Short Baseline Reactor Neutrino Experiments

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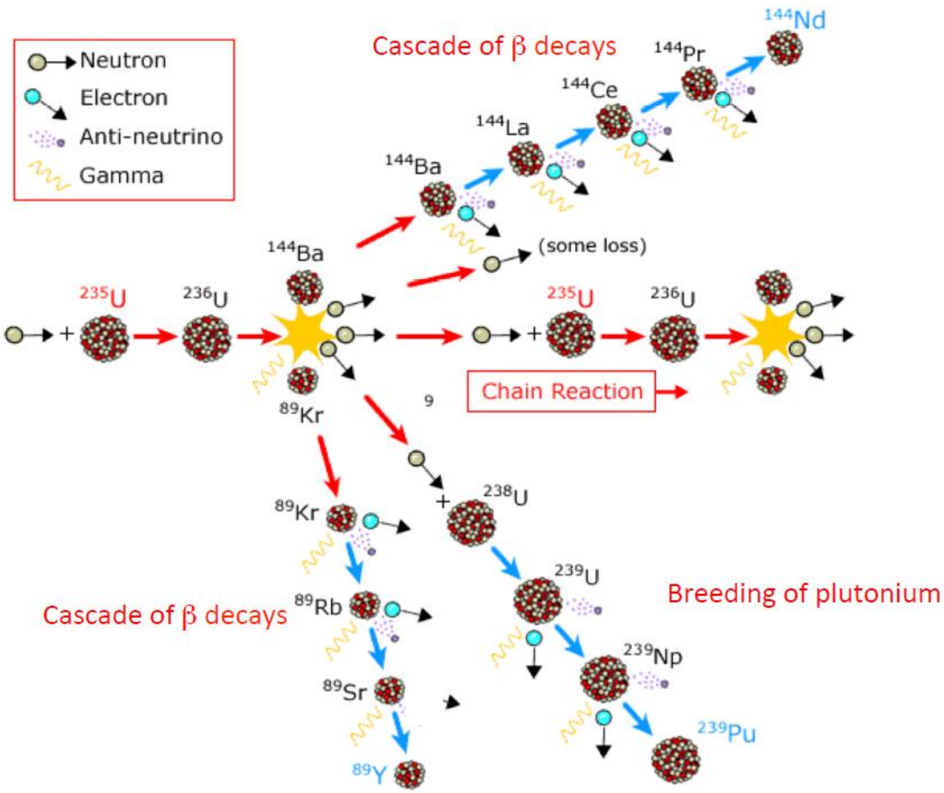
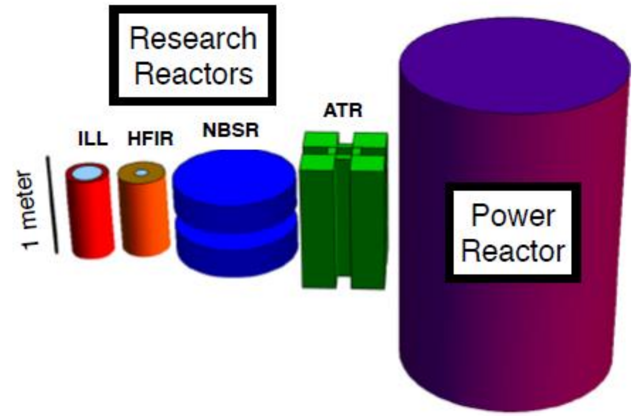
Nuclear Reactor as Antineutrino Source





- ❑ Nuclear reactors produce pure $\bar{\nu}_e$ from beta decays of fission daughters
  - Low energy: < 10 MeV
- ❑ 6 $\bar{\nu}_e$ / fission
- ❑ 2 x 10^{17} $\bar{\nu}_e$ / sec / MW_{th}

- ❑ Commercial reactors in Nuclear Power Plants have low-enriched uranium (LEU) cores
  - Mixture of fissions: ^{235}U (~55%), ^{239}Pu (~30%), ^{238}U (~10%), ^{241}Pu (~5%)
  - Large power: ~3 GW_{th}
- ❑ Research reactors have highly-enriched uranium (HEU) cores
  - ^{235}U fission fraction ~99%
  - Lower power, few tens of MW_{th}
  - compact size

Reactor Neutrino Spectrum

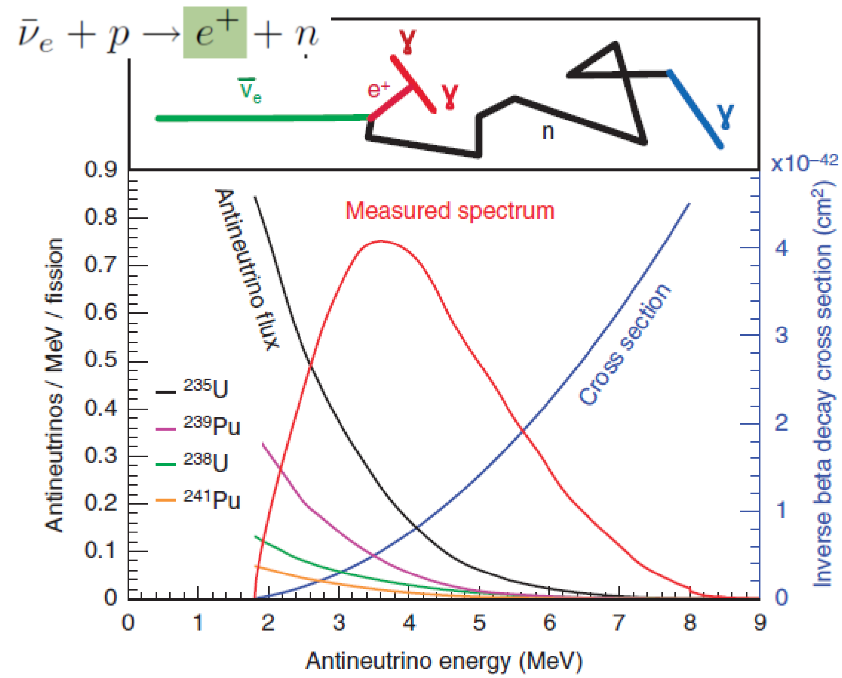
$$S(E_\nu) = c \cdot \sum_i f_i \cdot s_i(E_\nu) \cdot \sigma(E_\nu)$$

isotope fission fraction

isotope neutrino spectra

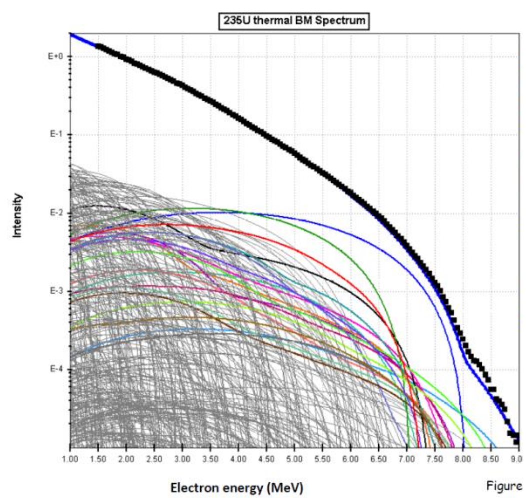
IBD cross section

reactor thermal power, energy released per fission, baseline, target protons, detection efficiency, oscillation, etc.



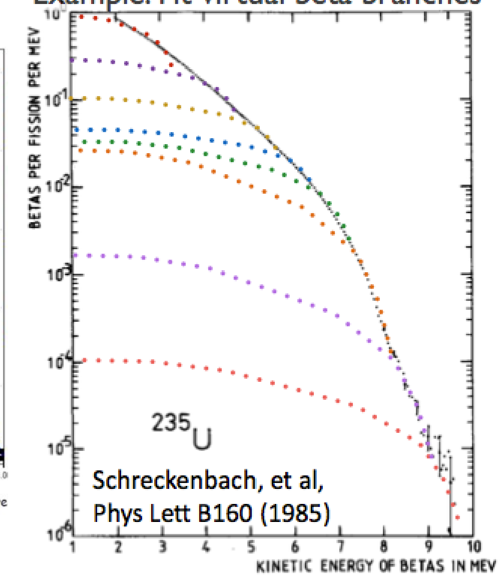
Prediction of isotope neutrino spectra

- Summation (*ab initio*) method
  - sums over 6000 tabulated beta decay branches
  - ~10% uncertainty due to missing data in the database and forbidden decays
- Conversion method
  - measure total outgoing beta-decay electron spectrum for each isotope. (*Experiments done at ILL in the 1980s*)
  - Predict corresponding anti-neutrino spectra with >30 virtual branches. ~2.5% uncertainty

