







A search for a ~eV sterile neutrino at the ILL

Laura Bernard, on behalf of the Stereo collaboration

ENIGMASS 7th december 2017, LPSC, Grenoble

- 1. The reactor & gallium antineutrino anomalies
- 2. The Stereo detector
- 3. Status of the experiment
- 4. Backgrounds
- 5. Neutrino candidates

Oscillation mecanism : change identity along propagation



Interaction basis
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
Propagation basis (mass eigenstates)

Oscillation amplitudes

Contains 3 angles
$$\theta_{12}, \, \theta_{23}, \, \theta_{13}$$

Mass splittings:

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Oscillation frequencies

$$P(\nu_x \rightarrow \nu_y) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L(m)}{E(MeV)})) \qquad \text{(in a 2 families case)}$$

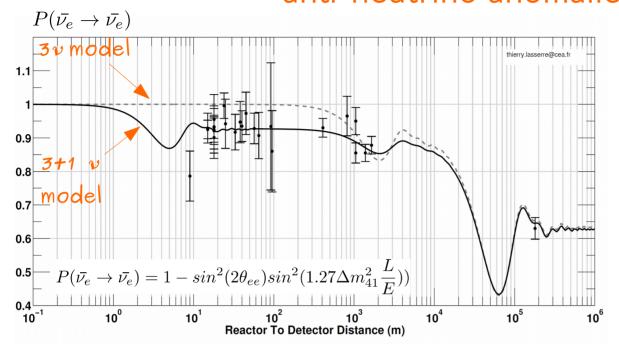
Appearance experiments

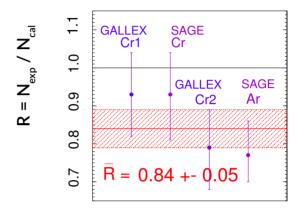
Probability for an v_x to be detected in a different state than what it was produced :

$$P(v_x \rightarrow v_y) = f(\theta, \Delta m^2, Energy, Distance)$$

Probability for an v_x to stay in the same state :

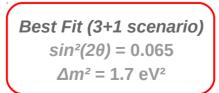
$$P(v_x \rightarrow v_x) = 1 - P(v_x \rightarrow v_y)$$

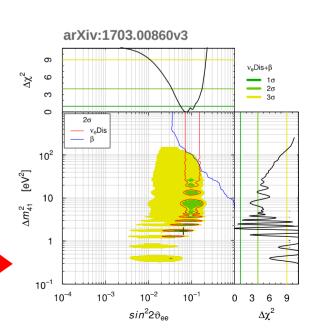


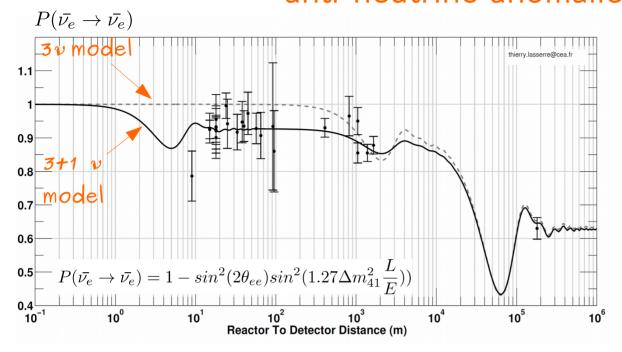


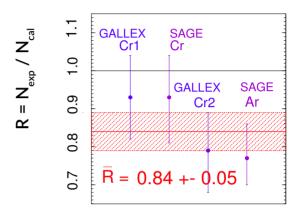


- Several measures at short distances (< 1 km) from reactor cores
- > Deficit of ~6%, 2.7 σ significant
- Compatible with other anomalies : GALLEX / SAGE
- Two hypothesis:
 - New oscillation towards sterile v
 at short base line
 - Potential bias in the prediction spectra









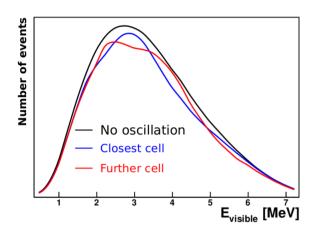


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- We need clear measurements in the best fit region :
- → Rule out or agree on the presence of a new oscillation : independent from the prediction
 - → Constrain the neutrino spectra from reactors



