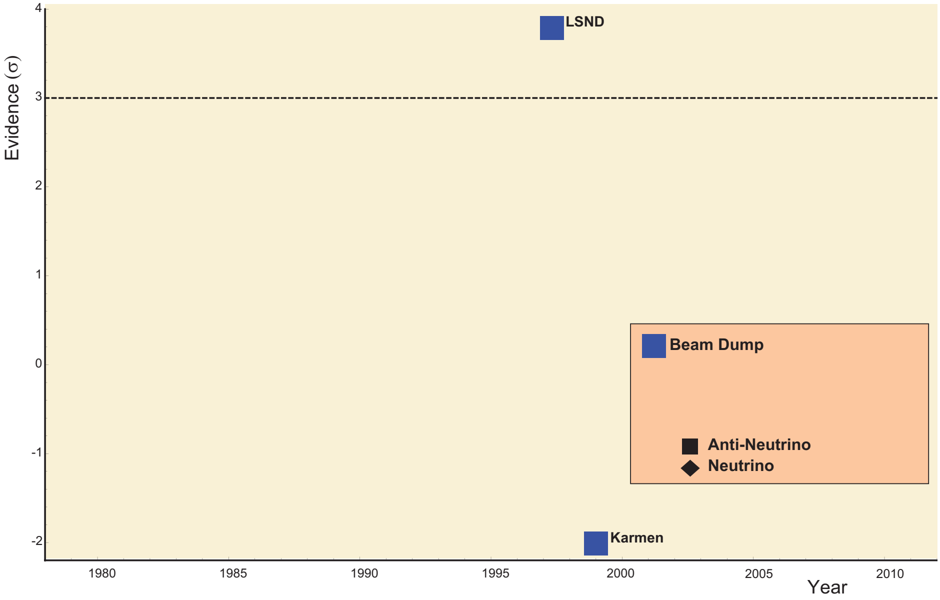
Mauro Mezzetto
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

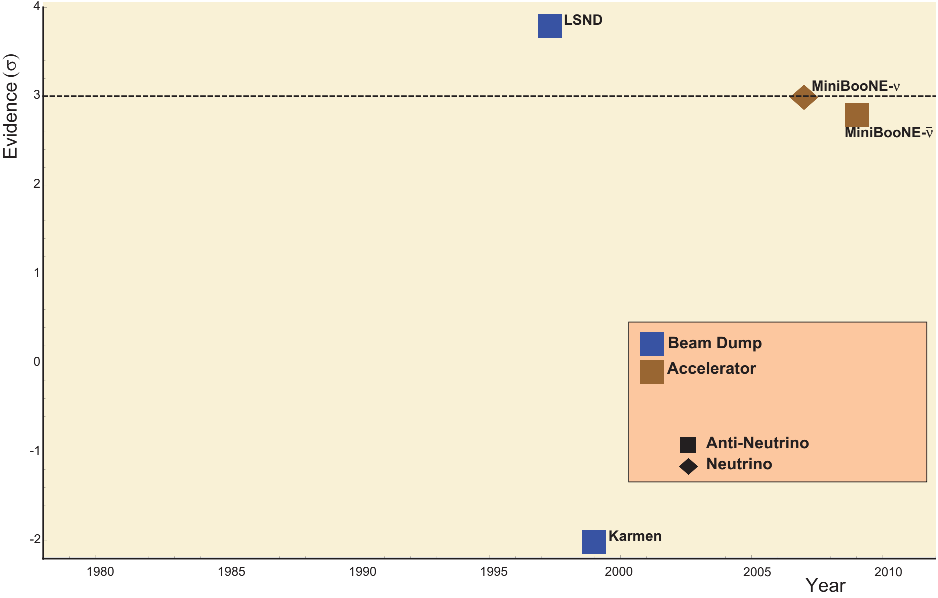
" Sterile Neutrinos"

