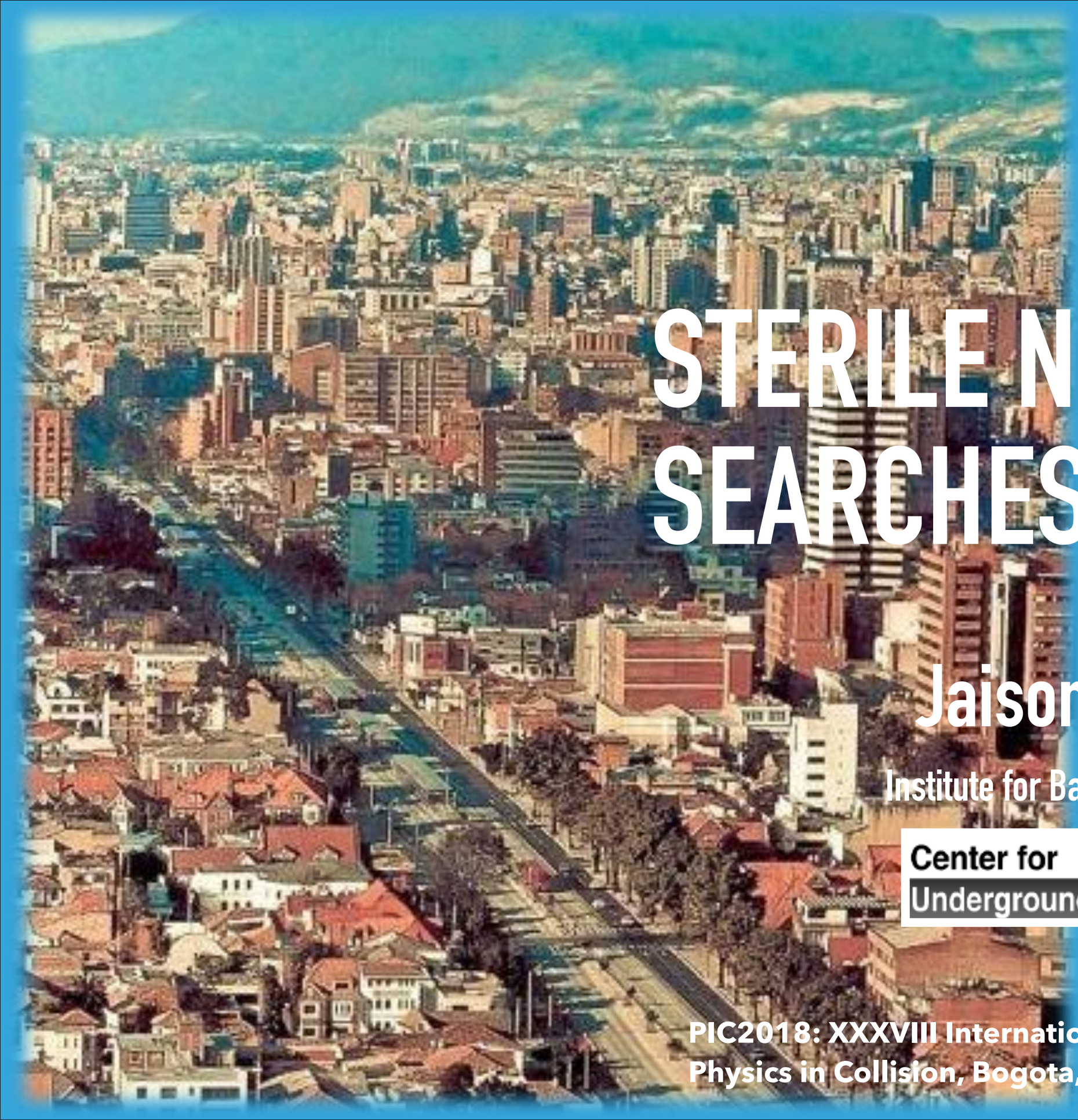


STERILE NEUTRINO SEARCHES

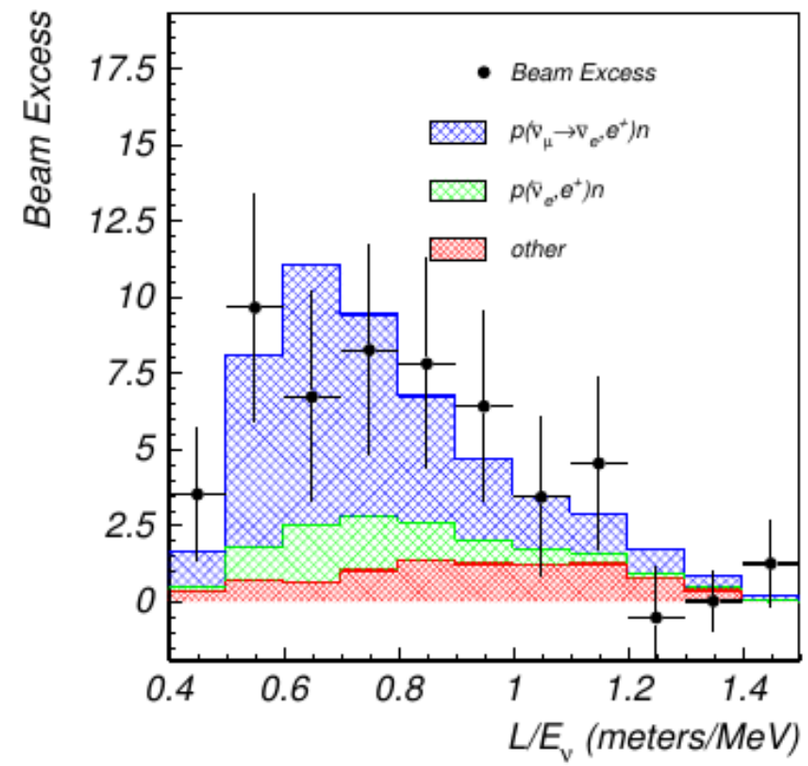
Jaison Lee

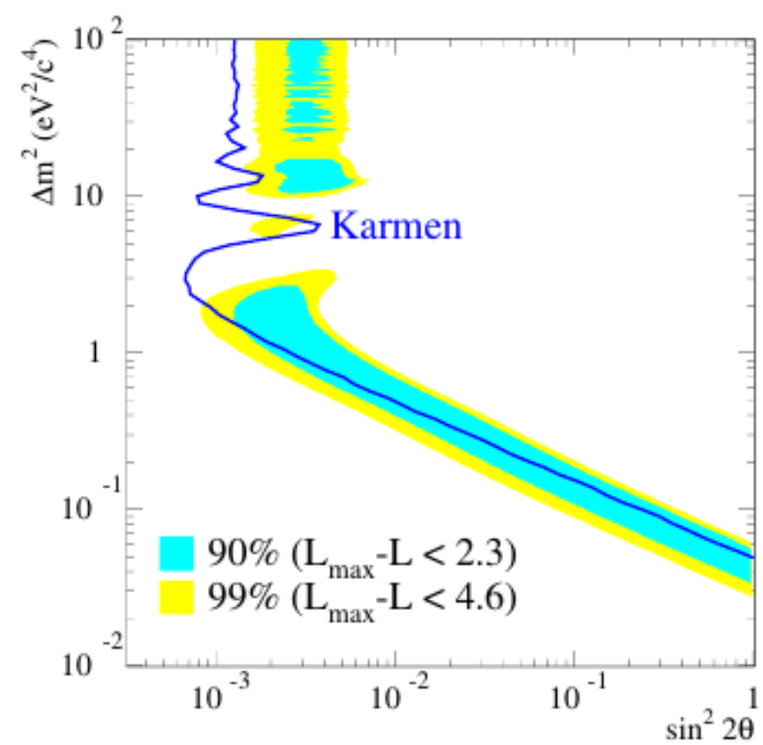
Institute for Basic Science

Center for Underground Physics

PIC2018: XXXVIII International Symposium on Physics in Collision, Bogota, Columbia

- The **LSND** experiment observed an excess of events in a beam.
- The **Karmen** collaboration did not confirm the claim, but couldn't fully exclude it either.
- The signal is compatible with **neutrino oscillation** $\Delta m^2 \geq 0.1\text{eV}^2$.
- To explain **LSND** result, one needs **new neutrino mass eigenstates**.





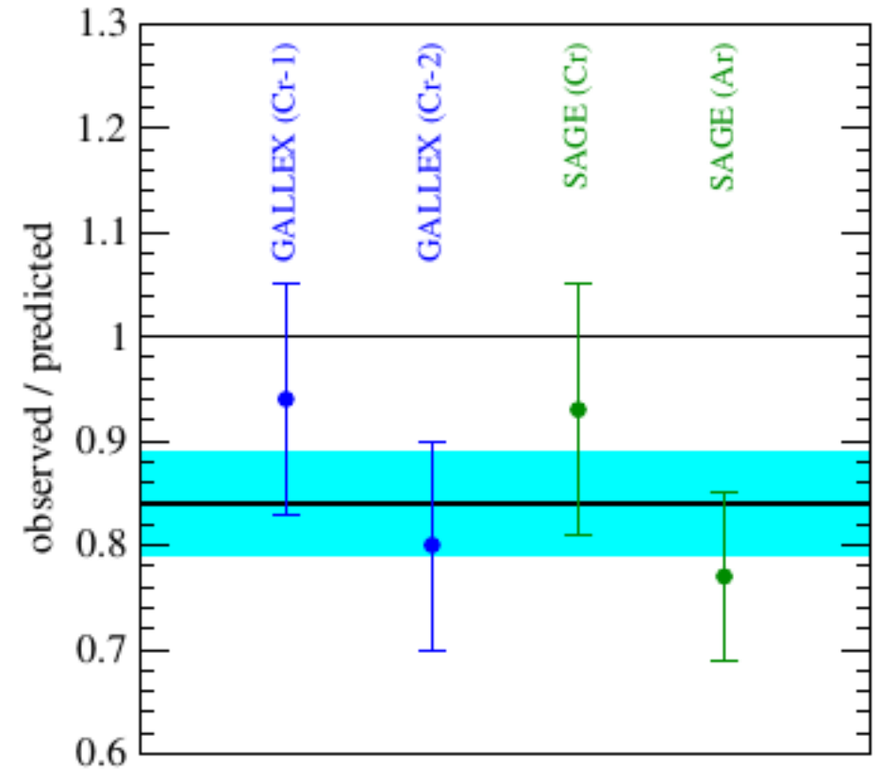
A. Aguilar-Arevalo *et al*. [LSND collab], Phys. Rev. D 64 (2001) 112007 [hep-ex/0104049].
B. Armbruster *et al*. [KARMEN collab], Phys. Rev. D 65 (2002) 112001 [hep-ex/0203021].

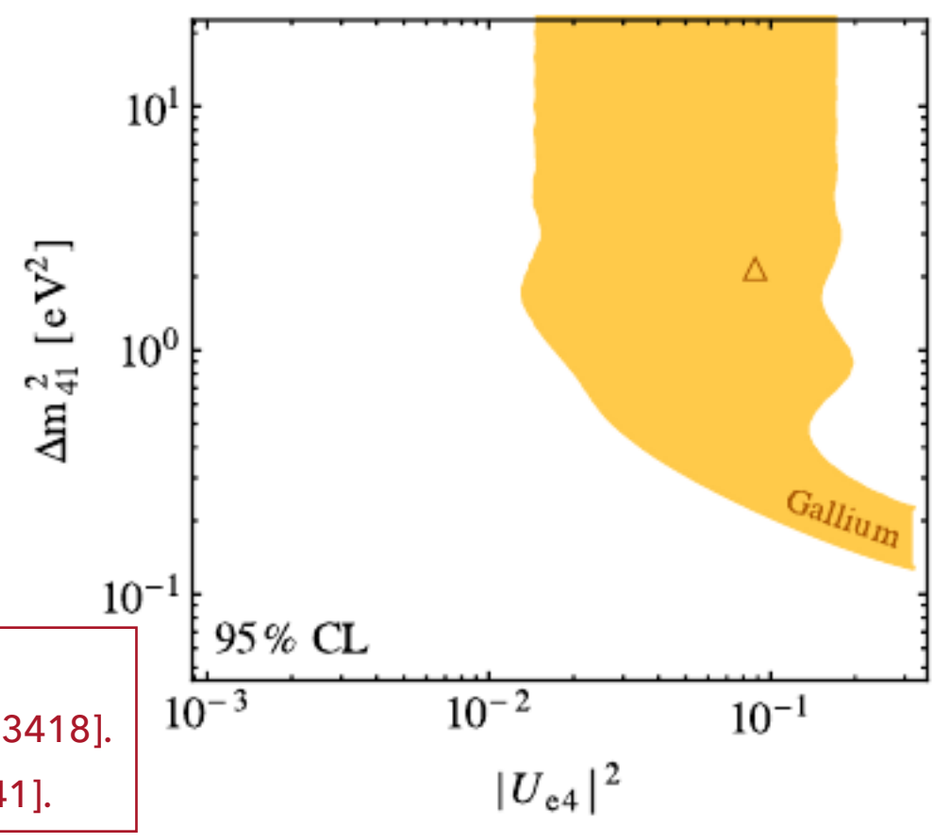
- The **GALLEX** and **SAGE** solar neutrino experiments were calibrated with intense neutrino sources 51**Cr** and 37**Ar**.

- These measurements show a **significant deficit** with respect to the predicted values:

$$R = 0.84 \pm 0.05$$

- 3σ deficit can be interpreted by **neutrino oscillation**, $\Delta m^2 \geq 1\text{eV}^2$





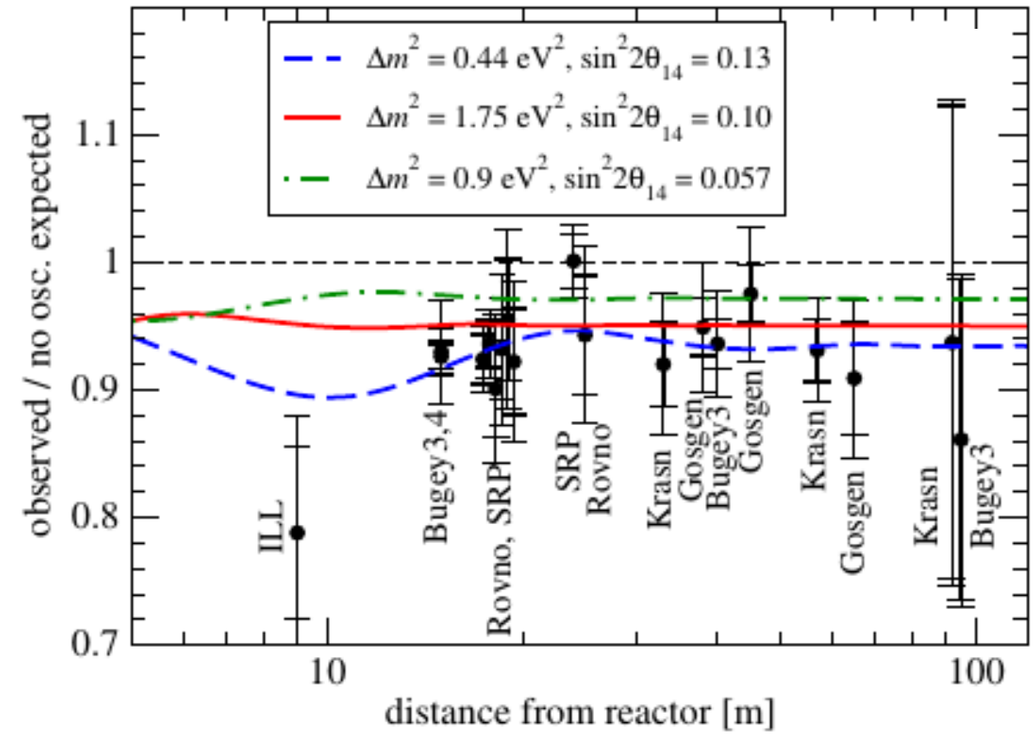
F. Kaether et al., Phys. Lett. B685 (2010) 47–54 [arXiv:1001.2731].
J. Abdurashitov et al. [SAGE collab], Phys. Rev. C59 (1999) 2246–2263 [hep-ph/9803418].
J. Abdurashitov et al. [SAGE collab], Phys. Rev. C73 (2006) 045805 [nucl-ex/0512041].

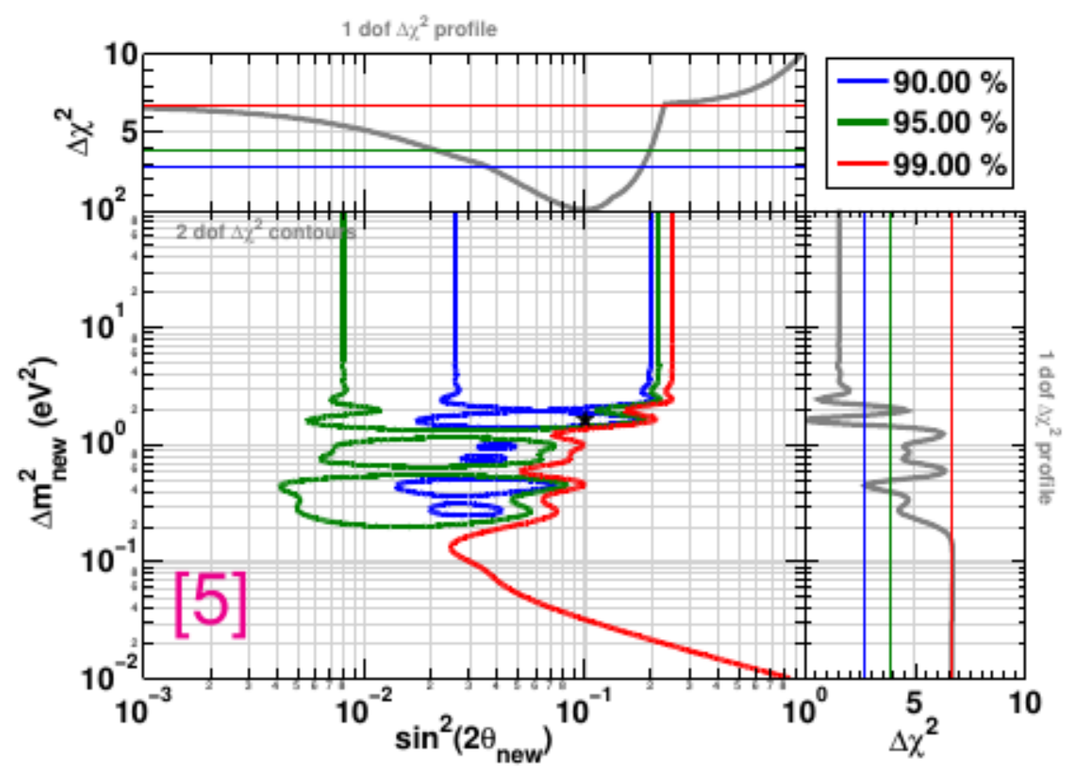
REACTOR ANTINEUTRINO ANOMALY

- The reactor neutrino flux was reevaluated, this calculation result in a small increase of the flux by about 3.5%.
- All reactor short-baseline experiment are actually observing a deficit.

$$R = 0.927 \pm 0.023$$

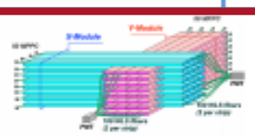
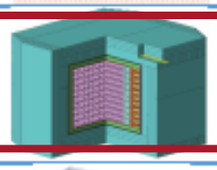
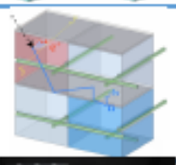
- These anomaly could be interpreted as being due to SBL neutrino oscillation $\Delta m^2 \geq 1\text{eV}^2$ or incorrect flux.





