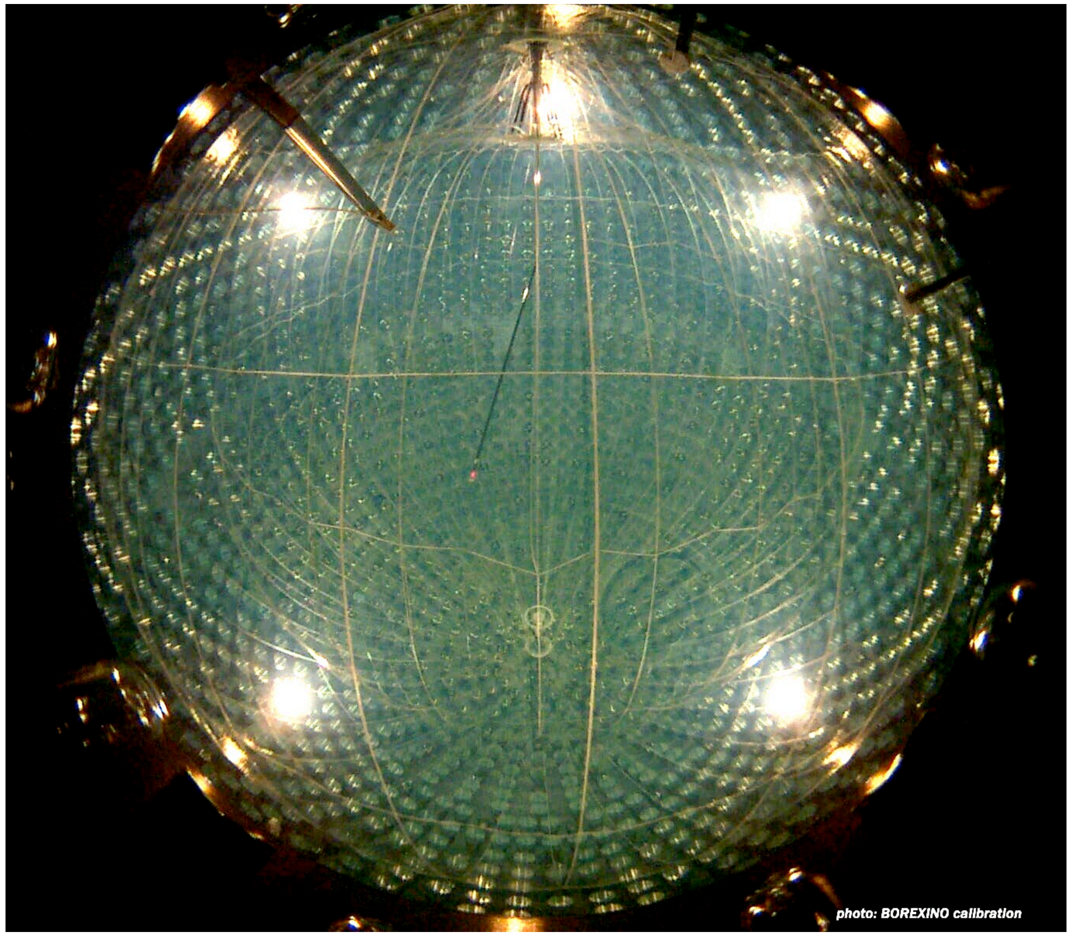


Short Distance Neutrino Oscillations with BoreXino

Laboratori Nazionali del Gran Sasso

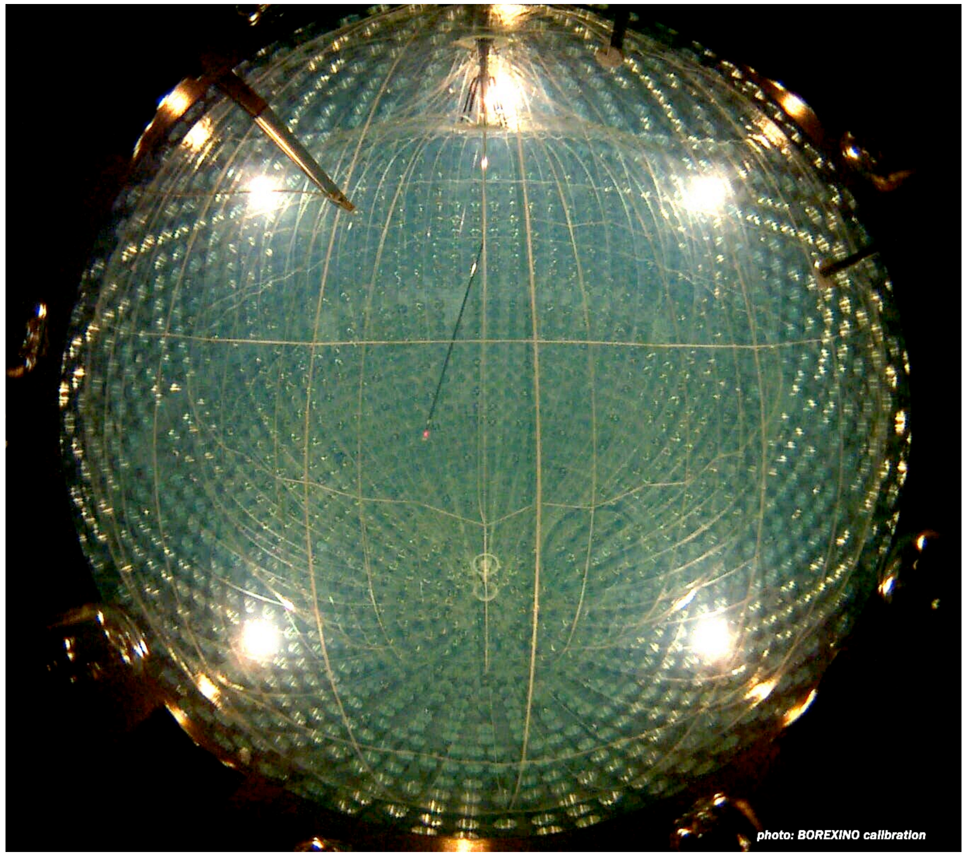
Jul. 4th, 2013

Marco Pallavicini
on behalf of the Borexino Collaboration

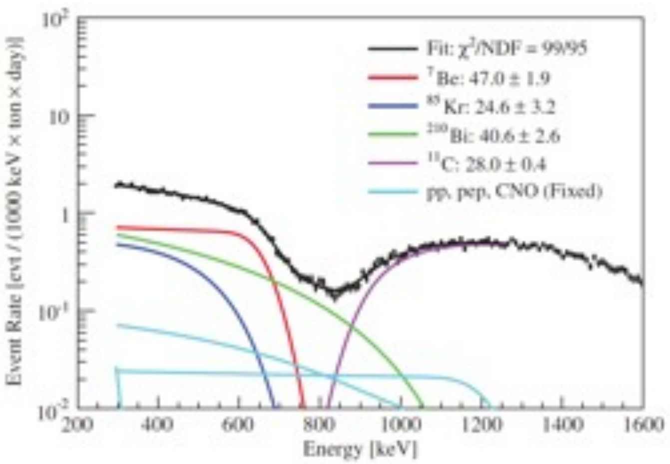
Dipartimento di Fisica – Università di Genova & INFN Sezione di Genova

Borexino experiment

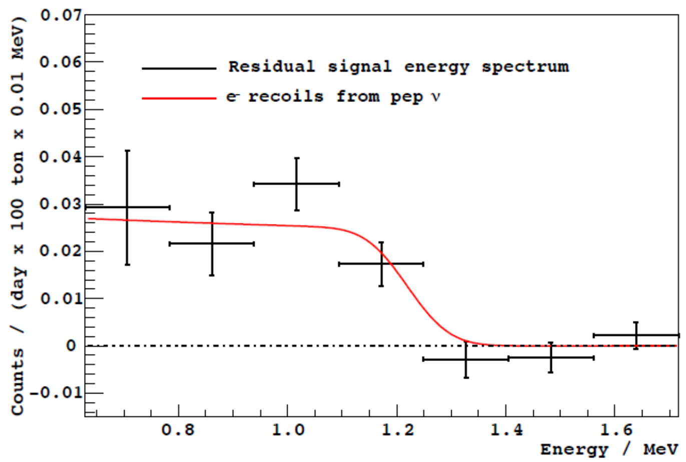
- Mainly, **a solar neutrino experiment**
  - $\nu + e^- \rightarrow \nu + e^-$ in organic liquid scintillator
    - **Very low background** obtained with **selection, shielding** e **purifications**
    - Low energy threshold, good energy resolution, spatial reconstruction, pulse shape α/β identification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

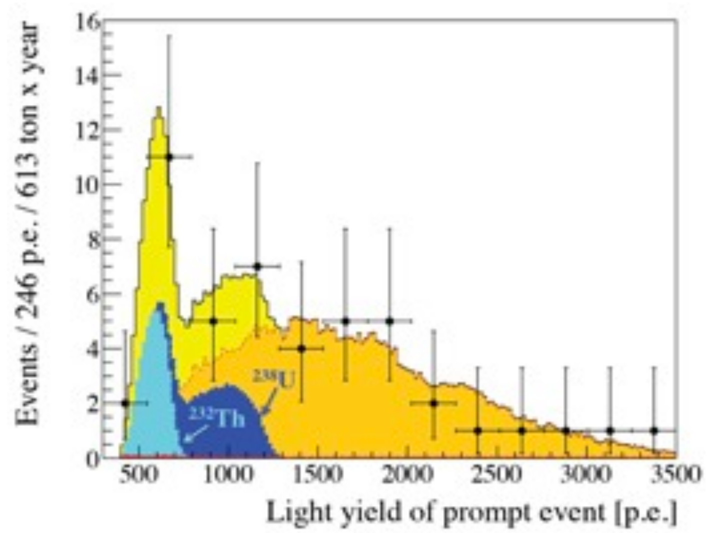


Phys. Rev. Lett. 107, 141302 (2011)



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

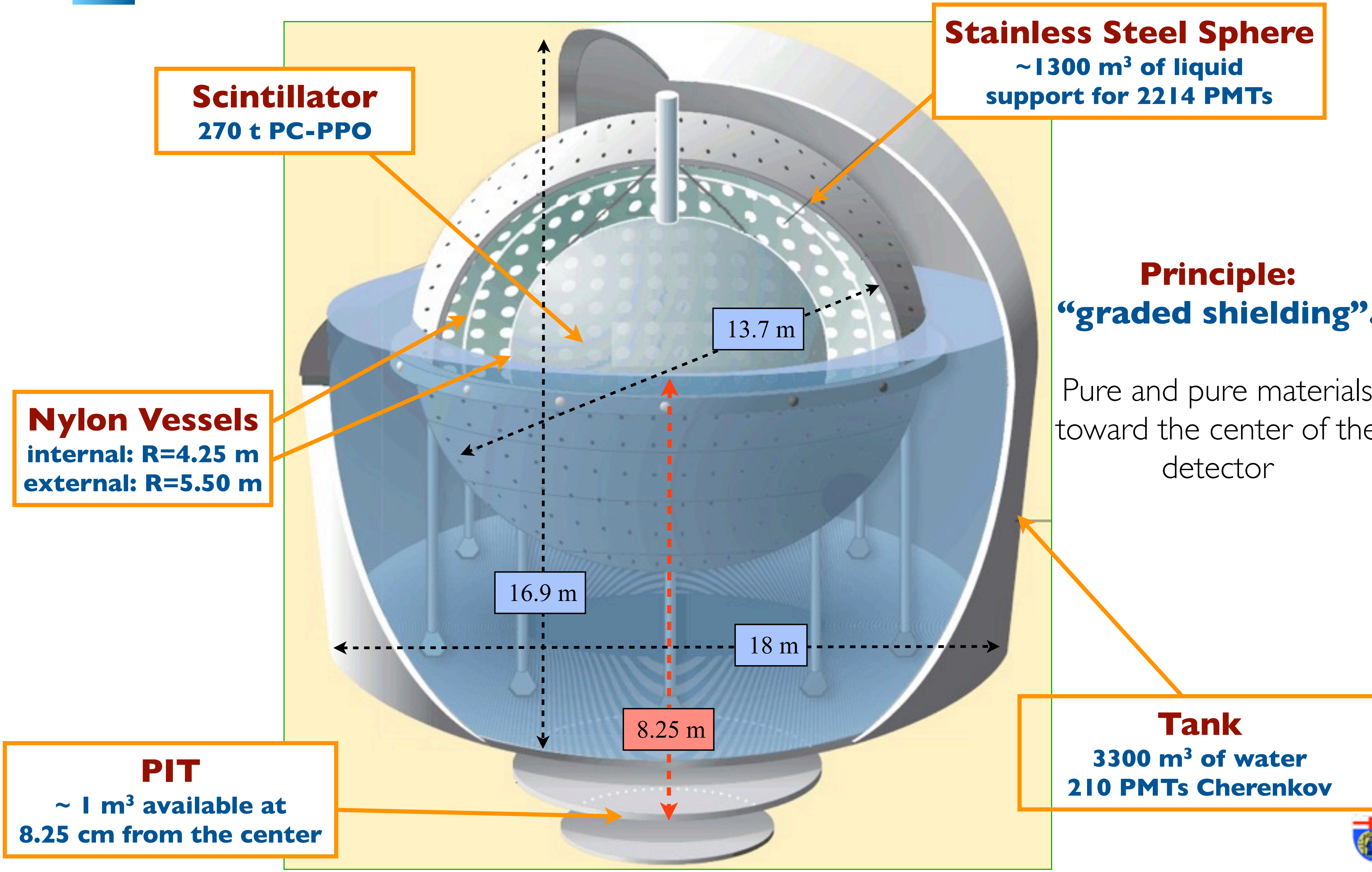




- **sub-MeV ν_e detection:** proved by **^{7}Be** and ***pep***
- sensitivity: as low as a few cpd/100 t
  - *pep:* 3.1 ± 0.6(stat) ± 0.3(sys) cpd/100 t

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

The detector



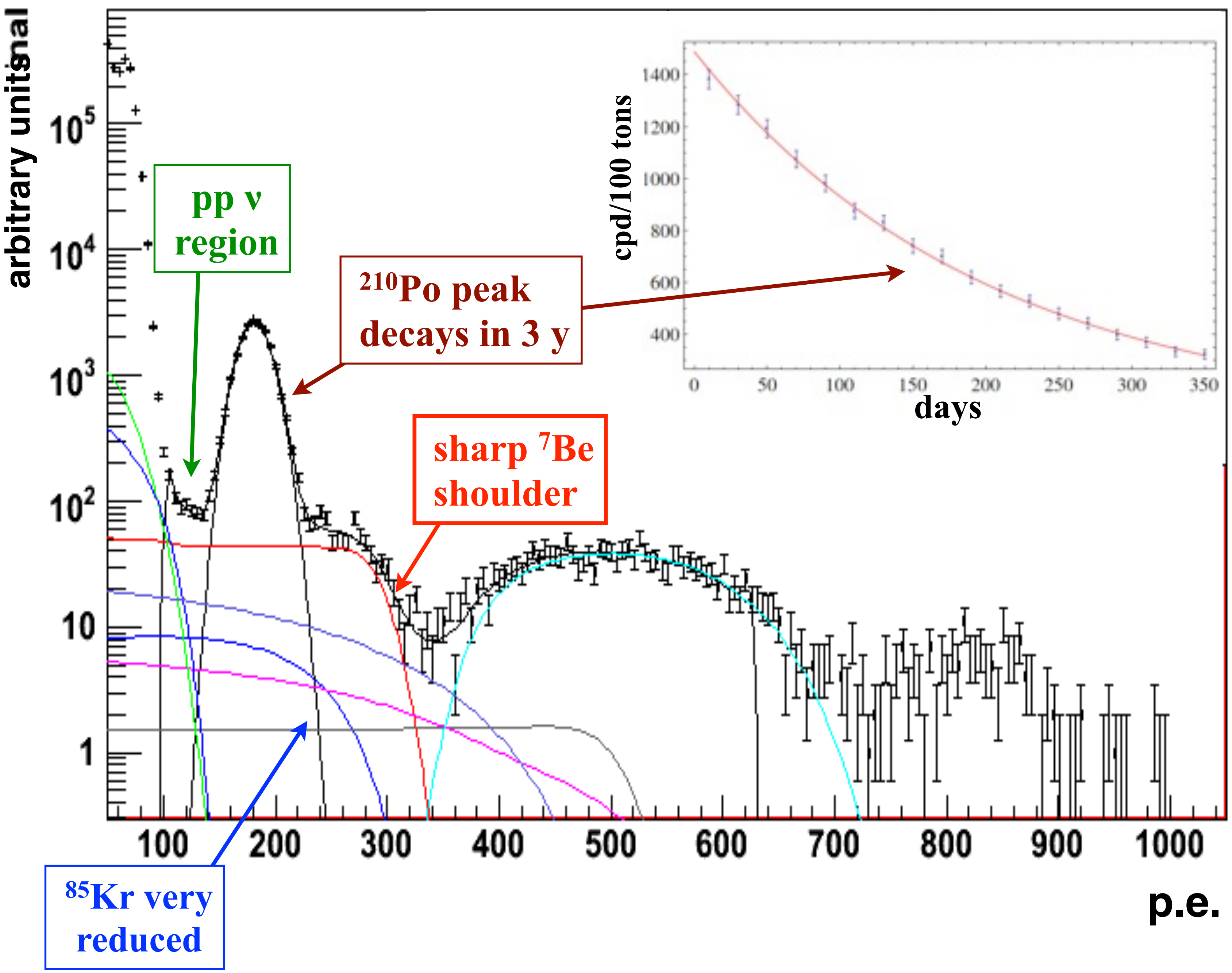
Principle: "graded shielding".

