# Light sterile neutrino oscillation searches.

**Neutrino Oscillation Workshop 2018, *Ostuni, Italy***

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# Summary

# Summary

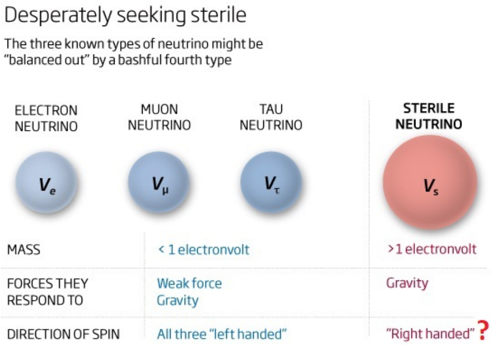
# What's the role of sterile neutrinos?

## Why to call them "sterile"?

- ... because Standard Model forces have no influence on them.

## Which properties?

- massive fermion, spin 1/2
- do not carry any charge for any SM force



# Sterile neutrinos energy scale

### Where to search them?

- ... mass scale is a free parameter.
- from $\approx$ $eV$ towards $10^{15}$ $GeV$

### Phenomenology

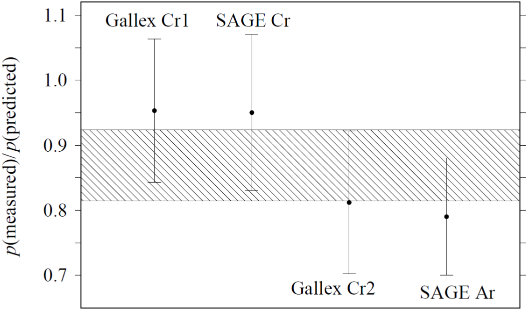
1. $10^9 - 10^{15}$ $GeV$...heavy $\nu_{sterile}$ motivated by Grand Unified Theory, baryon assymmetry & leptogenesis.
2. $10^2 - 10^9$ $GeV$...linked with early Universe studies.
3. $1$ $keV - 10^2$ $GeV$...cosmology, $\nu_{sterile}$ decays.
4. $1$ $eV - 1$ $keV$...light $\nu_{sterile}$ cannot solve cosmological problems, but other observed anomalies (RAA, Ga, etc.).

**Focused on light sterile neutrinos $\sim eV$.**

# Summary

# Gallium solar $\nu$ experiments

Use of intense artificial $^{51}Cr$ and $^{37}Ar$ radioactive sources inside the detectors.
Parameter $R = \frac{measured}{predicted}$ $^{71}Ga$ $rates$[1]




[1] "Measurement of the solar neutrino capture rate with gallium metal. III: Results for the 2002 - 2007 data-taking period." by J. N. Abdurashitov et al., DOI: 10.1103/PhysRevC.80.015807, 2009.

# Gallium solar $\nu$ experiments

Final[2] average ratio $R^{Ga} = 0.76^{+0.09+0.17+0.24}_{-0.08-0.15-0.21}$
Anomaly statistically significant at a level of about $\sim 3.0\sigma$
This is known as the "Gallium anomaly"!

[2] "Statistical Significance of the Gallium Anomaly" by C. Giunti, M. Laveder, DOI: 10.1103/PhysRevC.83.065504, 2011.

# Reactor Antineutrino Anomaly

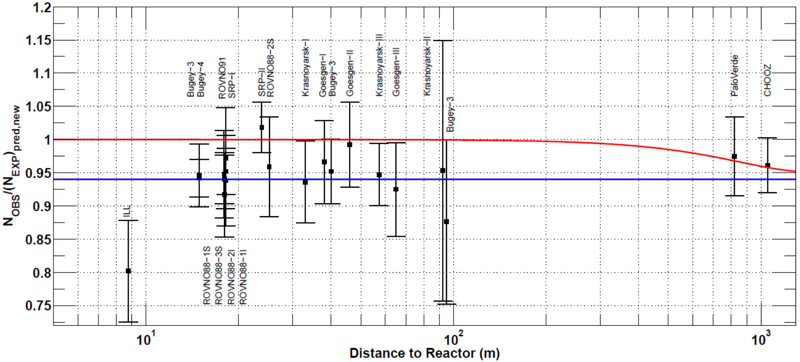
## Reactor $\nu$ experiments

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

Survival probability: $P_{ee}(L) = 1 - sin^2(2\Theta_i)sin^2(1.27\frac{\Delta m_i^2[eV^2]L[m]}{E_{\bar{\nu}_e}[MeV]})$

where: $\Delta m_i^2 = \Delta m_{21}^2$, $\Theta_i \sim \Theta_{12}$ if $L >\sim 10\ km$, long baseline

$\Delta m_i^2 = \Delta m_{31}^2$, $\Theta_i = \Theta_{13}$ if $L <\sim\ km$, short baseline



# Reactor Antineutrino Anomaly

Mean ratio[3] $N_{obs}/N_{pred} = 0.943 \pm 0.023 < 1$
This deficit is known as the "Reactor Antineutrino Anomaly"!
RAA & Ga $\rightarrow \nu_e$ disappearance anomaly

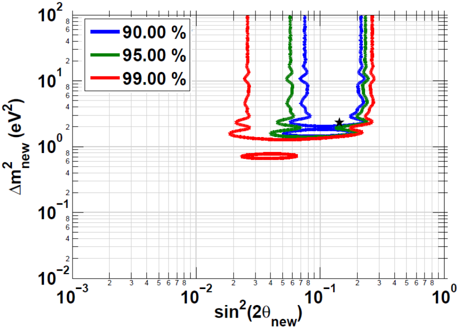
**Possible explanation?**

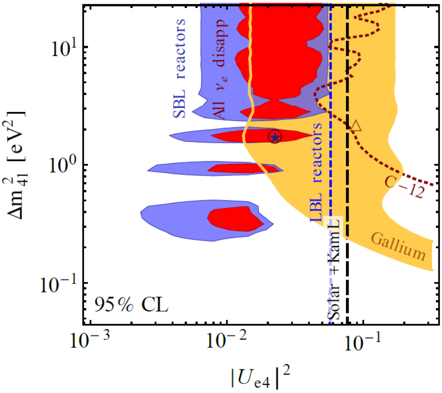
- Erroneous prediction of the antineutrino flux from the reactors
- The $4^{th}$ neutrino - $\nu_{sterile}$

[3] "The Reactor Antineutrino Anomaly" by G. Mention et al., DOI: 10.1103/PhysRevD.83.073006, 2011.

# 3+1 neutrino hypothesis

Allowed regions from the combination of all anomalies[3 4]
$| \Delta m^2_{new} | > 1.5\ eV^2$ (95 % C.L.)
$sin^2(2\Theta_{new}) = 0.14 \pm 0.18$ (95 % C.L.)

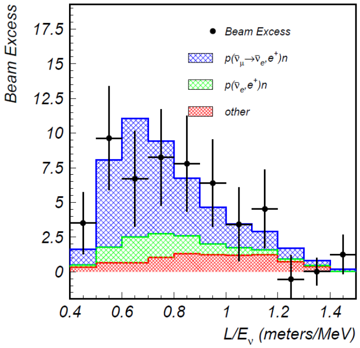



[4] "Sterile neutrino oscillations: the global picture" by J. Kopp et al., DOI: 10.1007/JHEP05(2013)050, 2013.

