Solar neutrino with Borexino: results and perspectives

(Phase II and SOX).

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The International Workshop on Prospects of Particle Physics: Neutrino Physics and Astrophysics (PPP-2014), "Valdai" resort, Novgorod region, Russia

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the Borexino Collaboration

Gran Sasso

Perugia

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK
Heidelberg

Hamburg

Budapest

Milano

Genova

München

Kraków

Kurchatov Moscow

JINR Dubna

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UMass Amherst

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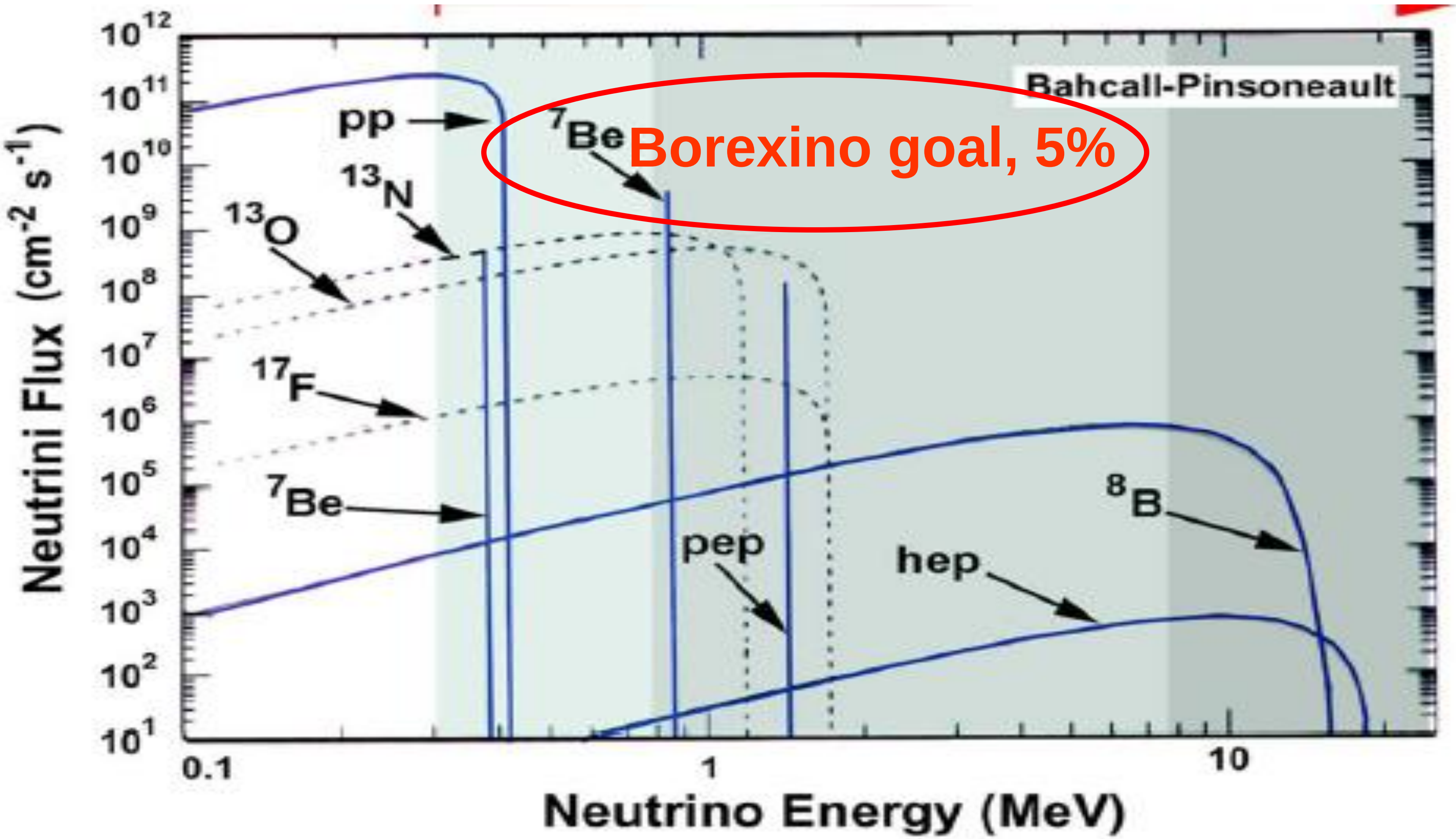
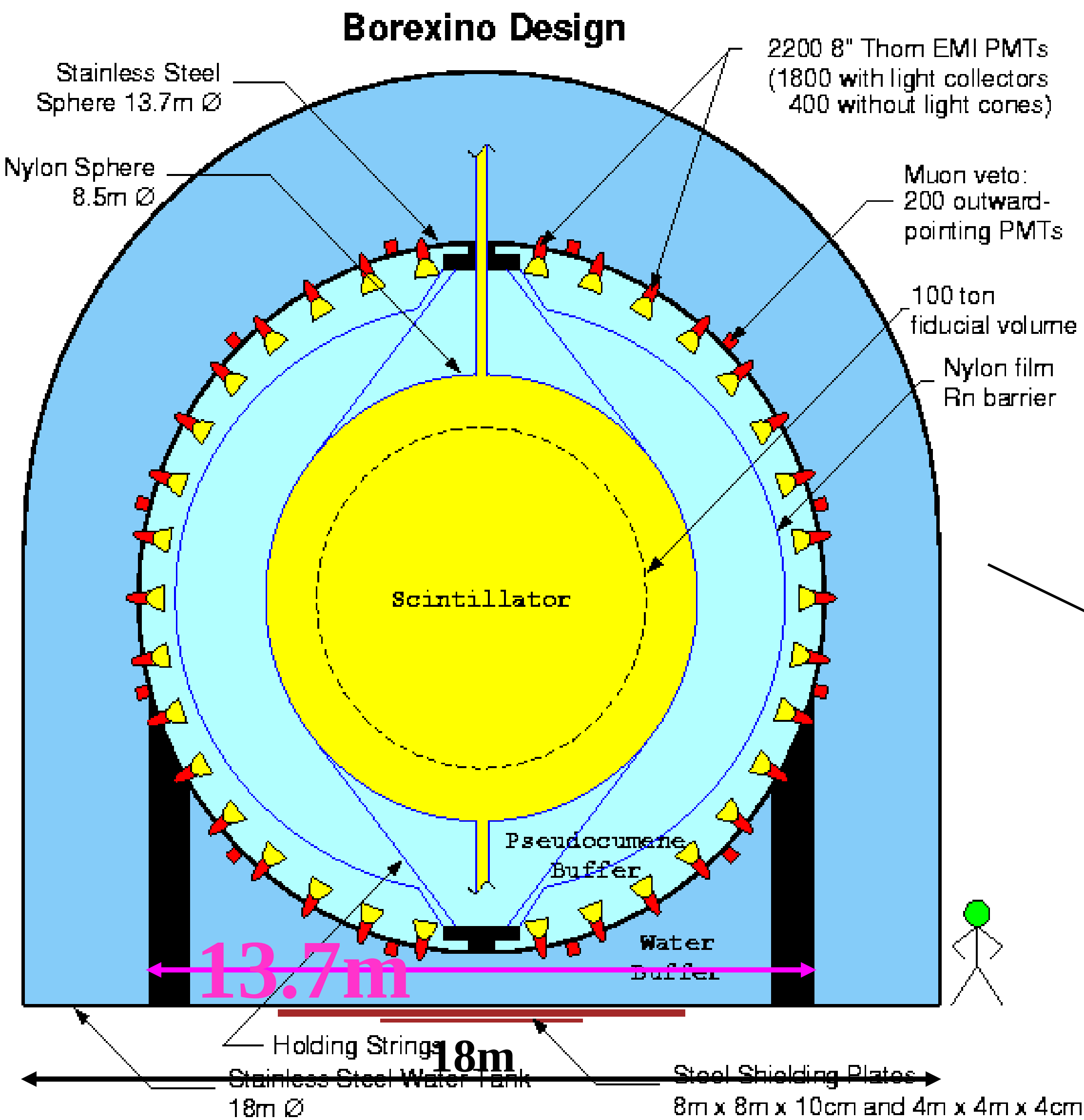


50 events/d/100t expected (ν_e and ν_μ elastic scattering on e^-) or $5{\cdot}10^{-9}$ Bq/kg (typically: drinking water ~10 Bq/kg; human body in ^{40}K: 5 kBq)

Low energy->no Cherenkov light->No directionality,

no other tags-> extremely pure scintillator needed

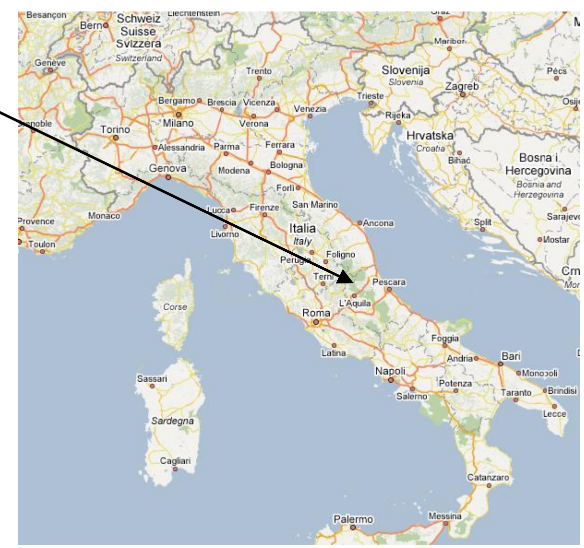
BOREXINO *(in operation from May,2007)*



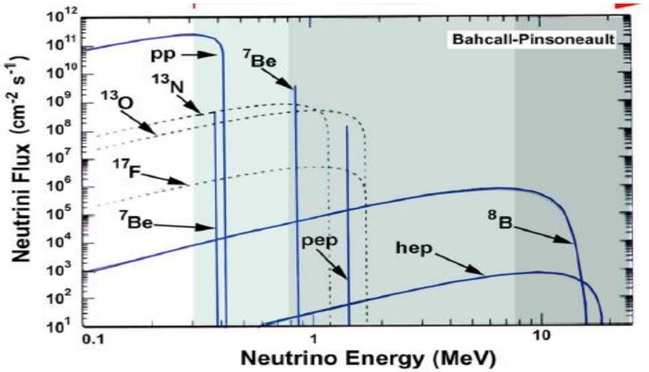
•278 t of liquid organic scintillator PC + PPO (1.5 g/l)

