NEOS
Reactor neutrino experiments at short baseline

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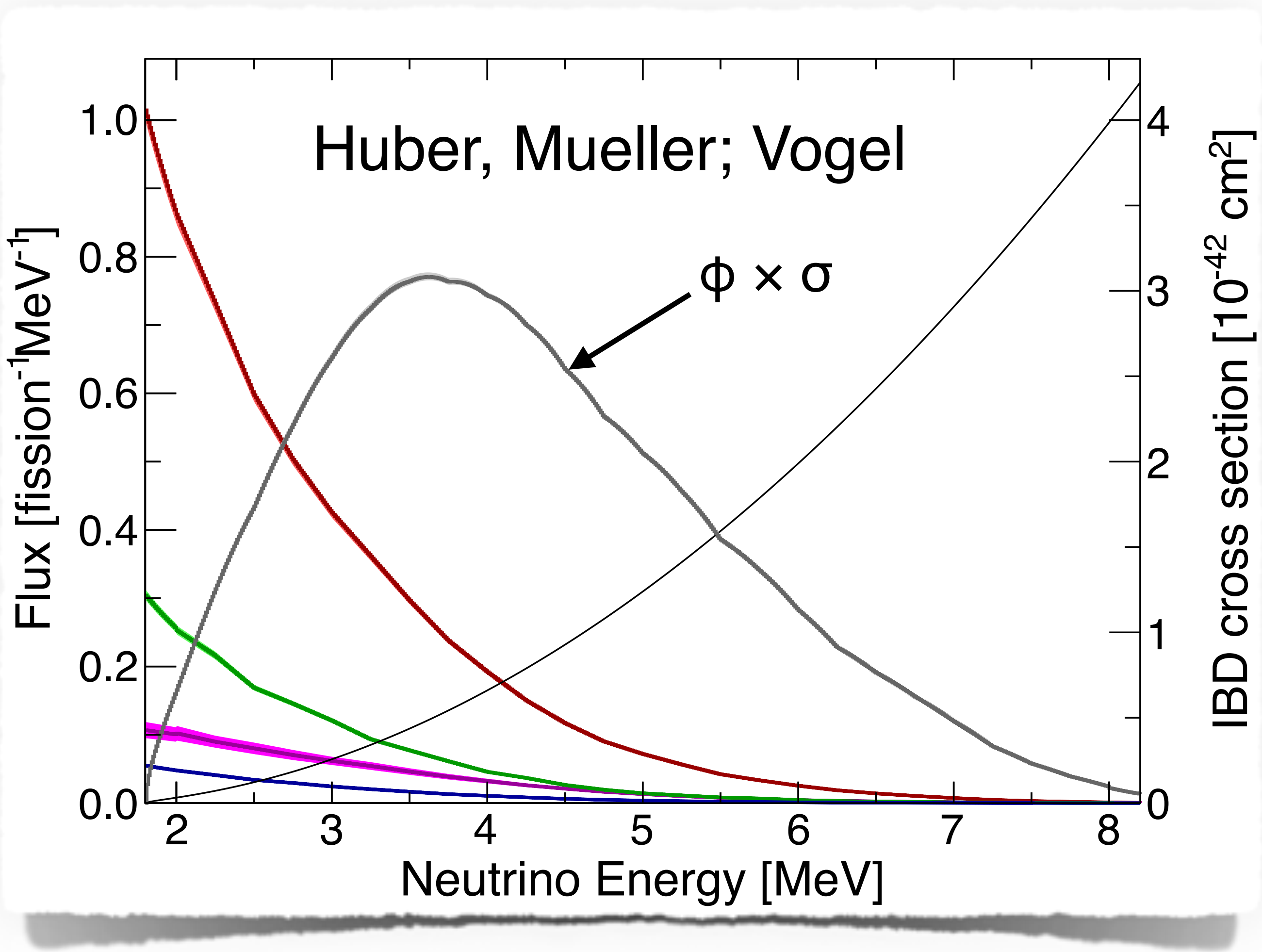
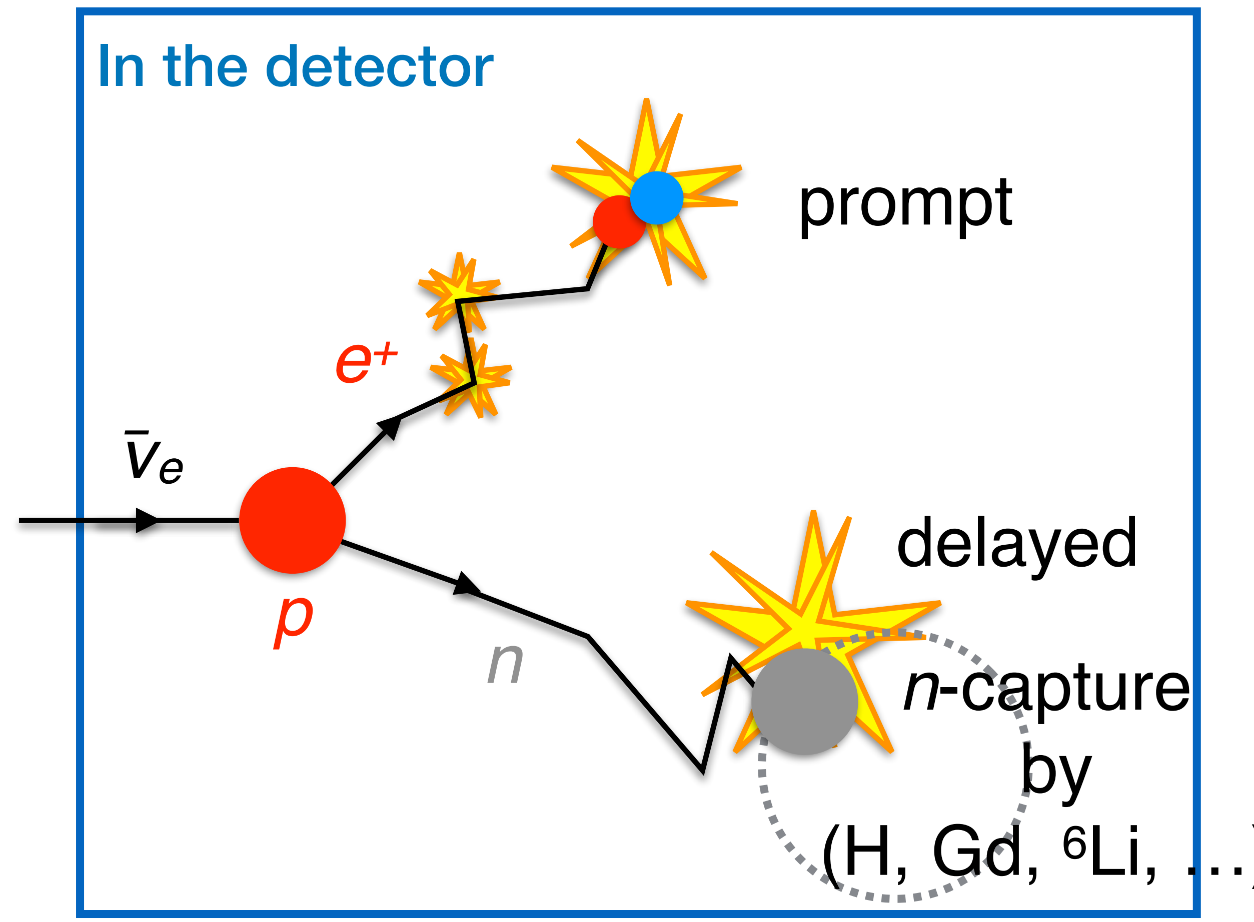
CENTER FOR UNDERGROUND PHYSICS ibs

Outline

- Reactor neutrino
- Reactor antineutrino anomaly
- Short baseline oscillation
- Reactor SBL experiments
- NEOS

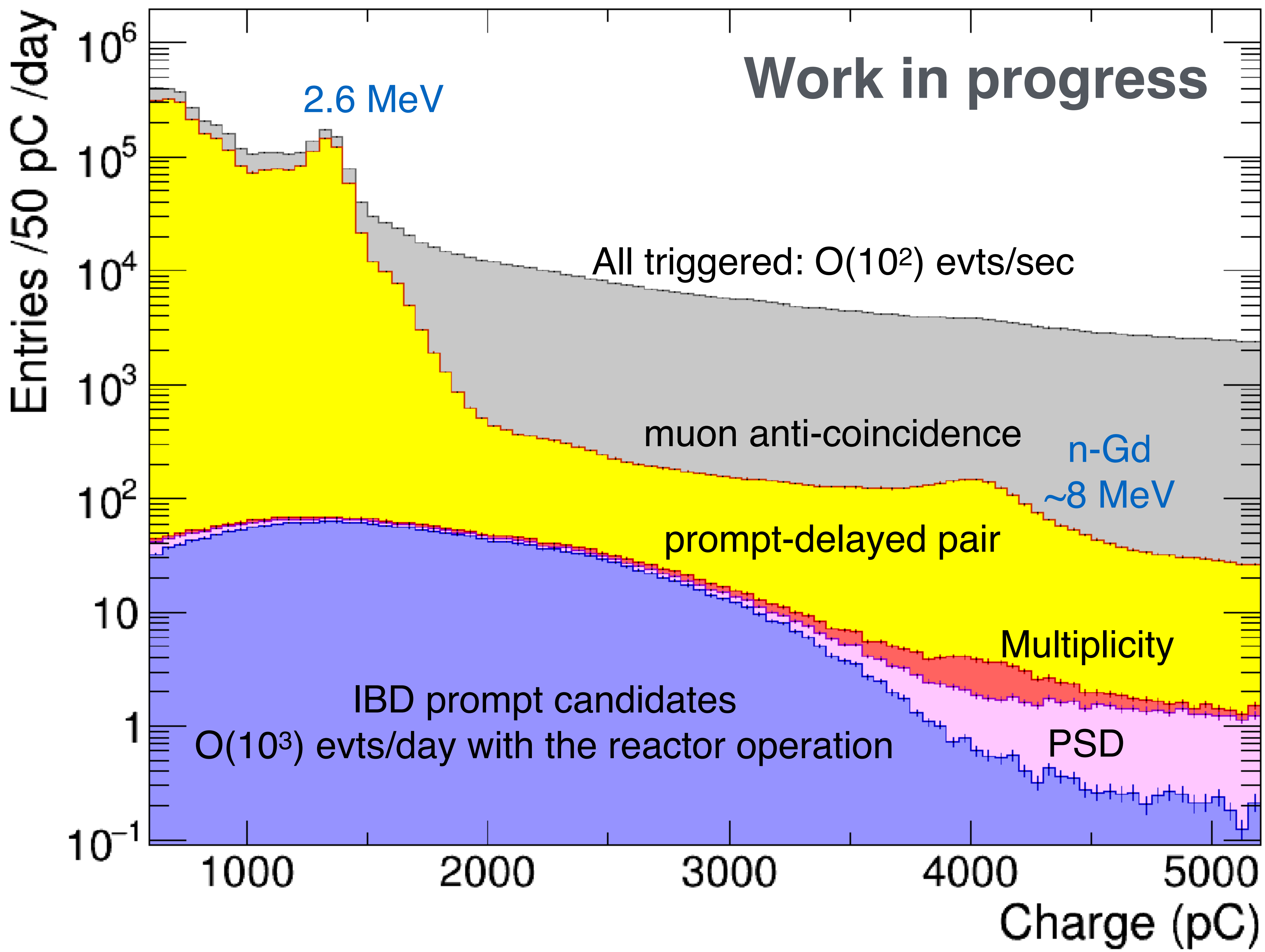
Reactor neutrino and its detection





- Average of 6, 7 β-decays and anti-ν_e's from a fission of an element.
- 2×10^{20} ν / 4π / GWt
  - O(10k) inverse beta decay events occurs in 1000 kg of organic scintillator with 10% mass of hydrogen atom at 10 m distance from a GWs thermal power reactor.

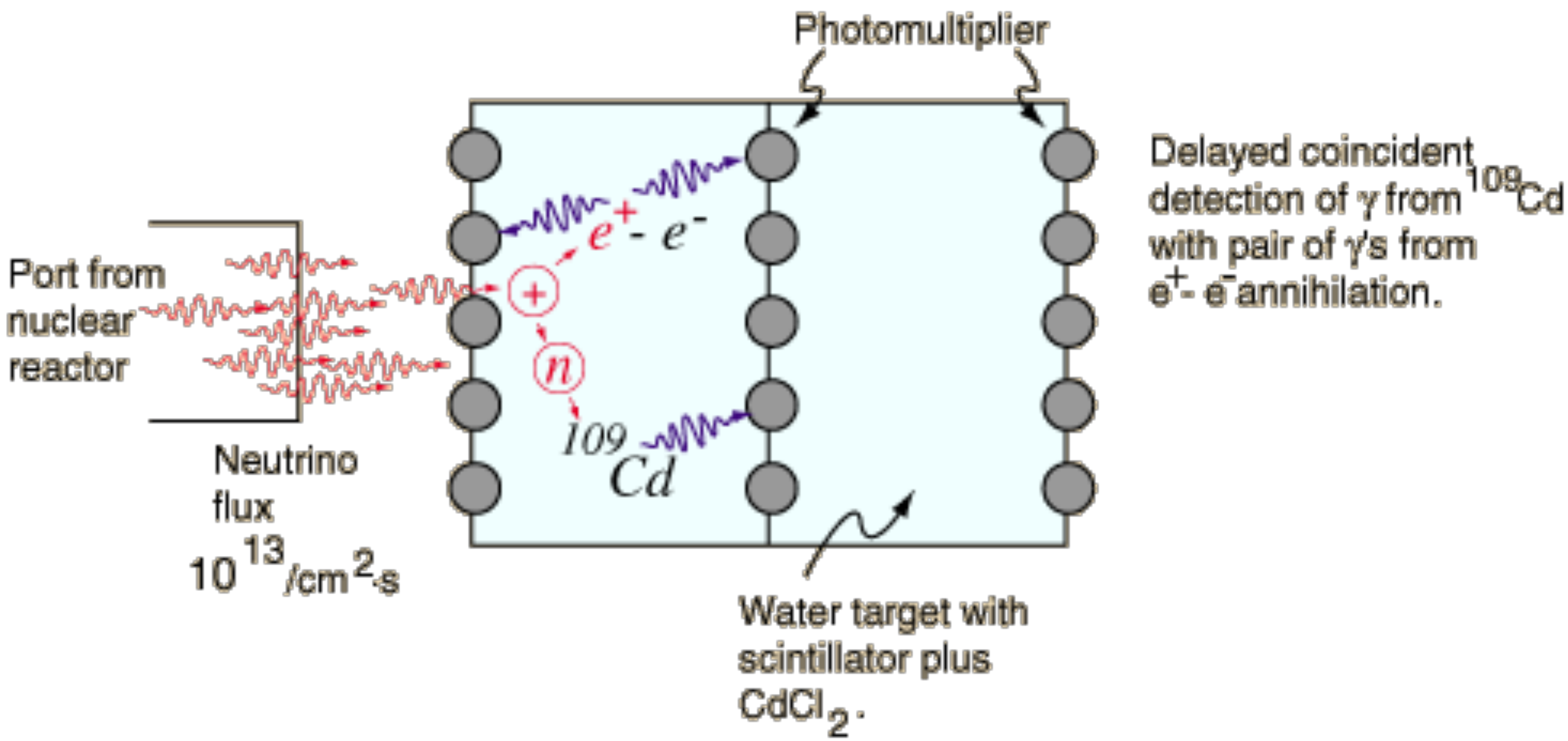
Background and IBD



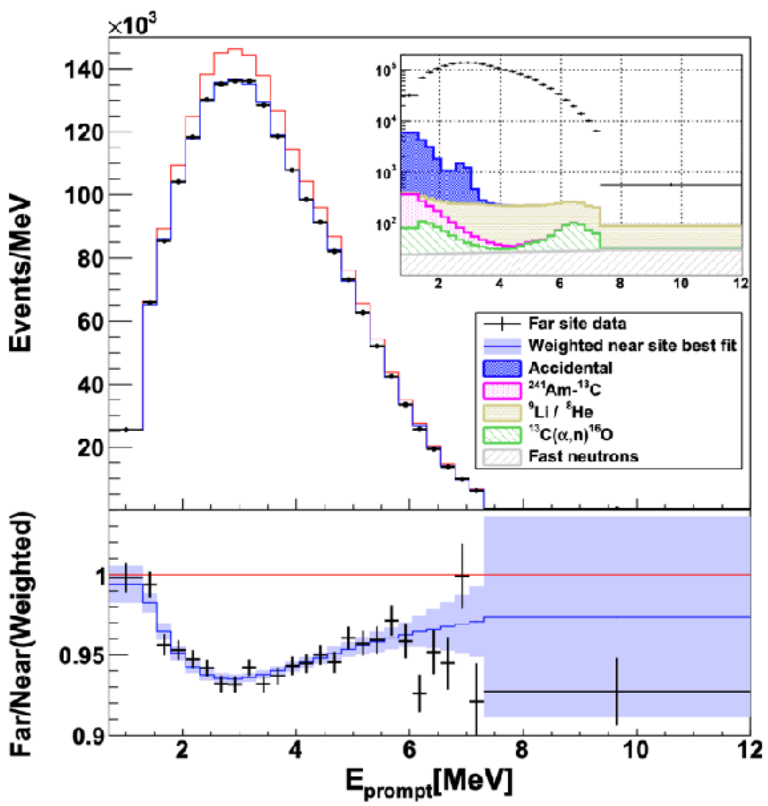
Cowan & Reines (1956)

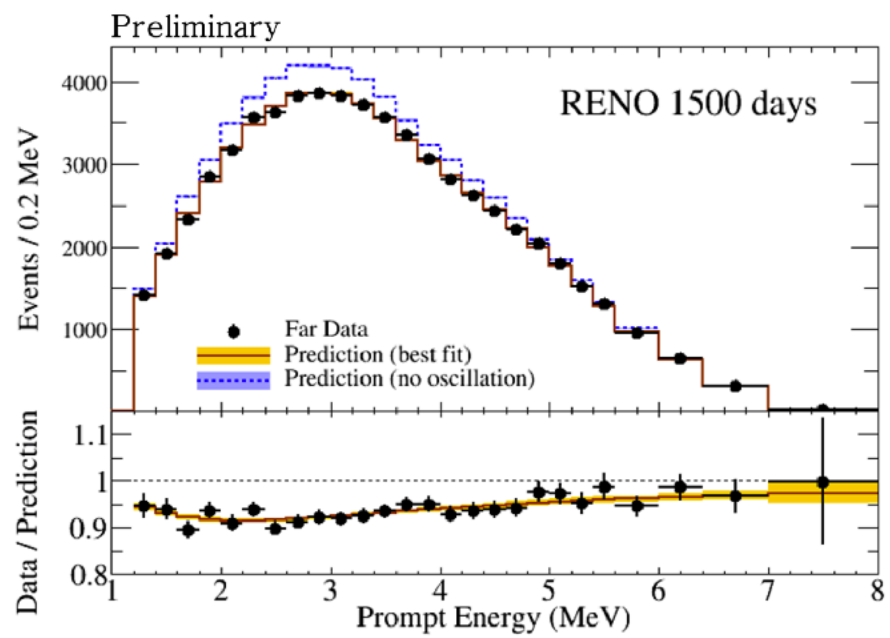
- Using inverse beta decay of electron anti-neutrinos from a nuclear reactor.

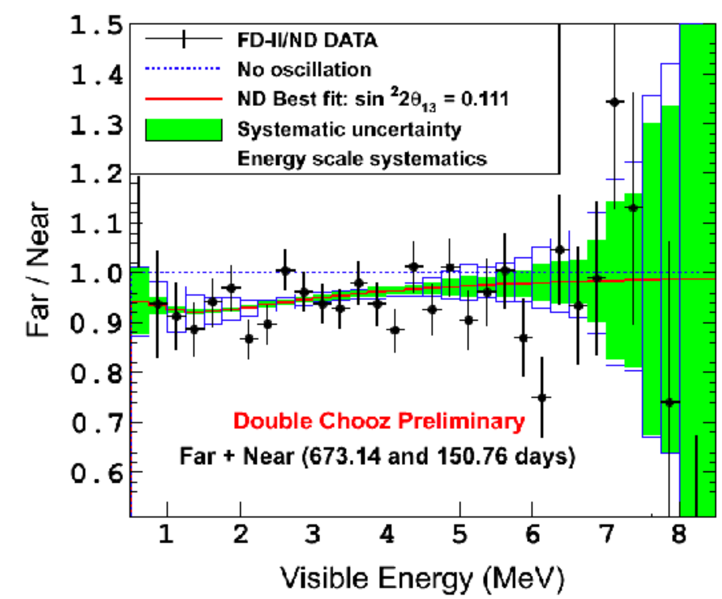
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Reactor θ_{13} experiments





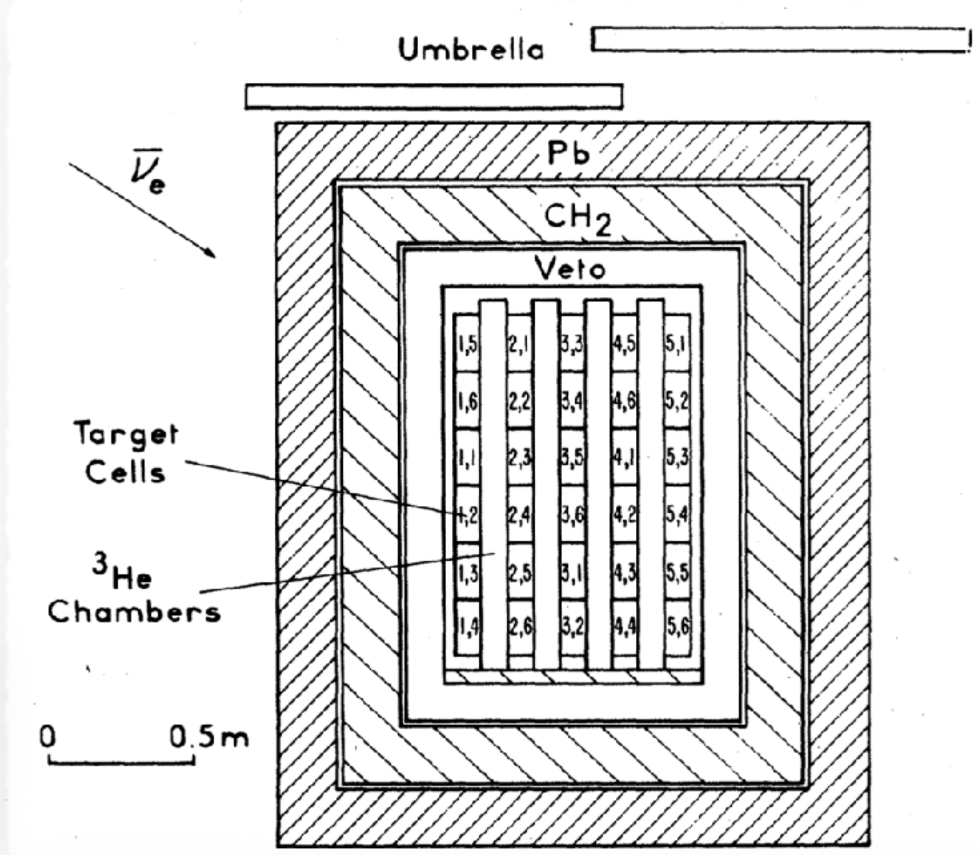


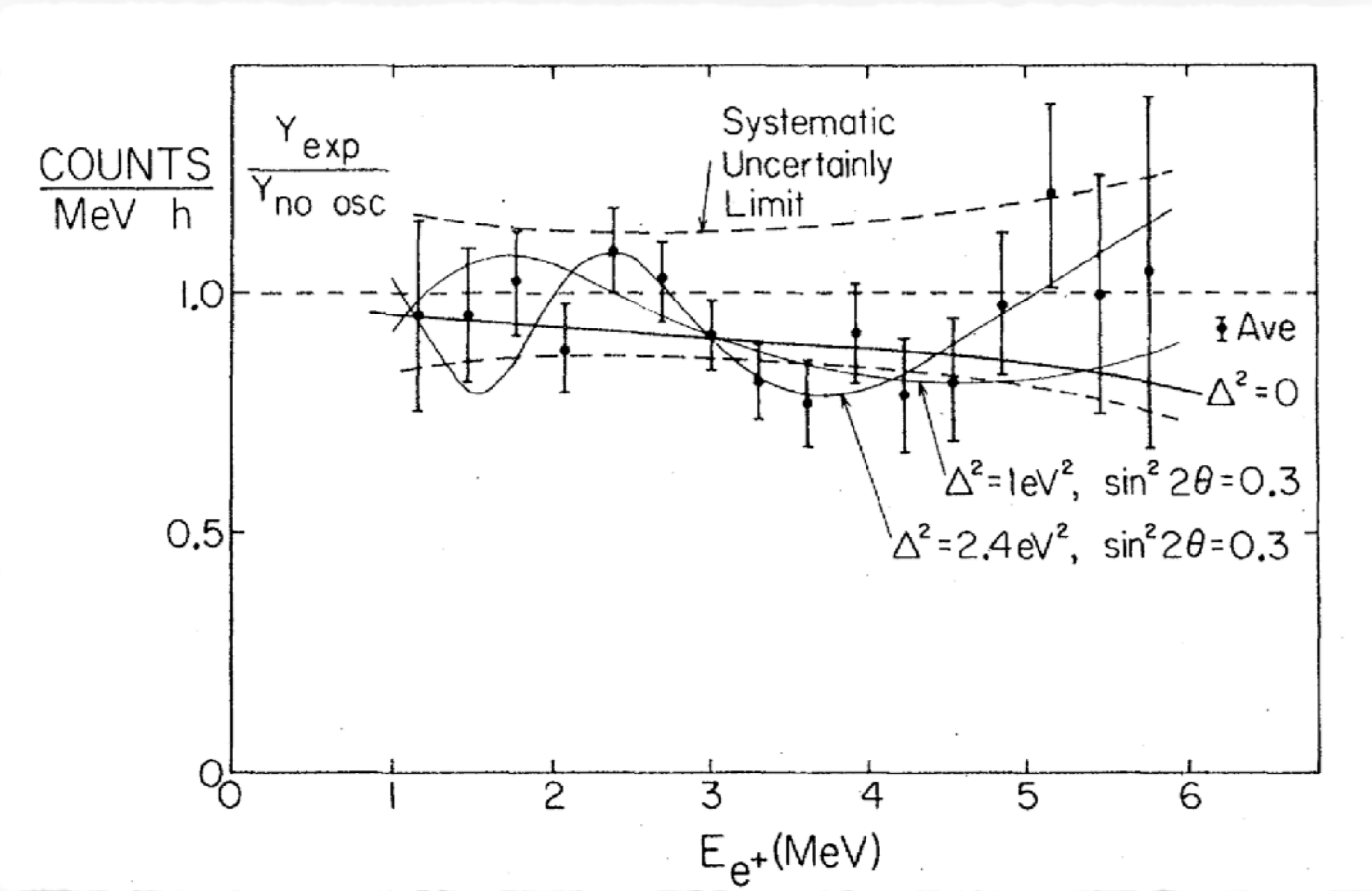
- Using multiple commercial reactor cores (~10 GWth),
- Far (at 1-2 kilometers, oscillation) to near (at ~ a few hundred meters, no oscillation) measurement ratio.