Pure and pure materials toward the center of 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 10^{-19} g/g**
- ^{232}Th
  - **< 2.9 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
- **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**

ERC Ideas approved

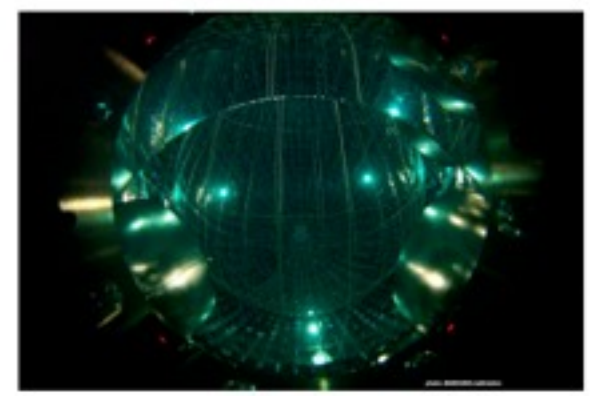
European Research Council
ERC-2012-AdG

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)

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

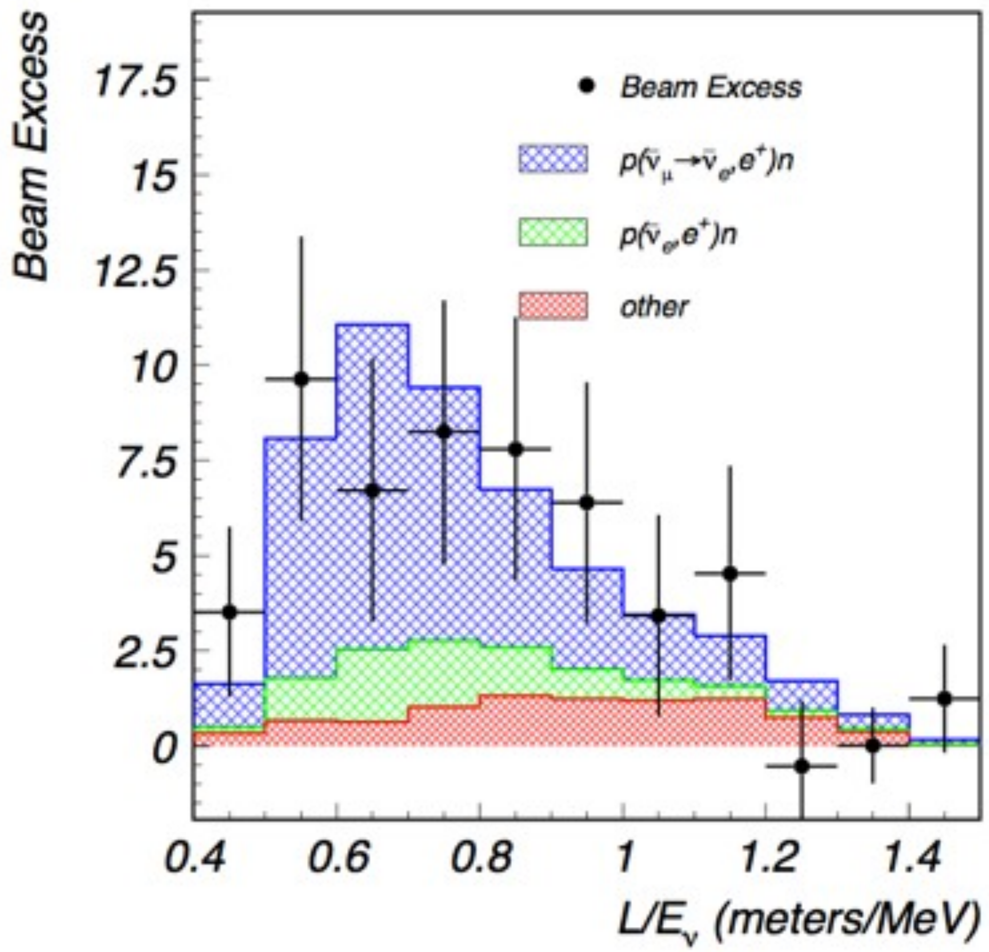
a very incomplete list!

See White Paper and references therein:
arxiv: 1204.5379

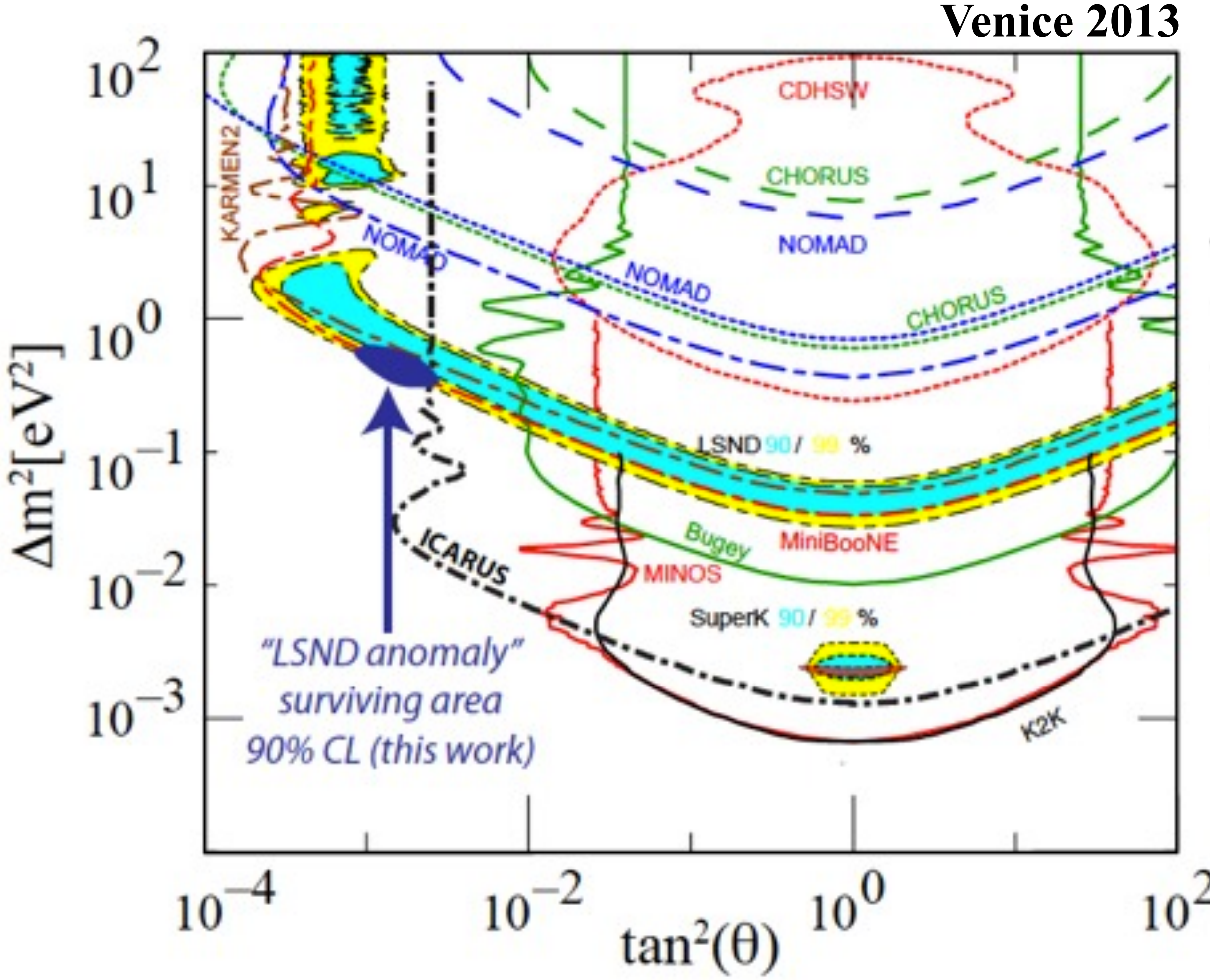
The Science case – I

- A few well known experimental results do not match the standard three-flavors scenario. In particular:

  - **LSND (Los Alamos)** in **2001** measured **a ν_e excess using ν_μ beam**
    - Apparently, a clear effect: **87.9 ± 22.4 ± 6.0 (3.8 σ)**
    - **L/E NOT compatible** with "solari" oscillations
    - LSND region recently reduced by Icarus data, but not excluded



Venice 2013



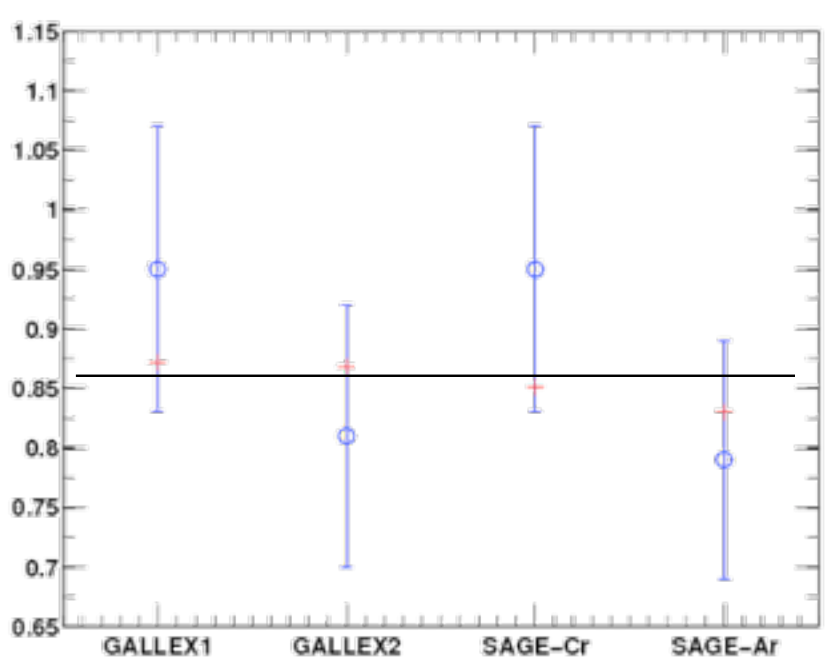
The Science case – II

- **Gallex and SAGE** in the 90's has made a calibration of their detector with an **artificiale neutrino source**
  - Strong enough to produce a detectable neutrino flux (about the Sun at 10 m)
    - A portable Sun!
  - Both experiments show a deficit w.r.t. expectations

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

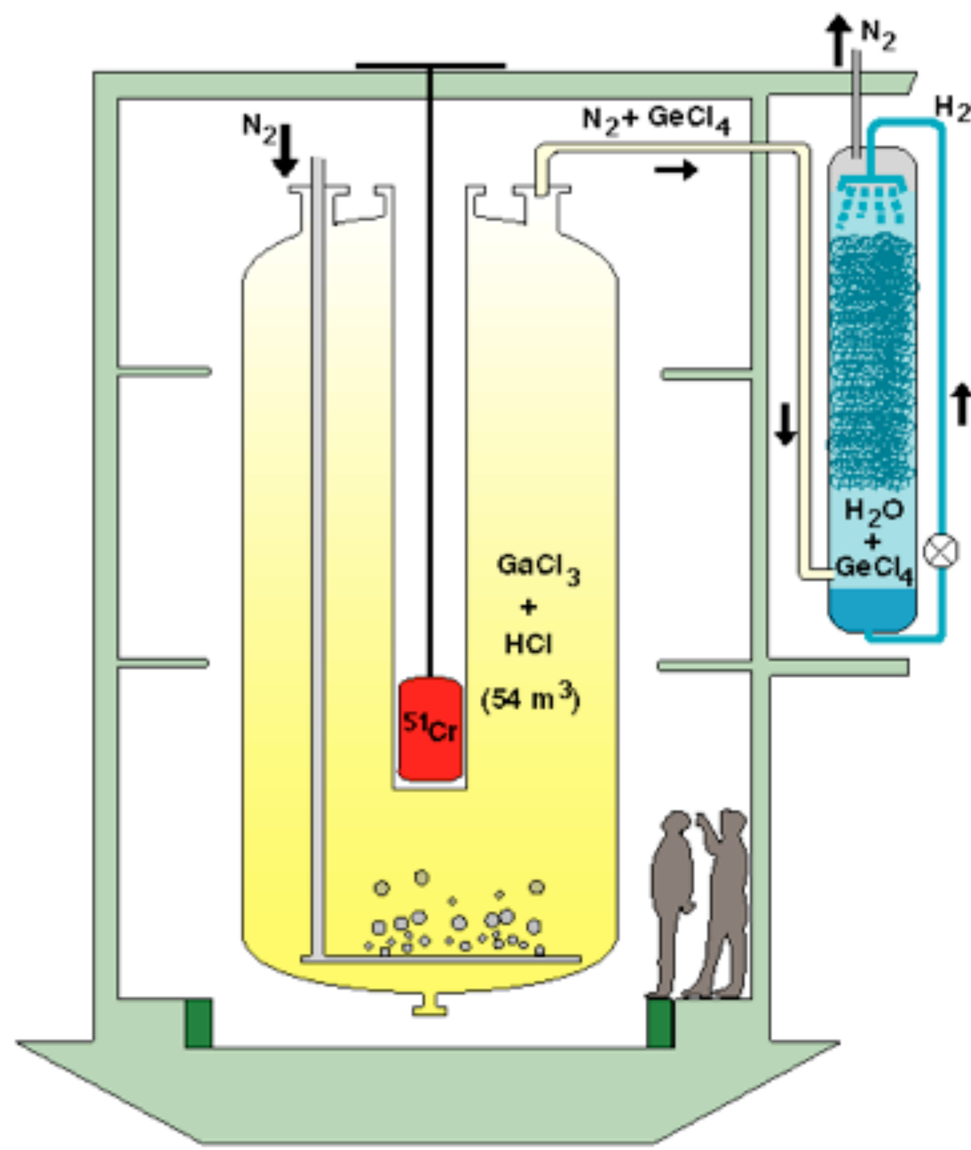
C. Giunti et al. arxiv:1210.5715 (hep-ph)

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



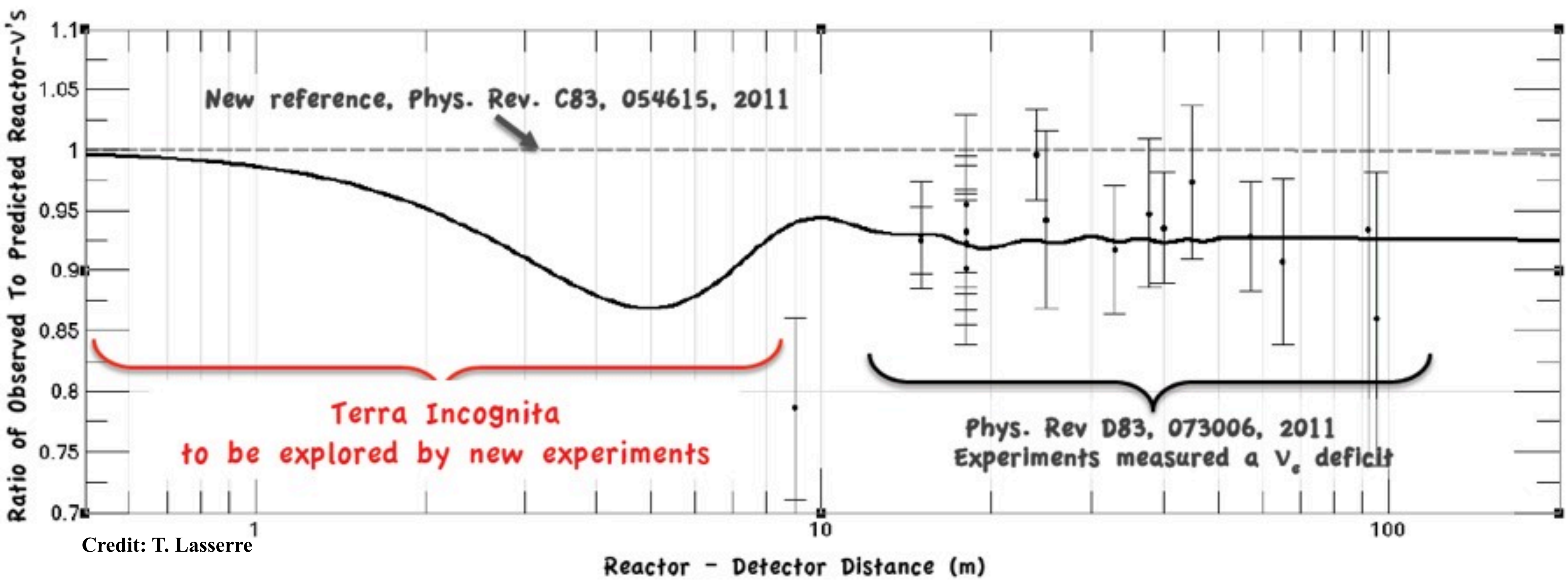
<R>=0.85 ±0.05

~ 3 σ effect



The Science case – III

- Reactor anomaly
  - **Many experiments at small L/E from reactors**
    - Supposedly better calculations of **reactor neutrio fluxes** released recently
    - With these new calculations, **neutrino deficit at small L/E is observed**



Credit: T. Lasserre

Comments on the Science case

- In my opinion, taken individually, each anomaly is **weak:**
  - popular arguments, e.g.
    - LSND region not clearly confirmed by Miniboone, allowed region shrinked significantly by Icarus
    - Gallex and SAGE calibrated their detector with sources. Can we trust the efficiency so much to believe the anomaly ?
    - Can we trust the supposedly better reactor fluxes ? Were previous measurements biased by older calculations?