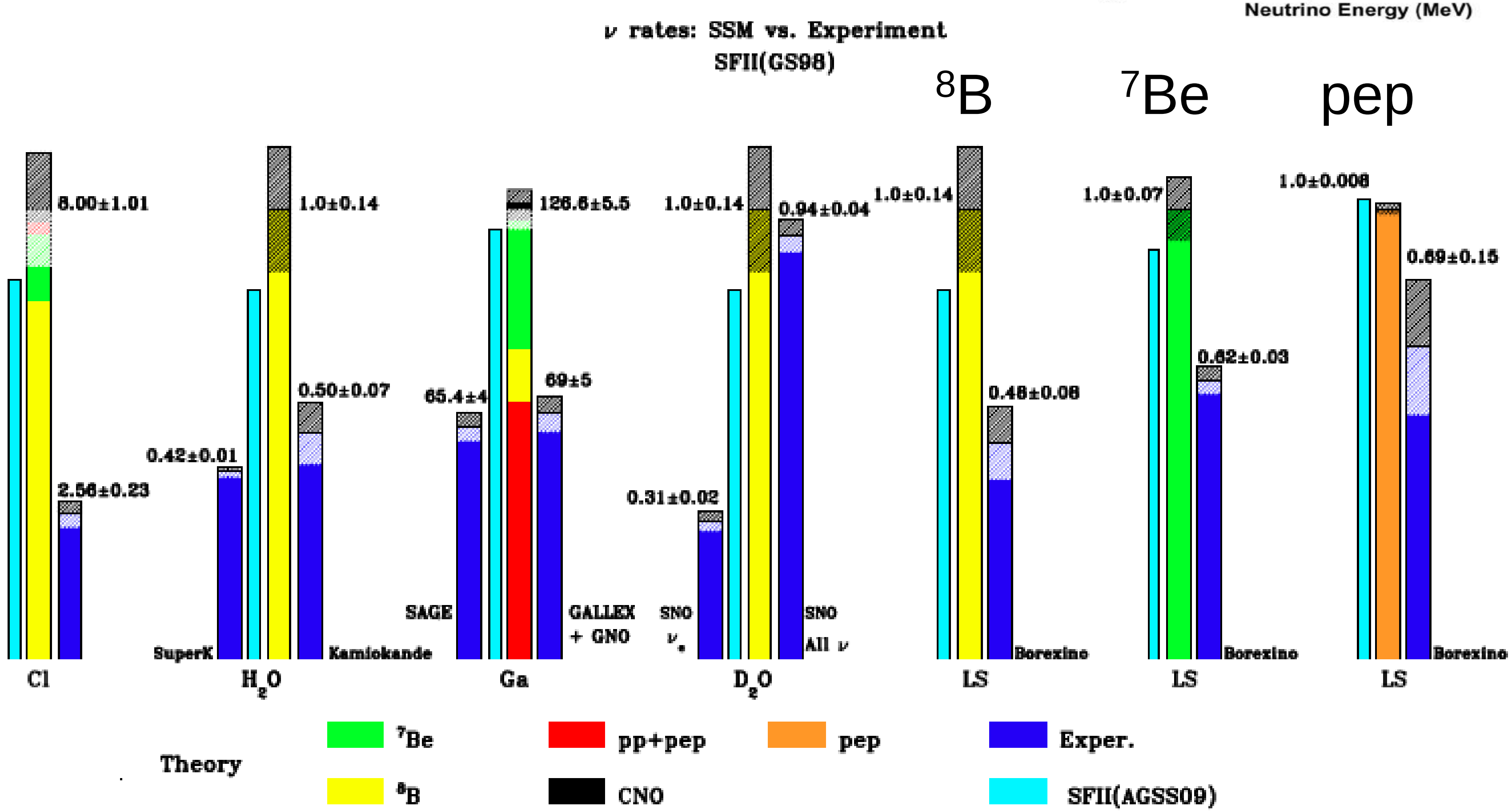
• (ν,e)-scattering with 200 keV threshold

•Outer muon detector



Solar experiments vs models





Borexino

Borexino Phase I results

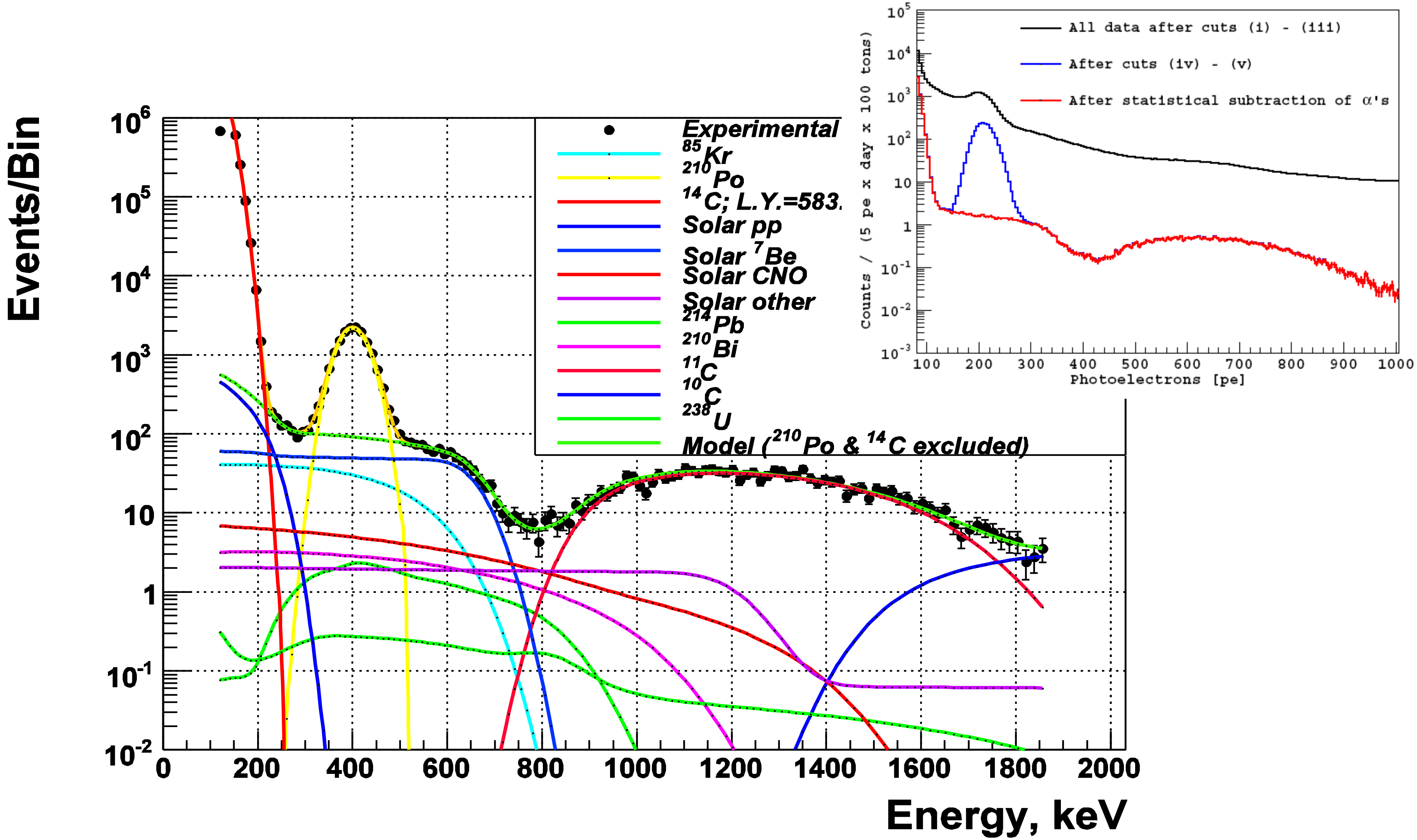
- **^{7}Be neutrino flux 4.6% [Phys. Rev. Lett. 107 (2011) 141302]:**
  $46 \pm 1.5(stat)^{+1.6}_{-1.5}(syst)$ cpd/100t   740.7 days
- Asymmetry of ^{7}Be neutrino flux **[**Physics Letters B 707 (2012) 22–26 **]**:
  A(D/N) = 0.001 ± 0.012 (stat) ± 0.007 (syst)   **740.9 days**
- **Effective magnetic moment of neutrino [**PRL 101, 091302 (2008)**]**
  $\mu_{eff} < 5.8 \cdot 10^{-11}\ \mu_B$ 90% C.L.   192 days
- **^{8}B neutrino flux ~20%** (Phys.Rev.D82 (2010) 033006):
  E>3 MeV:0.22±0.04(stat)±0.01(syst) cpd/100 t
  E>5 MeV:0.13±0.02(stat)±0.01(syst) cpd/100 t   488 days

  Borexino is the first LS detector sensitive to 8B neutrino
- **pep- neutrino measurement and CNO-neutrino limit** [PRL 108, 051302 (2012)]:

  R_{pep}=3.1**±0.6 (stat) ±0.3(syst)**

  R_{CNO} < 7.9 cpd/100t @ 95% C.L.   ≈500 astro days
- **Seasonal variations of ^{7}Be neutrino flux [arXiv:1308.0443v1 [hep-ex] 2013]**
  evidence of the annual modulation signal with a significance higher than 3 sigma.
  ≈850 astro days

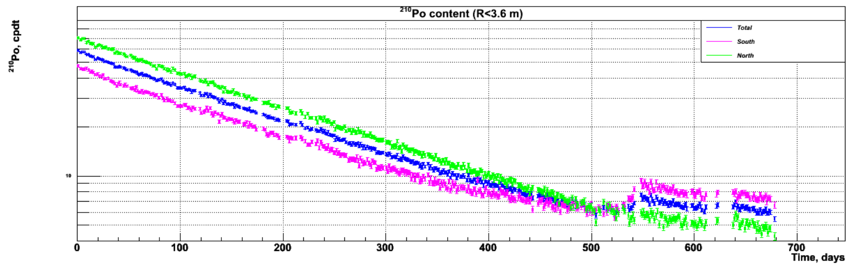
Borexino energy spectrum (inner 75 t)



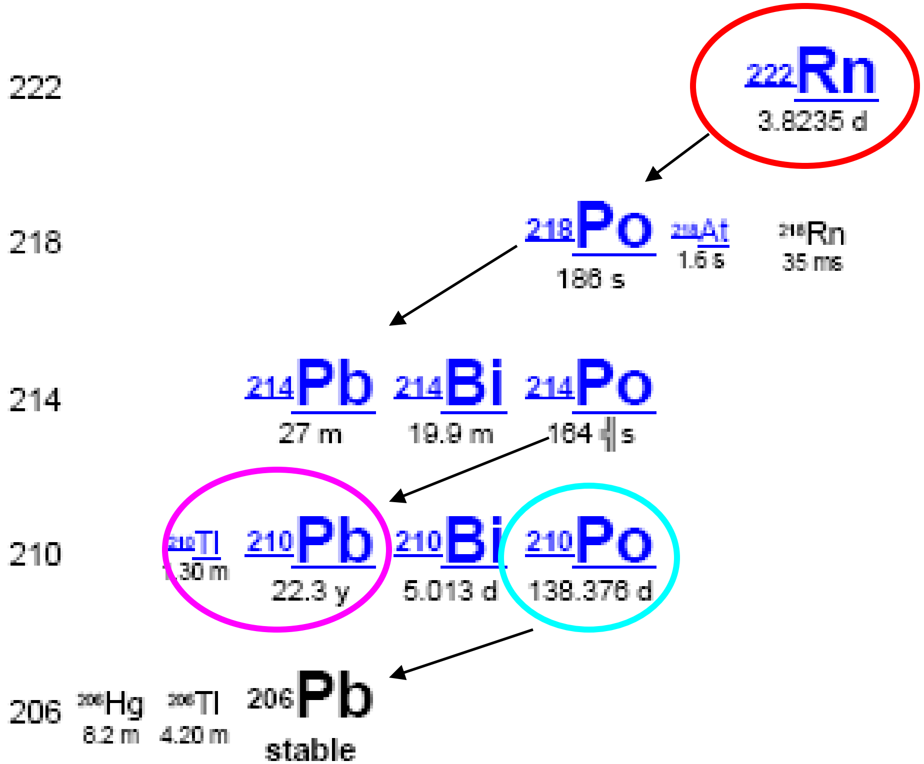
LS purity in Borexino:

Background	Typical abundance (source)	Borexino goals	Borexino-I measured
^{14}C / ^{12}C [g/g]	10^{-12} (cosmogenic)	~10^{-18}	$(2.69\pm0.06)\cdot10^{-18}$
^{238}U [g/g] (by ^{214}Bi-^{214}Po)	$2\cdot10^{-5}$ (dust)	~10^{-16} (1 μBq / t)	$(1.6\pm0.1)\cdot10^{-17}$
^{232}Th [g/g] (by ^{212}Bi-^{212}Po)	$2\cdot10^{-5}$ (dust)	~10^{-16}	$(5\pm1)\cdot 10^{-18}$
^{222}Rn [cpd/100t]	100 atoms/cm^3 (air) (emanation from materials)	<10	~1
^{40}K [g/g]	$2\cdot10^{-6}$ (dust)	~10^{-18}	$<0.4\cdot10^{-18}$ (90% C.L.)
^{210}Po[cpd /t]	(surface contamination)	Not specified	70 (initial, $T_{1/2}$=134 d; not in equilibrium with ^{210}Bi); <1 now
^{210}Bi [cpd/100t]		Not specified	20-70
^{85}Kr [cpd /100 t]	1 Bq/m^3 (air)	~1	30 ± 5 cpd/100t
^{39}Ar [cpd /100 t]	17 mBq/m^3(air)	~1	<<^{85}Kr

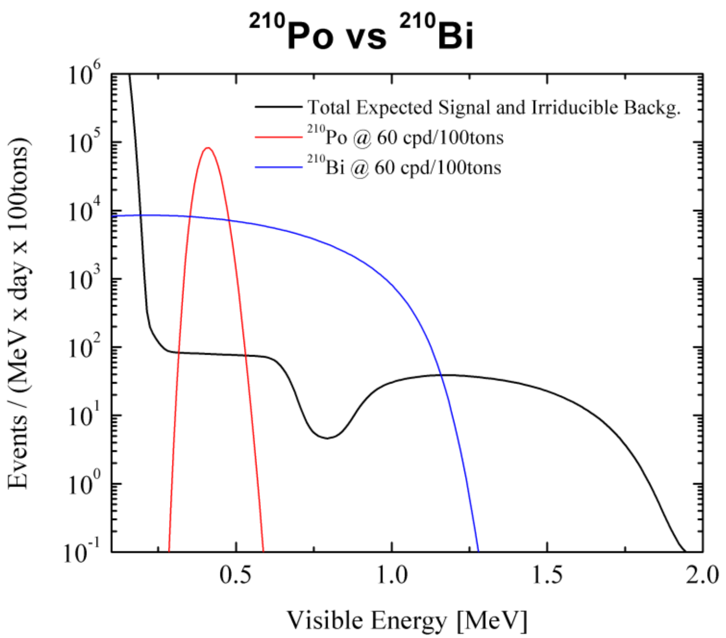
^{210}Po & ^{210}Bi



210Po content (R<3.6 m)
210Po, cpdt
Total
South
North
0
100
200
300
400
500
600
700
Time, days

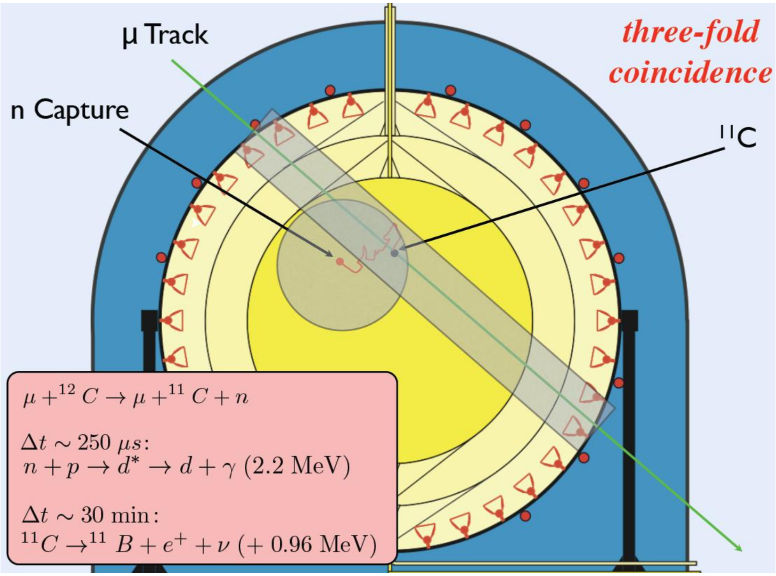


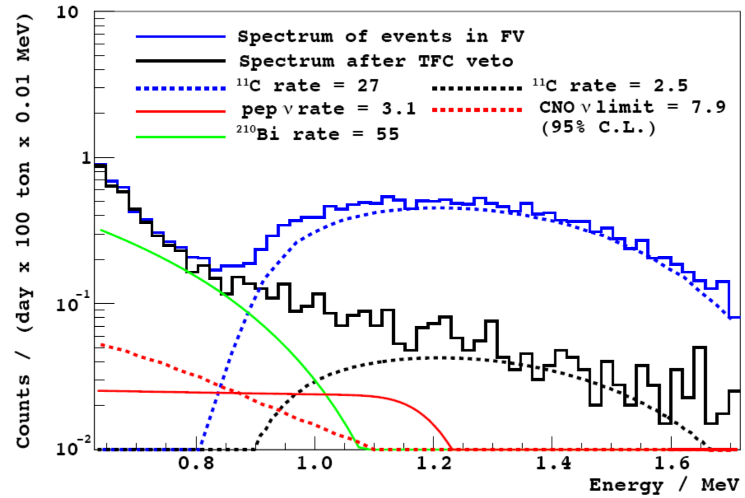
222
218
214
210
206
222Rn
3.8235 d
218Po
186 s
218At
1.5 s
218Rn
35 ms
214Pb
27 m
214Bi
19.9 m
214Po
164 μs
210Tl
1.30 m
210Pb
22.3 y
210Bi
5.013 d
210Po
138.376 d
206Hg
8.2 m
206Tl
4.20 m
206Pb
stable



210Po vs 210Bi
Total Expected Signal and Irriducible Backg.
210Po @ 60 cpd/100tons
210Bi @ 60 cpd/100tons
Events / (MeV x day x 100tons)
Visible Energy [MeV]
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0.5
1.0
1.5
2.0

