# Precision Measurement of the Beryllium-7 ν's with the Borexino Detector

## First results of the Annual Flux Modulation

Szymon Manecki, VirginiaTech
on behalf of the
Borexino Collaboration

# Borexino Results

- pep & CNO limit : Phys. Rev. Lett. 108 (2012) 051302.
- $^{8}$B > 3 MeV: Phys. Rev. D 82 (2010) 033006.
- Geo-neutrinos: Phys. Lett. B 687 (2010) 299-304.
- $^{7}$Be @ 17%: C. Arpesella at al. (Borexino collaboration).
- $^{7}$Be @ 10%: Phys. Rev. Lett. 101 (2008) 091302.
- $^{7}$Be @ 5%: Phys. Rev. Lett. 107 (2011) 141302.
- $^{7}$Be $A_{dn}$: Physics Letters B 707 (2012) 22-26.
- $^{7}$Be Annual Flux Modulation (in preparation).

pep & CNO: Moriond '12

New geo-results [1]coming soon!

[1]Neutrino Telescopes, Venezia, Mar 11, 2013

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$^{7}$Be Flux Measurement

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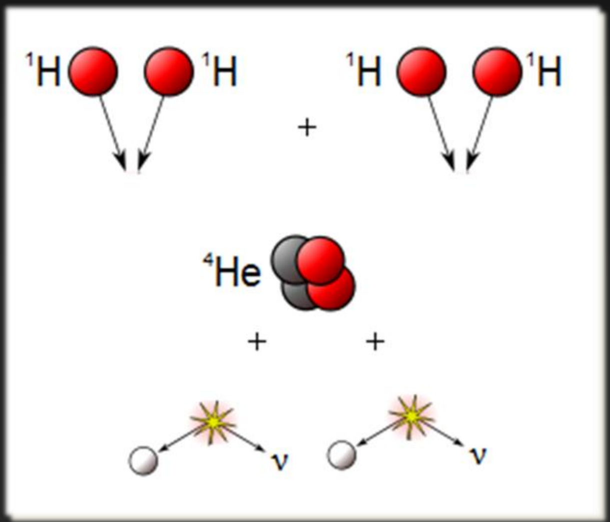
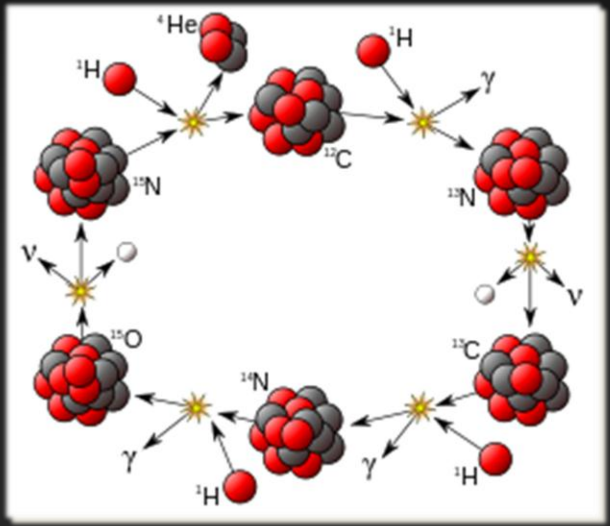
# Solar Physics

Energy production in the Sun:




Density ~146 g/cm$^3$
Temp. ~15.5 mln K




pp chain→ 99% of energy in the Sun

Each complete pp cycle releases about 26.73 MeV

After only 8mins. Solar-ν to reach Earth

CNO cycle→ minor contribution (<1%)

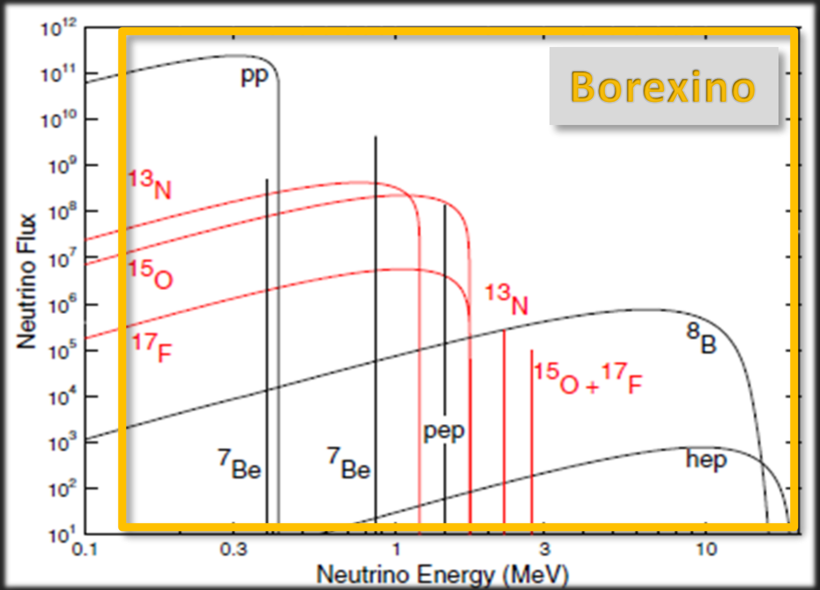
Dominant only in stars of much larger mass

# Solar Physics

Solar-ν spectrum is a combination of continuous and monochromatic lines, depending on whether it is a two- or three- body process, for instance:

$p + p \rightarrow {}^2H + e^+ + \nu_e$ — pp — Continunous

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$ — ${}^7Be$ — Monochromatic



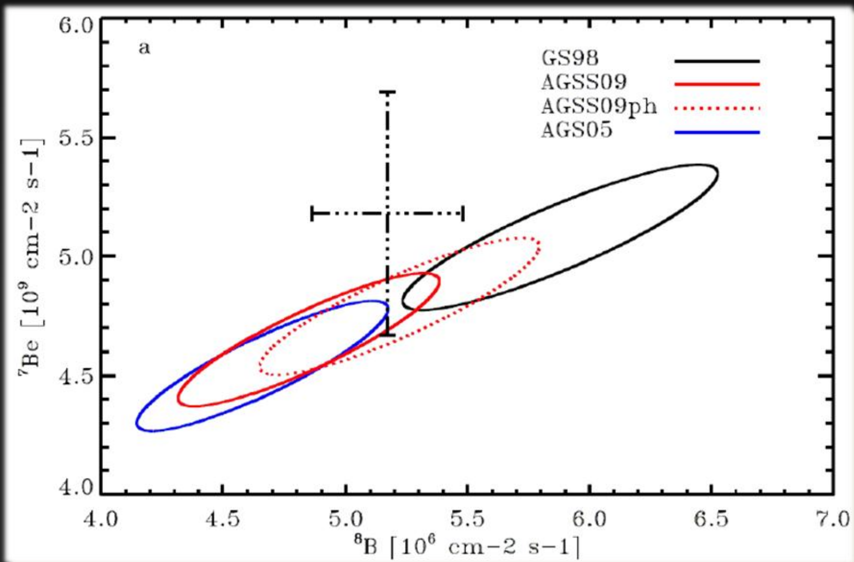

Prediction from SSM (2008):

- pp ±0.5%
- ${}^7$Be ±5.8%
- pep ±1.1%
- ${}^8$B ±11.3% (!)
- hep ±15.5% (!)

- CNO overall ±15.5 to 20.0% (Fluxes strongly dependent on the metallicity models of the Sun.)

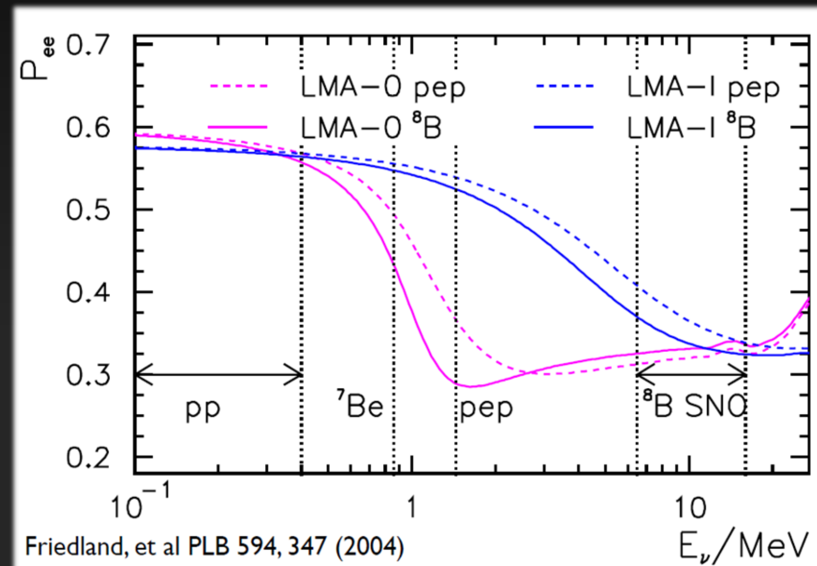
# Motivation

## Solar Physics




- Solar abundance problem: Neither of the models give the answer.
- Verification of the Luminosity constr-aint ($L_\gamma/L_\nu = 1$)
- Solar origin of neutrinos confirmed with the annual modulation check

## Solar-ν Physics




- Study of the $\nu_e$ survival probability: In high-E, dominated by MSW eff.
- Recombination in Earth probed with the Day-Night asymmetry study
- Vacuum vs MSW oscillation verified with the annual modulation pattern

# Borexino Collaboration

Princeton University

VirginiaTech 1872 Invent the Future

JINR 1956-2006 DUBNA

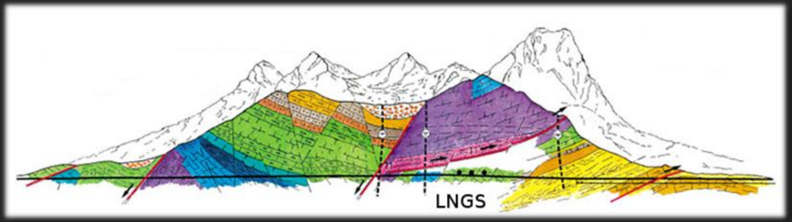
Max-Planck-Institut für Kernphysik

INFN

# Borexino Location

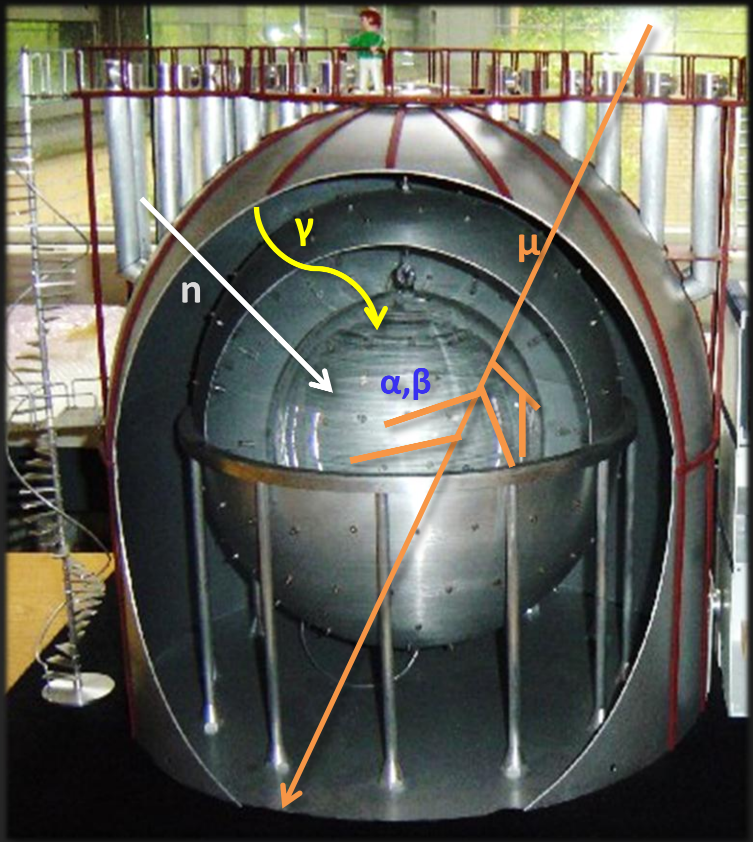
## LNGS

The Borexino experiment is located in the national park of Gran-Sasso as part of the national research facility .


Natural coverage by the  Gran-Sasso mountains provides the required shielding from the Cosimc rays.