- Anomalies
- Fits
- Requirements for future experiments
- New initiatives

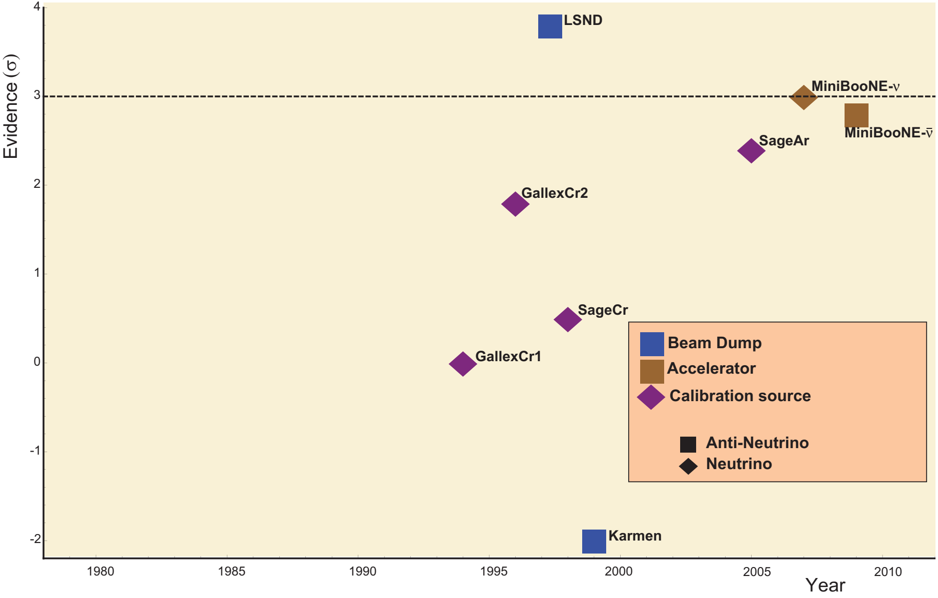
A long standing set of anomalies



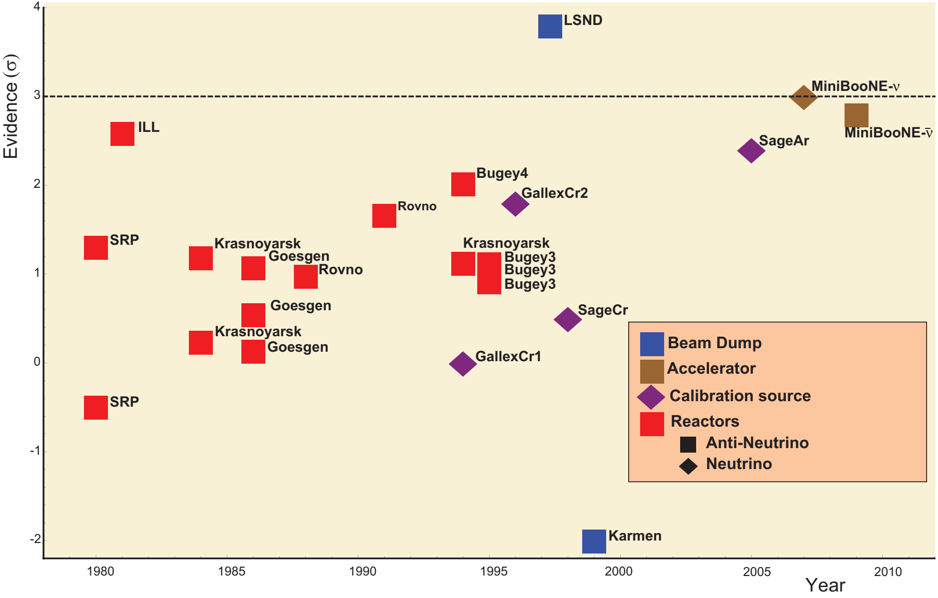
A long standing set of anomalies



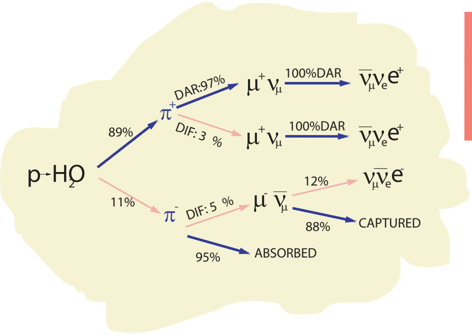
A long standing set of anomalies



A long standing set of anomalies



LSND at the Los Alamos LAMPF: a 3.8 σ evidence

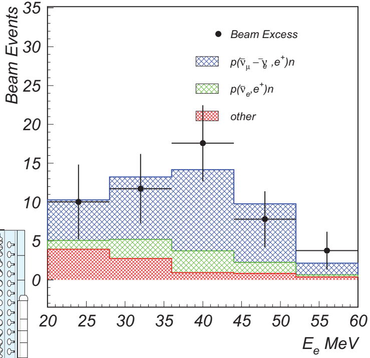


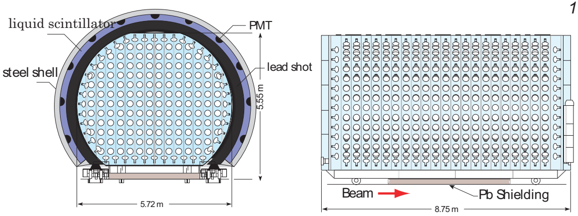
prompt positron signal, energy range.

$\overline{\nu}_e p \to e^+ n$

$n + p \xrightarrow[\tau \simeq 186\ \mu s]{} d + \gamma(2.2\,MeV)$

delayed correlated photon.

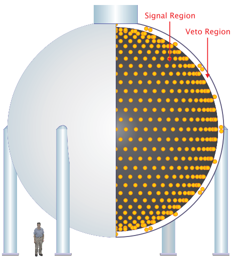


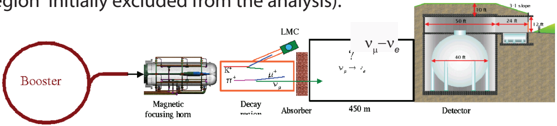


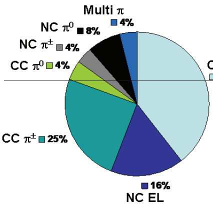
MiniBooNE experiment at FNAL Booster

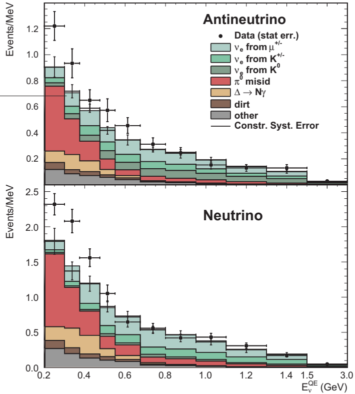
Overall a 3.8 σ excess of events. Mostly in the low energy region, where the experiment has poor control of the backgrounds (region initially excluded from the analysis).

MiniBooNE Detector







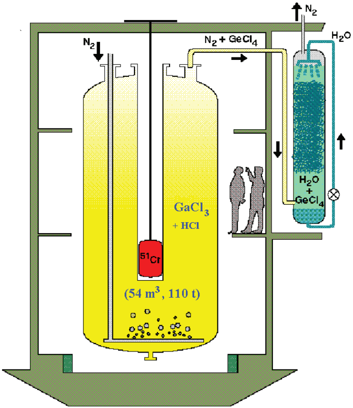


Property	LSND	MiniBooNE
Proton Energy	798 MeV	8000 MeV
Proton Intensity	1000 μA	4 μA
Proton Beam Power	798 kW	32 kW
Protons on Target	28,896 C	284 C
Duty Factor	6×10^{-2}	8×10^{-6}
Total Mass	167 t	806 t
Neutrino Distance	30 m	541 m
Events for 100% ν_μ ? ν_e Transmutation	33,300	128,077

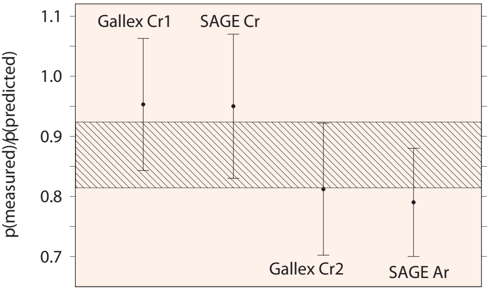
Gallium Anomaly

Hampel et al 1998, Kaether et al 2010, Abdurashitov et al 1998, Abdurashitov et al 2005

4 exposures of Gallex and Sage to ^{51}Cr and ^{37}Ar sources
Originally designed and funded as calibration of the detection efficiency
Now interpreted as neutrino disappearance (assuming perfect calibration)



Giunti, Laveder, Mod. Phys. Lett. A22 (2007)2499



Reactor Neutrino Anomaly

Nuclear reactors: electron spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu are translated to $\overline{\nu}_e$ flux

