Borexino: recent solar and terrestrial neutrino results and description of the SOX project - Short Distance Neutrino Oscillations with Borexino

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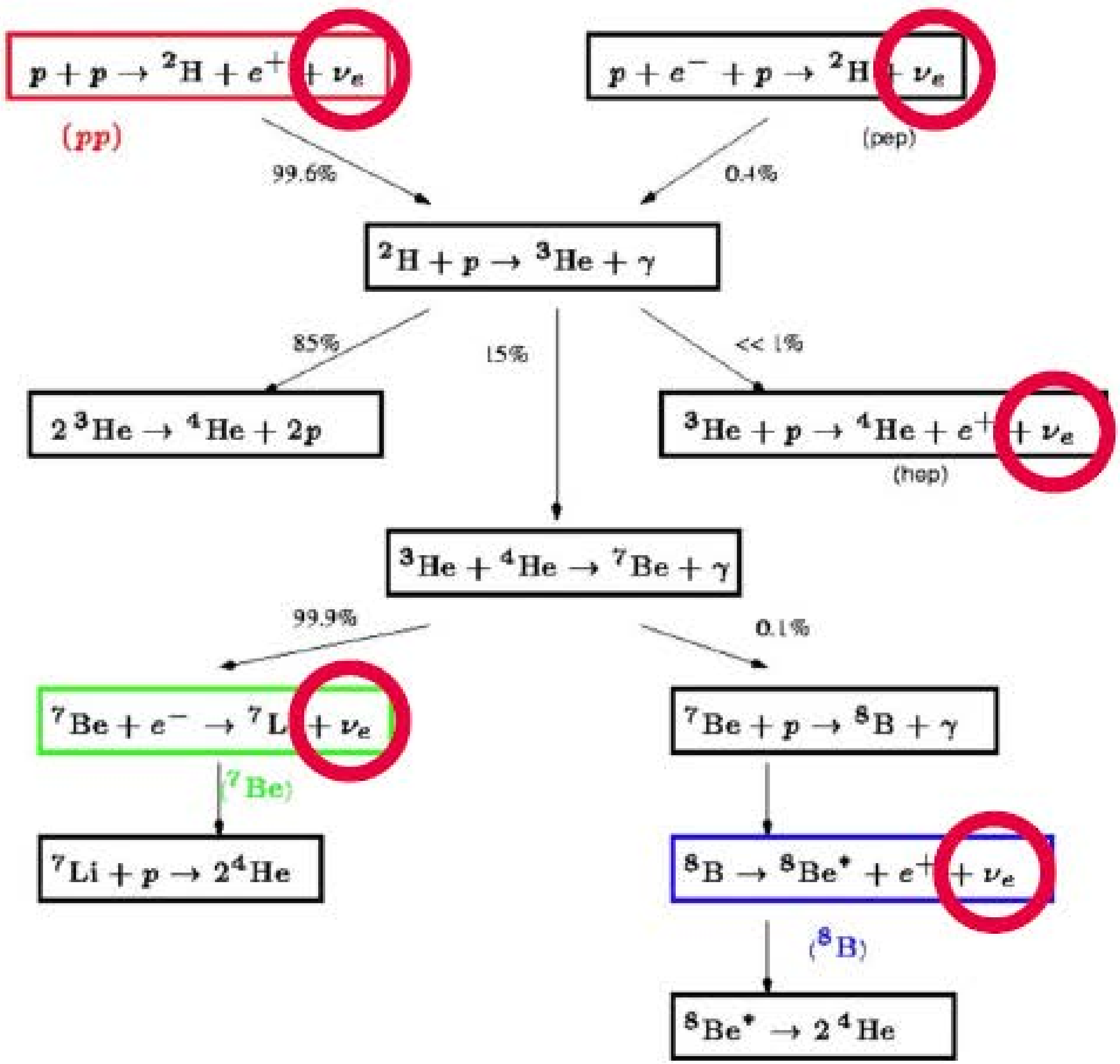
On behalf of the Borexino Collaboration

Stockholm – EPS HEP
20/7/2013

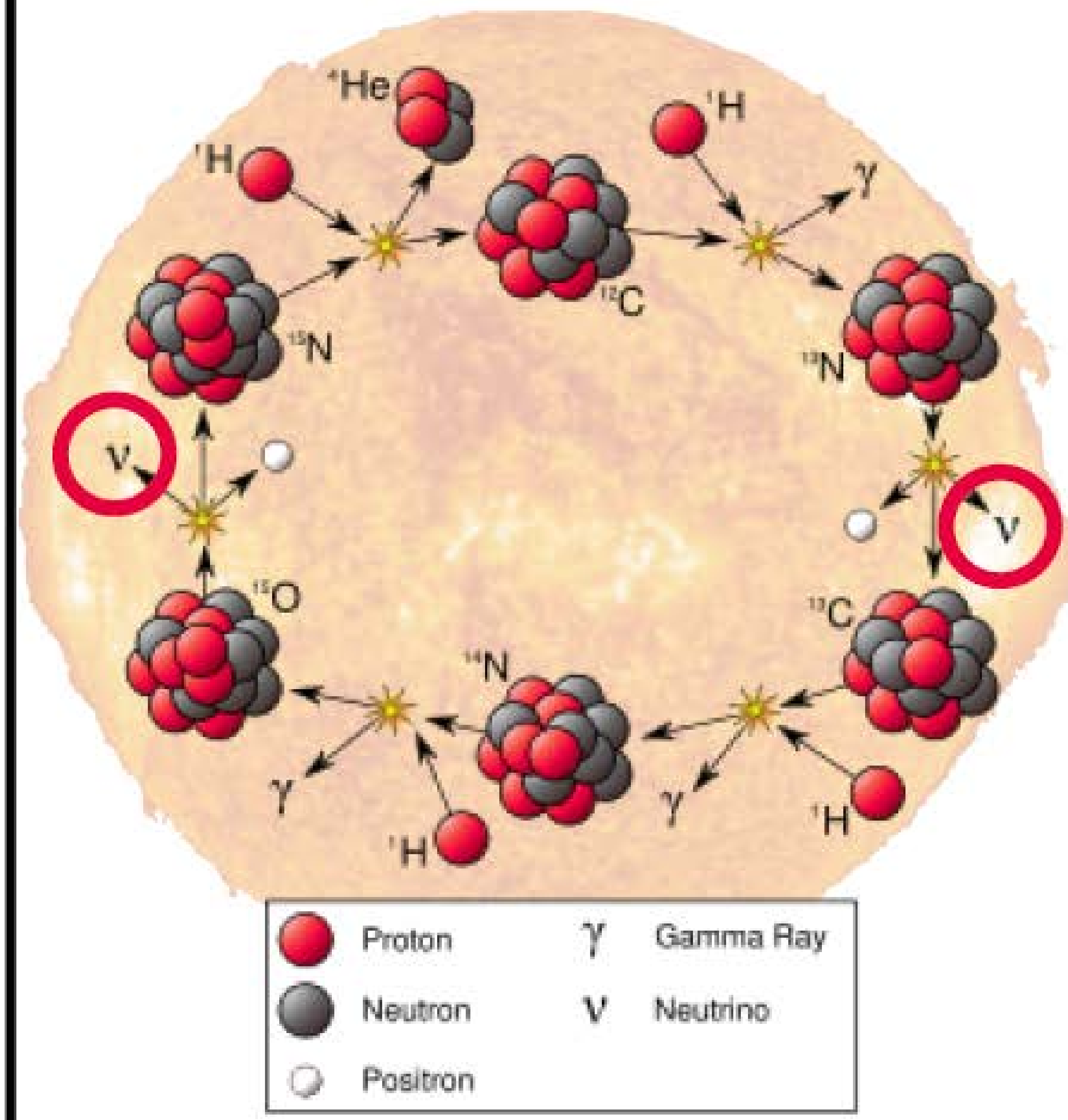
Solar Neutrinos

pp Chain



CNO Cycle

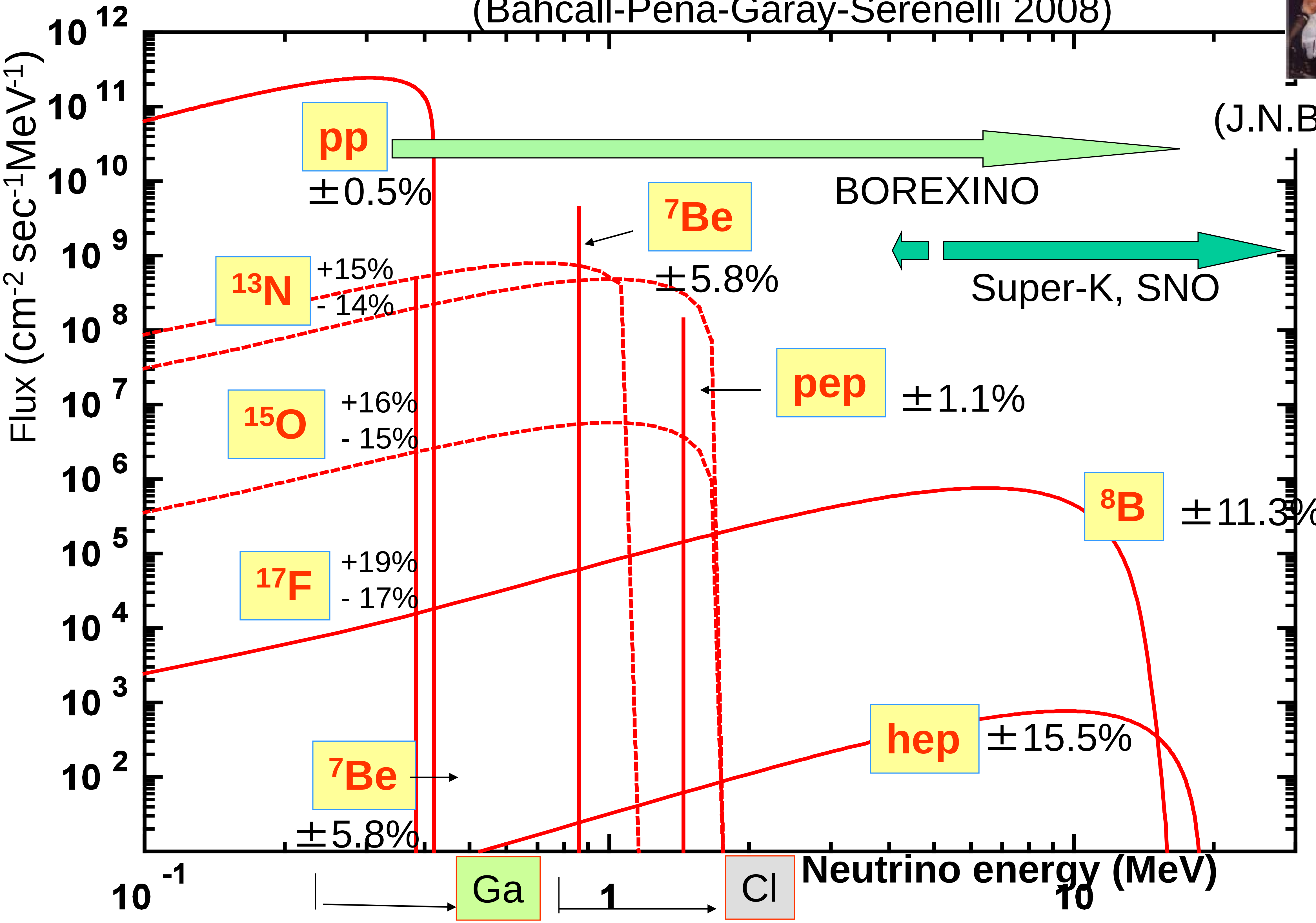
(contributes ~1% of solar energy)

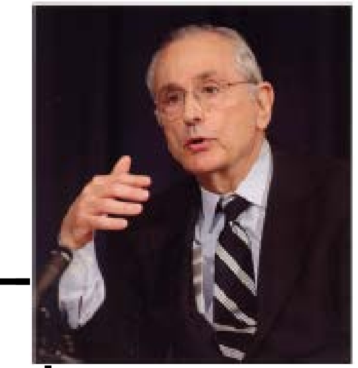


Solar neutrino spectrum

predicted by the Standard Solar Model (SSM)

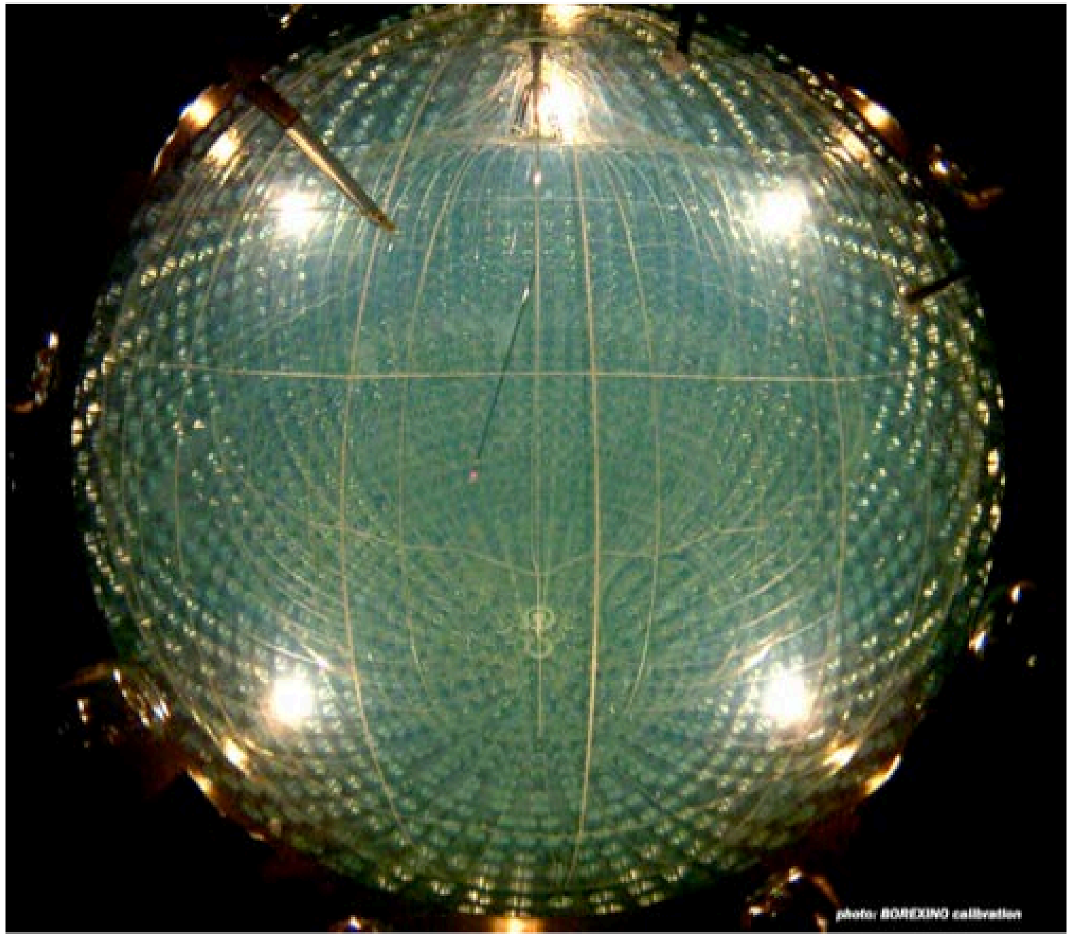
(Bahcall-Pena-Garay-Serenelli 2008)





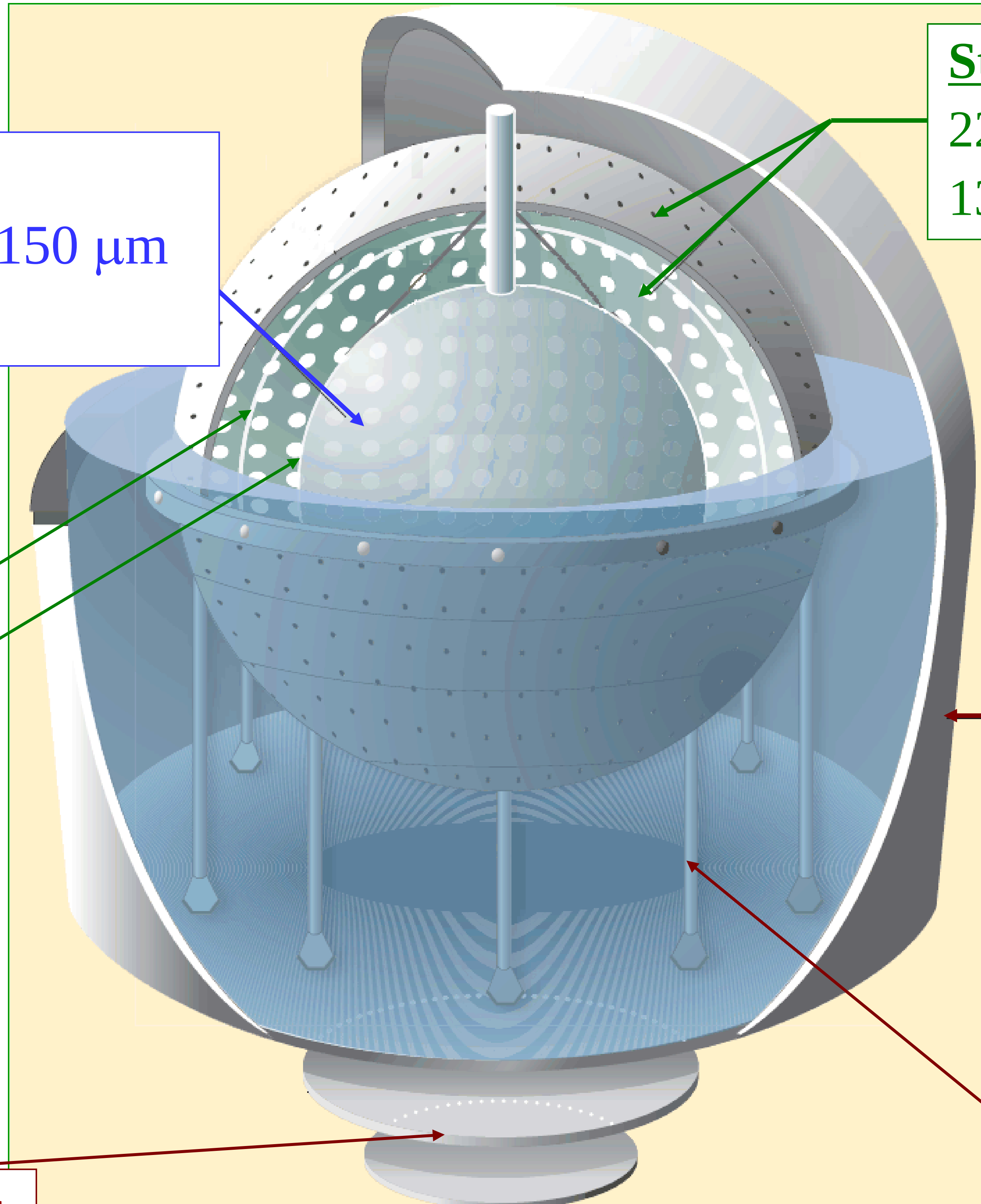
(J.N.Bahcall)

Surface metallicity puzzle still open…



Many accomplishments of Borexino in the solar neutrino arena and beyond…

Borexino at Gran Sasso: low energy real time detection



Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel

Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Design based on the principle of graded shielding

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

Neutrino electron scattering

$\nu e \rightarrow \nu e$

20 legs

Carbon steel plates

Detection principle

$$\nu_x + e \rightarrow \nu_x + e$$

Elastic scattering off the electron of the scintillator
threshold at ~ 60 keV (electron energy)

Goals: (in read already accomplished) ^{7}Be flux (862 keV), ^{8}B with a lower threshold down to 2.2 MeV, pep (1.44 MeV), possibly pp and CNO in the future, Geo-antineutrinos (Phys.Lett.687,2010), Supernovae neutrinos, **all requiring ultra-low background especially the solar measurements – the big challenge of the experiment!**

Further proposed measurements with ν and $\bar{\nu}$ artificial sources for sterile neutrino search (second part of the talk)

