Rencontres de Moriond
Electroweak Interactions
La Thuile, March 25-31, 2024

Search for sterile neutrinos
(Mini-review)

Mikhail Danilov

There are several experimental 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: Signif. > 6σ
   Not confirmed by MicroBoone arXiv:2110.14054v2 but not excluded
2. SAGE and GALEX ν_e deficit (GA) confirmed by BEST: Signif. > 5σ
   arXiv: 2109.11482, arXiv: 2201.07364 , PRL 128.232501
3. Reactor $\bar{\nu}_e$ deficit (RAA): Signif. ~ 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,
   Perisse etal(BESTIOLE) arXiv:2304.14992V2
4. Neutrino-4 claim of sterile neutrino observation
   $\Delta m^2 = 7.3 \pm 1.17\ eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ Signif.=2.7σ
   Phys.Rev.D 104, 032003 (2021)

These are statistically strongest laboratory indications of physics BSM!

3+1 ν model is usually used in analysis with extended 4x4 PMNS matrix U_{ij}

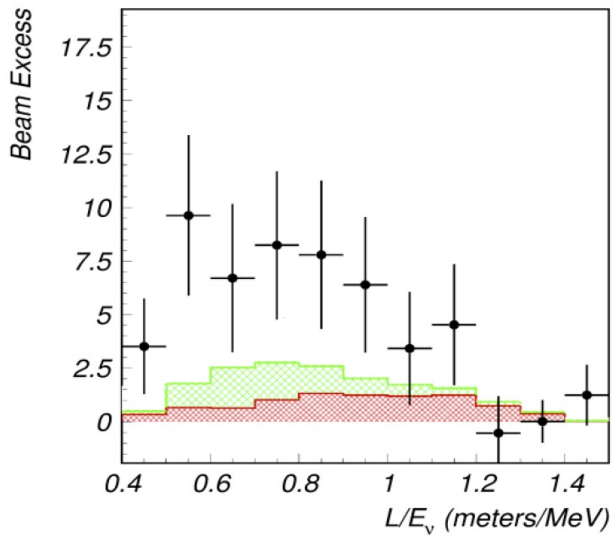
$P_{ee} \approx 1 - \sin^2 2\theta_{ee} \sin^2(\Delta m^2_{14} L/4E)$ with $\sin^2 2\theta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2)$

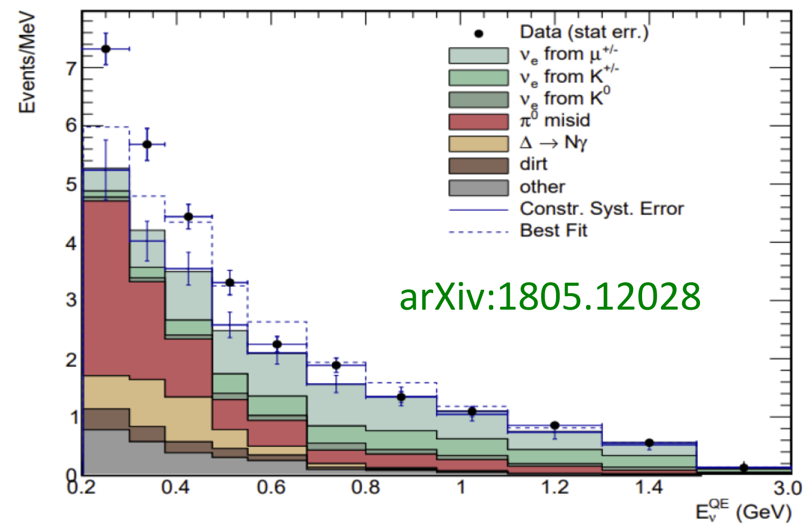
$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2(\Delta m^2_{14} L/4E)$ with $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$

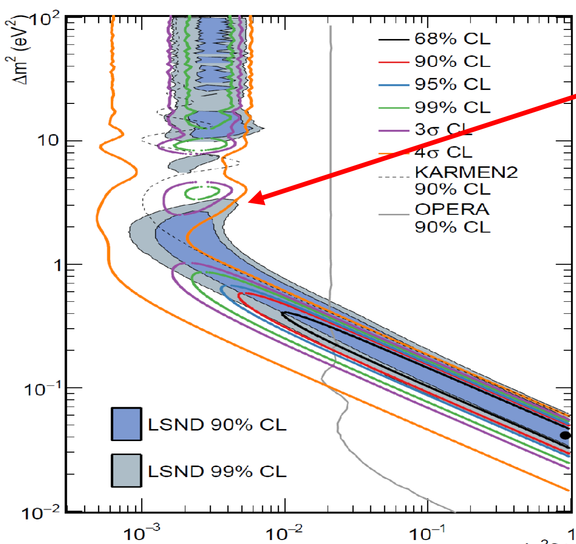
$P_{\mu e} \approx \sin^2 2\theta_{\mu e} \sin^2(\Delta m^2_{14} L/4E) \sim 4|U_{e4}|^2 |U_{\mu 4}|^2 \approx \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}/4$

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







arXiv:1805.12028

Can be explained by sterile neutrinos with wide range of parameters

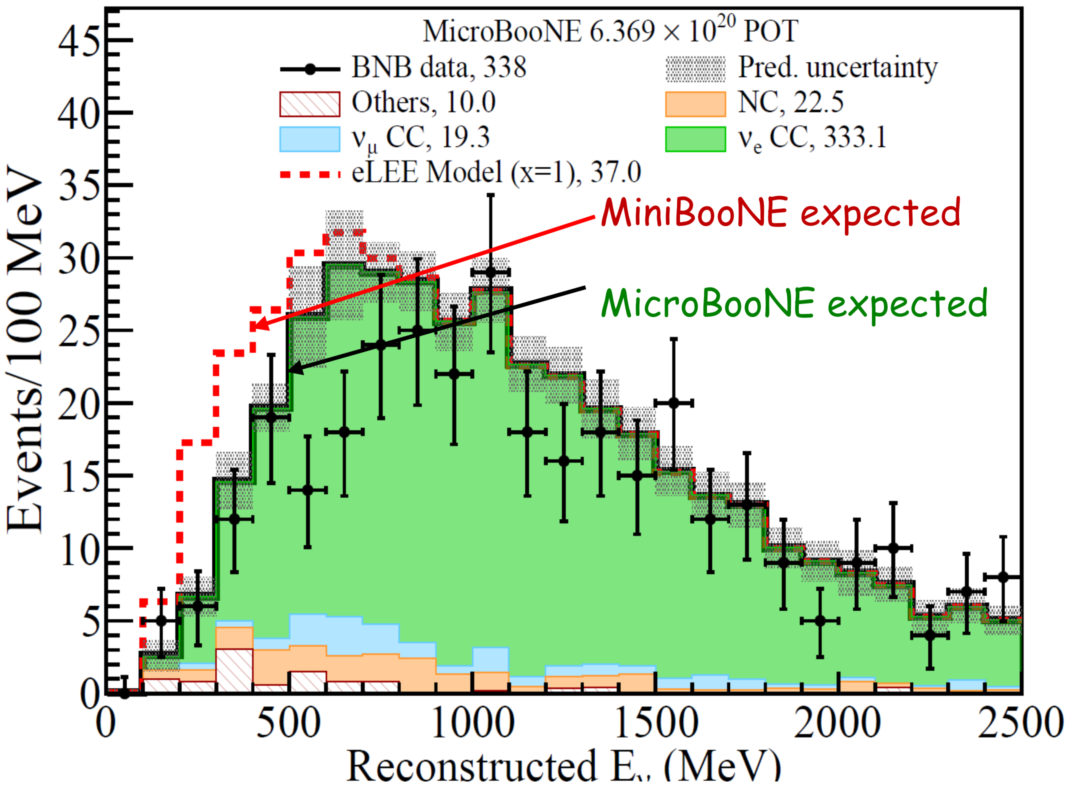
ν_e appearance requires ν_μ and ν_e disappearance

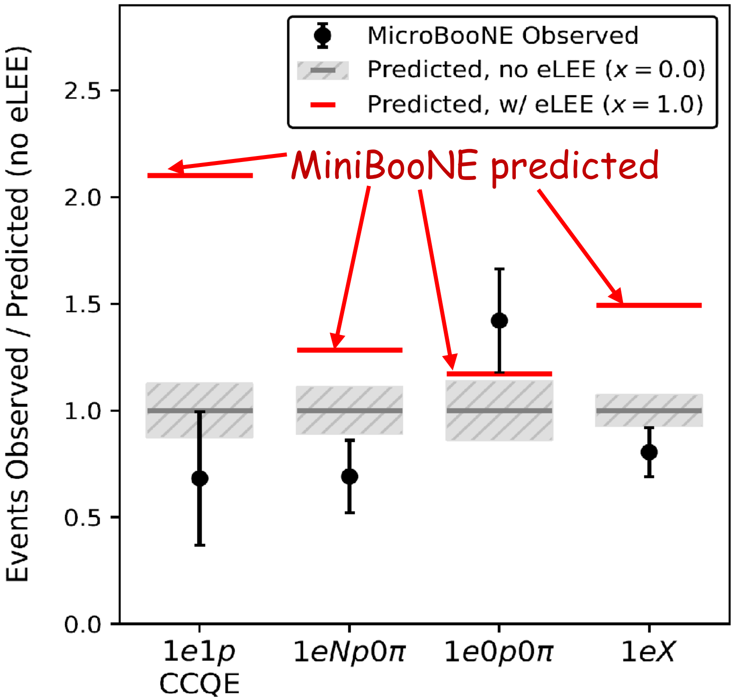
$P_{\mu e} \sim \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2\,|U_{\mu 4}|^2 \approx \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}/4$

