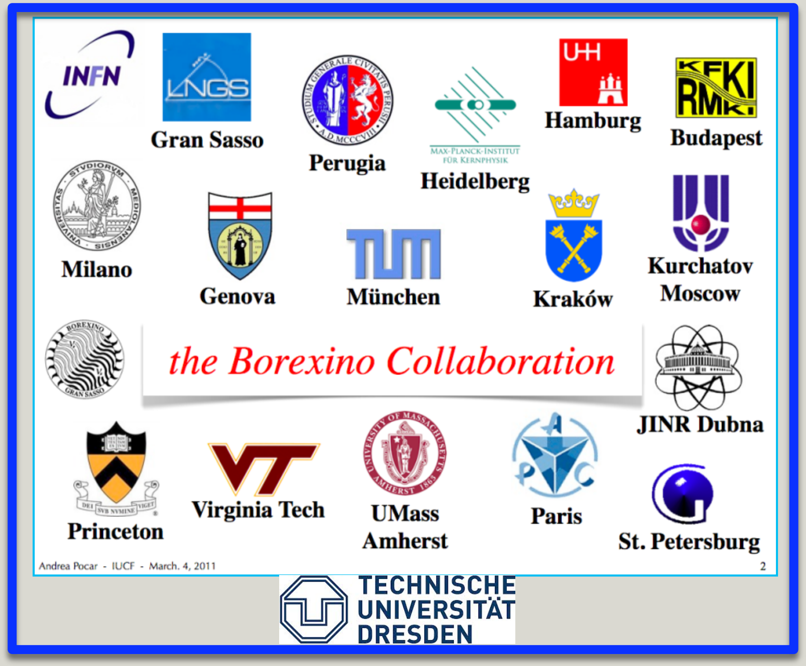
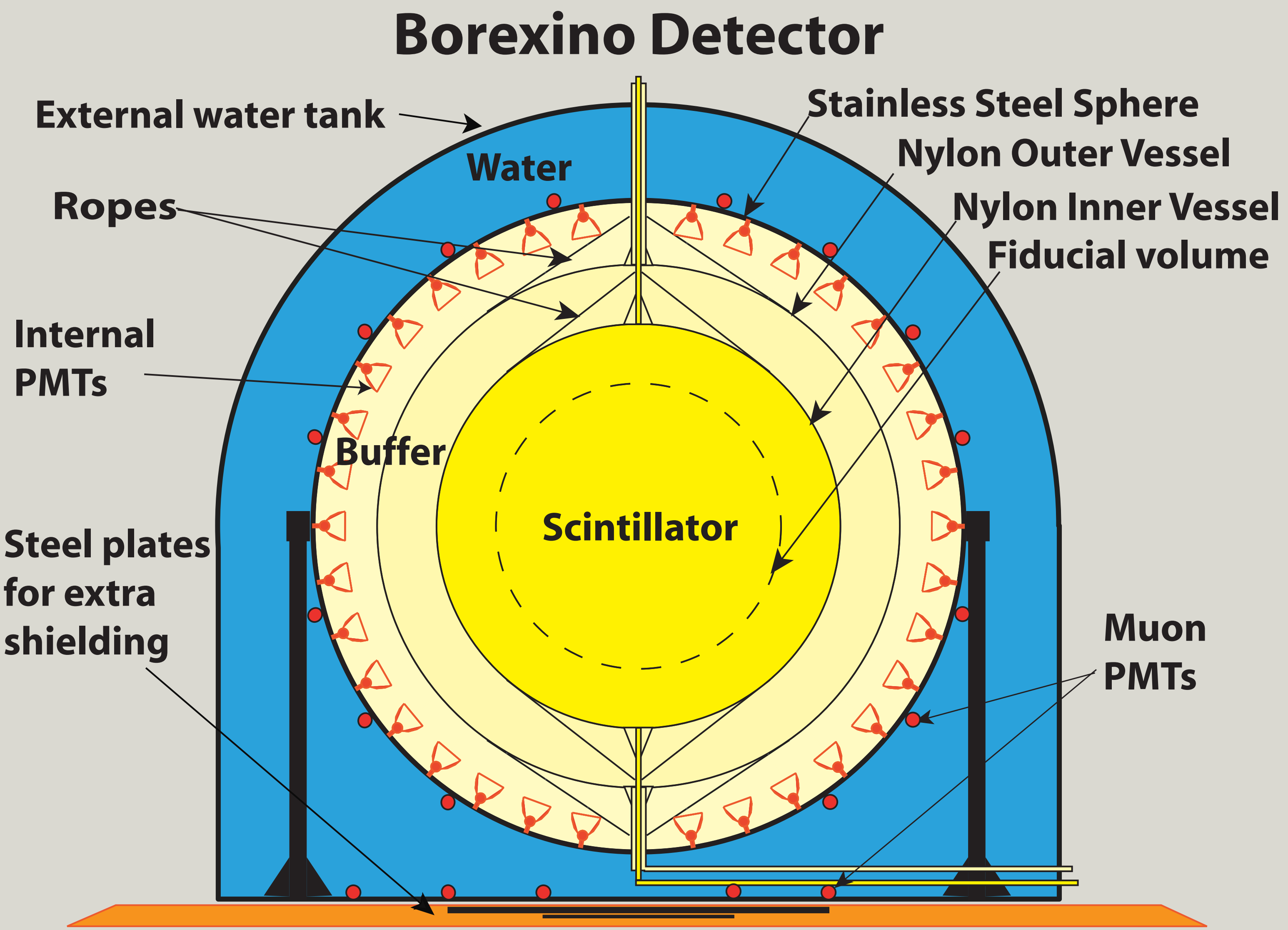
Status report of the Borexino experiment

Livia Ludhova for Borexino Collaboration

Presented at LNGS Scientific Committee, April 15th 2014



Borexino experiment in hall C at LNGS



Outlook

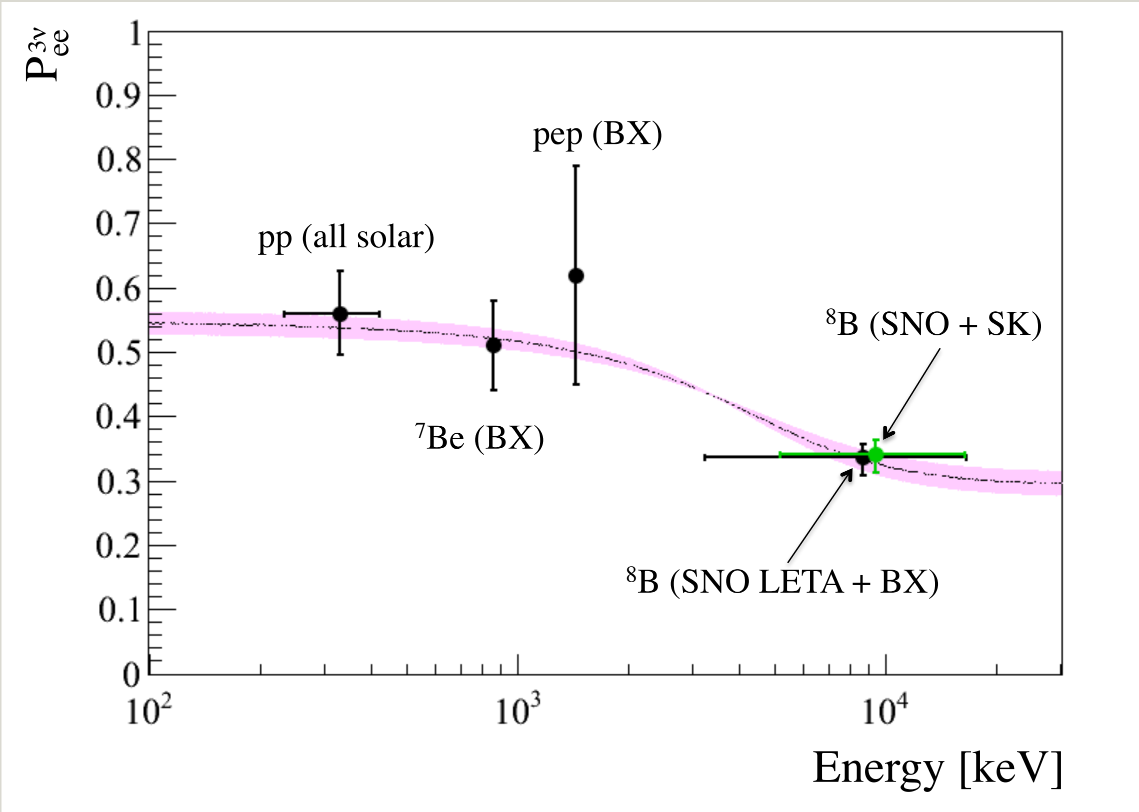
- Borexino has started the taking data in May 2007;
- Borexino Phase I (May 2007 - May 2010) produced several results: small summary of the main achievements;
- Borexino Phase II after 6 cycles of purification with water extraction performed between May 2010 and August 2011: radiopurity levels;

