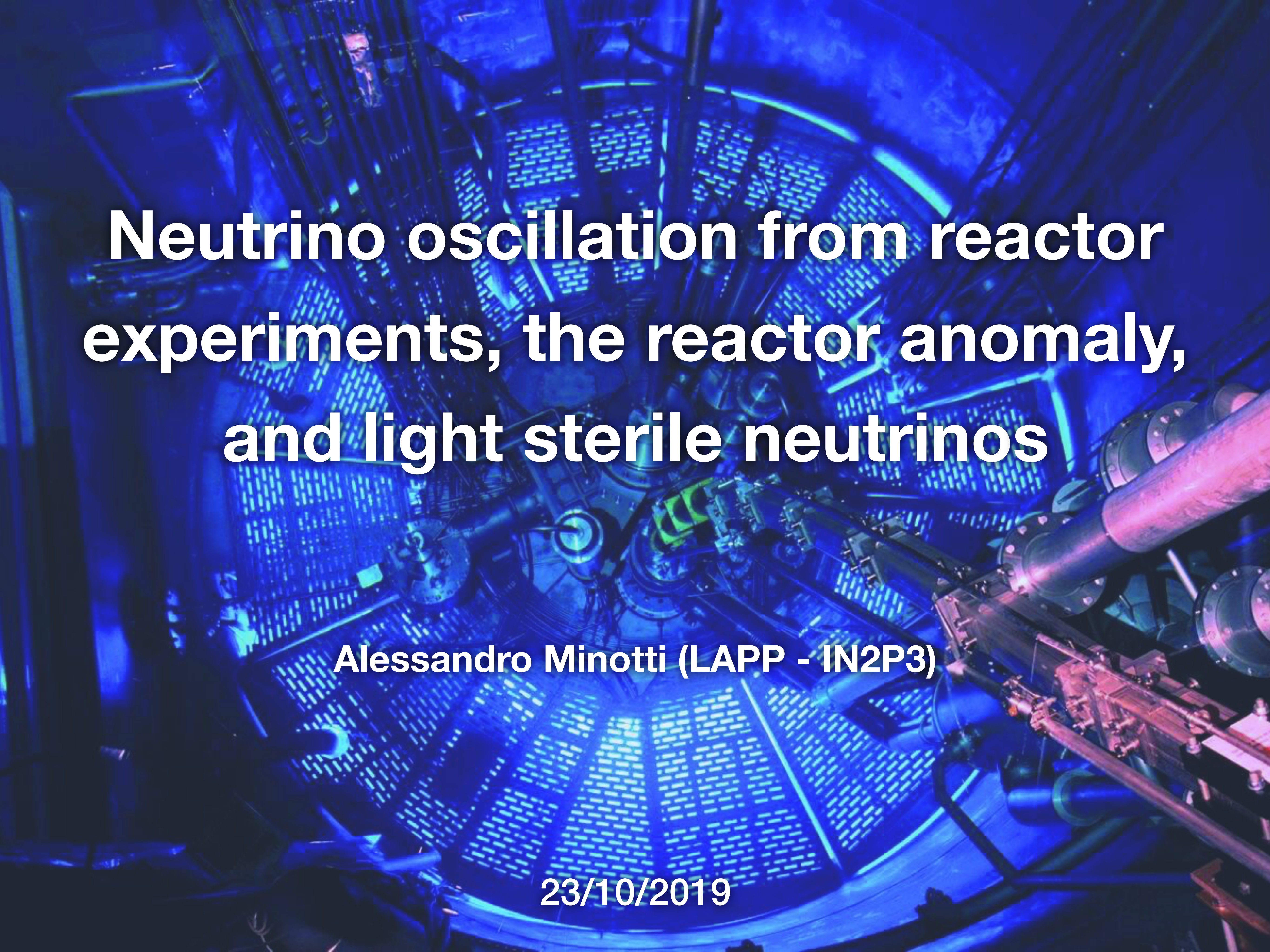

Neutrino oscillation from reactor experiments, the reactor anomaly, and light sterile neutrinos

Alessandro Minotti (LAPP - IN2P3)

23/10/2019

Outline

- Neutrino mixing and reactor neutrinos
- Anomalies challenging the 3-family framework
- The quest for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino flux and spectral estimation
- The future of reactor neutrinos: JUNO

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- **Neutrino mixing and reactor neutrinos**
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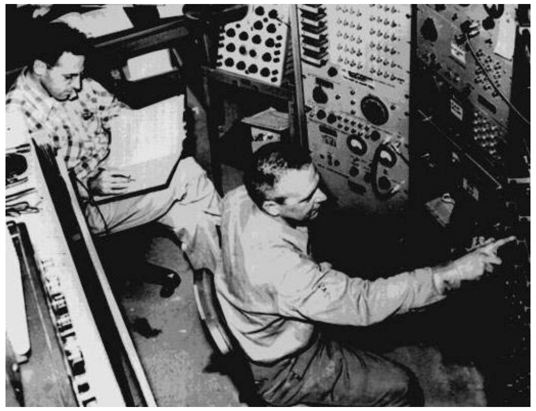
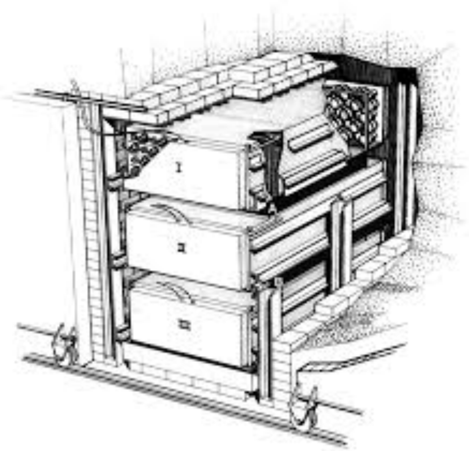
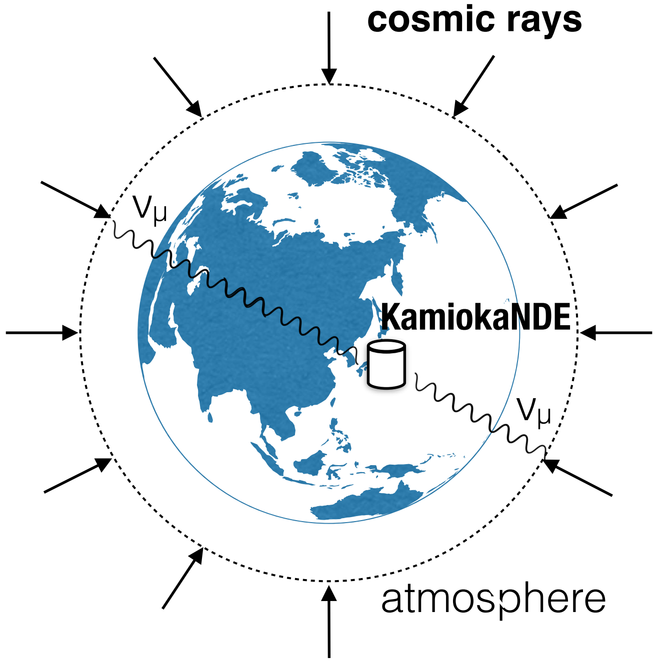
Discovery of the Neutrino

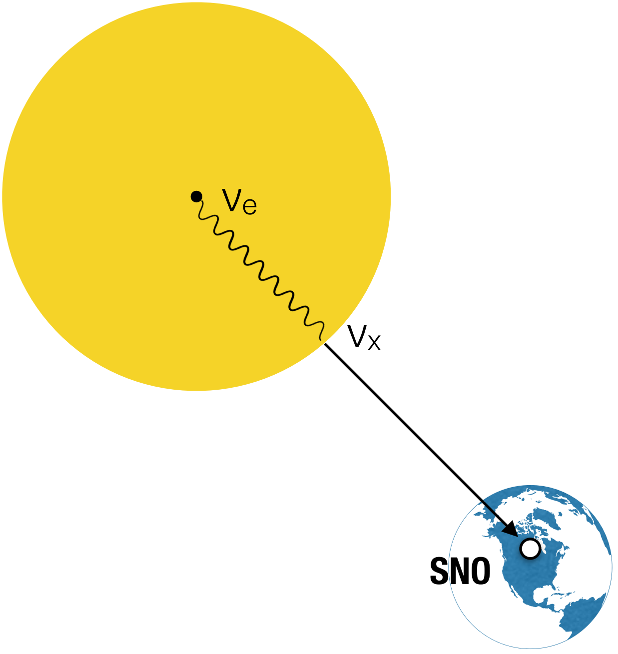
- **Cowan and Reines** used a reactor to **discover the neutrino** in 1956

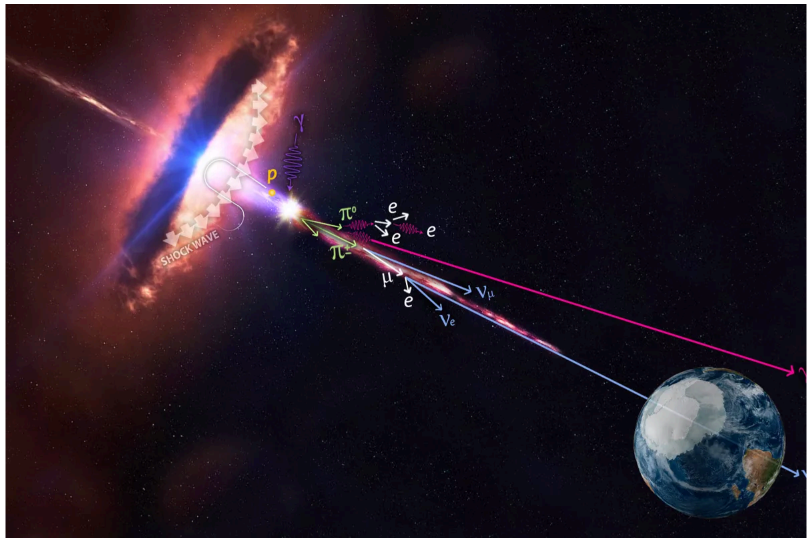




- Since then we observed neutrinos from the sun, atmosphere, distant astronomical objects, earth crust, and produced neutrino beams in accelerators



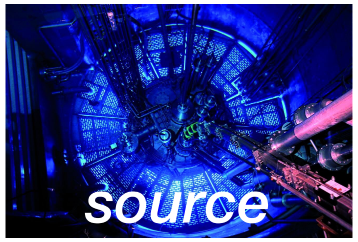




- Basic strategy of **massive detectors** (water- & scintillator-based) and detection technique exploited for years in several generations of experiments

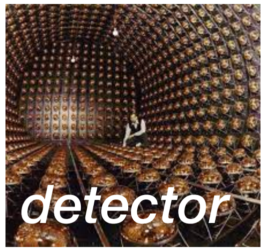
Neutrino Oscillation

- Neutrinos produced with a given flavour can be detected as a different one



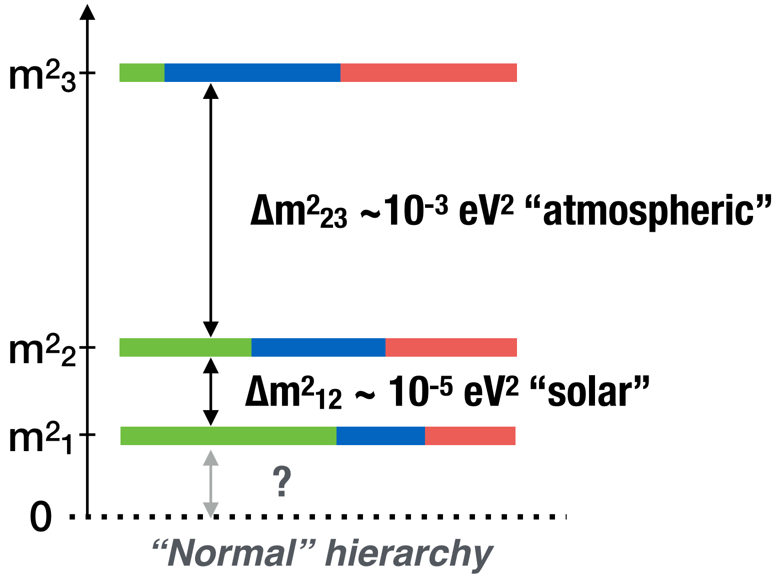
ν_e $\xrightarrow{\nu_1 \quad \nu_2 \quad \nu_3}$ ν_e? ν_μ? ν_τ?

$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$



- **Mixing** of flavour eigenstates and mass eigenstates: **U_{PMNS}** ⇒ **massive neutrinos**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



- **From oscillation we determine** U_{PMNS} parameters (mixing angles **θ_{ij}**) & squared-mass splittings **Δm^2_{ij}**

$$P_{\nu_\alpha \to \nu_\beta} = \langle \nu_\beta(L) | \nu_\alpha \rangle \simeq sin^2(2\theta_{ij}) sin^2(1.27\Delta m^2_{ij} L/E)$$

Neutrino Mixing Parameters

- Values of the mass splittings Δm^2 are very different (hierarchical) → U_{PMNS} parameters can investigated in different energy-baseline (L/E) ranges (sectors)

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{-i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector

- atmospheric neutrinos
- long-baseline neutrino beams

θ_{13} sector

- reactor neutrinos

★ CP-violating phase

Solar sector

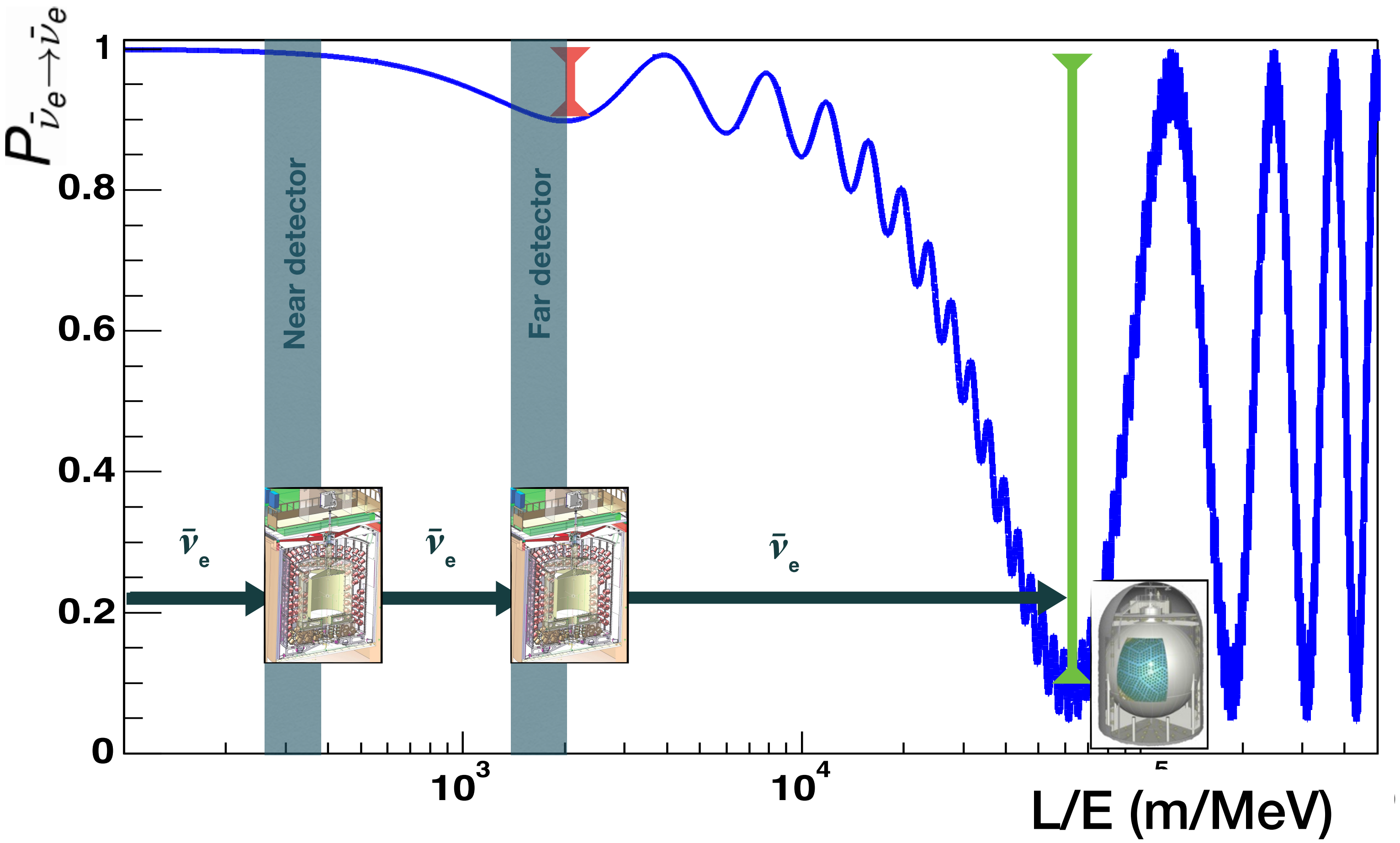
- solar neutrinos
- reactor neutrinos

- Reactor neutrinos contribute to two sectors at different baselines

- CP-violating phase and neutrino mass ordering are not yet known

Reactor Antineutrino Oscillation

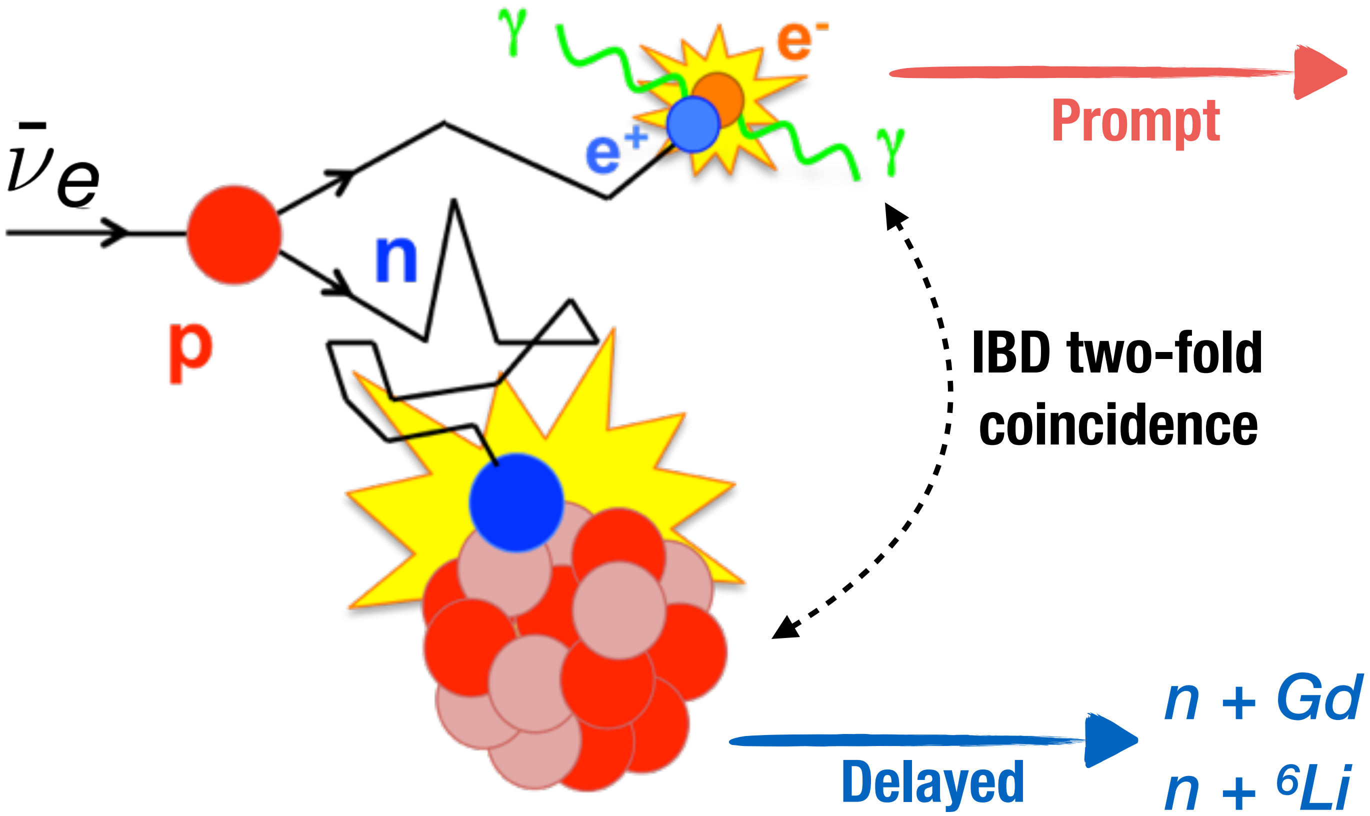
$$P_{\bar{\nu}_e\to\bar{\nu}_e} \simeq 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{23} L/4E) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta m^2_{12} L/4E)$$

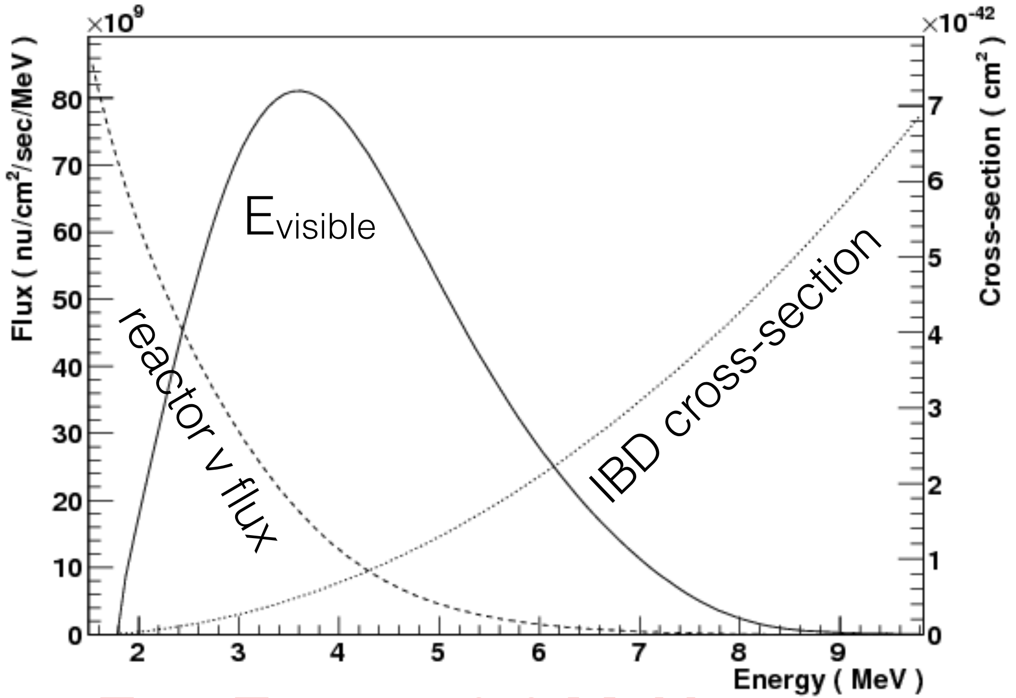


- **~50 km** → sensitive to **θ_{12}, Δm^2_{12}** (KamLAND)
- **~1 km** → sensitive to **θ_{13}** (Double Chooz, Daya Bay, RENO)

Reactor Antineutrino Detection

- **Signal**: **I**nverse **B**eta **D**ecay $\bar{\nu}_e \, p \to e^+ \, n$





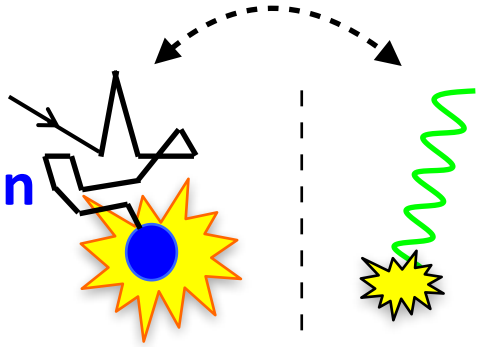
$E_\nu \simeq E_{visible} + 0.8\,\text{MeV}$

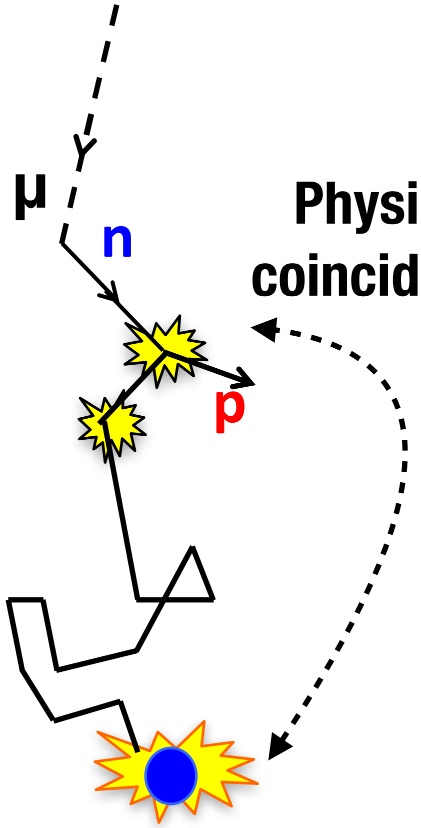
$n + Gd \to Gd^* + \gamma\text{'s}\ (8\,\text{MeV})$

$n + {}^6Li \to \alpha + {}^3H\ (4.78\,\text{MeV})$

- **Background**
  - Cosmic induced (fast n, n-γ from μ spallation)
  - Accidental coincidences between reactor n_{th} leakage, high-E γ's from n-capture on metals or natural radioactivity)

Accidental coincidence

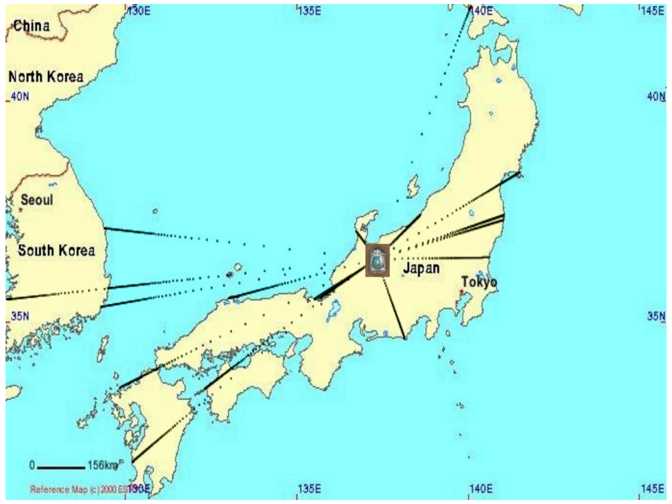




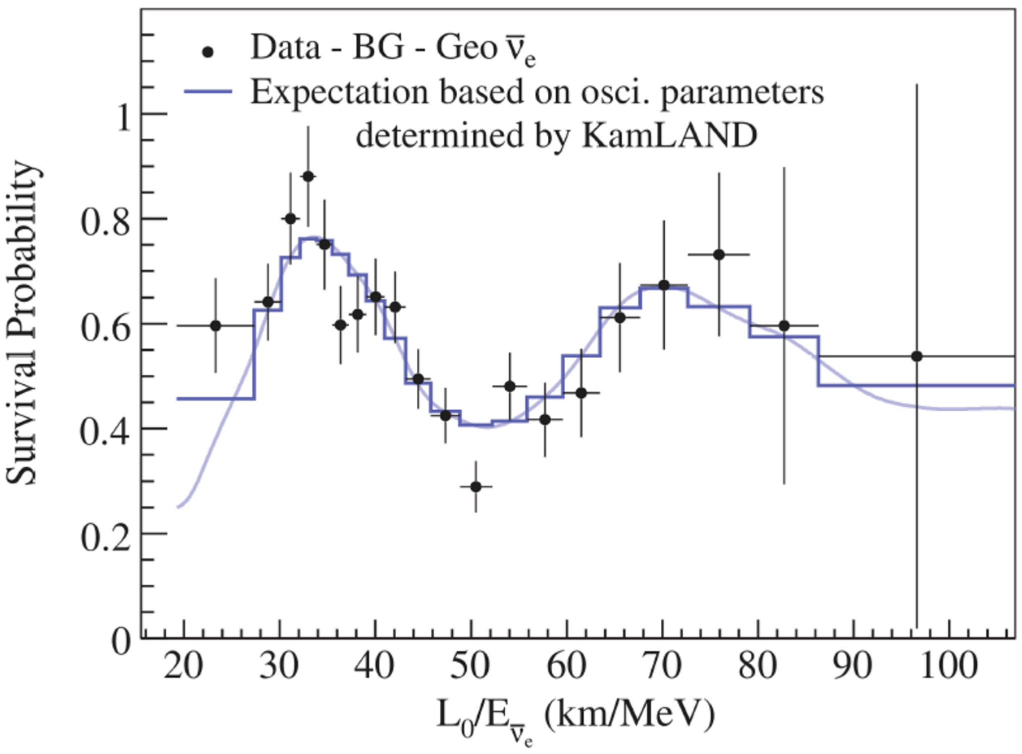
Physical coincidence

KamLAND and the Solar Neutrino Sector

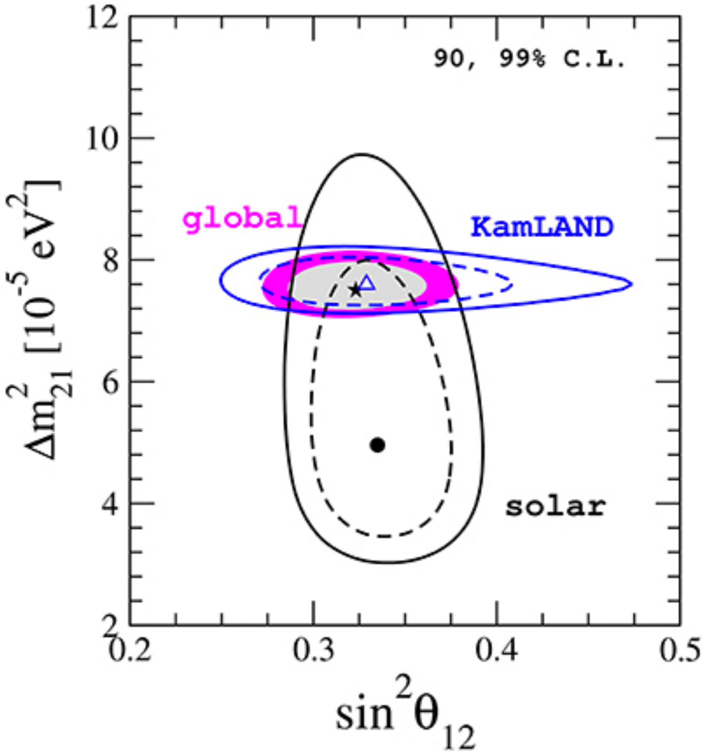
- **KamLAND** provided **accurate measurements** in the solar sector (θ_{12}, Δm^2_{12})



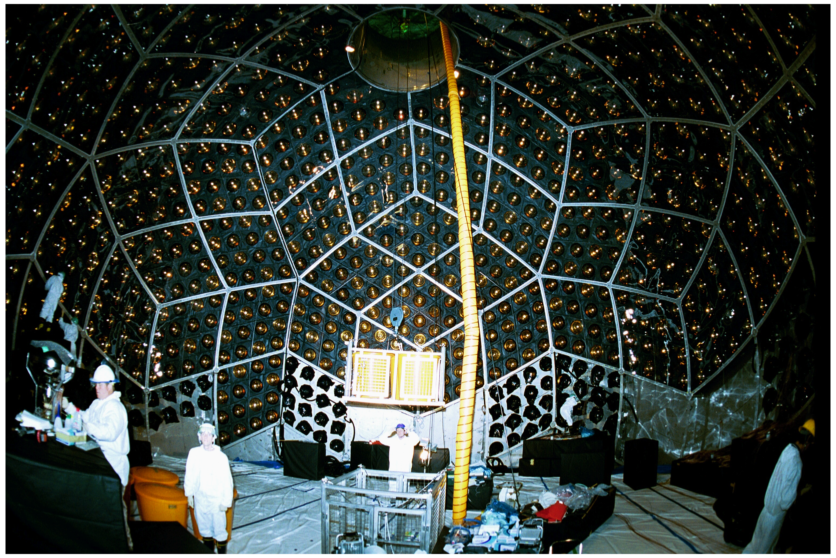
S. Abe et al. (KamLAND), Phys. Rev. Lett. **100.22** (2008): 221803.

