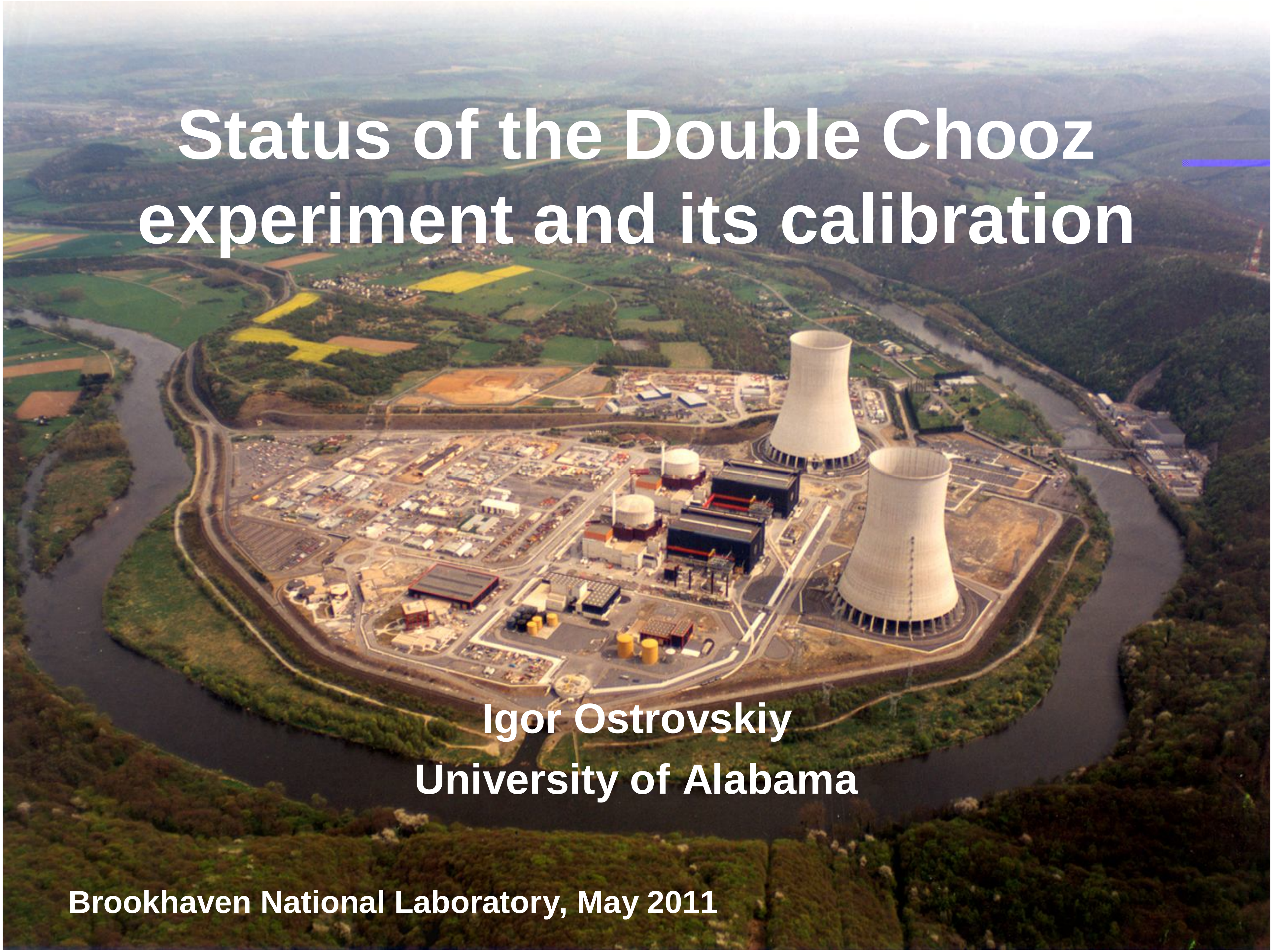


Status of the Double Chooz experiment and its calibration

Igor Ostrovskiy

University of Alabama

Brookhaven National Laboratory, May 2011

Outline

- Introduction
  - Neutrino oscillations
  - θ_{13}
- Double Chooz
  - Concept
  - Sensitivity
- Far detector
  - Design
  - Calibration systems
  - Construction of the far detector
  - First “blessed” plots from commissioning data
- Summary

Introduction: Neutrino

- Results from a number of different experiments – solar, reactor, atmospheric, and accelerator, can be consistently explained assuming that the neutrino has a nonzero mass, and different flavors can mix (neutrino oscillation)

Neutrino	
Composition:	Elementary particle
Family:	Fermion
Group:	Lepton
Interaction:	weak interaction and gravitation
Antiparticle:	Antineutrino (possibly identical to the neutrino)
Theorized:	1930 by Wolfgang Pauli
Discovered:	1956 by Clyde Cowan, Frederick Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire.
Symbol:	ν_e, ν_μ^0, ν_τ^0
No. of types:	3 – electron, muon and tau
Mass:	Nonzero, see Mass below
Electric charge:	0
Color charge:	0
Spin:	½

from Wikipedia

Introduction: Neutrino oscillation

The idea is that neutrinos are observed as flavor eigenstates (ν_l), but propagate as mass eigenstates (ν_i):

$$\nu_l = \sum_i U_{li} \nu_i$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

$$\begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \end{array}$$

If neutrino masses are different from zero, the relative phases of the mass wave functions will periodically change with time, resulting in observable oscillation in flavor

$$P_{ee} = 1 - c_{13}^4 sin^2(2\theta_{12}) sin^2(1.266\frac{\Delta m_{21}^2 L}{E}) - c_{12}^2 sin^2(2\theta_{13}) sin^2(1.266\frac{\Delta m_{31}^2 L}{E}) - s_{12}^2 sin^2(2\theta_{13}) sin^2(1.266\frac{\Delta m_{32}^2 L}{E})$$

Introduction: Oscillation Parameters

Oscillations depend on the mass squared differences and the mixing angles

Only upper limit is known on θ_{13} (CHOOZ, Palo Verde)
The CP violating phase (δ) is completely unknown.
$\sin^2(2\theta_{13})$ ~<0.15 90% C.L. CHOOZ
though $\sin^2(2\theta_{13}) = 0.036^{0.051}_{0.028}$ (global analysis by KamLAND, Oct'10)

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric oscillations
Measured by K2K, SK, Minos.
$|\Delta m^2_{31}| = (2.43 \pm 0.13) \cdot 10^{-3}$ eV^2,
$\sin^2(2\theta_{23}) > 0.95$

Solar oscillations
Measured by solar experiments (Homestake, SAGE, GALLEX/GNO, SNO) and KamLAND
$\Delta m^2_{21} = (7.59 \pm 0.21) \cdot 10^{-5}$ eV^2,
$\tan^2(\theta_{12}) = 0.457^{+0.04}_{-0.029}$

Introduction: θ_{13}

- It is important to improve our knowledge of θ_{13}
  - to complete our understanding of neutrino oscillations
  - to see if we can measure CP violation in the foreseeable future
- Increasing sensitivity for θ_{13} is possible using reactor neutrinos and accelerator neutrino beams
- The reactor measurement has the following advantages over the accelerator beams:
  - no ambiguity from matter and CP violation effects
  - smaller costs and faster time scale

Double Chooz: The concept

1. The Chooz-B nuclear power plant (France) emits ~ 10^{21} electron antineutrinos per second
2. Detect the neutrinos with *two* detectors through the inverse β-decay reaction:

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

3. Instead of comparing measured rate/spectrum with calculated ones, based on reactor information (CHOOZ approach), compare the data between the Far and the Near detector
4. Analyze the (hopefully!) observed deficit of neutrinos in the far detector in terms of neutrino oscillations:

$$P_{ee} = 1 - sin^2(2\theta_{13}) sin^2(1.266 \frac{\Delta m^2_{atm} L}{E})$$

After 3 years of data taking, the sensitivity down to $\sin^2(2\theta_{13}) < 0.03$ can be achieved

Double Chooz: The challenge

- To reach the claimed sensitivity several conditions have to be met:
  - Small systematic error
    - Major reduction comes from using the relative calibration of the neutrino flux (near detector) instead of the absolute one
    - Additional reduction by using fewer selection cuts and using same batch of the scintillator for both detectors to cancel error on the number of free protons
  - Increased statistics
    - Both far and near detectors will have twice the sensitive volume of CHOOZ, hence increased event rate
    - More stable formulation of Gd loaded scintillator will allow to run the experiment longer
  - Low background
    - Special consideration is given to avoid high background rates, so the errors on additional selection cuts and background subtraction can be avoided/reduced
- While the main advantage comes from using two detectors to cancel reactor related systematics, the far only phase can improve on the current best limit (CHOOZ) in just a few months of data taking

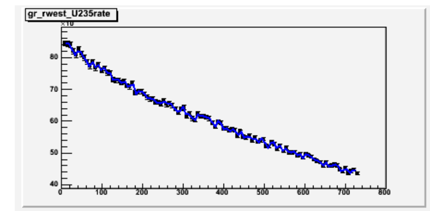
Systematic errors

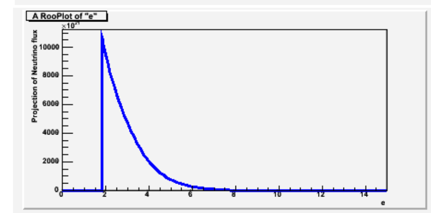
Error %	CHOOZ	Double Chooz
Reactor		
Production cross section	1.9	
Core power	0.7	
Energy per fission	0.6	
Solid angle/Barycenter		0.07
Detector		
Detection cross section	0.3	
Target mass	0.3	0.2
Target free H fraction	0.8	
Dead time (electronics)	0.25	
Analysis		
positron fiducial cut	0.1	
positron energy cut	0.8	0.1
neutron fiducial cut	0.1	
neutron capture (% Gd)	1.0	0.3
neutron energy containment	0.4	0.2
inter-event time	0.4	0.1
inter-event distance	0.3	
neutron multiplicity	0.5	
Total	2.7	<0.6

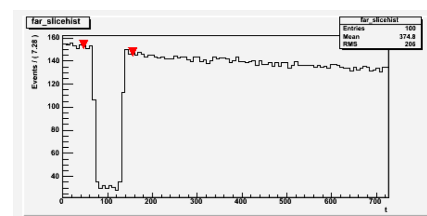
Few words on reactor errors

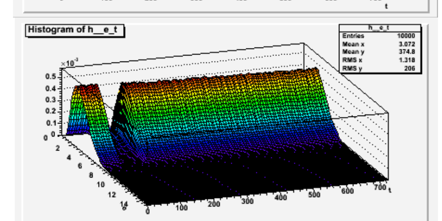
$$S(E_\nu) = \sum_i^{\text{isotopes}} f_i \left(\frac{dN_{\nu i}}{dE_\nu} \right)$$