# Borexino Detector




- 3600 m.w.e of rock (μ)
- Cherenkov water detector
- Inner PMTs (Rn emanation)
- Quenched scintillator
- Active scintillator
- Fiducial mass (γ)
- Fast neutrons

| Background | Typical abundance | Goal | Measured |
|---|---|---|---|
| $^{238}U$ | 2 x$10^{-5}$ (dust) g/g | $10^{-16}$ g/g | (1.6 $\pm$ 0.1) x $10^{-17}$ g/g |
| $^{232}Th$ | 2 x $10^{-5}$ (dust) g/g | $10^{-16}$ g/g | (5 $\pm$ 1) x $10^{-18}$ g/g |

# Detector Calibration

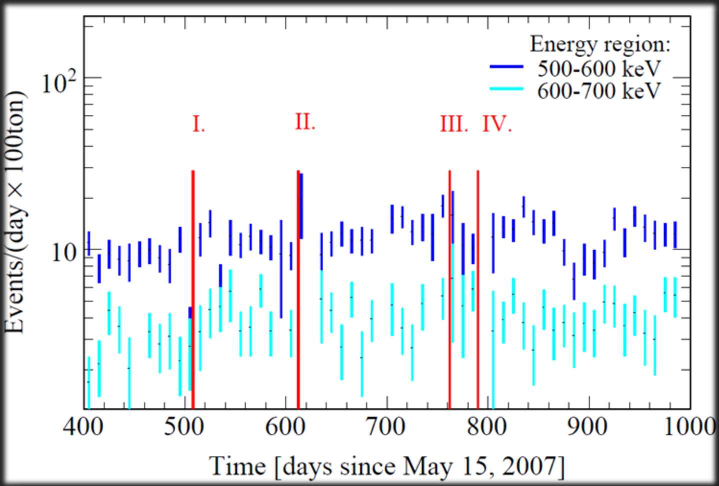
arXiv:1207.4816v1

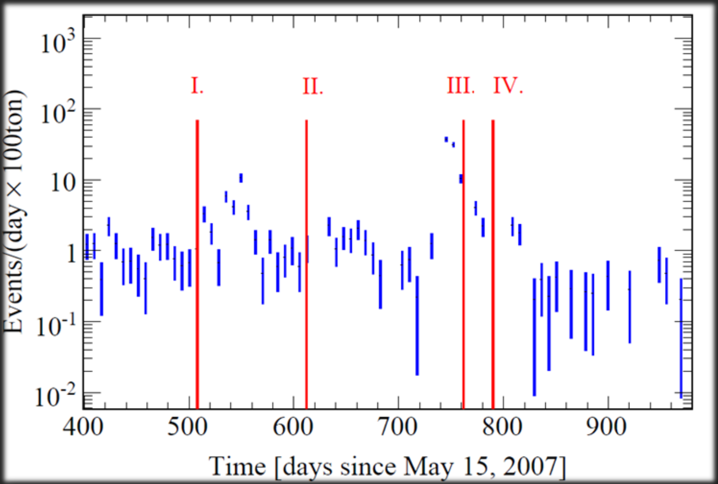
# Detector Calibration

Radio-purity

Constraints

- The purity of the scintillator must be preserved (U/Th at $10^{-17}$g/g)
- No external light leakage allowed
- Work in a pressurized environment
- No physical contact with the 125µm thin nylon vessel



# Detector Calibration

## Radio-purity

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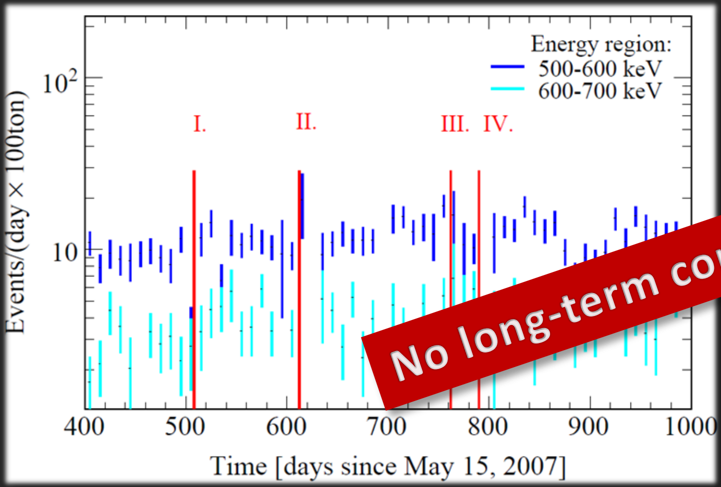
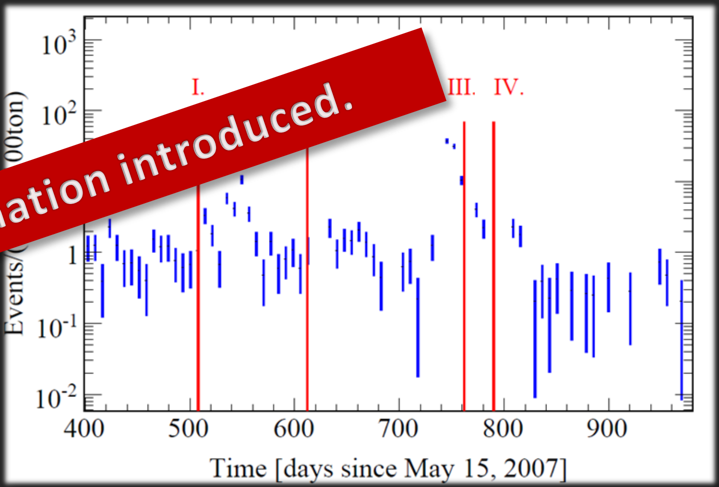



No long-term contamination introduced.

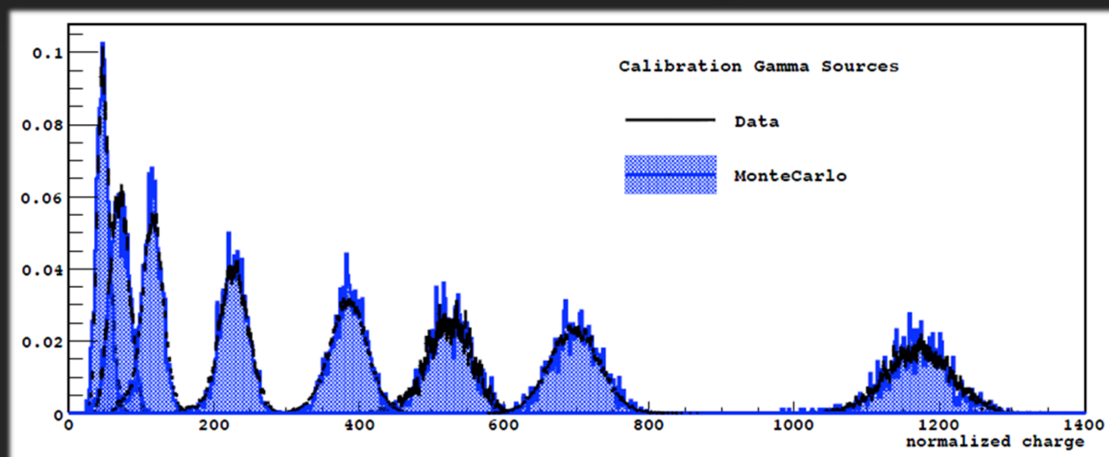
# Detector Calibration

## Results

| Type | γ | | | | | | | | β | | α | n | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Src. | $^{57}Co$ | $^{139}Ce$ | $^{203}Hg$ | $^{85}Sr$ | $^{54}Mn$ | $^{65}Zn$ | $^{60}Co$ | $^{40}K$ | $^{14}C$ | $^{214}Bi$ | $^{214}Po$ | n-p | n-$^{12}C$ | n-Fe |
| MeV | 0.122 | 0.165 | 0.279 | 0.514 | 0.834 | 1.1 | 1.1, 1.3 | 1.4 | 0.15 | 3.2 | 7.69 (0.84) | 2.23 | 4.94 | ~7.5 |

| Systematics | | |
|---|---|---|
| Livetime | 0.1% | 0.04% |
| Scintillator ρ | 0.2% | 0.05% |
| Event Selection Loss | 0.3% | 0.1% |
| Position Reconstruction | 6.0% | +1.3%/ -0.5% |
| Energy Scale | 6.0% | 2.7% |
| TOTAL | 8.5% | +3.6%/ -3.4% |

Monte-Carlo Tuning

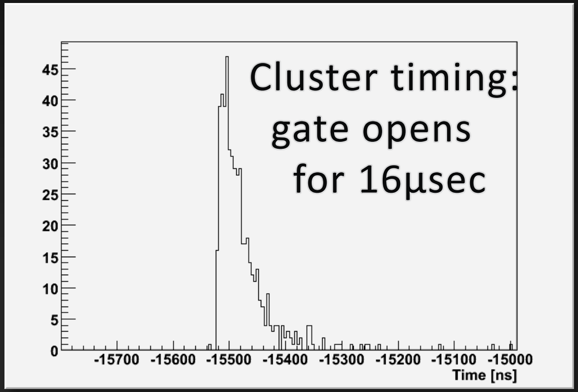



Energy and Position resolution at 1 MeV:
5% [energy]; ~10-15cm [position]

# Borexino Signal

# Borexino Signal

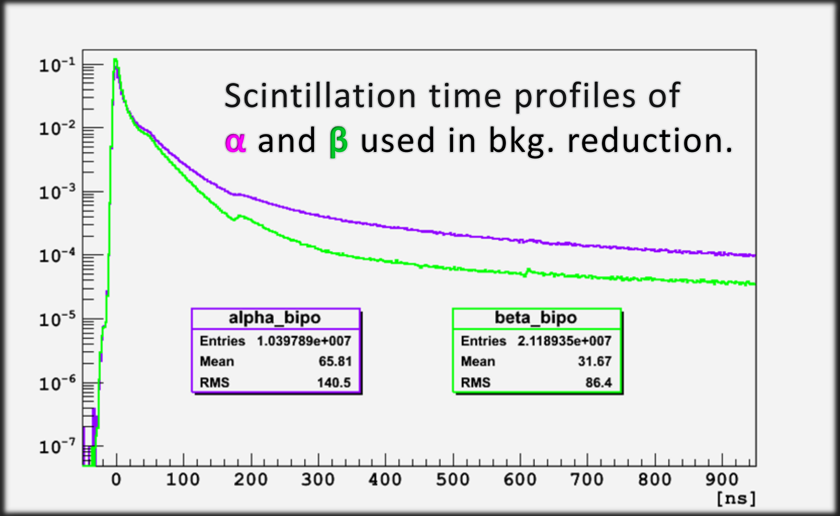
- PMTs receive scintillation light from scattered electrons and γ particles
- DAQ triggers when 25 PMTs receive signal within 60ns

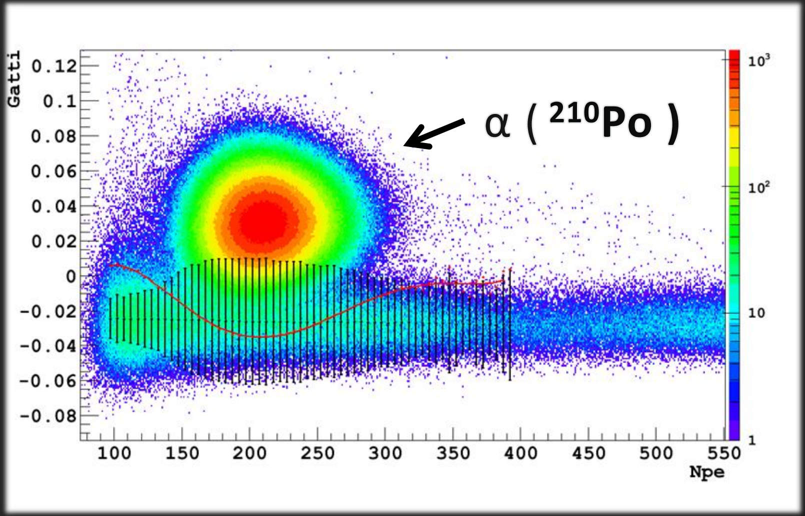



PMT time-of-flight distribution used for position reconstruction

Number of hits, or charge used for energy determination

Light yield: (500±12) p.e./MeV

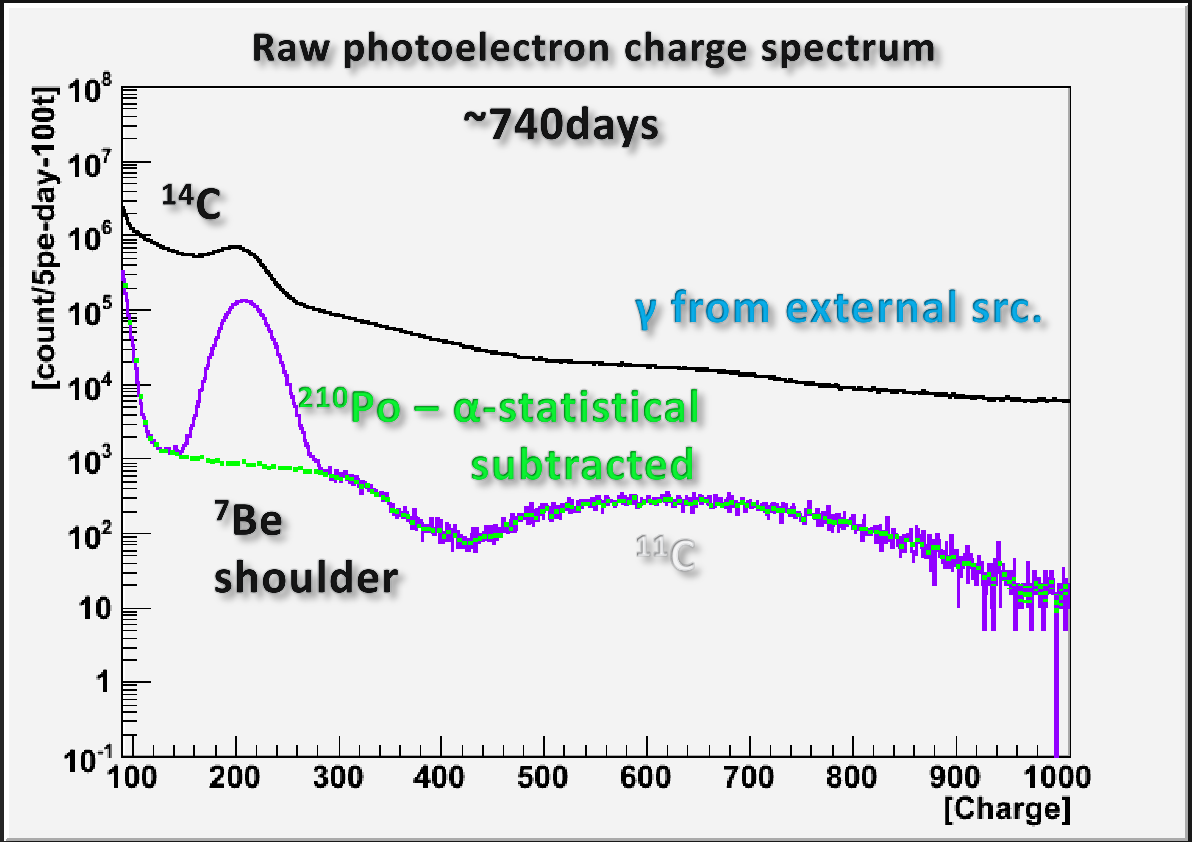


# Beryllium-7
# Flux Measurement

# $^{7}$Be Flux

## Selection of events




Major cuts :