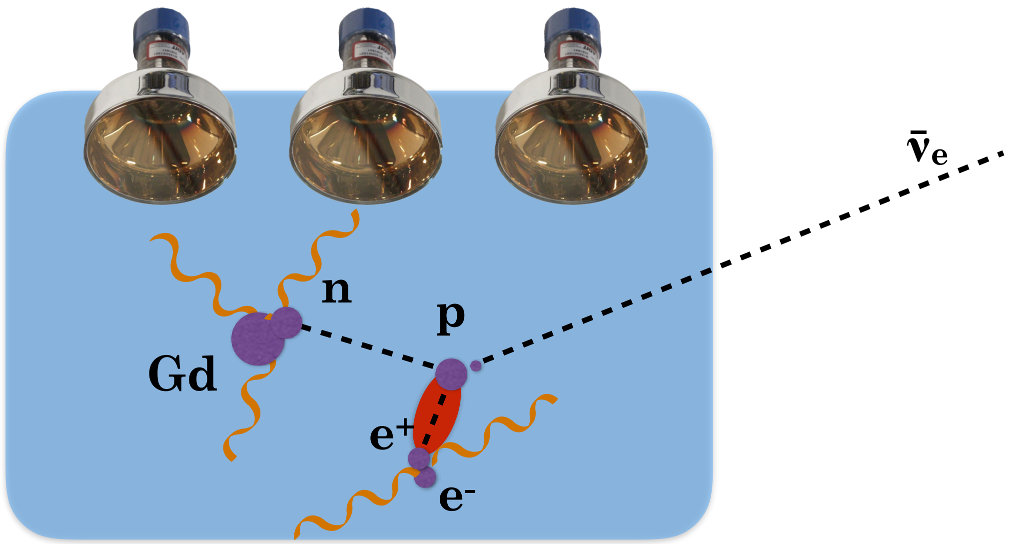


Farzan, Y. et al. Front.in Phys. 6 (2018)



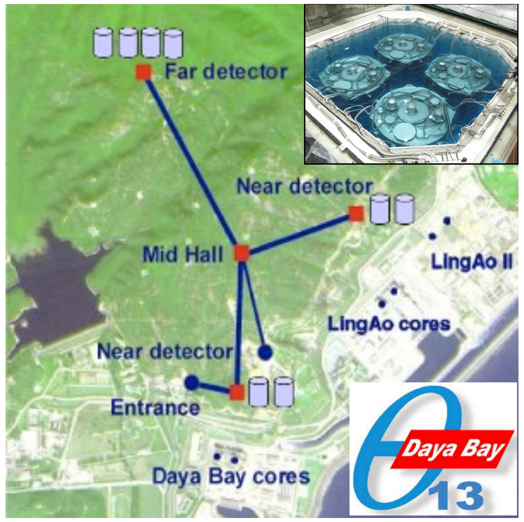
- **Scintillator + PMT** technique will be used **to detect reactor antineutrinos** for decades

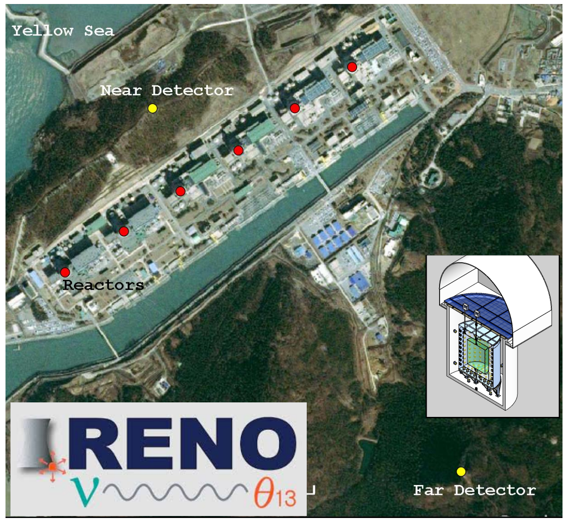




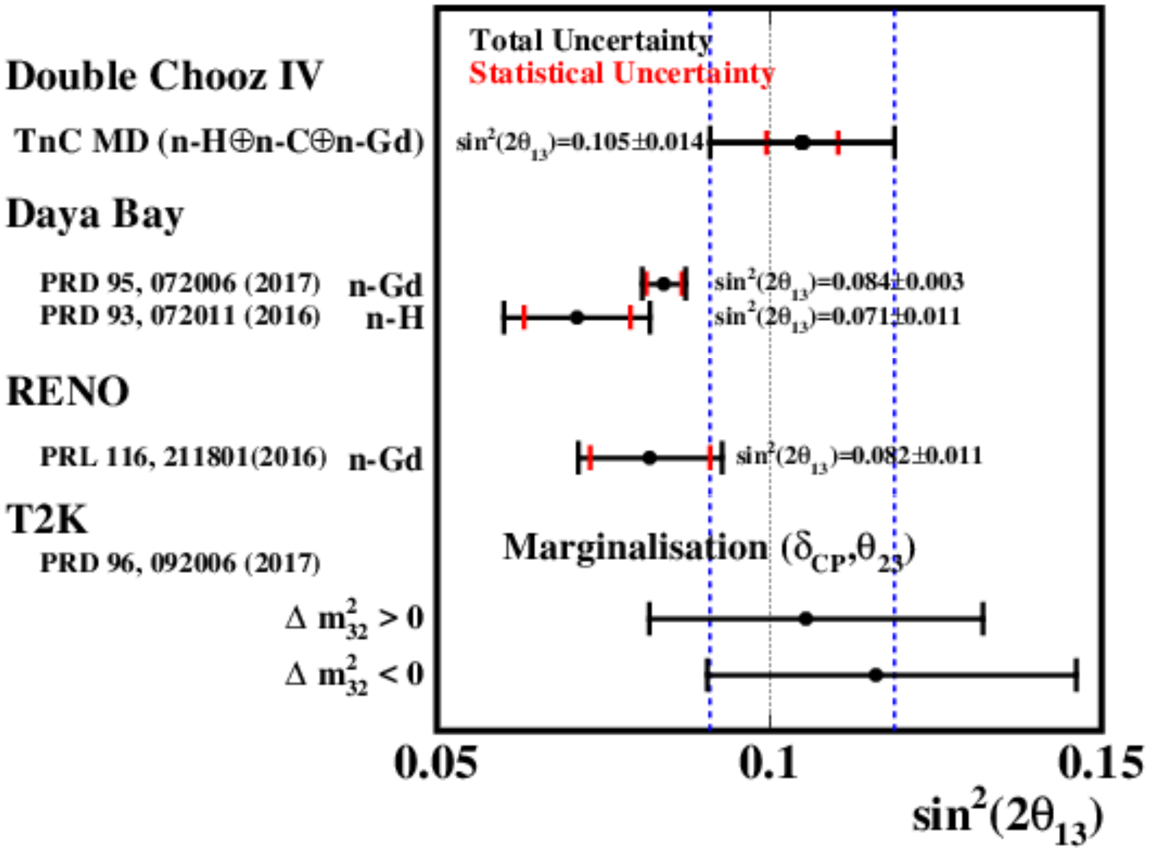
The Measurement of θ_{13}

- **Three experiments searching for θ_{13}** in the early 2010's with similar techniques





- **θ_{13}** used to be the missing mixing angle in U_{PMNS}, now is the one **measured with the highest precision (~3%)**



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Antineutrino Spectrum Estimation

- In low-enriched-uranium (LEU) facilities four isotopes contribute to neutrino spectrum (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu), their fraction $\boldsymbol{\alpha_k}$ evolves with time (burnup)

$$N_{IBD}(E_{\bar{\nu}_e}, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{\boxed{P_{th}(t)}}{\boxed{\langle E_f \rangle (t)}} \times \boxed{\langle \sigma_f \rangle (E_{\bar{\nu}_e}, t)}$$

reactor thermal power

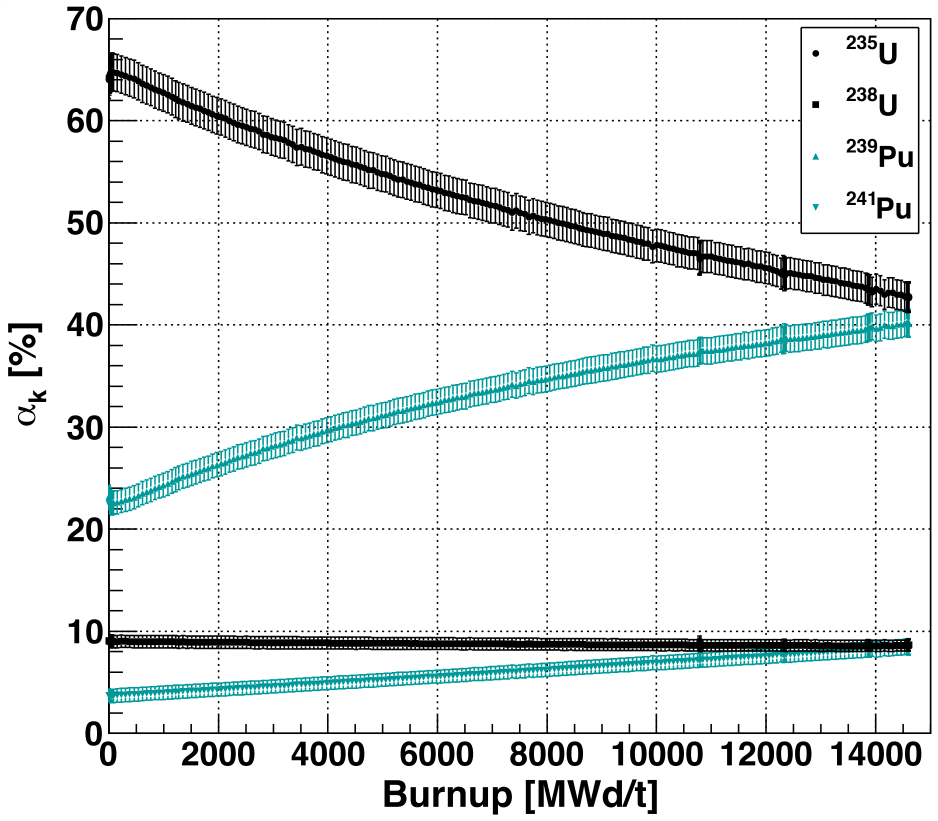
average energy released per fission

$$\langle E_f \rangle = \sum_k \alpha_k(t) \, \langle E_f \rangle_k$$

average IBD cross-section per fission

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

- IBD cross-section from theoretical calculations



- **Single $\bar{\nu}$ spectra** *$S_k(E)$* unavailable, **obtained from global β spectrum** ($\mathcal{O}\,10^3$ branches)
  - Start with known branches from nuclear data tables…
  - … and complement with *effective decay branches*

Reactor Antineutrino Anomaly

- Mueller (^{238}U)-Huber (^{235}U, Pu) IBD rate calculation

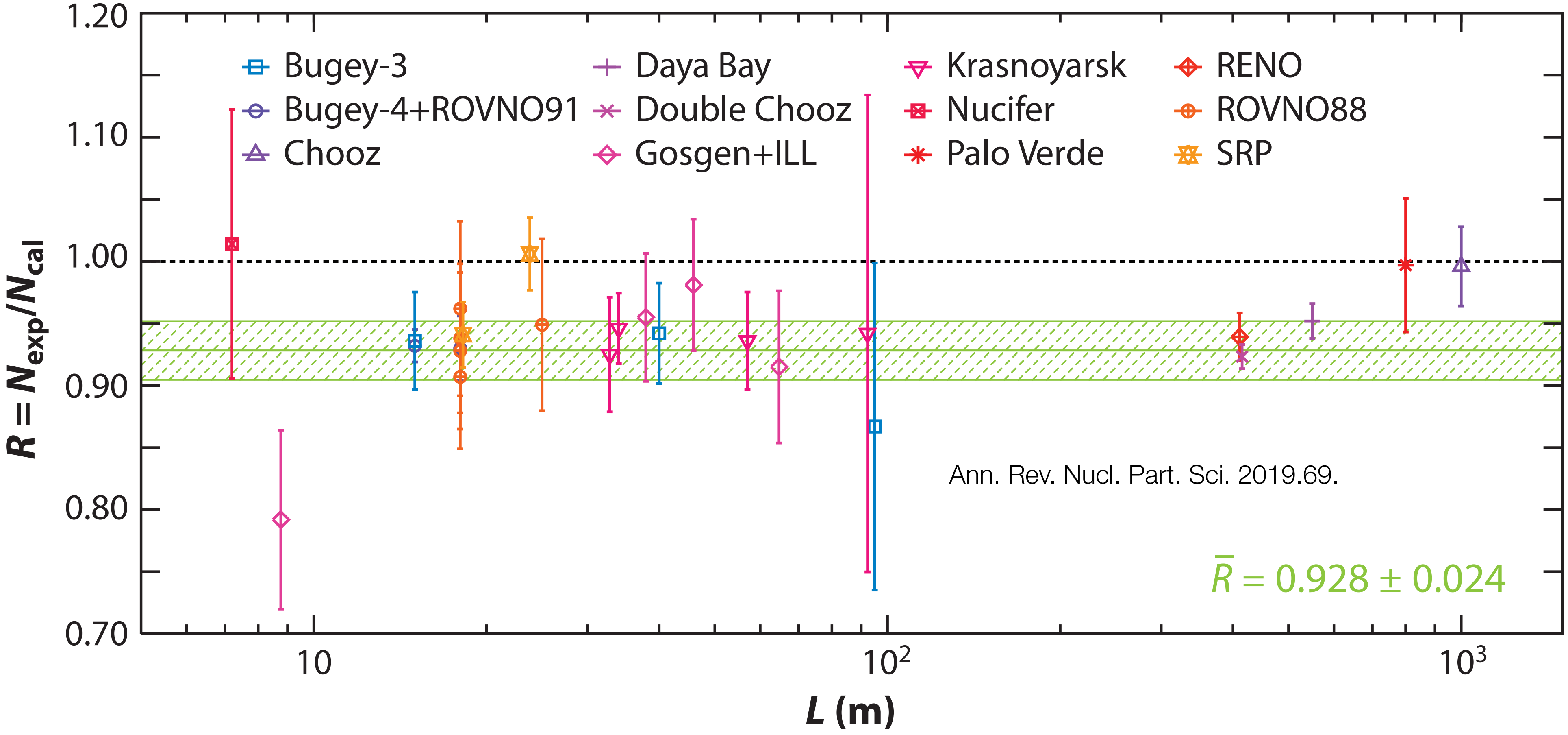
Mueller et al., Phys. Rev. C **83.5** (2011): 054615

Huber P., Phys. Rev. C **84.2** (2011): 024617

- **Rate excess of ~6% in the model** compared to previous short baseline measures

Mention et al., Phys. Rev. D **83.7** (2011): 073006

- Discrepancy confirmed by Double Chooz, Daya Bay and RENO near detectors



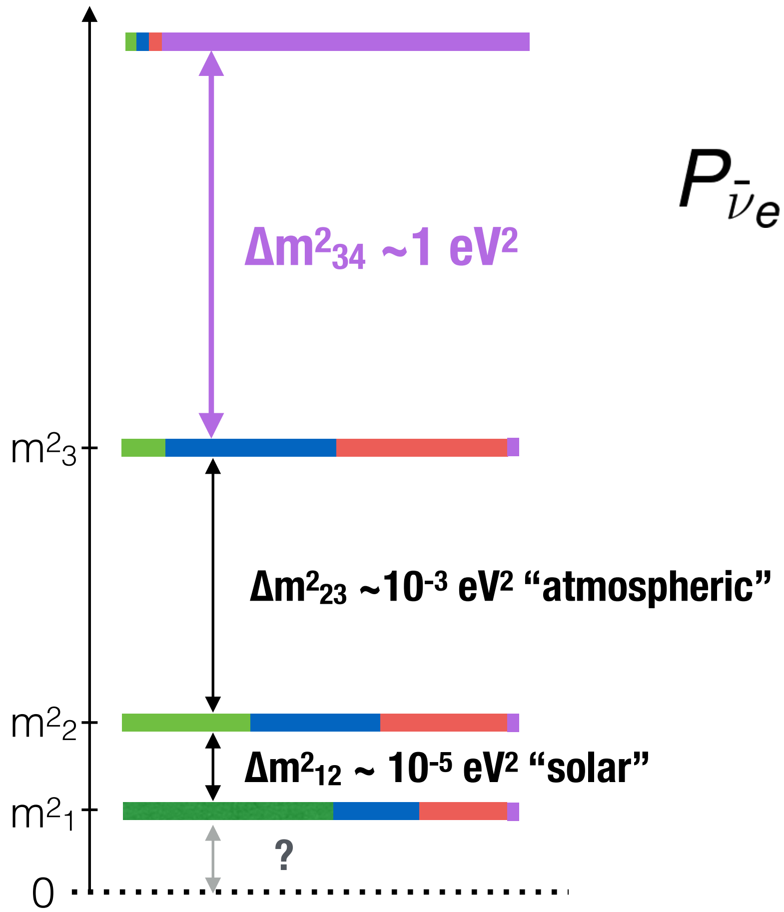
Ann. Rev. Nucl. Part. Sci. 2019.69.

The Light Sterile Neutrino

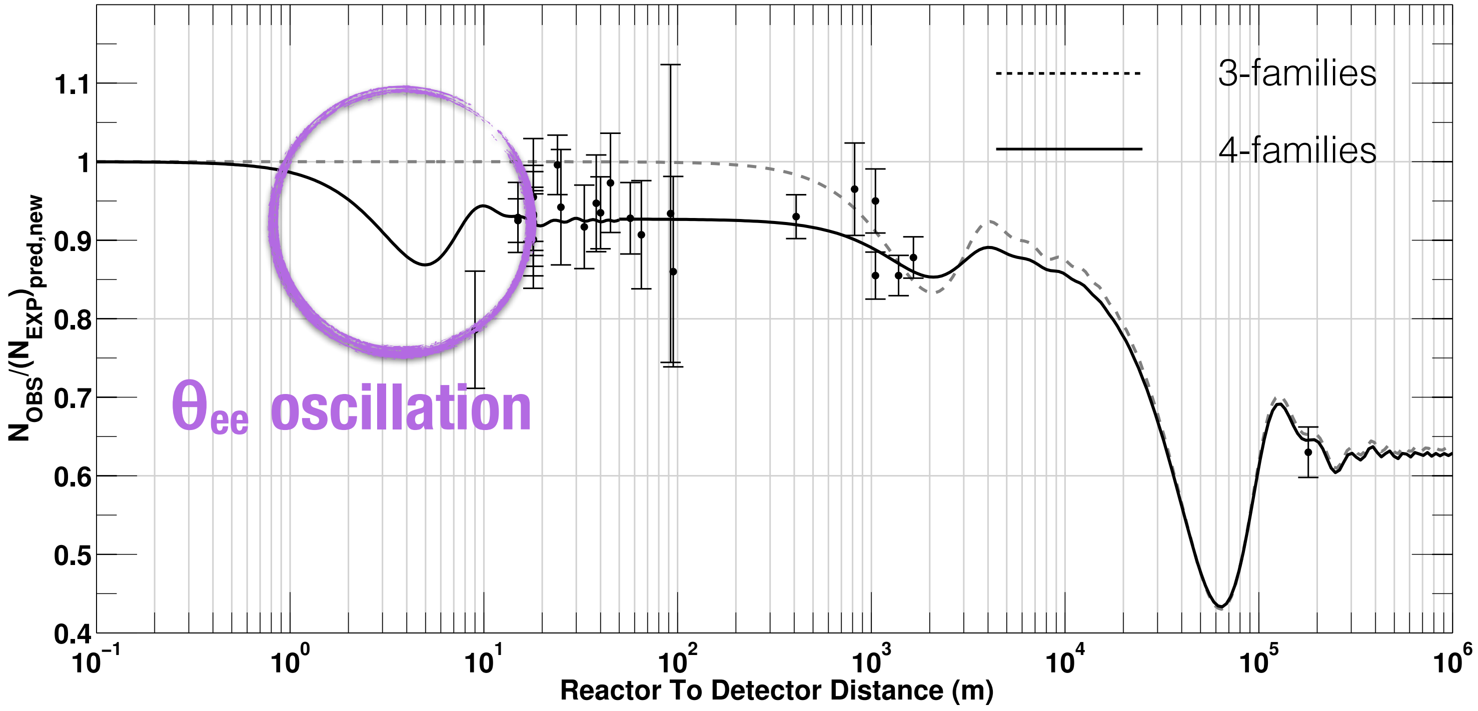
- Adding a **new neutrino** (0.1-1 eV mass) consisting almost exclusively of an **extra sterile flavour** can account for the observed deficit

- **Sterile neutrinos** do not interact weakly but **mix with standard neutrinos**

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



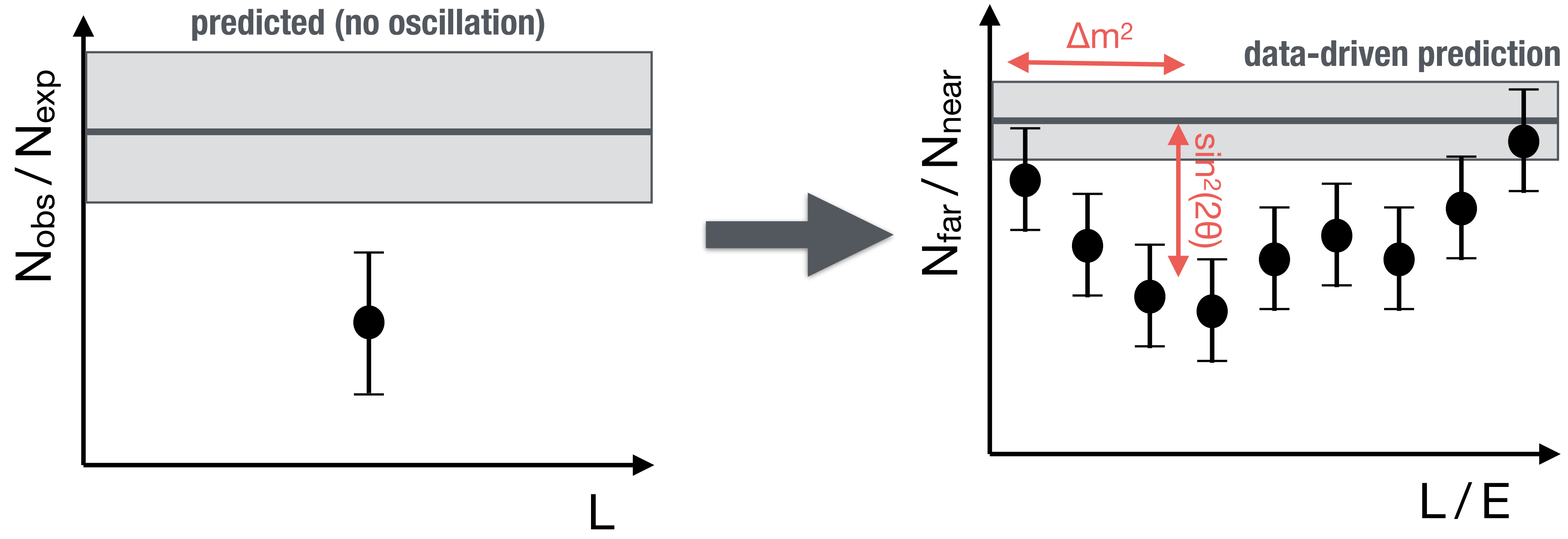
$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L \lesssim 10m) \simeq 1-\sin^2(\theta_{ee}) \sim^2 (1.27\Delta m^2_{14} L/E)$$



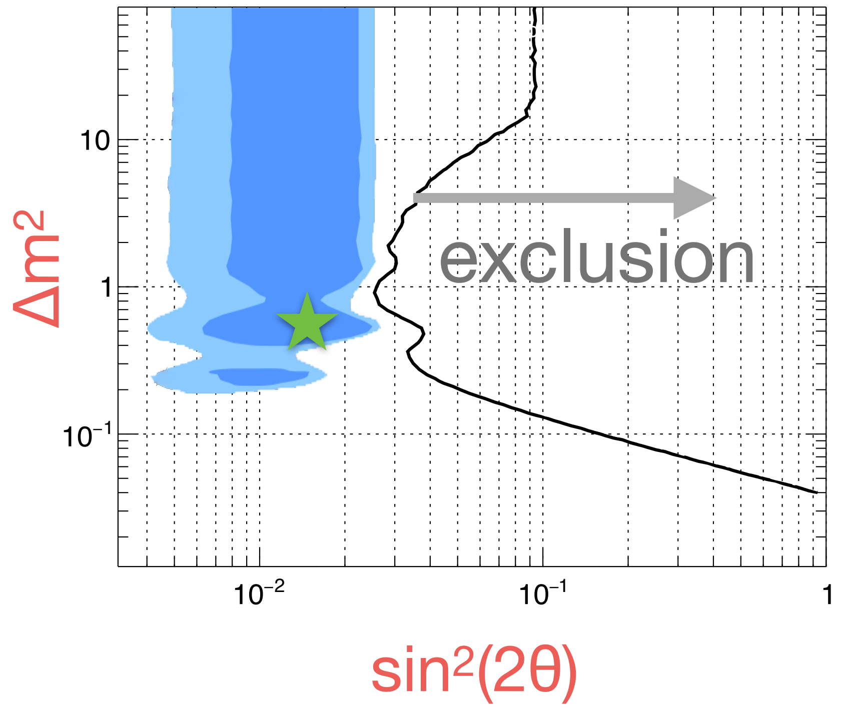
θ_{ee} oscillation

Search for the Light Sterile Neutrino

- Difficulty in predicting neutrino rate limits the sensitivity of past measurements, need to **disentangle the oscillating signature from the absolute rate**



