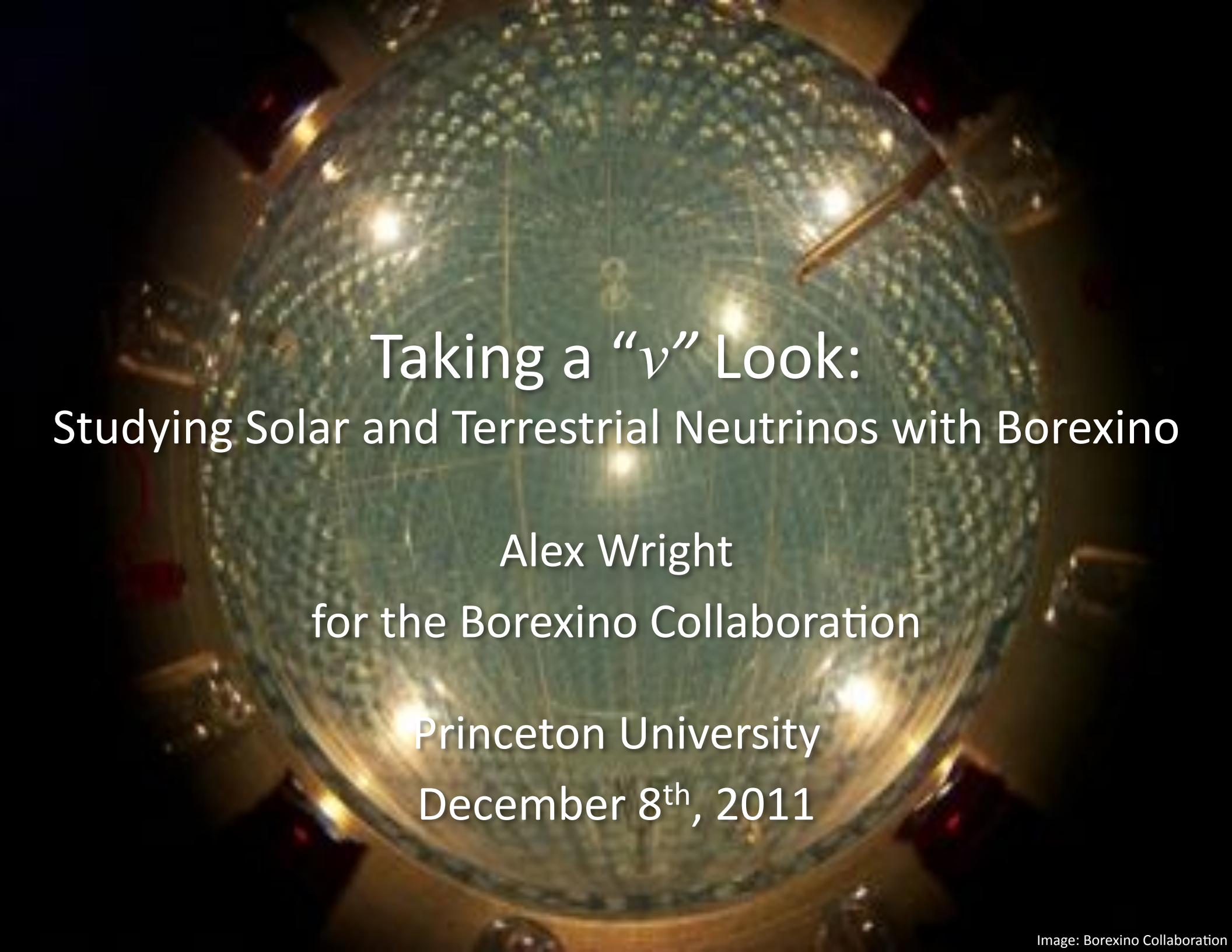




Taking a “ ν ” Look: Studying Solar and Terrestrial Neutrinos with Borexino

Alex Wright
for the Borexino Collaboration

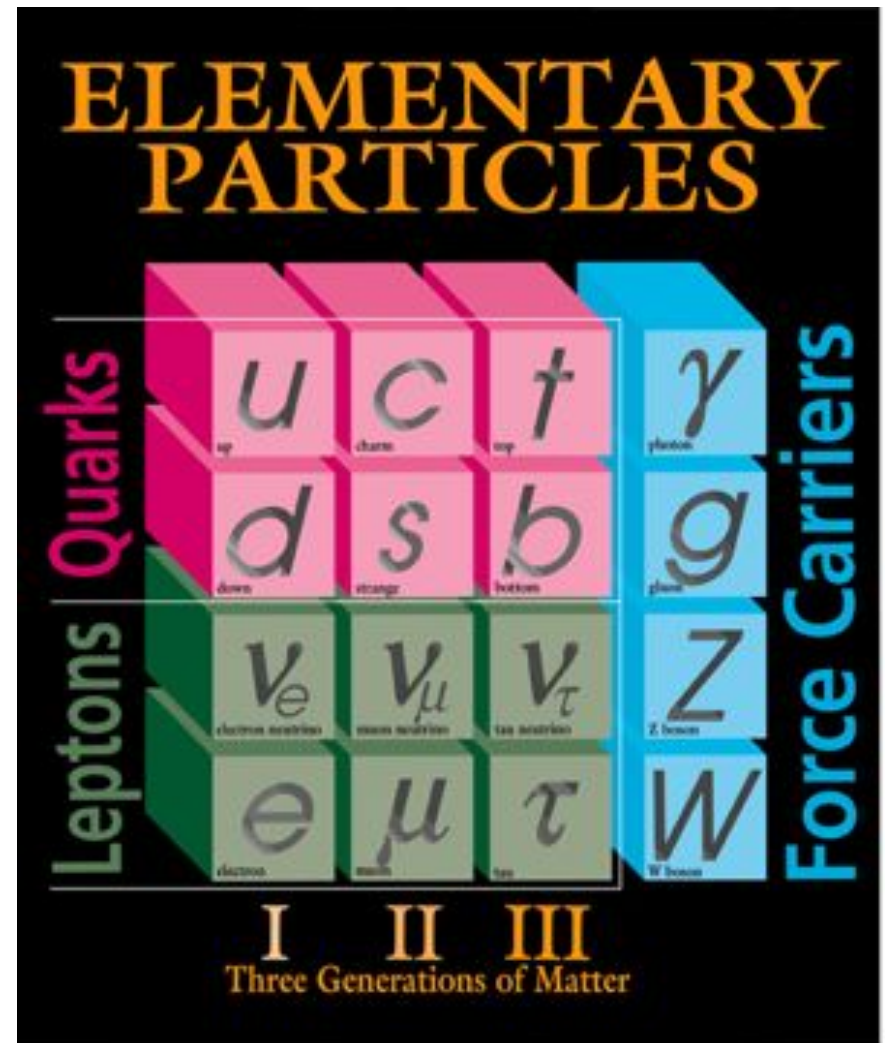
Princeton University
December 8th, 2011

Outline

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

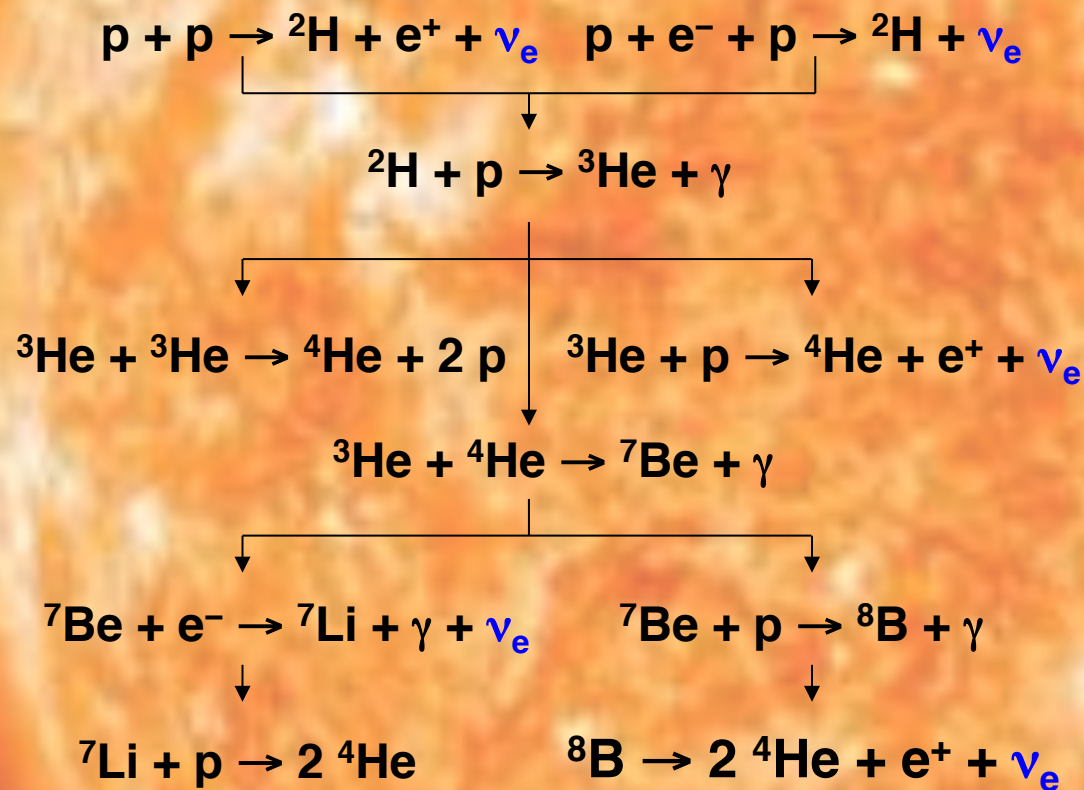
Neutrinos

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

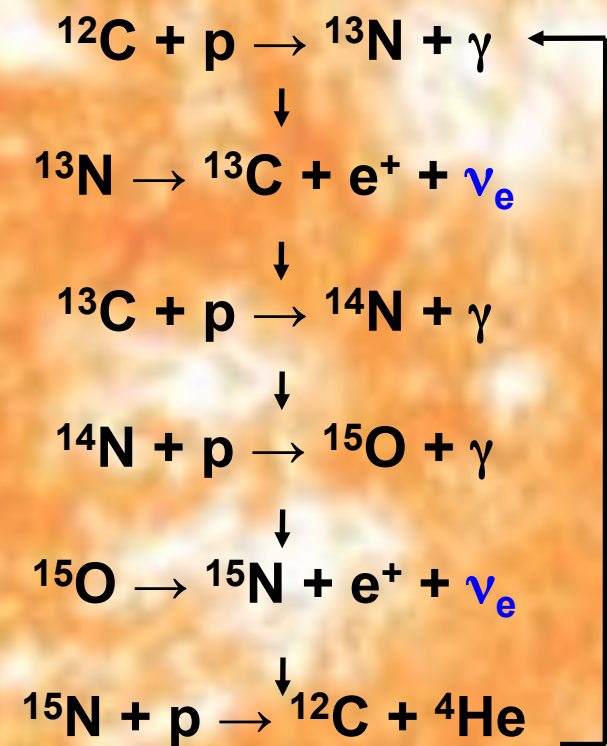


Neutrinos From the Sun

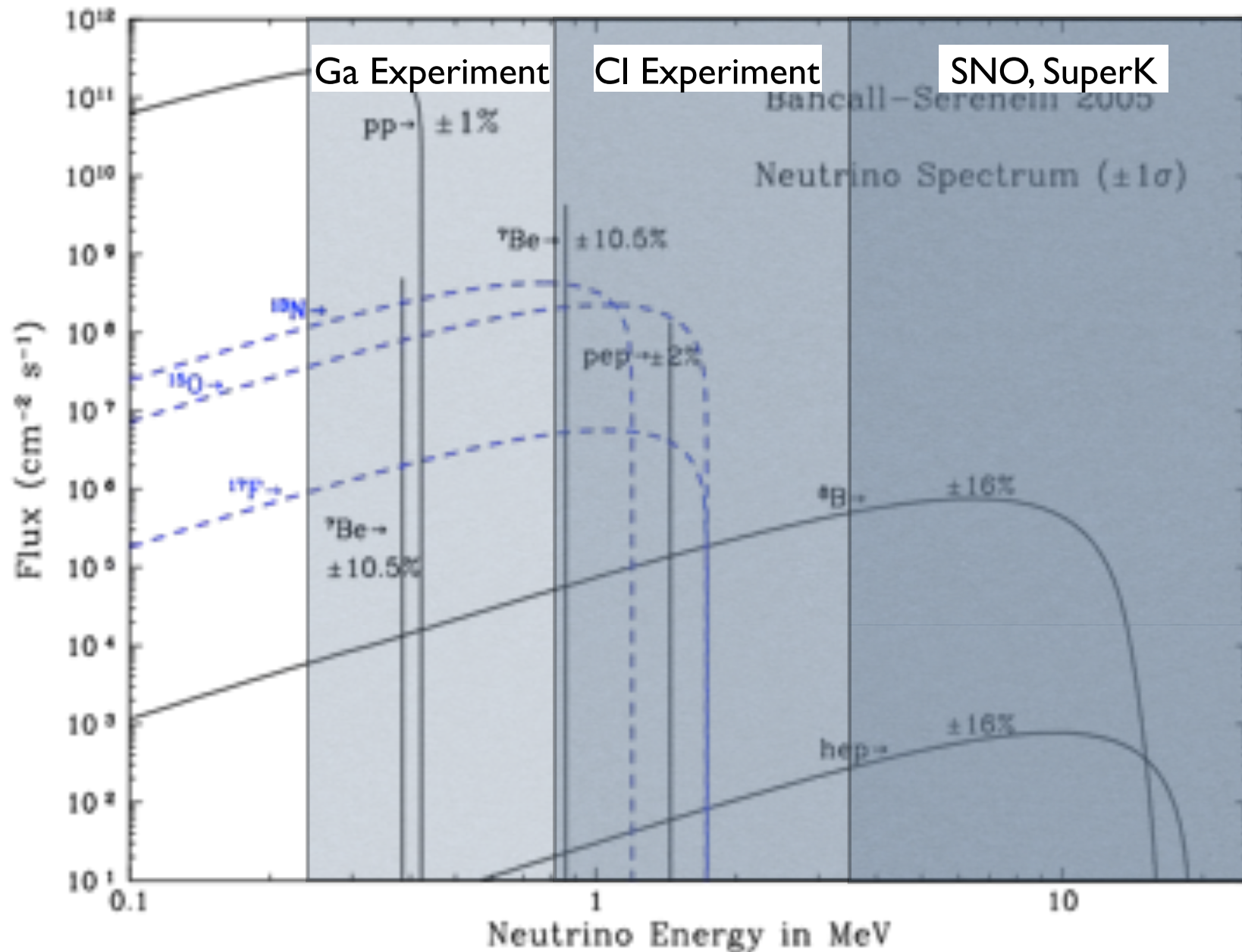
p-p Solar Fusion Chain



CNO Solar Fusion Cycle

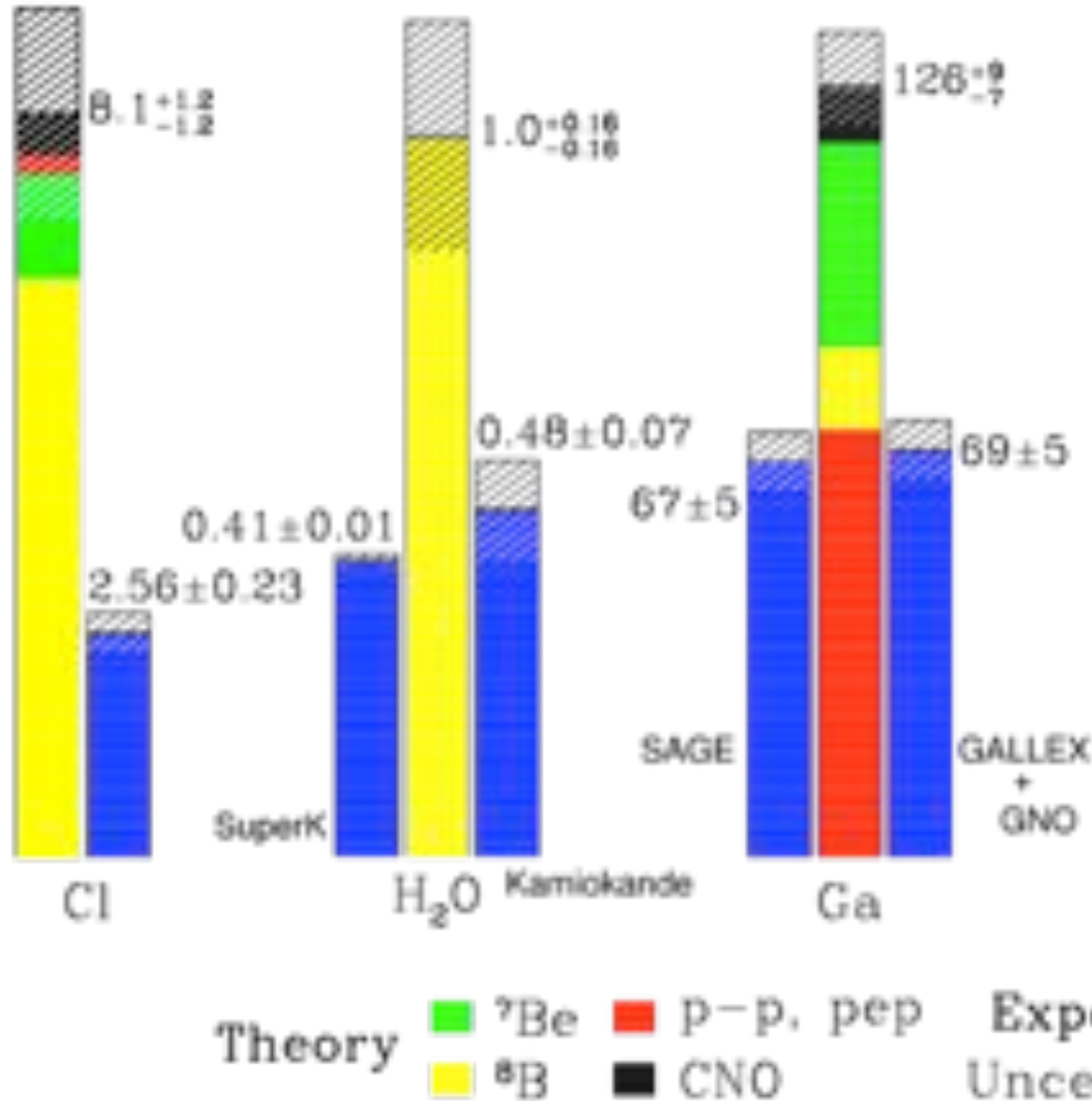


Neutrinos From the Sun



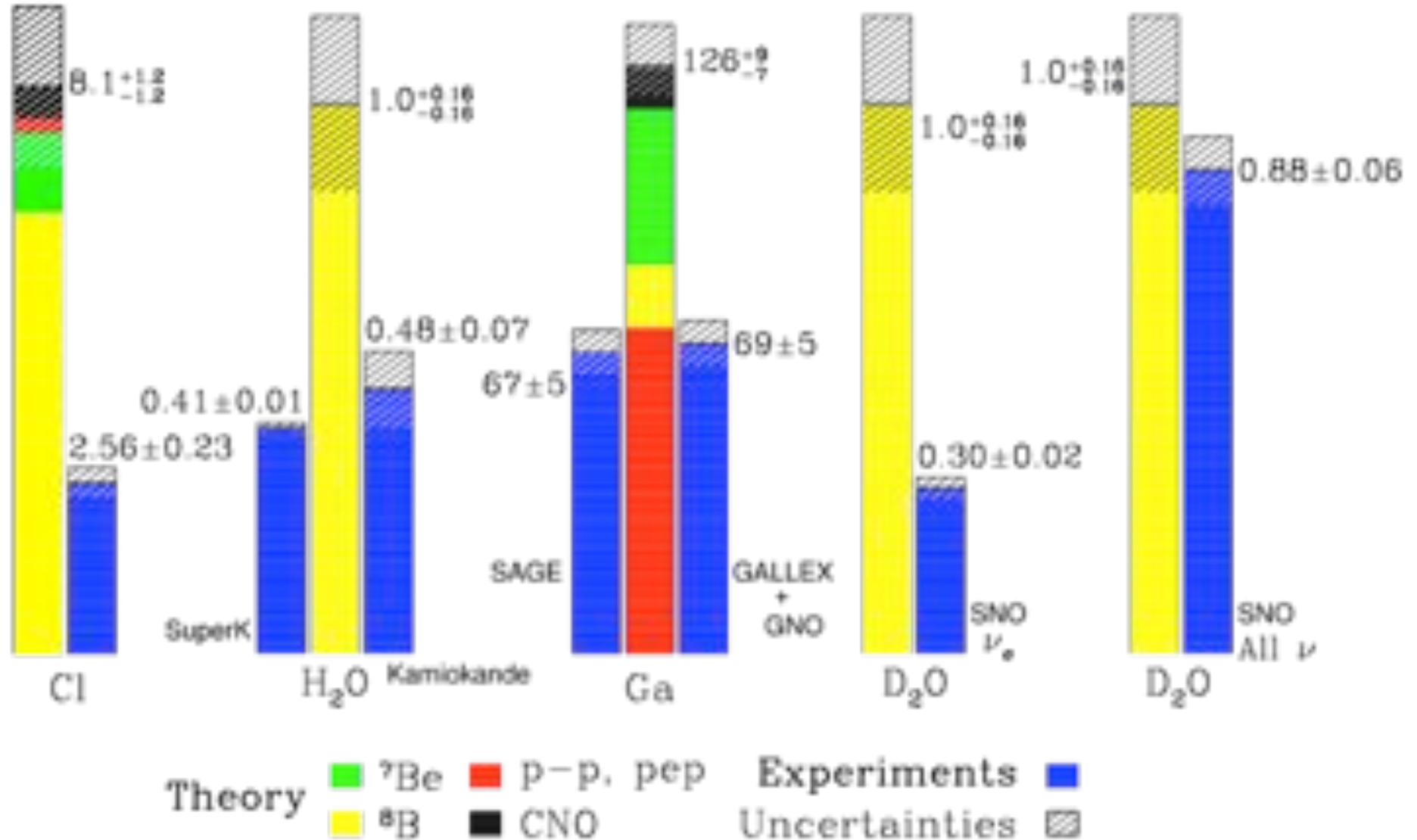
The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



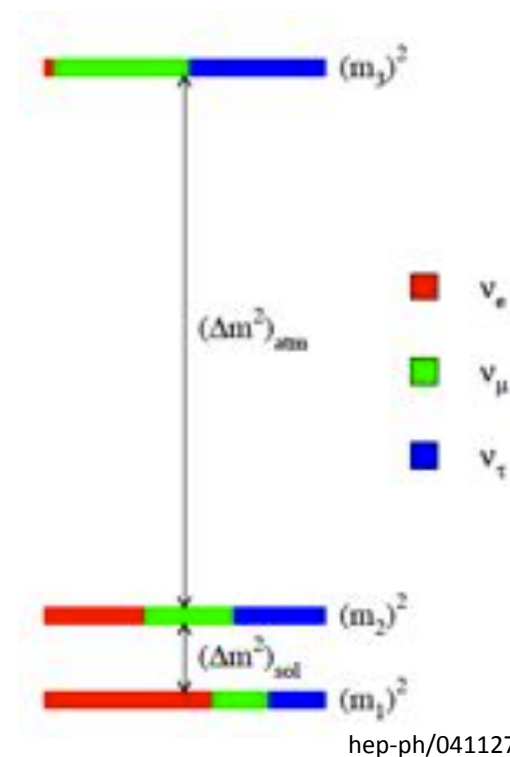
The Solar Neutrino Problem

Bahcall-Serenelli 2005 [BS05(OP)]