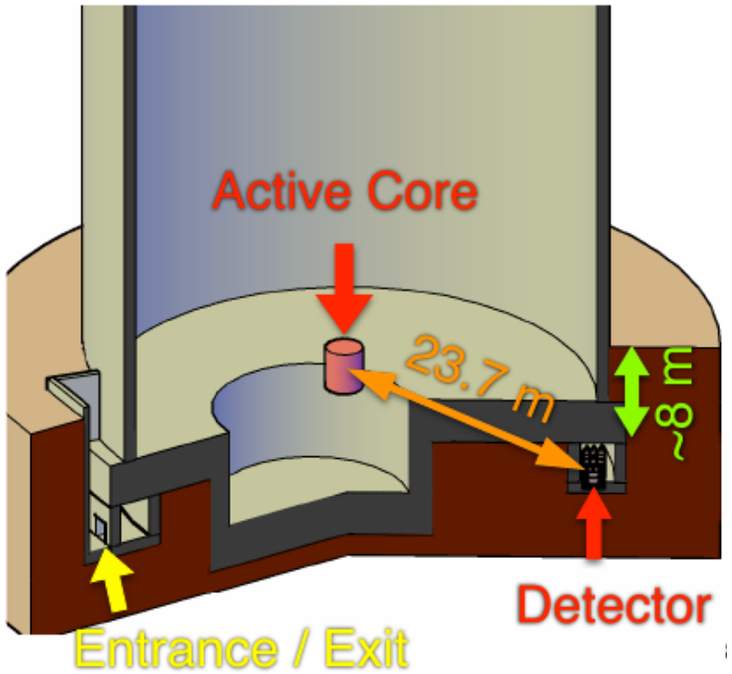
T.A. Mueller et al., Phys. Rev. C83 (2011) 054615 [arXiv:1101.2663].
P. Huber, Phys. Rev. C 84 (2011) 024617 [arXiv:1106.0687].
G. Mention et al., Phys. Rev. D83 (2011) 073006 [arXiv:1101.2755].

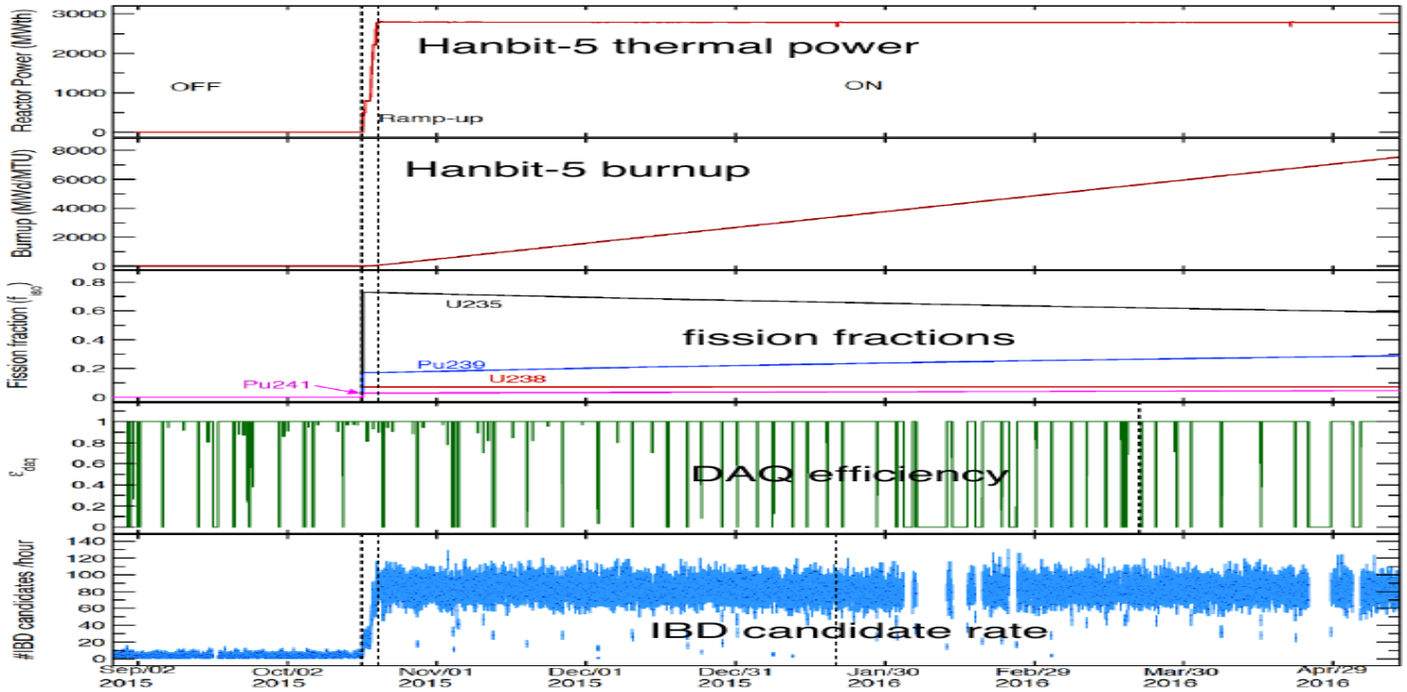
$\nu_e(\bar{\nu}_e)$ DISAPPEARANCE - REACTOR ANTINEUTRINO OSCILLATION

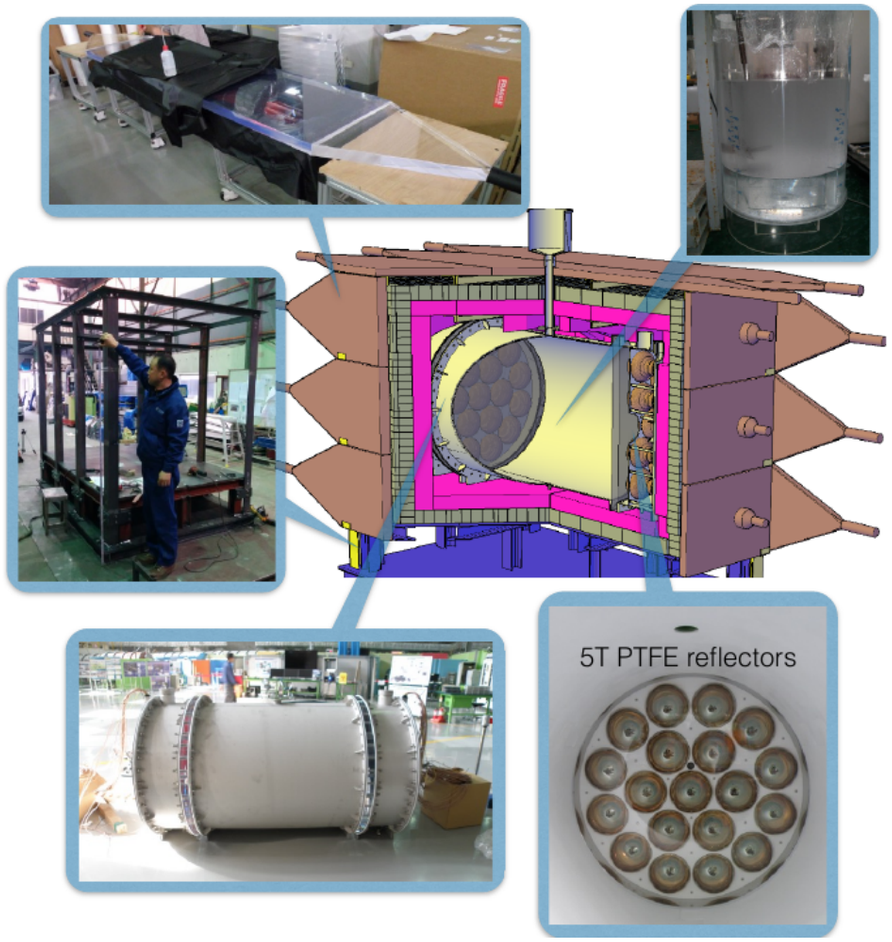
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

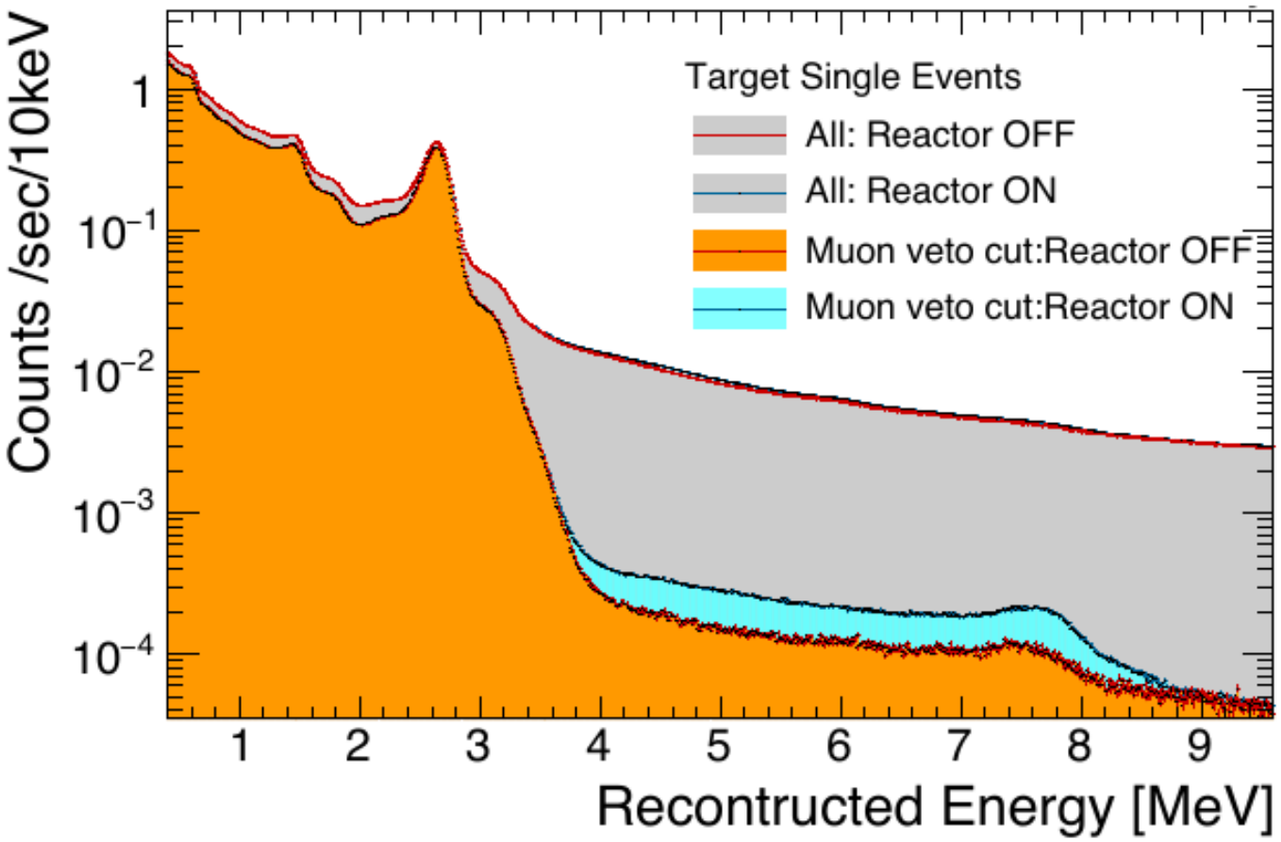
NEOS

- Using commercial reactor (2.8 GWth)
- Baseline = 23.7 m
- Overburden ~ 20 m.e.w.
- Homogenous GdLS (1008L) neutrino target
  - energy resolution: 4.8% @ 1 MeV
- Physics data taking: Aug. 2015 ~ May 2016
  - 46 live days of reactor off
  - 180 live days of reactor on
- 1977 (85) IBD candidates/day during on (off), S/B ~ 22.

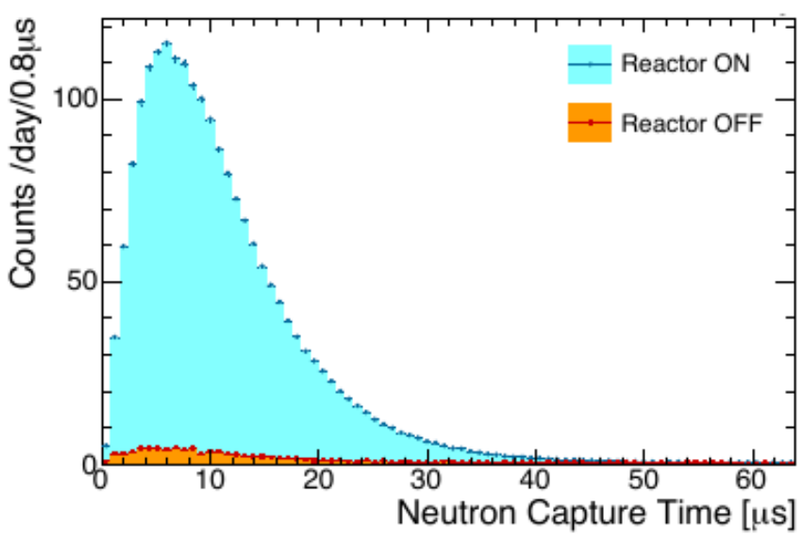


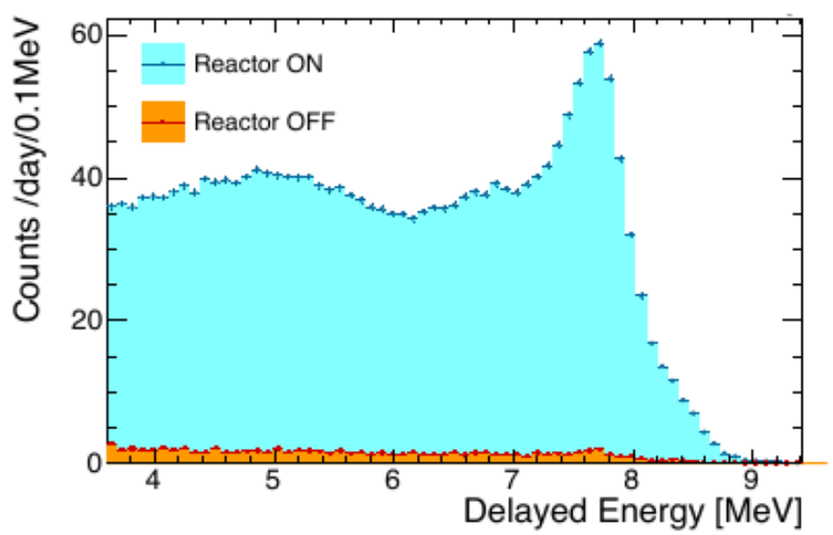


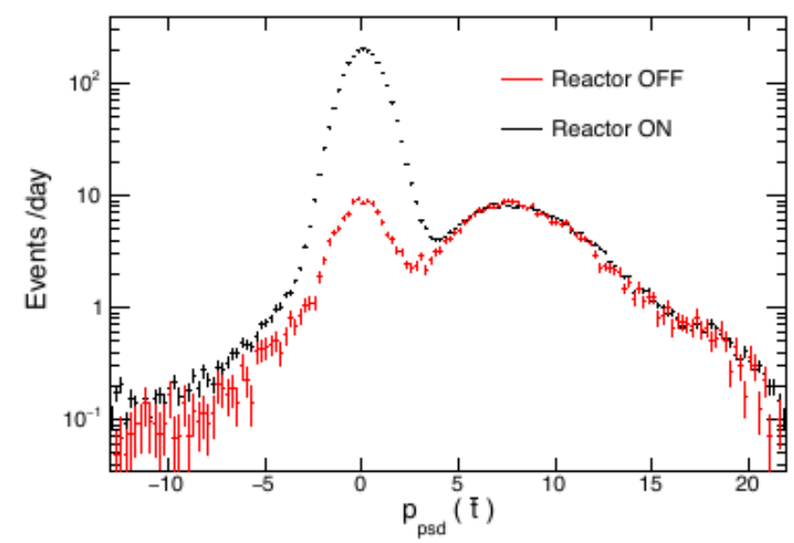




- neutron capture time:1~30 μs
- delayed energy: 4~10 MeV
- muon veto time: 150 μs
- multiplicity: no other event within 30 μs before / 150 μs after.
- pulse shape discrimination reduces 70% of background.