- Oscillation parameters (Δm^2, θ) are tested against data
  - Oscillation hypothesis ⇒ **contour plot** + **best fit**
  - Null hypothesis ⇒ **exclusion plot**



Not the Only Anomaly

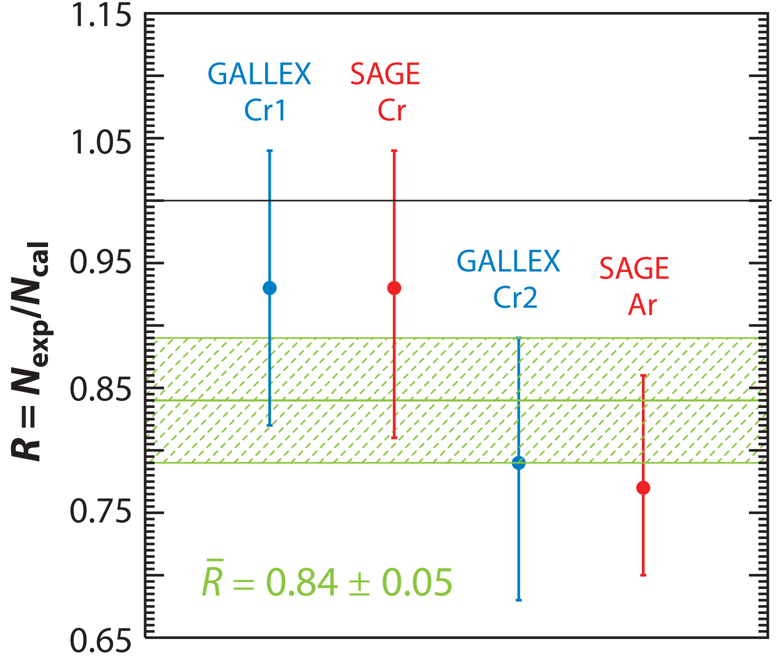
- **Gallium anomaly** - **disappearance of ν_e** measured with radioactive sources in gallium experiments GALLEX and SAGE (rate only)

- **LSND/MiniBooNE anomaly** - energy-dependent event **excess in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel** consistent with an active-sterile oscillation with **$\Delta m^2 \gtrsim 0.1$ eV^2**

- **All these anomalies can be explained by the existence of a light sterile neutrino**

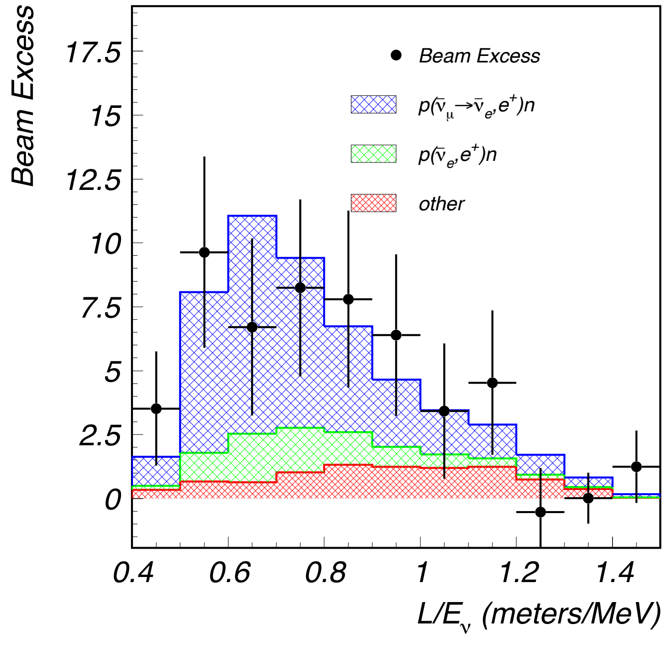
Phys. Lett. B **685:47** (2010)

Phys. Rev. C **73:045805** (2006)



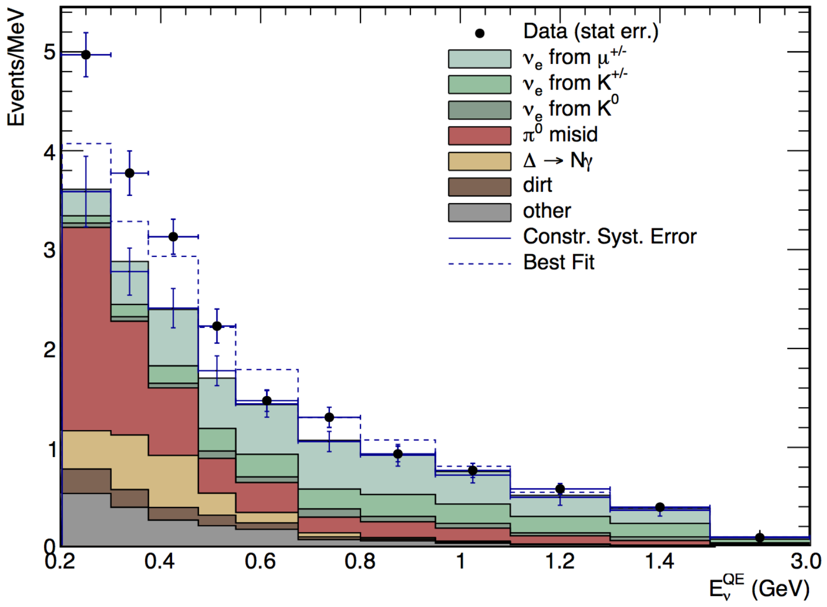
Phys. Rev. D **64:112007** (2001)

LSND



Phys. Rev. Lett. **121**, 221801 (2018)

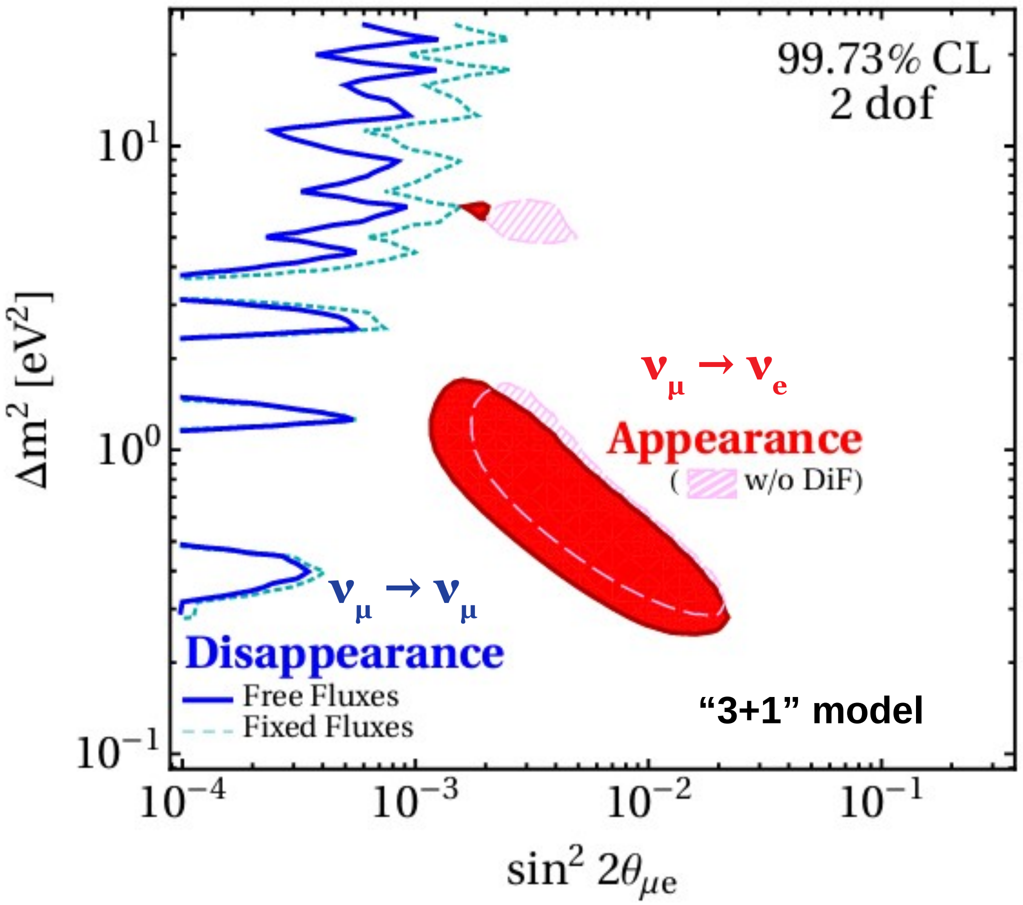
MiniBooNE



Combining Anomalies

- A global simple solution combining all these anomalies is not possible
- In addition, **LSND/MiniBooNE anomaly** ($\nu_\mu \rightarrow \nu_e$) is **highly disfavoured** by disappearance ($\nu_\mu \rightarrow \nu_\mu$) results
- The **Reactor/Gallium anomaly** remains yet **to be tested**

Dentler M, et al. JHEP **08:010** (2018)



"3+1" model

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P_{\nu_e \rightarrow \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{\nu_\mu \rightarrow \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

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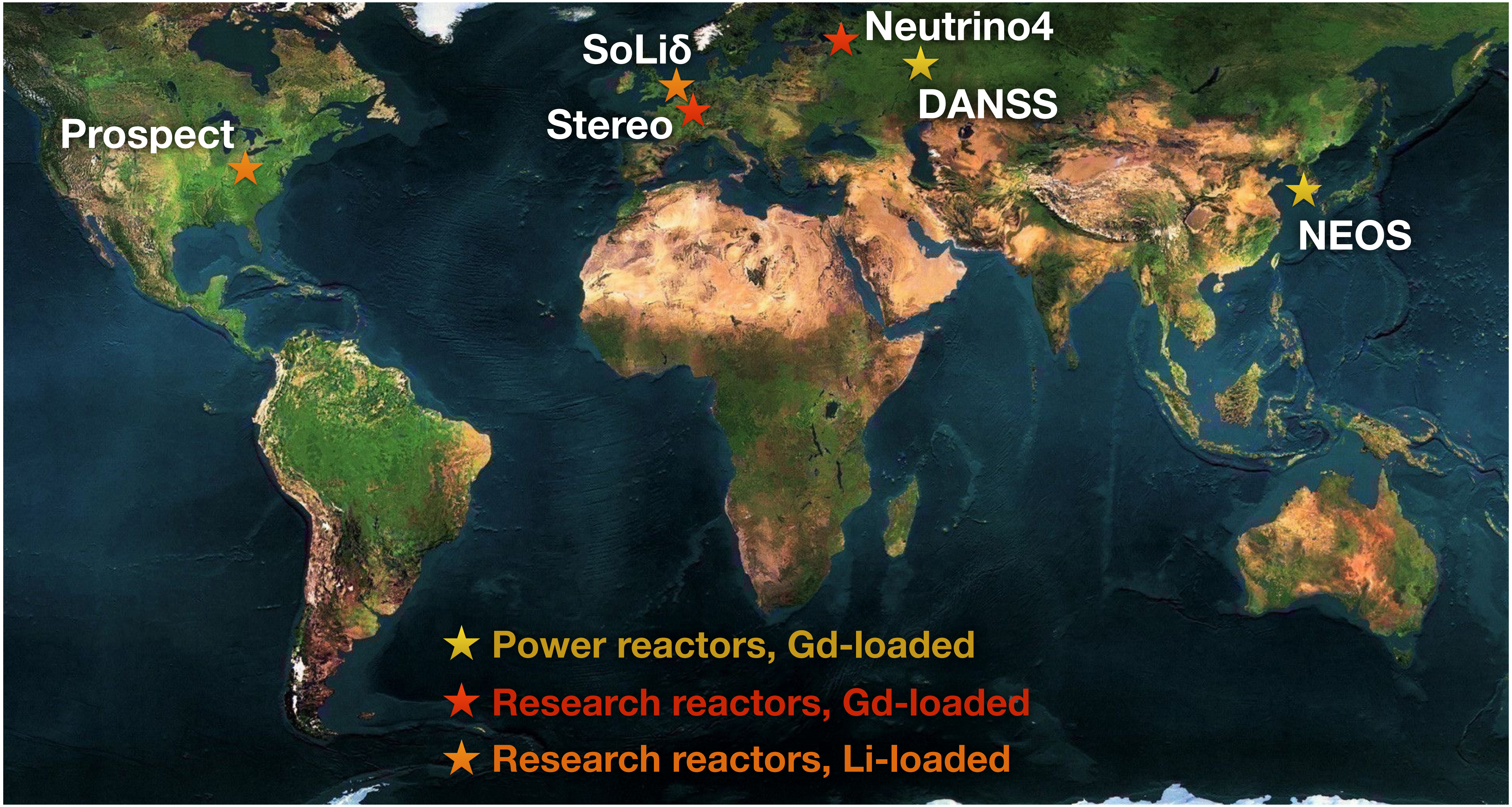
A World-Wide Hunt

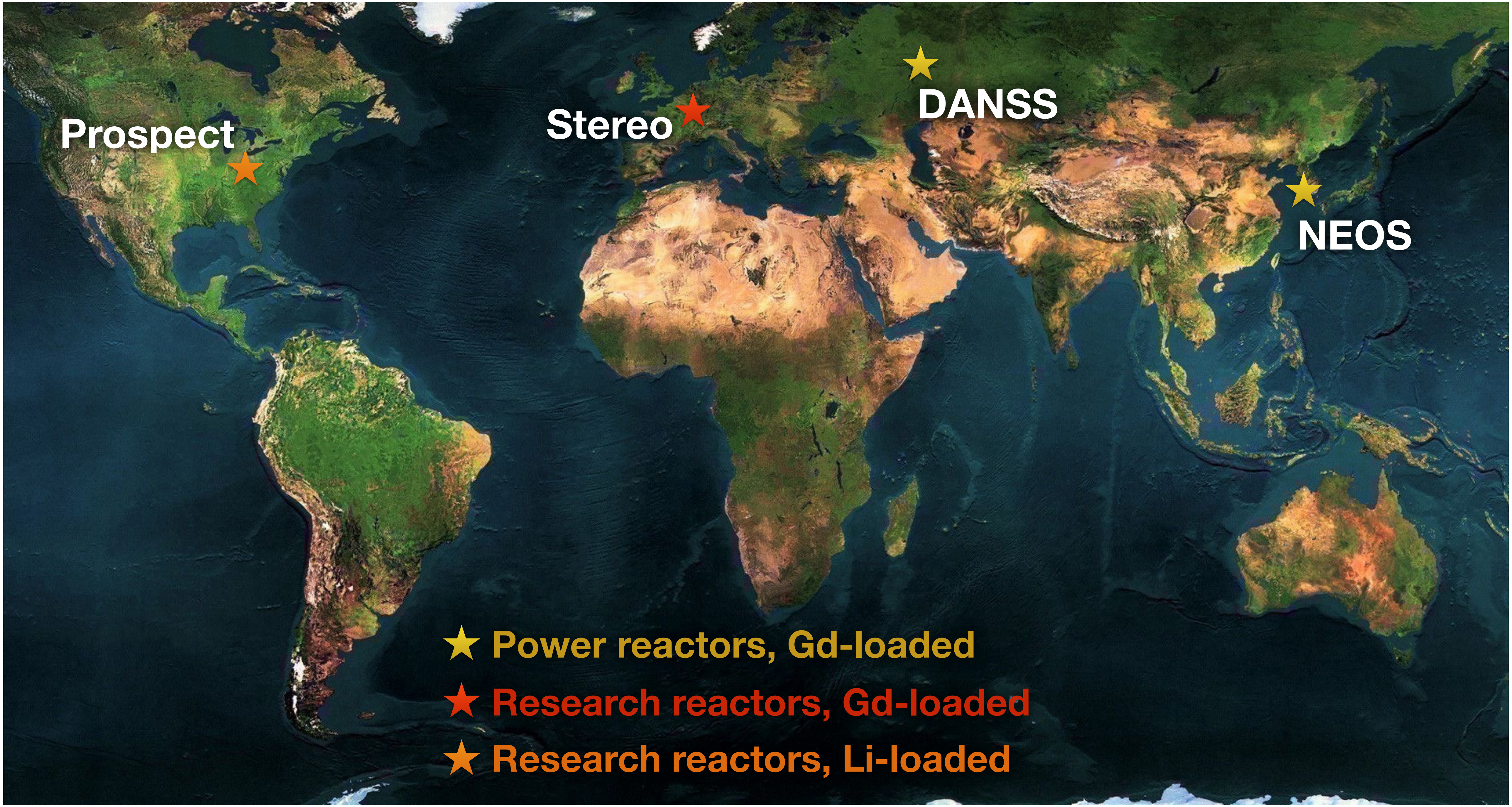


★ Power reactors, Gd-loaded

★ Research reactors, Gd-loaded

★ Research reactors, Li-loaded

A World-Wide Hunt (This Talk)

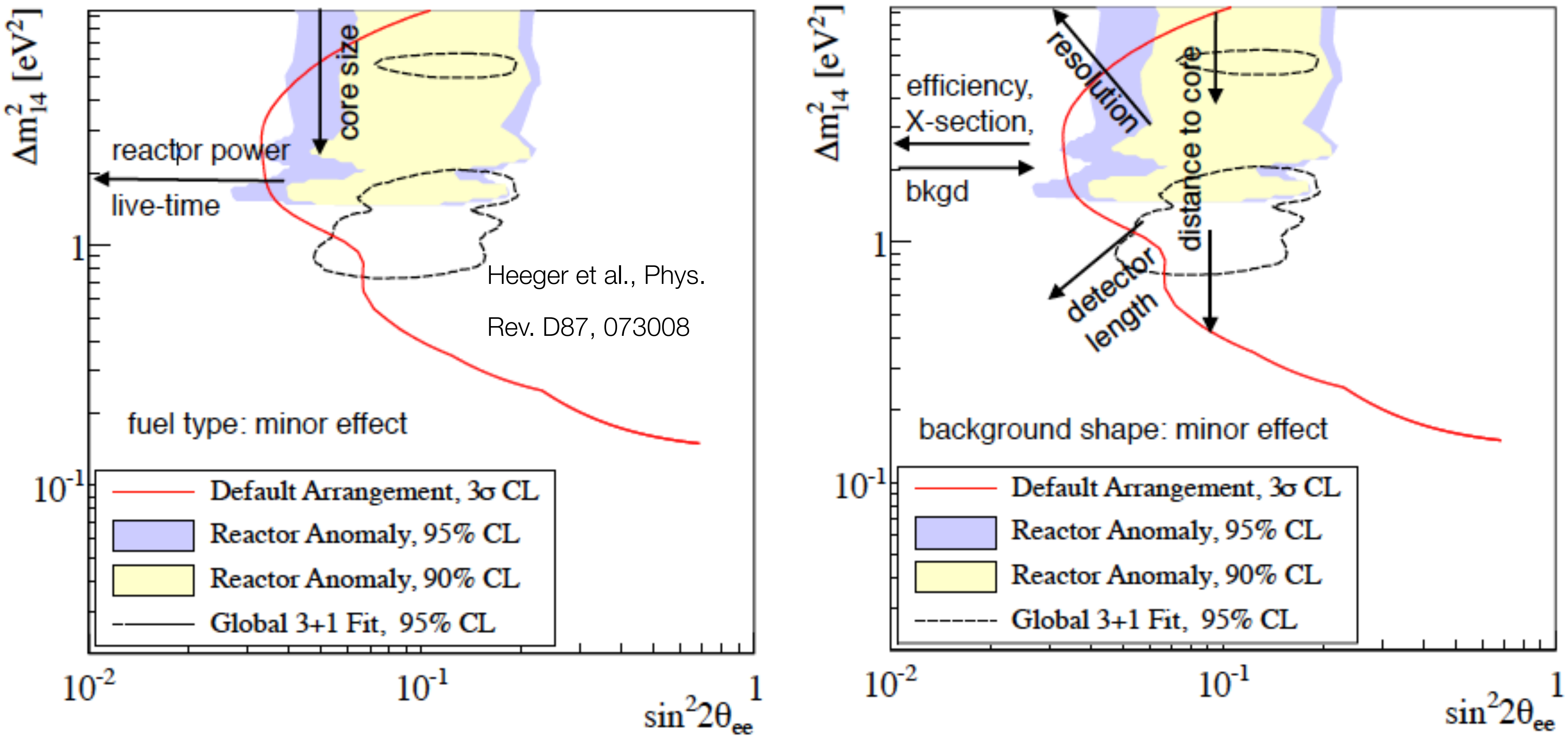


★ Power reactors, Gd-loaded

★ Research reactors, Gd-loaded

★ Research reactors, Li-loaded

Commercial vs Research Reactors



Heeger et al., Phys. Rev. D87, 073008

★$\Delta m^2 > 10$ eV^2
$L_{osc} < E_{res}$

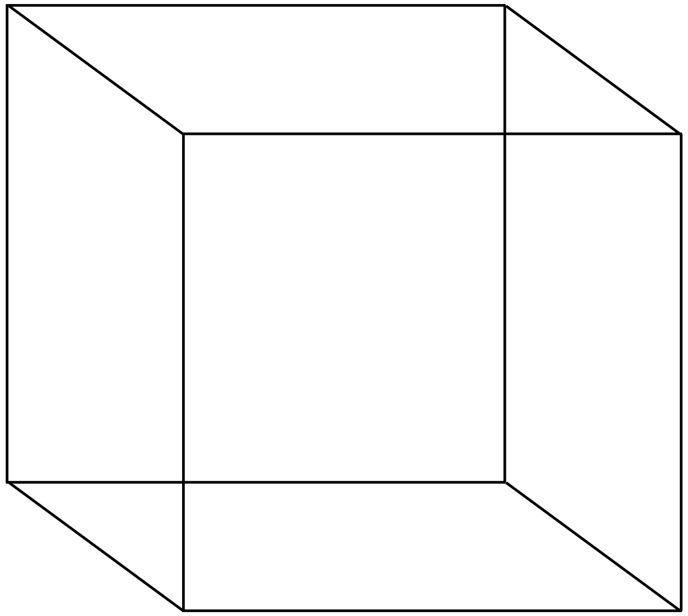
★$\Delta m^2 \sim 1$ eV^2
Can resolve oscillation

★$\Delta m^2 < 0.1$ eV^2
$L_{osc} > L_{detector}$

- Compact-core research reactors (HEU)
  - Good L resolution (short baseline & compact core), no fuel evolution (reduced sys.)
  - $\mathcal{O}10^2$ MW thermal power, limited space, background from reactor facility
- Commercial reactors (LEU)
  - $\mathcal{O}$GW thermal power, better overburden
  - Lower ensitivity @ low energy, fuel evolution (burnup)

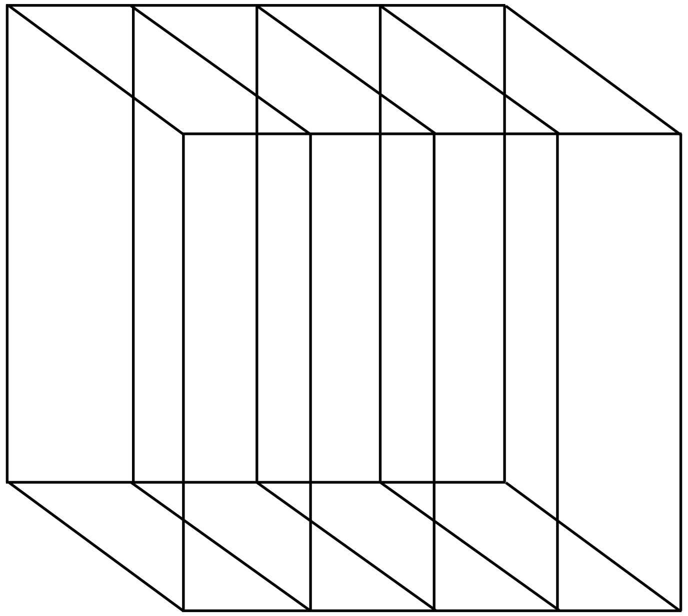
Comparing Different Technologies

no-segmentation



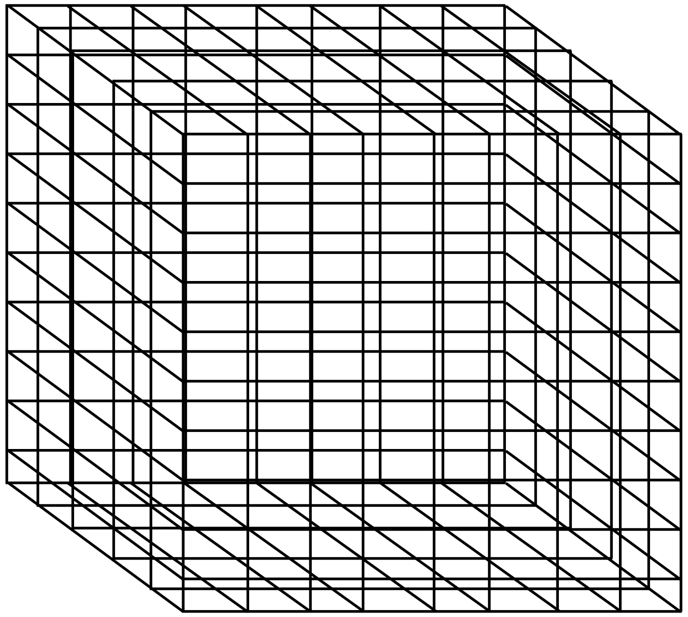
★compare $\bar{\nu}$ spectrum with prediction

“coarse” segmentation



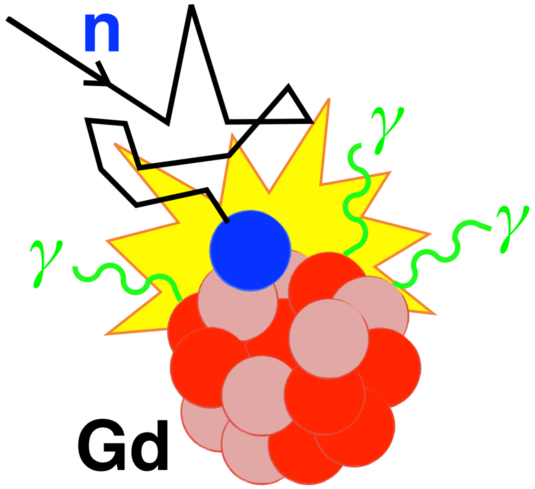
★compare spectra in different segments

“fine” segmentation

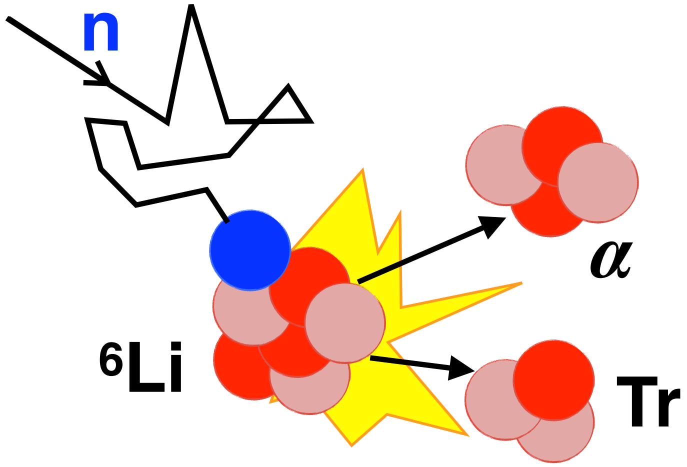


★Background rejection using topology

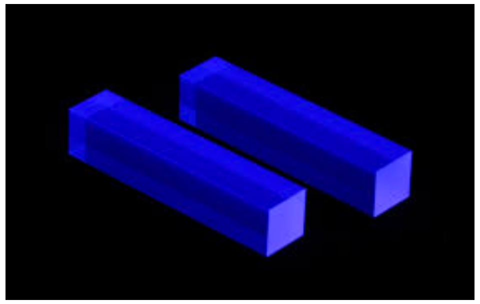
★Ultimate size limited by dead matter / inter calibration



