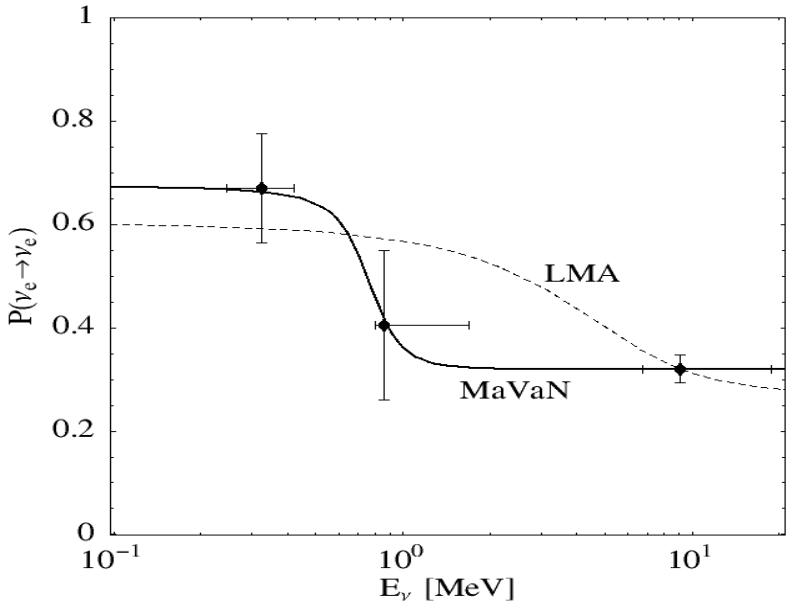
## Non-Standard Interactions

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



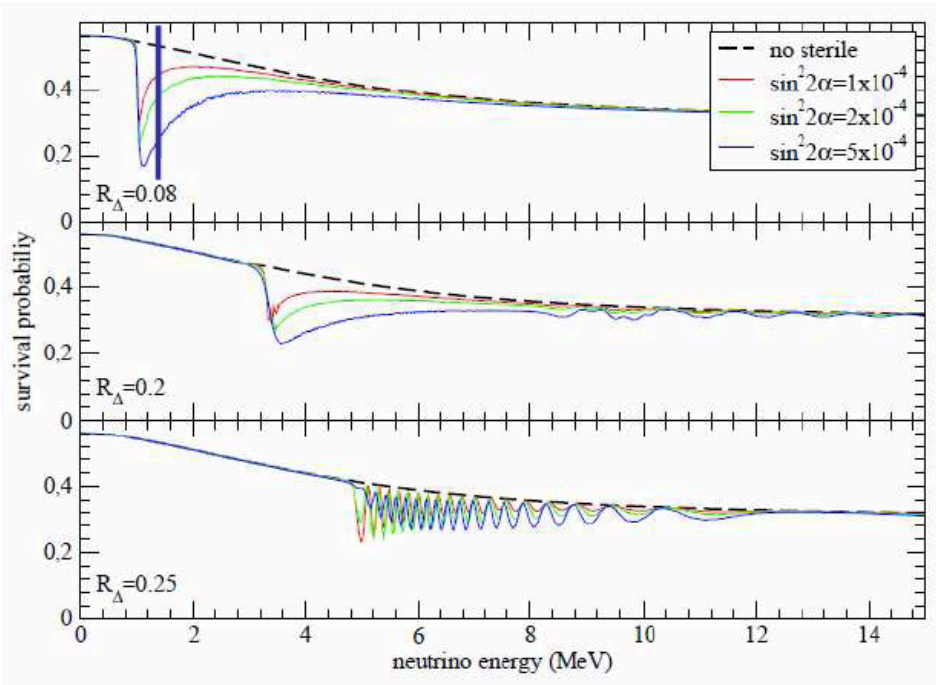

## Mass Varying Neutrinos

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

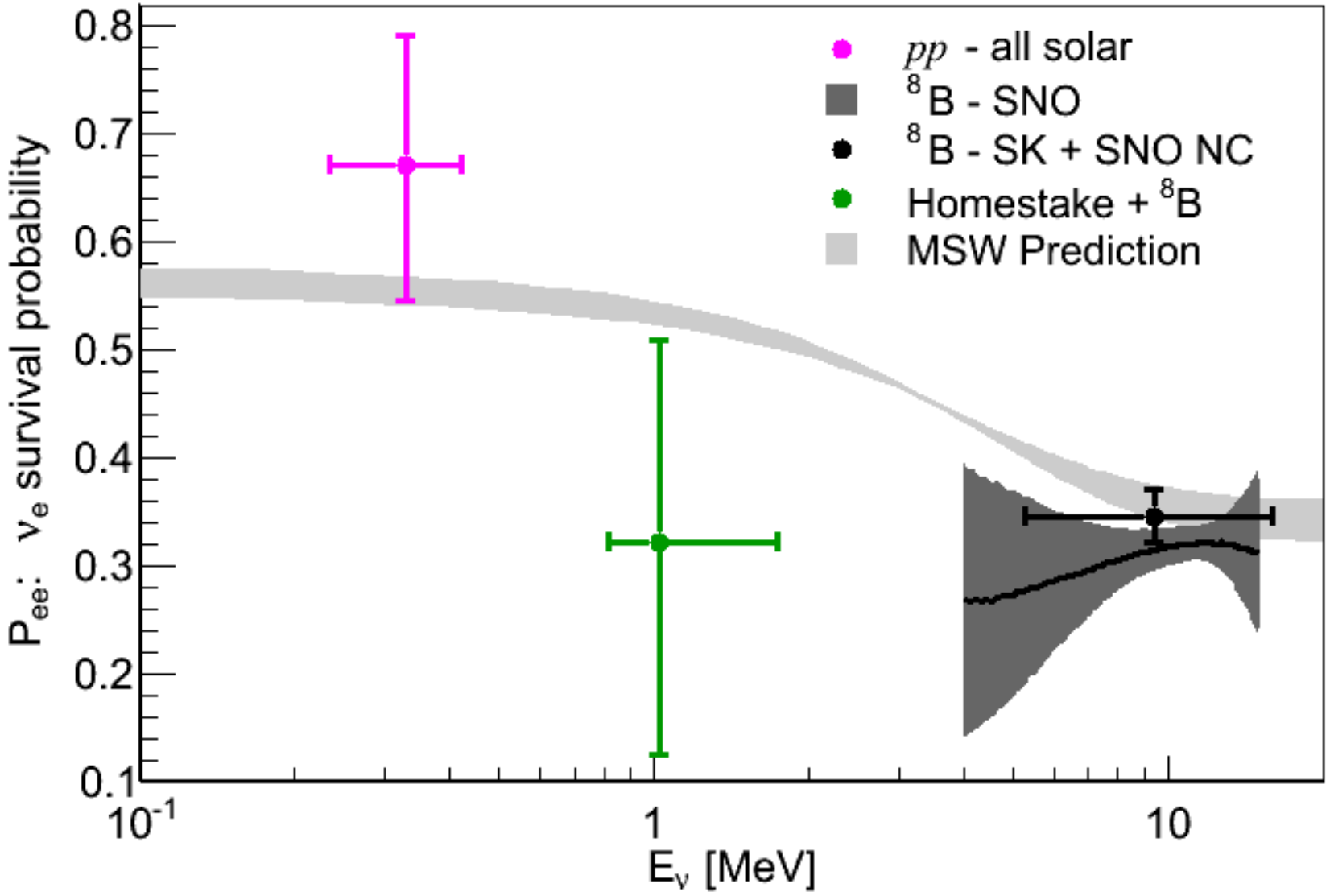



## Sterile Neutrinos

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

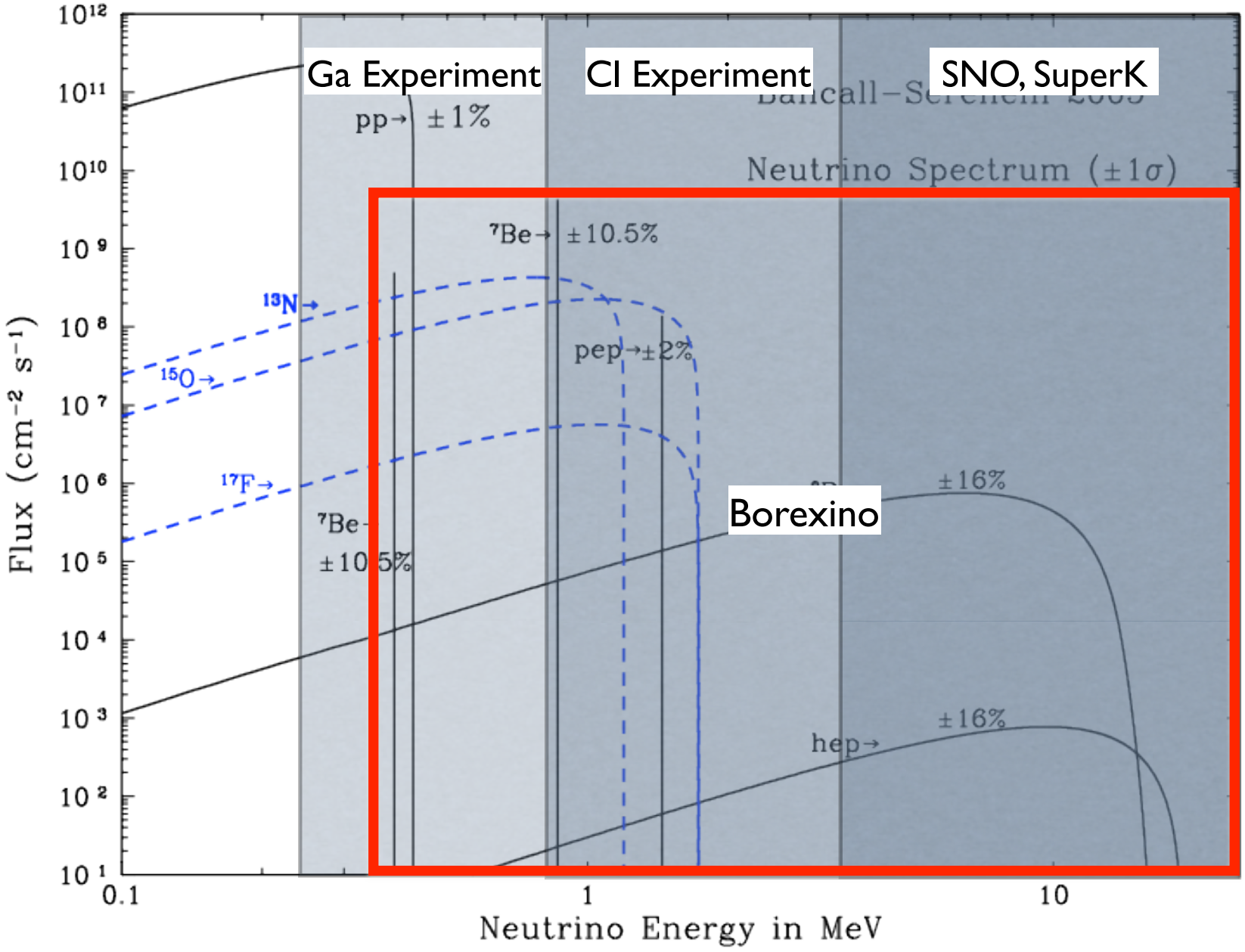


# Constraints on Transition Region Without Borexino

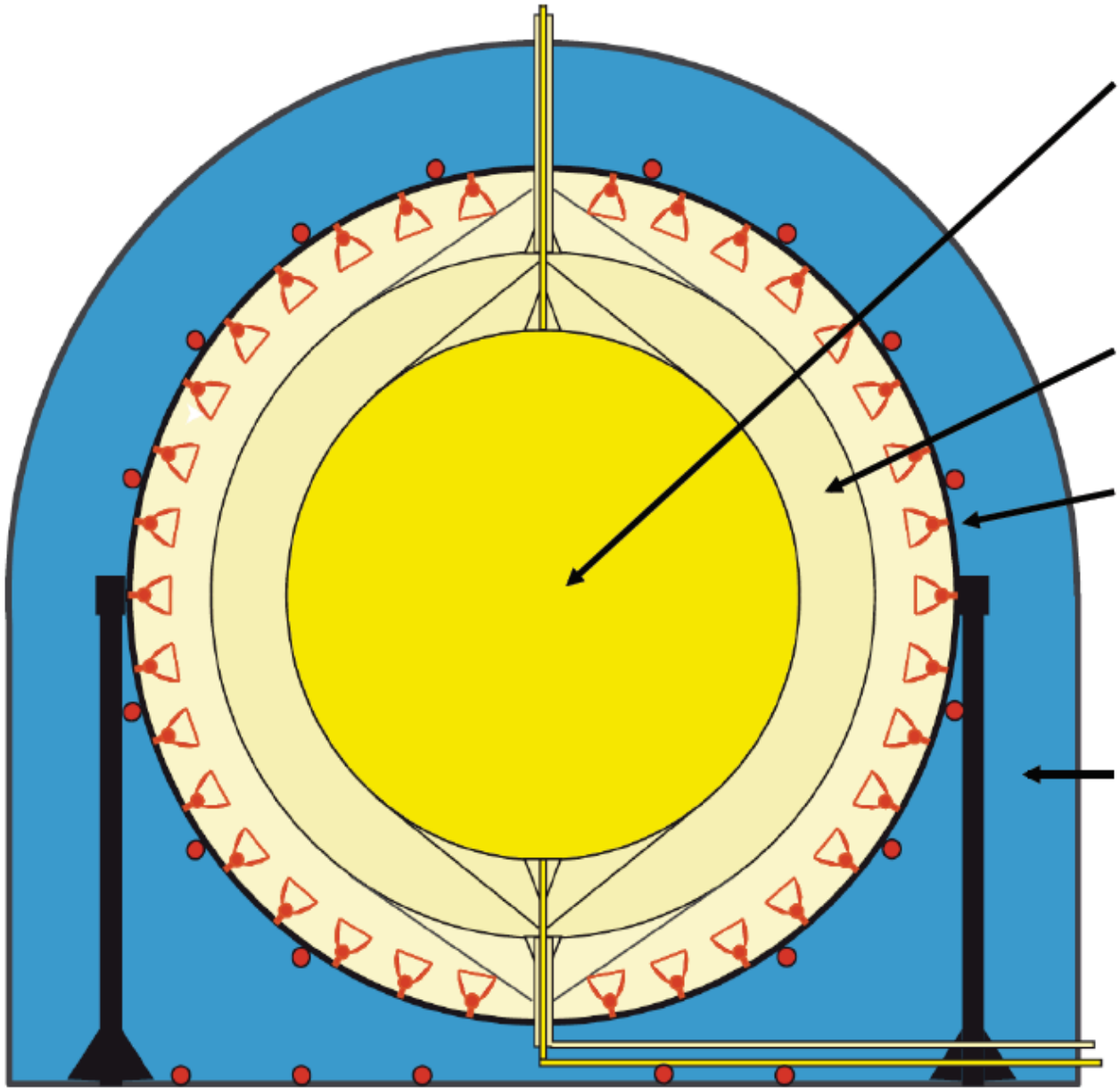



**Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated.** ***Real-time measurements needed in the transition region.***

# 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

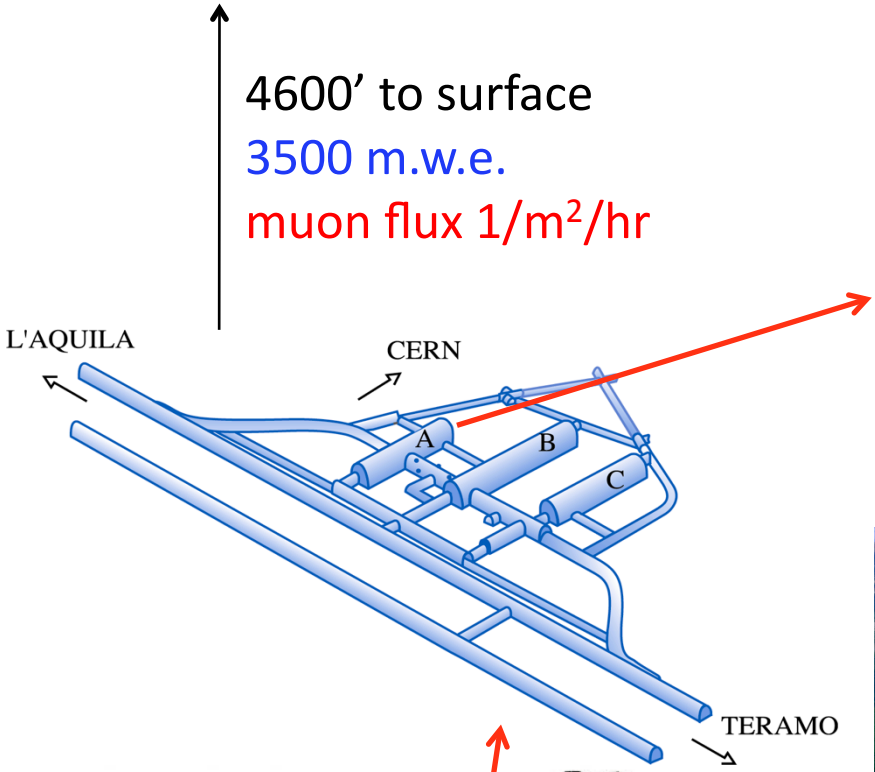
**non-scintillating buffer**

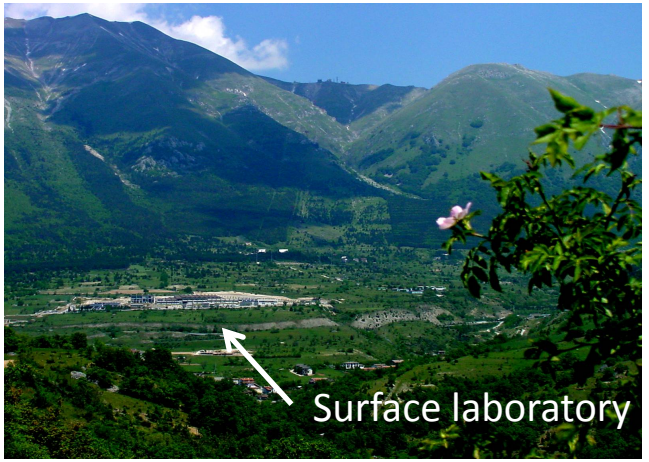
**stainless steel sphere**
6.85 m in radius
2212 inward-facing PMTs