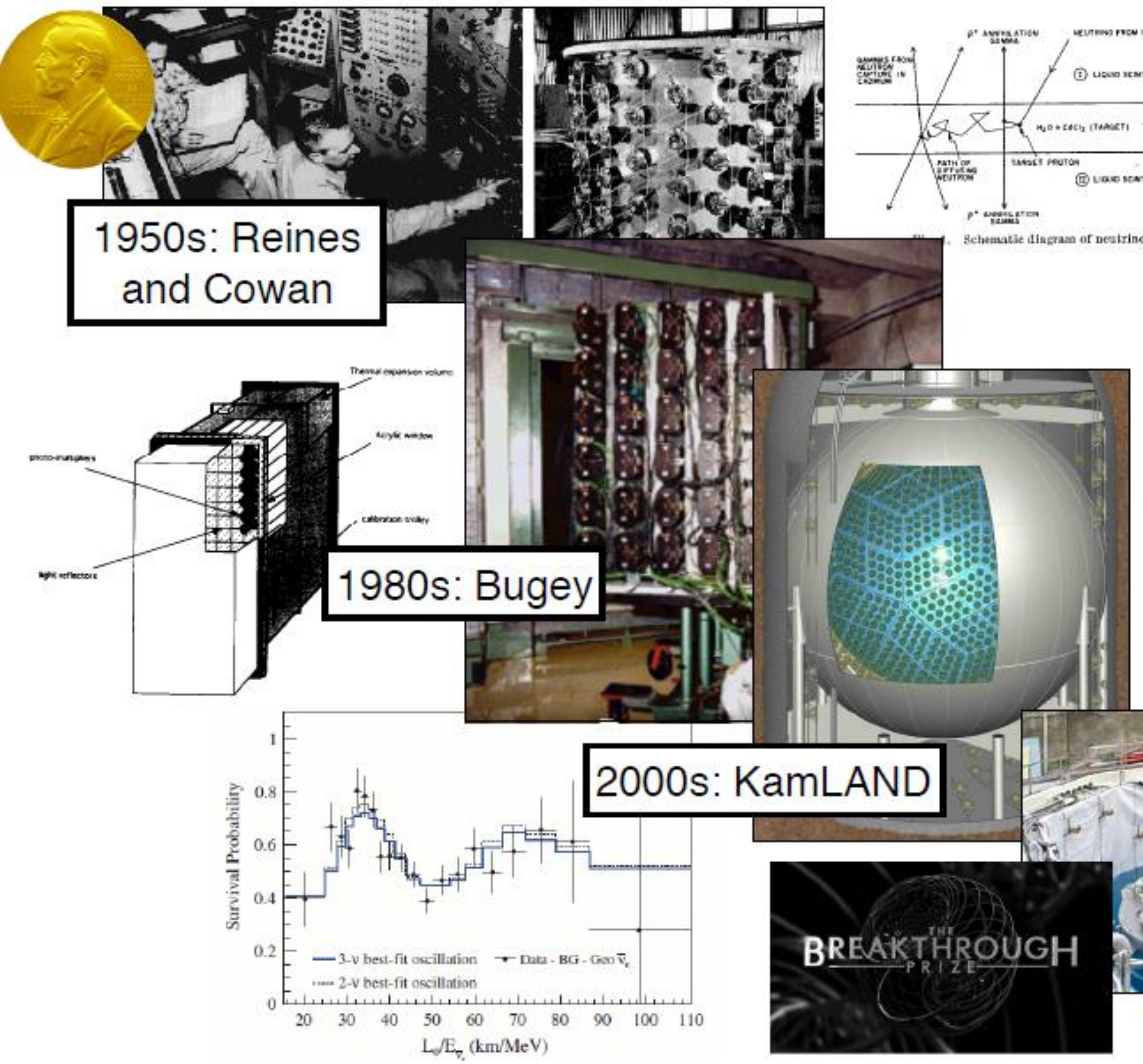


Sonzogni et al, PRC 91, 011301

Example: Fit virtual beta branches

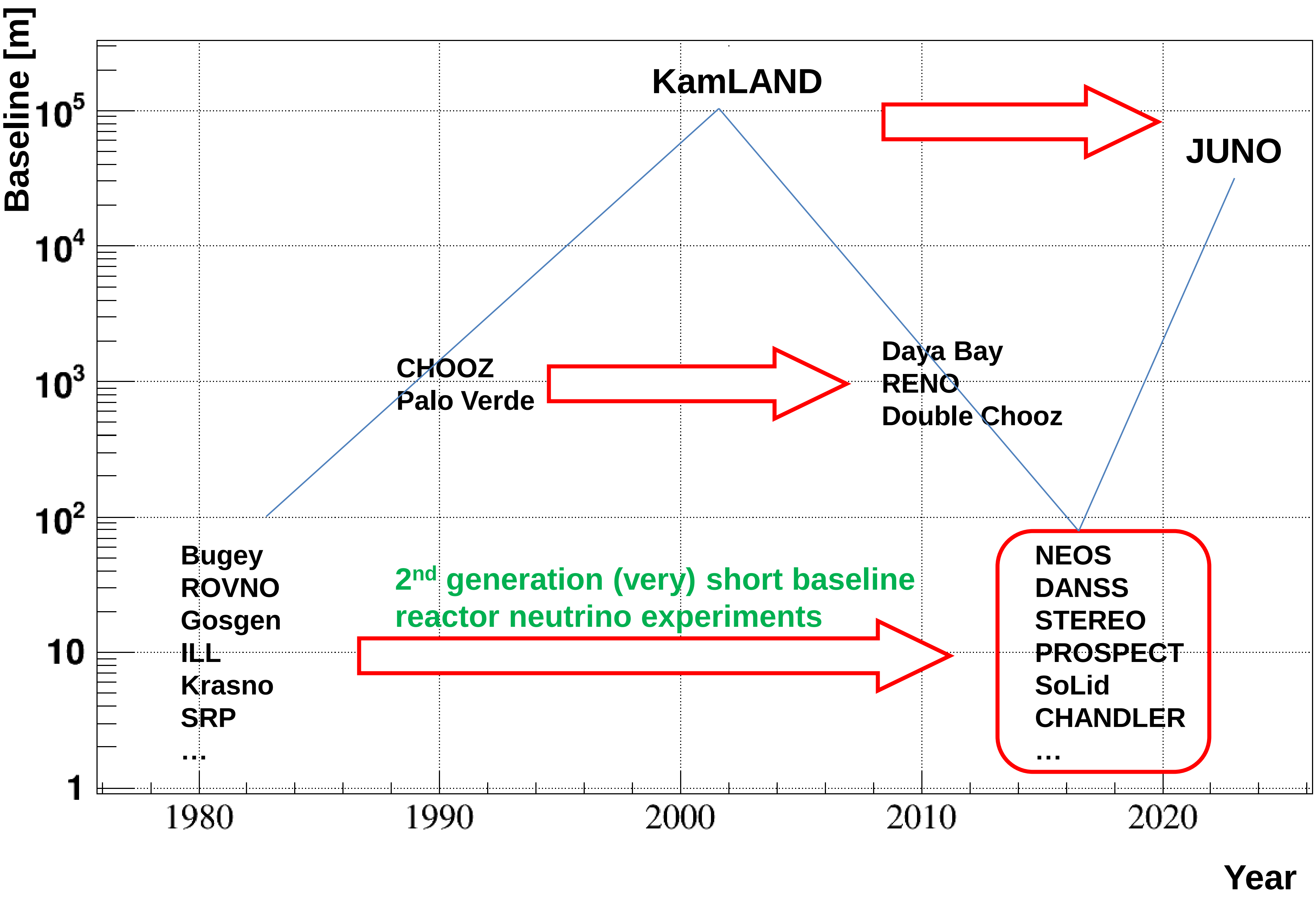


Reactor Neutrino Experiments

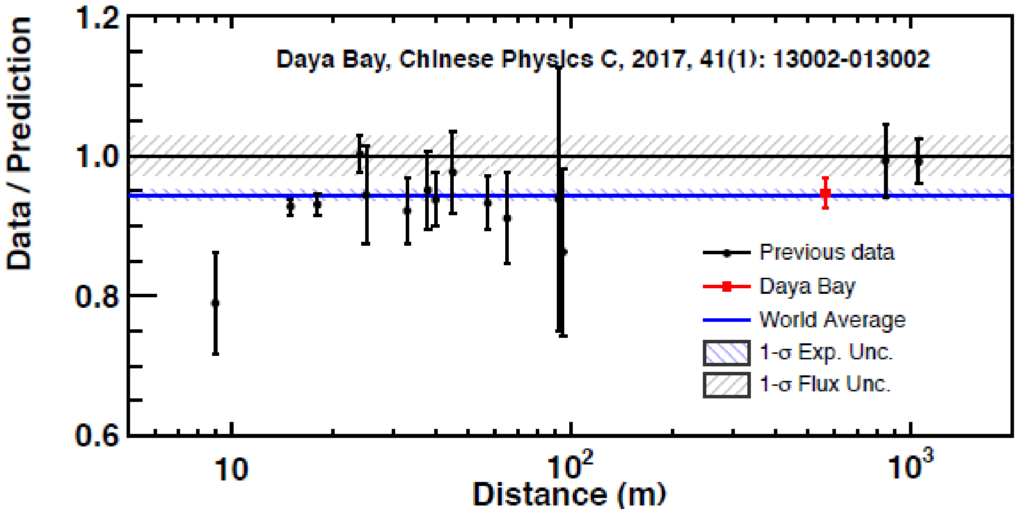


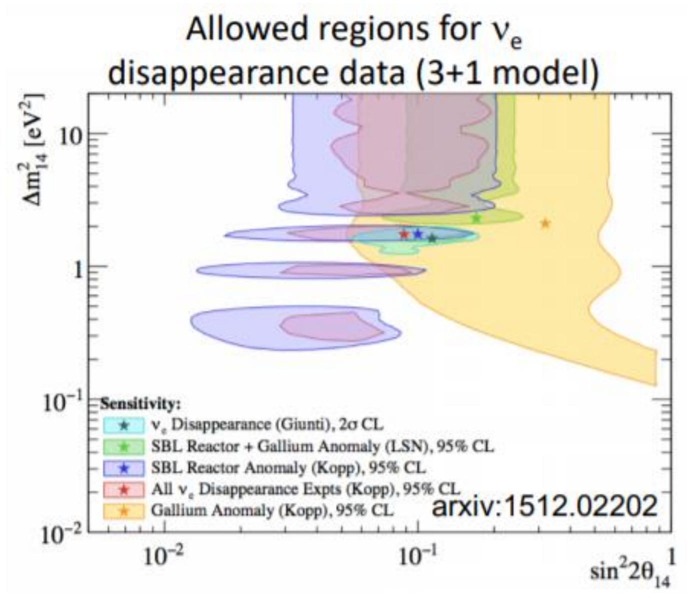
- Currently hold the best precision of
  - Δm^2_{21} (KamLAND)
  - θ_{13} (Daya Bay)
- Comparable precision to accelerator-based exp.
  - $|\Delta m^2_{32}|$ (Daya Bay)
- In the future JUNO will reach even better precision for
  - Δm^2_{21}, $|\Delta m^2_{32}|$, θ_{12}, Mass Hierarchy

Image credit: K. Heeger


Baseline [m]
10⁵
10⁴
10³
10²
10
1
1980
1990
2000
2010
2020
Year
KamLAND
JUNO
CHOOZ
Palo Verde
Daya Bay
RENO
Double Chooz
Bugey
ROVNO
Gosgen
ILL
Krasno
SRP
…
2nd generation (very) short baseline
reactor neutrino experiments
NEOS
DANSS
STEREO
PROSPECT
SoLid
CHANDLER
…

Motivation: Reactor Antineutrino Anomaly (RAA)

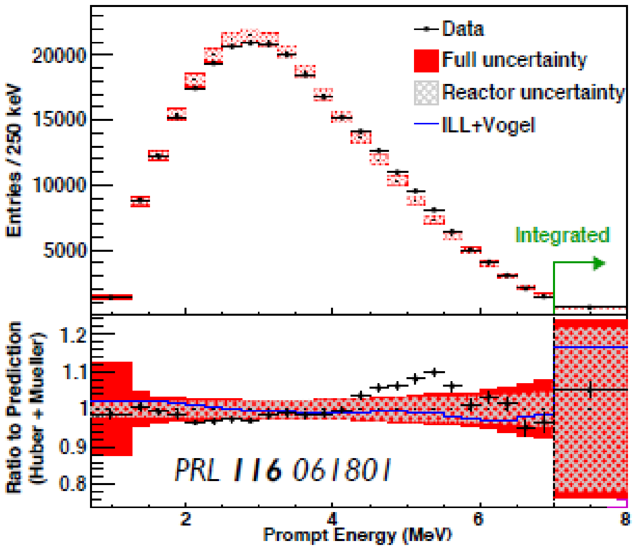




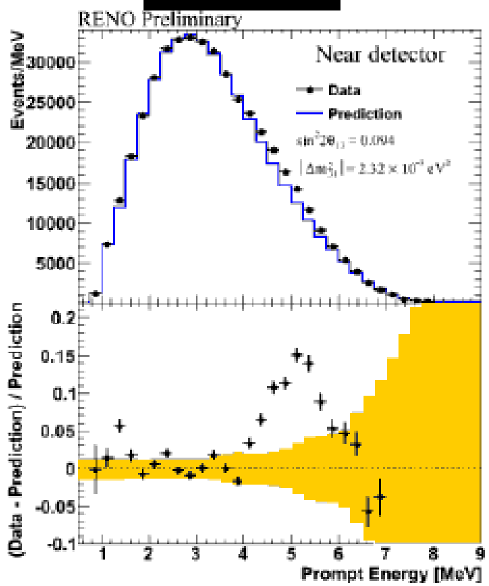
- Comparing with the latest reactor model predictions (Huber-Muller model @2011; uncertainty: ~2.5%), the past SBL reactor experiments in the 1980s measured ~6% deficit in total flux.
  - Confirmed by modern reactor θ_{13} experiments (Daya Bay, RENO, DC)
- eV-scale sterile neutrinos?
  - Similar region as Gallium anomaly (ν_e disappearance) and LSND/MiniBooNE anomaly (ν_e / $\overline{\nu}_e$ appearance). ***see Georgia Karagiorgi's talk next***
  - But no L/E distortions have been observed yet
- Or problems from reactor model predictions?

