Reactor anomaly and searches of sterile neutrinos in experiments at very short baseline

G. MENTION

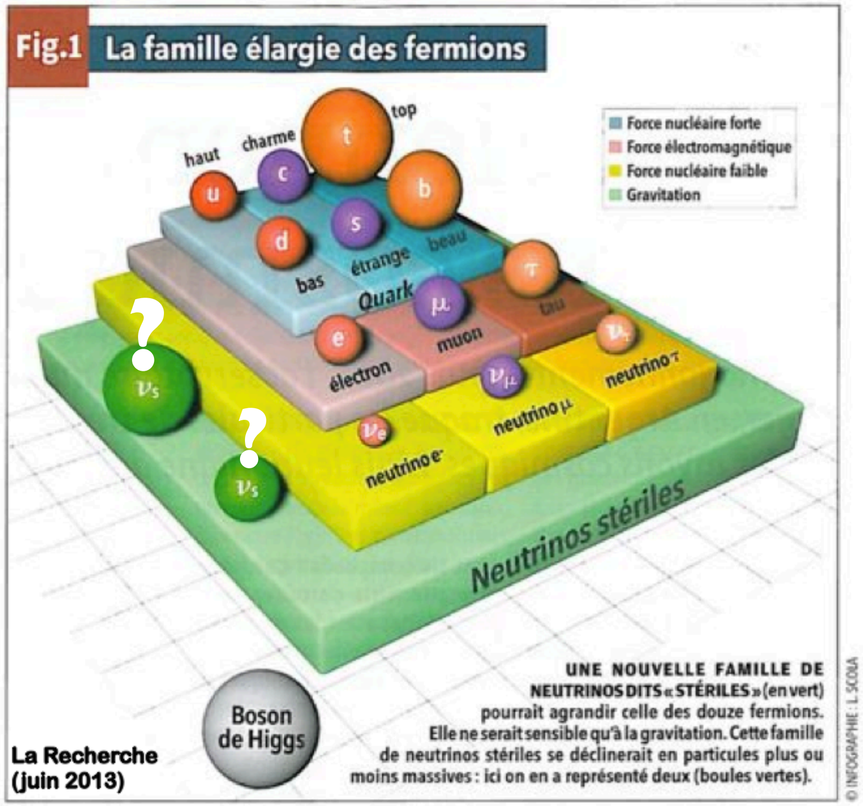
CEA Saclay
Irfu / SPP

July 17th, 2013

Content

Is the standard 3 neutrino mixing picture correct?

- The peaceful realm of the 3 active ν
- The disturbing anomalies
- Outlooks and prospects
- White paper and foreseen experiments to tackle these anamalies
- Conclusion

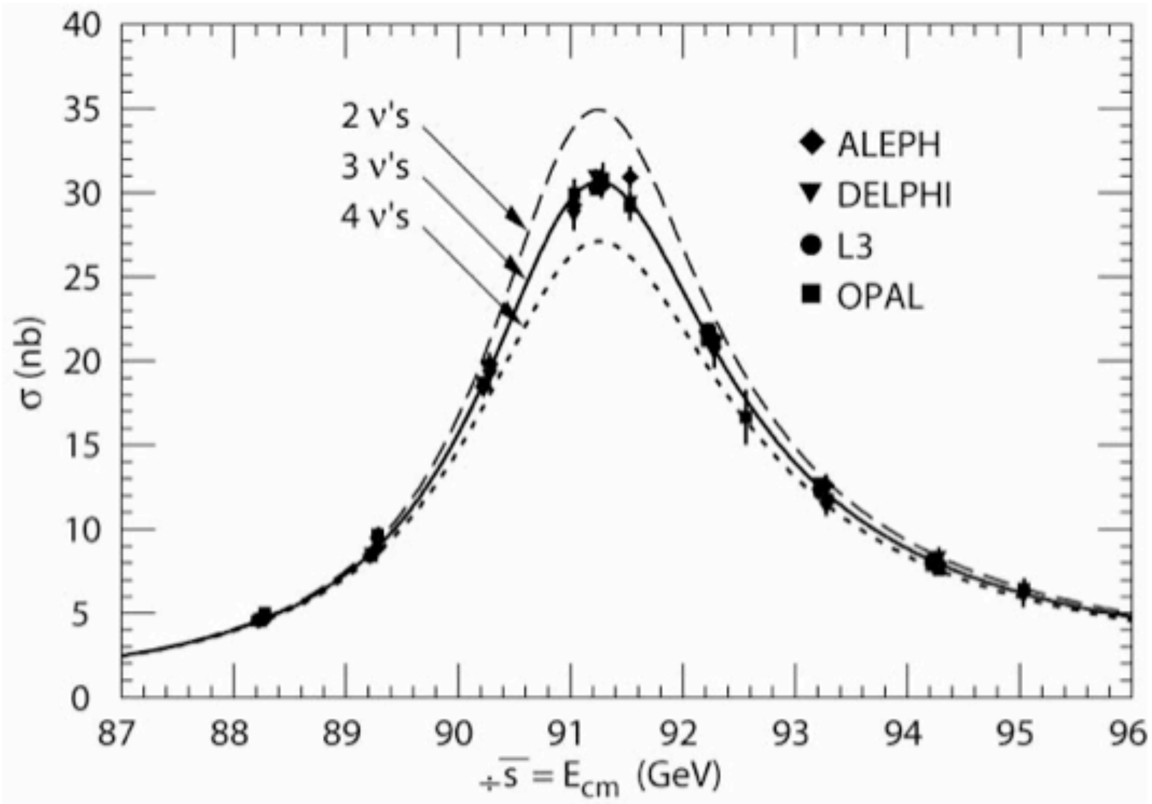


3 ν and that's all?

Large Electron-Positron collider data: exactly 3 active, light ν flavors

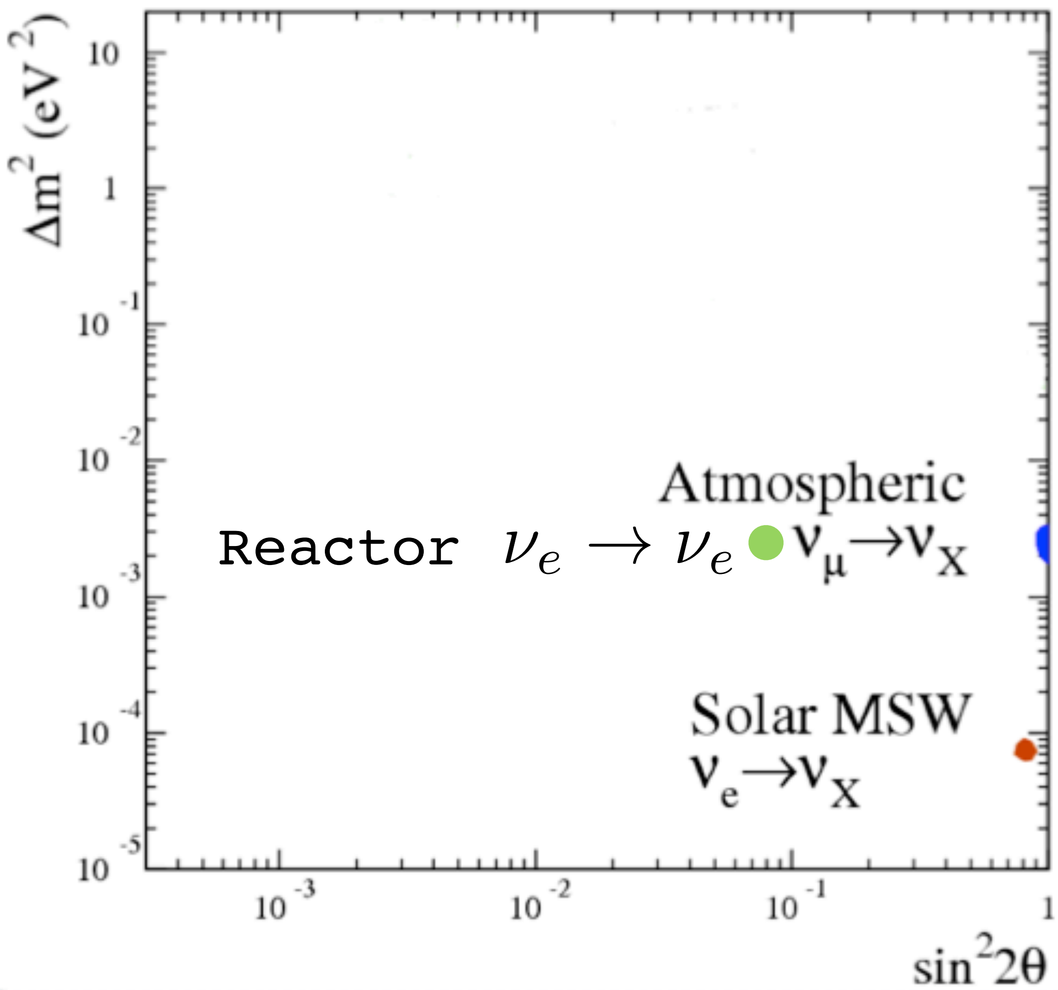
We also know of 3 ν's: ν_e, ν_μ, ν_τ

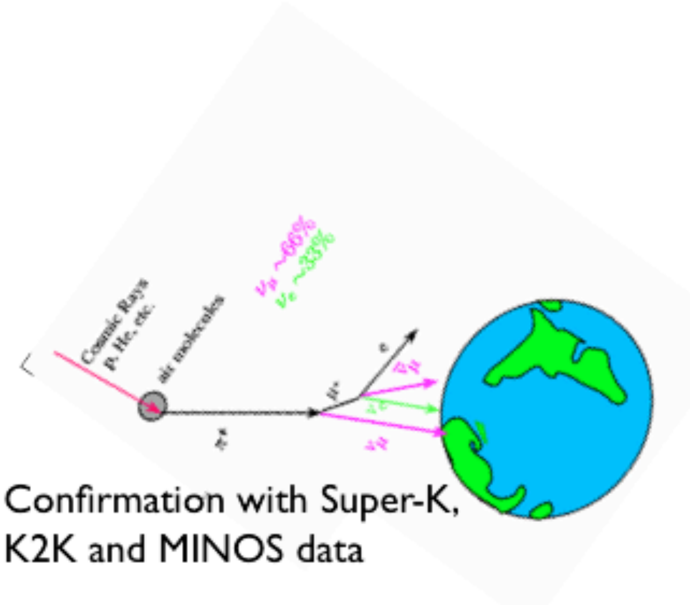
3 ν's require two independent sets of Δm^2 mixing



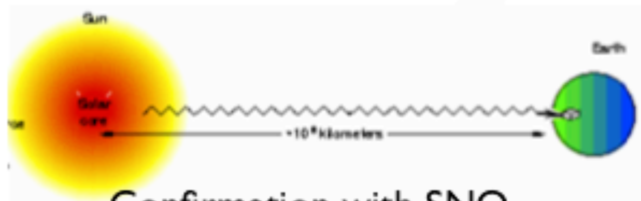
Neutrino oscillations

This is observed and confirmed!