1) Muons, and fast cosmogenics,

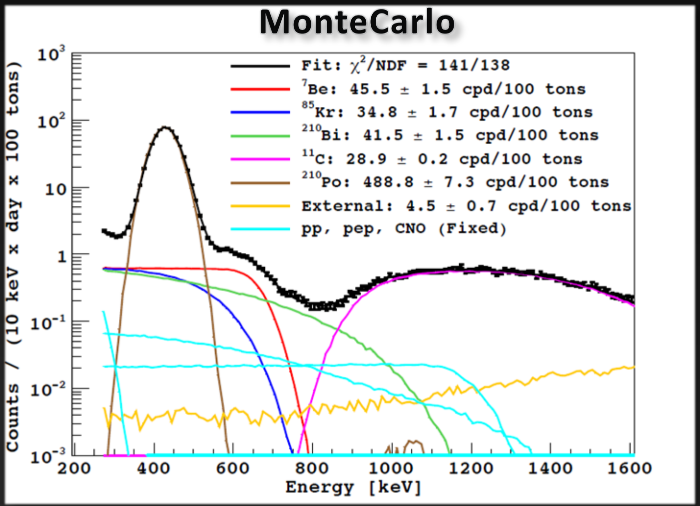
   Electronics noise

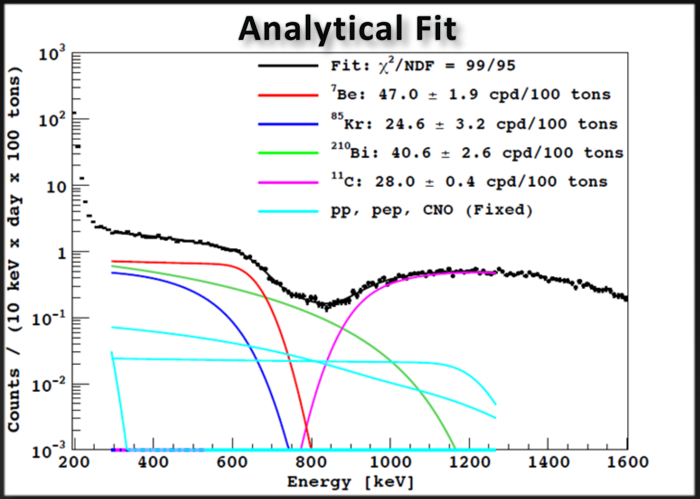
2) Fiducial Volume 1/3 active mass

3) α- subtraction (Gatti parameter)

# $^7$Be Flux

## Spectral Fit Results




SSM w/ no oscillations, HMetallicity
$74 \pm 5_{theor}$

**Measured Rate:**
$^7$Be: $46.0 \pm 1.5_{stat}{}^{+1.6}_{-1.5\,sys}$ cpd/100t

No oscillation excluded at 5σ

**MSW-LMA Prediction**

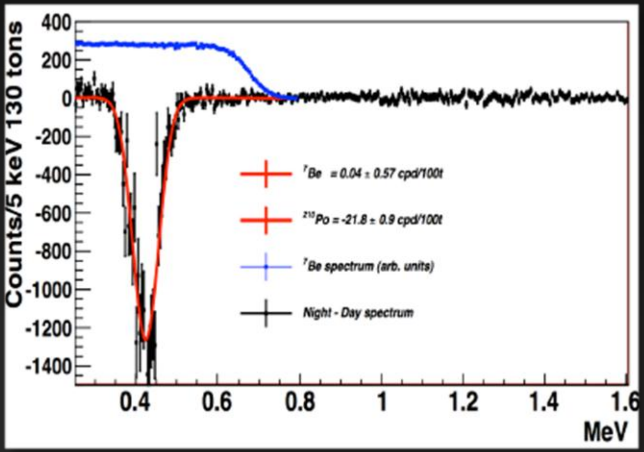
$47.2 \pm 3.4$

**MSW-LMA scenario:**
$\Phi(^7Be) = (4.87 \pm 0.24) \times 10^9$ /cm$^2$/sec
$f_{Be} = 0.97 \pm 0.05_{stat} \pm 0.07_{syst}$

# Beryllium-7
# Day-Night Asymmetry

# Day-Night Asymmetry

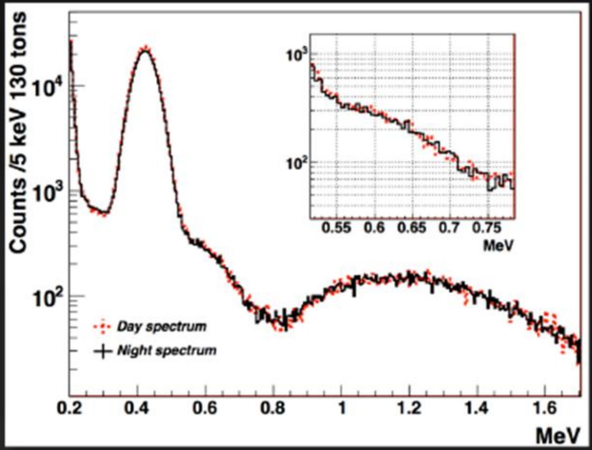
Searching for increased count rate during the day




$A_{nd}$ = 0.007 ± 0.073$_{stat}$

No asymmetry observed

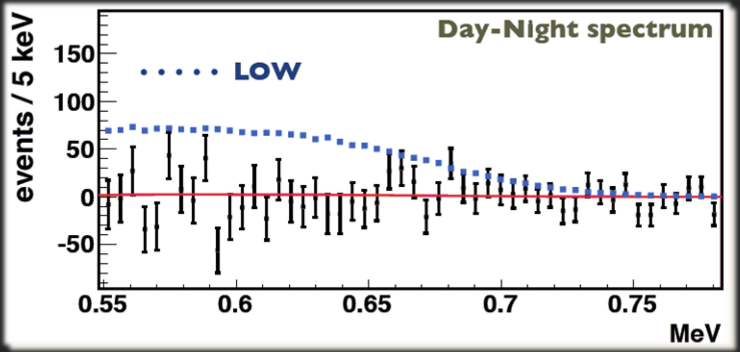
$$A_{dn} = 2 \times \frac{R_N - R_D}{R_N + R_D}$$




$A_{nd}$ = 0.001 ± 0.012$_{stat}$ ± 0.007$_{sys}$

LOW

11% - 80% =




LMA

= < 0.1%

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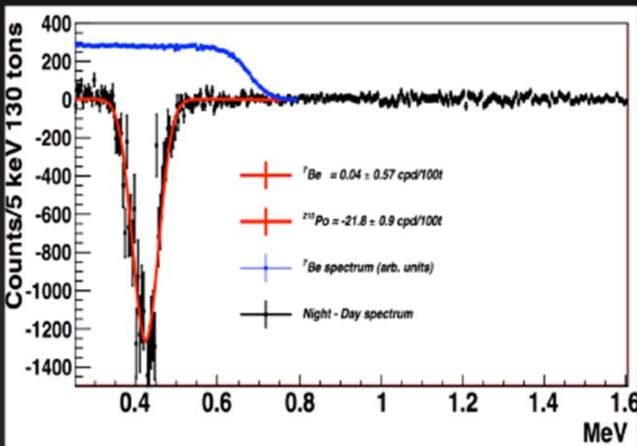


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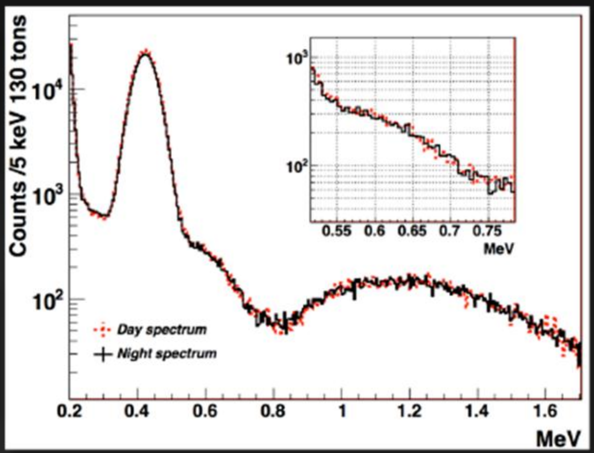
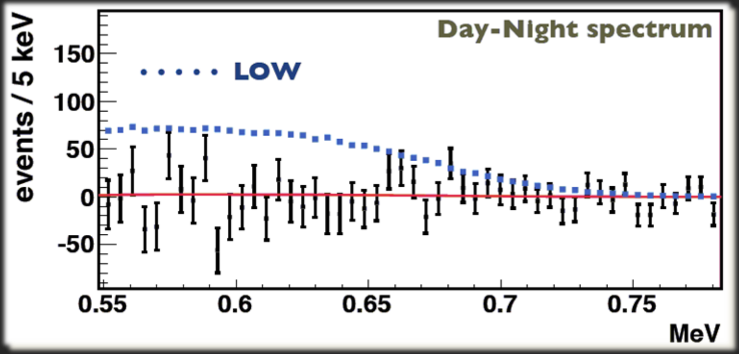



$A_{nd}$ = 0.001 ± 0.012$_{stat}$ ± 0.007$_{sys}$

LOW

11% - 80% =

REJECTED



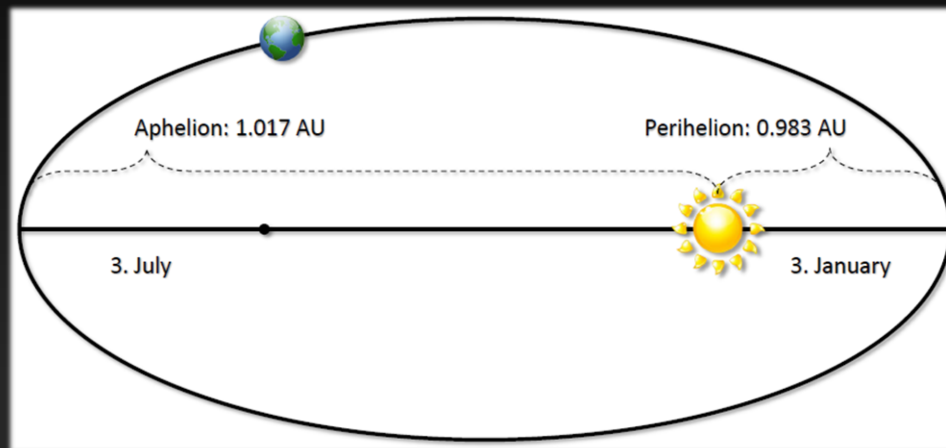

LMA

= < 0.1%

# Beryllium-7
# Annual Modulation

# Annual Modulation

Min Flux:
Jul. 3rd




Max Flux:
Jan. 3rd

An ellipse of (current)

$\varepsilon$ = 0.0167

$$r(\theta) = \frac{\beta}{1 - \epsilon \sin(\theta - \theta_0)};$$

"Normal" oscillations:

MSW : ~1/r²

"Anomalous" oscillations:

Vacuum : ~~~1/r²~~

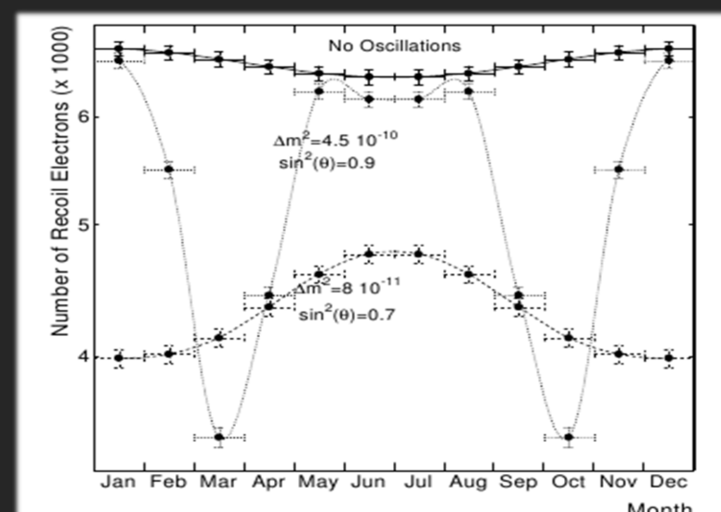



Figure from: PRD, Vol. 60, 093011

# Before Borexino

2004

**Super-Kamiokande ($^8B$):**

$\varepsilon$ = 0.0252±0.0072

$\varphi_0$ = 13±18 days

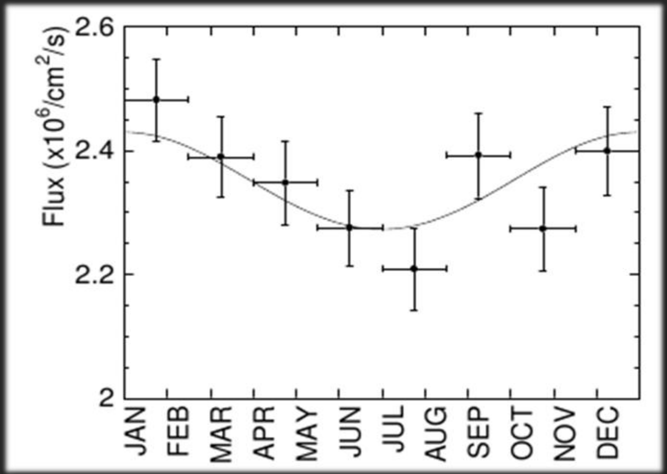
- SK-I (low energy data)
  1496 live days
- $T_{eff}$ > 5 MeV

2005

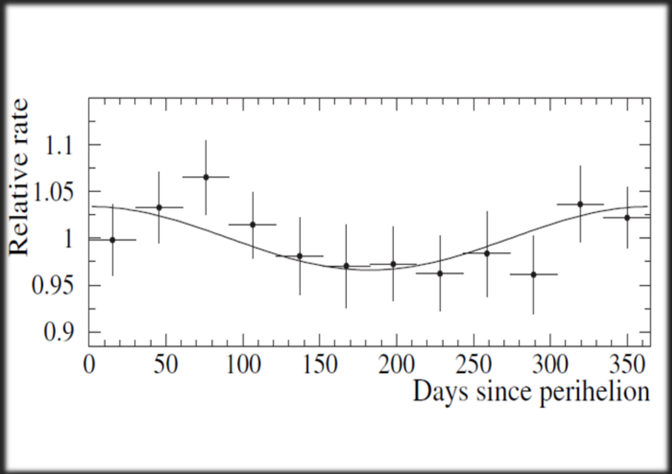
**SNO Collaboration ($^8B$):**

$\varepsilon$ = 0.0143±0.0086

- $D_2O$ + Salt Phase
  312.9 + 398.6 live days
- $T_{eff}$ > 5 $MeV_{(D2O)}$ or
  $T_{eff}$ > 5.5 $MeV_{(salt)}$