Challenge to Reactor Model: Spectrum “bump”

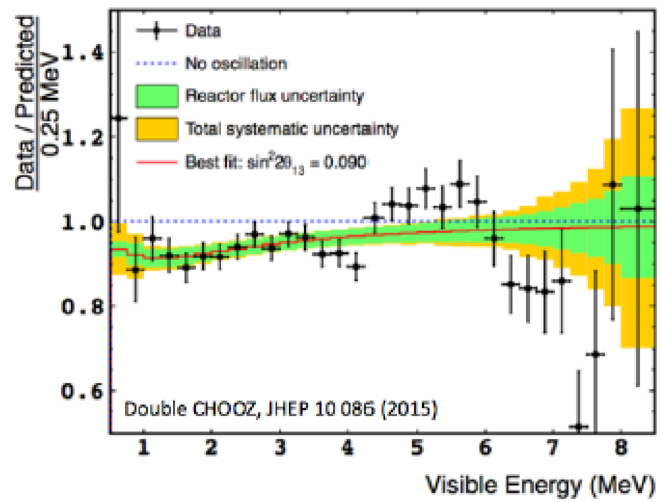
Daya Bay



RENO



Double Chooz

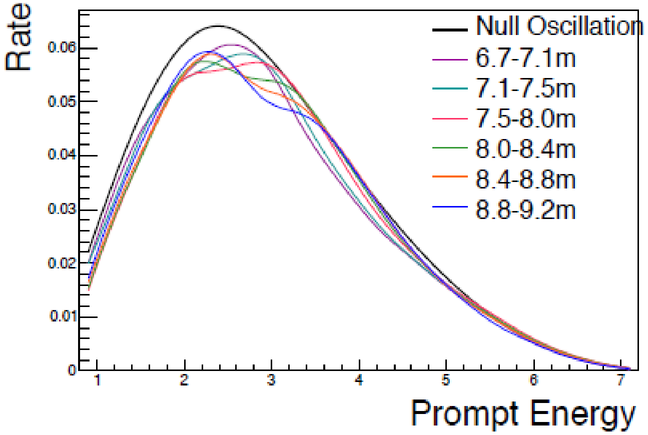


- Bump in (4 – 6 MeV) prompt energy region (when compared to the model prediction) observed in 2014 by three θ_{13} experiments (Daya Bay, RENO, DC). Later also seen by NEOS (2016).
- Cannot be explained by detector effects such as energy response
- Cannot be explained by sterile neutrino oscillations
- Indicates the reactor model uncertainty is under-estimated

Strategies of new generation SBL reactor experiments

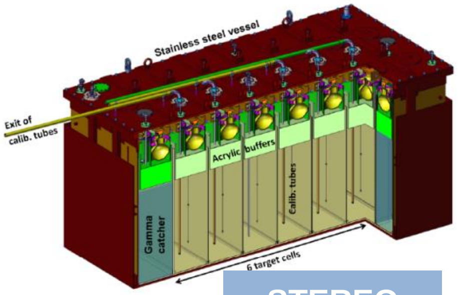
- Reactor-model-independent search for sterile neutrinos
  - Measure relative spectrum distortion at different baselines
  - Look for multiple “wiggles” in the L/E space
  - Target toward 0.3-10 eV^2 region
- Increase L/E reach
  - Prefer to use research reactors (compact core < 1m^3)
  - Movable detectors
  - 3D position localization
    - Detector segmentation
    - ^{6}Li loaded scintillator
  - High energy resolution

BASELINE-DEPENDENT OSCILLATION ILLUSTRATION

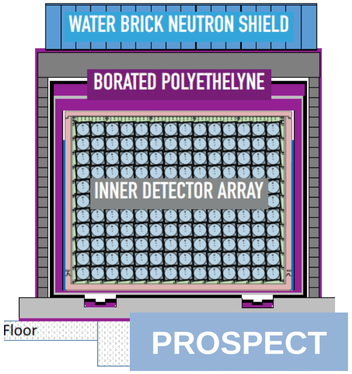


Neutrino4

DANSS



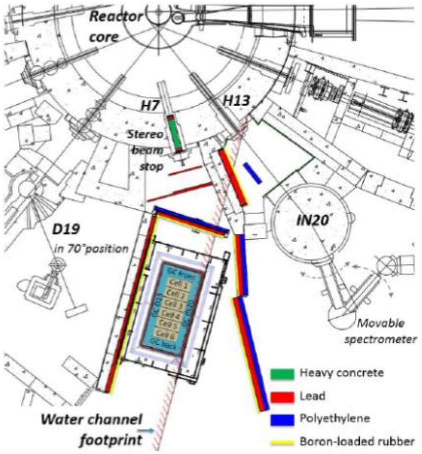
STEREO



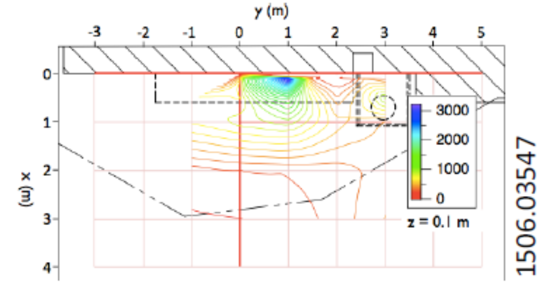
PROSPECT

Biggest challenge: Background Reduction

- Ambient beamline-related background
  - Targeted “hot-spot” shielding
- Near-surface cosmogenic background due to limited overburden
  - Careful multi-layer shielding design aided by simulation
  - Pulse shape discrimination (PSD) capability
- Be careful about reactor on vs off background subtraction
  - Time-dependent cosmogenic flux
  - Time-dependent detector performance

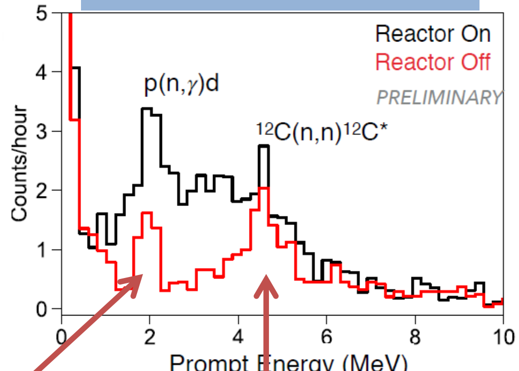


STEREO, ILL

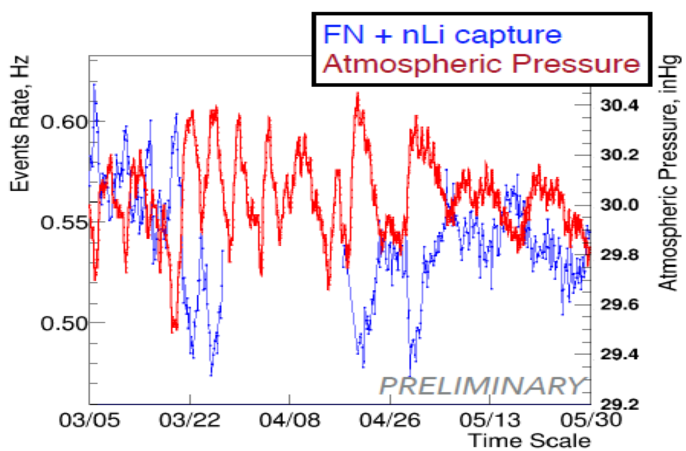


γ-ray intensity variation at HFIR

PROSPECT

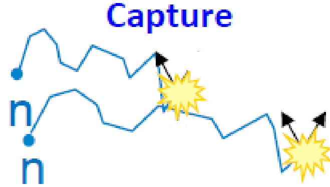


S/B ~ 1.4

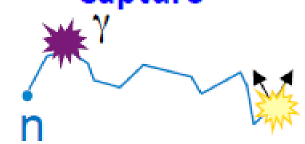


PROSPECT, HIFR

Multiple Neutron Capture



Inelastic Scatter/ Capture

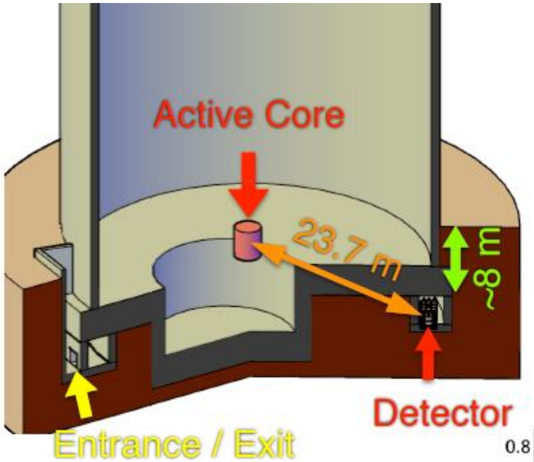


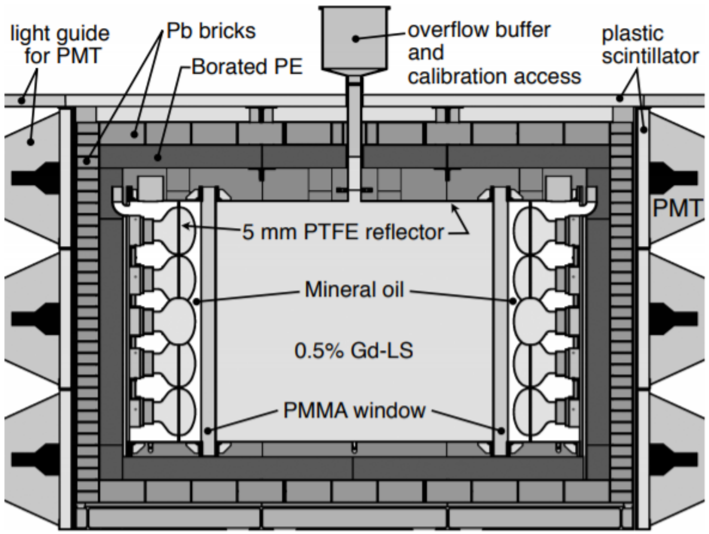
Finished phase I | Taking data | Planned