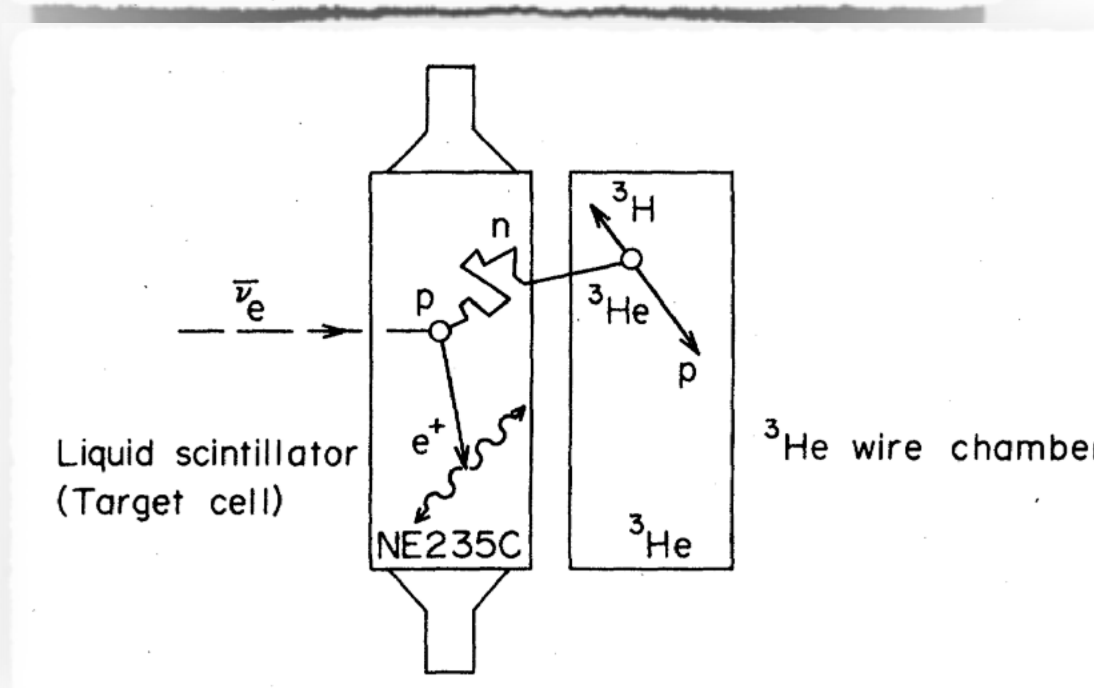
Institut Laue-Langevin (ILL) experiment

- 57 MWth reactor.
- 8.76 m baseline.
- Liquid scintillator + ^{3}He-wire counter

H. Kwon (1981)

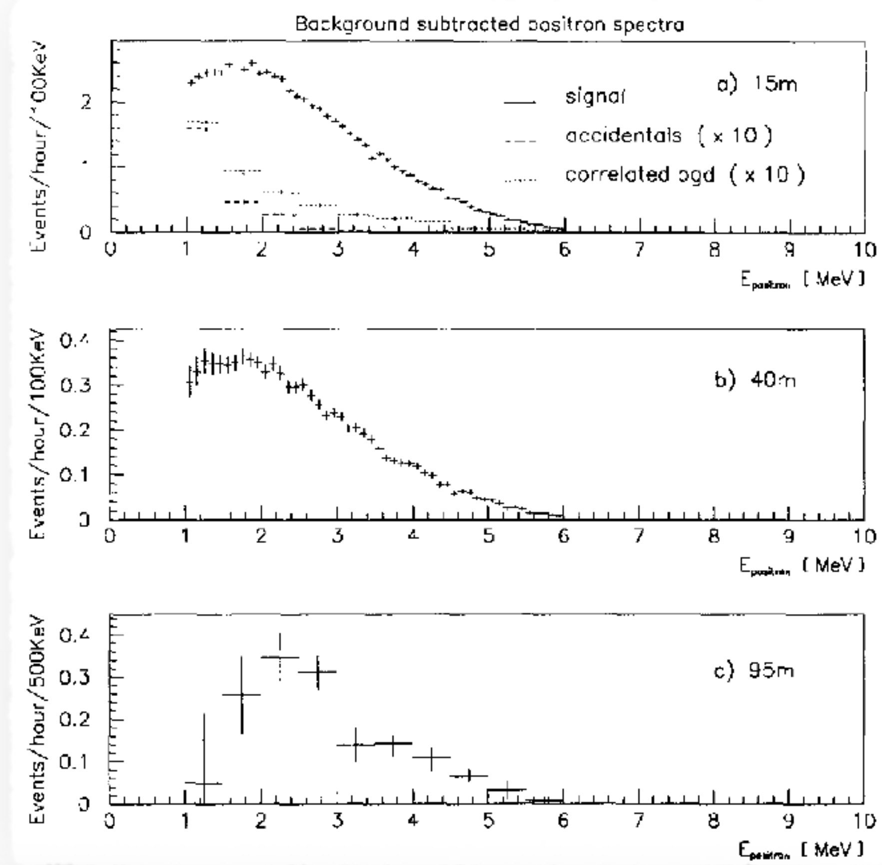


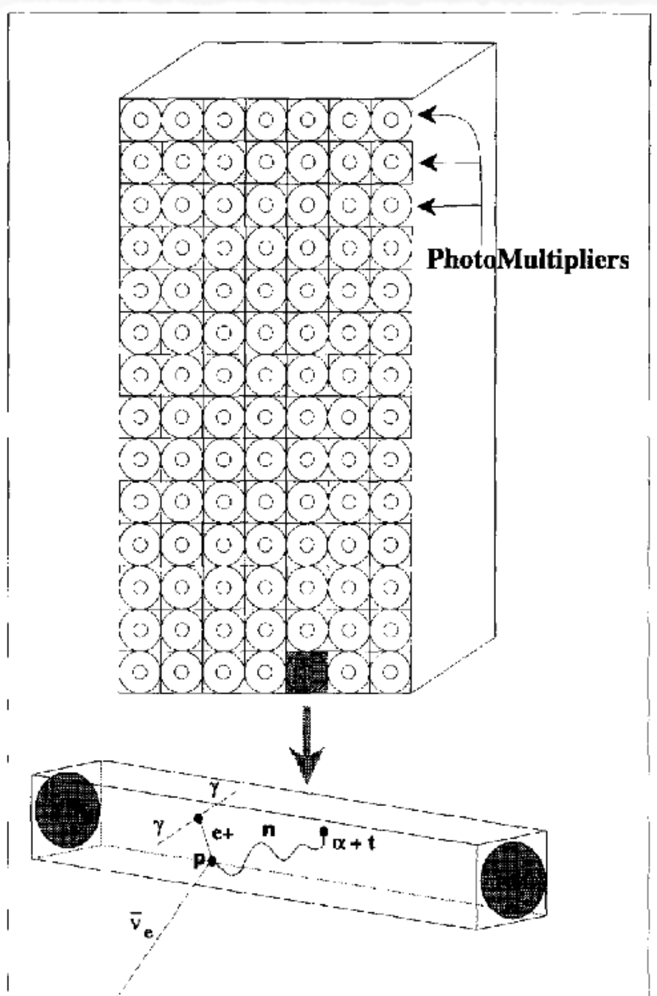




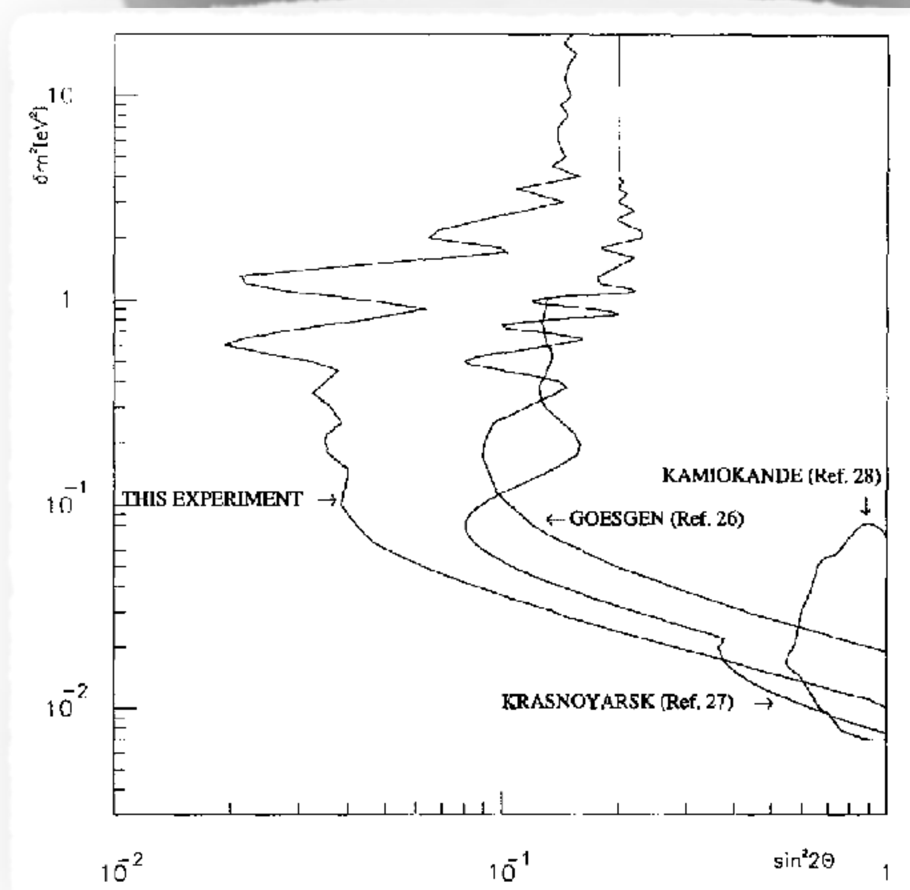
Bugey-3

- 2.8 GW commercial reactor,
- 15/40/95 m baseline,
- ^{6}Li loaded liquid scintillator detector

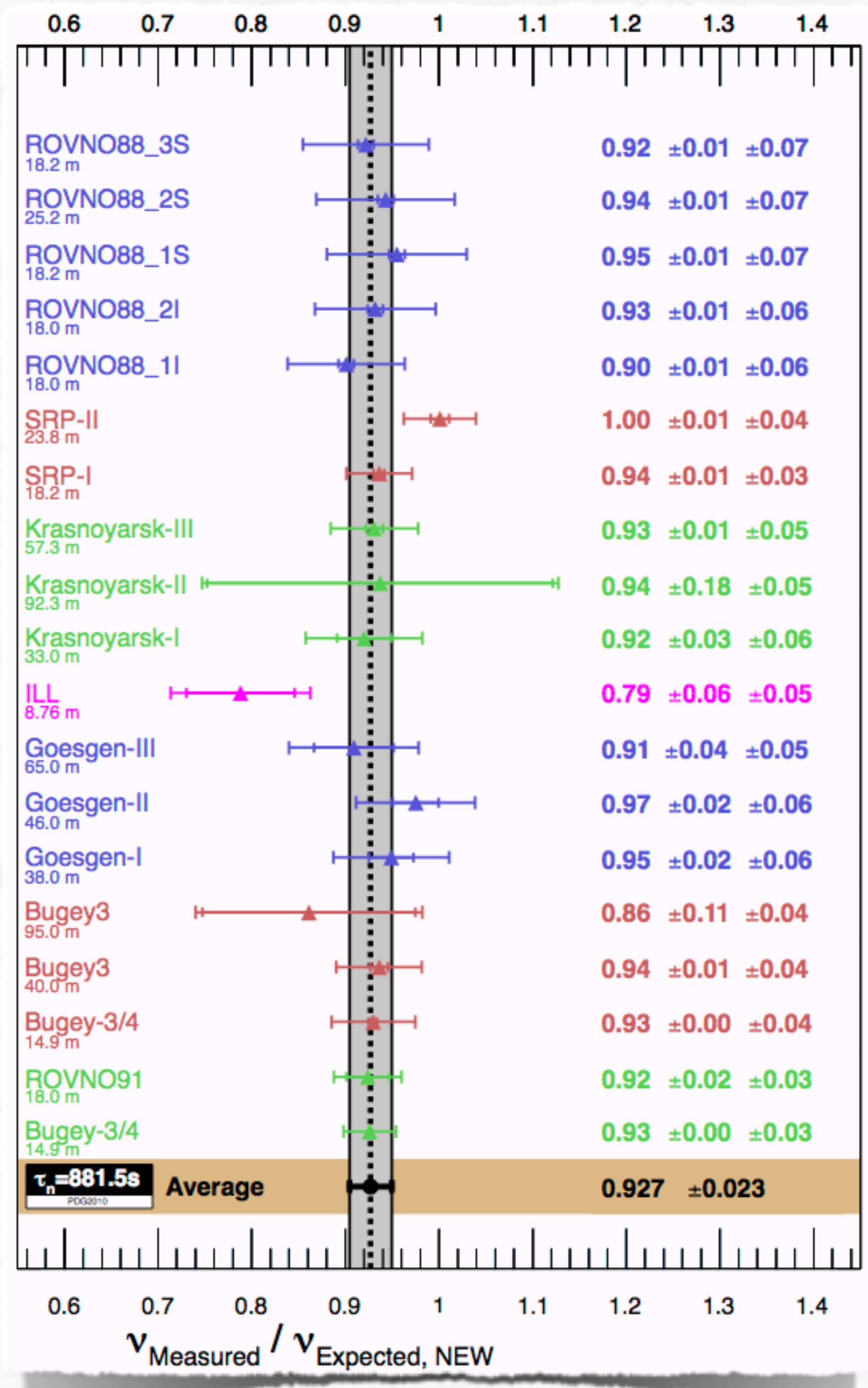


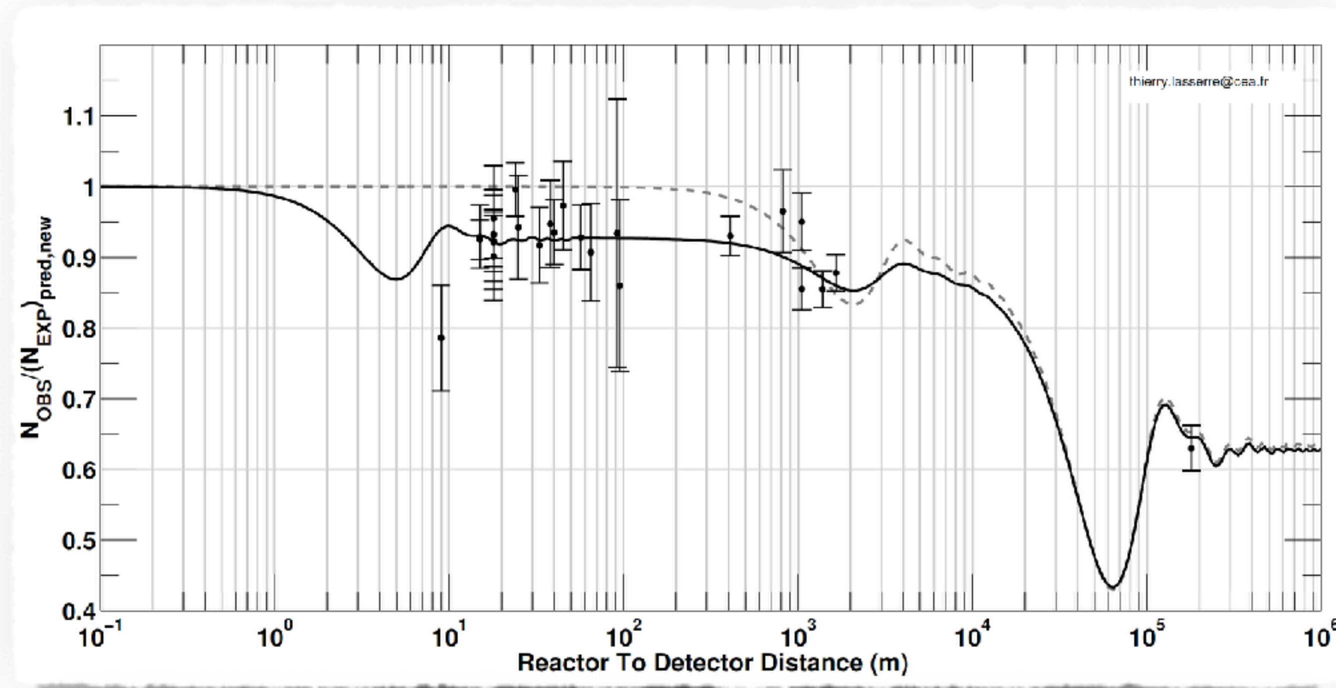


Achkar (1995)



Reactor antineutrino anomaly





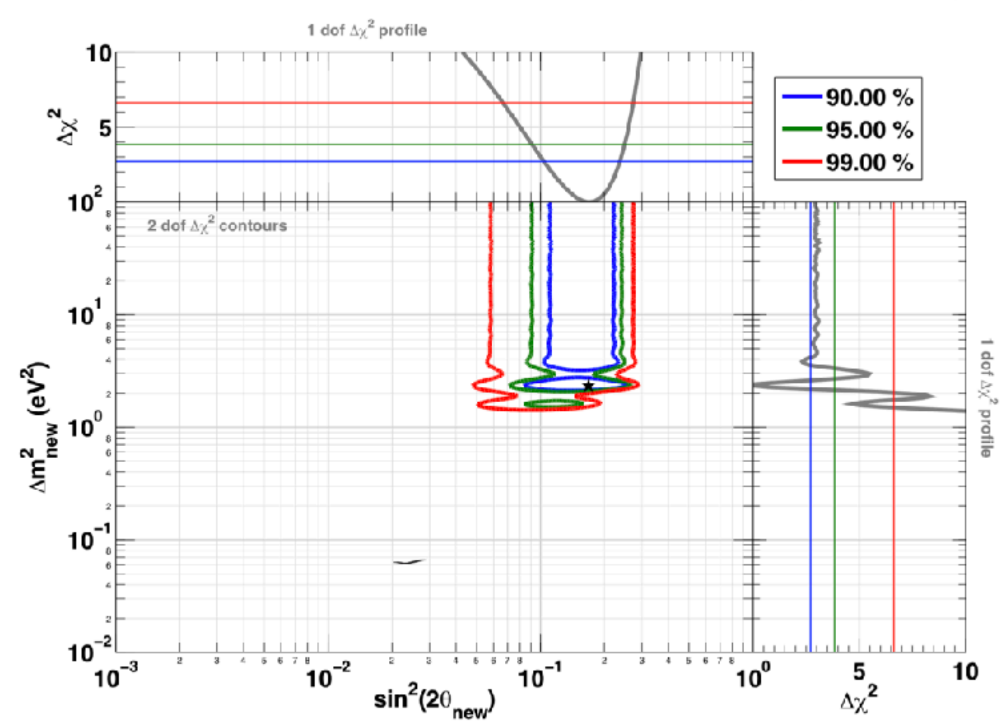
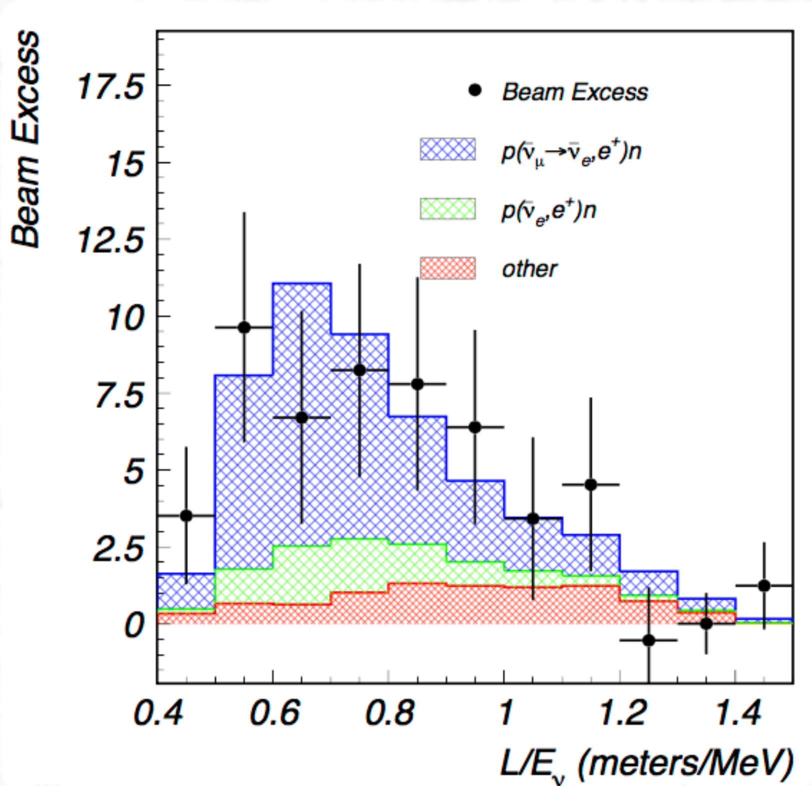
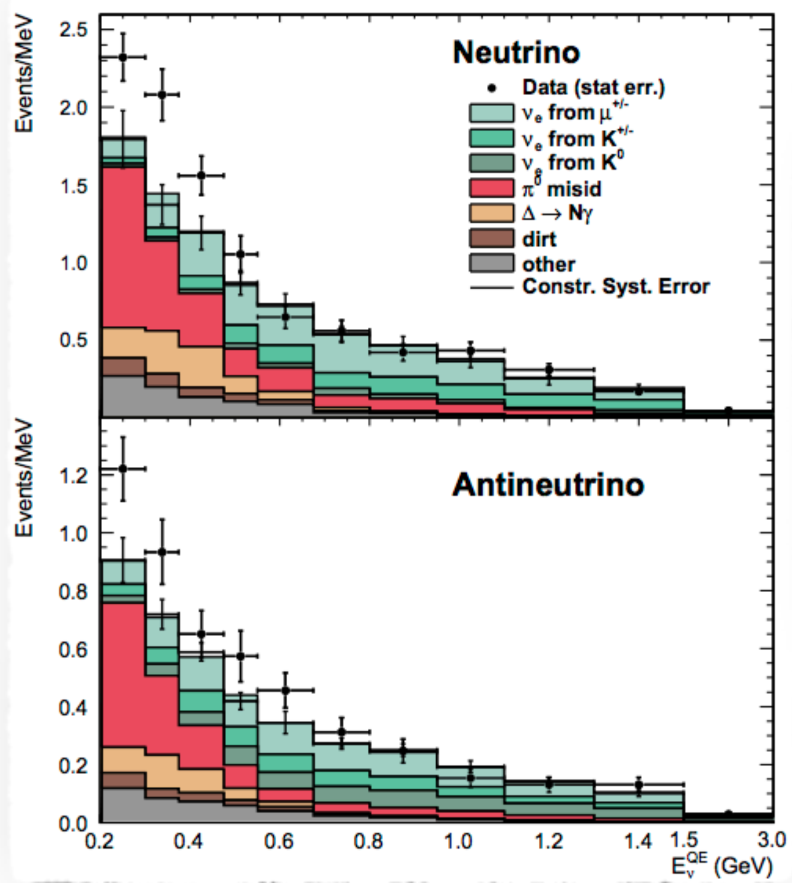


Figure 60. Allowed regions in the $\sin^2(2\theta_{new})$–Δm^2_{new} plane from the combination of reactor neutrino experiments, the Gallex and Sage calibration sources experiments, and the ILL and Bugey-3-energy spectra. The data are well fitted by the 3+1 neutrino hypothesis, while the no-oscillation hypothesis is disfavored at 99.97% C.L (3.6 σ).

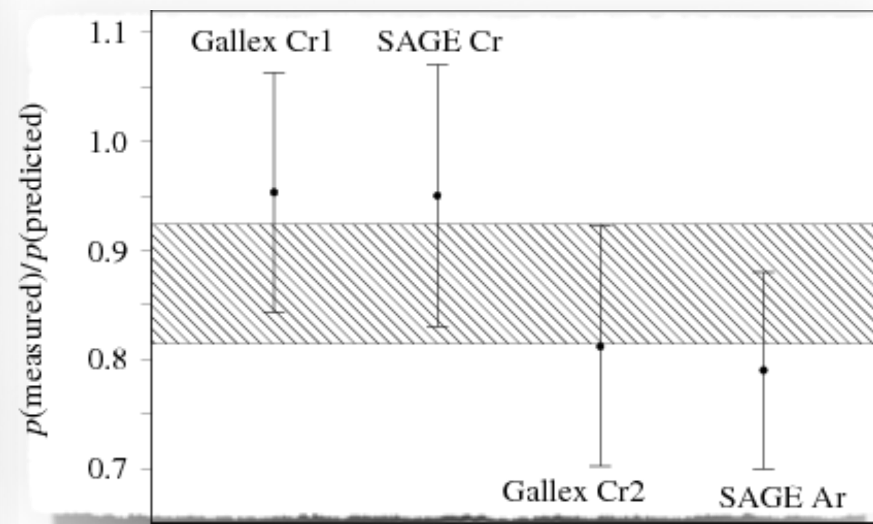
Other anomalies / conflicts (before 2017)



PRD 64 (2001) 112007



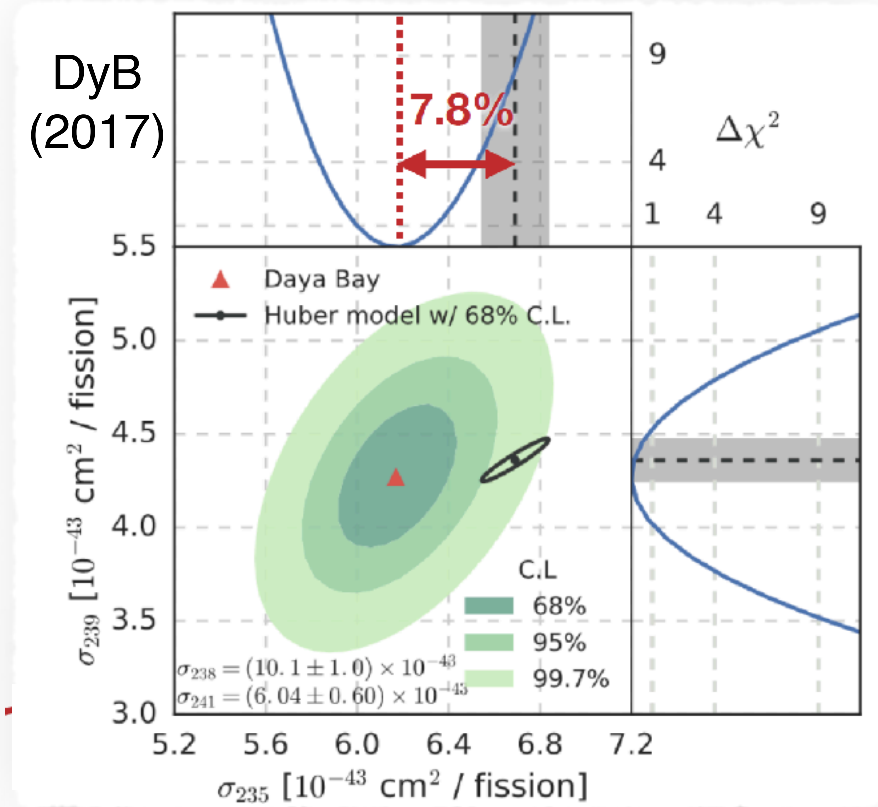
PRL 110 (2013) 161801

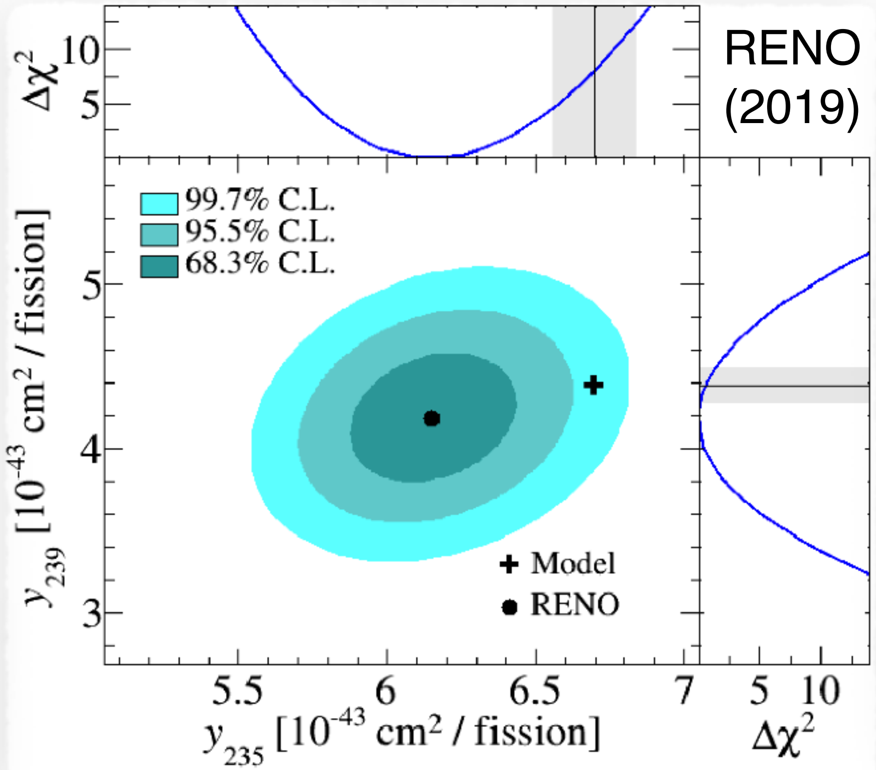


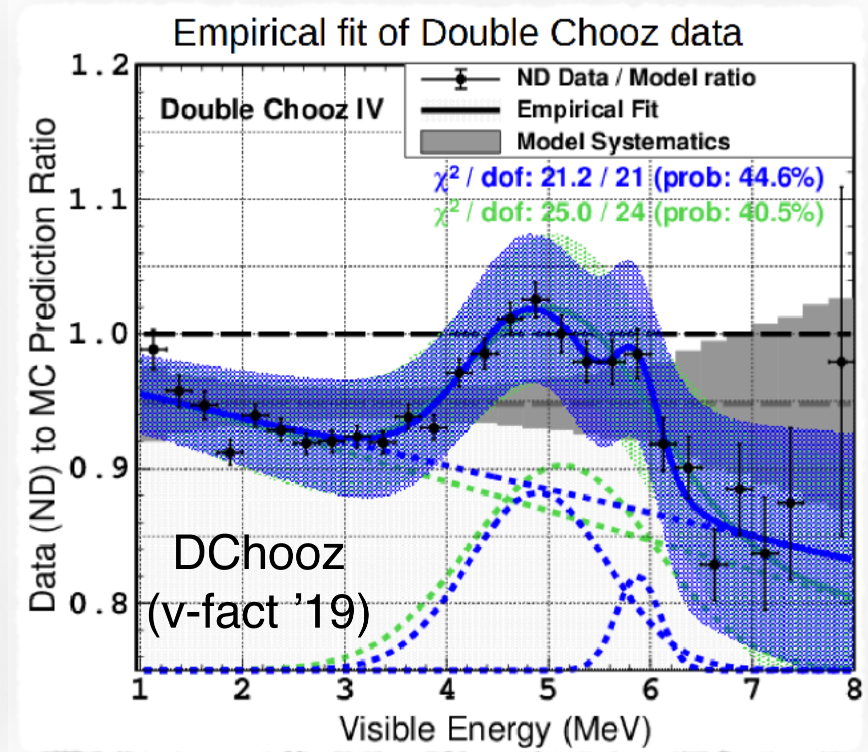
PRC 80 (2009) 015807

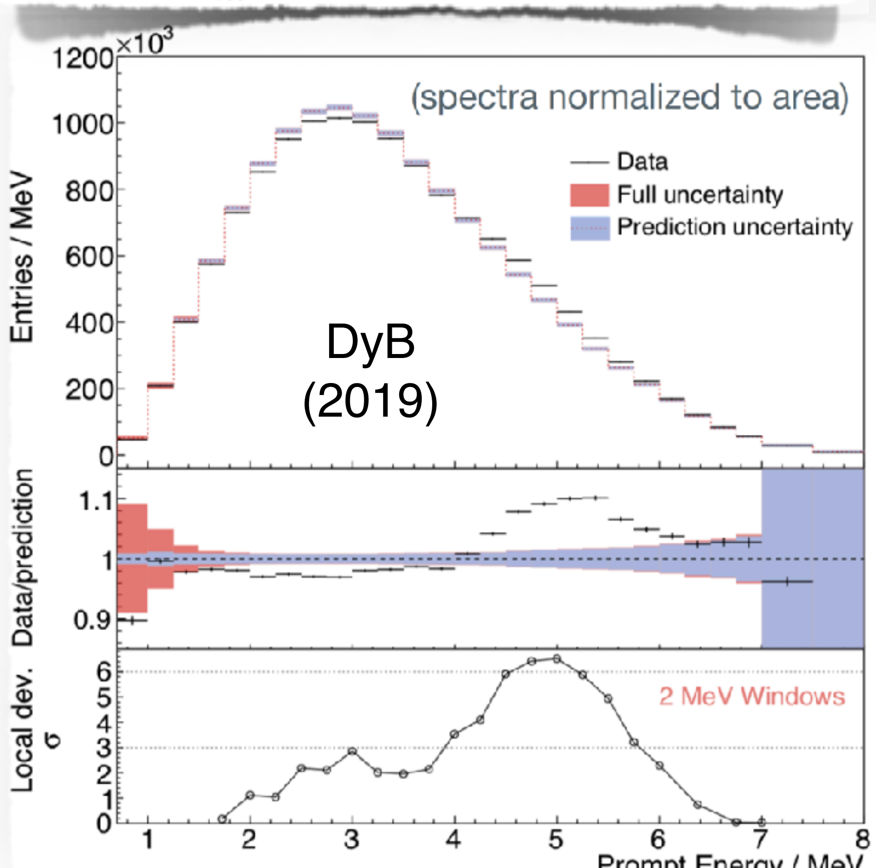
- LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance event excess with $\Delta m^2 > 0.2$ eV^2 (>3σ)
- MiniBooNE: ν mode disfavors / $\bar{\nu}$ mode consistent with LSND result $\Delta m^2 \sim 1$ eV^2
- GALLEX / SAGE: 2.9σ deficit from expected
- KARMEN, MINOS, IceCube, … : negative results

Miscalculated flux?