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



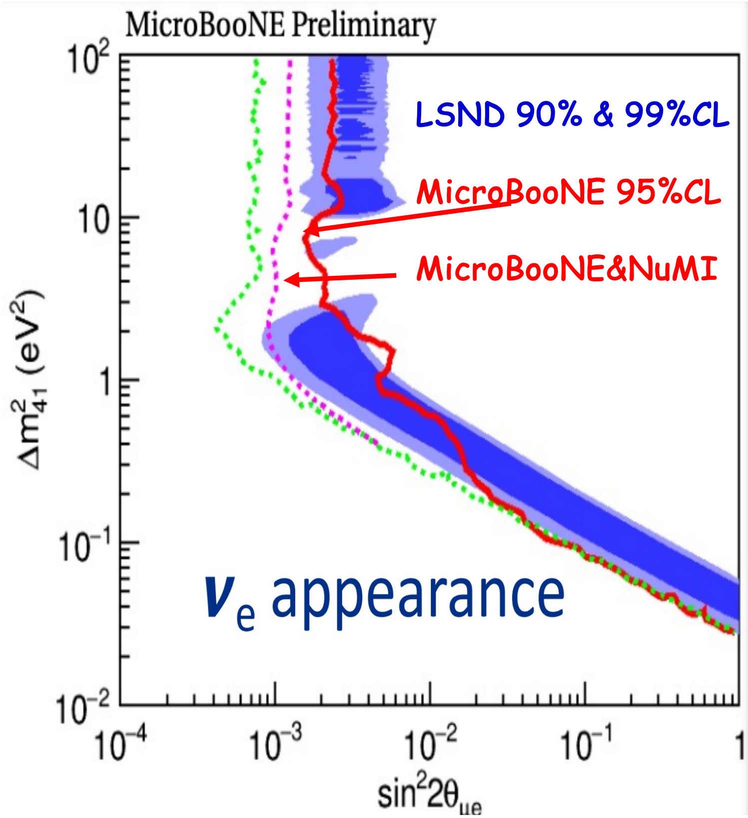


Comparison in different channels

MiniBooNE ν_e LEE central value excluded with >3σ

But not the whole parameter space!

MicroBooNE does not exclude MiniBooNE+LSND results completely



arXiv:2111.10359 and arXiv:2210.10216

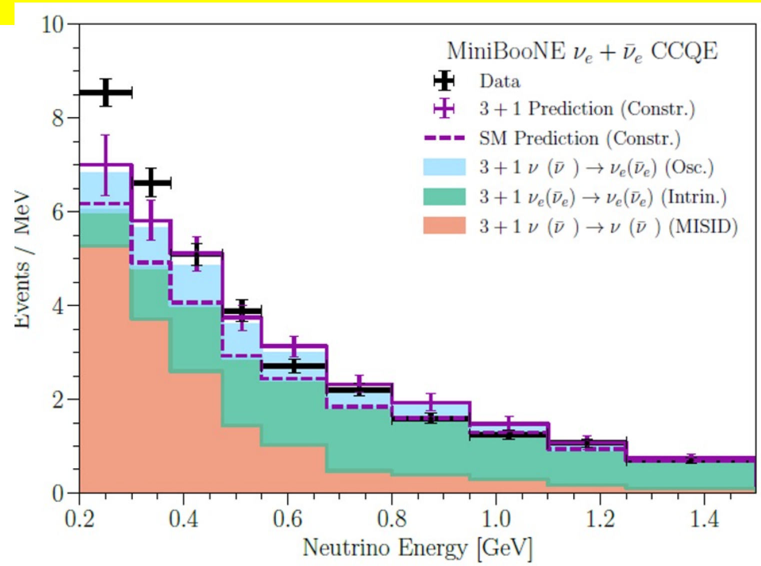
Reduced sensitivity due to cancelation in ν_e appearance and disappearance.

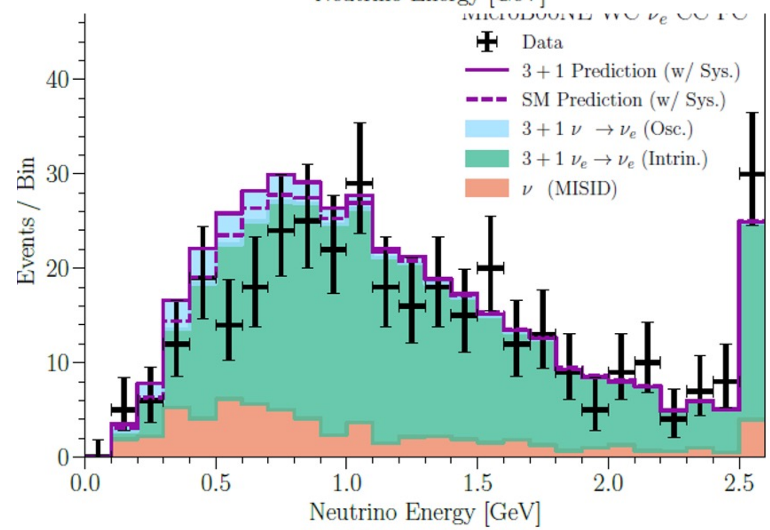
Break cancelation with NuMI beam (4%ν_e) Results soon!

MICROBOONE-NOTE-1116-PUB

Joint MiniBooNE and MicroBooNE analysis (including ν_e and ν_μ disappearance)

arXiv:2201.01724



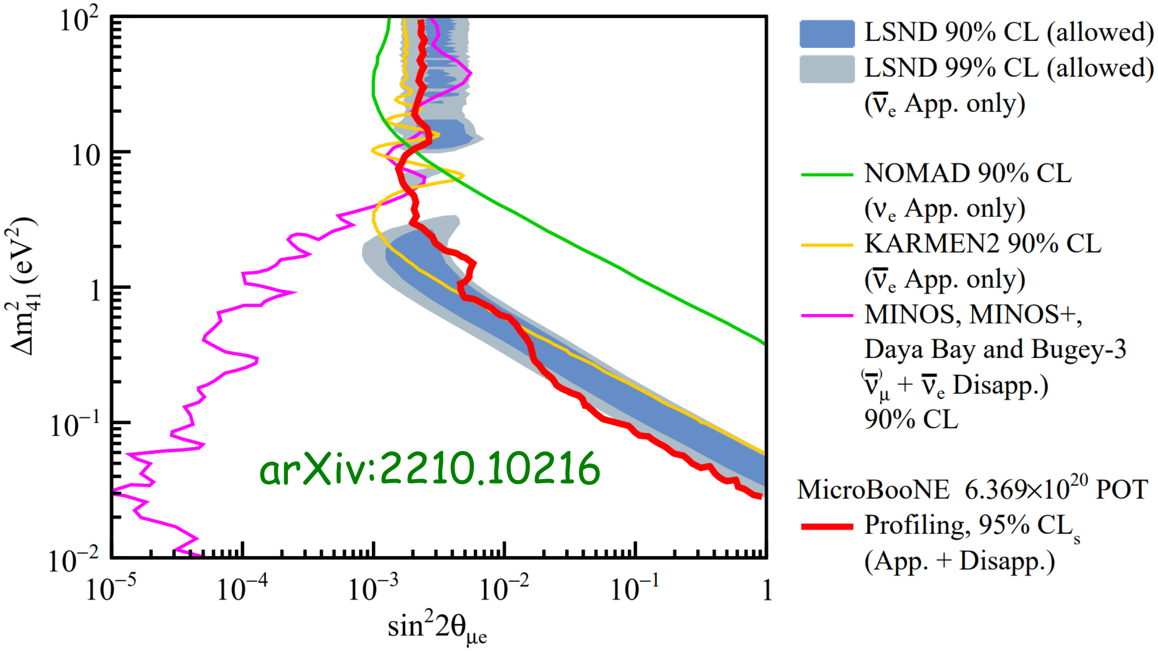


Reduces MiniBooNE significance from 4.6σ to 3.4σ

Fit quality is very poor!

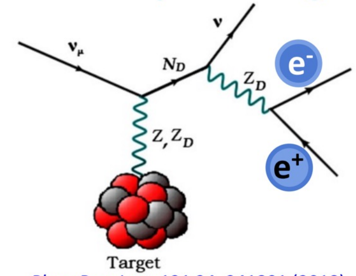
But 3+1 scenario is still preferred

Appearance and Disappearance results are in contradiction



Many BSM explanations

HNL Upscattering



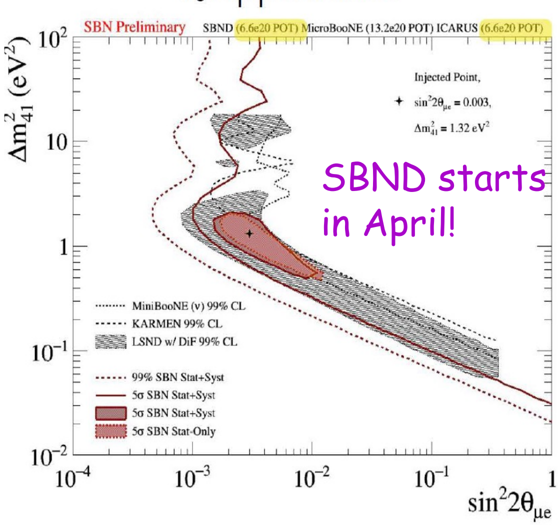
Phys. Rev. Lett. 121 24, 241801 (2018)
Phys. Rev. D 99 071701 (2019)
Phys. Lett. B 820 136531 (2021)