Results made possible by

a) **Ultra-low background**

b) **Thorough calibration of the detector with internal and external sources**

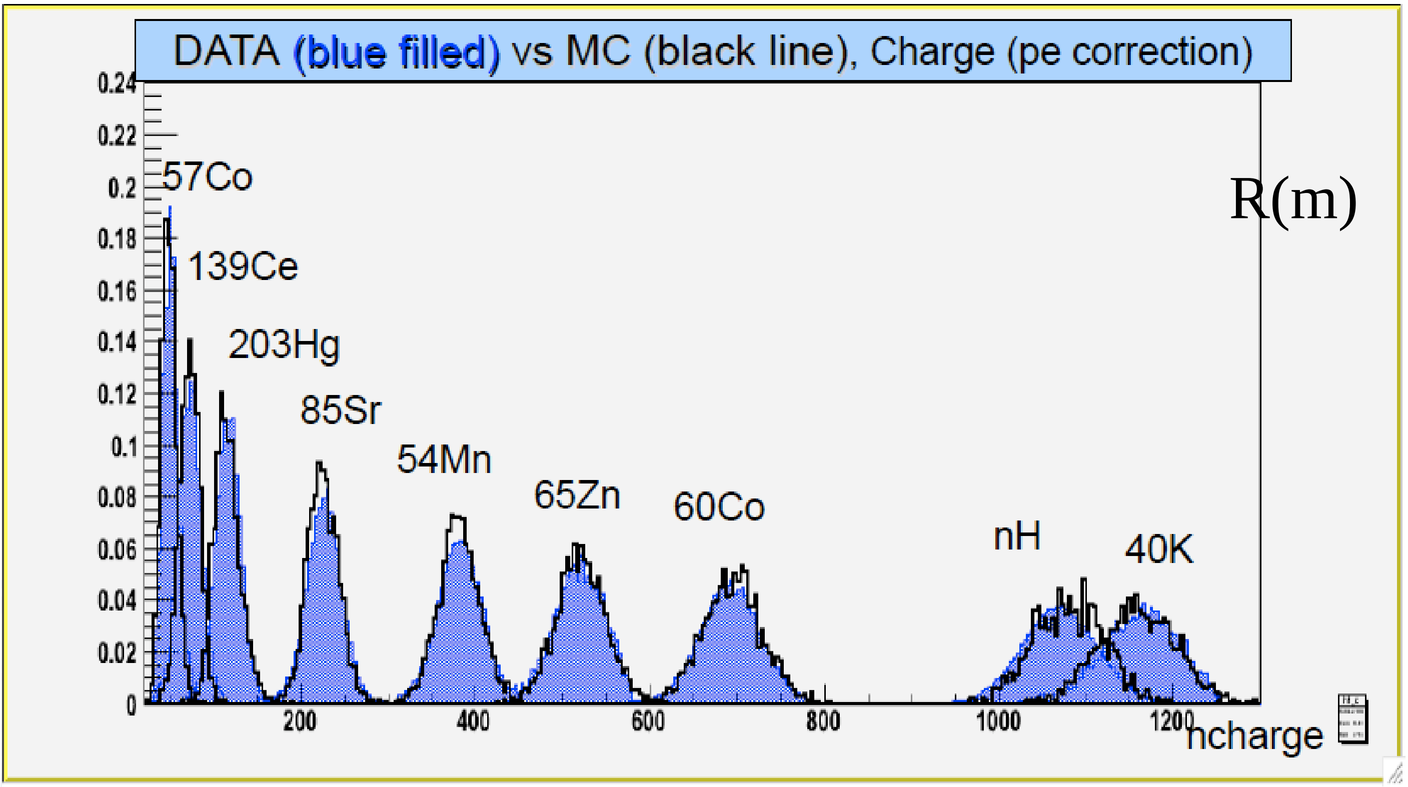
c) **A detailed MC able to reproduce accurately the calibration results**

d) **High statistics**

→ Extraction of the fluxes through a data-to-model fit

Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	**Achieved**
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	**<$10^{-10}$$s^{-1}$ m^{-2}**	underground water detector	Cerenkov PS analysis	< 10^{-10} eff. > 0.9992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	~10^{-12} g/g	~10^{-18} g/g	selection	threshold	~ 2 10^{-18} g/g
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	**<10^{-16} g/g**	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	$(1.67 \pm 0.06)10^{-17}\, g/g$ $(4.6 \pm 0.8)10^{-18}\, g/g$
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	<10^{-6} Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	<10^{-18} g/g	distillation, W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		**<1 c/d/t**	distillation, W.E., filtration, cleanliness	fit	**May '07: 70 c/d/t Jan '10: ~1 c/d/t**
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	<10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	<1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	**< 1 cpd 100 t**	N_2 stripping	fit	**30 ± 5 cpd/100 t**

Low energy range (0.14-2 MeV) calibration



Energy scale-Resolution

$$\frac{5\%}{\sqrt{E}}$$ from 200 keV to 2 MeV

Beyond 2 MeV: A little worse due to the less accuracy in the calibration

@ MC tuned on γ source results

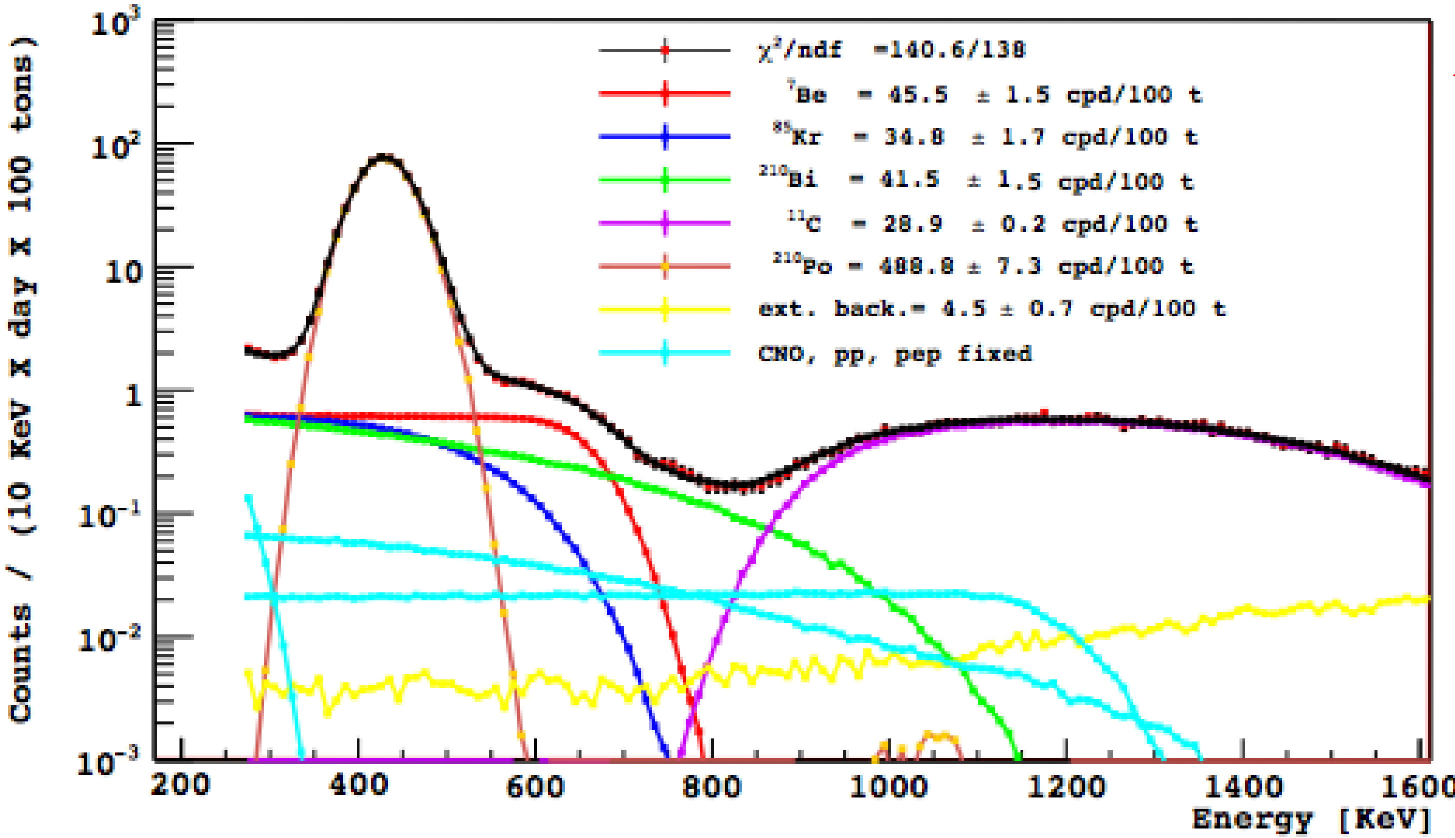
@ Determination of Light yield and of the Birks parameter k_B

L.Y. ⟶ obtained from the γ calibration sources with MC: **511 p.e./MeV**

↘ left as free parameter in the total fit in the analytical approach

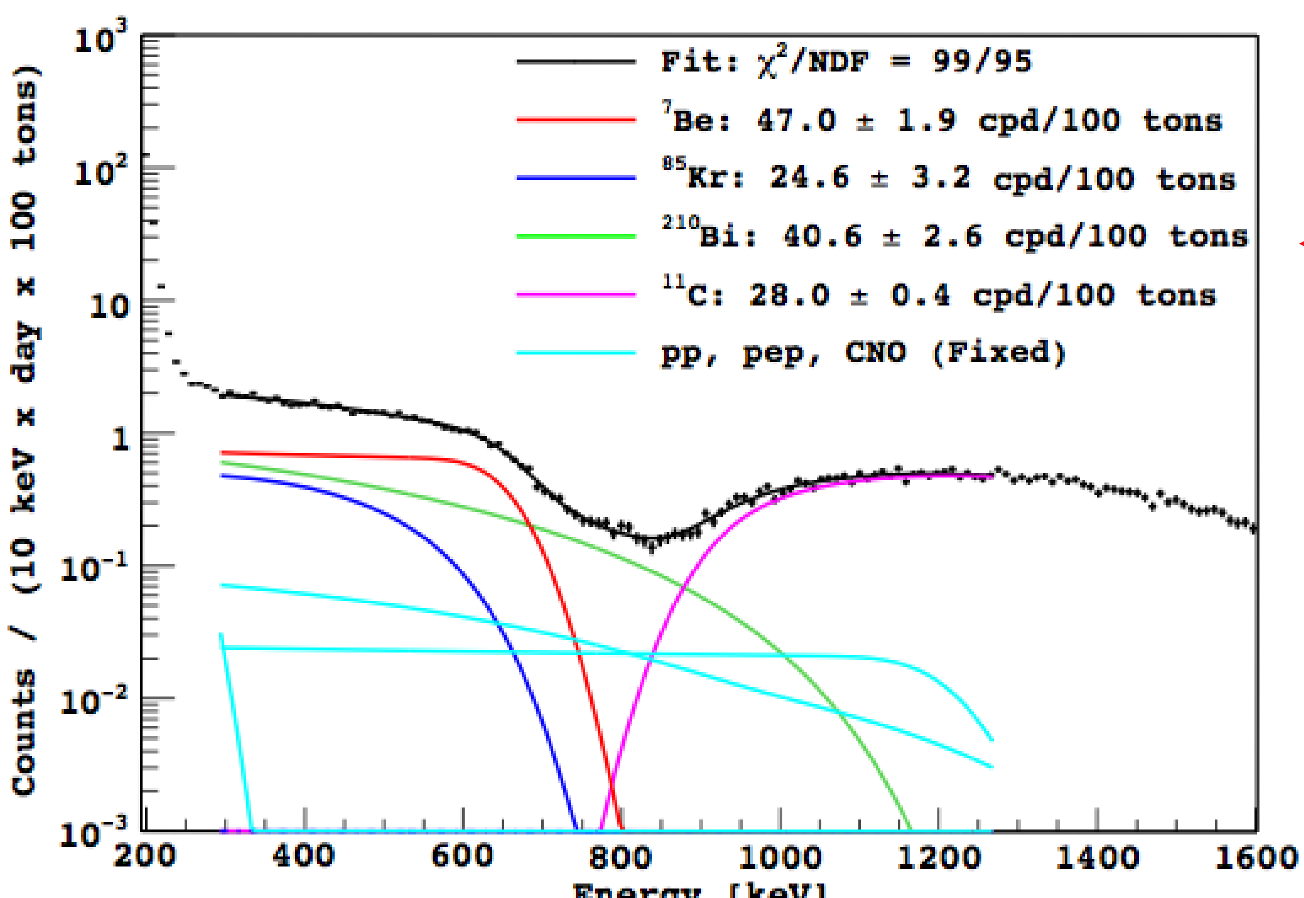
@ Precision of the energy scale global determination: **1.5%** (1 σ)

@ Fiducial volume uncertainty: $\left.\right\rangle^{+0.5}_{-1.3}\,\%$ (1 σ)



MC- fit range: 250-1600 keV
Soft α subtraction

pp, pep, CNO fixed, according MSW-LMA high metallicity
free parameters: ^{7}Be, ^{85}Kr, ^{210}Bi (β emitter) , ^{11}C, ^{210}Po (α emitter), ^{14}C, ^{214}Pb (β emitter)



Analytical- fit range 300- 1250 keV
statistical α subtraction via PSD

The ^{7}Be flux is extracted via a multi-component fit

Result

^{7}**Be(0.862): 46±1.5 (stat.)** $\left.\right\rangle {}^{+1.5}_{-1.6}$ **(syst)cpd/100 tons**

Corresponding to an equivalent ν_e flux of $(2.78 \pm 0.13) \times 10^{9}\ cm^{-2}s^{-1}$
By assuming the MSW-LMA solution the absolute ^{7}Be solar neutrino flux measure is $(4.84 \pm 0.24) \times 10^{9}\ cm^{-2}s^{-1}$
The ratio of our measurement to the SSM prediction is fBe=0.97 ± 0.09

Other main components in the fit

$$^{85}\mathrm{Kr}\quad 28.0 \pm 2.1_{stat} \pm 4.7_{syst}$$
$$^{210}\mathrm{Bi}\quad 40.3 \pm 1.5_{stat} \pm 2.3_{syst}$$
$$^{11}\mathrm{C}\quad 28.5 \pm 0.2_{stat} \pm 0.7_{syst}$$

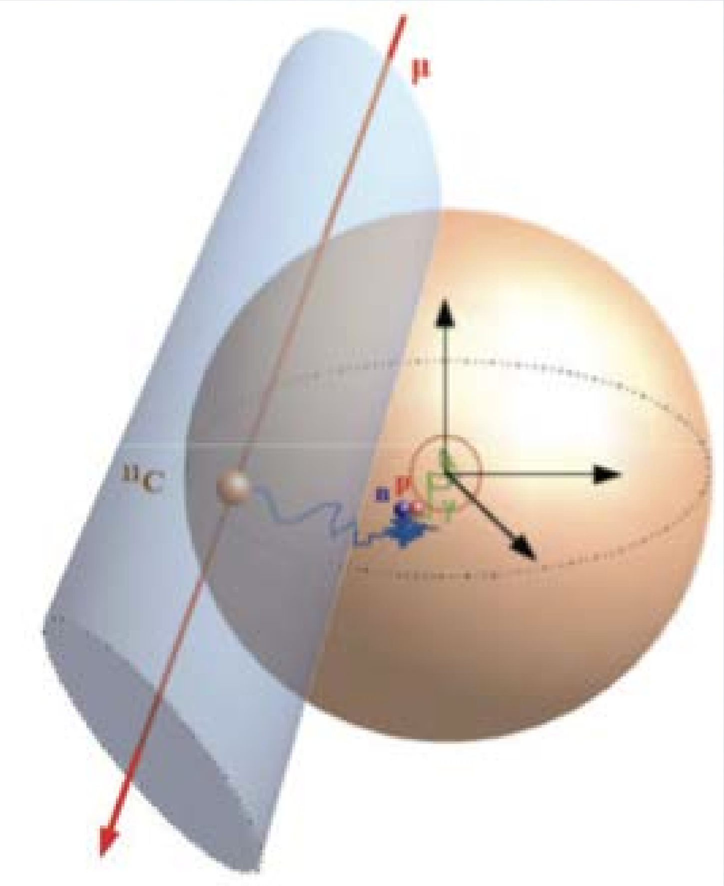
^{85}**Kr** in very good agreement with the correlated coincidence determination

Unprecedented better than 5% precision in low energy solar neutrino measurements

Associate result zero day night asymmetry – as expected

FIRST DETECTION of PEP neutrinos

- Borexino obtained first evidence of **pep neutrinos**
  - Thanks to the very low background and analysis tools developed for ^{11}C rejection
    - Three fold coincidence tagging of ^{11}C events
    - **β+ - β** separation exploiting **positronium** induced pulse shape distortion
    - Multivariate maximum likelihood test using all available information



- **Three-fold coincidence**

$\mu + {}^{12}C \rightarrow n + {}^{11}C + \mu$

236 μs

No convection
^{11}C doesn't move

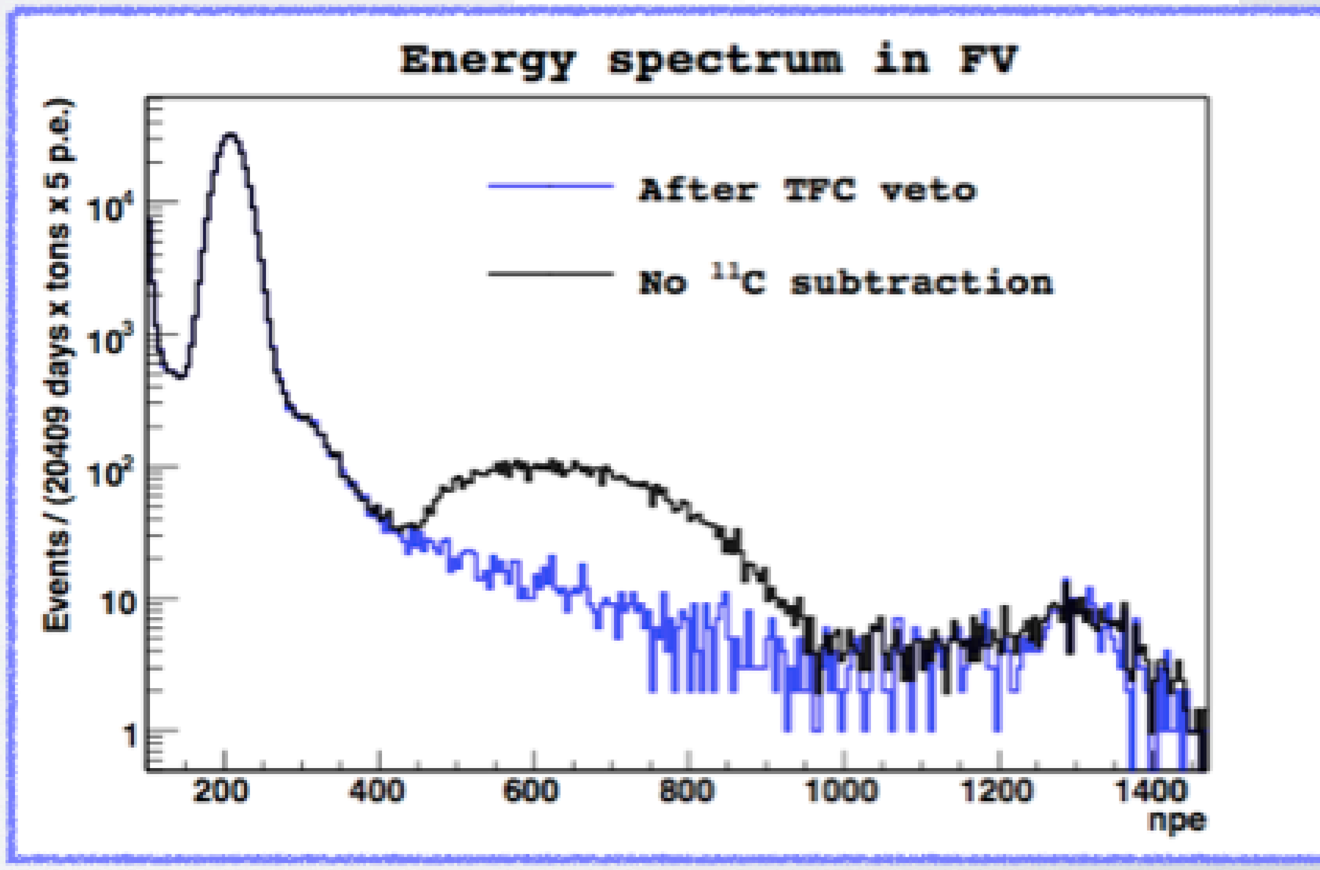
29.4 min

$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$

Quick neutron thermalization and capture yields clear tag

$n + p \rightarrow D + \gamma$ (2.2 MeV)

