STEREO

Sterile neutrinos search at the ILL reactor

An update for the ENIGMASS plenary meeting Nov.2013

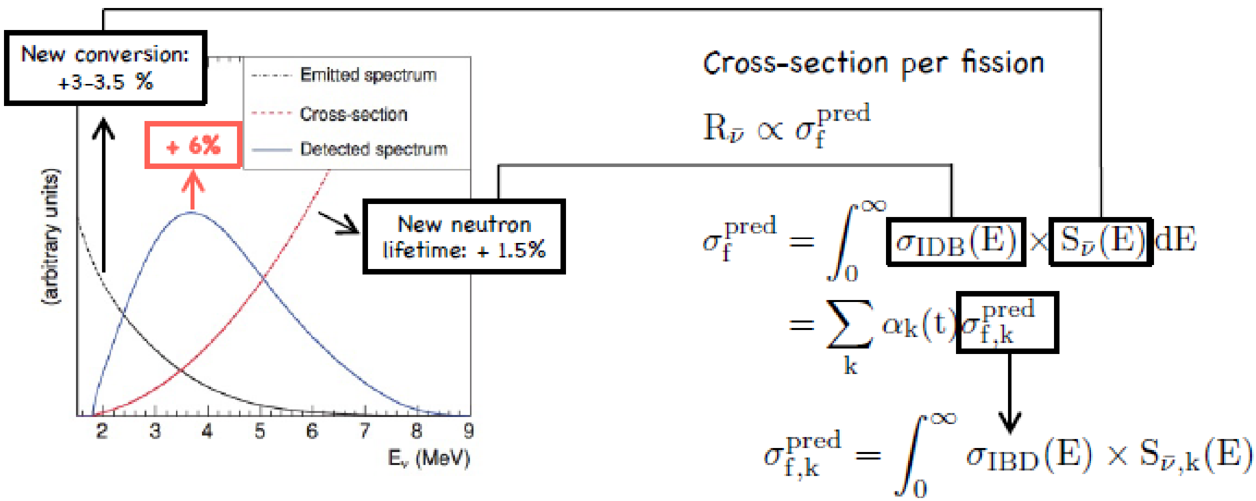
LPSC : S. Kox, J. Lamblin, F. Montanet, J.S Réal, A. Stutz, S.Zsoldos(PhD), postdoc Enigmass under selection

LAPP : P. Del Amo Sanchez, H. Pessard, L.Manzanillas (PhD)

Scientific Context

- Revision of cross-section per fission : impact on predicted rates
  - New b to n conversion: $+3 - 3.5\ \%$ (using spectra measured at ILL, Shrekenbach et al. 1982,85,89)
  - off-equilibrium corrections: $+\ 1\%$
  - New neutron lifetime, (measured at ILL : PDG 2011)

    $\tau_n = 881.5 \pm 1.5\ s$ à $\sigma_{IBD} \approx \frac{1}{\tau_n}$: $+1.5\ \%$



- **Increased predicted neutrino flux by 3 to 6%**

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Scientific Context

Enigmass
The enigma of mass

- Revisiting 19 experiments at L ≤ 100 m
  - Normalization accounting for core composition
  - Dealing with correlations between experiments

  Deficit : R= 0.927 ± 0.023

è **RAA is a 3 σ effect** Mention et al. 1101.2755

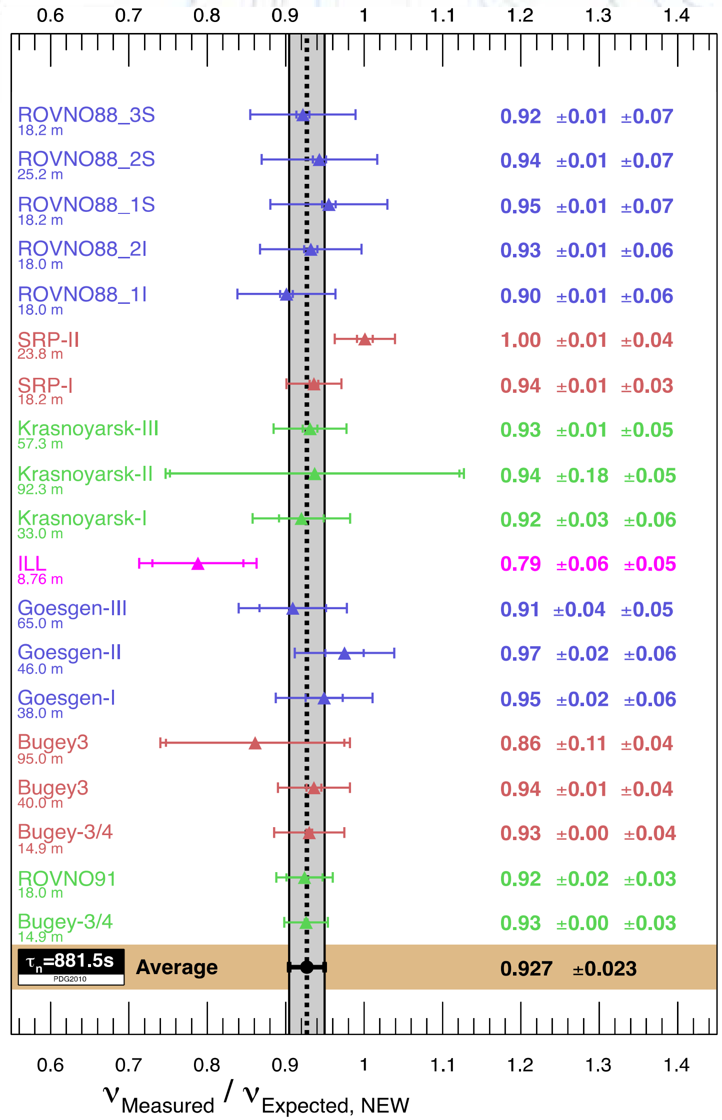
Recent update accounting for km-baseline expts
and new theta13 from DayaBay
Deficit : R= 0.938 ± 0.024

è **RAA is still significant 2.7 σ effect.**

+ other hints : Ga source calibration + etc…

- Possible explanations:
  - Bad luck with Statistics?
  - Common bias in flux prediction?
  - Common experimental bias?

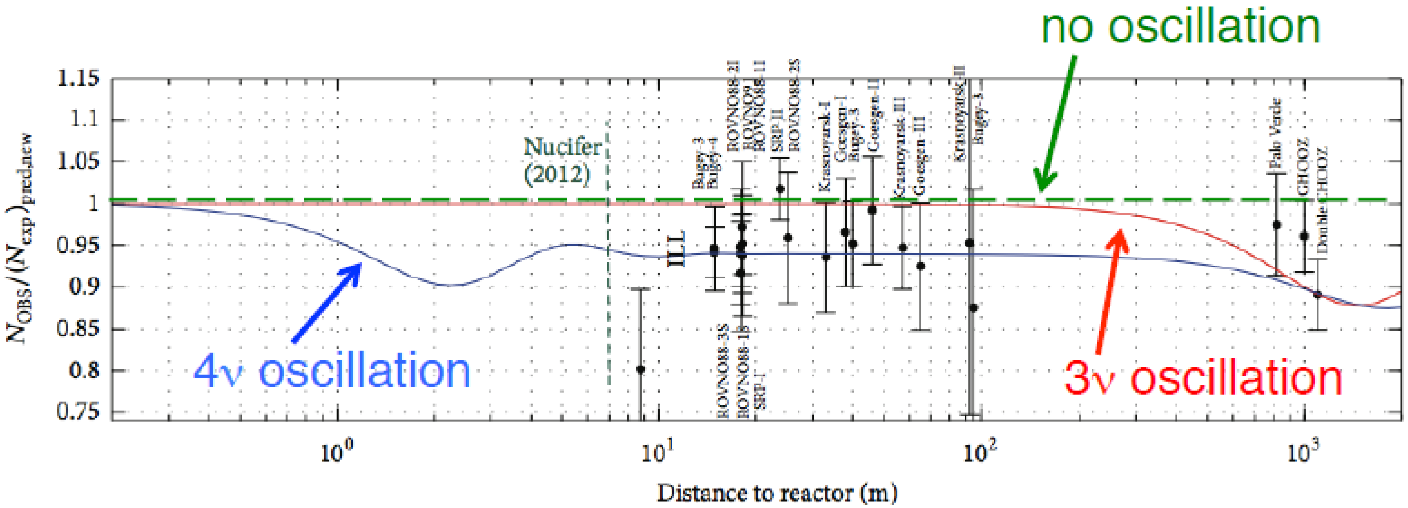
Or new physics at short distance?



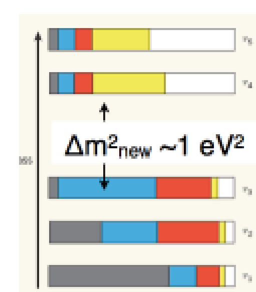
arXiv:1204.5379

Science case for a 4th sterile neutrino

- The Reactor Anomaly: a hint for a ν_s ?



  - An extra (sterile) neutrino with small mixing angle and a mass O(eV) or heavier would have oscillated @10-100m ® averaged out ® reduction by $\frac{1}{2}\sin^2\theta_S \approx 0.06$
  - Active 3 neutrinos unitarity tested @ few % ® consistent

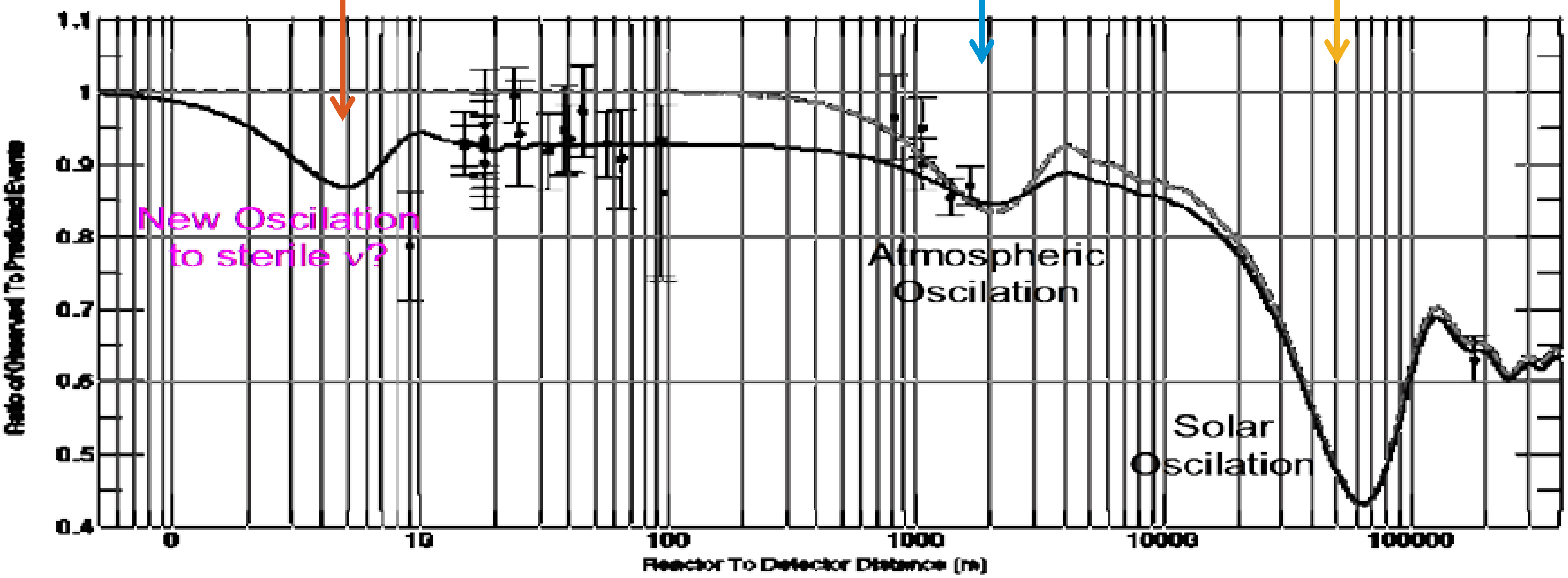


Science case for a 4th sterile neutrino

- A new sterile neutrino with small mixing and mass O(eV).
- "Sterile" means no weak interaction coupling !