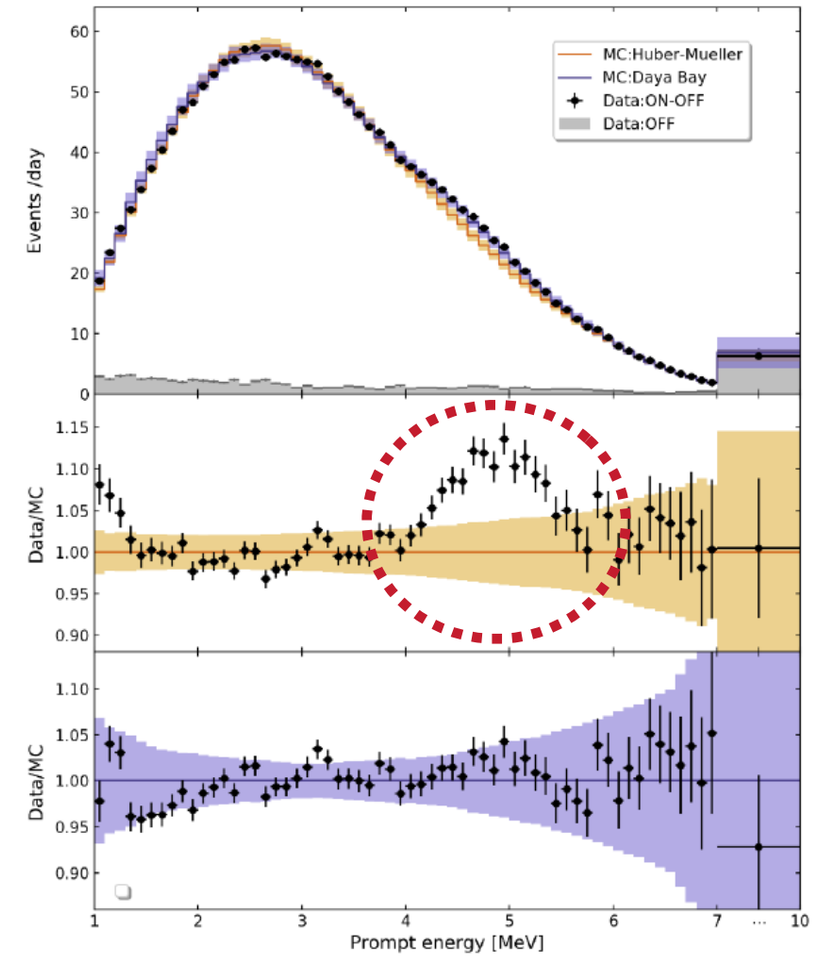


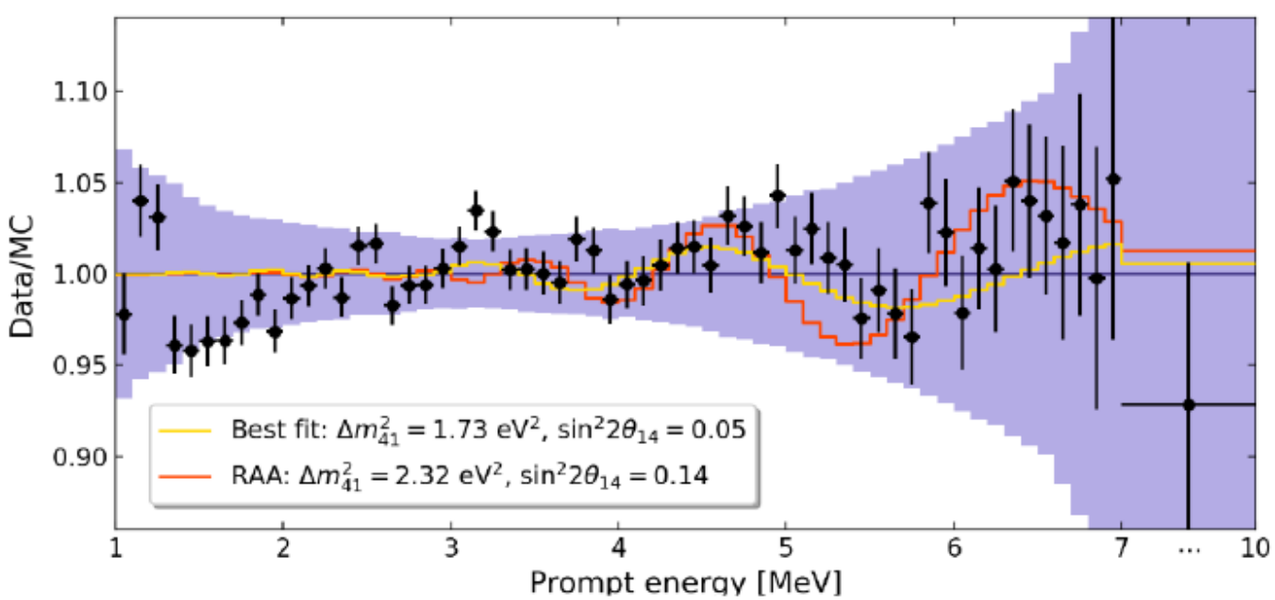


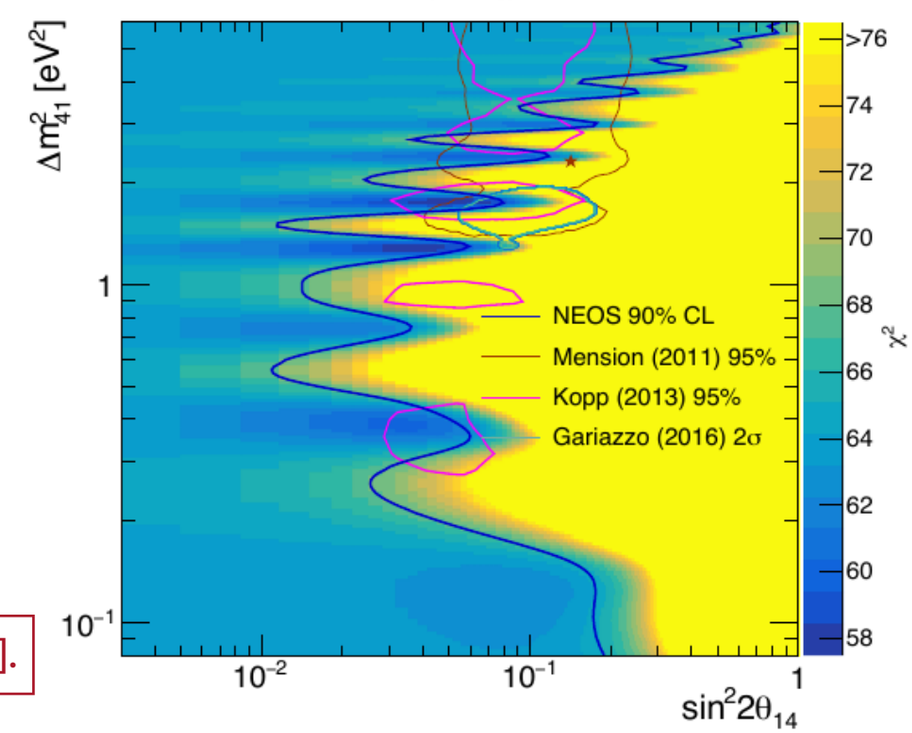


NEOS

- Spectral anomaly observed (vs Huber-Mueller normalization)
- Fit with the Daya Bay shape
  - Best fit: $\Delta m^2_{41} = 1.73\text{eV}^2,\ \sin^2 2\theta_{14} = 0.05$
    $\Delta m^2_{41} = 1.3\text{eV}^2,\ \sin^2 2\theta_{14} = 0.04$
- No strong sign of active-to-sterile neutrino oscillation
- Fine structures in neutrino spectrum or oscillation?



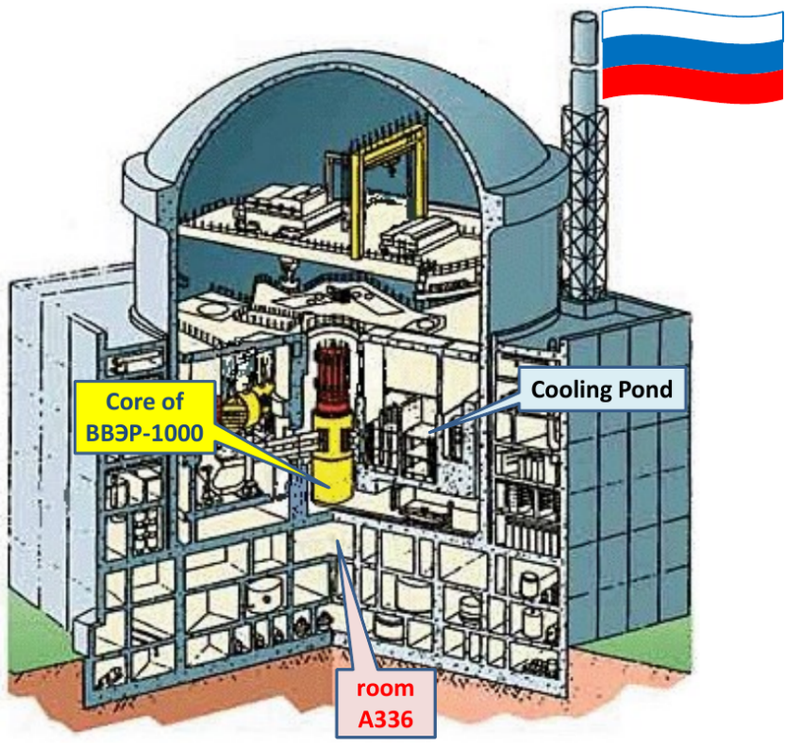


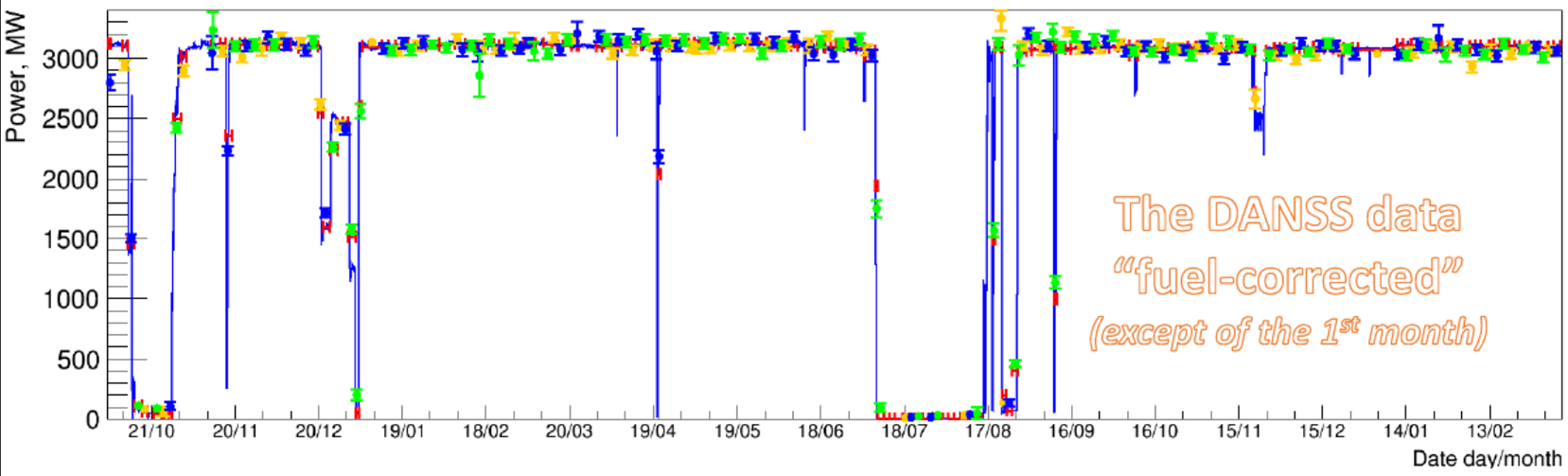


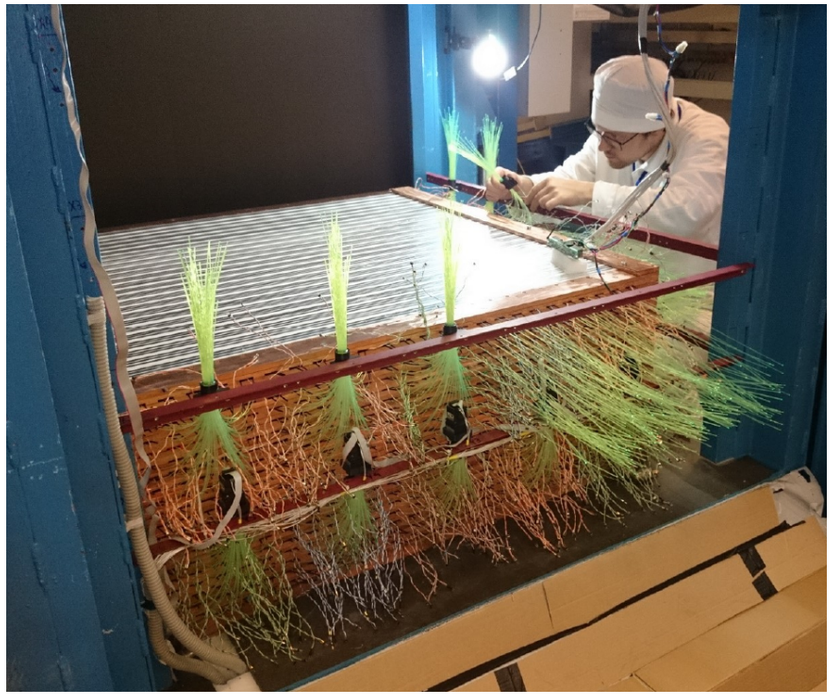
Y. J. Ko et al. [NEOS collab], Phys. Rev. Lett. 118 (2017) 121802 [arXiv:1610.05134].

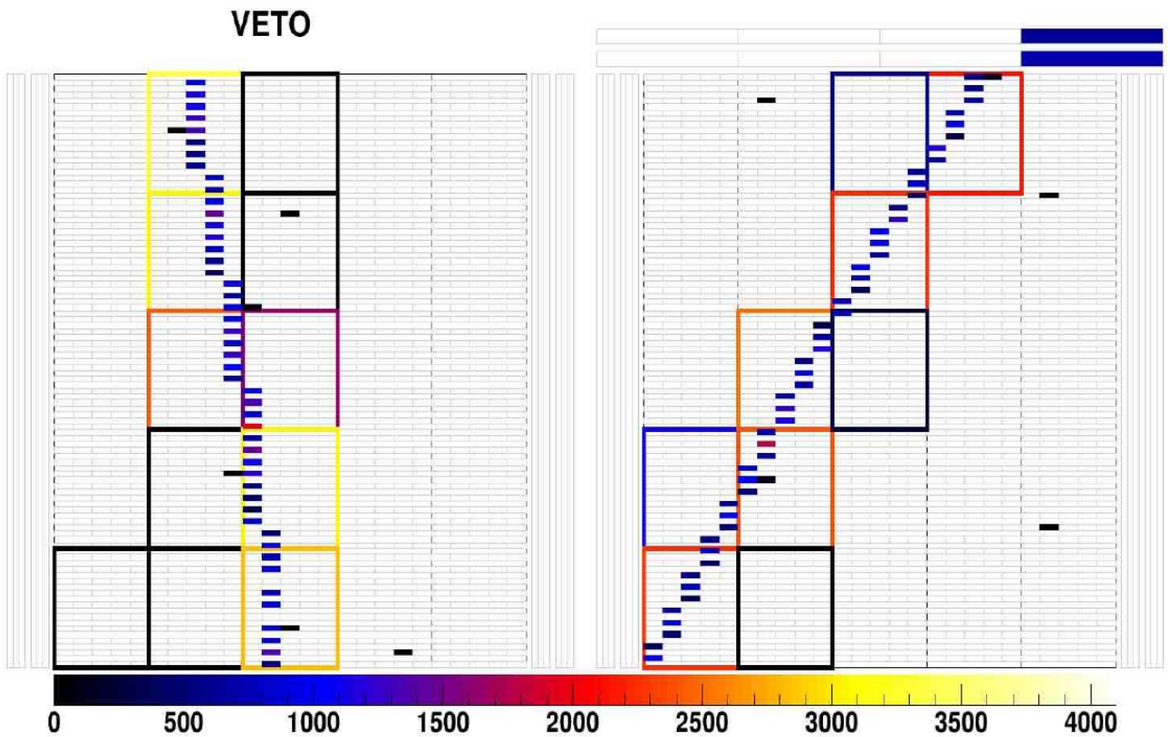
DANSS

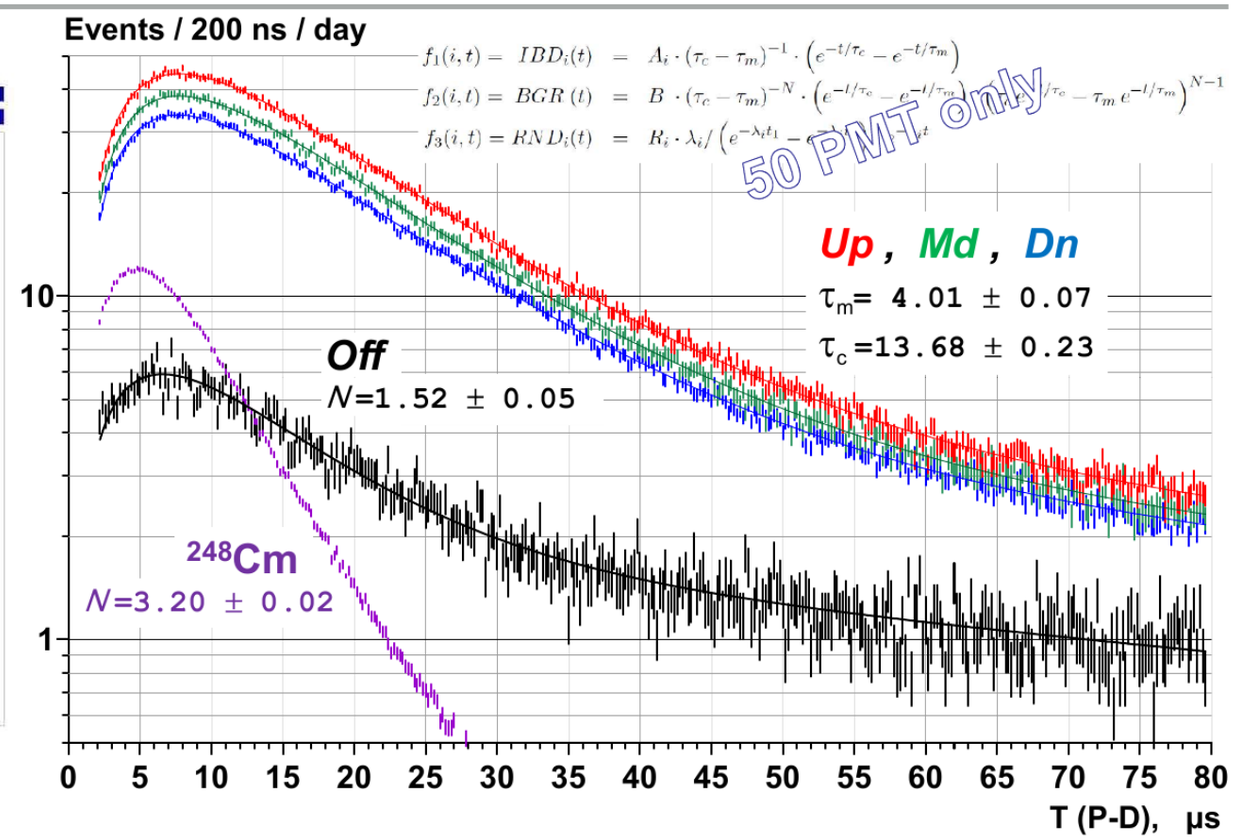
- Pressurized water reactor (3.1 GWth)
- Baseline: 10.7(up), 11.7(md), and 12.7 m(dn)
- Overburden: ~ 50 m.w.e.
- Polystyrene-base plastic scintillator strip with Gd-loaded reflector (1.6 mg/cm2)
  - highly segmented with 2500 individual strips
  - 2500 SiPMs and 50 PMTs
- Data taking since Apr. 2016
- 4910(133) IBD events/day