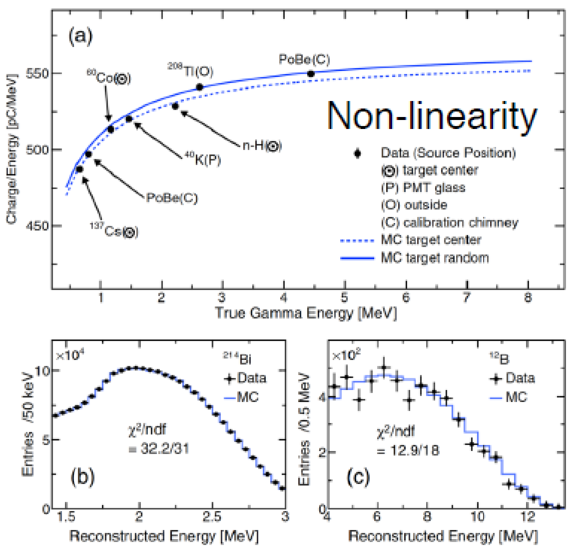
Apologize if I missed any

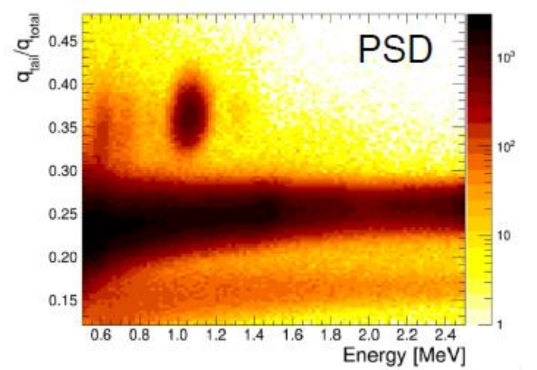
Experiment	Reactor	Baseline (m)	Overburden (m.w.e)	Mass (ton)	Segmentation	Energy res. (@ 1 MeV)
NEOS (South Korea)	LEU 2.8 GW	23.7	~20	1.0	none	5%
Nucifer (France)	HEU 70 MW	7.2	~12	0.6	none	10%
NEUTRINO4 (Russia)	HEU 100 MW	6 - 12	~10	0.3	2D	
DANSS (Russia)	LEU 3.1 GW	10.7 - 12.7	~50	1.1	2D	17%
STEREO (France)	HEU 58 MW	9 – 11	~15	1.6	1D 25 cm	8%
PROSPECT (USA)	HEU 85 MW	7 - 12	< 1	1.5	2D 15cm	4.5%
SoLid (UK Fr Bel US)	HEU 70 MW	6 - 9	~10	1.6	3D 5cm	14%
CHANDLER (USA)	HEU 75 MW	5.5 - 10	~10	1.0	3D 5cm	6%
NuLAT (USA)	HEU 20 MW	4	few	1	3D 5cm	4%

NEOS



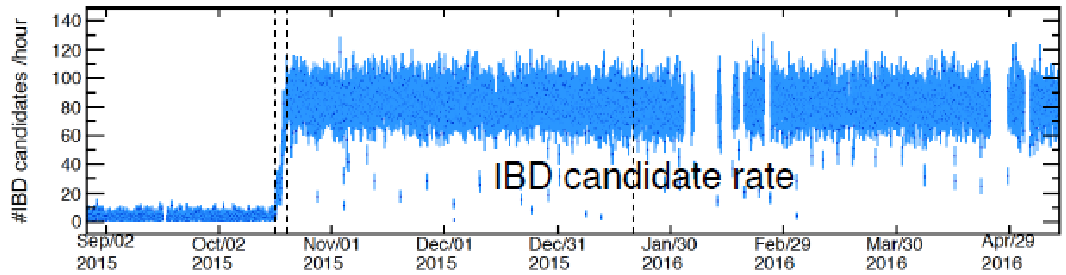


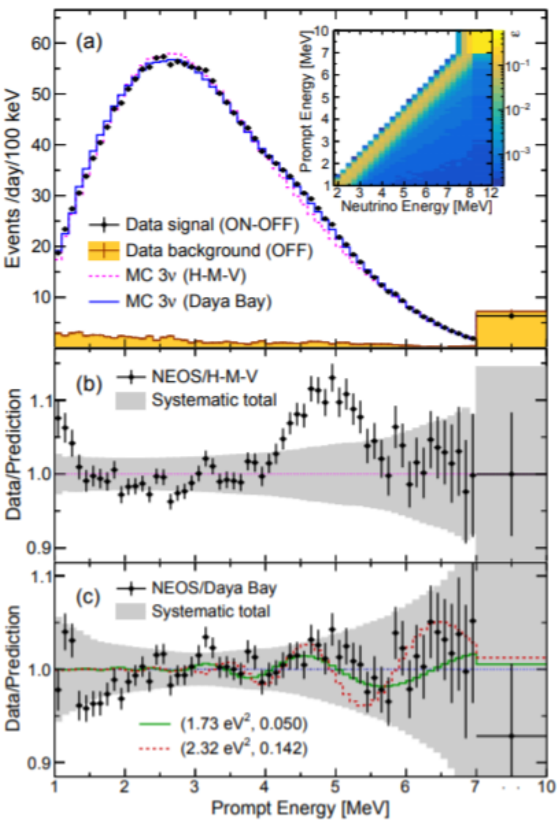




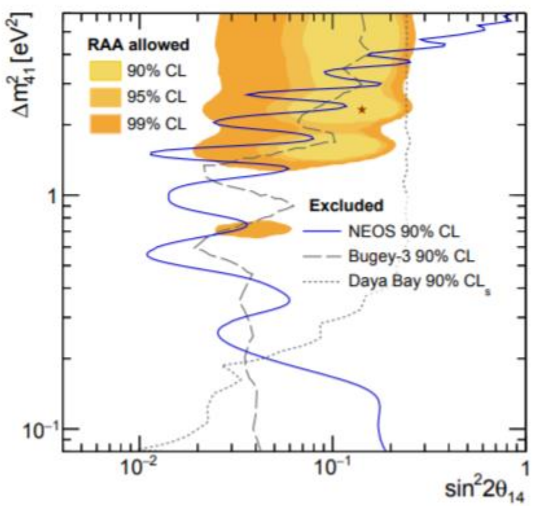
- Reactor
  - Hanbit-5 reactor, Korea
  - LEU, 2.8 GW, Φ=3.1m, H=3.8m
  - Overburden > 20 m.w.e
  - Baseline: 23.7 m
- Detector
  - Homogeneous 0.5% Gd-loaded LS (LAB+UG-F): total 1 ton
  - Cylindrical stainless steel tank (Φ=103cm, L=121cm) with PTFE reflector
  - 38 8” PMTs in mineral oil buffer, σ(E) ~5% at 1 MeV
  - Shielding: 10 cm B-PE (n), 10 cm Pb (γ) + active muon veto

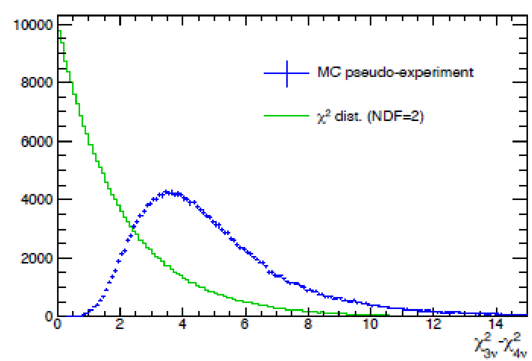
NEOS





Phys. Rev. Lett. 118, 121802 (2017)

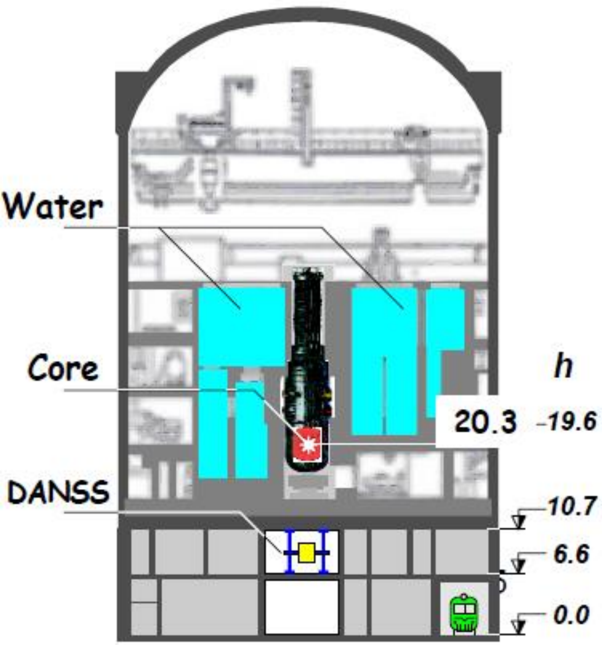


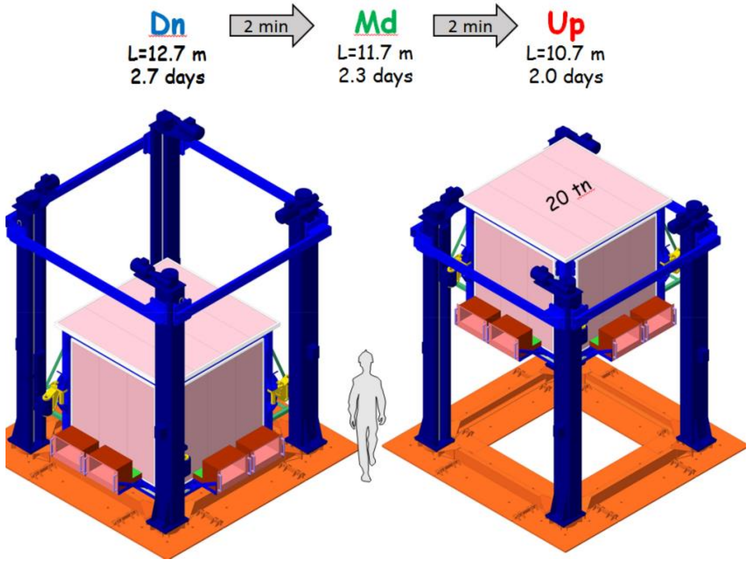


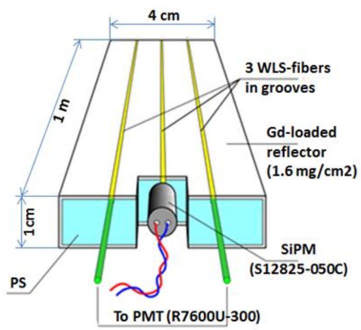
Best-fit 4ν: (1.7 eV^2, 0.05)
$\Delta\chi^2$ = 6.5, p-value = 0.22