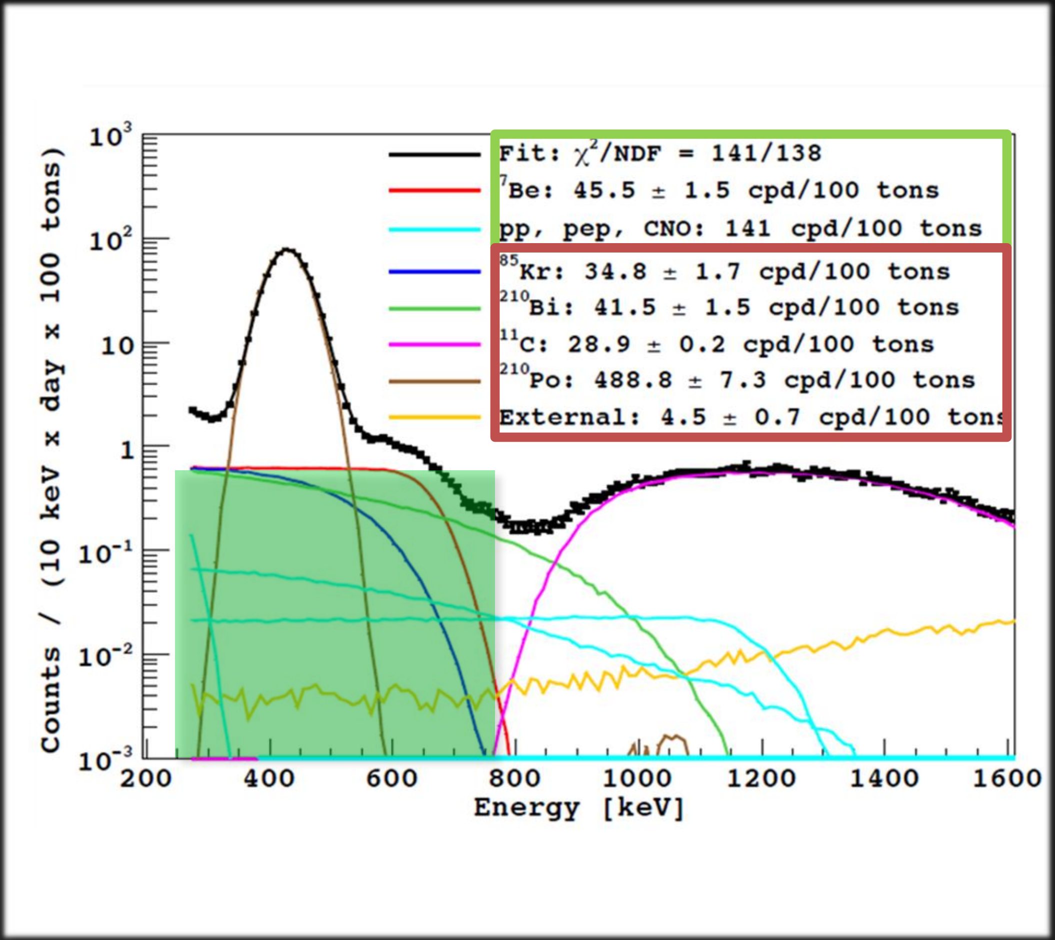

PRD, Vol. 69, 011104(R)




PRD, Vol. 72, 052010

# Borexino Spectrum

No spectral shape for the Signal/Background identification




**SIGNAL**

- [210; 760] keV
- I.2008 – V.2010

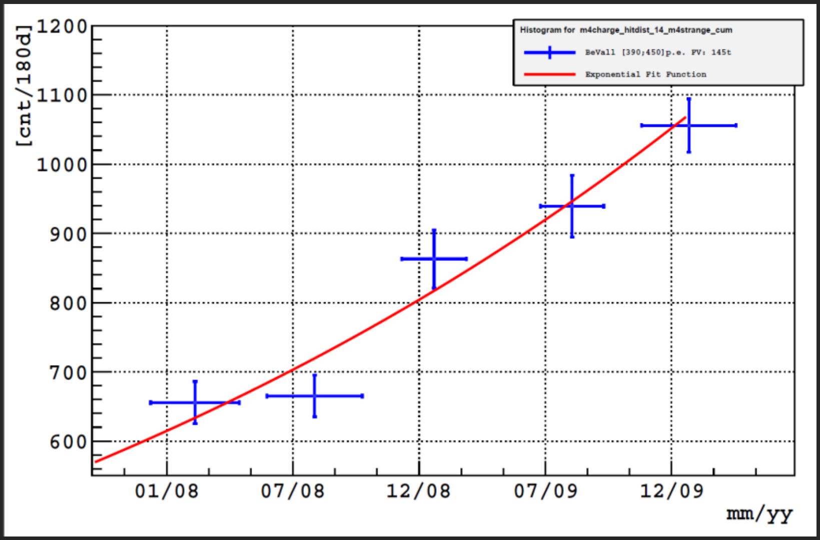
**BACKGROUNDS**

- Irreducible:
  $^{210}$Bi ($\beta^-$ $Q_{keV}$ =1162.1)
  ~40 cpd/100t
  $^{85}$Kr ($\beta^-$ $Q_{keV}$ =687.1)
  ~30 cpd/100t
- Reducible:
  $^{210}$Po (+ Gatti)
  Ext_ γ (FV cut)

# Borexino Data

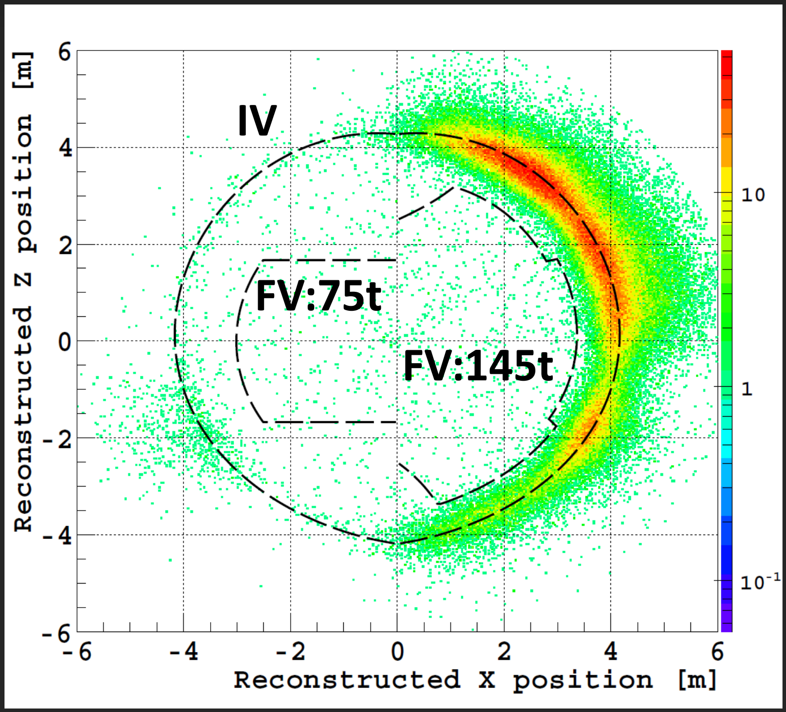
**Building up $^{210}Bi$:**

- Definite origin remains unknown ( possible release from the IV ),
- Spectral shape and count-rate almost identical with $^{7}Be$-ν,
- Impossible to eliminate with any of the software cuts,
- Reduced during the purification.




**IV dependent Ext_ γ:**

- Choice of a dynamic Fiducial Vol. affected by the Ext_ Gamma's,
- Spatial cut defined using Ext_ source calibration data.



# Phase I Sensitivity

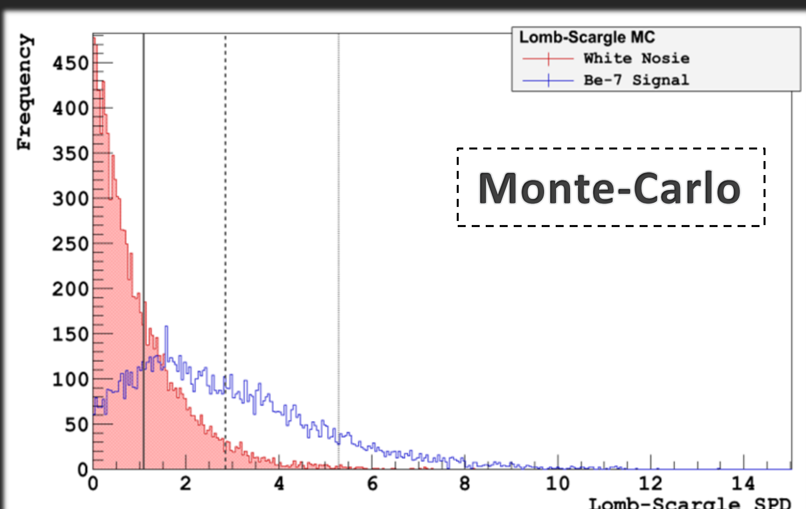
## Lomb-Scargle

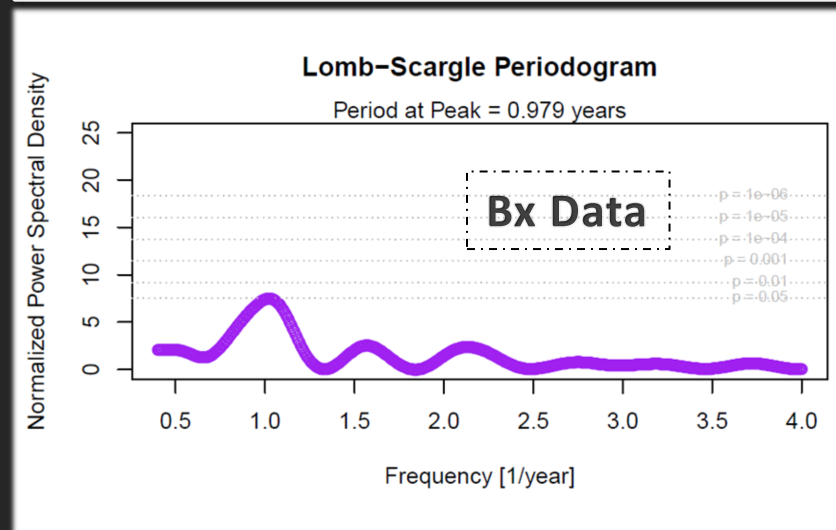
$$SPD() = \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_j (X_j-\bar{X})\cos\omega(t_j-\tau)\right]^2}{\sum_j \cos^2\omega(t_j-\tau)} + \frac{\left[\sum_j (X_j-\bar{X})\sin\omega(t_j-\tau)\right]^2}{\sum_j \sin^2\omega(t_j-\tau)}\right\};$$

$$\sigma^2 = \frac{1}{N-1}\sum_{j=1}^{N}(X_j-\bar{X})^2;\ \tan 2\omega\tau = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}.$$

Monte-Carlo simulation of the solar flux annual modulation:

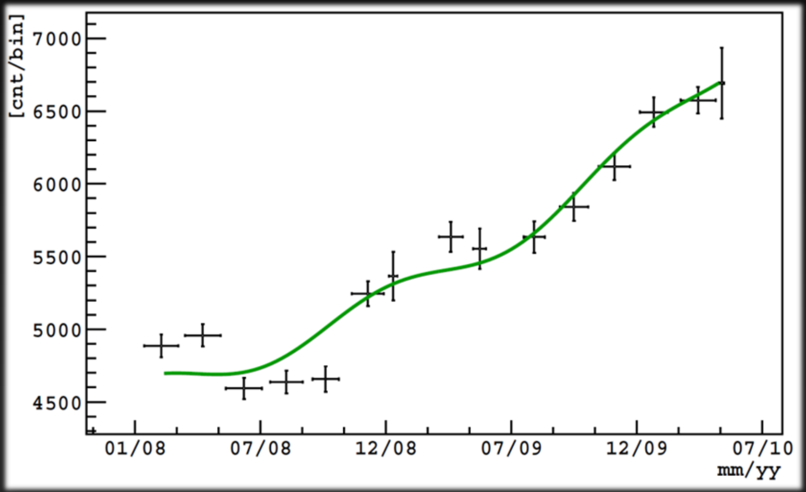
- Signal and backgrounds assumed as in the data
- $10^4$ simulations, for each calculate LS SPD at 1 year and plot Signal (Blue) & Background (Red)

