Recent Borexino results and prospects for near future

Recontres de Moriond 2014
Electroweak Interactions and Unified Theories
La Thuile 15-22nd Mar 2014

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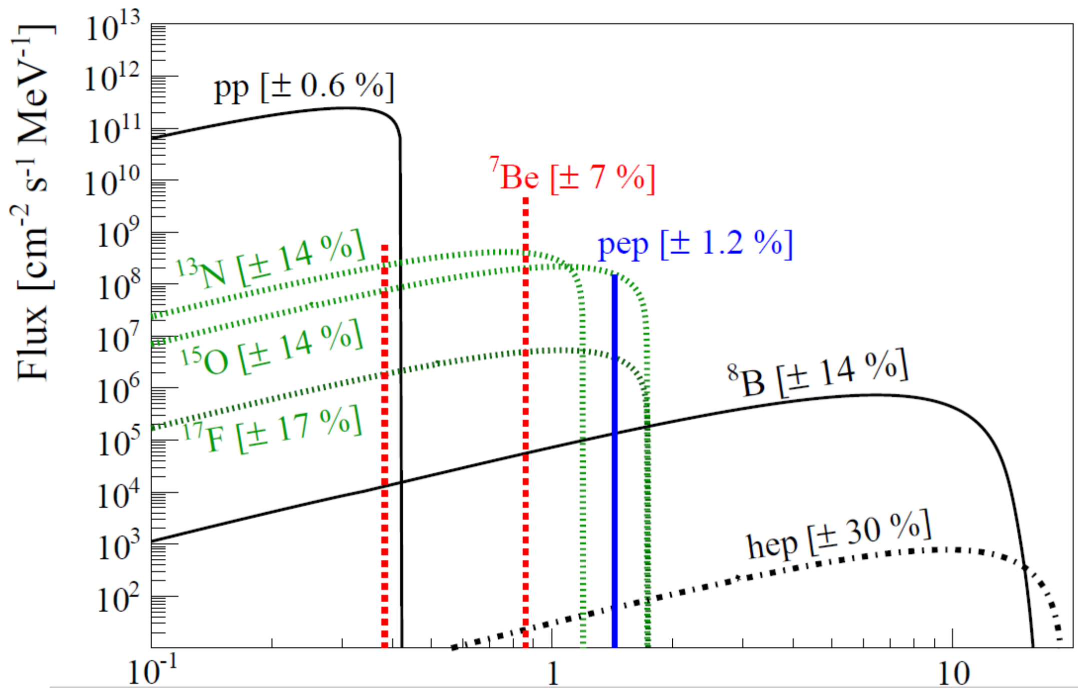
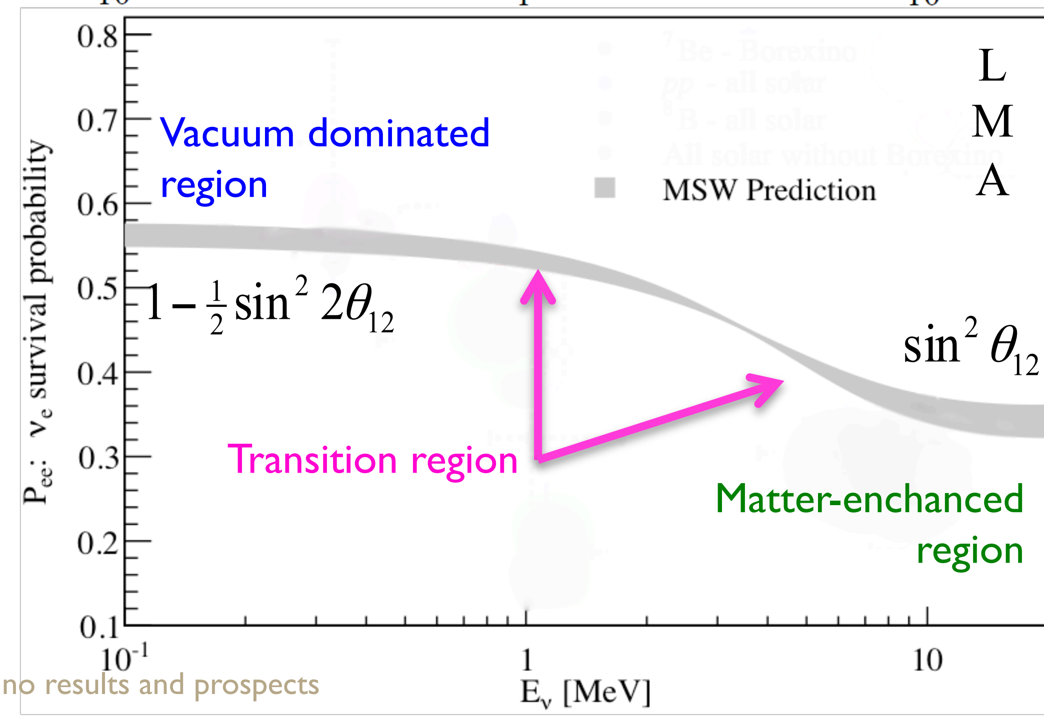
Why Borexino?

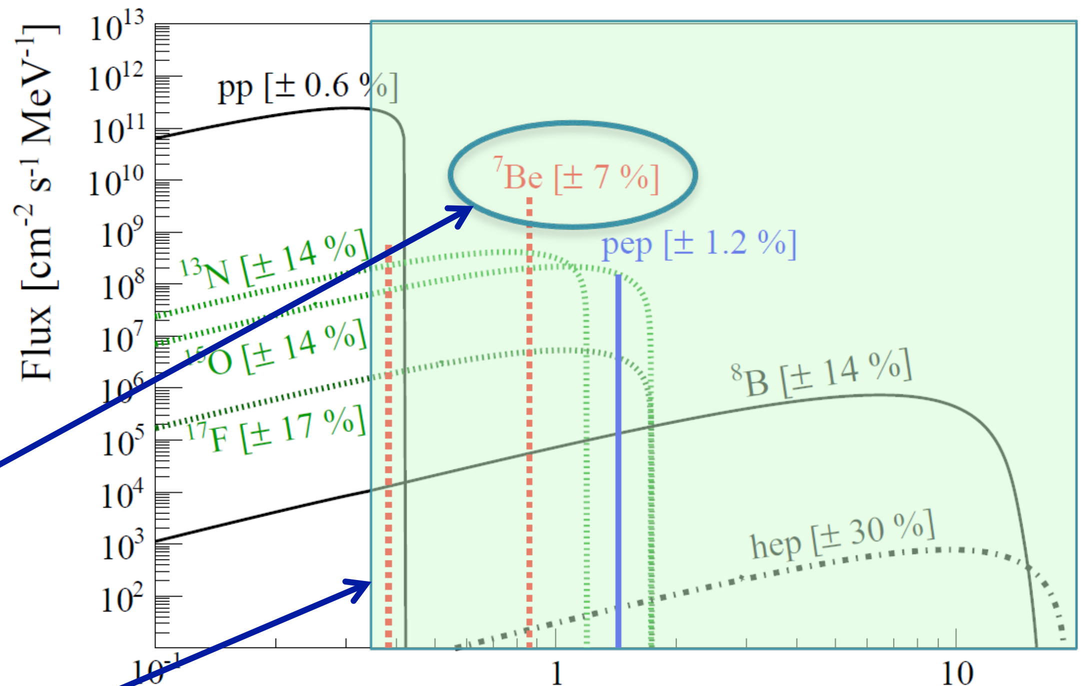


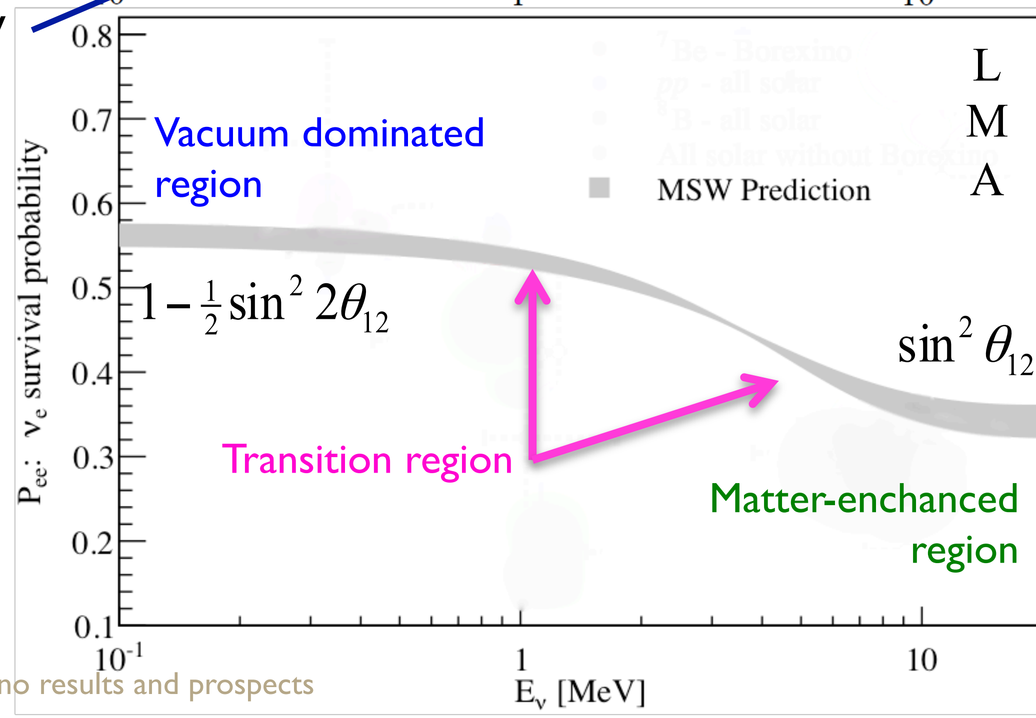


Why Borexino?

Borexino design goal: ^{7}Be

Borexino design threshold ~250keV



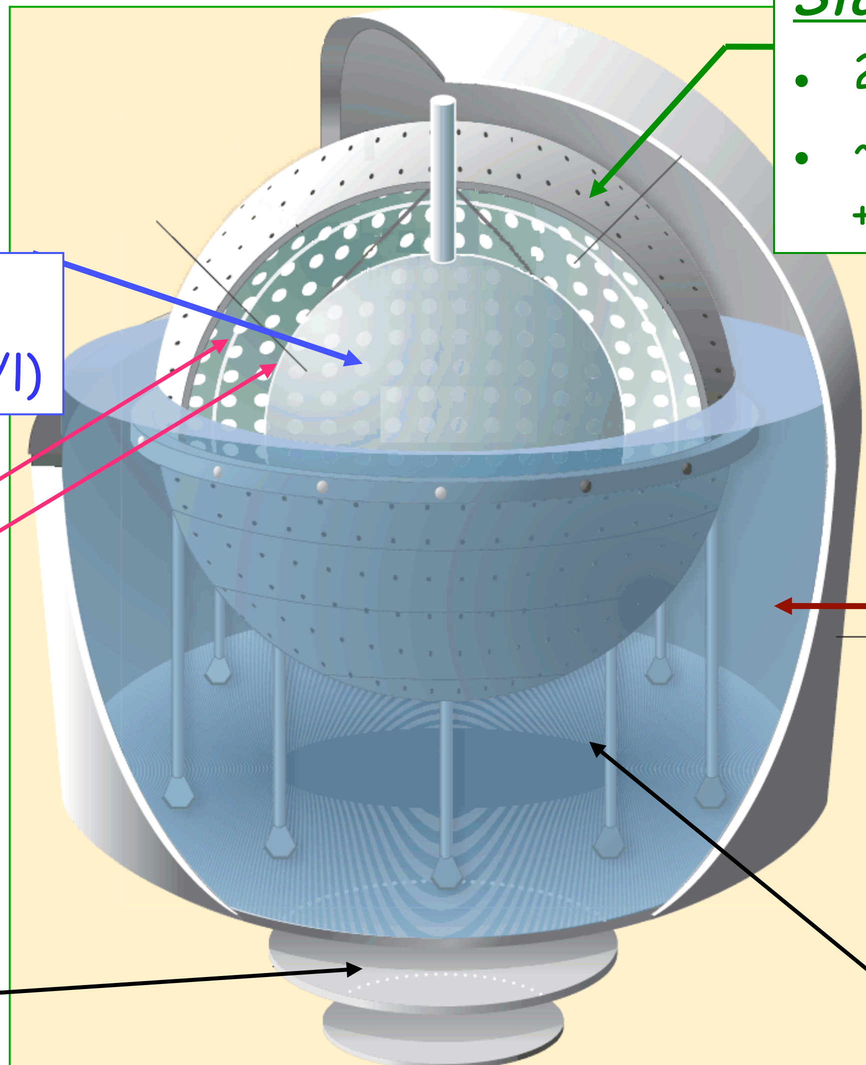


The Borexino Detector

Neutrino electron scattering
ν e -> ν e

Scintillator:
270 t PC+PPO (1.4 g/l)

