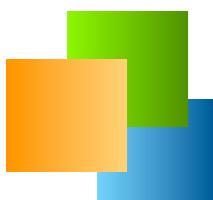


Short Distance Neutrino Oscillations with BoreXino

Neutrino Telescopes
Venezia, Mar. 13th, 2013

Marco Pallavicini
on behalf of the Borexino Collaboration

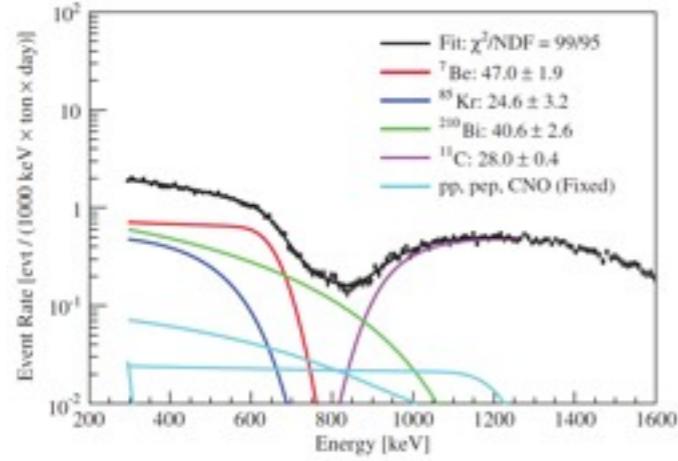
Dipartimento di Fisica – Università di Genova & INFN Sezione di Genova



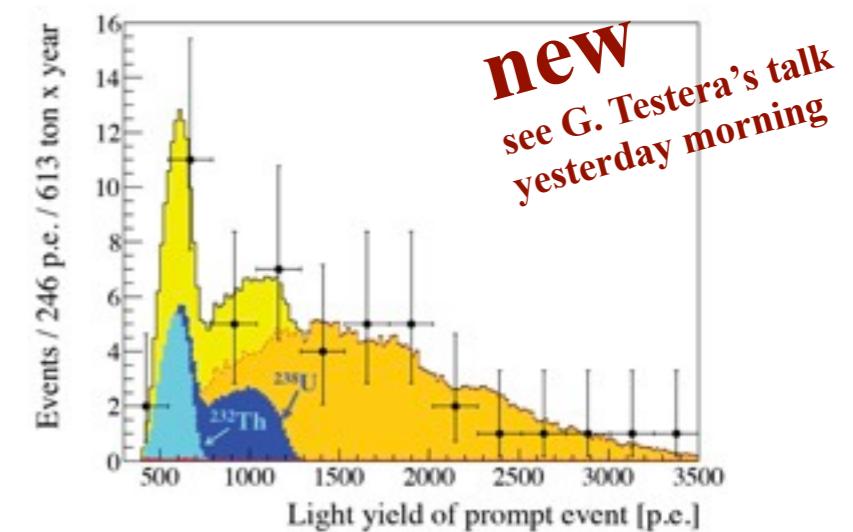
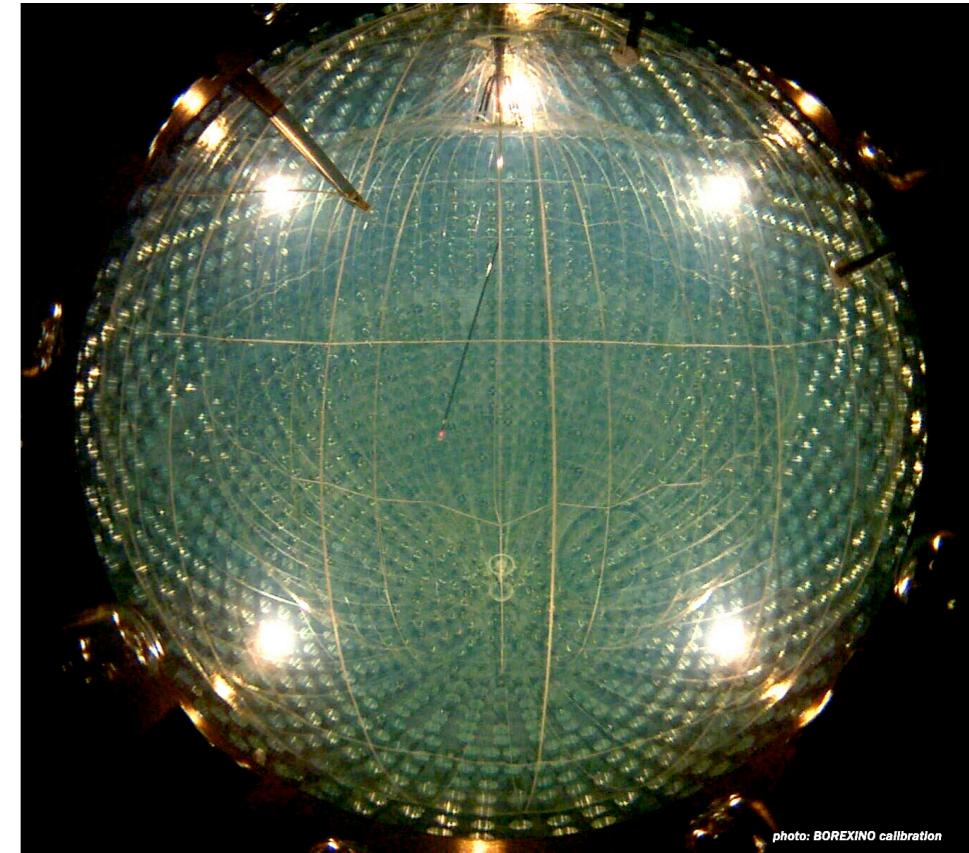
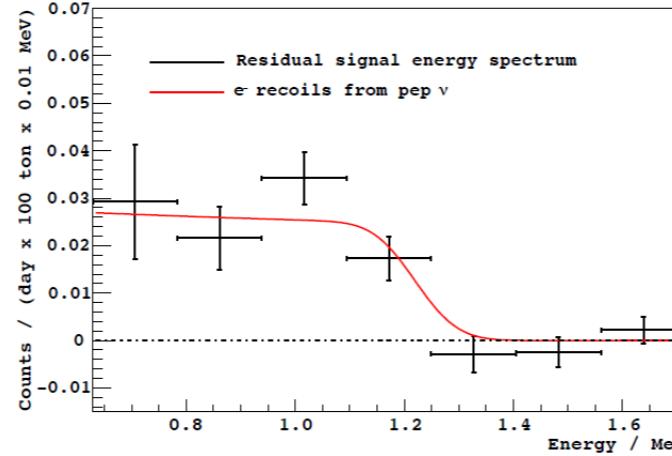
Borexino experiment

- Mainly, **a solar neutrino experiment**
 - $\nu + e^- \rightarrow \nu + e^-$ in organic liquid scintillator
 - **Very low background** obtained with **selection, shielding e purifications**
 - Low energy threshold, good energy resolution, spatial reconstruction, pulse shape α/β identification
 - but also
 - Very good anti-neutrino detection (e.g. geo-neutrinos)

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



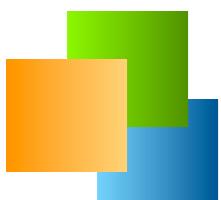
Phys. Rev. Lett. 108, 051302 (2012)



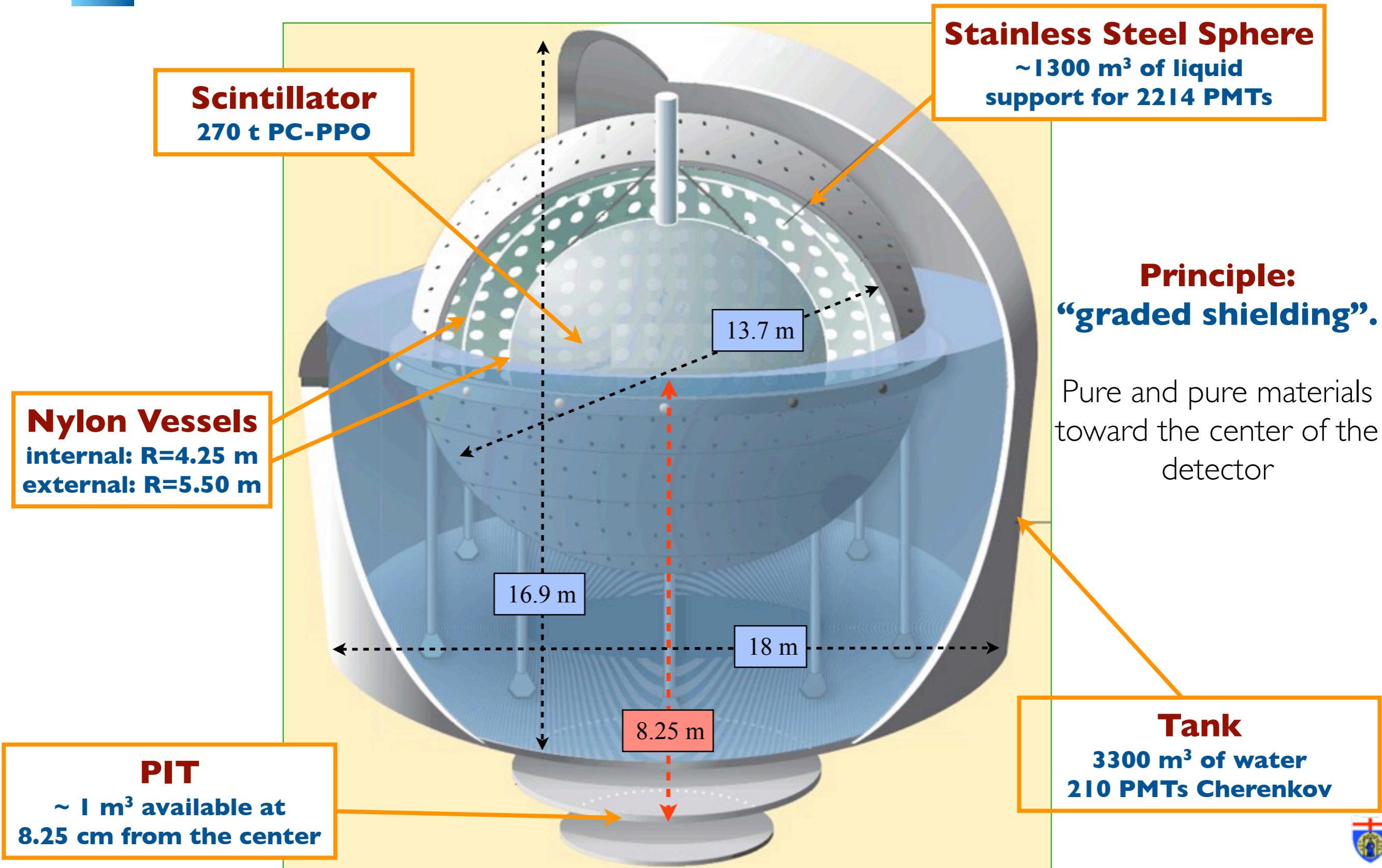
- **sub-MeV ν_e detection:** proved by **^7Be** and **pep**
- sensitivity: as low as a few cpd/100 t
 - **pep:** $3.1 \pm 0.6(\text{stat}) \pm 0.3(\text{sys})$ cpd/100 t

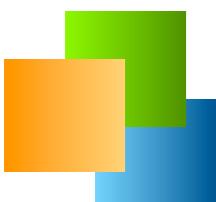
- **$\bar{\nu}_e$ detection:** proved by **geo-neutrinos**
- total background:
 - **<< 1 events / year** in the whole volume