Sterile REactor Oscillation experiment



Goal : probe the sterile neutrino hypothesis by measuring the $v_{_{
m e}}$ spectra from ILL (Institut Laue Langevin) reactor at different distances

→ 6 cells segmented detector

Strategy: relative comparison of spectral distortion between cells

$$P(\bar{\nu_e} \to \bar{\nu_e}) = 1 - \sin^2(2\theta_{ee})\sin^2(1.27\Delta m_{41}^2 \frac{L}{E}))$$

International collaboration of ~ 20 researchers











A worldwide effort / competition

NFOS

(Korea)

Solid

Stereo

(Belgium)

Ce-Sox

(Italy)

DANSS

(Russia)

PROSPECT

(US)

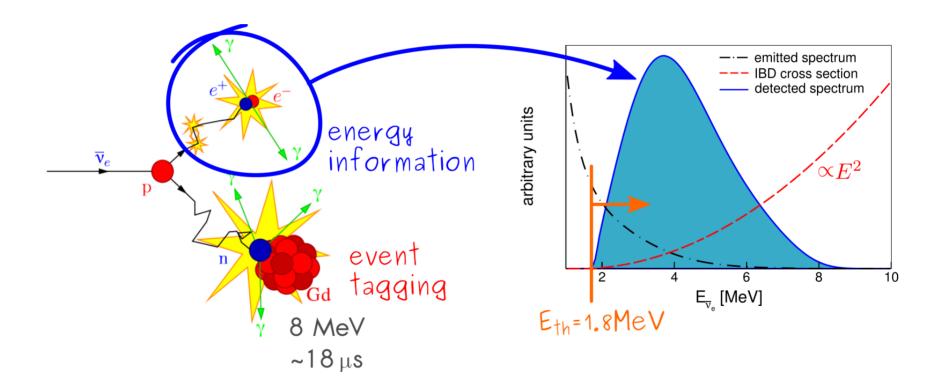
Neutrino-4

(Russia)

(France)

Detection principle

- > Inverse Beta Decay in liquid scintillator doped with Gd : $\bar{\nu}_e + p \rightarrow e^+ + n$
- > Neutrino event = correlated event = Prompt + Delayed



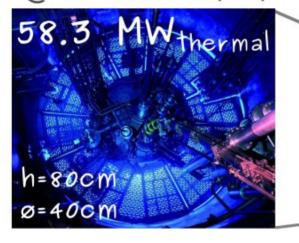
Prompt event: energy deposition + annihilation $\rightarrow E_{v} = E_{vis} + 0.782 \text{ MeV}$

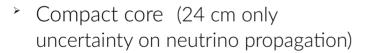
Delayed event: thermalization + neutron capture on Gd ($\sim 3 \gamma$ emission)

Neutrino source

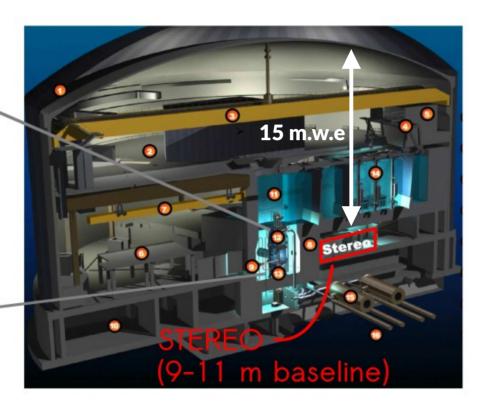
ILL research reactor

@ Grenoble (FR)





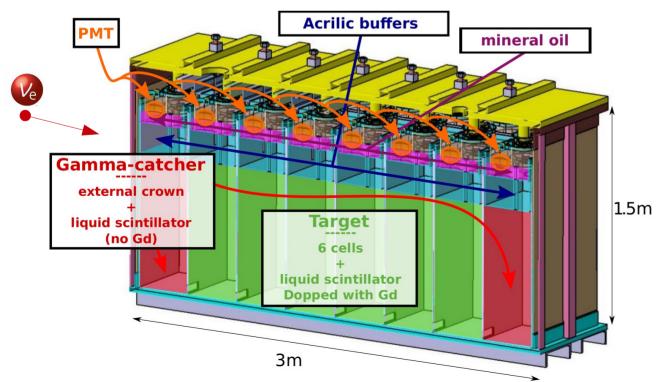
- Highly enriched ²³⁵U (93%)
- Intensity ~ 10¹⁸ antineutrinos/sec
- 3-4 cycles of 50 days/year

