Status of Borexino

What Borexino is doing?

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Borexino phase 1 - May 2007- May 2010
Purification campaign- May 2010-October 2011
Borexino phase2- October 2011-Fall 2015

Phase 2 main conditions:

1- Radiopurity (after the new purification campaign)

Nuclide	Rate(cpd/100 tons)	Remarks
^{85}Kr	< 6.4 cpd/100 tons	No candidates observed since oct. 2011 (phase 2)
^{232}Th equiv.	< 2.2 10^{-18} g/g	Two candidates observed in the last 315 live days
^{238}U equiv.	3.3±1.4 10^{-19} g/g	
^{210}Bi	18±1.5 cpd/100 tons	Perhaps still going down slowly- see interpretation in the text
^{210}Po	400 cpd/100 tons	Due to its lifetime its rate will be at the same order of magnitude as ^{210}Bi ≥ 1 year from oct.2012.

2- Detector left undisturbed and untouched as much as possible

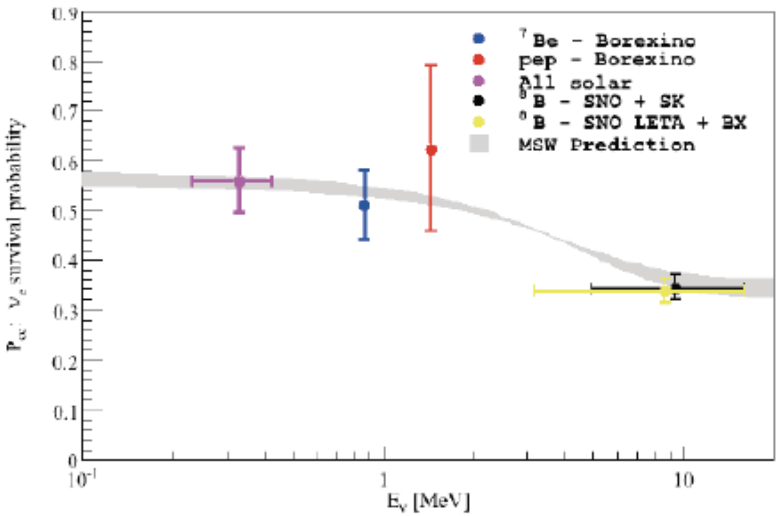
The physics case of Borexino phase 2

1- **Stellar** Physics: **CNO**- is theorized to be the primary channel for Hydrogen burning in stars more massive than the Sun, and the primary channel for hydrogen burning in the Universe: **never measured!!**

2- **Solar** physics: **direct measurements of all fluxes**(except hep)
first direct measurement of the **pp** flux (without luminosity constraint); **CNO-** low vs high metallicity- ~ 30% of difference between the two fluxes; reduction of the uncertainties of the ^{7}Be and pep measurements

3-**Neutrino** physics: **transition region-** NSI, ultra-light sterile neutrino:

pep flux with higher precision;
^{8}**B** in the range 3.-5. MeV
$\nu_e - e$ elastic scattering



@ **artificial source**:
# **sterile neutrino**
# NSI via $\nu_e - e$ e.s
# ν_e magnetic moment
# Weinberg angle

NSI

effective four fermion interactions

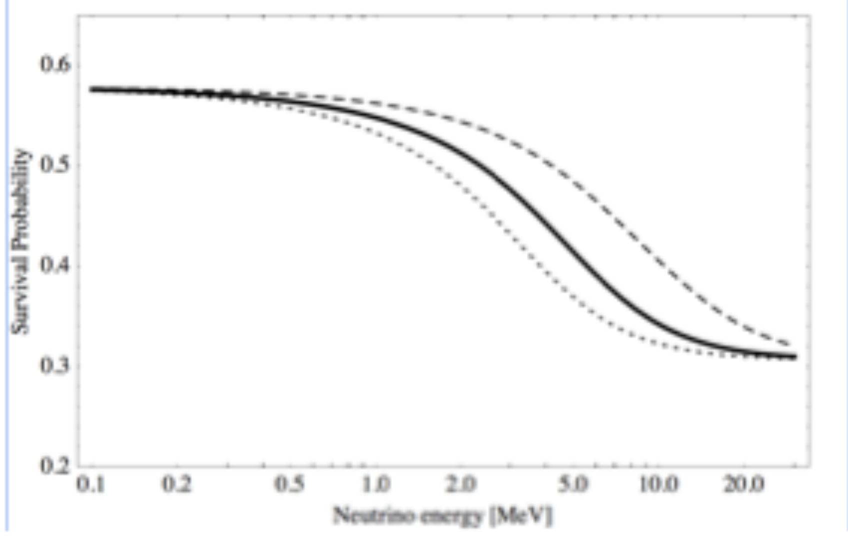
$$\ell_{NSI} = -2\sqrt{2}G_F \varepsilon_{\alpha,\beta}^{e,u,d} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

f and f' =electron or the light quarks; C can be L or R, i.e. the chirality of the operator P, ε is a dimensionless parameter which, coupled with the weak coupling constant, parameterizes the strength of the interaction.

