ICPPA-2018
MEPhI Moscow
October 22-26

Search for sterile neutrinos at very short baseline reactor experiments

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Many plots are taken from recent neutrino conferences
Many thanks to authors

3 Generation ν oscillations are well measured

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

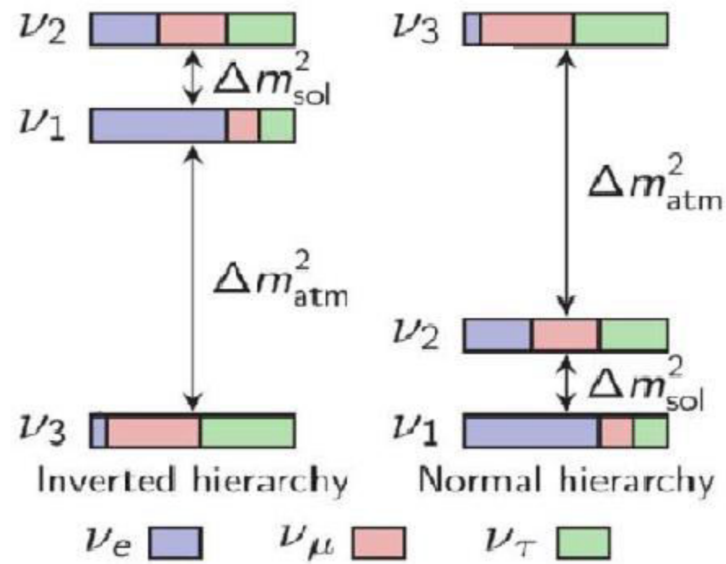
$\theta_{23} \sim 45°$
Atmospheric
Accelerator

$\theta_{13} \sim 8°$
Reactor
Accelerator

$\theta_{12} \sim 34°$
Solar
Reactor

$|\Delta m^2_{31}| \sim 2.4\text{x}10^{-3}\ \text{eV}^2$

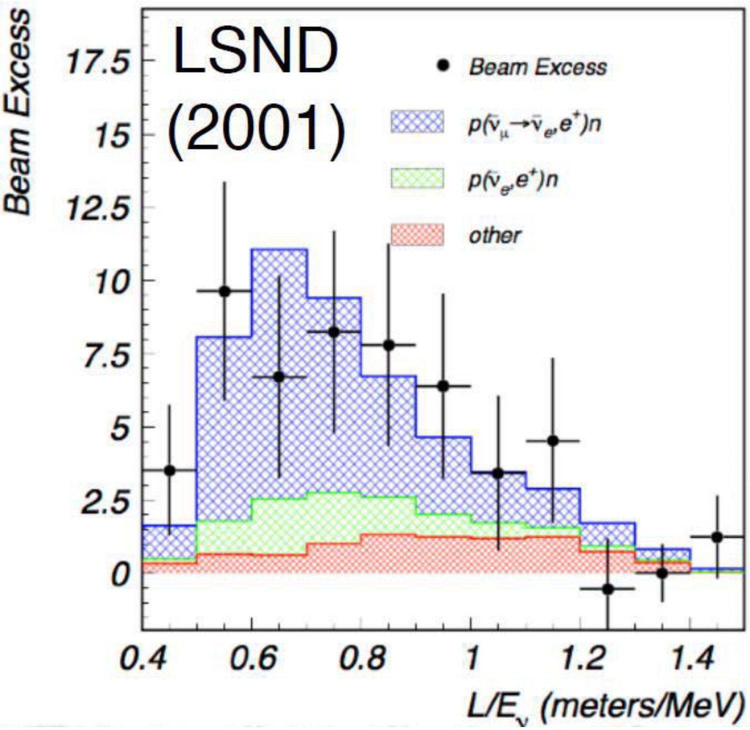
$\Delta m^2_{12} \sim 8\text{x}10^{-5}\ \text{eV}^2$

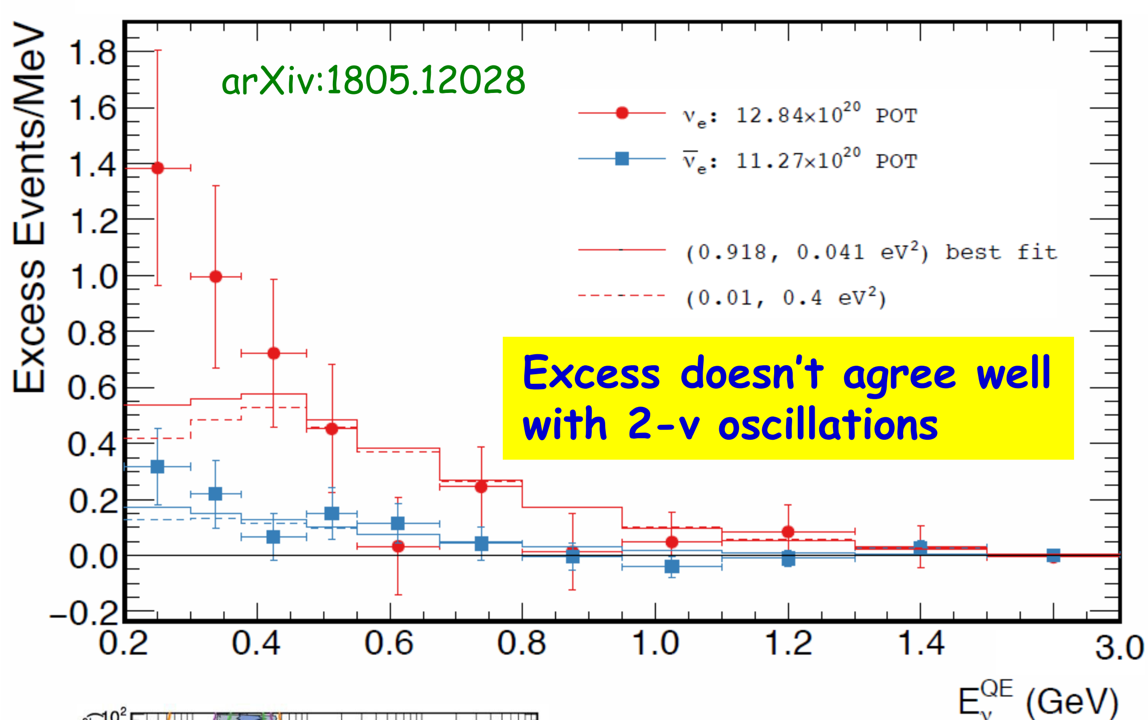


Zhe Wang
NOW-2018

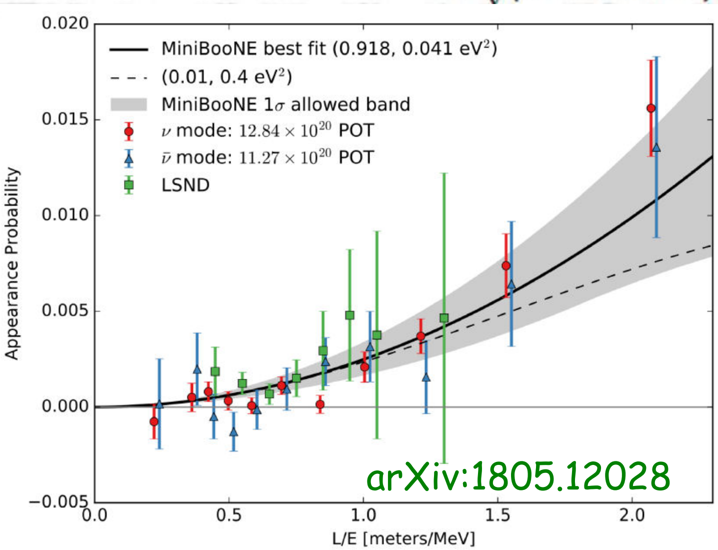
Z boson width gives N_ν(active)=2.9840±0.0082

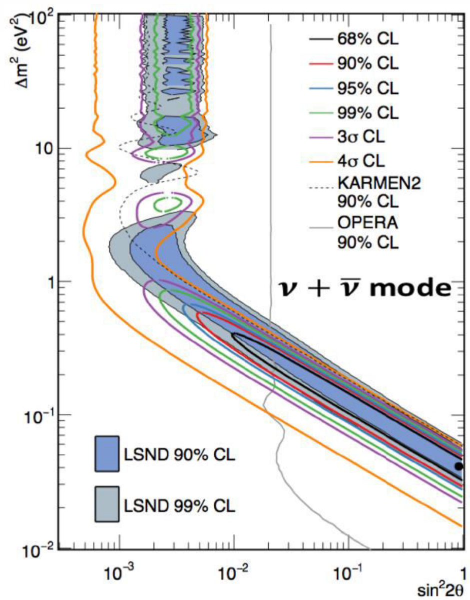
However there are hints of 4th (sterile) neutrino





Excess doesn't agree well with 2-ν oscillations





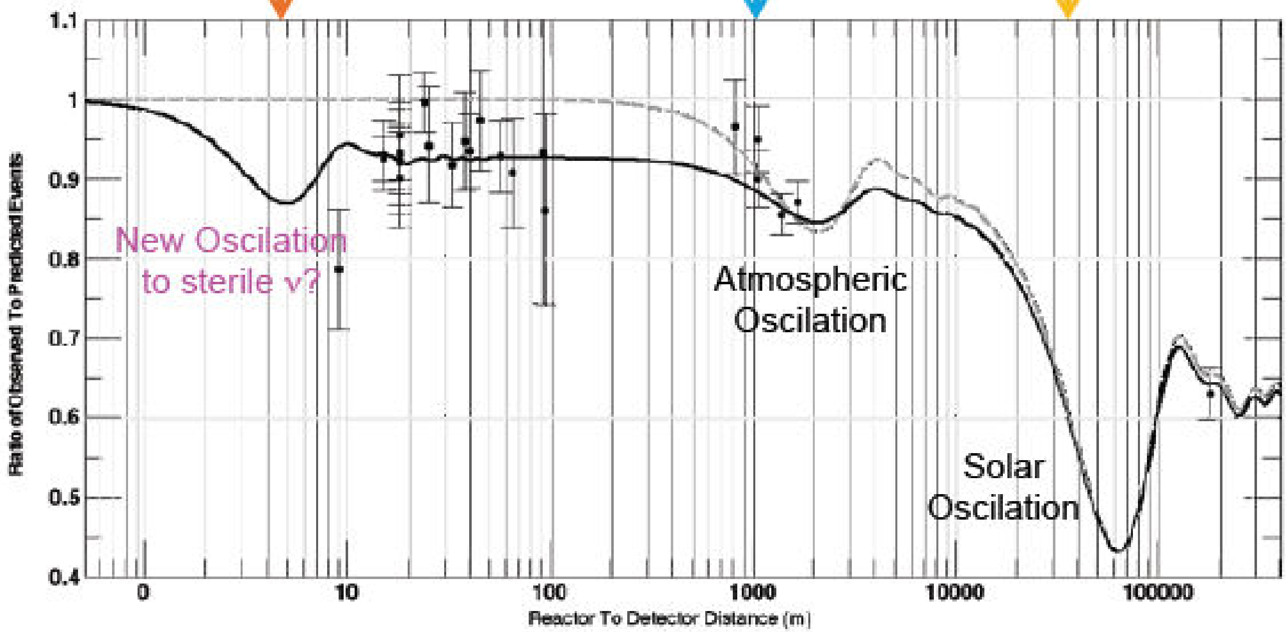
MiniBooNE 4.8σ
LSND 3.8σ
Combined 6.1σ

Hints of 4^{th} neutrino

SAGE and GALEX ν_e deficit 084±0.05
Reactor $\bar{\nu}_e$ deficit (H-M prediction)

Indication of a sterile neutrino(s)
$\Delta m^2 \sim 1\ eV^2$
$Sin^2 2\theta_{14} \sim 0.1$
=> Short range neutrino oscillations

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



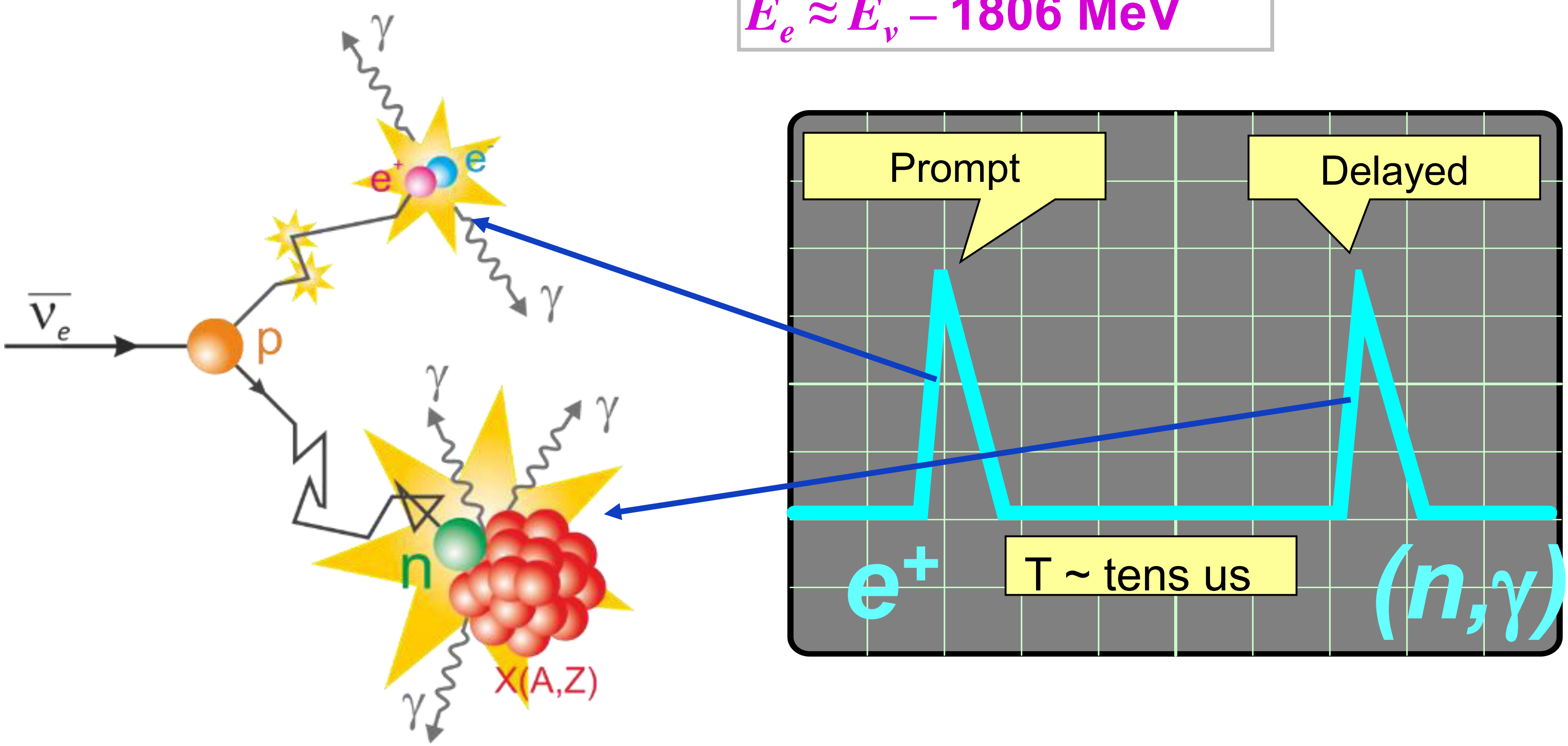
G. Mention et al. Phys Rev D 83 073006 (2011)

New measurements R=0.952±0.014±0.023 (Daya Bay)
R=0.918±0.018 (RENO)

Antineutrino detection

Inverse Beta-Decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$

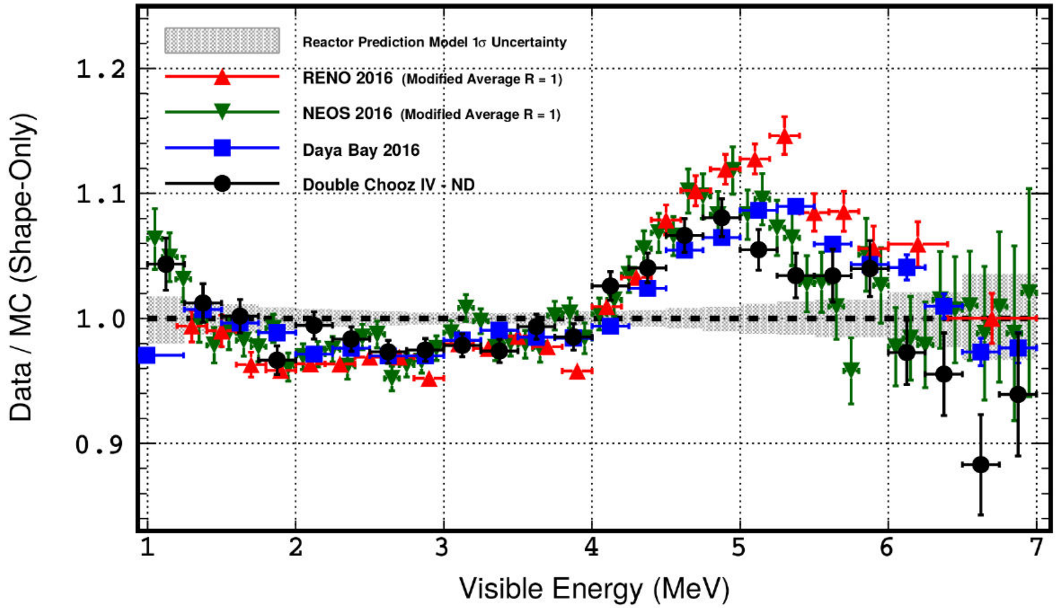
$E_e \approx E_\nu - 1806$ MeV



Reactor models do not describe well antineutrino spectrum

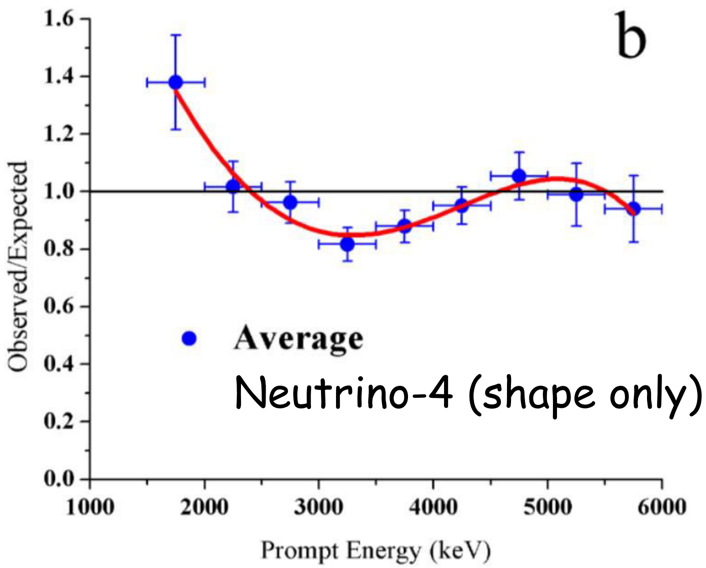
Measurements at one L not sufficient to observe oscillations

