SOX: Short Distance Neutrino Oscillations with BoreXino

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on behalf of the Borexino Collaboration
NRC Kurchatov Institute

16 Lomonosov Conference

SOX: **S**hort distance ν_e **O**scillations with Bore**X**ino

- **Science**
  - Motivations
    - Search for **sterile neutrinos** or other **short distance effects on P_{ee}**
    - Measurement of θ_W at low energy (~ 1 MeV)
    - Measurement of neutrino magnetic moment
    - Measurement of g_V e g_A at low energy
- **Technology**
  - Neutrino source: **^{51}Cr**
  - Anti-neutrino source: **^{144}Ce**
- **Project stages**
  - **SOX-A** - **^{51}Cr external**
  - **SOX-B** - **^{144}Ce external**
  - SOX-C - **^{144}Ce internal**

ERC Ideas approved

European Research Council
ERC-2012-AdG

Advanced Investigator Grant
SOX: Short distance neutrino Oscillations with BoreXino

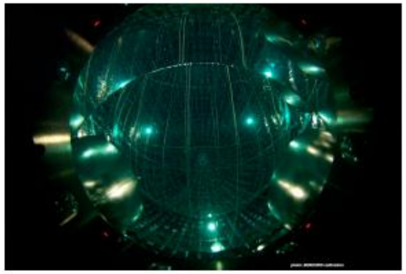
SEVENTH FRAMEWORK PROGRAMME

"Ideas" specific programme

European Research Council

Grant agreement for Advanced Grant

Annex I - Description of Work



Project acronym: SOX
Project full title: Short distance neutrino Oscillations with BoreXino
Grant agreement N. 320873
Duration: 60 months
Date of preparation of annex 1: 23 - 10 - 2012
Principal Investigator: Prof. Marco Pallavicini
Host Institution: Istituto Nazionale di Fisica Nucleare (INFN) and Laboratori Nazionali del Gran Sasso (LNGS)

Borexino Detector

Two Neylon Ballons (~100 μm)

internal: R=4.25 m

external: R=5.50 m

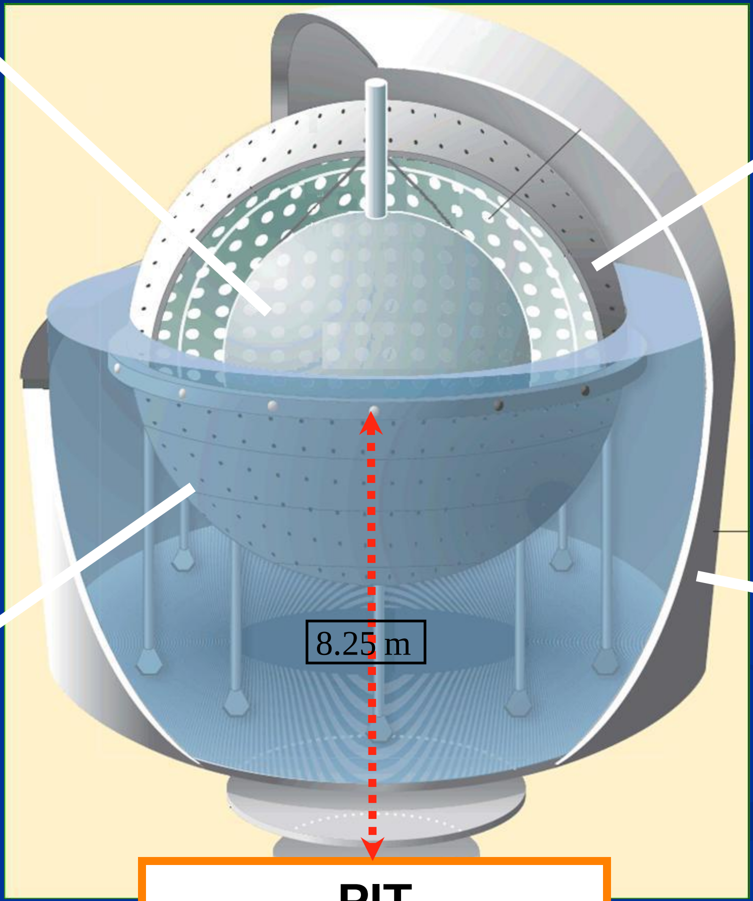
Target

∅ 8.5 м, V = 340 м^3, 278 ton of liquid scintillator (C_9H_{12} + 1.5 g/l PPO)

Inner Buffer ∅ 11.5 m with C_9H_{12} + DMP

Stainless Steel Sphere

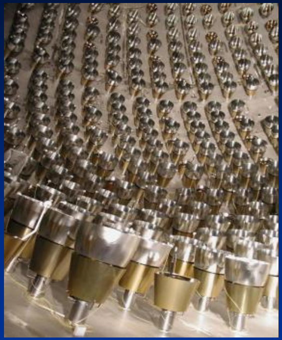
(∅ = 13.7 m, V = 1340 m^3) ?



PIT

~ 1 m^3 at

8.25 m from the center



2212 PMT (ETL 9351) mounted on the inner surface of Stainless Steel Sphere

Water tank

(∅ =18 m, V = 2400 m^3) Water Cherenkov muon veto with 208 PMT and also passive shielding from external γ , n.

Detection principle

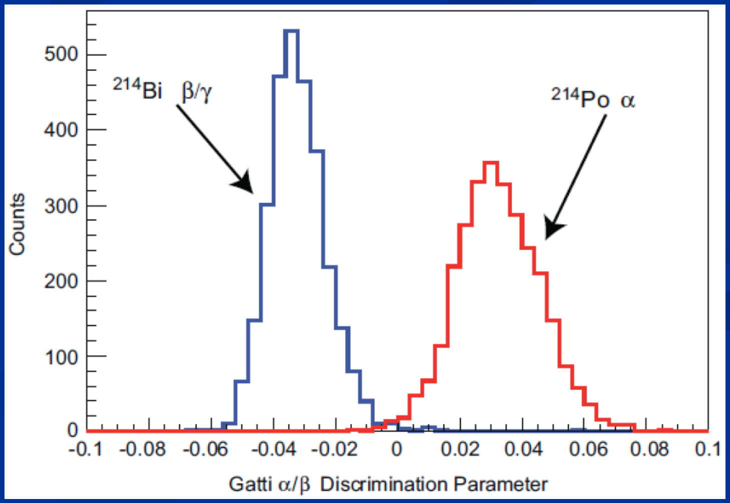
- Neutrino elastic scattering on electrons of liquid scintillator:

  $\nu + e^- \rightarrow e^- + \nu$;
- Scattered electrons cause the scintillation light production;
- **Advantages**:
  - Low energy threshold (~ 0.2 MeV);
  - High light yield (510 ph.el. / MeV) and a good energy resolution;
  - Event position reconstruction;
  - alpha/beta pulse shape discrimination.

ENERGY RESOLUTION
10% @ 200 keV
8% @ 400 keV
6% @ 1 MeV

SPATIAL RESOLUTION
35 cm @ 200 keV
16 cm @ 500 keV

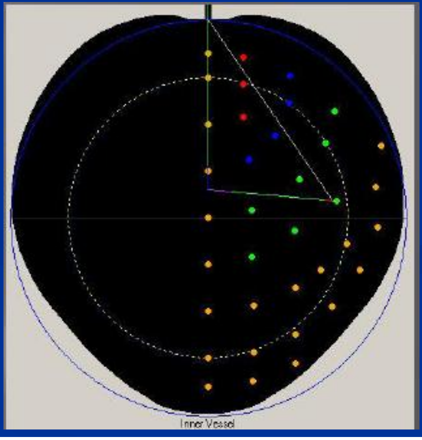
α / β separation (^{214}Bi - ^{214}Po)



Calibration with radioactive sources

source	γ								β		α	n (AmBe)		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n+^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

- Absolute source position: LED and CCD cameras ($\pm$ 2cm);
- 300 points through the whole scintillator volume;



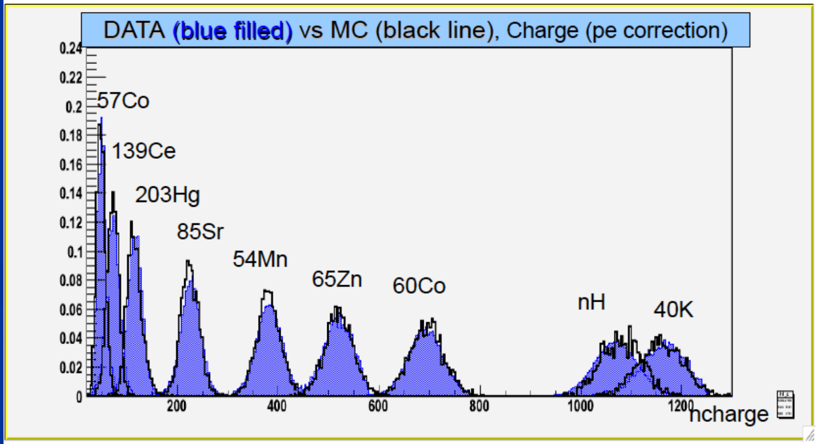
- Detector response as a function of position;
- Fiducial volume definition and tuning of the spatial reconstruction algorithm:

  Fiducial volume uncertainty: (+0.5, -1.3) %

- Energy scale definition:

1.5% (1 σ) calibration in the 0-7 MeV range.

- Tuning of the full Monte Carlo simulation .



Neutrino and antineutrino detection in Borexino

solar neutrino detection

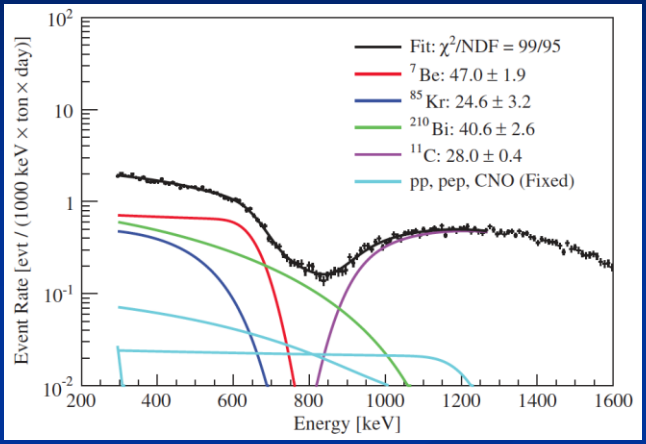
$$\nu + e^- \rightarrow \nu + e^-$$

Very low background due to **the shielding** and **purifications**

Low energy threshold , good energy resolution

and spatial reconstruction, pulse shape α / β identification

- **sub-MeV ν detection:** proved by ^{7}**Be** and ***pep***
- sensitivity: as low as a few cpd/100 t
  - *pep:* 3.1 ± 0.6(stat) ± 0.3(sys) cpd/100 t

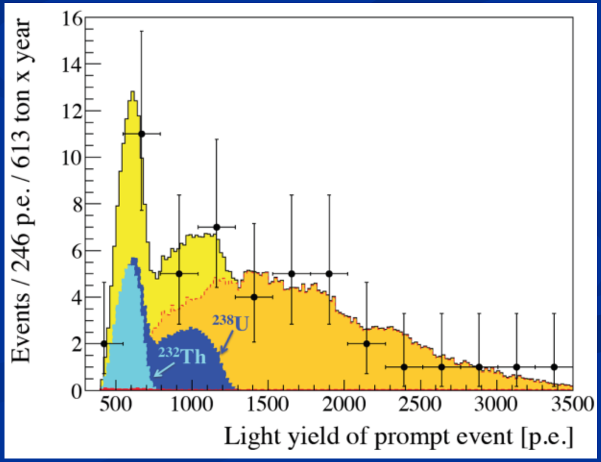


Phys. Rev. Lett. 107, 141302 (2011)

geo and reactor anti-neutrino detection

$$\tilde{\nu}_e + p \rightarrow n + e^+$$

Geo antineutrino rate ~ 7 events/300 ton/ year



Physics Lett. B 722, 4–5 (2013)

Artificial neutrino sources

- The use of artificial neutrino **source for calibration in Borexino** dates back to the beginning of the project
  - ^{51}Cr successfully implemented by Gallex (LNGS) and SAGE (Russia)

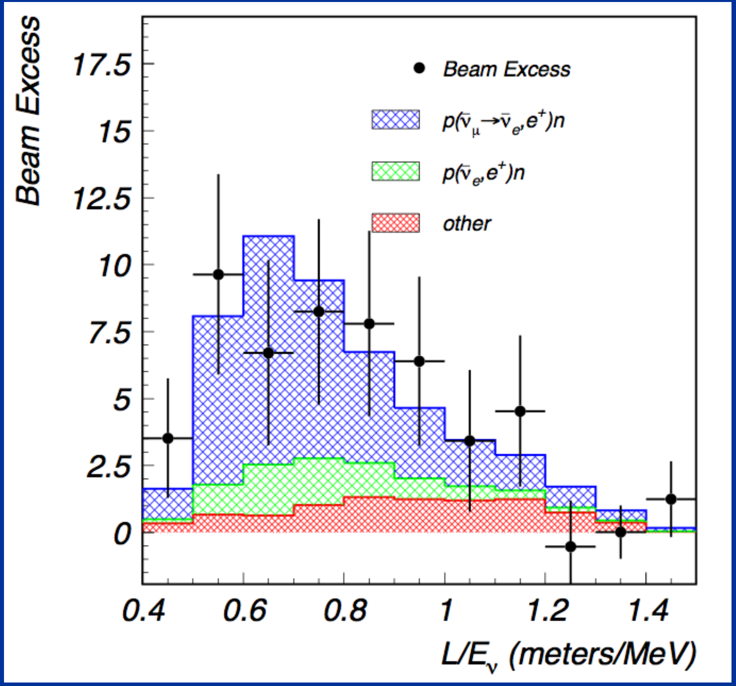
- **Today the idea of artificial neutrino sources renewed to search for sterile neutrinos:**