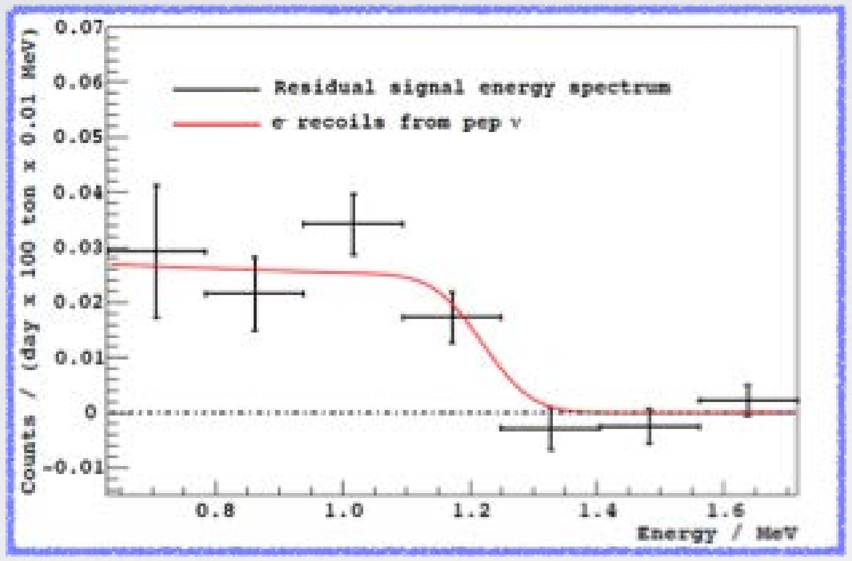
PHYSICAL REVIEW C 74, 045805 (2006)



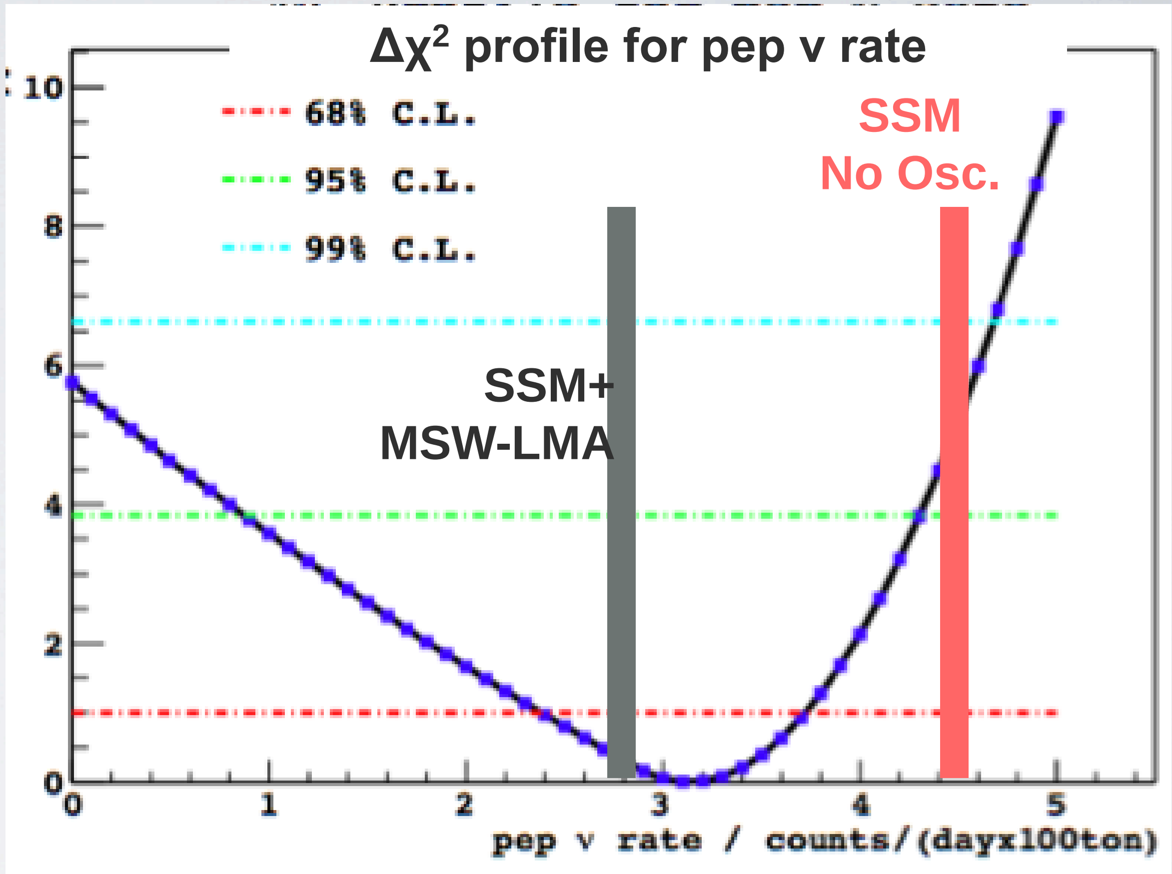
FIRST DETECTION of PEP neutrinos

- Rate: **3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**

PRL 108, 051302 (2012)



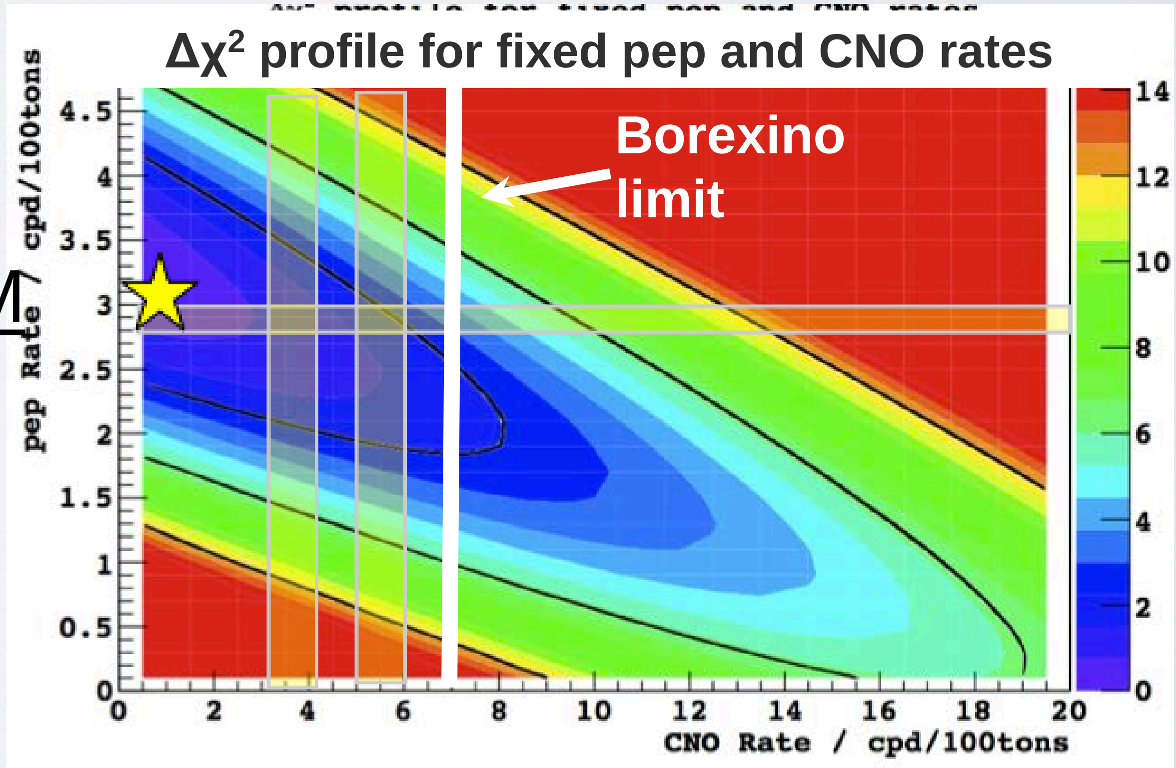
- No oscillations excluded at **97% c.l.**
- Absence of pep solar ν excluded at **98% c.l.**



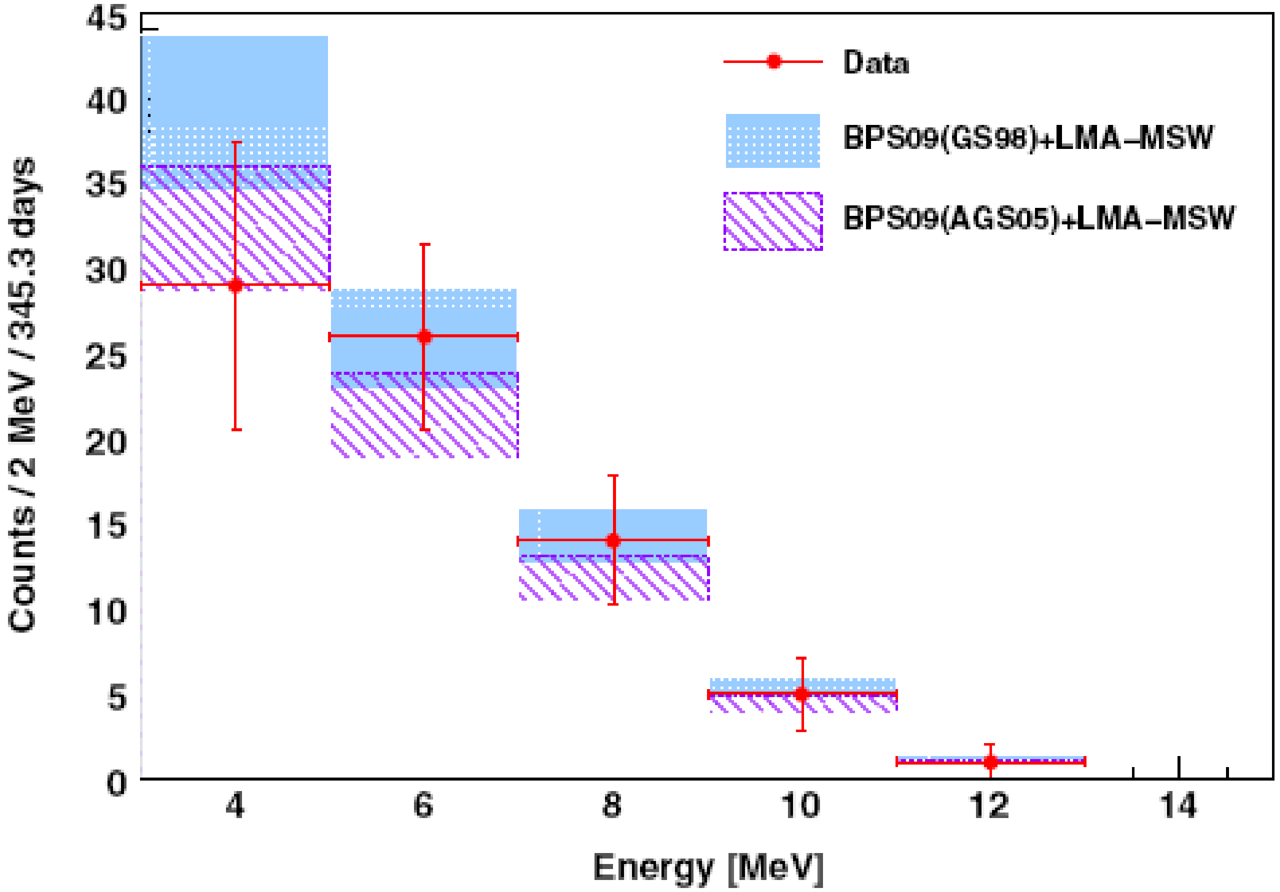
- Assuming MSW-LMA:
  - $\Phi_{pep} = 1.6 \pm 0.3\ 10^{8}\ cm^{-2}\ s^{-1}$

- CNO limit obtained <u>assuming pep @ SSM</u>
  - **CNO rate < 7.1 cpd/100 t (95% c.l.)**

    (1.5 times the SSM prediction)



^8B with lower threshold at 3 MeV



Exp. ^8B spectrum vs models

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ $[10^6\ cm^{-2}\ s^{-1}]$
SuperKamiokaNDE I [7]	5.0	$2.35\pm0.02\pm0.08$
SuperKamiokaNDE II [2]	7.0	$2.38\pm0.05^{+0.16}_{-0.15}$
SNO D_2O [3]	5.0	$2.39^{+0.24}_{-0.23}\ ^{+0.12}_{-0.12}$
SNO Salt Phase [26]	5.5	$2.35\pm0.22\pm0.15$
SNO Prop. Counter [27]	6.0	$1.77^{+0.24}_{-0.21}\ ^{+0.09}_{-0.10}$
Borexino	3.0	$2.4\pm0.4\pm0.1$
Borexino	5.0	$2.7\pm0.4\pm0.2$

Data compatible with both high metallicity and low metallicity models

SSM; H.M.$(2.7\pm0.3)\ x10^6 cm^{-2}s^{-1}$
L.M.$(2.2\pm0.2)\ x10^6 cm^{-2}s^{-1}$