- **BUT**
  - All anomalies **point consistently in the same direction,** i.e. deficit at small L/E
  - If **any** of them is **true**, **new physics is mandatory**
    - High risk, high gain
  - **Methodologically,** the only way to discard a wrong measurement is to **do a better one**
    - We can’t dismiss data based on theoretical prejudice

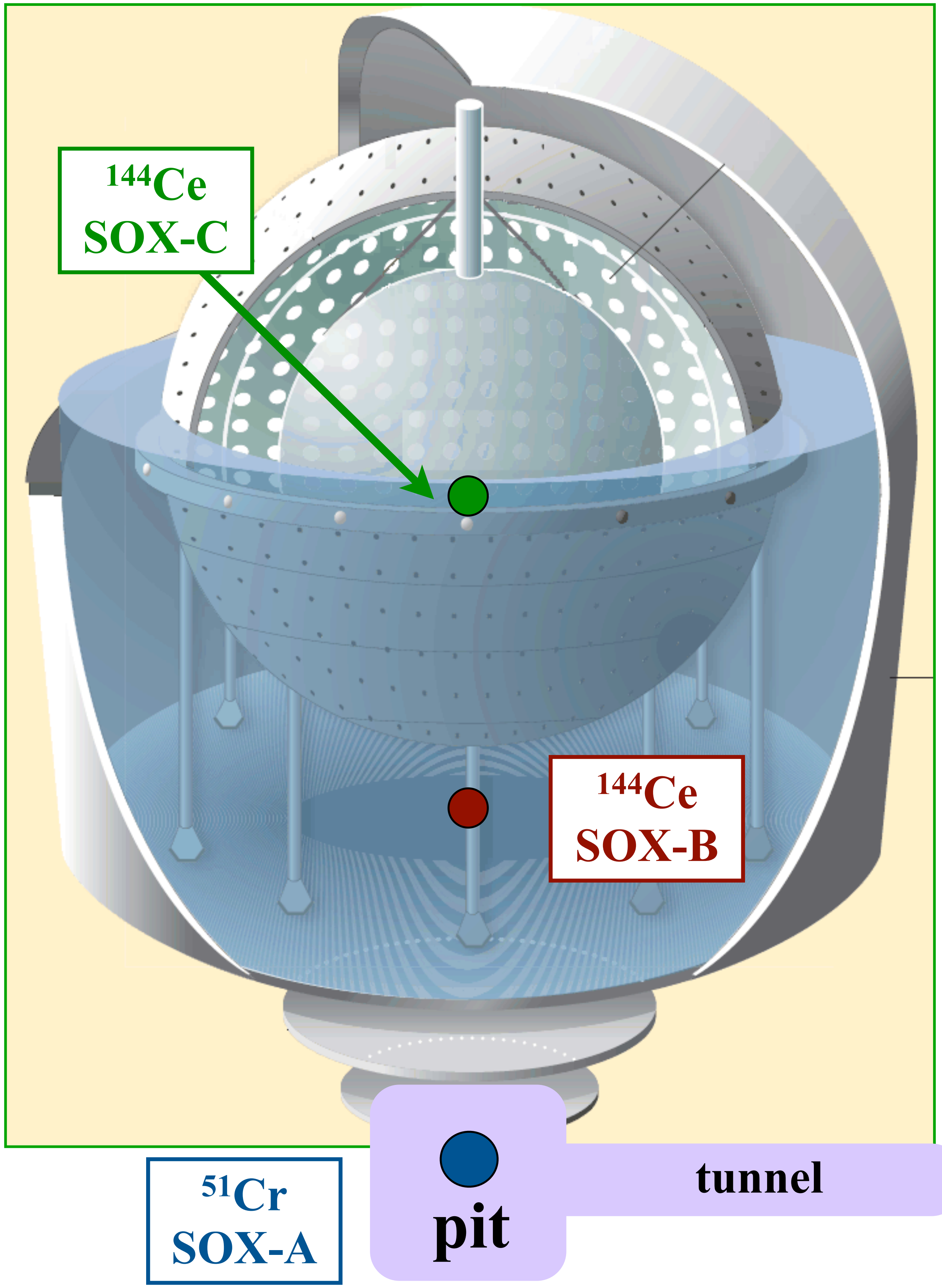
SOX: Three Phases

- **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]**

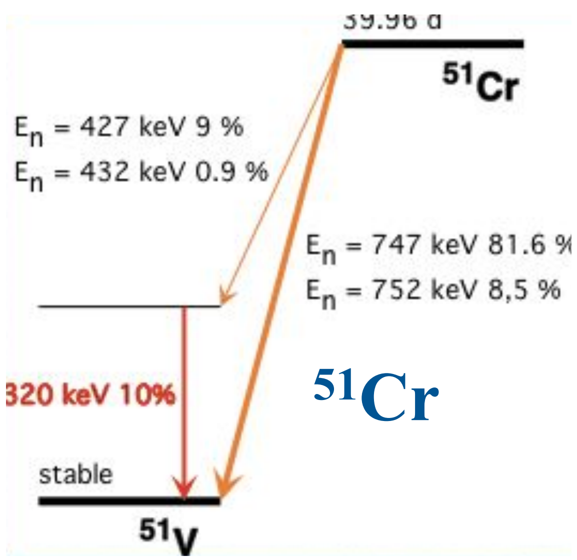
- **SOX-B**
  - **^{144}Ce-^{144}Pr** source in W.T.
  - PPO everywhere to enhance sensitivity
  - **7.15 m** from center **[2015/2016 ?]**

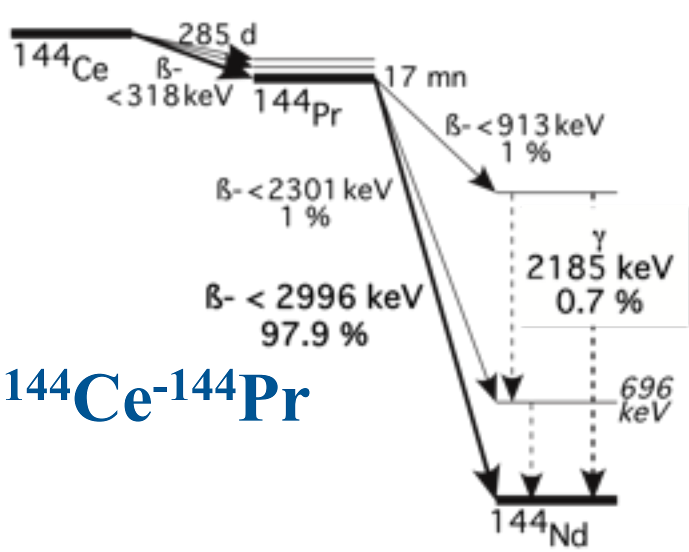
- **SOX-C**
  - ^{144}Ce-^{144}Pr source in the center
  - **Only after the end of solar program**
  - More effort and more time **[>2016]**

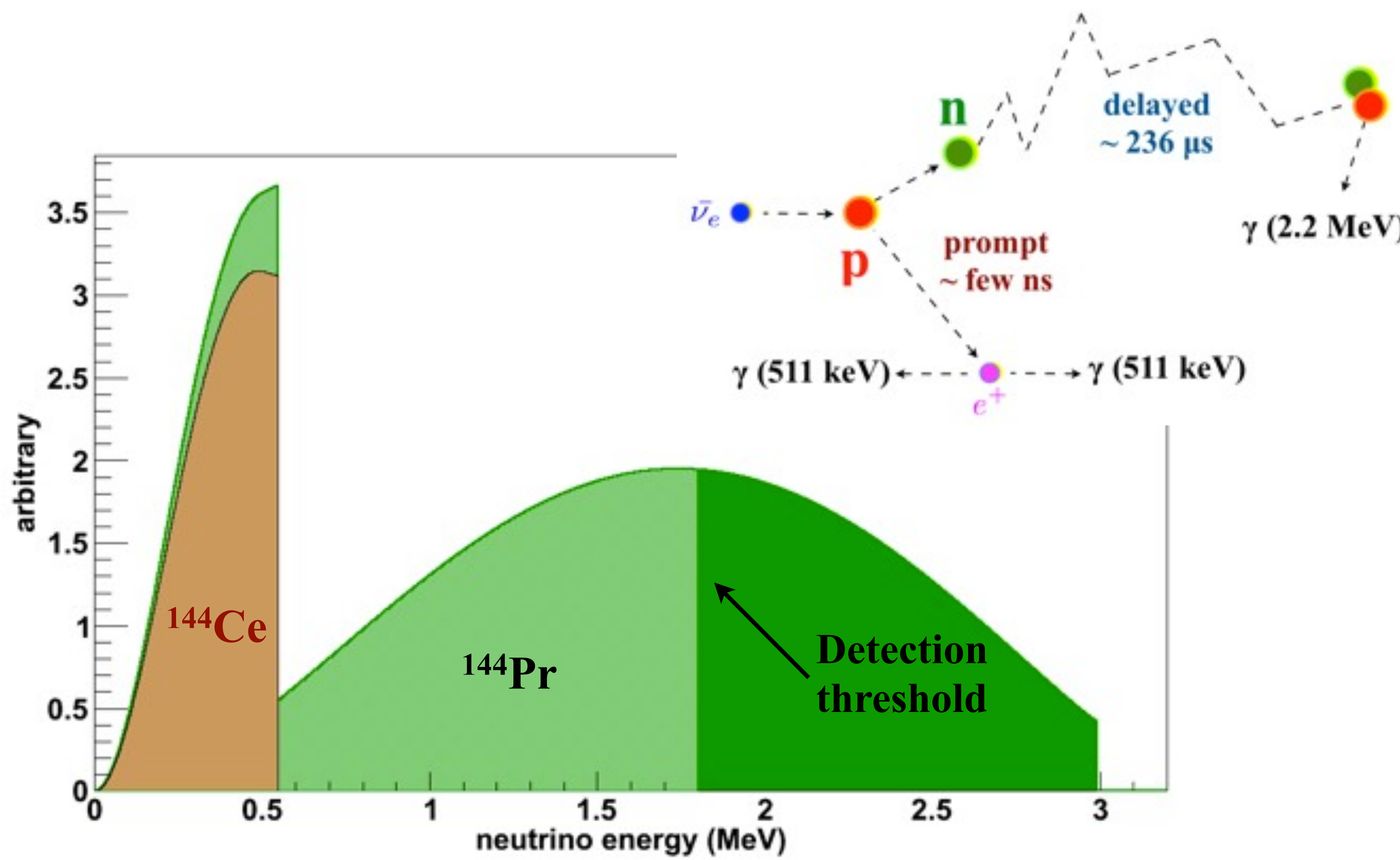


Artificial neutrino sources

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%)	0.746	0.011	0.19
^{144}Ce-^{144}Pr $\bar{\nu}_e$	Chemical extraction from spent nuclear fuel	411	β-	<2.9975	0.314	7.6







The tunnel beneath the detector

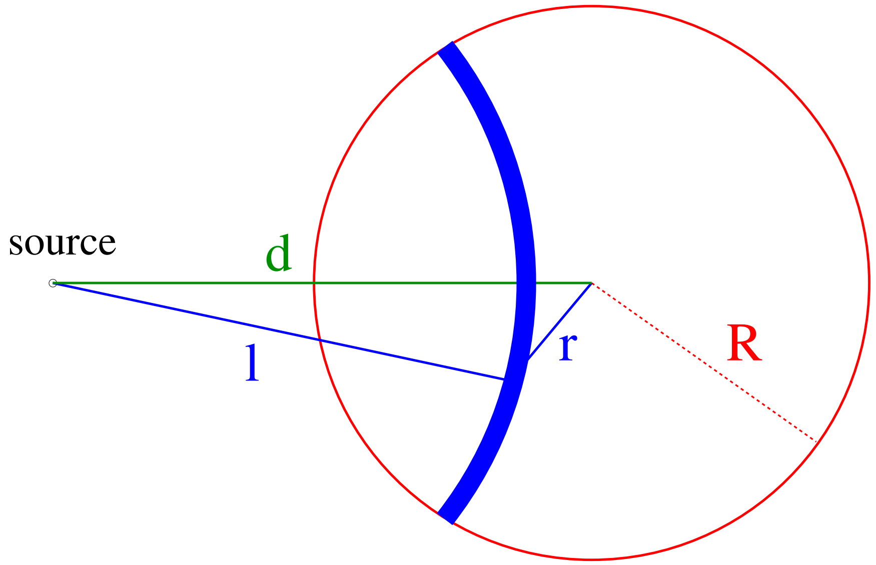
Data analysis: two techniques

- **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 51Cr 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**

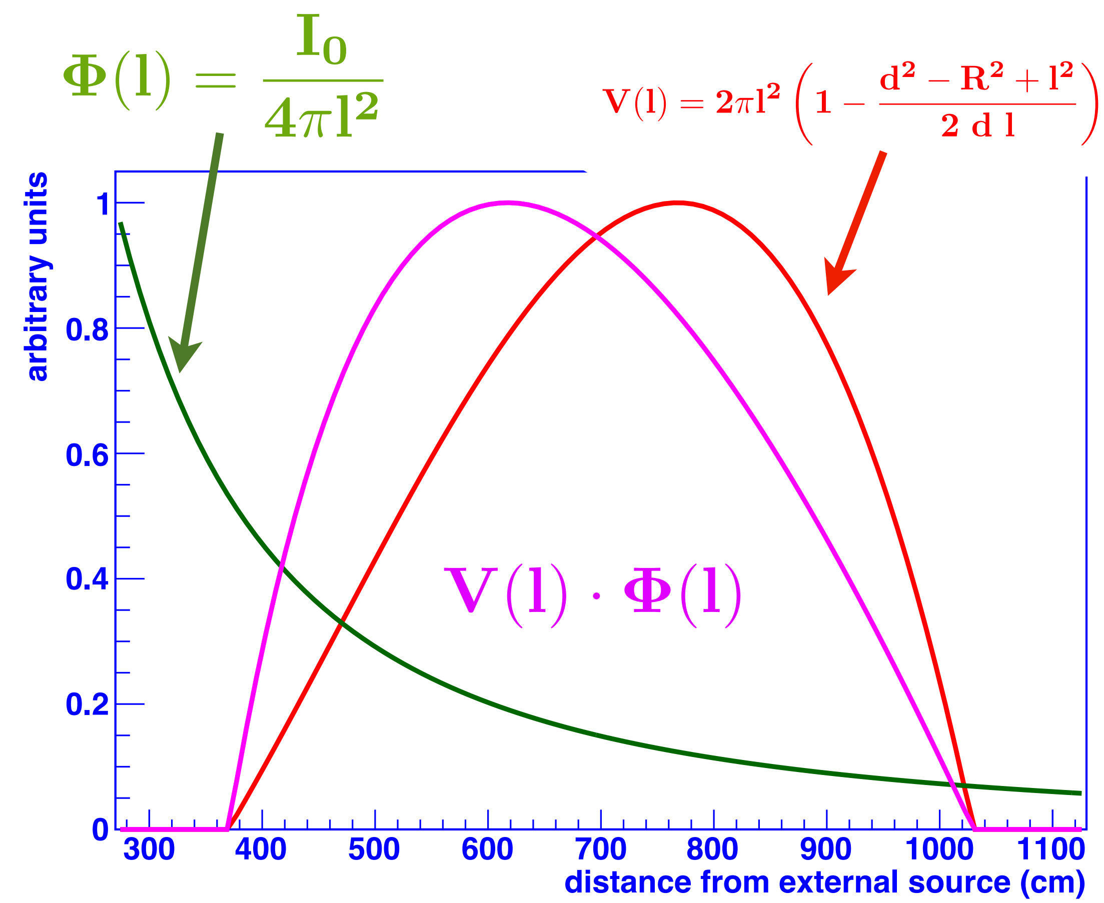
$$\Phi(l) = \frac{I_0}{4\pi l^2}\tau e^{-\frac{t_D}{\tau}}\left(1 - e^{-\frac{t}{\tau}}\right)$$

- **Oscillations (one sterile)**

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

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

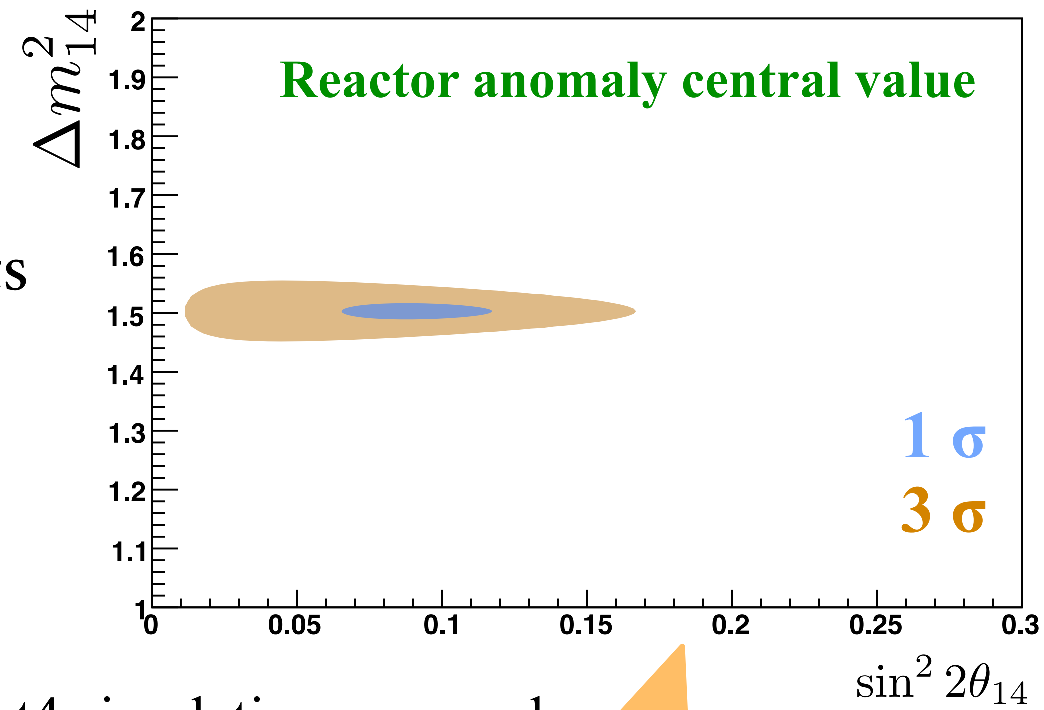
$$\mathbf{N_0(l, T_1, T_2) = n_e\ \Phi(l)\ V(l)\ P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E, T)}{dT} dT}$$



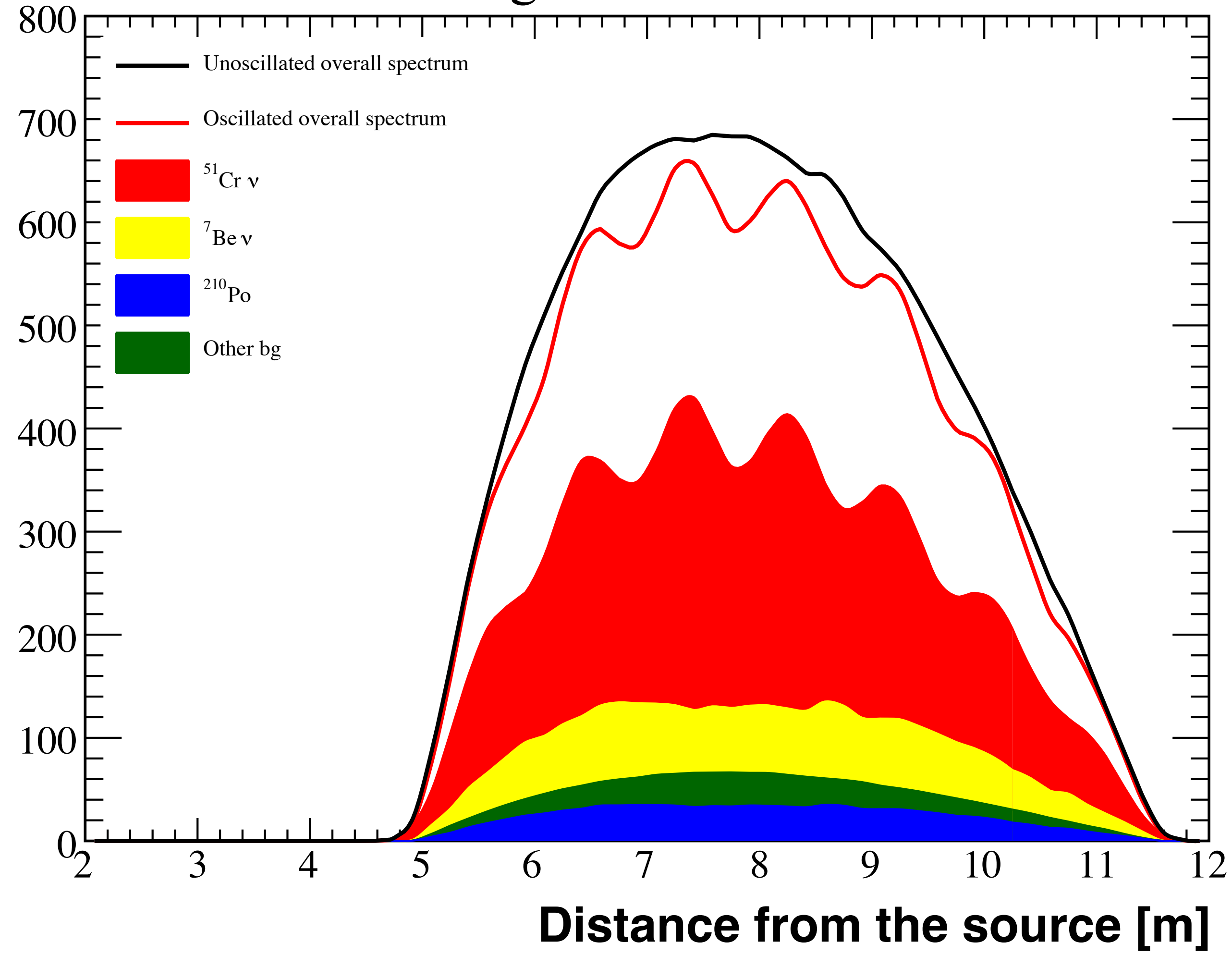
N.B.: The distribution of events is not uniform even without oscillations

