XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024 Milan, Italy

Sterile neutrinos: review of negative hints

Mikhail Danilov

There are several indications of a new neutrino with $\Delta m^2 \sim 1\ eV^2$, $Sin^2 2\theta_{ee} \sim 0.1$, Must be Sterile since $\Gamma_z \rightarrow N_\nu = 3$

1. LSND, MiniBooNE: ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams: > 6σ
   Not confirmed by MicroBooNE arXiv:2110.14054v2 but not excluded
   Increased sensitivity with NuMI beam but not sufficient
   FNAL SBNP and JSNS2 will clarify the situation

2. SAGE and GALEX ν_e deficit (GA) confirmed by BEST: > 5σ
   arXiv: 2109.11482, arXiv: 2201.07364 , PRL 128.232501
   GA looks solid, but ν_s explanation is practically excluded

3 Reactor ν_e deficit (RAA): ~ 3σ
   Explained by KI (arXiv:2103.01684), DayaBay, RENO, STEREO experiments and new reactor neutrino flux models?

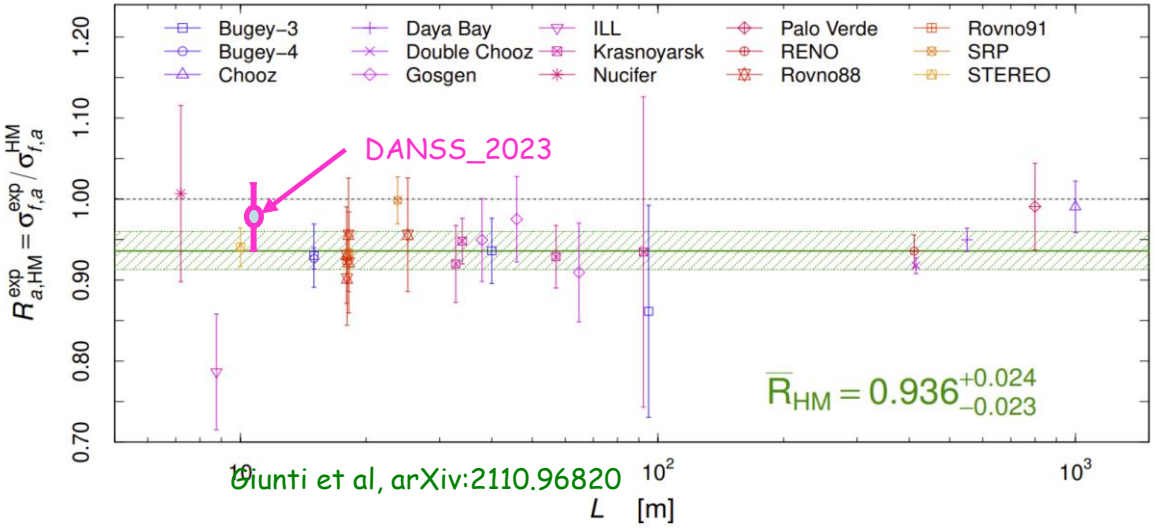
4. Neutrino-4 claim of sterile neutrino observation
   $\Delta m^2 = 7.3 \pm 1.17 eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ 2.7σ Phys.Rev.D 104, 032003 (2021)
   Serious tension with many experiments but not excluded

These are statistically strongest laboratory indications of physics BSM!

Reactor Antineutrino Anomaly (RAA)

New calculations of antineutrino flux in 2011 were ~6%(2.5σ) above experiment

Mueller et al, arXiv:1101.2663, Huber arXiv:1106.0687, Mention et al, arXive:1101.2755 (RAA)



Deficit of ν_e can be explained by oscillations to sterile ν_s with m~ 1 eV
In model with 3 active and 1 sterile neutrino (3+1 model) survival probability at short L

$$P_{ee}=1-\sin^2 2\theta_{ee}\ \sin^2(\Delta m^2_{14} L/4E)$$

with $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$, where U is 4x4 extended PMNS matrix

Recent DANSS results are consistent with HM model

New (2019-2022) neutrino flux models

HKSS conversion model Hayen et al arXiv:1908.08302 **increases RAA to 2.9σ**

$\overline{R}_{HKSS} = 0.925^{+0.025}_{-0.023}$ Giunti et al, arXiv:2110.96820

EF summation model Estienne et al arXiv:1904.09358 **decreases RAA to 1.2σ**

$\overline{R}_{EF} = 0.960^{+0.033}_{-0.031}$ Giunti et al, arXiv:2110.96820

Letourneau etal, model arxXiv:2205.14954 **describes STEREO spectrum➔ No RAA**

KI conversion model arXiv:2103.01684 **No RAA**

Perisse etal(BESTIOLE) arXiv:2304.14992V2 **No RAA**

New measurements indicate smaller contribution from ^{235}U

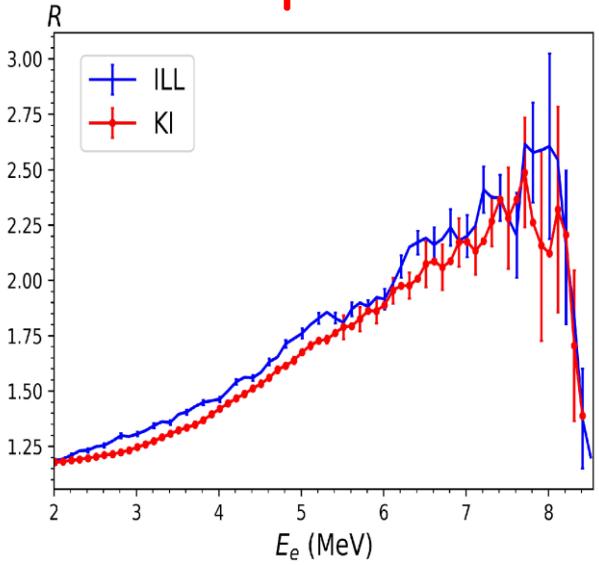
Kurchatov Inst group observed 5.4% smaller ratio of β yields for $^{235}U/^{239}Pu$ arXiv:2103.01684

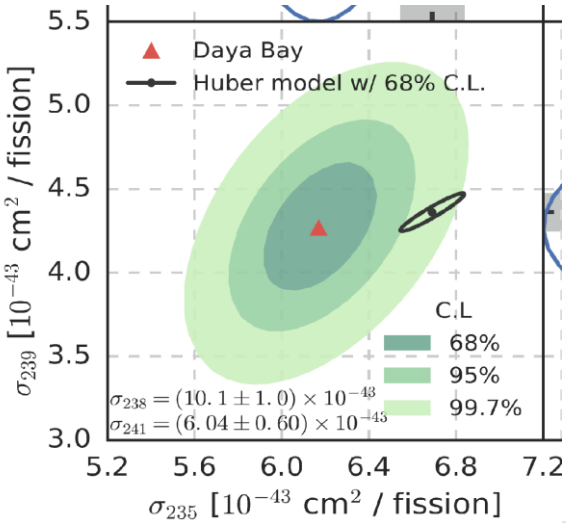
This can explain RAA!

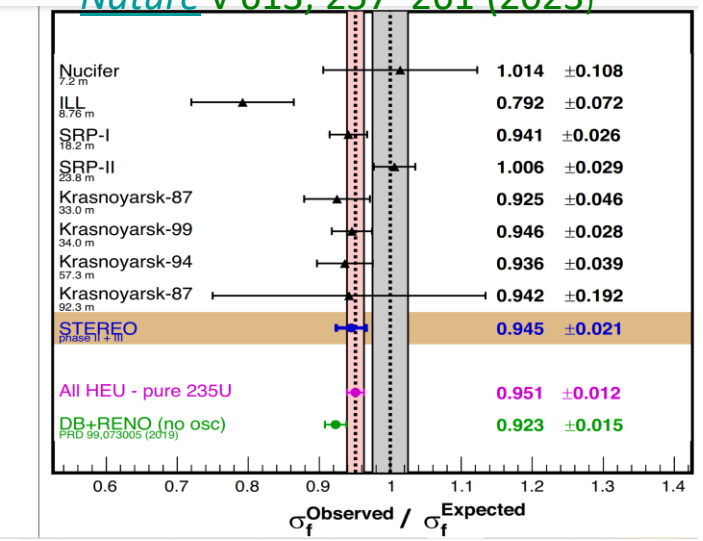
DayaBay, RENO, STEREO observed smaller ^{235}U flux than in HM model which is based on ILL results

Phys. Rev. Lett. **123**, 111801, Phys. Rev. Lett. **122**, 232501

Nature v 613, 257–261 (2023)





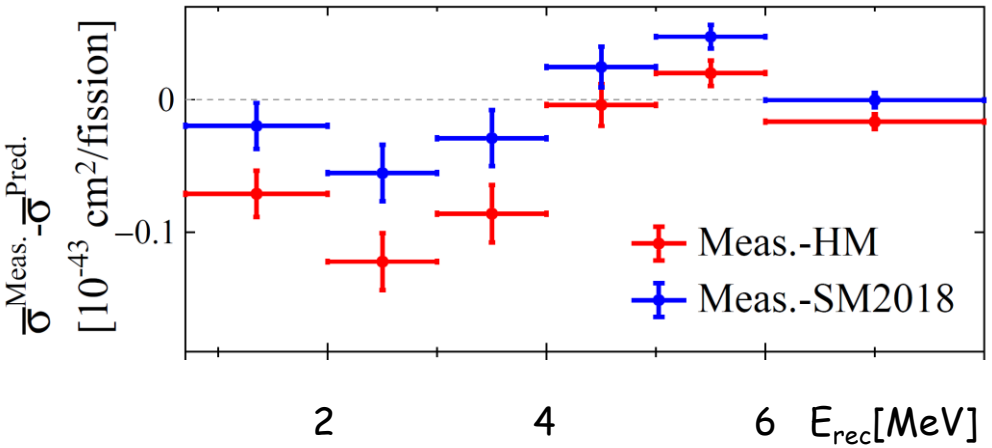


New measurements of ^{235}U contribution are smaller than HM model

New reactor models predict smaller ν flux

Is RAA solved? Not completely!