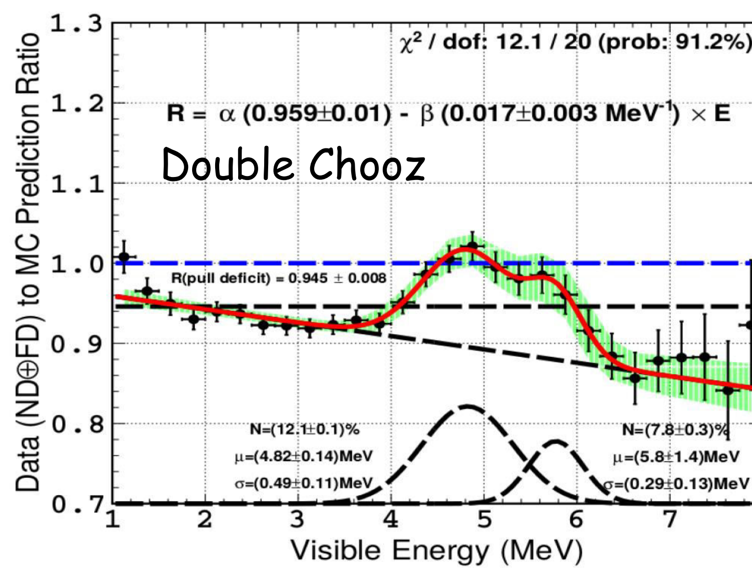
All recent experiments observe a bump at 4-6MeV



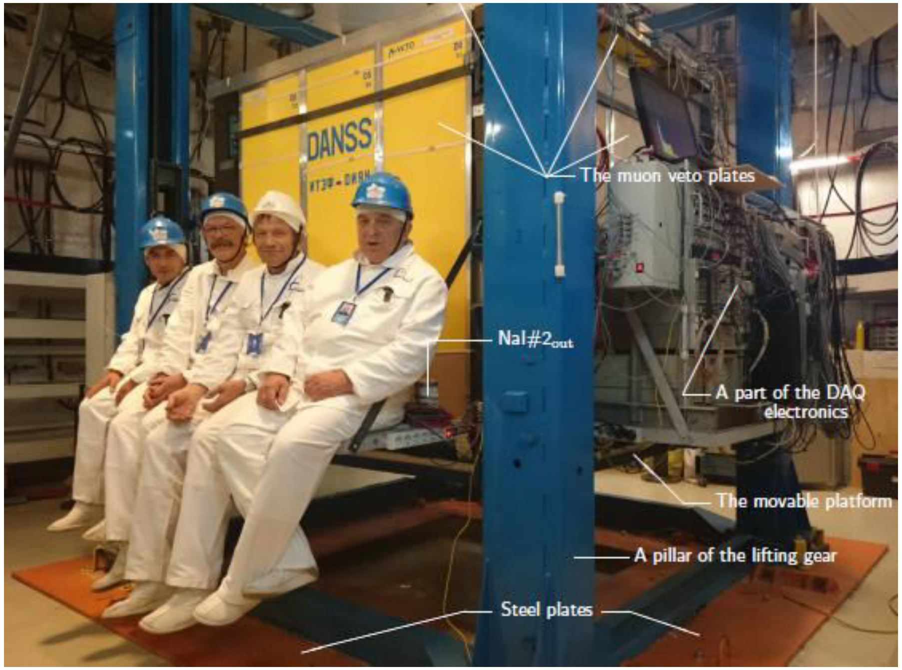
T.Bezerra
NOW-2018

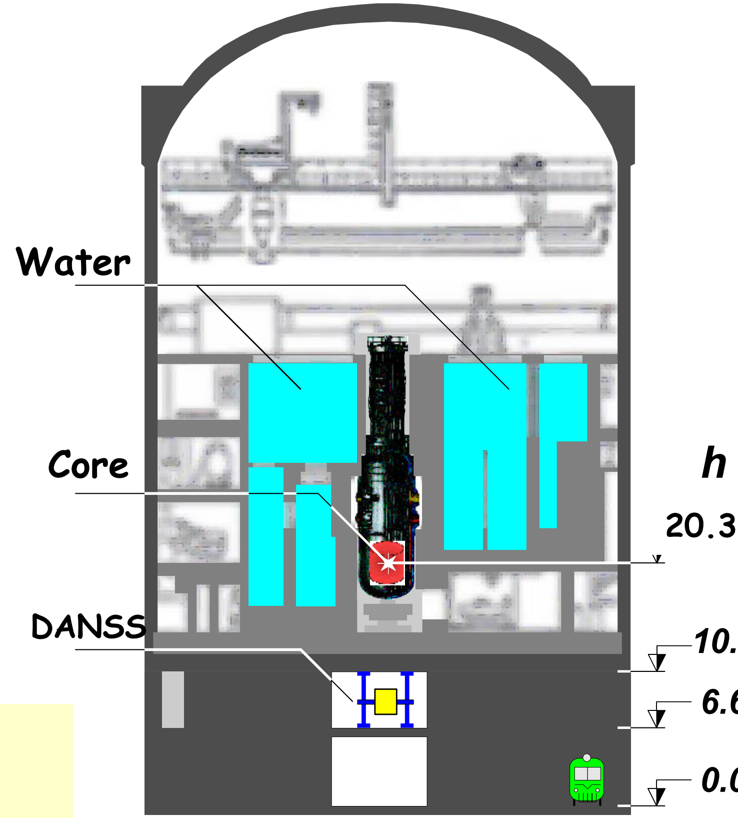
Or a dip? (more pronounced in Neutrino-4)





DANSS at Kalinin Nuclear Power Plant





DANSS - 2500 solid scintillator 1m long strips

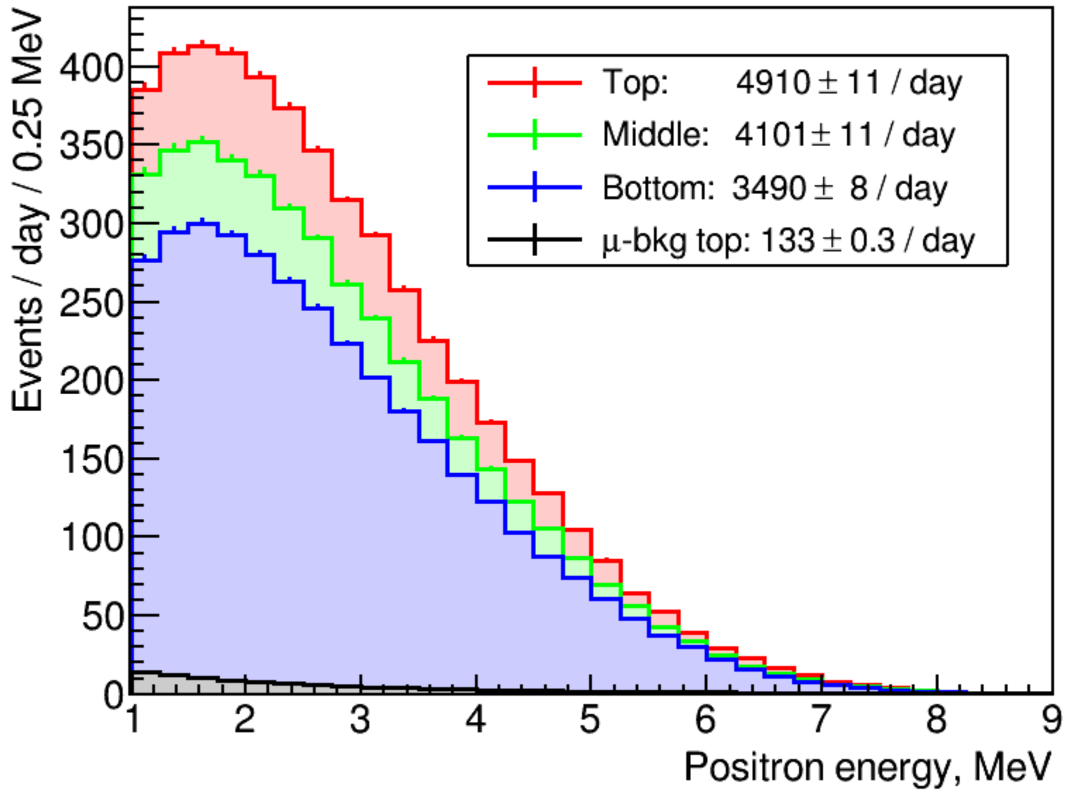
DANSS is installed on a movable platform under 3GW WWER-1000 reactor (Core:h=3.7m, ∅=3.1m) at Kalinin NPP.
~50 mwe shielding => μ flux reduction ~6!
No cosmic neutrons!

Detector distance from reactor core 10.7-12.7m (center to center). It is changed 3 time a week

Fuel contribution to ν flux at beginning and end of campaign

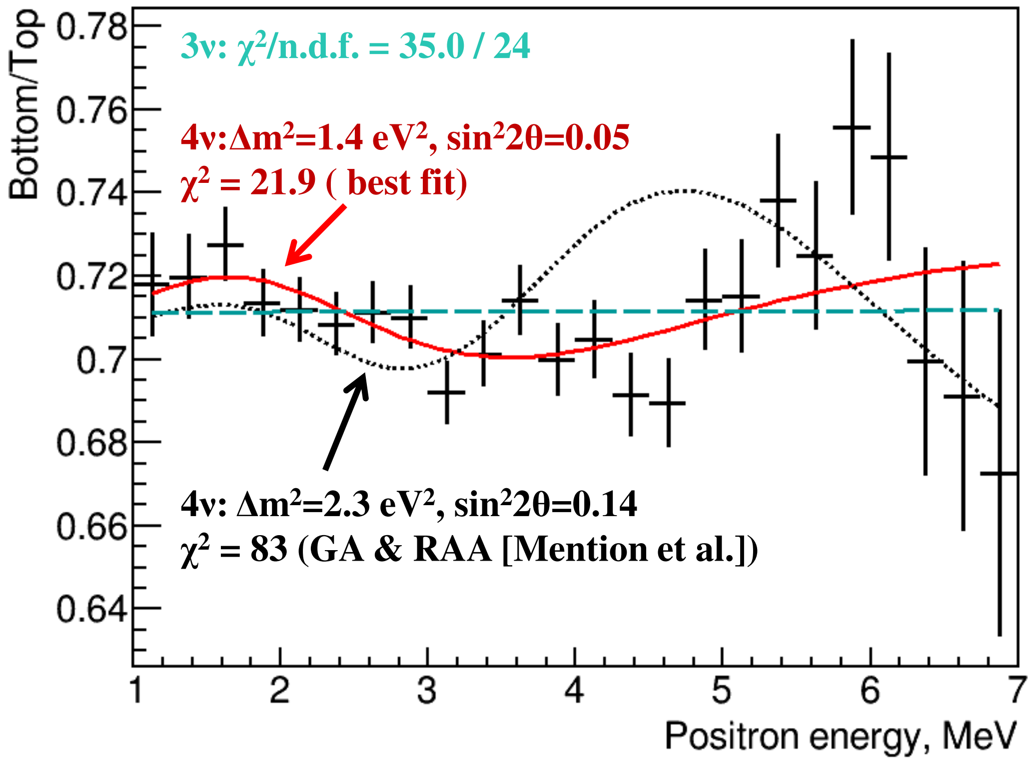
235U	63.7%	44.7%
239Pu	26.6%	38.9%
238U	6.8%	7.5%
241Pu	2.8%	8.5%

Positron spectrum



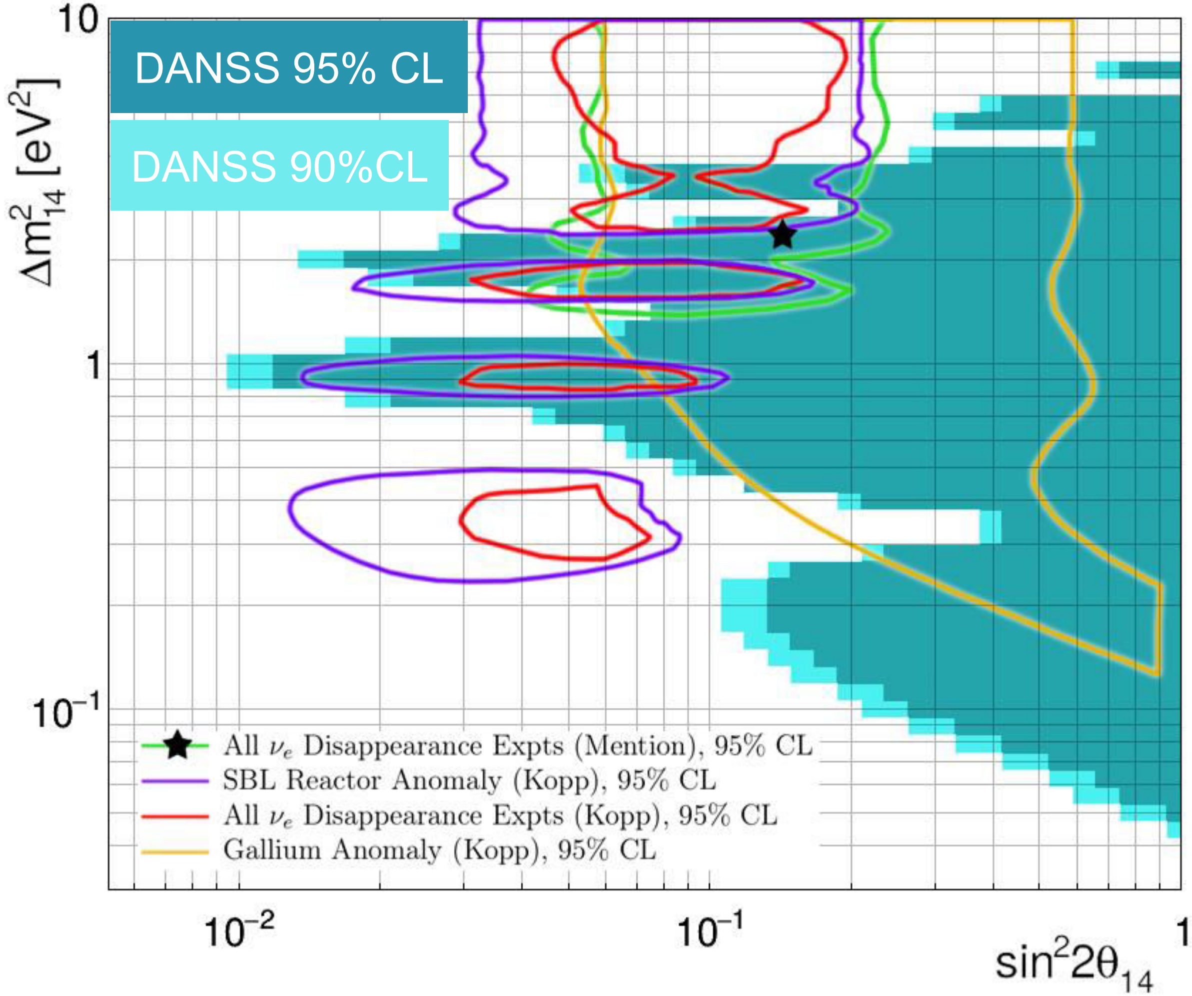
- 3 detector positions. Changes 3 times a week
- About 5000 neutrino events/day in detector fiducial volume of 78%
  S/B=33 (for 'Top' position closest to the reactor.)
- Continuous detector calibration with cosmic muons
- Very modest energy resolution of ~28% at 1 MeV
- Very large size of the reactor core (⌀ 3.2m, h=3.7m)
- → Smearing of the oscillation pattern