Oscillation matrix element with NSI

$$\begin{pmatrix} \sqrt{2}G_F N_e(1+\varepsilon_{ee}) & 0 & 0 \\ 0 & \sqrt{2}G_F N_e \varepsilon_{\mu\mu} & 0 \\ 0 & 0 & \sqrt{2}G_F N_e \varepsilon_{\tau\tau} \end{pmatrix}$$

Transition region



$\varepsilon_{ee}, \varepsilon_{\mu\mu}, \varepsilon_{\tau\tau} = 0.25, 0., -0.5$, (punctuated line)

-0.25. 0., 0.5 (dashed line)

pep, ^{8}B (3.-5. MeV)

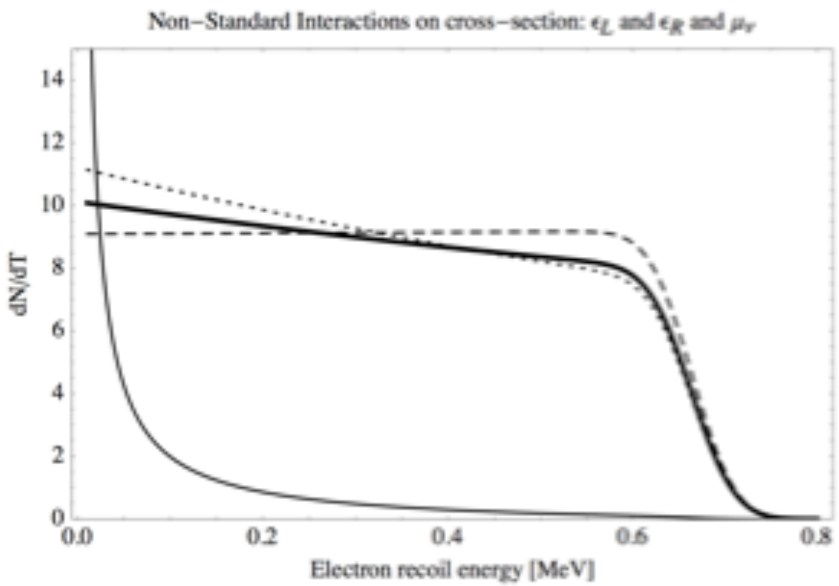
NSI (cont.)

ν−e elastic scattering (big advantage with mono-energetic fluxes)

$$\frac{d\bar{\sigma}(T)}{dT} = \frac{2G_F^2 m_e}{\pi}\left[\bar{g}_{eL}^2 + \bar{g}_{eR}^2\left(1-\frac{T}{E_{\nu_e}}\right) - \bar{g}_{eL}\bar{g}_{eR}\frac{m_e T}{E_{\nu_e}}\right]$$

$$\bar{g}_{\alpha L} = g_{\alpha L} + \varepsilon_{\alpha L} \qquad \bar{g}_{\alpha R} = g_{\alpha R} + \varepsilon_{\alpha R}$$

where α concerns the neutrino flavor, $g_{\alpha R} = \sin^2\theta_W$ and $g_{\alpha L} = \sin^2\theta_W \pm \frac{1}{2}$ (in the last case + is valid for α=e and – is applied when α=μ and τ).



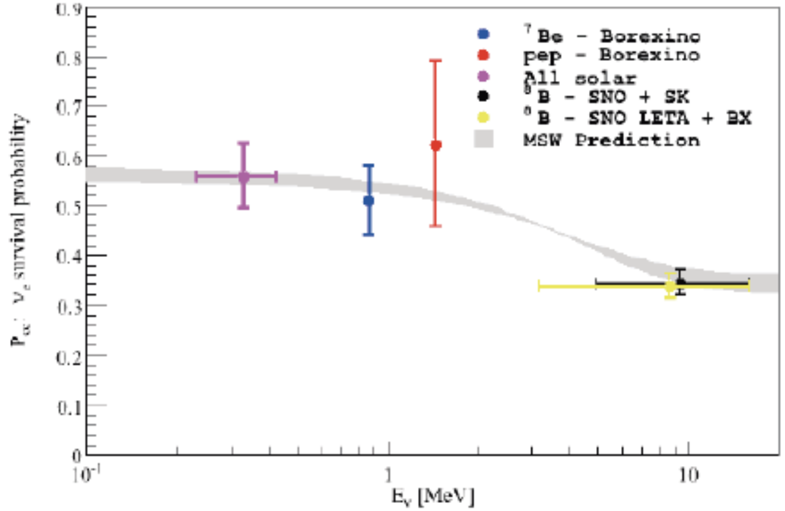
$\varepsilon_{eL}, \varepsilon_{eR} = 0.01, 0.2$ (dashed line)

-0.01,-0.05 (punctuated line)

^{7}Be, ^{51}Cr source

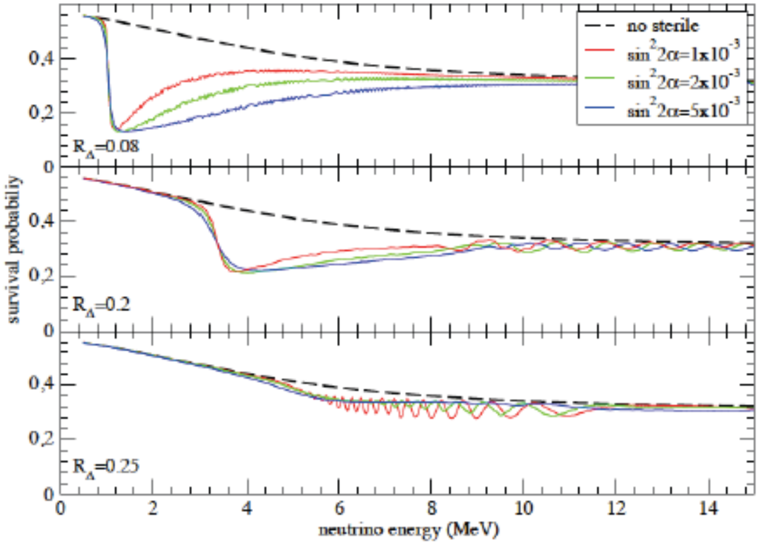
Ultra-light sterile neutrino

Systematic lack of the up-turn, even if the evidence is always weak (<2 σ -SNO, SK, Kamland, Borexino)-also Homestake shows a suppression stronger than expected.