Schreckenbach 82, 85

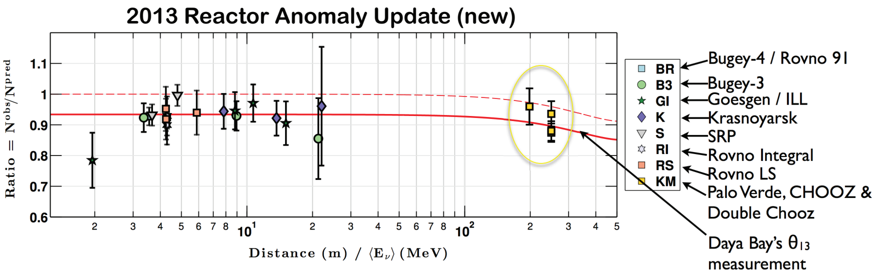
Experiments originally reported no deviations from predictions

A recalculation of fluxes lead to ~ 3% increase -> exp. results reinterpreted as a deficit evidence

Müller et al 2011, Huber 2011

Maybe with ~5% systematic errors

Hayes et al., arXiv 1309.4146



- **2013 result: μ = 0.936 ± 0.024, 2.7σ deviation from unity (T. Lasserre, TAUP 2013)**

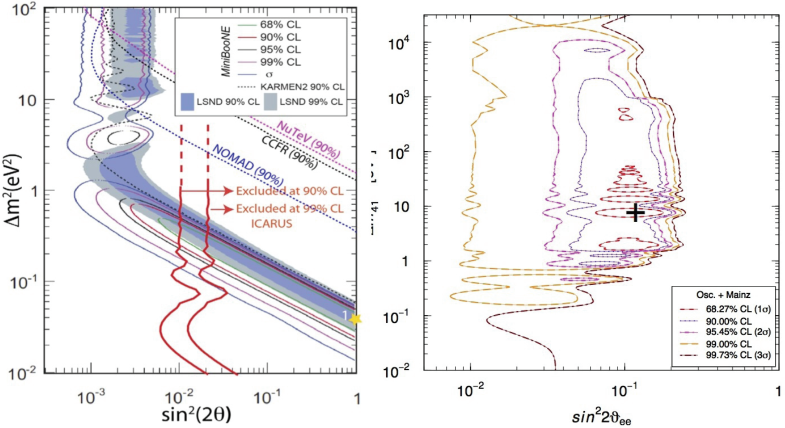
Empirical 2ν fits

M. Antonello et al., arXiv:1307.4699

$\bar{\nu}_\mu \to \bar{\nu}_e$

C. Giunti et al., Phys.Rev. D86 (2012) 113014

$\nu_e \to \nu_e$



Modelling (the 3+1 case)

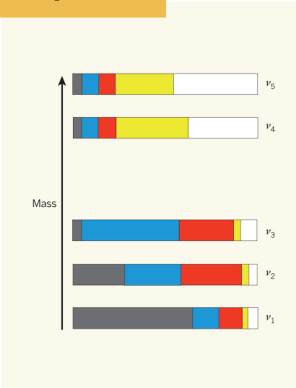
$$P^{SBL}_{\overset{(-)}{\nu_\alpha} - \overset{(-)}{\nu_\beta}} = \sin^2 2\theta_{\alpha\beta} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$P^{SBL}_{\overset{(-)}{\nu_\alpha} - \overset{(-)}{\nu_\alpha}} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$\alpha, \beta = e, \mu, \tau, s$

$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$,

$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \ (1 - |U_{\alpha 4}|^2)$



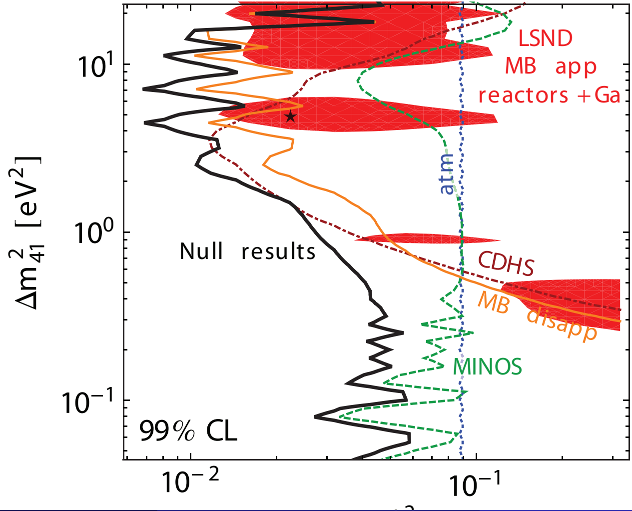
In a 3+1 model, oscillations depend from 2 additional mixing angles and 1 additional Δm^2 (assuming that steriles are much heavier than standard neutrinos)

So ν_e appearance and disappearance are linked by ν_μ disappearance !

What about ν_μ disappearance?

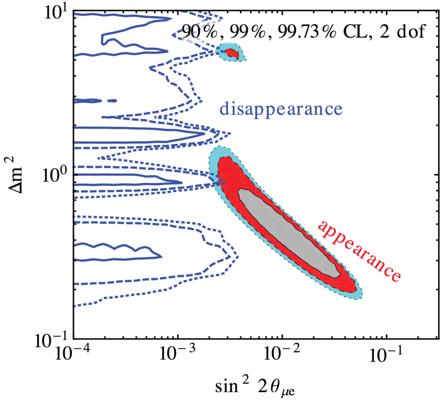
Null results from several different experiments, including atmoshperic neutrinos in SK

Kopp et al., JHEP 1305 (2013) 050 [arXiv:1303.3011]

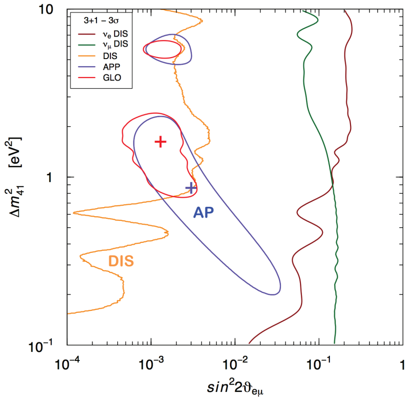


Global fits

J. Kopp et al., **arXiv:1303.3011**



C. Giunti et al., **arXiv:1302.6720**



Tension between appearance and disappearance results, not resolved even enlarging the model to 3+2 neutrinos

Counting neutrinos with Cosmology

Planck results aren't model independent or unambiguous
But Cosmology is not favoring sterile neutrinos anymore
Limits on absolute neutrino masses are becoming quite stringent

Planck 2013 results. I. Overview of products and scientific results

An exploration of parameter space beyond the basic set leads to: (a) firmly establishing the effective number of relativistic species (neutrinos) at 3; (b) constraining the flatness of space-time to a level of 0.1%; (c) setting significantly improved constraints on the total mass of neutrinos, the abundance of primordial Helium, and the running of the spectral index of the power spectrum.