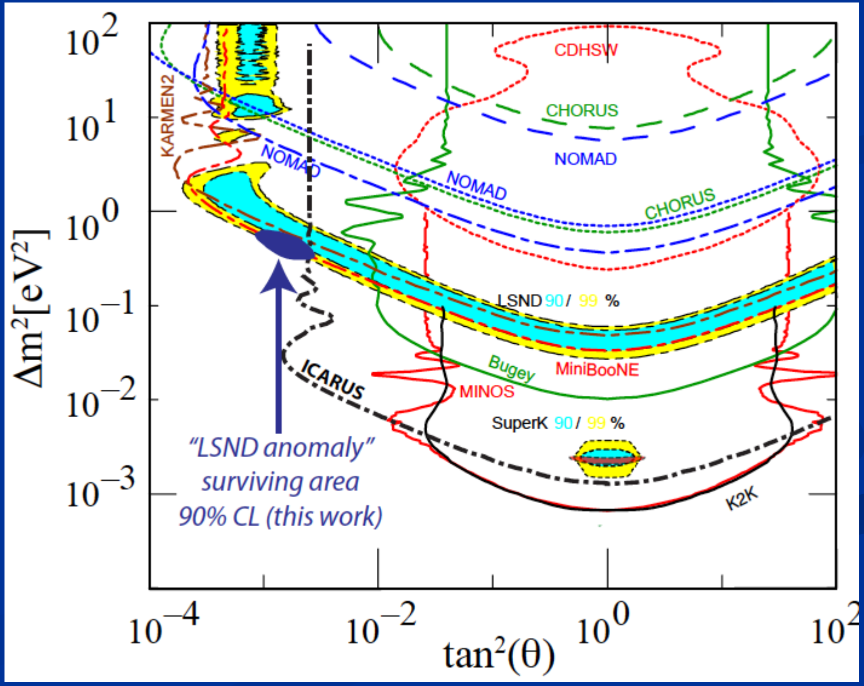
  White Paper on sterile neutrino: arxiv:1204.5379

- **SOX proposal - ERC 320873 - Feb. 2012 - approved Oct. 2012**

Scientific motivation - I

- A few well known experimental results do not match the standard three-flavors scenario. In particular:
  - **LSND (Los Alamos)** in **2001** measured **a $\tilde{\nu}_e$ excess in $\tilde{\nu}_\mu$ beam**
    - Big effect: **87.9 ± 22.4 ± 6.0 (3.8 σ) at L/E$_\nu$~ 0.5−1.0 m/MeV**
    - **L/E NOT compatible** with standard 3-flavour oscillations
    - LSND region recently reduced by Icarus data, but not excluded





Eur. Phys. J. C (2013) 73:2345

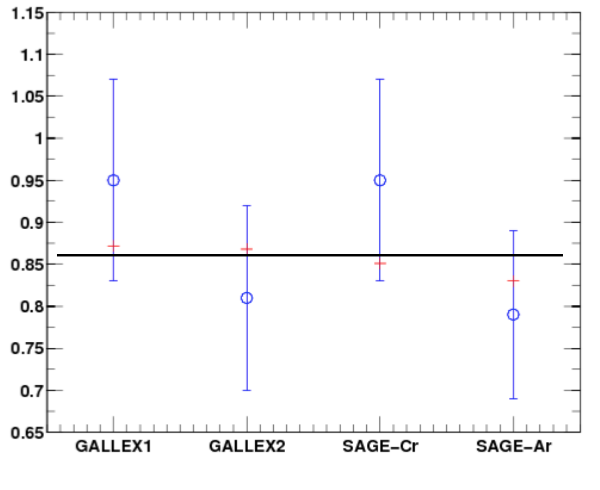
Scientific motivation - II

- **Gallex and SAGE** in the 90's has made a calibration of their detector with an **artificial neutrino source**
- Both experiments show a deficit w.r.t. expectations

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

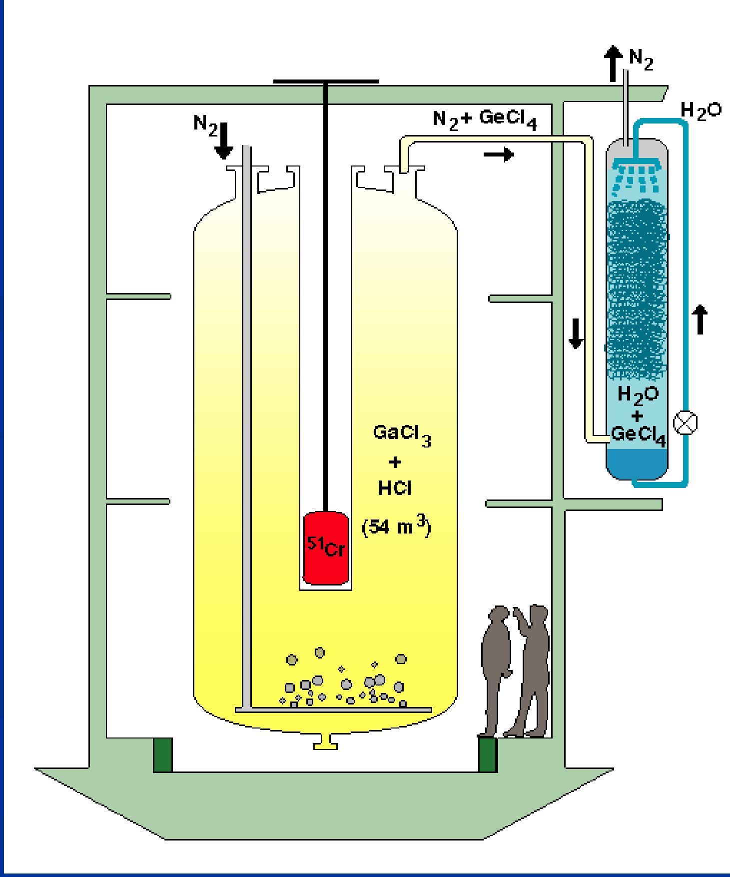
C. Giunti et al. arxiv:1210.5715 (hep-ph)

	G1	G2	S1	S2	AVE
R_B	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
R_{HK}	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
R_{FF}	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
R_{HF}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$



<R>=0.85 ±0.05

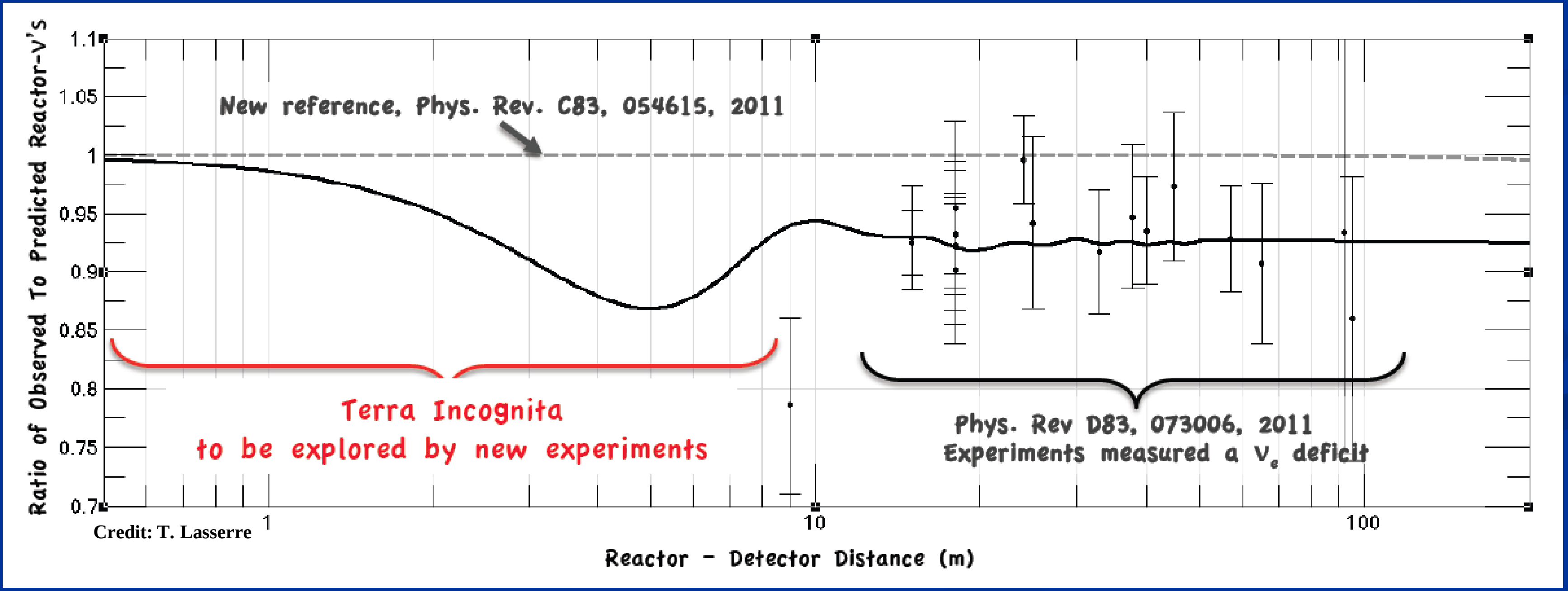
~ 3 σ effect



Scientific motivation - III

- Reactor anomaly

- **NEW analyses of al the experiments at reactors**
  - New calculations of **reactor antineutrino fluxes and specters** released recently
  - With these new calculations, **neutrino deficit is observed**



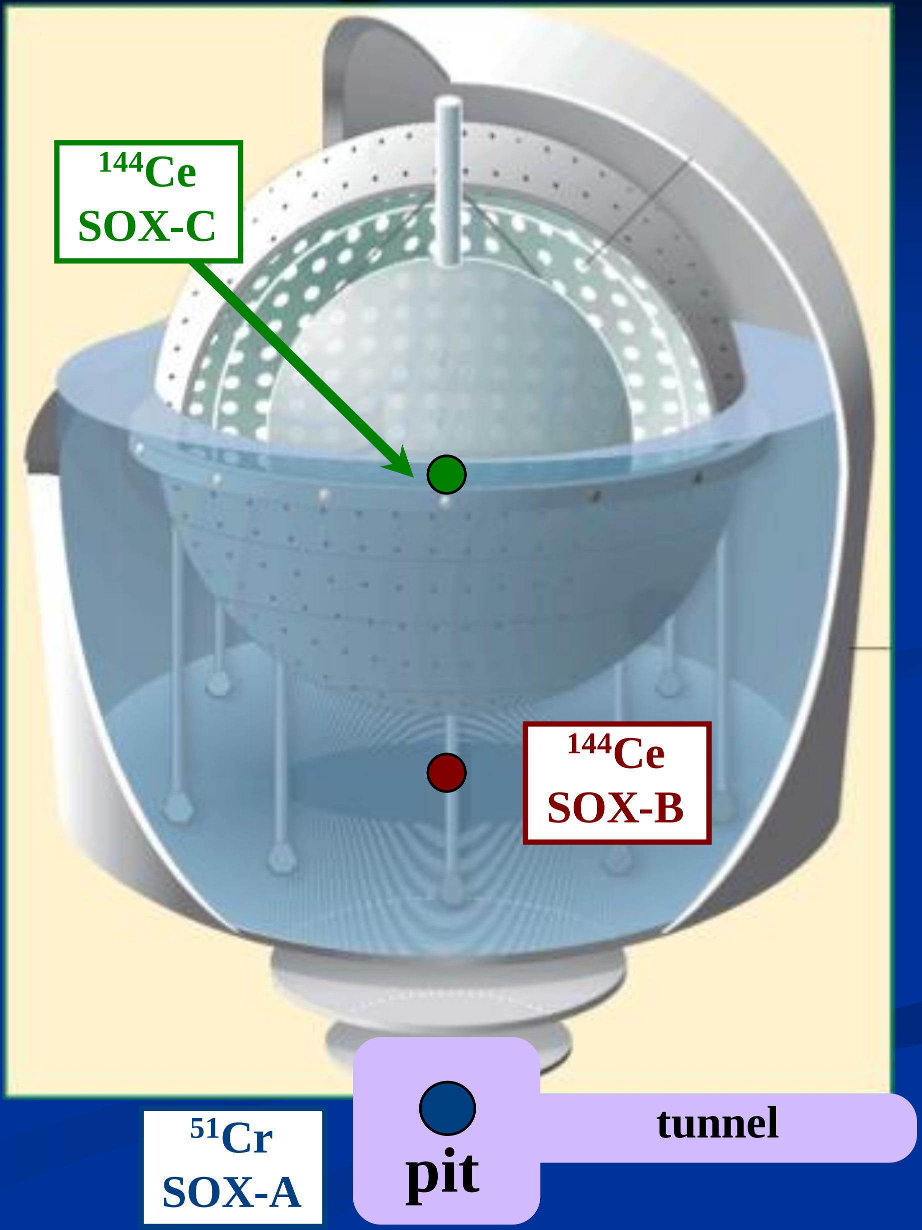
Scientific motivation - IV

- Different theoretical models with the extension of standard 3-flavour oscillations. Most promising mass scale ~1eV, (see-saw type I with light sterile neutrinos, **3+1 or 3+2** models).

