NEUTRINO 2022

XXX International Conference on Neutrino Physics and Astrophysics

Virtual Seoul **May 30 (Mon) - June 4 (Sat), 2022**

Sterile neutrinos:
experimental results with reactors

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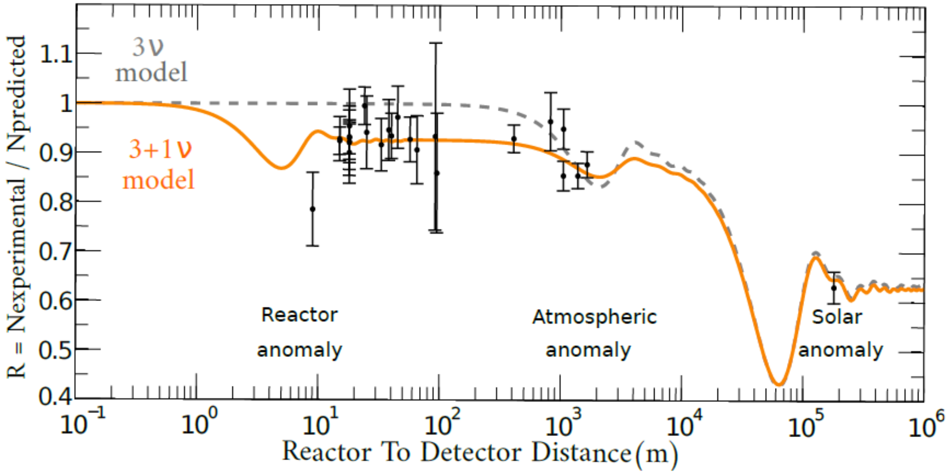
Physics case : indications for a sterile neutrino

→ See Talk by Joachim Kopp ←

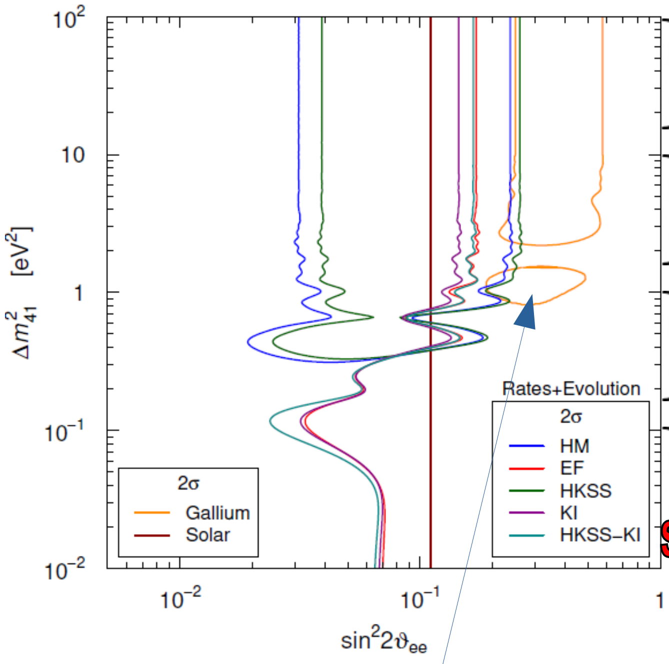
1.Reactor Antineutrino Anomaly (RAA)

- Apparition in 2011 [PRD 83 (2011) 073006] after reevalutation of neutrino fluxes (Huber [PRC 84 (2011) 024617], Mueller [PRC 83 (2011) 054615])
- Could be explained by additionnal short-distance oscillation to a sterile state



- Experimental challenge of the last decade : probe oscillations with L≈10m
- Complementary constraints from SBL and VSBL experiments

Giunti et al, arXiv:2110.06820



L = 1m

L = 10m

Very short baseline (VSBL)

L = 100m

L = 1km

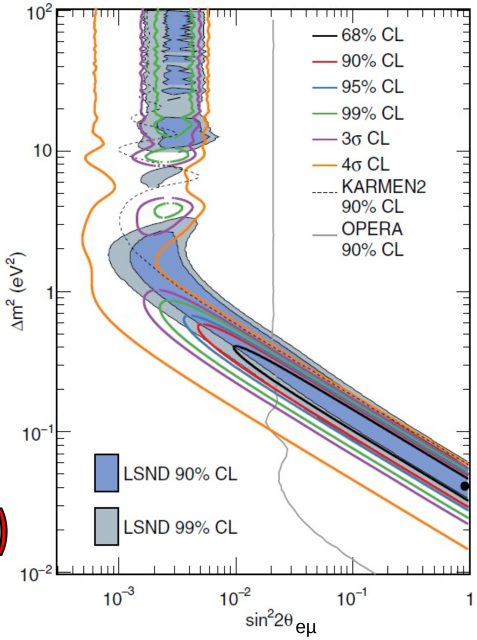
Short baseline (SBL)

2.Gallium anomaly

GALLEX, SAGE + BEST

3. $\bar{\nu}_\mu$ disappearance anomalies

LSND, MiniBooNE



PRL 121 (2018) 221801

A world-wide effort with reactors

Key aspect : **distance to reactor** (L) $\Delta m^2_{41} \simeq 2-10\ \text{eV}^2 \times \left(\frac{10\ m}{L}\right)$

Very short baseline (VSBL)
- L ~ O(10 m)
- access to large Δm^2
- restricted space available, high background environnement

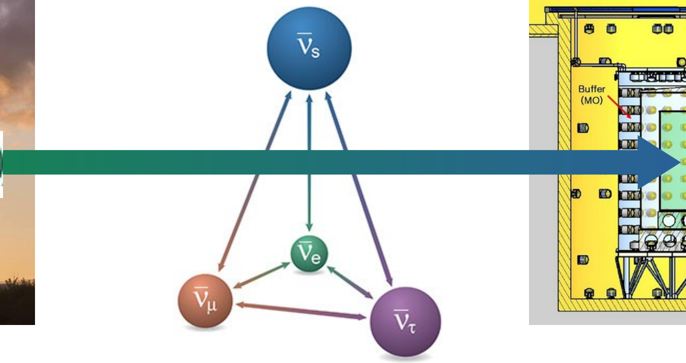
← **Complementary Δm^2 coverage** →

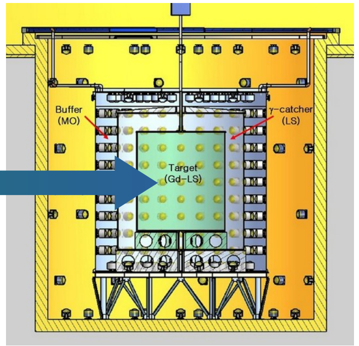
Short baseline (SBL)
- L ~ O(1 km)
- restricted to smaller Δm^2
- larger detectors possible
- no reactor background

Research reactors (HEU)
- lower power, lower stat
- compact core (Ø ≈ 0.5m)
- *pure ^{235}U (irrelevant)*

Commercial reactors (LEU)
- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

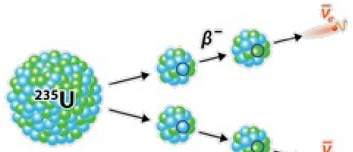
Reactor antineutrinos





Antineutrino flux

Fission fragments of U, Pu undergo β-decays → $\bar{\nu}_e$ flux



→ See Reactor Neutrino session ←

Oscillation

Survival probability

$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}\,L}{4E_{\bar{\nu}_e}}\right)$$

only required for L ≈ 1km

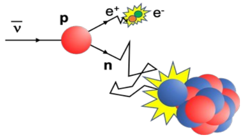
Oscillation peak (highest sensitivity)

$$\Delta m^2_{41} \simeq 2 - 10\ \text{eV}^2 \times \left(\frac{10\ m}{L}\right)$$

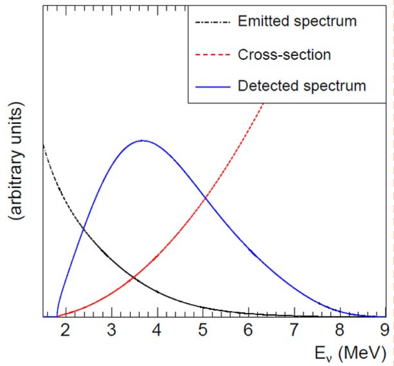
2-10 eV^2 @ 10m 10^{-2}-10^{-1} eV^2 @ 1km

Detection

Inverse β-decay : $\bar{\nu}_e\, p \rightarrow e^+\, n$



e+e- annihilation, then *n* capture

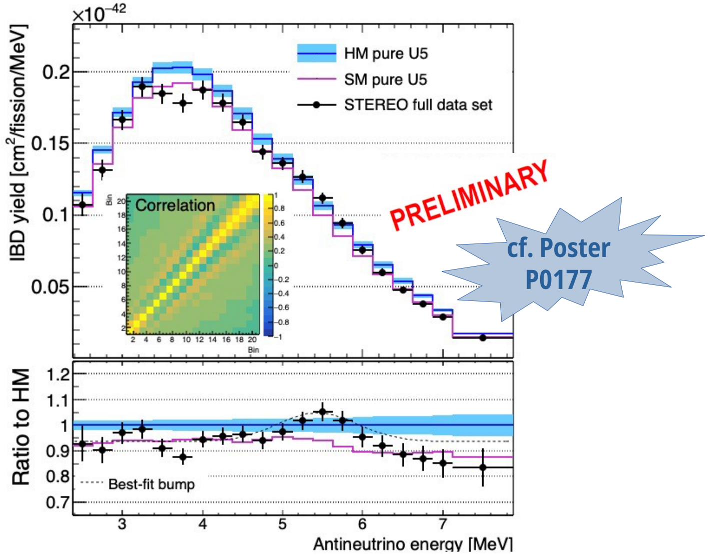


Useful energy range is E_ν ~ 2-8 MeV

The importance of relative measurements

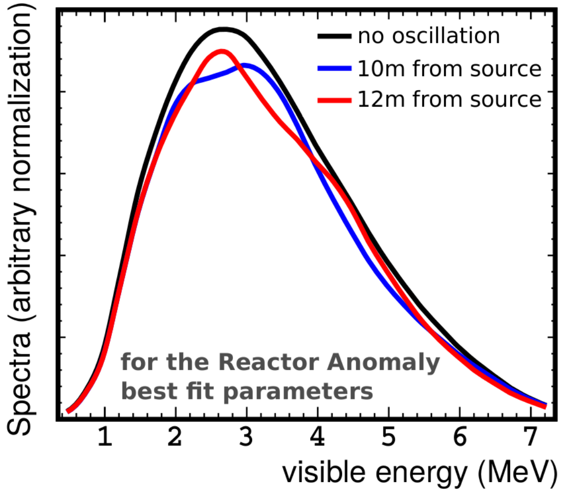
- Flux predictions do not match measurements
  - Notably the « 5 MeV bump », first seen by Daya Bay, RENO, Double Chooz

