STATUS OF THE SOX PROJECT

ICPPA 2015
October 6th, 2015

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- For two decades, neutrinos have been the origin of **many important discoveries:**
  - Masses, once zero “by ignorance”, are non-zero
  - Oscillations extend and complete the CKM quark mixing
  - Matter Oscillations exist, due to neutral currents

- Important discoveries might be ahead:
  - CP violation in the lepton sector (CPT ?)
  - Majorana or Dirac ’s ? $0\nu\beta\beta$
  - Sterile neutrinos ?
  - Right handed neutrinos and see-saw mechanisms ?

- The astronomical importance of neutrinos from space is immense, so is their role in the cosmic evolution.

- Neutrinos, so far, fit the standard model but at the same time indicate physics beyond SM through the mass term
  - 3 flavours, 3 mixing angles, two small mass splittings (Δm^2=2.4 10^{-3} eV^2, δm^2=8.10^{-5} eV^2)
    - Unknown absolute mass scale and neutrino mass ordering ("hierarchy")
  - No more than 3 coupled to Z^0 (LEP, 1992)

- BUT
  - Weak couplings are relatively poorly measured, so there is **room for small corrections**
  - Physics beyond standard model is called by neutrinos masses
    - Either right-handed neutrinos to build Dirac mass terms or Majorana fields to build Majorana mass terms and possibly explain small mass through see-saw
  - A few experimental results sing out of tune

SCIENTIFIC MOTIVATIONS

- Some experiments show **anomalies** at small L/E, which *may* be interpreted as mixing of one or more sterile neutrinos with known states

  - In a short schematic list:

    - LSND/MiniBoone $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ and $P(\nu_\mu \rightarrow \nu_e)$ [recently narrowed by Icarus/Opera/Minos] down to a small region of **mass ~ 1 eV**

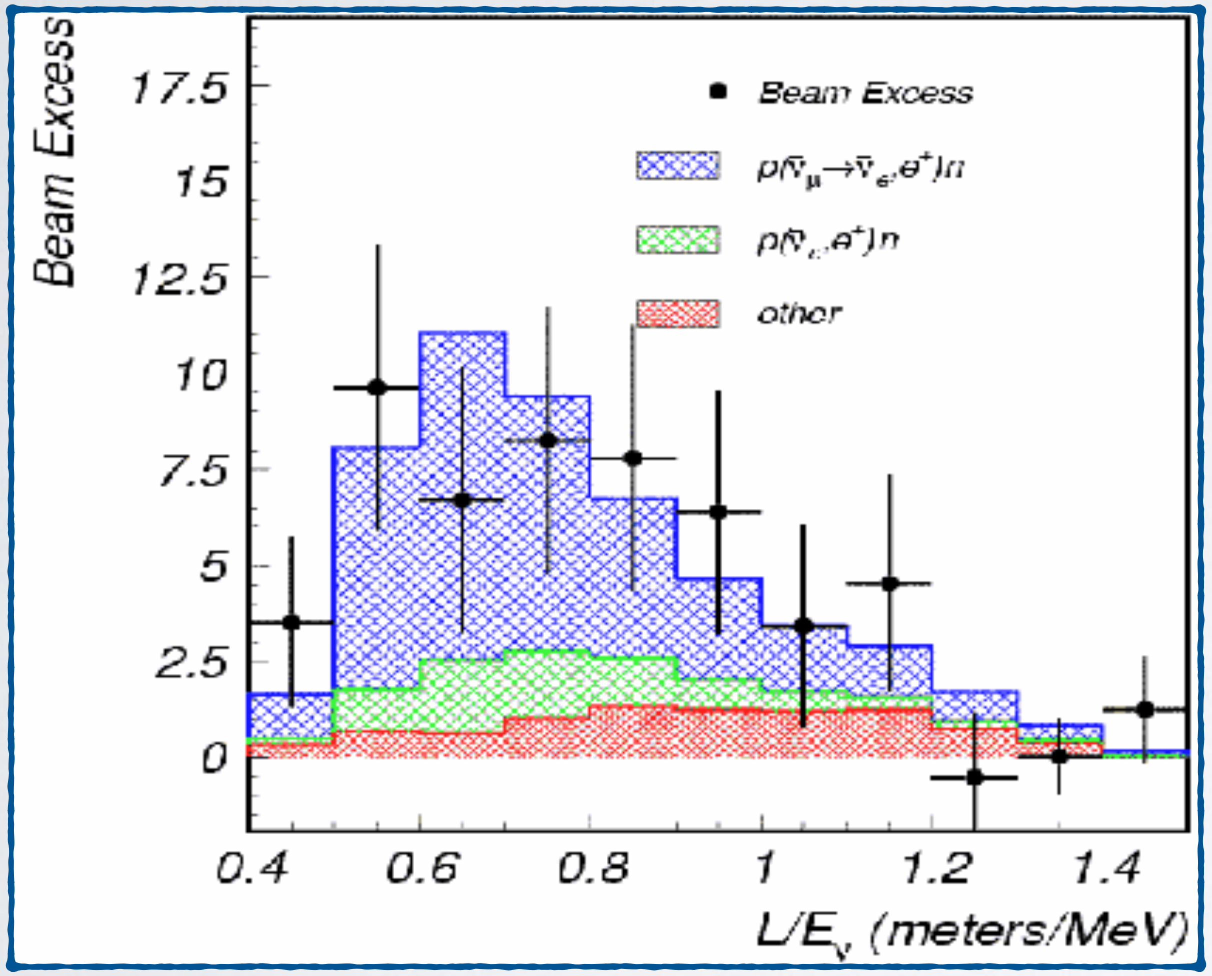
    - **Reactors** at 5-100 m distance

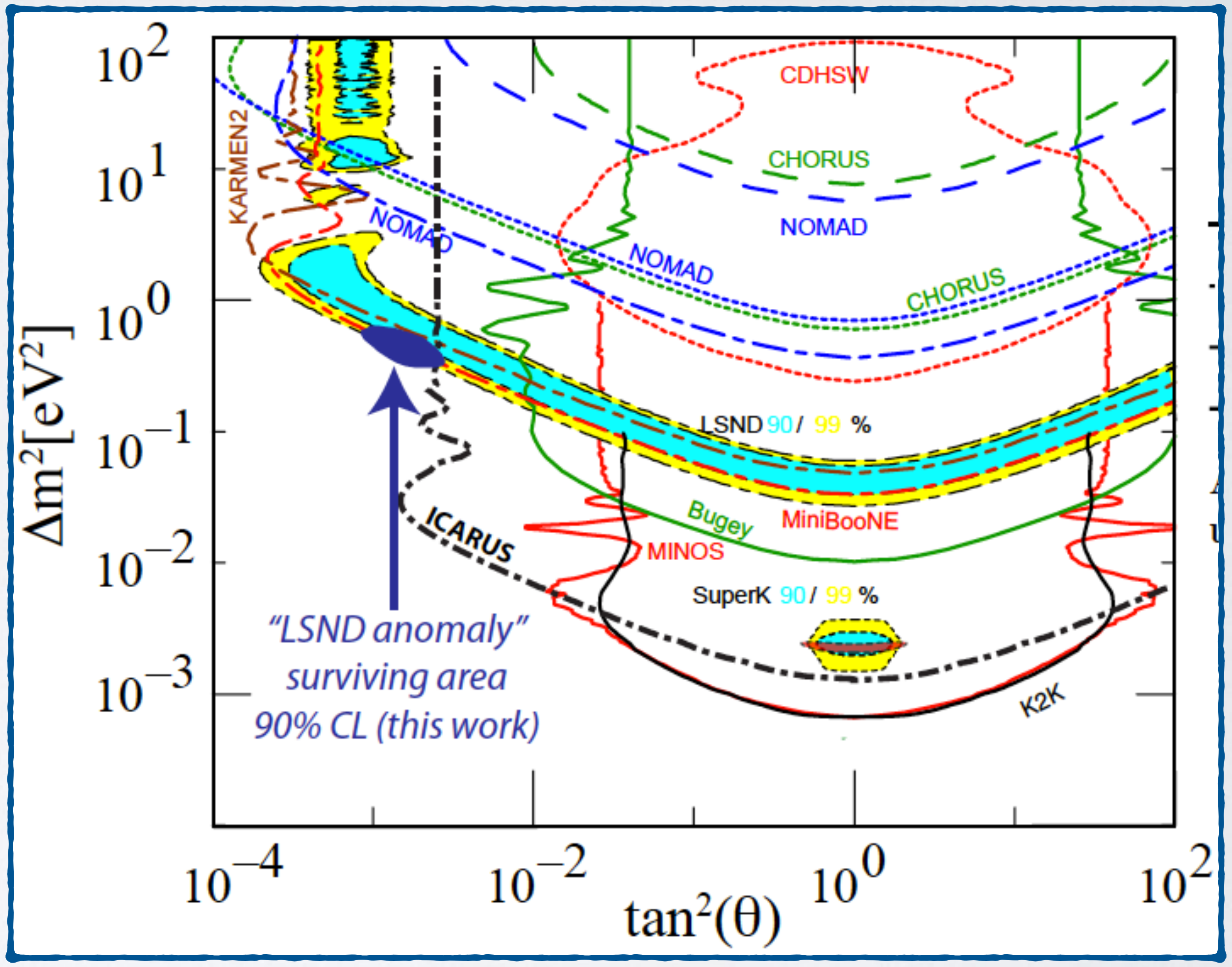
    - Low energy neutrino **sources** with Gallium detectors

    - Some analysis of cosmological data (now disfavoured by Planck data)

  - The 2nd and 3rd are *directly* probed by reactor and source experiments

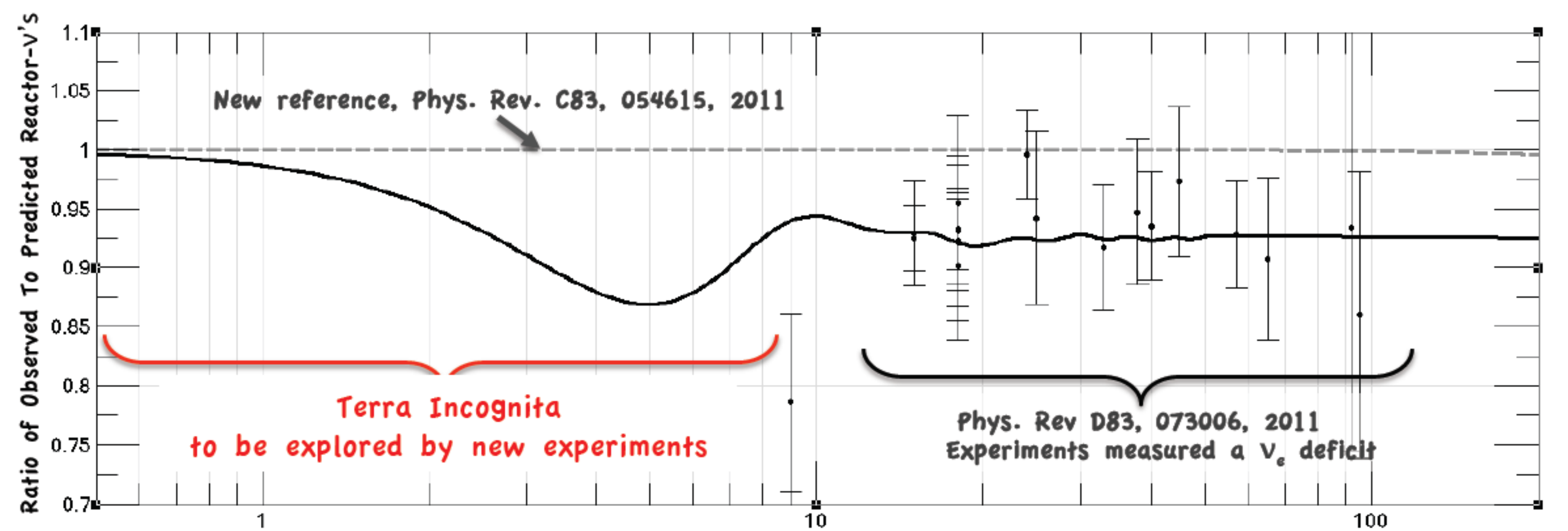
- Appearance experiment $\nu_\mu \rightarrow \nu_e$
  - Not explained by standard neutrinos





Warning: see A. Palazzo 1503.03966v3 for a discussion about Icarus and Opera limits

