10th International Conference on New Frontiers in Physics
Kolymbari, Crete, 23.08-03.09, 2021

Search for sterile neutrinos at very short baseline reactor experiments

- **Mikhail Danilov LPI (Moscow)**

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

ν oscillations in 3 generations are well measured

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

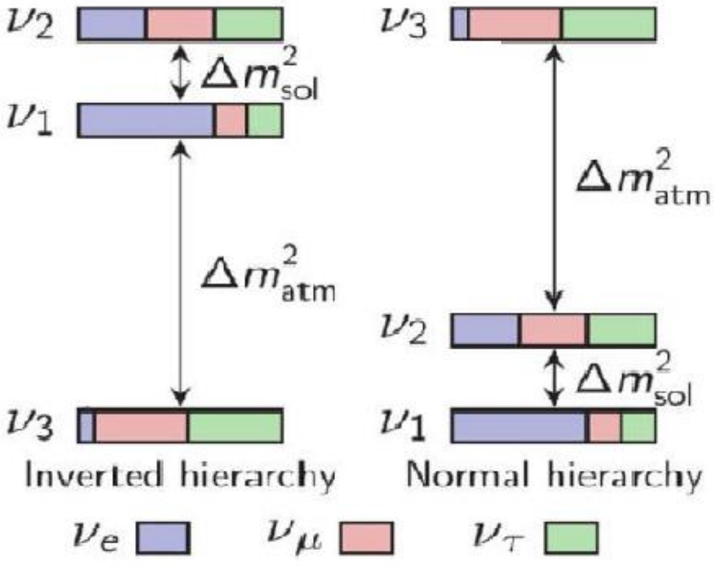
$\theta_{23} \sim 45°$
Atmospheric
Accelerator

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

$\theta_{12} \sim 34°$
Solar
Reactor

$|\Delta m^2_{31}| \sim 2.4\times10^{-3}\ eV^2$

$\Delta m^2_{12} \sim 8\times10^{-5}\ eV^2$



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

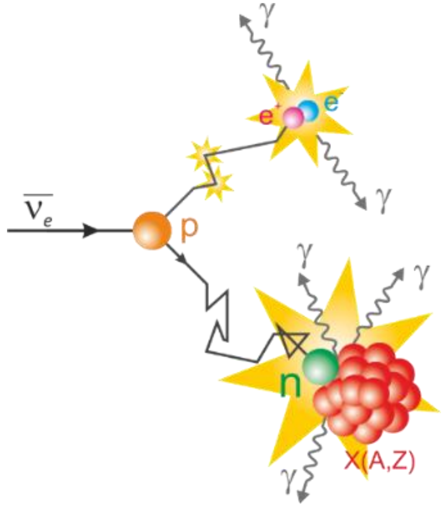
There are several indications of 4^{th} neutrino

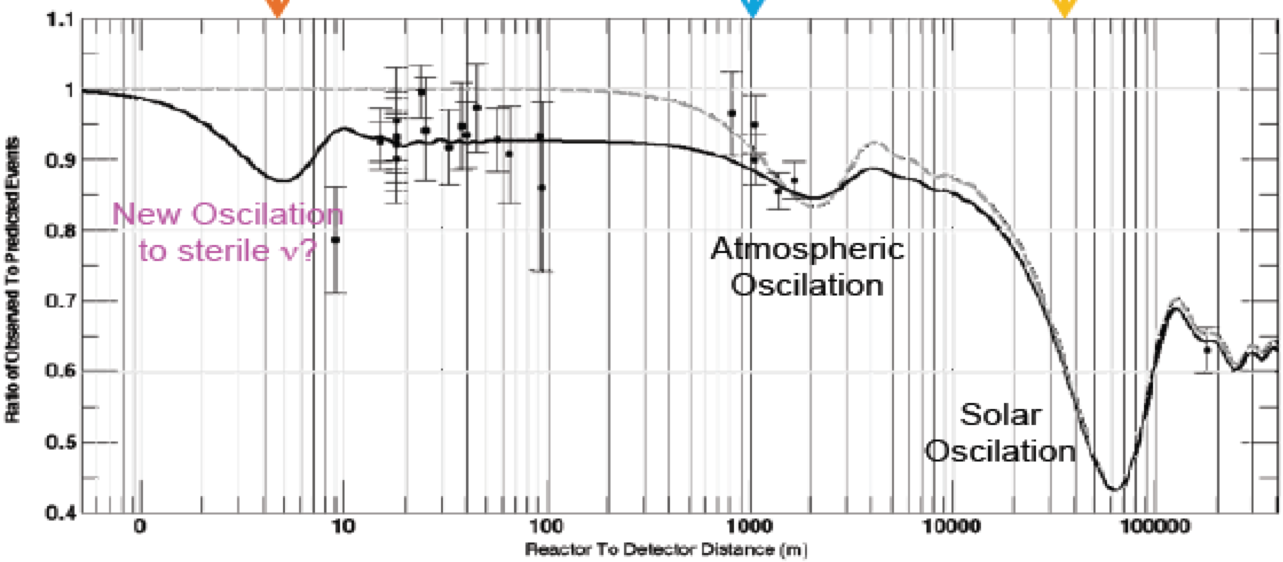
LSND, MiniBoone: $\bar{\nu}_e$ appearance
SAGE and GALEX ν_e deficit (GA)
Reactor $\bar{\nu}_e$ deficit (RAA)

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

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

Inverse Beta Decay (IBD) process



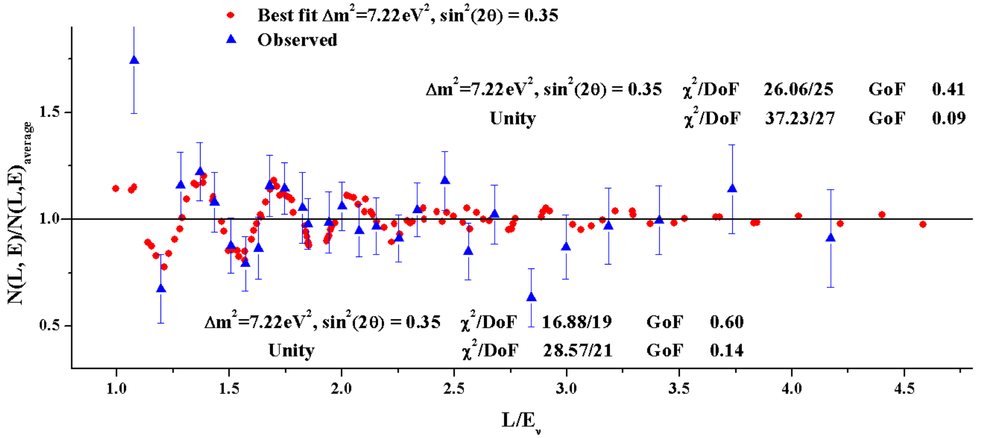


G. Mention et al. Phys Rev D 83 073006 (2011)

Reactor models are based on ILL measurements of 235U, 239Pu, 241Pu electron spectra.
Recently Kurchatov Inst. Group observed 5.4% smaller ratio of e- yields for 235U/239Pu (arXiv:2103.01684v1). This can explain the RAA!

Recent (2018) indications of sterile neutrinos

NEUTRINO-4: Δm^2~7eV^2 $\sin^2 2\theta$~0.35! JETP Lett. 109 (2019) no.4, 213; Arxiv:2005.05301 Phys.Rev.D 104, 032003 (2021)

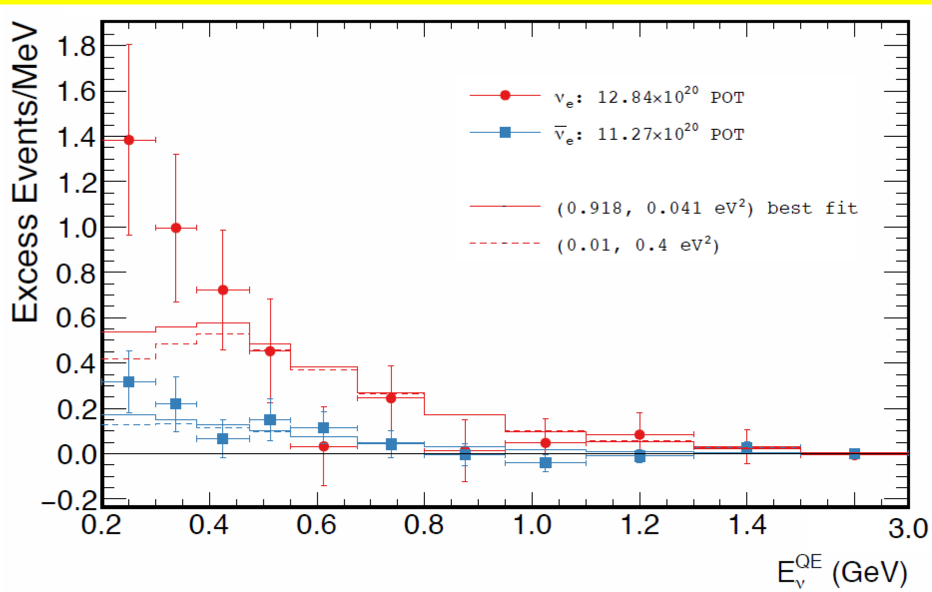


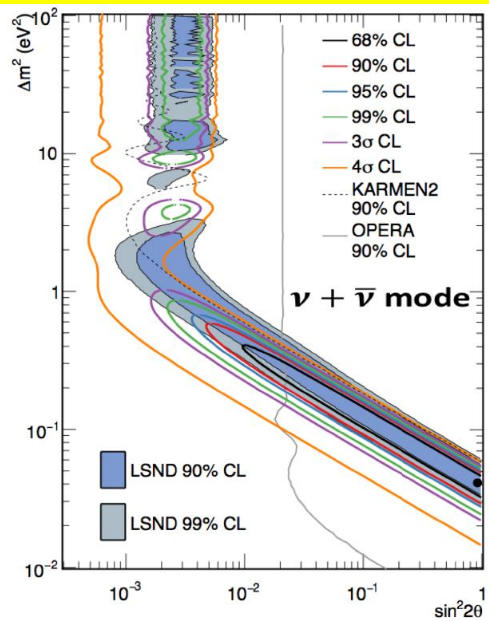
NEUTRINO-4 claimed observation of sterile neutrinos although significance is only 2.7σ and there are concerns about validity of the analysis:

M.D., N.Skrobova JETP Lett.112,199(2020)

C.Giunti et al. Phys.Lett.B 816(2021)136214

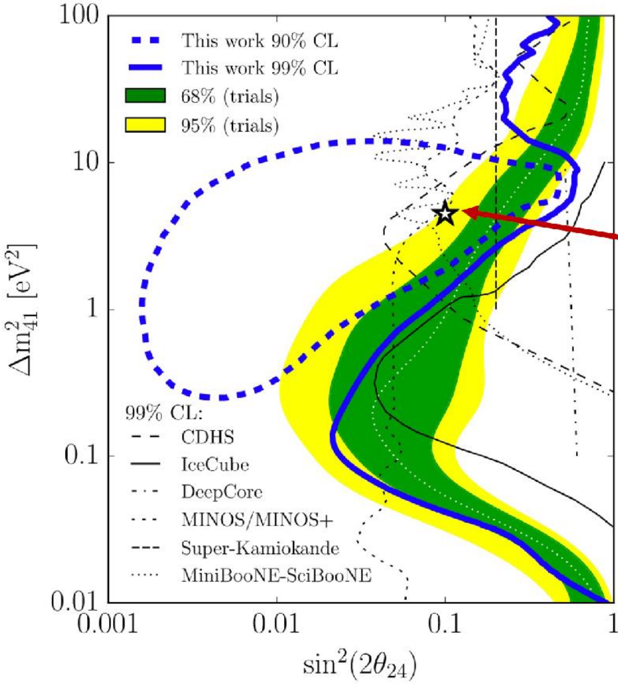
MiniBooNE ν_e excess of 4.8σ (6σ with LSND) Phys.Rev.Lett. 121 (2018) no.22, 221801





Very weak indication of ν_μ disappearance in ICE Cube (but with large Δm^2 as in Neutrino -4)

$P(\nu_\mu \rightarrow \nu_\mu)$



PRL 125, 141801 (2020)

- 8 years of atmospheric ν_μ

ν_μ disappearnce channel

- Best fit (frequentist):
  - $\Delta m^2_{41} = 4.5$ eV^2
  - $\sin^2(2\theta_{24}) = 0.10$

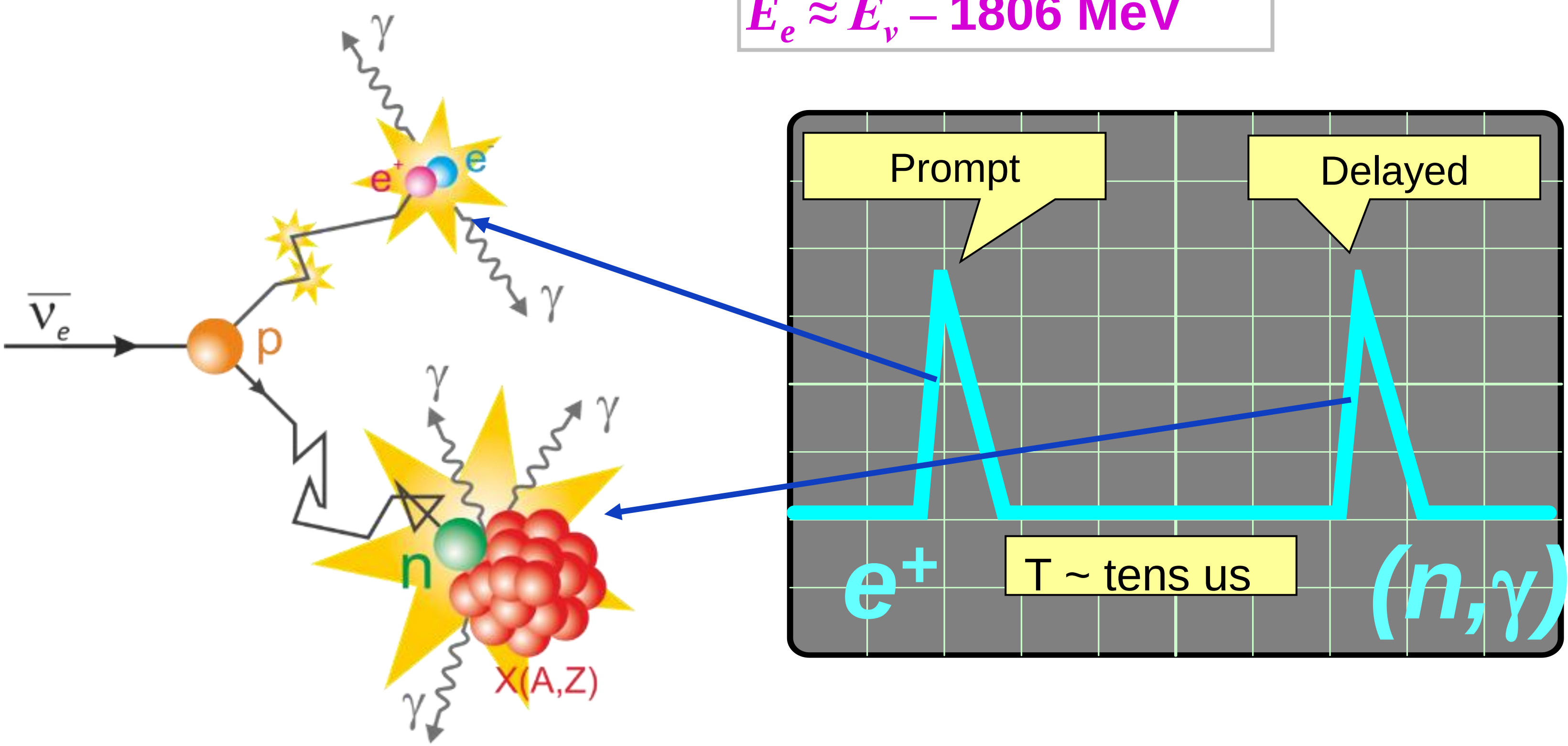
→ **Consistent with Null hypothesis (p-value: 8 %)**