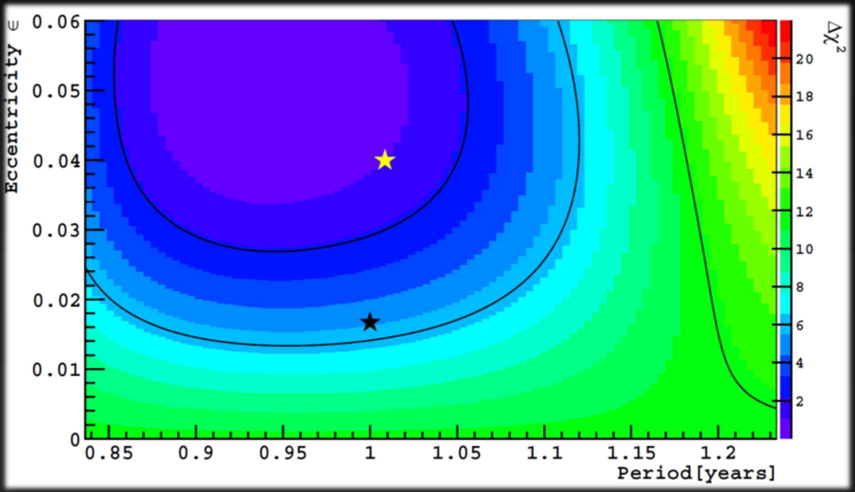


# Phase I Results

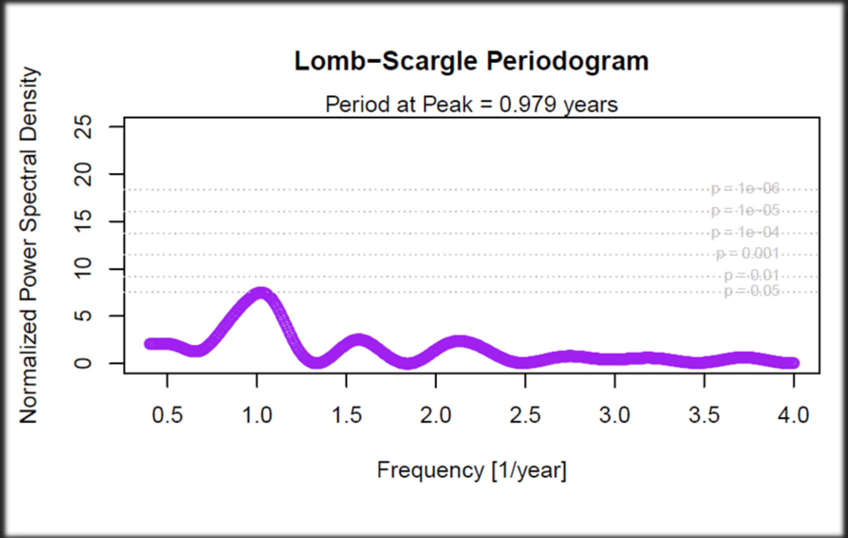
$X^2$ Sin Fit



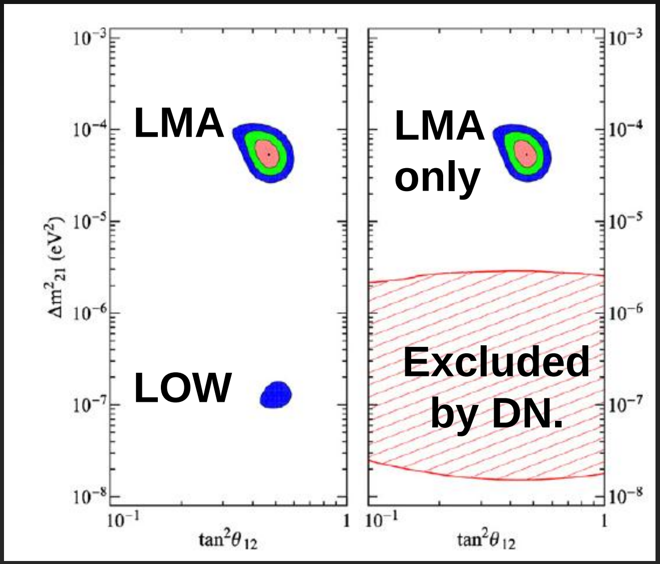

Annual amplitude modulation results with Borexino:

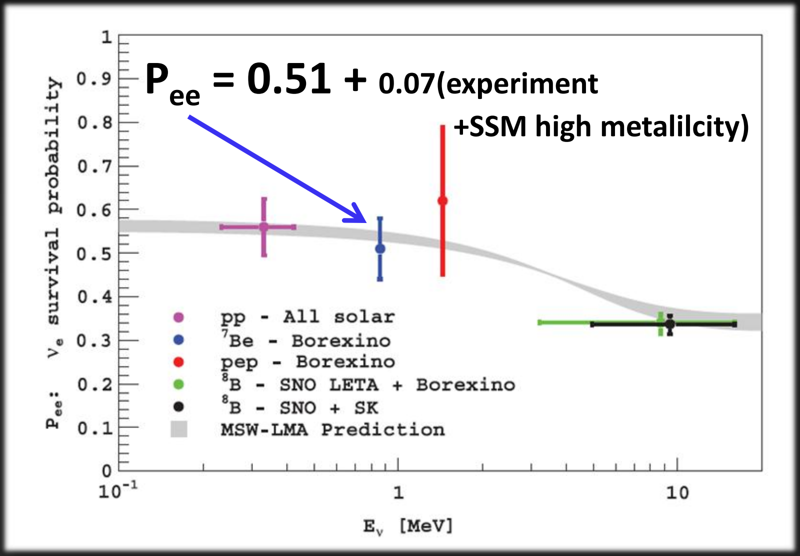
- Lomb-Scargle:
  T = 0.979 y
- Fit:
  ε = 0.0398±0.0102(within 2σ)
  T= 1.01±0.07 y



# Impact of the Results

- Clear agreement with the MSW-LMA solution ($A_{ND}$ and Flux)

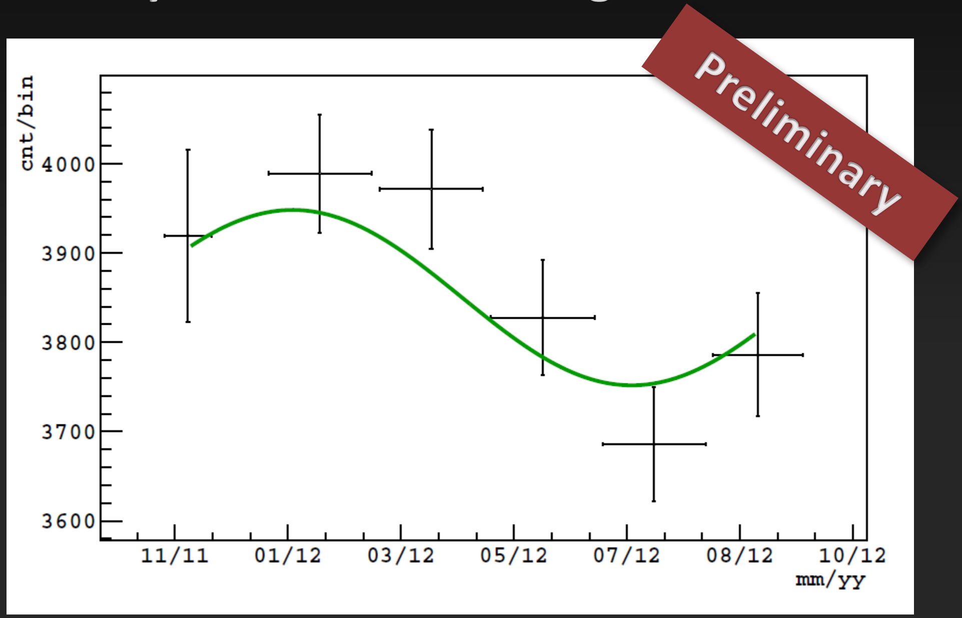



- From the annual flux modulation study, no indication of anomalous oscillation pattern (in agreement with the MSW-LMA scenario)
- Within error bars, both High- and Low-Metallicity Models are in agreement with the Borexino data.

# Near Future

- Entering Phase II with remarkably low internal backgrounds
  - $^{85}$Kr
    < 8.8 cpd / 100 t
    2007-2010: 31.2 ± 5
  - $^{210}$Bi
    16 ± 4 cpd / 100 t
    2007-2010: 41.0 ± 2.8
  - $^{238}$U
    < 9.7 $10^{-19}$ g/g
  - $^{232}$Th
    < 2.9 $10^{-18}$ g/g




- Preparations for sterile neutrino search are advancing (R&D)

  $^{51}$Cr (external) neutrino source: 5-10 MCi
  - During Phase 2

  $^{144}$Ce (internal) anti-neutrino source: 50-100 kCi
  - After the solar neutrino physics

# La Fine

Astroparticle and Cosmology Laboratory – Paris, France

INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy

INFN e Dipartimento di Fisica dell'Università – Genova, Italy

INFN e Dipartimento di Fisica dell'Università– Milano, Italy

INFN e Dipartimento di Chimica dell'Università – Perugia, Italy

Institute for Nuclear Research – Gatchina, Russia

Institute of Physics, Jagellonian University – Cracow, Poland

Joint Institute for Nuclear Research – Dubna, Russia

Kurchatov Institute – Moscow, Russia

Max-Planck Institute fuer Kernphysik – Heidelberg, Germany

Princeton University – Princeton, NJ, USA

Technische Universität – Muenchen, Germany

University of Massachusetts at Amherst, MA, USA

University of Moscow – Moscow, Russia

Virginia Tech – Blacksburg, VA, USA


Thank you!

# Backup

# pep and CNO

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

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

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

(…)

p-e-p process,
Mono-E neutrinos E = 1.44 MeV
Low flux (1/400 total solar flux)
1.2% predicted uncertainty

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

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

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

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

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

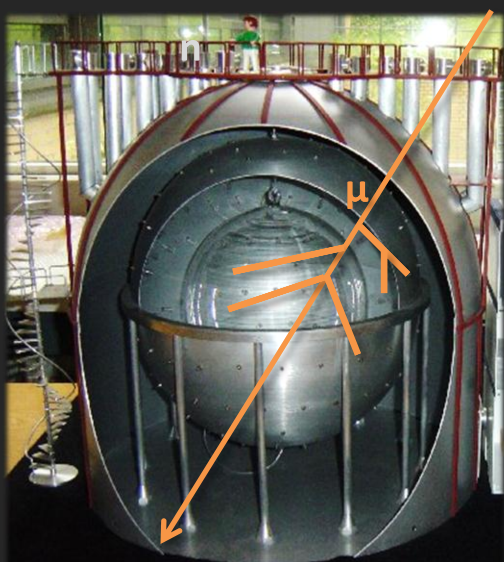
(…)

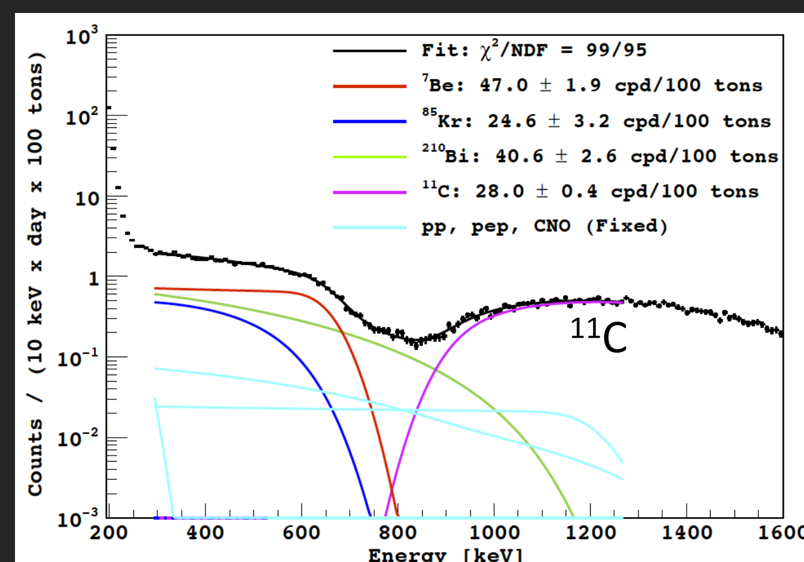
C-N-O cycle
Continuous spectrum Q = 1.74 MeV
Low flux (comparable to pep)
Highly sensitive to metall. models.

# pep and CNO detection

More difficult than $^{7}$Be neutrino detection
Low signal: few events/day/100tons
Dominant background: cosmogenic β+ emitter $^{11}$C
27cpd/100tons → signal/background ~ 0.1

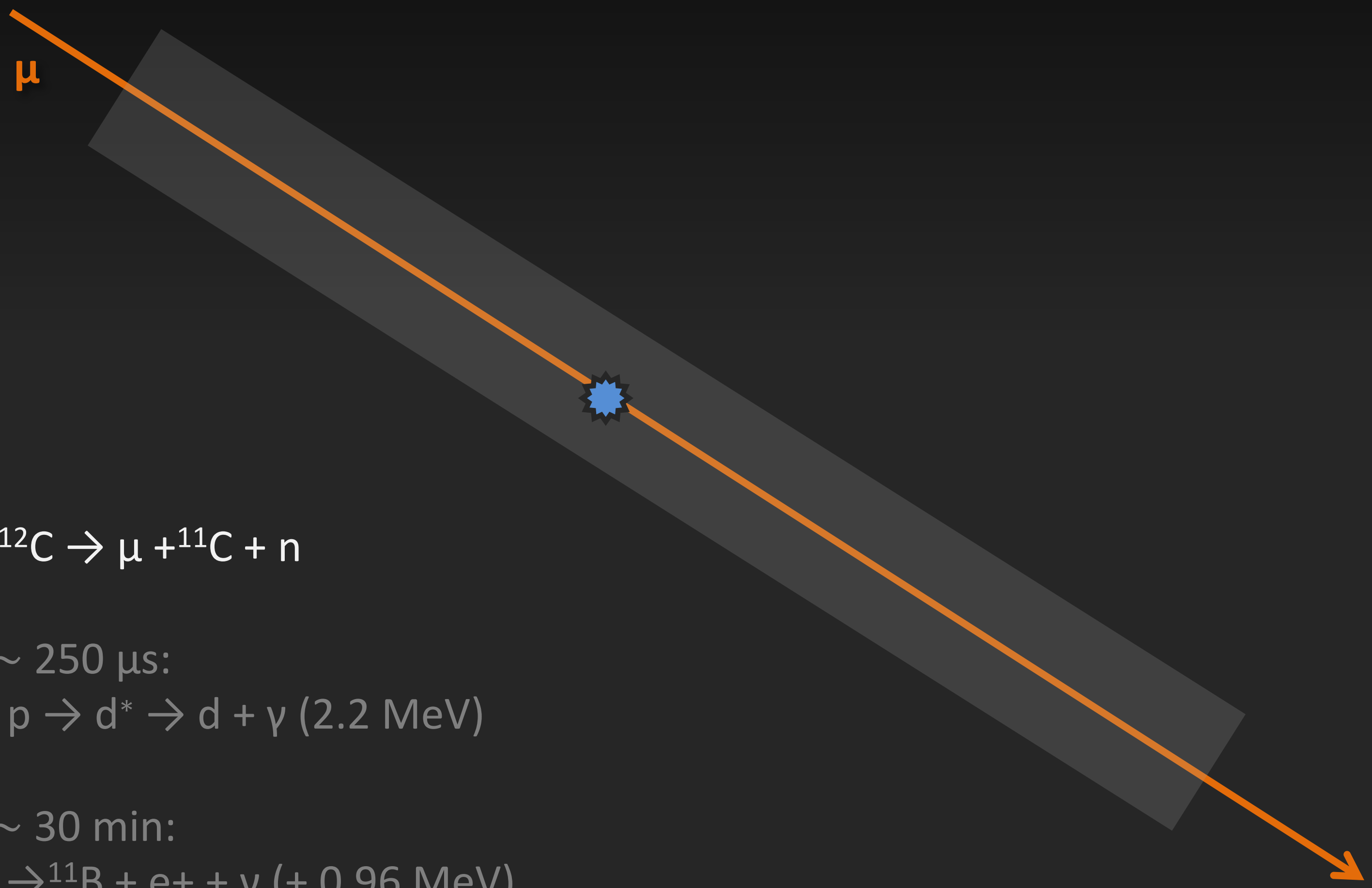
Need novel techniques to suppress $^{11}$C background:
Three Fold Coincidence
$e^{+}/e^{-}$ Pulse Shape Discrimination