- **New calculations of reactor fluxes** (Phys. Rev. C83, 054615, 2011)
  - Many improvement, in principle: fuel evolution, cross sections, neutron lifetime
- New flux is higher, spoiling previously found agreement (G. Mention et al., Phys. Rev. D 83, 073006, 2011)
  - 6.5 % effect (~ 3 σ)
    - Error on flux prediction ?
    - Missing new physics ?
      - **Reactor:** unknown nuclear effects in reactor (well possible, see e.g. 5 MeV excess)
      - **Neutrino:** short distance physics, e.g. oscillations to one or more sterile (exciting! the reason we are here)



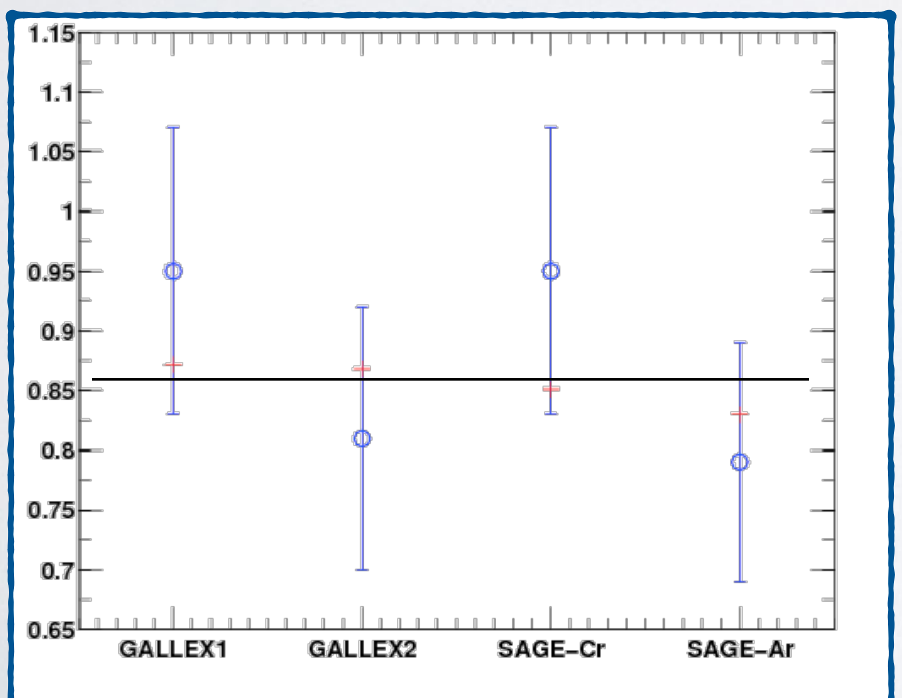
Credit: T. Lasserre

- **Gallium anomaly** (disappearance of electron neutrinos)
  - In the ’90s Gallex and SAGE have measured the neutrino flux using sources made with ^{51}Cr e ^{37}Ar and observed a deficit

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

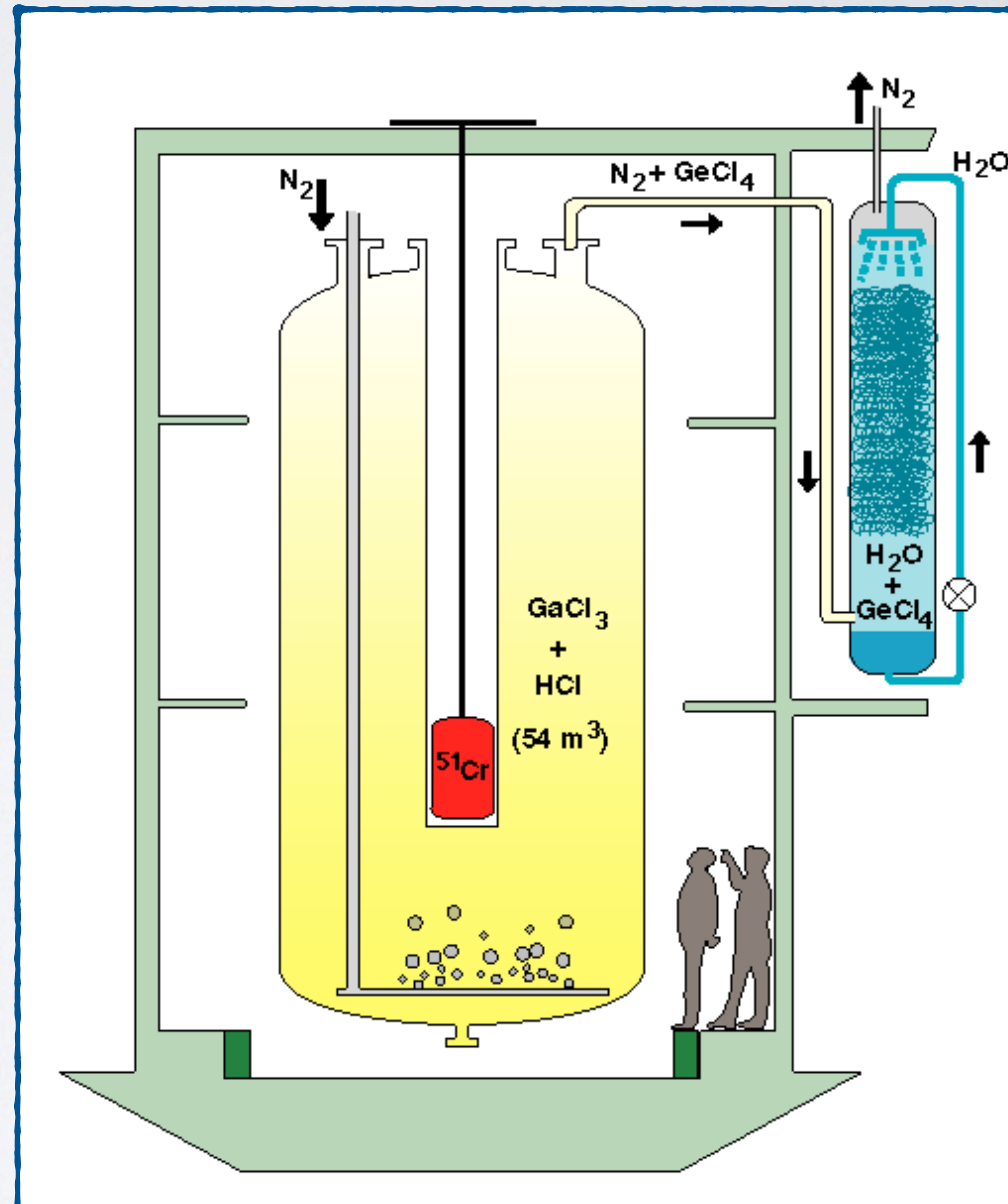
C. Giunti et al. arxiv:1210.5715 (hep-ph)

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



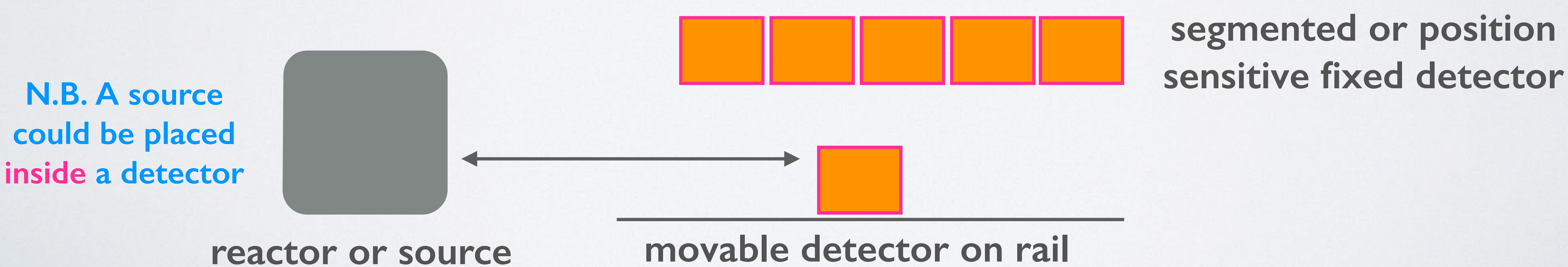
$\langle R \rangle = 0.85 \pm 0.05$

~ 3 σ effect

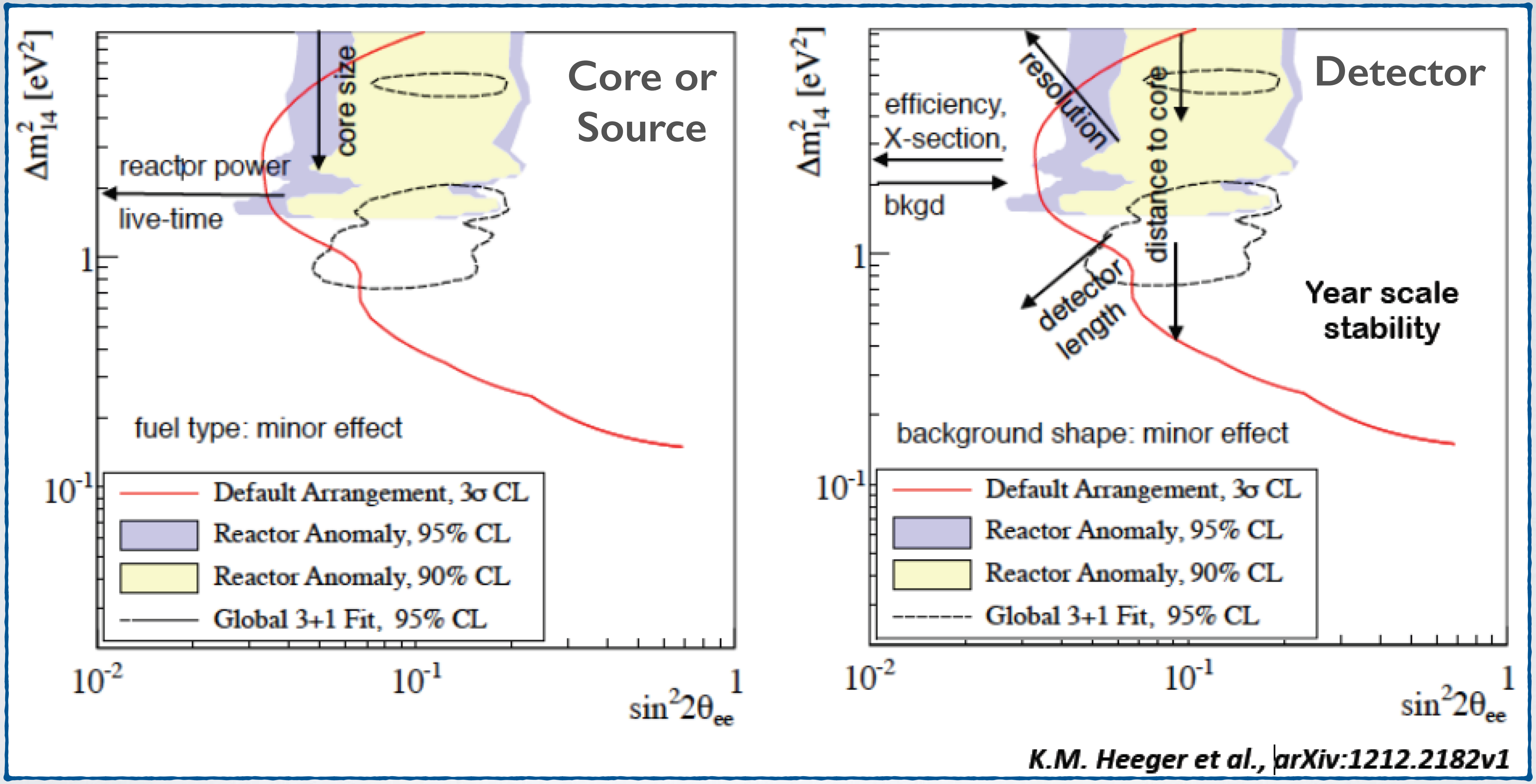


SOURCE AND REACTOR EXPERIMENTS

- Two main elements:
  - **A source of (1-10 MeV) $\bar{\nu}_e$ or ν_e**
    - A reactor ($\bar{\nu}_e$ only) or a powerful radioactive source ($\bar{\nu}_e$ and ν_e)
  - **The capability to measure the interaction rate as a function of the distance from the source**
    - Option 1: movable detector from a few up to ~20 m from the source
    - Option 2: the detector is large and it is either **segmented** or has the capability to **reconstruct efficiently the neutrino interaction point**
- Signatures:
  - Deviation from $1/R^2$ behaviour for movable detectors (Option 1)
  - Direct observation of oscillation pattern for Option 2