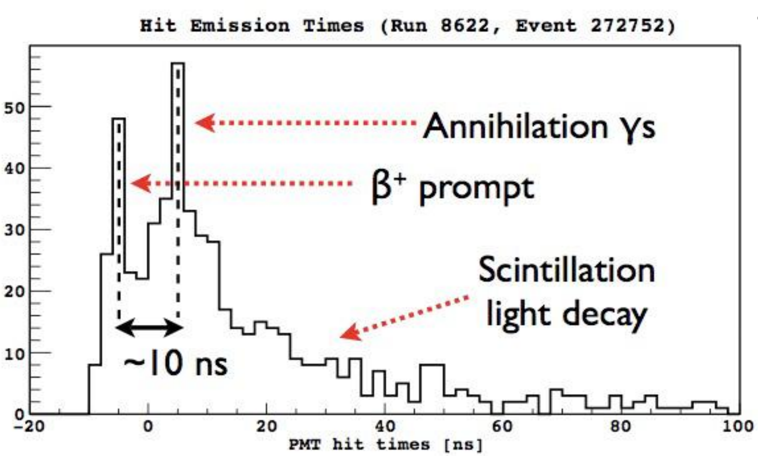
Rejection of ^{11}C background



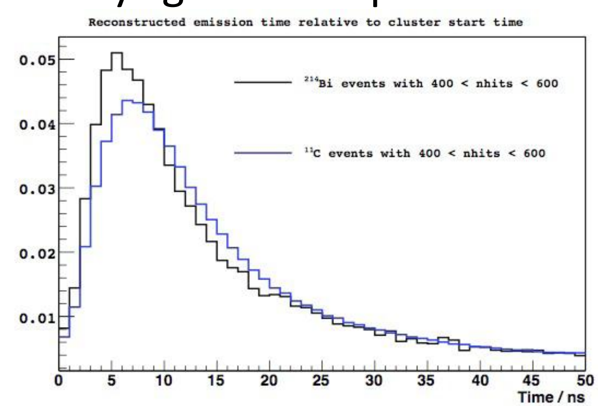


Background reduction in ^{11}C - 91% with 51.5% live-time loss

e^+/e^- discrimination



50% of β^+ decays give *ortho* positronium ($t_{1/2}$ = 3 ns).



Borexino status (December 2013)

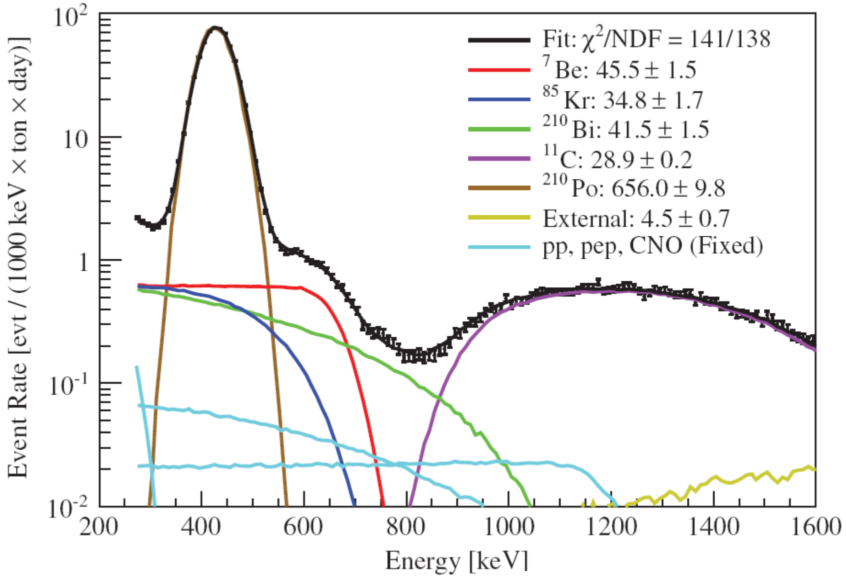
- **The basic physics program fulfilled (but no measurements with neutrino sources). A number of important physics results are obtained beyond the original program, as a result of much better purification in U-Th than needed for Be-7 neutrino measurement (Final results:** arXiv:1308.0443v1 [hep-ex])
- **After successful detector calibration campaign in 2010 scintillator repurification campaign was performed. In few cycles of purification we reduced significantly the known contaminants:**
- ^{85}Kr: consistent with zero cpd/100t (from spectral fit);
- ^{210}Bi : from ~70 cpd/100 tons down to 20 cpd/100tons) ;
- ^{238}U (from ^{214}Bi - ^{214}Po tagging) < 9.7 10^{-19} g/g at 95% C.L.
- ^{232}Th: < 1.2 10^{-18} g/g at 95% C.L. (2 events in ~600 days)

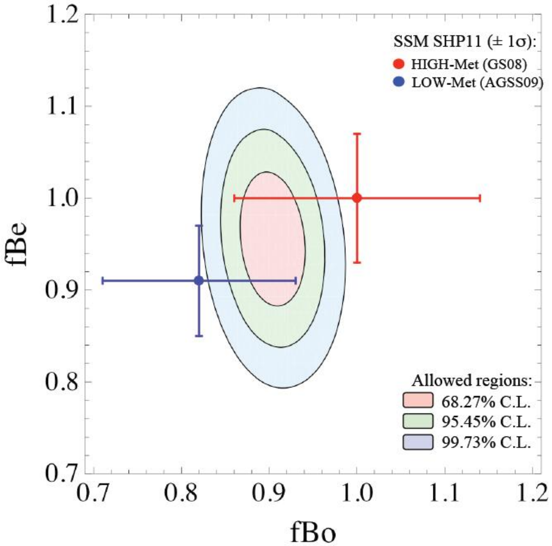
  ^{210}Po is decaying (200 cpd/100 tons in May 2013), Radon: (5.4 $\pm$ 1.1) 10^{-19} g/g , estimation of the ^{210}Bi content from ^{210}Po evolution in time under study.
- **Borexino Phase II: about 2 years of data with "pure" scintillator has been collected, data taking continues.**

Borexino Phase II
Physics program

- **Improvement of ^{7}Be neutrino flux measurement (3%) and seasonal variations.**
- **pp-neutrino flux measurement with 15% precision**
- **Precision *pep* neutrino measurement (>3σ)**
- **Geoneutrino flux measurement with higher statistics**
- **B-8 neutrino measurement with x4 statistics (aiming 10%)**
- **Measurement (or establishing strong limits) on the CNO neutrino flux.**
- **Measurements with artificial neutrino sources (search for sterile neutrino, neutrino magnetic moment, other nonstandard neutrino interactions). Project SOX: Short distance Oscillations with BoreXino. EU grants for source.**

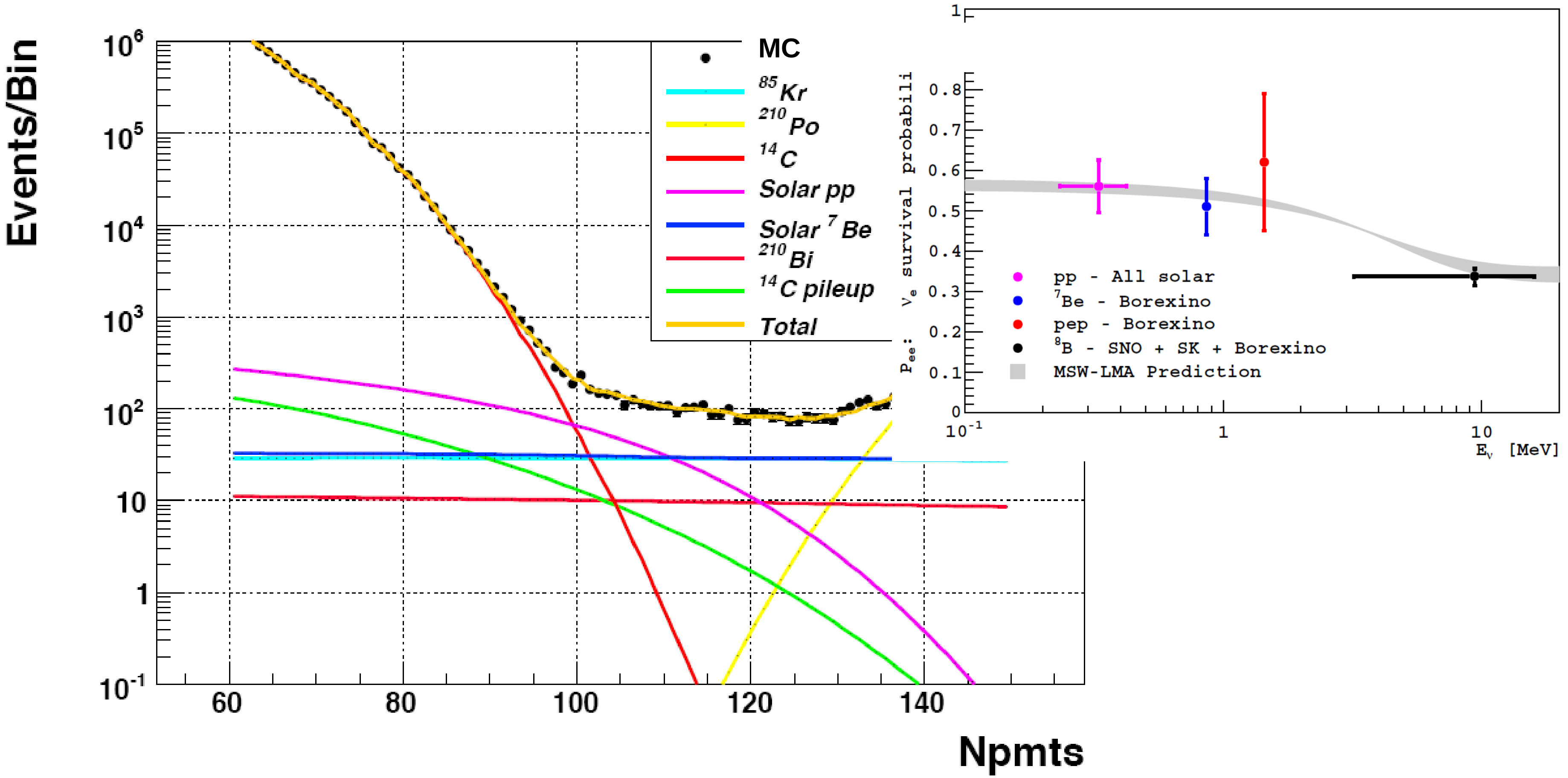
Precise measurement of ^{7}Be and CNO neutrino: clue to the problem of heavy elements abundancies in the Sun