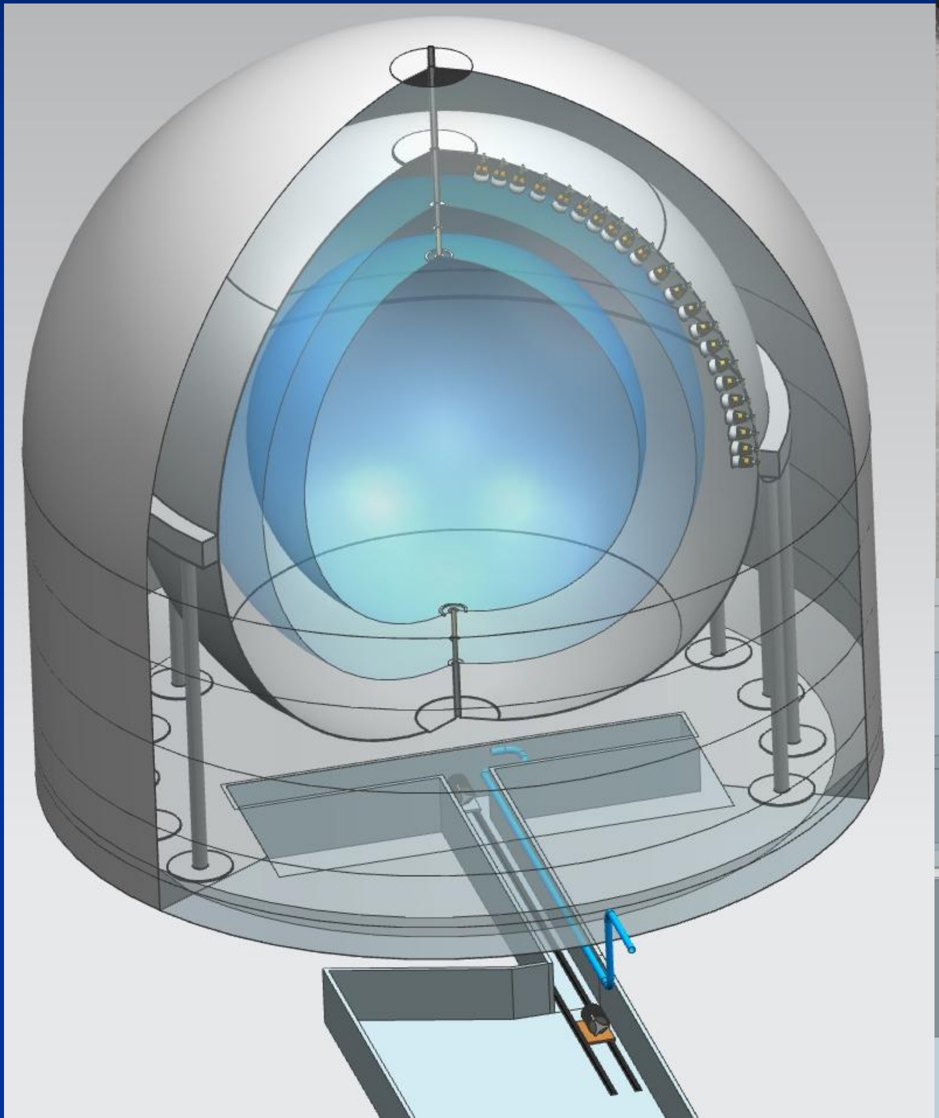
- ✤ Sterile neutrino as a dark matter candidate

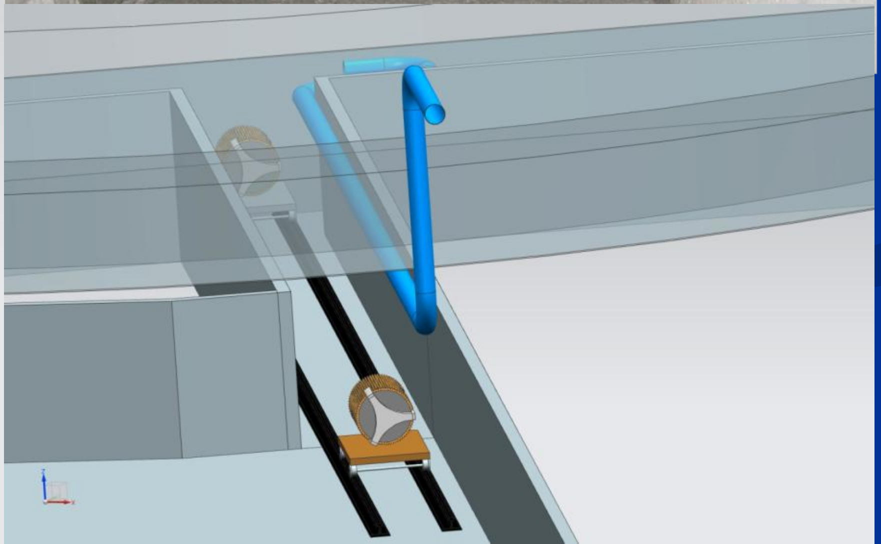
SOX: Three Stages

- **Mission: test the existence of low L/E ν_e and/or $\bar{\nu}_e$ anomalies by placing well known artificial sources close to or inside Borexino**
- **SOX-A**
  - **^{51}Cr** source in pit beneath detector
  - **8.25 m** from center **[2015/2016]**
- **SOX-B**
  - **^{144}Ce-^{144}Pr** source in W.T.
  - PPO everywhere to enhance sensitivity
  - **7.15 m** from center **[2015/2016 ?]**
- **SOX-C**
  - ^{144}Ce-^{144}Pr source in the center
  - **Only after the end of solar program**
  - More effort and more time **[>2016]**



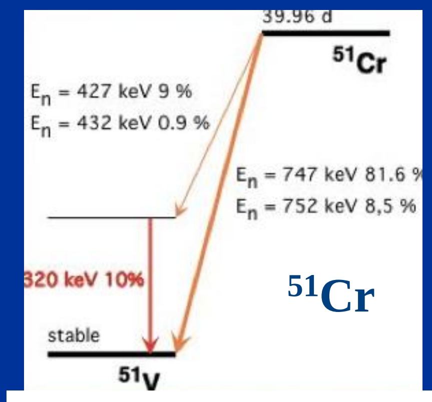
Location for ^{51}Cr source

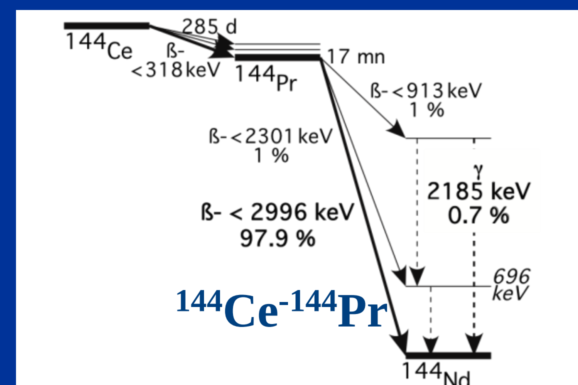




Artificial neutrino sources

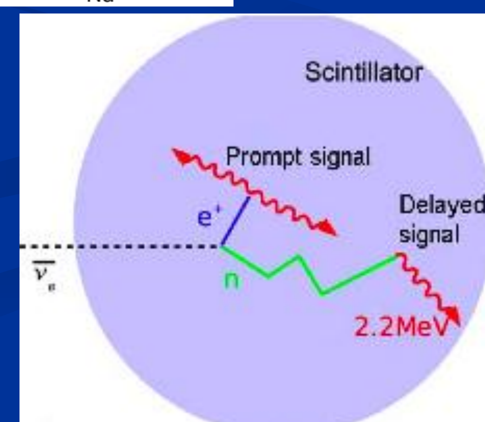
Source	Production	τ (days)	Decay mode	Energy [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr ν_e	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \gtrsim 5.\ 10^{14}\ cm^{-2}\ s^{-1}$	40	EC γ 320 keV (10%)	0.747	0.011	0.19
^{144}Ce-^{144}Pr $\tilde{\nu}_e$	Chemical extraction from spent nuclear fuel	411	β-	<2.9975	0.314	7.6



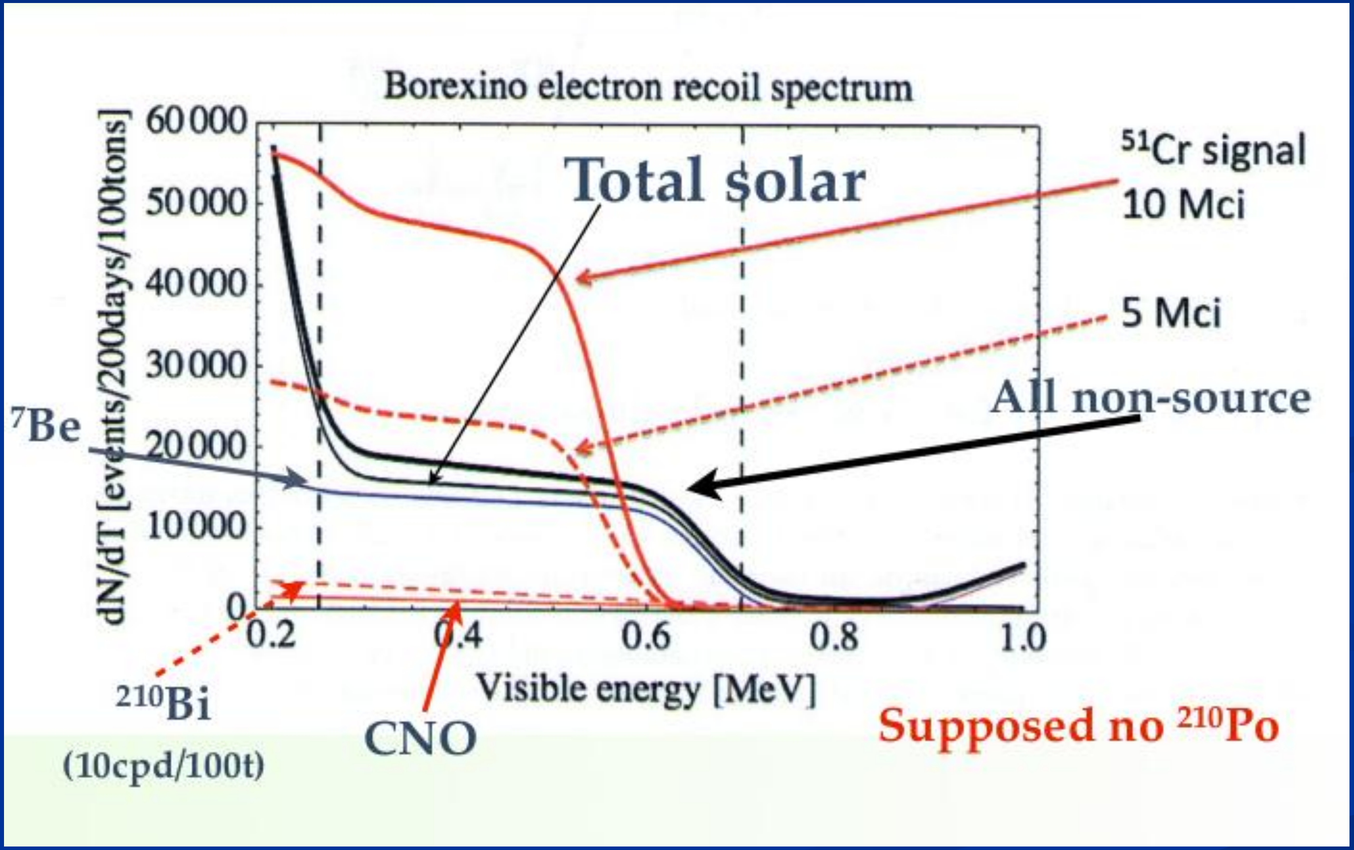


$$\nu + e^- \rightarrow \nu + e^-$$

$$\tilde{\nu}_e + p \rightarrow n + e^+$$



Electron energy specter from ^{51}Cr



Detector signal with external source

- Volume:

$$V(l) = 2\pi l^2 \left(1 - \frac{d^2 - R^2 + l^2}{2\ d\ l}\right)$$

- Flux and decay

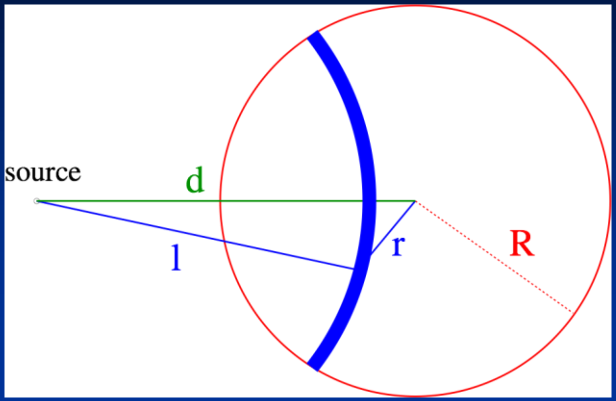
$$\Phi(l) = \frac{I_0}{4\pi l^2}\tau e^{-\frac{t_D}{\tau}}\left(1 - e^{-\frac{t}{\tau}}\right)$$

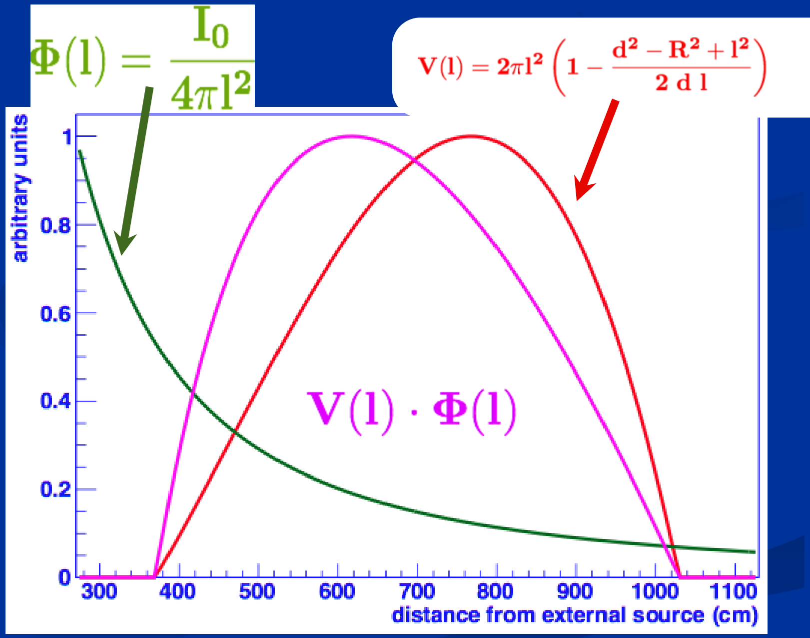
- Oscillations (one sterile)

$$\mathbf{P_{ee} = 1. - \sin^2(2\theta_s) \cdot \sin^2\left(\frac{1.27\ \Delta m^2\ l}{E}\right)}$$