Example for SOX–A

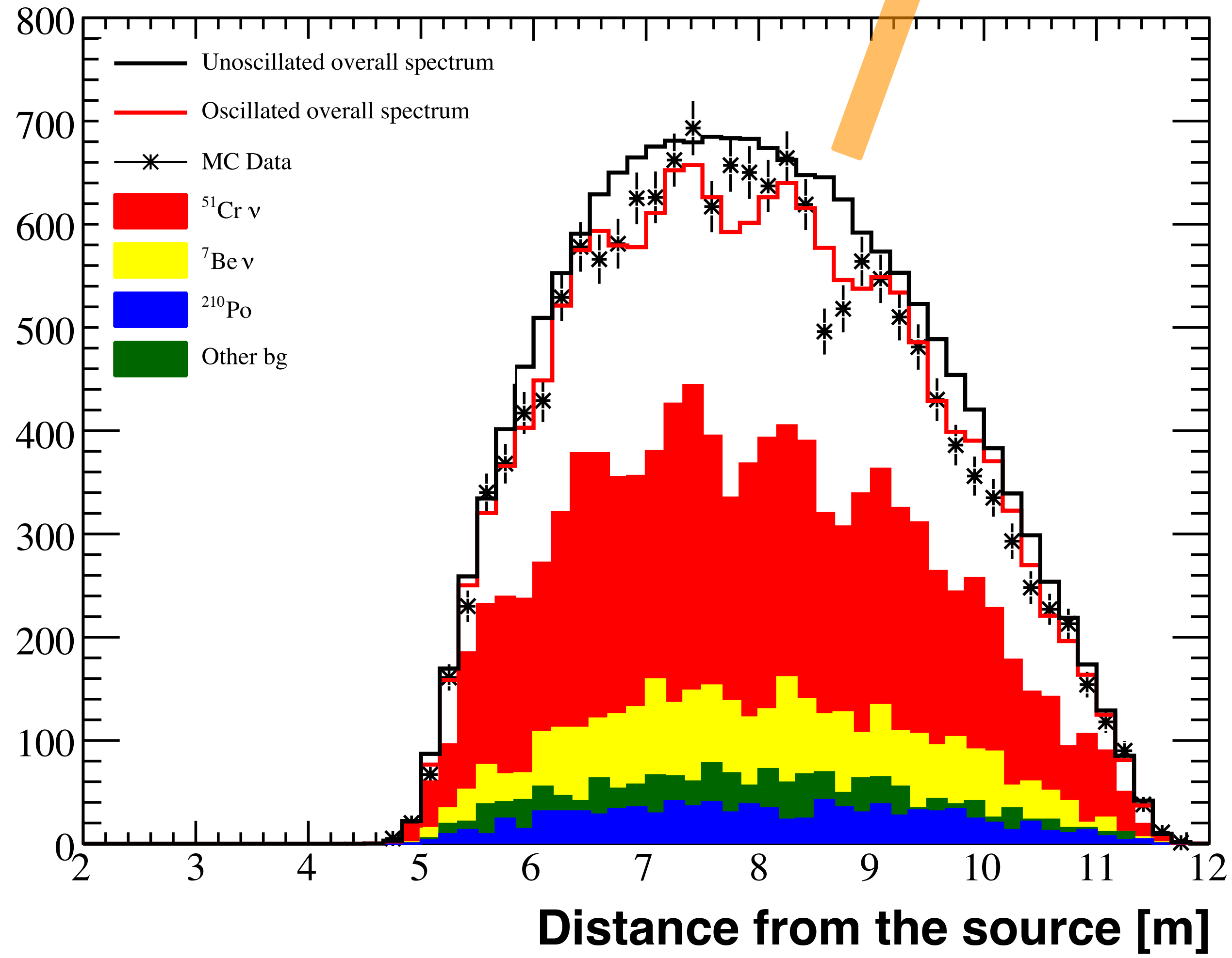
- **Waves** may be detected in the distribution of events as a function of the distance from source
  - With waves, both parameters can be measured



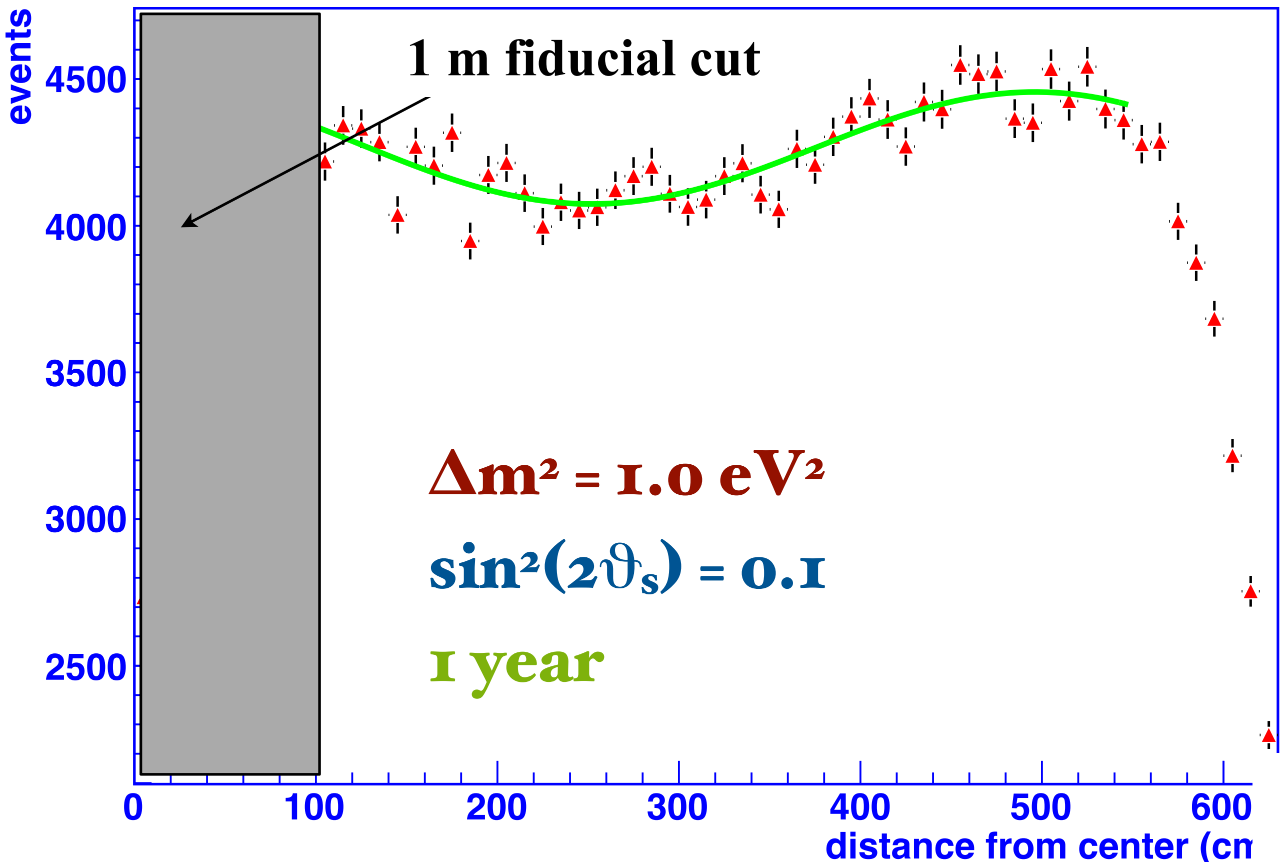
Ideal curves
Borexino Background - No fluctuations

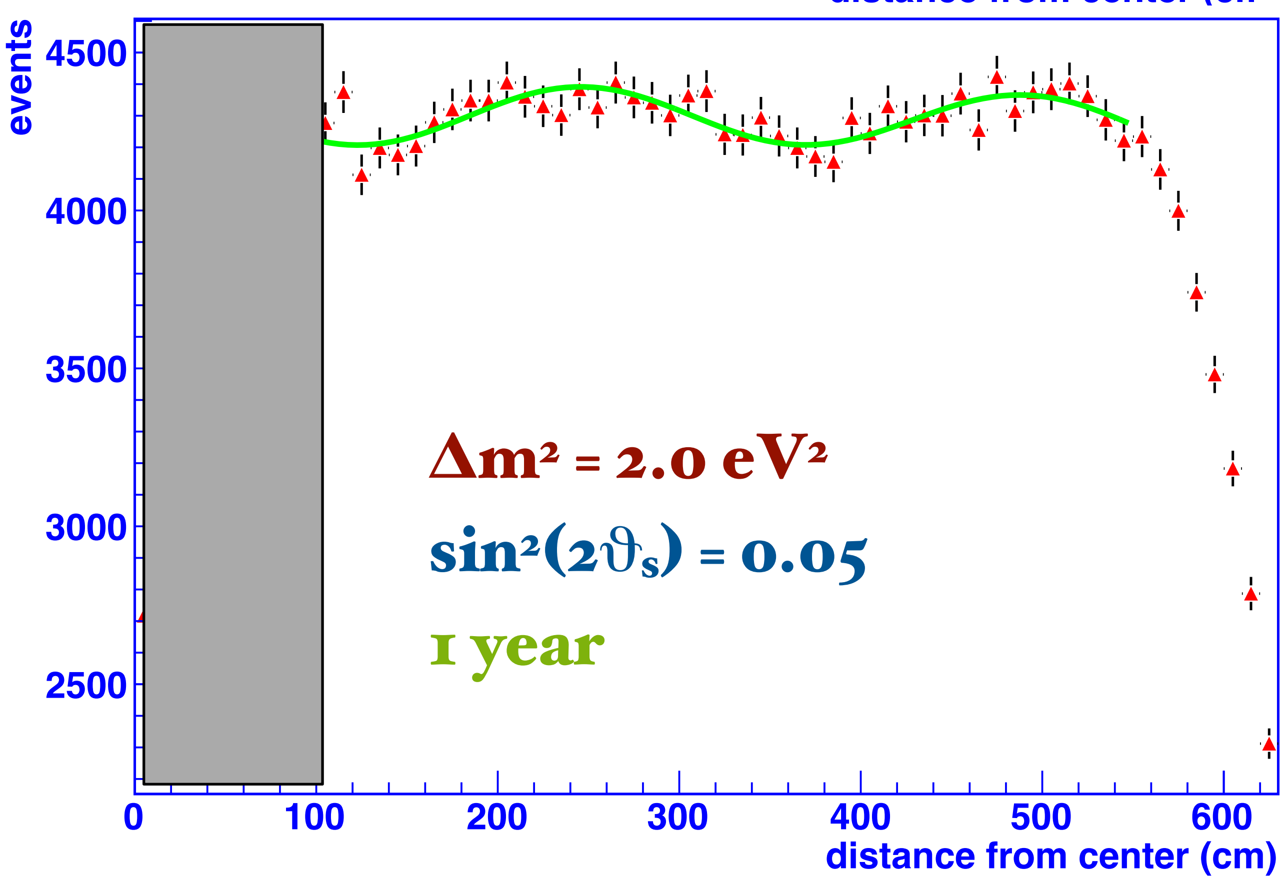


Full Geant4 simulation - example
Borexino Background

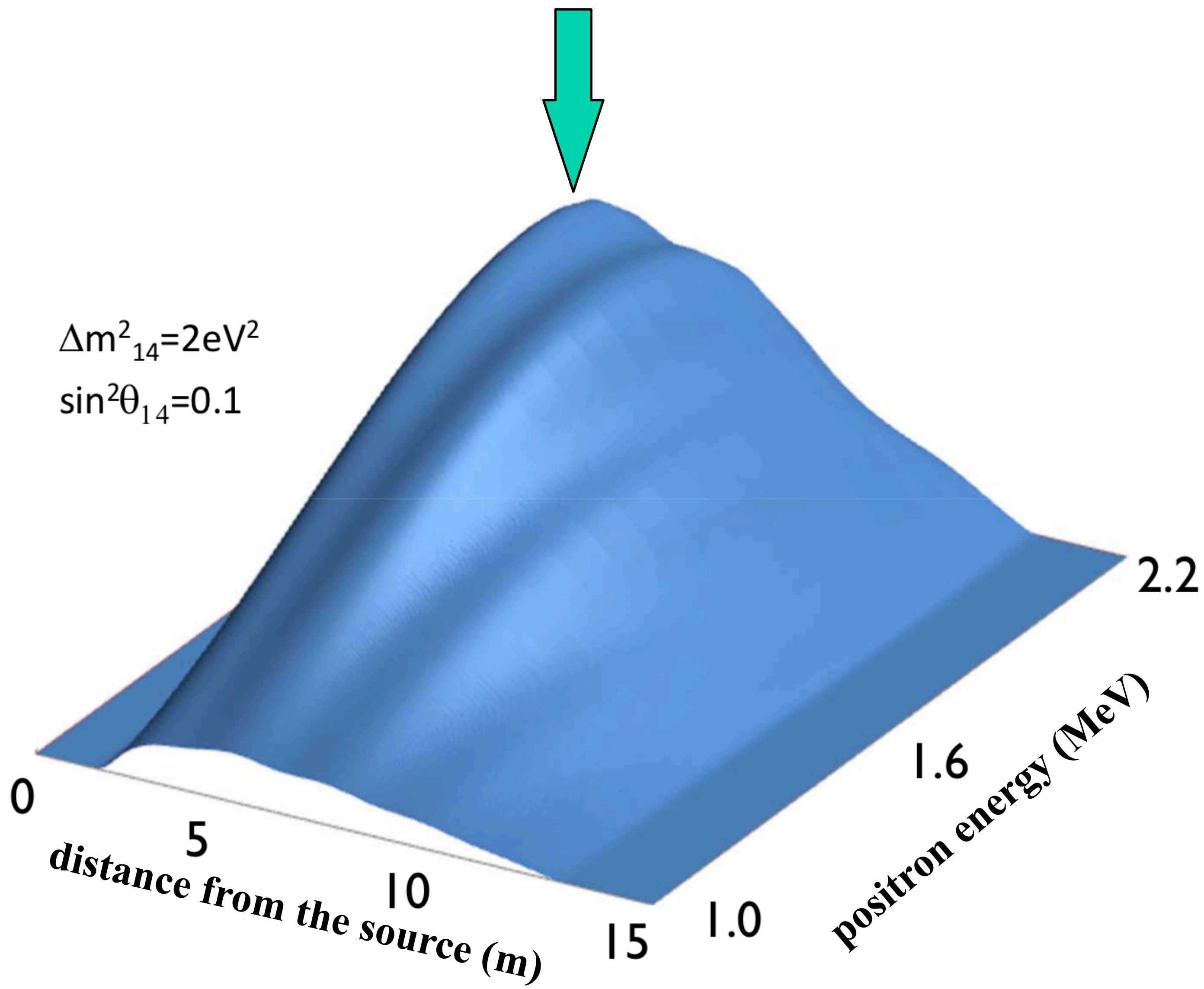


Waves with $\bar{\nu}_e$ and space–energy correlation



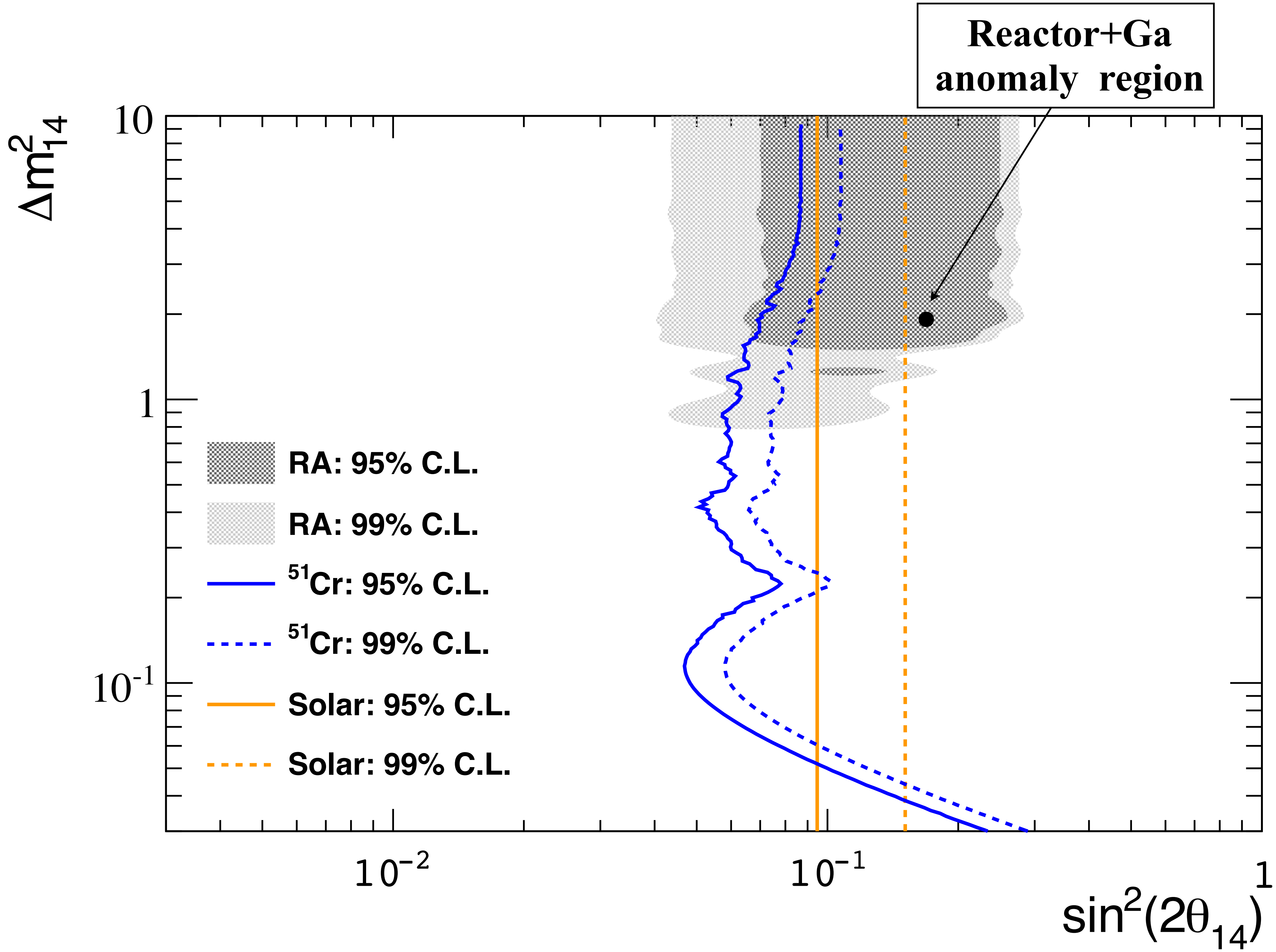


- **Space - Energy correlation**
  - With the **^{144}Ce-^{144}Pr** source (both **external SOX-B** and **internal SOX-C**) global fit exploiting **correlation between reconstructed event position and positron energy**