In this presentation I will focus on

- **Recently published results on Borexino Phase I/II data-set;**
- **SOX project: search for sterile neutrinos with Borexino with ^{51}Cr and ^{144}Ce (NEW!!) sources planned for 2015;**

Summary of Phase I (May 2007 – May 2010)

- ***Solar neutrino program:***
  - the first pep-neutrino detection and the best limit on CNO neutrino (2012);
  - ^{7}Be –neutrino rate with 5% pecision and its null day/night asymmetry (2011+2x 2008);
  - ^{8}B -neutrino rate measurement with T = 3 MeV threshold (2010);
- First observation of geo-neutrinos (2010);
- Limits on several rare or exotic processes;



Radiourity of Borexino in Phase II

• after 6 cycles of purification with water extraction performed between May 2010 and August 2011:

1) ^{85}Kr: strongly reduced: consistent with zero cpd/100 ton from the spectral fit;

2) ^{210}Bi : reduced from ~70 cpd/100 tons to ~20 cpd/100 ton;

3) ^{238}U (from ^{214}Bi - ^{214}Po tagging) $< 1.2\ 10^{-19}$ g/g at 95% C.L.

4) ^{232}Th: $< 1.2\ 10^{-18}$ g/g at 95% C.L. (2 events in ~600 days)

5) ^{210}Po decaying, currently about 120 cpd/100 ton

6) Radon: $(5.8 \pm 1.2)\ 10^{-2}$ cpd/100 ton

Recent Borexino publications

1. Measurement of **geo-neutrinos** from 1353 days of Borexino, Phys. Lett. B 722 (2013) 295-300.

2. **Cosmogenic backgrounds** in Borexino at 3800 m water-equivalent depth, JCAP 1308 (2013) 049.

3. **New limits on heavy sterile neutrino mixing in ^{8}B-decay** obtained with the Borexino detector, Phys. Rev. D 88 (2013) 072010.

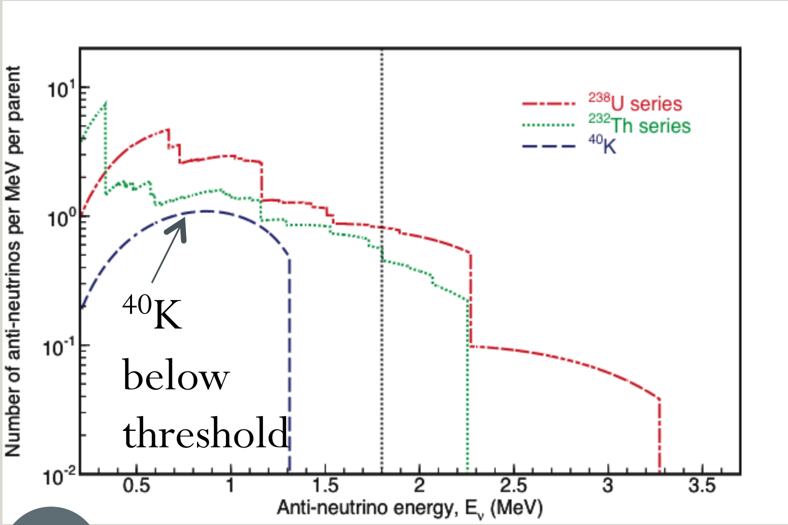
4. **Lifetime measurements of ^{214}Po and ^{212}Po** with CTF liquid scintillator detector at LNGS, Eur. Phys. J. A49 (2013) 92.

5. **SOX:** Short distance neutrino Oscillations with BoreXino, JHEP 1308 (2013) 038.

Geo-neutrinos:
antineutrinos from the decay of ^{238}U, ^{232}Th, ^{40}K in the Earth

Abundance of radioactive elements fixes the amount of radiogenic heat (nuclear physics);
Mass and distribution of radiogenic elements → geo-neutrino flux (cca 10^6 cm^{-2} s^{-1});
From measured geo-neutrino flux to radiogenic heat….

Main goal: determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;
Further goals: tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of the Earth'formation…..



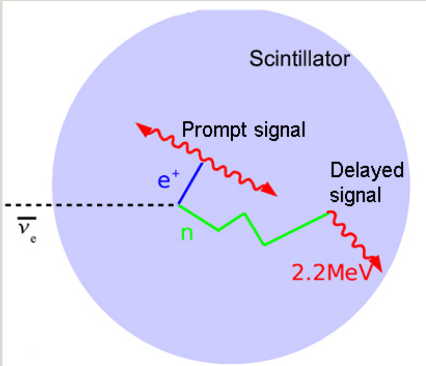
$$\bar{\nu} + p \rightarrow n + e^{+}$$ $E_{\nu} > 1.8$ MeV

- "prompt signal"

e+: energy loss + annihilation

- "delayed signal"

n capture after thermalization and 2.2 γ



Geo-neutrinos in Borexino

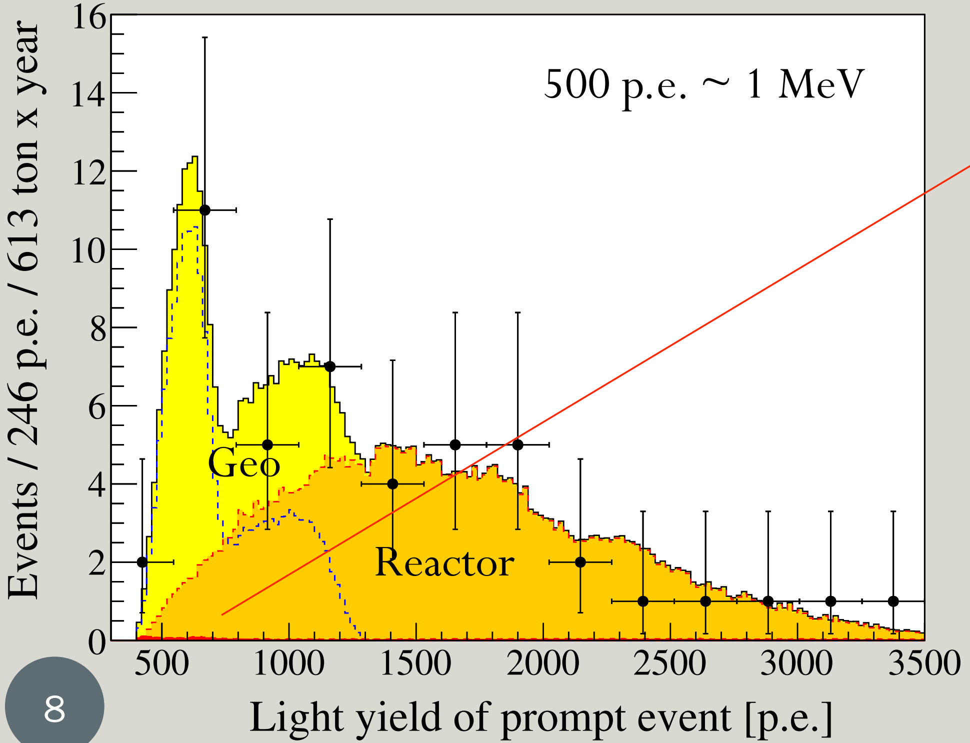
Previous result: G. Bellini et al. Phys. Lett. B 687 (2010) 299 with 252.6 ton-year exposure after cuts;

New result: G. Bellini et al. Phys. Lett. B 722 (2013) 295 with (613 ± 26) ton-year after cuts ;

Event selection (MC defined efficiency: 0.84 ± 0.01): **46 golden anti-neutrino candidates**

- $Q_{prompt} > 480$ p.e. and $Q_{delayed}$ (860,1300) p.e. (1 MeV ~ 500 p.e.), $\Delta R < 1$m, Δt (20 – 1280 μs),
- $Gatti_{delayed} < 0.015$ (must be "β-like"), 2 s veto after muons passing ID and 2 ms veto after external muons