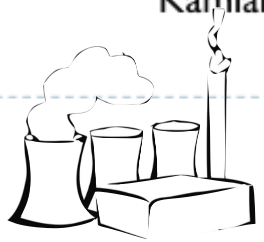


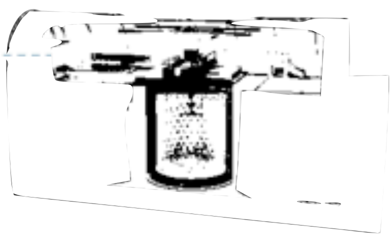


Confirmation with Super-K, K2K and MINOS data



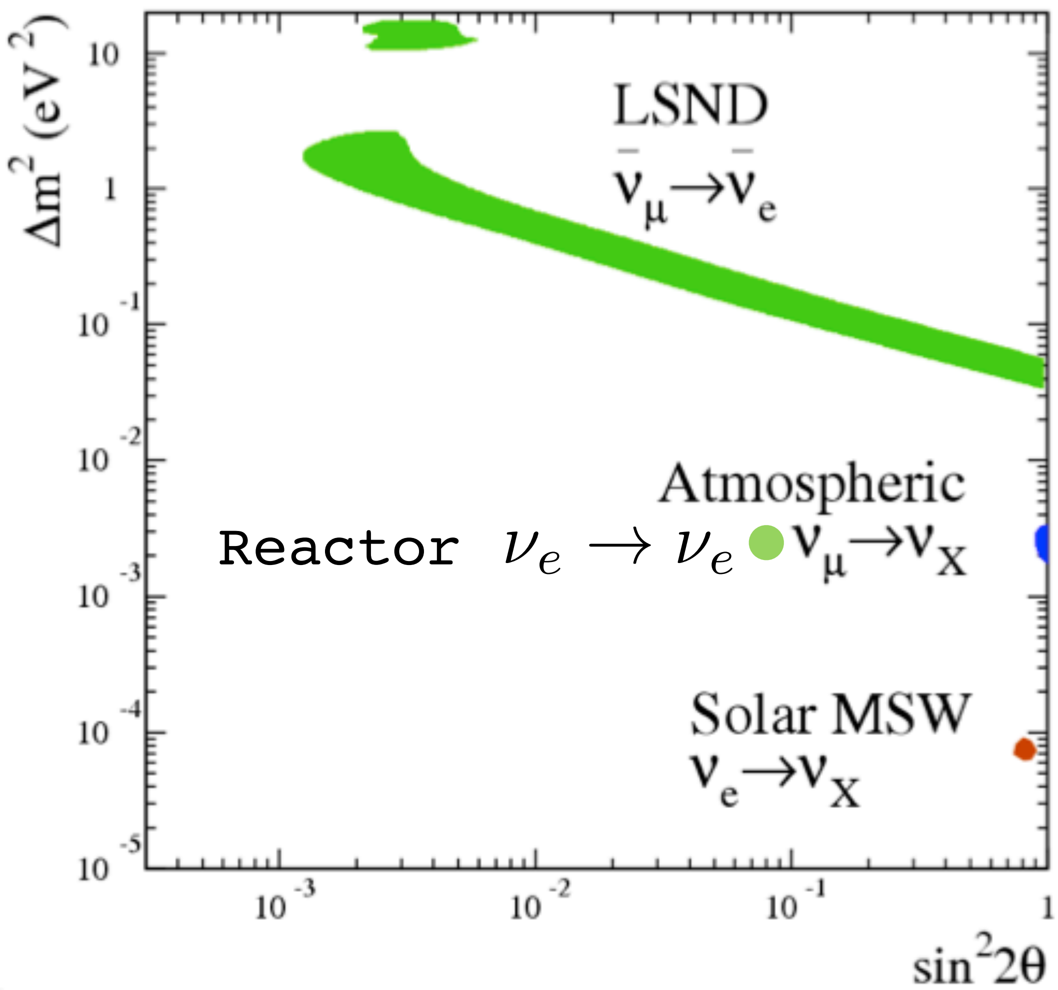
Confirmation with SNO, Kamland data





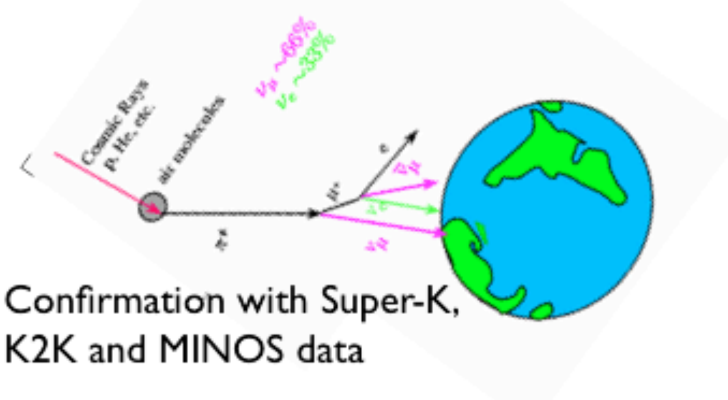
Neutrino oscillations

However…

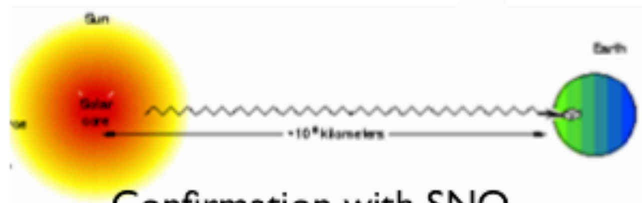


Evidence for high Δm^2 mixing from LSND experiment

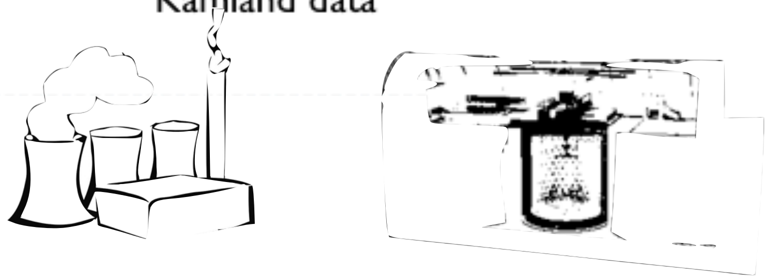
some hints from cosmology and reactor data as well



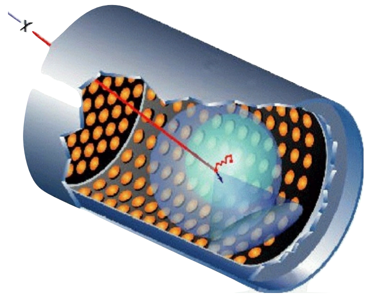
Confirmation with Super-K, K2K and MINOS data



Confirmation with SNO, Kamland data



LSND



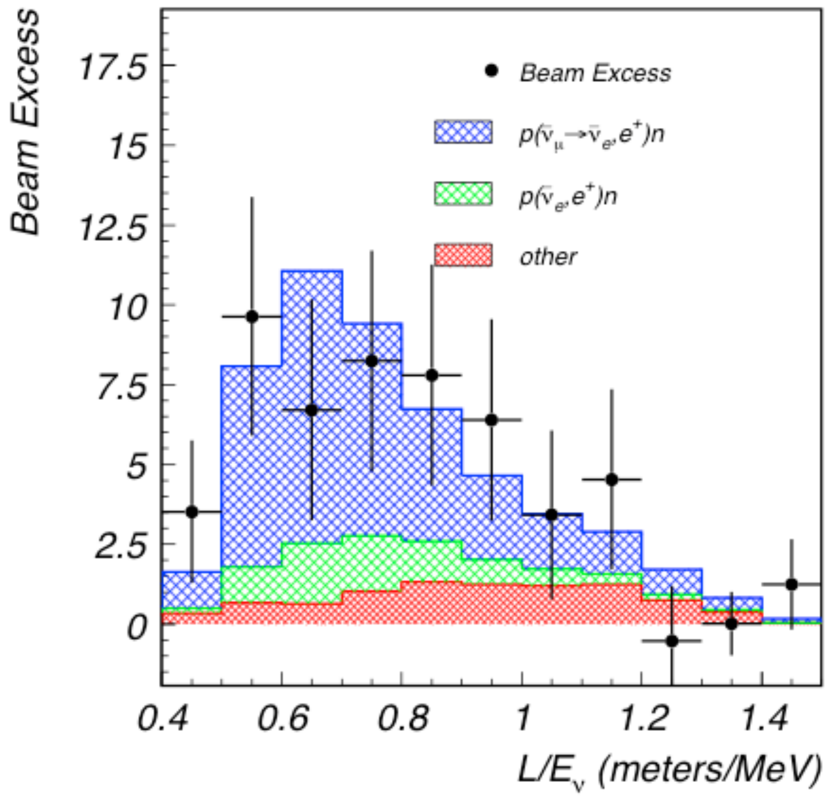
[LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

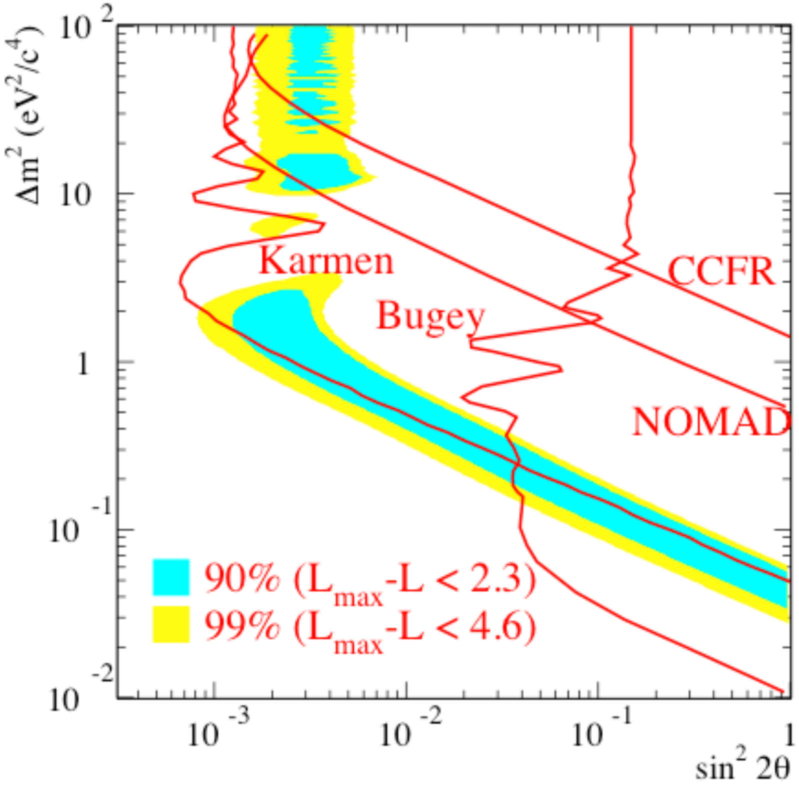
Channel: anti-$\nu_\mu \rightarrow$ anti-ν_e

Baseline: L ~ 30 m

Energy range: 20 MeV < E < 200 MEV

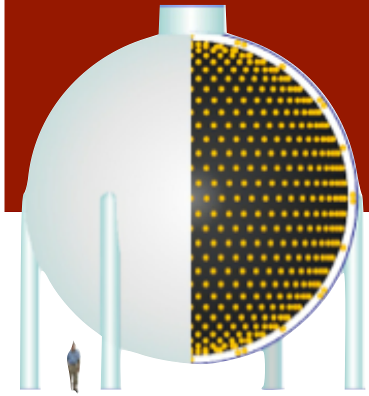
Highly controversial!





$$\Delta m^2_{\rm LSND} \gtrsim 0.2\,{\rm eV}^2 \qquad (\gg \Delta m^2_{\rm ATM} \gg \Delta m^2_{\rm SOL})$$

