Recent results and future perspectives of the Borexino experiment

Les Rencontres de Physique de la Vallée d'Aoste-

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(on behalf of the Borexino collaboration)

Outlook

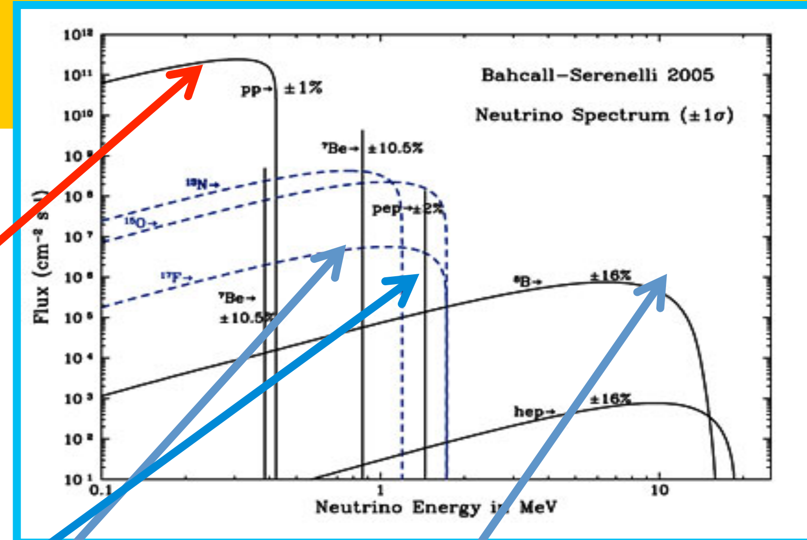
Borexino Phase 1 (May 2007 – May 2010)

- I will focus on solar neutrinos
  - ^{7}Be neutrinos;
  - ^{8}B neutrinos;
  - pep neutrinos;
- Borexino has also given important results on other topics:
  - Geo-neutrinos;
  - Search for rare or forbidden processes (axions from the Sun, limits on Pauli violating transitions...);
  - Speed of ν_μ from CNGS;

Borexino Phase 2 (started in October 2011)

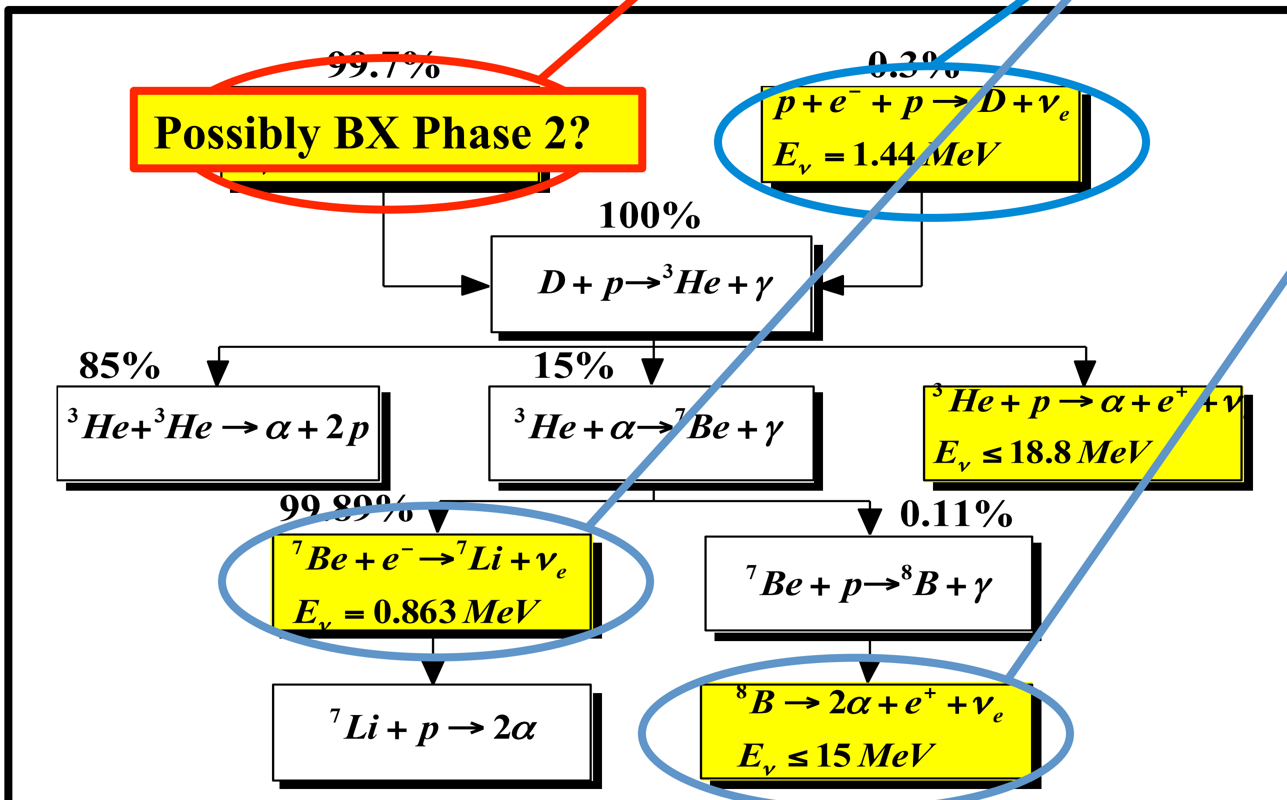
- Status and physics goals
  - Search for sterile neutrinos

Solar neutrinos

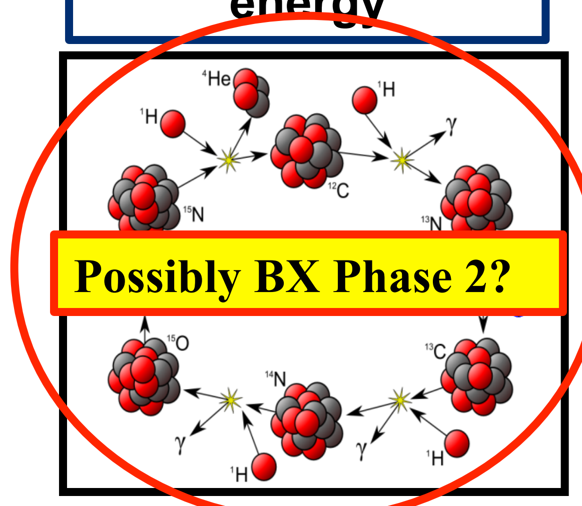


Solar neutrino spectrum: dominated by low-energy neutrinos (< 1MeV)

pp CYCLE:
~99% of the sun energy



CNO CYCLE:
<1% of the sun energy



Importance of studying solar neutrinos

Astrophysics:
Open issues: solar metallicity controversy
•Metallicity (the abundance of elements heavier than He) is used as input in the Standard Solar Model;
•The neutrino fluxes depend on it;
•Differences as large as 30-40% (for CNO);
•Differences of ~9% for ^{7}Be ν

Sources	$\Phi(\nu\ sec^{-1}\ cm^2)$ high-metallicity	$\Phi(\nu\ sec^{-1}\ cm^2)$ low-metallicity	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.1
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^7Be	$5.00(1\pm0.070)\times10^{9}$	$4.56(1\pm0.070)\times10^{9}$	8.8
^8B	$5.58(1\pm0.140)\times10^{6}$	$4.59(1\pm0.140)\times10^{6}$	17.7
^{13}N	$2.96(1\pm0.140)\times10^{8}$	$2.17(1\pm0.140)\times10^{8}$	26.7
^{15}O	$2.23(1\pm0.150)\times10^{8}$	$1.56(1\pm0.150)\times10^{8}$	30.0
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	38.4

•**Solar Model:** Serenelli, Haxton and Pena-Garay arXiV:1104.1639
•**High metallicity GS98** = Grevesse et al.*S. Sci. Rev. 85,161 ('98);*
•***Low metallicity AGS09*** = *Asplund, et al,* A.R.A.&A. 47(2009)481

Particle physics: the so-called "solar neutrino problem" has provided one of the first hints towards neutrino oscillations;
•Now we know that neutrinos oscillate in their path from Sun to Earth;
• "LMA solution": $\Delta m^2 = 7.6\times10^{-5}\ eV^2$; $tg^2\theta = 0.468$
Open issues: precision measurements of solar neutrino sources at low energies probe P_{ee} in the vacuum to matter transition region which is sensitive to new physics;

Borexino

- **Main goal**: detecting low energies solar neutrinos, in particular ^{7}Be neutrinos;
- **Detection principle:** scattering of neutrinos on electrons $\nu_x + e^- \rightarrow \nu_x + e^-$
- **Detection technique**: large mass of organic liquid scintillator;
- **Technique advantages**: high light-yield (higher than Cerenkov)
- **Technique disadvantages**: no directional information (unlike Cerenkov);

Signal is indistinguishable from background: high radiopurity is a MUST!