- Reactor systematics, what's in there?
  - Individual fission rates
    - four isotopes dominate neutrino production
    - evolve with time ("burn-up"), correlated with each other
    - calculated by reactor agency's (EdF) MC codes
  - Total thermal power
    - overall energy constraint on fissions from all fissile isotopes
    - most accurate measurement done through heat balance
    - uncertainty of ~0.4-0.7% and better is possible, but depends on details (type of flow meters used by EdF etc.)
  - Anti-neutrino spectrum from each isotope
    - ILL accurately measured β-spectra following fission of 3 isotopes
    - 1.9% normalization error, few % energy dependent error





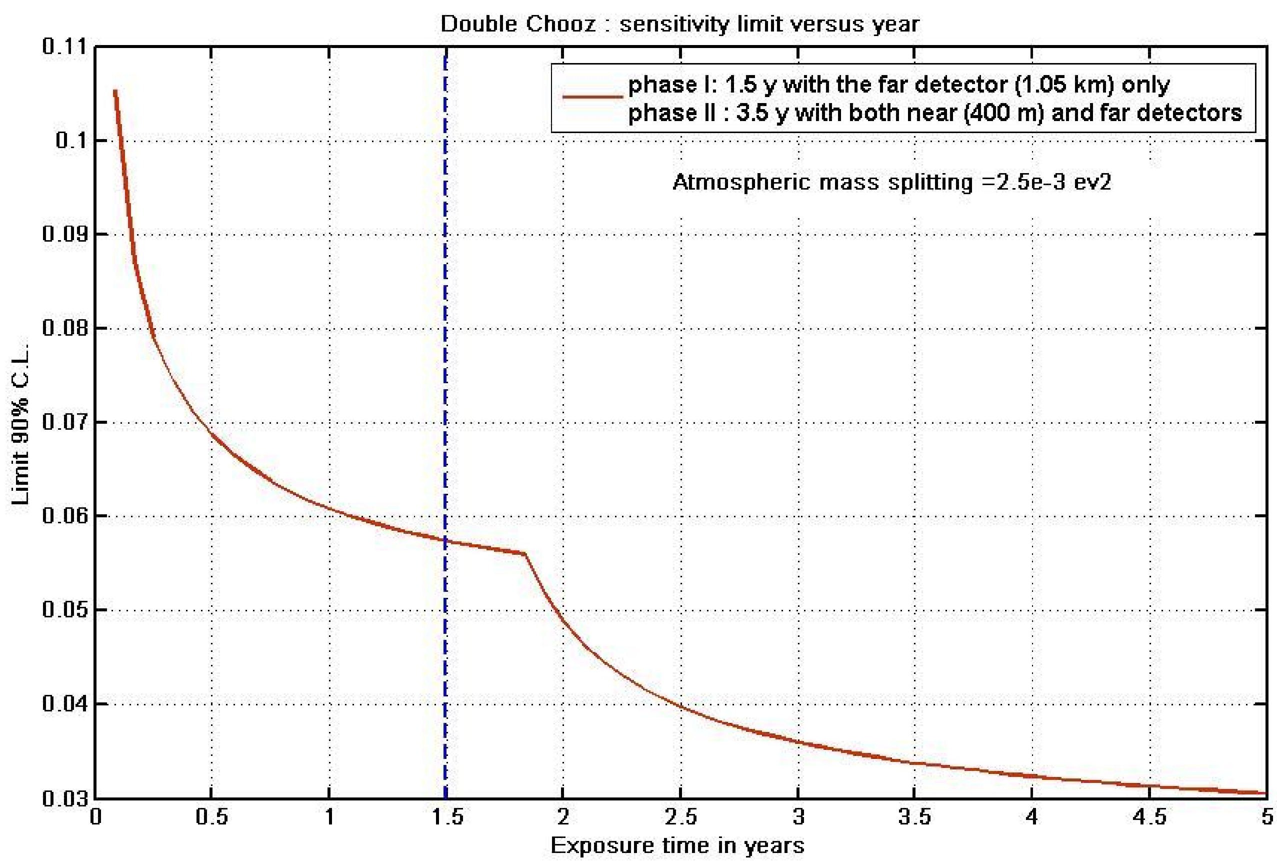




Few words on reactor errors

- Dominant uncertainty for far only phase
- Additional ambiguity stemming from recent re-evaluation of conversion procedure – “reactor anti-neutrino anomaly” arXiv:1101.2755v4

Double Chooz: the sensitivity timeline

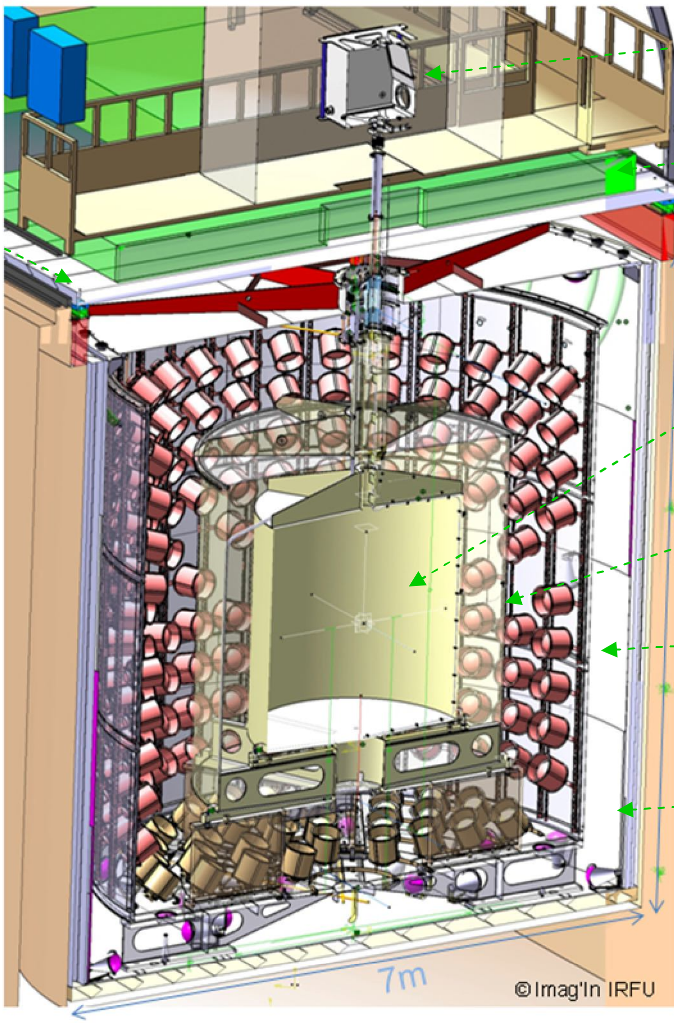


far/near detectors, reactors

Two twin pressurized-water reactors
Highest power yield in their class – 4.25GWth, 1.5GWe
Total thermal power produced by each core is carefully and constantly monitored

Far detector: Design

15cm steel shield



calibration glove box

outer veto plastic panels

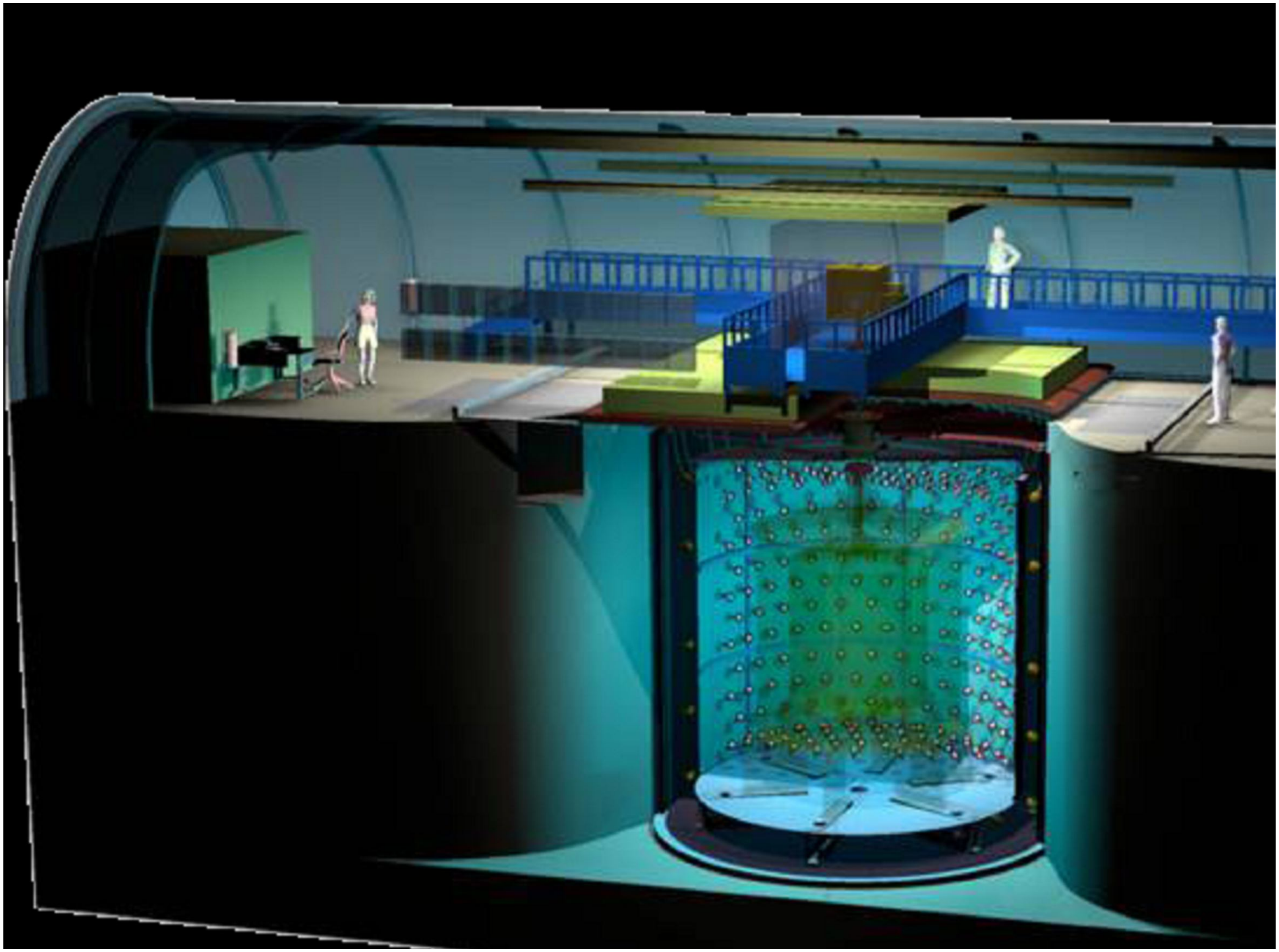
target volume 10.2m^3
Gd loaded liquid scintillator

gamma catcher (GC) 23m^3
liquid scintillator

buffer 110m^3 + 390 PMTs
non-scintillating oil

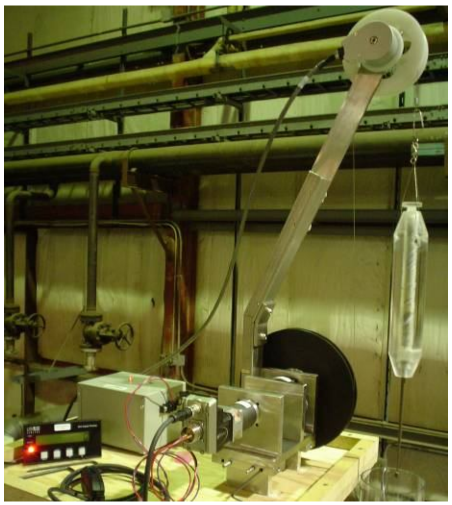
inner veto 90m^3 + 78 PMTs
liquid scintillator