CRUCIAL PARAMETERS



credit: D. Lhuillier

SOURCE EXPERIMENTS

Isotope	Type	Projects	Detection	Schedule	Activity	
^{51}Cr (EC)	ν_e	Gallex (90's)	radioch.	done	~100 PBq	done
^{51}Cr (EC)	ν_e	SAGE (90's)	radioch.	done	~100 PBq	done
^{37}Ar (EC)	ν_e	SAGE (90's)	radioch.	done	~100 PBq	done
^{51}Cr (EC)	ν_e	SOX-Cr	$\nu_e + e^- \rightarrow \nu_e + e^-$	2018 ??	~ 370 PBq	
^{51}Cr (EC)	ν_e	SAGE	radioch.	?	>110 PBq	ideas
^{51}Cr (EC)	ν_e	SNO+	$\nu_e + e^- \rightarrow \nu_e + e^-$	?	~370 PBq	ideas
^{37}Ar (EC)	ν_e	Ricochet	$\nu_e + e^- \rightarrow \nu_e + e^-$	?	185 PBq	
^{144}Ce (β)	$\bar{\nu}_e$	Daya Bay	inverse β	?	3.7-5 PBq	
^{144}Ce (β)	$\bar{\nu}_e$	SOX-Ce	inverse β	2016	3.7-5 PBq	approved

SOURCE PHYSICAL PARAMETERS

Source	Production Technique	τ (days)	Decay Mode	Energy [MeV]	Heat [W/kCi]
^{51}Cr	Irradiation of ^{50}Cr in nuclear reactor $\Phi_n \gtrsim 5.\ 10^{14}\ cm^{-2}\ s^{-1}$	40	EC γ 320 keV (10%)	746	0.19
^{37}Ar	Irradiation in fast neutron reactors	50	EC	813	small
^{144}Ce - ^{144}Pr	Chemical extraction from spent nuclear fuel	411	β^-	<2.997 5	7.6

SOX HISTORICAL BACKGROUND

- The idea of making a neutrino or anti-neutrino source experiment with BoreXino dates back to the birth of the project (1991)

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)

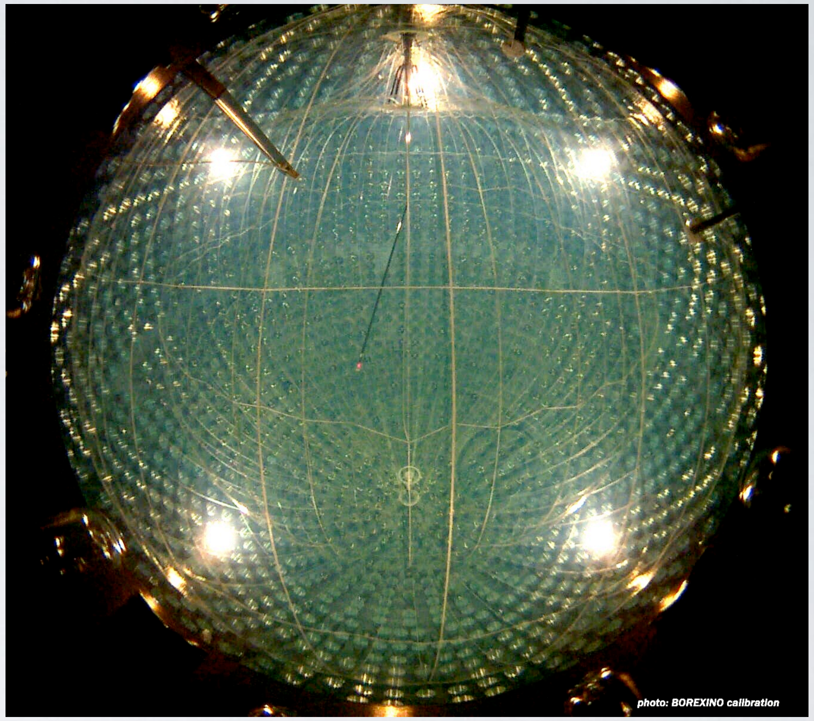
SAGE coll. PRC 59 (1999) 2246 **Done** (Cr51 and Ar37)
SAGE coll. PRC 73 (2006) 045805
C.Grieb,J.Link,R.S.Raghavan, Phys.Rev.D75:093006,2007
V.N.Gravrin et al., arXiv: nucl-ex:1006.2103
C.Giunti,M.Laveder, Phys.Rev.D82:113009,2010
C.Giunti,M.Laveder, arXiv:1012.4356

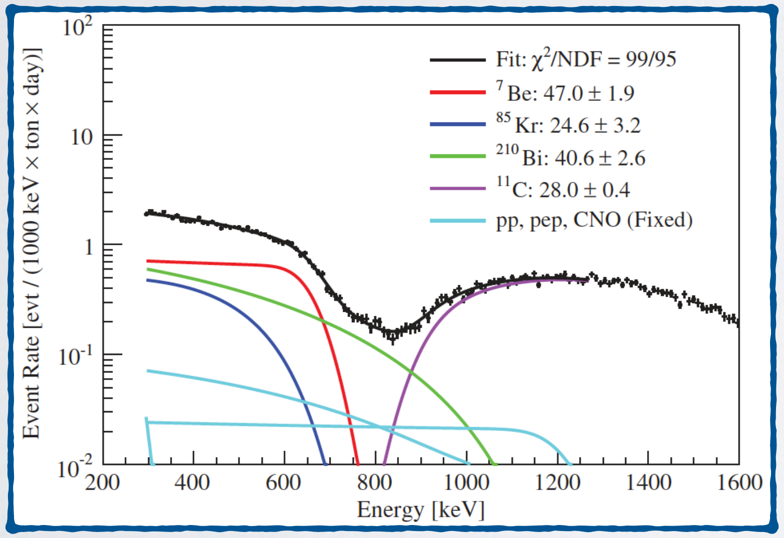
- SOX Proposal European Research Council 320873 - Feb. 2012 - APPROVED and FINANCED (P.I. Marco Pallavicini)
  - Original SOX proposal: ^{51}Cr neutrino source OR ^{144}Ce anti-neutrino source

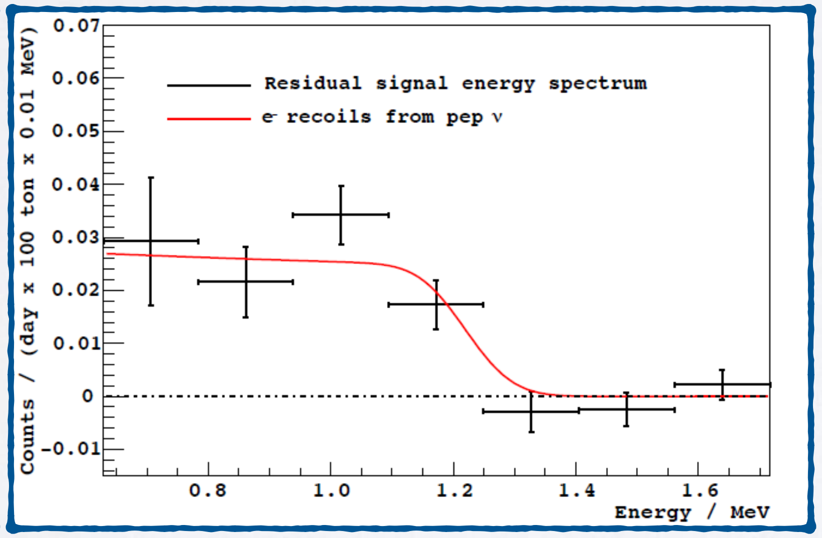
- **Jan. 2014: <u>agreement between CEA and INFN</u>** and Borexino Collaboration to merge the CELAND proposal with SOX
  - SOX-Ce (or CeSOX in France) using the Ce-144 source proposed and developed by the CEA group (another ERC project, P.I. T. Lasserre)

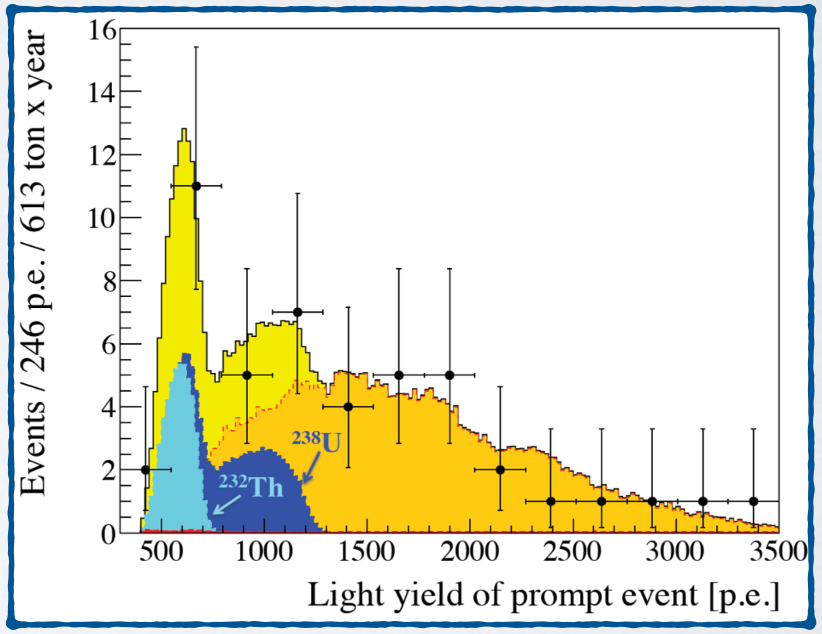
THE BOREXINO EXPERIMENT

- Mainly, a solar neutrino experiment:
  - $\nu + e^- \rightarrow \nu + e^-$ in an organic liquid scintillator
    - **Ultra-low radioactive background** obtained via **selection, shielding, and purifications**
    - Low energy threshold, good energy resolution, spatial reconstruction, and pulse shape identification
  - But also: anti-neutrinos (Geo, Reactor, SN, …)





