Review on eV-Scale Sterile Neutrino Searches at Short Baseline

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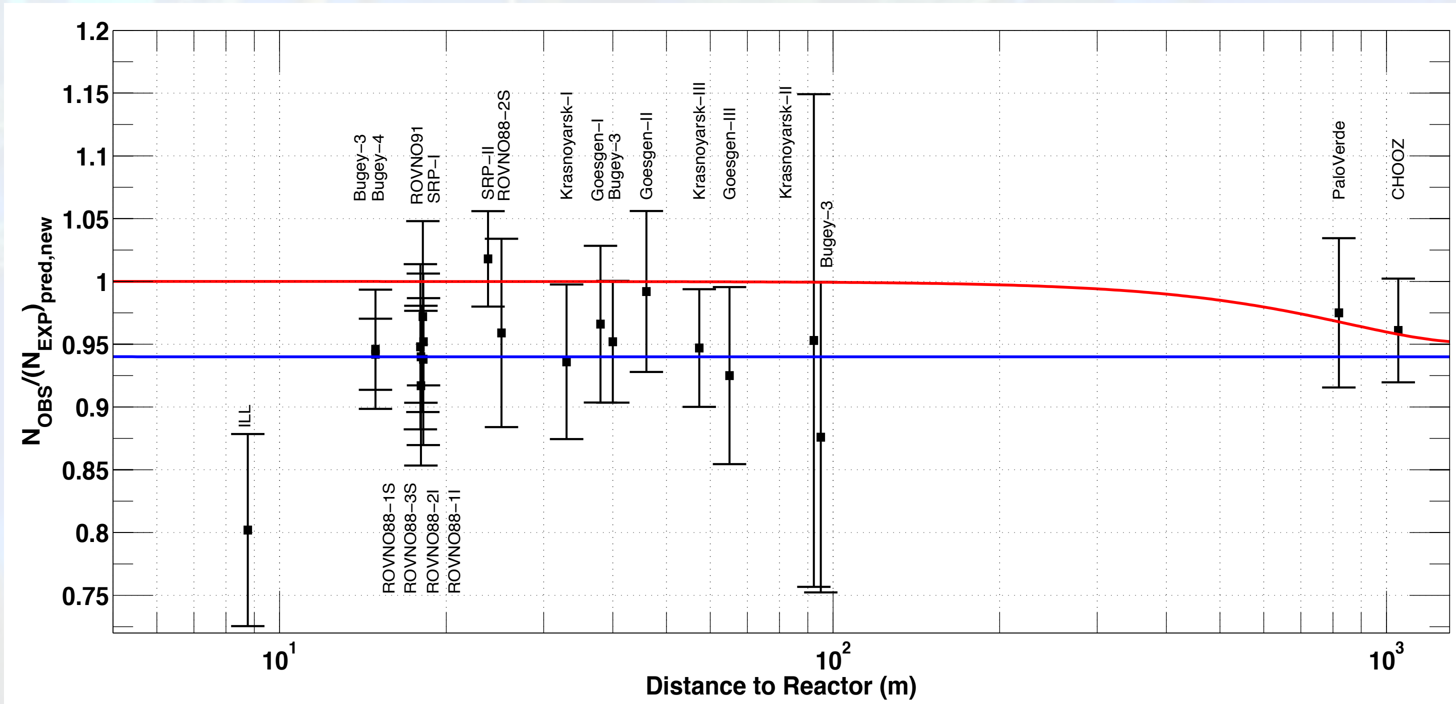
12th Rencontres du Vietnam - NuFact



Reactor Antineutrino Anomaly

- New computation of $\bar{\nu}$ **spectrum** for Double Chooz arXiv:1101.2755 → 5% precision and **~6% excess wrt results from previous reactor experiments = RAA**



- Possible explanations
  - Errors in previous experiments
  - Problems in the anti-neutrino spectrum prediction
  - **Oscillation with a sterile neutrino in the eV Δm^2 scale**

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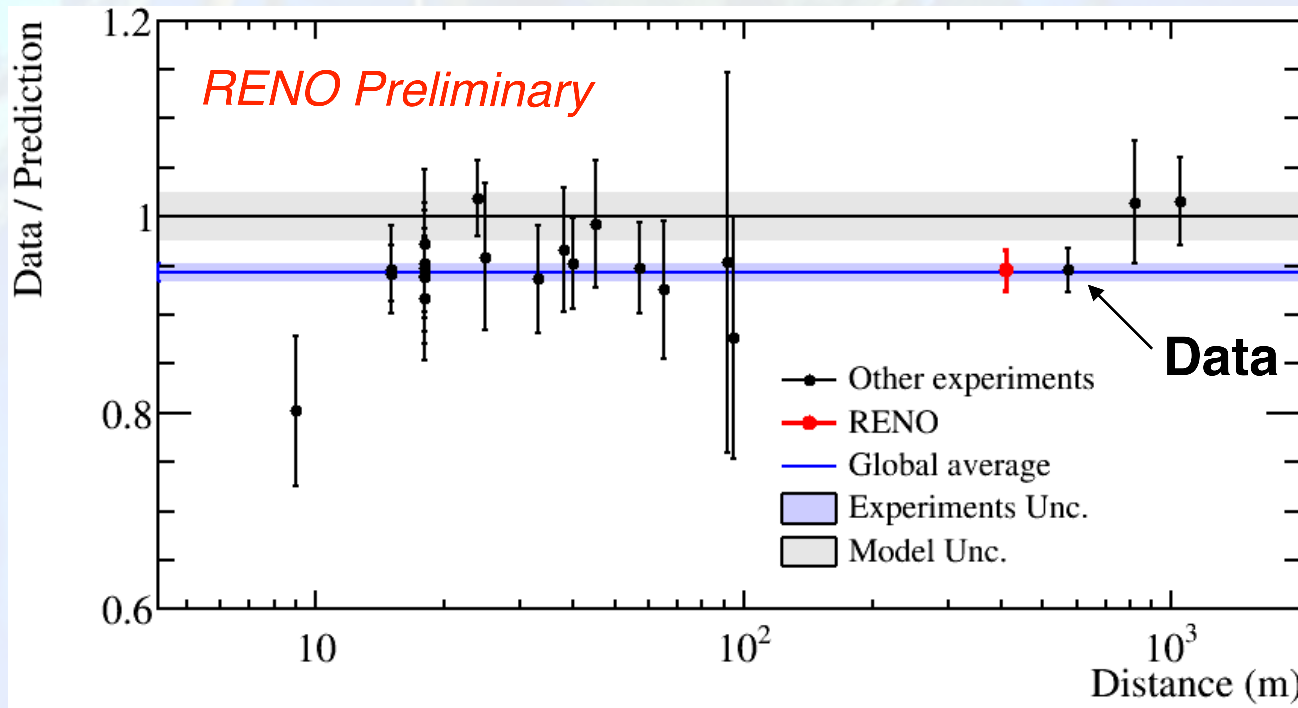


Data Bay arXiv:1508.04233

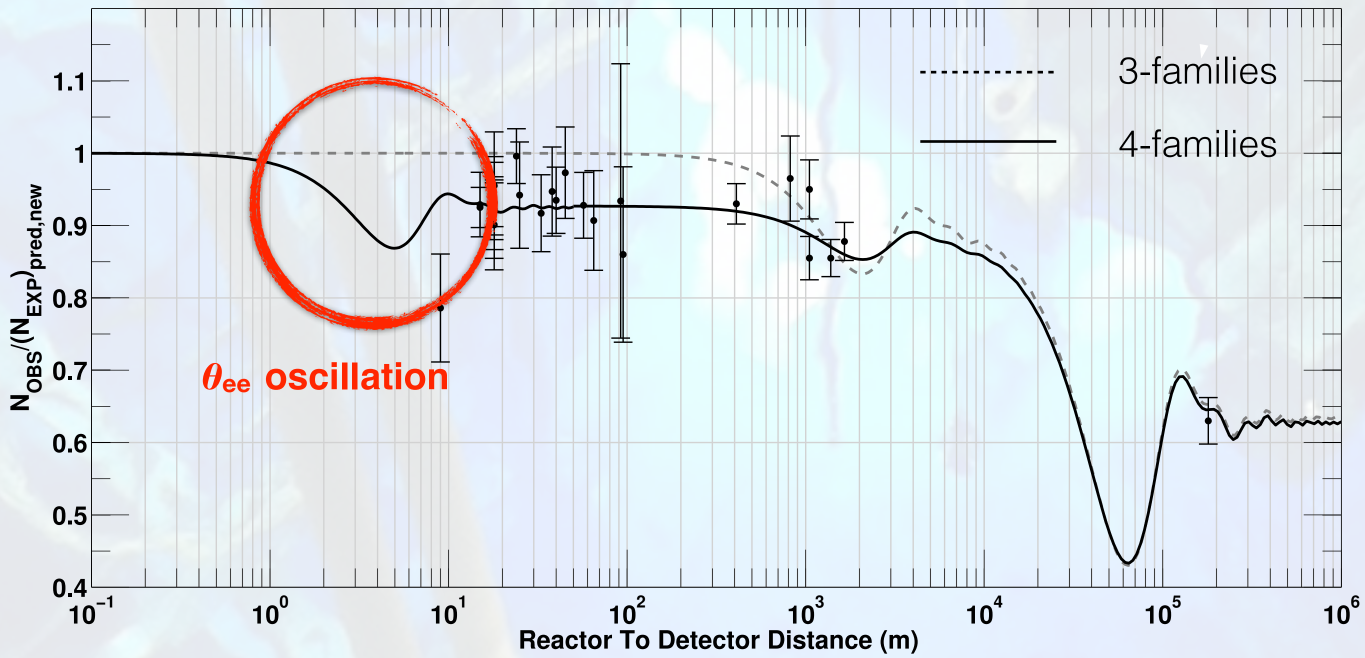
- Possible explanations
  - ~~Errors in previous experiments~~
  - Problems in the anti-neutrino spectrum prediction
  - **Oscillation with a sterile neutrino in the eV Δm^2 scale**

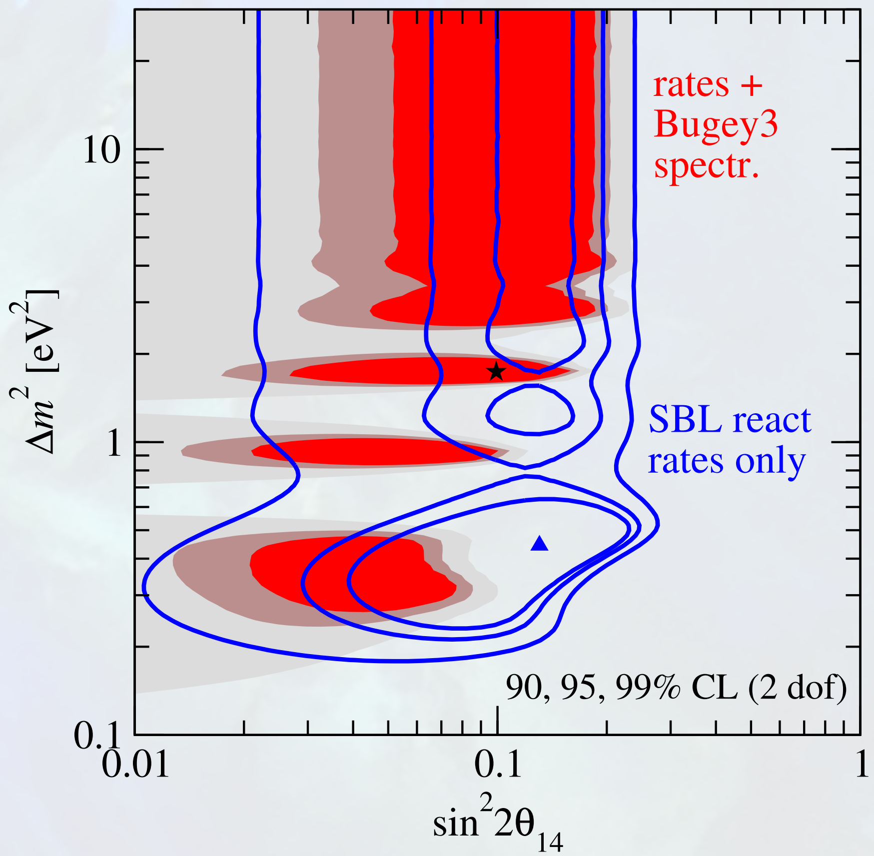
- Data Bay and Reno confirmed the anomaly (reactor related)

Light Sterile Neutrinos

- If we add a 4th neutrino with a 0.1-1 eV mass, @ very short baseline

$$P_{\nu_e \to \nu_e} \simeq 1 - \sin^2(2\theta_{ee}) \sin^2(\Delta m^2_{14} L/4E)$$



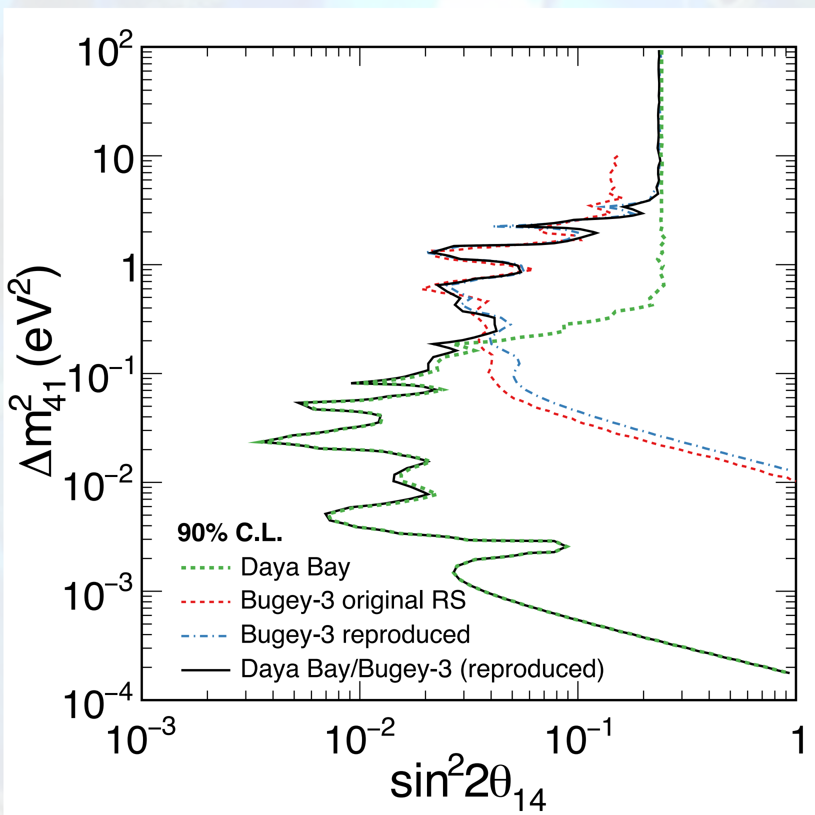


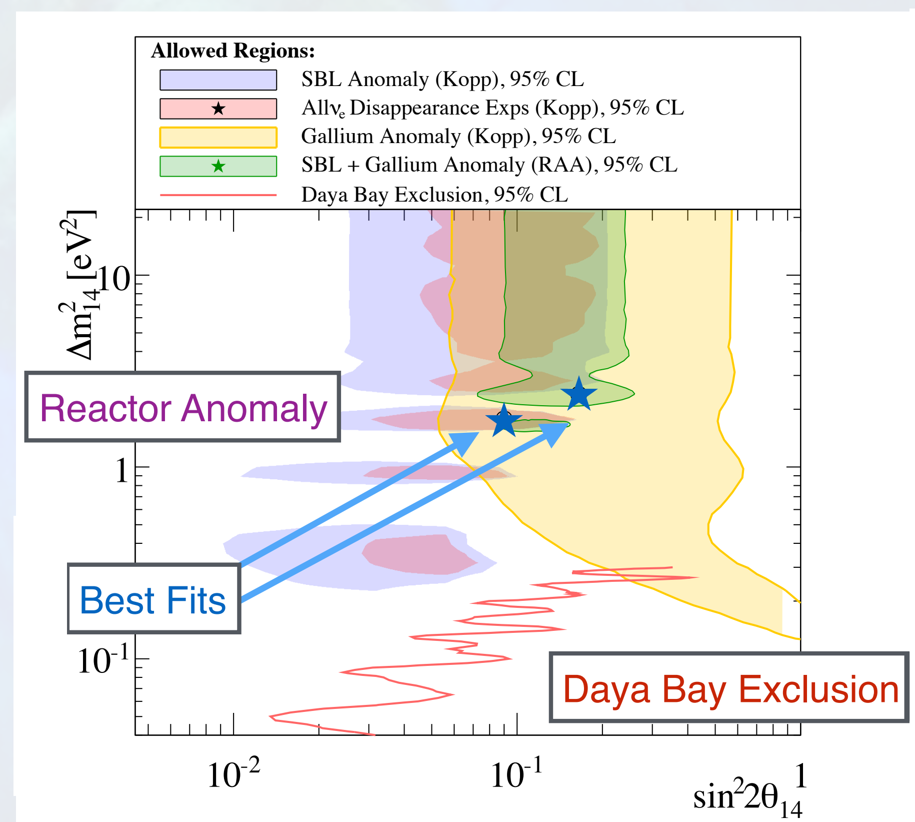
- **The existence of an ~eV sterile neutrino is supported by other anomalies** (LSND, MiniBooNE, Gallium anomaly)

- …but a global simple answer is **disfavoured by disappearance results**

Limits from Daya Bay + Bugey

- Current reactor neutrino experiments (Double Chooz, Daya bay, Reno) are little sensitive to a Δm^2~eV-driven oscillation (see accurate θ_{13} measurements)
- Nonetheless, Daya bay was was able to produce an exclusion plot combining results with Bugey-3

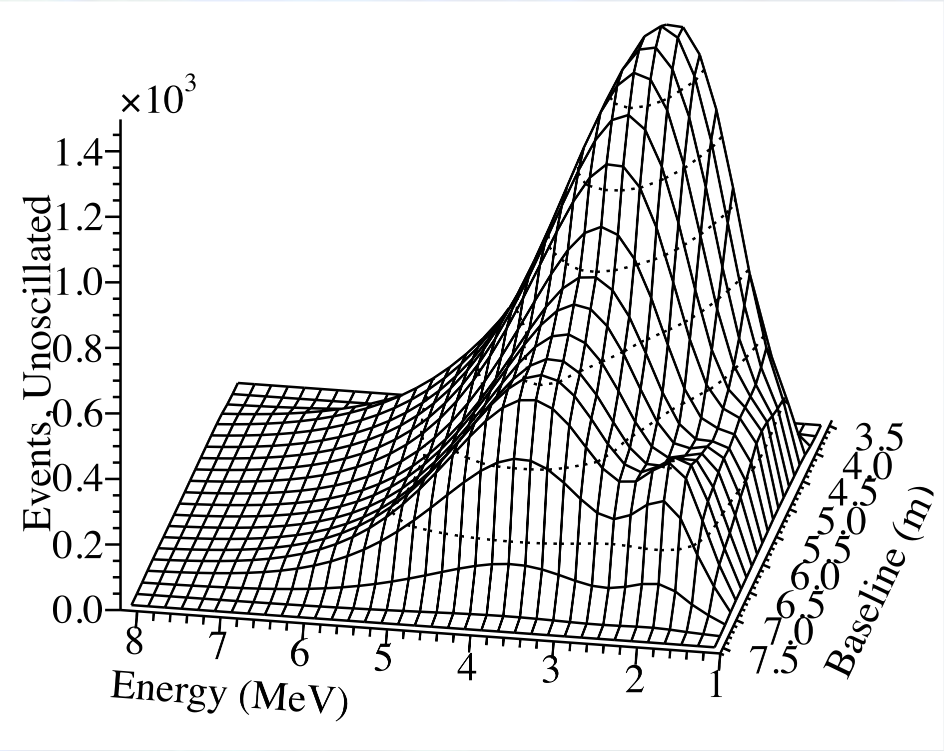




- To be more sensitive to the RAA, **need to go closer and see the oscillation**

Sterile Neutrino Search @ Very Short Baseline

- With…
  - **A source of neutrinos**
    - ✦ Reactor (pure $\bar{\nu}_e$)
    - ✦ Powerful radioactive source (ν_e or $\bar{\nu}_e$)
  - The capability to **measure the rate at different** (very short) **baselines**
    - ✦ Movable detector
    - ✦ Segmented detector or precise enough vertex reconstruction



arXiv:1212.2182

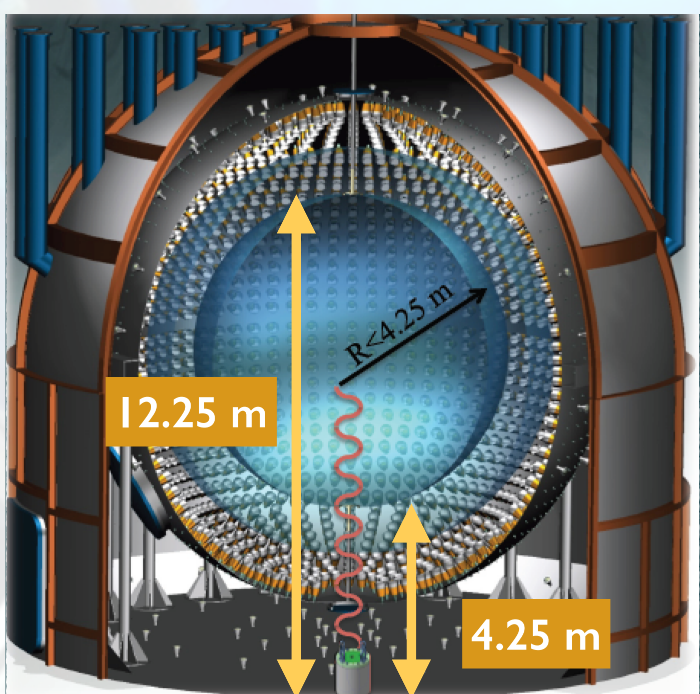
- …you can **confirm (disproof) the oscillation @ Δm²~1eV if you observe (not observe) a significant**
  - ✦ **Deviation from the $1/R^2$ flux variation (rate)**
  - ✦ **Distortion in the energy spectrum @ different distances (shape)**