ν flux	GS98	AGS09	$cm^{-2}s^{-1}$	Experimental results
pep	1.44±0.012	1.47±0.012	x 10^8	1.6±0.3 Borexino
^{7}Be	5.00±0.07	4.56±0.07	x 10^9	4.87±0.24 Borexino
^{8}B	5.58±0.14	4.59±0.14	x 10^6	5.2±0.3 SNO+SK+Borexino+Kamland 5.25±0.16+0.011-0.013 SNO-LETA
^{13}N ^{15}O ^{17}F	2.96±0.14 2.23±0.15 5.52±0.17	2.17±0.14 1.56±0.15 3.40±0.16	x 10^8	< 7.4 Borexino (total CNO)

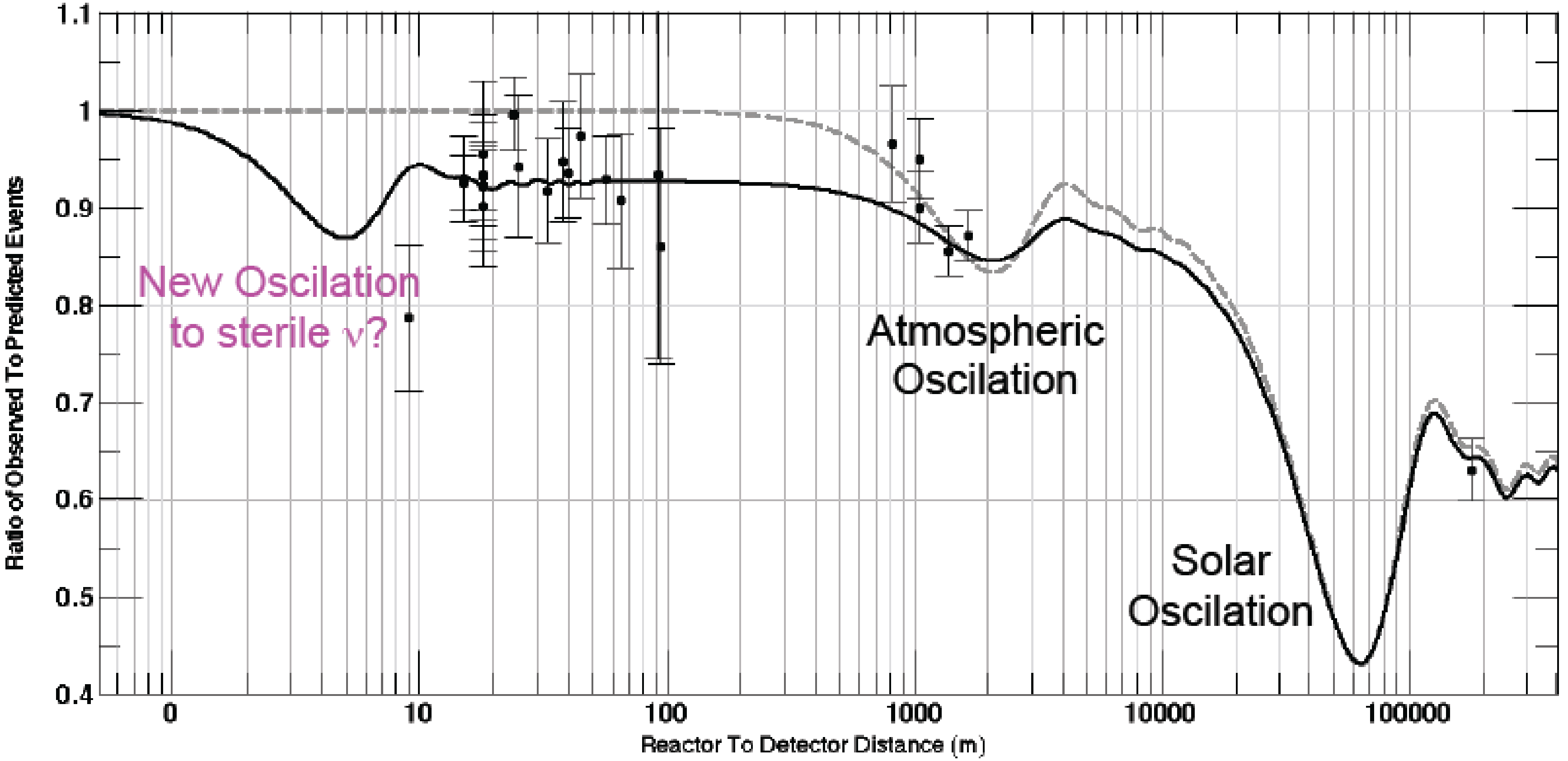
In work: pp-neutrino flux



Expected statistical precision of measurement ~10%

First ever direct pp-neutrino measurement

Oscillations on the short base(~1 m)



Borexino technical data

1.Mass: full 278 t;

“Standard” FV (R<3.02 m && |Z|<1.67 m) ~75 tones

2.Spatial resolution 14 cm @ 1 MeV

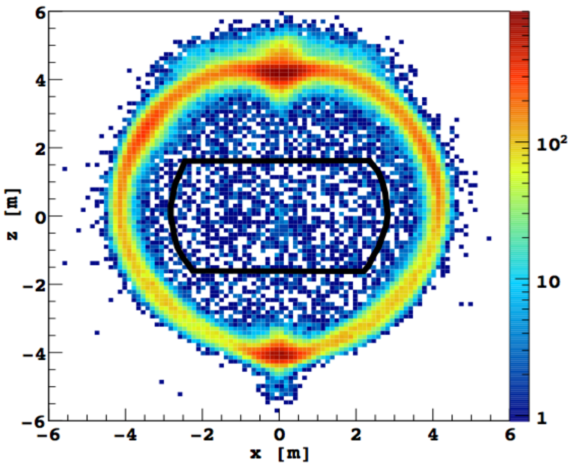
3.Light yield: >500 p.e./MeV/2000 PMTs (31% of 4π);

4.Energy resolution (1σ) within the FV: ~5% @ 1 MeV;

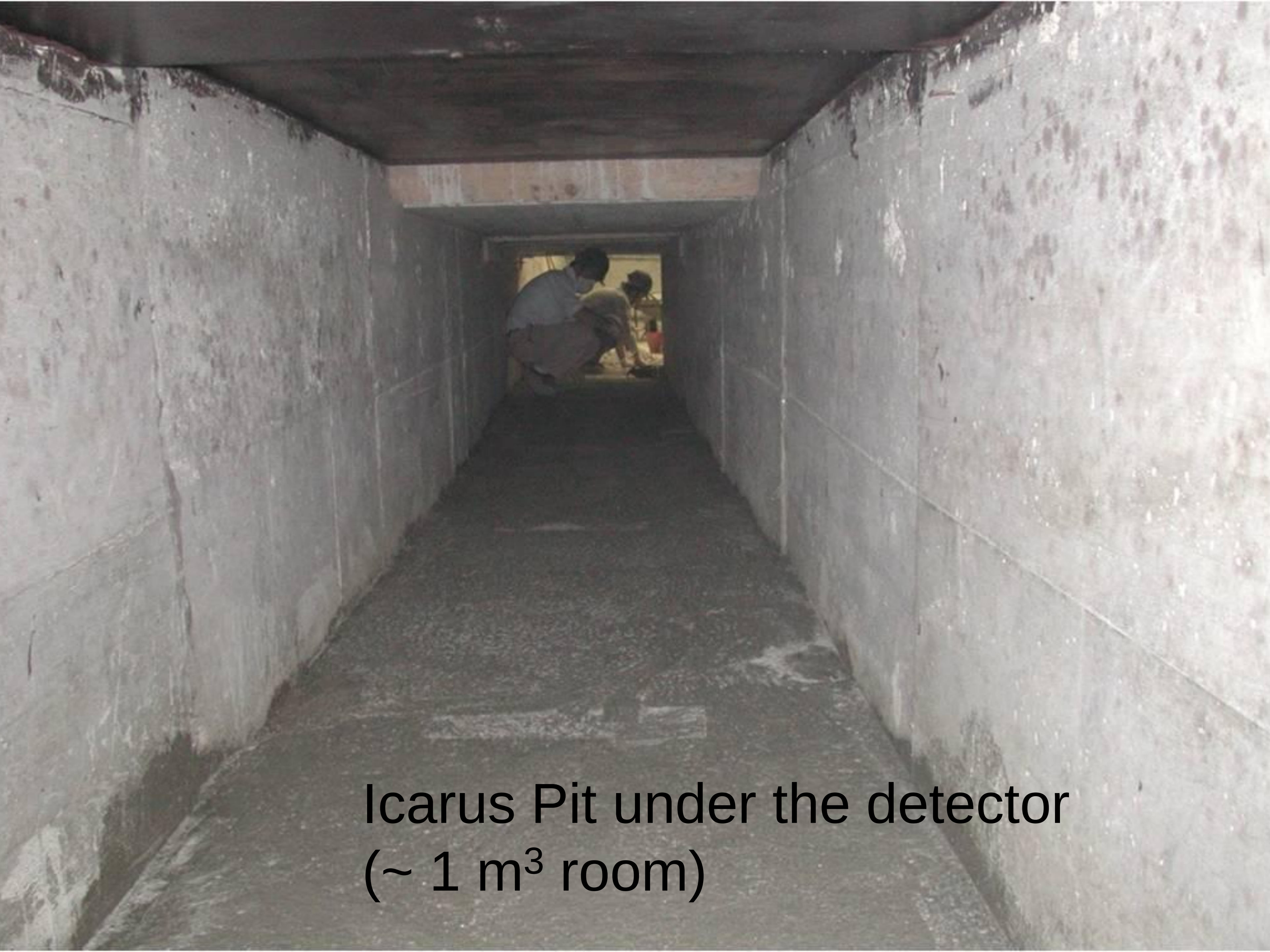
5.Practical threshold on the electrons recoil is 180 keV (corresponds to ~320 keV neutrino);

