Windows on the Universe

Searches for sterile neutrinos

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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

2. SAGE and GALEX ν_e deficit (GA) confirmed by BEST: > 5σ
   arXiv: 2109.11482, arXiv: 2201.07364 , PRL 128.232501

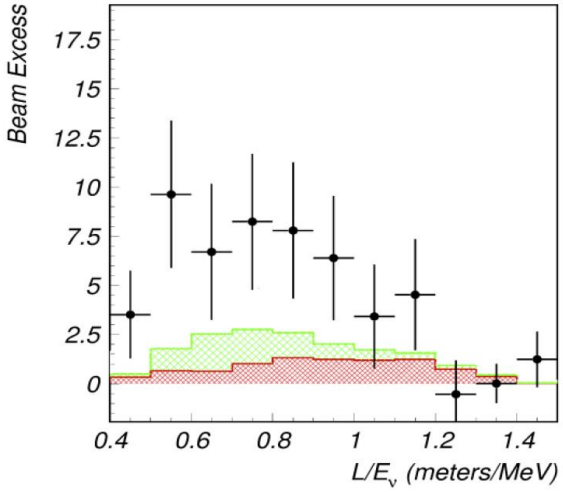
3 Reactor $\bar{\nu}_e$ deficit (RAA): ~ 3σ
   Explained by KI (arXiv:2103.01684), DayaBay, RENO experiments and new reactor neutrino flux models?
   Estienne et al arXiv:1904.09358, Letourneau et al, arxXiv:2205.14954

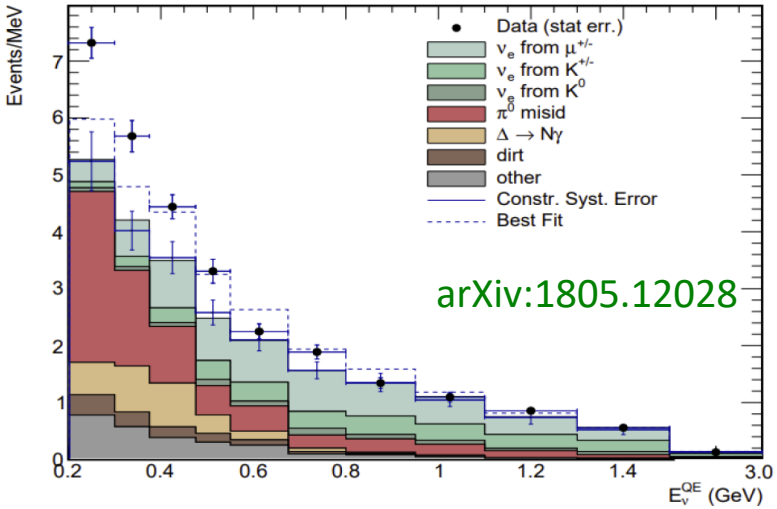
4. Neutrino-4 claim of sterile neutrino observation
   $\Delta m^2 = 7.3 \pm 1.17 eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ 2.7σ Phys.Rev.D 104, 032003 (2021)

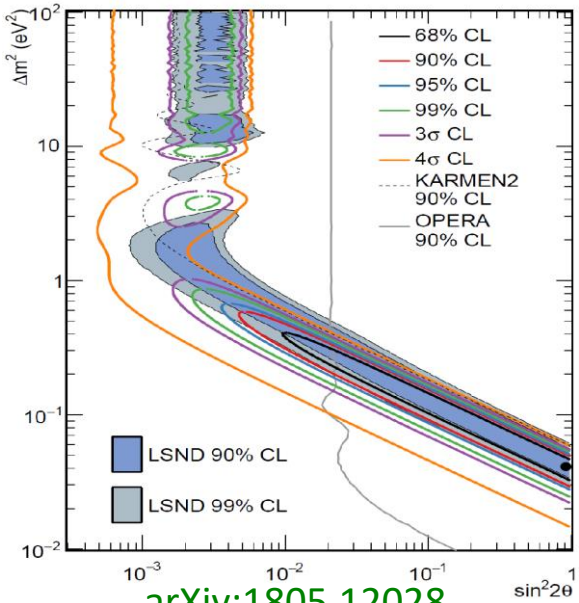
These are statistically strongest laboratory indications of physics BSM!

LSND and MiniBooNE anomalous ν_e appearance

In 1995 LSND observed excess of anti-ν_e in anti-ν_μ beam (~4.0σ)
In 2018 MiniBooNE observed excess of (anti)-ν_e in (anti)-ν_μ beam (~4.8σ)
Combined significance 6.0σ – Statistically strongest lab. indication of New Physics







ν_e excess could be explained by a sterile neutrino

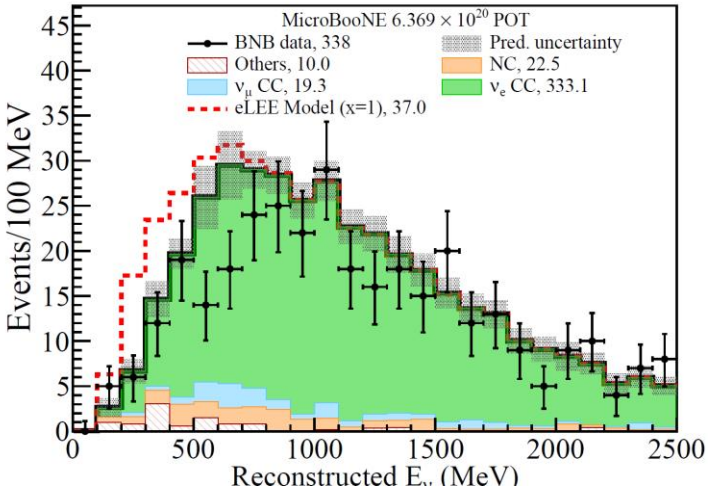
ν_e appearance requires ν_μ and ν_e disappearance

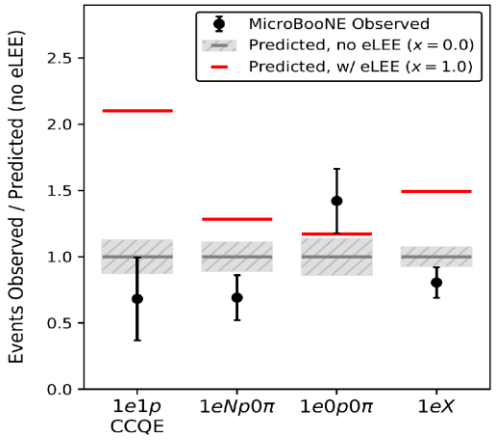
$P_{\mu e} \sim \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \approx \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}/4$

MicroBooNE did not confirm ν_e LEE arXiv:2110.14054

They observed even less ν_e than expected

The same neutrino beam (0.5% ν_e (anti-ν_e) only) , much better e identification

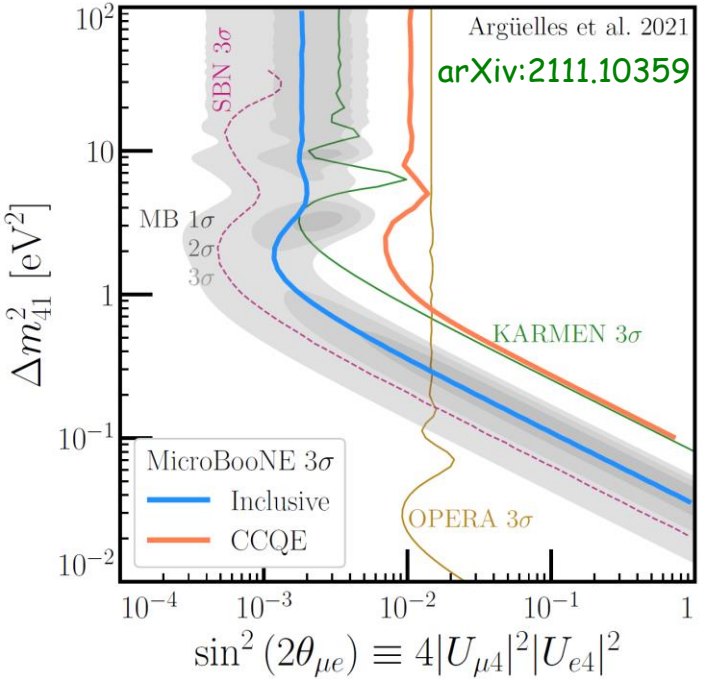




MiniBooNE ν_e LEE central value excluded with >3σ

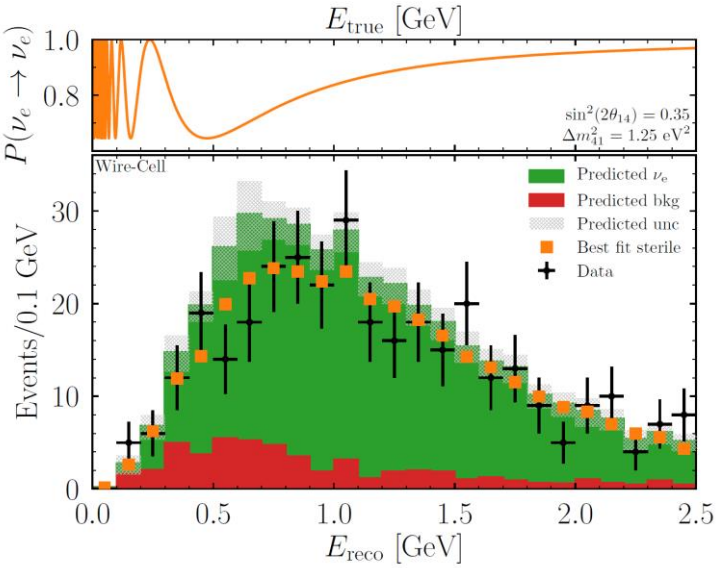
But not the whole parameter space!