MiniBooNE ν

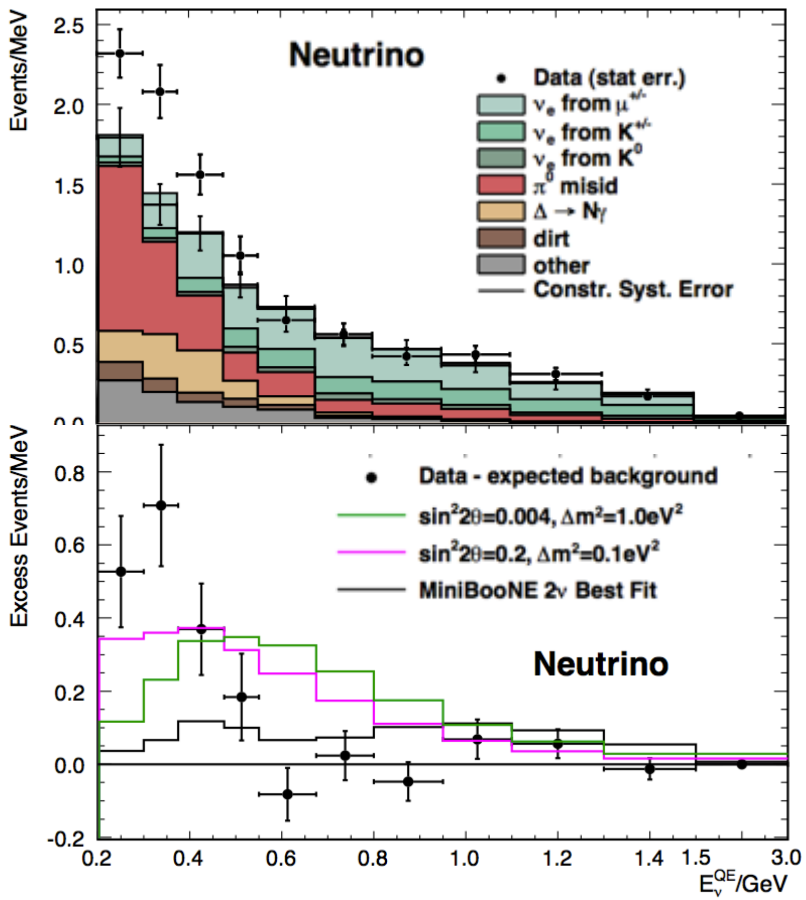


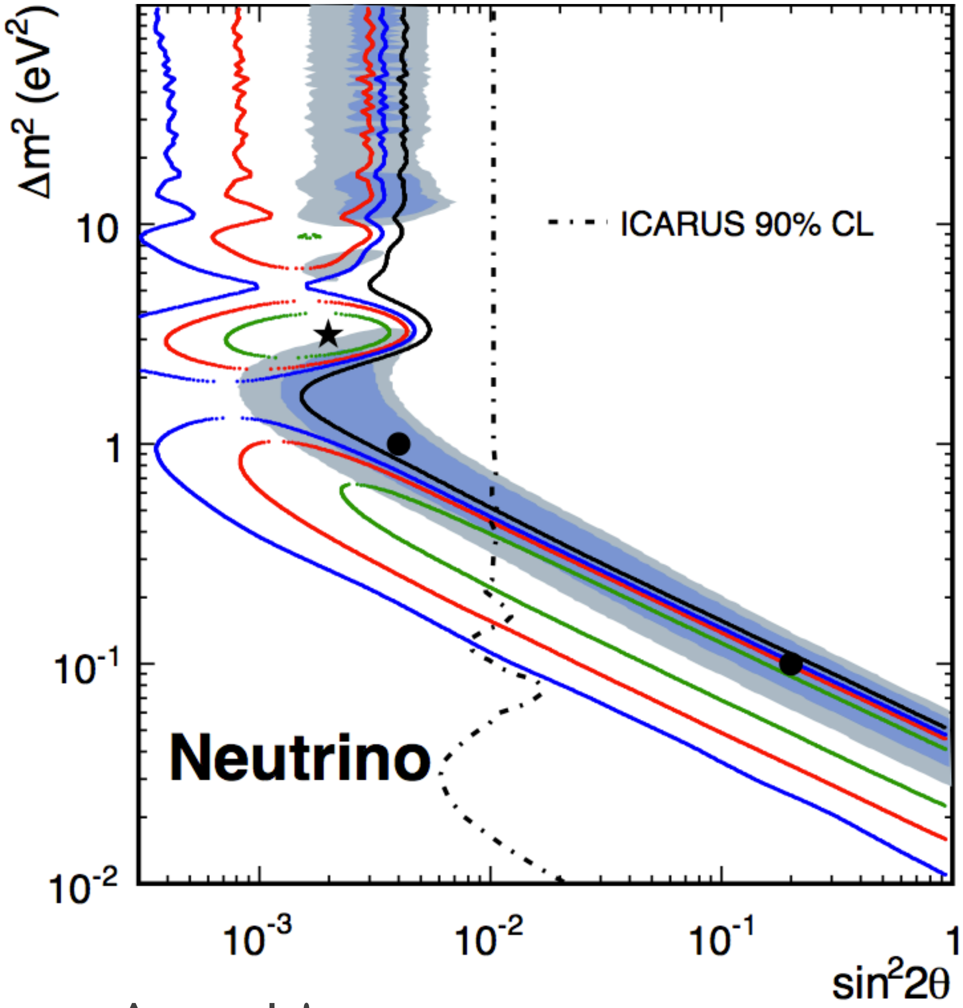
Channel: $\nu_\mu \rightarrow \nu_e$

Baseline: L ~ 541 m

Energy range: 475 MeV < E < 3 GeV

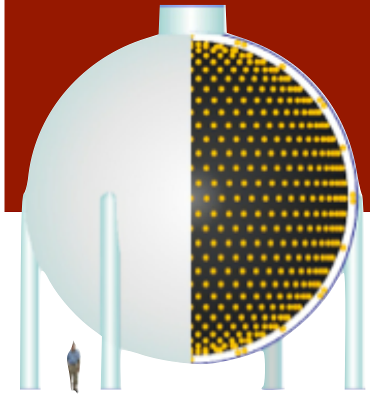
[arXiv,hep-ex:1303.2588]



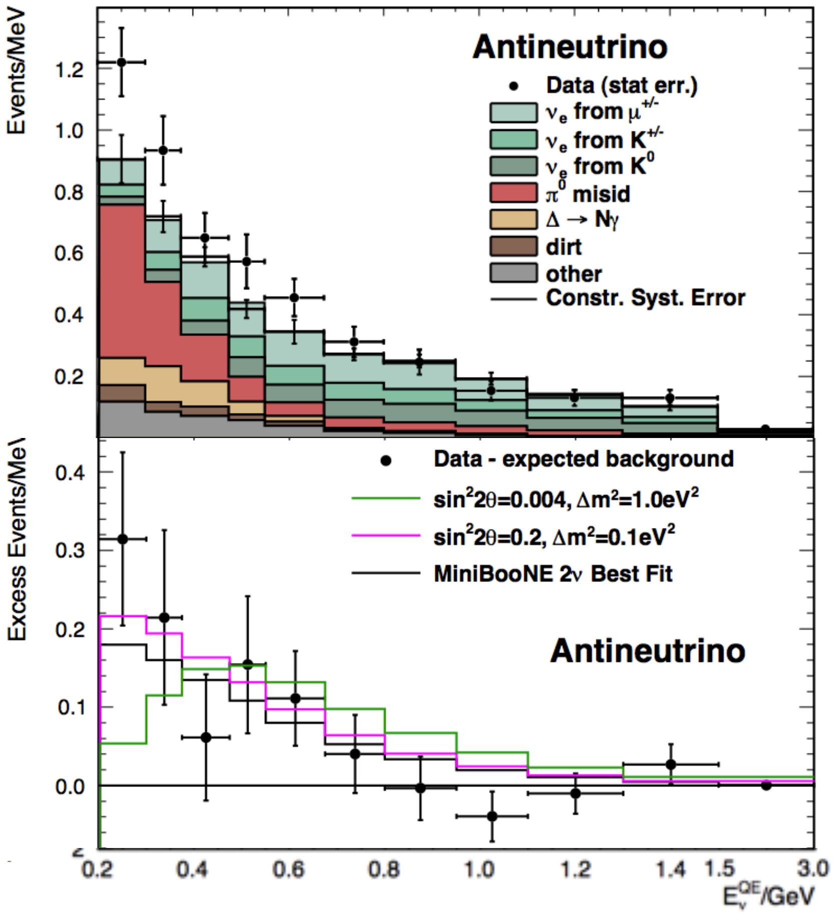


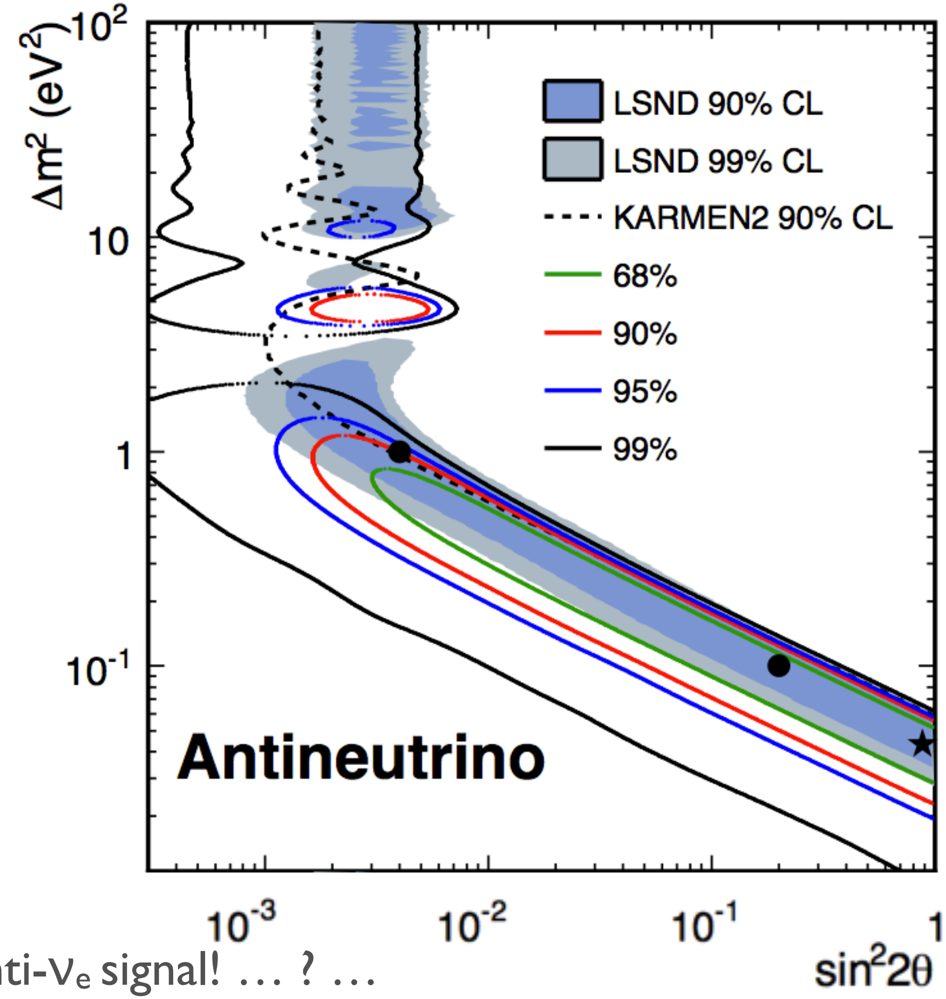
But => Low-Energy Anomaly!

MiniBooNE anti-ν



Channel: anti- ν_{μ} ➛ anti- ν_{e} [arXiv,hep-ex:1303.2588]
Baseline: L ~ 541 m
Energy range: 475 MeV < E < 3 GeV





Agreement with LSND anti-ν_μ ➛ anti-ν_e signal! … ? …
Similar L/E but different L and E, different backgrounds, beam,…

The Gallium anomaly

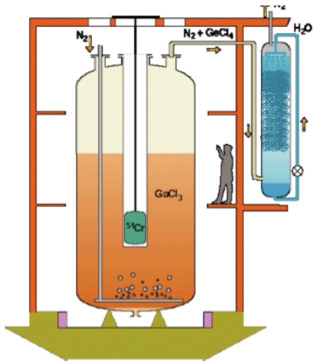
Based on Giunti & Laveder, PRD82, 053005 (2010)

Radiochemical experiments Gallex (left) & Sage (right)

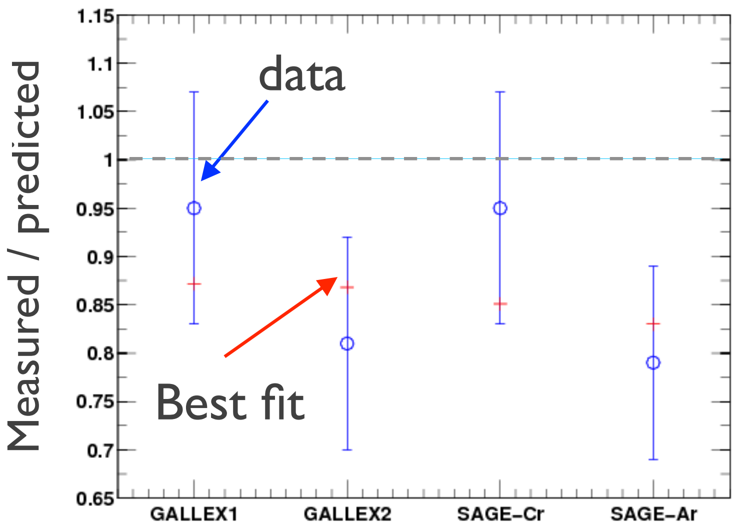
GALLEX ($GaCl_3$) and SAGE (liquid Ga) were radiochemical experiments, counting the conversion rate of ^{71}Ga to ^{71}Ge by (solar) neutrino capture [cannot detect anti-ν_e]