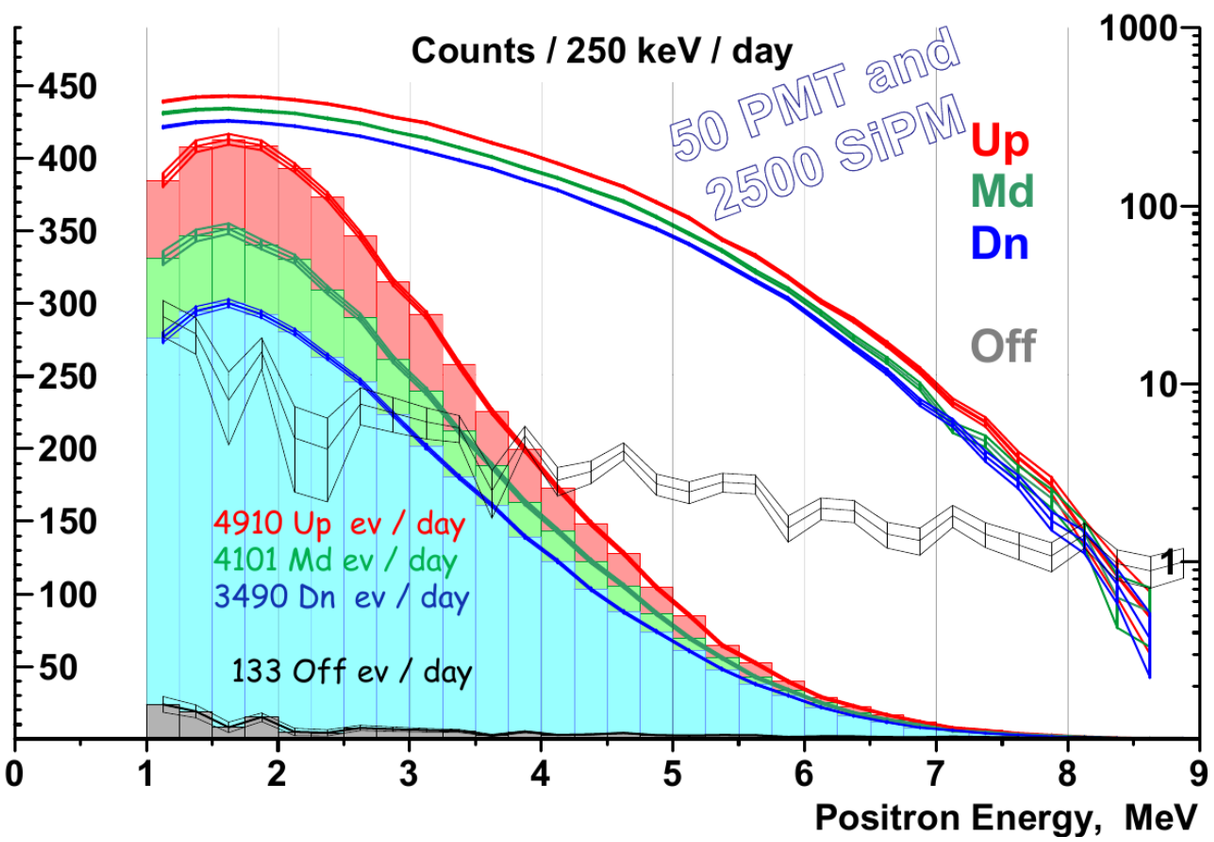


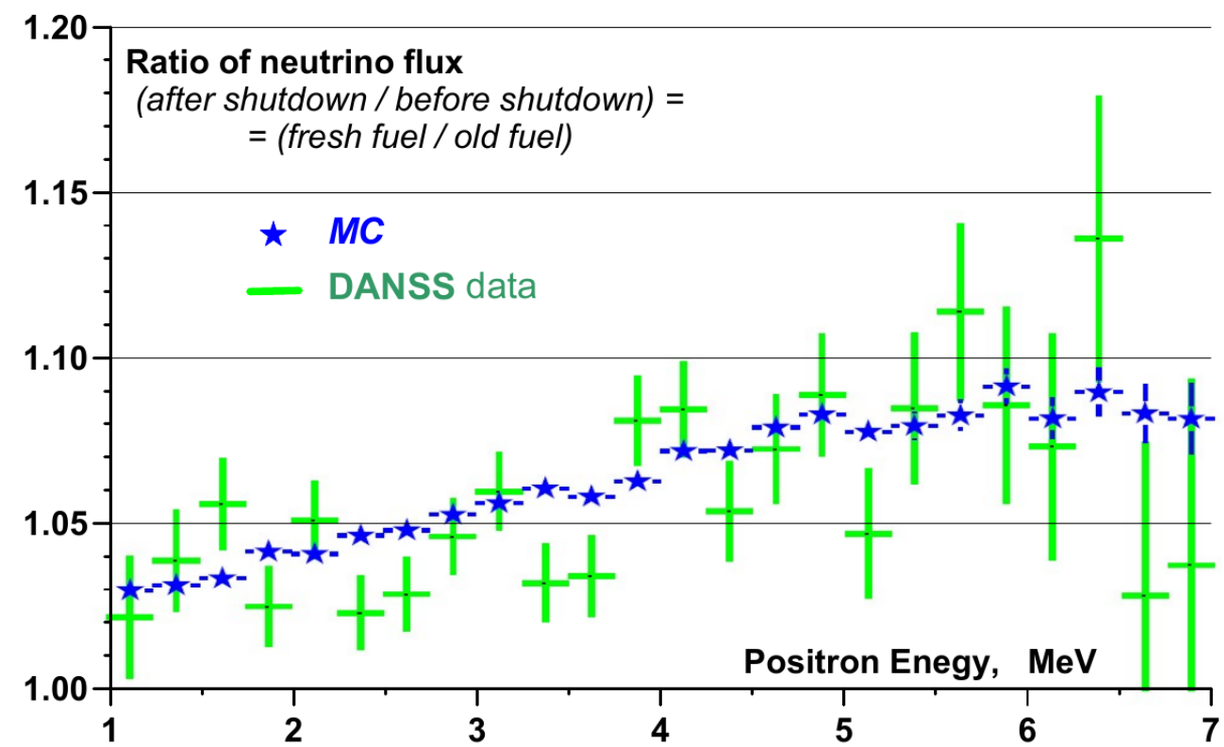





VETO
0
500
1000
1500
2000
2500
3000
3500
4000


Events / 200 ns / day
$f_1(i,t) = IBD_i(t) = A_i \cdot (\tau_c - \tau_m)^{-1} \cdot \left(e^{-t/\tau_c} - e^{-t/\tau_m}\right)$
$f_2(i,t) = BGR(t) = B \cdot (\tau_c - \tau_m)^{-N} \cdot \left(e^{-t/\tau_c} - e^{-t/\tau_m}\right) \cdot \left(e^{-t/\tau_c} - \tau_m e^{-t/\tau_m}\right)^{N-1}$
$f_3(i,t) = RND_i(t) = R_i \cdot \lambda_i / \left(e^{-\lambda_i t_1} - e^{-\lambda_i t_2}\right) \cdot e^{-\lambda_i t}$
50 PMT only
Up , Md , Dn
τ_m= 4.01 ± 0.07
τ_c =13.68 ± 0.23
Off
N=1.52 ± 0.05
^{248}Cm
N=3.20 ± 0.02
10
1
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
T (P-D), μs


Counts / 250 keV / day
50 PMT and 2500 SiPM
Up
Md
Dn
Off
4910 Up ev / day
4101 Md ev / day
3490 Dn ev / day
133 Off ev / day
450
400
350
300
250
200
150
100
50
1000
100
10
1
0 1 2 3 4 5 6 7 8 9
Positron Energy, MeV

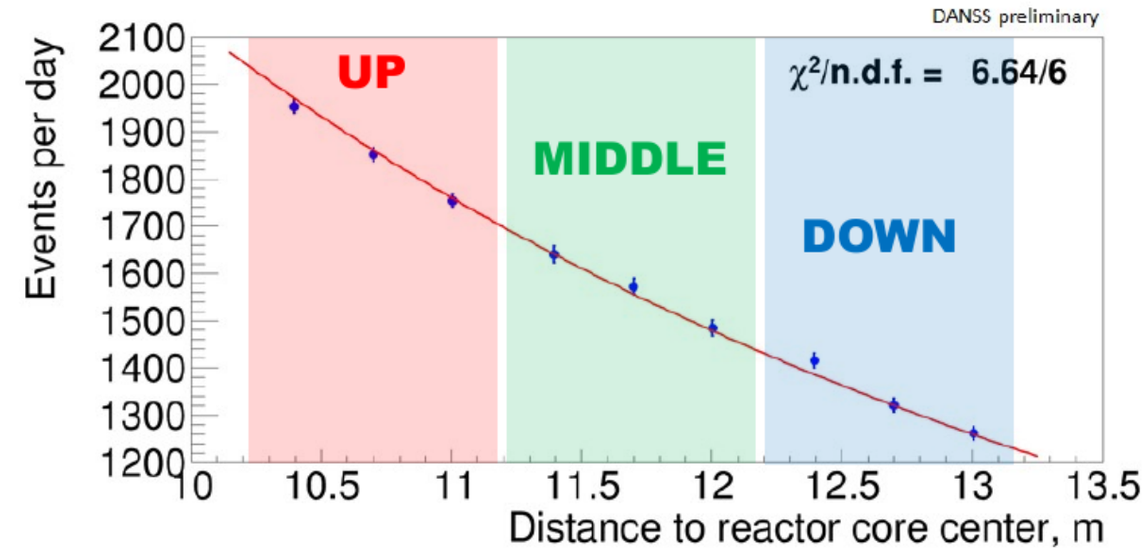

Ratio of neutrino flux
(after shutdown / before shutdown) =
= (fresh fuel / old fuel)
MC
DANSS data
1.20
1.15
1.10
1.05
1.00
1 2 3 4 5 6 7
Positron Enegy, MeV

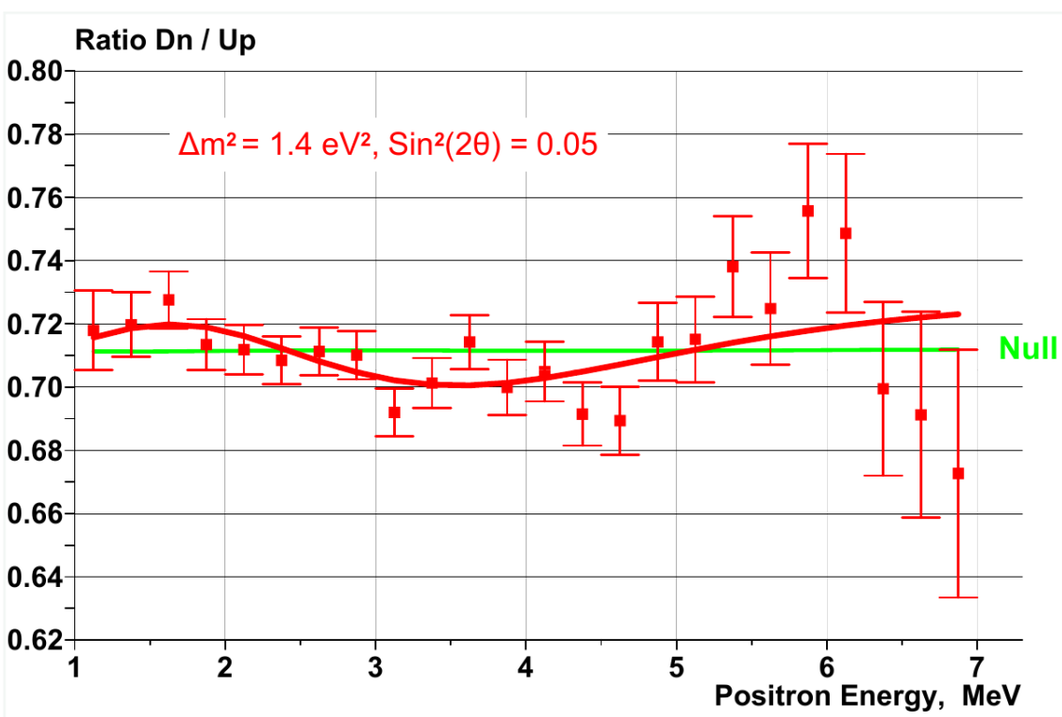
DANSS

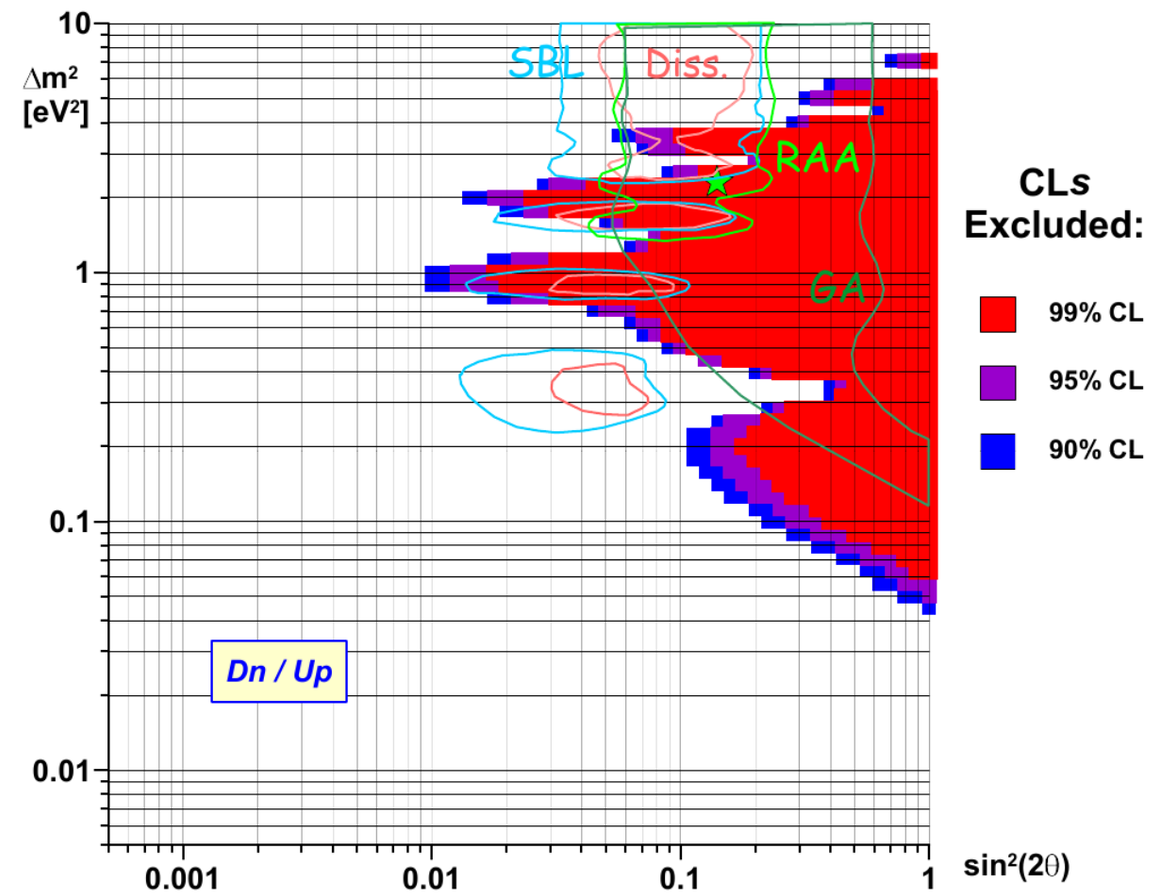
- IBD intensity follows the 1/L^2 dependence.
- Fit with md/up and dn/up (model independent)

$$\Delta m^2_{41} = 1.4\text{eV}^2, \;\; \sin^2 2\theta_{14} = 0.05$$

- DANSS data taking and analyses on-going

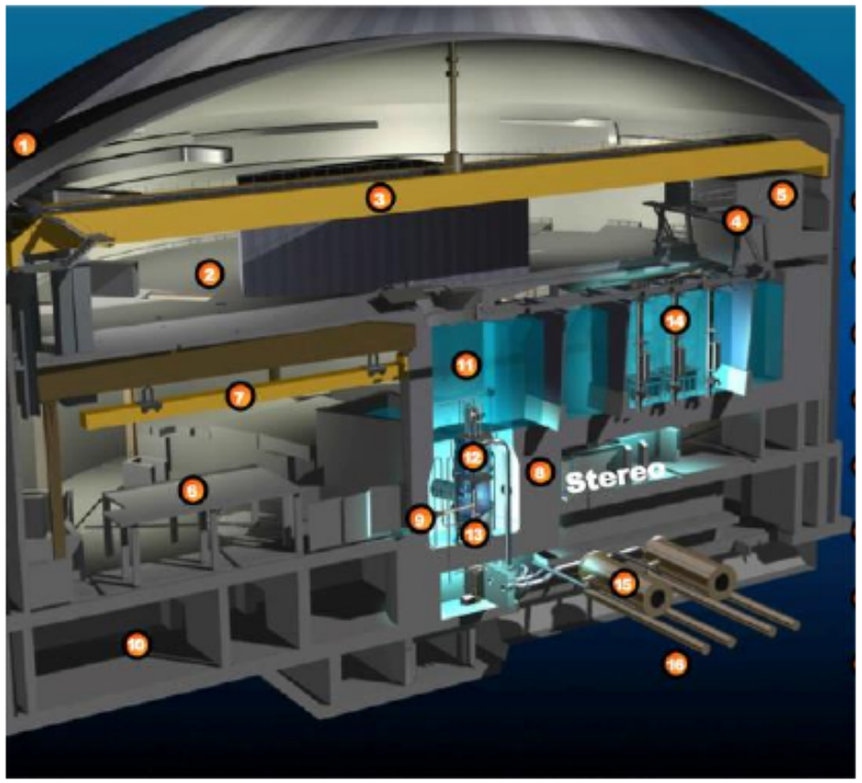


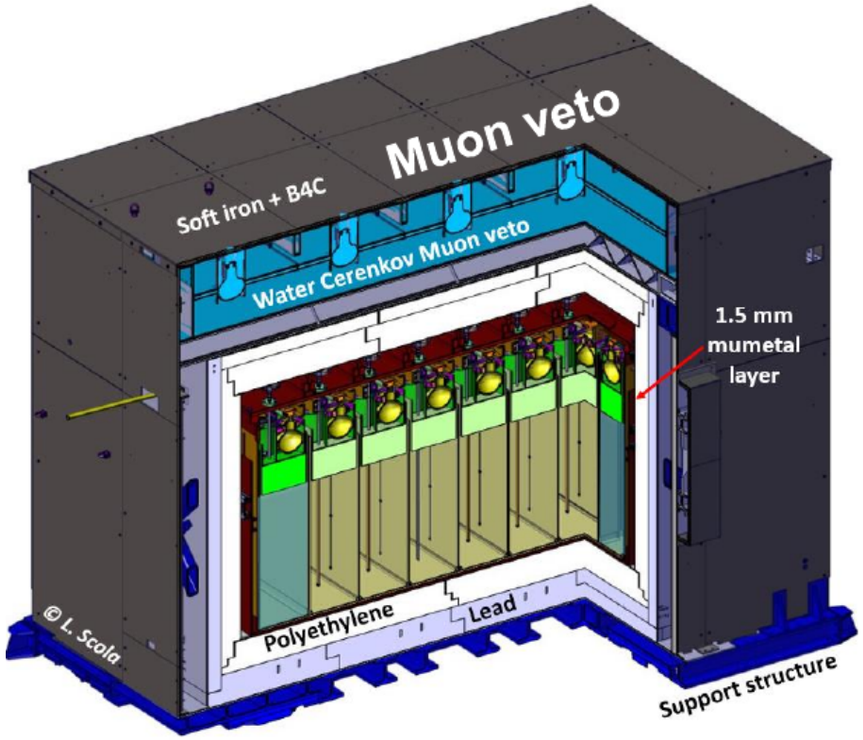


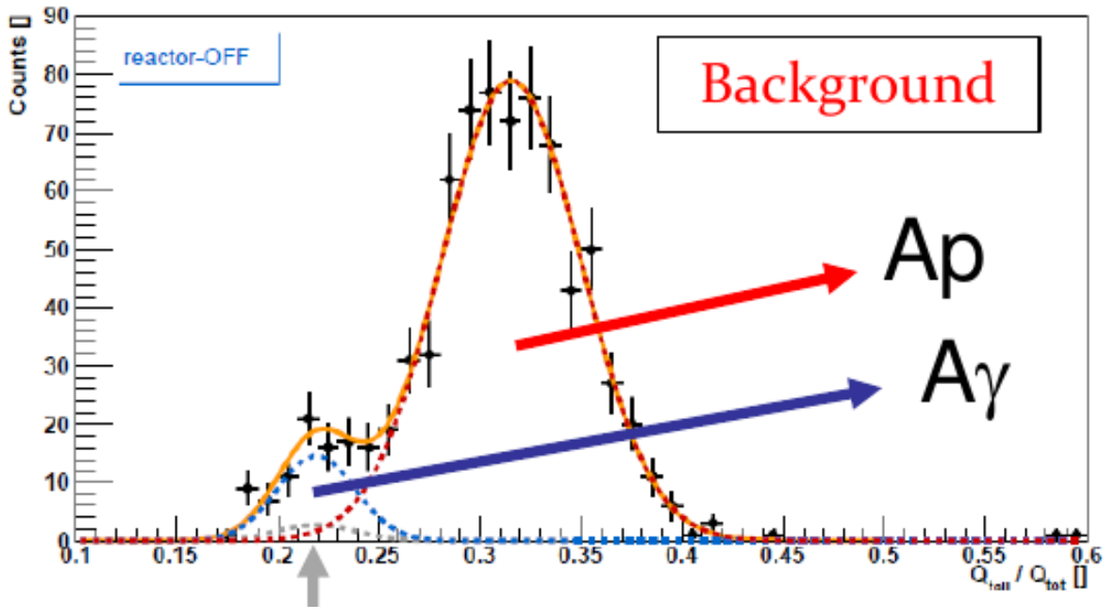


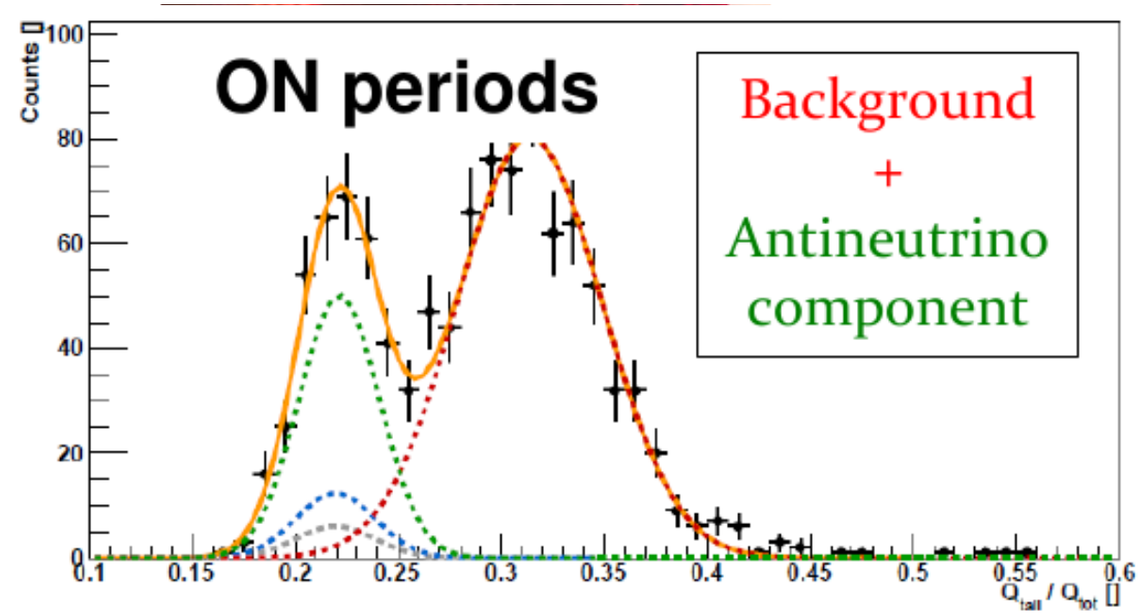
V. Egorov, Neutrino 2018

- 58 MW research reactor (ILL) with highly enriched fuel (235U, 93%)
- Compact core (Φ40x80 cm)
- Baseline: [9-11] m from core
- Shallow depth and gamma and neutron background due to experimental lines
- 6 cells filled with GdLS
- 66 days ON (396 IBD events/day)