The detector

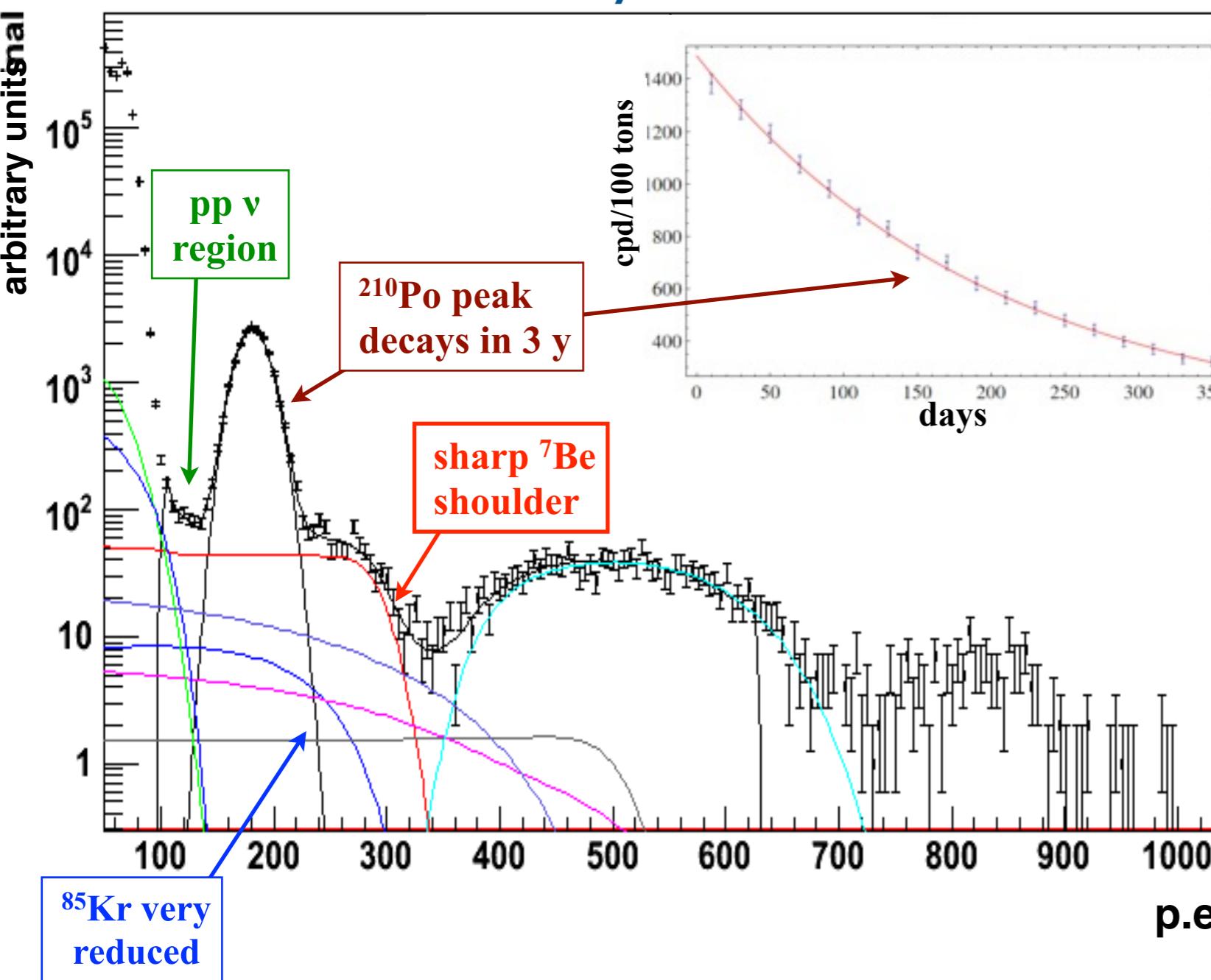




Borexino background today

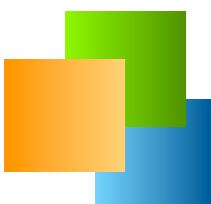
- A significant **purification** effort done in 2010/2011 to improve purity further
 - Very effective on ^{85}Kr , good on ^{210}Bi , excellent for ^{238}U and ^{232}Th

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
 - < $9.7 \cdot 10^{-19}$ g/g
- ^{232}Th
 - < $2.9 \cdot 10^{-18}$ g/g





SOX: Short distance ν_e Oscillations with BoreXino

● 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
- Check of $g_V e g_A$ at low energy

ERC Ideas approved

European Research Council
ERC-2012-AdG

Advanced Investigator Grant
SOX: Short distance neutrino Oscillations with BoreXino

SEVENTH FRAMEWORK PROGRAMME

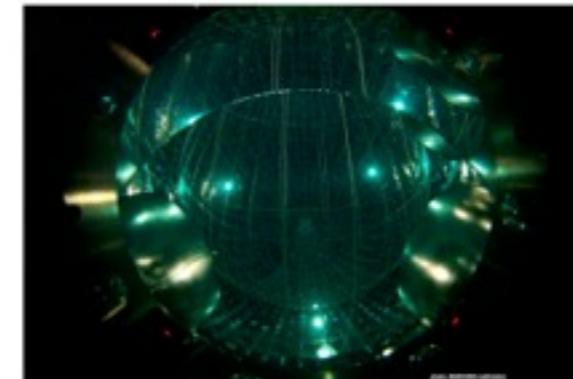
*"Ideas" specific programme
European Research Council*

Grant agreement for Advanced Grant

Annex I - Description of Work

● Technology

- Neutrino source: **^{51}Cr**
- Anti-neutrino source: **^{144}Ce**



● Project

- SOX-A - **^{51}Cr external**
- SOX-B - **^{144}Ce external**
- SOX-C - **^{144}Ce internal**

Project acronym: SOX

Project full title: Short distance neutrino Oscillations with BoreXino

Grant agreement N. 320873

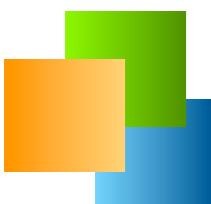
Duration: 60 months

Date of preparation of annex I: 23 - 10 - 2012

Principal Investigator: Prof. Marco Pallavicini

Host Institution: Istituto Nazionale di Fisica Nucleare (INFN) and Laboratori Nazionali del Gran Sasso (LNGS)





A long standing idea

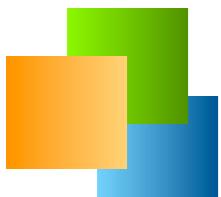
- The idea to deploy a **source in Borexino** dates back to the beginning of the project
 - Successfully implemented by Gallex (LNGS) and SAGE (Russia)
 - Recently, revised and re-proposed by many authors to search for **sterile neutrinos**
- N.G. Basov, V. B. Rozanov, JETP 42 (1985)
Borexino proposal, 1991 (Sr90)
J.N.Bahcall,P.I.Krastev,E.Lisi, Phys.Lett.B348:121-123,1995
N.Ferrari,G.Fiorentini,B.Ricci, Phys. Lett B 387, 1996 (Cr51)
I.R.Barabanov et al., Astrop. Phys. 8 (1997)
Gallex coll. PL B 420 (1998) 114 **Done** (Cr51)
A.Ianni,D.Montanino, Astrop. Phys. 10, 1999 (Cr51 and Sr90)
A.Ianni,D.Montanino,G.Scioscia, Eur. Phys. J C8, 1999 (Cr51 and Sr90)
SAGE coll. PRC 59 (1999) 2246 **Done** (Cr51 and Ar37)
SAGE coll. PRC 73 (2006) 045805
C.Grieb,J.Link,R.S.Raghavan, Phys.Rev.D75:093006,2007
V.N.Gravrin et al., arXiv: nucl-ex:1006.2103
C.Giunti,M.Laveder, Phys.Rev.D82:113009,2010
C.Giunti,M.Laveder, arXiv:1012.4356
SOX proposal - ERC 320873 - Feb. 2012 - approved Oct. 2012

a very incomplete list!

See White Paper and references therein:

arxiv:
1204.5379



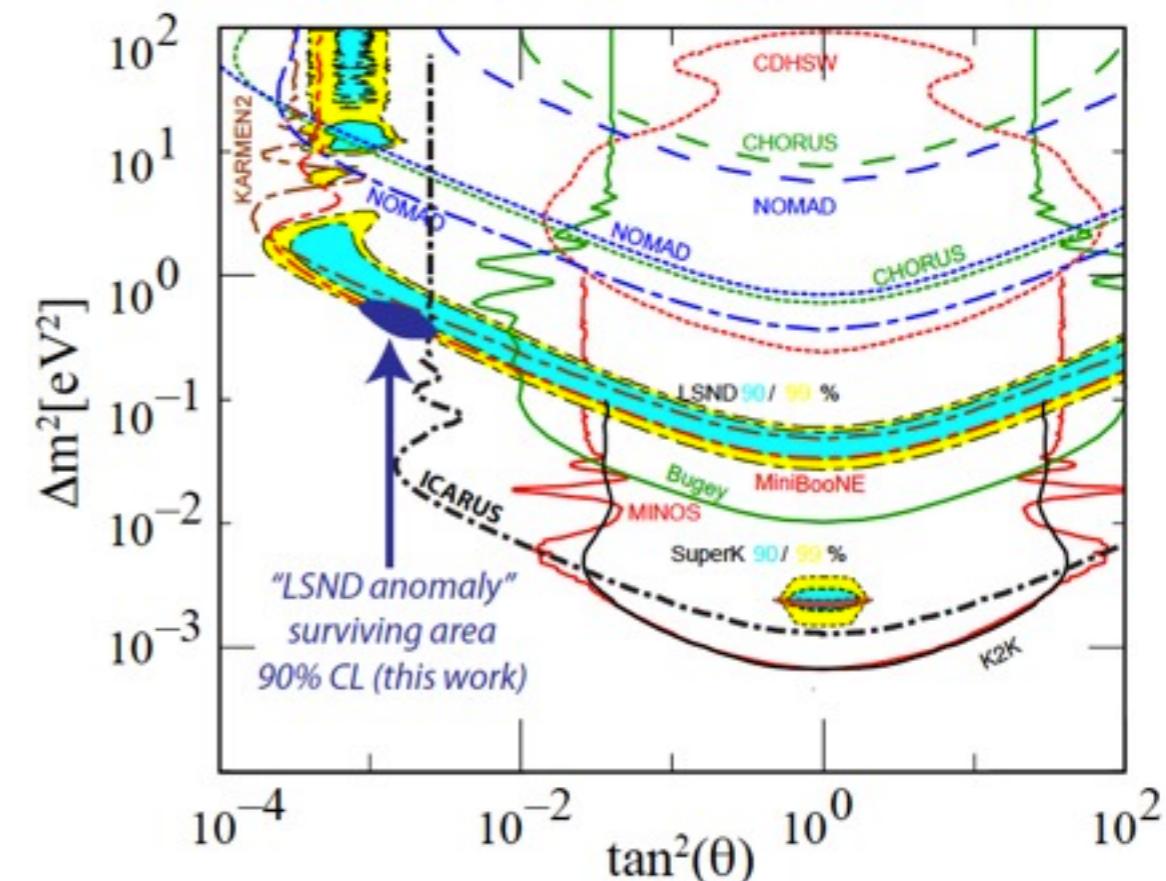


SOX: the Science case

- “anomalies”: a few experiments deviate from the standard 3-flavor mixing at $L/E \sim 1 \text{ m/MeV}$

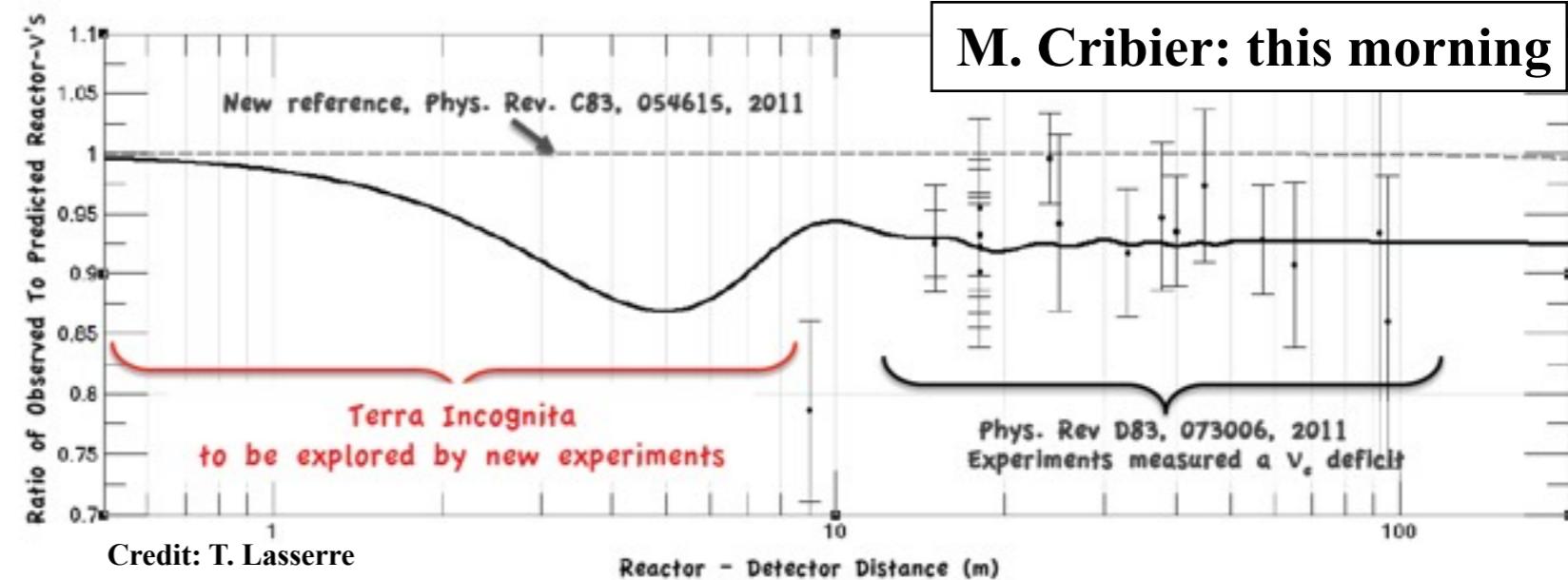
- **LSND 2001**

- Clear excess: $87.9 \pm 22.4 \pm 6.0$ (3.8σ)
- Partially confirmed by MiniBoone
- Allowed region restricted by ICARUS to $\Delta m^2 \sim 1 \text{ eV}^2$ (see R. Sulej talk and [1209.0122v4](#))



- **Gallium and Reactor anomalies:**

- deficit in observed flux at short distances
- $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

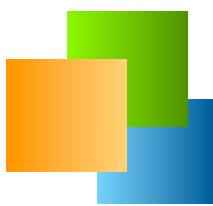


- **Astrophysics:**

- **WMAP 9 years:** $N_{\text{eff}} = 3.84 \pm 0.40$ (arXiv:1212.5226v2)
- weaker evidence than previous results
- Planck is coming!