Only ratio of positron spectra at different L is used in analysis



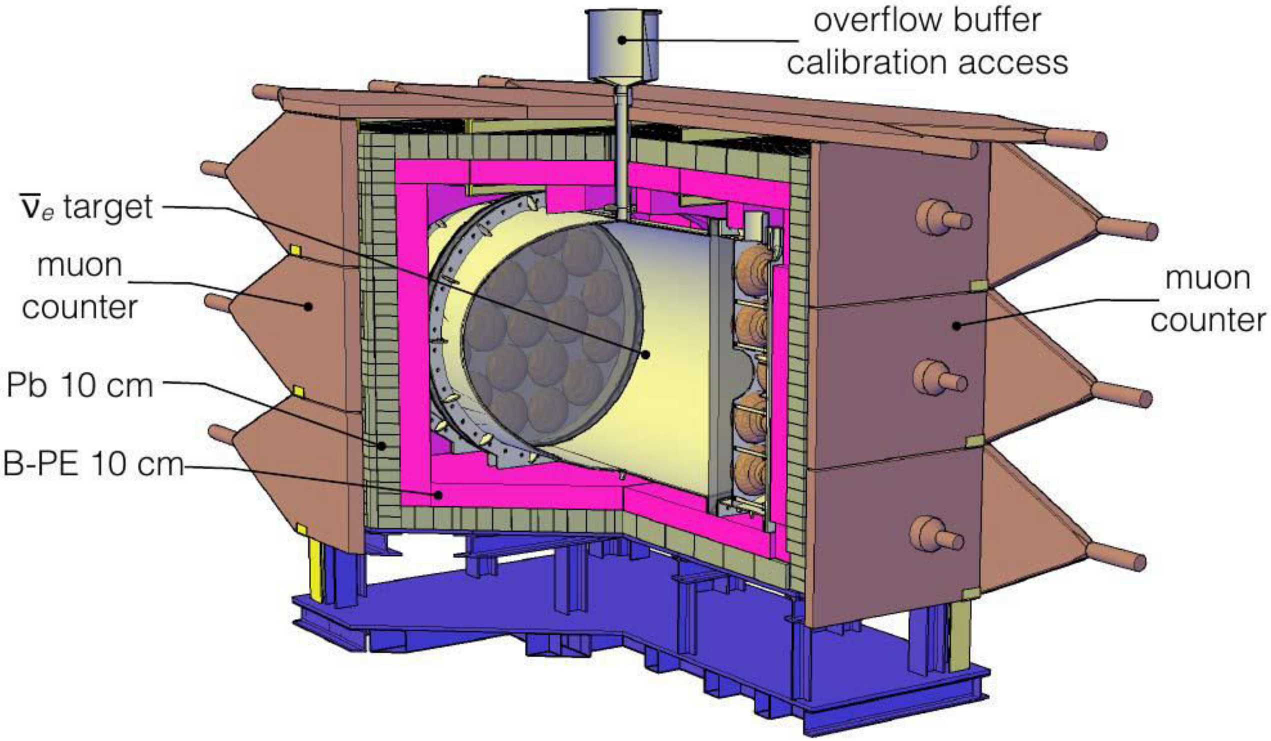
The most probable point for RAA is excluded at 5σ level

Exclusion region



A large fraction of allowed parameter region up to $\mathrm{Sin}^2 2\theta_{14} \sim 0.01$ is excluded by DANSS using only ratio of e+ spectrum at different L (independent on ν spectrum, detector efficiency,…)

NEOS



$1m^3$ LS
No segmentation

σ_E/E=5% at 1 MeV

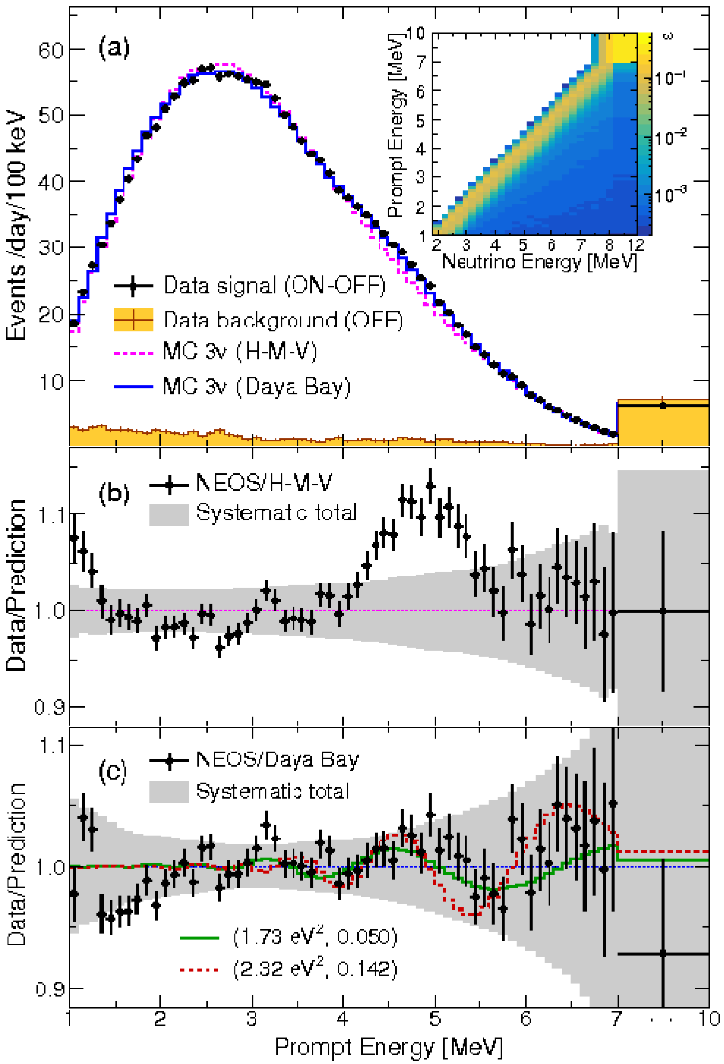
PSD removes 70% of background

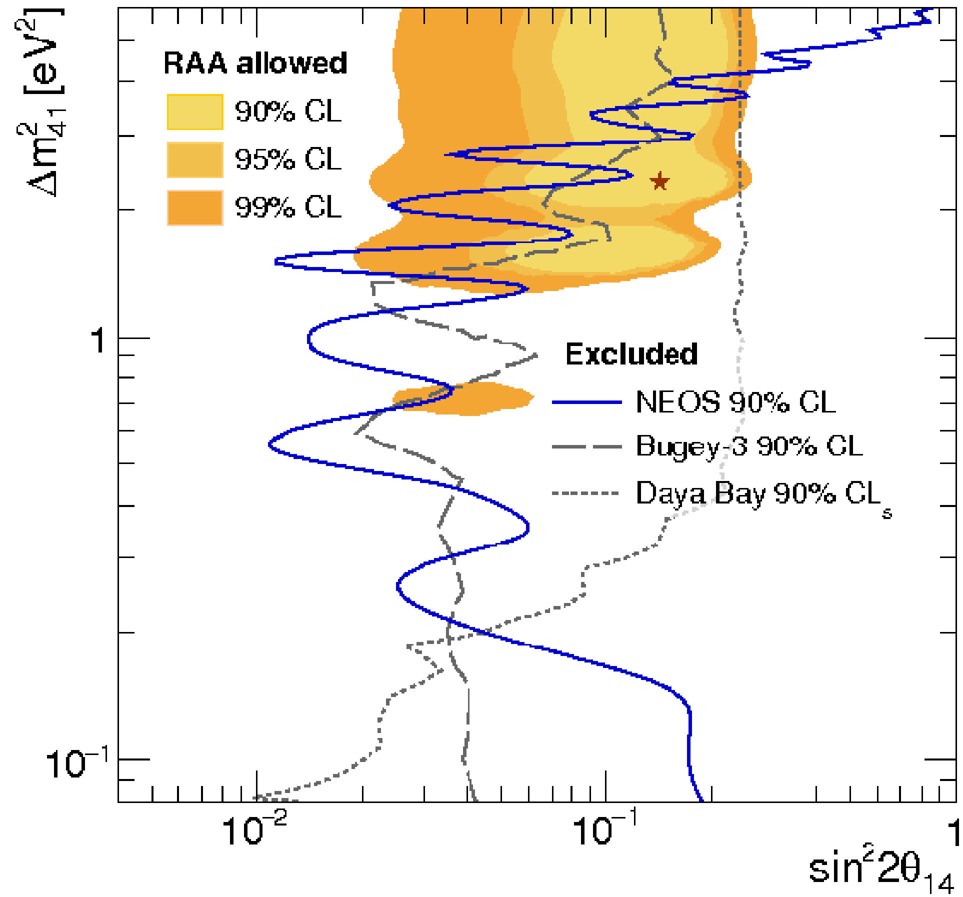
Depth 20mwe

S/B= 23

Only one L=24m

Large core size d=3.1m h=3.8m
Power 2815 MWt;





Normalized on ν spectrum from different reactor (Day Bay)
→ Could cause systematic uncertainties
Visible oscillation pattern not explained (spectrum fine structure?)

Neutrino-4

See talk by A.Serebrov

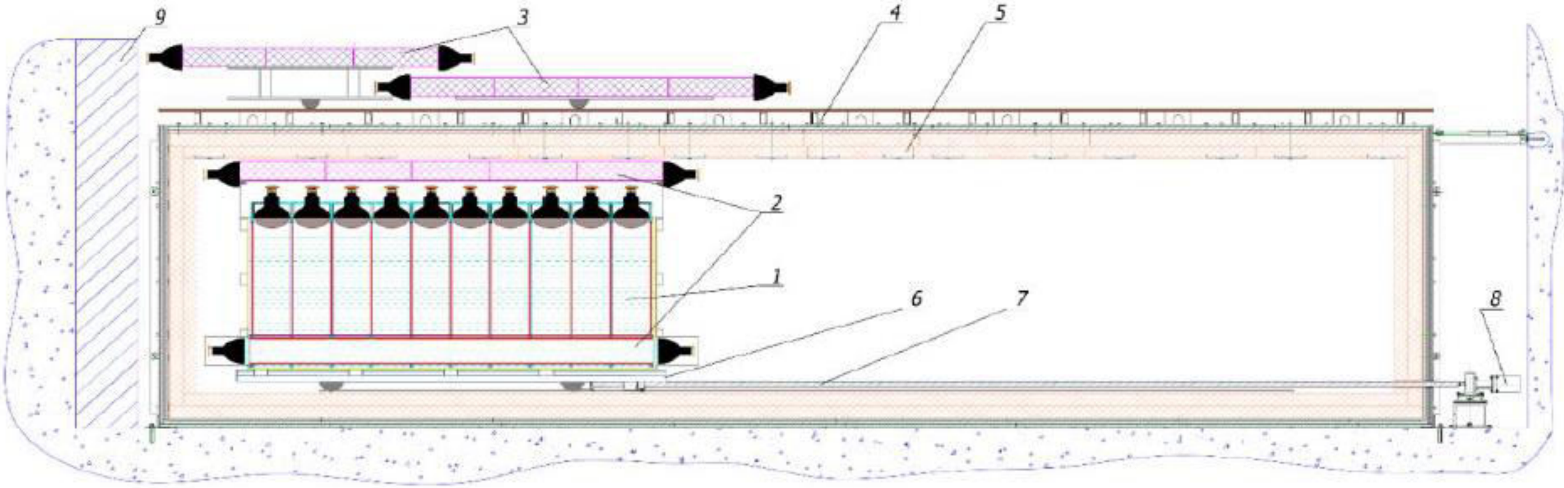


Fig. 1. General scheme of an experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9 –shielding against fast neutrons from iron shot.

85MW 235U Reactor (42x42x35cm3)

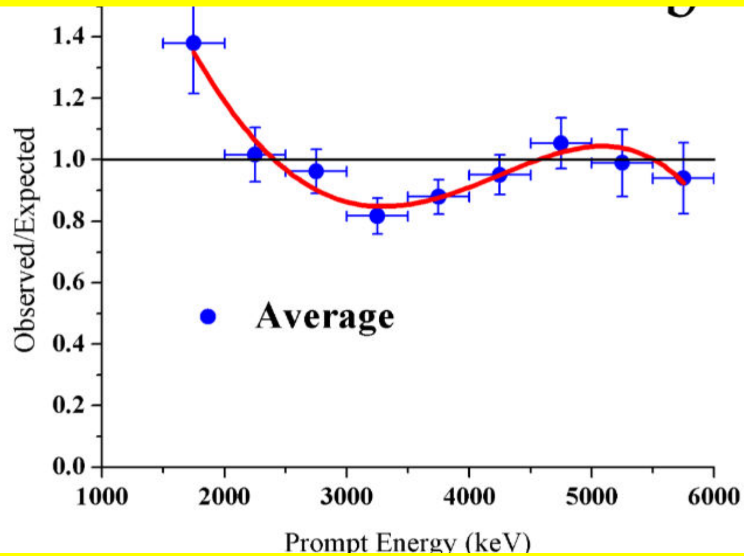
1.8m3 LS detector (5x10 sections)

L=6-12m σ_E/E~16% at 1MeV; ~200ev./day

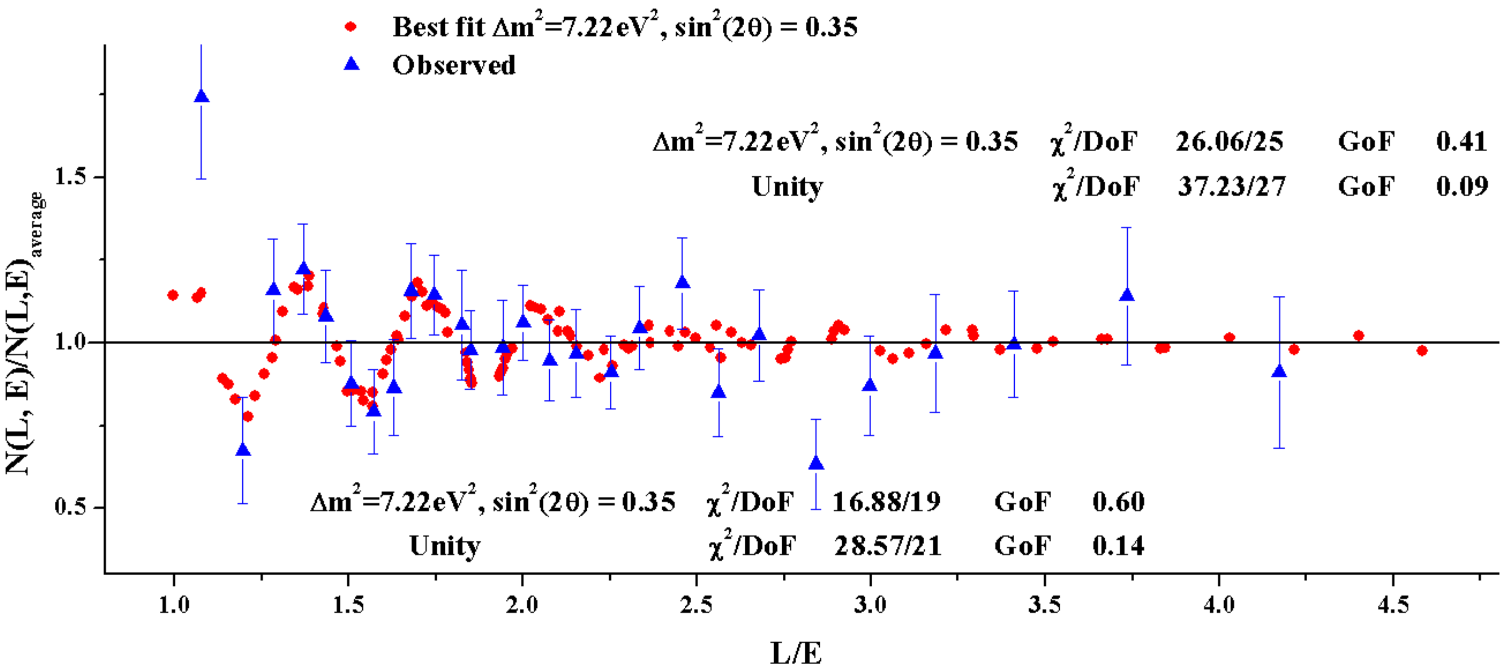
No PSD; 3.5mwe => S/B~0.54

480days ON 288days OFF

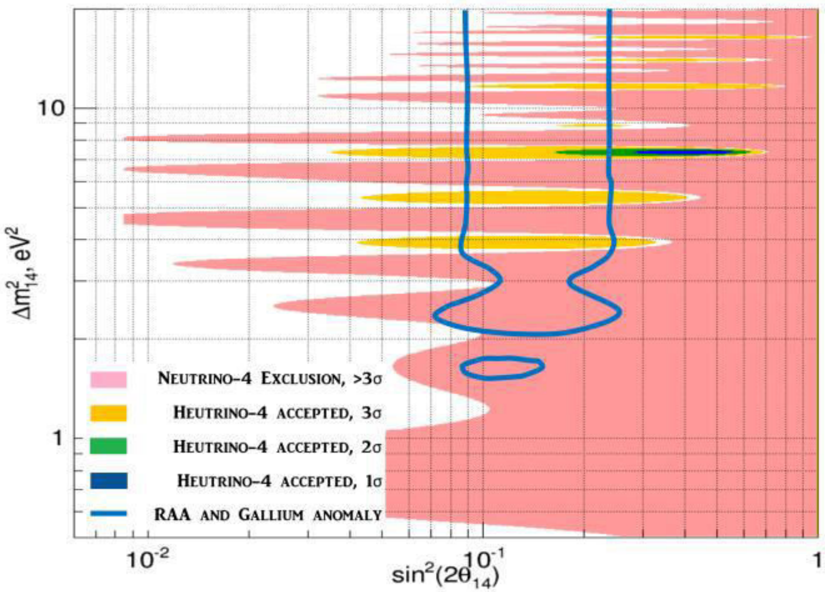
Large difference with predicted spectrum

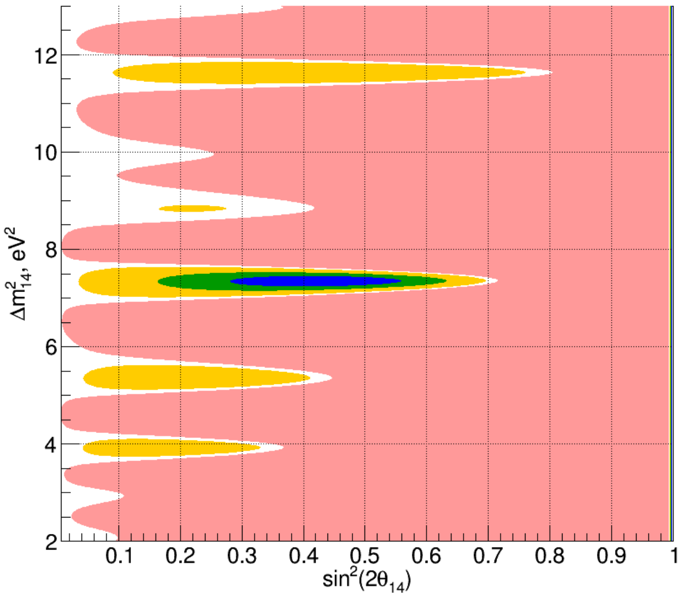


Indication of oscillations with large $\Delta m^2 \sim 7eV^2$ and $\sin^2 2\theta \sim 0.35$!