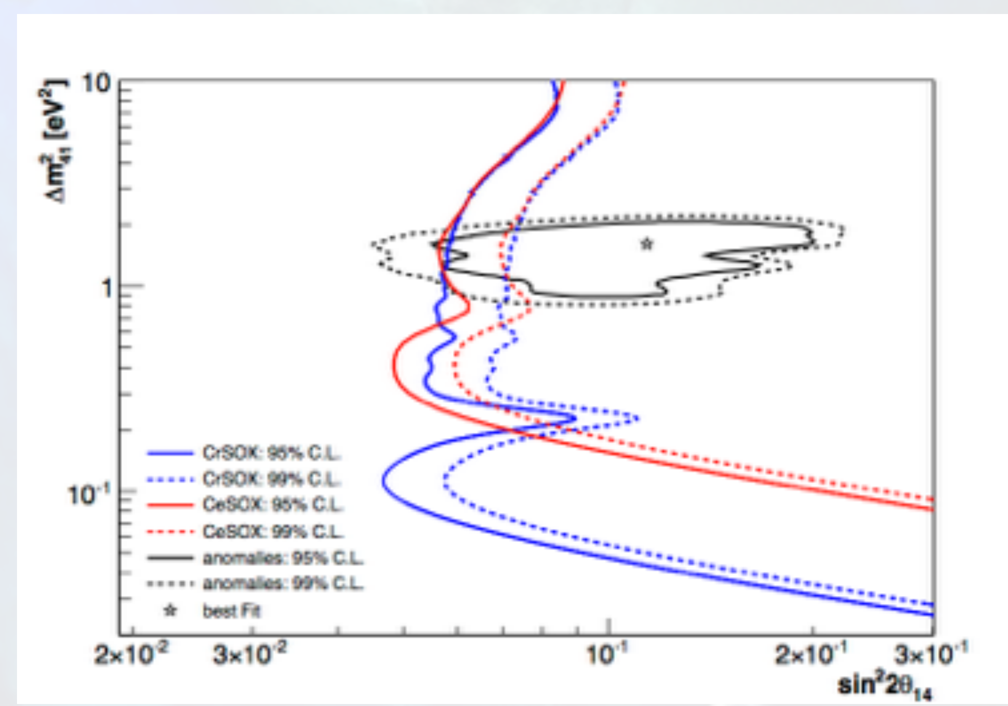
Sterile Neutrino Search with Sources: SOX

- **Main challenges for reactor $\bar{\nu}$ @ very short baseline: cosmic (surface level) and reactor-induced background**

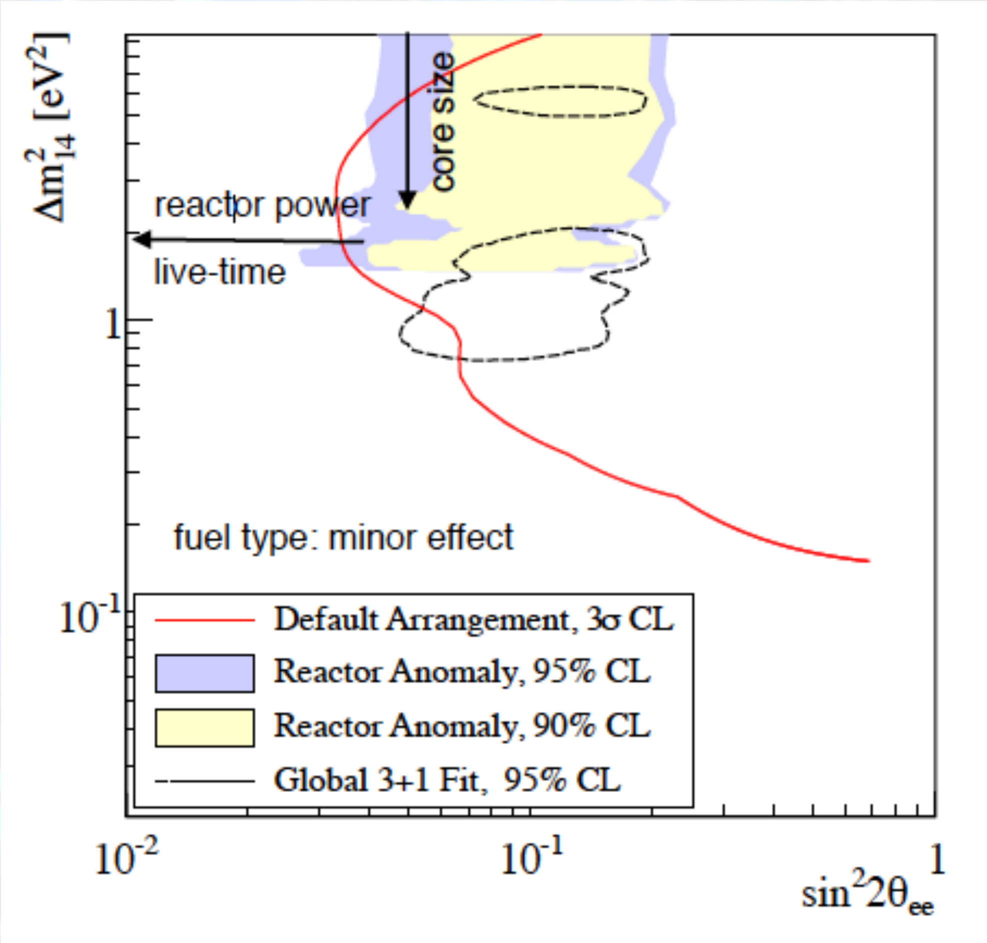
- **A ν source inside an underground detector** profits from strong **bkg suppression**, but is **not as powerful as a reactor** (up to the PBq compared to $10^{17}\,\bar{\nu}_e$/s MW_{th})

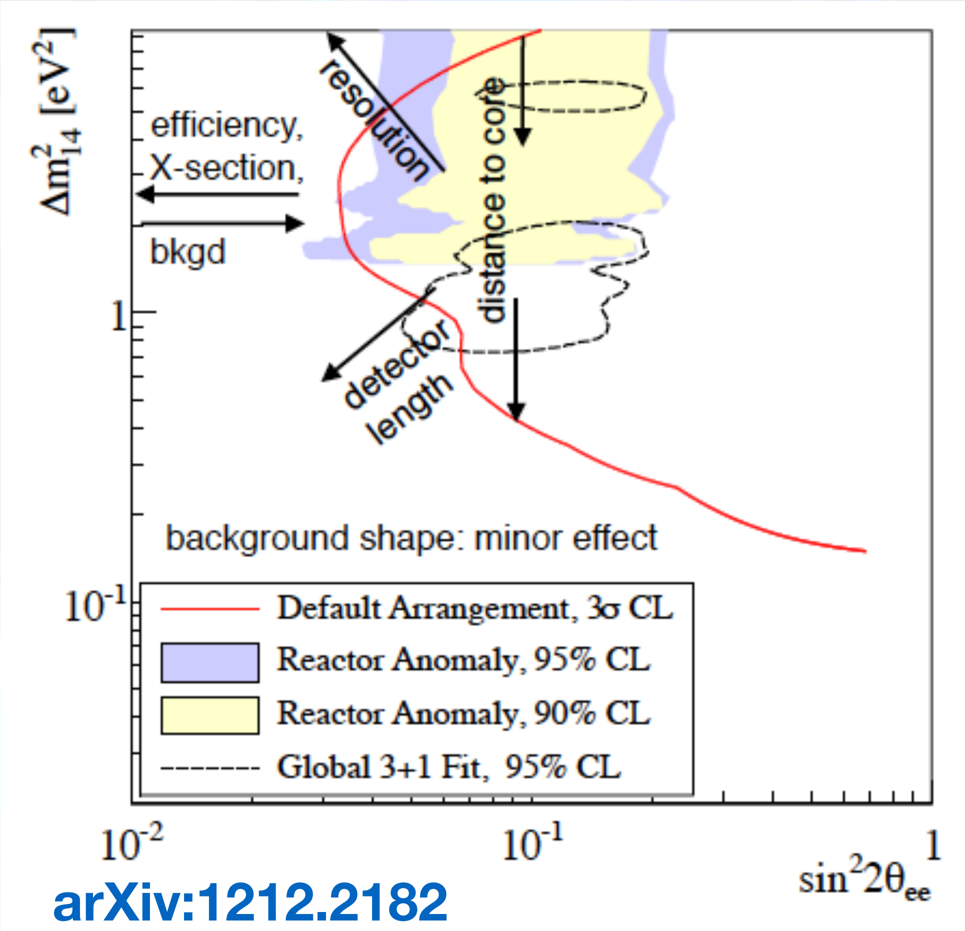
- **CeSOX uses ^{144}Ce and the BoreXino detector** (β^-, 285 days half life)
  - LS purification → quasi bkg-free experiment (10^4 IBDs/1.5 y vs ~1 accidental/y)
  - Good spatial (12 cm @ 2 MeV) and energy resolution (~3.5% @ 2 MeV)





Sterile Neutrino Search with Reactors

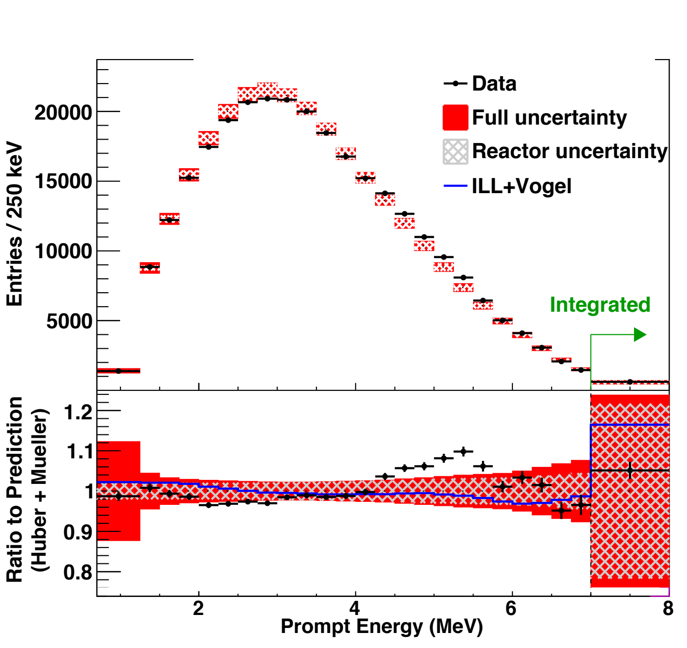




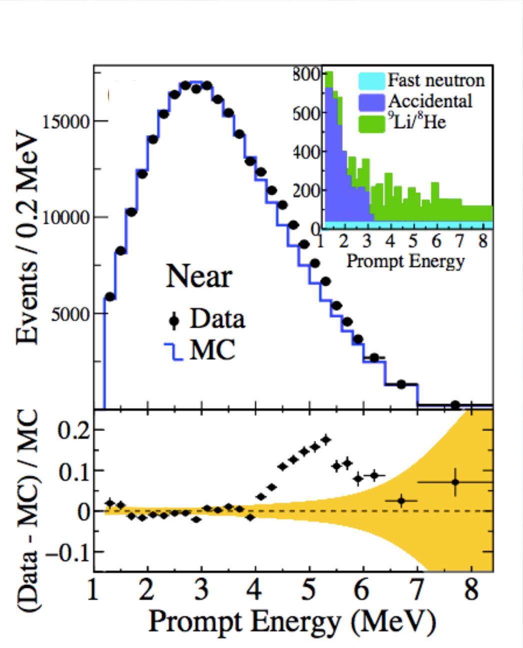
Compact-Core Research Reactors	**Commercial Reactors**
Shorter baseilne	Loose sensitivity on $\Delta m^2 \sim 1$ eV
Often HEU fuel	Fuel evolution (burnup)
$\sim 10^2$ MW thermal power	~GW thermal power
Less space / noise from reactor	Possibility of some overburden

Spectral Distortion @ 5 MeV

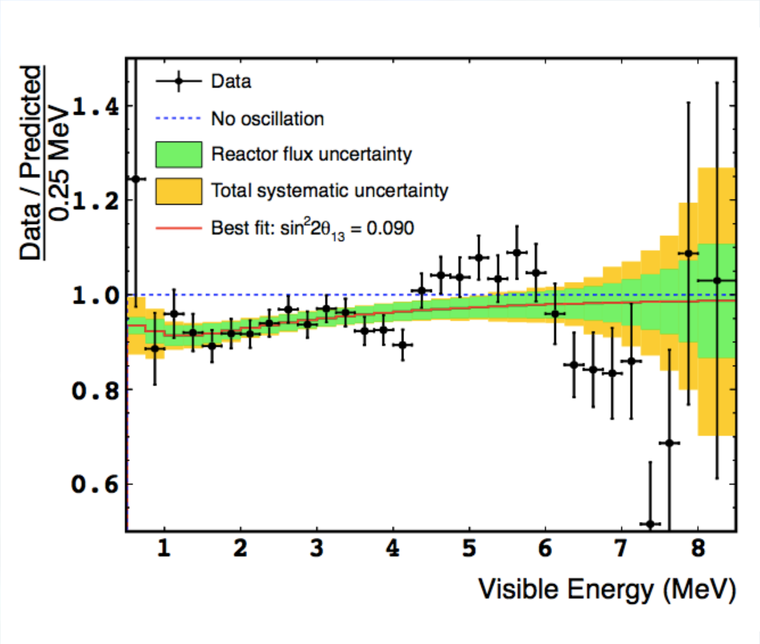
- **Anomalous spectral distortion @ 5MeV** in θ_{13} reactor neutrino experiments



arXiv:1508.04233

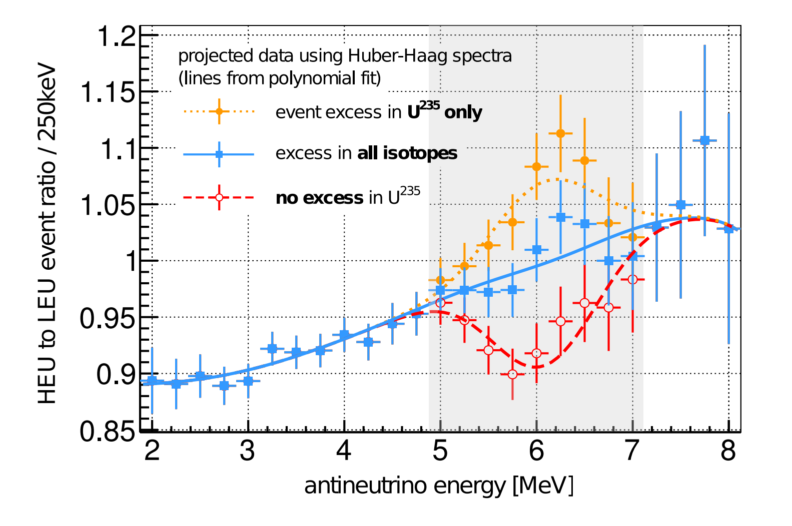


arXiv:1511.05849



arXiv:1406.7763

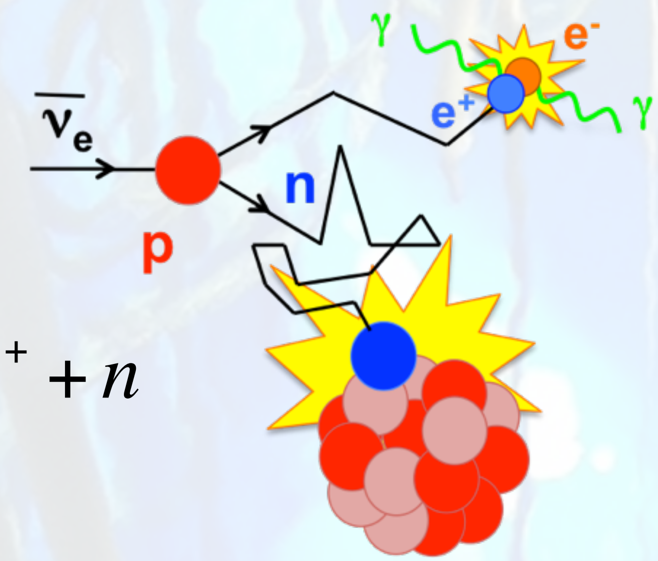
- **Accurate ^{235}U spectrum** measurement can
  - Help find out the **nature of the distortion**
  - Constrain existing reactor models



arXiv:15.12.xxx

Signal and Background

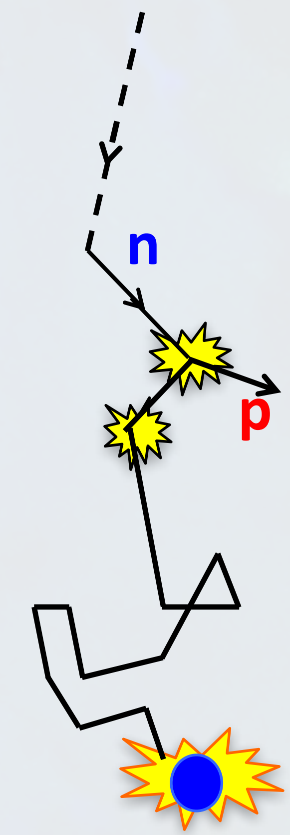
- **Signal: inverse beta decay (IBD)**



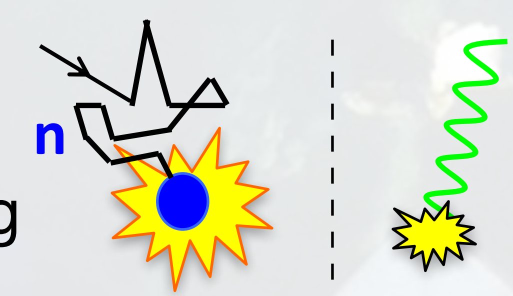
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- **Signature: two-fold coincidence**
  - Prompt: e^+ ionisation+annihilation (E_{e+} = 1-8 MeV, $E_\nu \simeq E_{e+}$ + 0.8 MeV)
  - Delayed: n-Capture
    - ✦ n+Gd→Gd*+γ's (8 MeV)
    - ✦ n+^{6}Li→α+^{3}H (4.78MeV)

- **Background: fast neutrons**
  - From cosmic μ spallation and reactor
  - Online rejection: overburden, active veto, PSD
  - Offline rejection: subtraction from reactor-off periods



- **Background: accidental coincidences**
  - Reactor related (n_{th} leakage, high-E γ's from n-capture on metals, ^{16}N, ecc.)
  - On-side measurements
  - Rejection with shielding and topological cuts