These results can be explained if a very light sterile neutrino exists and mixes very weakly with active neutrinos ($\sin\alpha << 1$), which have the smallest (solar) mass splitting. Due to the very small mass (0.003-0.004 eV), the contribution of these sterile neutrinos to the sum of neutrino masses is negligible.

Bounds are already given by ^{7}Be and partly also by pep (Borexino).



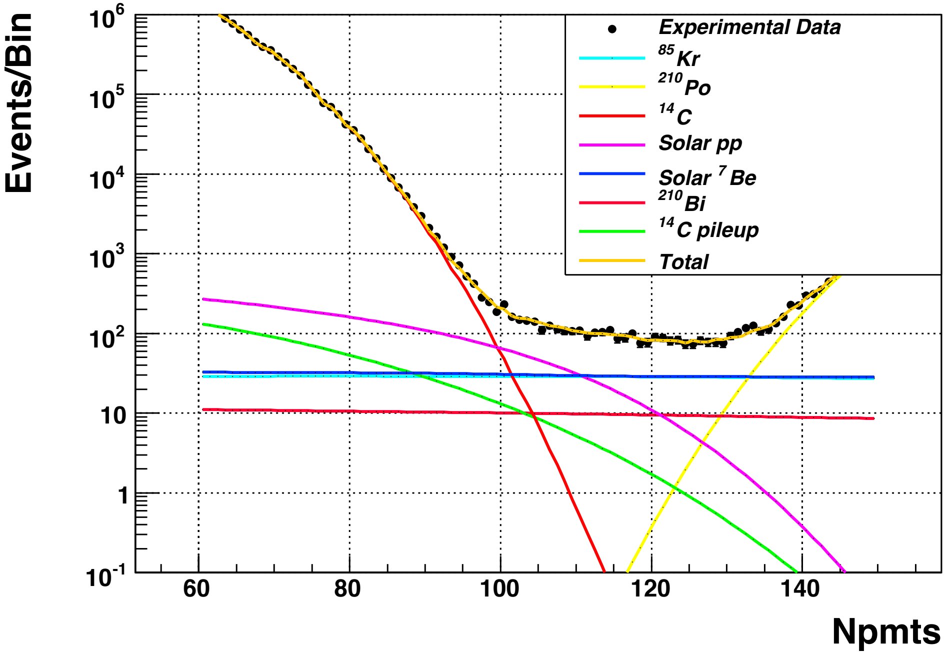
^{8}Be 3.-5. MeV

pep with strongly reduced uncertainty

What Borexino can measure in the phase 2?

pp

Never directly **measured-** the present uncertainty is constrained by the radiochemical esp., Borexino ^{7}Be measurements, and by the solar Luminosity. A pp flux measured directly can be compared with the solar luminosity



Analysis phase 1

range:~110-360 keV

Main problem:

^{14}C and its pile up

Advantages in phase 2 with Kr~0 ; ^{210}Bi reduced to ½---- **CO_2 test**

^7Be

Effort to reduce the total flux measurement uncertainty **to 3%.**

Is it possible?

Statistical error ±1.9 cpd/100 t

Systematic →

Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Position reconstruction	$^{+1.3}_{-0.5}$
Energy scale	2.7
Fit methods	2.0
Total Systematic Error	$^{+3.6}_{-3.4}$

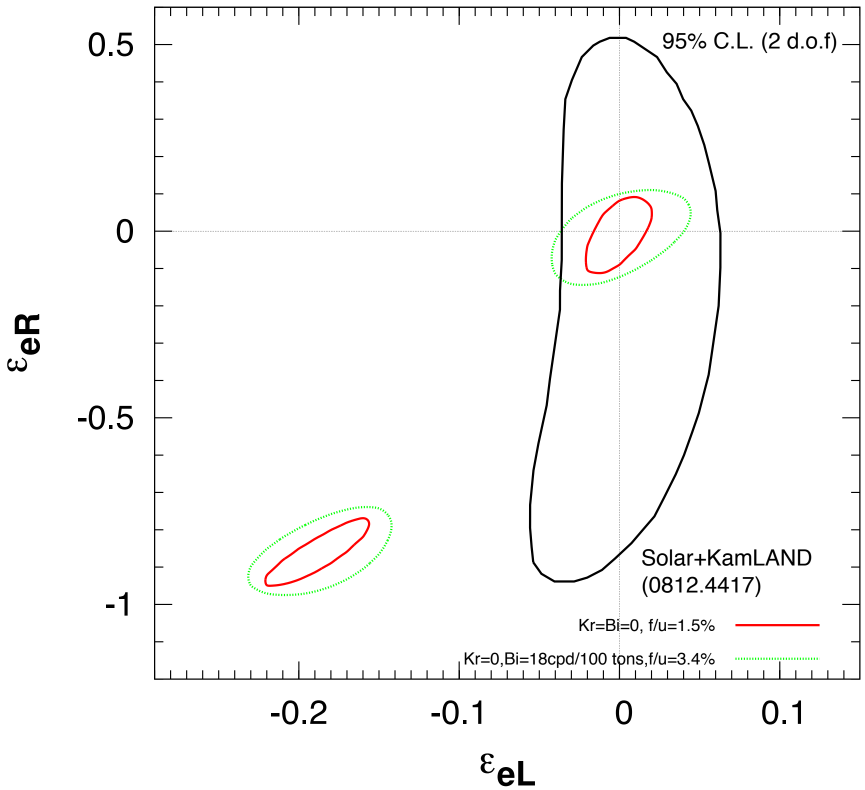
Tools:

- Relevant correlations among ^{7}Be, ^{85}Kr and ^{210}Bi rates and perhaps also ^{210}Po (with a minor role)-
- Statistics will be more than doubled;
- New multivariate fitter (energy spectra, radial distribution of the events as the sum of signal and background contributions.)
- Possible gain in the energy scale uncertainty from the a further calibration campaign.

(^{7}Be cont.)

1 A measurement of a flux as ^{7}Be neutrinos at 3% is important by itself also for the SSM

2 ν−e cross section vs electron recoiled energy-



Phase 2

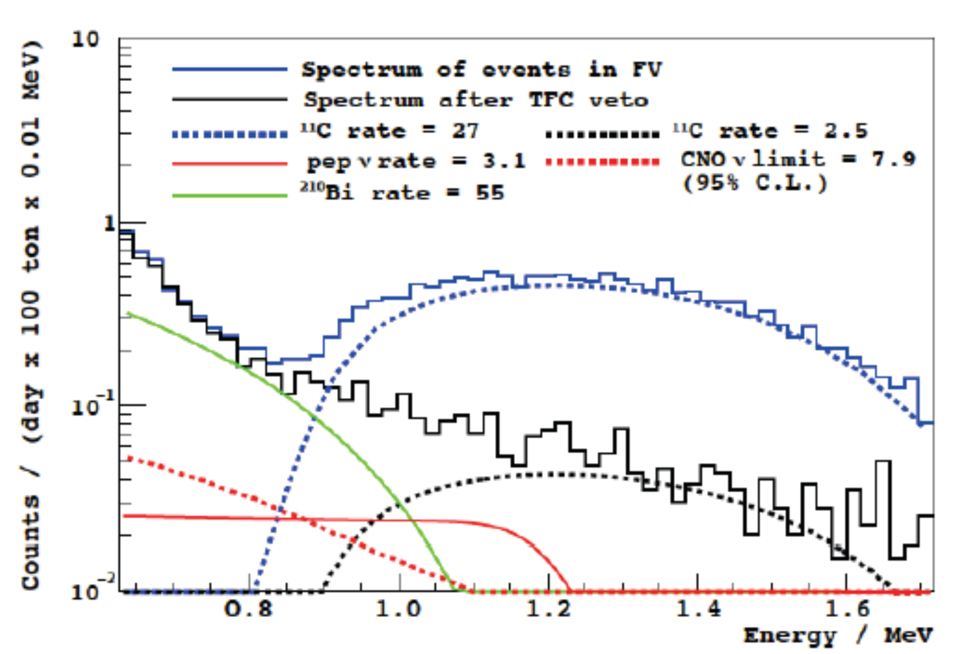
^{85}Kr=0
^{210}Bi=18 cpd/100 t
Flux uncertainty : 3.4 %

pep/CNO

First direct measurement of the CNO flux
Reduction of the pep flux uncertainty

Main problems: ^{210}Bi and ^{11}C

The constant presence of ^{210}Bi (now reduced to ~ 18 cpd/100 tons) suggests that it is produced by $^{210}Pb \longrightarrow {}^{210}Bi + {}^{210}Po$. Therefore we can assume that part of ^{210}Po is continuously produced together with ^{210}Bi. Now the ^{210}Po is ~180 cpd/100t and in < 1 year from now it will be at the same order of magnitude as ^{210}Bi ($\tau\,(^{210}Po) \sim 200$ d). The sensitivity of a fit on *^{210}Po vs time* could be enough to show an exponential $(\exp[t/\tau_{^{210}Po}])$ plus a constant, providing in this way the ^{210}Bi rate.



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^{8}B

Phase 1- ~488 live days-*Integrated flux from 3. MeV electron recoil energy (~3.2 MeV for ν)*

Main Background: ^{208}Tl internal and external: total contribution 0.084±0.02 cpd/100 t, to be compared with ^{8}B rate:~0.22 cpd/100t: external bck. rejected with FV (r<3m); internal MC evaluated and subtracted

*No energy spectrum fit (*continuous fit-oscillation impact)

But the total uncertainty *fully dominated* by the statistical error

Phase 2- ~ 1200 live days- internal ^{208}Tl halved-

On the basis of statistical considerations the rate uncertainty will be ~10% on the integrated flux; reduced to 9% if phase1+2 is considered.