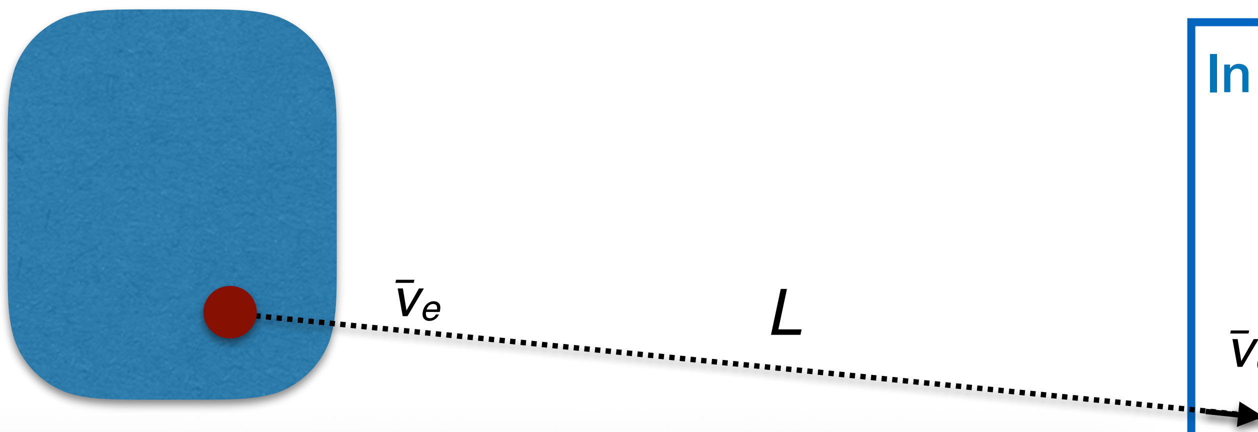


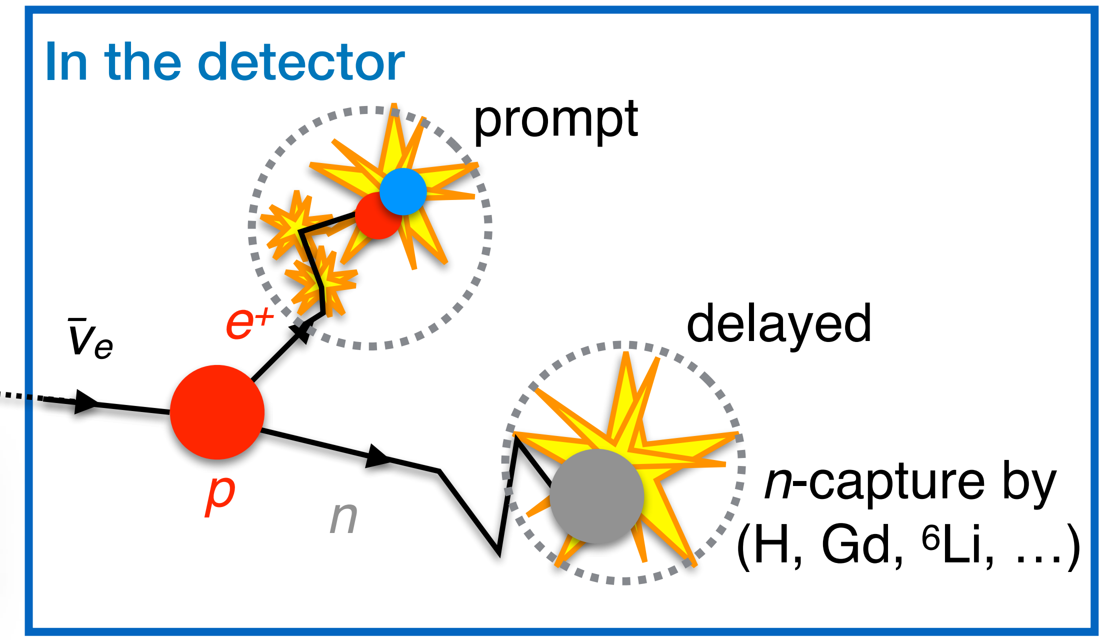




- Disagreement in rate and shape, at hundreds of meters distances from LEU reactors.
- Not likely an energy scale problem.
- Should be checked with new SBL data.

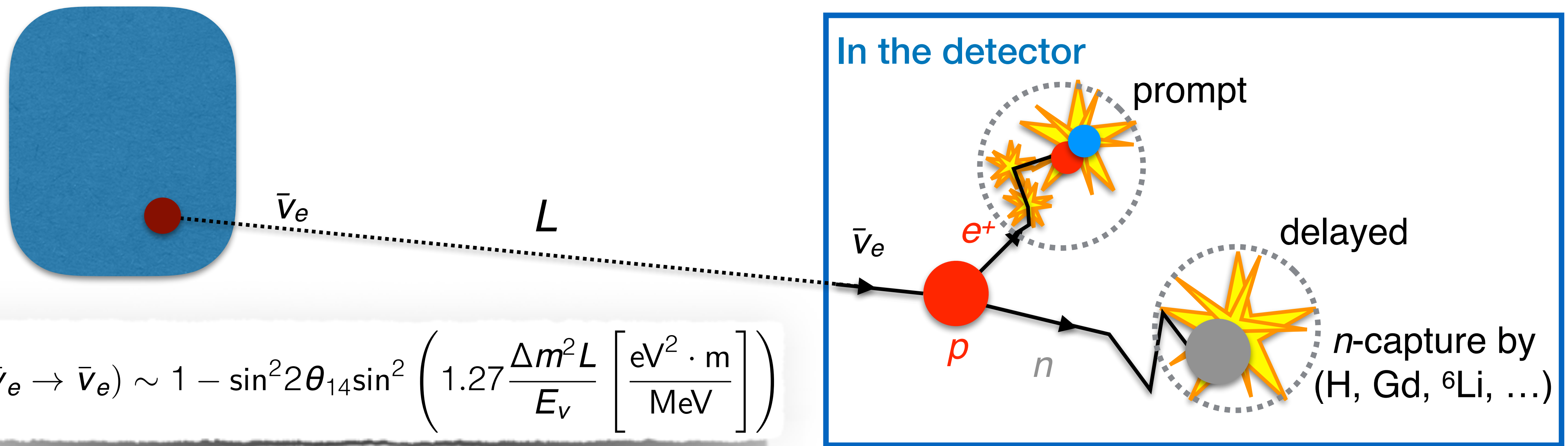
SBL oscillation





$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{14} \sin^2 \left(1.27 \frac{\Delta m^2 L}{E_\nu} \left[\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}} \right] \right)$$

SBL oscillation



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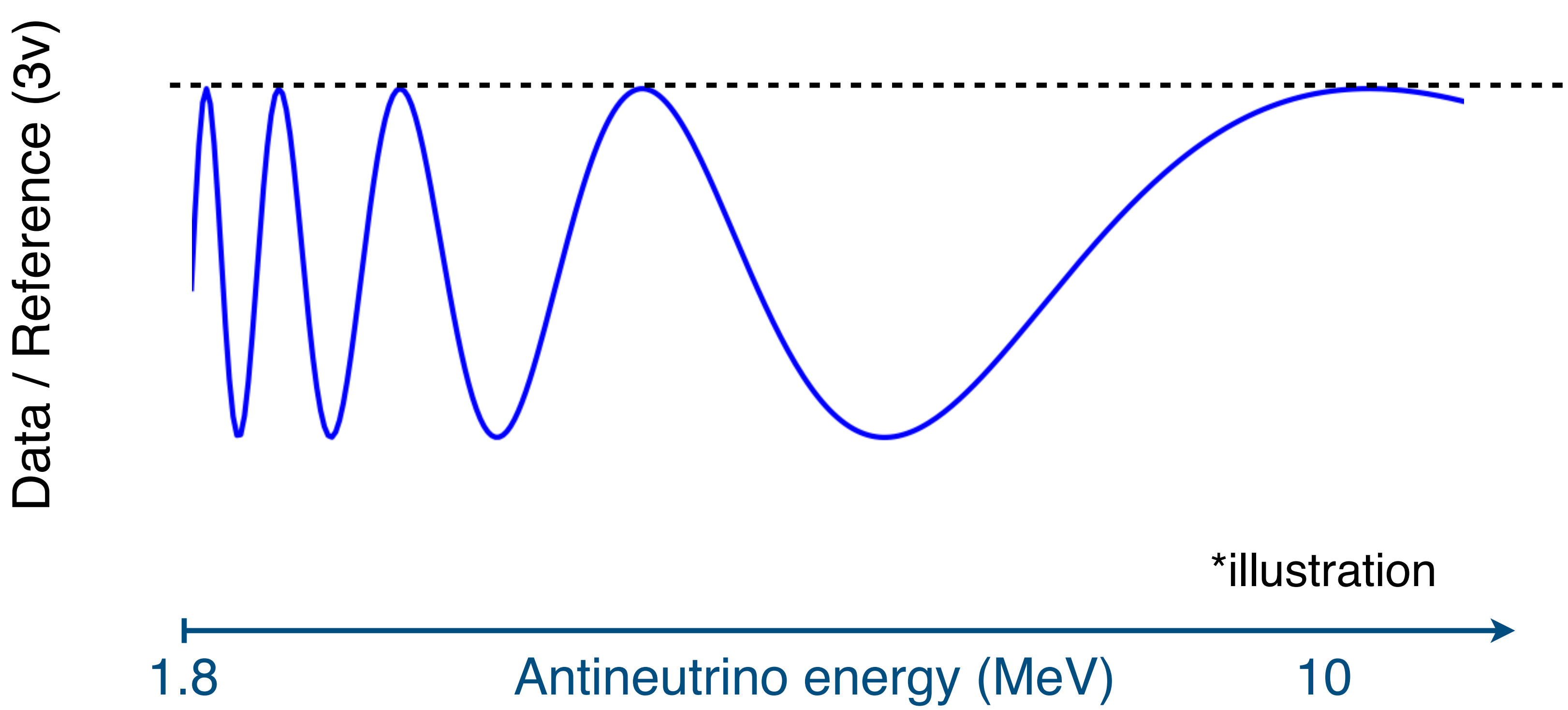
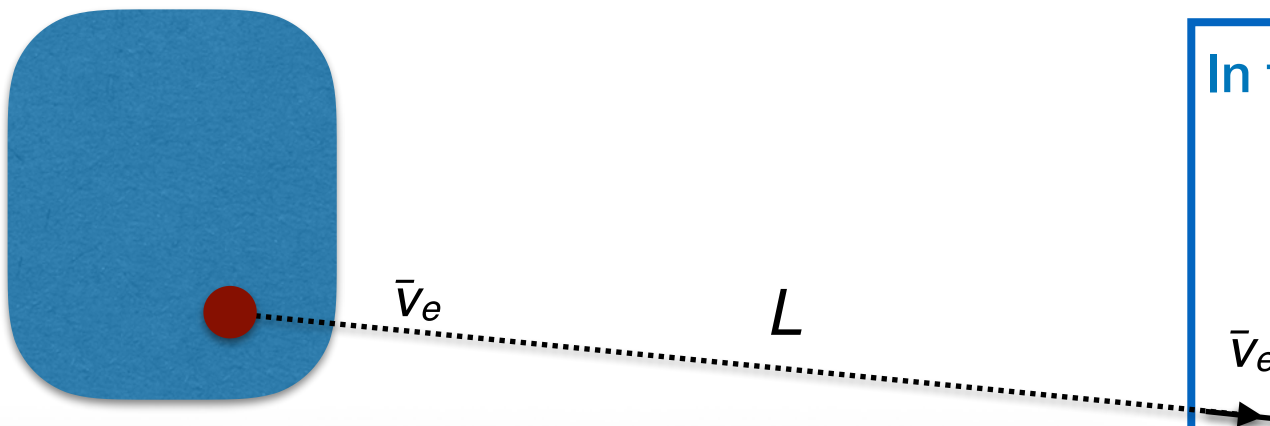
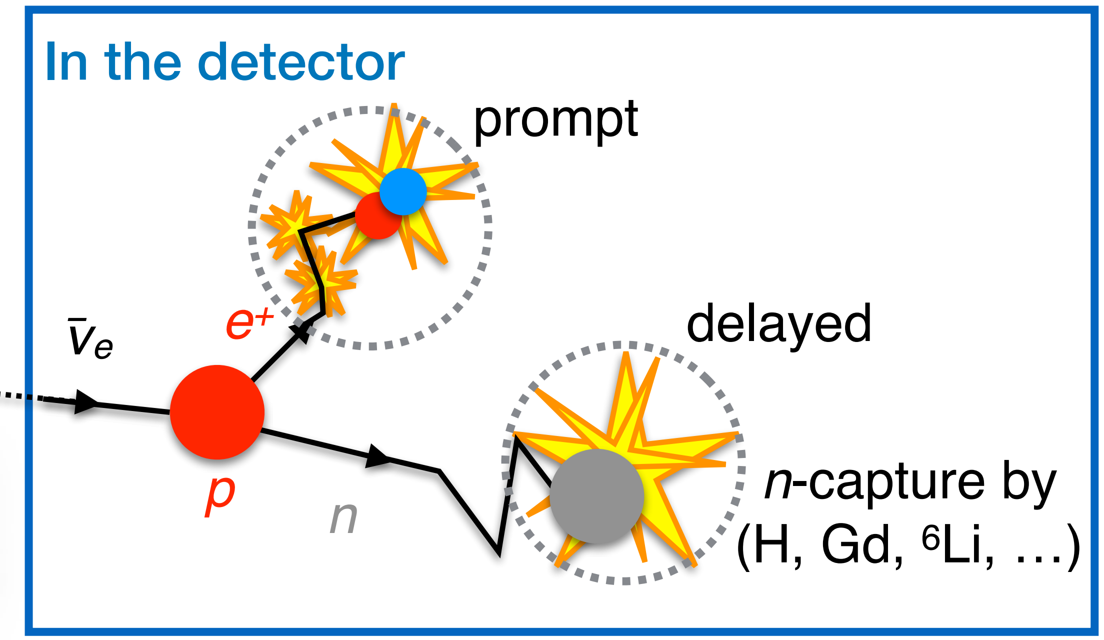


- 3+1 oscillation

SBL oscillation





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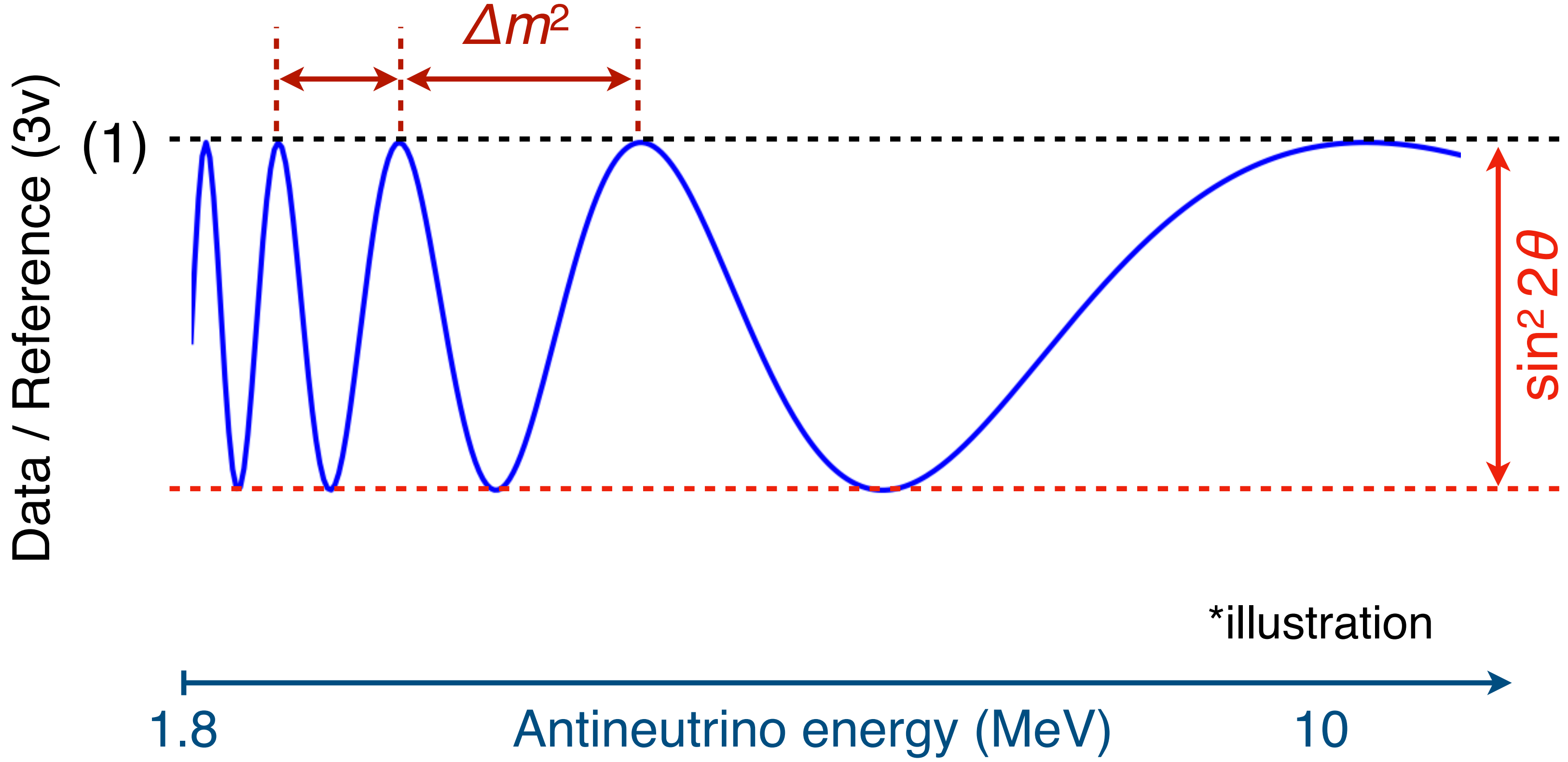
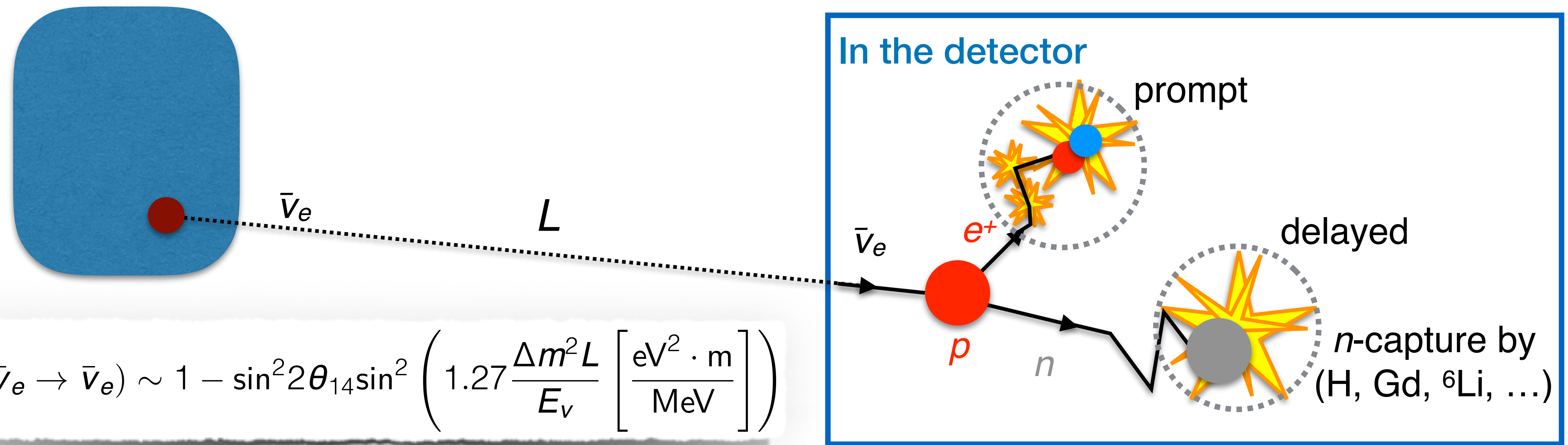


- 3+1 oscillation

SBL oscillation



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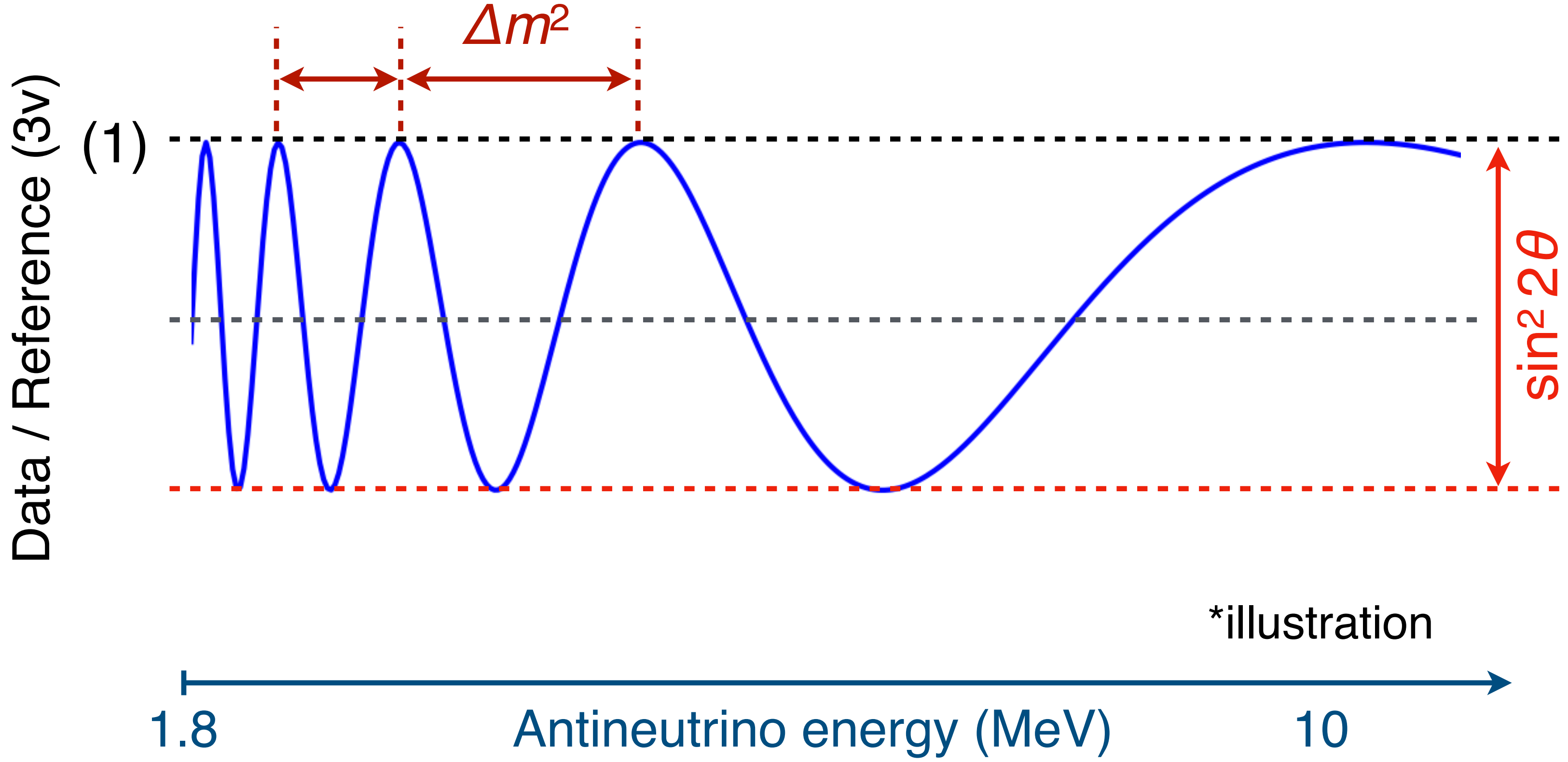

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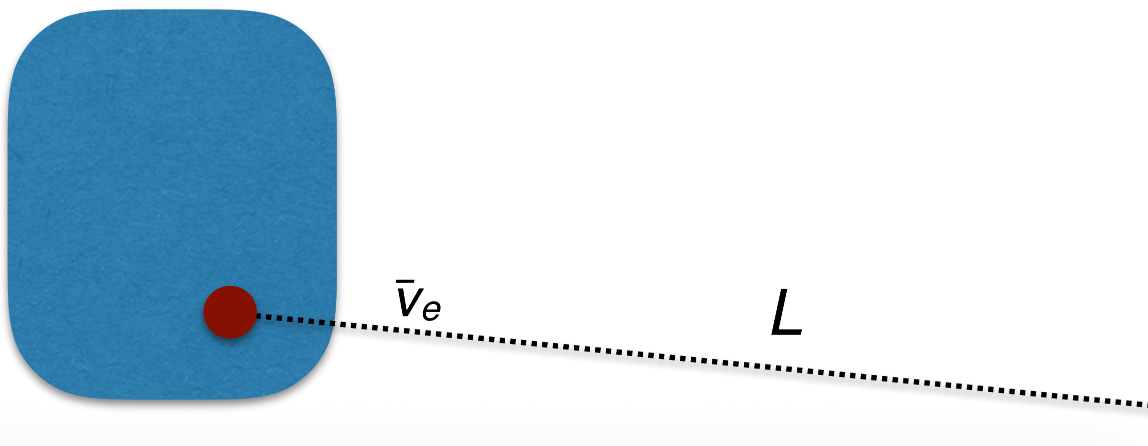