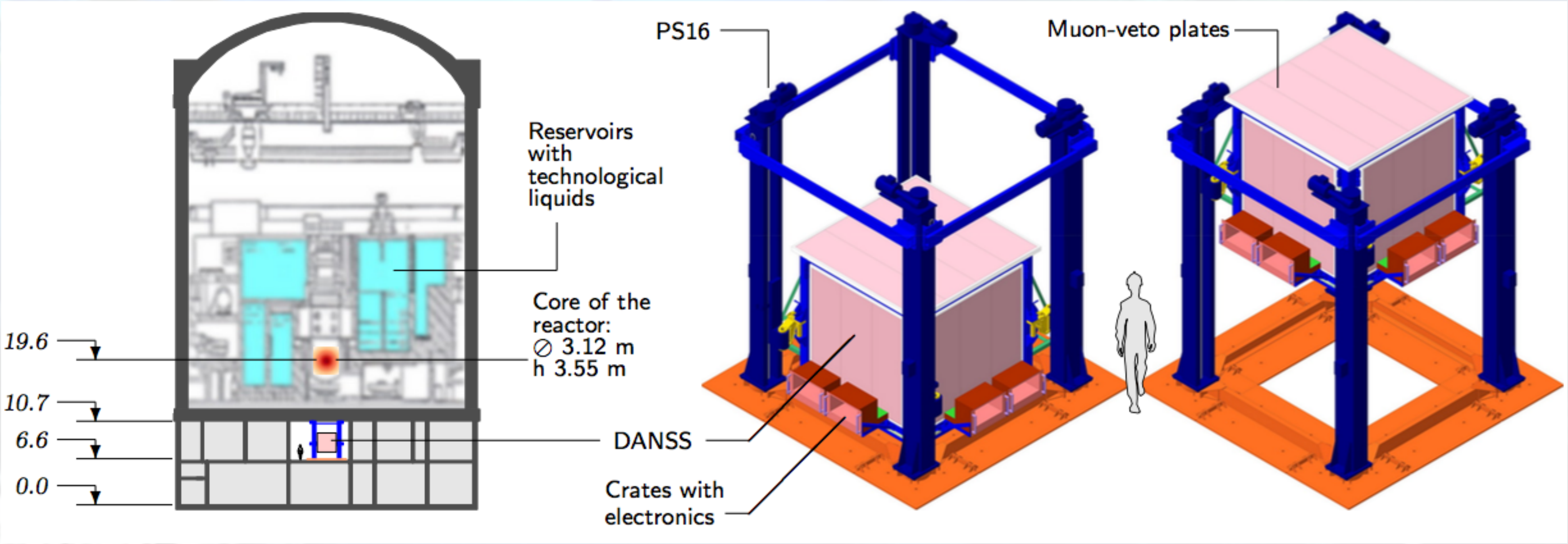
A Worldwide Effort

A Worldwide Effort

	P_{Th}	Overburden	Segmentation	Baseline	Material
Chandler	72 MW (^{235}U)	~10 mwe	6.2 cm (3D)	5.5 m	PS + Li layer
DANSS	3 GW (LEU)	~50 mwe	5 cm (2D)	10.7-12.7 m	Gd-doped PS
NEOS	2.8 GW (LEU)	~20 mwe	-	23.7 m	Gd-doped LS
Neutrino4	100 MW (^{235}U)	~10 mwe	10 cm (2D)	6-12 m	Gd-doped LS
NuLat	40/1790 MW (^{235}U/LEU)	few mwe	6.35 cm (3D)	4.7/24 m	Li-doped PS
Prospect	85 MW (^{235}U)	few mwe	15 cm (2D)	7-10 m	Li-doped LS
SoLiδ	72 MW (^{235}U)	~10 mwe	5 cm (3D)	5.5-10 m	PS + Li layer
Stereo	57 MW (^{235}U)	~15/18 mwe	25 cm (1D)	8.8-11.2 m	Gd-doped LS

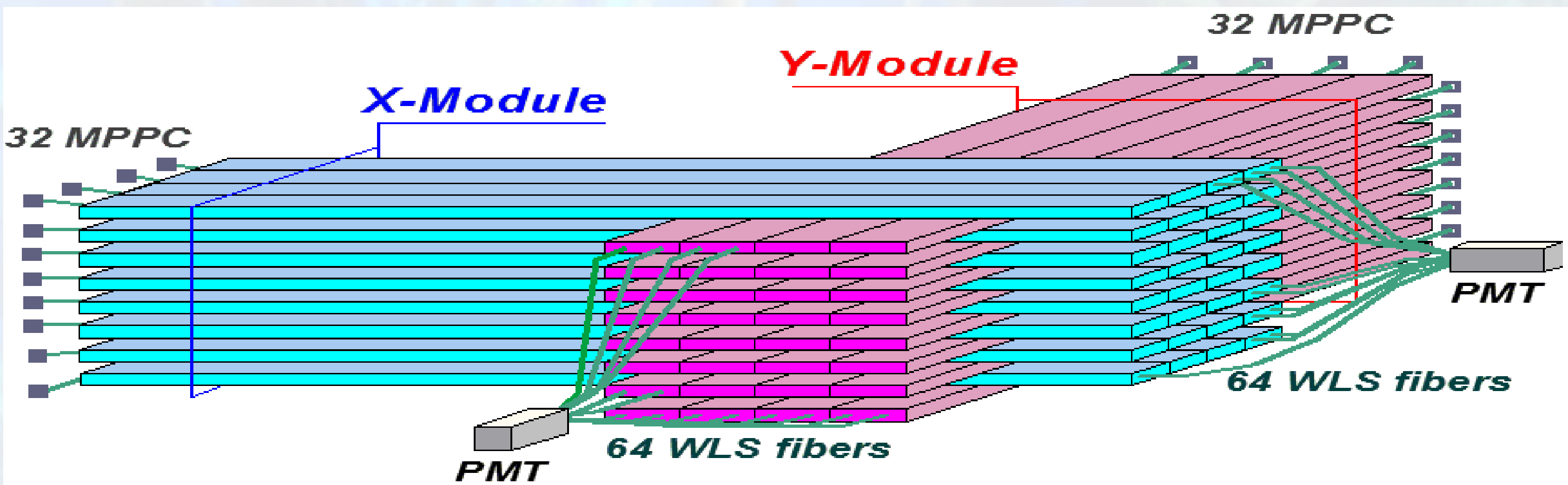
DANSS

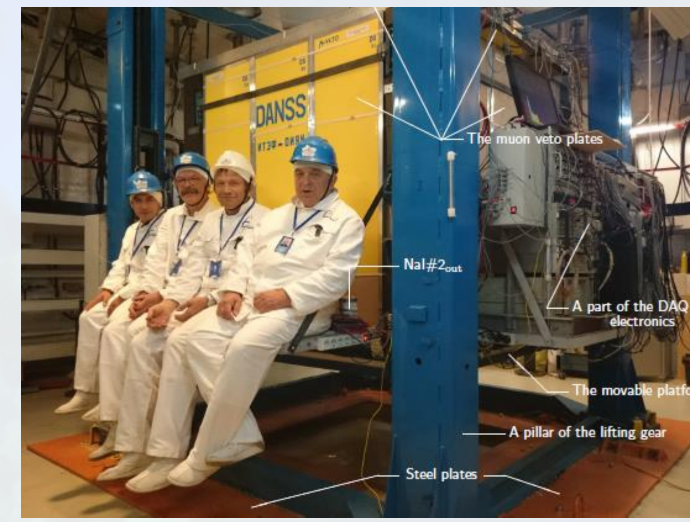
- @ the **3GW$_{th}$** **WWER-1000 reactor (h = 3.6 m, ⦰ = 3.1 m)**, in the Kalinin nuclear power plant
- **Beneath the reactor: ~50 mwe shielding** (factor 6 μ flux reduction)
- **Movable platform (up-down)**, distance detector-core **10.7-12.7 m**



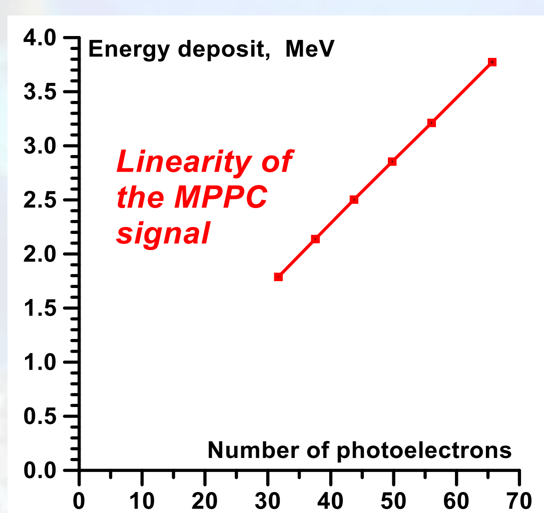
DANSS

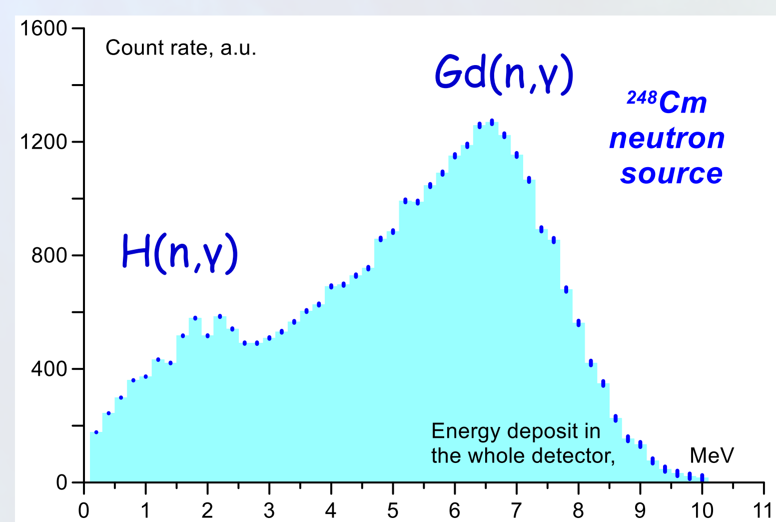
- Detector consisting of **X and Y modules of plastic scintillators (with Gd) + WLS**
  - **~20 pe/MeV, σ_E/E~16% @ 1 MeV**





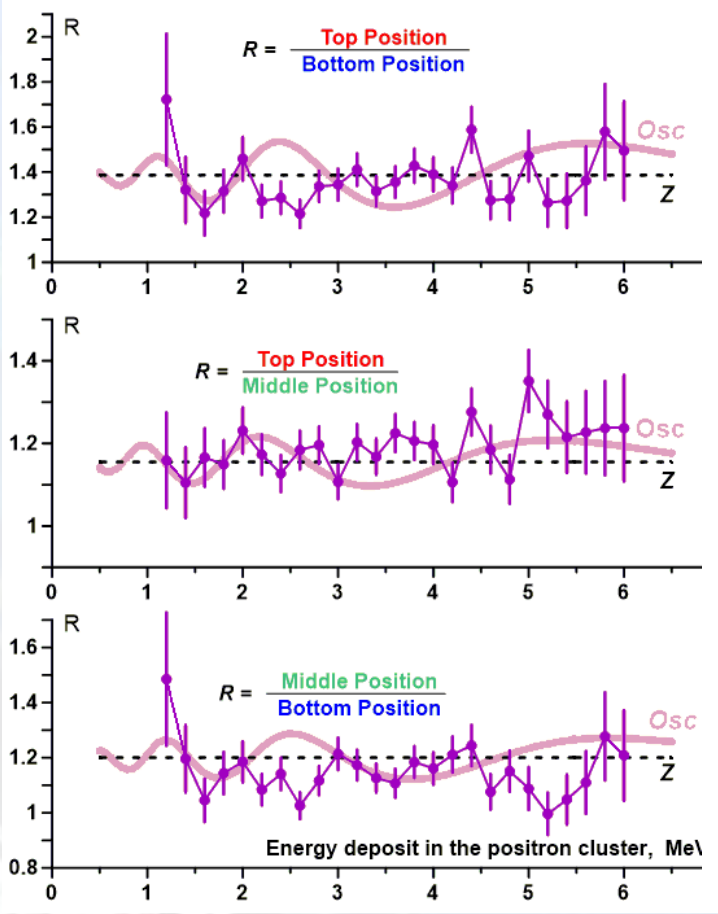
- **Calibration** with tagged **muon tracks** (assuming linear charge-E dependence above 1 MeV prompt energy threshold) and the **^{248}Cm** n source

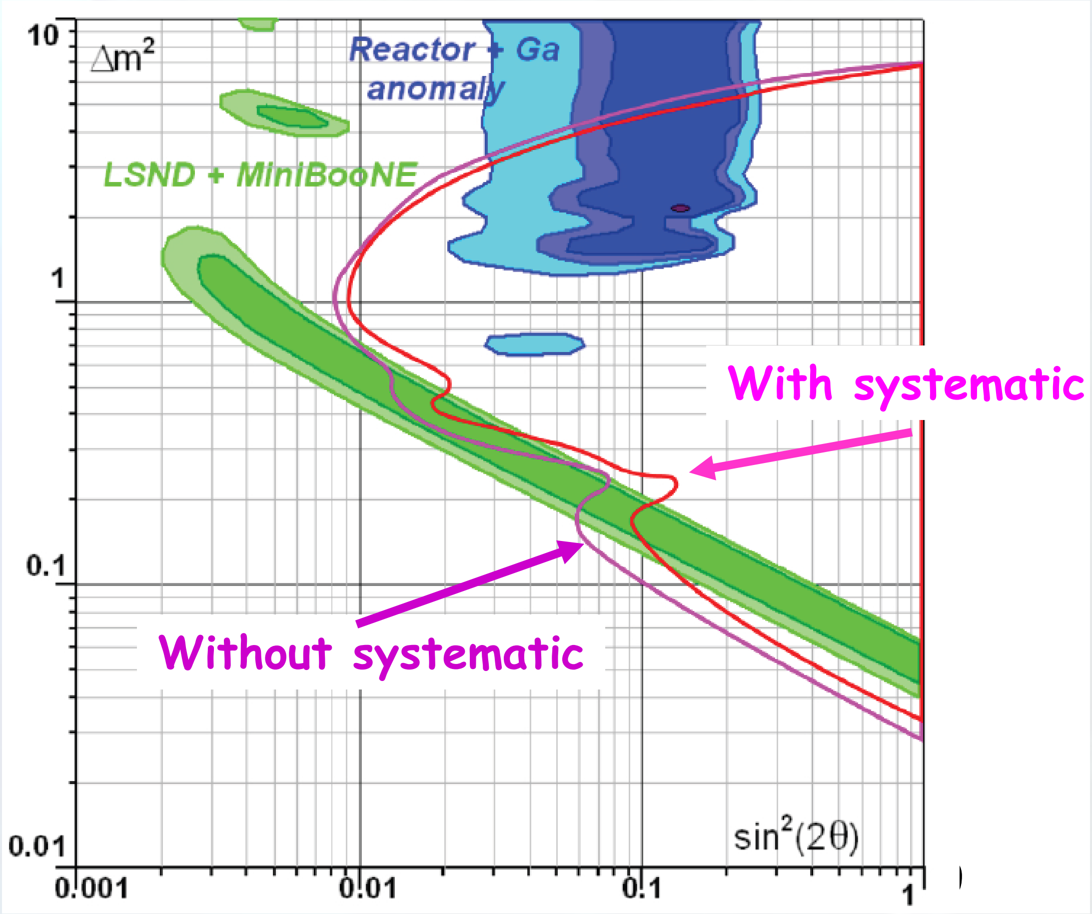




DANSS

- **Data taking running now! 5000 ν/day** (~5% cosmics in the 78% fiducial volume)
  - **First results of neutrino rates ratios** @ different positions with **27 days**
  - Now technical stop (shielding being improved), wait systematics before go public
- **Expected sensitivity with one year** (95% CL, systematics: 1% E scale + 1% bkg)

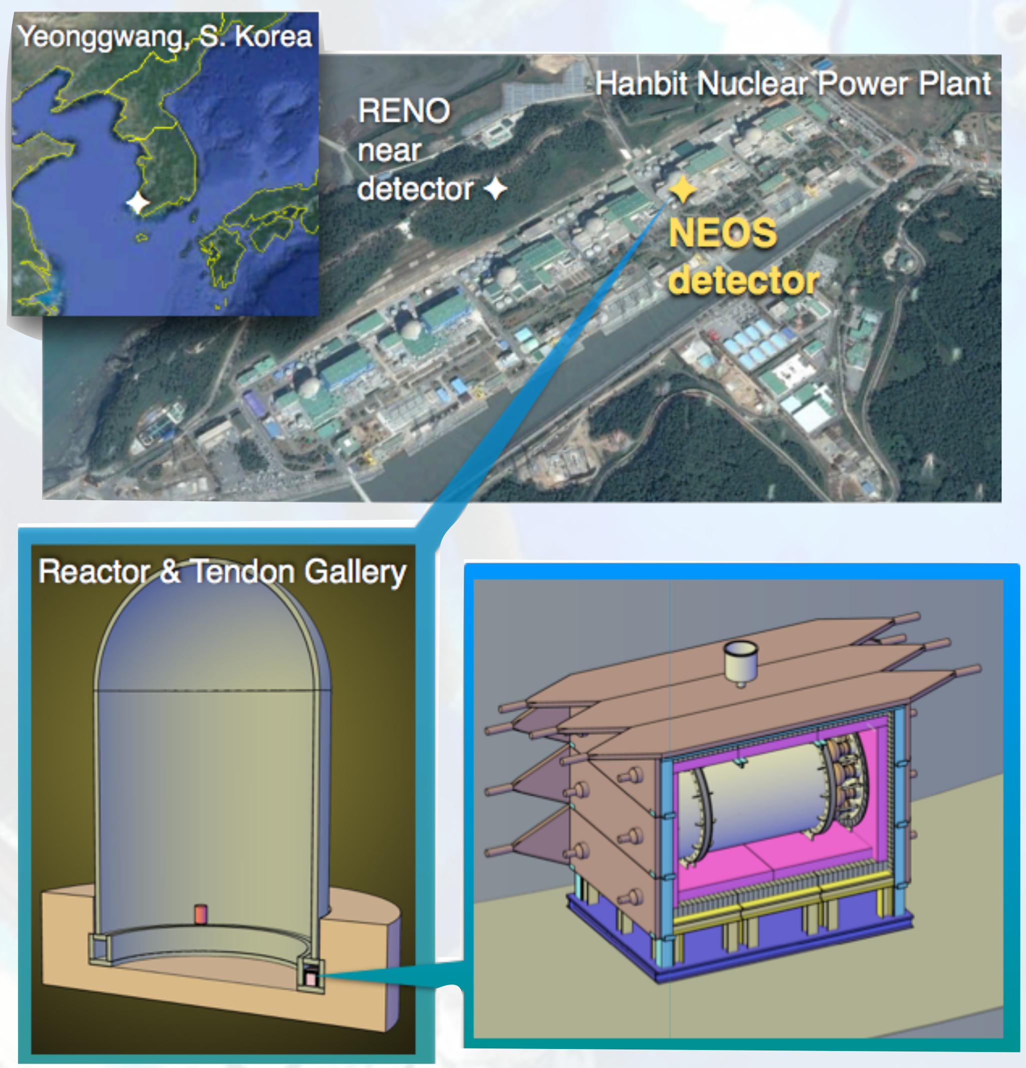


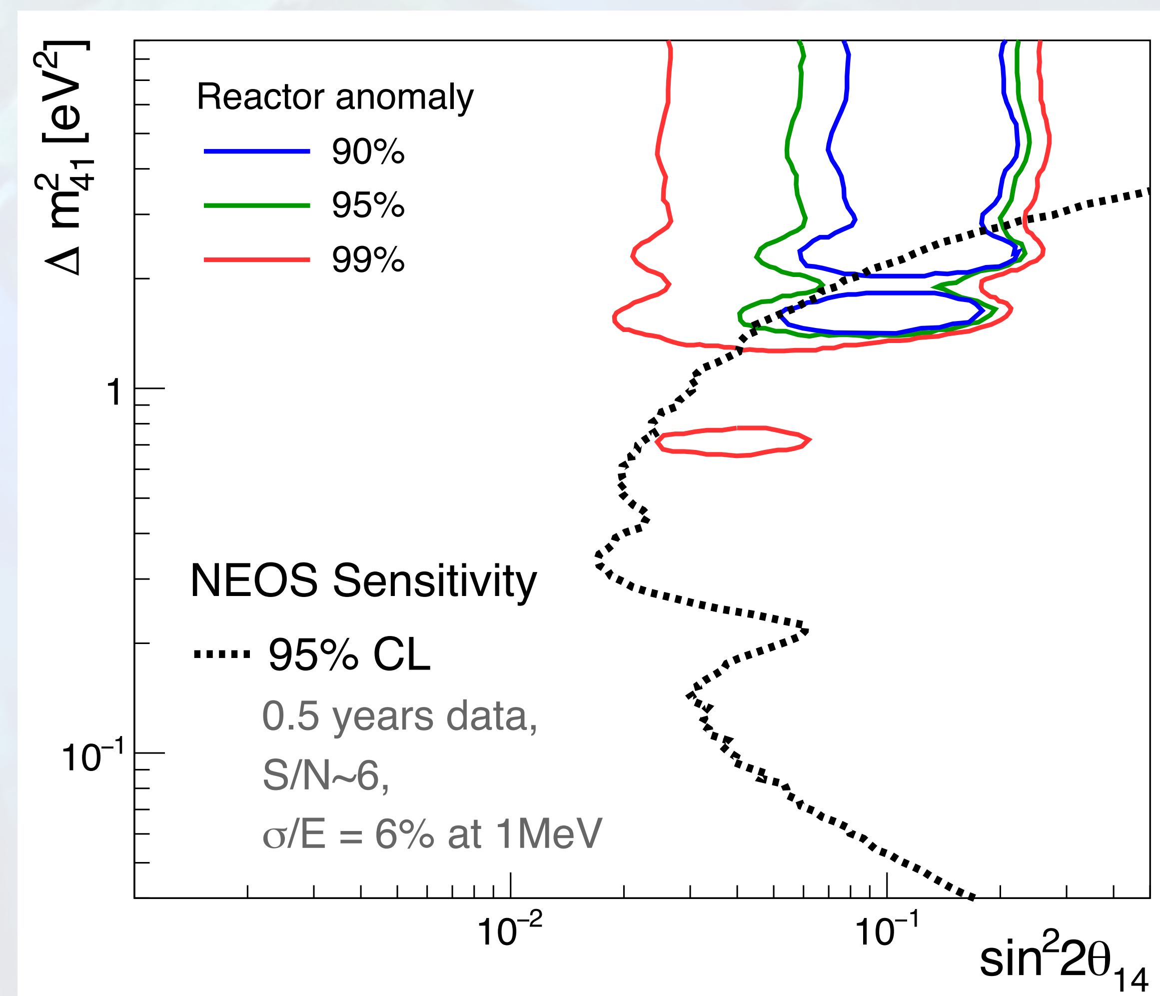


NEOS

- **@ the Yeonggwang reactor** (same as RENO): 5 cores of **2.8 GW$_{th}$, h = 3.7 m, ⌀ = 3.1 m,** 256 m between neighbour cores