★well-established, high E_{dep} and $\sigma_{capture}$



★Localised E_{dep}: quenched but can select via PSD



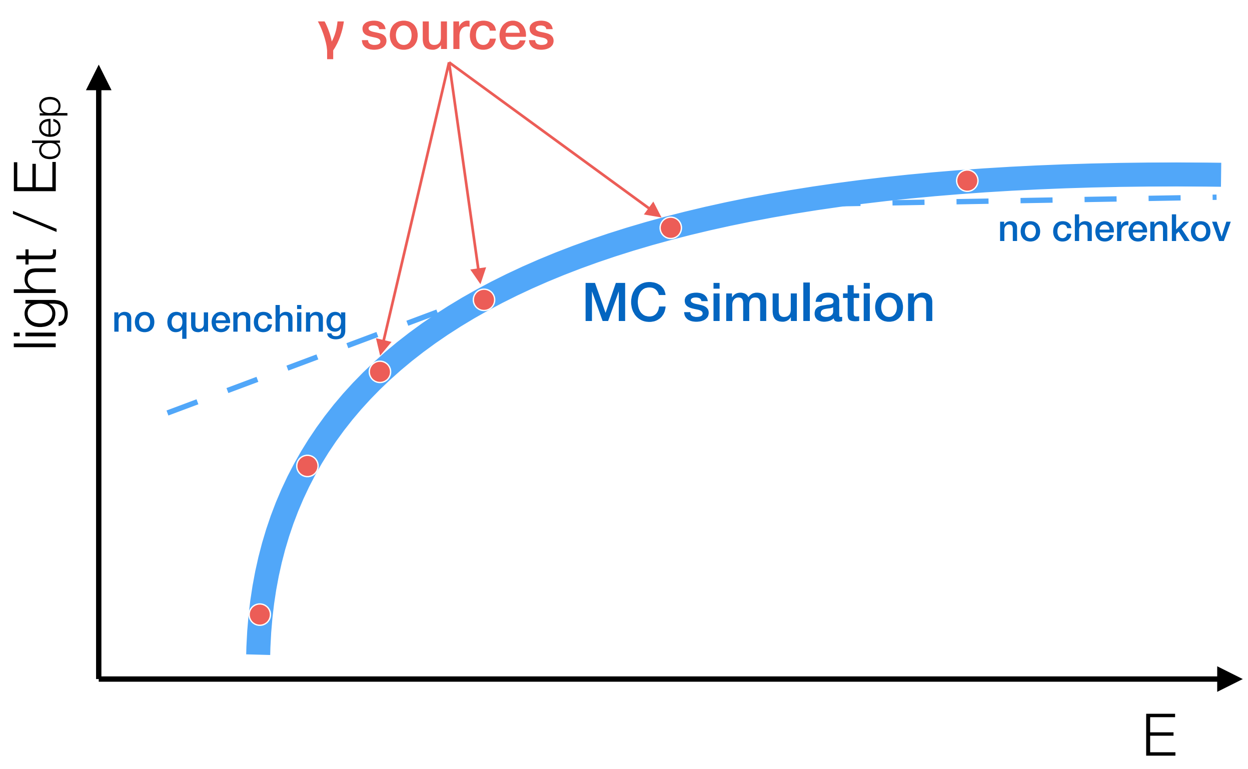
★better segmentation less edge-effects

★allows larger volumes

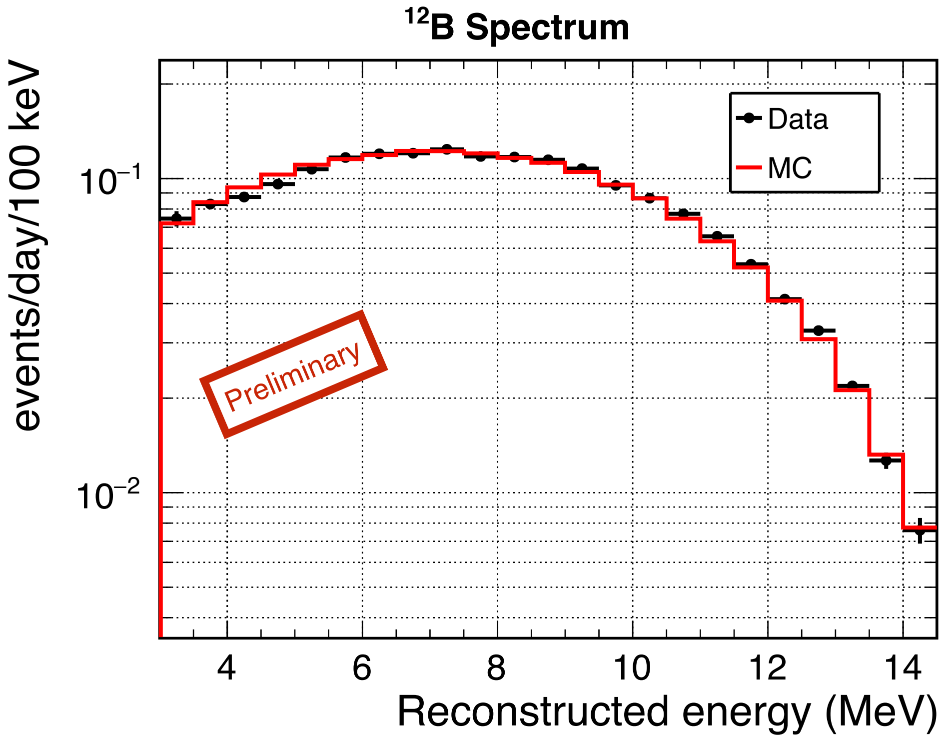
Energy Reconstruction

- **Detector response** (energy reconstruction)
  1. **Calibrated on monochromatic sources**
  2. Then **extrapolated to the whole IBD spectrum** using MC
  3. MC corrected for quenching at low energies & cherenkov at higher energies

- **Energy scale** can be **tested** using cosmogenic **^{12}B β-decay** (continuous spectrum)

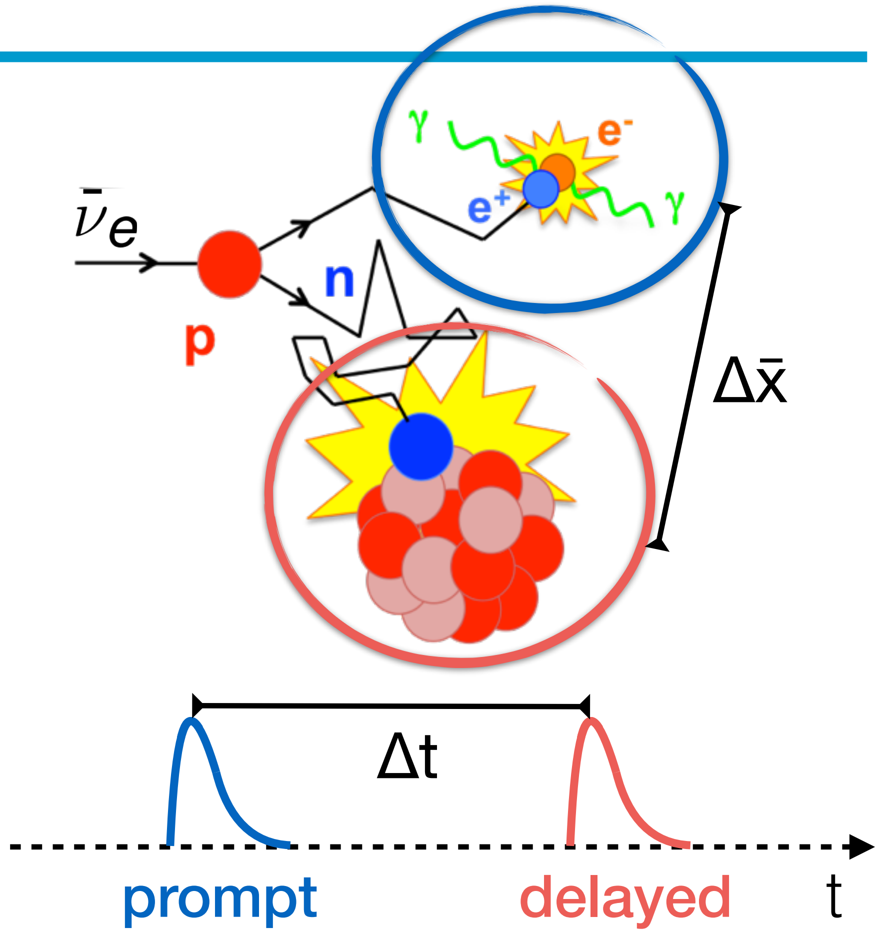


Almazán, H., et al. (STEREO), *Phys. Rev. Lett.* **121.16** (2018): 161801.



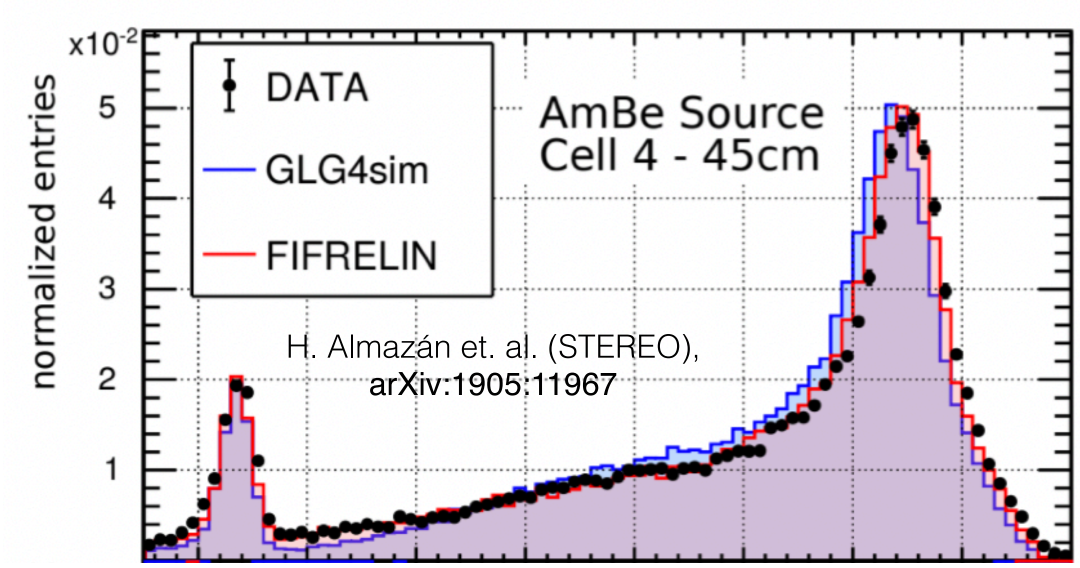
IBD Selection

- Selection of neutrino events based on
  - **IBD coincidence** and topology (E_{prompt}, $E_{delayed}$, Δt, $\Delta\bar{x}$)
  - Background rejection cuts and vetoes (active, software)
  - Pulse shape discrimination (PSD)



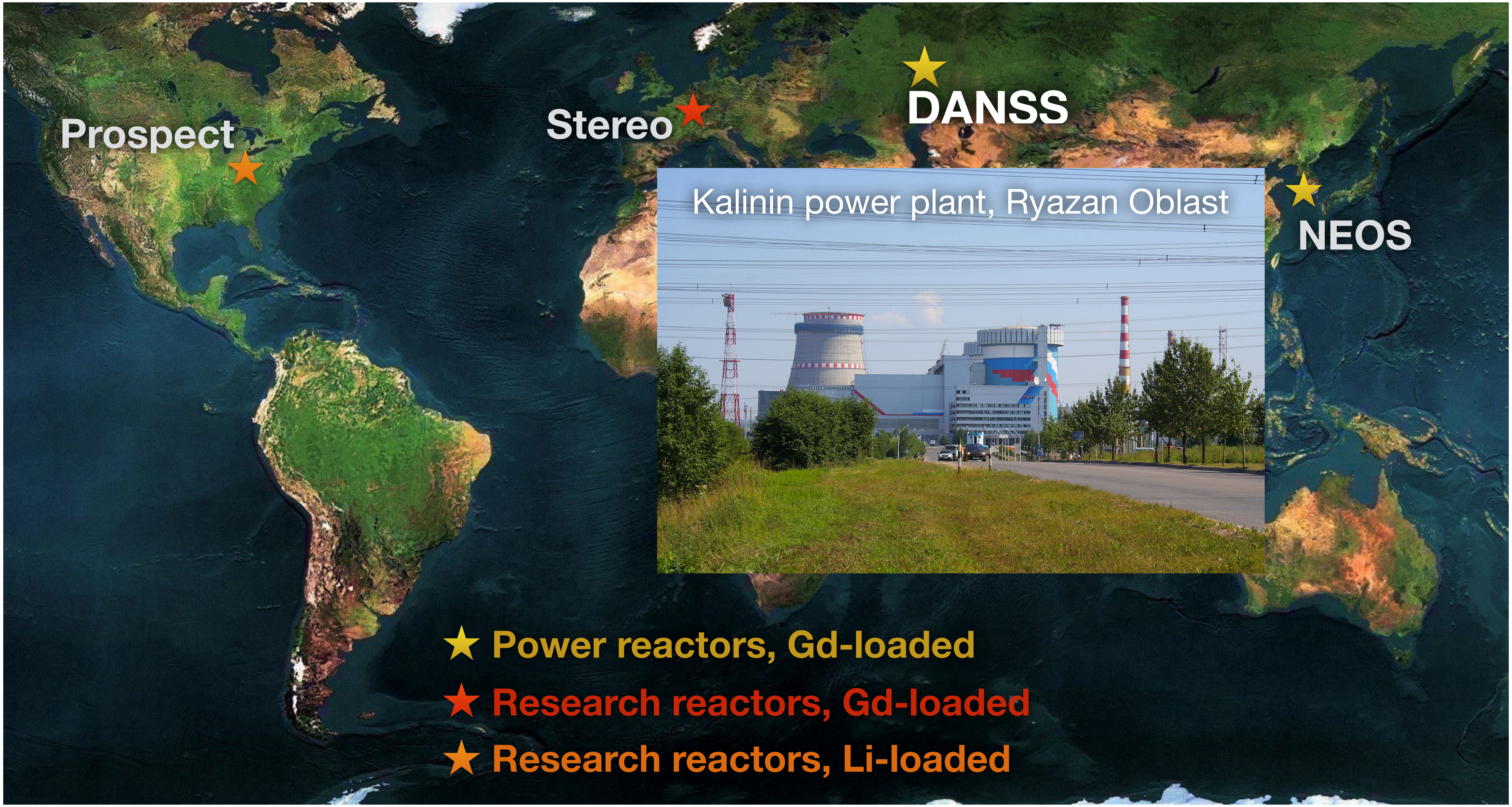
- **Accidental coincidences** and **cosmogenic background** estimated (reactor OFF) and **subtracted statistically** (high statistics → small error)

- Efficiency of topology cuts depends on the MC spectral shape of **Gd cascade**, recently an **improved MC simulation** using FIFRELIN software was **tested by STEREO**



H. Almazán et. al. (STEREO), arXiv:1905:11967

DANSS



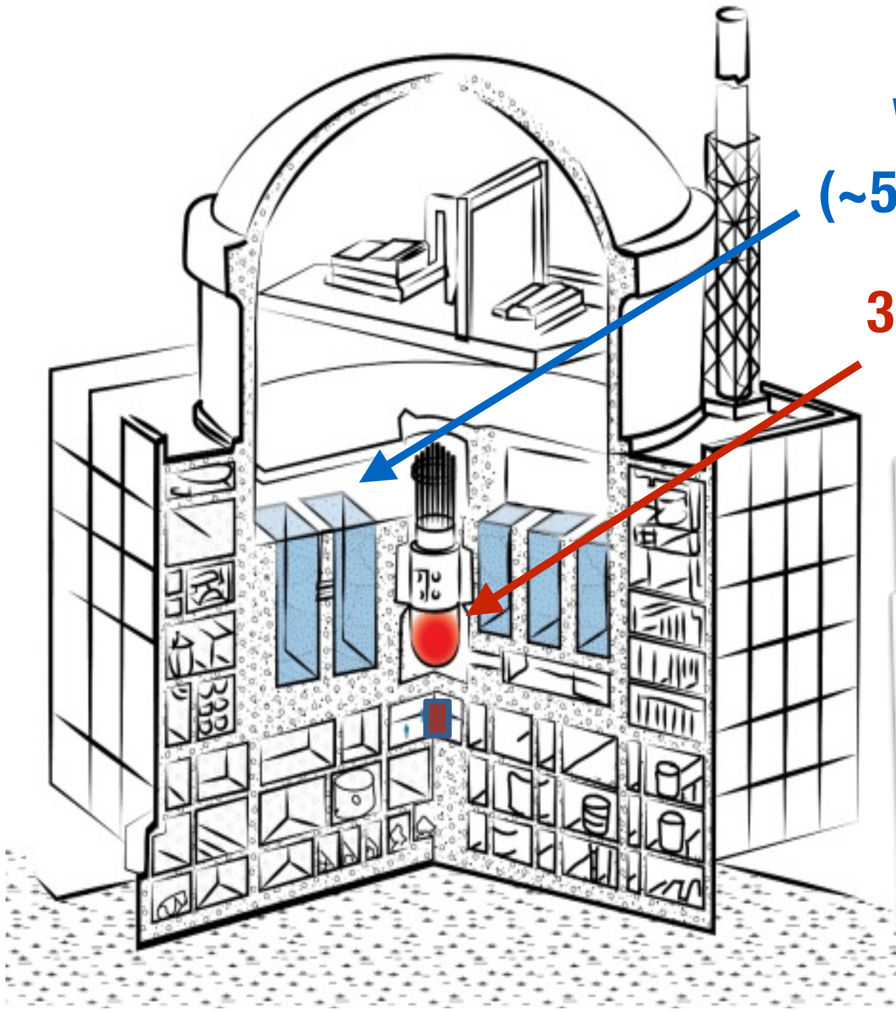
★ Power reactors, Gd-loaded

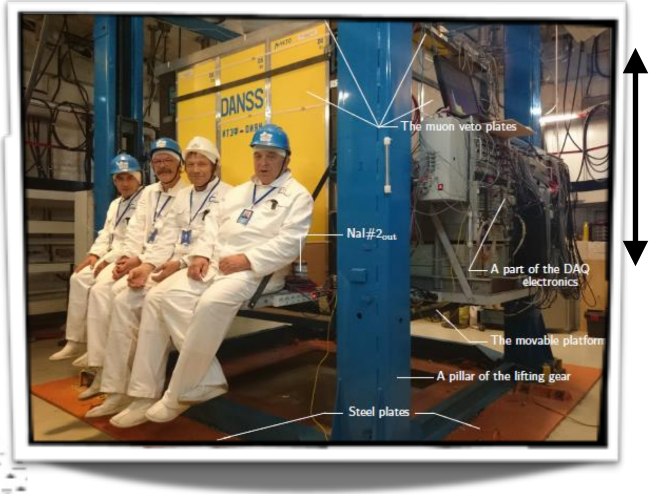
★ Research reactors, Gd-loaded

★ Research reactors, Li-loaded

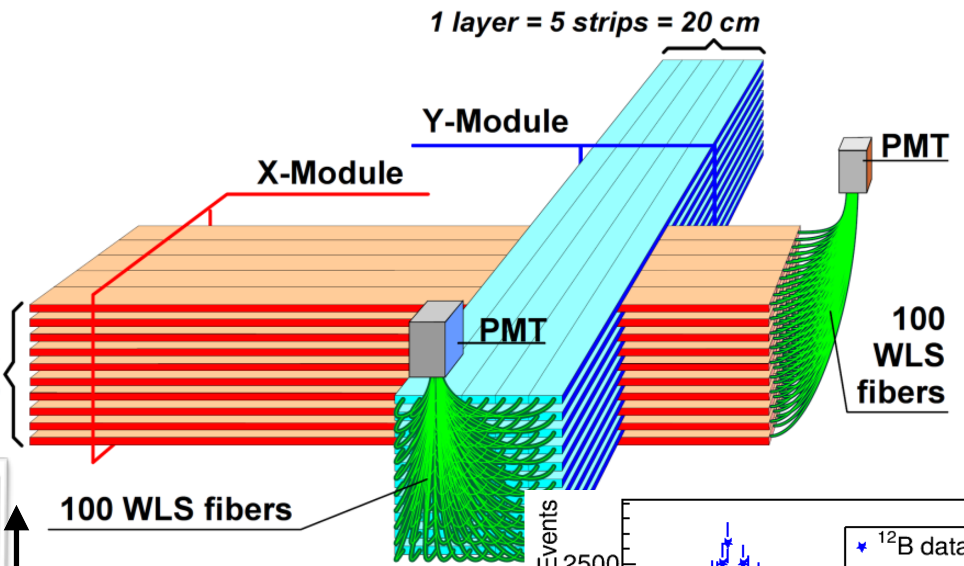
The DANSS Detector

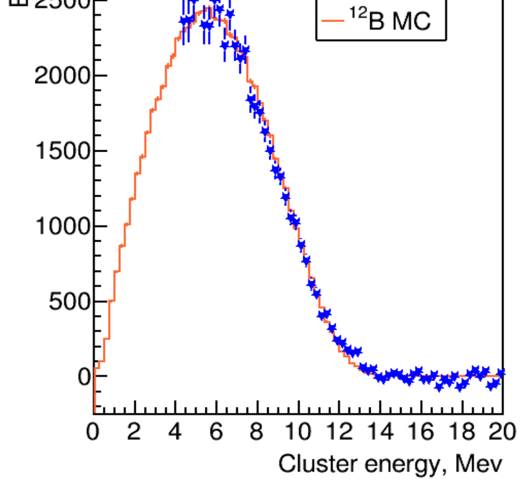
- **Movable detector** based on **Gd-doped segmented plastic scintillator** (combined readout), detector upgraded (SiPMT only) planned
- Background mitigation: overburden from reactor itself and water reservoir, rejection of comics from topology, fast n estimated from high-E region
- Energy calibration: anchored on μ's, energy scale systematics evaluated with ^{12}B (2%)





Movable Detector
(10.7-12.7 m below core)

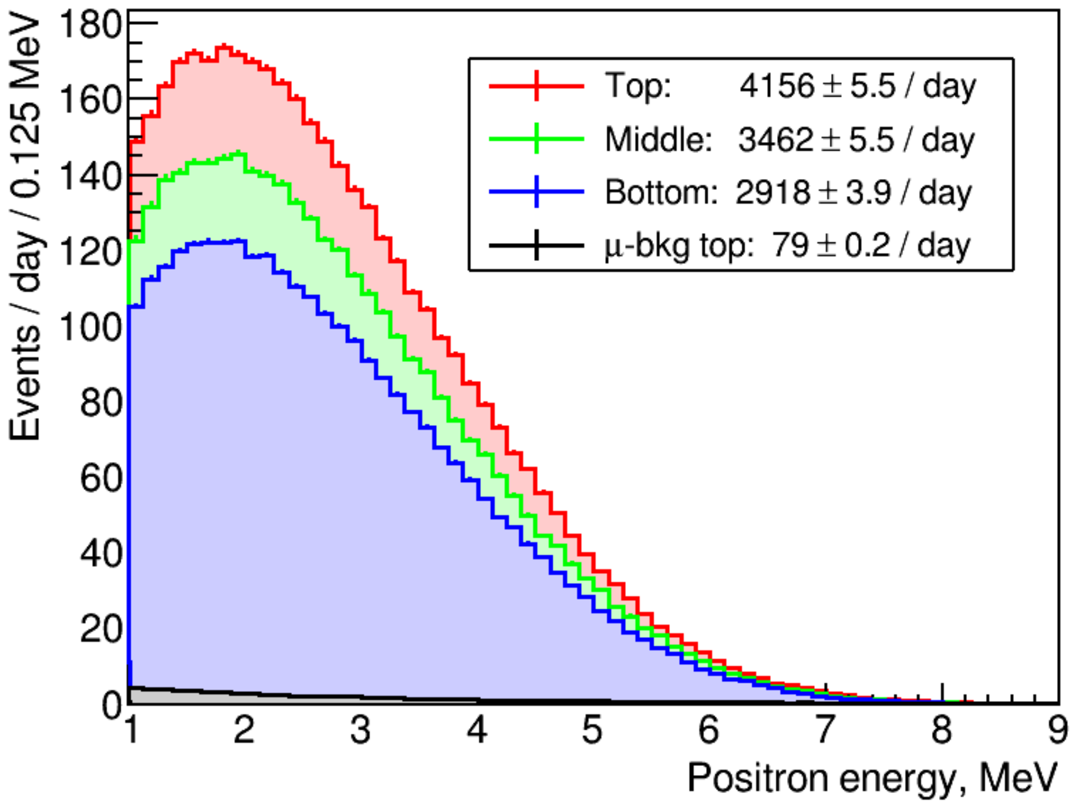


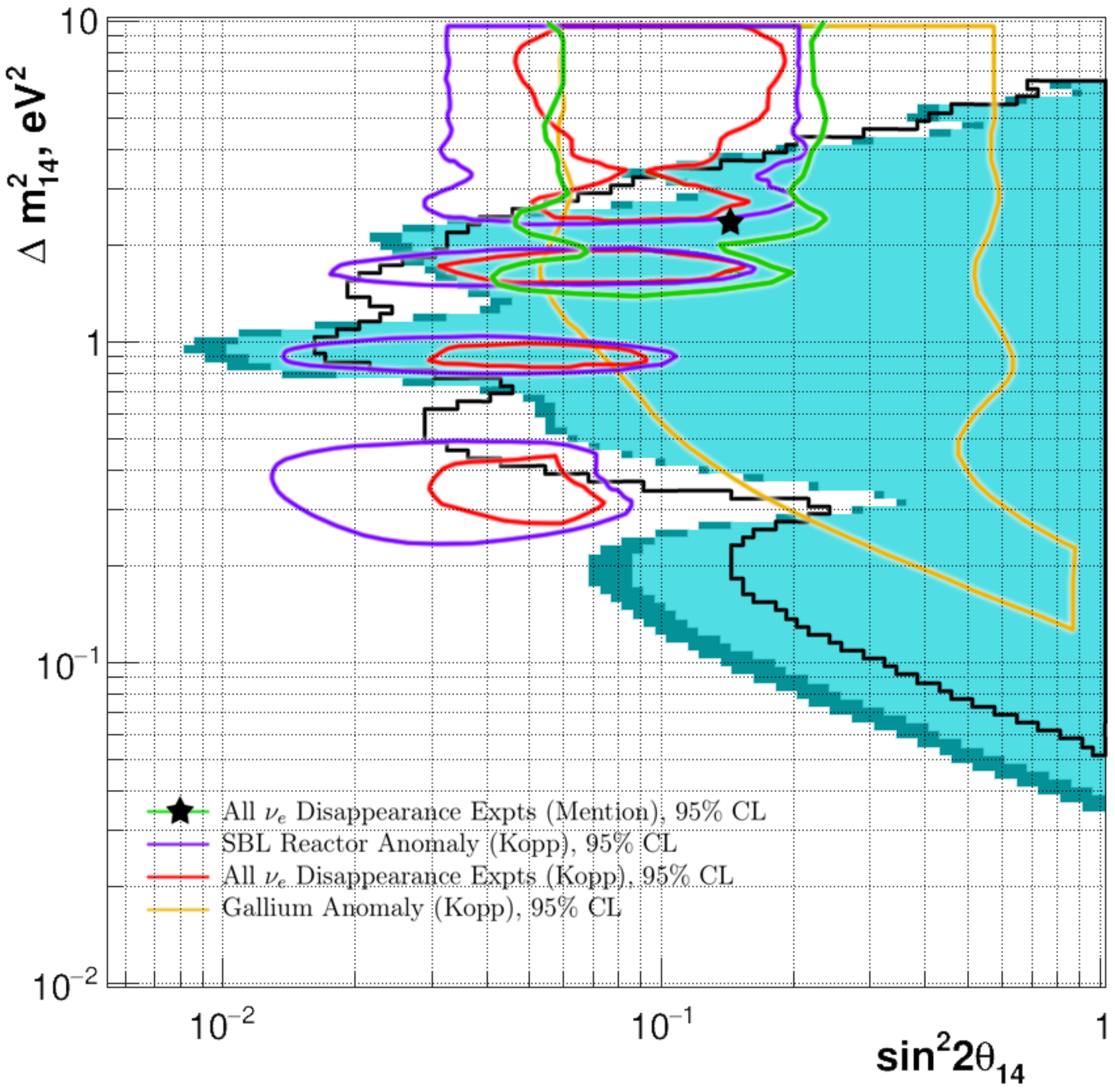


DANSS Results

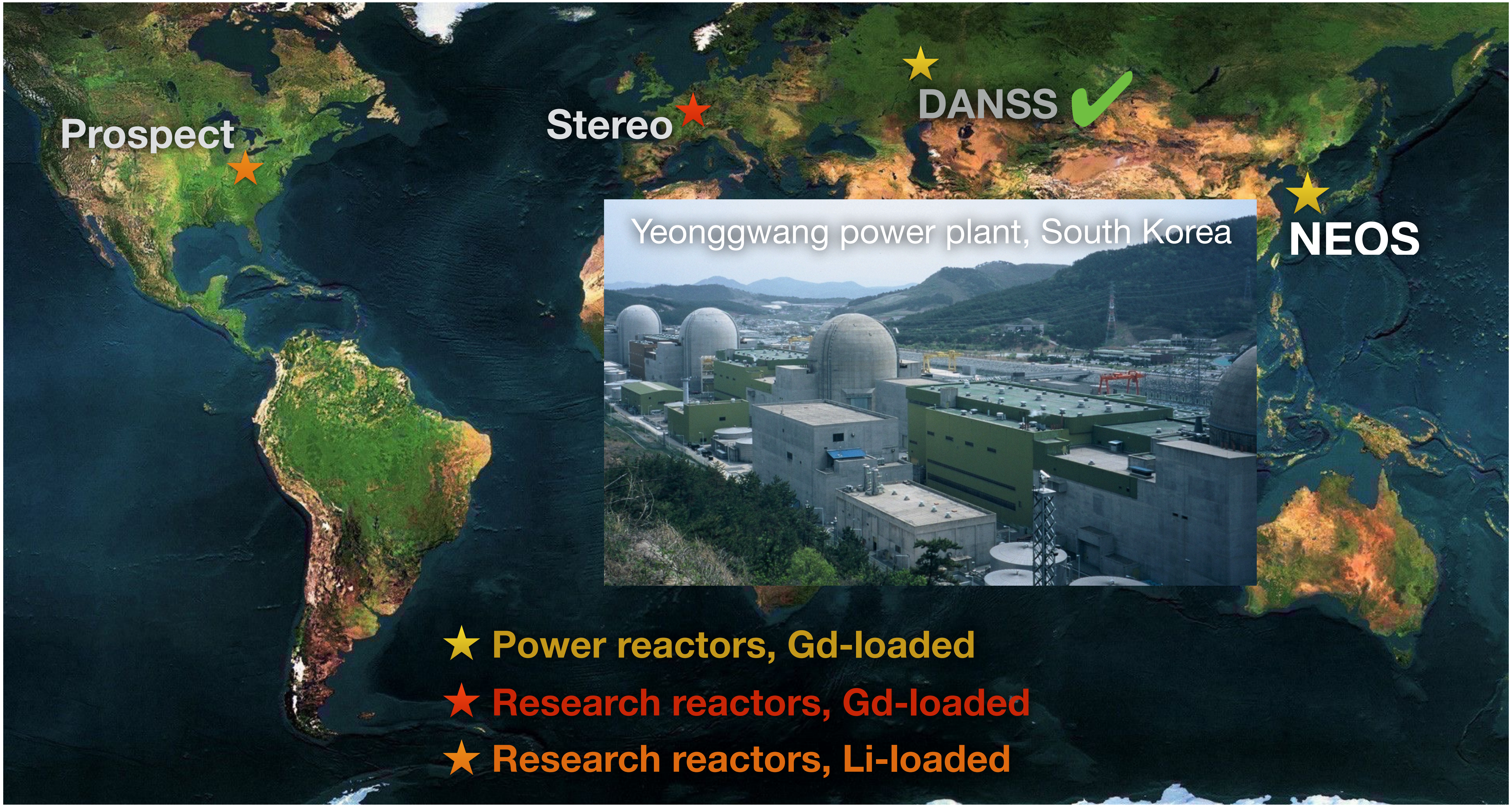
- 2.1×10^6 neutrinos (~4000/day) collected from April 2016, **excellent S/B (~50)**