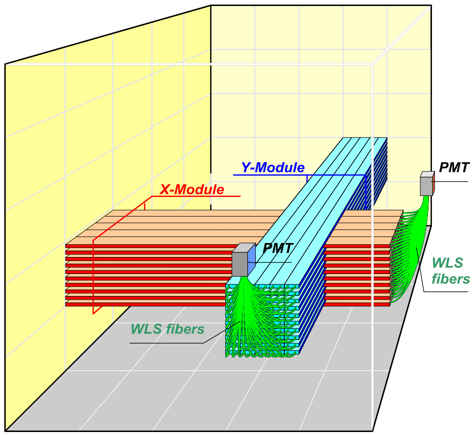
- Phase I physics data taking:
  - Aug 2015 - May 2016
  - 180 days reactor on
  - 46 days reactor off
  - 1977 (85) IBD events/day during on (off), S/B ~ 22
- Phase II plan:
  - Same reactor, same detector, resume from Sept 2018
  - one full burnup cycle (~500 days), longer background measurement
    - Spectrum evolution

DANSS





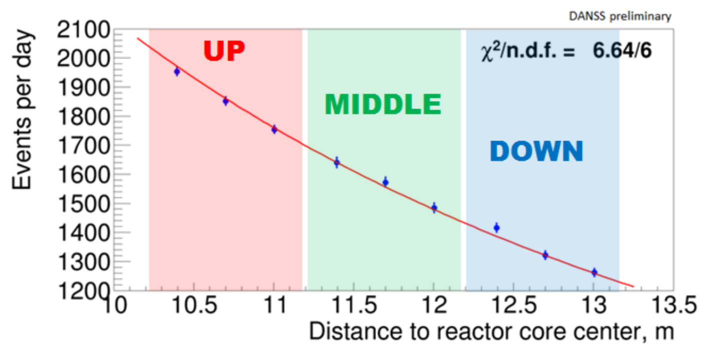


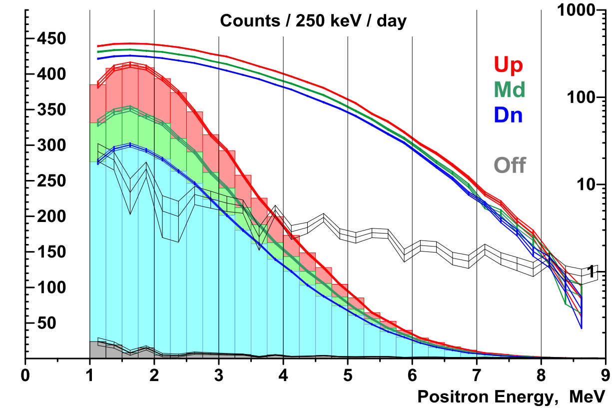


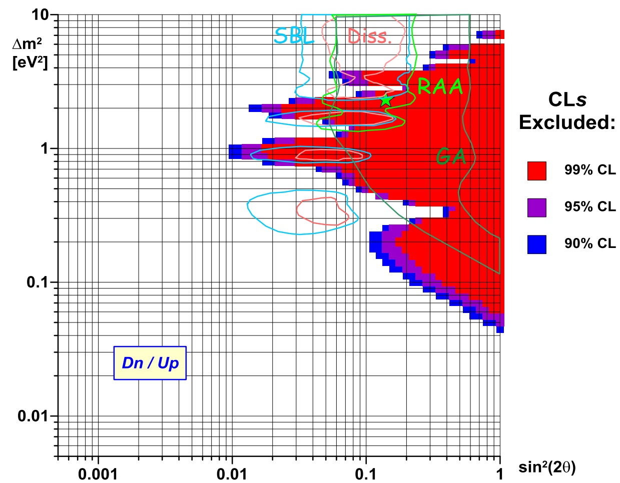
- Reactor
  - Kalinin NPP, Russia
  - LEU, 3.1 GW, Φ=3.2m, H=3.7m
  - Overburden > 50 m.w.e
  - Baseline: 10.7 – 12.7 m in three vertical positions; detector moves 3 times a week
- Detector
  - Highly segmented plastic scintillator strip (1x4x100 cm^3): total 1.1 ton
  - 0.35% Gd-loaded reflector surface coating
  - Dual readout: 2500 SiPMs + 50 PMTs through WLS fibers, σ(E) ~17% at 1 MeV
  - Shielding: multi-layer (Cu, CHB, Pb, CHB) + active muon veto

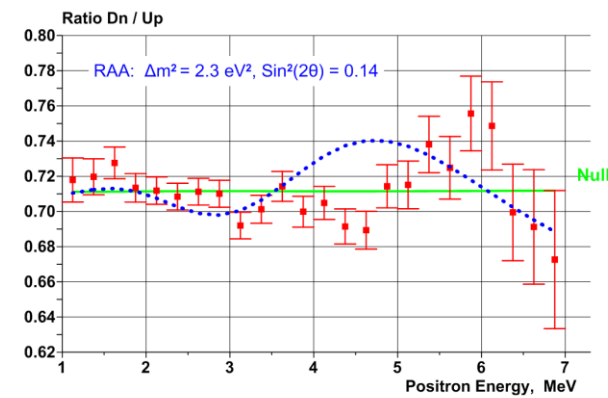
DANSS

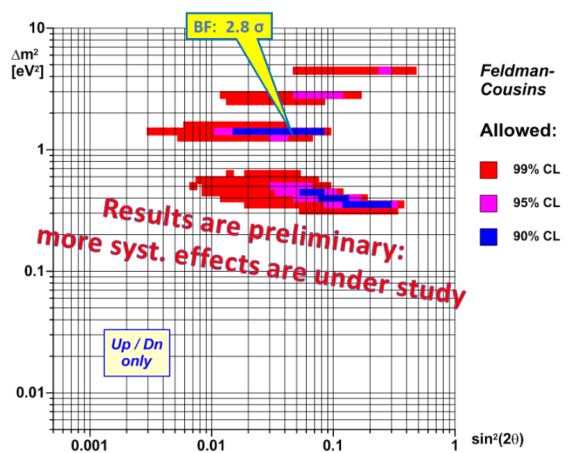
- Taking data since Apr 2016
- 4910 events/day (up positon.)
- Background: 133 μ-induced events/day (2.7% for up pos.)
- The RAA point (2.3 eV^2, 0.14) is excluded at 5σ level.
- The best fit at (1.4 eV^2, 0.05) has 2.8σ significance.
  - "more syst. effects are under study"