Sterile neutrino interpretation of LEE is not completely excluded

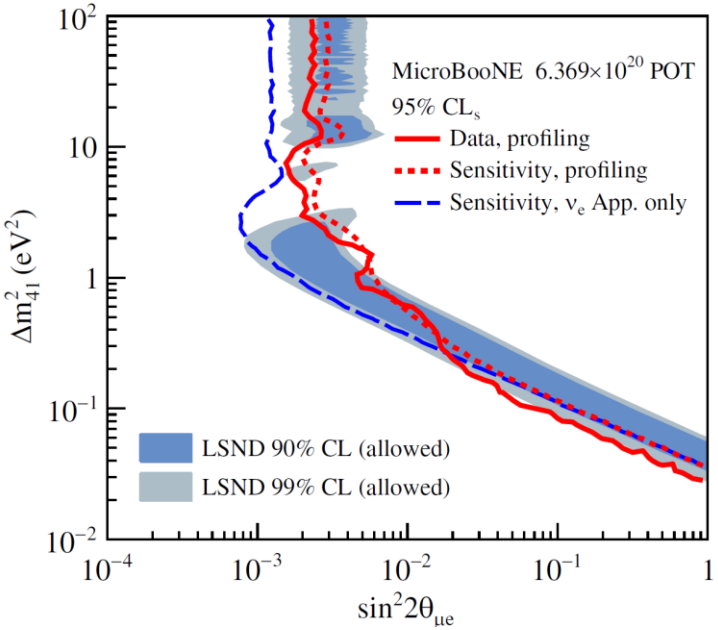


Deficit of ν_e in MicroBooNE could be explained by ν_e disappearance with
$\sin^2 2\theta_{ee} = 0.35$
$\Delta m^2_{14} = 1.25\ eV^2$
Significance 2.4σ

Denton arXiv:2111.05793
assuming ν_e disappearance only

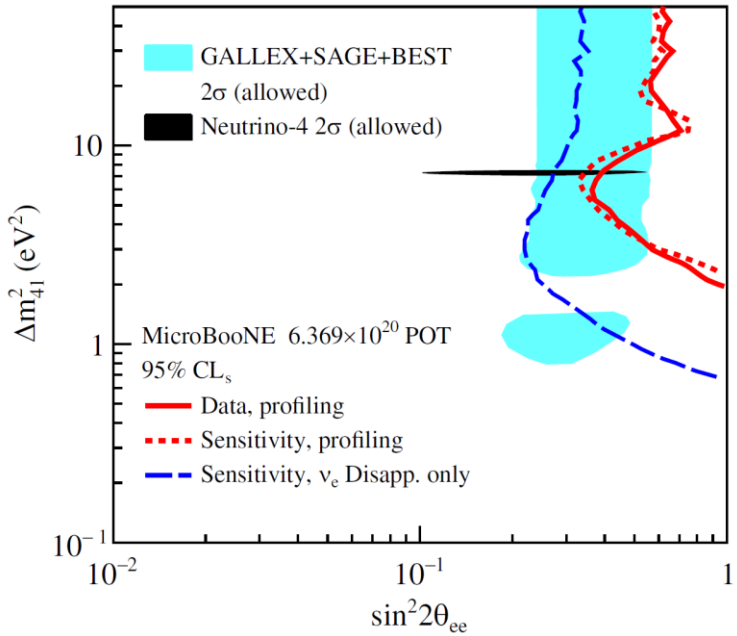


However analyses with all oscillations included are consistent with 3ν model at 1σ
arXiv:2111.10359 and arXiv:2210.10216.

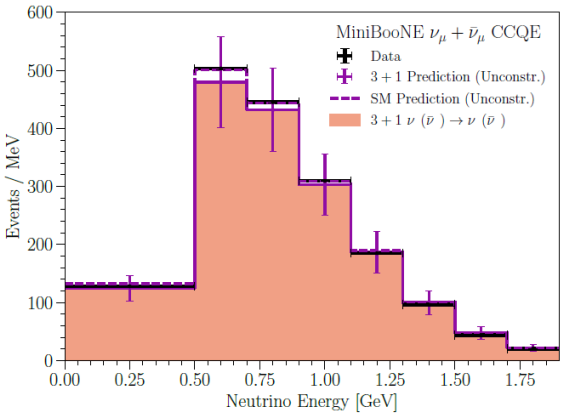


Reduced sensitivity due to cancelation in ν_e appearance and disappearance.

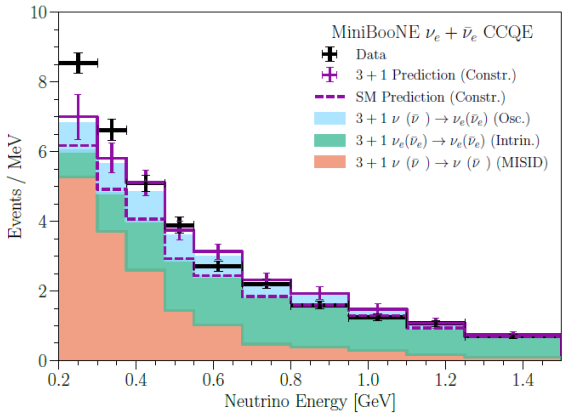
Break cancelation with NuMI beam (4% ν_e)



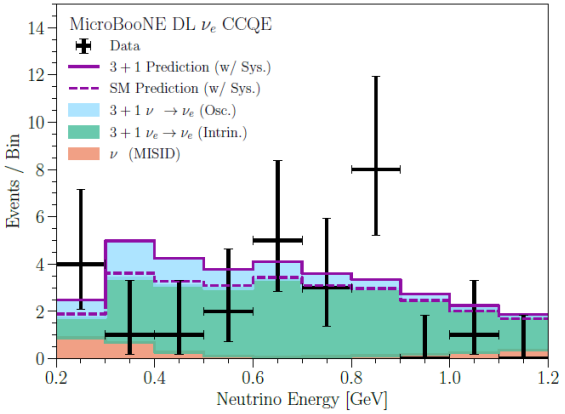
Joint MiniBooNE and MicroBooNE analysis
(including ν_e and ν_μ disappearance) arXiv:2201.01724

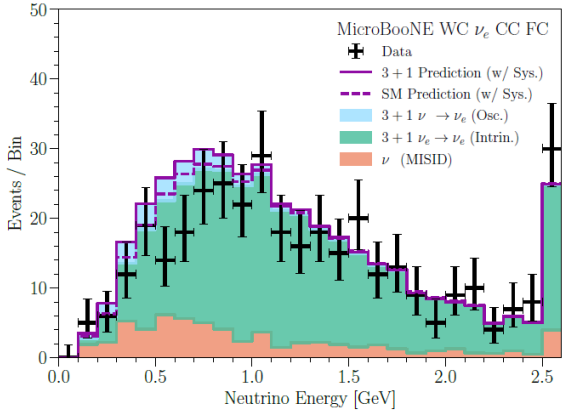


(a) MiniBooNE $\nu_\mu + \bar{\nu}_\mu$



(b) MiniBooNE $\nu_e + \bar{\nu}_e$

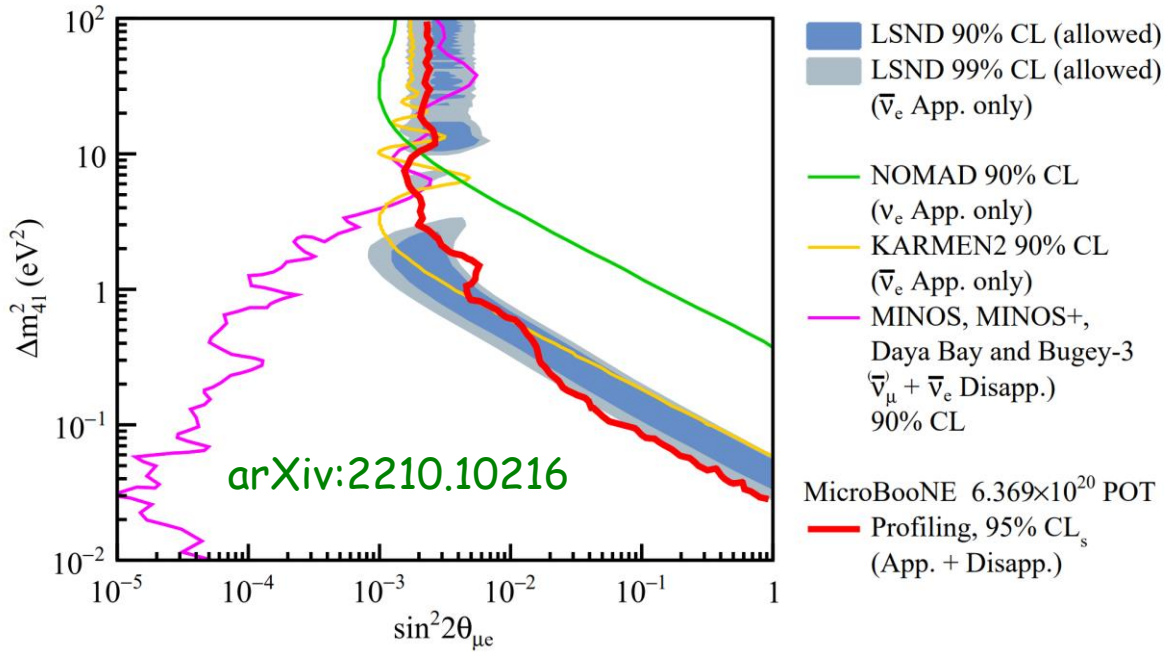




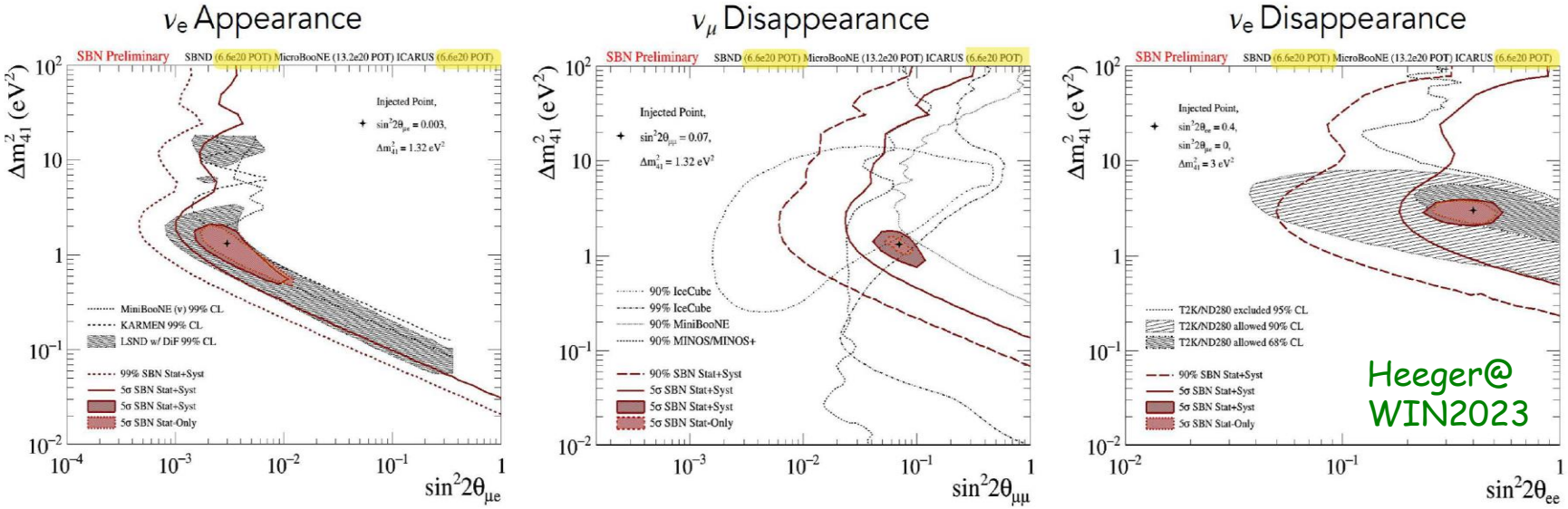
MiniBooNE significance of 4.6σ drops to 4.3(3.4)σ after MicroBooNE CCQE(Inclusive) channel inclusion

Joint Mini and MicroBooNE fit still prefers 3+1 model (3.4 σ) but fit quality is poor