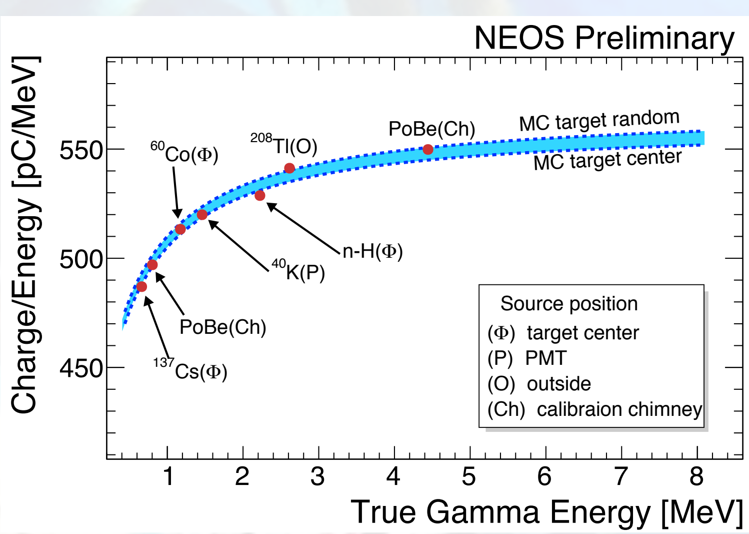
- **~30 mwe overburden, 23.7 m fixed baseline → sensitivity @ higher Δm²**

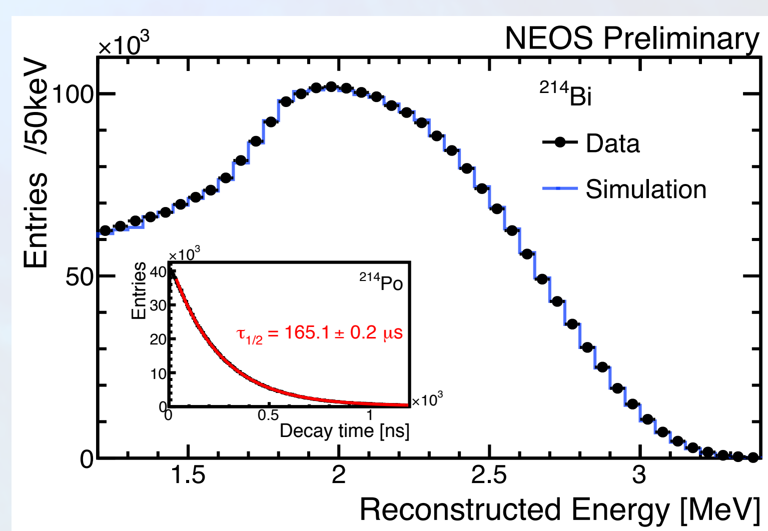


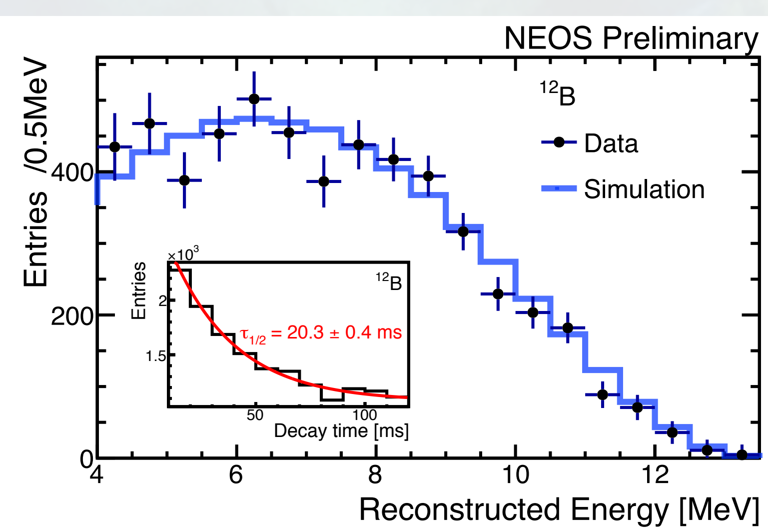


NEOS

- Target: **1000 l tank of 0.5% Gd-doped LS**
  - **19 8-inch phototubes on each side**
  - Active shielding: 5 cm-thick plastic scintillators
  - Passive shielding: 10 cm B-PE, 10 cm Pb
- Non-linear energy response, **σ_E/E~5% @ 1MeV**
- **Data-MC agreement tested with ^{212}Bi, ^{214}Bi, and ^{12}B**

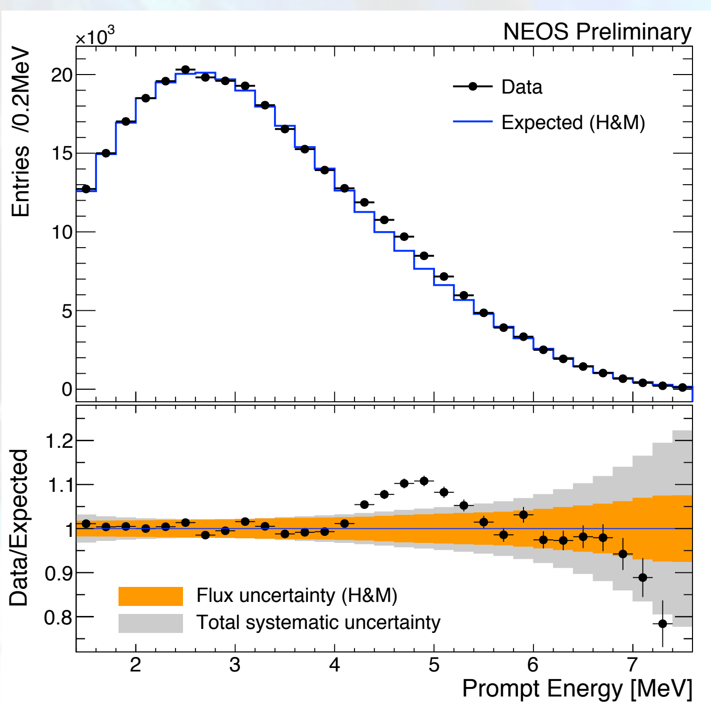


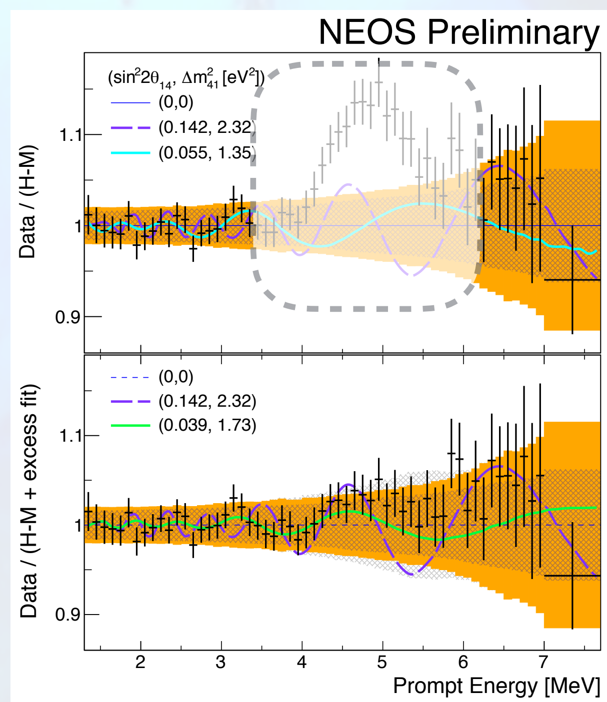


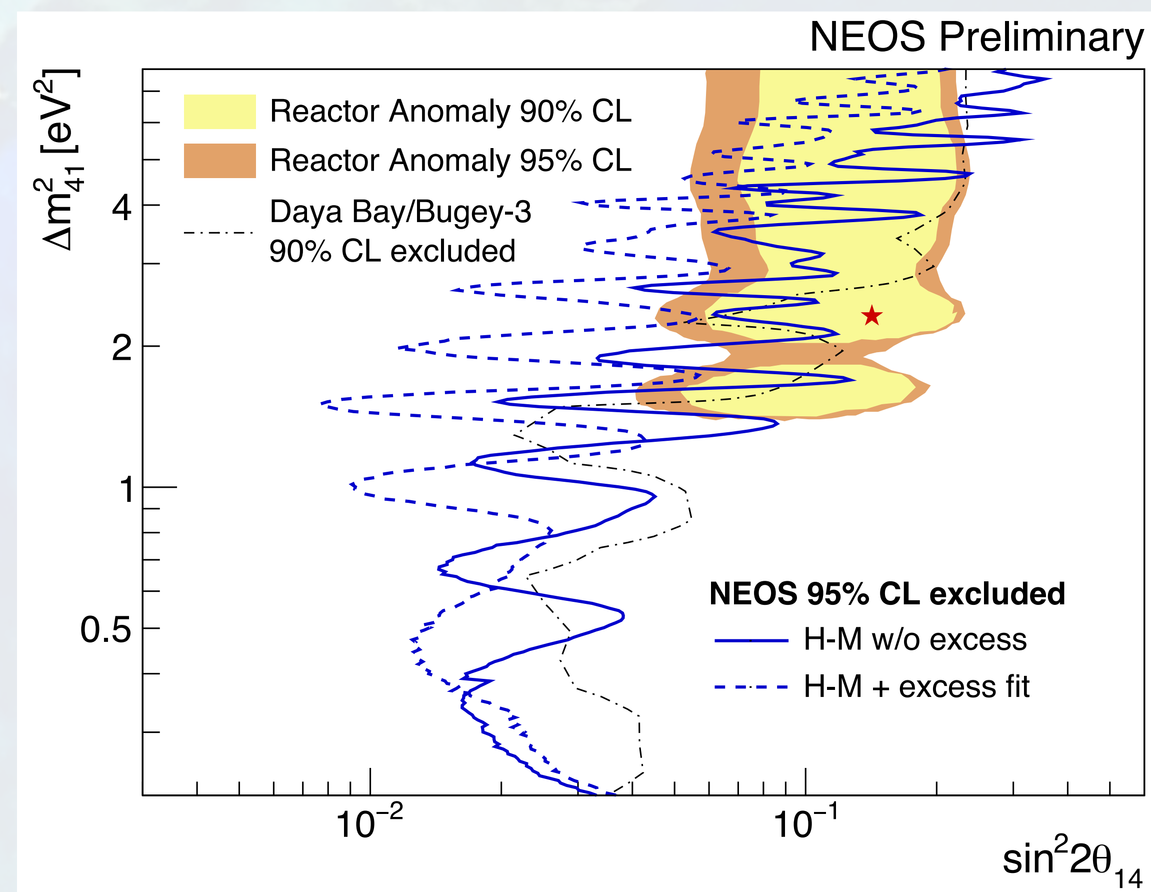


NEOS

- Data taken 07/15-05/16: **49 days with the reactor OFF, 180 days ON**
- **IBD counts ~ 2000/day with S/B~23**
- **Latest results with exclusion plot released @ ICHEP this year!**
- Two analysis: one with a oscillatory fit only (χ^2/NDoF = 52.3/38), one with the addition of a fit for the 5 MeV bump (χ^2/NDoF = 111/67)

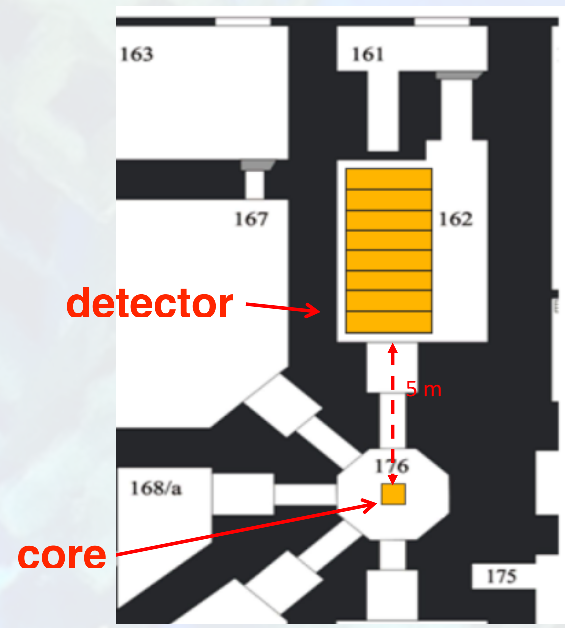


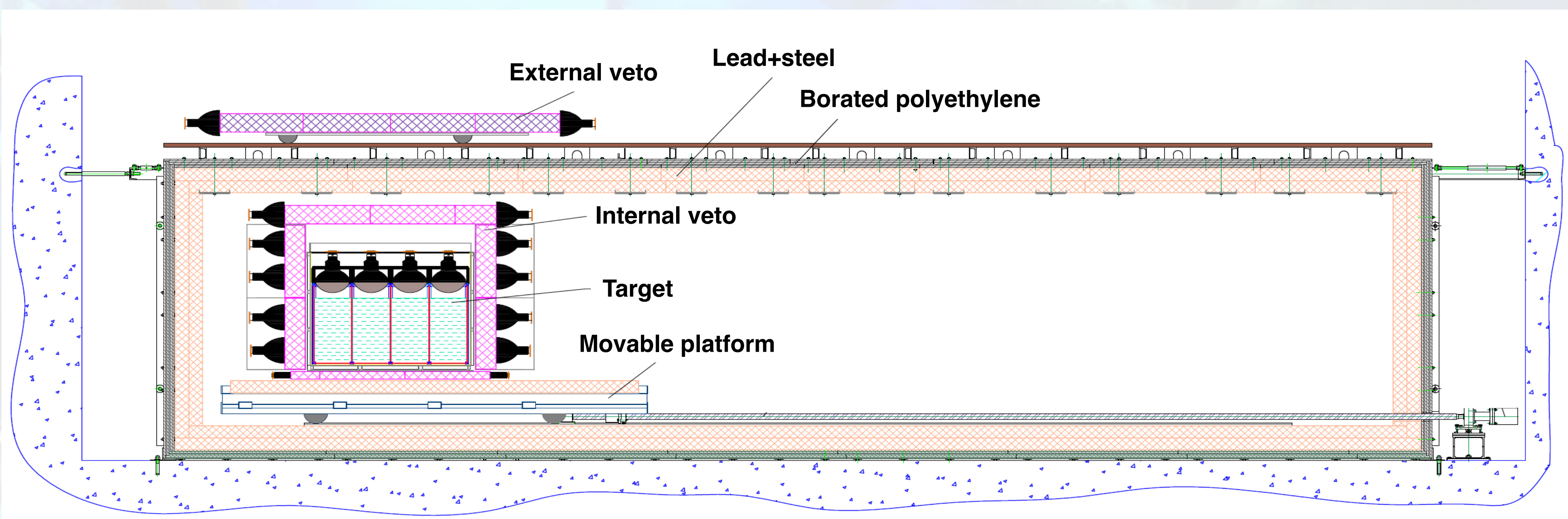




Neutrino-4

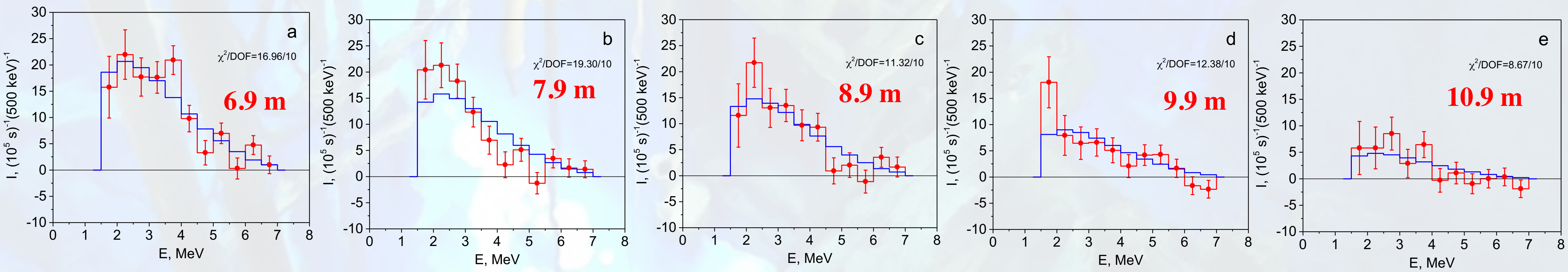
- @ the **100 MW$_{Th}$** compact-core **(35x42x42 cm^3) SM-3 reactor in Dimitrovgrad**
- Movable detector**: 6-12 m from core**
  - **Tank of LS + PMTs**
  - Passive shielding of 60 tons
  - Active internal and external veto

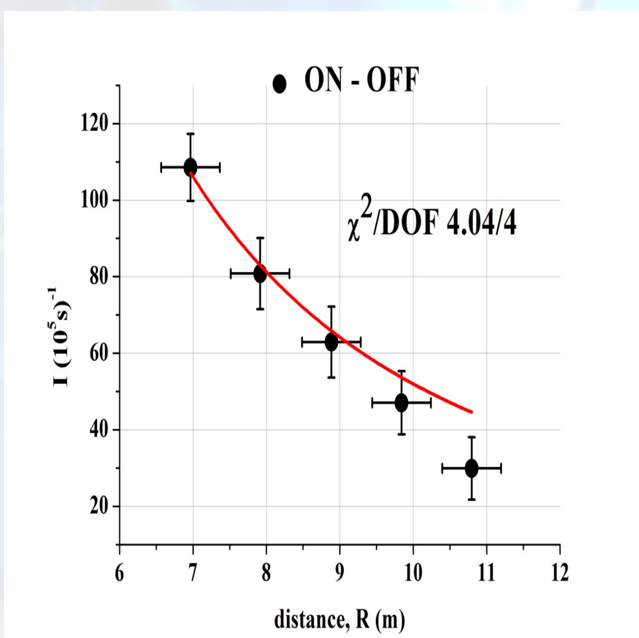


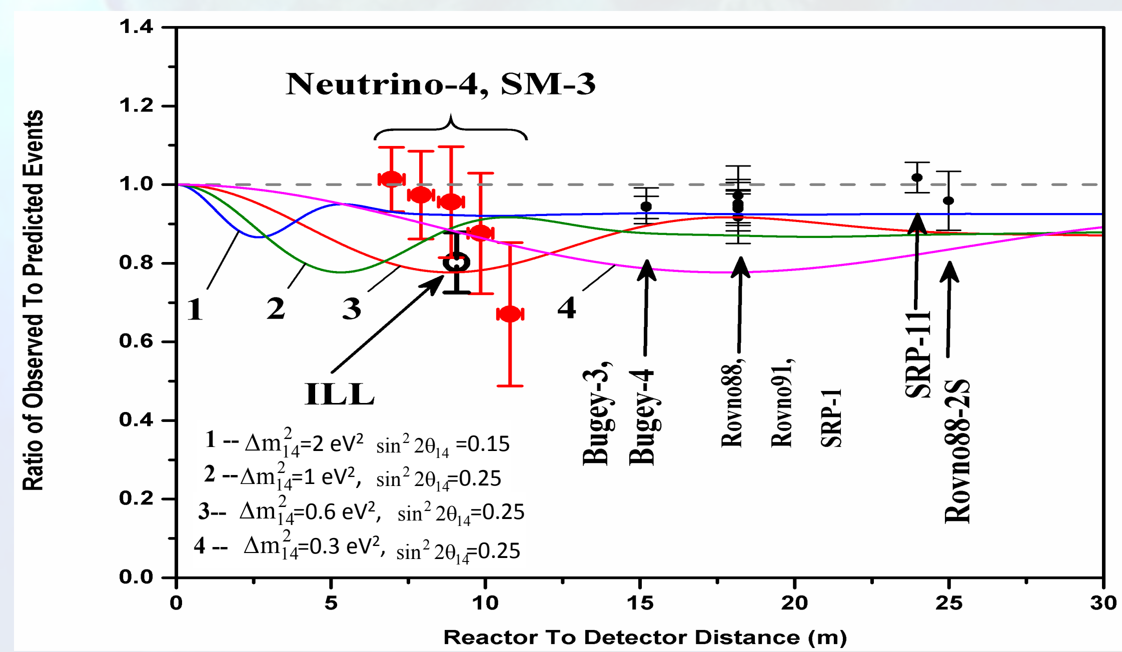


Neutrino-4

- **Preliminary results** with **prototype 350 l tank** divided in 4x4 sections, placed **in 5 positions** (rate-only analysis)





