Recent Borexino results and prospects for near future

ICNFP 2015
4th International Conference on New Frontiers in Physics
Crete, Greece – 23-30 Aug 2015

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Heidelberg

Hamburg

Budapest

Milano

Genova

München

Kraków

Kurchatov
Moscow

the Borexino Collaboration

JINR Dubna

Princeton

Virginia Tech

UMass
Amherst

Paris

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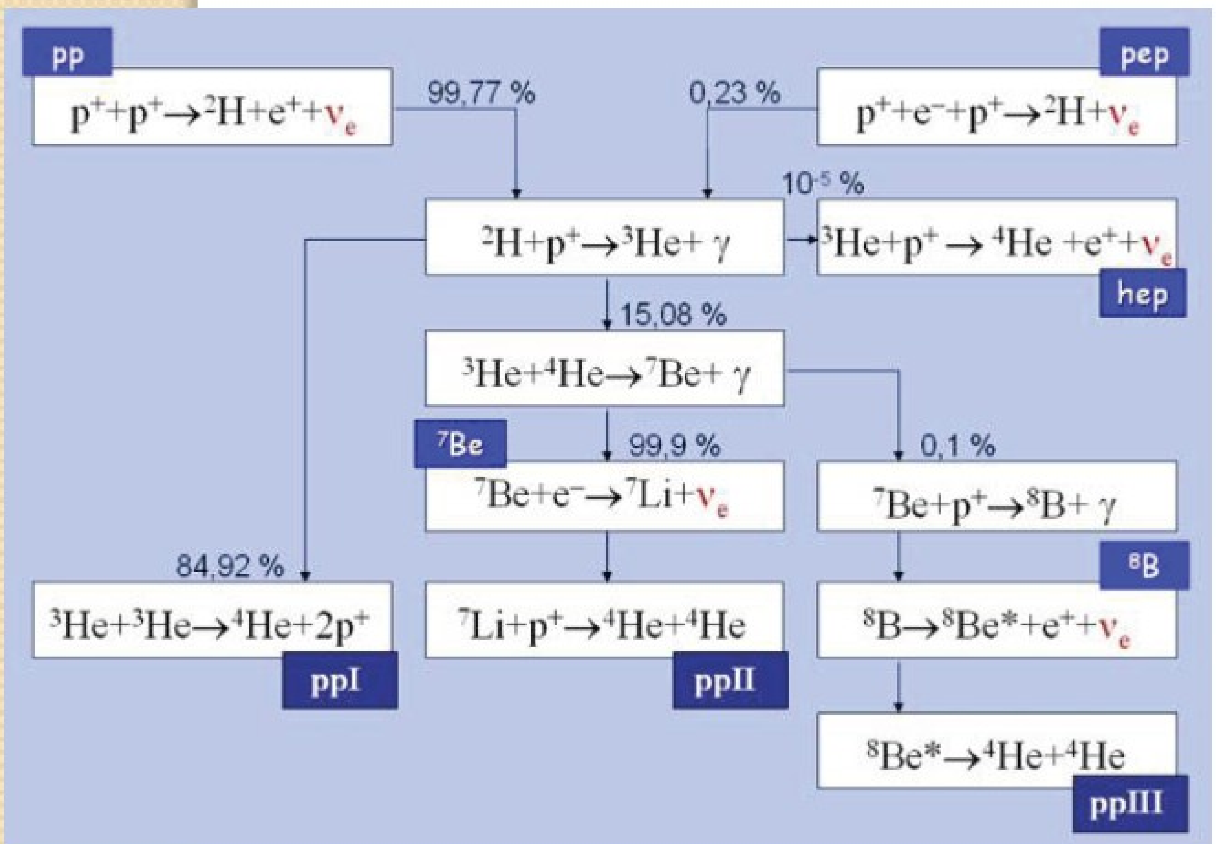
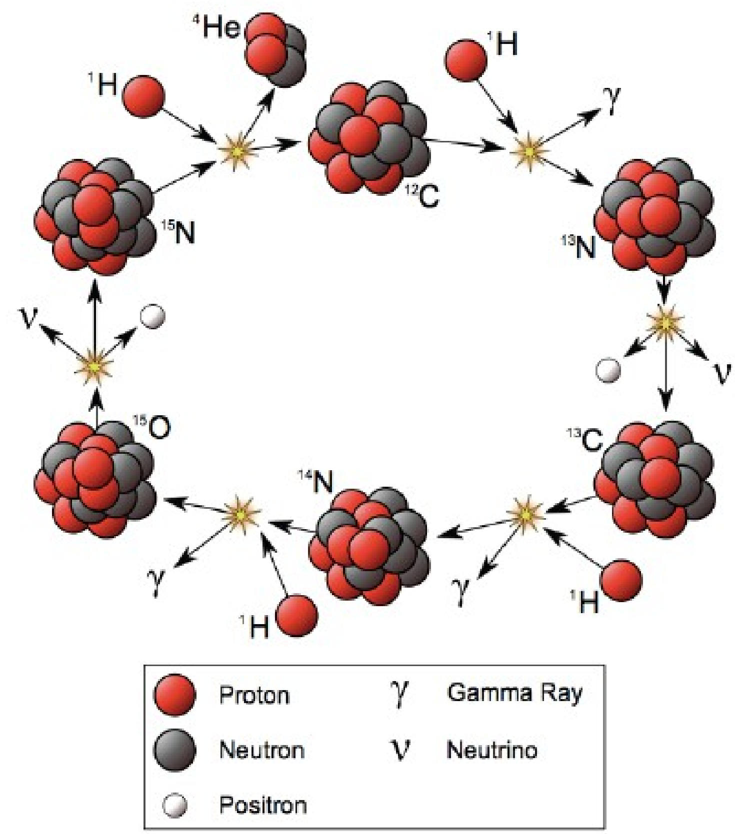
Energy production in the sun

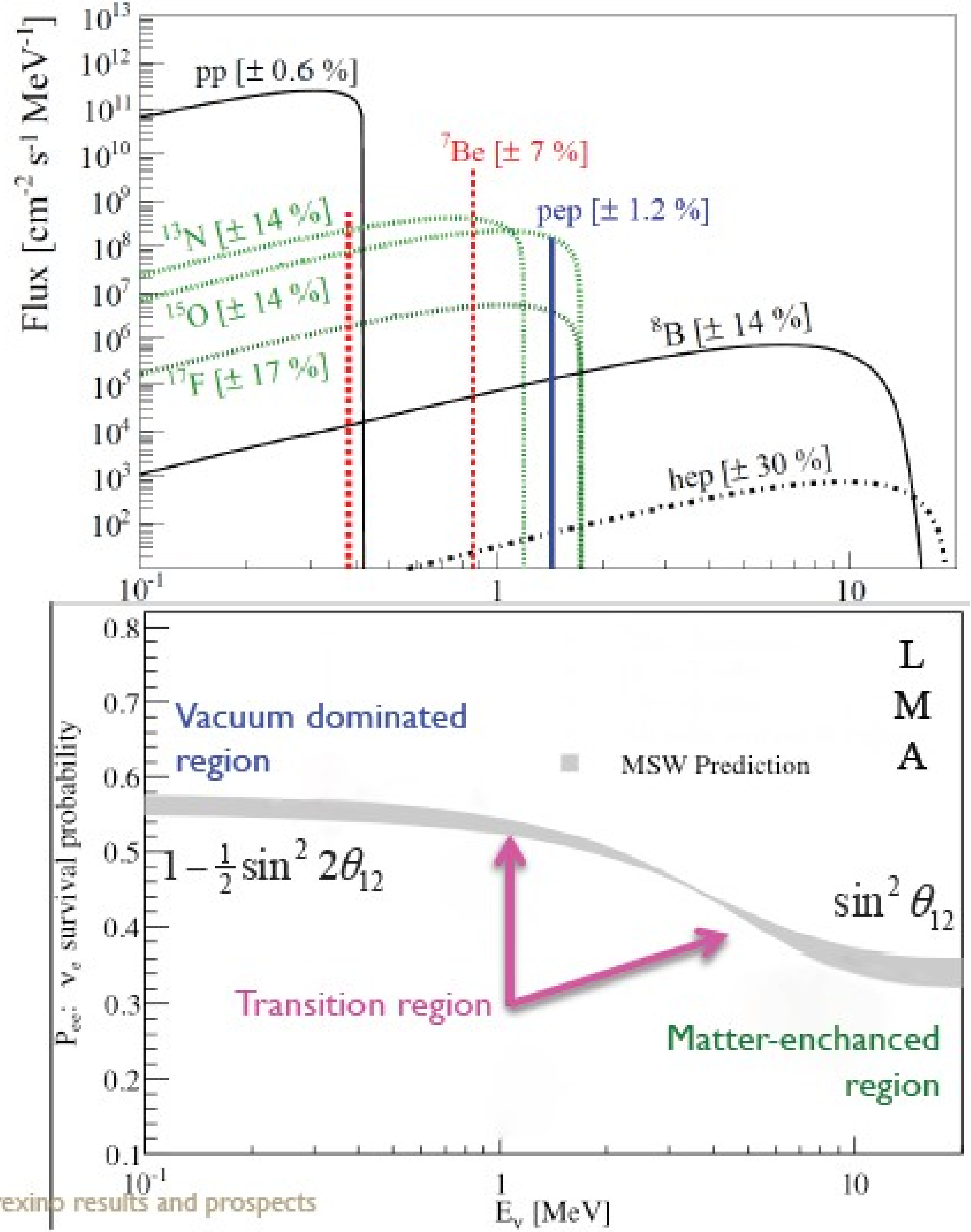
PP-chain
>99% energy production
5 ν species



CNO-cycle
<1% energy production
3 ν species



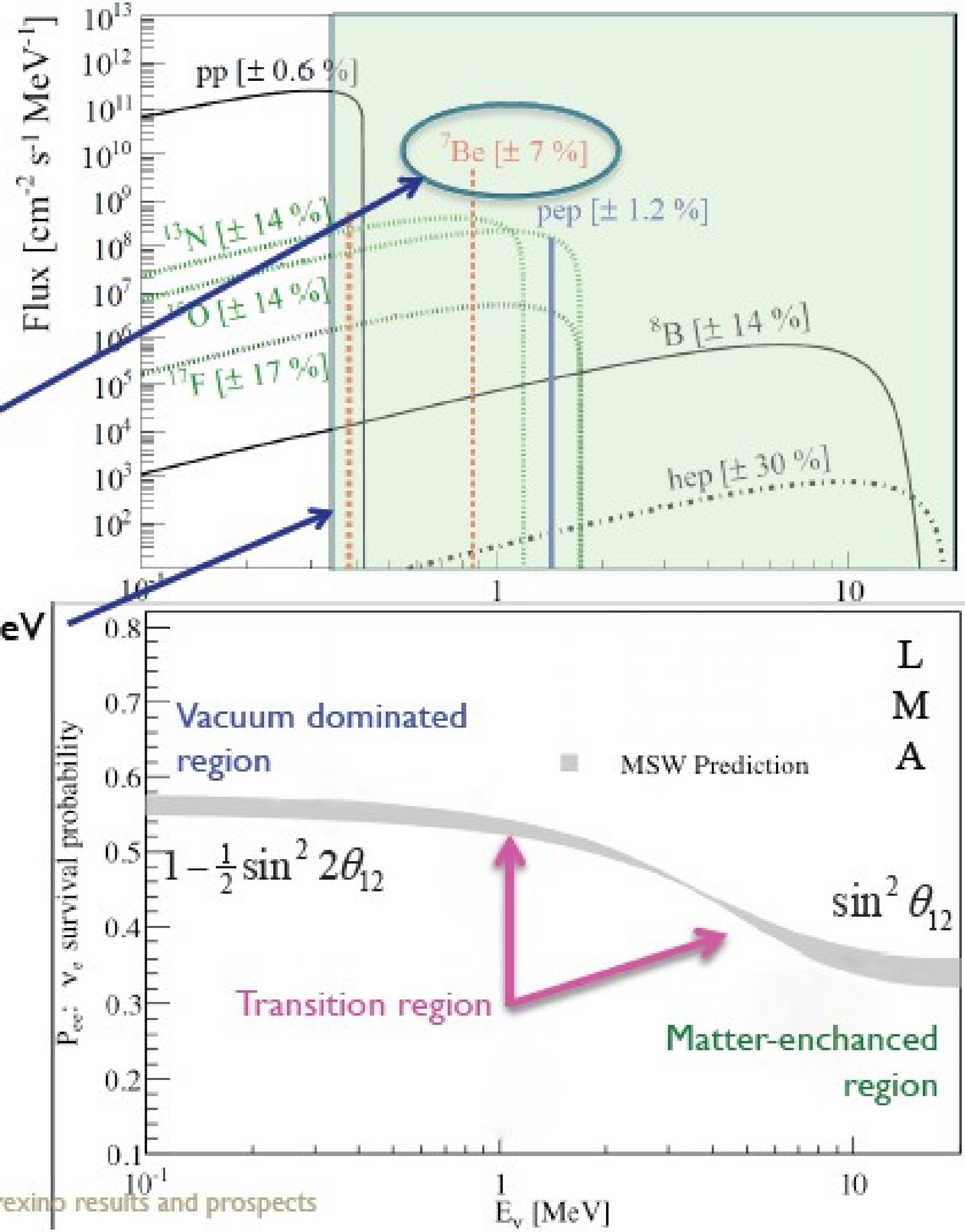
Why Borexino?