Appearance and Disappearance results are in contradiction



Short-Baseline Neutrino Program at FNAL and JSNS^2 will clarify the situation

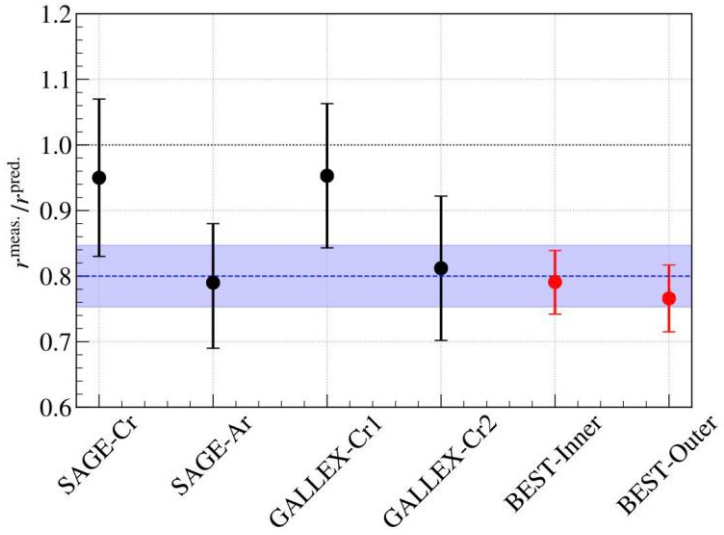


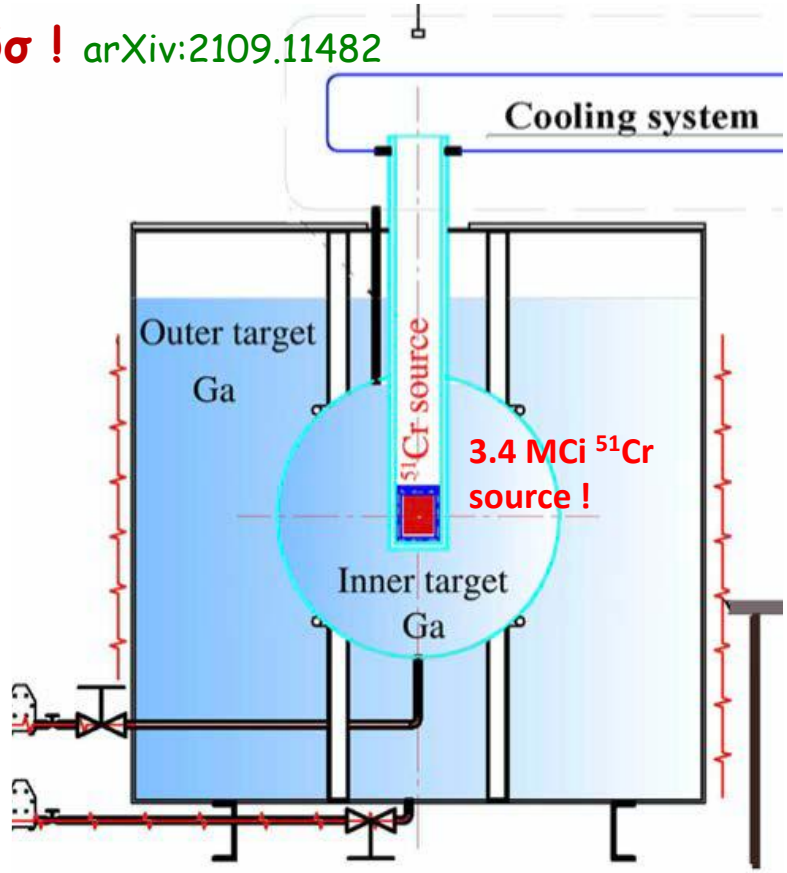
Gallium Anomaly (GA)

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



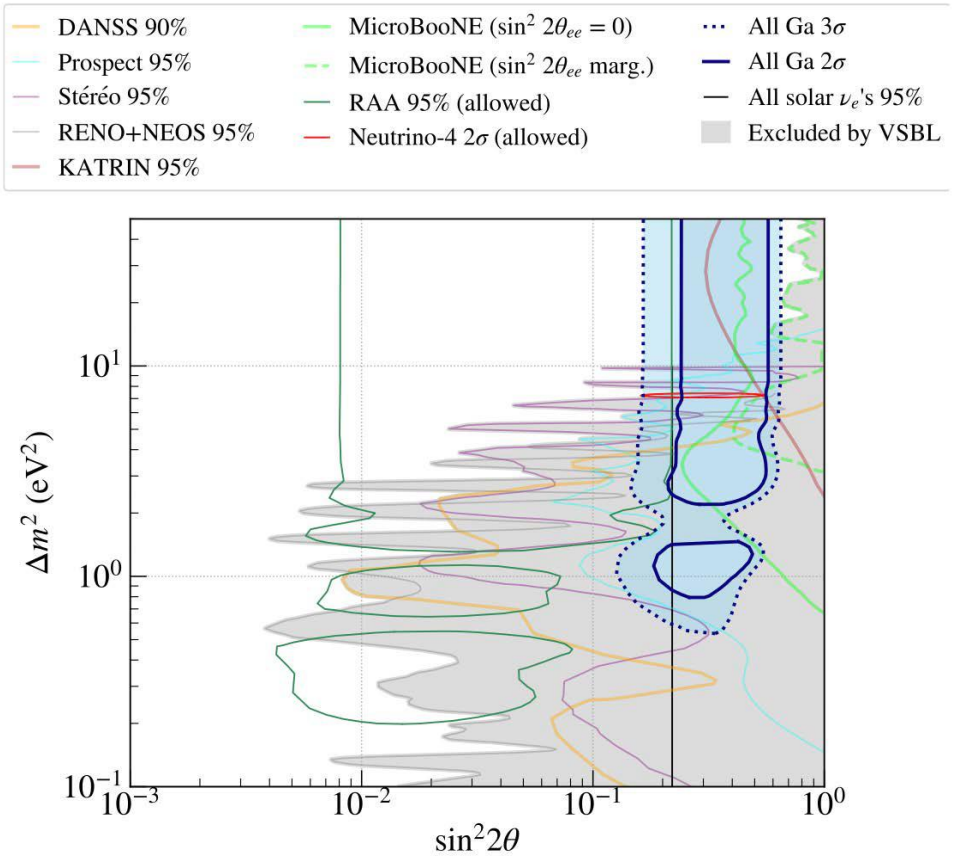


No difference between inner and outer targets Rin = 0.791±0.05 and Rout = 0.766±0.05

➔ 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

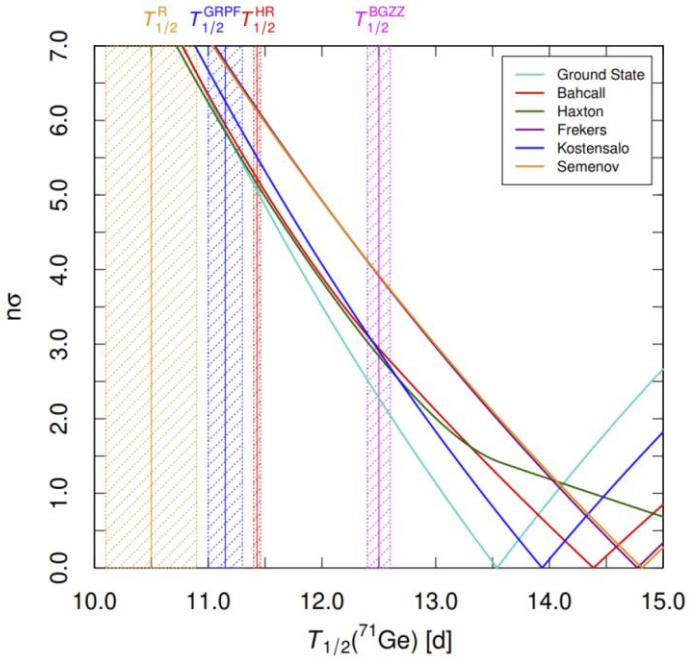
Possible conventional explanations of GA

Smaller cross-section for $^{71}Ga(\nu_e, e^-)^{71}Ge$

Recent reevaluation arXiv: 2303.13623V3 1% smaller σ than Bahcall model – not enough

Smaller ^{71}Ge half-life

Unexplained differences between measurements
Giunti etal arXiv:2212.09722
Second in accuracy result reduces significance to 3 σ level



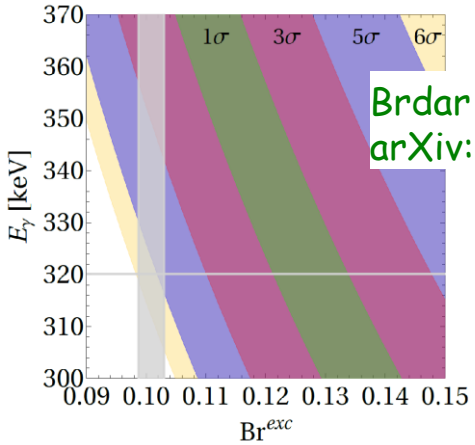
New yet undiscovered exited low-lying state of ^{71}Ga

Need 20% decays of ^{71}Ge to this state to explain GA

Reduction of cross section would increase measured ν_e pp flux above predictions based on total Solar luminosity
However discrepancy would be at ~2σ level only
Bergstrom et al, arXiv:1601.00972, Nature 562 (2018), no. 7728 505–510.

Wrong activity of radioactive source

Main heat in $^{51}Cr(e^-, \nu_e)V^{(*)}$ comes from
$V^* \rightarrow V+\gamma(320keV)$
2% increase of BR($^{51}Cr \rightarrow {}^{51}V^*$) would solve GA
(or additional new exited state)



Brdar et al
arXiv:2303.05528

Wrong efficiency of ^{71}Ge extraction

SAGE had one extraction with very high amount of extra Ge. Reason not clear.

Possible BSM explanations of GA

(From Brdar, Gehrlein, Kopp arXiv:2303.05528)

Sharp MSW resonance at E~750keV (main ^{51}Cr lines)

Interaction with ultra-light polarized vector DM φ

- Adjust parameters to avoid Solar constraints
- Decay to additional scalar and ν is needed to avoid early Universe constraints
- BEST with ^{65}Zn source – smoking gun test

Interaction with Dark Energy

Boehmer, Harko gr-qc/0701029, Tasinato 1402.6450, 1404.4883

Parametric resonance with scalar of vector DM

Petcov hep-ph/9805262, Akhmedov hep-ph/9805272,
Losada arXiv: 2205.09769

Decaying sterile neutrinos

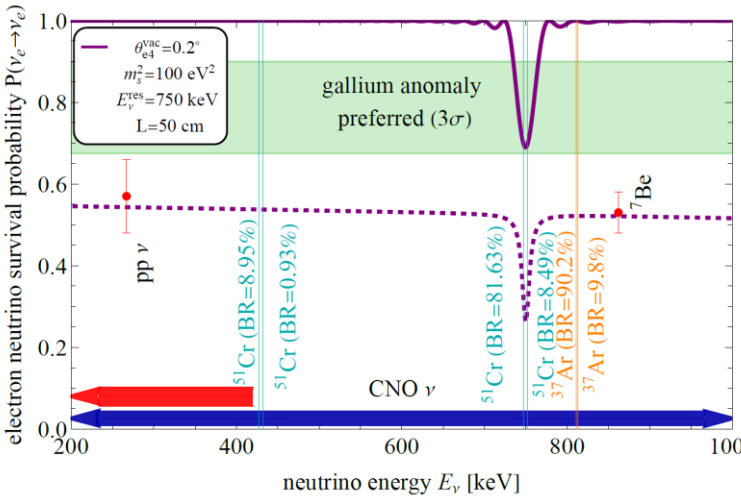
See Brdar et al,arXiv:2303.05528 and ref. therein