Nylon vessels:
(125 μm thick)
Inner: 4.25 m
Outer: 5.50 m
(radon barrier)



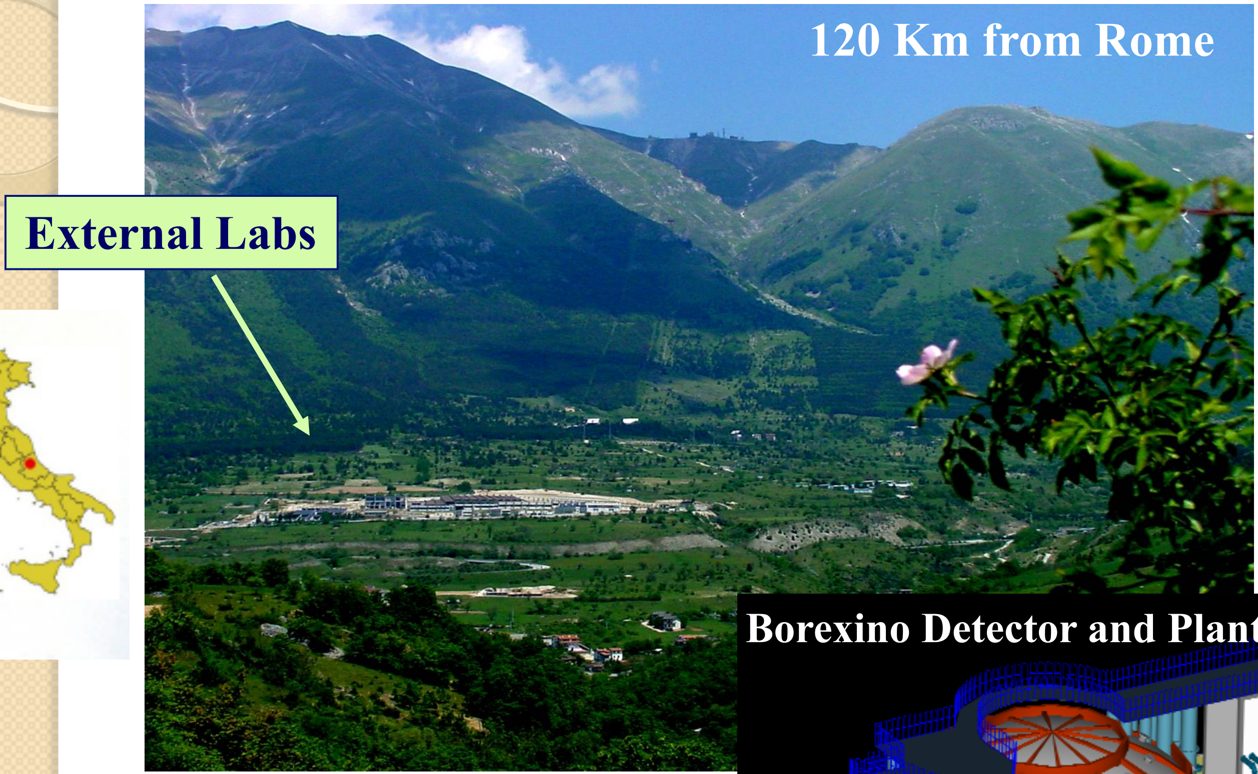
Stainless Steel Sphere:
- 2212 PMTs
- ~ 1000 m^3 buffer of pc +dmp (light queched)

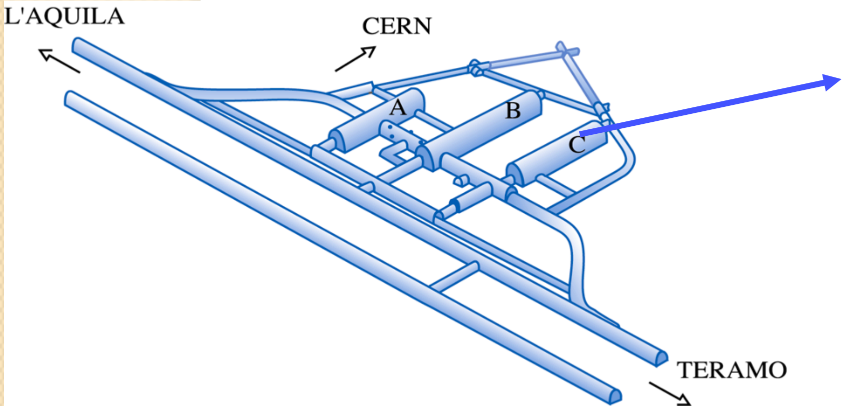
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

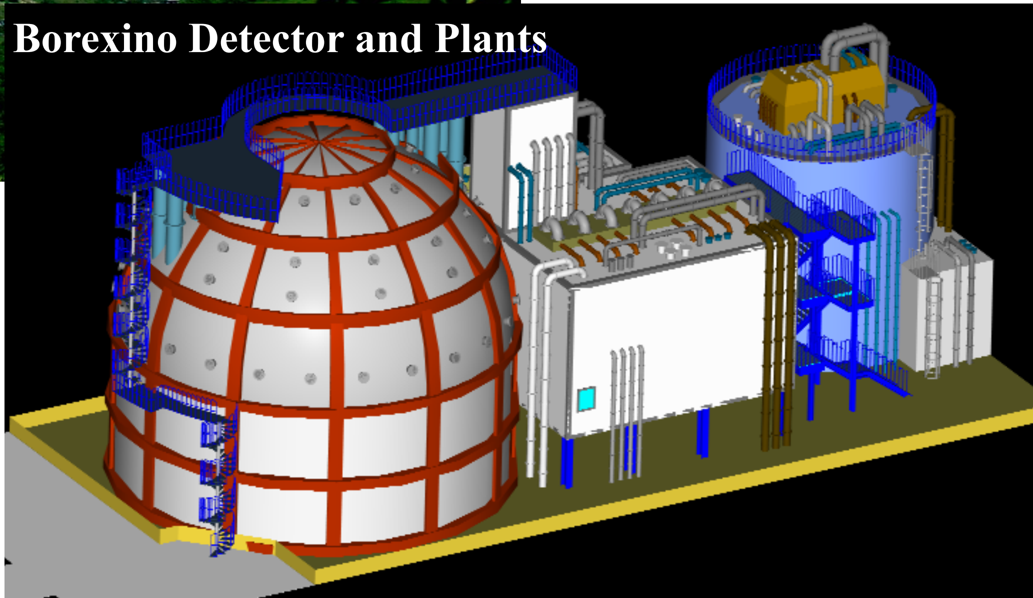
Carbon steel plates

20 legs

Experimental site



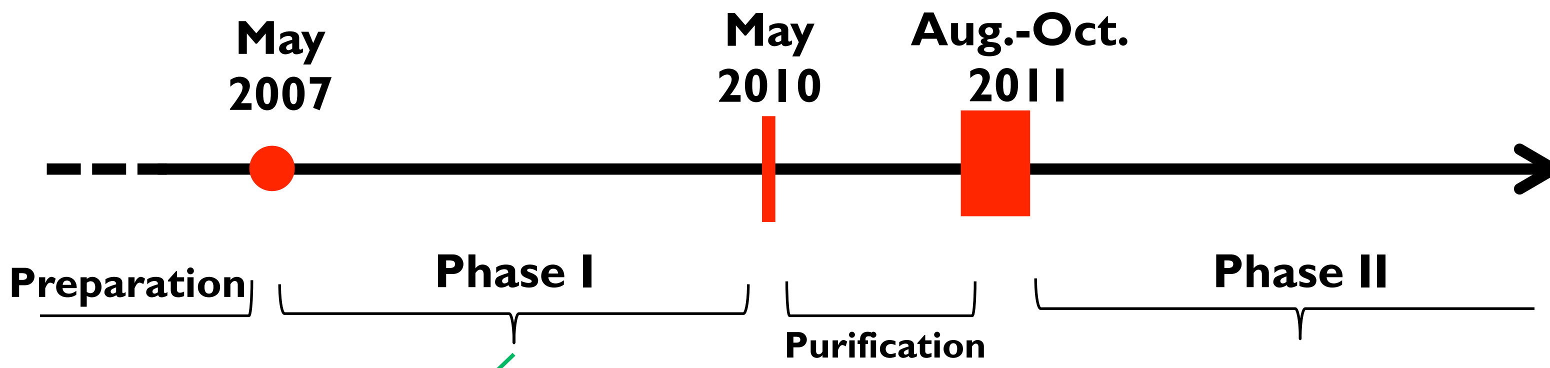




Laboratori Nazionali del Gran Sasso

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

Borexino data taking campaign



Phase I:

- (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

Phase II:

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

Phase I and Phase II:

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

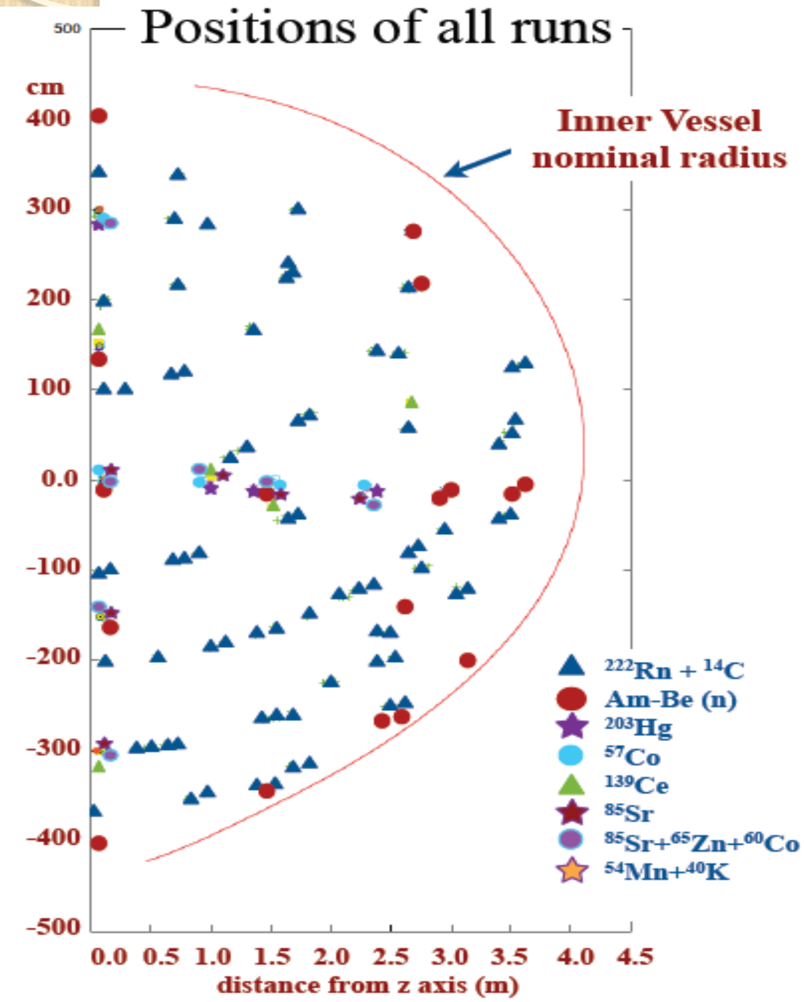
Borexino backgrounds

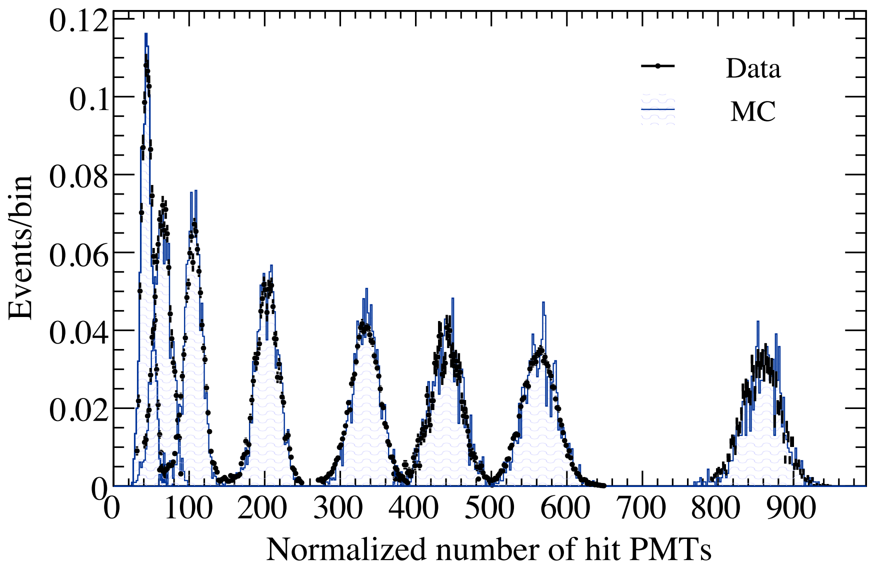
Isotope	Typical	Required	Before purification	After purification
^{238}U	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5) \cdot 10^{-18}$ g/g	$< 0.8 \cdot 10^{-19}$ g/g
^{232}Th	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \cdot 10^{-18}$ g/g	$< 1.0 \cdot 10^{-18}$ g/g
^{14}C/^{12}C	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



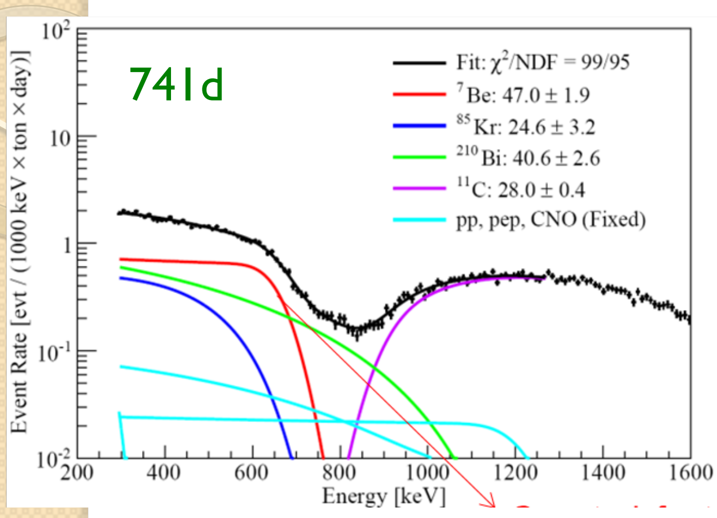


Energy scale uncertainty in the range 0.2÷2 MeV is better than **1.5%**

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}



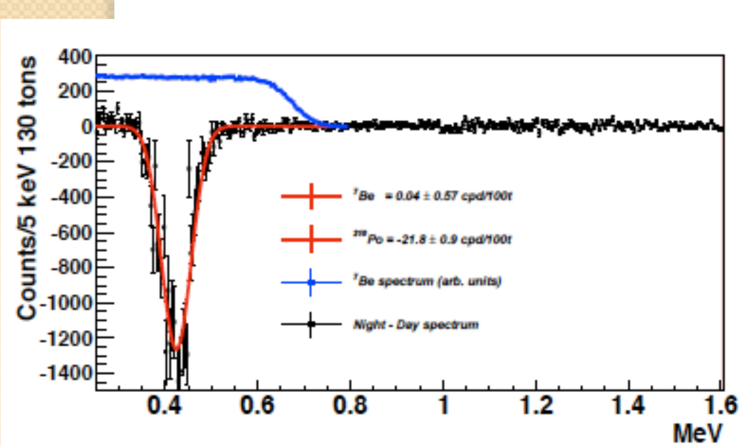
$$46.0 \pm 1.5(stat)^{+1.5}_{-1.6}(syst)\,/\,d\,/\,100t$$

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

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

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

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

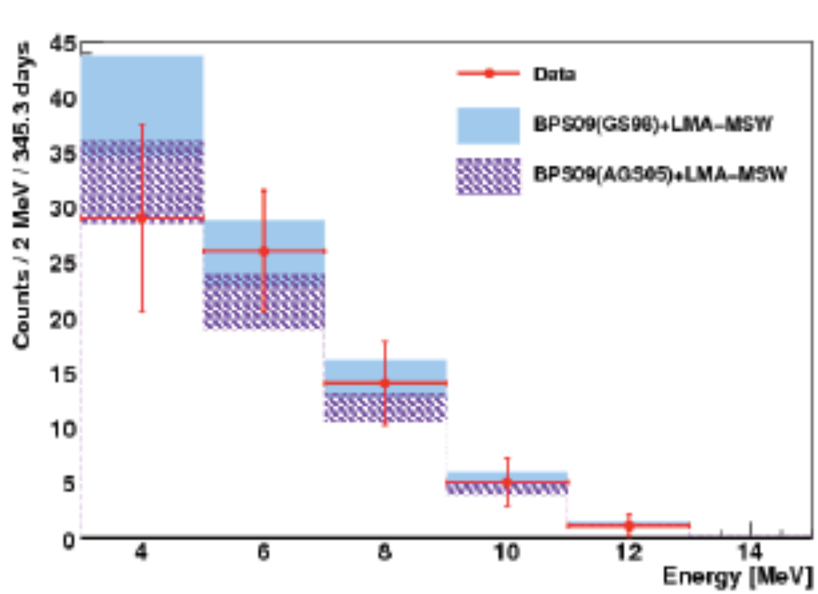


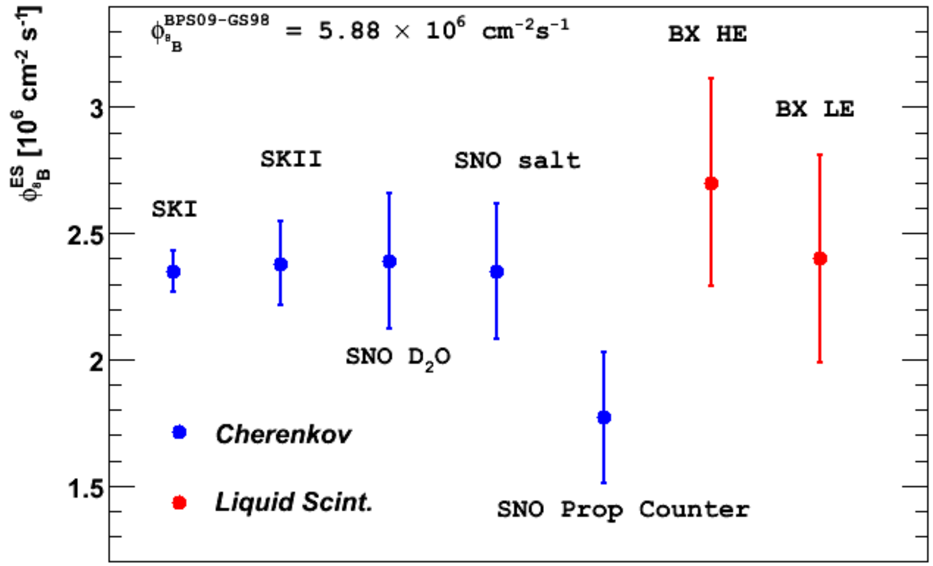
$$A_{DN} = \frac{N-D}{(N+D)/2} = 0.001 \pm 0.012\,(stat) \pm 0.007(sys)$$

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^{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

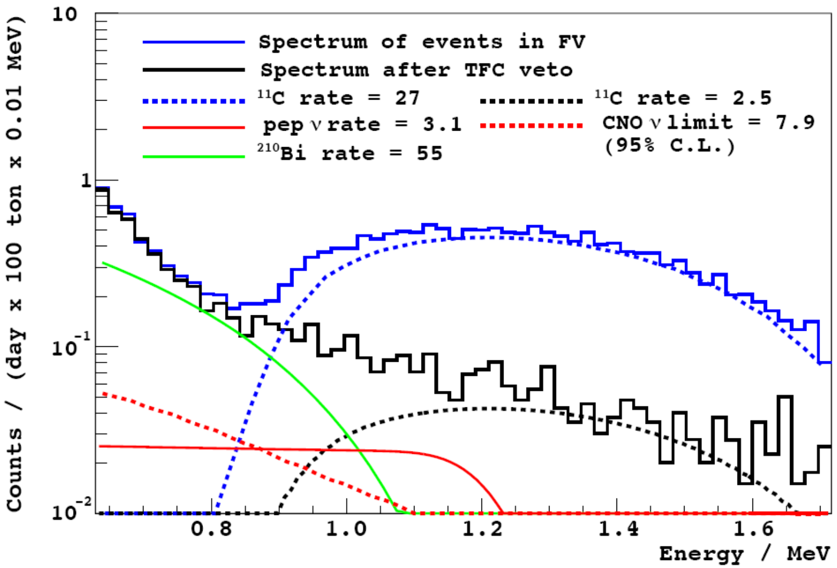
Phys. Rev. Lett. 108, 051302 (2012)

pep flux and CNO limits

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

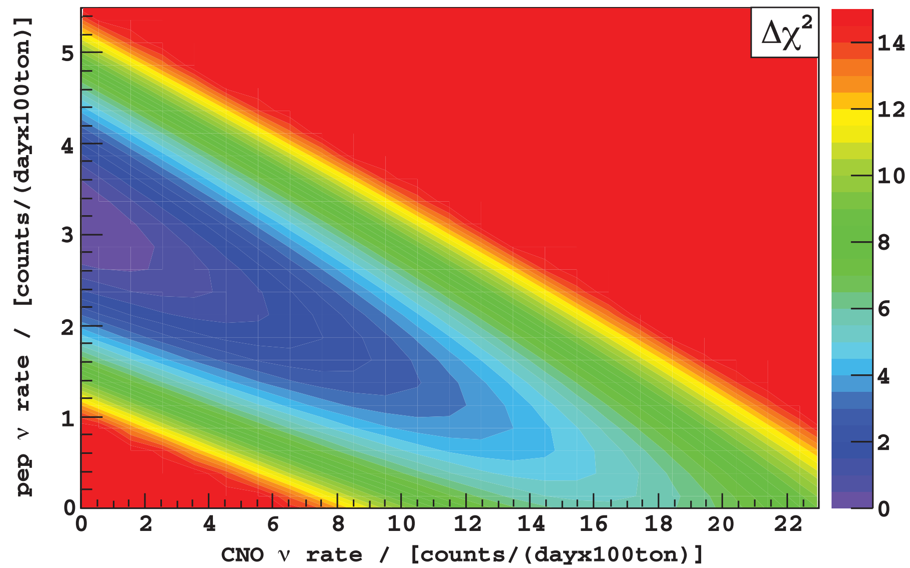
Φ^{LMA}_{pep} = (1.6 ± 0.3) × 10^8 cm^{-2} s^{-1}