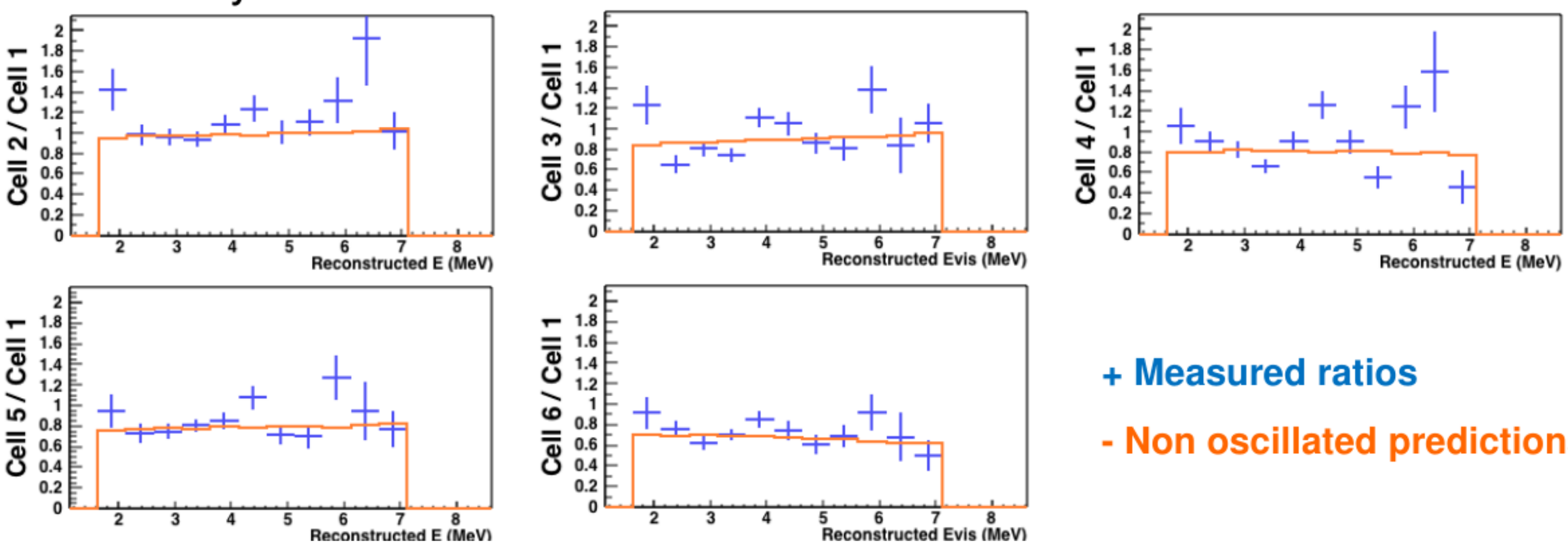








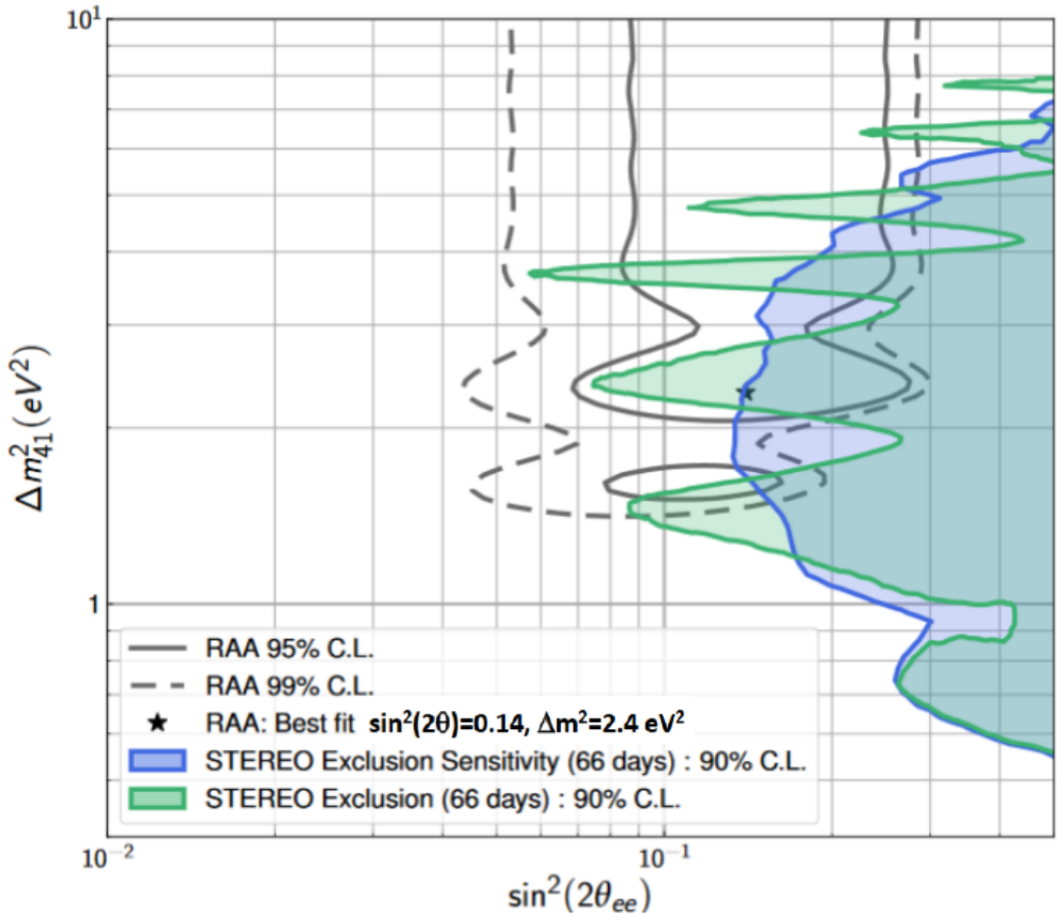
66 days ON data



+ Measured ratios

- Non oscillated predictions

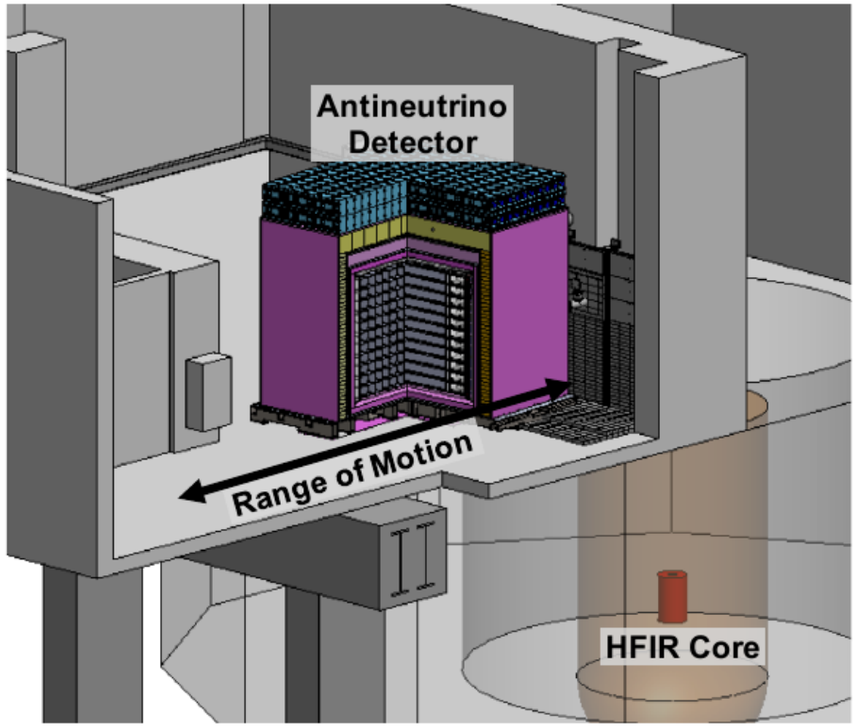
- An exclusion contour has been obtained using the ratio method and raster scan.
- Best fit value of the RAA rejected at 97.5% C.L.
- Data taking will continue until end of 2019 (>300 days of reactor-on data)



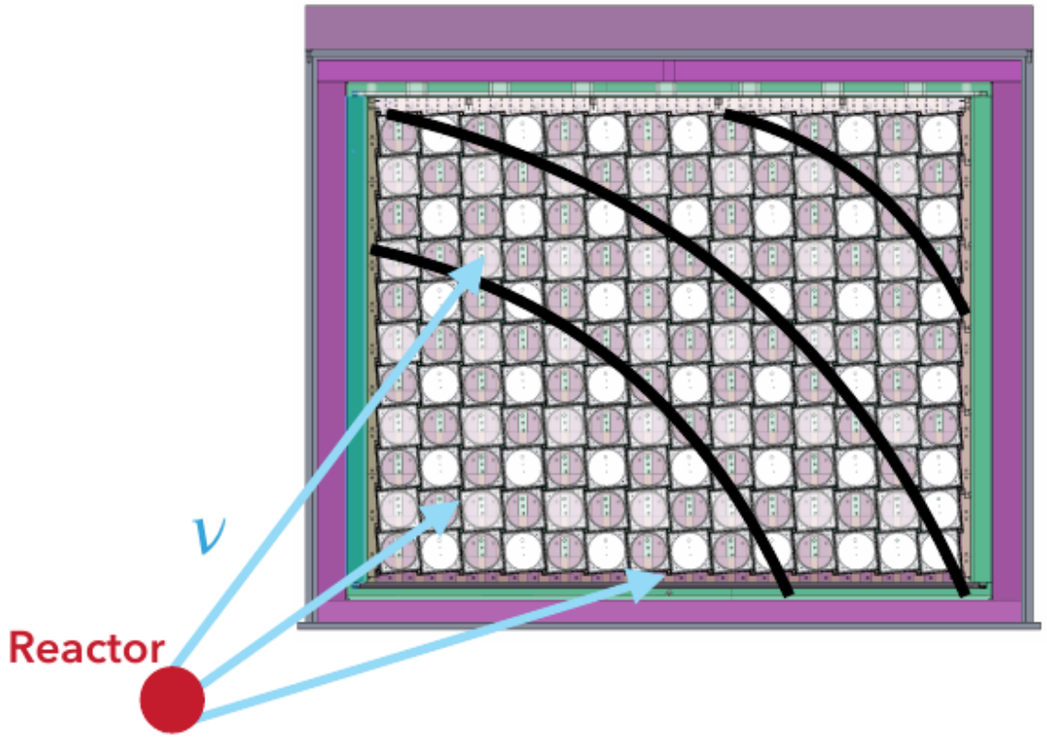
H. Almazán et al., arXiv:1806.02096.

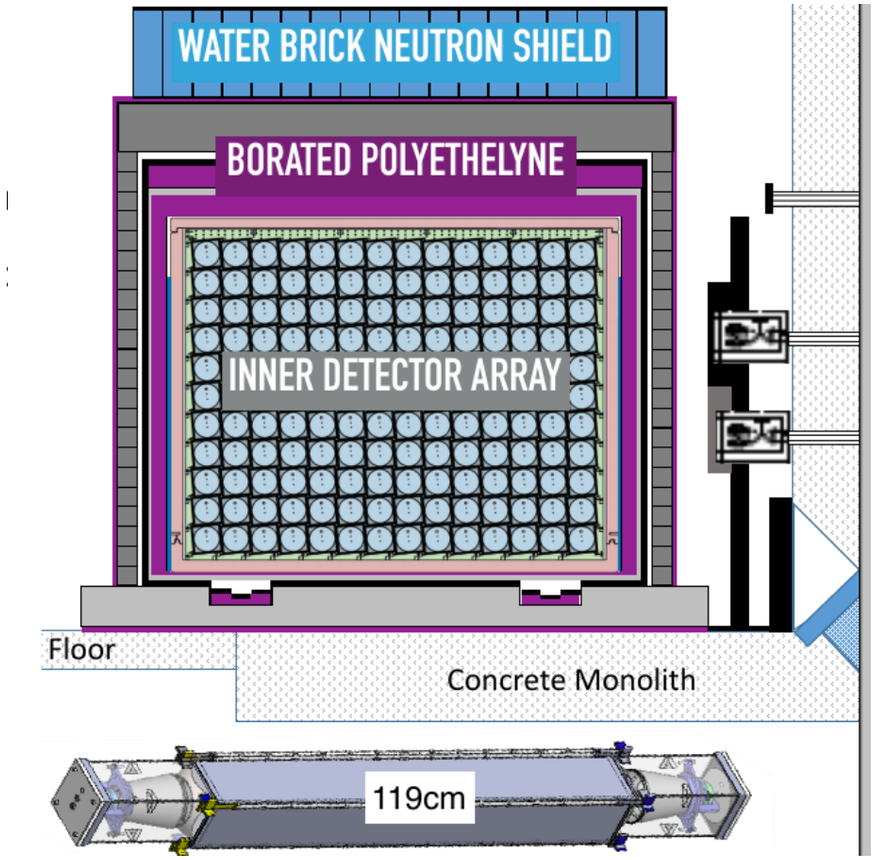
PROSPECT

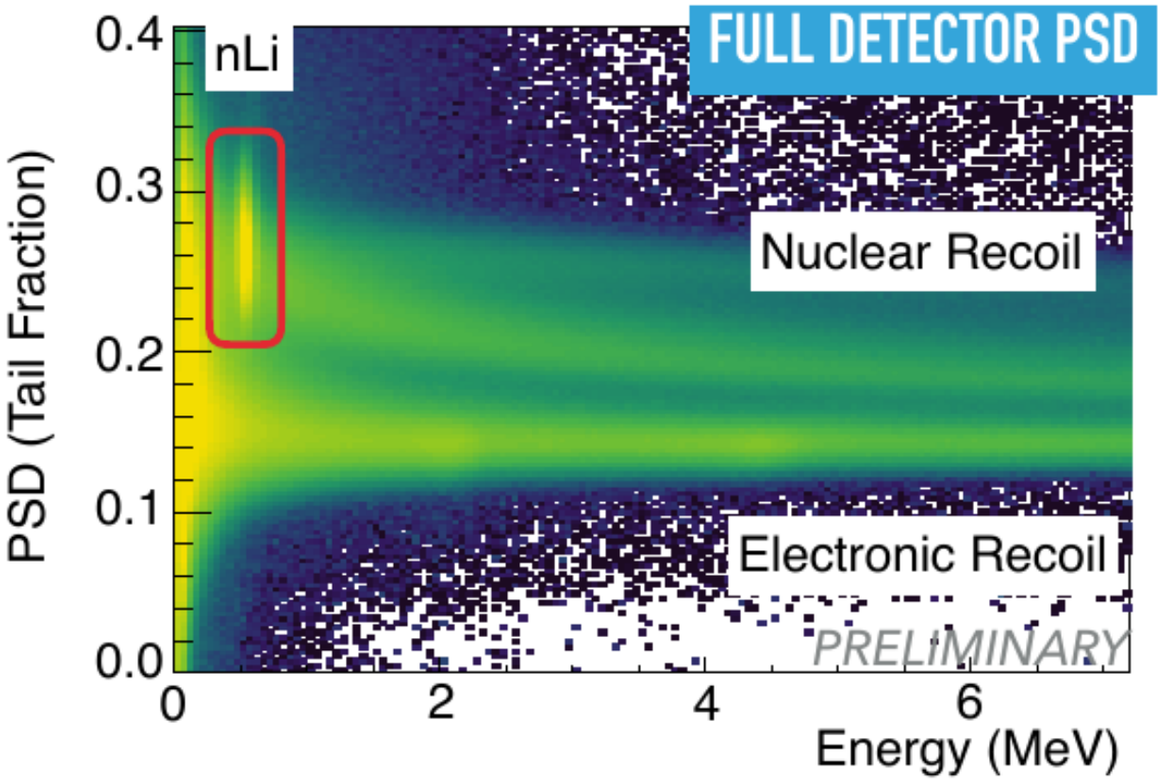
- 85MW highly enriched uranium reactor (>99% 235U fission)
- Compact core (Φ44x51 cm)
- 154 segments with 6LiLS (total mass 4ton)
- Measure neutrino spectrum for each baseline and compare shape to the detected full volume -> **reactor model-independent search for sterile neutrino**