GALLEX

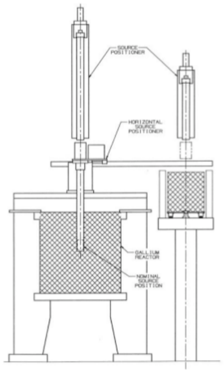
30.3 tons of Gallium in an aqueous solution : $GaCl_3$ + HCl



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



SAGE



30 to 57 tons of Gallium (metal) In 10 tanks

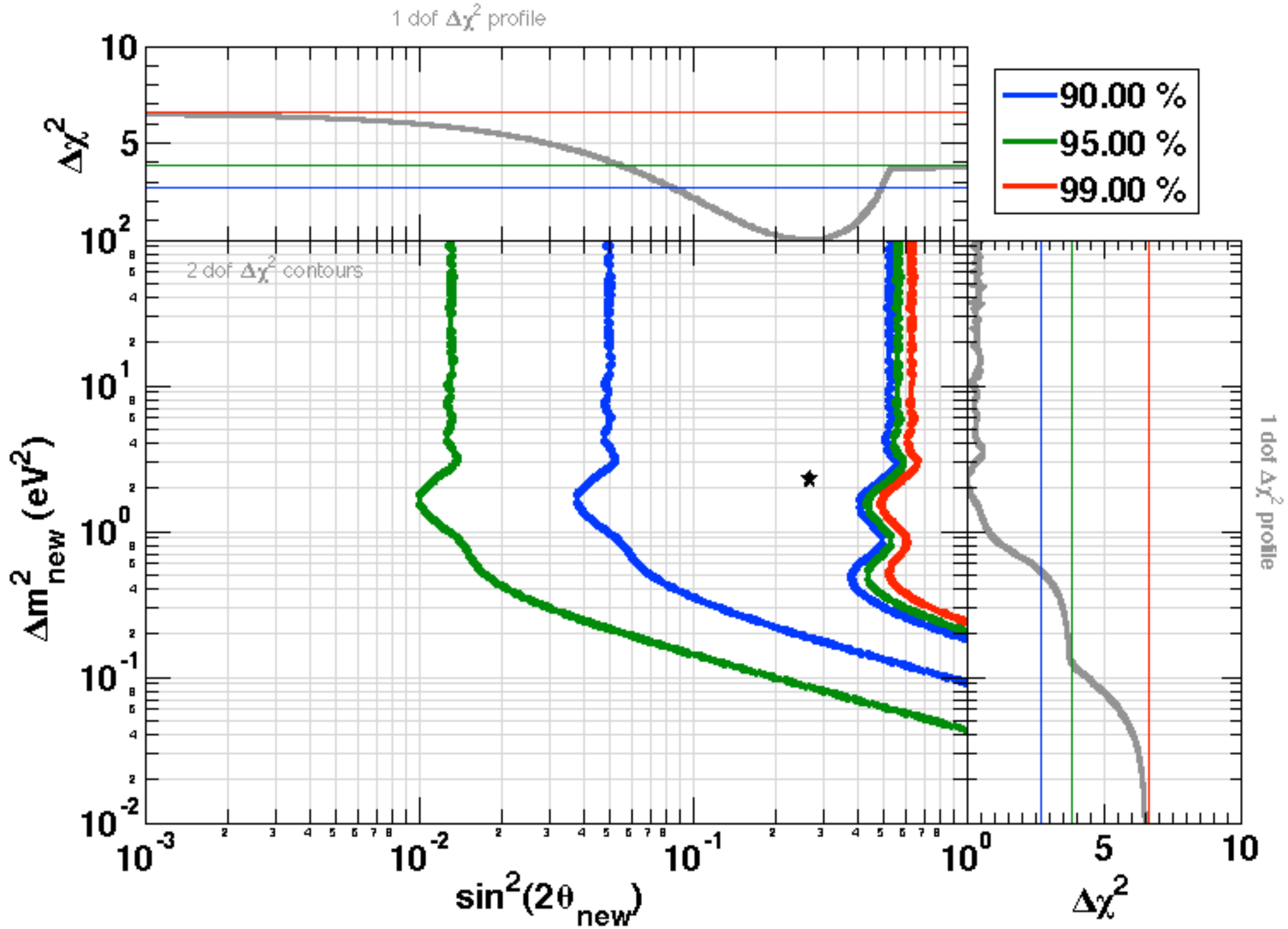
Calibration Data

2 runs at GALLEX with a ^{51}Cr source (720 keV ν_e emitter)
1 run at SAGE with a ^{51}Cr source
1 run at SAGE with a ^{37}Ar source (810 keV ν_e emitter)

All observed a **deficit** of neutrino interactions **compared** to the **expected activity:**

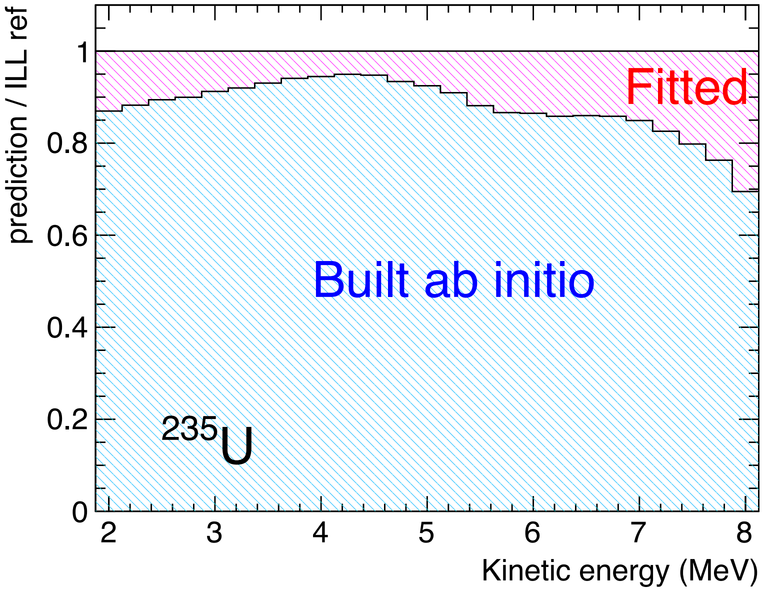
R = meas./pred. rates = 0.86 ± 0.06 (1σ)

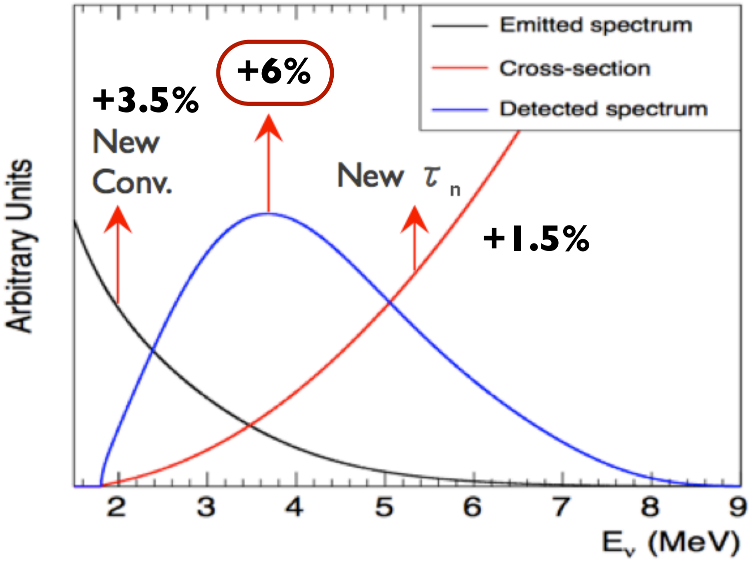
The Gallium anomaly



Effect reported in C. Giunti & M. Laveder in PRD82 053005 (2010)
Significance reduced by additional correlations in our analysis
No-oscillation hypothesis disfavored at 97.7% C.L.

Revised reactor neutrino spectra & VSBL reactor ν anomaly





[T. Mueller *et al.*, PRC83, 054615 (2011)]

anti-ν_e production from reactors $$\sum_{A,Z} \left\{ {}^A_Z X \longrightarrow {}_{Z+1}^{\ A}Y + e^- + \bar{\nu}_e \right\}$$

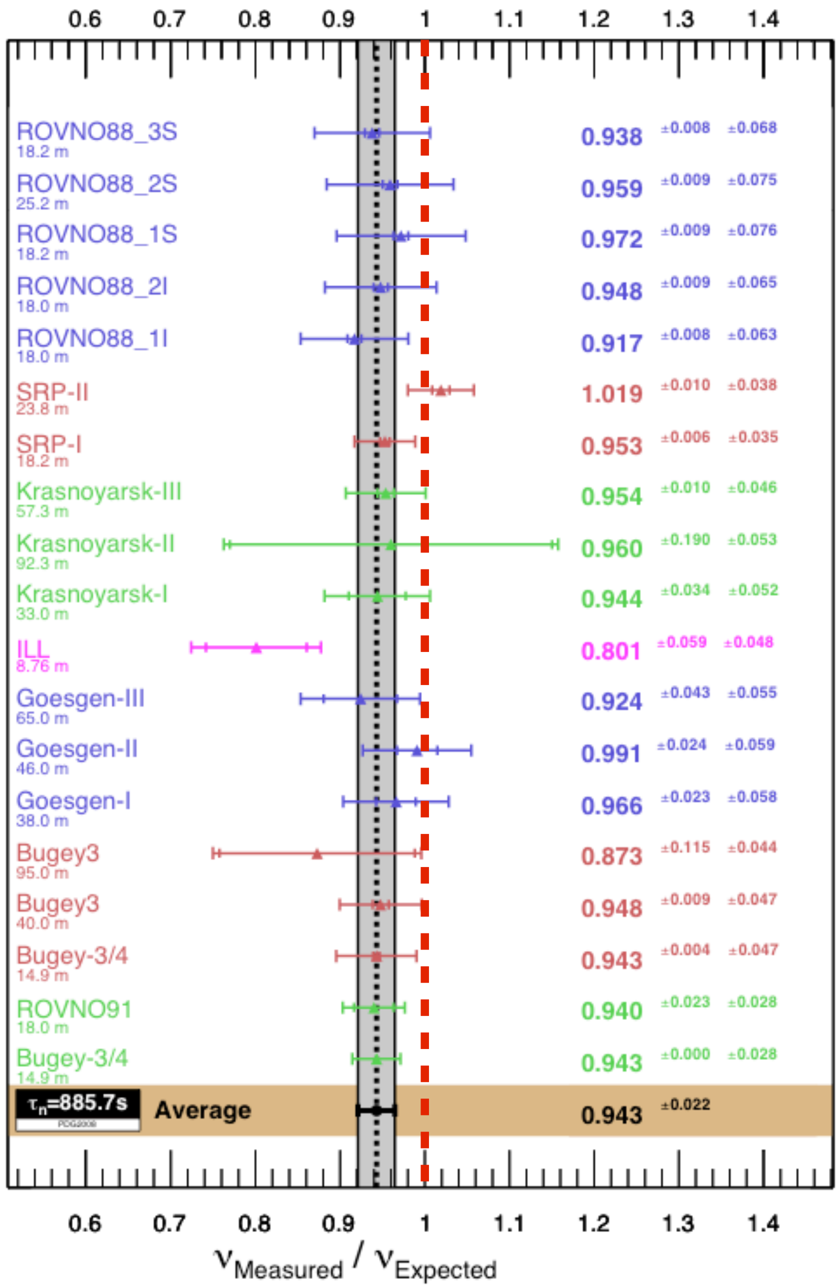
- Triggered by evaluation for single Double Chooz far detector phase.
- Improved conversion from β to ν spectra
  - Anchored to experimental ILL BILL-spectra of fission products
  - Conversion of individual β branch level; residuals fitted as in original ILL conversion
  - Off-equilibrium effects included
- Improved (& increased) neutron life time measurement; also improved weak magnetism and radiative corrections inclusion

$$\sigma_f^{pred} = \int_0^\infty S_{tot}(E_\nu)\sigma_{\mathrm{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{pred}$$

	old [3]	new	
$\sigma^{pred}_{f,^{235}U}$	6.39±1.9%	6.61±2.11%	+3.4%
$\sigma^{pred}_{f,^{239}Pu}$	4.19±2.4%	4.34±2.45%	+3.6%
$\sigma^{pred}_{f,^{238}U}$	9.21±10%	10.10±8.15%	+9.6%
$\sigma^{pred}_{f,^{241}Pu}$	5.73±2.1%	5.97±2.15%	+4.2%

Independently confirmed by P. Huber: arXiv:1106.0687.