P_{ee} = 0.62 ± 0.17 at 1.44 MeV

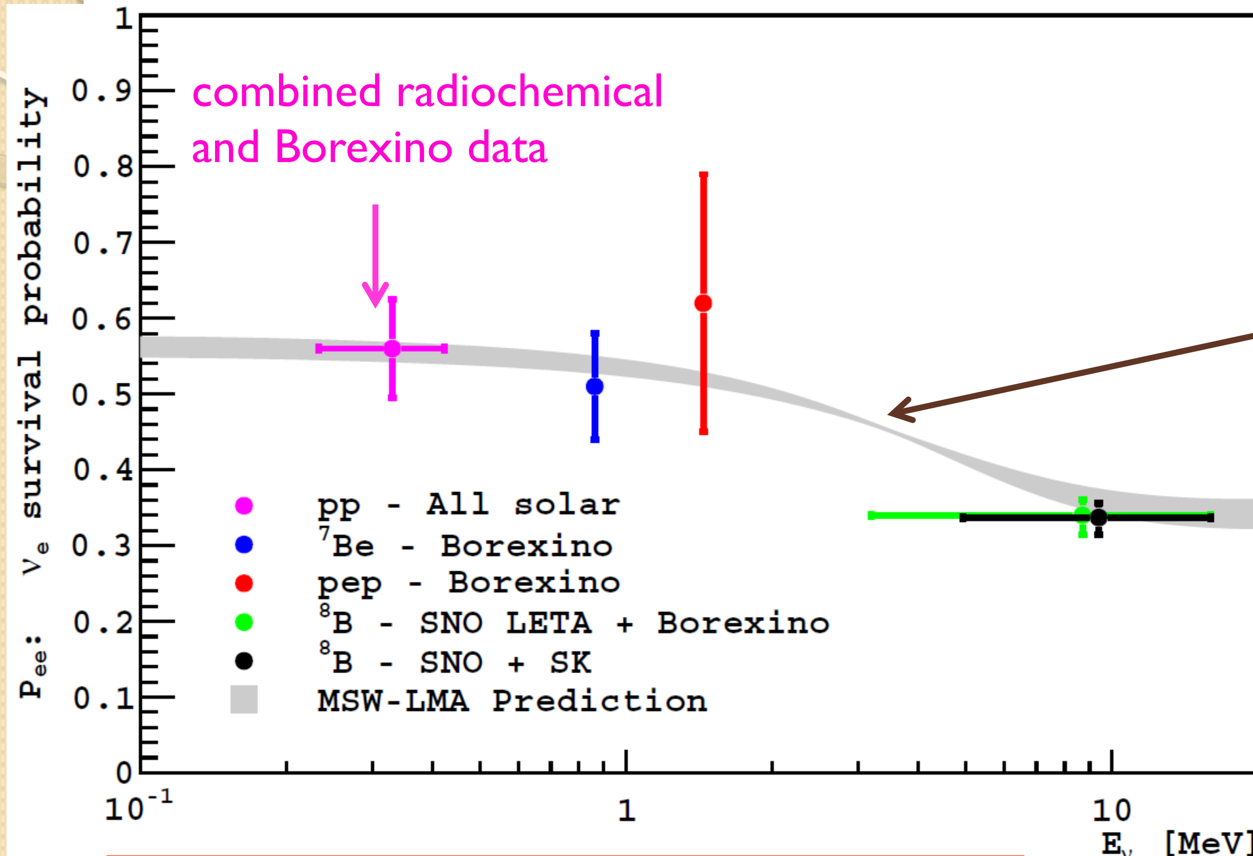


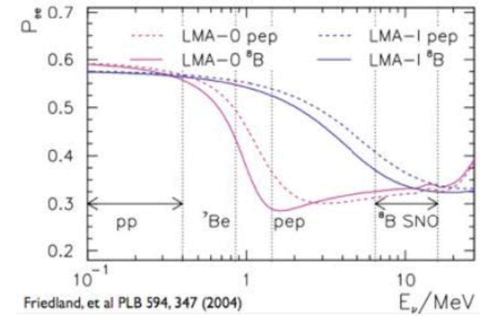
R < 7.1 cpd/100 t (95 % C.L.)

Φ^{LMA}_{CNO} < 7.7 × 10^8 cm^{-2} s^{-1} (95 % C.L.)



P_{ee} after Borexino





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

still missing!
pp and CNO
spectroscopy

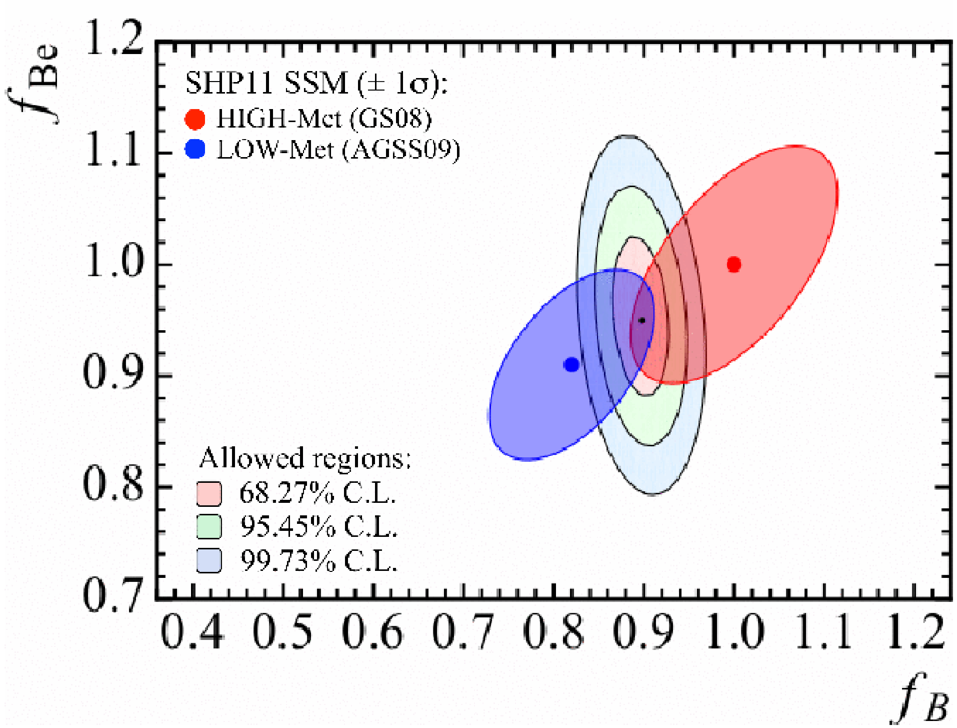
Two approaches to transition region:

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

Comparison with SSM: the metallicity puzzle

ν	Diff. %
pp	0.8
pep	2.1
^{7}Be	8.8
^{8}B	17.7
^{13}N	26.7
^{15}O	30.0
^{17}F	38.4



SHP11:
A.M. Serenelli, W. C.Haxton and C. Pena-Garay, Astro-phys. J. 743 (2011) 24

GS98:
N. Grevesse and A. J. Sauval, Space Sciences Reviews 85, 161 (1998)

AGSS09:
Aldo M. Serenelli *et al 2009* *ApJ* ***705 L123***

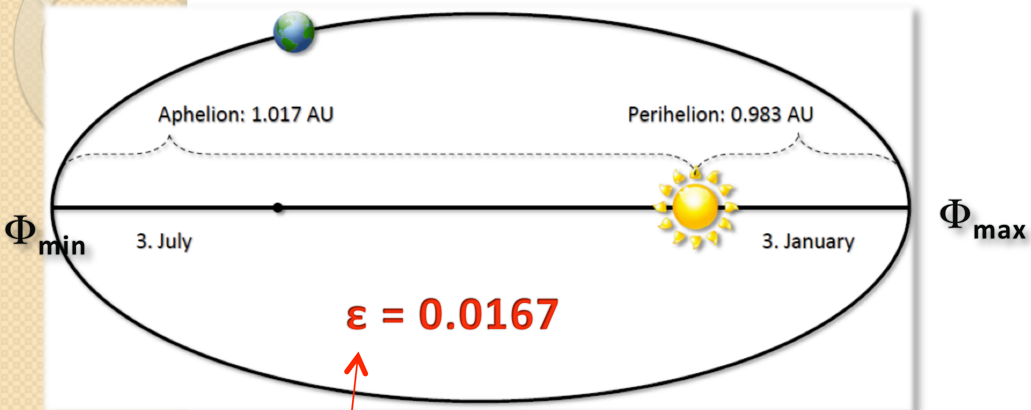
^{7}Be and ^{8}B currently cannot discriminate

↓

need to go for CNO

arXiv:1308.0443

^{7}Be- ν annual modulation



$$\Phi(t) = \Phi_0 \left(1 + 2\varepsilon \cos\left(\frac{2\pi t}{T} - \phi\right)\right)$$

$$\Phi_{max} - \Phi_{min} = 6.8\%$$

T = 1 year

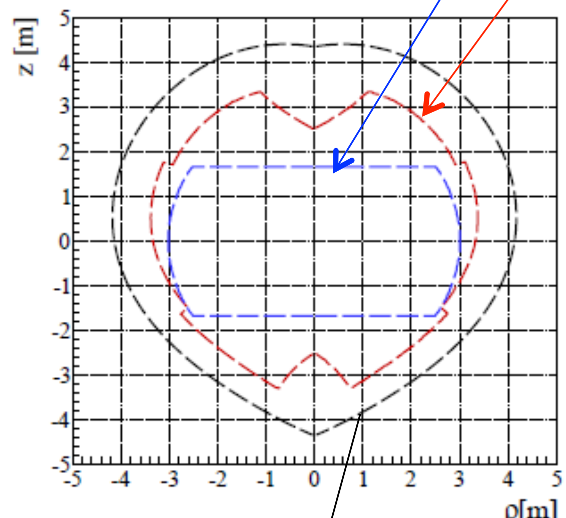
Mean flux measured by Borexino: 46 $\pm$ 1.5 $^{+1.5}_{-1.5}$ cpd/100 ton

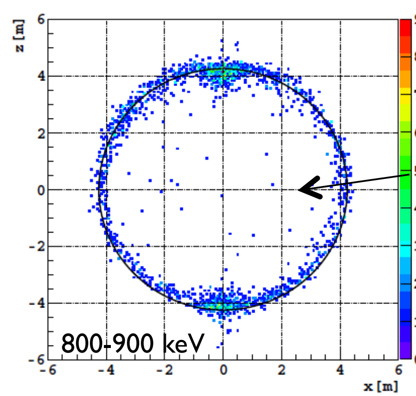
Spectral fit in sub-periods: too large stat. errors!