- Large Fiducial Volume: distance from the vessel > 25 cm



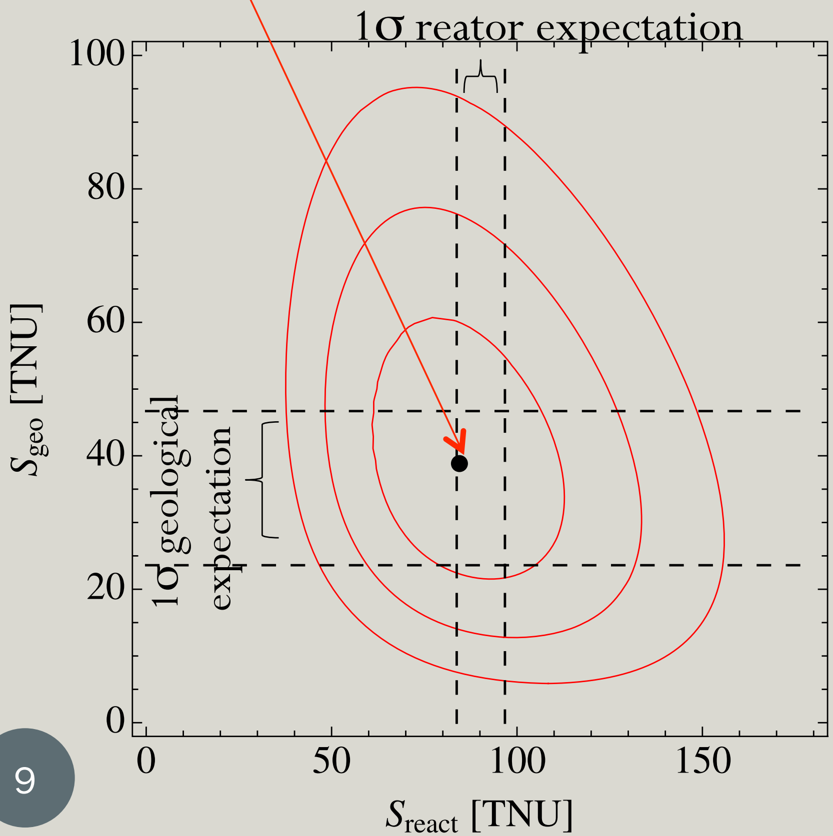
Background not due to reactors is very small

Background source	Events
$^{9}Li-^{8}He$	0.25 ± 0.18
Fast n's (μ's in WT)	<0.007
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080 ± 0.007
Accidental coincidences	0.206 ± 0.004
Time corr. background	0.005 ± 0.012
(γ,n)	<0.04
Spontaneous fission in PMTs	0.022 ± 0.002
(α,n) in scintillator	0.13 ± 0.01
(α,n) in the buffer	<0.43
Total	0.70 ± 0.18

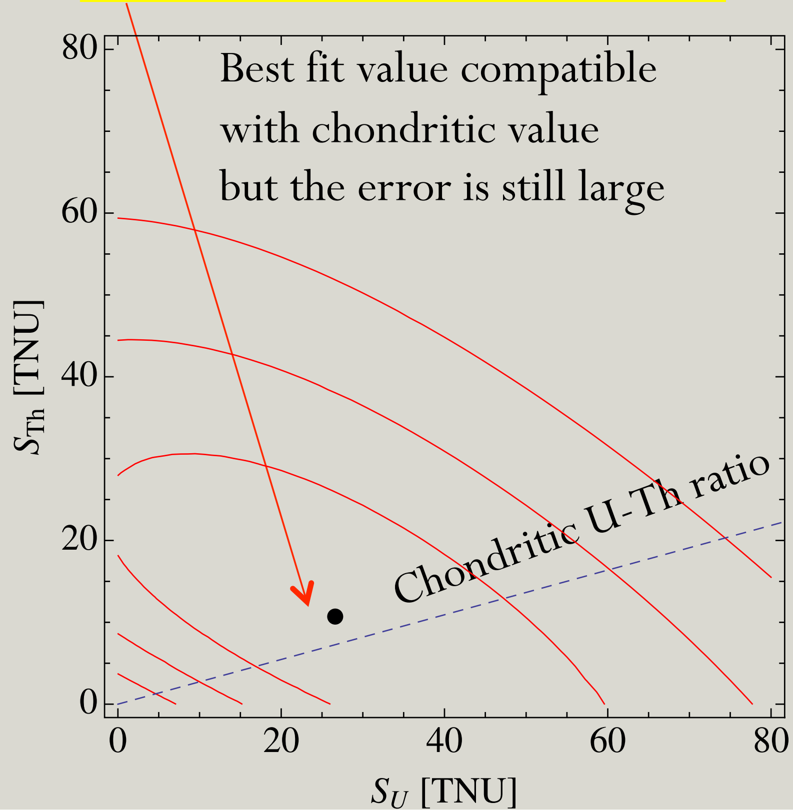
- Un-binned maximal likelihood fit with unconstrained geo and reactor components;
- $N_{reactor} = 31.2_{-6.1}^{+7}$ in agreement with expectation of 33.3 ± 2.4 events after oscillations;

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% eff

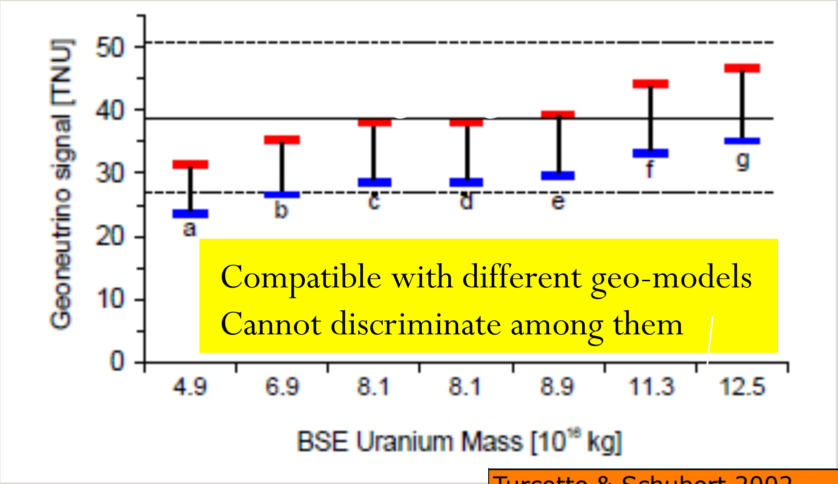
Fixed Th/U mass ratio to chondritic value of 3.9:
N_{geo} = 14.3 ± 4.4 events
S_{geo} = 38.8 ± 12.0 TNU



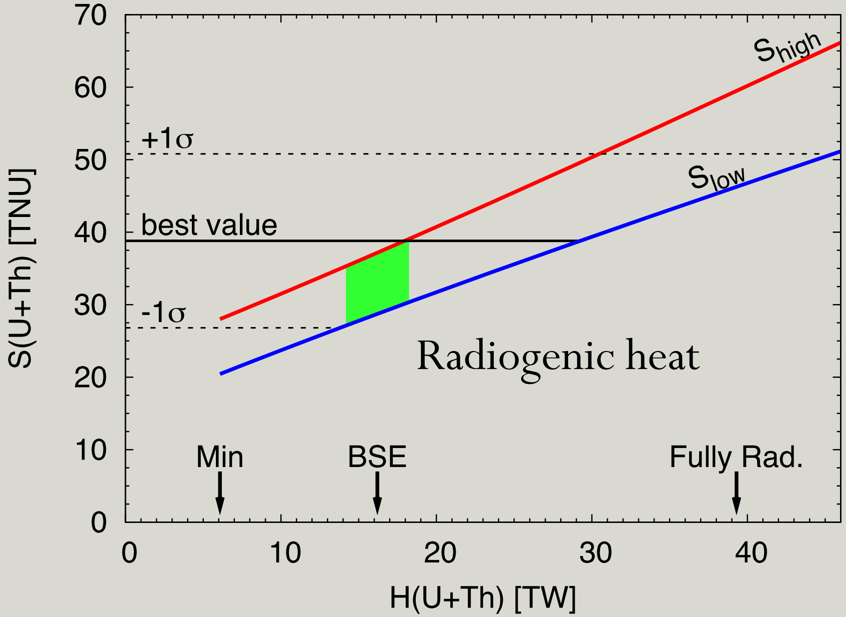
Th/U ratio free in the fit:
$S(^{238}U)$ = 26.5 ± 19.5 TNU
$S(^{232}T)$ = 10.6 ± 12.7 TNU