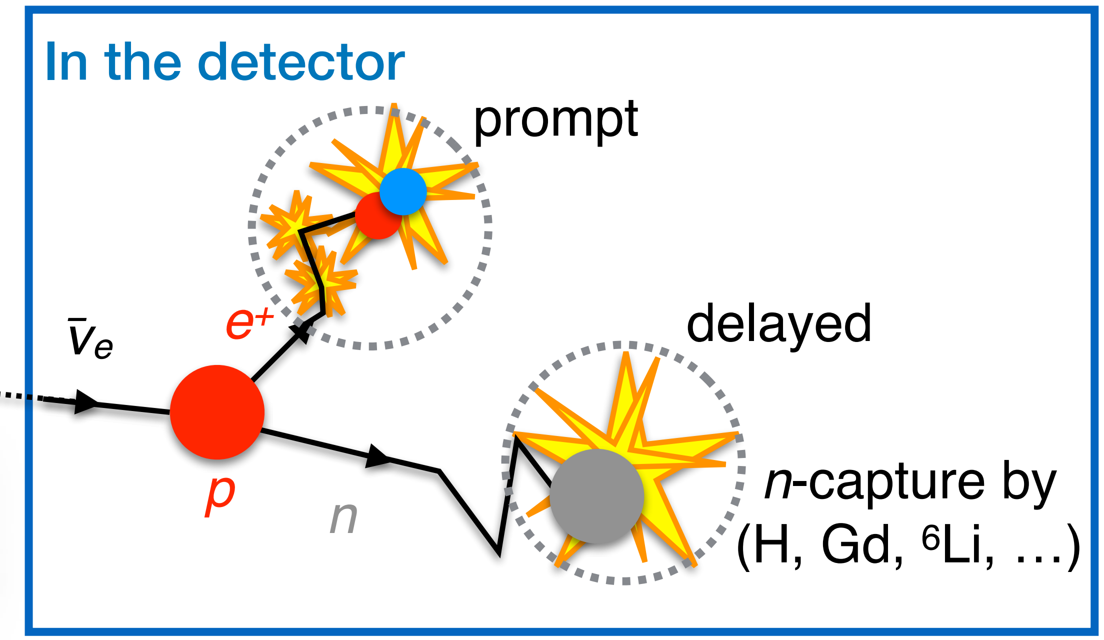

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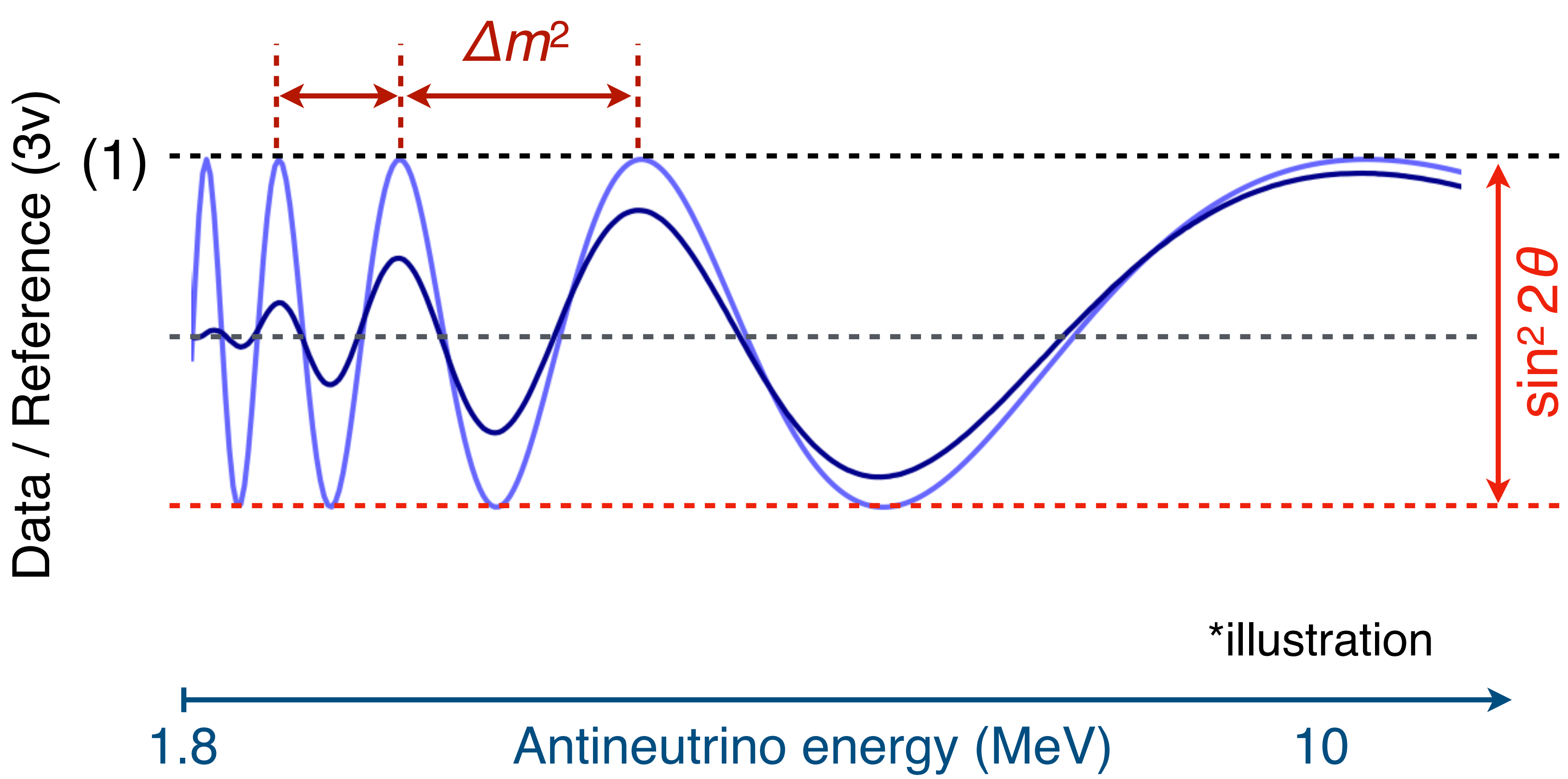
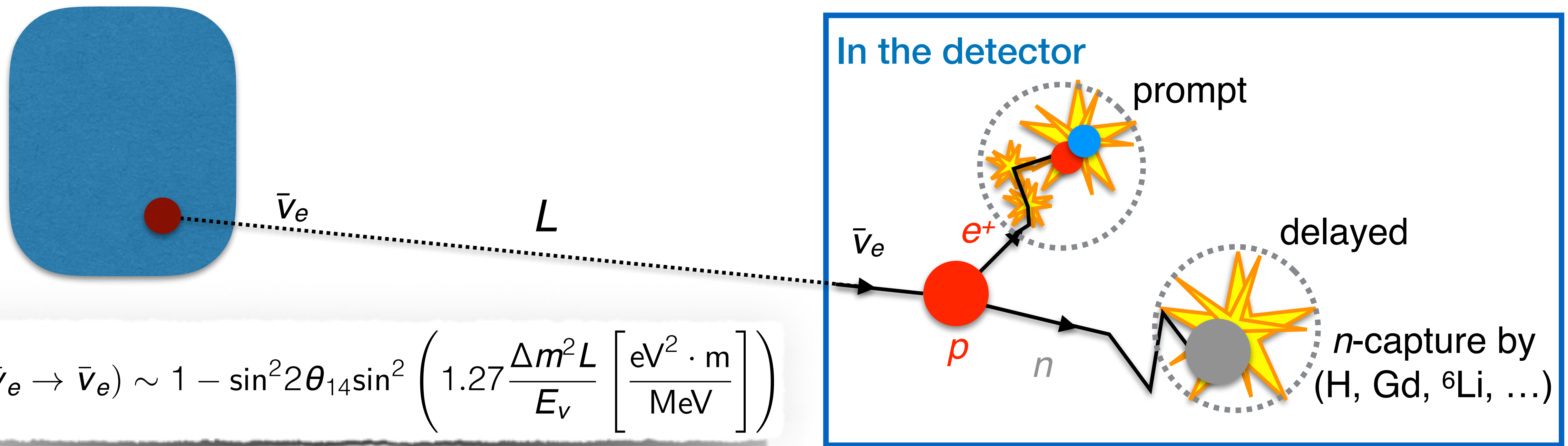


- 3+1 oscillation
- distance resolution

SBL oscillation



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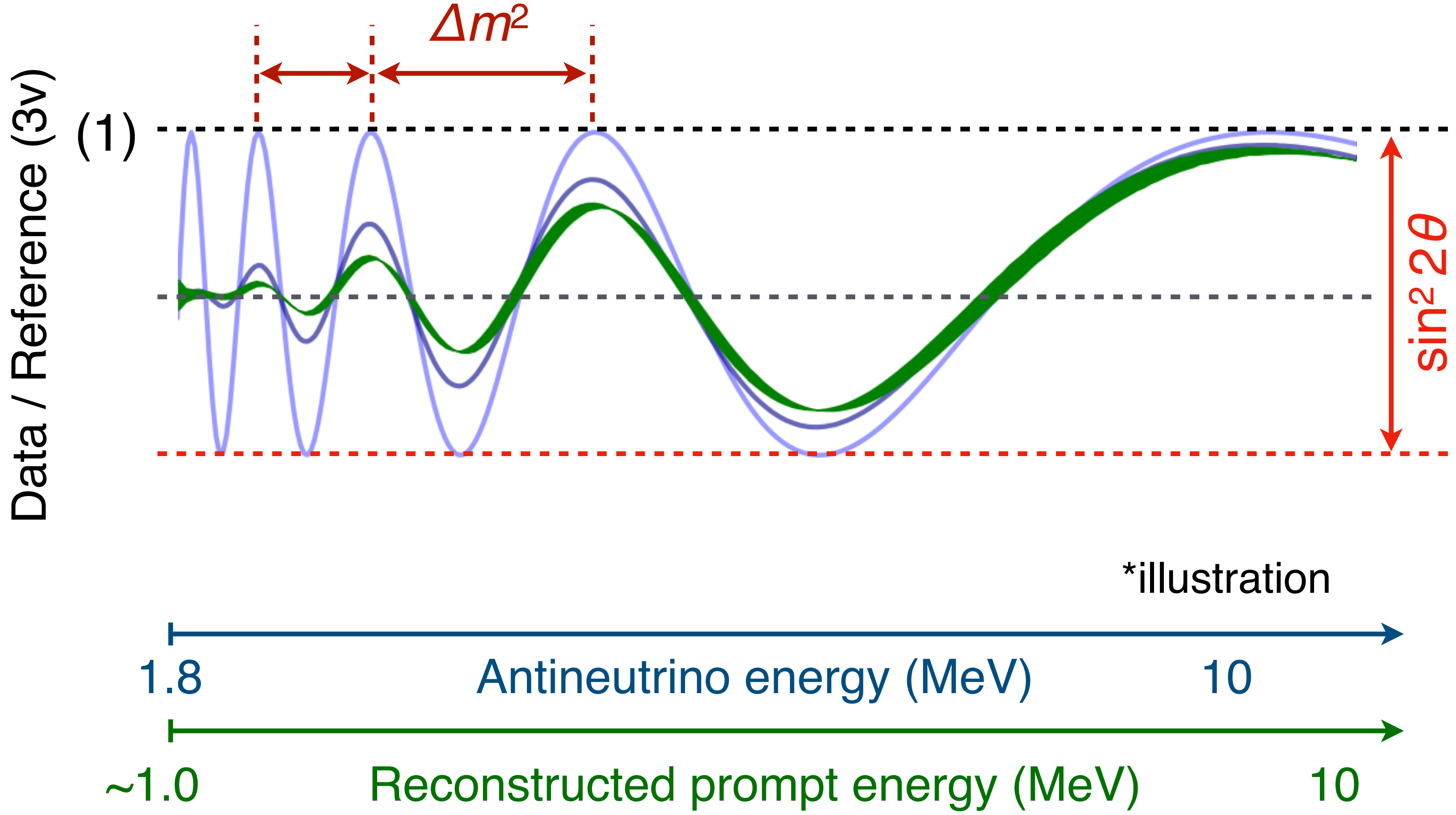
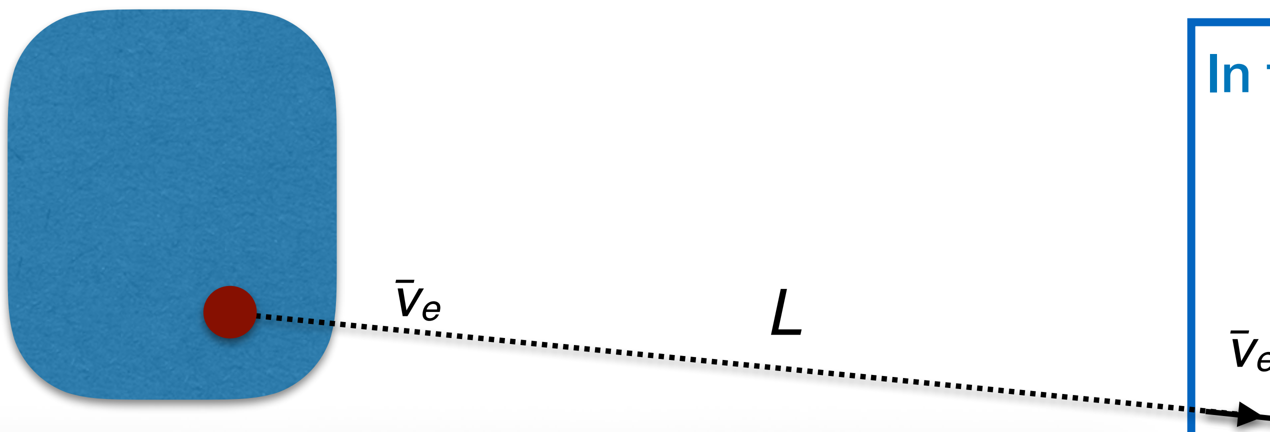
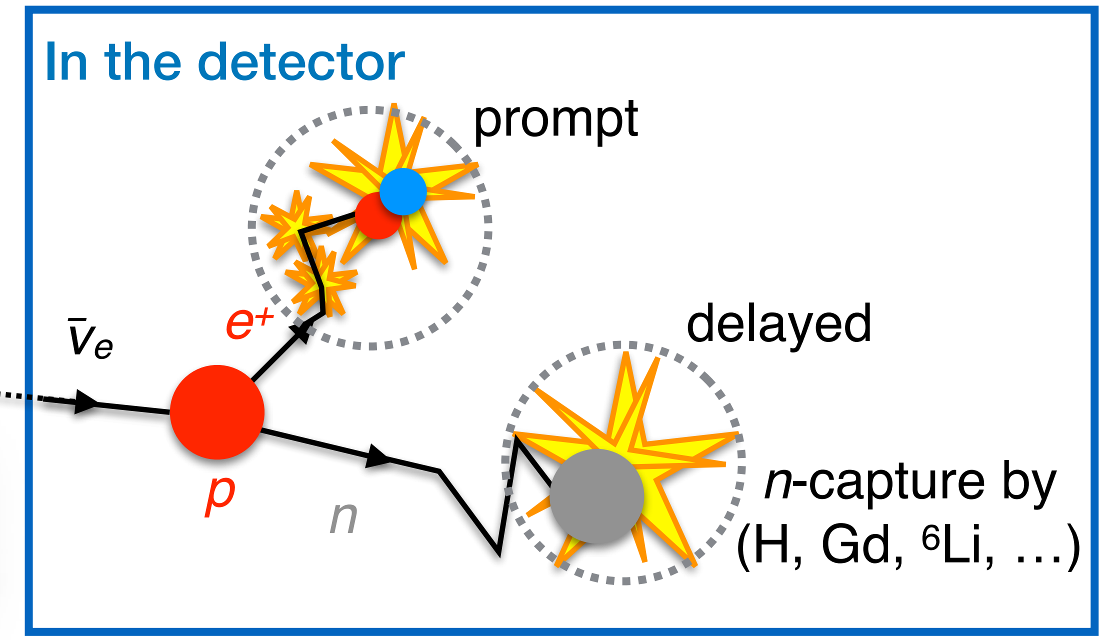


- 3+1 oscillation
- distance resolution
- energy reconstruction

SBL oscillation





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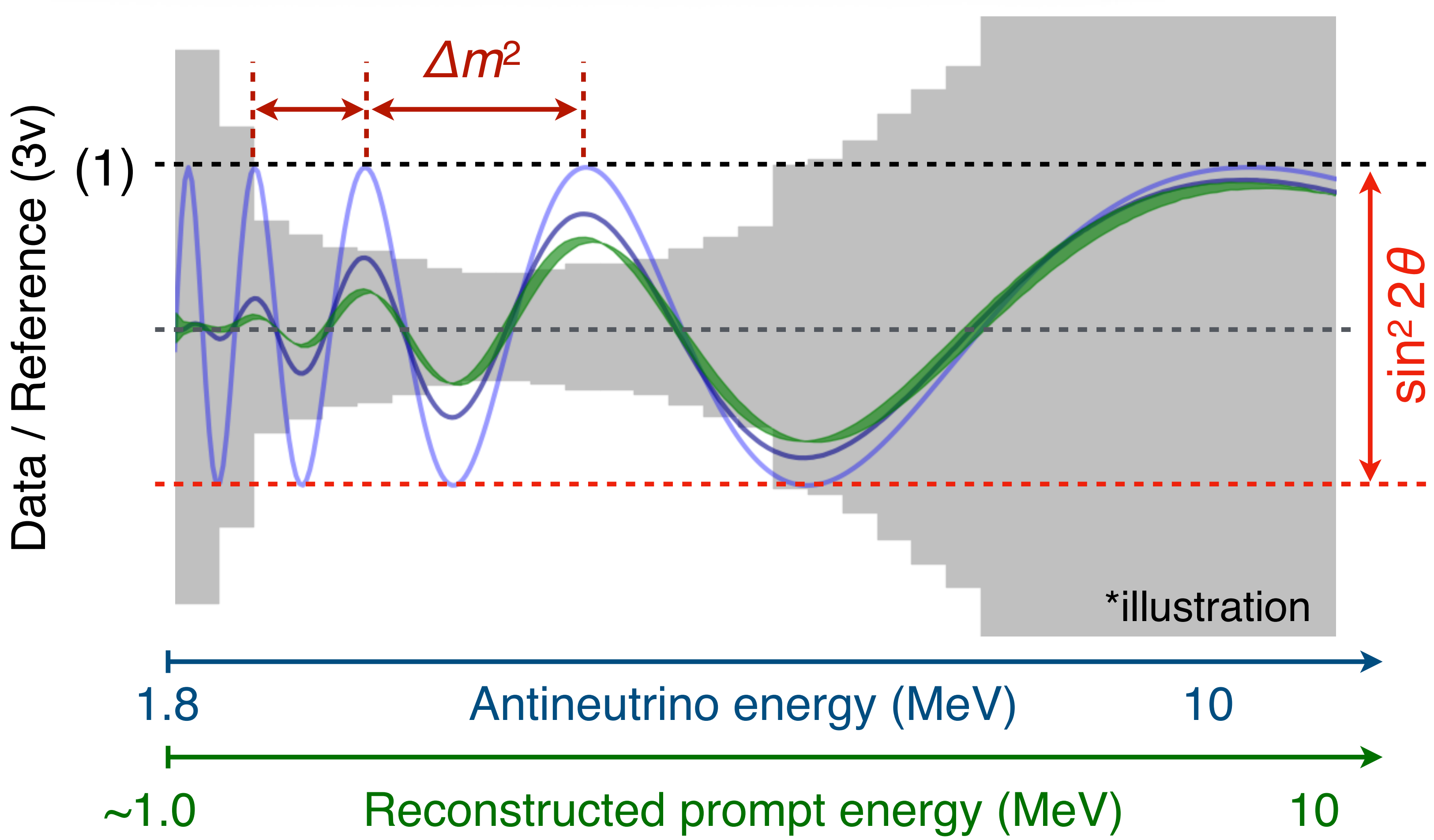
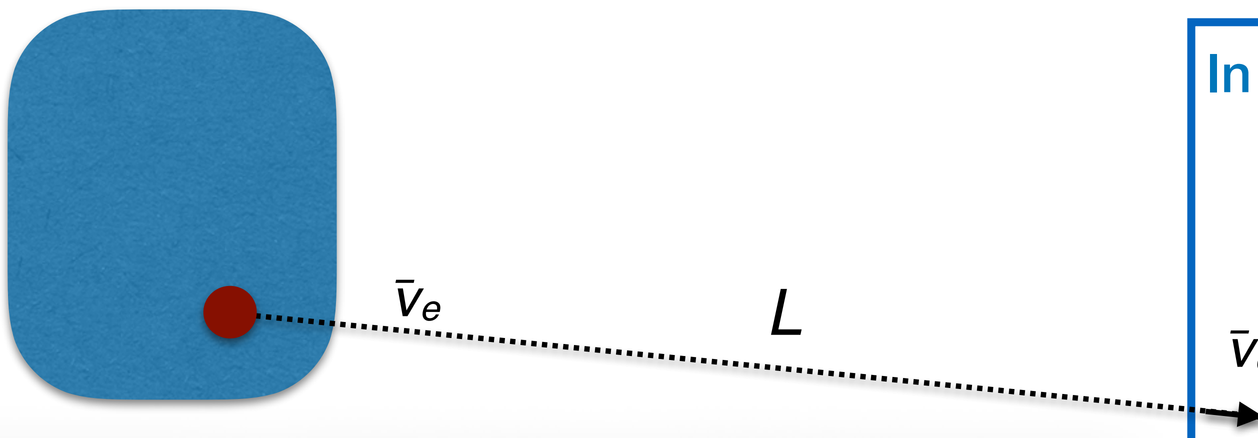
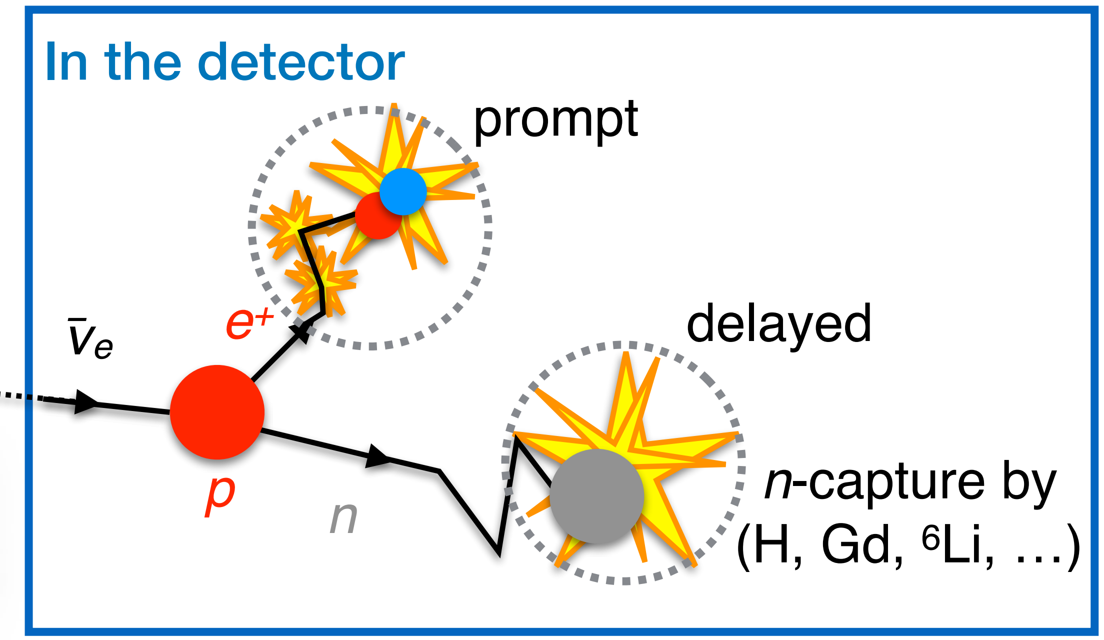


- 3+1 oscillation
- distance resolution
- energy reconstruction
- systematics

SBL oscillation





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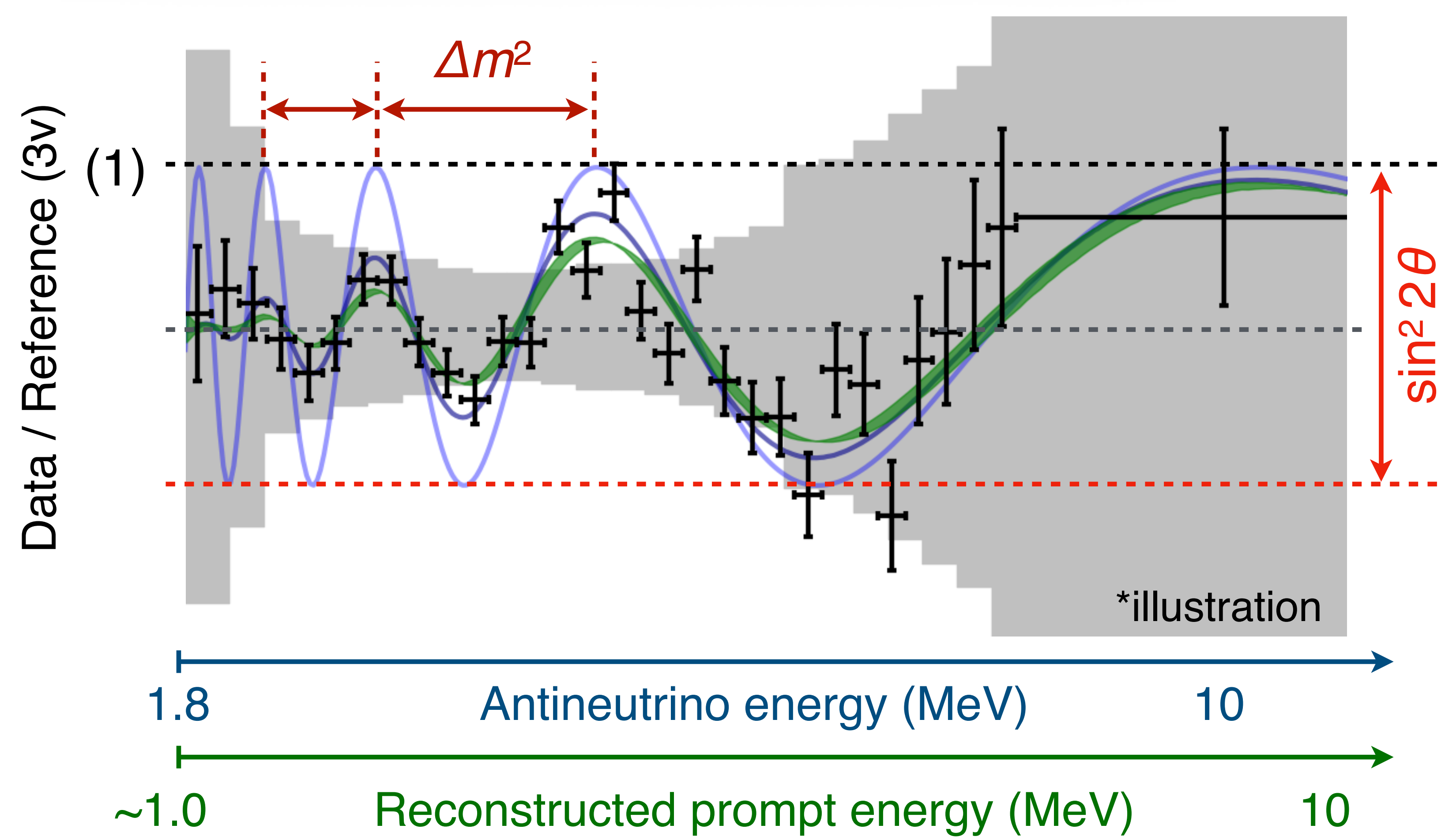
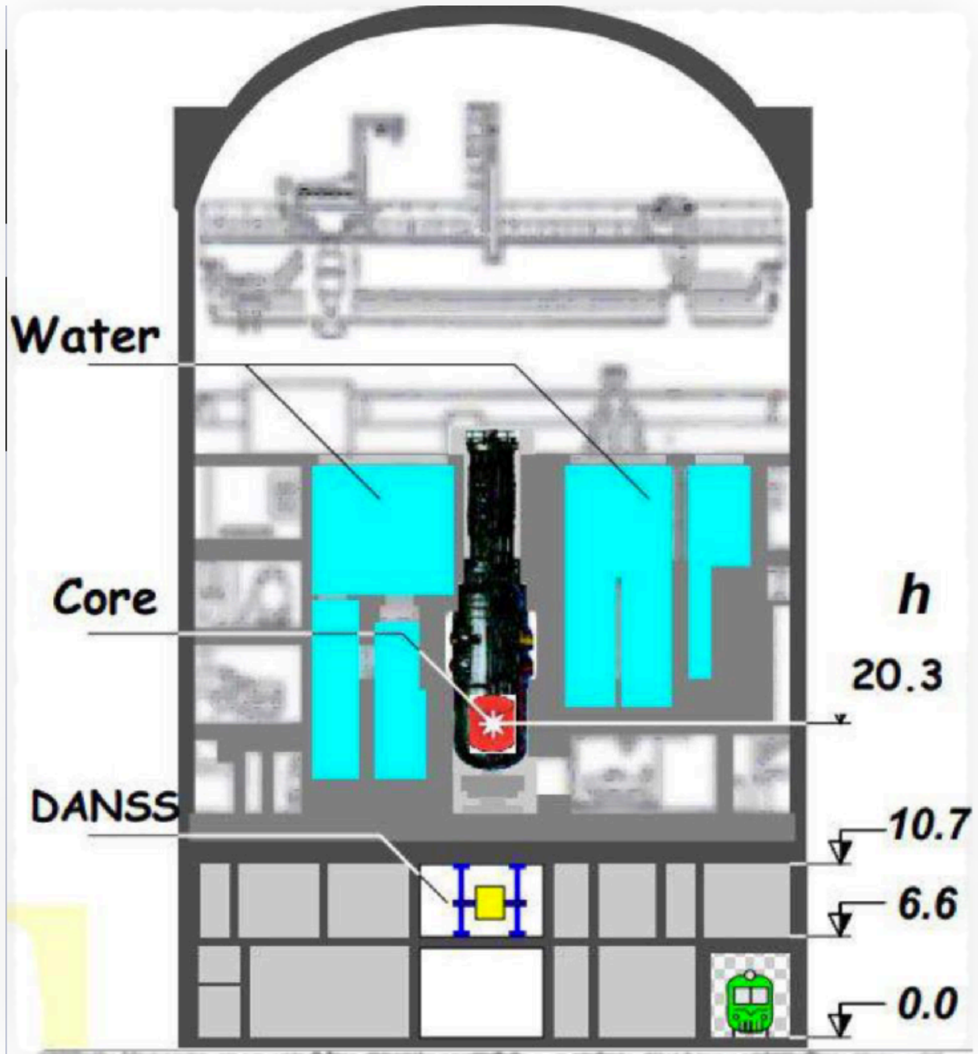