3 analysis methods (consistent results)

- Fit of the rate vs time;
- Lomb Scargle analysis;
- Empirical Mode Decomposition;

Enlarged, dynamic FV **(mean = 141 ton)**
(with respect to the ^{7}Be flux (75 ton))





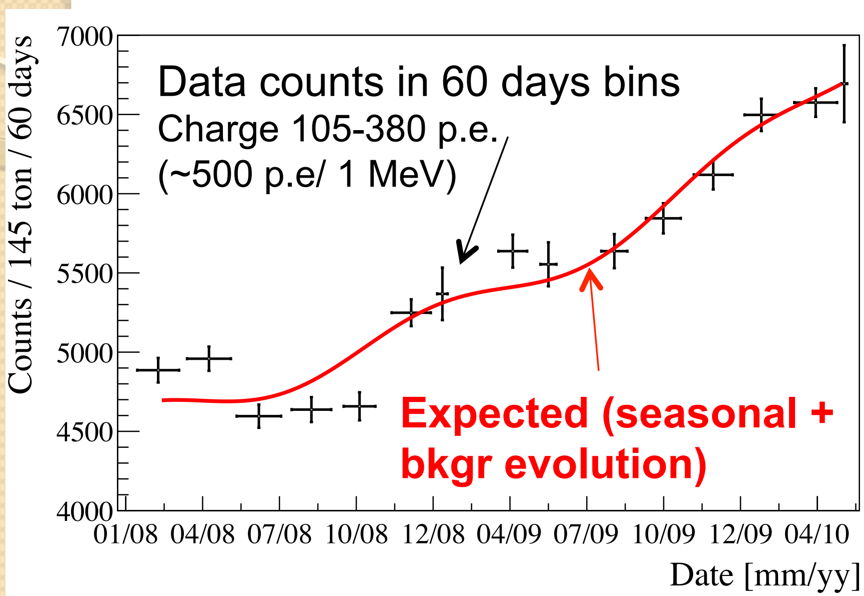
Reconstructed vessel shape = f (time, 1 week bin)

Based on ^{210}Bi on the vessel

arXiv:1308.0443

^{7}Be- ν annual modulation

Phase I, ~ 850d astr. time

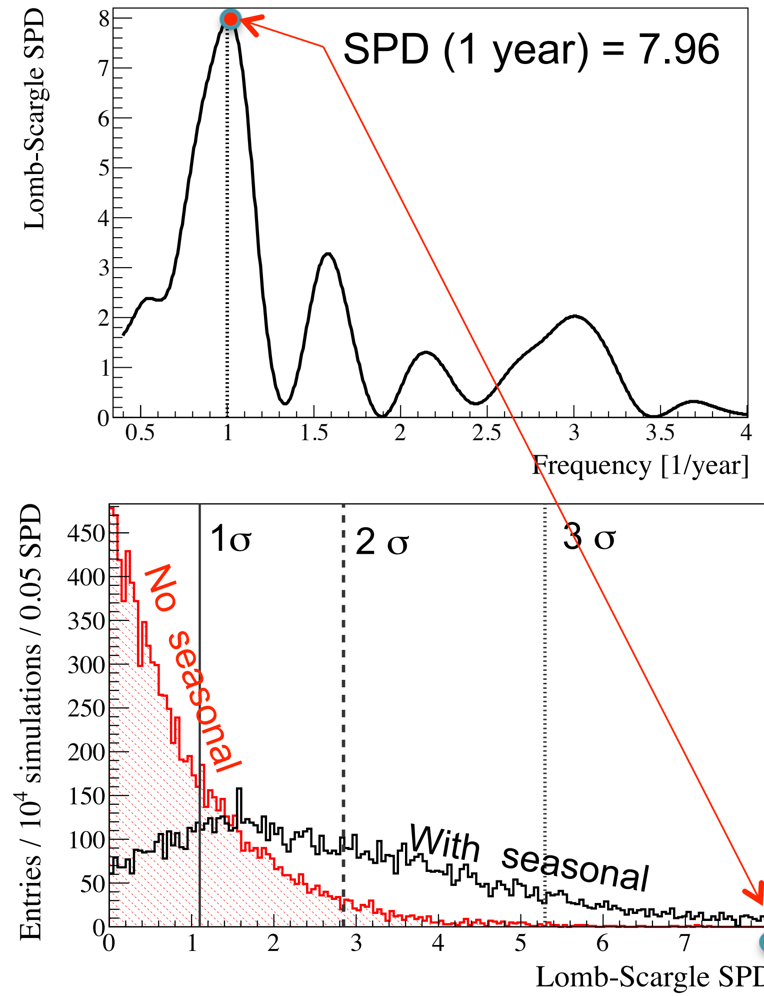


$$R = R_0 + \underbrace{R_{Bi} e^{\Lambda_{Bi} t}}_{\text{independently determined}} + \overline{R}\left[1 + 2\varepsilon \cos\left(\frac{2\pi}{T} - \phi\right)\right]$$

T=1year±0.07
φ=(0±14)d

R, ε, within 2σ from expected values

No seasonal escluded at > 3σ



Monte Carlo distribution of the Spectral Power Density (SPD) with real S/B ratio

JCAP08(2013)049

Cosmogenic Backgrounds

Cosmic Muons in LNGS

LNGS	Experiment	Year	10^{-4} μ m^{-2} s^{-1}	μ m^{-2} d^{-1}
Hall A	LVD	2009	3.31±0.03	28.5±0.2
Hall B	MACRO	1995	3.22±0.08	27.8±0.7
Hall C	BOREXINO	2012	3.41±0.01	29.46±0.08

Cosmogenic neutron production in organic liquid scintillator:

Yield =

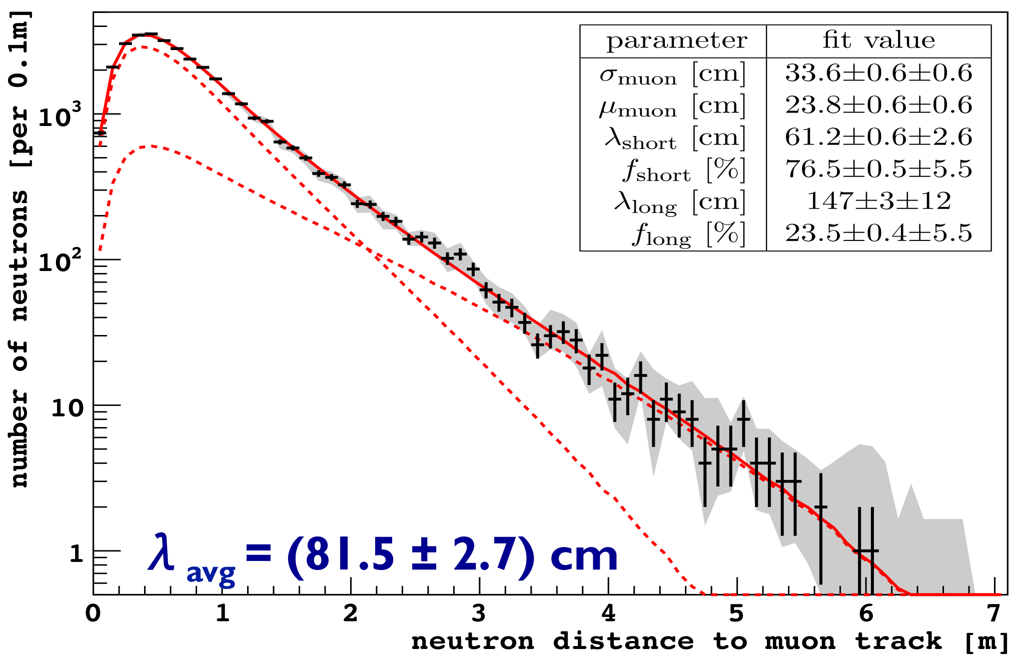
$(3.10 \pm 0.07_{stat} \pm 0.08_{syst})$

10^{-4} n/(μ g/cm^2)

Flux =

$(7.31 \pm 0.17_{stat} \pm 0.19_{syst})$

n/m^2/d



Isotopes productions rates (compared with simulations)

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Borexino and surrounded area simulated with Fluka and 4 Geant4 physics list
Muon energy and angular distributions from MACRO
$\mu^+/\mu^- = 1.38$ from OPERA

	GEANT4 Model III	GEANT4 Model IV	FLUKA	Borexino	KamLAND
	— $\langle E_\mu \rangle = 283 \pm 19\,\mathrm{GeV}$ —				$\langle E_\mu \rangle = 260 \pm 8\,\mathrm{GeV}$
Isotopes	Yield $[10^{-7}\,(\mu\,\mathrm{g/cm^2})^{-1}]$				
^{12}**N**	1.11 ± 0.13	3.0 ± 0.2	0.5 ± 0.2	< 1.1	1.8 ± 0.4
^{12}**B**	30.1 ± 0.7	29.7 ± 0.7	28.8 ± 1.9	56 ± 3	42.9 ± 3.3
^{8}**He**	< 0.04	0.18 ± 0.05	0.30 ± 0.15	< 1.5	0.7 ± 0.4
^{9}**Li**	0.6 ± 0.1	1.68 ± 0.16	3.1 ± 0.4	2.9 ± 0.3	2.2 ± 0.2
^{8}**B**	0.52 ± 0.09	1.44 ± 0.15	6.6 ± 0.6	14 ± 6	8.4 ± 2.4
^{6}**He**	18.5 ± 0.5	8.9 ± 0.4	17.3 ± 1.1	38 ± 15	not reported
^{8}**Li**	27.7 ± 0.7	7.8 ± 0.4	28.8 ± 1.0	7 ± 7	12.2 ± 2.6
^{9}**C**	0.16 ± 0.05	0.99 ± 0.13	0.91 ± 0.10	< 16	3.0 ± 1.2
^{11}**Be**	0.24 ± 0.06	0.45 ± 0.09	0.59 ± 0.12	< 7.0	1.1 ± 0.2
^{10}**C**	15.0 ± 0.5	41.1 ± 0.8	14.1 ± 0.7	18 ± 5	16.5 ± 1.9
^{11}**C**	315 ± 2	415 ± 3	467 ± 23	886 ± 115	866 ± 153
Neutrons	Yield $[10^{-4}\,(\mu\,\mathrm{g/cm^2})^{-1}]$				
	3.01 ± 0.05	2.99 ± 0.03	2.46 ± 0.12	3.10 ± 0.11	2.79 ± 0.31

in agreement with spectral fit result

G4 seems to reproduce better n-Yield, if n production in missing ^{11}C is not taken into account

Fluka and Geant4 reproduce results satisfactorily
notable exceptions like ^{12}B and ^{11}C

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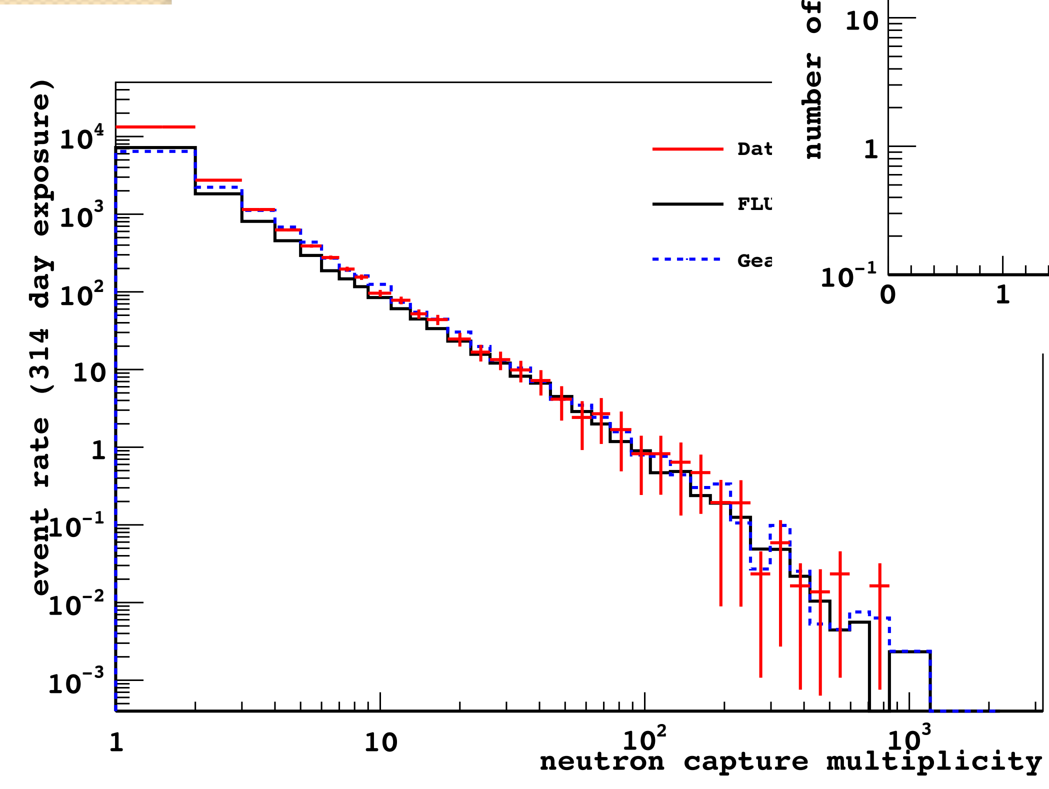
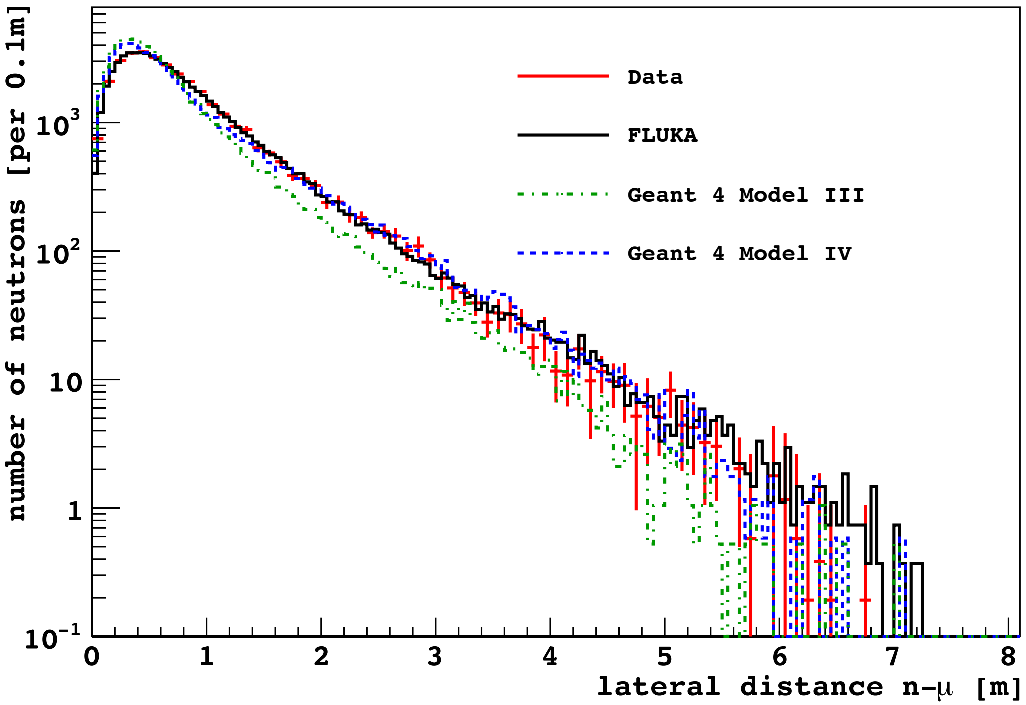
n multiplicity and lateral distance