Search for e+e- pairs

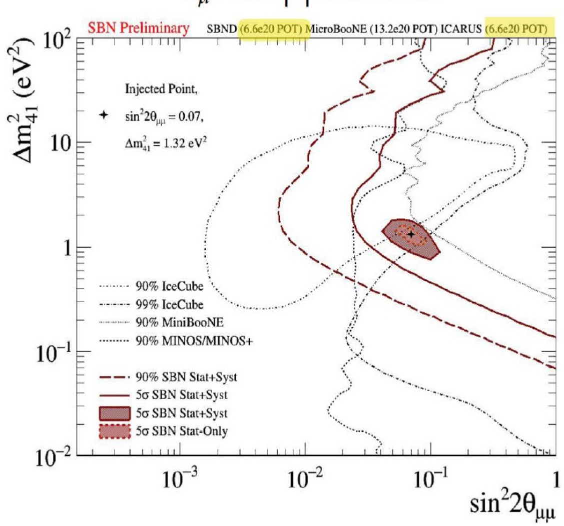
Basque(MicroBooNE) @NuPhys 2023

Short-Baseline Neutrino Program at FNAL and JSNS² will clarify the situation

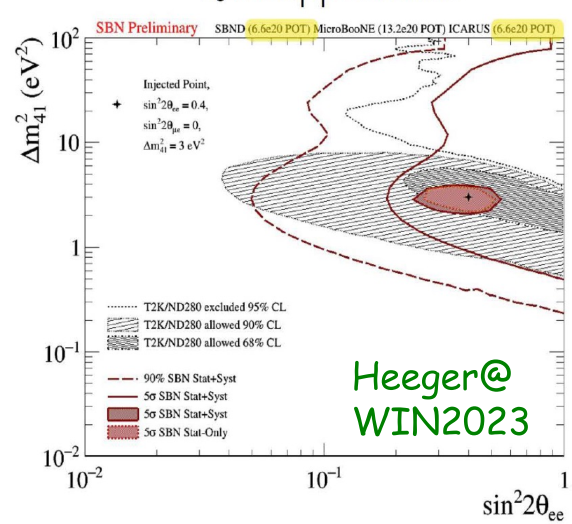
ν_e Appearance



ν_μ Disappearance



ν_e Disappearance

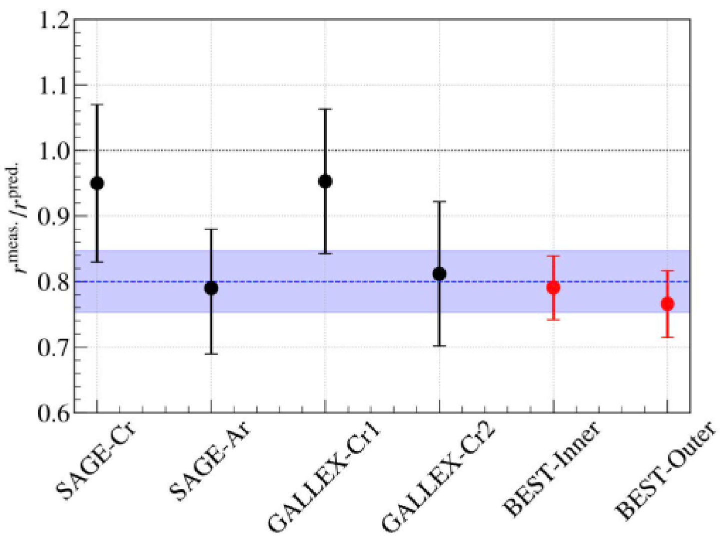


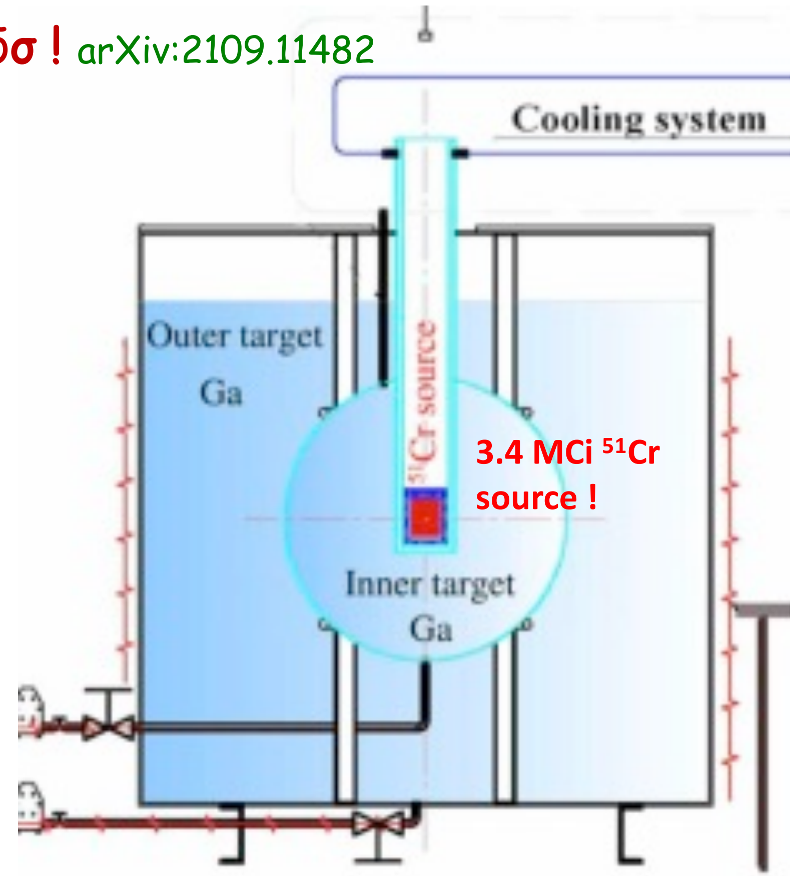
Gallium Anomaly (GA)

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



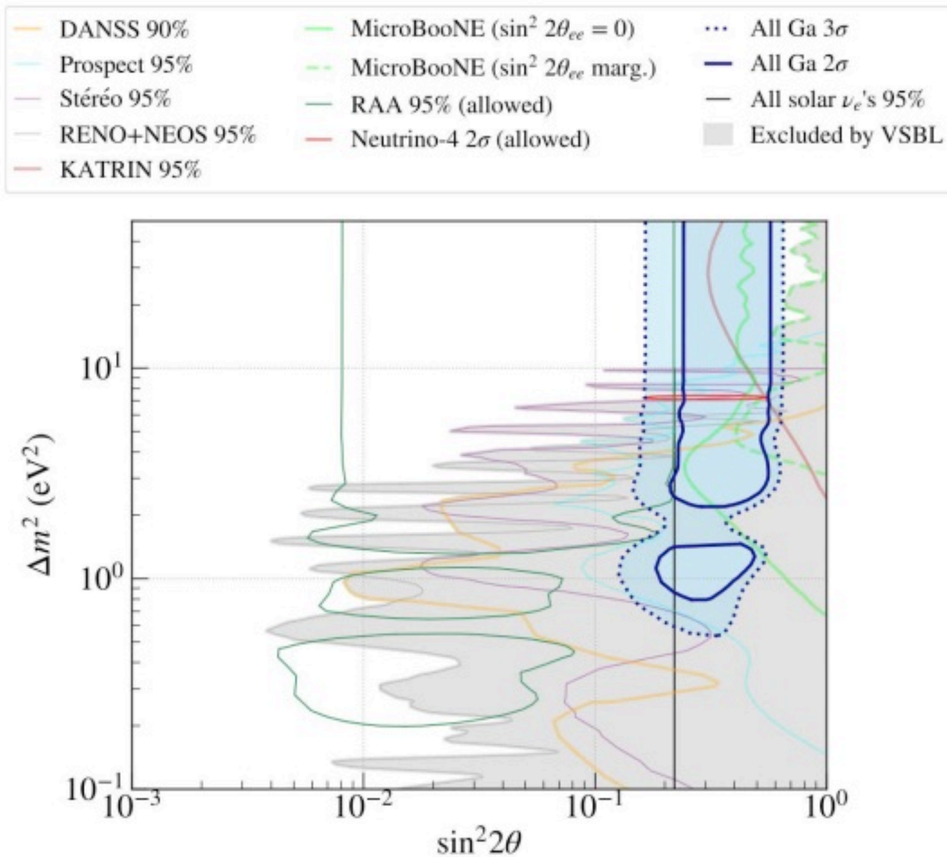


No difference between inner and outer targets Rin = 0.791±0.05 and Rout = 0.766±0.05

➔ 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 : $\sin^2 2\Theta_{ee} = 0.35\pm^{0.19}_{0.16}$ $\Delta m^2_{14}=1.25 \pm^{0.74}_{0.39}\mathrm{eV}^2$

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

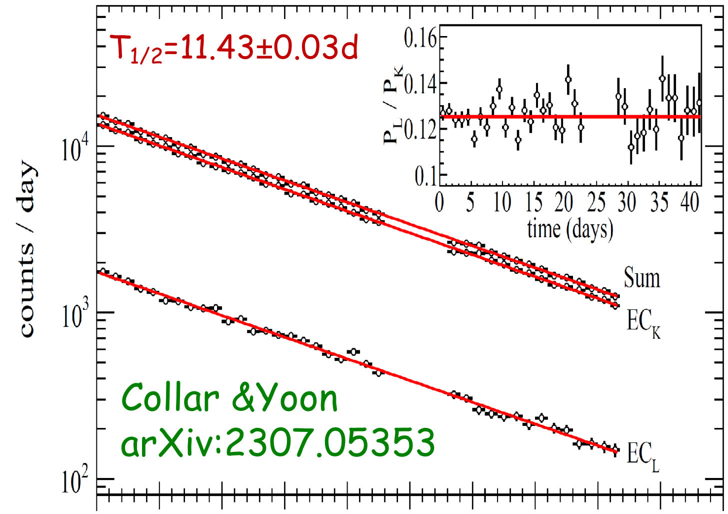
Smaller cross-section for $^{71}Ga(\nu_e, e^-)^{71}Ge$

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

But new measurements of ^{71}Ge half-life exclude this explanation



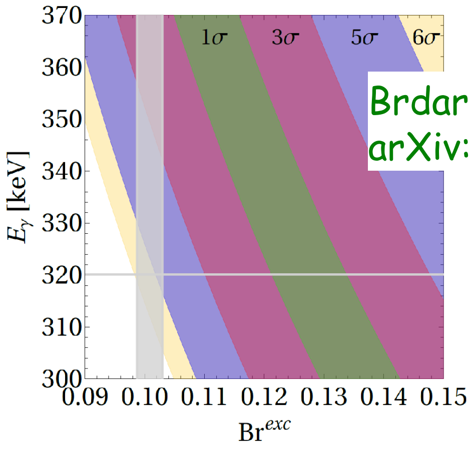
New yet undiscovered exited low-lying state of ^{71}Ga

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)
20% increase of BR($^{51}Cr \rightarrow {}^{51}V^*$) would solve GA
(or additional new exited state)



Wrong efficiency of ^{71}Ge extraction

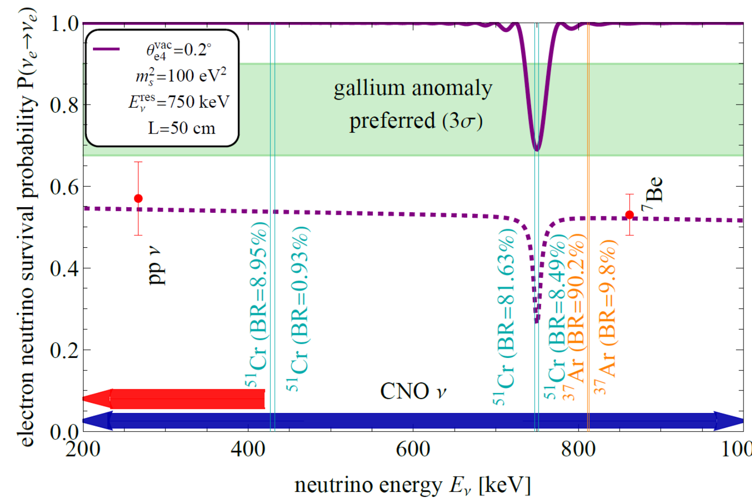
SAGE had one extraction with very high amount of extra Ge. Reason not clear.