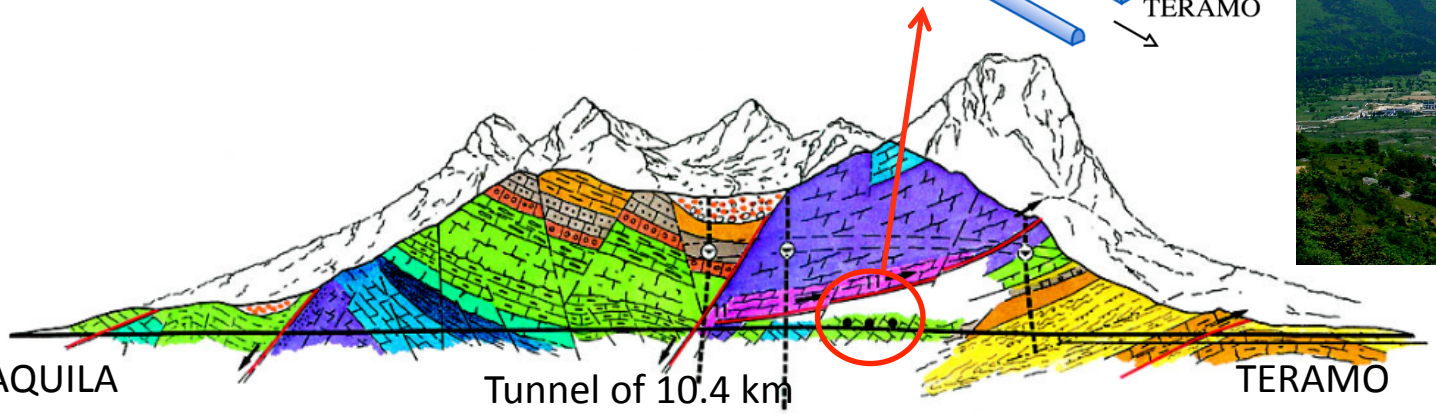
**outer water tank**
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

# 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

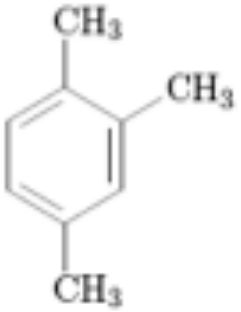
Princeton University – Princeton, NJ, USA

St. Petersburg Nuclear Physics Institute – Gatchina, Russia

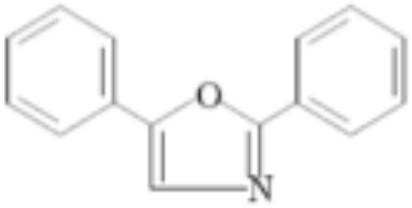
Technische Universität – Muenchen, Germany

University of Massachusetts at Amherst, MA, USA

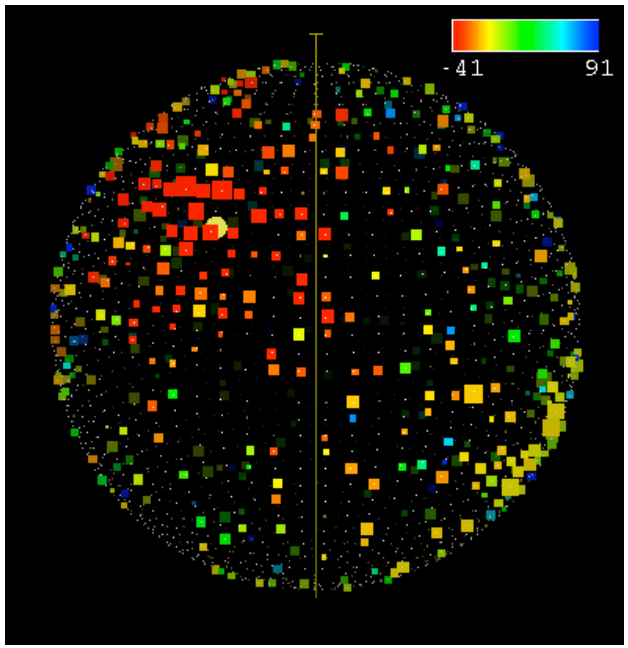
Virginia Polytechnic Institute – Blacksburg, VA, USA




# Detection Principle

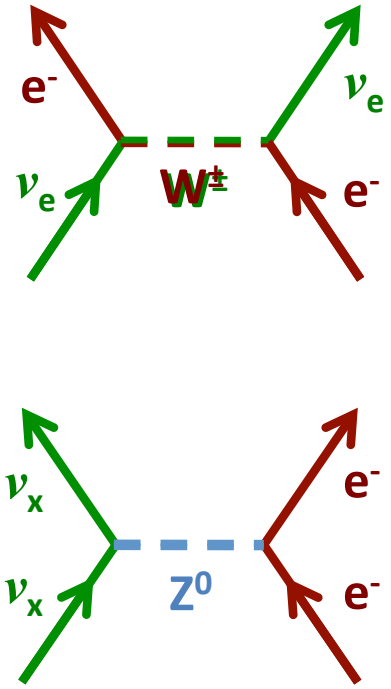


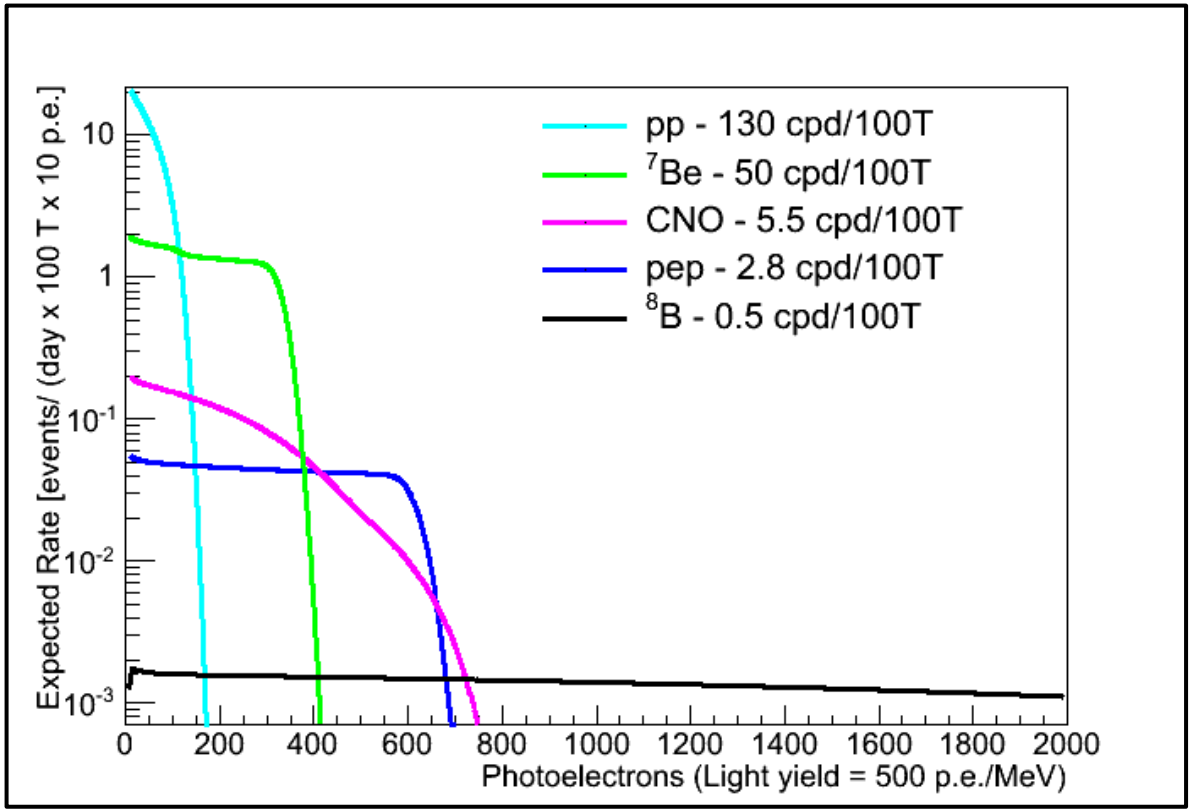

- Organic scintillator (pseudocumene + PPO) produces light when excited by charged particles
- ~12,000 photons/MeV, of which ~500 photons/MeV are detected by the photomultiplier tubes
  - Can detect events depositing < 50 keV
- Calorimetric measurement + pulse shape
  - Event energy from number of photons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



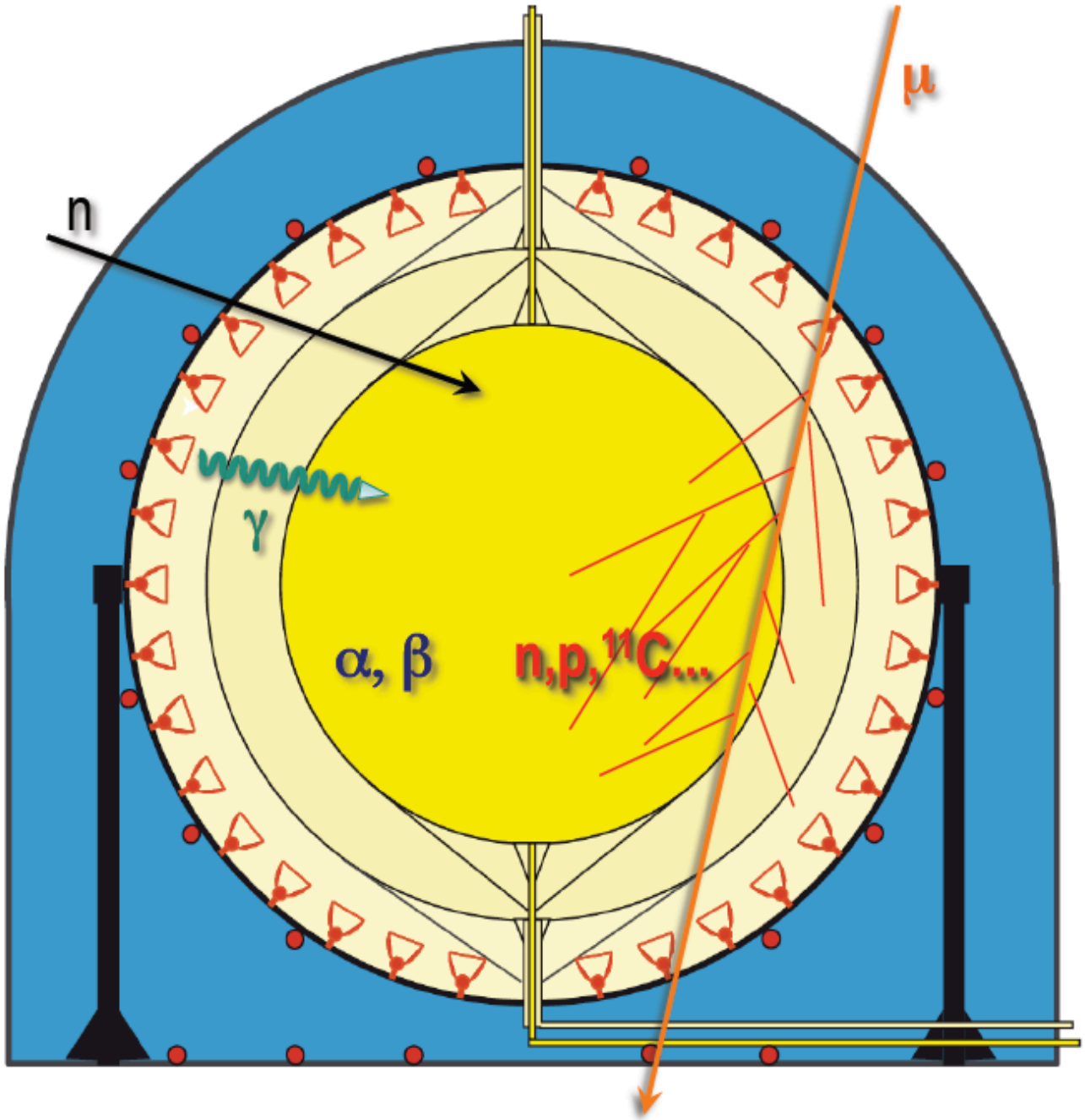
# Neutrino Detection

- 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 ...)

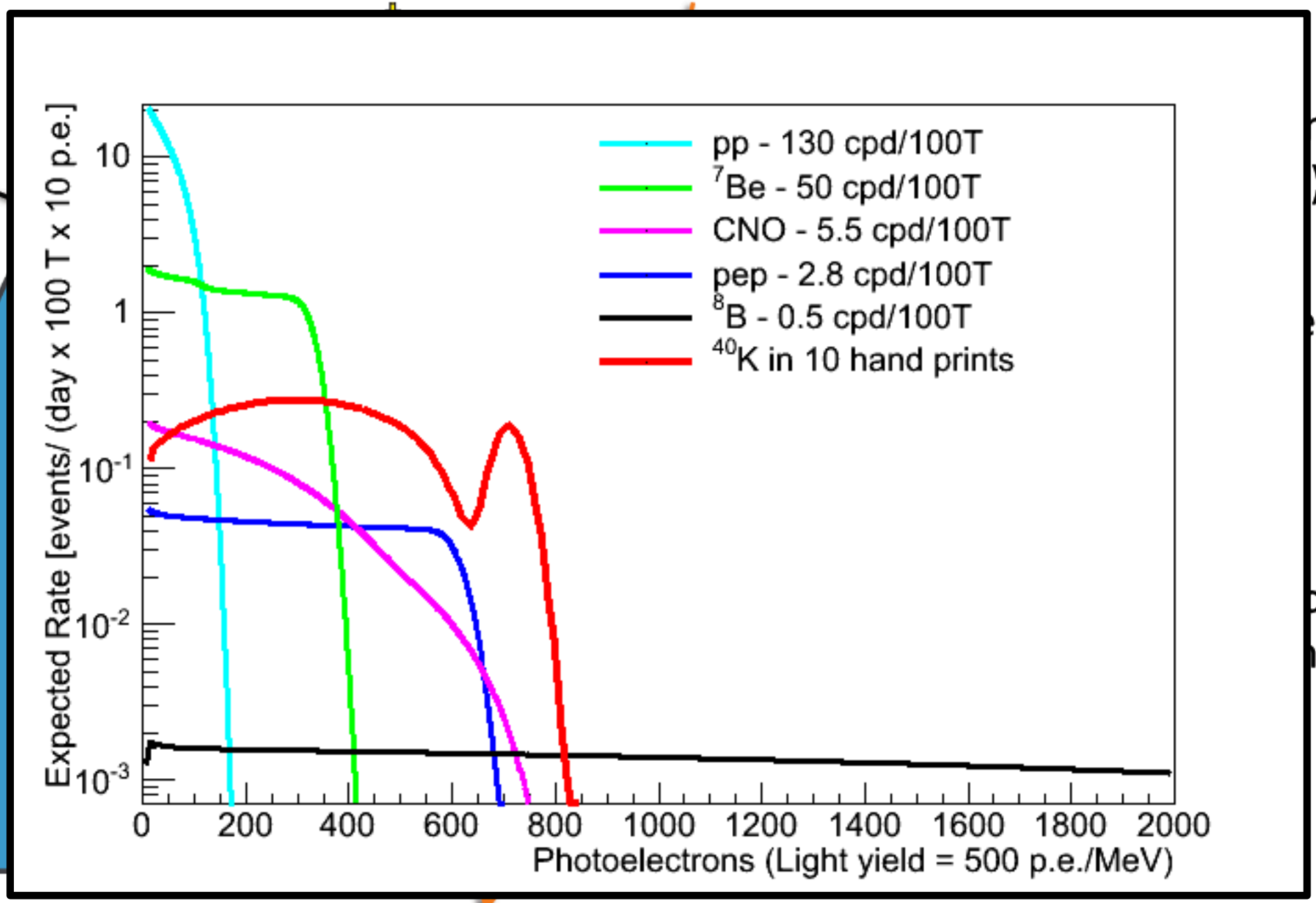
**Cosmic Muons**

**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.***

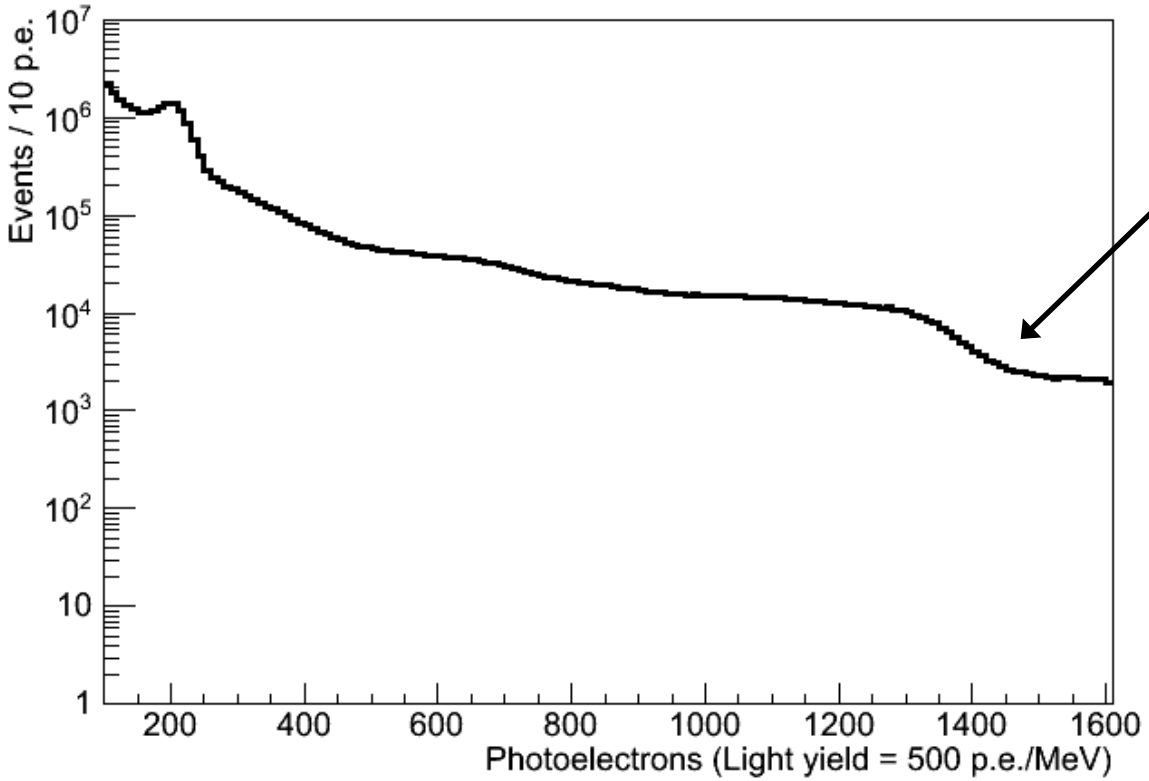
The Counting Test Facility III

| 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 | ~$5x10^{-18}$ g/g | Purification |
| $^{232}Th$ | Dust | $10^{-6}$ g/g | ~$4x10^{-18}$ g/g | Purification |
| $^{85}Kr$ | Air | 1 Bq/m$^3$ | ~$2x10^{-3}$ Bq/m$^3$ | LAKN |
| $^{222}Rn$ | Air | 20-100 Bq/m$^3$ | <$10^{-6}$ Bq/m$^3$ | Air exclusion |
| $K_{nat}$ | Dust | ~$10^{-3}$ g/g | <$2x10^{-15}$ g/g | Purification |
| μ | Cosmic | 200 s$^{-1}$m$^{-2}$ | $10^{-10}$ s$^{-1}$m$^{-2}$ | Underground, active veto |