STEREO final measurement



- Oscillations induce spectral distortions between baselines
  - Comparing **data(L)** to **no-oscillation** prediction depends on flux models
  - Comparing **data(L)** to **data(L')** is independent of flux models

$$P_{ee} = P_{ee}(L/E)$$



→ Comparison of baselines gives model- independent results

- Different detectors
- Different detector parts
- Movable detector

Short-baseline experiments

Short baseline (SBL)

★
- L ~ O(1 km)
- restricted to smaller Δm^2
- larger detectors possible
- no reactor background

Commercial reactors (LEU)

☆
- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

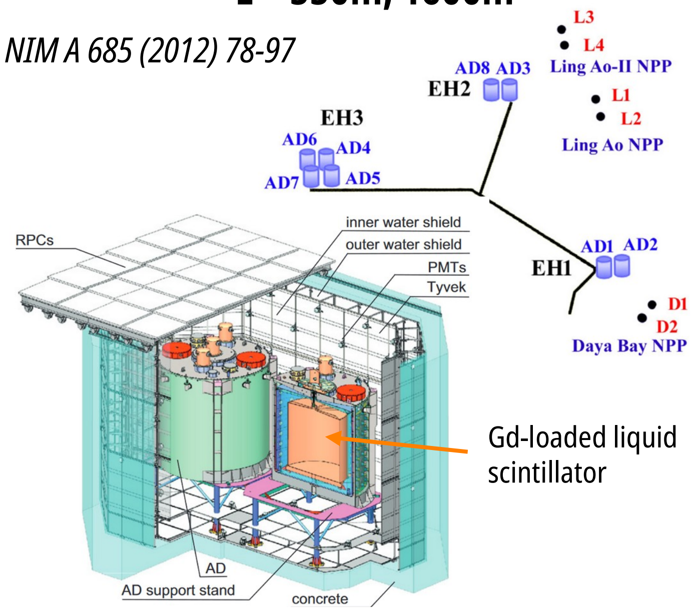
Short-baseline experiments

Daya Bay

Daya Bay and Ling Ao (II) NPPs

L = 550m, 1600m

NIM A 685 (2012) 78-97



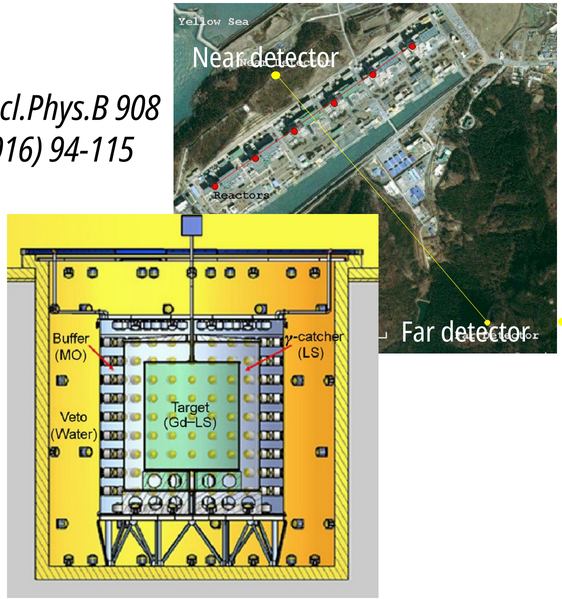
- 8 identical detectors (4 NDs + 4 FDs)
- Each 20t of Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

RENO

Hanbit NPP, Korea

L ≈ 300m, 1380m

Nucl.Phys.B 908 (2016) 94-115

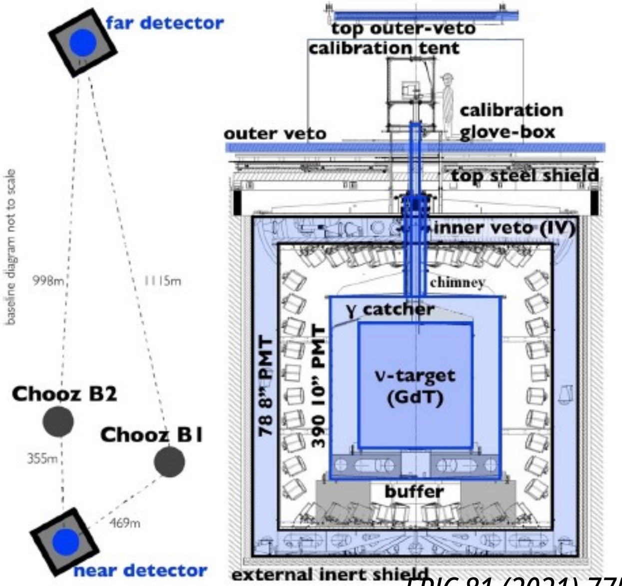


- Identical ND and FD
- 16t Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

Double Chooz

Chooz-B NPP, France

L = 400m, 1050m



EPJC 81 (2021) 775

- Identical ND and FD
- Gd-loaded liquid scintillator (GdT, 10m^3)
- Energy resolution 7% @1MeV

Daya Bay results

Analysis method

PRL 117 (2016) 151802

Method A.

- Look at difference between FD (N^f) and ND (N^n)

$$\chi^2 = \sum_{i,j} (N_j^f - w_j N_j^n)(V^{-1})_{ij}(N_i^f - w_i N_i^n)$$

with $w_i(\Delta m^2_{41}, \sin^2 2\theta_{14}, \sin^2 2\theta_{13})$

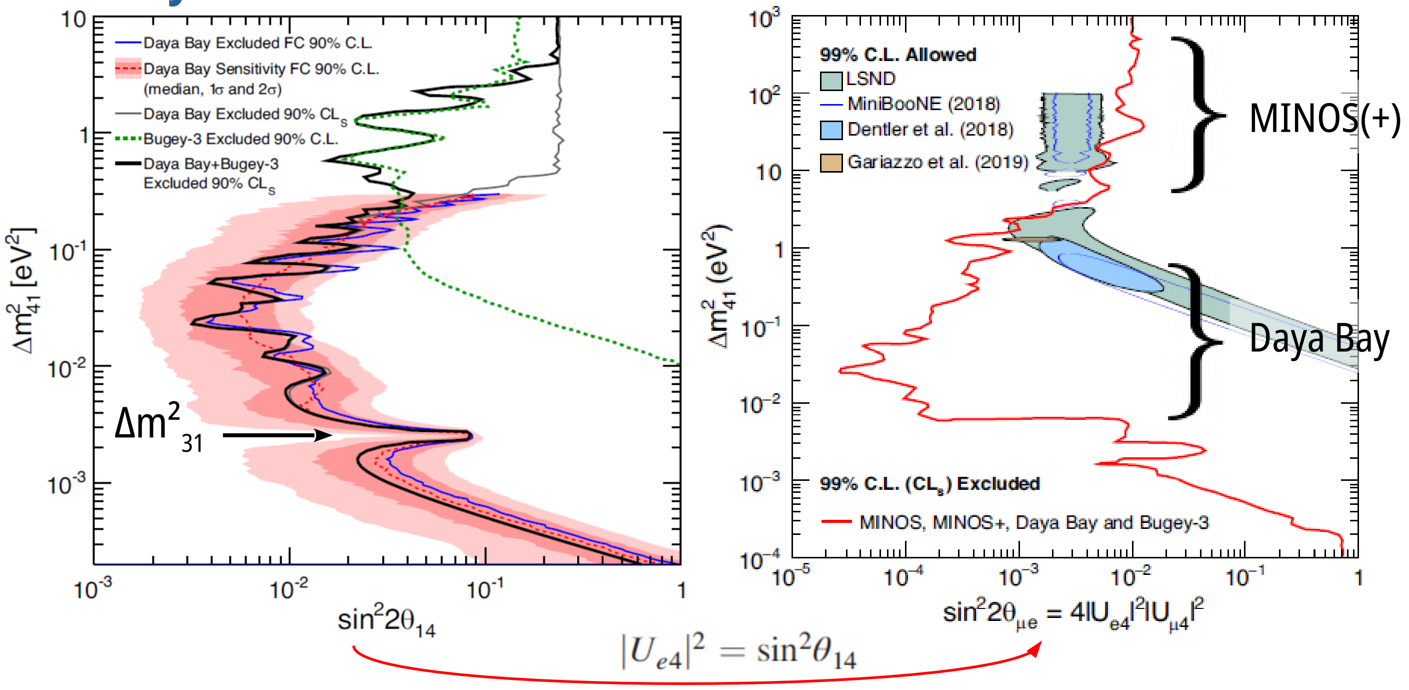
- CL contour

Method B.

- Joint fit of ND and FD data starting from flux predictions (Huber-Mueller)
- Increased flux uncertainties
- CLs contour

Analysis results

PRL 125 (2021) 071801



Only ≈1/3 of total data analyzed so far

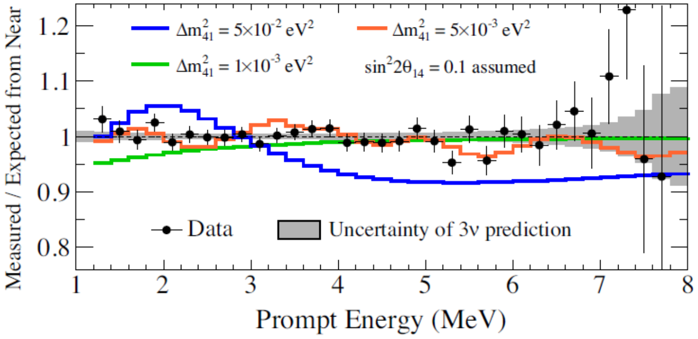
- **Highest sensitivity** in $\Delta m^2 \approx 10^{-2} - 10^{-1}$ eV^2
- Combination with MINOS(+) excudes part of LSND and global fits at **>99 % CL**

RENO results

Analysis method

- Use ratio FD/ND

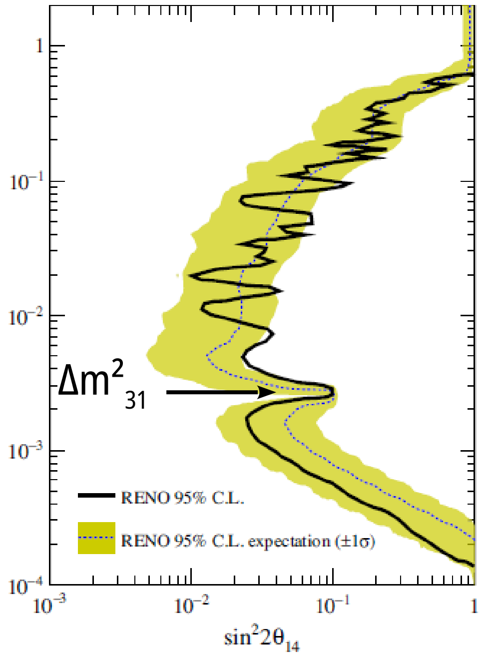
$$\chi^2 = \sum_{i=1}^{N_{\rm bins}} \frac{(O_i^{F/N} - T_i^{F/N})^2}{U_i^{F/N}} + \text{pull terms}$$



Future plans :
- Only 2200/3400 days analyzed
- 3 more years of data taking !

