Overview of reactor neutrinos

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Outline

- Reactor neutrinos – source and detection
- Oscillation probability
- Past measurements
- Future measurements
- Beyond standard oscillations
- Physics beyond oscillations
- Problems/discussions

Source

Flux of (anti)neutrinos from the beta decays of fissile nuclei and their unstable decay products

$$S_{\text{tot}}(E_\nu) = \sum_k f_k S_k(E_\nu)$$

Individual decay spectra of the various nuclei measured experimentally at ILL, France (1980s) : taken to be the 'standard' for the last ~35 years

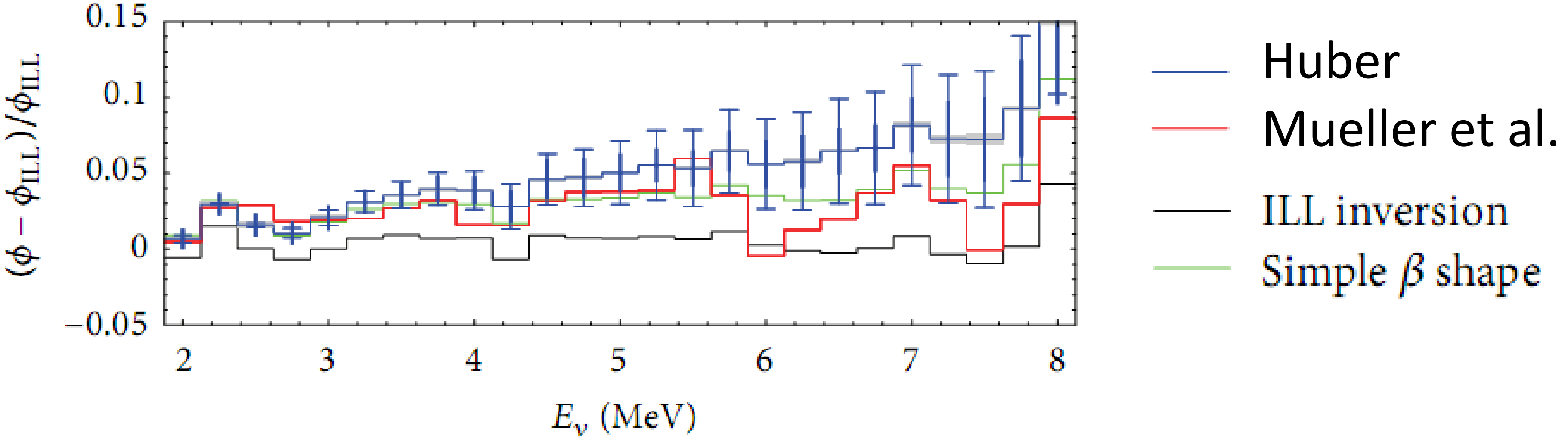
$$10^{20}\ \overline{\nu}_e\ \text{GW}^{-1}\text{s}^{-1}$$

The neutrino spectrum

- ILL measured the beta spectrum from the decay chain, and used this to reconstruct the neutrino spectrum
- This was done by introducing 30 ‘virtual branches’ with free parameters to be fitted to the data
- The sum of contributions from all the virtual branches matches the experimental data with a 3-4% error

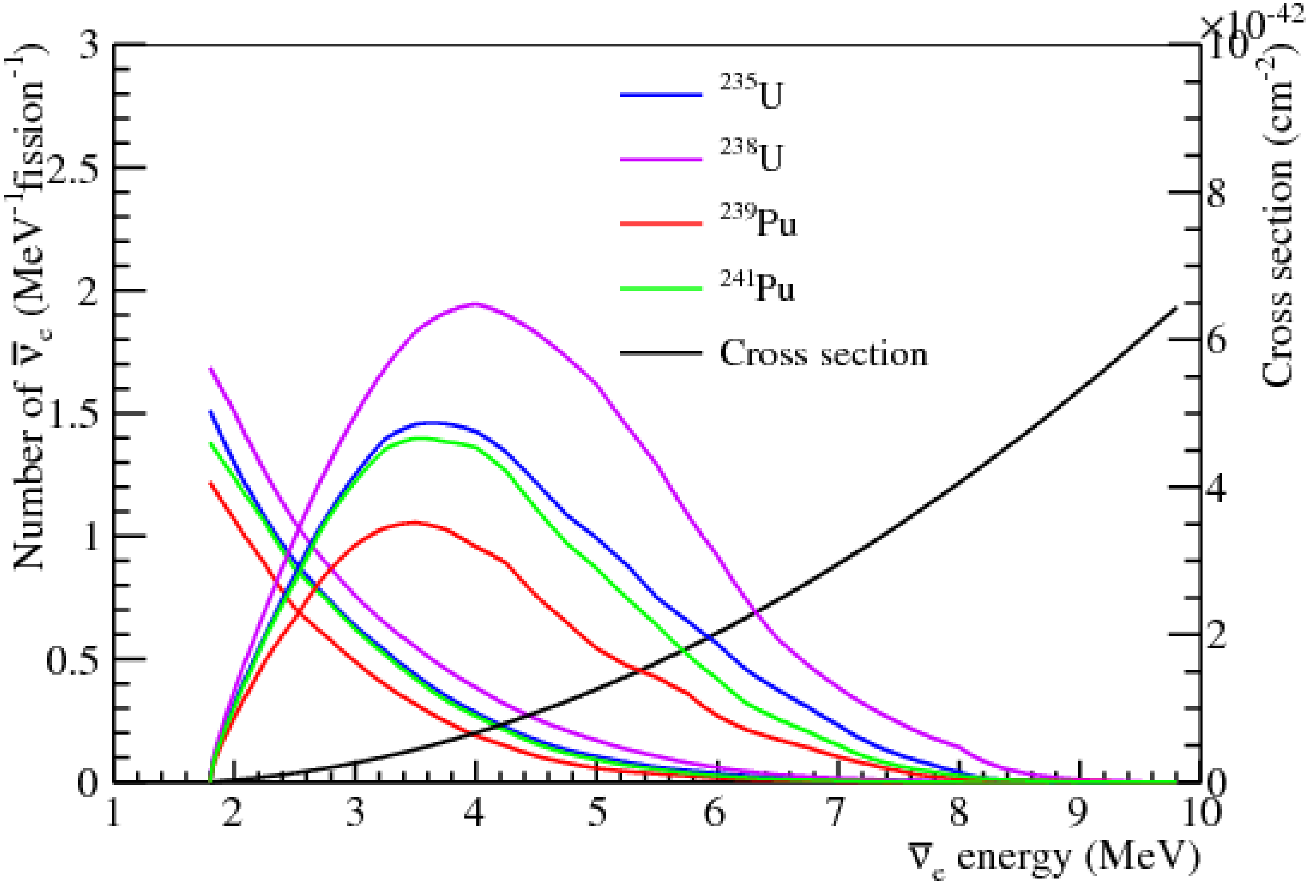
The reactor anomaly

- Mueller et al. performed an ab initio calculation of the neutrino flux and found an excess compared to experimental data
- Vogel et al. computed the flux using a hybrid method involving ab initio calculations + virtual branches and found a 3% excess over ILL (almost) independent of neutrino energy... can be explained using nuclear effects
- Huber revisited the ILL reconstruction using only virtual branches and updated nuclear corrections