Neutrino Oscillations

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



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

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

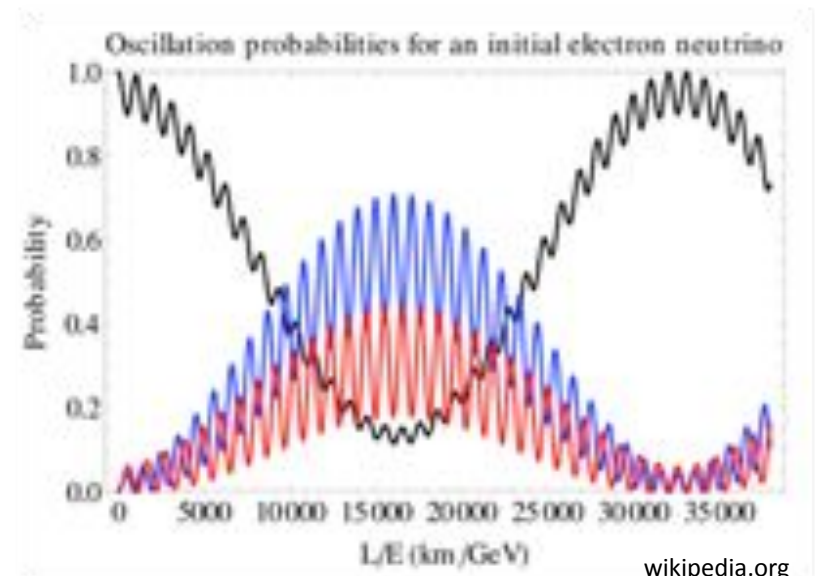
Neutrino Oscillations

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

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



Symmetry Magazine



Neutrino Oscillations

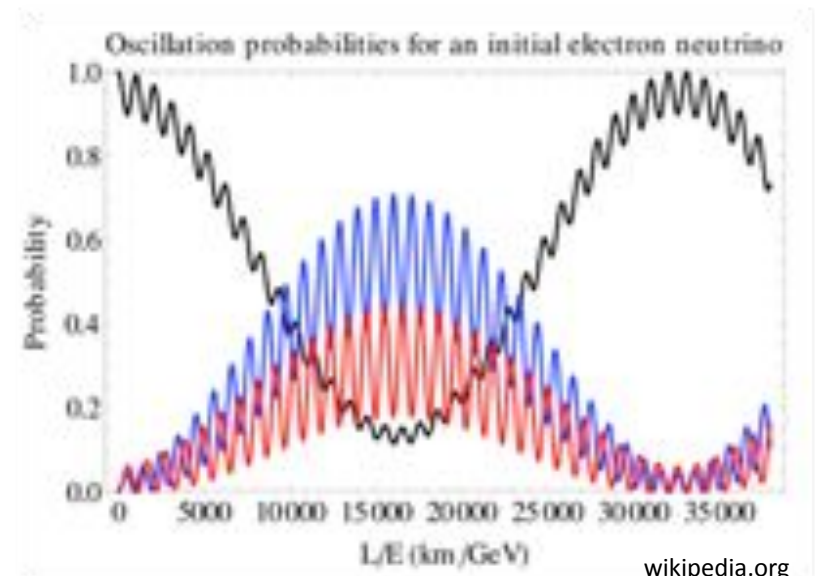
- Producing a neutrino in a flavour eigenstate produces a superposition of mass eigenstates
- Phase differences acquired in mass eigenstate propagation change apparent flavour content
- In solar neutrinos we see a phase averaged survival probability:

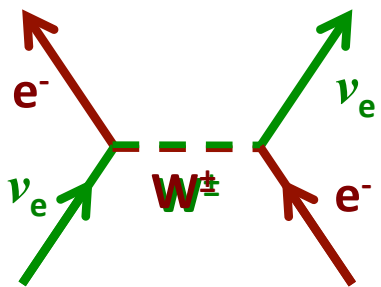
$$P_{ee} = \cos^4(\theta_{13}) \left(1 - \frac{1}{2} \sin^2(2\theta_{12}) \right) + \sin^4(\theta_{13})$$

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

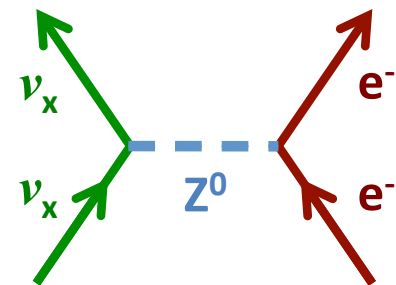


Symmetry Magazine





The Matter of Matter

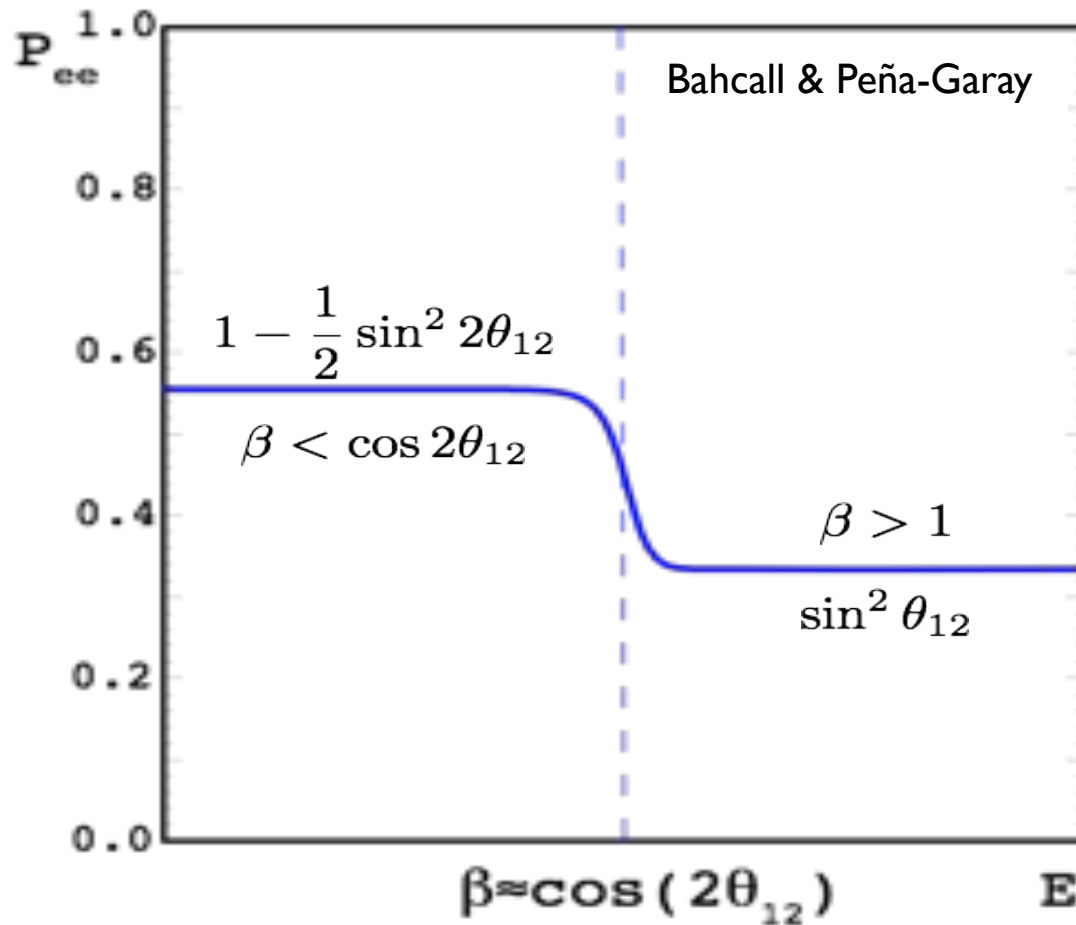


- When neutrinos propagate in matter, charged current interactions add an additional term to ν_e flavour in Hamiltonian mass matrix:

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

- 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

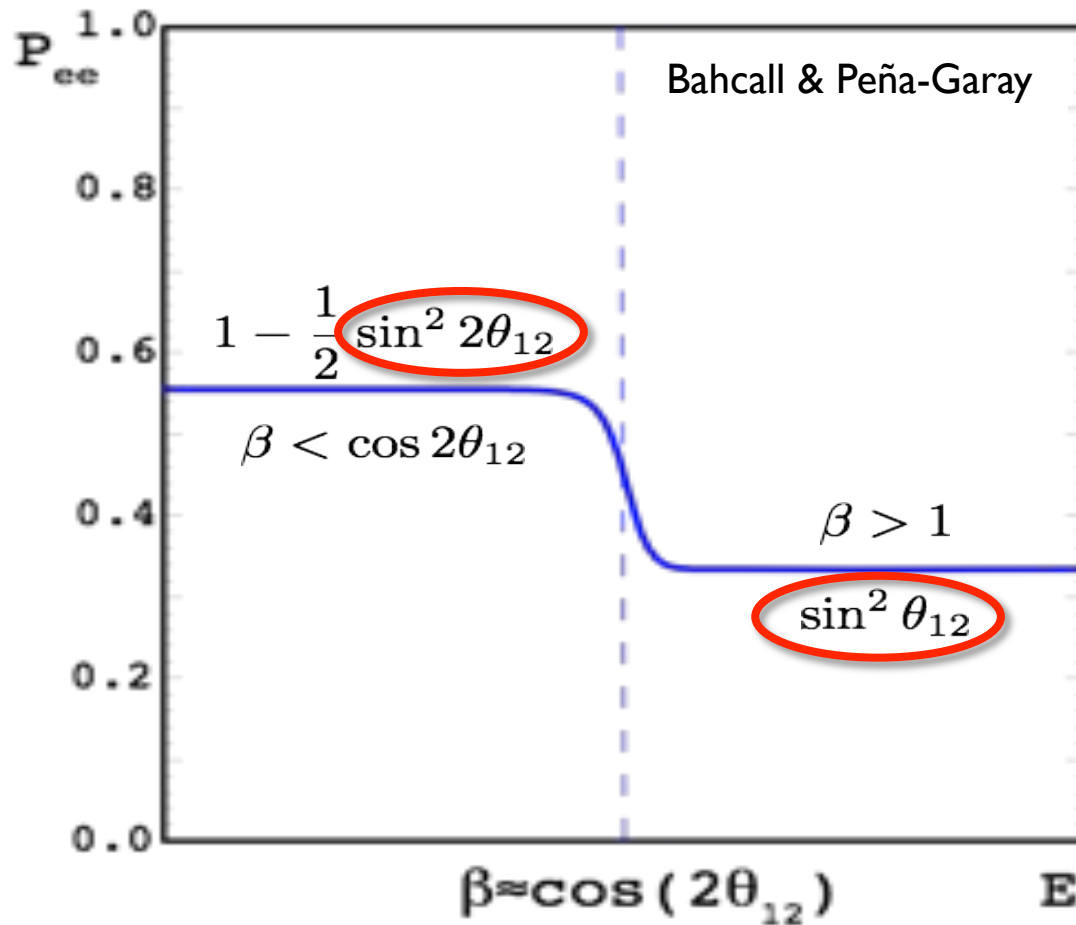


$$\beta = \frac{2^{3/2} G_F N_e}{\left(\frac{\Delta m^2}{E} \right)}$$

Low energy: Phase-averaged vacuum oscillations

High energy: Matter-dominated “resonant conversion”

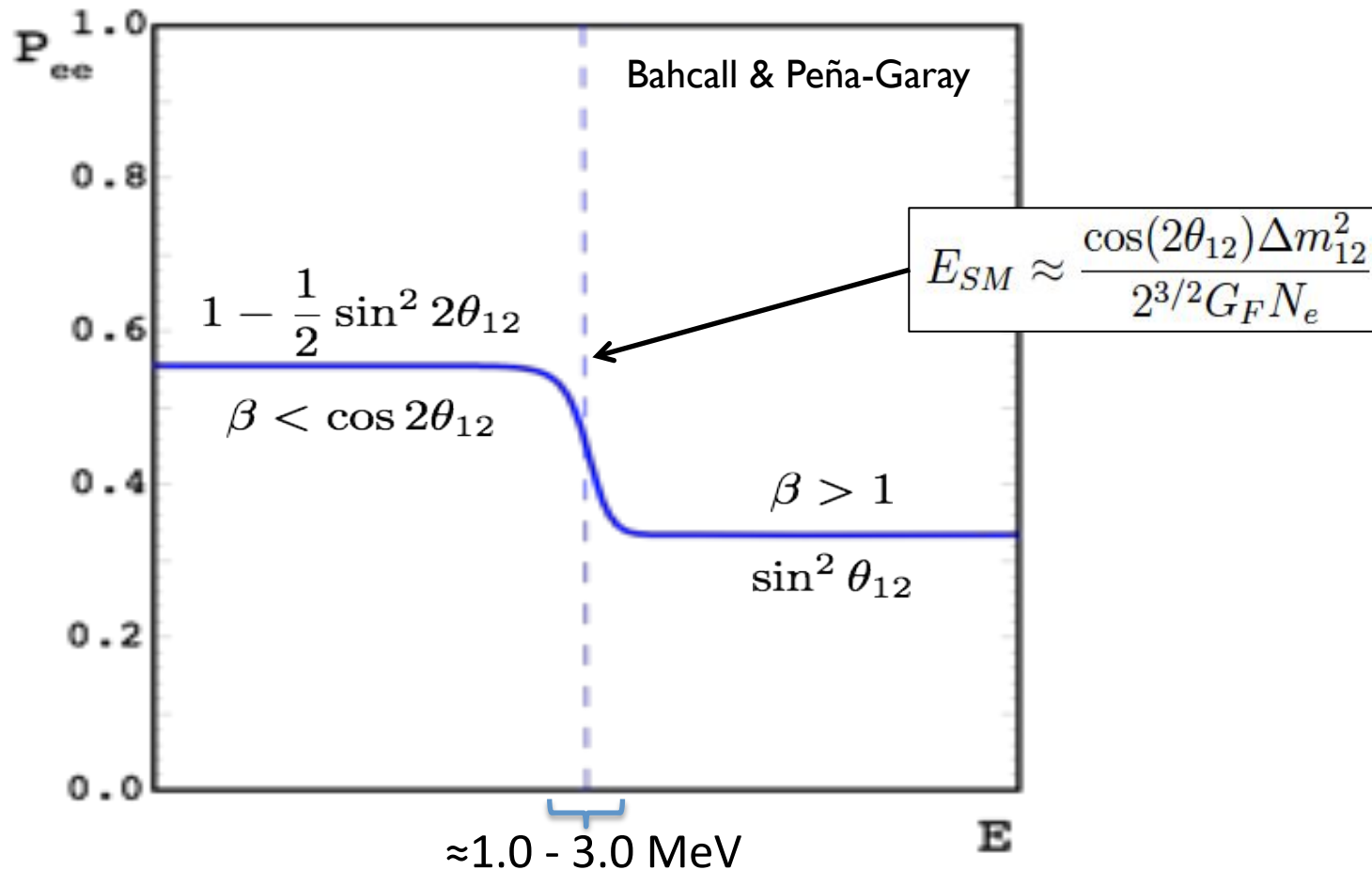
MSW Oscillation Regimes



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

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

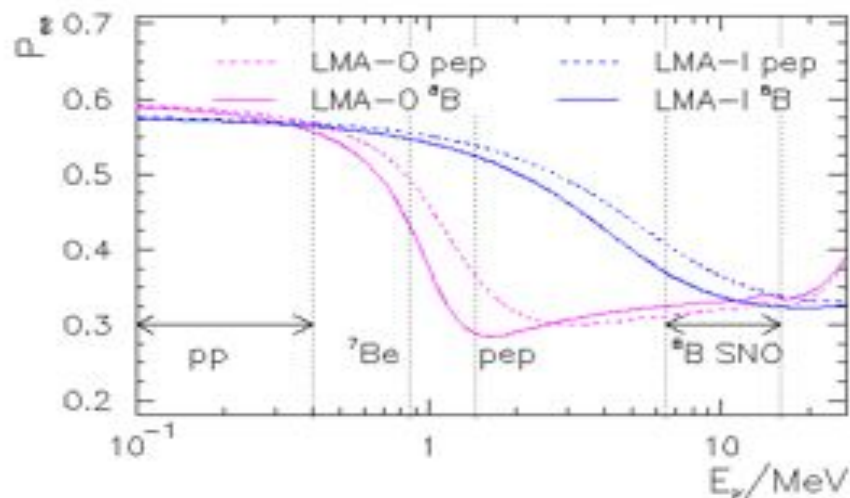


Look in “transition region” to confirm MSW and that we know what is going on!