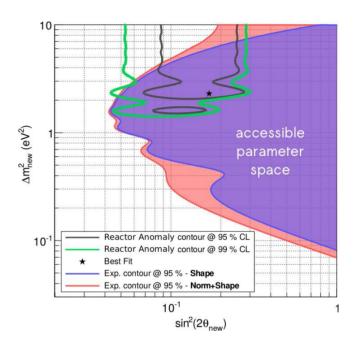


Challenging mitigation of the background due to neighbor experiments & cosmics

Segmented detector

- Target volume : ν detection
- \succ Gamma-catcher : collect γ 's escaping from the target
 - Improves detection efficiency & energy resolution
 - Serves as background veto
- > 48 PMTs:
 - 4 PMTs per target cell
 - > 4 / 8 PMTs per gamma-catcher cell

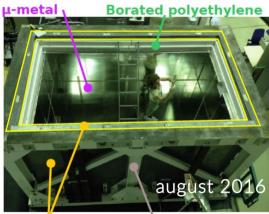




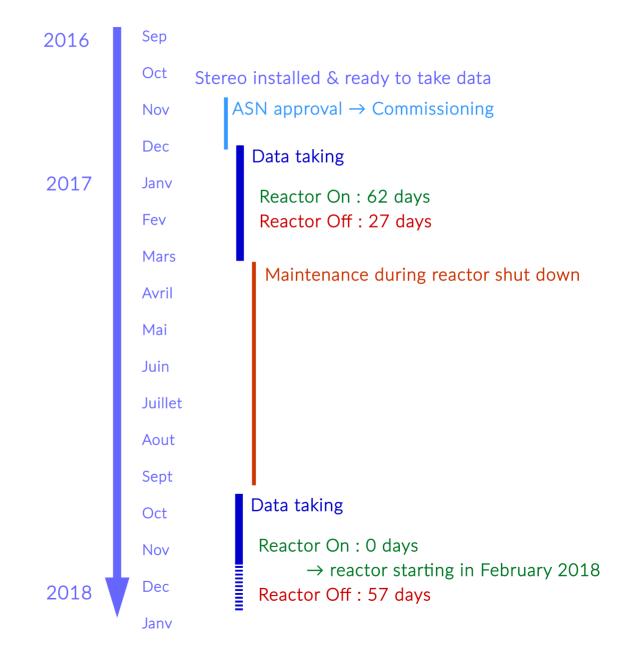
S/B = 1.5 300 days signal

Stereo Timeline



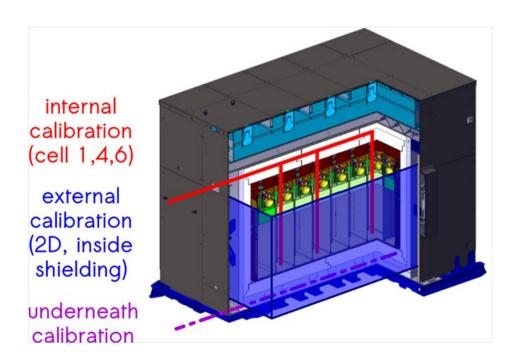


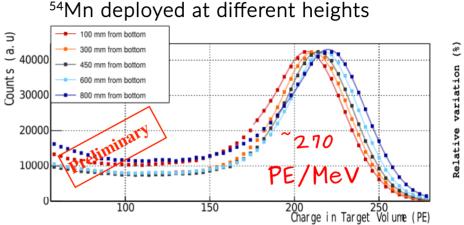


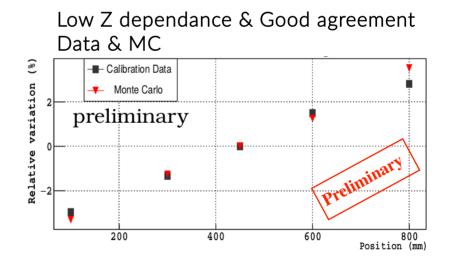


Calibration (LED + n & γ sources)