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}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$



SOX: Three Phases

- **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**

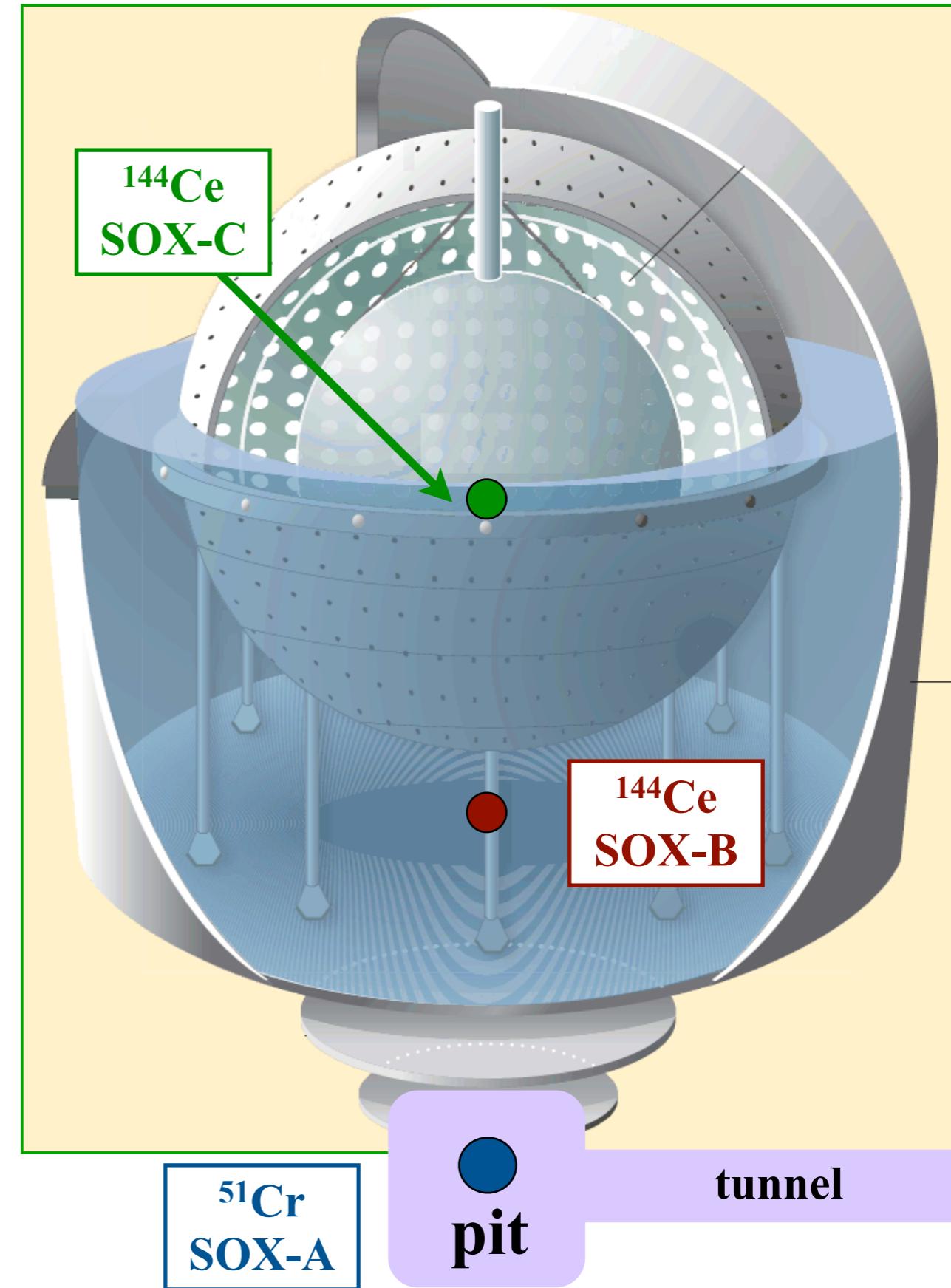
- ^{51}Cr source in pit beneath detector
- **8.25 m** from center **[2015/2016]**

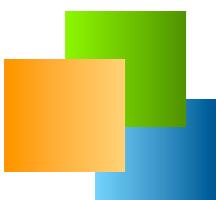
- **SOX-B**

- $^{144}\text{Ce}-^{144}\text{Pr}$ source in W.T.
- PPO everywhere to enhance sensitivity
- **7.15 m** from center **[2015/2016 ?]**

- **SOX-C**

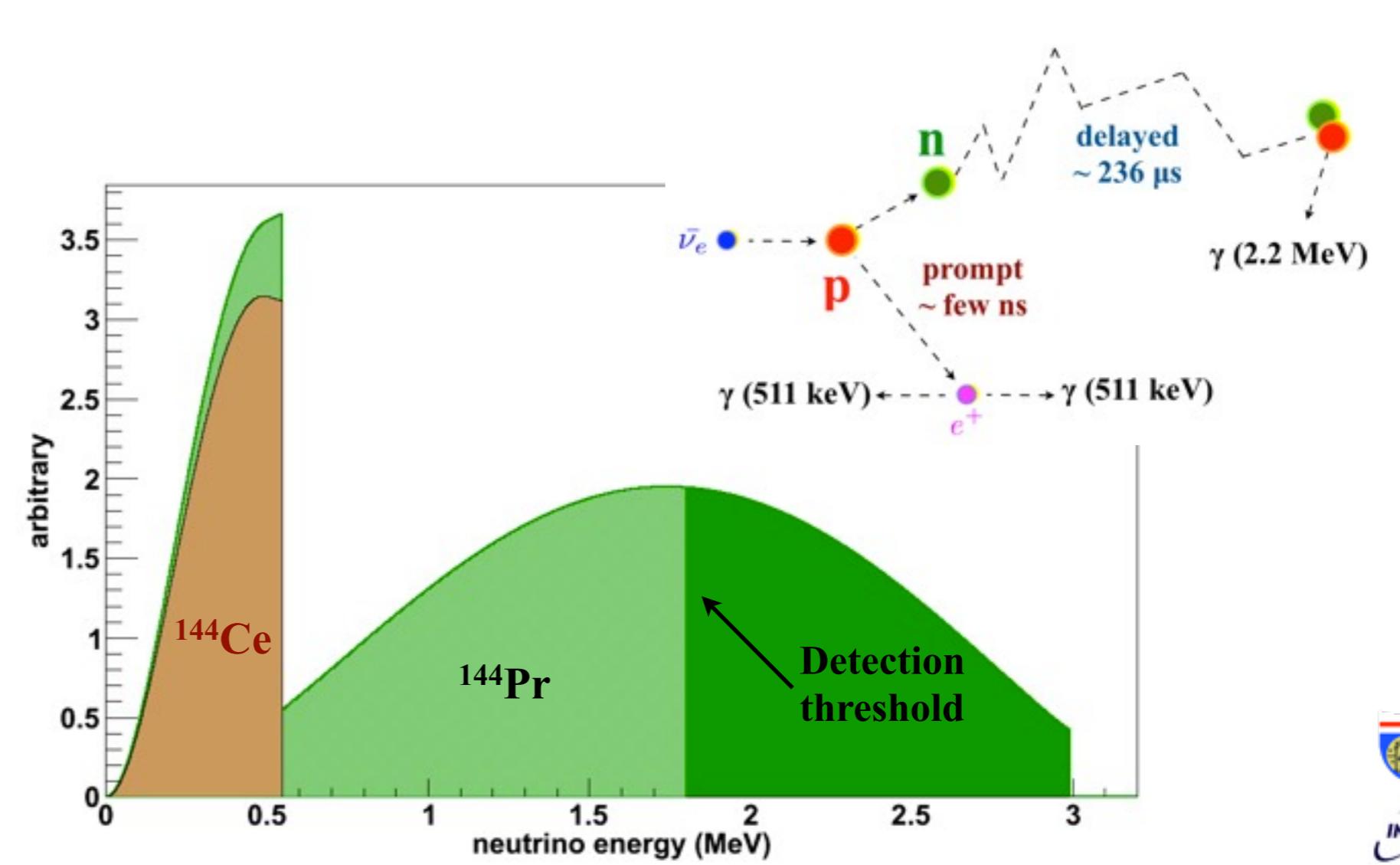
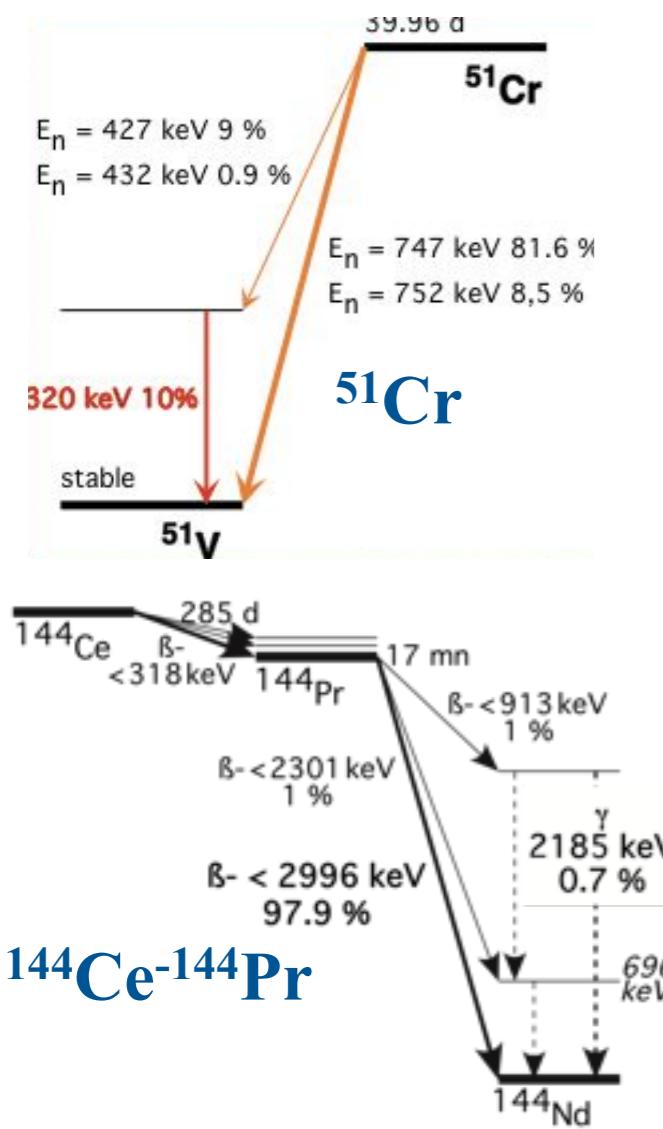
- $^{144}\text{Ce}-^{144}\text{Pr}$ source in the center
- **Only after the end of solar program**
- More effort and more time
[>2016]





Artificial neutrino sources

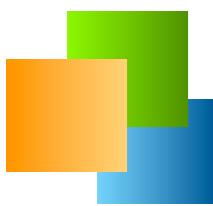
Source	Production	τ (days)	Decay mode	Energy [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr $\bar{\nu}_e$	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \gtrsim 5 \cdot 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$	40	EC γ 320 keV (10%)	0.746	0.011	0.19
$^{144}\text{Ce}-^{144}\text{Pr}$ $\bar{\nu}_e$	Chemical extraction from spent nuclear fuel	411	β^-	<2.9975	0.314	7.6





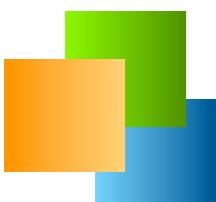
The tunnel beneath the detector





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
 - The relatively short life-time of ^{51}Cr yield 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 e 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