# $\nu_\mu \to \nu_e$ anomalous appearance: LSND

- $1^{st}$ excess of $\nu_e$ events in a $\nu_\mu$ beam observed by LSND, total excess of $87.9 \pm 22.4 \pm 6.0$ $\nu_e$-like events (1993-1998 years data)[5]

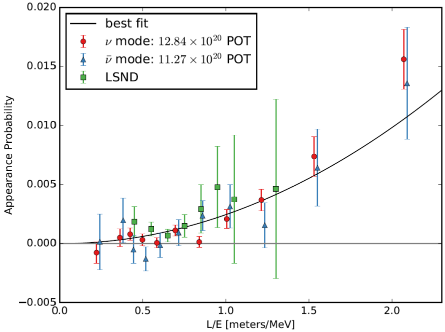



- LSND suggested $\nu$ flavor oscillations with a $\Delta m^2 \in (0.2, 10)\ eV^2/c^4$
- Recent MiniBooNE experiment verifies LSND results

[5] "Evidence for Neutrino Oscillations from the Observation of $\bar{\nu}_e$ Appearance in a $\bar{\nu}_\mu$ Beam", A. Aguilar et al., DOI:https://doi.org/10.1103/PhysRevD.64.112007, 2001

# MiniBooNE

- Total $\nu_e + \bar{\nu}_e$ charged-current quasi-elastic excess of $460.5 \pm 95.8$ ($4.8\sigma$) events[6]



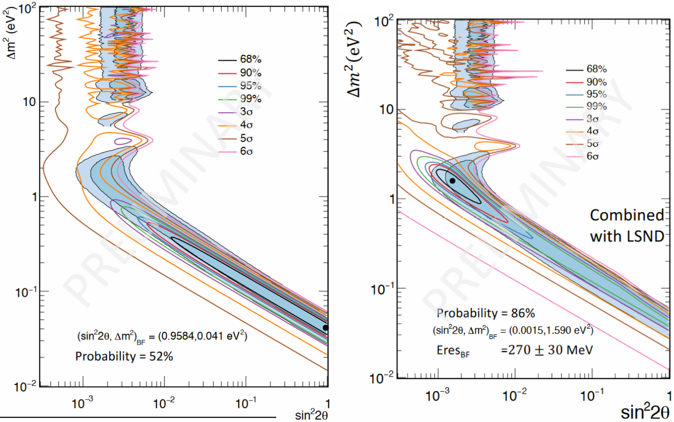

- Consistency with LSND results

[6] "Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment", A. A. Aguilar-Arevalo et al., arXiv:1805.12028v1 (hep-ex), 2018

# MiniBooNE

## MiniBooNE

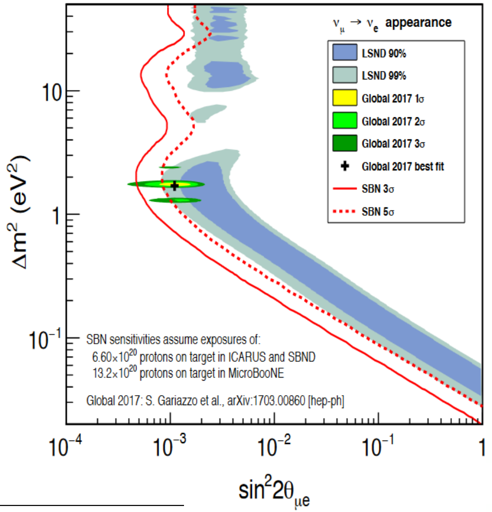
- LSND + MiniBooNE data $\rightarrow$ best fit point $\Delta m^2 = 0.041 eV^2$, $sin^2(2\Theta) = 0.958$[7] $\rightarrow$ MSW-Like Resonance Model could provide a better fit




[7] "Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment", A.A. Aguilar-Arevalo et al., arXiv:1805.12028, 2018 & "Updated MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation on Results", En-Chuan Huang Neutrino2018 talk.

# More answers?

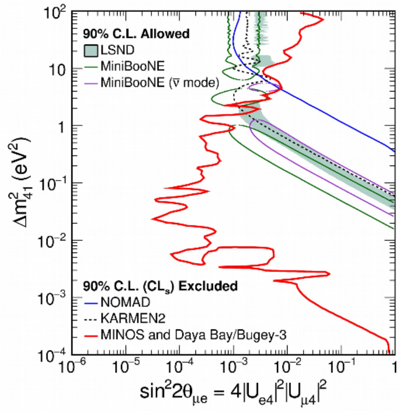
- Future: Fermilab SBN program...expected sensitivity[8]




[8] "MicroBooNE and the Future SBN Program", by R. Guenette, Neutrino 2018 talk.

# $\nu_\mu$ disappearance: MINOS & MINOS+

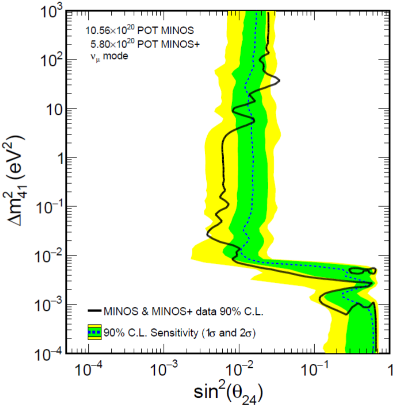
- Looking at $\nu_\mu$ disappearance, near & far detectors
- Results in tension with MiniBooNE&LSND experiments[9]




[9] "Search for sterile neutrinos in MINOS and MINOS+ using a two-detector fit", P. Adamson et al., arXiv:1710.06488, 2017, & "Recent Results from MINOS and MINOS+", A. Aurisano Neutrino2018 talk.

# MINOS & MINOS+

- Exclusion plot[9]



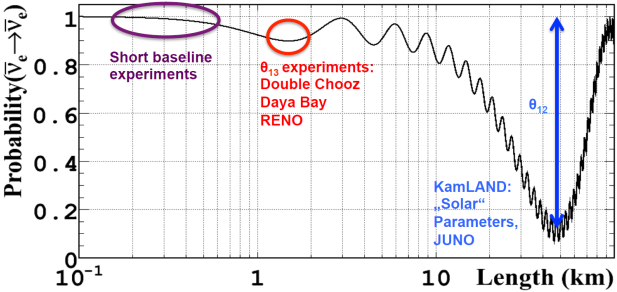

- No evidence of $\nu_{sterile}$ mixing

# Summary

# Daya Bay, Double Chooz, RENO

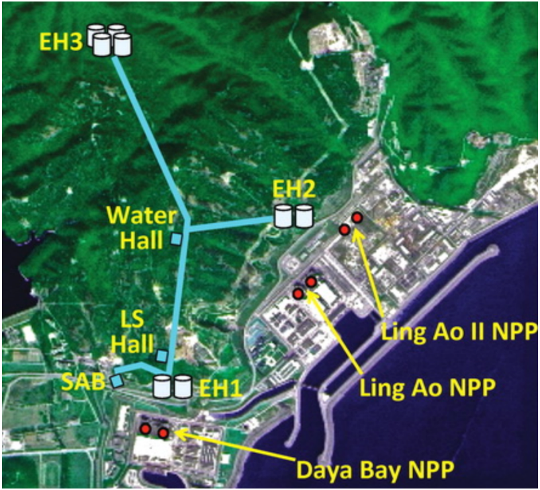
## Reactor neutrinos

- Designed to measure the $\Theta_{13}$, IBD + Gd loaded liq. scinillator. Far & near detectors.
- Use of industrial nuclear power plants (NPP) $\rightarrow$ Low Enriched Uranium (LEU) cores.
- Useful information for $\nu_{sterile}$ searches.



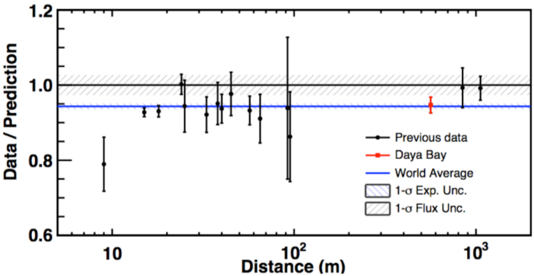
# Daya Bay

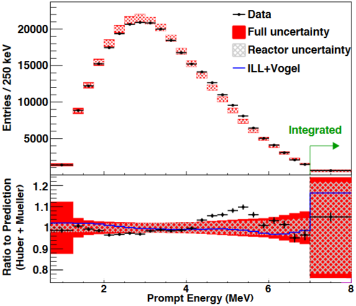
Common experimental setup: several reactors from NPP, several far & near detectors.