Planck 2013 results. XVI. Cosmological parameters

The impact of additional astrophysical data is particularly complex in our investigation of neutrino physics (Sect. 6.3). We will use the effective number of relativistic degrees of freedom, $N_{\rm eff}$ as an illustration. From the CMB data alone, we find $N_{\rm eff} = 3.36 \pm 0.34$. Adding BAO data gives $N_{\rm eff} = 3.30 \pm 0.27$. Both of these values are consistent with the standard value of 3.046. Adding the H_0 measurement to the CMB data gives $N_{\rm eff} = 3.62 \pm 0.25$ and relieves the tension between the CMB data and H_0 at the expense of new neutrino-like physics (at around the 2.3σ level). It is possible to alleviate the tensions between the CMB, BAO, H_0 and SNLS data by invoking new physics such as an increase in $N_{\rm eff}$. However, none of these cases are favoured significantly over the base ΛCDM model by the Planck data (and they are often disfavoured). Any preference for new physics comes almost entirely from the astrophysical data sets. It is up to the reader to decide how to interpret such results, but it is simplistic to assume that all astrophysical data sets have accurately quantified estimates of systematic errors. We have therefore tended to place greater weight on the CMB and BAO measurements in this paper rather than on more complex astrophysical data.

Summarizing the present status

- $\sim 3\sigma$ anomalies in 4 different fields
- None of them is fully convincing by itself.
- They can be compatible, but the global picture is not convincing
- Cosmology is not more supporting the existence of a fourth neutrino.
- ...seventeen years after the first LSND paper ...
- ...but several new proposals are now on the market.

No direct evidence of steriles whatsoever

- Steriles are not necessary to build up $\nu_\mu \to \nu_e$ transitions or ν_e disappearance
- They are invoked to accommodate a fourth δm^2 faking the LEP limit on three neutrinos.
- Their only possible direct signature is NC disappearance

Experimental Goals

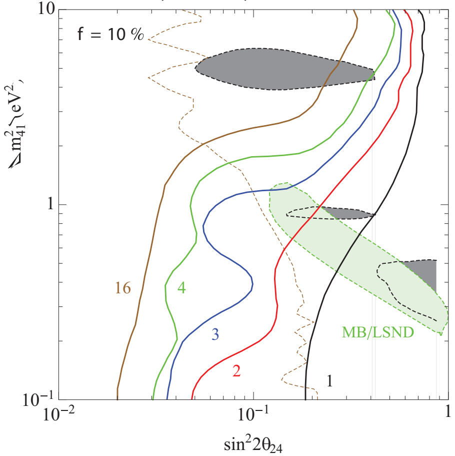
- Bring anomalies to evidences or get rid of them definitely.
- Provide a "Smoking Gun" signature of oscillations: close detectors or oscillation pattern
- Demonstrate they are **sterile neutrinos**: NC disappearance.
- Measure in the same experiment all the effects: $\nu_\mu \to \nu_e$ transitions, ν_e disappearance (these two effects could conflict in an accelerator experiment), ν_μ disappearance
- Measure both $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu$ transitions: this allow to discriminate 3+1 from 3+2 (in other words count the number of sterile neutrinos) and in case measure CP violation

The only setup so far proposed capable of providing all these features is Icarus/Nessie at CERN (or NuStorm instrumented with an iron magnetized and a liquid argon detector)

Steriles and IceCube

The MSW resonance and parametric enhancement of the ν_μ-ν_s oscillations lead to distortion of the zenith angle distribution of the muon-track events which can be observed by IceCube

Esmaili, Smirnov, arXiv 1307.6824



3 times the statistics of IceCube-79

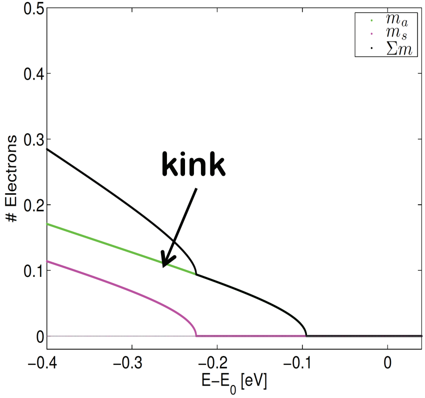
10% systematic error

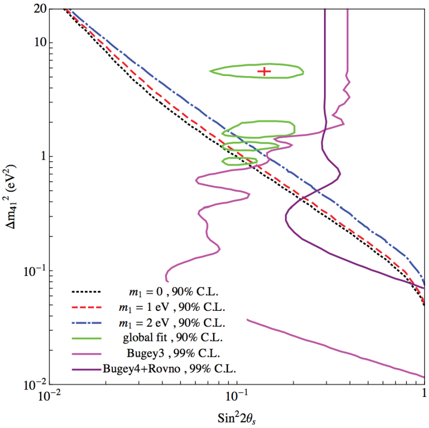
Solid lines are sensitivity for different number of energy bins

Dashed lines are fits from Kopp et al, 2013: numu disappearance (brown), nue appearance (green), global (grey)