Models do not describe experimental ν spectrum

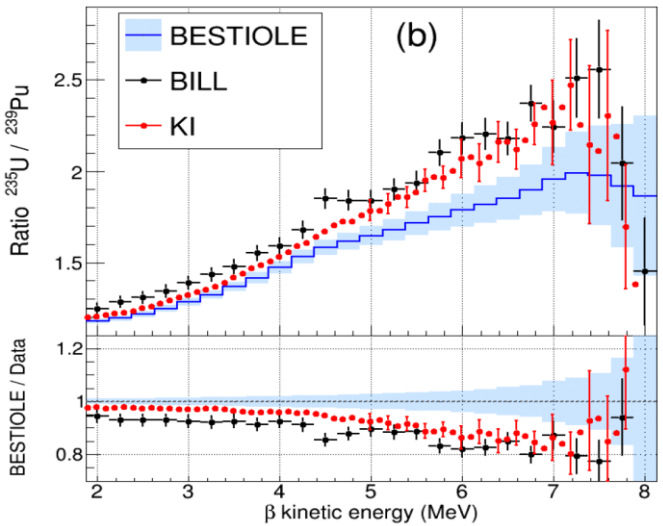


DayaBay arXiv:2210.01068v2

χ2/NDF and (σ) are very large

Model	$\bar{\sigma}^e$
HM	675/6 (25)
SM2018	748/6 (27)

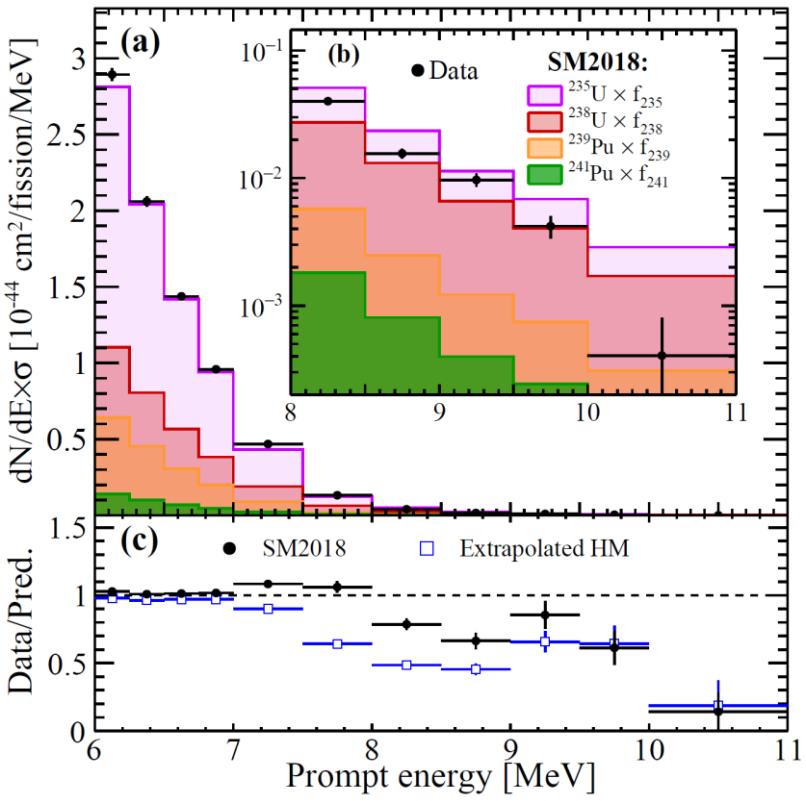
Conversion and summation models also disagree



Perisse etal, arXiv:2304.14992V2

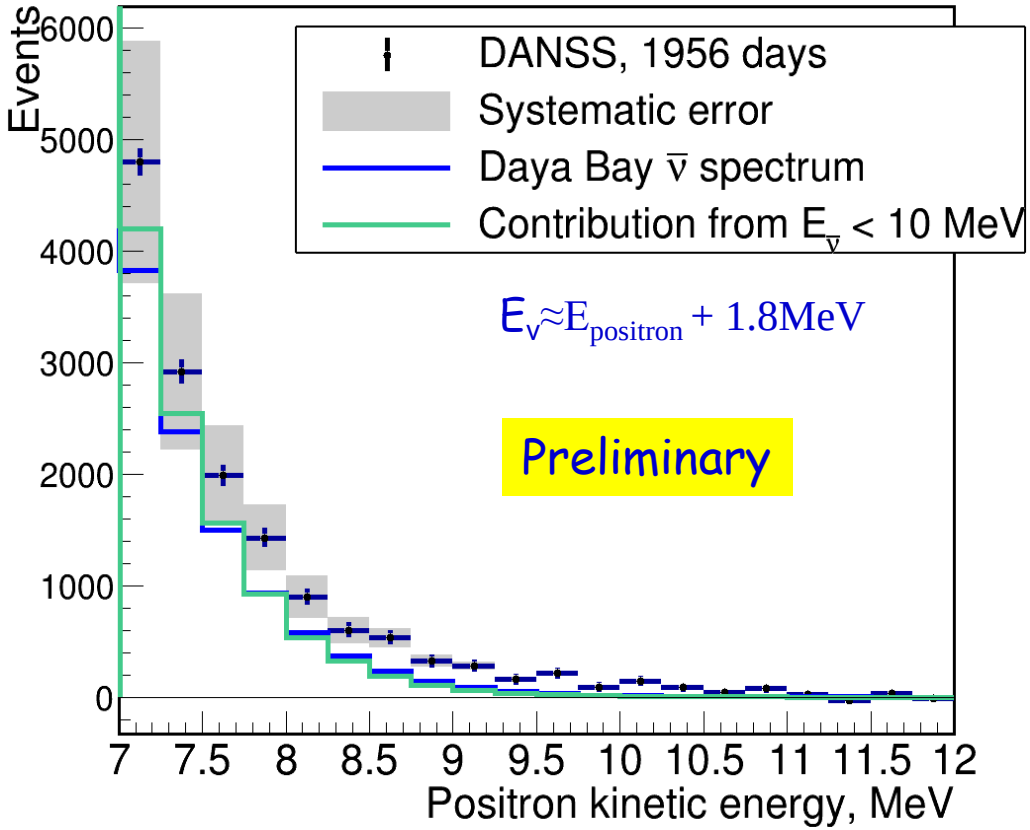
High energy part of ν spectrum is also not described by models

Daya Bay PRL 129 (2022) 4, 041801



DayaBay observed ν_e events with ν_e energy > 10 MeV (6.2σ)

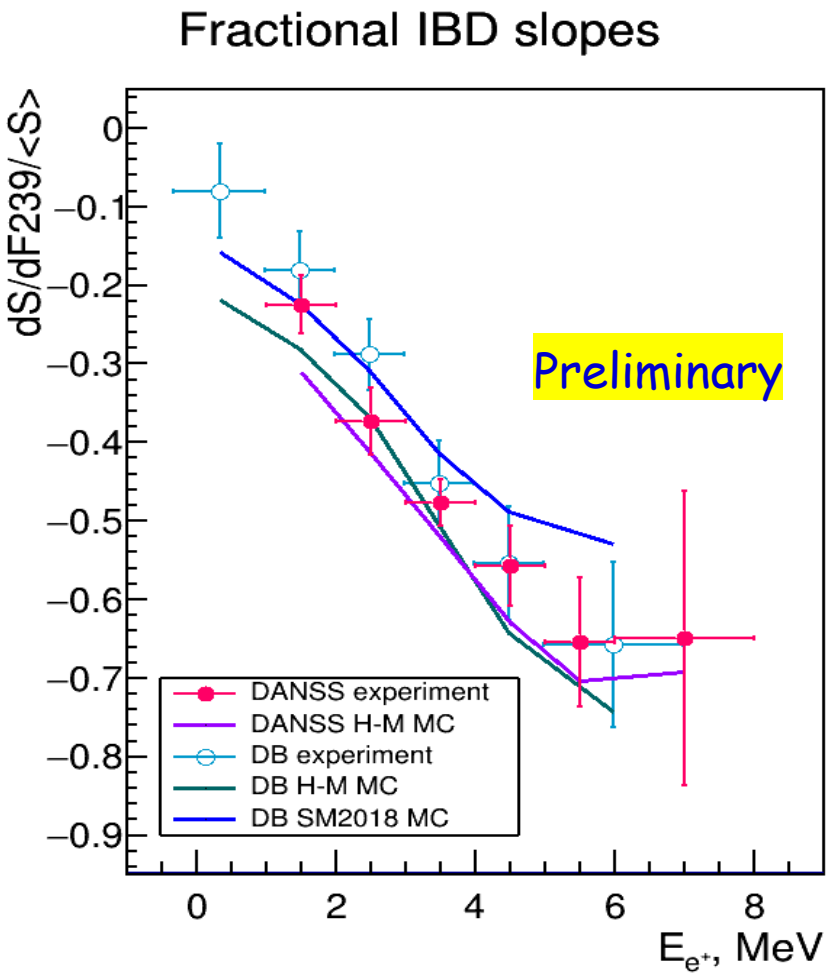
N.Skrobova, Poster #234

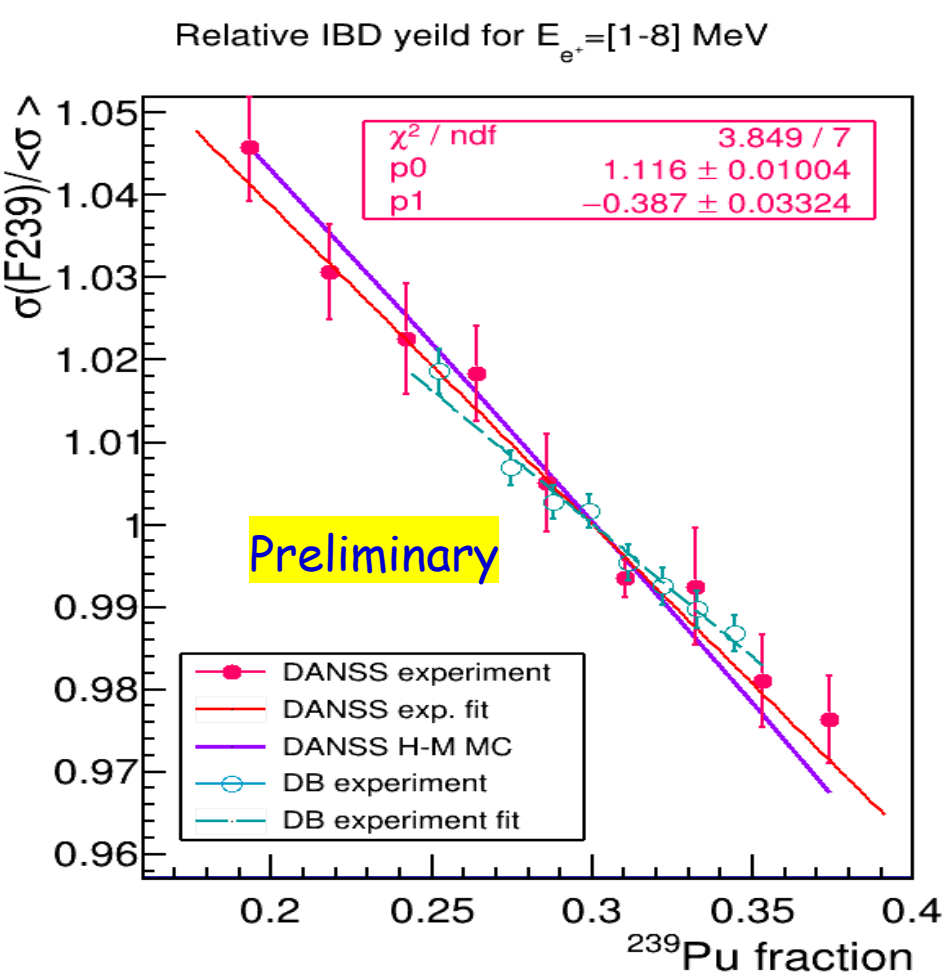


DANSS observes1561 ± 157^{stat} ± 168^{sys} (6.8σ) ν_e events with ν_e energy > 10 MeV