Why Borexino?

Borexino design goal: ^{7}Be

Borexino design threshold ~250keV



The Borexino Detector

Neutrino electron scattering

ν e -> ν e

Stainless Steel Sphere:

- 2212 PMTs
- ~ 1000 m^3 buffer of pc +dmp (light queched)

Scintillator:

270 t PC+PPO (1.4 g/l)

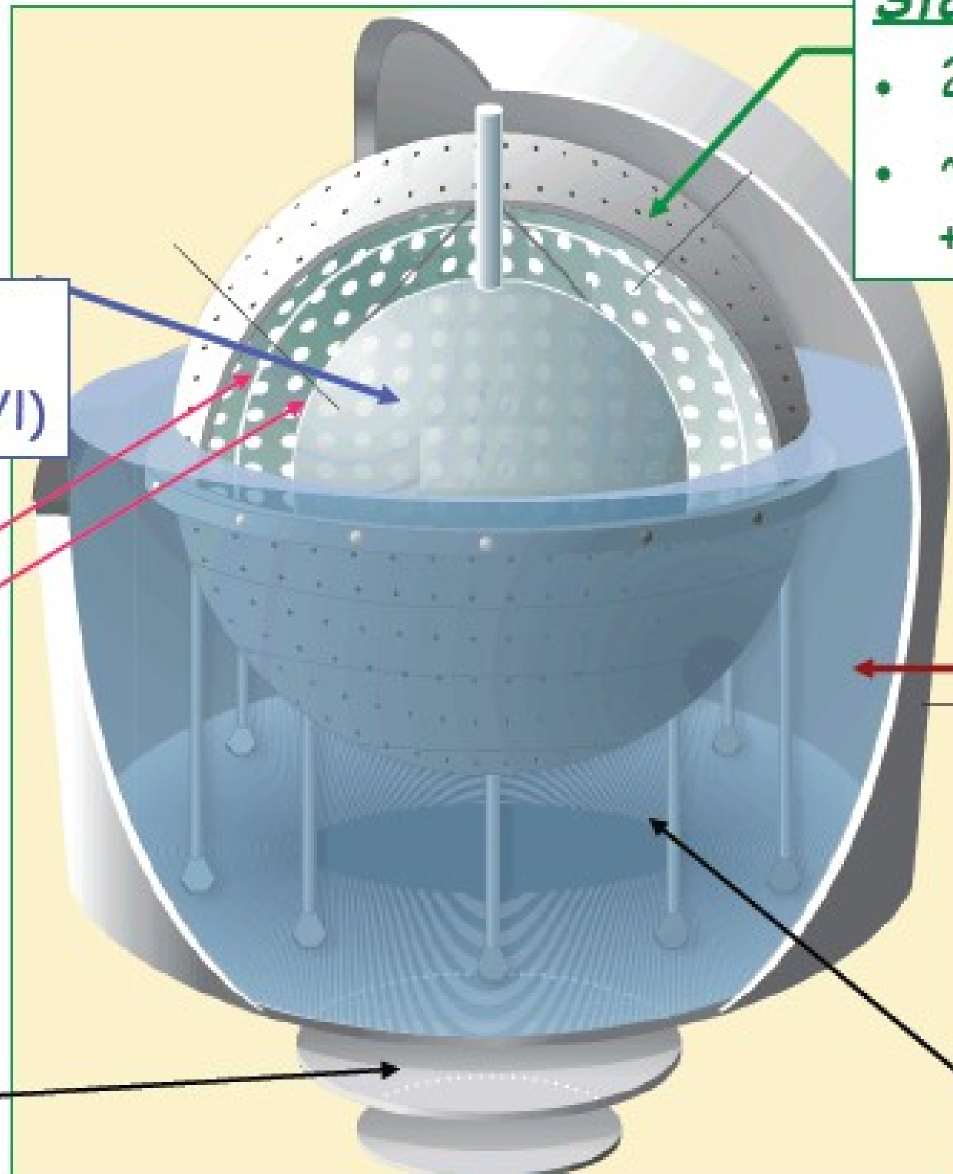
Nylon vessels:

(125 μm thick)

Inner: 4.25 m

Outer: 5.50 m

(radon barrier)



Water Tank:

γ and n shield

μ water Č detector

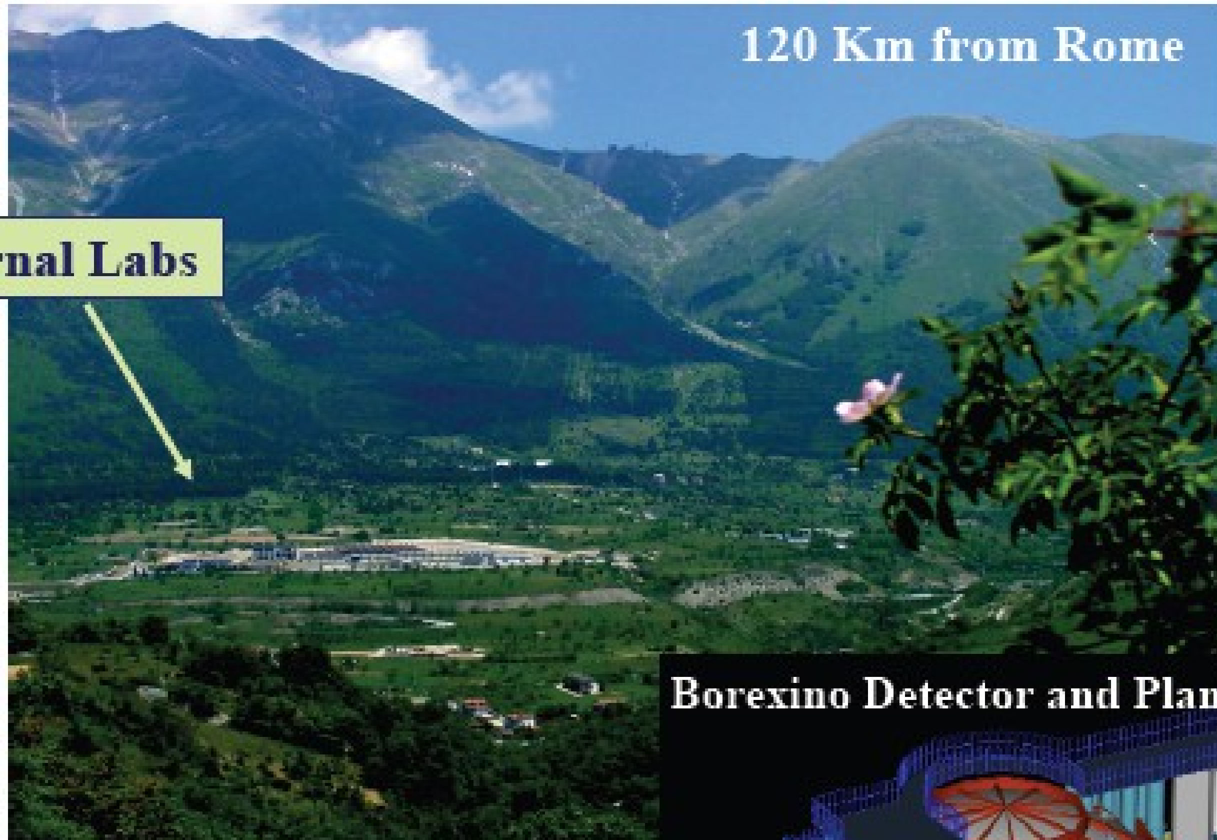
208 PMTs in water

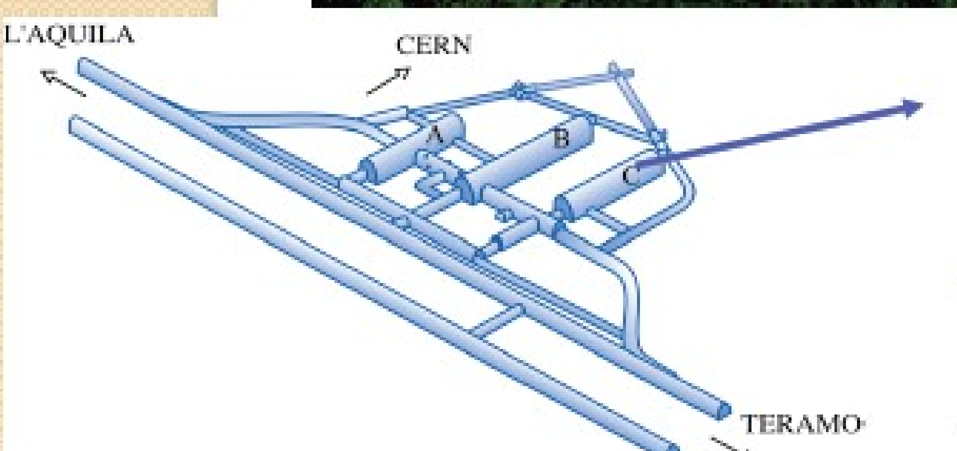
2100 m^3

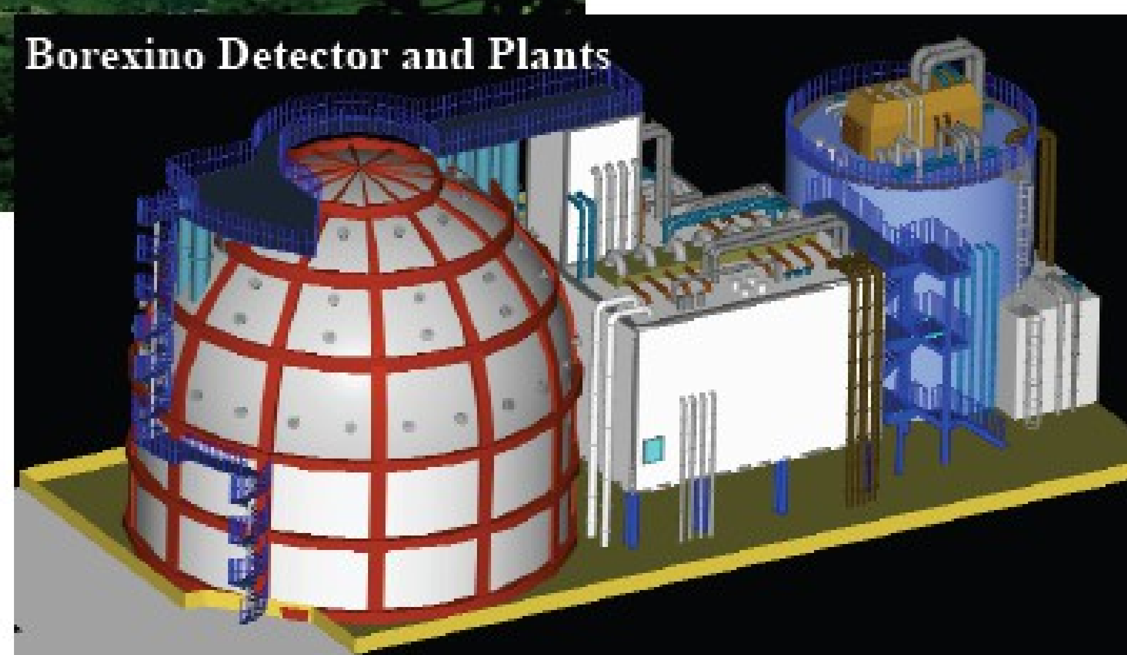
Carbon steel plates

20 legs

Experimental site



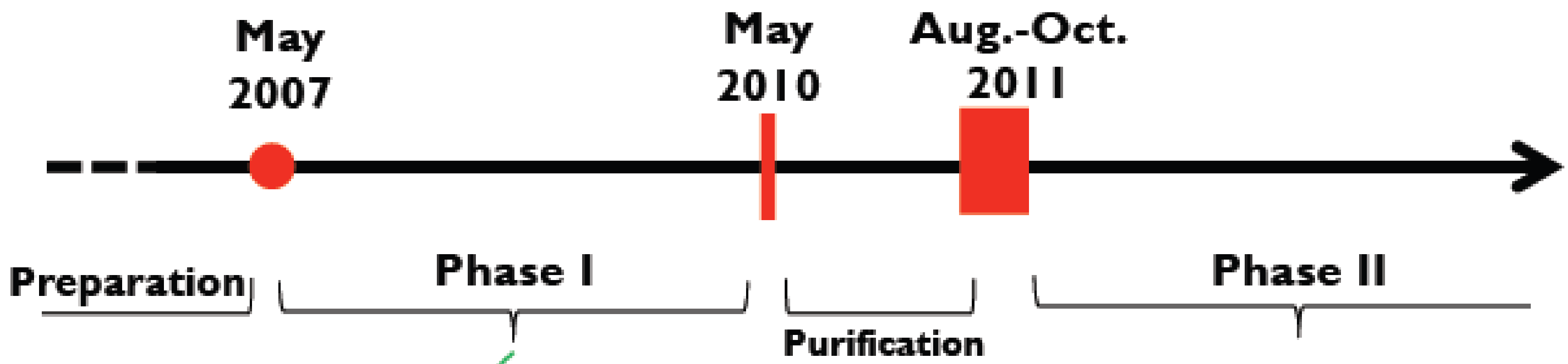




Laboratori Nazionali del Gran Sasso

Assergi (AQ)
Italy
1400m of rock shielding
~3800 m.w.e.

Borexino data taking campaign



- (First) solar ^{7}Be-ν measurement
- ^{7}Be-ν day-night asymmetry
- Low-threshold ^{8}B-ν
- First pep-ν detection
- Best upper limit on CNO-ν
- First geo-ν observation at > 4σ
- Muon seasonal variations
- Limits on rare processes

- Measurement of pp-ν flux
- Measurement of CNO-ν flux
- Short-base ν oscillations: SOX

- Neutrons and other cosmogenics
- ^{7}Be-ν seasonal modulation
- Updated geo-ν flux

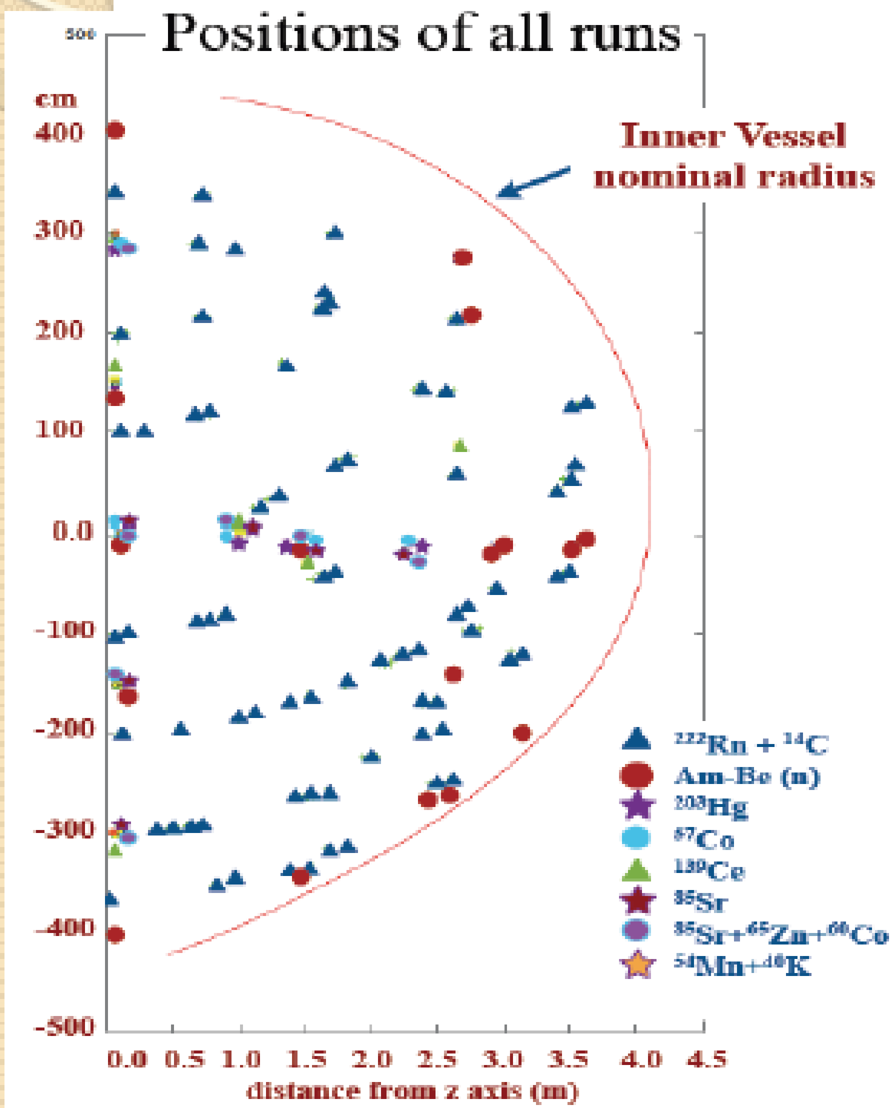
Borexino backgrounds

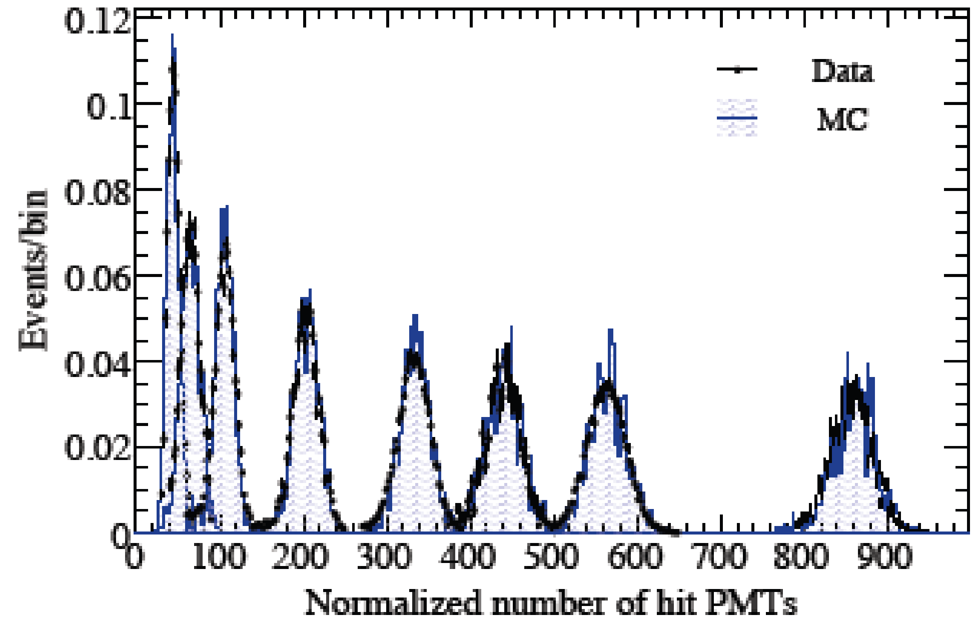
Isotope	Typical	Required	Before purification	After purification
^{238}U	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5) \cdot 10^{-18}$ g/g	$< 0.8 \cdot 10^{-19}$ g/g
^{232}Th	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \cdot 10^{-18}$ g/g	$< 1.0 \cdot 10^{-18}$ g/g
$^{14}C/^{12}C$	10^{-12} (cosmogenic)	$\leq 10^{-18}$	$(2.69 \pm 0.06) \cdot 10^{-18}$ g/g	unchanged
^{222}Rn	100 atoms/ cm^3 (air)	≤ 10cpd/100t	~1cpd/100t	unchanged
^{40}K	$2 \cdot 10^{-6}$ (dust)	$\leq 10^{-18}$ g/g	$\leq 0.4 \cdot 10^{-18}$ g/g	unchanged
^{85}Kr	1 Bq/m^3 (air)	≤ 1 cpd/100 t	(30 ± 5) cpd/100 t	≤ 5 cpd/100 t
^{39}Ar	17 mBq/ m^3(air)	≤ 1 cpd/100 t	<< ^{85}Kr	<< ^{85}Kr
^{210}Po		not specified	(~80) ~20 cpd/100 t	unchanged
^{210}Bi		not specified	(~20) ~70 cpd/100 t	(20 ± 5) cpd/100 t

JINST 7(2012)P10018

Borexino calibration

2008-2011: 4 internal + 1 external calibration campaigns



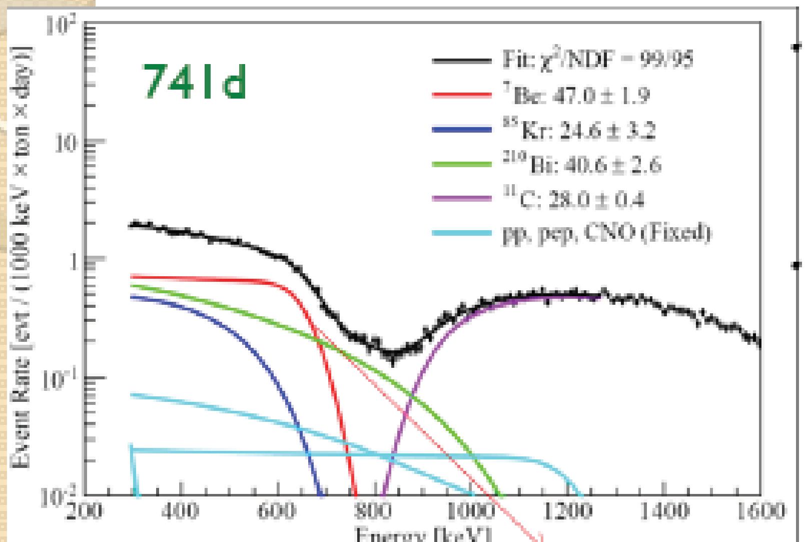


Energy scale uncertainty in the range 0.2÷2 MeV is better than 1.5%

Using 184 points of Rn calibration data, the Fiducial Volume uncertainty was taken to -1.3% +0.5%

Phys. Rev. Lett. 107, 141302 (2011)