- Oscillation hypotheses is tested by **comparing e^+ spectra at 2 different heights** $\forall(\theta,\Delta m^2)$



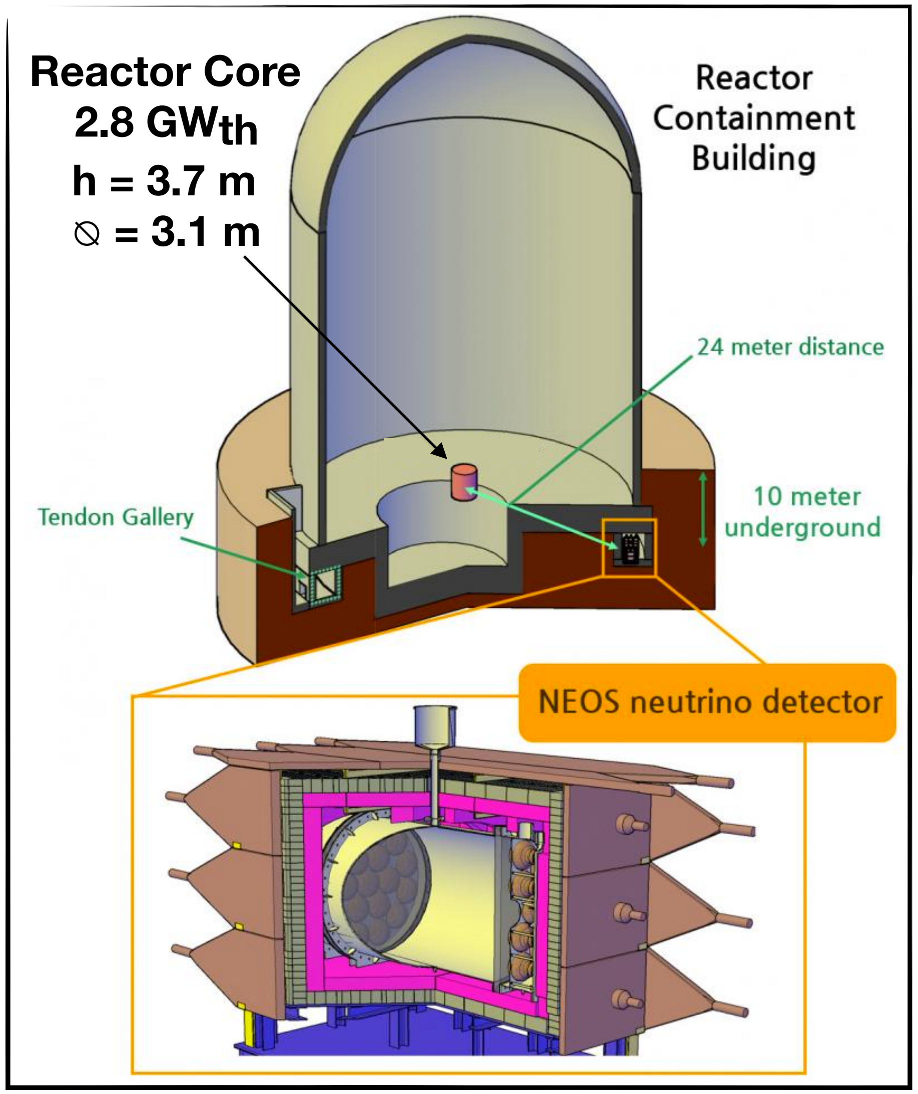


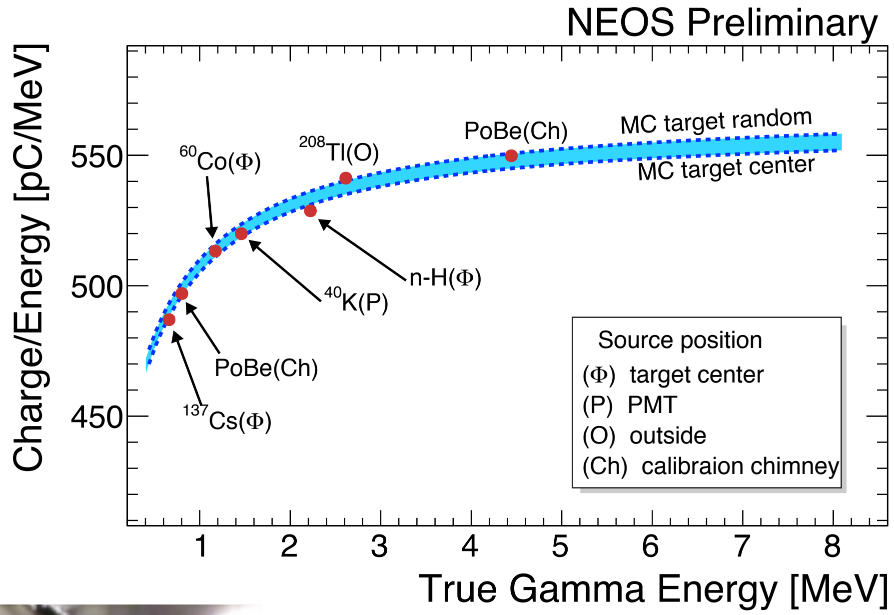
NEOS

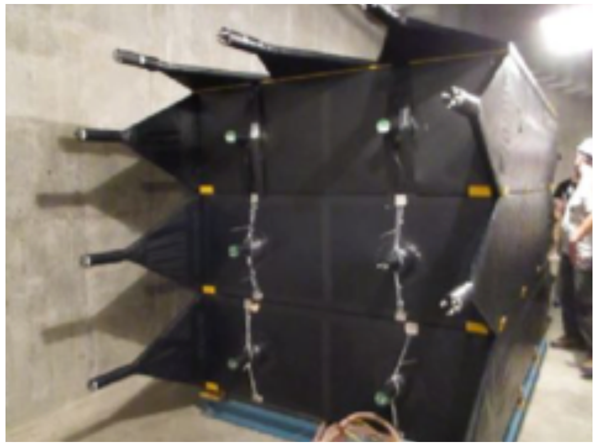

Prospect
Stereo
DANSS ✓
NEOS
Yeonggwang power plant, South Korea
★ Power reactors, Gd-loaded
★ Research reactors, Gd-loaded
★ Research reactors, Li-loaded

The NEOS Detector

- **Homogeneous 1000L Gd-loaded liquid scintillator**
- Background mitigation: B-PE + Pb passive shielding, muon veto (plastic scintillator)
- Energy calibration: several γ sources, energy scale tested on ^{12}B



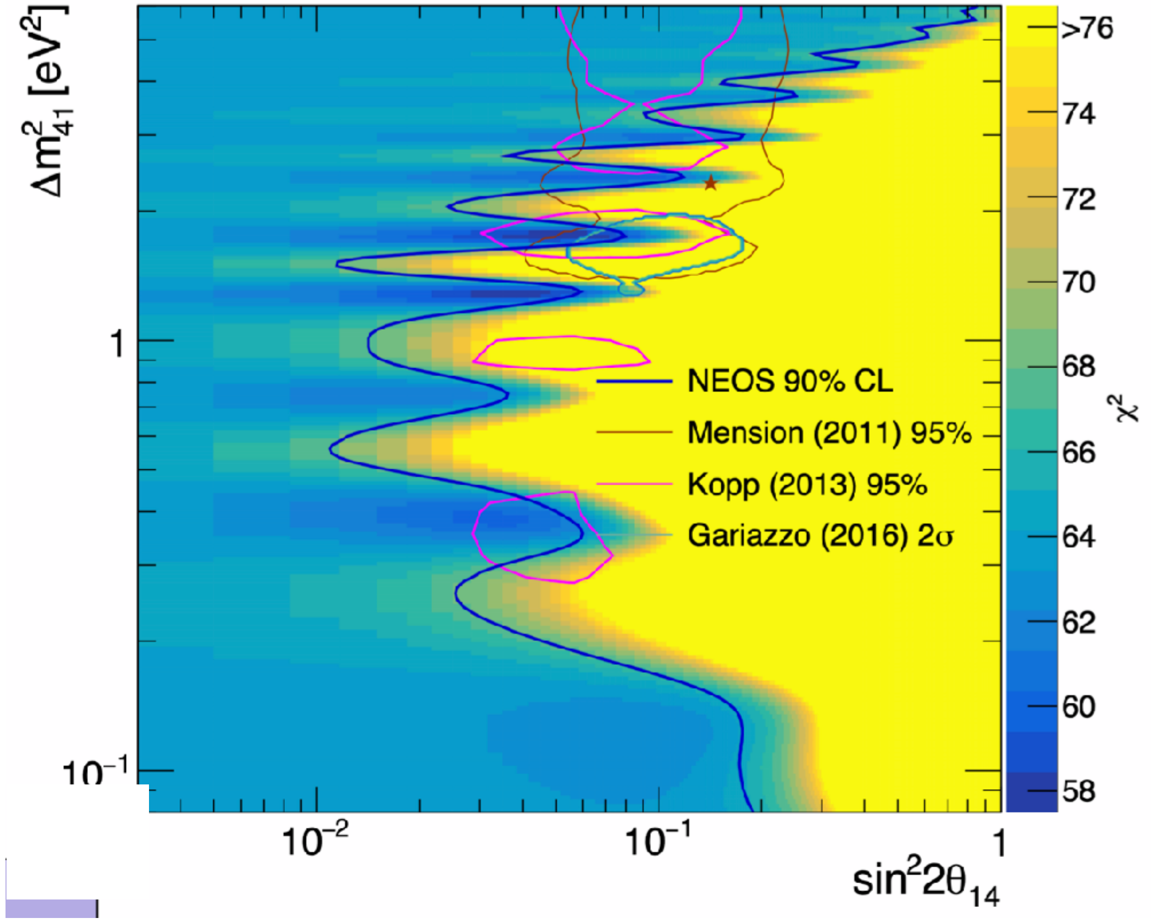


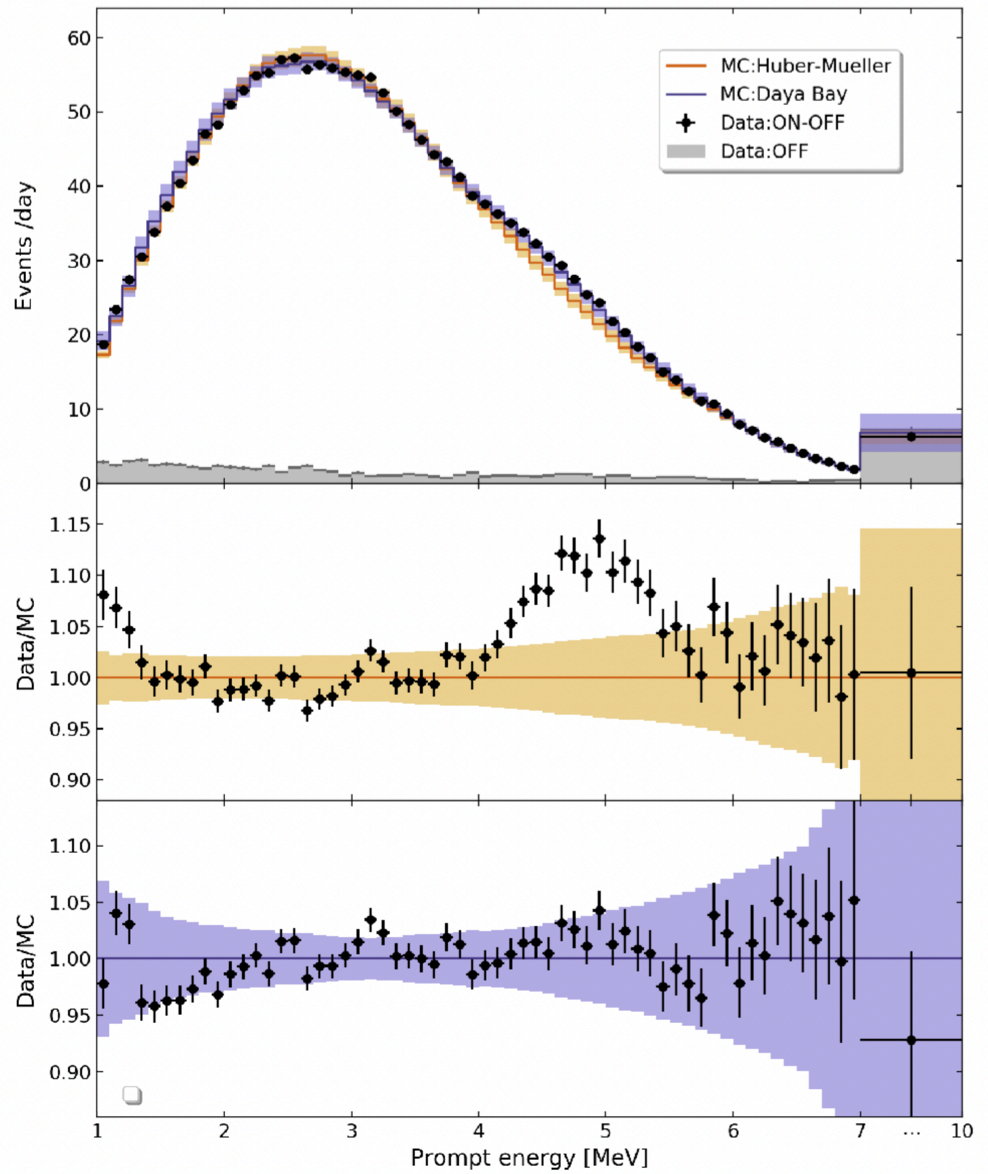


NEOS Results

- **Oscillation analysis on phase-I** (Aug 2015 ~ May 2016 = 46 days OFF + 180 days ON)
  - **High statistics** (~2000 ν/day) **and S/B**
  - **Systematics driven by comparison with Daya Bay** (deviations at low energy)

- Phase-II (Sep 2018 -) analysis in preparation
  - rate+shape fit, precision spectral measurements
  - expected factor 2 improvement exclusion region





STEREO

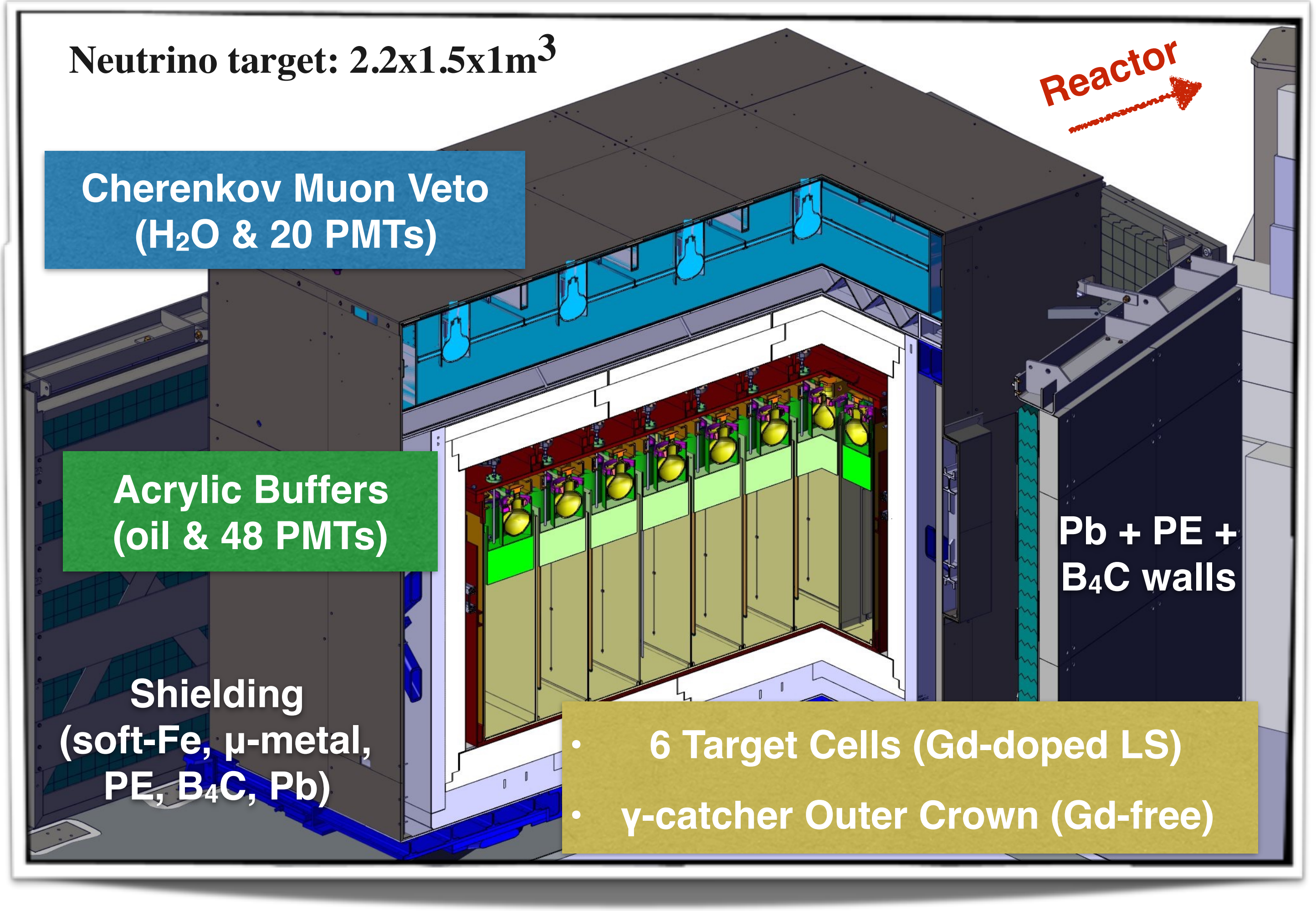
★ Power reactors, Gd-loaded

★ Research reactors, Gd-loaded

★ Research reactors, Li-loaded

The STEREO Experiment

- **6 cells** filled with **Gd-loaded liquid scintillator** (9-11 m from core)
- Energy calibration: anchored to ^{54}Mn, measured with different sources, tested on ^{12}B (~1.5% systematics)
- **PSD (Q_{tail}/Q_{tot})** to discriminate neutrinos from dominant remaining cosmic background (On and Off data model, time-dependent corrections)



Neutrino target: 2.2x1.5x1m^3

Reactor

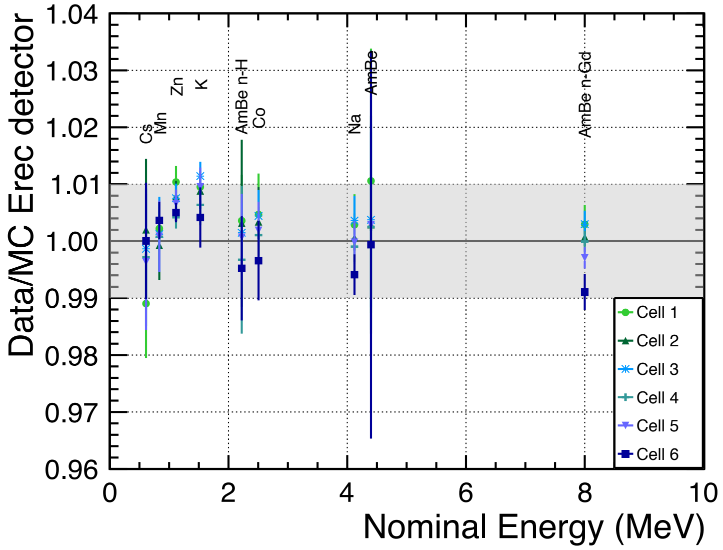
Cherenkov Muon Veto (H_2O & 20 PMTs)

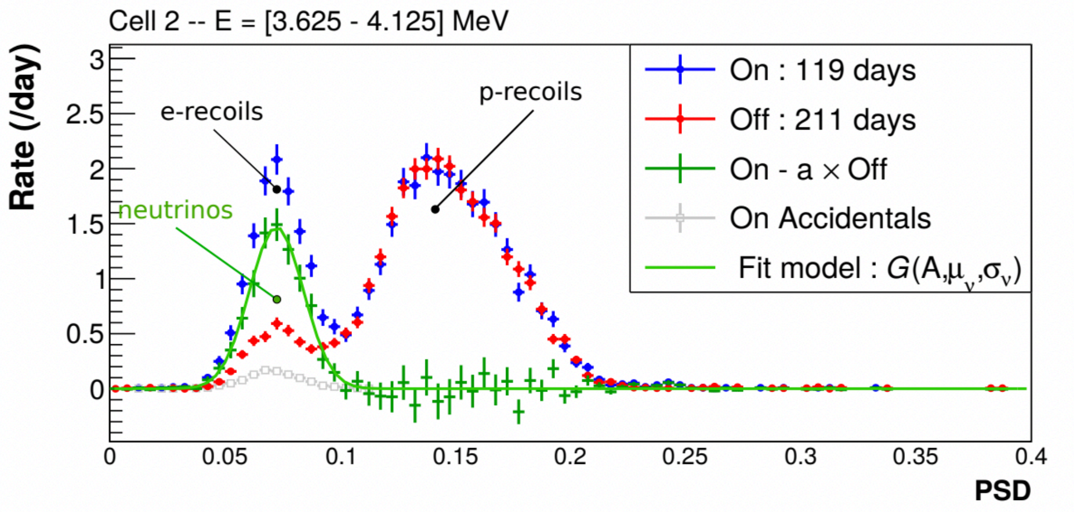
Acrylic Buffers (oil & 48 PMTs)

Shielding (soft-Fe, μ-metal, PE, B_4C, Pb)