- The number of ν_e-e^- events at distance l from the source, with detection threshold T_1 and maximum recoil energy T_2:

$$\mathbf{N_0(l, T_1, T_2) = n_e\ \Phi(l)\ V(l)\ P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E, T)}{dT} dT}$$

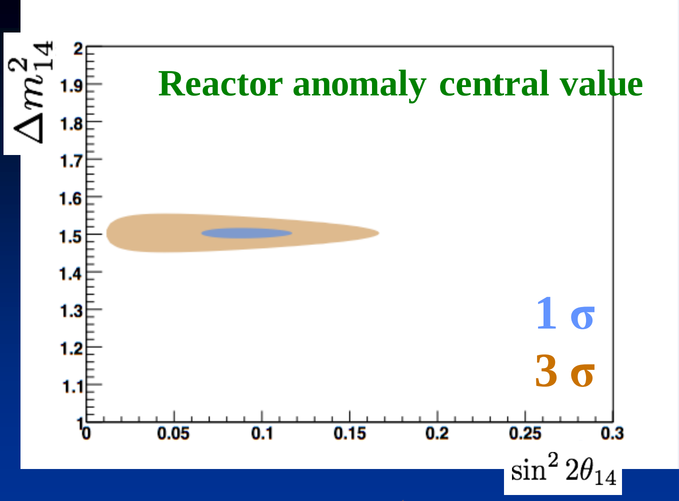




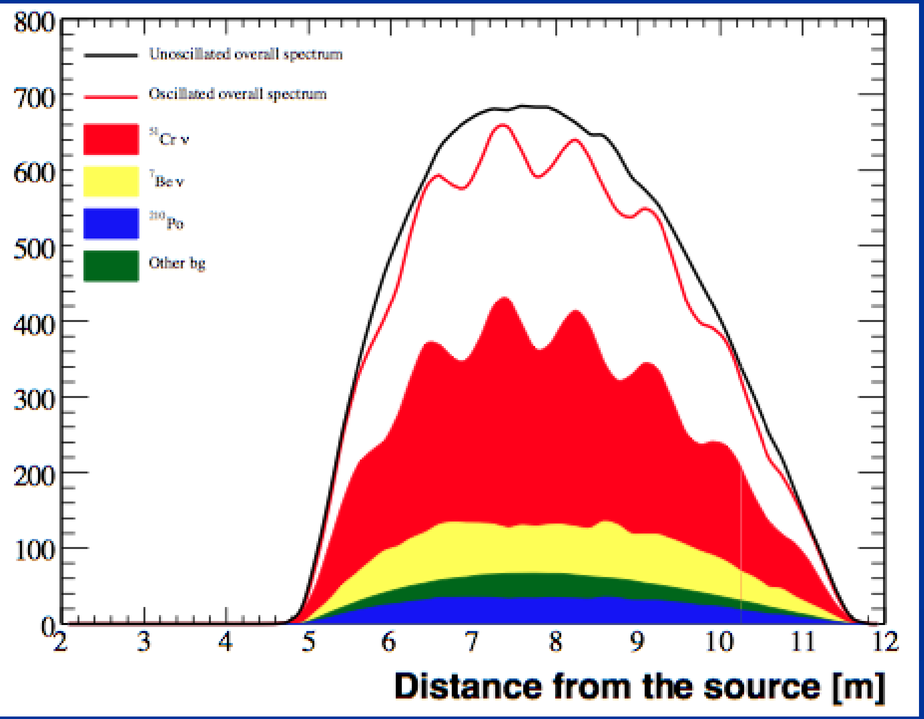
The distribution of events is not uniform even without oscillations

Geant 4 Monte-Carlo simulation for Cr51 source

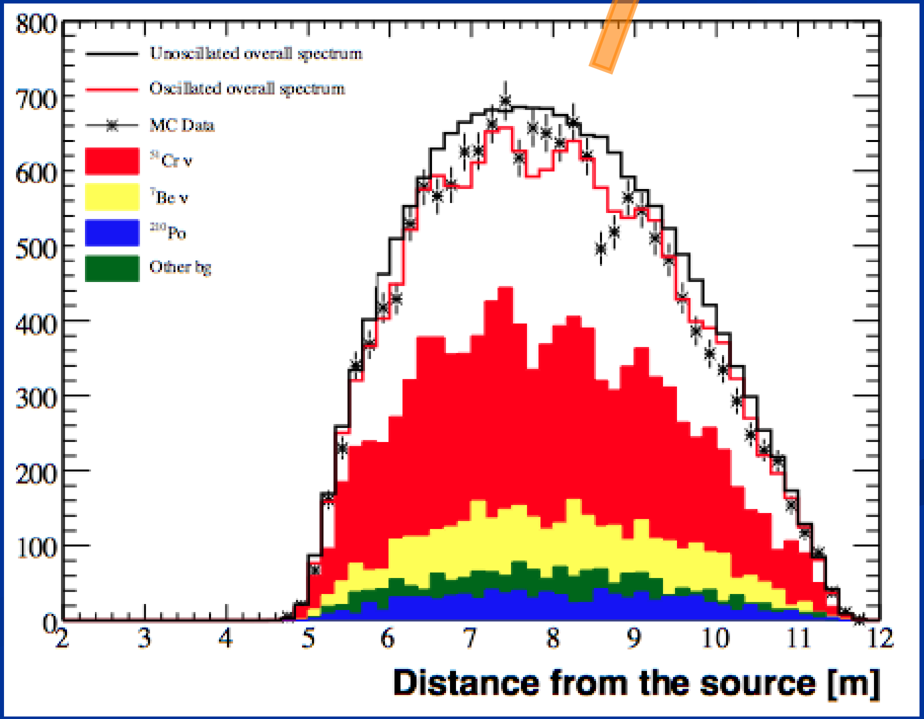
- **Waves** may be detected in the distribution of events as a function of the distance from source
  - With waves, both parameters can be measured



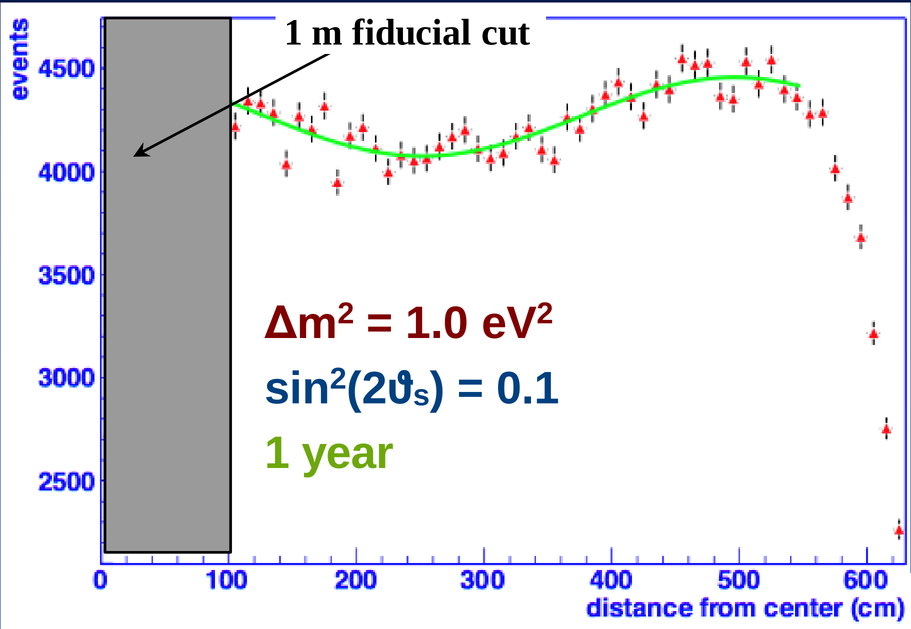
Analytical curves
Borexino Background - No fluctuations