Analysis results

PRL 125 (2020) 191801

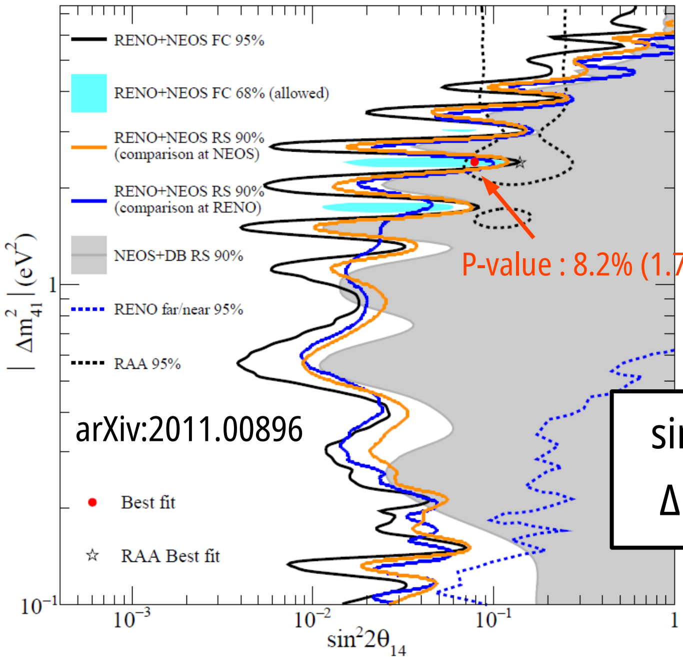


- Data agree with no-oscillation hypothesis (p-value ≈ 87%)
- RENO-NEOS signal has low significance (1.7σ)

RENO-NEOS analysis

- Use NEOS as prediction for RENO
- Use RENO-ND as prediction for NEOS

→ model independant analyses



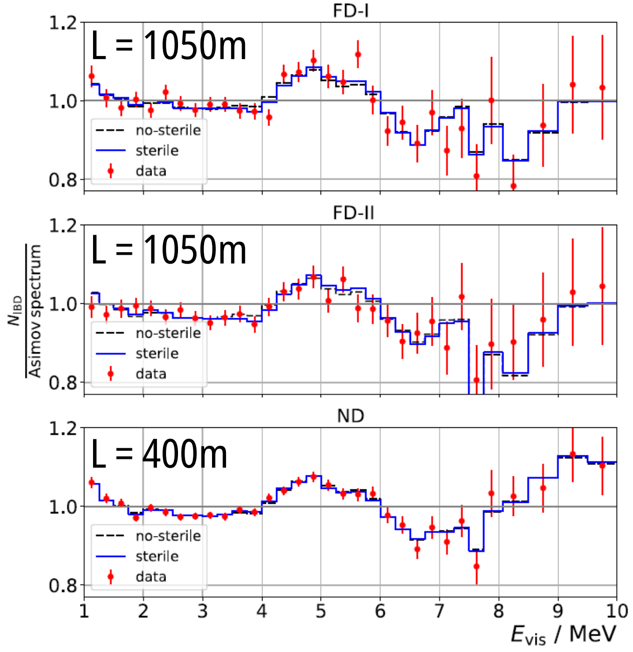
$\sin^2(2\theta_{14}) \approx 0.08$

$\Delta m^2_{14} \approx 2.4$ eV^2

Double Chooz results

Analysis method

- Joint fit of ND/FD datasets
- Free norm parameter in each bin → only relative difference matters
- Analysis independent of shape anomaly

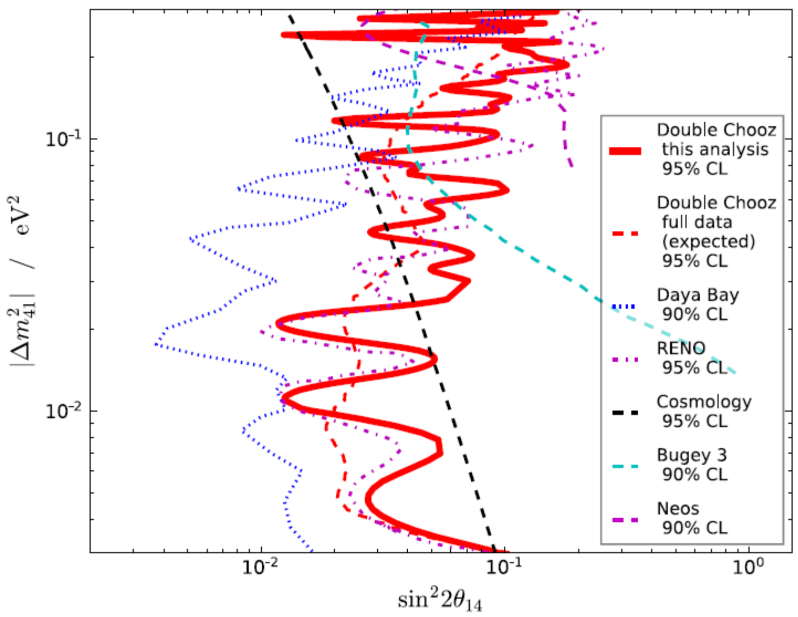


2011-13

2015-16

Analysis results

EPJC 81 (2021) 775



Inclusion of 2017 data is coming

- Data agree with no-oscillation hypothesis (p-value ≈ 25%)

Short-baseline summary

- Short baseline reactor neutrino experiments have **extended their study** of $\sin^2\theta_{13}$ in 3-flavor model to search for ($\sin^2\theta_{14}$, Δm^2_{14}) in 3+1 model
- **Very large antineutrino samples** (> 10^6), well-known detectors
- **Relative measurements** are performed using Near and Far Detectors, in order to be independent from flux predictions
- They provide **leading constraints** for Δm^2_{14} ranging **from Δm^2_{31} to 0.1 eV^2**
- **RENO-NEOS** observation has **low significance (1.7σ)**, needs confirmation
- RENO still taking data, Daya Bay and Double Chooz in the process of analyzing their full dataset
  → **More to come soon !**

Very-short-baseline experiments

* see talk by Jinyu Kim

Research reactors (HEU) ◊
- lower power, lower stat
- compact core (Ø ≈ 0.5m)
- *pure ^{235}U (irrelevant)*

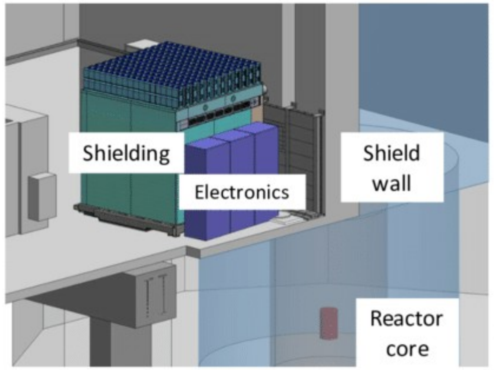
Very short baseline (VSBL)
- L ~ O(10 m)
- access to large Δm^2
- restricted space available, high background environnement

Commercial reactors (LEU) ☆
- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

Challenges of VSBL experiments

L~10m → vicinity of reactor core

- **Design constraints**
  Limited space, limited floor load in the reactor building
  → Constraints : size of detector, amount of shielding

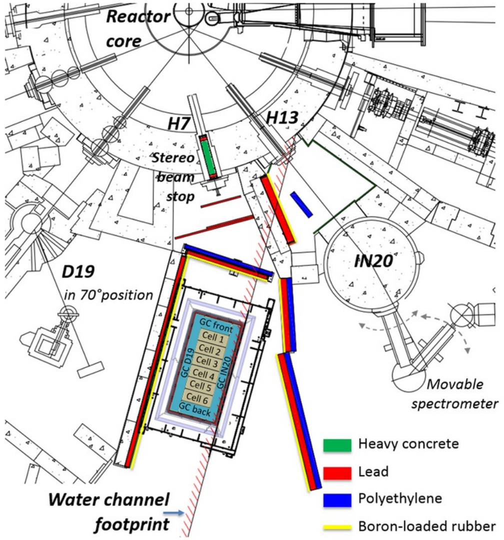


Example : PROSPECT ↑

- **Large backgrounds**
  - Cosmogenic : surface level → mild overburden (max ~10 m.w.e.)
  - Ambient fast neutron flux
  - Noise from surrounding experiments

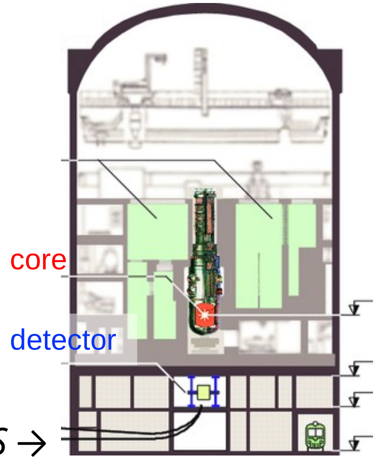
→ **Good S/B (~1) is challenging (HEU) !**

Example : STEREO →



- **Resolution on L/E** $\Delta m^2 \sim E/L$
  - Extended cores (LEU) : size ~3m
    → σ_L/L up to 15%
  - Small cores (HEU) : size ~0.5m
    → σ_L/L down to 3%
    → resolution on E is important !