® "Visible" only through its mixing with active neutrinos

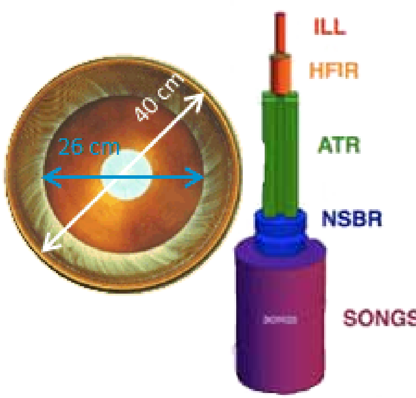
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{41}\frac{L}{E}\right) - c^2_{14}\sin^2 2\theta_{13}\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) - c^2_{14}c^2_{13}\sin^2 2\theta_{12}\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right)$$



G. Mention et al. Phys Rev D 83 073006 (2011)

STEREO at the forefront

- The RAA has triggered a strong worldwide activity around the search for sterile neutrinos.
  (white paper arXiv:1204.5379v1 [hep-ph] 18 Apr 2012)
- Numerous projects in preparation, some very challenging.
- STEREO is based on a well proven technology and is aiming at starting data taking early 2015.
- The ILL research nuclear reactor is an ideal place for a short baseline experiment : dense core, as close as 8m from the core, stable composition, frequent reactor off, …



- A target of opportunity is offered with a long reactor shutdown period Þ Installation completed before end of 2014 !!!

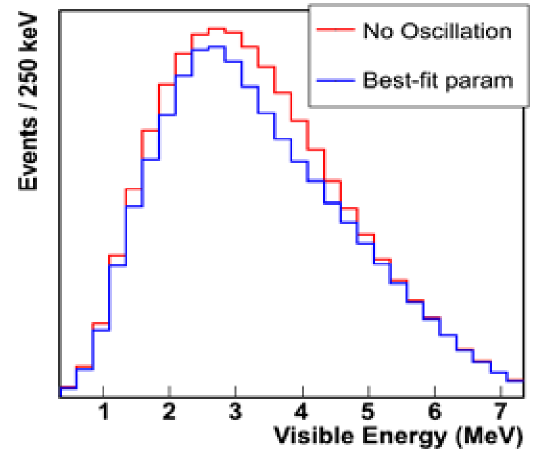
What makes STEREO the first of a new kind

- A robust and unambiguous analysis of the oscillation:

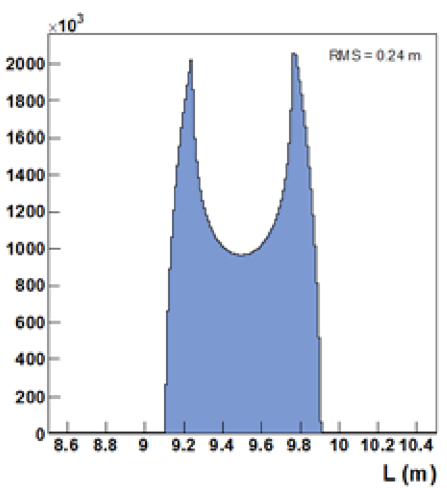
  "Shape and Normalization"

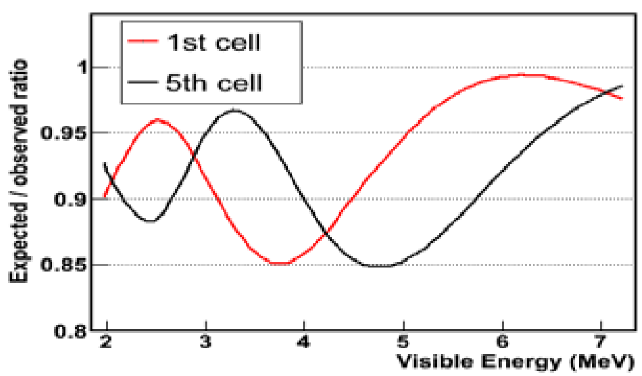
  - Observe energy spectrum deformation
  - Evolution of the phase with distance
  - Less dependent on the flux predictions

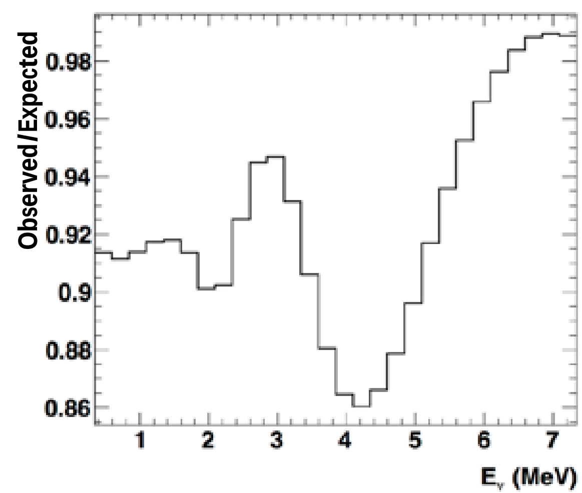
$$P_{\overline{\nu}_e \rightarrow \overline{\nu}_e} = 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \Delta m^2_{41} \frac{L}{E}\right)$$



- Requirements:
  - A good energy resolution
  - A reduced smearing with distance (source + detector)
  - Critical requirement : background effects to be fully mastered







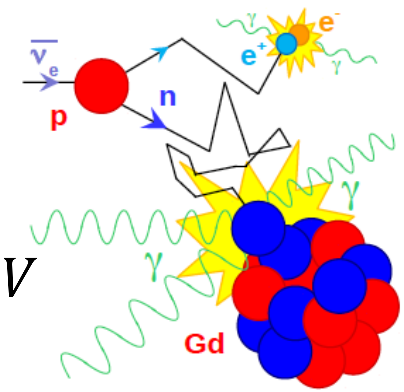
STEREO detection principle

- Inverse beta decay in Gd doped scintillator:

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

$$n + Gd \rightarrow Gd + n\gamma$$

$$e^+ + e^- \rightarrow \gamma_{511\mathrm{keV}} + \gamma_{511\mathrm{keV}}$$

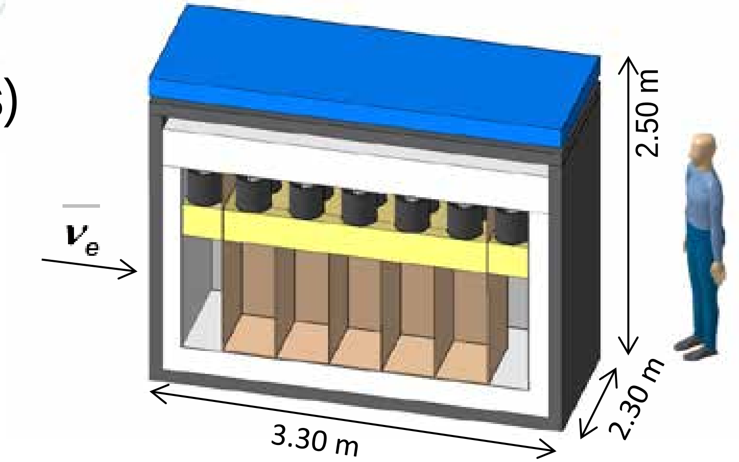


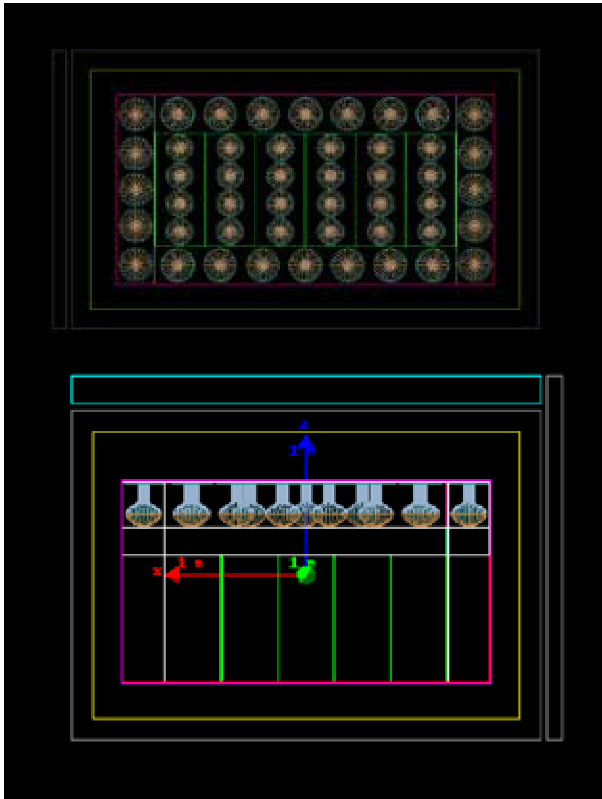
  - Threshold : $\Delta + m_e = M_n - M_p + m_e = 1.804\ MeV$
  - $E_n = 25\ keV$
  - $E_n \approx E_{vis} \approx E_\nu - \Delta + m_e \approx E_\nu - 0.782\ MeV$

- IBD tag: delayed coincidence.
  - Prompt signal : positron ionization and annihilation (γ_{511keV})
  - Delayed signal: neutron capture on Gd
    - Gamma-ray cascade, total energy $\approx 8MeV$ (≫natural radioactivity)
    - $\Delta\,T \approx$ 15 µs (0.2% Gd)

STEREO detection principle

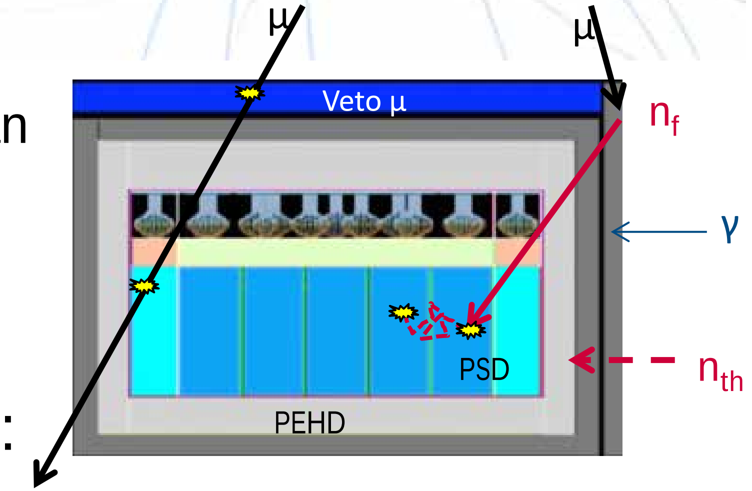
- $2m^3$ of liquid scintillator doped at 0.2% Gd (mass)
  - Target + neutron capture
  - 6 cells 40 cm along axis to the core
    $\delta L_{osc} \approx 32\ cm\ (1\sigma)$
  - 90x90 cm accoss
    - Passive vertex determination
    - Cell thickness comparable to the reactor core size
- 30cm outer crown 30 cm of non-doped scintillator
  - Improve energy resolution (gamma catcher) and neutron capture efficiency
  - Active veto against external background
- Light collection
  - From above using 24x8" and 24x10"PMTs (50% of the aera)
  - Buffer made of acrylic glass, 20 cm thick
    Improve cell response homogeneity.
  - Optical Buffer/PMT contact using mineral oil.