Implications for SBL reactor experiments: the reactor antineutrino anomaly



$$\chi^2 = \left(r - \overrightarrow{\mathrm{R}}\right)^T W^{-1} \left(r - \overrightarrow{\mathrm{R}}\right)$$

Weights: $W = \Sigma^2_{\mathrm{unc.}} + \Sigma_{cor.} C\, \Sigma_{cor.}$

with $\Sigma^2_{\mathrm{unc.}} = \Sigma^2_{\mathrm{tot.}} - \Sigma^2_{\mathrm{cor.}}$

The synthesis of published experiments at reactor-detector distances ≤ 100 m leads to a ratio R of observed event rate to predicted rate of

μ = 0.976 ± 0.024 (**OLD flux**)

With **NEW flux** evaluation, this ratio shifts to

μ = **0.943 ± 0.023**, **[2011 result]**

leading to a deviation from unity at 98.6% C.L.

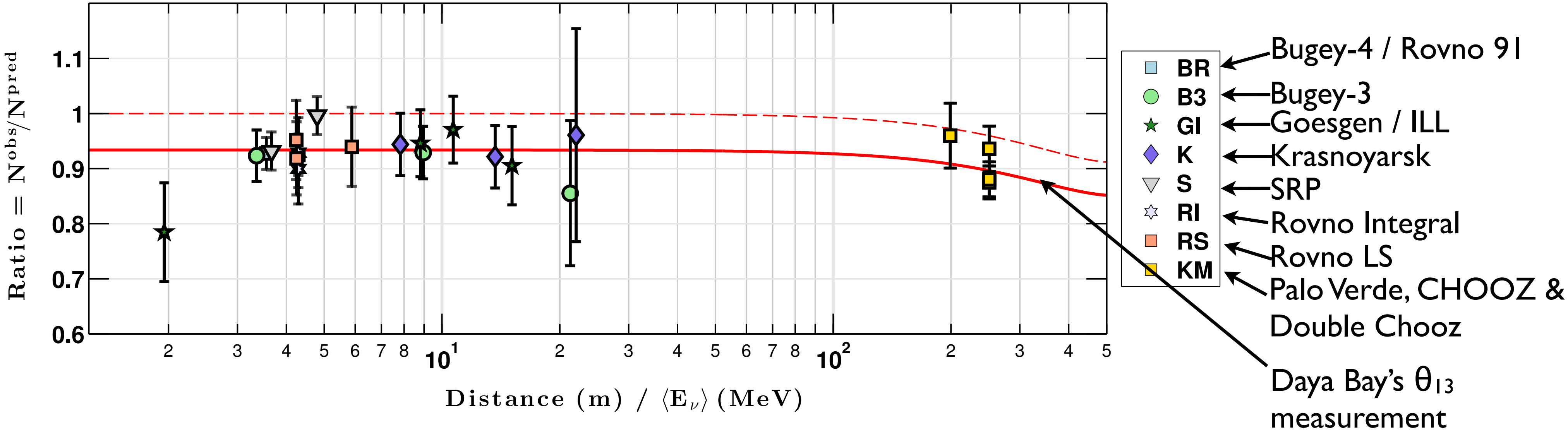
χ^2_{min} = 19.6/18

Update in White Paper on sterile neturinos: [hep-ph:1204.5379]

μ = **0.927 ± 0.023**, **[2012 result]**

Update with km scale experiments

Update of 2011 reactor anomaly publication [PRD83, 073006] ongoing, to be submitted soon



- Includes a refined and detailed treatment of correlations between the different measurements and predictions
- includes all knwon nuclear corrections to β-ν spectra. [combining: T. Mueller et al., PRC83, 054615 & P. Huber, PRC 84, 024617]
- Corrected for a statistical bias in the previous method
- Includes the latest updated neutron lifetime (τ_n =881.5 s).
- Includes km-scale baselines through correcting for θ_{13} deficit from Daya Bay's measured value.

[**2013 result** *to be submitted soon*]

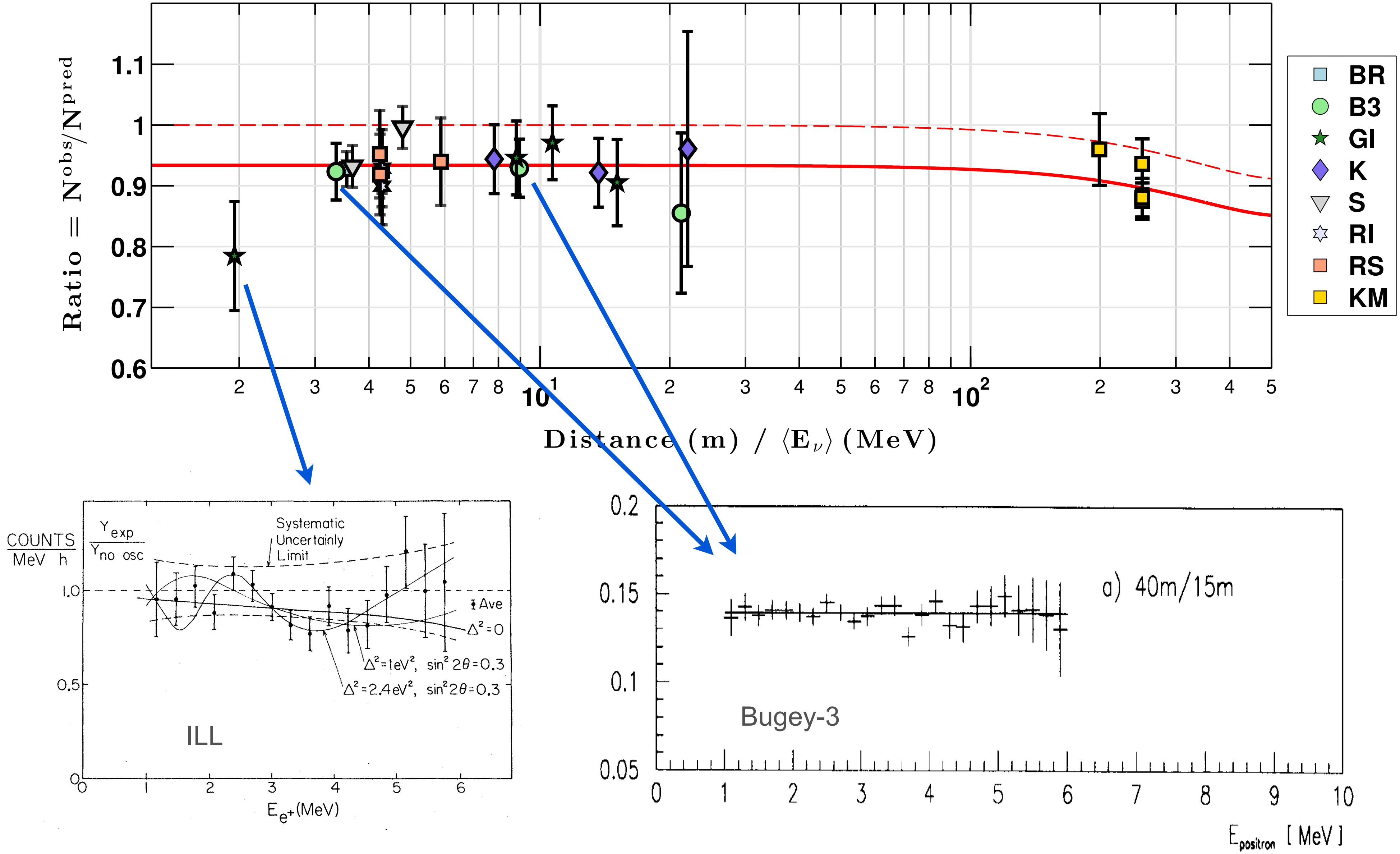
Preliminary updated result

μ = **0.936 ± 0.024**

χ^2_{min} / dof = 29.7 / 22

p-value = 13 %

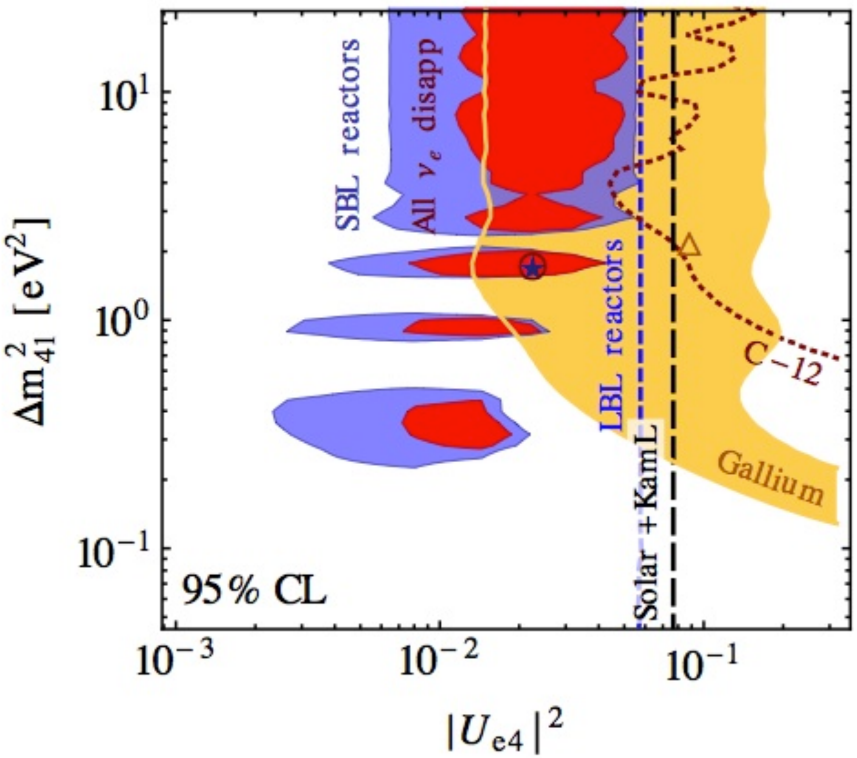
Energy spectrum shape information



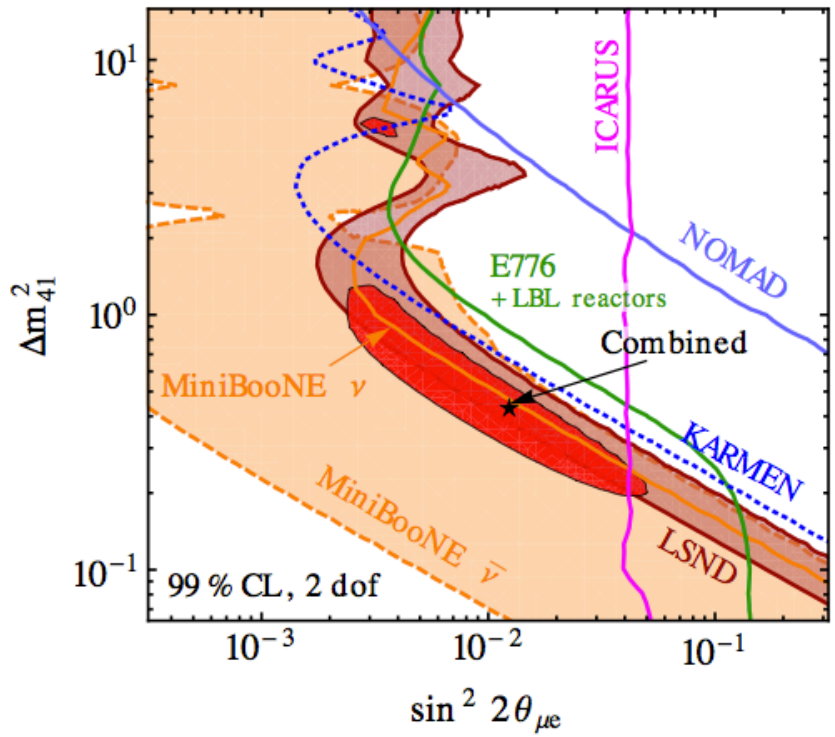
Combining all indications and exclusions
The global picture

from J. Kopp *et al.* [arXiv:hep-ph 1303.3011]

The measured anomalies could curiously be explained by a 4th (& 5th?) sterile neutrino with Δm^2 around the eV^2.