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

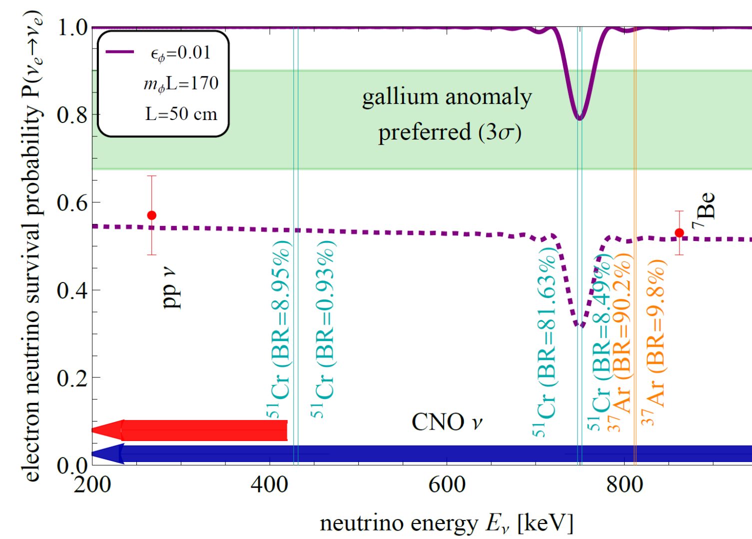


Interaction with Dark Energy

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

Several models with damping of oscillations were proposed

Broad mass ν_4 ➔ lost coherence

Banks et al. arXiv: 2311.06352, 2209.11270

Decaying neutrinos

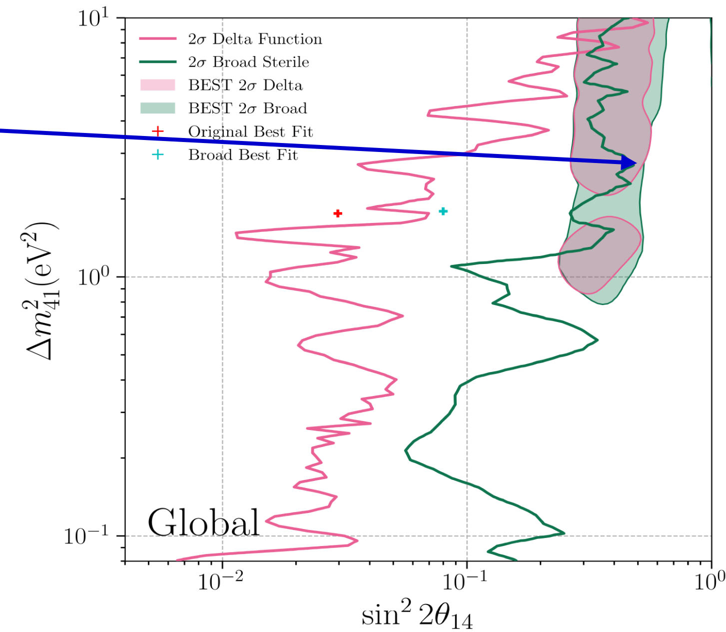
Hardin, et al, 2211.02610, JHEP 2023

Small Wave-packet ~10^{-4}nm ➔ loss of coherence

Argüelles et al arXiv: 2201.05108, PRD 2023

However estimates give much larger size > 10^2 nm

Akhmedov, Smirnov, 2208.03736, JHEP 2022



These models are in tension with reactor rates

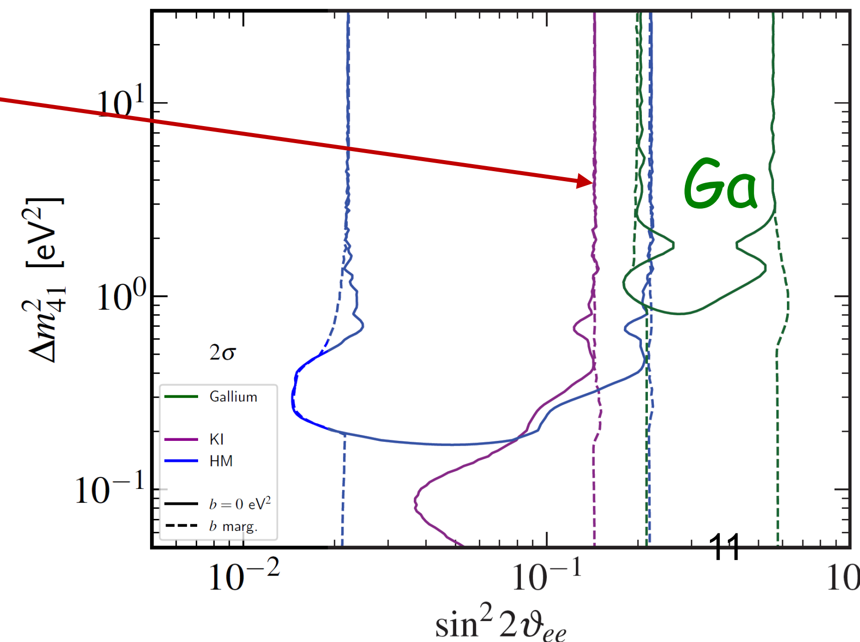
Giunti, Ternes, arXive: 2312.00565

Model with non-standard decoherence

without sterile neutrino

Farzan,Schwetz arXiv:2306.09422v1

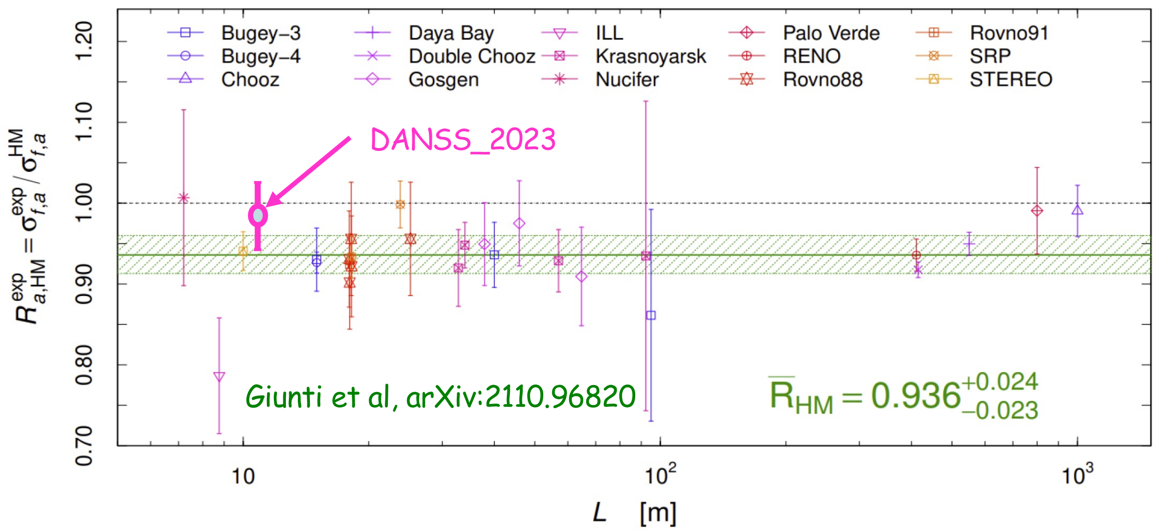
Can explain GA and LSND but not MiniBooNE



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 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:2110.96820ЛШ

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

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

Perisse etal(BESTIOLE) arXiv:2304.14992V2 **No RAA?** (No conclusion in paper)

New measurements indicate smaller contribution from ^{235}U

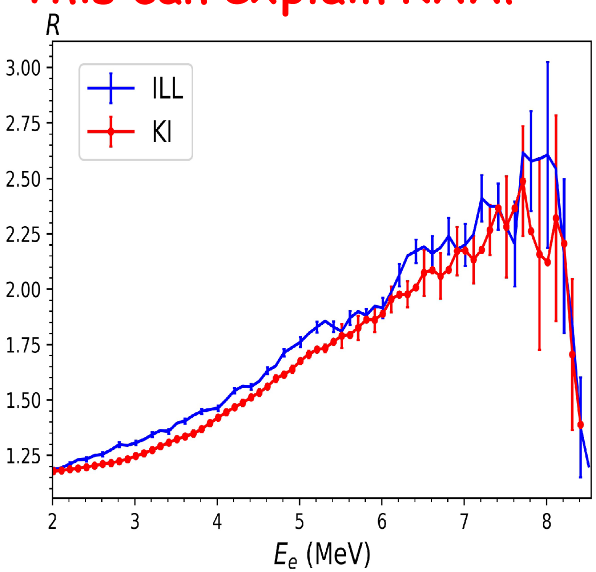
Kurchatov Inst group observed 5.4% smaller ratio of β yields for $^{235}U/^{239}Pu$ arXiv:2103.01684

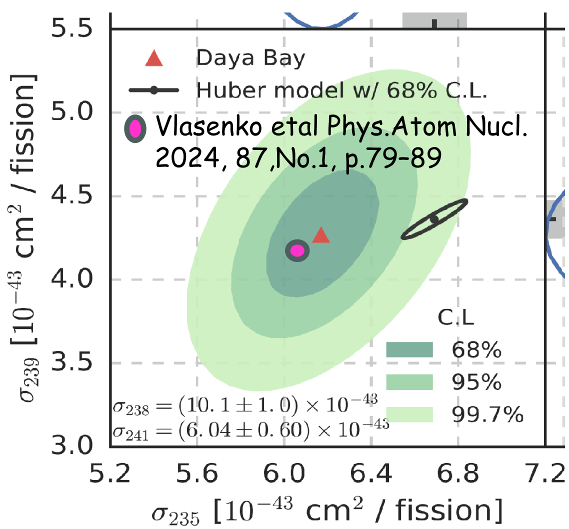
This can explain RAA!