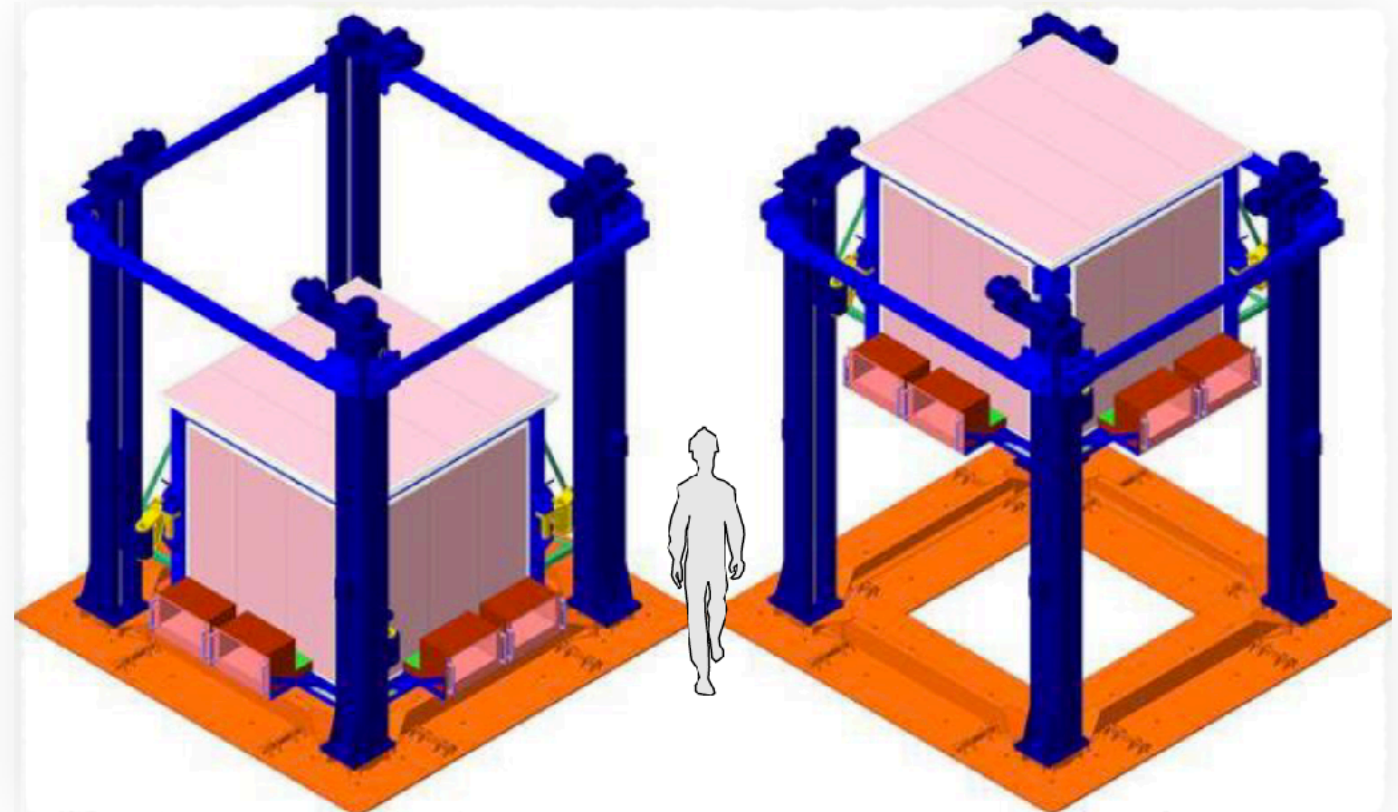
- 3+1 oscillation
- distance resolution
- energy reconstruction
- systematics
- background, statistics

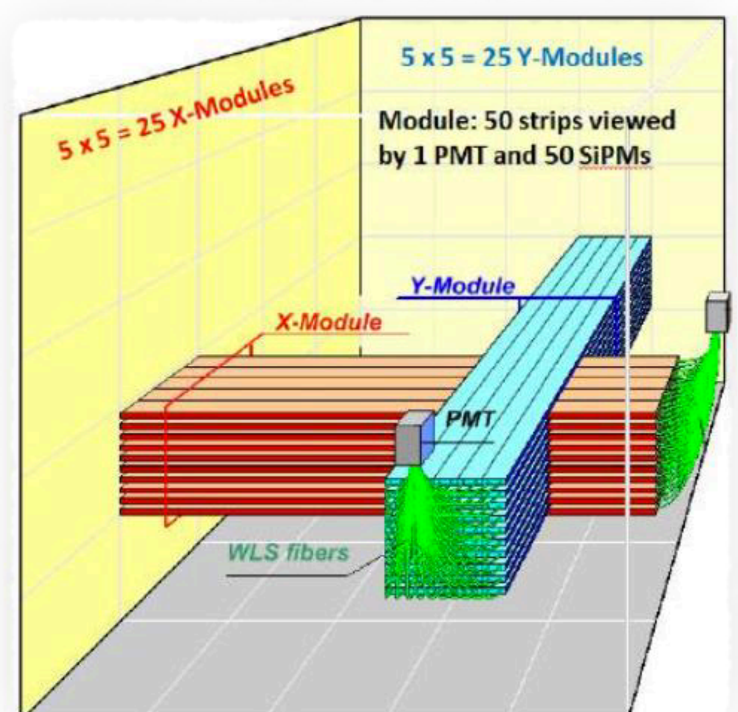
Active reactor SBL experiments

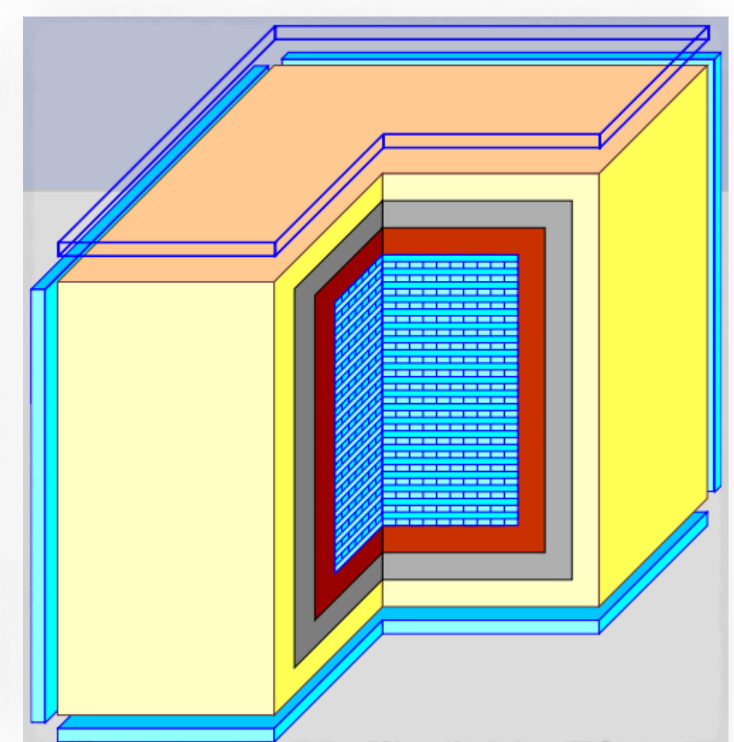
Experiment	Reactor	Baseline	Detector
DANSS	Commercial (KNPP), LEU, 3.1 GWt, Φ3.1 x H3.6 m	10.7~12.7 m	1m³ highly segmented plastic scintillator + Gd sheet movable detector
NEOS	Commercial (Hanbit-5), LEU, 2.8 GWt, Φ3.1 x H3.8 m	23.7 m	1000 L homogeneous Gd-LS, PSD
Neutrino-4	Research (SM-3), HEU, 100 MWt, 42 x 42 x 35 cm	6-12 m	1.42 m³ segmented Gd-LS, Movable detector
PROSPECT	Research (HFIR), HEU, 85 MWt, Φ0.4 x H0.5 m	7 m	3000 L semented 6Li-LS, PSD
STEREO	Research (ILL) HEU, 58.3 MWt Φ40 x H80 cm	10.3 m	1800 L segmented Gd-LS, PSD
Solid	Research (BR-2), HEU, 50-80 MWt, Φ50 x H90 cm	6-9 m	tons of plastic scintilllator cubes + LiF:ZnS sheet. PSD

DANSS TAUP2019



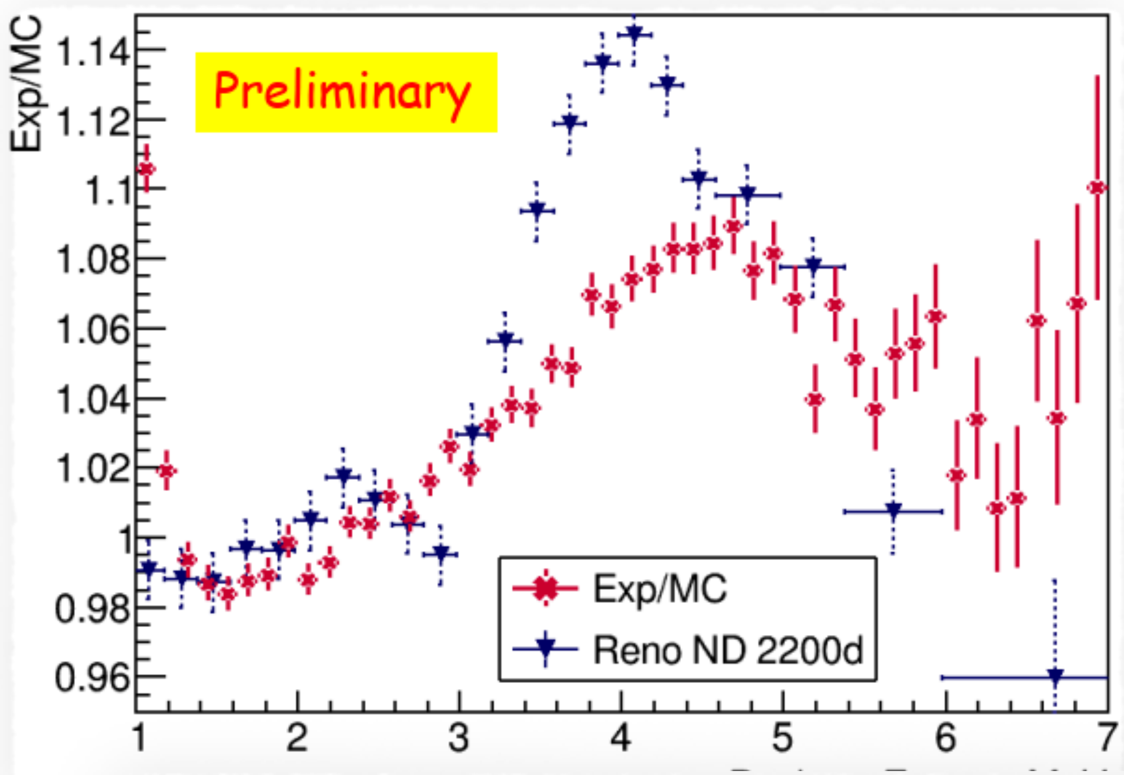


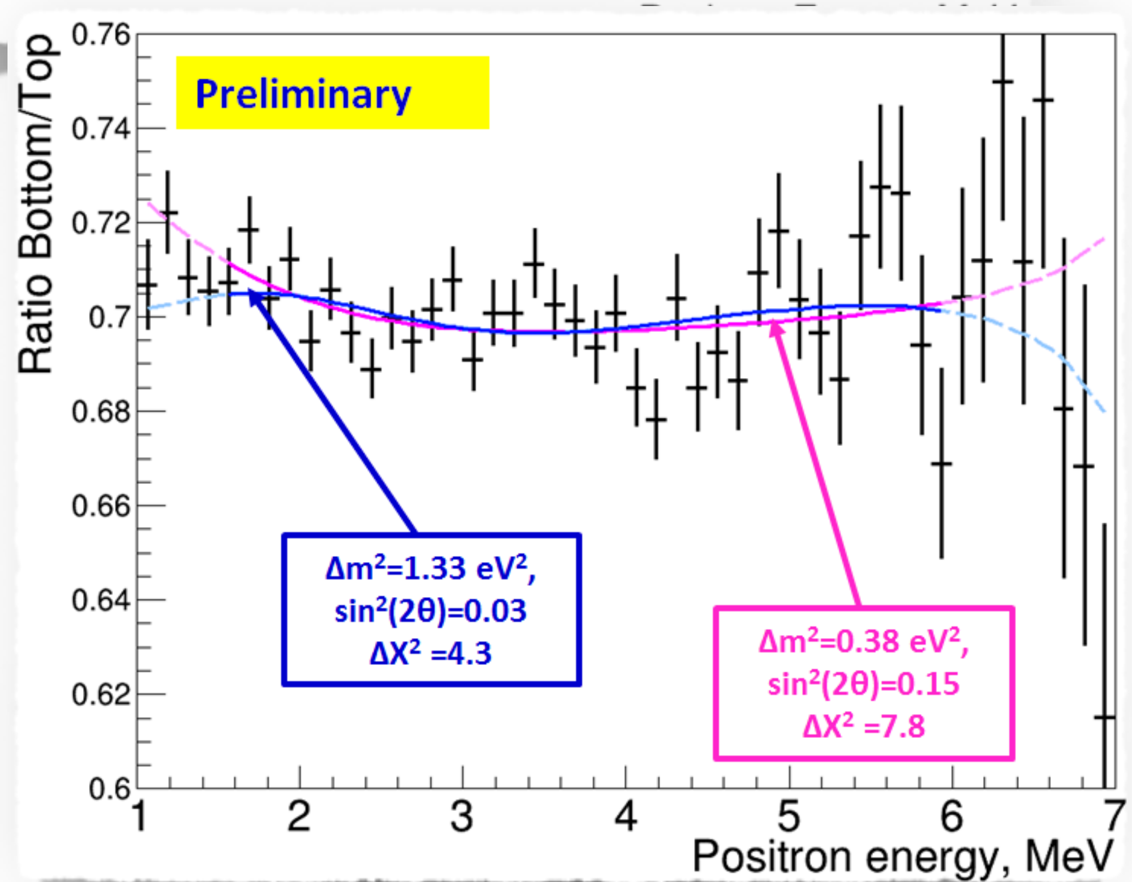




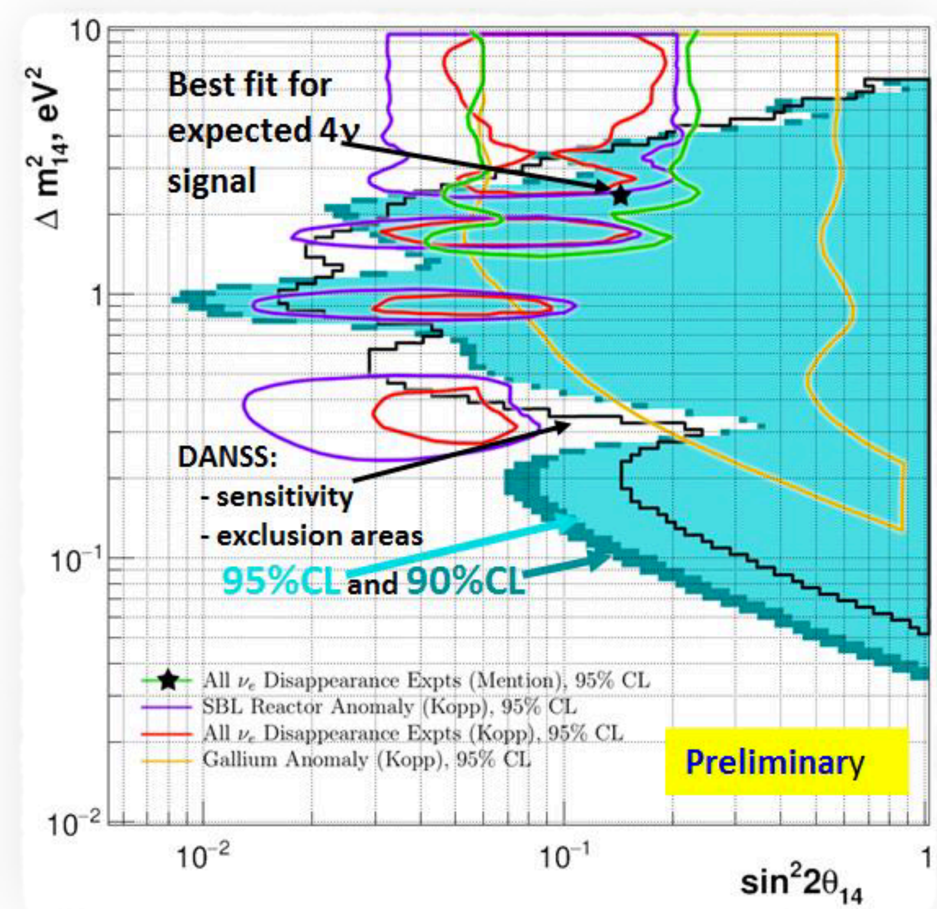
- Commercial 3.1 GWt reactor
- Detector moves between 10.7~12.7 m
- Extruded plastic scintillator strips covered with Gd sheets.

DANSS TAUP2019

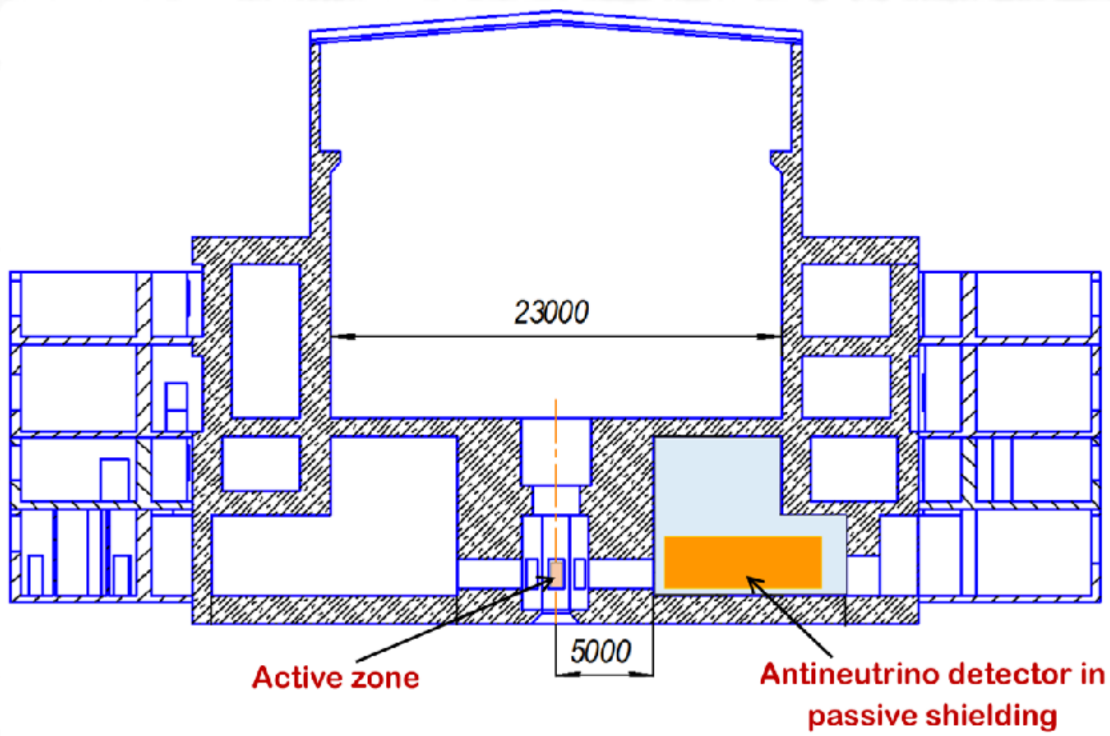


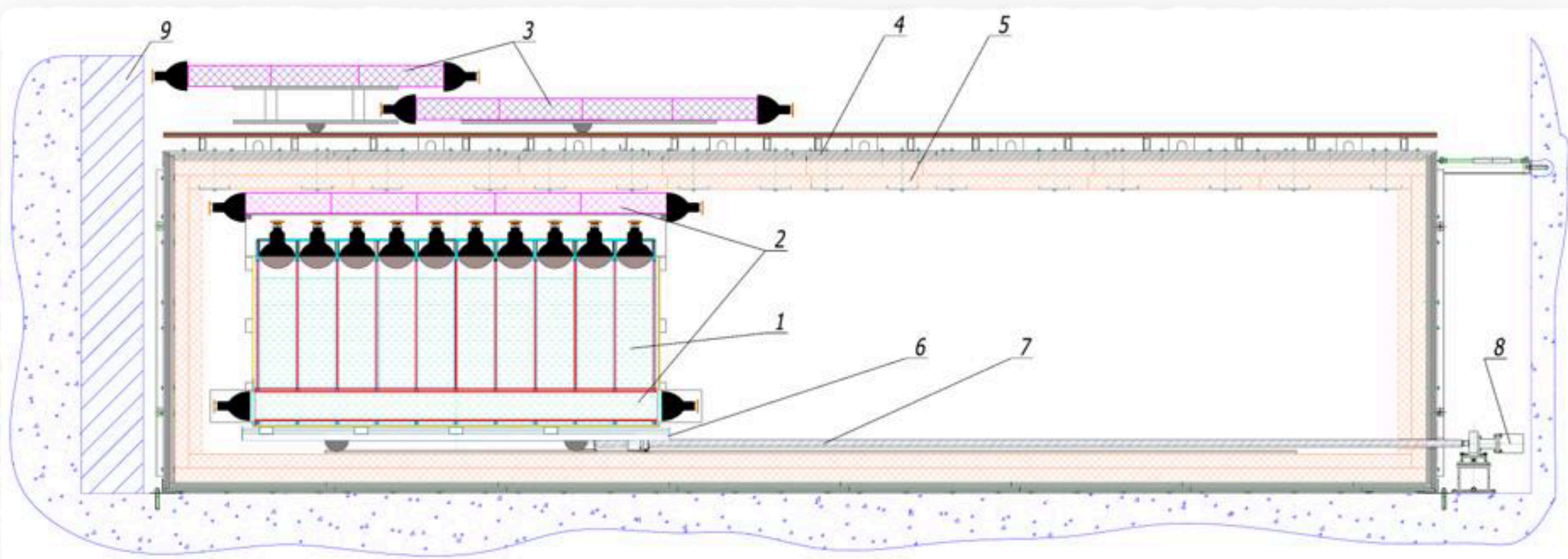


- Large statistics (~4k IBD/day).
- Not a good energy resolution.
- Updated (preliminary) result shows a sign of bump, and no sign for SBL oscillation.