Both Geant4 and Fluka show reasonble agreement with data

Phase II program

- **pp-ν flux measurement:**
  - first direct observation of neutrinos from the primary proton-proton fusion reaction taking place in the Sun's core.

2014

- Precision pep-ν neutrino measurement (> 3 σ).
- **Measurement (or strong limits) on CNO ν flux:**
  - first confirmation of fusion process that powers most stars.
  - can help resolve the solar "metallicity problem".

2015

- ^{7}Be-ν neutrino flux measurement at 3% and seasonal variation.
- Geo-ν flux measurement with higher statistics.
- ^{8}B-ν measurement with x4 statistics (aiming 10%).

2016-17

- **Measurements with artificial neutrino sources: Project SOX: Short distance Oscillations with BoreXino.**
  - search for sterile neutrino
  - measurement of neutrino magnetic moment

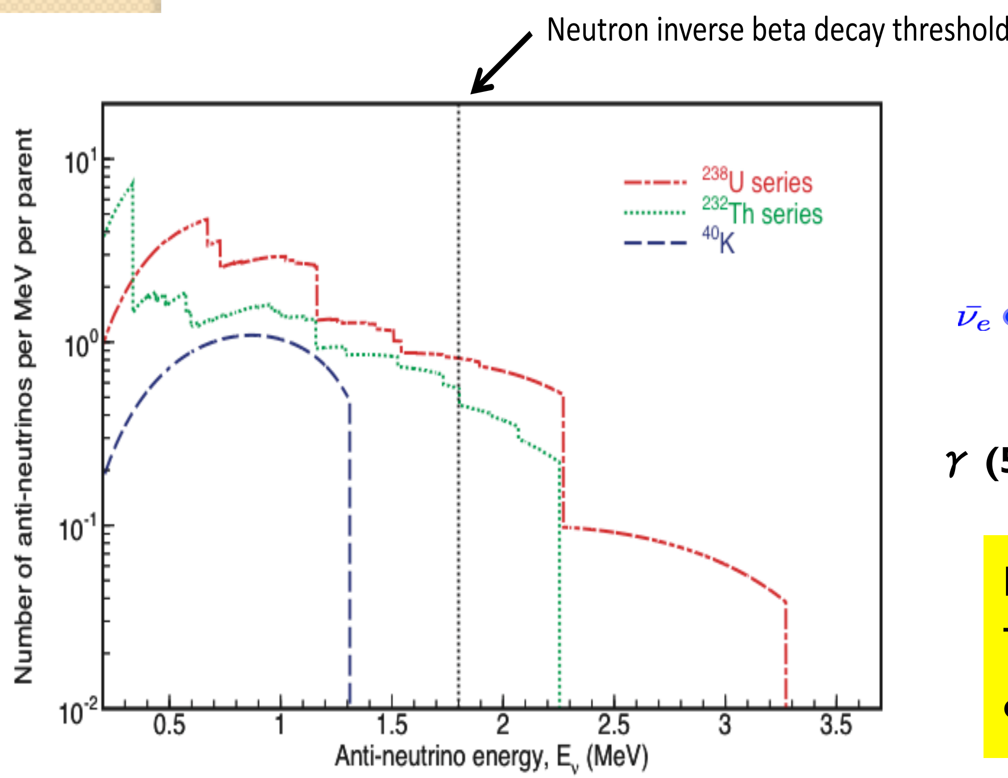
2015

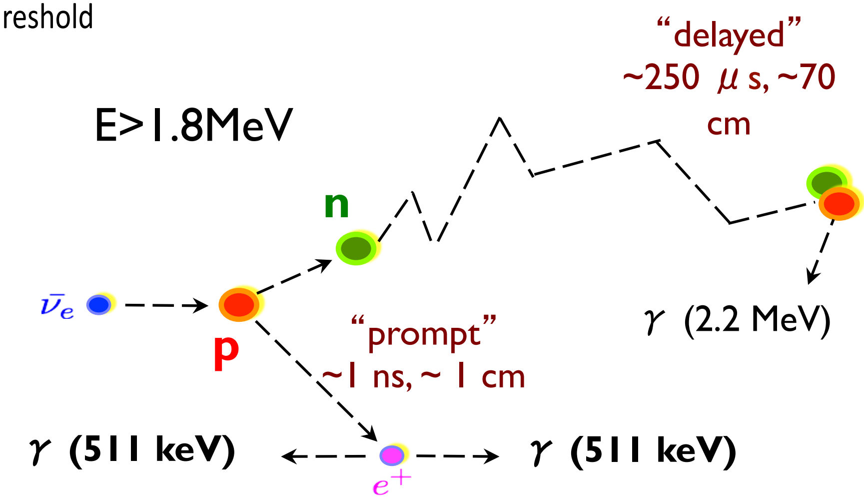
2016

Geo-neutrinos

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

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

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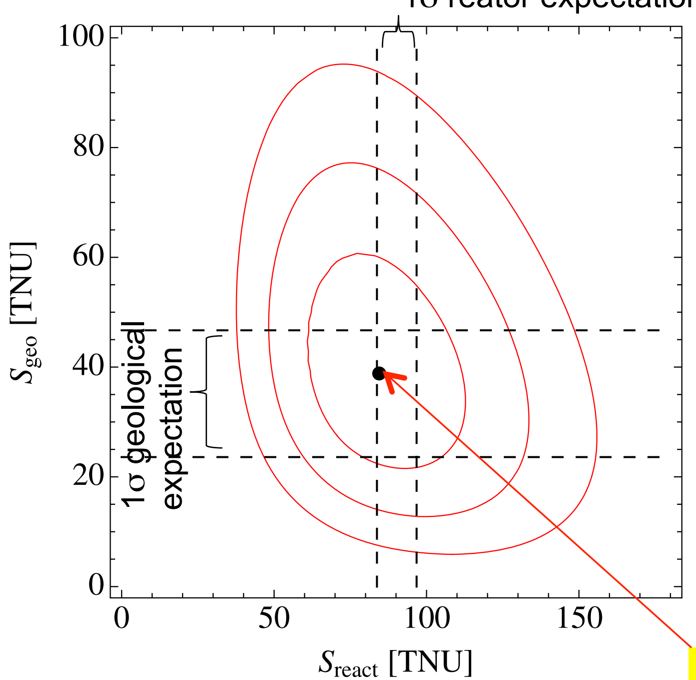
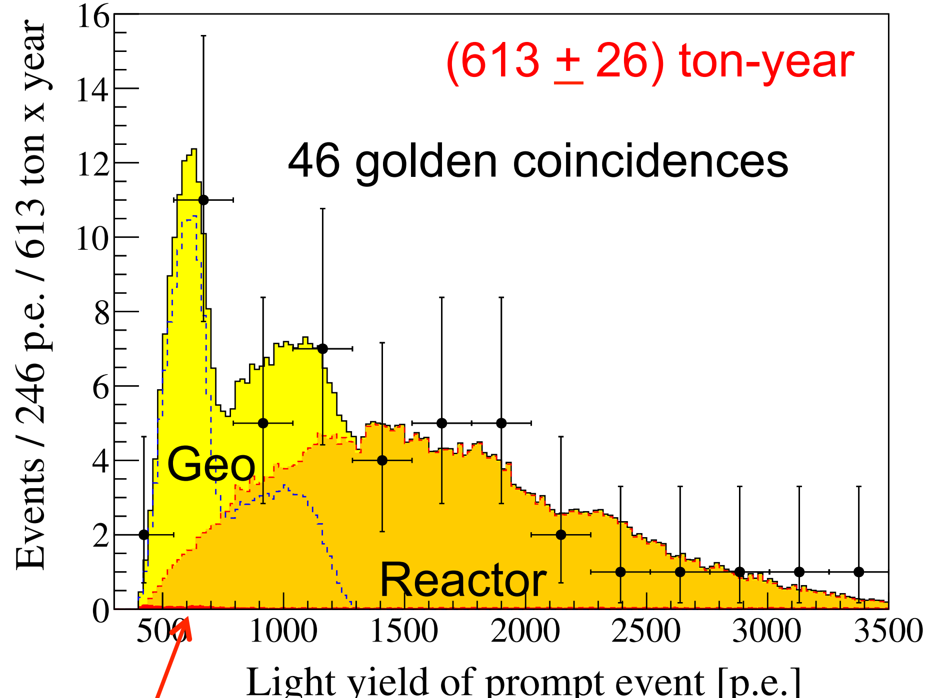
Geo-neutrinos: event selection

(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





Background not due to reactors is very small

Unbinned maximal likelihood fit with unconstrained geo and reactor component.

$N_{react} = 31.2_{-6.1}^{+7}$; expected 33.3±2.4 after oscillations.