# Three-Fold Coincidence

A Cabrdon-11 Veto



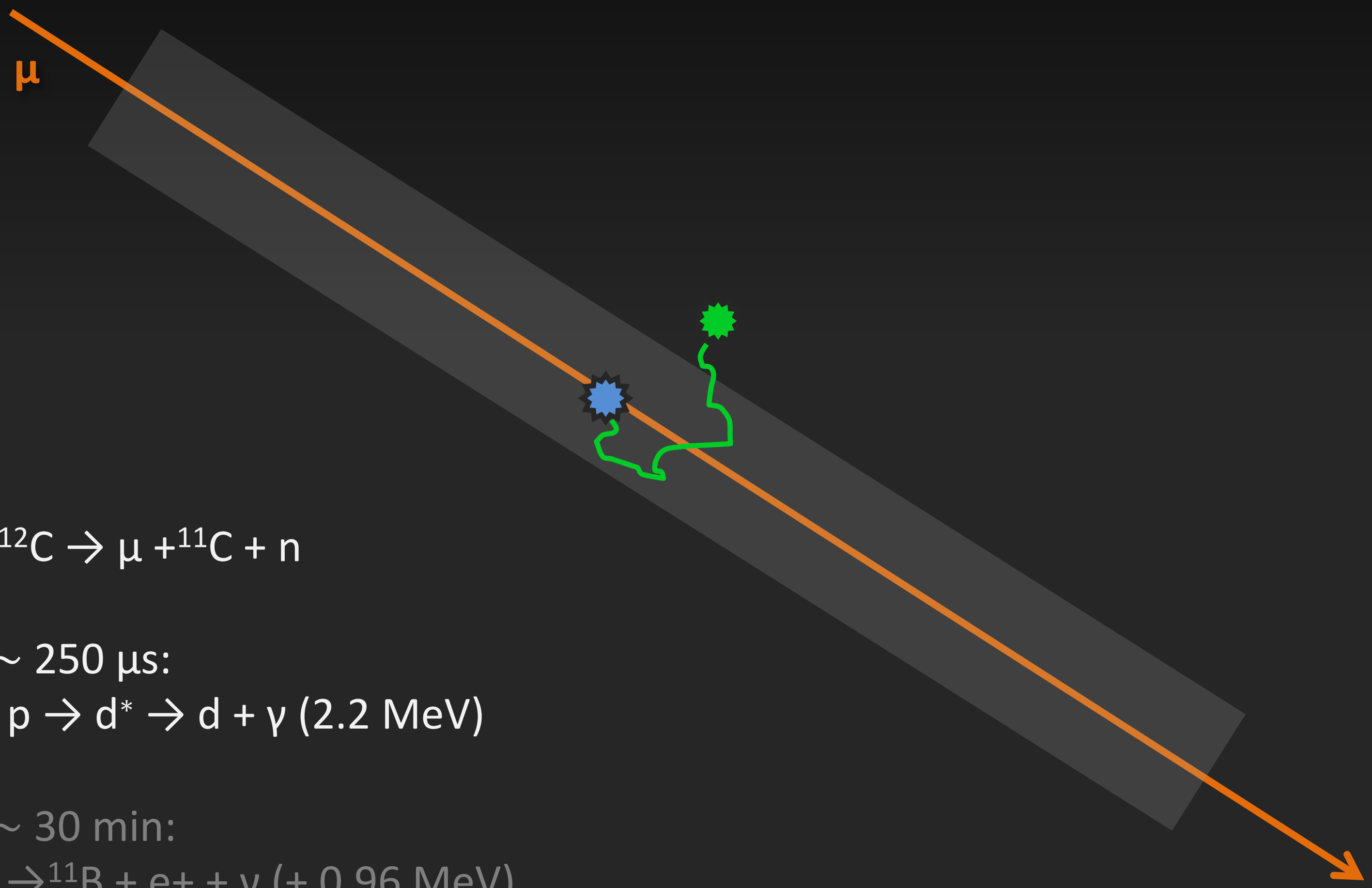

$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$\Delta t \sim 250\ \mu s$:
$n + p \rightarrow d^{*} \rightarrow d + \gamma$ (2.2 MeV)

$\Delta t \sim 30$ min:
${}^{11}C \rightarrow {}^{11}B + e+ + \nu$ (+ 0.96 MeV)

# Three-Fold Coincidence

A Cabrdon-11 Veto

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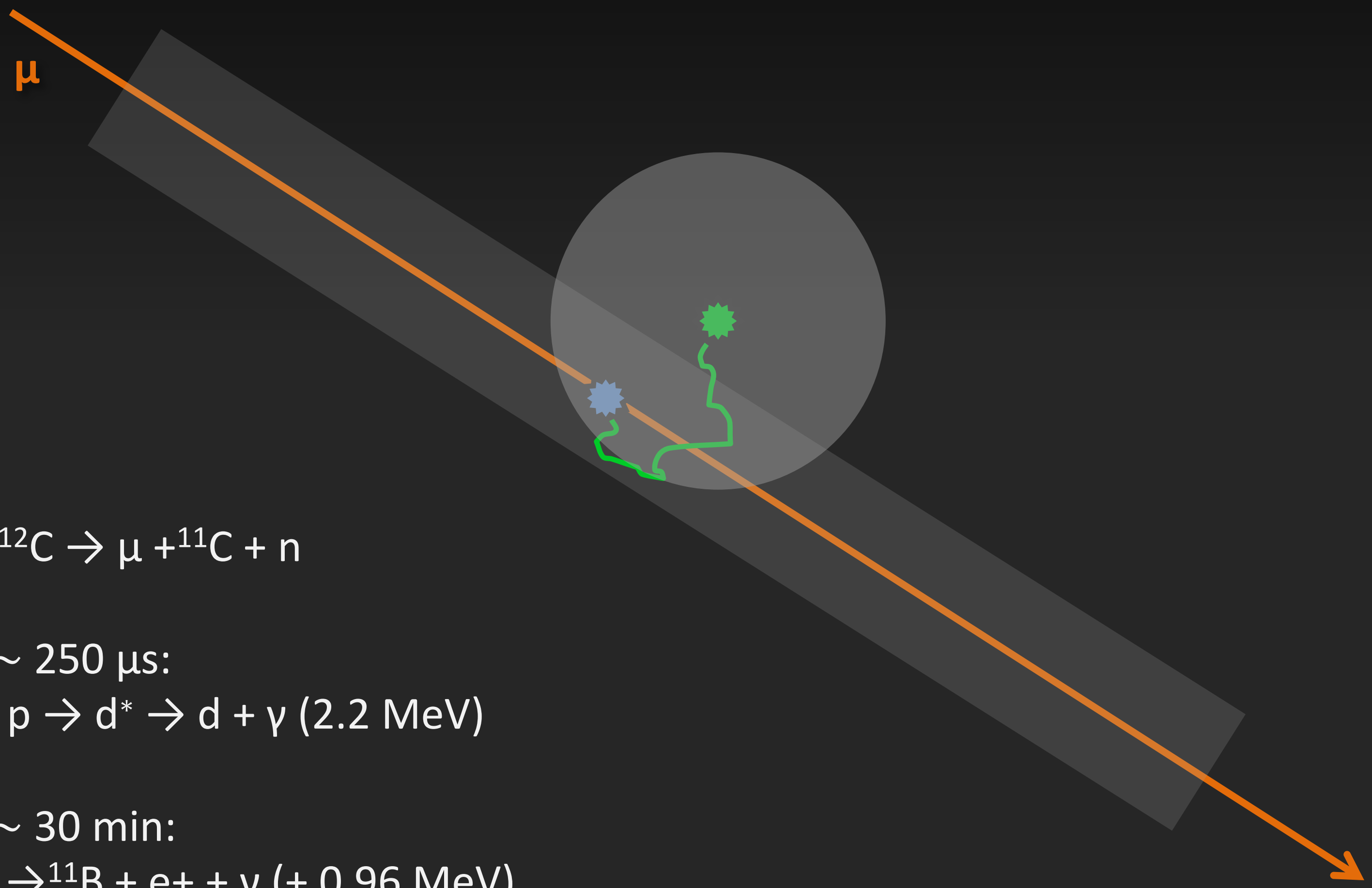



$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$\Delta t \sim 250\ \mu s$:

$n + p \rightarrow d^* \rightarrow d + \gamma\ (2.2\ MeV)$

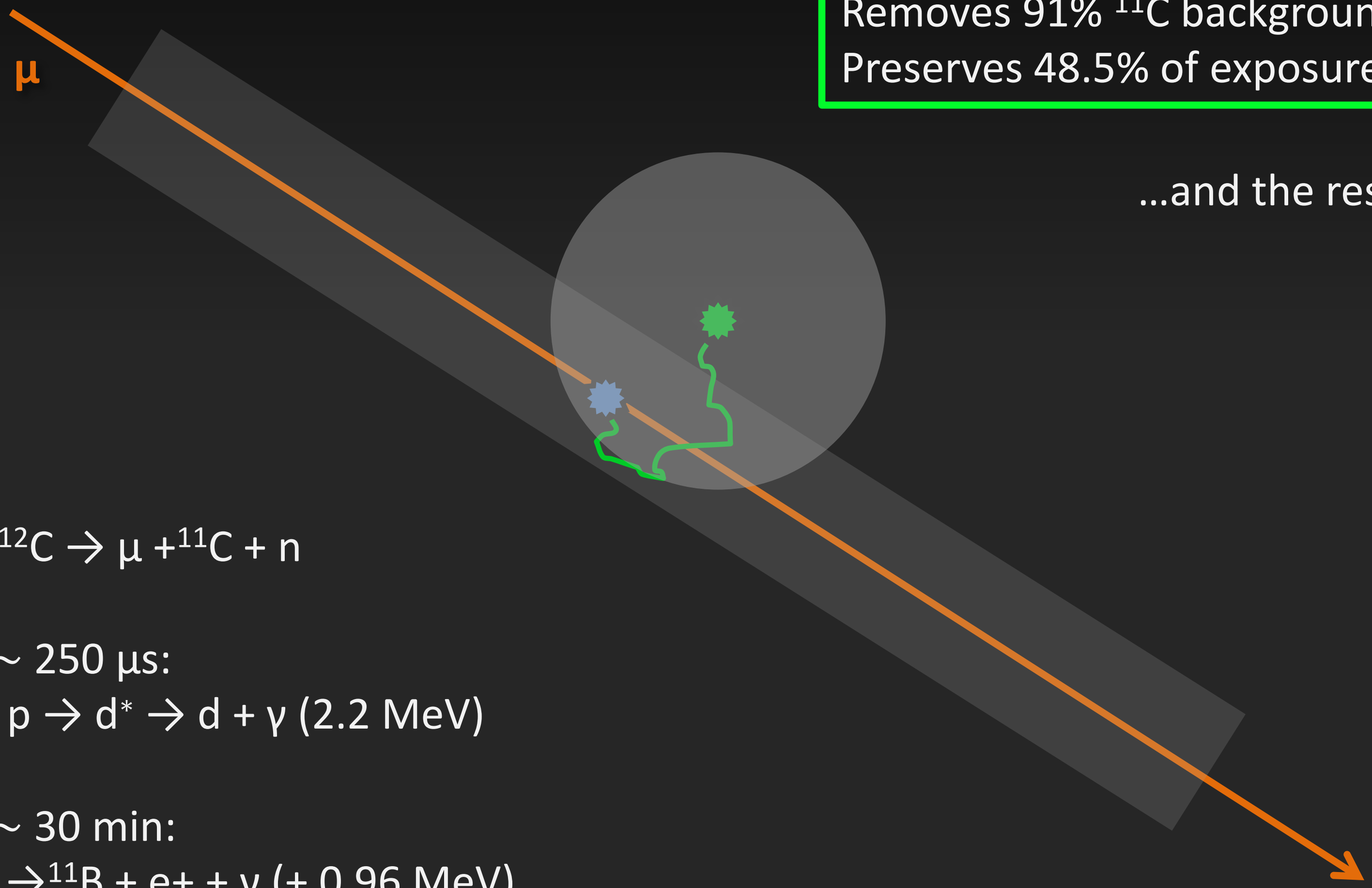
$\Delta t \sim 30$ min:

${}^{11}C \rightarrow {}^{11}B + e+ + \nu\ (+\ 0.96\ MeV)$

# Three-Fold Coincidence

A Cabrdon-11 Veto

Removes 91% $^{11}C$ background
Preserves 48.5% of exposure




...and the rest ?