^{7}Be neutrino flux and A_{DN}



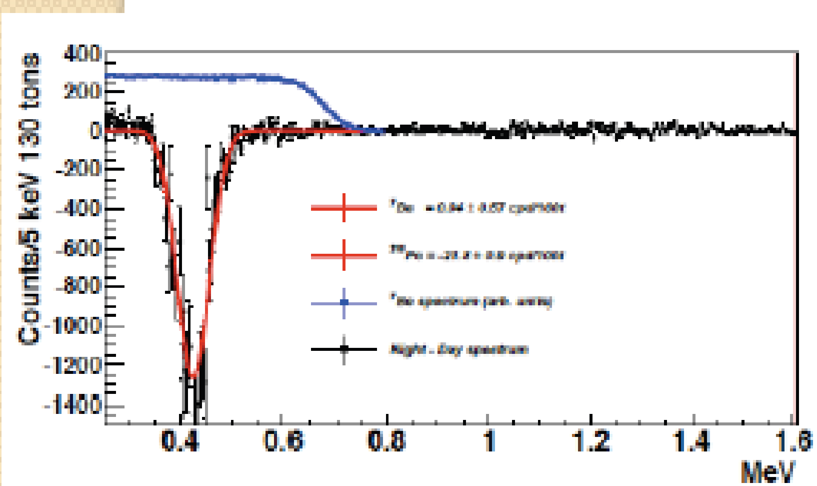
$$46.0 \pm 1.5(stat)^{+1.5}_{-1.6}(syst)/d/100t$$

for the first time the experimental error (4.8%) is smaller then theoretical error (7%)

$$\phi_{Be} = (3.10 \pm 0.15) \times 10^{9}\ cm^{-2}s^{-1}$$

$$P_{ee} = 0.51 \pm 0.07 \text{ at } 0.862 \text{ MeV}$$

Phys. Lett. B 707, 1 (2012) 22-26

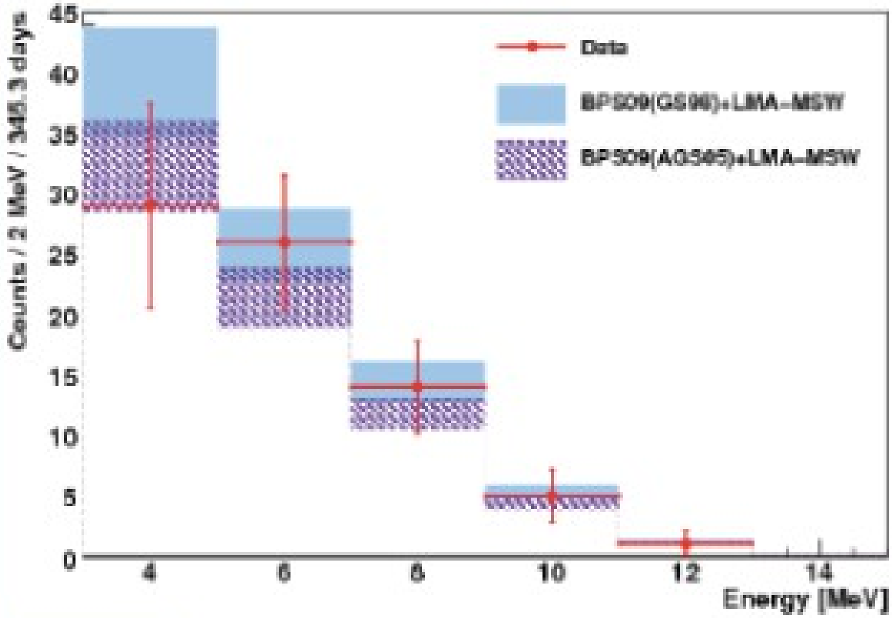


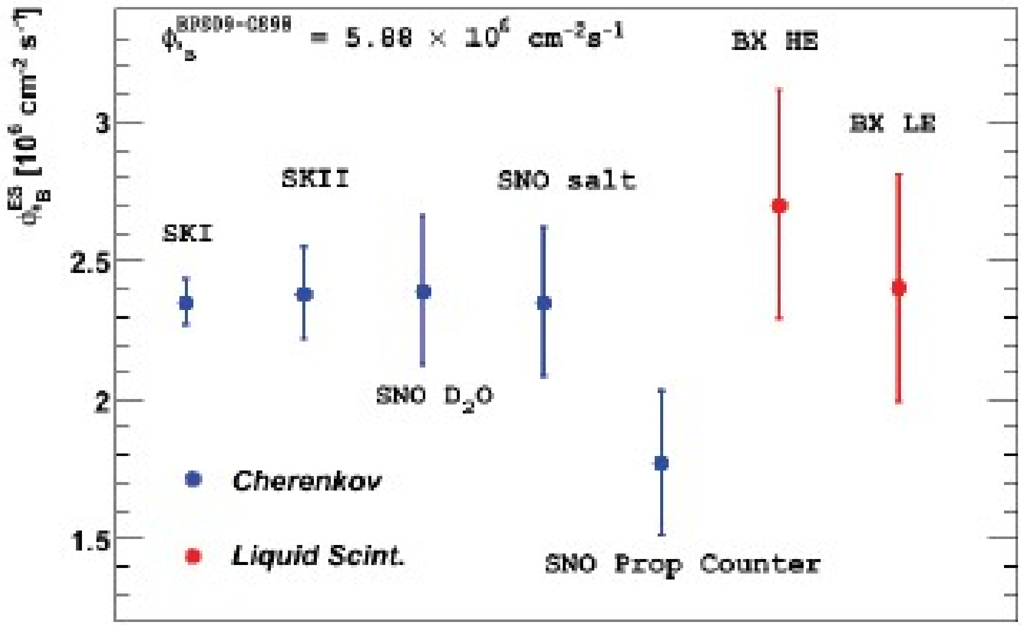
$$A_{DN} = \frac{N - D}{(N + D)/2} = 0.001 \pm 0.012\ (stat) \pm 0.007(sys)$$

Then solar neutrino results with Borexino can isolate the LMA region without the Kamland antineutrino data

PRD 82 (2010) 033006

^{8}B flux at 3MeV





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

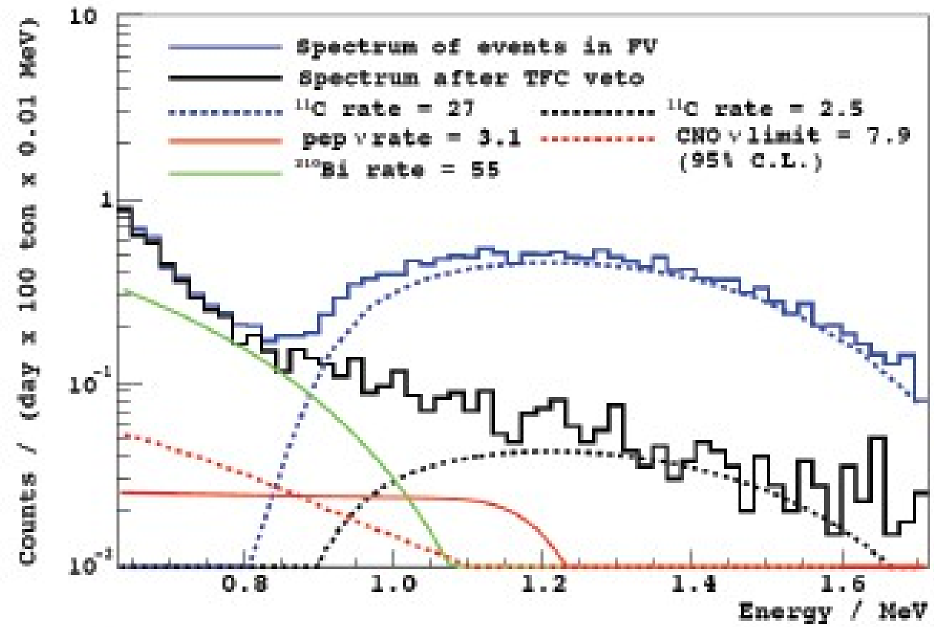
Phys. Rev. Lett. 108, 051302 (2012)

pep flux and CNO limits

$R = (3.1 \pm 0.6_{stat} \pm 0.3_{sys})$ cpd/100 t

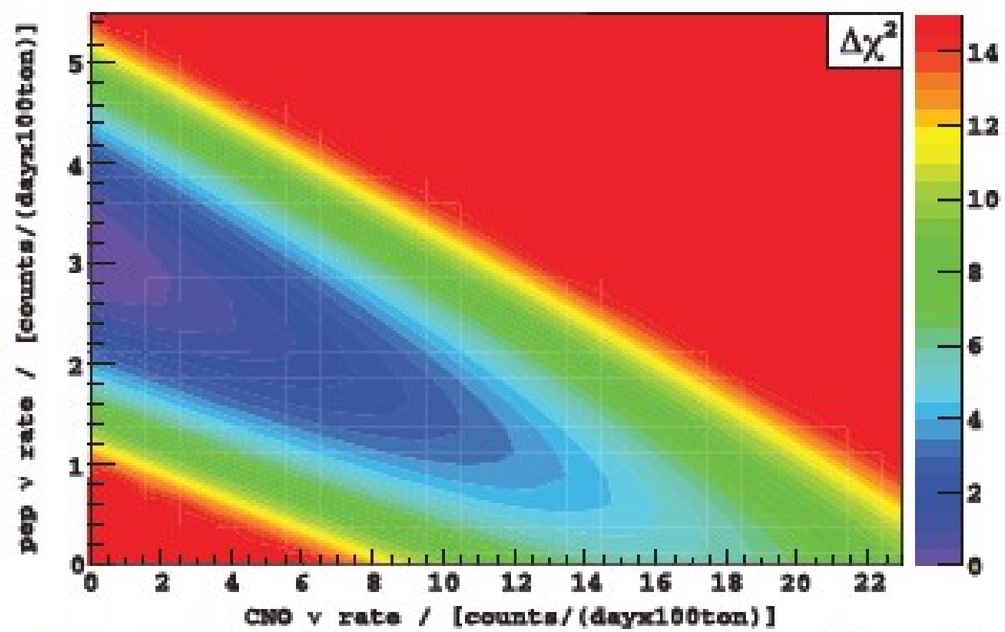
$\Phi^{LMA}_{pep} = (1.6 \pm 0.3) \times 10^{8}\ cm^{-2}\ s^{-1}$