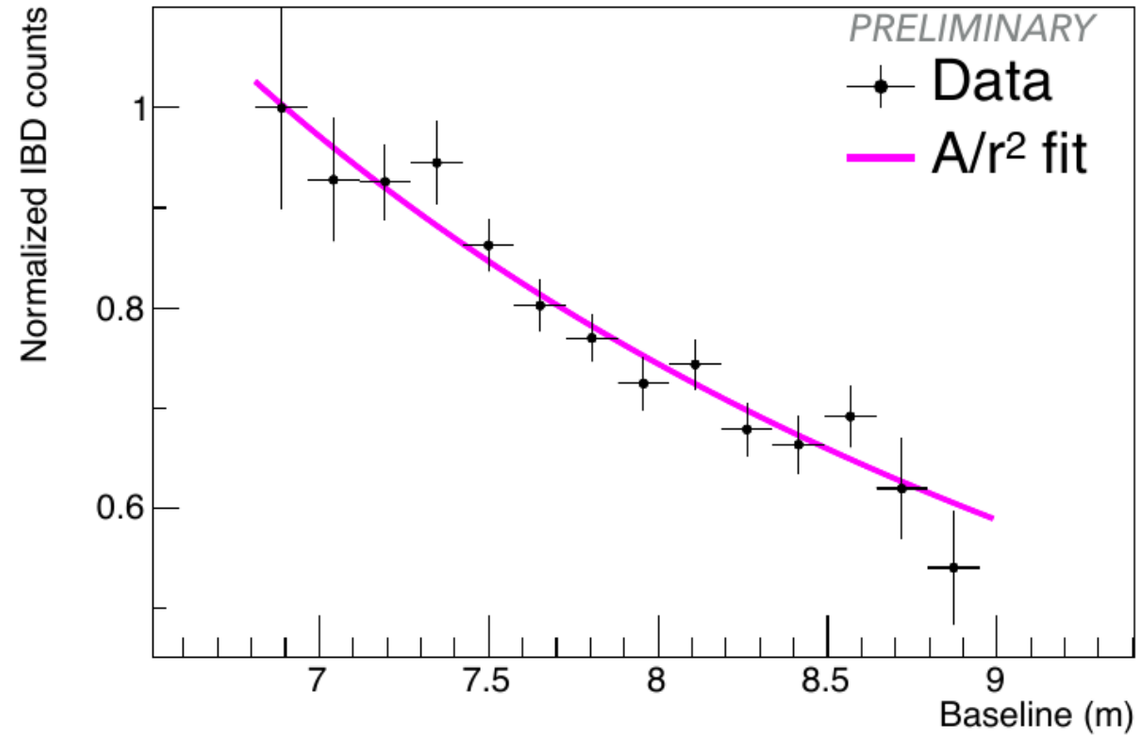


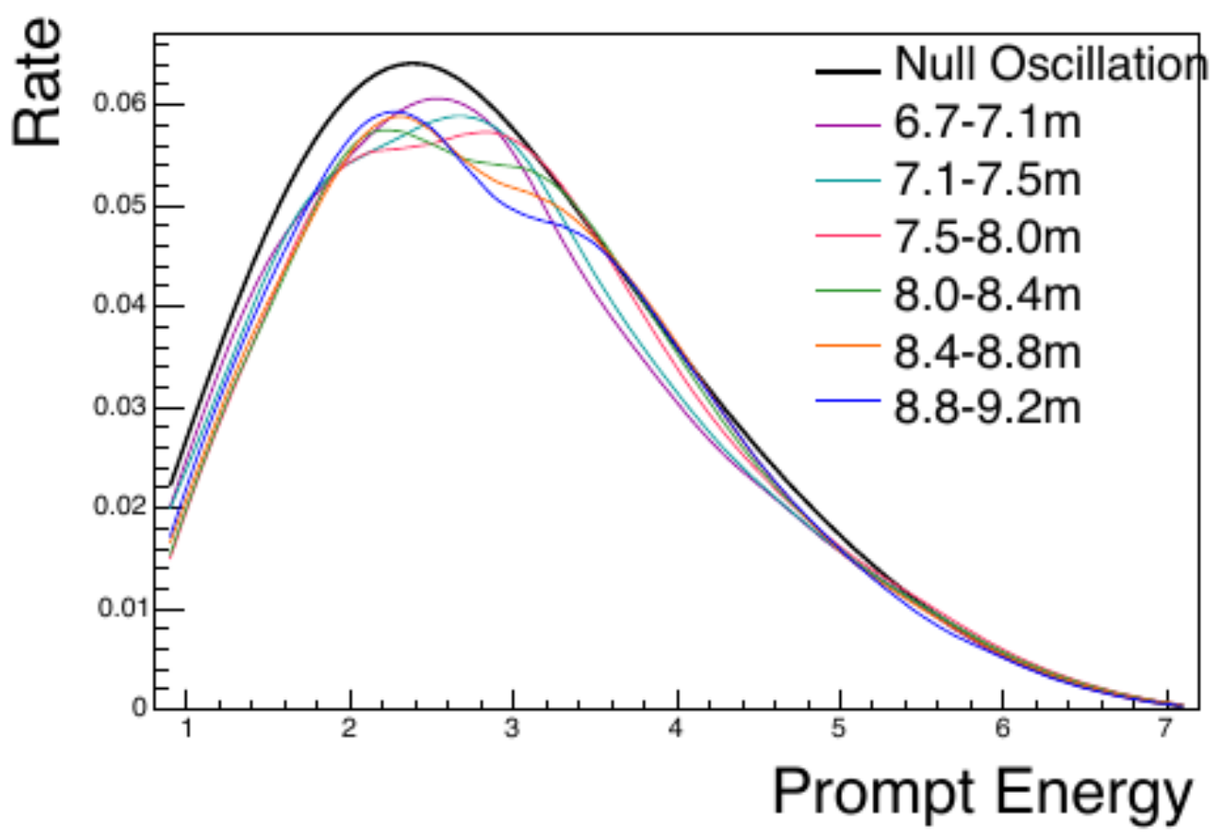
- 33 (28) days of reactor On(Off): 750 IBDs/day

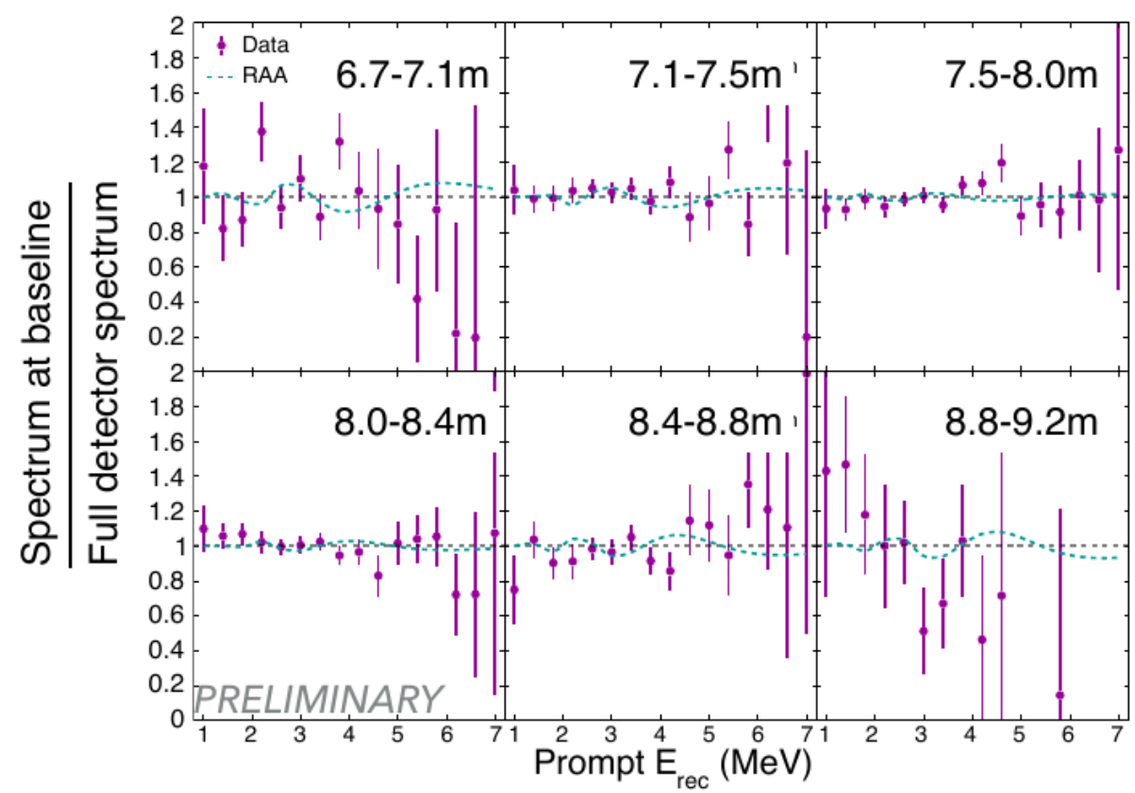




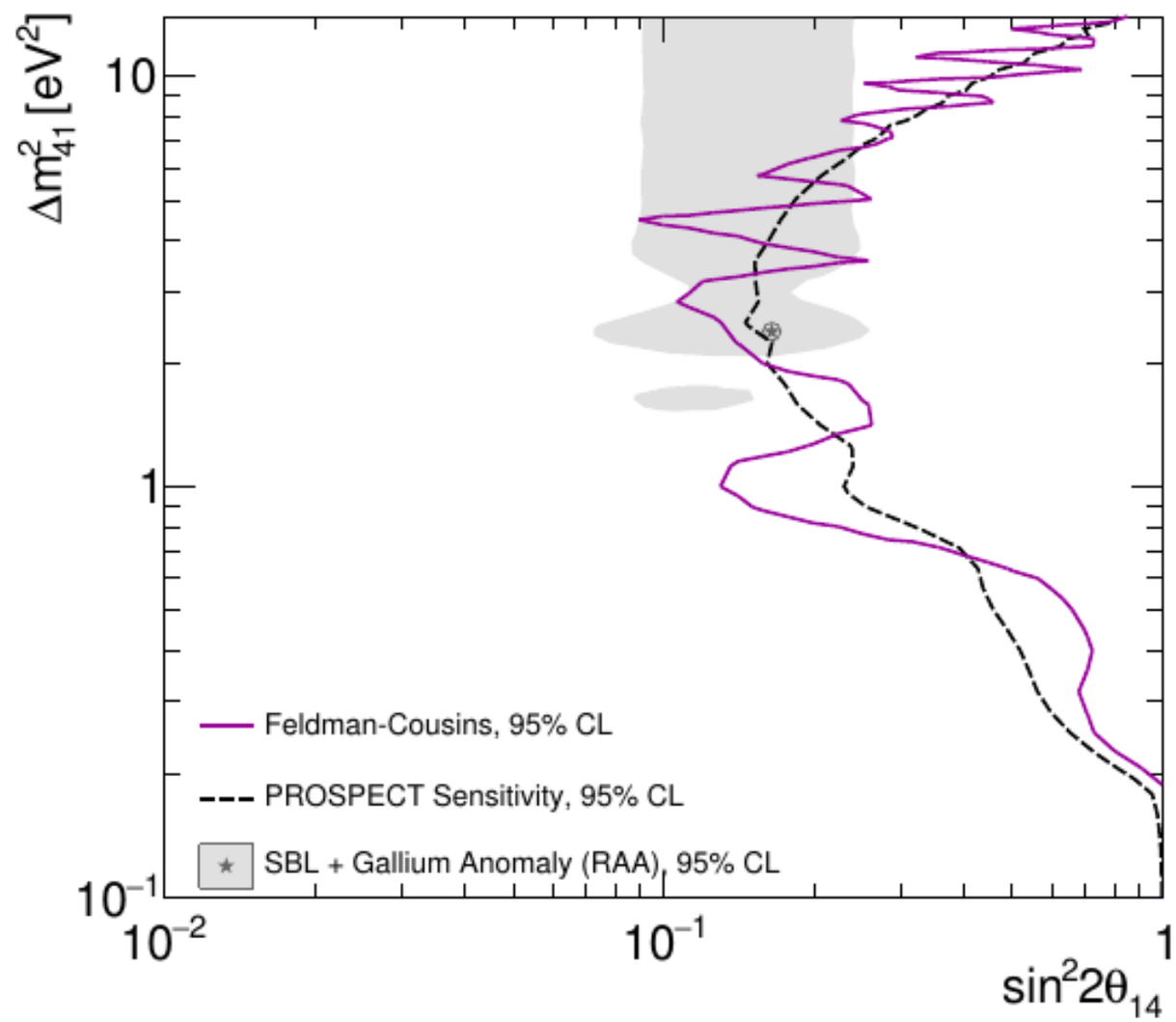

FULL DETECTOR PSD
nLi
Nuclear Recoil
Electronic Recoil
PRELIMINARY
PSD (Tail Fraction)
Energy (MeV)


PRELIMINARY
Data
A/r² fit
Normalized IBD counts
Baseline (m)


Null Oscillation
6.7-7.1m
7.1-7.5m
7.5-8.0m
8.0-8.4m
8.4-8.8m
8.8-9.2m
Rate
Prompt Energy


Data
RAA
6.7-7.1m
7.1-7.5m
7.5-8.0m
8.0-8.4m
8.4-8.8m
8.8-9.2m
Spectrum at baseline
Full detector spectrum
PRELIMINARY
Prompt E_rec (MeV)

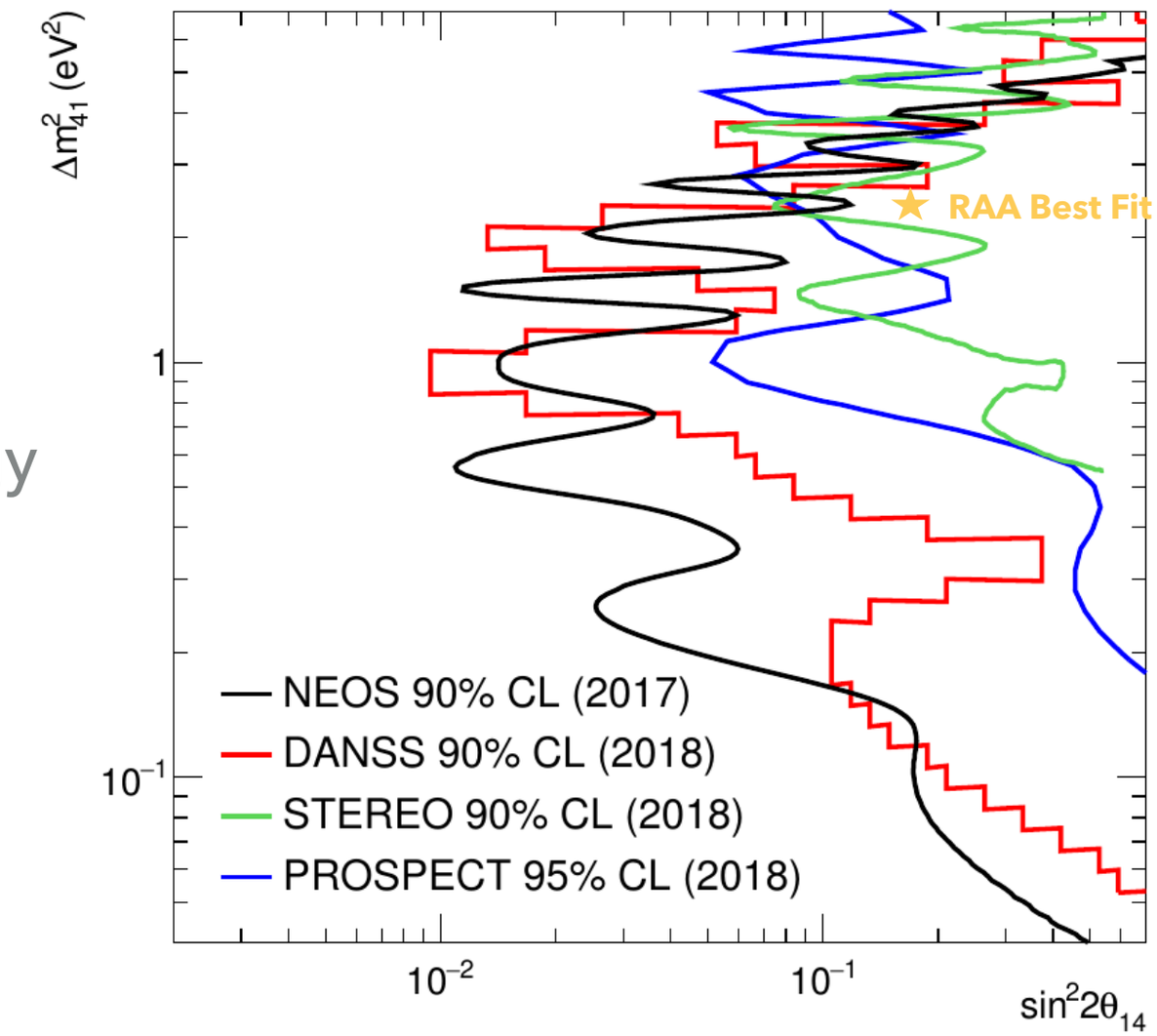
- 95% exclusion curve based on 33 days reactor on operation
- Disfavor RAA best fit at > 95% (2.3σ)



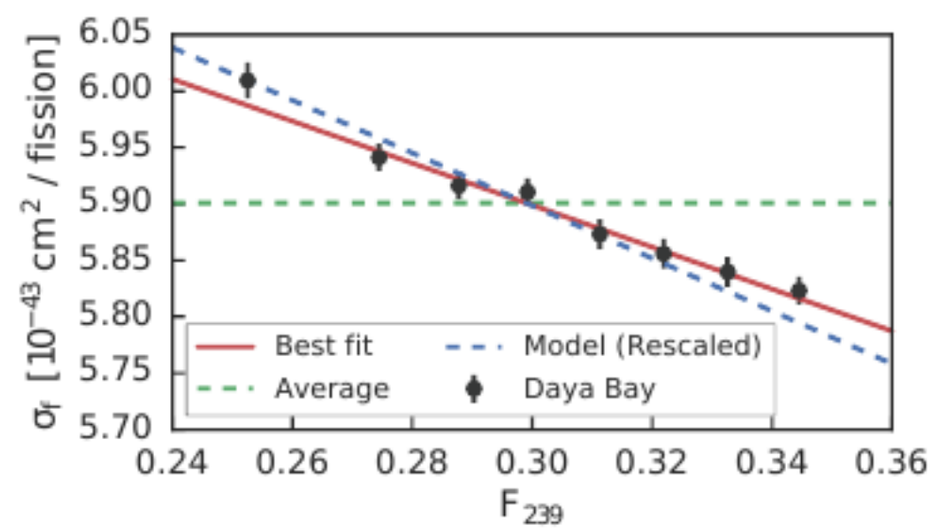
J. Ashenfelter et al., arXiv:1806.02784.

REACTOR NEUTRINO SUMMARY

- Four independent experiments exclude the RAA best fit.
- NEOS and DANSS oscillation agree with each other.
- NEOS and DANSS show small energy modulation. -> hint for SBL oscillation?
- NEOS has 5 MeV bump at prompt energy spectrum.



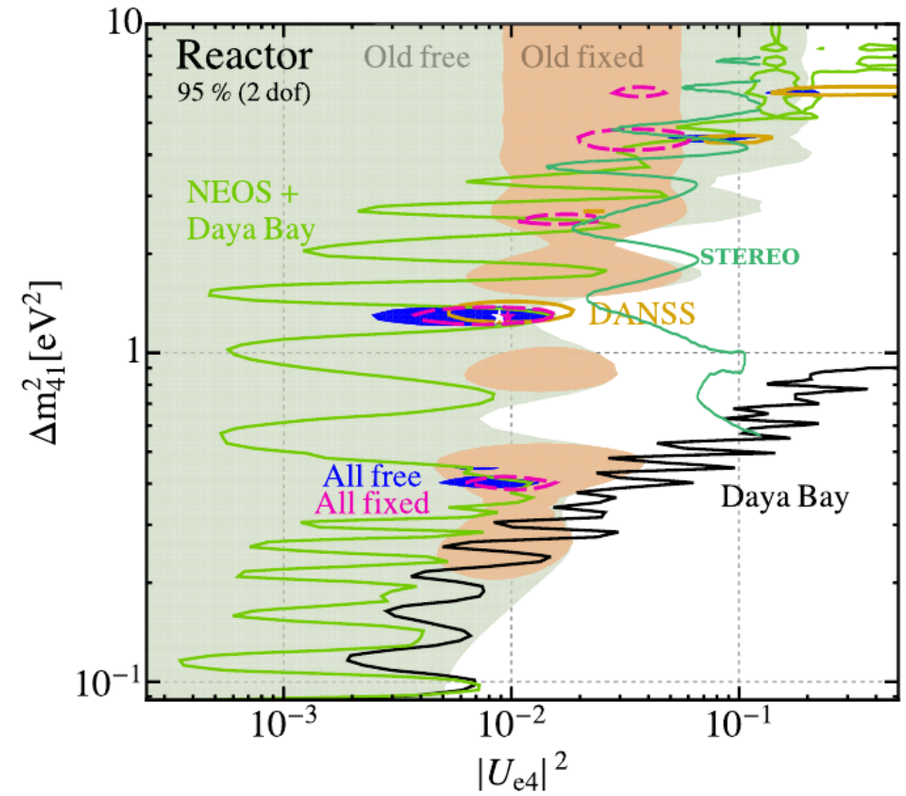
- Results on the overall IBD yield from Daya Bay:
  - 1.7σ below expectation
  - dependence on fuel composition is 3.1σ away from model