6.Muons detection efficiency close to 100%;

7.Triggers rate: 11 cps (mainly ^{14}C; ~100 Bq activity)

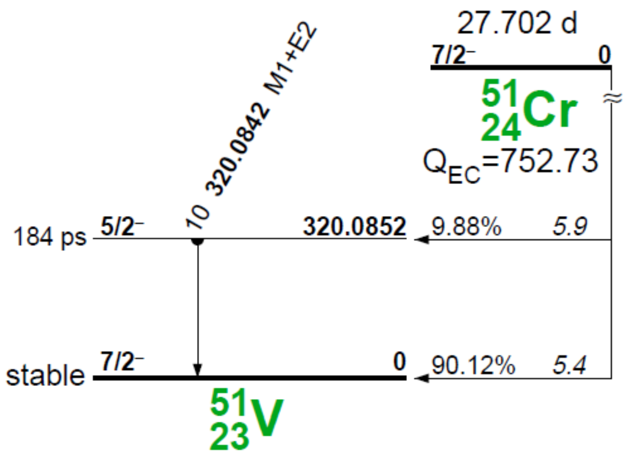


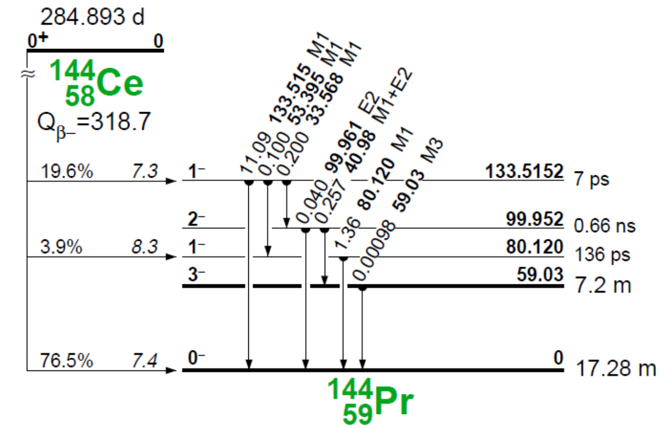
The Borexino is perfectly suited to host a short baseline neutrino oscillation experiment with E~1 MeV and L~1 m

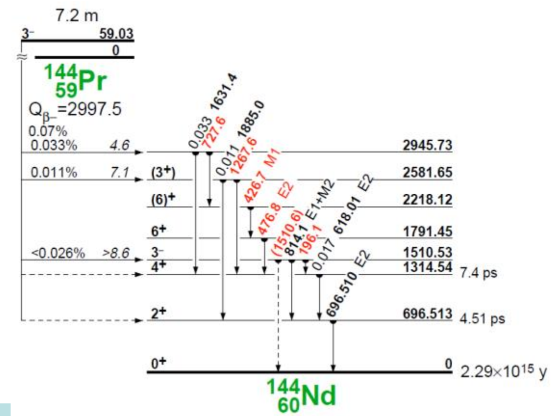


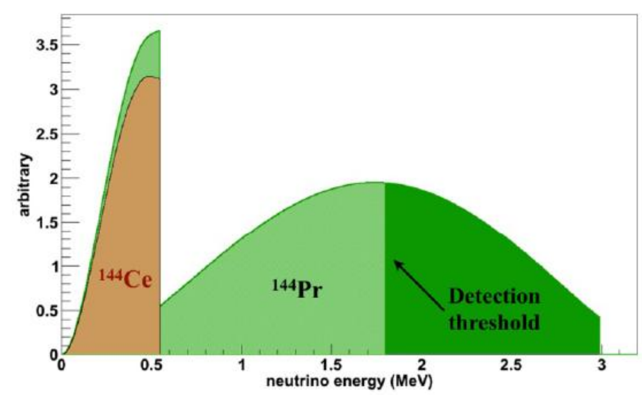
Icarus Pit under the detector
(~ 1 m^3 room)

Sources

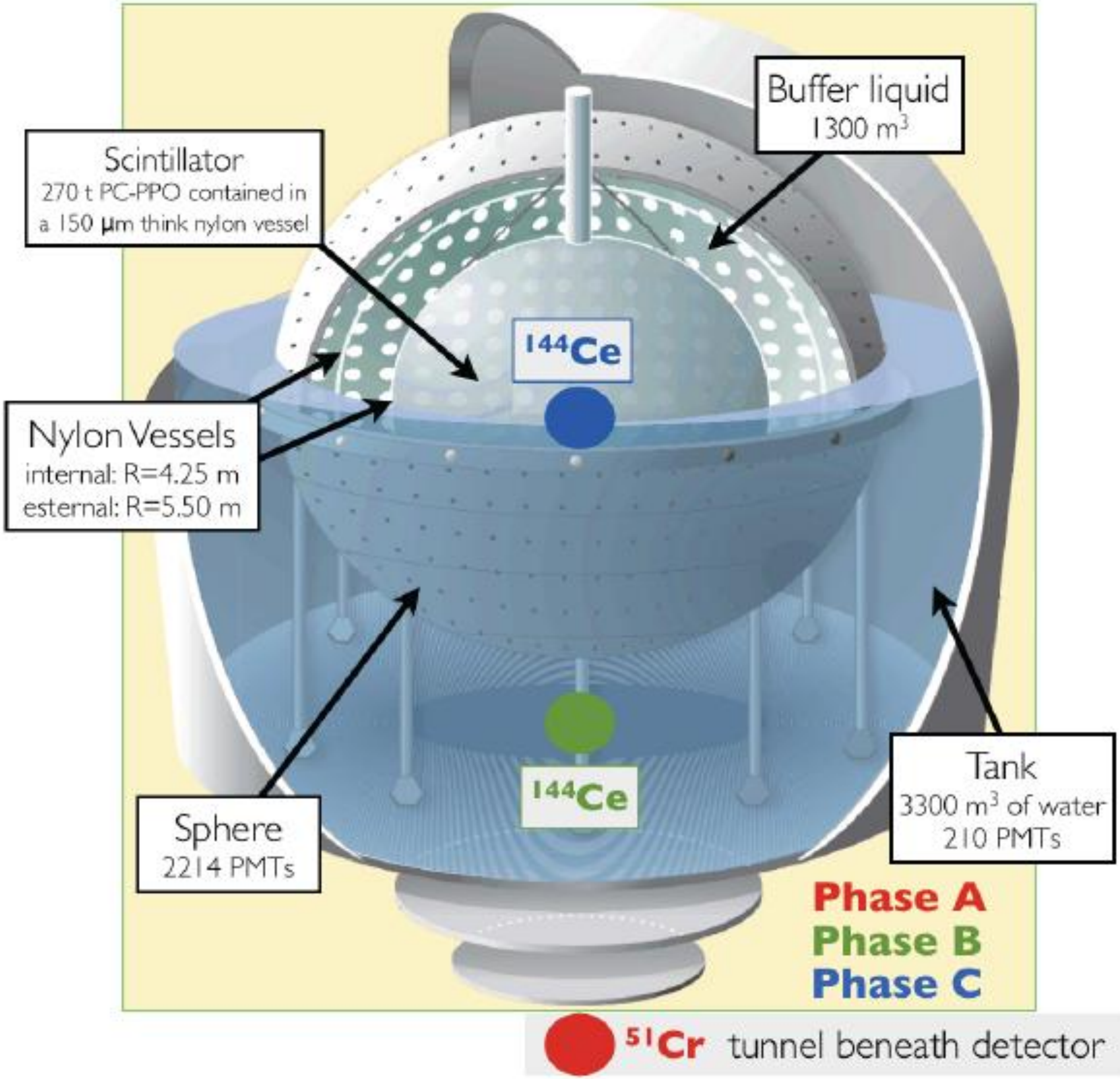






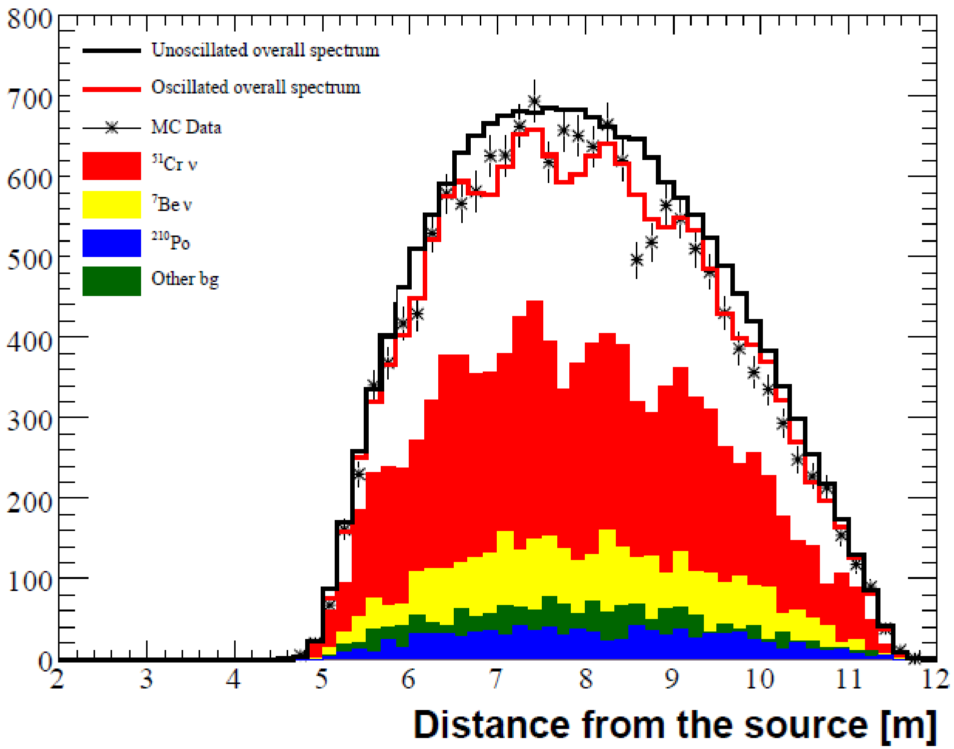


Source	decay	τ [days]	Energy [MeV]	Kg/MCi	W/kCi
^{51}Cr	e-capture (E_γ=0.32 MeV 10%)	40	0.7 90%	0.011	0.19
^{144}Ce-^{144}Pr	Fission product β^-	411	<2.9975 MeV 97.9%	0.314	7.6