- The expected rate of solar neutrinos in 100tons of BX scintillator is ~50 counts/day which corresponds to ~ 5 10^{-9} Bq/Kg;
- Just for comparison:
  - Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
  - Air is ~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
  - Typical rock is ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

BX scintillator must be 9/10 order of magnitude less radioactive than anything on earth!

Background suppression: 15 years of work

- **Internal background: contamination of the scintillator itself (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)**
  - Solvent purification (pseudocumene): distillation, vacuum stripping with low Argon/Kripton N2 (LAKN);
  - Fluor purification (PPO): water extraction, filtration, distillation,N_2 stripping with LAKN;
  - Leak requirements for all systems and plants < 10^{-8} mbar· liter/sec;
- **External background: γ and neutrons from surrounding materials**
  - Detector design: concentric shells to shield the inner scintillator;
  - Material selection and surface treatement;
  - Clean construction and handling;

Background suppression: achievements

•Contamination from ^{238}U and ^{232}Th chain are found to be in the range of ~10^{-17} g/g and ~5x×10^{-18} g/g respectively;

•**More than one order of magnitude better than specifications!**

•Three backgrounds out of specifications: ^{210}Po, ^{210}Bi and ^{85}Kr.

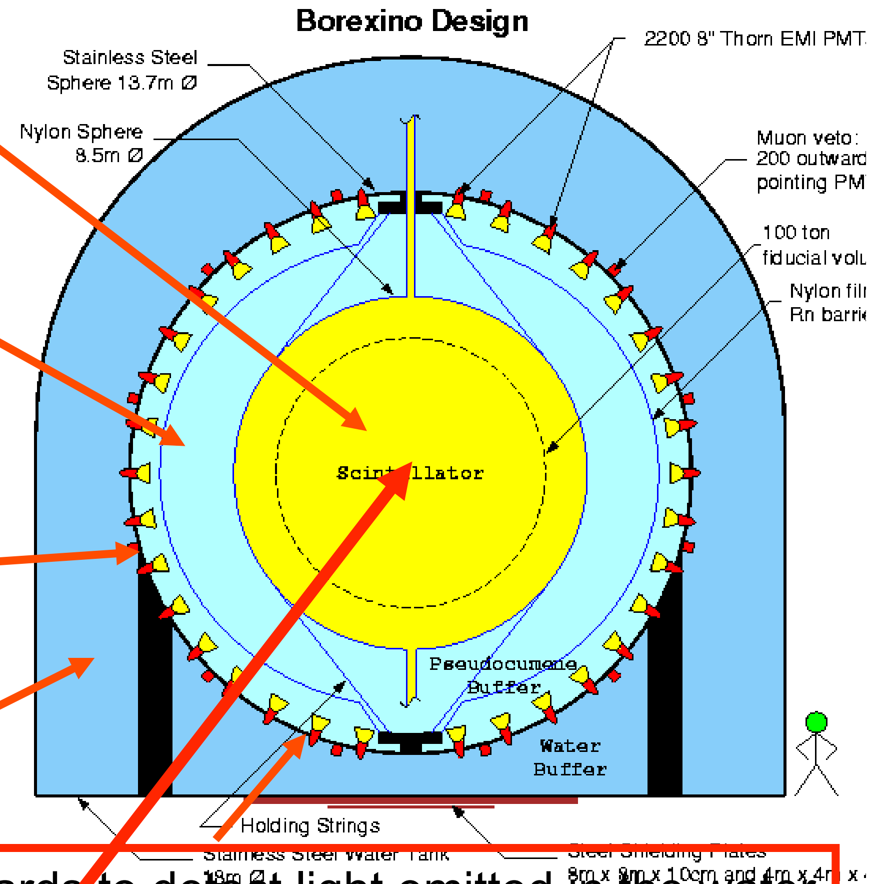
Borexino

Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius;

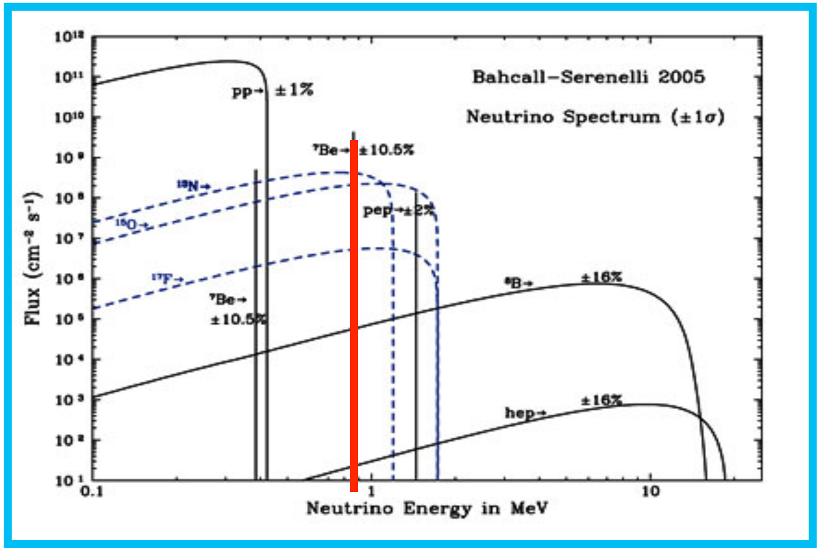
2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

2nd shield: 2000 tons of ultra-pure water contained in a cylindrical dome;