Geometry 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**

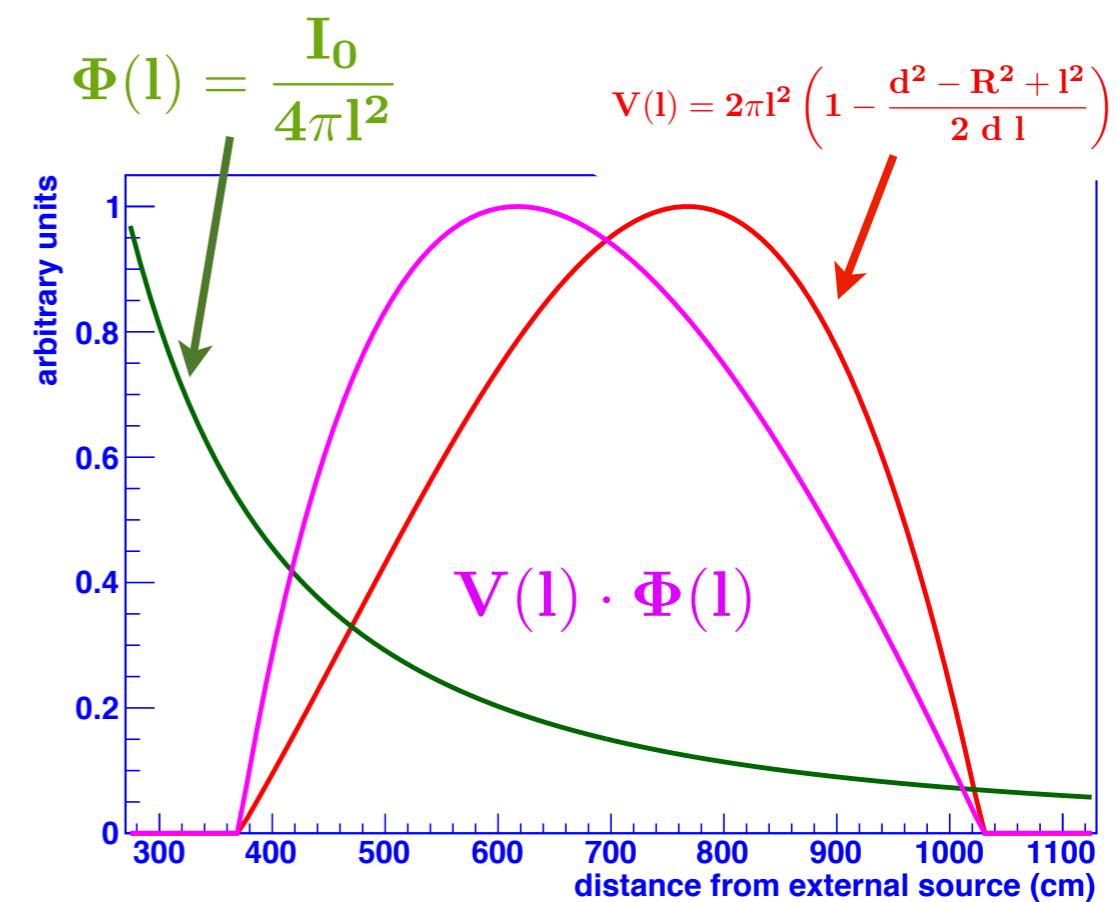
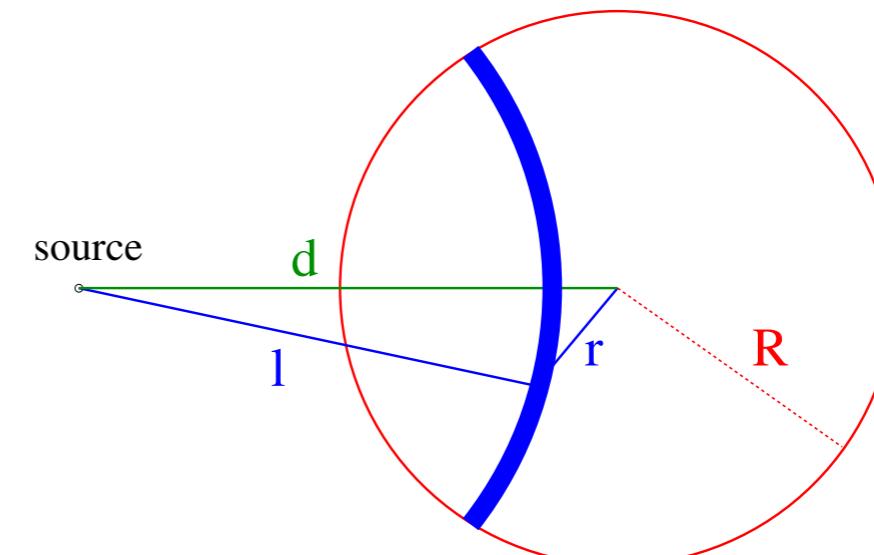
$$\Phi(l) = \frac{I_0}{4\pi l^2} \tau e^{-\frac{t_D}{\tau}} \left(1 - e^{-\frac{t}{\tau}} \right)$$

- **Oscillations (one sterile)**

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

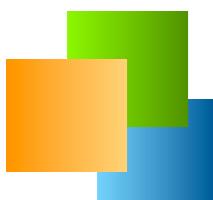
- The number of ν_e - e^- events at distance l from the source, with detection threshold T_1 and maximum recoil energy T_2 :

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



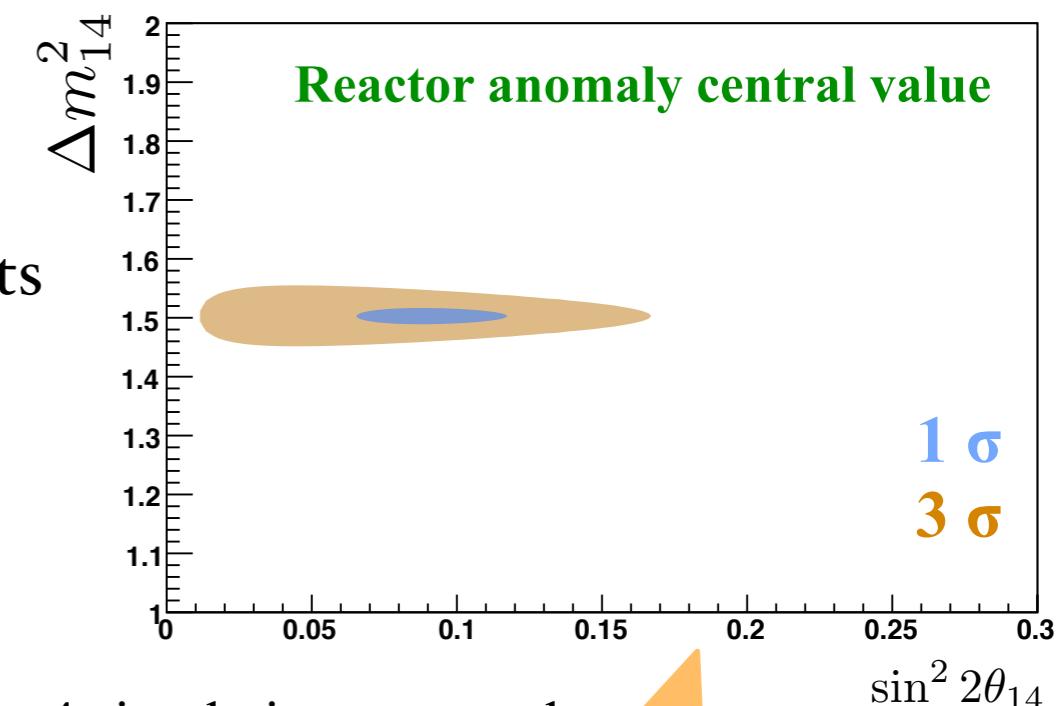
N.B.: The distribution of events is not uniform even without oscillations



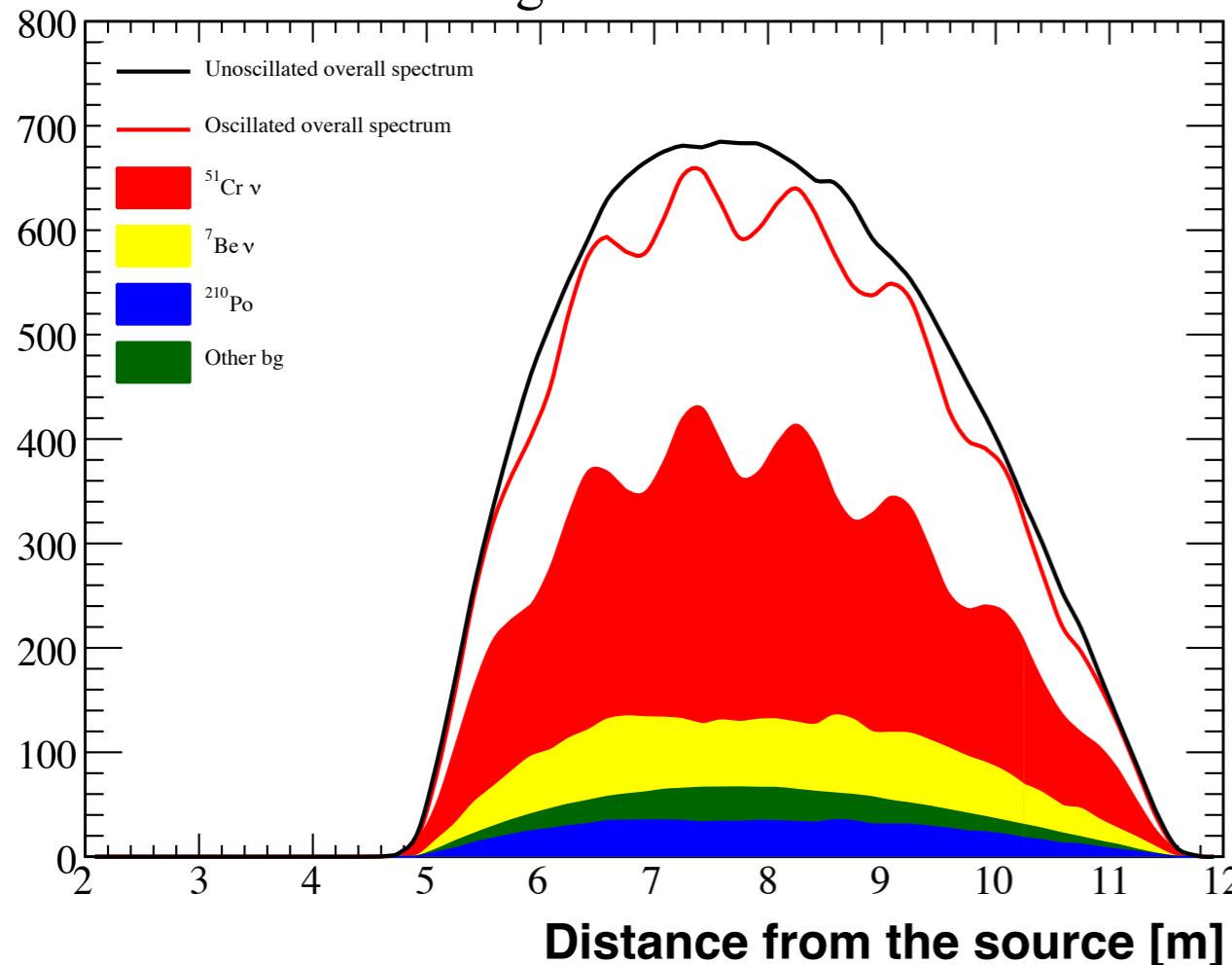


Example for SOX-A

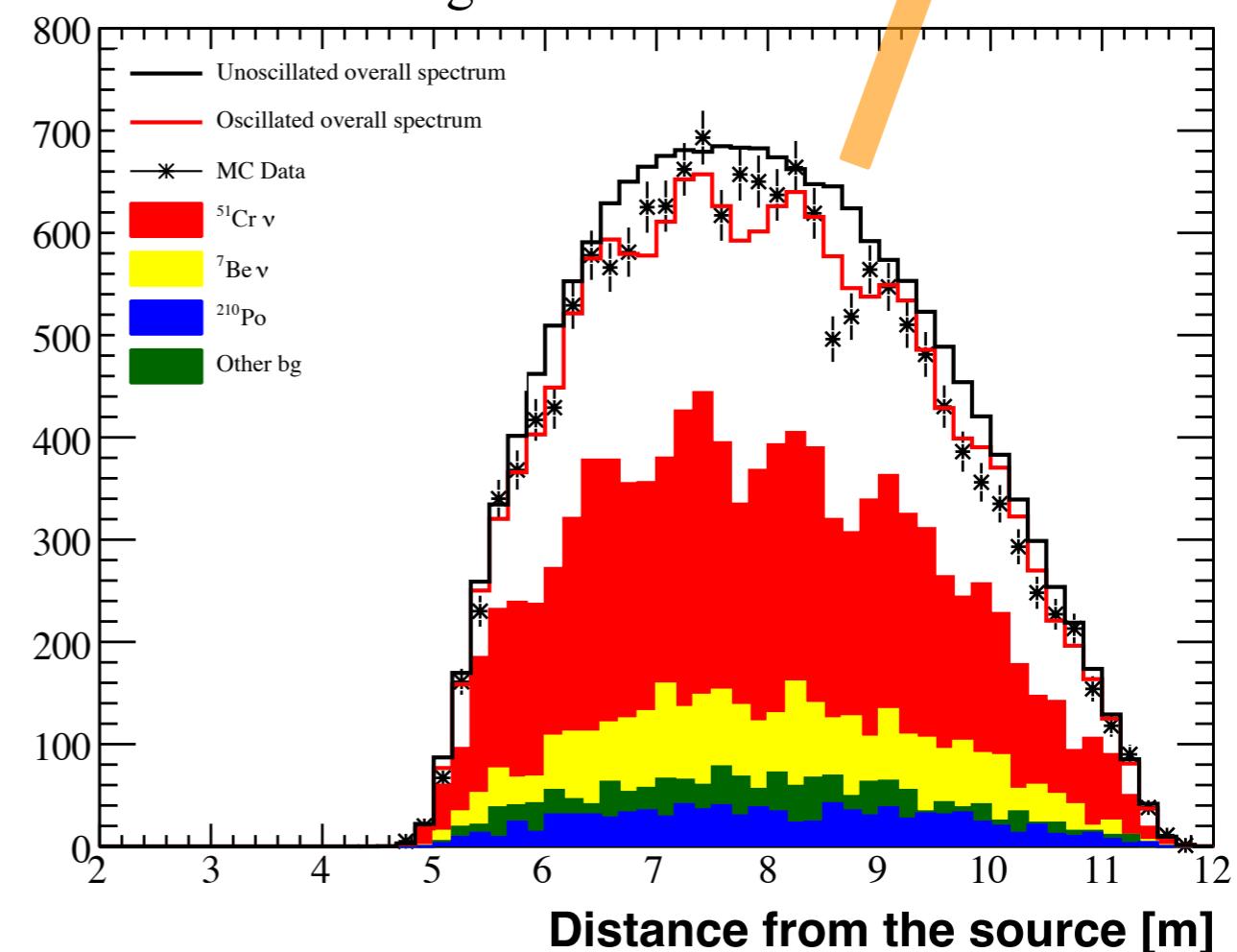
- Waves may be detected in the distribution of events as a function of the distance from source
- With waves, both parameters can be measured