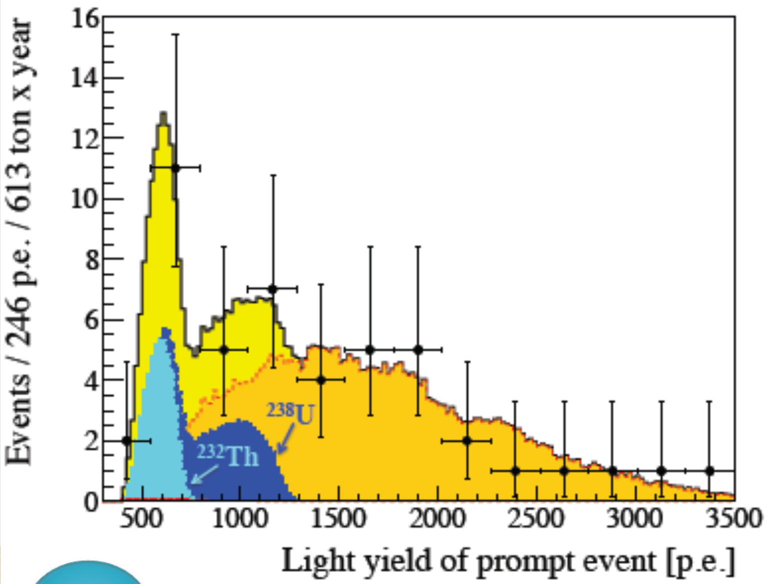
In the range 3.-5. the total uncertainty will be ~13% for the phase 2 and 14.8% for the phase 1+2 (the ^{208}Tl background is present mostly in the range 3.-5.MeV)

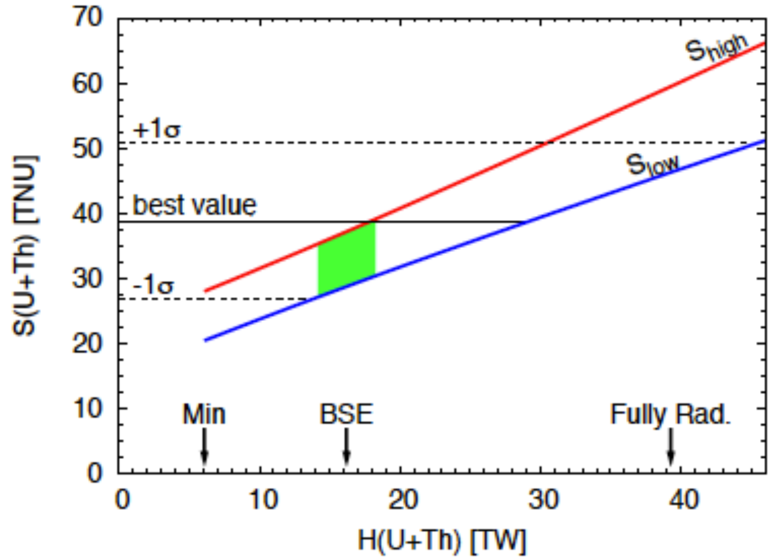
geoneutrinos

Analysis almost *totally decoupled* from the background due to the well tagged $\bar{\nu}$ interactions.

Recently released data (PLB-D-13-00307R1): 1353 live days- FV: 25 cm from the IV walls-14.3±4.4 geo-neutrinos- (4.5 σ C.L.)
Reactor $\bar{\nu}$; mean distance ~1169 km.; $31.2^{+7.0}_{-6.1}$ events (expected 33.3±2.4); no oscillation excluded at 99.9±0.2% C.L.

- Considering an expected contribution from the crust of 23.4±2.8 TNU, the signal from the mantle: 15.4±12.3 TNU and combined with Kamland : 14.1±8.1 TNU
- Ratio Th/U in agreement with the chondritic value (~ 1 σ)