200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

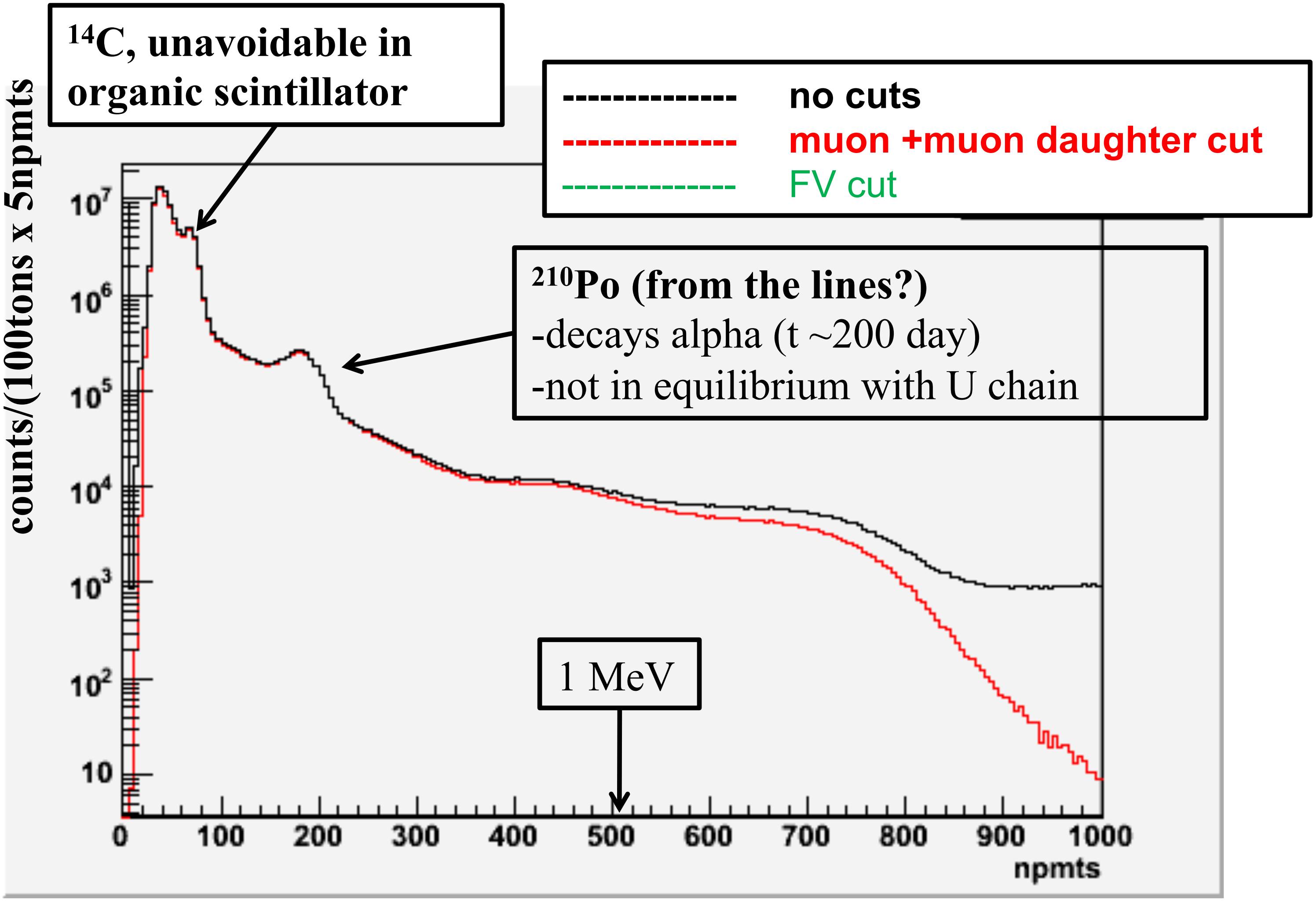
Only the innermost part of the scintillator is considered in the analysis (FV selection), in order to further reduce the external background.



Be7 neutrinos and their day-night asymmetry

^{7}Be neutrino rate: precision measurement (5%)

Data after 750 days (normalized to 100tons)



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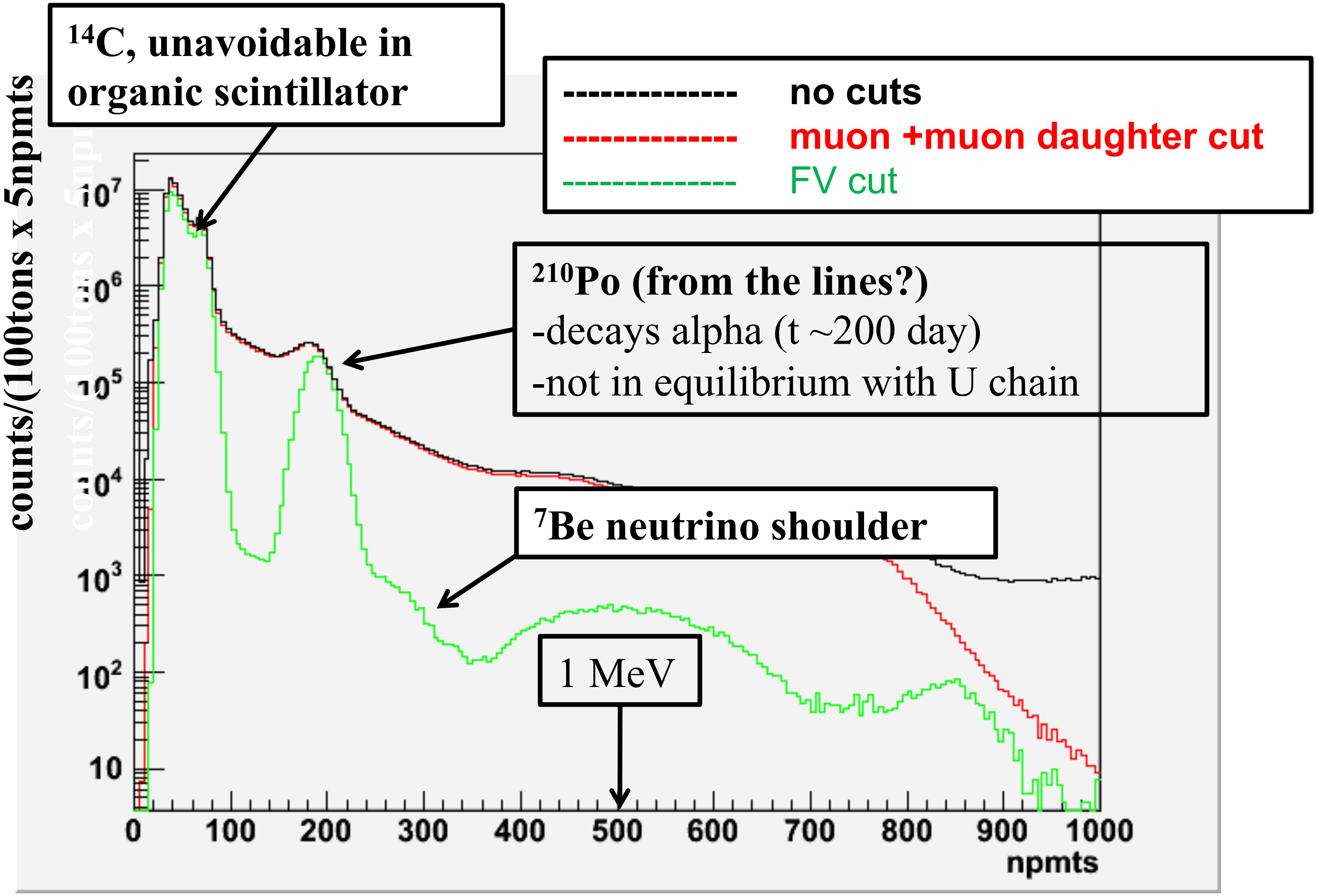
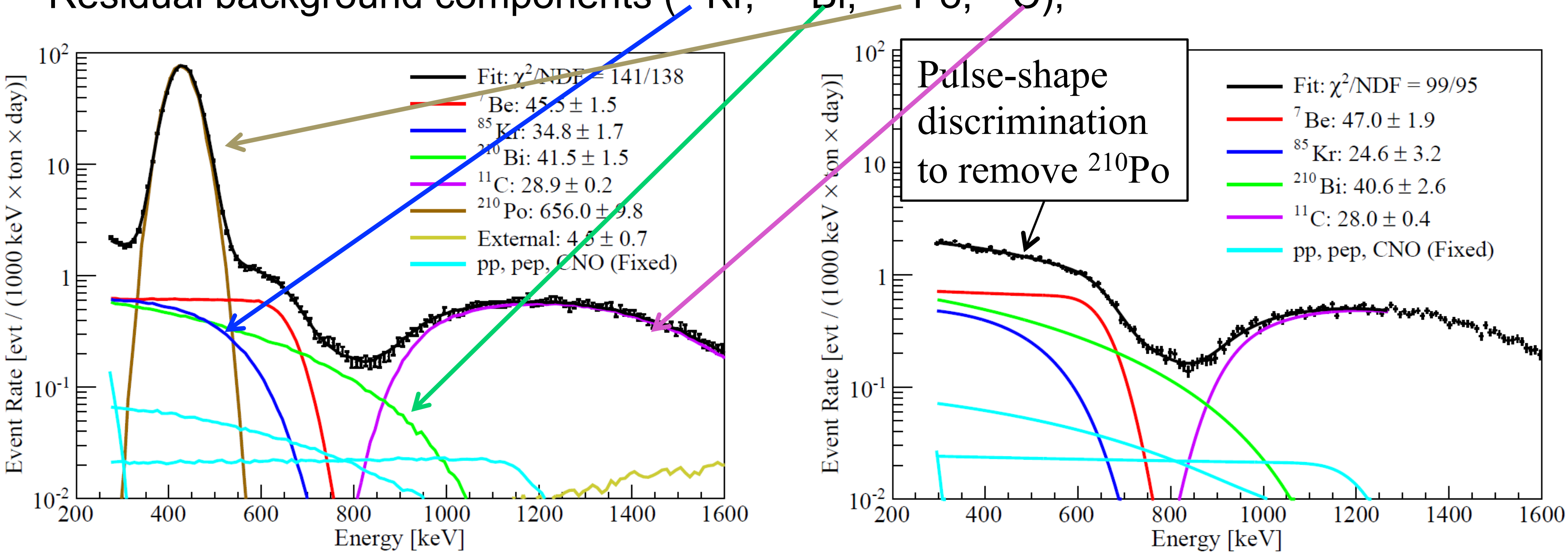