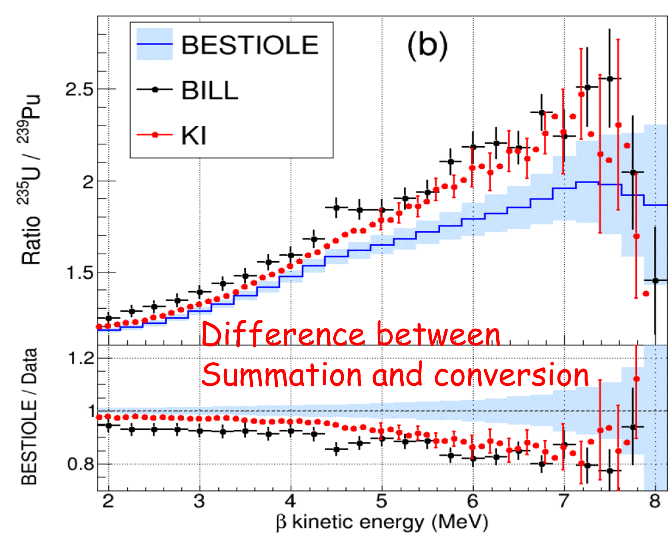
DayaBay, RENO, STEREO observed smaller ^{235}U flux than in HM model which is based on ILL results

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

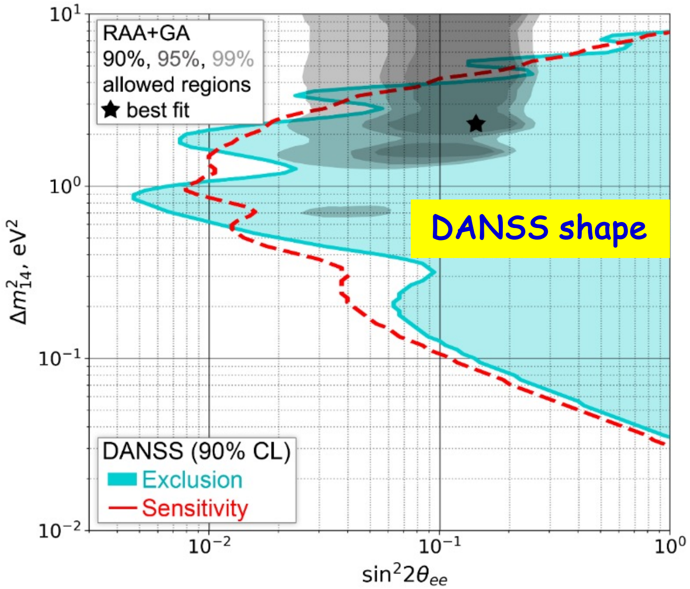
Nature v 613, 257–261 (2023)

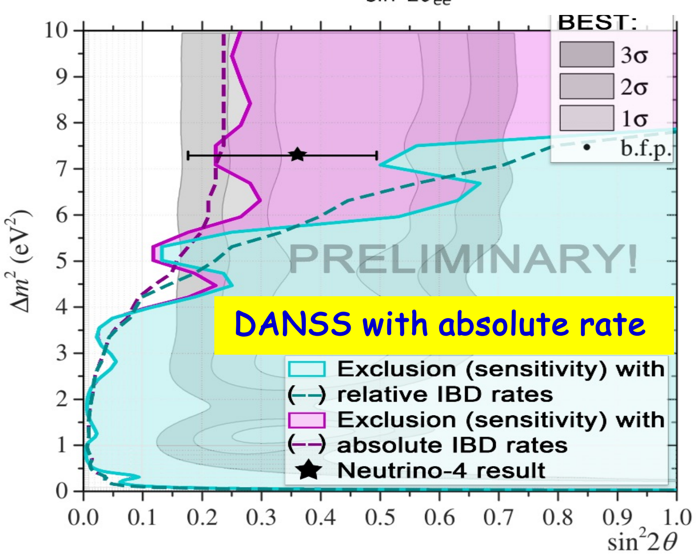


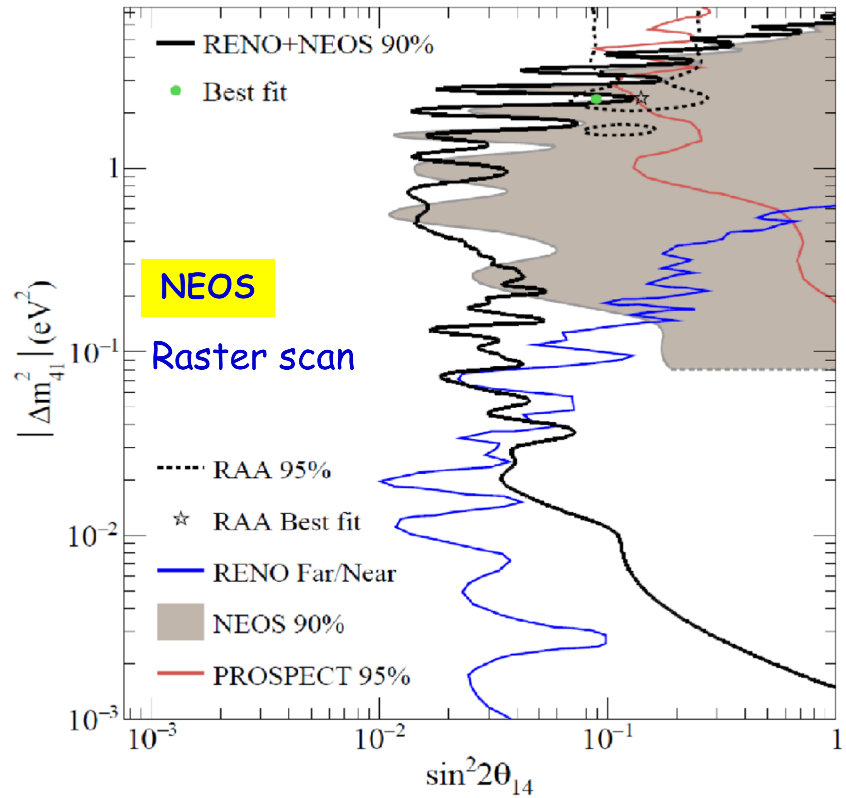




Spectral analysis







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

Practically all parameters preferred by BEST and best fit Neutrino-4 point are excluded

(Bugey-3 –similar conclusions arXiv:2002.00301)

Detector upgrade is planned

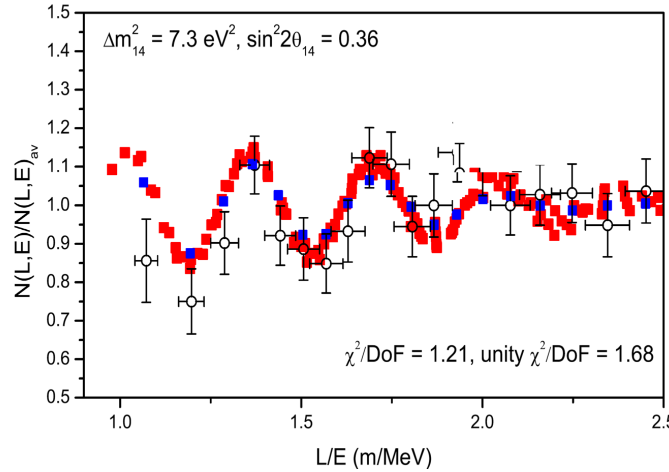
NEOS-II took data 500 days in 2018-2020

Results on ν_s search expected at Neutrino 2024

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)



There were concerns about 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

Neutrino-4 and BEST results agree nicely

Serious tension of Neutrino-4 result with

- Absolute reactor ν flux
- Solar neutrino limits
- 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)

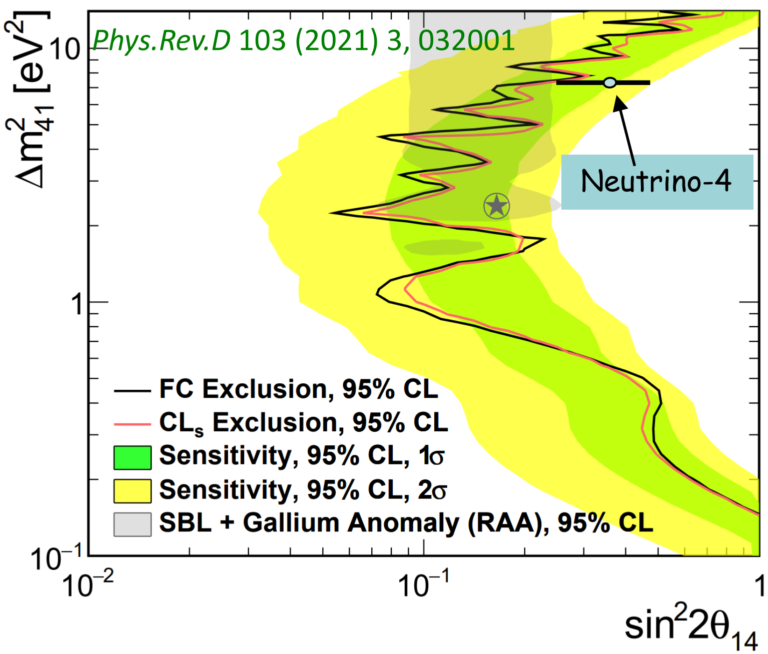
New experiments are needed to confirm or discard Neutrino-4 result