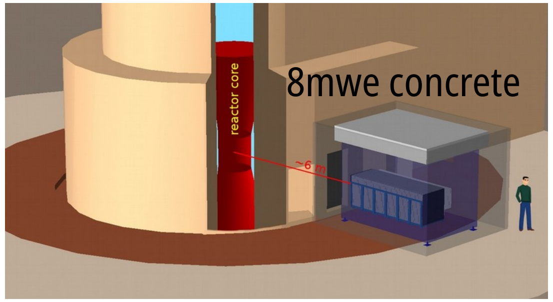
Example : DANSS →



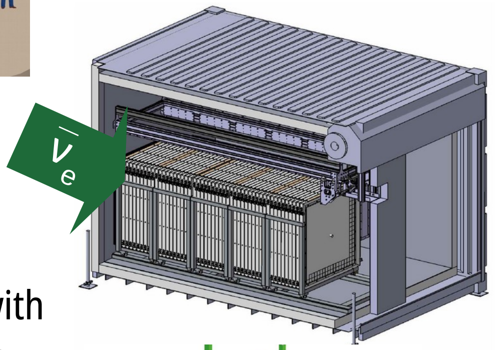
The Solid experiment

JINST 16 (2021) P02025;
D.Gabinski's talk at Nufact21

Reactor BR2 Mol, Belgium



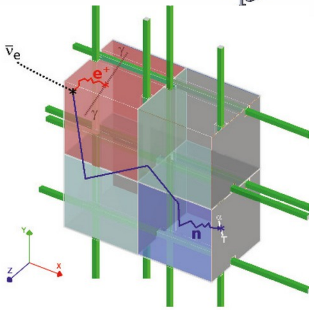
40-80 MW HEU reactor
Compact core Ø<50cm, h=90cm



Segmented detector

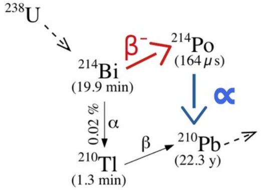
L ≈ 6.3 – 8.9m

- 12.8k scintillator cubes $(5cm)^3$ with ^{6}LiF:ZnS foils → double scintillation
- Pulse shape discrimination on LiF:ZnS
- 1.6t fiducial volume
- 12% resolution @1MeV
- Selection based on event topology



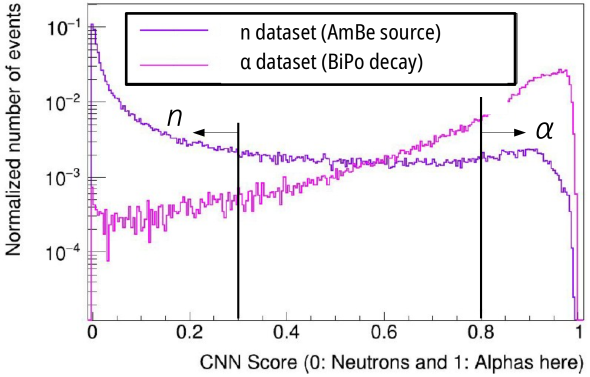
Bi-Po background rejection

Unexpectedly high contamination of ^{6}LiF:ZnS
(2 orders of magnitude above IBD)



→ BiPonator

Machine Learning PSD method to separate α/n



94 % α rejection for
80 % neutron efficiency

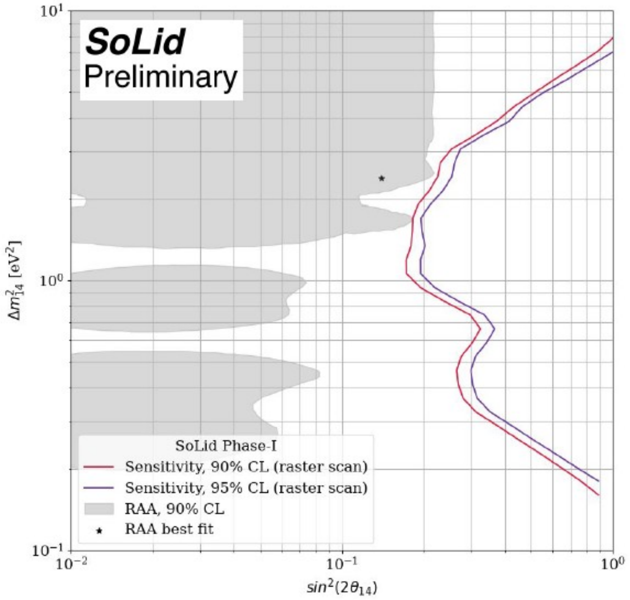
≈90 $\bar{\nu}_e$/day with S/B = 1/3

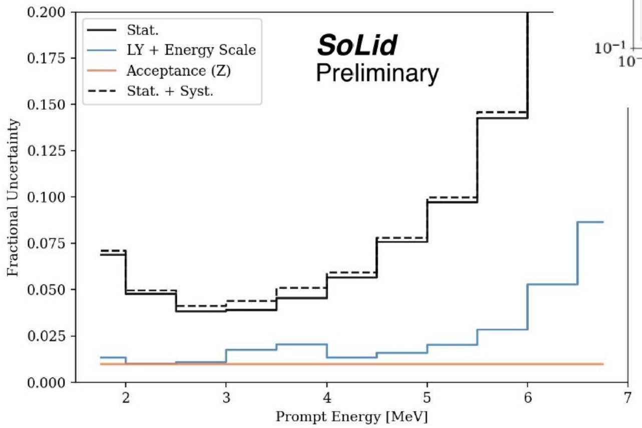
Solid results

D.Gabinski's talk at Nufact21

Analysis status

- Currently working on phase-I data (2 yrs of data)
- Analysis will be stat. limited

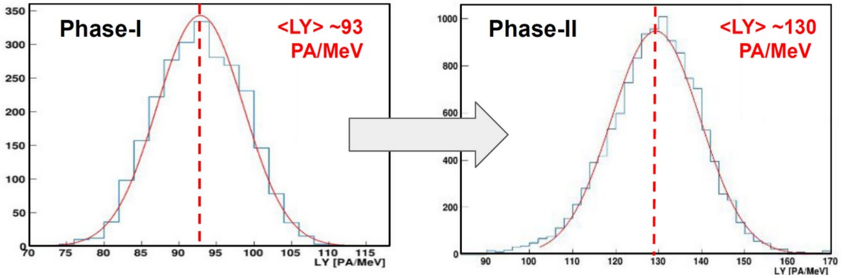




First exclusion contour coming soon !

Solid Upgrade

- Detector upgrade with improved MPPCs
  - 40 % more light yield
  - Better energy resolution
  - Improved reconstruction of annihilation gammas → event topology

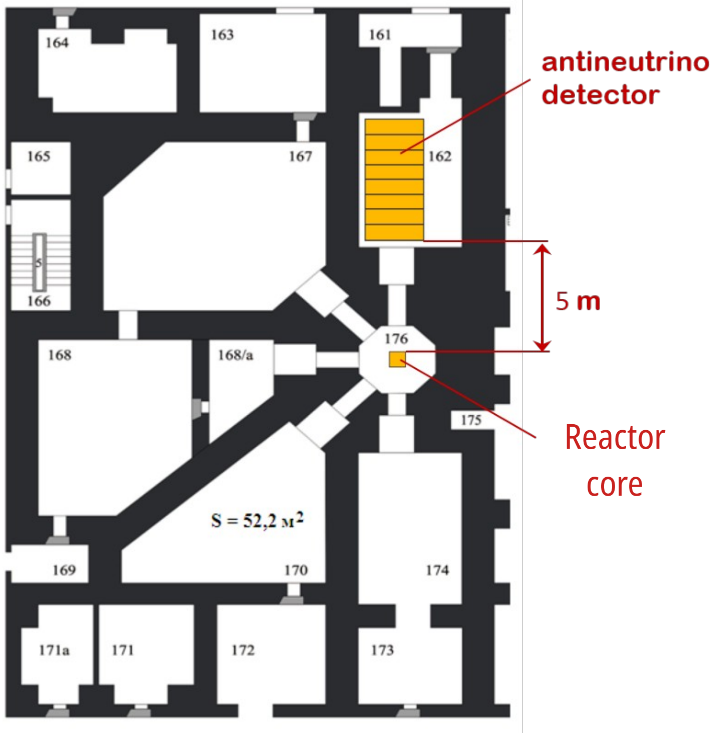


- Phase-II detector taking data since late 2020

The Neutrino-4 experiment

PRD 104 (2021) 032003

Reactor SM-3 Dimitrovgrad, Russia



90 MW HEU reactor
Compact core 42x42x35cm
Highly enriched ^{235}U fuel

Movable segmented detector

L ≈ 6.4 – 11.9m with 23 cm steps (24 positions)

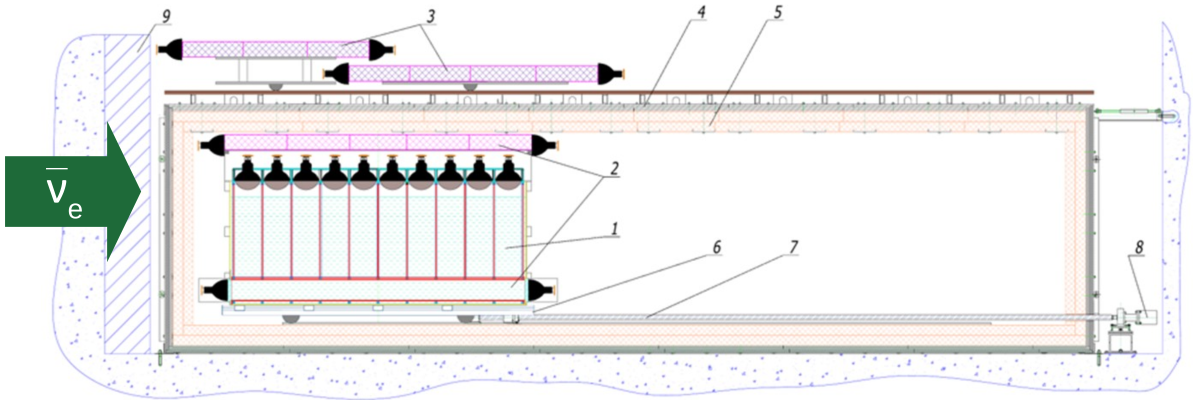
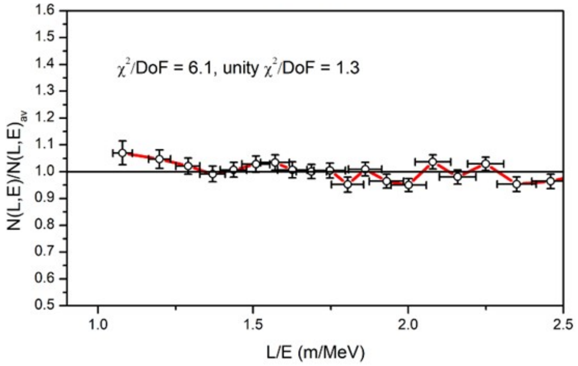


FIG. 18. General scheme of an experimental setup. 1—detector of reactor antineutrino, 2—internal active shielding, 3—external active shielding (umbrella), 4—steel and lead passive shielding, 5—borated polyethylene passive shielding, 6—moveable platform, 7—feed screw, 8—step motor, 9—shielding against fast neutrons made of iron shot.