Searches for sterile neutrinos are very exciting
Many experiments are searching for sterile neutrinos with m~eV including 9 reactor experiments

Antineutrino detection

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

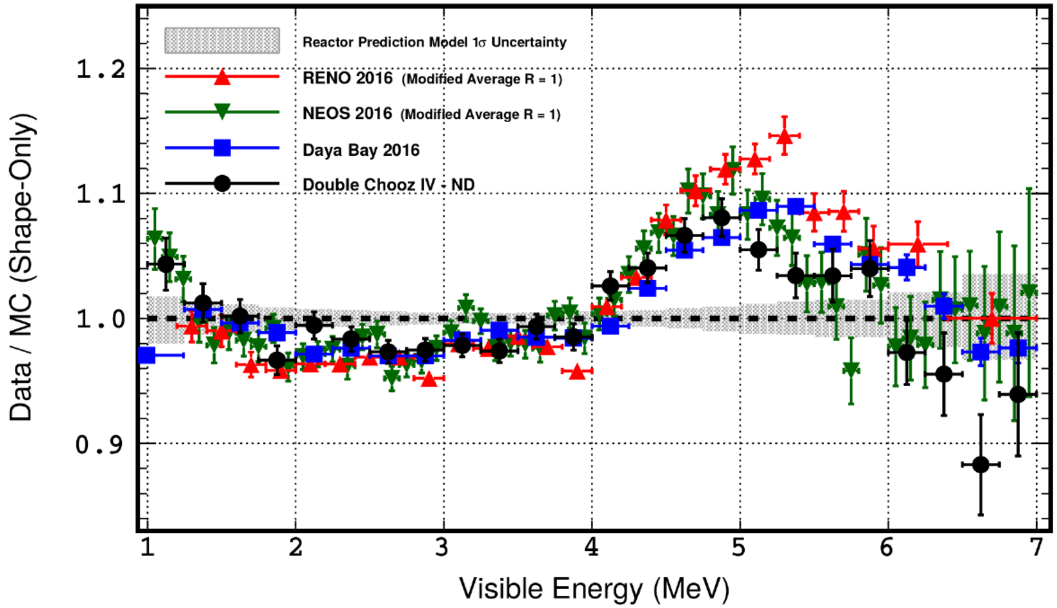
$E_e \approx E_\nu - $ **1806 MeV**



Reactor models do not describe well antineutrino spectrum

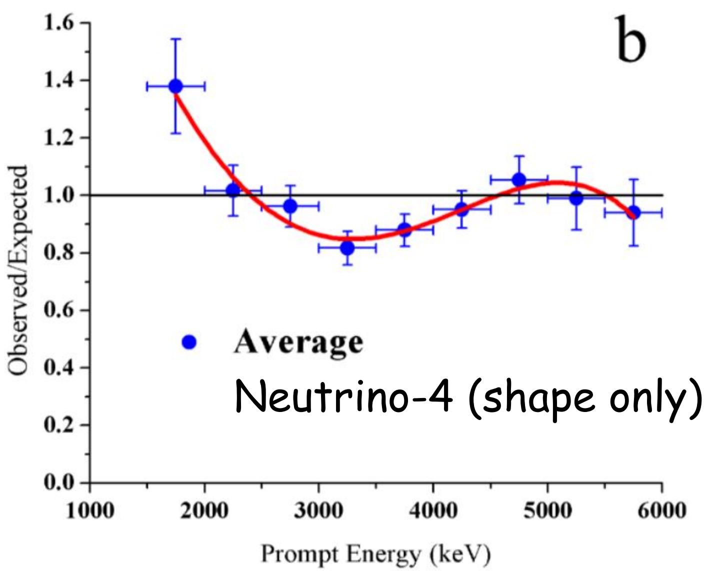
Measurements at one L not sufficient to observe oscillations

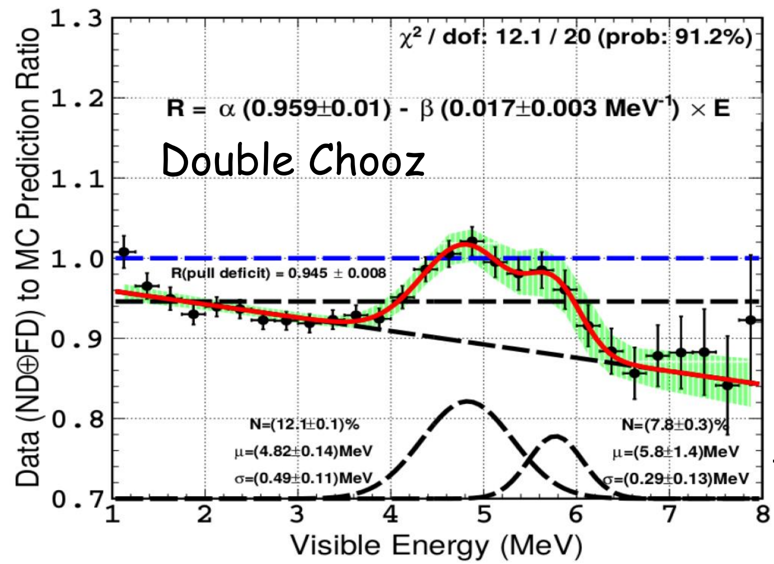
All recent experiments observe a bump at 4-6MeV



T.Bezerra
NOW-2018

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





Is Reactor Antineutrino Anomaly Real?

Reactor models are based on ILL measurements of β spectra from 235U, 239Pu, 241Pu n-induced fission isotopes

Recently Kurchatov Inst. Group observed 5.4% smaller ratio of β yields for 235U/239Pu (arXiv:2103.01684v1). This can explain the RAA!

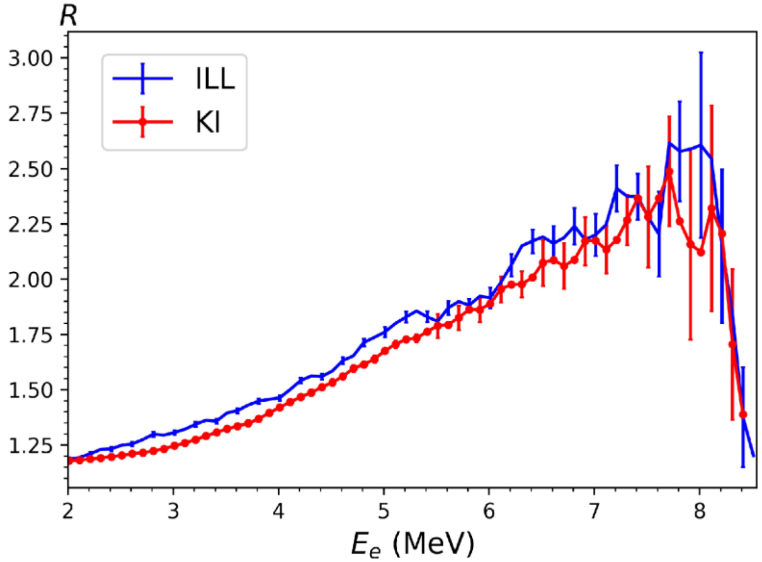


FIG. 1. Ratios $R = {}^e S_5/{}^e S_9$ between cumulative β spectra from ^{235}U and ^{239}Pu from ILL data [11] (blue) and KI data [10] (red). Total electron energies are given. Only statistical errors are shown.

$({}^5\sigma_f/{}^9\sigma_f)_{KI} = 1.45 \pm 0.03$ - 5.4% smaller than ILL

DayaBay and RENO observed smaller 235U flux than in Huber-Mueler model (based on ILL results)

$({}^5\sigma_f/{}^9\sigma_f) = 1.44 \pm 0.10$ - 5.4% smaller than ILL

(Phys. Rev. Lett. **123**, 111801 and Phys. Rev. Lett. **122**, 232501)

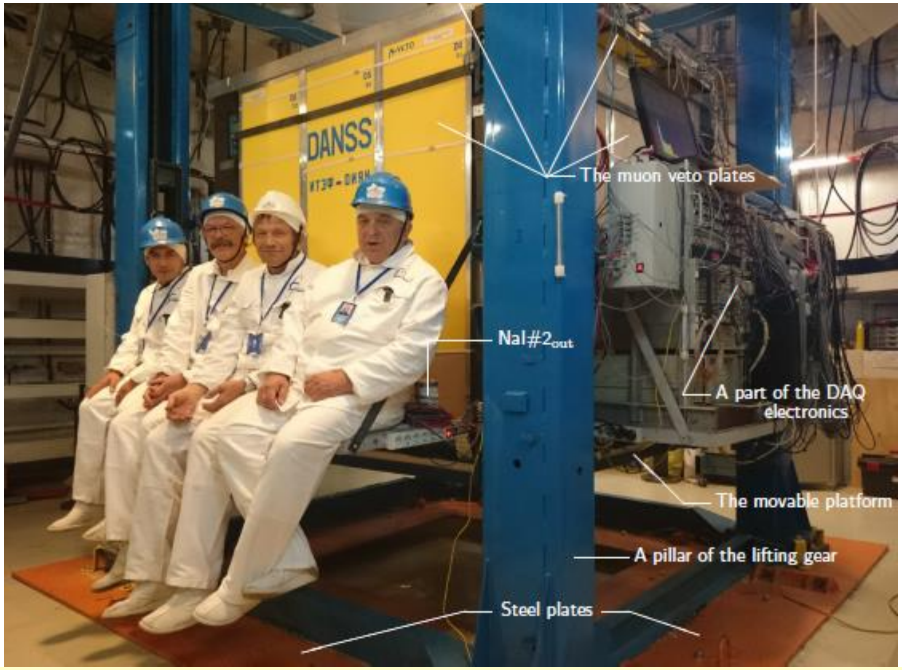
238U contribution should be also reduced since it is normalized on 235U

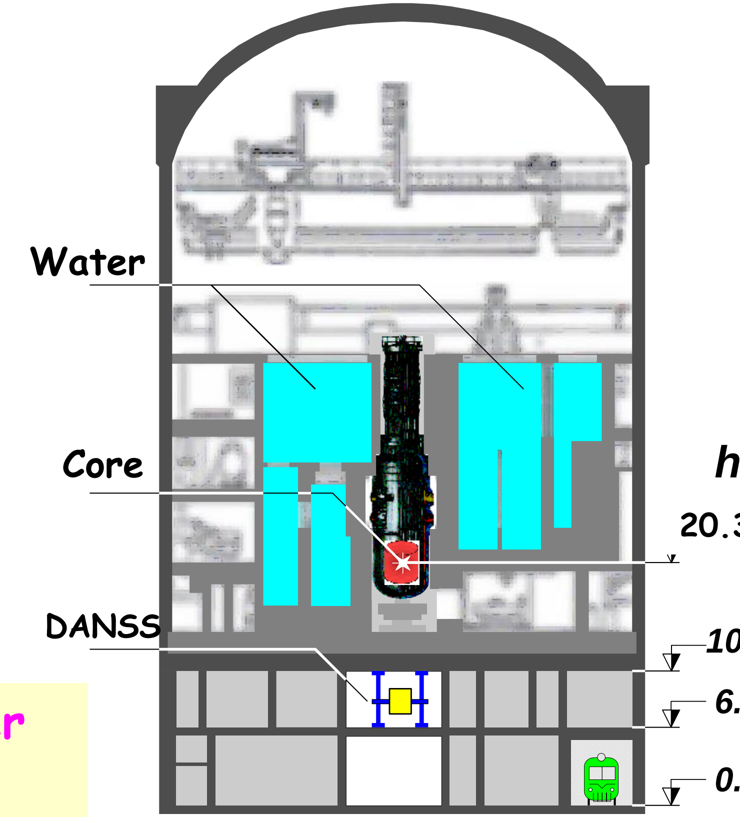
With new values for 235U and U238 contribution measured ν fluxes agree with predictions
→ No Reactor Antineutrino Anomaly? – Wait till confirmation of KI results

In any case modern searches for sterile ν do not use predictions for absolute ν fluxes and predicted shape of the reactor ν spectra.
Instead relative measurements at different L are studied

Comparison of Very Short Base Line reactor experiments

DANSS at Kalinin NPP collected 5.5M IBD events in 5 years



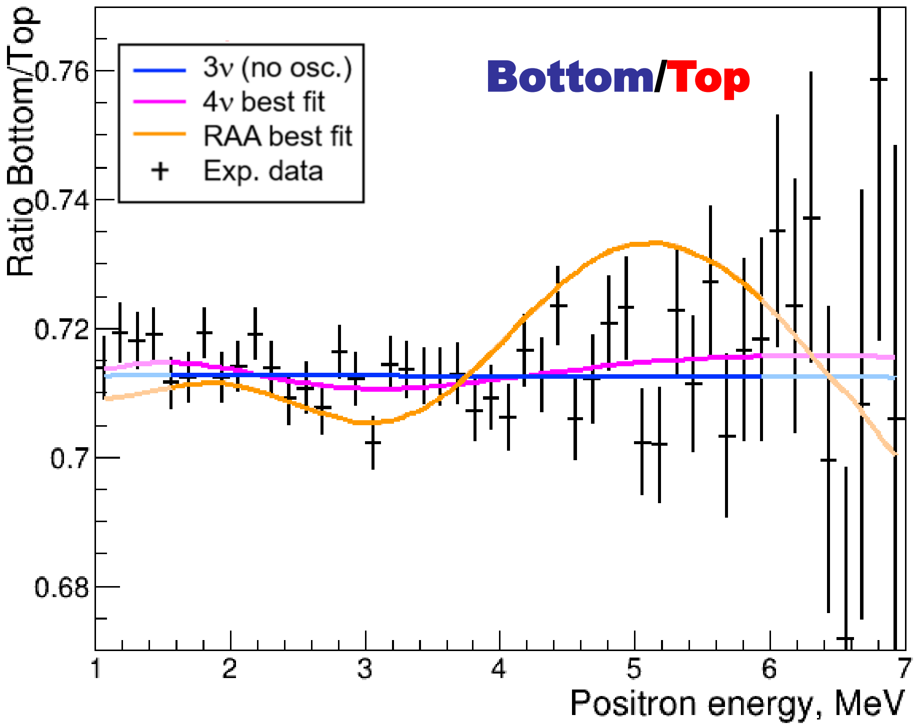


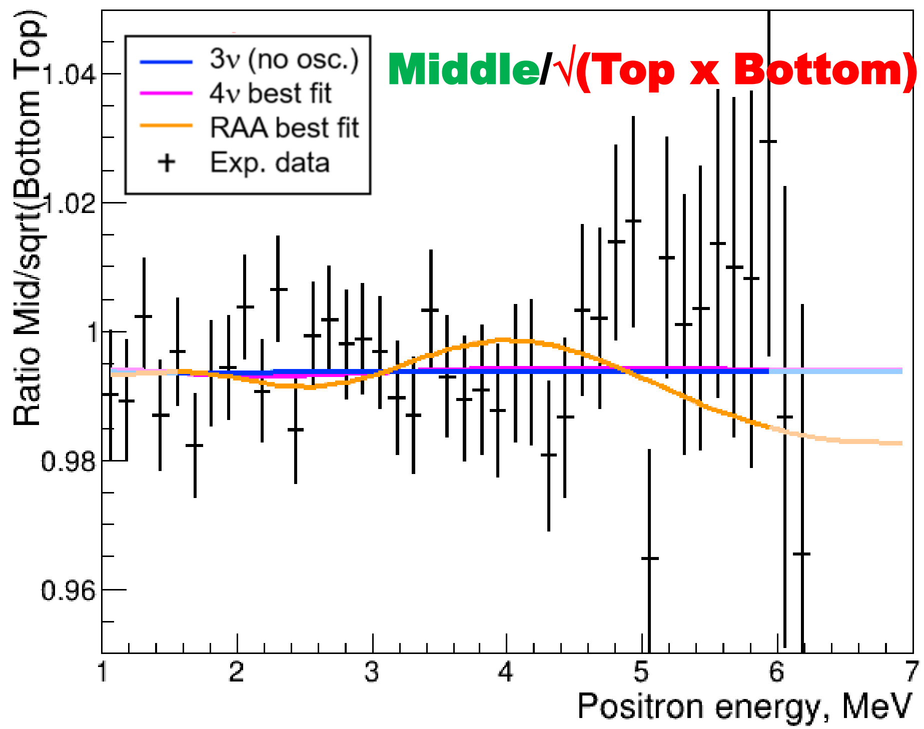
DANSS is installed on a movable platform under 3.1 GW WWER-1000 reactor (Core:h=3.7m, ∅=3.1m) at Kalinin NPP.
~50 mwe shielding => μ flux reduction ~6!
No cosmic neutrons!
Detector distance from reactor core 10.9-12.9m (center to center) changed 2-3 times a week!
5000 IBD events/day at top detector position
Trigger: ΣE(PMT)>0.5-0.7MeV=>Read 2600 wave forms (125MHz), look for correlated pairs offline.