Far lab

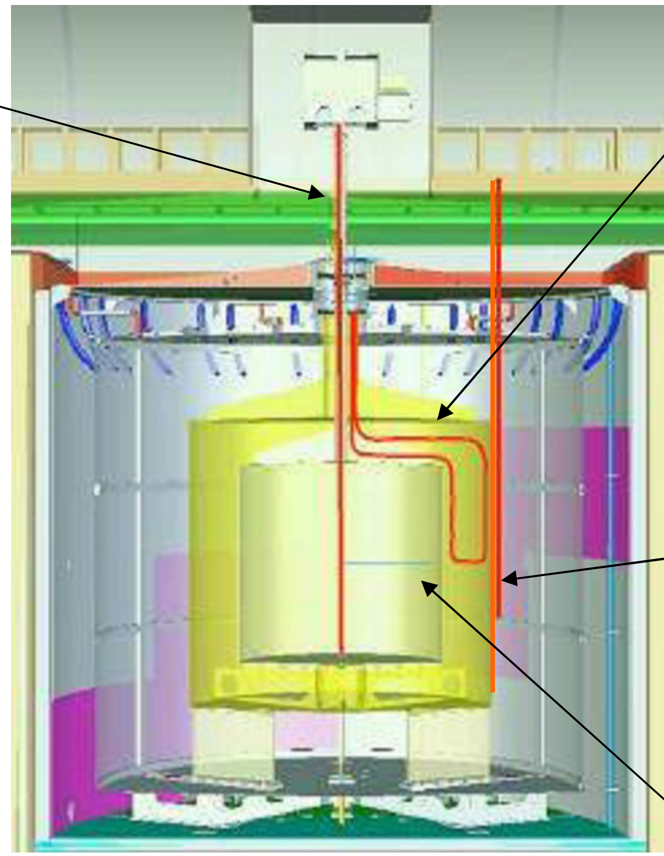


Far detector: Calibration systems

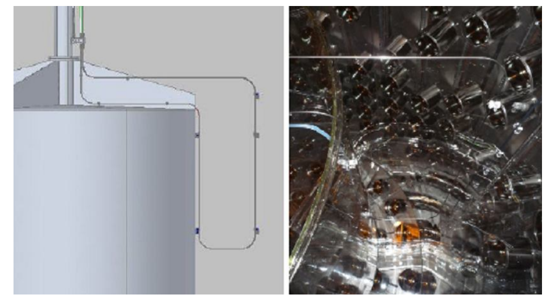
Z-axis fish line



Target volume
• Tagged Cf-252 and untagged gamma and neutron sources
• Laser ball and LED flasher

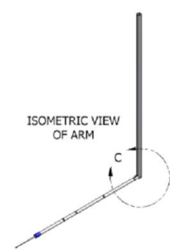


Gamma-catcher guide tube



• Untagged gamma and neutron sources

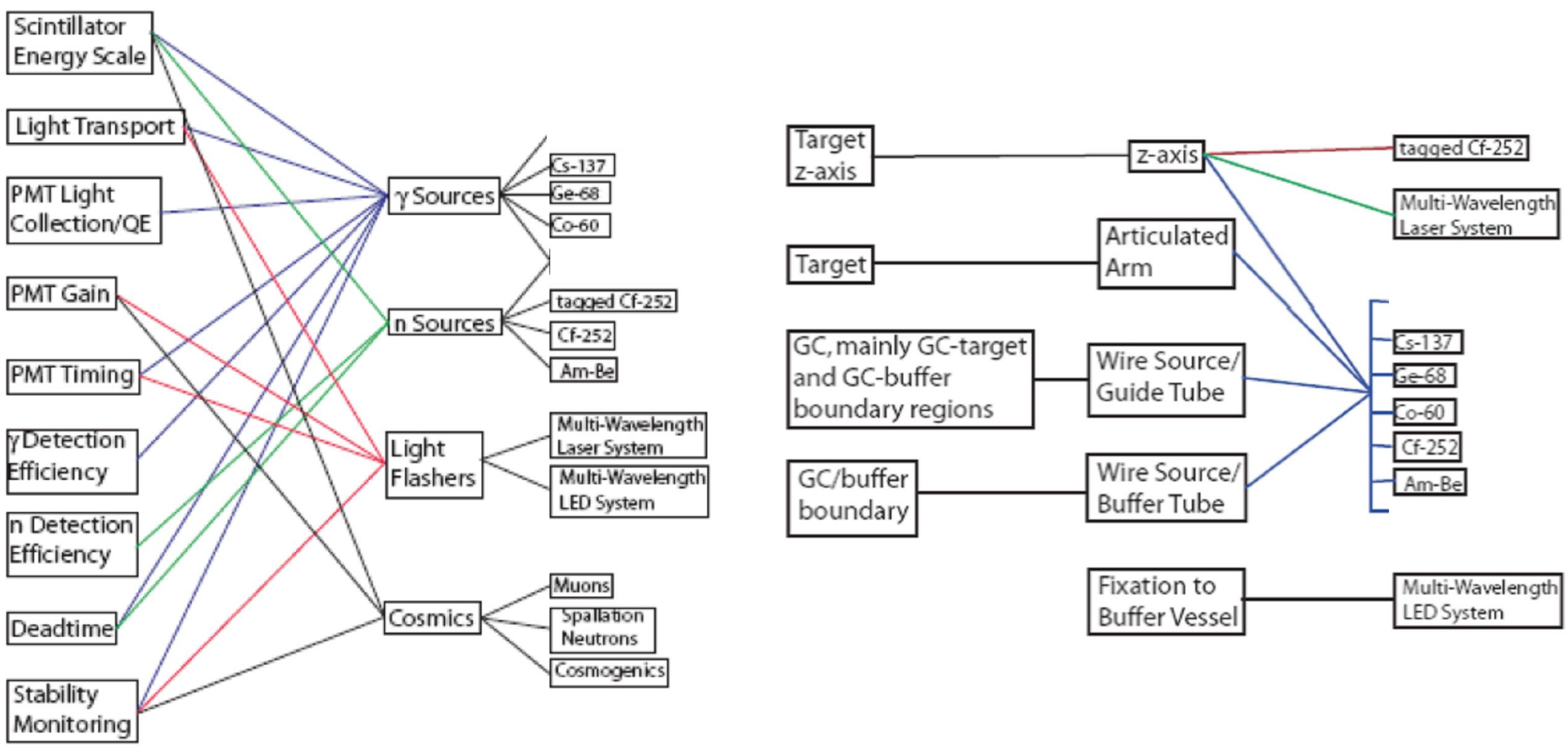
Buffer tube



Articulated arm

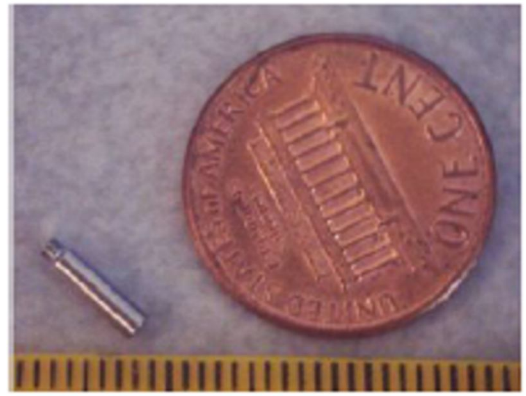
Also: Embedded LED systems in Buffer and Inner Veto

Calibration tools



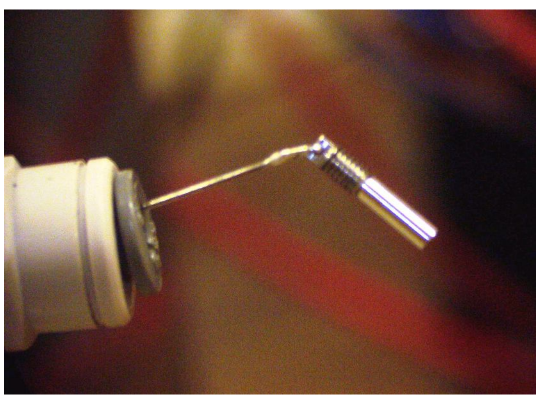
Untagged sources

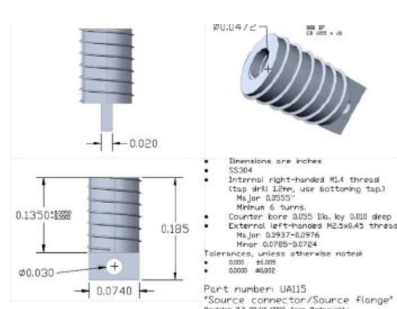
- Double encapsulated
- Leak-tested to ISO standards
- 2mm diameter outer capsule
    - low absorption/shadowing
    - possibly smallest composite neutron source (AmBe)
- Same source can be deployed with any system in both detectors