$P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV

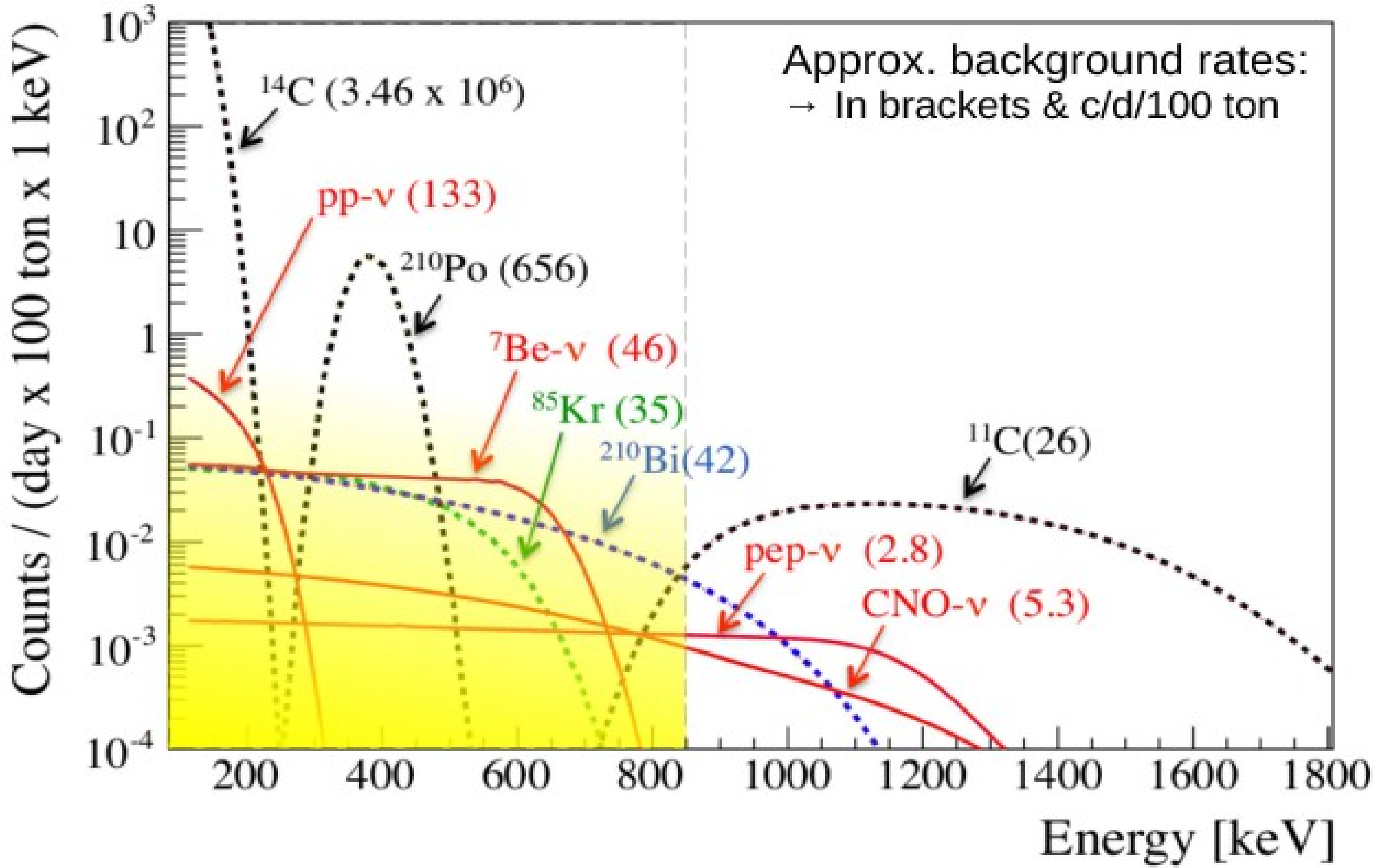


R < 7.1 cpd/100 t (95 % C.L.)

$\Phi^{LMA}_{CNO} < 7.7 \times 10^{8}\ cm^{-2}\ s^{-1}$ (95 % C.L.)



pp neutrino analysis



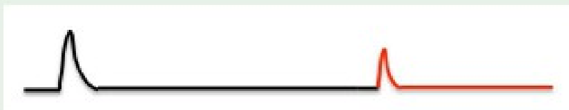
Neutrino energy: < 420keV

Electron recoil energy: < 264keV

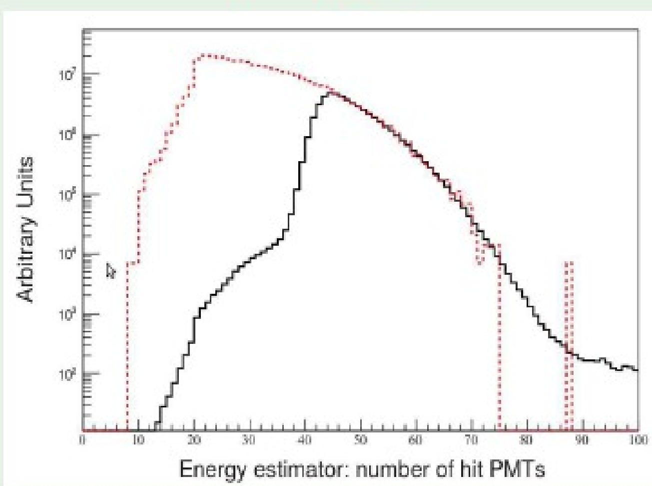
This analysis threshold: 165keV
(cmp. design thresh. 250KeV, radiochem. exp. 233keV)

^{14}C background issues

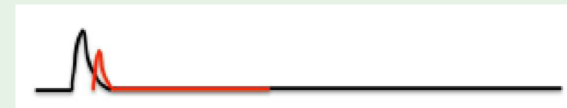
Pure ^{14}C β spectrum



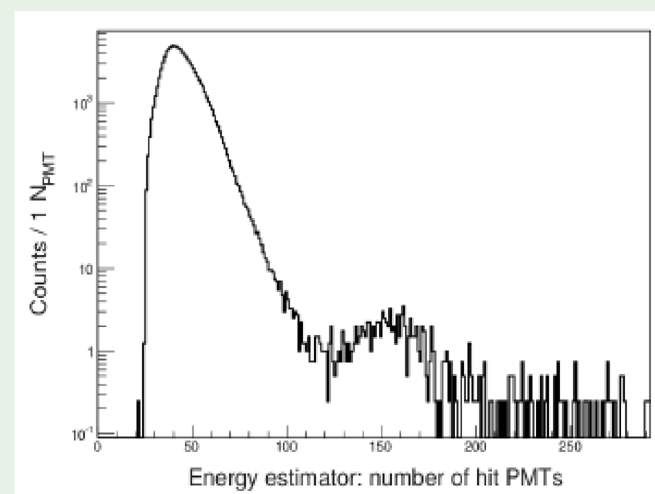
- Trigger problem:
  - Total rate: $\sim$30 Hz for E_{th} $\sim$50 keV
  - ^{14}C expected rate: (10-100) c/s/100ton
  - Aquisition window: 16μs;
  - Events with E close to E_{th}: often problematic
- Solution for ^{14}C close to E_{th}: Trigger with two random events: 2. event (^{14}C) unaffected by E_{th}
  $\rightarrow$ Spectral shape threshold: 100 keV $\rightarrow$ 50 keV
  $\rightarrow$ ^{14}C rate: (40$\pm$1) c/s/100ton



^{14}C pile-ups

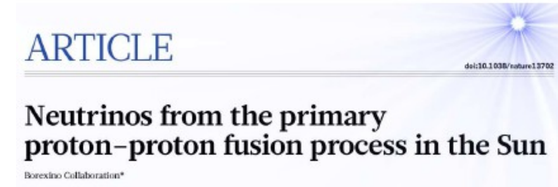


- Pile-up problem:
  - ^{14}C overlap with PMT dark rate, ^{14}C, ^{210}Po
  $\rightarrow$ Spectral shape hardly known
  $\rightarrow$ Position reco. largely fails
  Expected rate: (6-600) c/d/100ton
- Solution: Generate 'synthetic' pile-ups:
  - Overlap artificially uncorrelated data with regular events
  $\rightarrow$ ^{14}C pile-up rate: (154$\pm$10) c/d/100ton



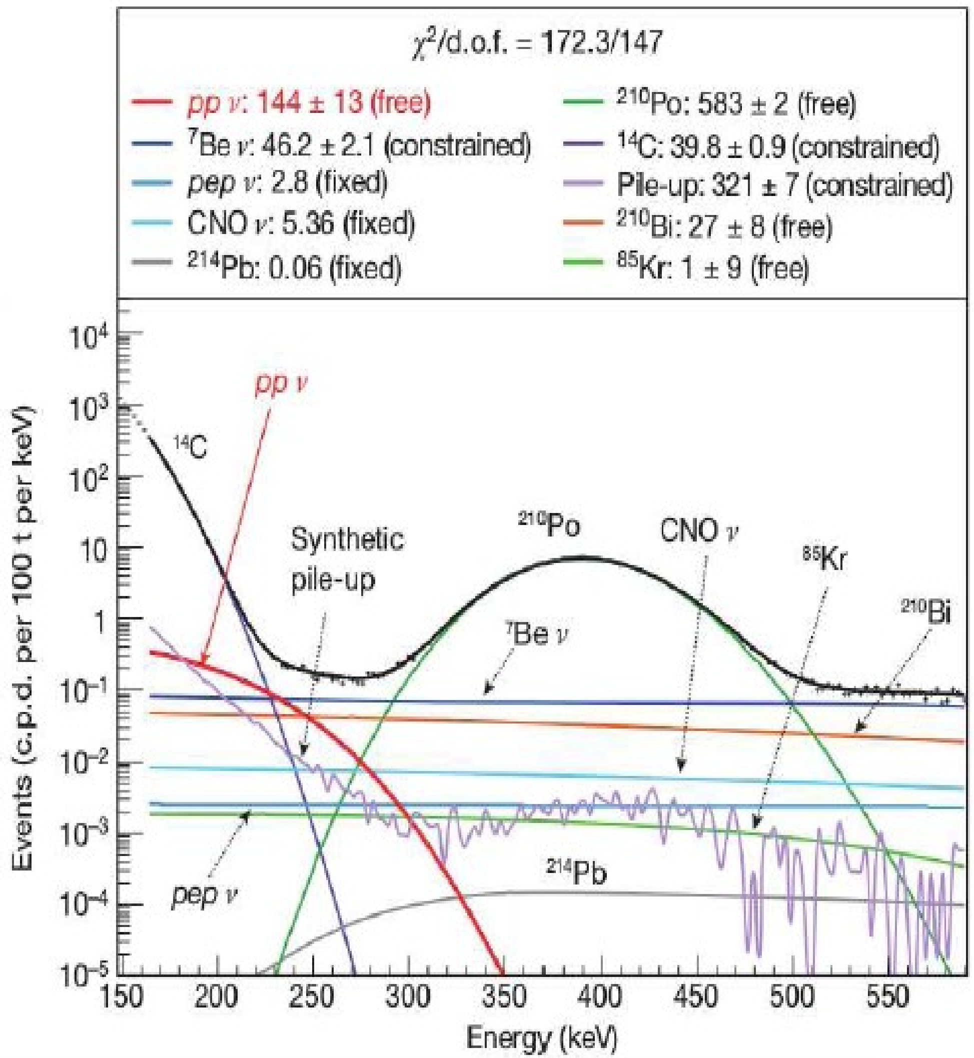
Nature, Vol. 512, Aug 28, 2014

pp neutrino results


ARTICLE

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*



Parameter	Systematics:
energy estimator	±7%
fit energy range	
data selection	
pile-up evaluation	
fiducial mass	±2%