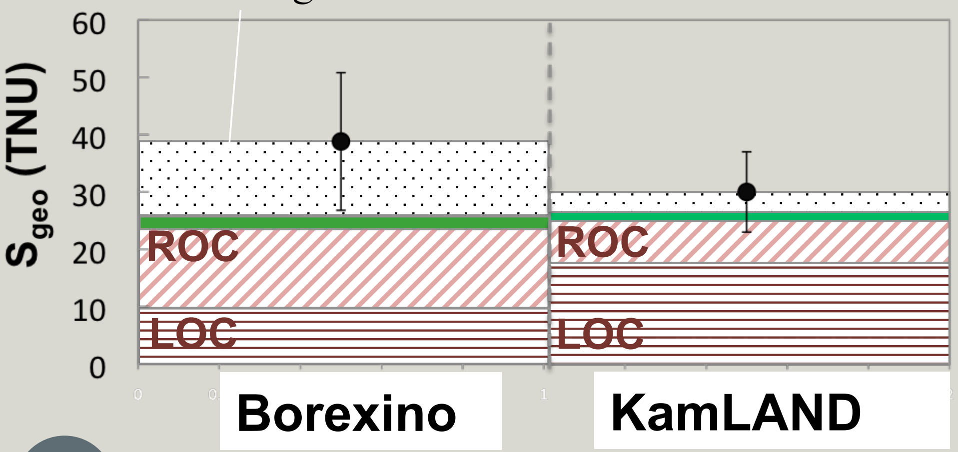
Geo-neutrinos in Borexino: implications



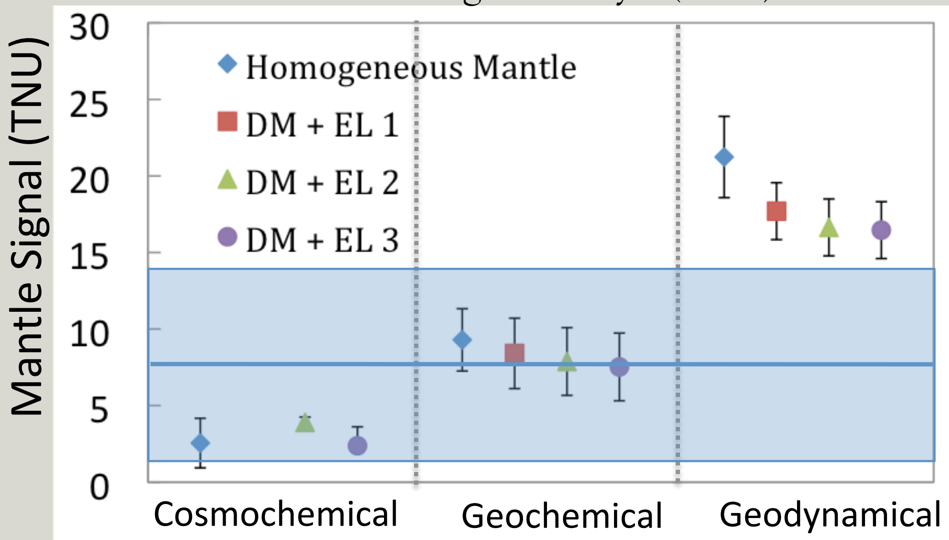
Turcotte & Schubert 2002	(g)
Anderson 2007	(f)
Palme & O'Neil 2003	(e)
Allegre at el. 1995	(d)
Mc Donough & Sun 1995	(c)
Lyubetskaya & Korenaga 2007	(b)
Javoy et al.2010	(a)



L.L. & S. Zavatarelli: Adv. High En. Phys. (2013) 425693.



PRD 88 (2013) 33001

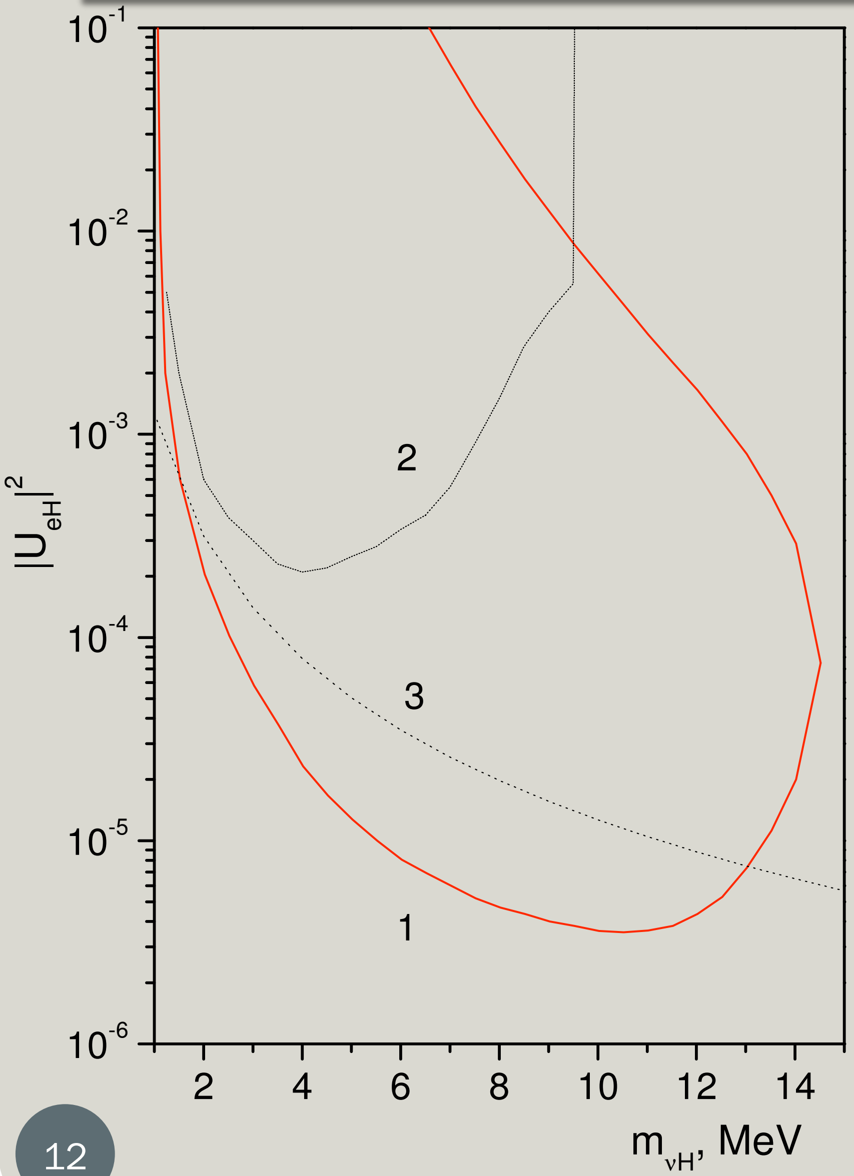


Cosmogenic background in Borexino at 3800 m water-equivalent depth, JCAP 1308 (2013) 049.

	GEANT4 Model III	GEANT4 Model IV	FLUKA	Borexino	KamLAND
	— $\langle E_\mu \rangle = 283 \pm 19$ GeV —				$\langle E_\mu \rangle = 260 \pm 8$ GeV
Isotopes	Yield $[10^{-7} (\mu\, g/cm^2)^{-1}]$				
^{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 $[10^{-4} (\mu\, g/cm^2)^{-1}]$				
	3.01 ± 0.05	2.99 ± 0.03	2.46 ± 0.12	3.10 ± 0.11	2.79 ± 0.31

Table 4. Predicted yields for cosmogenic products obtained from GEANT4 (Model III and IV) and FLUKA are compared to data from Borexino . Also shown are results from the KamLAND experiment [9]. Note that the production yields depend on the number of carbon atoms per weight and the muon energy spectrum. Thus, a 10 – 20 % difference between KamLAND and Borexino results is expected.

New limits on heavy sterile neutrino mixing in ^{8}B-decay obtained with the Borexino detector, Phys. Rev. D 88 (2013) 072010



If heavy ν_H's with mass > 2 m_e are produced in the Sun via the decay $^8B \rightarrow {}^8Be + e^+ + \nu_H$ in a side branch of pp chain, they would undero the observable decay into a light neutrino:
$\nu_H \rightarrow \nu_L + e^- + e^+$

$$\Phi(E_{\nu_H}) = |U_{eH}|^2 \sqrt{1 - \left(\frac{m_{\nu_H}}{E_{\nu_H}}\right)^2} \Phi_{^8B}(E_\nu),$$

Mixing parameter vs ν_{H}-mass:
Areas inside the lines are excluded:

1: Borexino

2: reactor experiments

3: from pion decay

Lifetime measurements of ^{214}Po and ^{212}Po with CTF liquid scintillator detector at LNGS, Eur. Phys. J. A49 (2013) 92.