^{7}Be neutrino rate: precision measurement (5%)

- Residual background components (^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C);

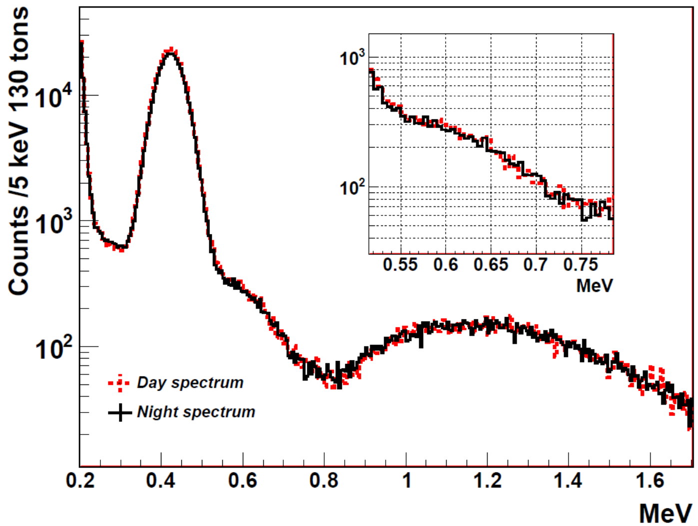


$$^{7}\text{Be rate (862 keV line)} = 46.0 \pm 1.5\,(\text{stat})\,^{+1.5}_{-1.6}\,(\text{sys})\ \text{cpd}/100\text{tons}$$

- This result confirms neutrino oscillations;
- However it doesn’t allow to discriminate between low and high metallicity (the result is in between expectations from low and high metallicity);

^{7}Be neutrinos: day-night asymmetry

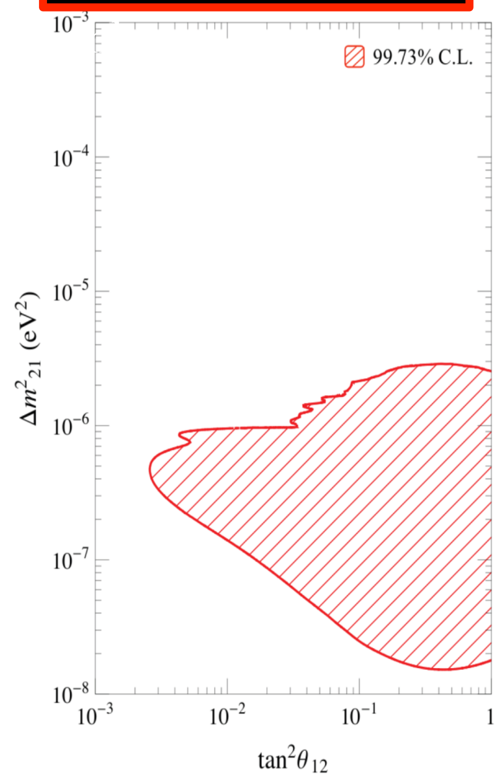
•In the MSW framework, the neutrino rate at Night (when neutrinos cross Earth) could be significantly larger than the rate during the Day, because of regeneration effect;



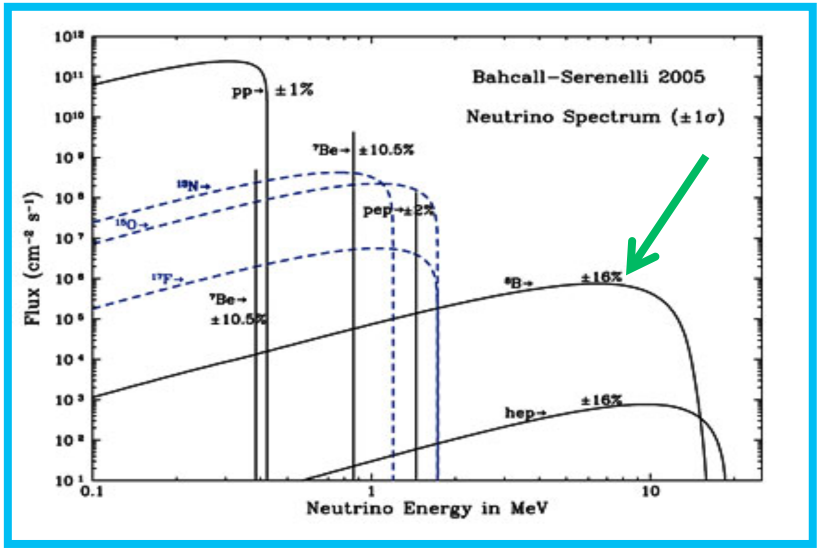
•Divide spectrum in day and night (Day=360.35 d and Nights=380.63 d);
•Subtract day from night spectrum;
•Fit the residual spectrum with the ^{7}Be shoulder + constant;
•It is consistent with 0 in agreement with the LMA expectations;

A_{dn} = 0.001 ± 0.012(stat) ± 0.007(sys)
No asymmetry within errors

Fit to BX ADN



Low solution excluded at more than 8σ by Borexino data only

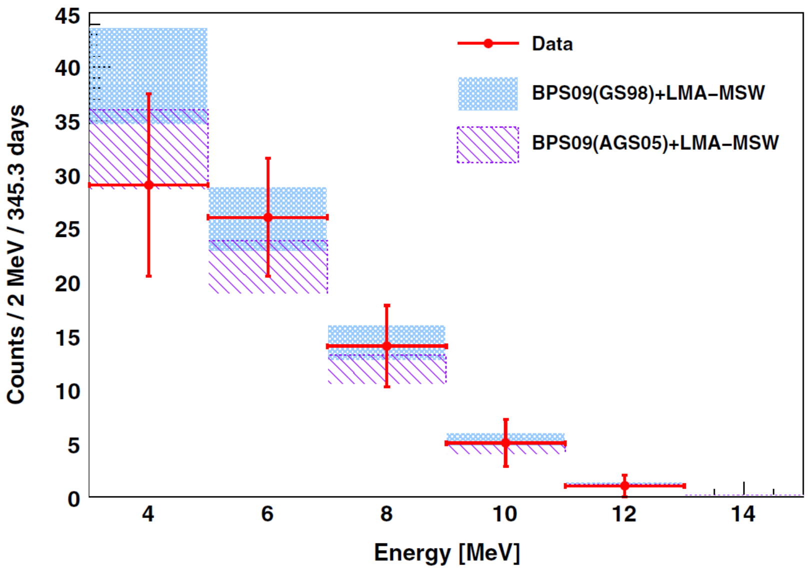


^{8}B solar neutrinos

^{8}B neutrinos with low energy threshold (T_e >3 MeV)