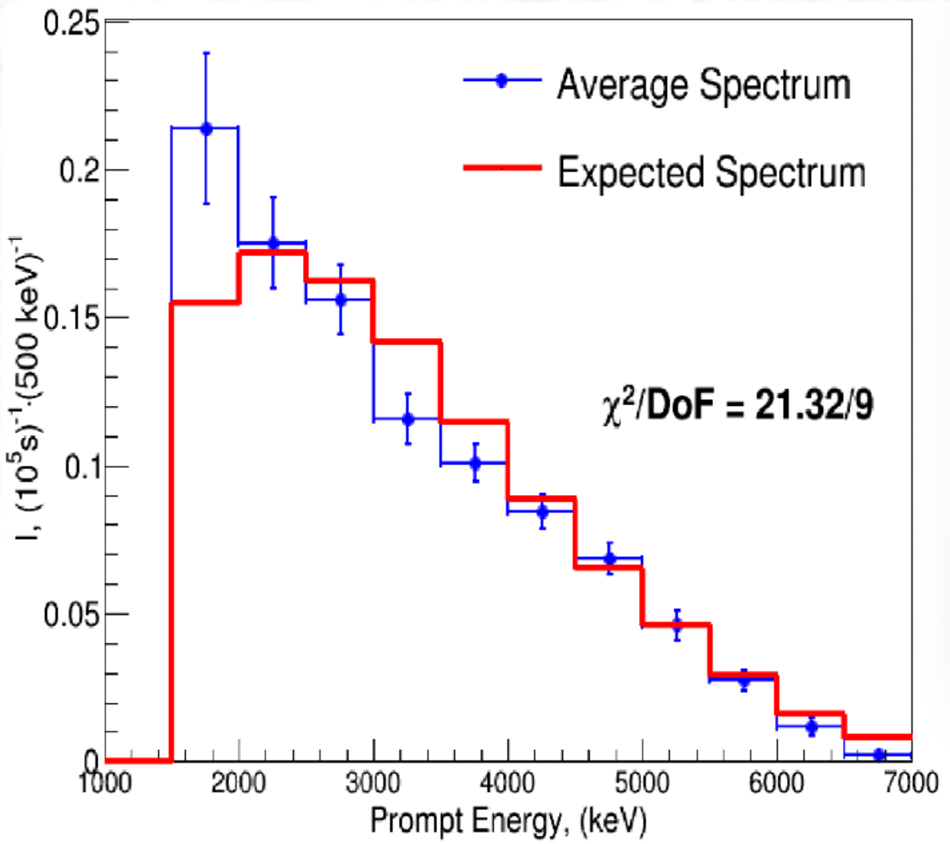


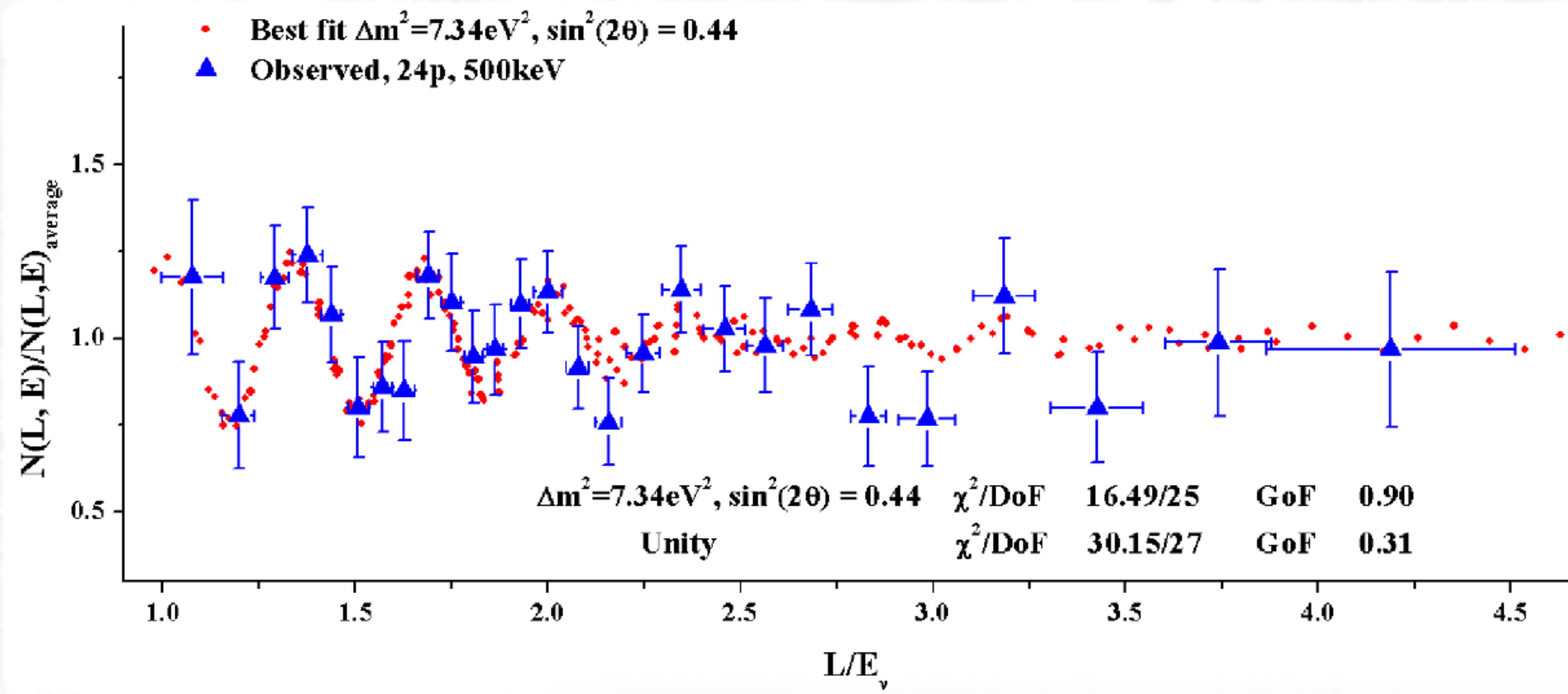
Neutrino-4 AAP2018

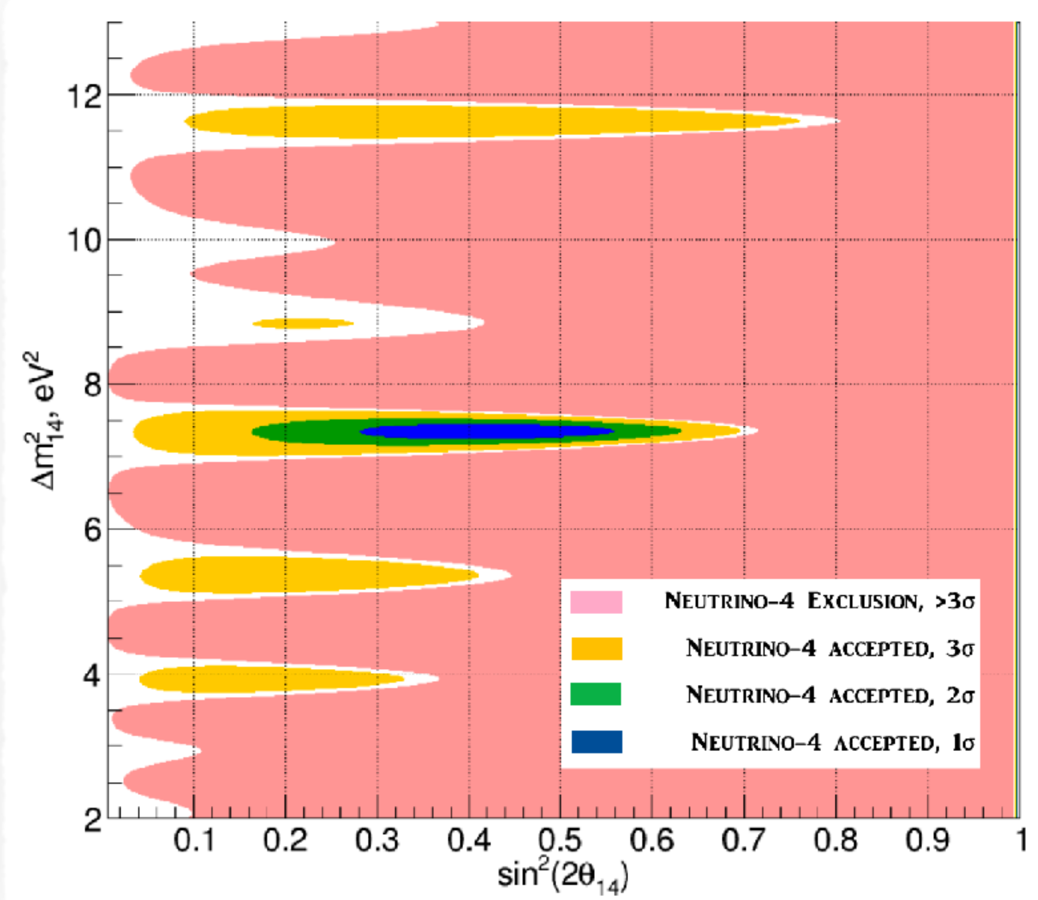




Neutrino-4 AAP2018

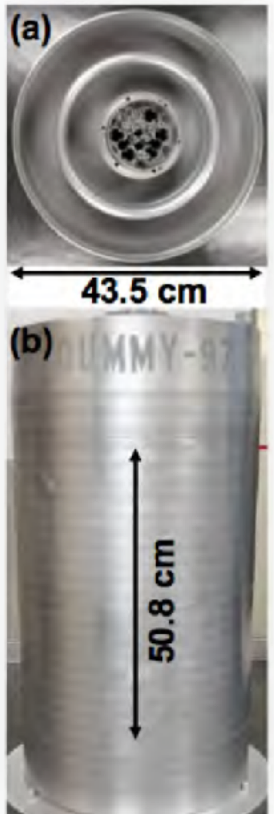


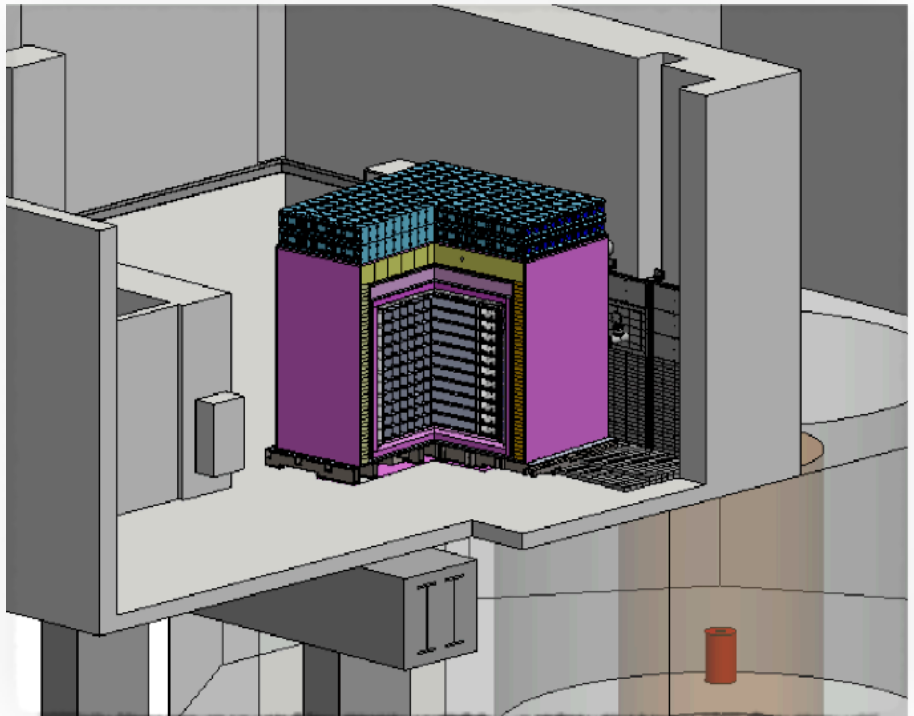


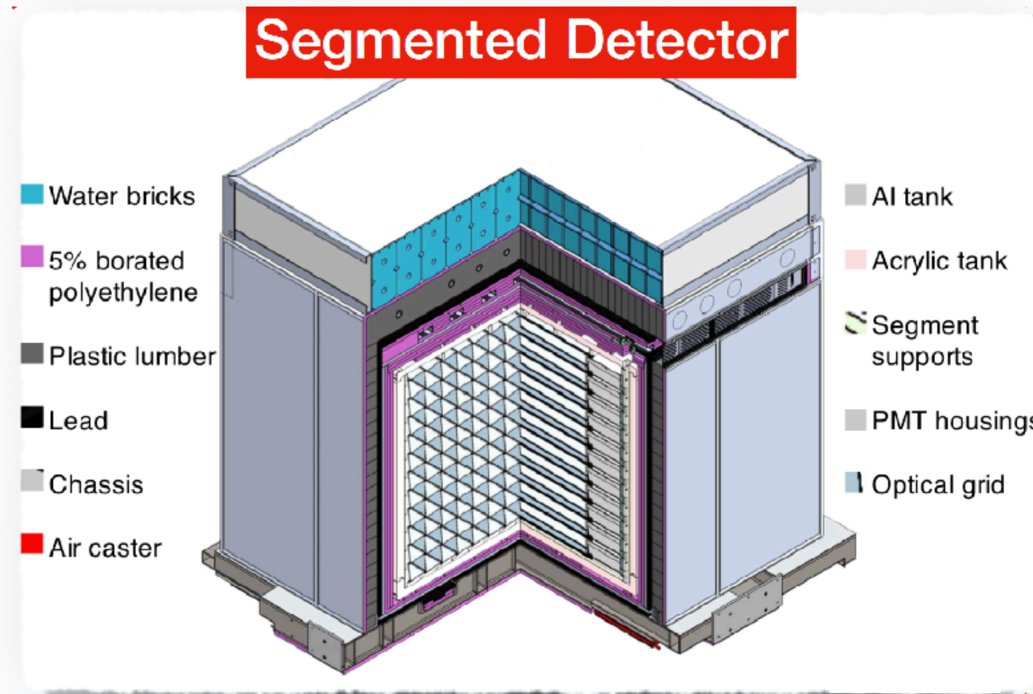


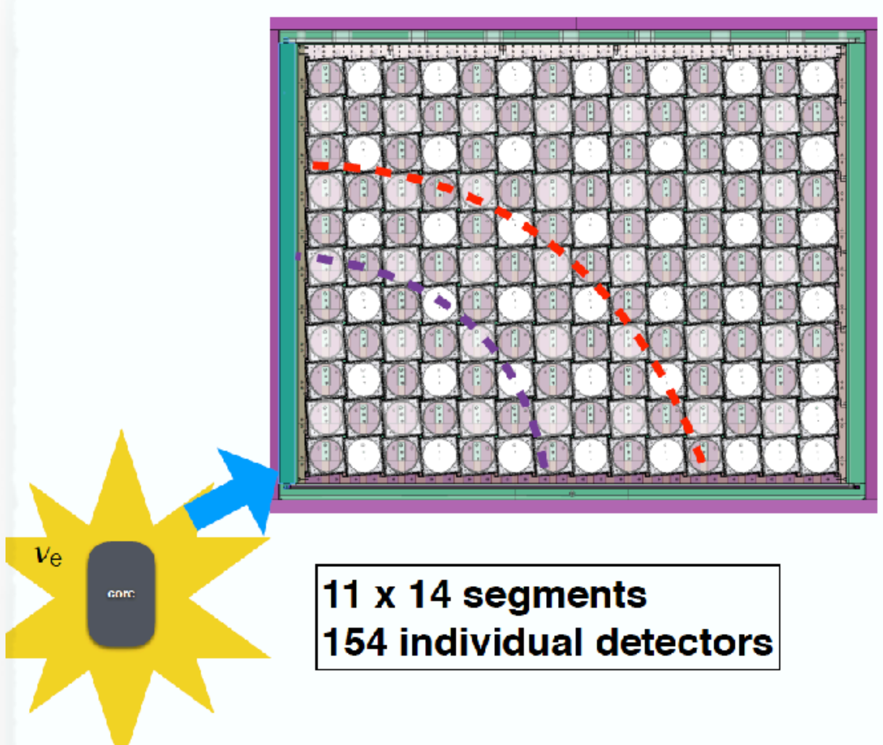
- Surprising result in L/E spectrum.
- Distortions in the averaged spectrum
- χ^2/NDF for no-osc not that bad.
- Needs more systematic/statistical improvement.

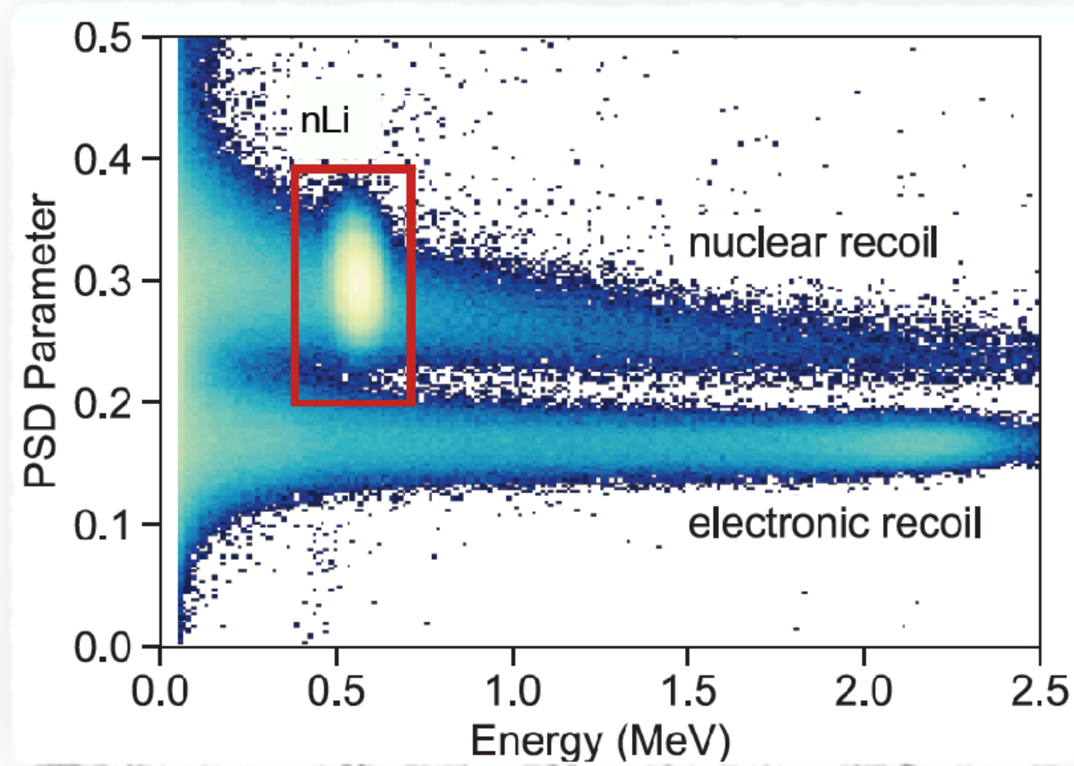
LP2019


(a)
43.5 cm
(b)
50.8 cm

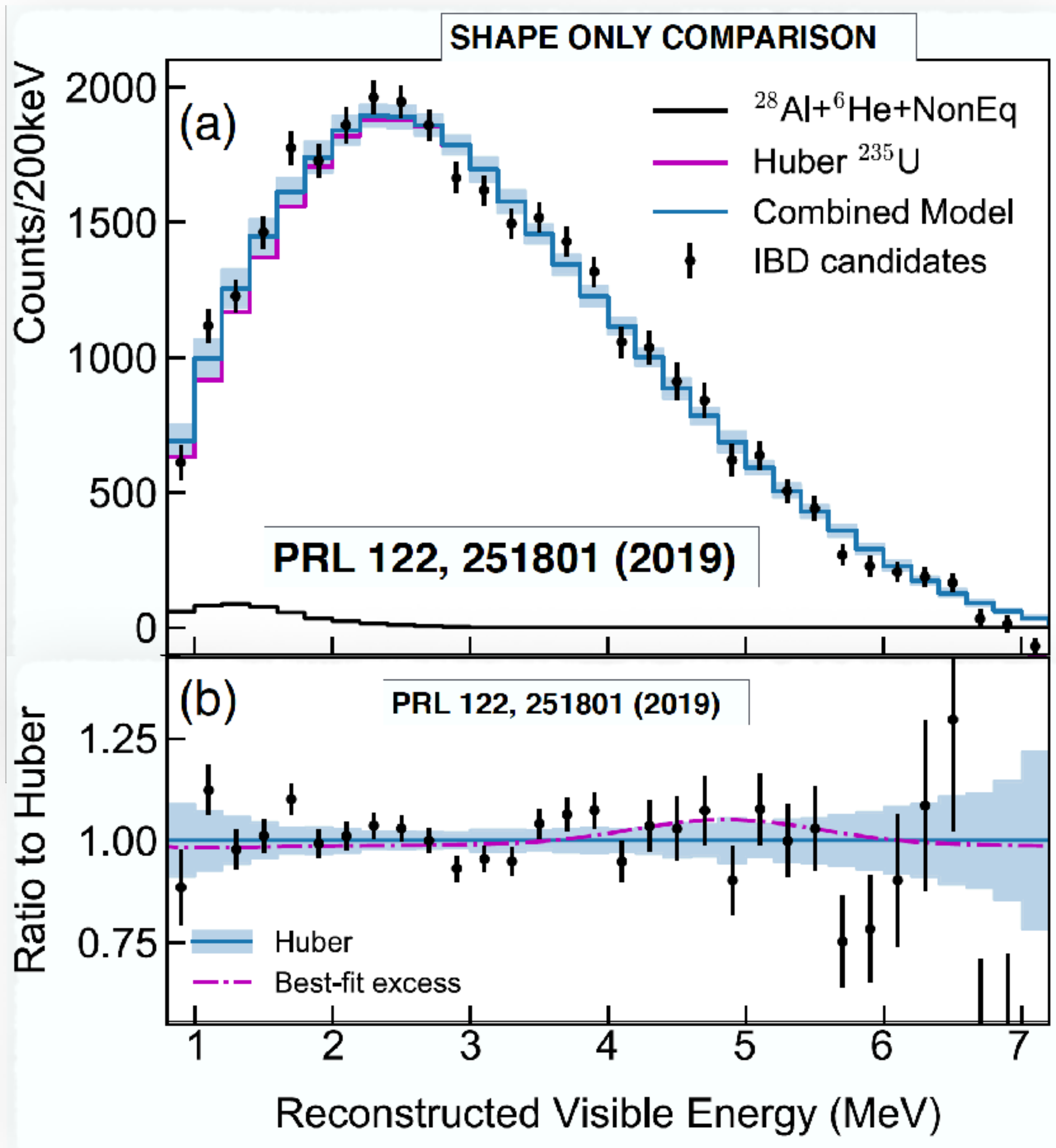


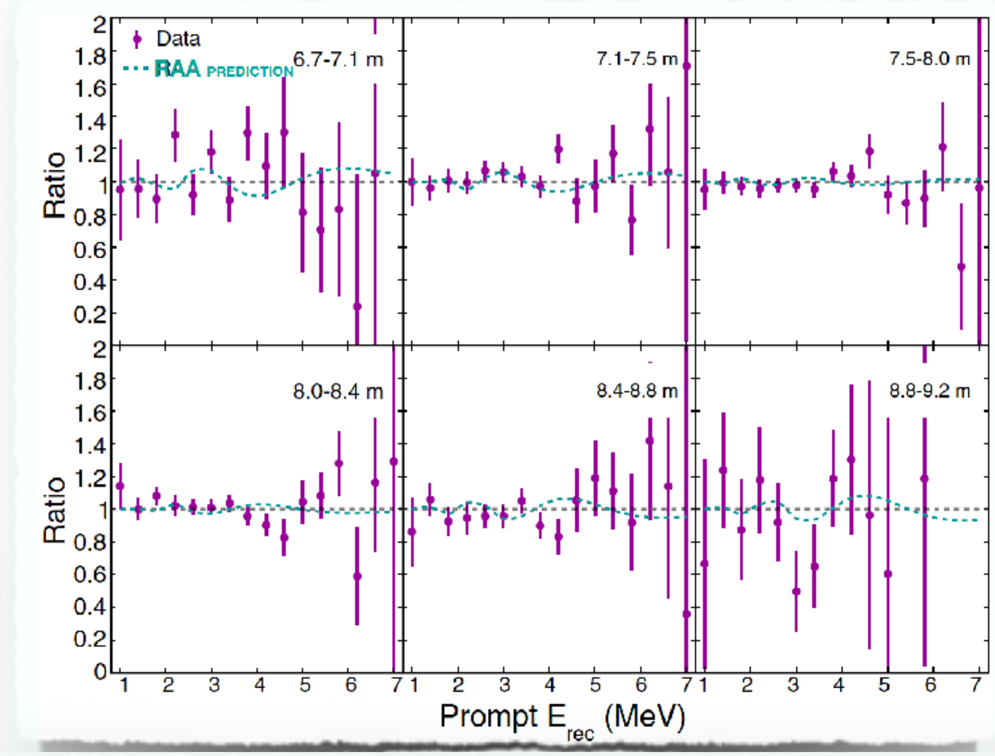

Segmented Detector
Water bricks
5% borated polyethylene
Plastic lumber
Lead
Chassis
Air caster
Al tank
Acrylic tank
Segment supports
PMT housings
Optical grid

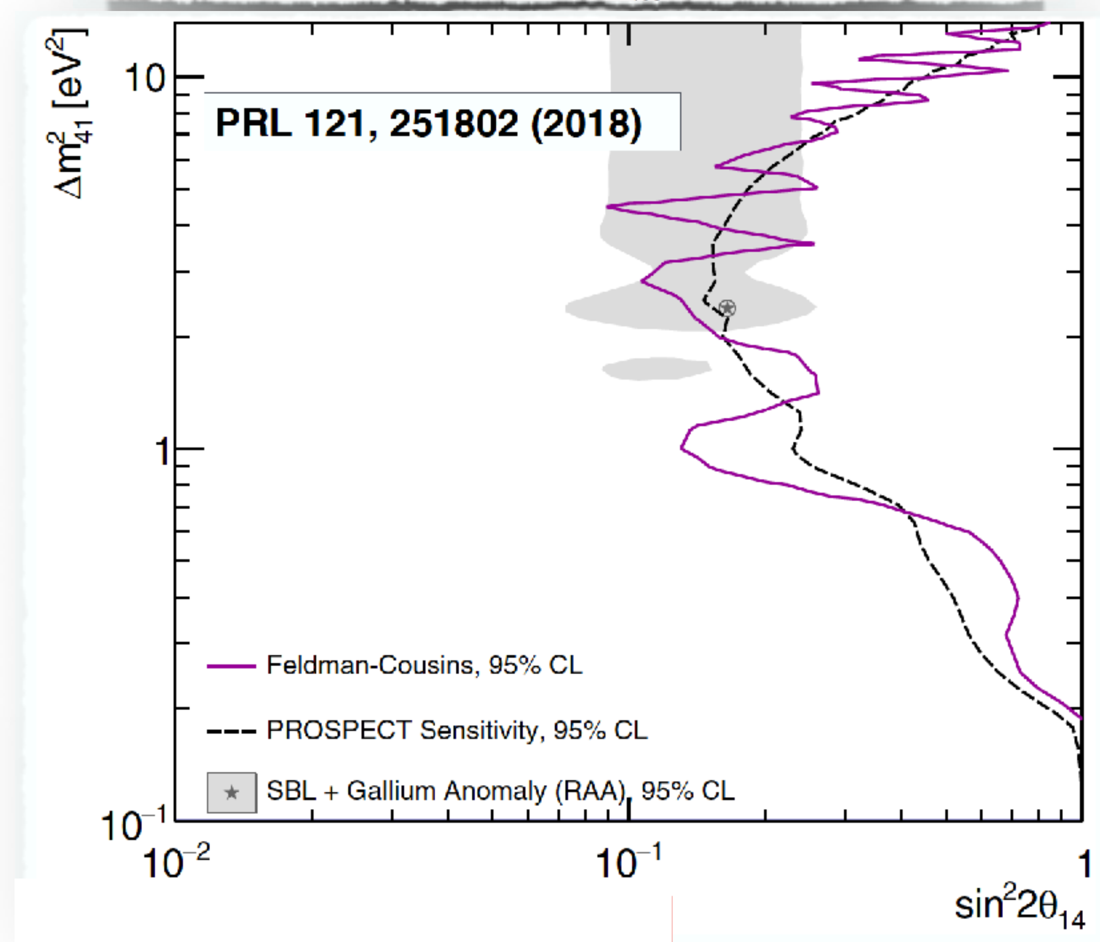

ν_e
11 x 14 segments
154 individual detectors


nLi
nuclear recoil
electronic recoil
PSD Parameter
Energy (MeV)
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
2.5

LP2019

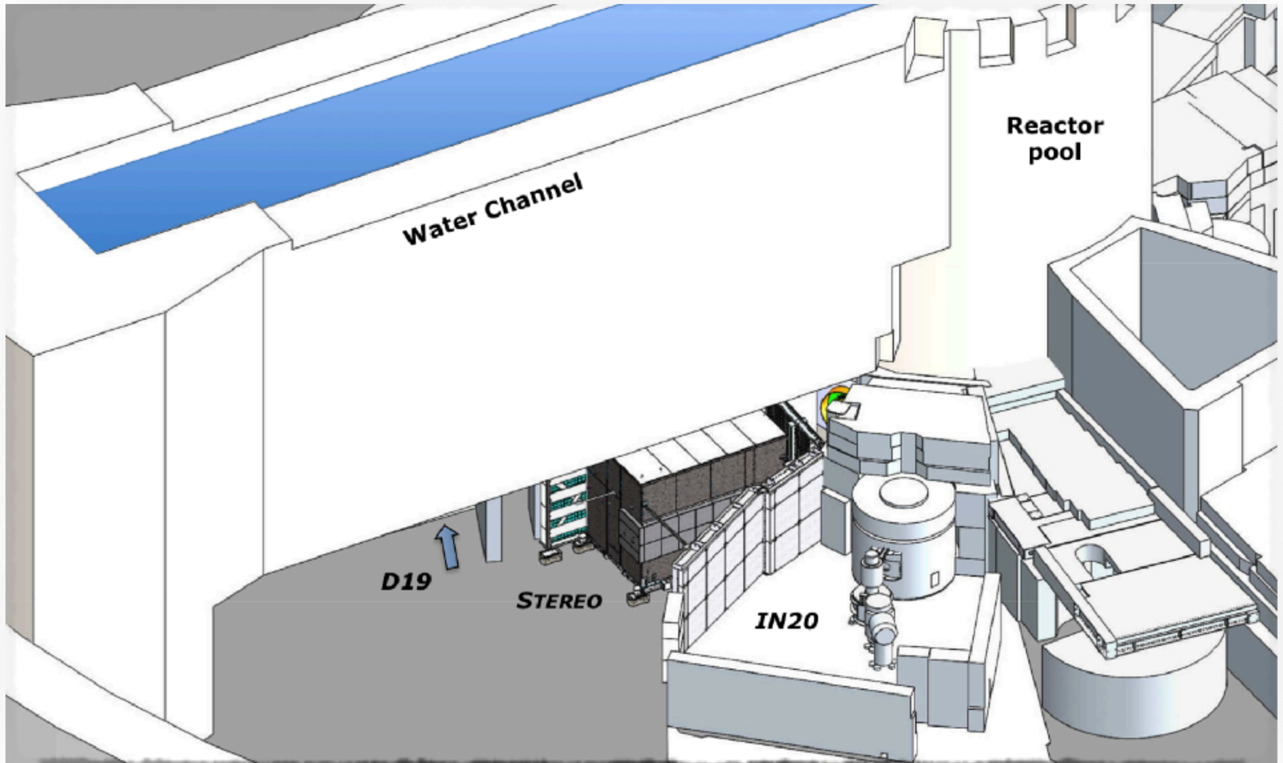


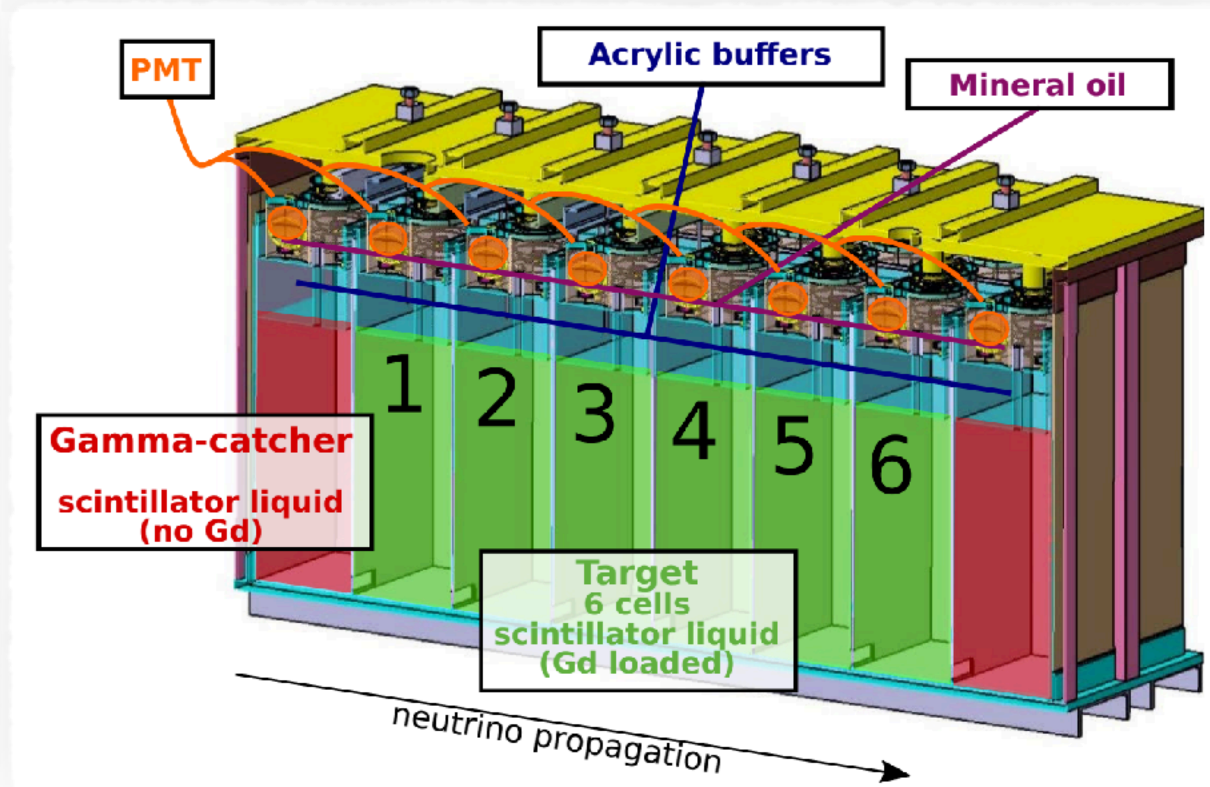


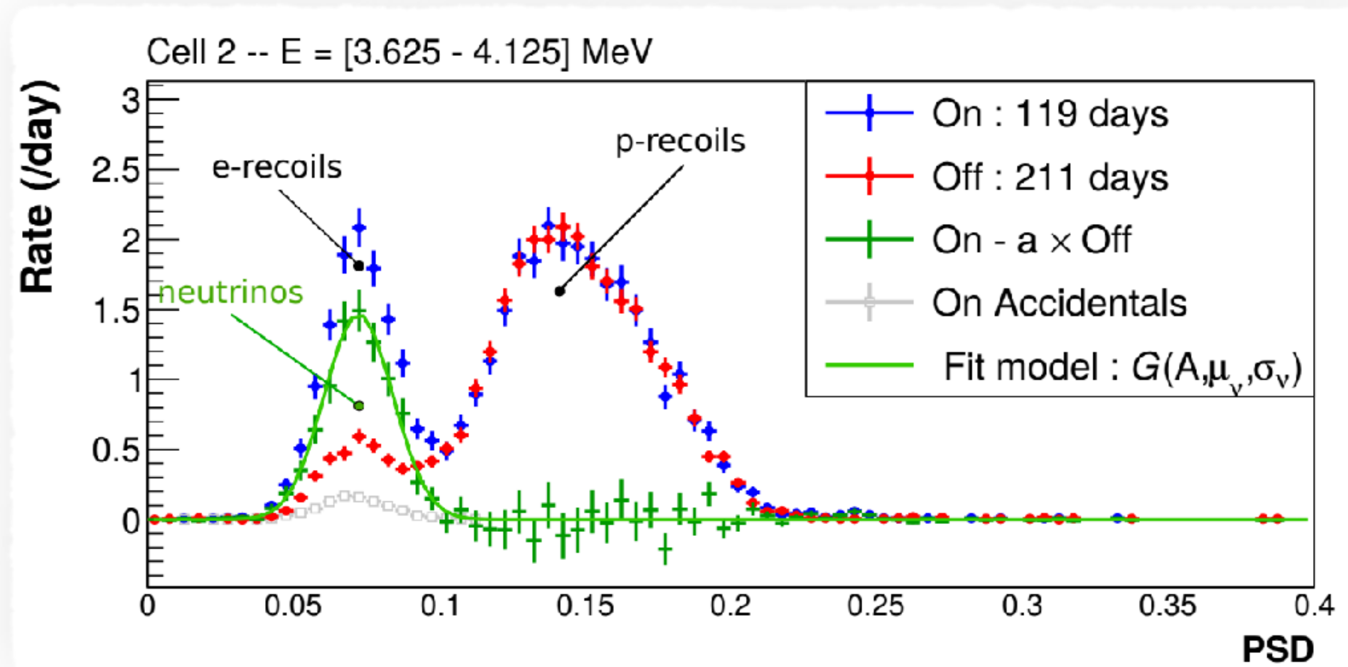


- comparison between groups of segments for oscillation analysis.