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

$\Delta t \sim 250\ \mu s$:
$n + p \rightarrow d^* \rightarrow d + \gamma$ (2.2 MeV)

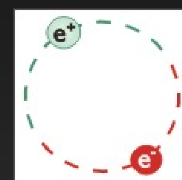
$\Delta t \sim 30$ min:
$^{11}C \rightarrow ^{11}B + e^+ + \nu$ (+ 0.96 MeV)

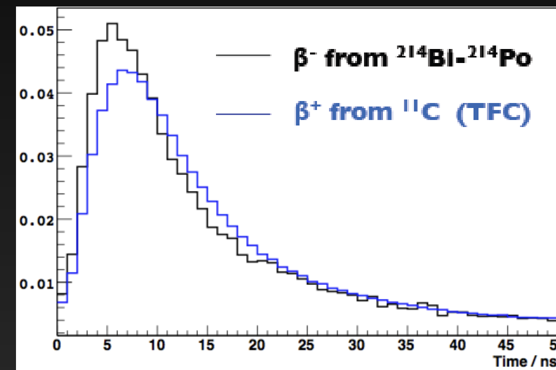
# e+/e- Discrimination

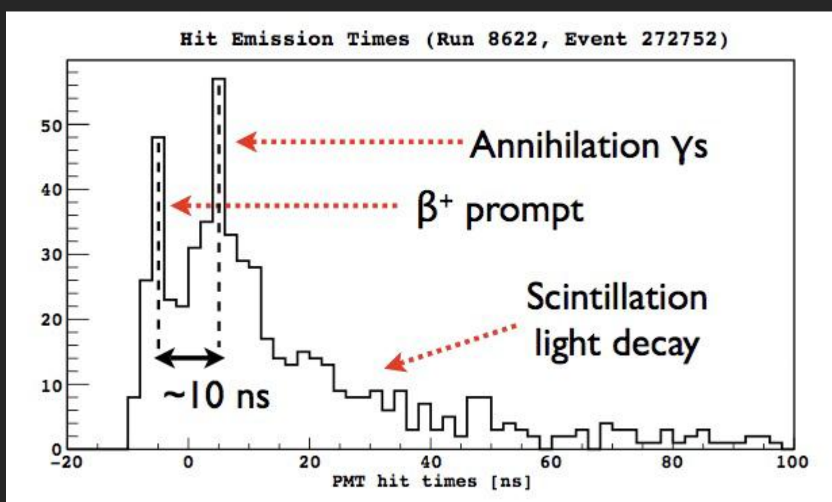
A Cabrdon-11 Veto

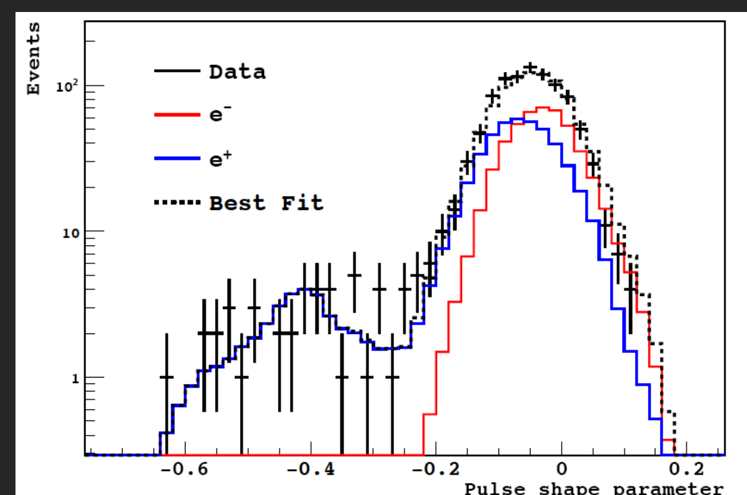
Positrons form ortho-positronium in ~ 50% of cases (in PC)

- Scintillation signal delayed by ~ 3 ns
- Pulse shape is different
- Parameters measured in dedicated experiment



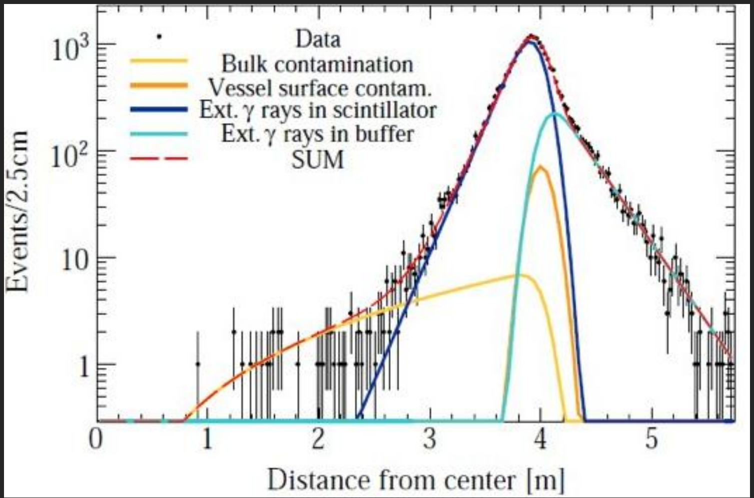
# External Backgrounds

Radioactive decays in peripheral structure: $^{208}Tl$ from PMTs...

- Spatial distribution external bkg → NON homogeneous
- Spatial distribution internal bkg and neutrinos → homogeneous
- Spatial distribution from Monte Carlo simulation and external calibration source ($^{228}Th$)
- Fiducial Volume: minimize γ-rays without sacrifice too many events

Final fit done with multivariate likelihood fit:

- External background identified by means of its spatial distribution
- $^{11}C$ by means of BDT variable
- Energy used to disentangle other β backgrounds ($^{210}Bi$ in particular)



# First detection of pep

Rate: $3.1 \pm 0.6_{stat} \pm 0.3_{sys}$ cpd/100 t

No oscillations excluded at 97% c.l.

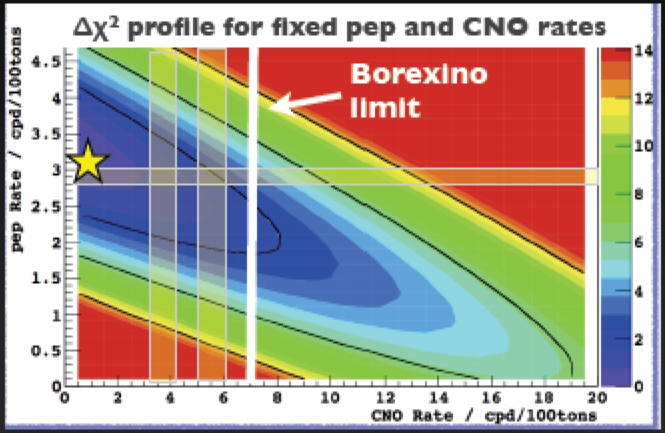
Absence of pep solar ν excluded at 98%

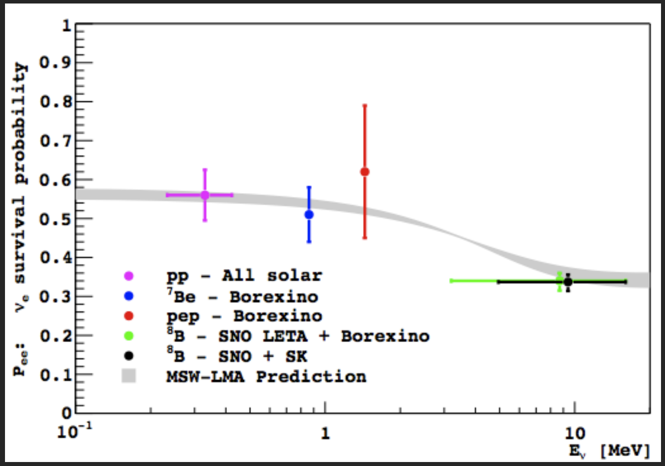
Assuming MSW-LMA:

$\Phi_{pep} = 1.6 \pm 0.3$ 108 $cm^{-2}$ $s^{-1}$

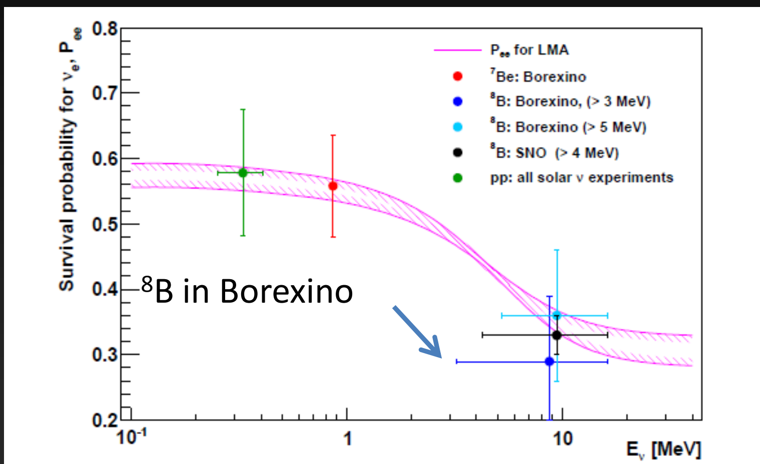
CNO limit obtained assuming pep @ SSM

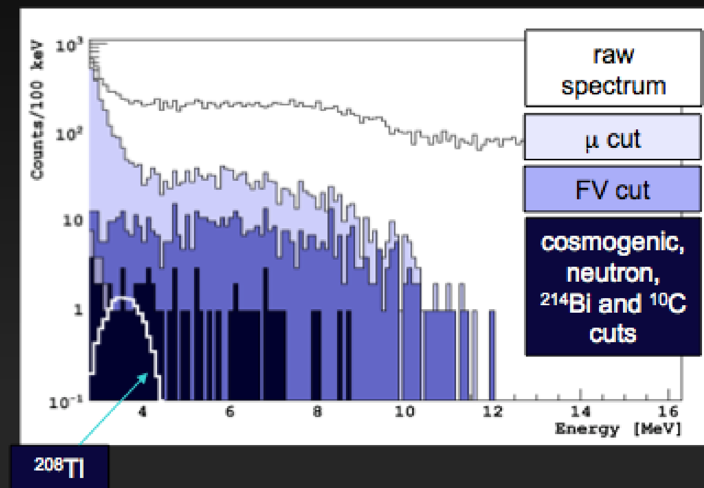
CNO rate < 7.1 cpd/100 t (95% c.l.)



# Boron-8



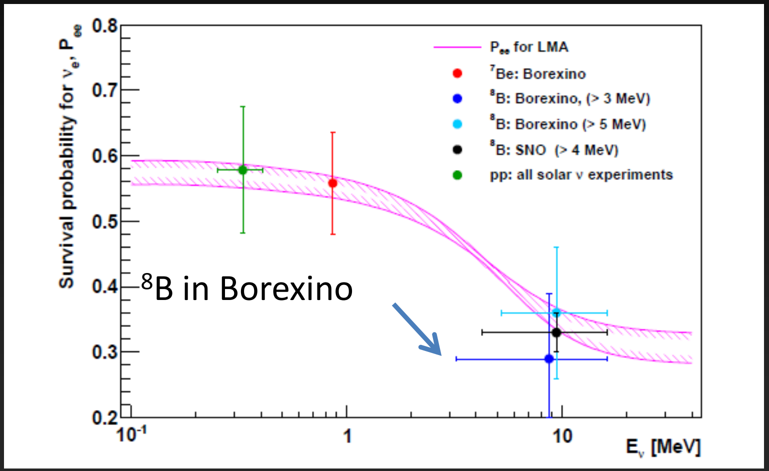



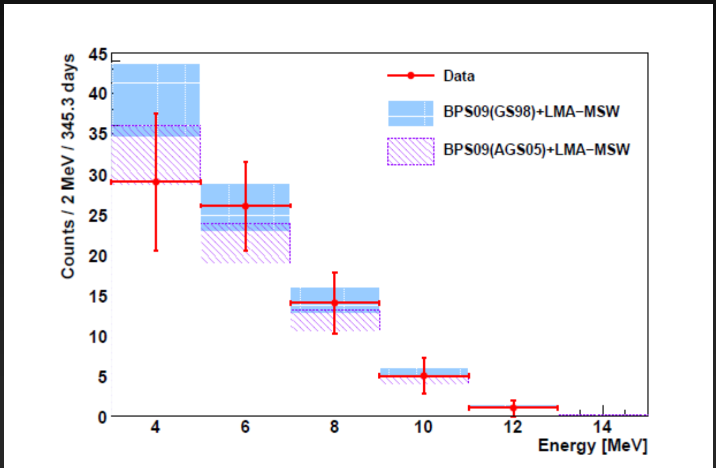

$^{8}B$ ν with 3 MeV energy threshold in Borexino

Important to probe the oscillation scenario

- Removal of muons and events after muons within 2ms ( neutrons, afterpulses, short lived isotopes, electronics artefacts)
- Identify $^{10}C$ via 3 fold coinc. (muon-neutron-10C decay)
- $^{11}Be$ statistically subtracted

# Boron-8




$^8$B ν with 3 MeV energy threshold in Borexino

Important to probe the oscillation scenario

| | 3.0–16.3 MeV | 5.0–16.3 MeV |
|---|---|---|
| Rate [c/d/100 tons] | 0.22±0.04±0.01 | 0.13±0.02±0.01 |
| $\Phi^{ES}_{exp}$ [$10^6$ cm$^{-2}$s$^{-1}$] | 2.4±0.4±0.1 | 2.7±0.4±0.2 |
| $\Phi^{ES}_{exp}/\Phi^{ES}_{th}$ | 0.88±0.19 | 1.08±0.23 |