SOX-A sensitivity

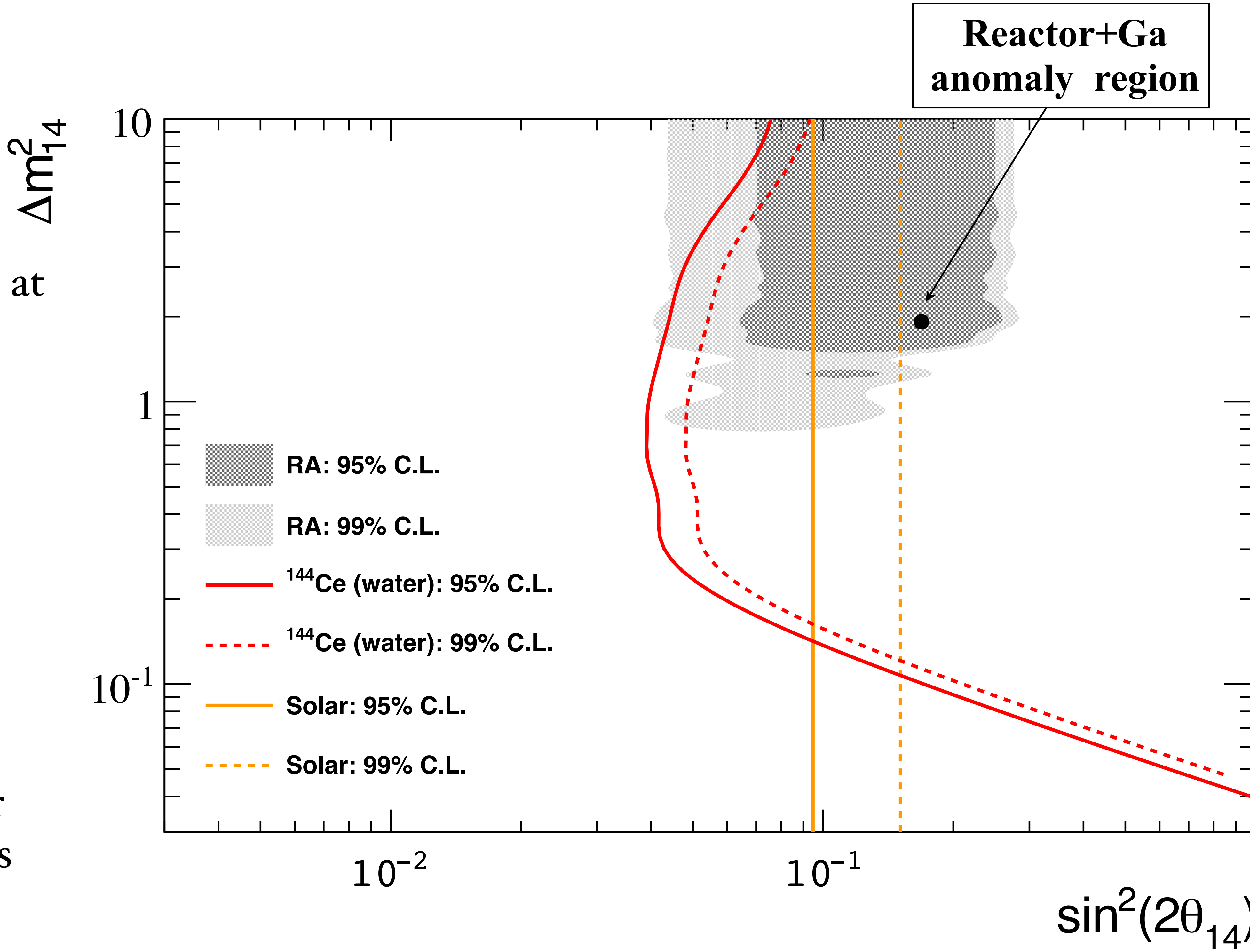
- **SOX-A:**
  - **^{51}Cr** source at **8.25 m** from the center
  - **10 MCi**
  - 1% precision in source activity
  - 1% in FV determination



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

SOX–B sensitivity

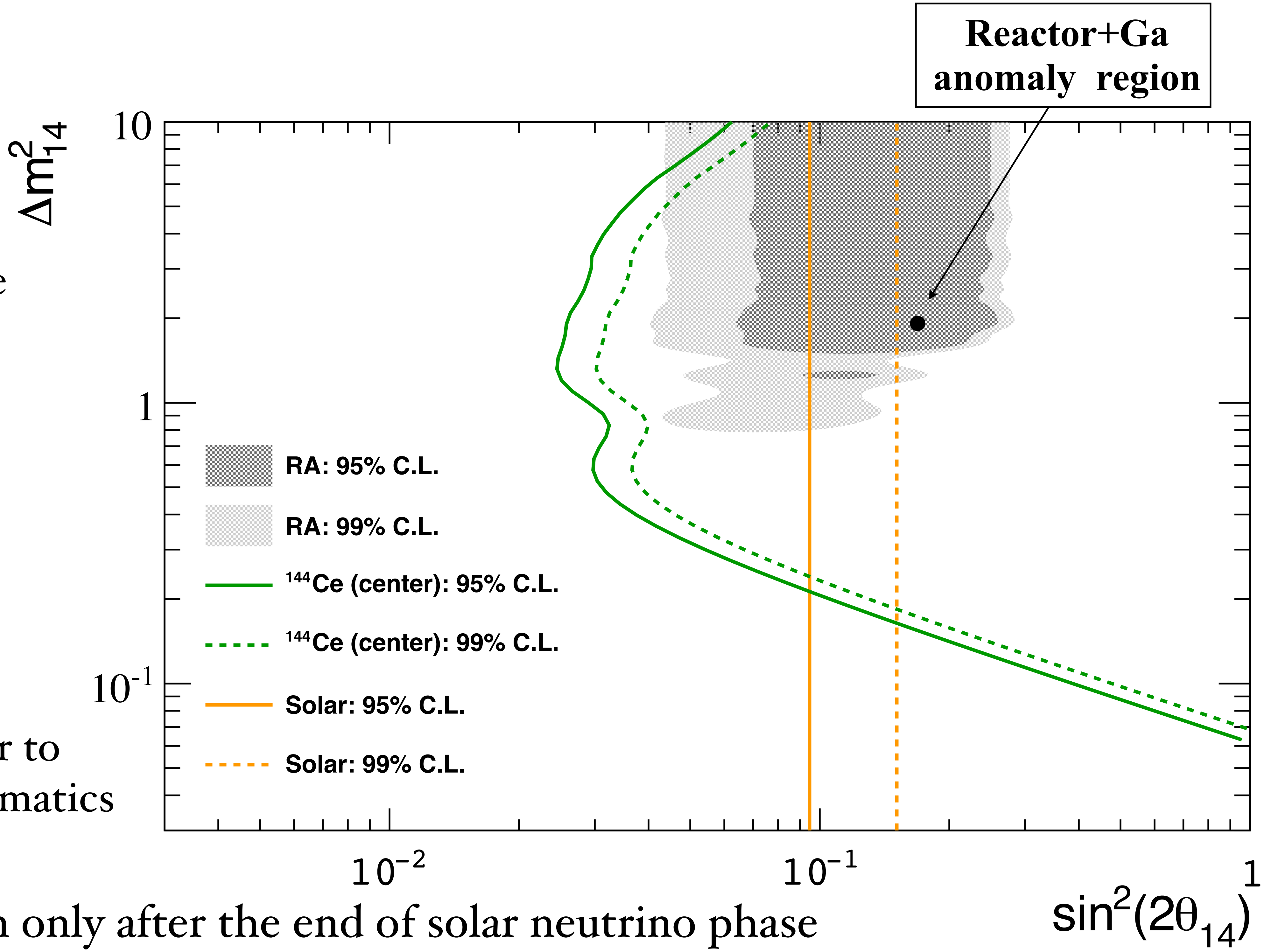
- **SOX-B**
  - **^{144}Ce-^{144}Pr** source at **7.15 m** from the center
  - **75 kCi**
  - 1.5% precision in source activity
  - 2% bin-to-bin error to include all effects



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

SOX–C sensitivity

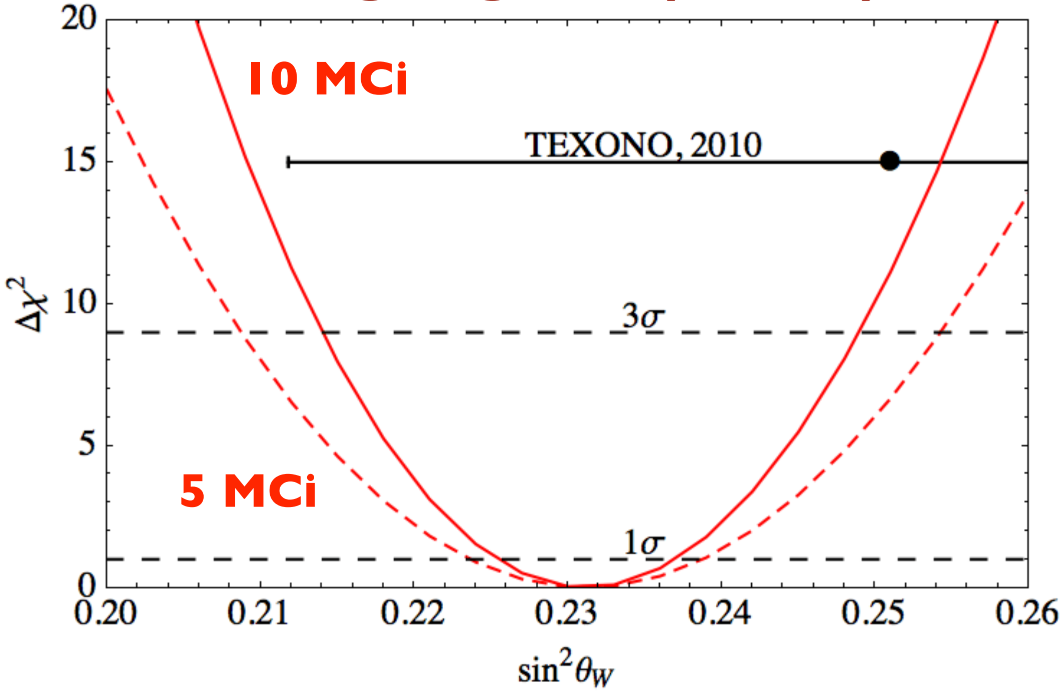
- **SOX-C:**
  - ^{144}Ce-^{144}Pr source in the center
  - ~50 kCi
  - 1.5% precision in source activity
  - 2% bin-to-bin error to include other systematics



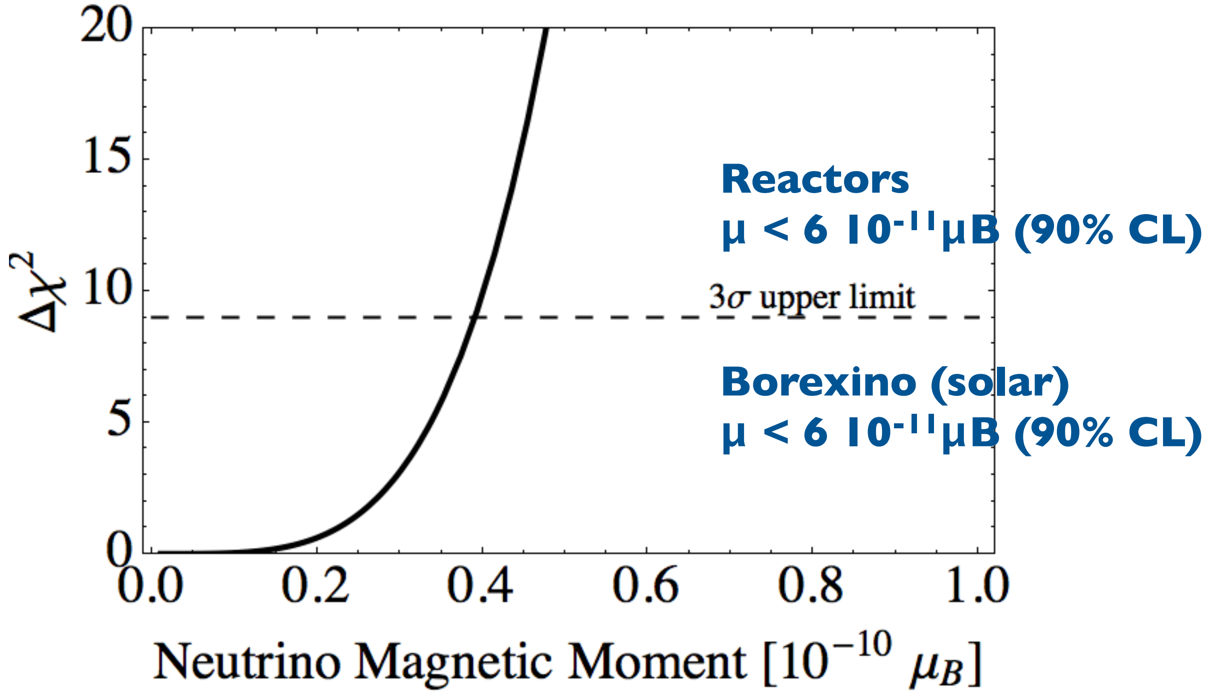
- SOX-C can happen only after the end of solar neutrino phase
  - 2016-2017 is a realistic scenario
  - desicison to be taken after SOX-A and/or SOX-B results

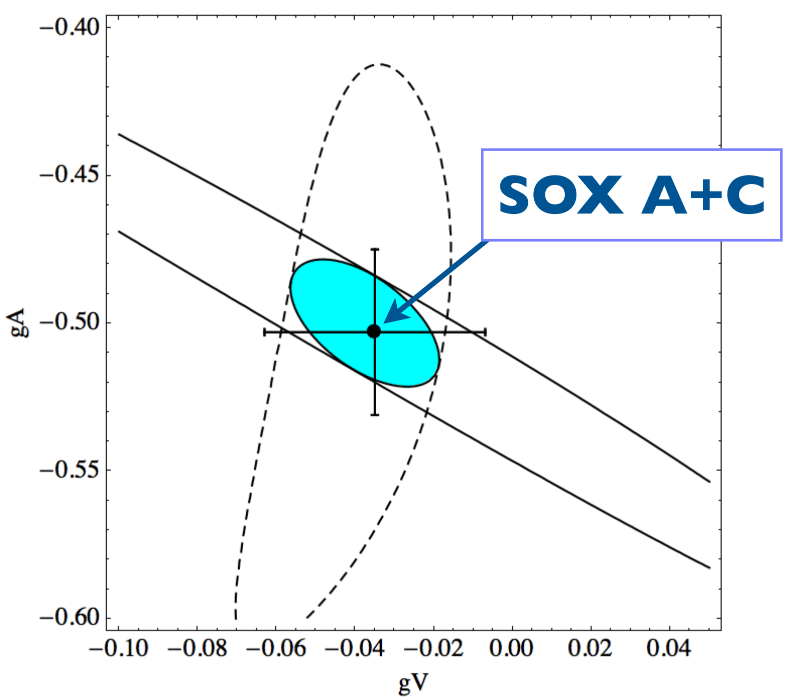
Other low energy neutrino physics

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



Magnetic moment





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

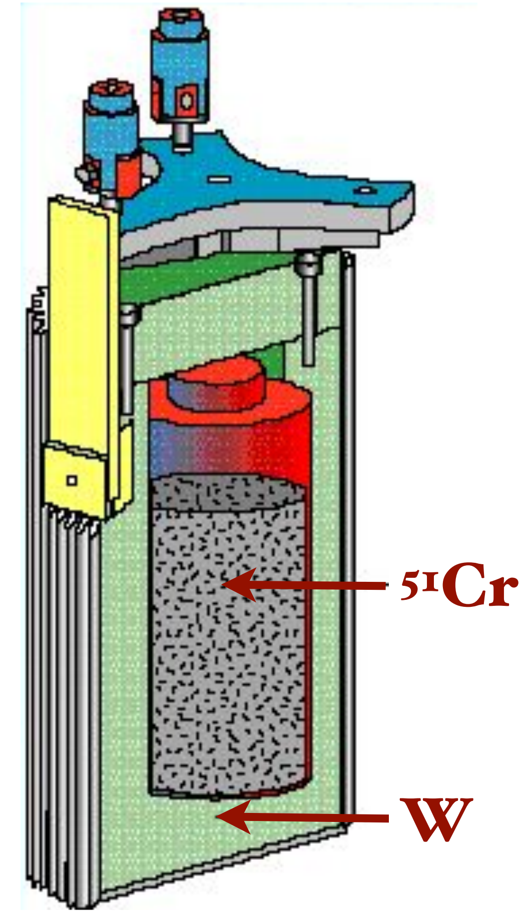
- With both sources (SOX-A and B or C)
  - Independent measurement of gv e ga
  - Test of SM EW running at very low energy
  - Standard Model
    - $g_V = -1/2 + 2\sin^2\vartheta_W = -0.038$
    - $g_a = -1/2 = 0.5$