Steriles and Katrin

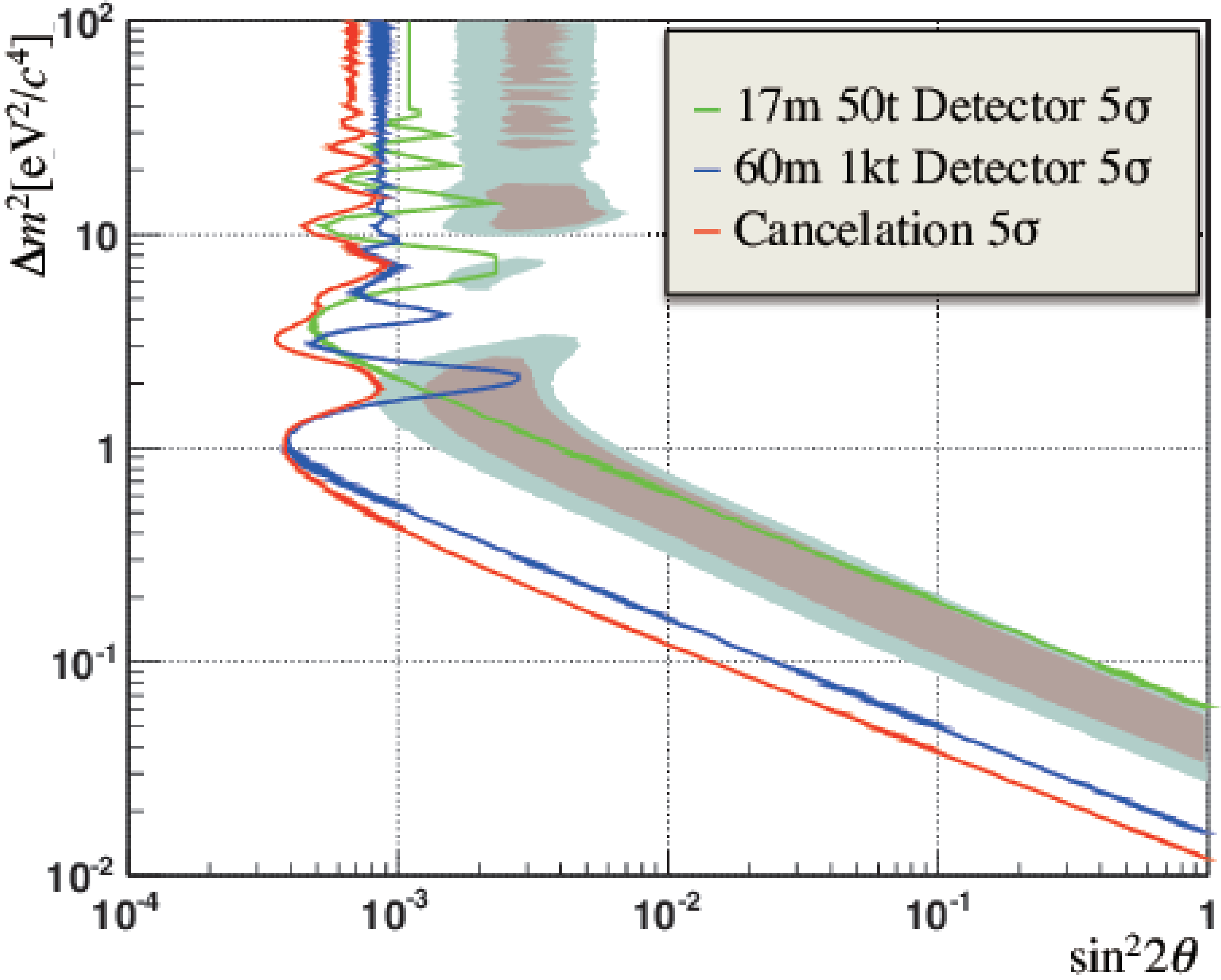
Katrin can test the ν_e disappearance anomalies with its nominal sensitivity





LSND replica at J-PARC MLF

Proposal in arXiv:1310.1437, signed by JPN and Los Alamos
First phase (approved): 25 ton detector at 17 m from the target
Second phase: 1 kton detector at 60 m



Proposals at neutrino beams

MicroBooNE Data taking in 2014. A 170 ton Liquid Argon TPC located along the Booster neutrino beam line at Fermilab. The experiment will measure low energy neutrino cross sections and investigate the low energy excess events observed by the MiniBooNE experiment.
A LoI has been submitted at FNAL to add a close detector (LAr1-ND) and eventually a 1 kton LAr far detector (LAr1) to MicroBooNE (see also arXiv:1309.7987)

Icarus/Nessie (arXiv:1203.3432, see next slide) The new neutrino beam line has not been included in the CERN medium term plan.

IsoDAR arXiv:1205.4419. A novel, high-intensity source of electron antineutrinos, based on new generetion cyclotrons (60 MeV, 0.8-1.6 mA), from the production and subsequent decay of ^{8}Li ($\langle E_\nu \rangle = 6.4$ MeV). The detector could be an existing 1 kton scintillator-based detector (Kamland). Very good sensitivity to ν_e disappearance at $\Delta m^2_2 \sim 1eV^2$ featuring the ability to distinguish between the existence of zero, one, and two sterile neutrinos.

NuStorm, arXiv:1308.0494. The stage 0 of a Neutrino Factory: neutrino beam from muon decays. Muons are stored in a decay ring without any cooling and acceleration. A milestone for the development of new generation neutrino beams, with good (outstanding) capabilities in sterile neutrinos and cross section measurement. Price tag around 200-300 M$.

ICARUS-NESSiE

A coupled system of LAr detectors and Muon Spectrometers

NEAR SITE *@300 m :*

LAr mass = 119 t

Iron magnet mass = 840 t

5 interactions/spill

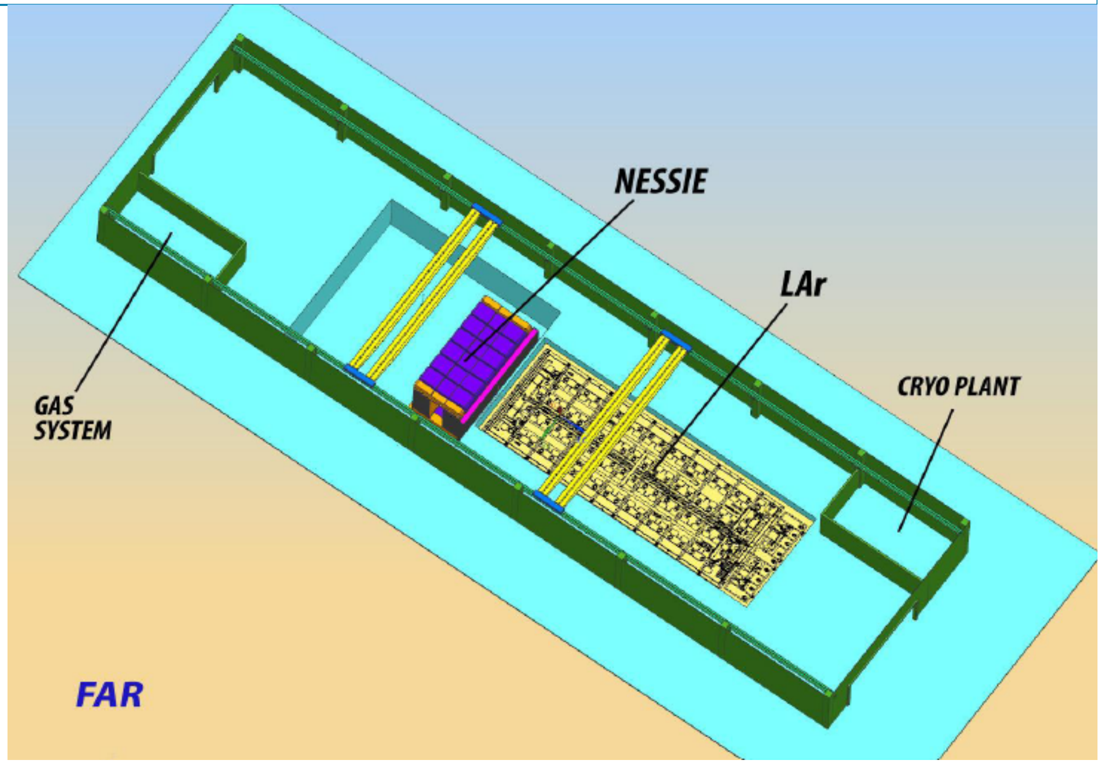
$2 \cdot 10^{13}$ p/spill (with "+" polarity)