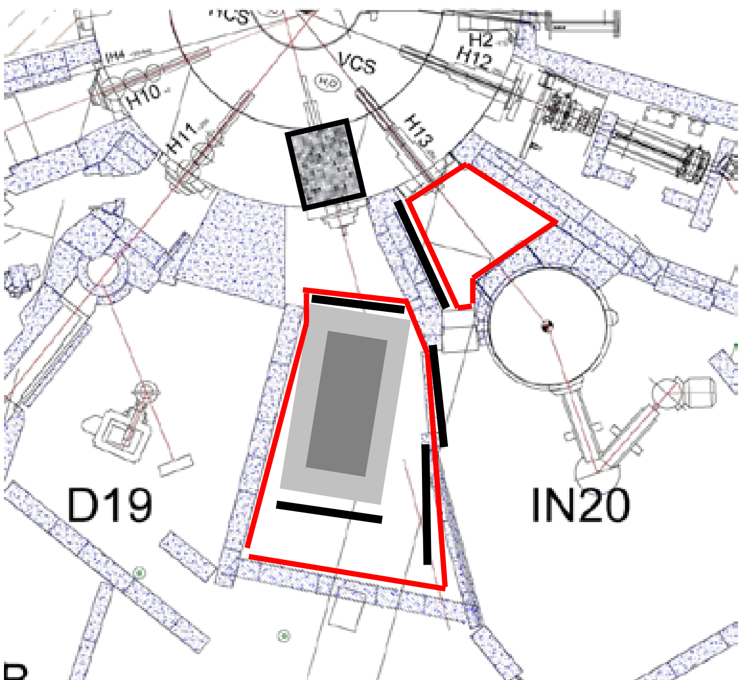
STEREO detection principle

- Active shielding :
  - outer crown "gamma-catcher" acting as an active shielding
  - Cherenkov veto counter on top



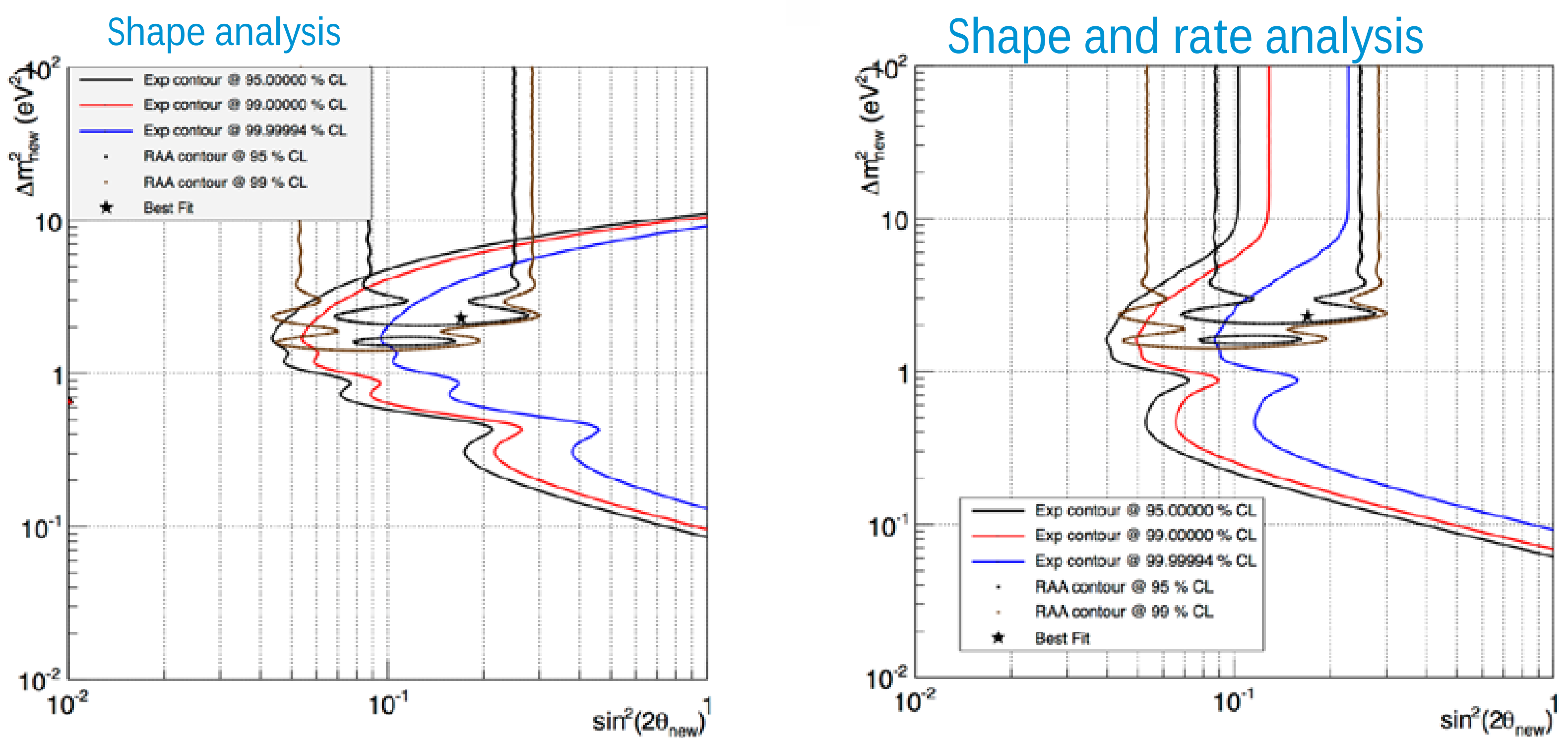
- Passive shielding all around the target:
  - 10 to 20cm lead
  - 15cm to 30cm borated PE

- External shielding:
  - to reduce gamma-ray
    and thermal & fast neutron flux
    in the casemate.



STEREO discovery potential

300 days reactor ON - 160 days OFF - S/B = 1.5



Expected signal 480 ν/ day

Challenge : S/B > 1.5 (≈ ILL-1)

STEREO discovery potential depends on a tight installation planning and on background rejection.

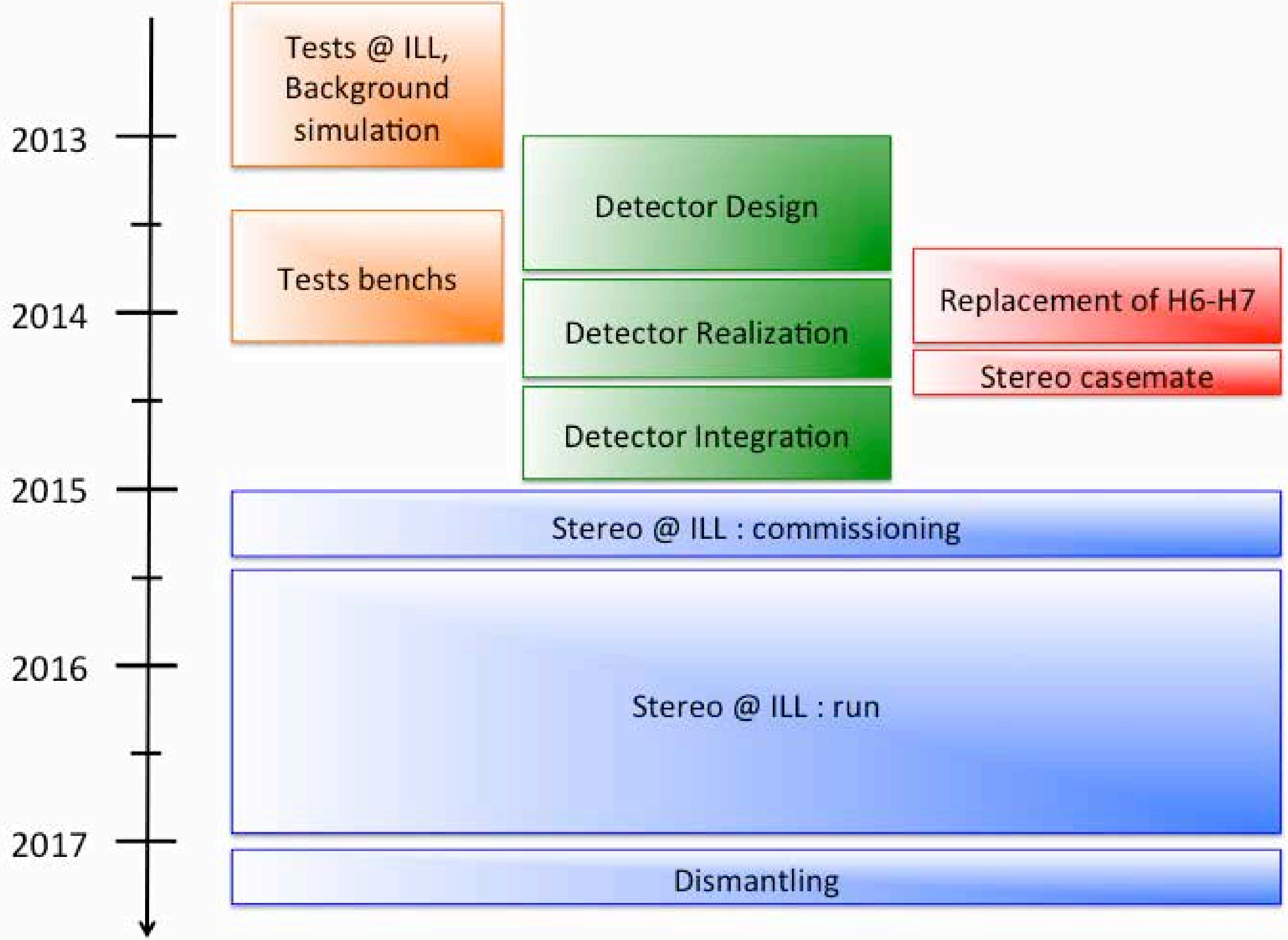
The Collaboration, the Work Packages

Partners	Responsibilities
CEA/Irfu	- Project coordination - Design and realization of the inner detector - Safety studies - Prediction of neutrino spectrum
IN2P3/LPSC	- Muon veto - Data acquisition & slow control, light injection - Fabrication and mounting of the shielding - Simulation coordination
IN2P3/LAPP	- Calibration system - Design of the shielding, fabrication of support structures
MPIK-Heidelberg	- Liquid scintillators and filling system - PMT's
ILL	- Design and realization of beam stopper - Safety studies - Coordination of on-site installation
Casablanca Univ.	- Mechanics of external lead walls