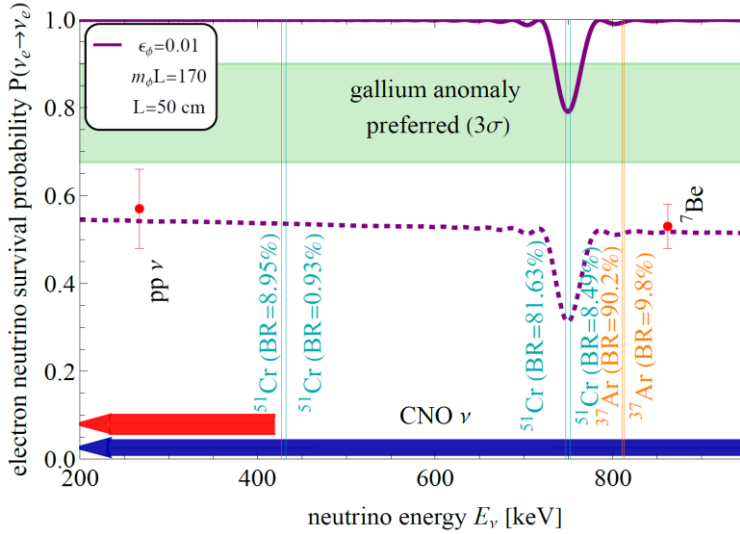
ν_s decays fast to S+ ν_e ➔

no ν_e flux reduction in reactor experiments but E is smaller and IBD rate is smaller

Does not solve tension with reactor results

Many other BSM ideas to resolve GA

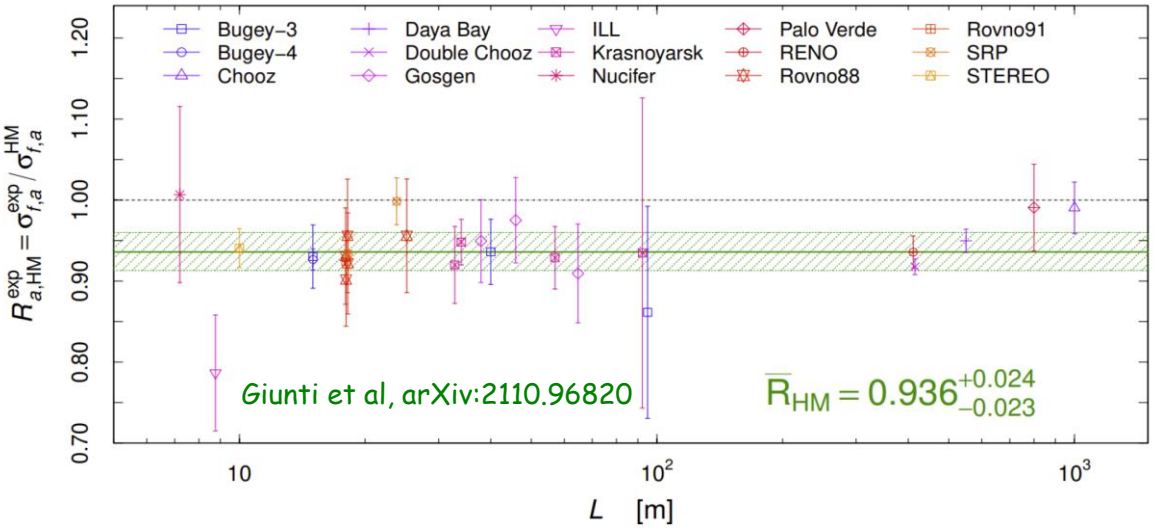




Reactor Antineutrino Anomaly (RAA)

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

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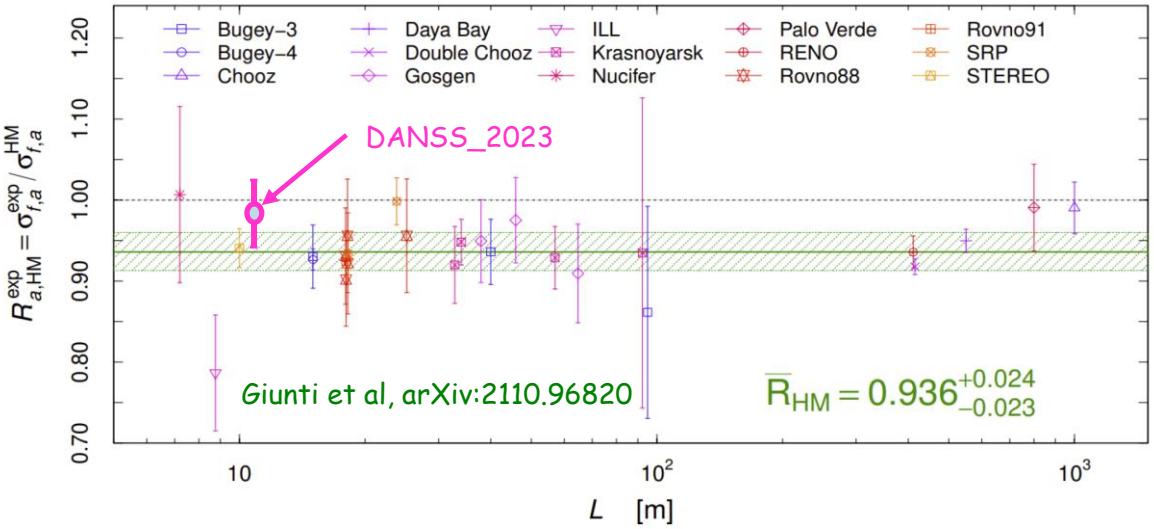

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Recent DANSS results are consistent with HM model

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**

New measurements indicate smaller contribution from ^{235}U

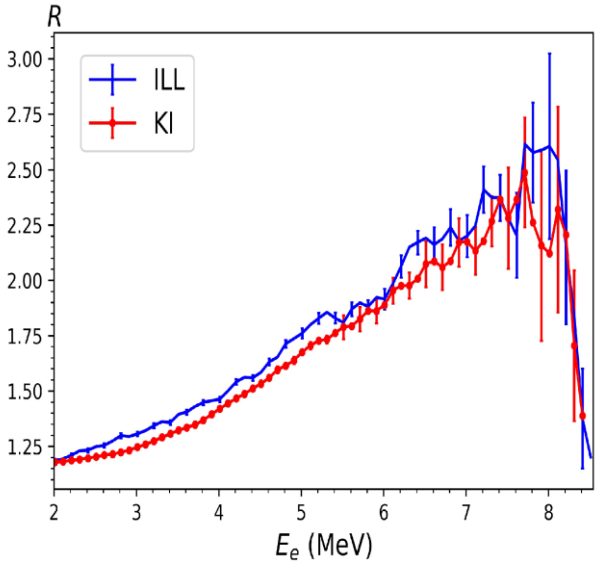
Kurchatov Inst group observed 5.4% smaller ratio of β yields for $^{235}U/^{239}Pu$ arXiv:2103.01684

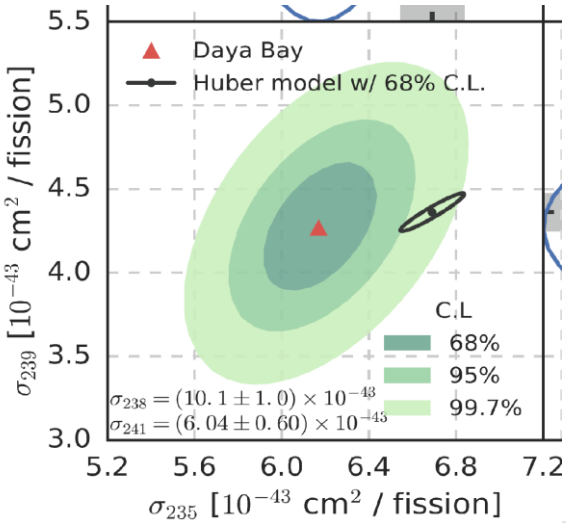
This can explain RAA!

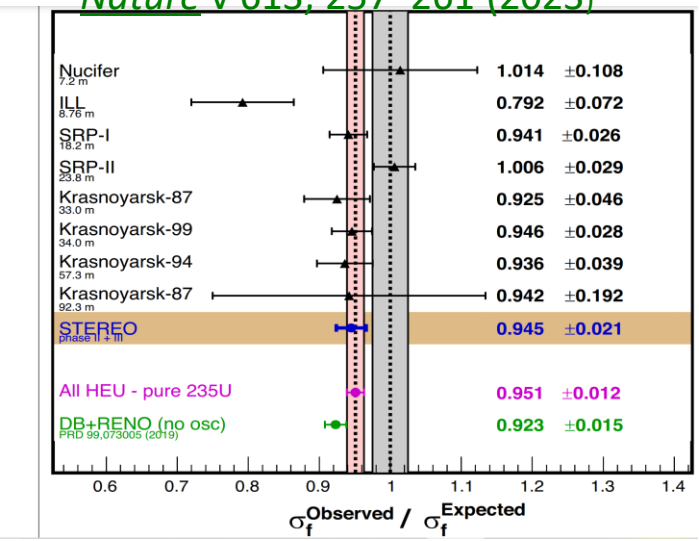
DayaBay, RENO, STEREO observed smaller ^{235}U flux than in HM model which is based on ILL results

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

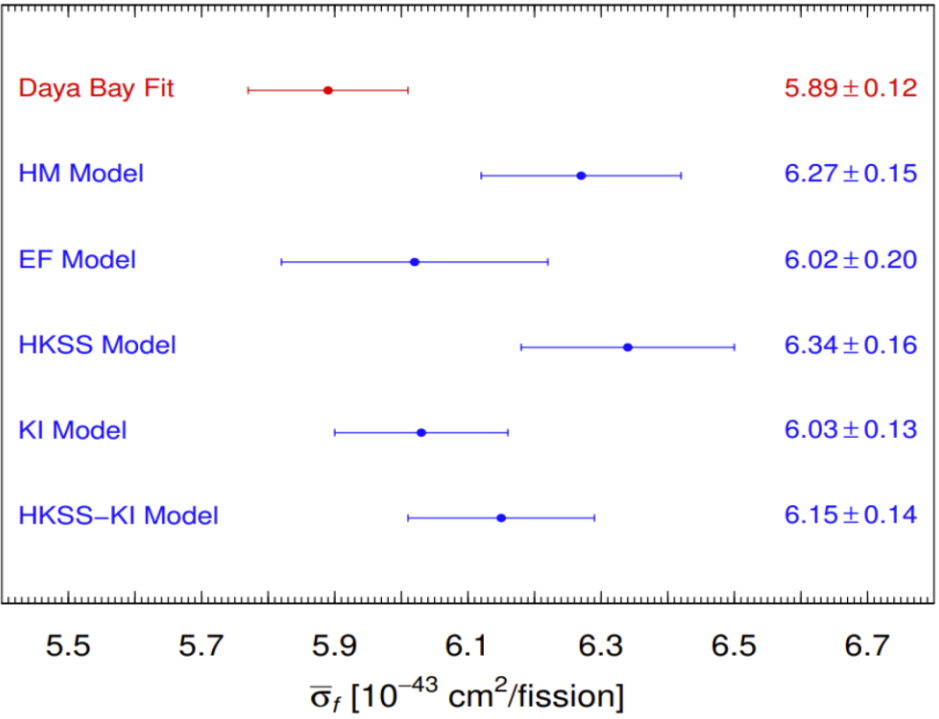
Nature v 613, 257–261 (2023)