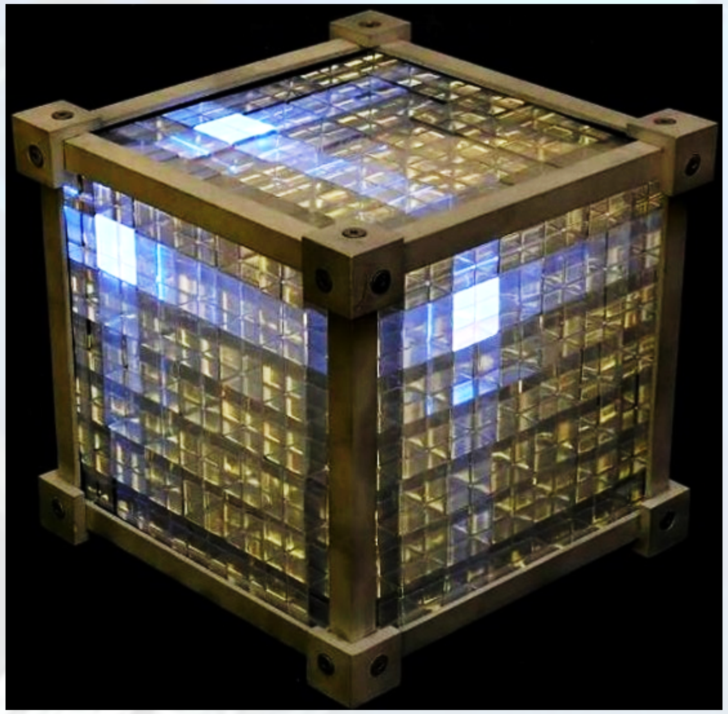


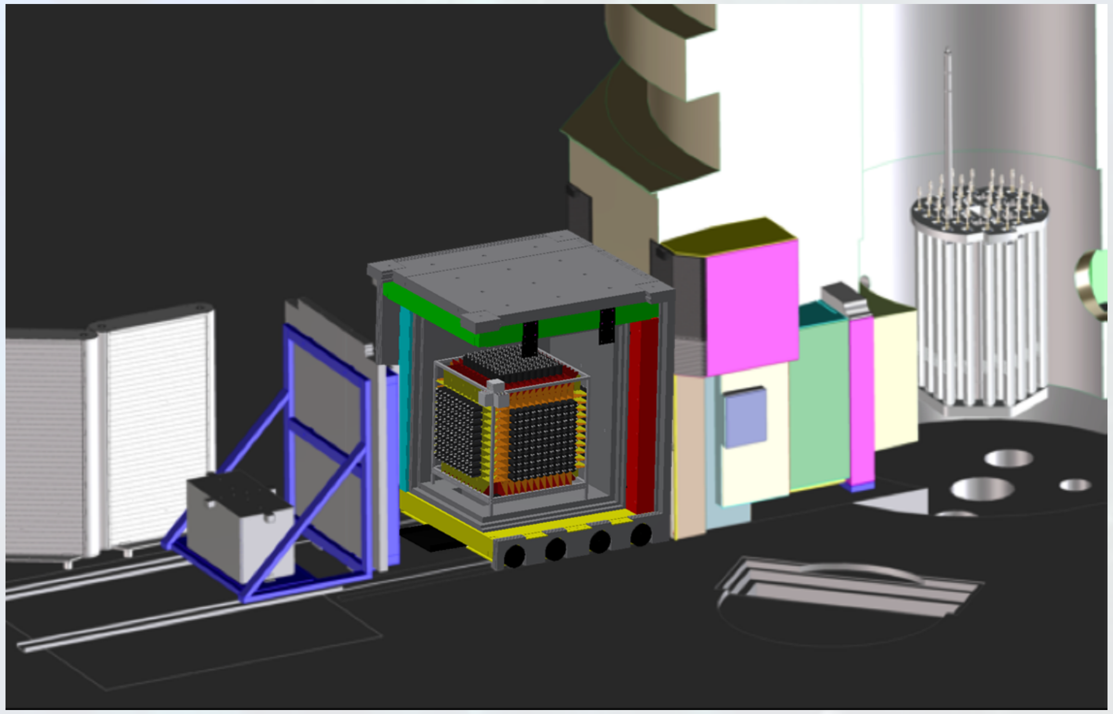
- **Full scale detector (3m^3 for 5x10 sections) aims to 1.5-3% statistical accuracy after 2 y of data taking**

NuLat

- **Finely 3D segmented detector: 15x15x15 ^{6}Li-loaded** (0.5%) **plastic scintillator cubes** (6.35 cm/side), spaced by thin air gaps (~0.127 mm) **arXiv:1501.06935**

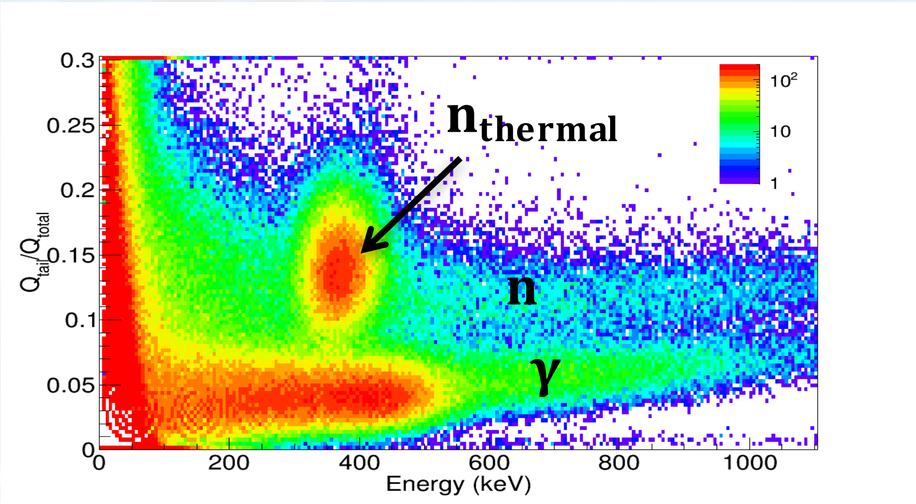
- Raghavan Optical Lattice: detection material with high n (n_{PS} = 1.54) divided into cells by a lower n material (n_{air} ~ 1)
  - **Total internal reflection:** $\theta_{critic} = 45^{\circ}$ → **light guided along 3 axis** to 6 PMTs
  - Very good light collection and resolution: **600 pe/MeV, σ_E/E~4% @ 1MeV**

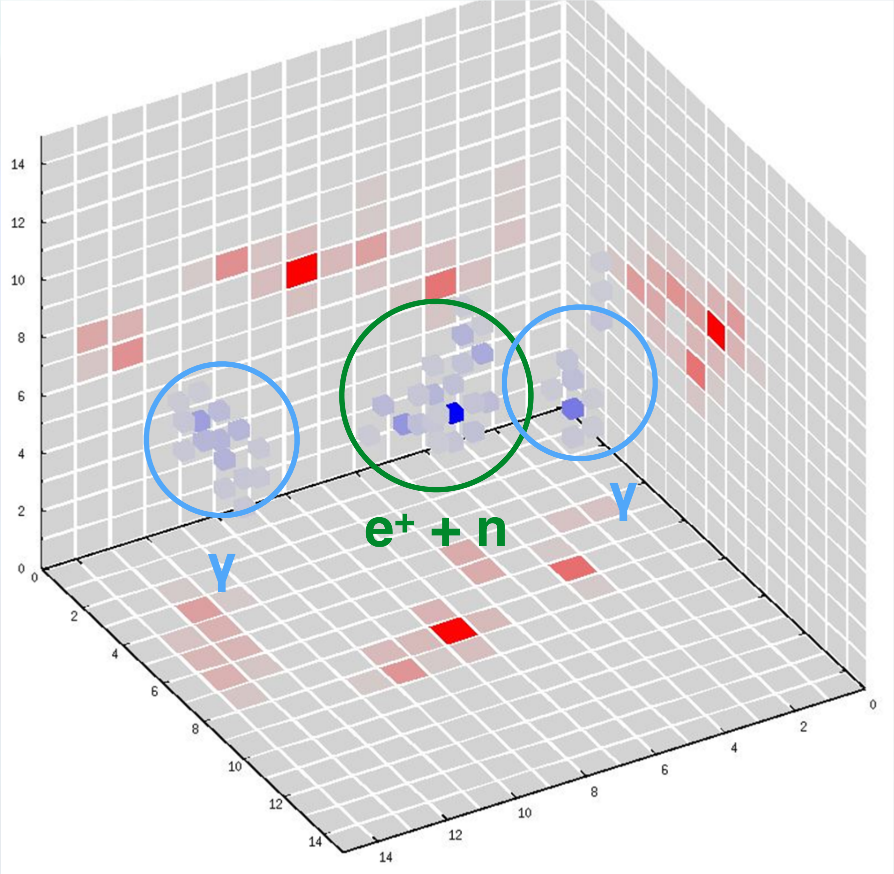




NuLat

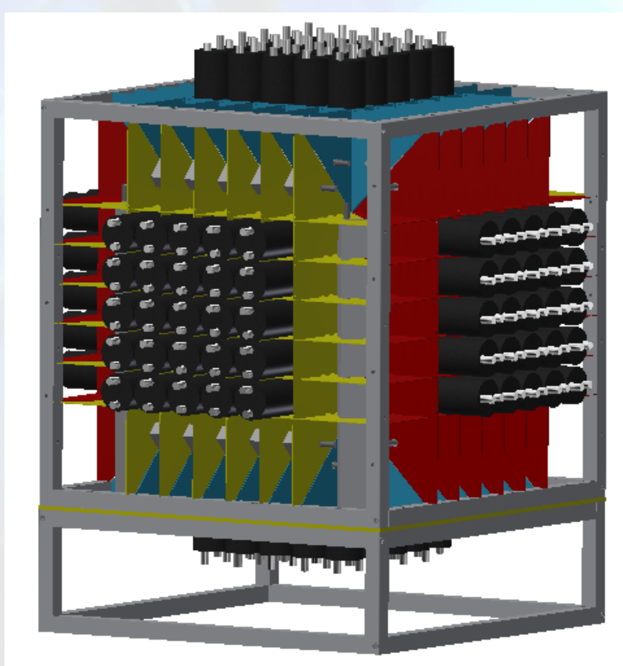
- IBD selection and background rejection based on topology/PSD
  - IBD: large deposit in one cell (e^+ scintillation) + small halo (e^+ annihilation, 0.1-1.0 MeV) + 7 μs-delayed n-capture with mono-E PSD (~400 keV, 65% in a near cell)
  - Gammas: no halo (single Compton) or big halo (multiple Compton)
  - Cosmogenic β emitters: no halo
  - Fast neutrons: PSD

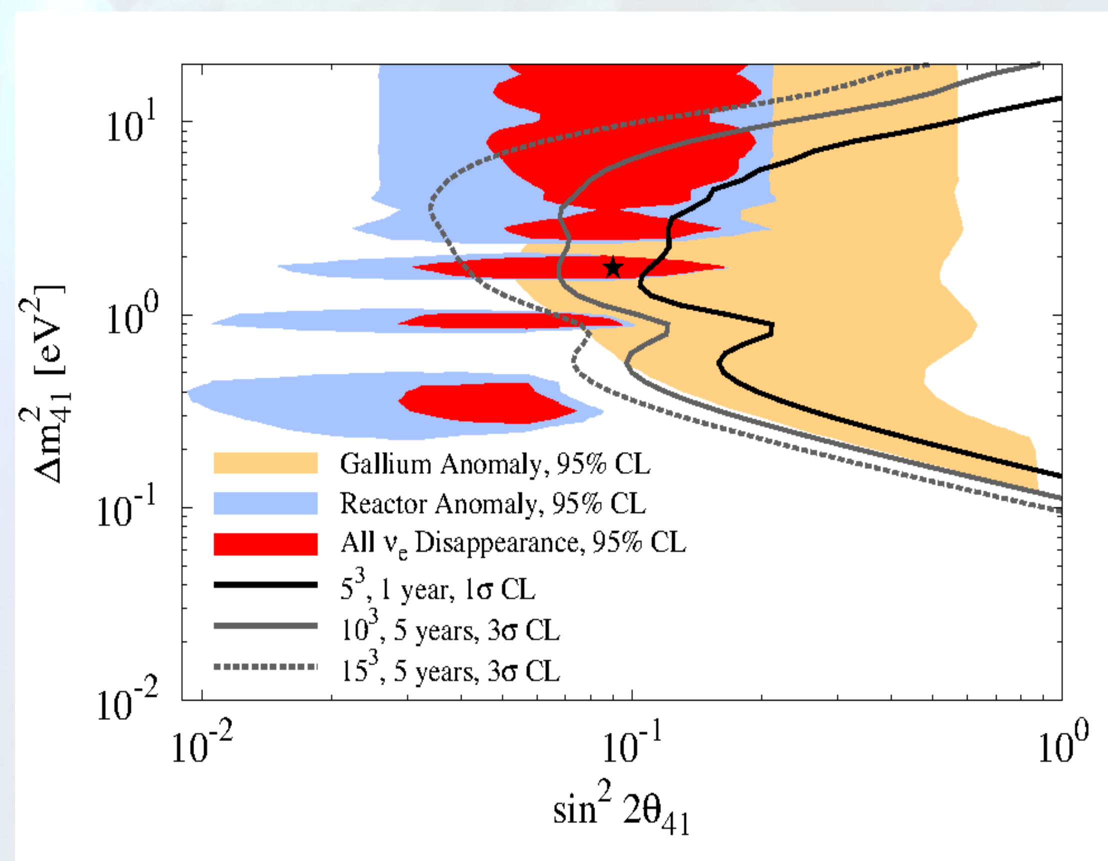




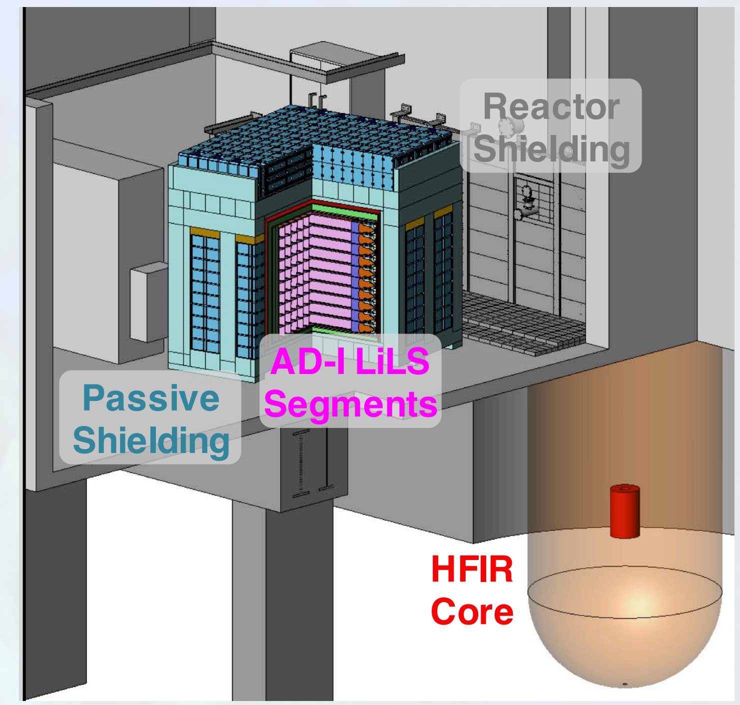
NuLat

- **5x5x5 demonstrator under construction**: final assembly in **fall 2016**
- **Deployment at 2 reactors: NIST (Maryland) and North Anna (Virginia)**
- Successful 5x5x5 demonstration will lead to the next (15x15x15) stage

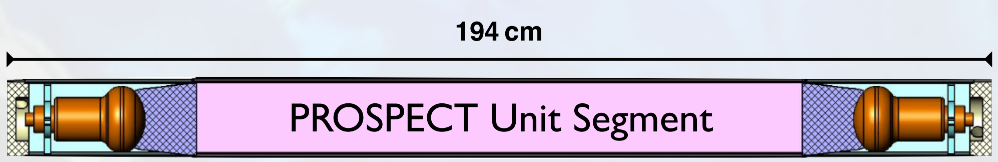


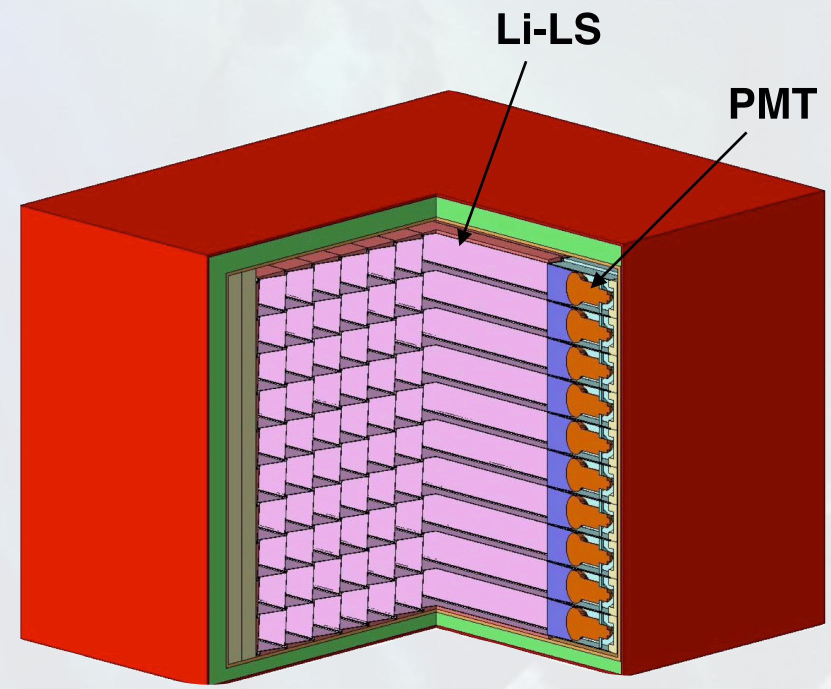


- @ **Oak Ridge** compact-core **(h = 0.5 m, $\varnothing$ = 0.2 m)** **85 MW_{th}** HFIR reactor



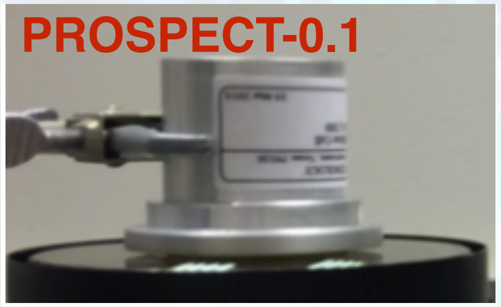
- Two detectors/phases:
  - **Near detector 7-10 m from core (sterile ν search + ^{235}U spectrum)**
  - Far detector 15-18 m from core (improved oscillation study if sterile ν is confirmed)
- Phase-I detector: segmented LS tank
  - **3 ton Li-loaded LS** (with PSD capability)
  - **120 ~25 l optical segments**: identify multiple-particle interaction, reject showers