Detection

Inverse beta decay: $\overline{\nu}_e + p \rightarrow e^+ + n$



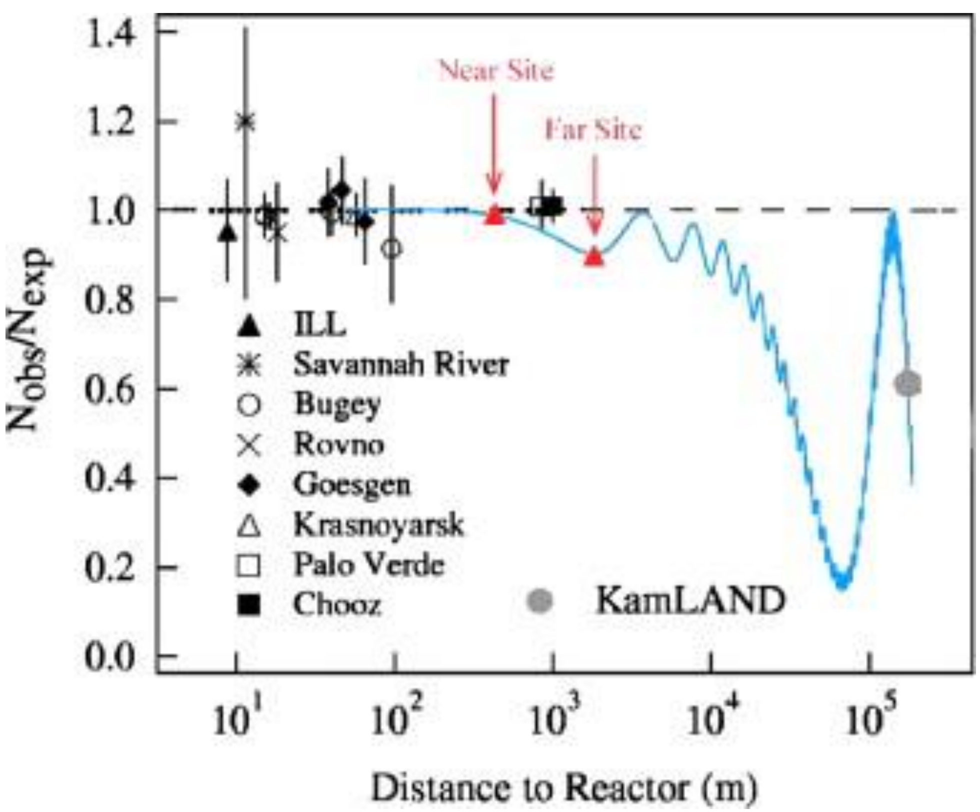
$e^+ e^-$ annihilation

Capture on nucleus

Oscillation probability

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

reactor parameters **solar parameters**



Oscillation probability

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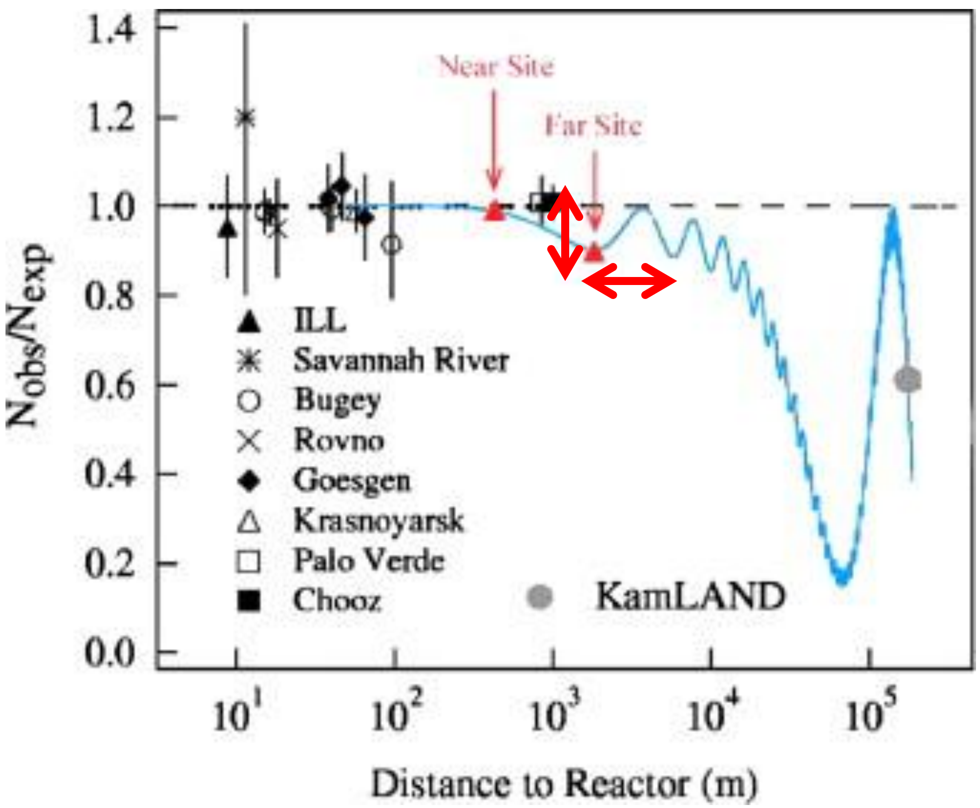
reactor parameters **solar parameters**

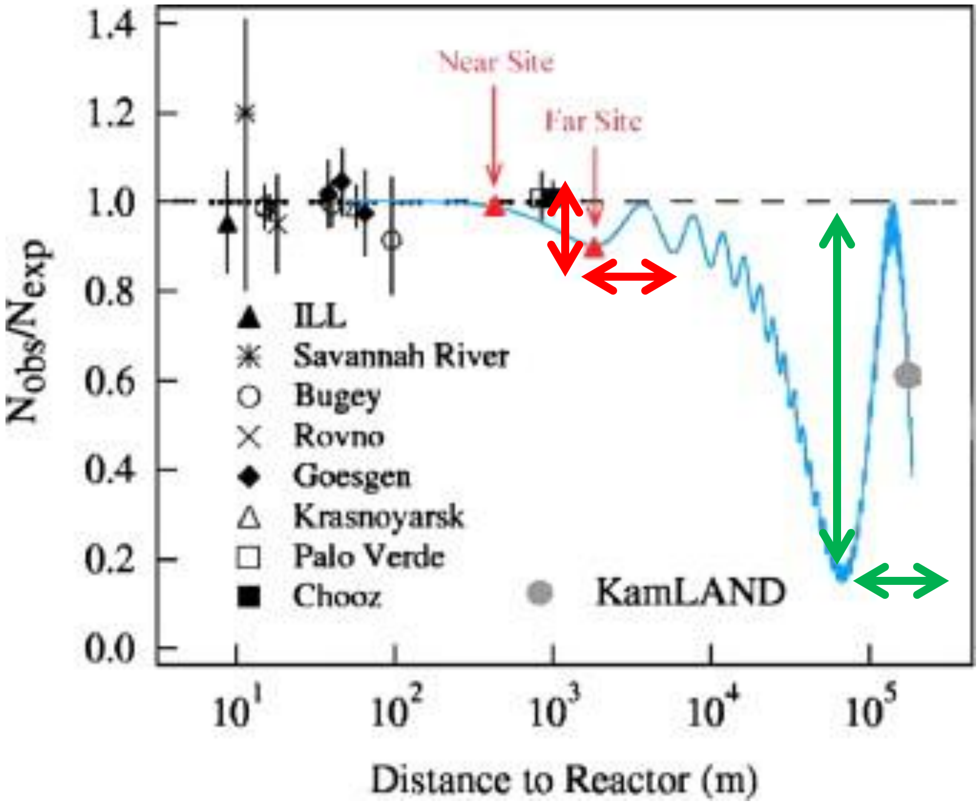


$$\Delta m^2_{31} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$$

Oscillation probability

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

reactor parameters **solar parameters**



$$\Delta m^2_{31} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{21} = 7.5 \times 10^{-5}\,\mathrm{eV}^2$$

Effective parameters

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\equiv 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right)$$

$$\Delta m_{ee}^2 = \Delta m_{31}^2 - \sin^2\theta_{12}\Delta m_{21}^2$$

Effective mass-squared difference relevant for electron neutrino disappearance experiments

Parke et al. 0503283

Past measurements

- KamLAND
  - 55 reactors in Japan
  - Flux-averaged baseline of 160 km

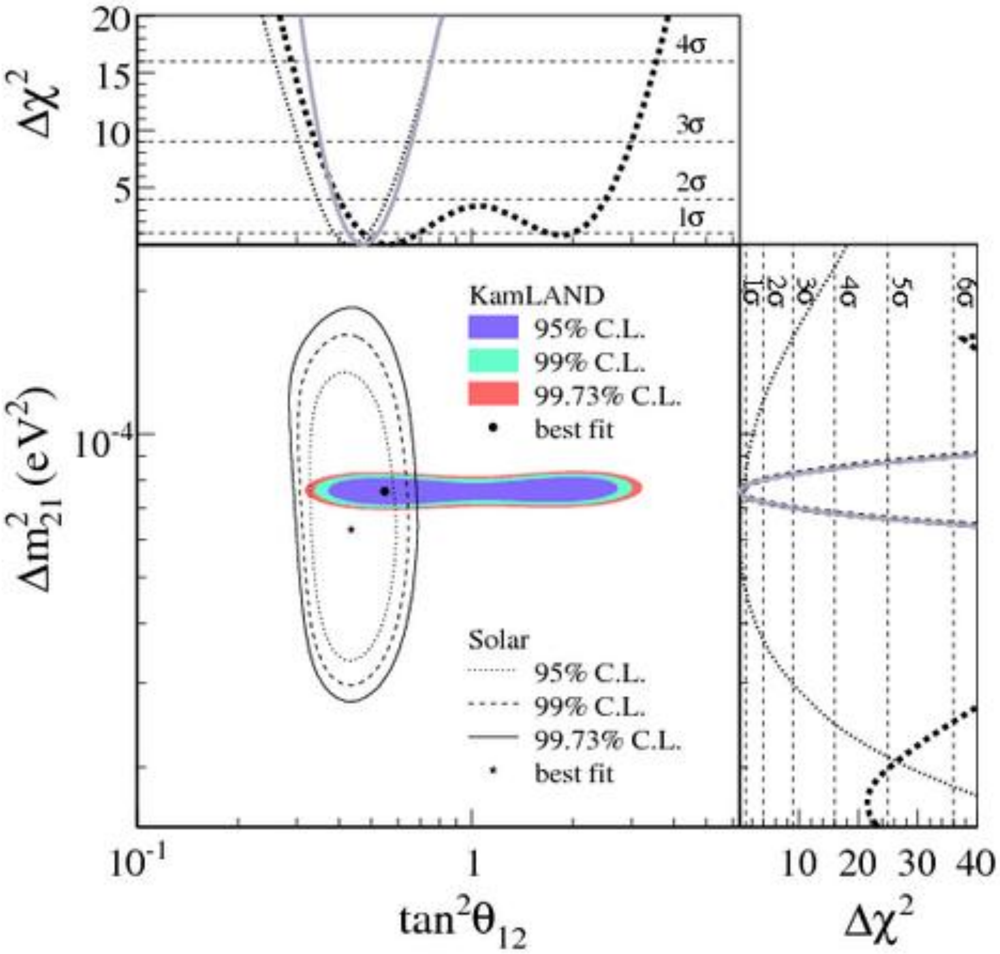
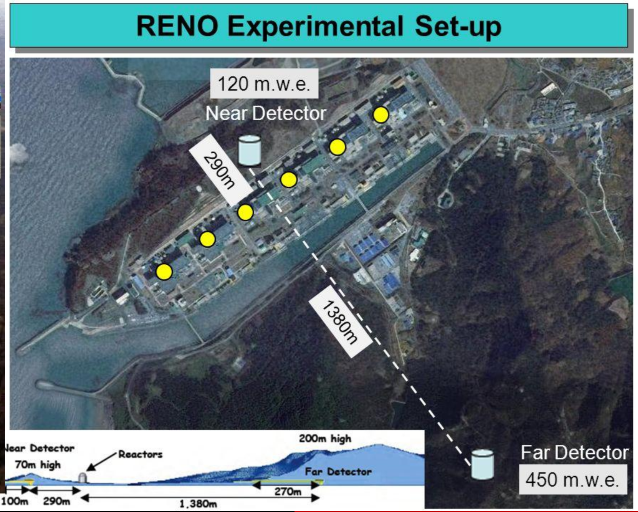
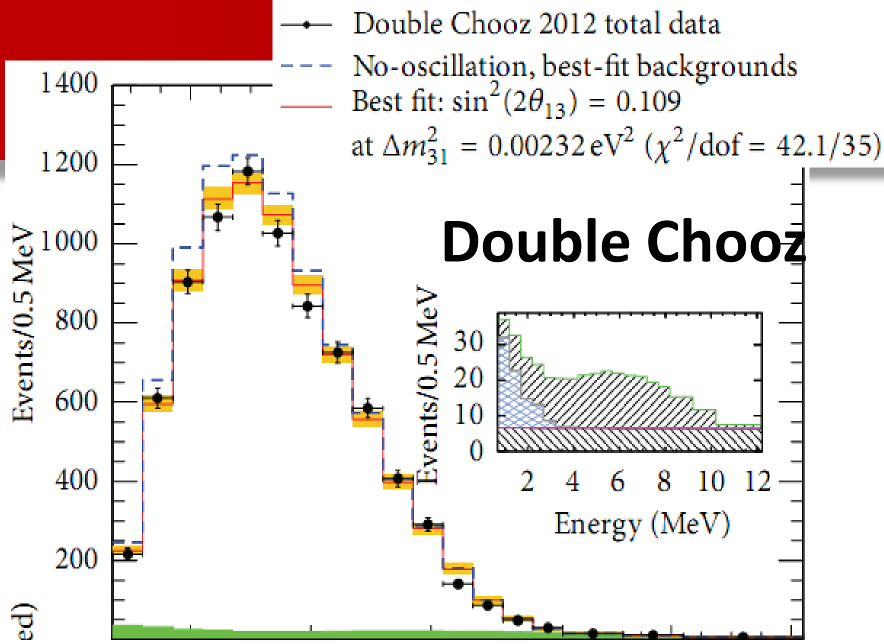