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

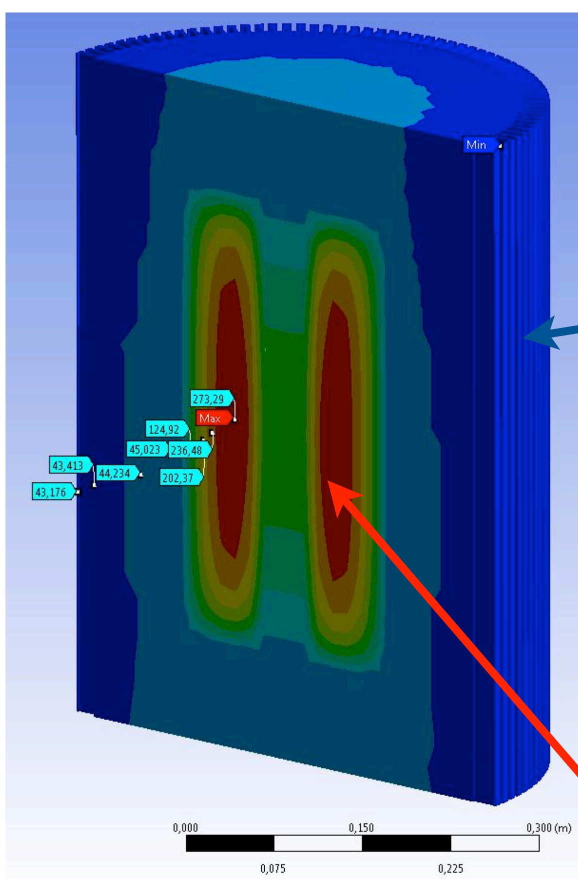
$$g_A^{\nu e} = -0.503 \pm 0.006(\mathrm{stat}) \pm 0.016(\mathrm{syst}).$$

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)
  - Candidate reactors: Russia (best), USA, Europe
  - **190 W/MCi** from photons
  - ~few μSv/h on surface (required < 100)



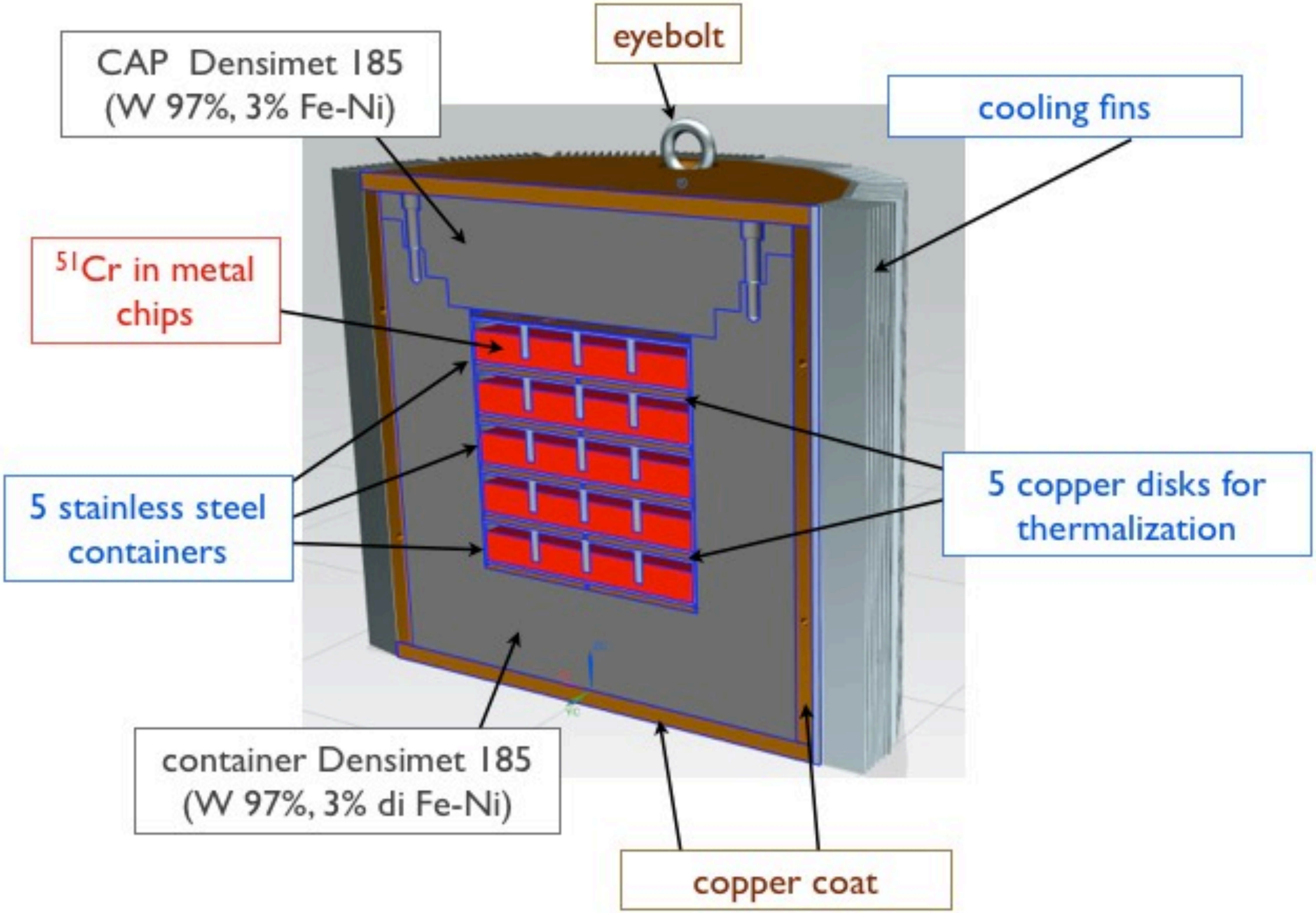
- **BUT**: careful **thermal design** to handle **10 MCi (2 kW)**
  - Preliminary studies are encouraging



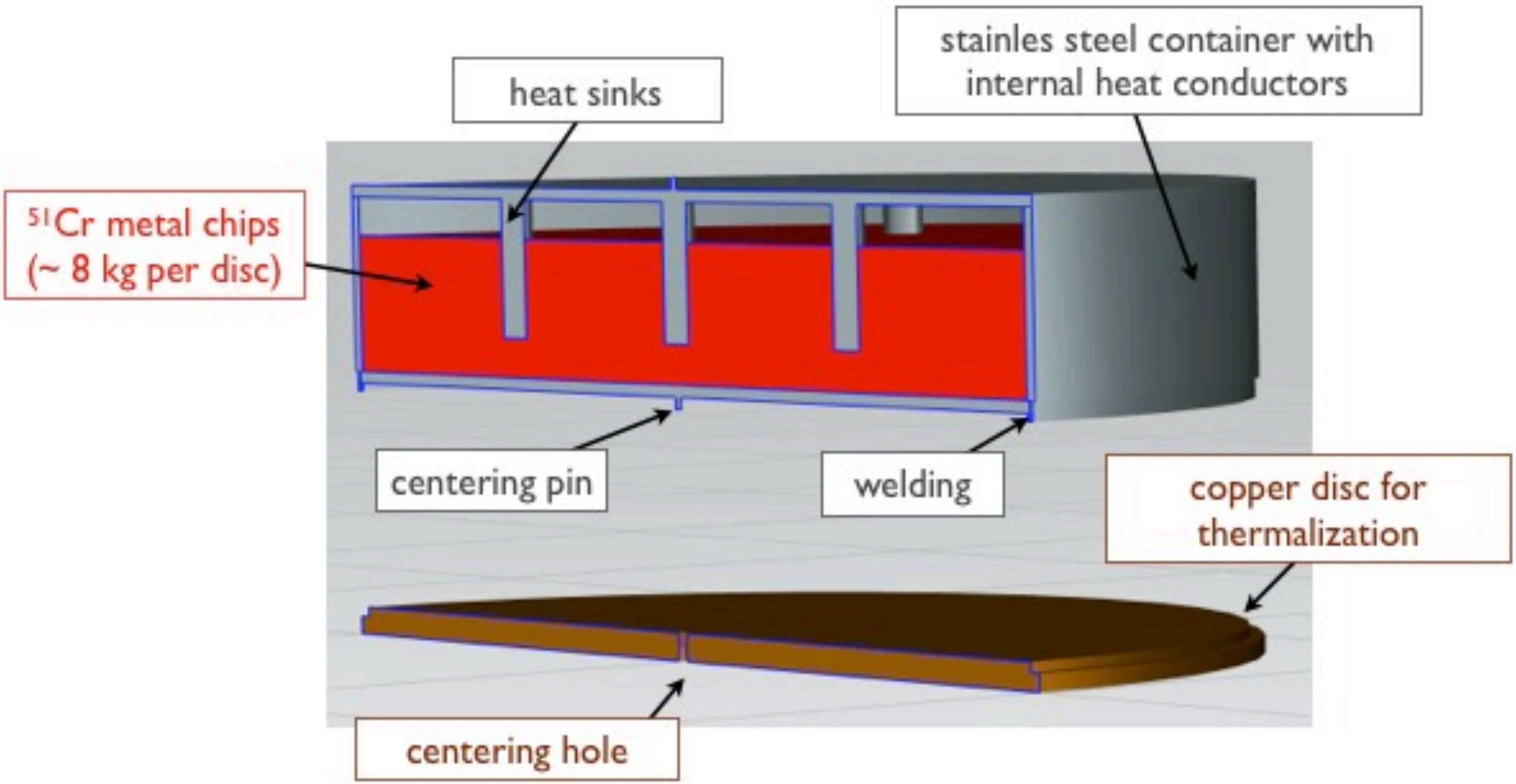
External T must be acceptable
Current value: T=90°C