Possible New Physics in Transition Region

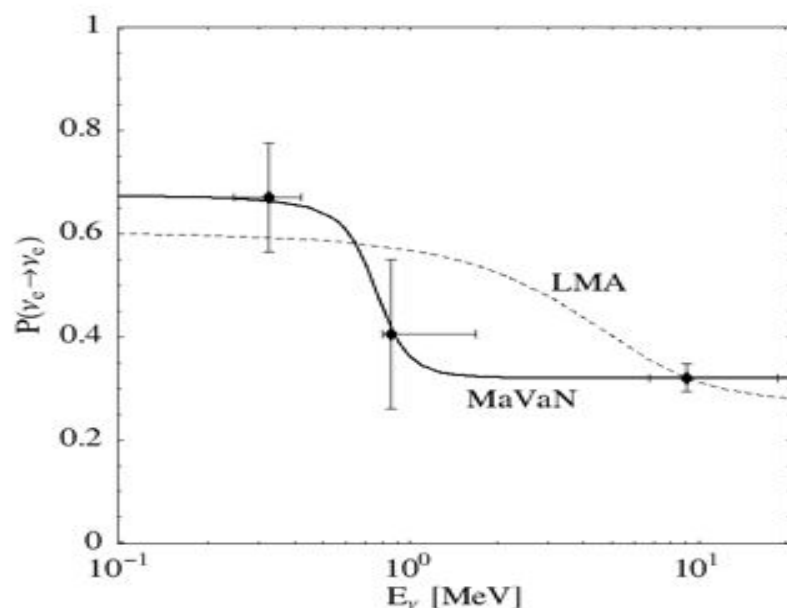
Non-Standard Interactions

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



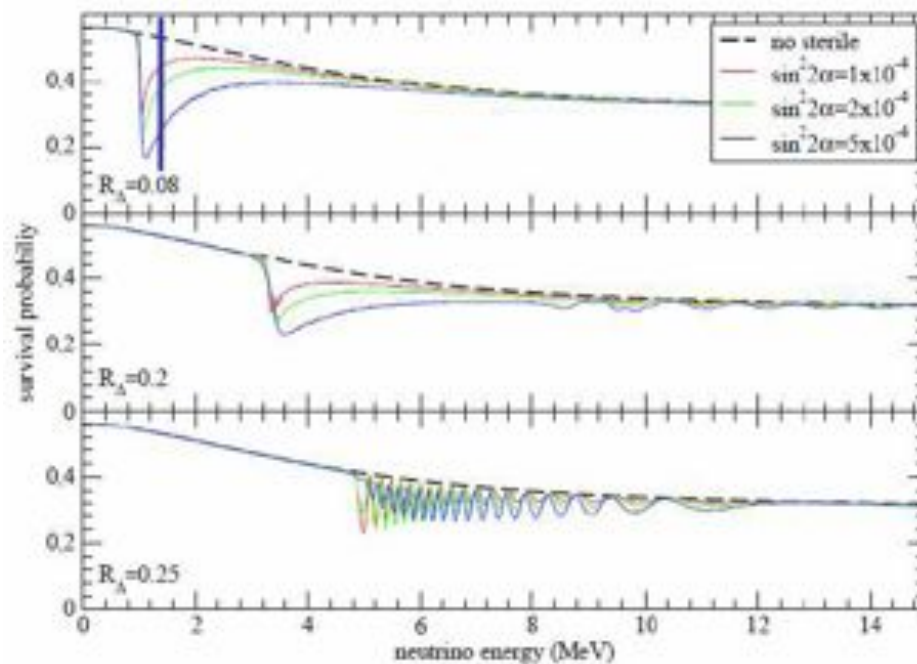
Mass Varying Neutrinos

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

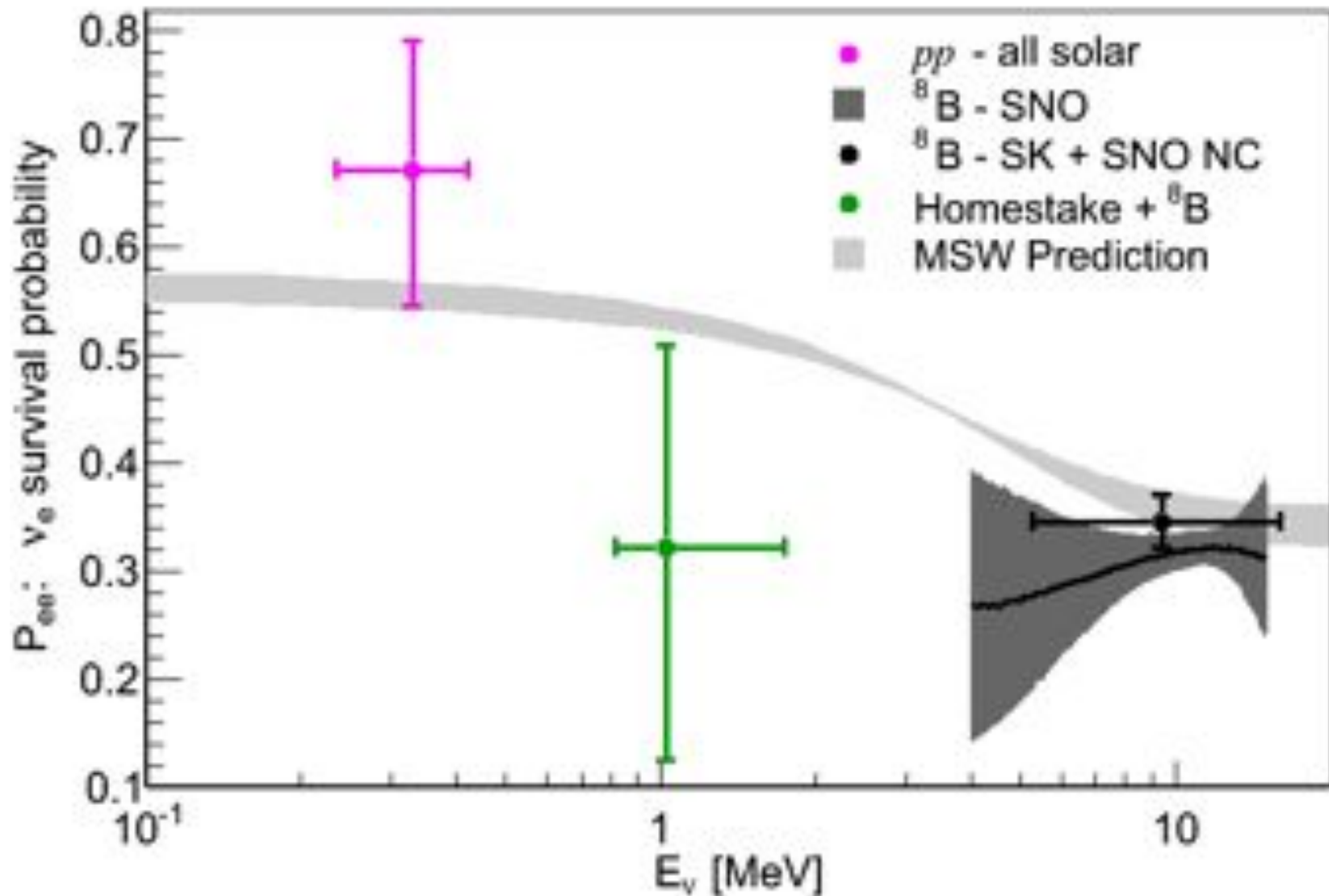


Sterile Neutrinos

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

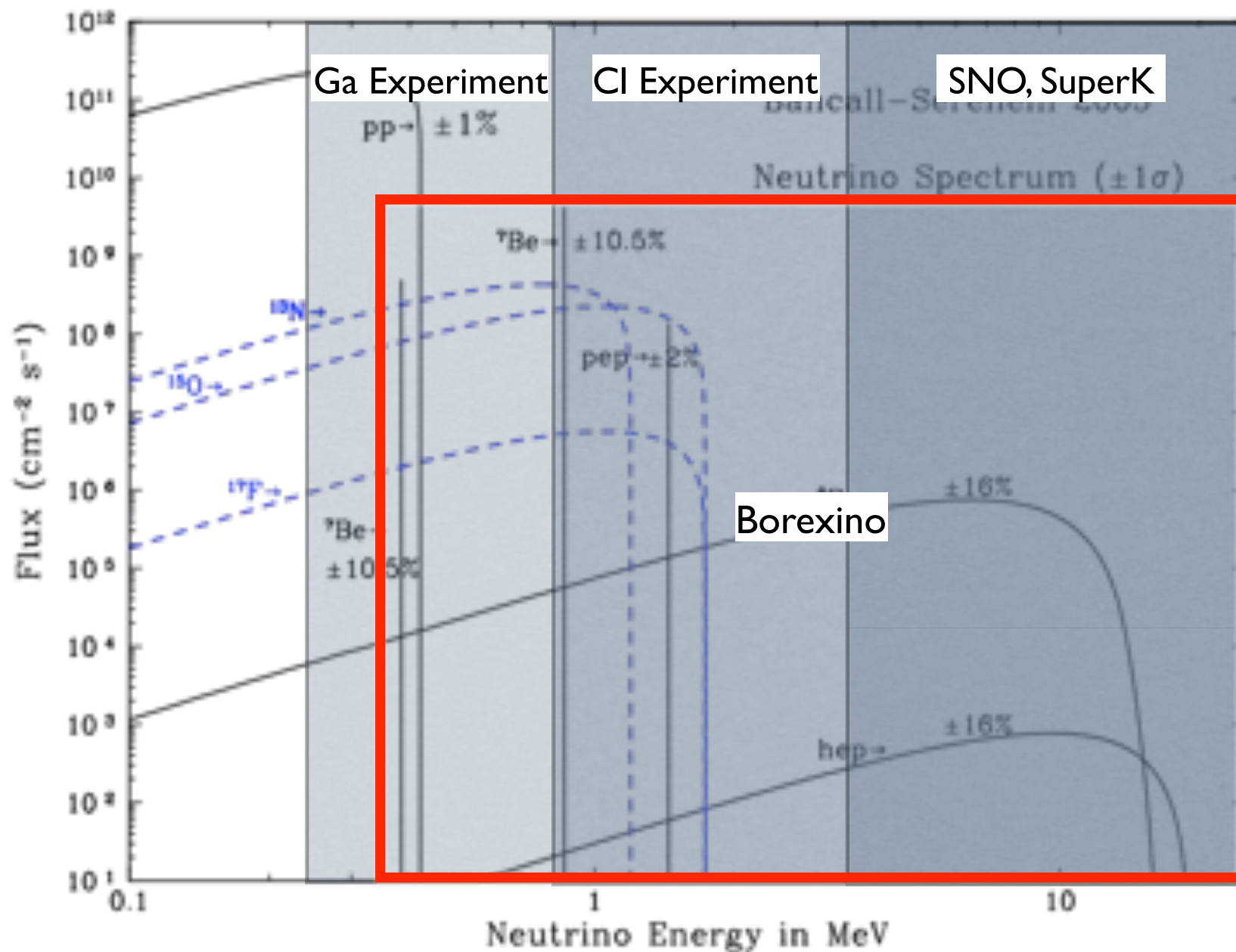


Constraints on Transition Region Without Borexino

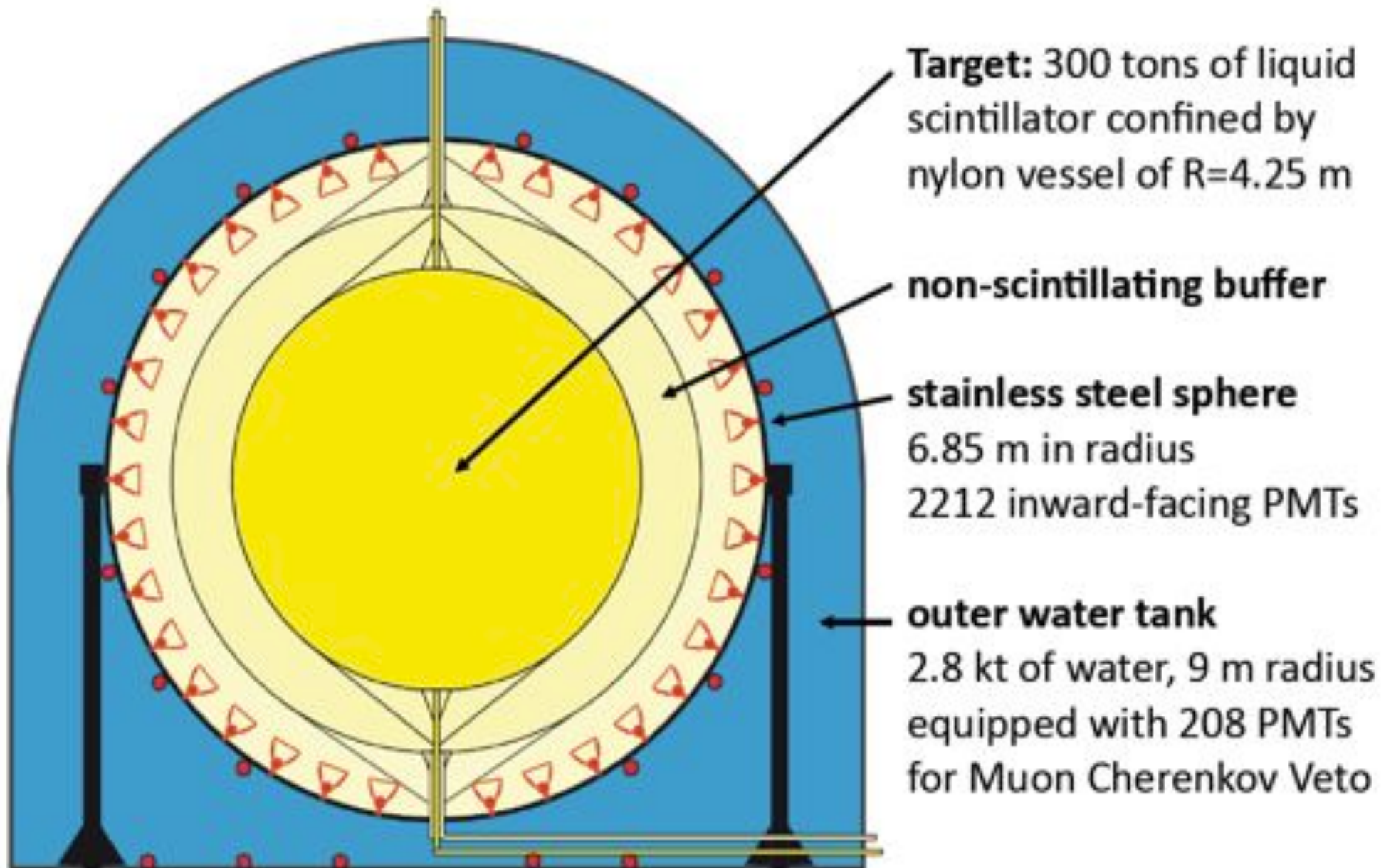


Subtractions required in interpreting the radiochemical results mean that the data points are (anti-) correlated. *Real-time measurements needed in the transition region.*

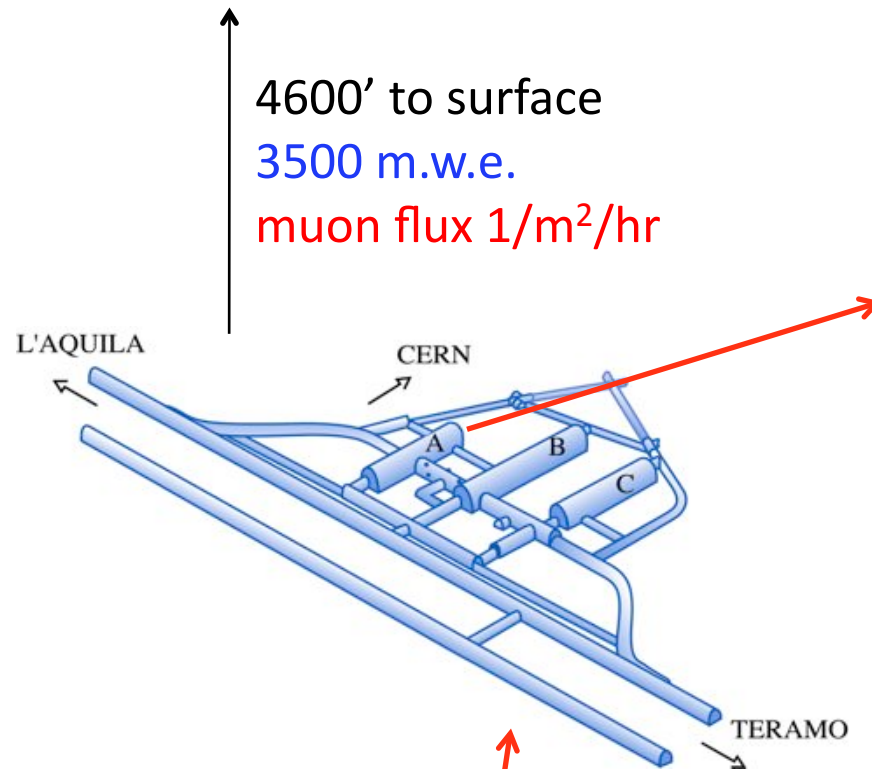
Borexino: Real-time Detection Below 50 keV



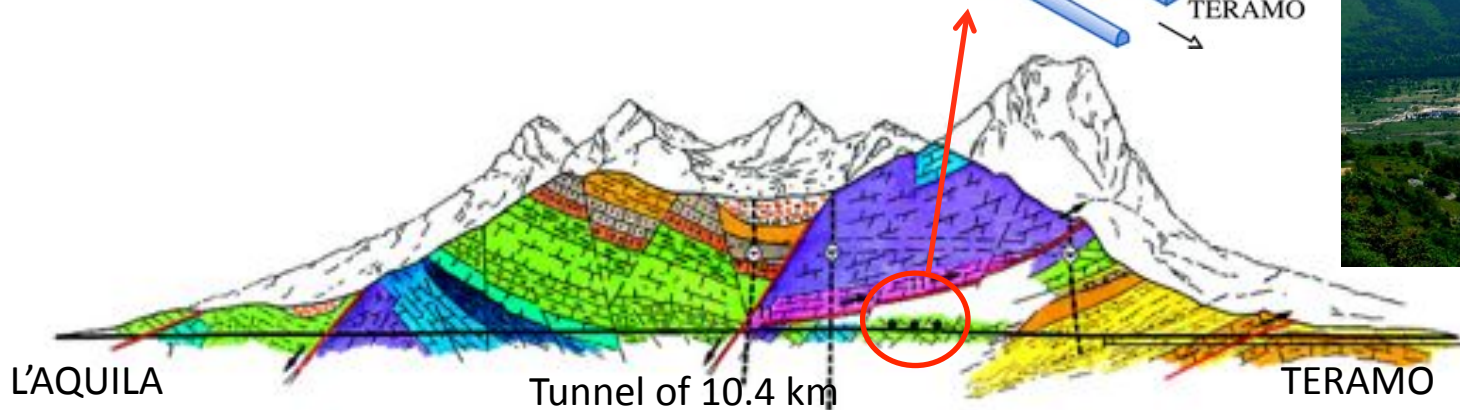
The Borexino Detector



Laboratori Nazionali del Gran Sasso

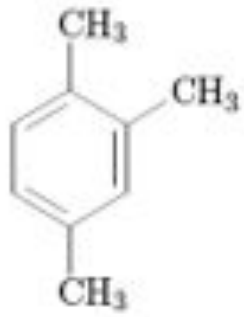


4600' to surface
3500 m.w.e.
muon flux $1/\text{m}^2/\text{hr}$

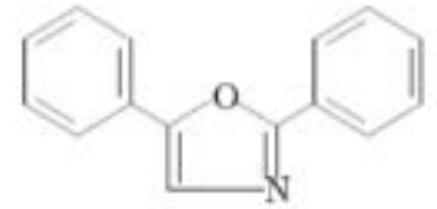


Borexino Collaboration

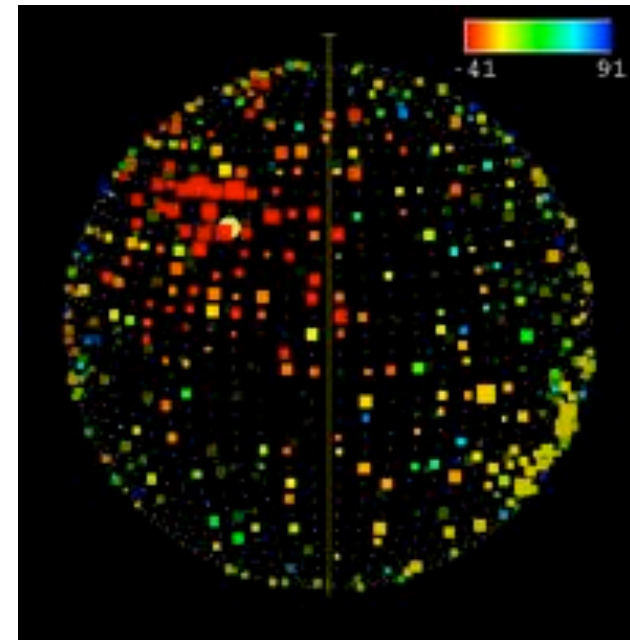
- Astroparticle and Cosmology Laboratory – Paris, France 
- INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy 
- INFN e Dipartimento di Fisica dell'Università – Genova, Italy 
- INFN e Dipartimento di Fisica dell'Università – Milano, Italy 
- INFN e Dipartimento di Chimica dell'Università – Perugia, Italy 
- Institut für Experimentalphysik – Hamburg, Germany 
- Institute of Physics, Jagellonian University – Krakow, Poland 
- Instituto de Física 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 für Kernphysik – Heidelberg, Germany 
- Princeton University – Princeton, NJ, USA 
- St. Petersburg Nuclear Physics Institute – Gatchina, Russia 
- Technische Universität – München, Germany 
- University of Massachusetts at Amherst, MA, USA 
- Virginia Polytechnic Institute – Blacksburg, VA, USA 



Detection Principle

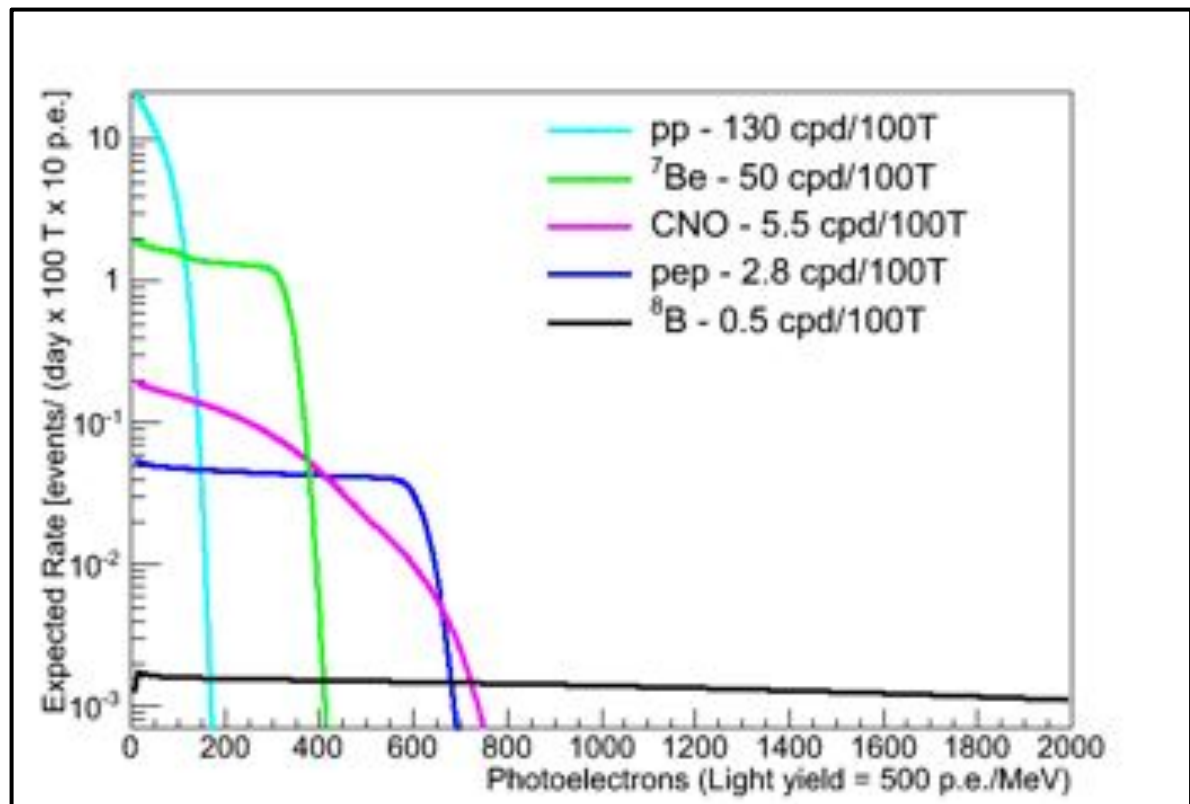
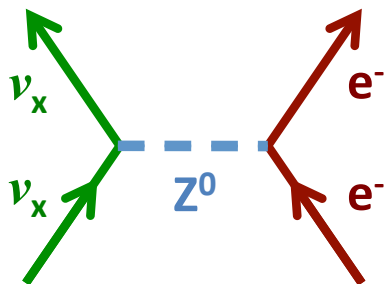
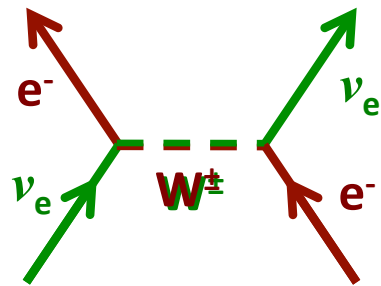


- Organic scintillator (pseudocumene + PPO) produces light when excited by charged particles
- ~12,000 photons/MeV, of which ~500 photons/MeV are detected by the photomultiplier tubes
 - Can detect events depositing < 50 keV
- Calorimetric measurement + pulse shape
 - Event energy from number of photons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

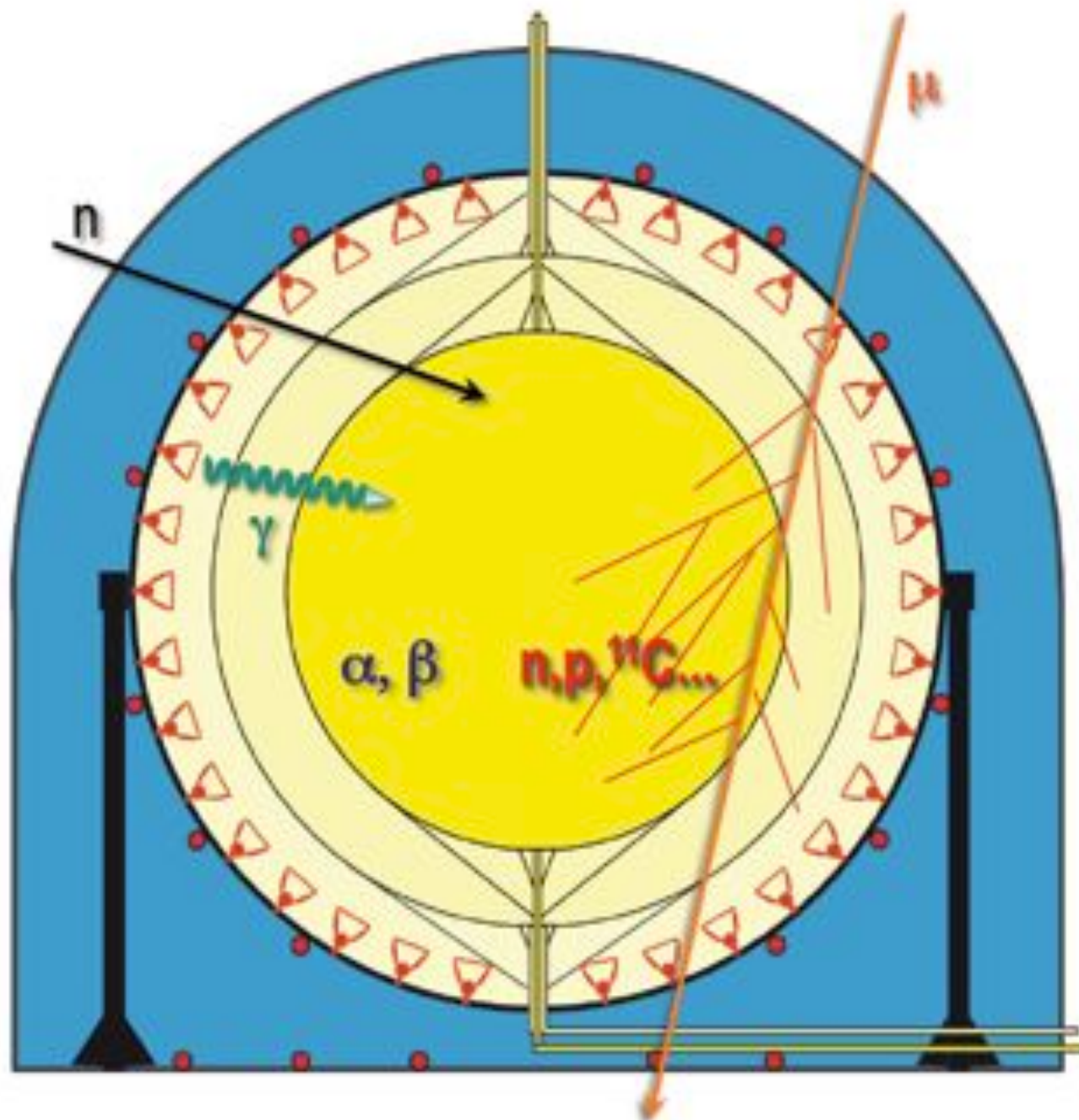


Neutrino Detection

- 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,⁴⁰K)

External Gamma-Rays

from buffer, steel sphere,
PMT glass (^{40}K , ^{208}Tl ...)

Cosmic Muons

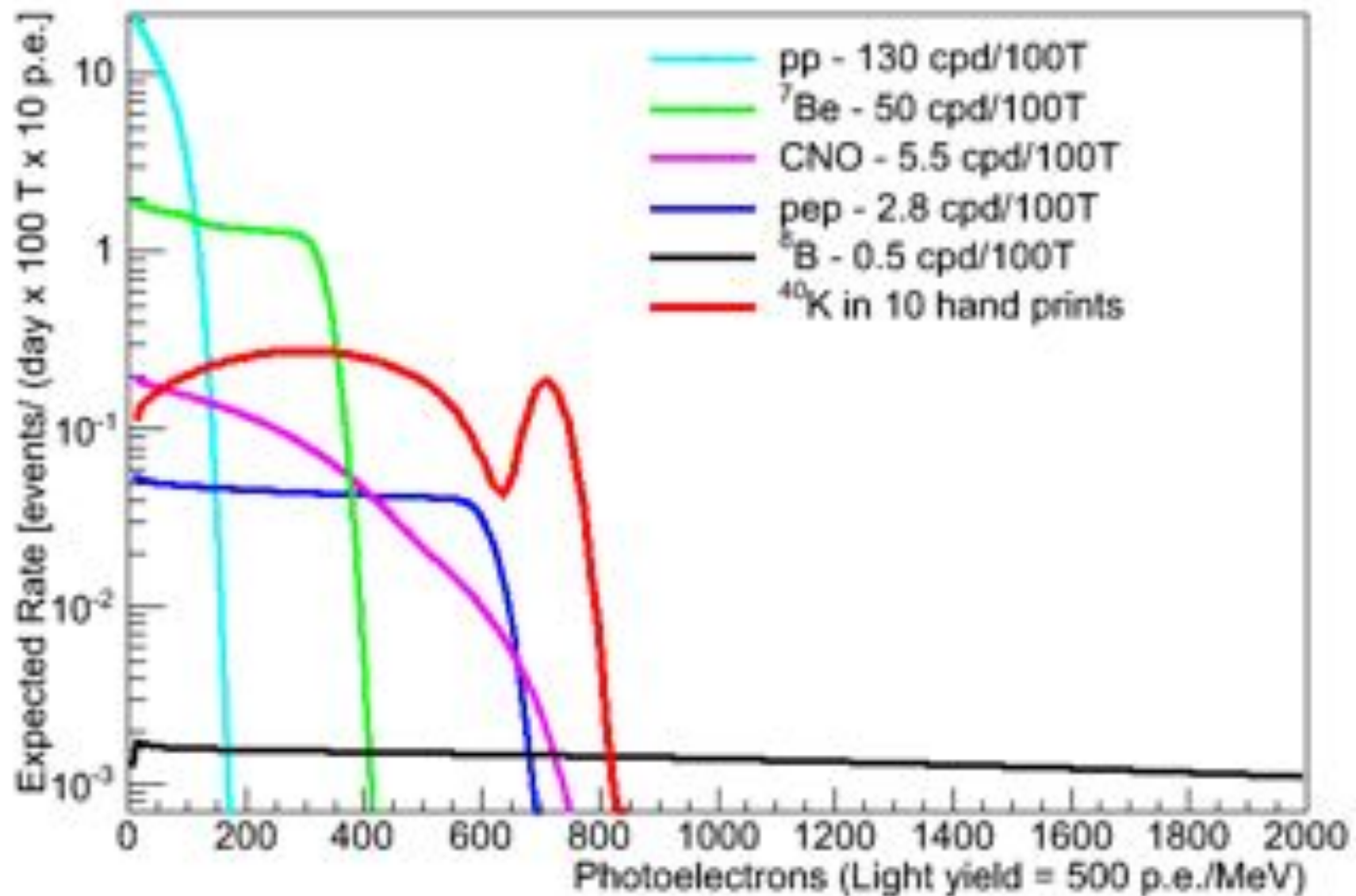
Cosmogenics

neutrons and radionuclides
from muon-spallation and
hadronic showers

Fast Neutrons

from external muons

Central Challenge: Background Reduction



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



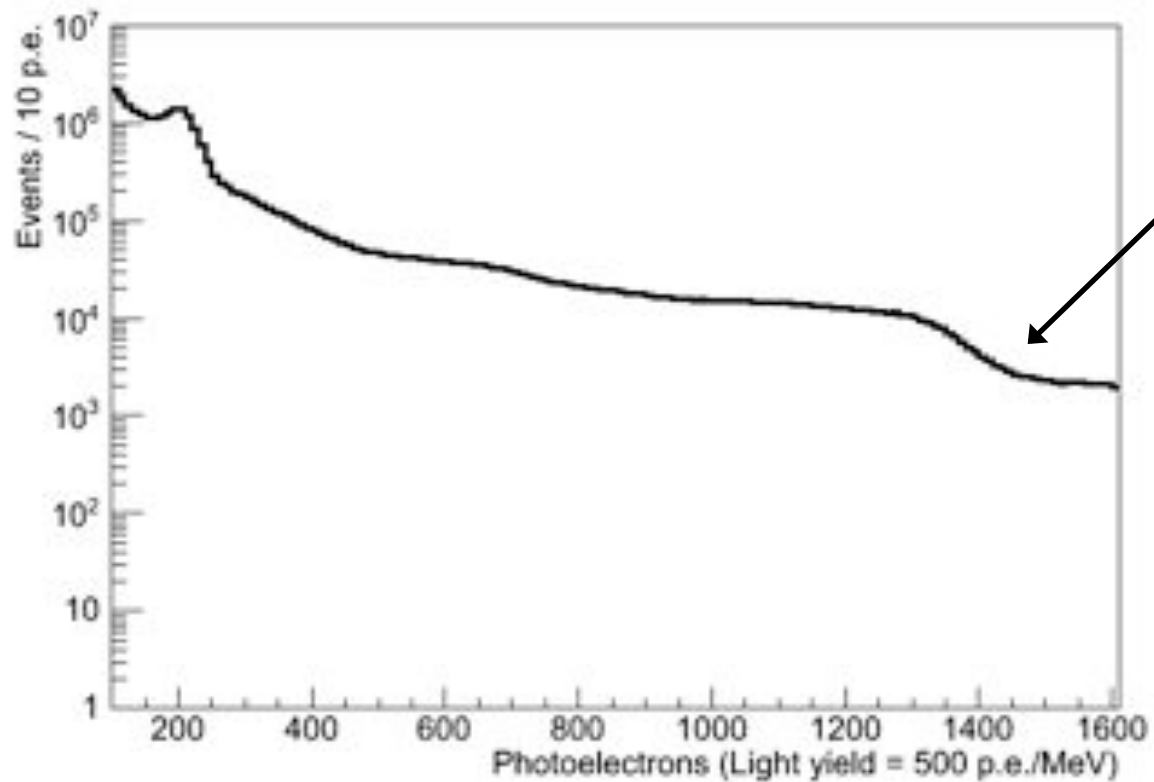
The Counting Test Facility III

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	$\sim 5 \times 10^{-18} \text{ g/g}$	Purification
^{232}Th	Dust	10^{-6} g/g	$\sim 4 \times 10^{-18} \text{ g/g}$	Purification
^{85}Kr	Air	1 Bq/m^3	$\sim 2 \times 10^{-3} \text{ Bq/m}^3$	LAKN
^{222}Rn	Air	$20\text{-}100 \text{ Bq/m}^3$	$< 10^{-6} \text{ Bq/m}^3$	Air exclusion
K_{nat}	Dust	$\sim 10^{-3} \text{ g/g}$	$< 2 \times 10^{-19} \text{ g/g}$	Purification
μ	Cosmic	$200 \text{ s}^{-1}\text{m}^{-2}$	$10^{-10} \text{ s}^{-1}\text{m}^{-2}$	Underground, active veto