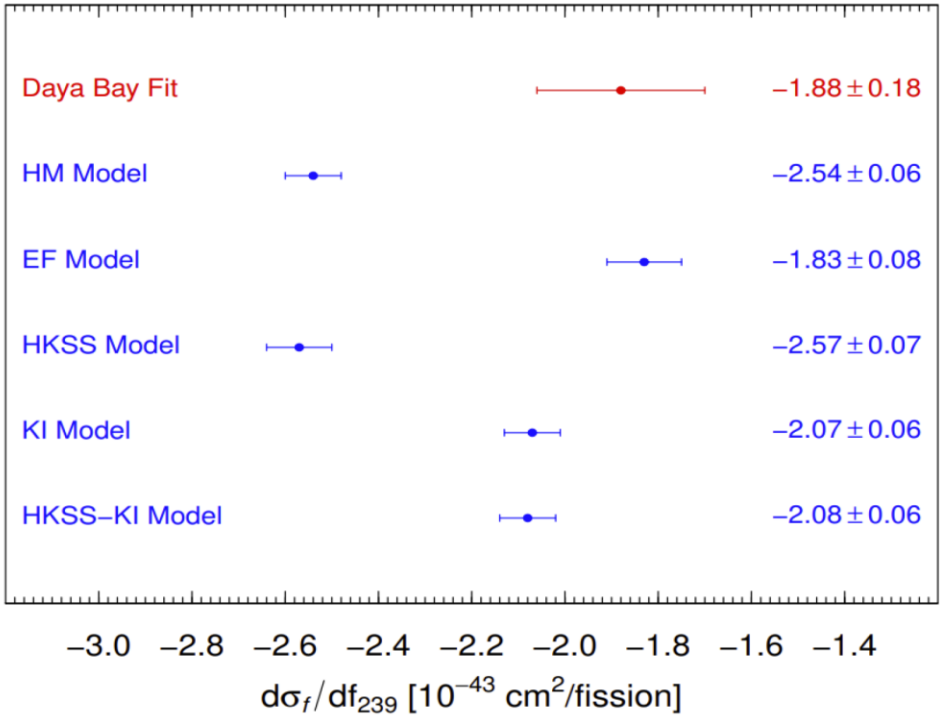






Data comparison with models Giunti et al, arXiv:2110.96820



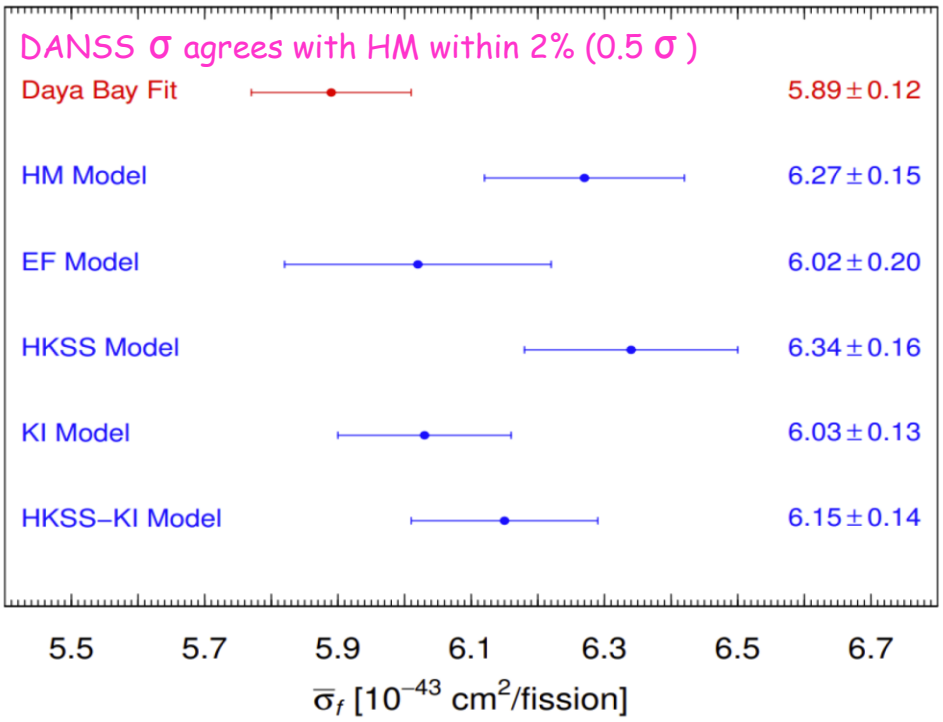


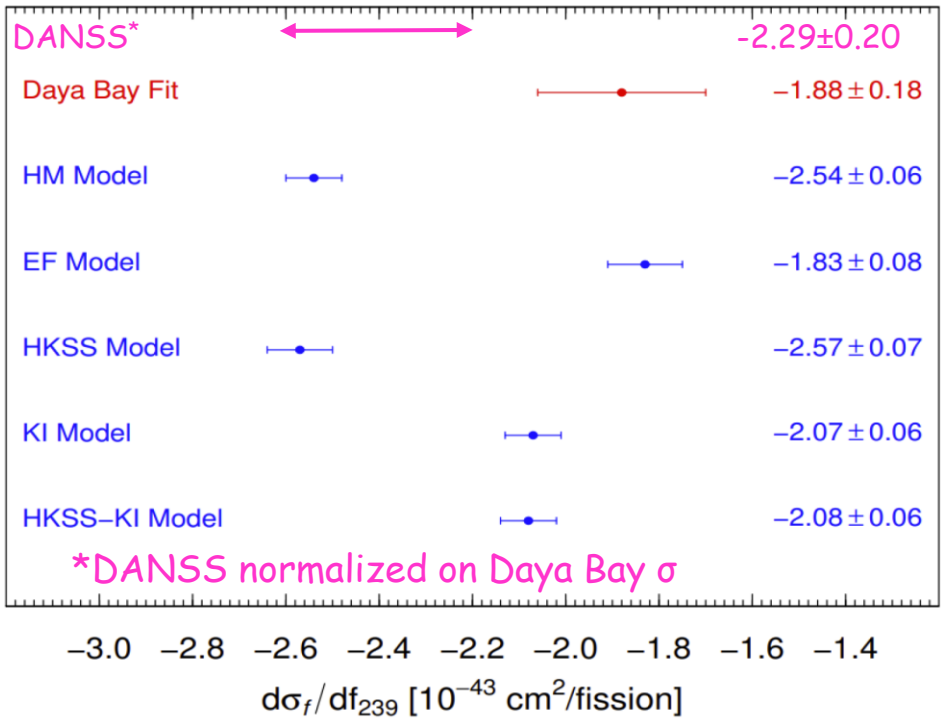
Daya Bay and RENO results agree with EF and KI models

Tension with HM (2.6σ) and HKSS (2.8σ) models

RAA understood? Probably YES! However errors are still large

Data comparison with models Giunti et al, arXiv:2110.96820





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And recent DANSS results are consistent with HM model

Skrobova LaThuile_23

Model independent searches for ν_s at reactors

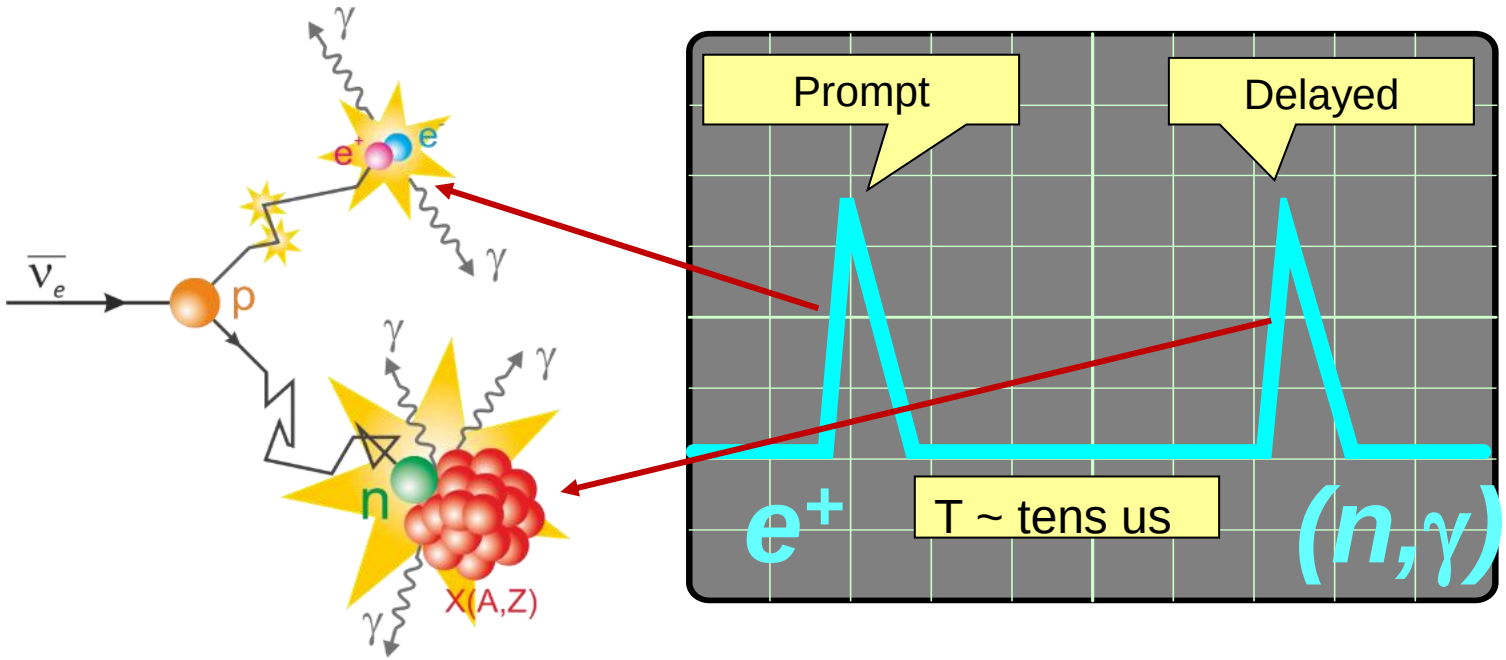
Reactor models do not describe well antineutrino spectrum

➔ Compare ν spectra at different L – model independent

Antineutrino detection at reactors with Inverse Beta Decay (IBD)