•CTF served as an ultrasensitive tool for measuring the radioactivity levels unreachable by any other existing method. At the end of 2012 it was dismounted to host Dark Side.

• measurements with ^{222}Rn (^{214}Po), and ^{232}Th and ^{220}Rn (^{212}Po) inserted in the CTF in 2011-2012;

• study of decay times of ^{214}Po and ^{212}Po isotopes through $^{214/212}$Bi(beta) – $^{214/212}$Po(alpha) decay coincidences:

- Long acquisition time window of ~7 mean lives;
- Excellent signal-to-background ratio > 1000;
- Large statistics;
- **mean lifetime of ^{214}Po = 236.00 ± 0.42 (stat) ± 0.15 (sys) μs;**
- **mean lifetime of ^{212}Po = 425.1 ± 0.9 (stat) ± 1.2 (sys) ns.**

SOX: Short distance ν_e Oscillations with BoreXino

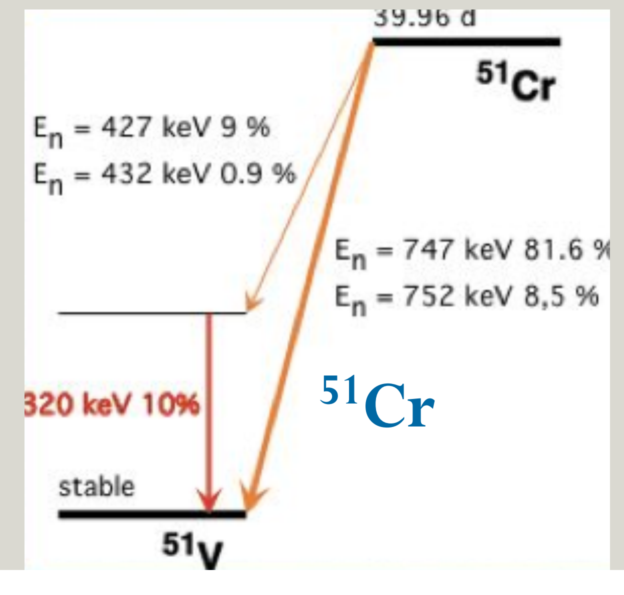
- **Science motivations:**
  - Search for **sterile neutrinos** or other **short-distance effects on P_{ee};**
  - Measurement of Weinberg angle θ_W at low energy (~ 1 MeV);
  - Improved limits of the neutrino magnetic moment;
  - Measurement of the vector g_V and axial g_A current coefficients at low energy;
- **Technology**
  - Neutrino source: **^{51}Cr**
  - Anti-neutrino source: **^{144}Ce**
- **Project:**
  - ERC advanced grant for **^{51}Cr** (M. Pallavicini INFN-Genova);
  - ERC starting grant for **^{144}Ce** (T. Lasser APC-Paris: **NEW: this project has recently moved from KamLAND/CeLAND to Borexino);**
  - Additional funding from INFN, USA, Germany;

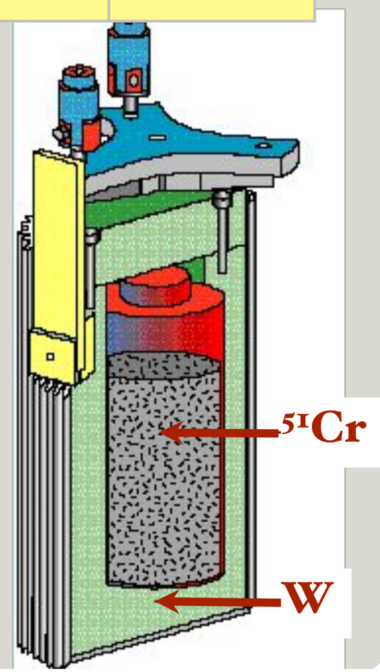
- Concept is the same as in Gallex 1994 (source is currently in Italy)
  - **~36 kg**, **^{50}Cr enriched** at **38%** irradiated in a high neutron flux reactor:
  - Candidate reactors: USA (OakRidge) and Russia (Mayak);
  - **190 W/MCi** from photons;
  - ~few μSv/h on surface (required < 100);
  - careful **thermal design** to handle **10 MCi (2 kW);**

^{51}Cr ν_e source

$\nu_e - e^-$ scattering

Source	Production	τ (days)	Decay mode	Energy [keV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr ν_e	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \gtrsim 5.\ 10^{14}\ cm^{-2}\ s^{-1}$	40	EC γ 320 keV (10%)	750(90%) 430(10%)	0.011	0.19



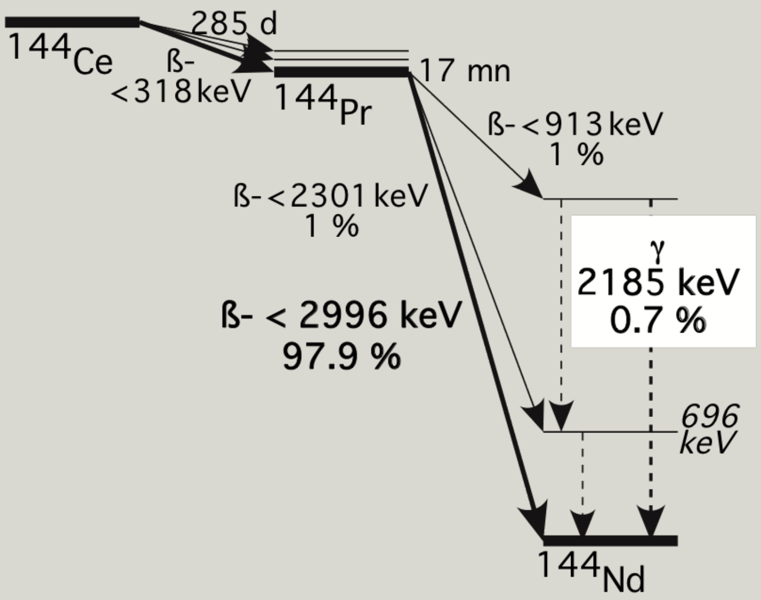


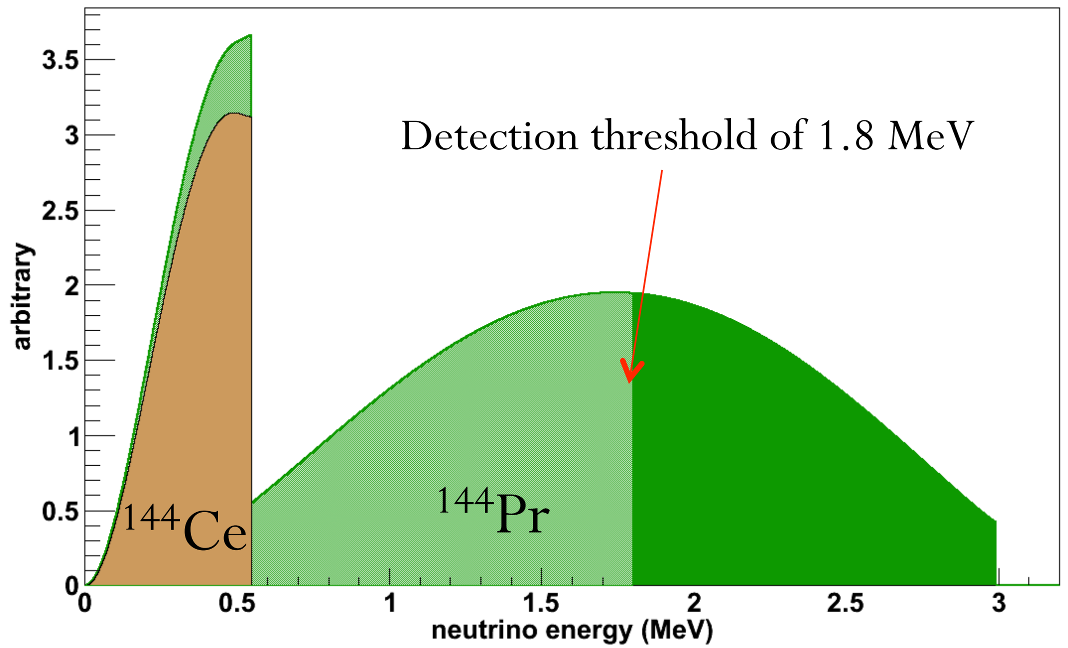
^{144}Ce – 144Pr anti-νe source:

$$\bar{\nu} + p \rightarrow n + e^{+}$$

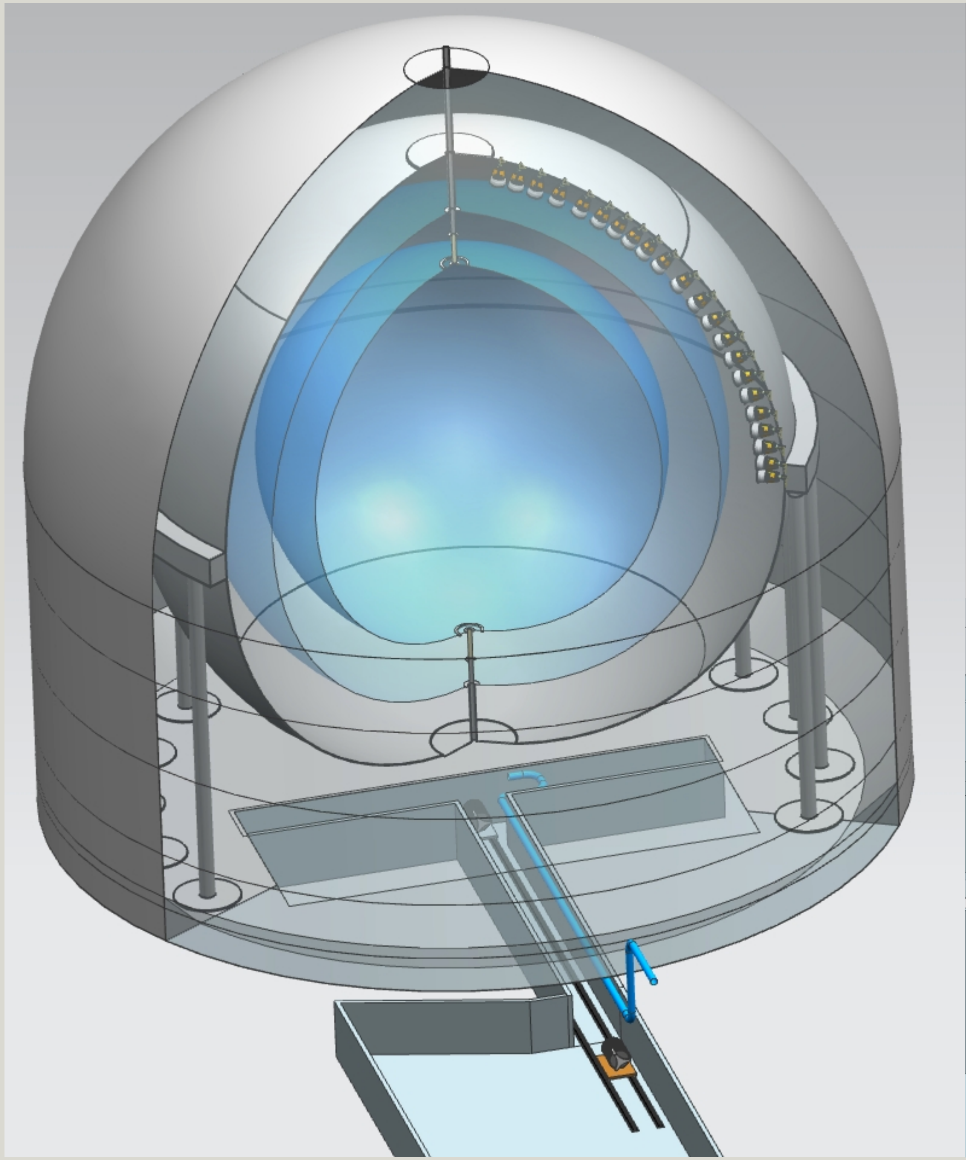
$E_{\nu} > 1.8$ MeV

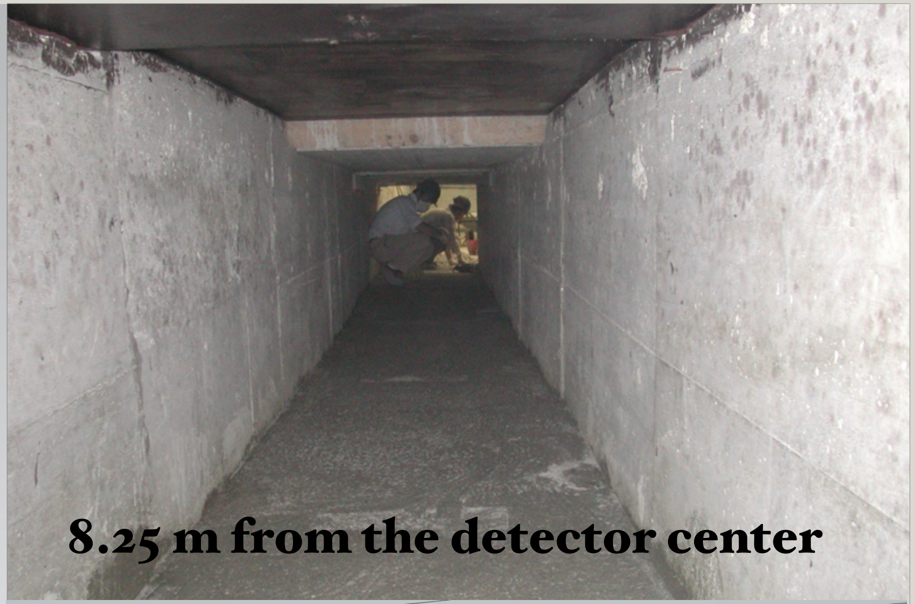
Source	Production	τ (days)	Decay mode	Energy [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{144}Ce-^{144}Pr anti-ν_e	Chemical extraction from spent nuclear fuel	411	β-	<2.9975	0.314	7.6