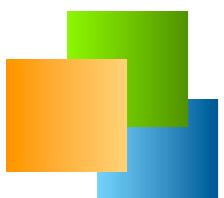


Ideal curves
Borexino Background - No fluctuations

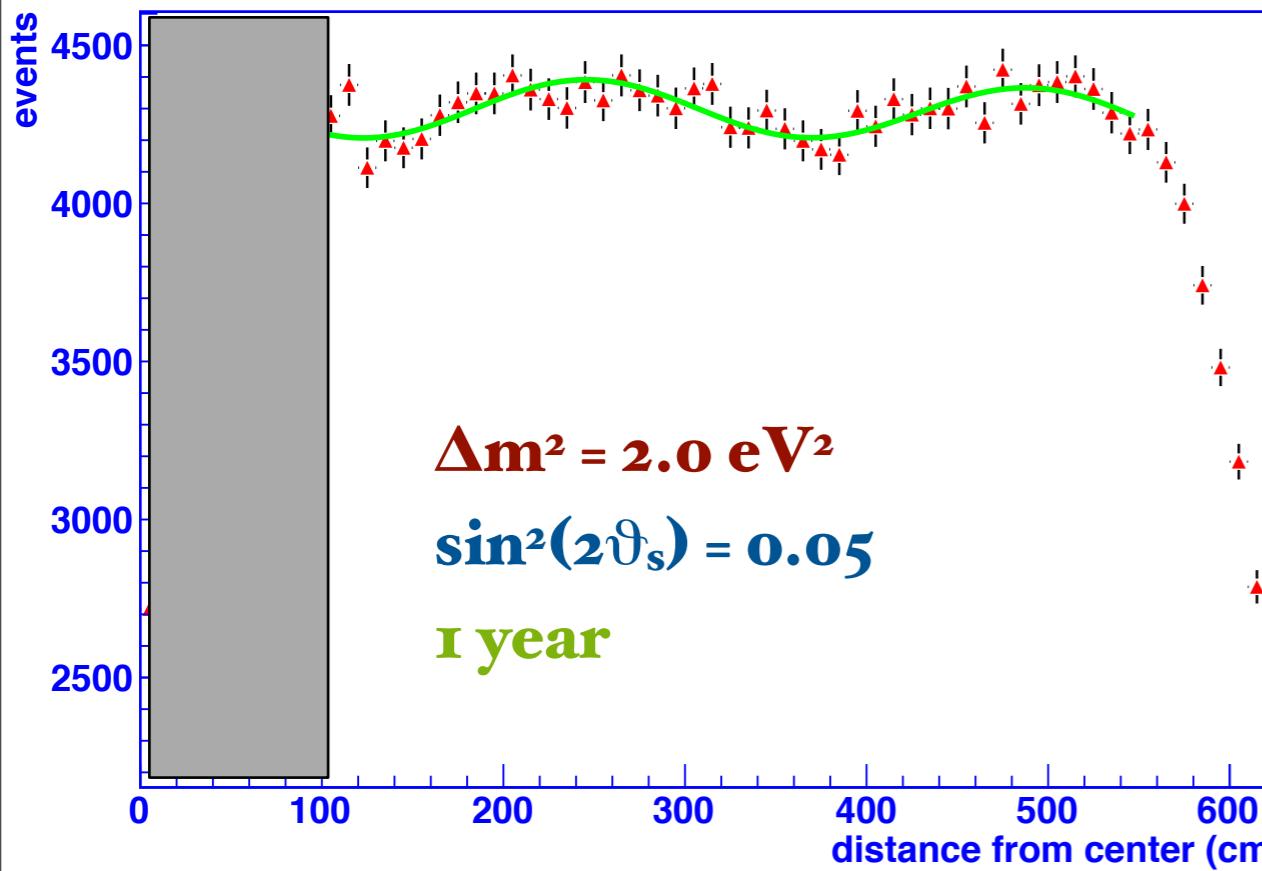
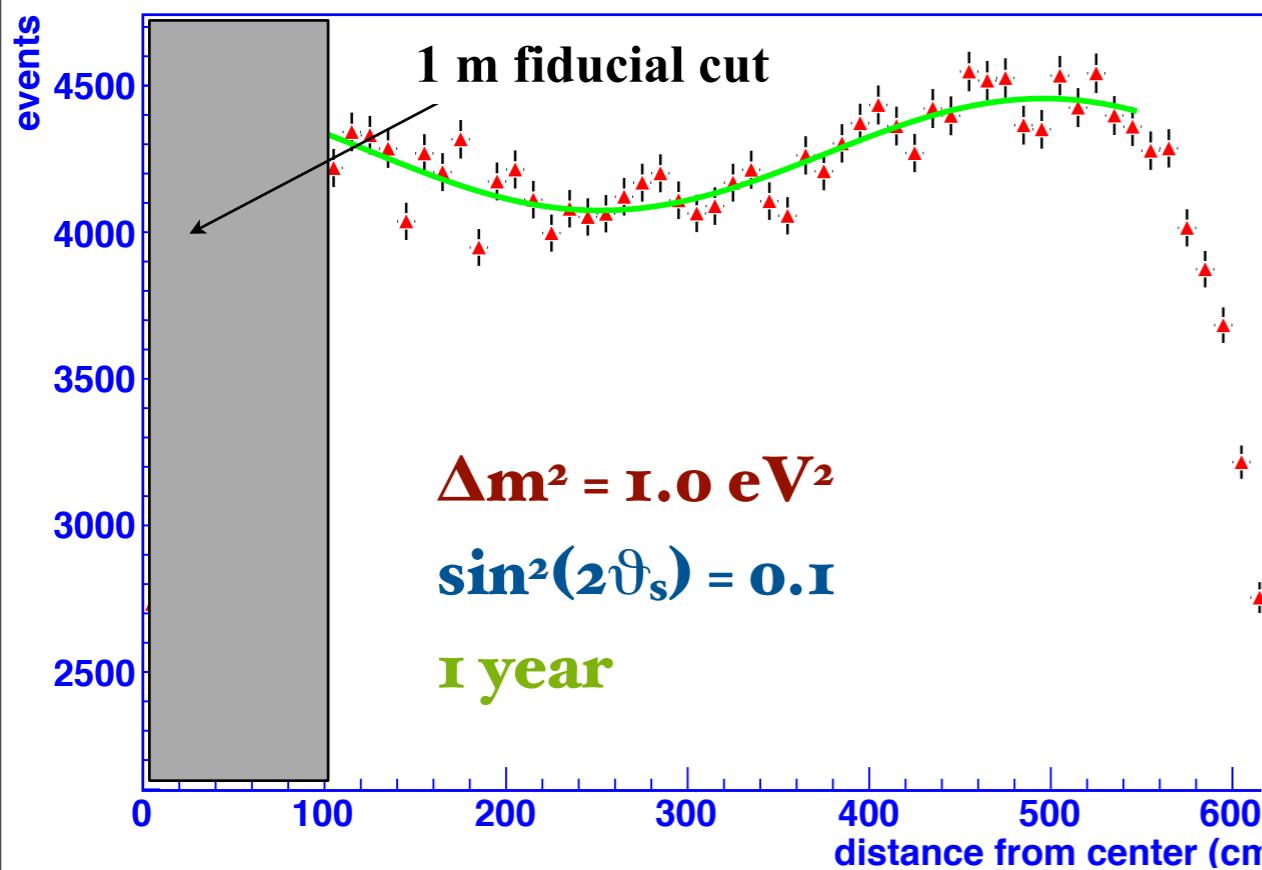


Full Geant4 simulation - example
Borexino Background



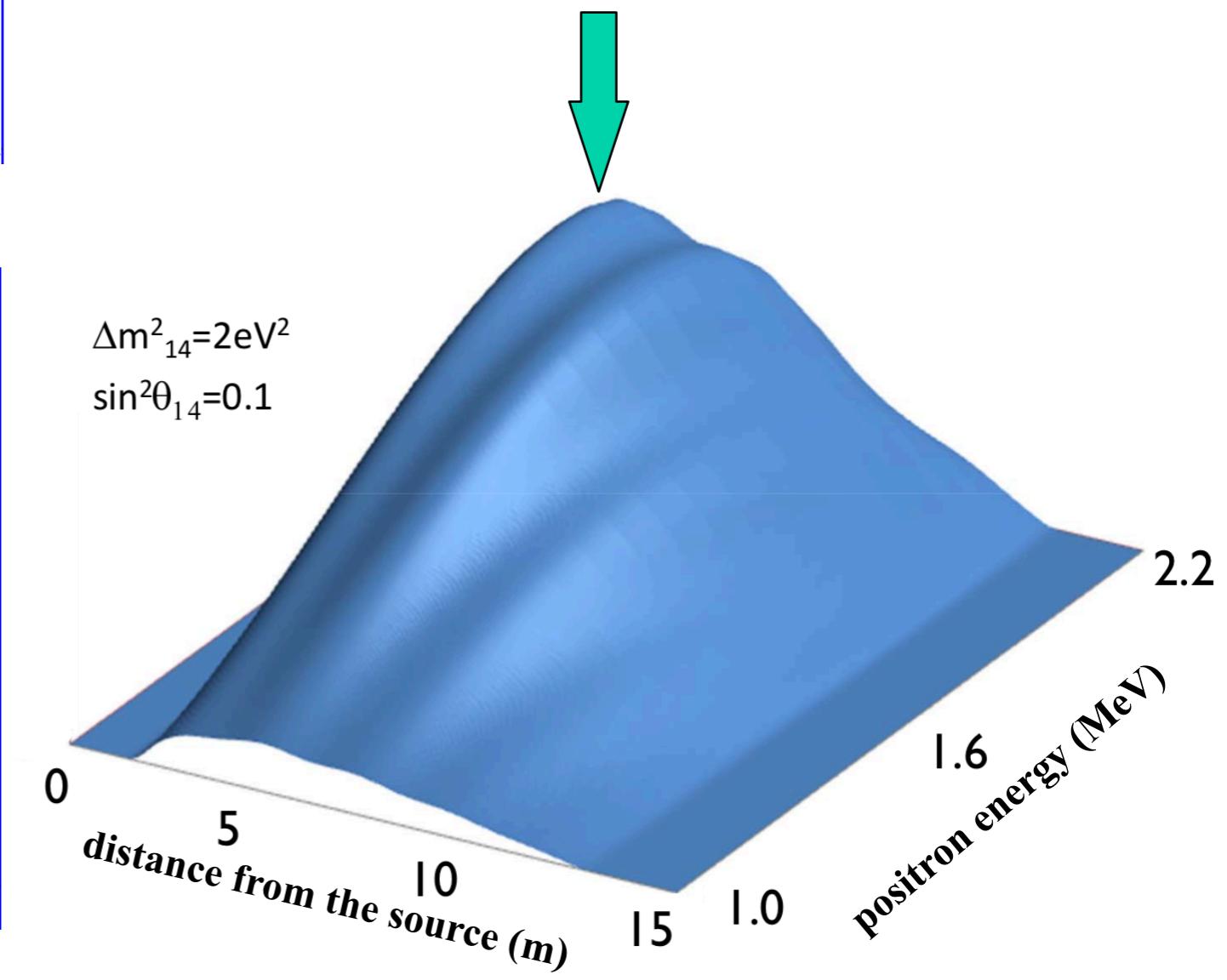


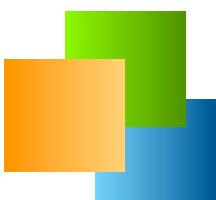
Waves with $\bar{\nu}_e$ and space-energy correlation