- Light pulses from LED (465nm): single PE
- Set of sources regularly placed inside the detector
- → ⁵⁴Mn is the reference calibration point

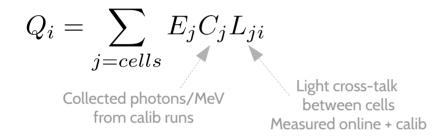


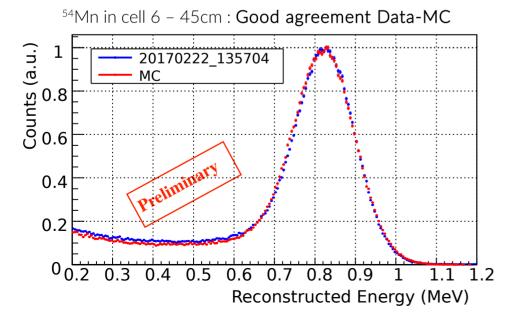


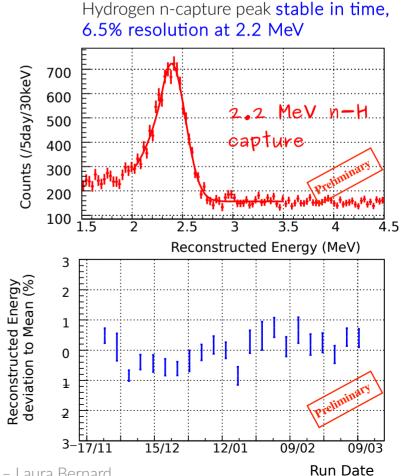


Energy reconstruction

- Energy reconstruction tool developed to take into account unexpected effects:
 - Photon acceptance reduced in cell 4 & front GC cell, due to mineral oil leak
 - Light cross talks between cells have evolved along data taking, with values higher than expected (→ pb fixed for phase 2)



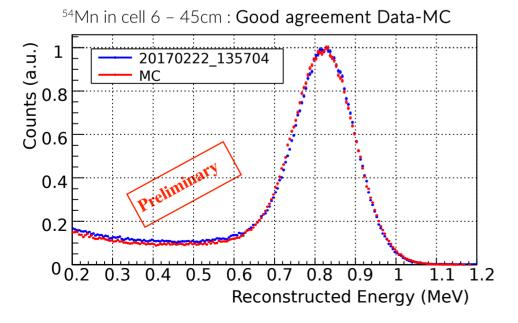




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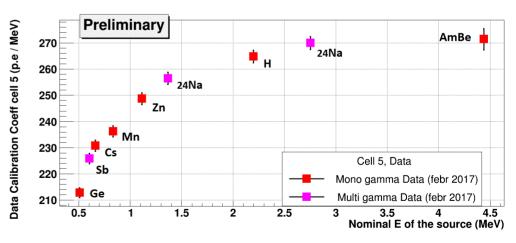
- Energy reconstruction tool developed to take into account unexpected effects:
 - Light cross talks between cells have evolved along data taking, with values higher than expected (→ pb fixed for phase-II)
 - Photon acceptance reduced in cell 4 & front GC cell, due to mineral oil leak

$$Q_i = \sum_{j=cells} E_j C_j L_{ji}$$
Collected photons/MeV between cells from calib runs Measured online + calib



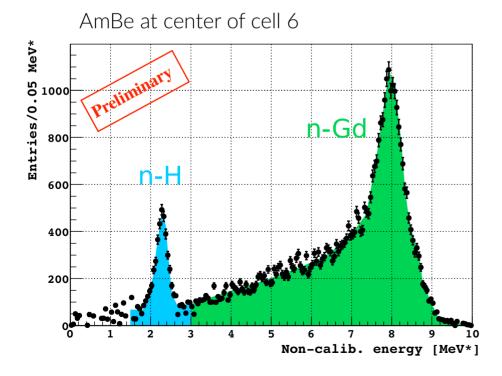
Quenching curve: Non-linear light production in the large dE/dx regime (low E – Bragg peak)