# Daya Bay

$R^{1230days}_{data/prediction} = 0.952 \pm 0.014(exp.) \pm 0.023(model) < 1 \rightarrow$ RAA
Low Enriched Uranium reactor experiment observes spectral deviations[10]



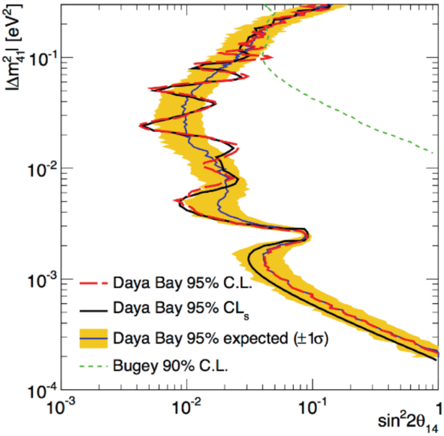




- Indication of incorrect flux predictions being partially responsible for RAA
- Short baseline & HEU cores → better probe of spectral anomaly nature

[10] "Improved measurement of the reactor antineutrino flux and spectrum at Daya Bay", F. P. An et al. 2017 Chinese Phys. C 41 013002. & "Latest results from Daya Bay", J. Pedro Ochoa-Ricoux talk Neutrino2018.

# Daya Bay

Exclusion contours for light $\nu_{sterile}$[11]
No evidence of a light $\nu_{sterile}$ in the $2 \times 10^{-4} \leq | \Delta m^2_{41} | \leq 0.2\ eV^2$ region

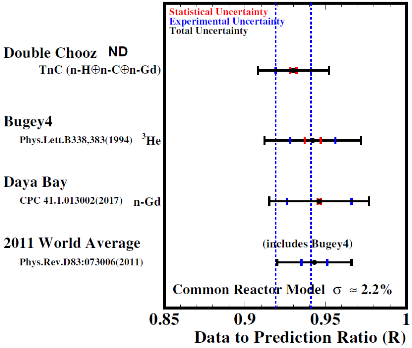


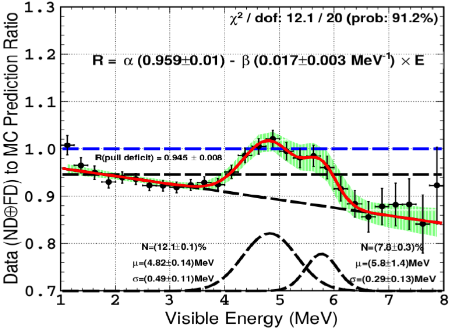

[11] "Improved Search for a Light Sterile Neutrino with the Full Configuration of the Daya Bay Experiment", by F. P. An et al., DOI: 10.1103/PhysRevLett.117.151802, 2016.

# Double Chooz

$R^{101days}_{data/prediction} = 0.944 \pm 0.016(stat) \pm 0.040(syst) < 1 \rightarrow$ RAA

Again, LEU core experiment that observes spectral deviations[12]



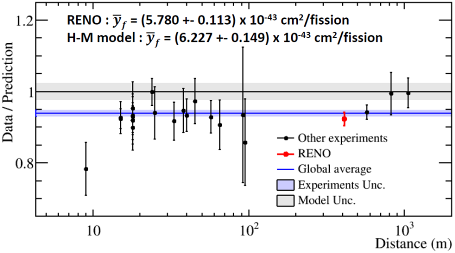

[12] "Indication of reactor $\nu_e$ disappearance in the Double Chooz experiment", Y. Abe et al, DOI: 10.1103/PhysRevLett.108.131801, 2012. & "New Results from the Double Chooz Experiment", Ch. Buck Neutrino2018 talk.

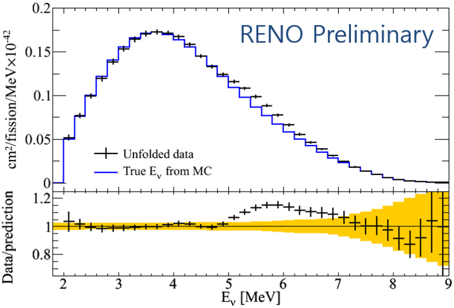
# RENO

$R^{2200days}_{data/prediction}(Huber\ Mueller\ model) = 0.924 \pm 0.018$

$R^{2200days}_{data/prediction}(ILL\ Vogel\ model) = 0.966 \pm 0.019 < 1 \rightarrow$ RAA

Again, LEU core experiment observes spectral deviations[13]

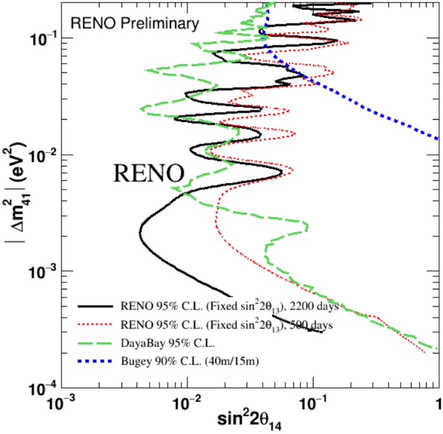



[13] "New Results from RENO", H. Seo talk at ICHEP2018. & "Observation of energy and baseline dependent reactor antineutrino disappearance in the RENO experiment", J.H. Choi et al., DOI: 10.1103/PhysRevLett.116.211801, 2015.

# RENO

Exclusion contours for light $\nu_{sterile}$ with 2200 data days[14]
Very stringent limits for a light $\nu_{sterile}$ in the $|\Delta m^2_{41}| < 10^{-2}\ eV^2$ region

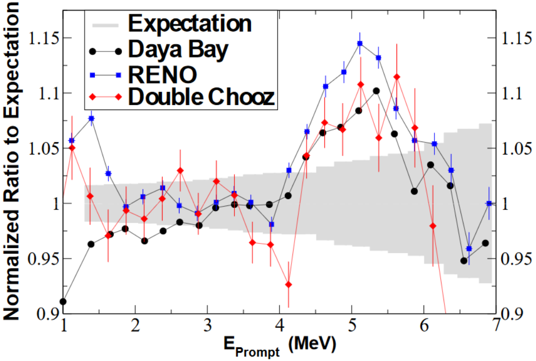



[14] "Search for Sterile Neutrinos at RENO", by J. Seo, Neutrino2018 poster.

# Daya Bay, Double Chooz, RENO

**To sum up...**

- All see $R_{data/prediction} < 1$ deviation of several $\sigma$
- Spectral distorsion in 4-6 MeV energy region appears[15]
- Exclusion of light $\nu_{sterile}$ in the very low region of $| \Delta m^2_{41} | < 10^{-1}\ eV^2$

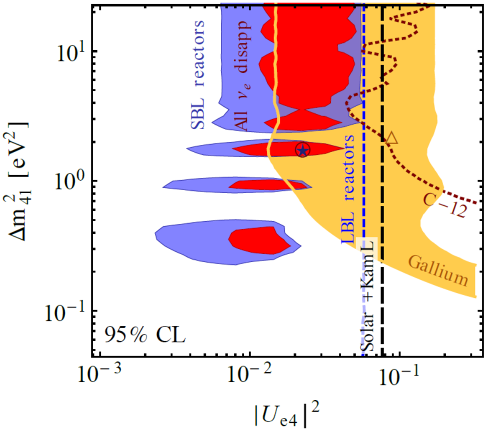



[15] "Status of Reactor Antineutrino Flux Predictions", by A. Hayes, Neutrino2018 talk.