STEREO TAUP 2019

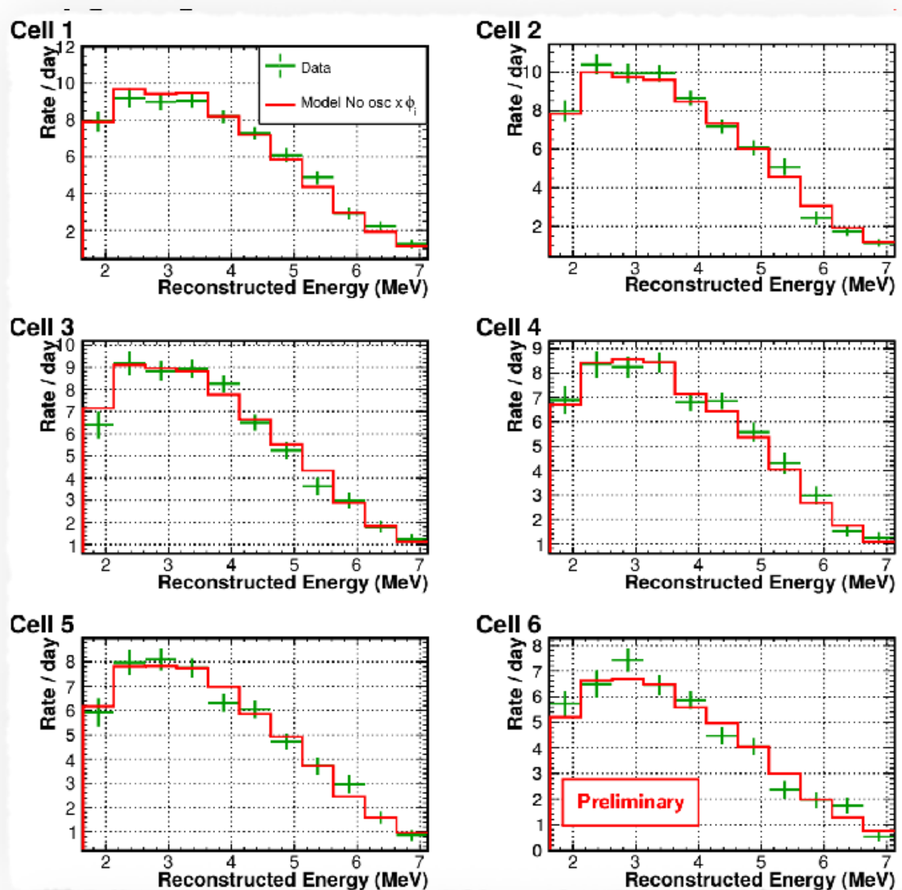


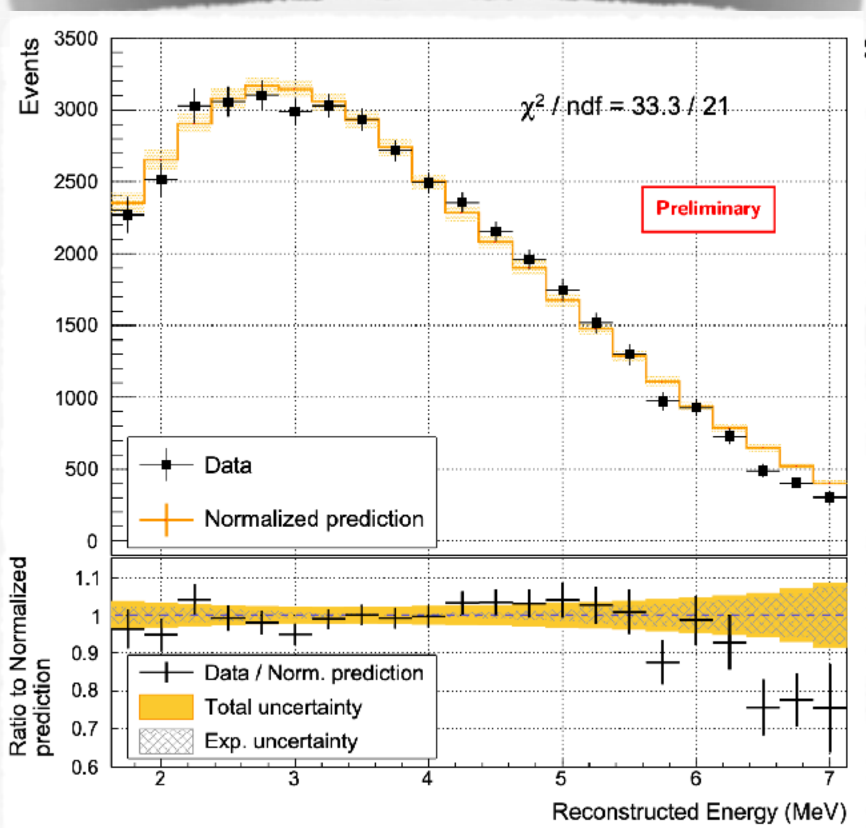


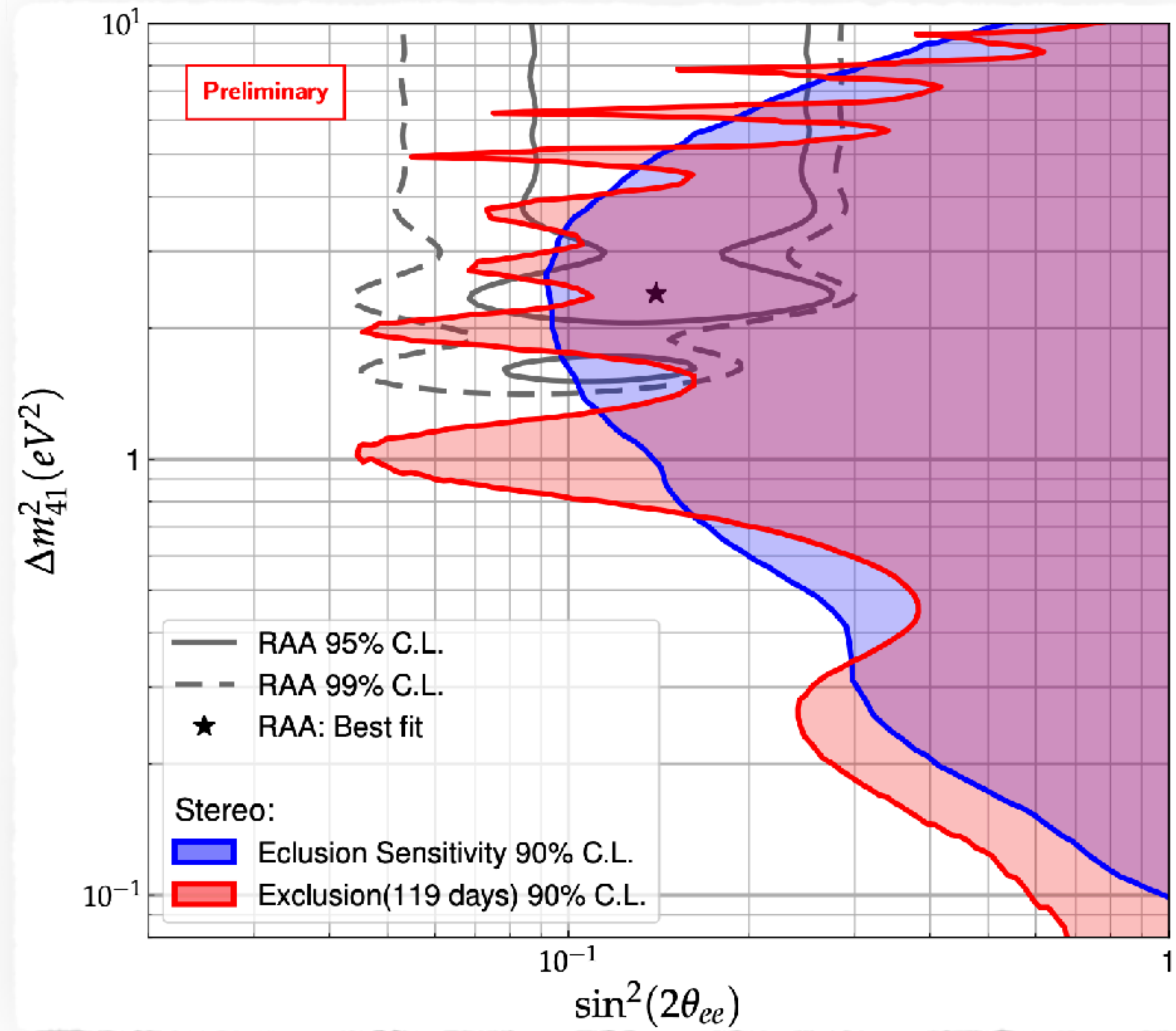


- 58.3 MWt research reactor
- Segmented cells have distance resolution
- Gd-LS with PSD capability

STEREO TAUP 2019





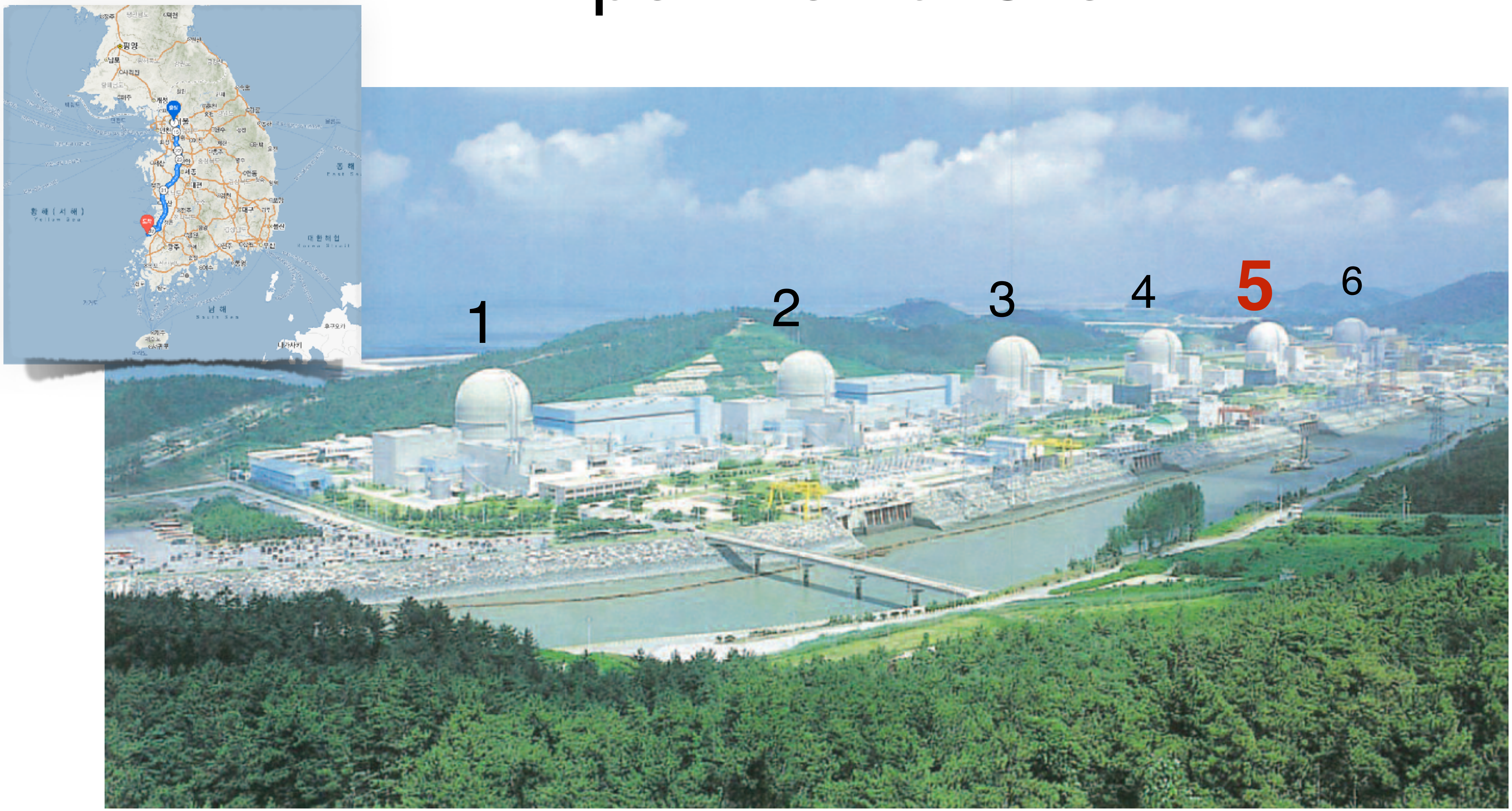


- Comparison between cells for oscillation study, disfavors RAA.
- Expecting more statistical precision.

NEOS

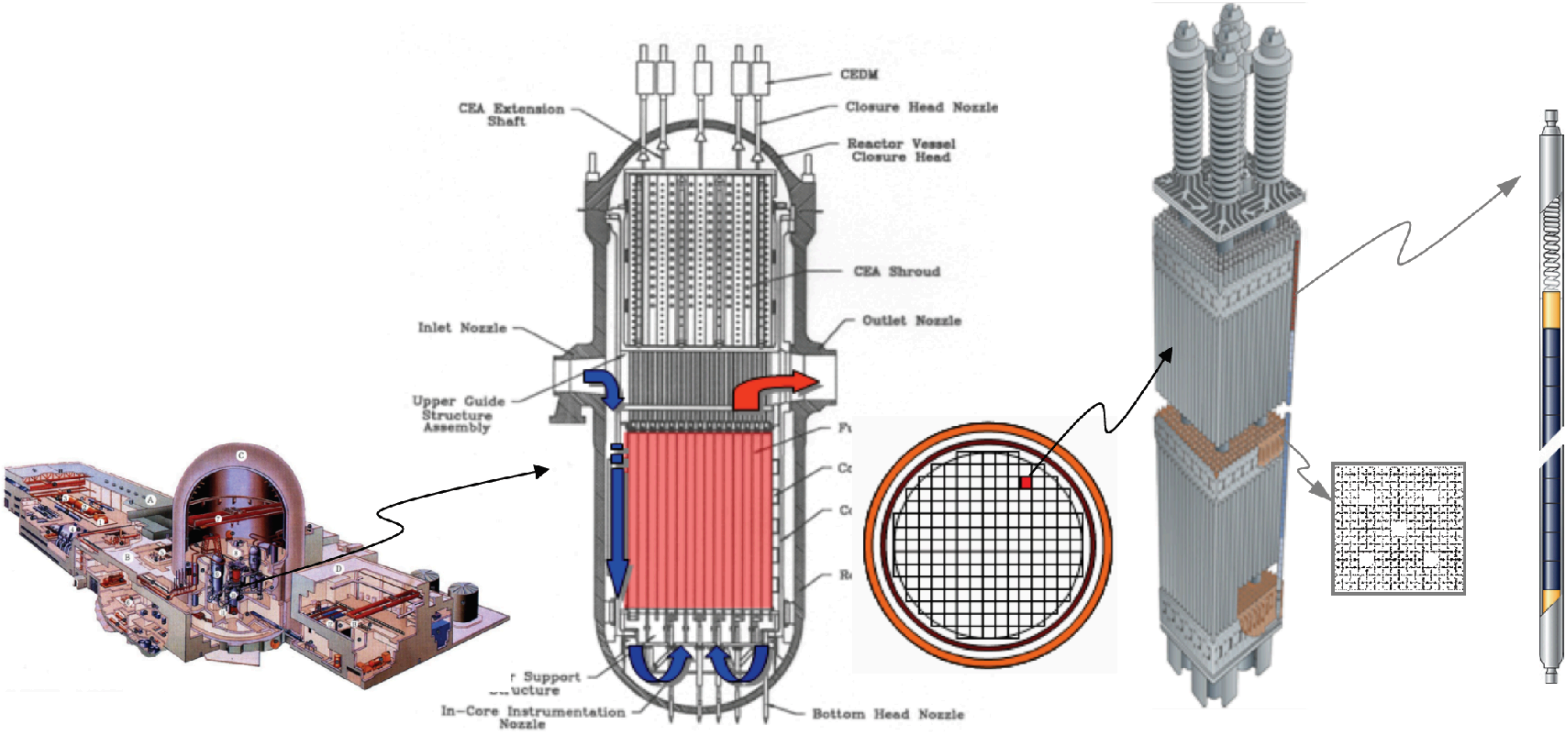
- Neutrino Experiment for Oscillation at Short baseline,
- Test of RAA and search for active-to-sterile neutrino oscillation with $\Delta m^2 \sim 1\ \mathrm{eV}^2$,
- Project launched in 2011,
- Using a commercial reactor core and 1000 L of homogeneous Gd-loaded liquid scintillation detector,
- Phase-I data taking: Aug 2015 ~ May 2016,
  Phase-II data taking: Sep 2018 ~ Now (~ Summer 2020),
- 20 collaboration members from 7 institutes.

Experimental site



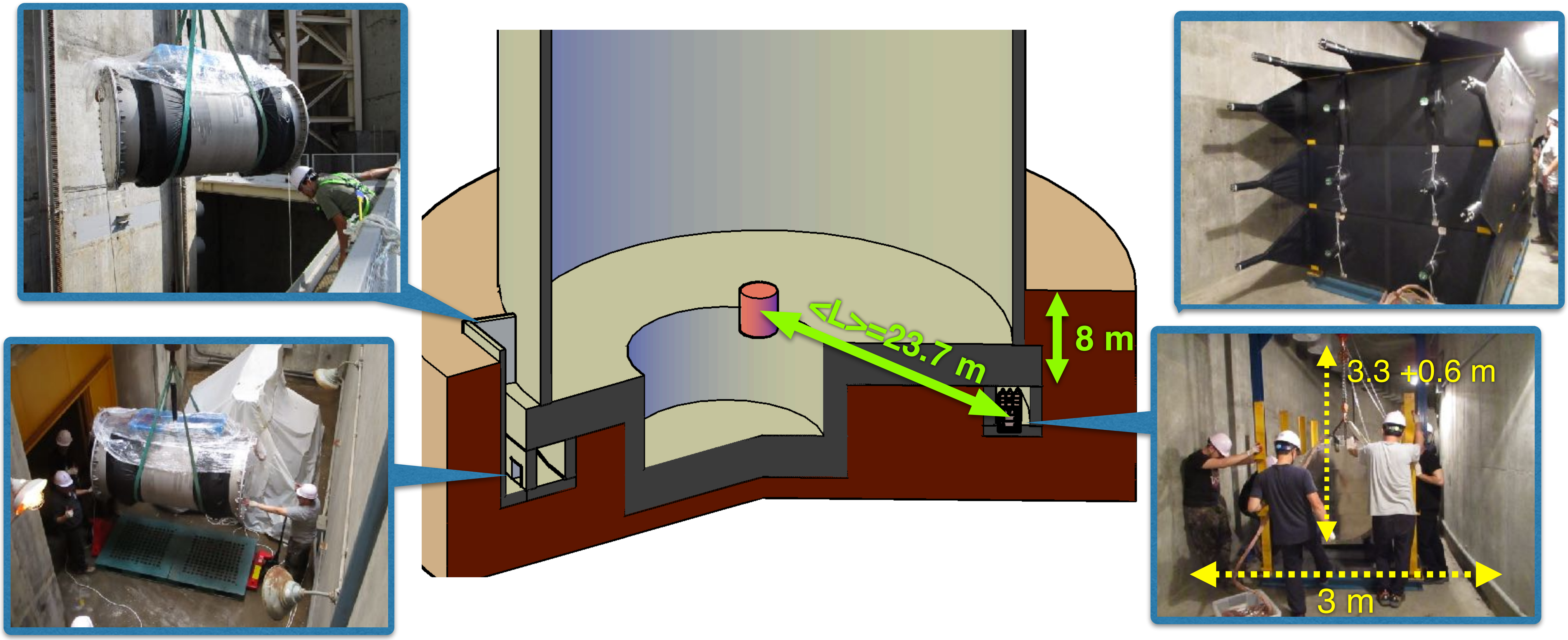
- Hanbit-5 reactor, Yeonggwang (靈光, ghost light), Korea,
- Distance between neighboring cores: 256 m (less than 1% contribution from each of them; 24 m between Hanbit-5 and the NEOS detector),
- Same reactor complex used for RENO experiment

Active reactor core



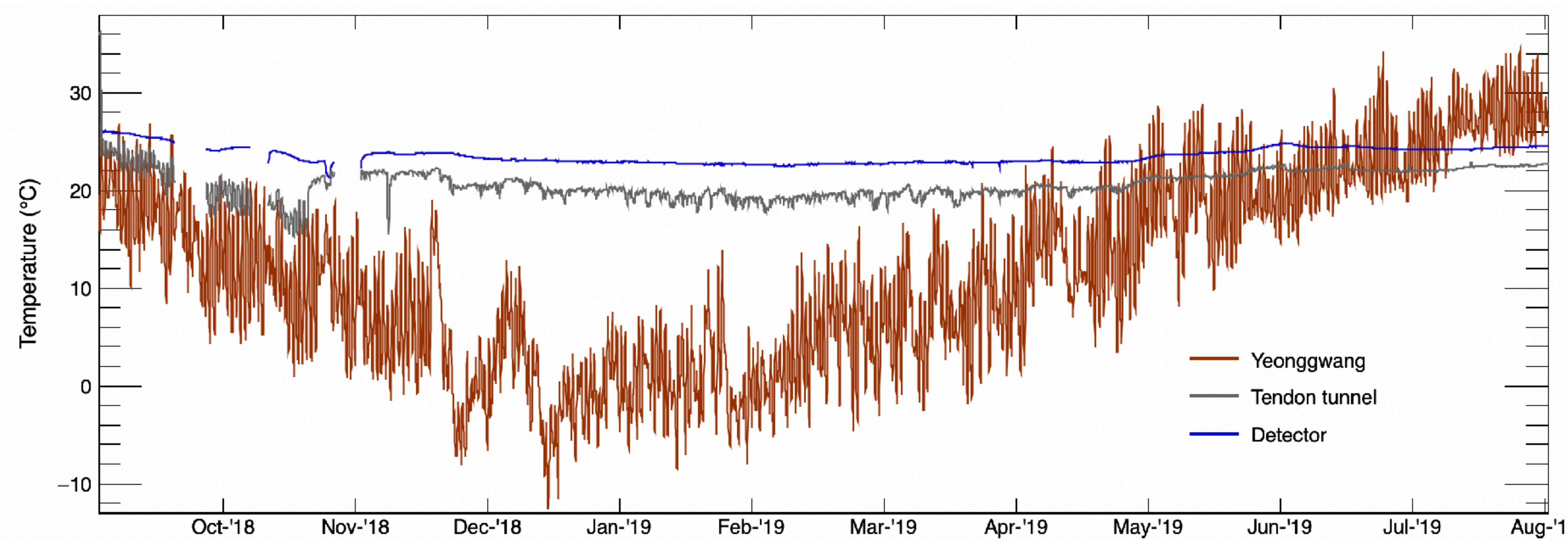
- •OPR-1000 reactor, 2815 MWth
- •177 fuel rod assemblies, low enriched uranium-235 (LEU).
- •Refueling by changing ~1/3 of fuel rods for each burn-up cycle (~1.5 year)
- •Active core size: 3.1 m (ϕ), 3.8 m (h)

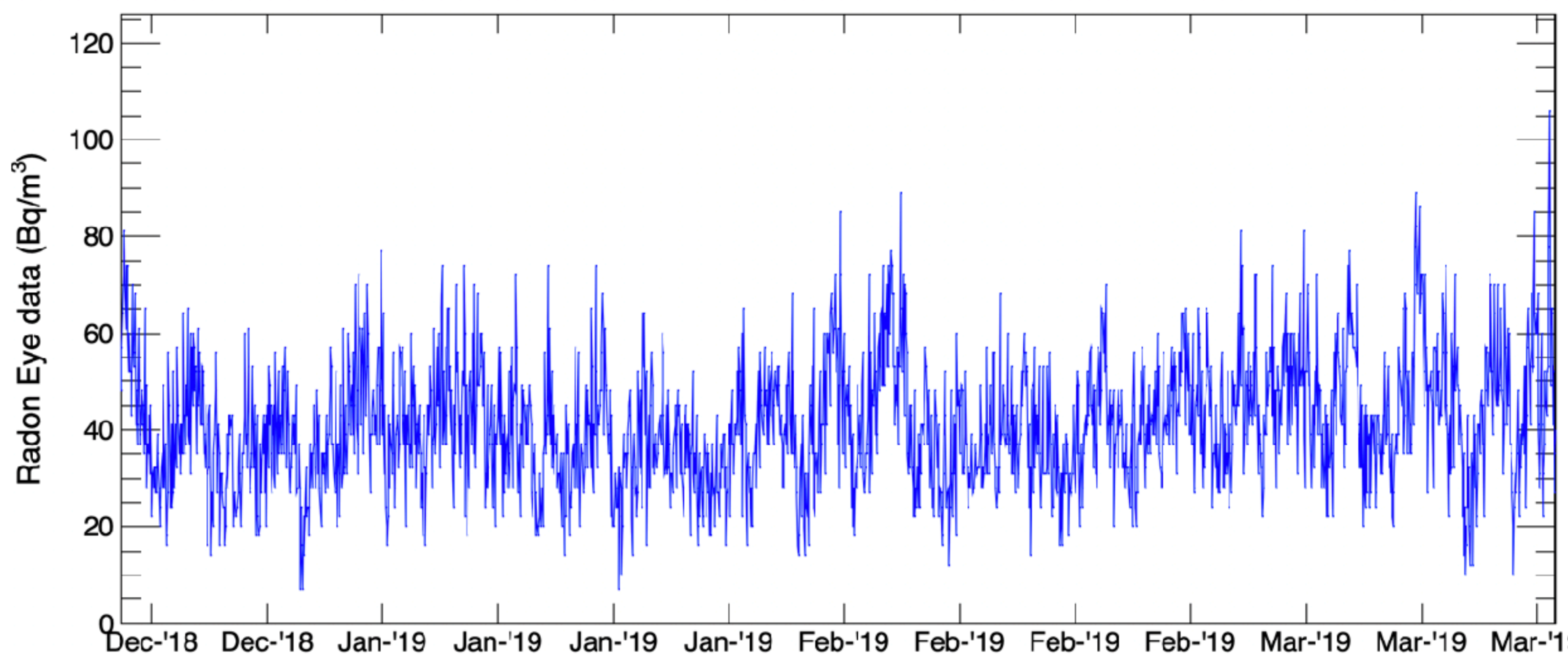
Tendon gallery



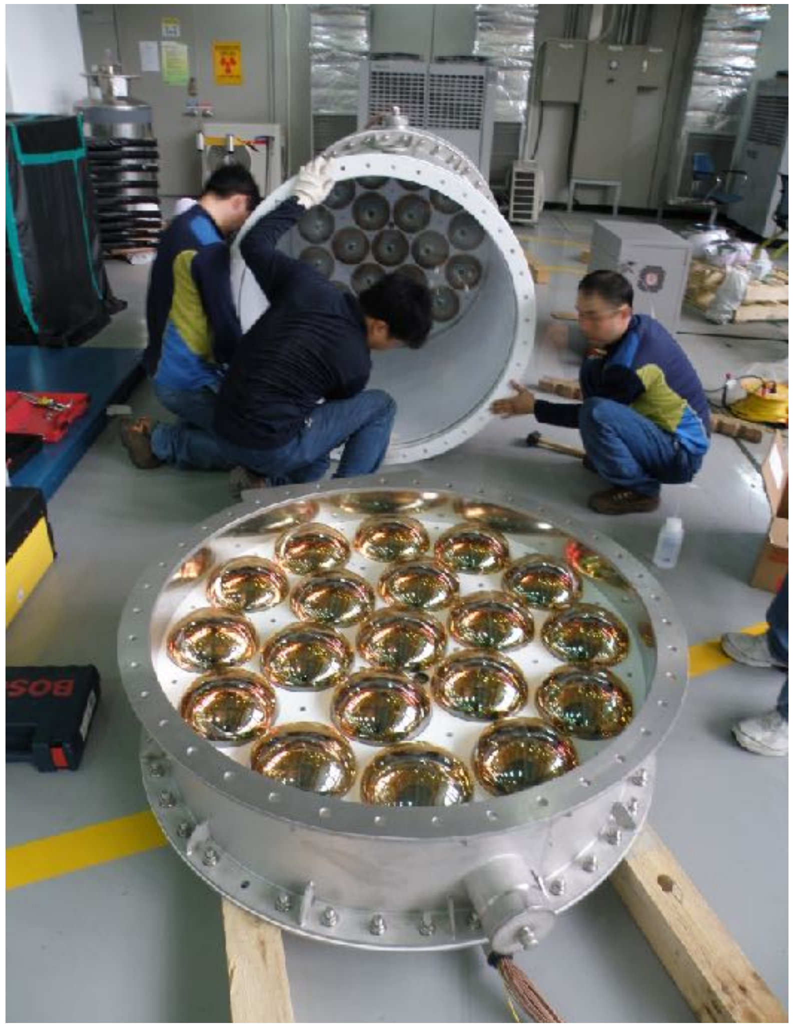
- Not a radioactivity controlled area: no background related to reactor operation,
- Muon rate: about 1/5 of surface (~0.17 μ/cm^2/min),
- Maintenance work every 5 years.

Environmental condition





NEOS detector



Homogeneous 1000 L
(Φ103 x L121 cm) volume,
0.5% Gd-doped LS,
90% LAB+ 10% UG-F,
seen by 2 x 19 8-inch PMTs,
PTFE reflector on inner walls.

10 cm thick B-PE,
10 cm thick Pb
for passive shieldings.

Muon counter:
3(5)-cm thick plastic scintillator
panels surround the most outside
except for bottom.