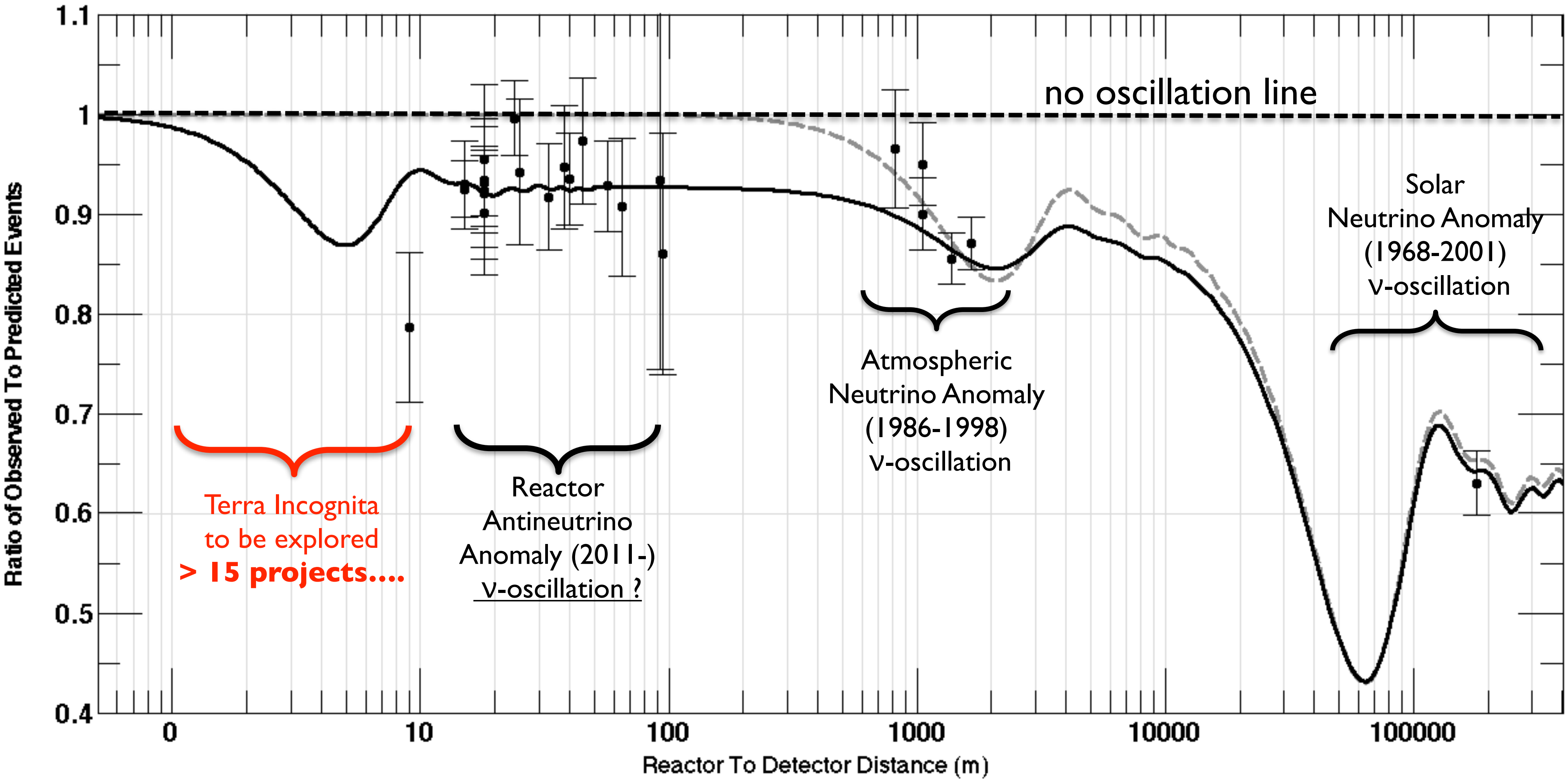
The picture in ν_e to ν_e sector is globally coherent



Some severe tension in μ to e appearance with respect to μ disappearance experiments

Another global picture

Reactor experiments from 30 feet to 110 miles



Anomalies overview

- Agreement between anomalies:
  - LSND and MiniBooNE anti-ν_μ ➛ anti-ν_e
  - Gallium anomaly and Reactor antineutrino anomaly

- Two experimental tensions among the anomalies:
  - [LSND & MiniBooNE anti-ν_μ➛anti-νe] vs. MiniBooNE ν_μ ➛ν_e
  - [LSND & MiniBooNE anti-ν_μ➛ anti-ν_e] vs. anti-ν_e & anti-ν_μ disappearance limits

- [+ Furher info from Cosmology pointing toward sterile neutrino, not addressed here.]

- A white paper on this topic reviewing the current status about sterile neutrino oscillations:

- Despite tensions, there are a number of results and hints that suggest that there may be oscillations to sterile neutrinos with $\Delta m^2 \sim 1$ eV^2

- Further running and new experiments are being planned to address this possibility

⇒ Establishing the existence of sterile neutrinos would be a major result!

⇒ These are certainly exciting times for neutrino physics!

Near future

- Already scheduled experiments to work on non-proliferation
- They add up to their potentials the study of sterile neutrino at short baselines (high Δm^2): Nucifer, SCRAAM, DANSS, MARS=>Solid...
- New dedicated efforts specific for sterile neutrino searches: Stereo, CeLAND, SOX, ICARUS-NESSiE,...

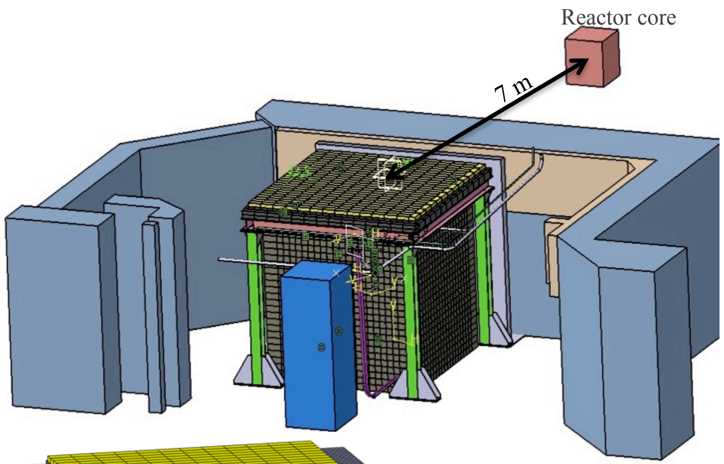
Experimental projects

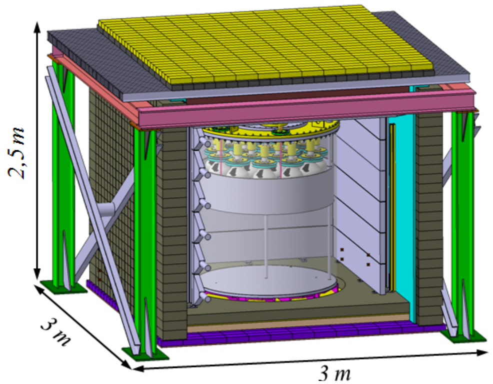
White paper on sterile neutrinos [hep-ph:1204.5379]

Experiment type	Appearance / Disppearance	Oscillation channel	Projects
Reactor	Disappearance	ν_e bar to ν_e bar	**Nucifer**, **Stereo**, Scraam, Neutrino-4, DANSS, Poseidon, **Solid**, CARR...
Radioactive source	Disappearance	ν_e bar to ν_e bar ν_e to ν_e	**CeLAND**, **SoX**, Sage2, SNO+, LENS-S,...
Cyclotron	Disappearance	ν_e bar to ν_e bar	IsoDAR
Pion/Kaon decay-at-rest	Appearance & Disappearance	ν_μ bar to ν_e bar ν_e to ν_e	OscSNS, CLEAR, DAEδALUS, KDAR
Pion decay in flight	Appearance & Disappearance	ν_μ to ν_e ν_μ bar to ν_e bar ν_e to ν_e ν_μ to ν_μ	MINOS+, MicroBooNE, Lar1kton +MicroBooNe, **Icarus/Nessie @ CERN**
Low-E neutrino factory	Appearance & Disappearance	ν_e to ν_μ ν_e bar to ν_μ bar ν_μ to ν_μ ν_e bar to ν_e bar	νSTORM @ Fermilab

Next slides are just a few of them: projects in bold = in Europe.

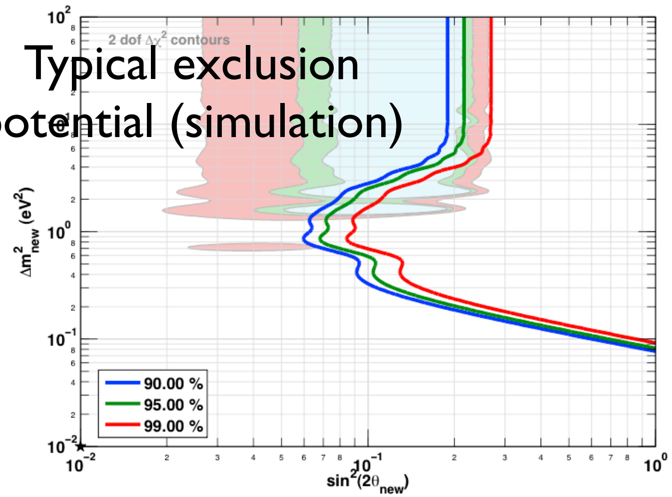
Nucifer





1 m³ detector installed @ CEA Saclay, Osiris reactor

Typical exclusion potential (simulation)



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + \mathrm{Gd} \rightarrow 3\gamma\,(8\mathrm{MeV})$$

Initial goal: non-proliferation prototype detector.

Reactor core size: ~ (60 cm)^3
Detector size : 1.2x0.7m (850 L)
baseline <L>=7.0 m δL= 0.3 m
=> Δm^2 ~ eV^2 oscillations are not washed out!

Detector ready and operational.

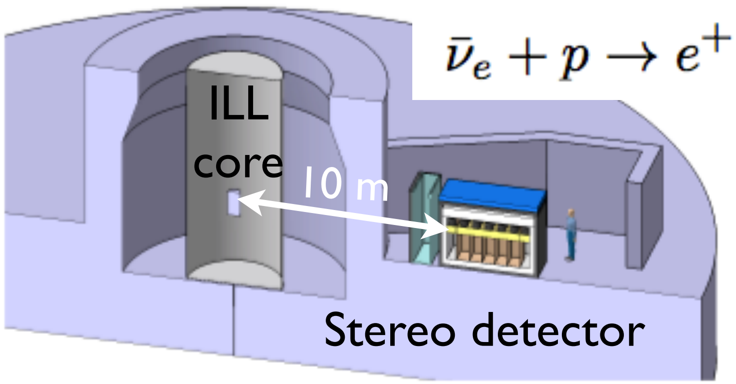
Currently: two reactor cycles of data (2x 20 days). Large γ bkg from reactor yet. Will improve shielding again. Reactor is off for maintenance and will start again before end of year.

Nucifer is not an optimized detector for such a measurement BUT can be the first at this so short baseline to bring information on this anomaly after ILL exp. in 1981.

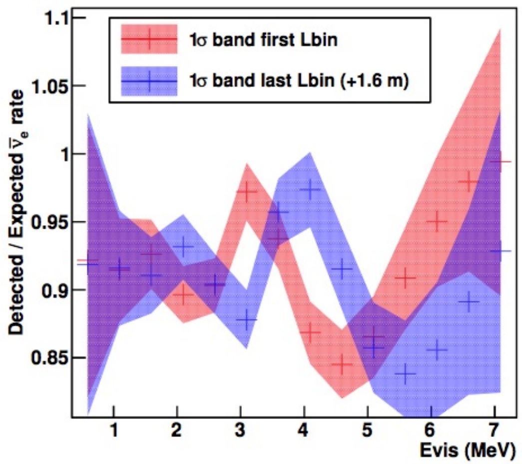
Stay tuned!!!