Pb + PE + B_4C walls

- **6 Target Cells (Gd-doped LS)**
- **γ-catcher Outer Crown (Gd-free)**





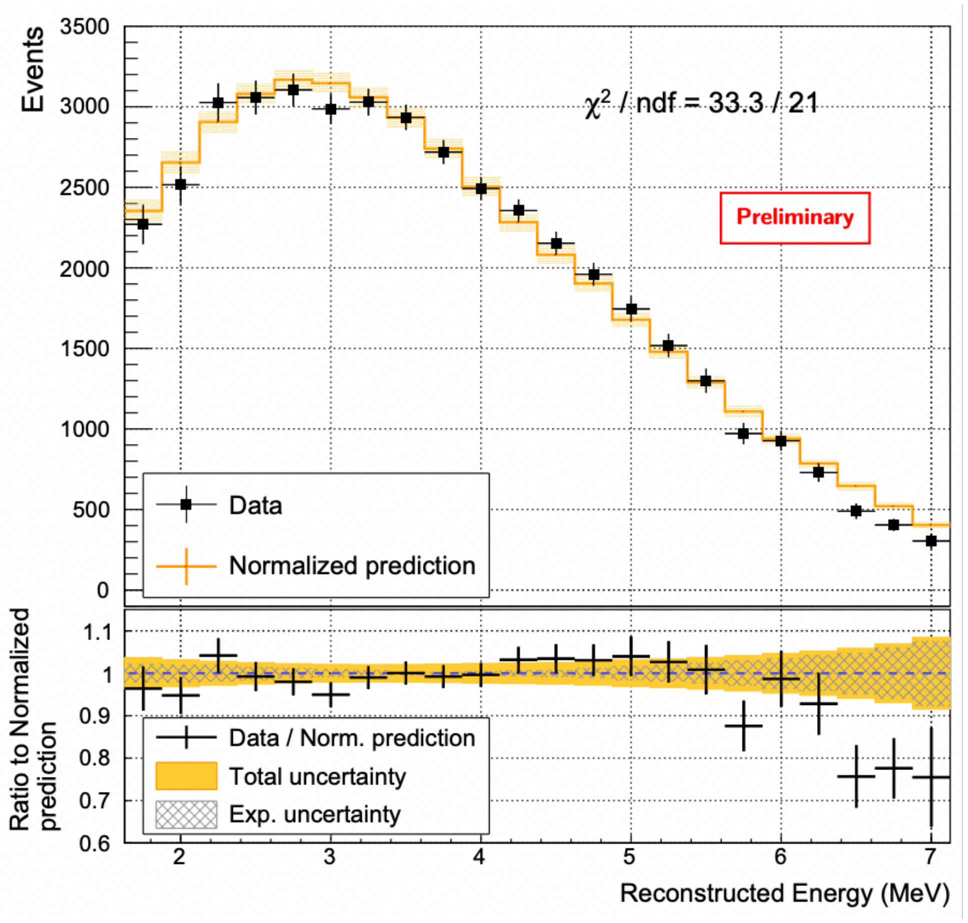
STEREO Results

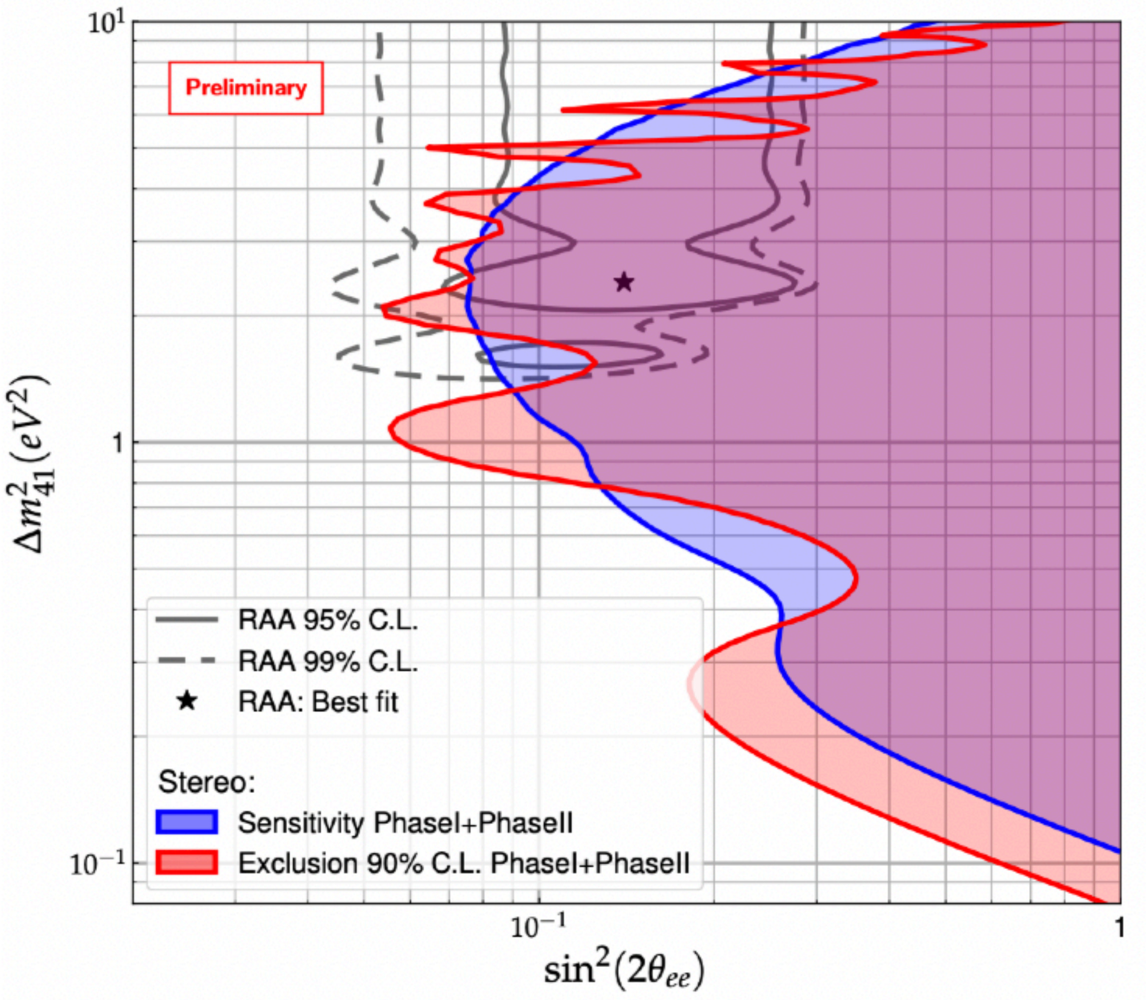
- **Phase-I and -II combined analysis** (65.5 k events, 185 days ON + 233 OFF), S/B ~1 after PSD

- Compact core & short baseline → **little damping of oscillation**

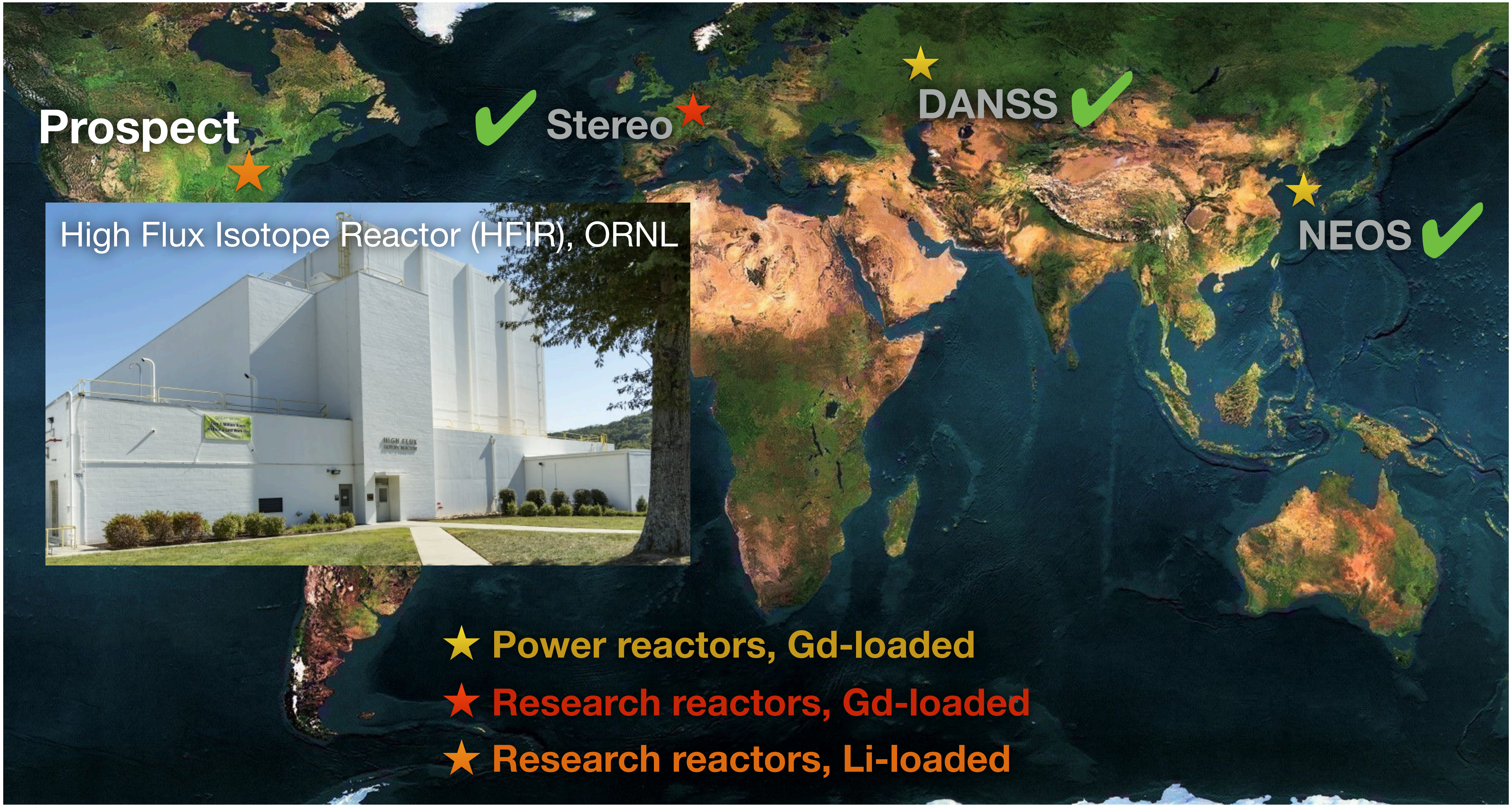
- **Little overburden**, noise from reactor facility (core, neighbours)

- Pure ^{235}U spectrum measurement





PROSPECT



High Flux Isotope Reactor (HFIR), ORNL

★ Power reactors, Gd-loaded

★ Research reactors, Gd-loaded

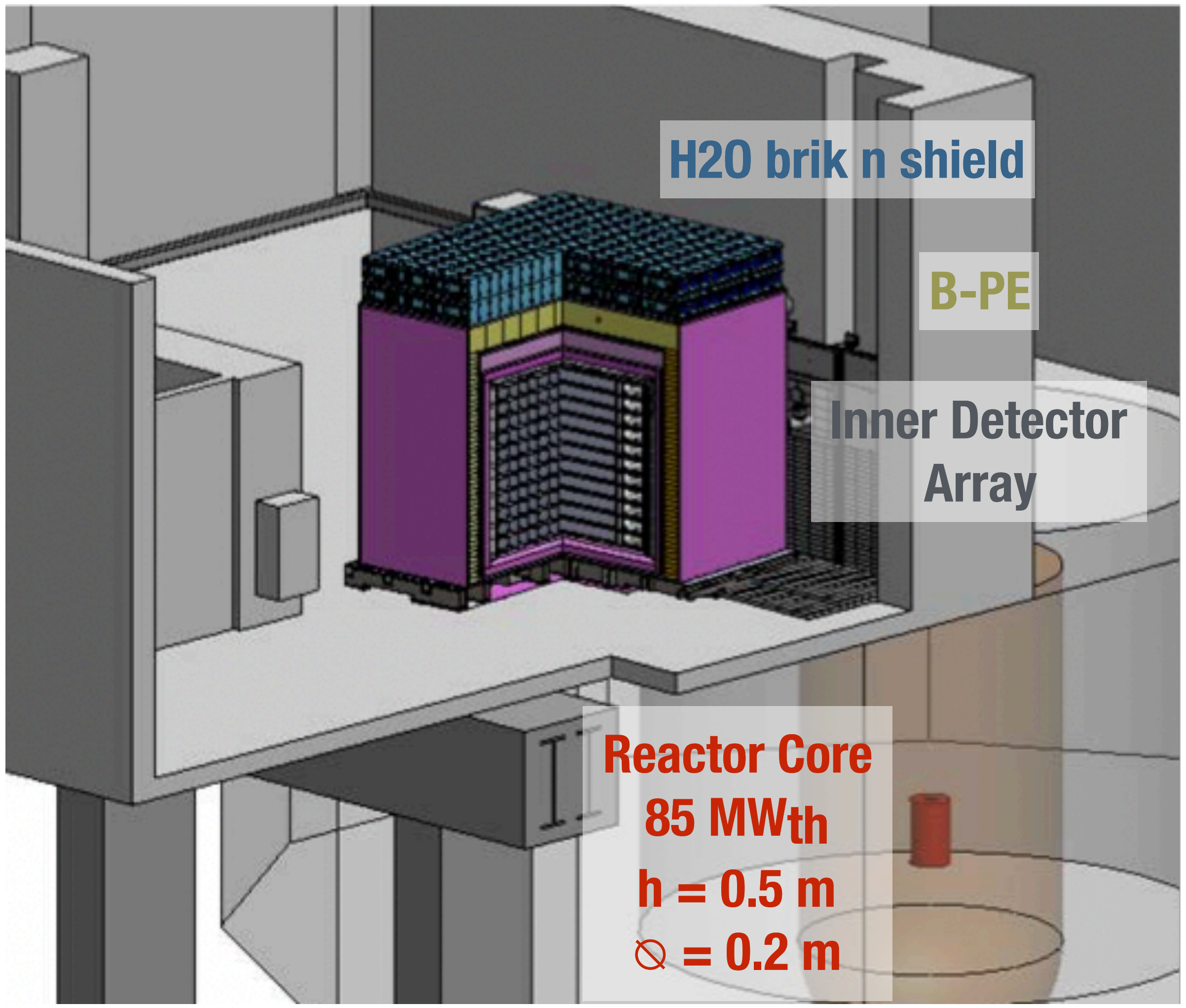
★ Research reactors, Li-loaded

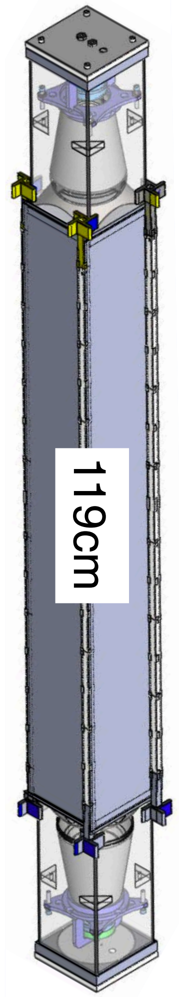
The PROSPECT Experiment

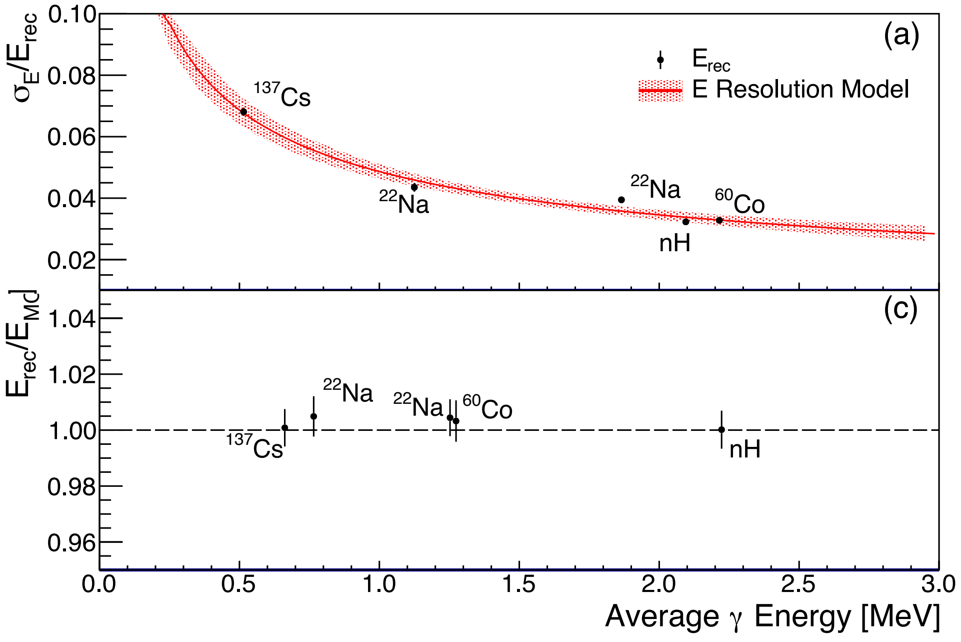
- **4000 L ^{6}Li-loaded liquid scintillator** (3,000 L fiducial volume), **11x14 optically separated segments** with double-ended PMT readout (good E_{res}, 3D reconstruction)

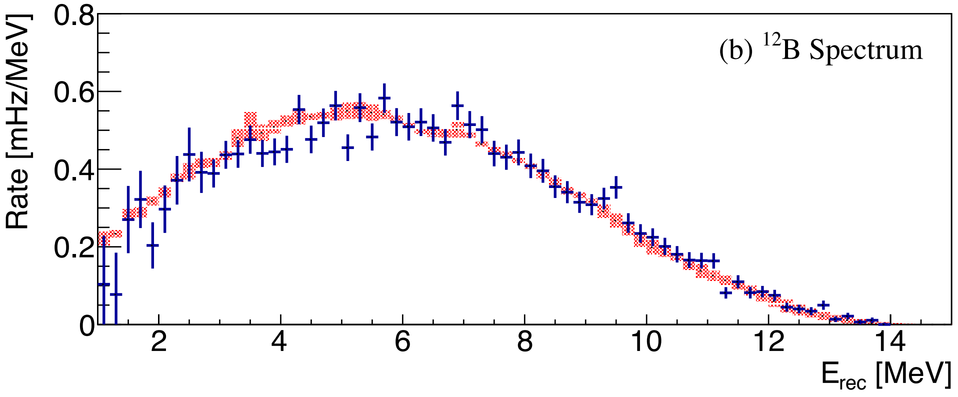
- Background mitigation: PSD + veto + topological cuts + fiducialisation, for a S/B > 1

- Energy reconstruction: γ sources (^{137}Cs, ^{60}Co, ^{22}Na), energy scale tested on ^{12}B







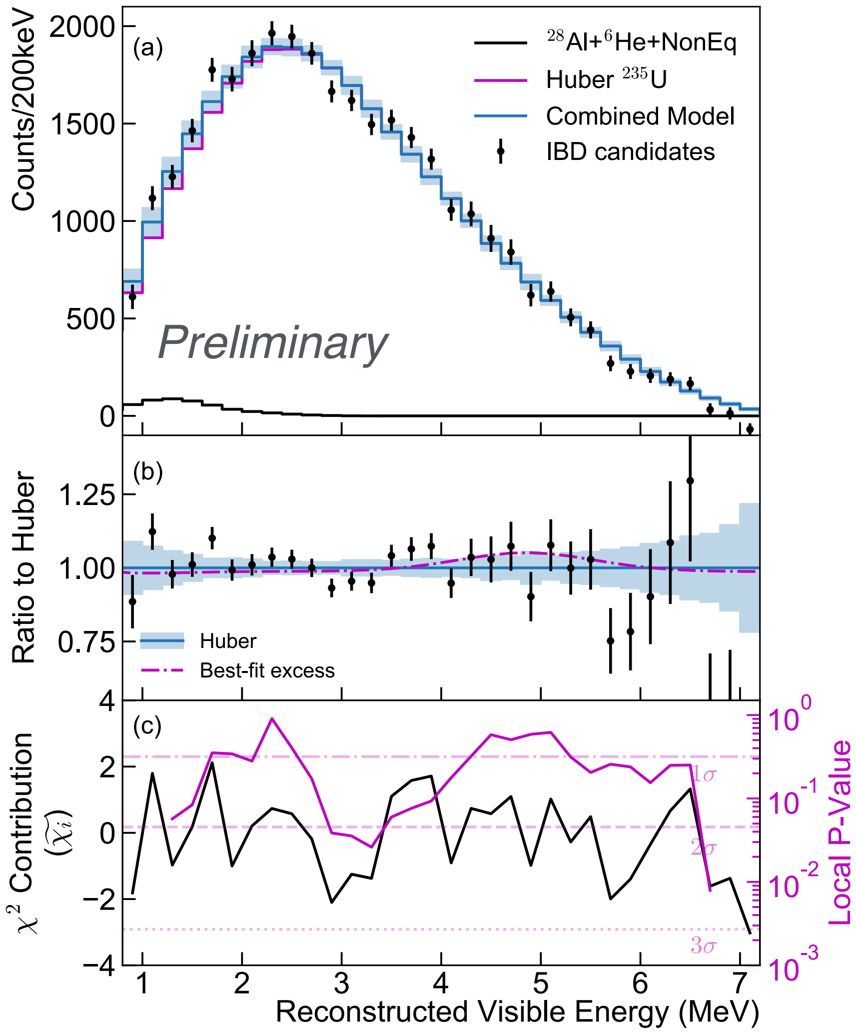


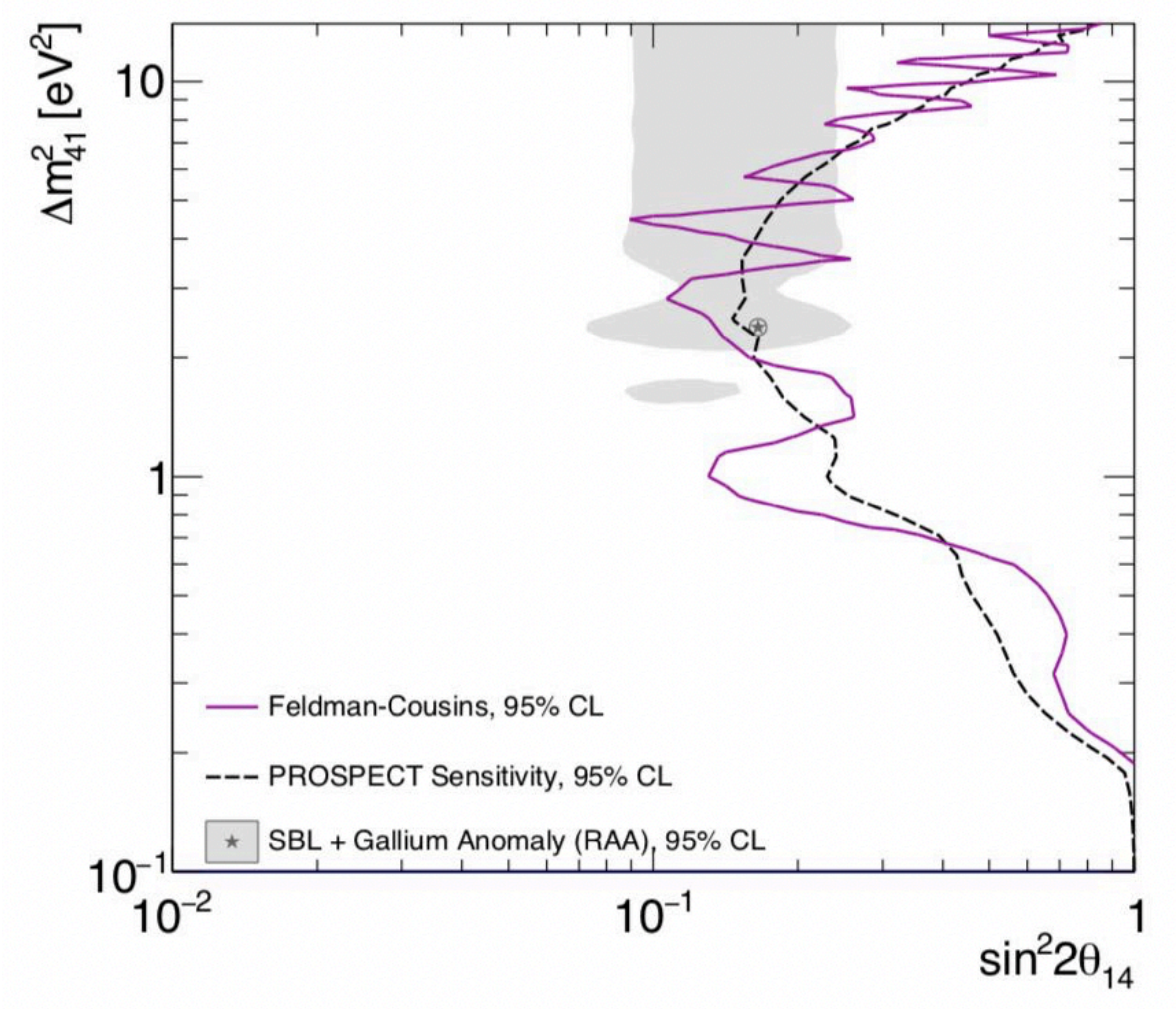
PROSPECT Results

- **High statistics** (24.6 k neutrinos, 33 days ON + 28 days OFF) **and S/B for a HEU**

- **Currently detector under reparation and reactor shutdown**

- Pure ^{235}U spectrum measurement





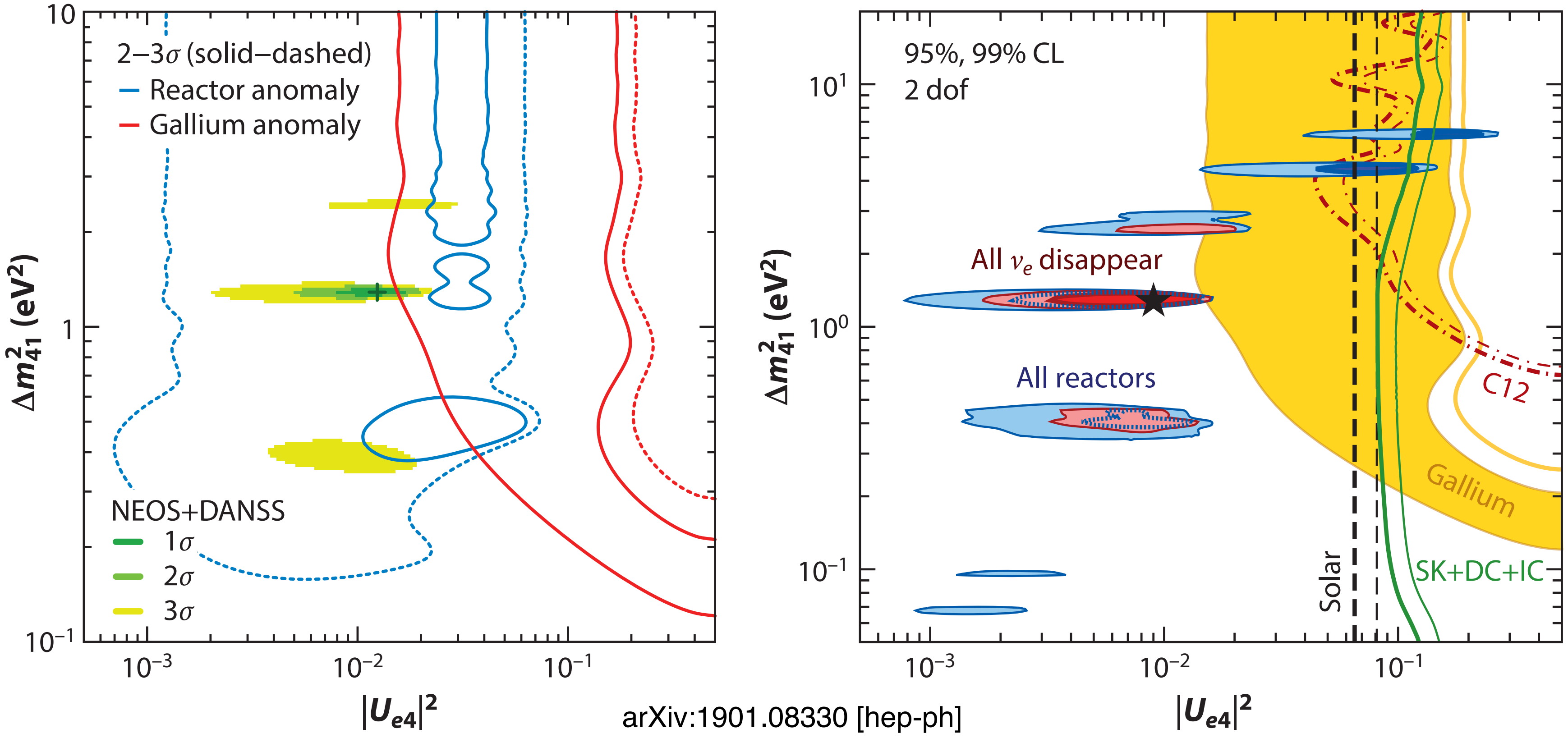
The Global Picture

- **Global fits** of reactor neutrino rate measurements including shape analysis of DANSS and NEOS still **favour active-sterile neutrino oscillation**

- DANSS & NEOS have similar best-fit values (matching features in experimental spectra)

- STEREO and PROSPECT results not yet sensitive enough to exclude region

- Combined analysis require careful treatment of systematics and a common frequentist approach



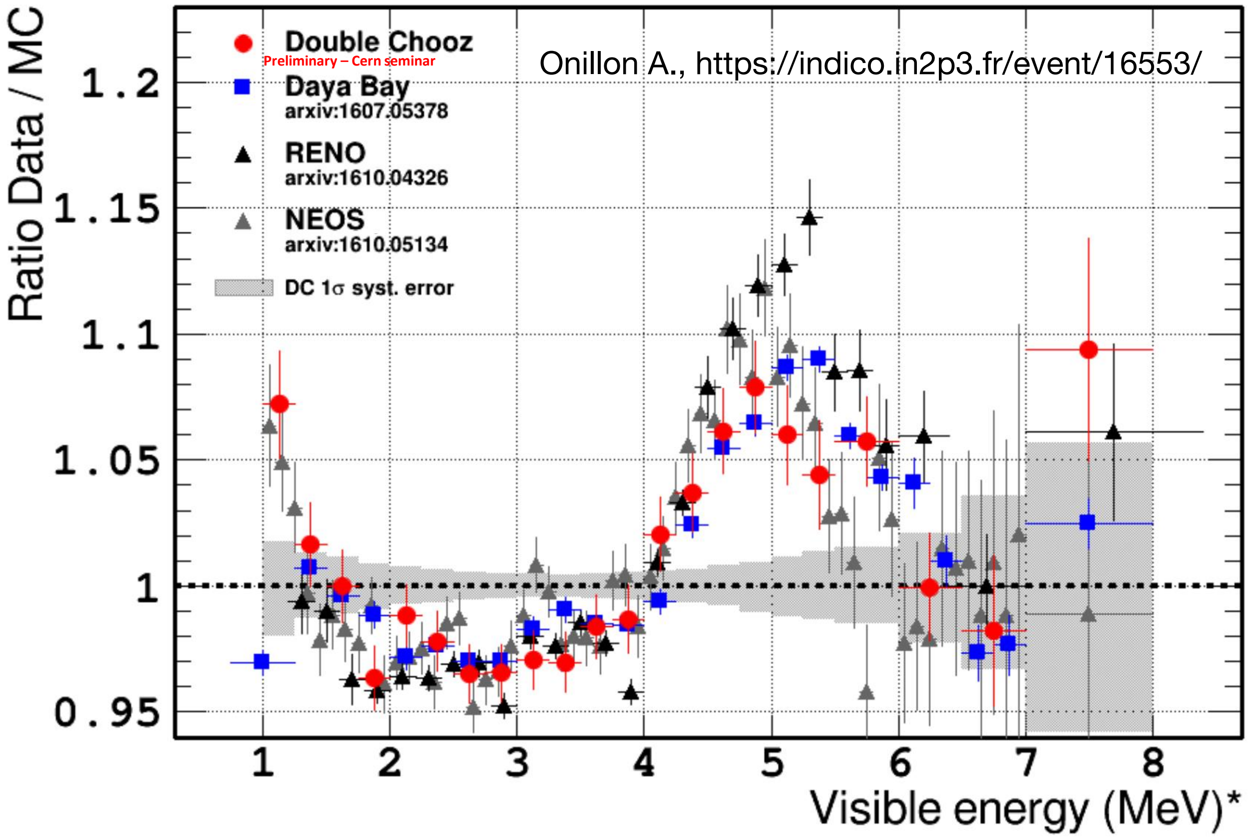
arXiv:1901.08330 [hep-ph]