Fraction of high energy ν_e events is somewhat larger than at Daya Bay

IBD rate dependence on ^{239}Pu fission fraction $(d\sigma/dF239)/\langle\sigma\rangle$ agree better with models

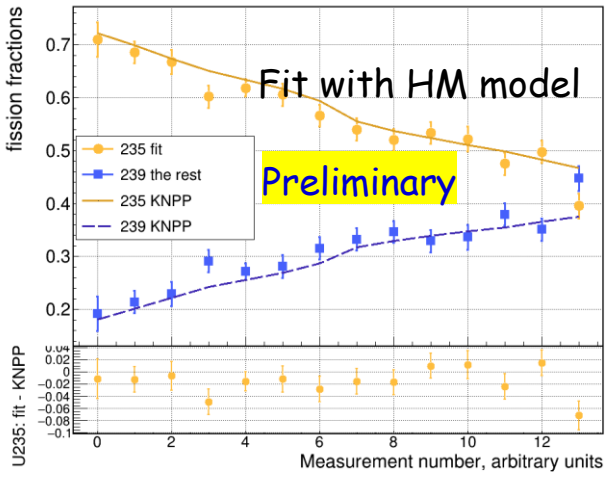


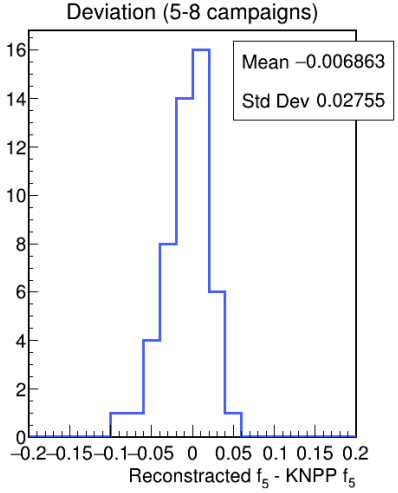


DANSS slope is more steep than DayaBay one and agrees with HM model

DANSS has twice larger range of ^{239}Pu fission fraction

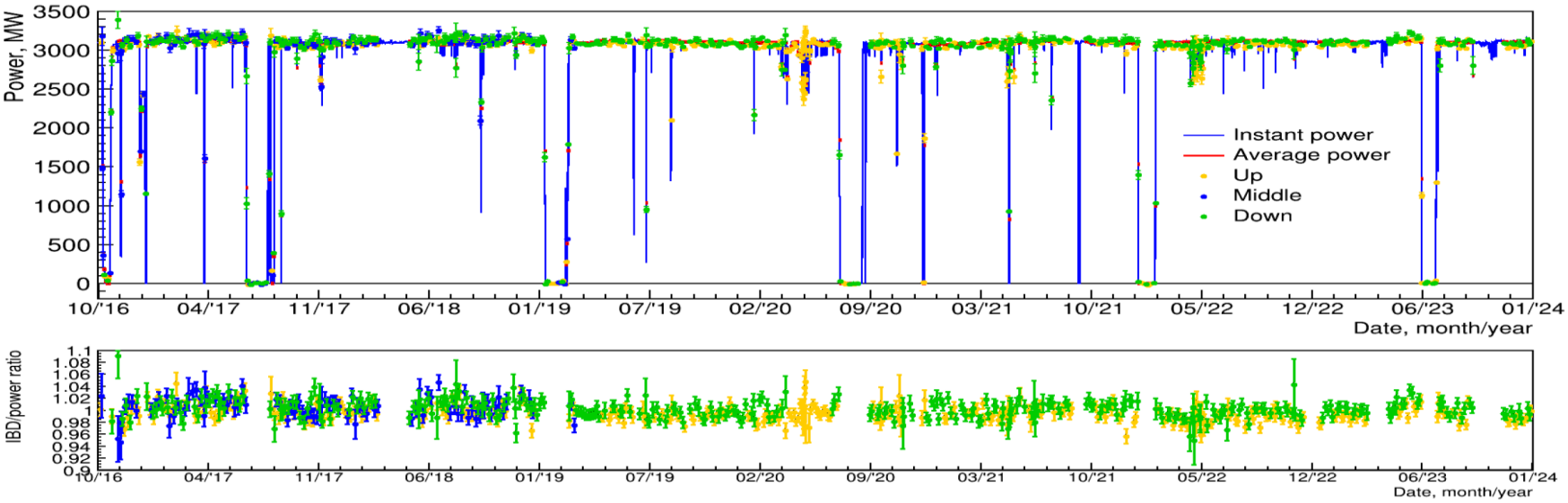
DANSS measured ^{235}U fission fraction with ~3% accuracy using fit of e^+ spectrum



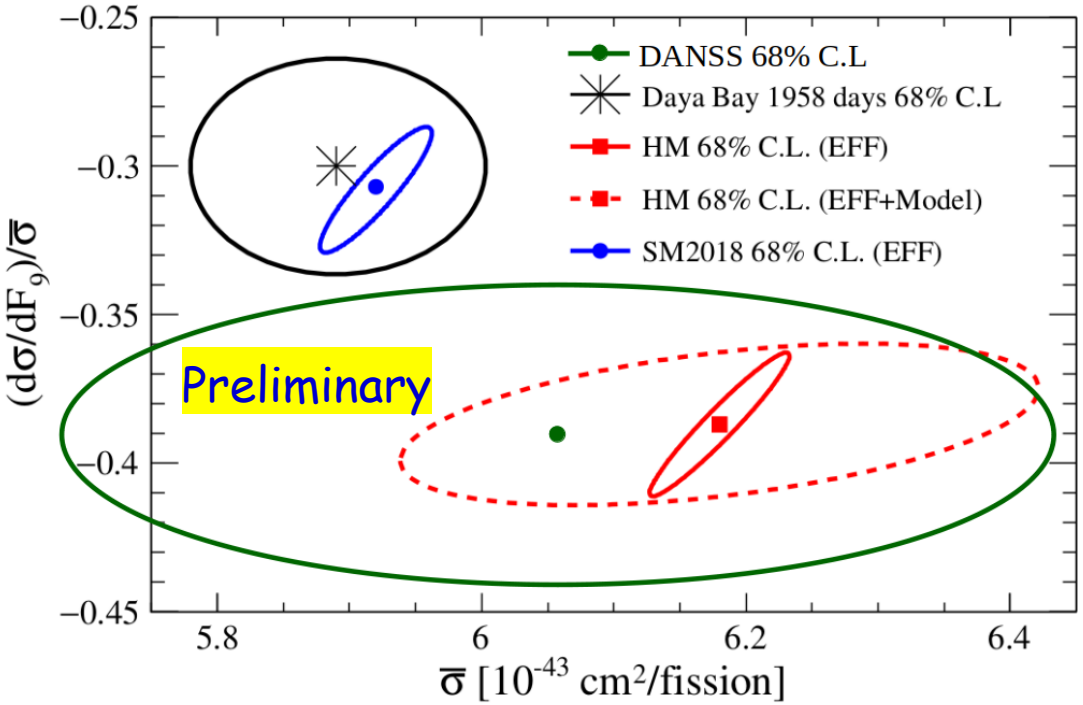


N.Skrobova, Poster #234

DANSS measured reactor power remotely using ν with 1.3% accuracy in 3 days during 7 years
IBD rate was normalized to reactor power during 1 month in 2016
Corrections for the fuel evolution were made using HM model



Comparison of σ and (dσ/dF239)/<σ> with models



DB results are consistent with SM2018 model
DANSS results are consistent with HM model but errors are large

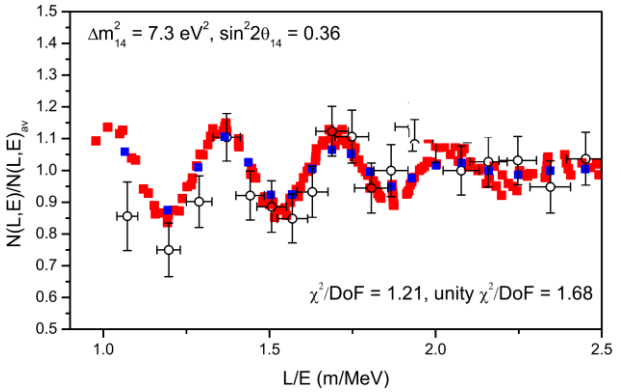
RAA is probably solved by smaller contribution from ^{235}U but energy spectrum should be modified in reactor models.

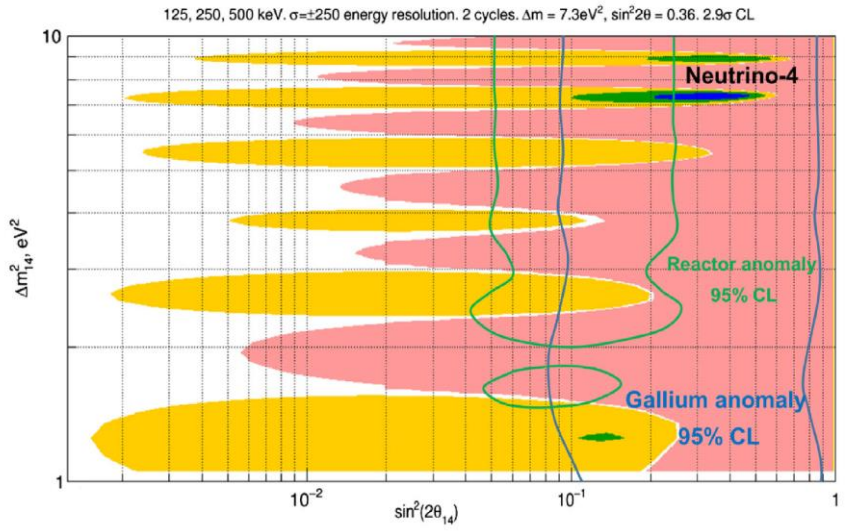
Phenomenological approach by Daya Bay shows that ad hoc modification of ^{235}U spectrum and modification of spectrum of all isotopes work equally well

Daya Bay arXiv:2210.01068v2

Neutrino-4

Indication of oscillations with large $\Delta m^2 \sim 7.3 \pm 1.17 eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$
Significance 2.7 σ
Phys.Rev.D 104, 032003 (2021)





SM-3 85MW ^{235}U Reactor
(42x42x35cm^3)
(Dimitrovgrad, Russia)

1.8m^3 LS detector (5x10 sections)

L=6-12m, $\sigma_E/E \sim 16\%$ at 1MeV

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

720 days ON 860 days OFF
~200ev./day

There were 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.
Neutrino-4 replied to these critical comments: JETP Lett.112 p.487, arXive:2006.13639

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
Neutrino-4 says it reduces 2.8σ to 2.5σ (for const resolution σ=250keV)

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 from 2.9 σ 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

Comparison with other experiments

Neutrino-4 and BEST results agree nicely
Phys. Rev. Lett. 128, 232501 (2022),
Phys. Rev. C 105, 065502 (2022)