Borexino Neutrino Results

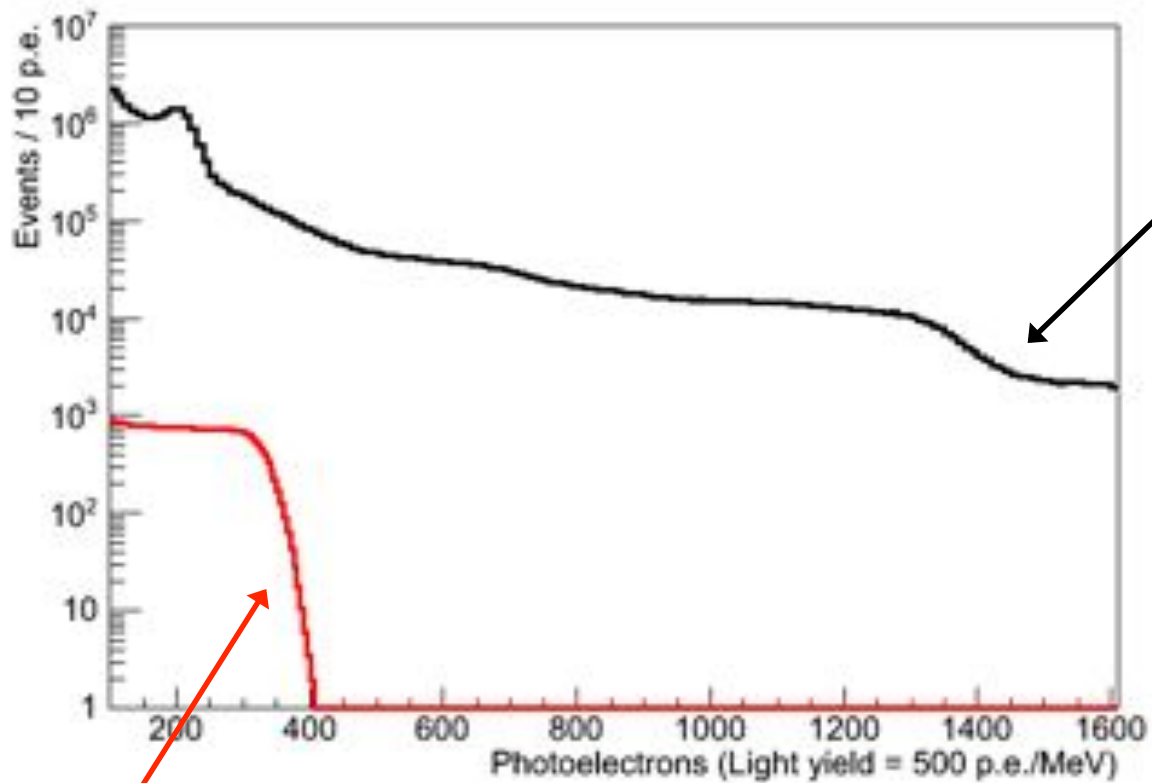
- ^7Be Flux
 - ($\pm 30\%$) – Phys. Lett. B **658**:101 (2008).
 - ($\pm 10\%$) – Phys. Rev. Lett. **101**:091302 (2008).
 - ($\pm 5\%$) – Phys. Rev. Lett. **107**:141302 (2011).
- ^7Be Day-Night Asymmetry
 - arXiv:1104.2150 (2011), accepted by Phys. Lett. B
- ^8B Flux + Spectrum ($T_{\text{eff}} > 3.0 \text{ MeV}$)
 - Phys. Rev. D **82**:033006 (2010).
- *pep* and CNO flux
 - arXiv:1110.3230 (2011).
- 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

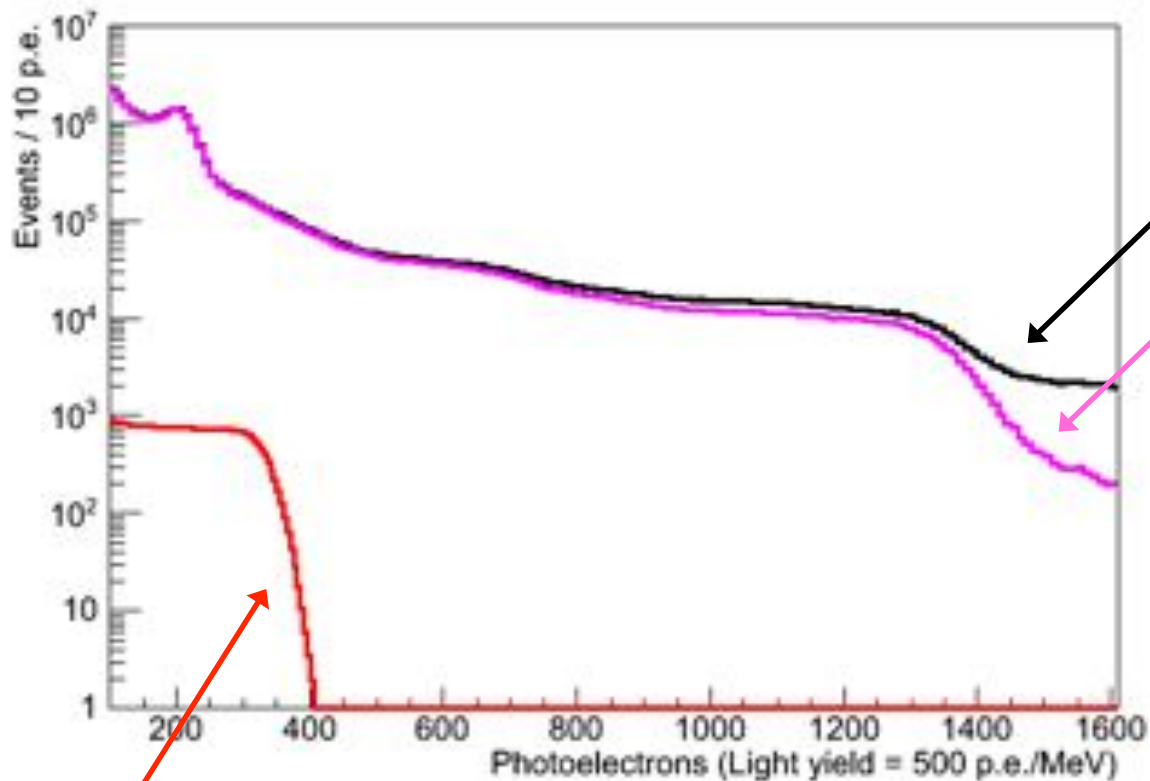
Borexino Data



All data: 740 live days

Expected ^7Be signal

Borexino Data

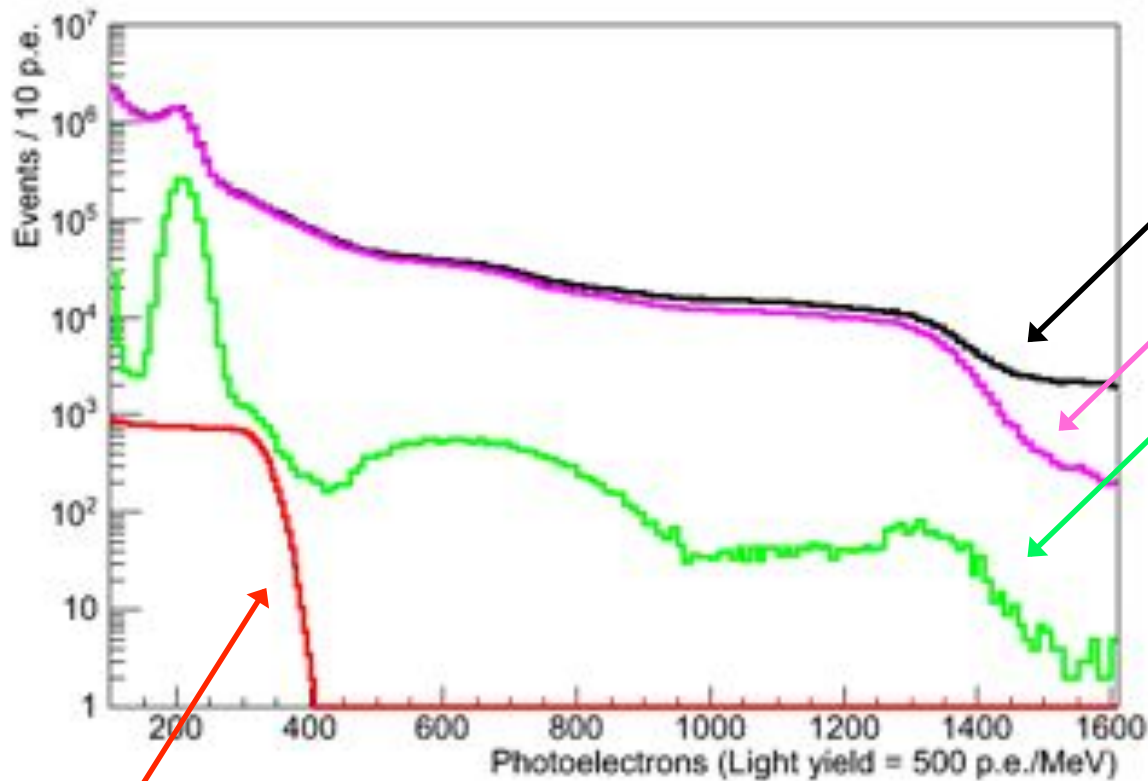


All data: 740 live days

Remove muons + muon followers (2 ms)

Expected ^7Be signal

Borexino Data



Expected ^7Be signal

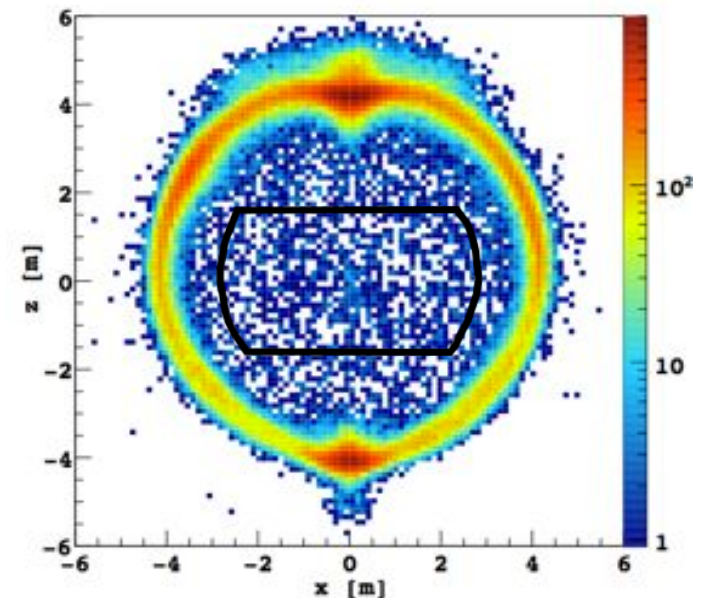
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

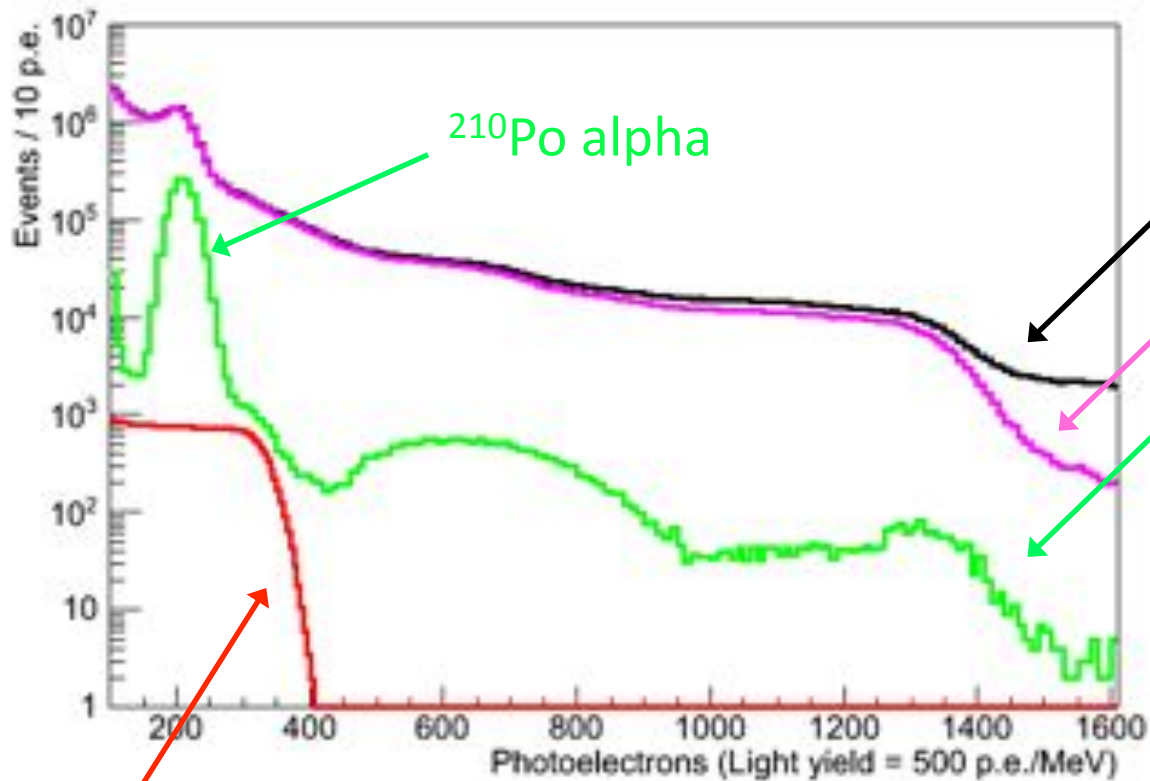
$R < 3.02\text{m}$

$|z| < 1.67\text{m}$



Fiducial mass = 75.6 tonnes

Borexino Data



Expected ^7Be signal

^{210}Po alpha

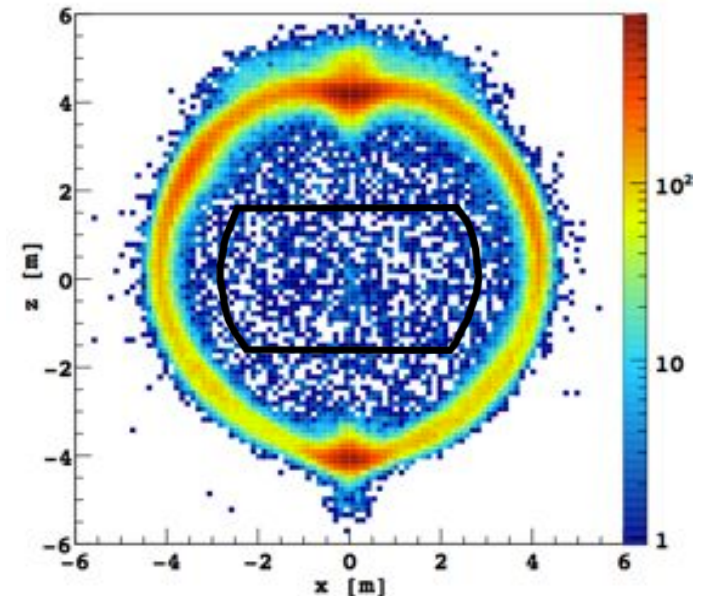
All data: 740 live days

Remove muons + followers

Fiducial Volume + high level

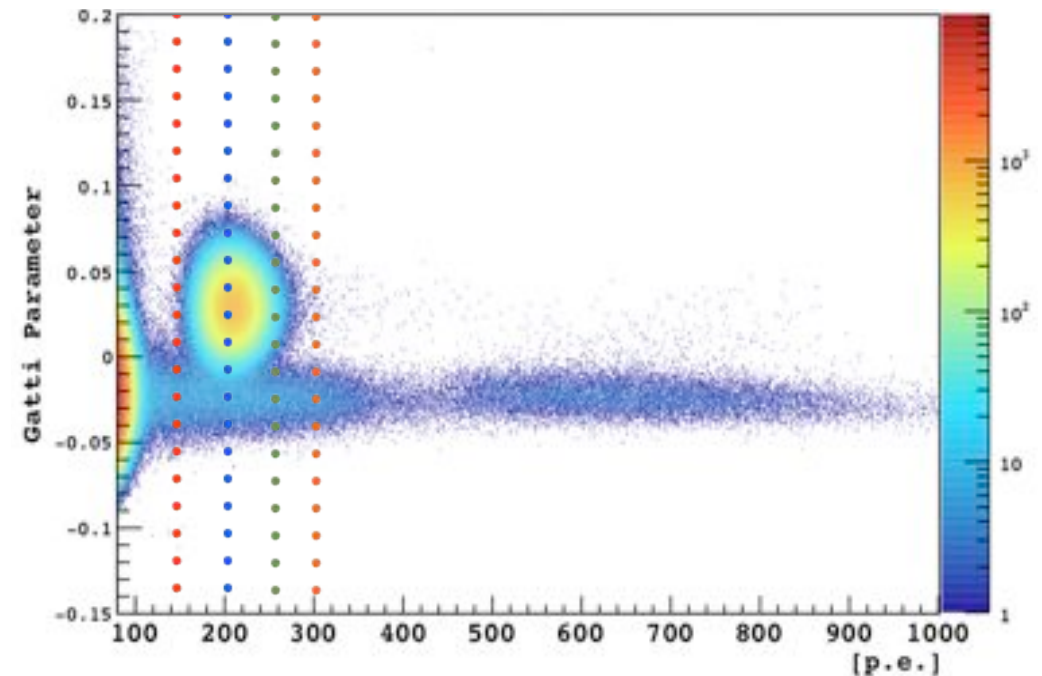
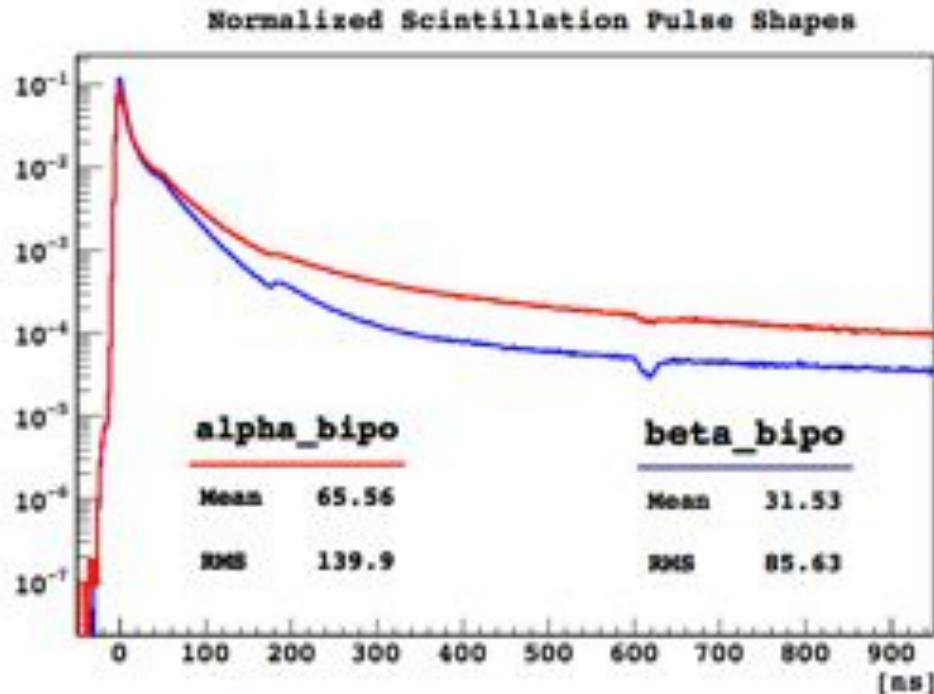
$R < 3.02\text{m}$

$|z| < 1.67\text{m}$



Fiducial mass = 75.6 tonnes

Alpha Pulse Shape Discrimination

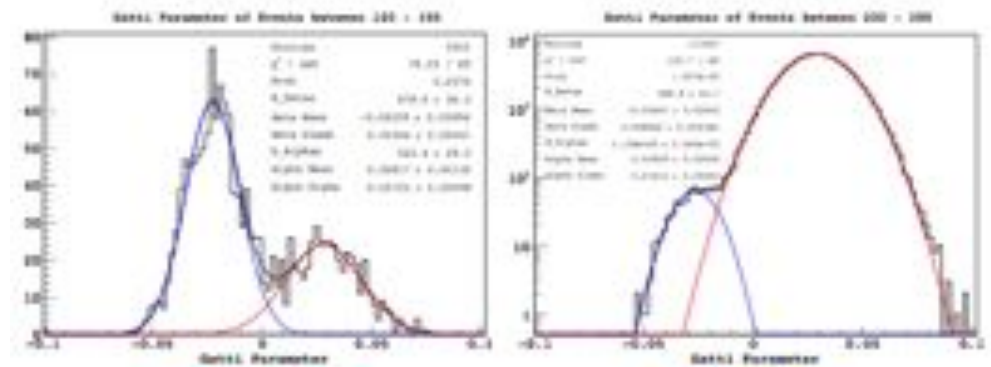


$$g_e \equiv \sum_{t=0}^{\infty} e[t] \cdot w[t]$$

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

$e[t]$: Event Time Profile

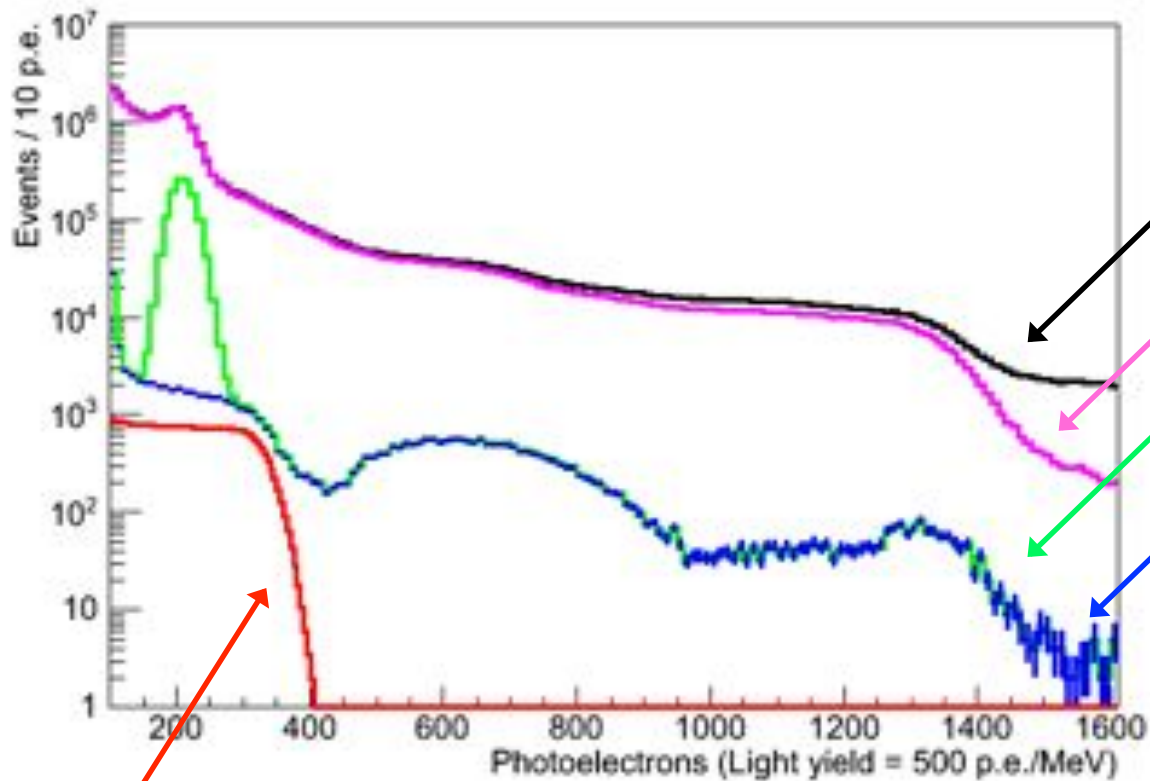
$r_{\alpha/\beta}[t]$: Reference time profile



150 p.e.