Space - Energy correlation

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





SOX-A sensitivity

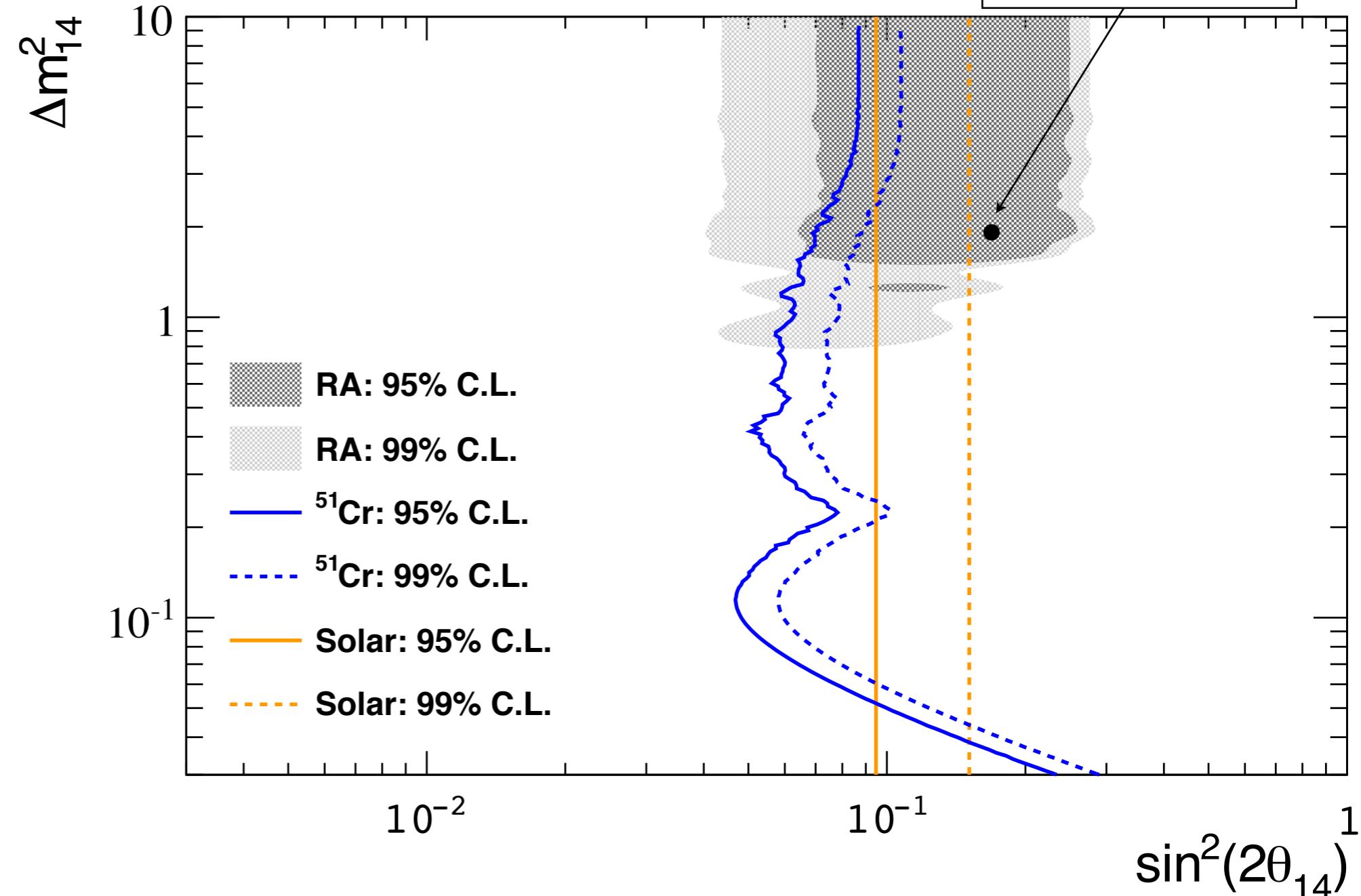
- **SOX-A:**

- **51Cr** source at **8.25 m** from the center

- **10 MCi**

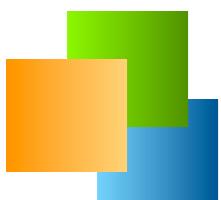
- 1% precision in source activity

- 1% in FV determination



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

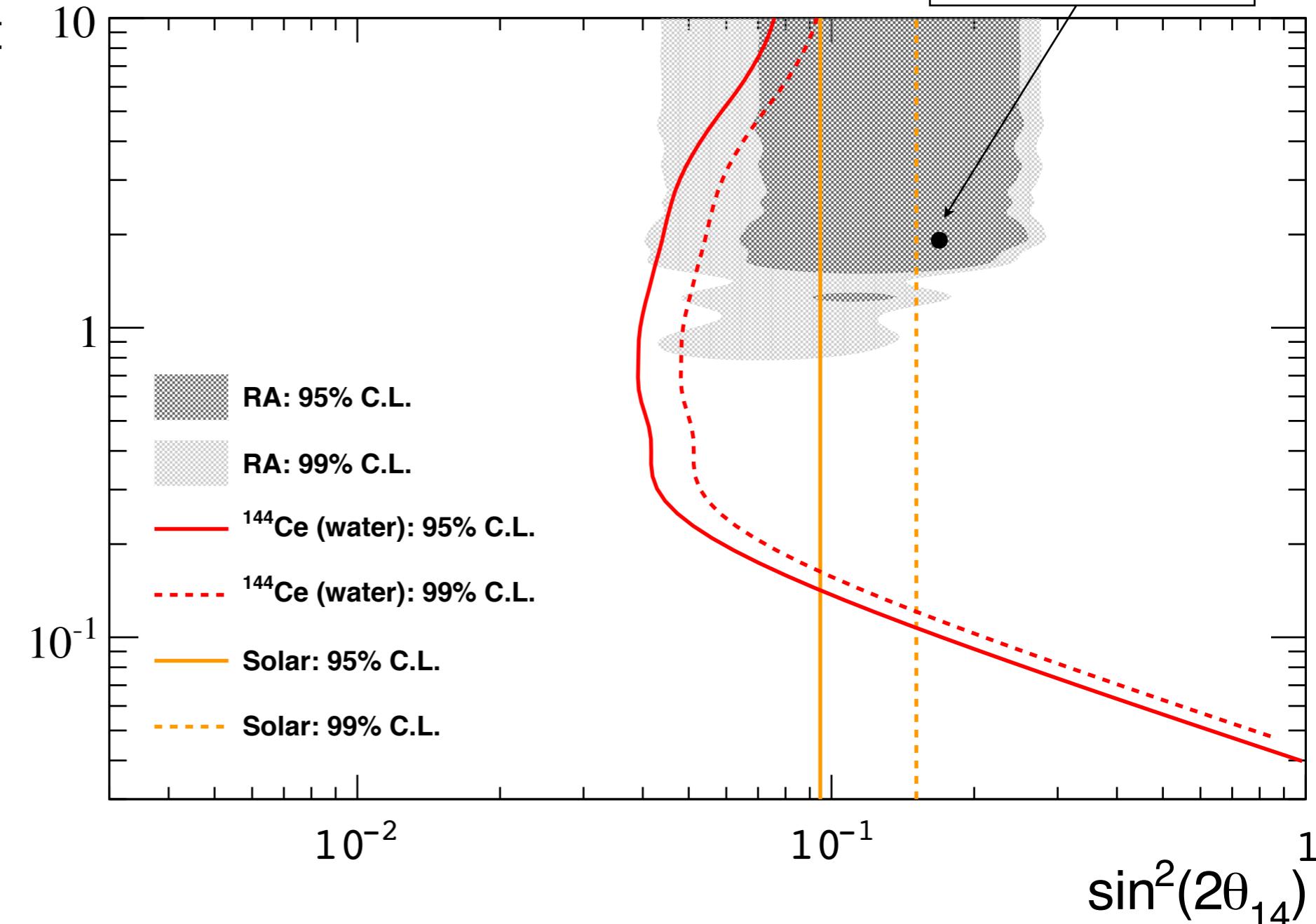




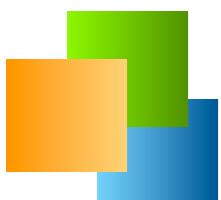
SOX-B sensitivity

- **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



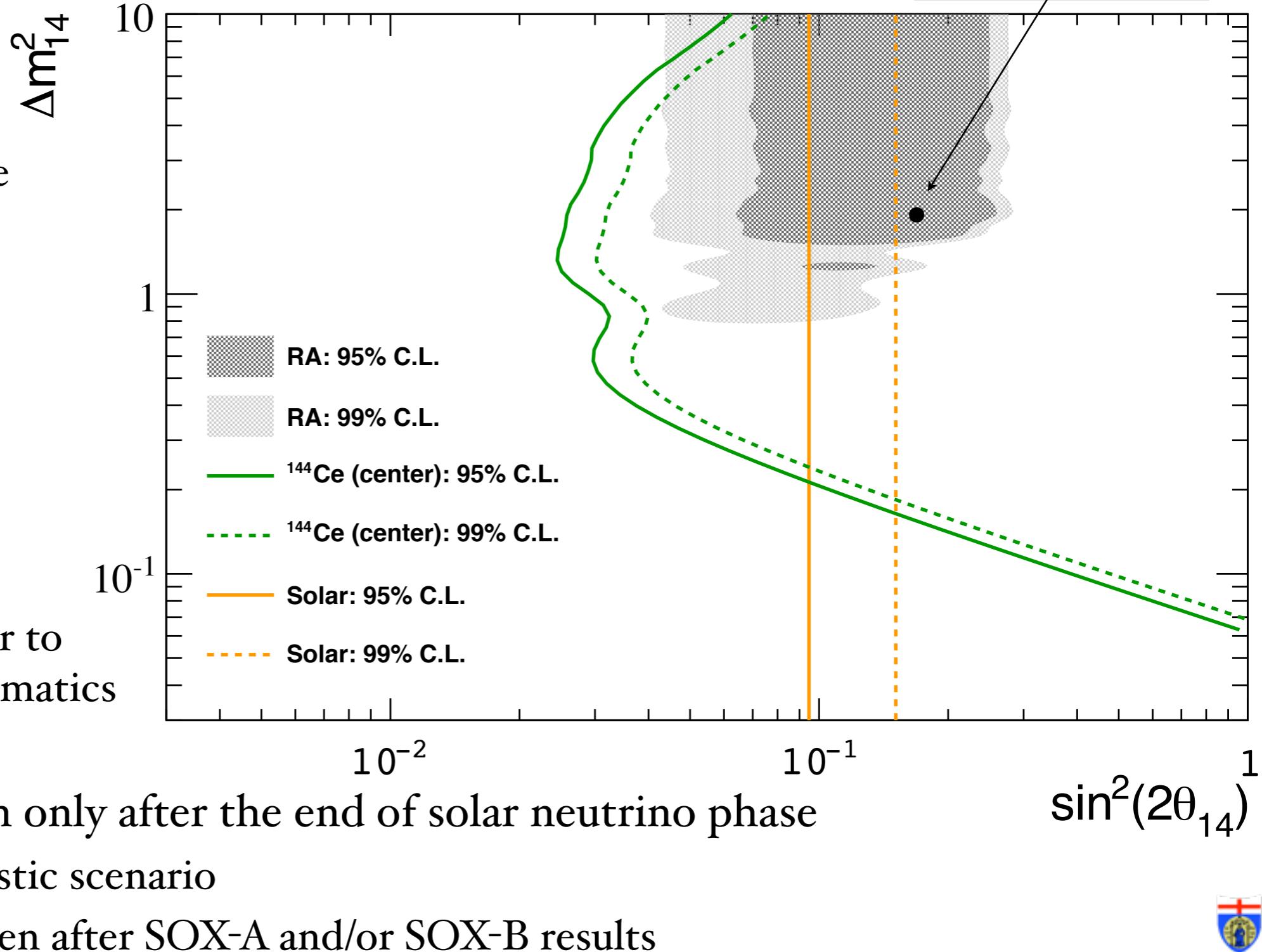
- SOX-B can happen any time during next solar neutrino phase
- 2015 is a realistic scenario - 1 y of data taking



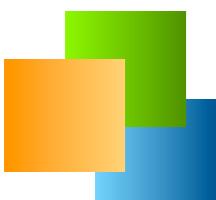
SOX-C sensitivity

- **SOX-C:**

- **^{144}Ce - ^{144}Pr source in the center**
- **$\sim 50 \text{ kCi}$**
- **1.5% precision in source activity**
- **2% bin-to-bin error to include other systematics**

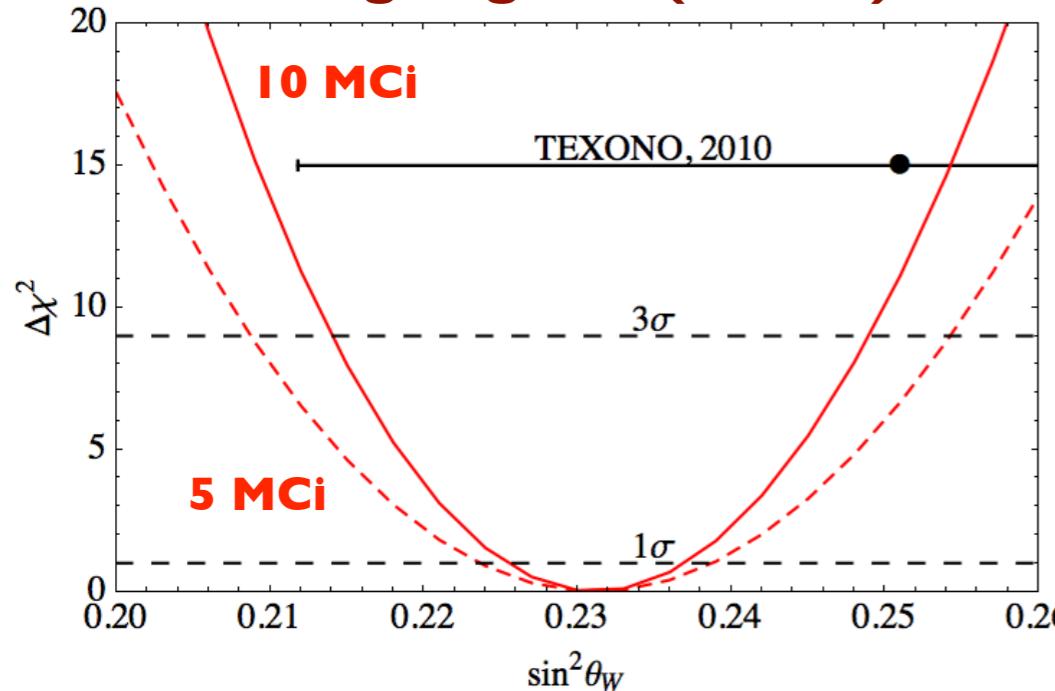


- SOX-C can happen only after the end of solar neutrino phase
 - 2016-2017 is a realistic scenario
 - decision to be taken after SOX-A and/or SOX-B results