Indication of oscillations with large $\Delta m^2 \sim 7 eV^2$ and $\sin^2 2\theta \sim 0.35$





Major Advantages

Compact reactor core with large power
Segmented and movable detector
Very short distances to core (6-12) m
No background from other experiments
Model independent analysis

Major Disadvantages

No PSD
Small overburden (3.5 mwe)
Small S/B=0.54
Modest σ_E/E=16% at 1 MeV

Major concerns

Equal response of cells is assumed, not corrected for n detection efficiency

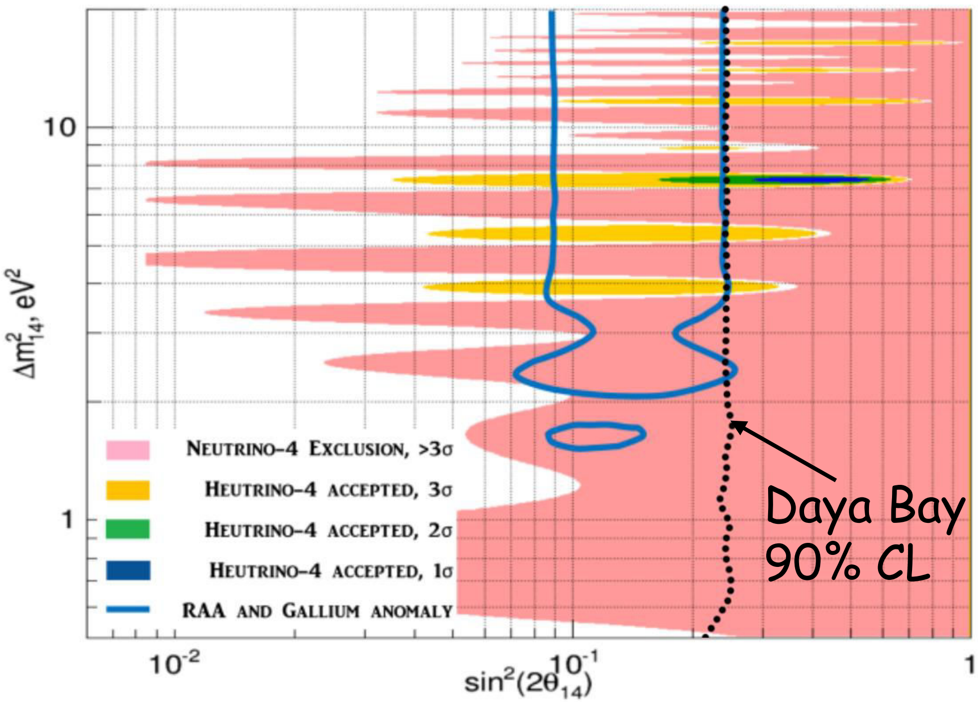
However, measurements at one distance are averaged over different cells

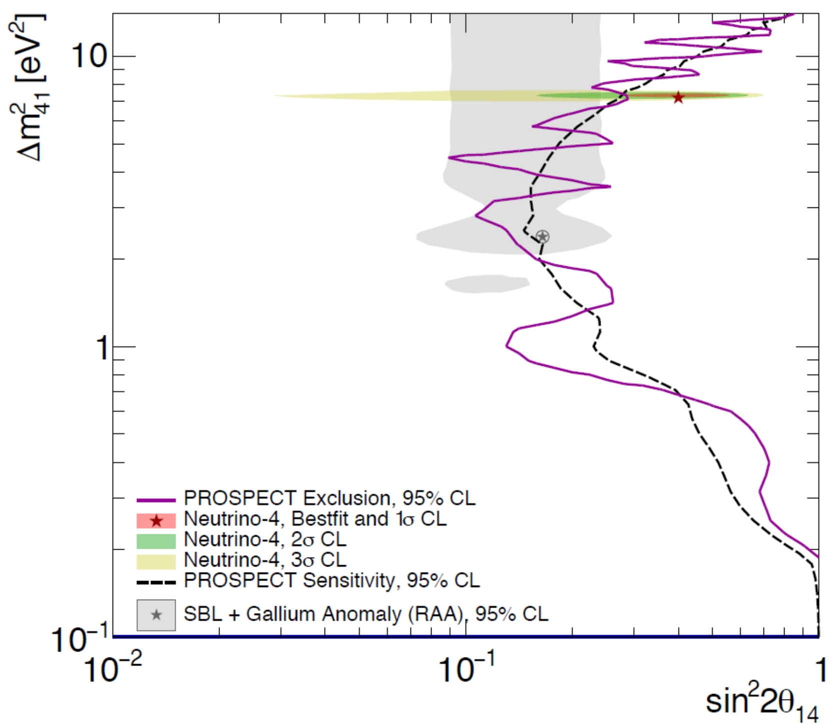
The detector response IS NOT INCLUDED into fit.

This should lead to smearing of the oscillation pattern

Tensions with upper limits from other experiments

(Daya Bay, RENO (both rely on predicted ν flux), PROSPECT)

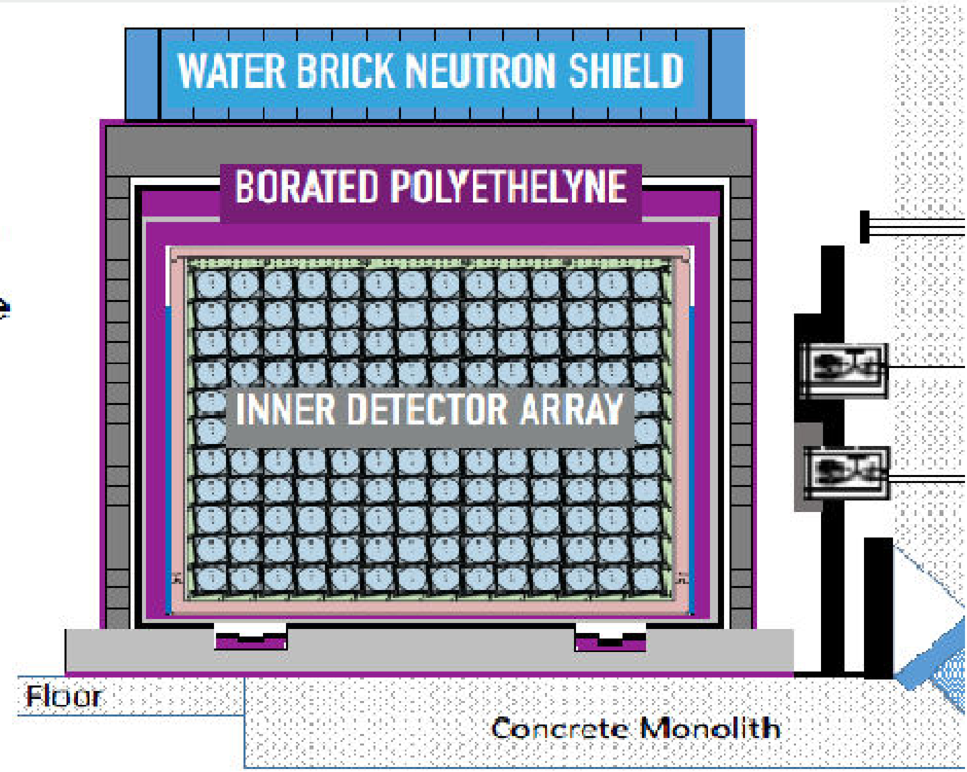


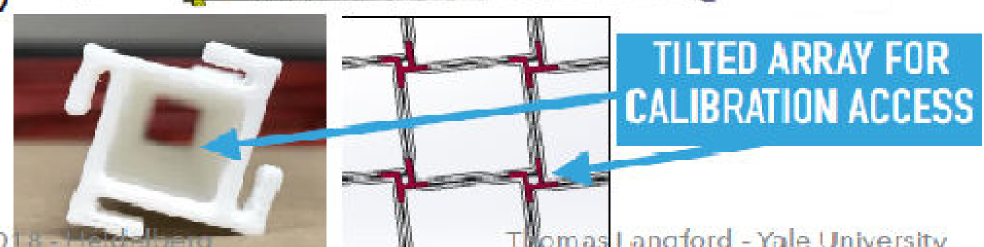


PROSPECT

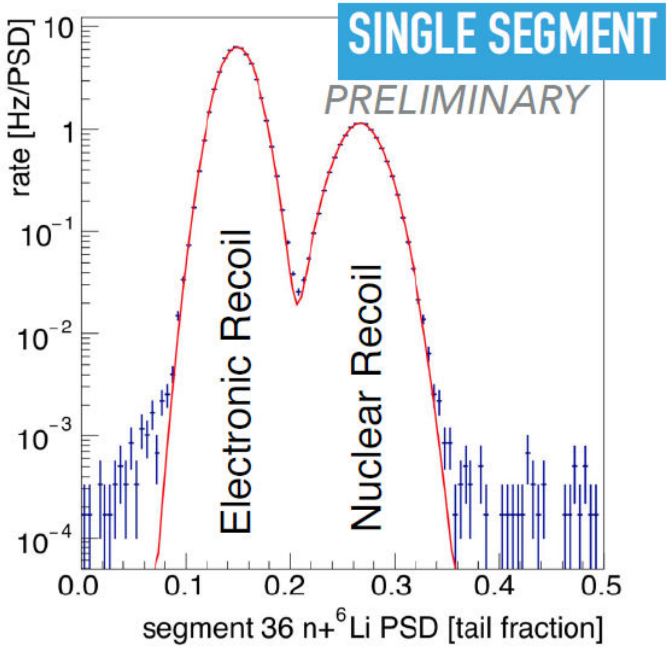
PROSPECT DETECTOR DESIGN

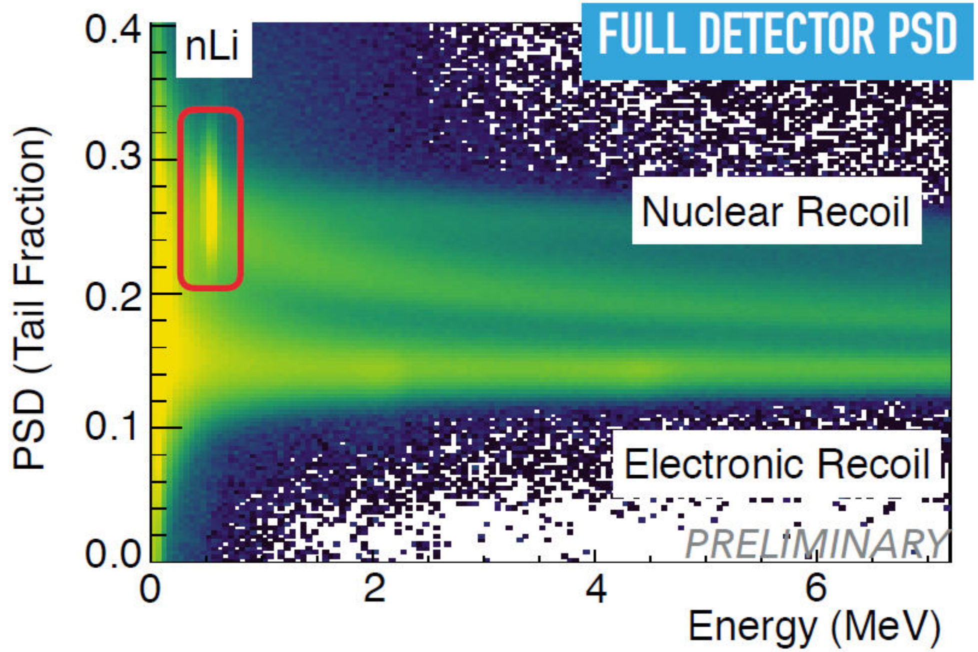
- 154 segments, 119cm x 15cm x 15cm
  - ~25liters per segment, total mass: 4ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods
- **Segmentation enables:**
  1. Calibration access throughout volume
  2. Position reconstruction (X, Y)
  3. Event topology ID
  4. Fiducialization
- Double ended PMT readout for full (X,Y,Z) position reconstruction
- **Optimized shielding to reduce cosmogenic backgrounds**





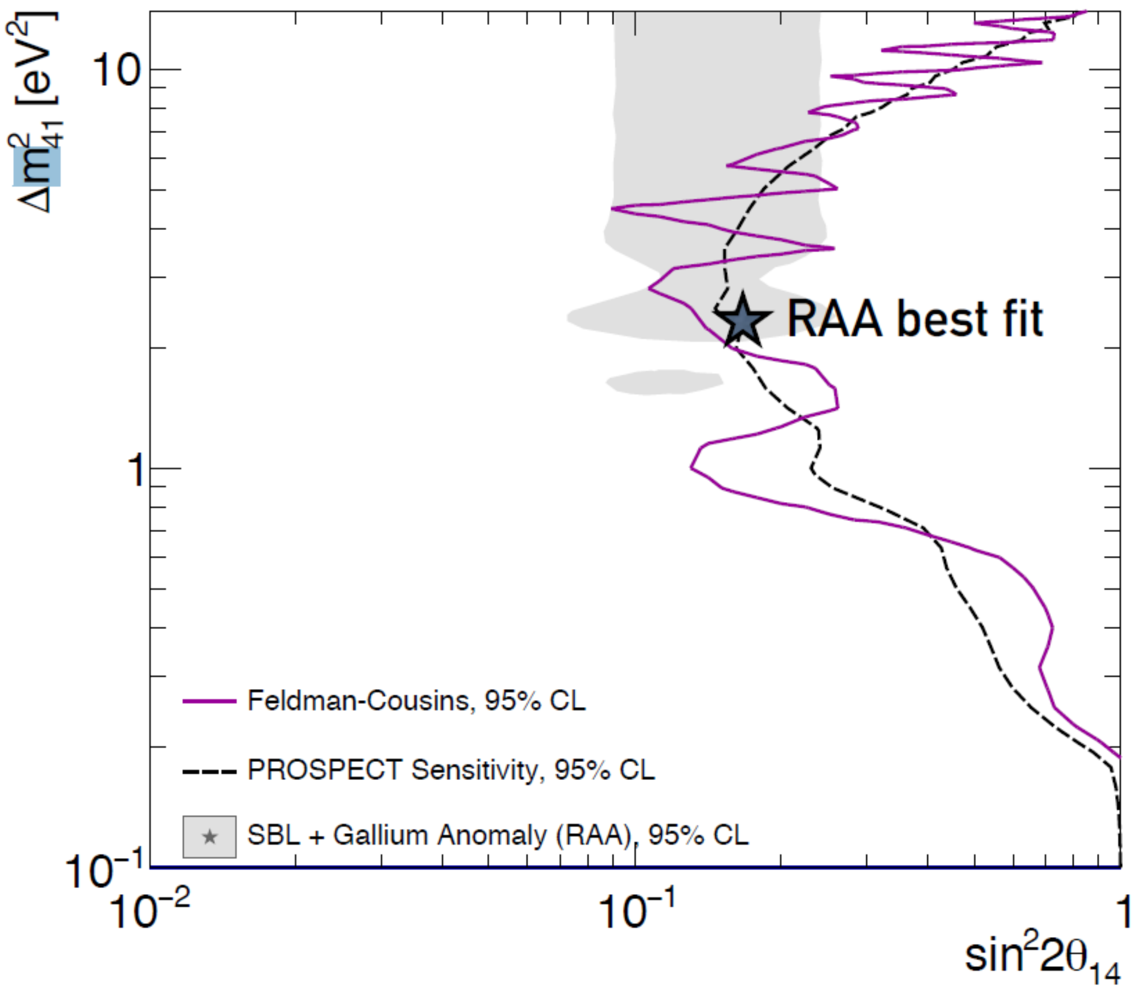
Pulse Shape Discrimination of background



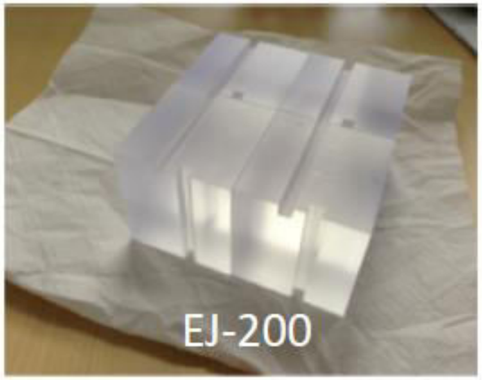


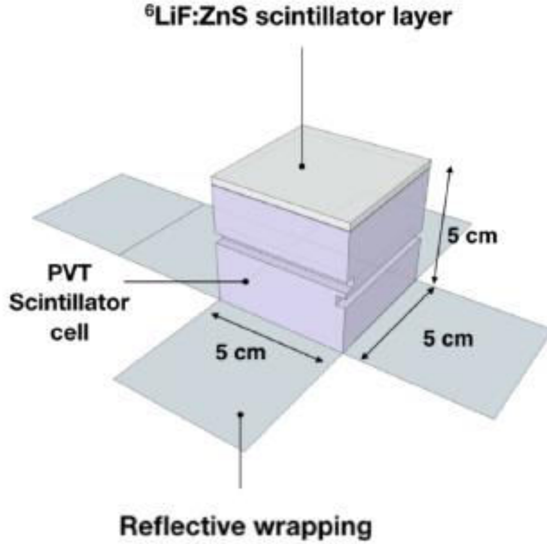
Excellent PSD allows to achieve S/B=1.36 on earth surface
Excellent energy resolution of 4.5% at 1 MeV
Localized detection of neutrons
Elaborate calibration system