Serious tension of Neutrino-4 result with

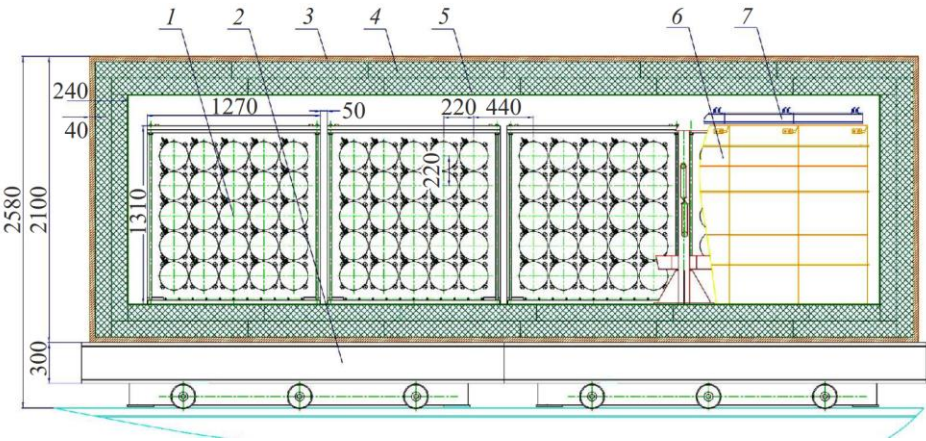
- Predictios for absolute reactor ν flux compared with experimental results (Bugey-3, Daya Bay, DANSS)
- Solar neutrino data
- PROSPECT and STEREO experiments
  See e.g. Giunti et al arXiv:2101.06785

However Neutrino-4 result can't be excluded
A.Serebrov et al,
JETP v137, p.55(2023)

New experiments are needed to confirm or discard Neutrino-4 result

Neutrino-4 upgrade

Serebrov et al, Techn. Phys., 2023,V.68,No1, 15



- New 5.4m^3 LS(0.2% Gd) detector in a new hall
100 sections with 2 PMT readout, PSD, L=6-15m
Sensitivity 2.7 times better than at Neutrino-4
Start of data taking - end 2024!
Old setup was upgraded (PSD, Electronics)
Taking data since end 2023!
Sensitivity twice better than at Neutrino-4

DANSS

2500 plastic scintillator counters with WLS readout ($1m^3$)

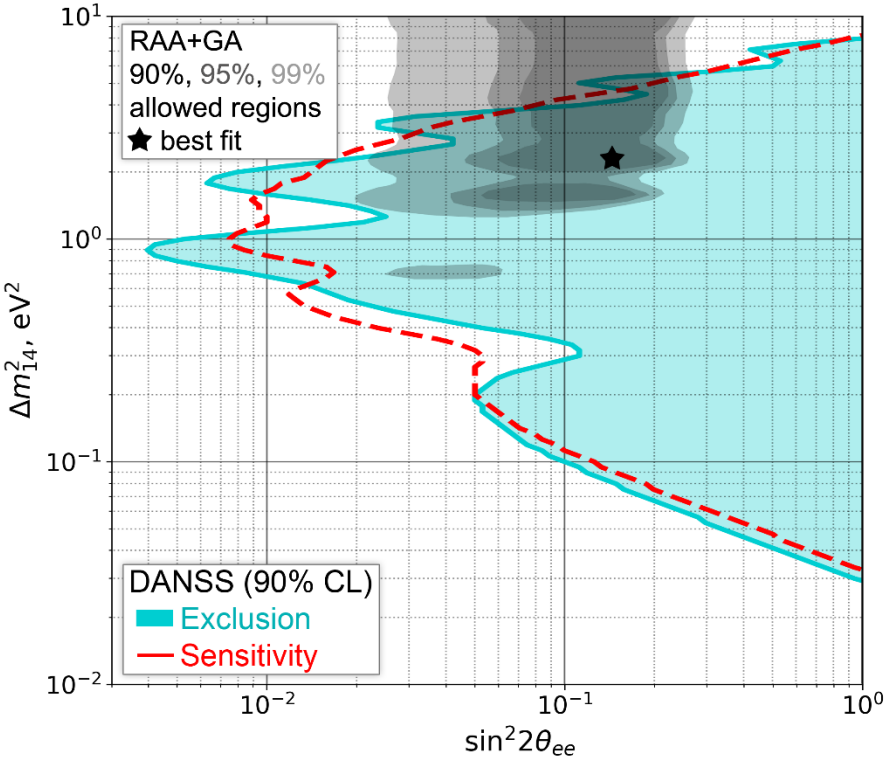
L: 10.9-12.9m Changed 2-3 times a week

50 mwe overburden, S/B>50

Energy resolution $33\%/\sqrt{E}$

Kalinin NPP (Russia) 3.1GW
(Core:h=3.7m, ∅=3.1m)

8M IBD-events in >7 years



Exclusion region calculated using Gaussian CLs method using E_{e+} in 1.5-6 MeV region

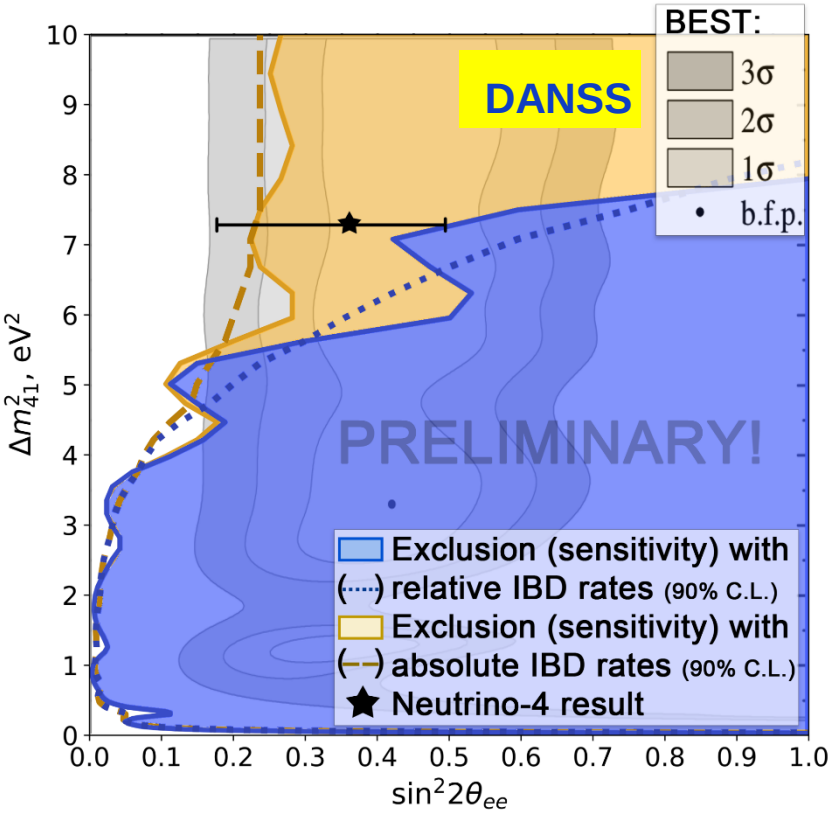
The most stringent limit reaches $\sin^2 2\theta < 4 \times 10^{-3}$ level.

A very interesting part of 4v parameters is excluded.

The most probable point of RAA is excluded at >5σ CL already in 2018

Best 4v fit point is not statistically significant (2σ)

Results with absolute ν rates

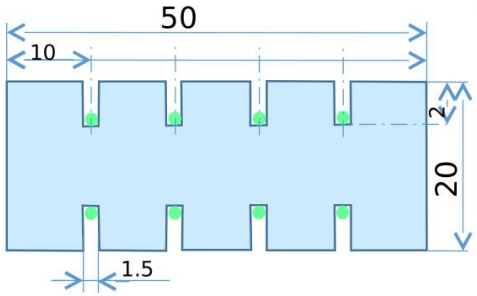


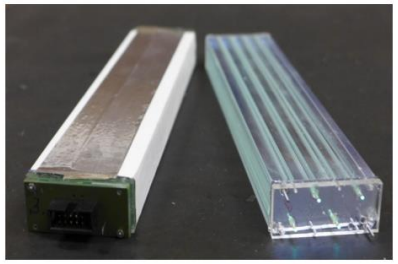
Practically all parameters preferred by BEST and N4 best fit point are excluded
KI model gives even stronger limits

Similar to Daya Bay and Bugey3 results
PRL 125, 071801 (2020), arXiv:2404.01687v2
Exclusions depend on assumed uncertainty in reactor ν flux (5%)

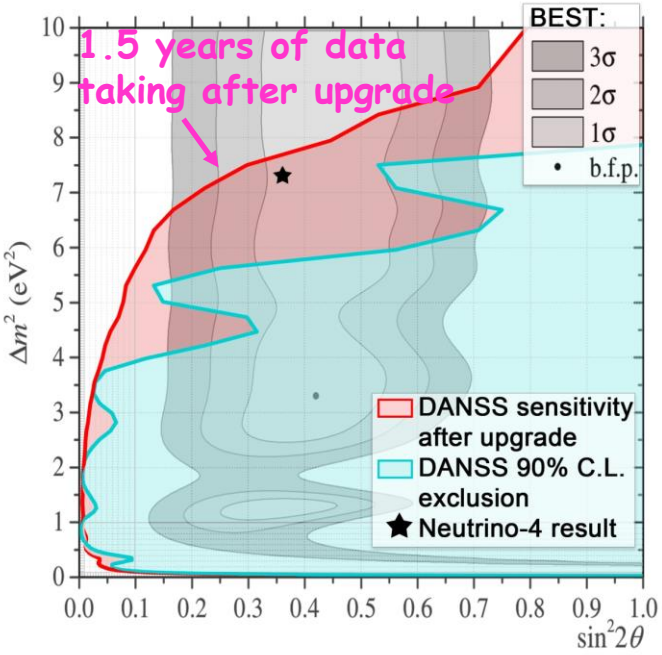
DANSS upgrade

New scintillator counters with good uniformity of response and fast YS2 WLS fibers readout from both sides. Light yield 130p.e./MeV
JINST 17 (2022) P01031