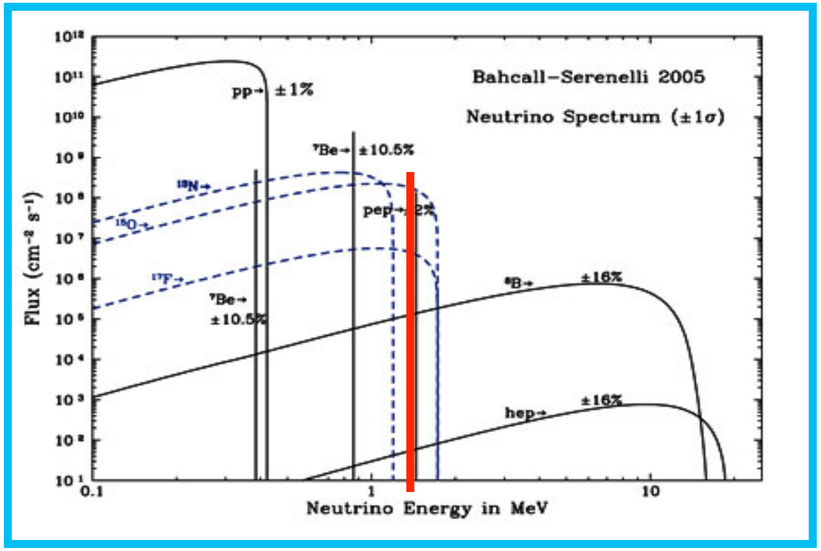
Analysis performed on 488 live days of data-taking (from Jul2007 to Aug 2009)

Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90 ± 13	55 ± 7
^{11}Be subtraction	79 ± 13	47 ± 8
Residual subtraction	75 ± 13	46 ± 8
Final sample	75 ± 13	46 ± 8
BPS09(GS98) ^{8}B ν	86 ± 10	43 ± 6
BPS09(AGS05) ^{8}B ν	73 ± 7	36 ± 4



Rate of ^{8}B neutrinos (E>3 MeV) = 0.22 ± 0.04 (stat) $\pm$ 0.01 (sys) cpd/100t

- The result is consistent with the one of SuperK and SNO
- **Borexino is the only experiment which can probe simultaneously the Pee in the vacuum and matter dominated regimes**

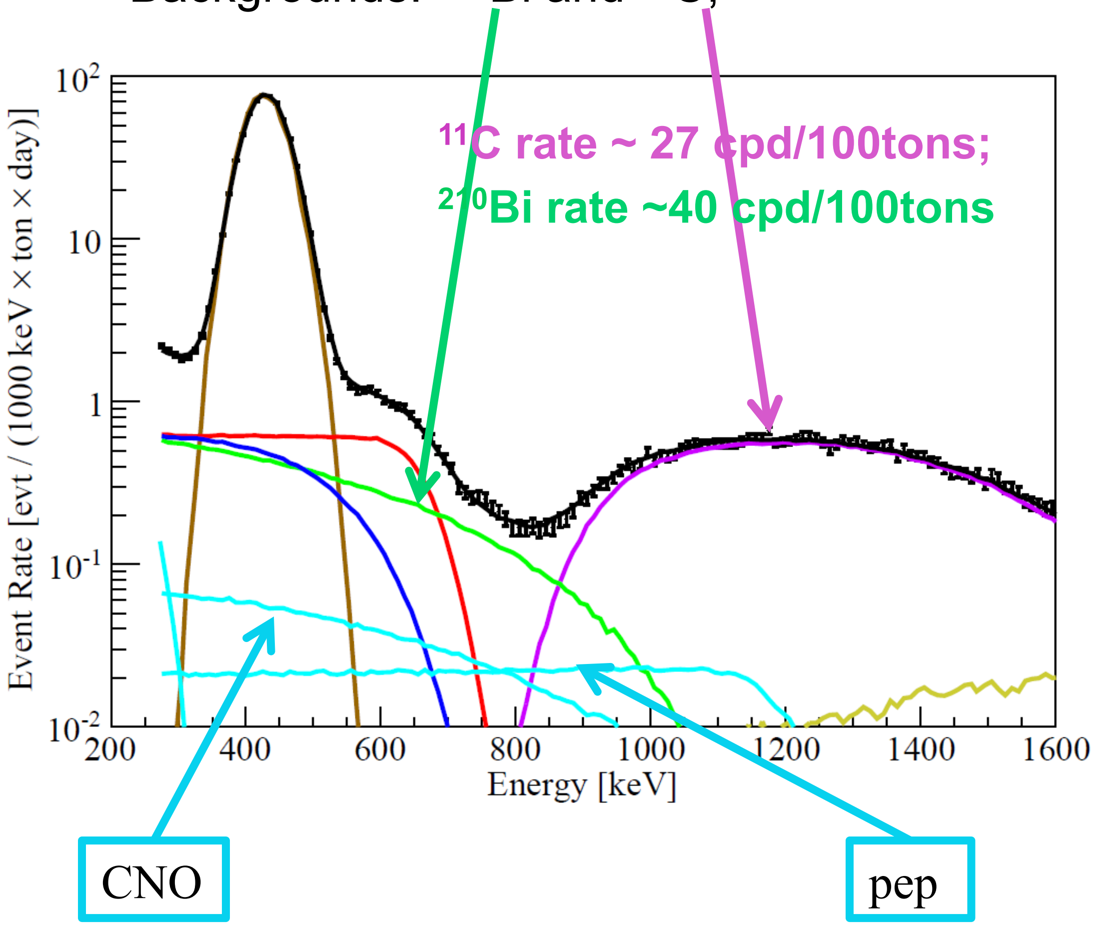


First evidence of pep neutrinos and limits on CNO

First evidence of pep solar neutrinos and limit on CNO

Backgrounds

- Difficulties of this analysis:
  - Very tiny rates (few counts /day/100tons);
  - Backgrounds: ^{210}Bi and ^{11}C;



^{11}C is produced by muons crossing BX

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

It is possible to suppress the ^{11}C background by

- three-fold coincidence;
- pulse-shape discrimination;

First evidence of pep solar neutrinos and limits on CNO

Three-fold coincidence technique:

- ^{11}C is produced by muons crossing BX

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

${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
t~30min

$n + p \rightarrow d + \gamma$
$\tau \sim 260 \mu s$

- Space and time veto after the coincidence of a muon and a neutron

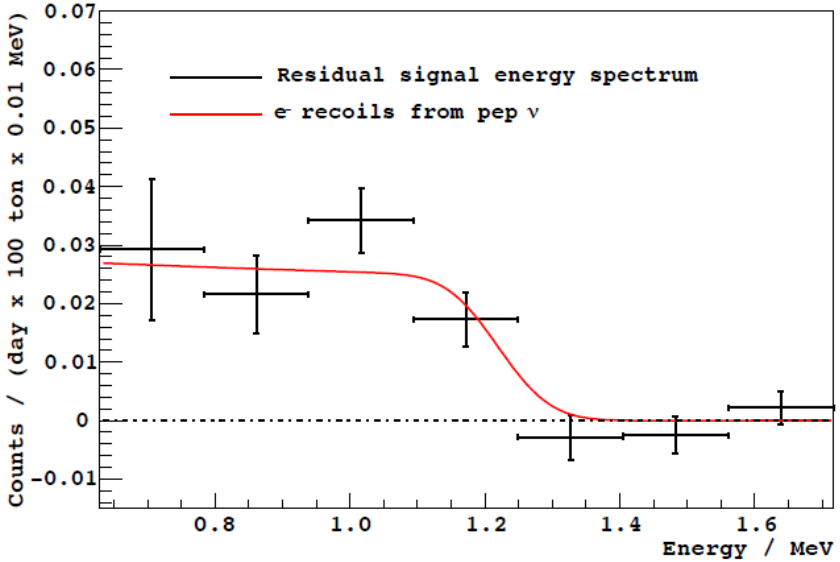
e+/e- pulse shape discrimination

(PRC 83-015522 (2011))

- Based on the small differences between the time distribution of the scintillation signal for e^{+} (background) and e^{-} (signal);
- Differences are due to the fact that e+ forms ortho-positronium which has a non-negligible lifetime and also to the presence of annihilation gamma rays