# Long/short → very short baseline

**To have more answers...**

- Very short baseline reactor experiments
- Use Highly Enriched Uranium cores to check spectral distorsion
- Verify light $\nu_{sterile}$ existence for the higher values of $|\Delta m^2_{41}| > 10^{-1}\ eV^2$



# Summary

## Today's short baseline reactor experiments

| | Core Φ | Core $H$ | $P_{th}$ | $^{235}U$ % | Baseline (m) |
|---|---|---|---|---|---|
| **NEOS** | 3.1 m | 3.8 m | 2.8 GW | $\sim 4$ | 23.7 |
| **DANSS** | 3.2 m | 3.7 m | 3.1 GW | $\sim 4$ | 10.7 - 12.7 |

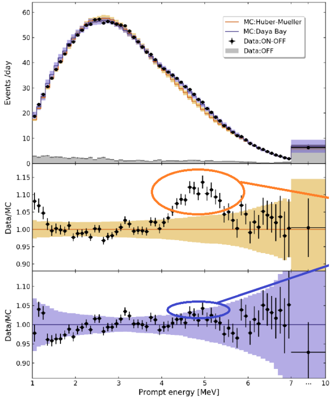
| | Core Φ | Core $H$ | $P_{th}$ | $^{235}U$ % | Baseline (m) |
|---|---|---|---|---|---|
| **STEREO** | 40 cm | 80 cm | 58 MW | 93 | 9-11 |
| **SOLID** | 50 cm | 90 cm | 50-80 MW | 93 | 6-9 |
| **PROSPECT** | 44 cm | 51 cm | 85 MW | $> 93$ | 7-9 |

Core size and fuel composition impact on systematics & $\nu$ rates.

- Focused on light sterile neutrino search!

# NEOS

- Gd loaded liq. scintillator target, 23.7 m baseline
- Spectral anomaly using Huber Mueller model for predicted flux[16]

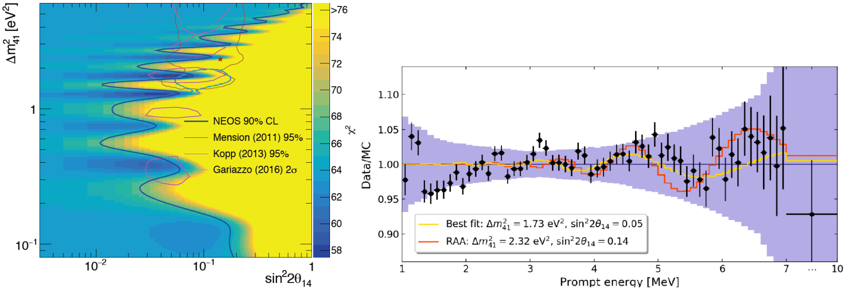



Bump decreases when using Daya Bay spectrum as predicted model

[16] " Sterile Neutrino Search at the NEOS Experiment", Y. J. Ko et al., DOI: 10.1103/PhysRevLett.118.121802, 2016.

# NEOS

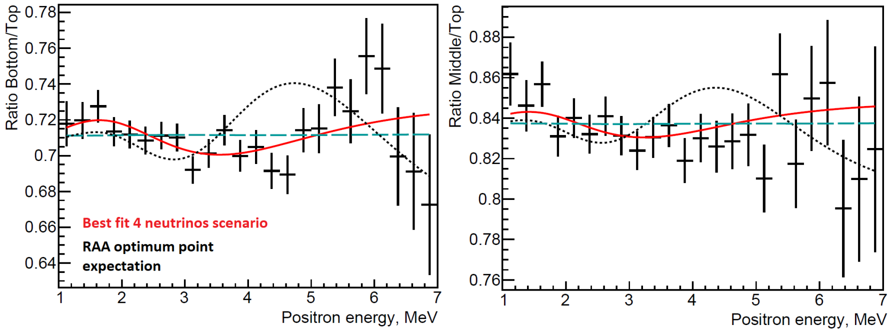
- Exclusion plots for $|\Delta m^2_{41}| > 10^{-1}\ eV^2$ region[16]
- Normalization to Daya Bay spectrum
- Ongoing experiment!




- No strong evidence for light $\nu_{sterile}$ existance with $\Delta m^2 \sim 1\ eV^2$, $sin^2(2\Theta) \sim 0.1$
- Best fit at $\Delta m^2_{41} = 1.73\ eV^2$, $sin^2(2\Theta_{14}) = 0.05$
  with $\chi^2(3\nu) - \chi^2(4\nu) = 6.5$, $p - value = 0.22$

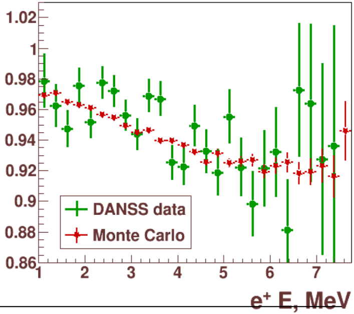
# DANSS

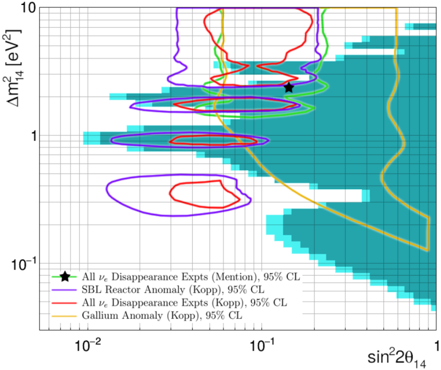
- High segmentation of 1 $m^3$ plastic scintillator target, Gd loaded.
- Detector under reactor core. 3 baselines: down - 12.7 m., middle - 11.7 m., top - 10.7 m.
- Ratio of spectra for bottom/top and middle/top detector positions[17]
  Best fit: $\Delta m^2_{41} = 1.4\ eV^2$, $sin^2(2\Theta_{14}) = 0.05$, $2.8\sigma$ significance. $\Delta\chi^2$ with the $3\nu$ case is 13.



# DANSS

- DANSS observes spectrum dependence on the fuel composition and data agree with Huber Mueller prediction.
- Exclusion plot[17] - RAA best fit $\Delta m^2_{41} = 2.4\ eV^2$, $sin^2(2\Theta_{14}) = 0.14$ excluded at $5\sigma$ level
- Ongoing experiment! ☞ *D. Svirida talk, Session IV, 16.25-16.50.*

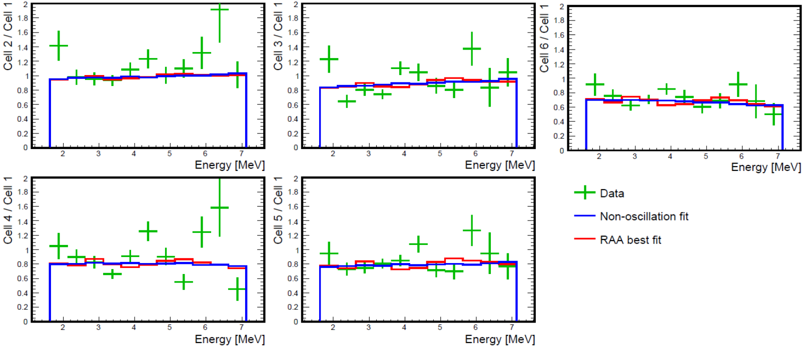



[17] "Search for sterile neutrinos at the DANSS experiment", I. Alekseev et al., arXiv:1804.04046v2 (hep-ex), 2018. "Reactor antineutrino physics with DANSS experiment", I. Alekseev ICHEP2018 talk.

# STEREO

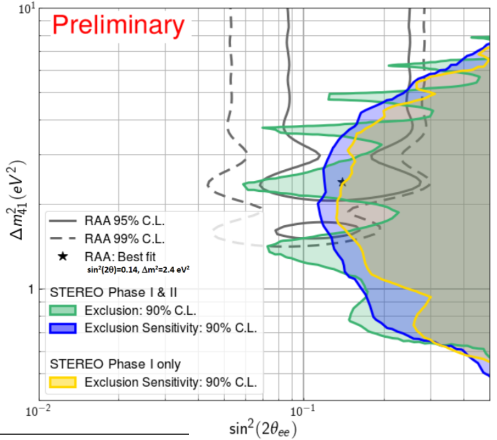
- Liq. scintillator target - 6 cells, Gd loaded.
- HEU compact core, baseline 9-11 m.
- Ratio of spectra for $\frac{cell_i}{cell_1}$ ...independent of predicted reactor spectrum[18]!