Funding

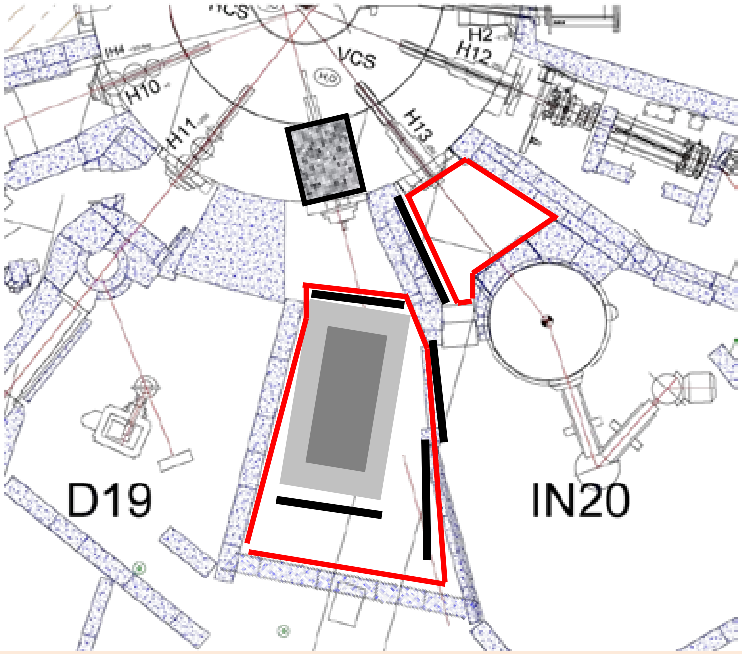
- 990 k€ ANR grant, Oct 2013 – March 2017, shared between CEA and IN2P3 labs. Part of shielding budget and a 2 years postdoc were cut + extra lead and B4C shielding needed.
- 50 k€ Irfu funds for prototype cell.
- AGIR fund from UJF (pôle SMINGUE) 10 k€ for electronics prototyping.
- Liquids and PMTs to be provided by MPIKH.
- Beam stopper and site reconfiguration by ILL
- External shielding mechanics by Univ. of Casablanca

Planning



2013
2014
2015
2016
2017
Tests @ ILL, Background simulation
Tests benchs
Detector Design
Detector Realization
Detector Integration
Replacement of H6-H7
Stereo casemate
Stereo @ ILL : commissioning
Stereo @ ILL : run
Dismantling

Recent actions



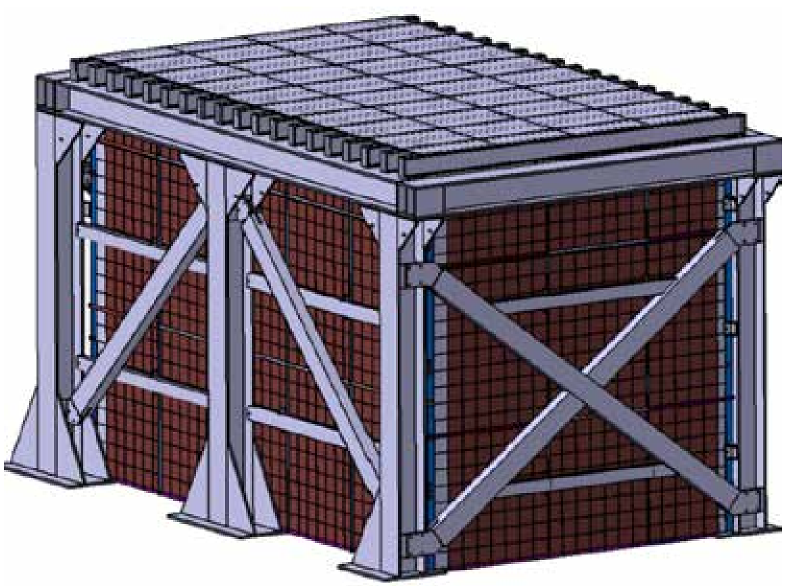
Additional shielding installed during the ILL long shutdown

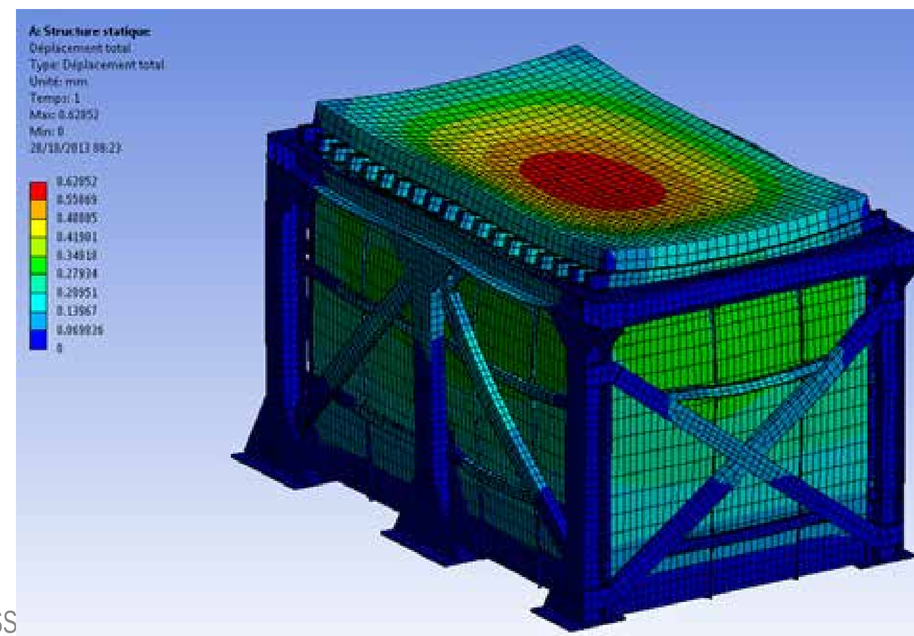
Benefit from the first cycles to validate and optimize the external shielding before the detector

- Background measurement campaigns
  - Localizing sources
  - Defining action
  - Input to detector simulation
- Improving the experiment environment @ILL
  - H7 plug replacement, ^{6}Li suppression upstream
  - Reinforced H7/STEREO casemate
  - H13 (neighboring casemate, source of most of the fast neutrons and gamma-rays): shielding to be reinforced

Recent actions

- Designing and proof-testing the detector and shielding support structure @LAPP





Recent actions

Calibration systems:

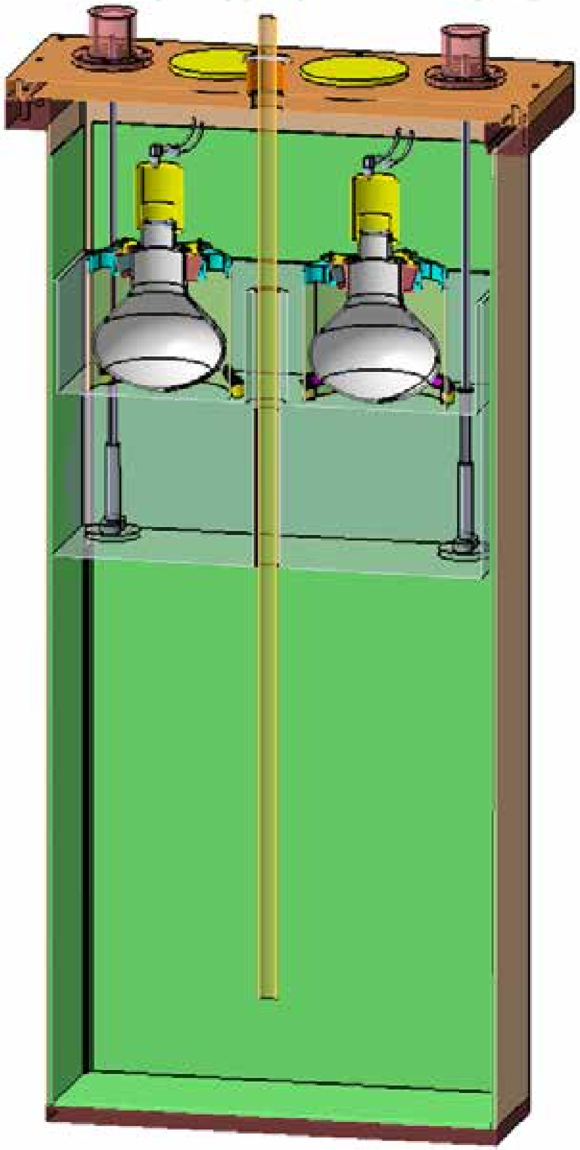
LED (@LPSC) and Radioactive sources (@LAPP).

- Energy resolution is critical
- Absolute calibration (with g and *n* sources)
- Liquid optical properties, linearity studies, cross-calibration and fast system tests with LEDs)

All systems are currently at the conceptual design level.

Recent actions

- Full size cell prototype under construction @Saclay
- Will allow
  - tests of PSD on different scintillators,
  - calibration system tests,
  - FE electronics tests
  - etc…



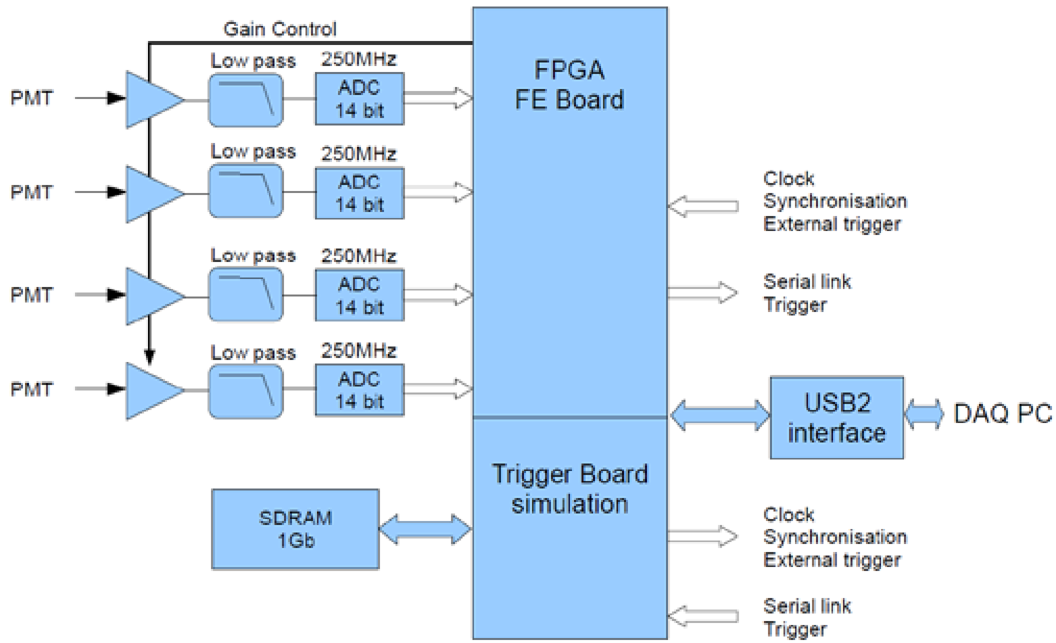
Recent actions

Electronics @ LPSC

Custom front-end + trigger + DAQ electronics based on FPGA.