First evidence of pep solar neutrinos and limit on CNO

Multivariate analysis:



Fit simultaneously:

- Radial distribution of events;
- Energy distribution of events;
- Pulse-shape distribution of events;

Both pep and CNO rates are parameters of the fit

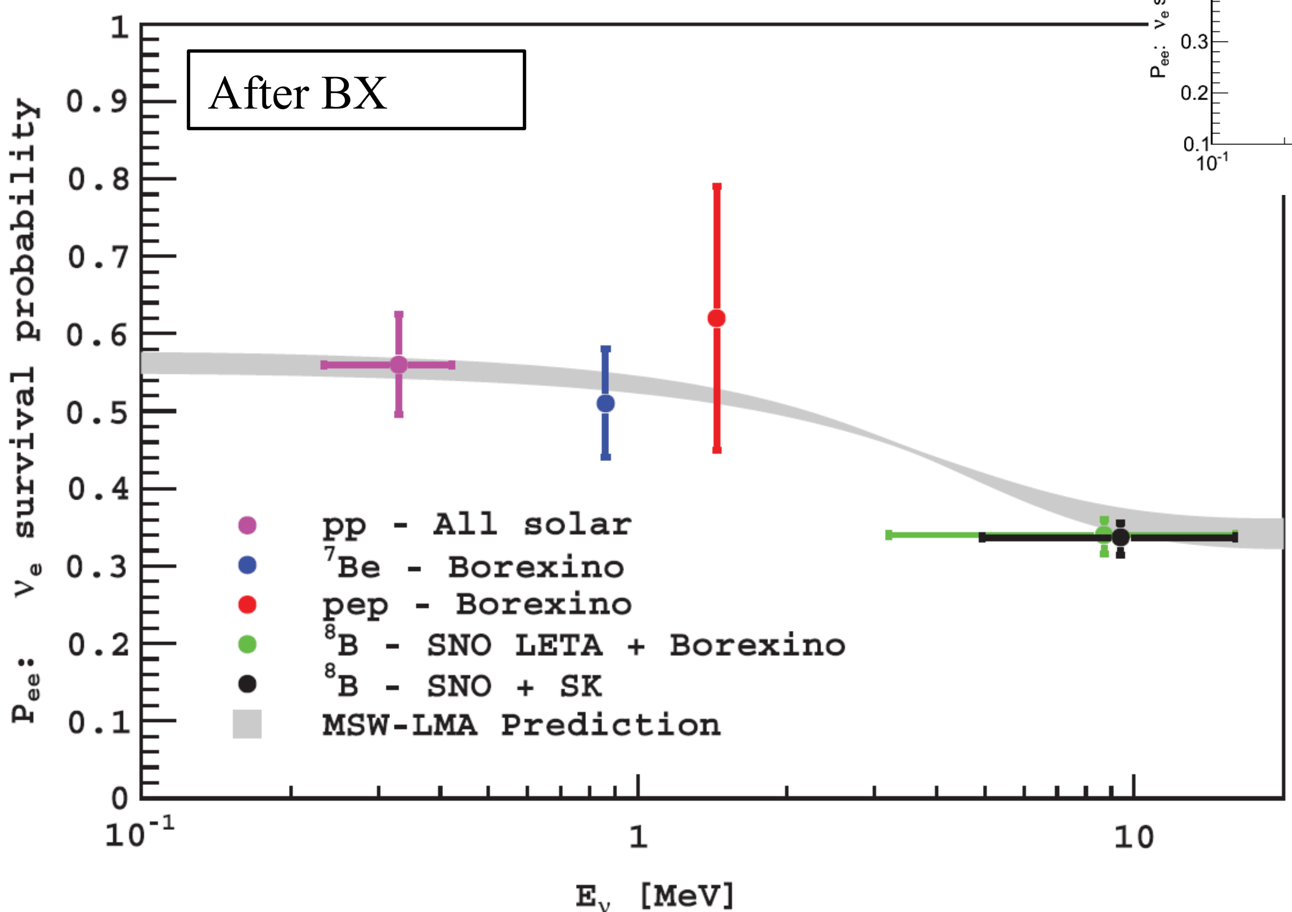
ν	Interaction rate [counts/(day · 100 ton)]	Solar-ν flux [10^8 cm^{-2} s^{-1}]	Data/SSM ratio
pep	$3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}}$	1.6 ± 0.3	1.1 ± 0.2
CNO	<7.9 $(<7.1_{\text{stat only}})$	<7.7	<1.5

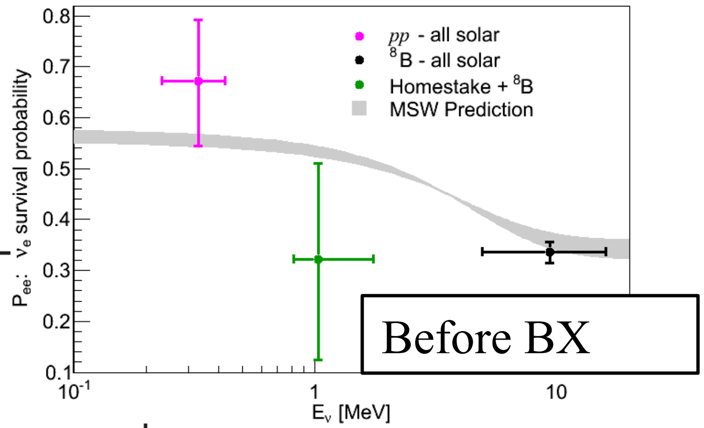
The current result on CNO doesn't allow to discriminate between low and high metallicity hypothesis

Implications of Borexino data on oscillation parameters

Borexino has performed a spectroscopy in real-time of solar neutrinos

Borexino has been able of probing Pee at different energies, giving a confirmation of the LMA hypothesis





We are not stopping here: Borexino Phase 2

Borexino Phase 2

Borexino Phase 2 started in October 2011 after a new purification campaign in 2010-2011

Physics goals

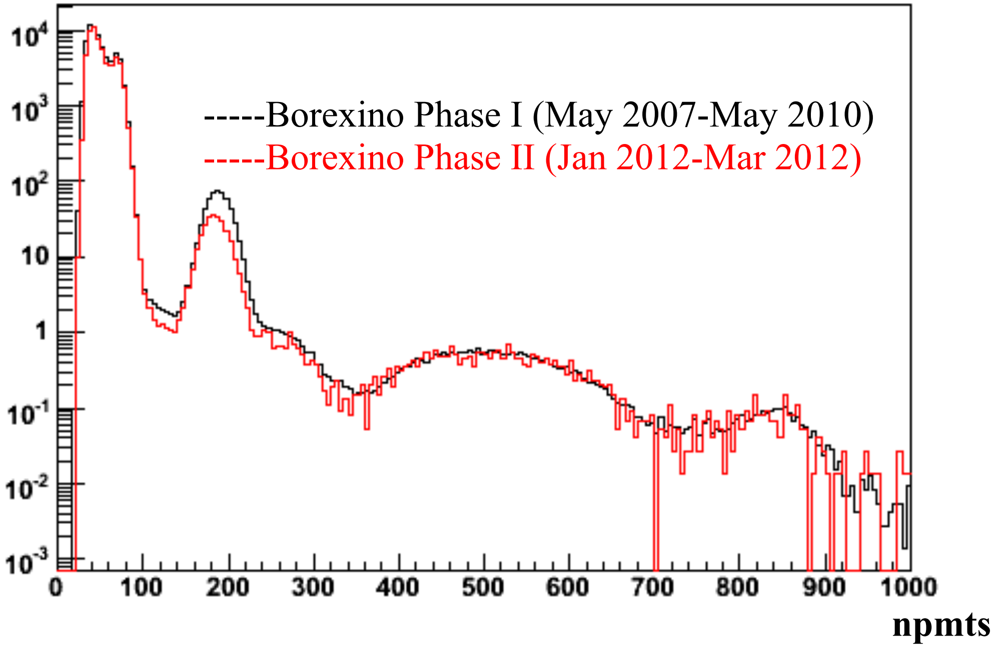
- Improve limit on CNO (observation?) → ^{210}Bi suppression required;
- Improve significance of pep signal (3σ or more)→ ^{210}Bi suppression required;
- Search for pp neutrinos → ^{85}Kr suppression required;
- Improve precision on ^{7}Be neutrinos → ^{210}Bi and ^{85}Kr suppression required;

Purification status

- 6 cycles of purification with water extraction have been performed between May 2010 and August 2011;
- The purification was very successful in removing Kr (now consistent with 0);
- It substantially removed ^{210}Bi (from ~70 cpd/100tons → 20 cpd/100tons);
- Extreemely low background levels for what concerns U and Th;

Borexino Phase II

Comparison between Phase I and Phase 2 data;



The BX scintillator has never been so clean!