- 1m^3 liquid scintillator + Gd
- Assumed flat 250 keV resolution
- About 300 $\bar{\nu}$ / day (S/B ≈ 0.54)
- Cosmic background dominates, but no strong L/E dependence →



Neutrino-4 results

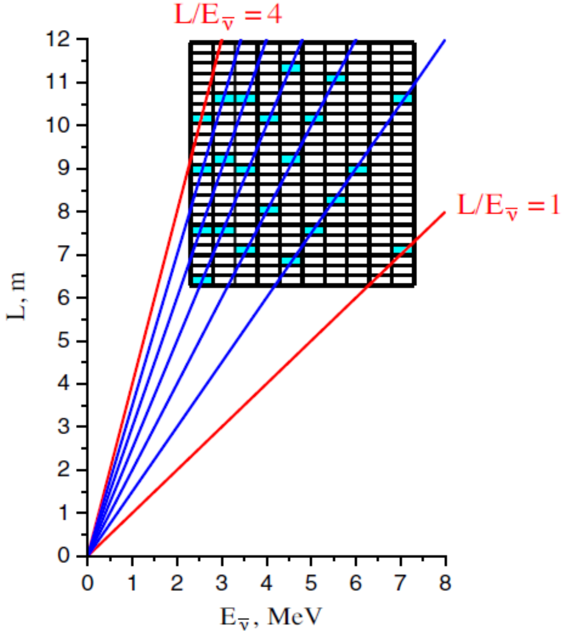
PRD 104 (2021) 032003

Analysis method

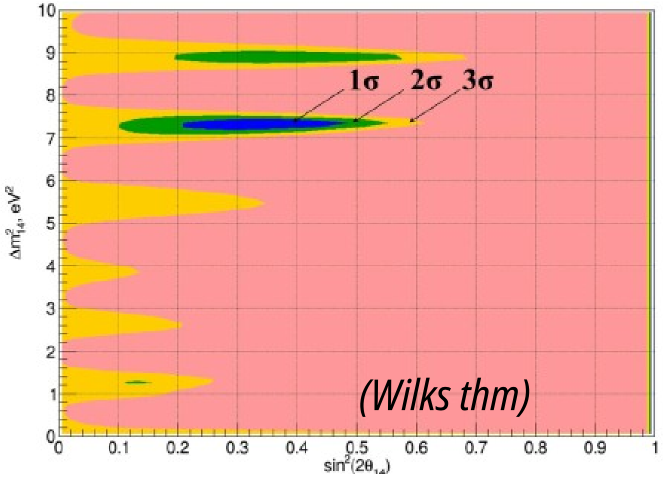
- Relative measurement using ratio to baseline-averaged spectrum

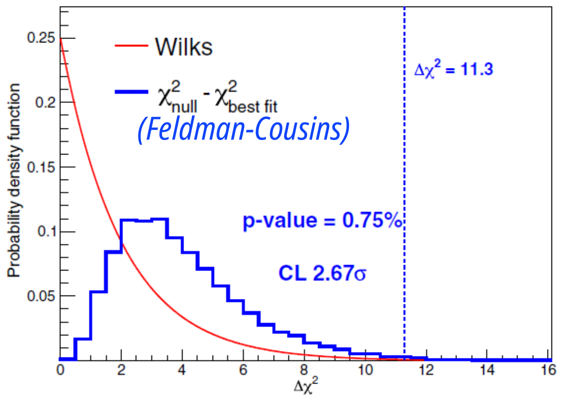
$$R_{ik}^{\rm exp} = (N_{ik} \pm \Delta N_{ik}) L_k^2 / K^{-1} \sum_k^K (N_{ik} \pm \Delta N_{ik}) L_k^2$$

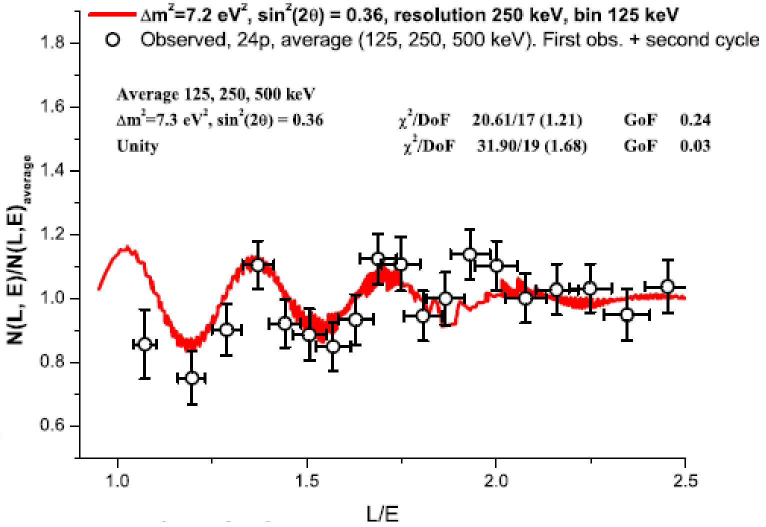
- Summation of R_{ik} in L/E space



Analysis results







$\sin^2(2\theta_{14}) \approx 0.36$

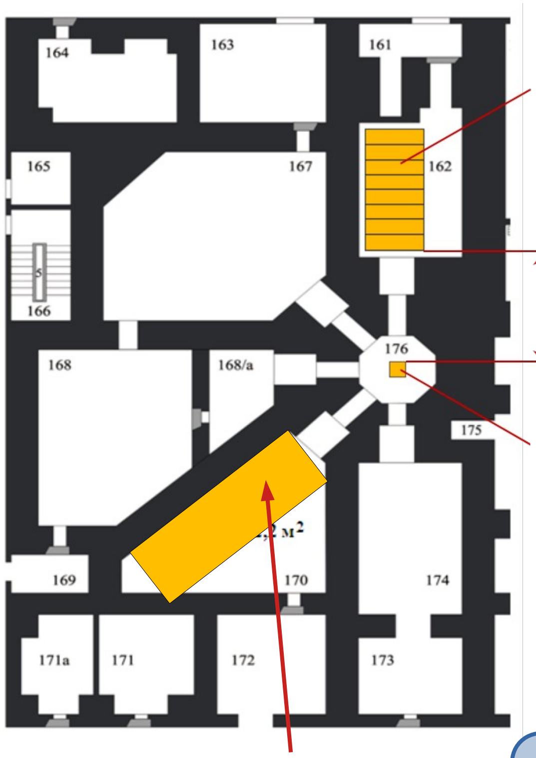
$\Delta m^2_{14} \approx 7.3$ eV^2

***2.9σ** with Wilks thm*

***2.7σ** with F-C*

Neutrino-4 future plans

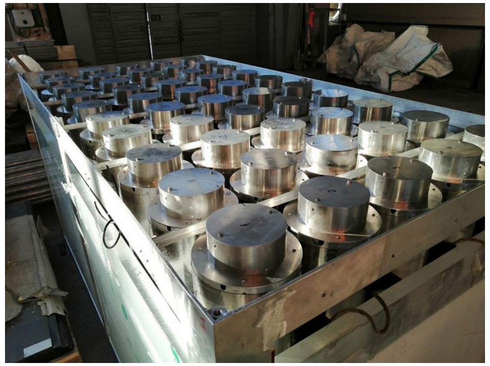
R.M. Samoilov, talk at Nucleus 2020



Installation 2022
Data taking 2023-24

Current

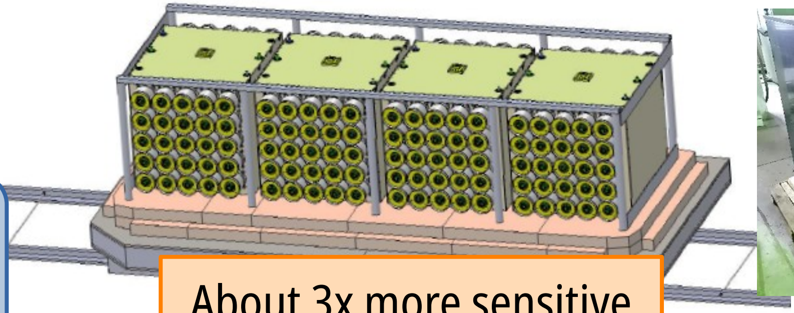
10x5 cells, single-PMT readout



Upgrade

4 sub-detectors with 5x5 cells, double-PMT readout

- New scintillator → PSD capability, reduce correlated bkg
- More Gd → reduce accidental background



About 3x more sensitive

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

The PROSPECT experiment

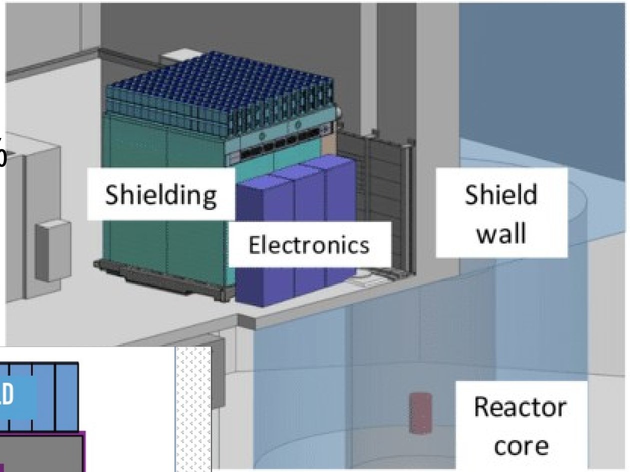
NIM A922 (2019) 287-309
https://prospect.yale.edu