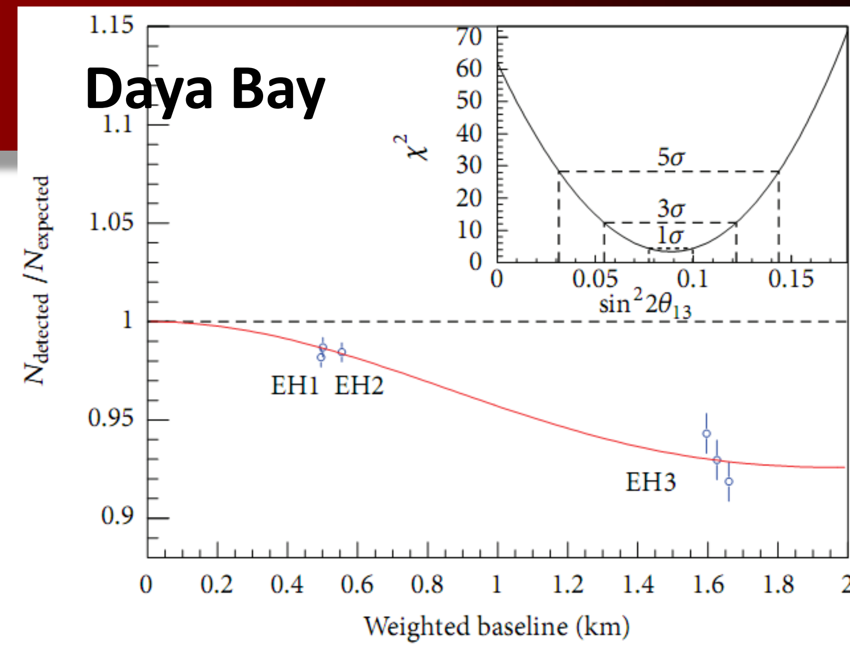
Table 1 | Key parameters of the reactor θ_{13} experiments.

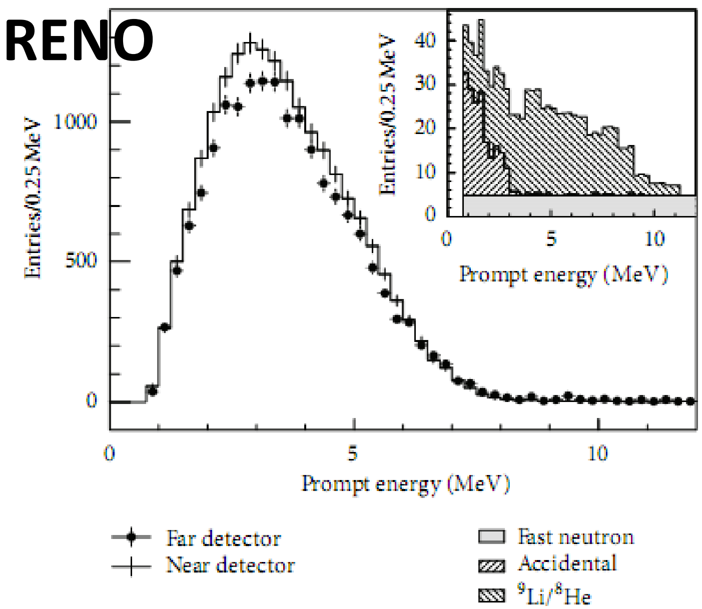
	Power (GW_{th})	Baseline (m)	Mass (ton)
CHOOZ[53]	8.5	1,050	5
PALO VERDE[54]	11.6	750-890	12
Double Chooz[23]	8.5	400	8
		1,050	8
RENO[22]	16.8	290	16
		1,380	16
Daya Bay[20]	17.4	360	2×20
		500	2×20
		1,580	4×20

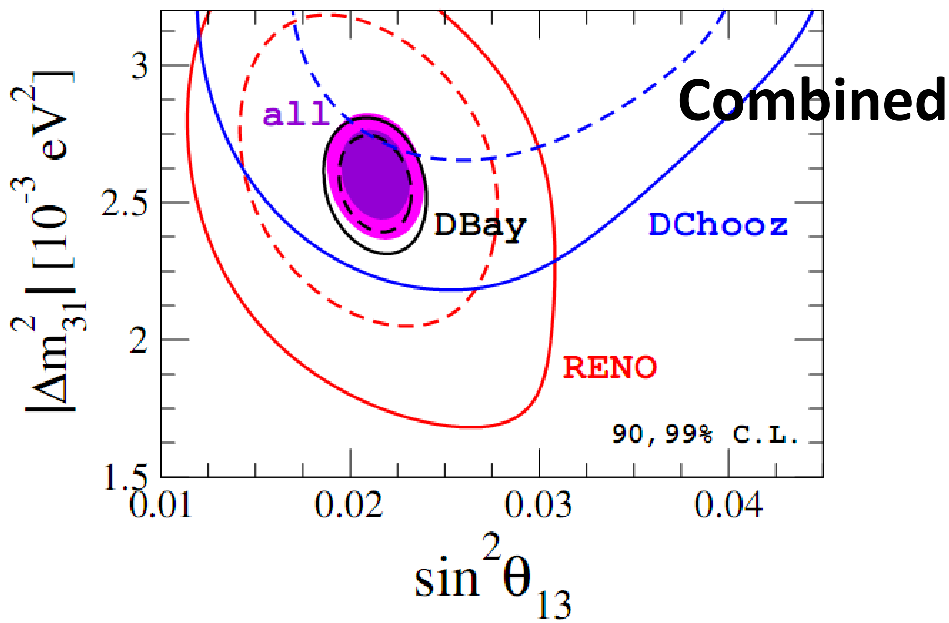
Vogel et al. 1503.01059

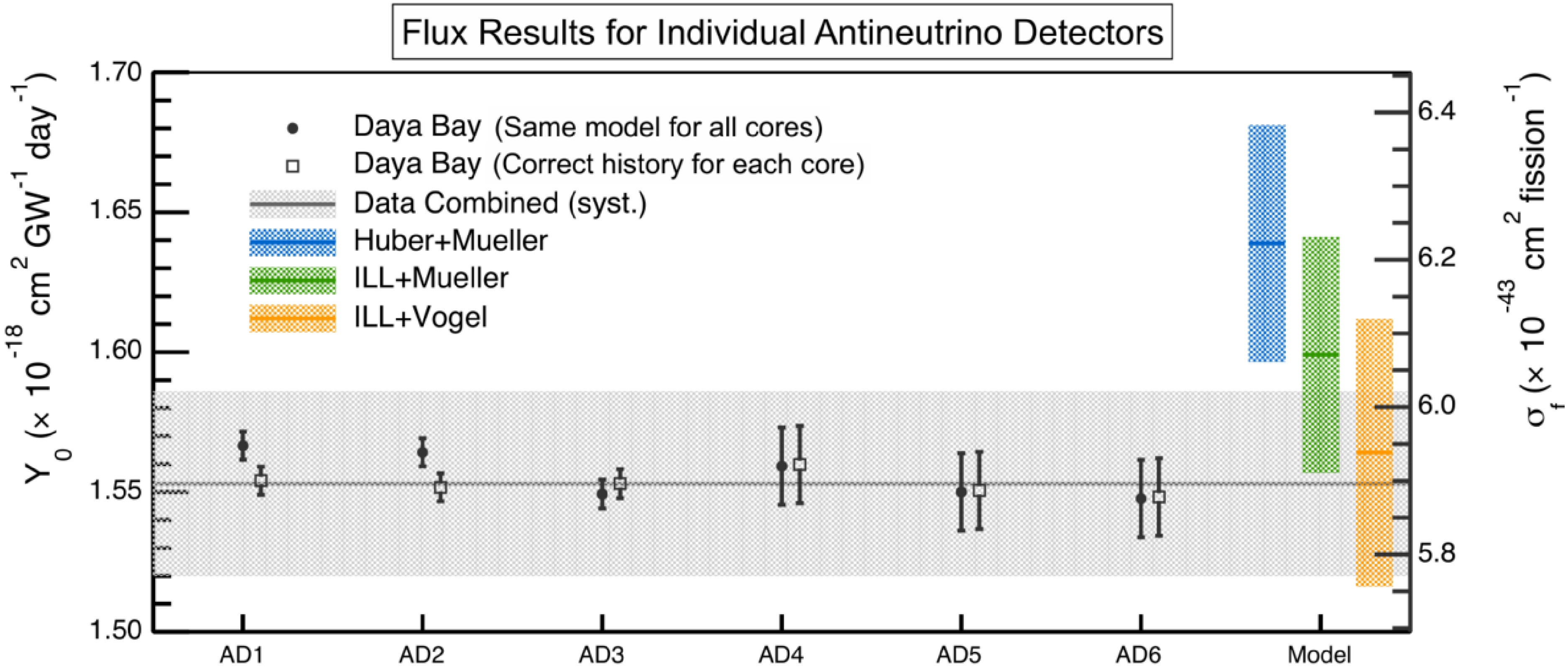



Double Chooz
Double Chooz 2012 total data
No-oscillation, best-fit backgrounds
Best fit: $\sin^2(2\theta_{13}) = 0.109$
at $\Delta m^2_{31} = 0.00232\,\mathrm{eV}^2$ ($\chi^2/\mathrm{dof} = 42.1/35$)
Events/0.5 MeV
Energy (MeV)