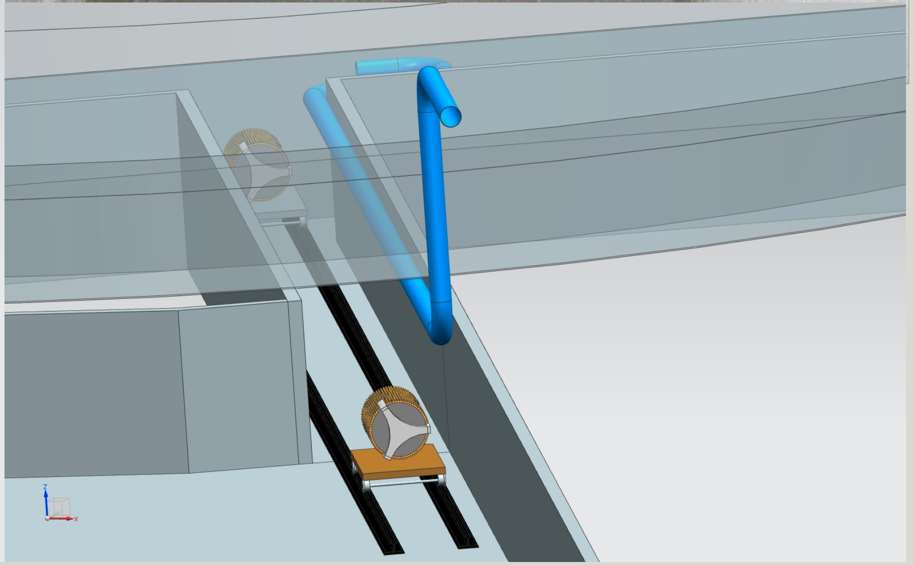




Location for both sources: Borexino pit







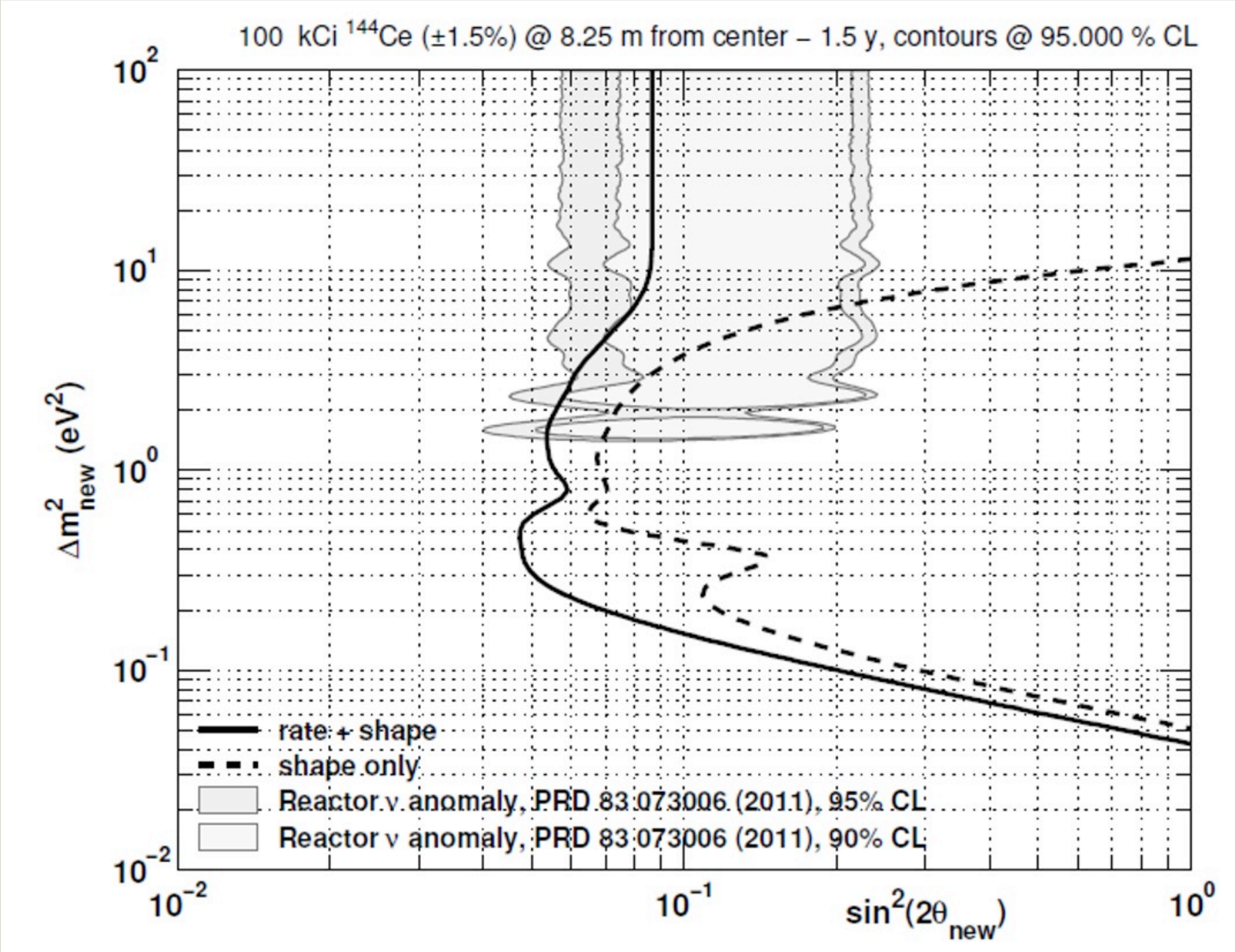
Data analysis: two techniques

- **Total counts:** standard **"disappearance"** experiment
  - Total number of events depends on θ_{14} and (weakly) from Δm^2_{14}
  - Sensitivity depends on:
    - Statistics (source activity)
    - Error on activity (in particular) and on efficiency (FV cut for ^{51}Cr)
  - The relatively short life-time of ^{51}Cr yields useful time-events correlation
    - The background is constant while the signal is not.

- **Spatial waves** [C.. Grieb et al., Phys. Rev. D75: 093006 (2007)]
  - With expected Δm^2 ~ 1 eV^2 and **~ 1 MeV energy,** the wavelength is smaller than detector size (~11 m max) and bigger than resolution (~ 15 cm)
    - The distribution of events as a function of distance to source shows waves;
    - **Direct measurement of Δm_{14}^2 and θ_{14}**
    - Very powerful and independent. Does not depend on knowledge of source activity.

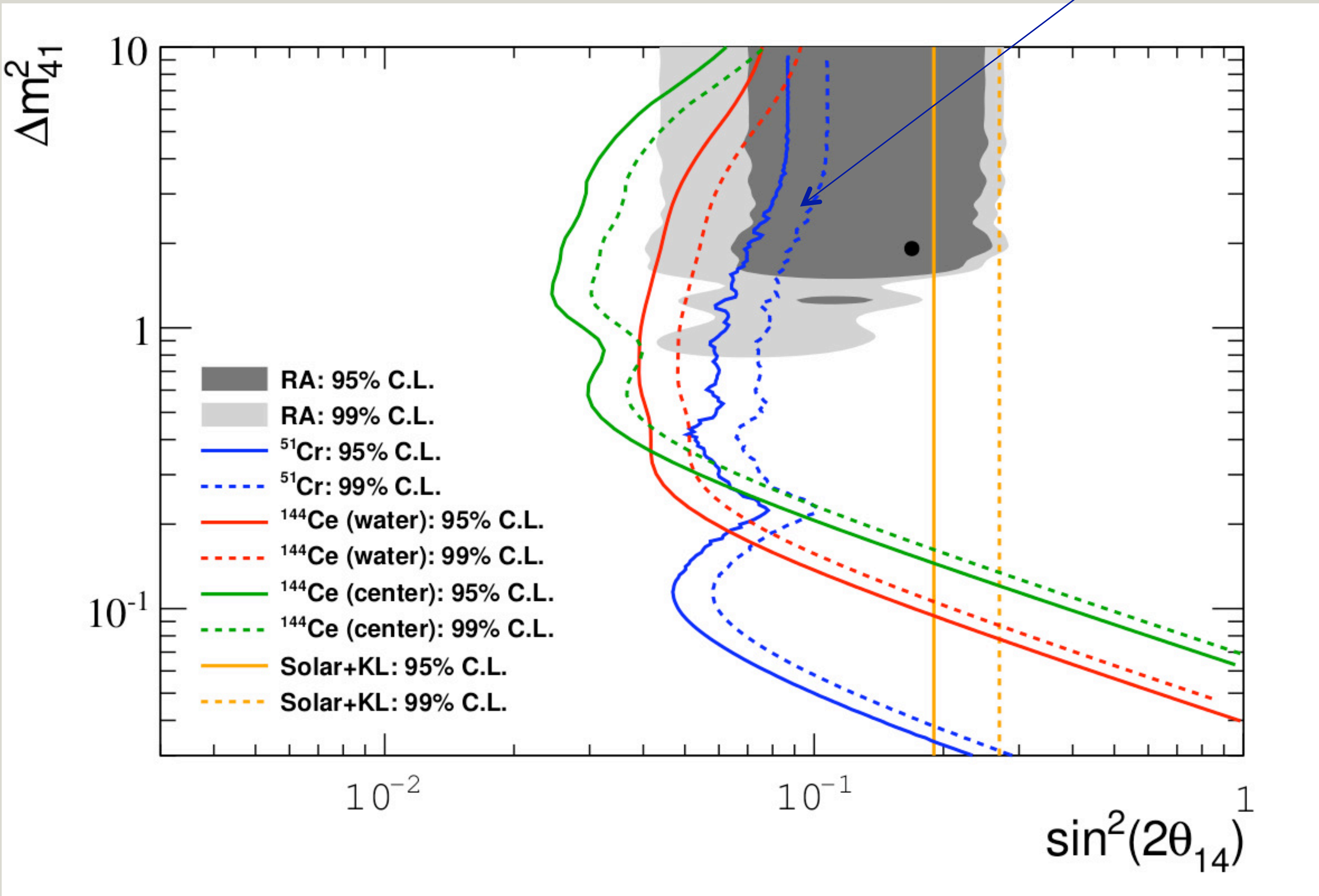
- The two techniques can be combined in a single counts-waves fit.