DC untagged source
ruler notches are mm

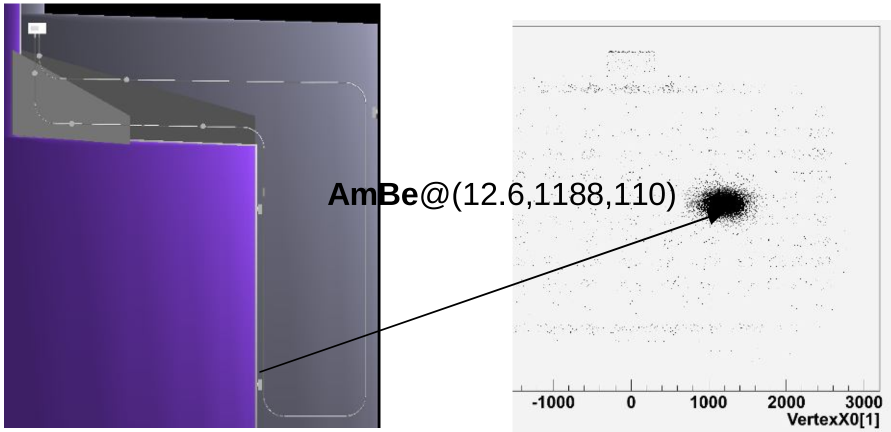
AmBe inner
capsule (tungsten)

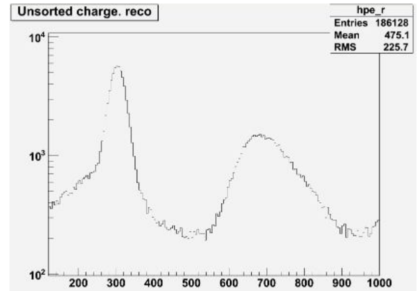


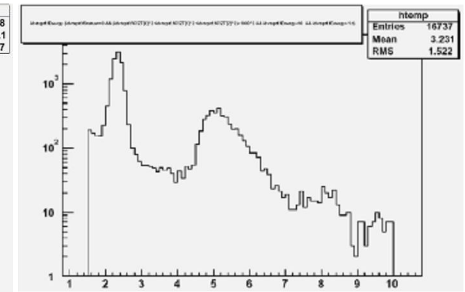


Source MC

Separated at thesis defense?



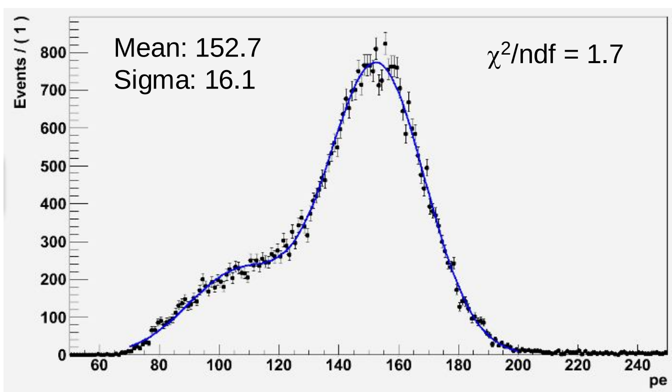


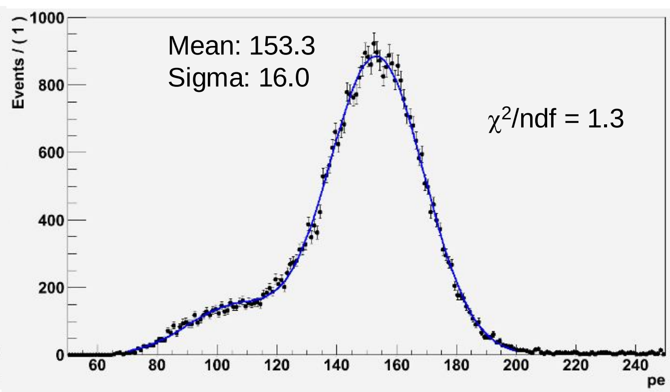


DC Monte-Carlo

E.A. Yakushev, N. Tolič, M. Koga and T. Classen
Report on KamLAND calibration with AmBe source. August 3/2003

Capsule **Ge-68**@(12.6,1188,110) No Capsule





Sum of two Crystal Ball shapes

0.39±0.17% shift in peak position

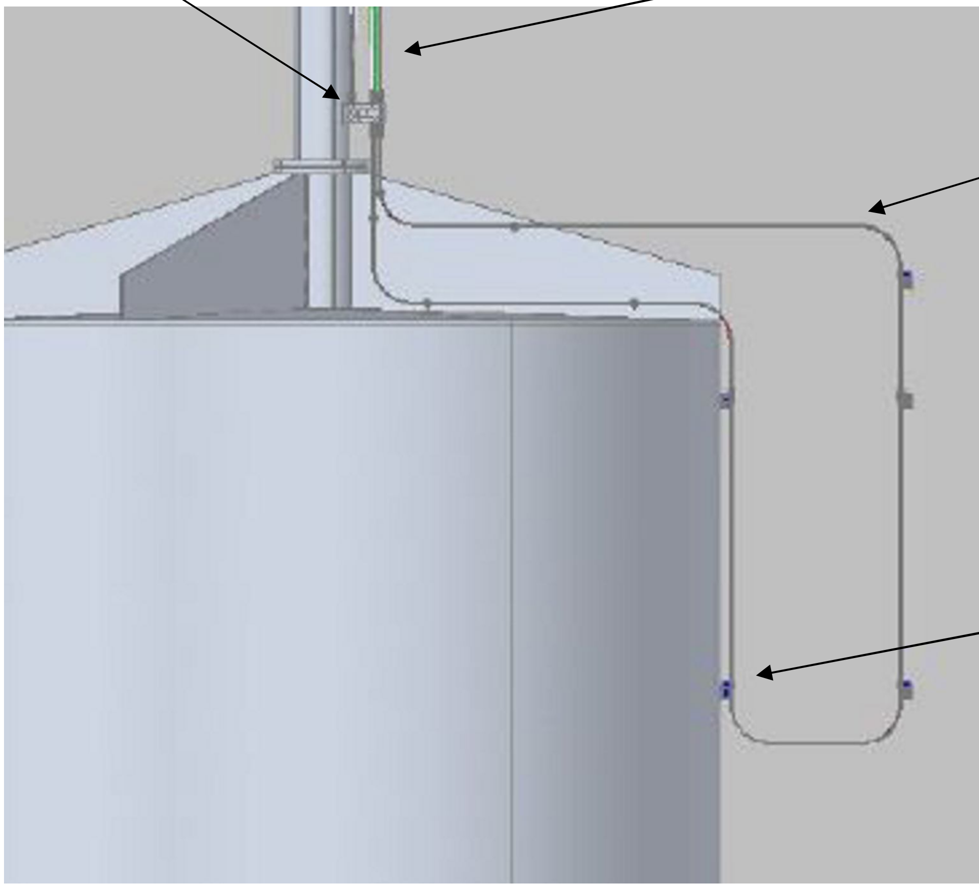
The guide tube system

- The guide tube (GT) is a calibration system allowing deployment of radioactive sources in the gamma catcher region (GC)
- The GT is an embedded system. Its integration with the acrylic vessels is a difficult task posing significant risk to the experiment
- The design of the guide tube should be highly reliable and address the risks associated with deploying radioactive sources inside the detector, and at the same time provide as little “disturbance” to the physics (absorption/shadowing) as possible

The guide tube system

Sensor box improves positioning by providing zero/scale calibration for encoders

Teflon “inner sleeve” guarantees smooth transitions of a source through the interfaces, provides “last resort” disaster recovery option



Snapshot from the CAD model shows the guide tube attached to the target vessel

SS304 outer tube provides safe rigidity, mechanical stability, minimum occupied volume and shadowing. Chemically compatible with the scintillator

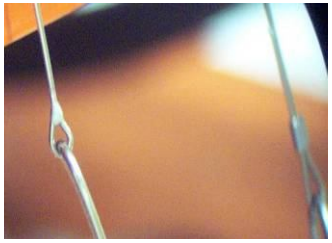
Looped shape allows disaster recovery option by pushing the loose source through

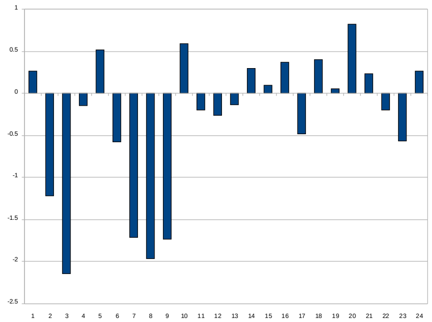
Few acrylic fixations provide interface with the acrylic vessels.

Full scale prototype

• A full scale prototype was built at the UA and operated for >1yr to develop, test, and practice all aspects of design, installation, and operation of the system

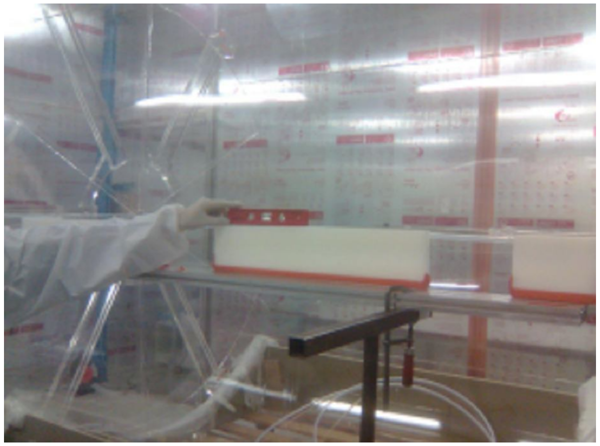
Various tests were performed to address different aspects of GT operation – chemical compatibility with scintillator, mechanical stresses, radiopurity, disaster recovery





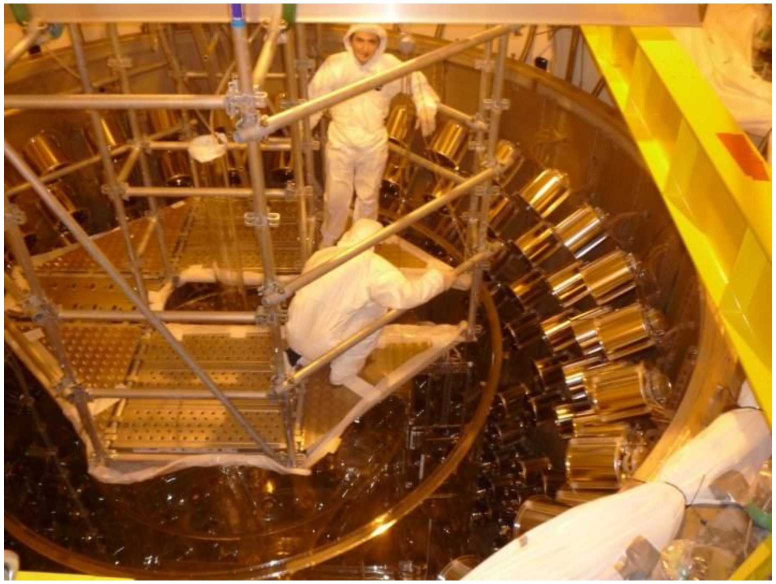
Difference between capsule position as derived from survey+code and wire driver encoders. Y – difference, mm, X – hole number. Average = -0.31mm, RMS = 0.85mm