[18] "Sterile neutrino exclusion from the Stereo experiment with 66 days of reactor-on data", H. Almazan et al., arXiv:1806.02096v1 (hep-ex), 2018.

# STEREO

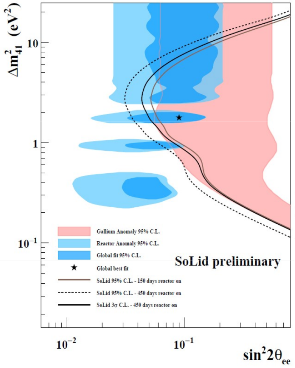
- Results are compatible with the null oscillation hypothesis (66 + 47 data days)
- RAA best fit $\Delta m^2_{41} = 2.4\ eV^2$, $sin^2(2\Theta_{14}) = 0.14$ is excluded at 98% $C.L.$[19]
- Ongoing experiment! Data taking until end of 2019 $\rightarrow \geq 300$ reactor ON data days

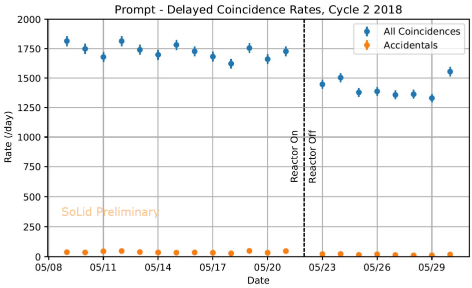



[19] "Latest results of the STEREO experiment", J. Lamblin talk at Neutrino2018.

# SOLID

- High segmentation, plastic scintillator target, Li loaded, HEU core
- Constructed in 2017 and commissioned in Nov-Dec 2017, ongoing experiment
  ☞ *L. Kalousis talk, Session IV, 16.50-17.15.*
- Sensitivity plot and first preliminary analysis rates[20]

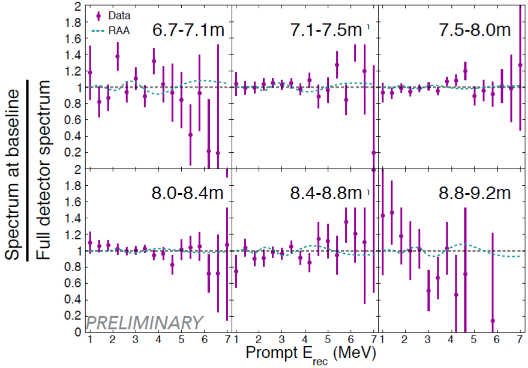



[20] "SoLid: Search for Oscillations with a Lithium-6 Detector at the SCK-CEN BR2 reactor", N. Van Remortel talk at Neutrino2018.

# PROSPECT

- Segmentation & Li loaded liq. scintillator, baseline 7-9 m. HEU core
- Ratio of spectra at different baselines to the total detector spectrum[21]

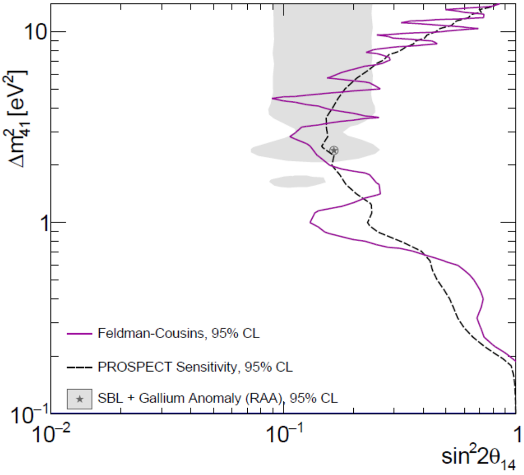



- No significant deviations from unity → compatibility with the no-oscillation hypothesis

[14] "First search for short-baseline neutrino oscillations at HFIR with PROSPECT", J. Ashenfelter et al., arXiv:1806.02784v3 (hep-ex), 2018.

# PROSPECT

- Exclusion plot[21] with 33 data days - RAA best fit value excluded at 2.2$\sigma$ level
- Ongoing experiment!



## Some features of ongoing short baseline reactor experiments

| | $\sigma/E\%$ | **average rate/day** | $n$ **capture** |
|---|---|---|---|
| **DANSS** | 17 | $4101 \pm 11$ | Gd |
| **NEOS** | 5 | $\sim 1976$ | Gd |
| **STEREO** | 9 | $396 \pm 4.7$ | Gd |
| **PROSPECT** | 4.5 | $\sim 750$ | Li |
| **SOLID(preliminary)** | 14 | $\sim 1750$ ON &$\sim 1375$ OFF | Li |

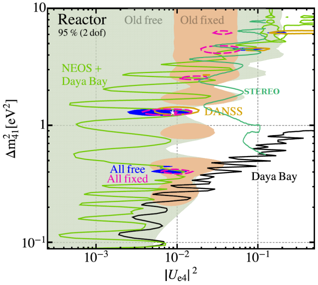
# Today's short baseline reactor experiments

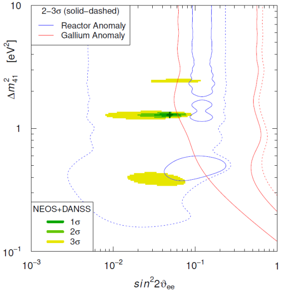
**To sum up...**

- Spectral distorsion at 4-6 MeV region: NEOS - yes, DANSS - no...both use LEU cores, Gd-doped...Different fuel burn-up analysis?...Waiting for HEU core experiments results.
- Ratio of spectra at different baselines...independant from predicted flux models!...No strong evidence of $\nu_{sterile}$ oscillations from NEOS, DANSS, STEREO & PROSPECT results. But! Small energy modulations might be hints of $\nu_{sterile}$ *(NEOS)*.
- Exclusion plot...all exclude RAA best fit point ($\Delta m^2_{41} = 2.4\ eV^2$, $sin^2(2\Theta_{14}) = 0.14$) at at least $\sim 95\%\ C.L.$

# RAA best fit $\Delta m^2_{41} = 2.4eV^2$, $sin^2(2\Theta_{14}) = 0.14$ exclusion from reactor experiments

- But!...Updated global analysis[22] suggests the new best fit value with Daya Bay, NEOS & DANSS results...$\Delta m^2_{41} \approx 1.3eV^2$




Combined DANSS & NEOS analysis[23] → best fit at
$\Delta m^2_{41} = 1.29 \pm 0.03\ eV^2$, $sin^2(2\Theta_{ee}) = 0.049 \pm 0.011$

[22] "Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos", M. Dentler et al., DOI: 10.1007/JHEP08(2018)010, 2018.

[23] "Model-Independent $\nu_e$ Short-Baseline Oscillations from Reactor Spectral Ratios", S. Gariazzo et al., DOI: 10.1016/j.physletb.2018.04.057, 2018.