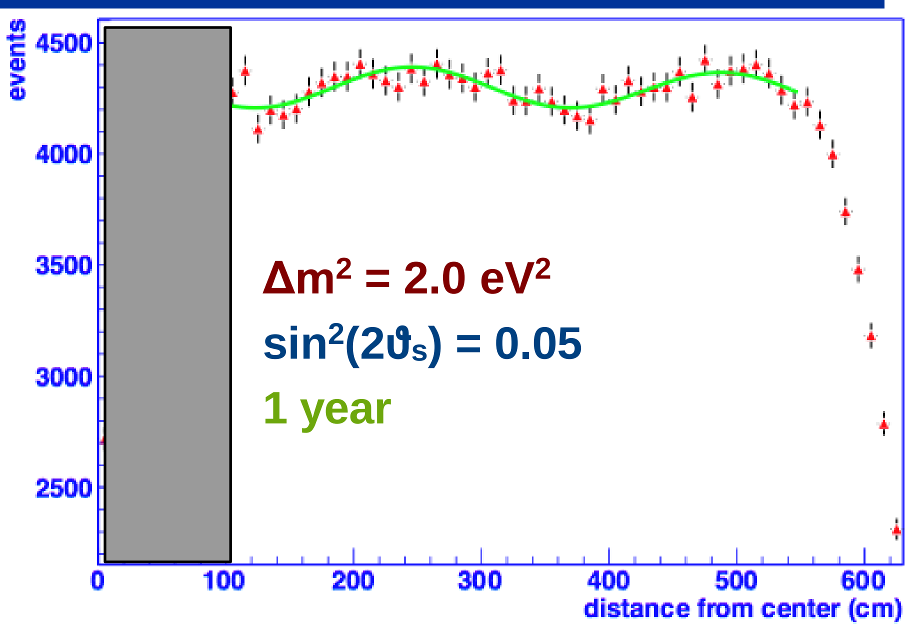


Full Geant4 simulation - example
Borexino Background

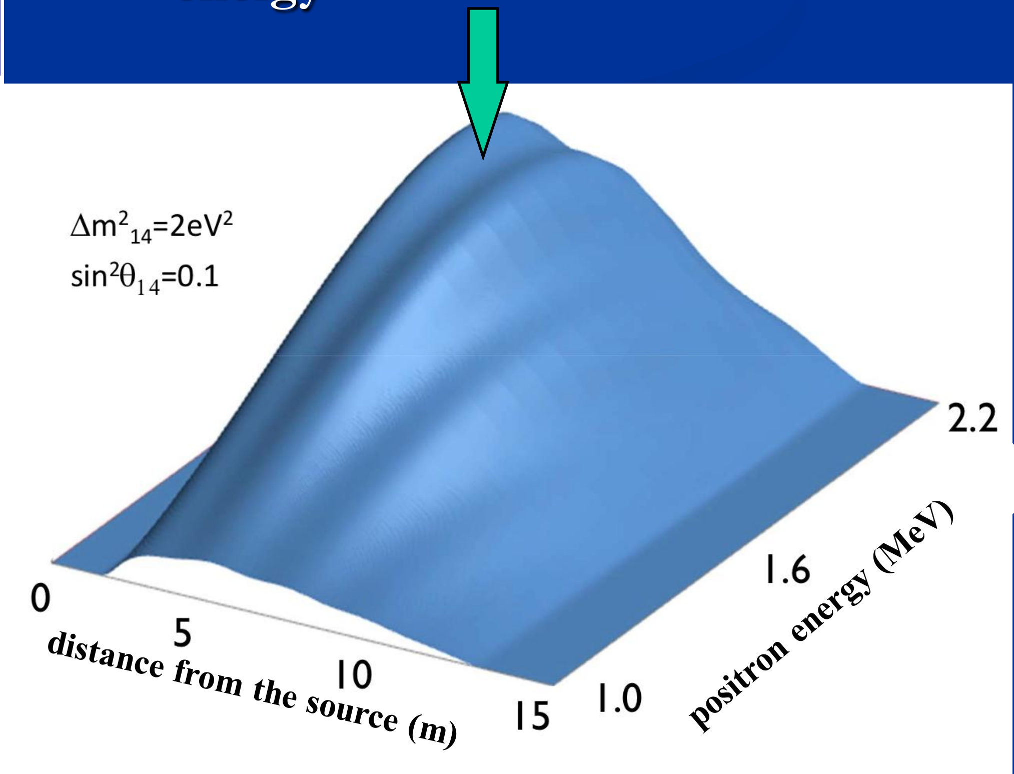


Space-energy correlation



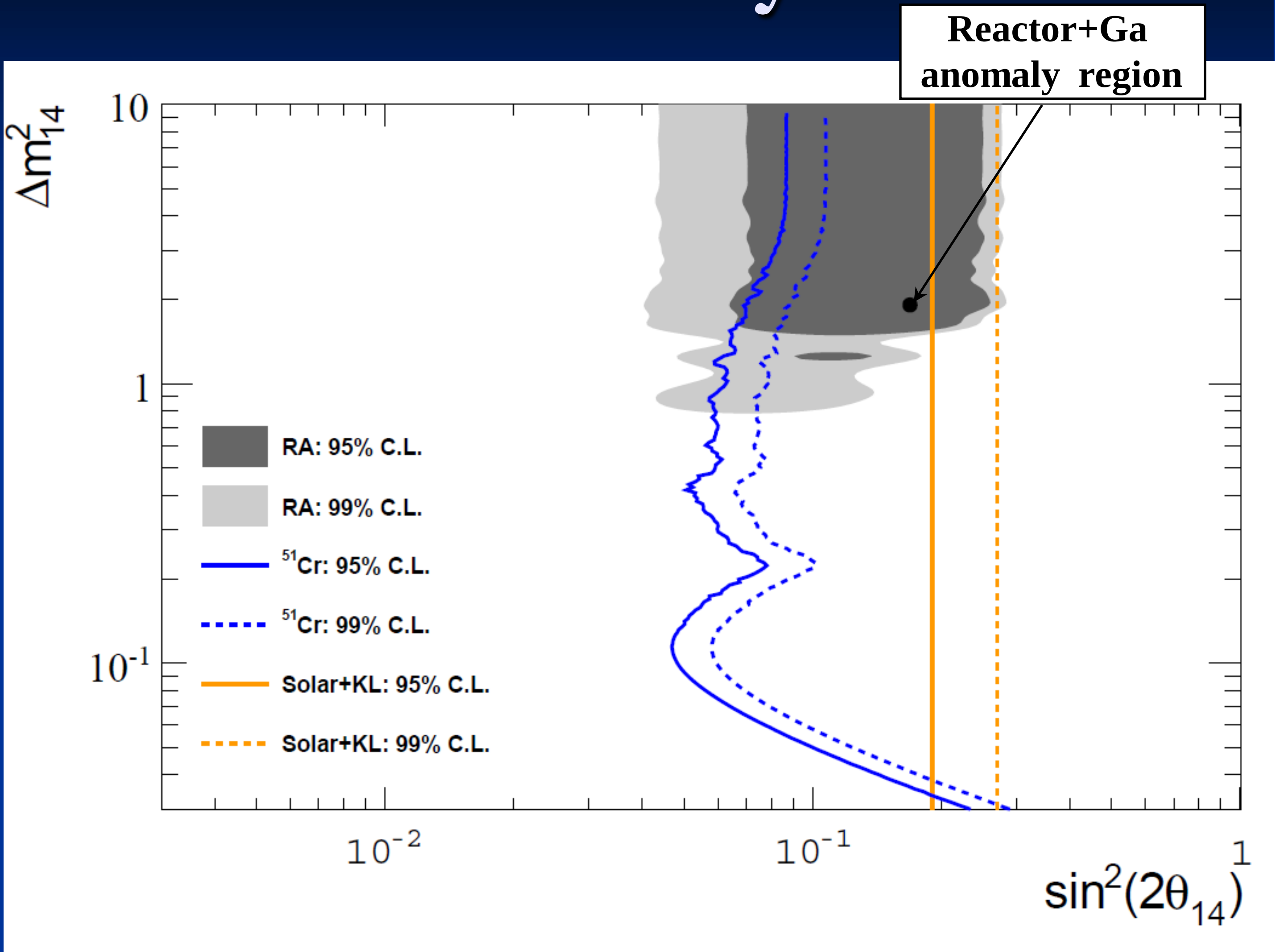


- With the ^{144}**Ce-**^{144}**Pr** source (both **external SOX-B** and **internal SOX-C**) global fit exploits the **correlation between reconstructed event position and positron energy**



SOX-A sensitivity

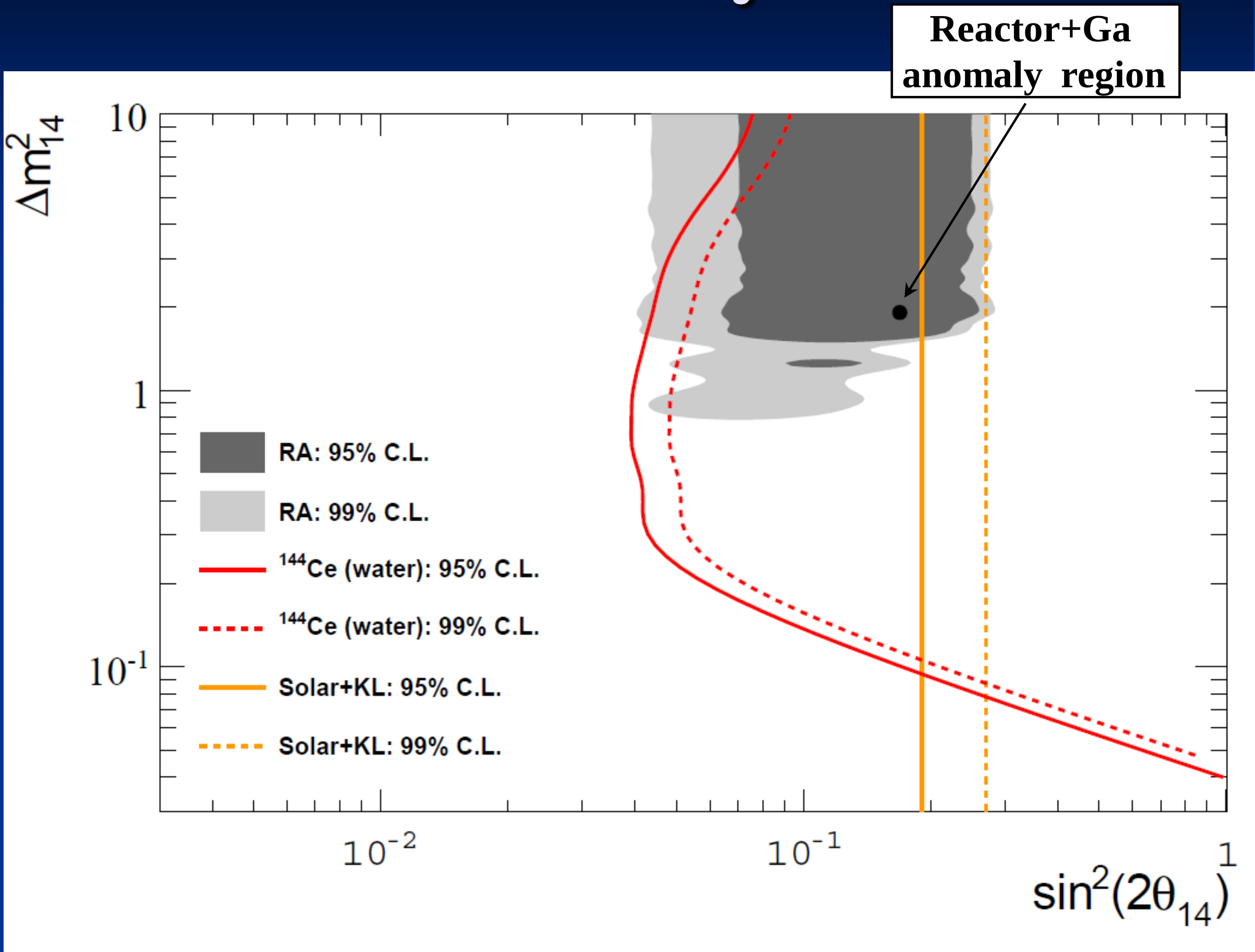
- **SOX-A:**
  - ^{51}Cr source at 8.25 m from the center
  - 10 MCi
  - 1% precision in source activity
  - 1% in FV determination



- Phase I can happen any time during next solar neutrino phase
  - 2015 is realistic scenario

SOX-B sensitivity

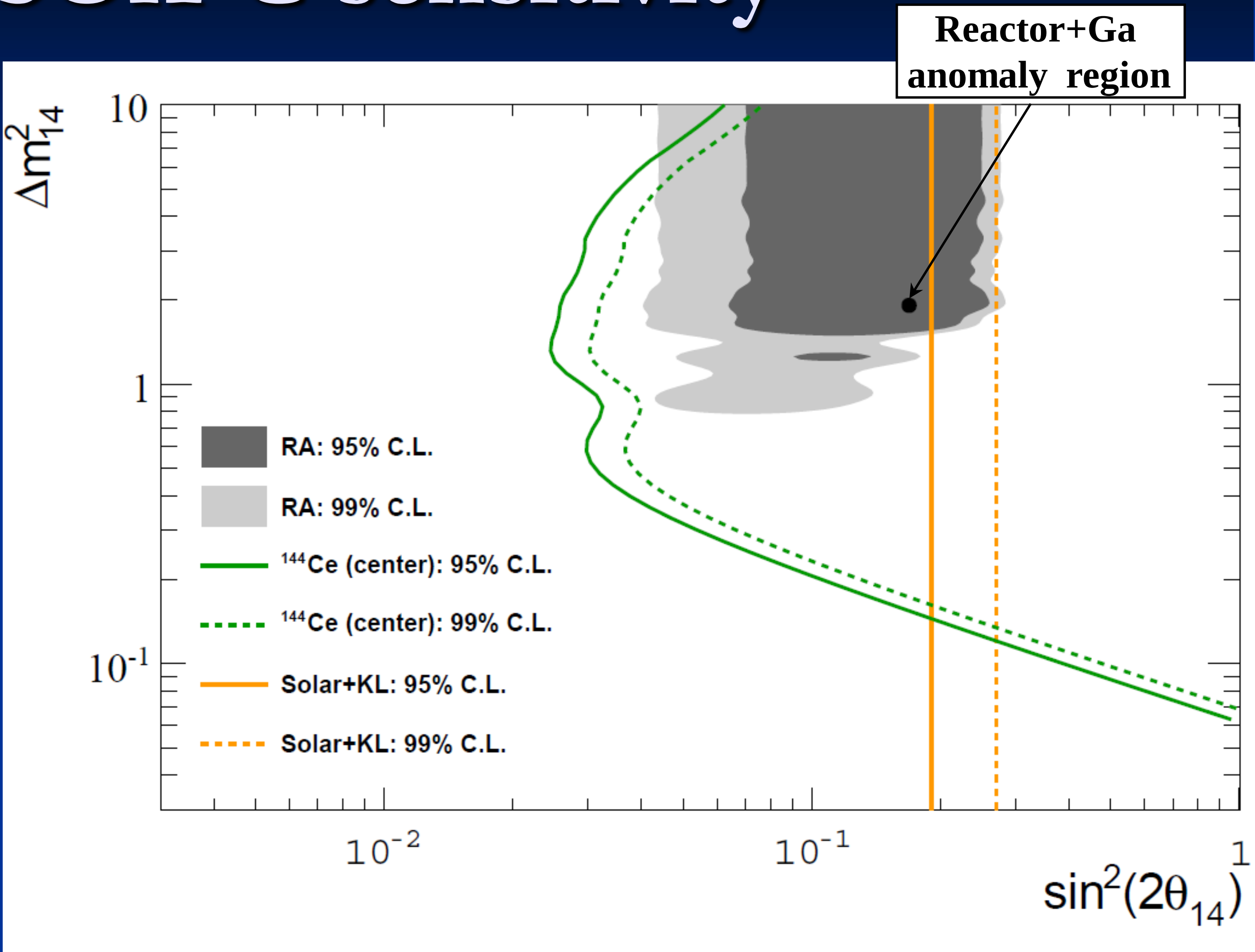
- **SOX-B**
  - ^{144}Ce-^{144}Pr source at 7.15 m from the center
  - 75 kCi
  - 1.5% precision in source activity
  - 2% bin-to-bin error to include all effects
  -



- SOX-B can happen any time during next solar neutrino phase
  - 2015 is a realistic scenario – 1,5 year of data taking

SOX-C sensitivity

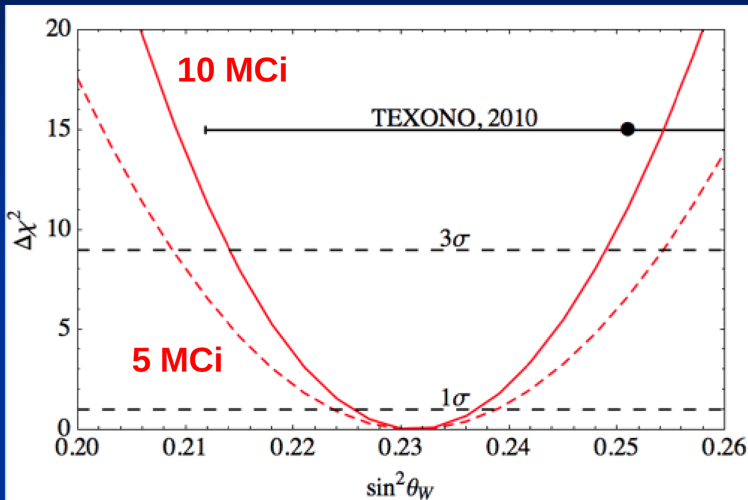
- **SOX-C:**
  - ^{144}Ce-^{144}Pr source in the center
  - 50 kCi
  - 1.5% precision in source activity
  - 2% bin-to-bin error to include other systematics



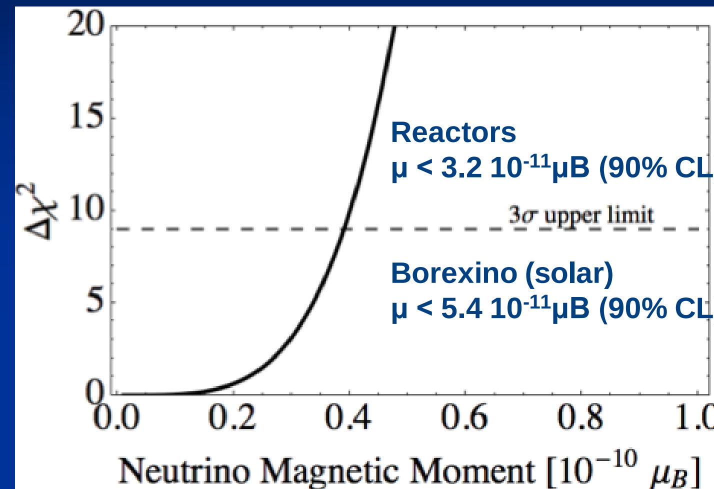
- SOX-C can happen only after the end of solar neutrino program
  - 2016-2017 is a realistic scenario
  - decision to be taken after SOX-A and/or SOX-B results