Installation



Fixtures were glued to the Target vessel under UA supervision at the manufacturer facility in Bussang, France

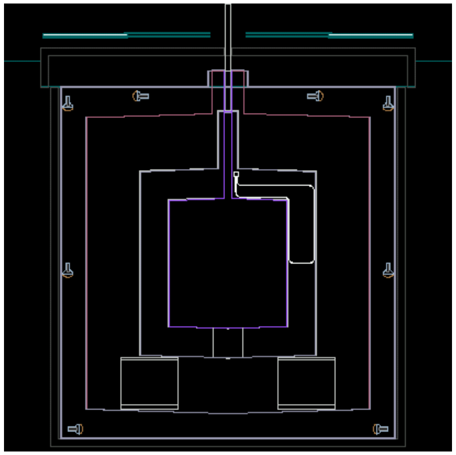
An *ad-hoc* clean tent (measured to be ISO 7) was set up for the assembly of the tube near the far site



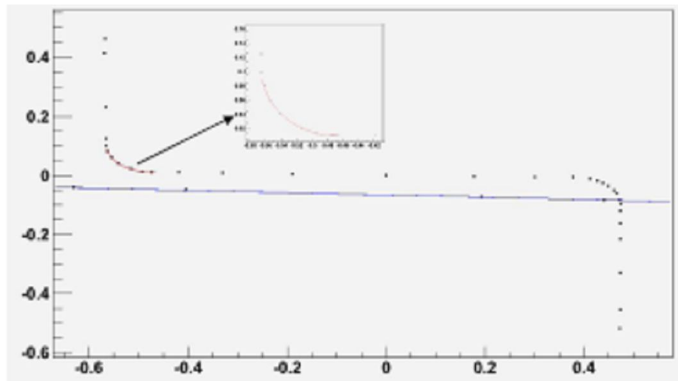
The guide tube was successfully integrated into the far detector, fall 2009