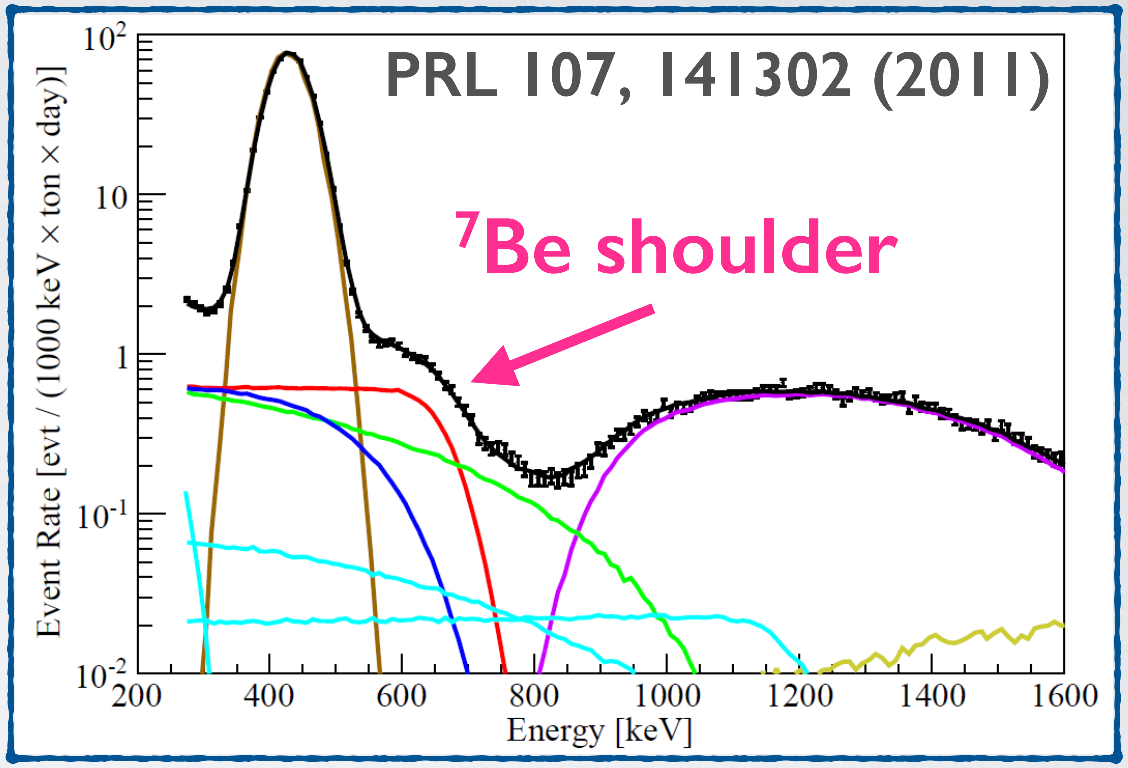




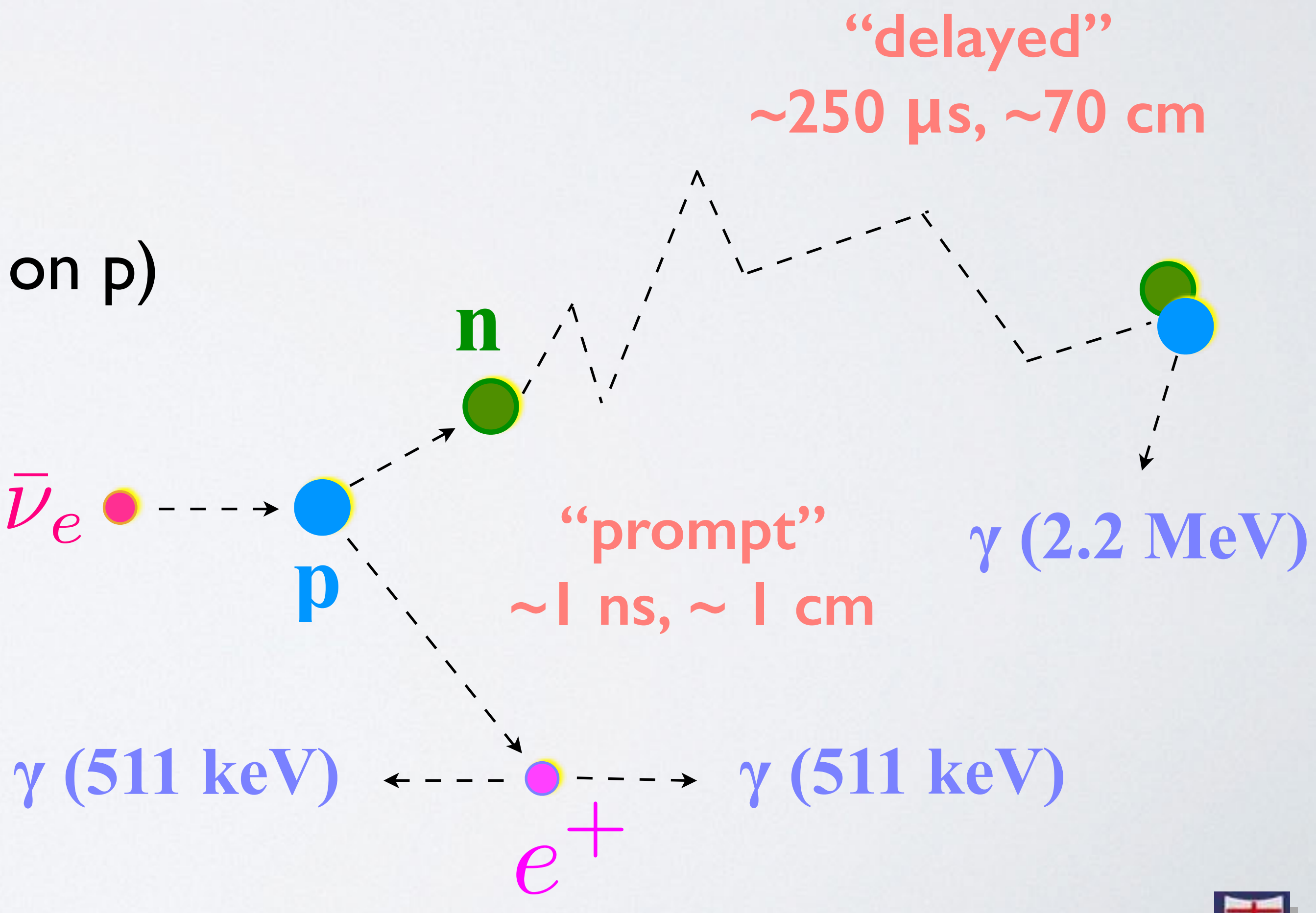
- **Sub-MeV neutrino detection capability**
  - Proved by ^{7}Be, pep, pp solar neutrino detection down to a few cpd/100 ton
- **Anti-neutrino detection capability**
  - Proved by geo-neutrino detection down to a few background events per YEAR in 300 t

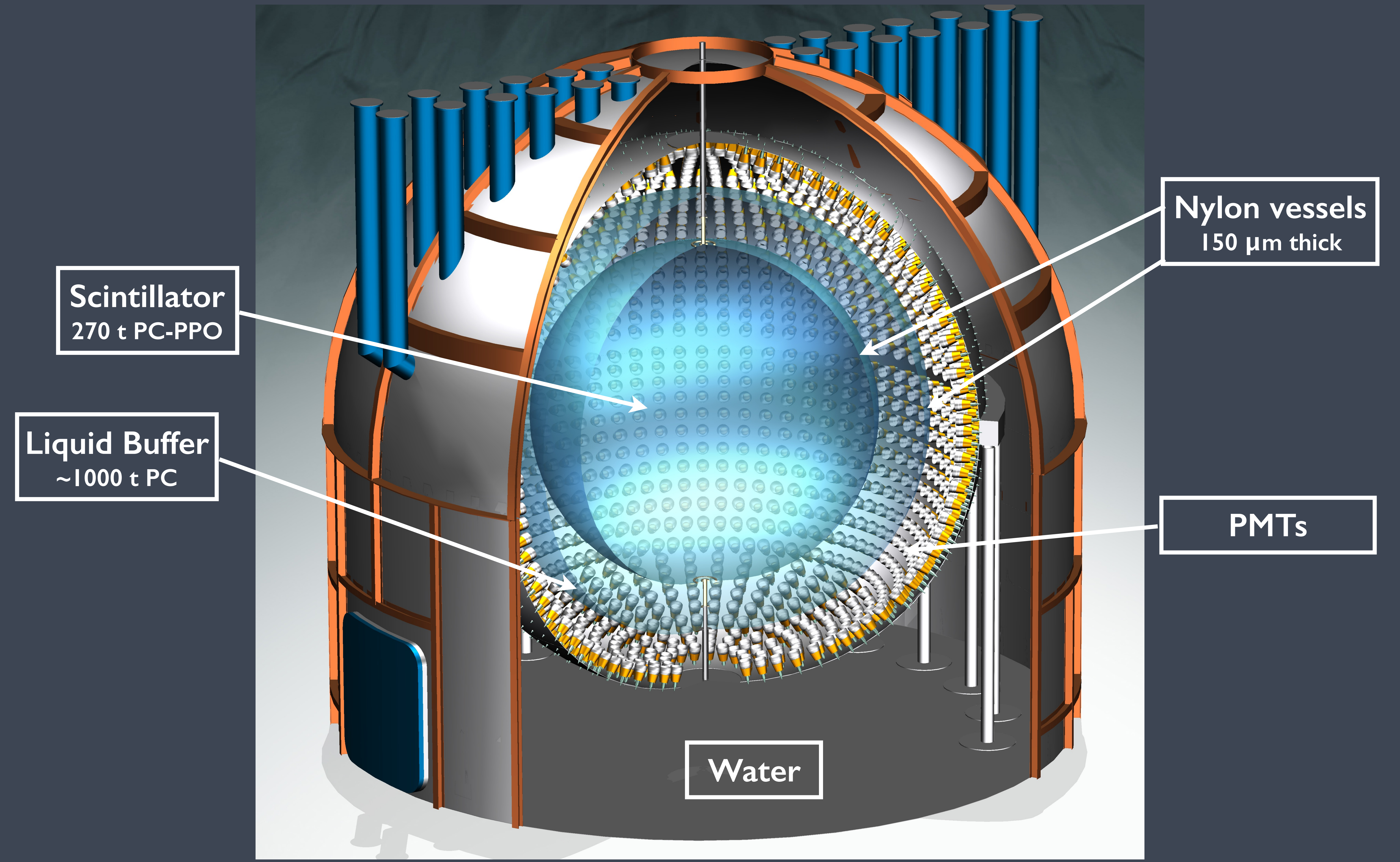
BOREXINO DETECTION CAPABILITIES

- **Neutrinos**
  - Compton-like on electrons :
    - $\nu + e^- \rightarrow \nu + e^-$
  - Mono-energetic ν_e produce the characteristic shoulder
  - Main background: ^{7}Be solar ν_e !
    - ~ 45 cpd 100 t target

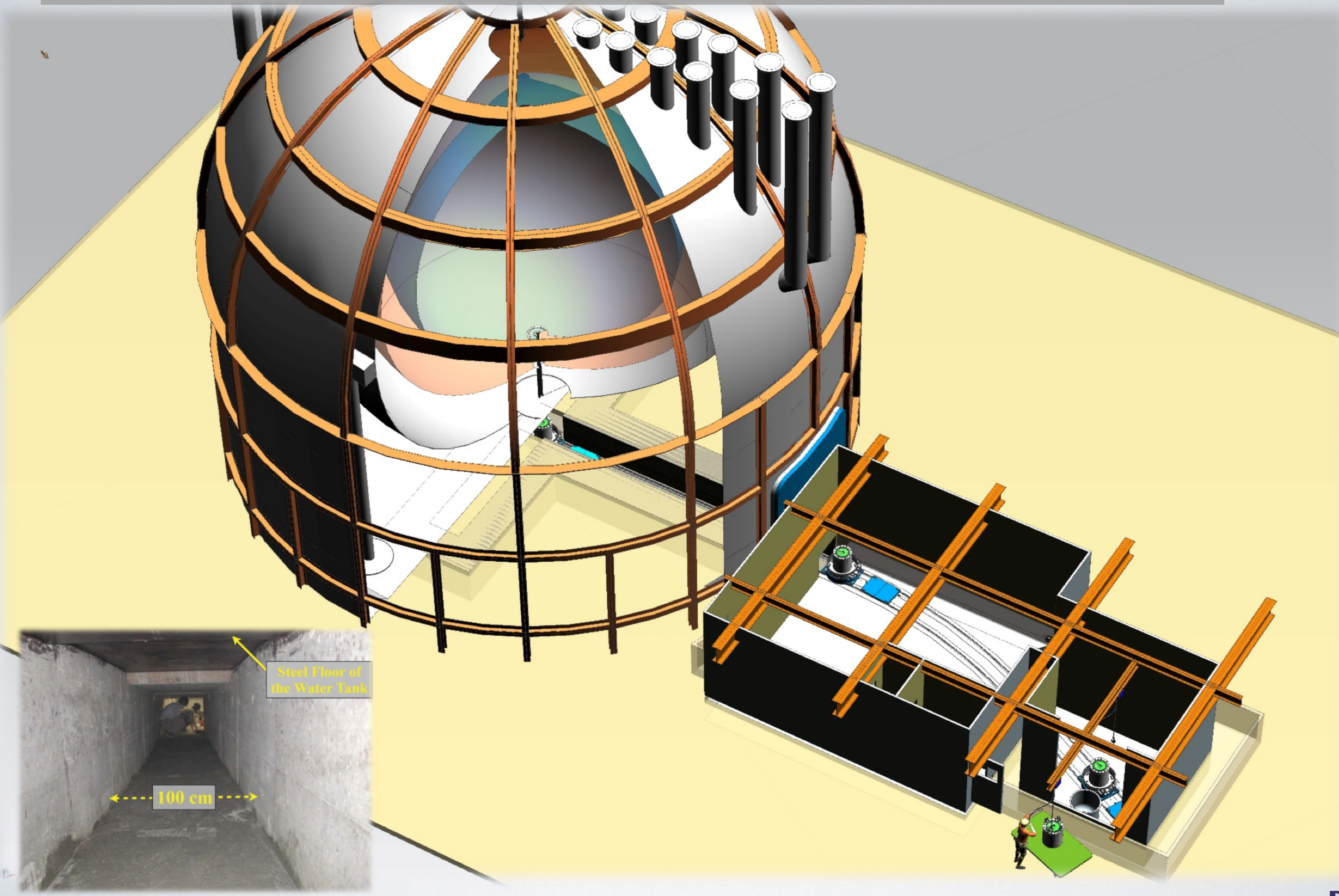


- **Electron anti-neutrinos**
  - Standard Reines-Cowan delayed coincidence technique (inverse β decay on p)
  - Extremely small background:
    - 4 geo-neutrinos ev/y in 300 t
    - 9 reactor
    - 0.4 random coincidences