Outline

- Neutrino mixing and reactor neutrinos
- Anomalies challenging the 3-family framework
- The quest for the light sterile neutrino
- **Sterile neutrinos vs reactor neutrino flux and spectral estimation**
- The future of reactor neutrinos: JUNO

Spectral Distortion at 6 MeV

- **Anomalous spectral distortion @ E_ν ~ 6 MeV** in θ_{13}-aimed neutrino experiments
- **Model uncertainties perhaps underestimated**
- Peak position not identical (or event present) in all experiments → energy scale?
- Can be due to **unknown branches** (isotope related) → accurate ^{235}U spectrum measurement can isolate source of the distortion and constrain models

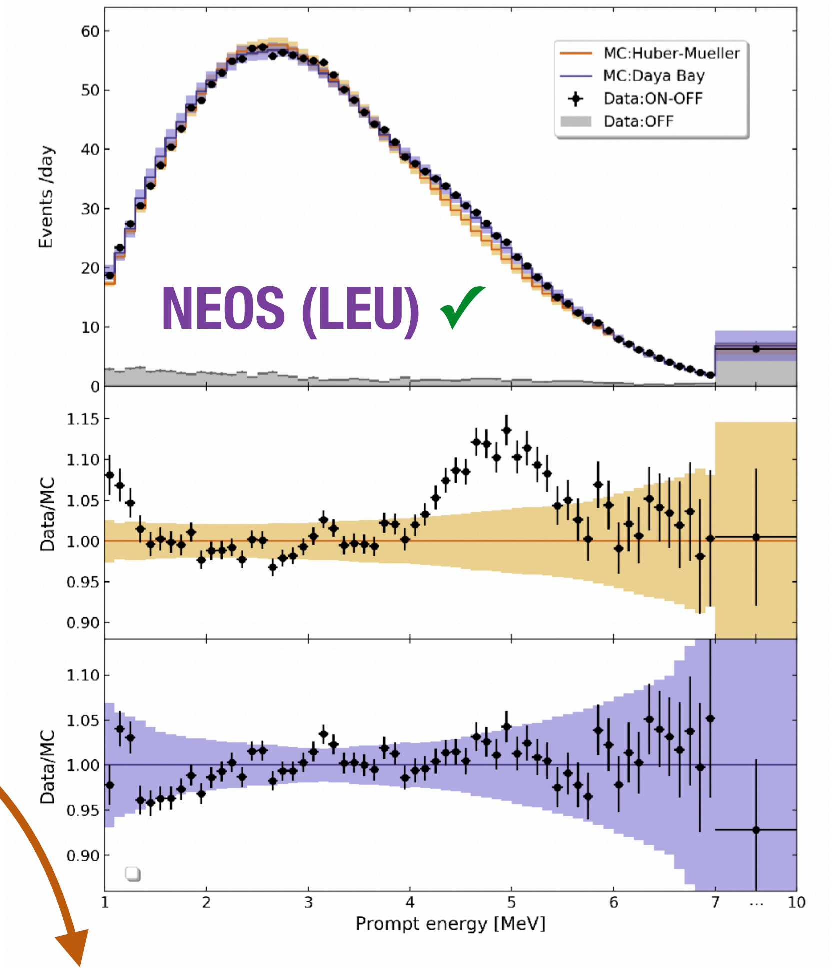


Onillon A., https://indico.in2p3.fr/event/16553/

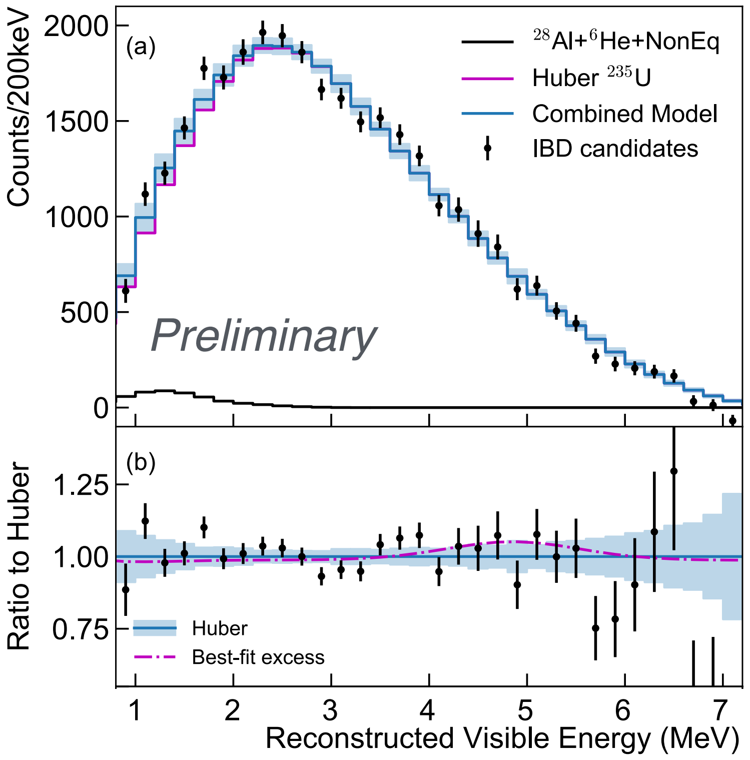
* can slightly differ from one experiment to another due to detector effects

Spectral Distortion and New Results

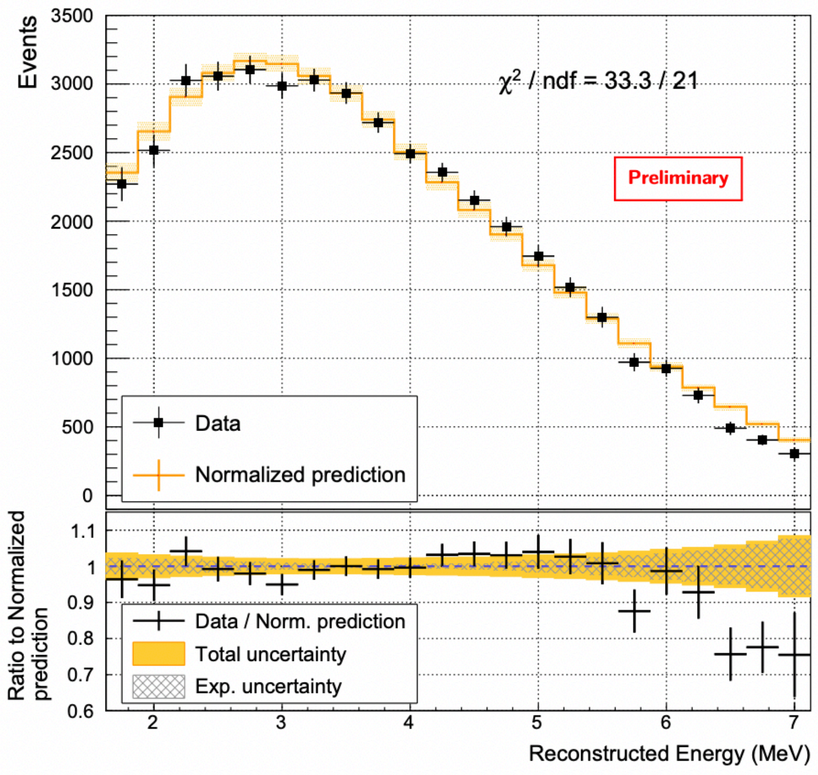
- Is the spectral distortion isotope-related?
  - **STEREO and PROSPECT** with HEU (**~100% ^{235}U**) see little to **no excess**
  - **NEOS** with LEU (**^{235}U + ^{239}Pu**) **confirms the excess** seen by Double Chooz, Data Bay, RENO
  - **DANSS** with LEU (**^{235}U + ^{239}Pu**) hint of an excess, **hard to conclude** with E scale and poor E$_{res}$ (~20%)

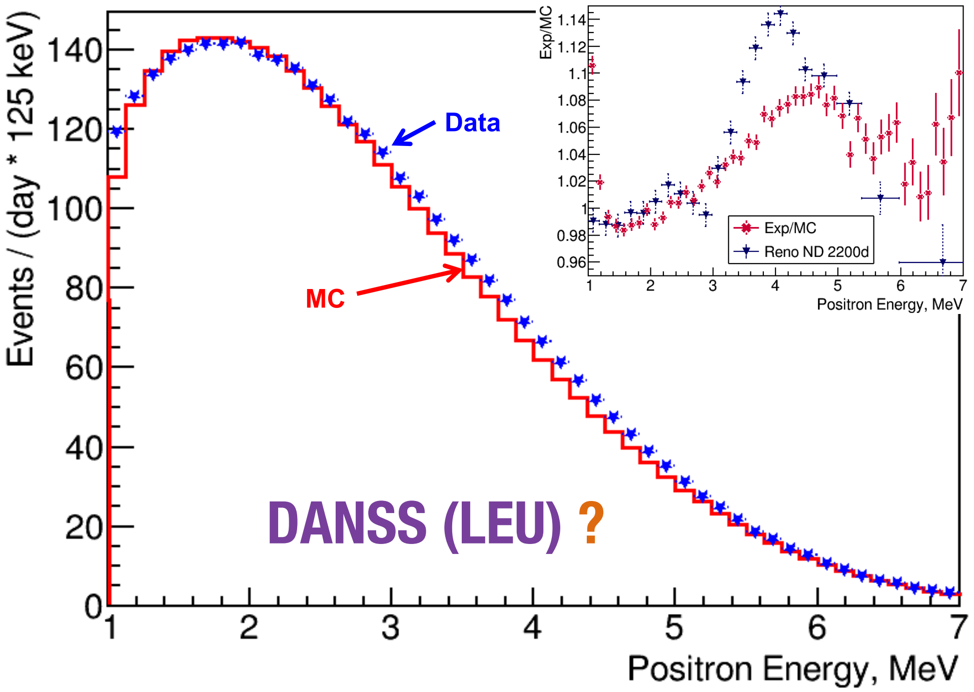


PROSPECT (HEU) ✘



STEREO (HEU) ✘





An Exotic Hypothesis

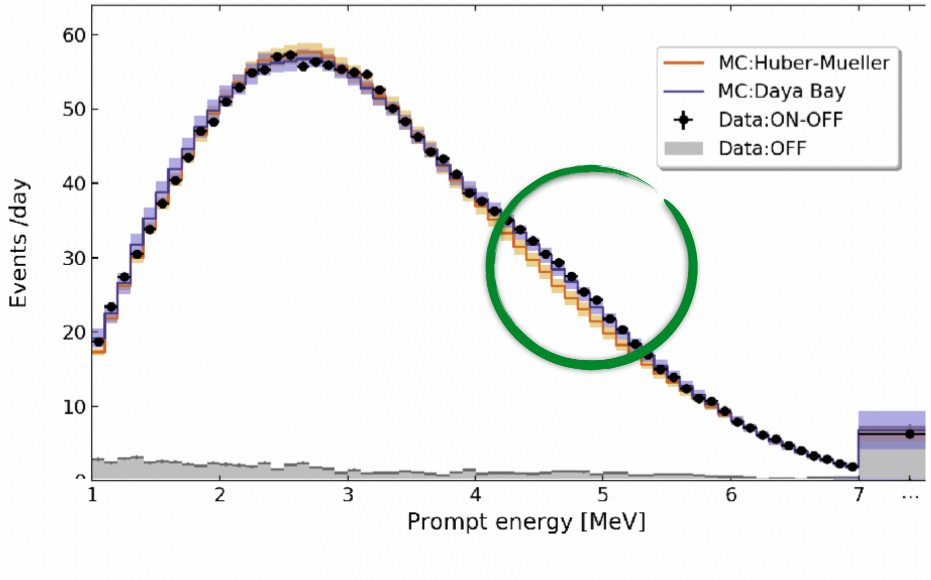
- Both Reactor Antineutrino Anomaly and 5 MeV bump can be explained by effective models including a light **sterile neutrino interacting with ^{13}C via a new gauge boson**

$$^{13}C\ \bar{\nu} \rightarrow {}^{12}C^{*}\ \bar{\nu}\ n \rightarrow {}^{12}C\ \gamma_{(4.4\ \mathrm{MeV})}\ (n)p$$

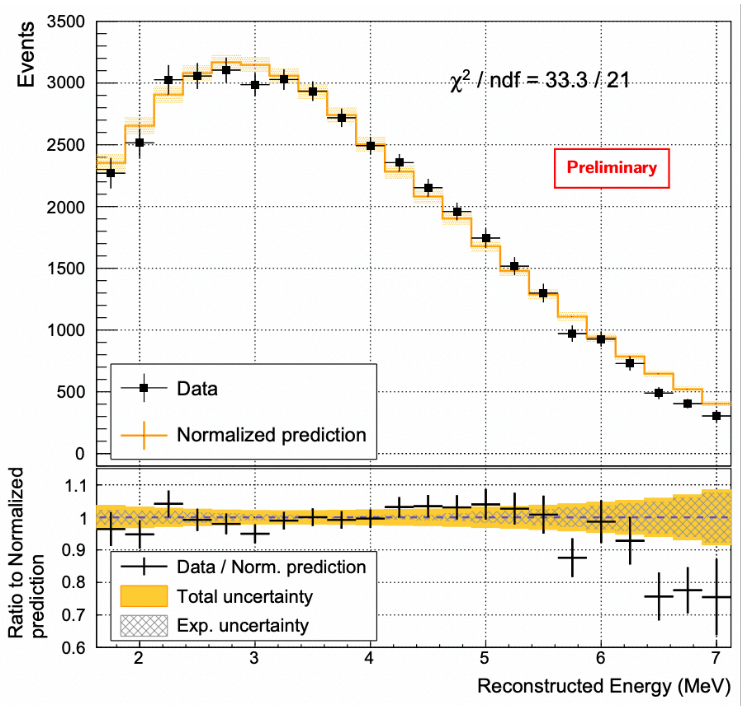
- Need high-energy antineutrinos ($E_{\bar{\nu}} > 9.4\ MeV$), in some models but not detected so far

- Implies presence of **5 MeV bump only if 4.4 MeV *γ*** from ^{12}C de-excitation **is detected**

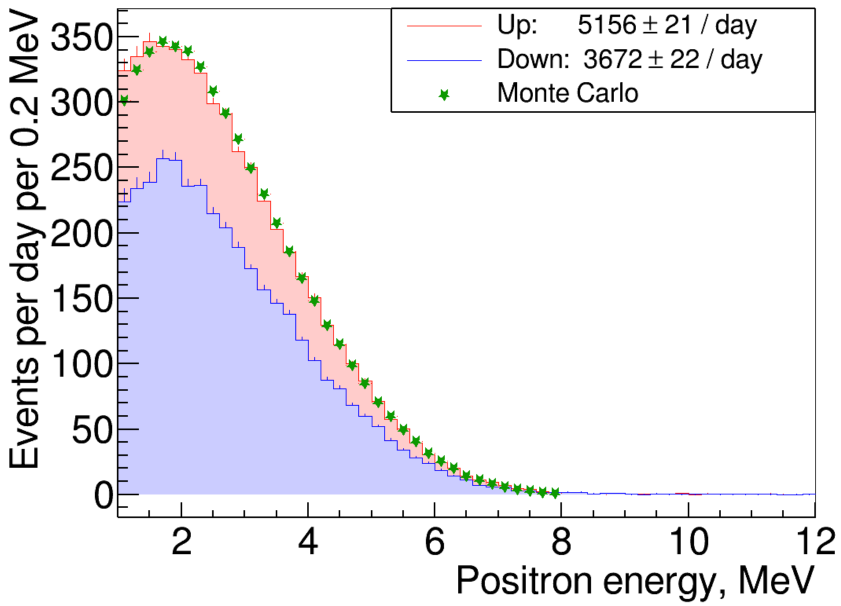
NEOS (not segmented) ✓



STEREO (coarsely segmented) ?



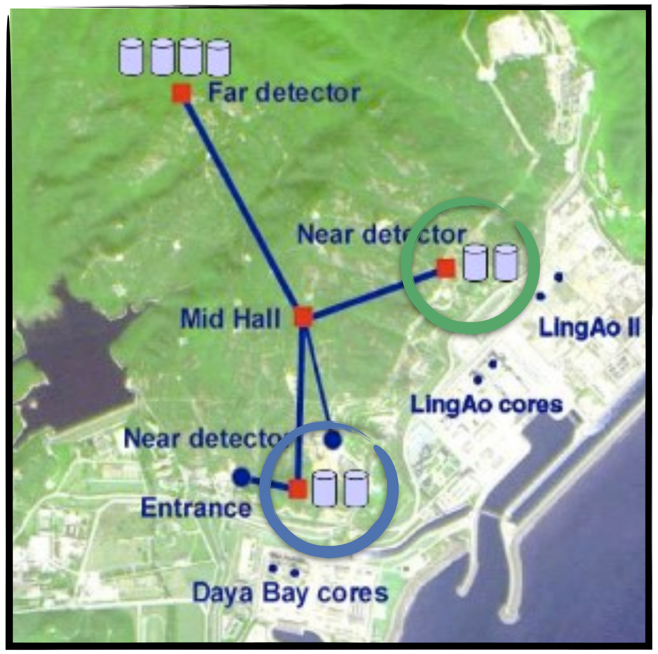
DANSS (finely segmented) ✗

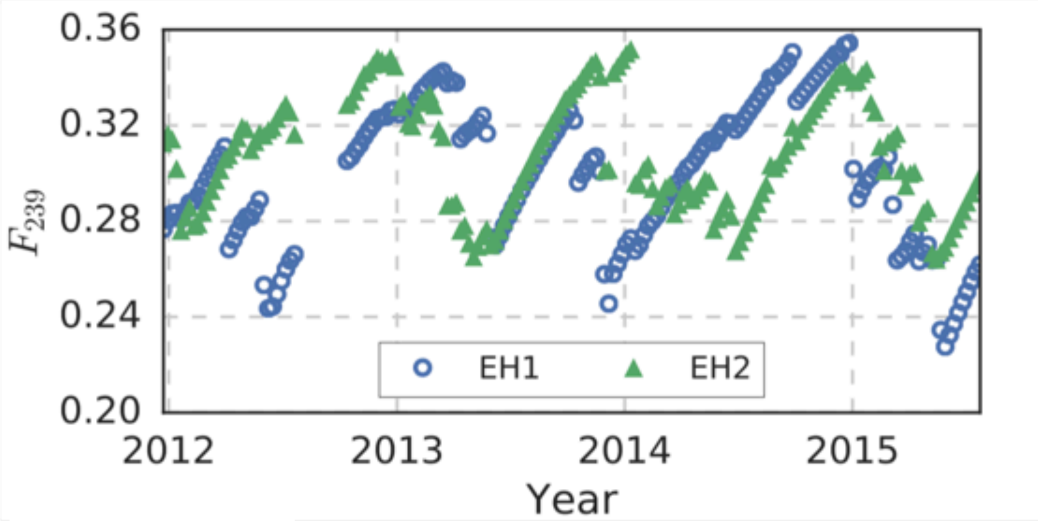


Reactor Flux Decomposition by Isotope

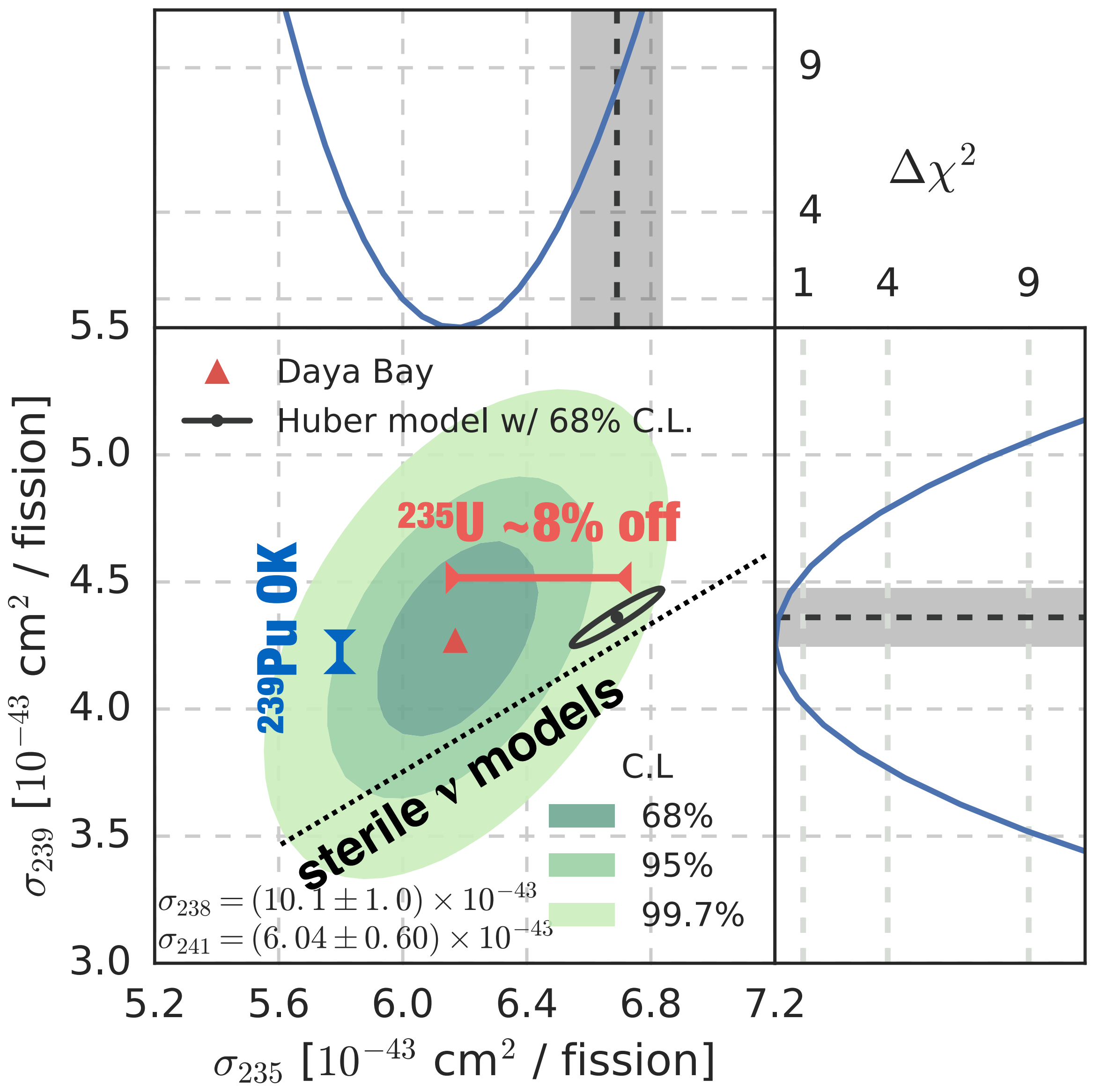
- Thanks to the huge statistics (~10^6 IBD) **Daya Bay** and RENO can **separate ^{235}U and ^{239}Pu contribution to neutrino flux**

- **Rate deficit** comes mainly **from ^{235}U** → **sterile neutrino hypothesis disfavoured**





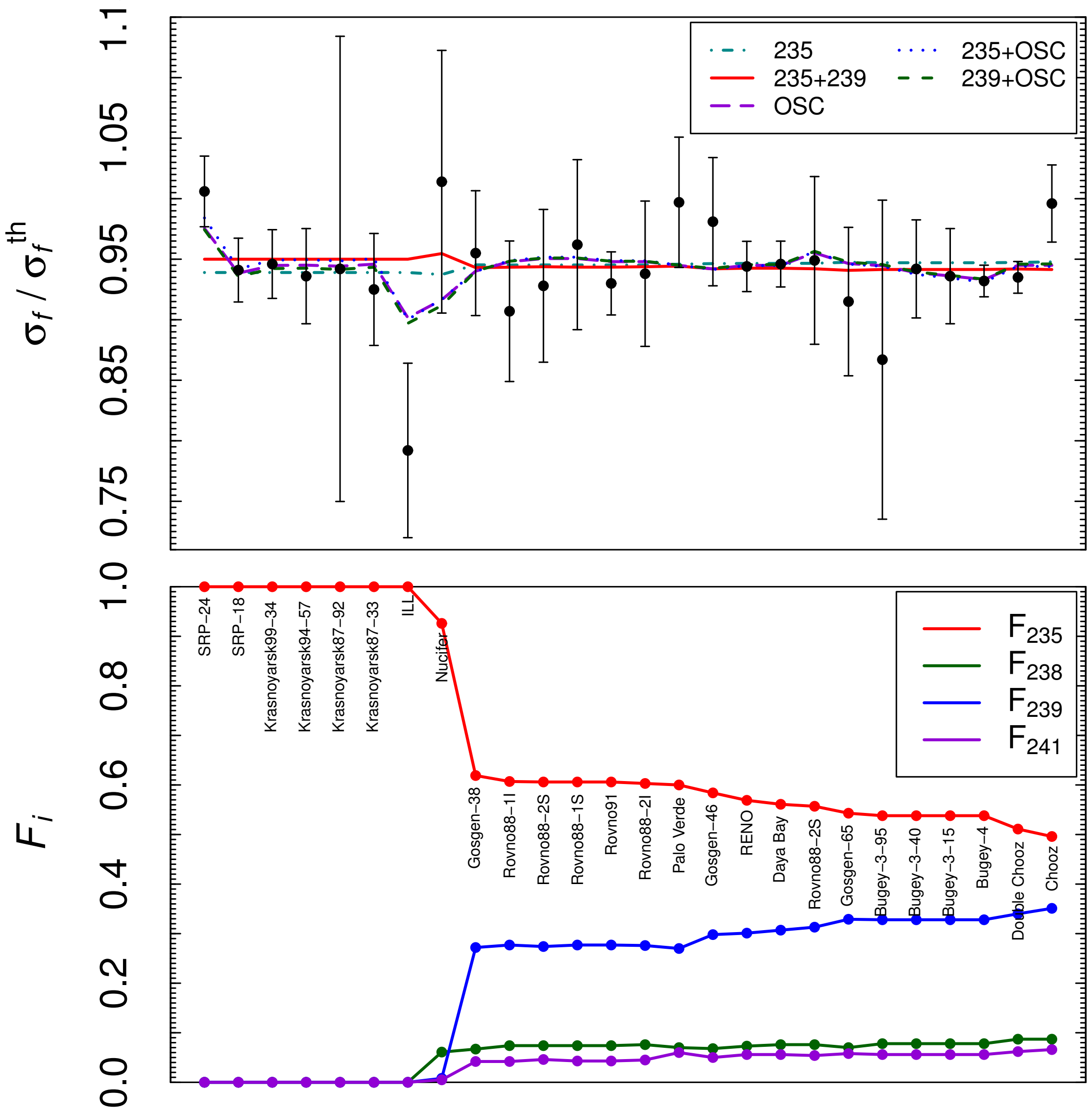
arXiv:1704.01082v2 (Jun 2017)