200 p.e.

Borexino Data



Expected ^7Be signal

All data: 740 live days

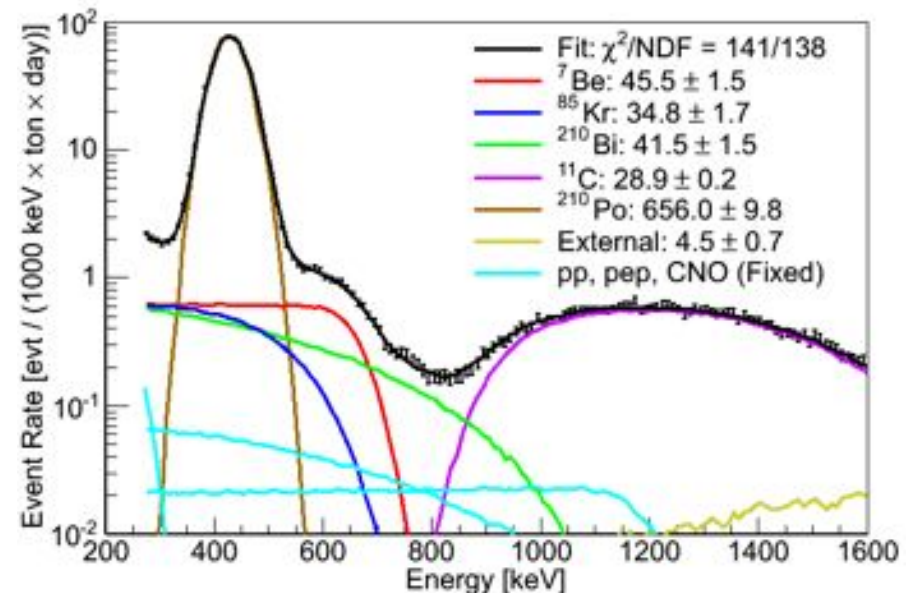
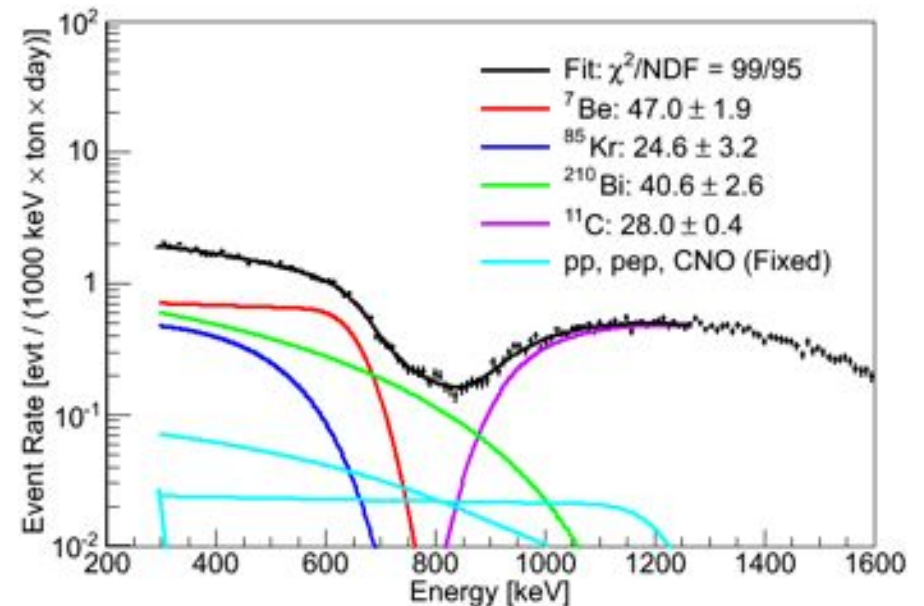
Remove muons + followers

Fiducial Volume + high level

Statistically subtract alphas

^7Be Signal Extraction

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



Precision ^7Be Flux Result

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

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

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

Systematic Uncertainties

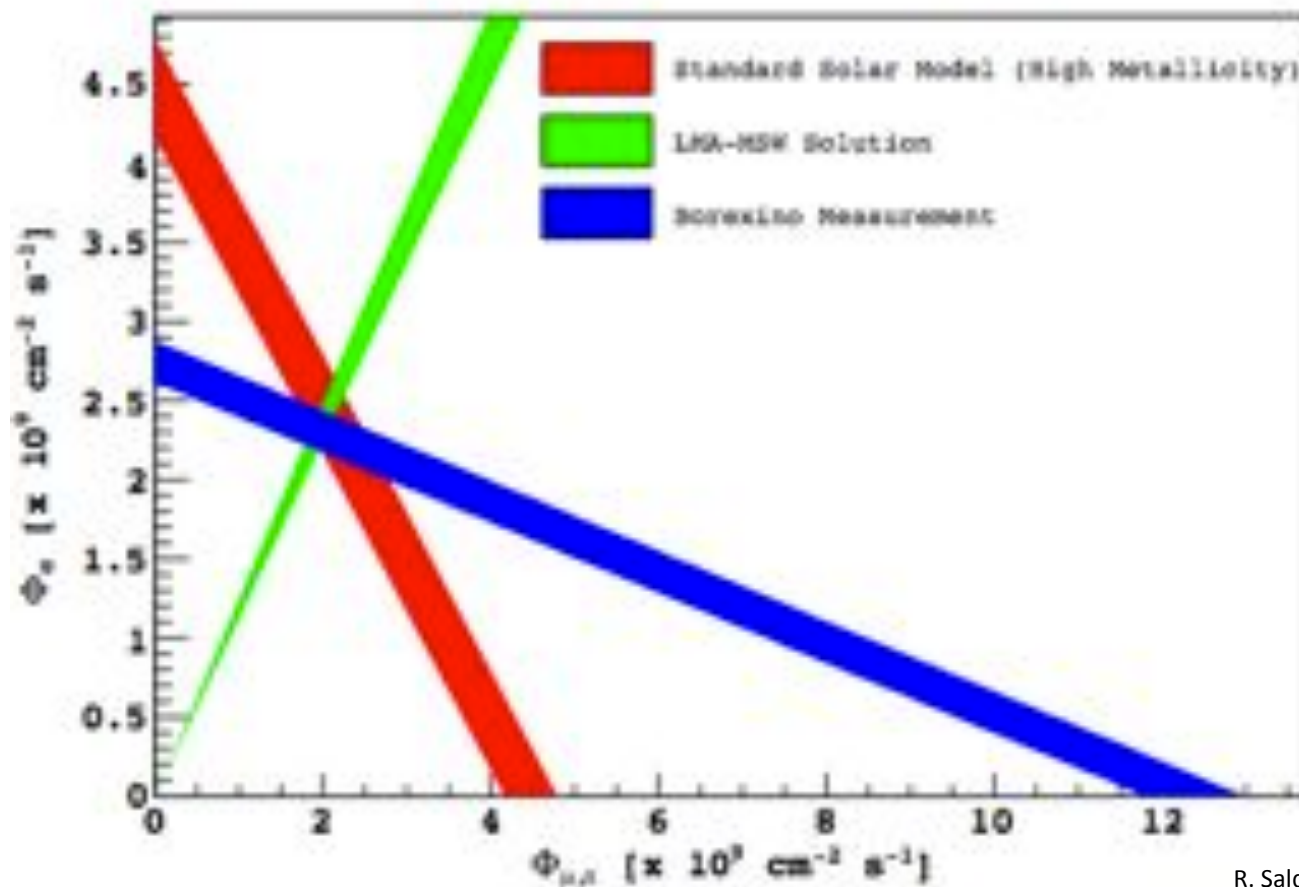
Trigger Efficiency	0.1%
Scintillator Density	0.05%
Livetime	0.04%
Cut Sacrifice	0.1%
Fiducial Mass	${}^{+0.5}_{-1.3}\%$
Energy Scale	2.7%
Fit Methods	2.0%
Total	${}^{+3.4}_{-3.6}\%$

Precision ${}^7\text{Be}$ Flux Result

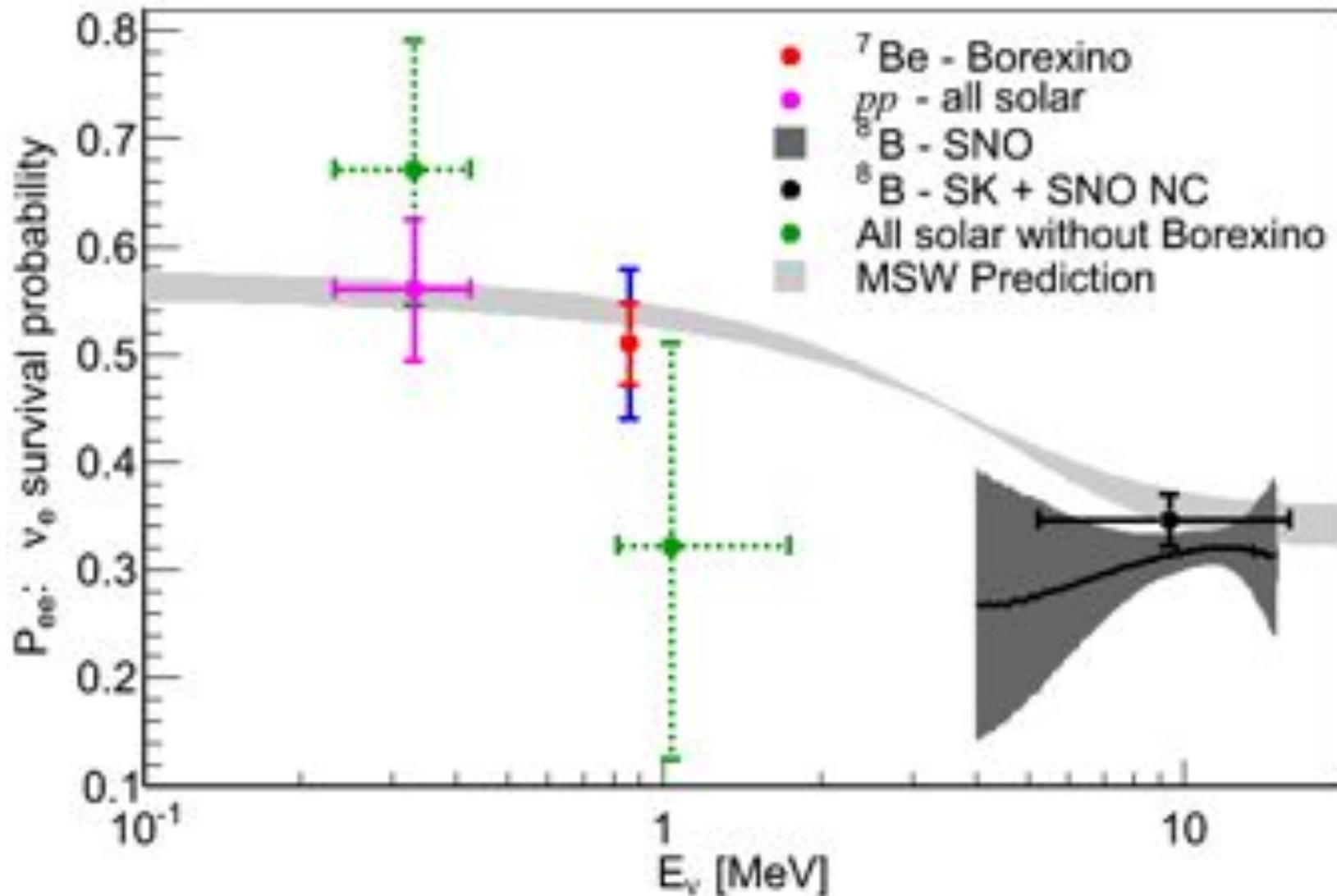
(Phys. Rev. Lett. **107**:141302 (2011))

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

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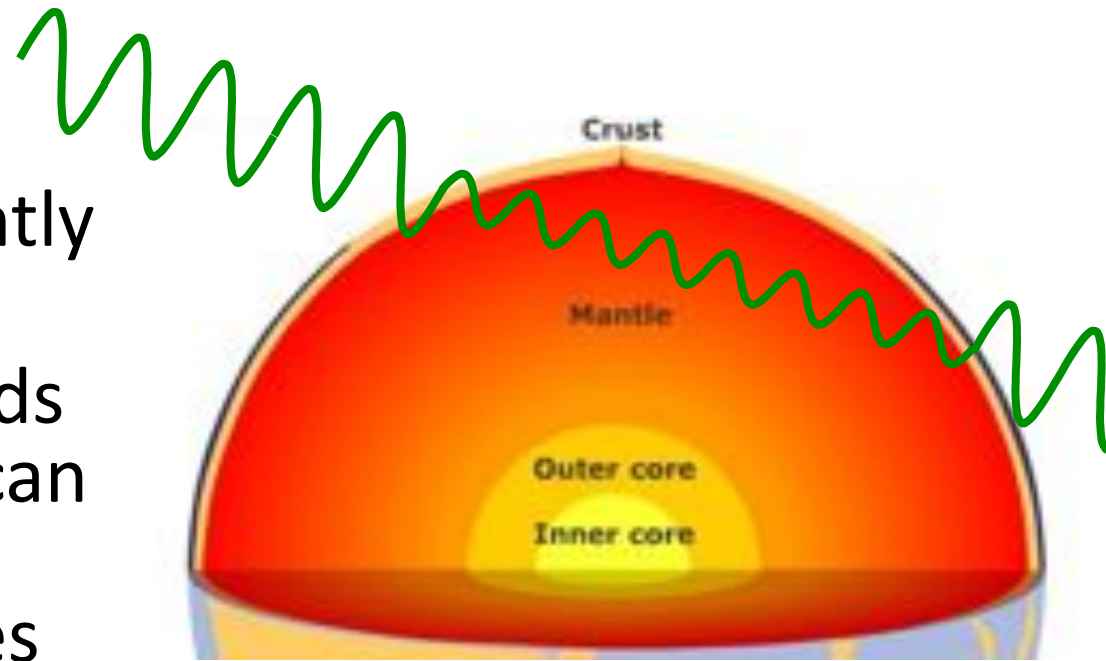
Precision ${}^7\text{Be}$ Flux Result



Significantly improved constraint on low energy P_{ee} .

^7Be Day-Night Effect

- As solar neutrinos (diabatically) enter the earth, ν_e can be coherently regenerated
- Size of the effect depends on mixing parameters, can cause the effective day and night neutrino fluxes to be different



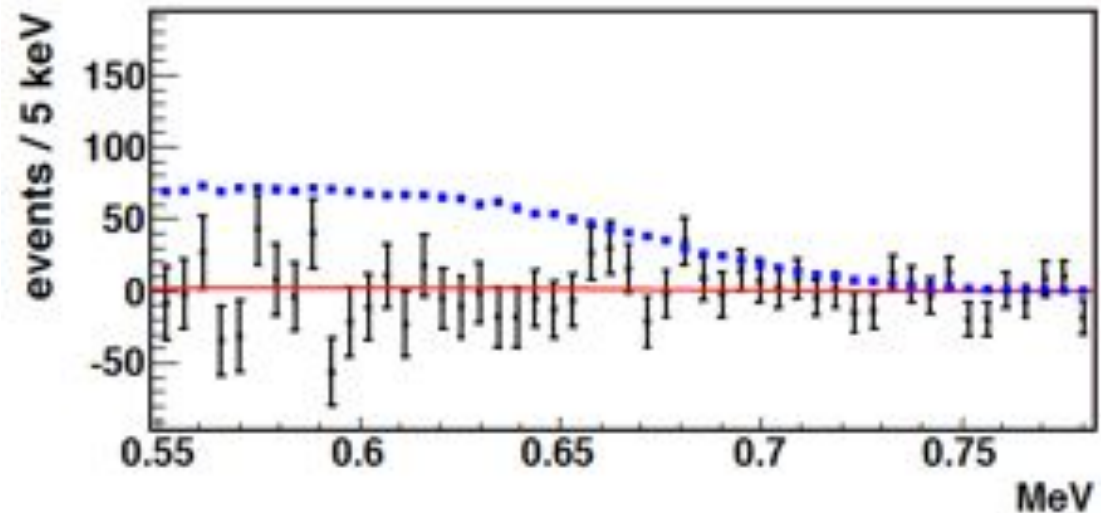
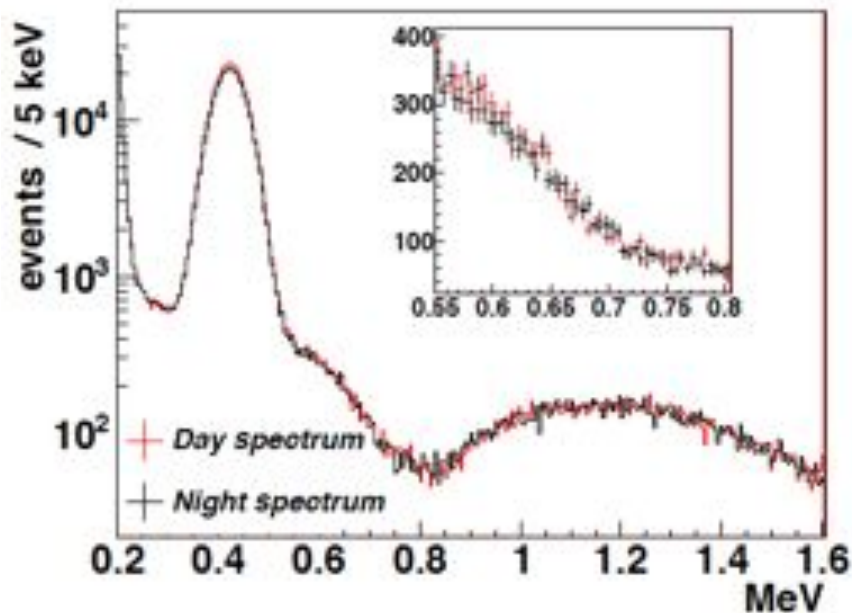
www.education.ezinemark.com

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

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

^7Be Day-Night Asymmetry Search

(arXiv:1104.2150; PLB in press)



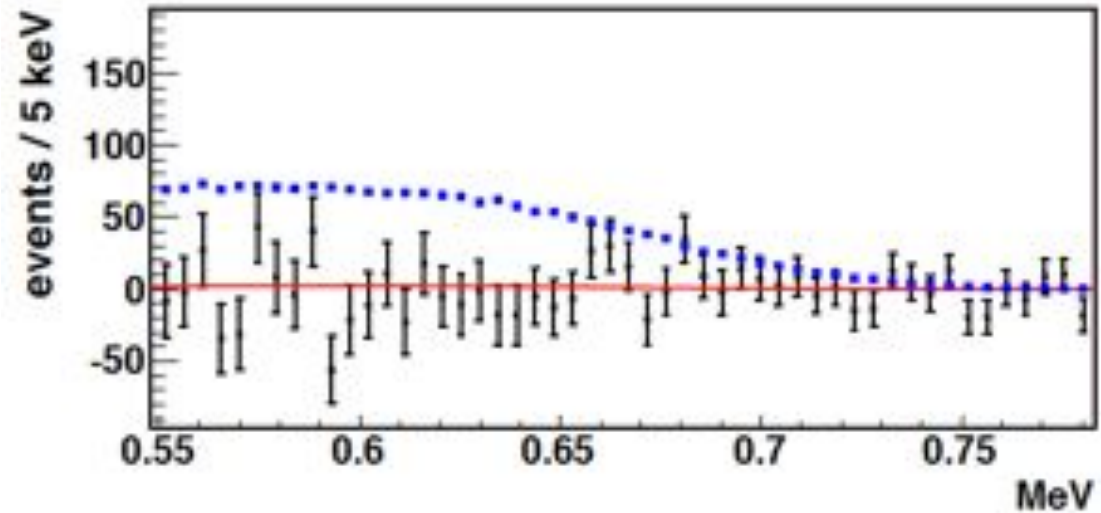
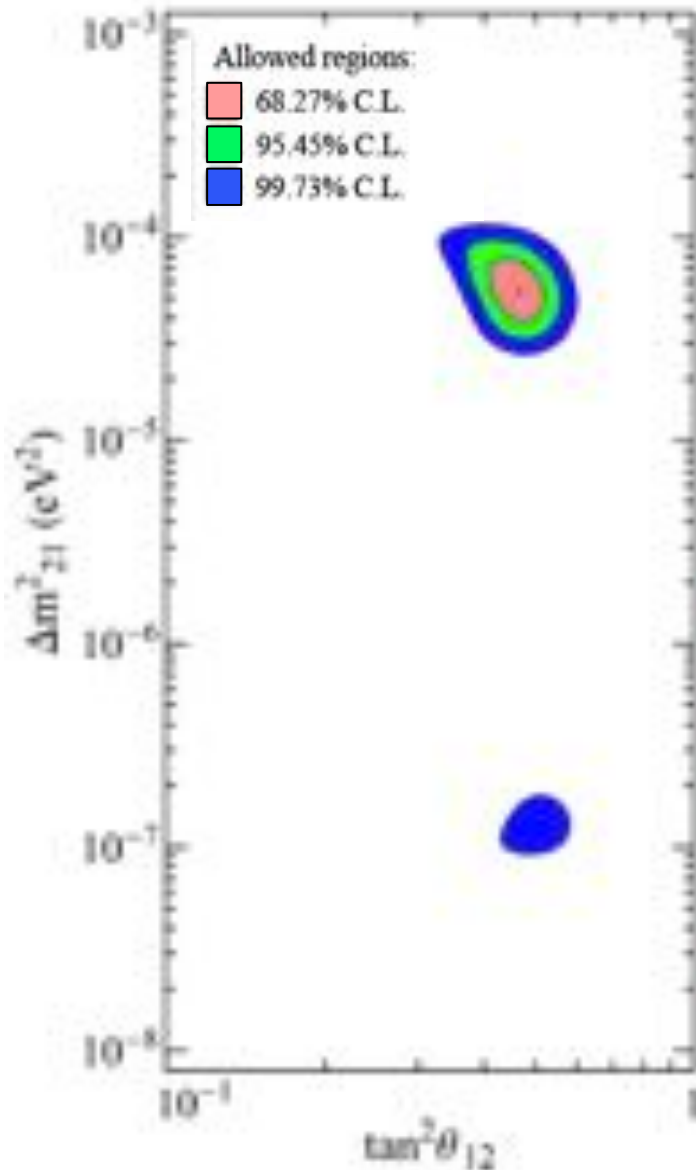
$$A_{\text{dn}}(862 \text{ keV}): 0.001 \pm 0.012_{\text{stat}} \pm 0.007_{\text{sys}}$$

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

Source of error	Error on A_{dn}
Live-time	$< 5 \cdot 10^{-4}$
Cut efficiencies	0.001
Variation of ^{210}Bi with time	± 0.005
Fit procedure	± 0.005
Total systematic error	0.007