Nylon vessels
150 µm thick
Scintillator
270 t PC-PPO
Liquid Buffer
~1000 t PC
PMTs
Water

LOCATION OF THE SOURCE



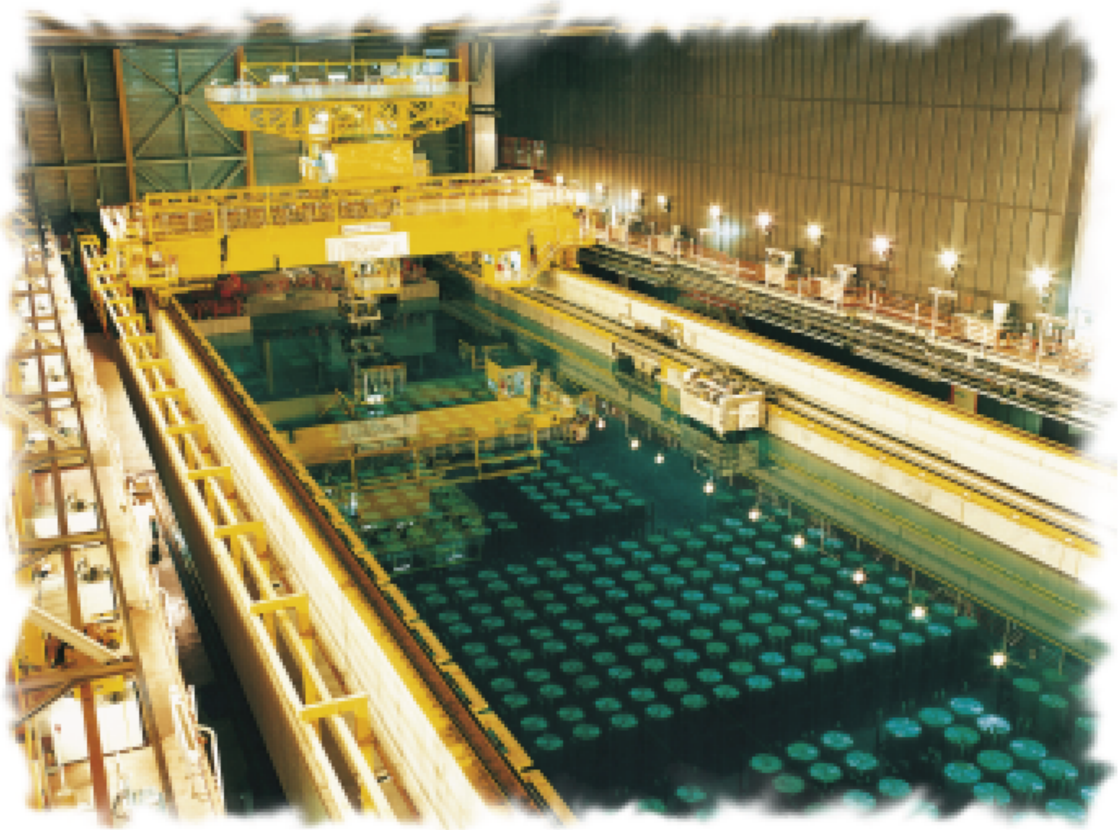
- The making of a 100-150 kCi ^{144}Ce CeANG is not a trivial business
  - Essentially a unique vendor (Mayak, Russia)
  - A humongous amount of paper work for authorisations (in Russia, France, Italy)
  - Many technical problems to be solved for:
    - CeANG **production**
    - CeANG **transportation**
    - Usage and **insertion beneath** Borexino
    - High precision **measurement of the activity** and of the neutrino flux

- Synergy between CEA and Borexino Collaboration
  - CEA: source production and transportation
  - INFN: site preparation and Borexino detector preparation
  - CEA/INFN/TUM: High precision calorimetry
  - Borexino Collaboration: high precision MC, data analysis, calibrations

CE-144 PRODUCTION

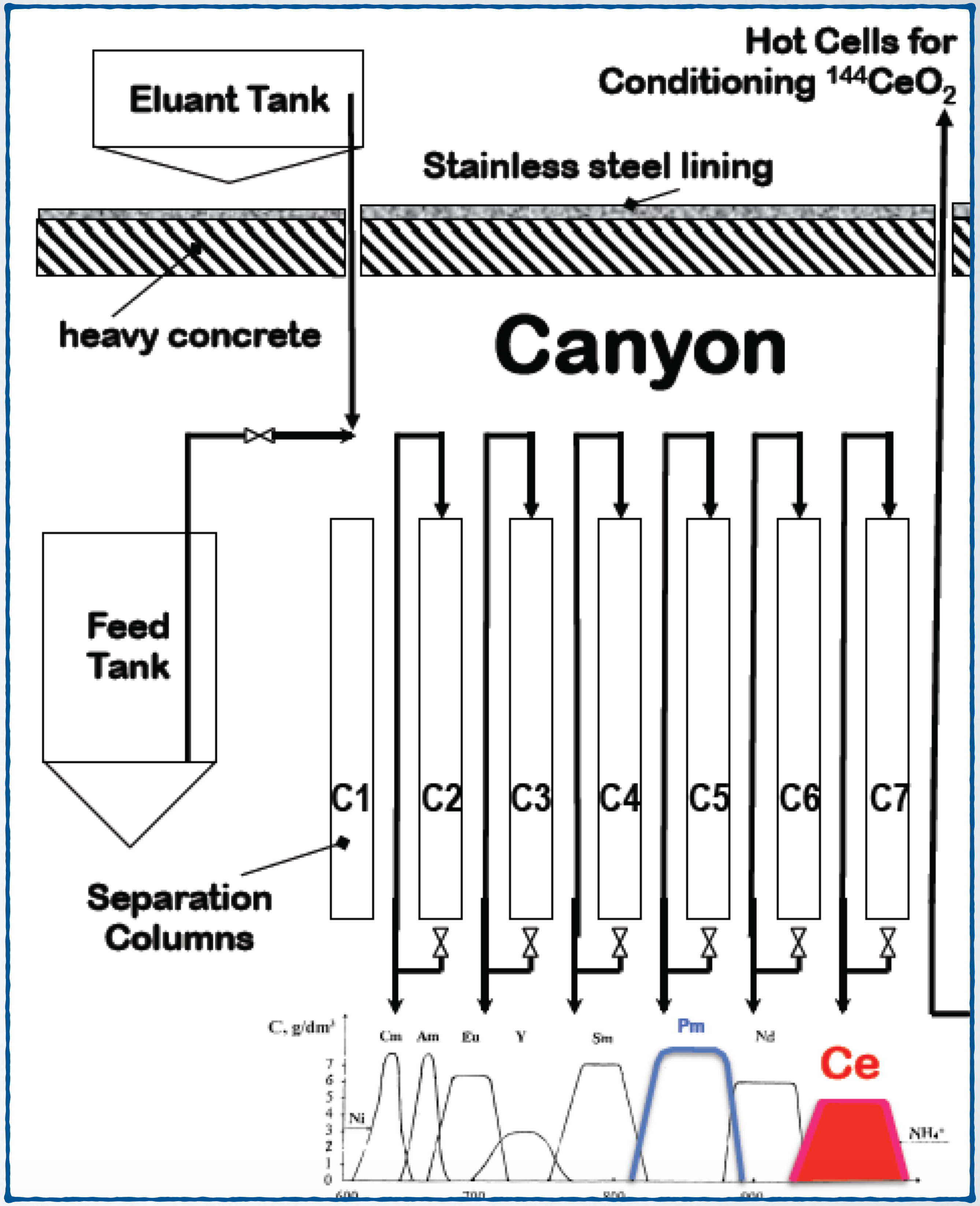
- ^{144}Ce
  - Produced as “waste” in nuclear cores
    - 5.5% in fission prod. of U
    - 3.7% in fission prod. of Pu
    - 411 days lifetime
- Selection of best fuel at Cola NPP
  - Shorter cooling time < 2 y
- Delivery from Cola to Mayak
  - TUK-6 container
- Mayak received fresh fuel March 2015
  - Could be supplemented by fuel from research reactor (high U enrichment)

- Radiochemical plant
  - Standard process (PUREX) used to treat spent nuclear fuel
  - Production of and separation of CeO2
  - Encapsulation of powder
  - Activity measurement
- Radioisotope Plant
  - Source fabrication
  - Certification ISO 9978
  - Loading into W shield
  - Loading into transportation cask



CE-144 PURIFICATION

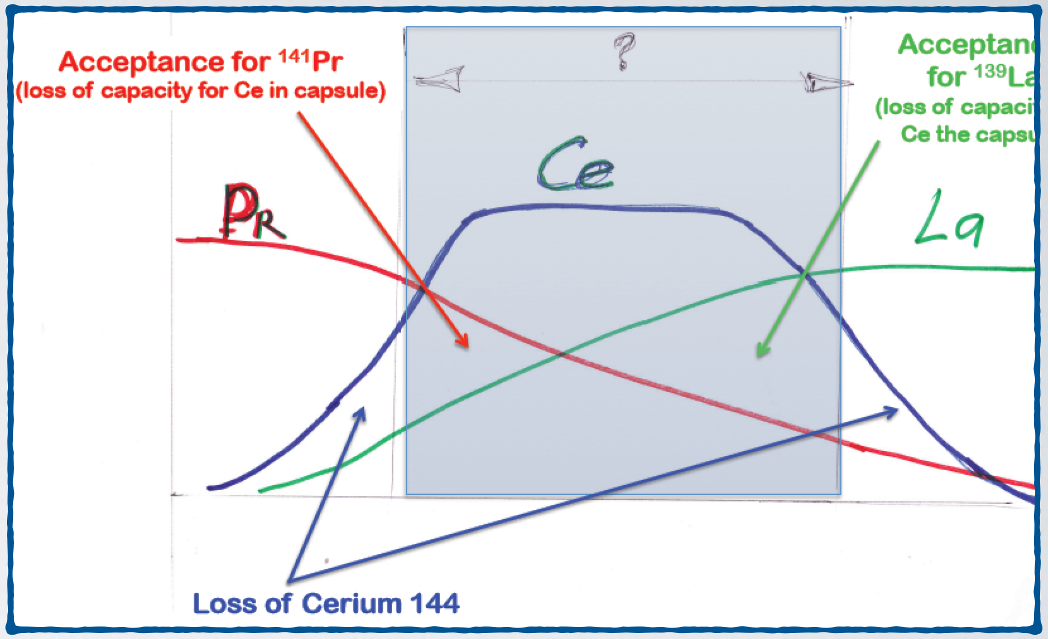
- Complexing agent displacement chromatography for Rare Earths Elements(REE)
- Spent Nuclear Fuel
  - Mayak: 100 t PUREX / year
  - 1 ton SNF
    - 13 kg REE (22 g Ce-144 (3y, 70 kCi))
- Production
  - Start now
  - Delivery Aug.-Oct 2016
    S. Petersburg harbour
  - @LNGS end of 2016