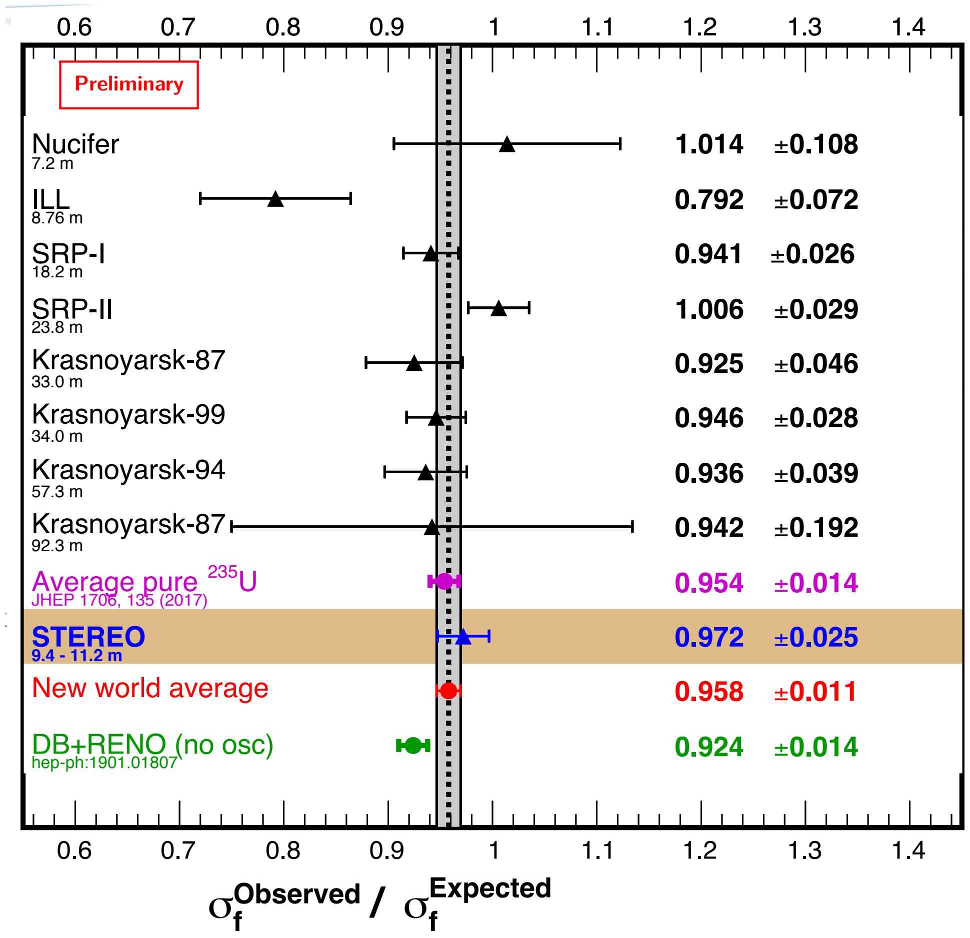


Reactor Flux and ^{235}U

- Previous measurements show **no dependency of flux deficit from fuel composition**
- ^{235}U and ^{239}Pu fluxes are normalised on separate "vintage" β-spectrum measurements @ ILL
  - Precision can be improved
  - Need corrections tuned on single experiment

Giunti et al., arXiv:1708.01133v1 (Aug 2017)





Bernard L. (STEREO), Rencontres de Moriond 2019

- New **flux estimation** from **STEREO** (~100% ^{235}U)
- **Deficit confirmed** for ^{235}U but results compatible with no anomaly

Summary of Sterile Neutrino Searches with Reactors

- Various **anomalies challenge the three-family neutrino oscillation framework**

- Existing anomalies are **hard to combine** in a common framework

- Search for a **global solution**
  - Make more **complex models** (3+2, ν_S decay)
  - Look for **other solutions beyond the Standard Model**

- Recent **reactor short baseline experiment** are rapidly accumulating data to
  - **Proof or exclude** the **active-sterile oscillation**
  - Constrain models and test validity of rate and shape predictions

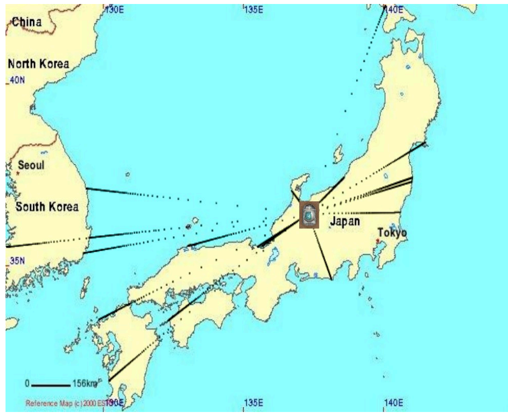
Outline

- Neutrino mixing and reactor neutrinos
- Anomalies challenging the 3-family framework
- The quest for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino flux and spectral estimation
- **The future of reactor neutrinos: JUNO**

History of Reactor Neutrino Experiments

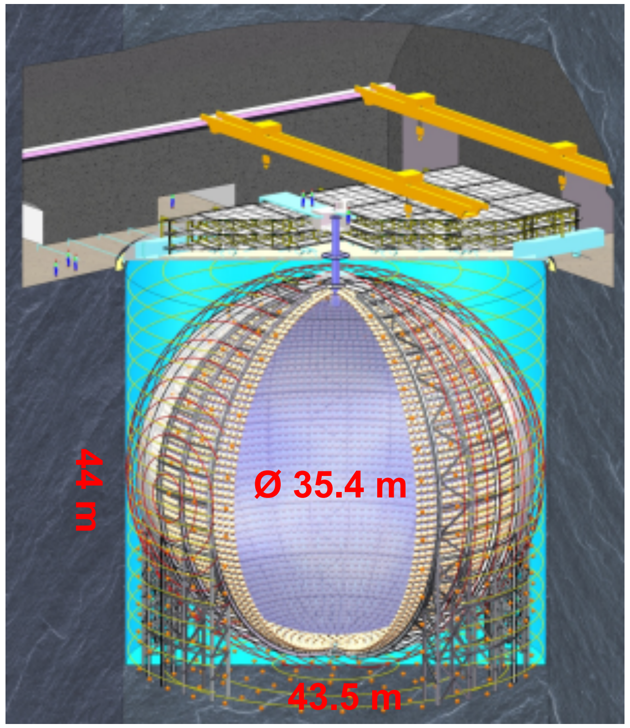
Mass/Baseline

- kt mass
- 50 km baseline
- **Measure θ_{12}**



- 10-100 t mass
- ~ km baseline
- **Measure θ_{13}**

- ~ t mass
- ~10m baseline
- **Search for ν_s**

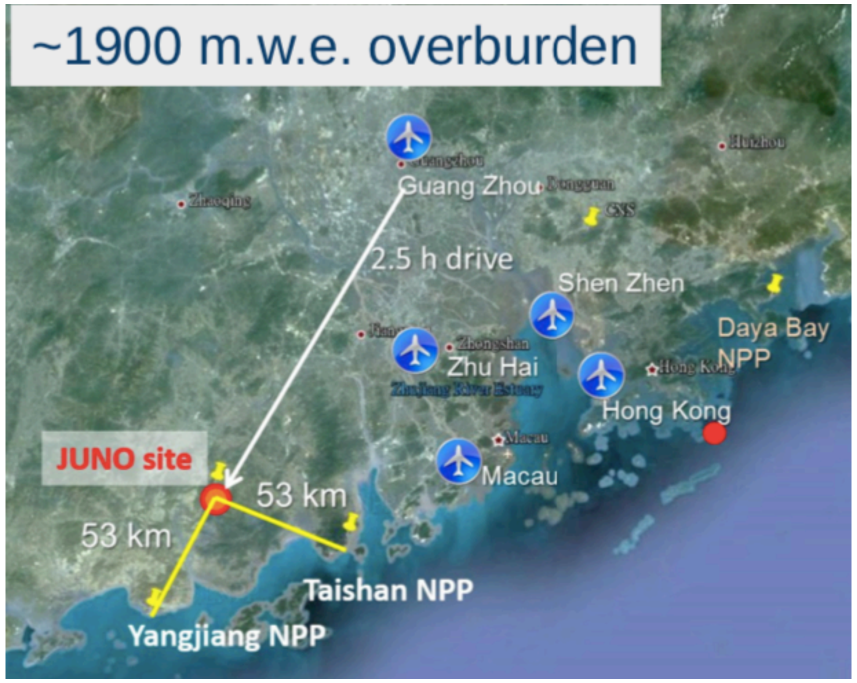


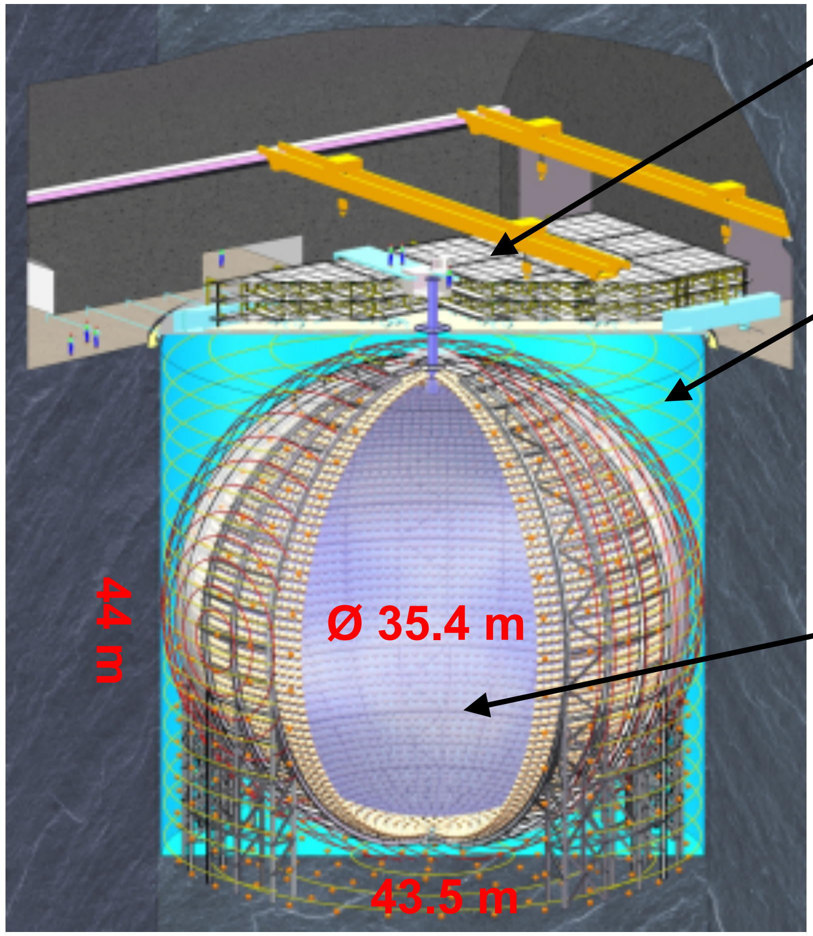
- 20 kt
- 50 km baseline
- **Wide program**

Time

JUNO

- **The next generation of reactor neutrino experiment: JUNO**
- Similar baseline of KamLAND (sensitive to θ_{12}, Δm^2_{12}-driven oscillation) and technology
- But **unprecedented detector mass** (**20 kt liquid scintillator** target) **and performances**
- **Data taking in 2021**





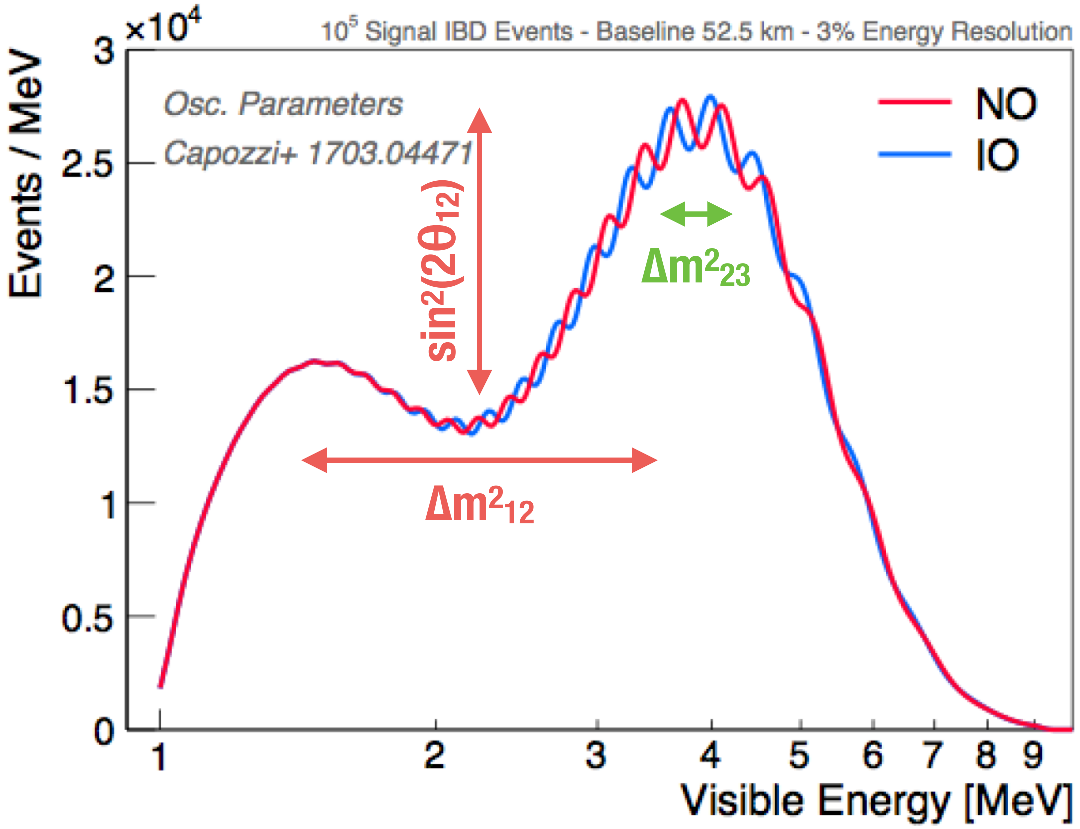
Top μ tracker
- 3 plastic scintillator layers
- ~50% coverage

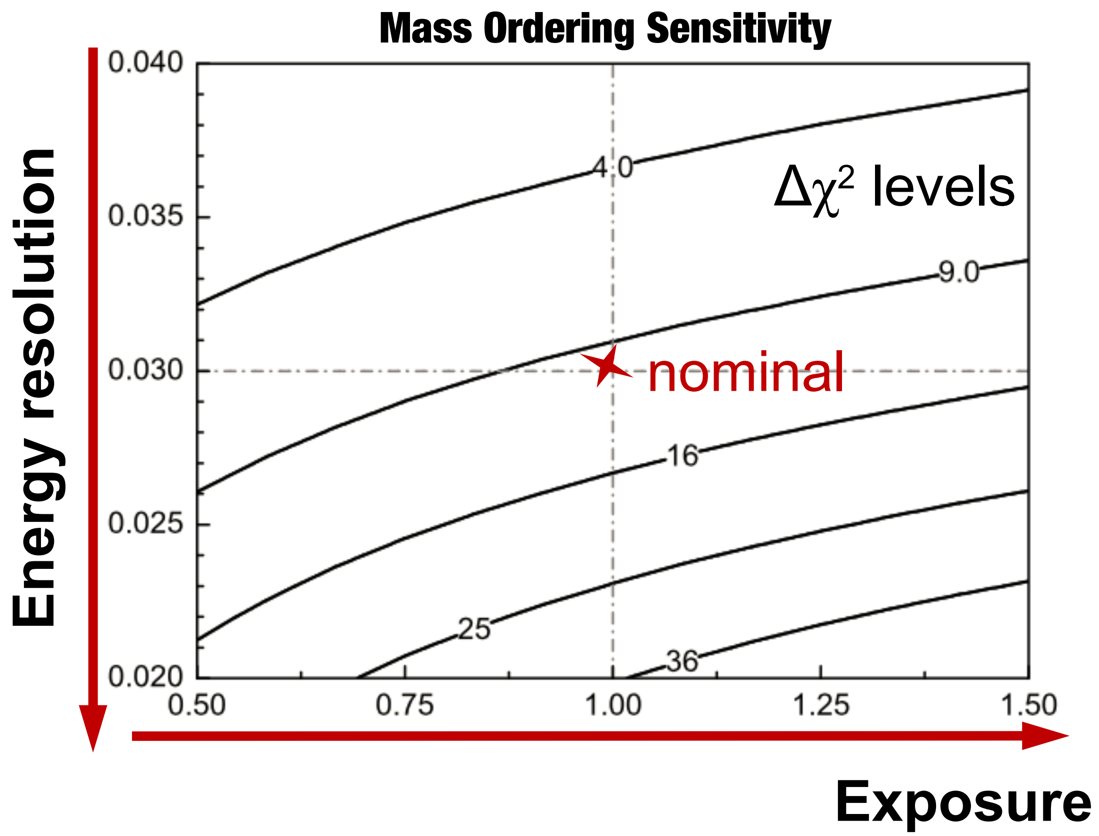
H_2O Cherenkov μ veto
- 2400 20” PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%

Central Detector
- Acrylic sphere with 20 kt LS
- **17571 large PMTs** (20”)
- 25600 small PMTs (3”)
- 78% PMT coverage

A Glance at JUNO Rich Scientific Program

- **Precision measurement of** oscillation parameters (probing U_{PMNS} below the ~% level)
- **Neutrino mass ordering** - requires challenging **energy resolution (< 3% @ 1 MeV)** and **energy scale uncertainty (< 1%)**
- Neutrinos from supernovae, sun (^{7}Be & ^{8}B), atmosphere (complementary mass-hierarchy), geo-neutrinos, proton decay (K mode)





Conclusions

- From the **discovery of the neutrino** to the **measurement of the neutrino mixing parameters**, **nuclear reactors** have proved indispensable in the study of such particles

- The **estimation of reactor neutrinos rates and spectra** that are required for such measurements is not trivial, and there are **discrepancies with experimental results**

- A deficit in the observed neutrino flux at short baseline, prompted a number of **experiments** worldwide **looking for evidence of sterile neutrinos at the eV scale**

- Recent results from **NEOS**, **DANSS**, **STEREO**, and **PROSPECT** are **excluding the allowed region** for active-sterile neutrino oscillation, although not fully rejecting it yet

- The **combination of their results** will help **resolve the reactor anomalies** by testing the sterile neutrino hypothesis and constraining reactor models in the near future

- Meanwhile, **JUNO** will exploit reactor neutrinos, with a detector of **unprecedented scale and performances**, to unveil the **neutrino mass hierarchy** and bring the precision on the neutrino mixing parameters to the % level

Thank You For Your Attention!

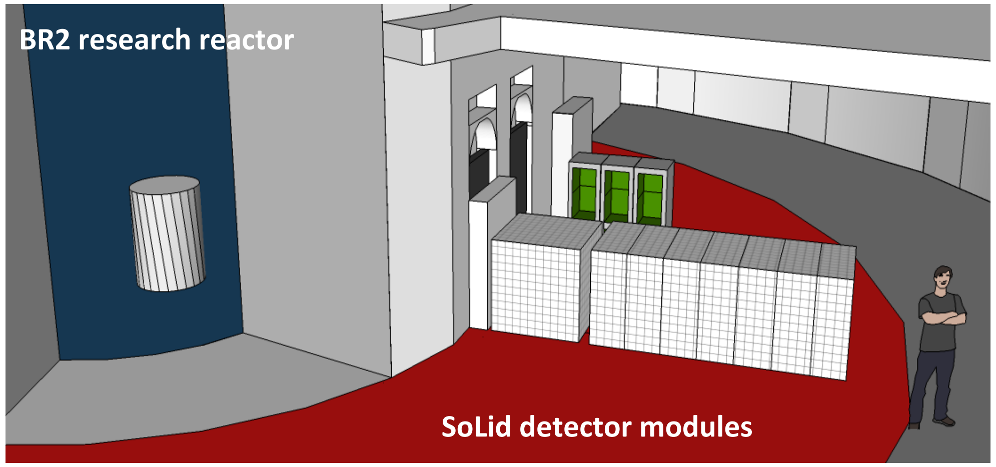
Extra Slides

A World-Wide Hunt - Table

	Core P_{Th}	Core Size	Overburden	Segmentation	Baseline	Material
Chandler	72 MW (^{235}U)	⦸ = 50 cm	~10 mwe	6.2 cm (3D)	5.5 m	PS + Li layer
DANSS	3 GW (LEU)	h = 3.6 m ⦸ = 3.1 m	~50 mwe	5 cm (2D)	10.7-12.7 m	Gd-doped PS
NEOS	2.8 GW (LEU)	h = 3.7 m ⦸ = 3.1 m	~20 mwe	-	23.7 m	Gd-doped LS
Neutrino4	90 MW (^{235}U)	35x42x42 cm^3	few mwe	22.5 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)	h = 0.5 m ⦸ = 0.2 m	few mwe	15 cm (2D)	7 m	Li-doped LS
SoLiδ	72 MW (^{235}U)	⦸ = 0.5 m	~10 mwe	5 cm (3D)	5.5 m	PS + Li layer
Stereo	58 MW (^{235}U)	⦸ = 37 cm	~15 mwe	25 cm (1D)	8.8-11.2 m	Gd-doped LS

SoLi∂

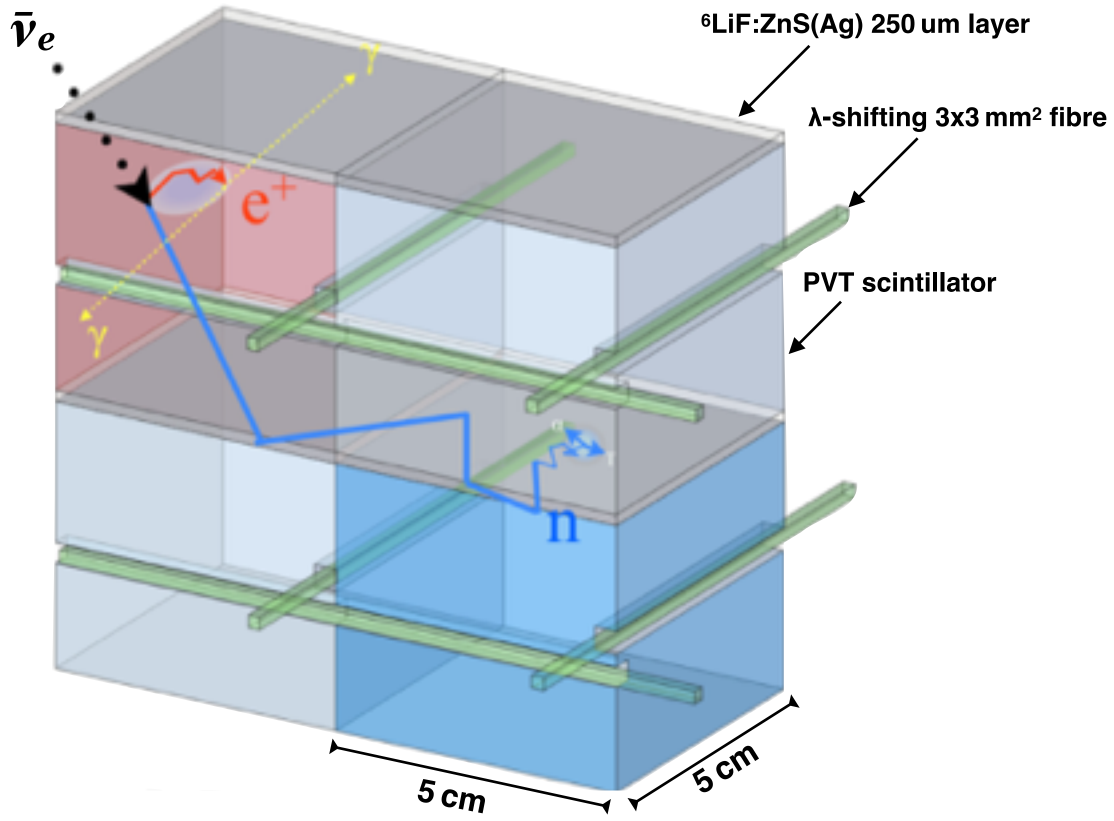
- @ 60 MW_{th} compact-core (0.5 m diameter) BR2 reactor in Mol (Belgium), baseline range ~ 5.5 - 10 m

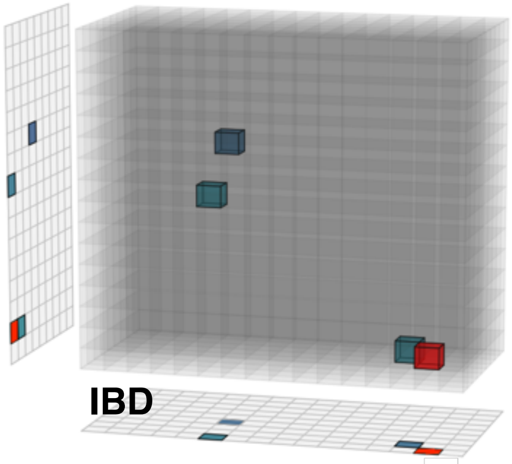


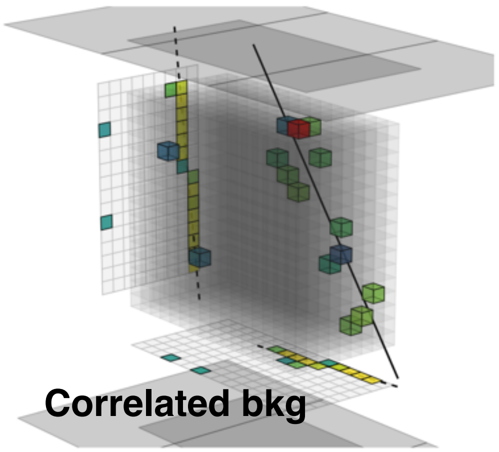
- Highly 3D segmented detector
  - $5\times5\times5$cm^3 PVT cubes (optically separated)
  - ^{6}LiF:ZnS(Ag) for neutron identification
  - Optical fibers and silicon PMTs

- Event topology used to identify IBD's

- Currently under commissioning







Sterile Neutrinos and Cosmological Constraints

- The existence of a light sterile neutrino clashes with cosmological observations
  - **$\Sigma m_\nu \lesssim 0.23$** from cosmic lensing
  - **$N_{eff} \lesssim 3.38$** from Plank measurements

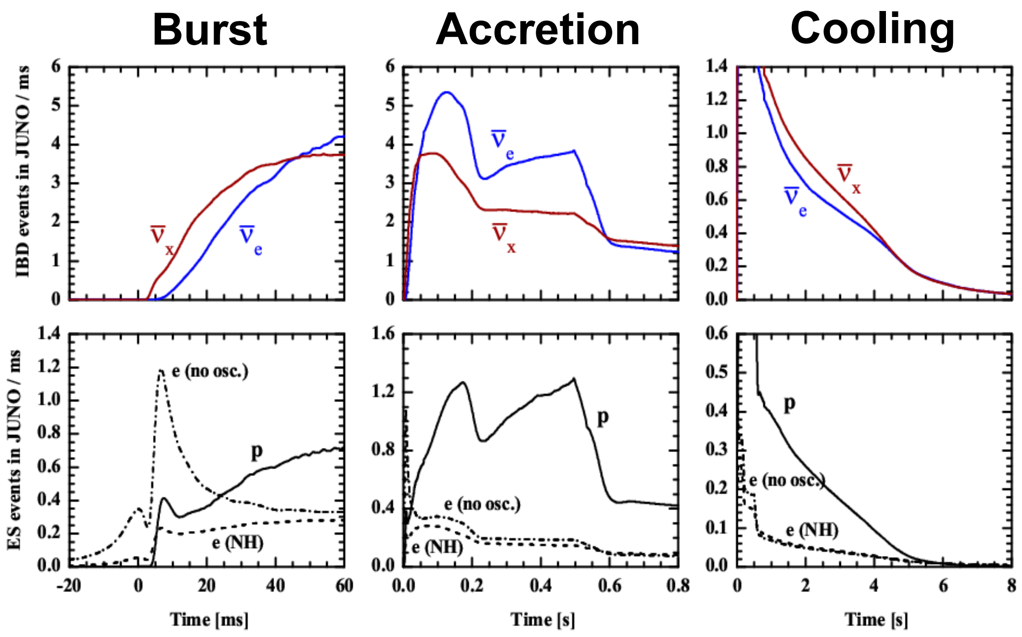
- Standard picture: ν_s production via oscillation at $T \gtrsim$ MeV (big bang nucleosynthesis)

- Many ways to avoid the tension, e.g.:
  - Entropy production @ $T <$ MeV Fuller, Kishimoto, Kusenko, arXiv: 1110.6479
  - Mixing suppression in early Universe if ν_s is charged under hidden force mediated by new gauge boson (dark photon)

    Dasgupta, Kopp, arXiv:1310.6337

A Deper Look into JUNO Rich Scientific Program

- JUNO will be able to observe the 3 phases of core-collapsing supernovae
  - Main channel: IBD



	Statistics	+BG, +1% bin-to-bin +1% EScale , +1% EnonL
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{ee}	0.27%	**0.44%**

- JUNO will investigate open issues with solar neutrinos (oscillation parameters, metallicity problem, matter oscillation effect)

- JUNO will extend current limits on p decay
  - is sensitive to the $p \rightarrow k^+ v$ channel (good in liquid scintillator, invisible in water cherenkov)
  - Triple-coincidence signal (K^+ & K decay