Sensitivity plot for ^{144}Ce source in the pit



Sensitivity plot for ^{51}Cr source in the pit

10 MCi; 1% precision in source activity; 1% in FV determination



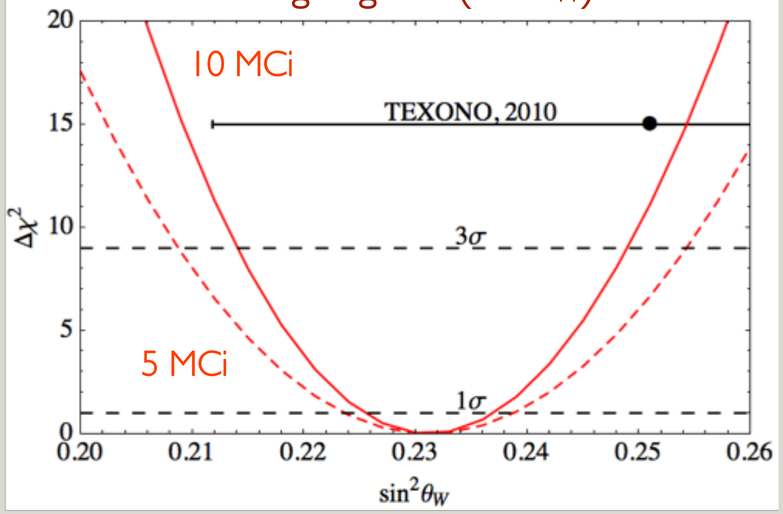
Near future and conclusions

- Borexino Phase II: data with improved radiopurity
- pp-solar neutrino rate measurement to be completed soon: major progress in the analysis, how to treat ^{14}C and its pile-up;
- Study of the improved pep and CNO measurement ongoing;
- ^{51}Cr ad ^{144}Ce source measurements (in the Borexino pit) estimated for 2015: which source first? The one which will be ready first!
- DAQ with ^{51}Cr: few months
- DAQ with ^{144}Ce: 1.5 year
- Long term: after completion of the solar neutrino program, possible SOX phase C with ^{144}Ce source placed inside the detector: improved sensitivity but some HW changes required;

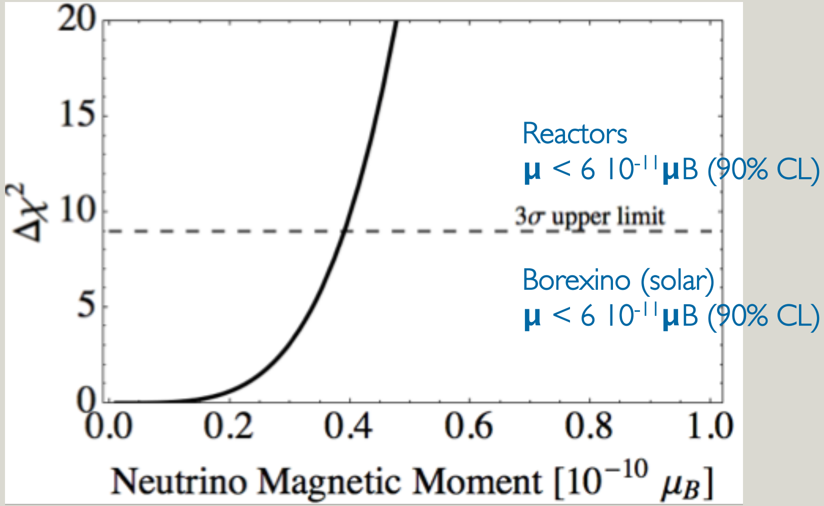
Backup

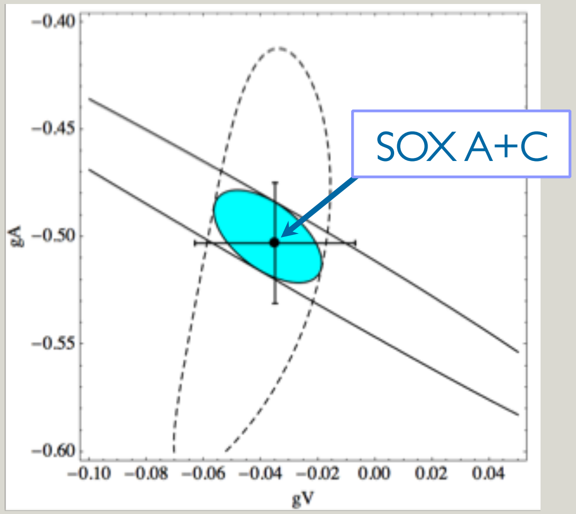
Other low energy neutrino physics

Weinberg angle: $\delta(\sin^2\vartheta_W)$=2.6%



Magnetic moment





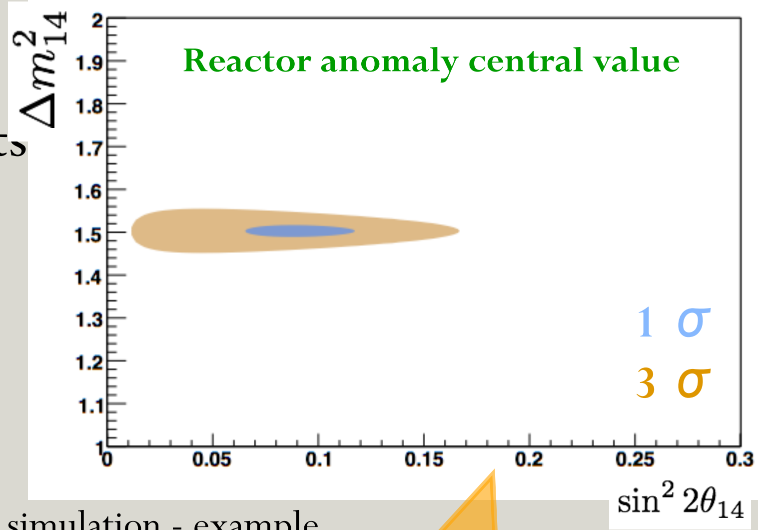
CHARM II (1994)
ν_μ ES su e- E ~ 10 GeV

- With both sources (SOX-A and B or C)
  - Independent measurement of gv e ga
  - Test of SM EW running at very low energy
  - Standard Model
    - $g_V = -1/2 + 2\sin^2\vartheta_W = -0.038$
    - $g_a = -1/2 = 0.5$

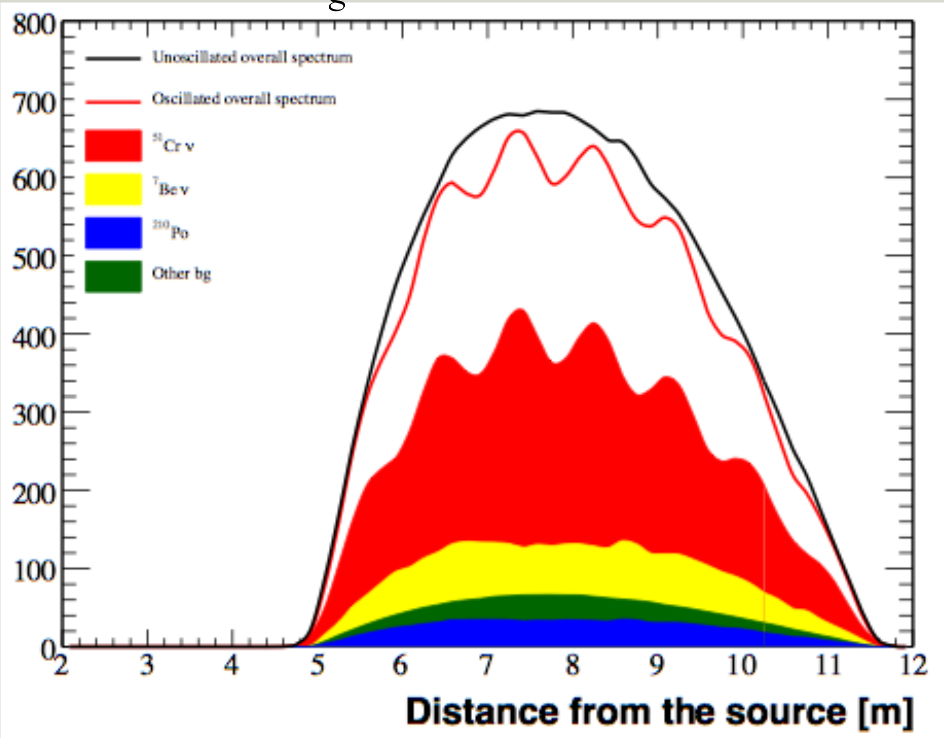
$$g_V^{\nu e} = -0.035 \pm 0.012(\text{stat}) \pm 0.012(\text{syst}),$$

$$g_A^{\nu e} = -0.503 \pm 0.006(\text{stat}) \pm 0.016(\text{syst}).$$

- **Waves** may be detected in the distribution of events as a function of the distance from source
  - With waves, both parameters can be measured



Ideal curves
Borexino Background - No fluctuations



Full Geant4 simulation - example
Borexino Background