^7Be Day-Night Asymmetry Search

Global Solar, without Borexino

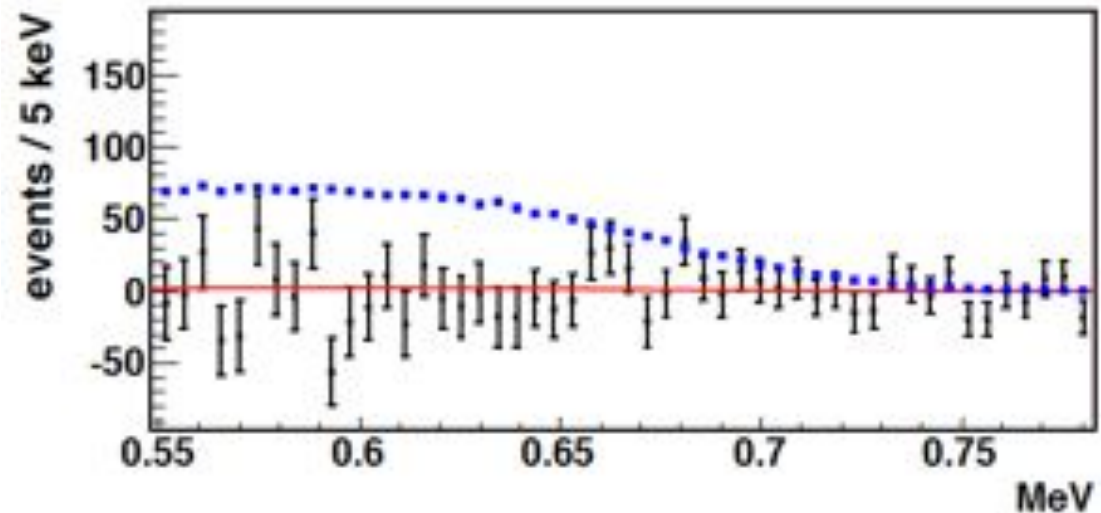
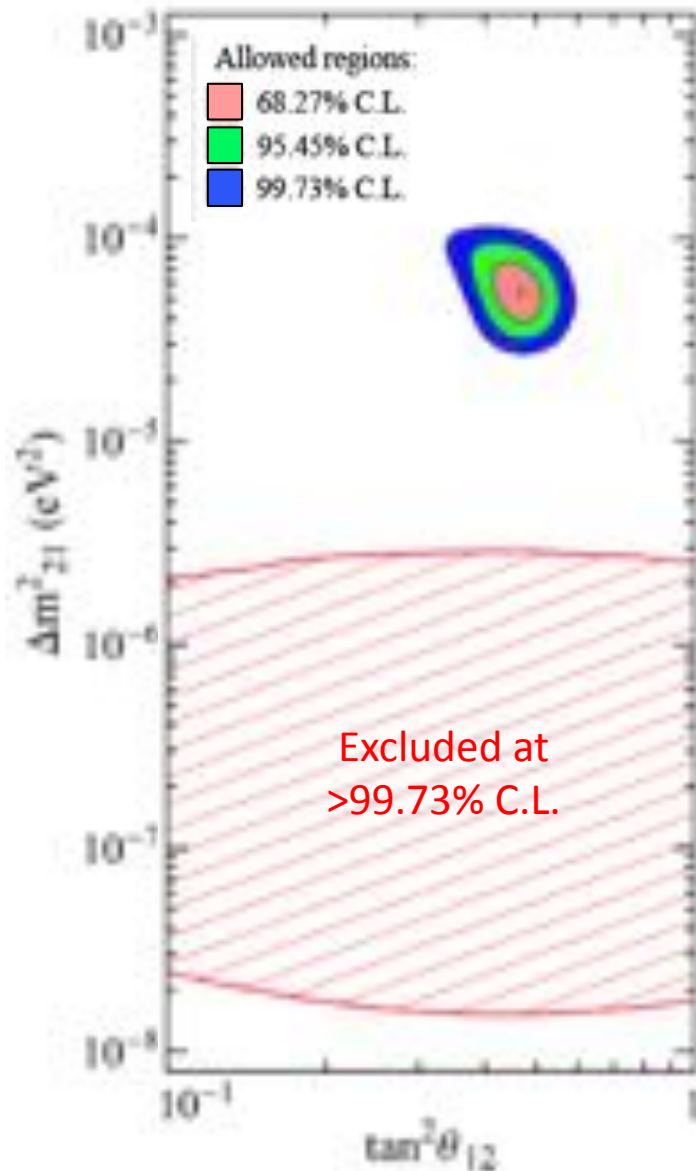


$$A_{\text{dn}}(862 \text{ keV}): 0.001 \pm 0.012_{\text{stat}} \pm 0.007_{\text{sys}}$$

Source of error	Error on A_{dn}
Live-time	$< 5 \cdot 10^{-4}$
Cut efficiencies	0.001
Variation of ^{210}Bi with time	± 0.005
Fit procedure	± 0.005
Total systematic error	0.007

^7Be Day-Night Asymmetry Search

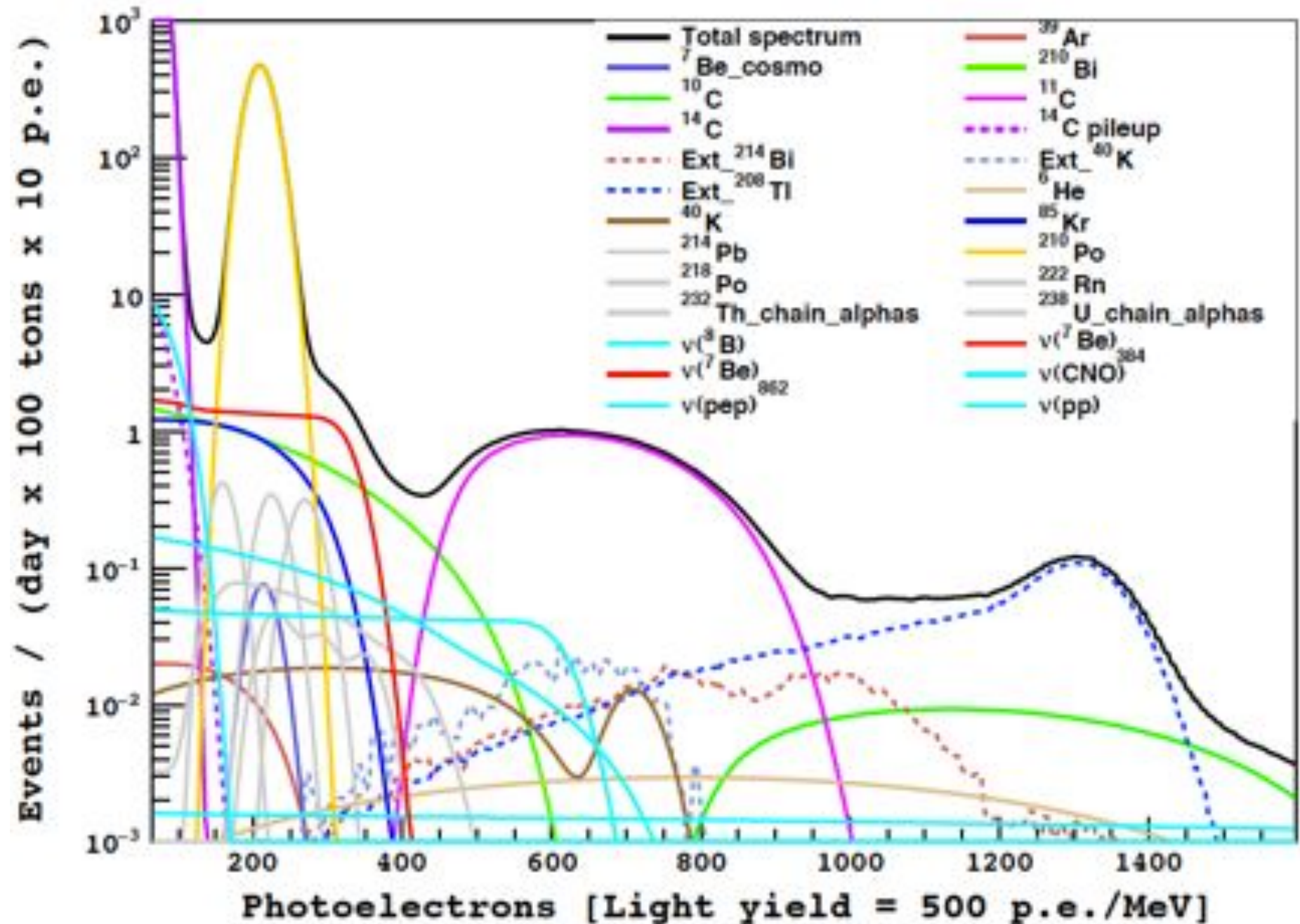
Global Solar, with Borexino



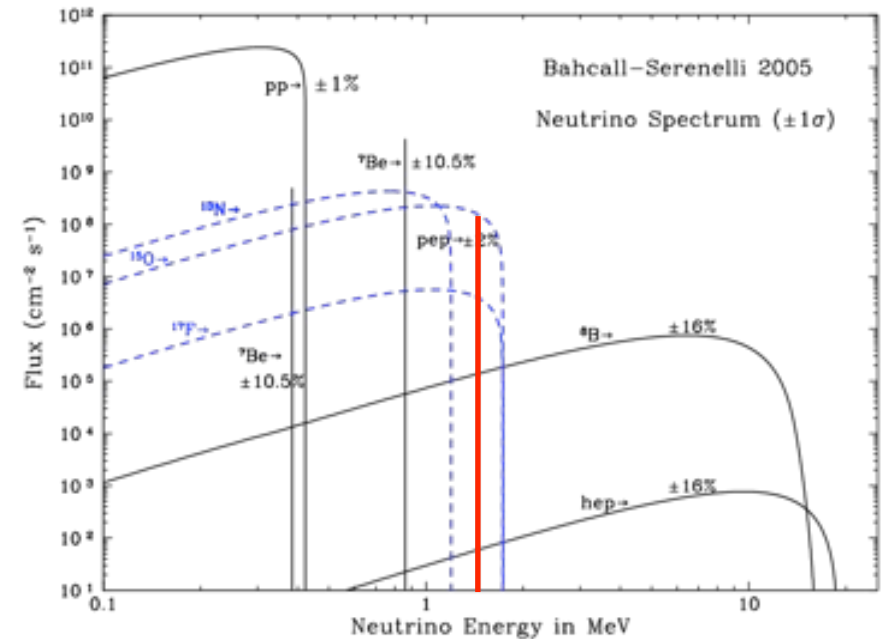
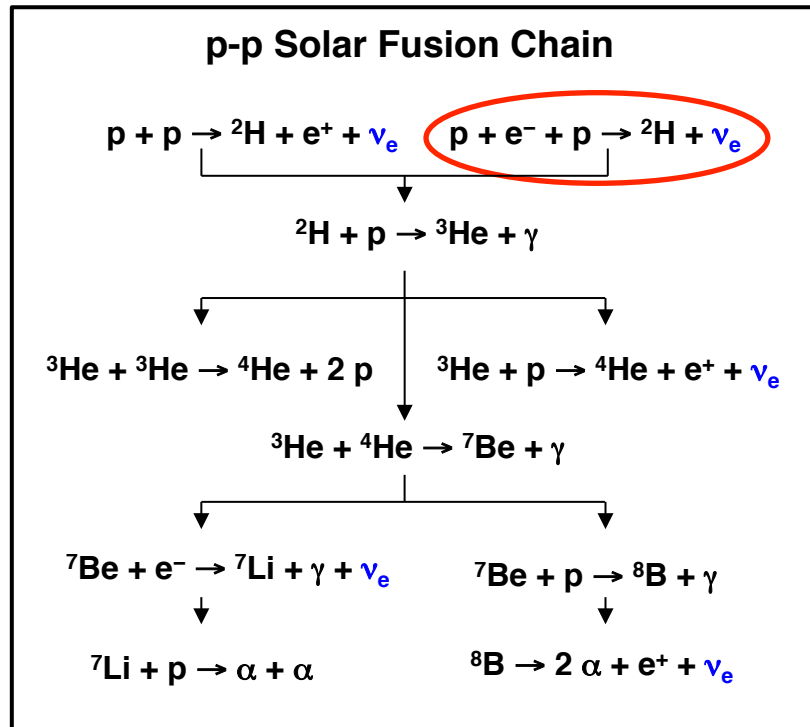
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“Into the Muck”: *pep* and CNO Neutrinos



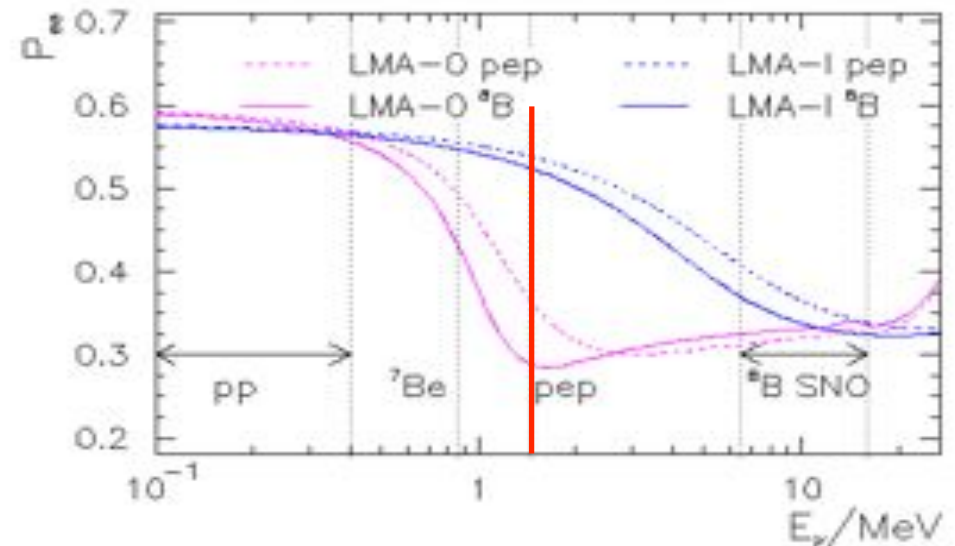
pep Neutrinos



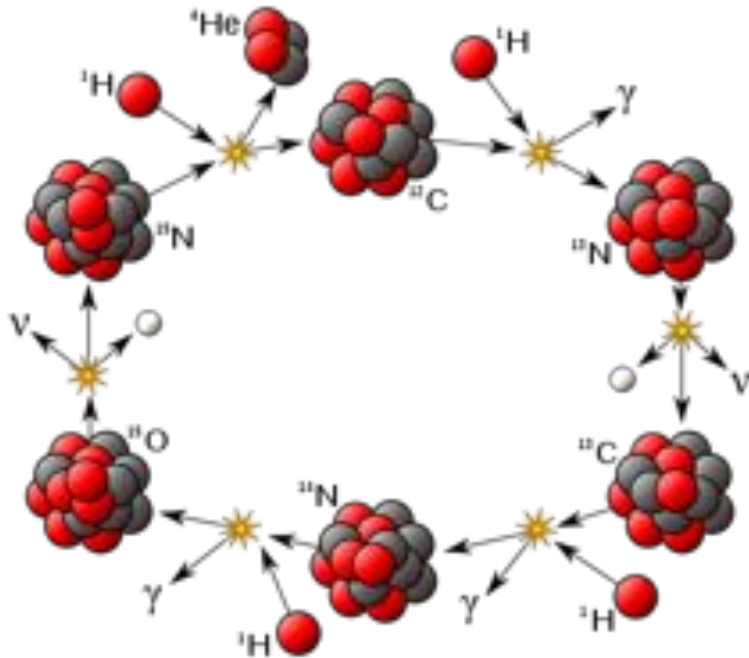
First direct look at solar p-p fusion.

Precision test of Standard Solar Model and oscillations.

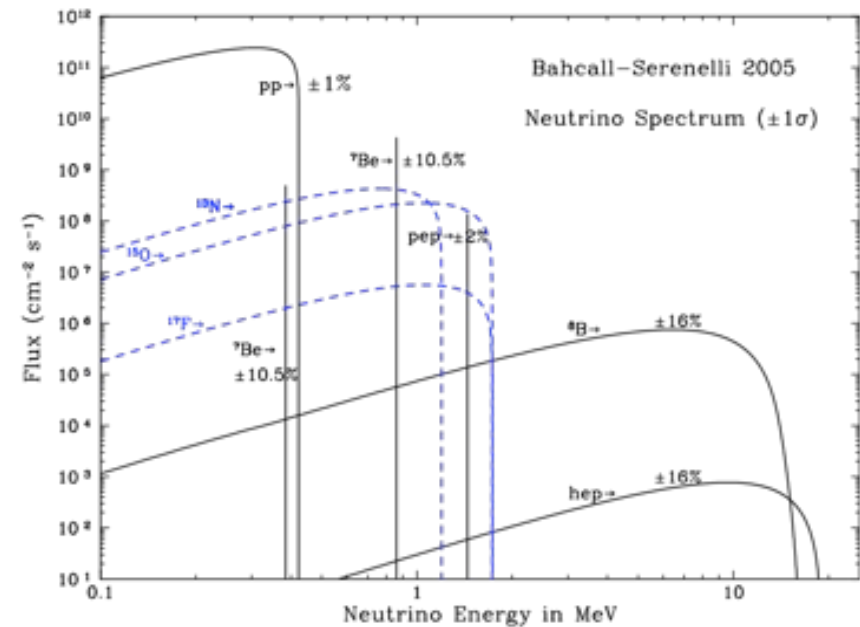
Ideal energy to probe transition region.



CNO Neutrinos

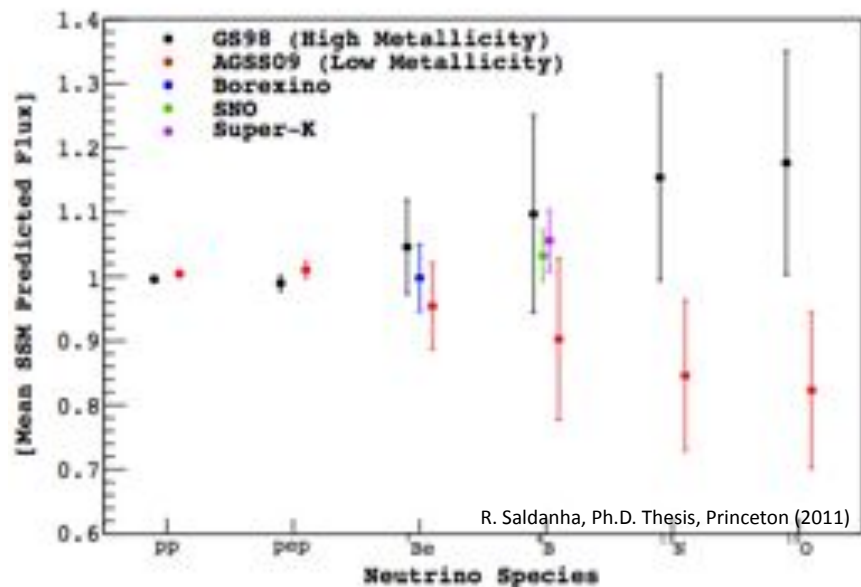


Wikimedia.org



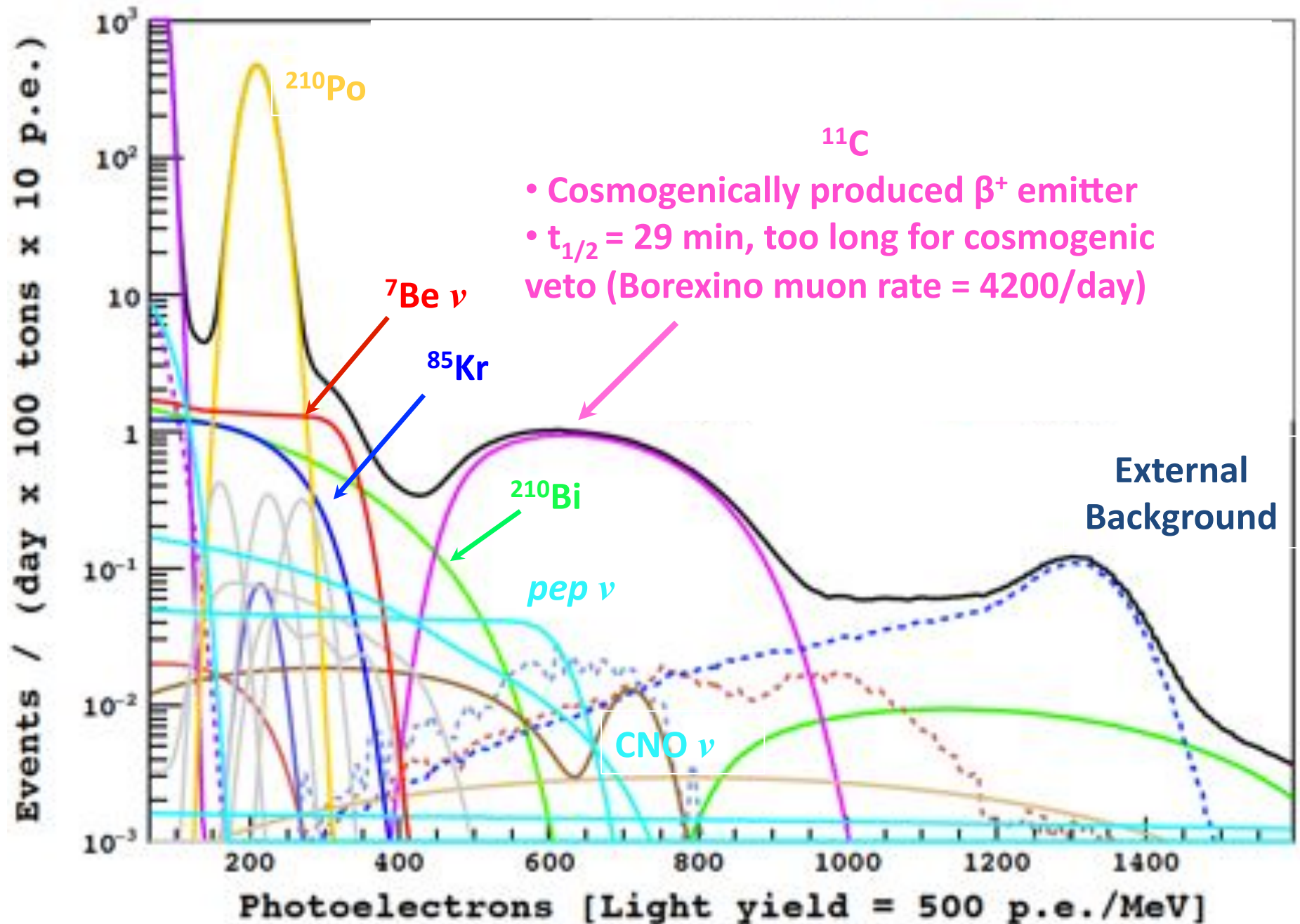
First direct evidence for CNO cycle.

Measure solar metallicity.