FAR SITE *@1600 m:*

LAr mass = 476 t

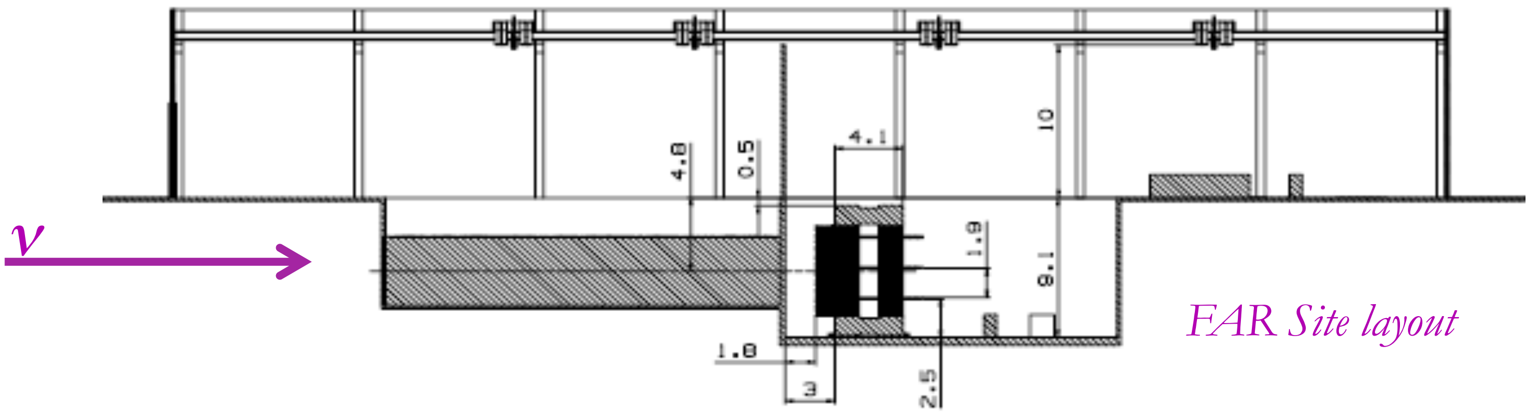
Iron magnet mass = 1515 t

0.65 interactions/spill



Observation ν_μ, ν_e CC, NC channels

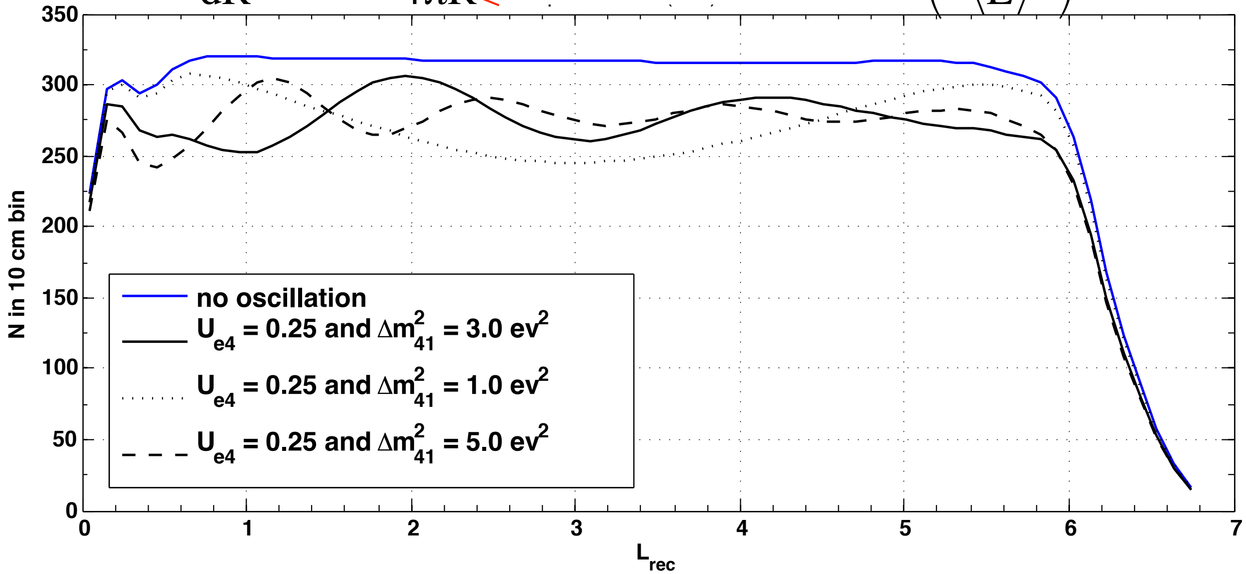
Charge separation and muon momentum

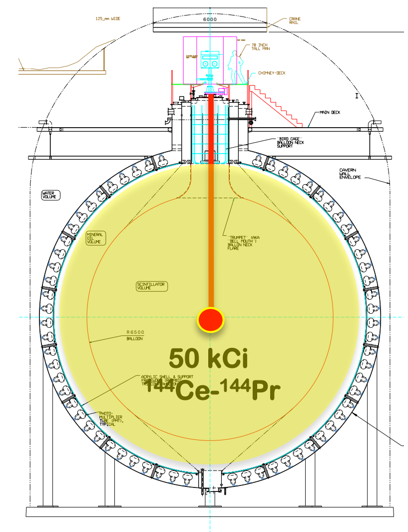


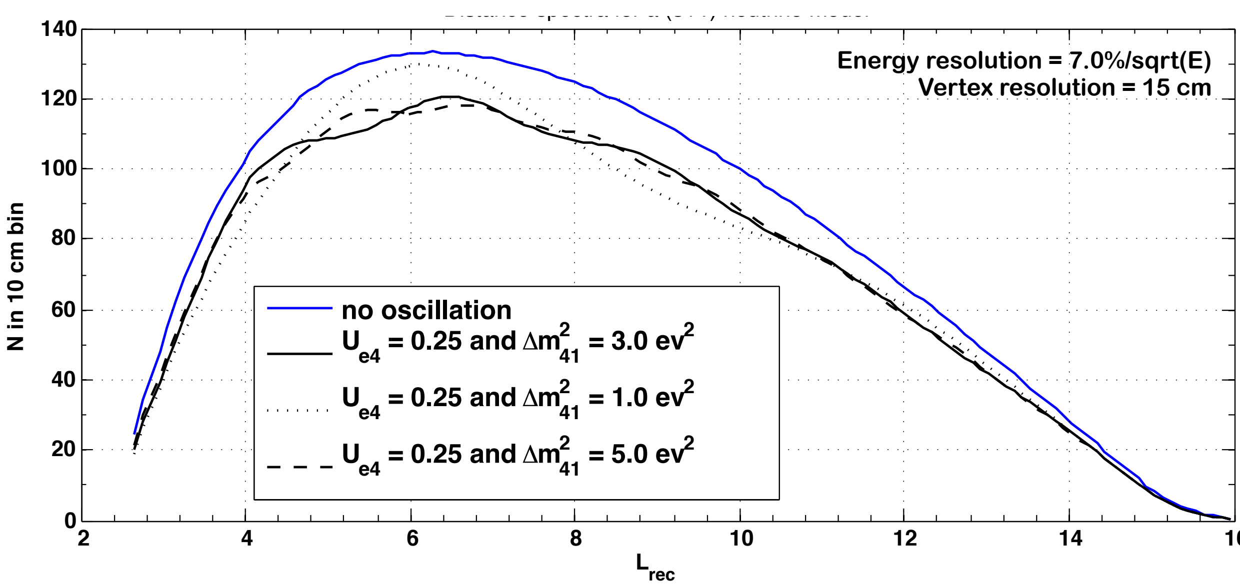
FAR Site layout

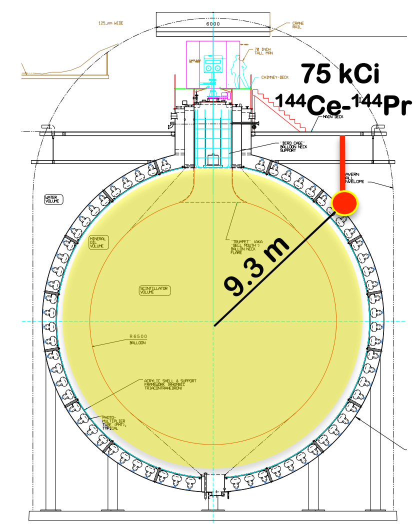
Search for $\overline{\nu}_e \rightarrow \overline{\nu}_s$ with $^{51}Cr/^{144}Ce$

$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{\cancel{4\pi R^2}} \times \langle\sigma\rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E\rangle}\right)$$









^{144}Ce-^{144}Pr: CeLAND (KamLAND)

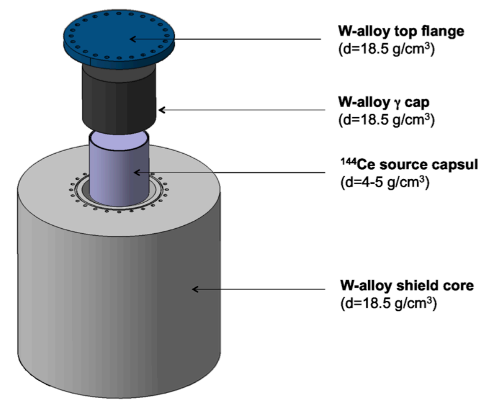
- 75 kCi of ^{144}Ce-^{144}Pr (CeO_2)

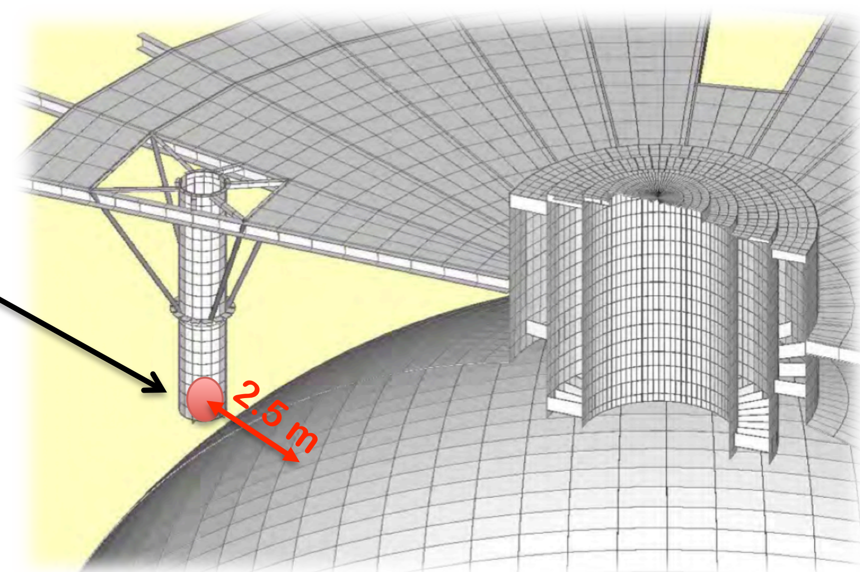
- **Production feasible at Mayak Facility (RU) in 2014 (1 y)**
  - Standard SNF reprocessing
  - Ce extraction through displacement chromatography

- **Need 16 cm tungsten-shield**

- **KamLAND being prepared**
  - Deployment
    - in water veto (3-16 m)
    - In Xenon Room (5-18 m)
  - Run in // with KamLAND-zen