Fuel fission fractions: average start and end of campaign [%]

235U	54.1	63.7	44.7
239Pu	33.2	26.6	38.9
238U	7.3	6.8	7.5
241Pu	5.5	2.8	8.5

Ratio of positron spectra





- Fit in 1.5-6 MeV range (to be conservative)
- Using current statistics 2016-2020 (~5 million IBD events)

  we see no statistically significant indication of 4ν signal:

  ΔX^2=-3.2 (< 1.3σ) for 4ν hypothesis best point Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.014
- RAA has been excluded with ΔX^2= 107.
- RAA was excluded by DANSS with more than 5σ already in 2018

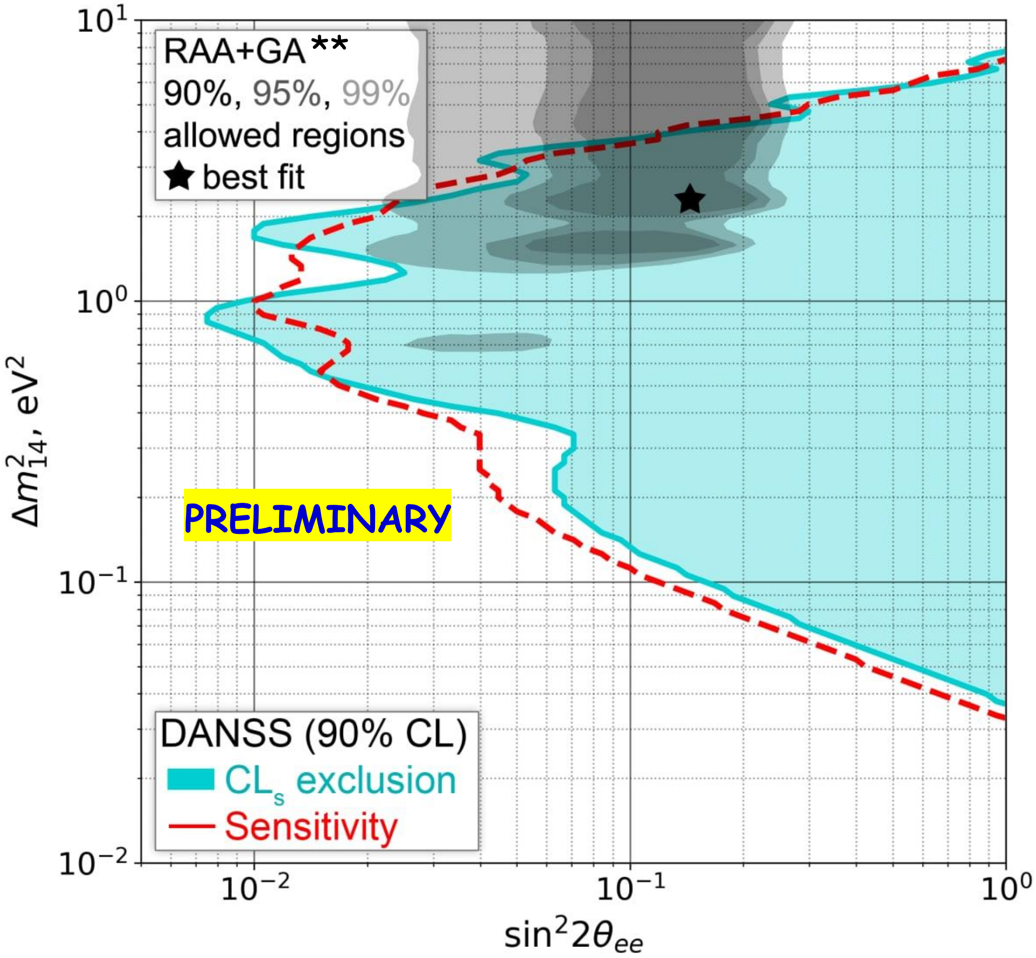
  (arXive:1804.04046v1)

The DANSS results

- Exclusion region was calculated using Gaussian CLs method (for e^+ in 1.5-6 MeV to be conservative),
- New data make limits more smooth in reasonable agreement with sensitivity
- The most stringent limit reaches

$\sin^2 2\theta < 8\times10^{-3}$ level (best in the world).

- A very interesting part of 4ν parameters is excluded.
- The most probable point of RAA+GA is excluded at 5σ confidence level (already in 2018)



** - G.Mention J.Phys.:Conf.Ser. 408 (2013) 012025

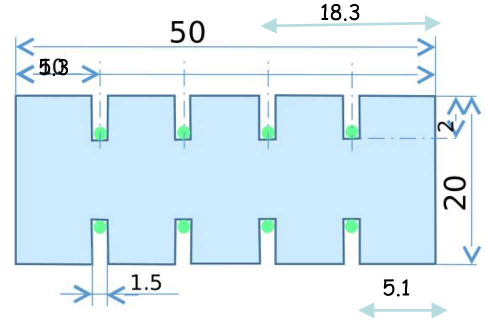
The DANSS upgrade

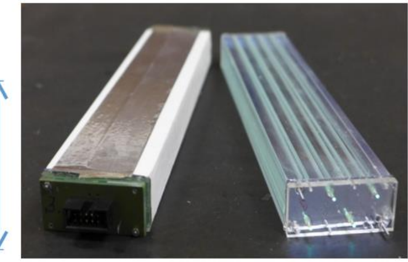
Main goal: to reach resolution **13%/√E**
w.r.t. current very modest 34%/√E.

New geometry:

Strips: **2x5x120 cm, 2-side 4**SiPM readout
Structure: **60 layers x 24 strips: 1.7 m³**
Setup uses **the same shielding and moving platform.**
Gd is in foils between layers.
Upgrade will be finished in 2022

New scintillator strips

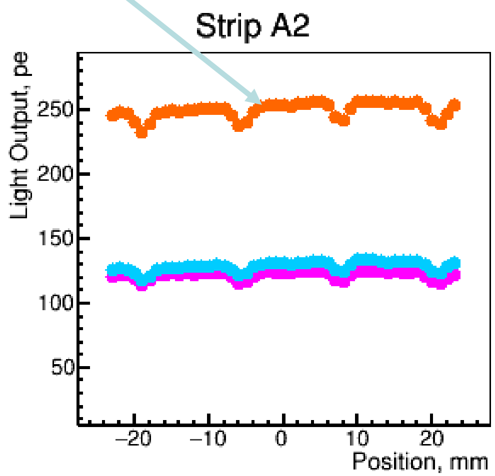


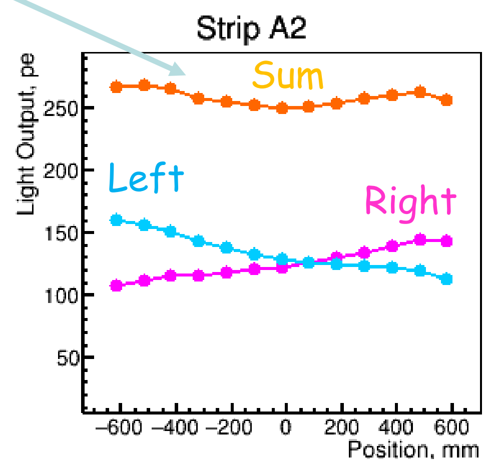


WLS fiber positions were optimized for better uniformity of response

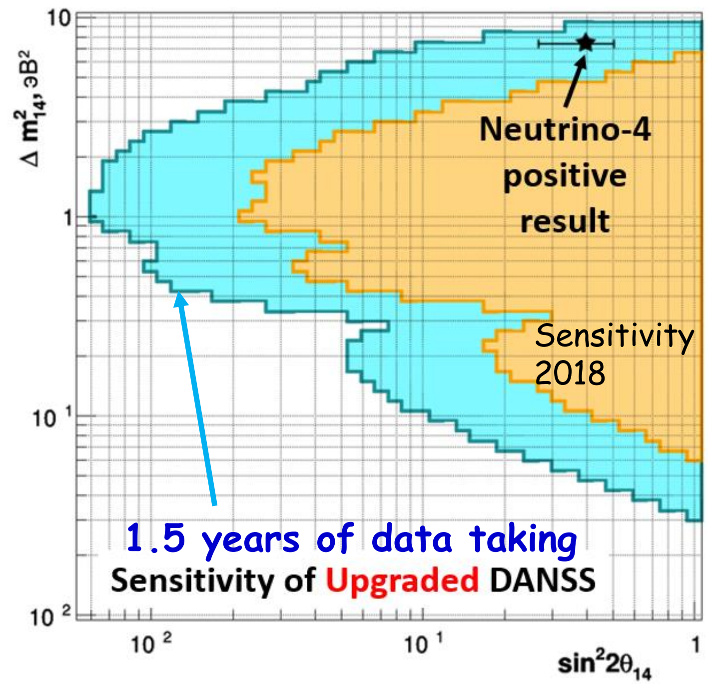
Strip tests at π-beam

Transverse and longitudinal responses are very uniform



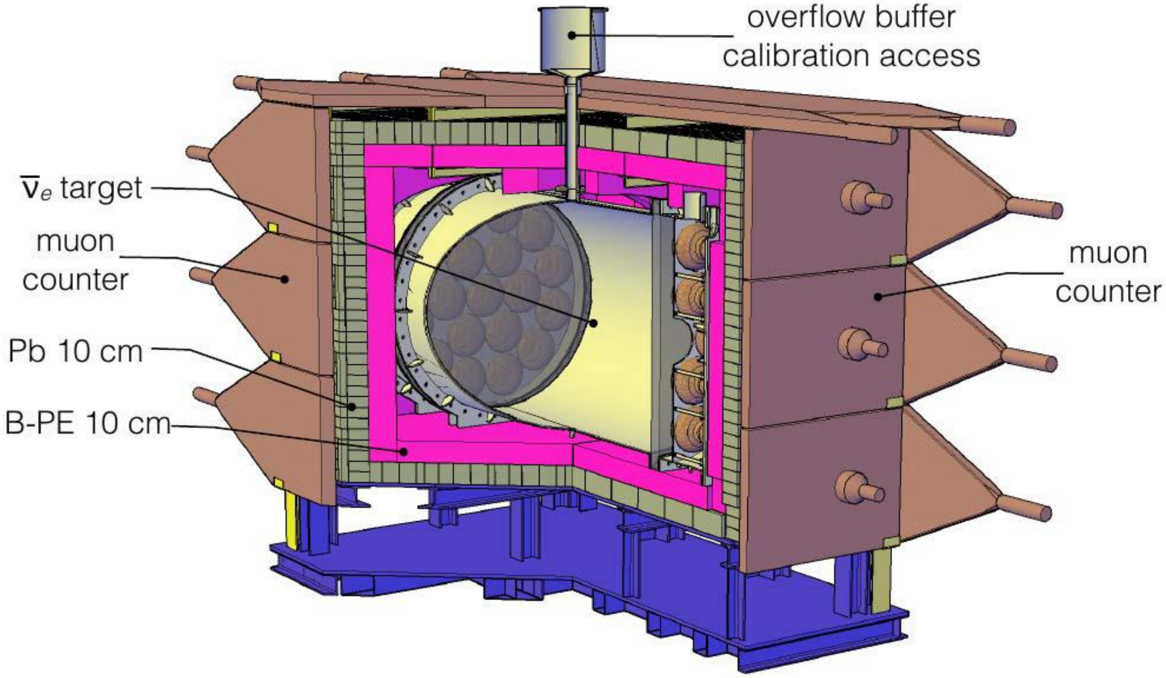


Longitudinal nonuniformity can be further corrected
More work on SiPM-WLS fiber connection is needed



Neutrino-4 claim can be tested

NEOS



ν spectrum normalized to another reactor
Collected new data but problems with Gd
Recently RENO used NEOS data and
measured ν flux to improve NEOS limits

$1m^3$ LS
No segmentation

σ_E/E=5% at 1 MeV

PSD removes 70%
of background

Depth 20mwe

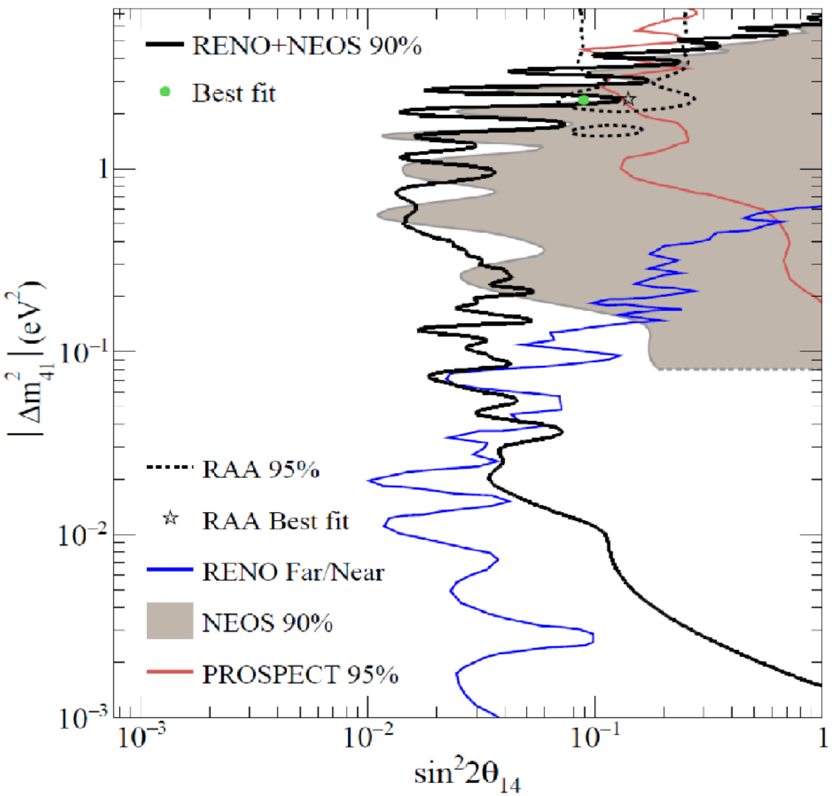
S/B= 23

Only one L=24m

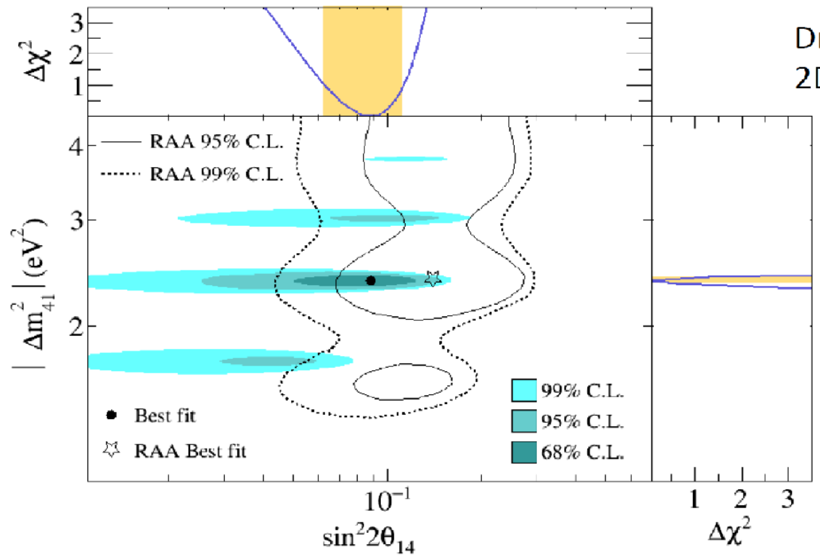
Large core size
d=3.1m h=3.8m
Power 2815 MWt;