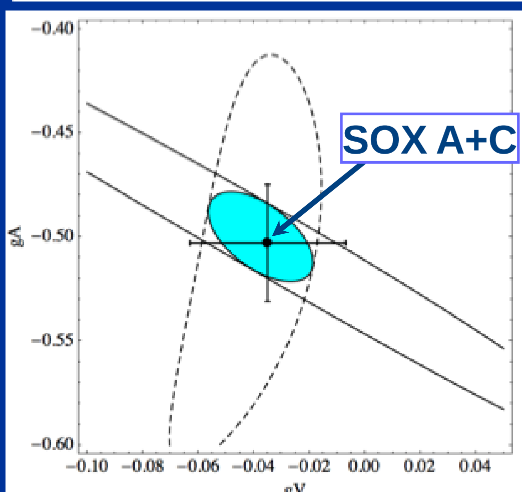
Low energy neutrino physics

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



Magnetic moment





- With both sources (SOX-A and B or C)
- Test of SM EW running at very low energy
- Constraints on neutrino NSI
- Independent measurement of g_V & g_A
  - $g_V = -1/2 + 2\sin^2\theta_W = -0.038$
  - $g_A = -1/2 = 0.5$

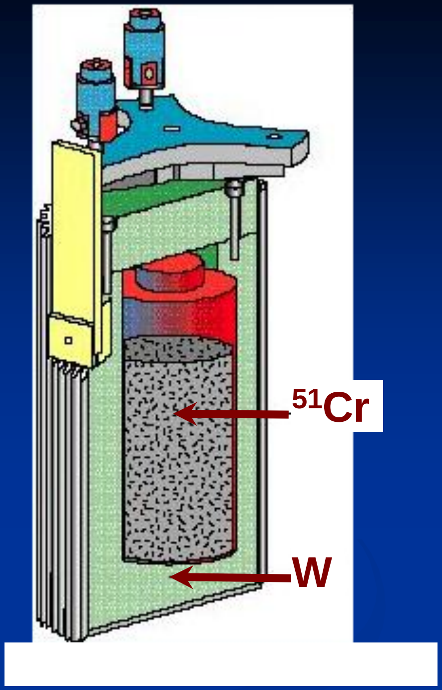
CHARM II (1994)
ν_μ + e^- E ~ 10 GeV

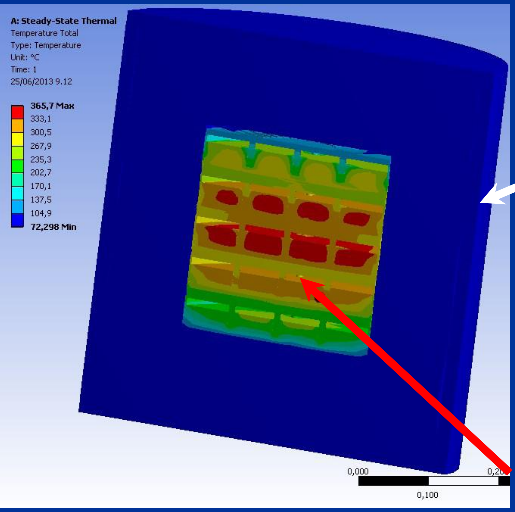
$$g_V^{\nu e} = -0.035 \pm 0.012(\text{stat}) \pm 0.012(\text{syst}),$$

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

Technology: ^{51}Cr source

- 36 kg of ^{50}Cr enriched at 38 % will be irradiated at reactor (Russia or USA) with high neutron flux $\Phi_n \gtrsim 5.10^{14}\ cm^{-2}\ s^{-1}$ and delivered to Gran-Sasso (the logistic and safety tasks)
- 190 W/MCi from gammas
- ~ few μSv/h on the surface (required < 100)
- Thermal special design to handle 2 kW (10 Mci)

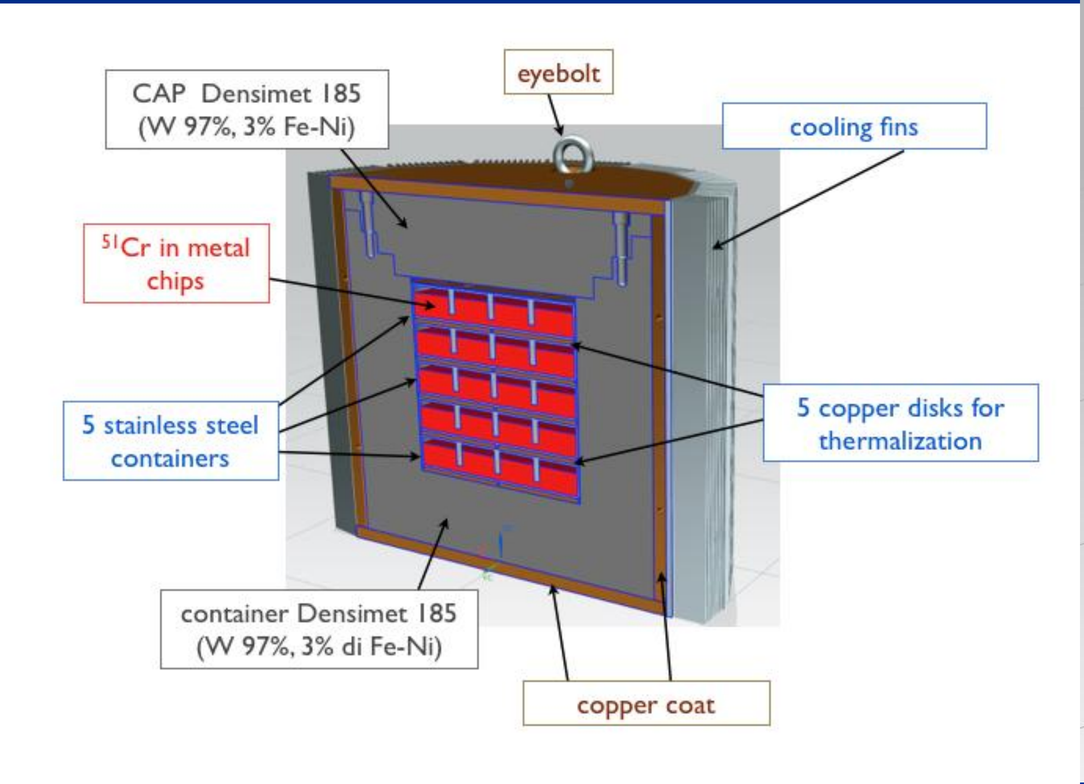


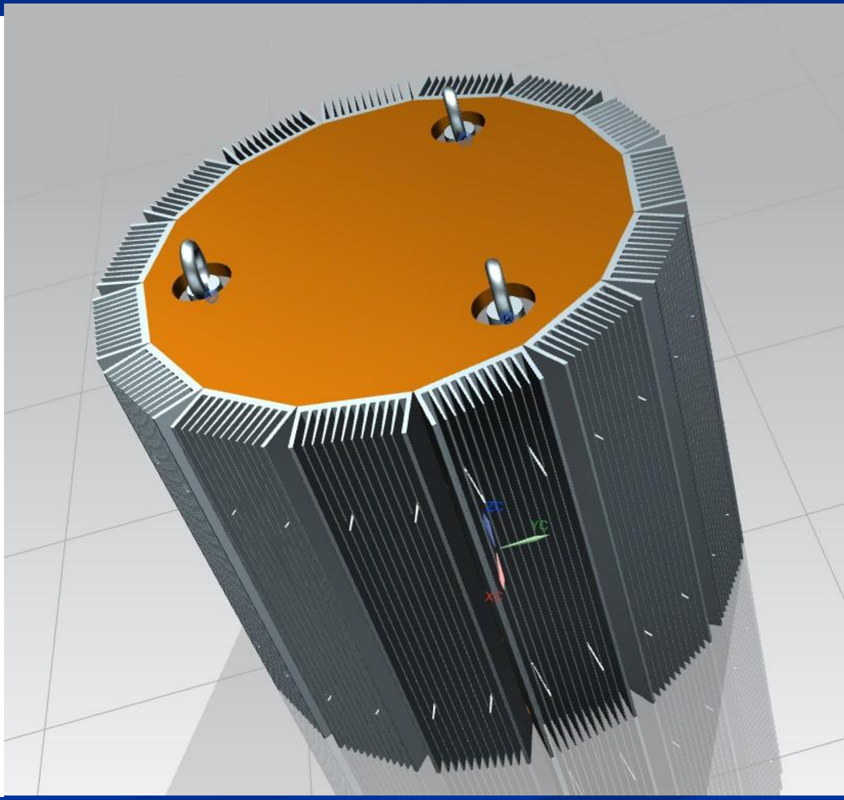


External T must be acceptable
Current value: T=90° C

Internal T must be below syntherization (750° C)
Current value: T=260 ° C

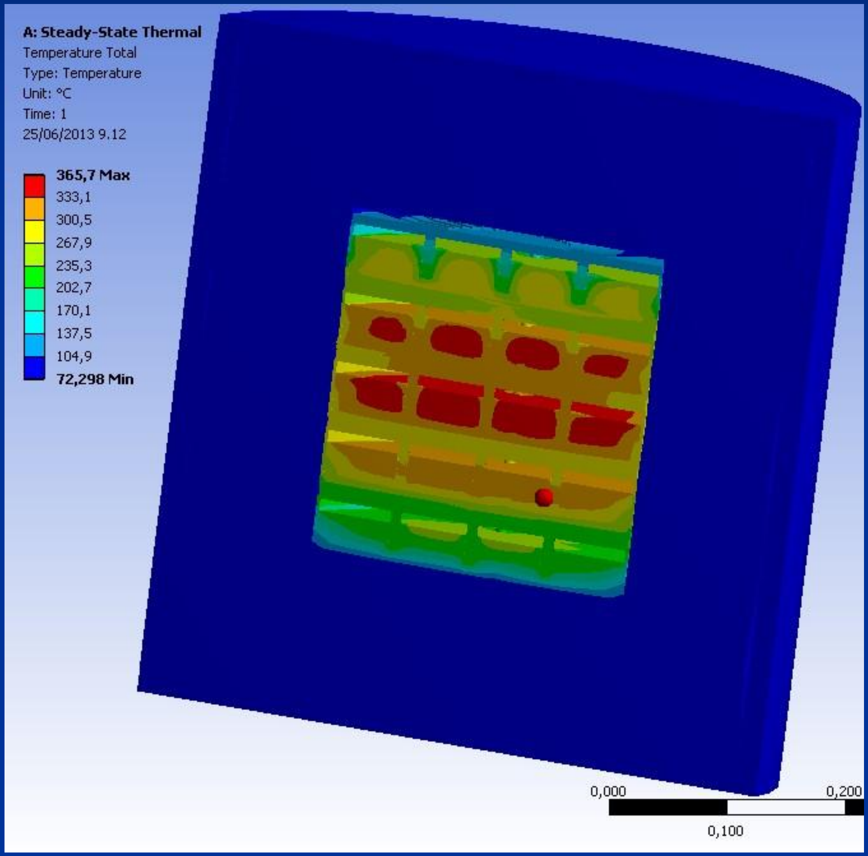
Technology: ^{51}Cr encapsulation



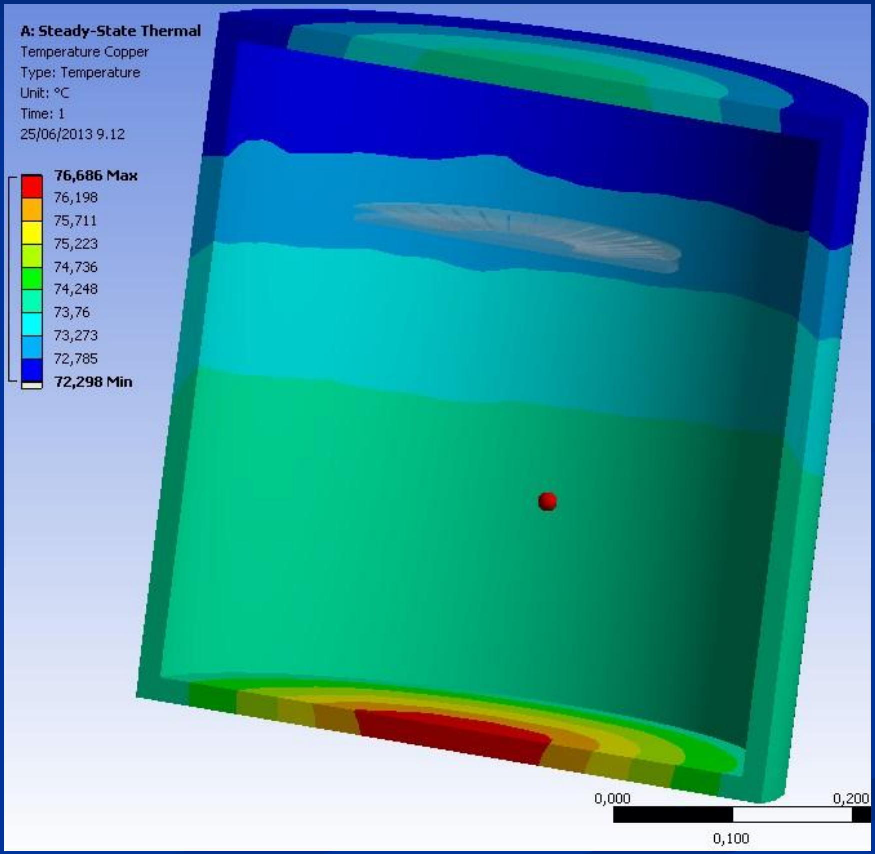


Thermal studies

Bulk temperatures



Surface temperatures



Precise determination of the source activity

- Particularly important at relatively high $\Delta m^2 > 2\ eV^2$ where the measurement relies essentially on the disappearance effect. Not important in the region where the oscillometric measurement dominates the sensitivity