# Borexino Neutrino Results

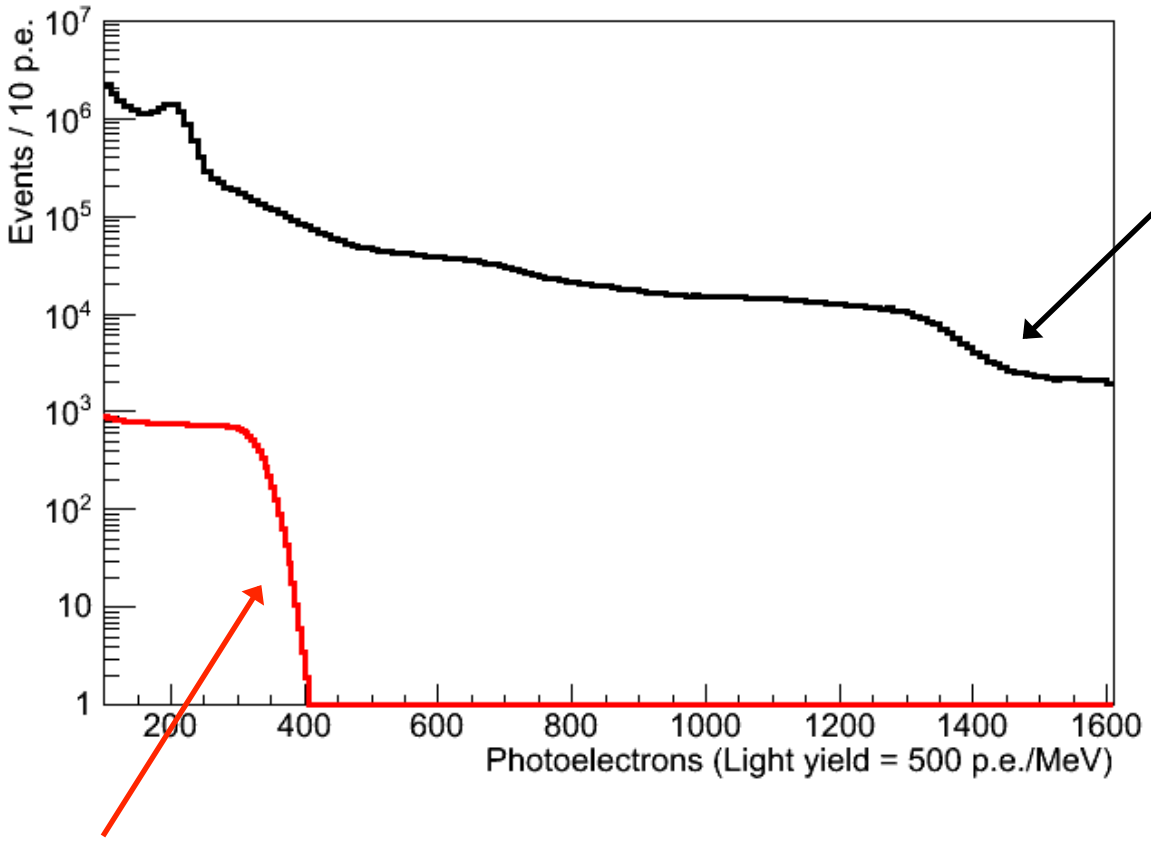
- $^{7}$Be Flux
  - (±30%) – Phys. Lett. B **658**:101 (2008).
  - (±10%) – Phys. Rev. Lett. **101**:091302 (2008).
  - (±5%) – Phys. Rev. Lett. **107**:141302 (2011).
- $^{7}$Be Day-Night Asymmetry
  - Phys. Lett. B **707**:22 (2012).
- $^{8}$B Flux + Spectrum ($T_{eff}$ > 3.0 MeV)
  - Phys. Rev. D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

# Borexino Data




All data: 740 live days

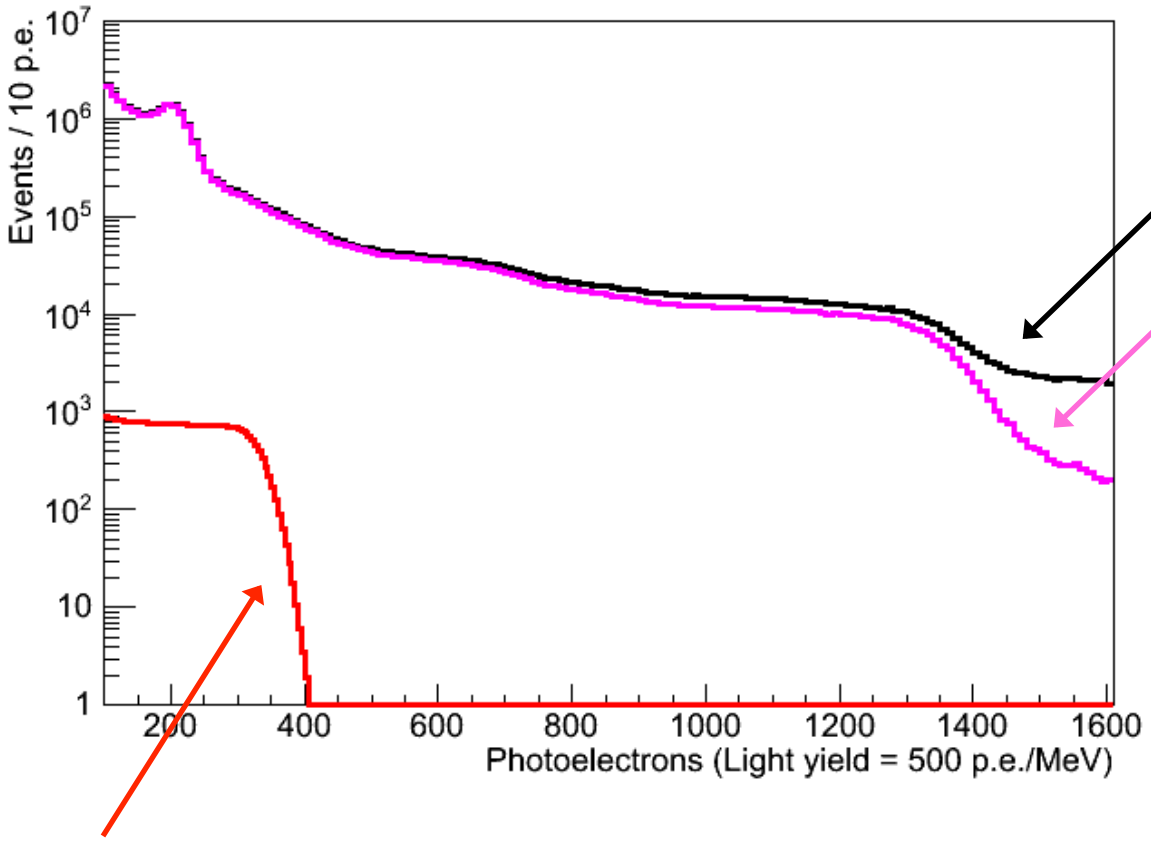
# Borexino Data




All data: 740 live days

Expected $^7$Be signal

# Borexino Data

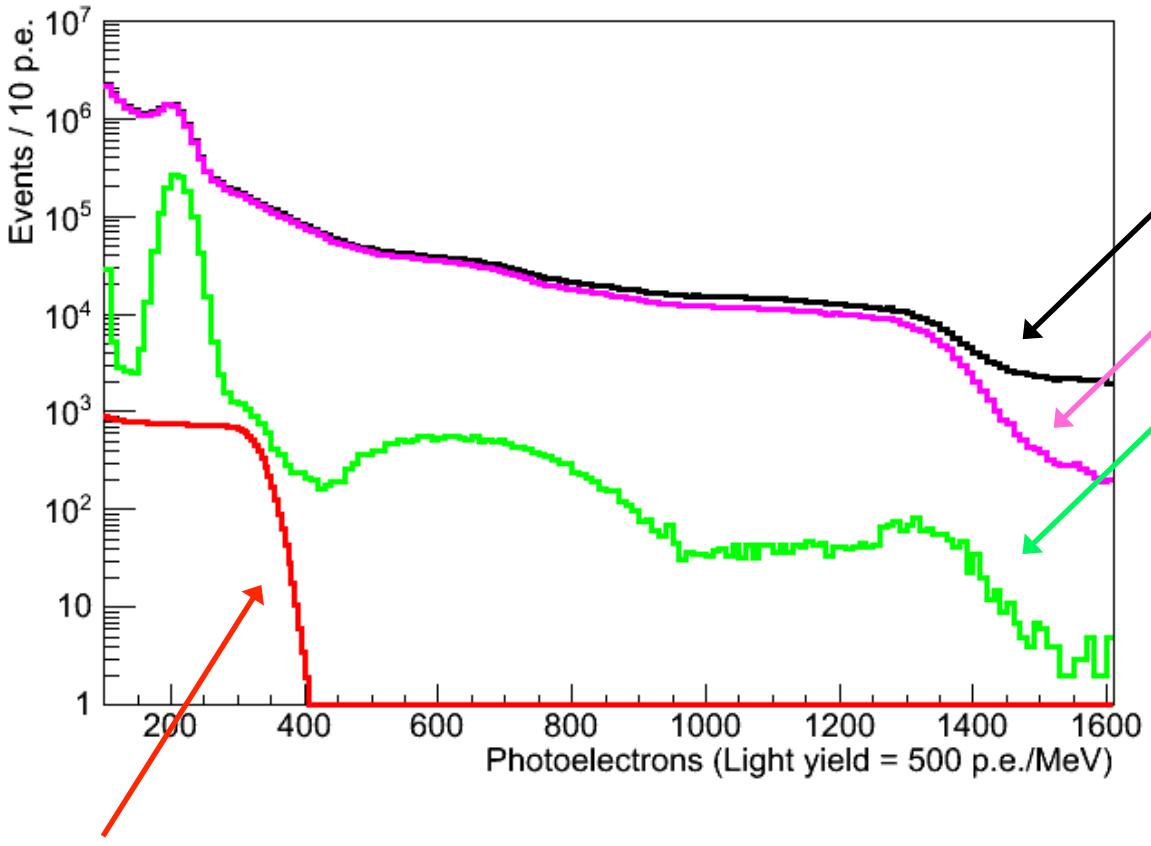



All data: 740 live days

Remove muons + muon followers (2 ms)