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

$E_e \approx E_\nu$ – 1806 MeV



DANSS

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

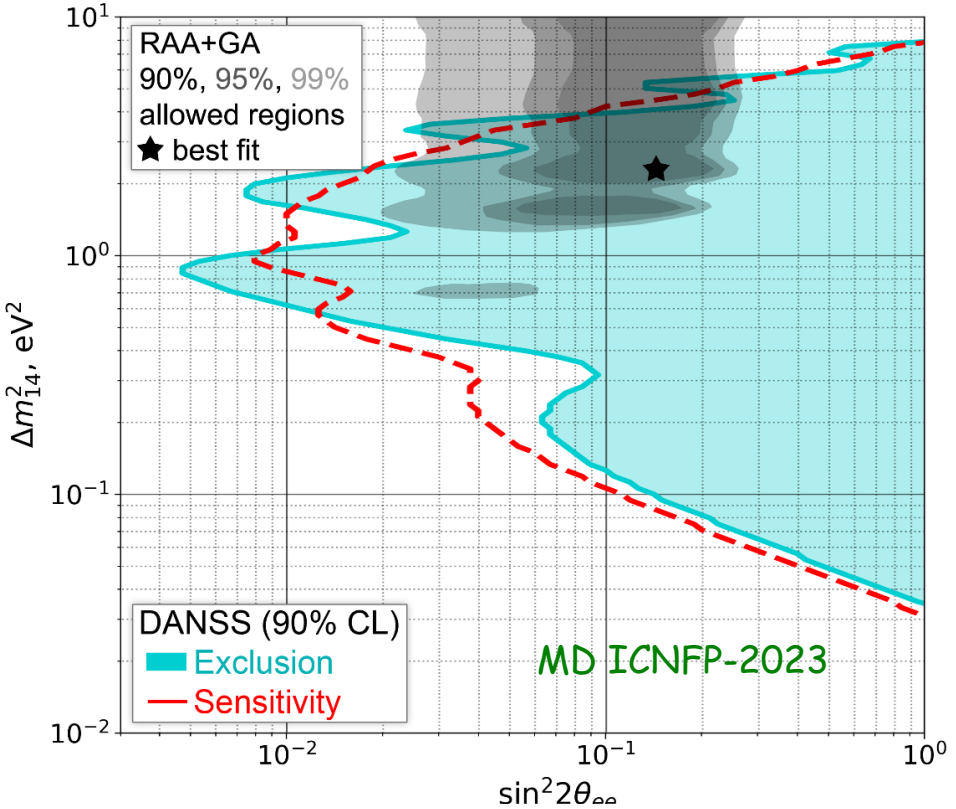
L: 10.9-12.9m Changed 2-3 times a week

50 mwe overburden, S/B>50

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

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

7.7M IBD-events in 6.5 years



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

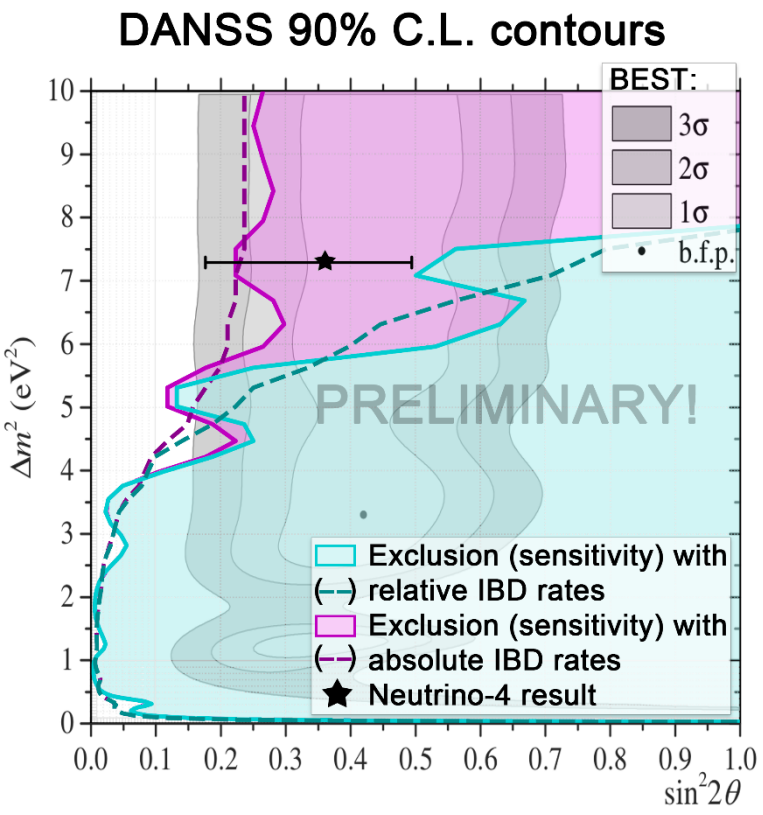
The most stringent limit reaches $\sin^2 2\theta < 5 \times 10^{-3}$ level.

A very interesting part of 4ν parameters is excluded.

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

Best 4ν fit point is not statistically significant (<2.1σ)

Results with neutrino absolute counting rates



Practically all parameters preferred by BEST are excluded

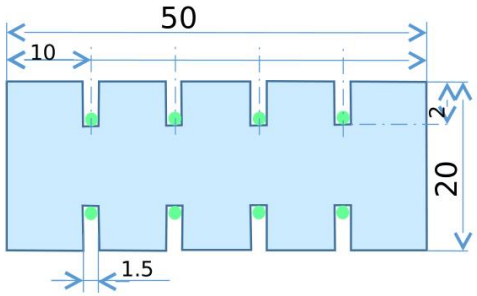
Similar to Daya Bay-Bugey3 results

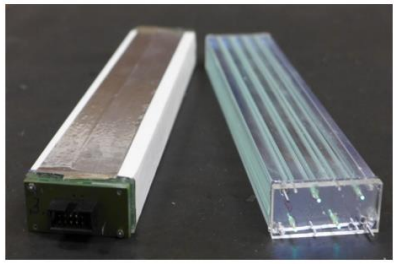
Exclusions depend on assumed uncertainty in reactor ν flux (5%)

DANSS upgrade

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

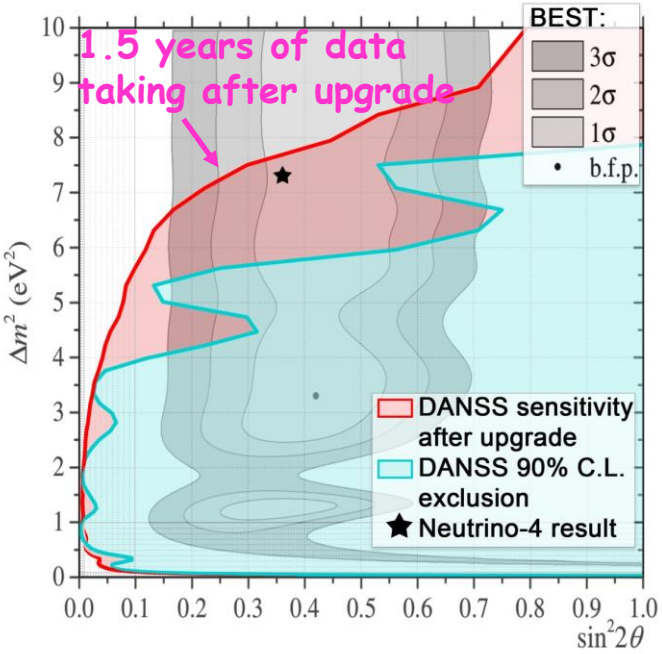
JINST 17 (2022) P01031





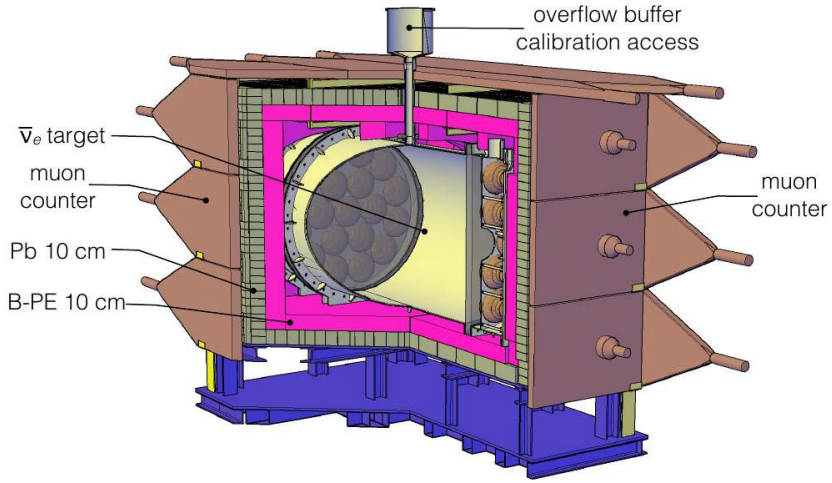
Expected energy resolution 12%/√E

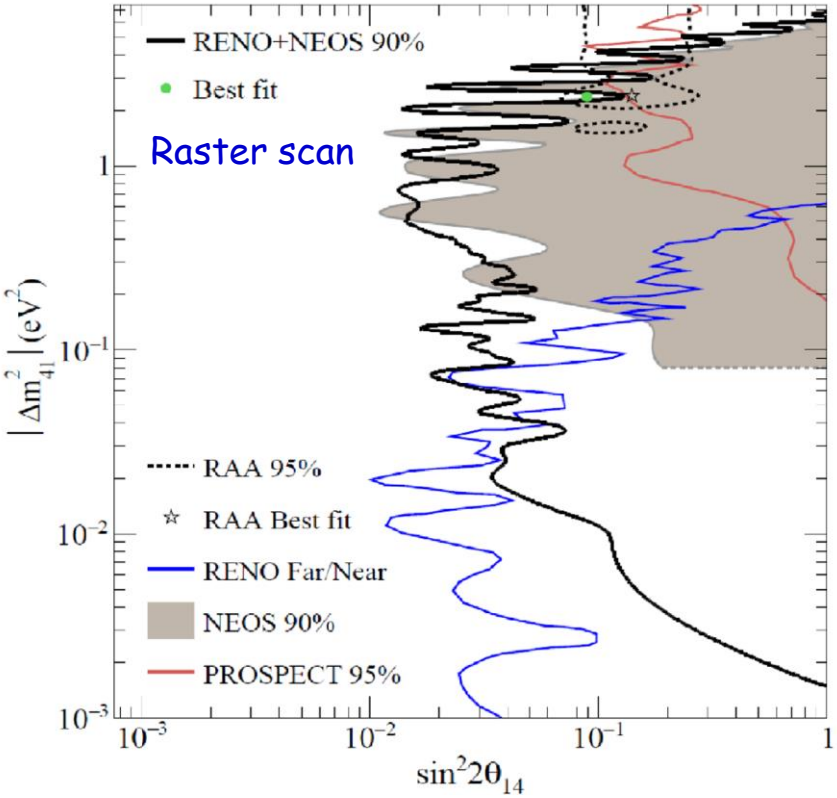
1.7 times larger detector volume



NEOS

arXiv:2011.00896





1m^3 LS. No segmentation

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

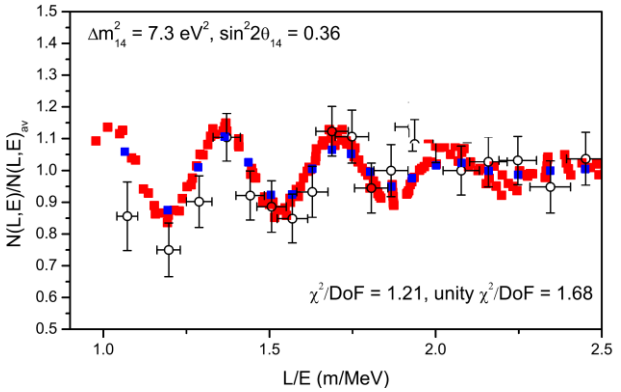
Only one L=24m
Compared with Daya Bay or RENO

Strong limits on sterile neutrino parameters
Best point (ΔM^2=2.37 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 expected in 2023
Seon-Hee Seo, Priv.Comm.