Daya Bay
$N_{\mathrm{detected}}/N_{\mathrm{expected}}$
χ^2
5σ
3σ
1σ
$\sin^2 2\theta_{13}$
EH1 EH2
EH3
Weighted baseline (km)


RENO
Entries/0.25 MeV
Prompt energy (MeV)
Far detector
Near detector
Fast neutron
Accidental
^{9}Li/^{8}He


Combined
all
DBay
DChooz
RENO
90, 99% C.L.
$|\Delta m^2_{31}|\,[10^{-3}\,\mathrm{eV}^2]$
$\sin^2\theta_{13}$

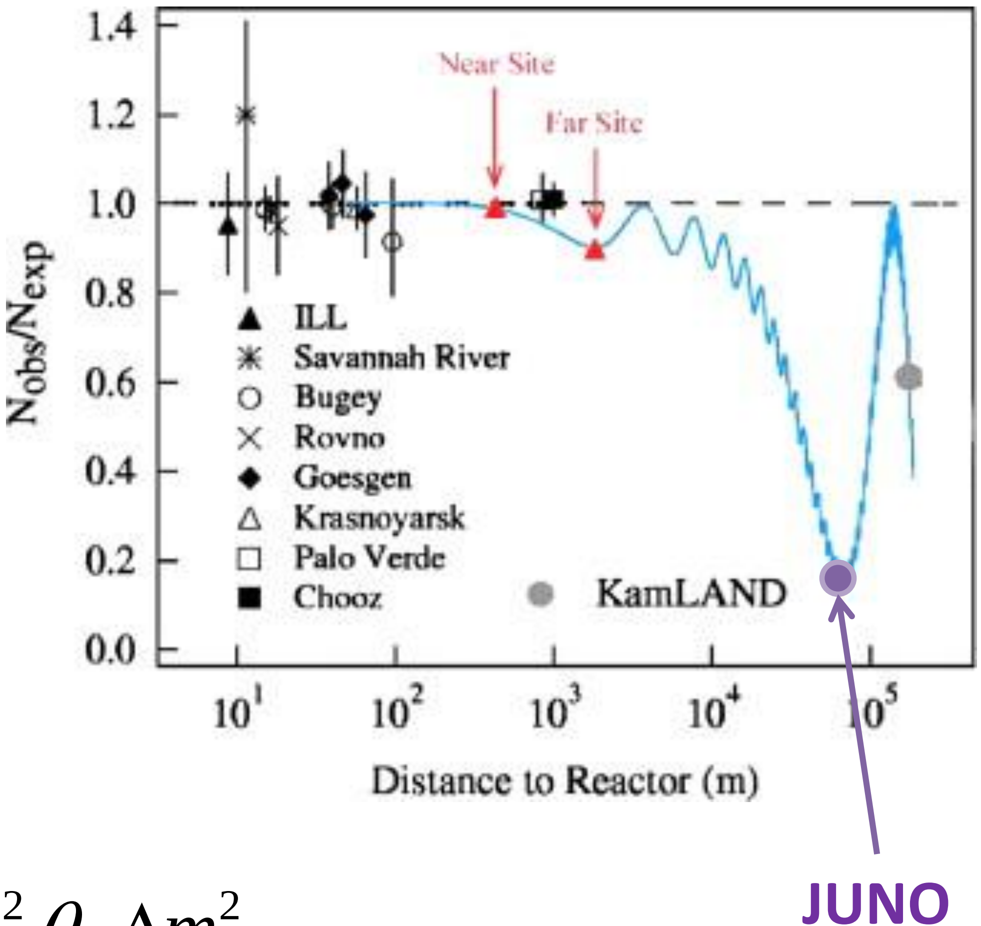


Flux Results for Individual Antineutrino Detectors
Daya Bay (Same model for all cores)
Daya Bay (Correct history for each core)
Data Combined (syst.)
Huber+Mueller
ILL+Mueller
ILL+Vogel
1.70
1.65
1.60
1.55
1.50
6.4
6.2
6.0
5.8
AD1
AD2
AD3
AD4
AD5
AD6
Model

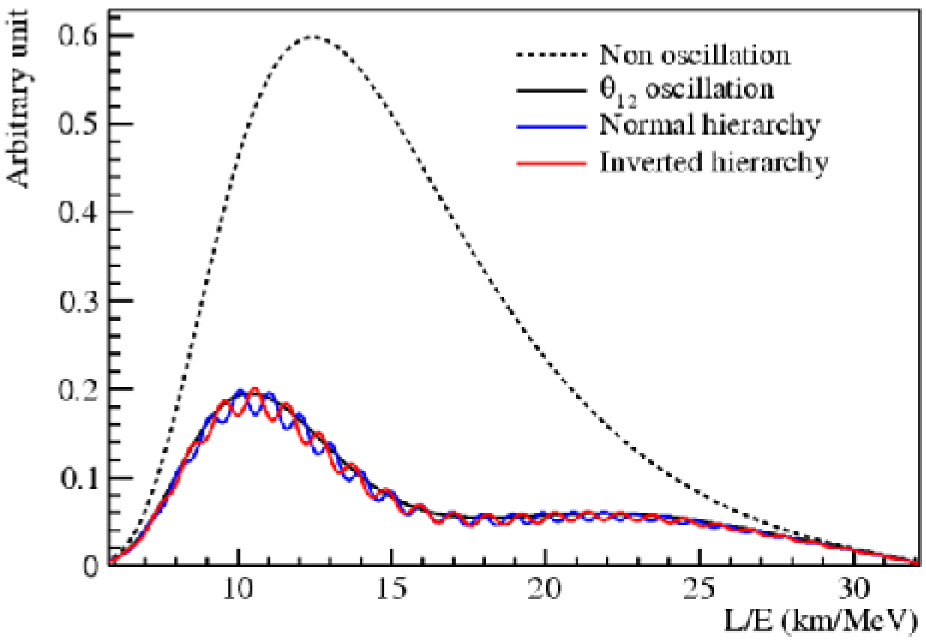
Future measurements

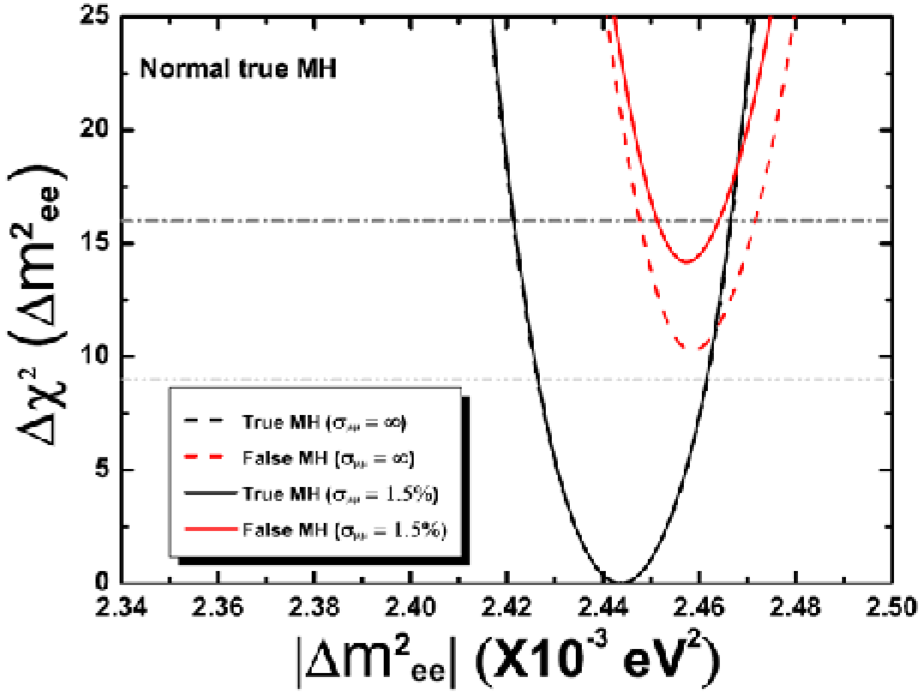
$$\Delta m_{ee}^2 = \Delta m_{31}^2 - \sin^2\theta_{12}\Delta m_{21}^2$$

Effective mass-squared difference relevant for electron neutrino disappearance experiments



$$\left(\Delta m_{31}^2\right)^{IH} = -\left(\Delta m_{31}^2\right)^{NH} + 2\sin^2\theta_{12}\Delta m_{21}^2$$