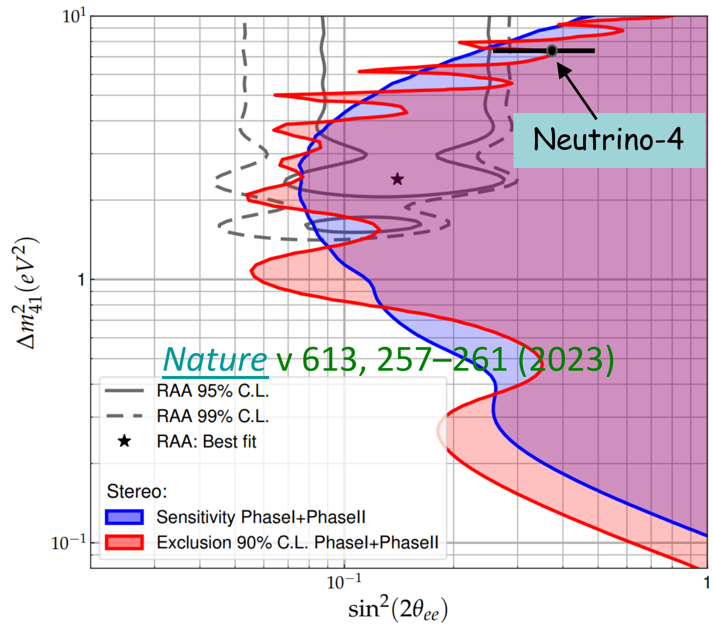
Neutrino-4 upgrade

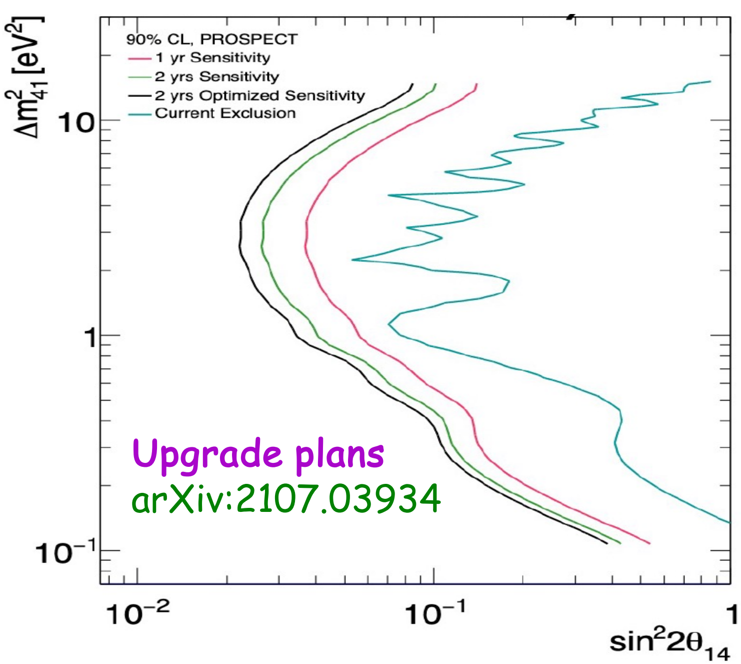
Serebrov et al, Techn. Phys., 2023,V.68,No1, 15

$5.4 m^3$ LS(0.2% Gd) detector in a new hall
100 sections with 2 PMT readout
PSD, L=6-15m
Sensitivity 3 times better than at Neutrino-4
Start of data taking in Autumn 2024
Old setup upgraded with PSD started data taking in January 2024

PROSPECT and STEREO





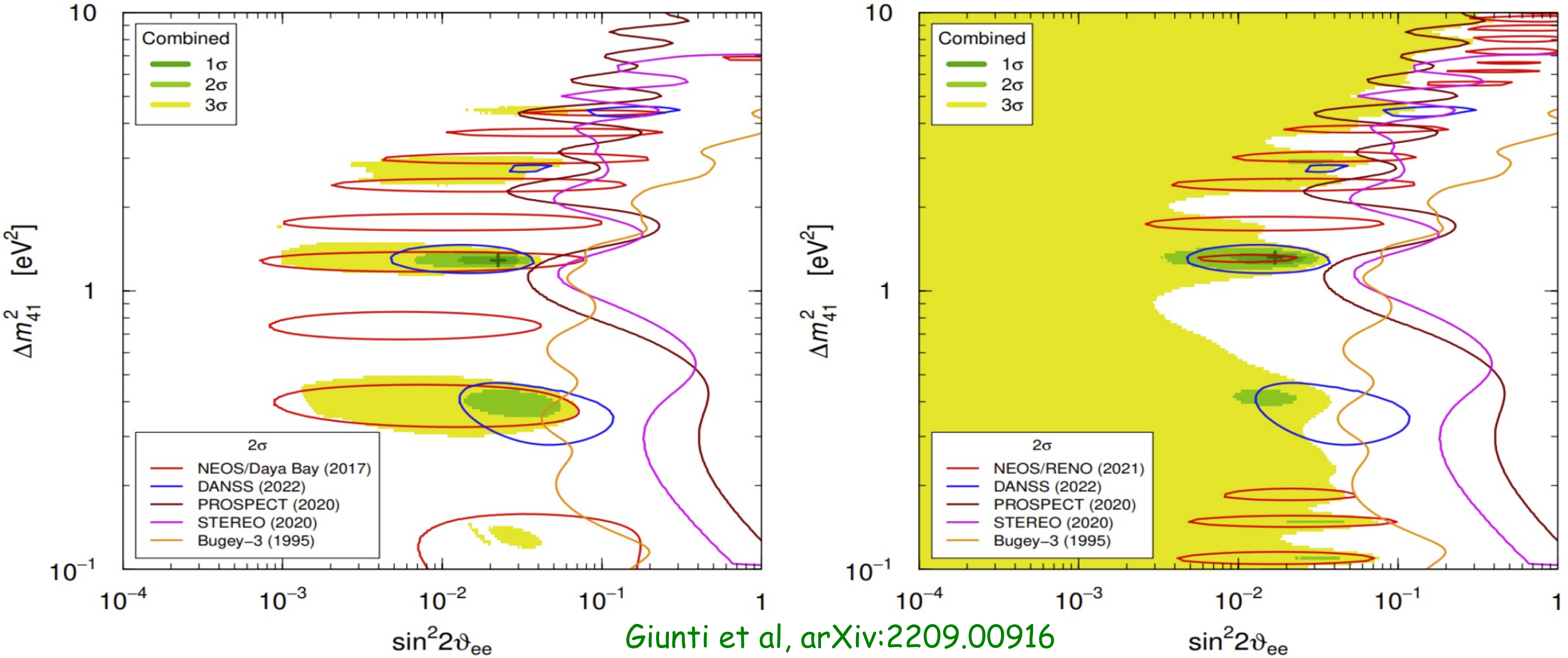


Prospect and STEREO obtained stronger limits at large Δm^2 than DANSS and NEOS

These limits are in tension with Neutrino-4 result but do not exclude it completely

PROSPECT plans to upgrade detector and significantly increase its sensitivity

Combined fit of SBL experiments without Neutrino-4



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
(see Berryman et al arXiv:2111.12530)
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
- MicroBooNE(NuMI), SBNP and $JSNS^2$ will soon clarify the situation

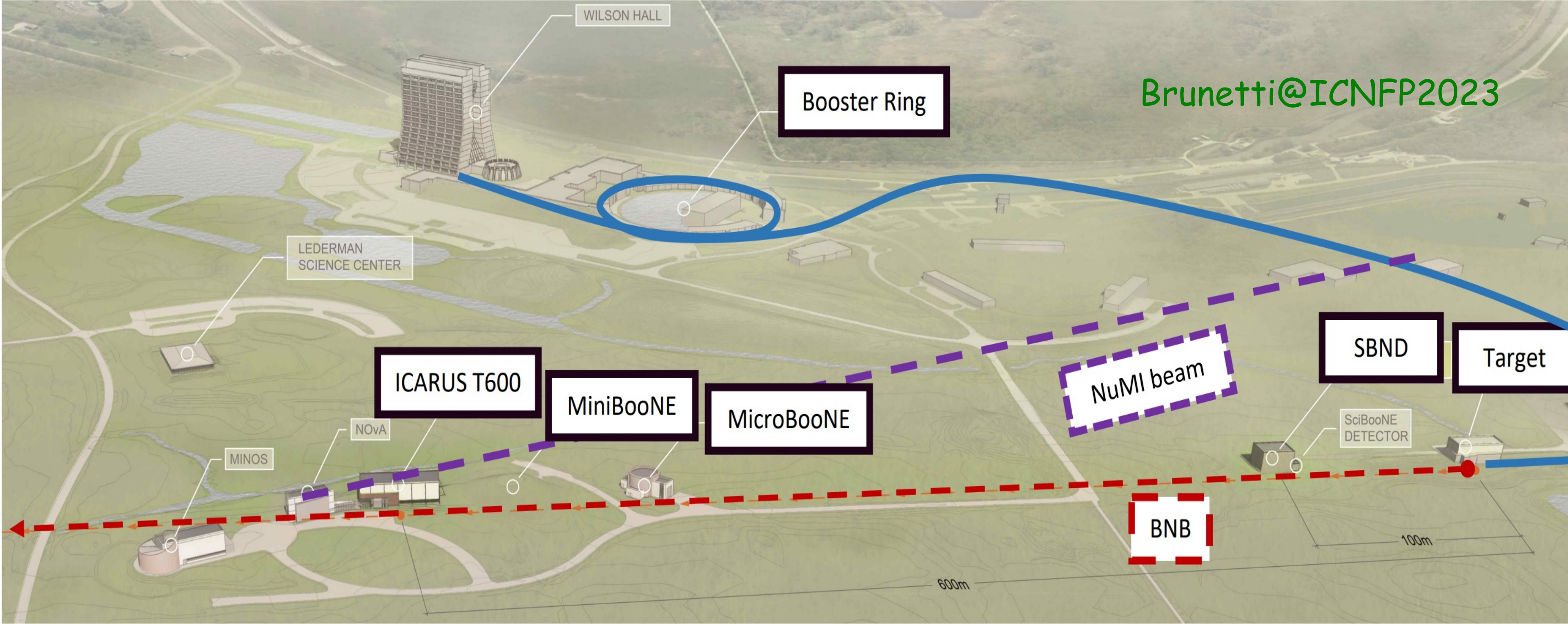
-GA is in serious tension with many experiments but agrees with Neutrino-4
-Many ideas of possible conventional or BSM explanation but not convincing
- ν_s explanation of GA is still marginally possible
- BEST with ^{65}Zn source – smoking gun test for many explanations