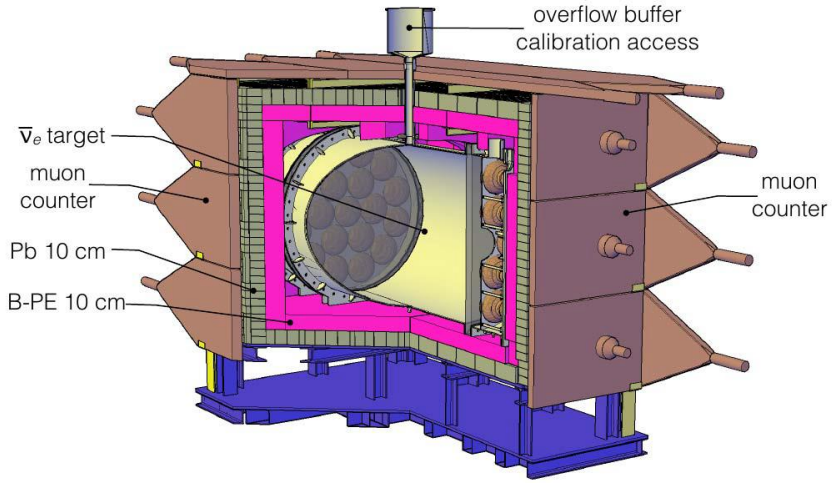


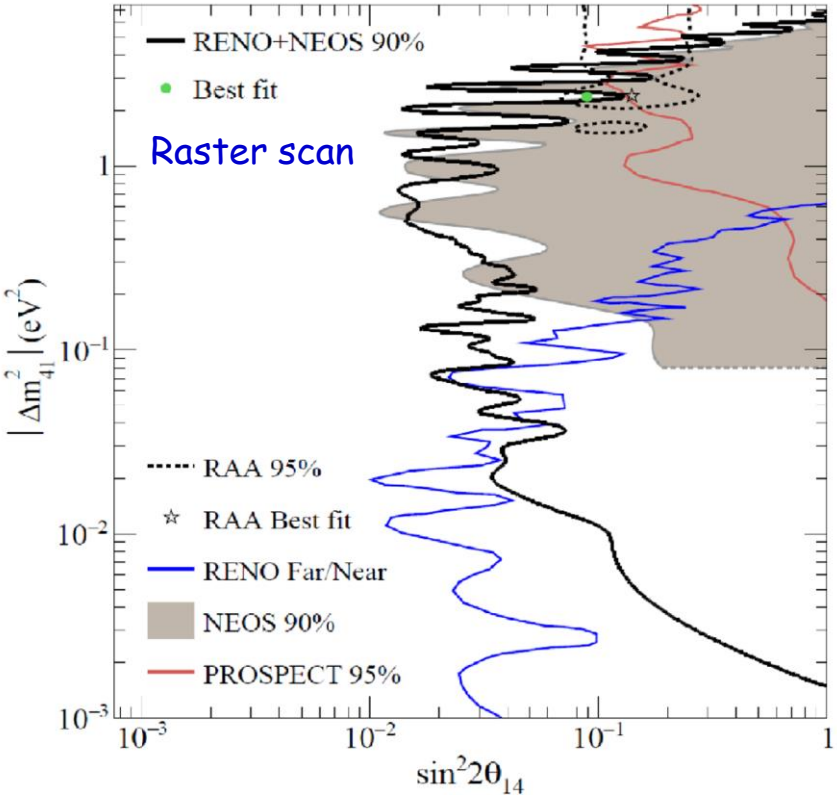
Expected energy resolution 12%/√E
1.7 times larger detector volume



NEOS

arXiv:2011.00896





1m^3 LS. No segmentation

ΔM^2=2.37

σ_E/E=5% at 1 MeV

PSD removes 70% of background

Depth 20mwe, S/B= 23

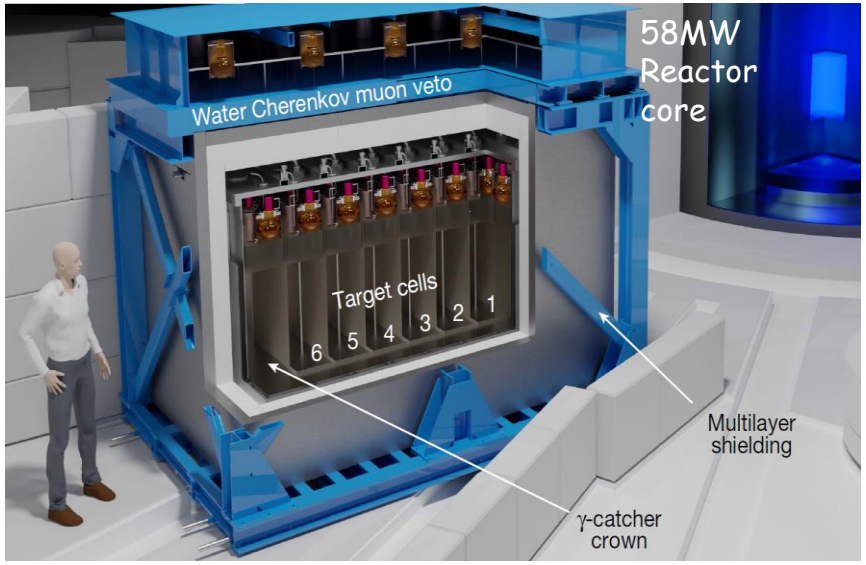
Hanbit NPP 2815 MW
Large core size d=3.1m h=3.8m

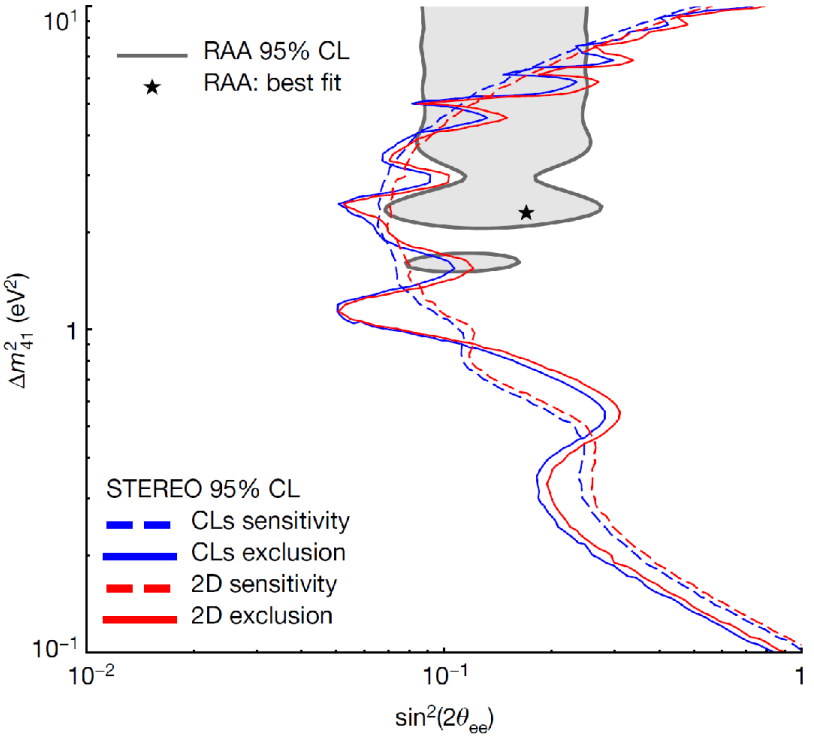
Only one L=24m
Compared with Daya Bay or RENO

Strong limits on sterile neutrino parameters
Best point (eV^2) agrees with RAA
but p-value is 13% only
FC limits are not shown
- hard to compare them with other experiments

NEOS-II took data 500 days in 2018-2020
Results on sterile ν search at the next talk!

STEREO





1.6 ton LS(Gd) 6 cells

L=9.4-11.2m

σ_E/E=9% at 1 MeV

PSD

S/B=0.9

ILL 58MW Reactor

Data consistent with no oscillations, p=0.52
Nature 613,257(2023)

Neutrino-4 best fit point excluded at 3.3σ
(but not the whole preferred region)

Large fraction of ν_s parameters
preferred by BEST was excluded

PROSPECT Final Osc: Probing L/E

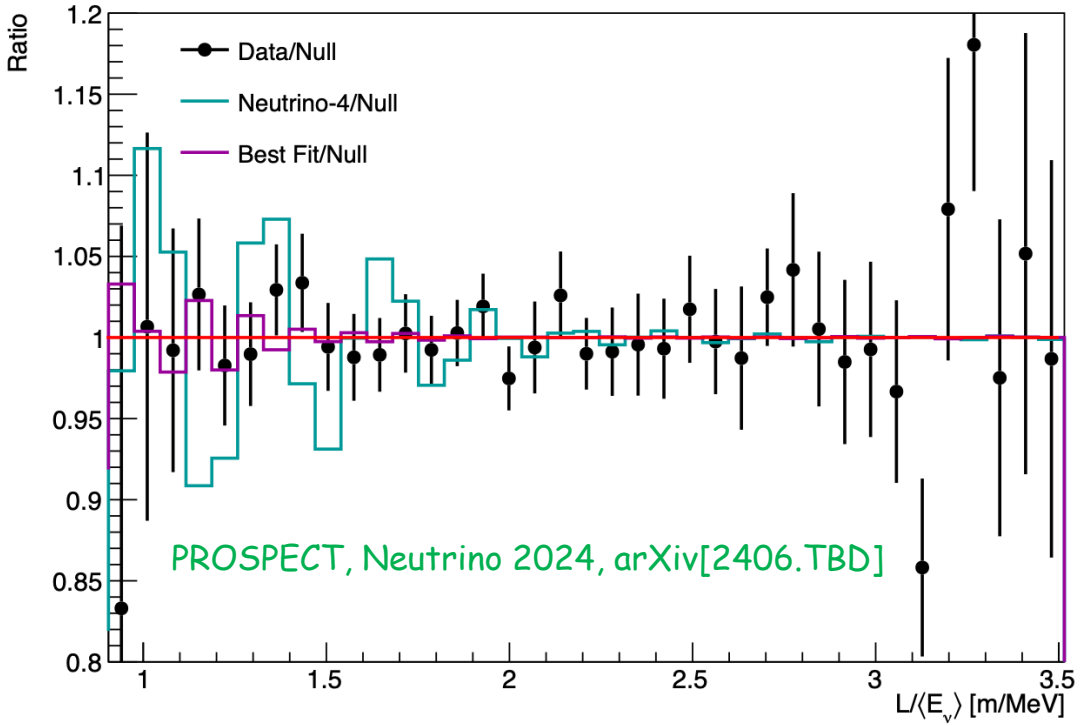
PROSPECT is a 4m^3 LS (^{6}Li) detector at 85MW HIFR reactor

PROSPECT increased S/B ratio from 1.4 to 3.9 by inclusion of segments with 1 PMT and more than doubled the statistical power