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

The neutrino generator

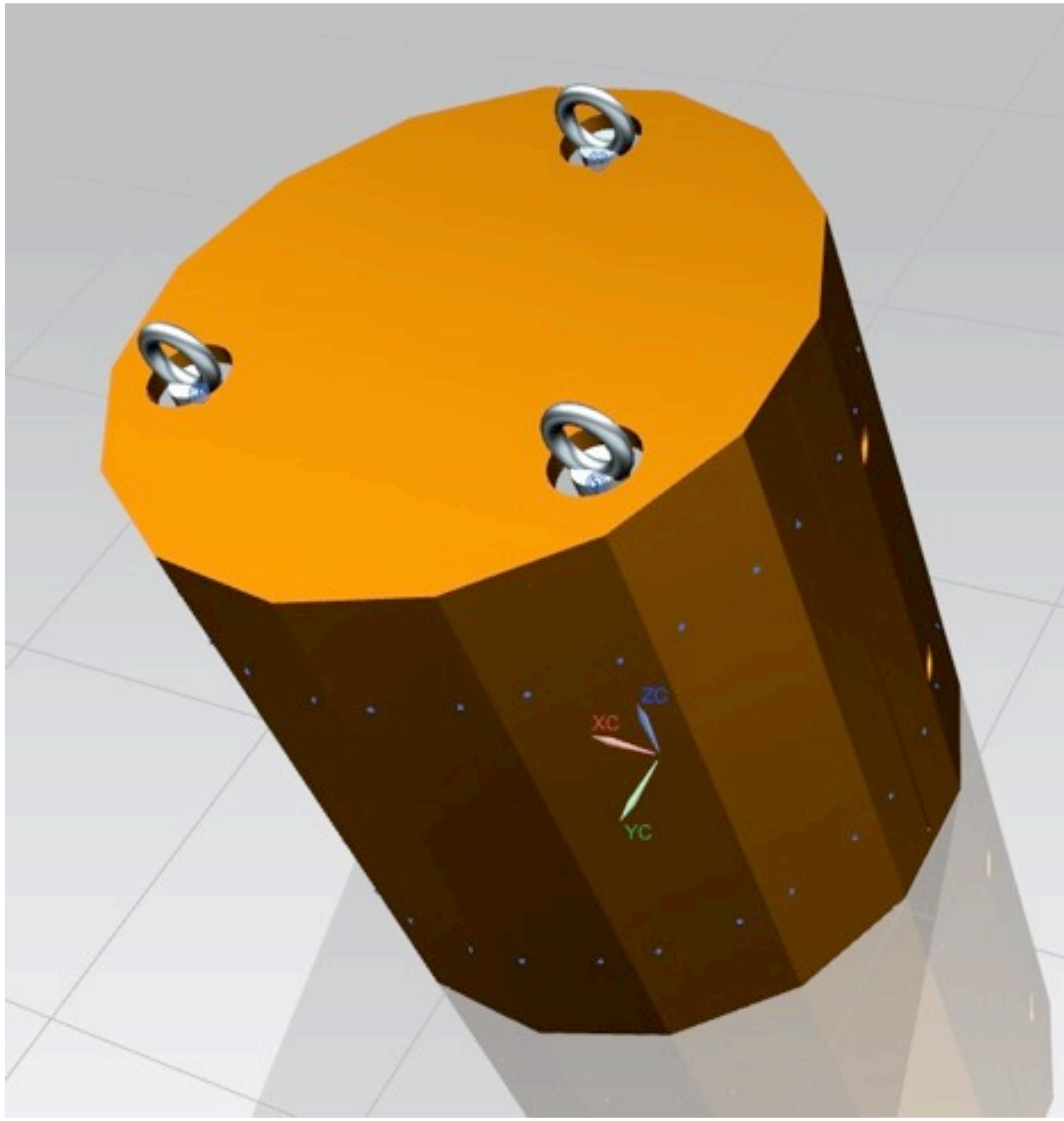


Internal design

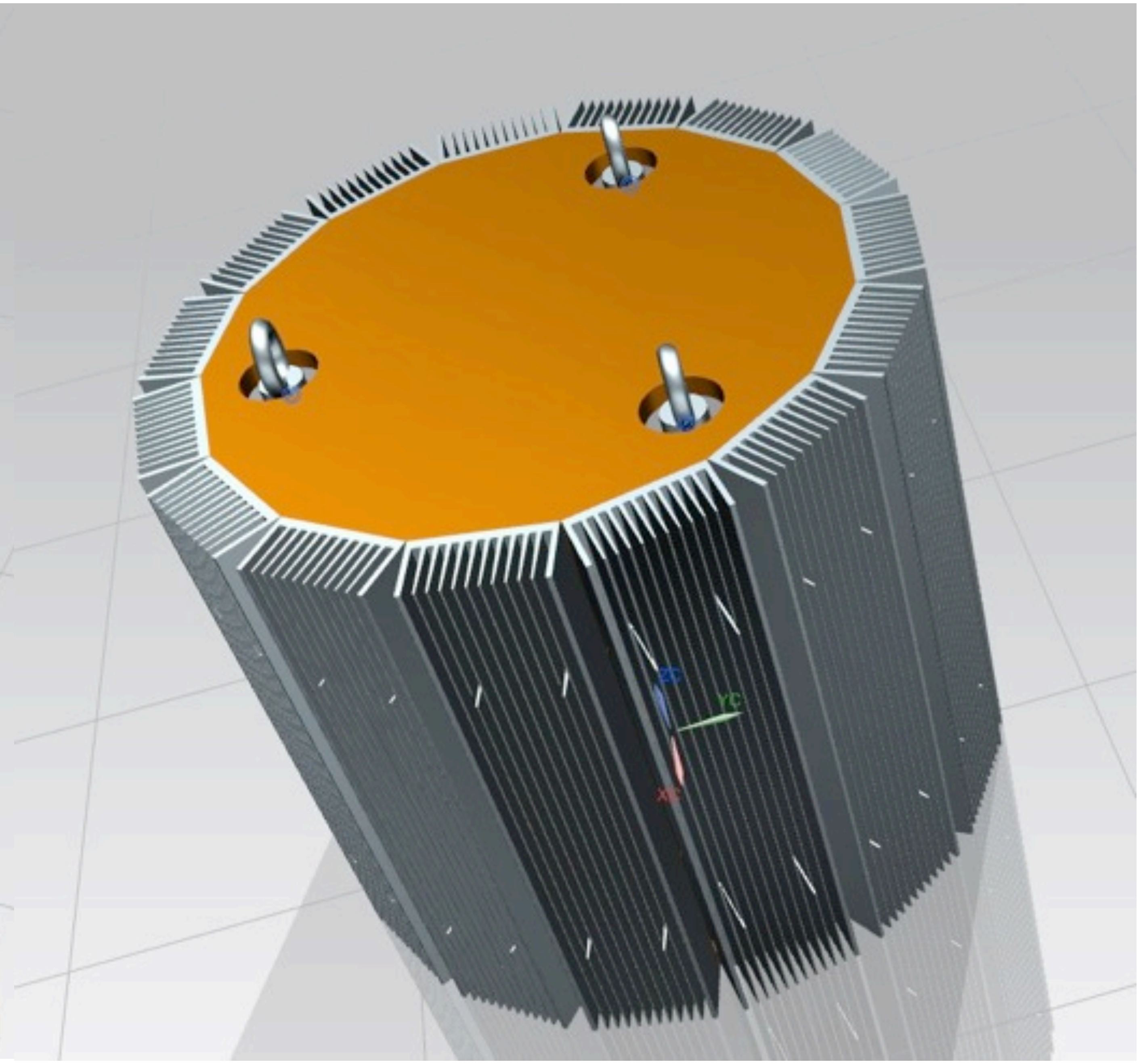


Final assembly

without cooling fins

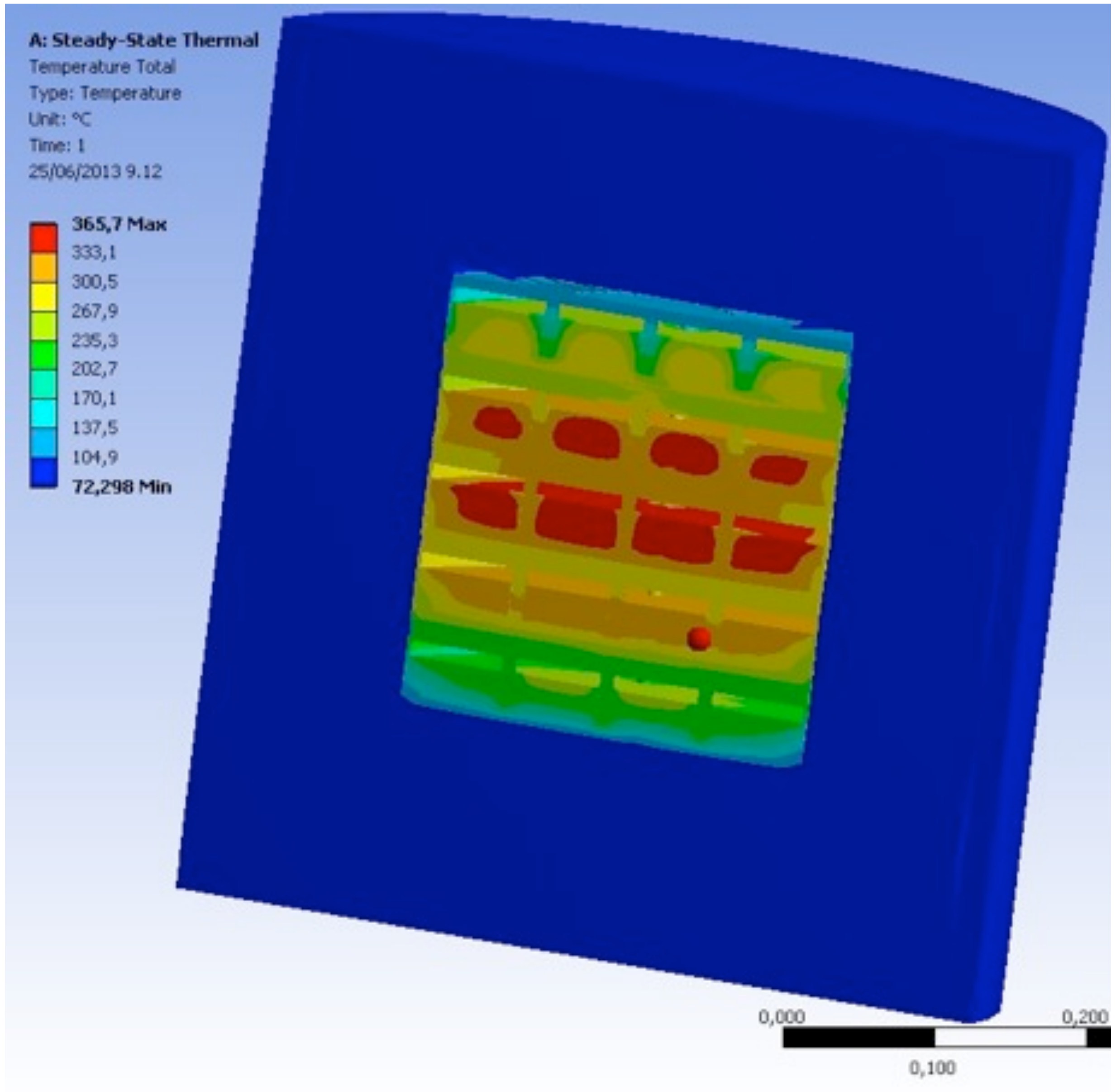


with cooling fins

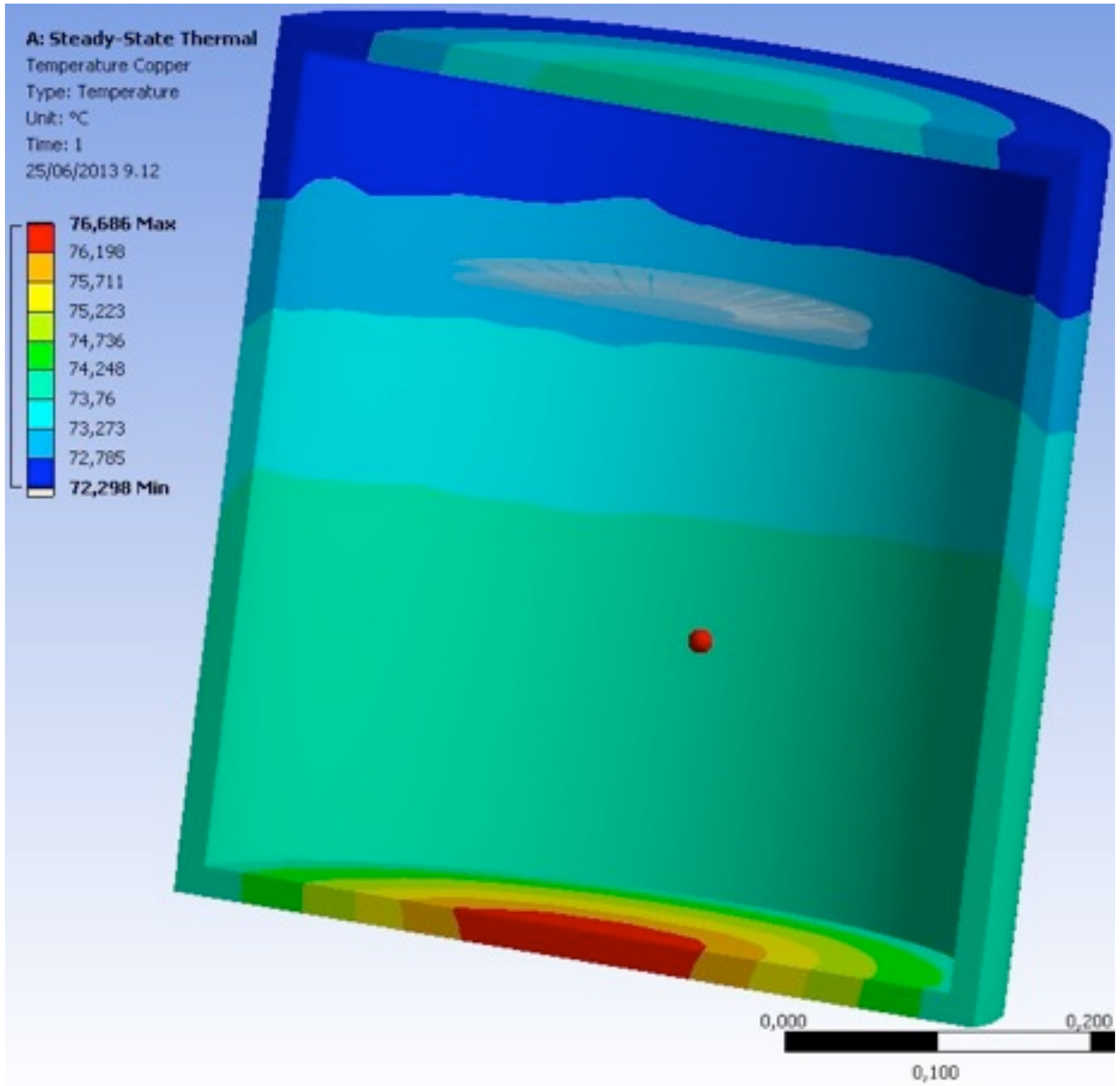


Thermal studies

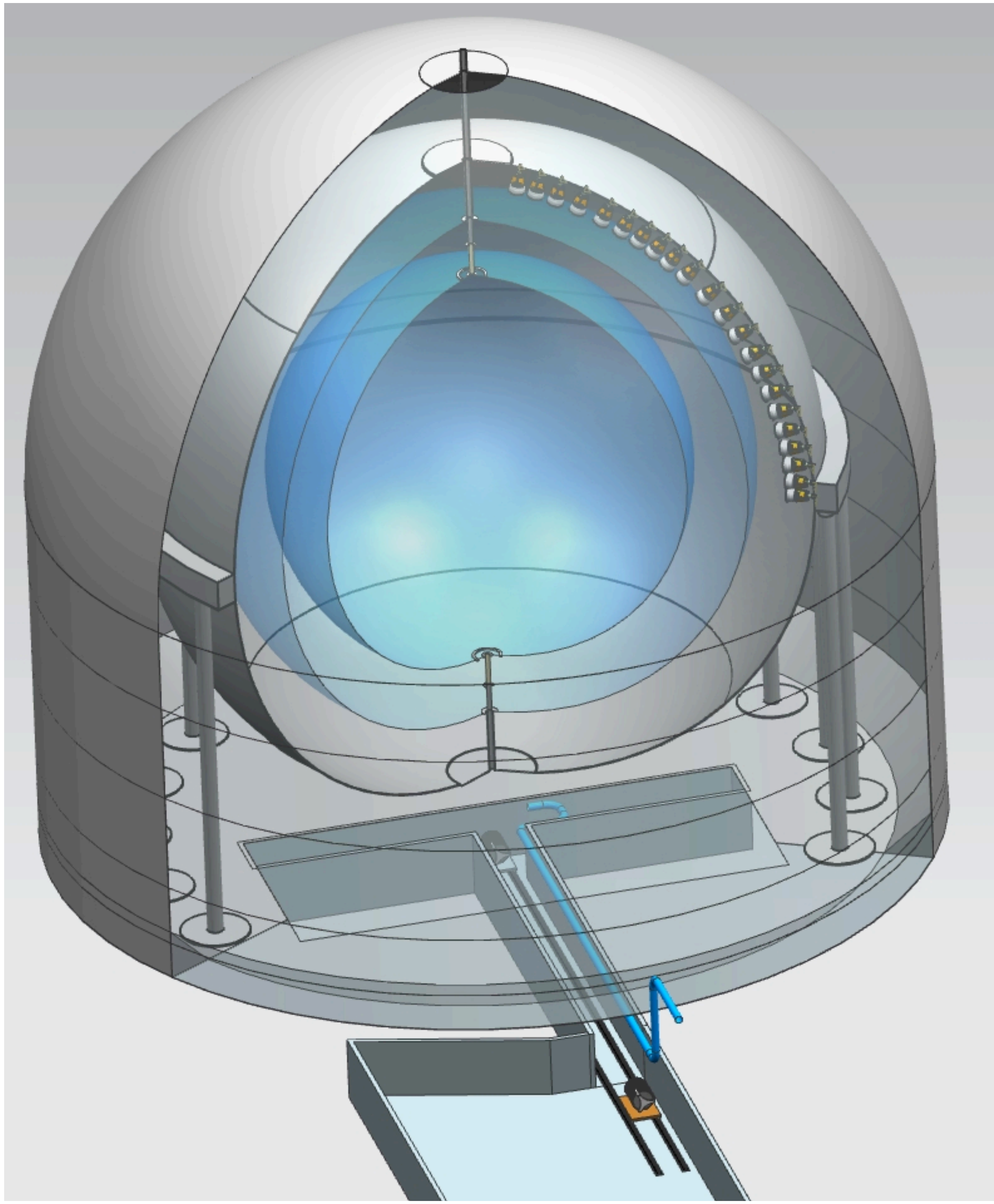
Bulk temperatures

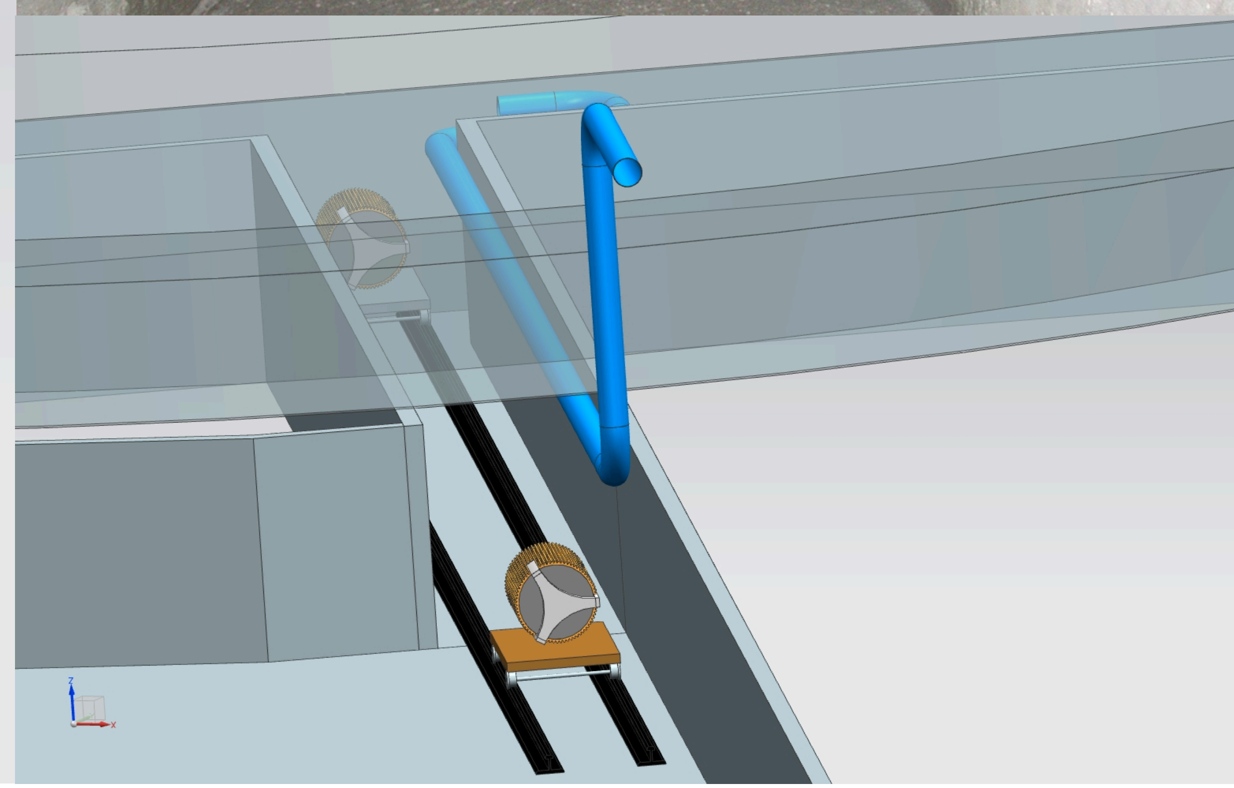


Surface temperatures



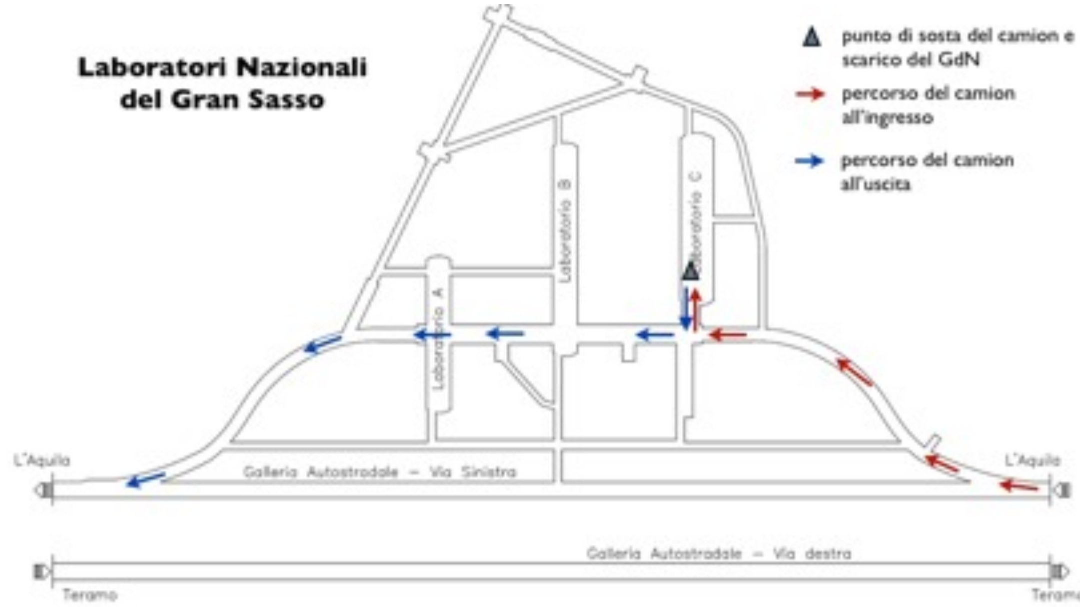
Technology: location for ^{51}Cr source

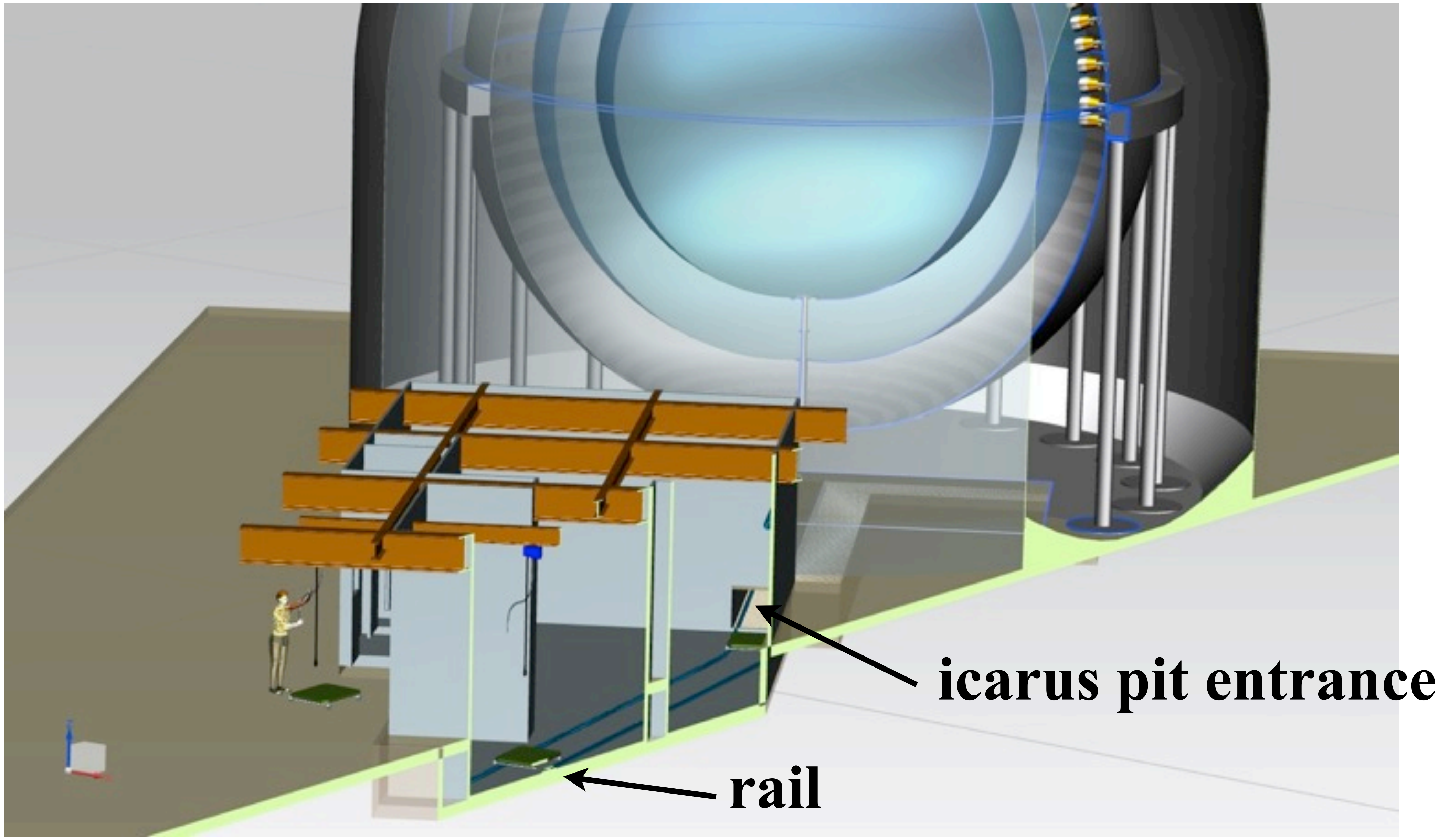




Logistics at the Lab

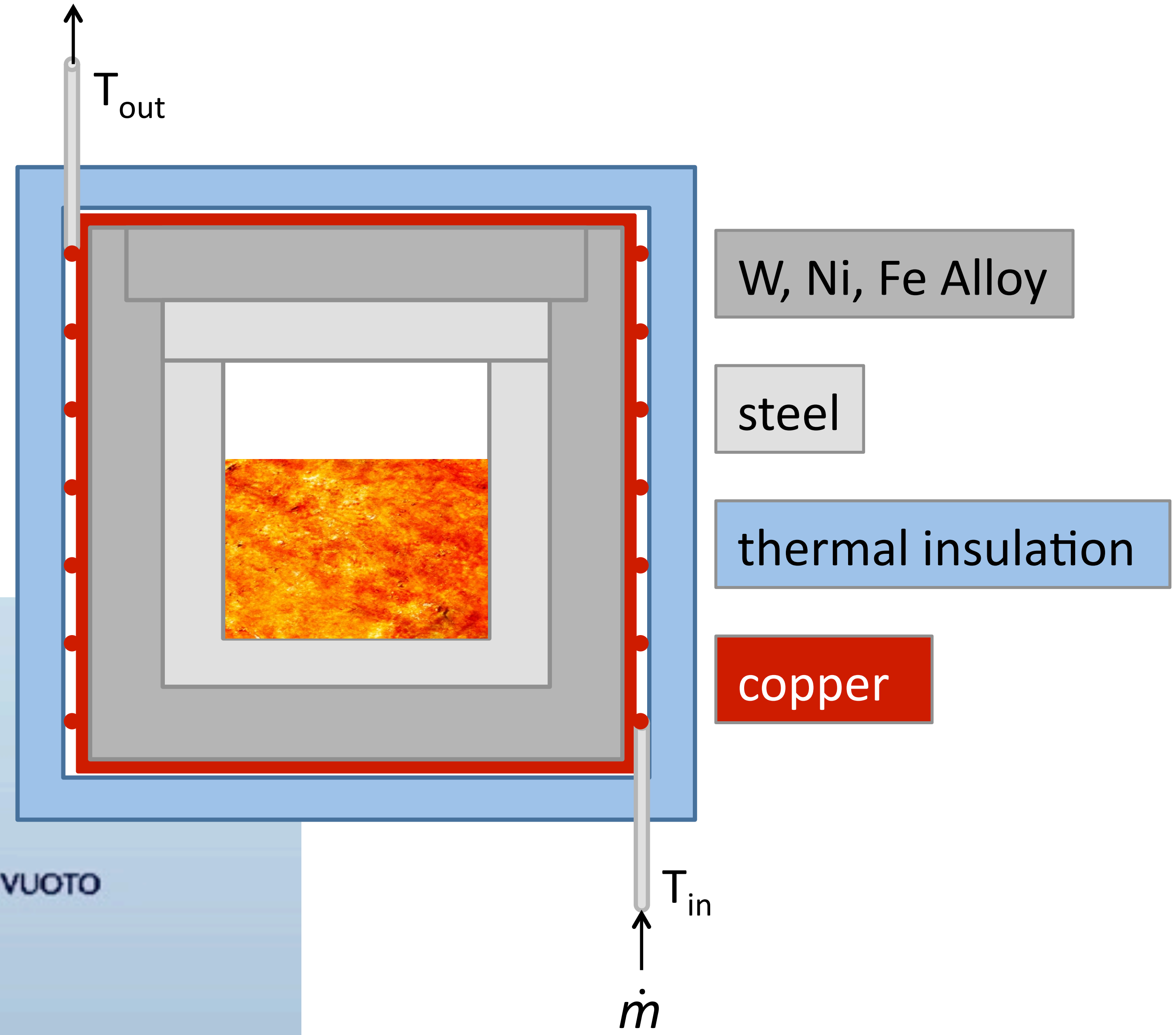
- The neutrino generator will enter undergroun directly