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)



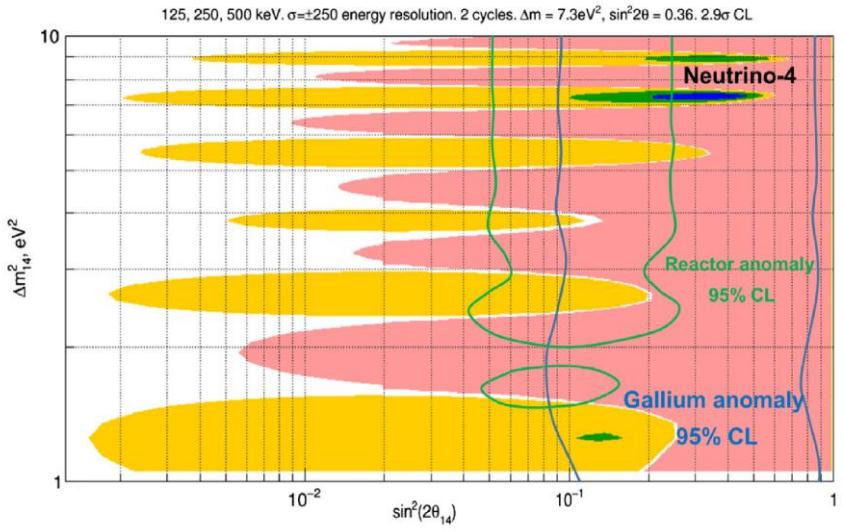
SM-3 85MW ^{235}U Reactor
(42x42x35cm^3)
(Dimitrovgrad, Russia)

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



Comparison with other experiments

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.
Neurino-4 addressed several concerns
This resulted in reduction of significance to 2.7σ

Neutrino-4 and BEST results agree nicely

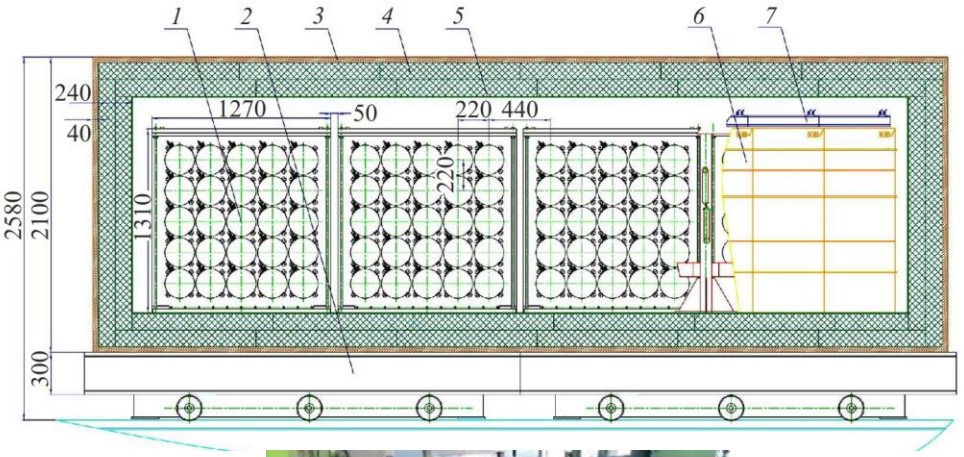
Serious tension of Neutrino-4 result with
- Predictios for absolute reactor ν flux compared with experimental results
- Solar neutrino data
- PROSPECT and STEREO experiments
  See e.g. Giunti et al arXiv:2101.06785

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



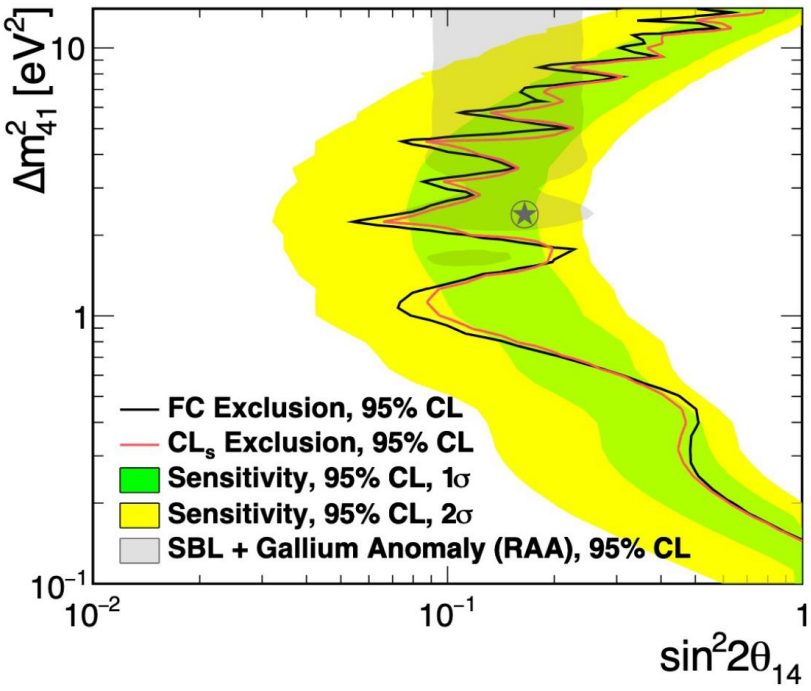
- New 5.4m^3 LS(0.2% Gd) detector in a new hall
- 100 sections with 2 PMT readout
- PSD
- L=6-15m

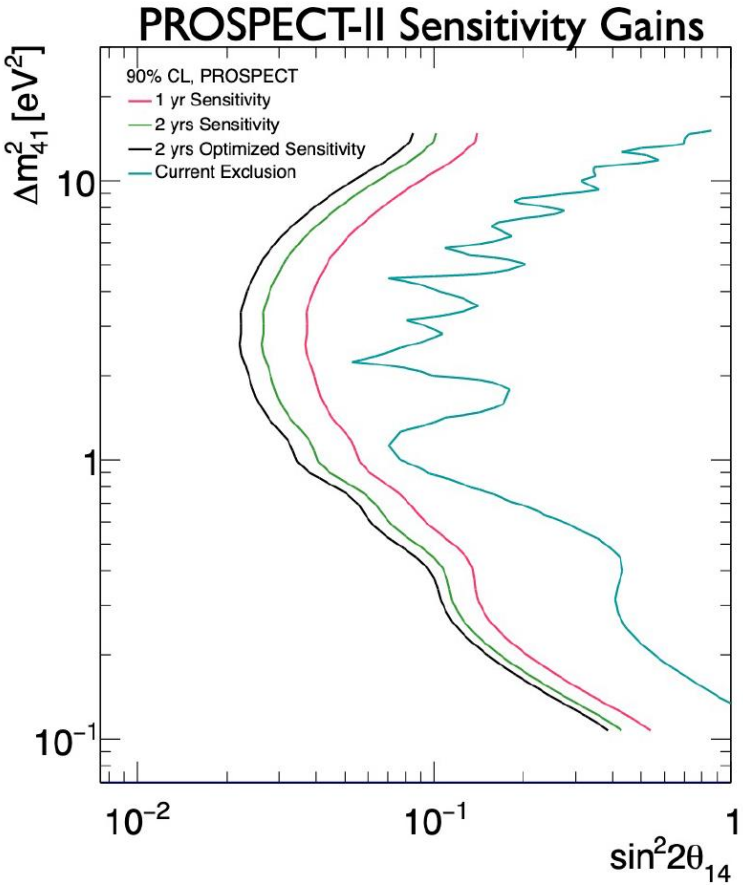
Sensitivity 2.7 times better than at Neutrino-4
Start of data taking in 2024!
Old setup will be upgraded in 2023 PSD

PROSPECT results and prospects

~50 K IBD

arXiv:2006.11210





4 ton LS (^{6}Li)

154 segments (42% do not work)

σ_E/E=4.5% at 1 MeV

PSD

S/B=1.36

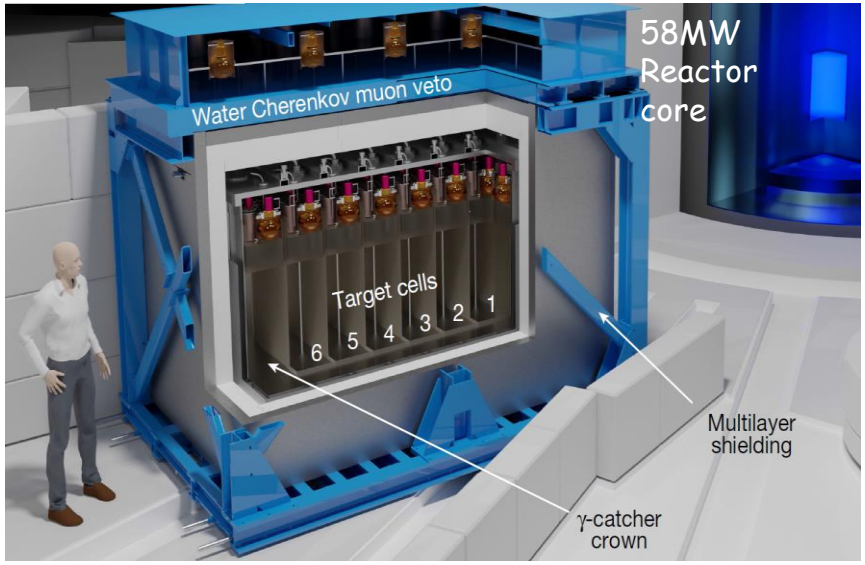
L= 6.7-9.2m

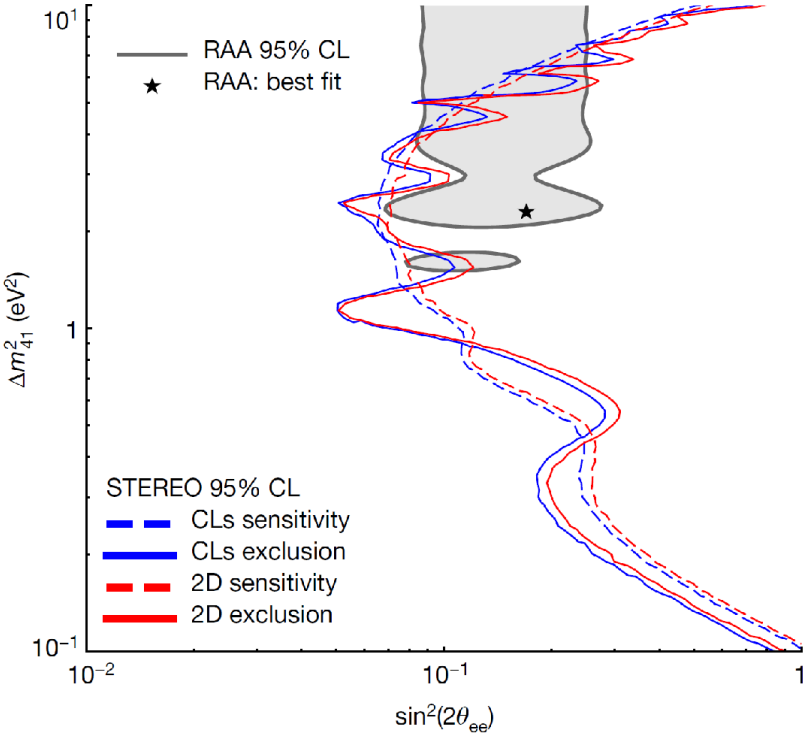
HFIR 85 MW

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

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

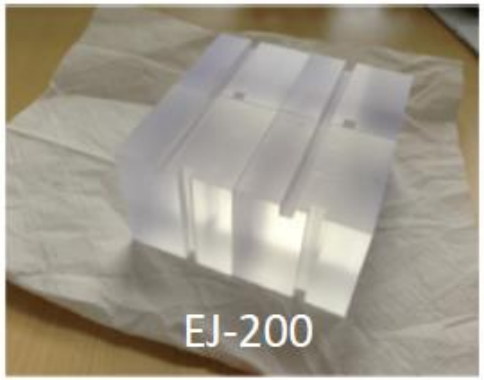
ILL 58MW Reactor

Data consistent with no oscillations, p=0.52

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

SoLid (No results so far because of background)