End of phase 2 : ~2500 live days

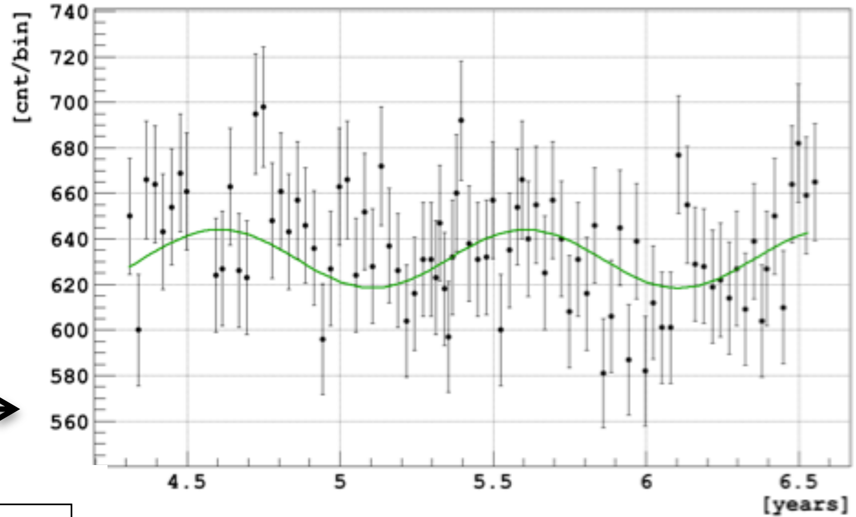
Seasonal variations

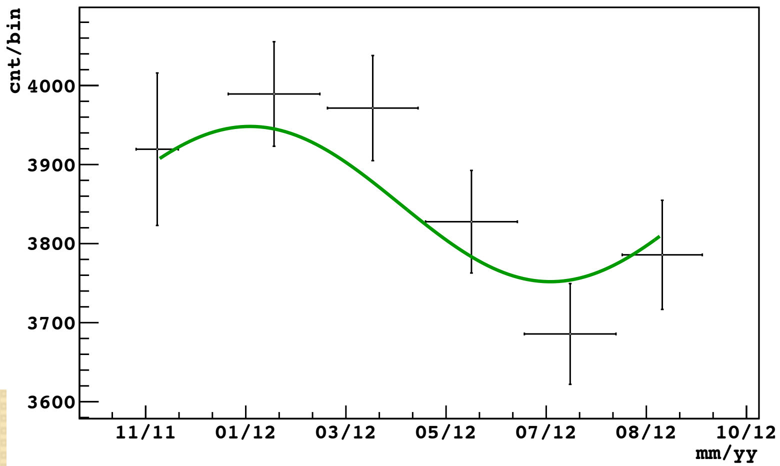
Main problem: ***detector stability***

Phase 1- result in agreement with the expectation, but with low significance

Phase 2- signal/noise ≥ 2
~36-38 l.months data taking
Hopefully detector untouched
and undisturbed

MC. with 28 l.months statistics
with Phase 2 conditions





Some results already
from phase 2 (1 year)

60 days bins

green=expected modulation

Sterile neutrino, NSI, neutrino magnetic moment, Weinberg angle

Sterile neutrino

- Reactor antineutrino flux deficit **(~6%)**
- ^{51}Cr (^{37}Ar) source for Gallex and Sage deficit
- Latest MiniBoone results seem agree with the LNSD excess of $\nu_e(\bar{\nu}_e)$

~3σ

Hypothesis: existence of a sterile neutrino(s), with a large mass-squared splitting: $\Delta m^2_{14} \cong \Delta m^2_{24} \cong \Delta m^2_{34} \cong 1eV^2$

@ ^{51}Cr source, 200-400 PBq, ~10Mci activation, installed in the tunnel below Bx detector (8.25m from the IV center) probably in the winter 2015
@ 2 lines around 750 eV
@ ≤ 3 months of running

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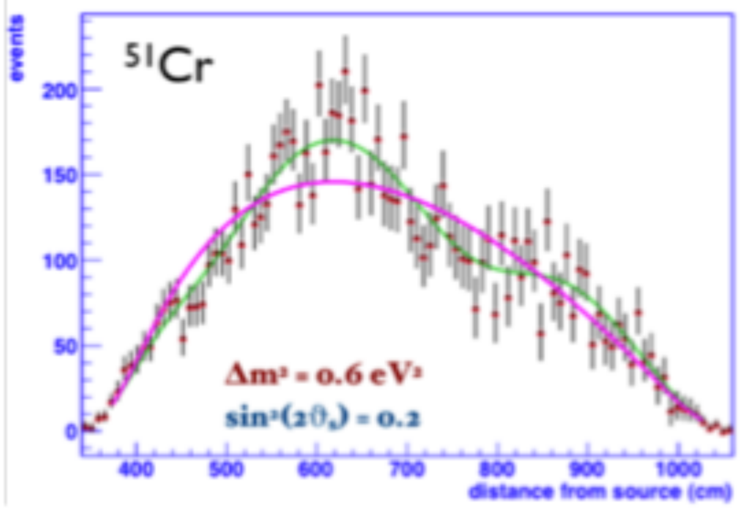
Appendix to the phase 2

2-4 PBq; ~50-100 kCi ^{144}Ce-^{144}Pr anti-neutrino source in the water tank, but activating also the buffer with PPO
continuous spectrum up to ~3 MeV; mean energy ~2.4 MeV.
~ 1.5 year

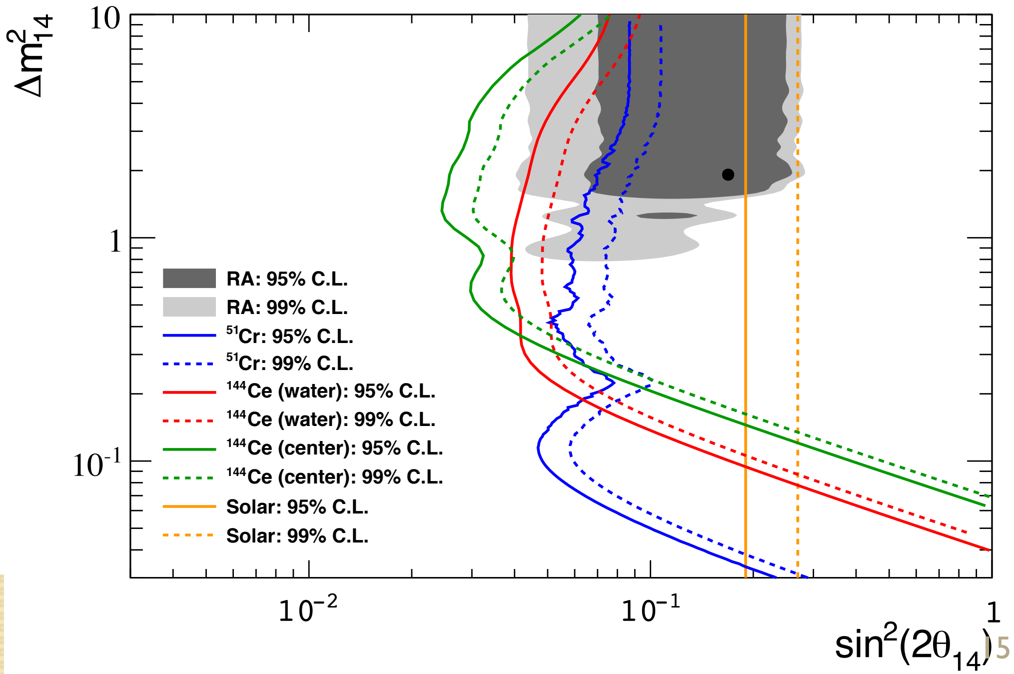
@ FV: expected background: ~11.8 cpd for ^{210}Po,others: 54 cpd;
in any case background rejected by a source on, source off analysis