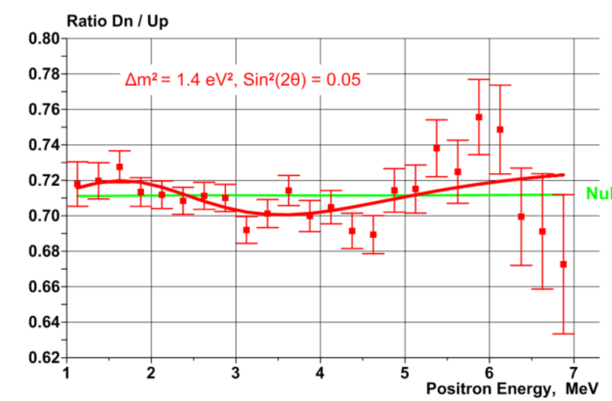


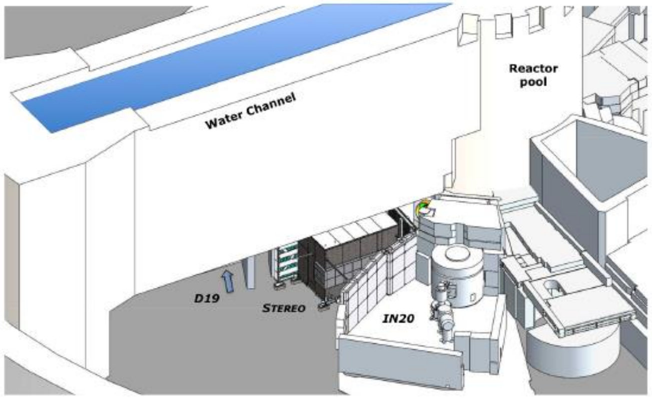


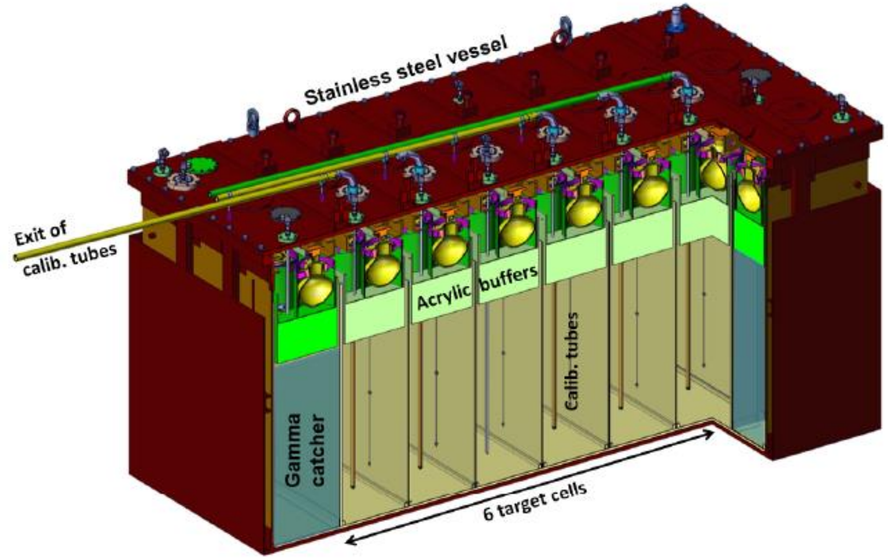


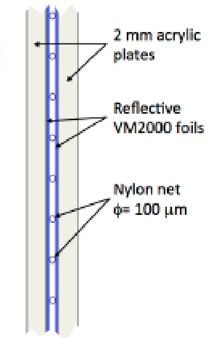


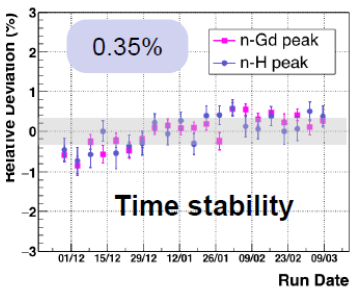


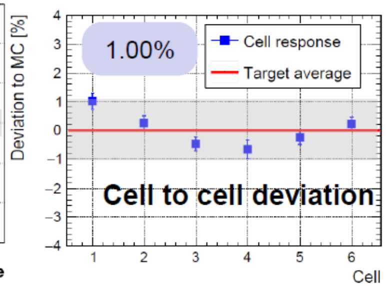


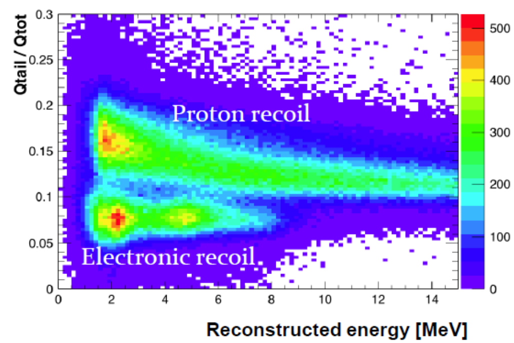


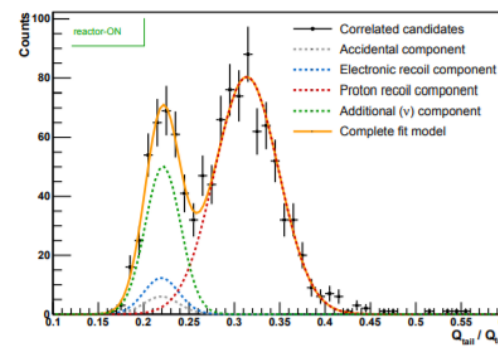








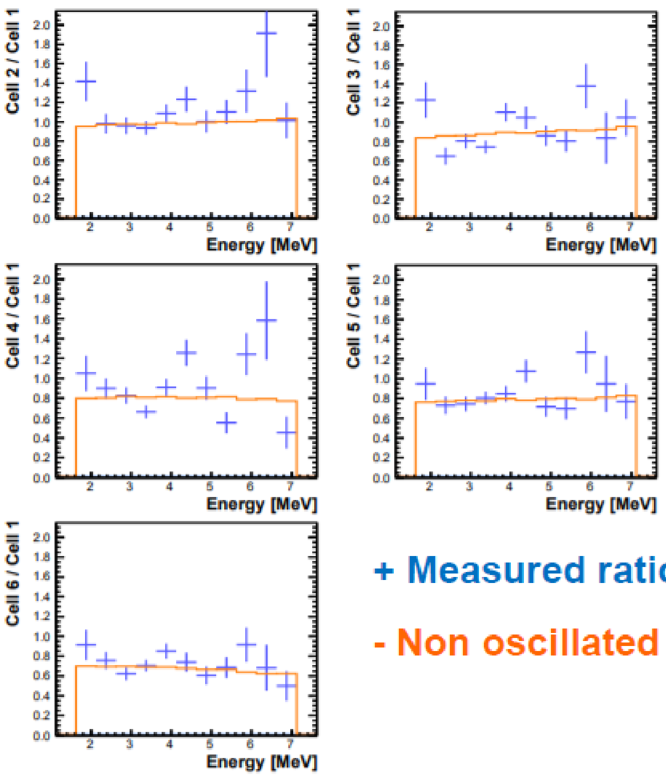




- Reactor
  - ILL reactor, France
  - HEU, 58 MW, Φ=40cm, H=80cm
  - Overburden ~15 m.w.e
  - Baseline: 9-11 m

- Detector
  - 6 target cells with 0.2% Gd-loaded LS: total 1.6 ton
  - 4 top PMTs per cell, σ(E) ~8% at 1 MeV
  - Surrounding gamma catcher with LS: containing escaping gamma ray + active shielding
  - Shielding: dedicated beamline shielding + multi-layer lead, BPE + active water Cerenkov muon veto

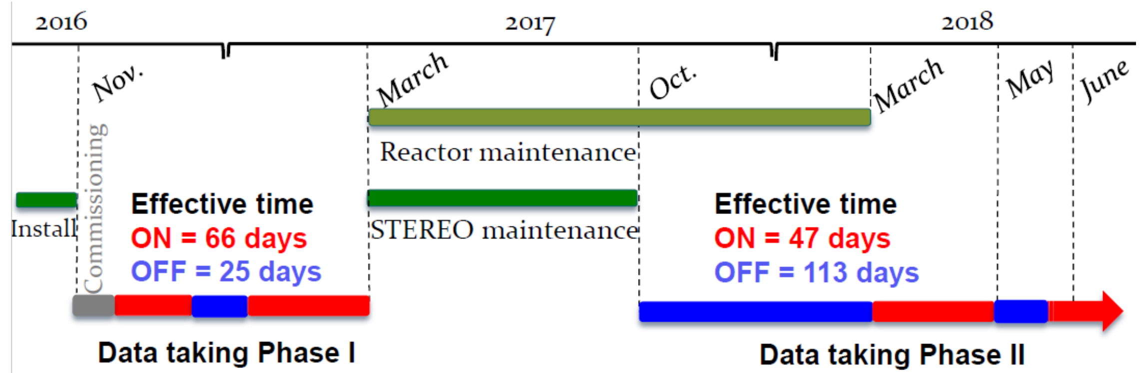
66 days-on data (Phase I)
ratio of cell 2-5 to cell 1



+ Measured ratios

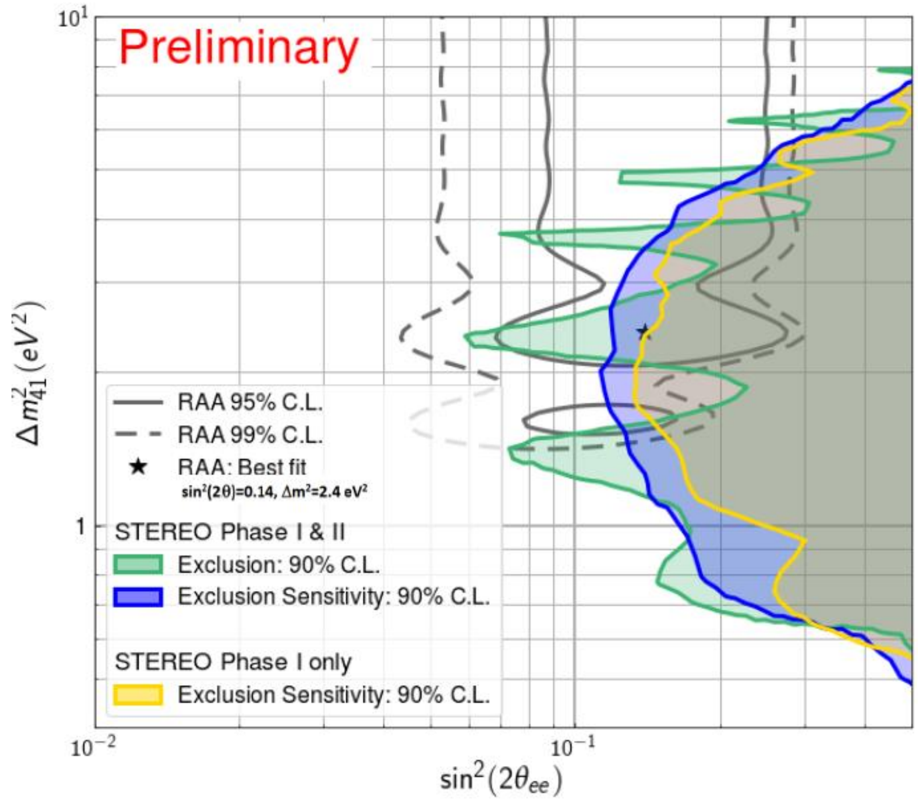
- Non oscillated predictions

- Data taking since Nov 2016. Now at phase II
- Results consistent with no oscillation
- The RAA best-fit point is excluded at 98% C.L.

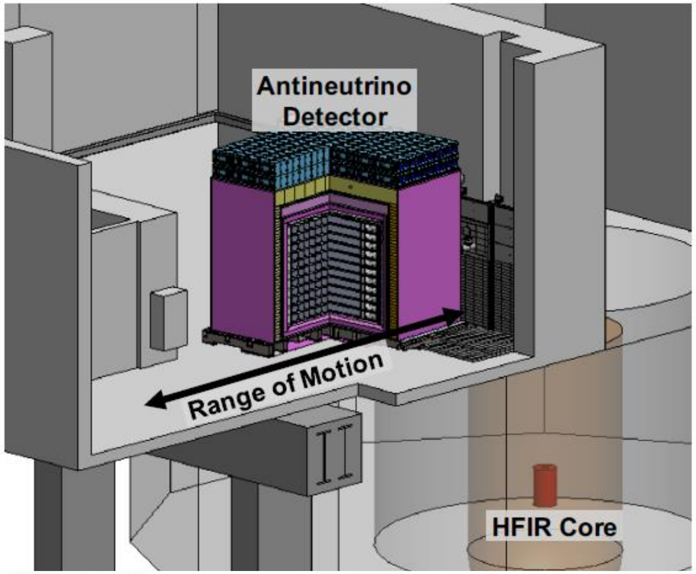


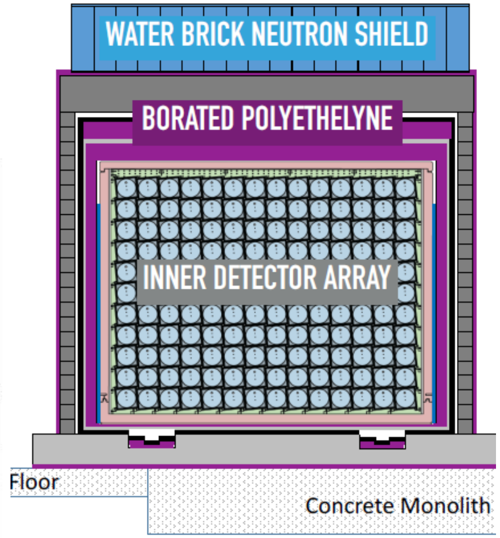
~ 400 antineutrino events/day

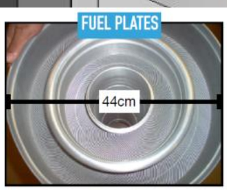
Improved optical coupling and light cross talk