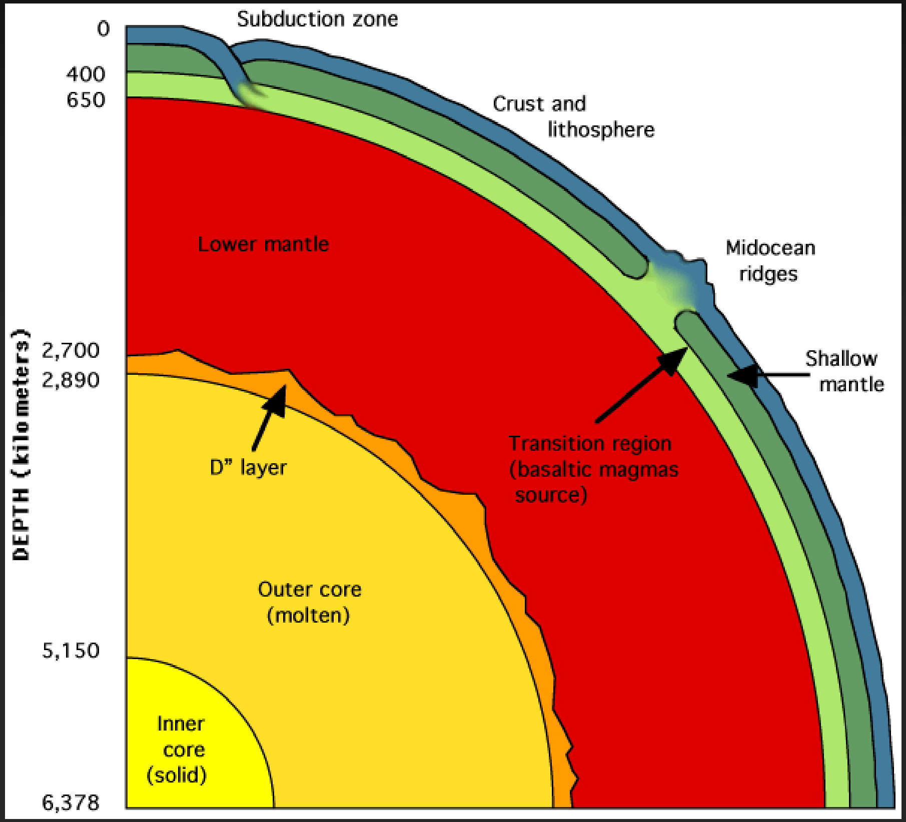
$^8$B solar neutrinos: electron recoil spectrum after the background subtraction

and comparison with the models

Results in agreement with LMA-MSW and solar models

# Geo-Neutrinos

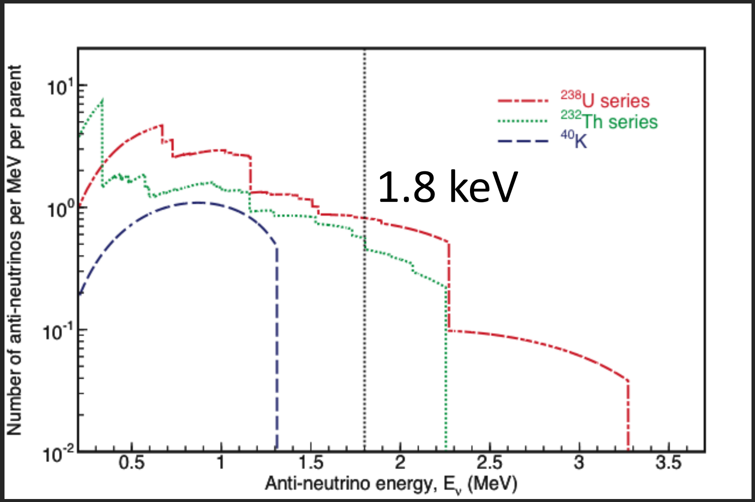
Geology




Crust: the uppermost part

OCEANIC CRUST

CONTINENTAL CRUST

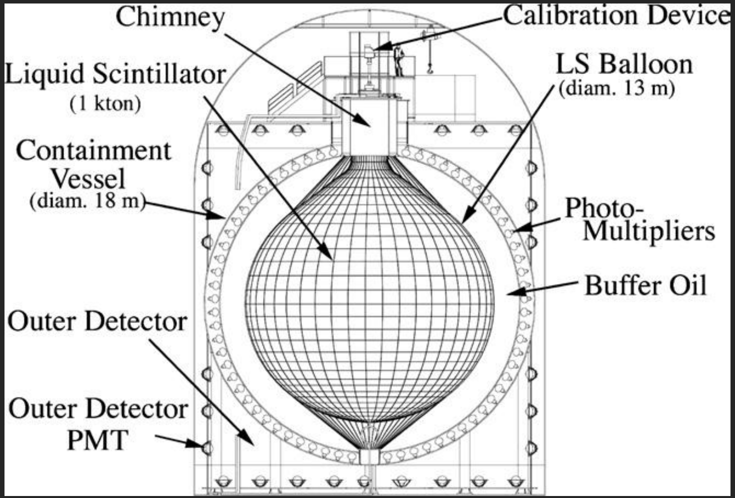


# Geo-Neutrinos

Global Status

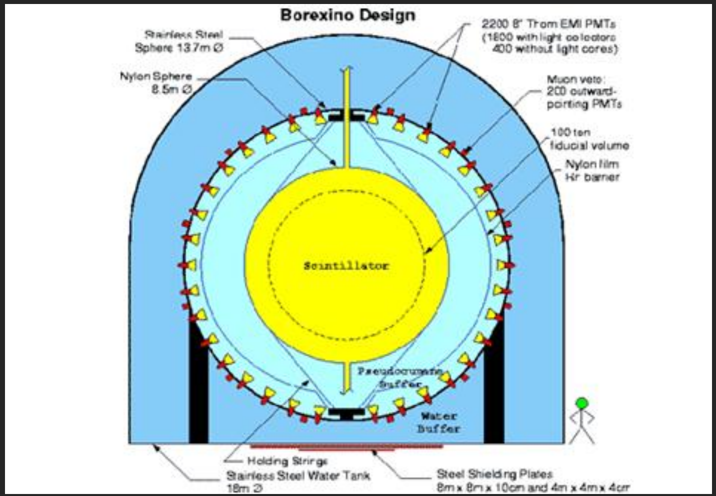
**KamLand in Kamioka**
OCEANIC CRUST

- Reactor antineutrinos;
- 1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
  (are the reactors in Japan still OFF ? )




**Borexino in Gran Sasso**
CONTINENTAL CRUST

- Solar neutrinos
- 280 tons;
- S(reactors)/S(geo) ~ 0.3
- DAQ started in 2007;



# Geo-Neutrinos

Detection

$$\bar{\nu}_e + p \rightarrow n + e^+$$

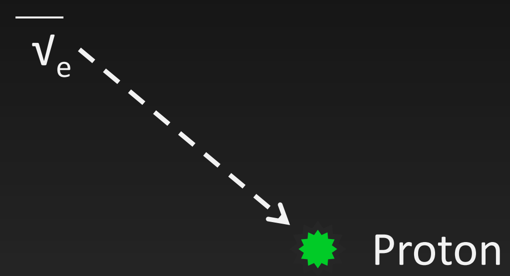
Energy threshold for antineutrino: 1.8 MeV
Excess energy carried away by positron

Coincidence Tagging:

Prompt Event: Scintillation from positron KE and annihilation
Delayed Event: Neutron Capture on hydrogen ($\tau \sim 250\ \mu s$)

# Coincidence Tagging

Geo-Neutrinos



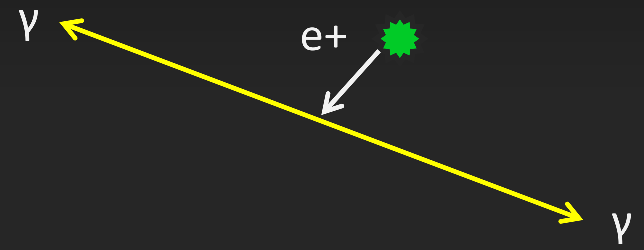

Inverse Beta Decay

Positron annihilation ( > 1.02 MeV)

Neutron Capture (2.2 MeV)

# Coincidence Tagging

Geo-Neutrinos

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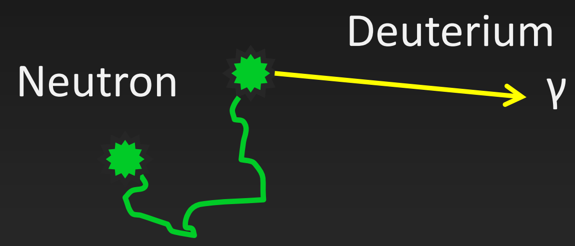
# Coincidence Tagging

Geo-Neutrinos



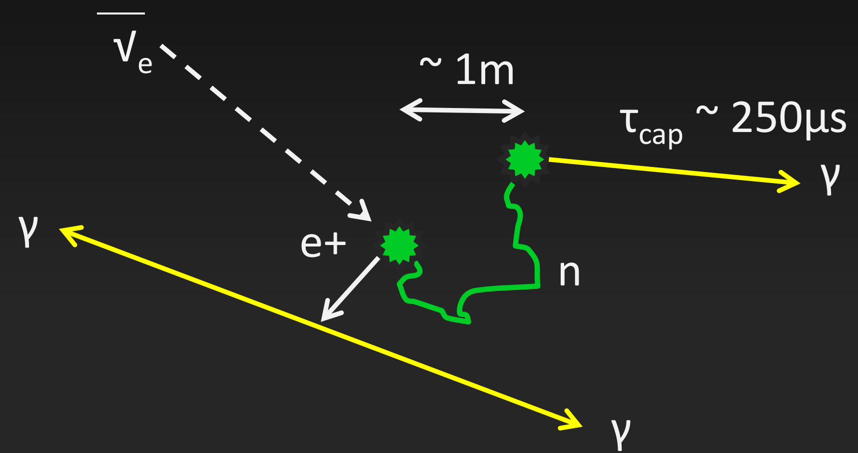

Inverse Beta Decay

Positron annihilation ( > 1.02 MeV)

Neutron Capture (2.2 MeV)

# Coincidence Tagging

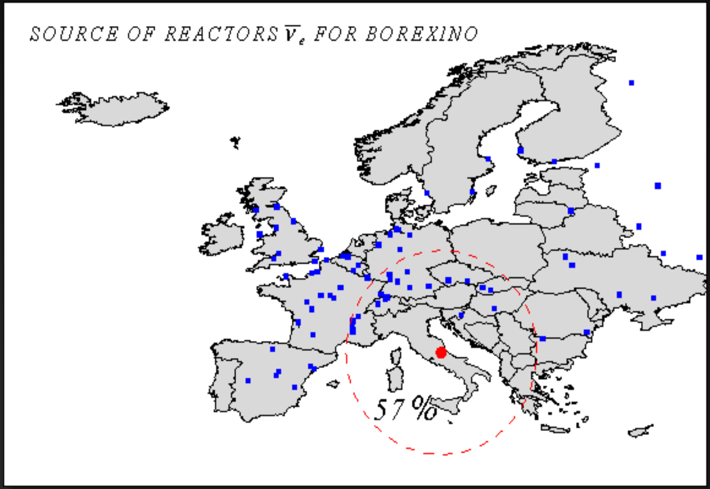
Geo-Neutrinos



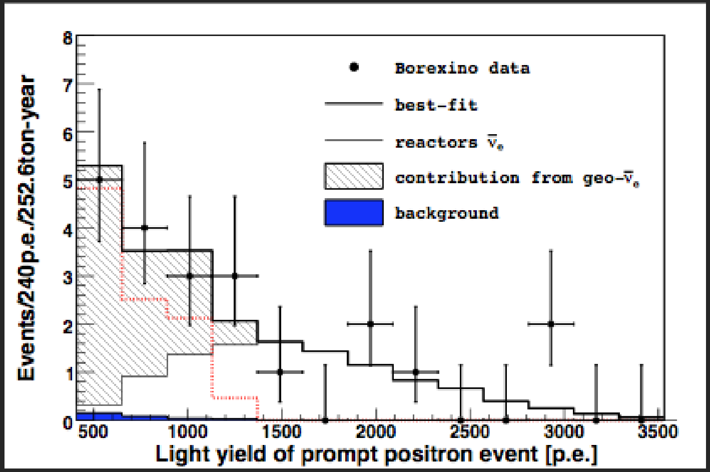

Use spatial and time correlation between events to effectively reduce background

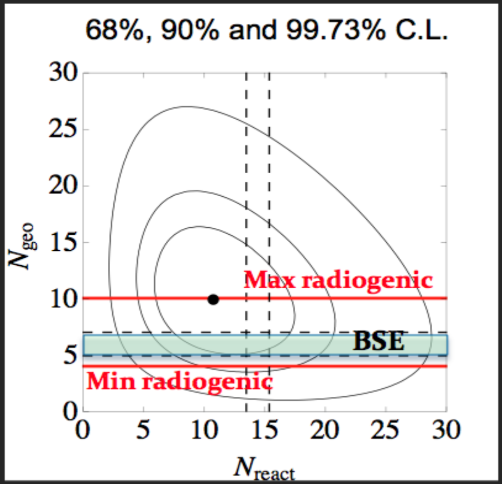
Coincidence allows us to use entire scintillating volume ( ~ 278 tons) for geoneutrino search

# Signal + Background




- Reactor antineutrinos
- $^{13}C(\alpha, n)^{16}O$ reactions
- $^{9}Li$ / $^{8}He$ cosmogenic events
- Fast neutrons

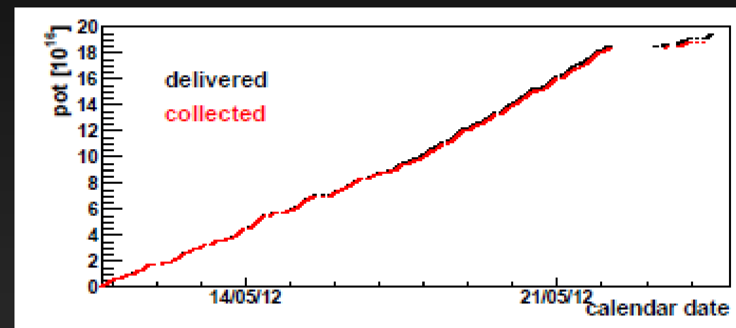


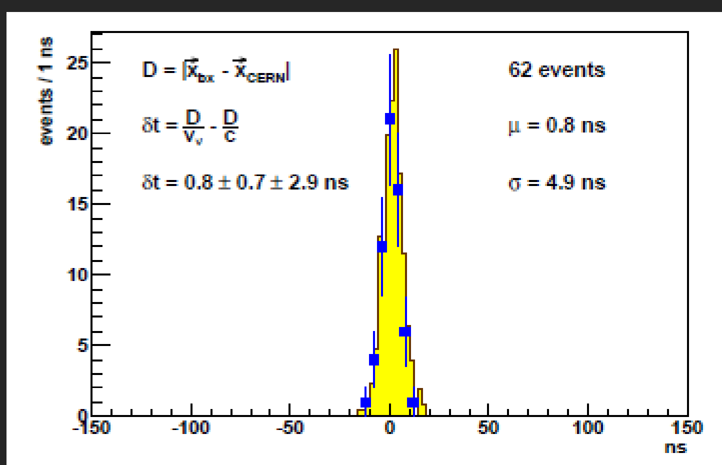



# Neutrino Speed

arXiv:1207.6860v1

<E> = 17 GeV muon neutrino
730 km – CERN to LNGS
√ mass < 2 ev/$c^2$
$\gamma > 10^{11}$
$\Delta t = 0.8 \pm 0.7_{stat} \pm 2.9_{sys}$




| Description | Error (ns) |
|---|---|
| Time-Link Calibration (GPS) | 1.1 |
| Borexino electronics delays | 0.5 |
| Delays at CERN | 2.2 |
| Light propagation in BX detector | 1.0 |
| Electronics resolution | 0.5 |
| Event selection stability | 1.0 |
| Geodesy measurement | 0.1 |
| Total systematic error | 2.9 |