- Signal digitization with signal analysis functions:
  Qtot, Qtail, full trace readout, timming, etc…
- Trigger and event building
- LED calibration driver

Current prototype :
Front end board where a part of the FPGA is used to simulate the trigger board.
Currently routing -> 20/10.
Manufacturing and cabling -> 15/11



Recent actions

VETO counter:

- Sign cosmic-rays induced background in stereo i.e. fast neutron induced by muons in shielding
- Large signal from minimum ionizing particle in stereo

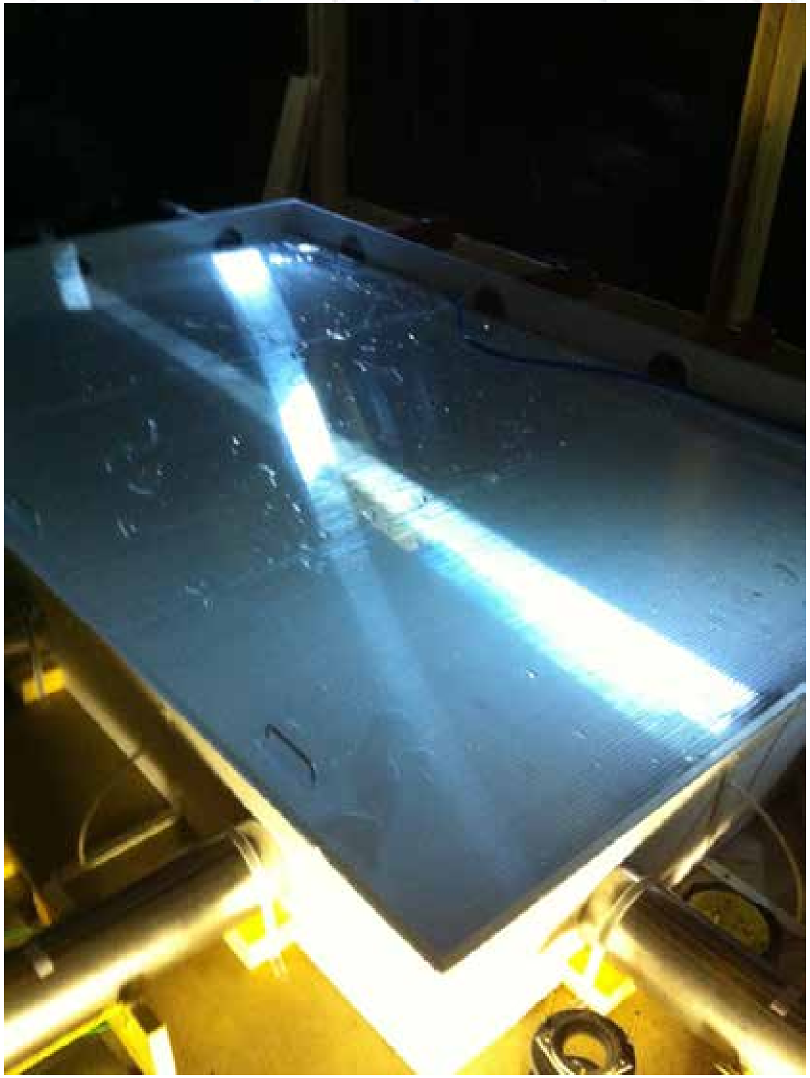
Requirements

- Fully efficient to cosmic muons,
- Quasi insensitive to background g-rays
- Made of non-flammable material

® Water Cherenkov

Prototype :

- Almost full size tank 3X2X0.25 m3
- 14 PMTs (5" XP4572, borosilicate)
- Complete coverage CR telescope.
- Tyvek diffuser being installed



Conclusions

- STEREO aims at a precise measurement at less than 10m from the compact core of the ILL research reactor.
- A distortion of the energy spectrum as a function of the distance to the core will provide a clear signature for a new oscillation, independently from flux calculations.
- The achievable sensitivity and the installation and data taking schedule will offer a high discovery potential.
- The challenging times schedule will require important efforts and support. The Enigmass postdoc position currently under selection will be essential to the success of the project and will have a good visibility.

BACKUP SLIDES

PhD - Postdocs

- LPSC-IN2P3:

1 postdoc funded by ENIGMASS

1 PhD student: Stéphane Zsoldos

- LAPP-IN2P3:

1 postdoc funded by ANR+IN2P3 (?)

1 PhD student: Luis Manzanillas

- CEA-Irfu

1 postdoc funded by ANR+Eurotalents (?)

1 PhD student: Maxime Pequignot

- MPIK-Heidelberg

1 postdoc : Antoine Collin

1 PhD student

- ILL

1 PhD?

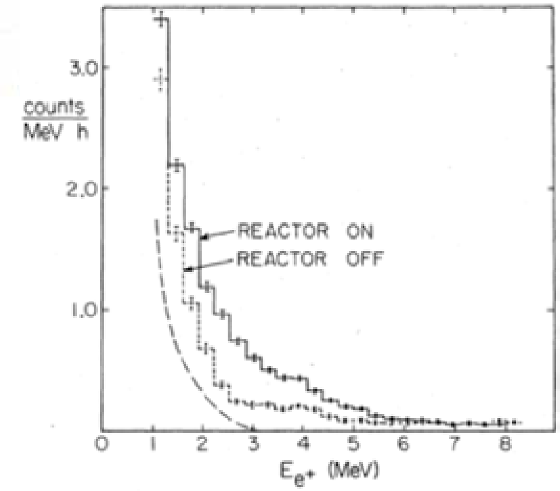
- Univ. Casablanca

1 PhD?

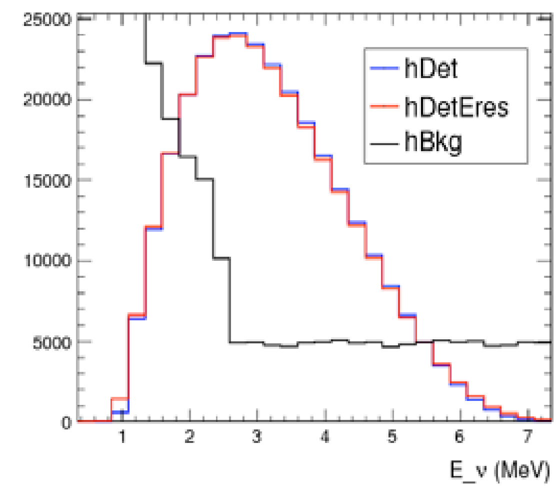
Expected performances

Puissance du réacteur	57 MW
σ (^{235}U) /fission	6.69 10^{-43} cm^2
Distance moyenne au cœur	10 m
Nombre de protons cibles	1,3 10^{29}
Seuil Evis à 2 MeV (E_ν > 2.8 MeV)	81 %
Efficacité neutron (Edep > 5 MeV)	64 %
Temps mort	5 %
δE/E @ 2 MeV	10 %
δL evt by evt	32 cm

- Signal attendu 480 ν/ jrs
- Challenge : S/B > 1.5 (≈ ILL-1)

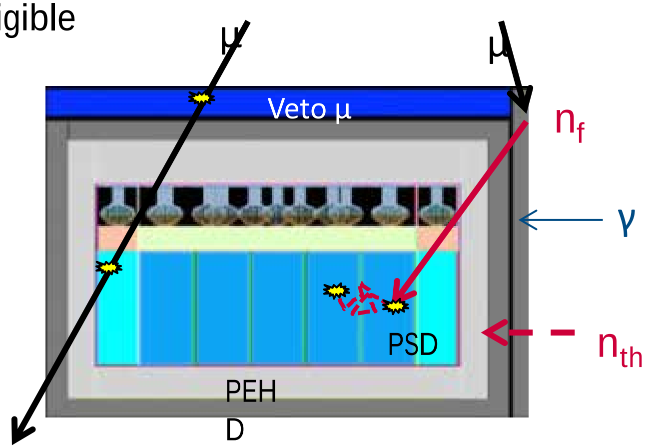


Phys. Rev. D 24.1097 1981



Backgrounds

- Reactor correlated backgrounds
  - Gamma-ays & thermal neutrons -> random background
  - Fast neutrons (prompt signal = recoil proton + delayed signal = neutron capture)
    This is a true coincidental background à must be reduce to negligible
  - External shieldings (mostly lead and B4C): heavy materials
    => floor load studies ok (10 T/m² ► 500 T/slab)



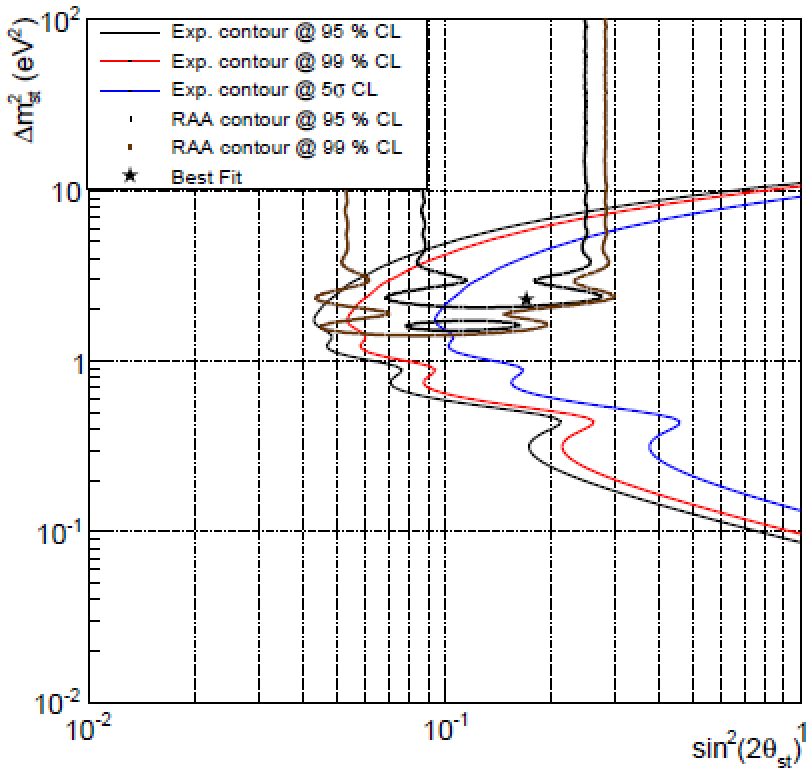
- Reactor independent backgrounds
  - Cosmic rays induced fast neutrons -> coincidental background
  - Water channel protecting (most of) the area
  - Material radioactivity -> random background
- The random bg is measured online with a good accuracy
  - $R_p \times R_d \times \Delta t < R_\nu$
  - Prompt signal: Edep > 2 MeV (γs) à Rp < 200 Hz
  - Delayed signal: 5< Edep< 10 MeV à Rd < 1 Hz
- The coincidental bg (non reactor correlated) is measured during off-periods
  - OFF ≈ 45 % of time
  - Coincidental rate before PSD analysis $< 5 \times 10^{-3}$ Hz