Recently RENO used NEOS data and measured ν flux to improve NEOS limits
Best point (ΔM^2=2.37 eV^2) agrees with best point of GA+RAA,
But p-value is 13% only because of systematic uncertainties

This point was excluded by DANSS



Drawn by Raster scan



Drawn by 2D-scan

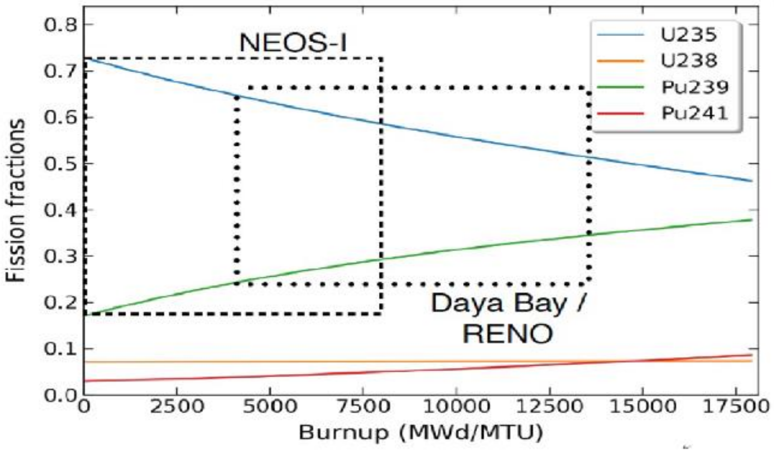
Best fit : $\boldsymbol{\Delta m^2_{41} = 2.37} \pm 0.03\ eV^2$, $\boldsymbol{\sin^2 2\theta_{14} = 0.09} \pm 0.03$

$\chi^2_{4\nu,min}/NDF = 23.2/57 \qquad \chi^2_{3\nu}/NDF = 34.9/59$

- P-value (assuming 3ν with MC) ~ 13%
- Weak hint for the sterile neutrino oscillation
- The best fit is compatible with the RAA allowed region

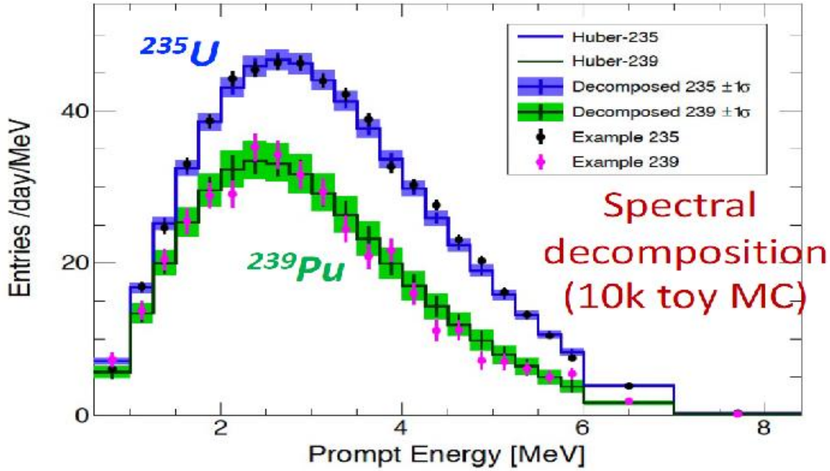
(arXiv:2011.00896)

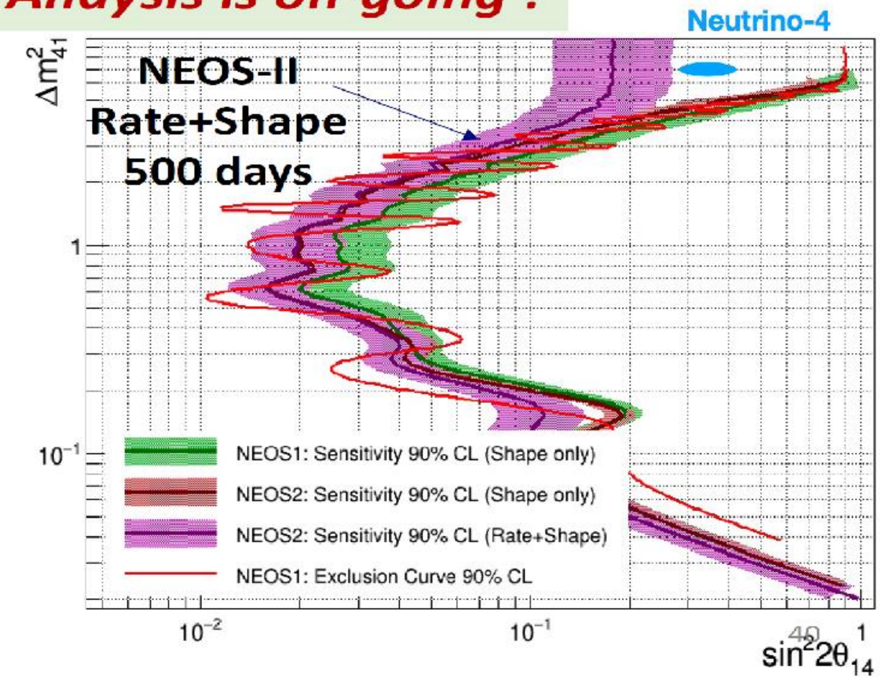
NEOS-II (2018 -- 2020)



- Refurbished detector from NEOS-I.
- Took full fuel cycle (500 days) + 2 OFF periods
- Time evolution of reactor ν flux/shape
- spectral decomposition (^{235}U, ^{239}Pu)
- Rate+Shape analysis

➢ ***Anaysis is on-going !***





S.Seo 20th Lomonosov Conference

Neutrino-4

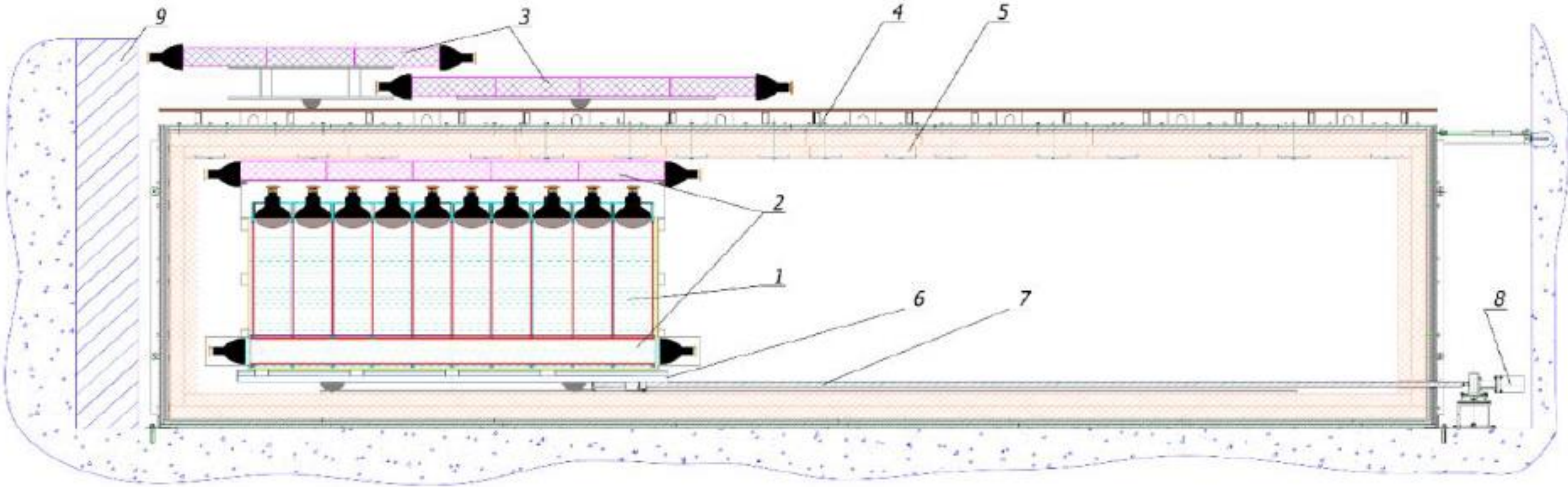


Fig. 1. General scheme of an experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9 –shielding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

720 days ON 860 days OFF

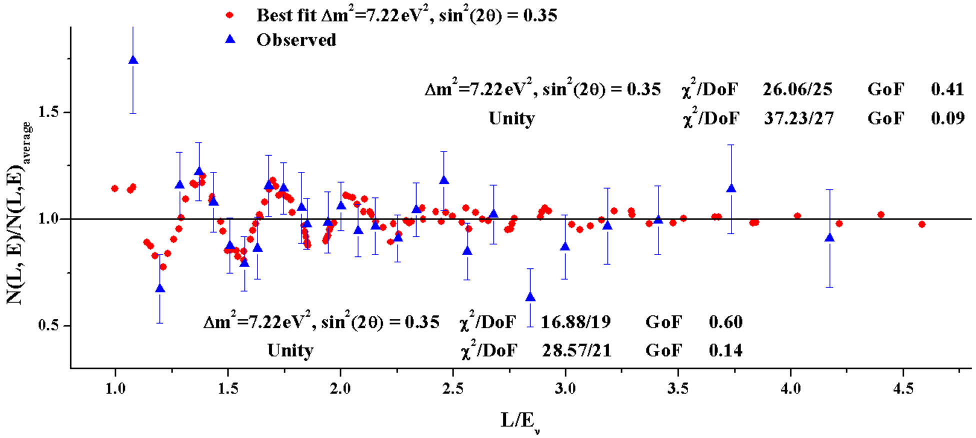
Major Advantages

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

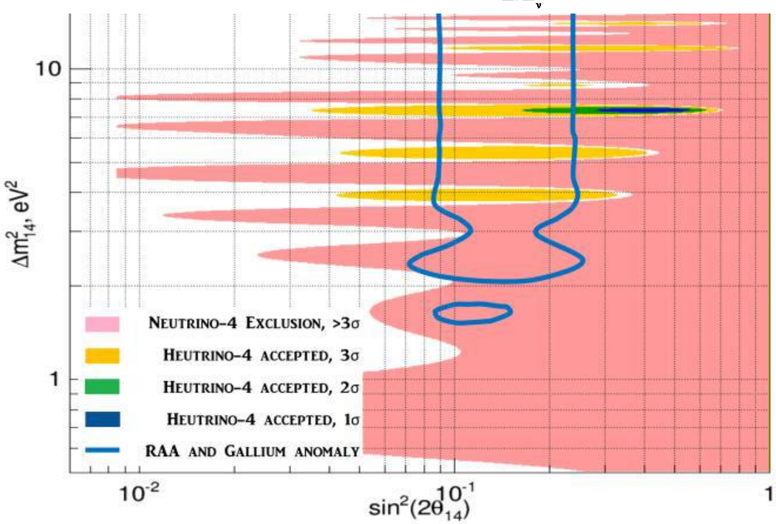
Major Disadvantages

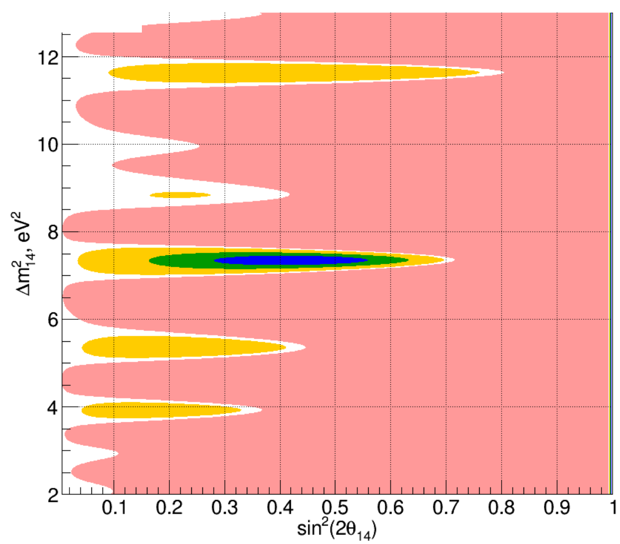
No PSD
Small overburden (3.5 mwe)
Small S/B=0.54
Modest σ_E/E=16% at 1 MeV

Indication of oscillations with large Δm^2~7.3±1.17eV^2 and $\sin^2 2\theta$=0.36±0.12



Significance 2.7 σ





There are concerns about validity of Neutrino-4 analysis

MD J.Phys.Conf.Ser. 1390 (2019) 1, 012049, MD, N.Skrobova JETP Lett. 112 (2020) 7, 452
C.Giunti Phys.Lett.B 816 (2021) 136214, M.Andriamirado et al. ArXiv:2006.13147,
Coloma et al. arXiv:2008.06083V2

1. Concerns about treatment of detector energy resolution:

Neutrino-4 argues that with a big width of the energy bin (500 keV) one should not take into account actual energy resolution (~16% /√E).

But for the most important region E>5MeV more that 50% of signal goes to neighbor E bins – This is huge effect which can not be neglected! (MD'19,MD&Skrobova'20)

Detailed simulations show that inclusion of E resolution decreases the significance to 2.2σ and moves the best point to $\sin^2(2\Theta_{ee})=1$, excluded by other measurements (Giunti'21)

Recently (Phys.Rev.D 104, 032003 (2021)) Neutrino-4 studied effects of E resolution but didn't include them properly

2. Background in outermost detector sections is not known (MD'19,MD&Skrobova'20)

Neutrino-4 shows that without these sections significance drops to ~2σ but does not take it into account in calculations of the significance

3.Wilks theorem used in analysis is not valid (Andriamirado'20 ,MD&Skrobova'20, Coloma'20)

Neutrino-4 shows that without this assumption significance drops to 2.7σ

4. Averaging the same data with different bins in E has no statistical meaning

(MD&Skrobova'20)

The best way to address these concerns is to do experiment sensitive to claimed ν_s parameters

Neutrino-4 future plans

Collaboration creates a new much better detector with 2 PMT per section, with pulse shape discrimination of background, with more Gd

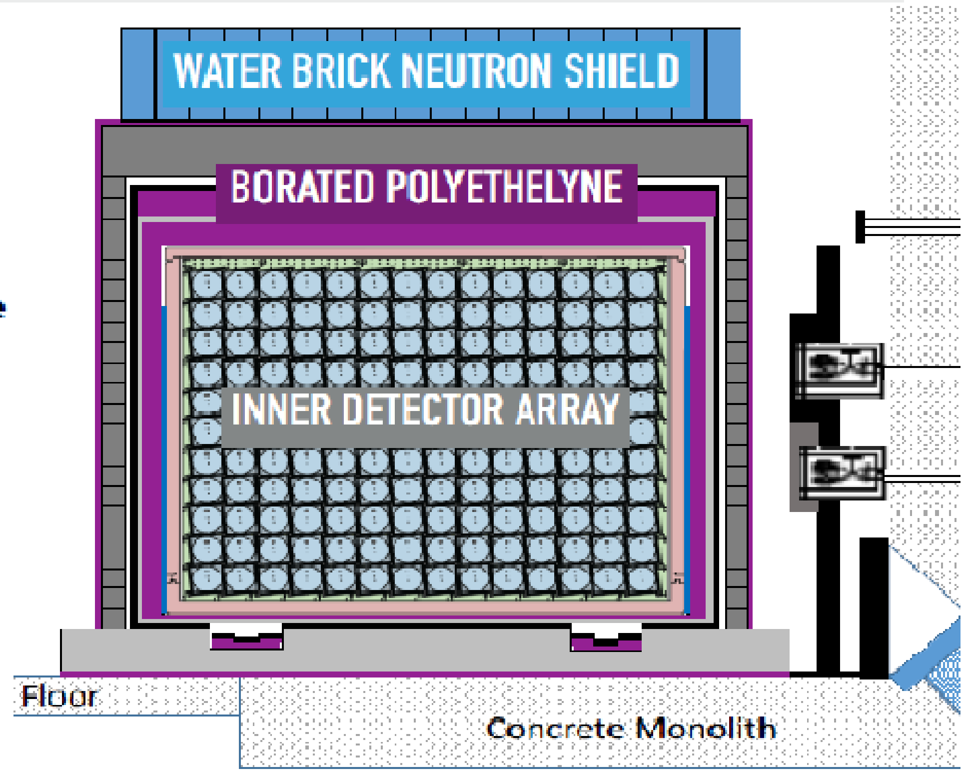
Sensitivity of the new detector will be 3 time better

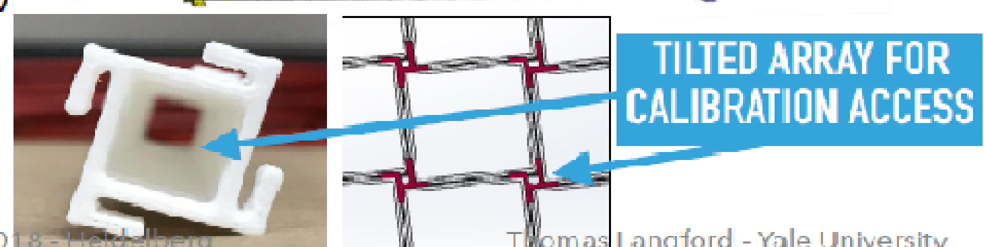
It will start data taking in 2022, initially at the same SM-3 reactor and then will move to the PIK reactor in St. Petersburg

This will be an excellent experiment sensitive to large Δm^2 !

