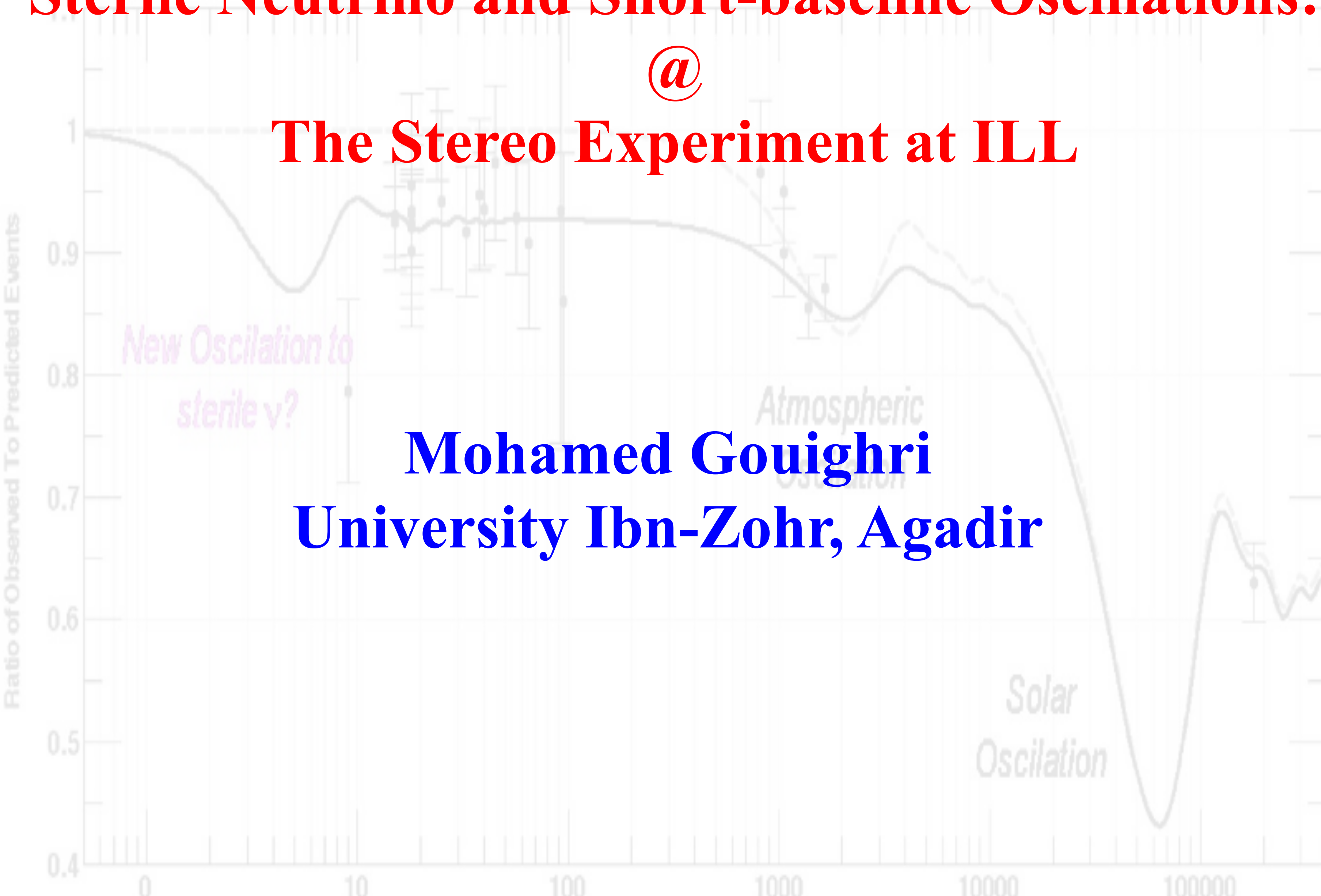
Sterile Neutrino and Short-baseline Oscillations:
@
The Stereo Experiment at ILL



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University Ibn-Zohr, Agadir

Rabat: December 17th, 2015 **Journées Scientifiques du GDRI P2IM**

Outline

- Active Neutrinos: SM and Beyond
- Light Sterile Neutrino and the Reactor Anomaly
- Oscillation Anomalies: A Global Fit
  - ✓ Nu-e Appearance
  - ✓ Nu-e Disappearance
  - ✓ Nu-mu Disappearance
  - ✓ Sterile Neutrino Oscillation: Global Picture
- Stereo Experiment @ ILL:
  - ✓ Detector description
  - ✓ Simulation and calibration of the detector: neutron sources,
  - ✓ Stereo Anomaly Contour Sensitivity

Standard Model

- Neutrinos are the only massless fermions
- Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R
- Neutrinos become massive
- Dirac mass $m_{\mathrm{D}}\overline{\nu_R}\nu_L$ + Majorana mass $m_{\mathrm{M}}\overline{\nu_R^c}\nu_R$
- It is likely that right-handed neutrinos are connected with new physics beyond the Standard Model

Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

$$\nu_R^c \rightarrow \nu_s \qquad \text{(left-handed)}$$

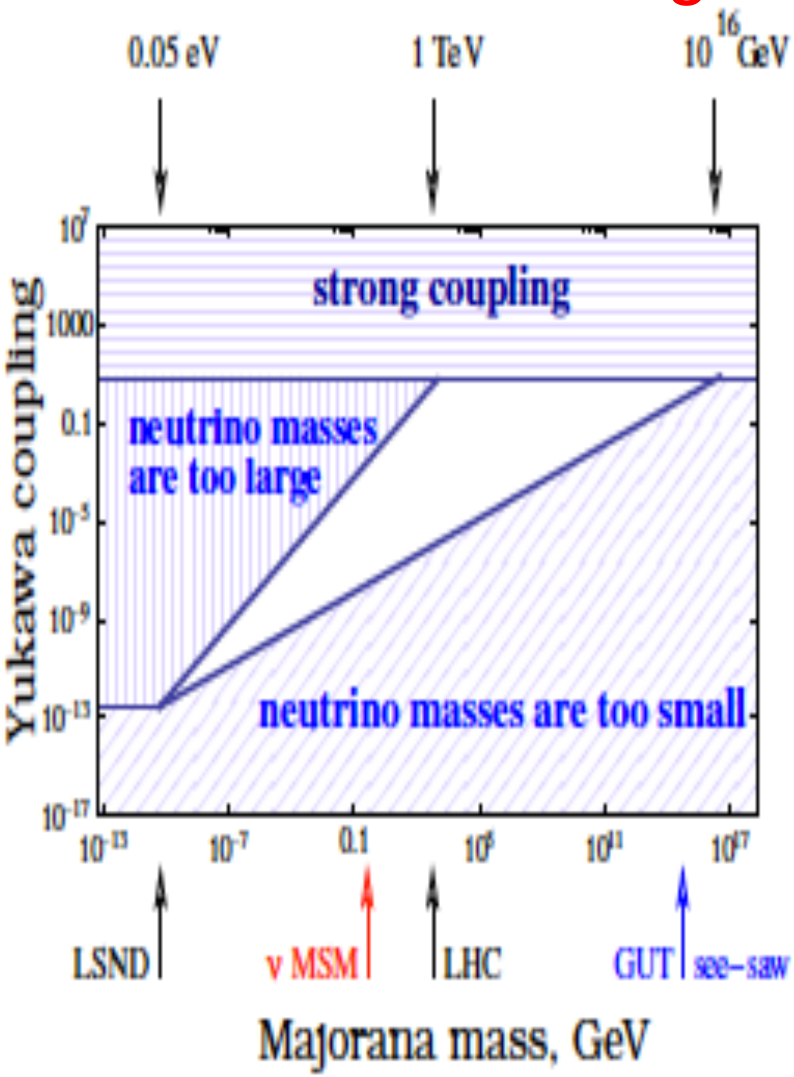
- Sterile means no standard model interactions

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into sterile neutrinos (ν_s)

- Observables:
  - ✓ Disappearance of active neutrinos
  - ✓ Indirect evidence through combined fit of data

- Extremely interesting and powerful window on new physics beyond the Standard Model

- Sterile neutrino may have large mass scale: See-saw, GUT, ν-MSM and LSND
- Sterile neutrino might be a sign of dark mater ….



	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see-saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	-
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Solar and Atmospheric Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$	Homestake Kamiokande GALLEX/GNO & SAGE Super-Kamiokande SNO BOREXino	$\to$ $\begin{cases} \Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{SOL}} \simeq 0.32 \end{cases}$
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	

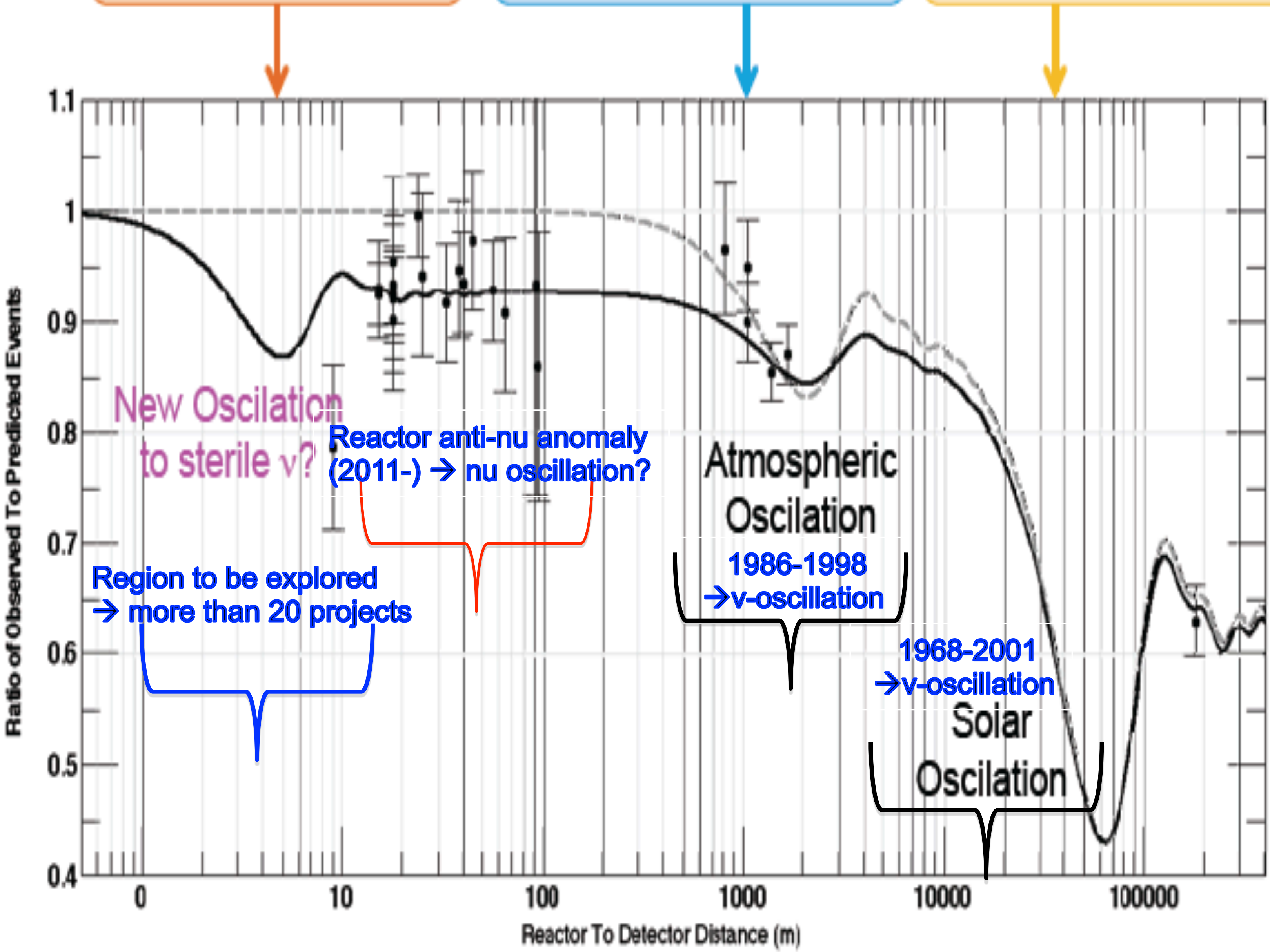
Atmospheric $\nu_\mu \to \nu_\tau$	Kamiokande IMB Super-Kamiokande MACRO Soudan-2	$\to$ $\begin{cases} \Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{ATM}} \simeq 0.50 \end{cases}$
Accelerator ν_μ disappearance	(K2K & MINOS)	