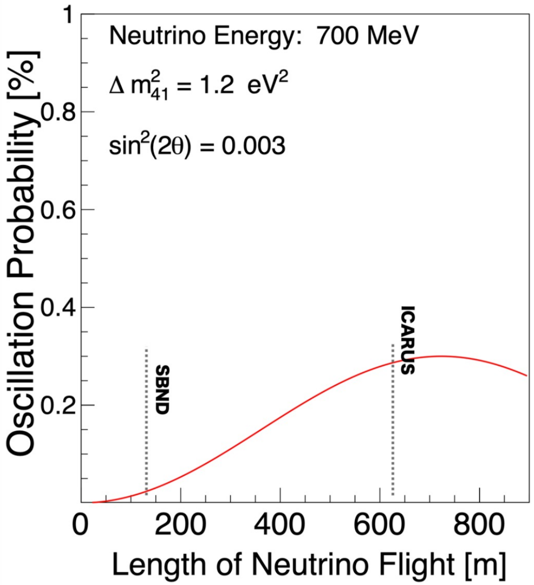
- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~3σ
- Neutrino-4 claim of ν_s observation is in tension with many results but not excluded
- Upgraded VSBL reactor experiments will clarify the situation
  Upgraded Neutrino-4+ is already taking data, Neutrino-4M will start in 2024

Cosmological constraints were not discussed but models exist which remove them
See e.g. Davoudiasl,Denton arXiv:2301.09651 Explains Ga, LSND, MiniBooNE, DM

Experimental evidence for ν_s is fading away but not excluded

Backup slides

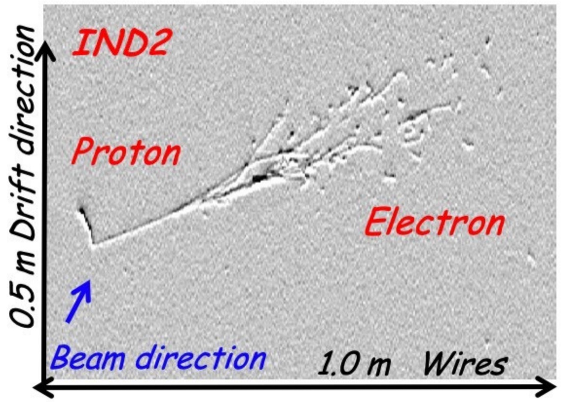




First SBND Physics Run from April-July 2024

Expected data will match the MicroBooNE entire dataset

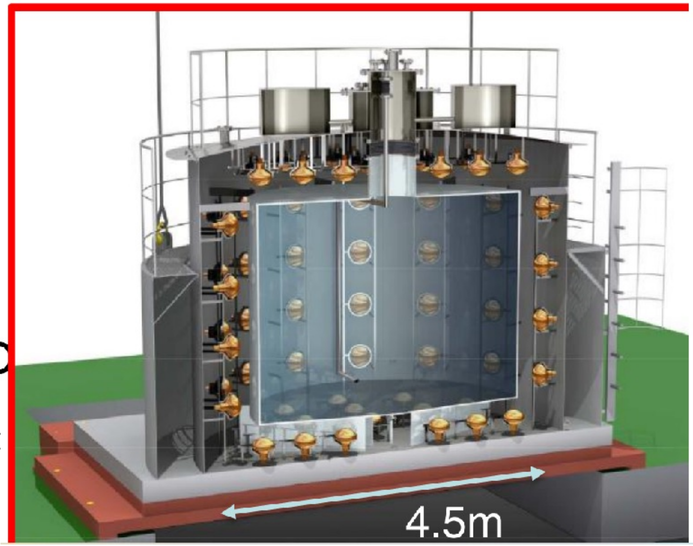
Nowak@NuPhys 2023

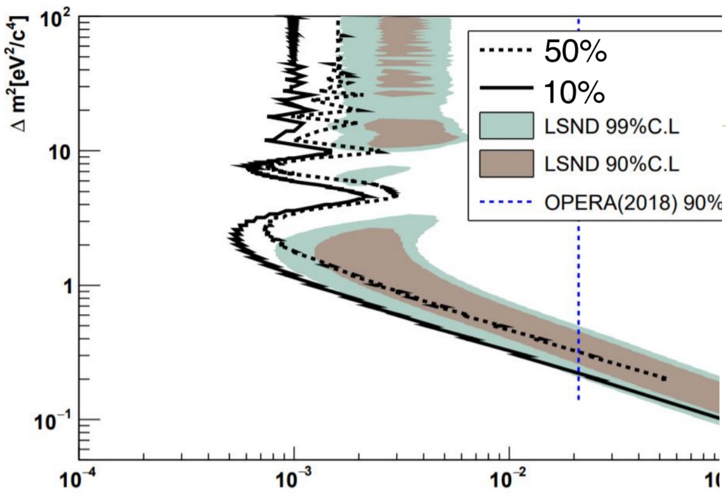


- QE ve CC event contained candidate, E_{DEP}~870 MeV:
  - ✓ proton candidate is upward going/stopping L= 13 cm;
  - ✓ e-shower is downward going.

JSNS^2 (J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

- Neutrino; μ^+(Decay at Rest) $\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Target volume ; Gd-loaded Liquid Scintillator
- Detection; IBD(Inverse Beta Decay)
- Baseline; 24m
- Beam: 3GeV Proton, 600kW
  Pulsed beam
- 10inch PMT x 120 (96 target, 24 Veto