N_{geo} = 14.3 ± 4.4 events
S_{geo} = 38.8 ± 12.0 TNU

Geo-neutrinos: implications

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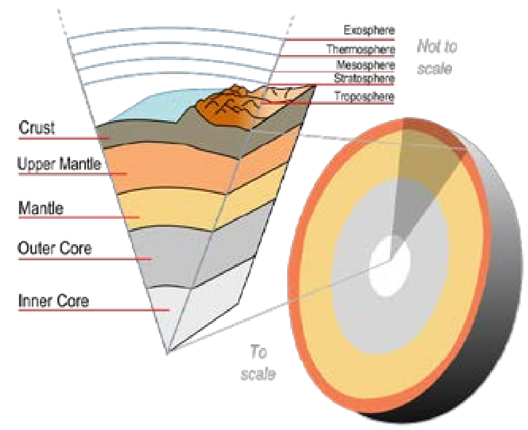
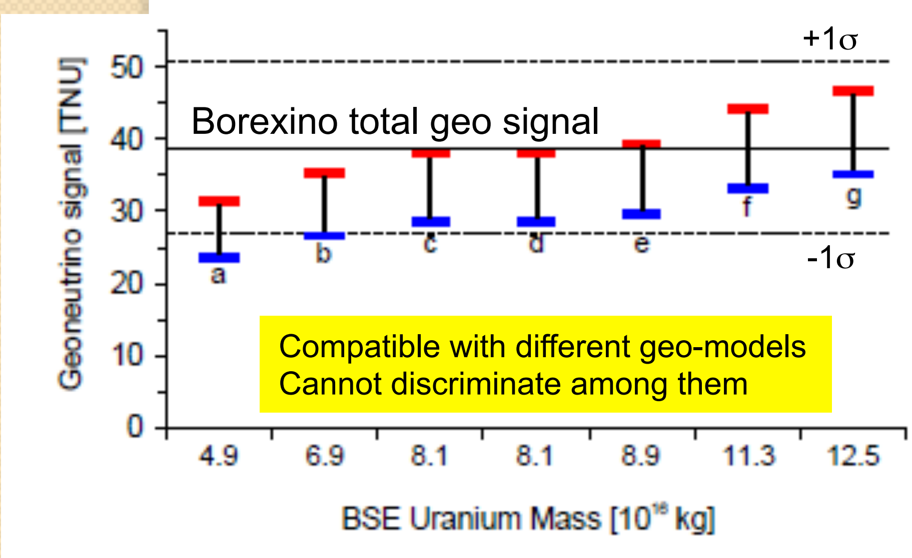
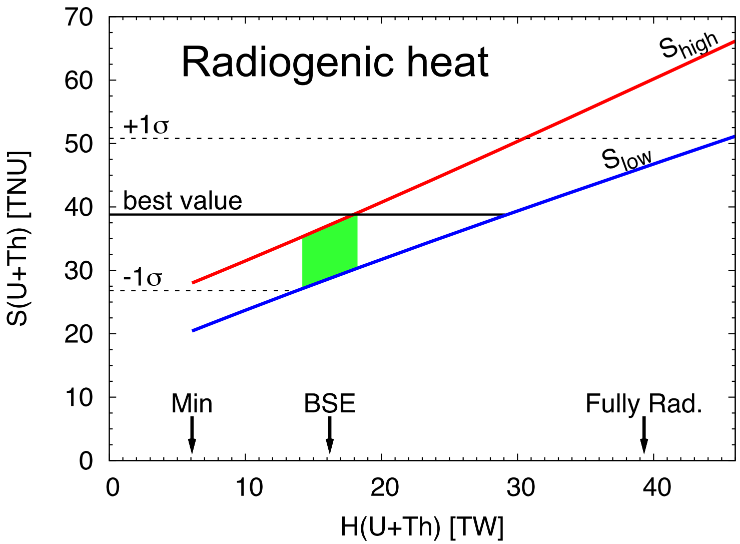
$$S_{Expected} = S_{LOCal} + S_{Rest\ Of\ Crust} + S_{Mantle}$$

	LOC (TNU)	ROC (TNU)	DATA (TNU)	MANTLE (TNU)	U+Th (TW)
Kamland	17.7±1.4	7.3±1.4	31.1±7.3	6.1±7.6	13±9
Borexino	9.7±1.3	13.7 ±2.5	38.8±12.0	15.4±12.3	23±14





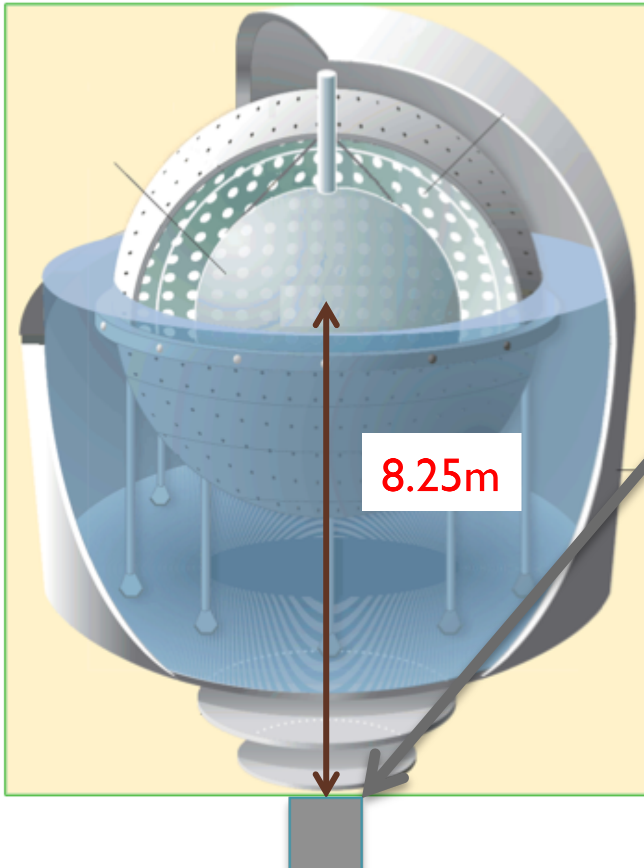


Assuming homogeneous mantle: Borex + KamLAND (Nature 2011) **14.1 ± 8.1 TNU**

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

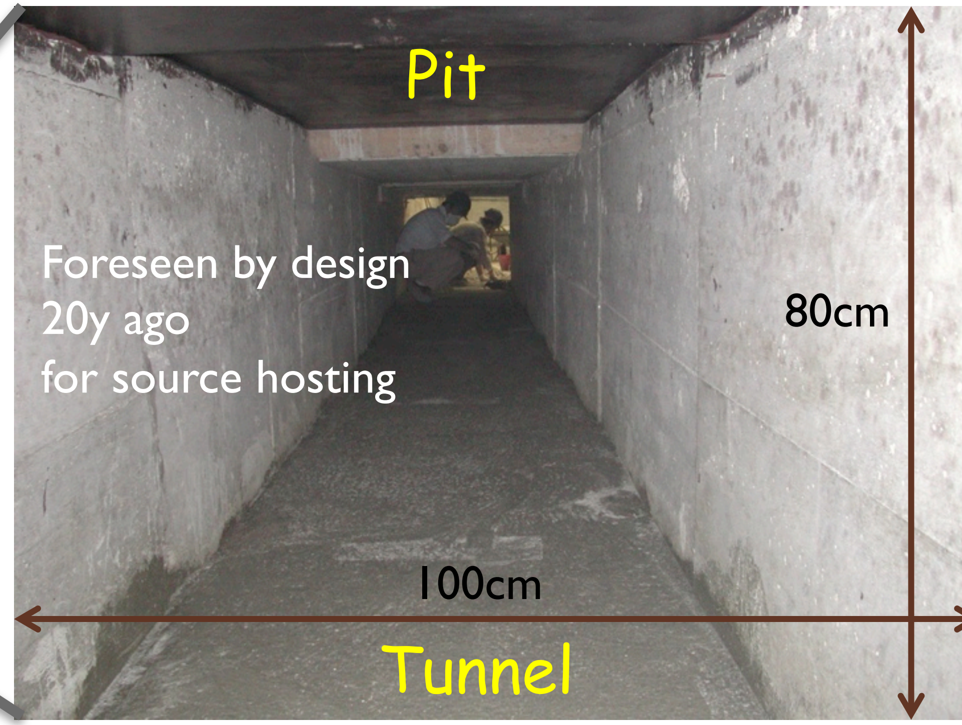
JHEP 08 (2013) 038

SOX concept



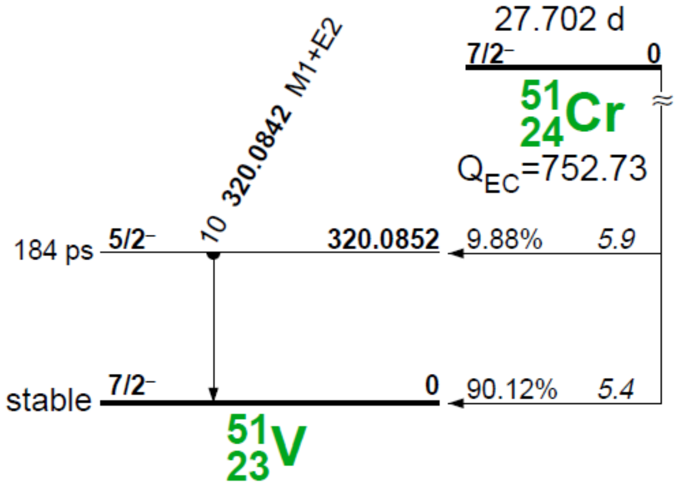
If reactor anomaly is interpreted in terms of oscillations into light sterile neutrinos it points to L/E ~ 1m/MeV

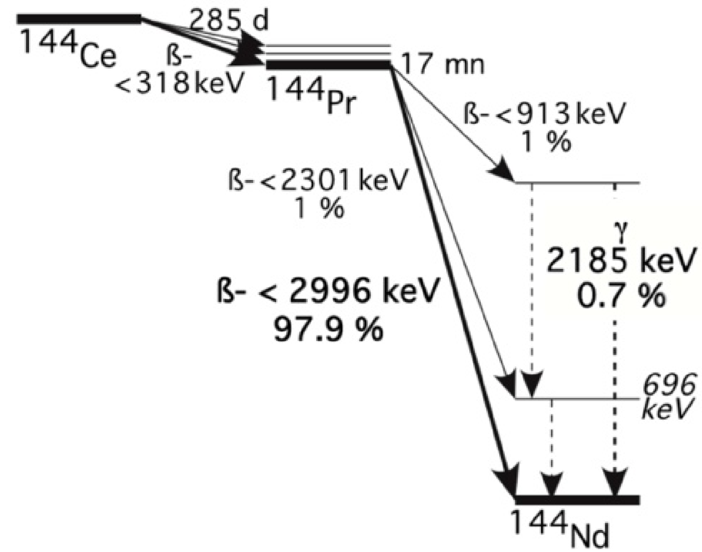
in Borexino with ~1MeV source:
resolution ~15cm < L < detector size ~10m



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

SOX: (anti)neutrino sources





Source	Production	Exp. activity	Decay mode	τ	Energy	kg/Mci	W/kCi
^{51}Cr	Gallex source	10MCi	e-capture (E_γ=0,32 MeV 10%)	40d	750 (90%) 430 (10%)	0.011	0.19
^{144}Ce-^{144}Pr	Fission product	75-150 kCi	β^-	411d	<3MeV	0.314	7.6

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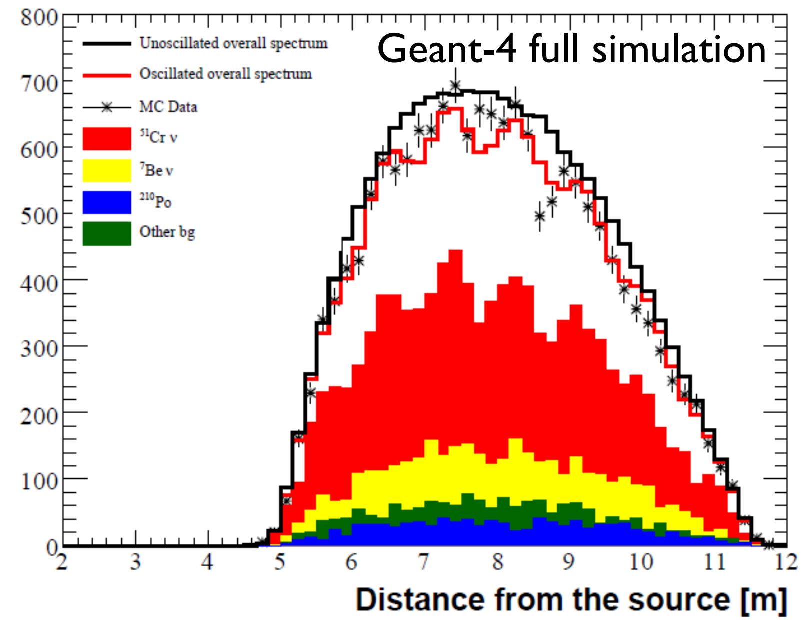
SOX ^{51}Cr run

- Source obtained by irradiation of the source used in Gallex
  - 38% enrichment.
- Mayak (Ru) vs. Oakridge (USA)
  - Both option are in the negotiations.
  - Source needs quick transportation!
- Source size ~15cm: comparable to position resolution
- Need to know FV at 1%:
  - ok (via calibrations).
- Need to know activity at 1%:
  - via Heat: calorimeter under design.
  - Gallex made 2%.
- Need to have constant backgrounds: currently so.