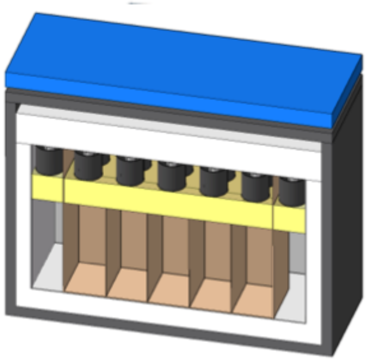
Stereo

$\bar{\nu}_e + p \rightarrow e^+ + n$



$n + \mathrm{Gd} \rightarrow 3\gamma\,(8\mathrm{MeV})$

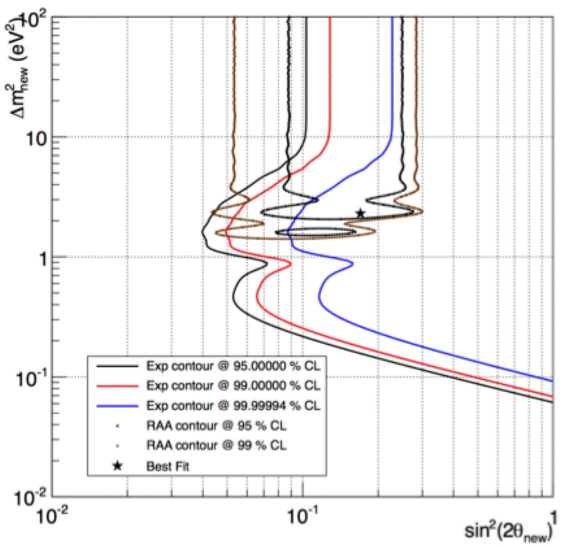




Homogeneous detector

2 m^3 LS+Gd

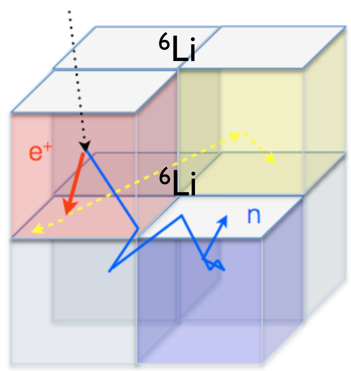
6 cells



- Detect antineutrino via well known inverse beta decay reaction
- Detect neutron via Gadolinium capture (<3γ>, E ~ 8 MeV)
- Short time coincidence (15 μs, 0.2% Gd), localization of interaction in cells
- Good energy resolution (5%@1MeV)
- 480 ν/day ; challenge S/B ~ 1.5 [ILL exp. (1981) ~ 1].
- short baseline ~ 10 m to probe $\Delta m^2 \sim 1$ eV^2
- compact reactors: ILL (France) [core size < 40 cm]
- Shape only oscillation search, and rate+shape analysis
- Start data taking in 2015.

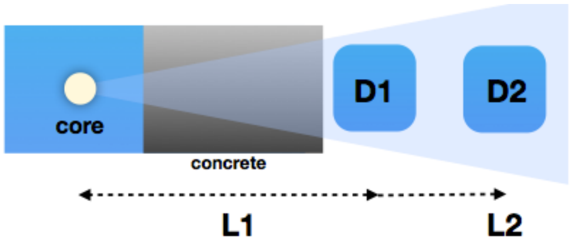
SoLiȡ

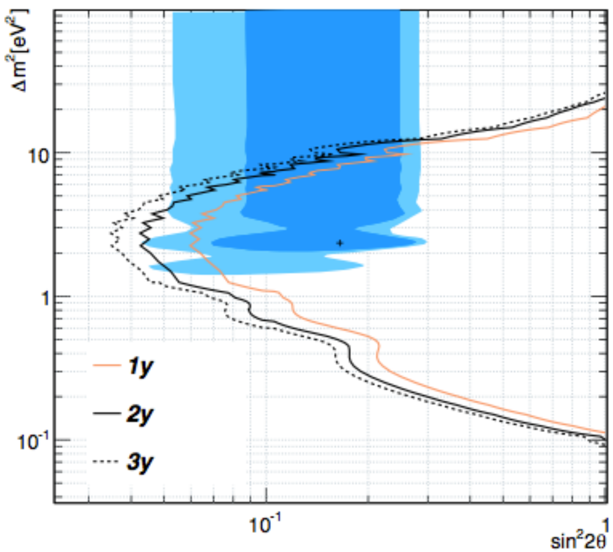
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



$$n + {}^6Li \rightarrow {}^3H + \alpha \ + 4.78\ MeV$$

many such cells
Highly segemented
~1.5 m^3 detector





5σ contours

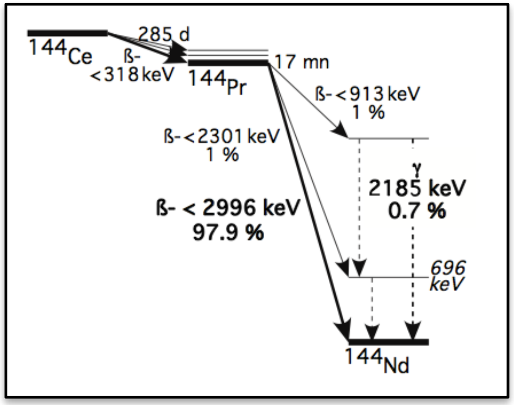
- Detect antineutrino via well known inverse beta decay reaction
- Detect neutron via reaction on Lithium-6 capture
- Time coincidence and 3D localisation of interaction
- short baseline < 10 m to probe $\Delta m^2 \sim 1$ eV^2
- compact reactors: ILL (France), BR2 (Belgium) [small cores < 50 cm]
- use ratio of spectra at two distances from the reactor
- Start data taking in 2015.

CeLAND

Poster by V. Fischer

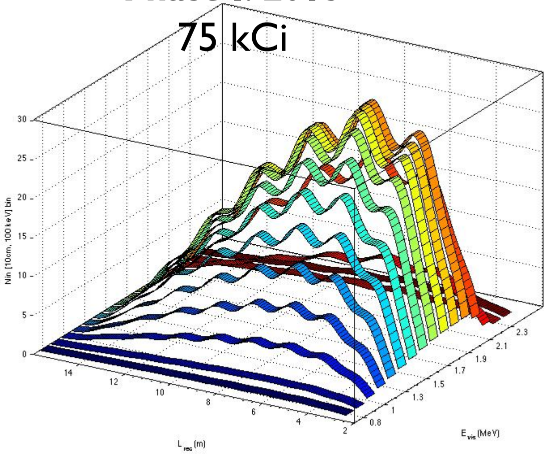
- A strong 75 kCi ^{144}Ce anti-ν_e source @ KamLAND
- Anti-ν_e detection (20 to 40 kevts/yr)
- A good resolution in position (15 cm)
- Background free thanks to anti-ν_e coincidences
- Lifetime ~ 1 yr (285 d)
- Compactness of the source (~ 5cm)
- W and Cu shield

[M. Cribier *et al.*, PRL 107 (2011) 201801]

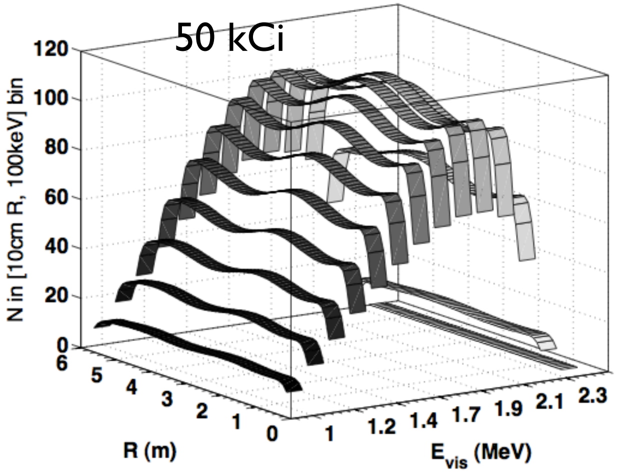


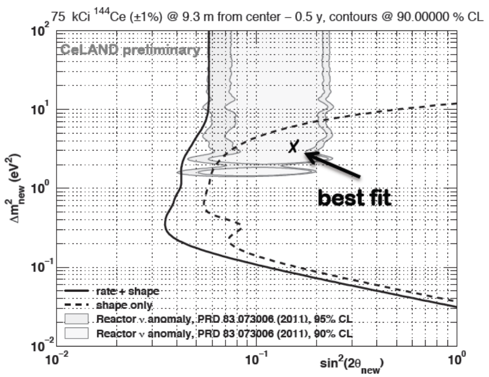
Real oscillation pattern vs. both **radius** & **energy**

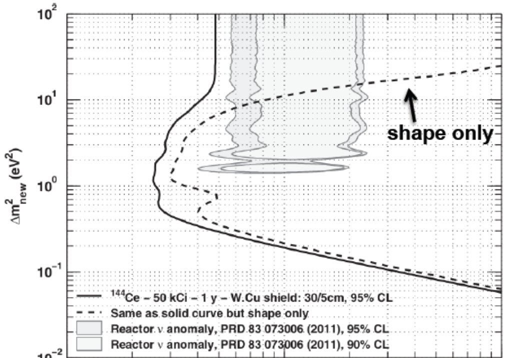
Phase I: 2015

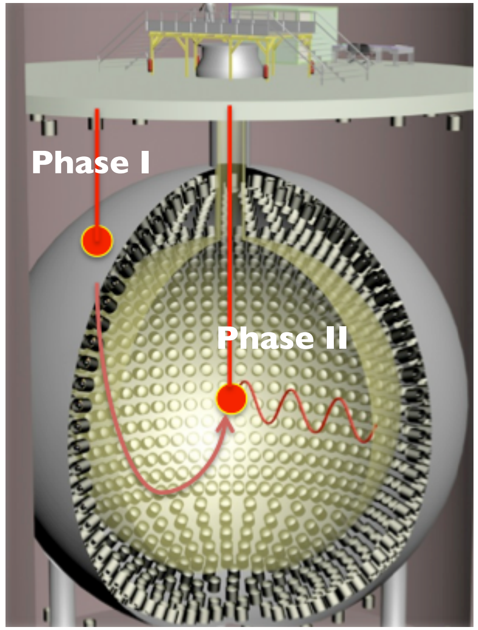


Phase II: 2016-2017 if feasible







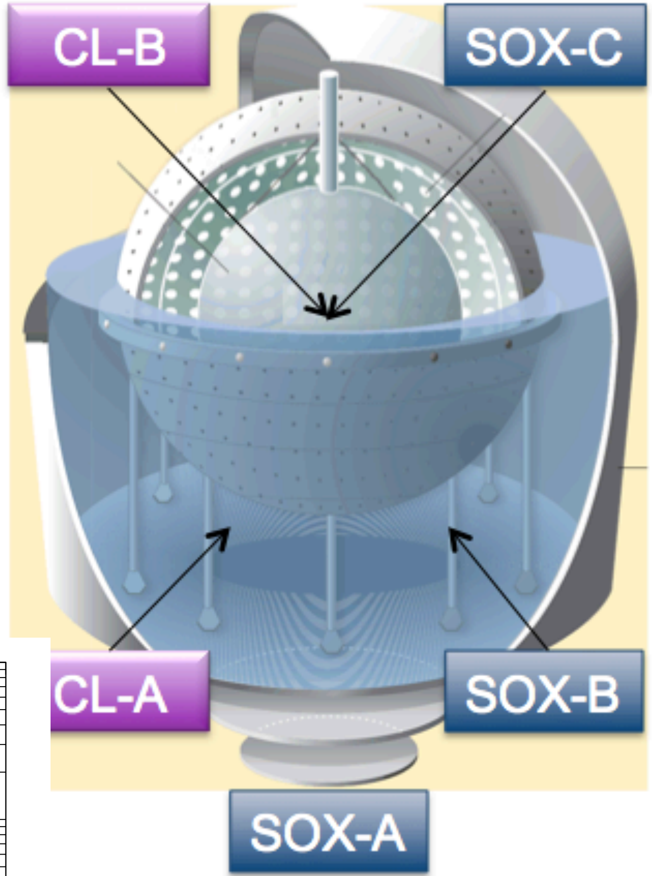


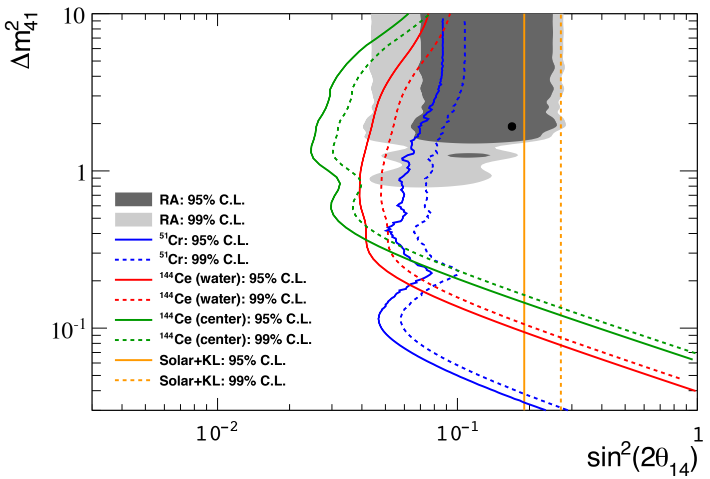
SOX

Detector: **KamLAND** (Borexino?)