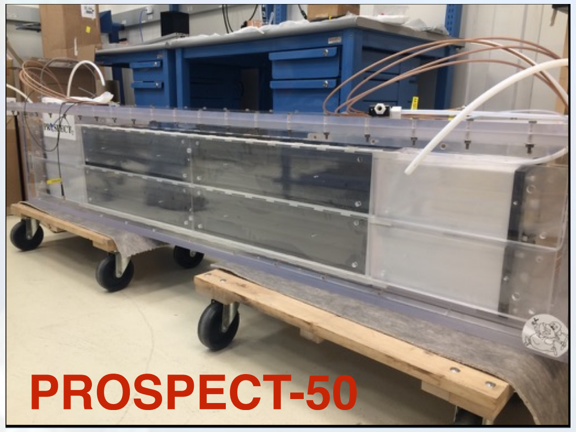
- **IBD selection based on PSD, topology, timing**

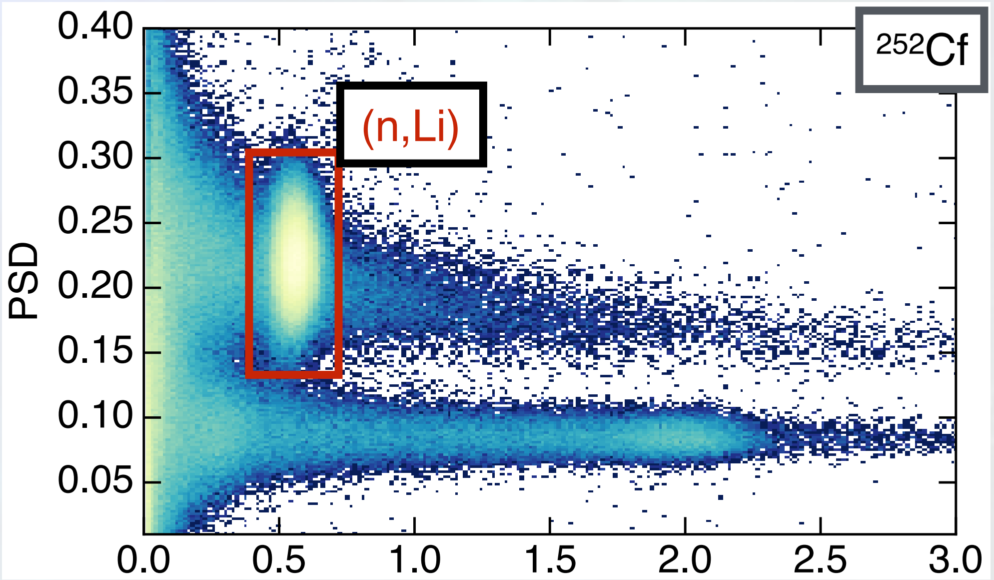
- A long history of R&D and prototypes



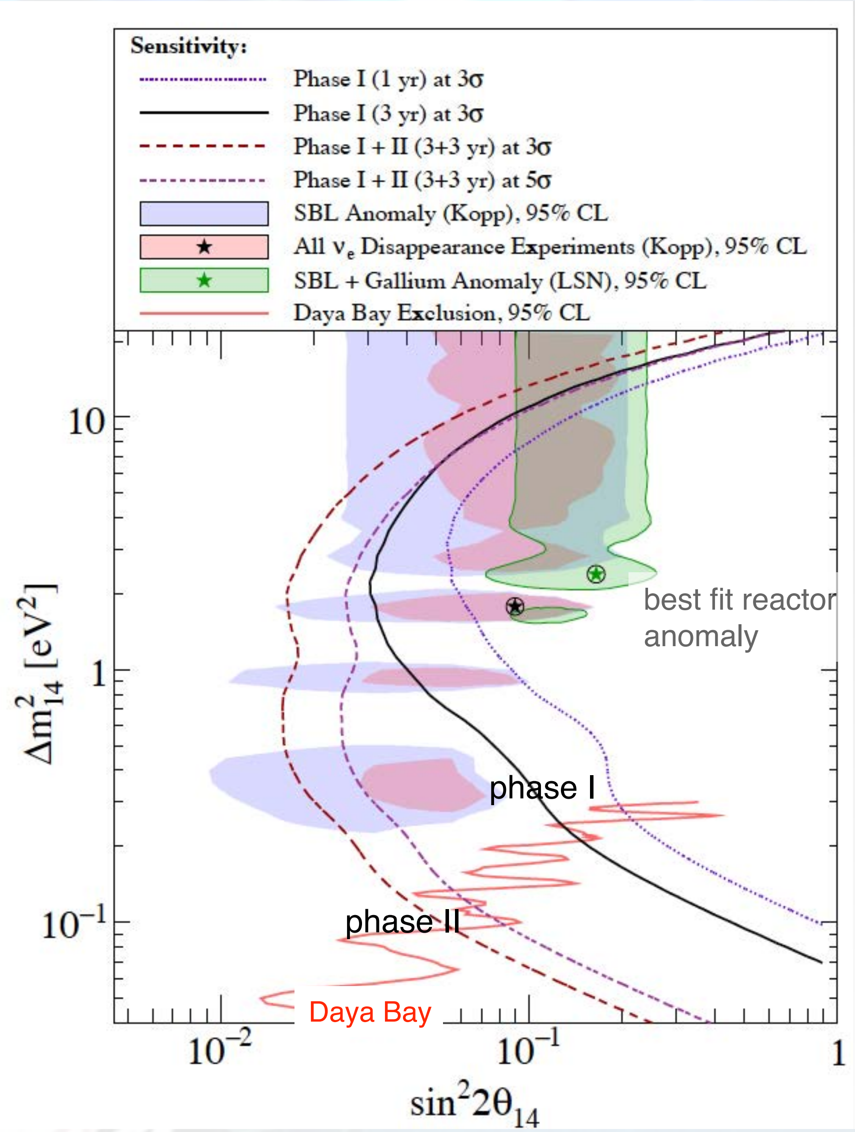
PROSPECT-2

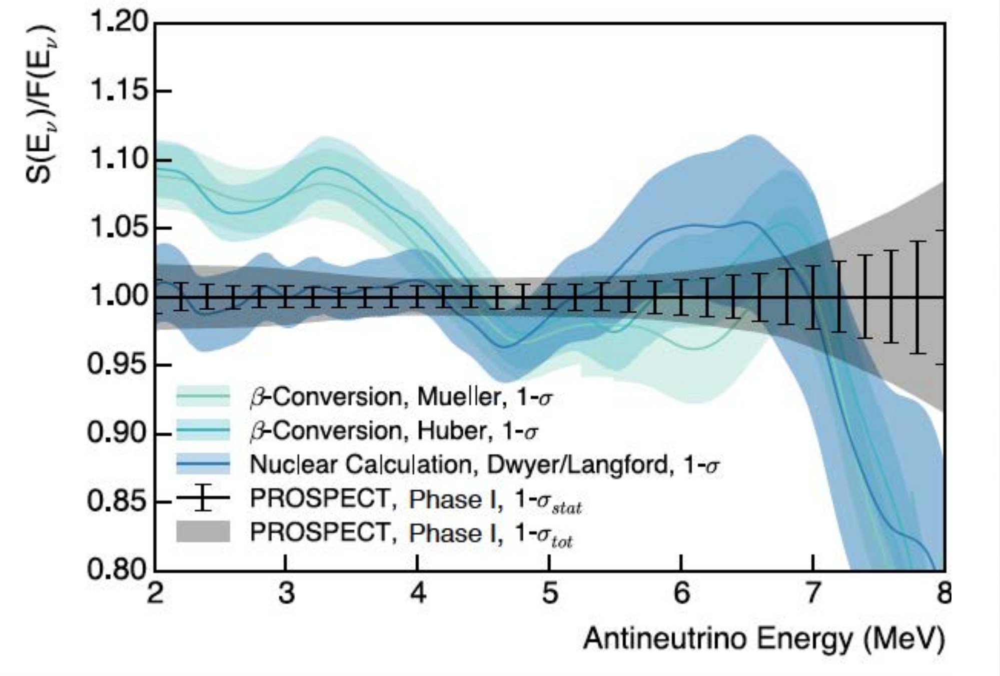
- First **segmented prototype PROSPECT-50** (2x25 l) taking data since **March 2016**
  - **550 pe/MeV, σ_E/E~5% @ 1MeV**
  - Tested n-Li detection via PSD



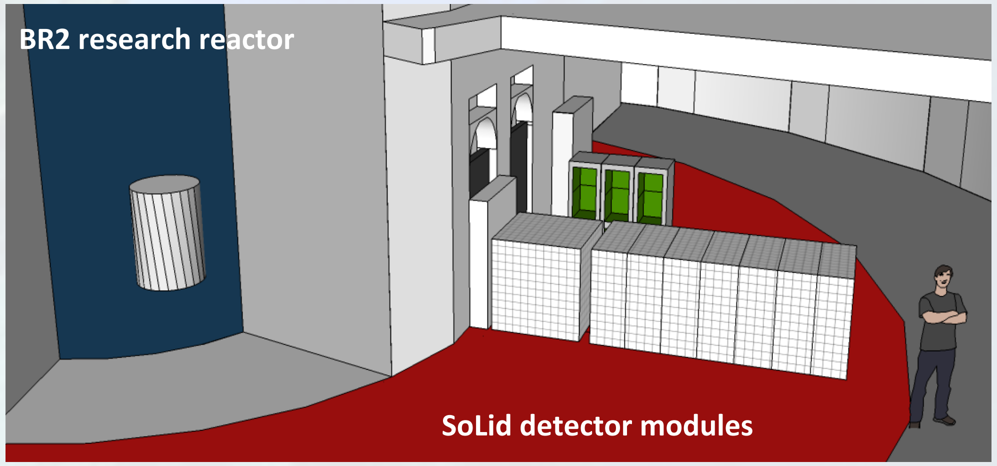


- **Full phase-I detector under construction, delivered in early 2017**
  - Expected **~700 IBDs/day** (S/B~1/1), high energy resolution **σ_E/E~4.5% @ 1MeV)**
  - **3σ coverage of the favoured region in 3y data taking** + test of reactor model

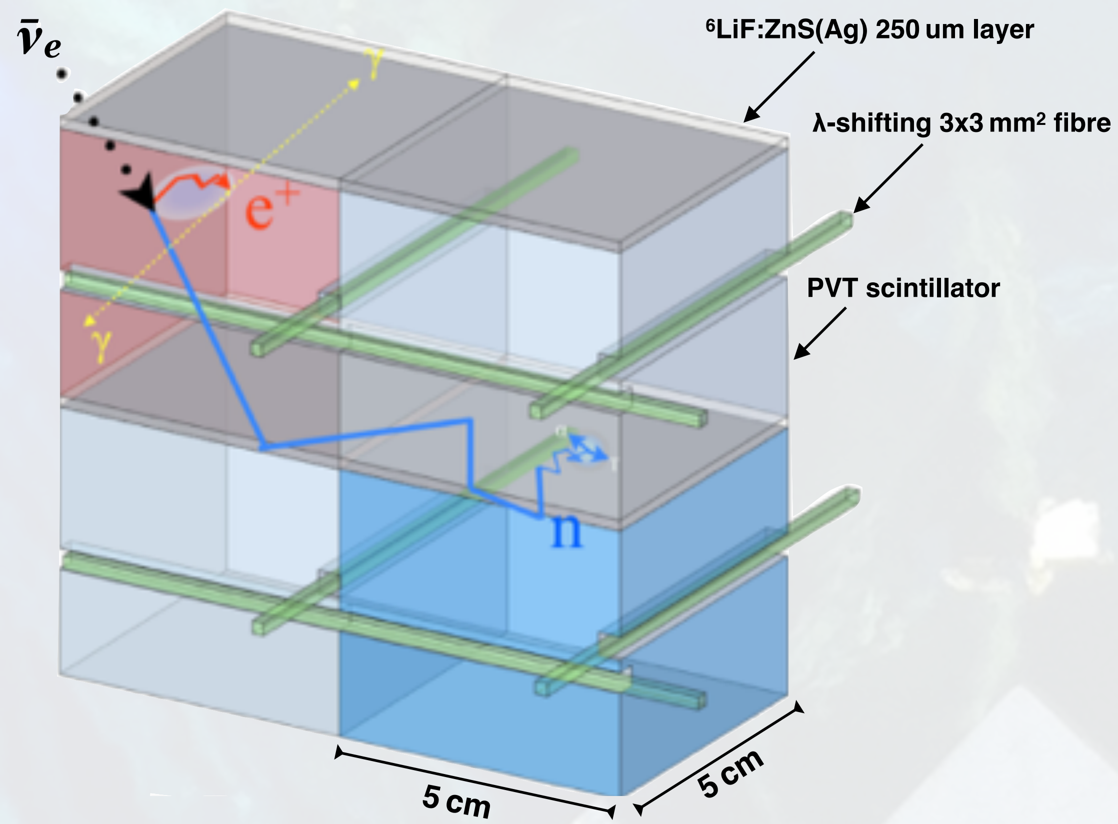




- @ **60 MW$_{th}$** compact-core **(0.5 m diameter) BR2 reactor** in Mol (Belgium), baseline range ~ **5.5 - 10 m**



- **Highly 3D segmented detector**
  - **5×5×5cm^3 PVT cubes** (optically separated)
  - **^{6}LiF:ZnS(Ag)** for neutron identification
  - Optical fibers and silicon PMTs

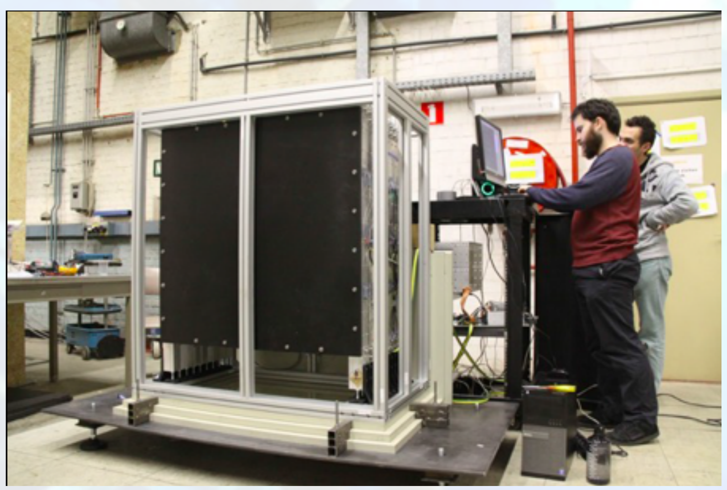


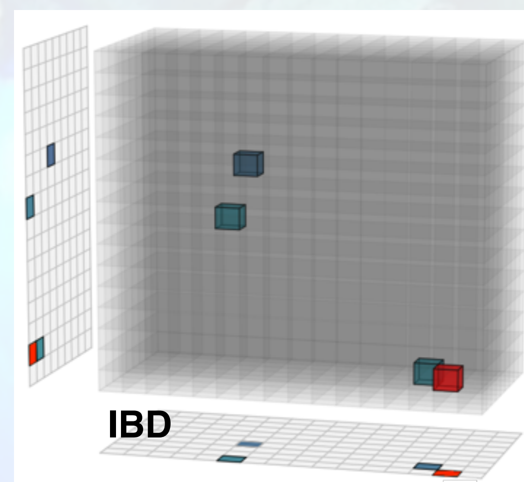
- Event topology used to identify IBDs
  - e$^+$ scintillation E deposit contained
  - e$^+$ annihilation γ's escaping the first cell
  - n-capture near first cell, identified via PSD

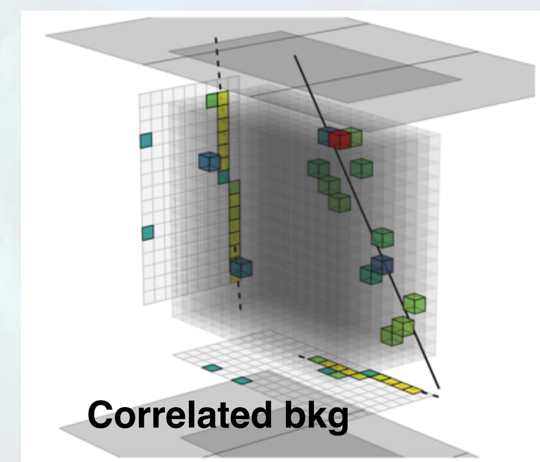
- **Prototype SMI deployed late 2014** (50 hr reactor on, long reactor off, calibration)

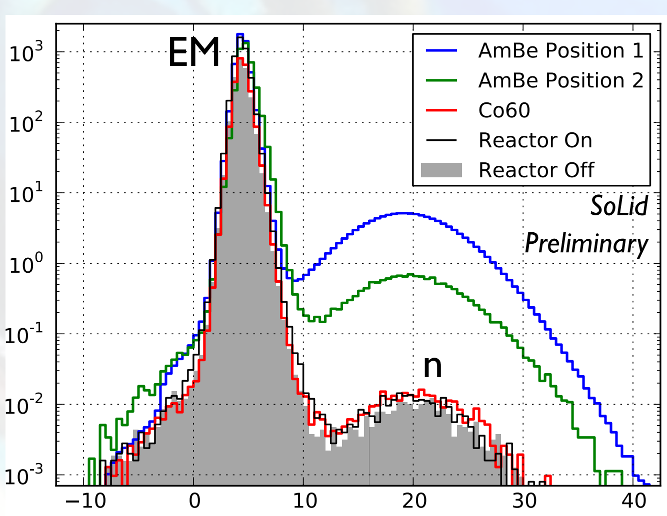
- Energy reconstruction and PSD algorithm validated (good population separation)

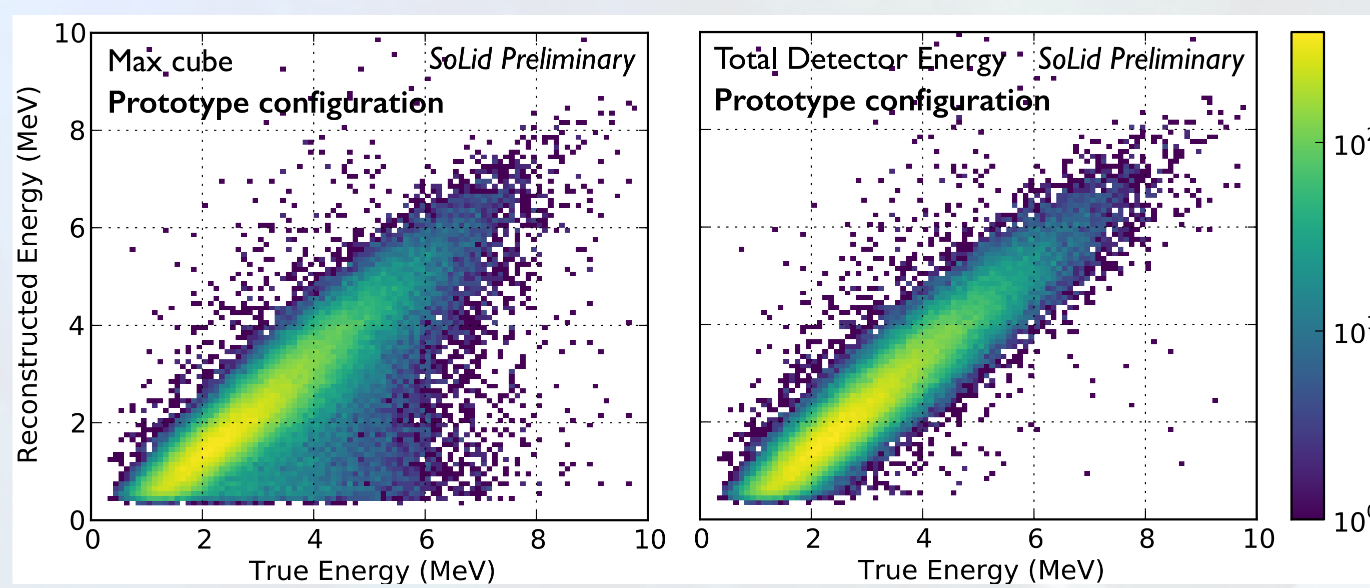
- IBD selection based on PSD, topology, timing (n detection efficiency ~70%)