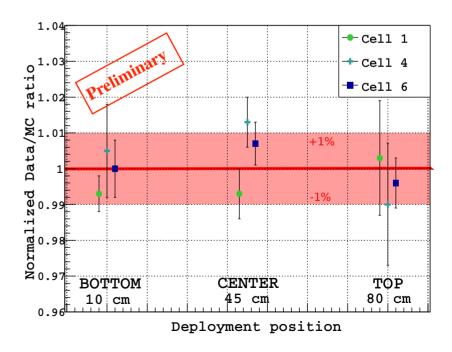
 \rightarrow MC tuning in progress



Detection efficiency

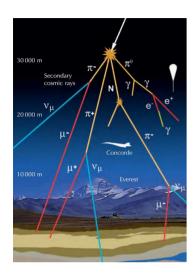
- Neutron capture efficiency using coincidences from AmBe source
- n-Gd fraction ~ 88.6 +- 0.2 %
- \rightarrow MC follows relative variations of n-H/n-Gd for different cells & z-positions \rightarrow validation of MC
- Fine-tuning of n-Gd fraction in MC so that absolute proportion of n-H/n-Gd is the same for data & MC
 - → We can rely on MC for the determination of n-capture efficiency





4. Backgrounds

Reactor ON / OFF background



Muon induced

- Fast neutrons (atmospheric showers)
- Stopping muons



Reactor induced

- Thermic neutrons
- γs from n-capture on metals



Radioactive decays

γ radiation from decays

A neutrino is a correlated pair !
Prompt + Delayed

~ 350 events /
day

Accidental background: 2 events coming from 2 different origins

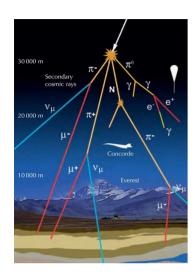
→ Shielding, topological cuts, **statistical subtraction** with shifted time window

Correlated background: 2 events produced by 1 incident particle

→ Overburden (15 m.w.e), muon veto, PSD, asymmetry light collection, topology, On-Off subtraction

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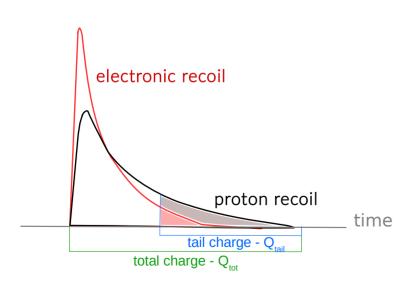
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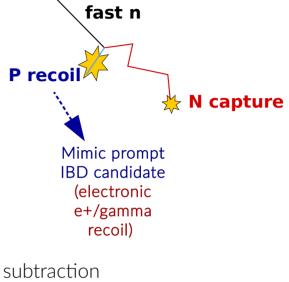
4. Backgrounds

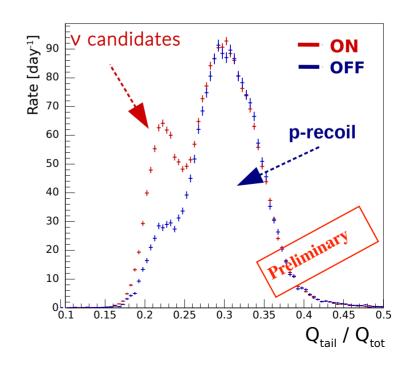
Muons induced background

Pulse Shape Discrimination for fast n discrimination

- ightarrow Q_{tail} / Q_{tot} different for proton recoil & electronic recoil in LS
- PSD distribution of IBD candidates in the target :
 - \rightarrow f.o.m = 0.65, improved to 0.7 for phase 2
 - → Superimposition of p-recoils population for ON & OFF
 - → No correlated background induced by reactor : ok for On-Off subtraction