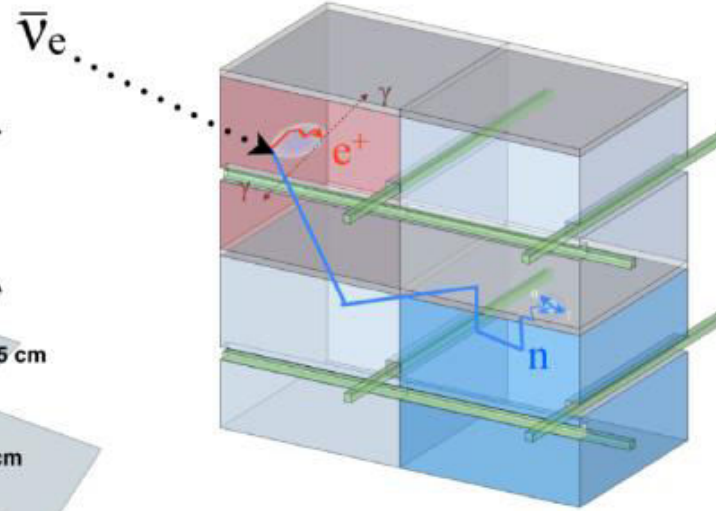
Interesting limits in wide range of masses after 33 days of reactor-on



SoLid

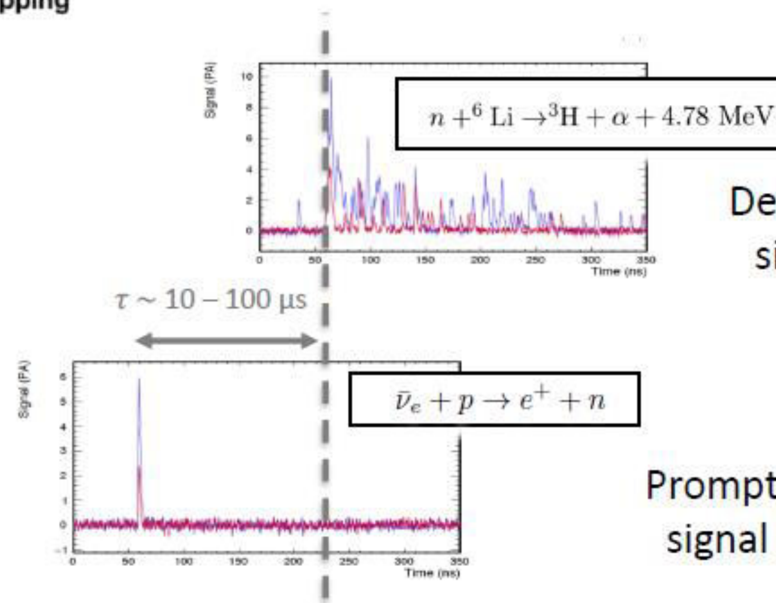






- $5 \times 5 \times 5$ cm^3 PVT cubes
  - Non-flammable scintillator
- Cubes are optically separated using Tyvek wraps
- ^{6}LiF:ZnS(Ag) screens for neutron identification
- Light collected through optical fibers and silicon photomultipliers (SiPMs require low-voltage)

For more information :
JINST **12** (2017) P04024

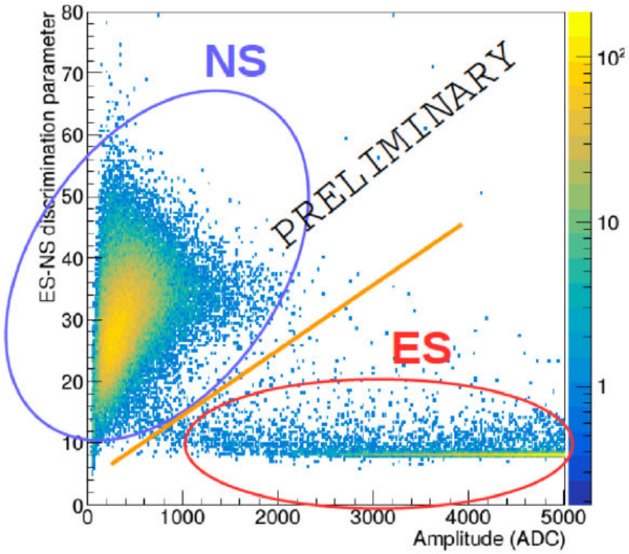


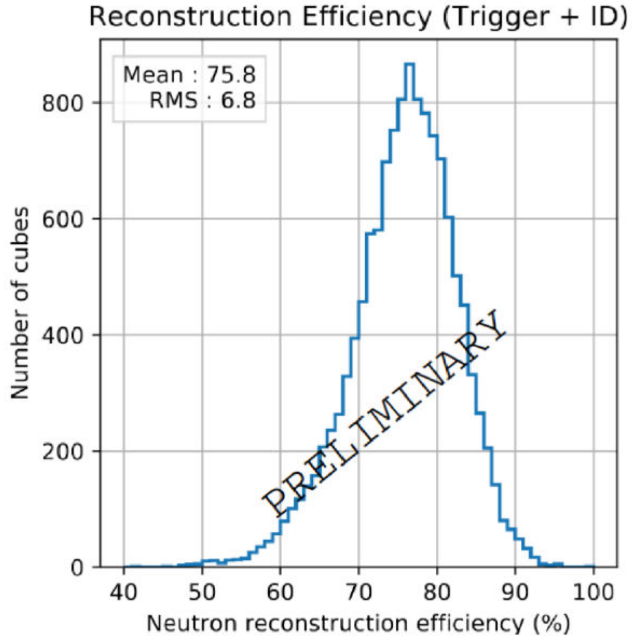
Delayed signal

Prompt signal

Squared BCF-91A fiber

Good pulse shape discrimination of background (# peaks over thresh)
In-situ measurements of neutron detection efficiency





Major Advantages

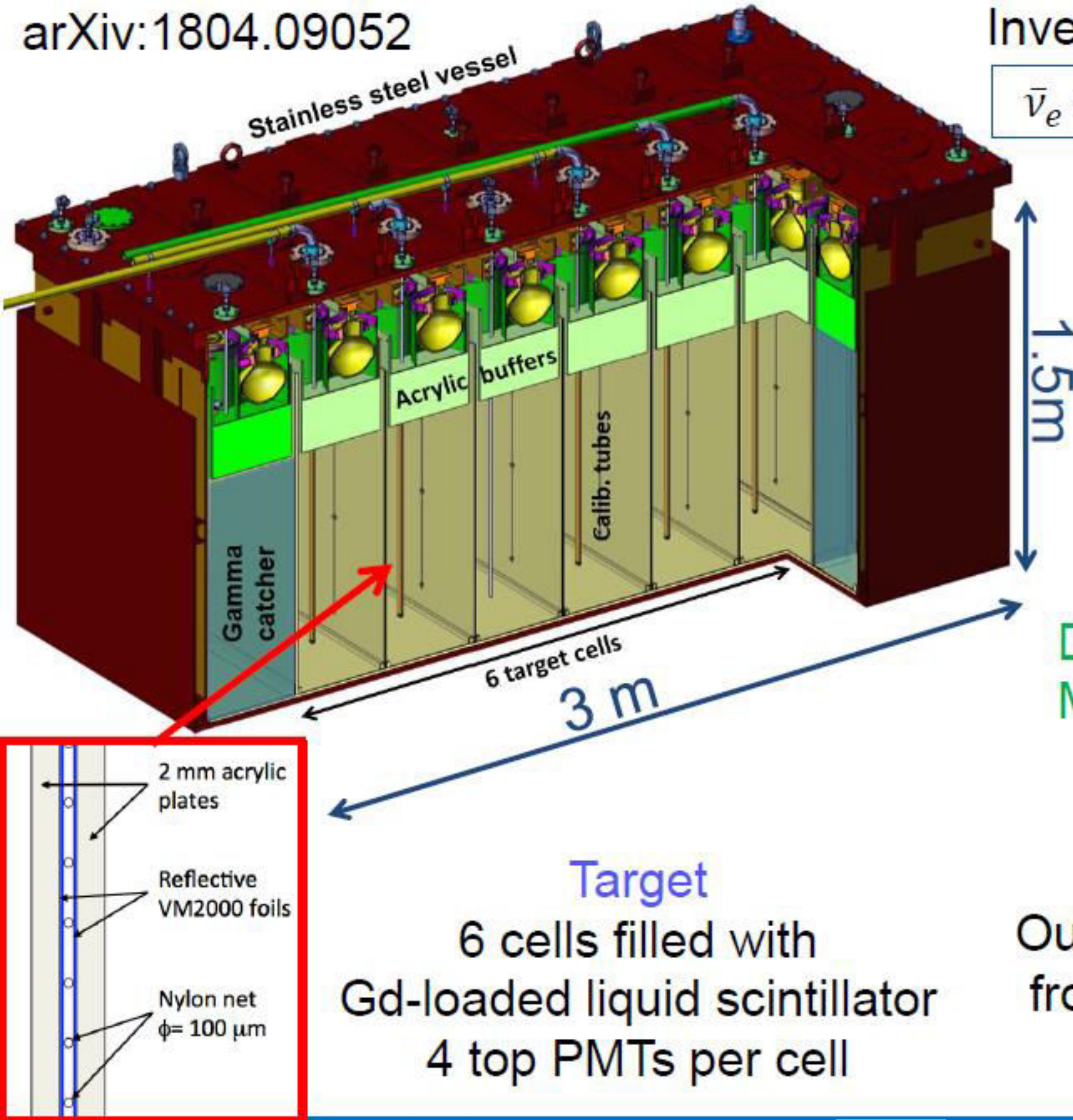
Compact reactor core with large power
Highly segmented detector -> 3D recons.
Very short distances to core (6-9) m
Good PSD of background -> S/B~3
Localized detection of neutrons
Elaborate calibration system

Major problems

Modest σ_E/E=14% at 1 MeV
Calibration challenge- 12800 cubes

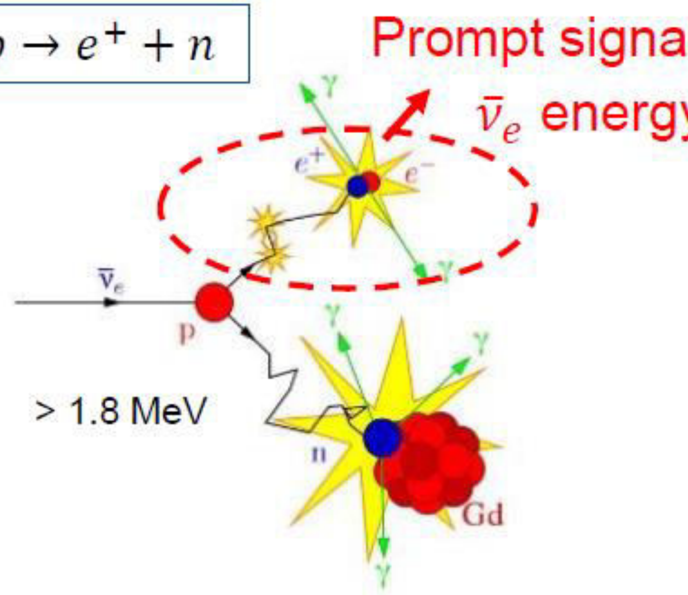
The STEREO detector

arXiv:1804.09052



Invert Beta Decay

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



Delayed signal

Mean neutron capture time $16\ \mu s$

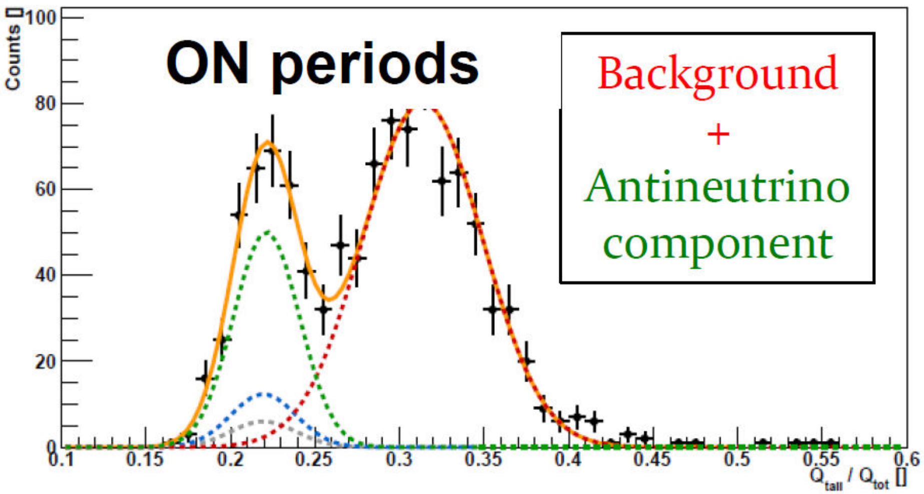
Target

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

Gamma-catcher

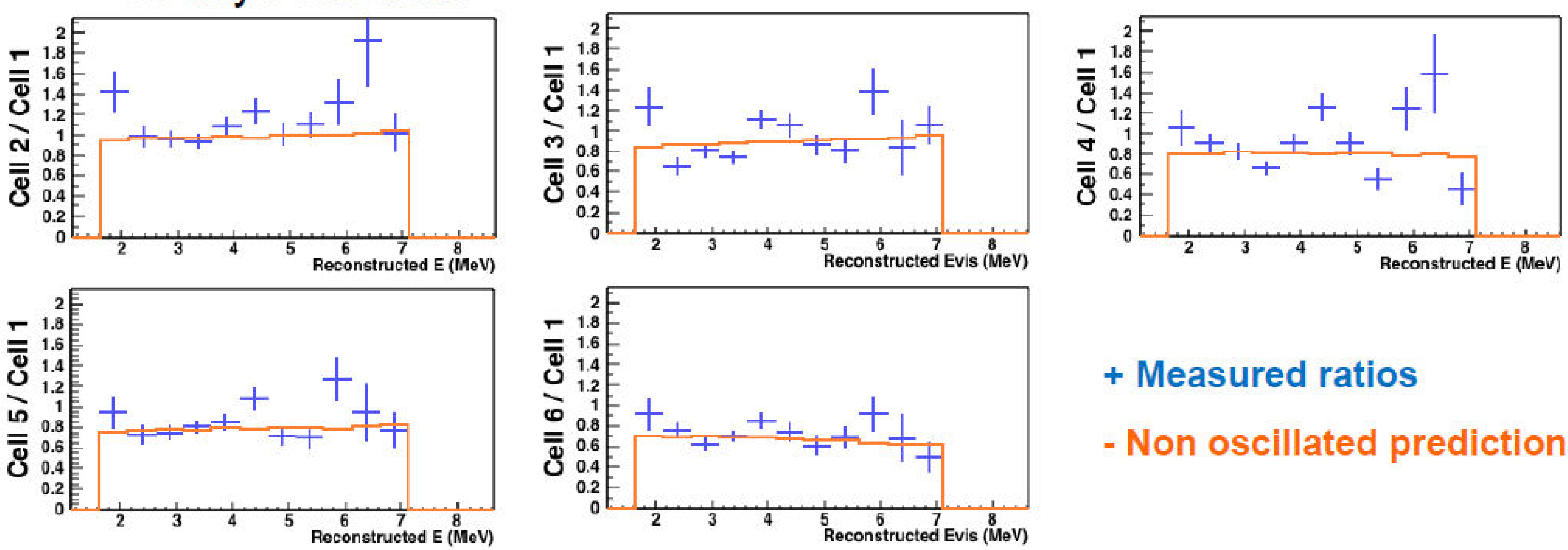
Outer-crown to detect γ's escaping
from the Target + active shielding
24 PMTs

First stage results



Good PSD
Coarse segmentation
Modest σ_E/E=9% at 1 MeV
Very modest S/B=0.9

66 days ON data



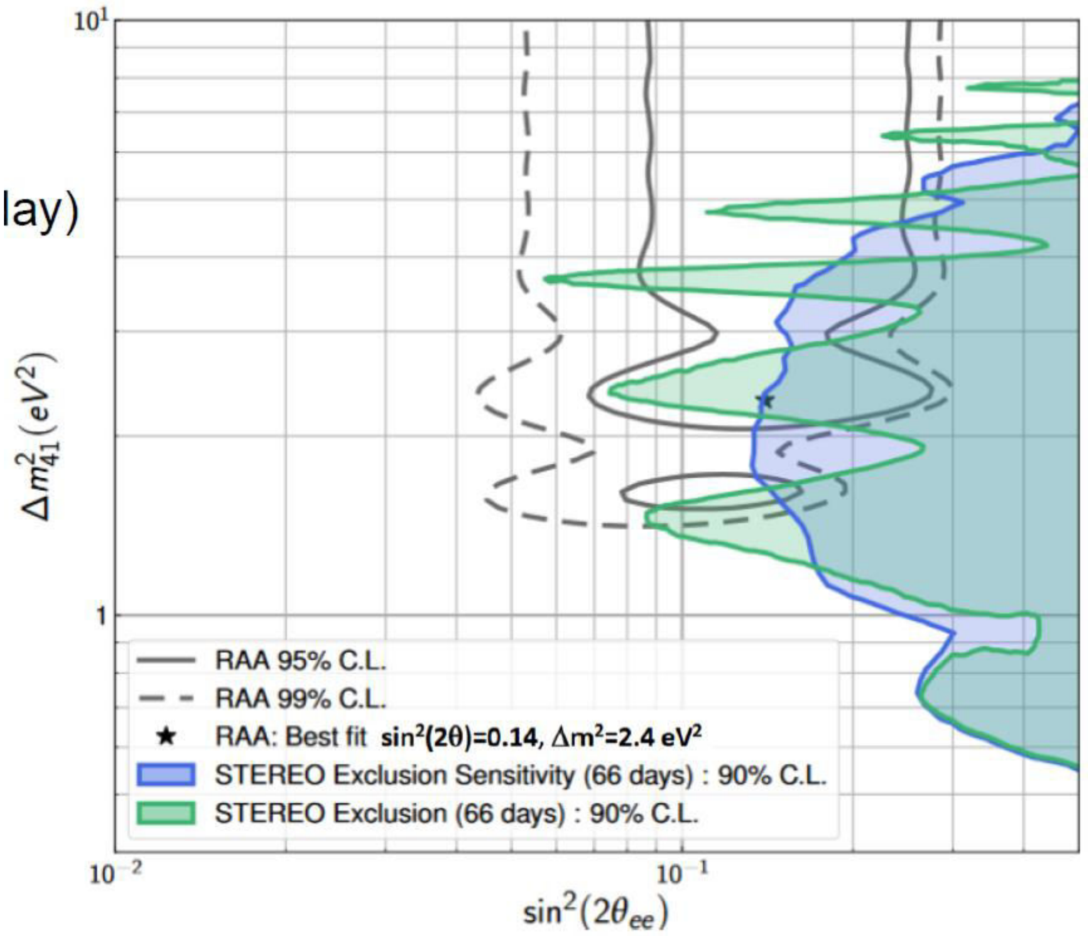
+ Measured ratios

- Non oscillated predictions

No sign of oscillations

Interesting limits after 66 days of reactor-on

lay)