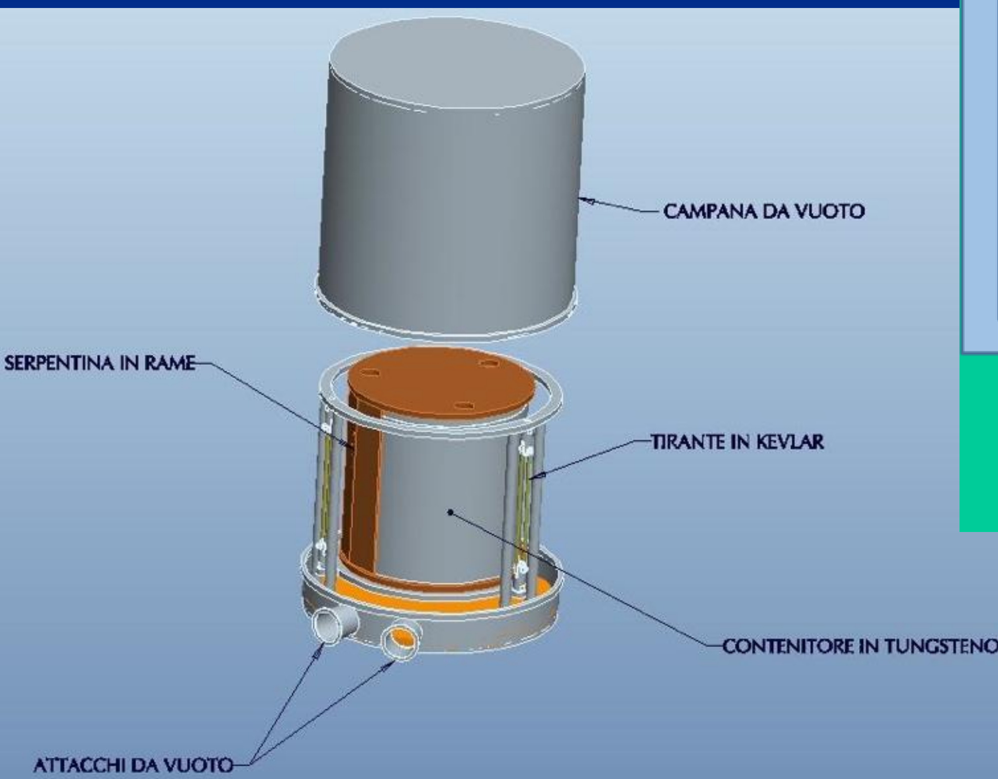
Sampling
√ Samples extracted from several positions in mixed material, at reactor
√ Ionization chamber measurements
√ Gamma-ray spectroscopy (HPGe) of dissolved samples

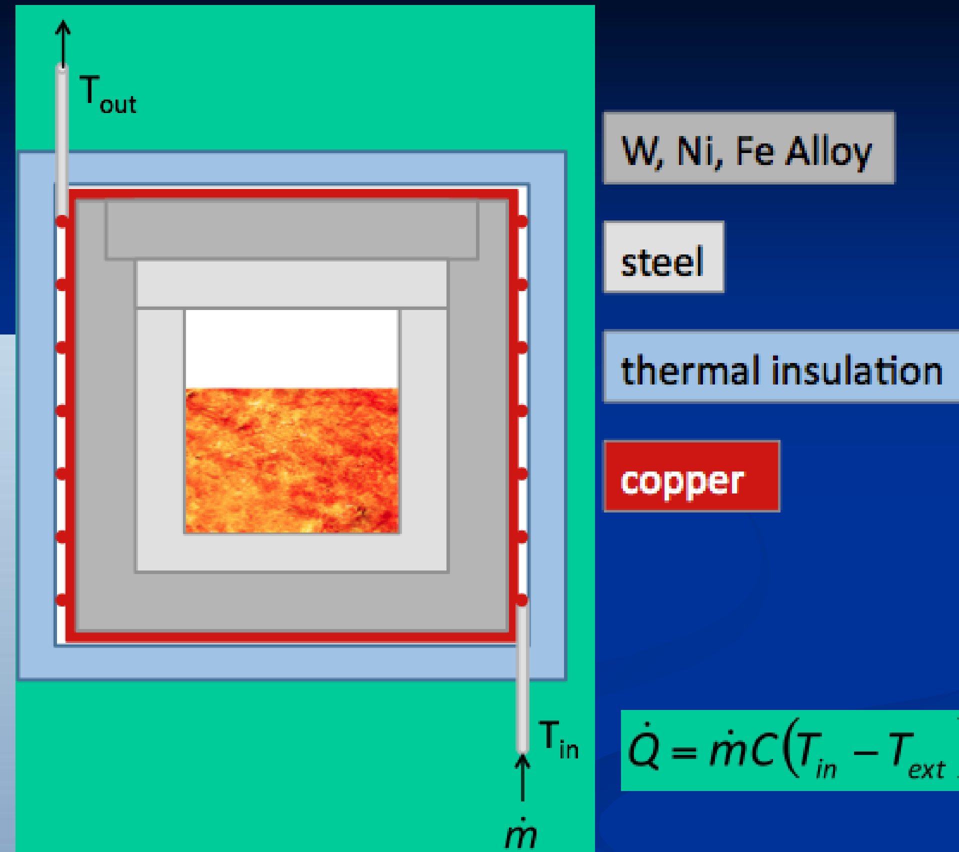
Calorimetry
√ Emmited radiations will heat up source and shield
√ Suspended and isolated container: designed as vacuum chamber, water flow measurement

Neutronics/gamma-scanning
√ Neutron flux in reactor + relevant capture cross-section
√ Gamma-ray measurement from the 320keV line from irradiation to hot-cell

Measurement of vanadium
√ Only daughter of 51Cr
√ Also produced ***during irradiation,*** complicating analysis
√ Ratio Cr/V constant

Calorimetry



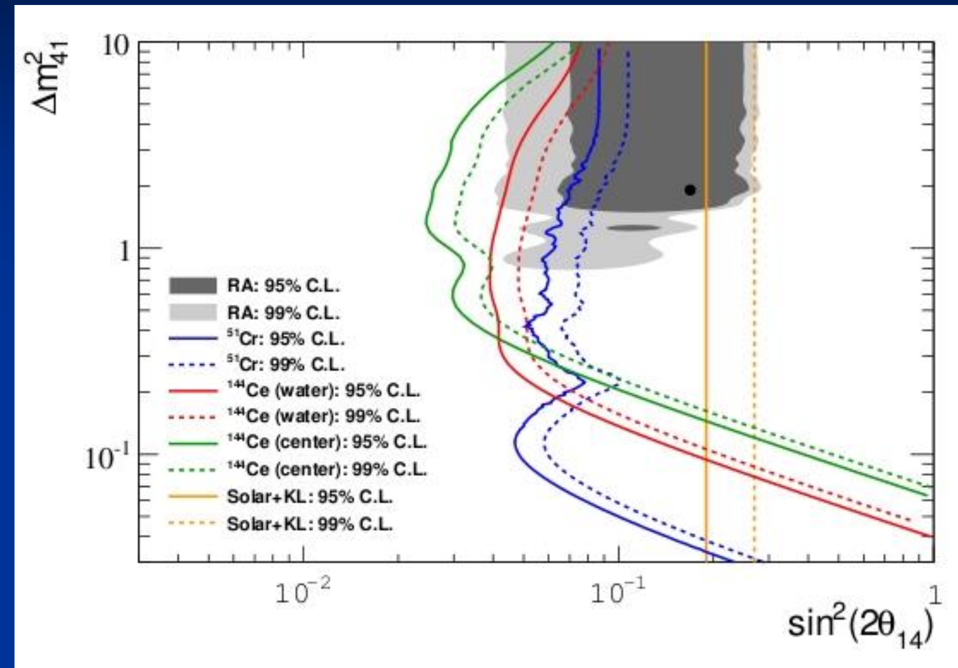


$$\dot{Q} = \dot{m}C(T_{in} - T_{ext})$$

Similar task is the measurement of reactor heat power
(accuracy 0.5 % in France)

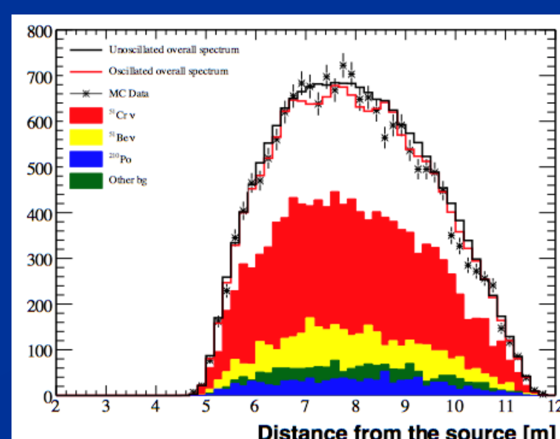
Conclusions

- Borexino plan to perform an extensive search of sterile neutrinos with neutrino and anti-neutrino sources

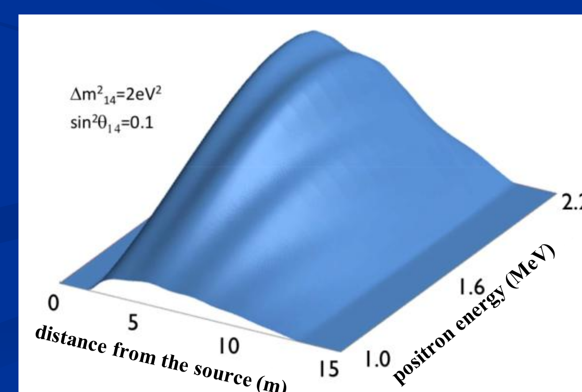


- **SOX-A**
  - ^{51}Cr neutrino source (external)
  - Tentative schedule: 2015-2016
- **SOX-B**
  - ^{144}Ce anti-neutrino source (external)
  - Tentative schedule: 2015-2016
- **SOX-C**
  - ^{144}Ce anti-neutrino source (internal)
  - After 2016

SOX-A



SOX-C



Спасибо за внимание !

Borexino Collaboration

Milano

Genova

Perugia

Dubna JINR (Russia)

Kurchatov Institute (Russia)

APC Paris

Petersburg Nucl. Phys. Institute

Princeton University

Virginia Tech. University

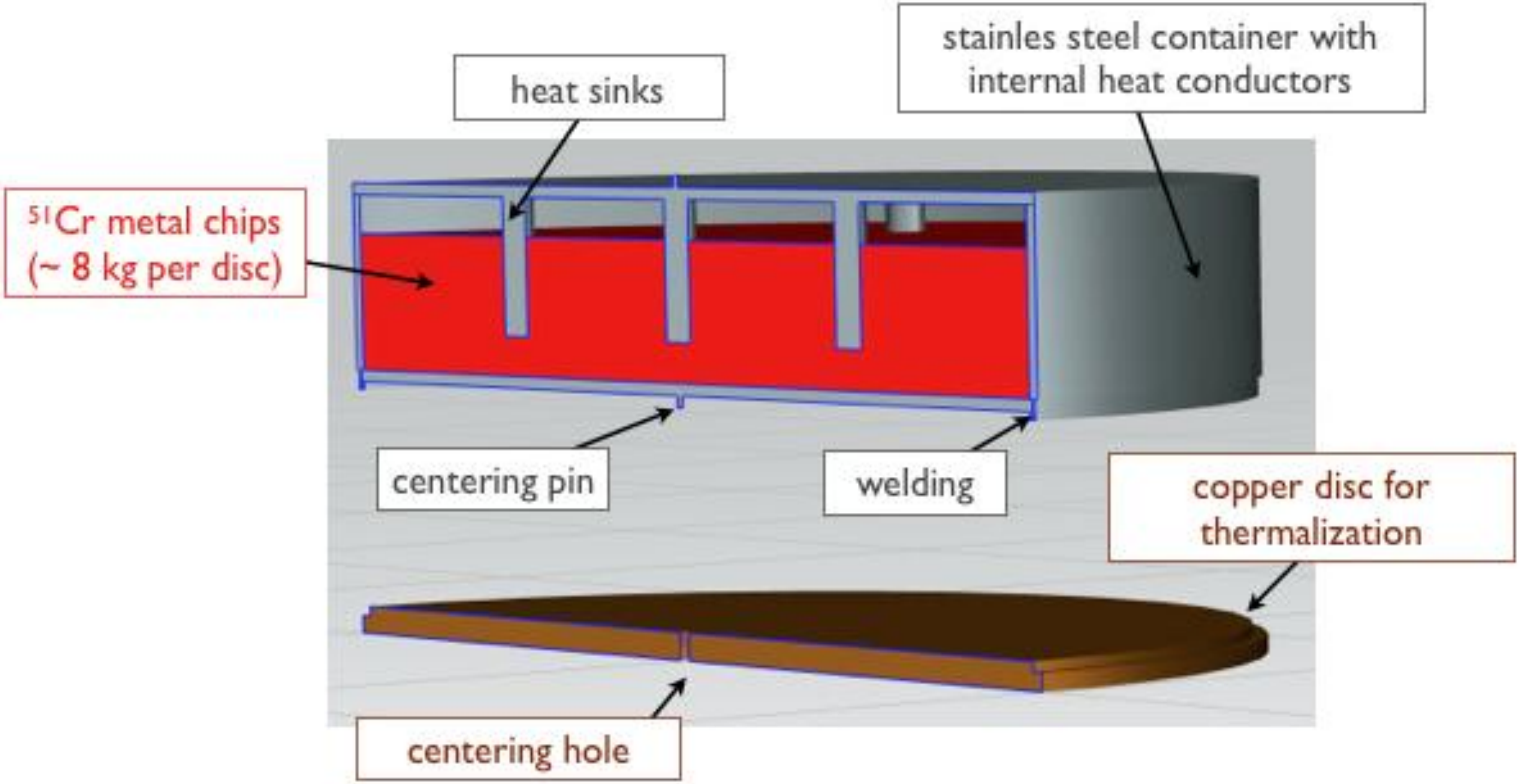
Munich (Germany)