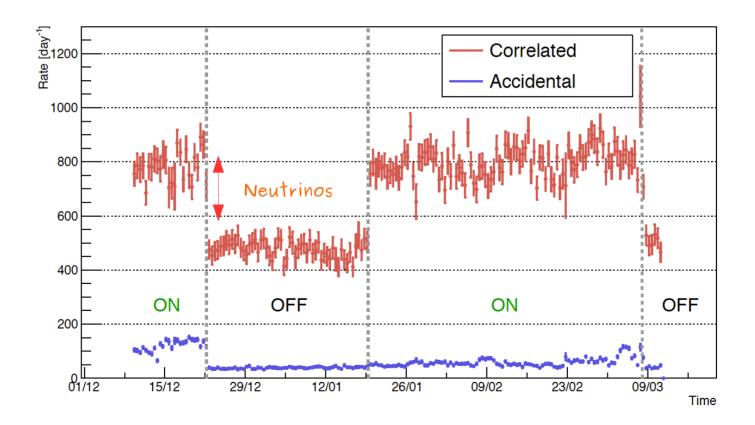




5. Neutrino candidates search

Correlated pairs rates

- Pair selection : Energy cuts, Topology, Isolation cuts (from μ stop & spalliation), PSD,PMT asymmetry ...
- Accidentals subtraction : very low accidental background (~50 events / day)
- Neutrino rate after dead time & pressure correction : ~ 350 /day



Conclusion

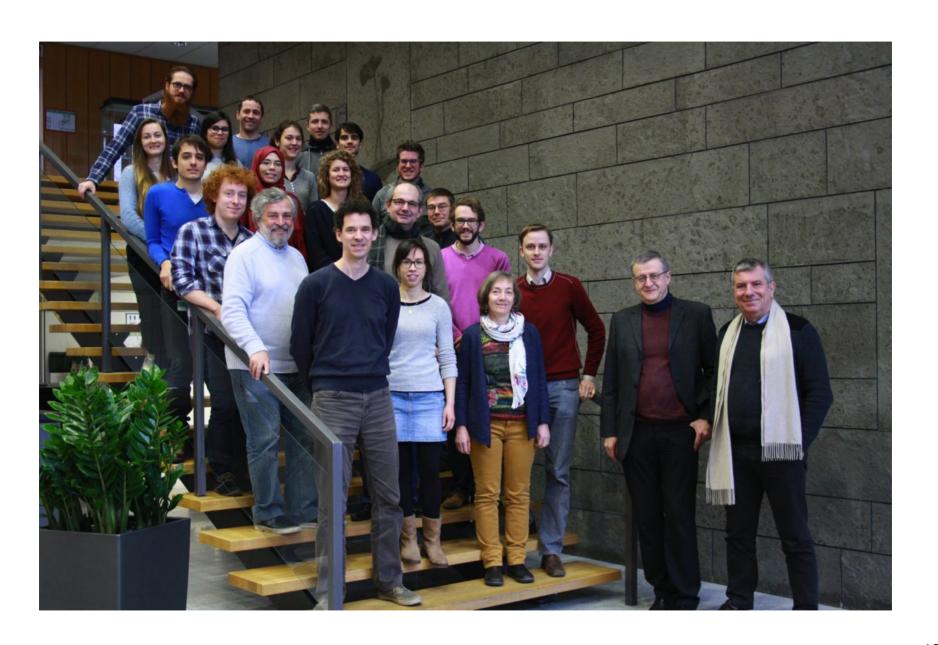
What has been done?

- ✓ Data taking: 62 days of On data + 26 days of Off-phase-I data + 57 days of Off-phase-II data
- Calibration, Energy reconstruction, Detector stability, Neutrino search, cosmic background understanding & reduction
- Detector repaired :
 - Light collection improved + light leaks are now stable, homogeneous & symmetric

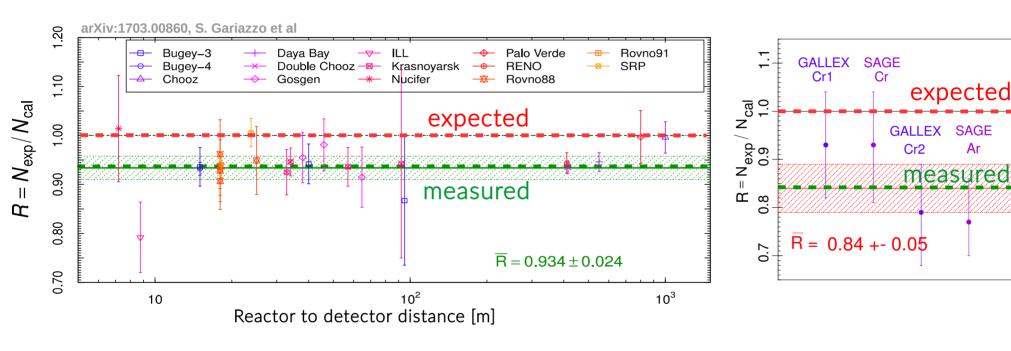
What's next?