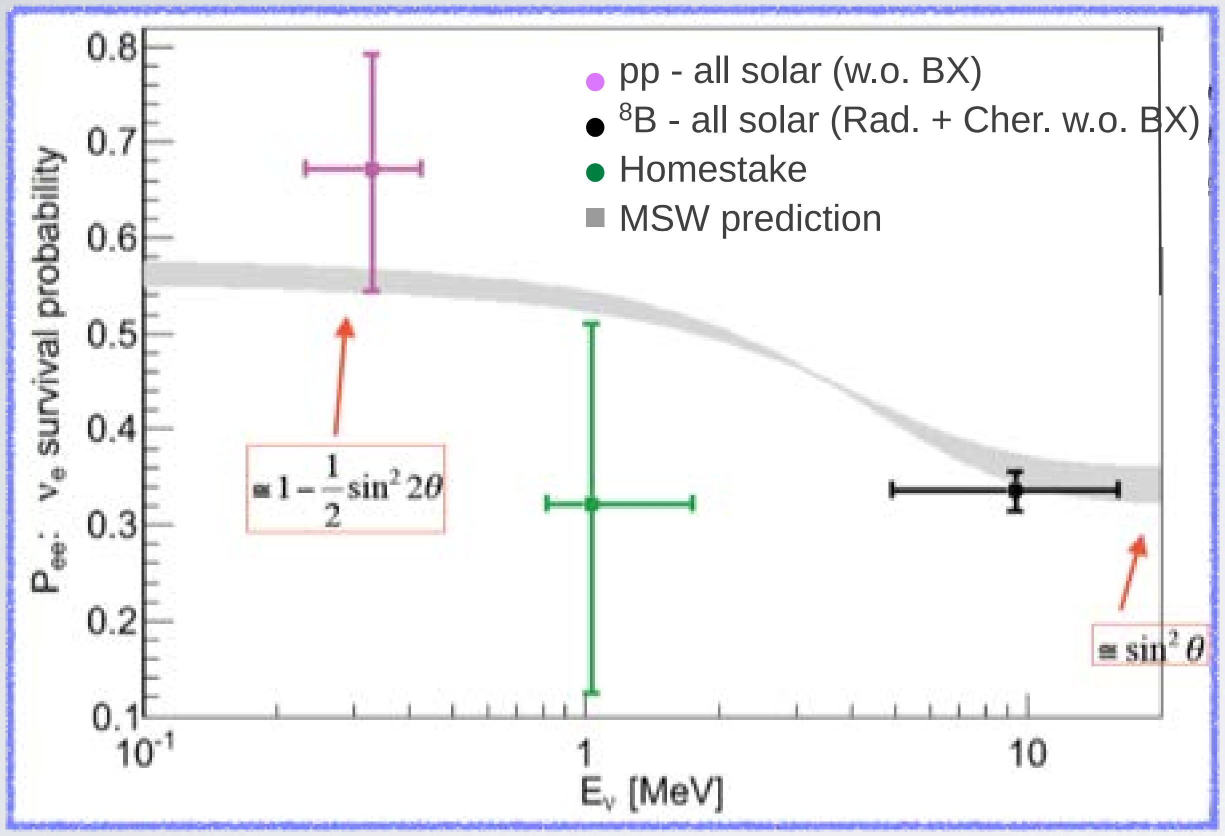
Systematic errors

Source	E>3 MeV		E>5 MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

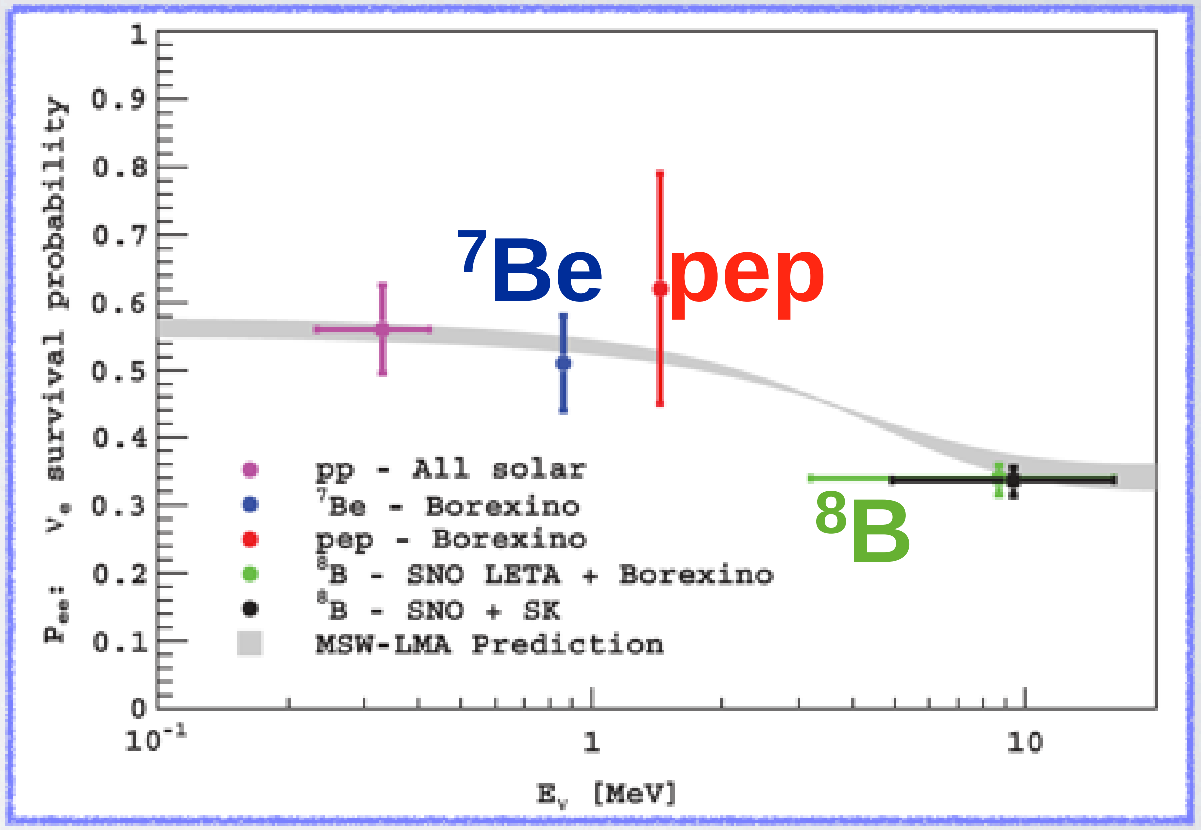
Phys. Rev. D, 82 (2010) 033006

BOREXINO VALIDATION AT LOW ENERGY OF THE LMA MSW OSCILLATION PARADIGM

Before Borexino

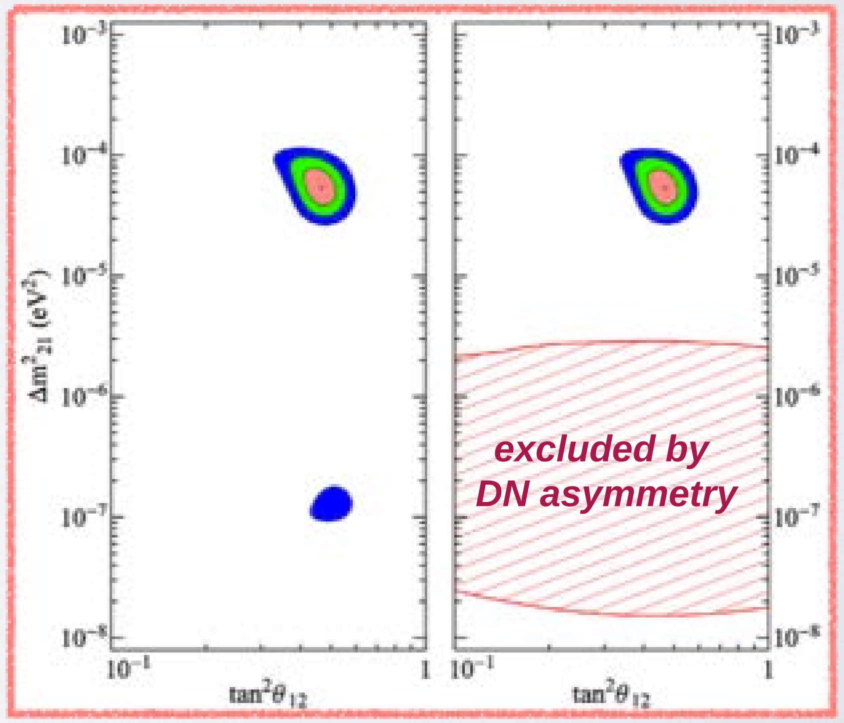


Borexino 2012

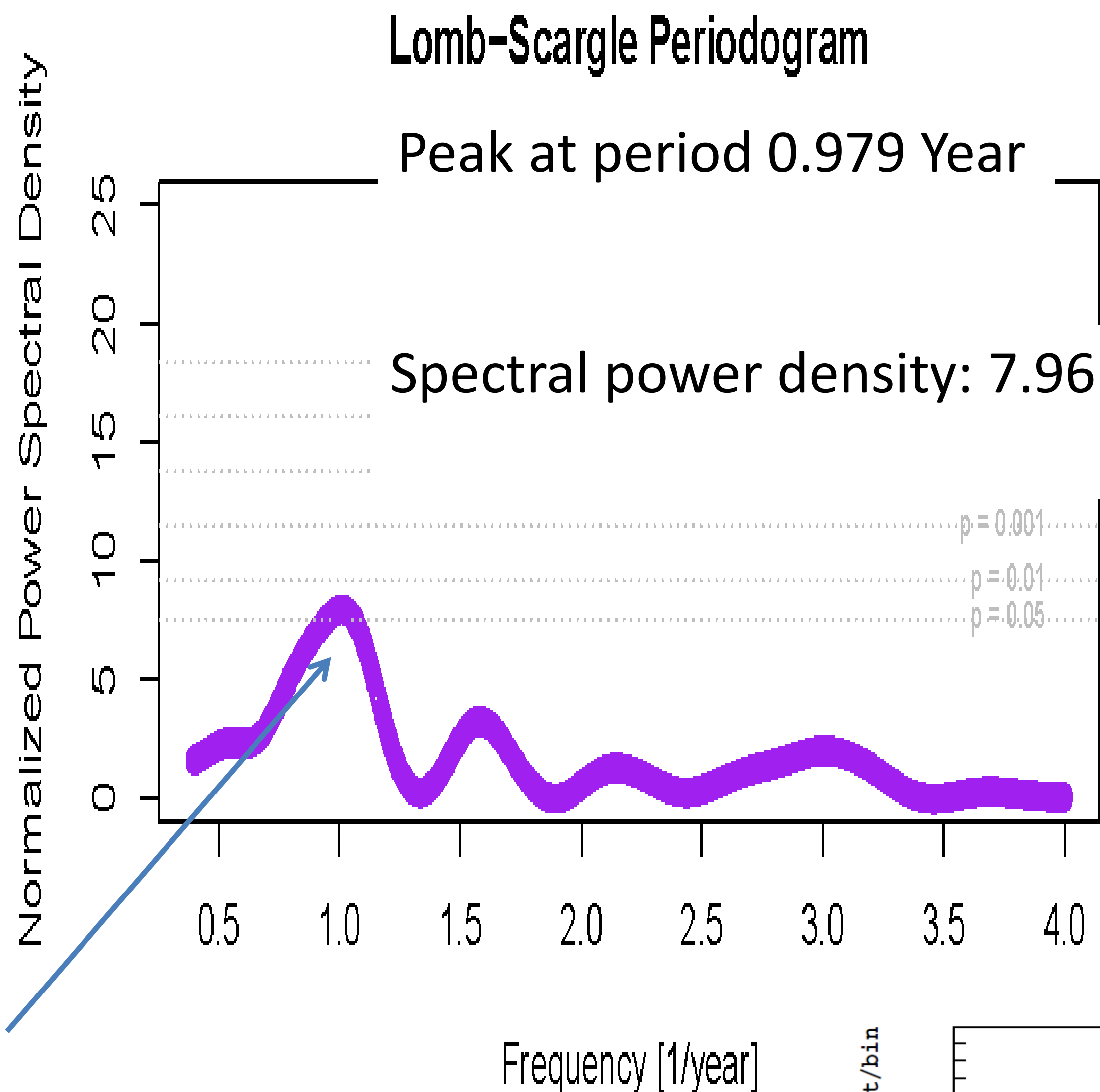


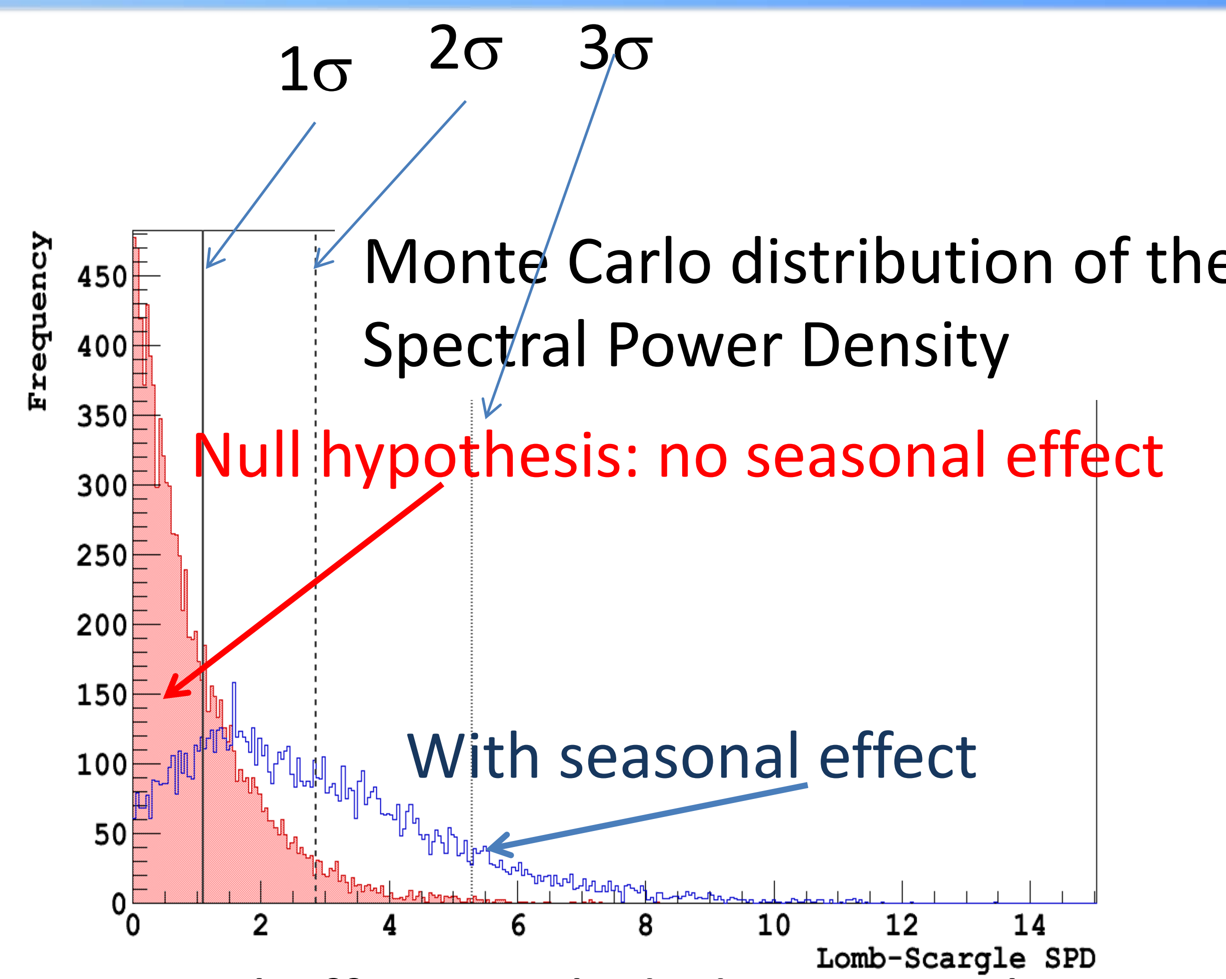
Additional program (Phase 2: 2012-2015) after 1 year and a half of successful purification which reduced further the backgrounds

- Improve ^{7}Be, ^{8}B → more test of MSW at Low energy probe of non standard physics (NSI) in the transition region of the Pee curve
- Confirm pep with stronger significance and reduced error
- Improve upper limit on CNO → probe metallicity (perhaps)
- Attempt direct pp measurement



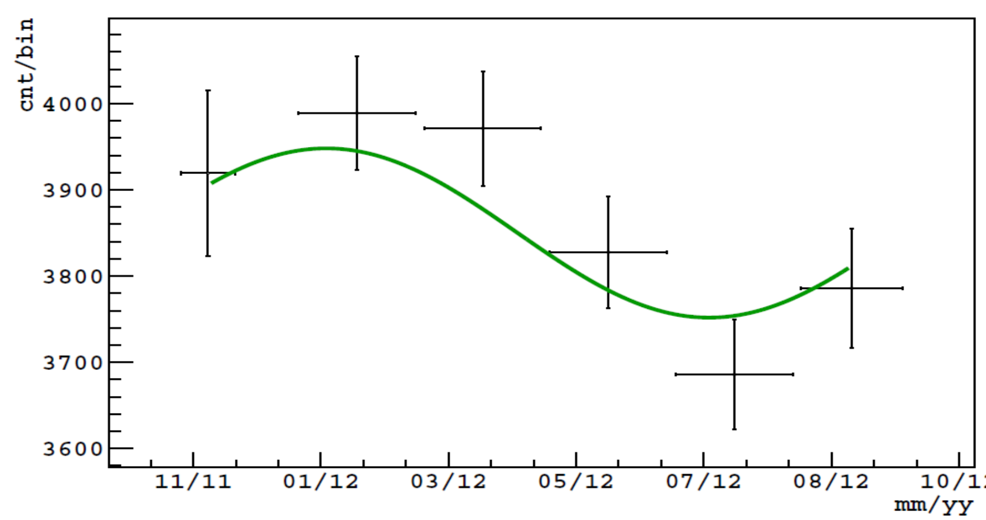
Annual modulation of the ν signal (PHASE 1): Lomb Scargle analysis





No seasonal effect: excluded at more than 3 σ

Peak at 1 year period



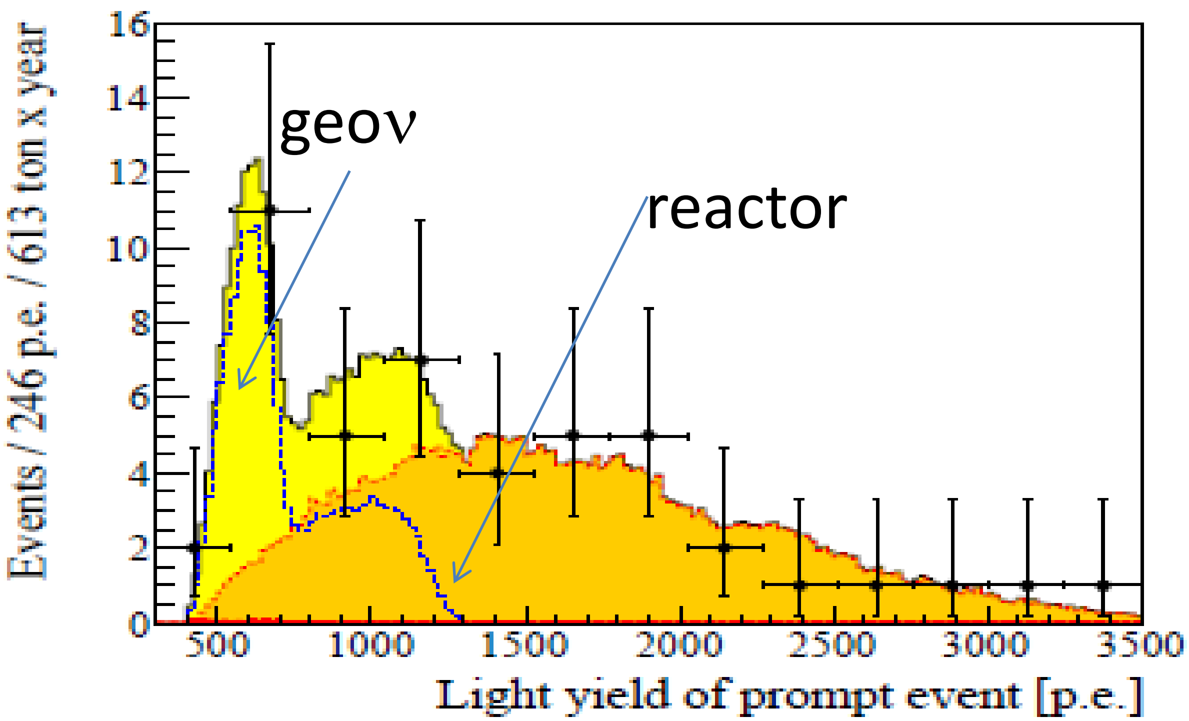
Preliminary results for phase II – unambiguous independent proof that we are observing solar ν's

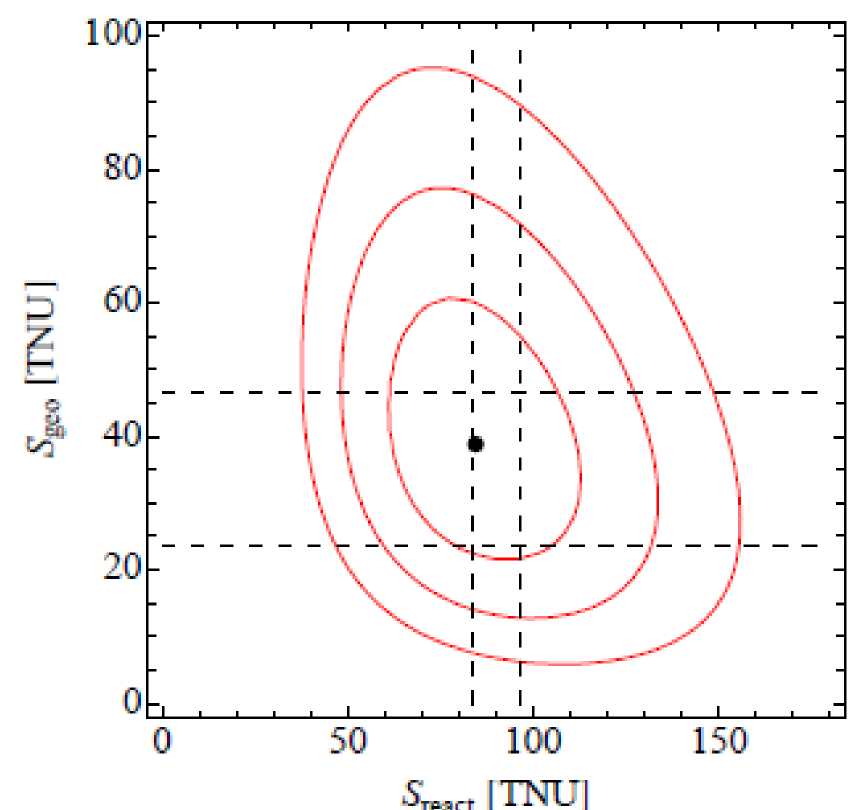
New geoν results: evidence of the signal

$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	Events	events	events	events	TNU	TNU
33.3±2.4	60.4±2.4	0.70±0.18	14.3±4.4	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$

Unbinned likelihood fit

No geoν signal: rejected at 4.5 σ C.L.





TNU = Terrestrial Neutrino Unit = 1 event / year/ 10^{32} protons

SOX: Short distance ν_e Oscillations with BoreXino

- **Science**
  - Motivations
    - Search for **sterile neutrinos** or other **short distance effects on P_{ee}**

    and also

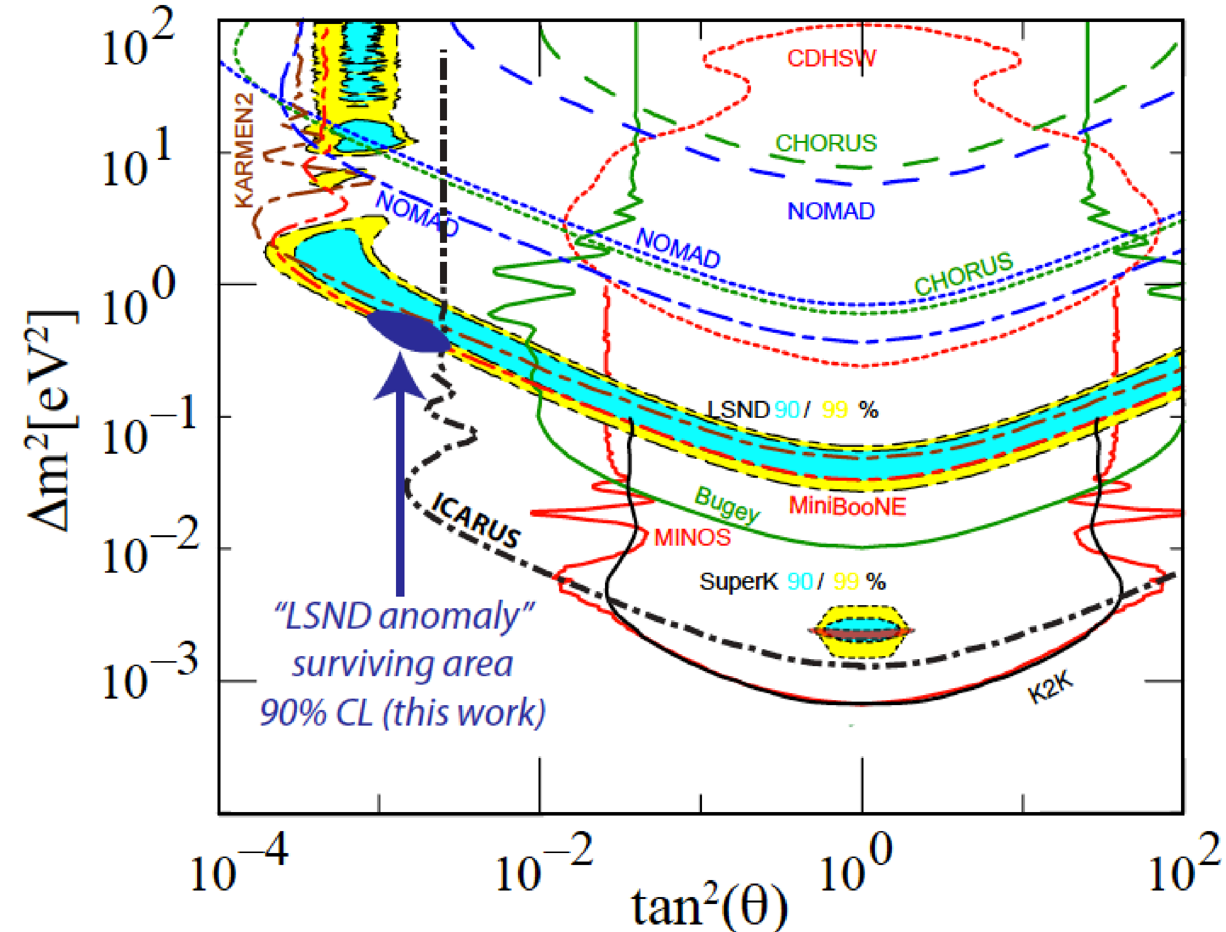
    - Measurement of ϑ_W at low energy (~ 1 MeV)
    - Improved limit on neutrino magnetic moment
    - Measurement of g_V e g_A at low energy
    - Constraints on neutrino NSI
- **Technology**
  - Neutrino source: **^{51}Cr**
  - Anti-neutrino source: **^{144}Ce**
- **Project**
  - SOX-A - **^{51}Cr external**
  - SOX-B - **^{144}Ce external**
  - SOX-C - **^{144}Ce internal**