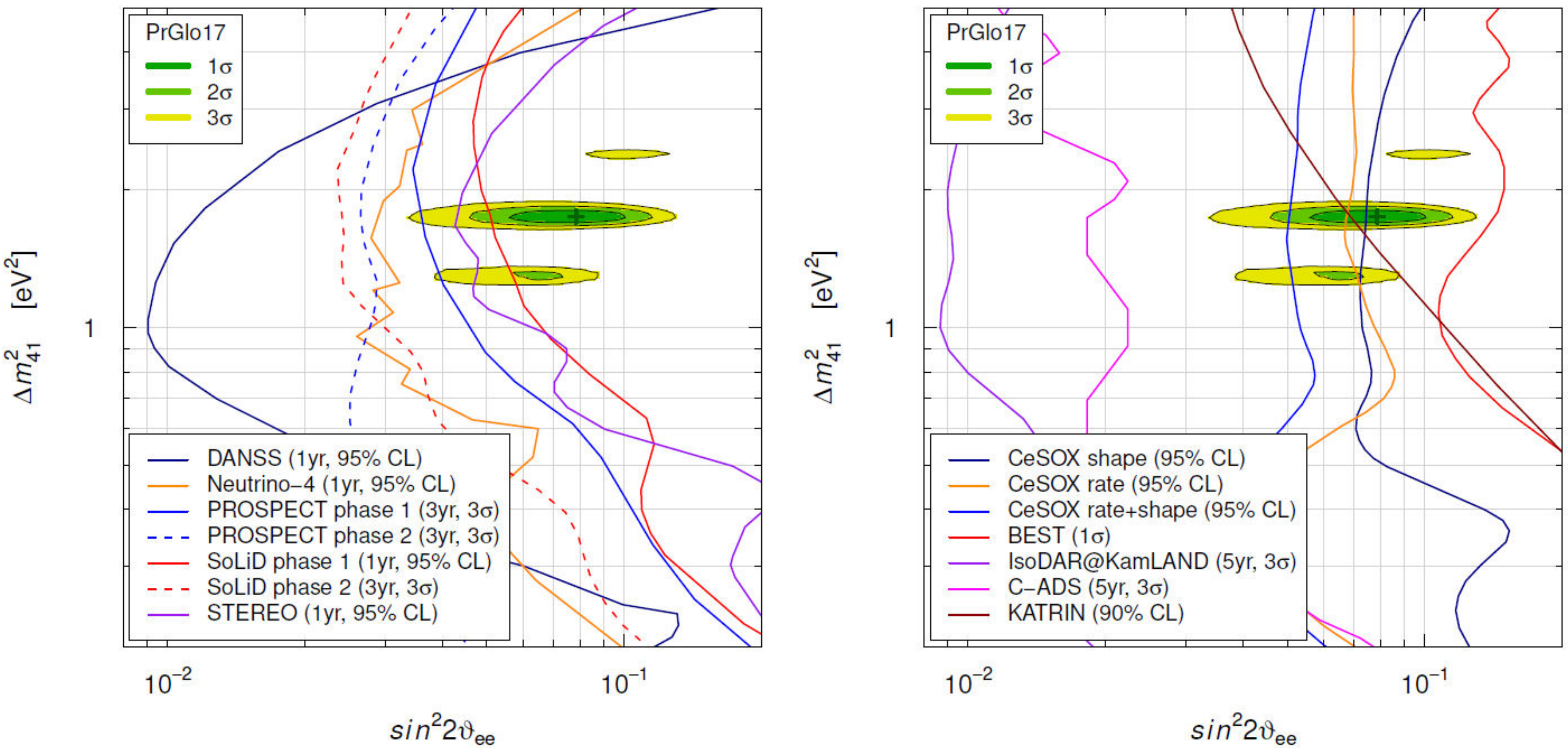


Comparison of experiments

	DANSS	NEOS	ν - 4	PROSPECT	SoLid	STEREO
Power [MWt]	3100	2815	90	85	50-80	58
Core size [cm]	**ø=3200 h=3700**	**ø=3100 h=3800**	42x42 h=35	ø=51 h=44	ø=50 h=90	ø=40 h=80
Overburden [mwe]	50	20	3.5	<1	10	15
Distance [m]	10.7-12.7 Movable	**24**	6-12 Movable	7-9	6-9	9-11
IBD events/day	5000	1965	**200**	750	~450	400
PSD/ Readout	- / 3D	+ / **1D**	- / 2D	+ / 3D	+ / 3D	+ / 2D
S/B	33	23	**0.54**	1.36	~3	**0.9**
σ_E/E [%] at 1 MeV	**28**	5	**16**	4.5	**14**	9

Red – good Black- bad

Compilation of expected sensitivities
[Gariazzo et al., JHEP06(2017)135]



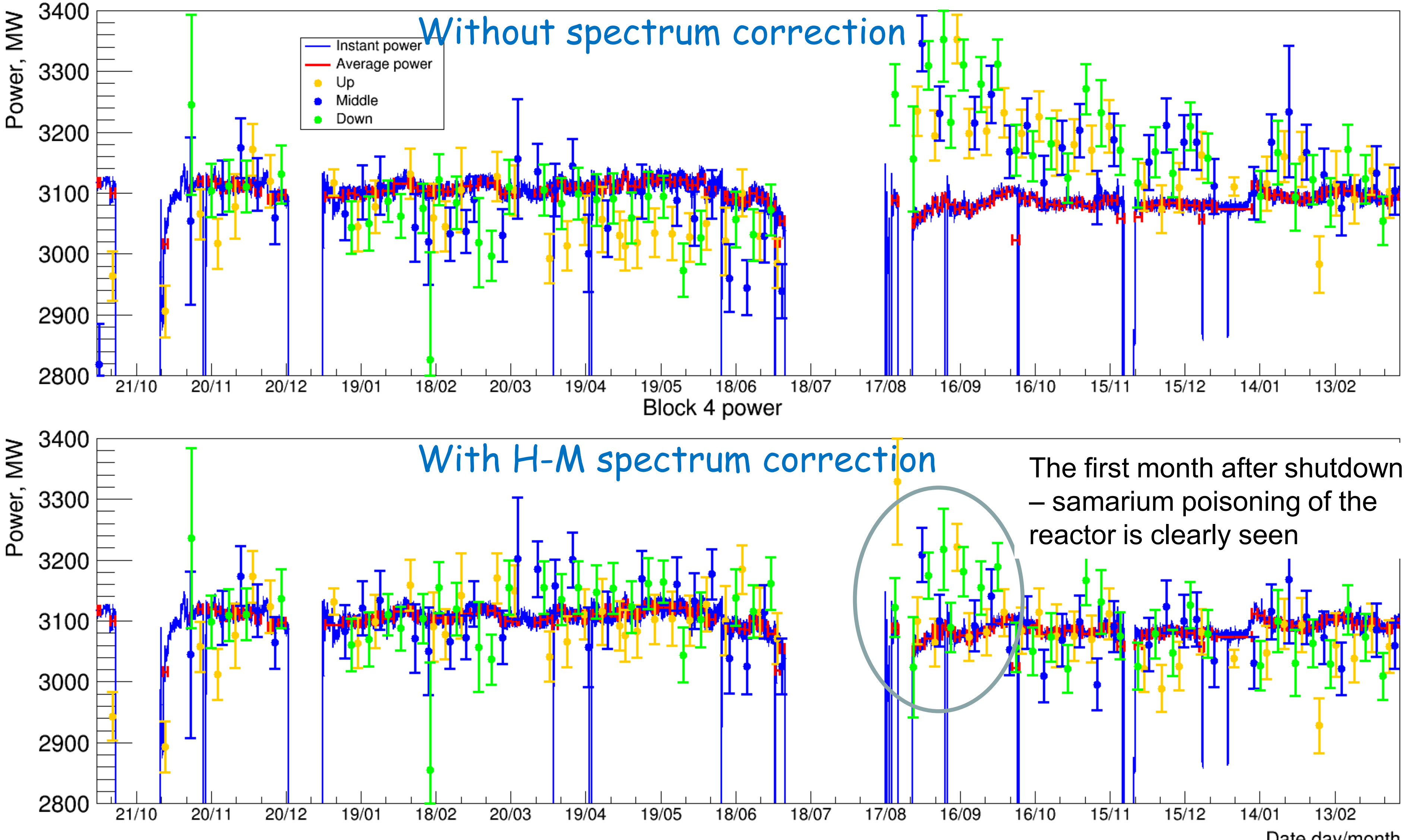
DANSS has highest sensitivity beyond $\sin^2(2\theta)$~0.01 but in limited mass range PROSPECT and upgraded NEUTRINO-4 have highest sensitivity at large Δm^2

ν source experiments can be very sensitive in wide range of Δm^2

Coherent ν scattering is also very promising (CONUS)

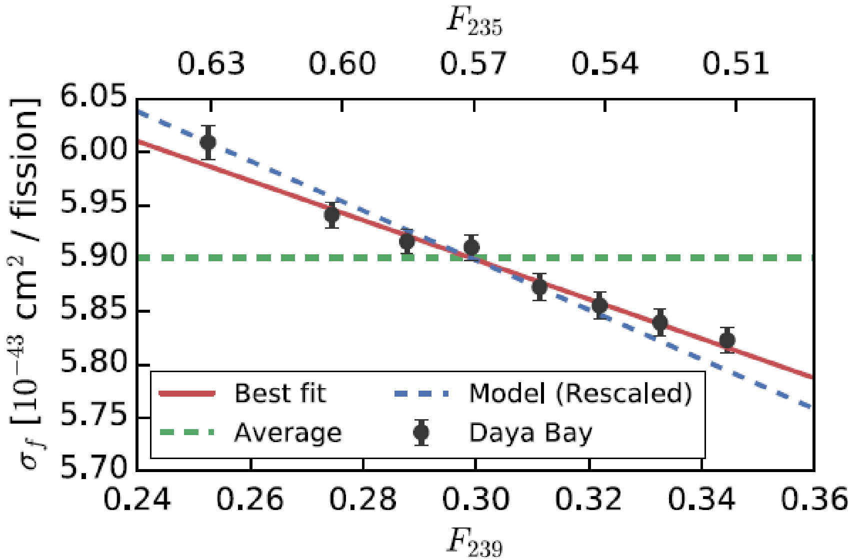
Spectrum evolution with fuel composition

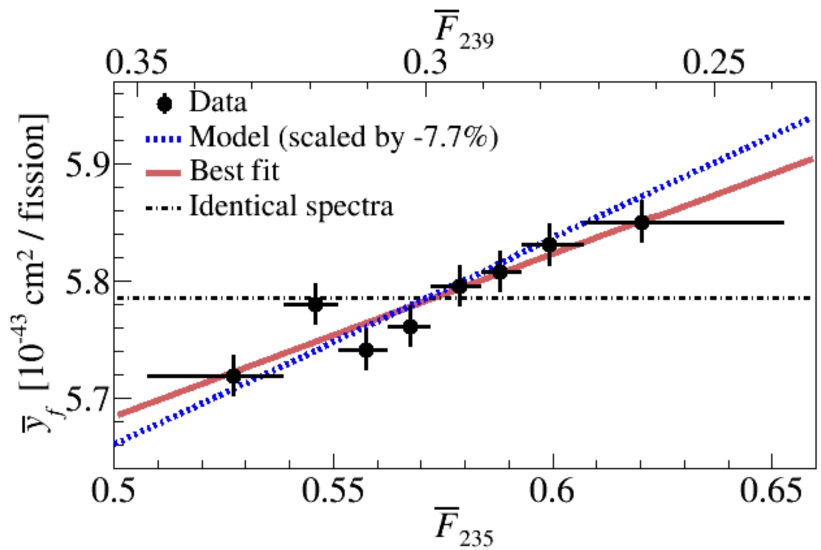
IBD rate (points) comparison with reactor power (blue line)



DANSS measures reactor power using ν with ~2% accuracy in 2 days

Daya Bay and RENO observed slightly slower spectrum evolution in comparison with Huber-Mueler model → Explanation of RAA?

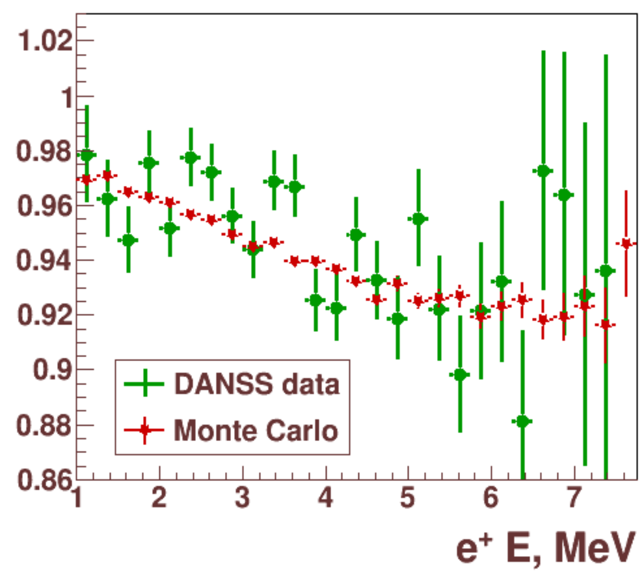




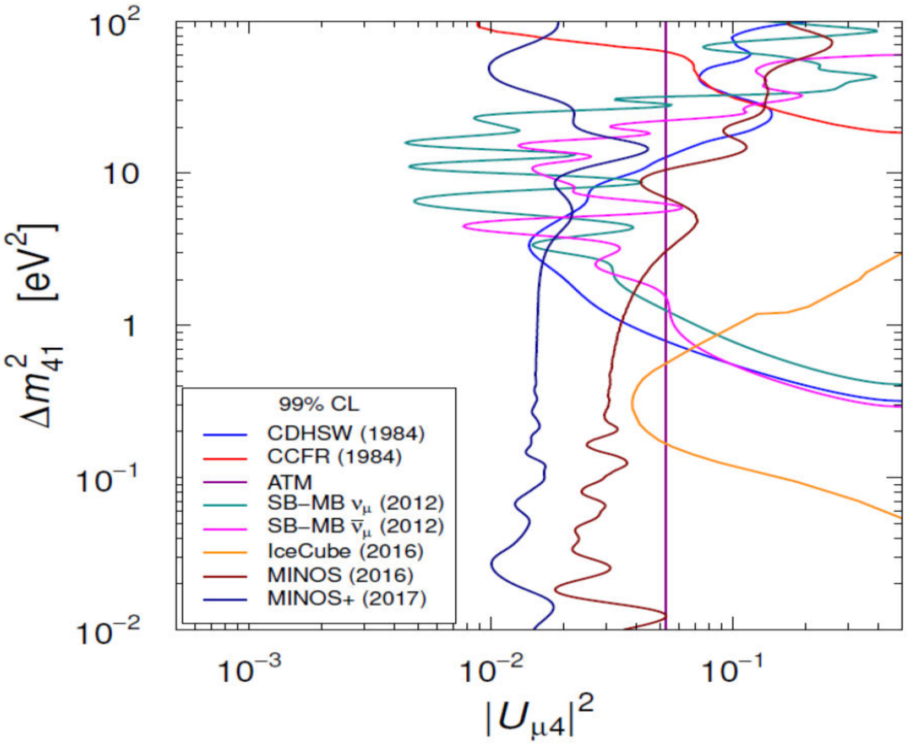
However preliminary DANSS results agree with H-M model

Ratio of e+ spectra at the end of campaign (3 months) to beginning

	Begin 4	End 4	Begin 5
^{235}U	63.7%	44.7%	66.1%
^{238}U	6.8%	6.5%	6.7%
^{239}Pu	26.6%	38.9%	24.9%
^{241}Pu	2.8%	8.5%	2.3%