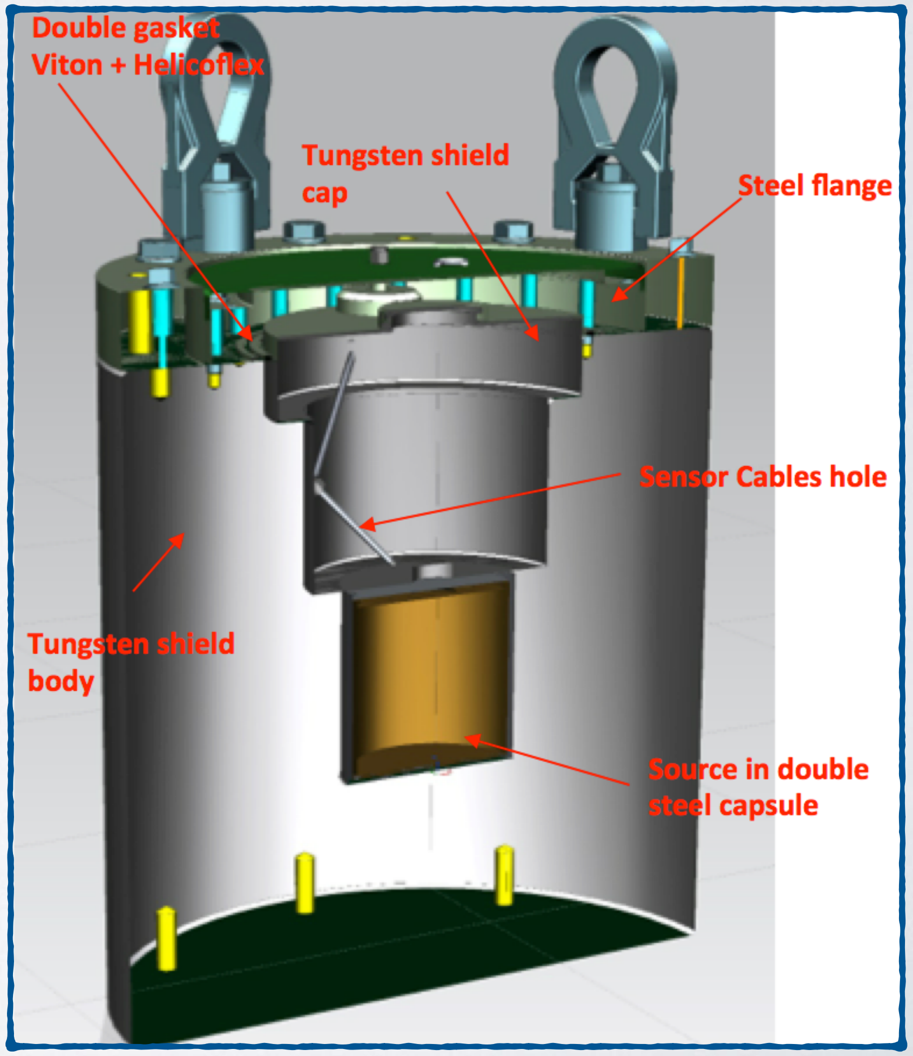


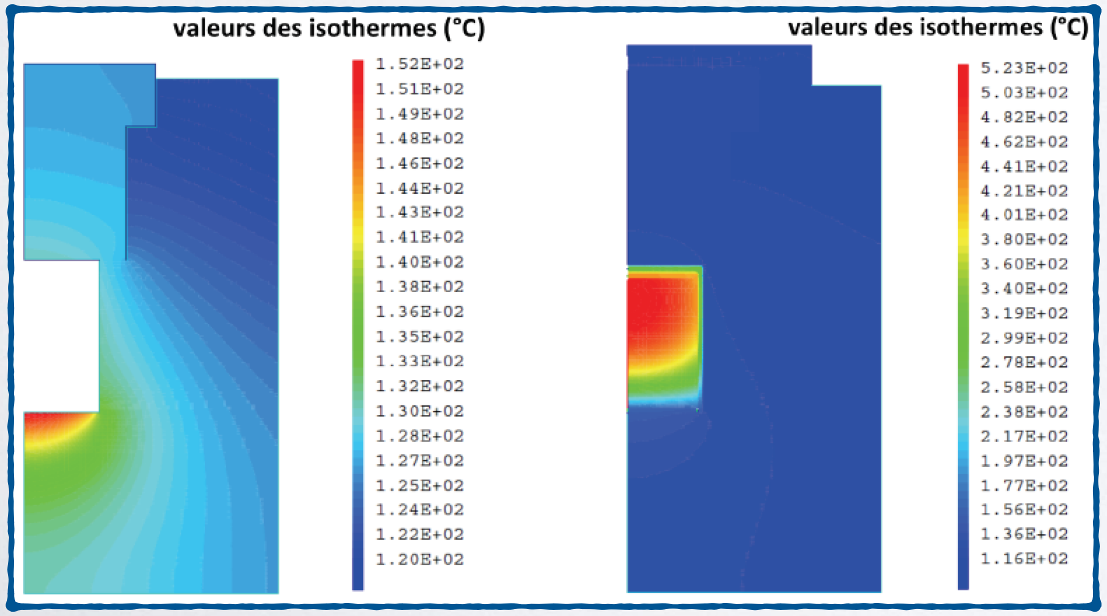
A VERY LONG STORY MADE SHORT: CeANG

for more details on CeANG see e.g.
T. Lasserre talk at Venice 2015

- Specs
  - >3.7 PBq (^{144}Ce only); powder 4-6 g cm^{-3} density
  - CeO_2 with Ce from fresh spent fuel (<2 y old)
  - Purity
    - Rare Earth: γ rate < 10^{-3} Bq/Bq w.r.t. ^{144}Ce
    - Pu and actinides: < 10^{-5} Bq/Bq w.r.t. ^{144}Ce(max 10^5 n/s)
  - Production
    - Key: separation of Ce from other REE with chromatography
    - CeO_2 powder sealed in a container
    - Container inserted into a 19 cm thick W shield
    - Internal T ~ 500 °C; surface T @ 20:°C ~ 80 °C