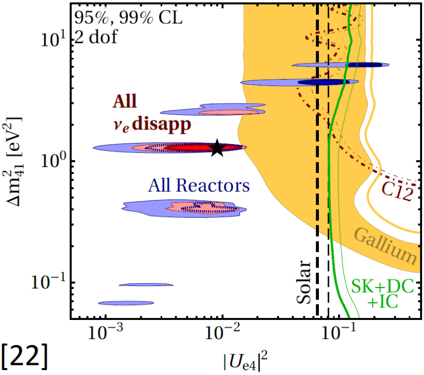
# Summary

# $\nu_{sterile}$ experiments

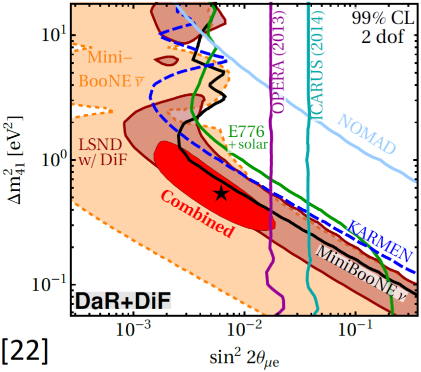
- Reactor neutrinos: very short baseline, $\nu_e$ disappearance anomaly
- Neutrino beams: $\nu_\mu \to \nu_e$ appearance anomaly
- Neutrino beams: $\nu_\mu$ disappearance

## New best fit estimations

- ☞ *Y. Li talk, Session IV, 16.00-16.25.*




[22]




[22]

# $\nu_{sterile}$ experiments

- New best fit values from different experiments (DANSS, NEOS...)$\Delta m^2_{41} \sim 1.3 - 1.7 eV^2$, $sin^2(2\Theta_{14}) \sim ?...0.05$ or $sin^2(2\Theta_{14}) < 0.01$
- Additional question: 4-6 MeV spectral anomaly in observed/predicted neutrino flux ratios
- No strong evidence for sterile neutrinos mixing. Neither, any proof to discard it completely!
- Waiting for present experiments results!

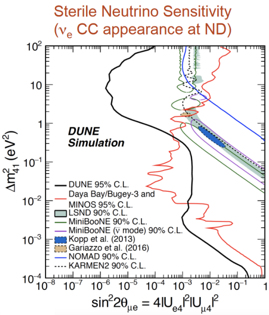
# Future experiments...

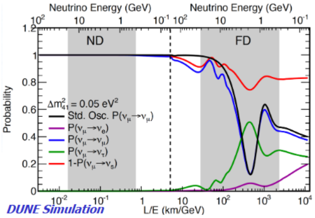
- Reactor neutrinos: **JUNO**...liq. scintillator, LEU cores from NPP.
- Neutrino beams:
  **SBN**...3 liq. Ar detectors, short baselines
  **DUNE**...near & far LArTPC detectors, long baselines

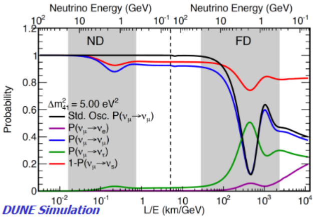
However, today's very short baseline experiments are the last ones from the "RAA trend"

# ...& goals

- **JUNO**: near detector *HERLSD*...Gd liq. scintillator at 30-50 m. baseline...Aim to energy resolution of 1.7% at 1 MeV!
  Can be used for $\nu_{sterile}$ research
- **SBN**: to adress the short baseline anomalies...next 5 years
- **DUNE**: main goals are $\nu$ oscillations, CP violation, mass ordering
  $\nu_{sterile}$ search by comparing near & far detectors[24].




[24] "Searching for Beyond the Standard Model Physics with the DUNE Experiment", A. Sousa & "DUNE: Status and Science", E. Worcester, Neutrino2018 contributions.

# Still a lot to discover!

☆ ☆ ☆ **Thank you for your attention!** ☆ ☆ ☆

✉ ✍ *viktoriya_srgyv@hotmail.com*

# Summary

# Additional plots about $\nu_{sterile}$ shown during NOW 2018

- OPERA by G. Sirri
- Antares by J. Brunner
- IceCube by A. Terliuk
- NO$\nu$A by M. Strait

# Combining $\nu_\tau$ and $\nu_e$

PRELIMINARY

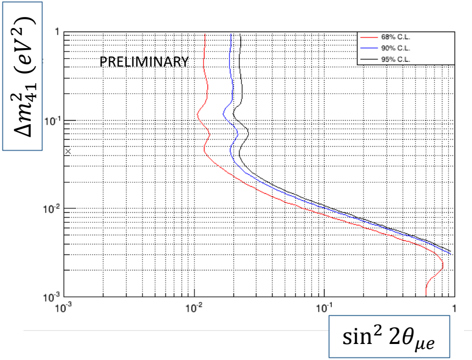
Exploiting **simultaneously** results of

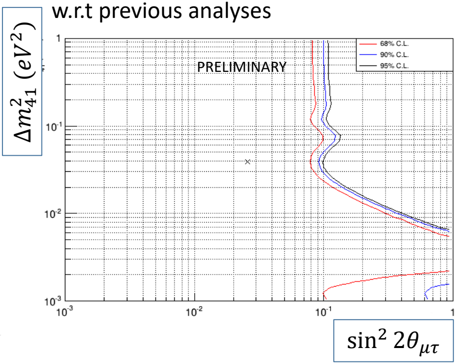
- $\nu_\tau$ search: 10 candidates
- $\nu_e$ search: 35 candidates

....

… to extract limits on the parameters of the 3 + 1 neutrino model

(Small) **exclusion power enhancement** w.r.t previous analyses



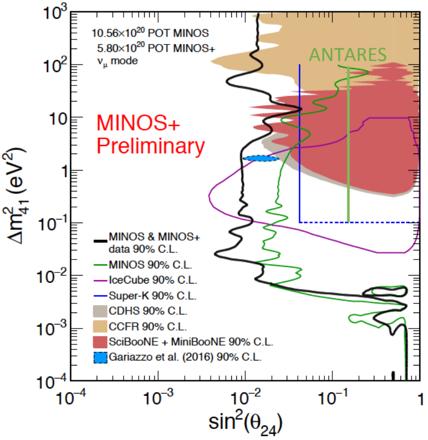




$\sin^2 2\theta_{\mu e} < 0.019$ [90% C.L.]
@ $\Delta m^2_{41} \sim 1$ eV$^2$

$\sin^2 2\theta_{\mu\tau} < 0.099$ [90% C.L.]
@ $\Delta m^2_{41} \sim 1$ eV$^2$

# Comparison with muon disappearance results

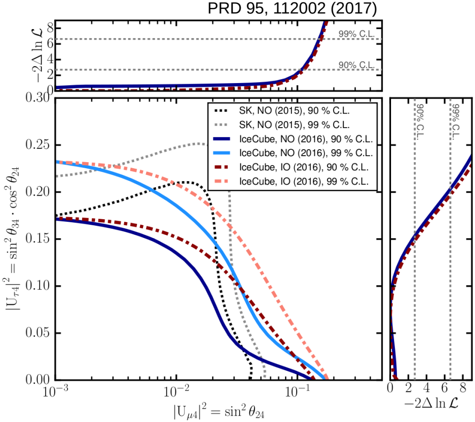
- Plot from recent MINOS+ analysis



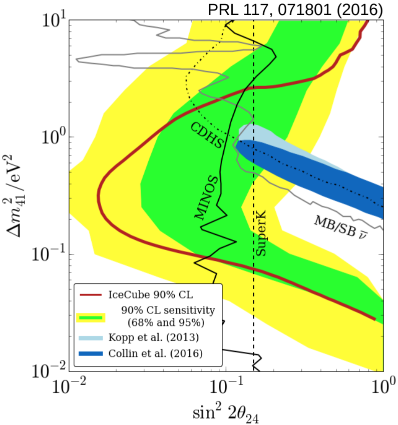
# Sterile neutrinos with IceCube

## Our limits

- Sterile neutrinos with DeepCore

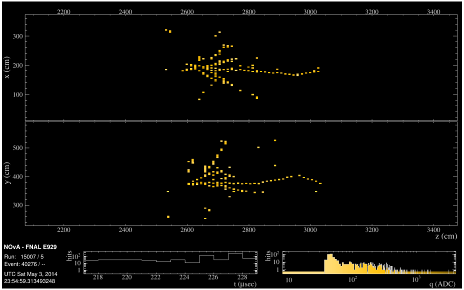


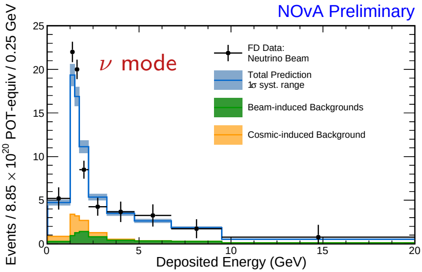

- TeV search for sterile neutrinos

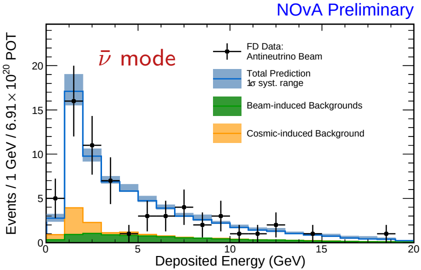



- Constraining limits on sterile neutrino mixing in muon and tau sectors

# Neutral Current Disappearance




- Neutrino beam:
  - Predict $188 \pm 13$ (syst.) (38 bg)
  - Observe 201
- Antineutrino beam:
  - Predict $69 \pm 8$ (syst.) (16 bg)
  - Observe 61
- No significant suppression of neutral current interactions observed for neutrinos or antineutrinos