Very strong limits on νμ disappearance



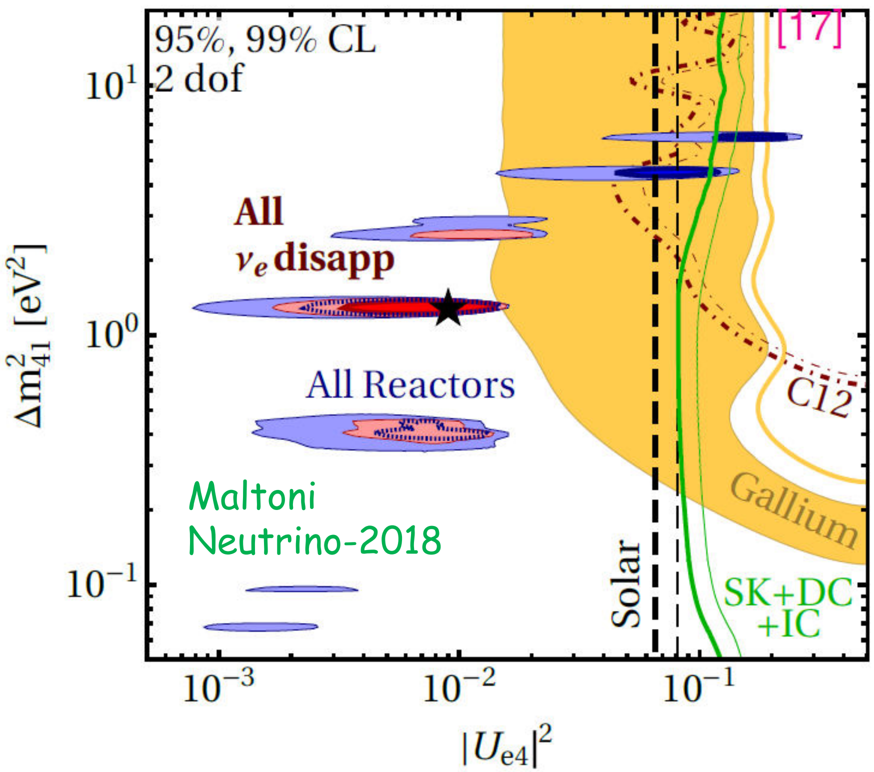
$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

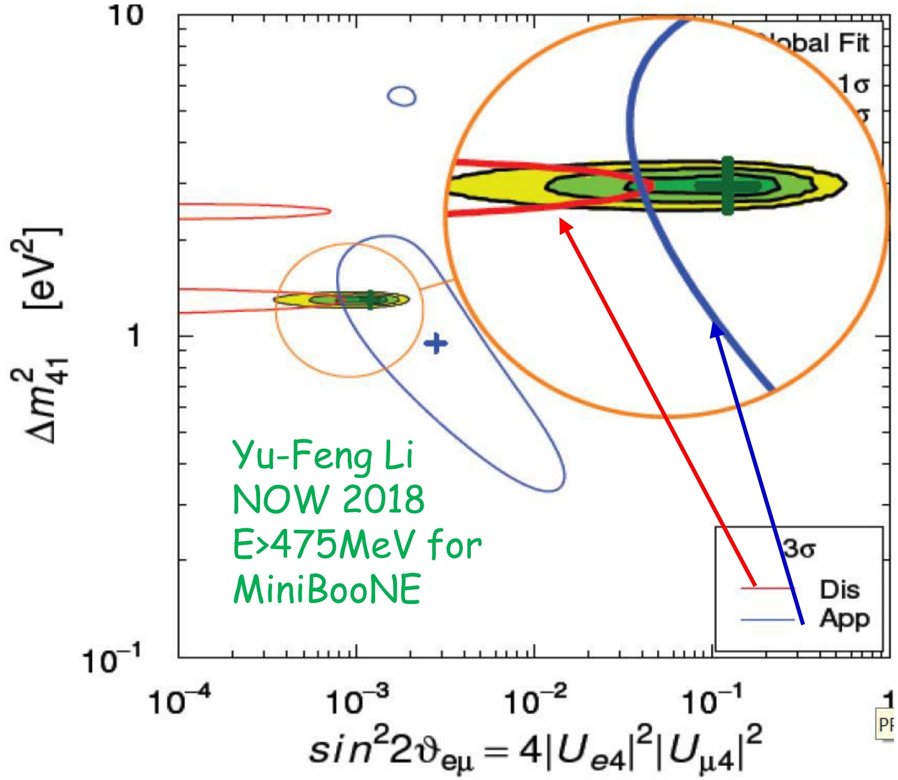
$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Strong limits on disappearance → strong limits on appearance

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

Appearance and disappearance experiments are not compatible even in "pragmatic" approach without low energy bins of MiniBooNE (NEUTRINO-4 results are not included yet)





Typical limits on $|Ue4|^2 < 0.01$ for $\Delta m^2 < 3eV^2$

Addition of 2-nd sterile neutrino does not help

Summary

Two new indications of sterile neutrinos in 2018:
MiniBooNE and NEUTRINO-4
Sterile neutrinos can not explain simultaneously
appearance and disappearance results

Reactor neutrino spectrum predictions are still quite uncertain
5 MeV bump not understood.
ν spectrum dependence on fuel differs from H-M model (but DANSS?)
Measurements at different distances in one experiment are required

DANSS demonstrated ability to measure reactor power using neutrinos
with ~2% accuracy in 2 days during more than 1 year

Strong limits on sterile neutrino parameters have been obtained by
DANSS and NEOS.

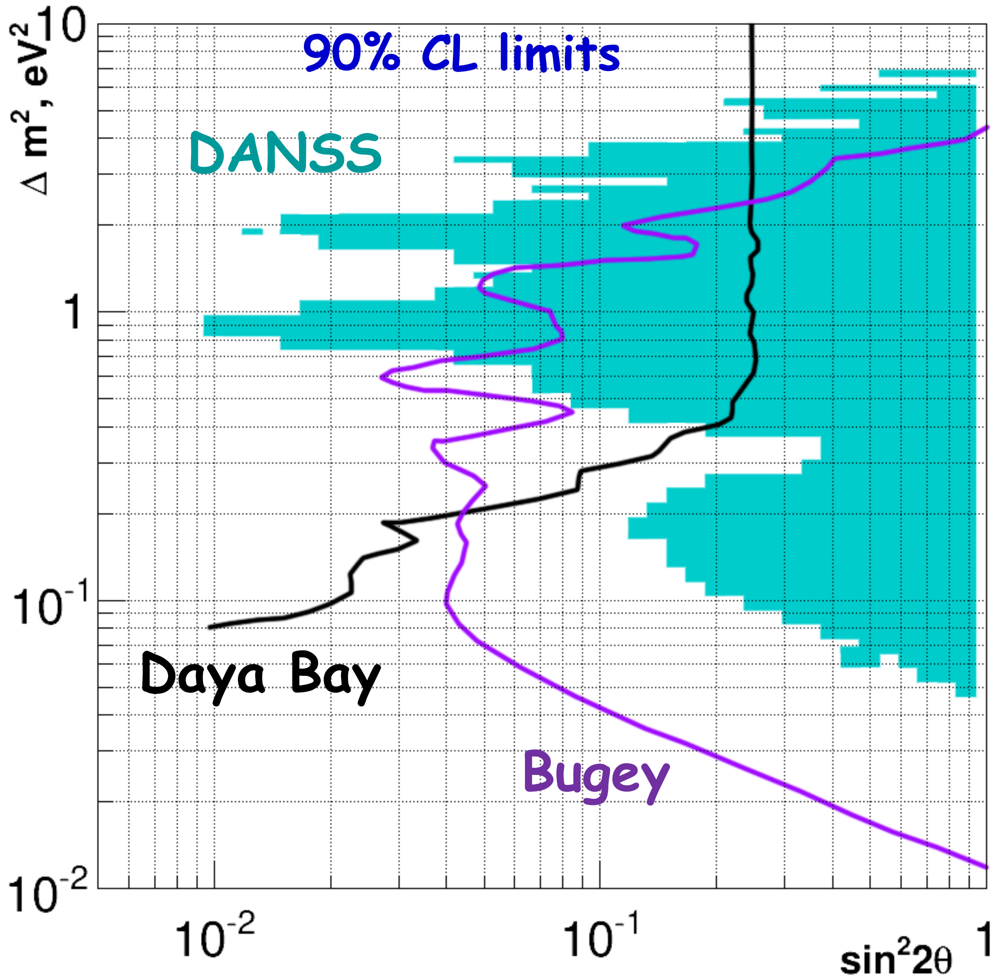
PROSPECT, STEREO and NEUTRINO-4 extended recently the limits
to higher values of Δm^2

New results with increased sensitivity are expected in the near future
from DANSS, NEOS, NEUTRINO-4, PROSPECT, SOLID and STEREO

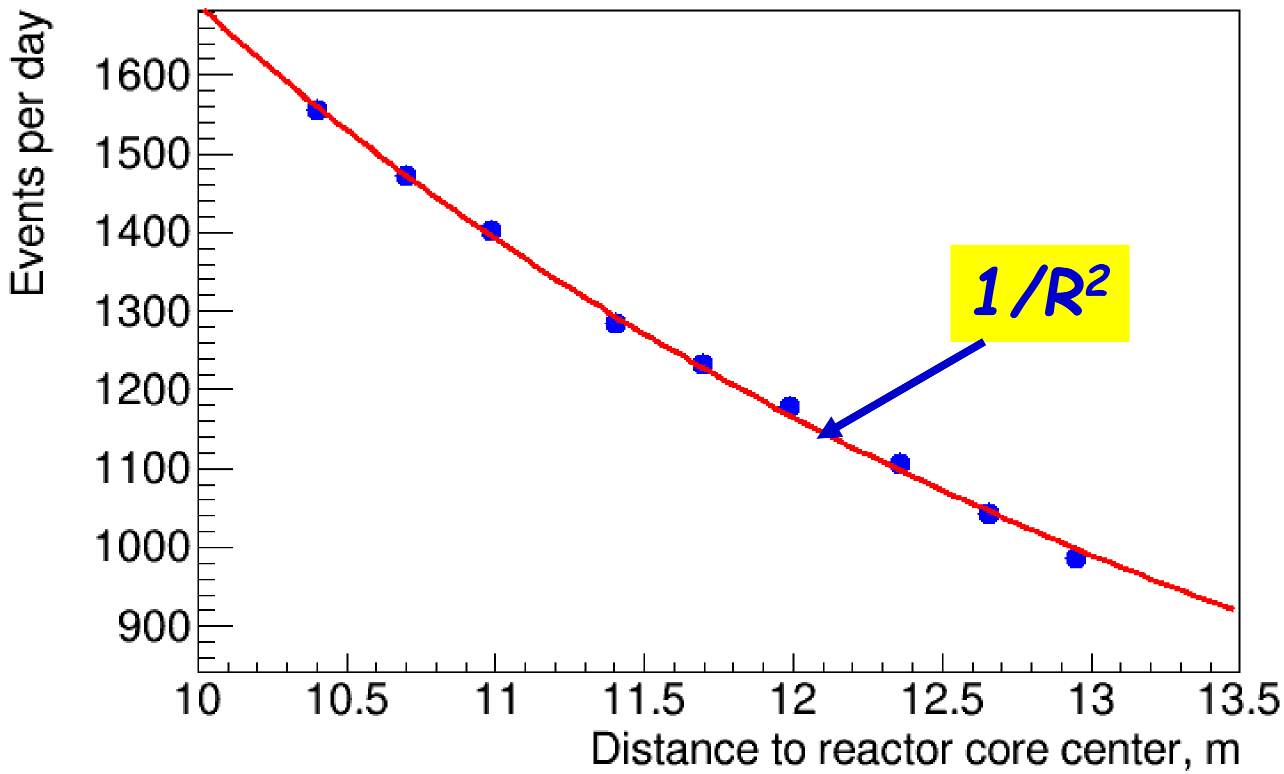
Backup slides

Comparison with experiments based on spectra ratio at different distances

NEOS is not included since it is normalized on spectrum from different experiment (and reactor)



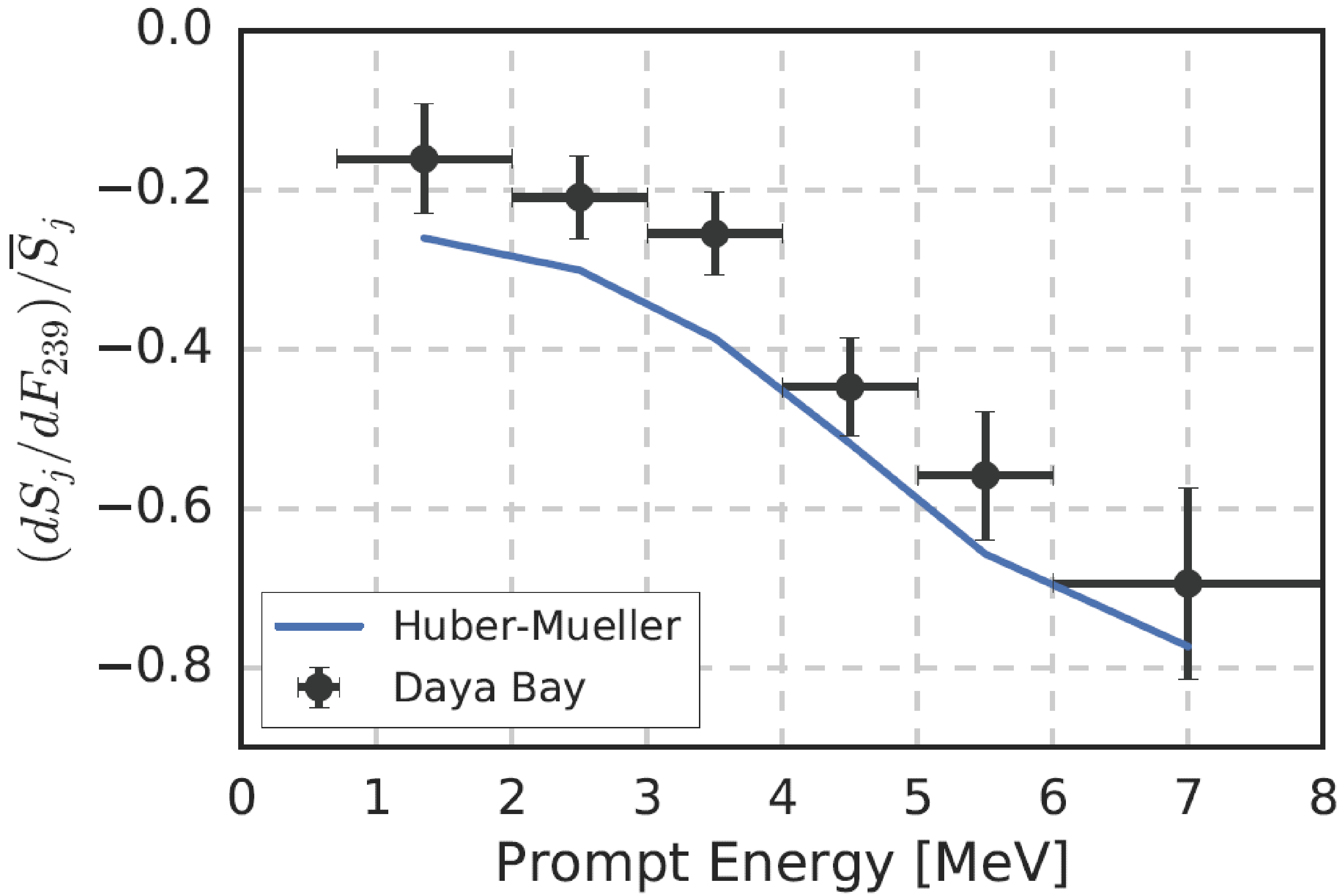
$\bar{\nu}$ counting rate dependence on distance from reactor core



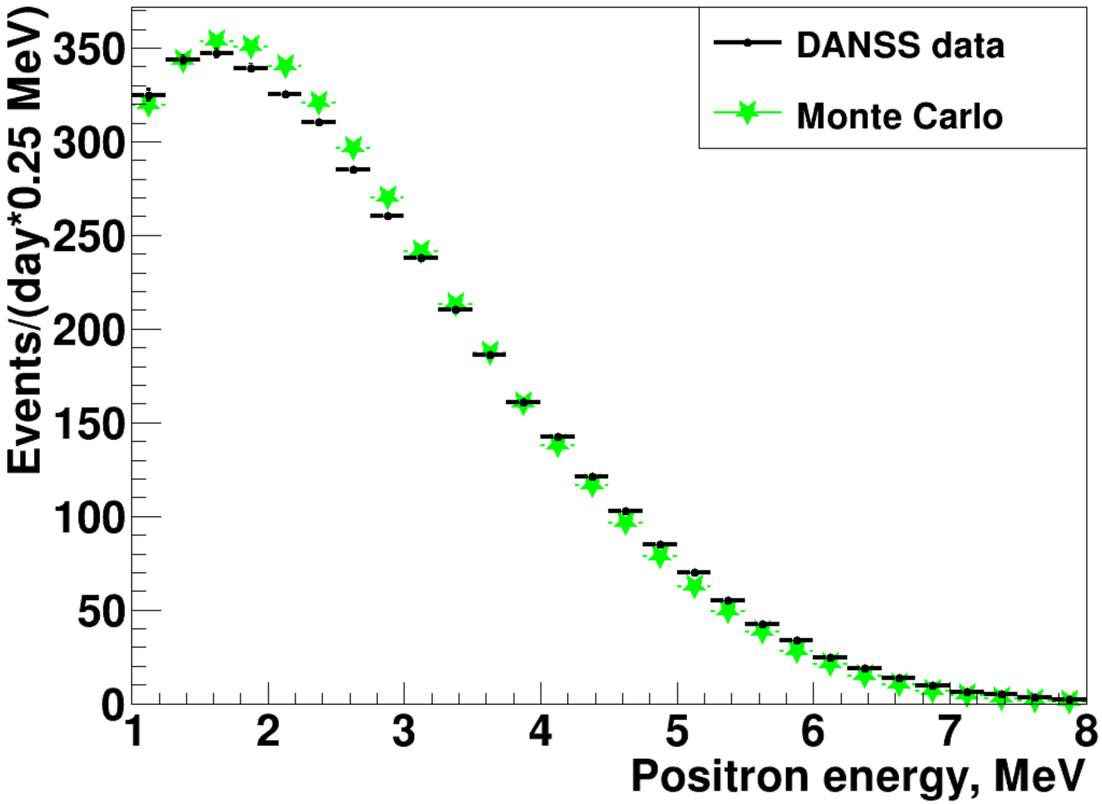
- **3 detector positions**
- **Detector divided vertically into 3 sections with individual acceptance normalization**

Rough agreement with $1/R^2$ dependence

Daya Bay measurements of spectrum evolution (smaller than MC predictions)