Expected $^7$Be signal

# Borexino Data



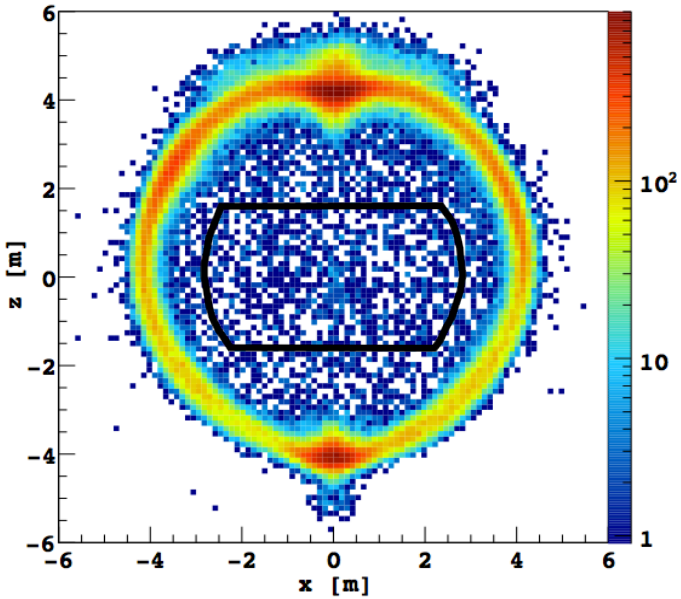

All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

R < 3.02m

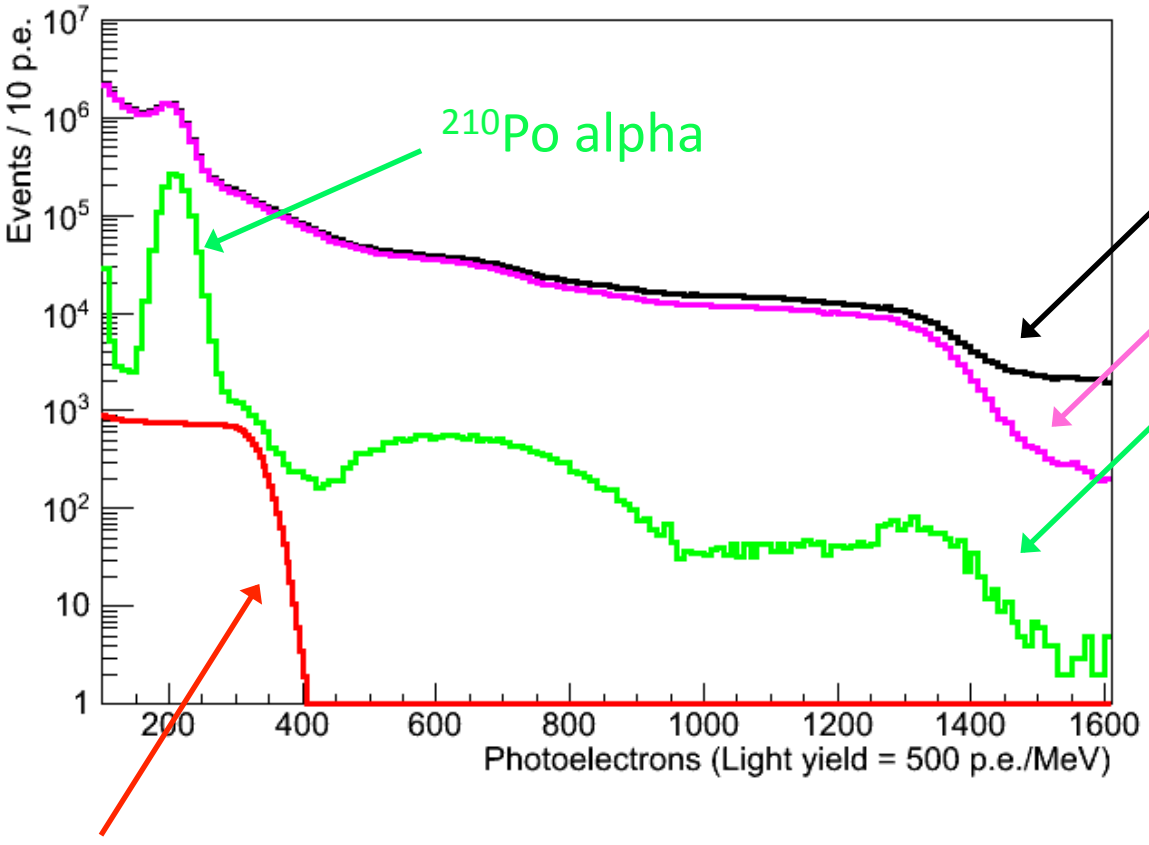
|z| < 1.67m



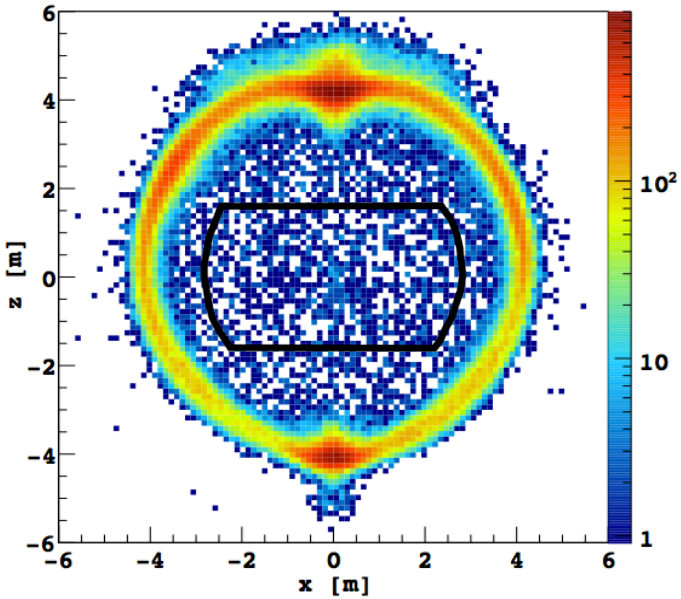

Fiducial mass = 75.6 tonnes

Expected $^7$Be signal

# Borexino Data

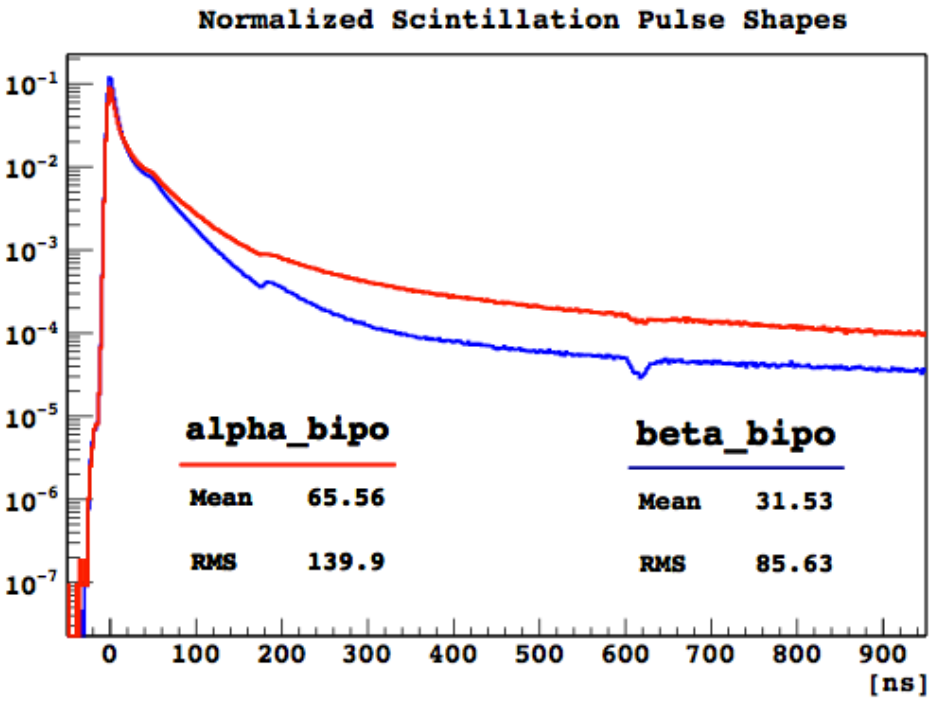


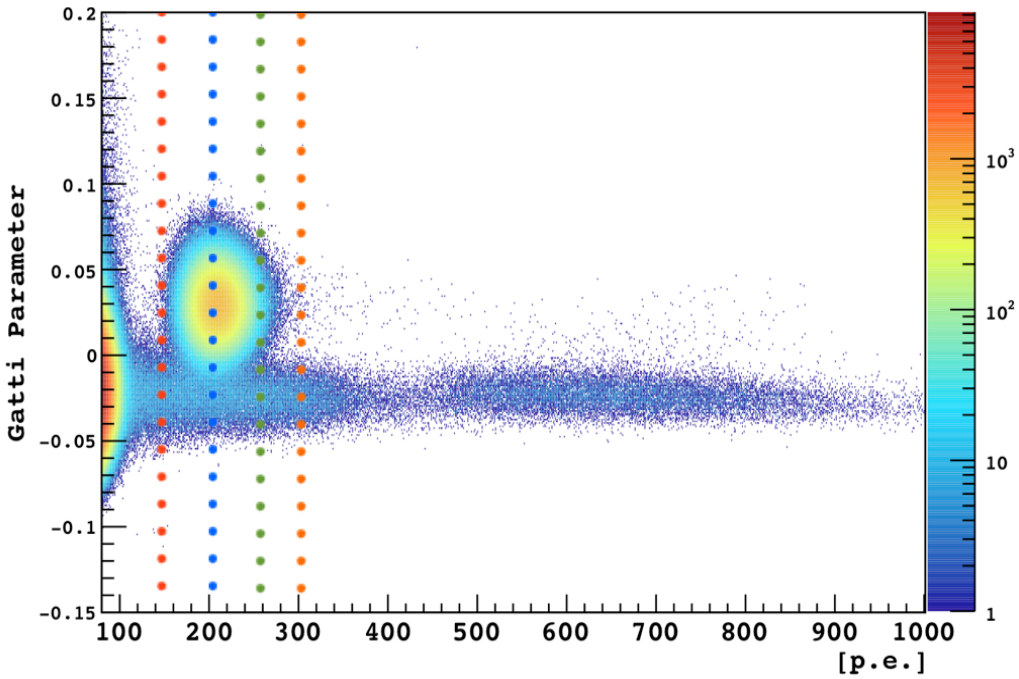

R < 3.02m
|z| < 1.67m




Fiducial mass = 75.6 tonnes

# Alpha Pulse Shape Discrimination



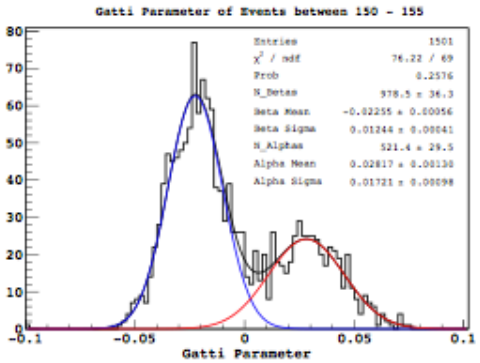




$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

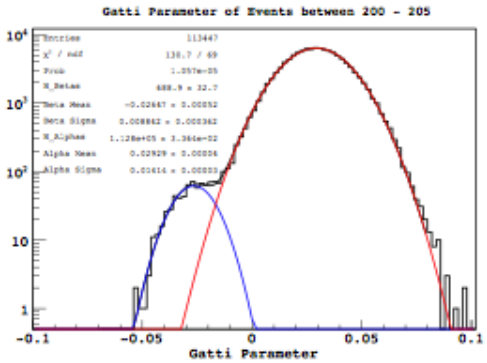
$$w[t] \equiv \frac{r_\alpha[t] - r_\beta[t]}{r_\alpha[t] + r_\beta[t]}$$

$e[t]$ : Event Time Profile

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

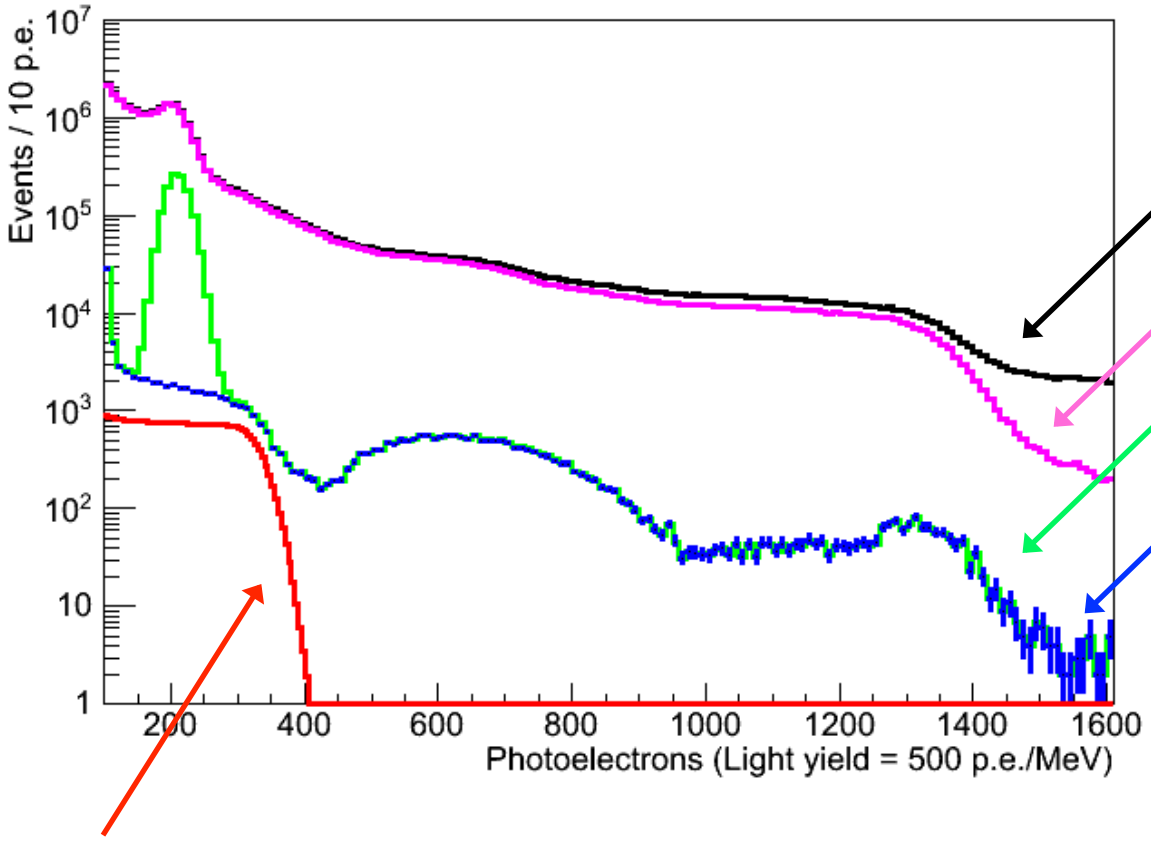



150 p.e.




200 p.e.

# Borexino Data




All data: 740 live days

Remove muons + followers

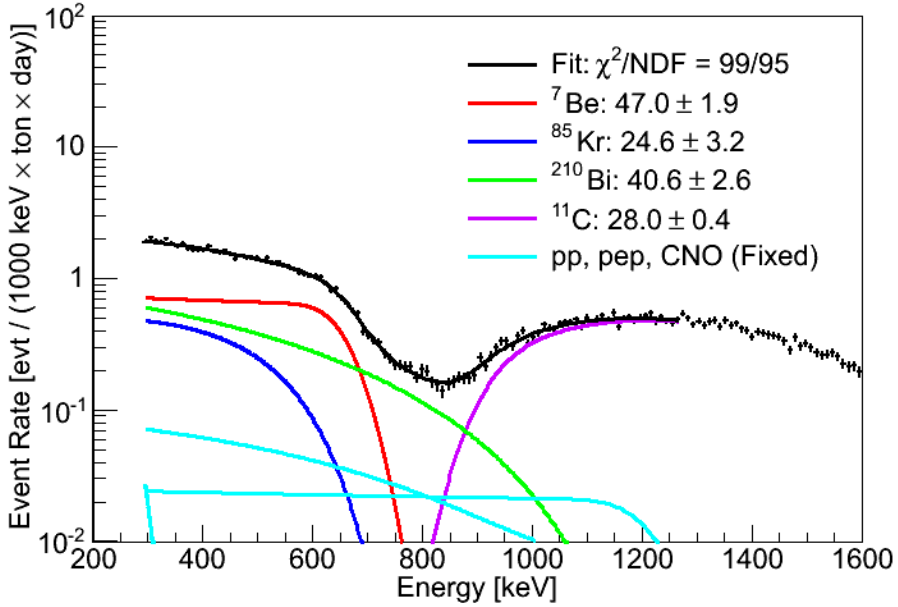
Fiducial Volume + high level

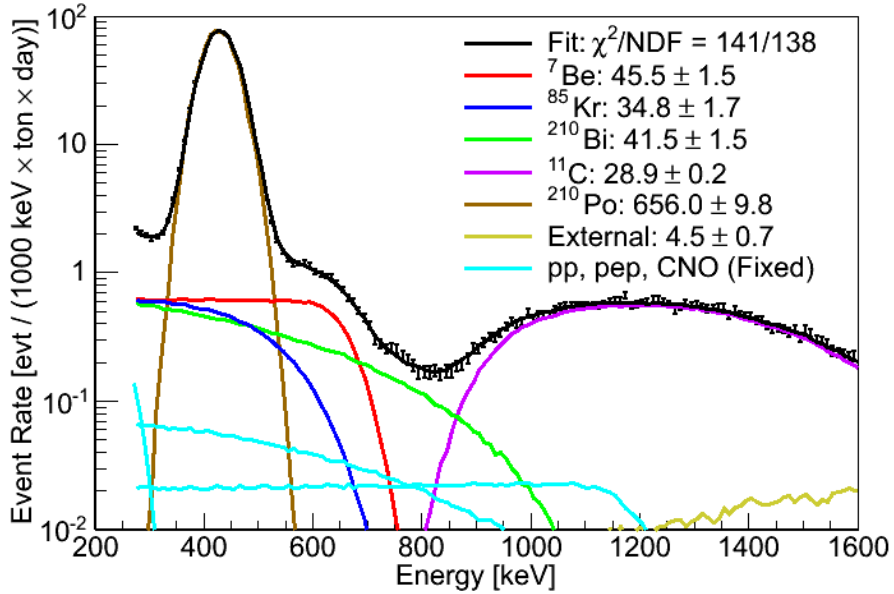
Statistically subtract alphas

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)**

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

| **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)**

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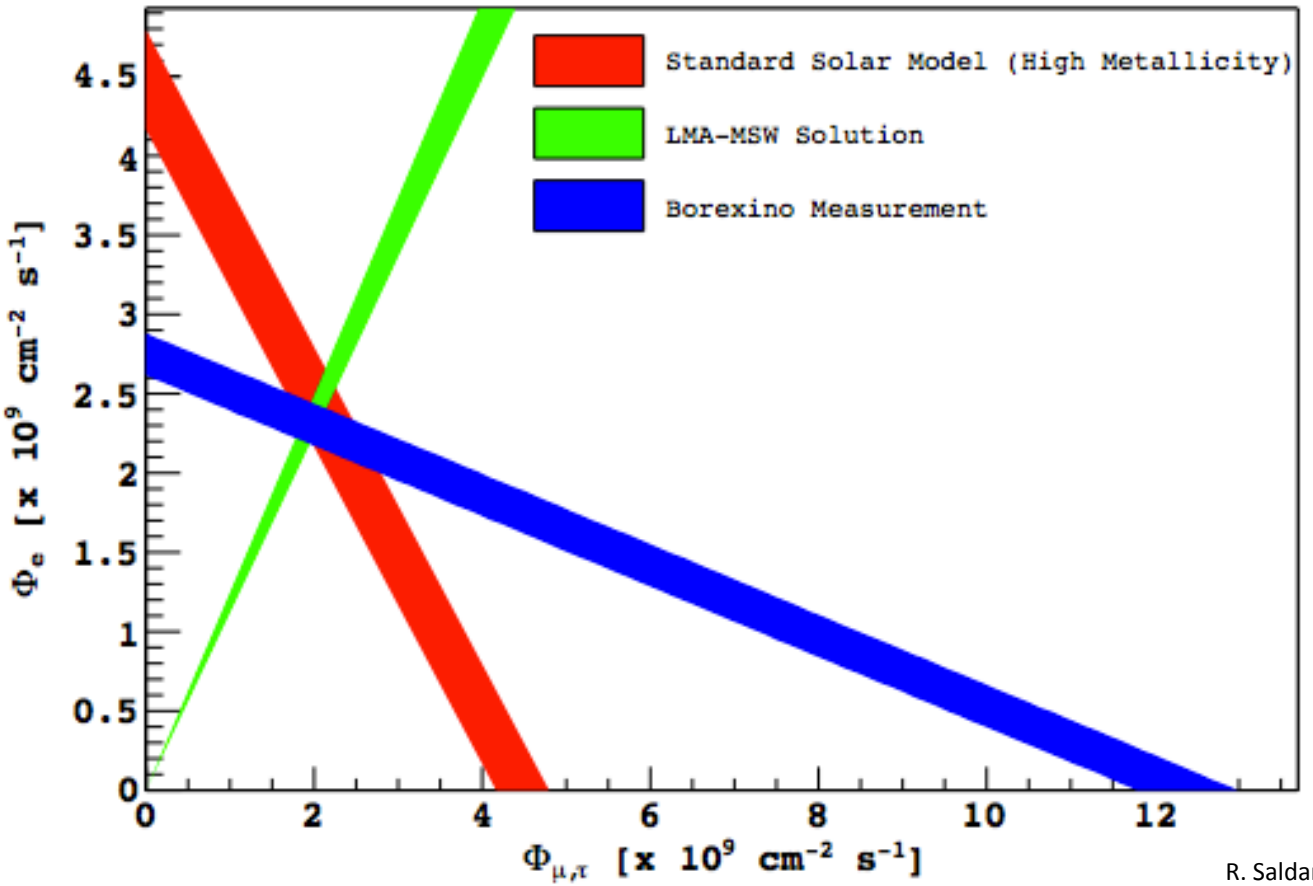
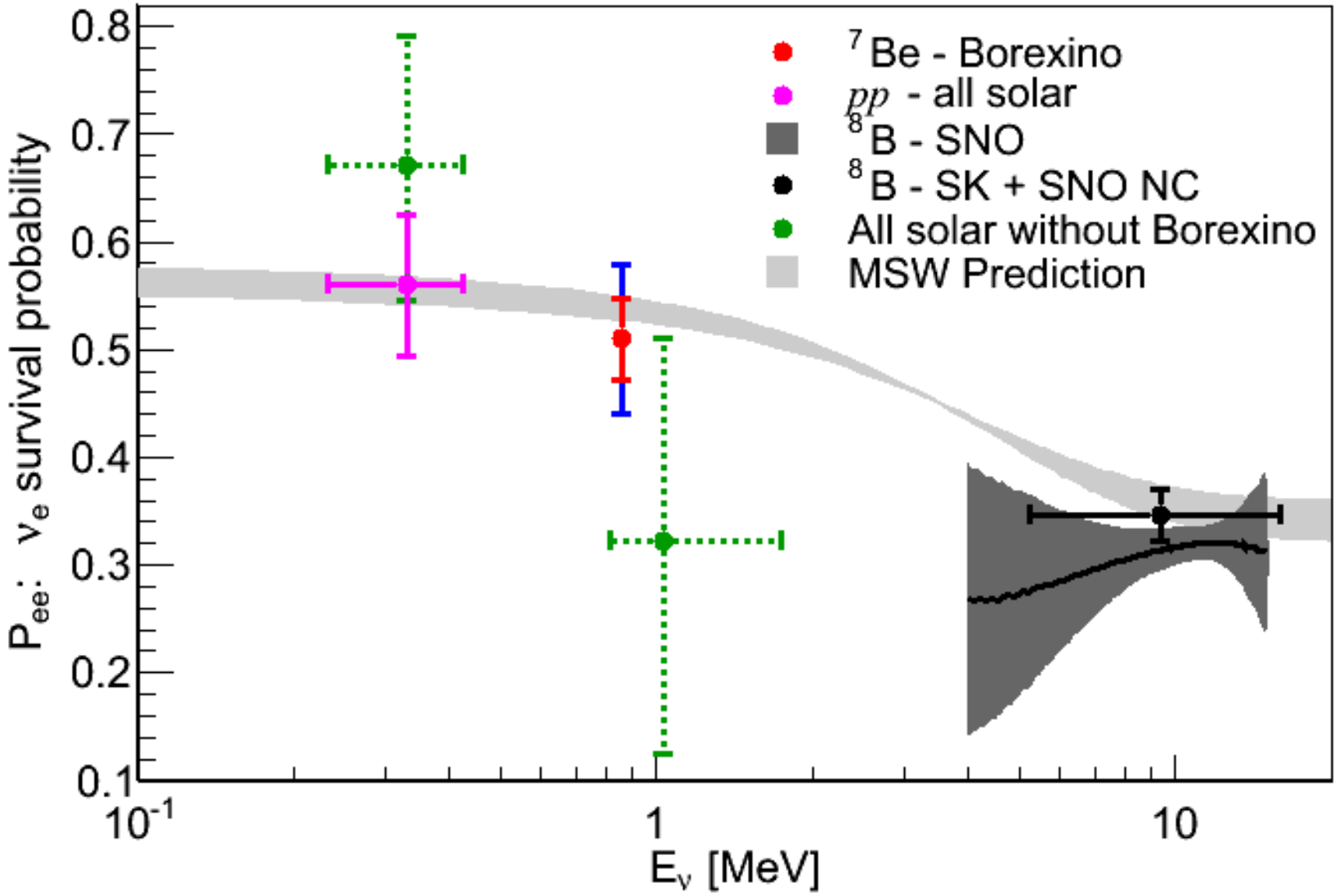