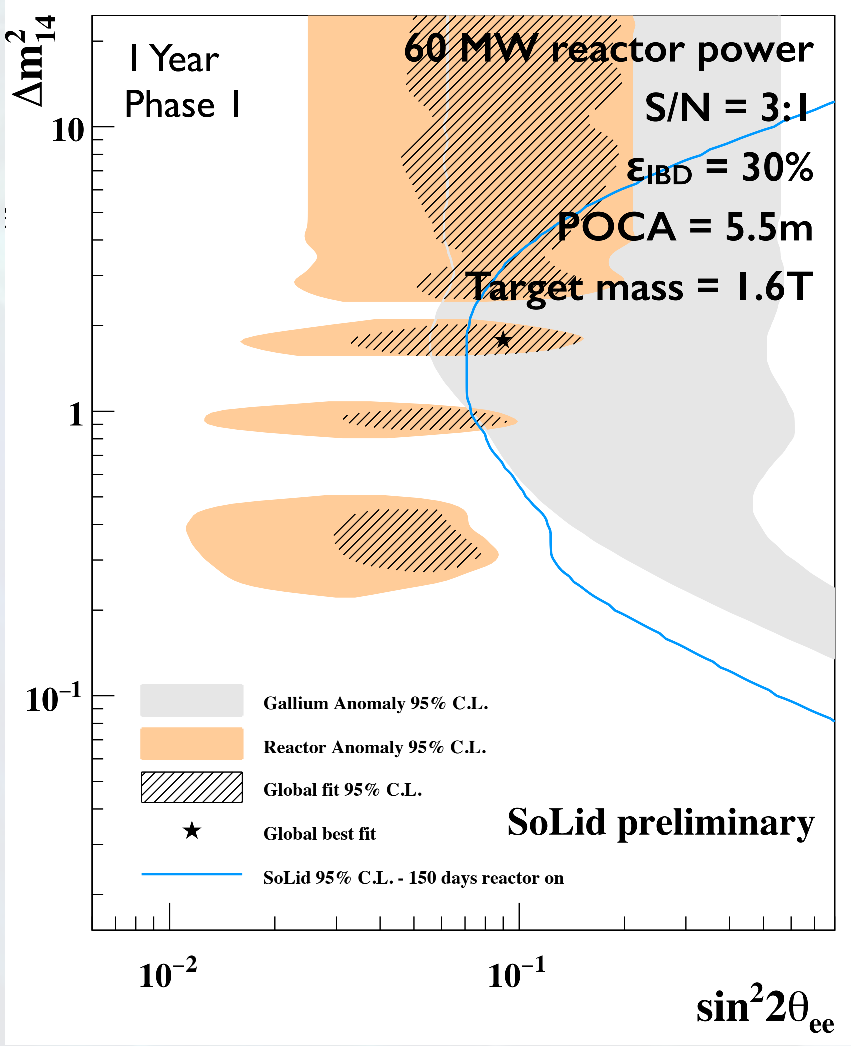






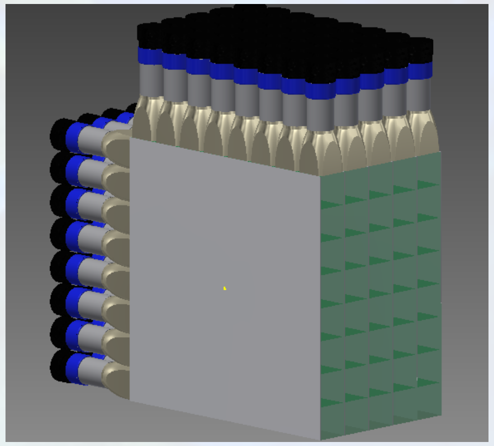
SoLid

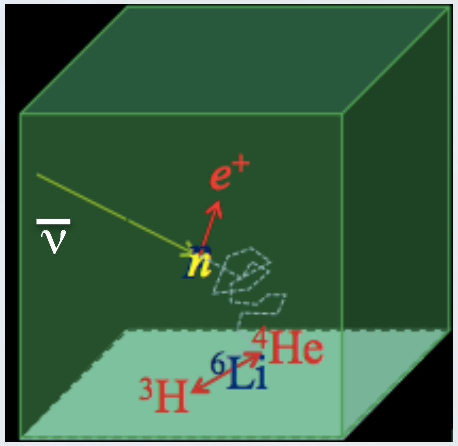
- Phase-I SoLid 1.6 t scale detector currently under construction, with upgrades
  - **reduced background** (container + water shielding)
  - **light yield** (material + number of fibres/cube doubled)
  - **neutron detection** (neutron ID @ trigger level)
- Expected **~50 pe/MeV** per cube, **$\sigma_E/E \sim 14\%/\sqrt{E}$**
- Aiming to **S:N ~ 3:1** with ε_{IBD} ~ 30%
- **Deployed early 2017**



CHANDLER: a SoLid Near Detector

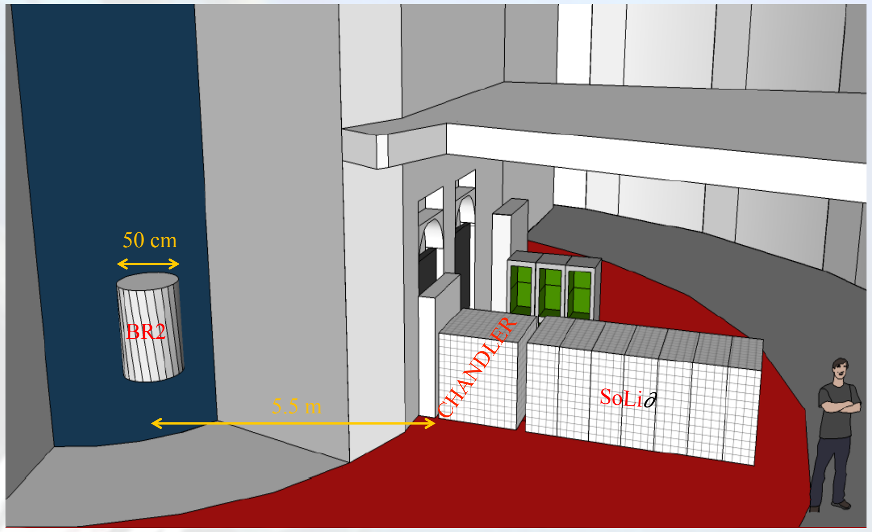
- **CHANDLER detector: 16x16x16 array of scintillator cubes** (6.2x6.2x6.2 cm^3)
  - Raghavan Optical Lattice: total internal reflection and very good light collection
  - **Sheets of $^{6}LiF:ZnS$ for n identification**

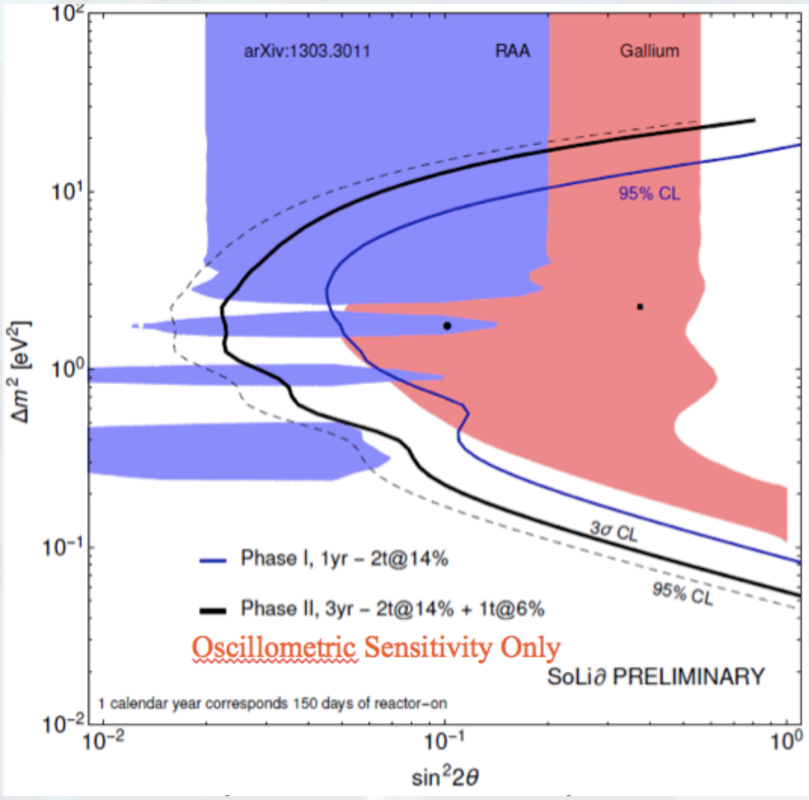




- **MiniCHANDLER** (8×8×5 system test) is fully funded, currently **under construction** and will be deployed at a commercial nuclear plant

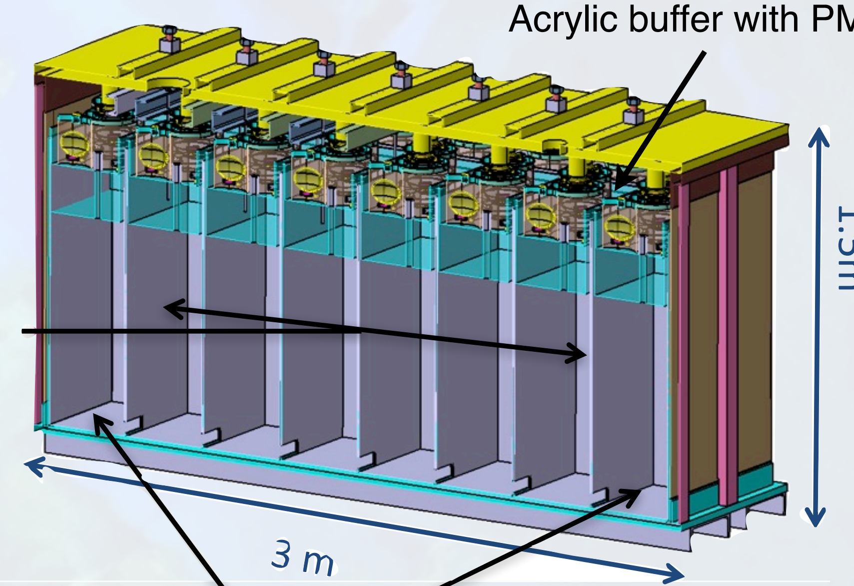
- CHANDLER planned to be deployed @ BR2 for the **SoLid phase-II: extended coverage to higher Δm^2**



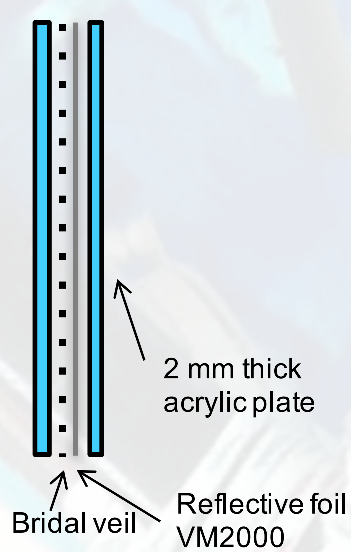


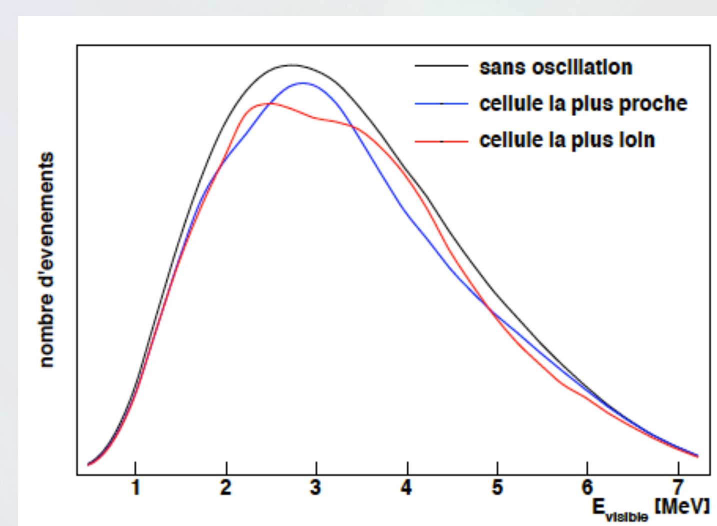
- The **STEREO detector** is placed **[8.9–11.1] m from the compact (<1m) 57 MW$_{th}$ ILL core**, in Grenoble
  - **6 target cells (Gd-doped LS)**
  - Outer crown (undoped LS)
  - 48 PMTs in upper acrylic buffer

arXiv:1604.08877

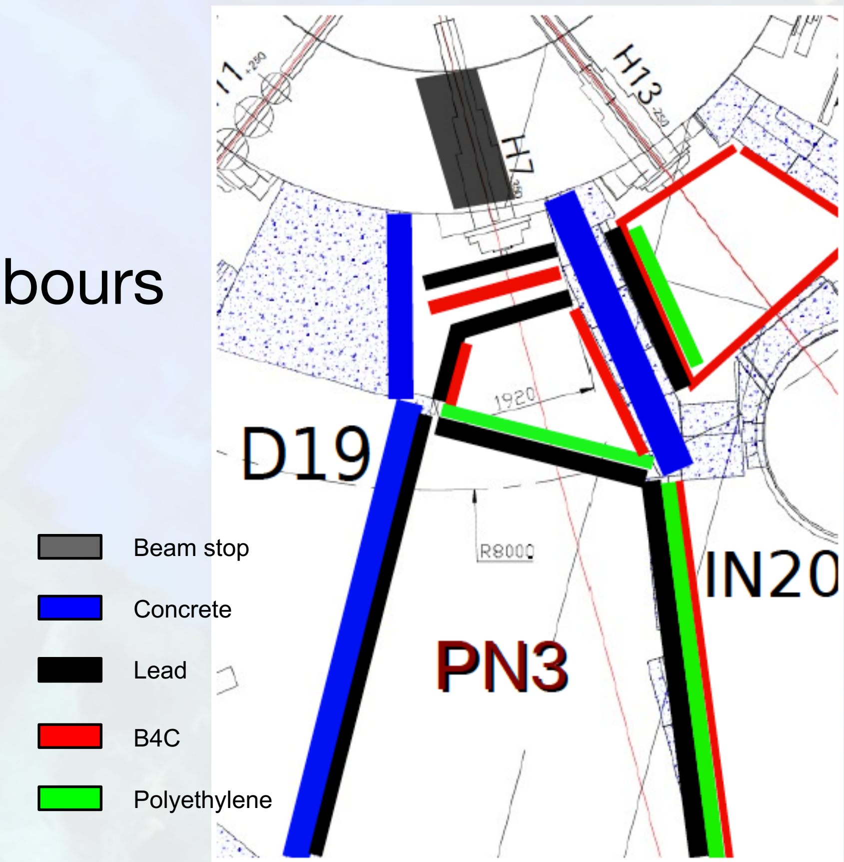


- VM2000 + air-gap + acrylic sandwiches (total reflection) to transport light to PMTs
- Looking for oscillation patterns: **relative shape in the 6 identical cells** (different L)

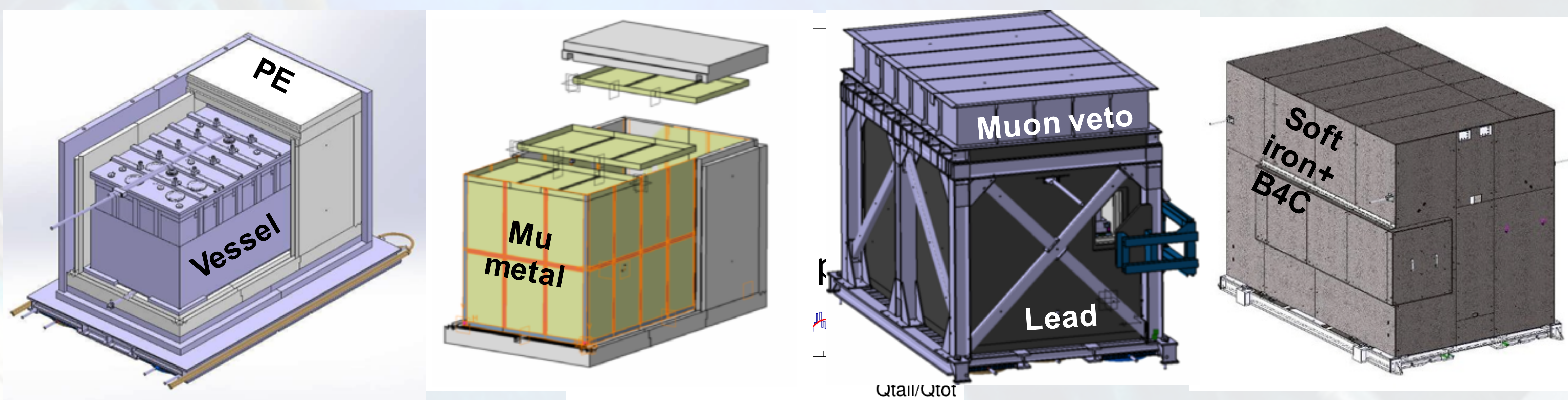




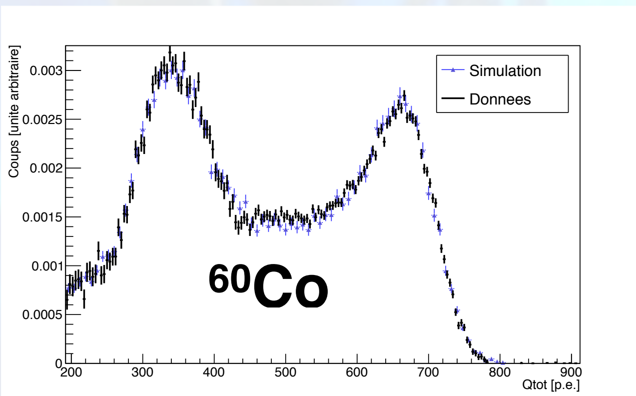
- Full on-site measurements for μ, n and γ backgrounds

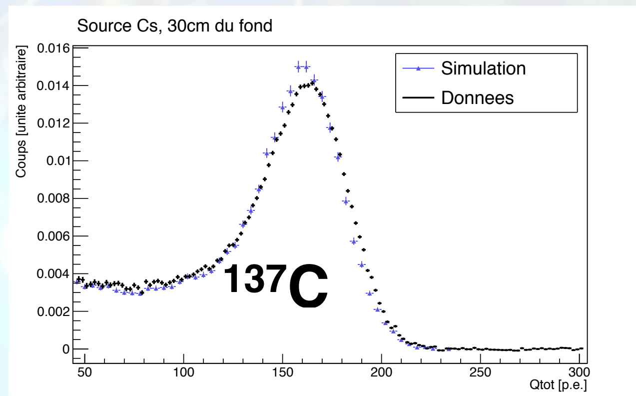


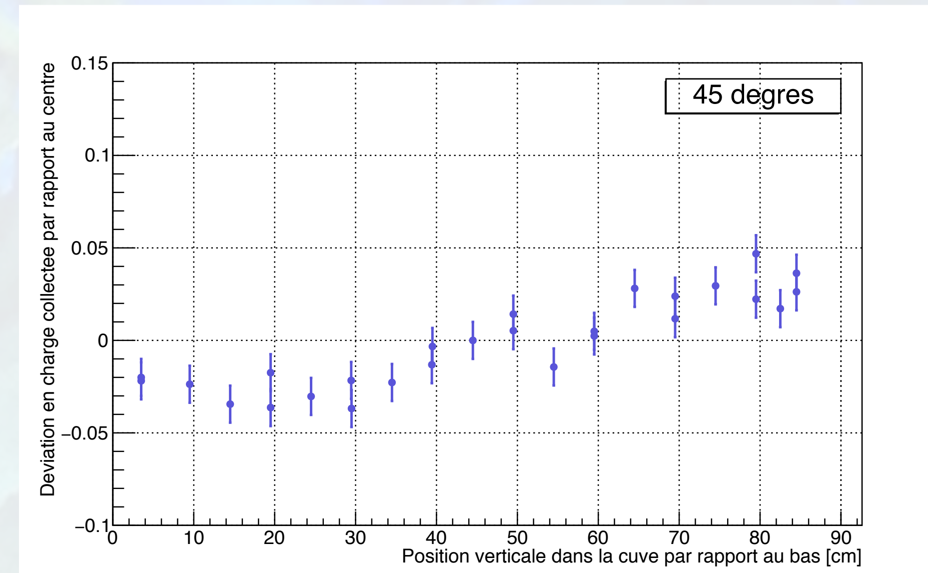
- **Reactor bkg reduced with shielding** from core/neighbours
  - μ-metal (magnetic fields)
  - Polyethylene + B^{4}C (reactor-induced neutrons)
  - Lead (reactor-induced γ-rays)
  - Soft iron (magnetic fields)
- **Cosmic background rejected with μ veto, online PSD + subtraction from off periods**