Implantation sur site

- Contraintes d'installation
  - Sécurité sismique
  - Sécurité incendie
  - Dossier ASN à déposer fin 2013
  - Travail en cours avec expert incendie et ingénieure de sécurité ILL

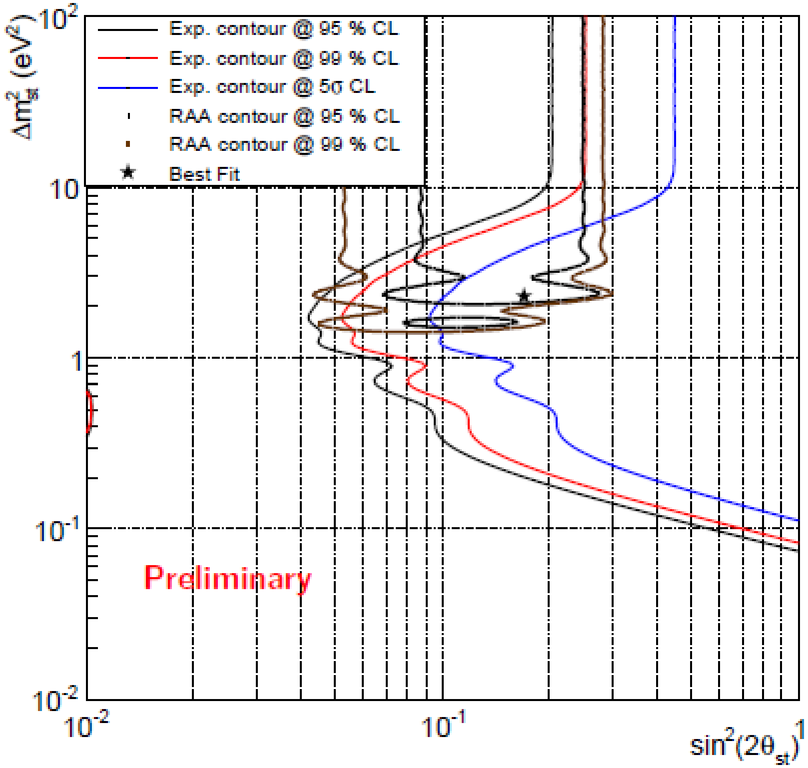
- Modification du détecteur par rapport au projet initial
  - Distance STEREO/réacteur : 10 m
  - Largeur de la cible réduite de 1.1 à 0.9 m
  - 6 cellules au lieu de 5

STEREO discovery potential



- 300 days ($\sim$5 ILL cycles)
- $L_0 = 9.8\,\mathrm{m}$
- Prompt energy threshold at 2 MeV
- Delayed energy threshold at 5 MeV (efficiency: $\sim$63 %)
- SoB = 1.5
- No norm information

STEREO discovery potential



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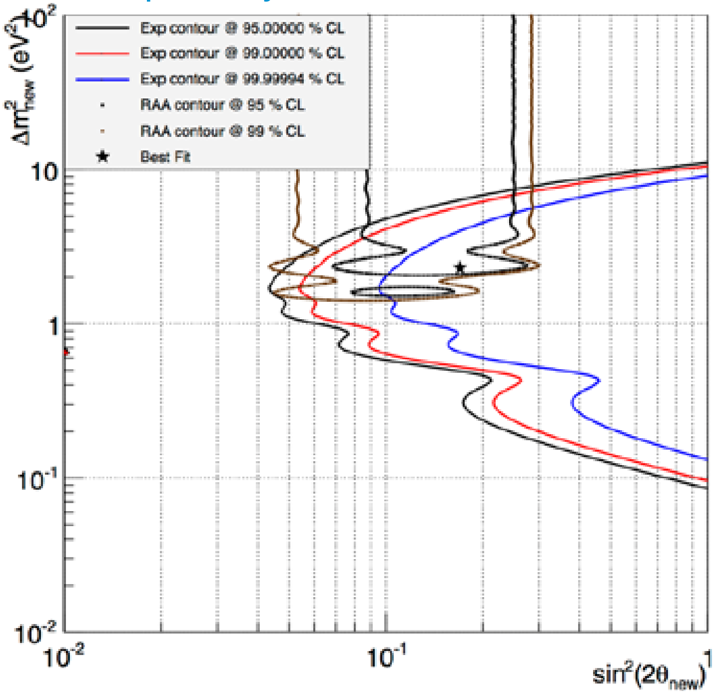
- Stereo discovery potential depends on tight installation planning and background rejection.

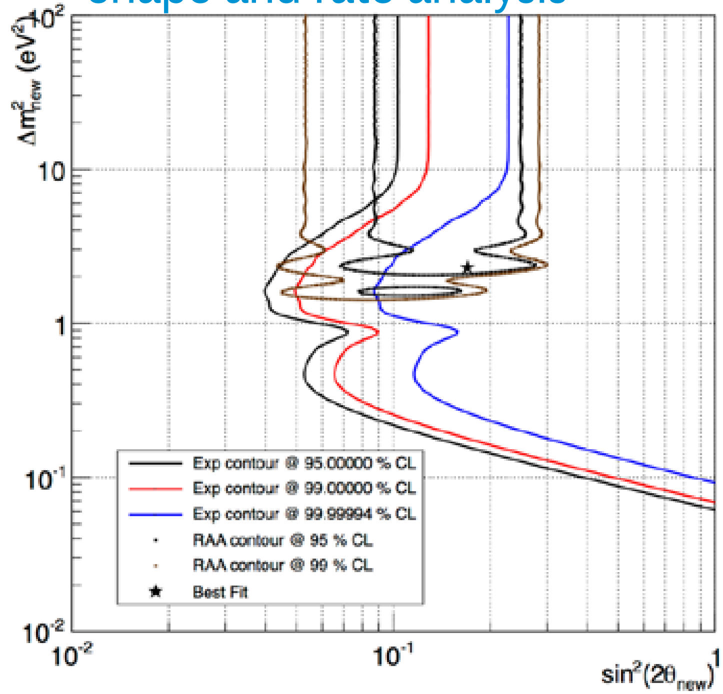
STEREO discovery potential

300 days reactor ON - 160 days OFF - S/B = 1.5

Shape analysis



Shape and rate analysis



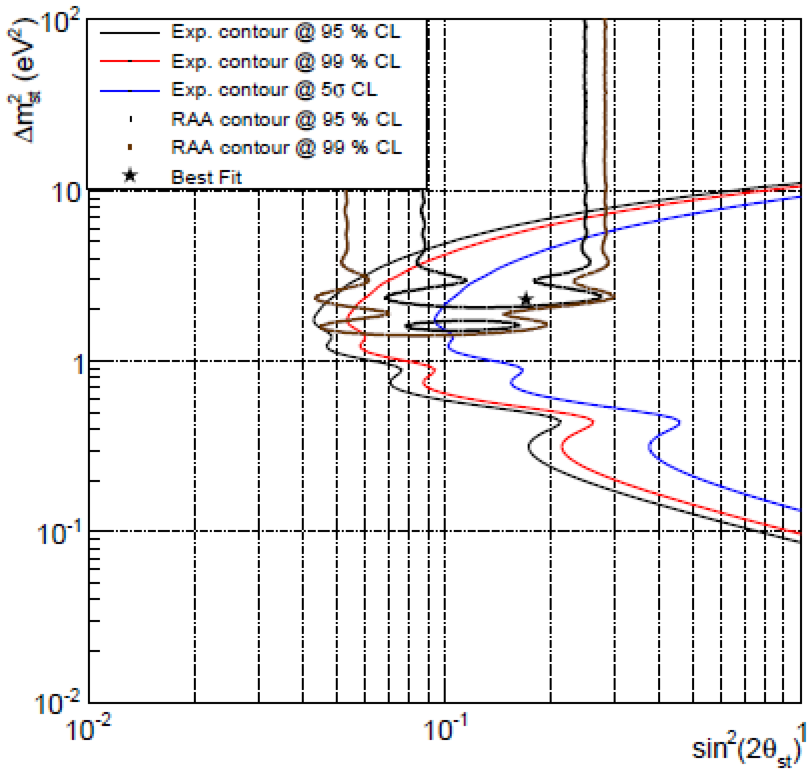
Systematic errors

- Fission spectrum 0.7 -> 4 %
- Weak magnetism (E-1.0)*1.0%/MeV
- Evt/evt distance res δL = 32 cm
- Source energy calibration 2.0 %
- Monitoring 1%

Normalization systematic errors 3.5%

- N_p 0.5%
- Spill in Spill out 1%
- Detection efficiency 2%
- Thermal power 2.0 %
- Fission spectrum 1.8 %

STEREO discovery potential



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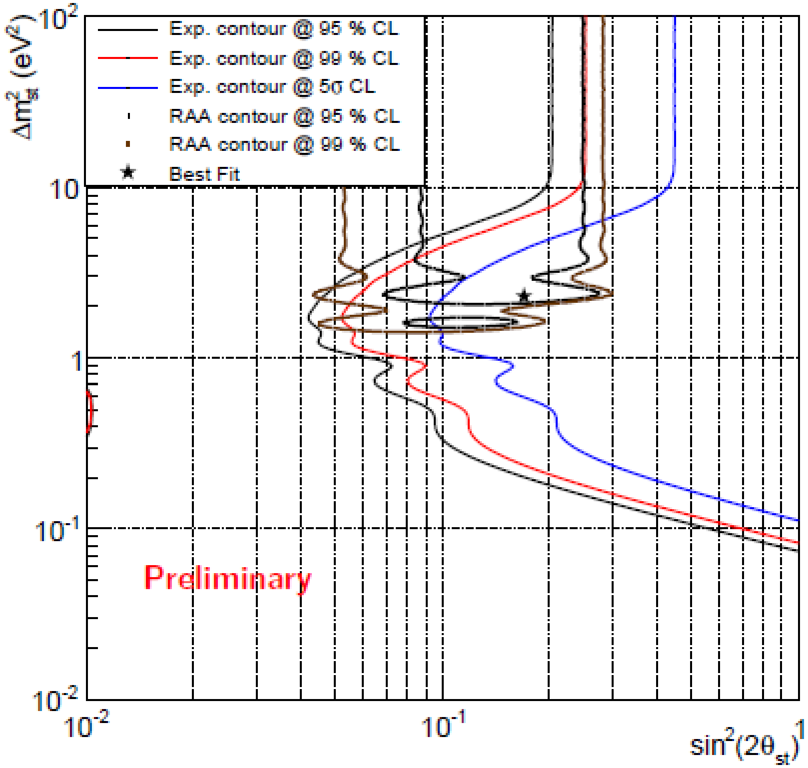