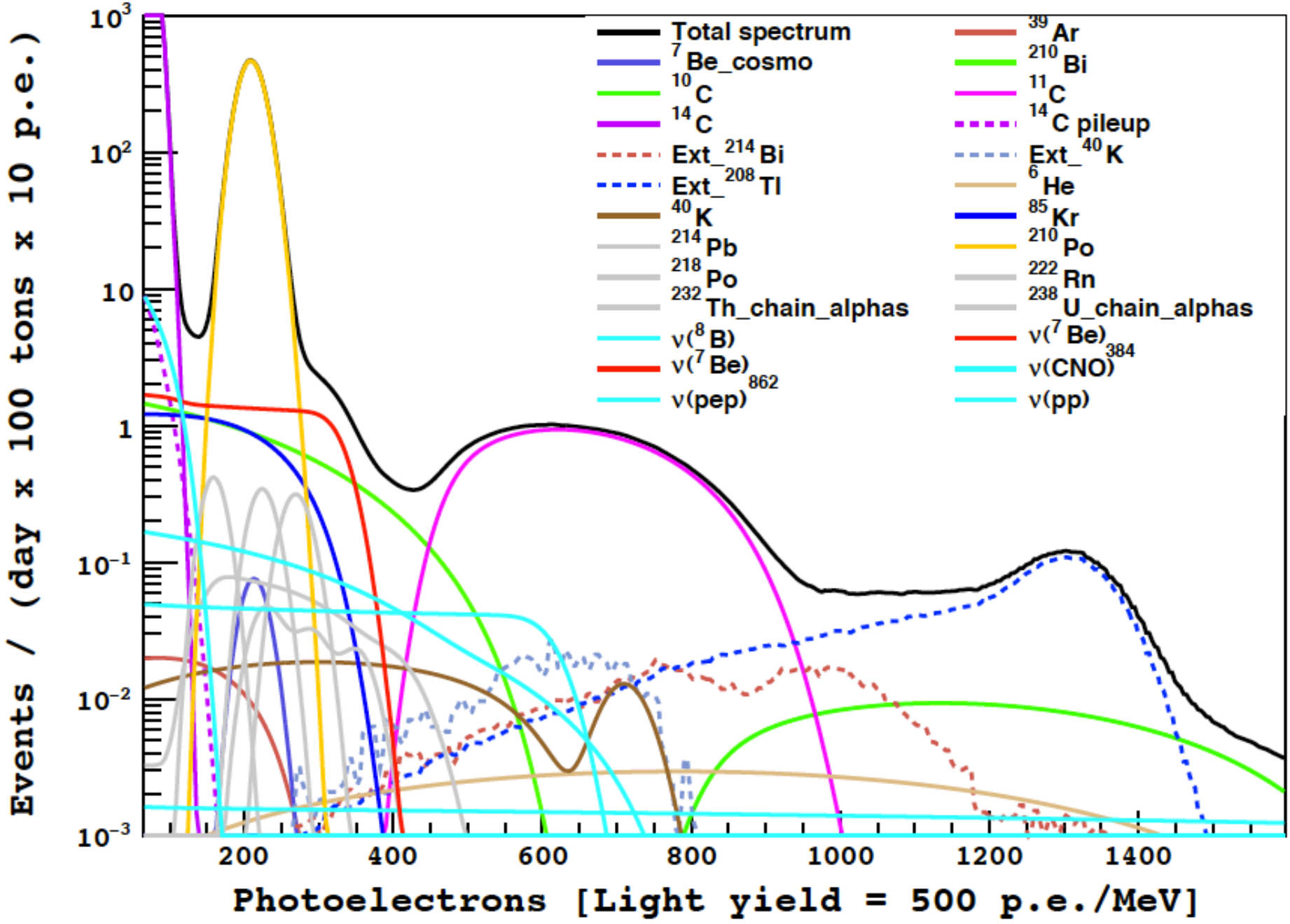

R. Saldanha, Ph.D. Thesis, Princeton (2011)

# Precision $^{7}$Be Flux Result

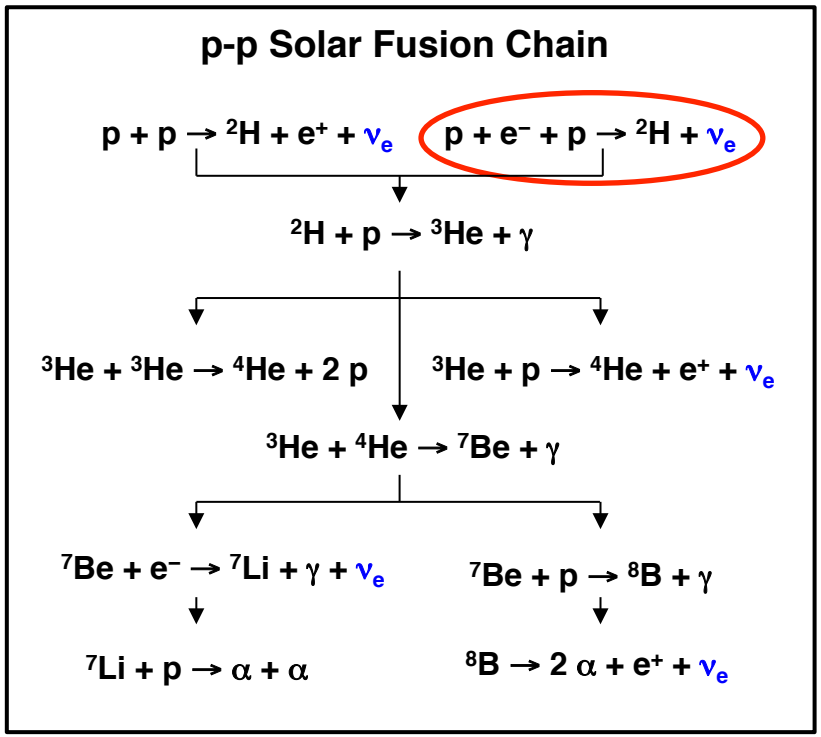


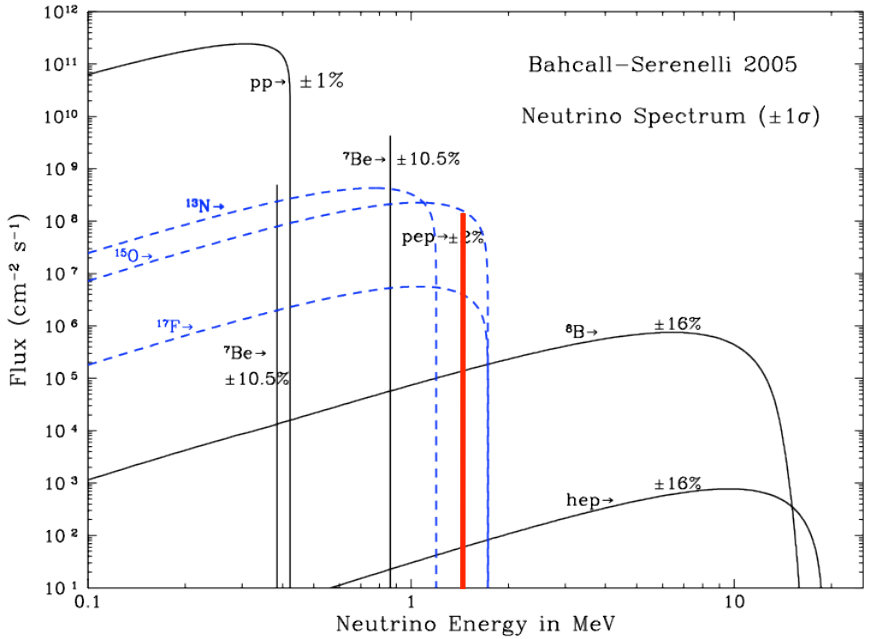

***Significantly improved constraint on low energy $P_{ee}$.***

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



# *pep* Neutrinos

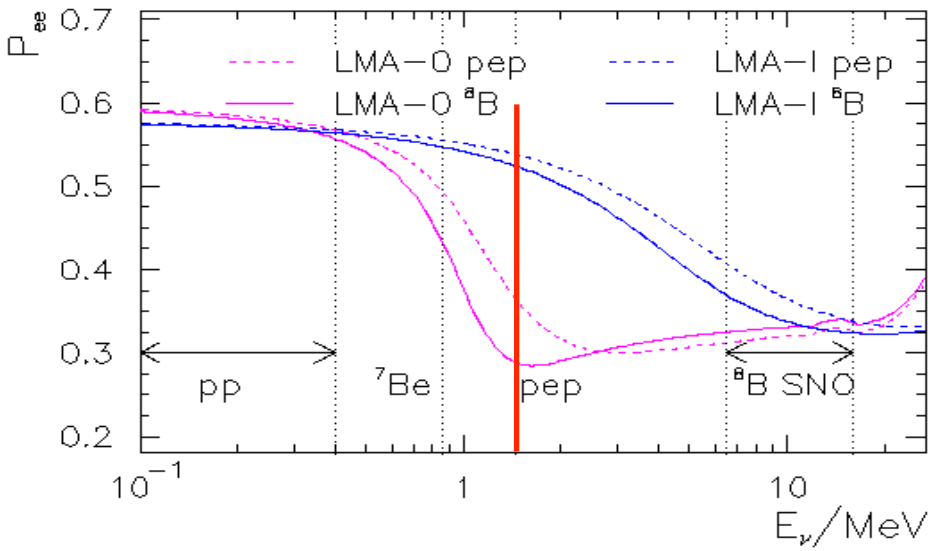


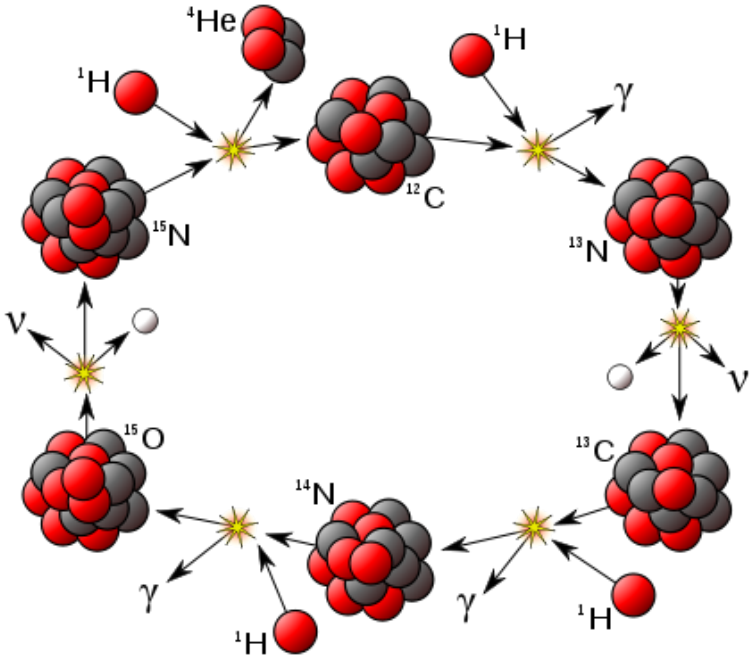

*First direct look at solar p-p fusion.*

*Precision test of Standard Solar Model and oscillations.*

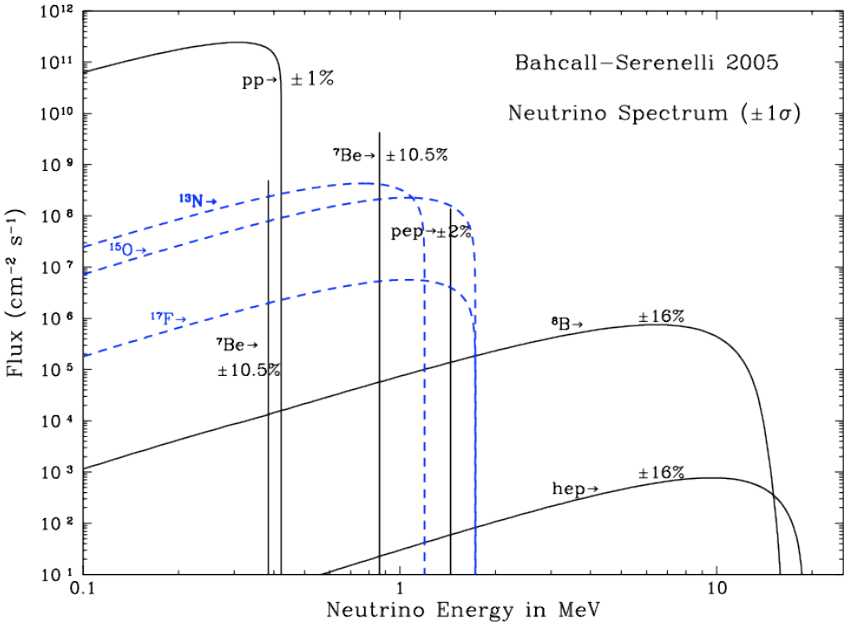
*Ideal energy to probe transition region.*