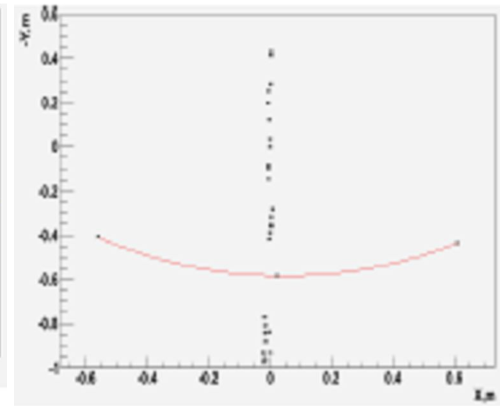
Guide tube in the far detector

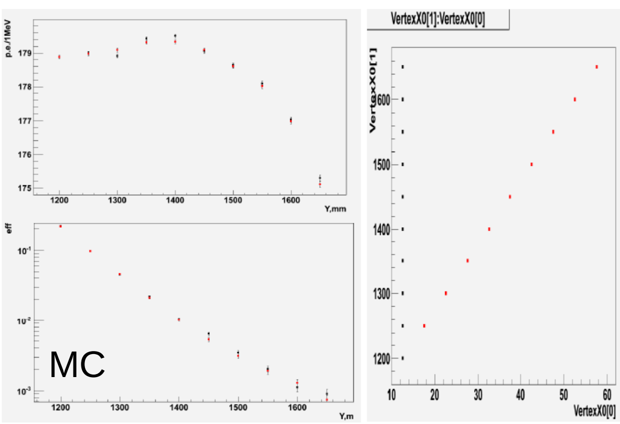
MC



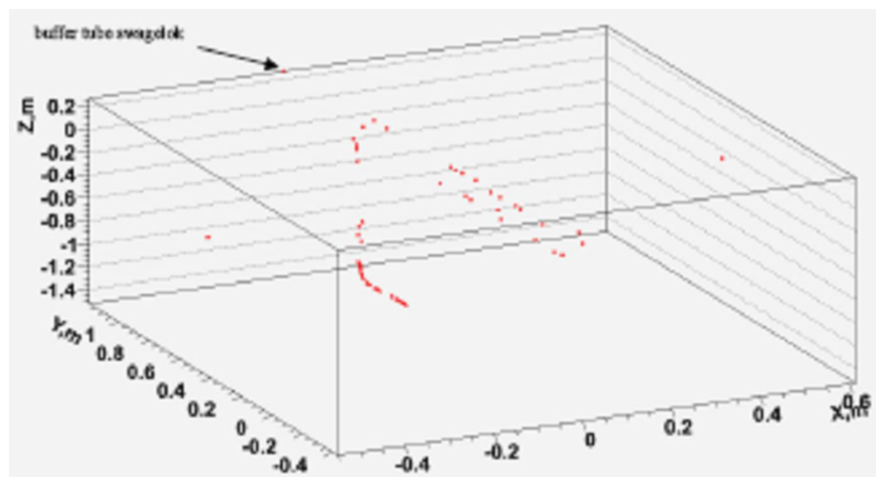
Reality







Effect of non-planarity is negligible



Far detector in pictures

Down the tunnel, Fall 2008

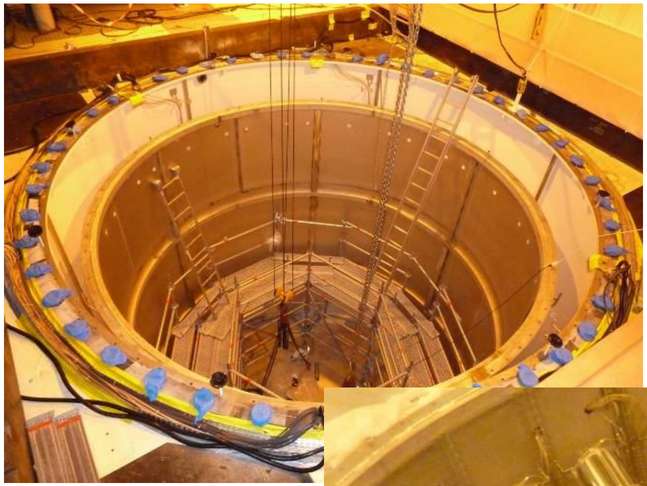
Lab before installation

Inner Veto in the pit

Inner veto PMTs

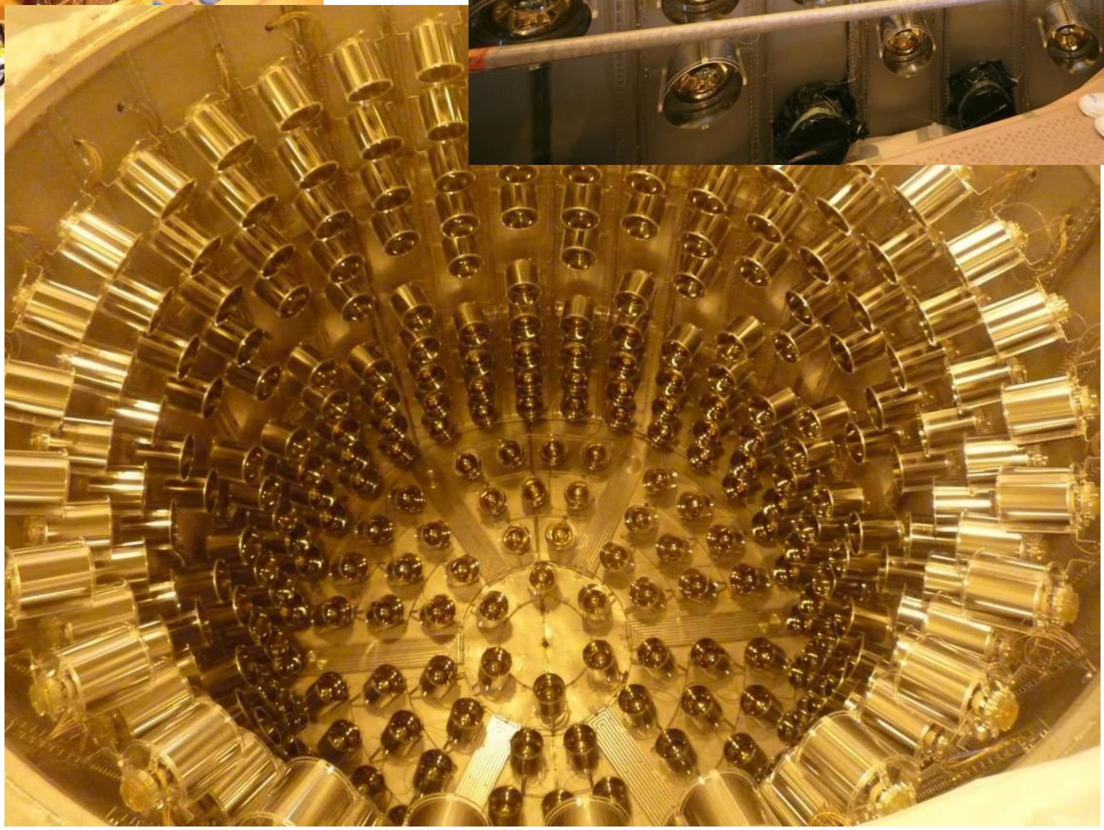
Jan-Feb 2009

Lab cleaning and installation of ISO7 clean tent before veto PMTs integration



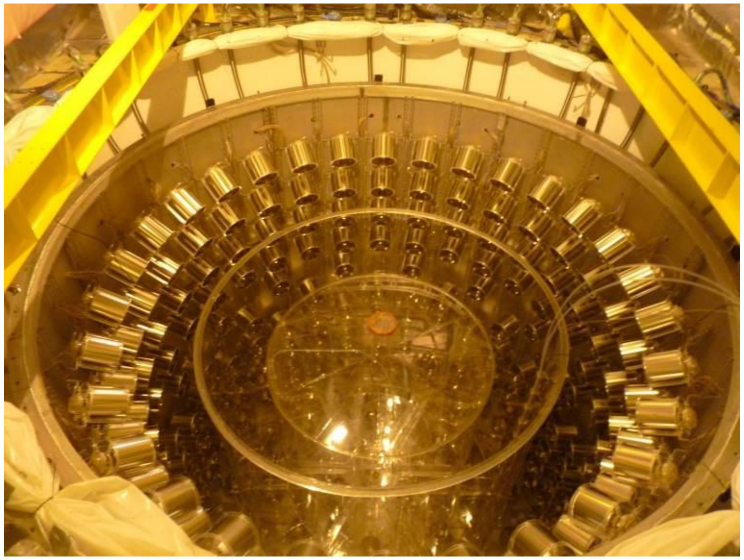
June-July 2009

Buffer vessel
and ID PMTs



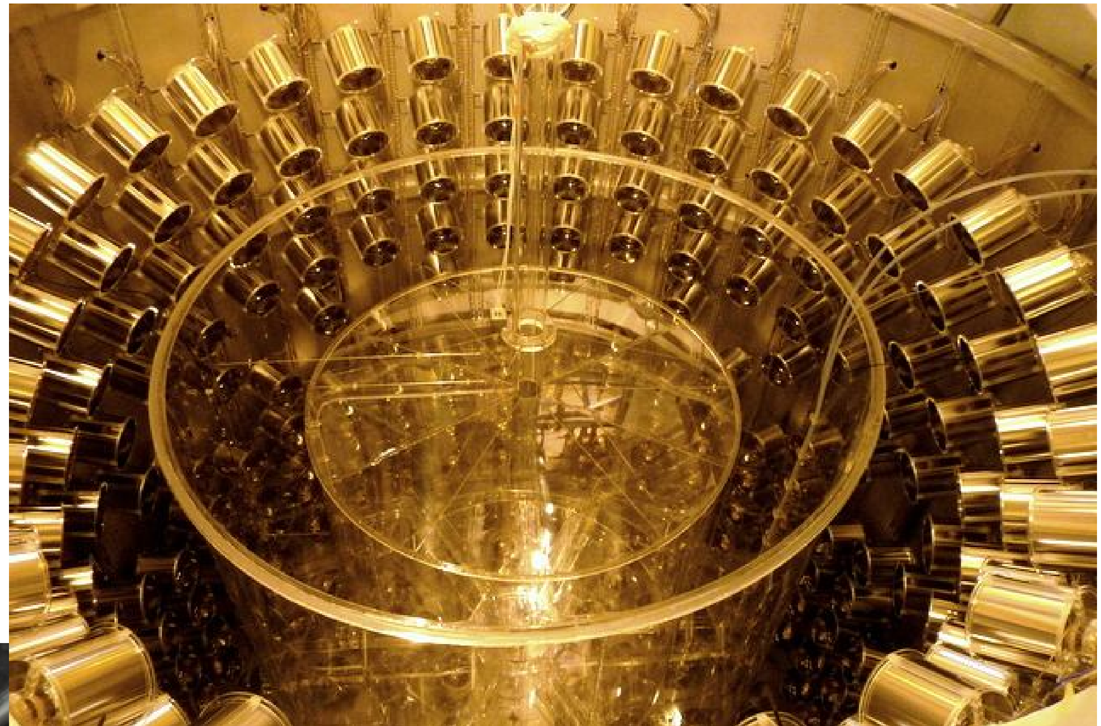
Gamma-Catcher

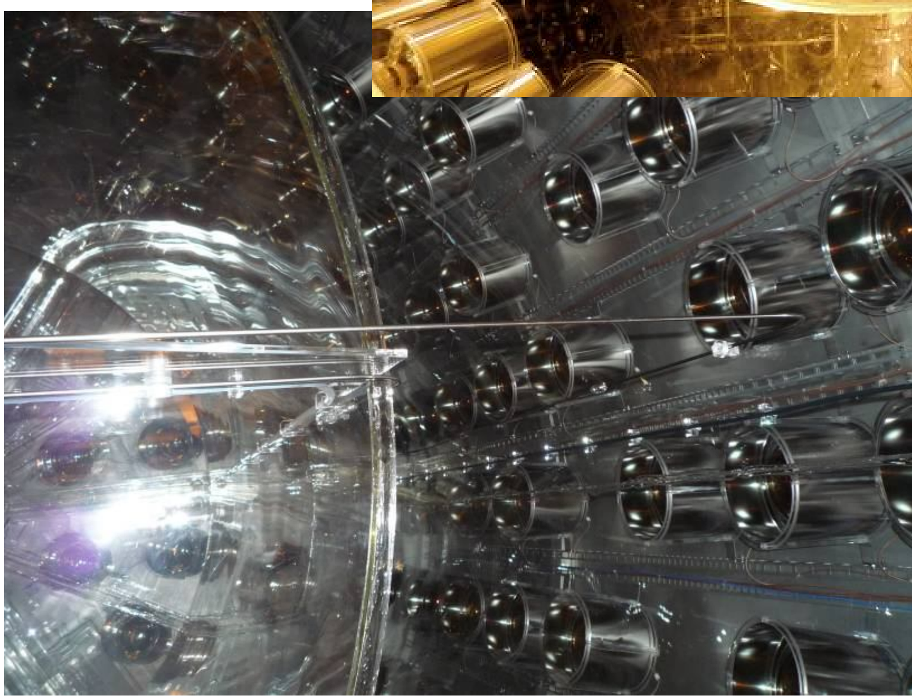
Gamma-catcher integration. Fall 2009

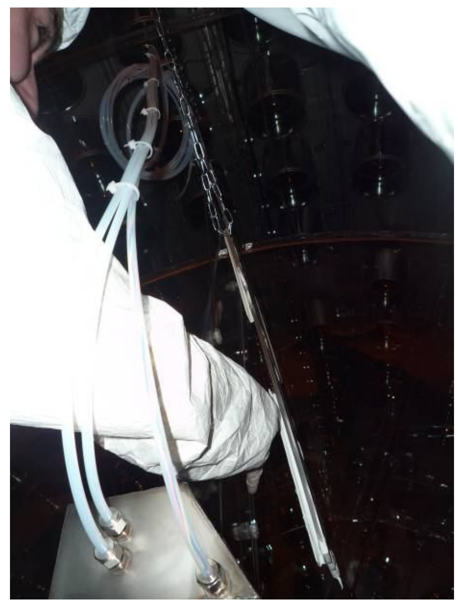


Target installed

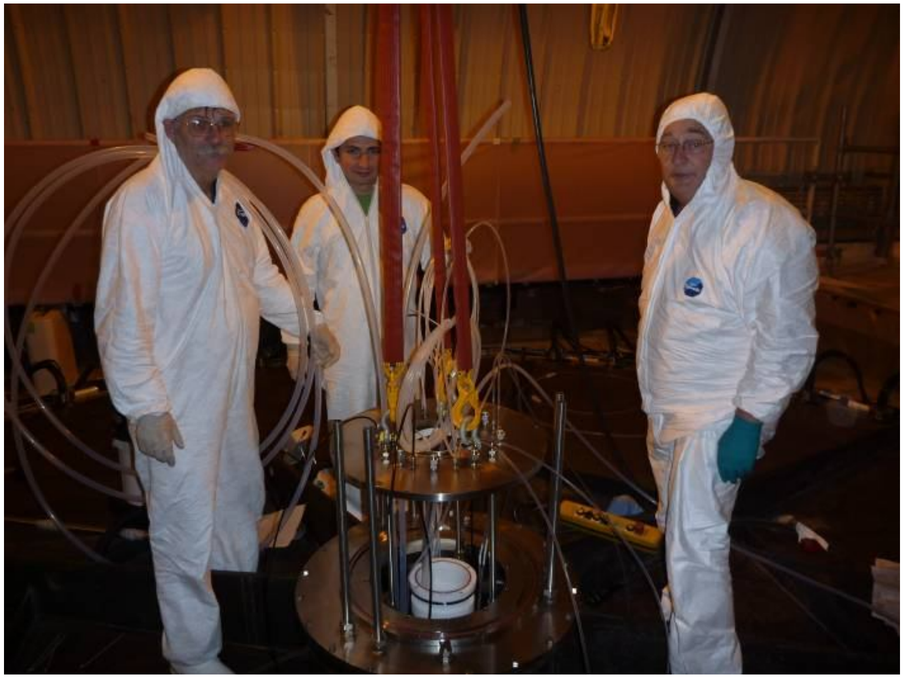
Guide tube integrated







Buffer lid closing



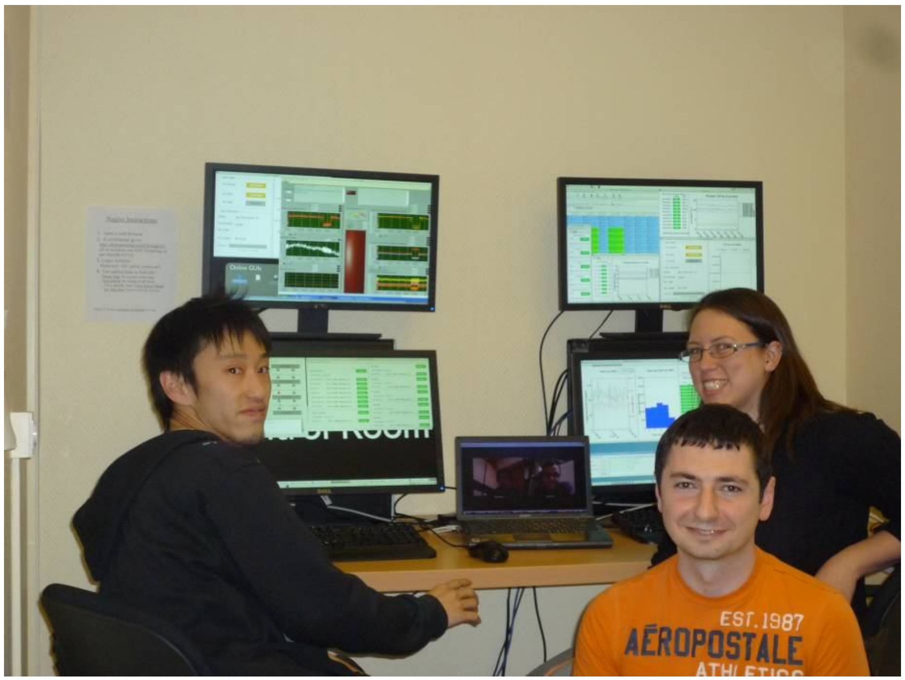
Closing the gamma-catcher flange

Inner veto closed

Top shielding installed. Dec 2010

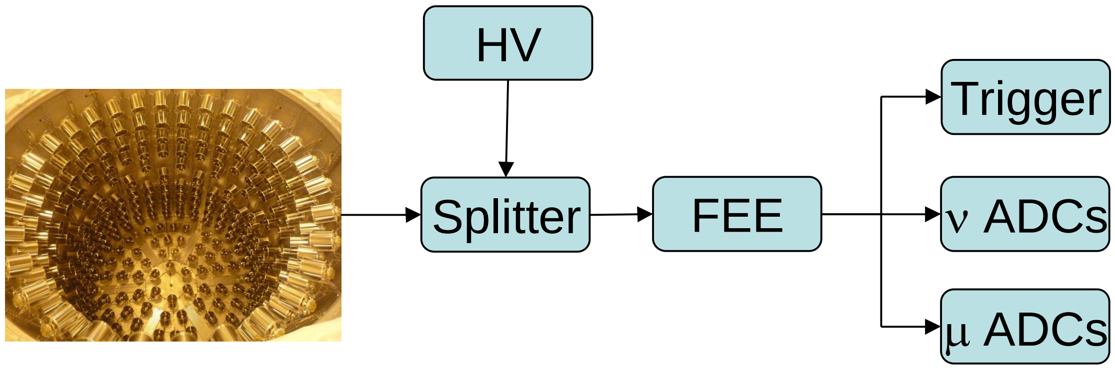
Far detector closed and filled end of 2010