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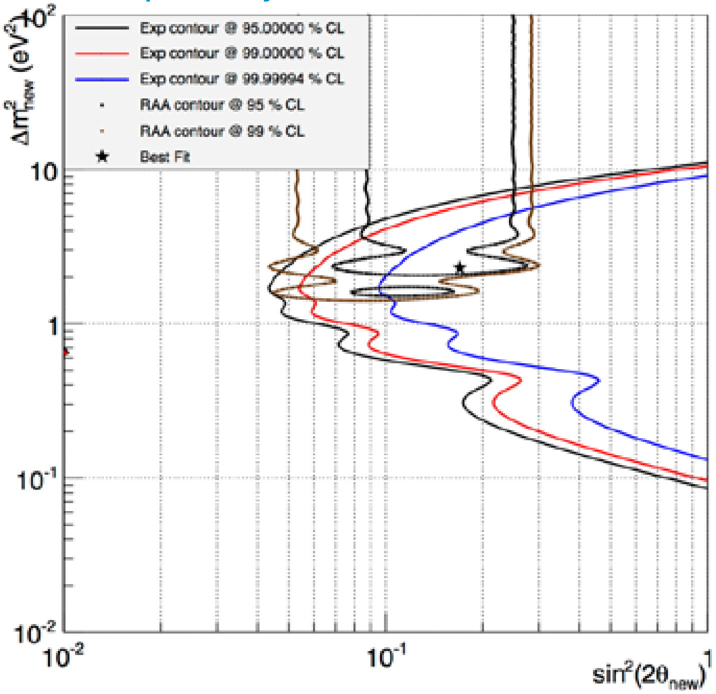
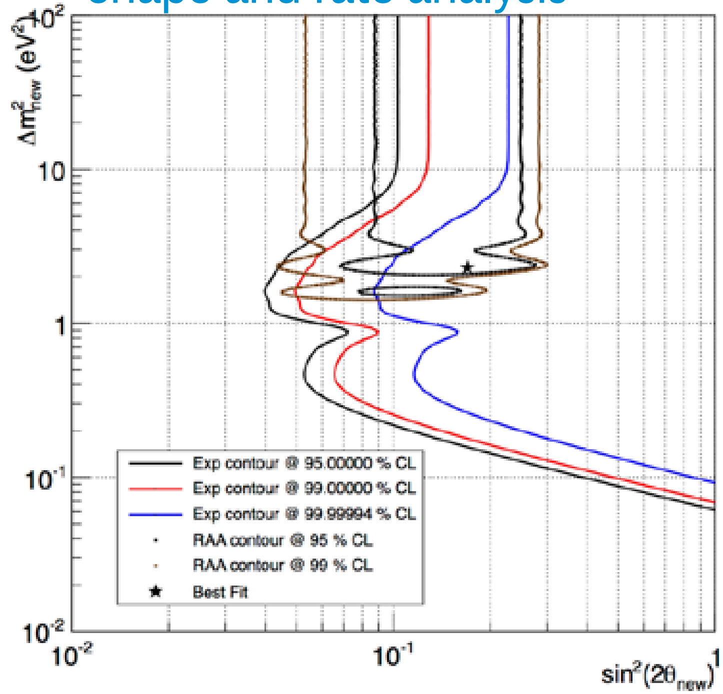


Shape and rate analysis



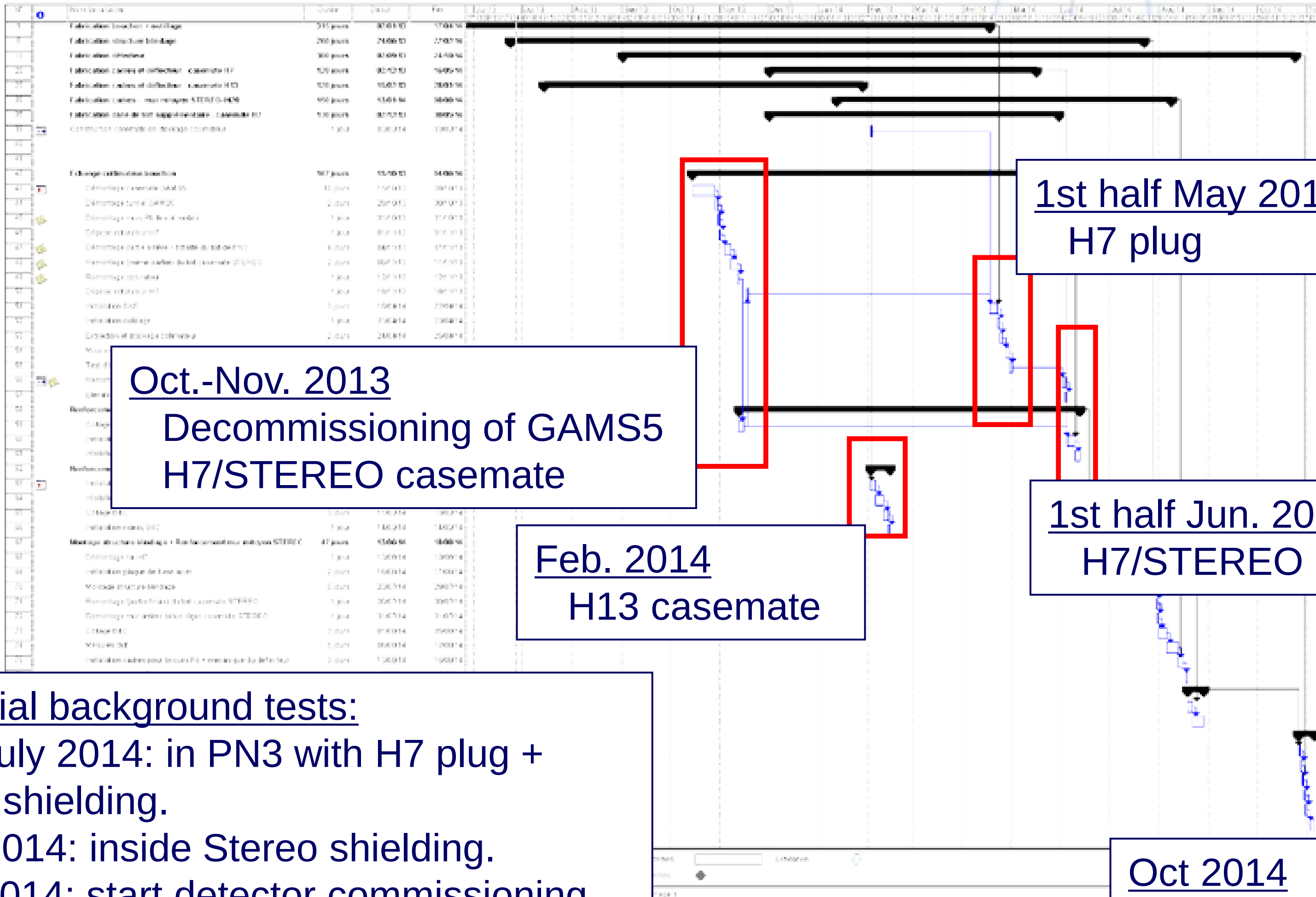
STEREO discovery potential depends on a tight installation planning and on background rejection.

- Monitoring 1%
- Fission spectrum 1.8 %

Recent actions

- Many interactions with ILL to prepare the experiment environment (H7 plug modifications, ^{6}Li removal, H13/IN20 frontend shielding etc…)
- In situ background measurements and identification of background sources.
- Optimizing detector geometry with full detailed simulation.
- Simulating background effects, optimizing shielding. Need for a factor ?? reduction.
- Single cell prototype at Saclay under construction.
- Front end and acquisition electronics prototype at LPSC.
- Optimizing liquid scintillator at MPIKH.
- VETO prototype at LPSC.
- Structural design of shieldings and supports at LAPP.
- Designing calibration system (LED at LPSC, sources at LAPP).

ILL schedule



1st half May 2014
H7 plug

Oct.-Nov. 2013
Decommissioning of GAMS5
H7/STEREO casemate

Feb. 2014
H13 casemate

1st half Jun. 2014
H7/STEREO casemate

Sequential background tests:
- June-July 2014: in PN3 with H7 plug + external shielding.
- Sept. 2014: inside Stereo shielding.
- Nov. 2014: start detector commissioning.