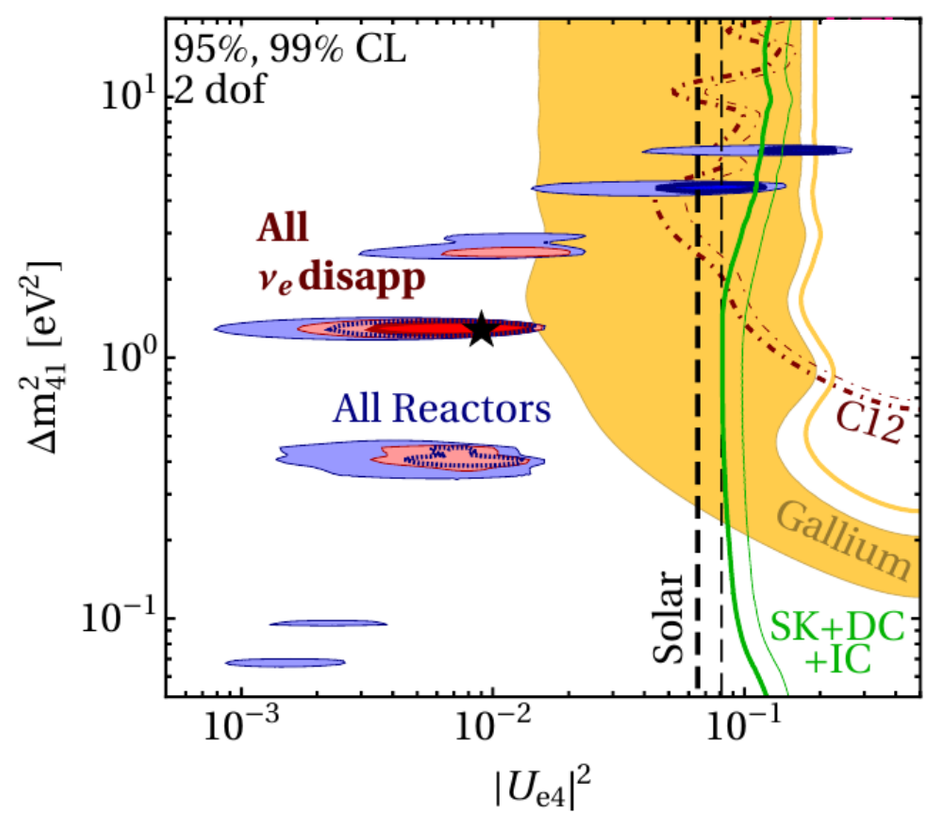


GLOBAL ANALYSIS

- Global analysis of all reactor data
  - two models:
    - Free: unconstrained normalizations for [235U, 238U, 239Pu, 241Pu]
    - Fixed: assumes Huber fluxes
  - **2.9σ(3.5σ)** hint for sterile neutrino from analysis with free(fixed) fluxes
  - fit dominated by DANSS+NEOS
- Reactor, gallium, Karmen, LSND, atmospheric, and solar neutrino
  - small tension between gallium and reactor data
  - hint for sterile slightly increase to **3.2σ(3.8σ)**
  - global best fit: $\Delta m^2_{41} = 1.3\text{eV}^2$

M. Dentler et al., arXiv:1803.10661.

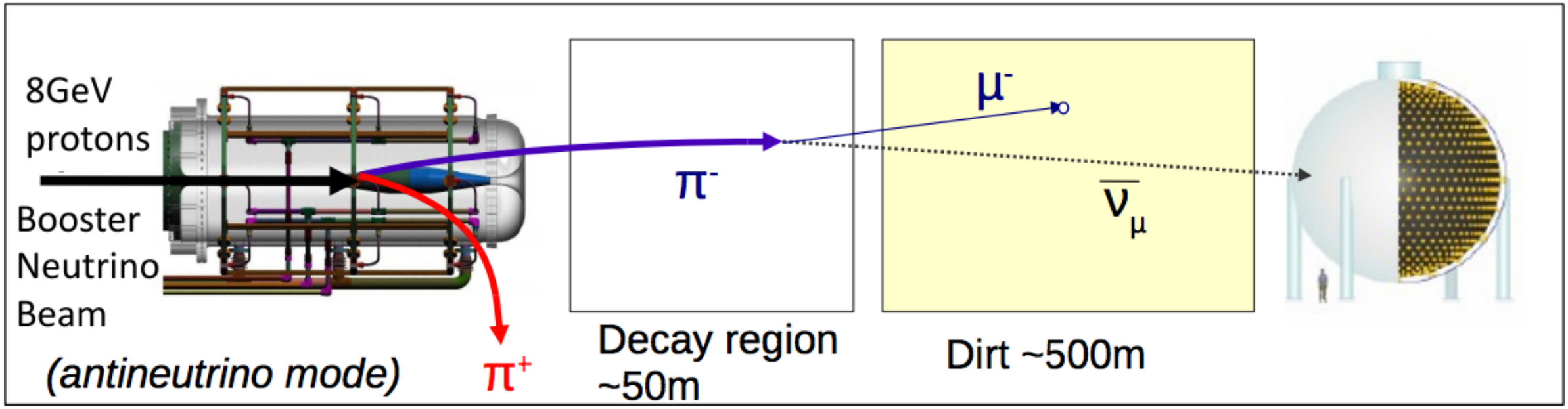




$\nu_\mu \rightarrow \nu_e$ APPEARANCE

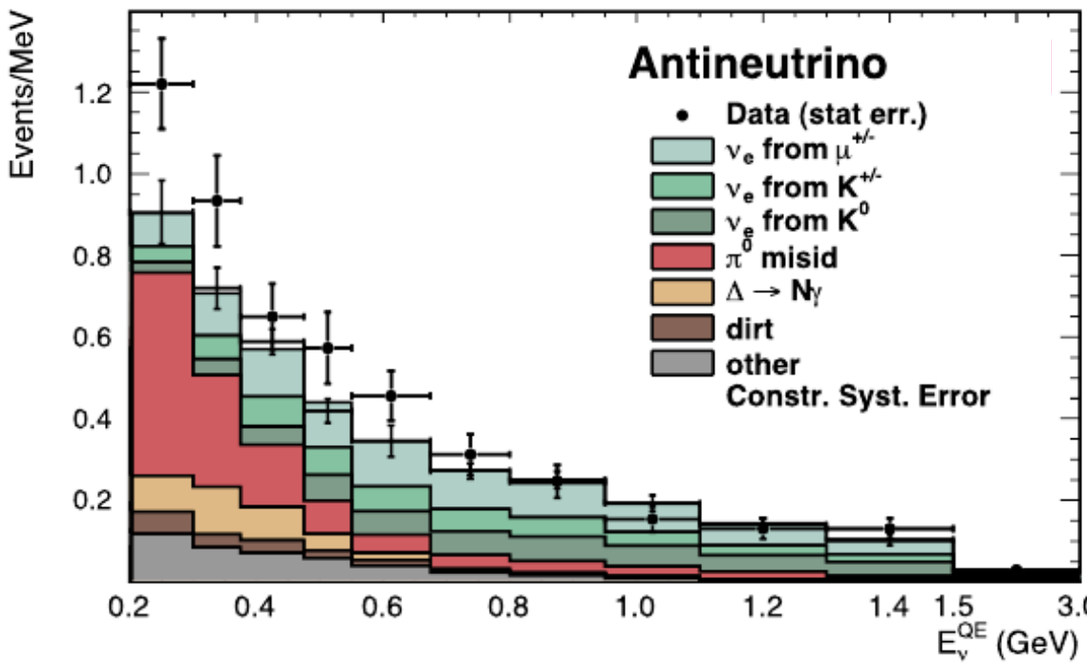
- MiniBoone results
- Future experiments
  - SBN (Short Baseline Neutrino)
  - JSNS2 (J-PARK Sterile Neutrino Search at J-PARK Spallation Neutron Source)

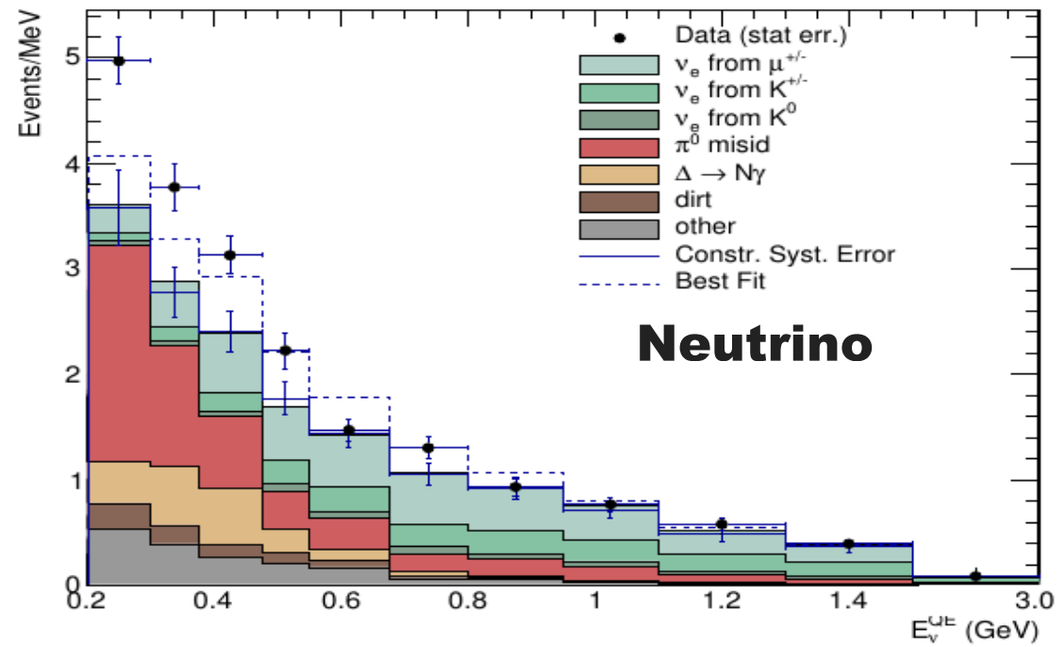
MINIBOONE



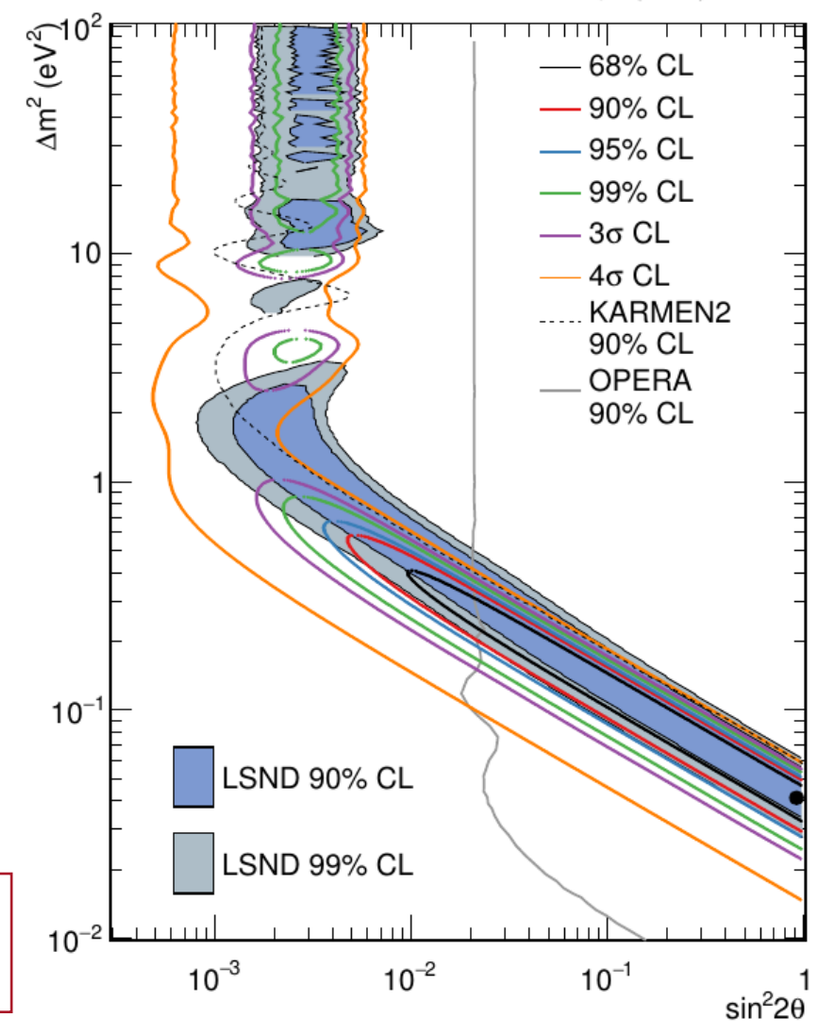
- MiniBooNE was approved in 1998, with the goal of addressing the LSND anomaly
- Similar L/E
  - LSND ~ 30m/30MeV
  - MiniBooNE ~ 500m/500MeV
- 800-ton mineral oil Cherenkov detector
- 11.27×10^{20} POT in ν mode + 12.84×10^{20} POT in $\bar{\nu}$ mode

MINIBOONE



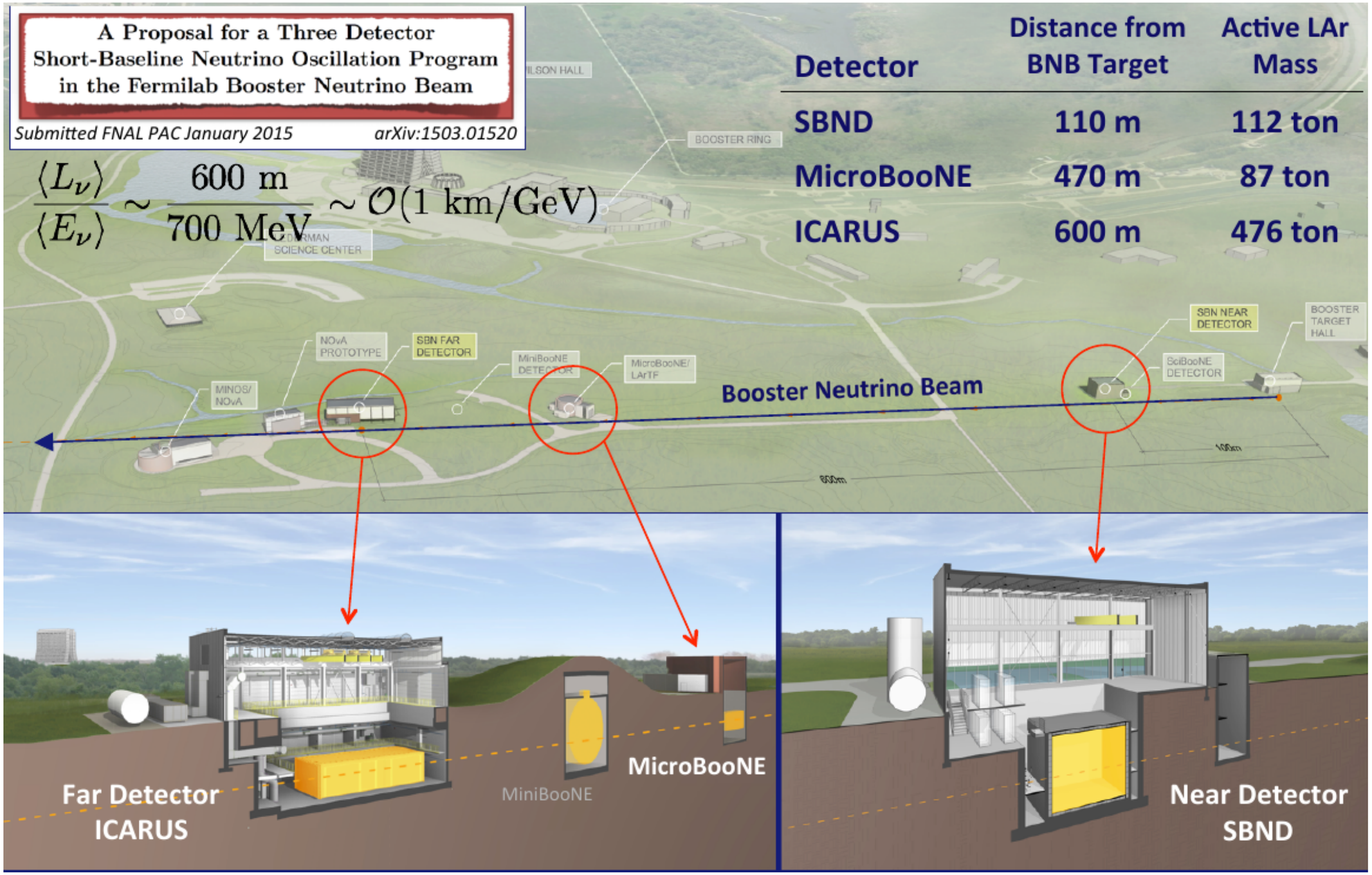


- Antineutrino data (2012)
  - antineutrino signal is compatible with 2ν oscillation.
  - antineutrino signal is compatible with LSND.
- Neutrino data (2018)
  - neutrino signal does not rule out LSND.
- Combined data
  - combined fit -> **4.8σ** evidence for sterile neutrino
  - with LSND (3.8σ), global preference for sterile neutrino is **6.1σ**.



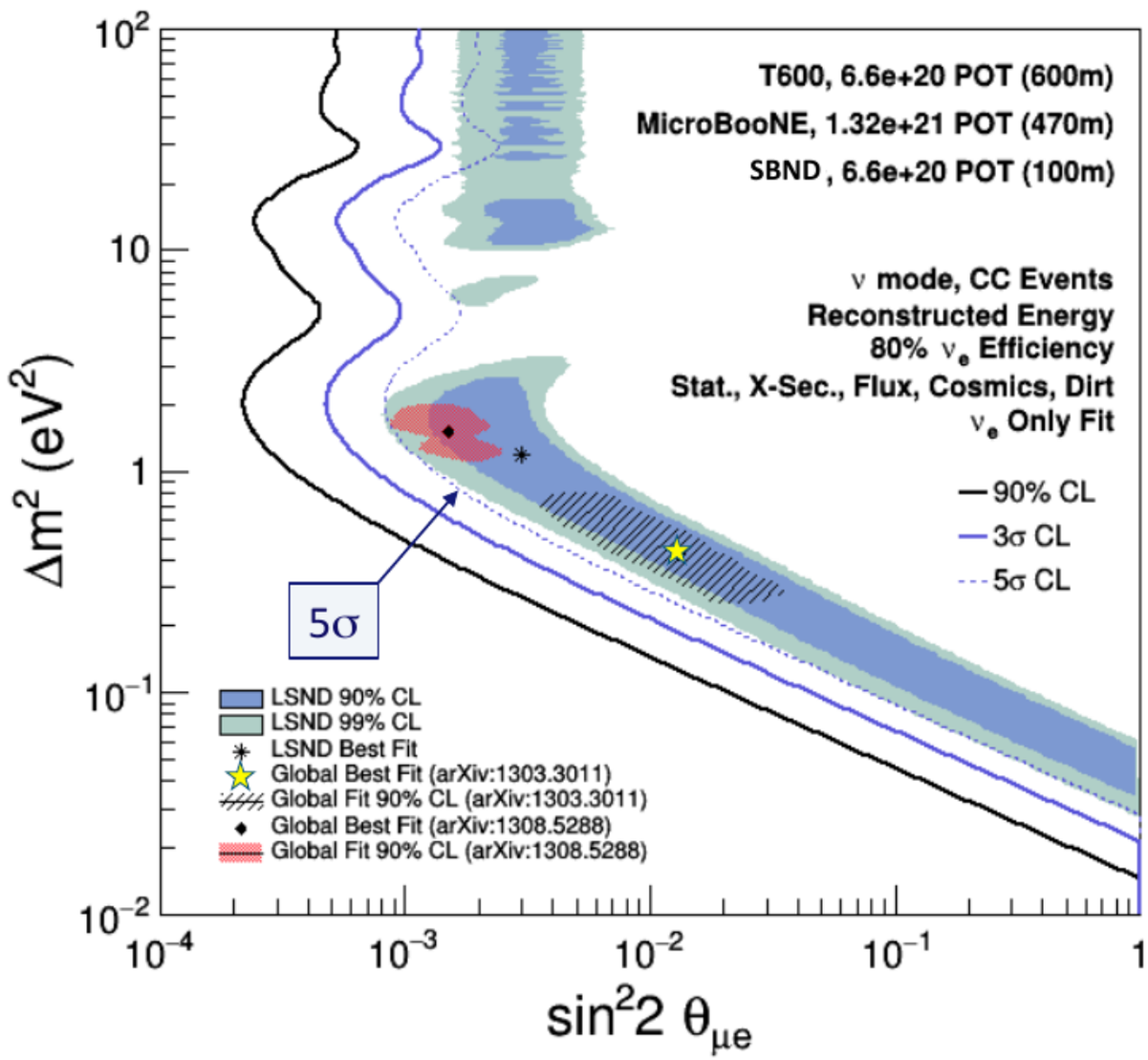
A.A. Aguilar-Arevalo et al. [MiniBooNE collab], PRL 110 (2013) 161801 [arXiv:1303.2588].
A.A. Aguilar-Arevalo et al. [MiniBooNE collab], arXiv:1805.12028.