# CNO Neutrinos

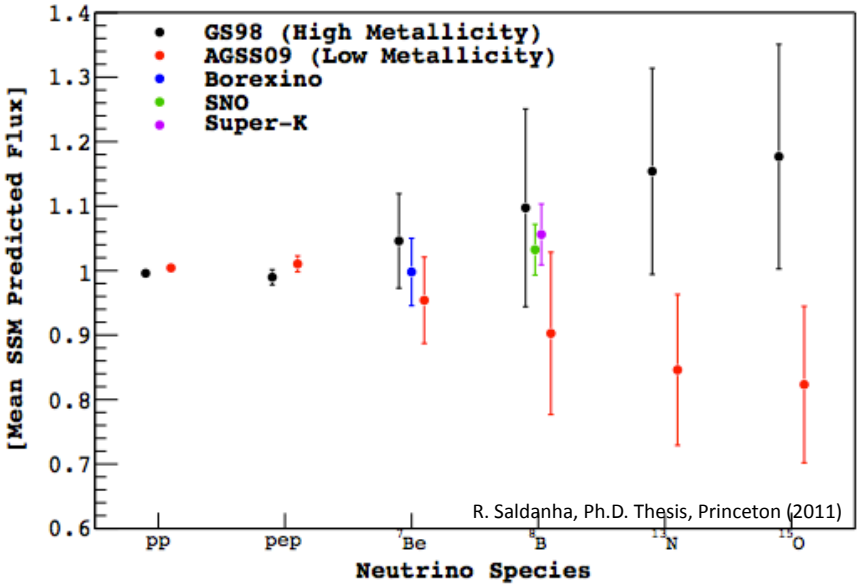



Wikimedia.org

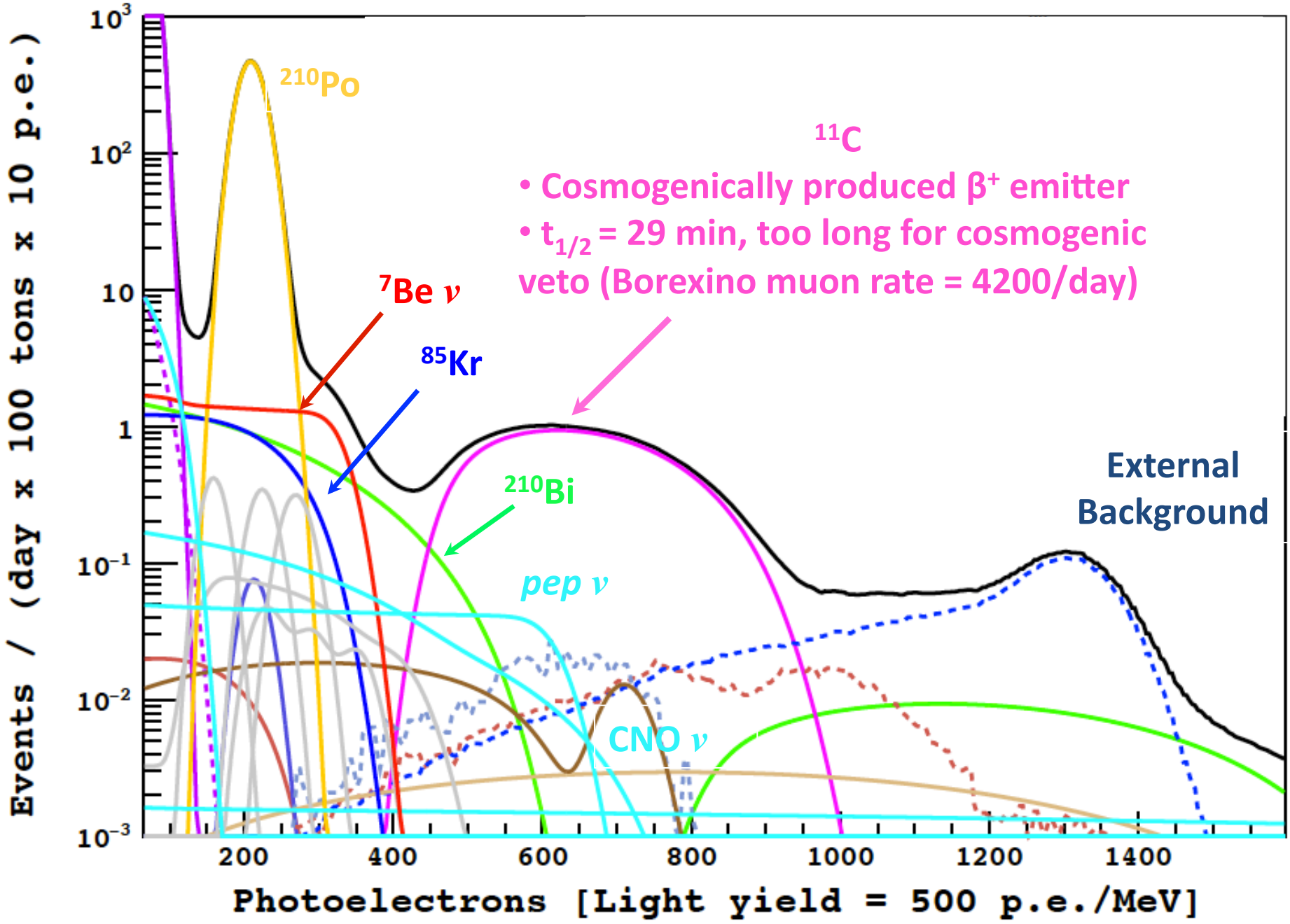



*First direct evidence for CNO cycle.*

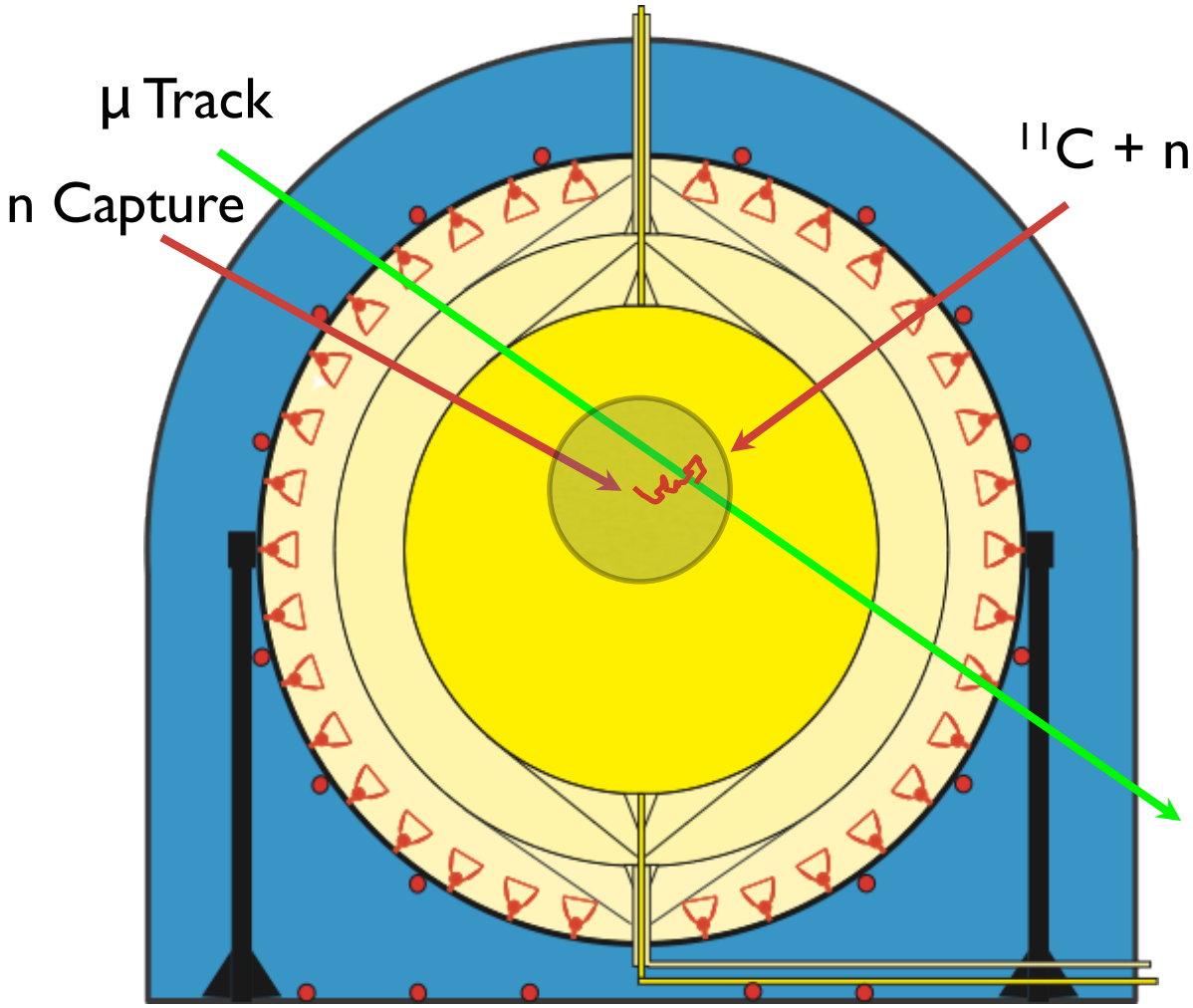
*Measure solar metallicity.*



# $^{11}$C Suppression



# Three-Fold Coincidence



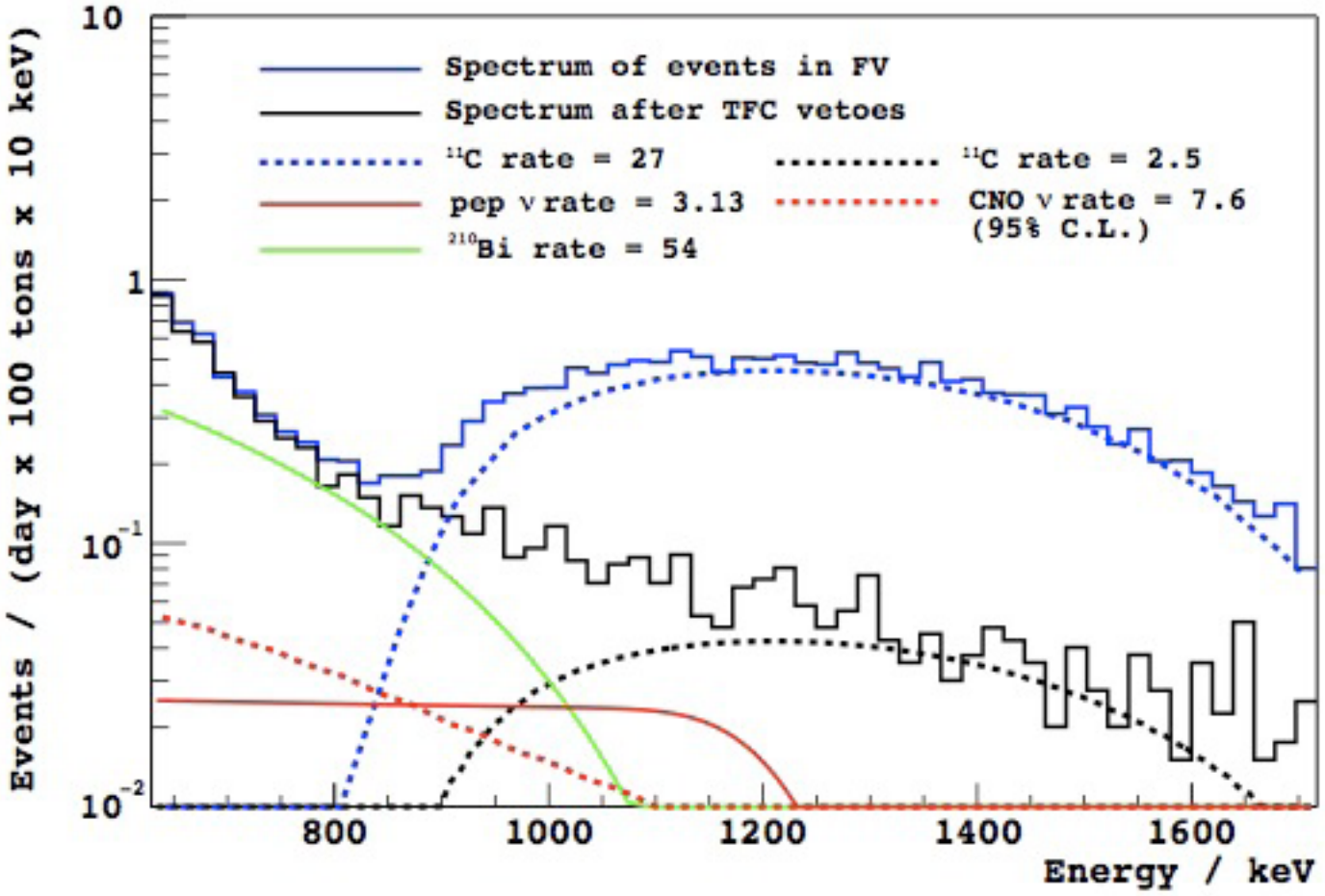

- Most $^{11}C$ produced via

  $^{12}C \rightarrow {}^{11}C + n$

- 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.***

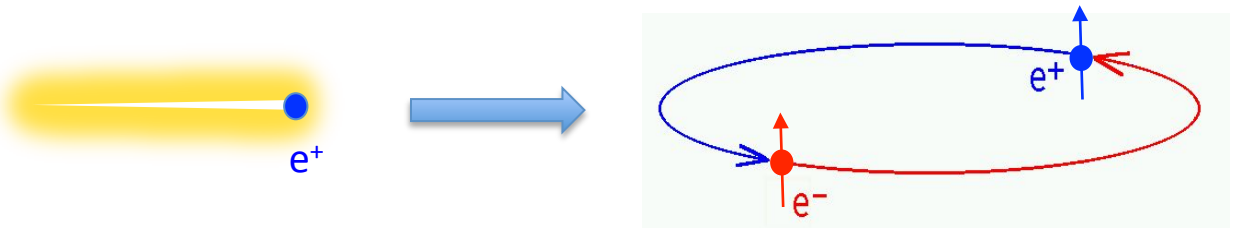
# Three-Fold Coincidence




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

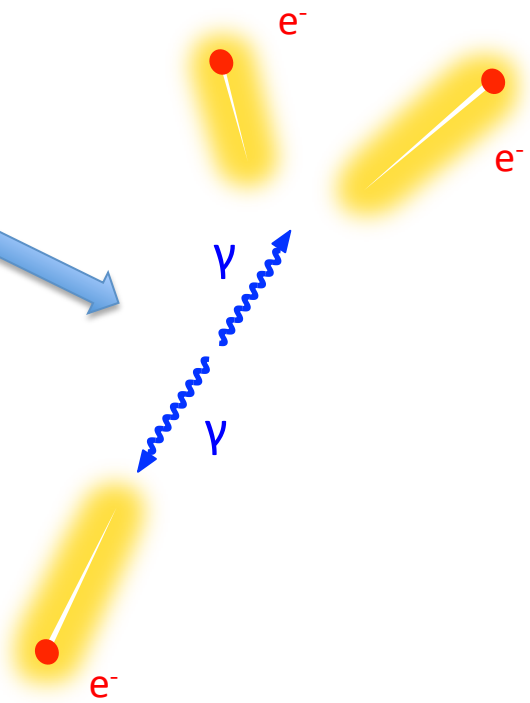
# $e^+/e^-$ Pulse Shape Discrimination

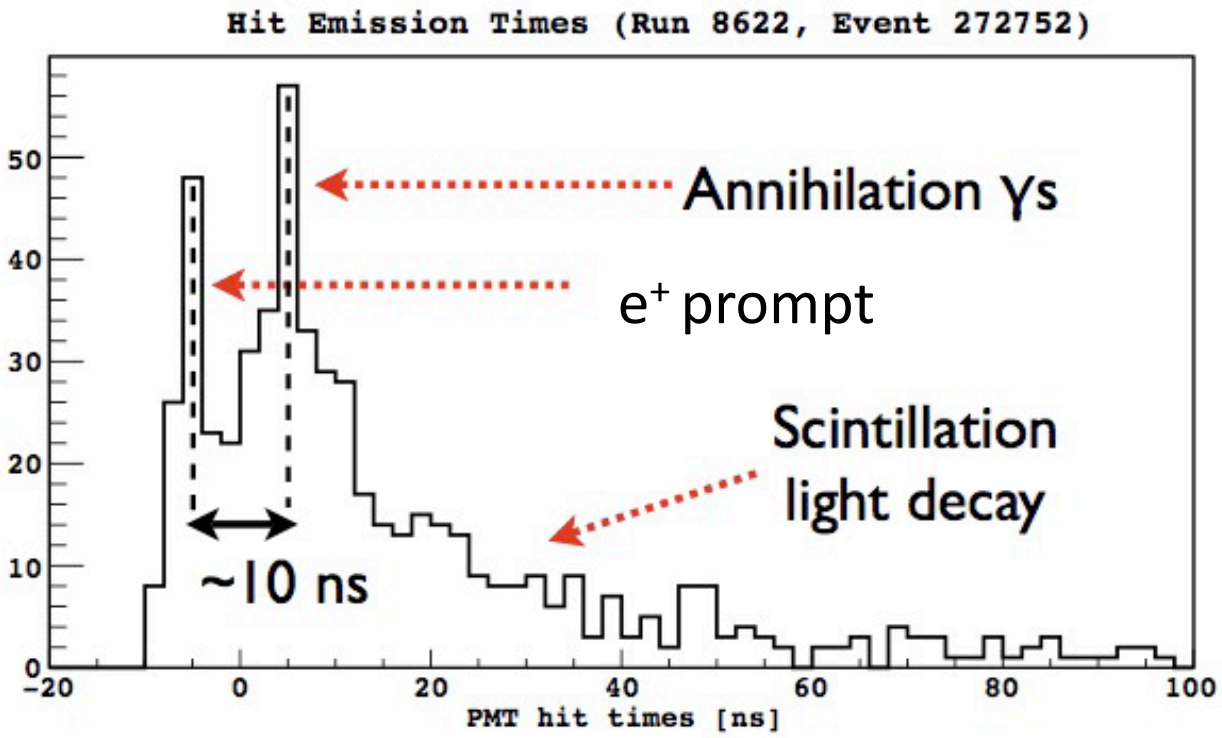
(PRC 83:015522 (2011))




*ortho*-positronium

$t_{1/2}$ = 3 ns



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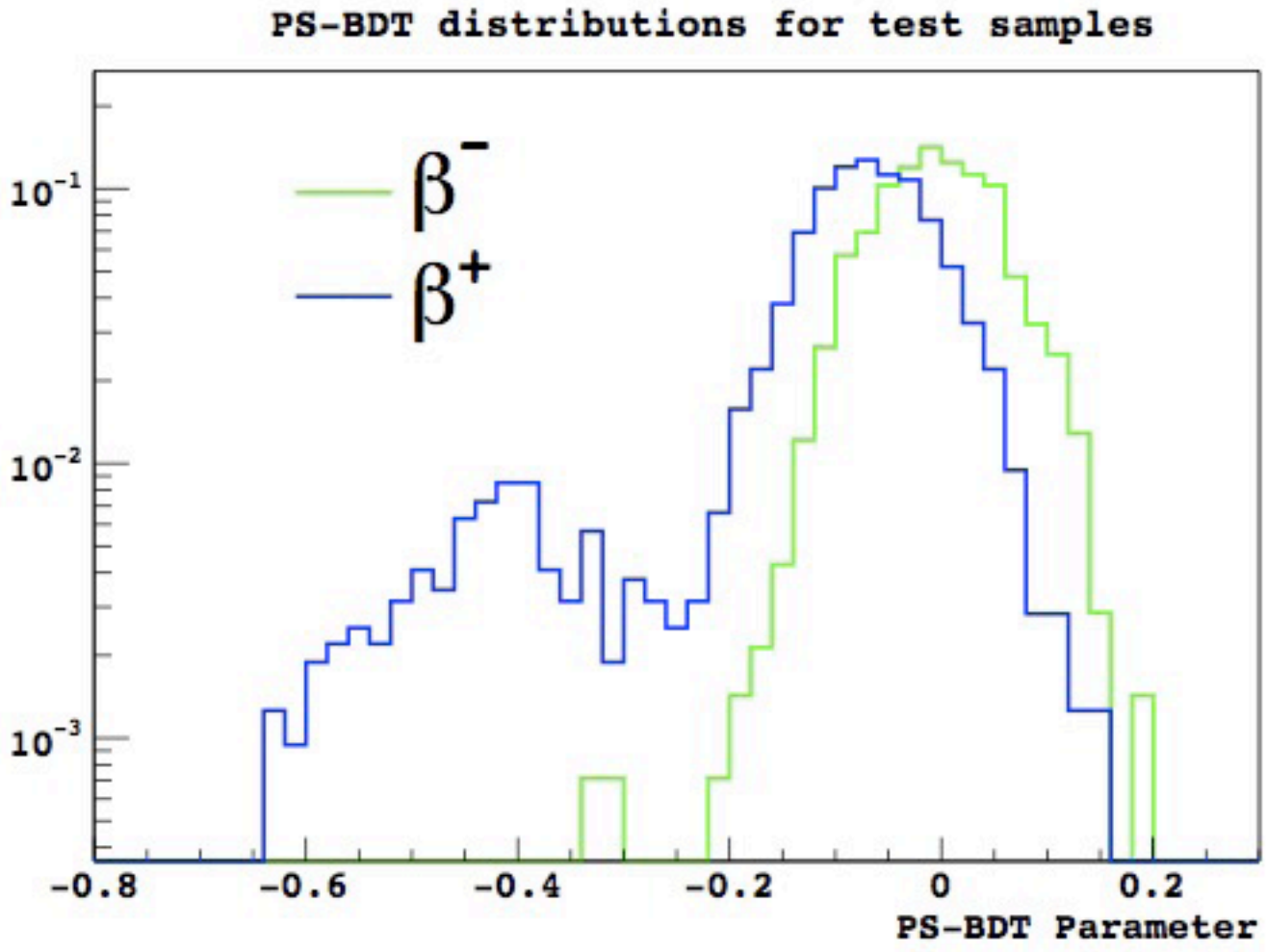
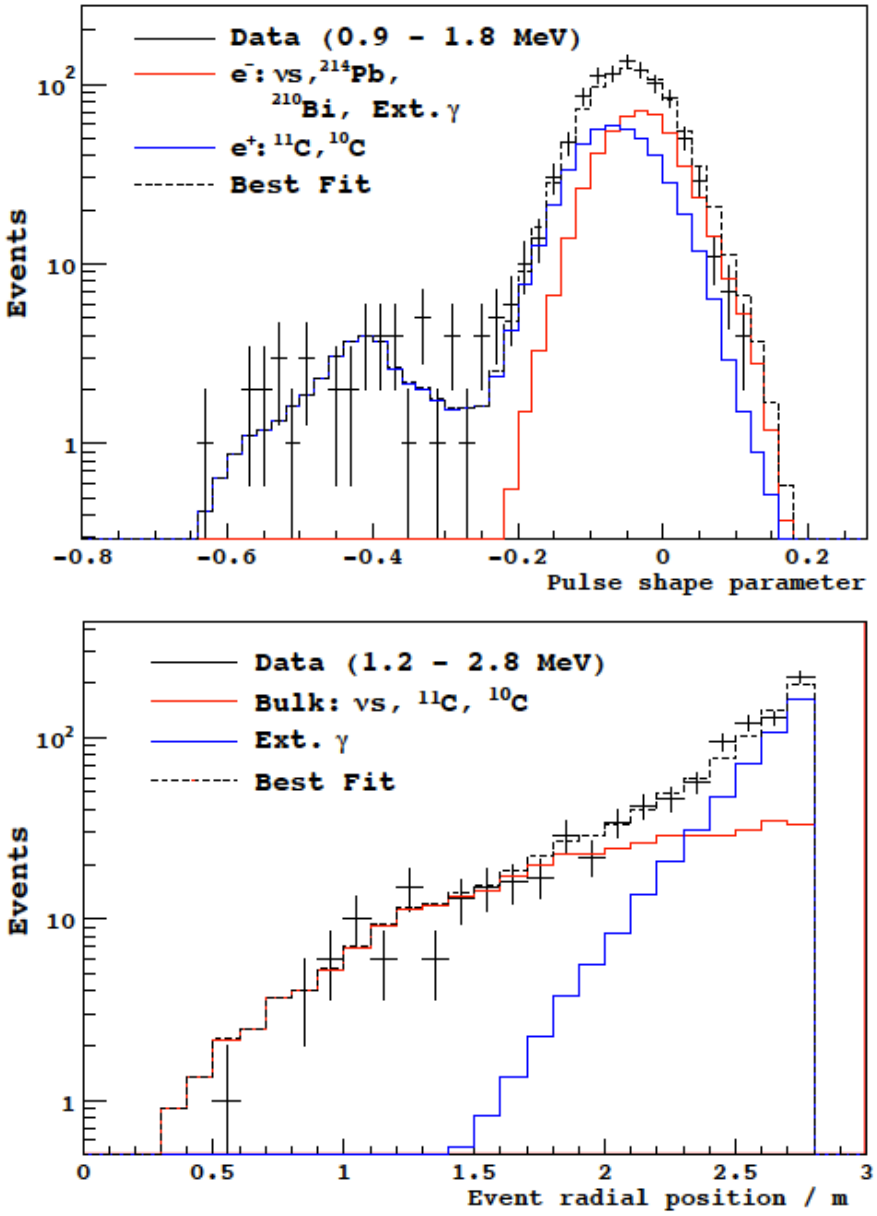