Buffer liquid
1300 m^3
Scintillator
270 t PC-PPO contained in
a 150 μm think nylon vessel
^{144}Ce
Nylon Vessels
internal: R=4.25 m
esternal: R=5.50 m
^{144}Ce
Tank
3300 m^3 of water
210 PMTs
Sphere
2214 PMTs
Phase A
Phase B
Phase C
^{51}Cr tunnel beneath detector

SOX Phase A (2014-2015)

- ^{51}Cr neutrino source of 200-400 PBq activity deployed at 8.25 m from the detector center. Uninvasive to detector, can be done in parallel to the regular solar neutrino data-taking.
- Recycling material used in Gallex calibration experiment (material is in Italy now). Activation can be performed in Russia or USA. Both option are in the negotiations stage. Works on source are funded by EU grants and grant in Russia.

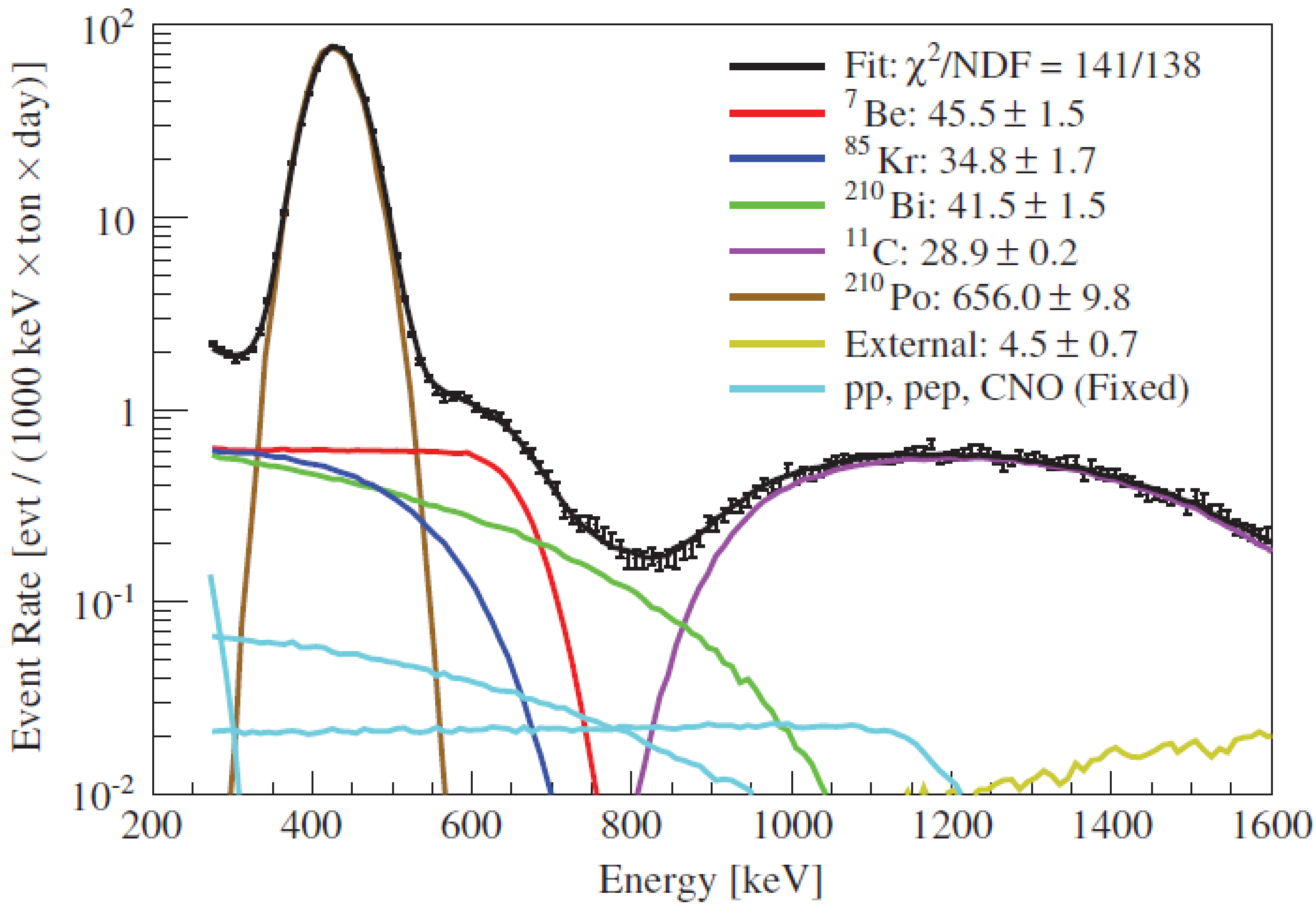


Geant-4 simulation:
$\sin^2(2\Theta_{14})=0.3$
and $\Delta m^2_{41}=2$ eV^2.

The signal (red band) is dominating at all distances from the source. The oscillatory behavior allows to reconstruct Θ_{14} and Δm^2_{41}

Sensitivity is enhanced by exploiting the fact that the life-time of the ^{51}Cr is relatively short (assuming constant background).

Backgrounds for neutrino source experiment



"Precision Measurement of the ^{7}Be Solar Neutrino Interaction Rate in Borexino" PRL 107, 141302 (2011). Expected background in 2014 is 54 cpd/133 t

^{51}Cr source experiment.

Inputs for MC modeling:

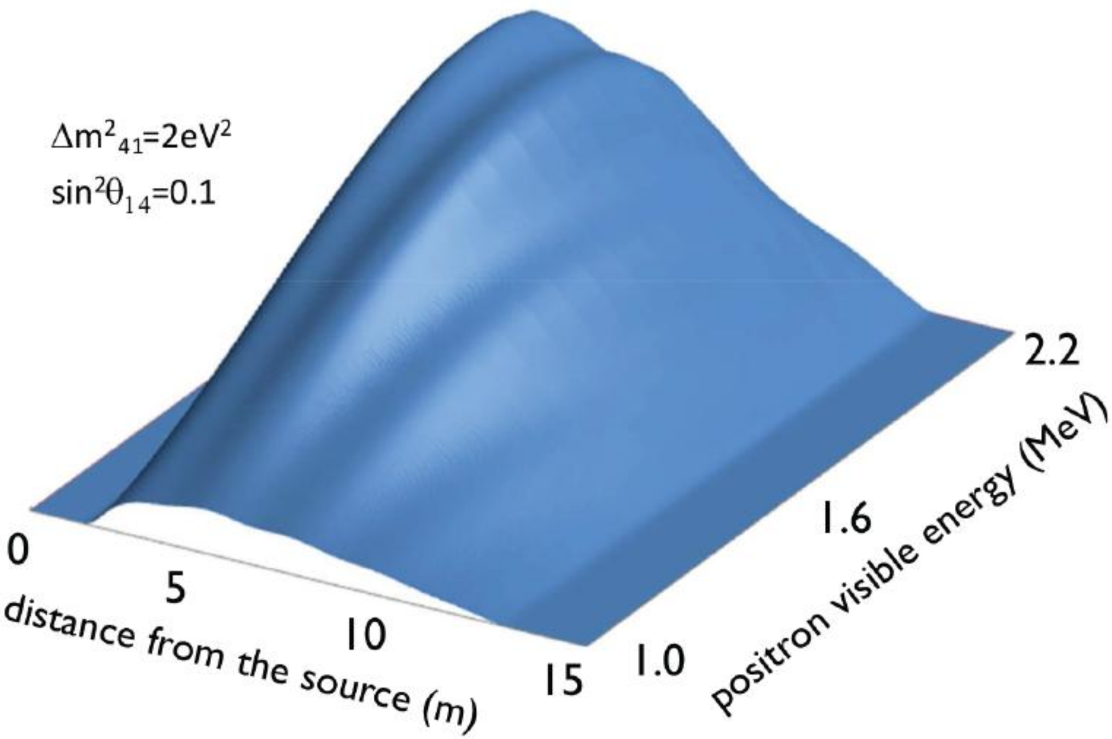
- 370 PBq (10 Mci) at 8.25 m from the center
- a period of 15 weeks of stable data taking before the source insertion (to constrain the background)
- 100 days of data taking with 90% duty cycle
- Assumed: 1% error in the measurement of the source activity, which is challenging but feasible (in 1995 Gallex experiment obtained about 2% precision).
- 1% error on FV: with a careful calibration by means of standard sources (already foreseen for solar physics), the achievement of better than 1% knowledge of fiducial volume is realistic.