Funded by the European Research Council with an ERC advanced grant amounting to 3.5 Meuros

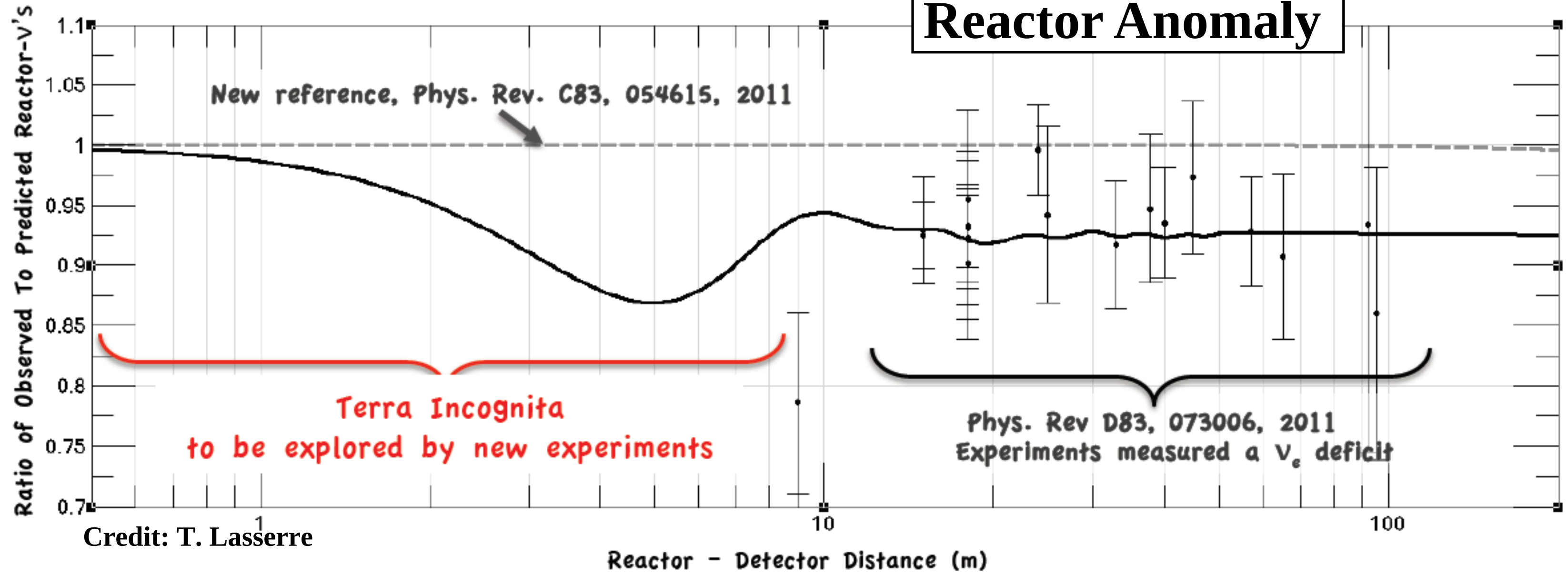
SOX is the "European" official project acronym

SOX: the Science case

- **"anomalies"**: a few experiments deviate from the standard 3-flavor mixing at **L/E ~ 1 m/MeV**
  - **LSND 2001**
    - Clear excess: **87.9 ± 22.4 ± 6.0 (3.8 σ)**
    - Partially confirmed by MiniBoone
    - Allowed region restricted by ICARUS to $\Delta m^2 \sim 1\ eV^2$ (see Eur. Phys. J. C (2013) 73:2345)



Reactor Anomaly



- **Gallium and Reactor anomalies:**
  - deficit in observed flux at short distances
  - $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

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

Gallium Anomaly

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

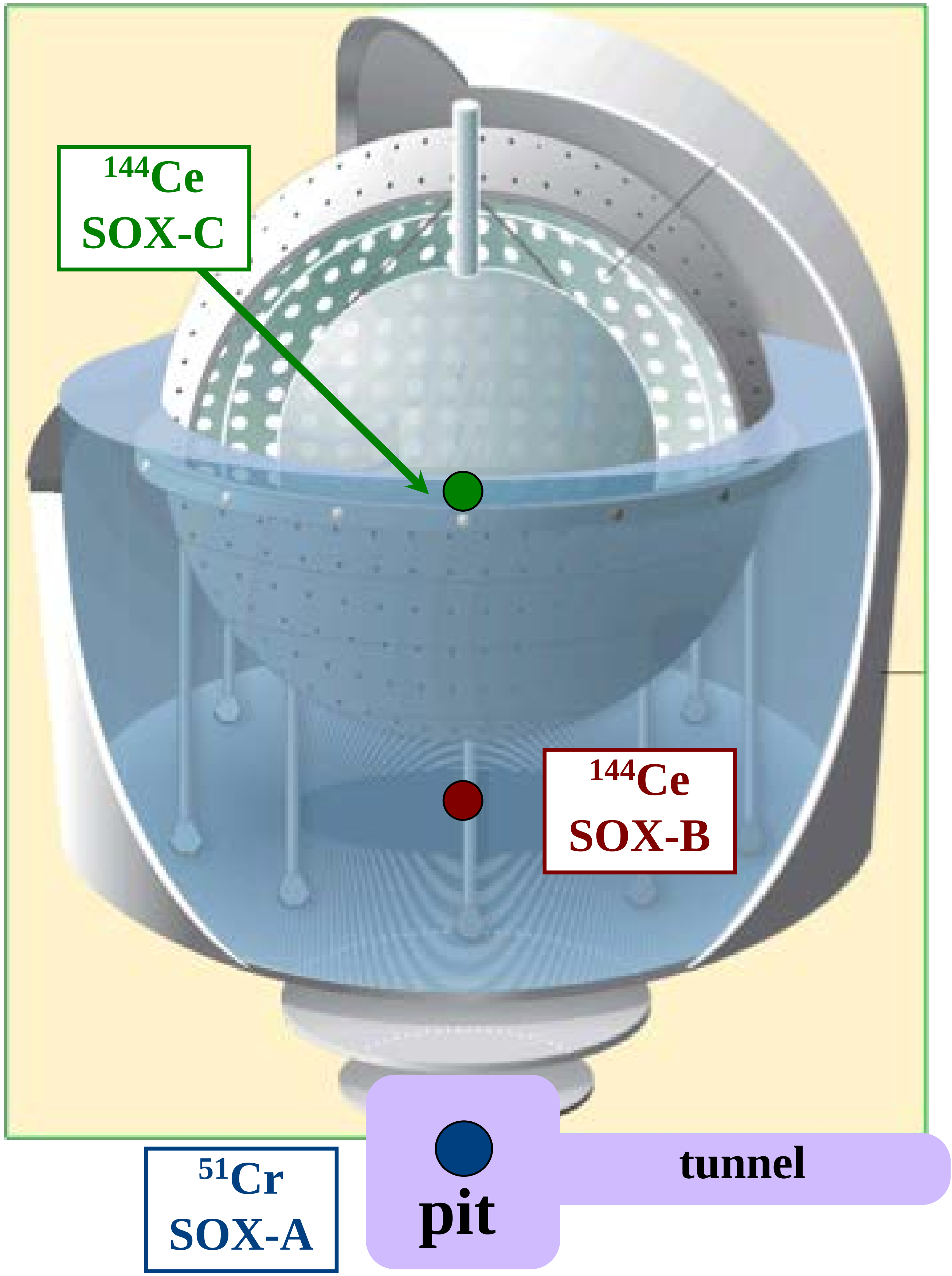
SOX: Three Phases

- **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 **[within 2015]**

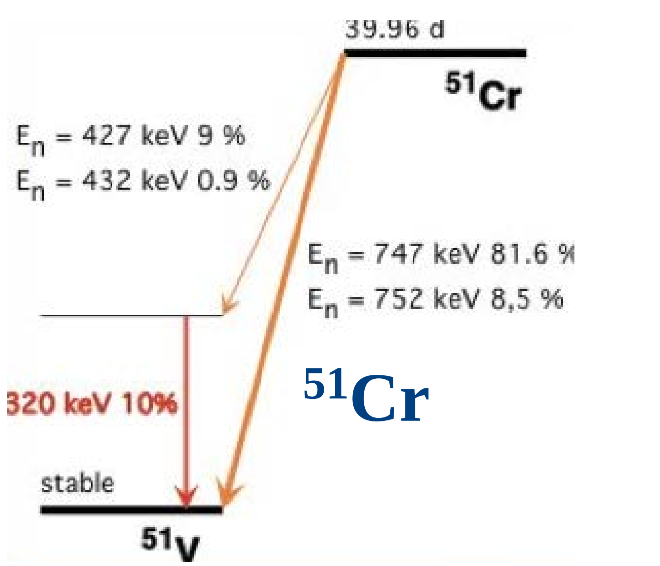
- **SOX-B**
  - **^{144}Ce-^{144}Pr** source in W.T.
  - PPO everywhere to enhance sensitivity
  - **7.15 m** from center **[2015/2016]**

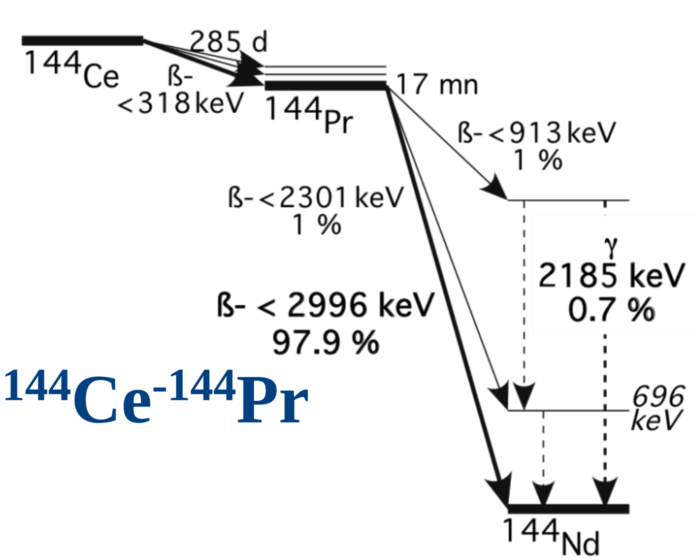
- **SOX-C**
  - ^{144}Ce-^{144}Pr source in the center
  - **Only after the end of solar program**
  - More effort and more time **[>2017]**

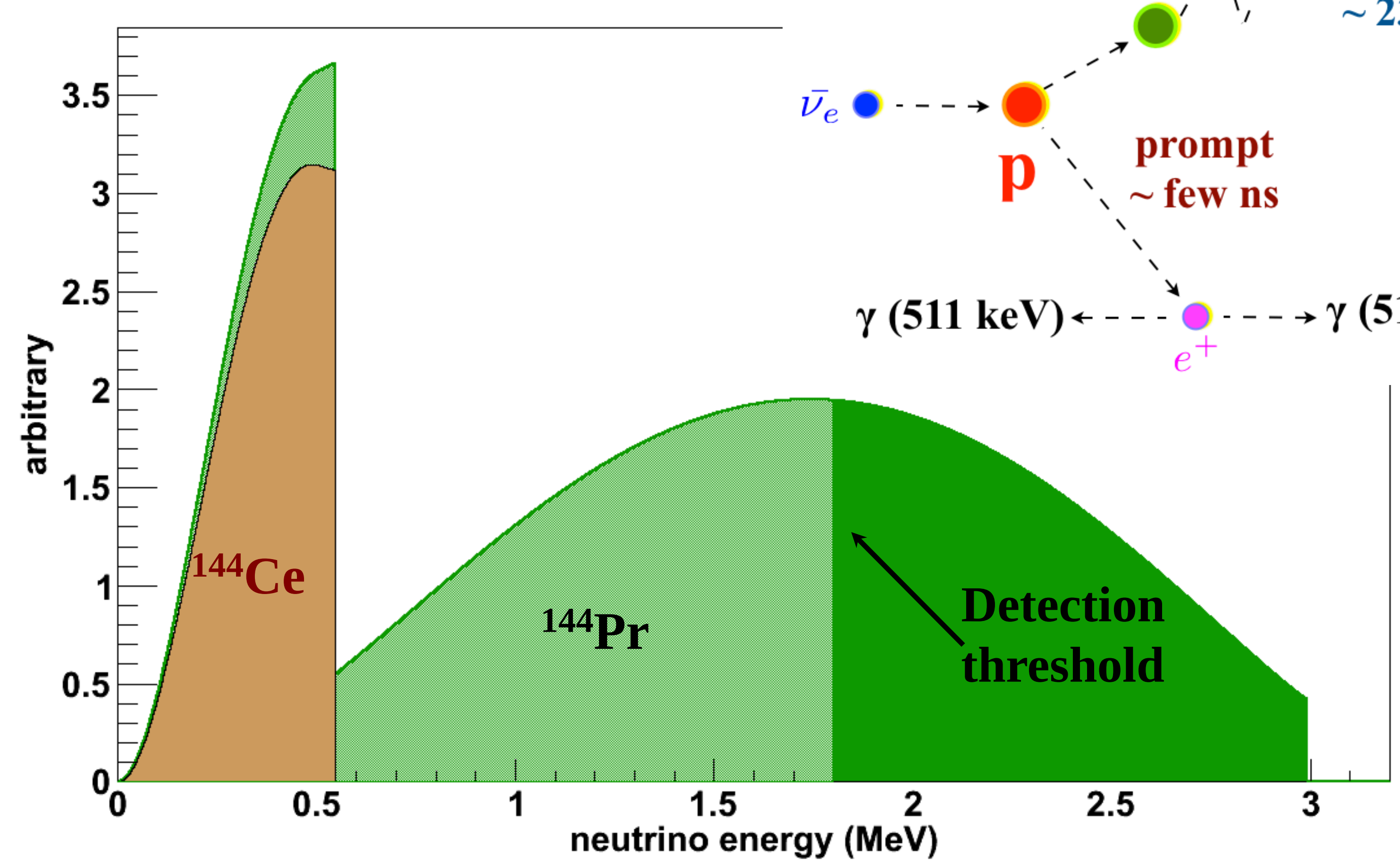


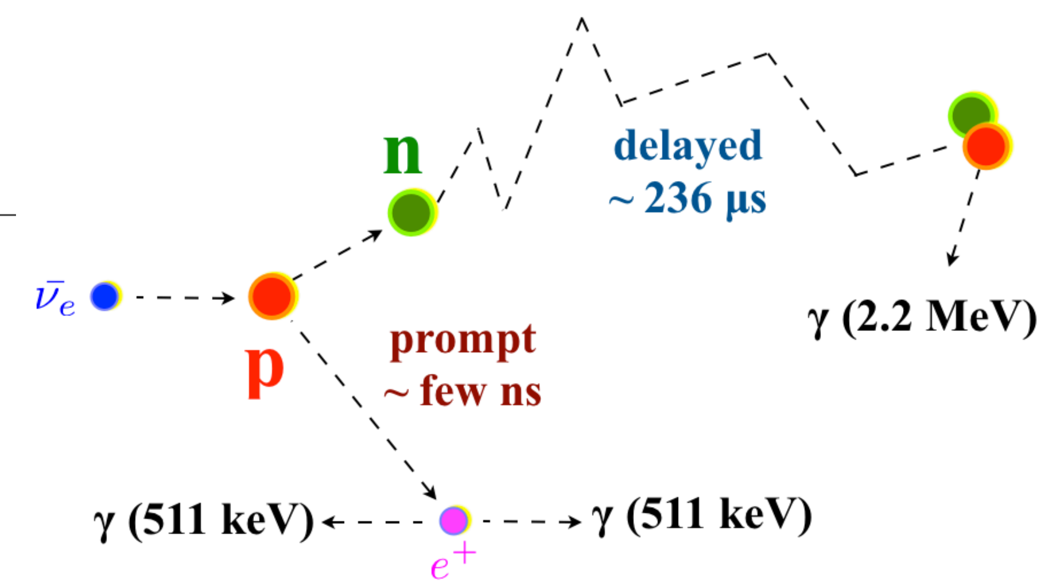
Artificial neutrino sources

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	1.1	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 and active volume)
    - 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
    - **Oscillometry analysis →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

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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**

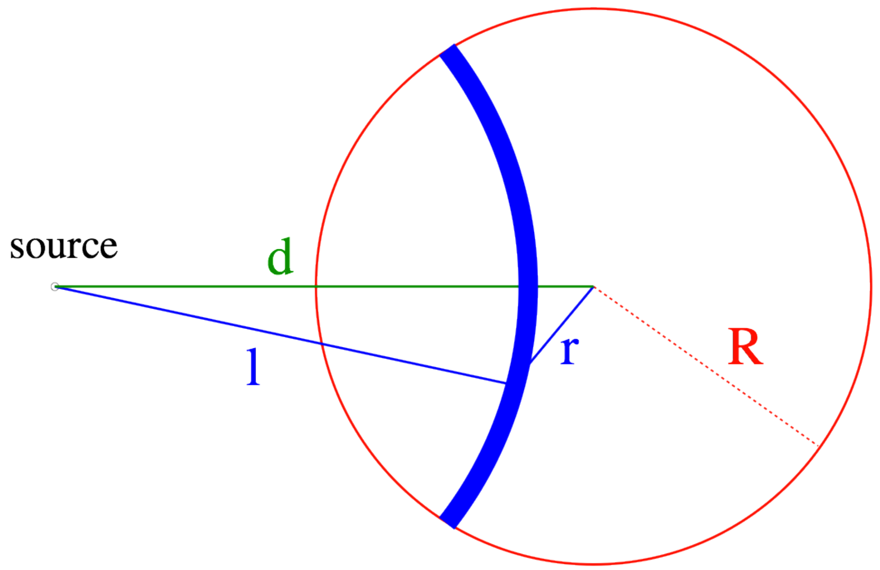
$$\Phi(l) = \frac{I_0}{4\pi l^2}\tau e^{-\frac{t_D}{\tau}}\left(1 - e^{-\frac{t}{\tau}}\right)$$