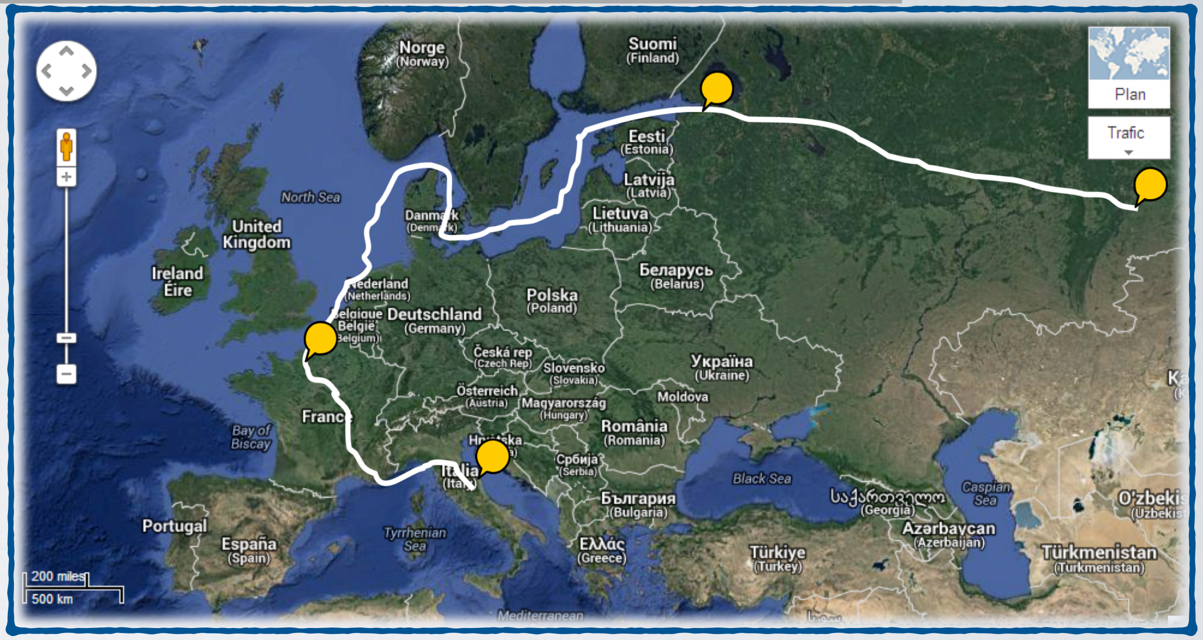


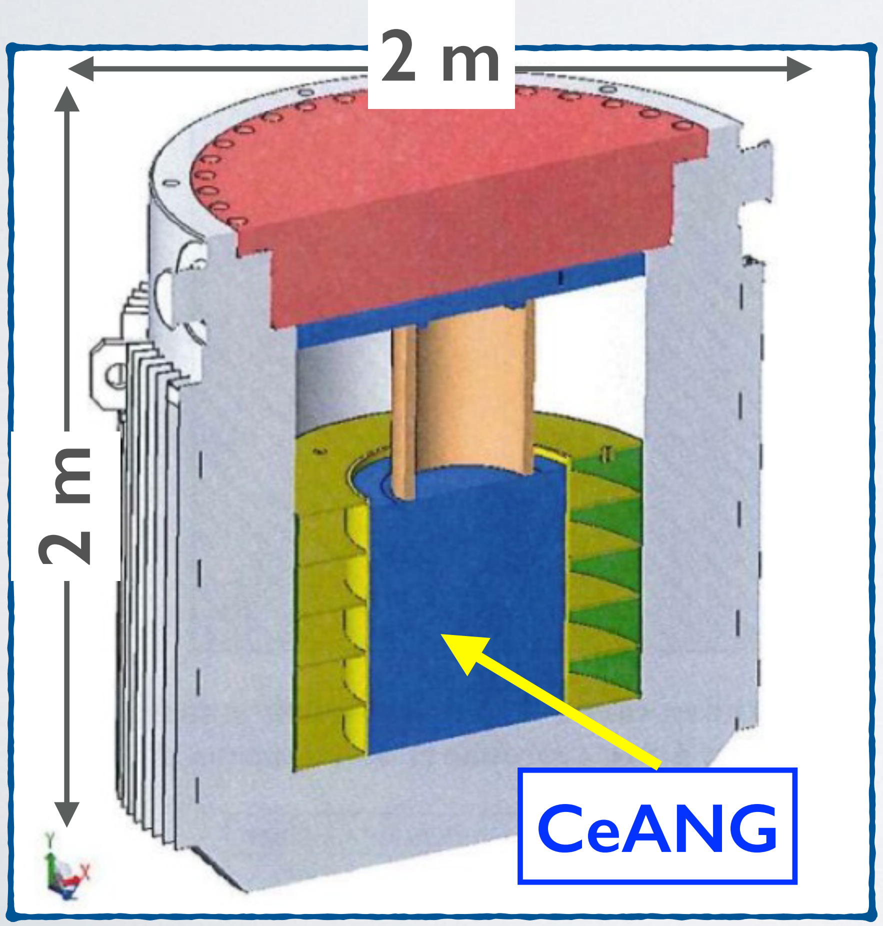


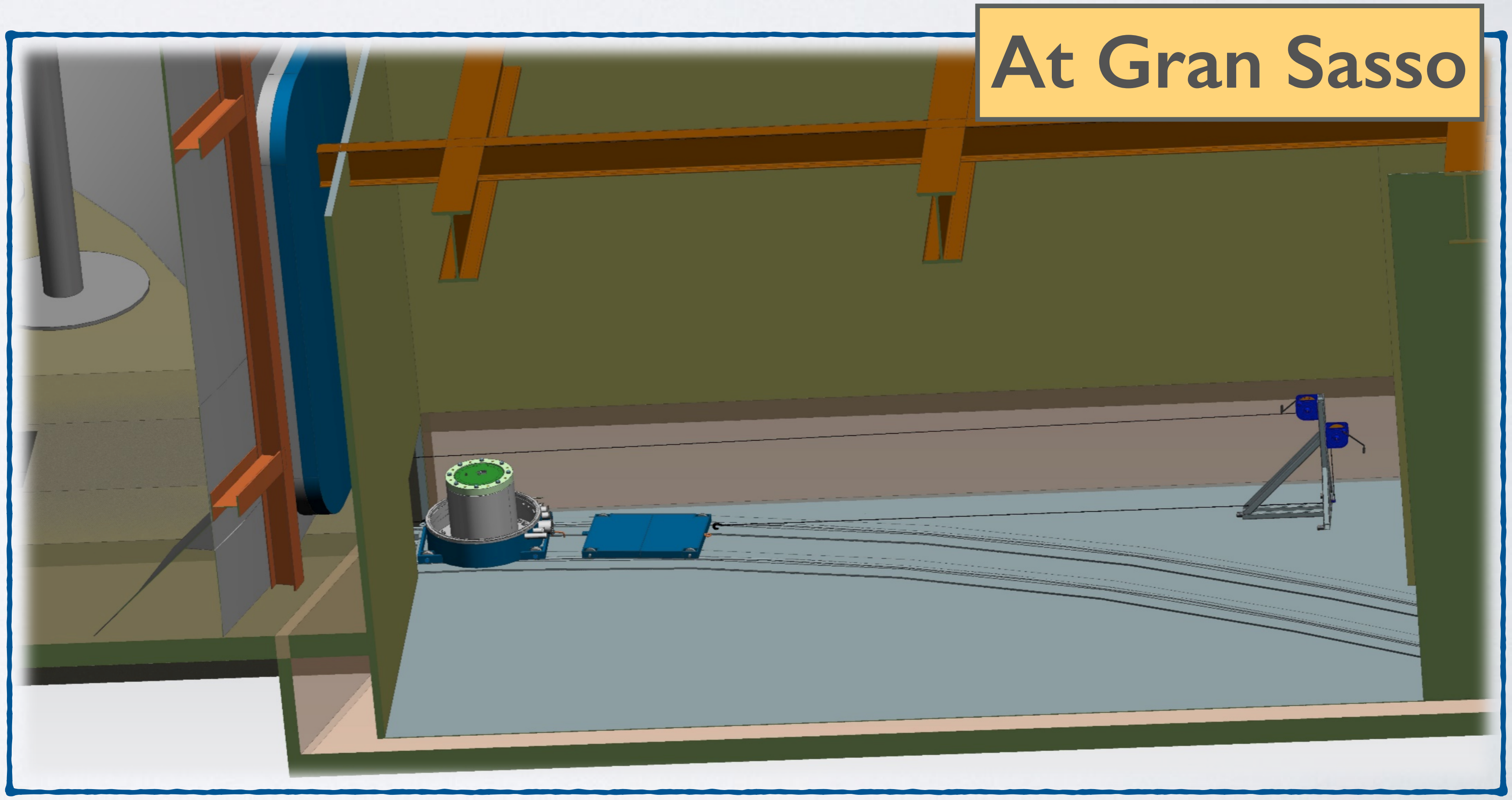
A LONG STORY MADE SHORT: TRANSPORTATION

for more details on CeANG see e.g. T. Lasserre talk at Venice 2015

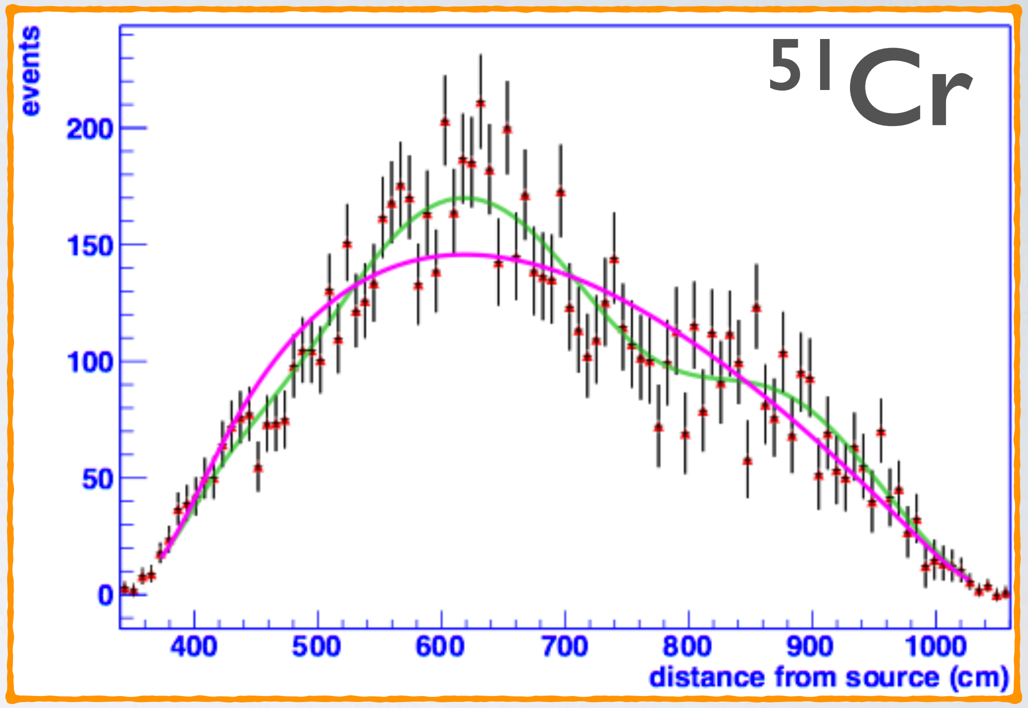
- A long way (~1-2 months):
  - Mayak → St. Petersburg by train
  - St. Petersburg → Le Havre by boat
  - Le Havre → Saclay → LNGS by truck
  - Container: TN MTR
    - **24 t** container for nuclear fuel (CEA)
  - IZOTOP (Russia), AREVA (Main contractor, France) + MIT (Italy) will handle the long journey

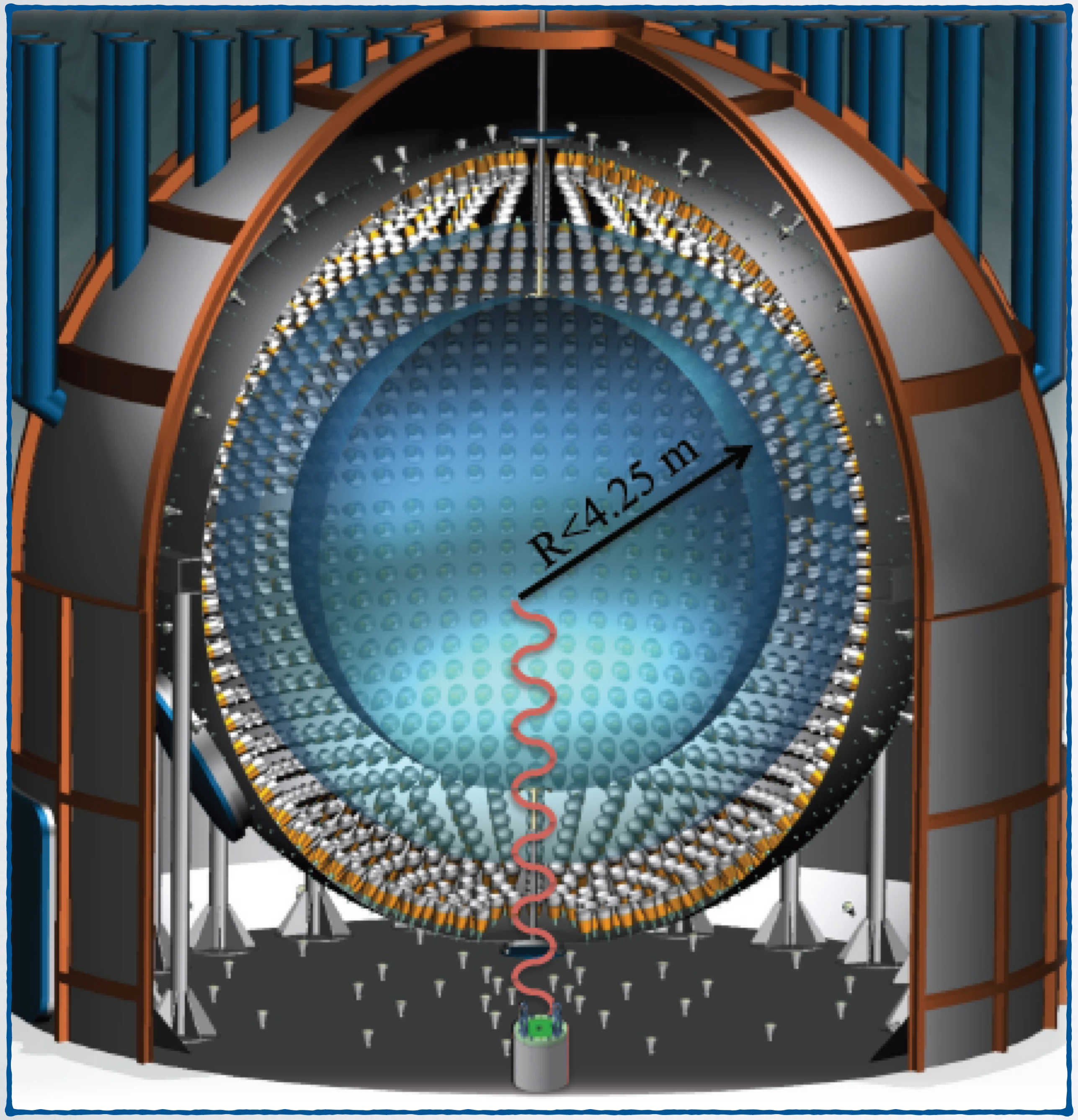


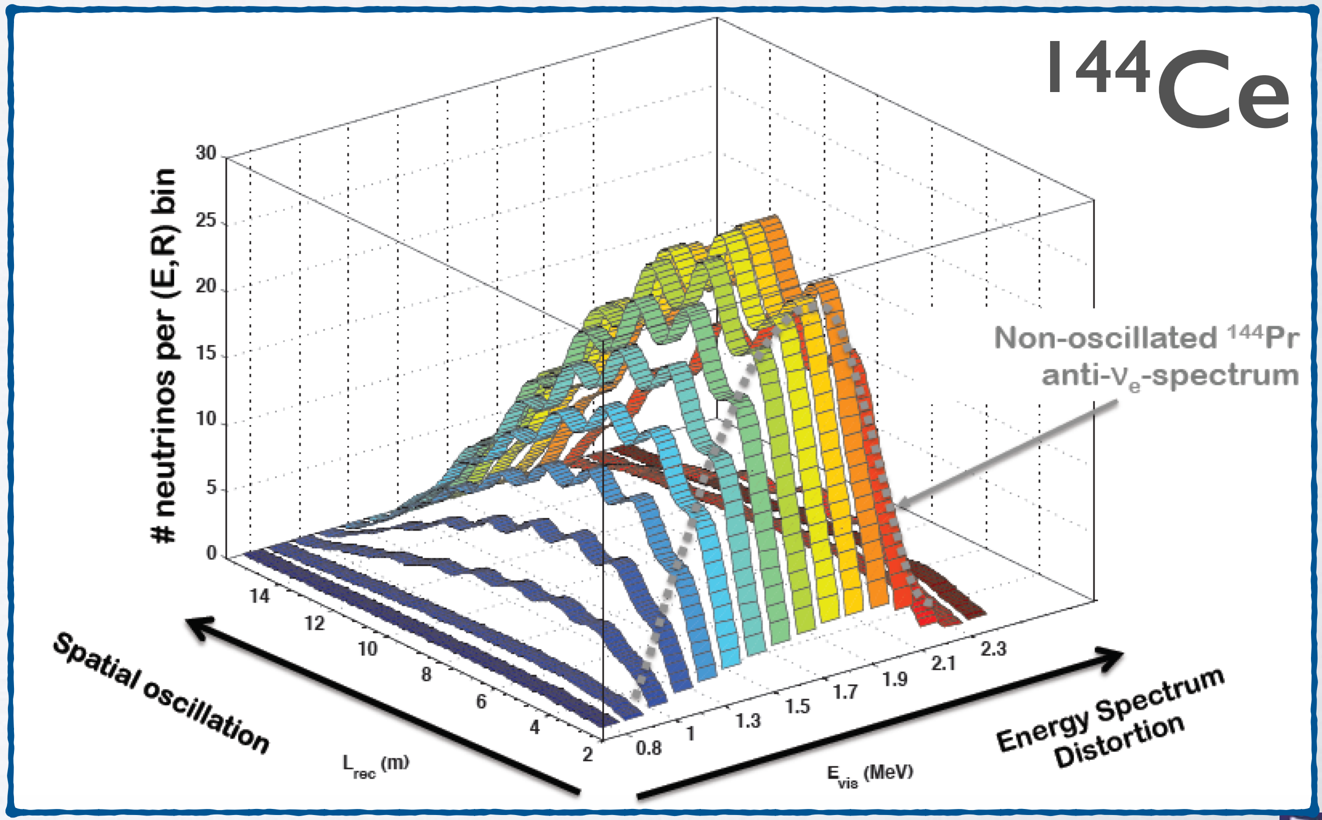




- SOX is at the same time a disappearance experiment and an oscillometry one
  - Goal: 1% knowledge of source activity (calorimetry)