# Summary

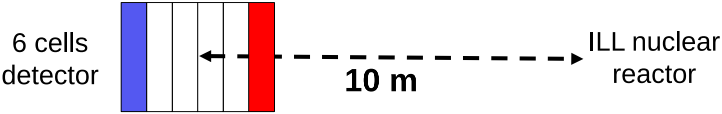
# STEREO details

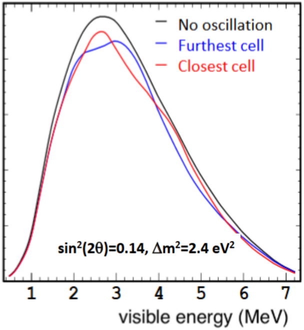
Presented on NEUTRINO 2018 by J. Lamblin.

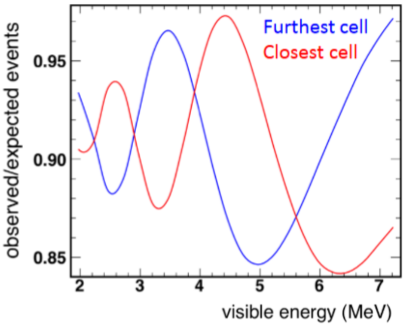
- Site & geometry
- Detector response
- IBD selection
- Ratio method

# The STEREO experiment

Goal: search for sterile neutrinos by measuring relative distortions of the $\bar{\nu}_e$ energy spectrum as a function of the distance to the source



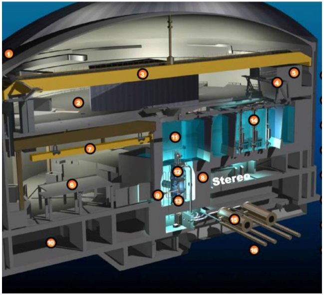




⇒ Independent from predicted energy spectrum (normalization + shape)

# ILL site

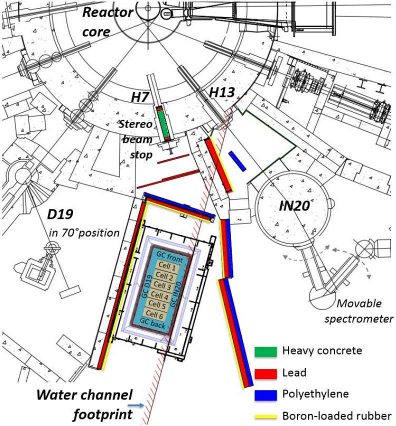


- 58 MW research reactor
- $10^{19}$ s$^{-1}$ $\bar{\nu}_e$ flux
- Highly enriched fuel: $^{235}$U (93%)
- 3-4 cycles of 50 days per year
- compact core Ø40 cm x 80 cm
- [9–11] m from core



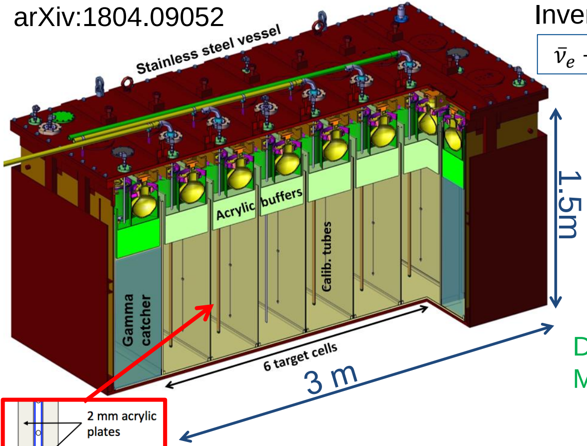

But :

- Shallow depth (cosmics)
- γ and neutron background due to experimental lines



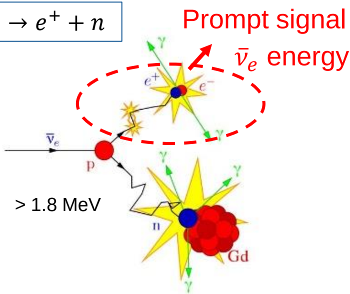
# The STEREO detector

arXiv:1804.09052



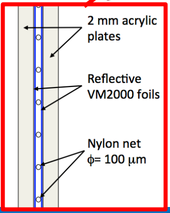

Invert Beta Decay

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




Delayed signal

Mean neutron capture time 16 $\mu s$




### Target

6 cells filled with
Gd-loaded liquid scintillator
4 top PMTs per cell

### Gamma-catcher

Outer-crown to detect $\gamma$'s escaping from the Target + active shielding

24 PMTs

# Detector response



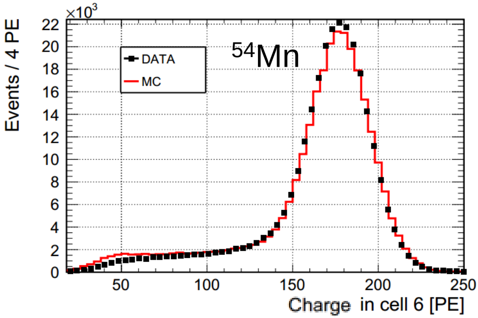
arXiv:1804.09052

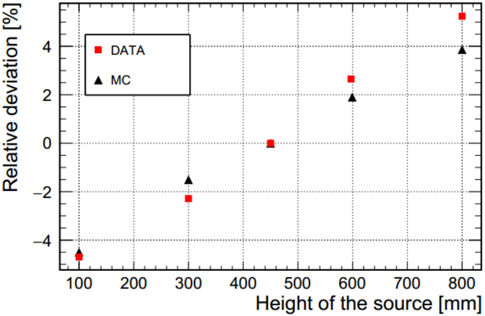
LED PMT calibration, stability and linearity (non-linearity better than 1%)

Radioactive sources internal and external calibrations

$^{68}$Ge, $^{124}$Sb, $^{137}$Cs, $^{54}$Mn, $^{65}$Zn, $^{24}$Na, $^{1}$H($n$,$\gamma$), AmBe

=> Tuning of the simulation: Light collection, LS properties

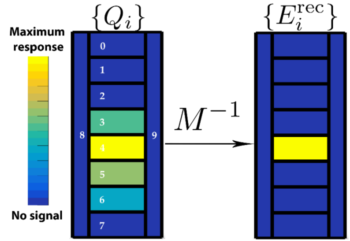


# Energy reconstruction



arXiv:1804.09052



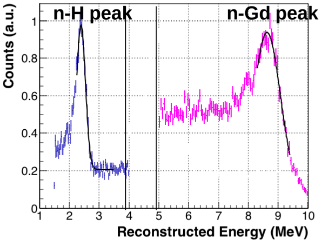

$$\begin{pmatrix} E_0 \\ E_1 \\ \vdots \\ E_9 \end{pmatrix} = M^{-1} \begin{pmatrix} Q_0 \\ Q_1 \\ \vdots \\ Q_9 \end{pmatrix}.$$

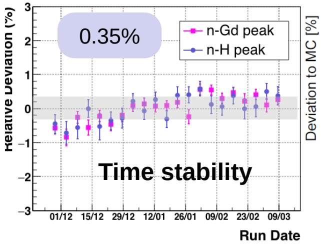
Collected photons/MeV from calibration runs.