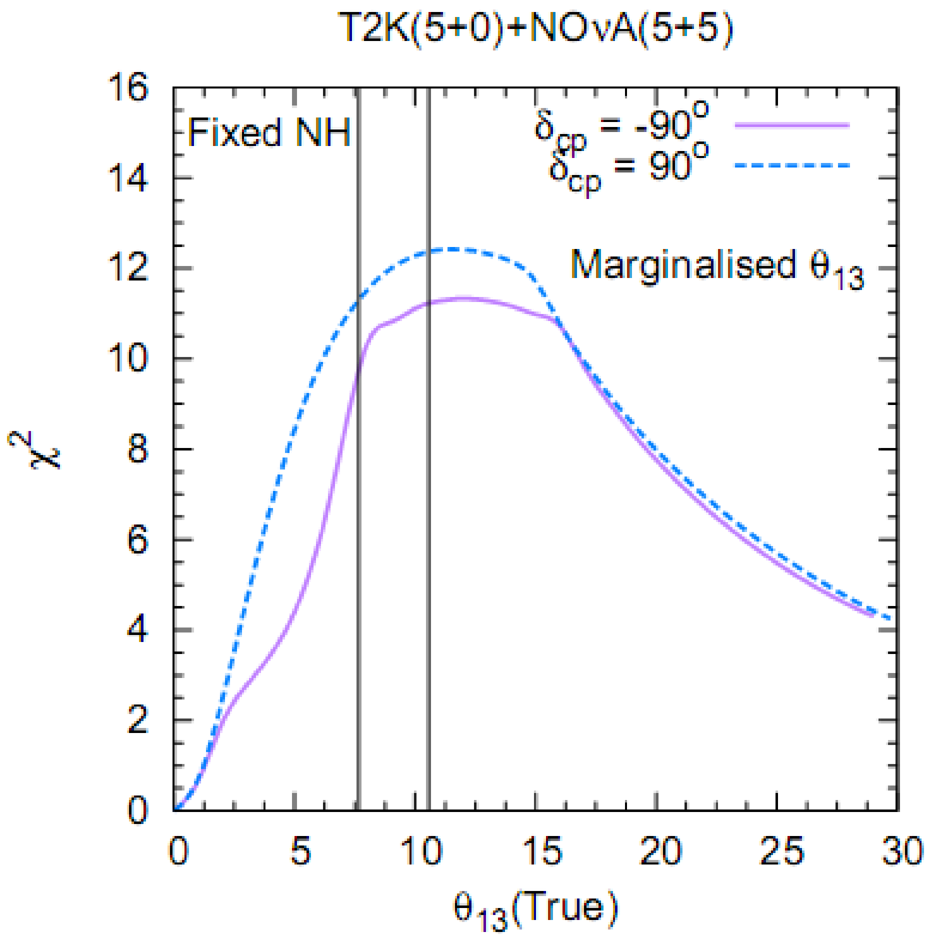


Good energy resolution crucial in order to resolve the wiggles

Sensitivity study at JUNO shows that a 20 kton detector with energy resolution of $3\%/\sqrt{E_{vis}(\mathrm{MeV})}$ is mandatory to achieve a significance of better than 3σ after 6 years

Synergies with other experiments

- CP Violation discovery



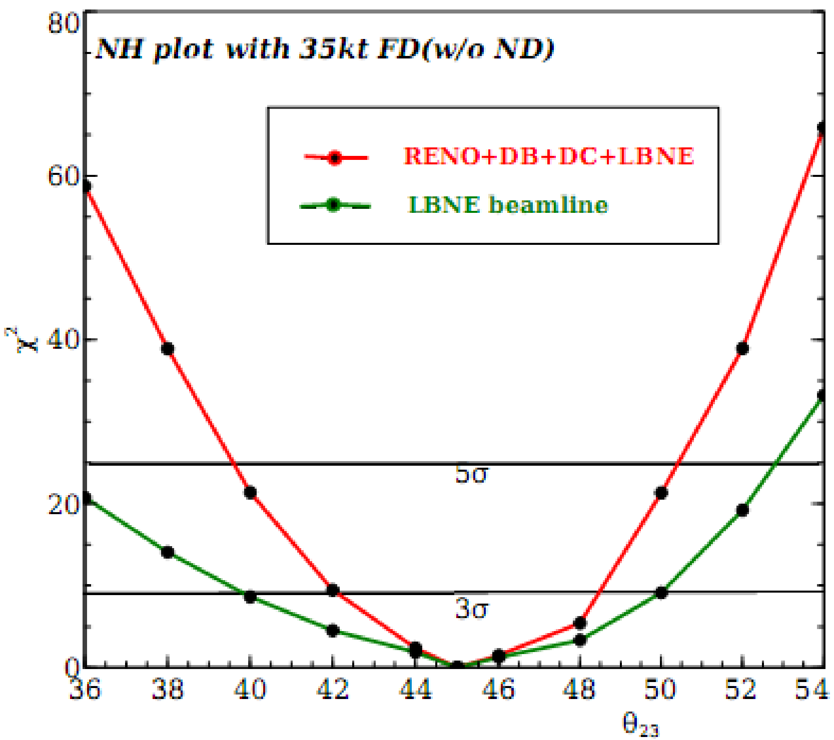
Ghosh et al. 1401.7243

Synergies with other experiments

- Octant sensitivity

Chatterjee et al. 1302.1370

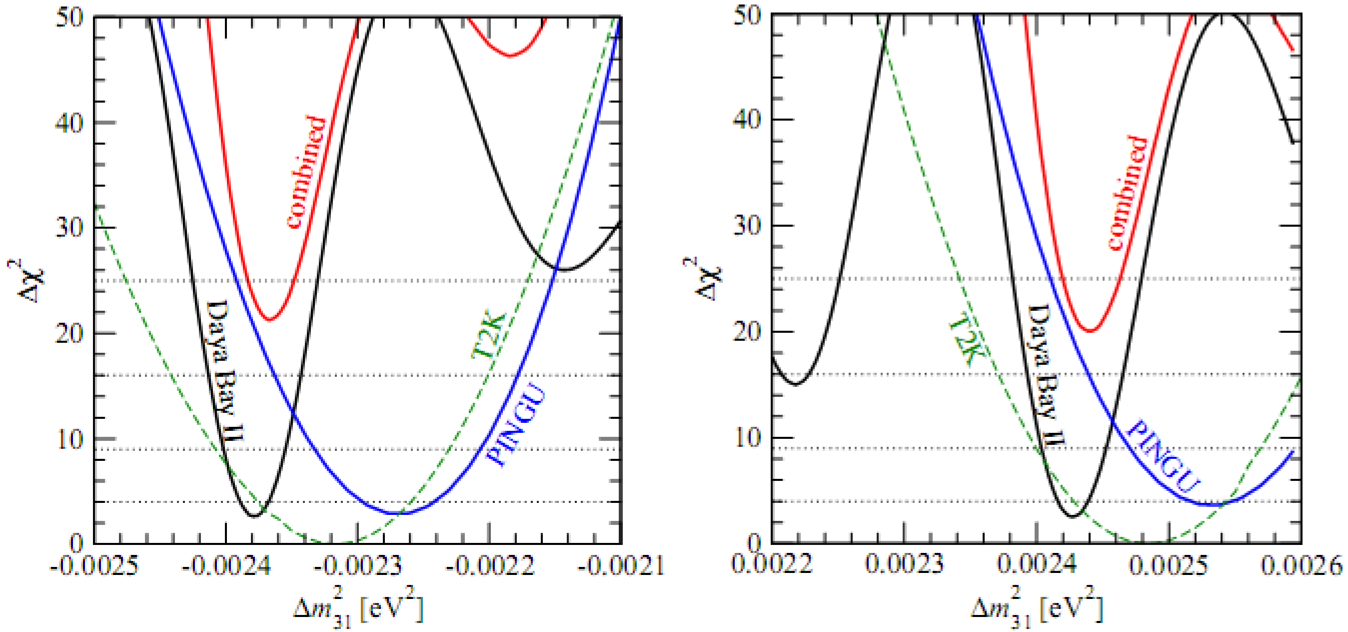
θ_{23}^{tr}	χ^2 (NOνA +T2K)	χ^2 (NOνA +T2K+prior)	χ^2 (NOνA +T2K+prior$_n$)
36	1.7 (5.8)	9.6 (14.8)	17.5 (26.7)
39	0.3 (0.6)	3.9 (7.3)	6.3 (12.0)
41	0.1 (0.1)	1.9 (3.6)	2.4 (5.4)
43	0.1 (0.1)	1.0 (0.8)	1.3 (1.1)
47	0.1 (0.1)	0.8 (1.0)	1.0 (1.3)
49	0.3 (0.5)	3.8 (2.3)	5.4 (3.1)
51	2.9 (1.5)	8.5 (6.0)	13.0 (8.2)
54	14.7 (9.4)	21.5 (16.1)	32.4 (22.6)



Bora et al. 1405.7482

$$\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right)$$
$$= 4\cos^2\theta_{13}\sin^2\theta_{23}(1 - \cos^2\theta_{13}\sin^2\theta_{23})$$