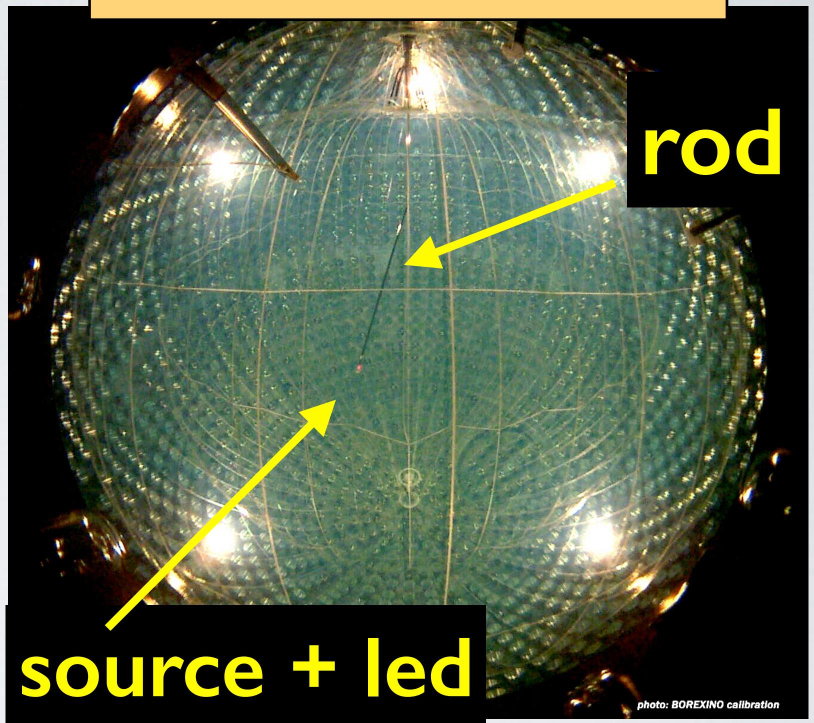


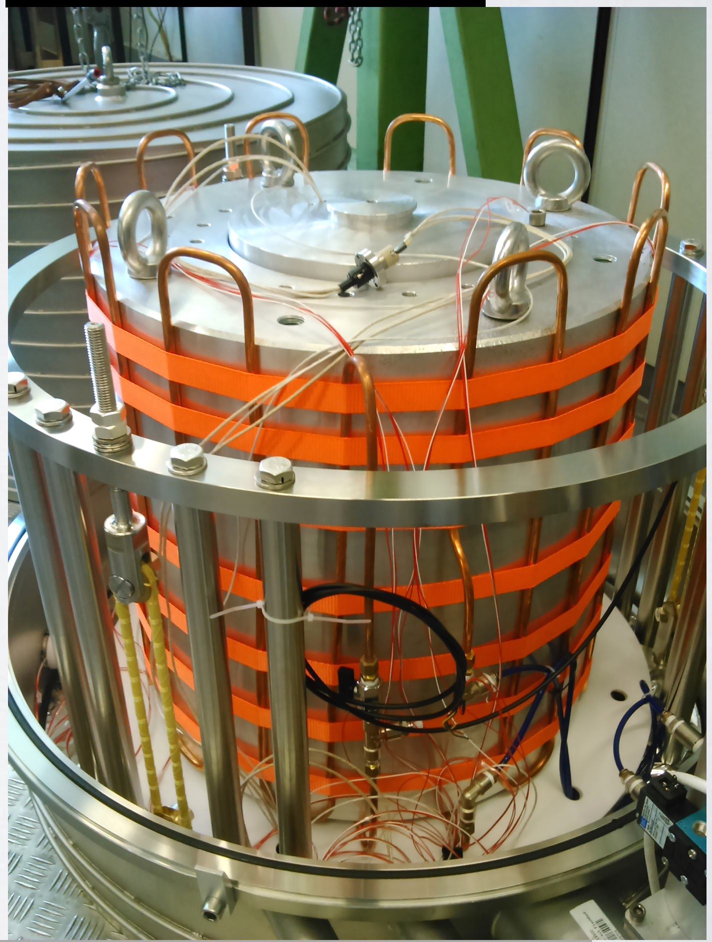


HIGH PRECISION CALORIMETRY

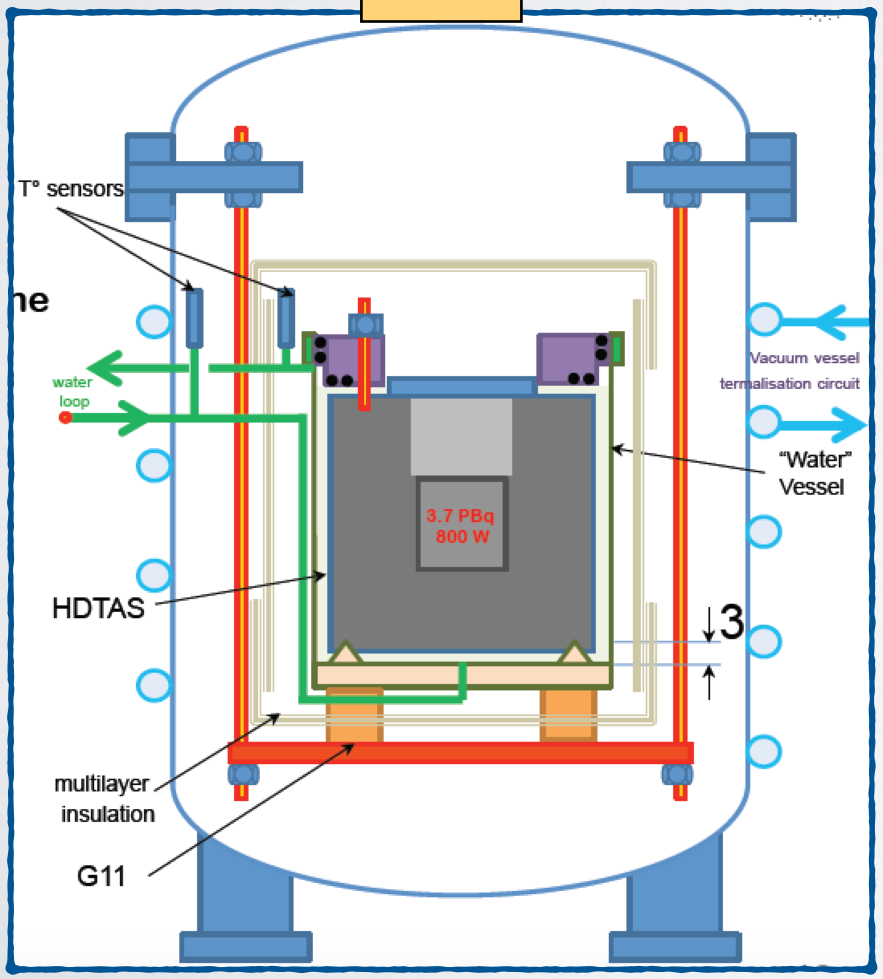
- Final sensitivity as disappearance experiment depends crucially on (waves detection does not!):
  - **Detector response:** well known from Borexino data
  - **Fiducial volume** (Calibration program in 2015)
  - Measurements of ^{144}**Ce β spectrum,** above 1.8 MeV (CEA)
  - **Activity:** Calorimetric measurement will reach 1% precision (two measurements with different devices)

Borexino Calibration

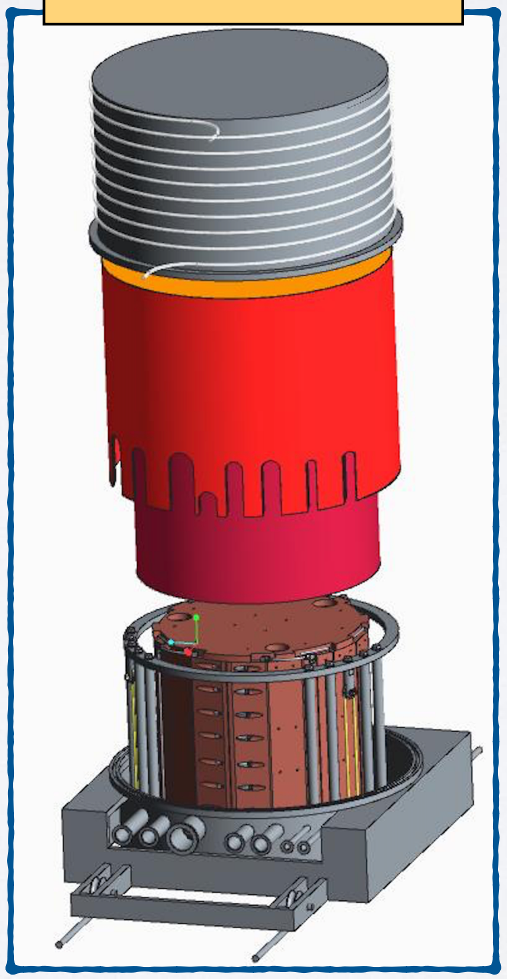




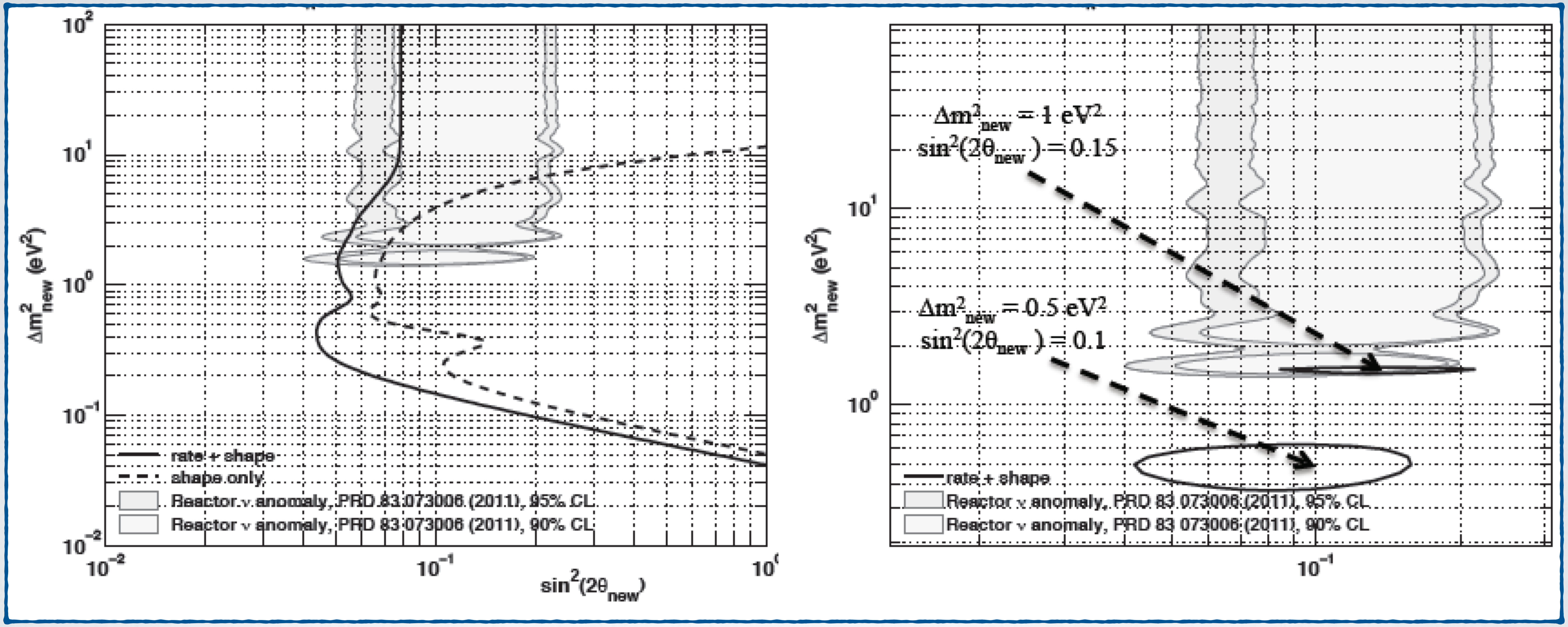
CEA



Genova/TUM



- **3.7 PBq** ^{144}Ce known at 1.5% and at 8.2 m from Borexino center



Exclusion (90% c.l.)   Discovery (99% c.l.)

- Contract for source production and delivery agreed in June in Moscow

CONCLUSIONS

- A rich experimental program exists, aiming at **confirming or rejecting reactor and gallium anomalies**
  - Several reactor experiments approved and many in R&D phase
  - One source experiment approved and many ideas
  - Many experiments have sensitivity to confirm or reject unambiguously
- This program is complemented by a crucial accelerator program (not covered)
- **Final comment:**
  - Standard Neutrinos have been ***exceptionally kind to us:***
    - δm^2 (solar) << Δm^2 (atm.)
    - Large angles, including ϑ_{13}
    - Maybe even large CP violation!
  - **Sterile sector might be rich, grumpy and cryptic**
    - It's too early to discuss interpretations.
    - We must asses the facts first.

Thanks