Obs. of oscillatory pattern

- Expected Δm^2 ~1 eV^2
- ν energy ~1 MeV
- Oscillation lenght= few m
- All know errors included

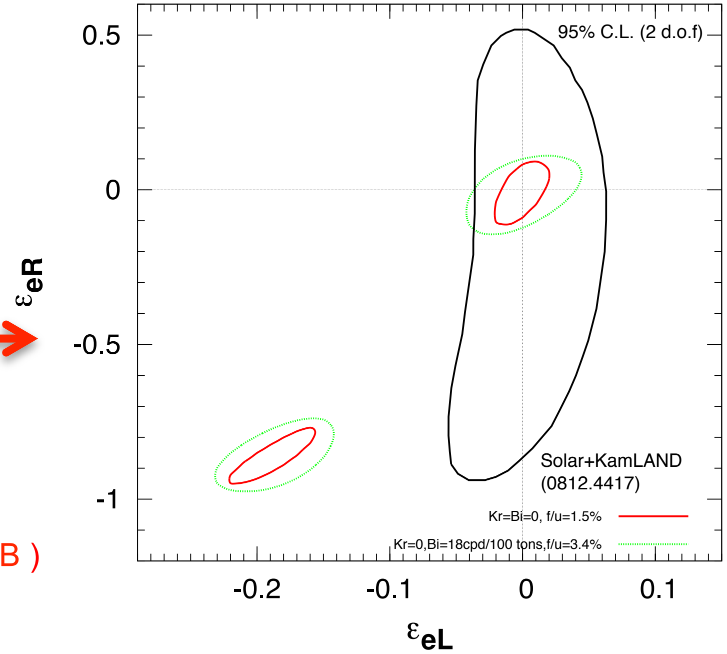


- MC 2000 data samples discovery potential



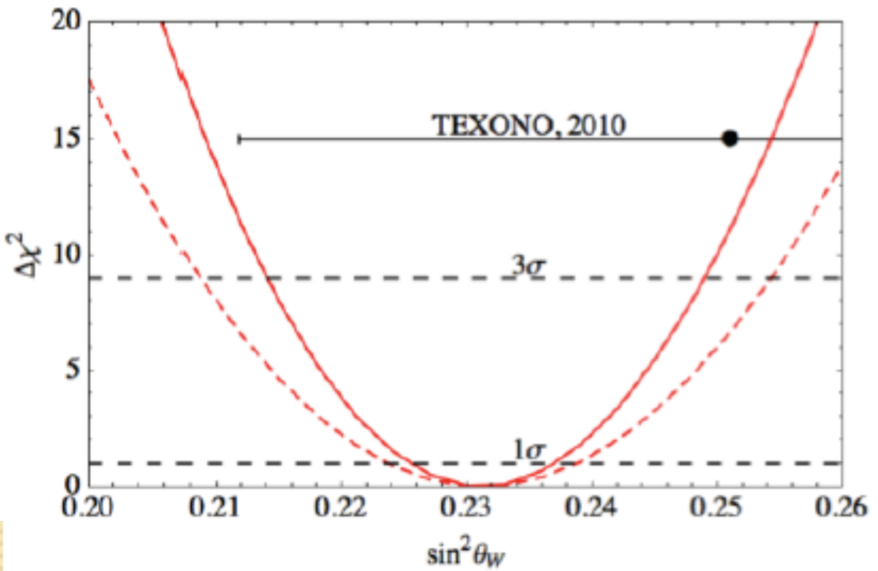
NSI: ν−e Elast. Scatt.

source on- source off
flux uncert. 1.5%
background negligible



ν_e magnetic moment:
expected limit ~2.9 10^{-11} μ_B
(Gemma 3.2 10^{-11} μ_B)

Weinberg angle:
~2.6% of uncertainty
on $\sin^2\theta_W$
(presently best
limit at low energy)