Two scales of Δm^2 $\Longleftrightarrow$ Three-Neutrino Mixing

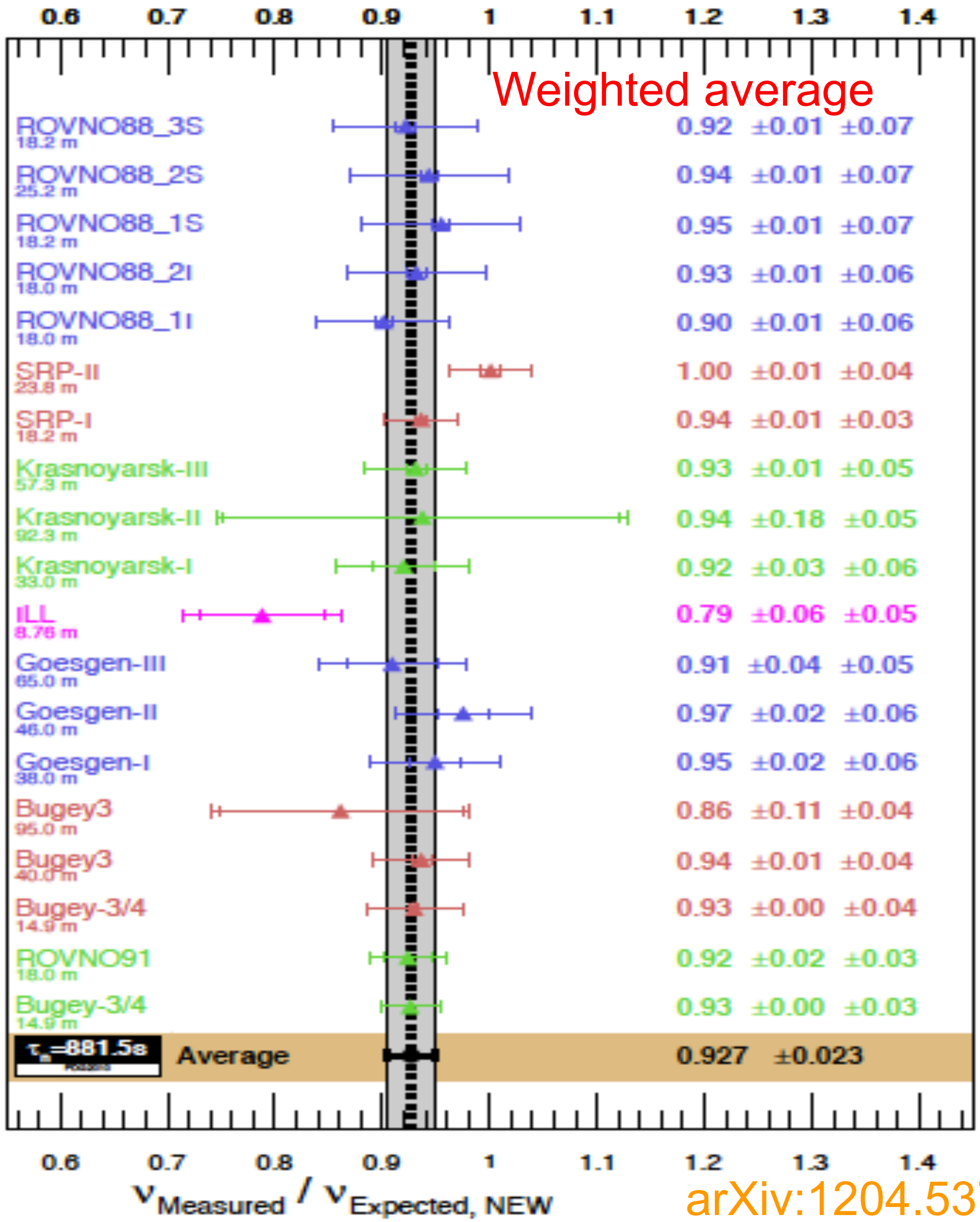
$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\Theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\Theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\Theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$



The Reactor Neutrino Anomaly



arXiv:1204.5379

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

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

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

r == $P_{ee} = 1 - \sin^2(2\theta_{new}) \sin^2\left(\frac{\Delta m^2_{new} L}{4E_{\bar{\nu}_e}}\right)$

→The synthesis of published SBL (Short BaseLine) experiments leads to a deficit of anti-ν: "R" = 0.927 ± 0.023

Total deficit of 7%

→The effect is statistically significant at more than 98.6% C.L (2.95σ)

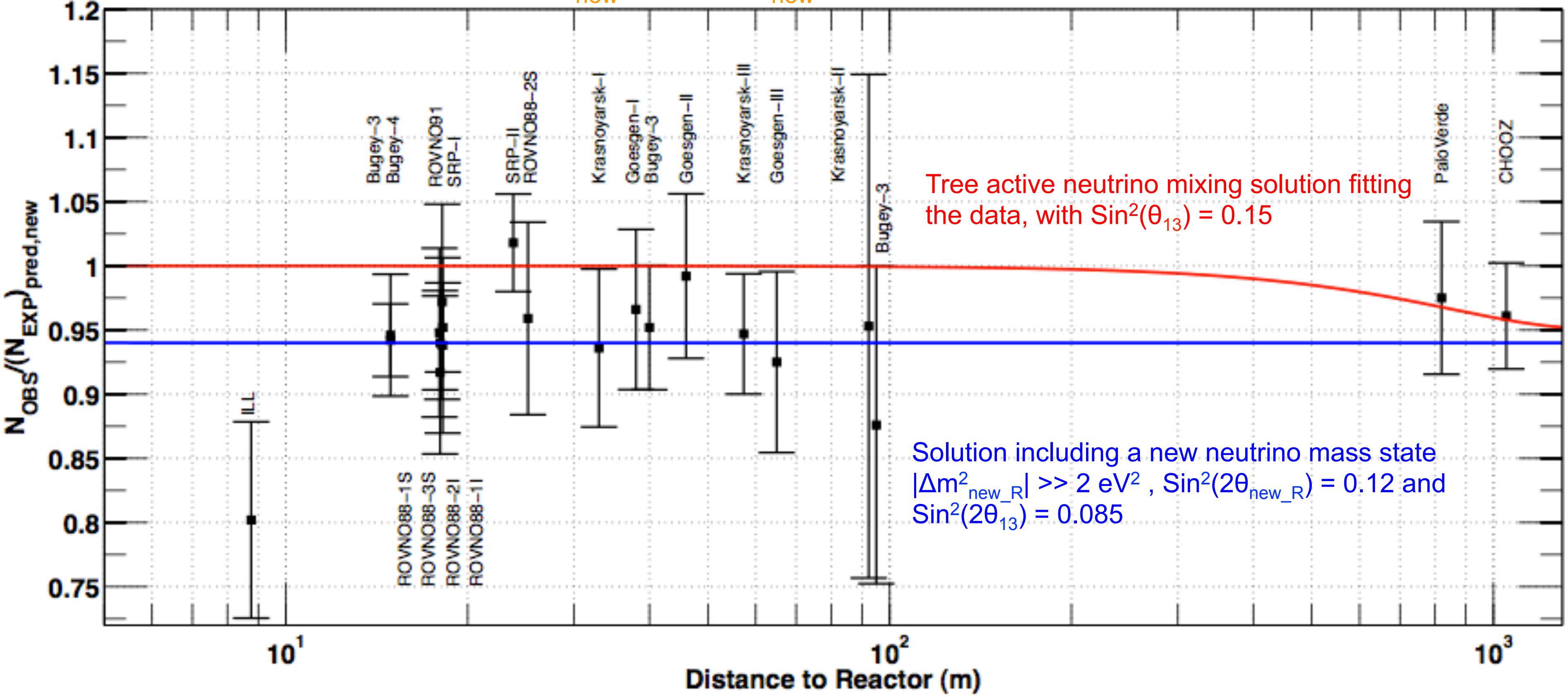
… (SBL neutrino anomaly)

Mention et all. 1101.2755

The Reactor Neutrino Anomaly

At least four alternatives:

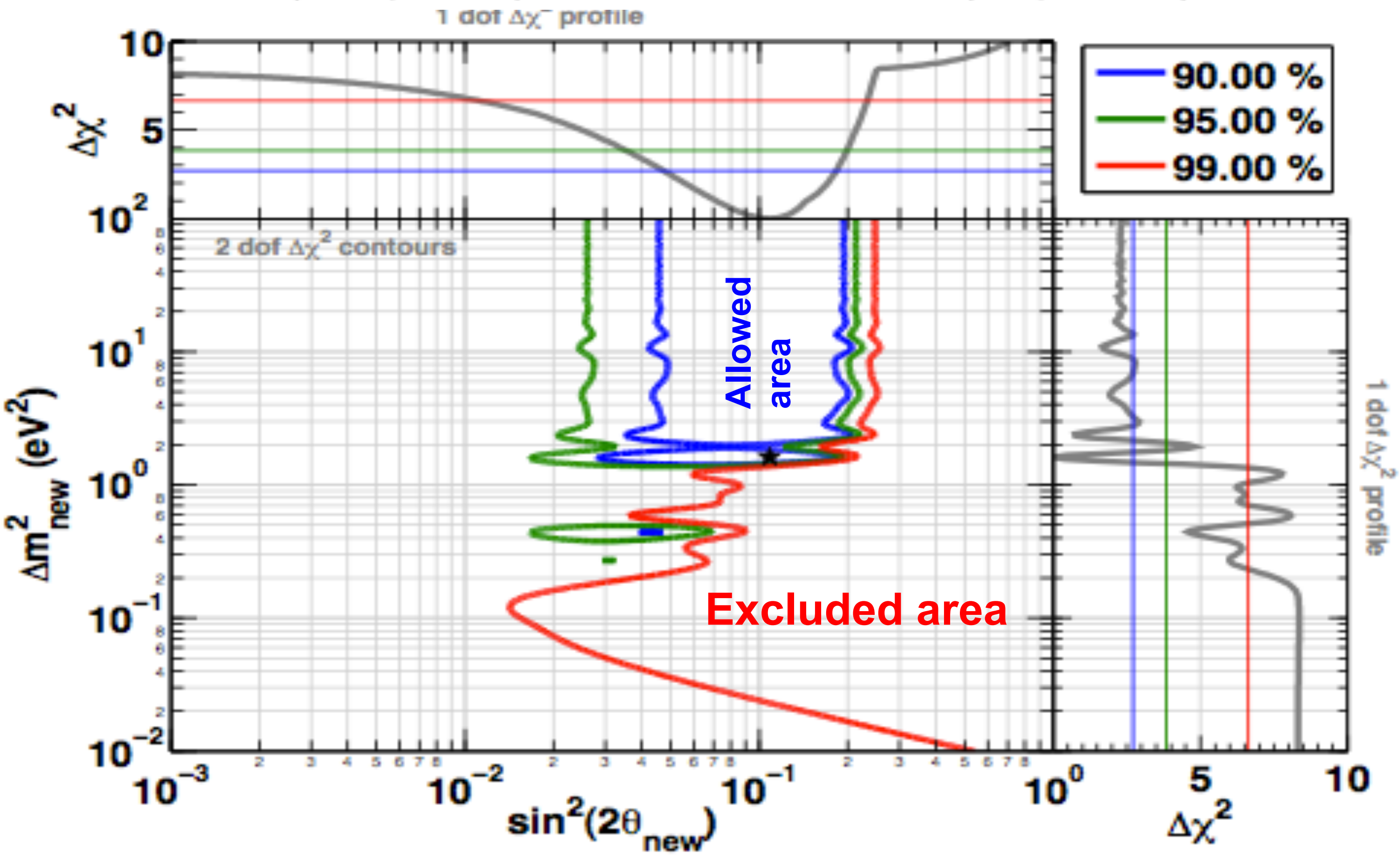
- The anomaly could be explained by a common bias in all reactor neutrino experiments?
- Measurements used different detection techniques (scintillator counters and integral detectors).
- Neutrons were tagged either by their capture in metal-loaded scintillator, or in proportional counters
- New physics at short baseline explaining a deficit of anti-ν_e
  - ✓ Oscillation towards a 4th Sterile neutrino?
  - ✓ a 4th oscillation mode with: θ_{new} and ΔM^2_{new}



The 4th Neutrino Hypothesis

- Combination data from reactors and MiniBooNE, no spectral shape information
- Fit to anti-ν_e disappearance hypothesis