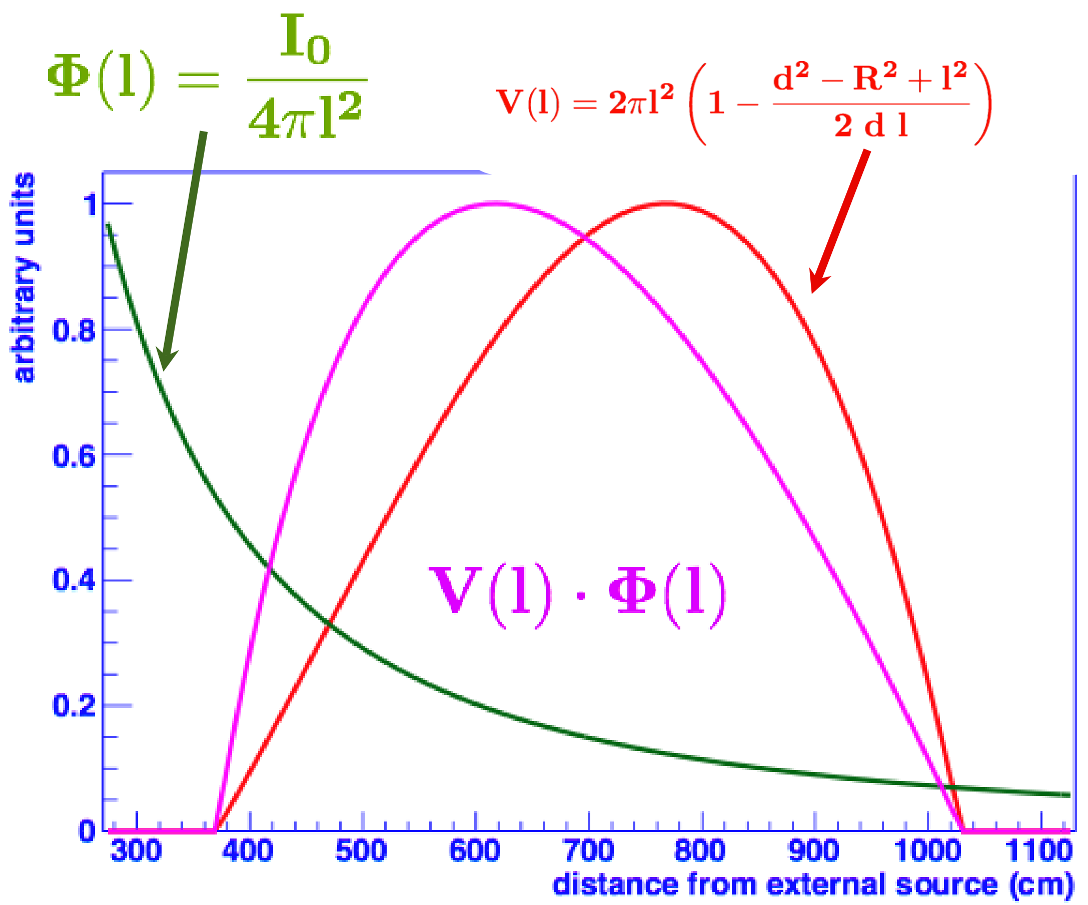
- **Oscillations (one sterile)**

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

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

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

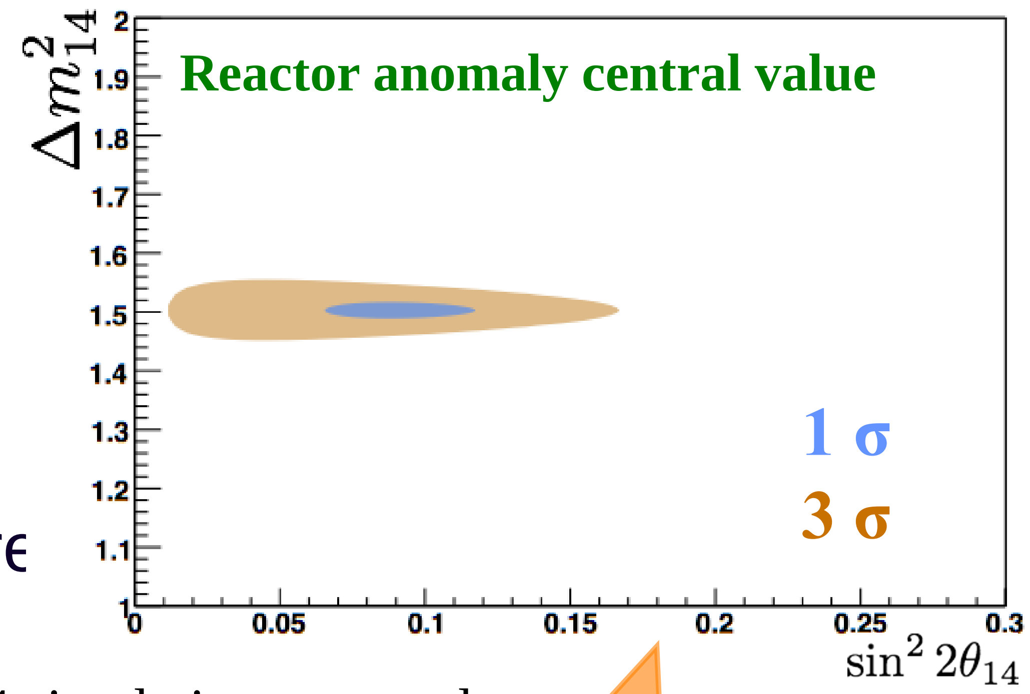




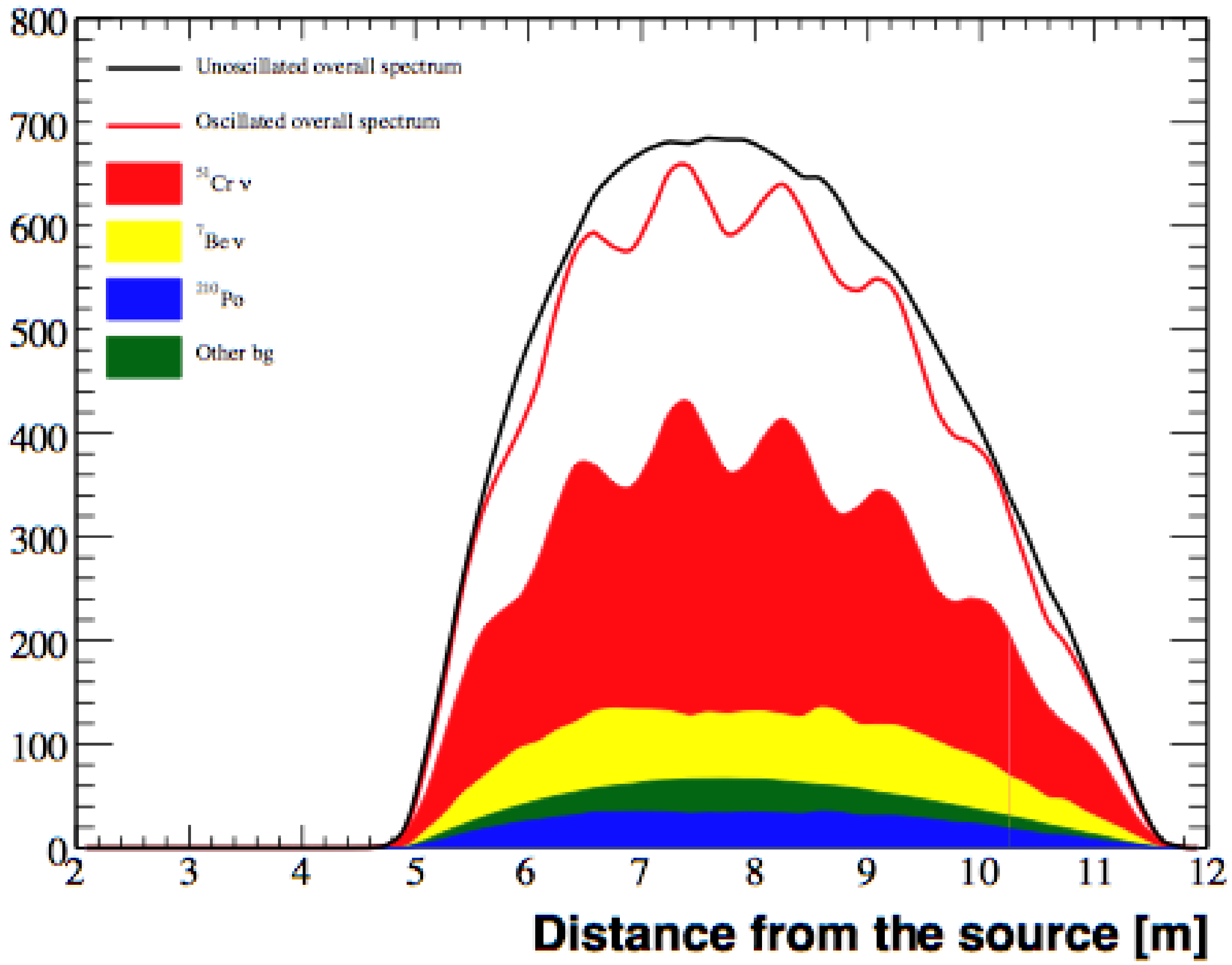
N.B.: The distribution of events is not uniform even without oscillations

Example for SOX-A

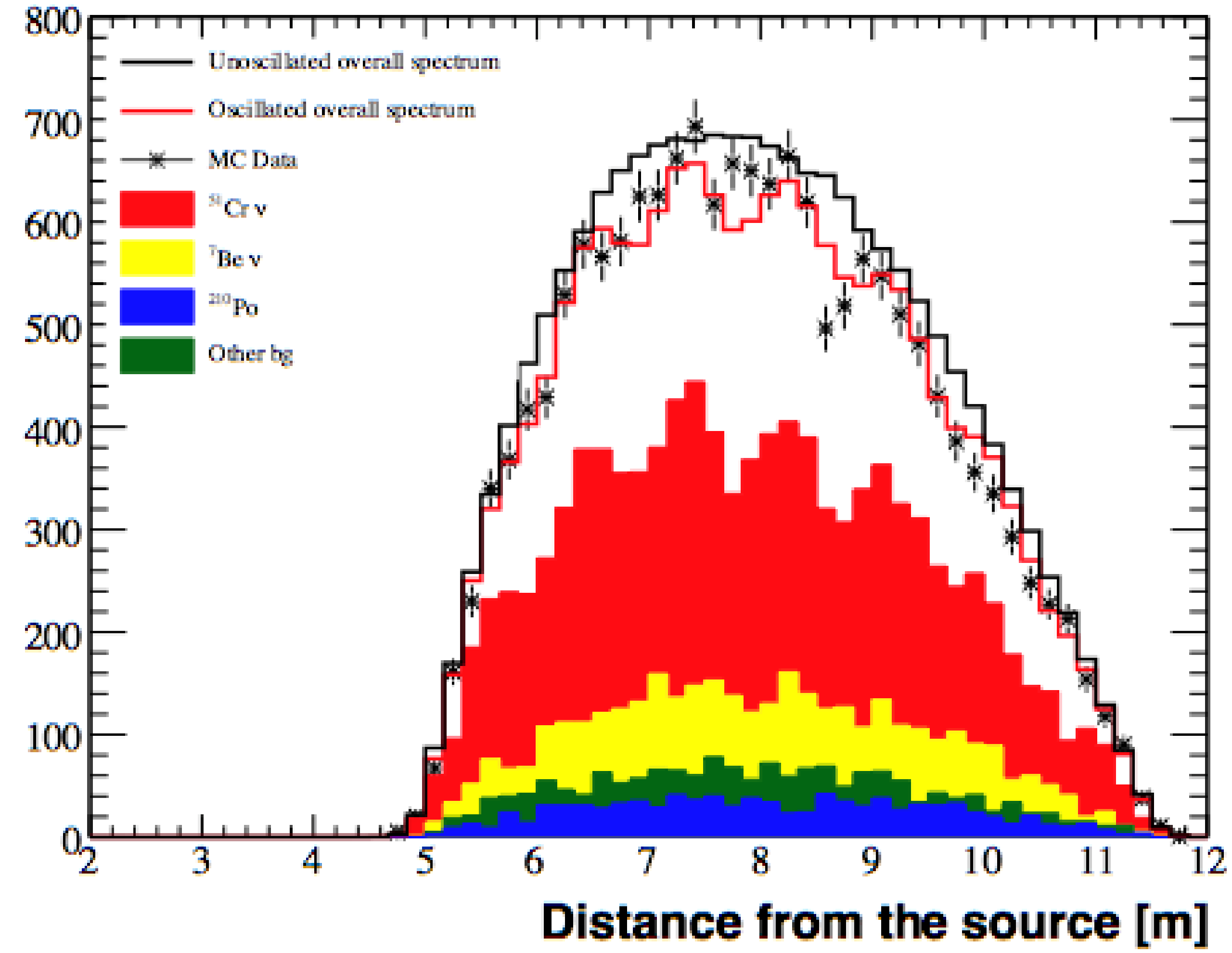
- **Waves** may be detected in the distribution of events as a function of the distance from source
  - With waves, both parameters can be measure



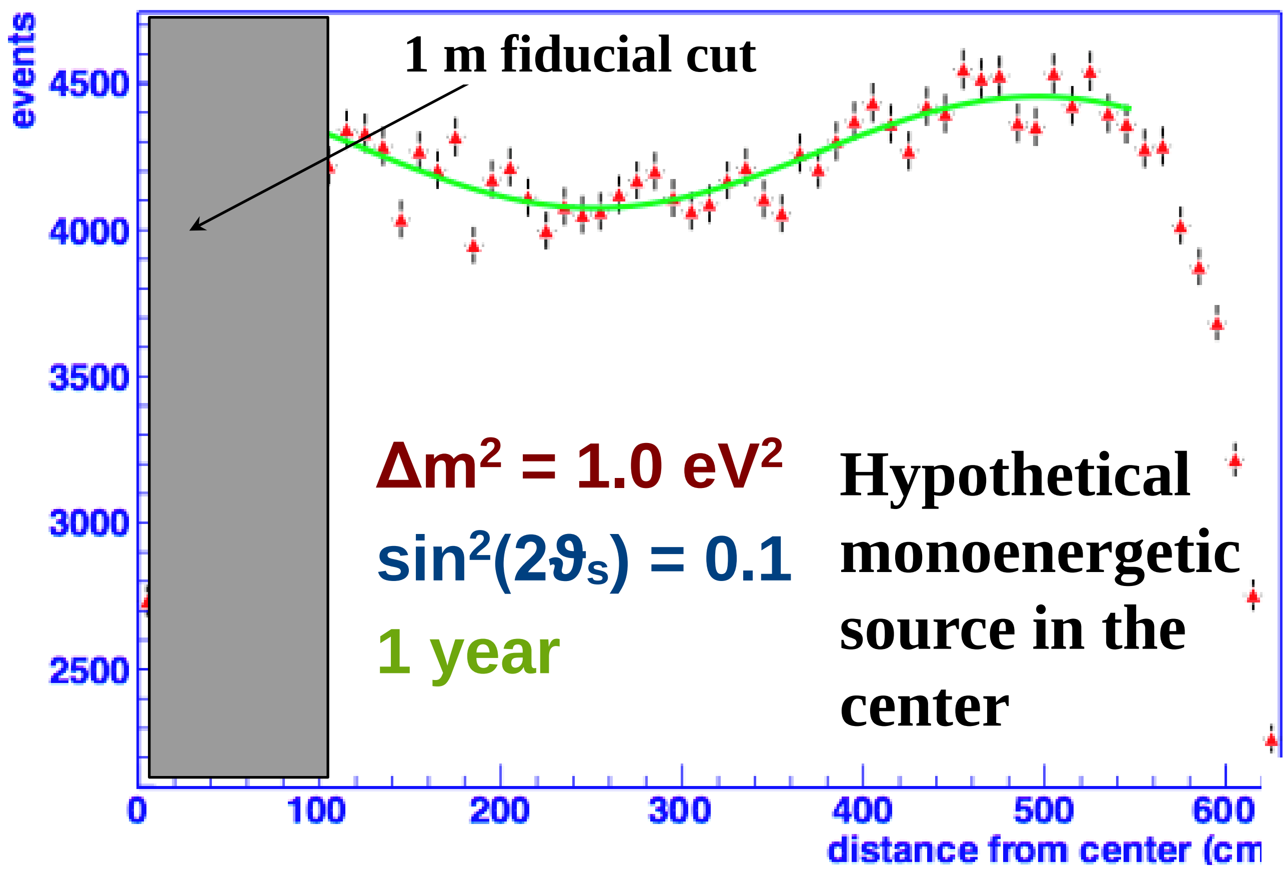
Ideal curves
Borexino Background - No fluctuations