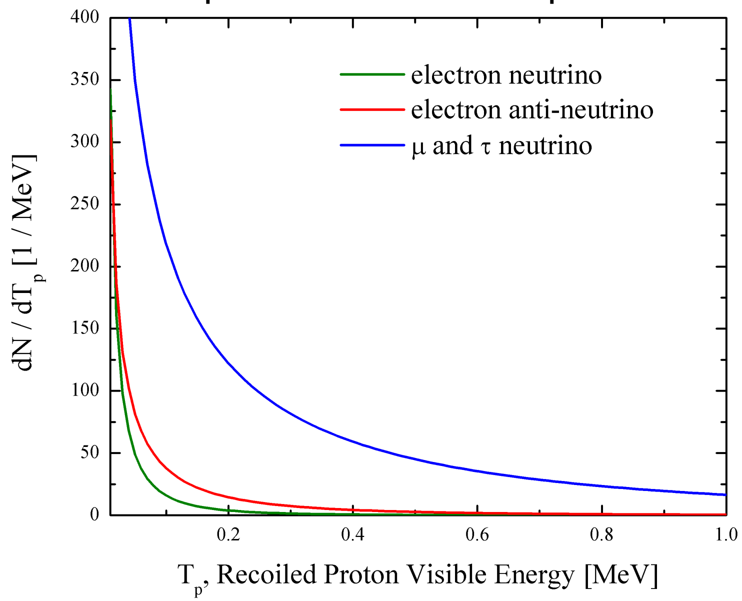
Supernova observatory (SNEWS – SuperNova Early Warning System.

galactic Supernova at 10 kpc

Detection channel	Normal Hierarchy	Inverted Hierarchy
$\bar{\nu}_e$ on protons ($E_\nu > 1.8$ MeV)	68	68
ν-p Elast. Scatt. ($E_\nu > 0.25$ MeV)	40	40
$^{12}C\ (\nu,\nu)^{12}C^*$ ($E_\gamma > 15.1$ MeV)	13	13
$^{12}C\ (\bar{\nu}_e, e^+)\ ^{12}B$ ($E_{\bar{\nu}_e} > 14.3$ MeV)	3	5
$^{12}C(\nu_e,e^-)^{12}N$ ($E_{\nu_e} > 17.3$ MeV)	6	4

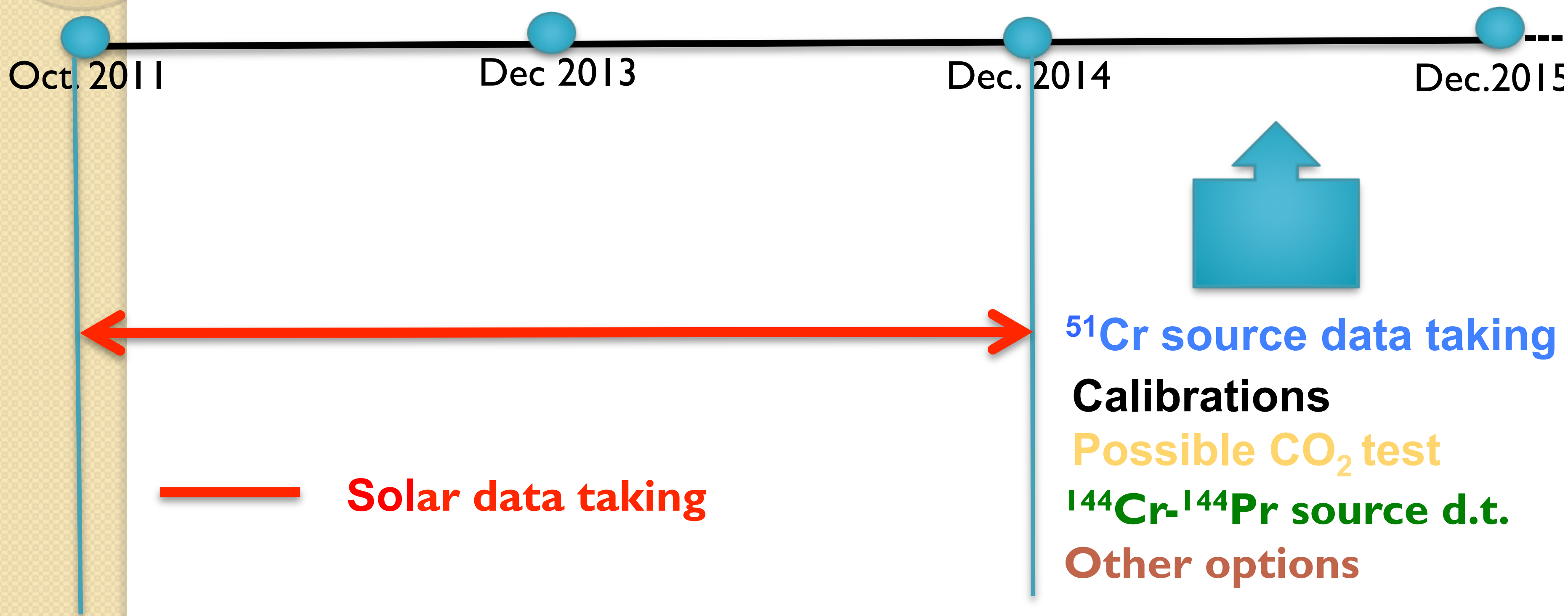
Burst in ~10 sec

Spectrum of recoiled protons



Very low threshold

Tentative schedule of the phase 2



Conclusion

Physics goals of phase 2

1- CNO cycle: Hydrogen burning in massive stars;
2- P_{ee} transition region shape: MSW-LMA model, NSI, ultra-light sterile neutrino;
3- ^{7}Be neutrinos and external source $\nu-e$ elastic scattering: NSI
4- Sterile neutrino (neutrino source)
5- Seasonal variation: (^{7}Be neutrinos)
6- Best determination of ν_e magnetic moment and lower Weinberg angle exp. uncertainty at low energy (source)
7- Upgraded Earth infos from geoneutrinos
9- Supernova observatory