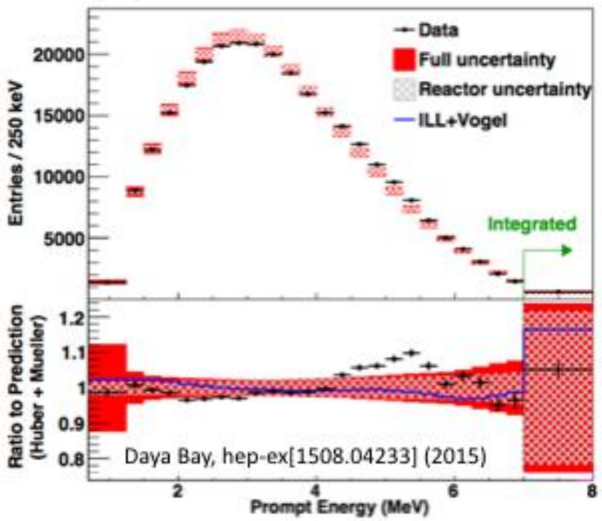
Synergies with other experiments



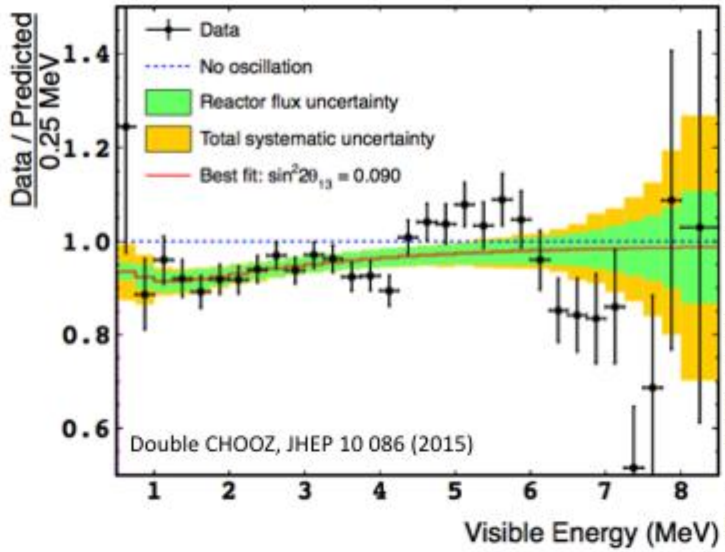
Blennow et al. 1306.3988

Figure 6: $\Delta\chi^2$ as a function of Δm^2_{31} with the wrong sign for PINGU, Daya Bay II, and the combination. For PINGU we assume 1 year of data with $\sigma_E = 2$ GeV and $\sigma_{\theta_\nu} = \sqrt{1\,\mathrm{GeV}/E_\nu}$, statistical errors only, and we minimize with respect to δ but keep all other oscillation parameters fixed. For Daya Bay II we take an exposure of 1000 kt GW yr and assume an energy resolution of $\sigma_E = 3.5\%\sqrt{1\,\mathrm{MeV}/E}$. The dashed curves corresponds to 5 years of neutrino data at 0.77 MW from T2K (not included in the "combined" curve). We take the true values $|\Delta m^2_{31}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.092$, $\sin^2\theta_{23} = 0.5$, $\delta = 0$, $\Delta m^2_{21} = 7.59 \cdot 10^{-5}$ eV^2. For the left (right) panel the true mass ordering is normal (inverted).

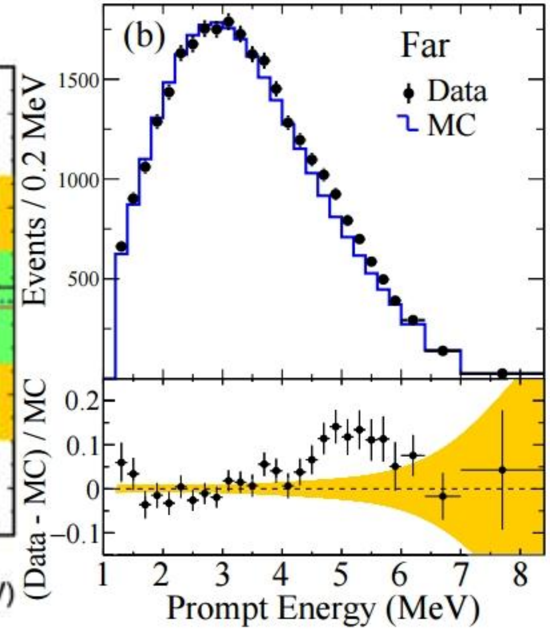
The 5 MeV excess



Daya Bay



Double Chooz

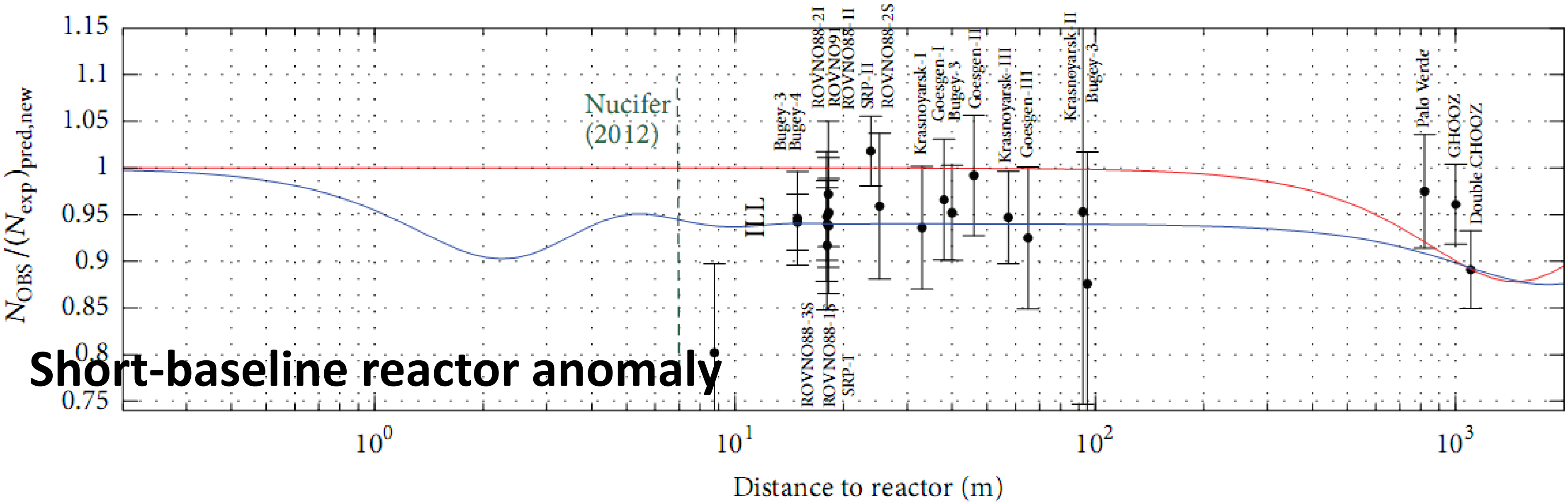


RENO

Excess correlated with beam power

New physics?

Other anomalies



Short-baseline reactor anomaly

	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_B	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R^k_H	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