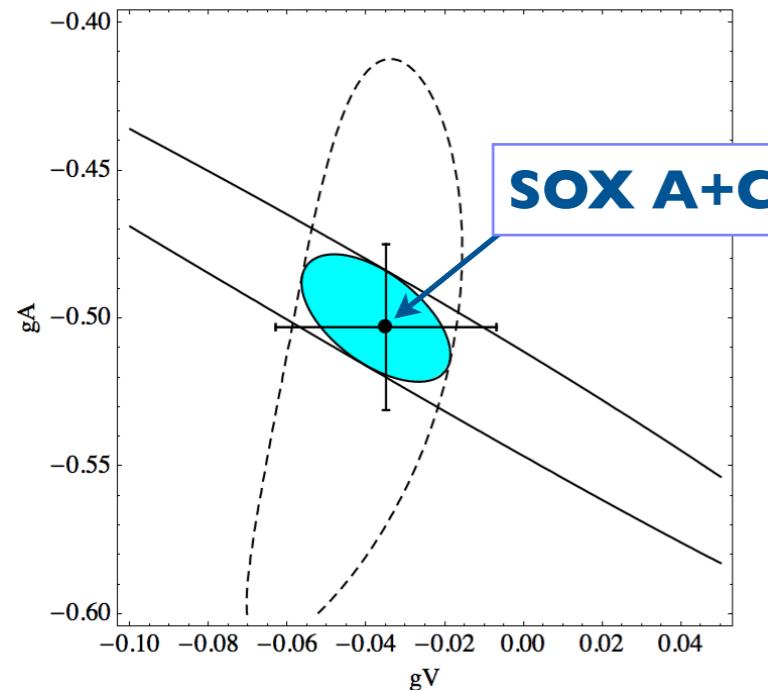
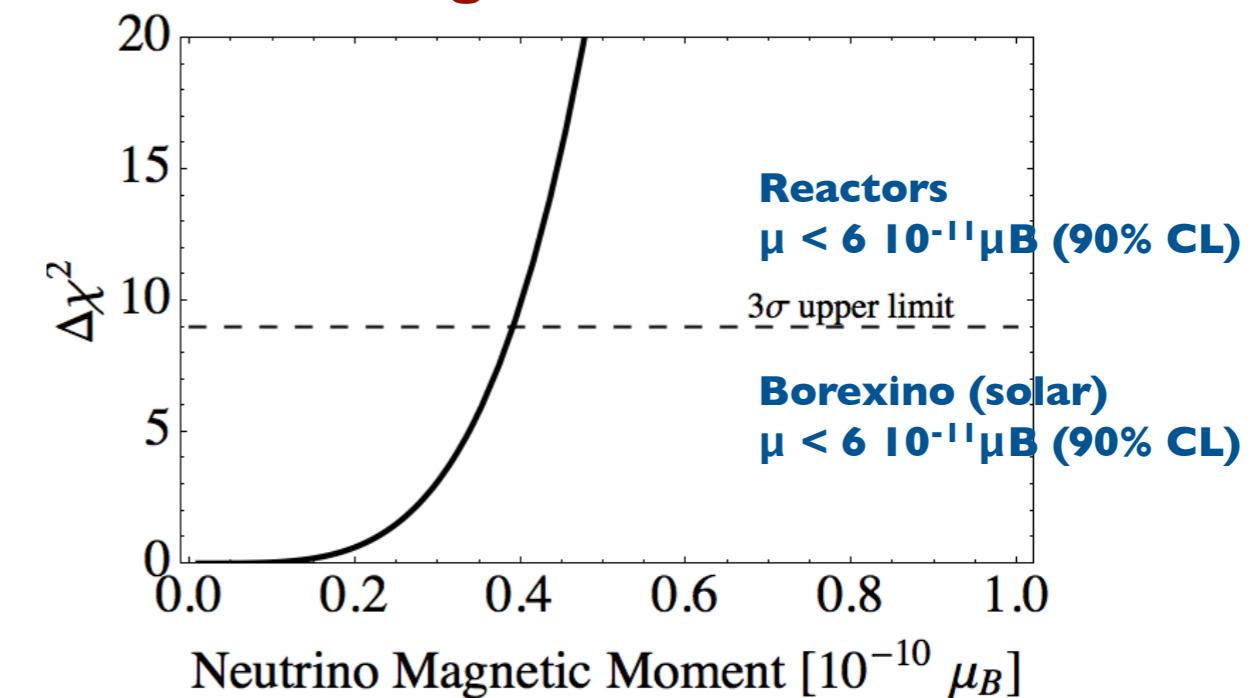


Other low energy neutrino physics

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



Magnetic moment



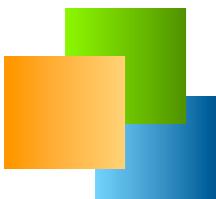
CHARM II (1994)
 ν_μ ES su e- E ~ 10 GeV

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

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

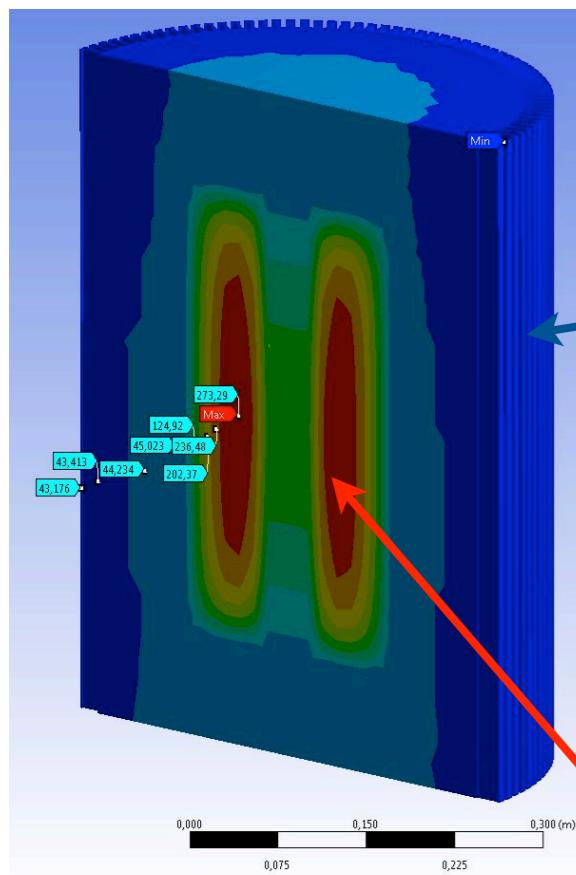
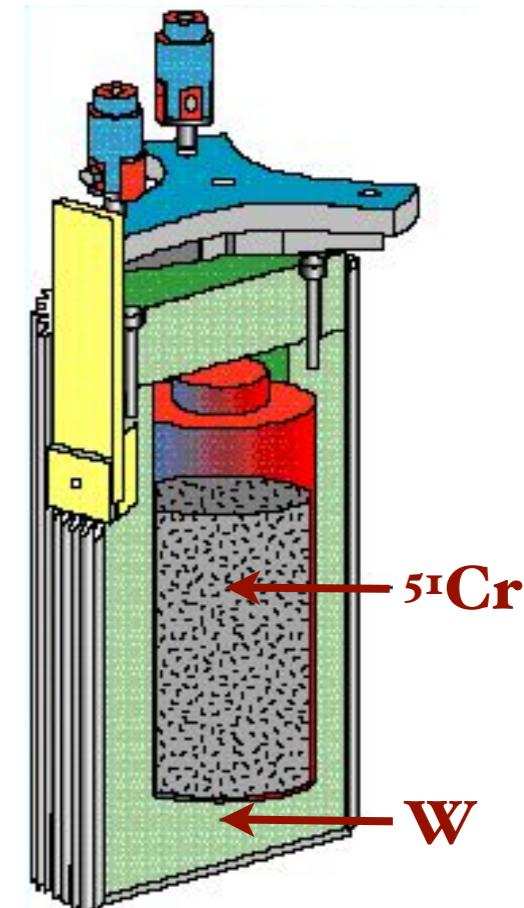
$$g_A^{\nu e} = -0.503 \pm 0.006(\text{stat}) \pm 0.016(\text{syst}).$$





Technology: ^{51}Cr source

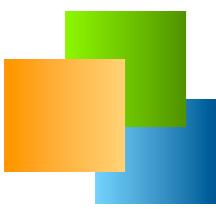
- Concept is the same as in Gallex 1994
 - ~36 kg, ^{50}Cr enriched at 38% irradiated in a high neutron flux reactor (we may use more material)
 - 190 W/MCi from photons
 - ~few $\mu\text{Sv}/\text{h}$ on surface (required < 100)
- BUT: careful thermal design to handle 10 MCi (2 kW)
 - Preliminary studies are encouraging



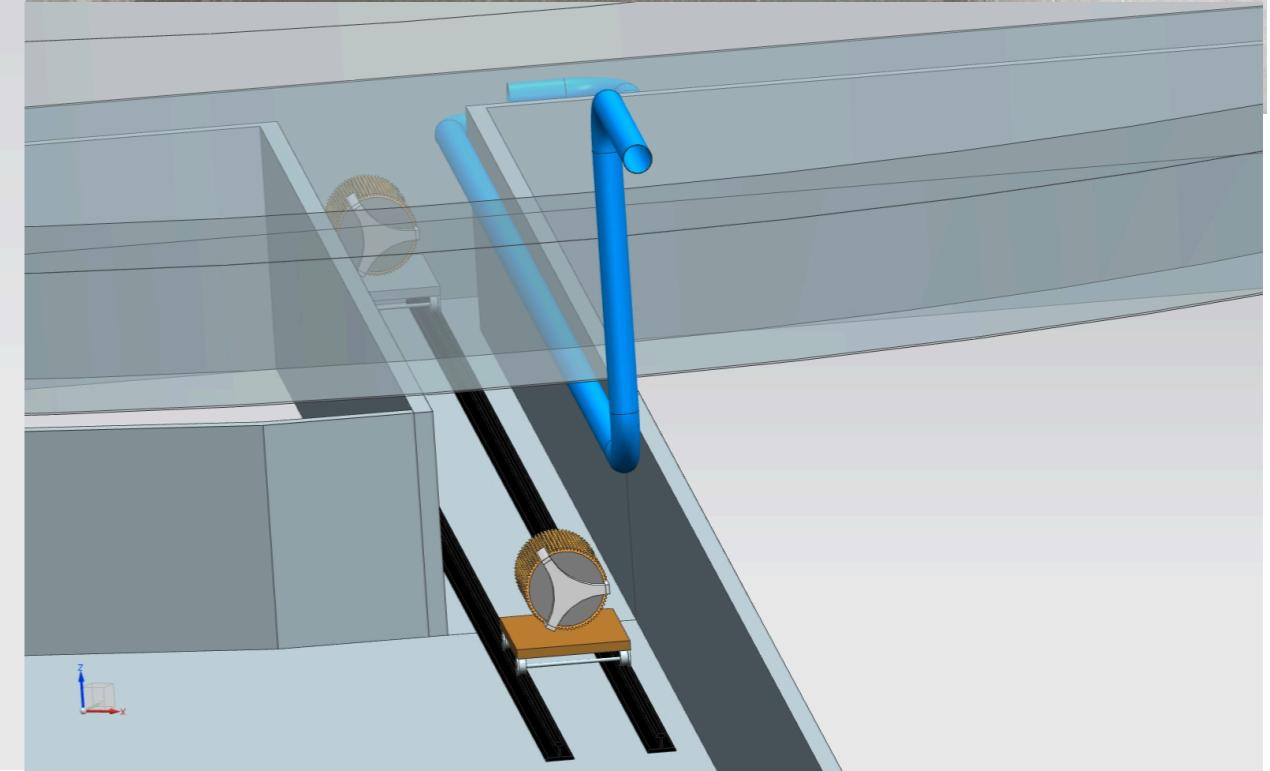
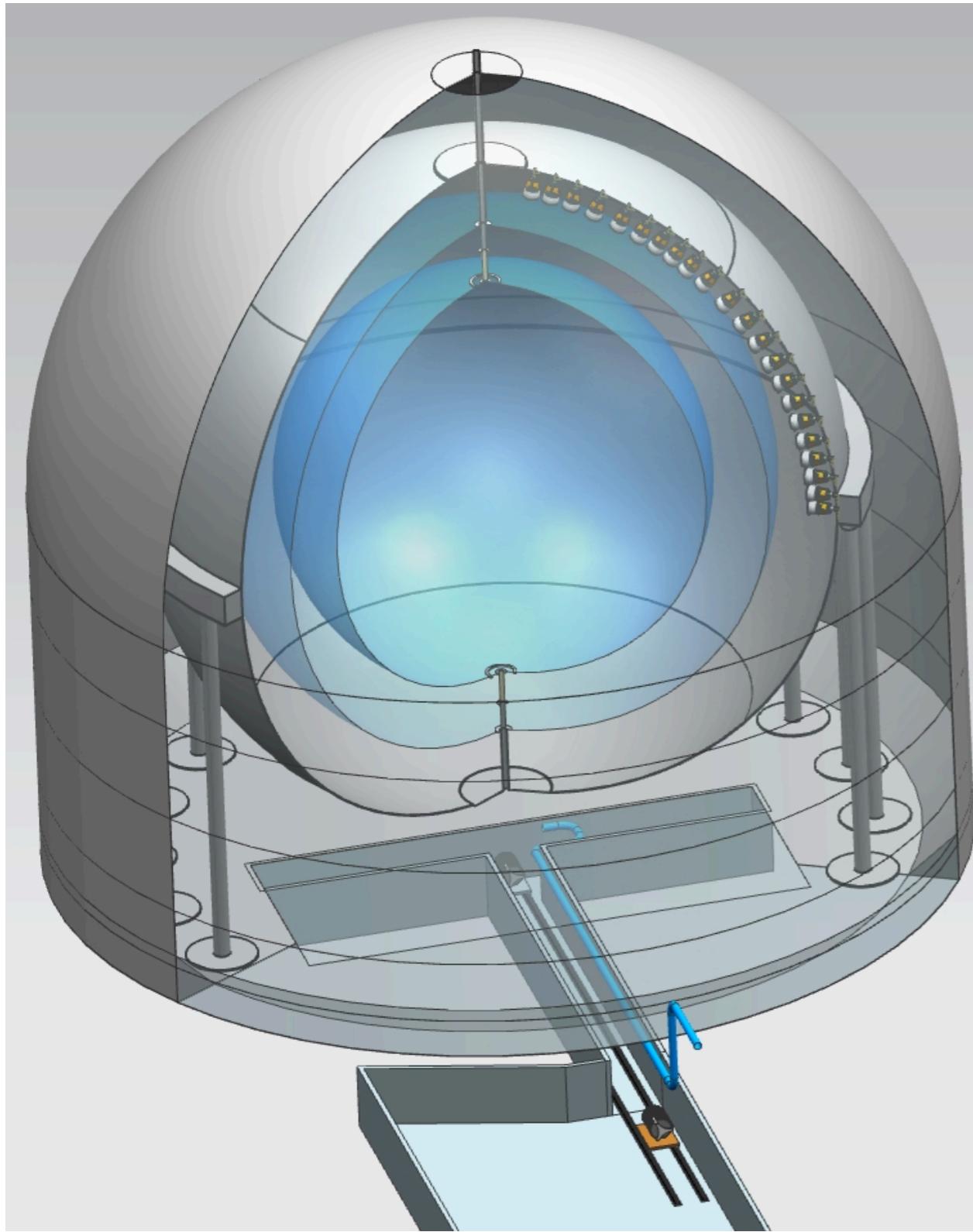
External T must be
acceptable
Current value: $T=90^\circ\text{C}$