  - It will stay in Hall C 4-6 months

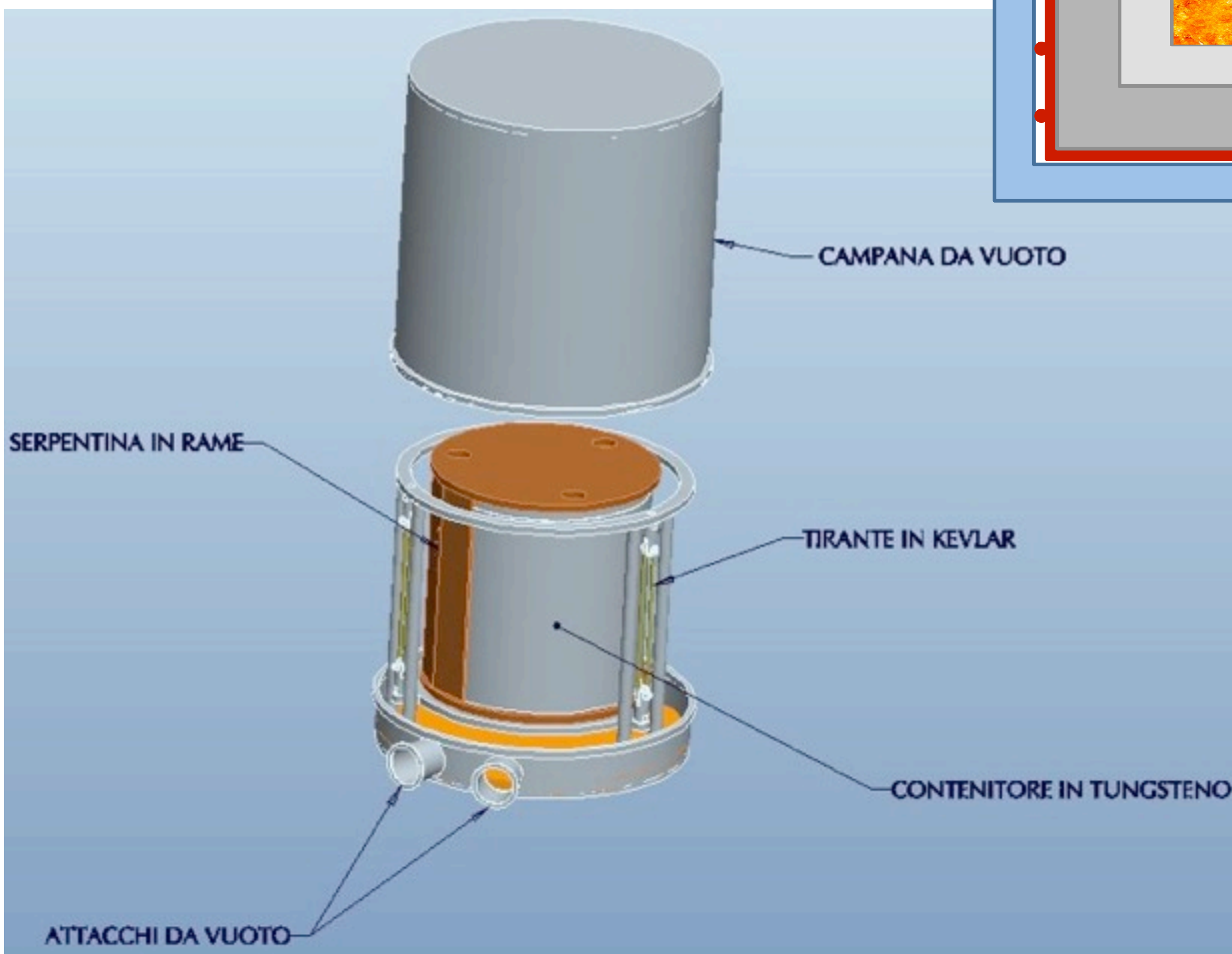




calorimetry

- The neutrino generator will actually stay within a **calorimeter** for precise measurement of the activity

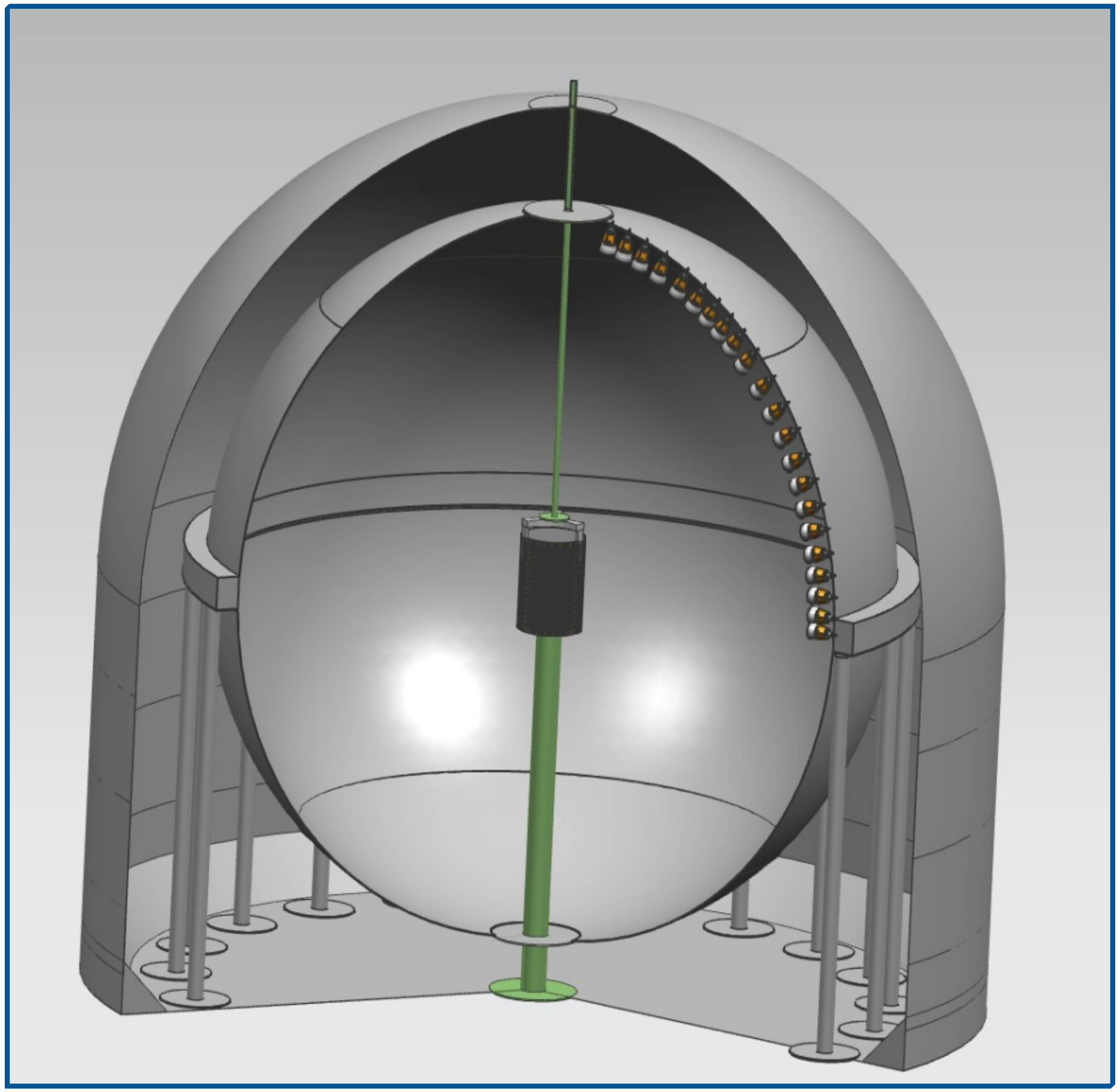




$$\dot{Q} = \dot{m}C\left(T_{in} - T_{ext}\right)$$

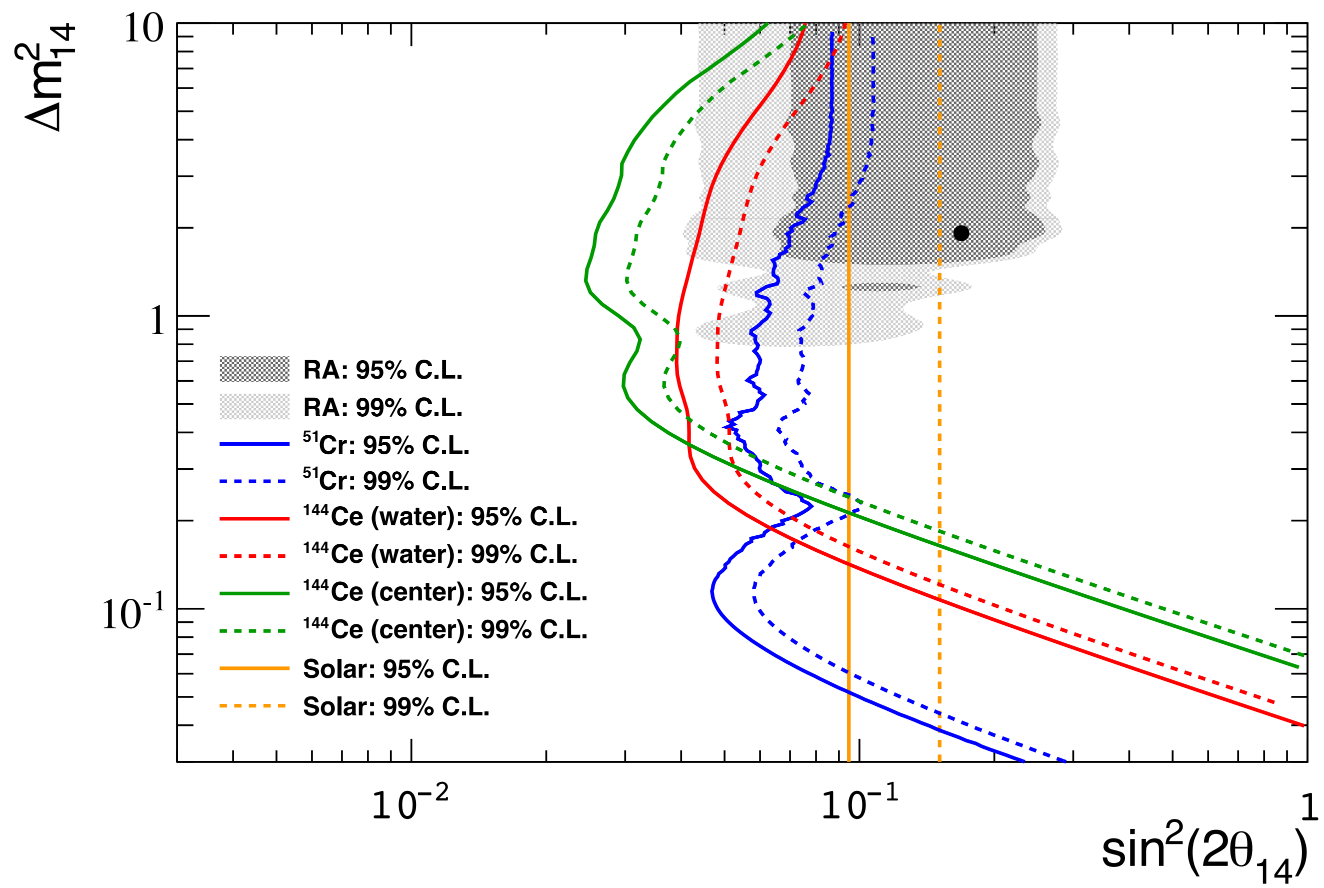
SOX–C: ^{144}Ce source inside detector

- Very **massive** source (see M. Cribrier talk this morning)
  - **~ 4 t** of shielding
  - Source: **spent nuclear fuel from Russia**
- **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.**



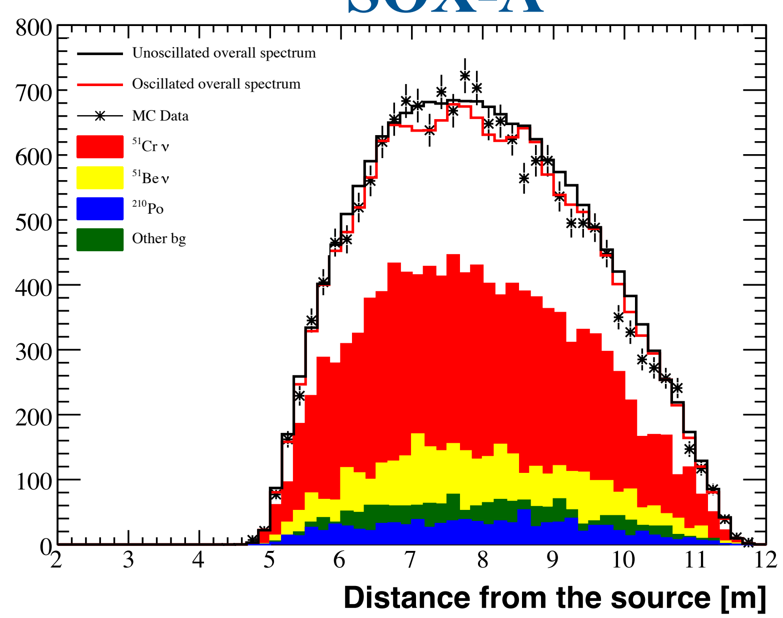
Summary

- 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)

SOX-A



SOX-C