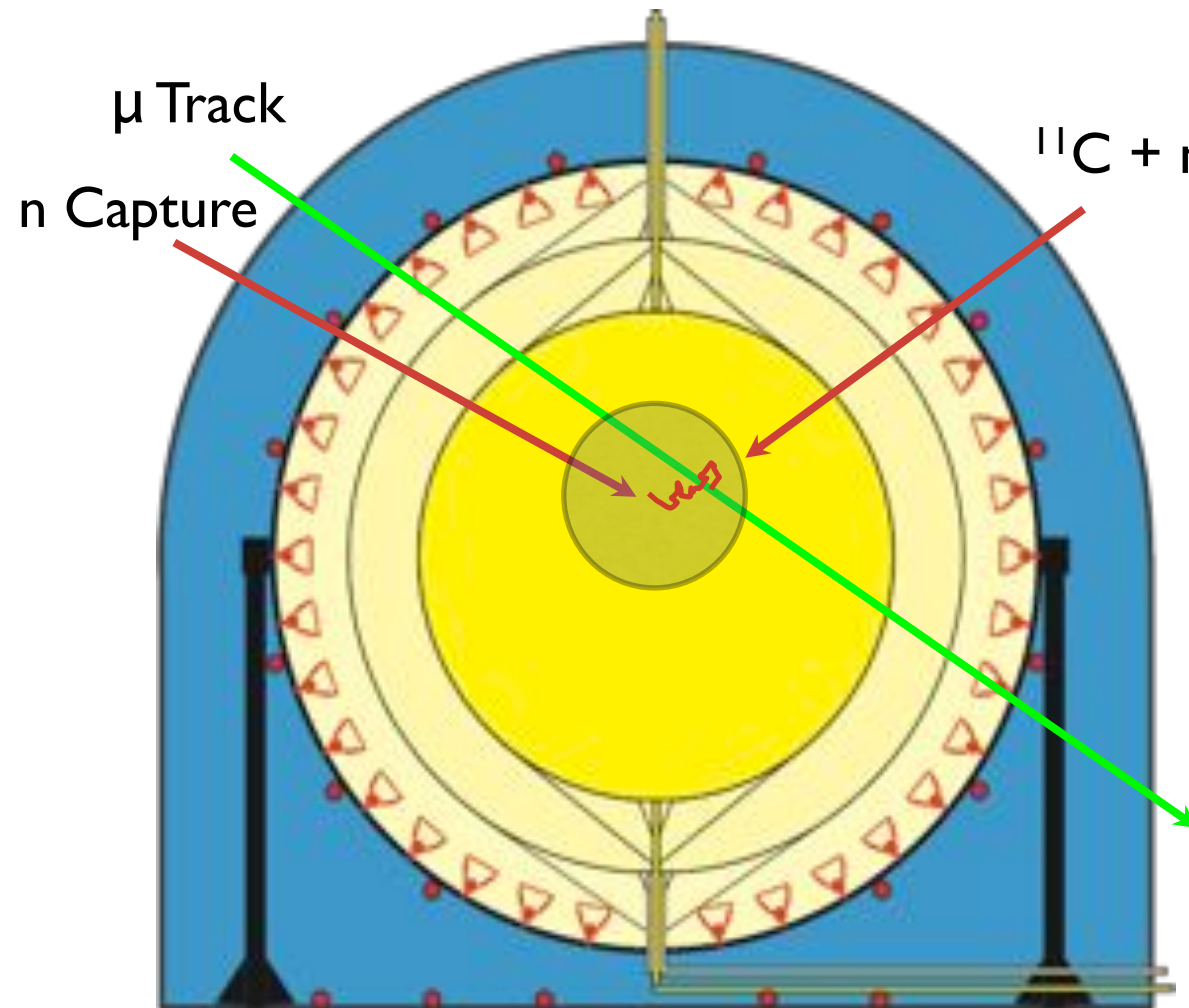


R. Saldanha, Ph.D. Thesis, Princeton (2011)

^{11}C Suppression



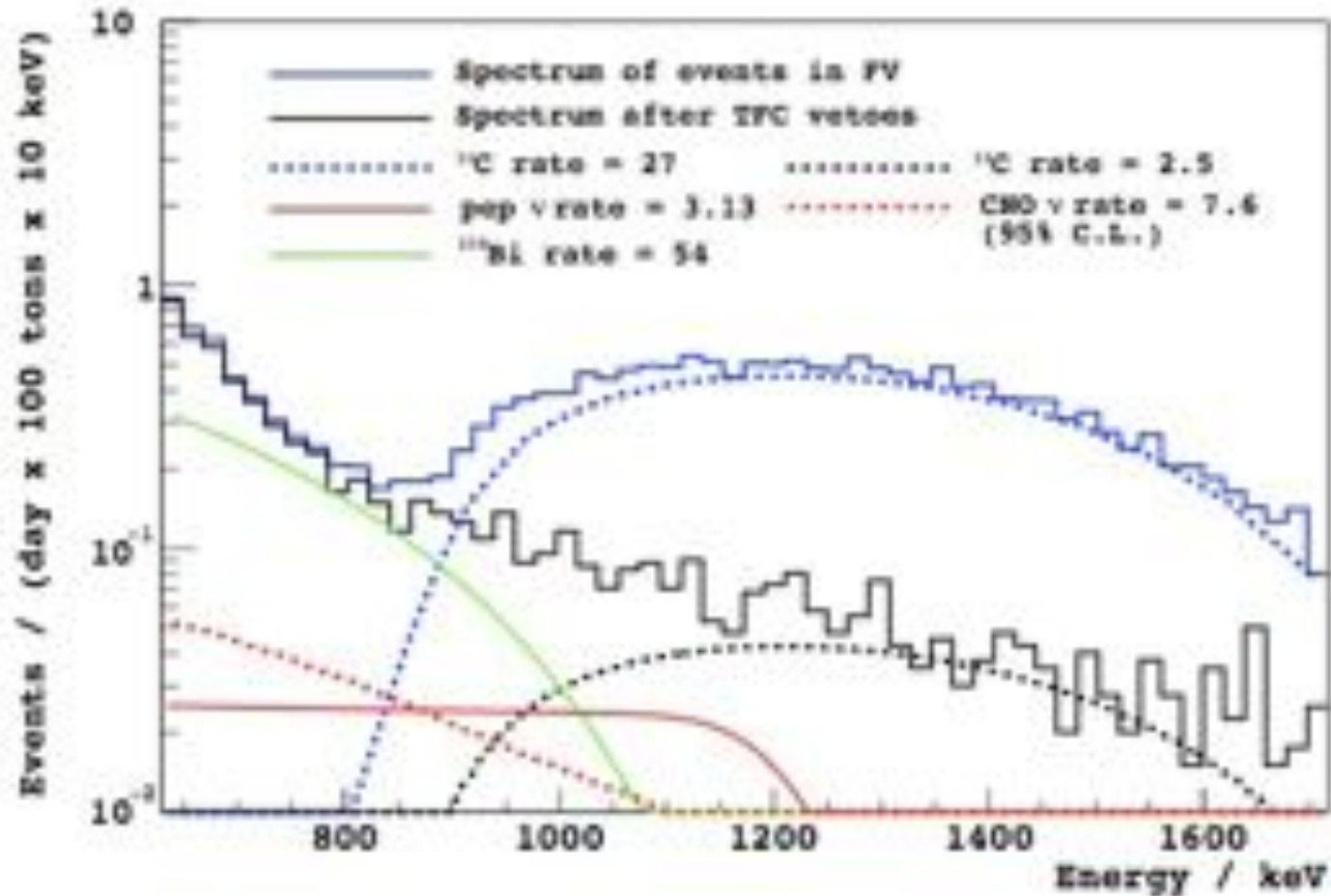
Three-Fold Coincidence



- Most ^{11}C produced via $^{12}\text{C} \rightarrow ^{11}\text{C} + n$
- 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.

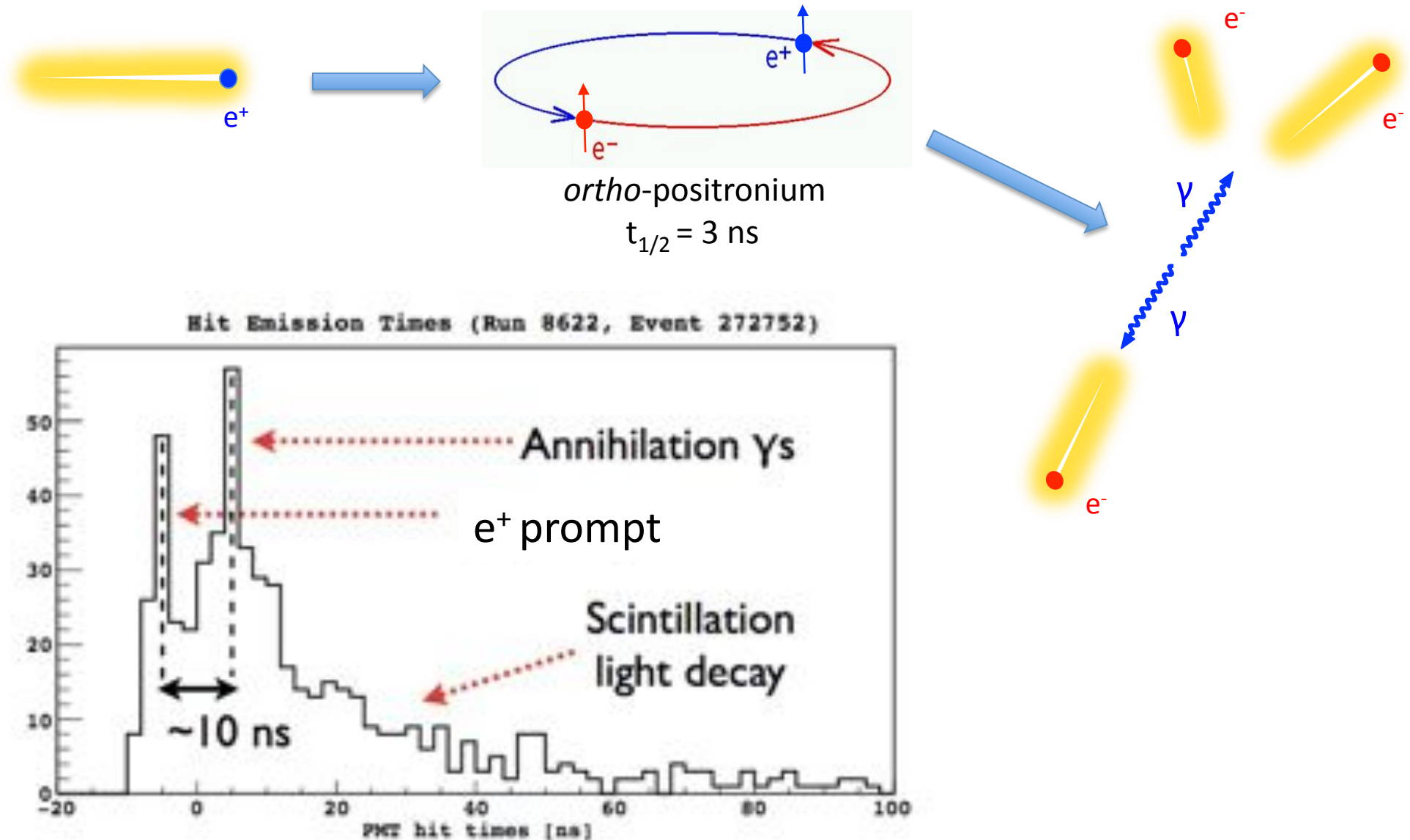
Three-Fold Coincidence



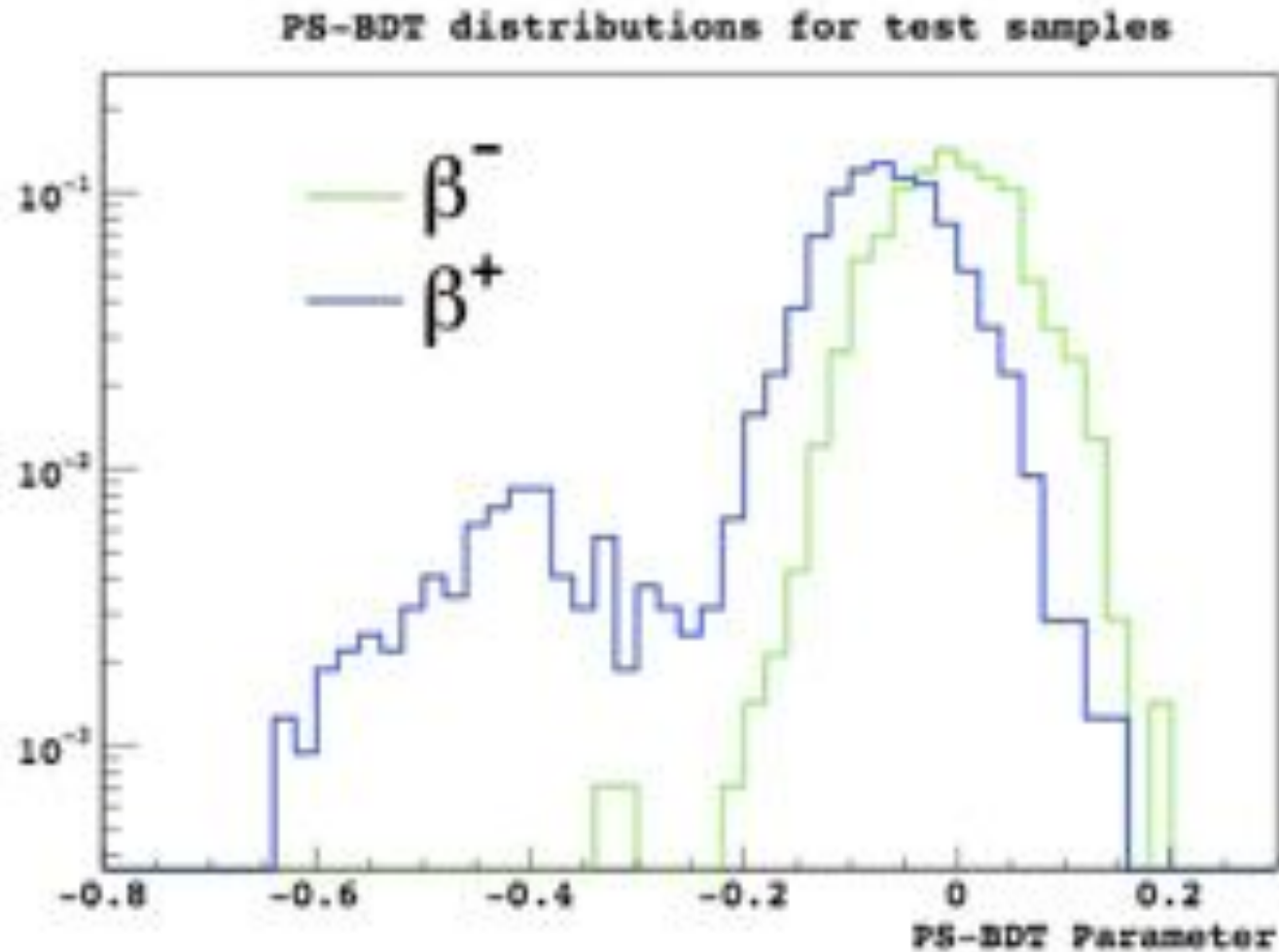
Remove 91% of ^{11}C and 51.5% of livetime.

e^+/e^- Pulse Shape Discrimination

(PRC 83:015522 (2011))



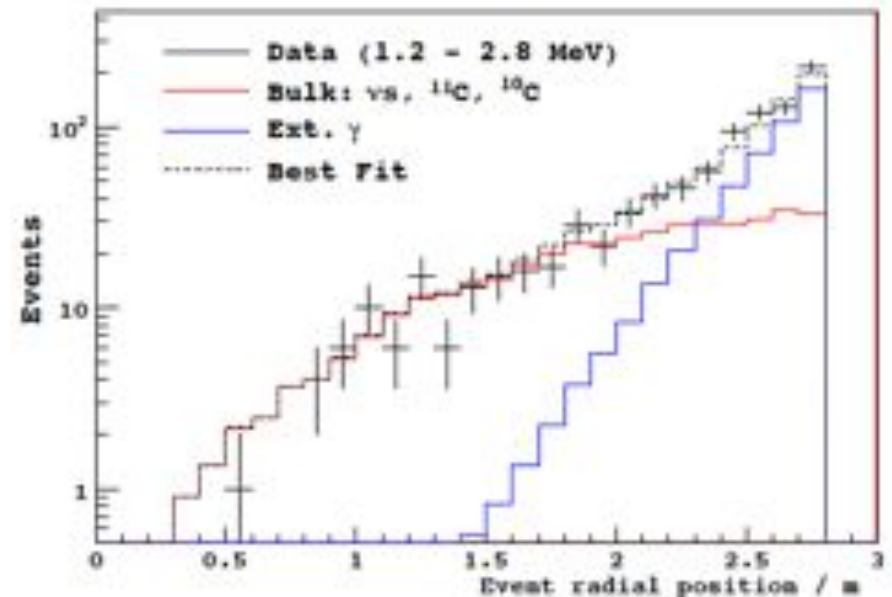
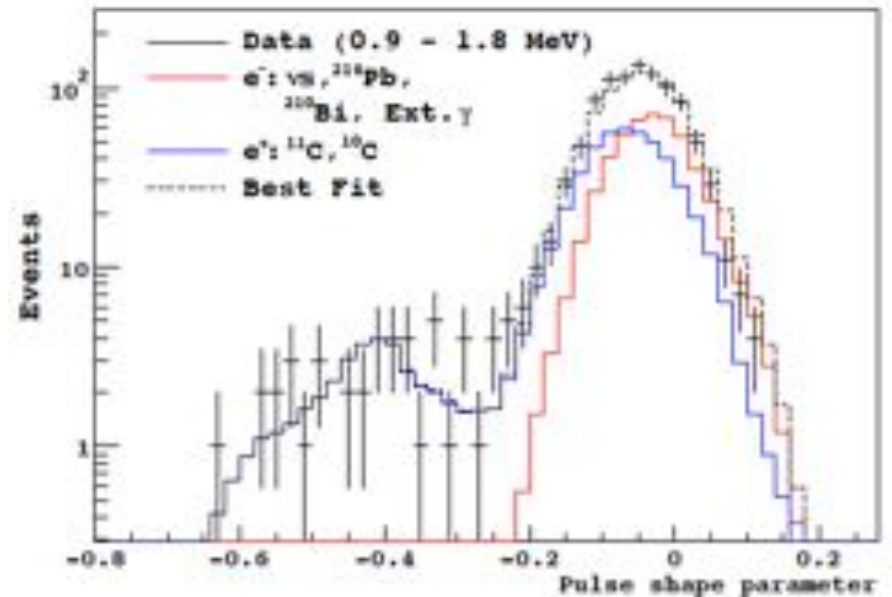
e^+/e^- Pulse Shape Discrimination



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

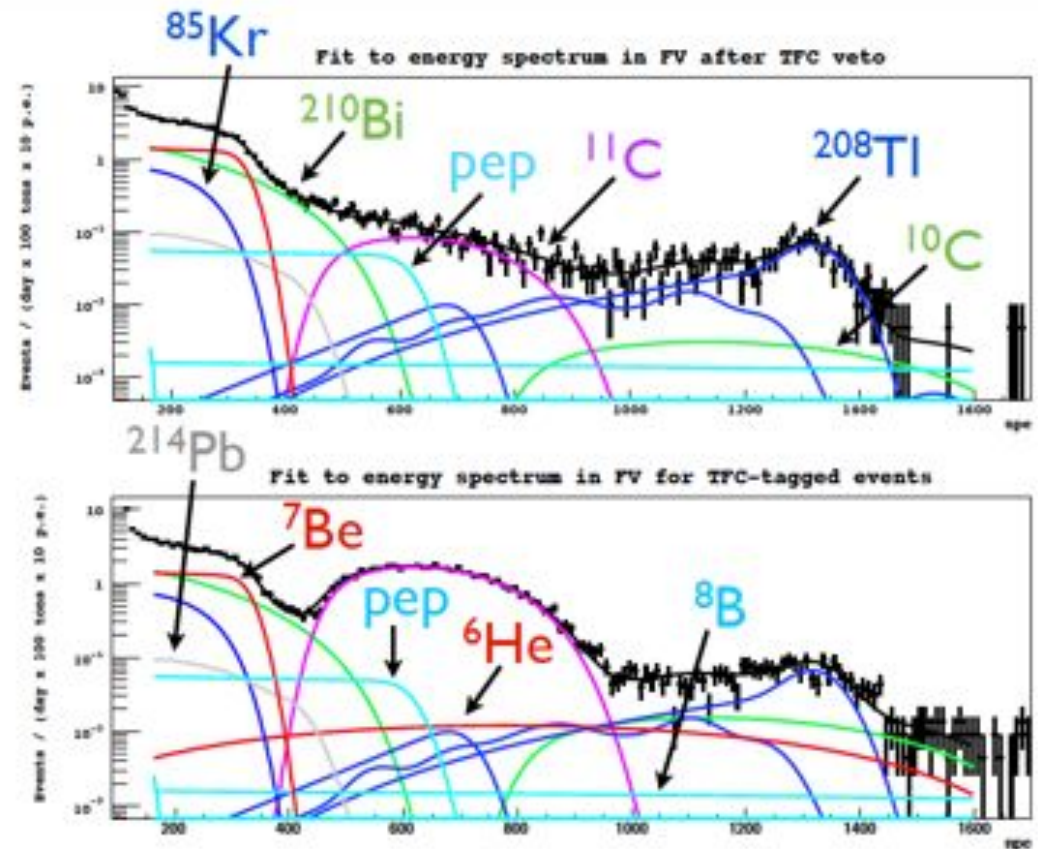
pep/CNO Fit

- 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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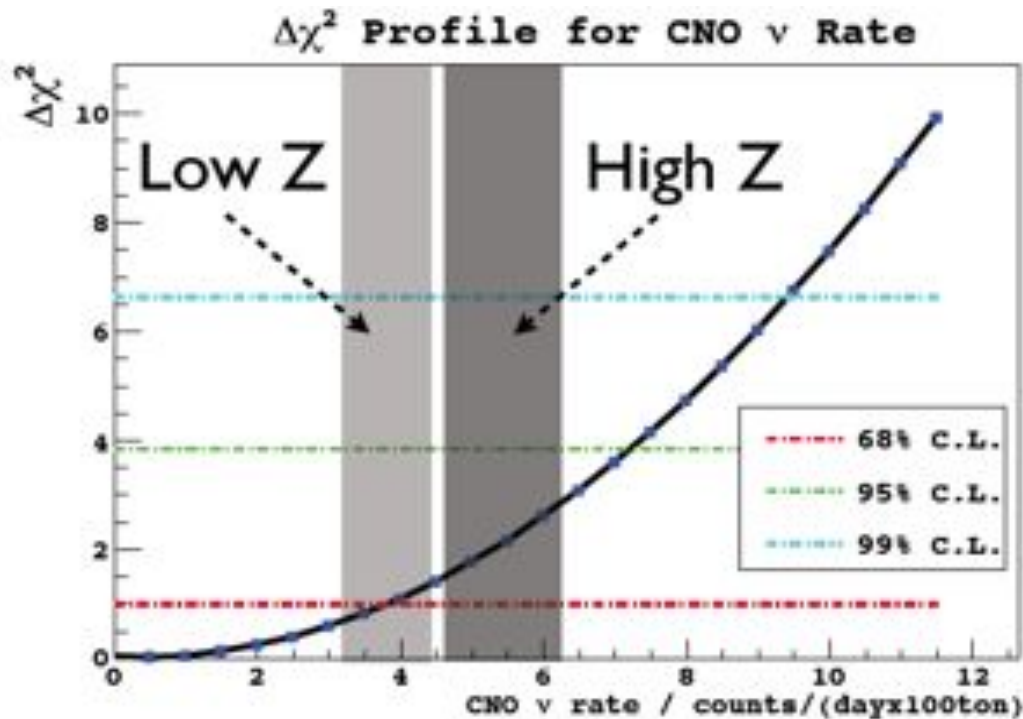


CNO Limit

(arXiv:1110.3230)

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

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



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

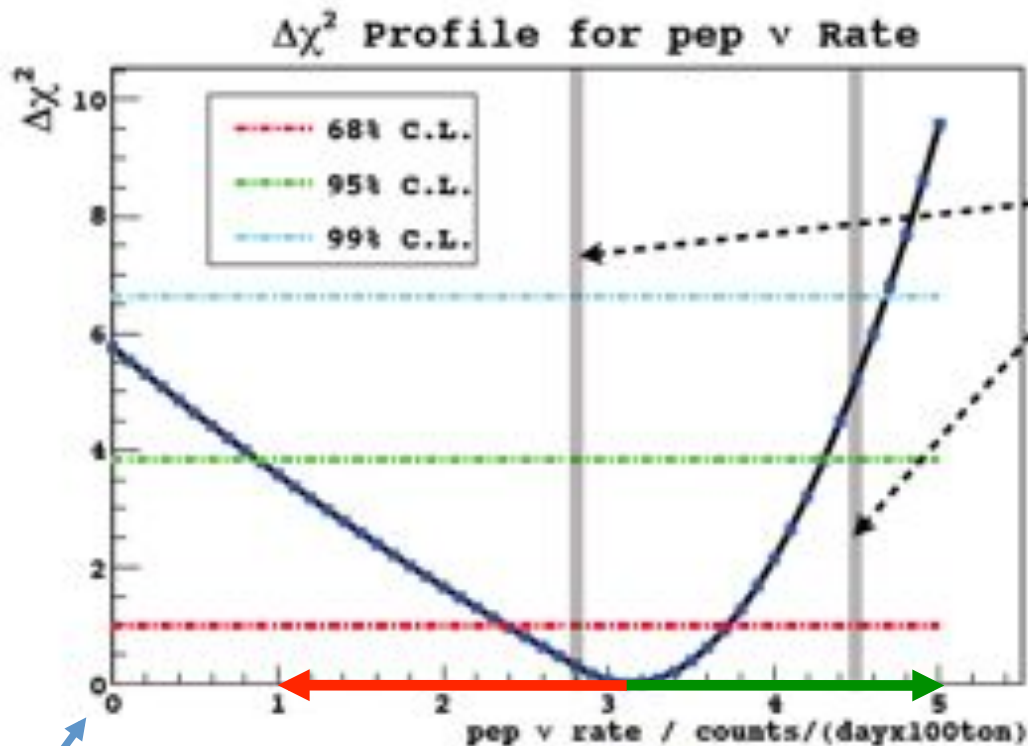
Sensitivity approaching predicted rates: most stringent limit to date.
Result consistent with both high and low metallicity models.

pep Result

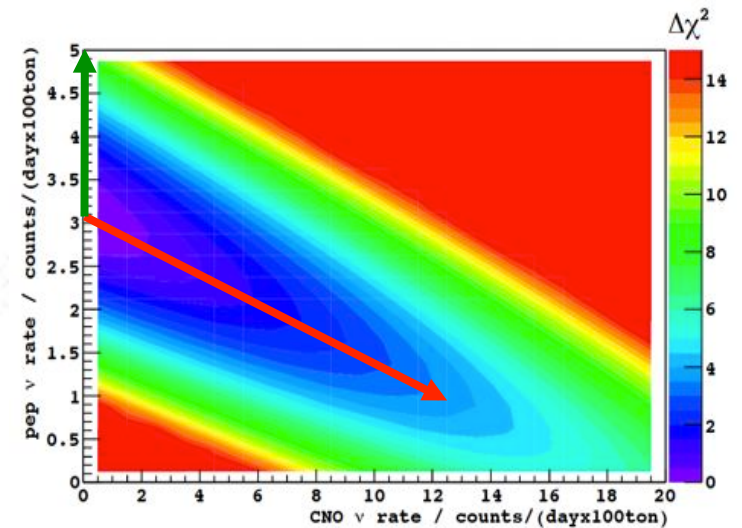
(arXiv:1110.3230)