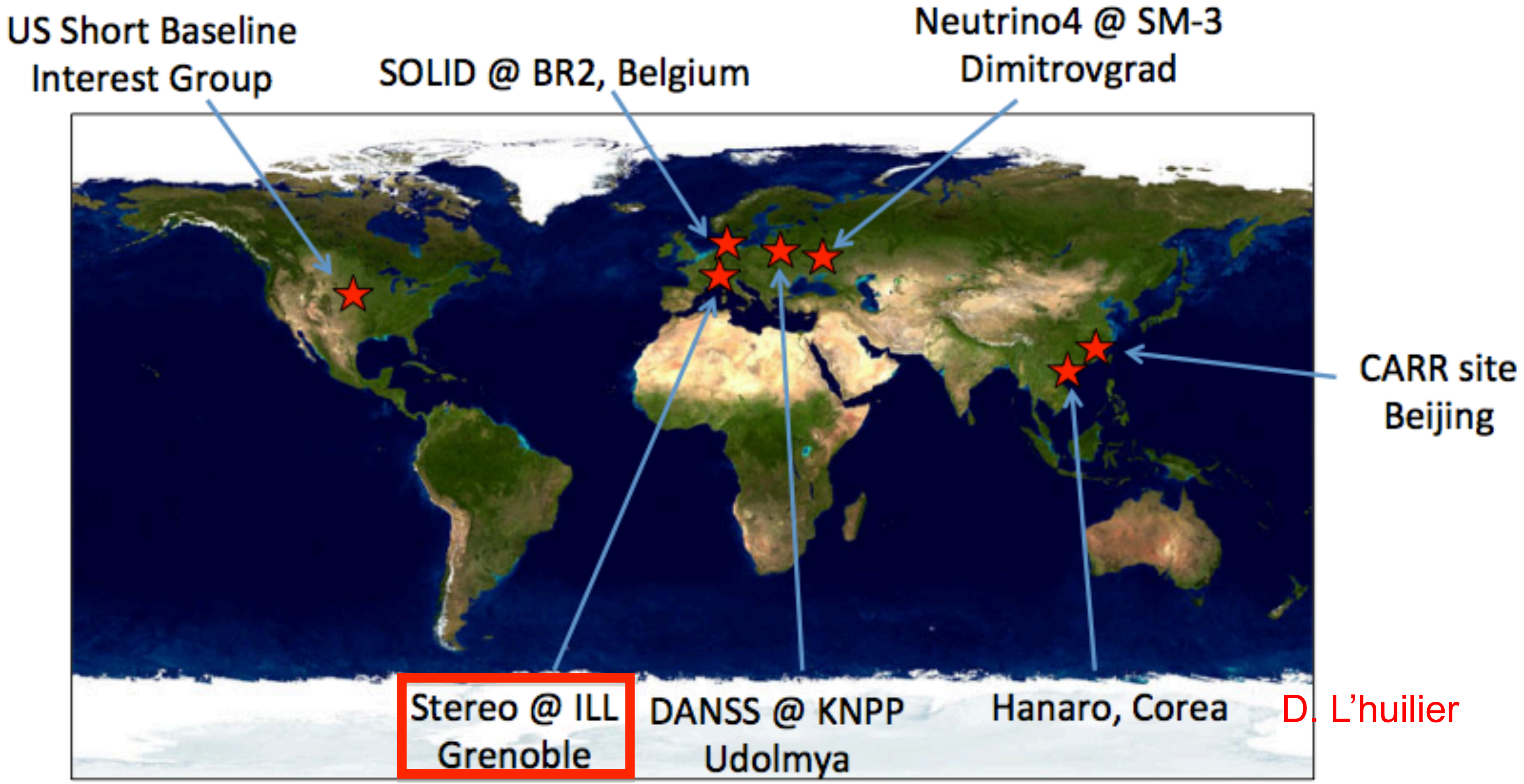
$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_{new} & \sin\theta_{new} \\ -\sin\theta_{new} & \cos\theta_{new} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{new} \end{pmatrix}$$



Absence of oscillations disfavored at 98.6% C.L

Future Reactor Efforts

- Future reactors will control reactor flux uncertainty by near/far measurements



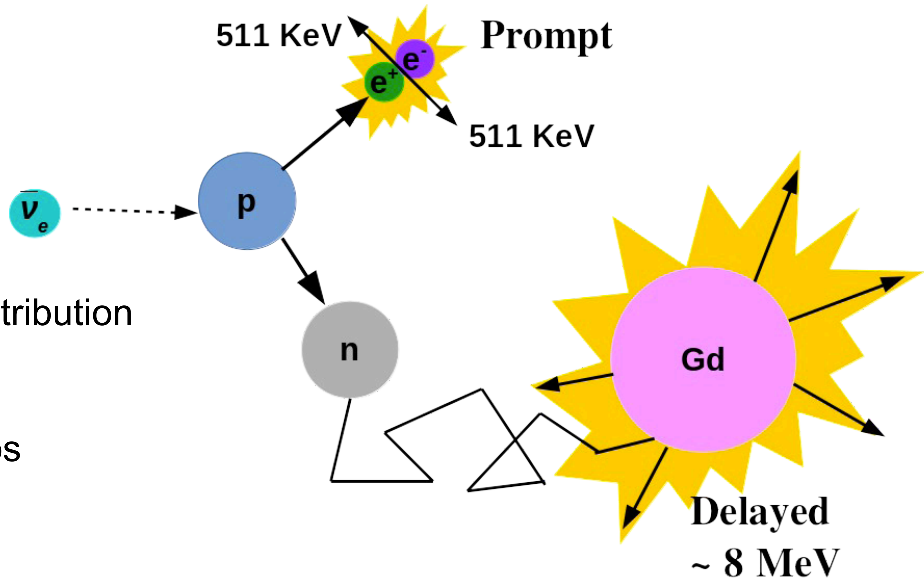
D. L'huilier

- The backgrounds at few meters from the reactor core is still an experimental challenge
- If solved, would provide detectors for potential safeguards applications

Motivation of Stereo Experiment

- The Stereo experiment aims to detect a clear signal of neutrino oscillation
- The distortion of the energy spectrum inside the detector.
- Stereo detector has to fulfill two main criteria:
    - ✓ a good energy resolution
    - ✓ a good precision in the vertex reconstruction

Experimental signature:



- Highly enriched ^{235}U as the nuclear fuel && small contribution of other isotopes
- Intense and pure production of electronic antineutrinos $\approx 1.9 * 10^{20}$ anti-ν/s/GW_{th}
- Detection with the inverse beta decay reaction in a liquid scintillator:

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

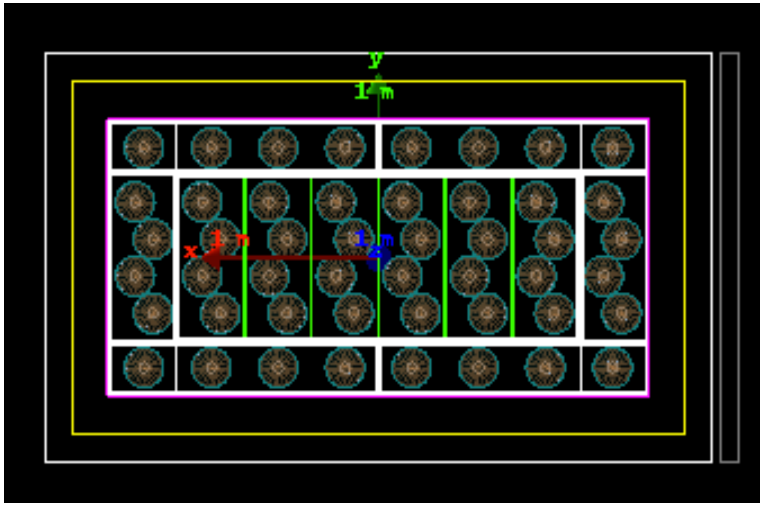
- A neutrino candidate is considered if a coincidence of a Prompt and Delayed signal in a time window of 50 μs

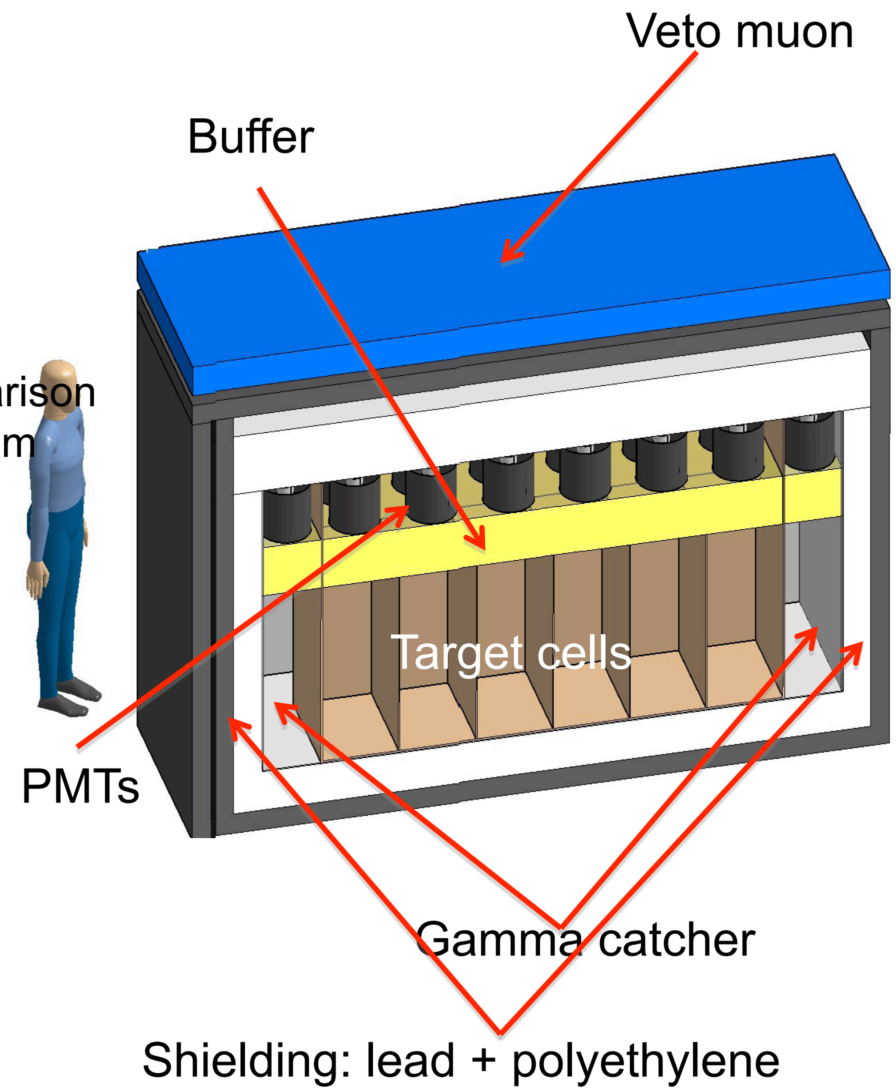
The Stereo Geometry

- Target vessel is divided in five 40 cm identical cells each is: 90 cm high and 1.10 cm wide
- The target is filled with 2 m^3 of liquid scintillator
- Data from cells exploit the energy and baseline dependence of the sought new oscillation pattern
- Unambiguous signature is provided by the comparison of the predicted energy spectrum with the spectrum measured in each cell