Heidelberg (Germany)

Jagiellonian U. Cracow (Poland)

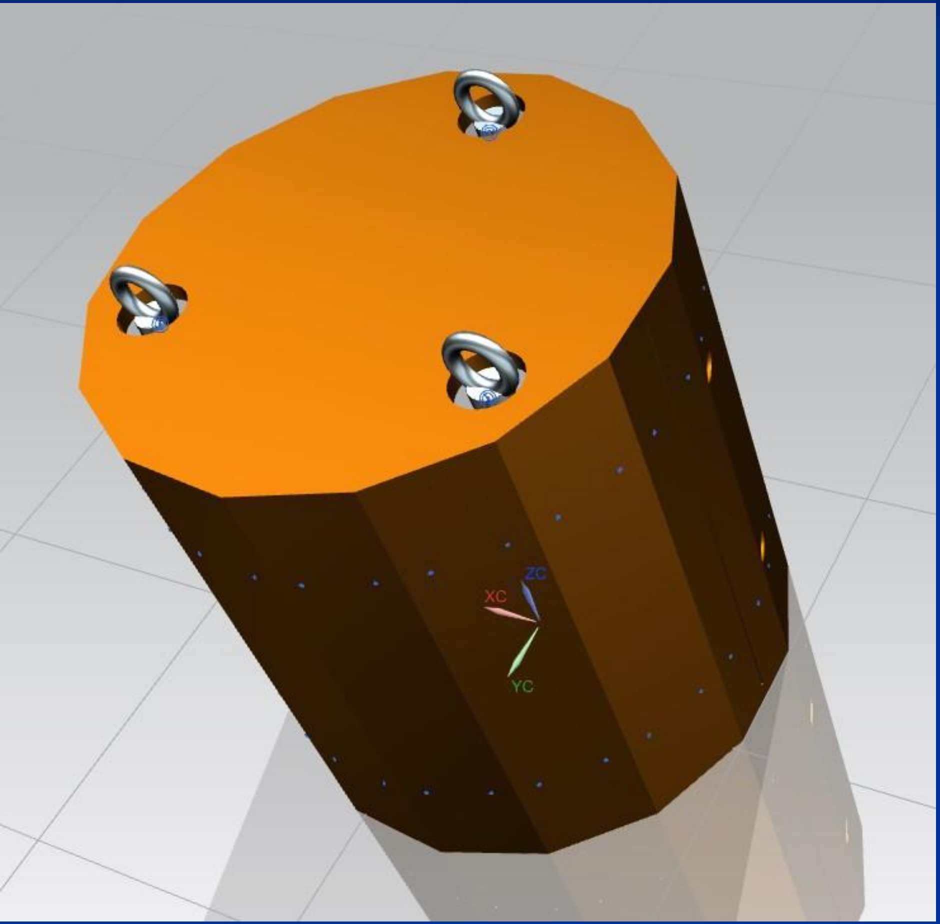
Back up slides

Internal design

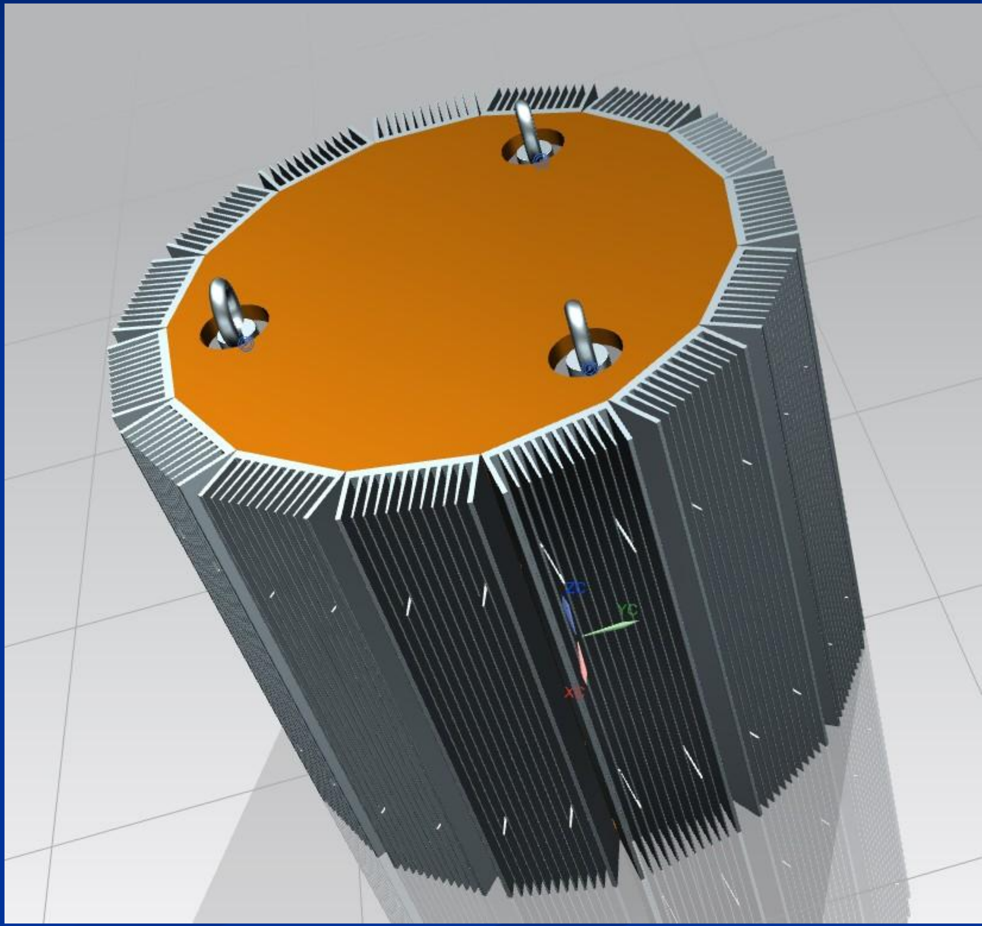


Final assembly

without cooling fins

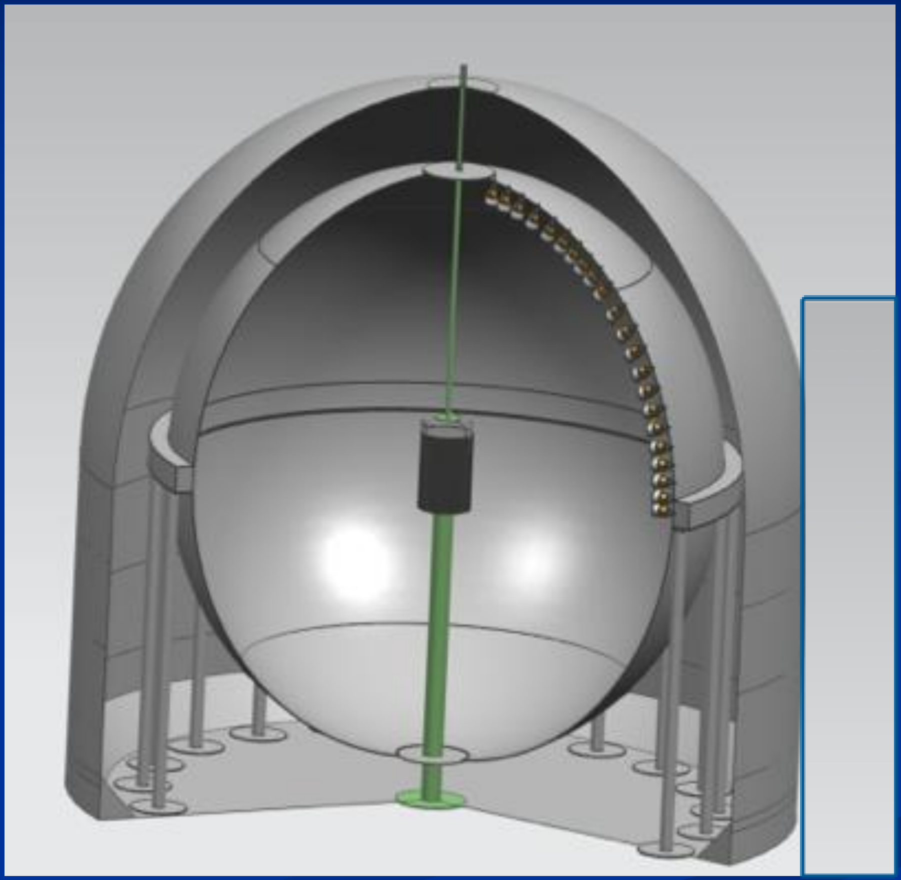


with cooling fins



SOX-C: ^{144}Ce source inside detector

- Massive source with ~ **4 t** of shielding
  - ^{144}Ce Source to be produced at Mayak plant (Russia) **from spent nuclear fuel**
- **DENSIMET (W)** shielding plus ultra-pure **copper layer** to reduce background
  - W is dirty for Borexino
  - γ background is a problem if rate too high
    - random coincidences make background
- Source deployment to be studied
  - Either from the top or from the bottom
  - PPO everywhere in the SSS to enlarge active volume (active radius up to **5.5 m**)

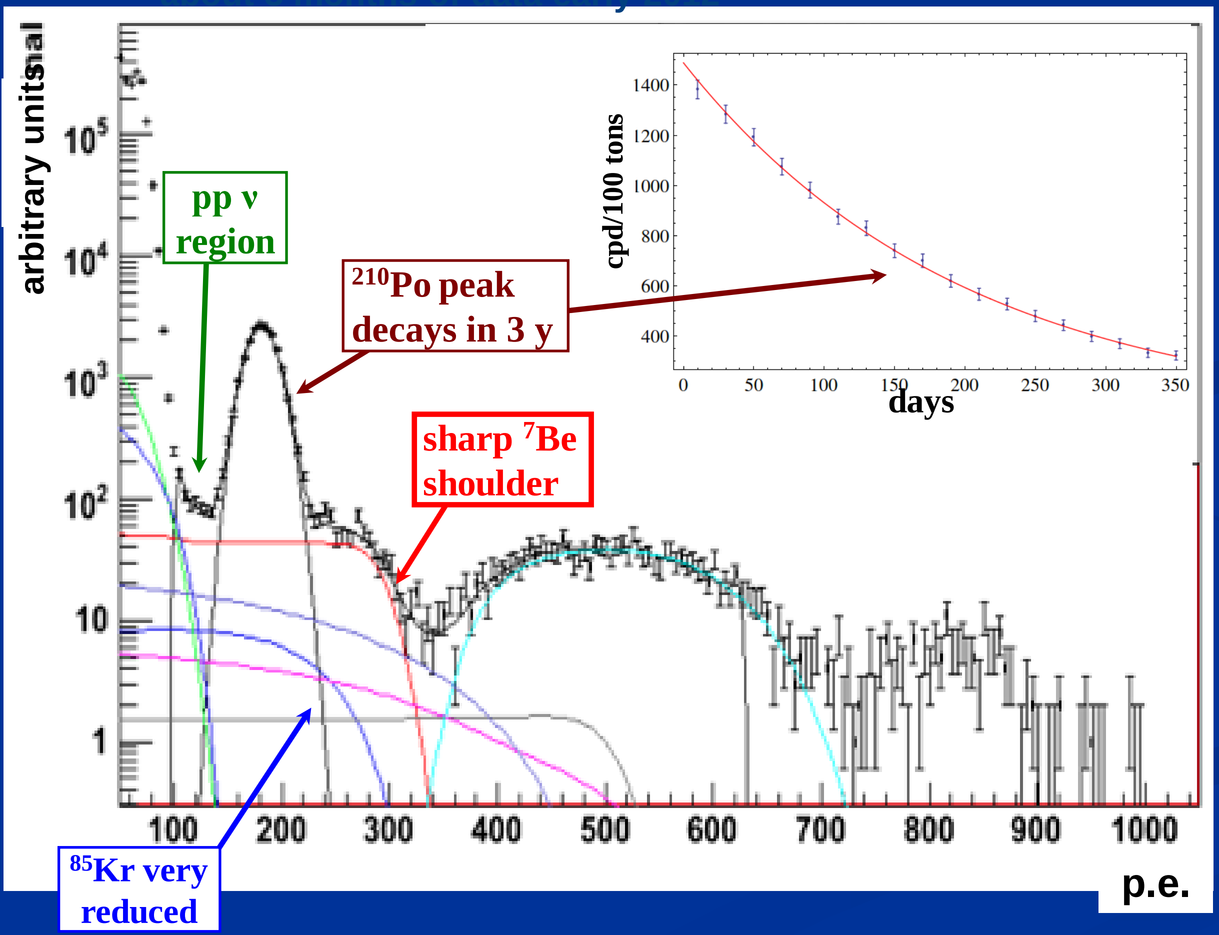


- **> 2016. No schedule yet.**

Borexino background today

- A significant **purification** effort done in 2010/2011 to improve purity further
  - Very effective on ^{85}**Kr**, good on ^{210}**Bi**, excellent for ^{238}U and ^{232}Th

about 3 months of data early 2012



- ^{85}Kr
  - **< 8.8 cpd / 100 t**
  - 2007-2010: 31.2 ± 5
- ^{210}Bi
  - **18 ± 4 cpd / 100 t**
  - 2007-2010: 41.0 ± 2.8
- ^{238}U
  - **< 9.7 10^{-19} g/g**
- ^{232}Th
  - **< 2.9 10^{-18} g/g**