Null hypothesis rejection: **10σ**

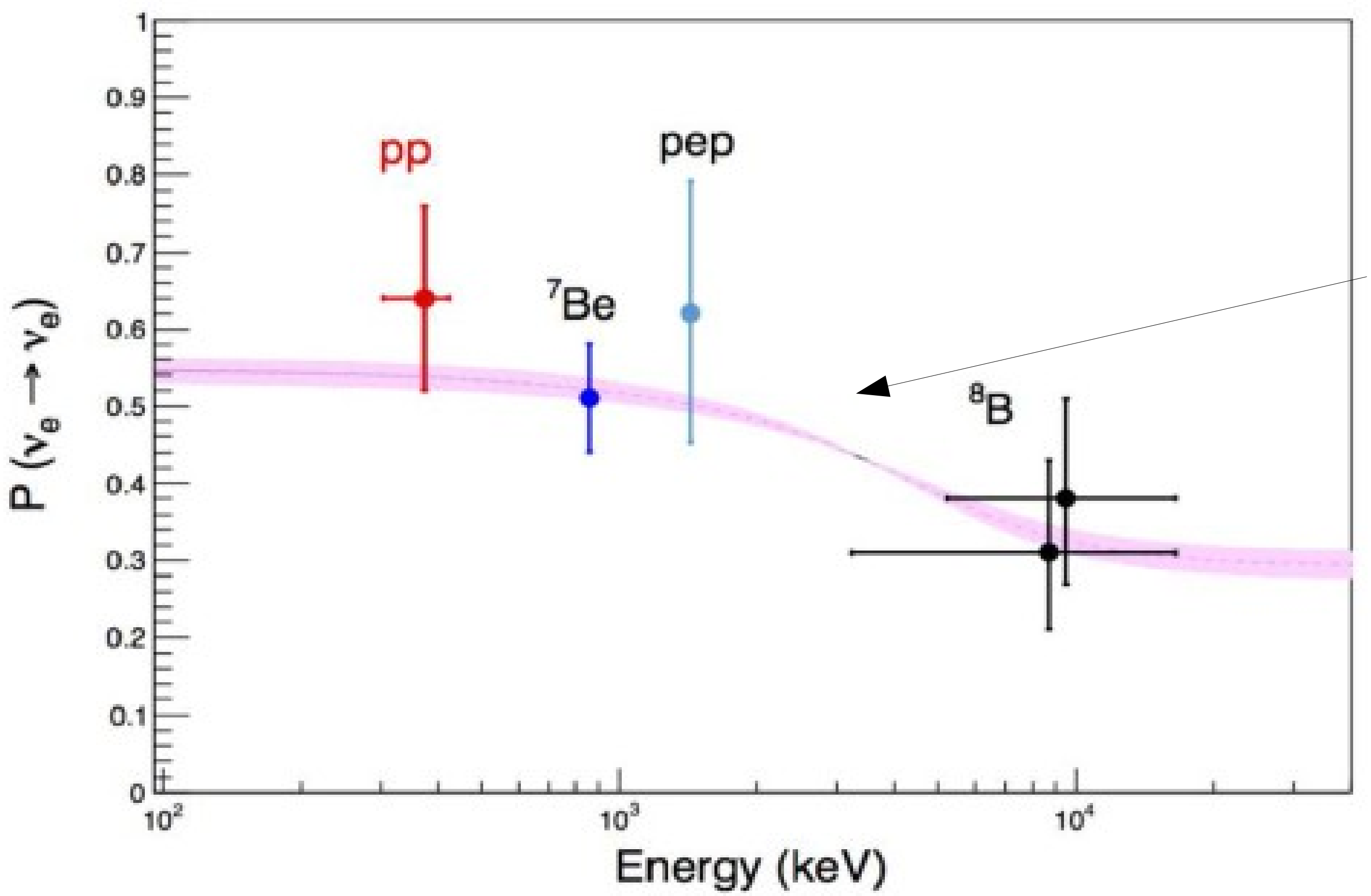
Expected: 131±2 c/d/100ton

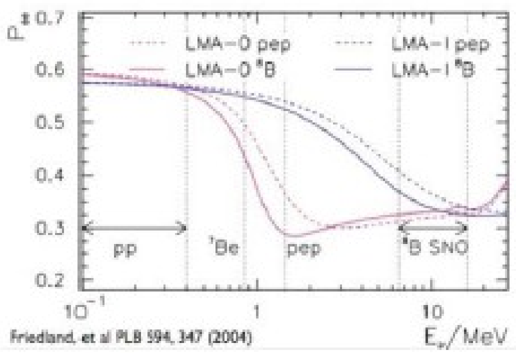
Interpretations:

1. If you believe SSM:
   - confirms MSW-LMA
2. If you believe MSW-LMA:
   - confirms SSM
3. If you believe both:
   - the sun is stable over 10^5 time span

Rate = 144±13(stat)±10(sys) c/d/100ton

P_{ee} after Borexino





In the transition region:
Is there room
for new physics?

Still missing: CNO neutrinos

Two approaches to transition region:

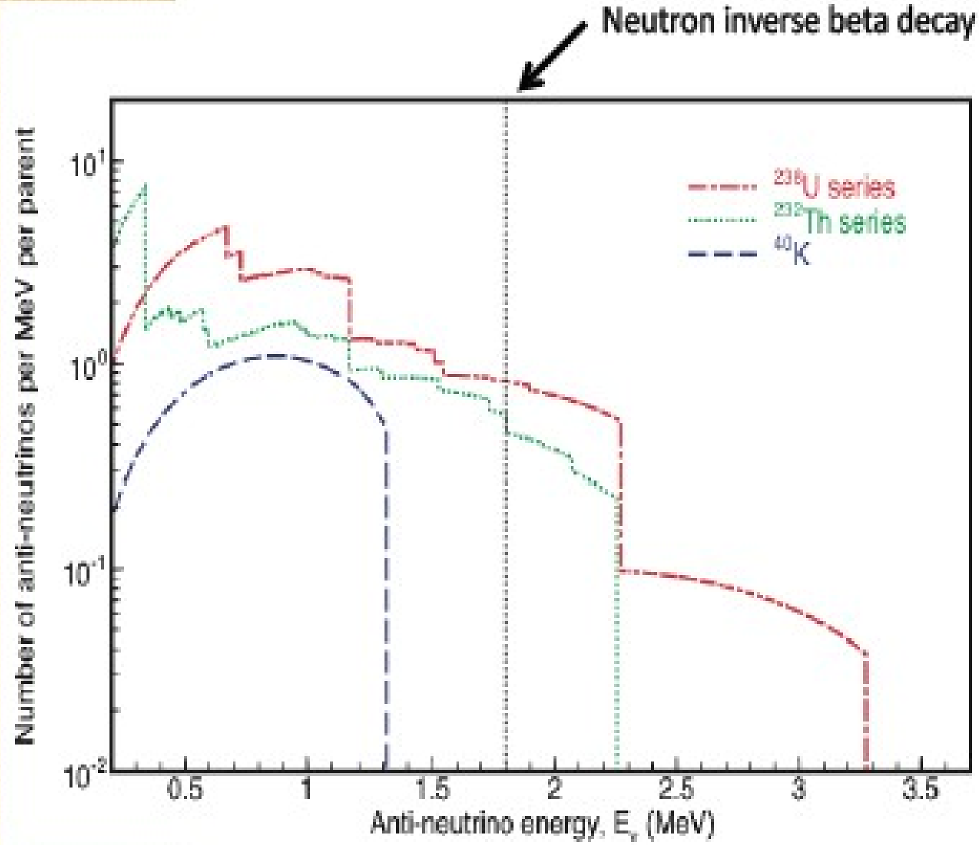
1. Reduce error on pep (and ^{7}Be) flux
2. Lower threshold on ^{8}B
   (upturn not yet observed by SNO-LETA)

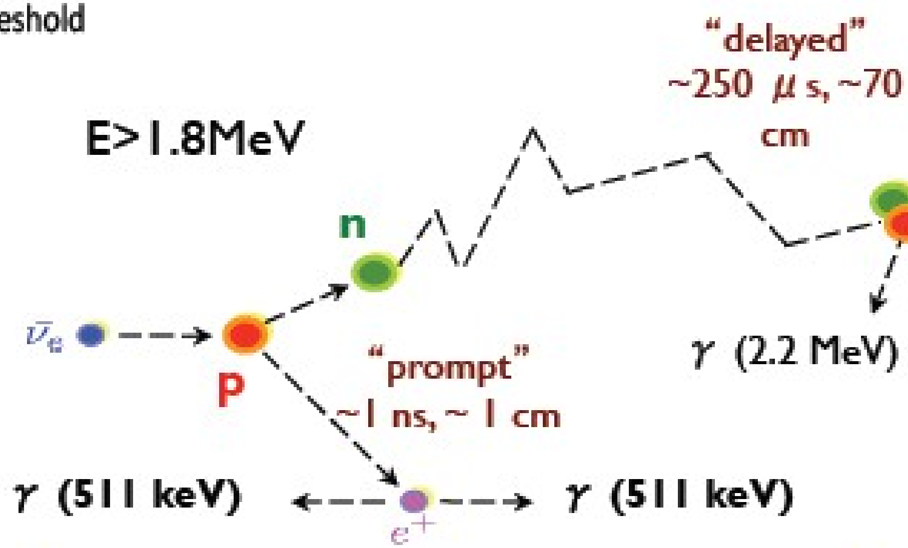
Borexino will work on both sides

Geo-neutrinos

$\Phi_{\bar{\nu}} \sim 10^6 \text{cm}^{-2}\text{s}^{-1}$

Decay	$T_{1/2}$ [10^9 yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\text{kg}^{-1}\text{s}^{-1}$]	ε_H [W/kg]
$^{238}\text{U} \rightarrow {}^{206}\text{Pb} + 8\,{}^4\text{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\text{Th} \rightarrow {}^{208}\text{Pb} + 6\,{}^4\text{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\text{K} \rightarrow {}^{40}\text{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}





K is not visible in liquid scintillator
Th/U ratio is "fixed" to 3.9 by analysis of chondrites

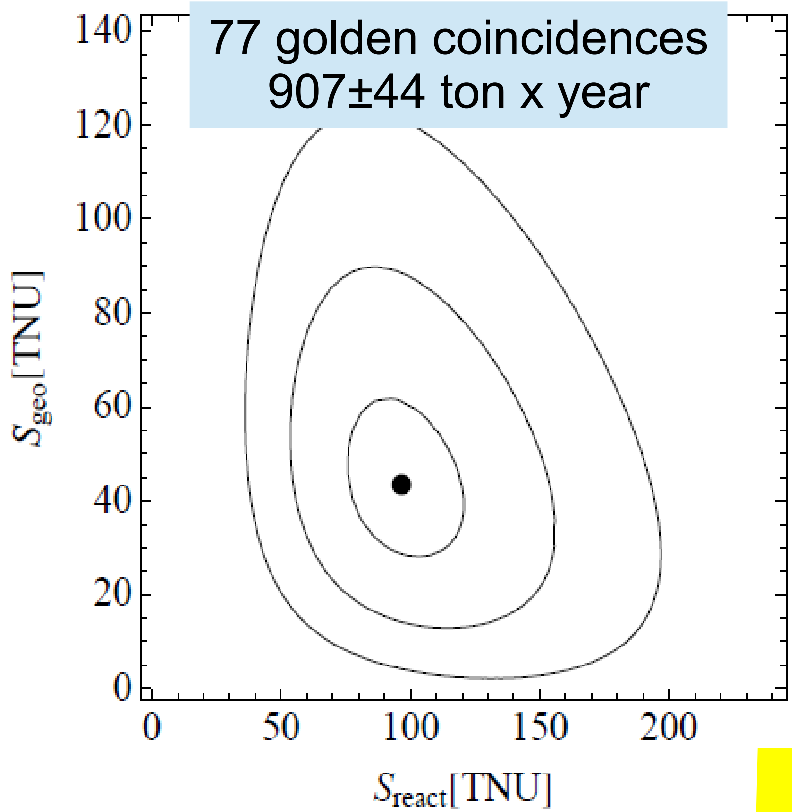
PRD 92 (2015) 031101(R)