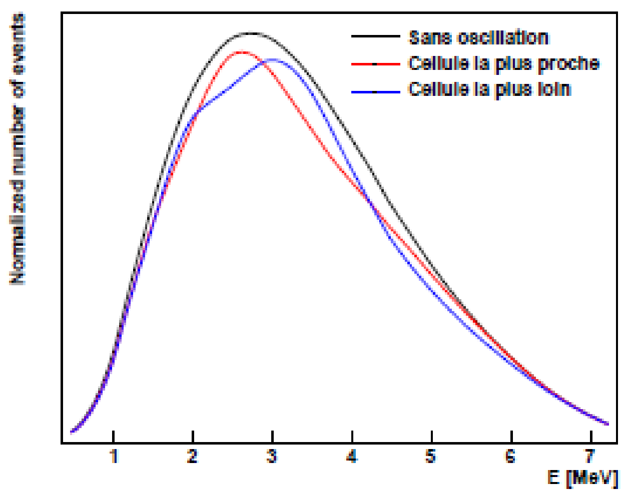
Oct 2014
Detector installation

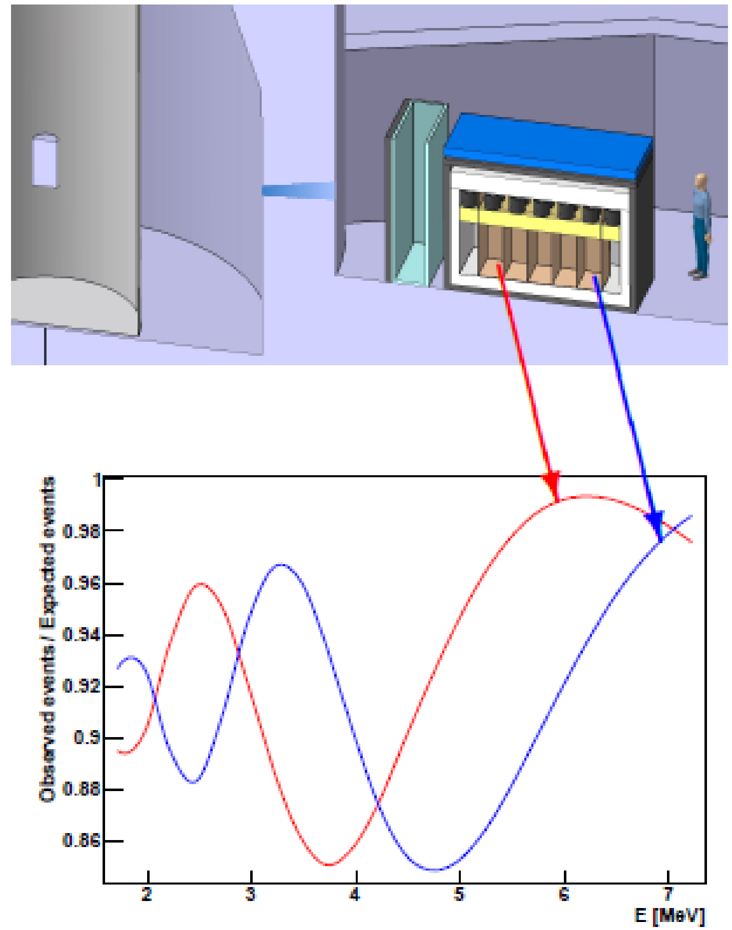
Calendrier

- Aout 2013- mi juin 2014 : Grand arrêt réacteur de 10 mois
  - Remplacement bouchon-collimateur
  - Couverture B4C des casemates PN3 et IN20
  - Montage des murs de plomb suplémentaires
- juin 2014 : 1 cycle court réacteur ON de 1 mois
  - test de bruit de fond de la casemate aménagée
- 3 cycles jusqu'à fin 2014
  - Installation de STEREO : blindages et détecteur
  - Tests de bruit de fond à chaque étape
- 2 cycles en 2015 pour comissionning
- 6 cycles d'avril 2015 à fin 2016 : Prise de données effectives
- Début 2017 : changement du tube H6-H7

Shape analysis

- Observe an unambiguous sign of oscillations
  - Spectral distortion both in energy and baseline,
  - Shape analysis, independent from reactor power and flux normalisation.

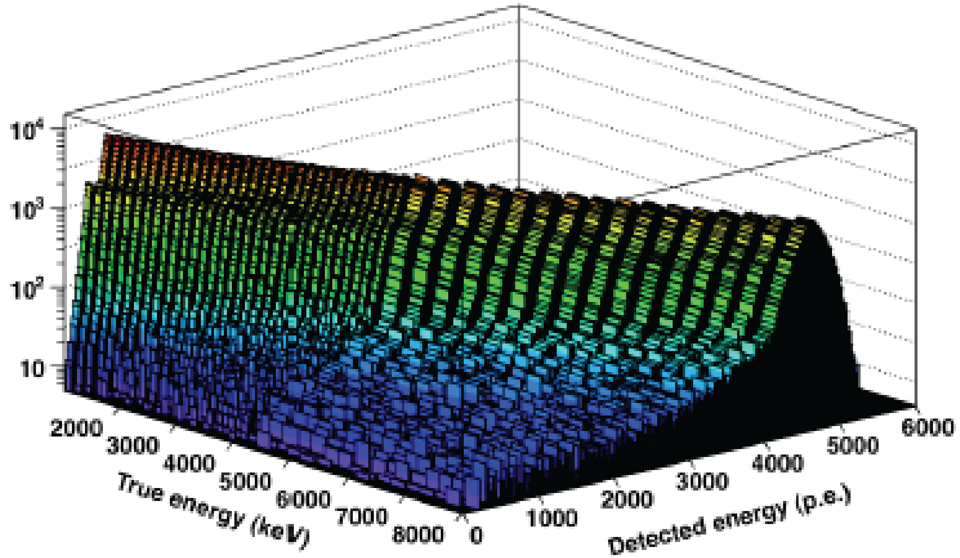


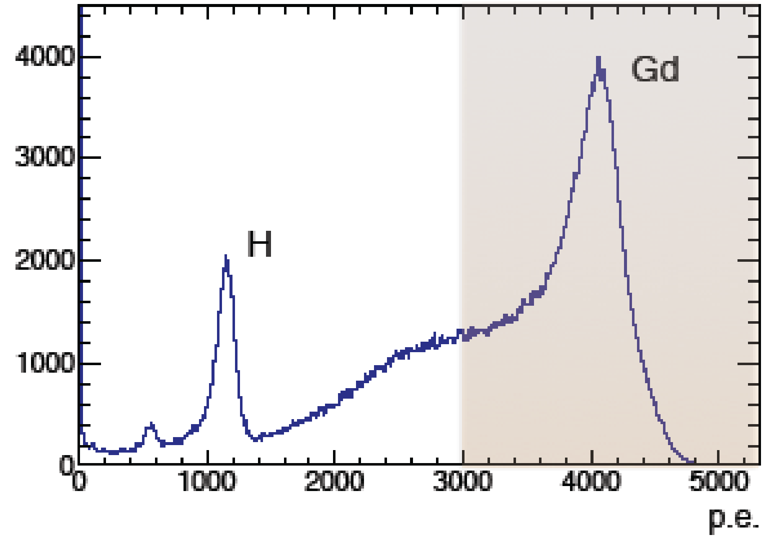


For the RAA+Gallium best fit values: $\Delta m^2_{new} = 2.3 \pm 0.1\,\mathrm{eV}^2$, $\sin^2(2\theta_{new}) = 0.17 \pm 0.04$

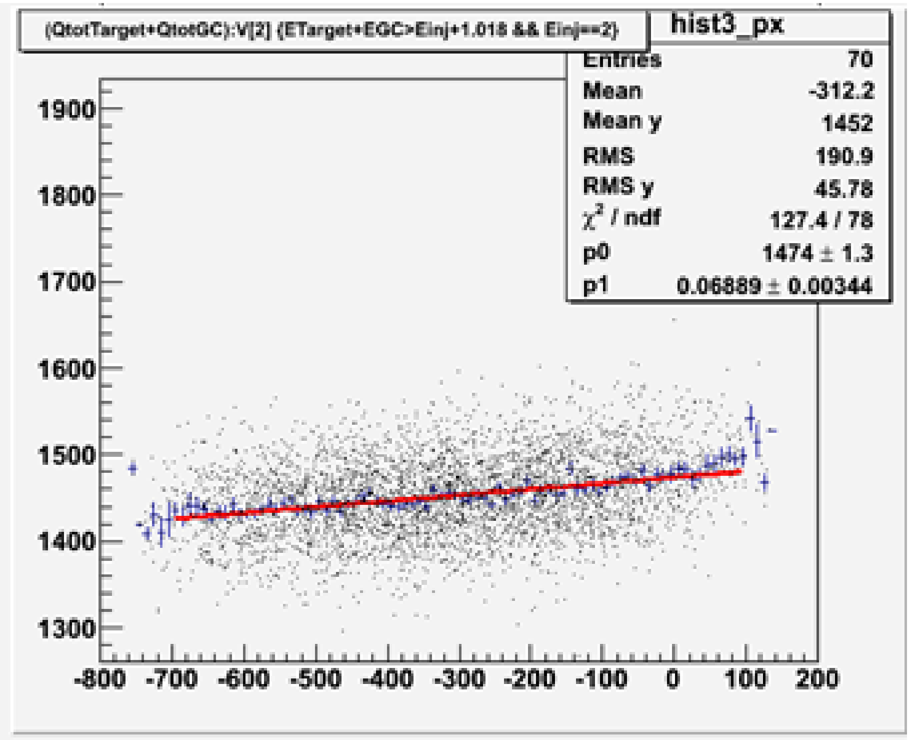
Sensitivity studies

- Energy resolution from a Geant4 simulation: A true energy to visible energy matrix describes the detector response.
- Resolution of vertex reconstruction: 25 cm in length.
- Detection efficiency simulated in Geant4.
- 9.8 m from the center of the core to the center of the detector.





Efficiency & Energy resolution

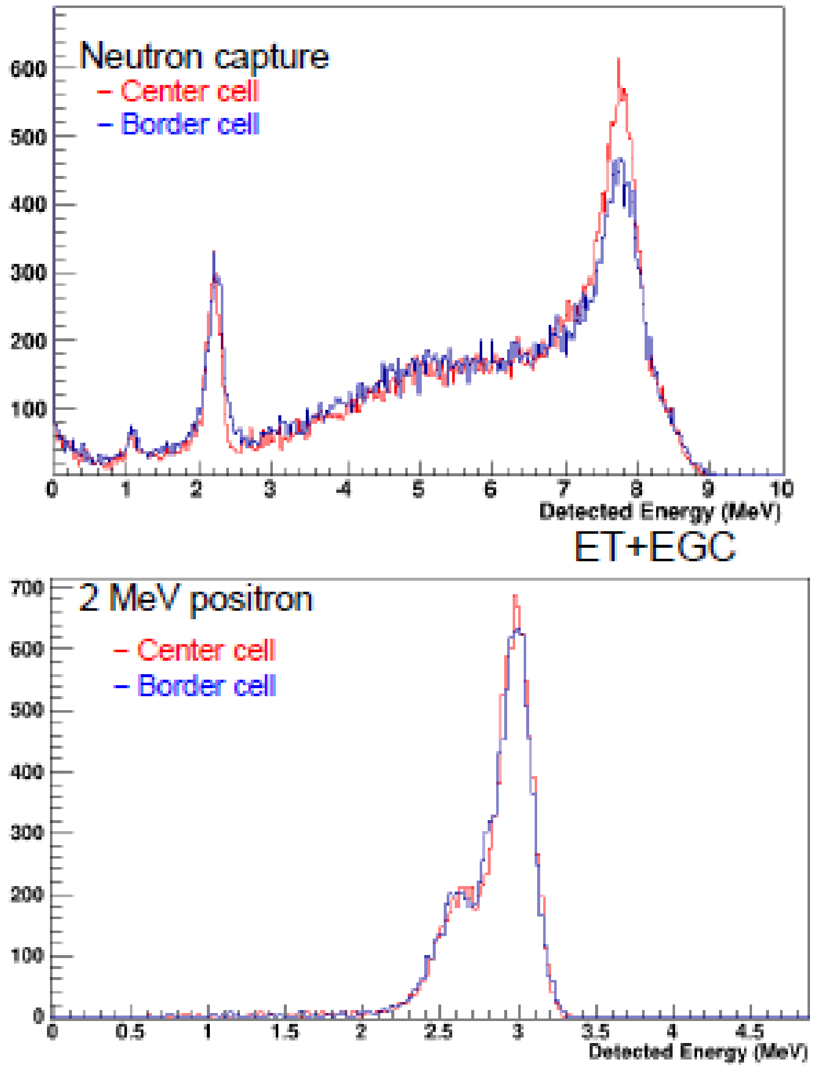


In cell homogeneity

⇓

calibration

Efficiency & Energy resolution



Cell to cell homogeneity is critical

⇓

Gamma catcher

+

calibration