C. Roca: Poster #470

No obvious oscillatory behavior is observed

D. Venegas-Vargas: Poster #383



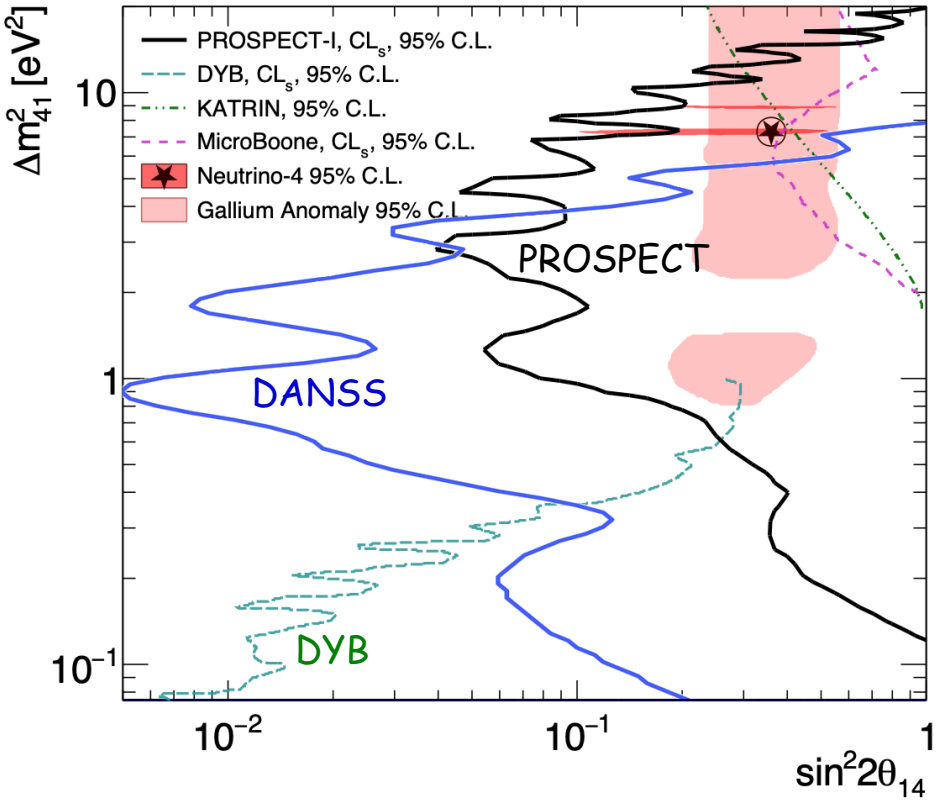
Thanks to B. Littlejohn for PROSPECT slides

PROSPECT Final Osc: Exclusion

D. Venegas-Vargas: Poster #383

- Tested sterile neutrino phase space using 990 energy (33) x baseline (6) x period (5) bins.
  - Used a 'relative spectral ratio' approach with a CNP χ^2 test statistic: compare each baseline's energy spectrum to the baseline-integrated spectrum
  - Final result is still statistics-limited.
- PROSPECT provides new world-leading limits on sterile neutrino oscillations
  - New regions of high-Δm^2 space are excluded at >95% CL, including all space below 10 eV^2 suggested by the Gallium Anomaly
  - Neutrino-4 best-fit point is ruled out at >5σ CL but not the whole Neutrino-4 allowed region

PROSPECT, Neutrino 2024, arXiv[2406.TBD]

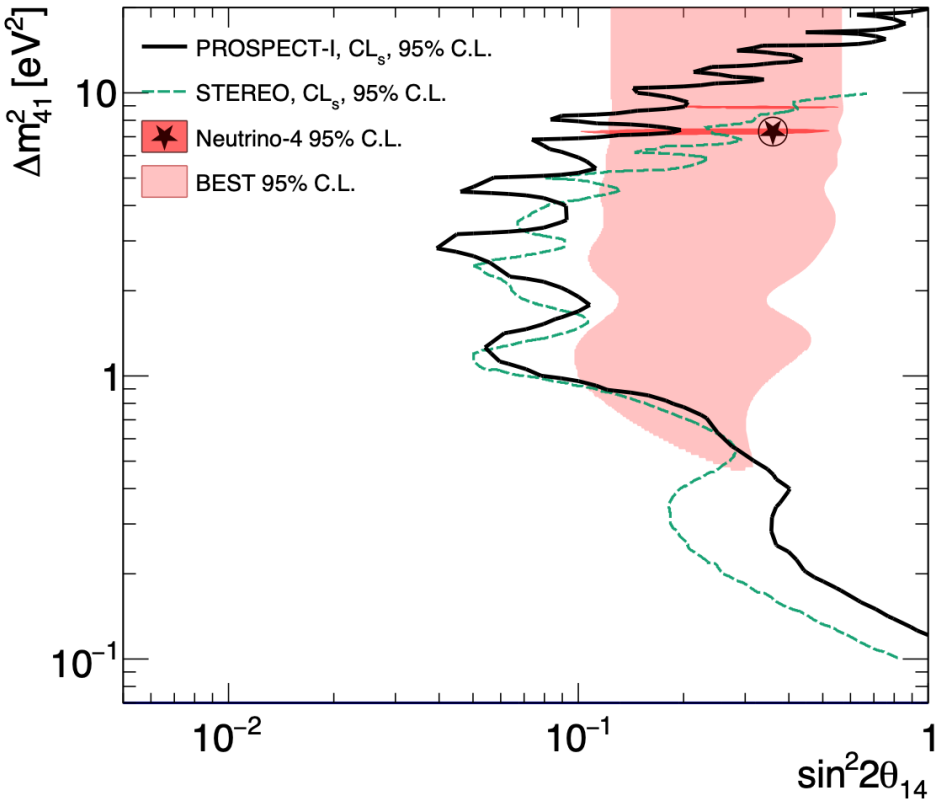


Strict limits on ν_s mixing in a huge range of Δm^2 by a combination of experiments

DPS Joint Oscillation Analysis

- A combination of Daya Bay, PROSPECT, and STEREO datasets offers new benefits for sterile oscillation searches

- PROSPECT and STEREO datasets have comparable statistical power
- Daya Bay's LEU-based ^{235}U spectrum measurement is directly comparable to HEU STEREO and PROSPECT measurements
- Additional sterile sensitivity unlocked by comparison of long (Daya Bay) and short (STEREO, PROSPECT) baseline energy spectra (a la NEOS/RENO)
- Analysis work started between three collaborations in late 2023. Stay tuned!

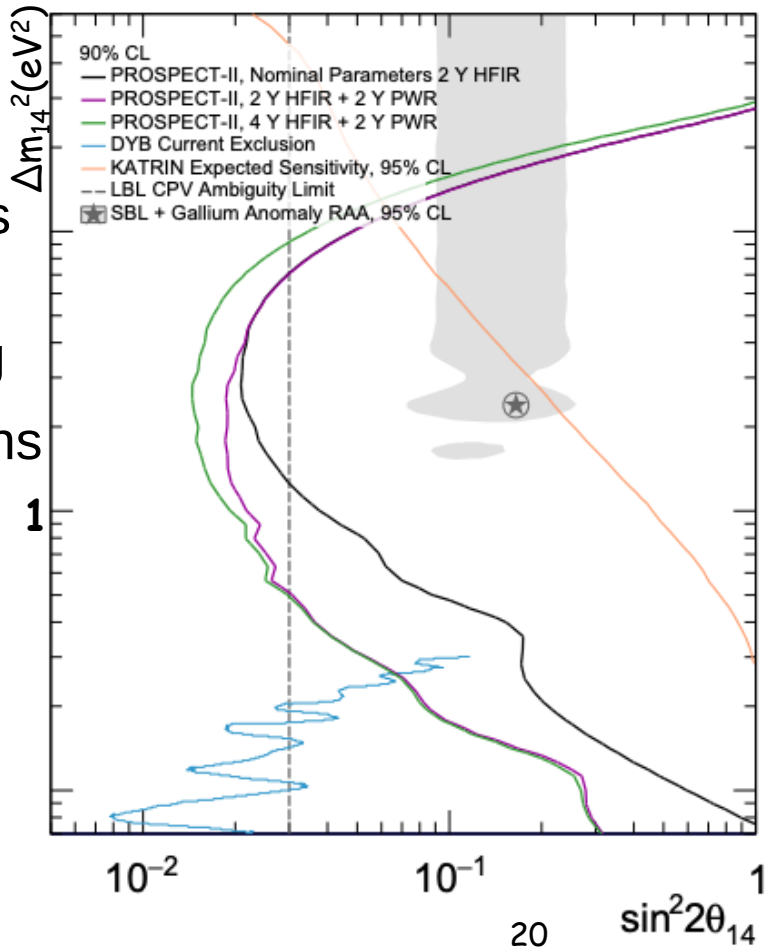


PROSPECT-II Future Physics Highlights

O. Benevides Rodrigues: Poster #421

- HEU campaign:
  - Close out remaining BEST and Neutrino-4 suggested space below 20 eV^2
  - Pin down e-flavor disappearance to few-% level at <10 eV^2 , benefitting anomaly and long-baseline CPV interpretations
- Subsequent LEU campaign:
  - First correlated probe of HEU/LEU types
  - Delivers more precise isotopic ν_e flux/ spectrum information, broadly benefiting reactor-CEvNS, nuclear data/applications

J Phys G 49 (2022)



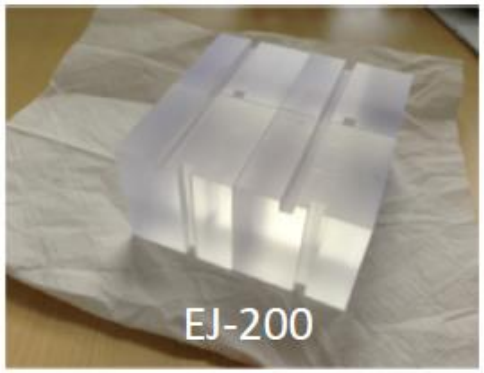
Gebre, Littlejohn, Surukuchi, PRD 97 (2018)

Fujikake, Littlejohn, Benevides Rodrigues, Surukuchi, PRD 107 (2023)

Case	Description	Precision on σ_i (%)				
		^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
-	Existing Global Data	1.3	26.4	25.2	-	42.6
1	HEU + LEU	1.6	11.1	4.6	-	10.5

SoLid

Background problems. Phase-I results are expected at ICHEP 2024

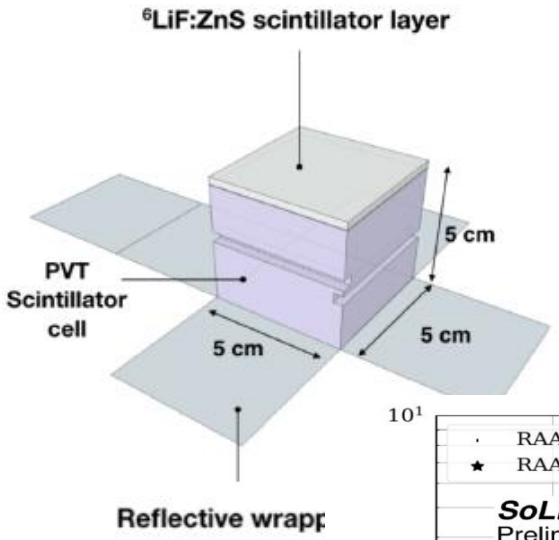


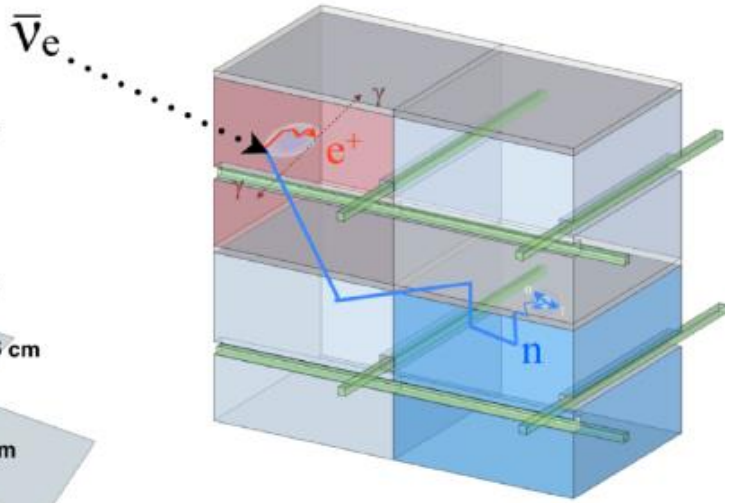
$5 \times 5 \times 5$ cm^3 PVT cubes (12800)

– Non-flammable scintillator

Cubes are optically separated using Tyvek wraps

^{6}LiF:ZnS(Ag) screens for neutron identification

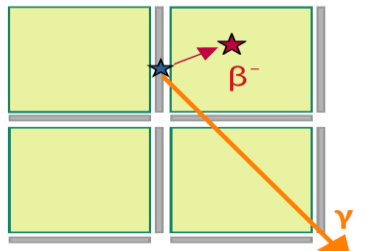


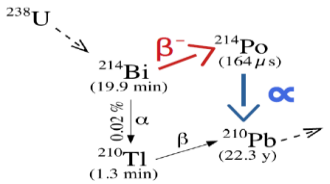


BiPo background

Internal radioactivity from ZnS layers contamination

External Radon decay.