Gallium anomaly

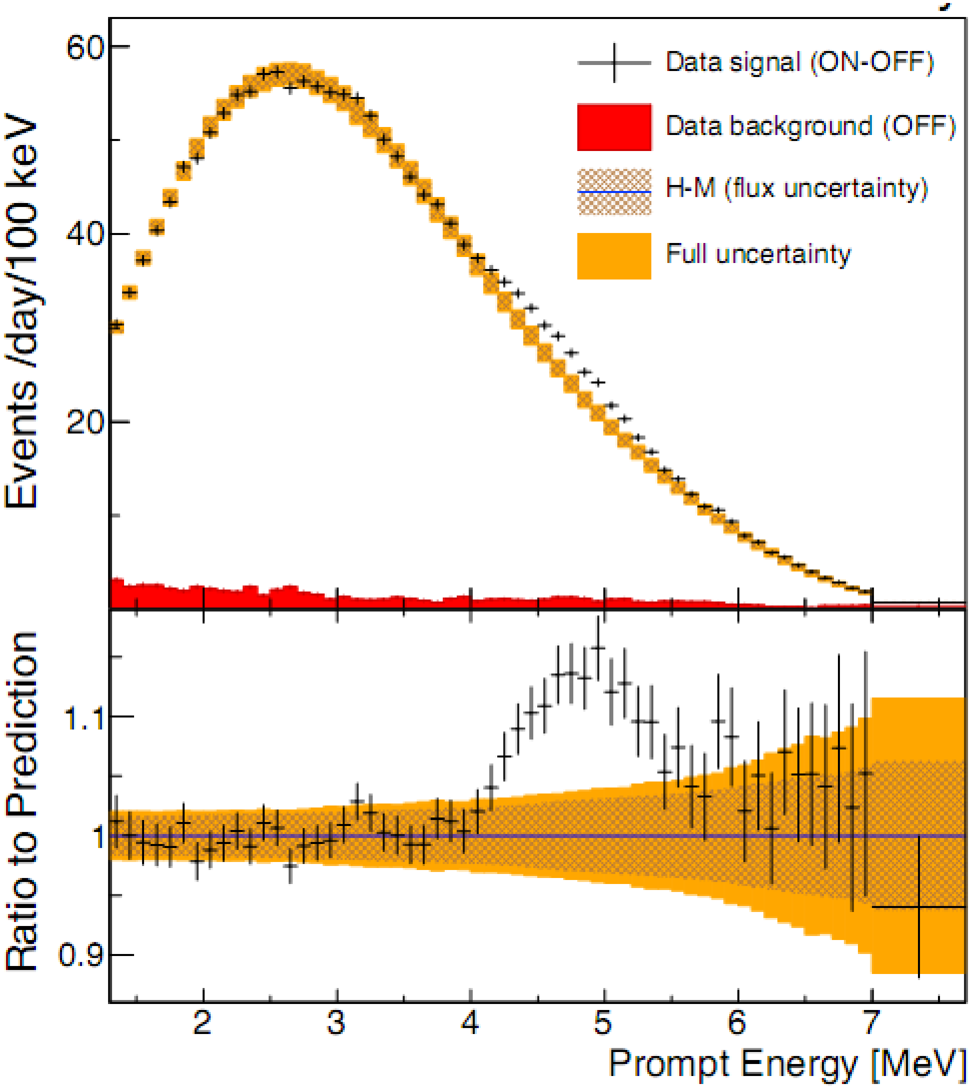
Sterile neutrino searches

NEOS (Korea): L = 24 m

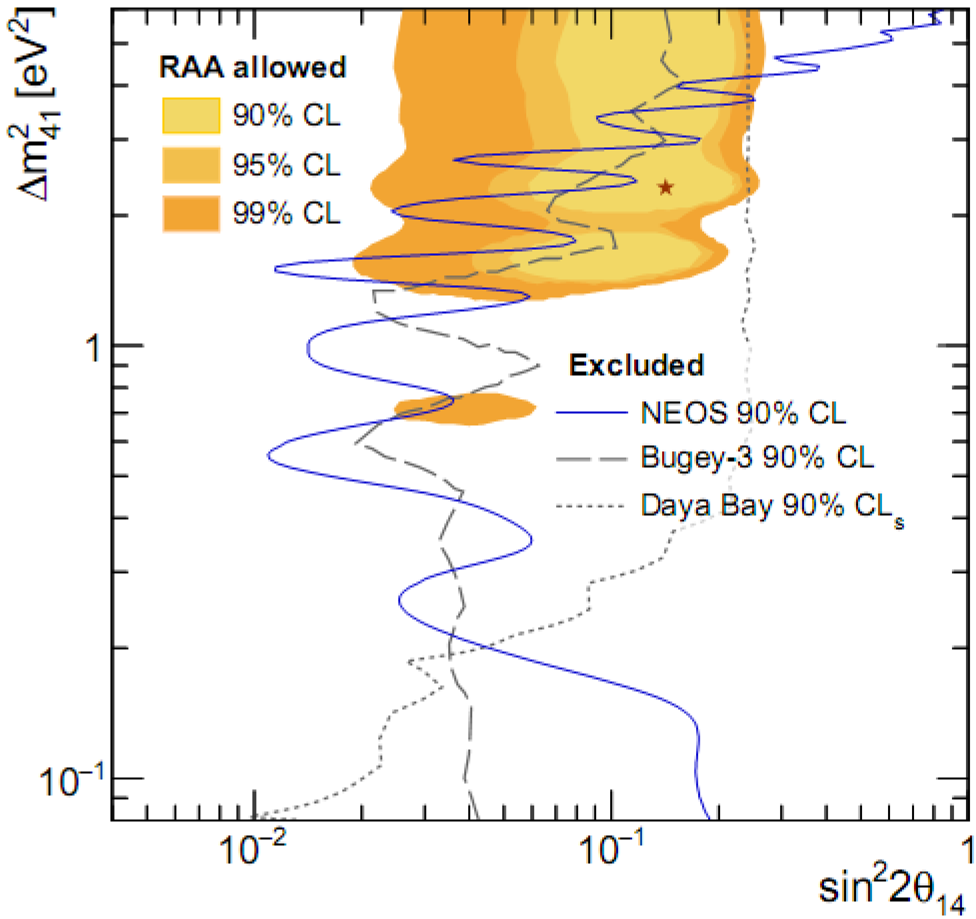
Oh, ICHEP 2016

NEOS + DayaBay
combined analysis → Pu-239 and Pu-241 are disfavoured as single sources of the 5 MeV excess

Huber 1609.03910



Sterile neutrino searches

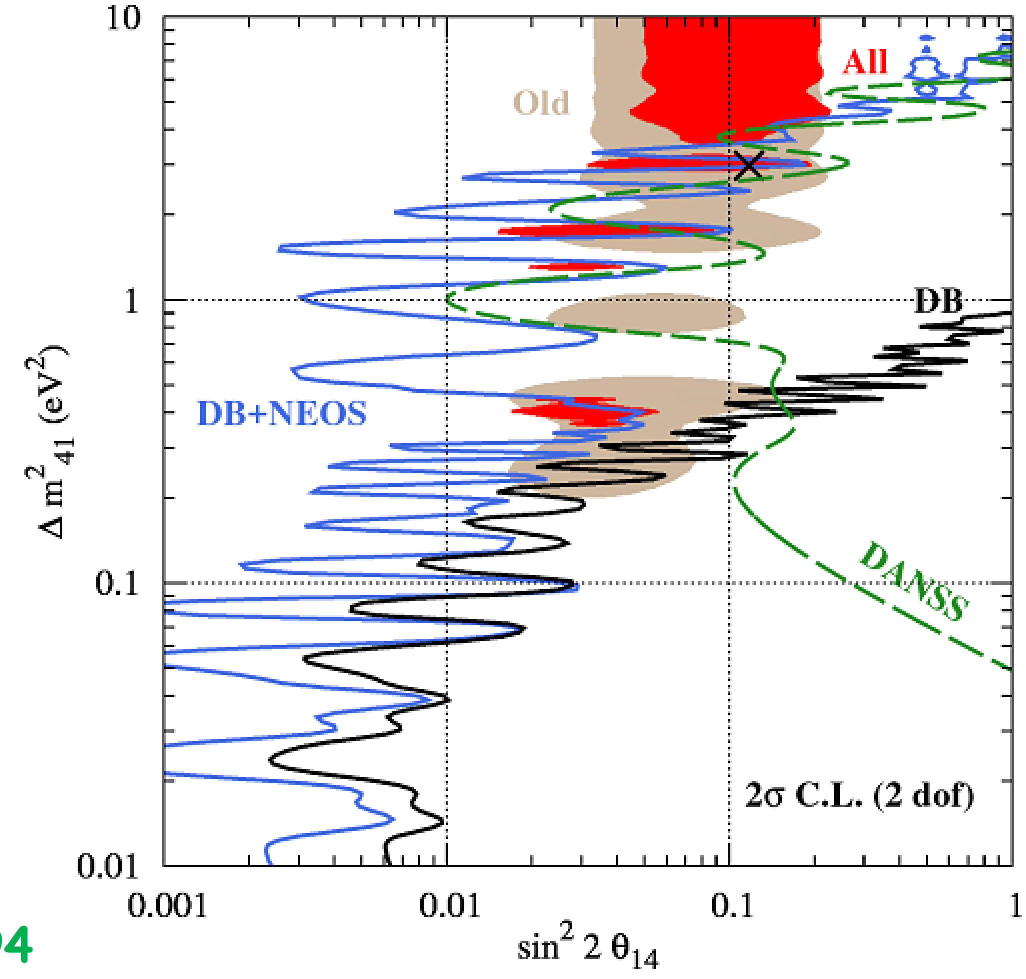


Ko et al. 1610.05134

Sterile neutrino searches

- DANSS (Russia)

  Mobile detector (L around 10 m)

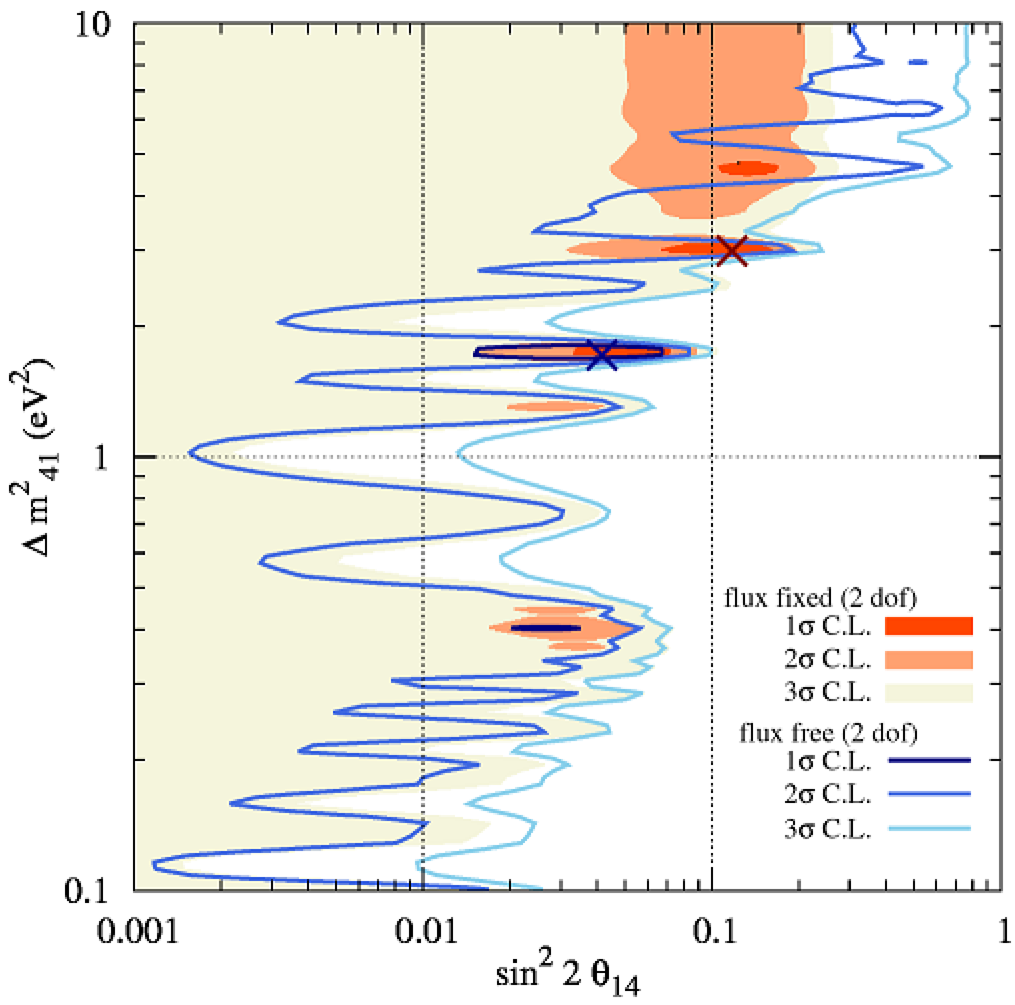


Dentler et al. 1709.04294

Sterile neutrino searches

Closed contour at 1 sigma, even with flux free

Dentler et al. 1709.04294



NSI searches

Daya Bay data	$\sin^2\theta_{13}$	$\lvert\varepsilon\rvert$
electron-type NSI parameters [ϕ_e free]		
Current (621 days)	$0.020 \leq \sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon_e\rvert$ unbound
Previous (217 days)	$0.019 \leq \sin^2\theta_{13} \leq 0.027$	$\lvert\varepsilon_e\rvert$ unbound
muon or tau-type NSI parameters [$(\delta - \phi_{\mu,\tau})$ free]		
Current (621 days)	$0.013 \leq \sin^2\theta_{13} \leq 0.036$	$\lvert\varepsilon_{\mu,\tau}\rvert \leq 0.052$
Previous (217 days)	$0.011 \leq \sin^2\theta_{13} \leq 0.045$	$\lvert\varepsilon_{\mu,\tau}\rvert \leq 0.070$
universal NSI parameters [δ free, $\phi = 0$]		
Current (621 days)	$0.020 \leq \sin^2\theta_{13} \leq 0.025$	$\lvert\varepsilon\rvert \leq 0.0013$
Previous (217 days)	$0.019 \leq \sin^2\theta_{13} \leq 0.028$	$\lvert\varepsilon\rvert \leq 0.0024$
universal NSI parameters [$\delta = 0$, ϕ free]		
Current (621 days)	$\sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon\rvert \leq 0.110$
Previous (217 days)	$\sin^2\theta_{13} \leq 0.026$	$\lvert\varepsilon\rvert \leq 0.116$