Far detector is On-line

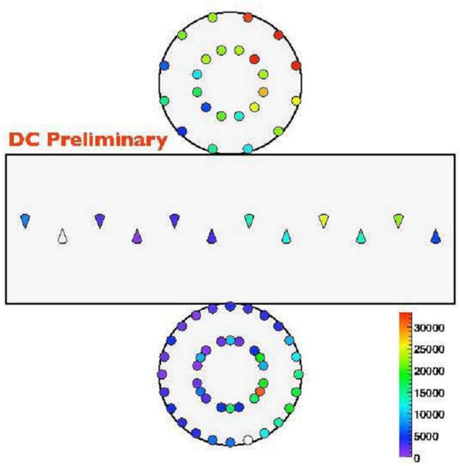


"DC is now officially running and accumulating neutrinos as we speak
Our first run...
Date: 18:00 13/4/2010.
RunNumber 11000.
Shifters: Herve, Masaki, Anatael, Junpei, Igor, Erica.
Comment: First Neutrino Physics Run of DC ..."

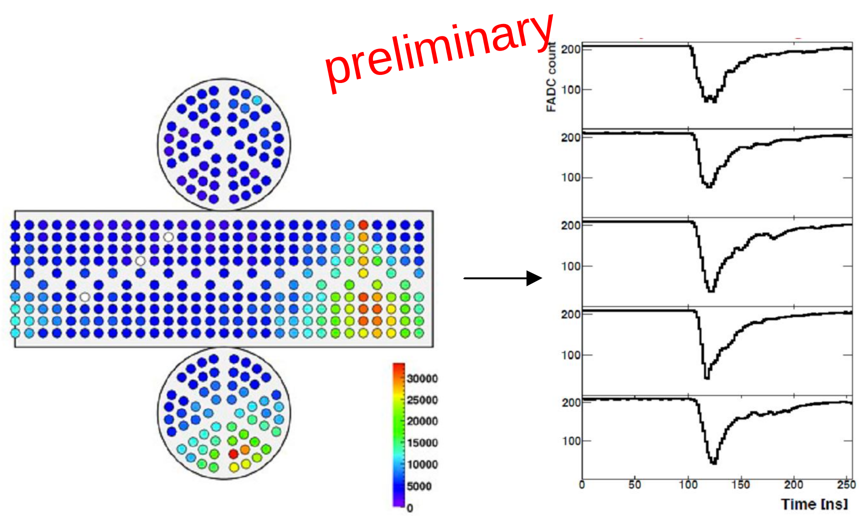
Far detector *is* On-line



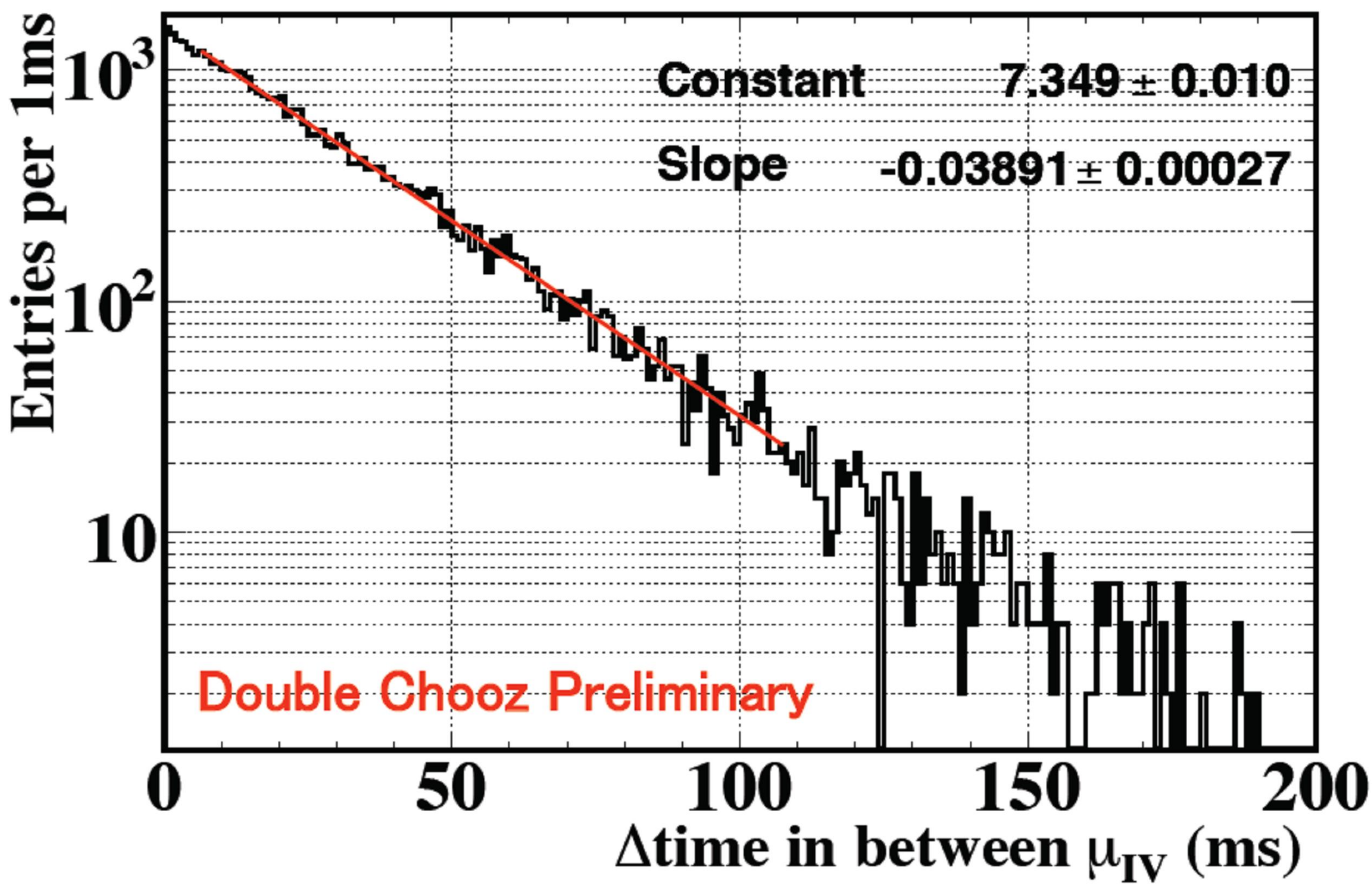
Muons on the event display



Inner Veto



Inner Detector

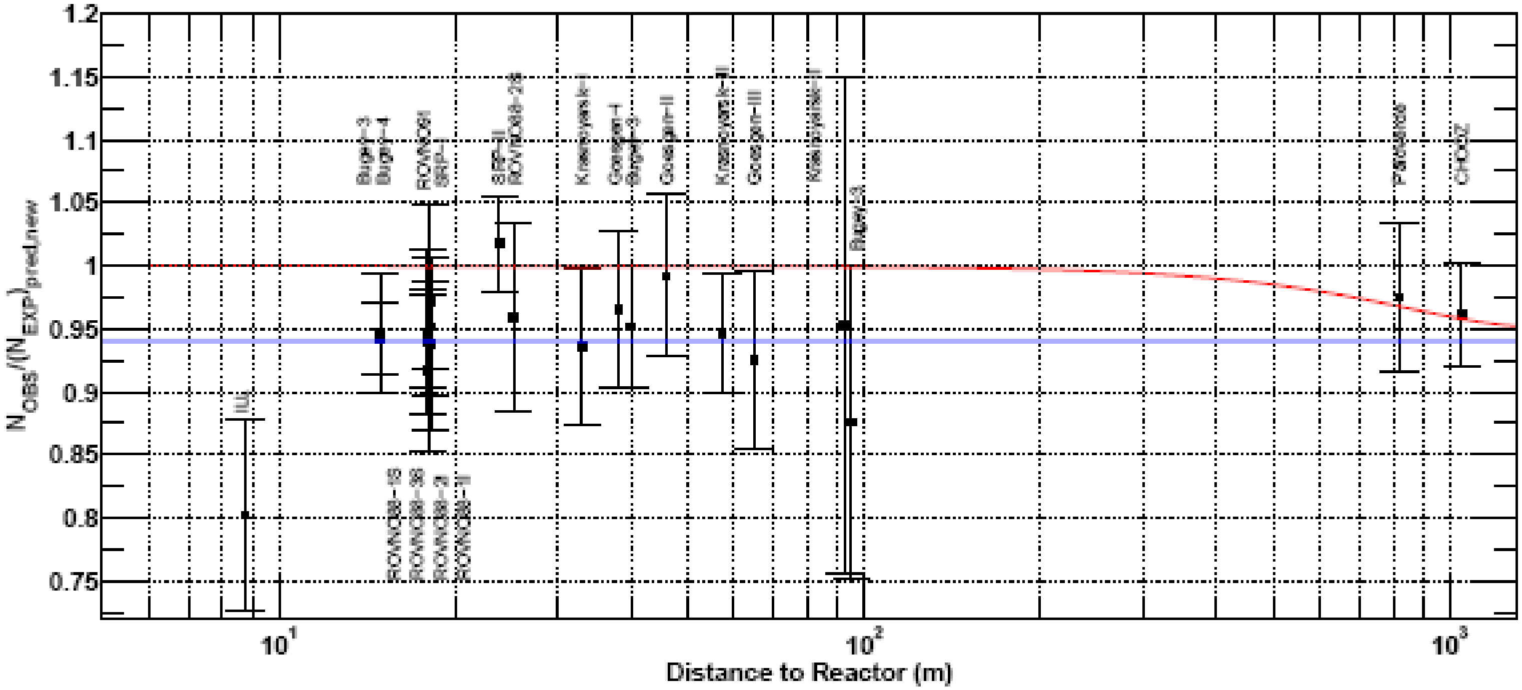


Entries per 1ms
10³
10²
10
Constant 7.349 ± 0.010
Slope -0.03891 ± 0.00027
Double Chooz Preliminary
0
50
100
150
200
Δtime in between μ_IV (ms)