- For the pep/CNO measurement it would be crucial to know the ^{210}Bi content independently;
- Considering the chain $^{210}Pb \rightarrow {}^{210}Bi \rightarrow {}^{210}Po$
- It may be possible to estimate the ^{210}Bi content from ^{210}Po evolution in time;
- We need to wait for the ^{210}Po out of equilibrium to decay

Sterile neutrino search with Borexino

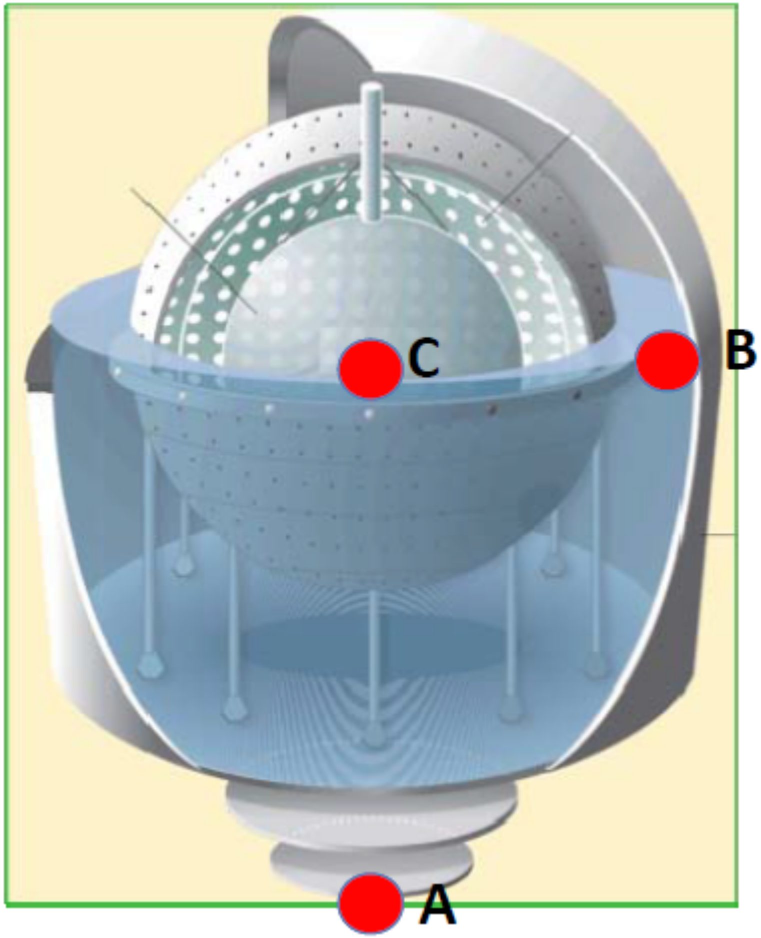
A Short Baseline neutrino oscillation experiment with Borexino:

SOX

Several experimental anomalies which could be solved by assuming one (or more) sterile neutrino;

- Gallium anomaly (arXiV:1006.3244);
- Reactor anomaly (arXiV 1101.2755);
- LSND/MiniBoone results;
- Cosmological hint for more than 3 neutrino families;

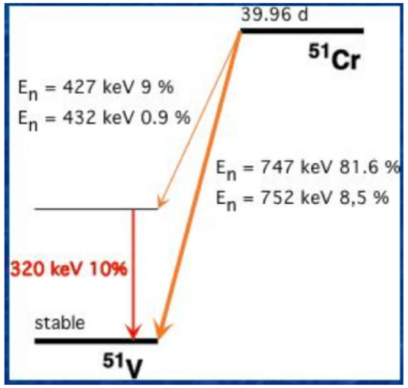
- These anomalies point towards $\Delta m^2 \sim 1\ eV^2$;
- Possibility to study this parameter space region with a short-baseline experiment L~meters; E~1 MeV;
- Radioactive source located close or inside the Borexino detector



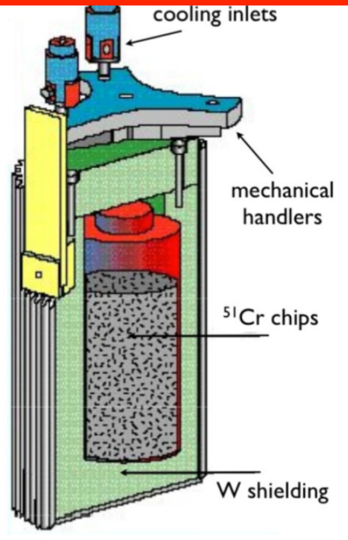
Sterile neutrino search with Borexino

Source of neutrinos: ^{51}Cr

- Most important line at ~ 750 keV;
- τ ~40 days;
- Same detecting reaction of solar ν
  $\nu+e \rightarrow \nu+e$
- Radioactivity and solar ν are background



(a)



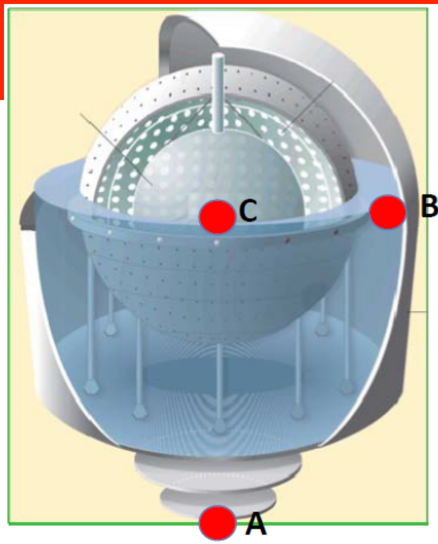
(b)

Source procurement

- Source formerly used in Gallex still available, 36 Kg enriched in ^{50}Cr (38.6%);
- Requires attivation by irradiation with neutrons
  - intense neutron flux
  - large irradiation volume to accomodate the source;
- Siloe reactor (used for Gallex) no more available;
- Possible alternatives, in Russia, USA and Netherland;

- ^{51}Cr source can be used only outside the detector, because of the irreducible γ background from source shielding;
- Required activity ~10MCi;

Sterile neutrino search with Borexino



Source of anti-neutrino: ^{144}Ce- ^{144}Pr

- β spectrum Q=2.99 Mev (^{144}Pr);
- τ ~411 days;
- Detecting reaction: inverse beta-decay $\nu+p \rightarrow n+e^+$
- Delayed coincidence tag→ very small background

- Due to the extremely efficient background rejection power of the coincidence tag it will be possible to insert the source directly in the detector (position C);
- It could be also inserted in the water shield (position B);
- Required activity ~50kCi;

Source procurement

- ^{144}Ce can be chemically extracted from exhausted nuclear fuel;
- Possibility to do it in Mayak industrial complex (Russia);

- Several technical difficulties (shielding, source holding system..)
- **Requires major hardware changes and could be done after the end of the Borexino solar neutrino program**