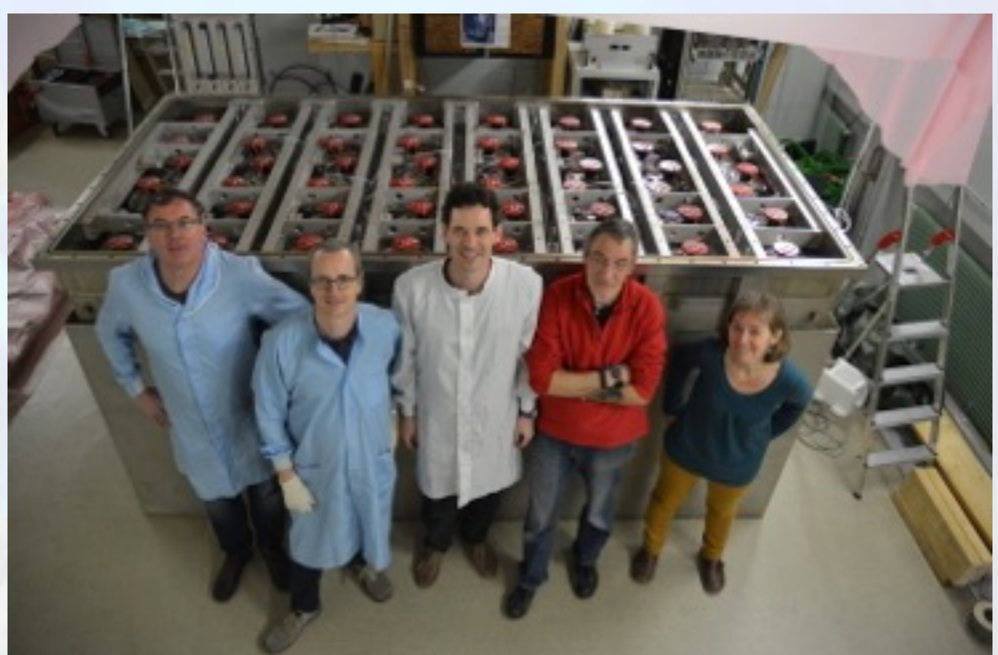
- Physics & simulation validated with a prototype

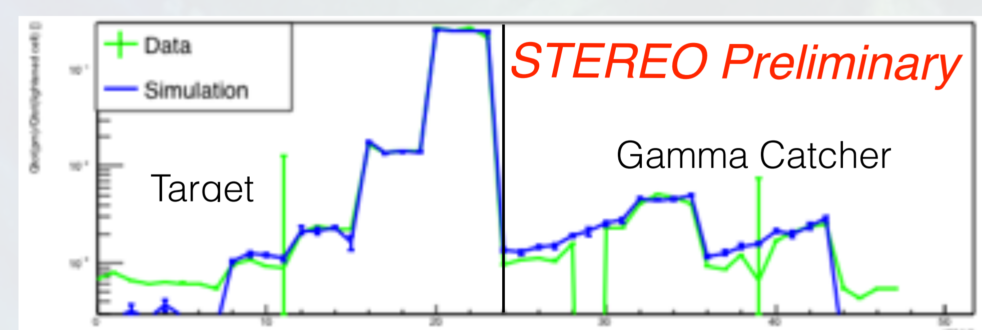






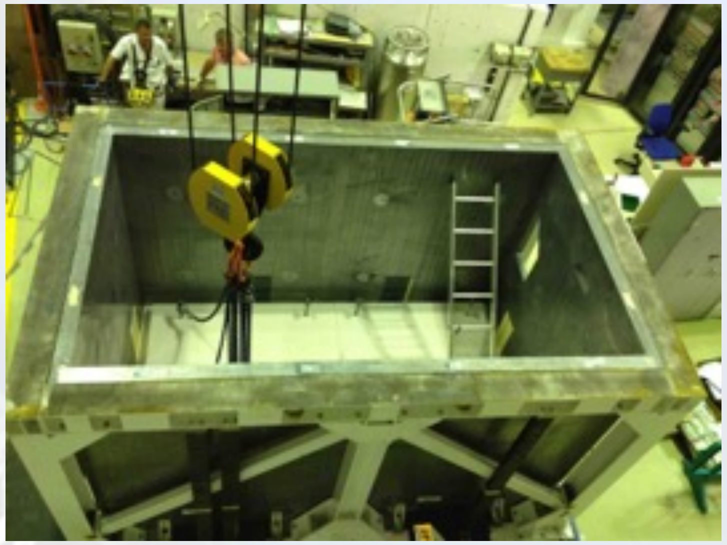
- **STEREO detector fully integrated**, first calibration runs taken with empty detector

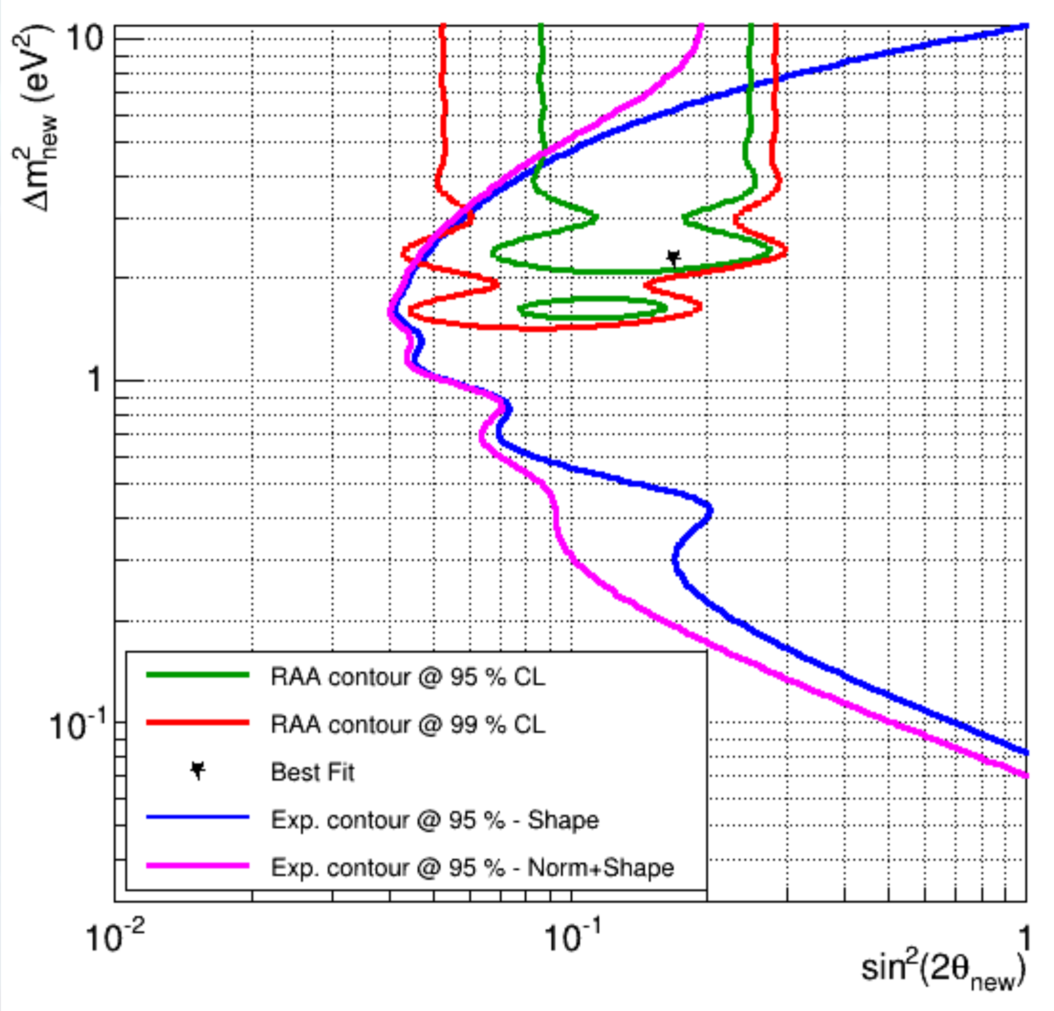




- STEREO detector is now @ ILL and waits for filling
- **Data taking this autumn, two reactor cycles expected by spring 2017**
- **STEREO aims to cover the reactor anomaly region in ~1 year of data taking**

- 400 ν/day in 300 days
- S/B = 1.5
- ν flux + 4% norm uncut
- Visible $E_{e+} > 2$ MeV
- $E_n > 5$ MeV ε_{det}=60%





Conclusions

- We are now entering an **exciting season of the sterile neutrino search era**
- **Reactor very short baseline experiments play a major role in the search of the sterile neutrino**
- **The RAA region can be covered in the year scale**
- These experiments can also shed light in the complex matter of reactor flux estimation
- The measure is challenging (near-surface cosmics level, reactor facilities)…
- …But many different techniques and technologies have been developed to reach this goal
- **SBL experiments are scattered all over the world, some are currently taking or about to take data, so stay tuned!**

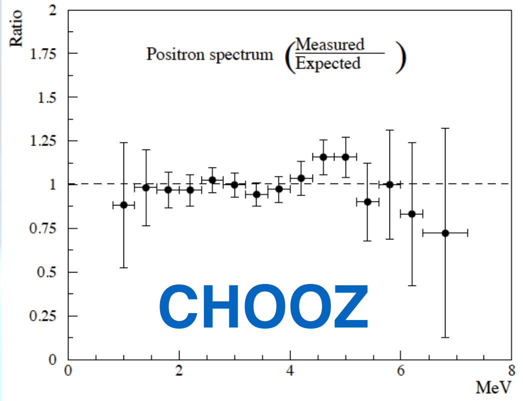
…thank you for you attention

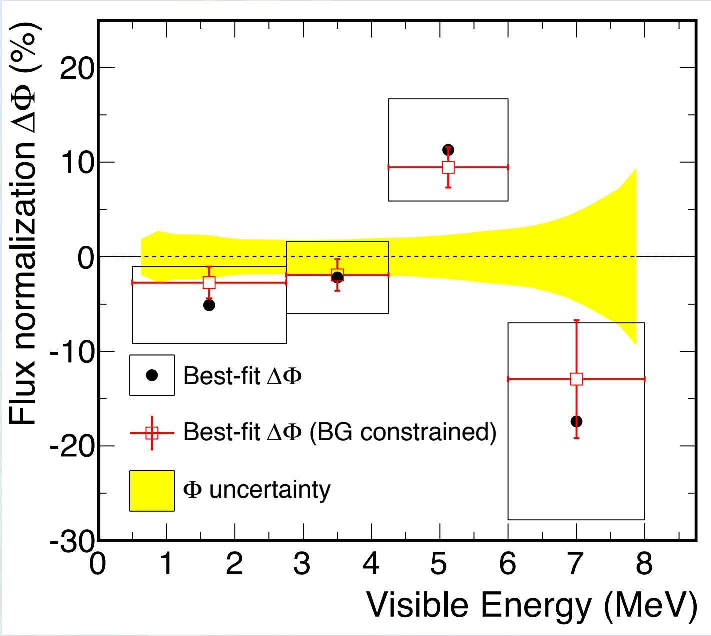
A special thank to: David Lhuillier, Leonidas Kalousis, Jelena Maricic, Derek Rountree, Pieter Mumm, Yoomin Ho, Anatolii Serebrov

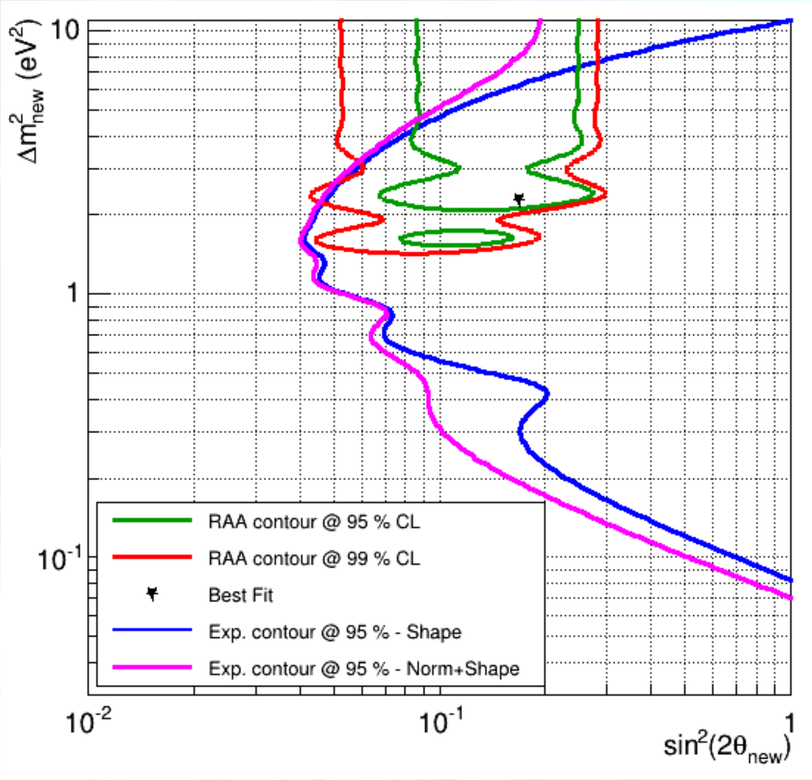
Backup

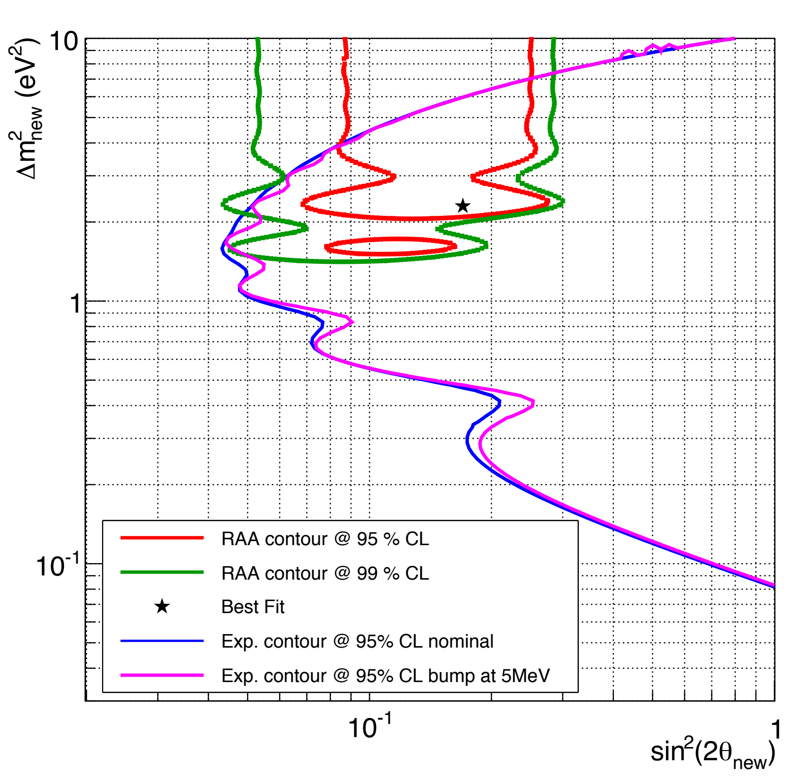
Spectral Distortion @ 5 MeV

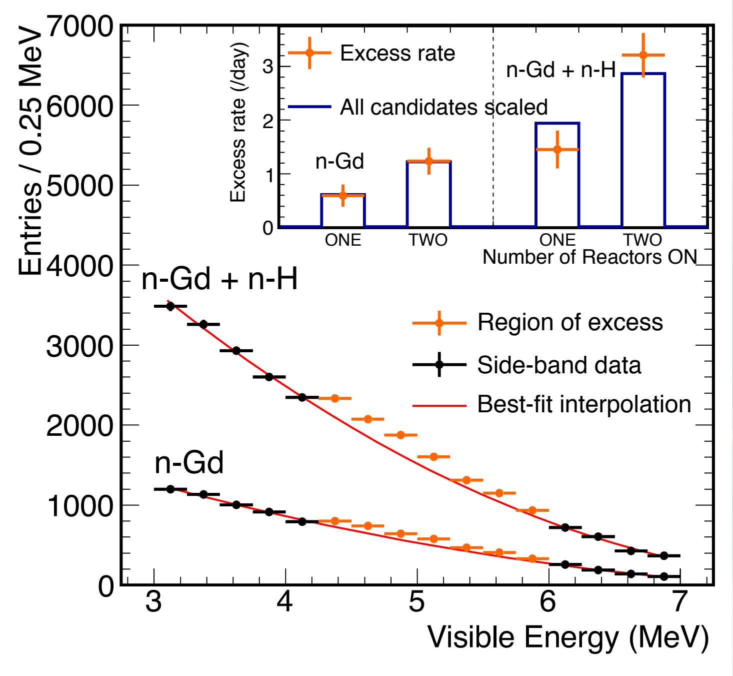
- 3σ (1.6σ) significance wrt flux prediction with (without) background constraint - origin still unknown
- First observed in Double Chooz (then Daya Bay & Reno)
- Slight impact on RAA sensitivity plot









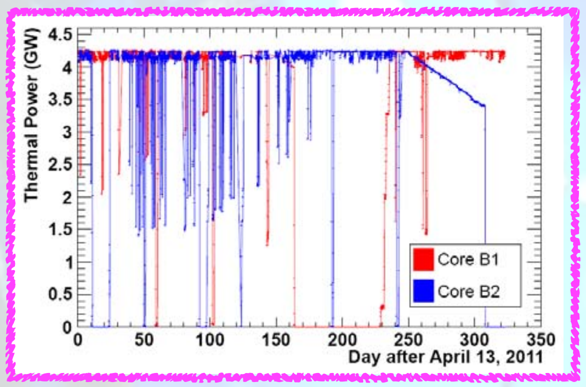


Neutrino Spectrum Prediction

- $\bar{\nu}_e$ produced in β-decay of fission products (^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U)

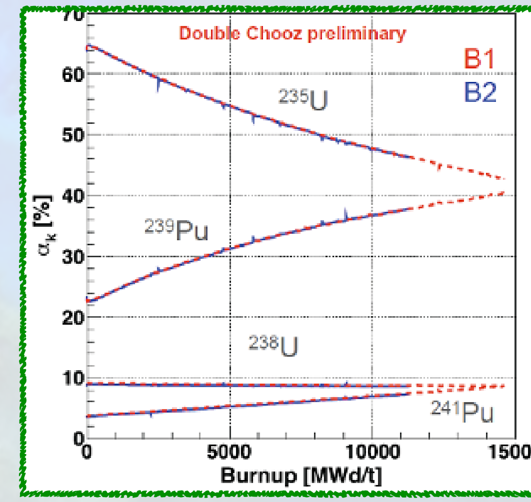
$$N_{\nu}^{\mathrm{exp}}(E,t) = \sum_{\mathrm{reactor}=1,2} \frac{N_p \epsilon}{4\pi L_R^2} \times \frac{P_{\mathrm{th,R}}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle (E,t)$$

Reactor thermal power



Average E released per fission

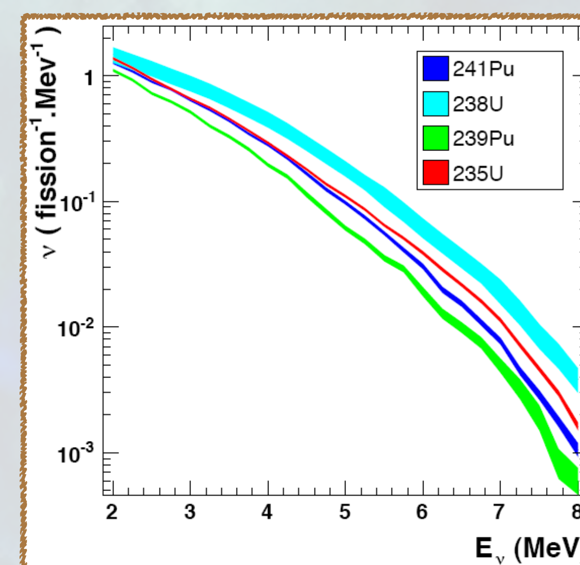
$$\langle E_f \rangle = \sum_k \boxed{\alpha_k} \cdot \langle E_f \rangle_k$$



Average cross section per fission, based on $\bar{\nu}$ spectrum

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \langle \sigma_f \rangle_k$$

$$\langle \sigma_f \rangle_k = \int dE \, \boxed{S_k(E)} \, \sigma_{IBD}(E)$$



- Single $\bar{\nu}$ spectra $S_k(E)$ not available, obtained from β spectrum
  - Ab initio - calculation branch-by-branch from decay schemes
  - Conversion - subtraction one-by-one of “virtual branches” from the measured global β spectrum

LSND and Gallium Anomalies

- Other anomalies suggesting the presence of extra sterile neutrinos at ~eV scale
  - ν_e appearence: LNSD & MiniBooNE excess in short-baseline $\nu_\mu \rightarrow \nu_e$ oscillations (somehow disfavoured by disappearance results)
  - ν_e disappearence: radioactive sources used to test SAGE & GALLEX obtained rates lower than expected