SOX Phases B and C (2016-2017)

- ^{144}Ce–^{144}Pr antineutrino source with 2-4 PBq activity.

B) at 7.15 m from the detector center (in water buffer);

C)at the detector's geometrical center;

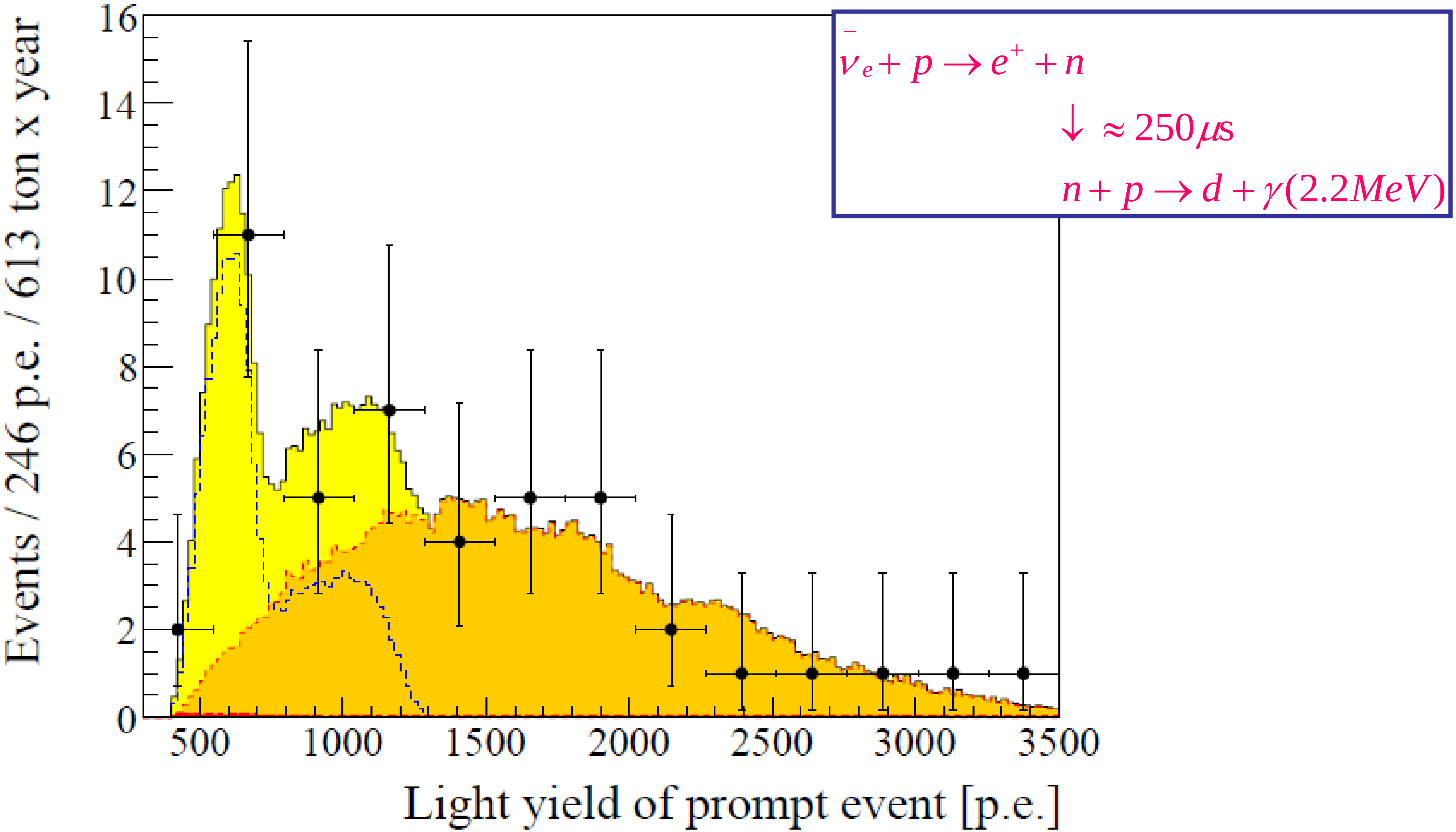


Compared to neutrino source:
very low background and larger cross-section.

Needs cooling,
needs to prevent convection
Stronger shielding requirements

Needs modifications of detector- after solar program (>2016-17)

Backgrounds for antineutrino source experiment



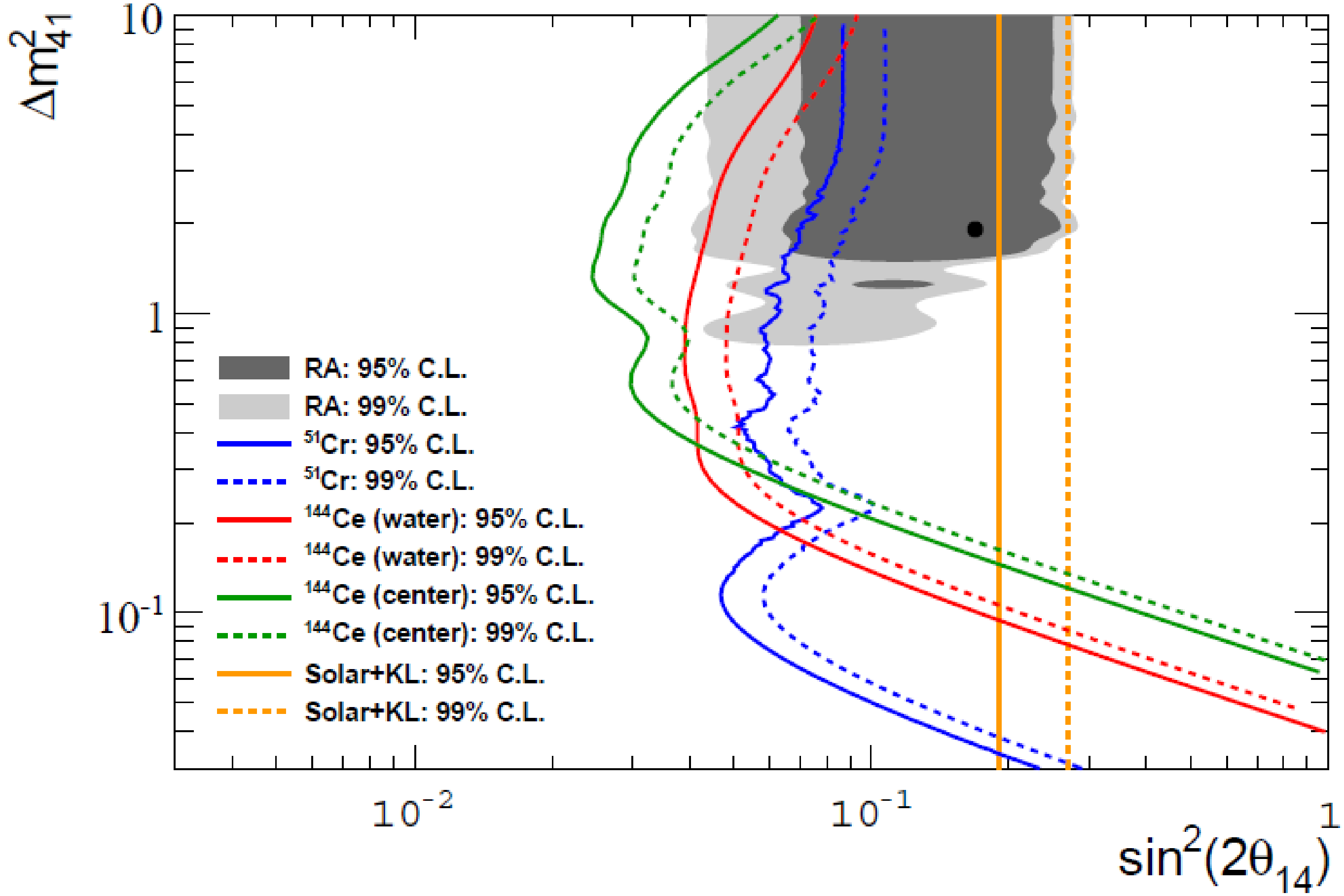
Measurement of geo-neutrinos from 1353 days of Borexino
Physics Letters B722 (2013) pp 295–300

^{144}Ce–^{144}Pr source experiment.

Inputs for MC modeling:

- 2.3 PBq (75 kCi)
- 1.5 yr of data taking with enlarged active volume (from actual 4.25 to 5.5 m)
- 1.5% source intensity knowledge;
- no fiducial volume cut and therefore no corresponding error. However, a 2% experimental systematic error is considered, uncorrelated between energy and space bins, to account for residual systematic effects.

SOX: sensitivity



Phase A (blue), Phase B (red) and Phase C (green). The grey area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95% and 99% C.L. are shown for all cases.

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In conclusion

- **Borexino achieved its main goal, but is still a challenging detector**
- **Due to achieved level of purification (much higher than it was needed for ^{7}Be neutrino detection) some measurements of solar neutrino fluxes beyond the original program were performed**
- **Borexino-II is operating with repurified LS, at new levels of radiopurity, two years of data are collected and are being analyzed aiming the pp-neutrino flux and CNO neutrino flux measurement.**
- **Borexino is an ideal detector to test the sterile neutrinos through the disappearance/wave effects**
  - **The proposed staged approach (^{51}Cr source and two ^{144}Ce–^{144}Pr experiments) is a comprehensive sterile neutrino search which will either confirm the effect or reject it in a clear and unambiguous way.**
  - **In particular, in case of one sterile neutrino with parameters corresponding to the central value of the reactor anomaly, SOX will surely discover the effect, prove the existence of oscillations and measure the parameters through the "oscillometry" analysis.**