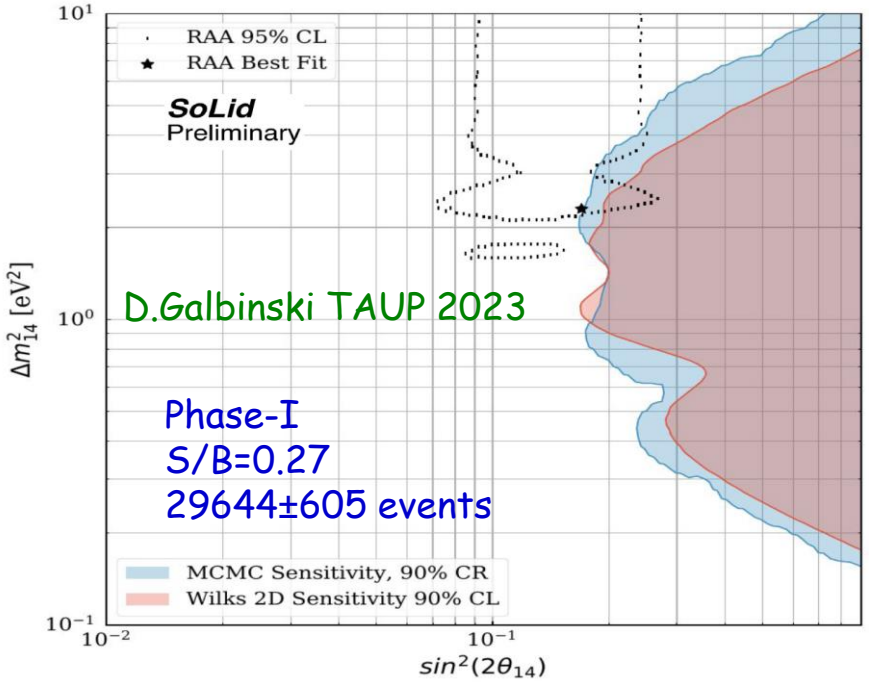




★ Prompt: β^- (+γ)

★ Delayed: α

$\Delta T_{prompt\text{-}delayed}$ ~ 250 μs



D.Galbinski TAUP 2023

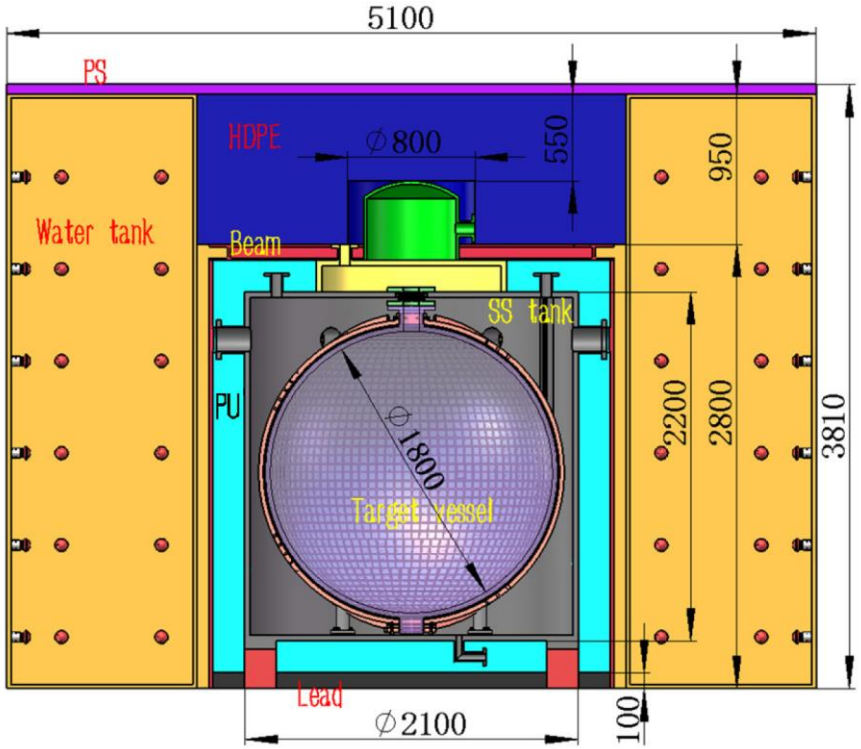
Phase-I
S/B=0.27
29644±605 events

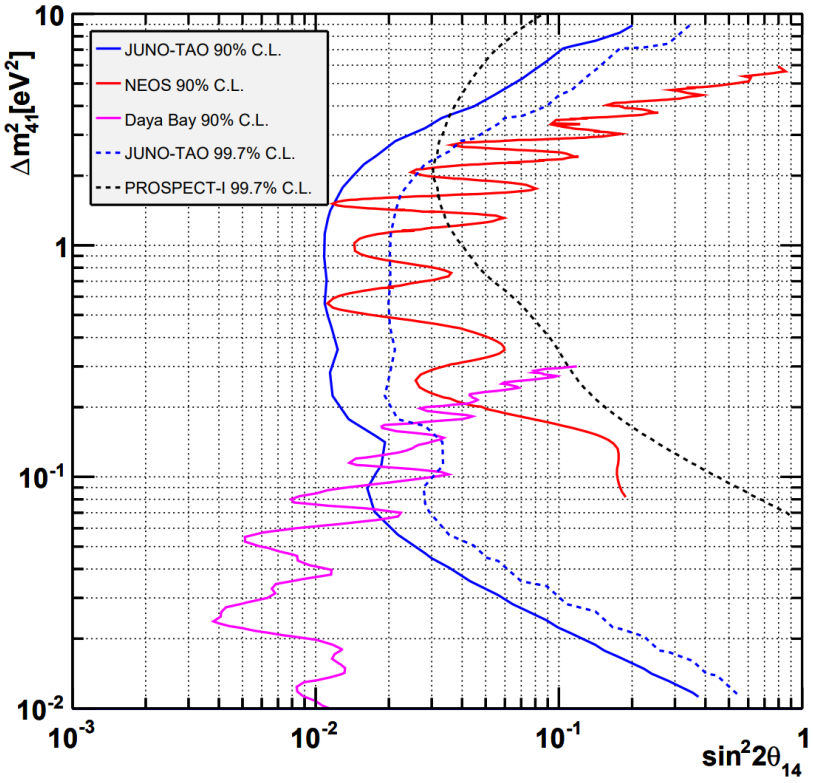
JUNO-TAO

arXiv:2005.08745v1, arXiv:2405.18008v1

A 2.8(1.0 fiducial) ton LS(Gd) with 10m^3 SiPM readout at 44m from 4.6GW reactor
Excellent energy resolution of 1.8% at 1 MeV. About 1000 IBD events/day

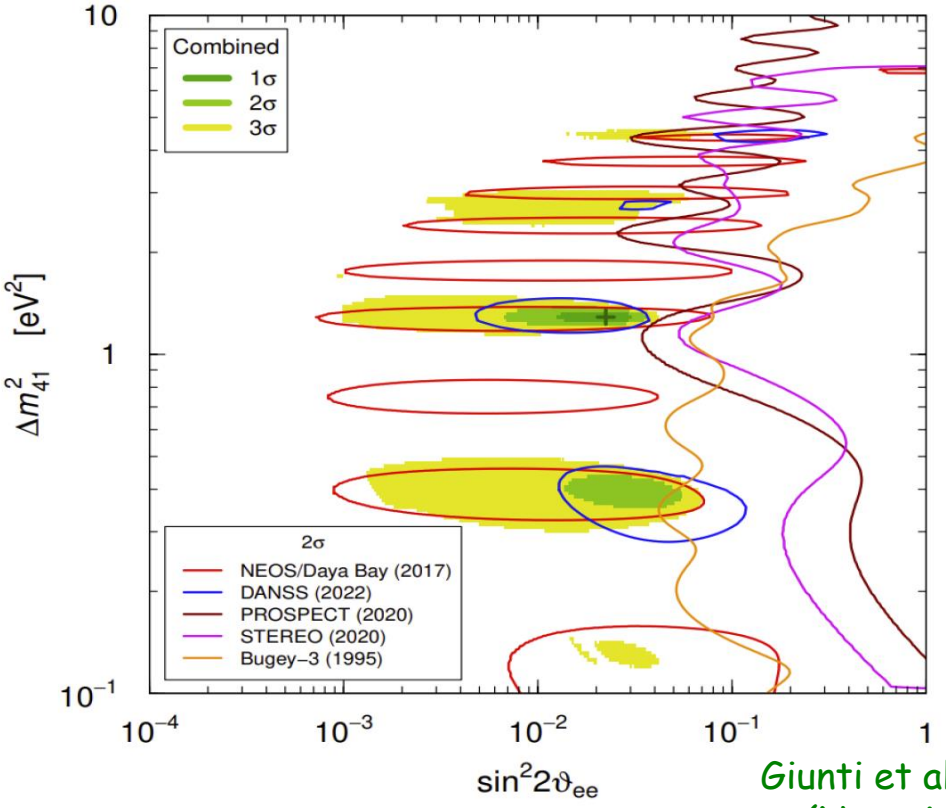
Sensitivity to ν_s estimated for 3 years and L=30m using Gaussian CLs method and 4 virtual detector segments. Should be shifted to lower Δm^2 (factor ~1.5)