*Boosted decision tree (BDT) discrimination parameter from pulse shape information.*

# *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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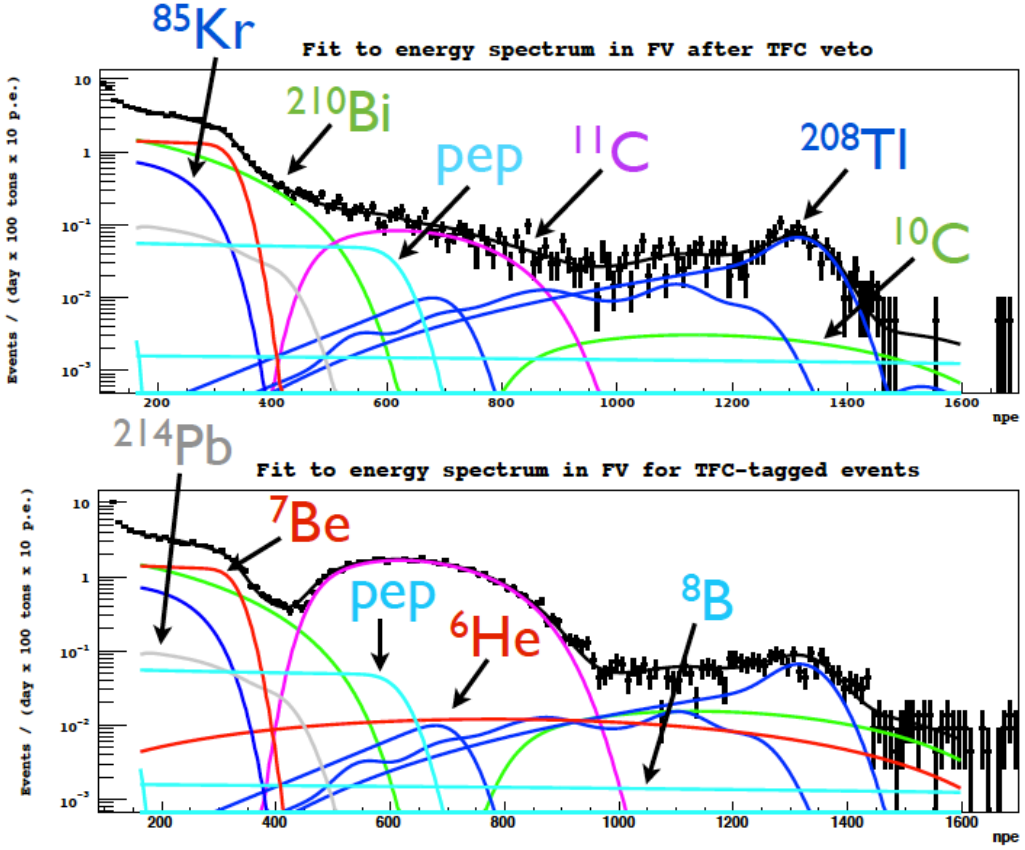
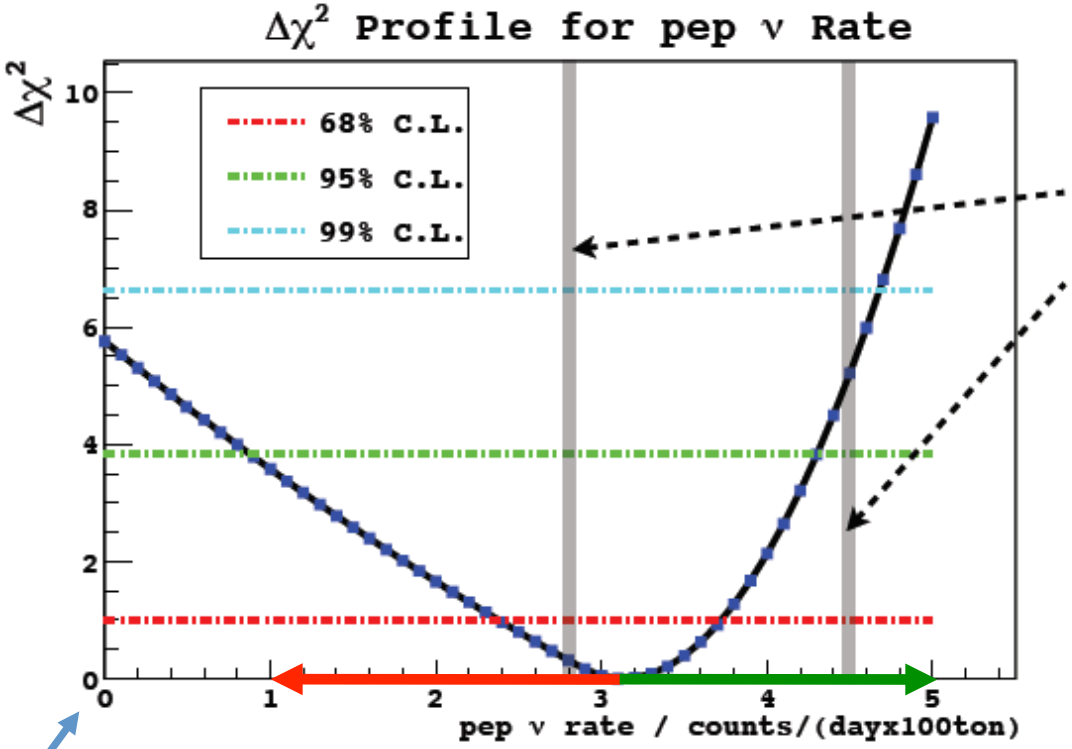


# *pep* Result

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

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

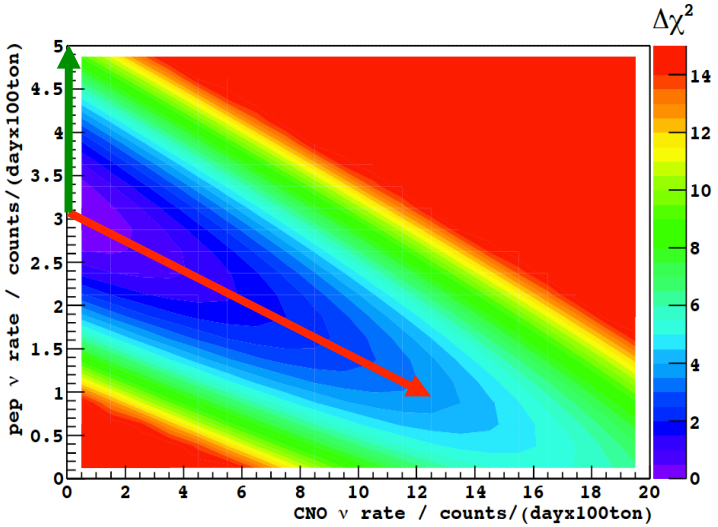
➡ $\Phi_{pep} = (1.6 \pm 0.3) \times 10^8\ cm^{-2}s^{-1}$ ➡ $P_{ee}(1.44\ MeV) = 0.62 \pm 0.17$




SSM Prediction

MSW-LMA

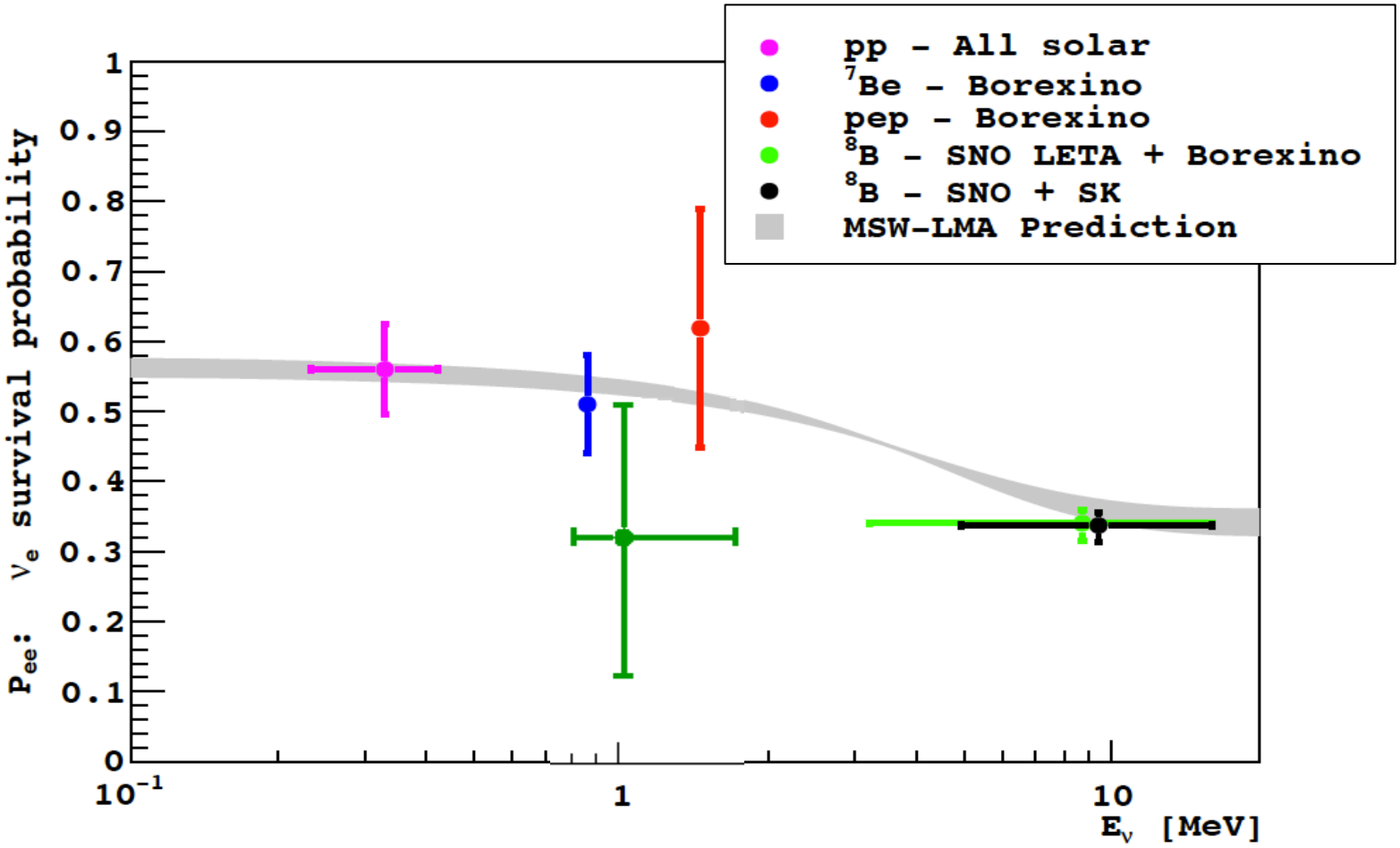
No Oscillation




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

# *pep* Result

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



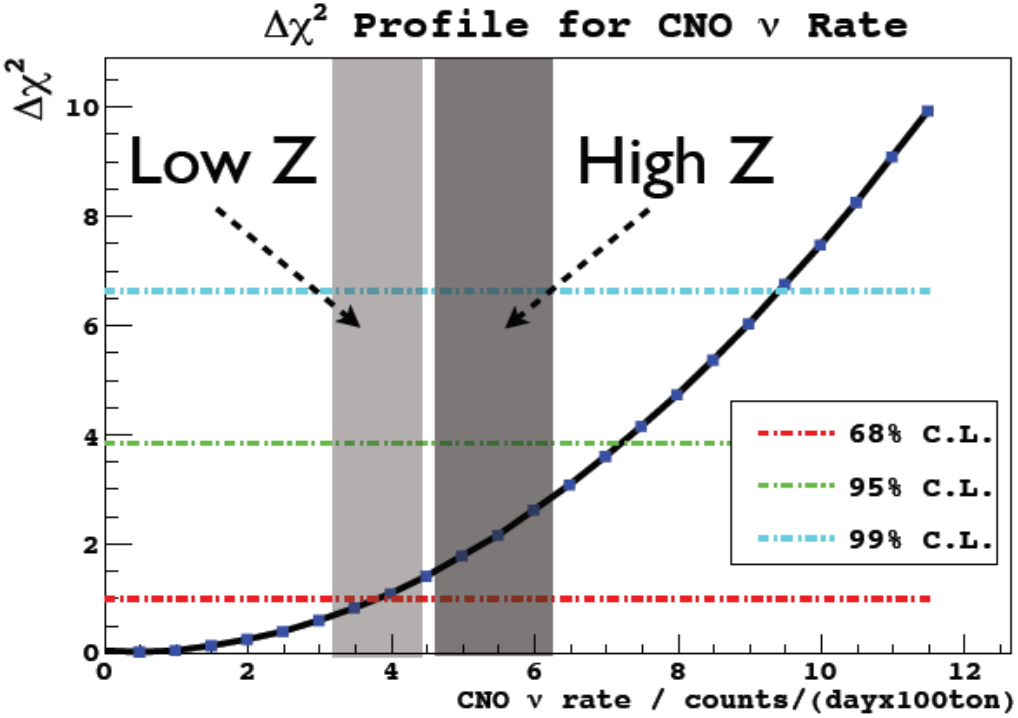

*We have succeeded in extracting the pep signal from the background – more precise results possible in the future!*

# 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 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.*

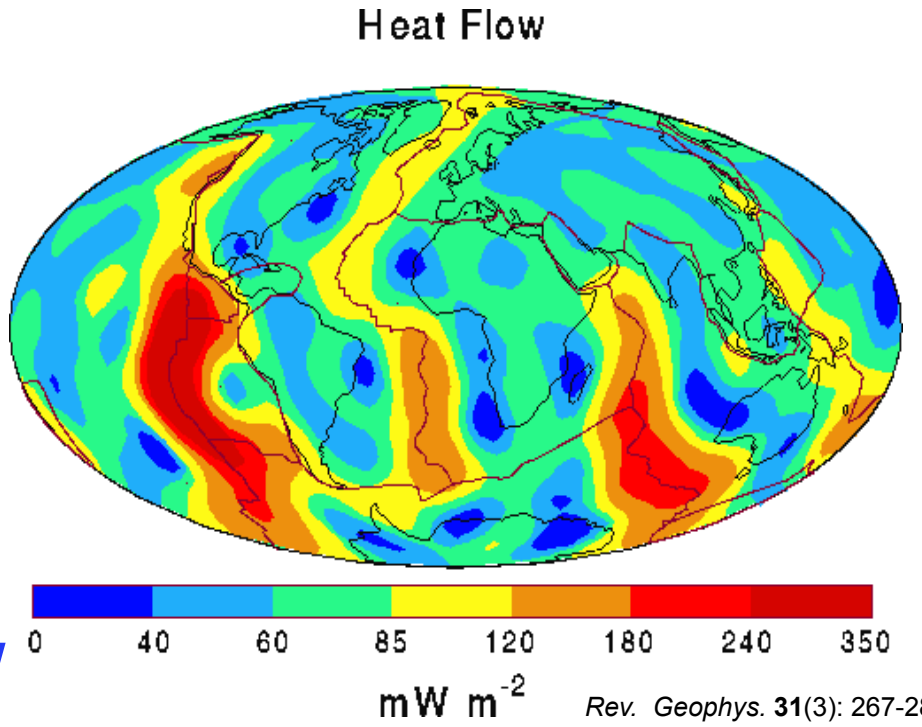
*Result consistent with both high and low metallicity models.*

# Geo-Neutrinos

- Antineutrinos from $\beta^-$ 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

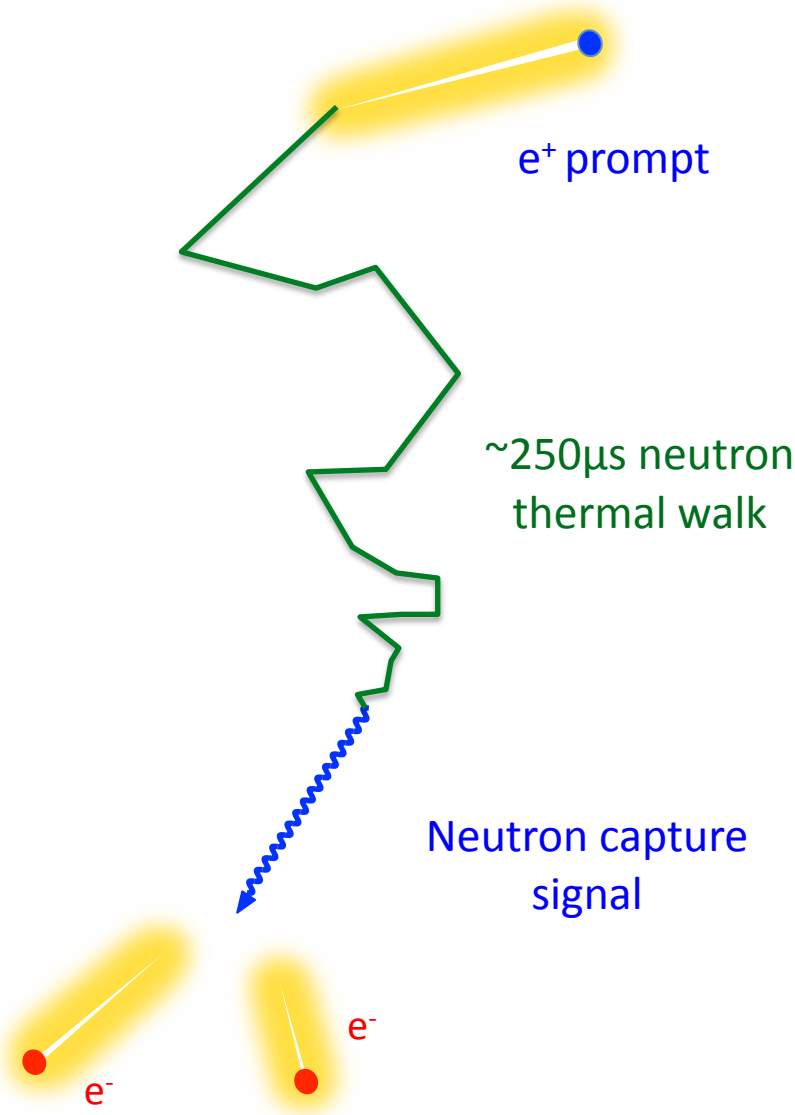



*Rev. Geophys.* **31**(3): 267-280 (1993)