Bottom line

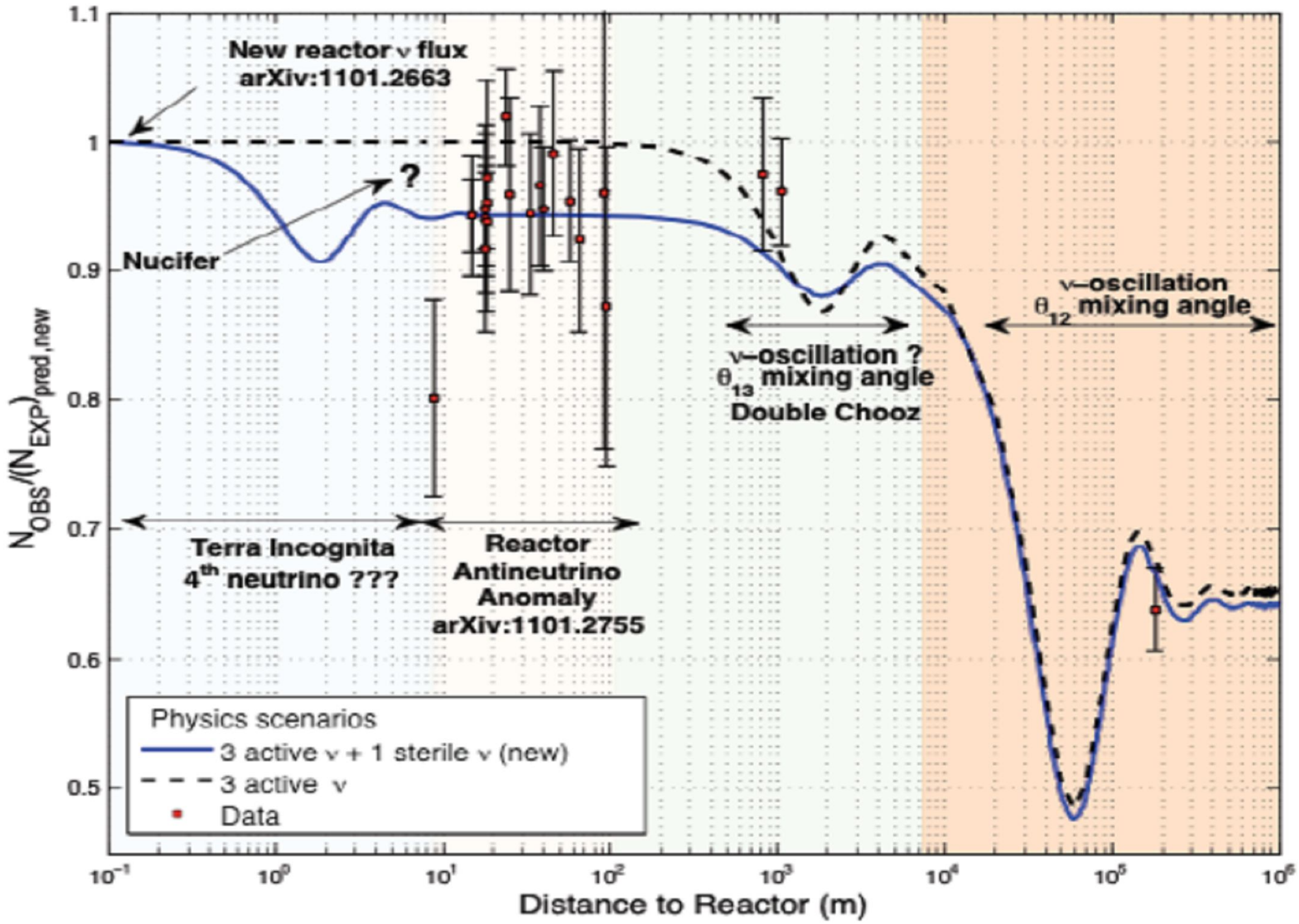
- Far detector is assembled, filled
  - OV panels are being put right now, but does not affect first data
- Online commissioning is complete and first physics run has started
  - expect fist result soon!
- Near detector should be on-line before end of 2012

Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
Double Chooz		Rate (d^{-1})	0.1 ± 0.1	0.3 ± 0.2	0.11 ± 0.11	< 0.1	1.0 ± 0.5
(69 ν/d)	Far	bkg/ν	0.1%	0.4%	0.2%	< 0.1%	1.4%
		systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.7 ± 0.9	0.15 ± 0.15	0.4	9 ± 5
(1012 ν/d)	Near	bkg/ν	< 0.1%	0.2%	< 0.1%	< 0.1%	0.9%
		systematics	<0.1%	<0.1%	<0.1%	<0.1%	0.5%



arXiv:1101.2755v4
Reactor anti-neutrino anomaly

The 4th Neutrino Hypothesis: need new experimental inputs !



- Experiments with baselines > 500 m
- How do you normalize the expected flux, knowing the fuel composition?

  in this slide assume Bugey-4 fuel comp.
- If **near + far detector**, **not an issue** anymore

Choices

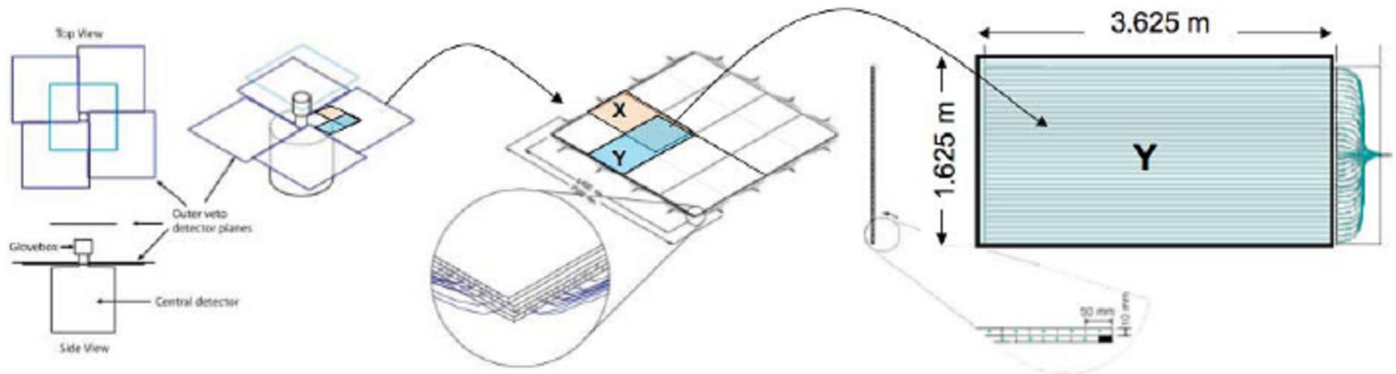
- σ_f^{pred}
  - Use $\sigma_f^{pred,new}$ =6.102 10^{-43} cm^2/fission ± 2.7%
  - Use $\sigma_f^{pred,old}$=5.850 10^{-43} cm^2/fission ± 2.7%
- σ_f^{exp}
  - Use σ_f^{exp} Bugey-4=5.750 10^{-43} cm^2/fission ± 1.4%

    Chooz's choice: use lower error (total 2.7% instead of 3.3%)

    Bugey-4 is a kind of "near detector" for Chooz
  - Use $\langle\sigma_f^{exp}\rangle=\sigma_f^{ano}$=5.39 10^{-43} cm^2/fission ± 1% (?)

    Average over short-baseline expts.

Outer Veto System



OV design for near detector consists of upper and lower tracking planes

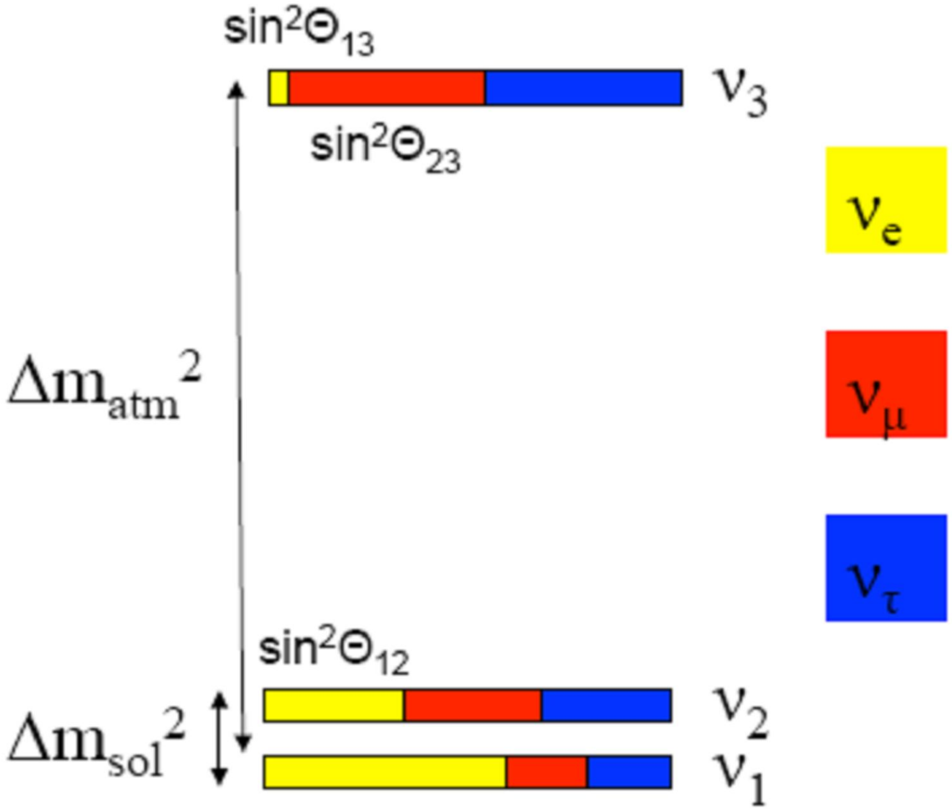
Each plane is fully active and consists of modules oriented in both X and Y directions

OV modules consist of 2 layers of 64 scintillator strips with WLS fibers connected to a multi-anode PMT

Full-scale OV module prototype

Electronics

From presentation by Z.Djurcic



sin²Θ₁₃
ν₃
sin²Θ₂₃
νe
Δm_atm²
νμ
ντ
sin²Θ₁₂
ν₂
Δm_sol²
ν₁