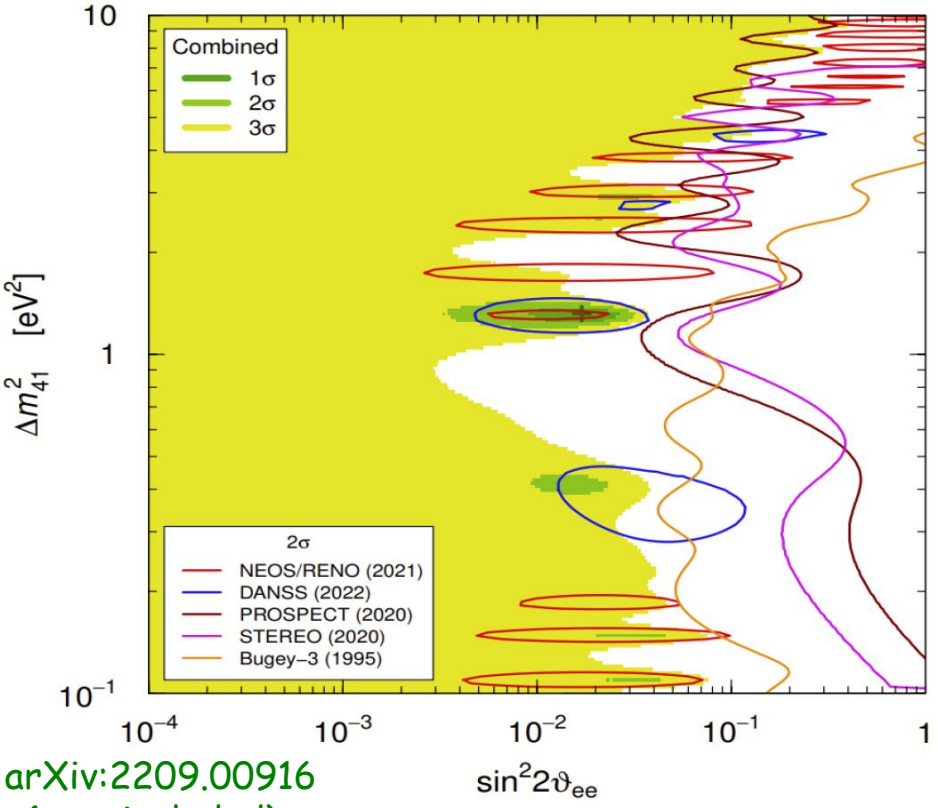




Start of data taking – end 2024

Combined fit of SBL experiments





Giunti et al, arXiv:2209.00916
(Neutrino-4 not included)

Fit with NEOS/Daya Bay - 3.1 σ
Fit with NEOS/RENO - 2.6 Weak indication of Sterile neutrino
But fit assumes validity of Wilks theorem ➔ overestimation of significance

Another fit (J.Berryman et al. *JHEP* 02 (2022) 055) gives even smaller significance of 1.1 σ
New experiments are needed to clarify the situation.
Upgraded DANSS, Neutrino-4, and PROSPECT will give answer in few years

Conclusions

- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments and new Reactor flux models.
  (Maybe due to too high σ of $^{207}Pb(n,\gamma)$ used in ILL analysis (see talk by A.Sonzogni))
  However measured antineutrino spectrum does not agree with models
  There is also disagreement between conversion and summation models

- Neutrino-4 claim of ν_s observation is in serious tension with many results but not excluded
  - Upgraded VSBL reactor experiments (DANSS, Neutrino-4+, PROSPECT-II) and KATRIN will clarify the situation with the Neutrino-4 claim.
  - Most probably Neutrino-4 will be the first to check its claim of ν_s observation
    However independent checks are very important

  - Reactor experiments with analysis of absolute ν rates exclude practically the whole range of ν_s parameters preferred by BEST
  - PROSPECT excludes BEST results up to 10 eV^2 at 95% CL
  - KATRIN excludes high Δm^2 region
    Upgraded VSBL reactor experiments KATRIN and JUNO-TAO will scrutinize BEST results in a reactor model independent way.
  - Global spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~(2-3)σ
    Upgraded VSBL reactor experiments will clarify the situation

Experimental evidence for ν_s is fading away

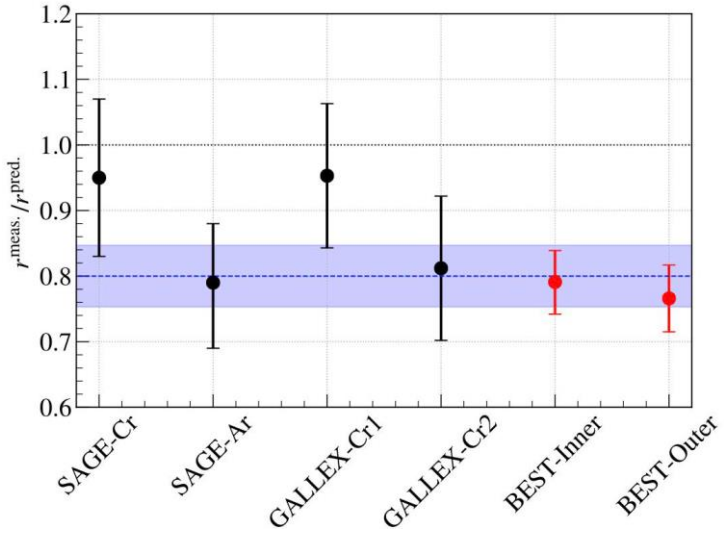
Backup slides

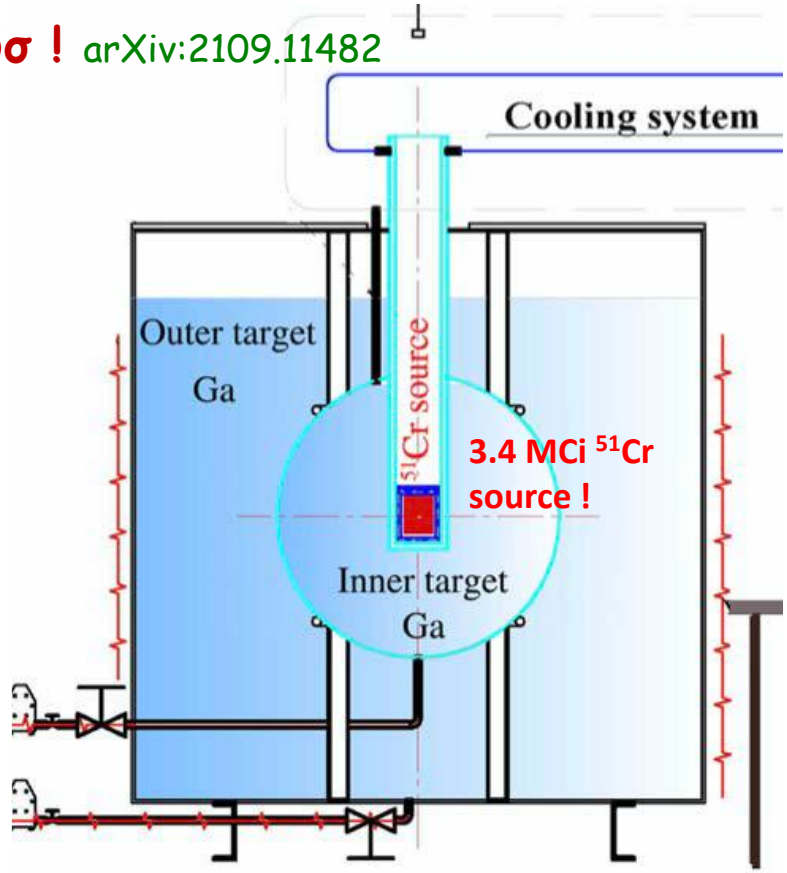
Gallium Anomaly (GA)

Deficit of ν events in GALLEX and SAGE calibrations with radioactive sources

➔ **GA – 3.0σ** (Giunti, Laveder 1006.3244)

Recently BEST confirmed GA with more than **5σ !** arXiv:2109.11482



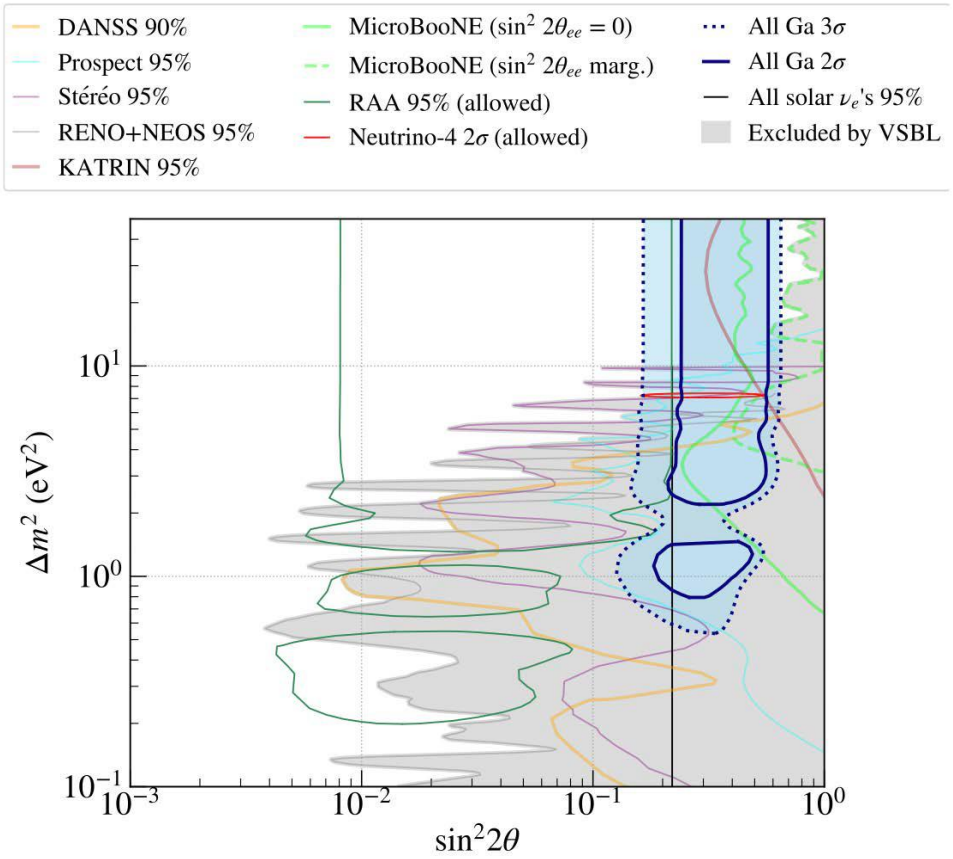


No difference between inner and outer targets Rin = 0.791±0.05 and Rout = 0.766±0.05

➔ No sign of oscillations. Only rate difference

Significant deficit implies large mixing

Serious tension with many experiments for ν_s interpretation



However perfect agreement with Neutrino-4 and MicroBooNE 2.4σ indication of ν_s : $\sin^2 2\Theta_{ee} = 0.35 \pm^{0.19}_{0.16}$ $\Delta m^2_{14} = 1.25 \pm^{0.74}_{0.39} eV^2$

Denton arXiv:2111.05793

➔ Look for alternative explanations of GA

See comprehensive review by Brdar, Gehrlein , Kopp arXiv:2303.05528

12B decay reconstruction in 2 production channels at DANSS