CL-A (2015)
75 kCi ^{144}Ce in the WT
6 months of data taking

CL-B (2016/2017)
50 kCi ^{144}Ce source in the center
1.5 y of data taking





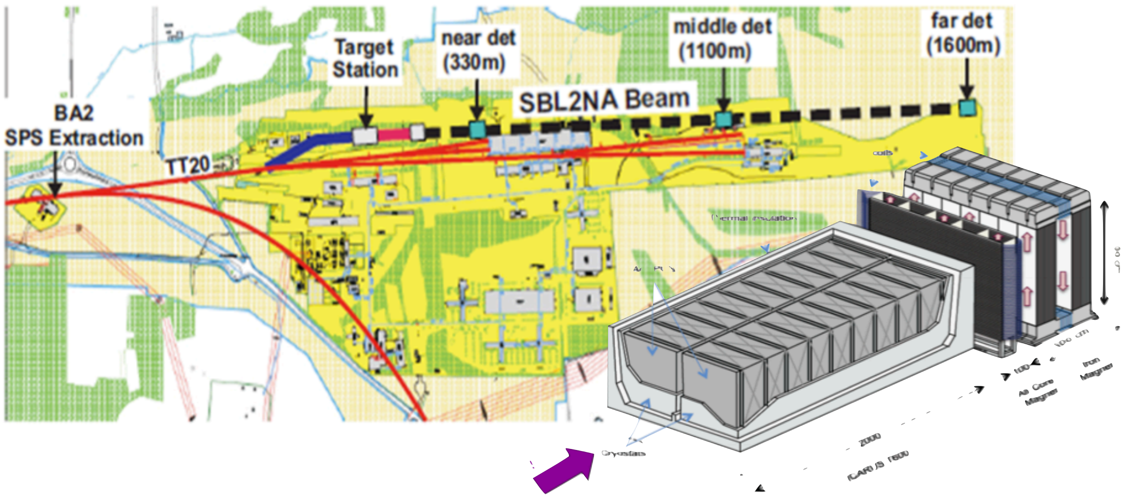
Detector: **Borexino**

SOX-A (2015)
10MCi ^{51}Cr in Icarus pit
8.25 m from the center
3 months of data taking

SOX-B (end 2015)
75 kCi ^{144}Ce source in W.T.. PPO everywhere to enhance sensitivity

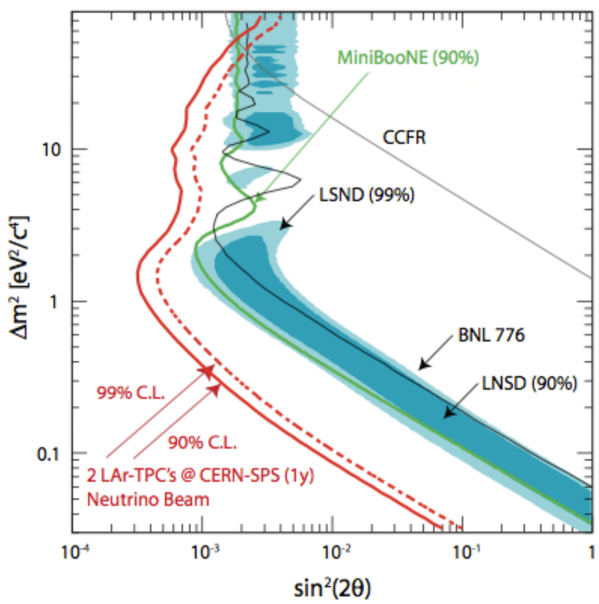
SOX-C (2016/2017)
50 kCi ^{144}Ce source in the center. Only after the end of solar program

ICARUS-NESSiE

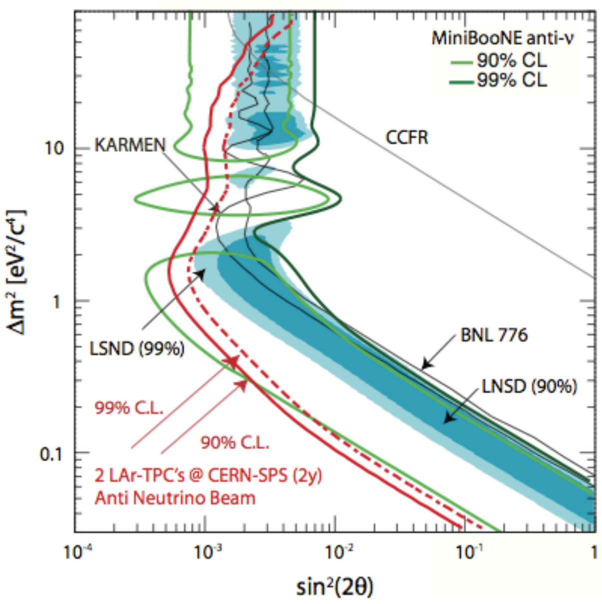


- Using CERN-SPS new ν_μ beam (E_ν ~ 2 GeV)
- 2 LAr-TPC (from ICARUS): near: 150 t, far: 600 t
- +magnetic spectrometers for charge determination
- Should start (both beam and detector data taking by end of 2015).

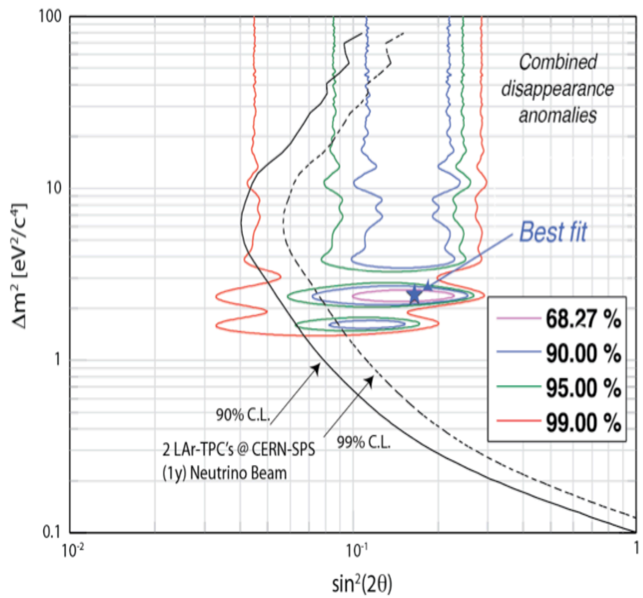
ν_μ to ν_e



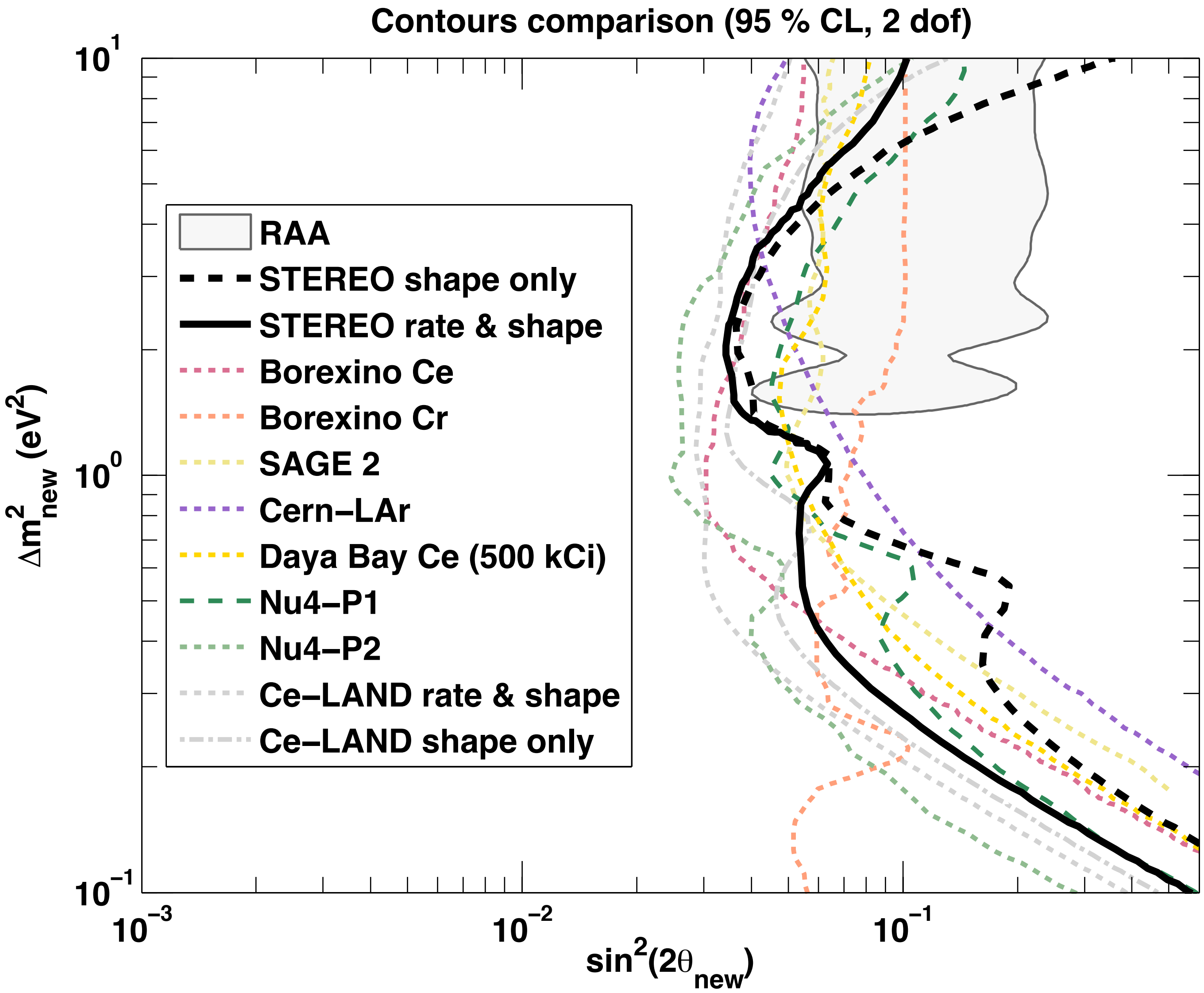
anti−ν_μ to anti-ν_e



ν_e to ν_e



Foreseen sensitivities to the Reactor anomaly



Conclusion

- These anomalies provide an exciting topic from the experimental and theoretical point of view.
- Not all the anomalies are consistent with each other. Ambiguous situation!
- These anomalies can be tested and either confirmed or refuted within near future (5-6 years time scale)
- A lot of experimental projects are foreseen to tackle this point.
- Most of the experiments focus on both L (baseline) and E (energy) information to provide a clear L/E unambiguous oscillation pattern if any.
- Establishing the existence of sterile neutrinos would be a major result!
- These are certainly exciting times for neutrino physics!