$\sin^2(2\Theta_{14})=0.3$
and $\Delta m^2_{41}=2$ eV^2.
Activity: 370PBq (10MCi)
Data taking: 90d

The oscillatory behavior allows to reconstruct Θ_{14} and Δm^2_{41}

Sensitivity can be enhanced by short life-time of the ^{51}Cr.

tentative schedule:
spring 2015
run for 3 months

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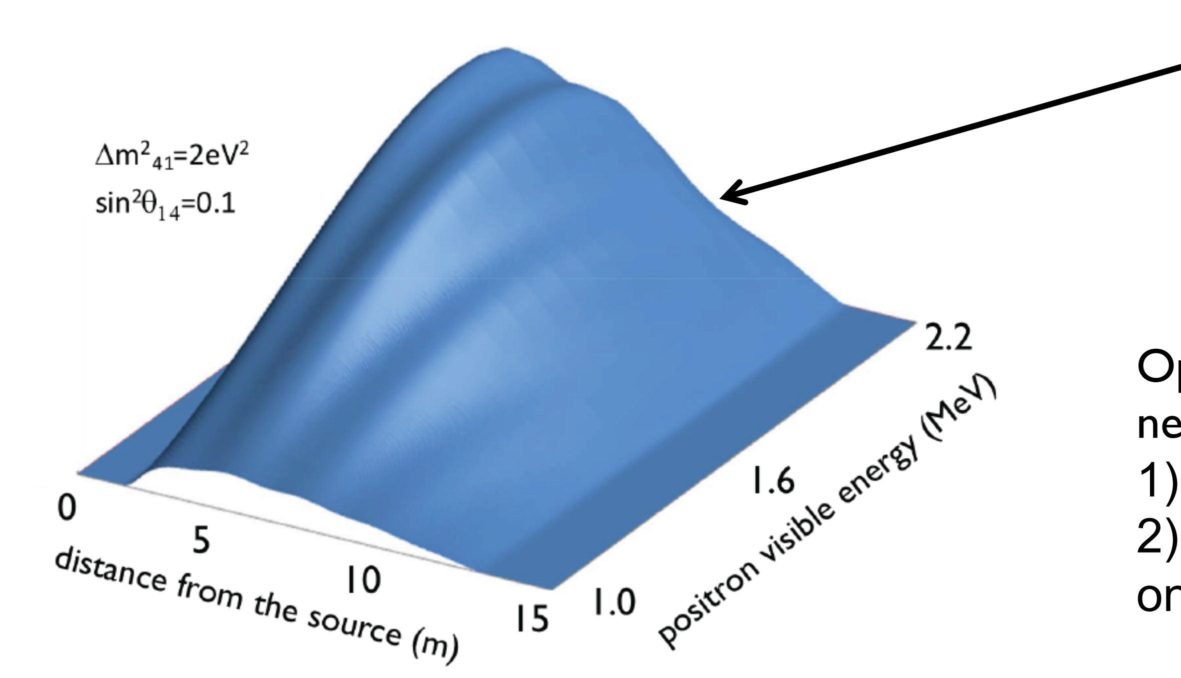
SOX ^{144}Ce-^{144}Pr run

- 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.
- Very hot: needs cooling.

tentative schedule:
late 2015
run for 1.5 year



Options of placing the source nearer to detector center:
1) at 7.15 m in water buffer
2) directly in the scintillator
only possible after solar run.

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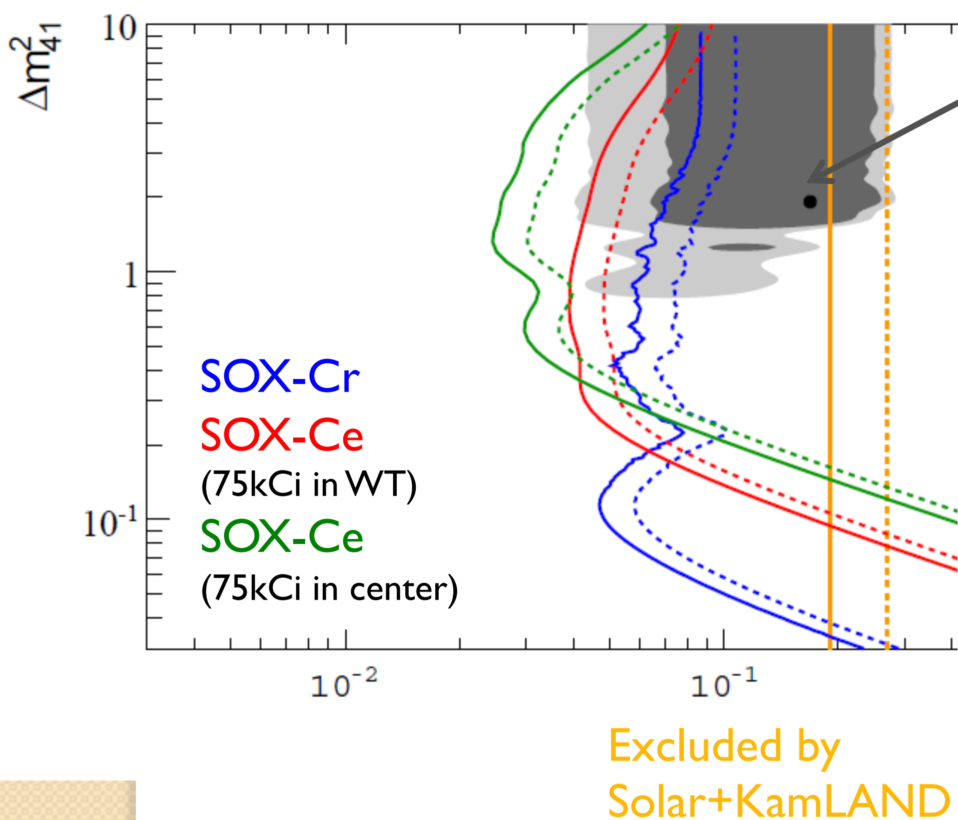
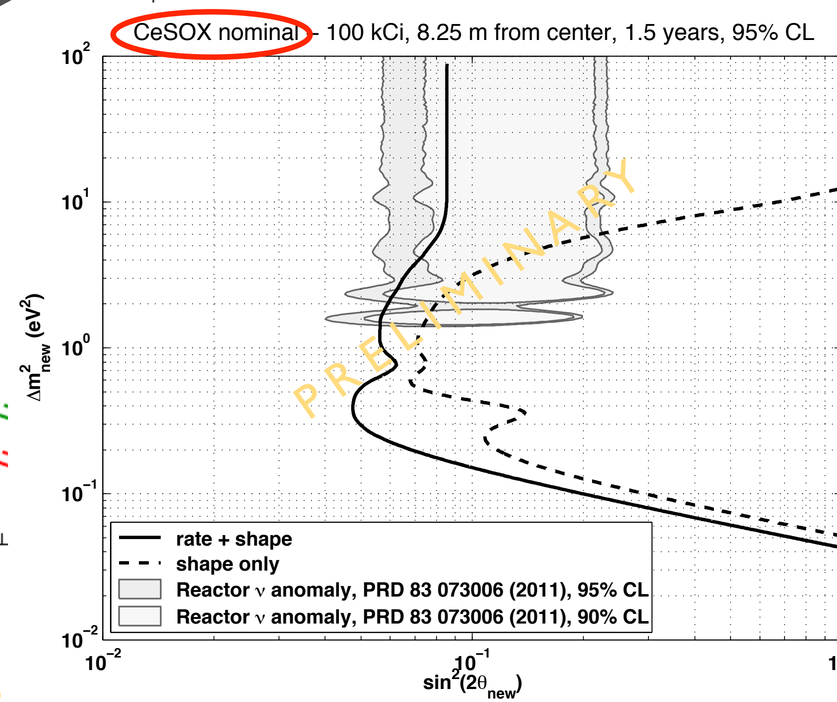
SOX: sensitivity

$$P_{ee} = 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\Delta m_{41}^2(eV^2)L(m)}{E(MeV)}$$

Reactor Anomaly



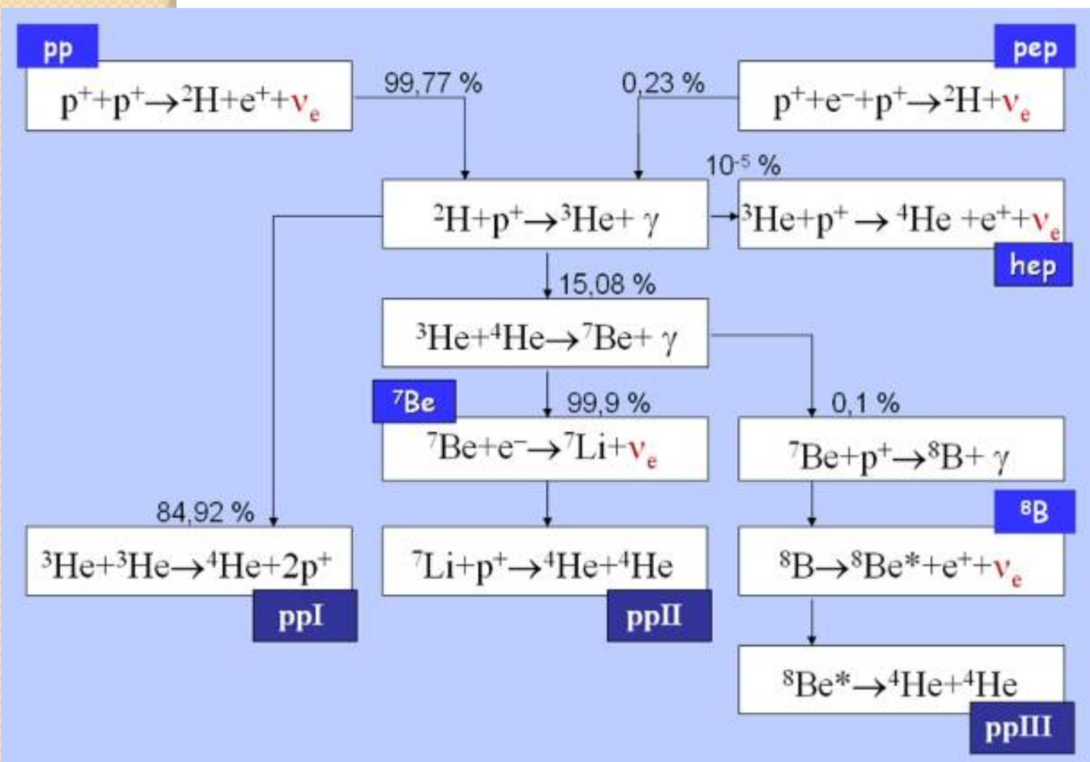


Conclusions

- Borexino detector is taking data since 2007 and is now its phase II.
  - The background levels are unprecedented and are still improving.
- Phase I brought fundamental results over a broad range of solar neutrinos (^{7}Be, ^{8}B, pep, CNO limits) and geo neutrinos.
- First Phase II result: pp-neutrino flux
  - to be released this year.
- Phase II next goal will be a measurement of CNO fluxes.
  - along with more stringent measurement of ^{7}Be, ^{8}B, pep, and geo.
- SOX project will test the Reactor Anomaly region for oscillations into sterile neutrinos.
  - a ^{51}Cr and a ^{144}Ce-^{144}Pr sources will be placed under the detector in 2015-16.
  - after solar run: eventually place Ce source inside.

Energy production in the sun

PP-chain
>99% energy production
5 ν species



CNO-cycle
<1% energy production
3 ν species