$$E_{vis} = E_{\bar{\nu}_e} - \Delta + m_e \simeq E_{\bar{\nu}_e} - 0.782\,MeV$$

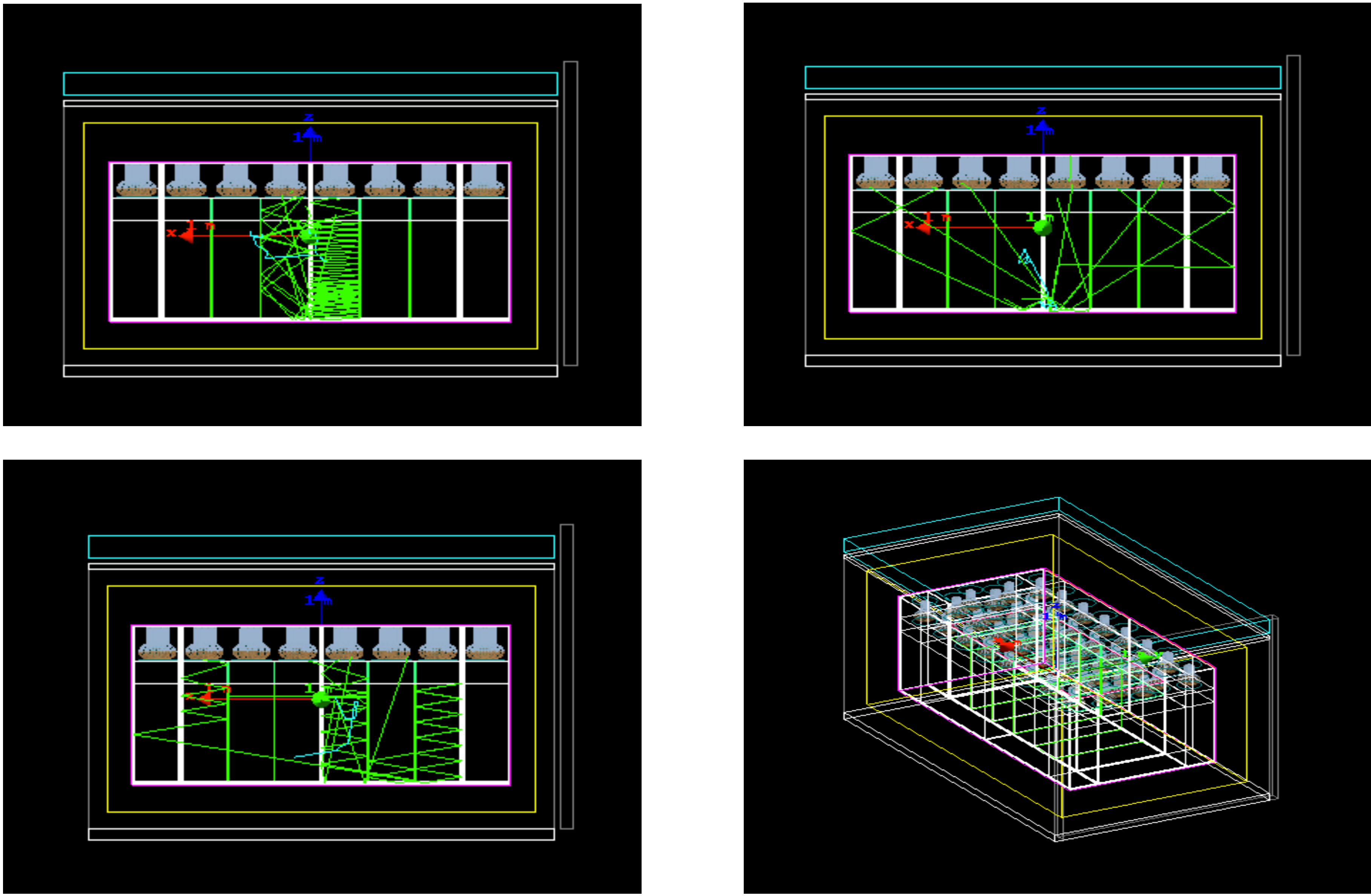
Geant4 visualization





The Stereo Geometry

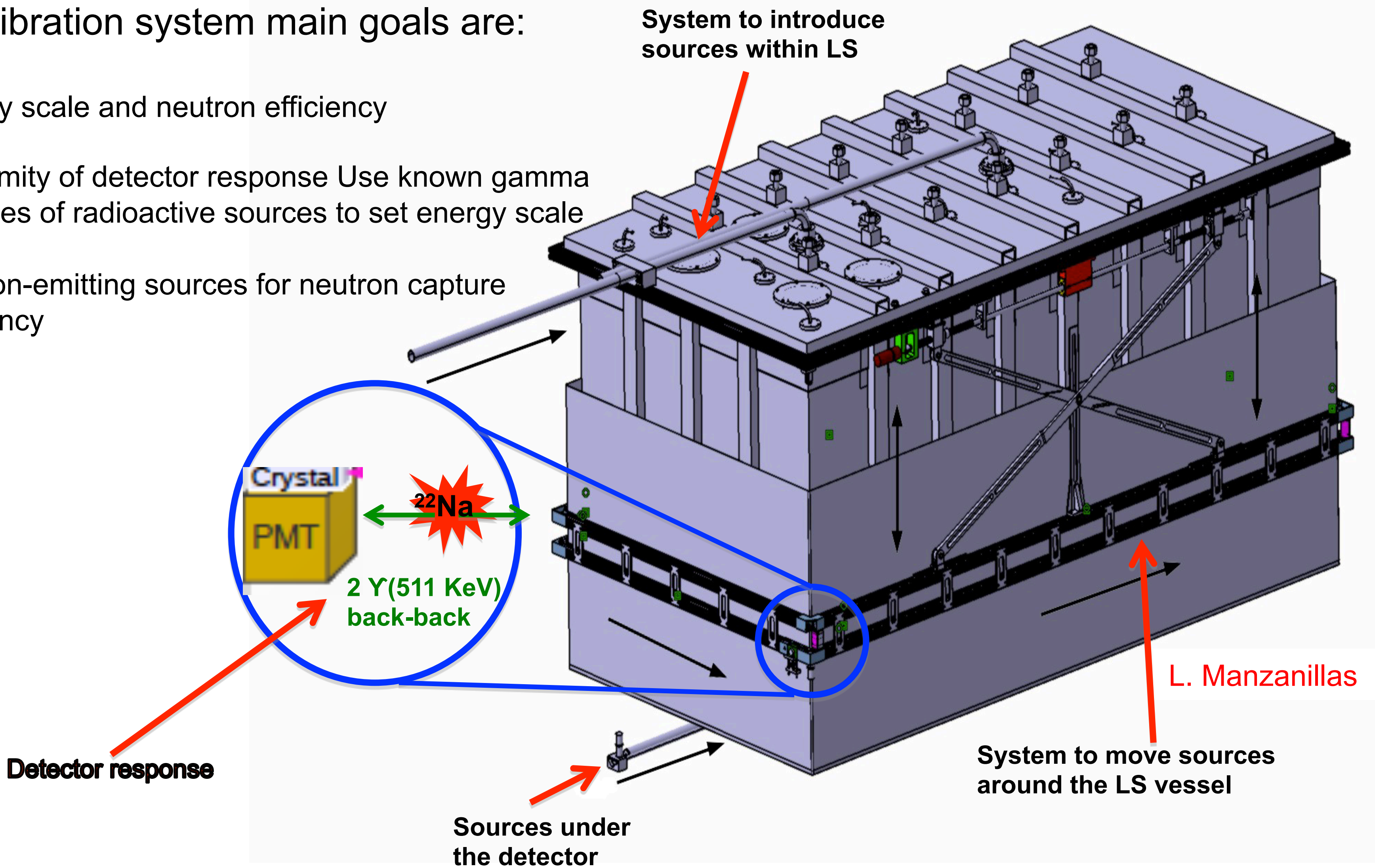
- Geant4 visualization of Stereo, target cell and response to sources



The Calibration System

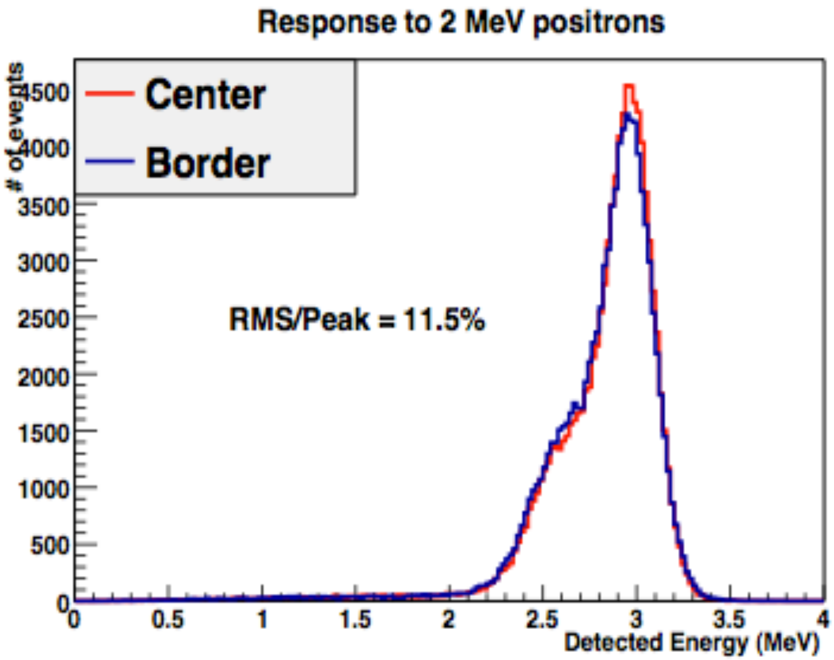
The calibration system main goals are:

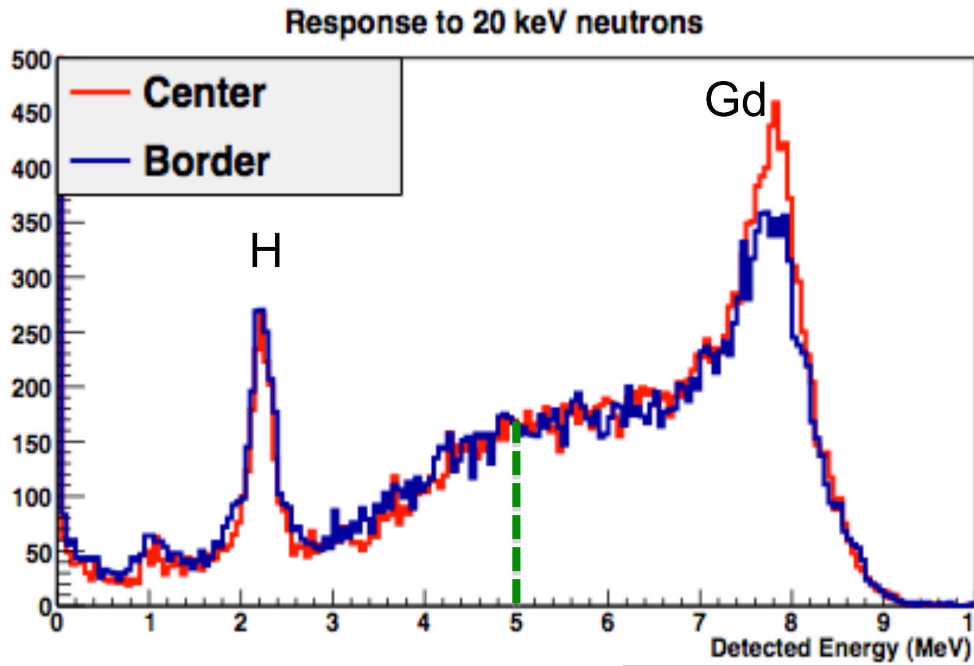
- energy scale and neutron efficiency
- uniformity of detector response Use known gamma ray lines of radioactive sources to set energy scale
- neutron-emitting sources for neutron capture efficiency



Simulations have shown that calibration of energy scale is possible from outside of the vessel containing the LS. n efficiency requires introduction of n sources inside LS.

Neutron Detection Efficiency

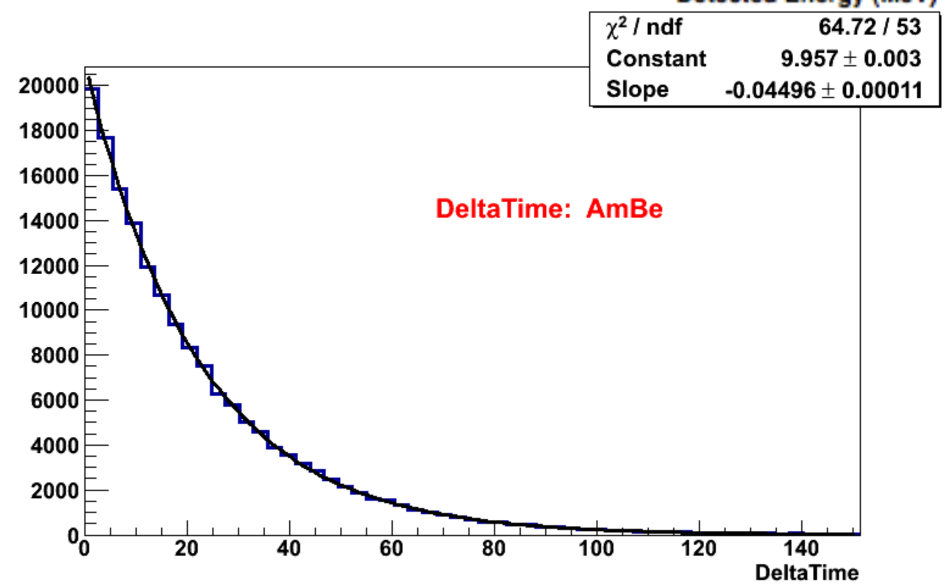




- ➢ Aprox 90% of captures are in Gd
- ➢ Capture time is: 15 μs Gd and 200 μs H

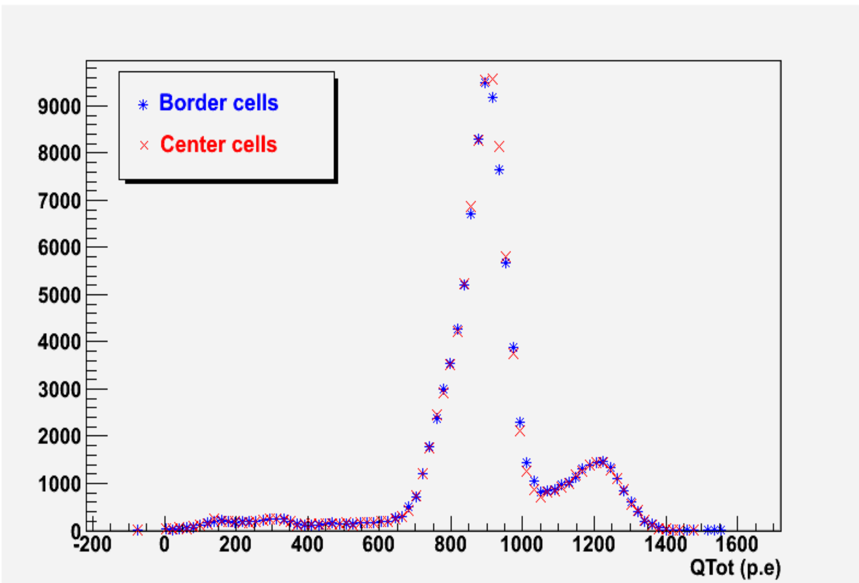
- ➢ Mean detection efficiency for neutrons:
  - ✓ 66% in the center cell
  - ✓ 60% in the border