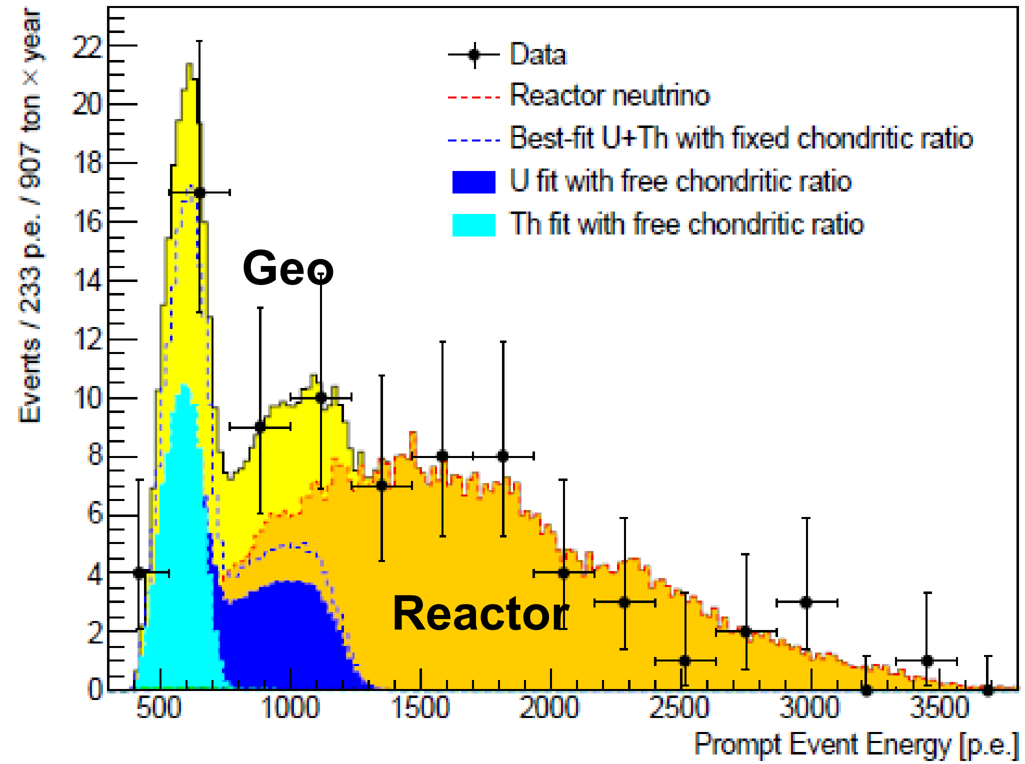
Geo-neutrinos: event selection

(MC-defined efficiency)
0.84 ± 0.01

Q_{prompt} > 480p.e.
$Q_{delayed}$ [860,1300]p.e.
ΔR (prompt-delayed) <1m
Δt (prompt-delayed) [20-1280]μs
$Gatti_{delayed}$ <0.015 (must be "β-like")
Large Fiducial Volume:
distance from the vessel > 25 cm

77 golden coincidences
907±44 ton x year





Background not due to reactors is very small

Unbinned maximal likelihood fit with unconstrained geo and reactor component.

S_{react} = 96.6 ± 15.9 TNU
Expected = 87 ± 4 TNU (after oscillations)

N_{geo} = 23.7 ± 6.1 events
S_{geo} = 43.5 ± 11.1 TNU

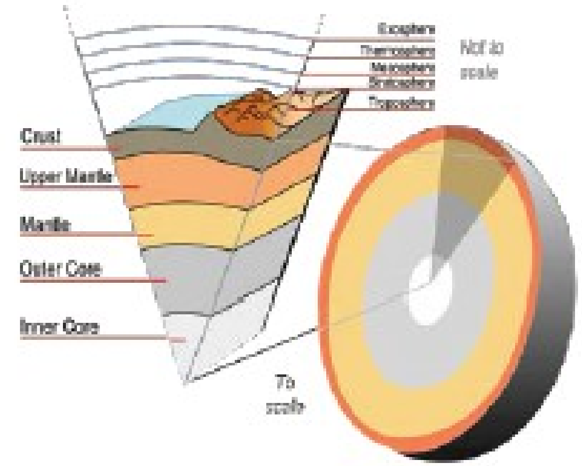
1 TNU = 1 event / 10^{32} protons / year

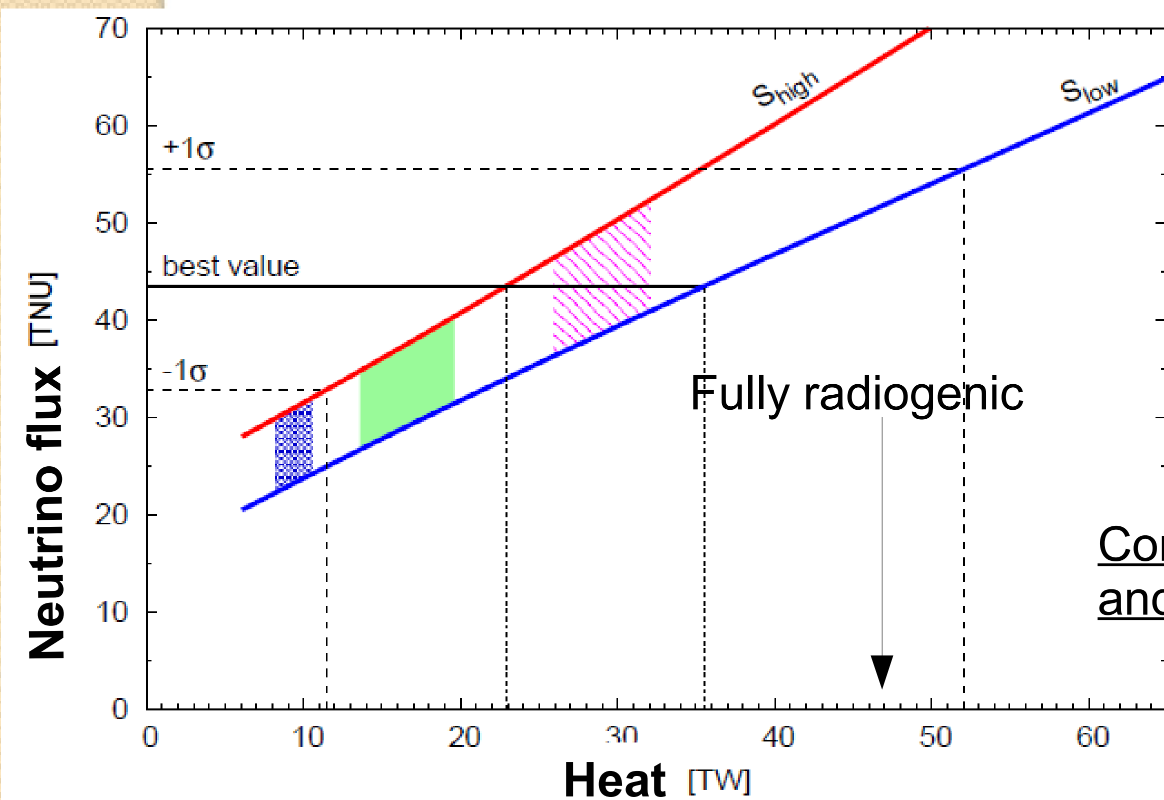
PRD 92 (2015) 031101(R)

Geo-neutrinos: implications

$$S_{Expected} = S_{LOCal} + S_{Rest\ Of\ Crust} + S_{Mantle}$$

- $S_{Expected}$: **43.5 ± 11.1 (data)**
- S_{LOCal}: **9.7 ± 1.3 (geological survey)**
- $S_{Rest\ Of\ Crust}$: **13.7 ± 2.5 (model)**
- S_{Mantle}: **$20.9^{+15.1}_{-10.3}$ (likelihood)**





No mantle contribution excluded at 98% C.L.

Compatible with different BSE flavors and mantle elemental distributions

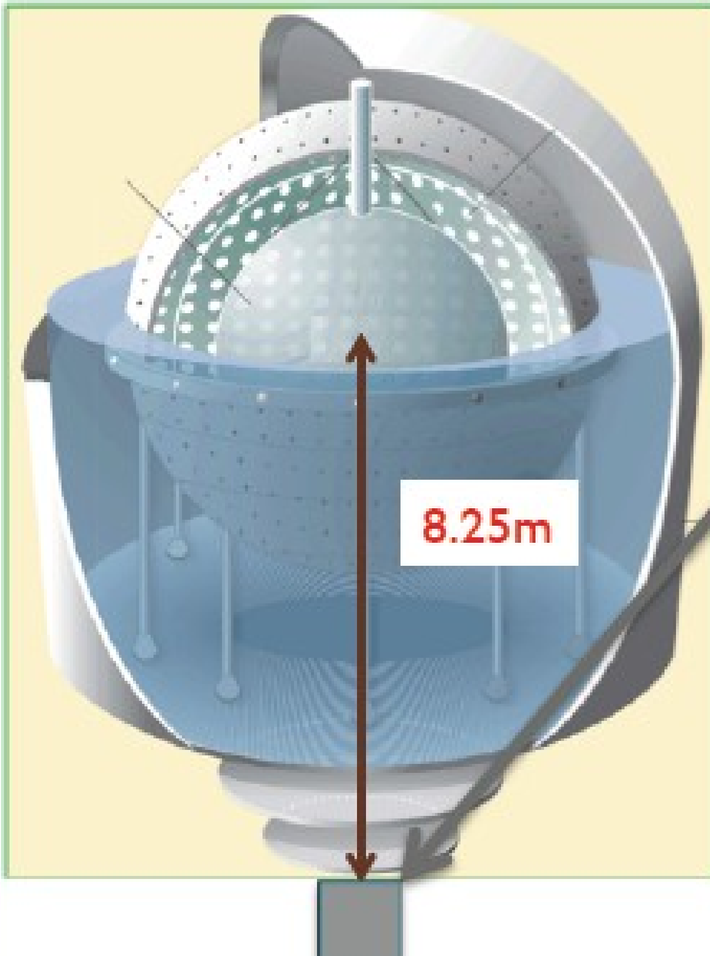
1 TNU = 1 event / 10^{32} protons / year

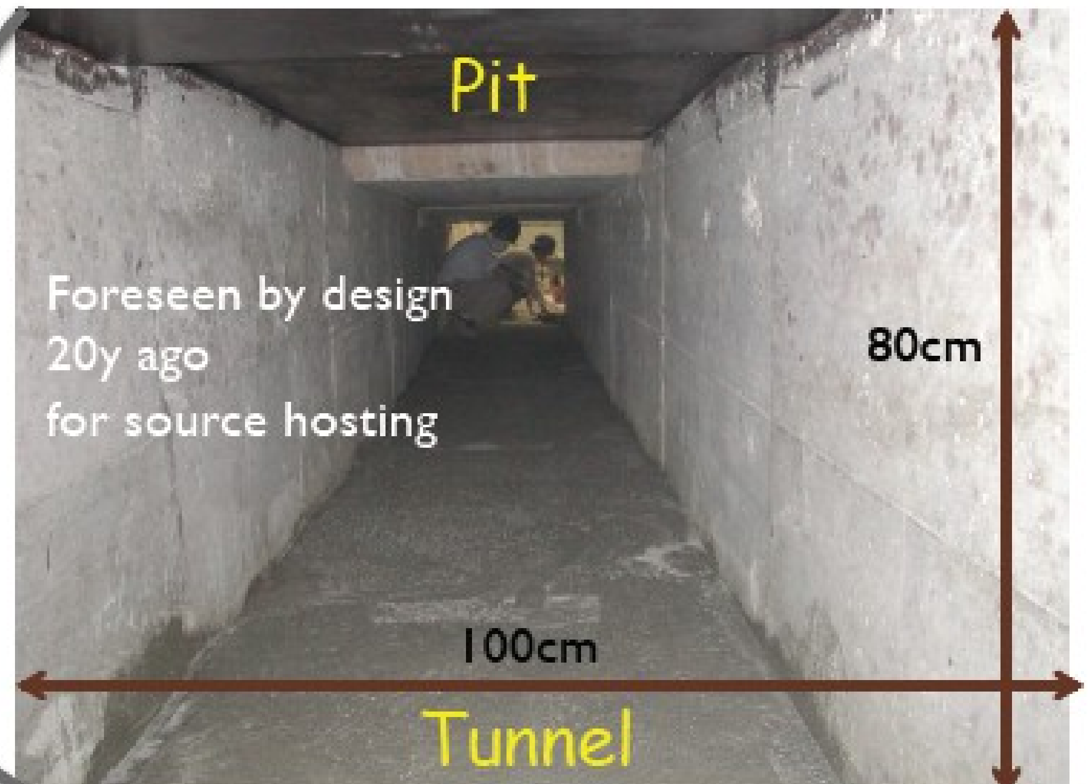
SOX concept

JHEP 08 (2013) 038

If reactor anomaly is interpreted in terms of oscillations into light sterile neutrinos it points to L/E ~ 1m/MeV