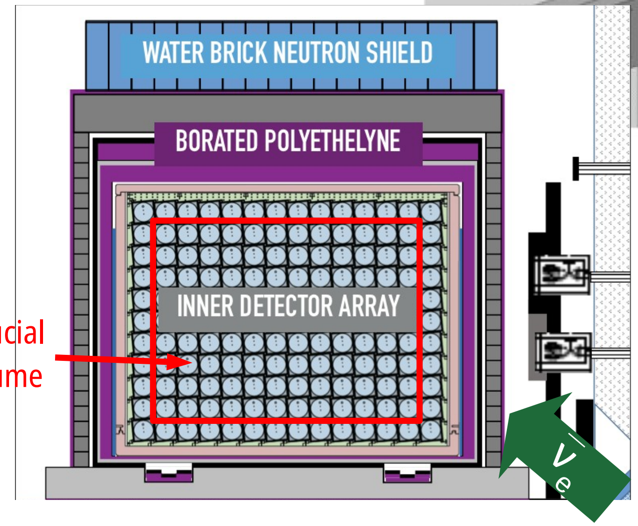
High Flux Isotope Reactor

Oak Ridge, USA

85 MW HEU reactor core with 46% duty cycle

Compact core Ø 44cm, h=51cm





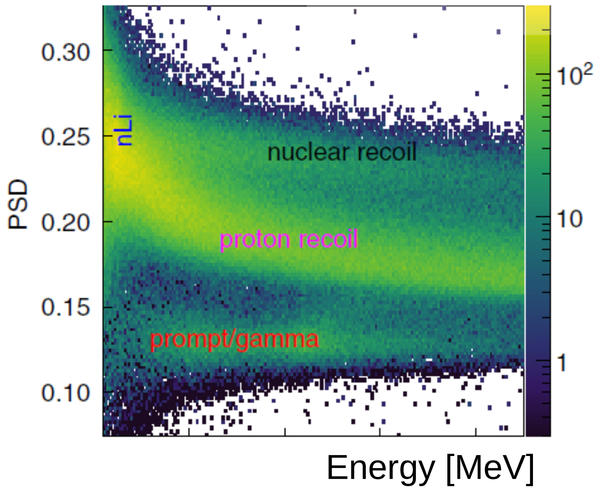
Segmented detector

L ≈ 6.7 – 9.2m

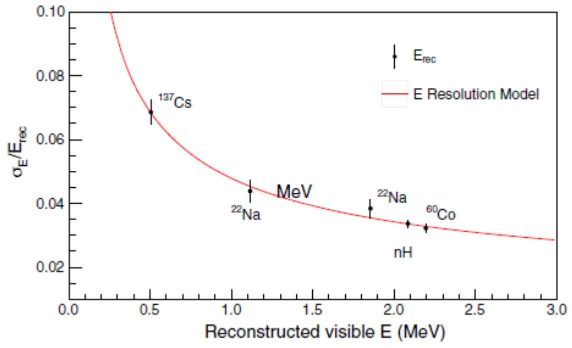
- 4t liquid scintillator + ^{6}Li
- 2D array of segments for fiducialization and bkgd suppression (no overburden)
- 500 $\bar{\nu}_e$/day, S/B = 1.4

PRD 103:032001 (2021)

Pulse shape discrimination



5% resolution @ 1 MeV

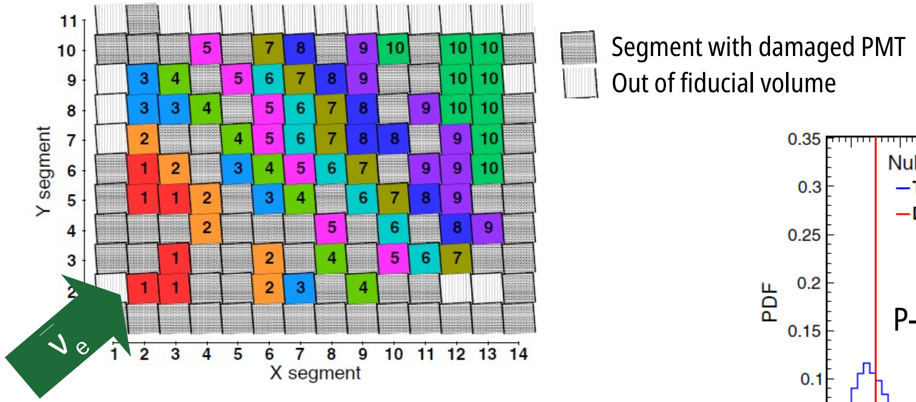


PROSPECT results

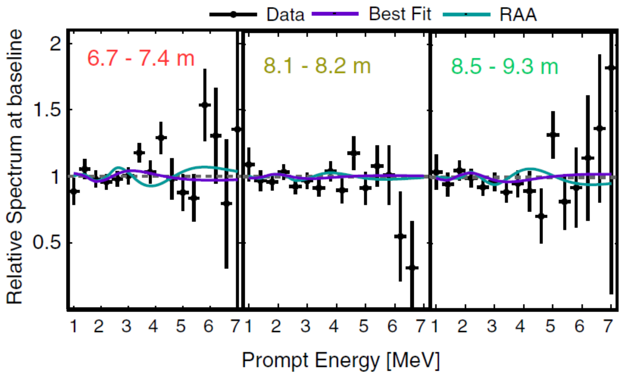
PRD 103 (2021) 032001

Analysis method

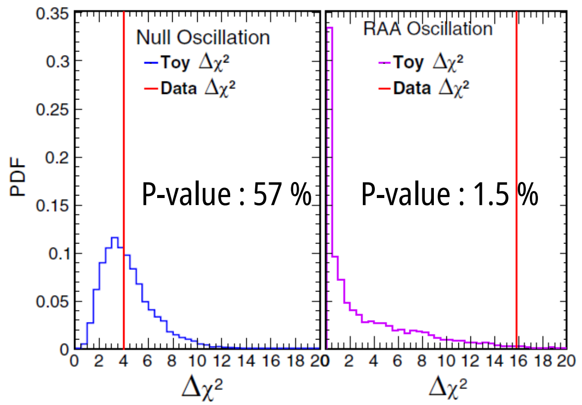
- Group segments with similar baseline

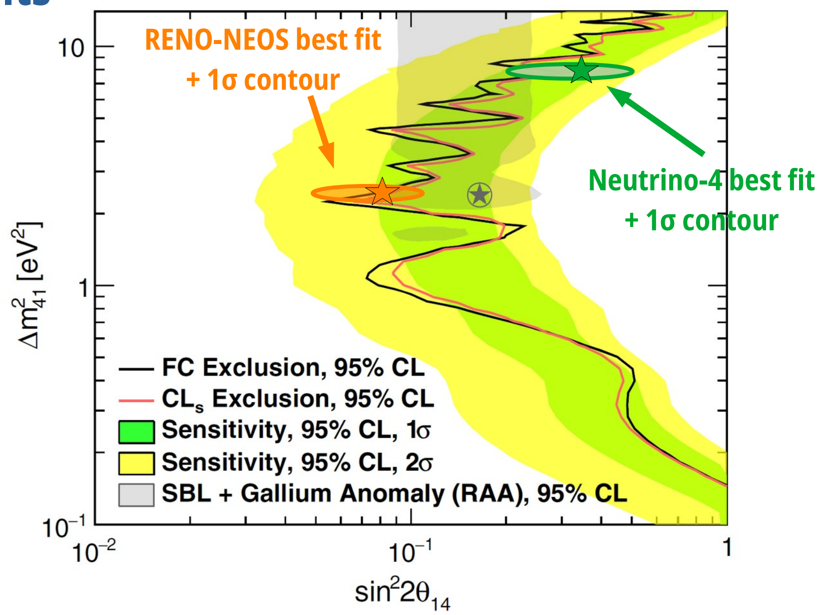


- Take ratio to baseline-average



Analysis results





Future plans :

1. Use single-PMT segments in analysis (stat x2)
2. PROSPECT-II upgrade (2023)

- **Rejection of the RAA+Gallium** best fit p-value = 1.5% (2.5σ)
- Neutrino-4 best fit + 1σ contour within sensitivity, **excluded at >95 % CL**
- RENO-NEOS best fit at the edge of exclusion contour

arXiv: 2107.03934, 2202.12343

→ posters : P0355, P0357, P0558, P0106 ←

The STEREO experiment

JINST 13 (2019) 07, P07009
www.stereo-experiment.org

Segmented detector

6 cells: **L ≈ 9.4 – 11.2 m** with 37cm step

- 1.6t liq. scintillator + Gd
- Pulse shape discrimination
- 9% resolution @ 1 MeV
- About 380 $\bar{\nu}_e$/day, S/B ≈ 1.1

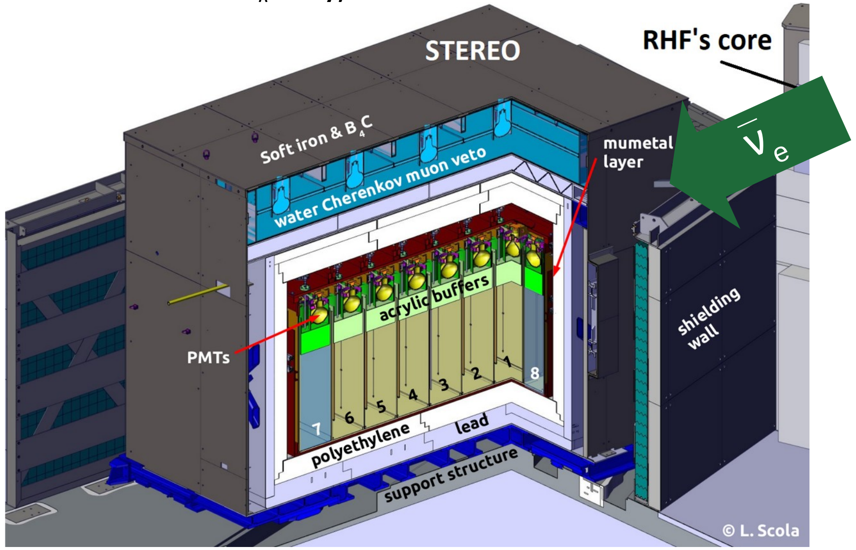
Réacteur Haut Flux (RHF)

ILL, Grenoble, France

58 MW HEU reactor

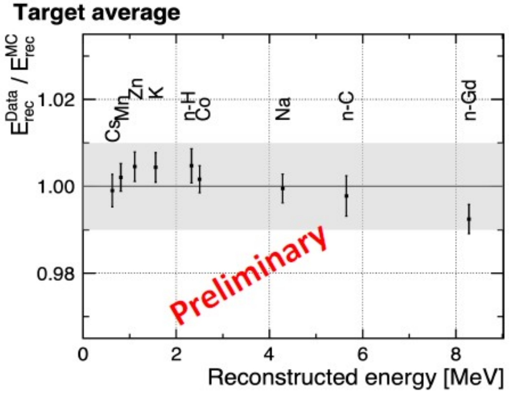
Compact core Ø 40cm, h=80cm

Noise from nearby instruments



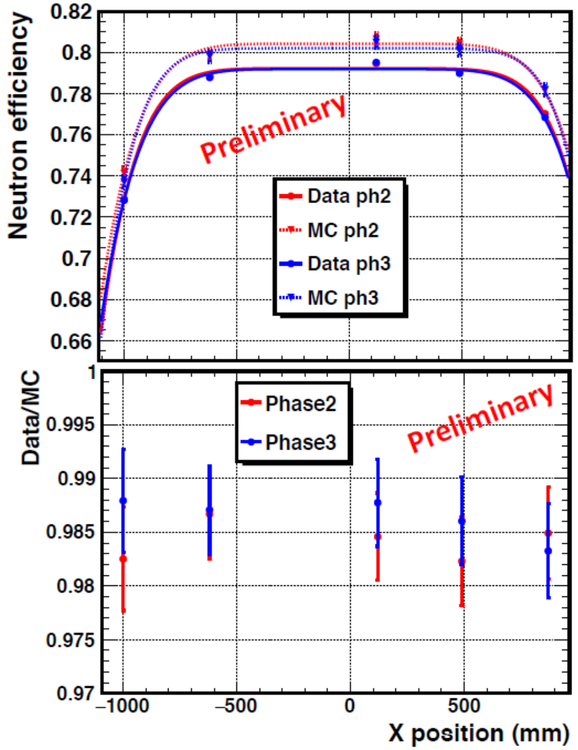
Finely tuned simulation

For each phase of data taking



Neutron efficiency measurement

Relative norm difference between cells ?