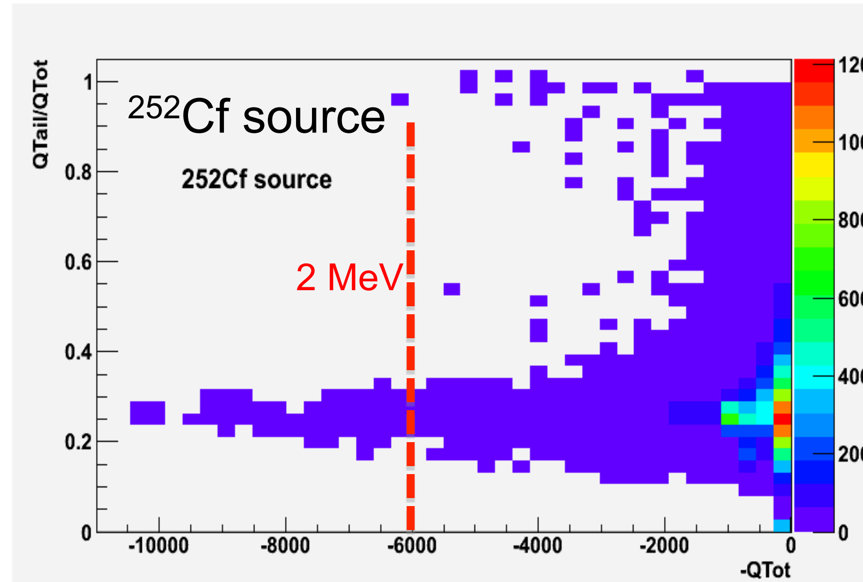
- ➢ Total energy of gammas cascade: 8 MeV

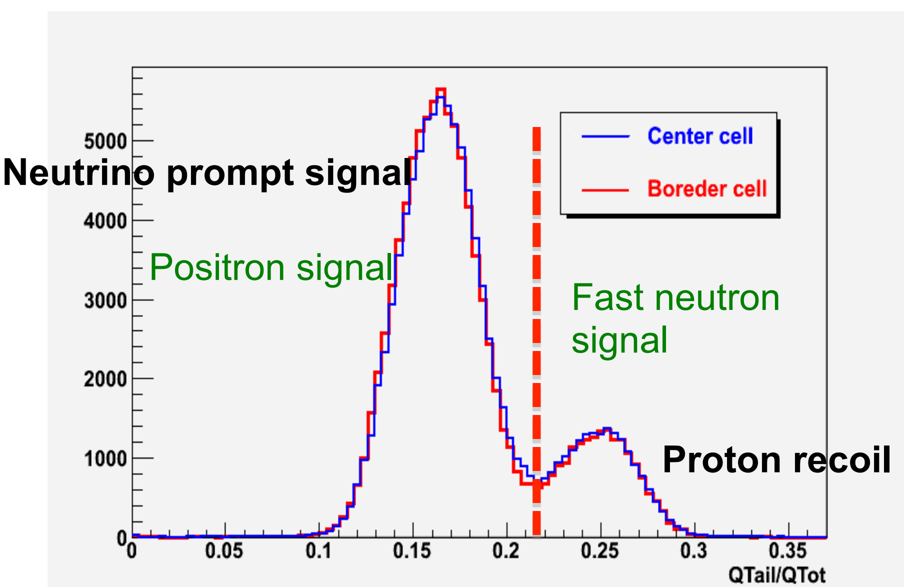


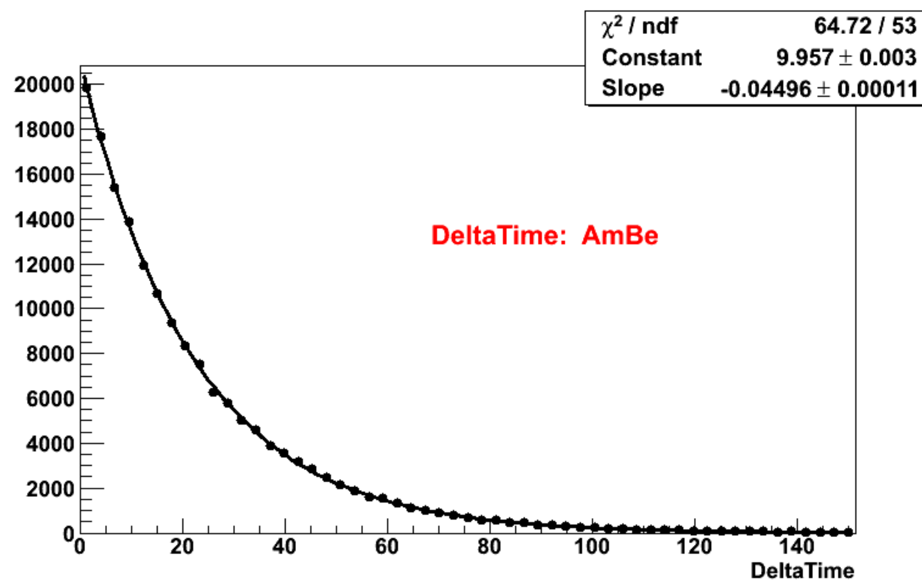
Calibration with Different Sources: Geant4

PMTs Collected charge in (p.e)

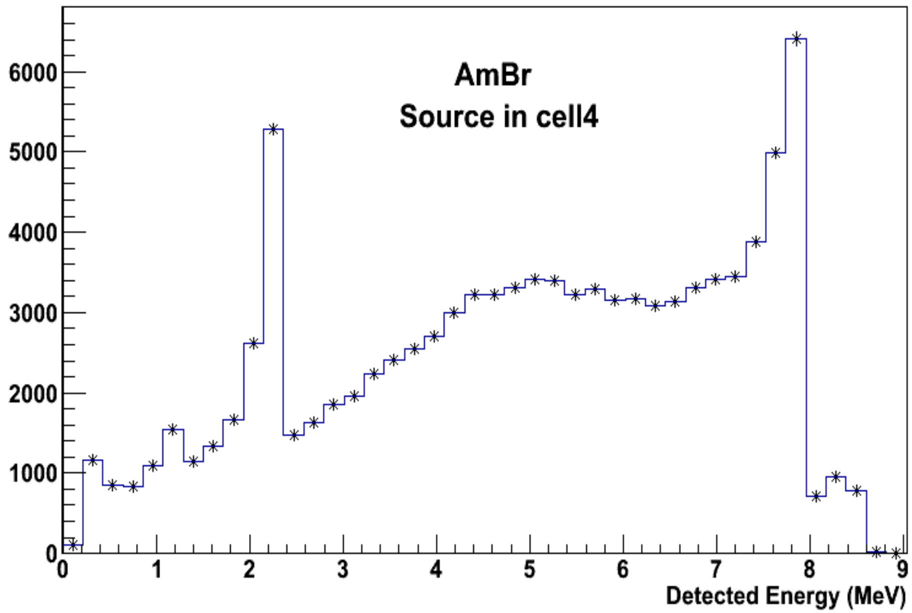


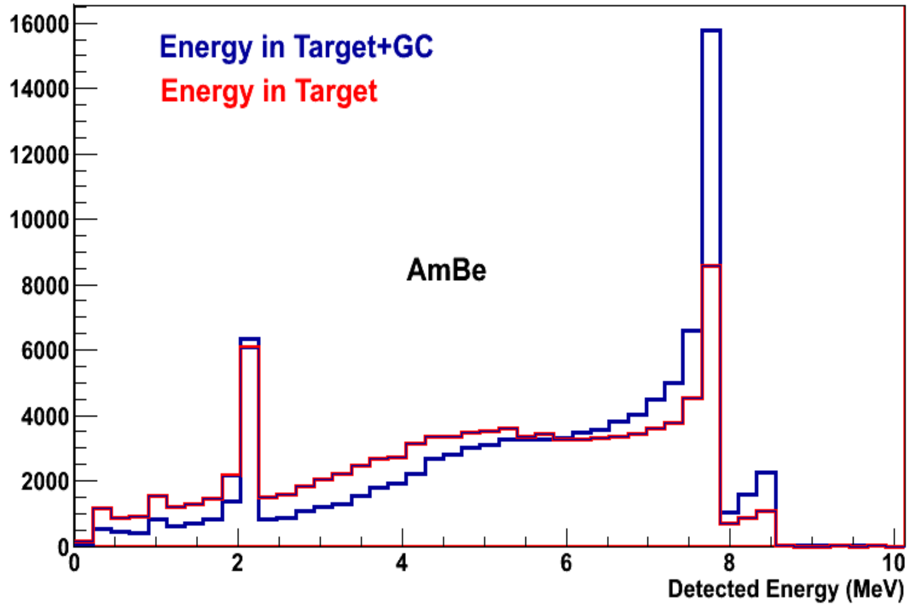






Neutron Detection Efficiency

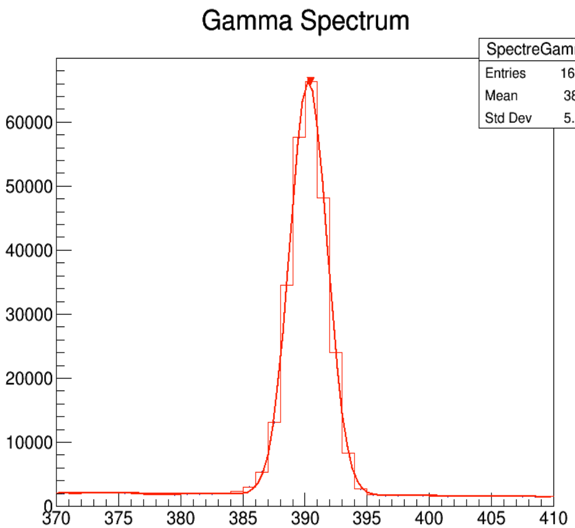


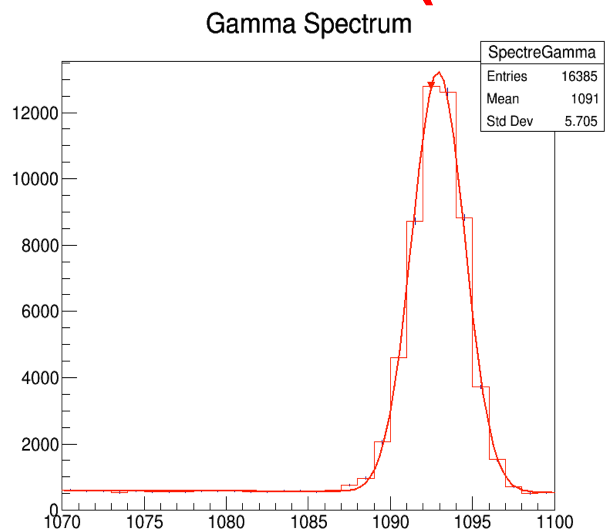


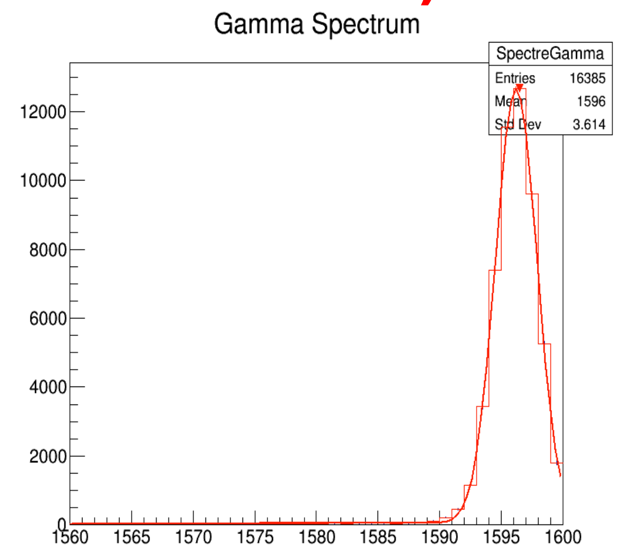
- A lot of gammas escape to other cells and GC ==> need E reconstruction of the entire detector

- Use proton recoil from ONE cell as Prompt signal ==> compute efficiency of individual cells

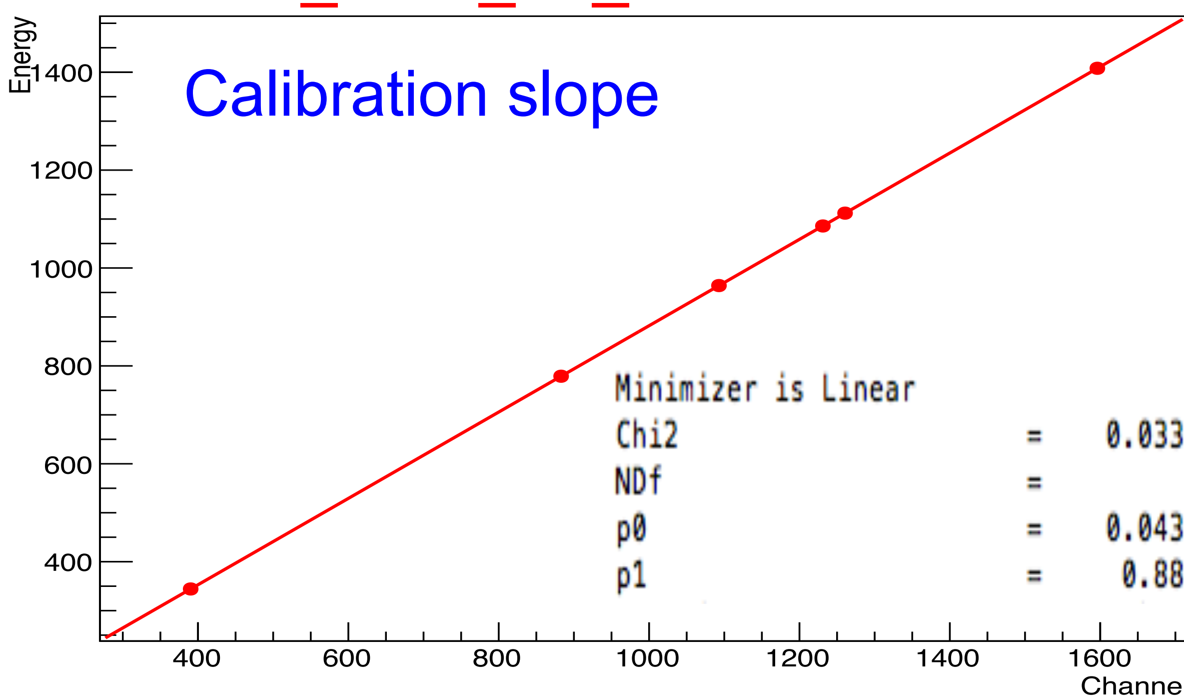
Calibration: 2014 data (Europium Source)