in Borexino with ~1MeV source:
resolution ~15cm < L < detector size ~10m

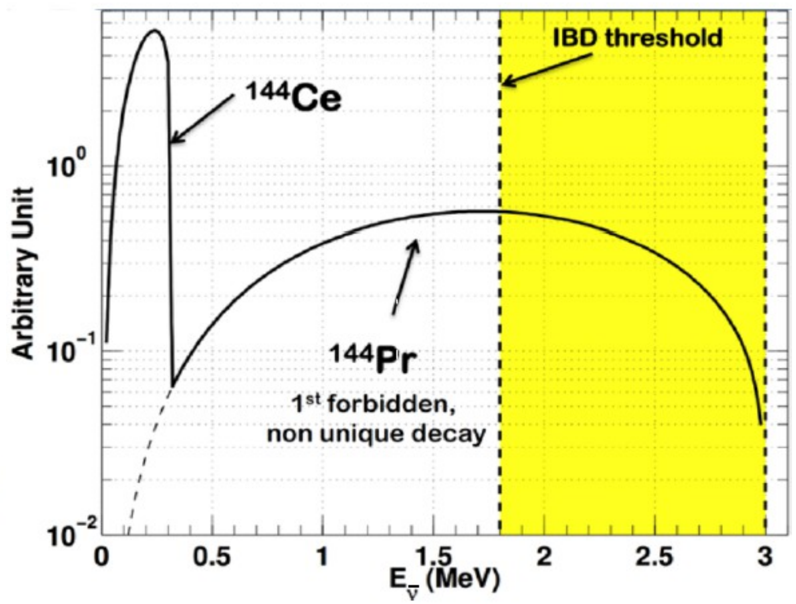


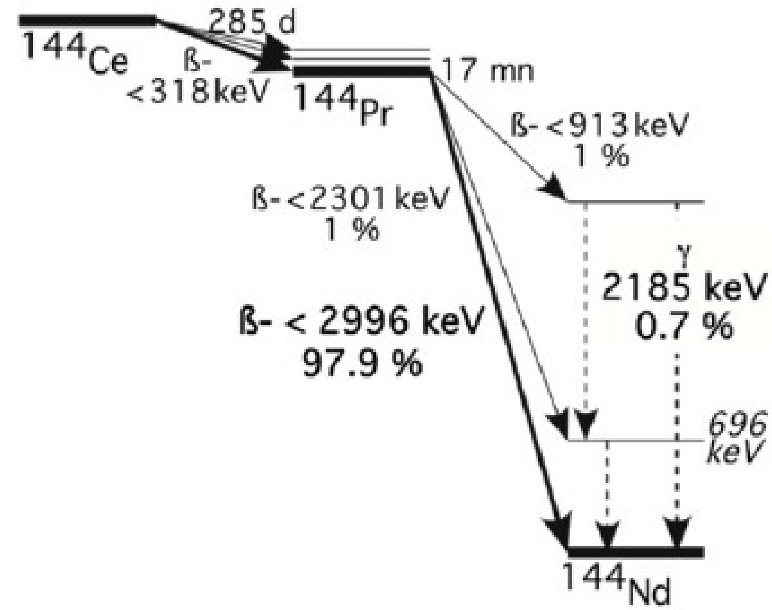


Uninvasive deployment:
no work on the detector
no risk of contamination
<u>does not terminate the solar run</u>

JHEP 08 (2013) 038

SOX: (anti)neutrino sources





^{144}Ce-Pr antineutrino generator up to 3MeV

Inverse Beta Decay detection tuned by geo-neutrino analysis

“long” half life: 285d

Activity : ~100kCi, > 10^{13} anti-nu /s

Must be determined at 1% precision: two calorimeters

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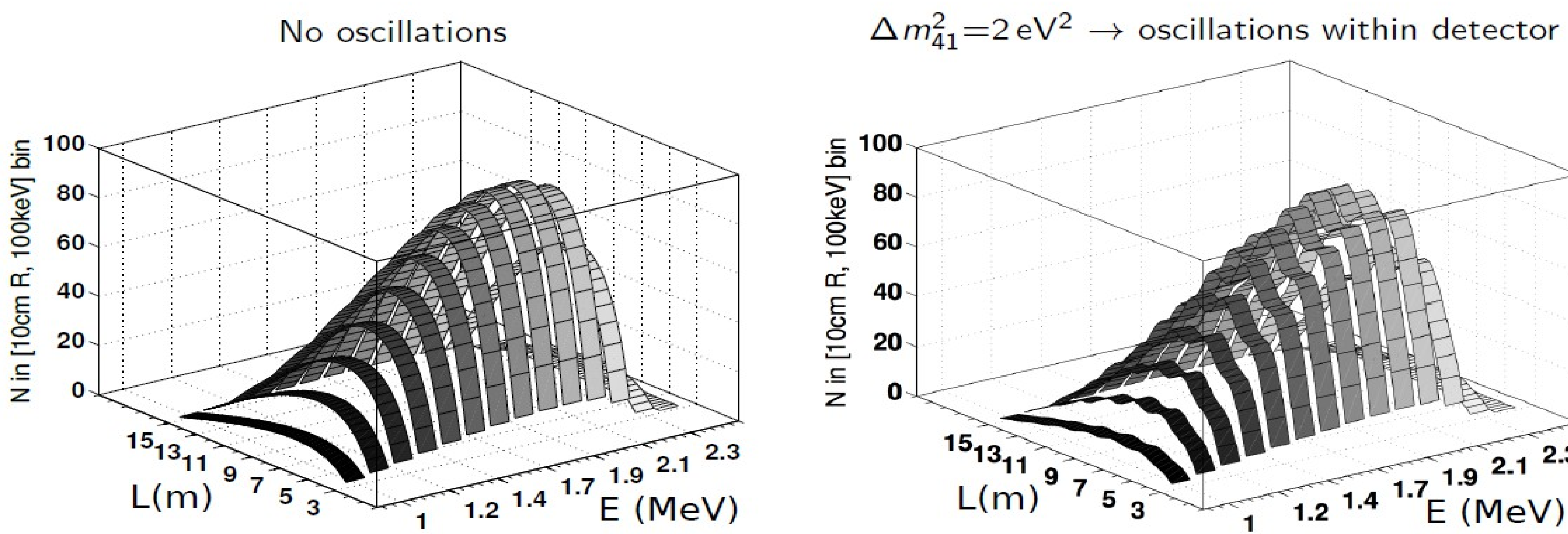
SOX ^{144}Ce-^{144}Pr run

- Source can be produced out of spent nuclear fuel in Mayak (Ru).
- Larger anti-nu cross section.
- Problem with 2.1 MeV gamma: needs tungsten shielding.

tentative schedule:
late **2016**
run for 1.5 year



[Cribier et al., PRL 107, 201801 (2011)]

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{ee})\sin^2\frac{\Delta m^2_{41} L}{4E}$$

SOX: sensitivity

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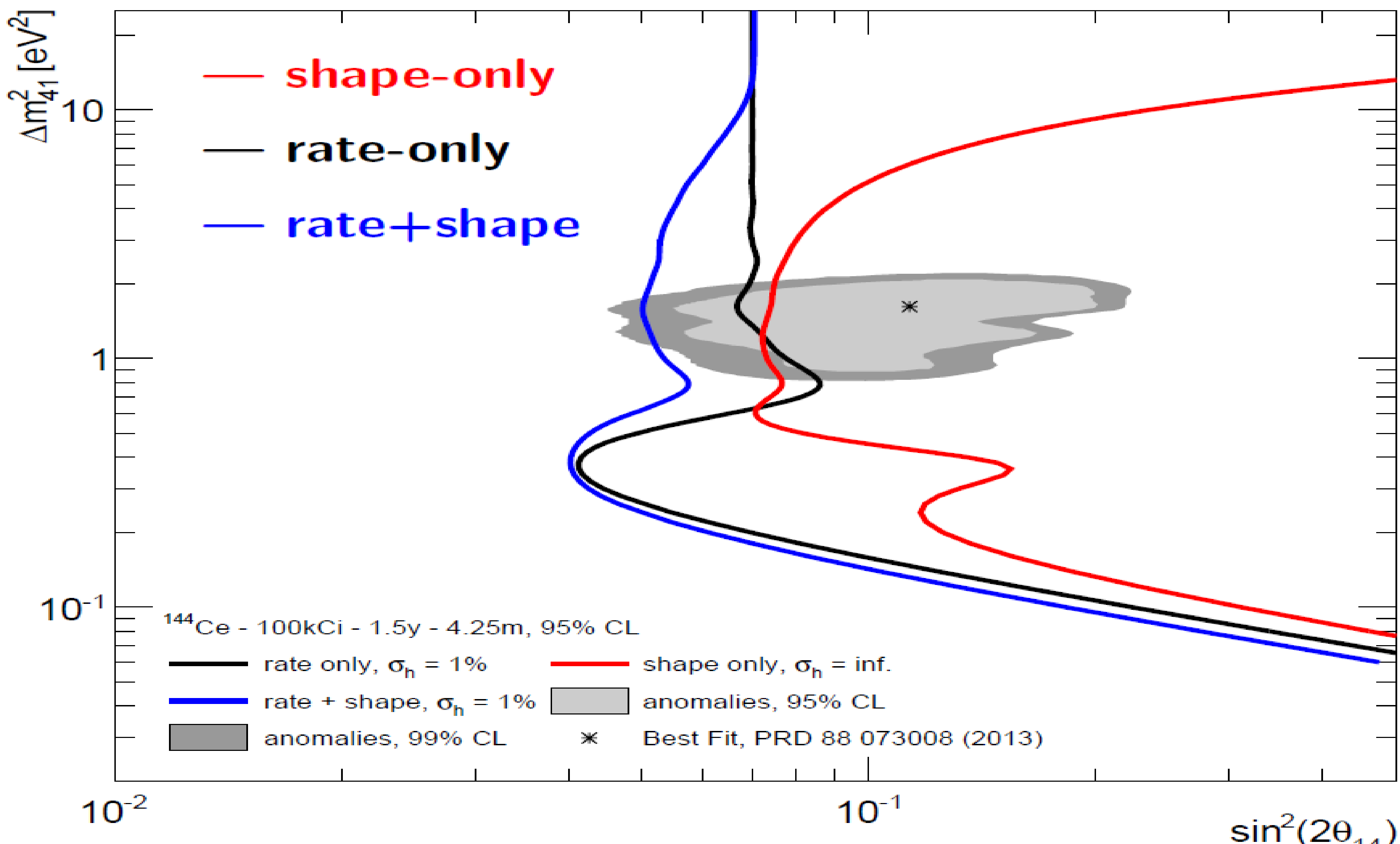

Conclusions and outlook

- ✔ Borexino is taking data regularly since 2007:
  - ✔ The *background levels are unprecedented* and still improving.
  - ✔ Phase-I brought fundamental results over a broad range of solar neutrinos (**^{7}Be, ^{8}B, pep, CNO limits**) and geo-nu.
- ✔ We are now <u>in Phase-II since 2012</u>:
  - ✔ **pp-neutrino flux** accomplished **DONE**
    - ✔ First direct observation of neutrinos from the primary proton-proton fusion reaction taking place in the Sun's core.
  - ✔ upcoming: **CNO flux measurement** (or stronger limits): **2016**
    - ✔ first confirmation of fusion process that powers most stars.
    - ✔ it could resolve the solar "metallicity problem".
  - ✔ Also pep, ^{7}Be, ^{8}B and geo-neutrino more stringent measurements.
- ✔ **SOX** project will test indications for **sterile neutrinos** with a ^{144}Ce-Pr source **2017**

Geo-nu systematics

^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221±0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α,n) in scintillator	0.165±0.010
(α,n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	< 0.43
untagged muons	0.12±0.01
Fission in PMTs	0.032±0.003
^{214}Bi-^{214}Po	0.009±0.013
Total	$0.78^{+0.13}_{-0.10}$
	< 0.65(combined)