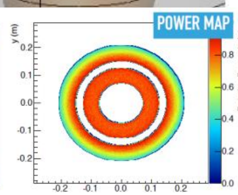


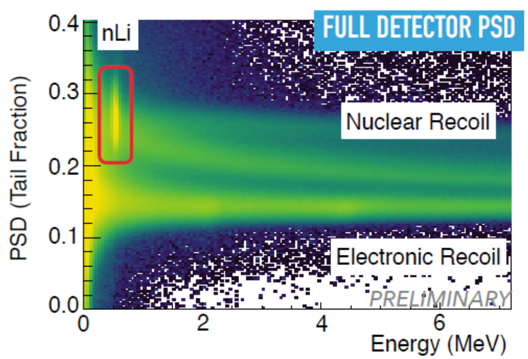
PROSPECT

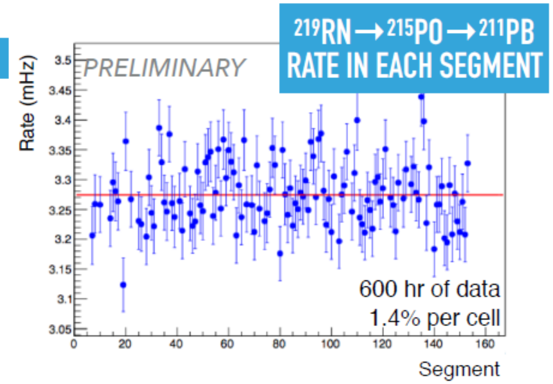




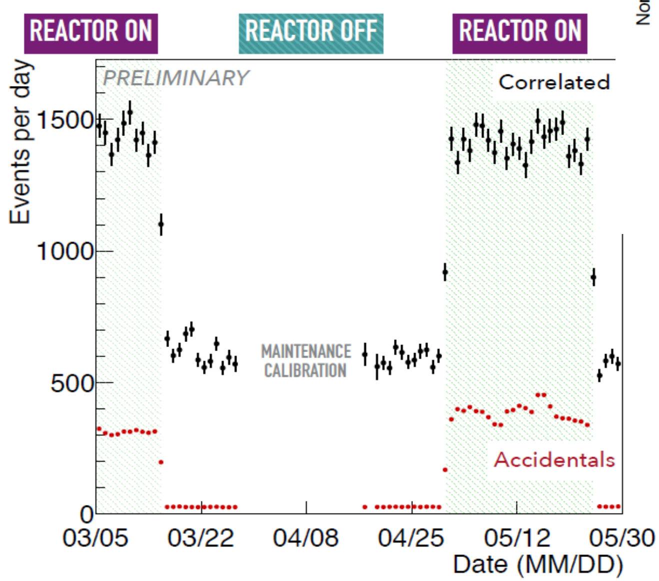


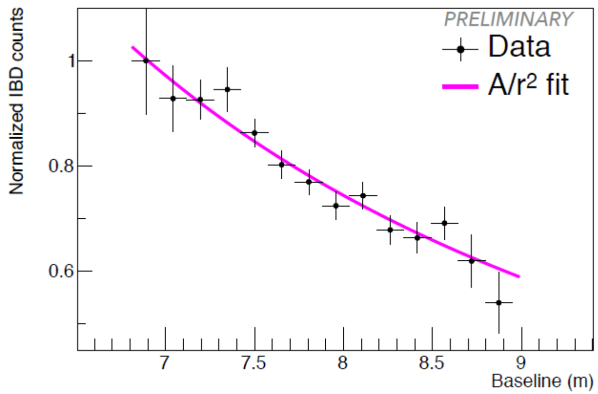


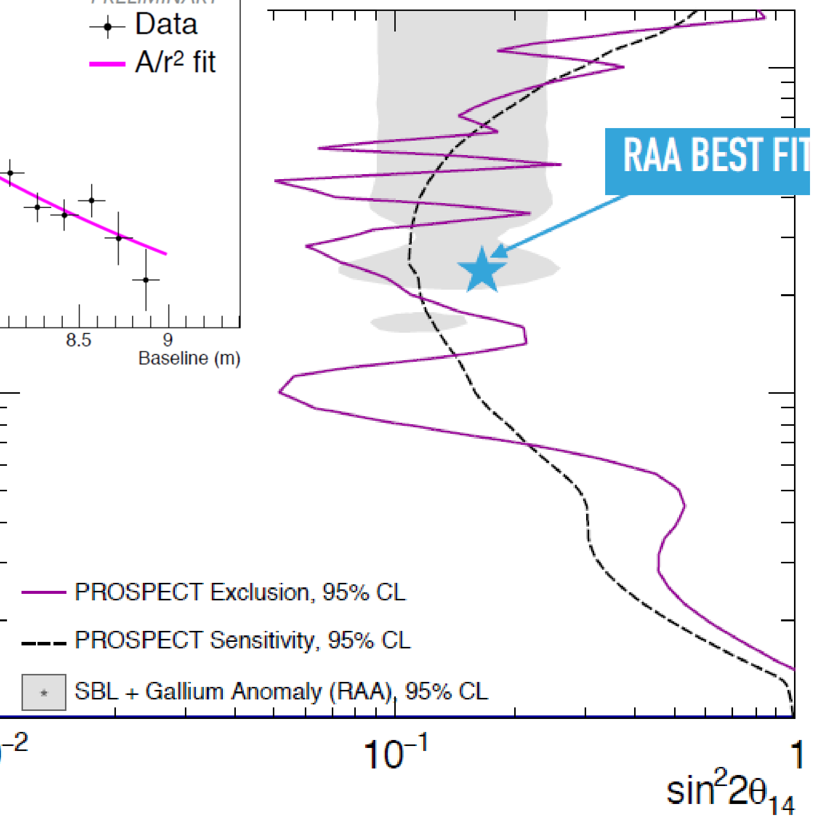


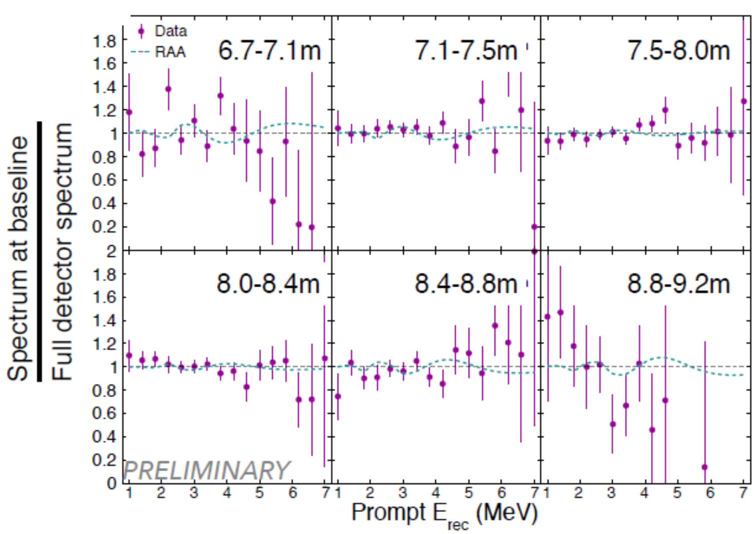


- Reactor
  - HIFR reactor at ORNL, U.S.A
  - HEU, 85 MW, Φ=44cm, H=51cm
  - Overburden < 1 m.w.e
  - Baseline: 7-12 m
- Detector
  - 154 segmented cells (15x15x119 cm^3) with 0.1% ^{6}Li-loaded LS: total 4 ton
  - Double-ended PMT readout for full 3D position reconstruction, σ(E) ~4.5% at 1 MeV
  - Shielding: dedicated beamline shielding + multi-layer (water, PE, BPE, Lead) + active outlayer muon veto (fudicialization)