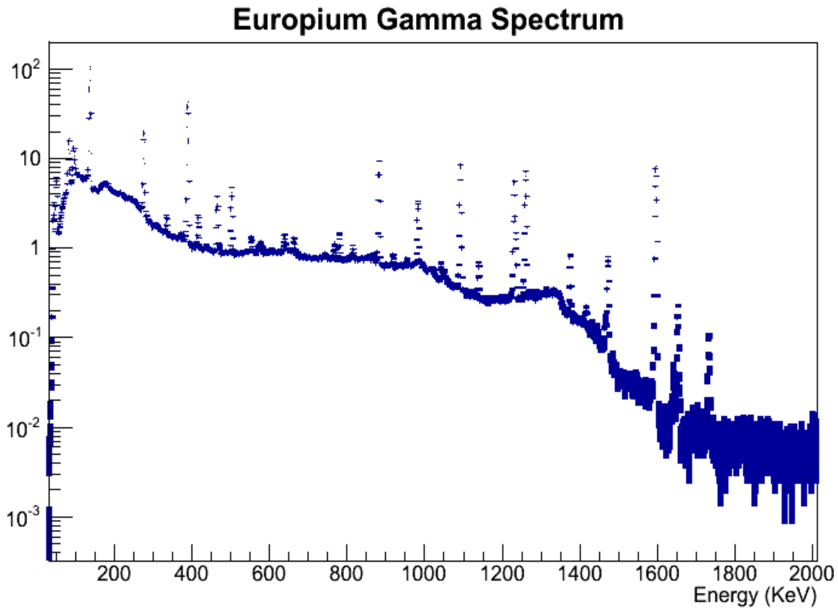


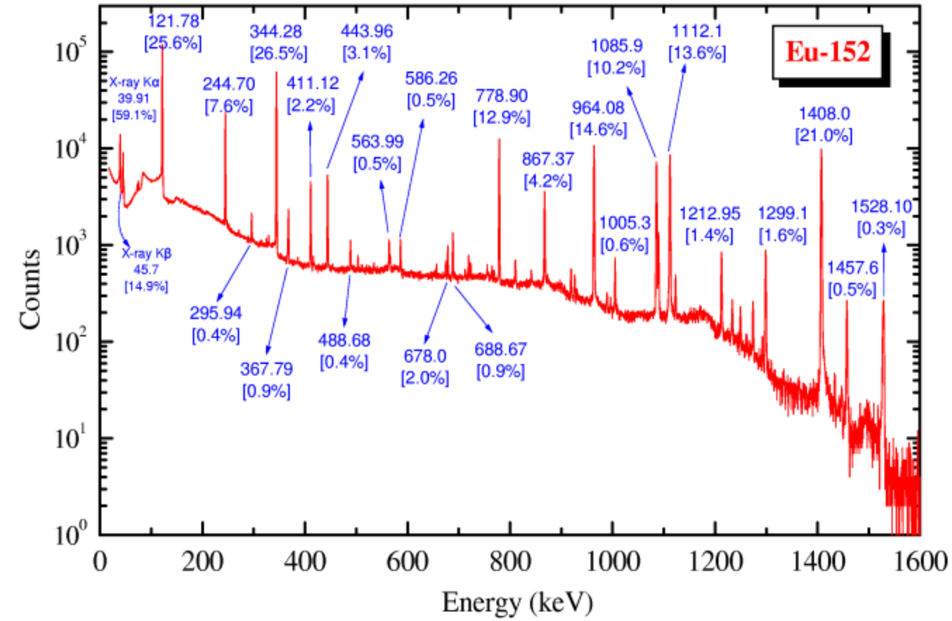
2014_07/07-11/calib_Ger2_Eu_11.07.2014.txt

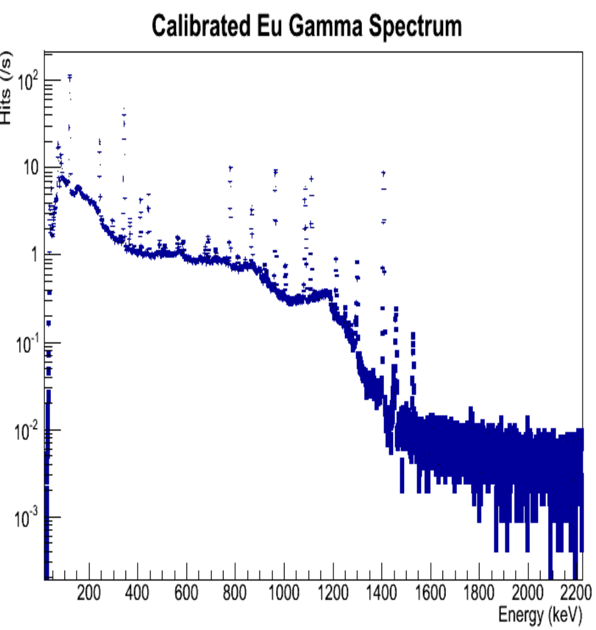


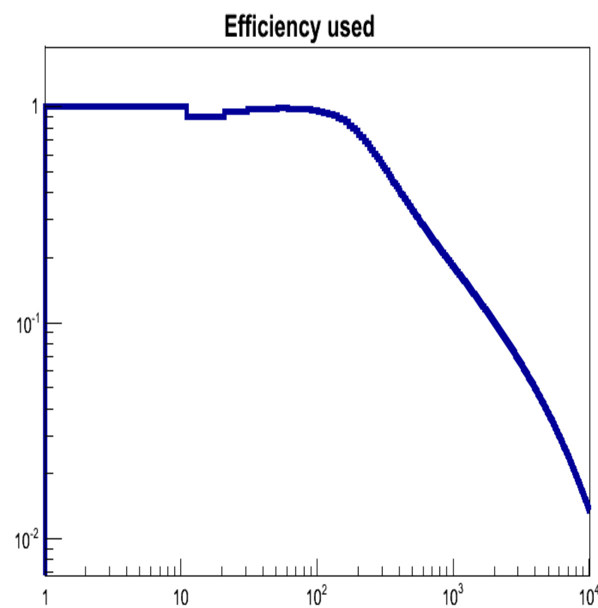

```
Minimizer is Linear
Chi2                    =     0.0335648
NDf                     =             4
p0                      =     0.0434945    +/-    0.114041
p1                      =      0.882051    +/-    0.000100153
```

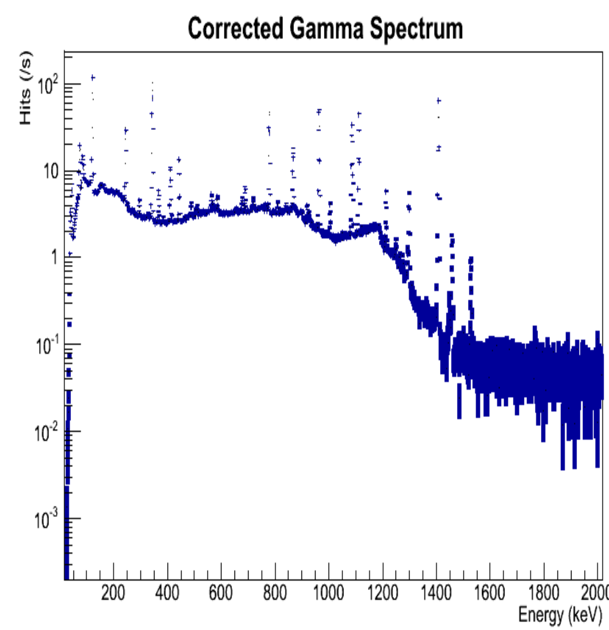
Calibration: 2014 data (Europium Source)