*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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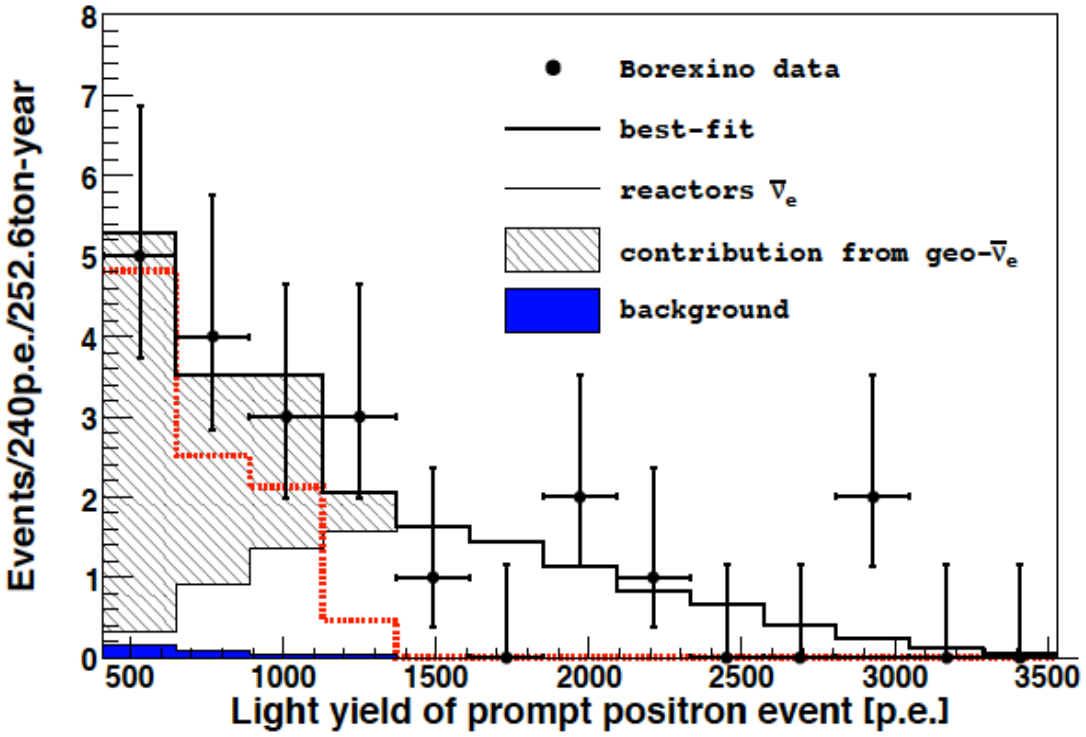
# Geo-neutrinos in Borexino

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

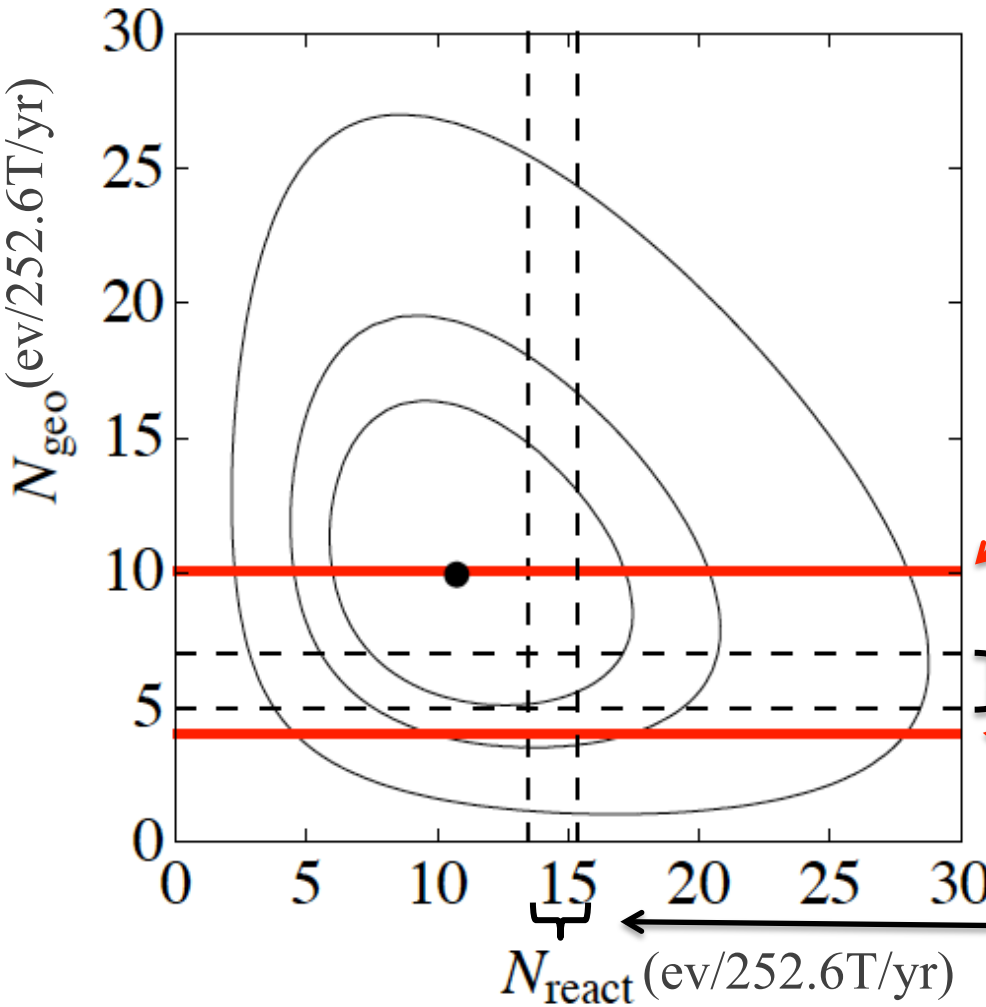
**Borexino Geo-Neutrino Rate: $3.9^{+1.6}_{-1.3}$ ev/100T/yr**




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




Expectation if entire heat flux from earth's interior is radiogenic.

Range of expectation for "standard" BSE models.

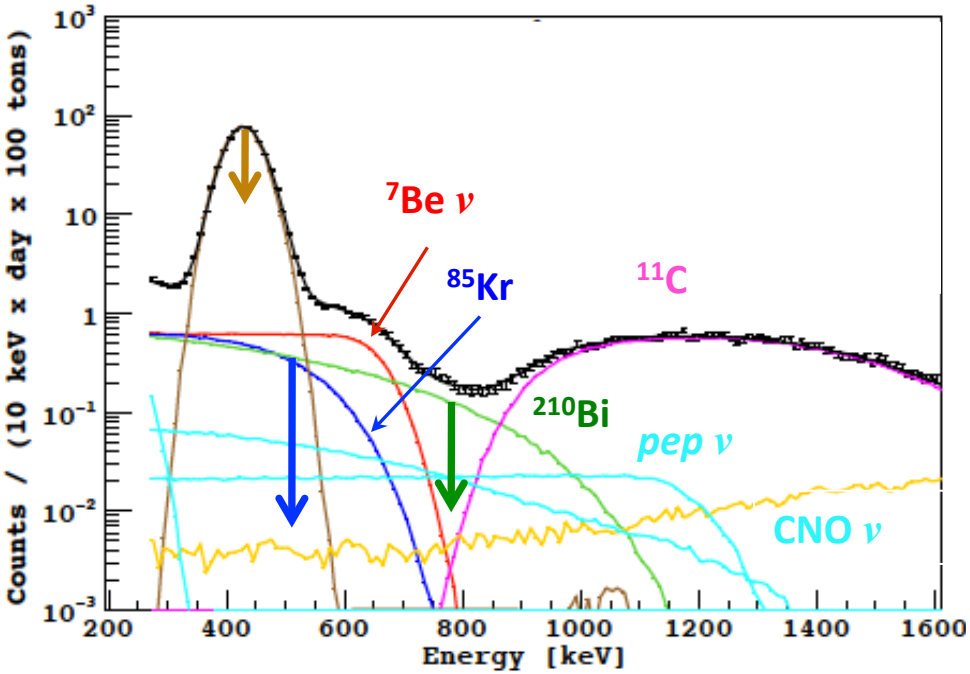
Expectation if all inferred radioactivity is removed.

Reactor neutrino expectation from reactor power outputs.

***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

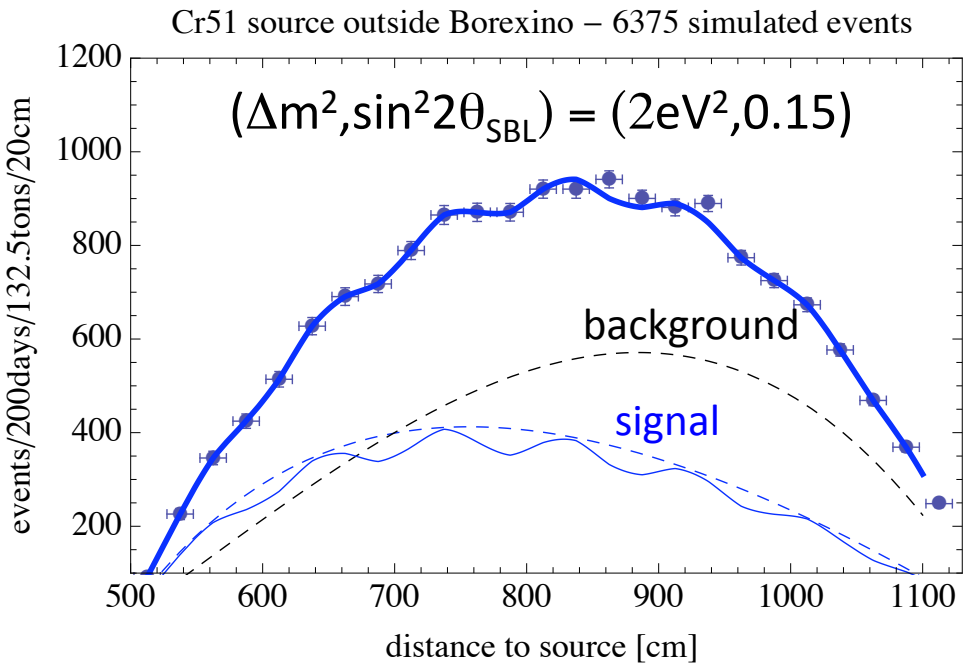
- Procedures to (further!) purify the scintillator underway since July 2010
  - No sign of $^{85}$Kr since January 2011
  - Moderate reduction in $^{210}$Bi
- Operations continue, with aim of further reducing $^{210}$Bi, perhaps $^{210}$Po
- Borexino will continue to take solar neutrino data for >3 more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




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

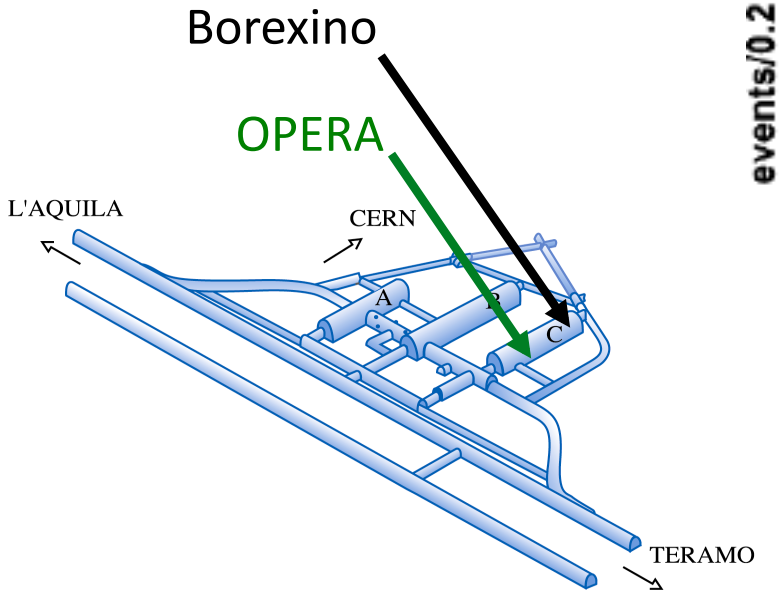
# Sterile Neutrino Search

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

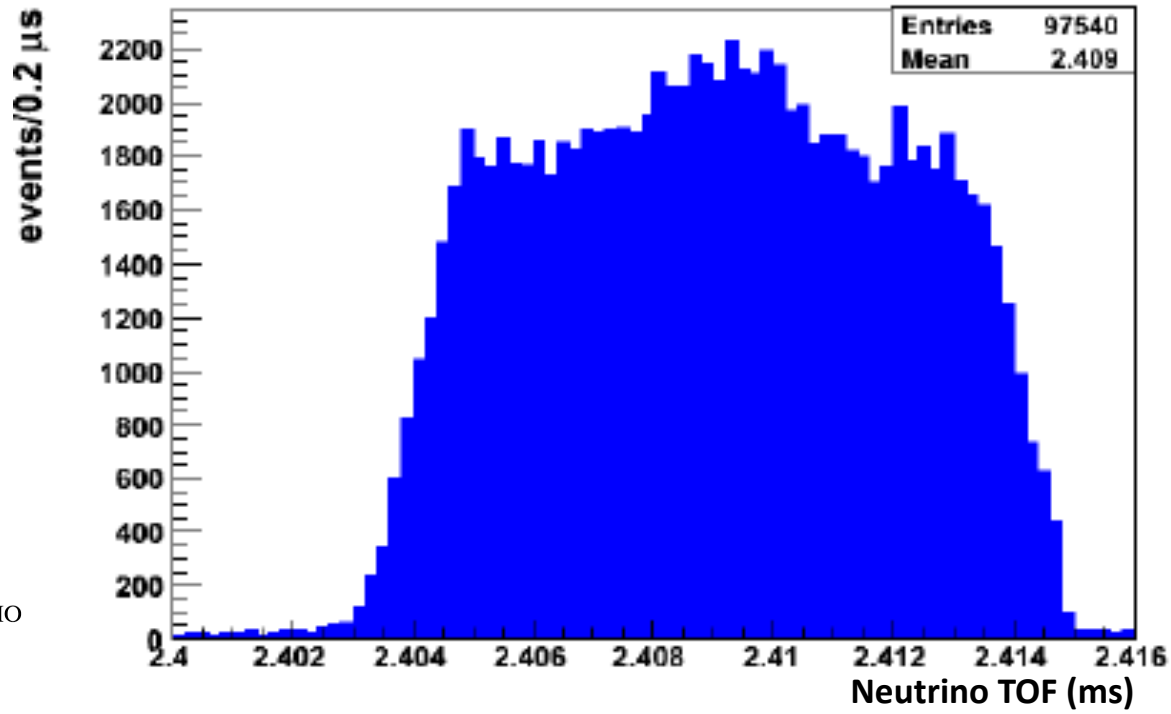


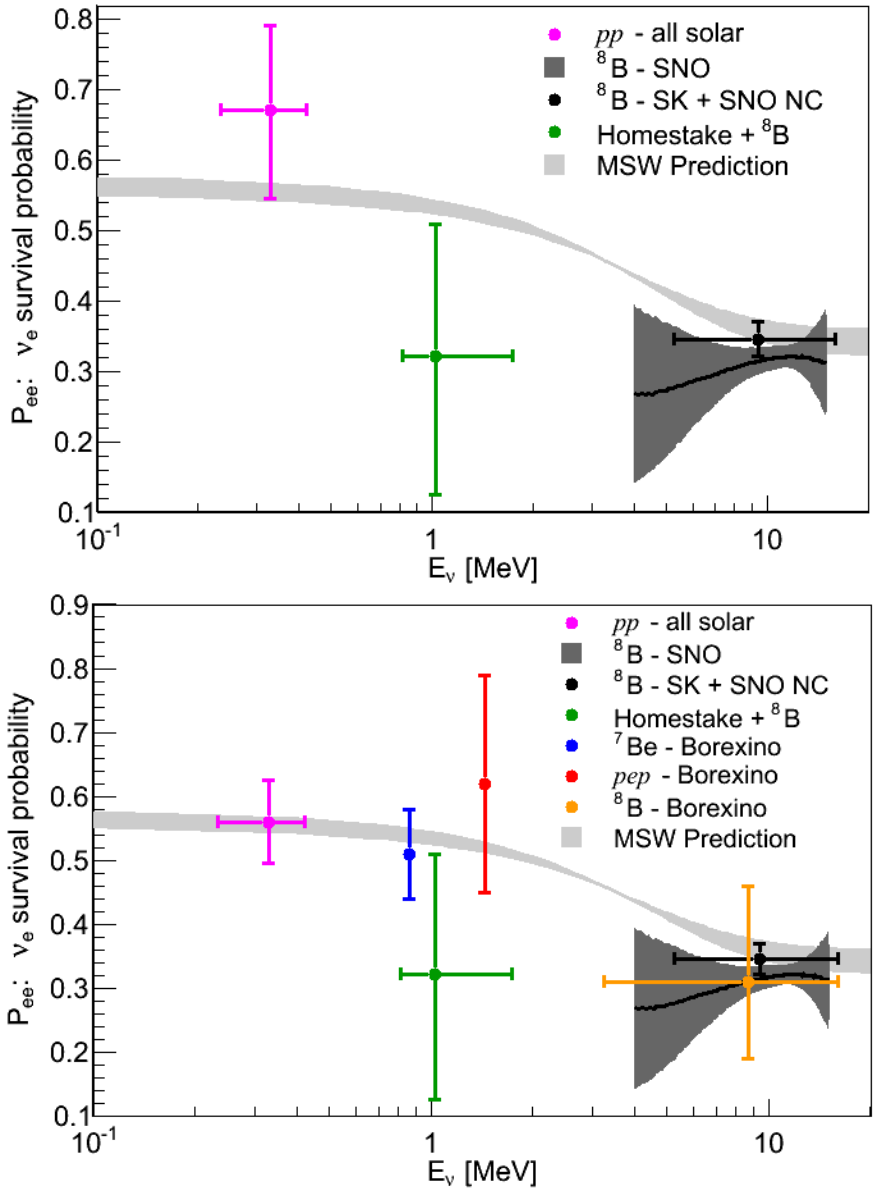
# Neutrino Time-Of-Flight

- 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!