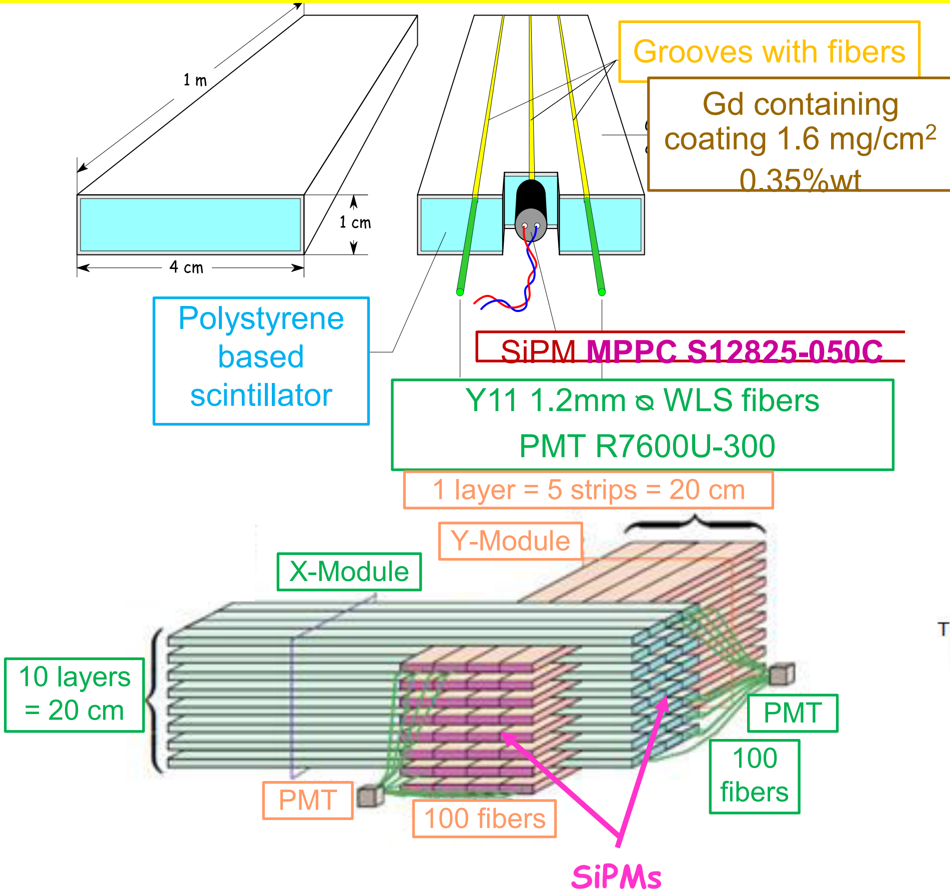


Positron spectrum (last 4 months of campaign)

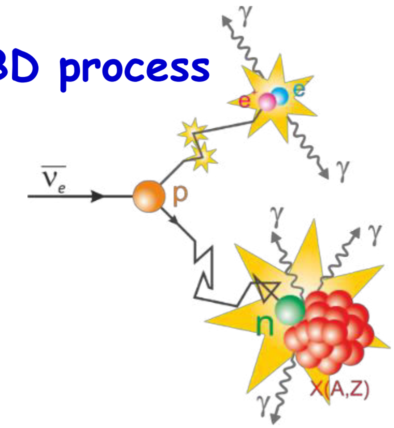


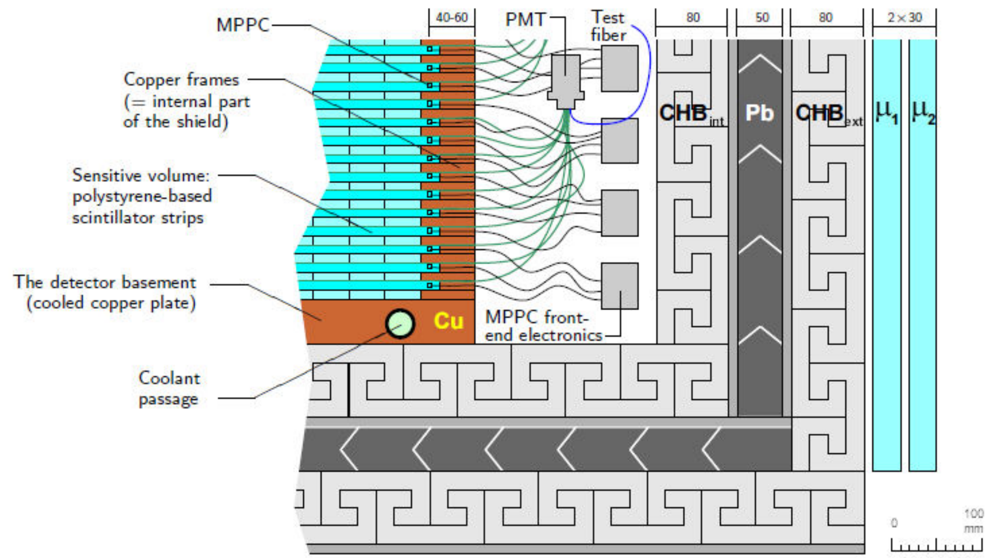
Rough agreement with MC.
(Theoretical neutrino spectrum was taken from Huber and Mueller)
More work on calibration is needed before quantitative comparison

DANSS Detector design (ITEP-JINR Collaboration)



IBD process

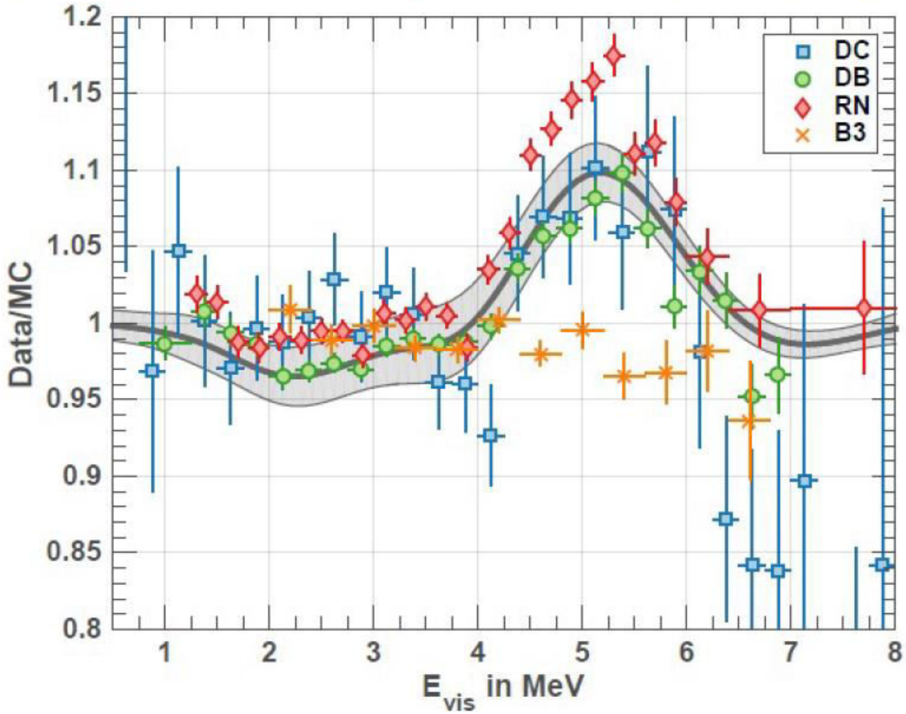


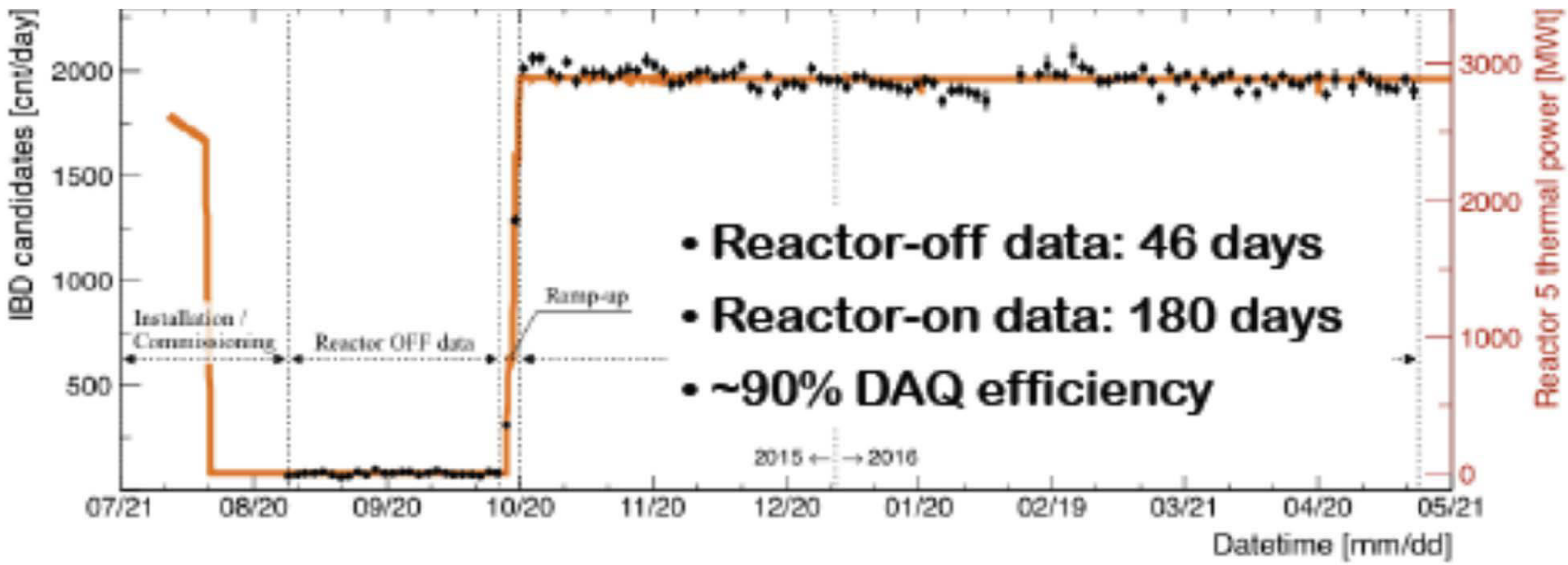


- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

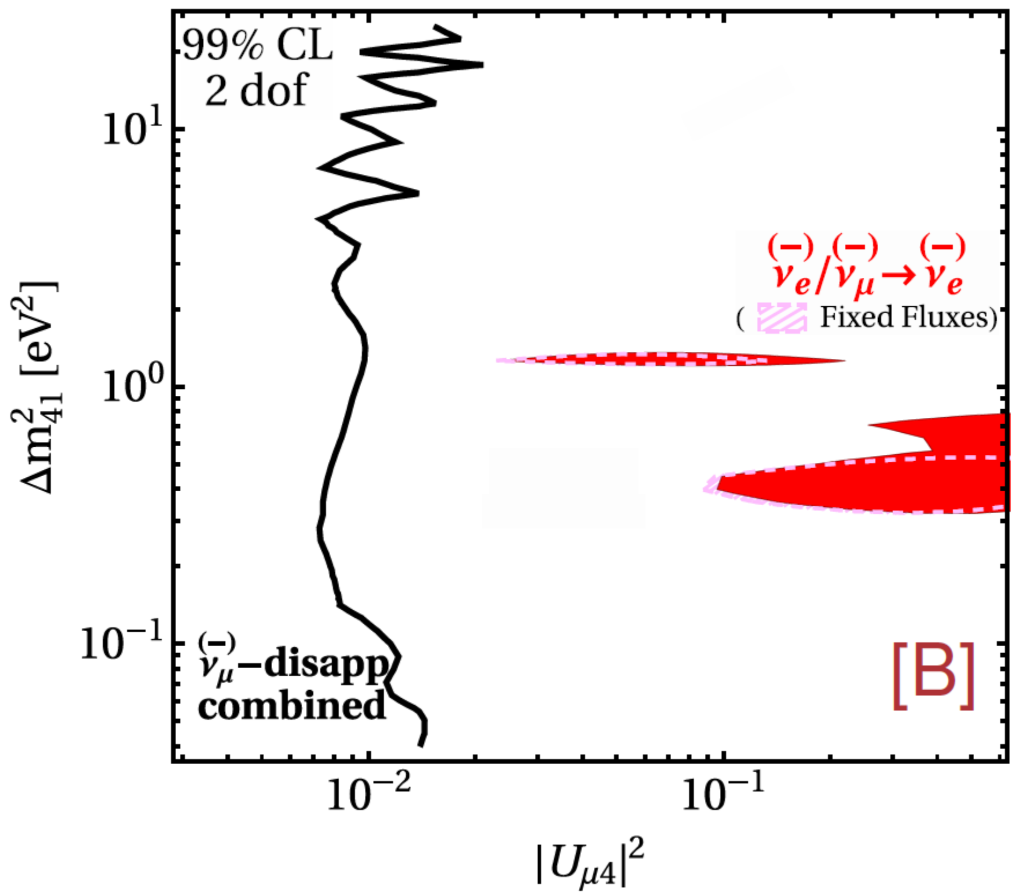
- Two-coordinate detector with fine segmentation – spatial information
- Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides

[G. Mention et al., Phys. Lett. B773(2017)307]

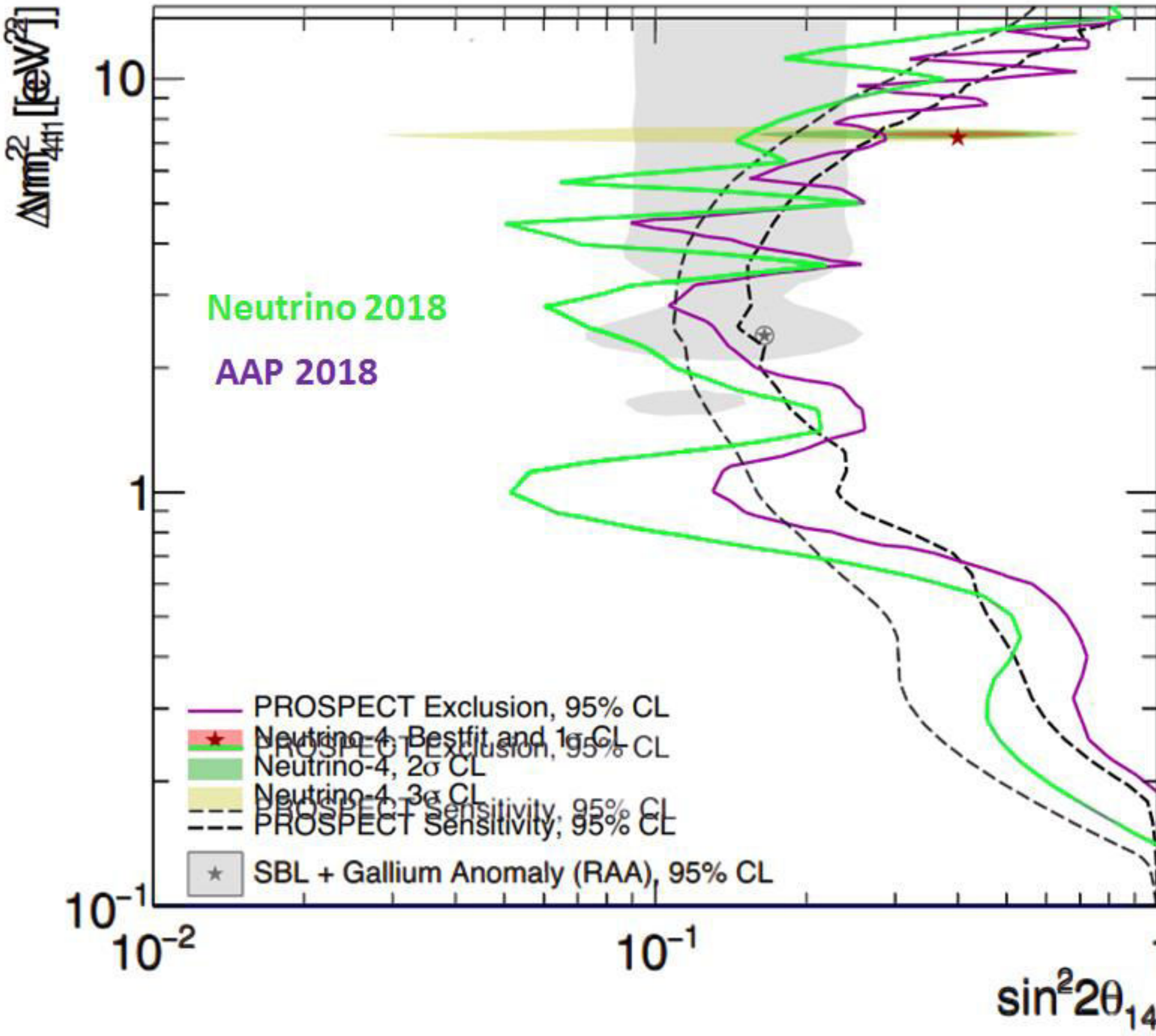




IBD rate agrees with reactor power within ~5%



99% CL
2 dof
Δm^2_{41} [eV^2]
10^1
10^0
10^{-1}
10^{-2}
$|U_{\mu 4}|^2$
$\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
(Fixed Fluxes)
$\overset{(-)}{\nu}_\mu$–disapp
combined
[B]



Δm^2_{41} [eV^2]
10
1
10^{-1}
10^{-2}
10^{-1}
1
$\sin^2 2\theta_{14}$
Neutrino 2018
AAP 2018
PROSPECT Exclusion, 95% CL
Neutrino-4, Bestfit and 1σ CL
PROSPECT Exclusion, 95% CL
Neutrino-4, 2σ CL
Neutrino-4, 3σ CL
PROSPECT Sensitivity, 95% CL
PROSPECT Sensitivity, 95% CL
SBL + Gallium Anomaly (RAA), 95% CL