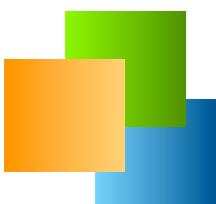
Internal T must be
below syntherization (750°C)
Current value: $T=260^\circ\text{C}$





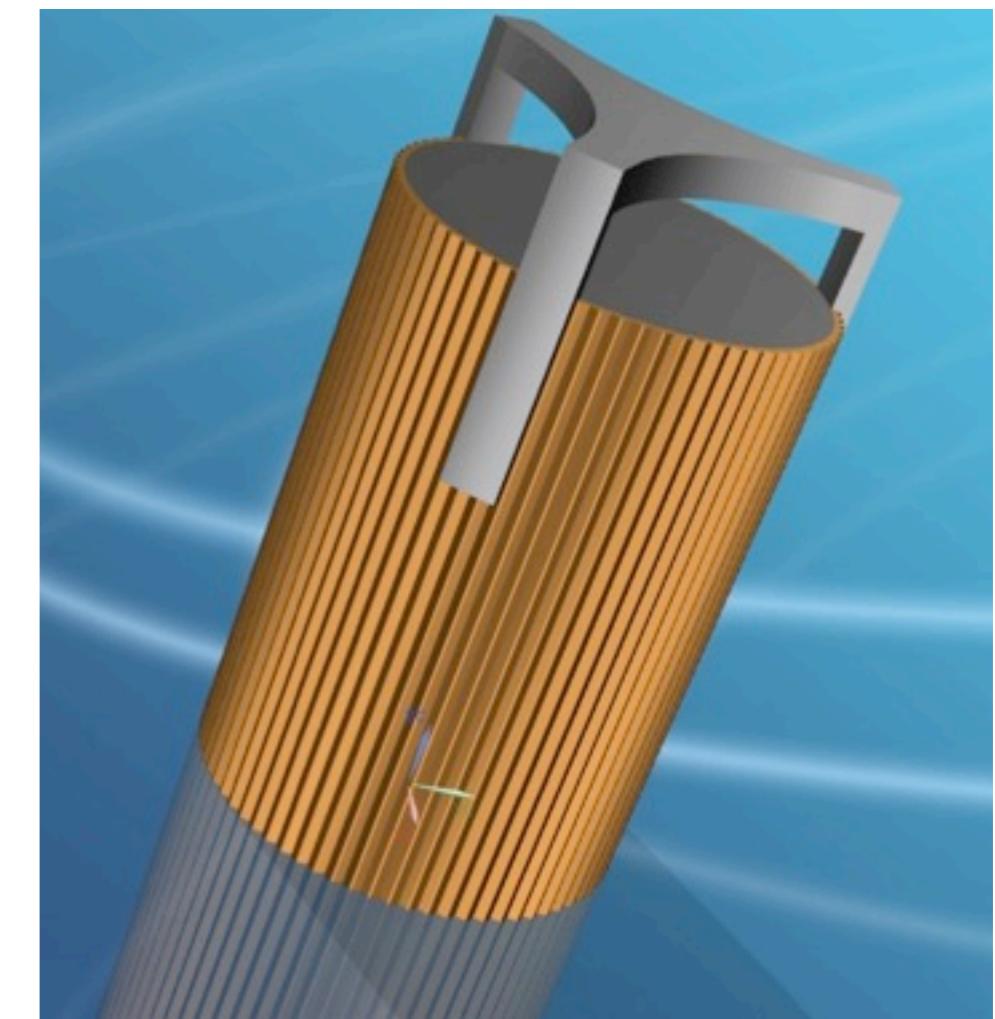
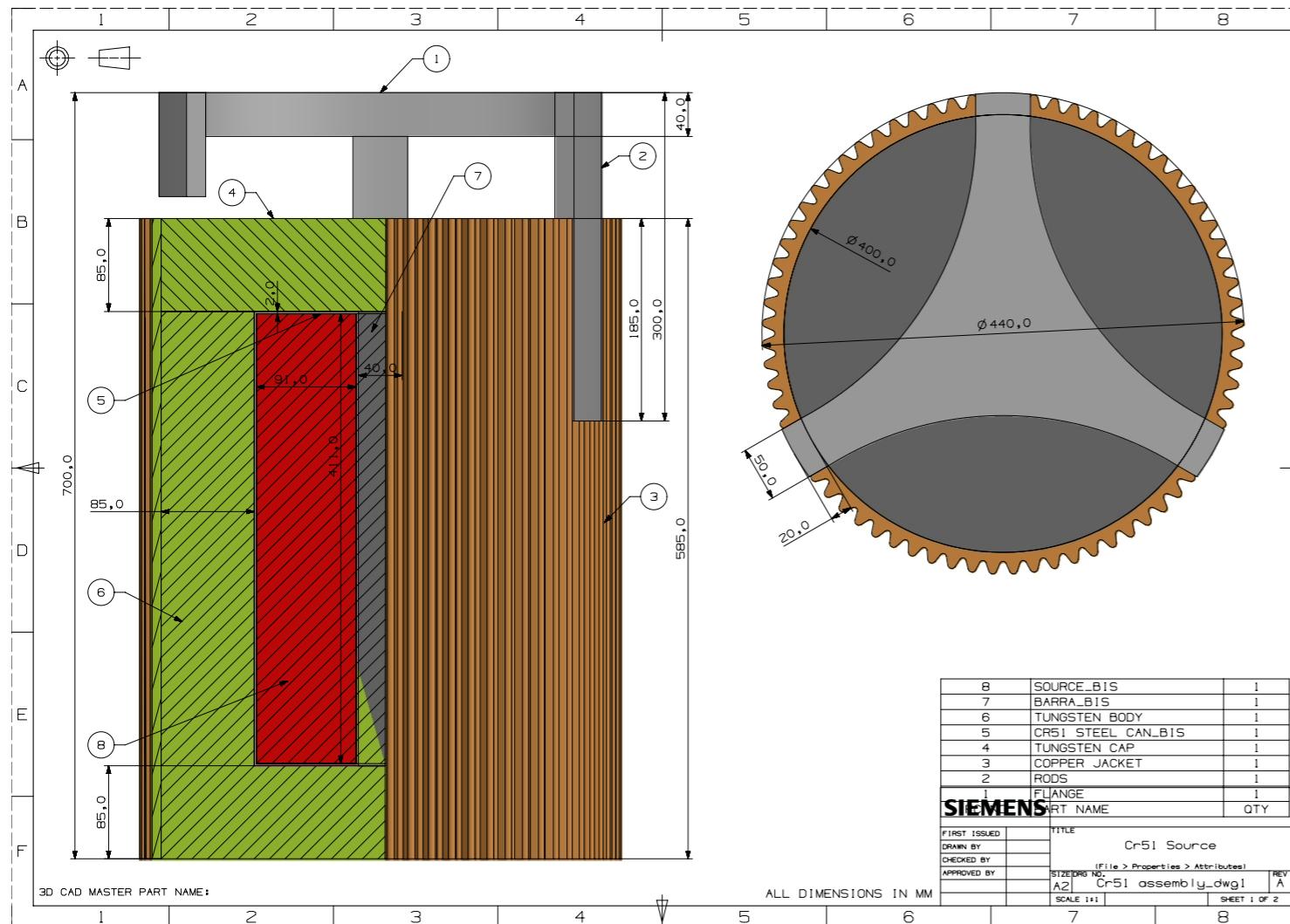
Technology: location for ^{51}Cr source

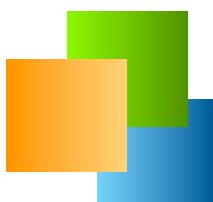




Technology: shielding

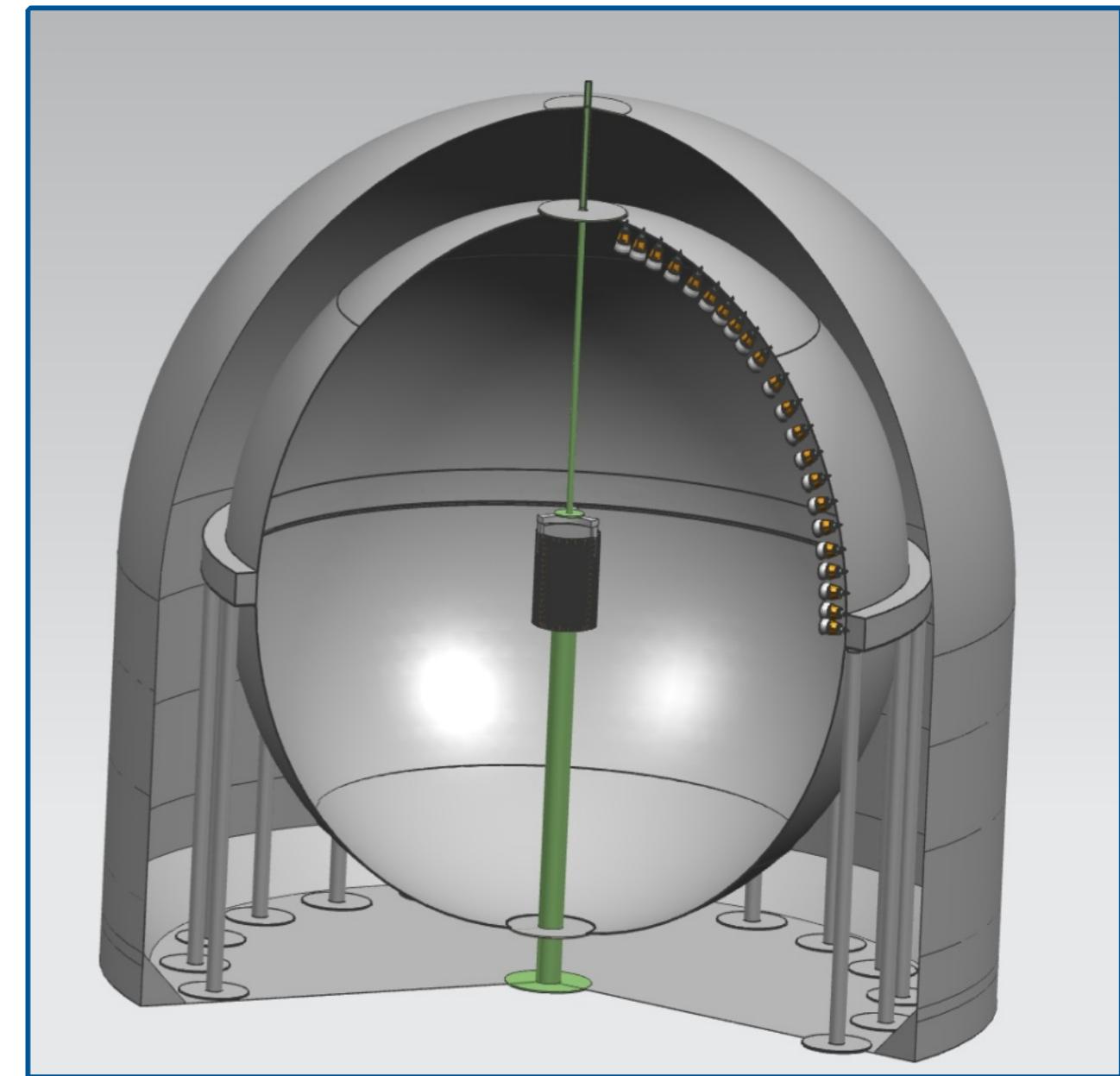
- Material: DENSIMET-I85 (W 97%, 3% Ni-Fe alloy)
- Weight: ~ 2 ton
 - Main problem not from ^{51}Cr (low energy photons) but from impurities at ppm level

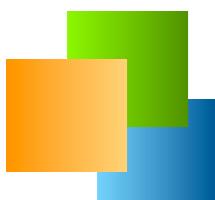




SOX-C: ^{144}Ce source inside detector

- Very **massive** source (see M. Cribrier talk this morning)
 - $\sim 4 \text{ t}$ of shielding
- **DENSIMET (W)** shielding plus ultra-pure **copper layer** to reduce background
 - W is very 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**)
 - New anti-neutrino trigger
 - Trigger on singles would be too hard, but this is not a problem
 - **> 2016. No schedule yet.**





Summary

- We 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 (TBD)
 - **SOX-C**
 - ^{144}Ce anti-neutrino source (internal)
 - No schedule (>2016)