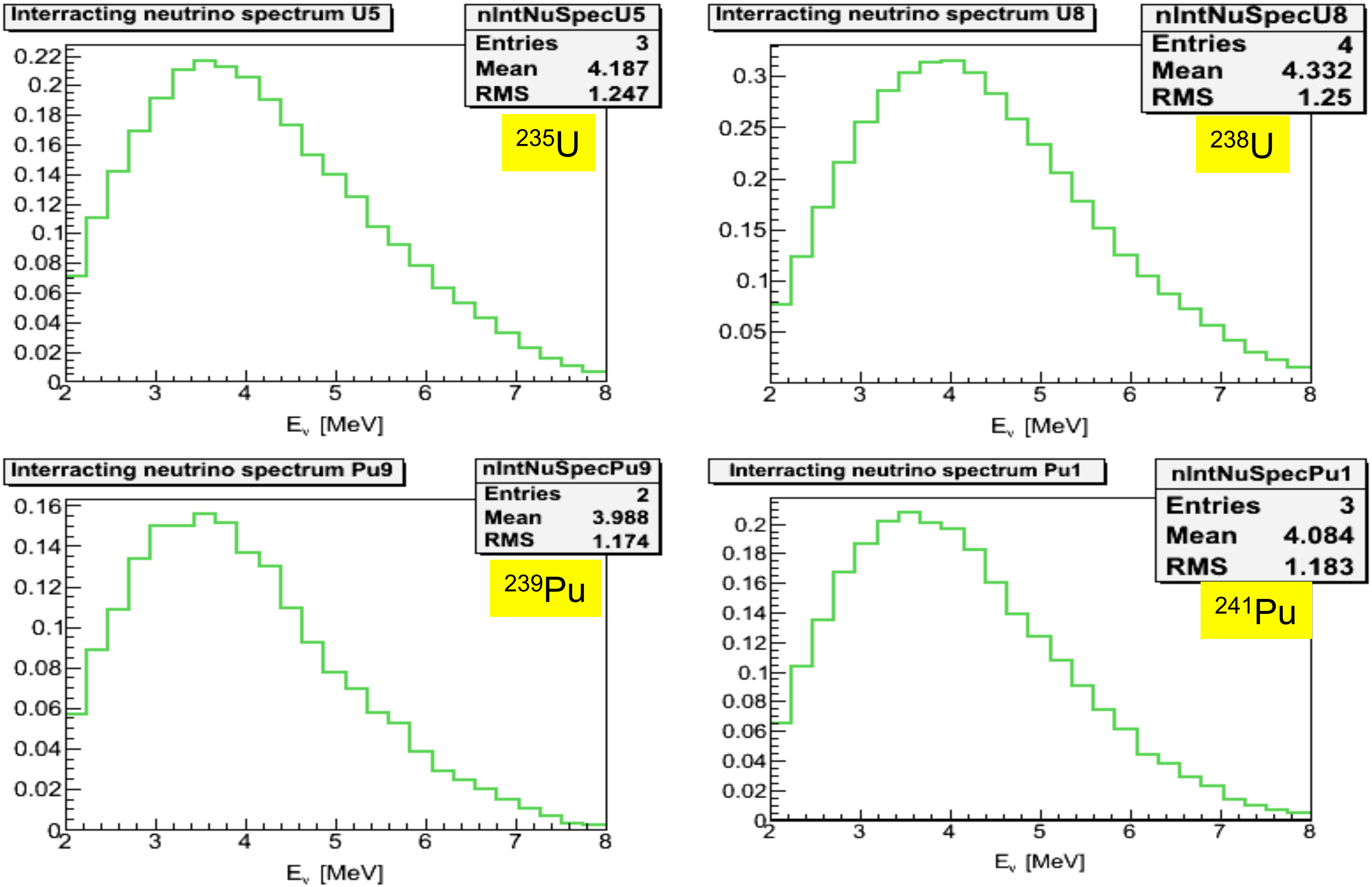


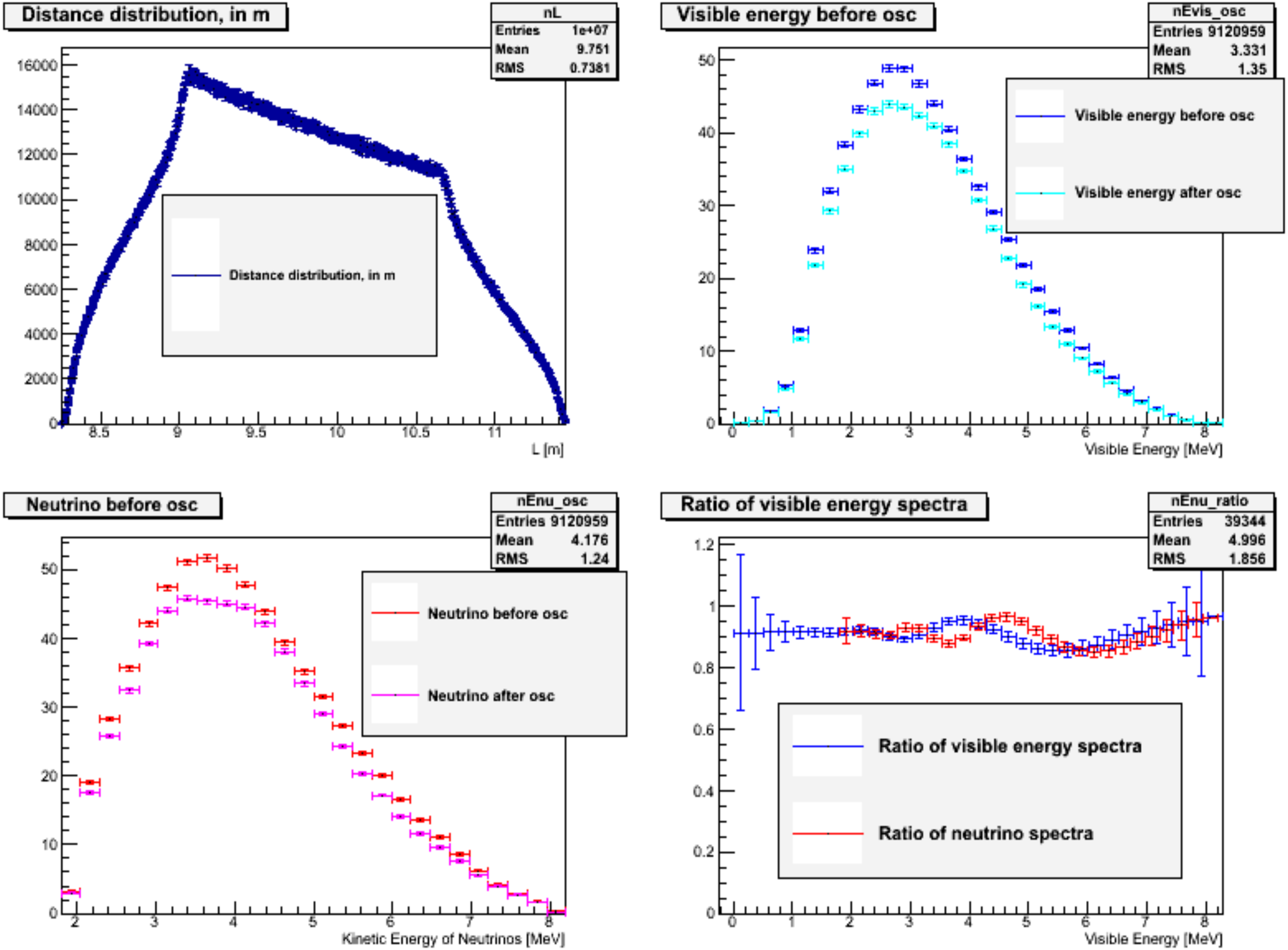




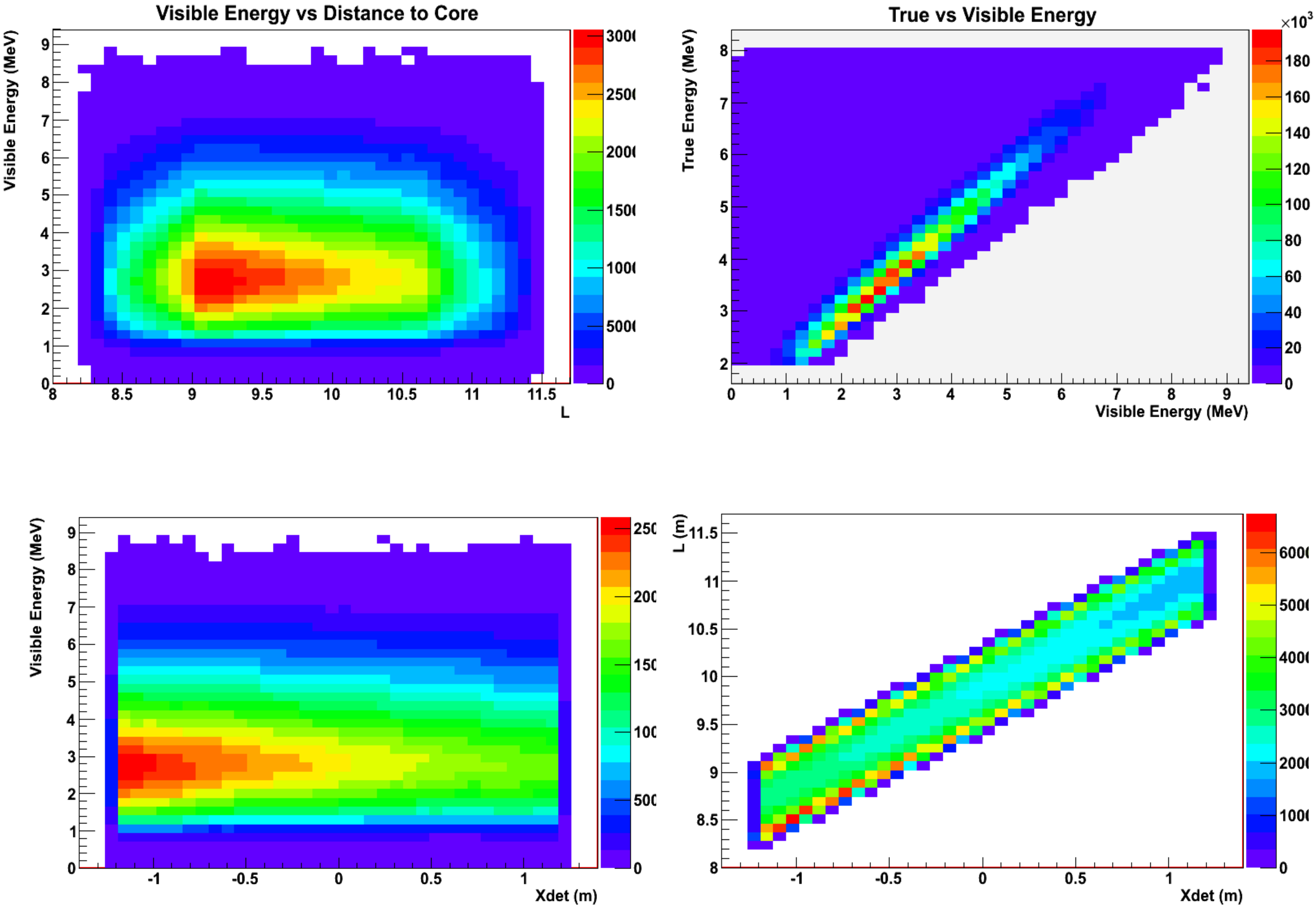
Towards Reactor Anomaly Sensitivity Contour

$$\Phi_{\bar{\nu}_e}(t, E_{\bar{\nu}_e}) = \frac{P_{th}(t)}{E_{235U}} S_{235U}(E_{\bar{\nu}_e})$$





Distance distribution, in m
nL
Entries 1e+07
Mean 9.751
RMS 0.7381
Distance distribution, in m
L [m]
Visible energy before osc
nEvis_osc
Entries 9120959
Mean 3.331
RMS 1.35
Visible energy before osc
Visible energy after osc
Visible Energy [MeV]
Neutrino before osc
nEnu_osc
Entries 9120959
Mean 4.176
RMS 1.24
Neutrino before osc
Neutrino after osc
Kinetic Energy of Neutrinos [MeV]
Ratio of visible energy spectra
nEnu_ratio
Entries 39344
Mean 4.996
RMS 1.856
Ratio of visible energy spectra
Ratio of neutrino spectra
Visible Energy [MeV]



Visible Energy vs Distance to Core
Visible Energy (MeV)
L
True vs Visible Energy
True Energy (MeV)
Visible Energy (MeV)
×10³
Visible Energy (MeV)
Xdet (m)
L (m)
Xdet (m)

Stereo Contours: Hypothesis

Data taking period: 300 days (6 reactor cycles)

Expected neutrino interactions (per day): 662

Position of the detector:

X = 9.85
Y = 0
Z = 0

300 days data taking (6 reactor cycles)

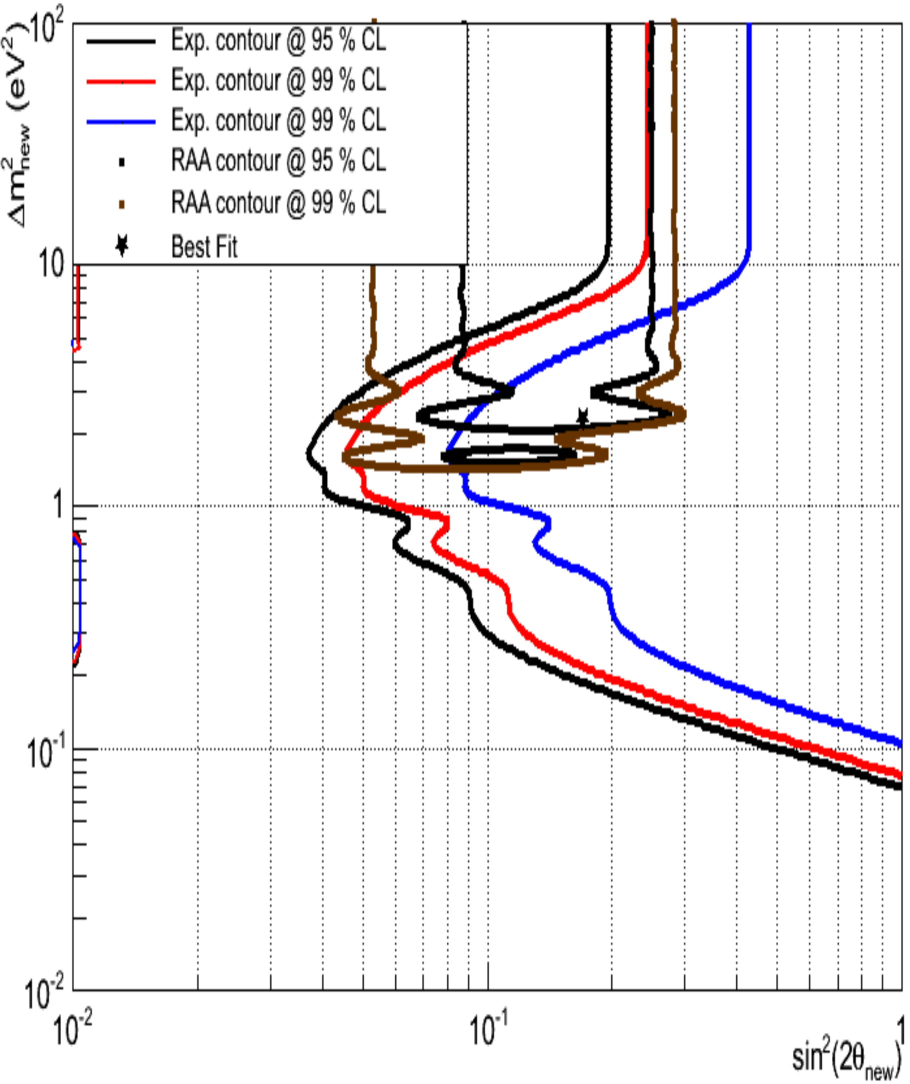
Systematics on the energy reconstruction: $\delta E_{scale} = 2\%$