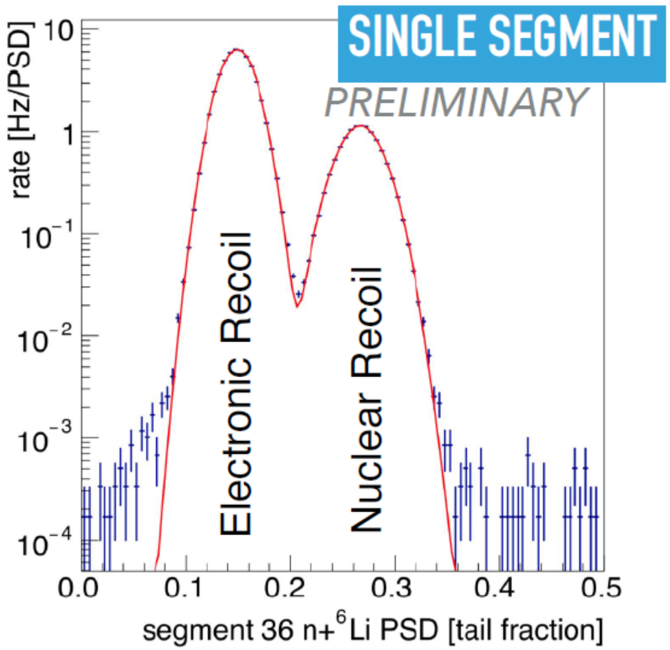
PROSPECT DETECTOR DESIGN

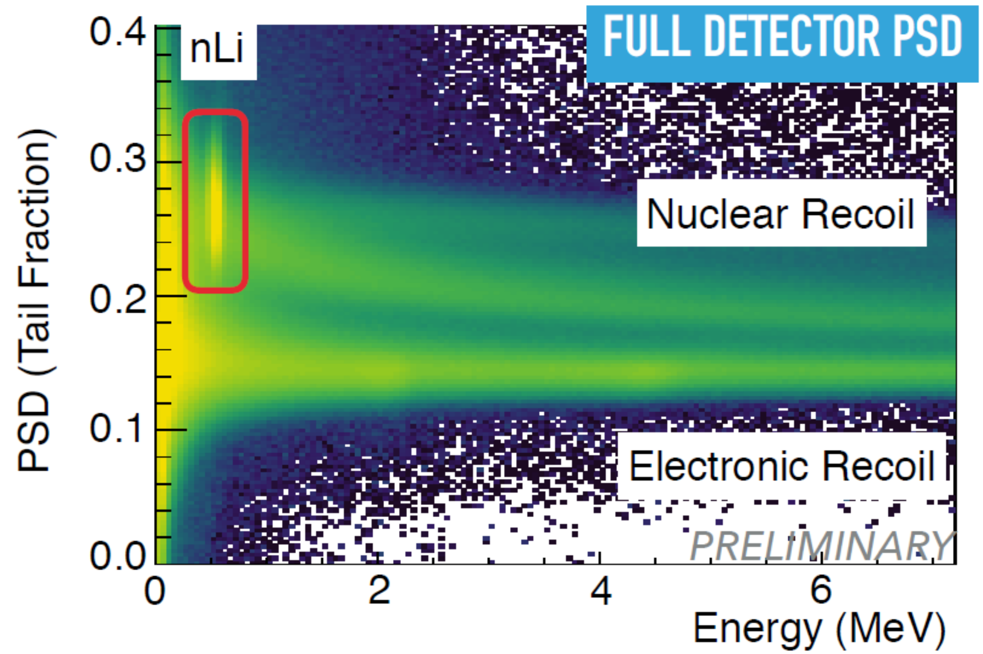
- 154 segments, 119cm x 15cm x 15cm
  - ~25liters per segment, total mass: 4ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods
- **Segmentation enables:**
  1. Calibration access throughout volume
  2. Position reconstruction (X, Y)
  3. Event topology ID
  4. Fiducialization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





Pulse Shape Discrimination of background



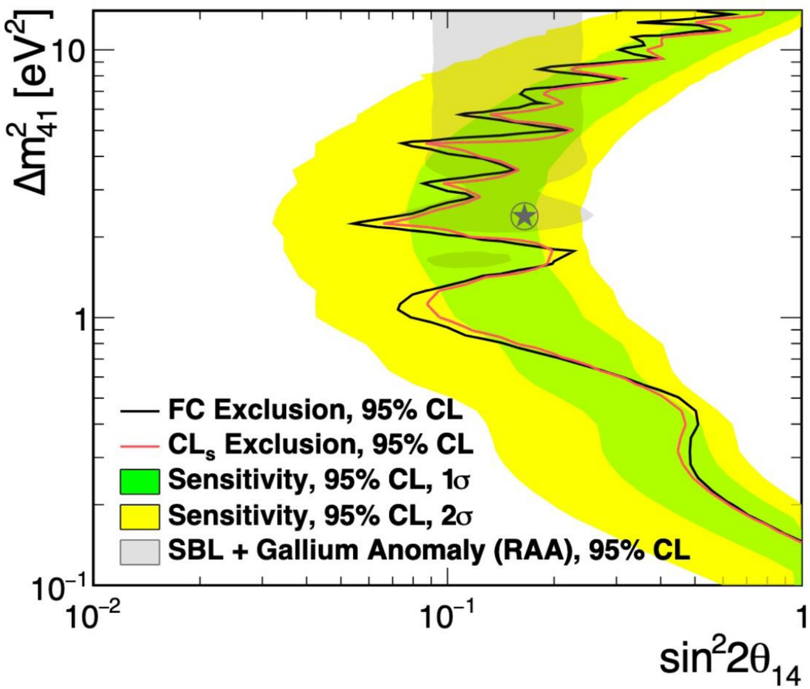


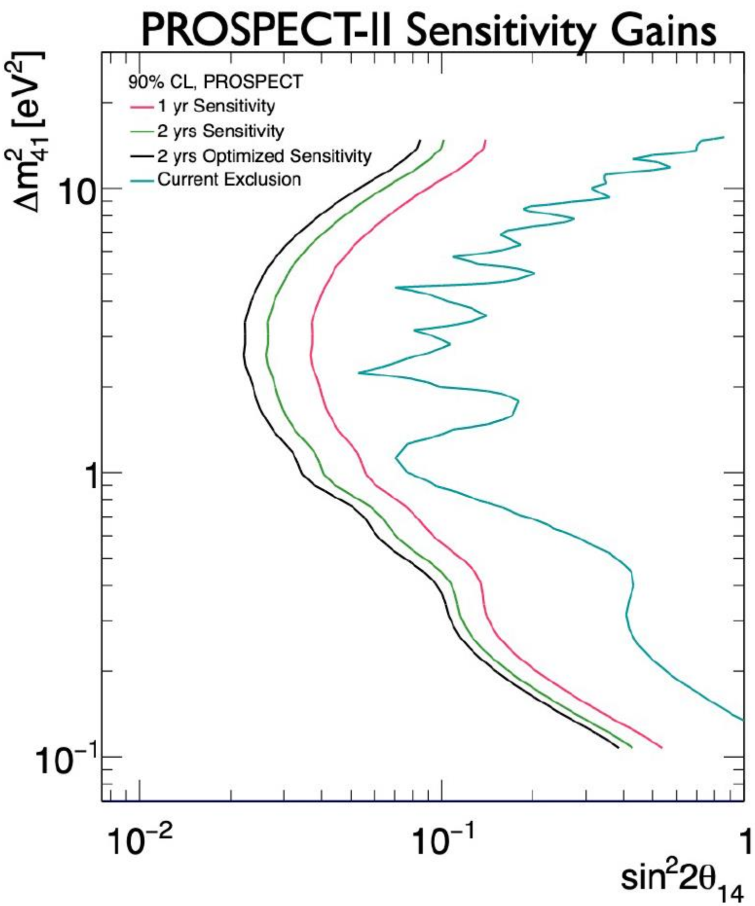
Excellent PSD allows to achieve S/B=1.36 on earth surface
Excellent energy resolution of 4.5% at 1 MeV
Localized detection of neutrons
Elaborate calibration system

Unfortunately 42% of 154 modules do not work properly due to PMT

PROSPECT results and prospects

~50 K IBD arXiv:2006.11210





Upgrade plans arXiv:2107.03934

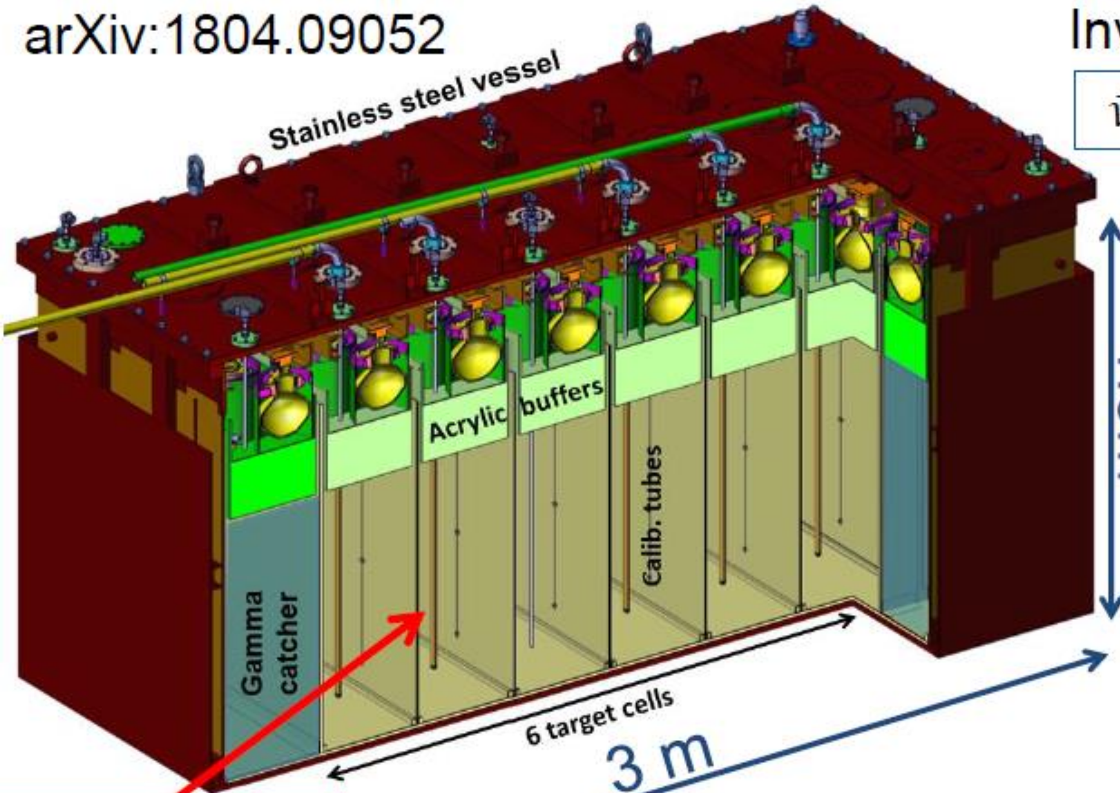
- PMT outside LS
- Section Length 1.17m→1.45m
- 6Li fraction 20% higher
- S/B 1.4 → 4.3
- N_{IBD}(effective) 15k → 200k

Data taking at HIFR before 2024

The STEREO detector

Data taking is finished

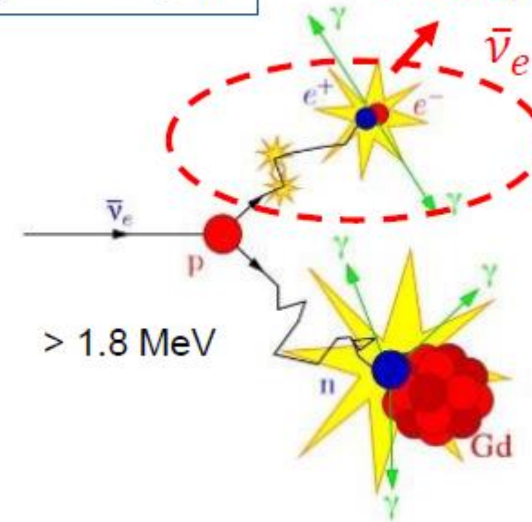
arXiv:1804.09052



Invert Beta Decay

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

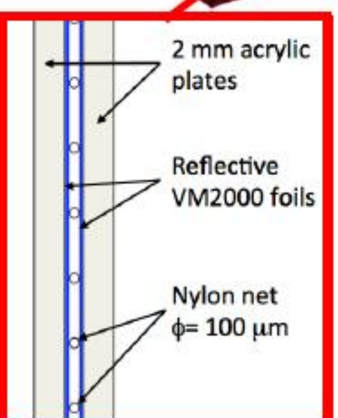
Prompt signa
$\bar{\nu}_e$ energy



> 1.8 MeV

Delayed signal

Mean neutron capture time 16 μs



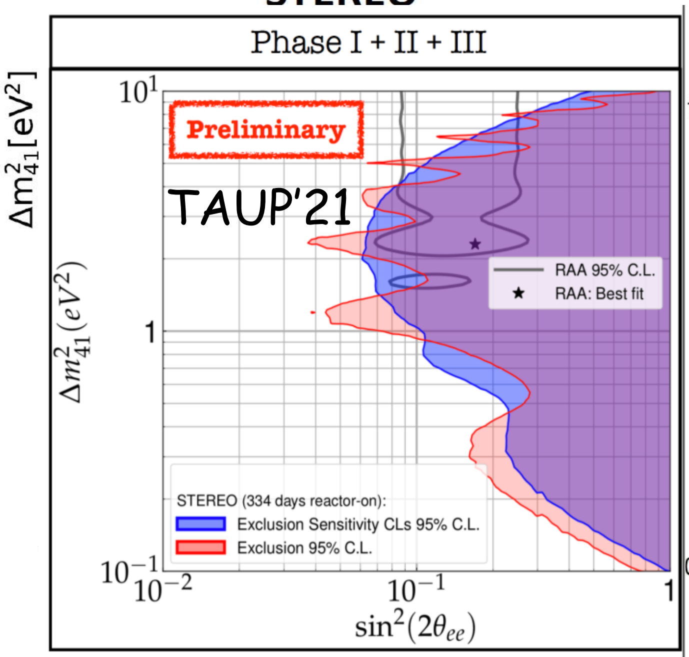
Target

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

Gamma-catcher

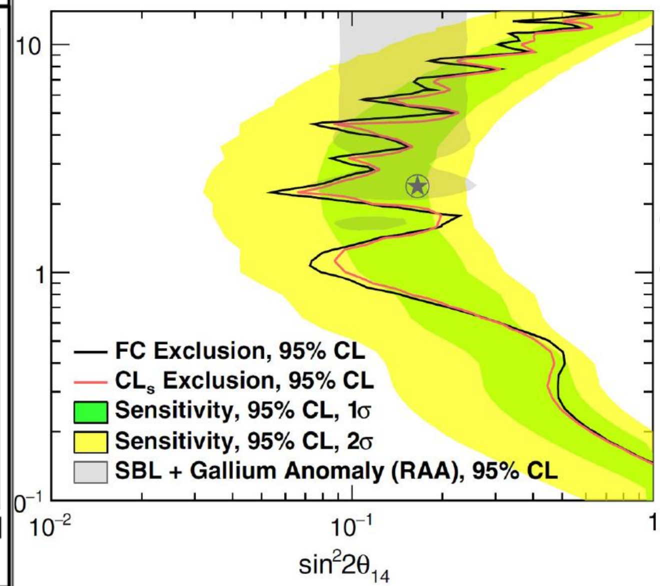
Outer-crown to detect γ's escaping
from the Target + active shielding
24 PMTs