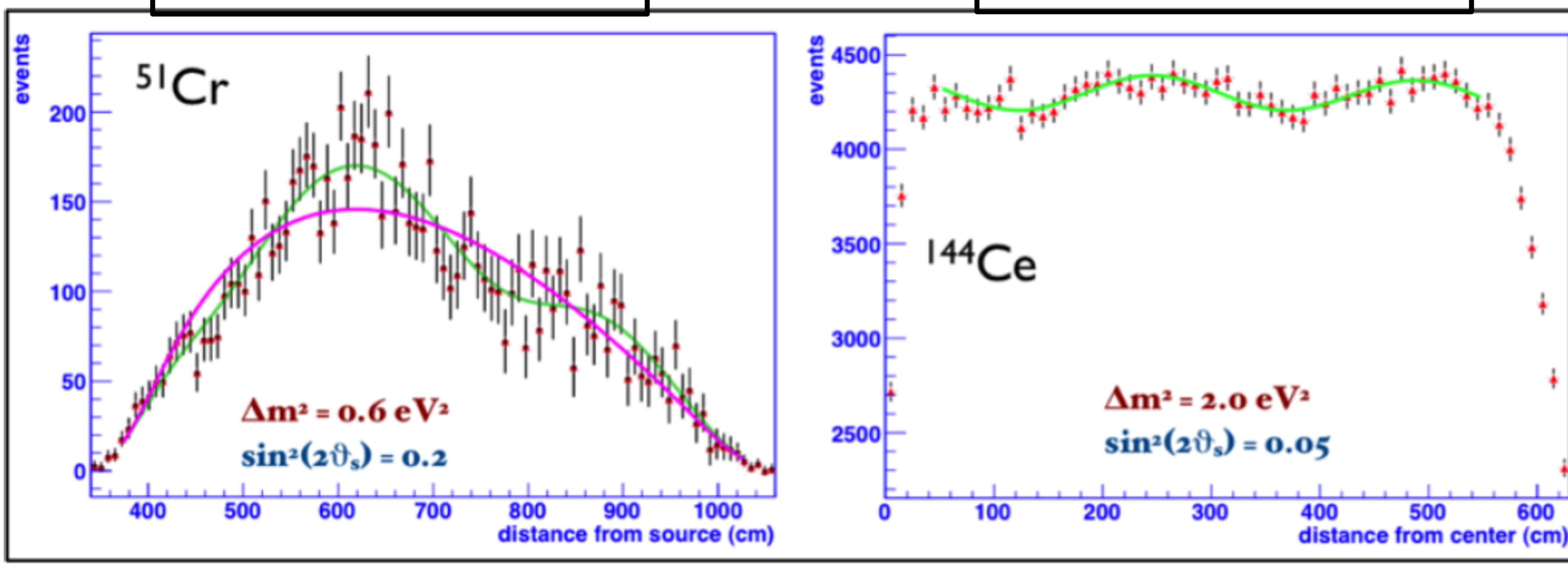
Sterile neutrino search with Borexino

Sensitivity studies

Analysis based on two observables:

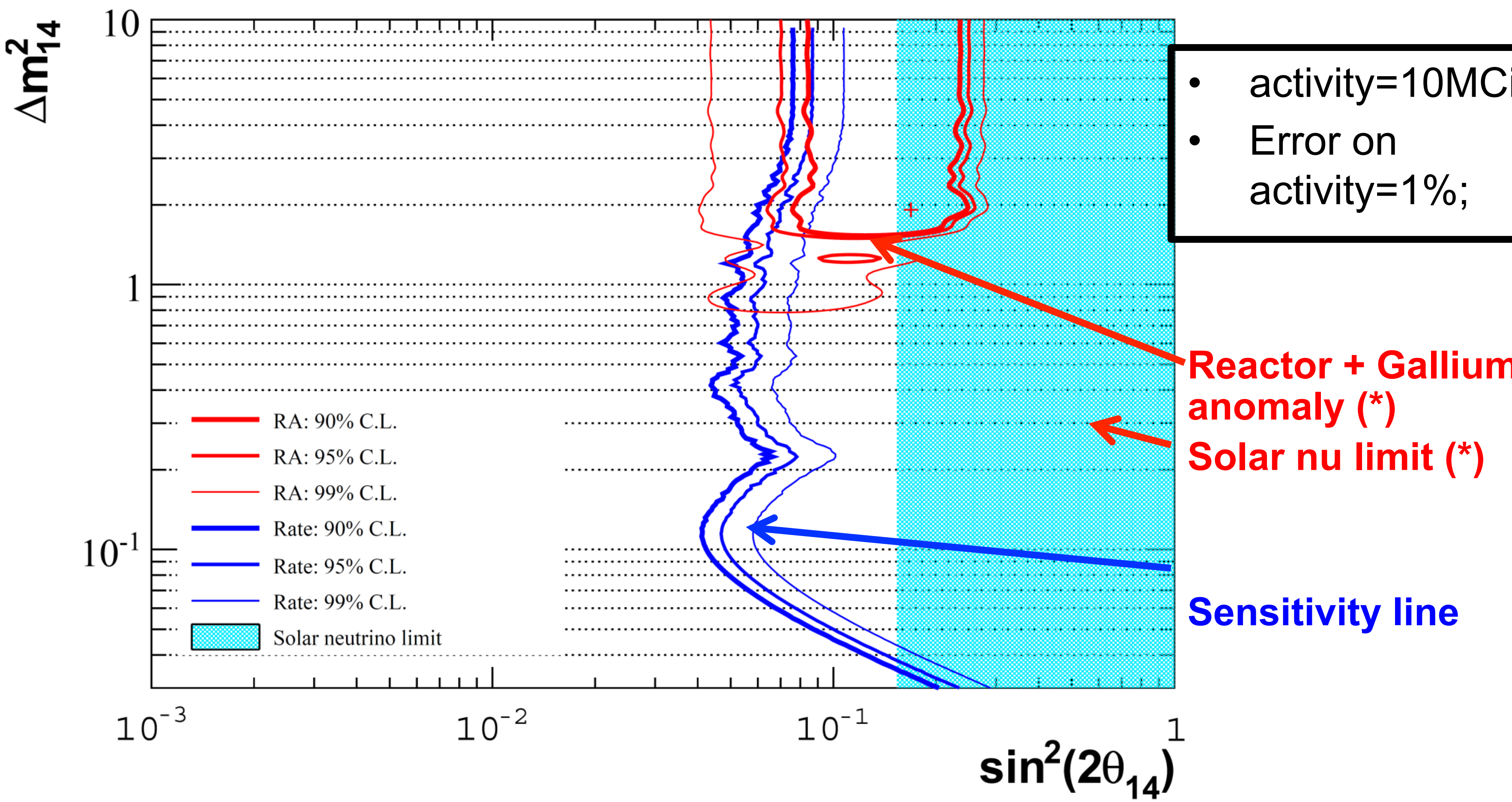
- Rate measurement (as in standard ''disappearence'' technique) (need to know the source activity very precisely ~1%);
- Observation of oscillation waves (L_{osc} ~ meters)

Source outside BX **Source inside BX**



Sterile neutrino search with Borexino

Sensitivity of the ^{51}Cr source outside BX



- activity=10MCi;
- Error on activity=1%;

(*) C. Giunti et al. Physical Review D, vol. 86, 113014, 2012 - arXiv:1210.5715

Summary and Perspectives

- Borexino Phase 1 was very successful

- **Borexino Phase 2 is starting:**
  - 6 purification cycles performed between May 2010 and August 2011;
  - Exceptional levels of radiopurity: ^{85}Kr rate consistent with 0, ^{210}Bi; reduced by a factor ~3, unprecedented levels of U and Th;
- **Goals concerning solar neutrinos:**
  - Improve limit on CNO neutrinos (possibly observation);
  - pp neutrinos (challenging!);
  - Improve significance of pep signal (3σ or more);
  - Improve precision on ^{7}Be neutrino rate (3% ?);
- **Search for sterile neutrinos with Borexino: SOX**
  - Preliminary work in progress (radioprotection, transportation..);
  - Search for the best reactor to irradiate the source;
  - Possibility to start the experiment with the ^{51}Cr source by the beginning of 2015;