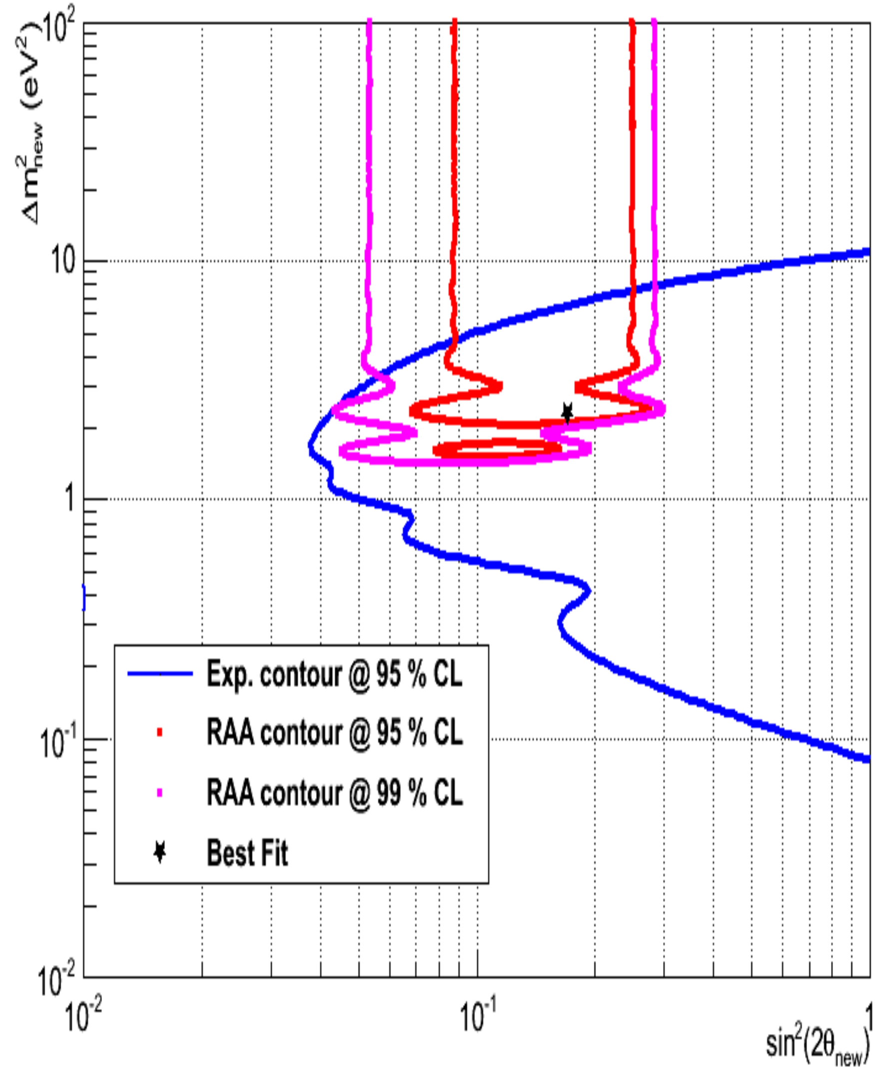
Signal / Background = 1.5

Prompt signal energy > 2 MeV

Delayed signal energy > 5 MeV

Stereo Contours





Conclusions

- Sterile neutrino explains not only existence of neutrino mass, but also its smallness.
- Sterile neutrino also explains LSND, Miniboone and reactor anomalies.
- Sterile neutrino is a good candidate for dark matter
- 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: L/E for Stereo is very optimistic
- Stereo is ready and will start data taken June 2016
  - ✓ Chance to explore with more precision the reactor anomaly
- The sensitivity covers the contour of the reactor anomaly
- Establishing the existence of sterile neutrinos would be a major result
- These are certainly exciting times for neutrino physics

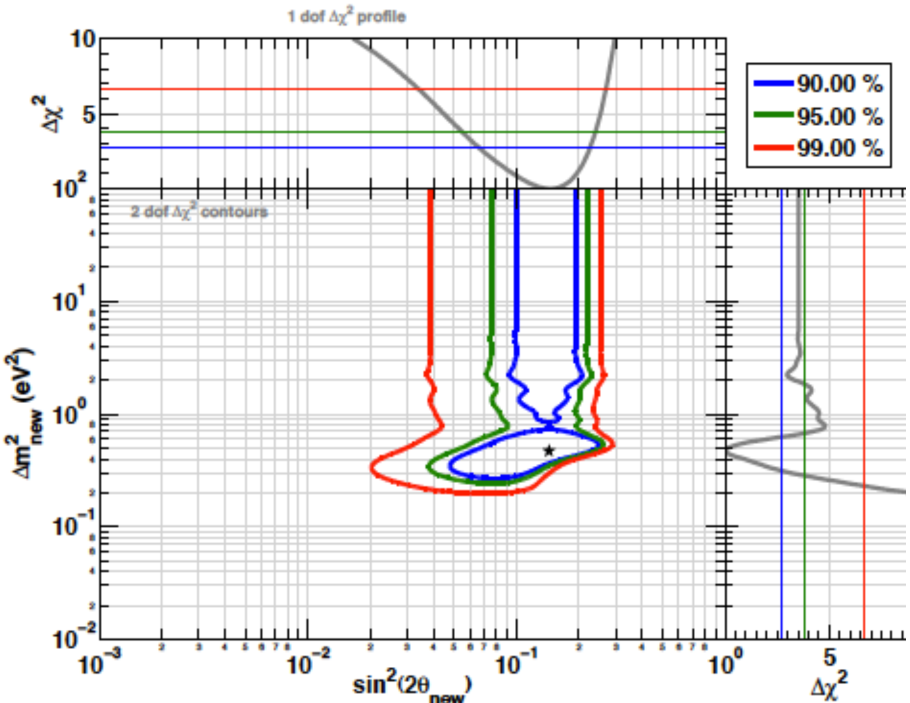
Thank you for your attention

Back-up

The 4th Neutrino Hypothesis

- The reactor antineutrino anomaly could be explained through the existence of a fourth nonstandard neutrino, corresponding in the flavor basis to a sterile neutrino ν_s

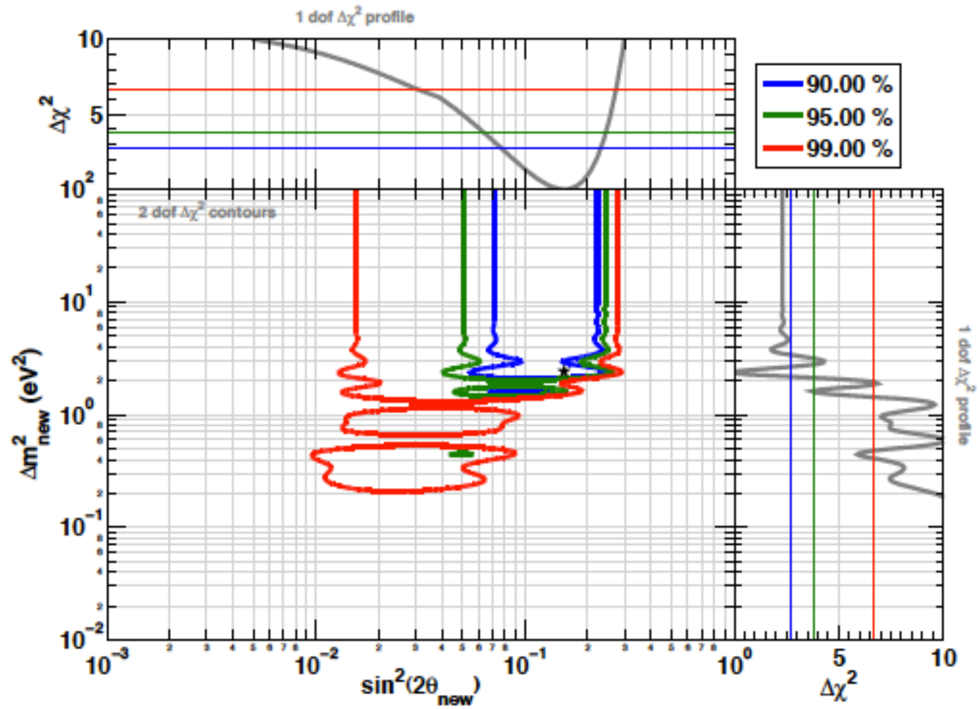
Reactor Rate+Only Analysis



Fit to data indicates:
$|\Delta m^2_{new\_R}| > 0.2$ eV^2 (99%) and $\sin^2(2\theta_{new\_R}) \approx 0.14$

The best fit point is at:
$|\Delta m^2_{new\_R}| > 0.5$ eV^2 and $\sin^2(2\theta_{new\_R}) \approx 0.14$

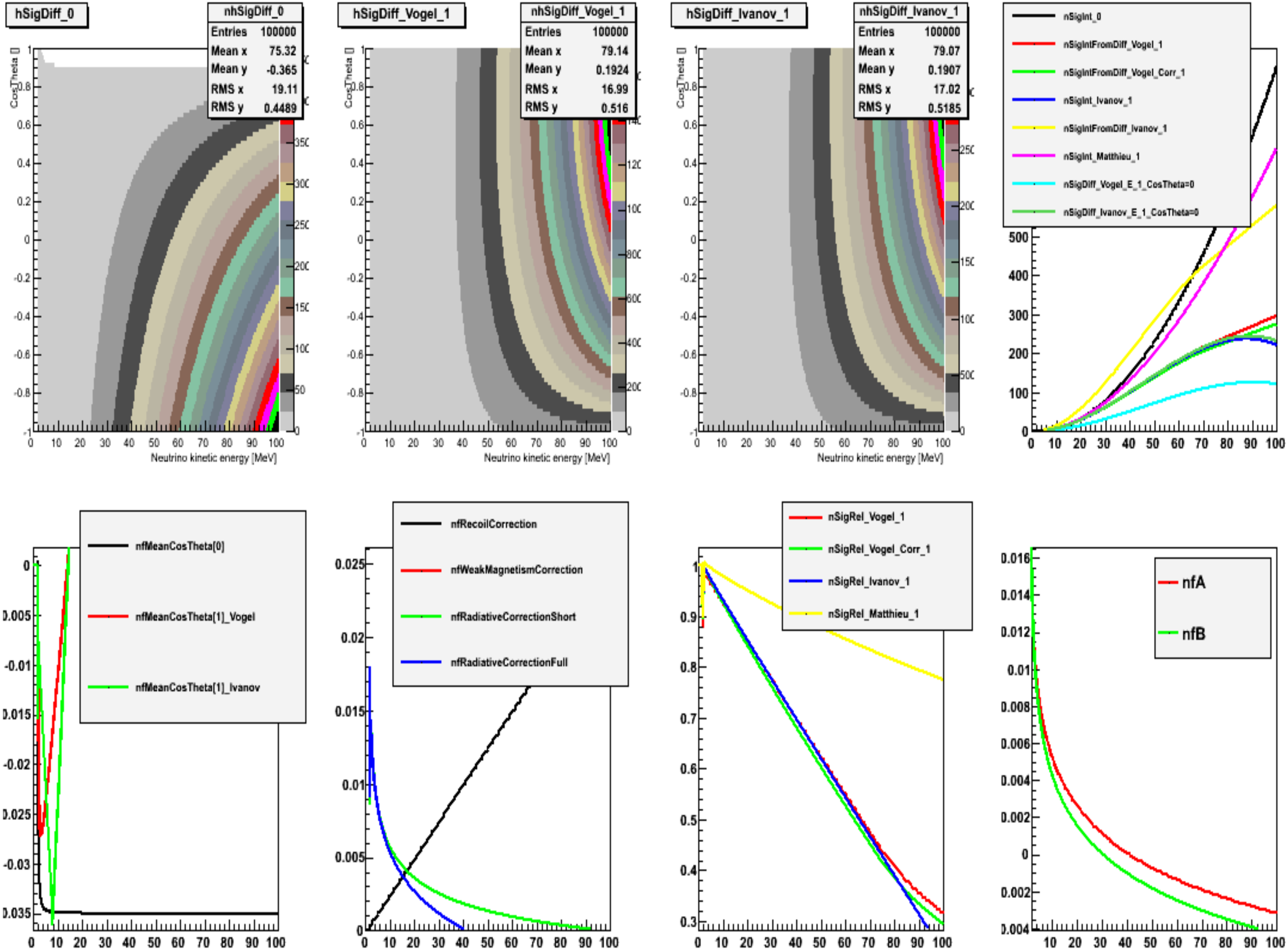
Reactor Rate+Shape Analysis



Solution including a new neutrino mass state
$|\Delta m^2_{new\_R}| \geq 1$ eV^2 , $\sin^2(2\theta_{new\_R}) \approx 0.15$

The no-oscillation analysis is excluded at 99.8% (3σ)

Uncorrelated	
Fission Spectrum	$0.7 \rightarrow 4.0\%$
Correlated	
Weak Magnetism	$(E-1.0)*1.0\%/MeV$
Evt. by evt. baseline uncertainty	$\delta L = 32$ cm
Energy scale from calib. sources	2.0%
Monitoring	1.0%
Normalization	
Np	0.5%
Spill in spill out	1.0%
Detection efficiency	2.0%
Thermal power	2.0%
Fission spectrum	1.8%
Total nomalization	3.5%


hSigDiff_0
nhSigDiff_0
Entries 100000
Mean x 75.32
Mean y -0.365
RMS x 19.11
RMS y 0.4489
hSigDiff_Vogel_1
nhSigDiff_Vogel_1
Entries 100000
Mean x 79.14
Mean y 0.1924
RMS x 16.99
RMS y 0.516
hSigDiff_Ivanov_1
nhSigDiff_Ivanov_1
Entries 100000
Mean x 79.07
Mean y 0.1907
RMS x 17.02
RMS y 0.5185
CosTheta []
Neutrino kinetic energy [MeV]
nSigInt_0
nSigIntFromDiff_Vogel_1
nSigIntFromDiff_Vogel_Corr_1
nSigInt_Ivanov_1
nSigIntFromDiff_Ivanov_1
nSigInt_Matthieu_1
nSigDiff_Vogel_E_1_CosTheta=0
nSigDiff_Ivanov_E_1_CosTheta=0
nfMeanCosTheta[0]
nfMeanCosTheta[1]_Vogel
nfMeanCosTheta[1]_Ivanov
nfRecoilCorrection
nfWeakMagnetismCorrection
nfRadiativeCorrectionShort
nfRadiativeCorrectionFull
nSigRel_Vogel_1
nSigRel_Vogel_Corr_1
nSigRel_Ivanov_1
nSigRel_Matthieu_1
nfA
nfB