STEREO



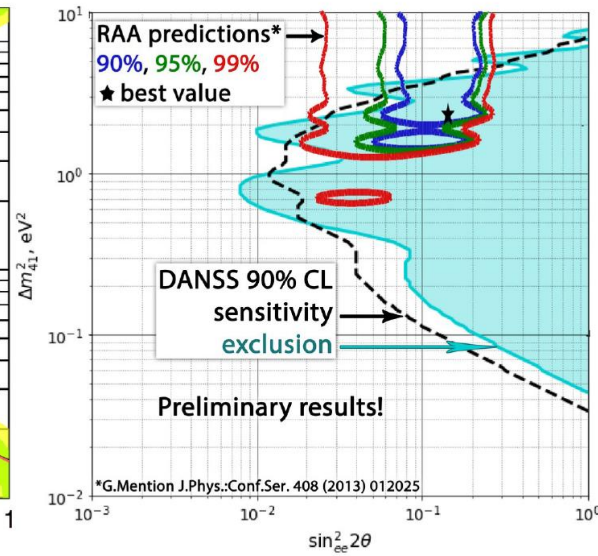
PROSPECT

PRD 103:032001 (2021)



DANSS

arXiv:2012.10255



RAA best-fit excluded > 4σ CL

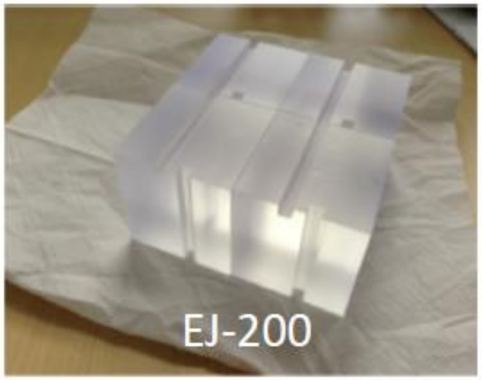
RAA best-fit excluded > 95% CL

RAA best-fit excluded > 5σ

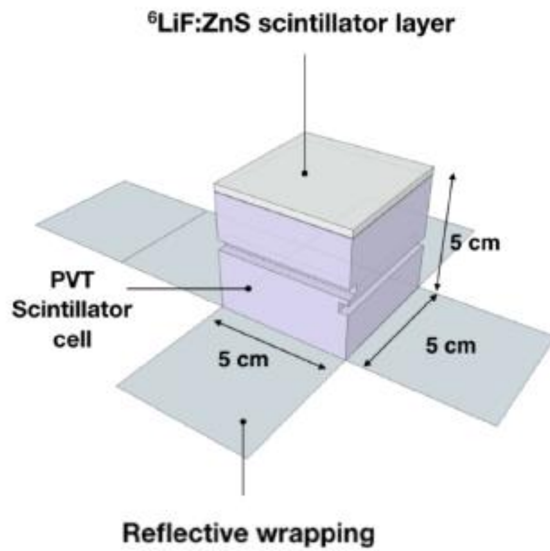
DANSS limits are much stronger at 1-2 eV^2 but Prospect and Stereo are better for large masses

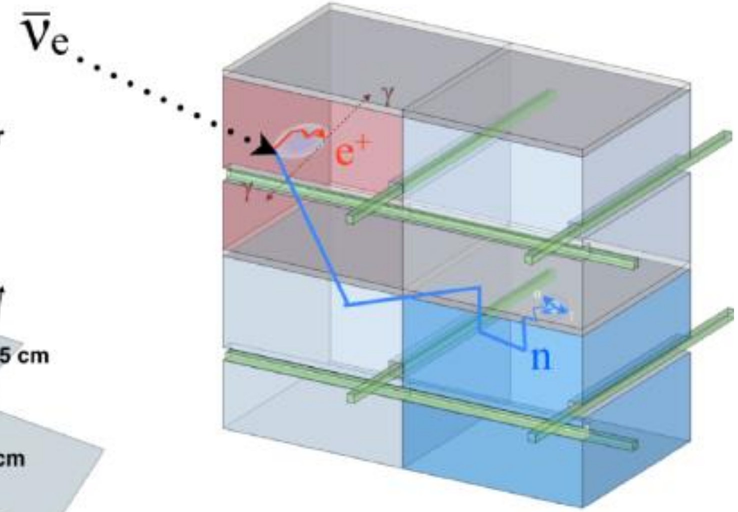
Some tension with Neutrino-4 result

SoLid

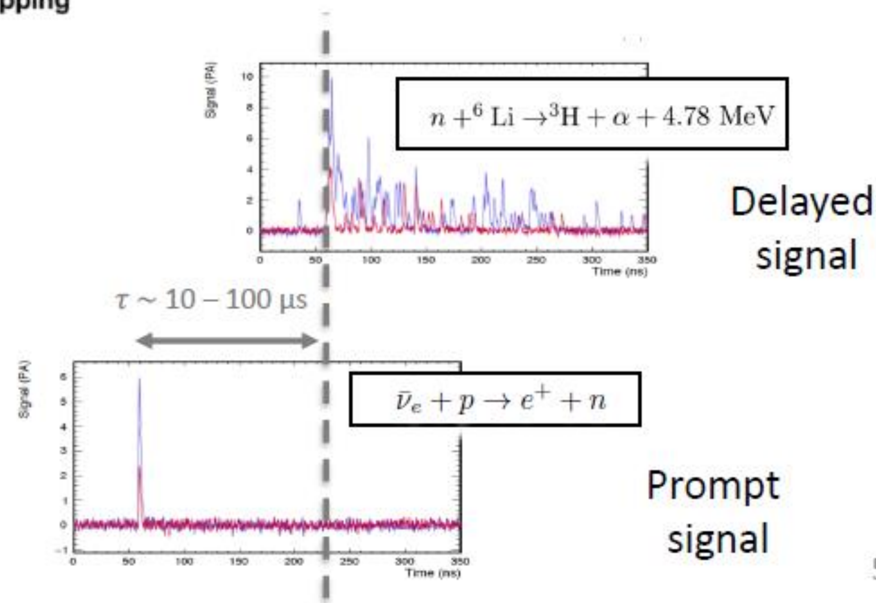


- $5 \times 5 \times 5$ cm^3 PVT cubes
  - Non-flammable scintillator
- Cubes are optically separated using Tyvek wraps
- ^{6}LiF:ZnS(Ag) screens for neutron identification
- Light collected through optical fibers and silicon photomultipliers (SiPMs require low-voltage)





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



Squared BCF-91A fiber

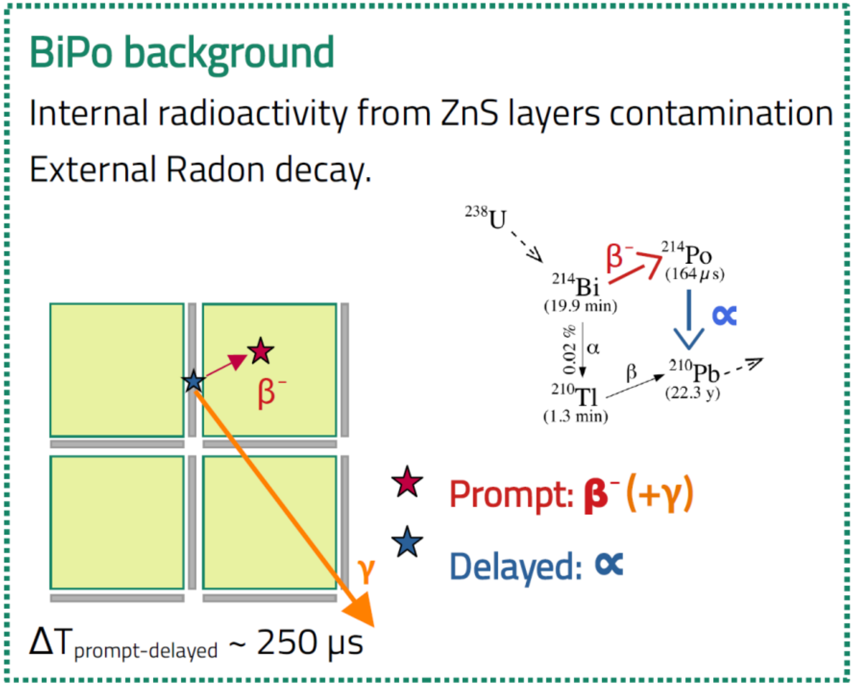
Good pulse shape discrimination of background (# peaks over thresh)
In-situ measurements of neutron detection efficiency

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
Large background!



With a complicated ML signal separation SoLid finally managed to observe IBD events.

No physics results so far

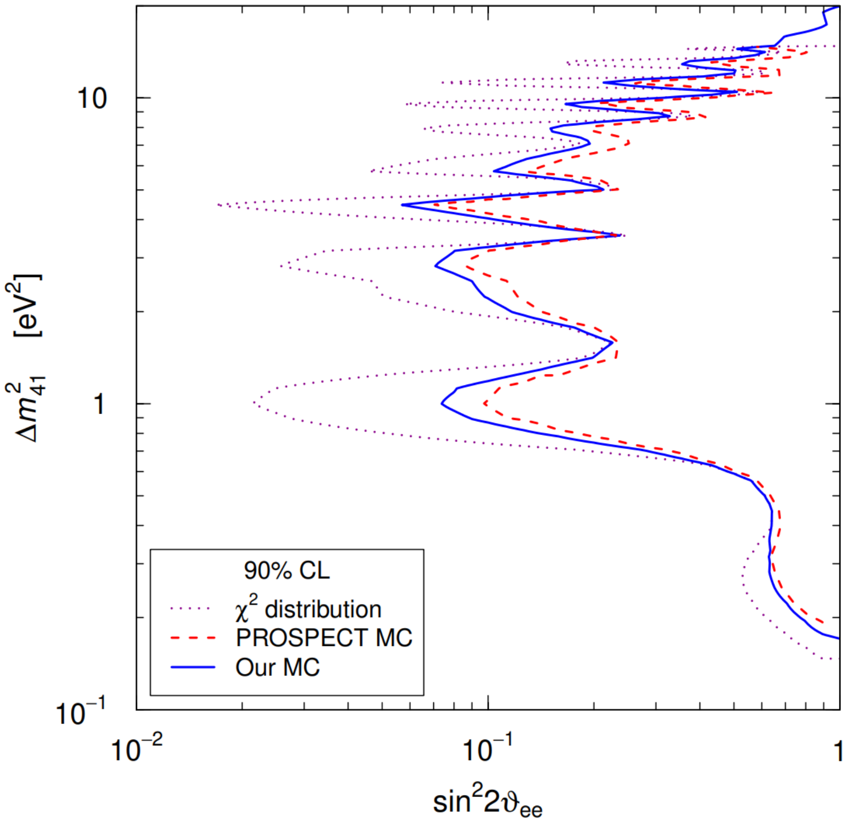
Comparison of experiments

	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]	10.9-12.9 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	58	23	**0.54**	1.36	**?**	**0.9**
σ_E/E [%] at 1 MeV	**33**	5	**16**	4.5	**14**	9

Red – good   Black- bad

MC estimates give smaller significance than X^2 with 2dof

C.Giunti arXiv:2004.07577



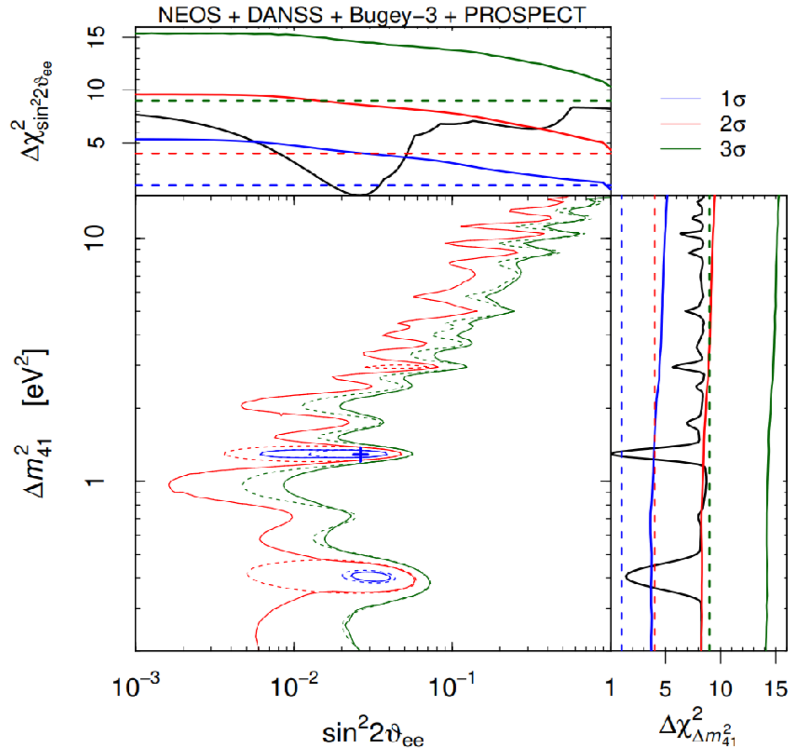


FIG. 3. Contours of the 1σ (blue), 2σ (red), and 3σ (green) allowed regions in the $(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ plane obtained with the combined analysis of the data of the four reactor spectral-ratio experiments NEOS [12], DANSS [14], Bugey-3 [26], and PROSPECT [27]. The solid lines represent the contours obtained with our Monte Carlo evaluation of the distribution of $\Delta\chi^2$, and the dashed lines depict the contours obtained assuming the χ^2 distribution. Also shown are the marginal $\Delta\chi^2$'s (black) for $\sin^2 2\vartheta_{ee}$ and Δm^2_{41}, together with the $\Delta\chi^2$ values corresponding to 1σ (blue), 2σ (red), and 3σ (green) obtained with the χ^2 distribution (dashed) and our Monte Carlo (solid). The blue cross indicates the best-fit point.