STEREO results

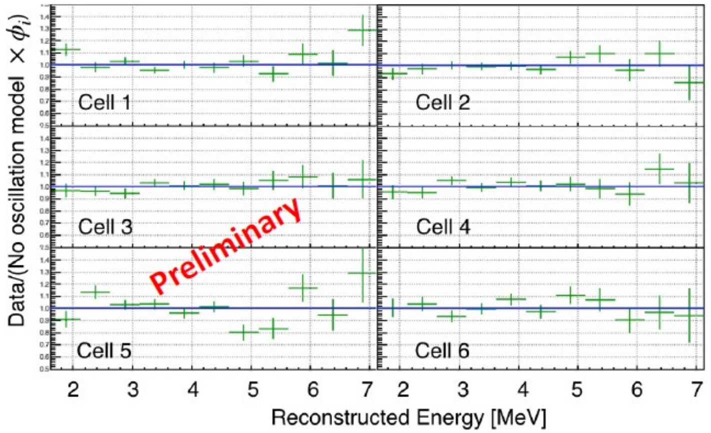
Analysis method

- Look for relative distortions between cells
- Free params ϕ_i absorb model dependence

$$M_{l,i} = M_{l,i}\left(\sin^2 2\theta_{14}, \Delta m^2_{14}; \vec{\alpha}\right)$$

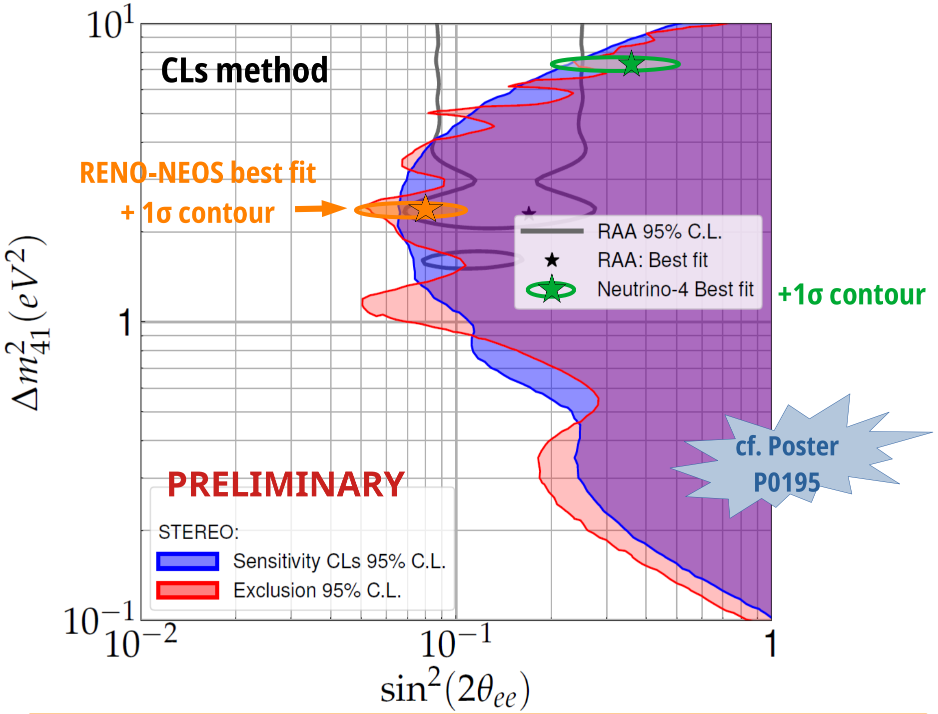
$$\chi^2 = \sum_{l=1}^{N_{\text{cells}}} \sum_{i=1}^{N_{\text{Ebins}}} \left(\frac{A_{l,i} - \phi_i M_{l,i}}{\sigma_{l,i}} \right)^2 + \text{pull terms}$$

Ph-3 Data over no-oscillation adjusted model $\phi_i M_{l,i}$



No sign of significant oscillations

Analysis results: final results w/ full dataset ! (107k neutrinos)

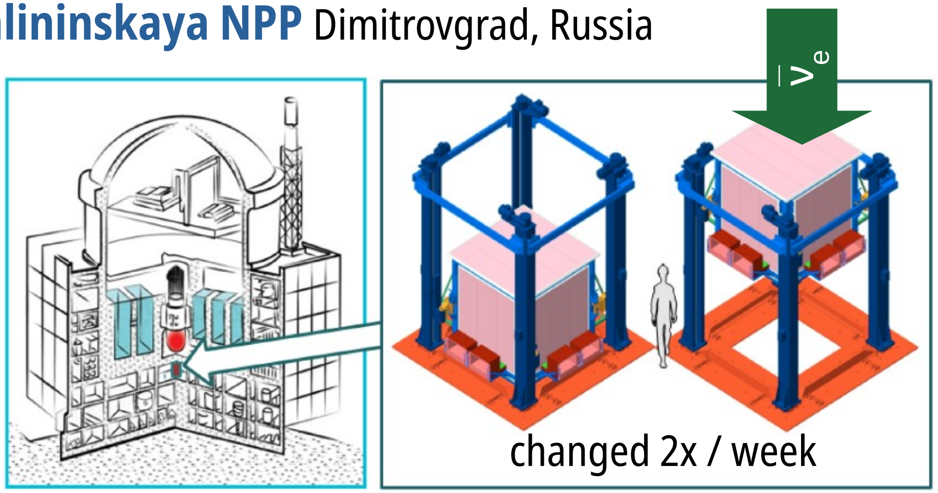


- **Strong rejection of the RAA** allowed 95% CL space
  RAA best-fit point : p-value < 10^{-4} (>4σ)
- Neutrino-4 best fit and 1σ contour within sensitivity
  Best-fit **rejected at 3.1σ** (p-value ~ 1.5 10^{-3})
- NEOS-RENO best-fit point excluded at 2.8σ

The DANSS experiment

JINST 11, P11011 (2016)

Kalininskaya NPP Dimitrovgrad, Russia



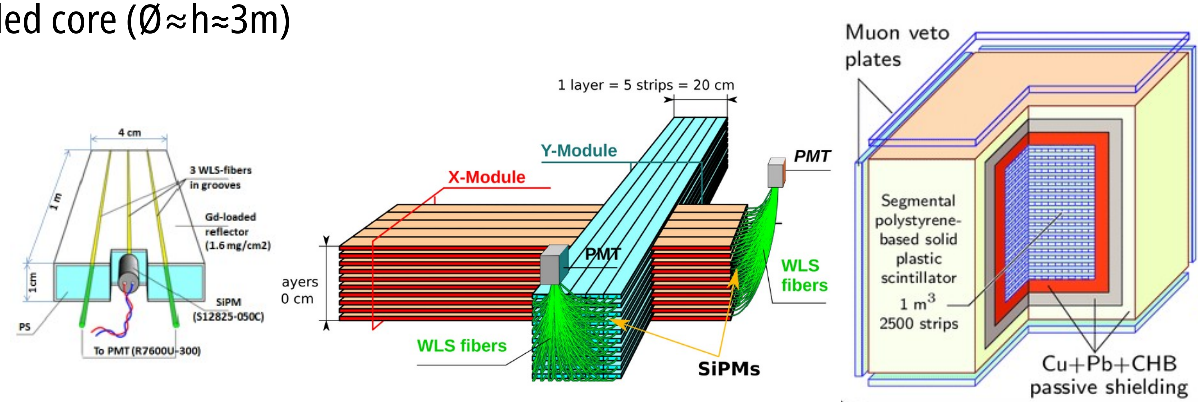
- 3 GW reactor
- Extended core (Ø≈h≈3m)

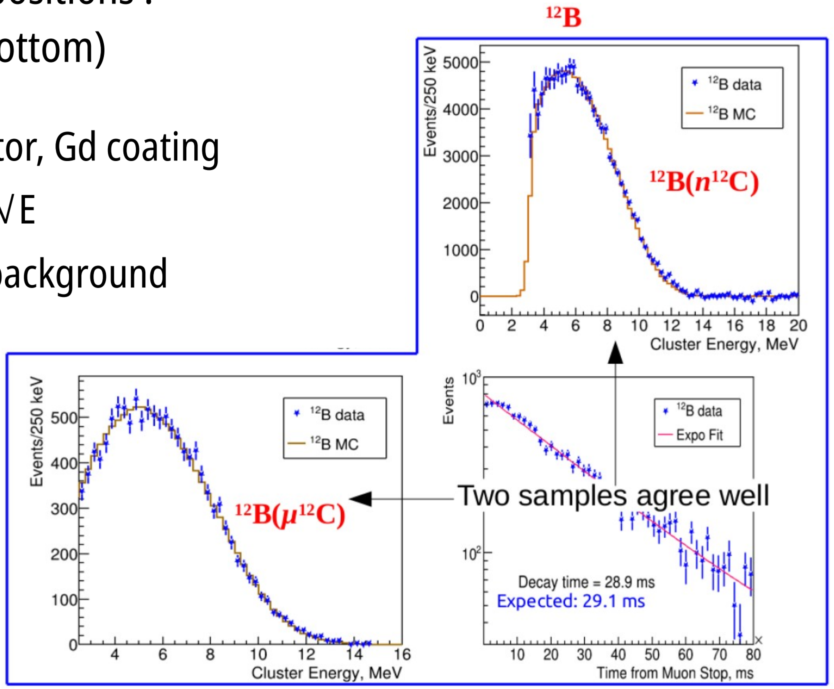
Movable detector

L ≈ 10 – 12m (3 positions : top, middle, bottom)

- $1m^3$ plastic scintillator, Gd coating
- Resolution of 34%/√E
- 5000 $\bar{\nu}_e$/day, 1.7% background

Energy scale determined with β-spectrum of ^{12}B ↓
(2 % systematics)