- Optimize cuts & define systematics for OFF subtraction
- Finalize energy reconstruction for spectral analysis
- Publication of results from phase-I by spring 2018. Phase-II expected to be completed by mid-2019
- > ... Wait for more neutrinos! (Reactor On, february / march 2018)

Thank you for your attention



Reactor Anti-neutrino & Gallium Anomalies



Second hypothesis :

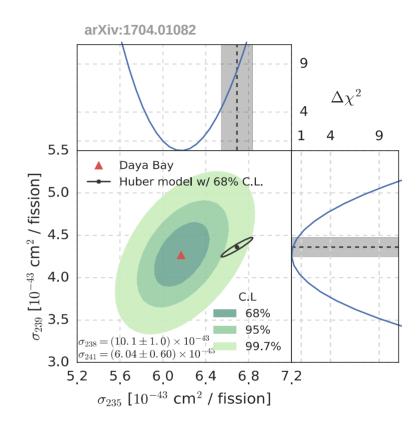
Potential bias in the prediction spectra

Example: Daya Bay result 2017

- Disfavor the hypothesis of a new oscillation at 2.6 significance
- Suggests that ²³⁵U may be the primary contributor to the RAA

Example: 4-6 MeV bump

- Seen by NEOS, DAYA BAY, RENO, Double Chooz
- Linked to predictions of different isotopes ? ...



We need clear measurements in the best fit region, at short base line

→ Constrain the neutrino spectra from reactors

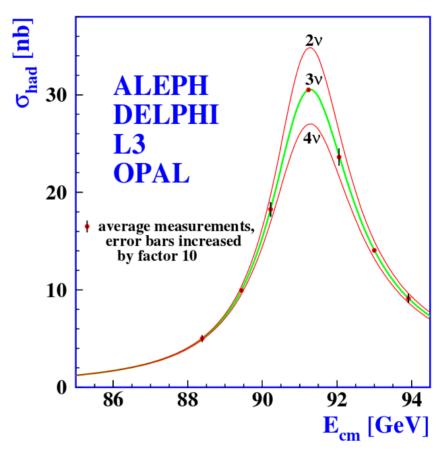
arXiv:hep-ex/0509008

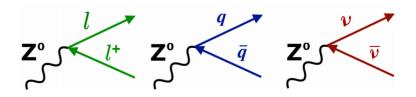
- Fit of the Z boson decay width as a function of the number of neutrinos sensible to weak interaction
- 1990s at CERN

2.9840 +- 0.0082 number of neutrinos coupling to weak interaction

If existence of a new neutrino, it can only be "sterile"

(no interaction with weak force, only gravitational)





Mounting at ILL, level C

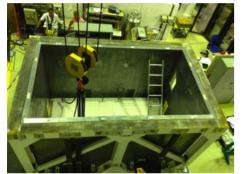
PE + mumetal

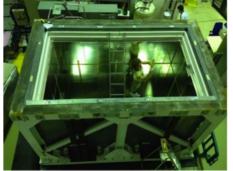
Lead walls: fast-n thermalization + capture

gamma's Magnetic field attenuation

Inner det vessel

PE roof



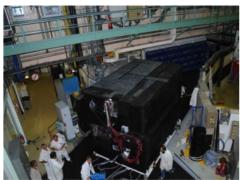






n absorbers (B4C)