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

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



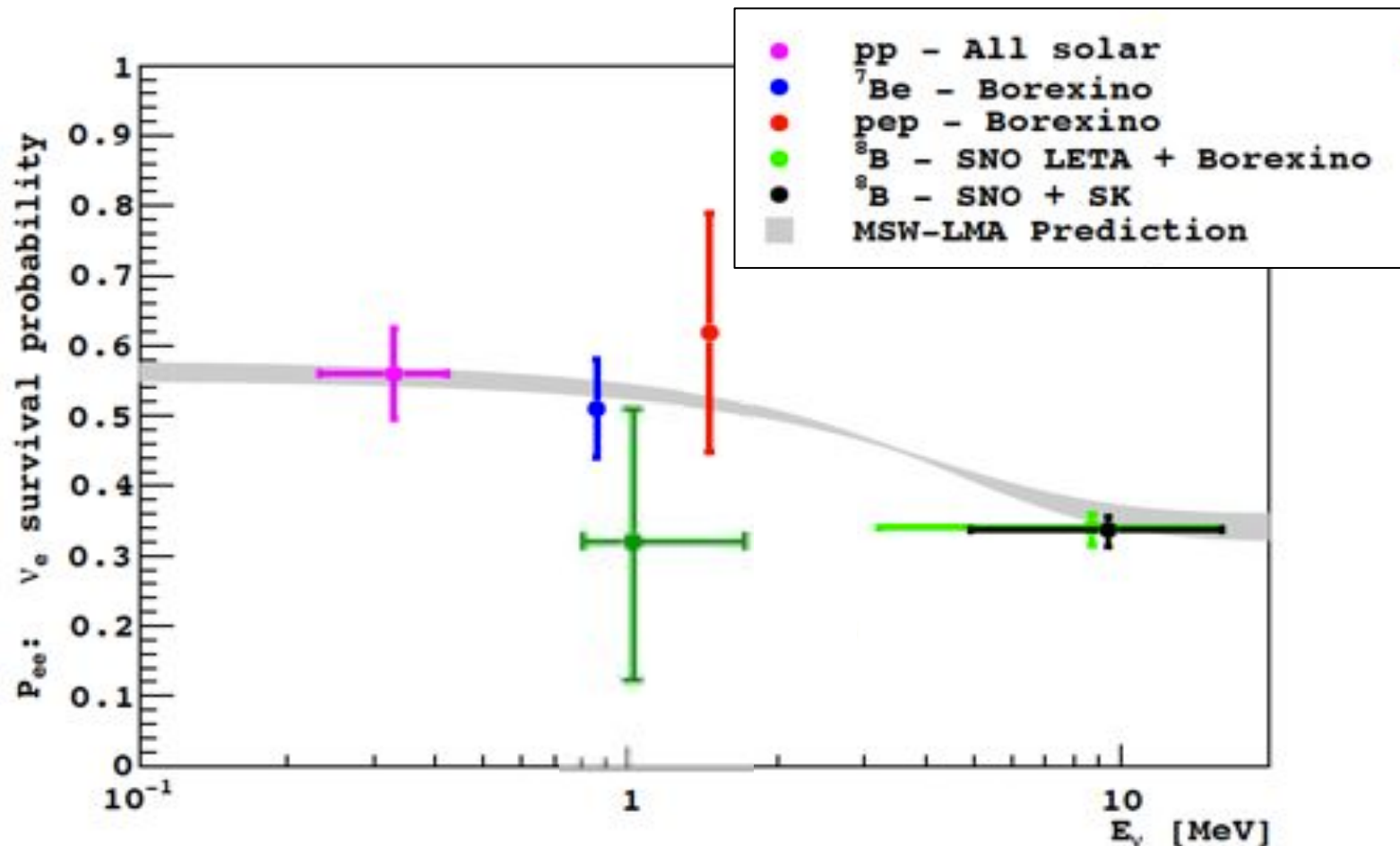
SSM Prediction
MSW-LMA
No Oscillation



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

pep Result

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



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

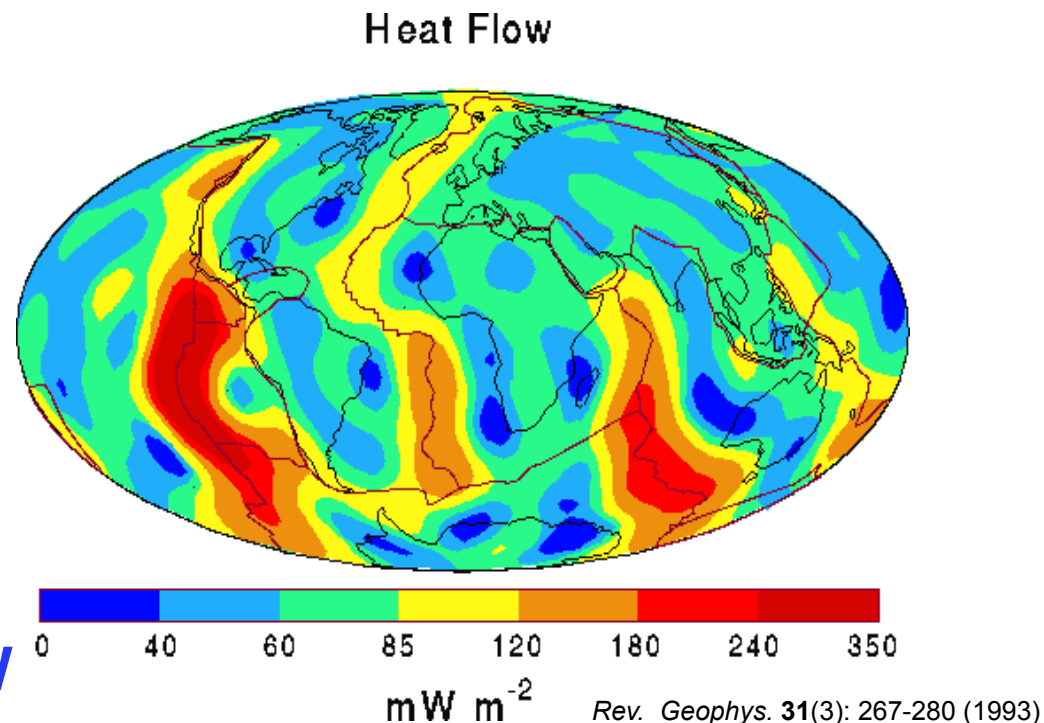
Geo-Neutrinos

- 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!

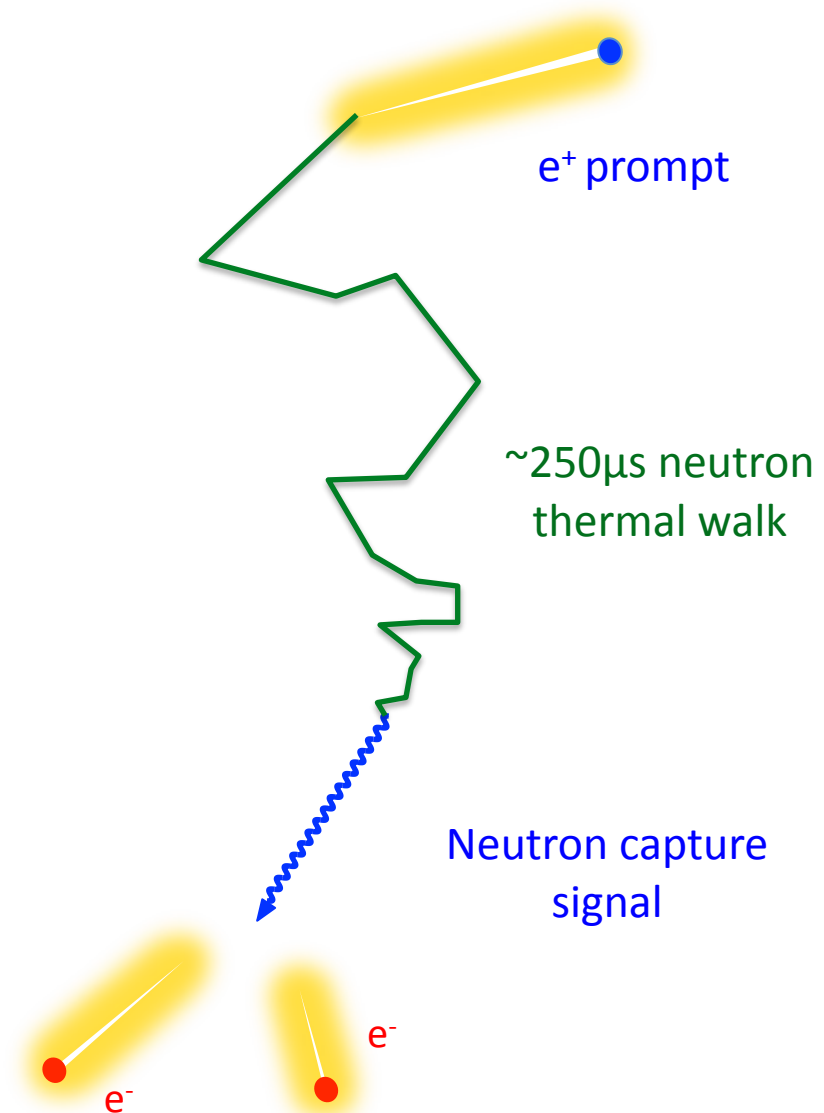
- Use geoneutrinos to measure the earth's radiogenic heat and chemical composition

Geophysics with neutrinos!



Detecting Geo-Neutrinos

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



Detecting Geo-Neutrinos

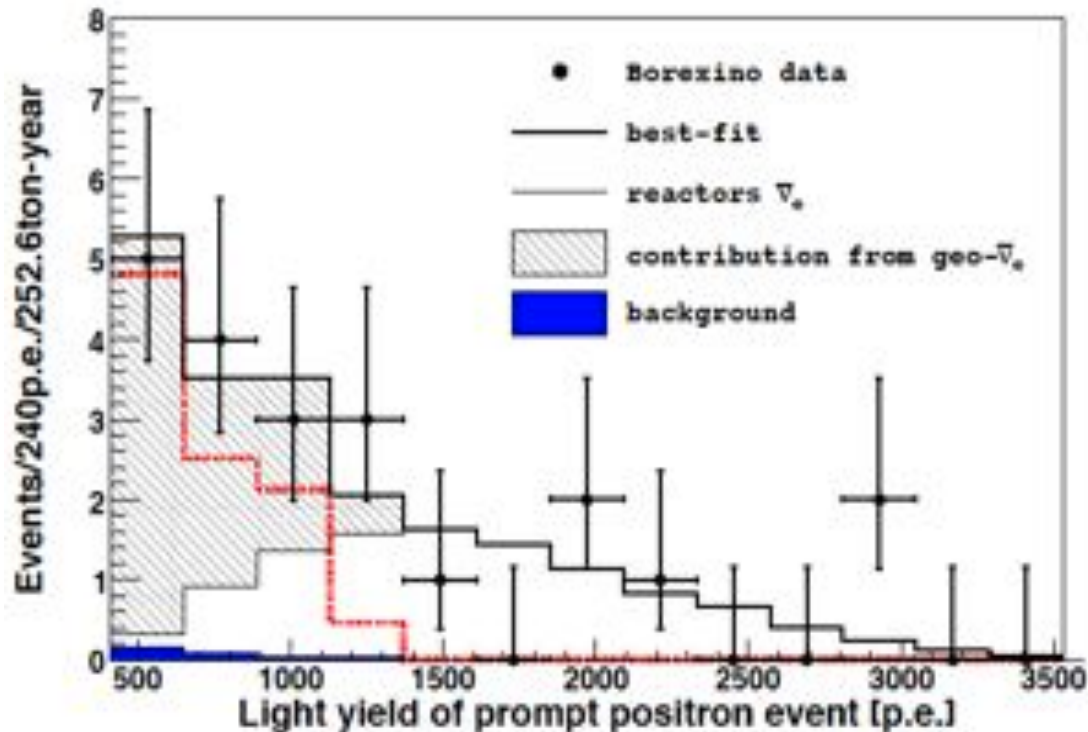
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Geo-neutrinos in Borexino

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

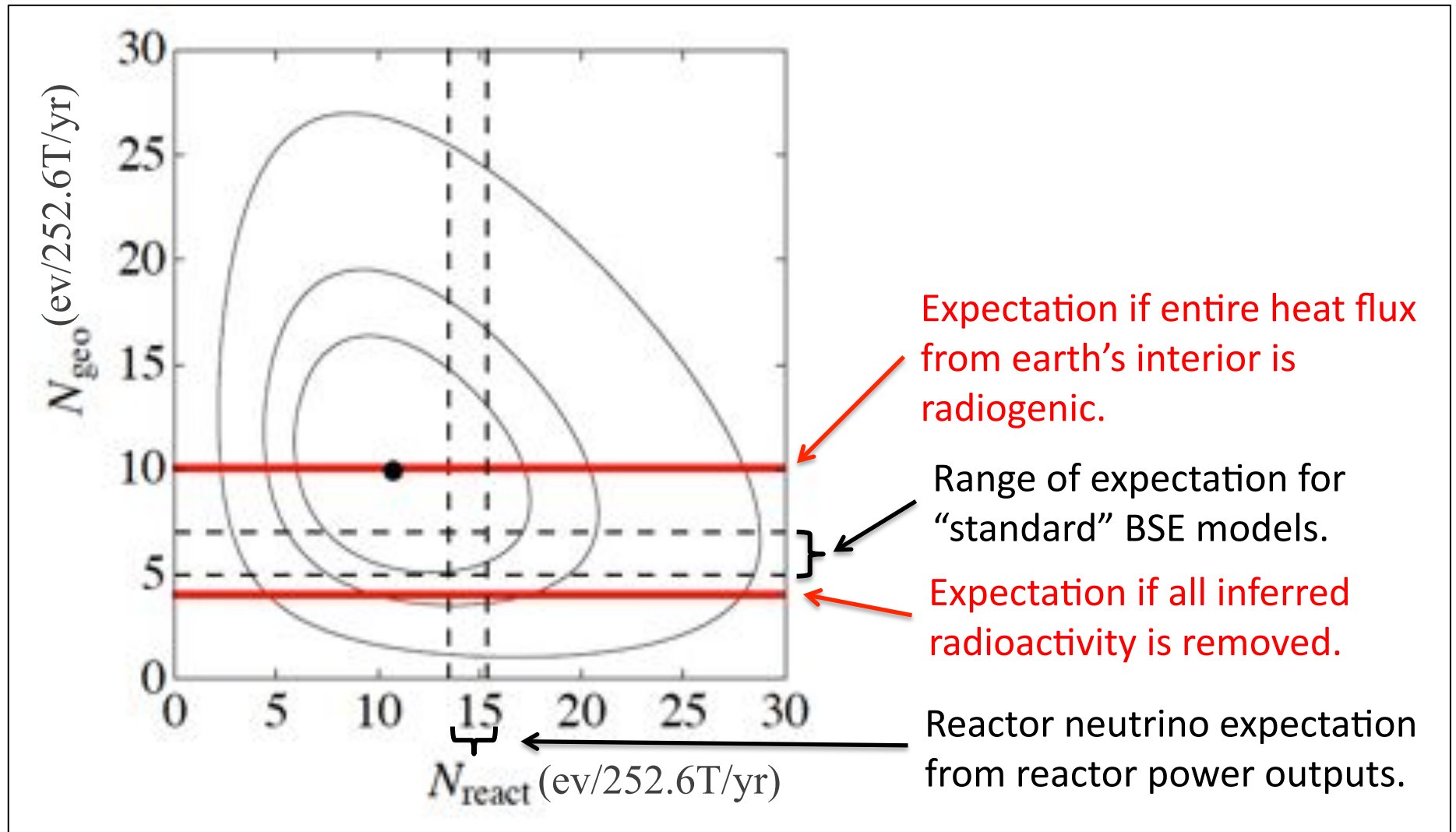
Borexino Geo-Neutrino Rate: $3.9^{+1.6}_{-1.3}$ ev/100T/yr



Delayed Co-incidence Backgrounds

Source	Background [events/(100 ton·yr)]
${}^9\text{Li}-{}^8\text{He}$	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

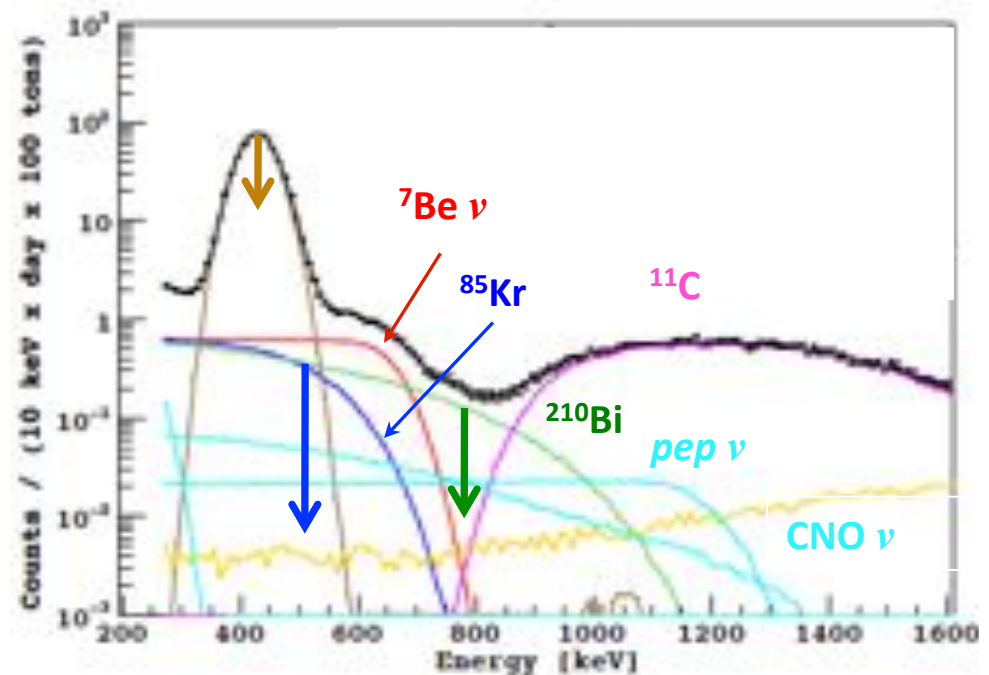
Geo-neutrinos in Borexino



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

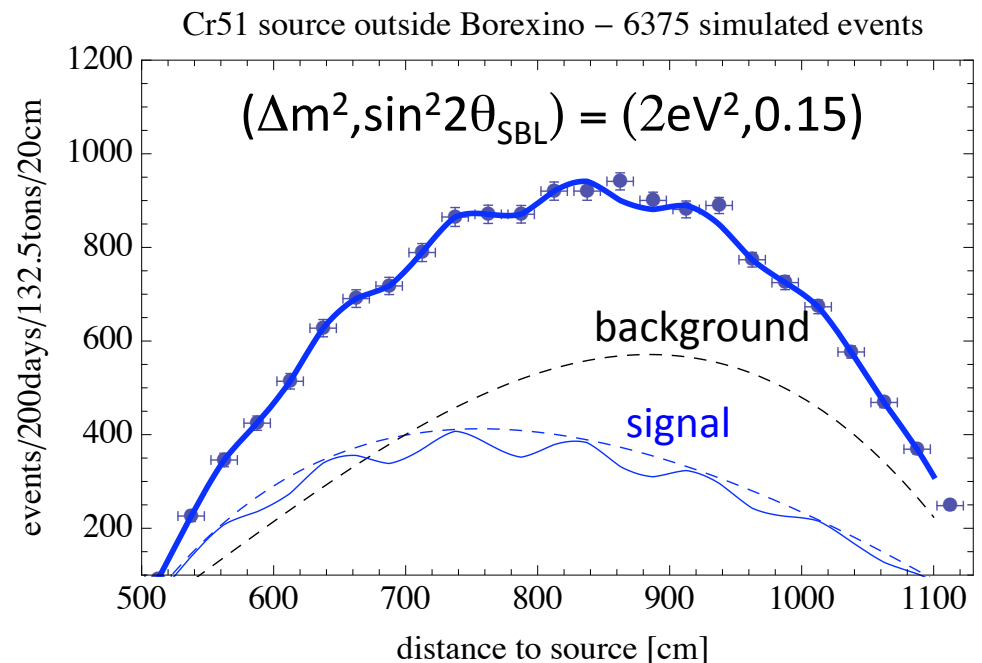
- Procedures to (further!) purify the scintillator underway since July 2010
 - No sign of ^{85}Kr since January
 - Moderate reduction in ^{210}Bi
- Operations continue, with aim of further reducing ^{210}Bi , perhaps ^{210}Po
- Borexino will continue to take data for >3 more years



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

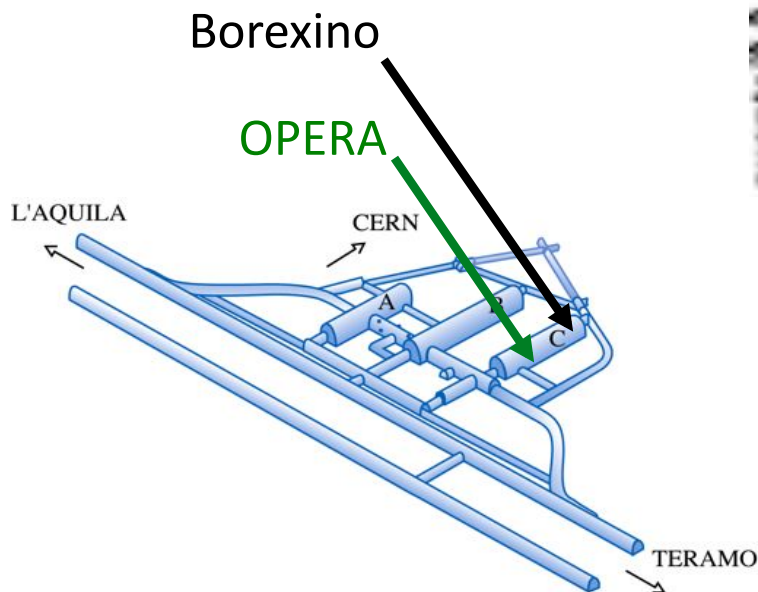
Sterile Neutrino Search

- 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!

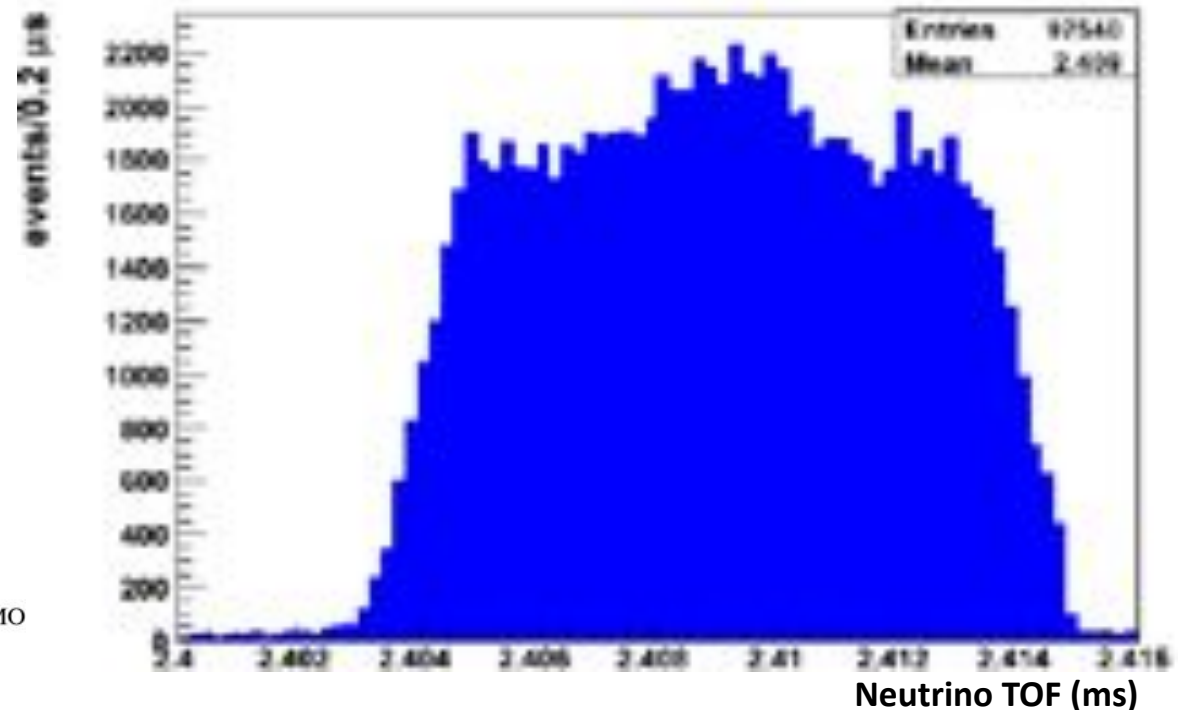


Neutrino Time-Of-Flight

- 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



Time Distribution of CNGS Neutrinos in Borexino



Summary

- Unprecedented radiopurity and new background suppression techniques give Borexino unique capability
 - Precision measurement of the ${}^7\text{Be}$ 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!