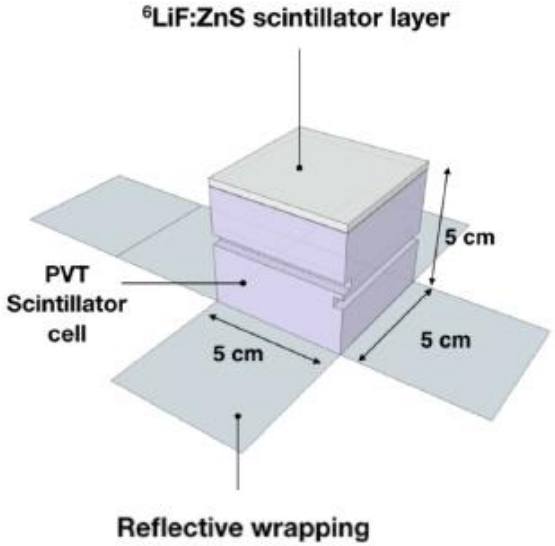


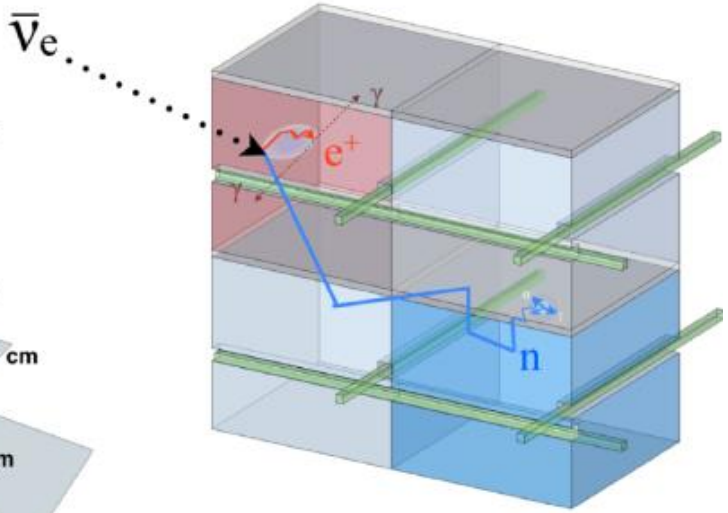
$5 \times 5 \times 5$ cm^3 PVT cubes (12800)

- Non-flammable scintillator

Cubes are optically separated using Tyvek wraps

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

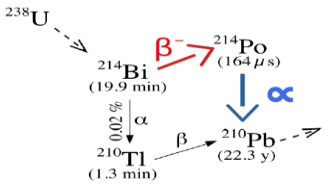


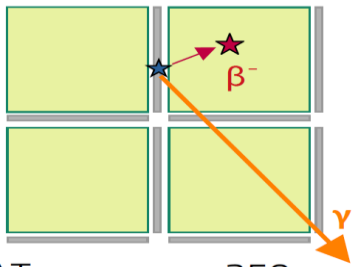


For more information :
JINST **12** (2017) P04024

BiPo background

Internal radioactivity from ZnS layers contamination
External Radon decay.

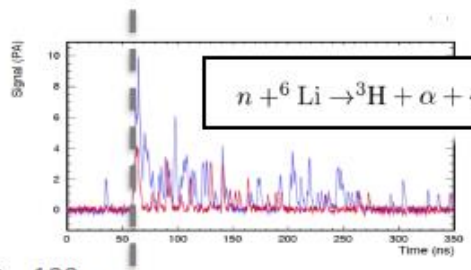




★ Prompt: β^- ($+\gamma$)

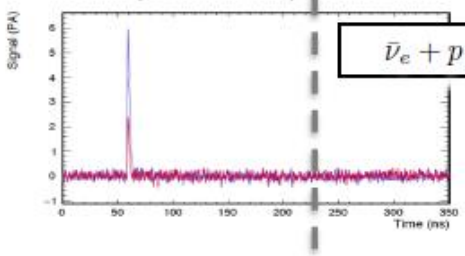
★ Delayed: α

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



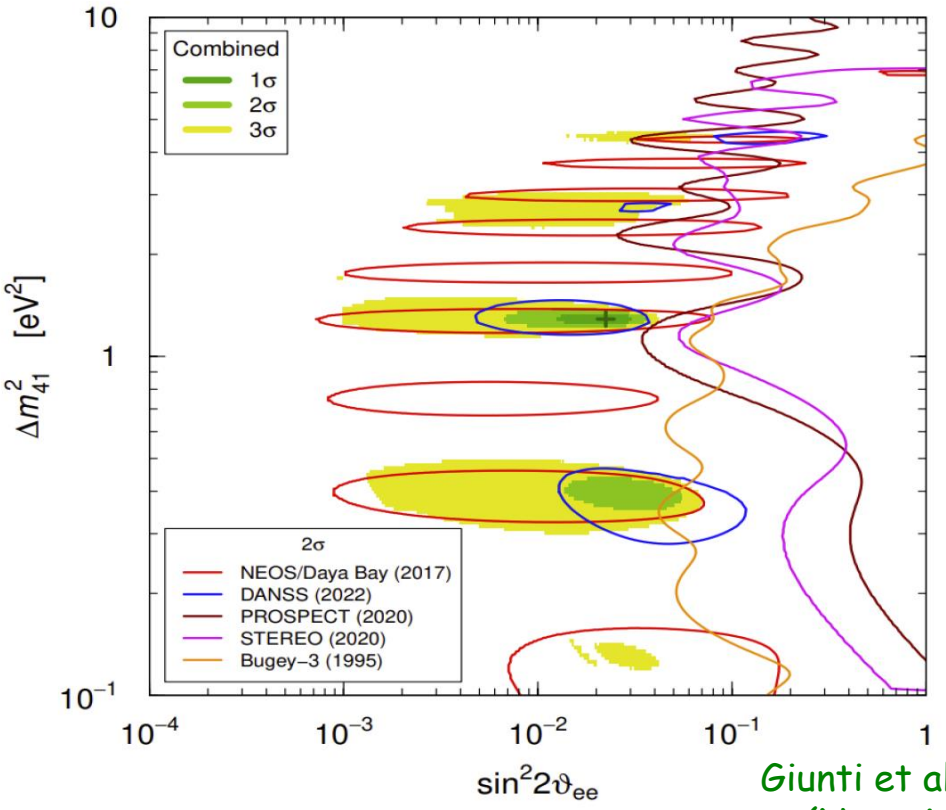
Delayed signal

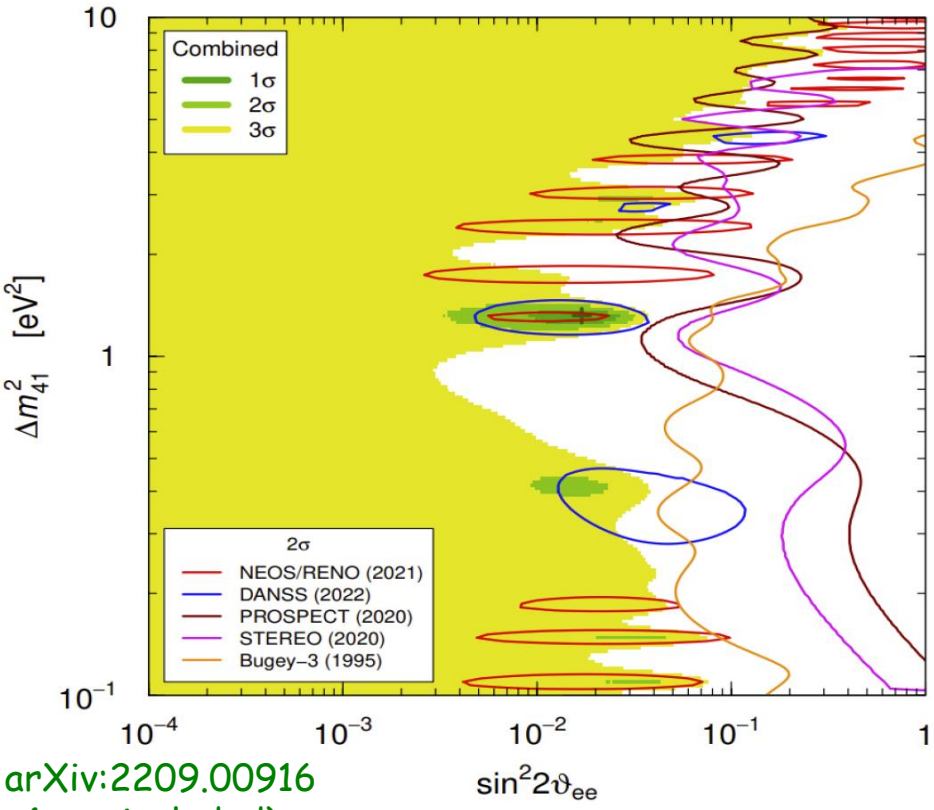
$\tau \sim 10 - 100$ µs



Prompt signal

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 σ
Weak indication of Sterile neutrino
But fit assumes validity of Wilks theorem ➔ overestimation of significance

New experiments are needed to clarify the situation.
Upgraded DANSS, Neutrino-4, and PROSPECT will give answer in few years

Conclusions

- LSND and MiniBooNE anomalies are disfavored by MicroBooNE
- ν_s explanation of LEE is still possible but contradicts disapp. experiments
- SBNP and JSNS^2 will clarify the situation

-GA is in serious tension with many experiments but agrees with Neutrino-4
-Many ideas of possible conventional or BSM explanation but not convincing
- ν_s explanation of GA is still marginally possible
- BEST with ^{65}Zn source – smoking gun test for many explanations

- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~3σ
- Neutrino-4 claim of ν_s observation is in tension with many results but not excluded
- Upgraded VSBL reactor experiments will clarify the situation.

Experimental evidence for ν_s is fading away