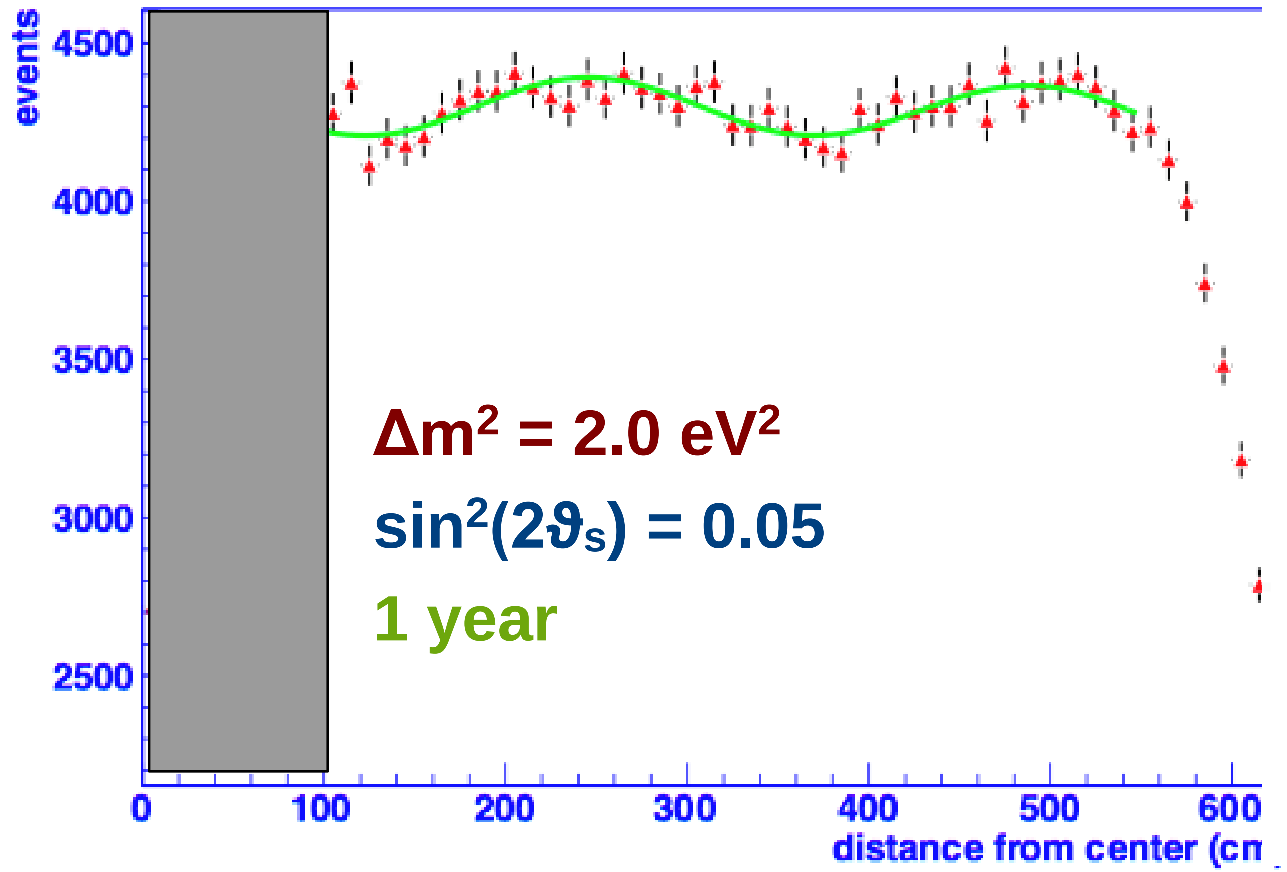


Full Geant4 simulation - example
Borexino Background

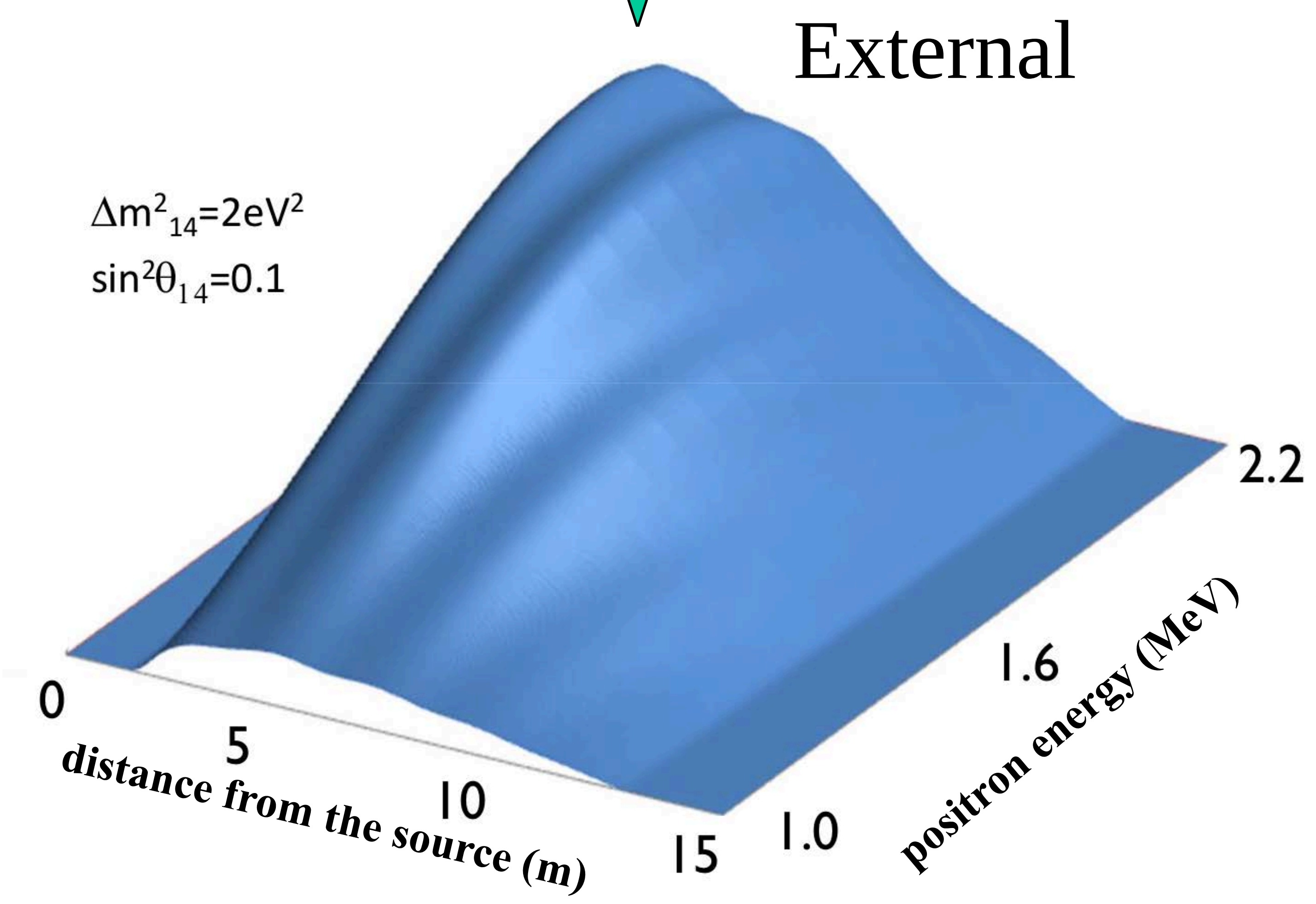


Waves with $\overline{\nu}_e$ and space-energy correlation

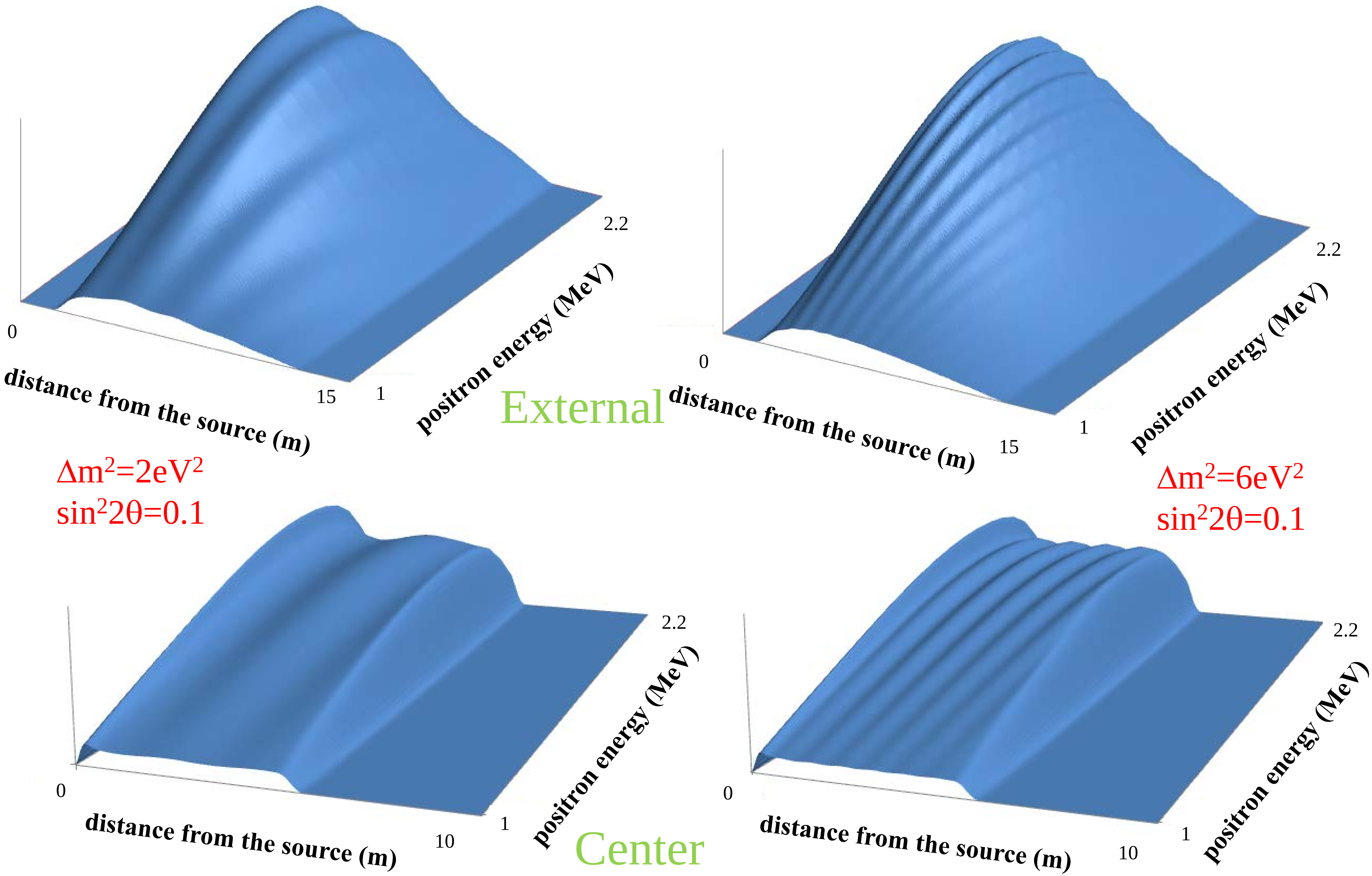




- **Space - Energy correlation**
  - With the **^{144}Ce-^{144}Pr** source (both **external SOX-B** and **internal SOX-C**) global fit exploiting **correlation between reconstructed event position and positron energy**

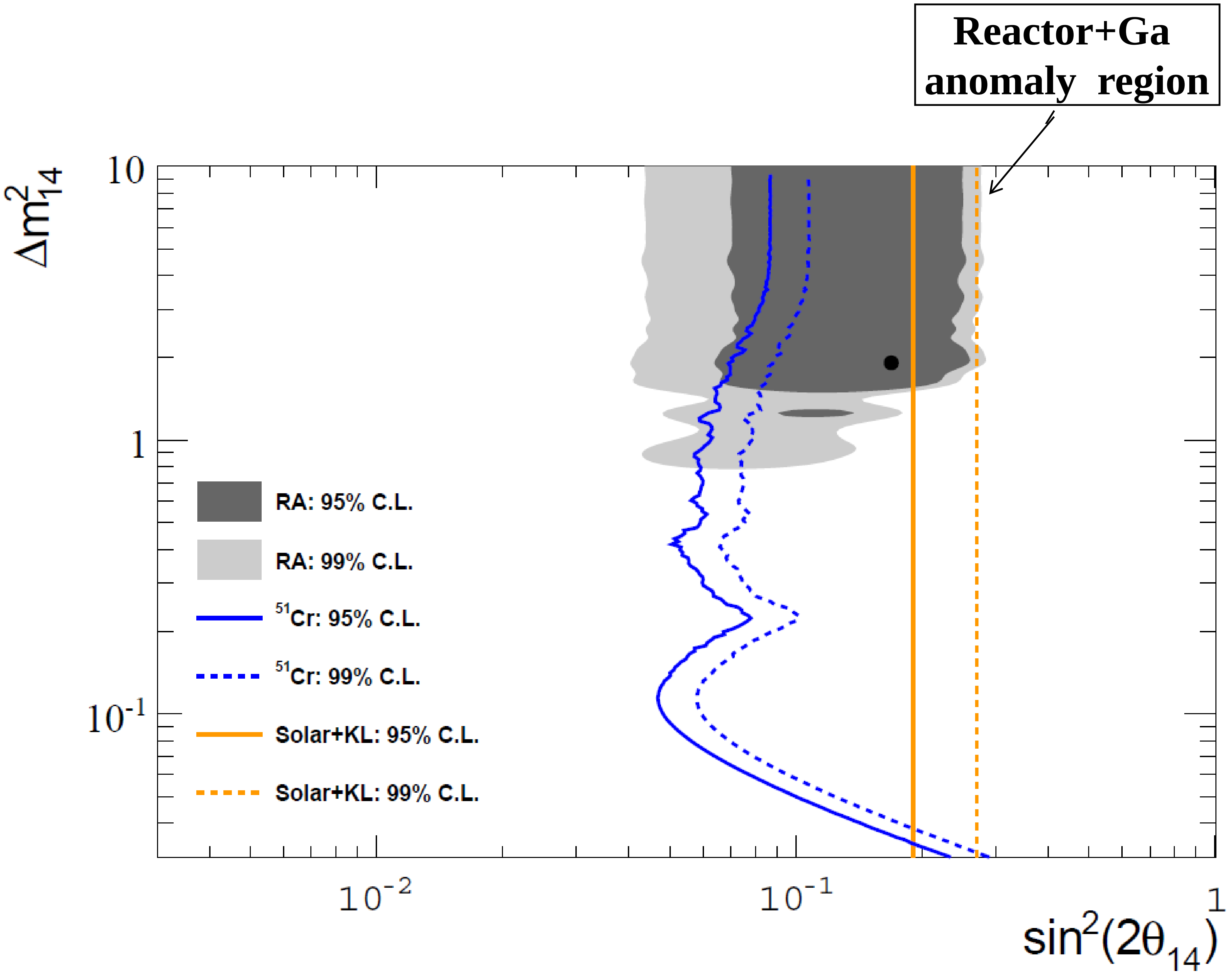


More examples of space-energy patterns for ^{144}Ce-^{144}Pr



SOX-A sensitivity

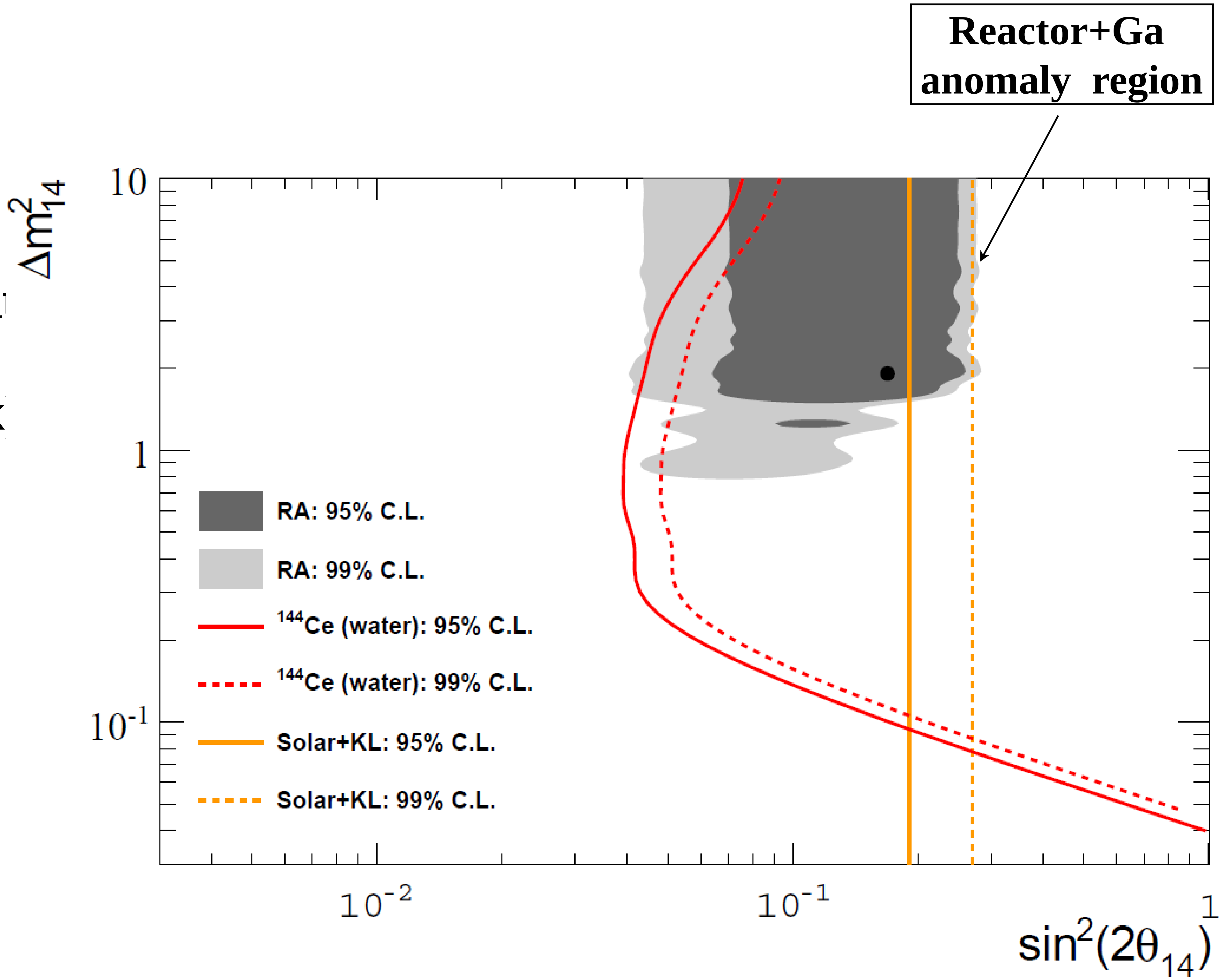
- **SOX-A:**
  - ^{51}**Cr** source at **8.25 m** from the center
  - **10 MCi**
  - 1% precision in source activity
  - 1% in FV determination



- Phase A can happen any time during next solar neutrino phase
  - 2014/15 is realistic – 3 months of data taking

SOX-B sensitivity

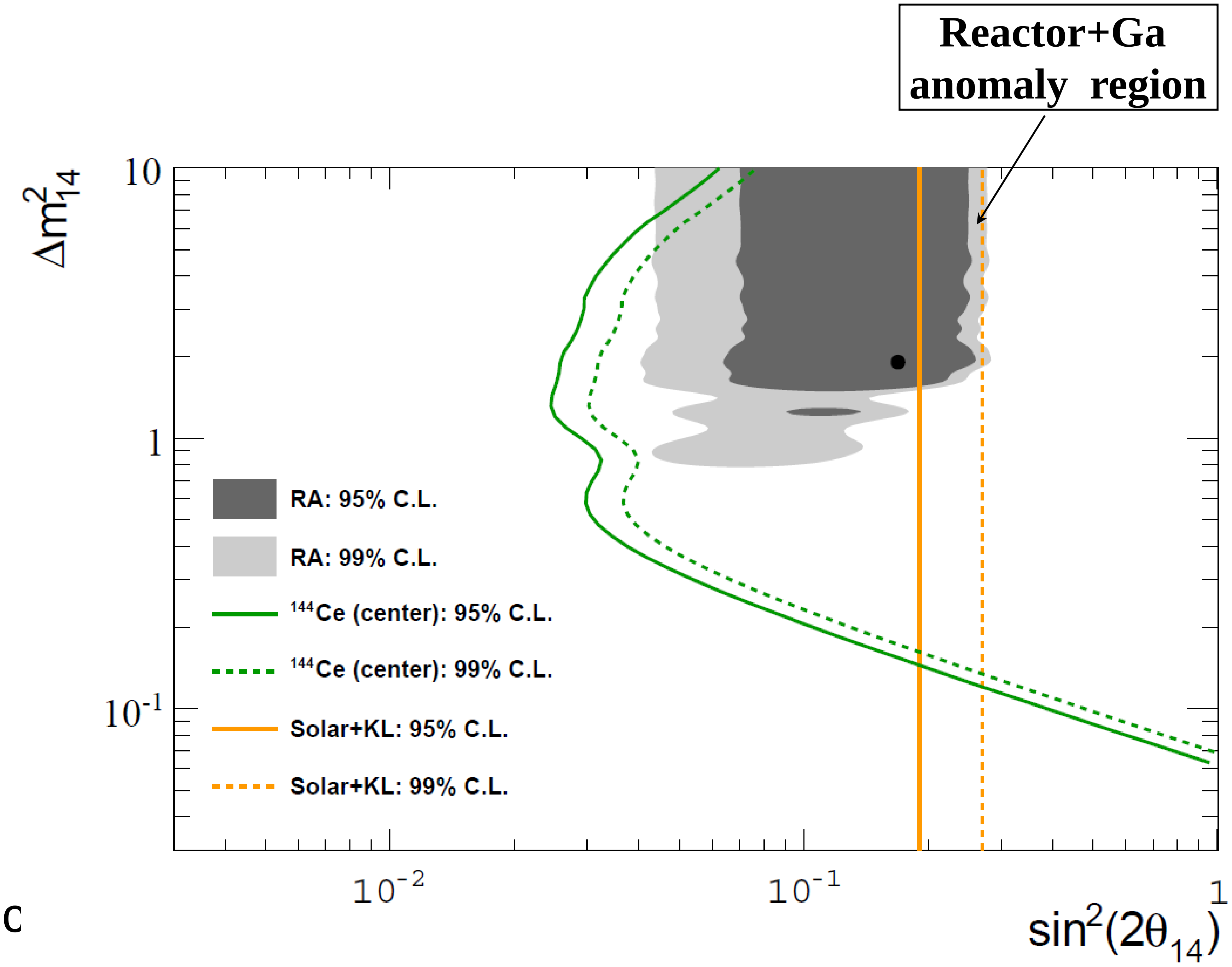
- **SOX-B**
  - ^{144}Ce-^{144}Pr source at 7.15 m from the center (in water tank
  - 75 kCi
  - 1.5% precision in source activity
  - 2% bin-to-bin error to include all effects



- SOX-B can happen any time during next solar neutrino phase
  - 2015/16 is a realistic scenario – 1.5 years of data taking

SOX-C sensitivity

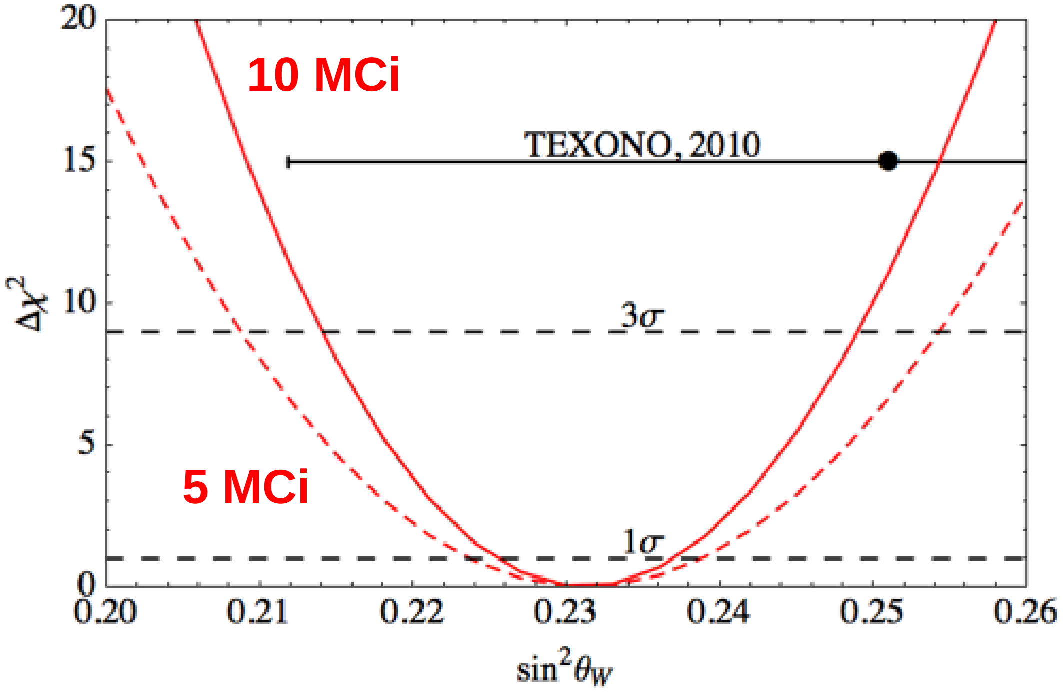
- **SOX-C:**
  - **^{144}Ce-^{144}Pr** source in the center
  - **75 kCi**
  - 1.5% precision in source activity
  - 2% bin-to-bin error to include other systematic