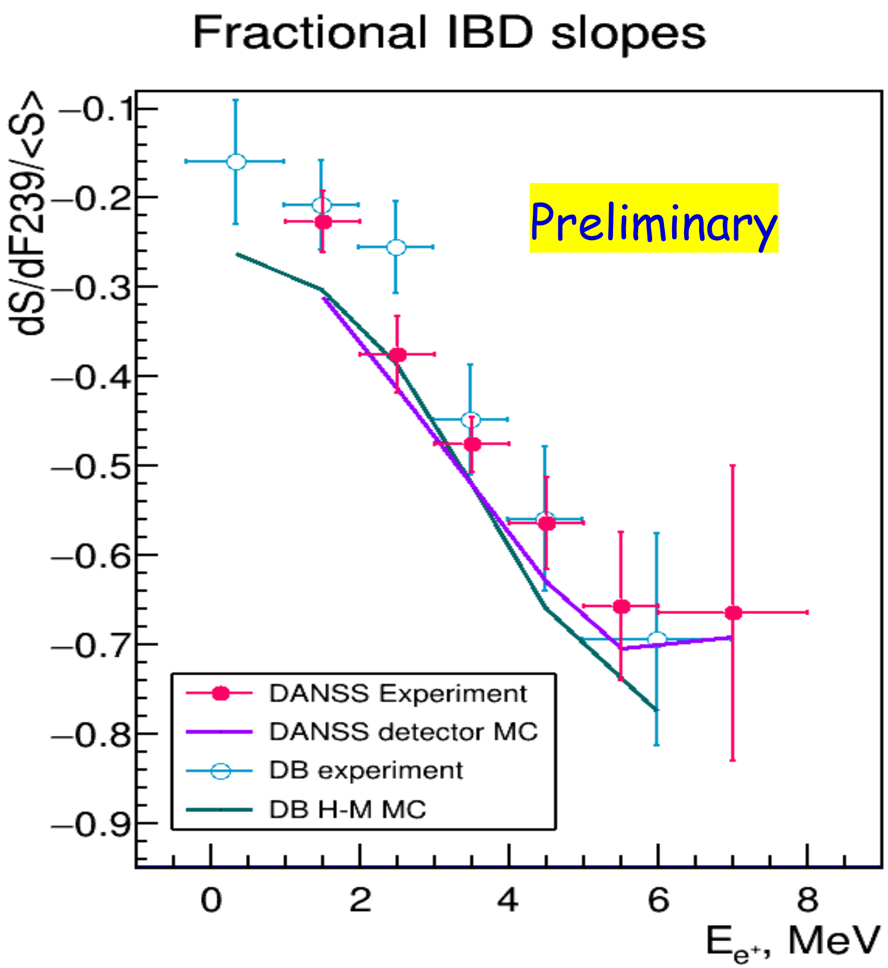


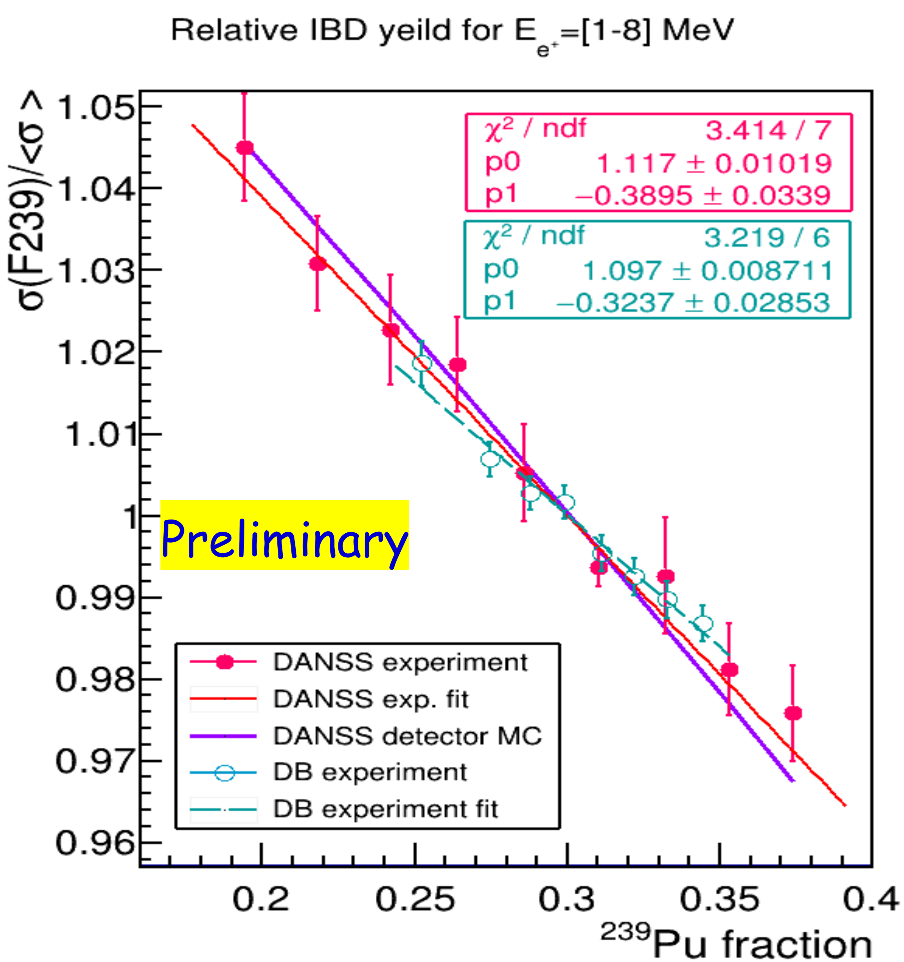


Hasogawa@CERN

Positron spectrum dependence on fuel composition is clearly seen

IBD rate dependence on 239Pu fission fraction (dσ/dF239)/σ(F239=0.3) for various Ee+
It is closer to H-M model than DayaBay results





Errors are dominated by systematics estimated from the spread between campaigns
Probably errors are overestimated

Determination of 235U / 239Pu contributions from the slope

$$N = \alpha \cdot (\sigma_8 f_8 + \sigma_1 f_1 + \sigma_5 f_5 + \sigma_9 f_9)$$

$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9 \right)$$

$$Sl = \left(\frac{dN}{df_9} \right) / N = \frac{\frac{\sigma_8}{\sigma_9} \frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9} \frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9} \frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$$

$$\frac{\sigma_5}{\sigma_9} = - \frac{\frac{\sigma_8}{\sigma_9}(Sl \cdot f_8 - \frac{df_8}{df_9}) + \frac{\sigma_1}{\sigma_9}(Sl \cdot f_1 - \frac{df_1}{df_9}) + (Sl \cdot f_9 - 1)}{Sl \cdot f_5 - \frac{df_5}{df_9}}$$

(σ_8/σ_9 and σ_1/σ_9 are taken from HM)

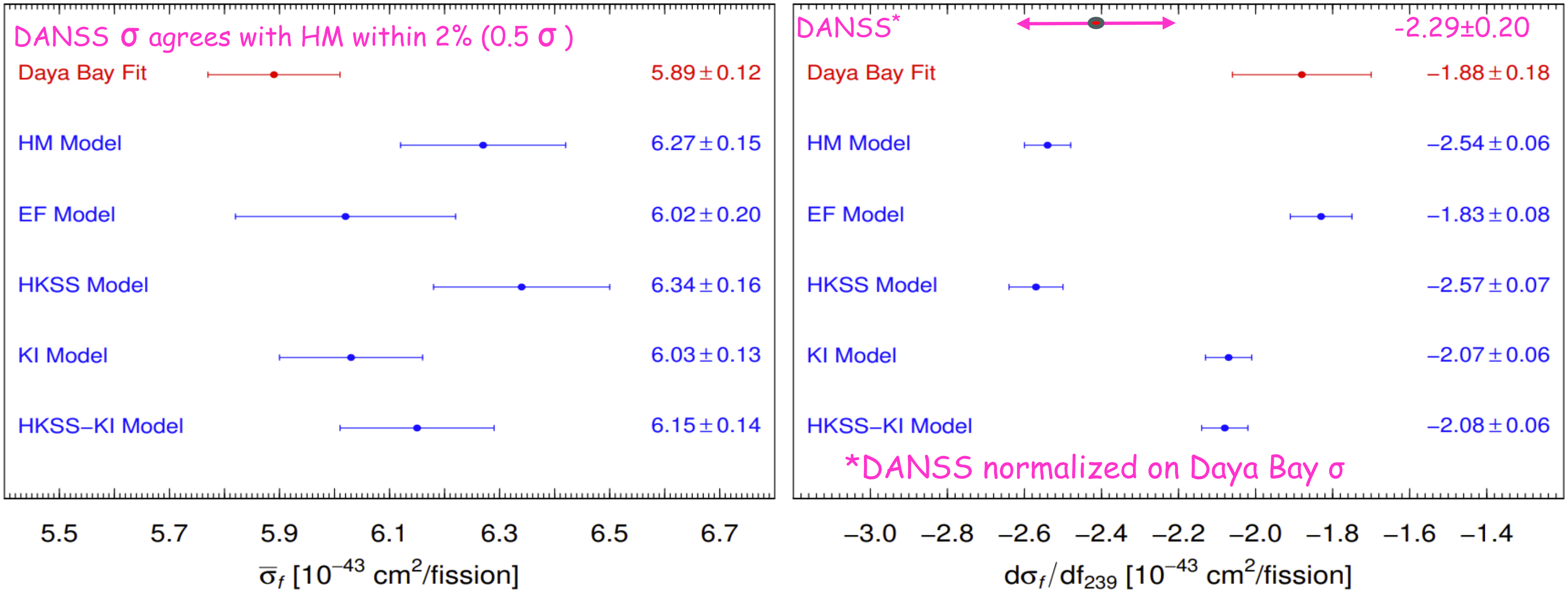
DANSS result $\sigma_5/\sigma_9 = 1.53 \pm 0.06$ is larger than Day Bay (1.445 ± 0.097) and agrees with HM (1.53 ± 0.05) .

Use of DB-Slope in our formula gives: $\sigma_5/\sigma_9 = 1.459 \pm 0.052$.

$\Rightarrow$ difference between DANSS and DB is due to slope

Maybe it's premature to say that RAA is solved by new σ_5/σ_9?

Data comparison with models Giunti et al, arXiv:2110.96820



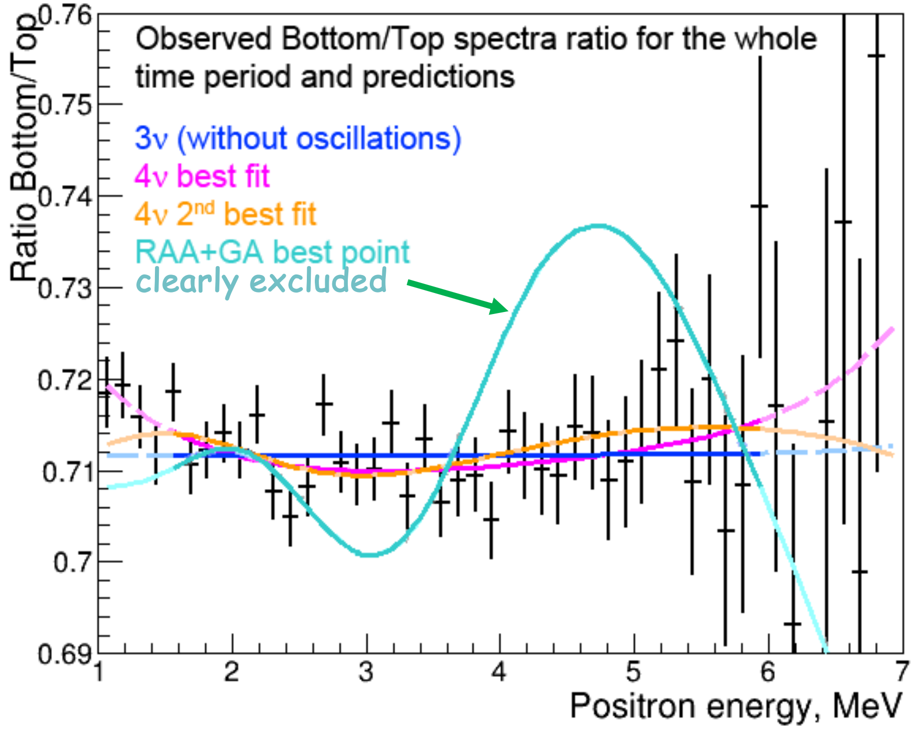
Daya Bay and RENO results agree with EF and KI models

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

RAA understood? Probably YES! However errors are still large

And recent DANSS results are consistent with HM model

Ratio of positron spectra



Fit in 1.5-6 MeV range (to be conservative)

(5.5 million IBD events with 1.5 MeV<E<6MeV)

There is no statistically significant evidence in favor of 4ν signal:

ΔX^2=-8.5 (2.1σ) for 4ν hypothesis best fit point Δm^2=0.35 eV^2 , sin$^2 2\theta$=0.06

ΔX^2=-5.7 for 4ν hypothesis second best fit point Δm^2=1.3 eV^2 , sin$^2 2\theta$=0.015

- ❖ **RAA has been excluded with ΔX^2= 194**
- ❖ **RAA was excluded by DANSS with more than 5σ already in 2018 (arXive:1804.04046v1)**