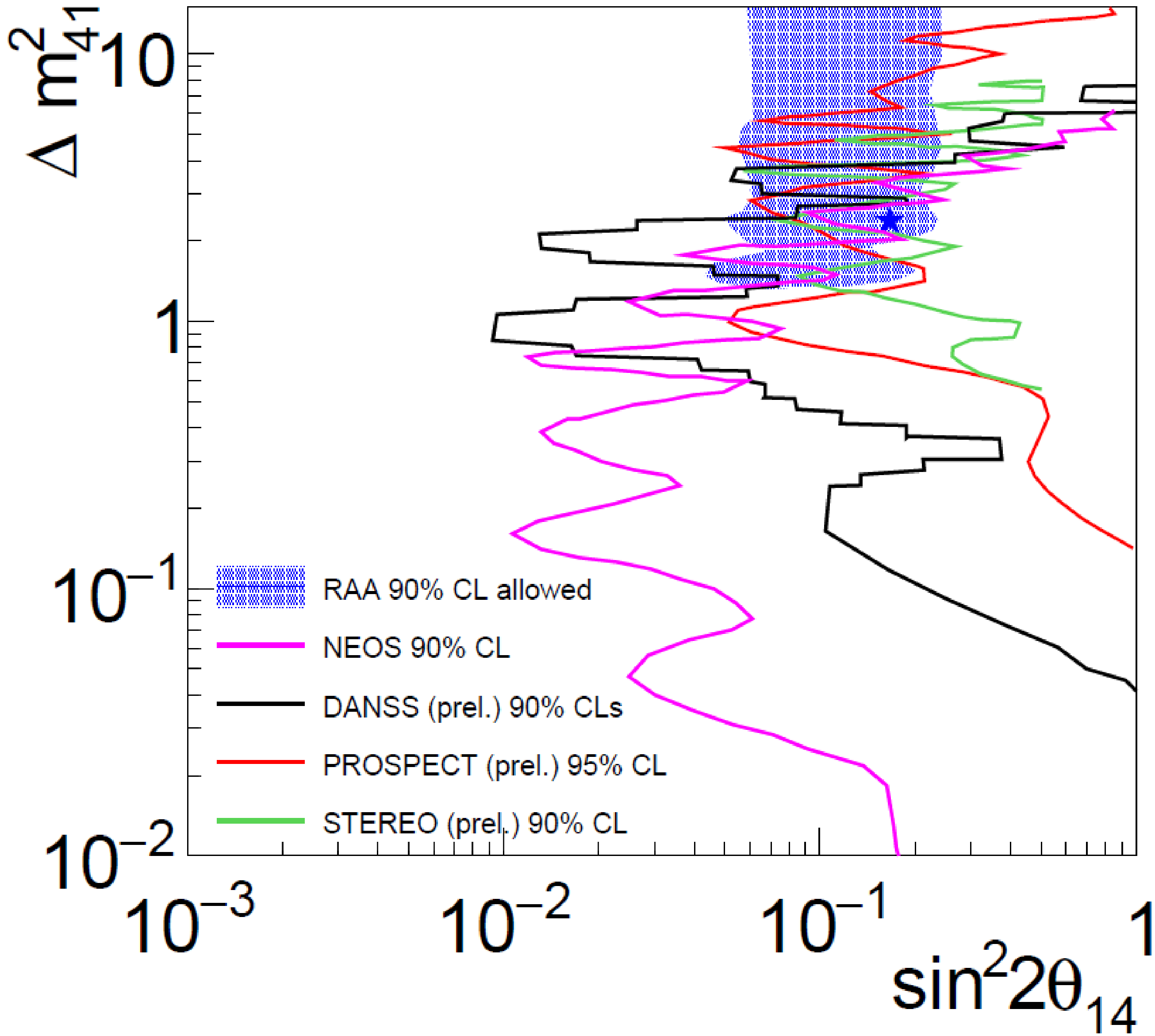




Parallel WG1 talk on Friday afternoon by N. Bowden

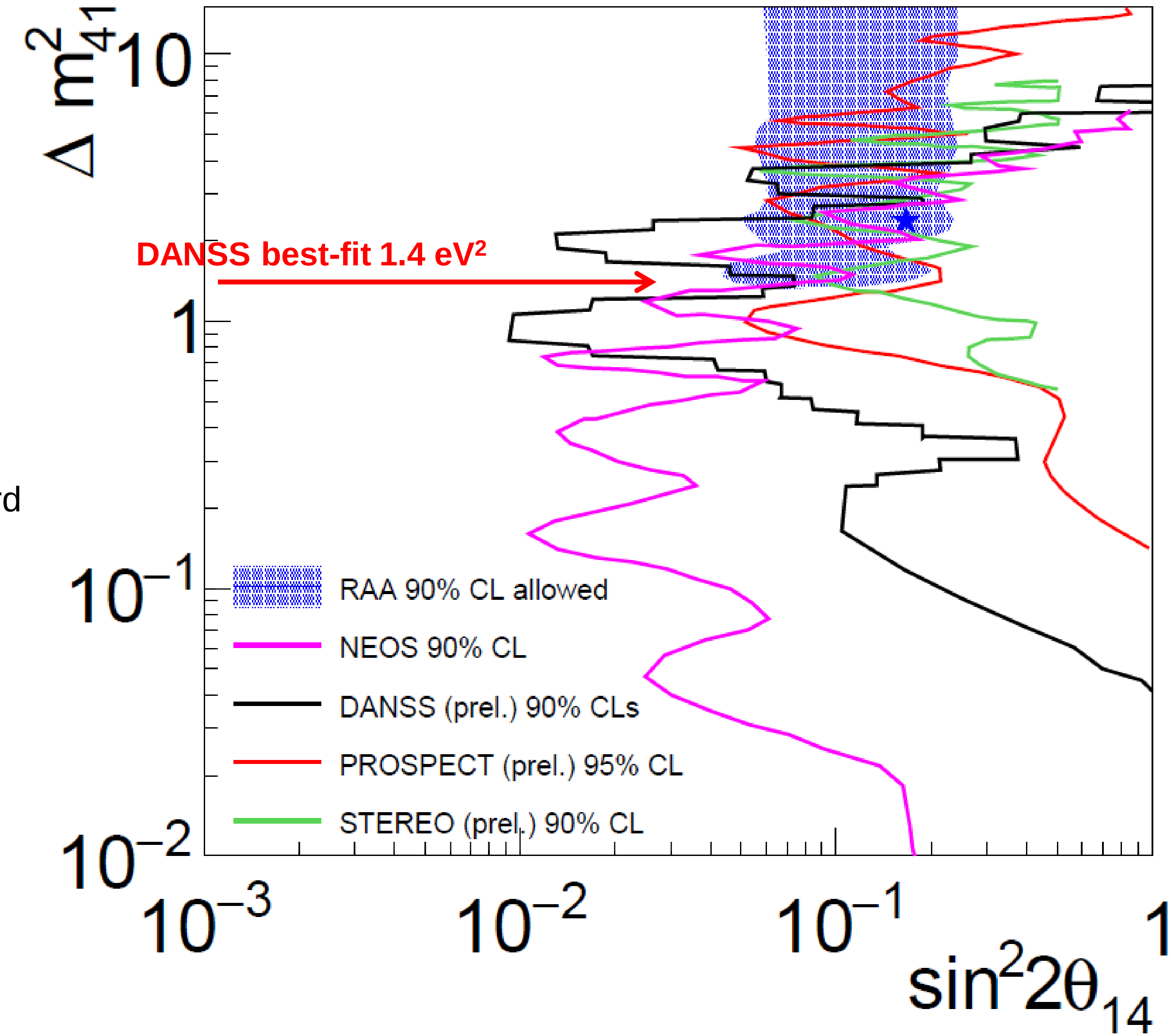
- Starting taking physics data since Mar 2018
- First results with 33 days on and 28 days off
- Correlated S:B = 1.36; ~750 antineutrinos / day
- Results consistent with no oscillation
- The RAA best-fit point is excluded at 95% C.L.

Put all 4 experiments together



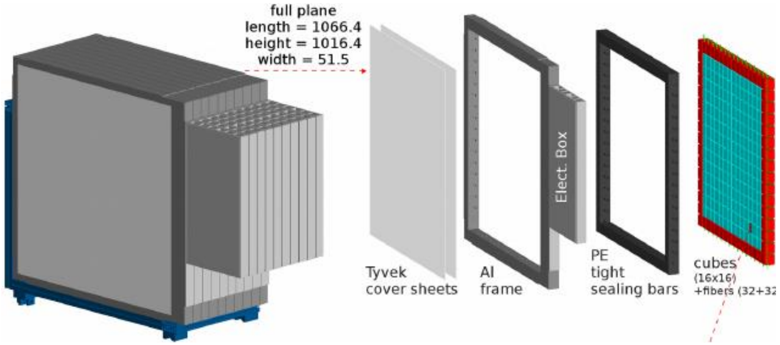
X. Qian and J-C Peng, arXiv:1801.05386

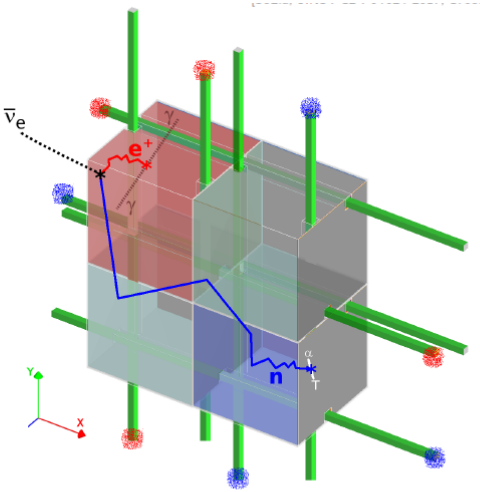
- Data fluctuation due to statistics and systematic uncertainties
- At 1.4 eV^2
  - DANSS, NEOS, PROSPECT all show downward fluctuation
  - STEREO shows upward fluctuation
- More statistics and better understanding of systematics is necessary
- Statistical analysis best practice:
  - Use Feldman-Cousins approach with full MC uncertainty fluctuation for correct C.L.
  - Use Gaussian CLs method for cross-checking exclusion regions



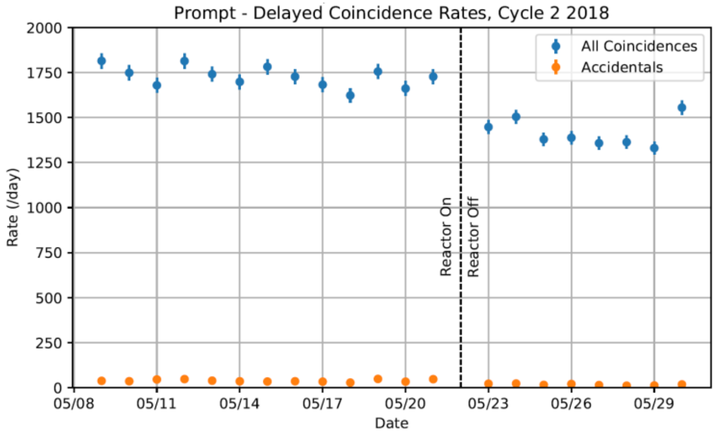
X. Qian and J-C Peng, arXiv:1801.05386

SoLid





1 module: 10 planes of 16 x 16 cubes



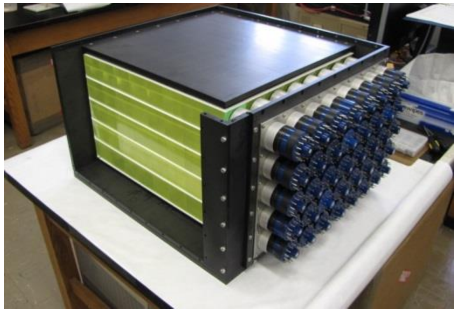
- Reactor
  - BR2 reactor, Belgium
  - HEU, 50-80 MW, Φ=50cm, H=90cm
  - Overburden ~10 m.w.e
  - Baseline: 6-9 m

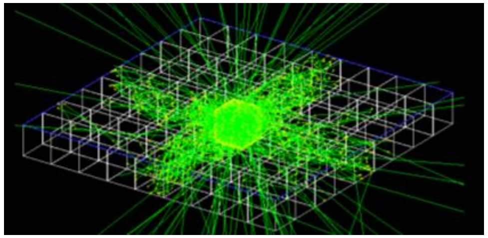
- Detector
  - PVT cubes of 5x5x5 cm^3 with two $^6LiF:ZnS$ neutron screens; Optically isolated with Tyvek; total 1.6 ton;
  - Readout via 4 WLS fibers towards 2 MPPC's (SiPMs) in either direction
  - Shielding: water + PE ceiling + Cd lining

- Status
  - Constructed a 1.6 ton detector (Phase1) in 2017 and commissioned it in Nov-Dec 2017
  - Taking physics data now and observed IBD-like events

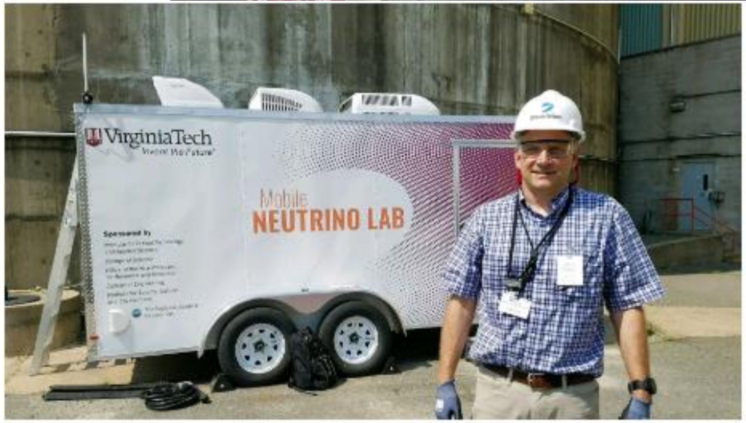
CHANDLER

http://cnp.phys.vt.edu/chandler/

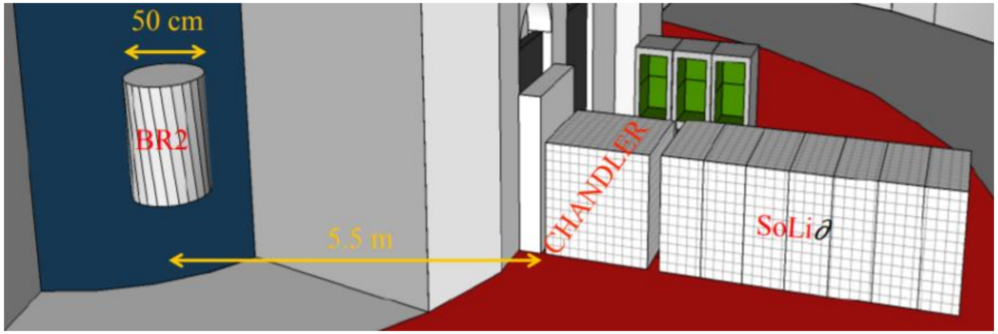


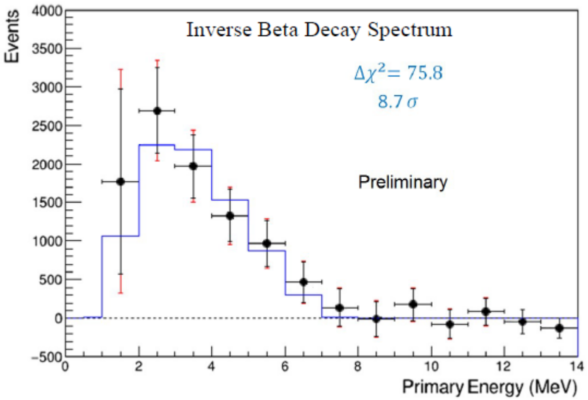


- 3D segmentation with optically connected cubes readout by total internal reflection.
  - Concept proposed by Raju Raghavan (VT) for LENS. Also adopted by NuLAT.



MiniCHANDLER: a full systems test (8×8×5) which was deployed for 4 months at the North Anna Nuclear Power Plant,





Plan to combine CHANDLER (1 ton) with SoLid phase II at BR2 to enhance the sensitivity

Summary

- A new generation of short baseline reactor neutrino experiments are taking data now.
- They aim to perform a reactor-model-independent search for sterile neutrinos through precision measurement of reactor antineutrino spectrum at different baselines.
- With the global effort we expect the reactor antineutrino anomaly problem to be answered in the next few years.

Stay tuned!