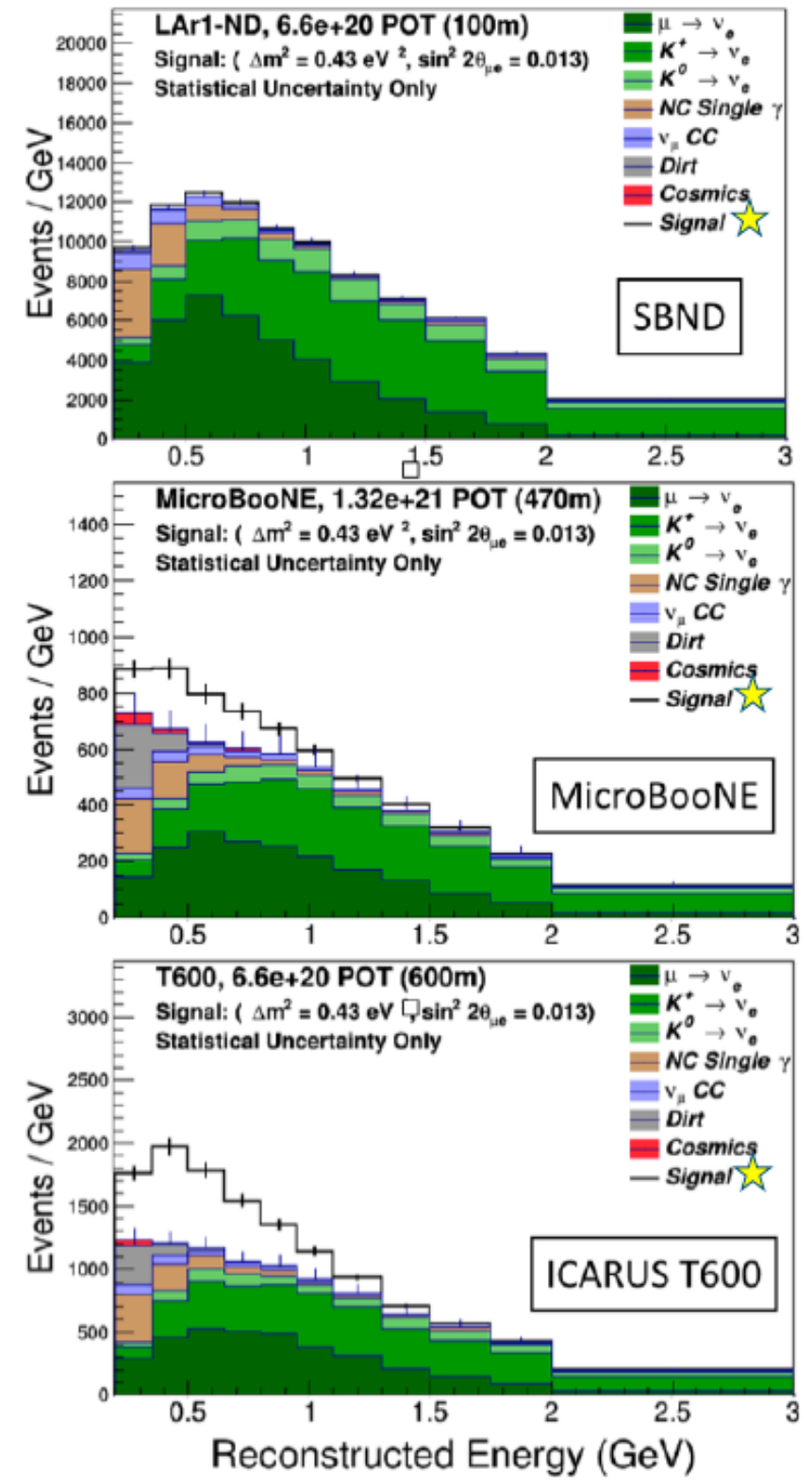
SBN PROGRAM @ FERMILAB



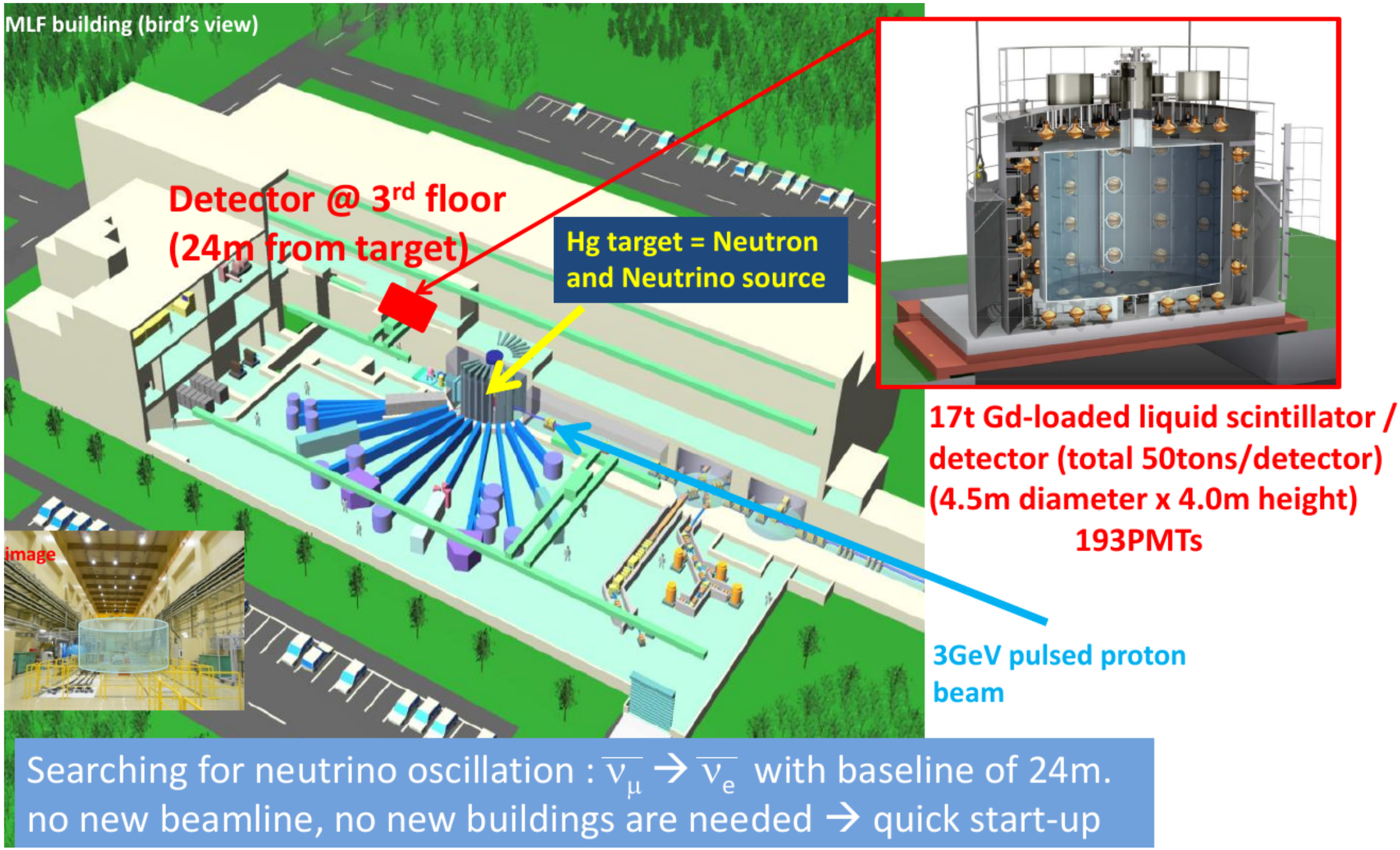
SBN PROGRAM @ FERMILAB

Definitive program to address LSND/MiniBoone anomalies in next ~5 years.





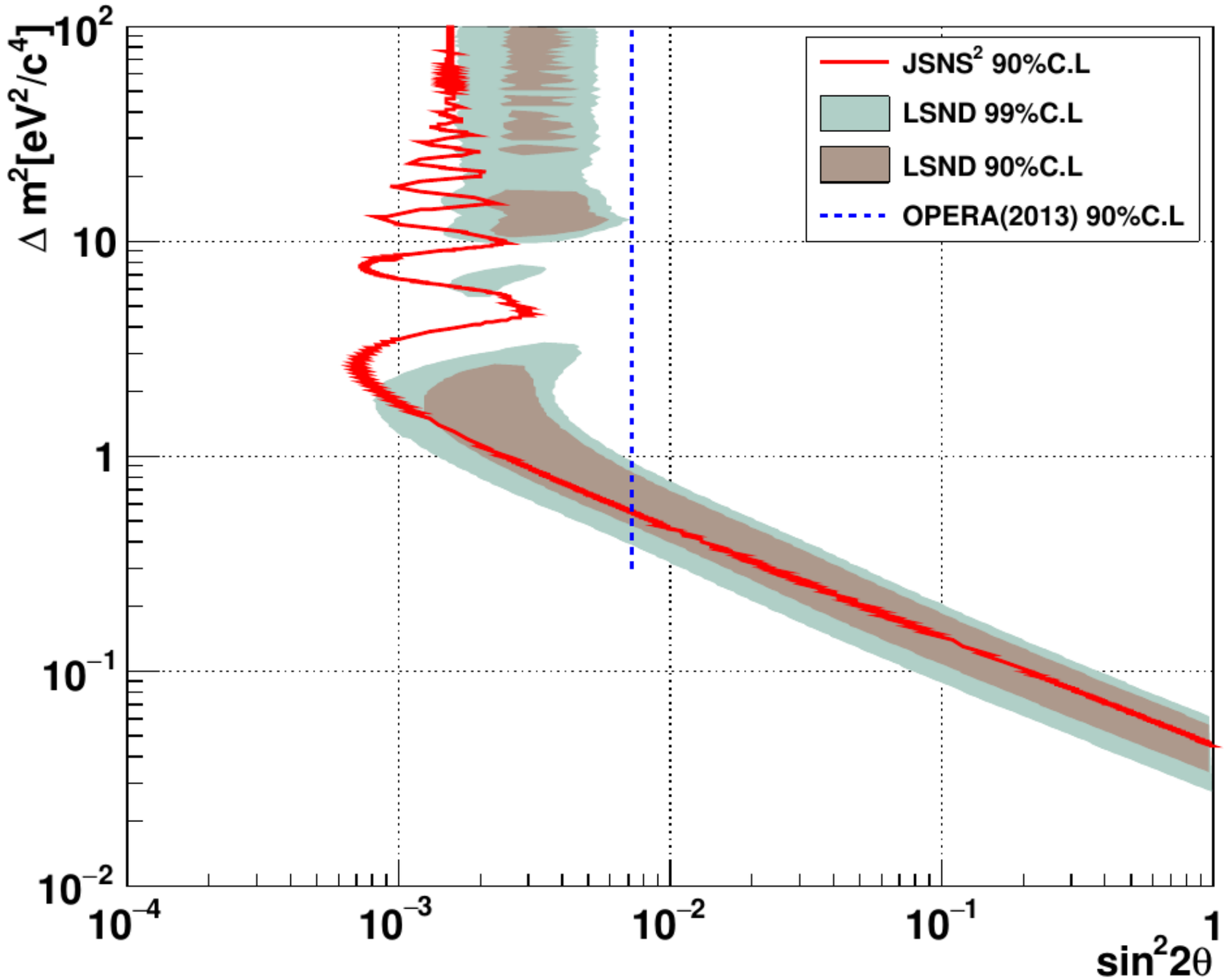
JSNS2 @ J-PARK



Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

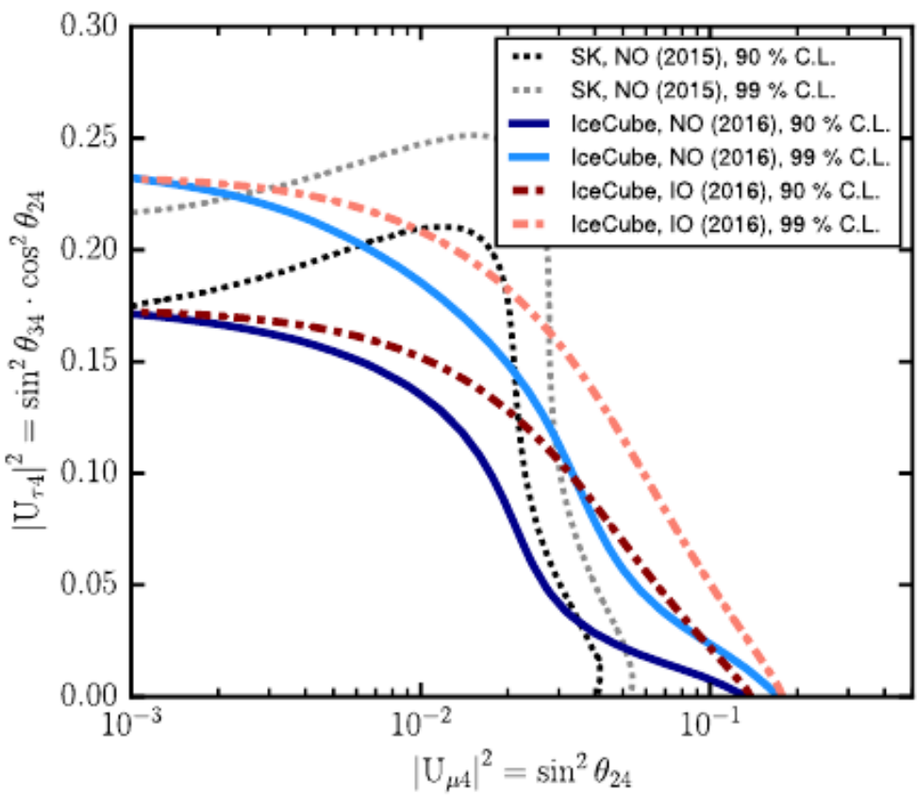
JSNS2 @ J-PARK

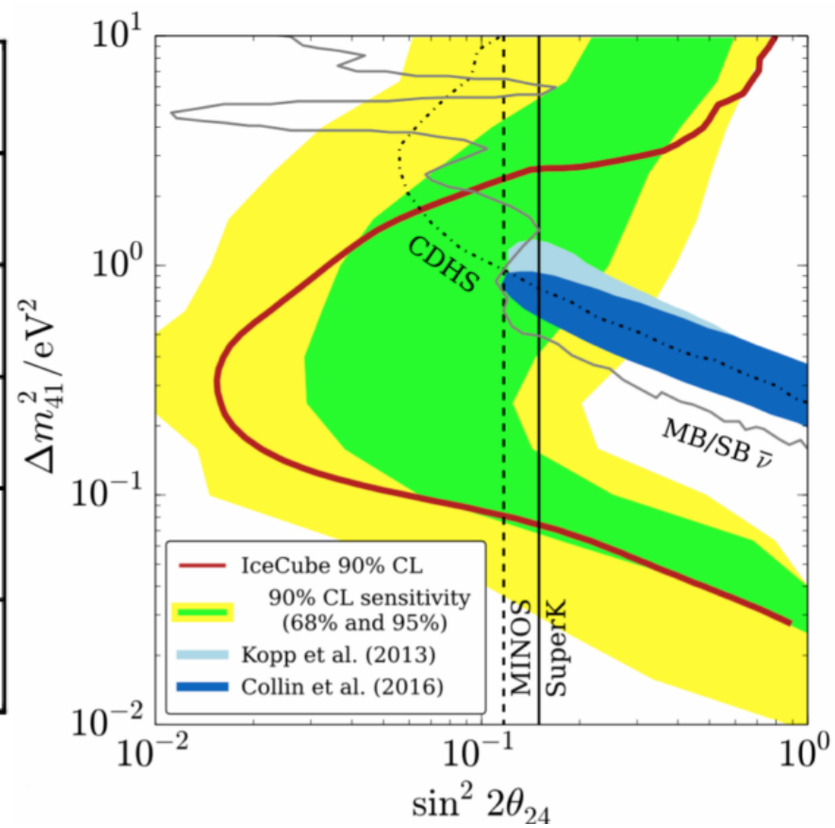
Sensitivity of the JSNS2 experiment with the latest configuration (1 MW × 3years × 1 detector).

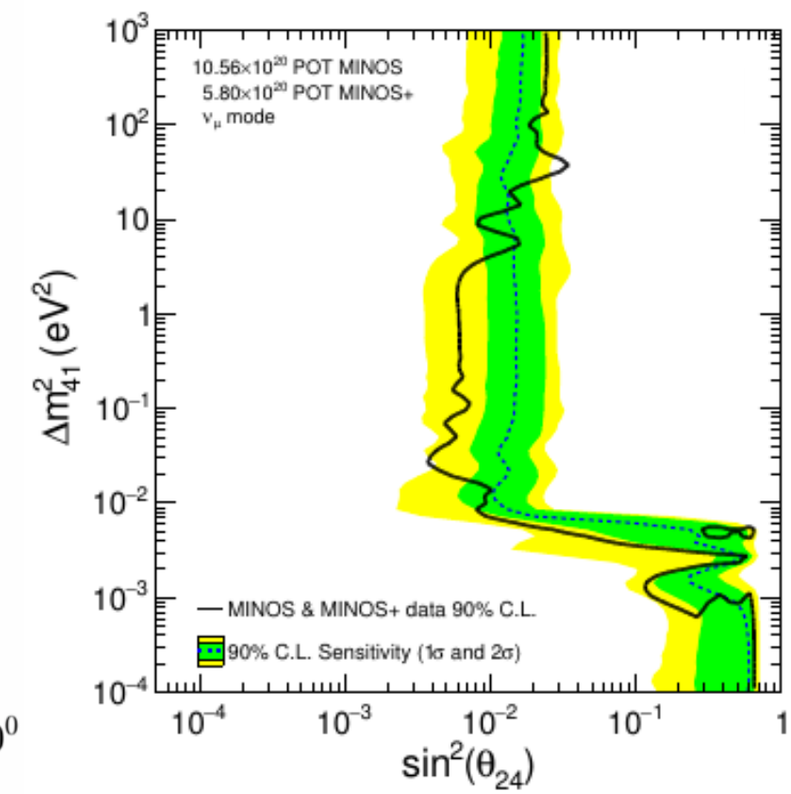


ν_μ DISAPPEARANCE: RECENT ATMOSPHERIC AND SBL DATA

- IceCube atmospheric data probe neutrino mixing with heavy state.
- Sterile neutrino oscillation also studied by NOvA using neutral-current data.
- Recent MINOS/MINOS+ analysis improves bound on neutrino disappearance.







M.G. Aartsen et al. [IceCube collab], Phys. Rev. D 95 (2017) 112002 [arXiv:1702.05160].

M.G. Aartsen et al. [IceCube collab], Phys. Rev. Lett. 117 (2016) 071801 [arXiv:1605.01990].

P. Adamson et al. [NOvA collab], Phys. Rev. D 96 (2017) 072006 [arXiv:1706.04592].

P. Adamson et al. [MINOS collab], [arXiv:1710.06488].

- Anomalies in $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance experiments still exist. Each of these anomalies can be individually explained by sterile neutrinos. But
  - reactor neutrino data face issues with **flux normalization** and the 5 MeV bump, as well as small tensions in reactor vs gallium and "rates" vs DANSS/NEOS
  - MiniBooNE data show an excess in low-E neutrino data, which is not so manifest in antineutrino data.
- No anomaly is found in $\nu_\mu \to \nu_\mu$ disappearance experiments.
- Many experiments are in progress or are being prepared. We expect these anomalies will be solved in the near future.