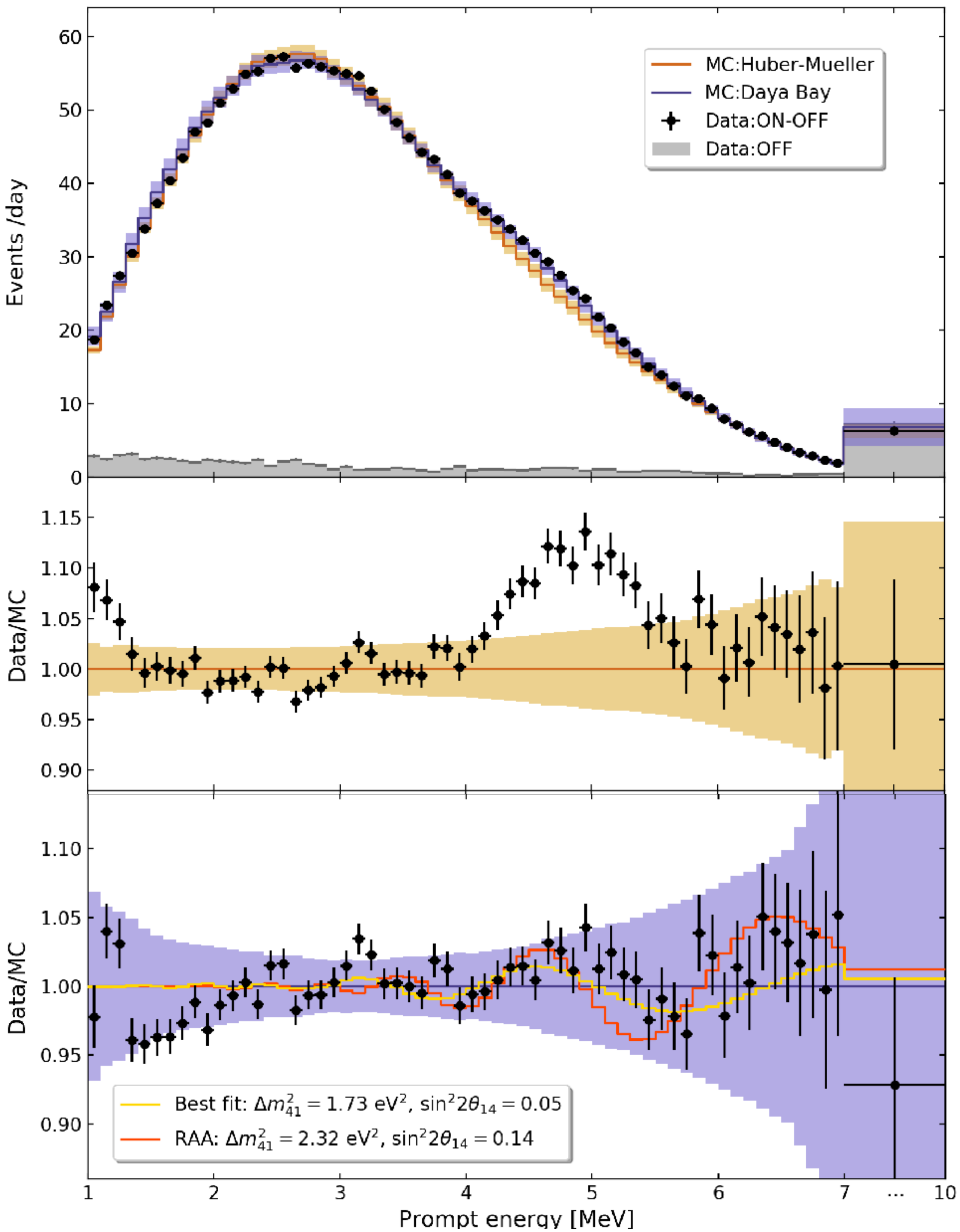
Data acquisition with

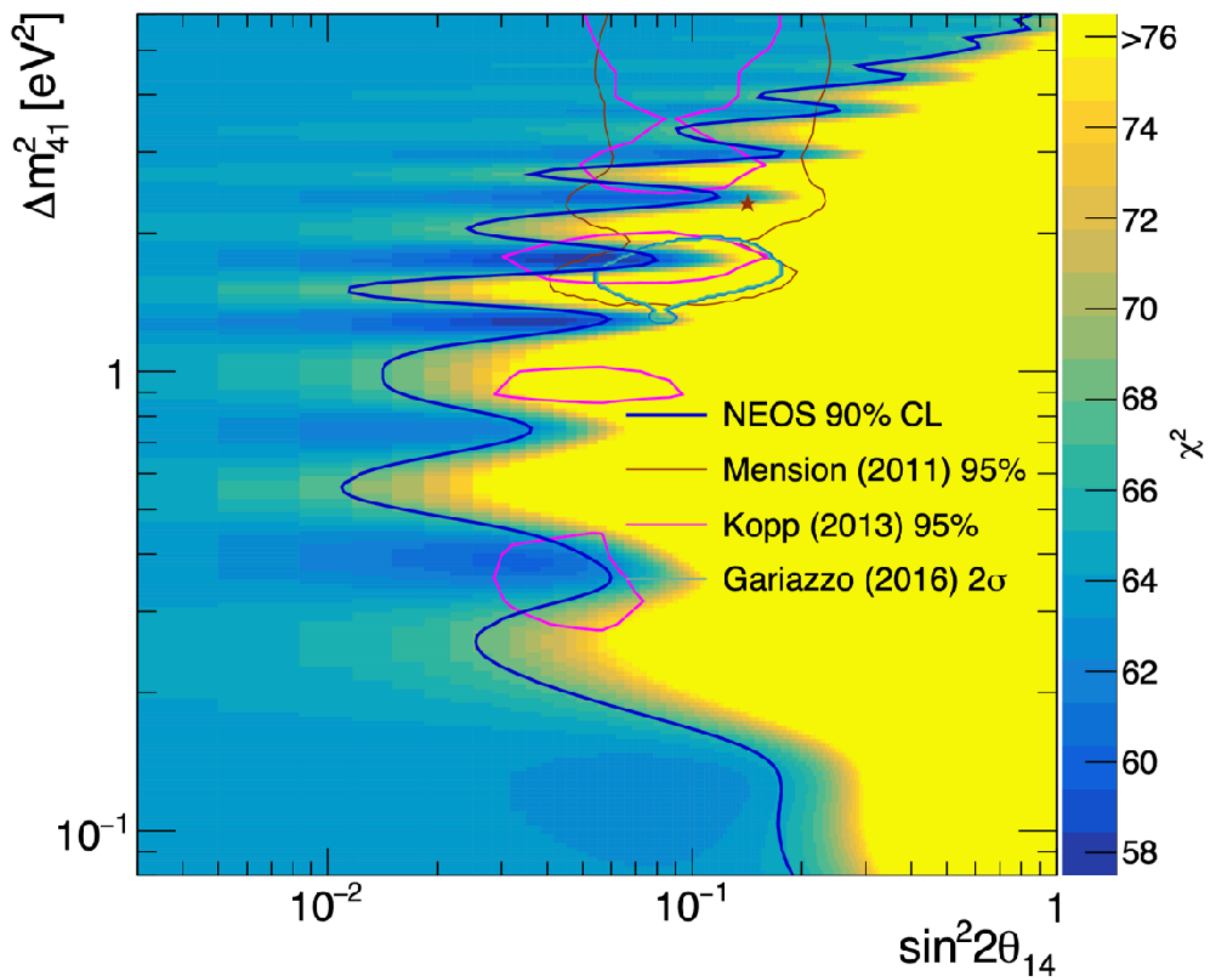
- 500 mega-sampling/sec FADC for target PMTs
- 62.5 mega-sampling/sec ADC for muon counter PMTs.

Slow monitoring: temperatures, radon level, PMT HVs.

Phase-I result

PRL 118 (2017) 121802





- LEU reactor, 24 m distance.
- The 5 MeV bump is there.
- Found no strong evidence of active-to-sterile oscillation, compared to Daya Bay spectrum.

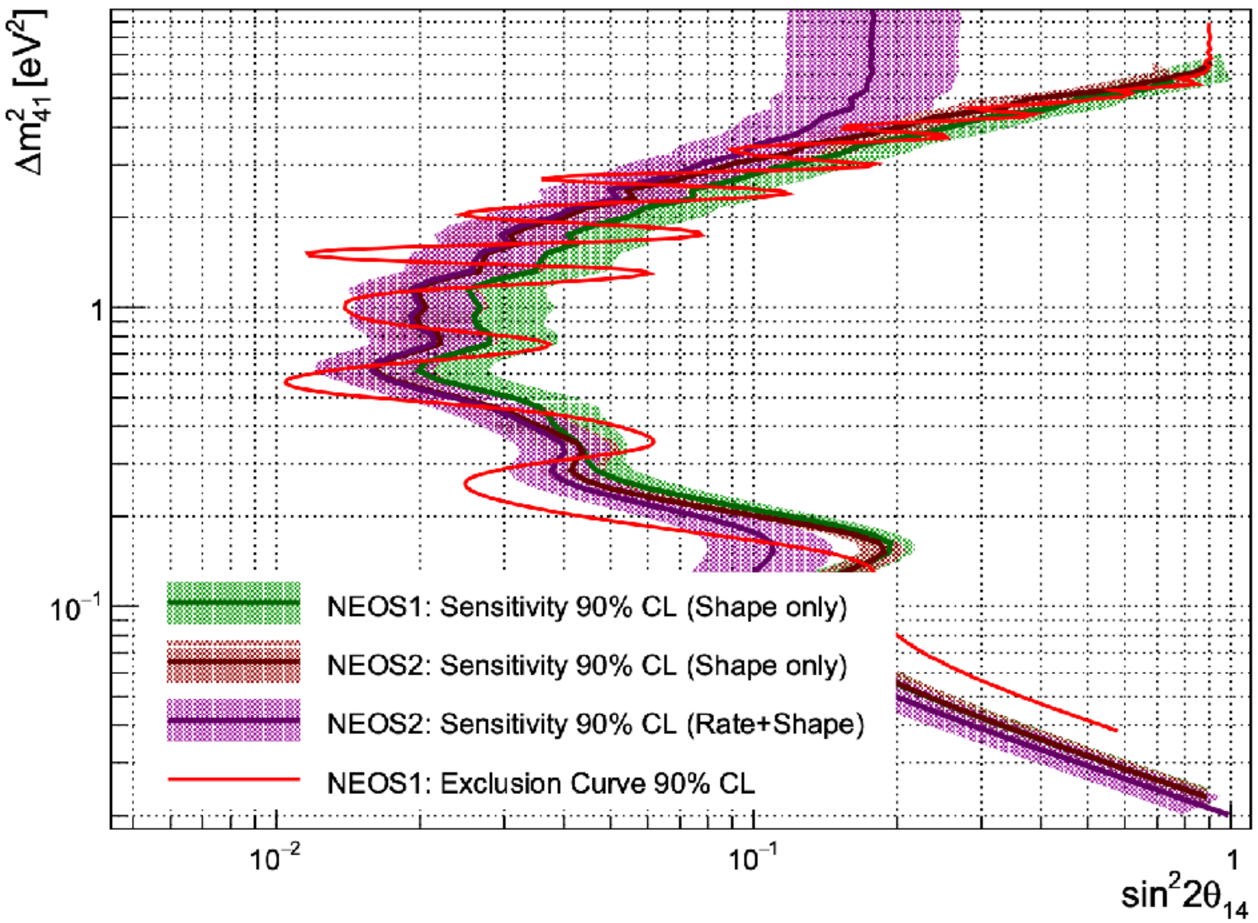
NEOS phase-II

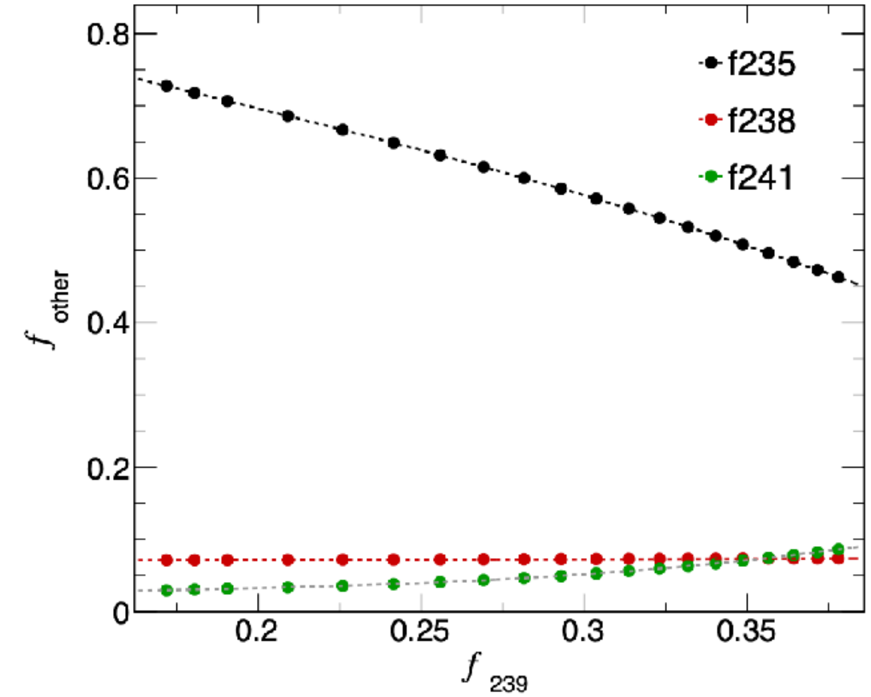
- Shape + rate analysis for sterile neutrino search, and/or,
- Precision measurement of the spectrum itself.
- Spectrum evolution with the fission fraction change.

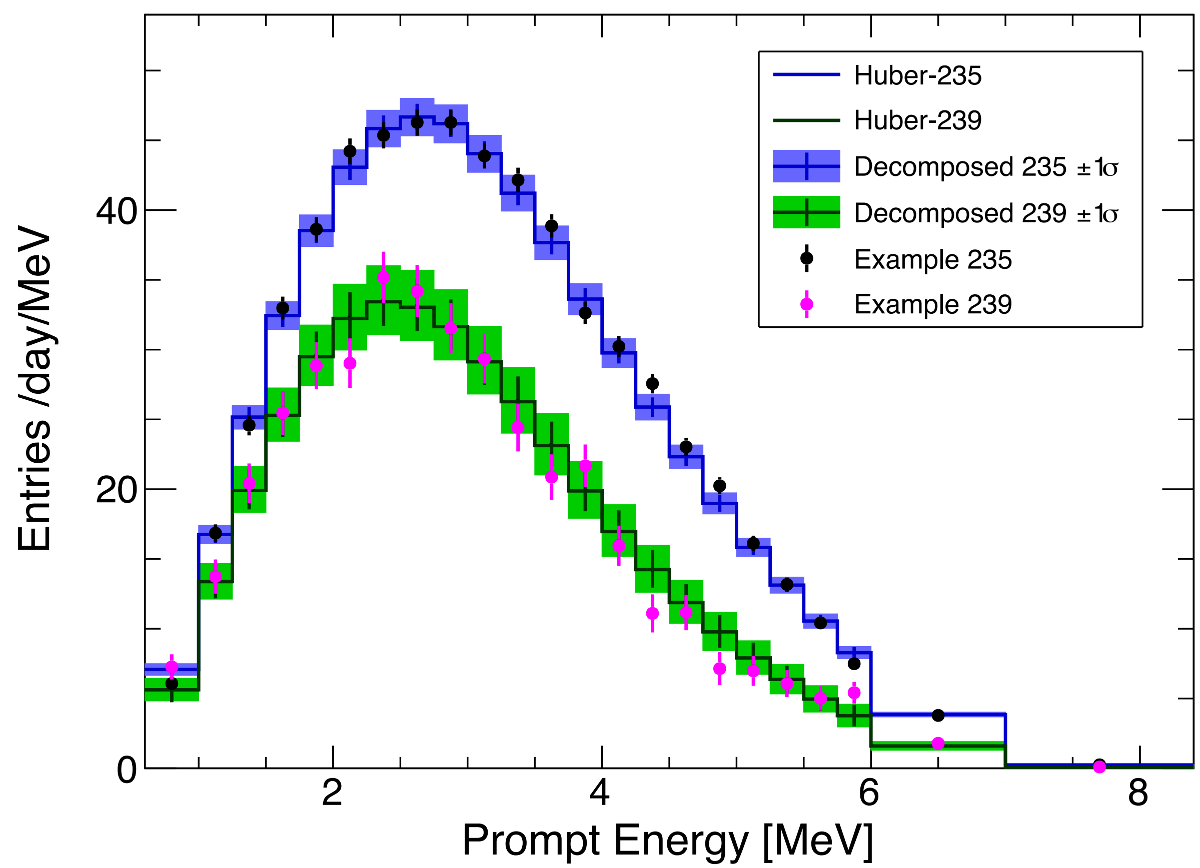
- Measuring a full operation cycle (~500 calendar days) + two background periods before/after the cycle (~100 days).
  - Phase-I: 46 days OFF + 180 days ON as DAQ livetime.
- Same detector, same reactor and same baseline as in phase-I.
  - Newly produced Gd-LS,
  - Minor modifications: leak-proof maintenance, muon counter plastic scintillator.

- Data taking started in September 2018.

NEOS phase-II

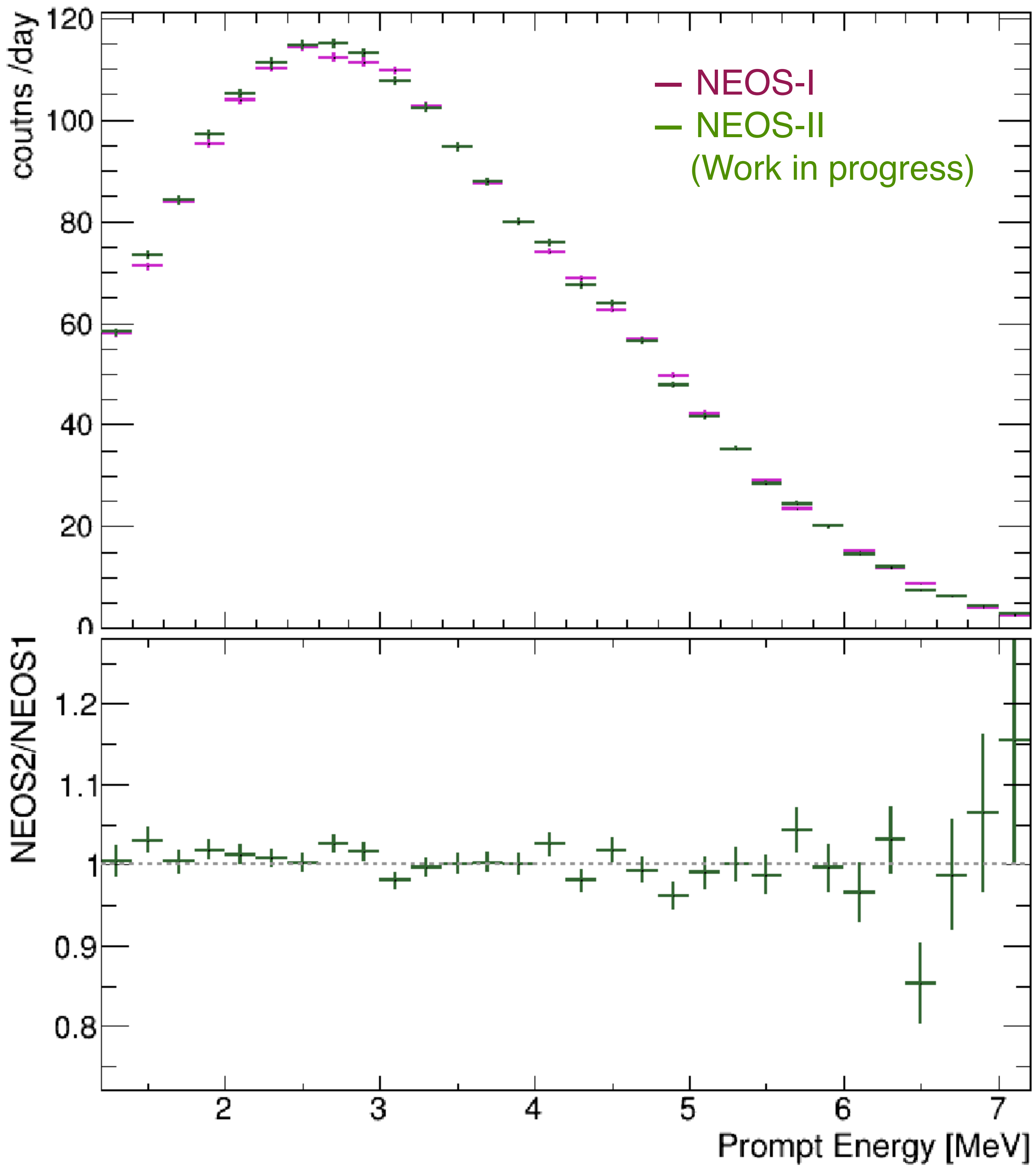






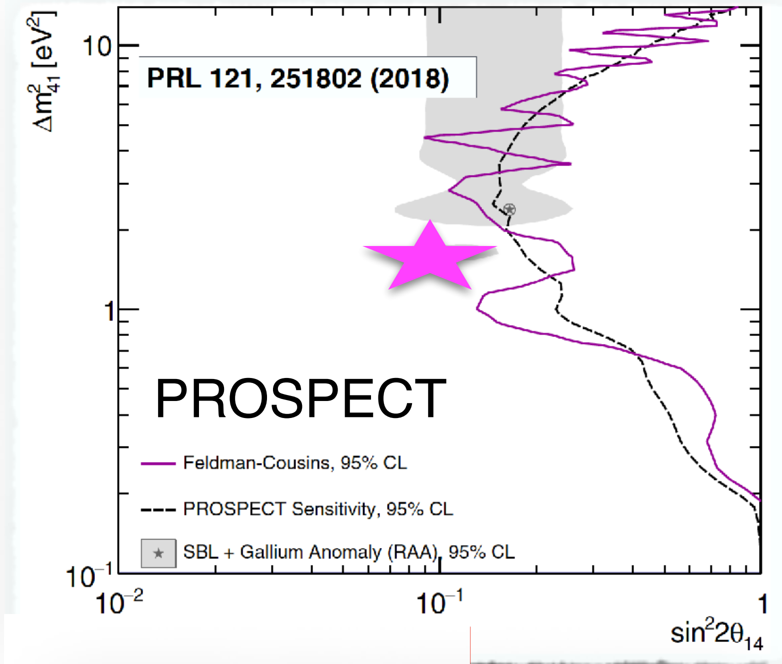
- Not a dramatic improvement of eV sterile neutrino search sensitivity,
- Decomposition of U/Pu spectra, benefitted by large fission fraction changes in a single LEU reactor.

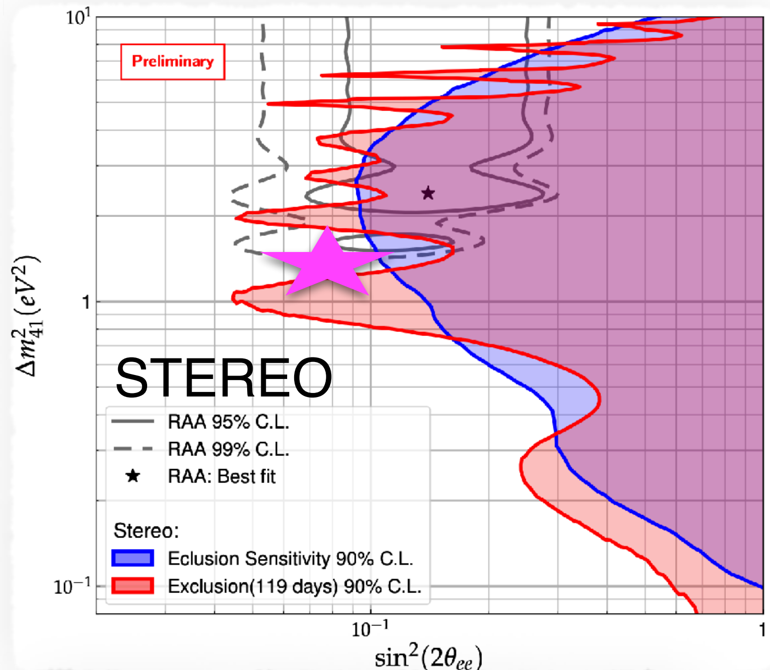
NEOS phase-II

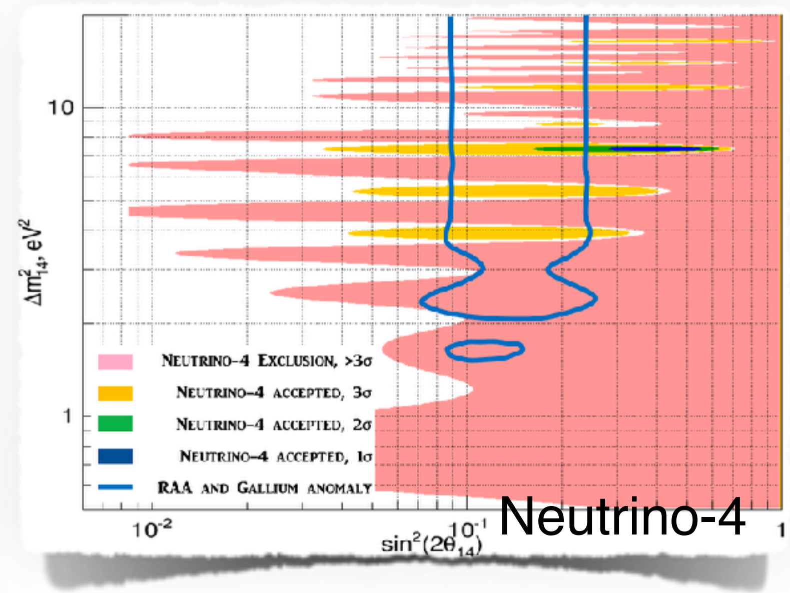


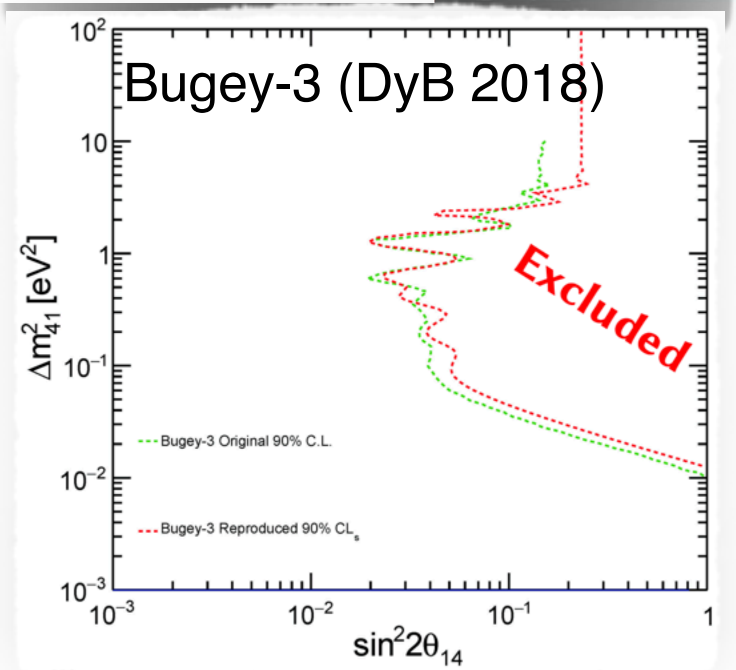
- On about half of planned data taking:
  - the second half of the fuel cycle and another maintenance period (~100 days) to measure.
  - measurement will be completed in Summer 2020.
- Monte Carlo simulation is being revised:
  - light-energy non-linearity,
  - n-Gd capture, etc.

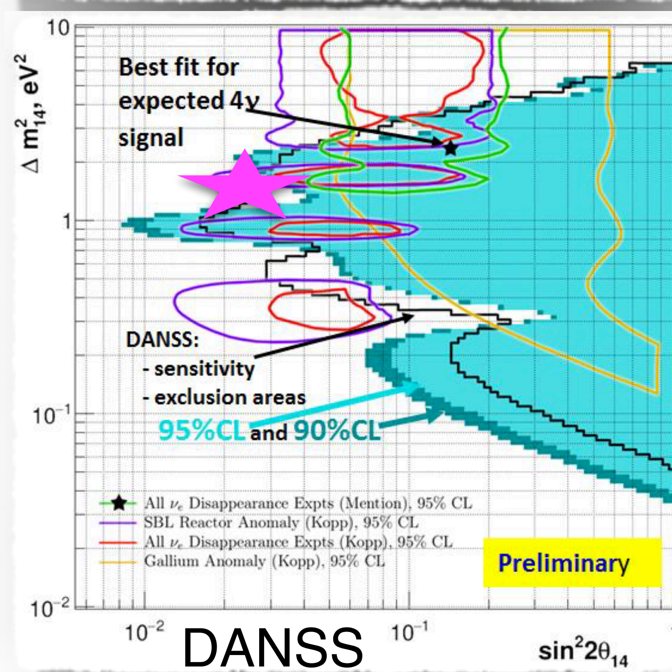
Reactor SBL together

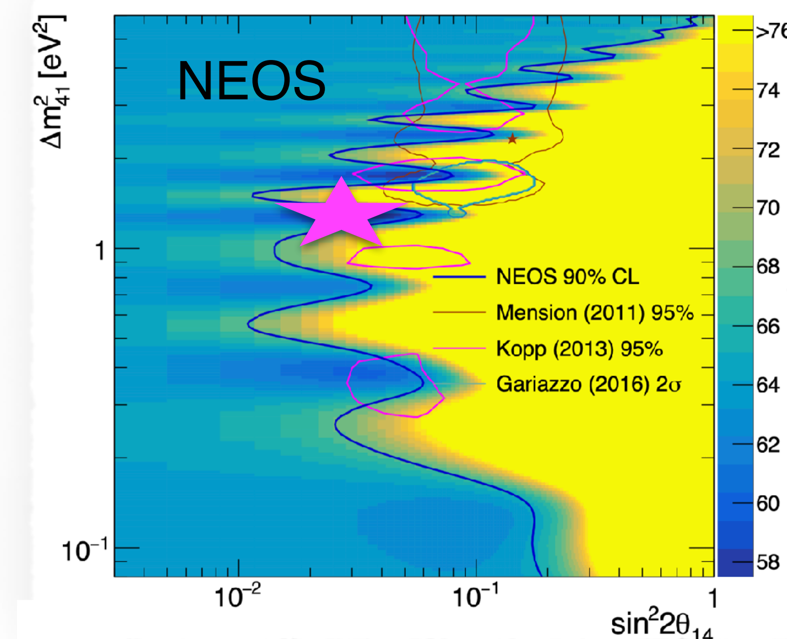












- The original RAA best fit values (0.14, 2.3 eV^2) are disfavored.
- Except for neutrino-4 (?), we share similar bays and capes around 1 eV^2.
  - Different detectors at different reactors, model dependent or independent.

Summary and closing

- Experimental efforts to find active-to-sterile neutrino oscillation with $\Delta m^2 \sim 1$ eV^2 are in progress.
- No strong positive signals, but interesting similarity.
- Sensitivity for $\sin^2 2\theta \lesssim 10^{-2}$ at reactor?
- Precision measurements of reactor spectra with different fuel elements compositions are also valuable.