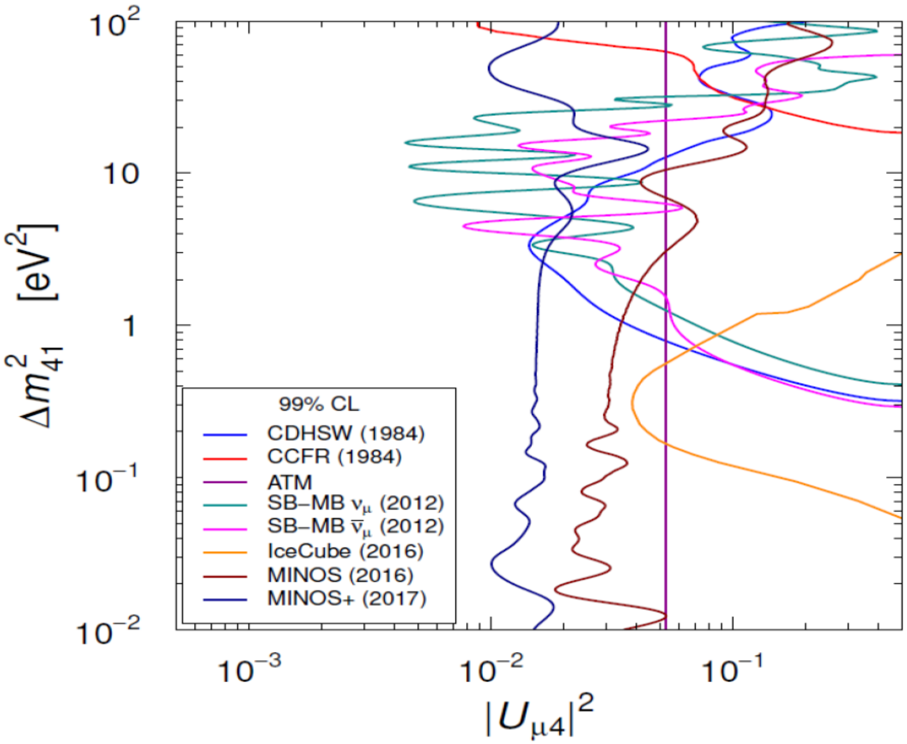
DANSS, NEOS, PROSPECT, Bugey-3 data

Significance of the best point

(Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.026)

is 1.8 σ only

Very strong limits on νμ disappearance



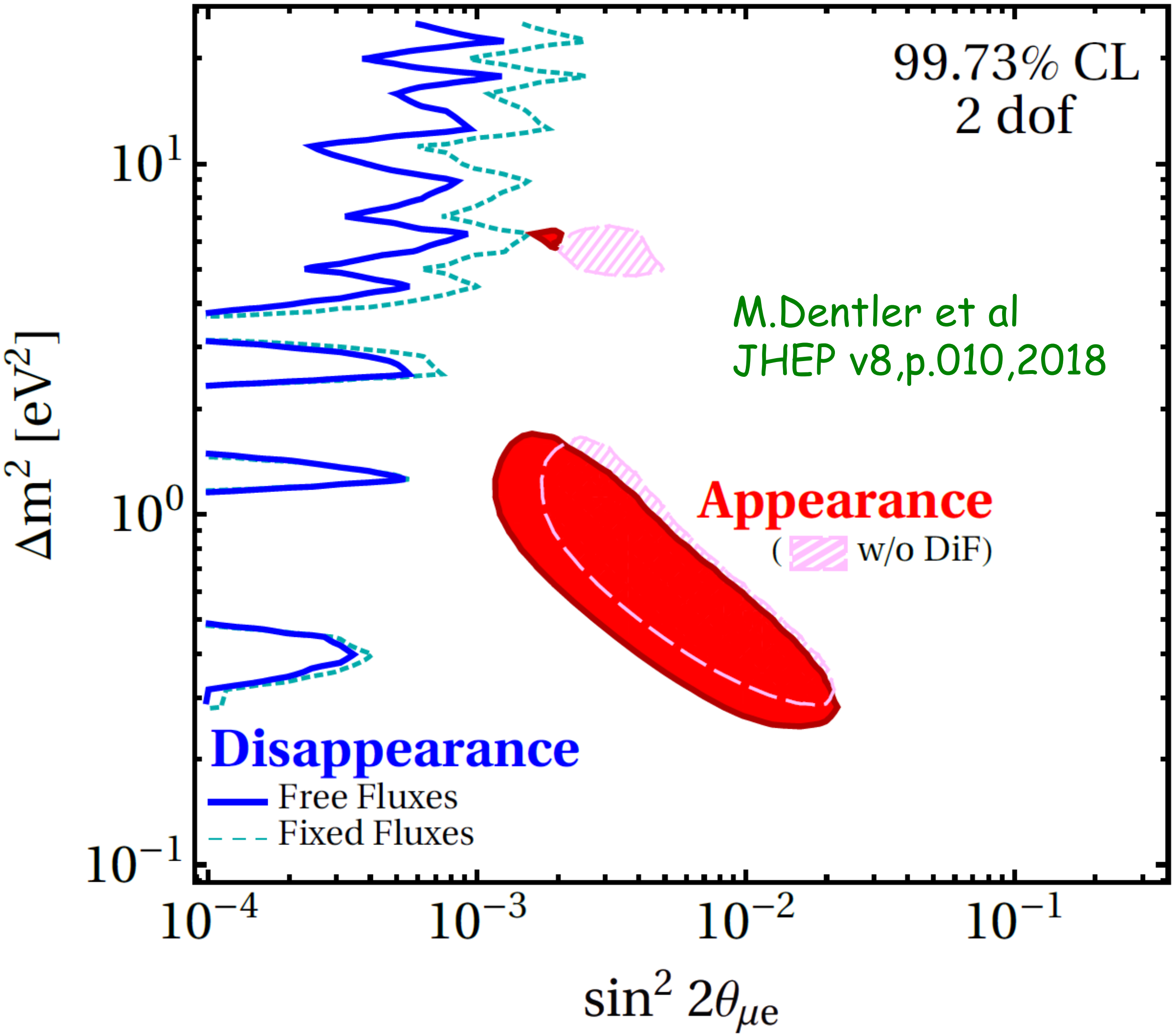
$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

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

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



Addition of 2-nd sterile neutrino does not help

Cosmological data strongly disfavor a sterile neutrino on ~ 1 eV mass-scale

However there are models that can accommodate such ν

For example in a model with additional pseudoscalar
a neutrino on ~ 1 eV mass-scale is allowed
(M.Archidiacono etal., arXiv: 2006.12885).
Moreover, this model alleviates tension between different H_0 measurements.

Combined fit with SBL reactor experiments gives m_s =1.14 eV

Summary

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

Strong limits on sterile neutrino parameters were obtained by DANSS and NEOS. PROSPECT and STEREO extended limits to higher Δm^2

Significance of sterile neutrinos in VSBL reactor experiments (w/o Neutrino 4) is ~2σ only

Reactor neutrino spectrum predictions are still quite uncertain
5 MeV bump not understood.
Measured X-section for 235U is 5% smaller than in H-M model

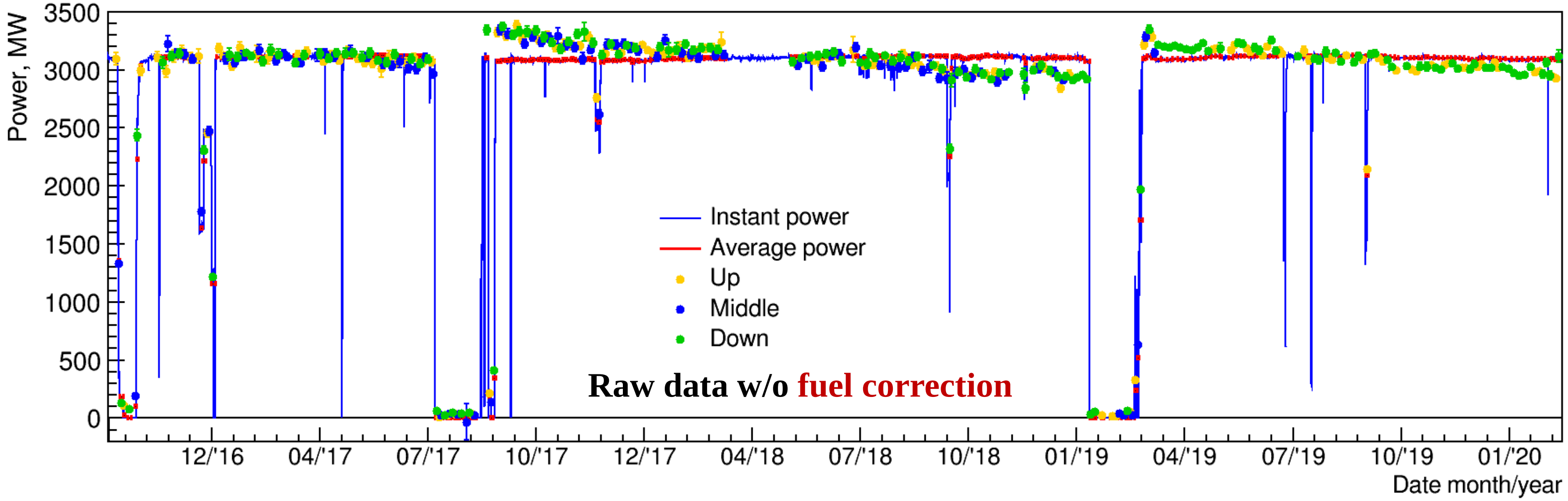
New measurement of beta spectra from 235U and 239Pu at KI give 5% smaller ratio than ILL results ->smaller X-section for 235U -->
RAA becomes weaker

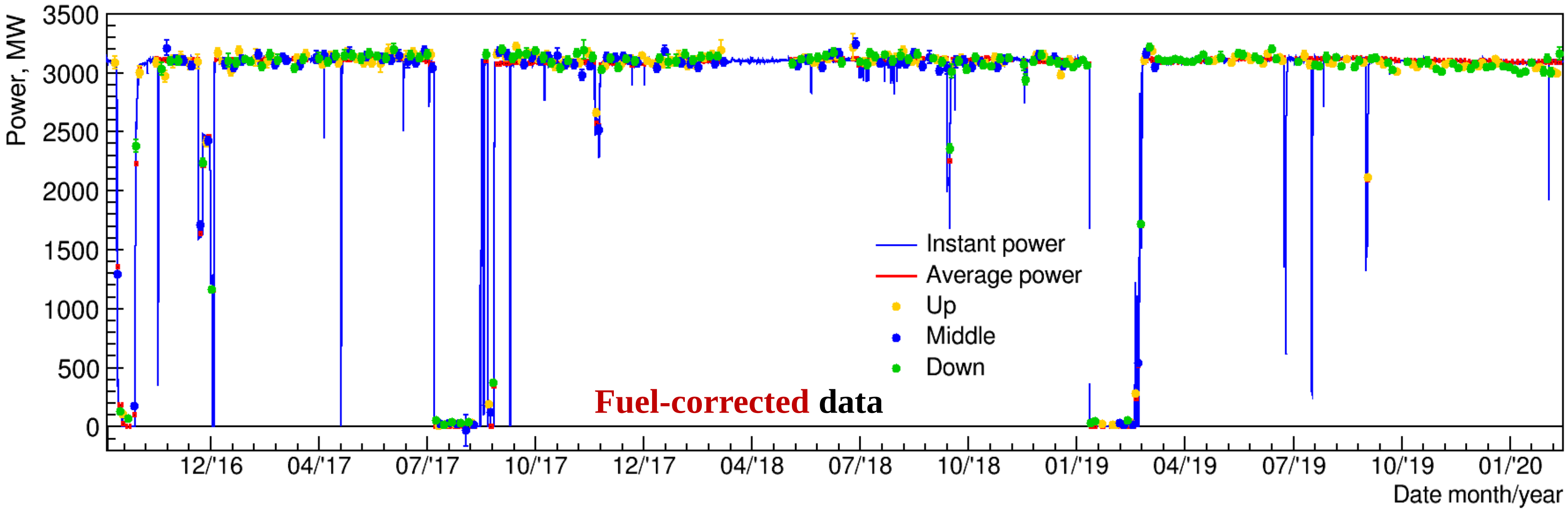
New results with increased sensitivity are expected in near future from DANSS, NEOS-II, NEUTRINO-4, PROSPECT, SOLID and