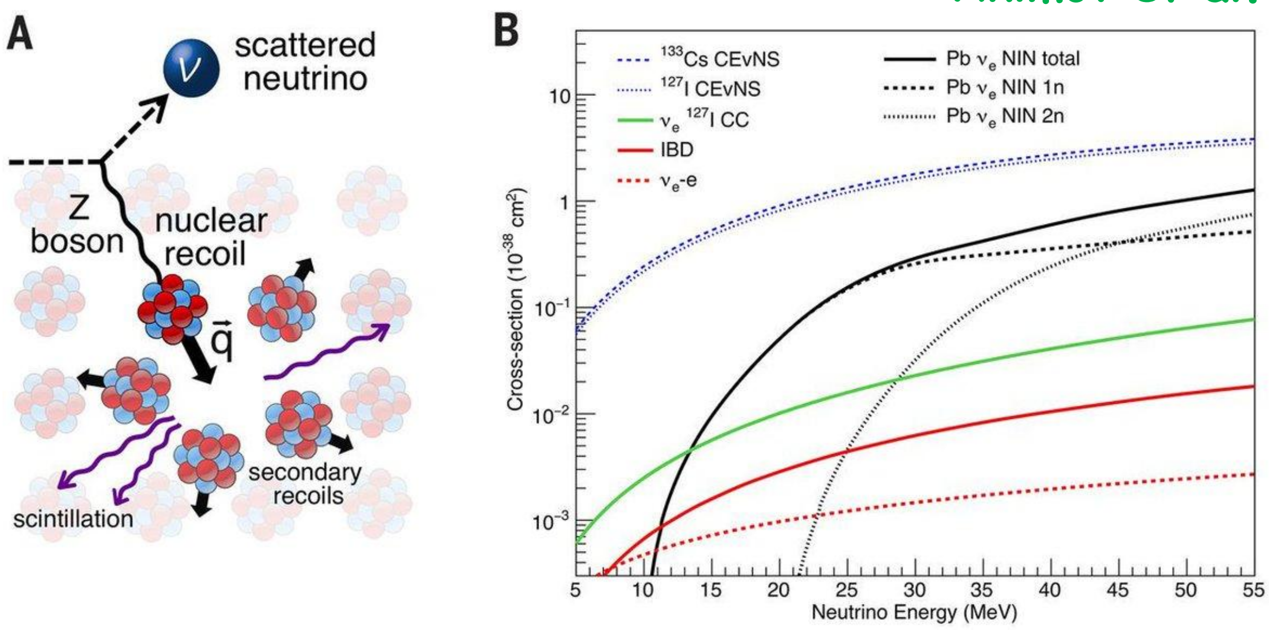
Agarwalla et al. 1412.1064

Neutrino scattering

Coherent elastic ν-nucleus scattering (CEvNS):

Predicted in SM; has only recently been measured at a DAR expt

Akimov et al. 1708.01294



Probe new physics at low energy, eg. NSIs and sterile neutrinos.

High flux at reactors can offset the small cross-section

Billard et al. 1612.09035

Neutrino magnetic moment, etc

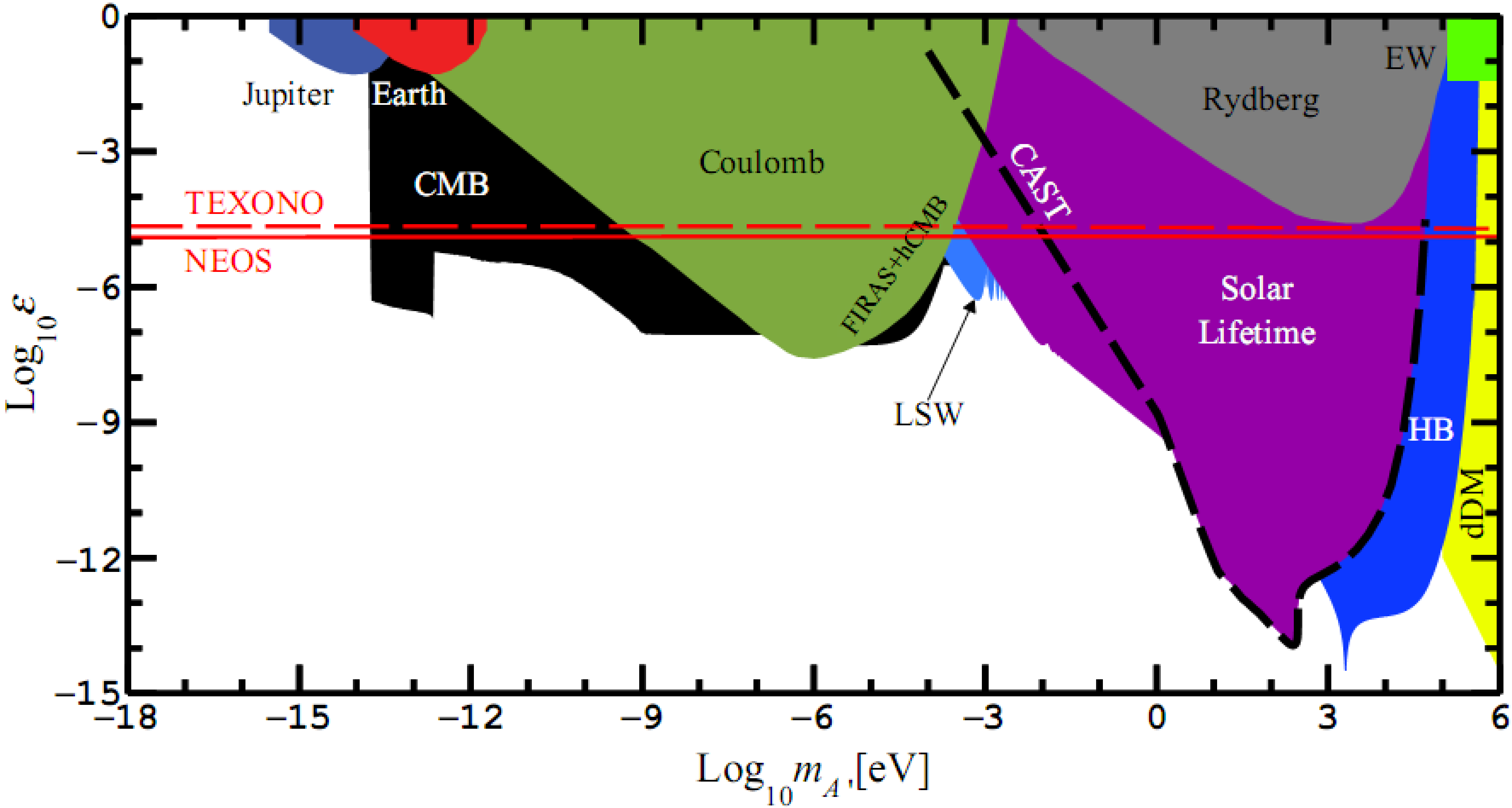
Table 1: Summary of the sensitivities obtained for $\sin^2\theta_W$ (1σ) and for the EM neutrino parameters (90% C.L.) at the TEXONO experiment. The results refer to various sensitivities and quenching factors. Comparing with Ref. [24] one sees that a substantial improvement in the sensitivity for the weak mixing angle $\sin^2\theta_W$, the magnetic moment $\mu_{\bar{\nu}_e}$ parameter and the neutrino charge-radius $\langle r^2_{\bar{\nu}_e}\rangle$ w.r.t. the COHERENT proposal.

	COHERENT [24]	TEXONO (this work)					
(Target, Threshold)	(100 kg ^{76}Ge, 10 keV$_{ee}$)	(1 kg ^{76}Ge, 100 eV$_{ee}$)					
Efficiency	67%	100%			50%		
Quenching	$Q_f = 1$	$Q_f = 1$	$Q_f = 0.20$	$Q_f = 0.25$	$Q_f = 1$	$Q_f = 0.20$	$Q_f = 0.25$
$\delta s^2_W(\bar{\nu}_e)$	0.0055	0.0010	0.0033	0.0025	0.0014	0.0046	0.0035
Uncer. (100%)	2.36	0.43	1.41	1.08	0.61	1.97	1.51
$\mu_{\bar{\nu}_e} \times 10^{-10}\,\mu_B$	9.46	0.40	0.98	0.83	0.47	1.17	0.99
$\langle r^2_{\bar{\nu}_e}\rangle \times 10^{-32}$ cm^2	-0.38 – 0.37	-0.07 – 0.07	-0.22 – 0.22	-0.17 – 0.17	-0.10 – 0.10	-0.32 – 0.31	-0.24 – 0.24

Kosmas et al. 1506.08377

Chen et al. 1411.0574

Dark photon limits



Park 1705.02470

Some questions

- Synergy of neutrino oscillation experiments with NEOS/DANSS in measuring sterile parameters/measuring standard parameters in spite of steriles
- Particle physics origin of the 5 MeV bump?
- CC-NSI searches at extremely short-baseline reactor experiments like DANSS (zero-distance effect)
- Constraining particular new physics models with CEvNS data