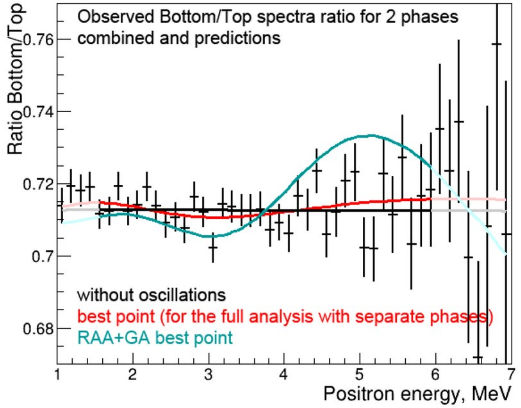
N. Skrobova, talk at Moriond-22

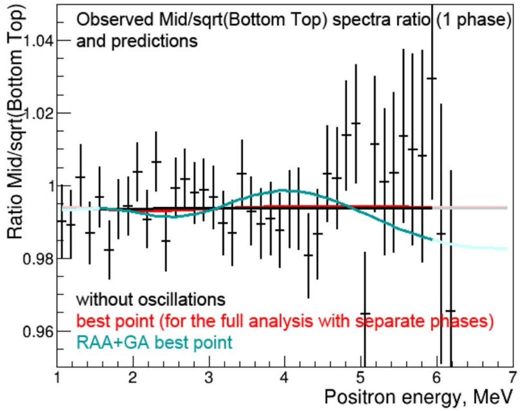
DANSS results

N. Skrobova, talk at Moriond-22

Analysis method

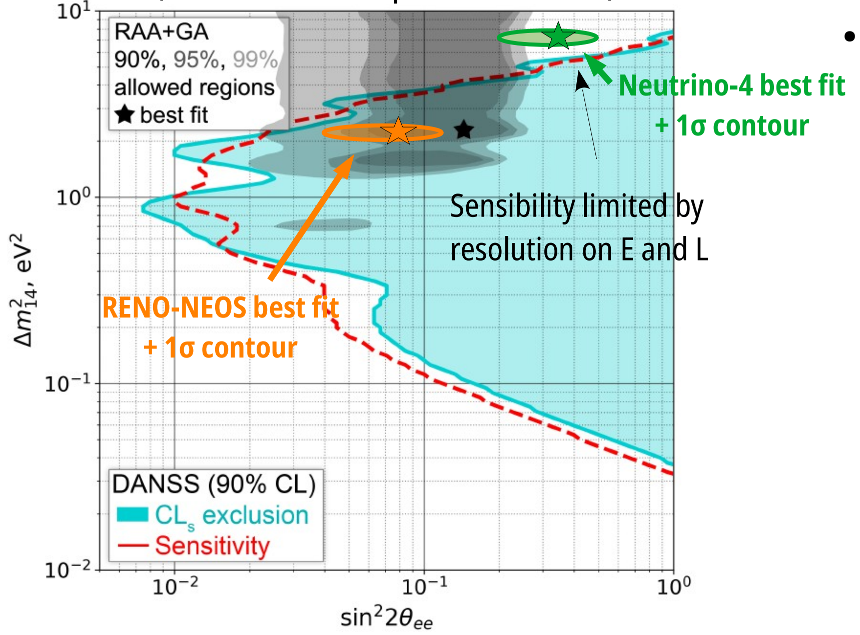
- Ratio of spectra at ≠ positions





Analysis results

(5M neutrinos – partial data set)



- **Rejection of the RAA + Gallium Anomaly**

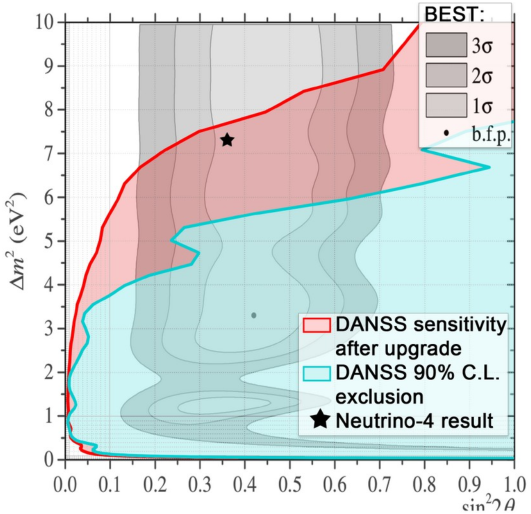
  best fit point exluded at >5σ

- RENO-NEOS best fit excluded at >90%CL

Upgrade plan

- Larger detector (x1.7 fiducial vol)
- Resolution 34%/√E → 13%/√E

  → sensitivity to higher Δm^2



≈1 yr for the upgrade
≈2 yr of data taking for
5-6M events

→ sensitivity to Neutrino-4 b.f. point

Very-short-baseline summary

- **The experimental challenge has been met** by the community to investigate L ≈ 10m oscillations !

- Segmented or movable detectors allows for **relative measurements** → **results independent of flux models**

- Reactor Antineutrino Anomaly parameter space **excluded at 95 % CL up to $\Delta m^2 \approx 5$ eV^2**, and 5-10 eV^2 region within PROSPECT-II sensitivity

- Neutrino-4 signal at $\Delta m^2 = 7.3$ eV^2, $\sin^2 2\theta = 0.36$ currently **excluded by PROSPECT (>95%CL)** and **STEREO (>3σ).** Neutrino-4, PROSPECT and DANSS upgrades will provide further insight by ≈2025

- RENO-NEOS combined analysis in tension with other experiments, but statistical significance is low (1.7σ)

Global picture and perspectives

Asset
Limitation
Upgrade

→ see talk by Jinyu Kim ←

Experiment	Solid	Neutrino-4	PROSPECT	STEREO	DANSS	NEOS
Power [MW]	40-80	90	85	58	3000	2800
Core type	compact	compact	compact	compact	large	large
Baseline [m]	6.3-8.9	6.4-11.9	6.7-9.2	9.4-11.2	10-12	23.7
Baseline comparison	segmentation	segmentation, movable	segmentation	segmentation	movable	none (RENO)
Scintillator mass/volume	1.6t	$1m^3$ $\sim 3m^3$	4t 4.8t	1.6t	$1m^3$ $1.7m^3$	$1m^3$
σ_E/E at 1 MeV [%]	12	25	5	9	34 13	4.8
Overburden [mwe]	8	3.5	0.5	15	50	20
S/B	1/3	0.54 $\sim$2	1.4 4.3	1.1	58	>20
	Analysis, data	Upgrade	Analysis, upgrade		Analysis, data, upgrade	

What is coming ?

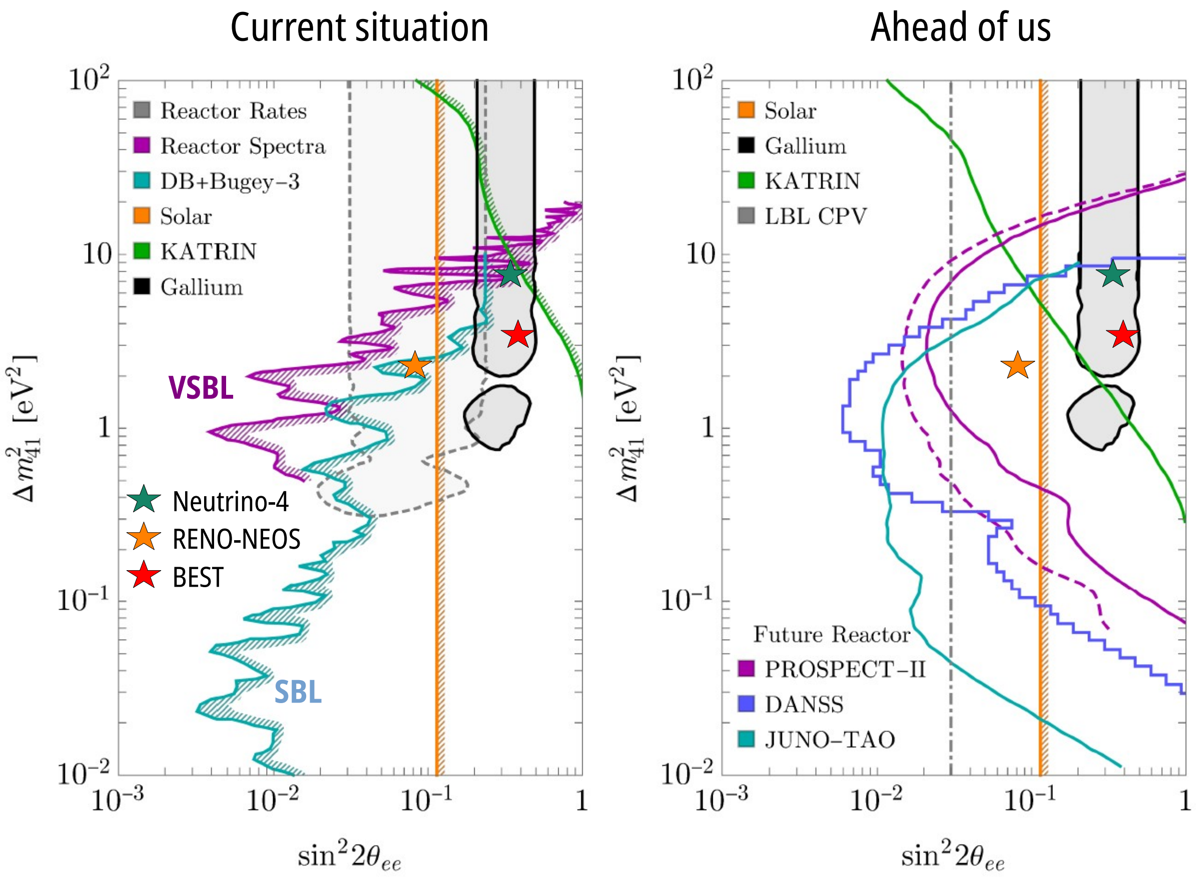
- **Analysis** → on-going analysis of already taken data
- **Data** → More data taking
- **Upgrade** → A future upgrade is planned

Experiment	Daya Bay	RENO	Double Chooz
Power [MW]	6 × 2900	6 × 2800	2 × 4250
Core type	large	large	large
Baseline [m]	550, 1600	300, 1380	400, 1050
Baseline comparison	ND vs FD	ND vs FD	ND vs FD
Scintillator mass/volume	8 × 20t	2 × 16t	2 × $10m^3$
σ_E/E at 1 MeV [%]	8	8	7
Overburden [mwe]	250, 860	120, 450	120, 300
S/B	50	40, 18	20, 11
	Analysis	Data	Analysis

PROSPECT, DANSS, Neutrino-4 upgrades will adress their limitations

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

Global picture and perspectives



Snowmass 2021 white paper 2203.07214

- **Complementary constraints** from SBL and VSBL allow to probe a large range of Δm^2
- KATRIN + Reactor constraints already **cover most of Gallium Anomaly parameters**
- **Reactor Anomaly** strength ($\leftrightarrow \sin^2\theta_{ee}$) still **depends on flux modelling**: not fully solved yet
- High-Δm^2 region of Reactor Anomaly will be covered by KATRIN
- Positive observations (BEST, Neutrino-4, RENO-NEOS) **in (strong) tension** with other experiments, to be confirmed in the next few years

Thank you !