Backup slides

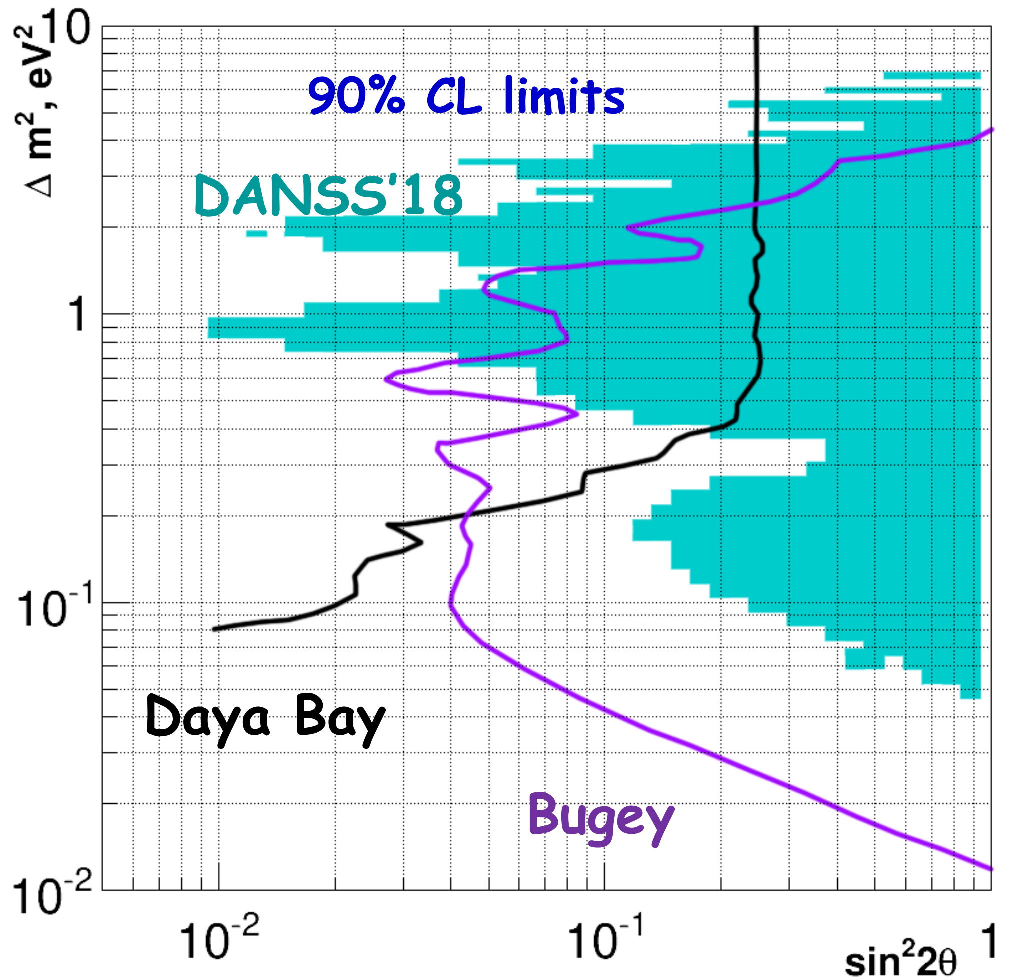
Sensitivity to fuel evolution

Top – Middle – Bottom data with and without fuel evolution correction

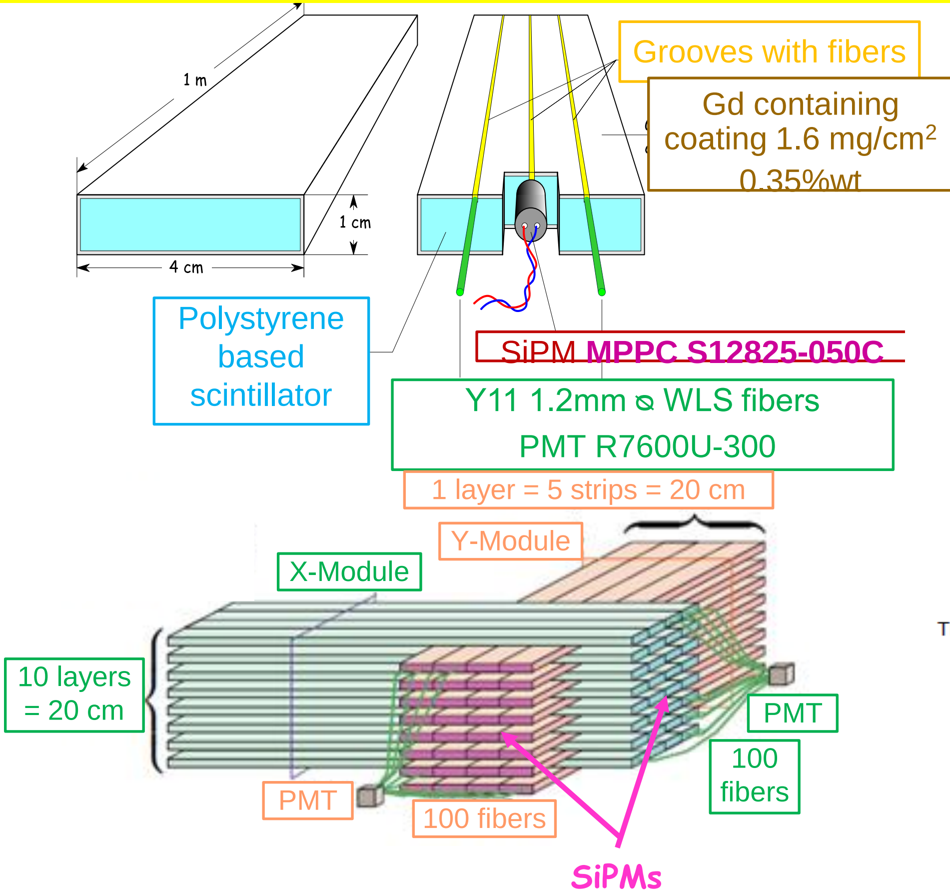


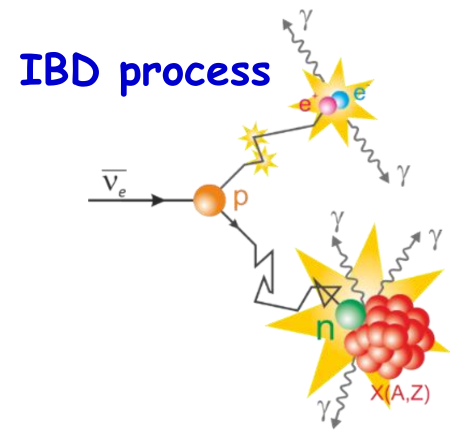


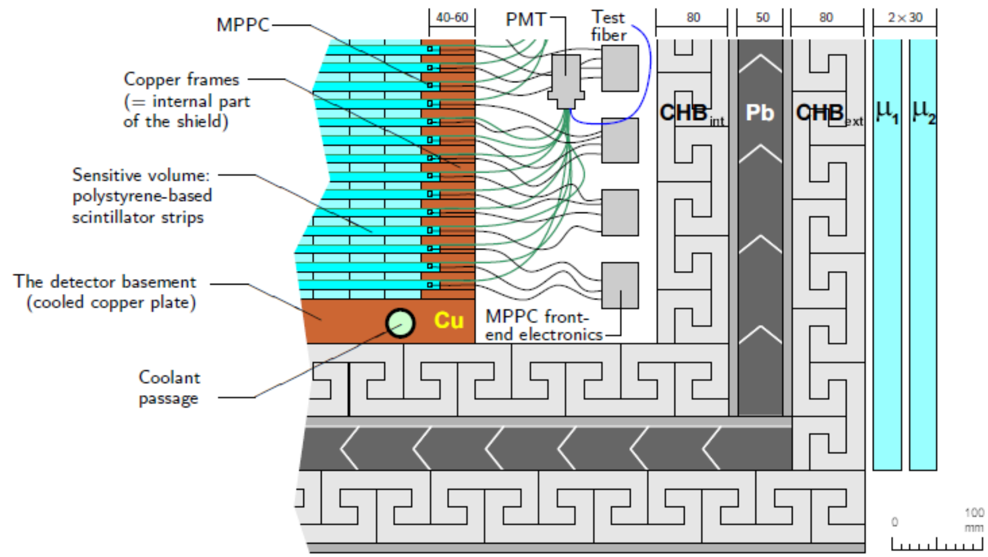
Comparison with experiments based on spectra ratio at different distances measured with identical detectors



DANSS Detector design (ITEP-JINR Collaboration)



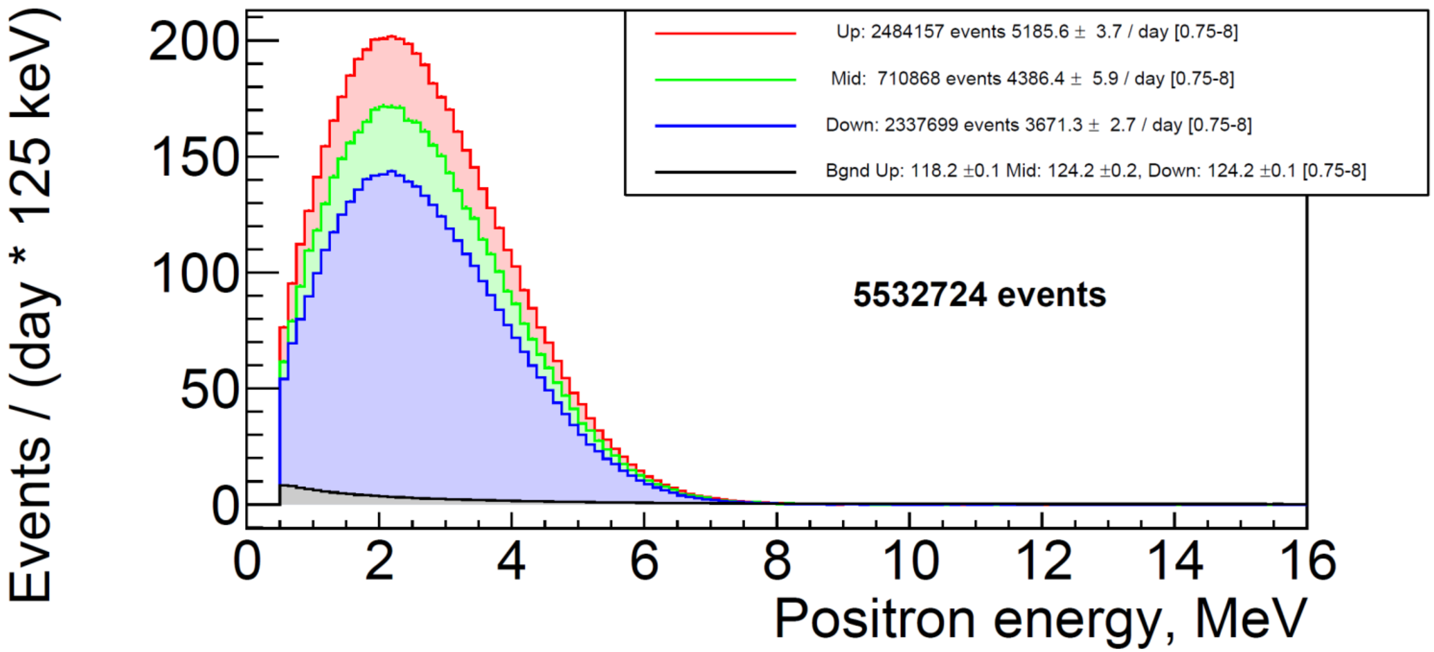




- **2500 scintillator strips with Gd containing coating for neutron capture**
- **Light collection with 3 WLS fibers**
- **Central fiber read out with individual SiPM**
- **Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module**

- **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**

Positron spectrum of IBD-signal



- ❖ **~5000 events/day in detector fiducial volume (78% of full volume) at 'Top' position.**
- ❖ **Cosmic background ~1.7% (Top position, E: 1.5-6MeV). Signal/Background >50!**
- **Continuous detector calibration with cosmic muons**
- **Very modest energy resolution of ~33% at 1 MeV**
- **Very large size of the reactor core (⌀ 3.1m, h=3.7m)**
- **→ Smearing of the oscillation pattern**

Daya Bay observed smaller 235U X-section than Huber model

STEREO also observed smaller X-section for pure 235U fuel

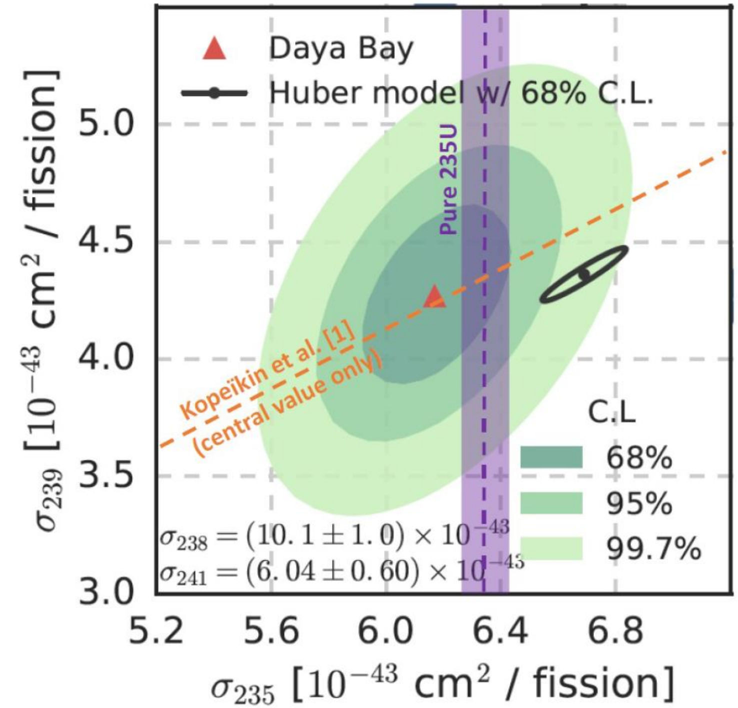
Kopeikin et al. remeasured recently ratio of cumulative beta spectra for 235U/239Pu and obtained 1.054 times smaller value than ILL (arXiv:2103.01684)

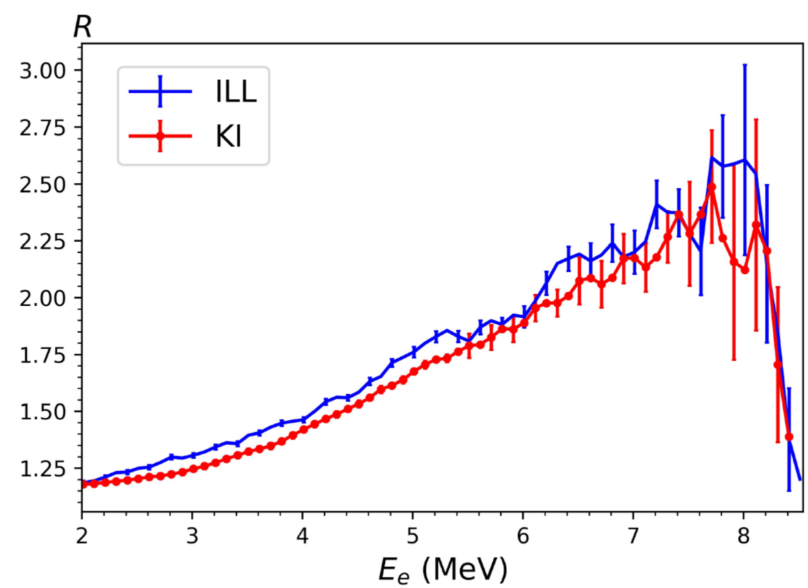
This leads to a smaller value of 235U antineutrino X-section (6.27+-0.13) in agreement with Daya Bay and STEREO

RAA becomes weaker

Modern experiments do not use absolute flux predictions

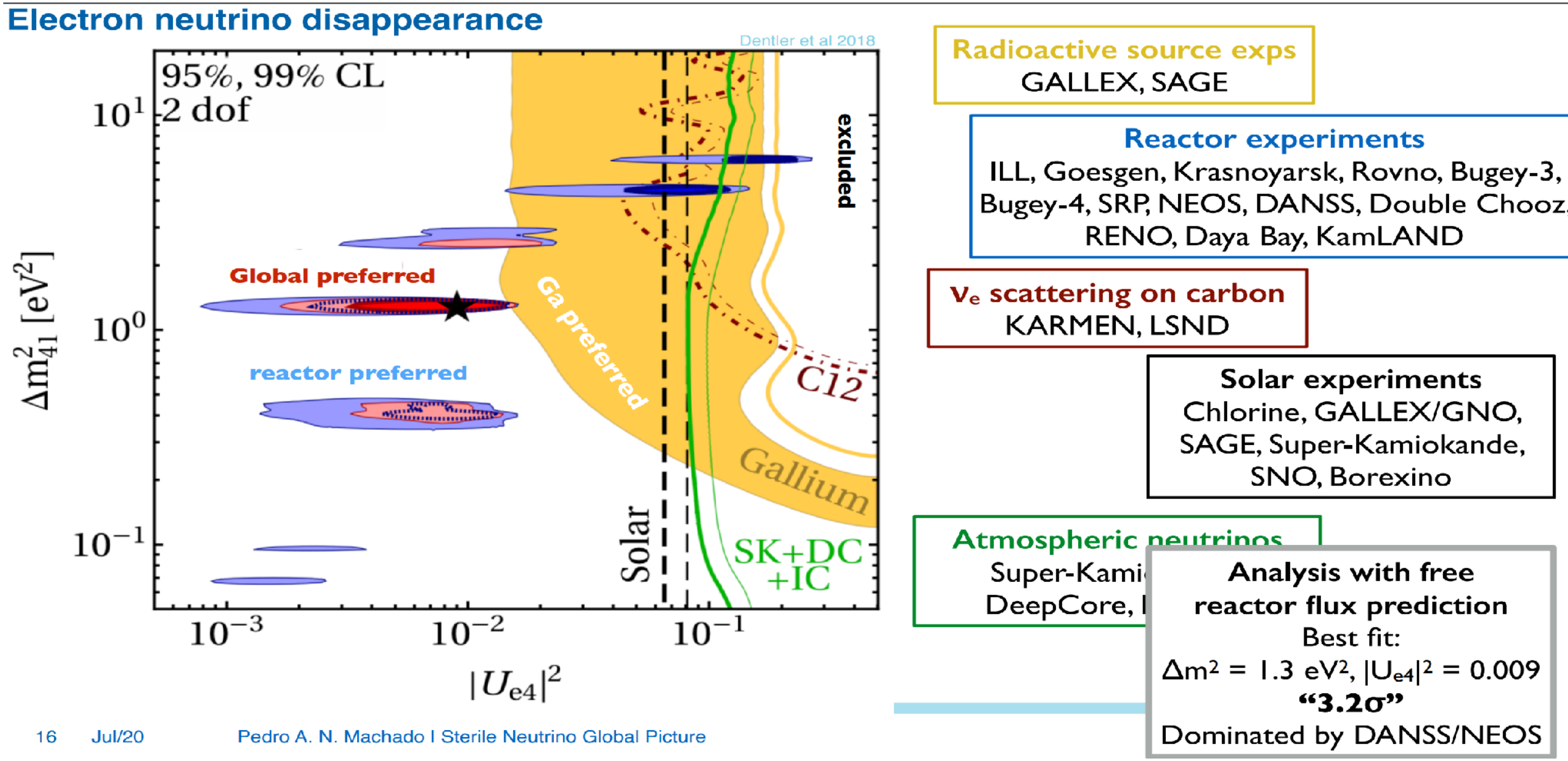
U/Pu cross sections per fission ↓





Global fit of disappearance data without Neutrino-4

(M.Dentler et al JHEP v8,p.010,2018)



Assumes χ2 distribution with 2 dof and old DANSS data (1year)
With 5 years of DANSS data significance of best point
($\Delta m^2 = 1.3$ eV^2 , $\sin^2 2\theta = 0.014$) is only ~ 1.3 σ