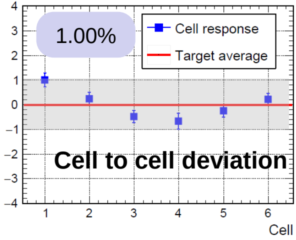
$$M_{ij} \doteq C_i L_{ij}$$

Light cross-talk cell j→i
Known from muon events and calibration runs

**Stability of the reconstructed n-H & n-Gd peaks – probing whole target volume**

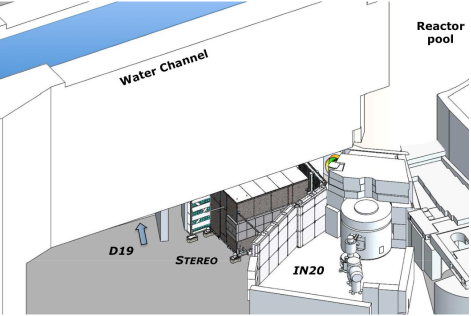


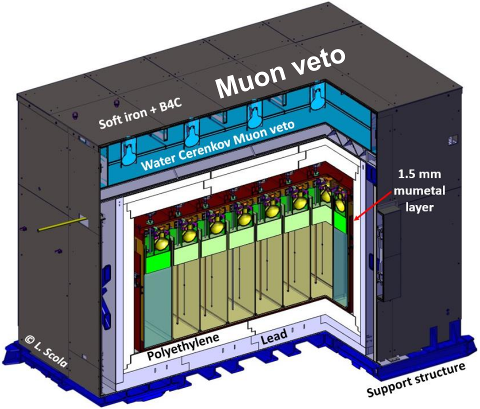
# Background shielding






## Cosmic background

- 15 m.w.e. (Water channel + reactor building)
- Water Cerenkov Muon Veto

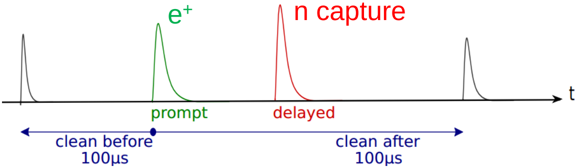



## Gamma and neutron background

- Lead
- Boron doped polyethylene
- Boron loaded rubber

# IBD selection






**Energy** 1.6 -7.1 MeV 4.5-10 MeV

**Pair selection** 0.25 µs < Δt < 70 µs

d < 60 cm

**Topology**

Event in Target

$E_{prompt}$ in Gamma-Catcher < 1.1 MeV

$E_{delayed}$ in target > 1 MeV

Prompt in one cell

$E_{prompt}$ in neighboring cell < 0.8 MeV

## Cosmic rays rejection

**Muon**

100 µs after a muon detected in the veto or in the detector

**Fast and/or multi-neutrons**

Isolation cut =100 µs before and after the pair

**Muon stop**

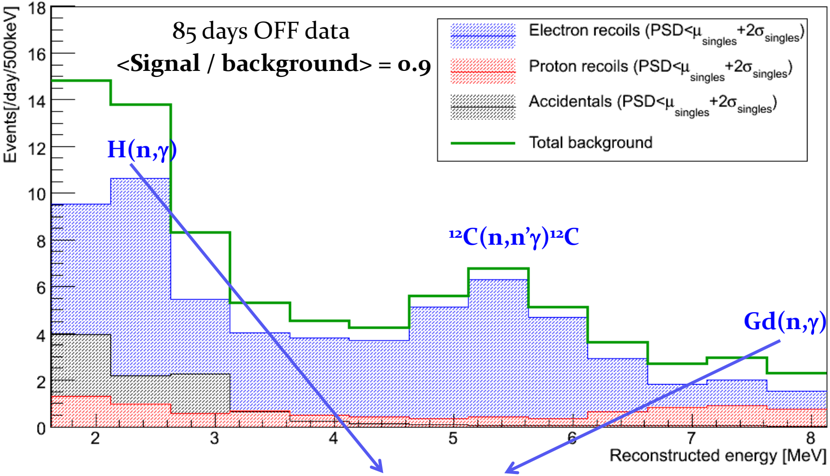
Prompt = muon

Delayed = Michel electron

At the top of the detector.

→ Cell charge asymmetry: $Q_{max}/Q_{tot} > 0.50$

# Reactor-off prompt energy spectrum




Prompt and delayed are γ from neutron captures

# Ratio method



**Cell 1 taken as reference**
→ compare measured and simulated **ratios**

$$R_{i,l}^{\mathrm{Data}} = \frac{\mathrm{Data}_{i,l}}{\mathrm{Data}_{i,1}} \qquad R_{i,l}^{\mathrm{MC}} = \frac{\mathrm{Model}_{i,l}(\alpha)}{\mathrm{Model}_{i,1}(\alpha)}$$

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{Ebin}}} \left(\overrightarrow{R_i^{\mathrm{Data}}} - \overrightarrow{R_i^{\mathrm{MC}}(\alpha)}\right)^t V_i^{-1} \left(\overrightarrow{R_i^{\mathrm{Data}}} - \overrightarrow{R_i^{\mathrm{MC}}(\alpha)}\right) + \sum_{l=1}^{N_{\mathrm{Cells}}} \left(\frac{\alpha_l^{\mathrm{Norm}}}{\sigma_l^{\mathrm{Norm}}}\right)^2 + \sum_{l=0}^{N_{\mathrm{Cells}}} \left(\frac{\alpha_l^{\mathrm{Escale}}}{\sigma_l^{\mathrm{Escale}}}\right)^2$$

$V_i$ : covariance matrix accounting for the reference cell common to all ratios.

| Pull terms | Cell to cell correlated | Uncorrelated |
|---|---|---|
| Energy scale ($\sigma^{\mathrm{Escale}}$) | 0.35% | 1.10% |
| Normalization ($\sigma^{\mathrm{Norm}}$) | - | 1.70% (3.40% cell 4) |

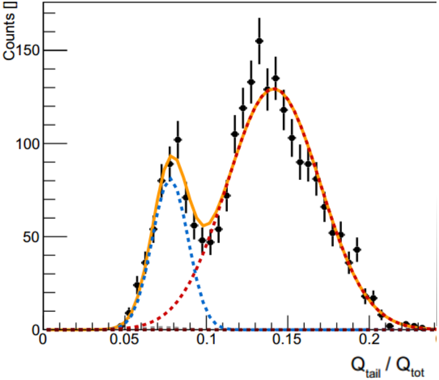
**→ Robust method, insensitive to: - Predicted spectrum shape**
**- Absolute normalization**

# What's new with phase-II?

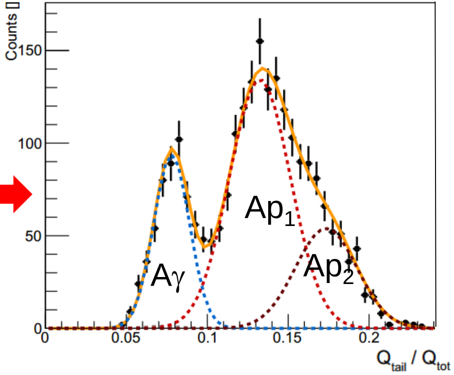


In phase-II, PSD is more stable
→ larger time binning

84 days OFF – 1 energy bin




Updated background model with an additional Gaussian (hypothesis of multi-proton recoils under study).




Again, only ratios ($A\gamma/Ap_1$ , $Ap_2/Ap_1$ , $\sigma p_1/\sigma p_2$) are transposed to the ON data