93 t setup moved on air cushions



Fire protection

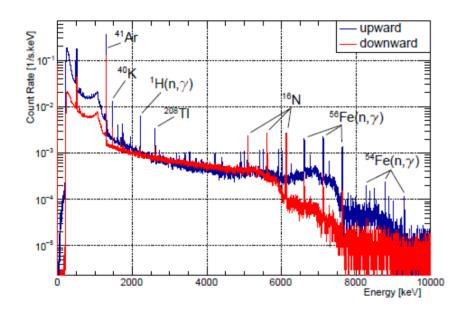


Liquid filling



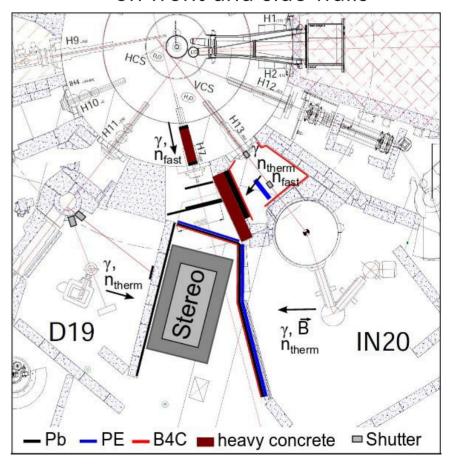
Reactor Sources of Background

- Extraction of neutron beams for neighboring experiments.
- Extensive campaigns of characterization of n and gamma sources before shielding design.



- Background of fast and thermal neutrons from side experiments →High E g's from n-capture on metals: ⁵⁶Fe(n, g) 7.6 MeV, ...
- Activation: ⁴¹Ar in air ($T_{1/2}$ ~2h, 1.3 MeV), primary water circuit (¹⁶O(n,p)¹⁶N, $T_{1/2}$ ~7s, 6.1 MeV).
- Stray magnetic fields.

Heavy passive shielding added on front and side walls



Energy Reconstruction

$$Q_i = \alpha_i^{\text{geom}} \sum_{j=\text{cells}} E_j^{\text{dep}} \times f_j \times L_{j \to i}$$

$$\text{photon acceptance cell i} \text{photons per MeV} \text{between cells per MeV}$$

 \rightarrow We don't have access to de-correlated parameters *alpha*, L & f

We only have access to alpha * f, and an effective light leaks coefficient

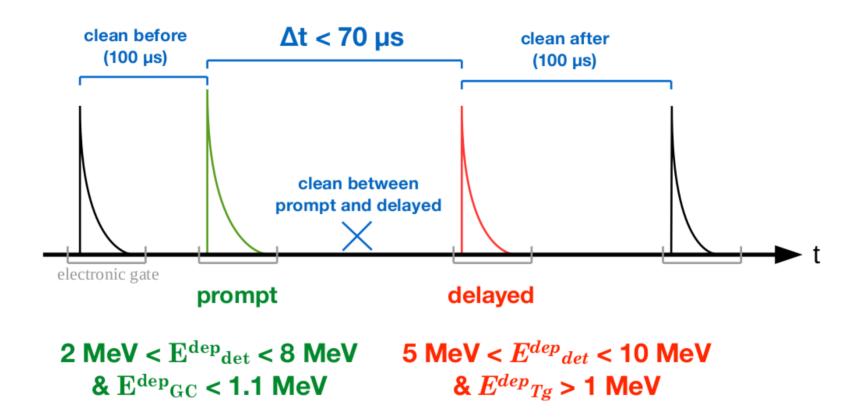
$$Q_{j} = \sum_{j=cells} E_{j} C_{j} L_{ji} = \sum_{j=cells} E_{j} M_{ji}$$
Collected photons/MeV from Cross-talk cells $j \rightarrow l$ calib runs Measured online + calib

$$\overrightarrow{E^{rec}} = M^{-1}\overrightarrow{Q}$$

→ The vector of deposited E in each cell is reconstructed by inverting the M matrix:

- ☐ Compare Data and MC at the level of E^{rec}, corrected to first order for light collection effects.
- Iterative fine-tune of C and LL coefficient for an accurate matching of experimental and simulated E^{rec} distributions from a ⁵⁴Mn source circulated in the calibration tubes.

Neutrino pair search



+ PMT asymmetry for muon stops

Correlated pairs rates

The shallow depth of the experiment induces a dependence of background on atmospheric pressure.

Measured online to correct the rates back to a reference pressure of 1024 hPa.