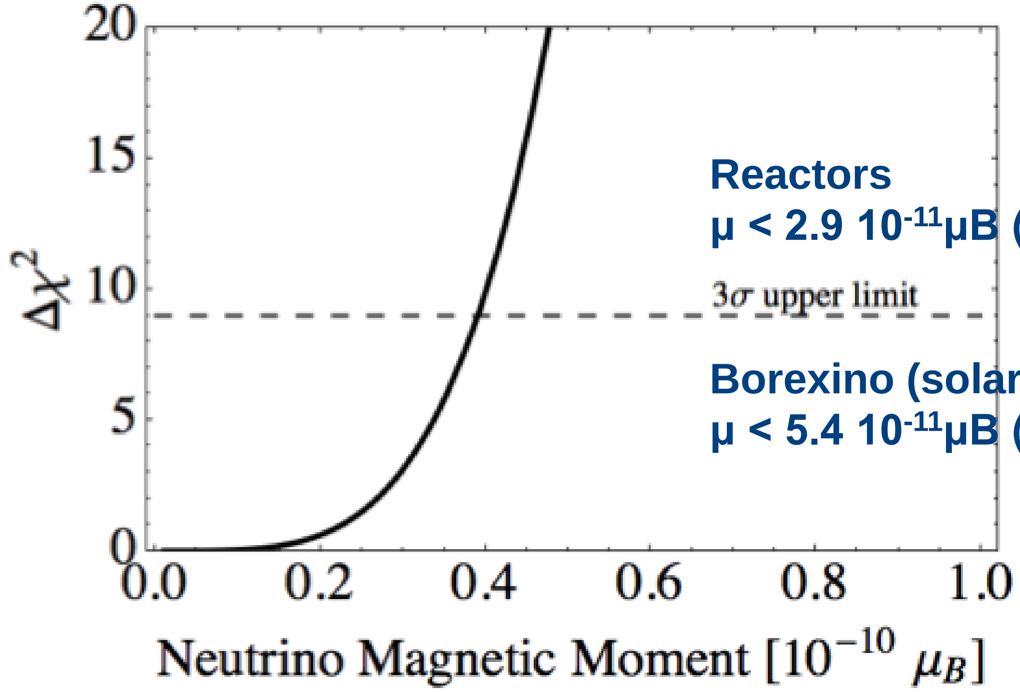
- SOX-C can happen only after the end of solar neutrino phase
  - 2017-2018 is in principle possible – 1.5 years of data taking
  - decision to be taken after SOX-A and/or SOX-B results

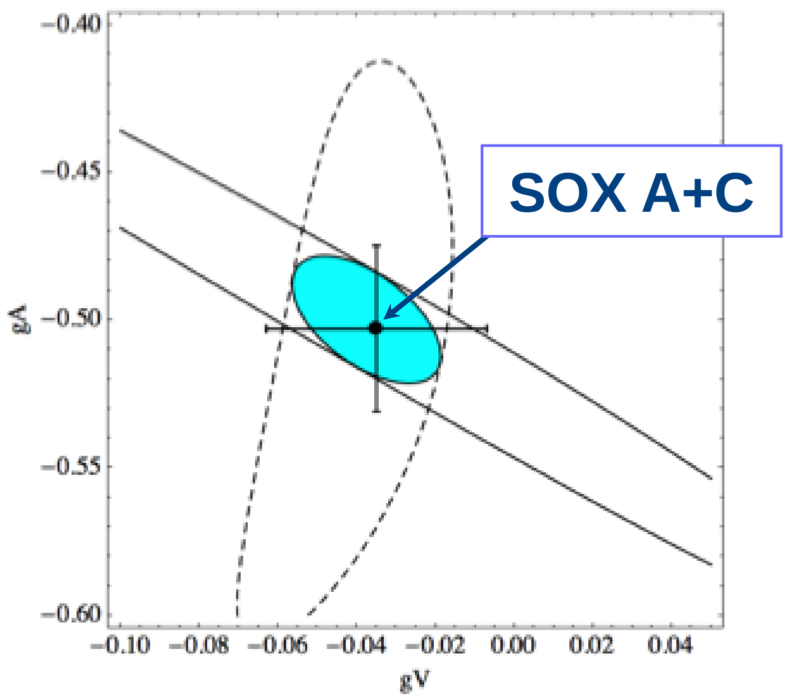
Other low energy neutrino physics

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



Magnetic moment





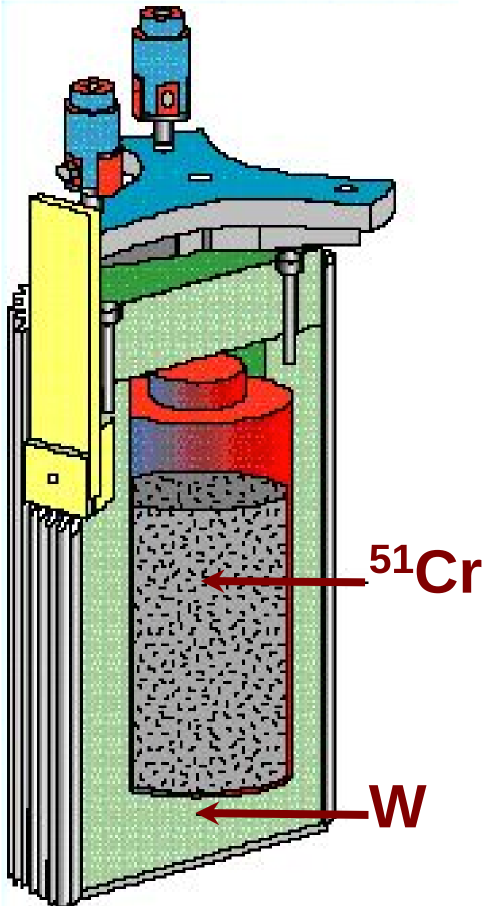
CHARM II (1994)
ν_μ ES su e- E ~ 10 GeV

- 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
    - **$g_V = -1/2 + 2\sin^2\vartheta_W = -0.038$**
    - **$g_a = -1/2 = 0.5$**

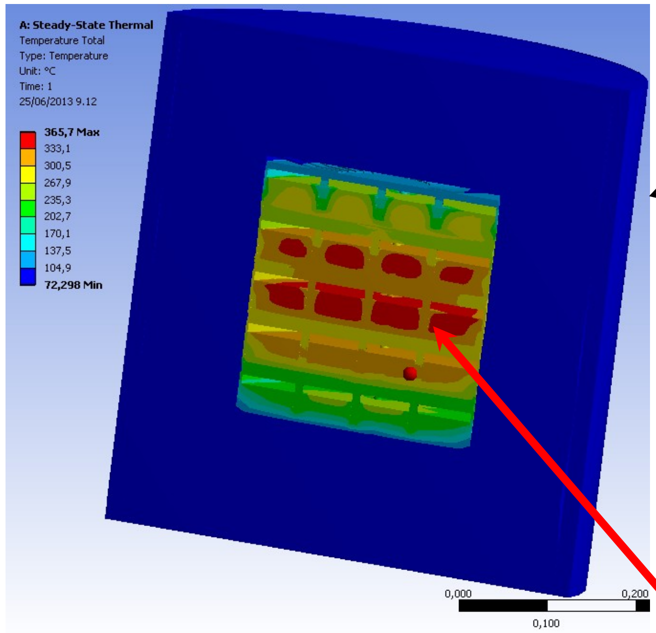
$$g_V^{\nu_e} = -0.035 \pm 0.012(\text{stat}) \pm 0.012(\text{syst}),$$
$$g_A^{\nu_e} = -0.503 \pm 0.006(\text{stat}) \pm 0.016(\text{syst}).$$

Technology of the ^{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 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=73°C

Internal T must be below synthetization (750°C)
Current value: T=365 °C

Precise determination of the source activity

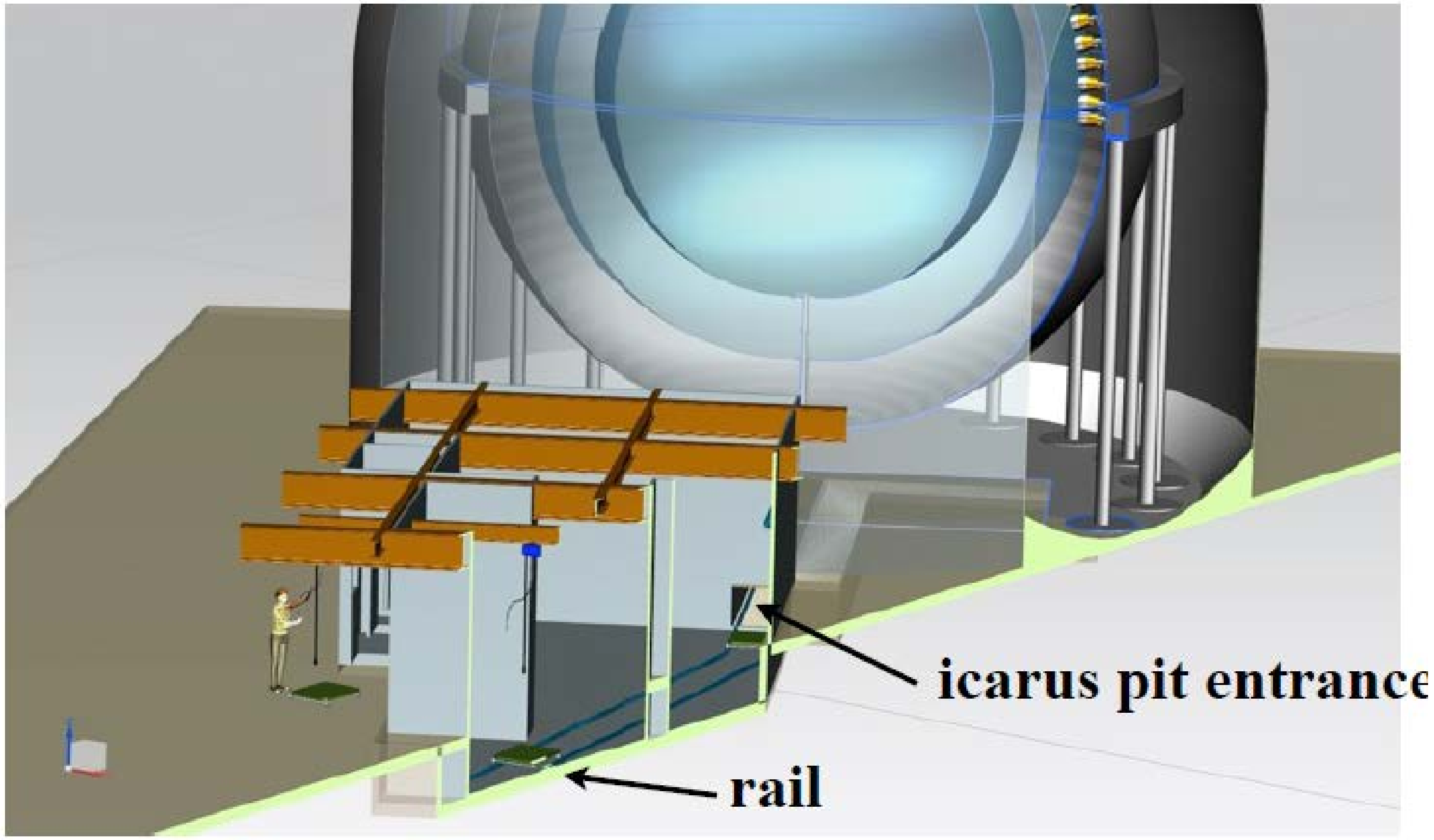
The technological effort encompasses also the precise determination of the source activity

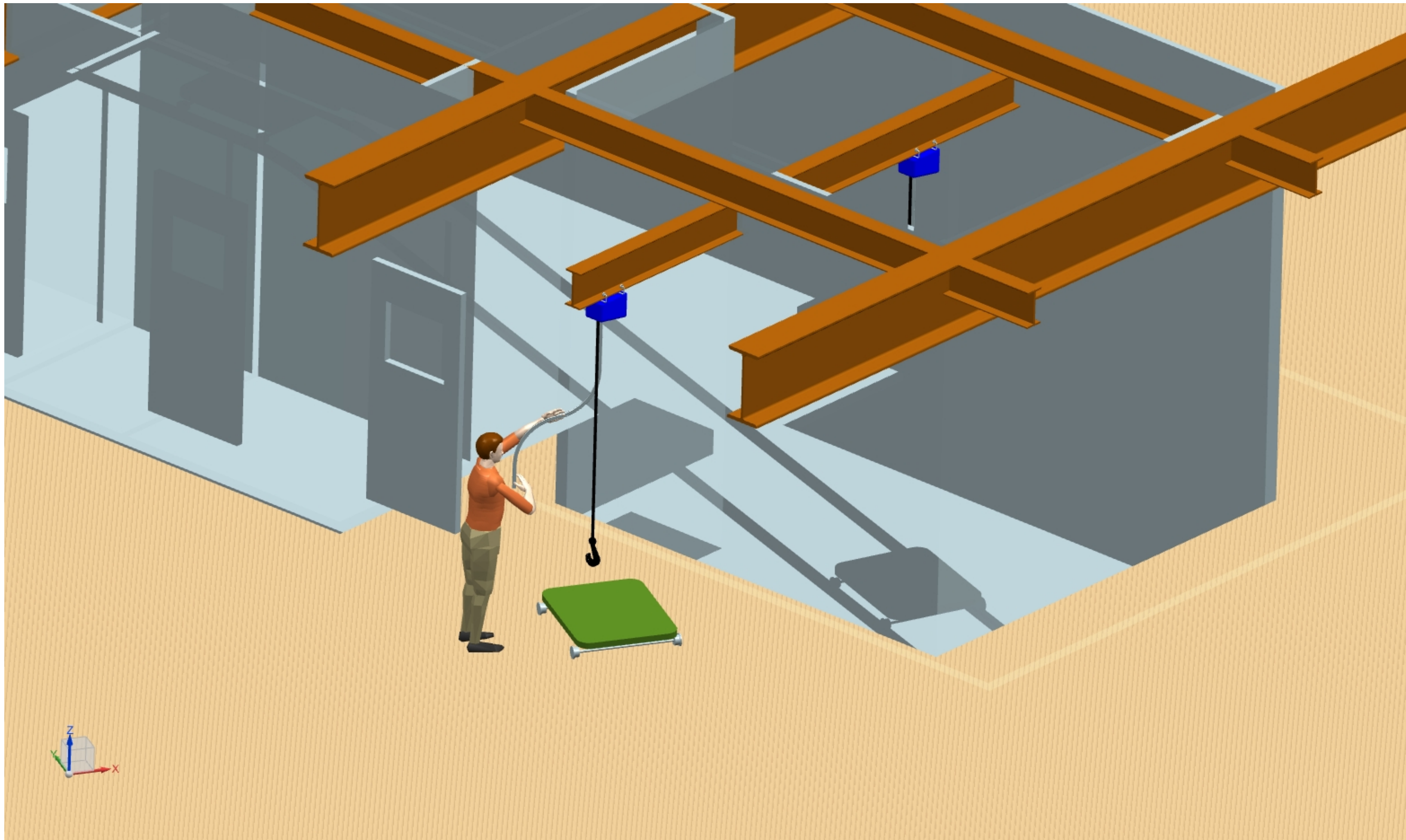
For ^{51}Cr particularly important at relatively high $\Delta m^2 > 2\ eV^2$ where the measure relies essentially on the disappearance effect

Not important in the region where the oscillometric measurement dominates the sensitivity

- In situ calorimetric measurement – calorimeter coupled to the source during the measurement period
- Gamma scanning at the reactor just after irradiation
- Post-decay ^{51}V determination

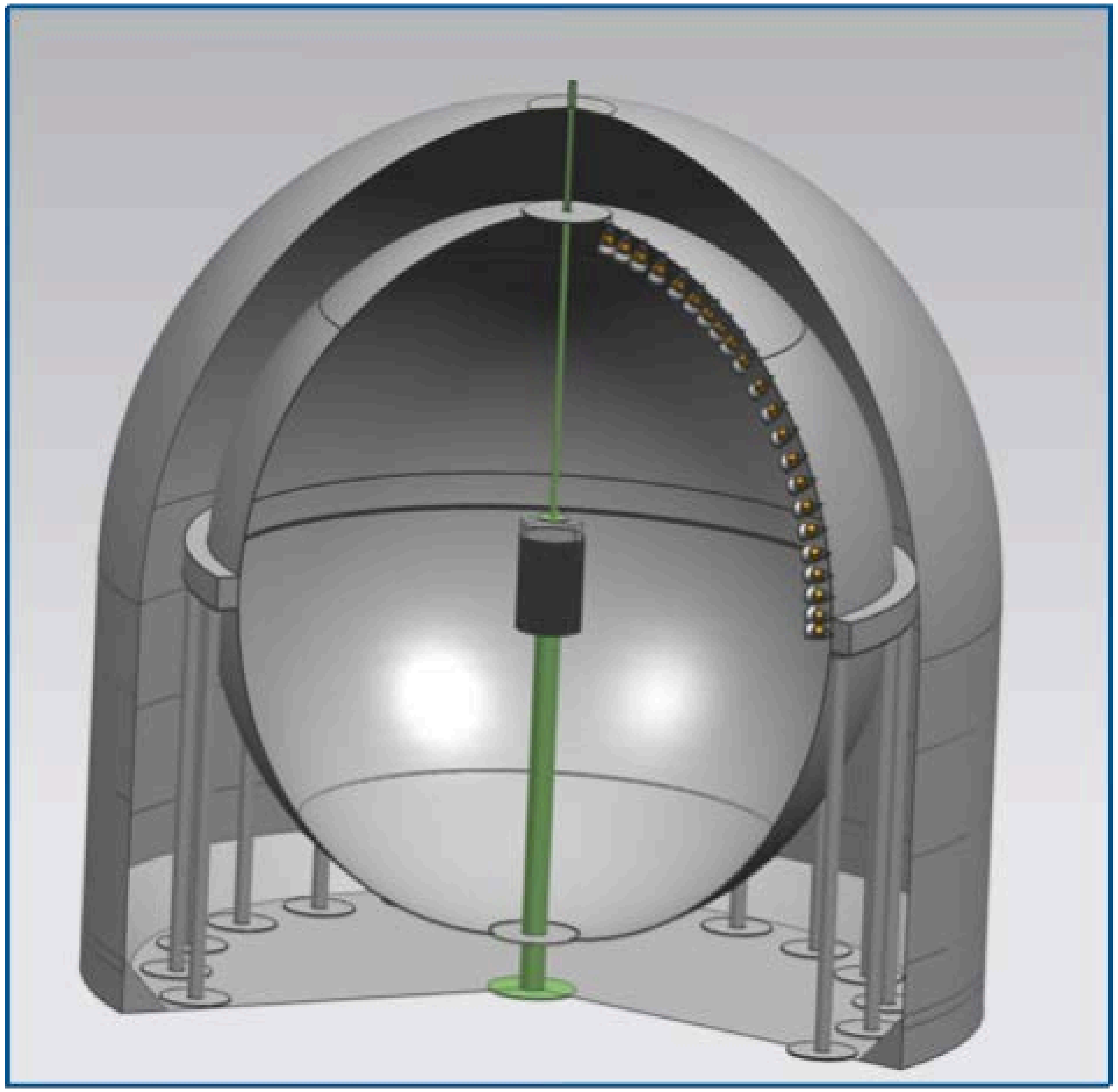
Detail of the source deployment procedure in the tunnel through the clean room





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

- Very **massive** source
  - **~ 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
  - **> 2017 for deployment in within the scintillator**

Conclusions I

Borexino has completed with great success the first round of solar and geo measurements thanks to the unprecedented purity achieved in the liquid scintillator

- ^{7}Be with unmatched 5% precision
- ^{8}B with a threshold as low as 3 MeV and first experimental specific detection of the pep component
- Overall and unique to date direct confirmation at low energy of the MSW-LMA oscillation solution
- Clean and convincing geo-neutrino signal detection

A new round of measurement has been started (phase II) after a purification effort which further suppressed the contaminants in the scintillator

- Complete solar neutrino spectroscopy with improved precision, possible probe of new physics in the transition region , depending upon the reached precision
- Further improved geo-neutrino results

Conclusions II

Source experiment to test the sterile neutrino hypothesis

- Neutrino Source Cr-51 SOX A – within phase 2
- Anti-neutrino source Ce-144 in water SOX B – appendix to phase 2
- Anti-neutrino source Ce-144 in tehe center – possibly beyond 2017