- Deployment in 2015





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

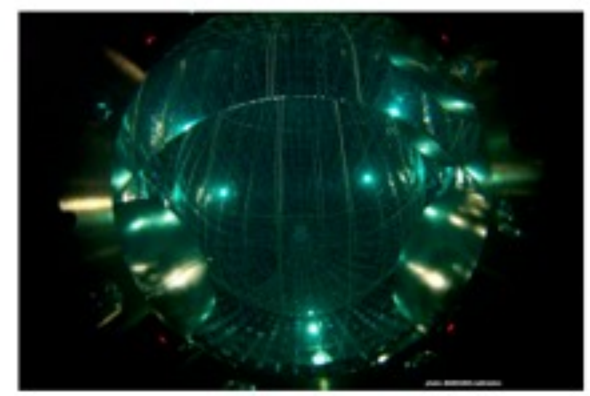
European Research Council
ERC-2012-AdG

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)***

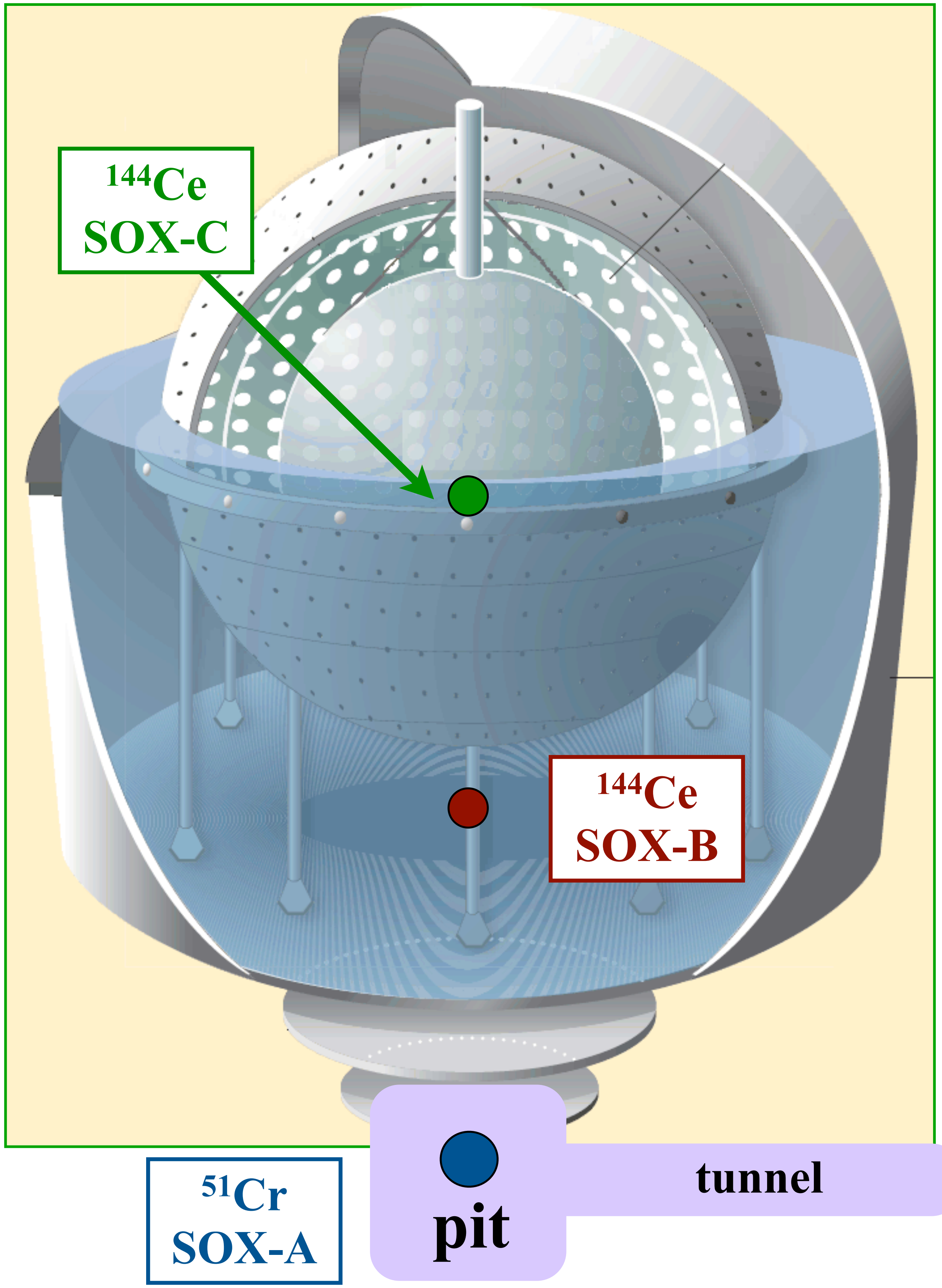
SOX: Three Phases

- **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 ?]**

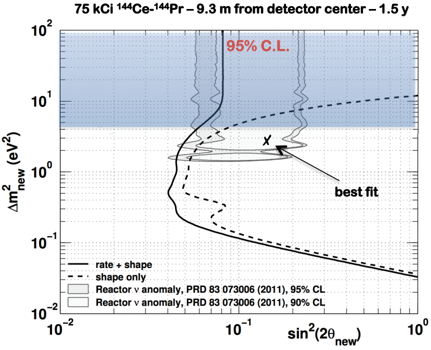
- **SOX-C**
  - ^{144}Ce-^{144}Pr source in the center
  - **Only after the end of solar program**
  - More effort and more time **[>2016]**



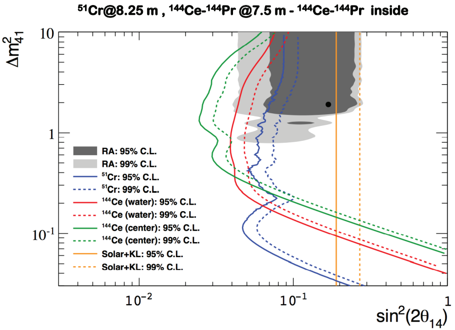
Wednesday, September 25, 13

Source sensitivities

CeLAND (KamLAND)



SOX (Borexino)



Reactor ν Proposals

Experiment Type	Projects	P_{Th}	M_{det}	L	Depth
Mature Gd-doped LS detector Technology	Nucifer (FRA)	70 MW	0.7 tons	7 m	Few mwe
	Stéréo (FRA)	50 MW	2 tons	[8-11] m	10 mwe
	Neutrino 4 (RU)	100 MW	2 tons	[6-12] m	Surf.
Highly segmented detector for background reduction	DANSS (RU)	1 GW	1 ton	[10-12] m	50 mwe
	SoLid (UK)	45-80 MW	3 tons	8 m	10 m
Enhanced neutron Tagging					
	Hanaro (KO)	30 MW	0.5 t	6 m	Few mwe
2 detector complex or Moving detector	US project	20-120 MW	-	4m & 15m	Surf.
	China project	-			
	DANSS/Neutrino4	Movable detector			

Conclusions

We are facing four sets of anomalies, they have begun to show up 17 years ago and their case became stronger in the latest years (with a peak in 2011).

None of the hints is convincing by itself.

Nevertheless they can be accommodated by a single model (with some tension).

Would the model be true we had access to outstanding discoveries (new neutrino states beyond the standard model, CP violation)

This makes the physics case very interesting and a new experimental campaign to falsify the anomalies or make the discoveries is both imperative and urgent.

Several different initiatives will be operative in the next years exploring almost all the allowed possibilities and being open to surprises.