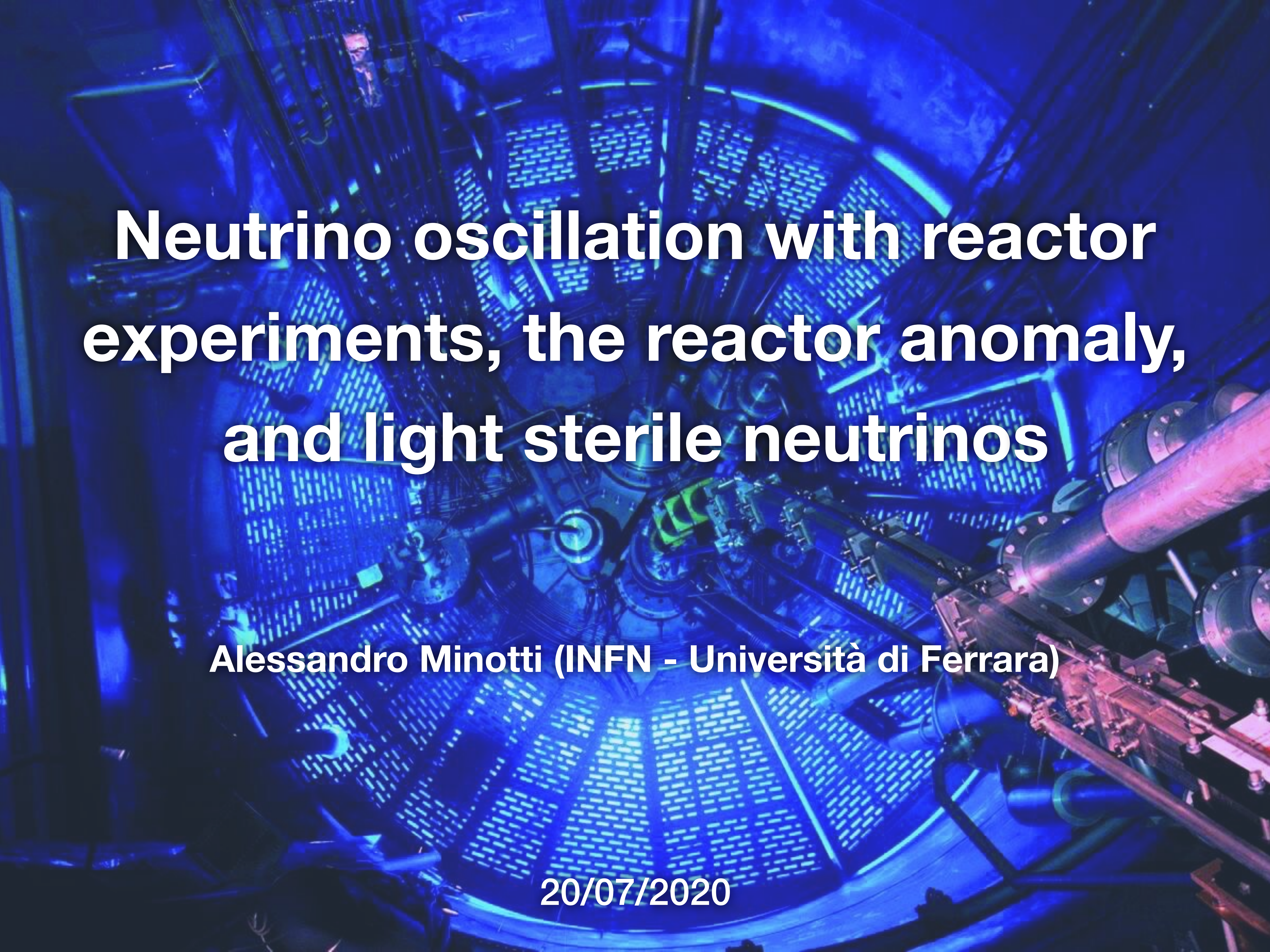


Neutrino oscillation with reactor experiments, the reactor anomaly, and light sterile neutrinos

Alessandro Minotti (INFN - Università di Ferrara)

20/07/2020

Outline

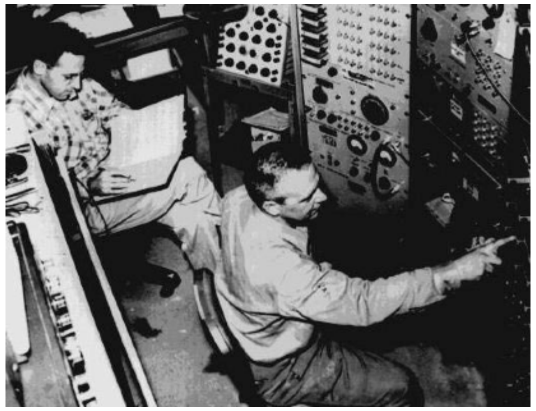
- Neutrino mixing and reactor antineutrinos
- Legacy of the 2nd generation of reactor neutrino experiment
- Anomalies challenging the 3-family framework
- The hunt for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino spectral estimation
- The future of reactor neutrinos: JUNO

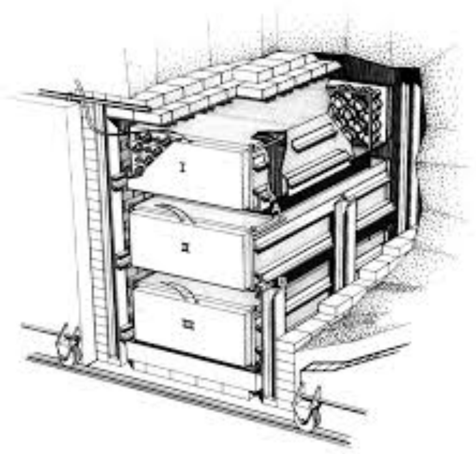
Outline

- **Neutrino mixing and reactor antineutrinos**
- Legacy of the 2nd generation of reactor neutrino experiment
- Anomalies challenging the 3-family framework
- The hunt for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino spectral estimation
- The future of reactor neutrinos: JUNO

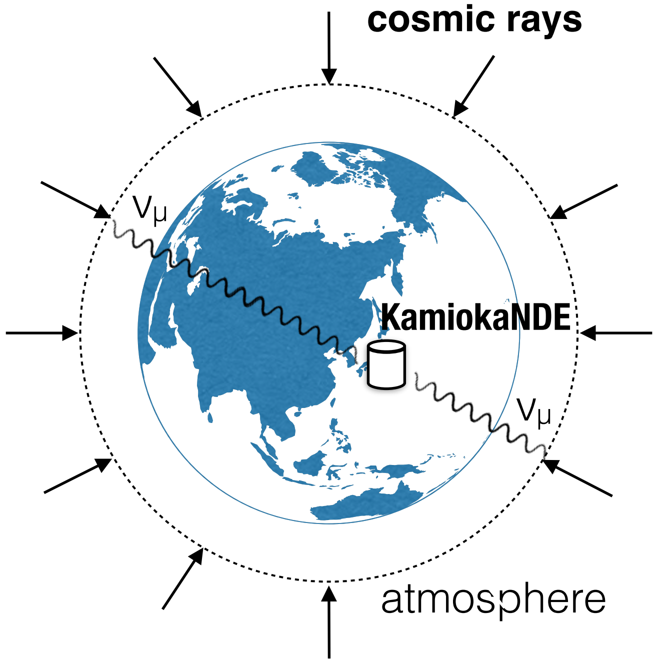
Discovery of the Neutrino

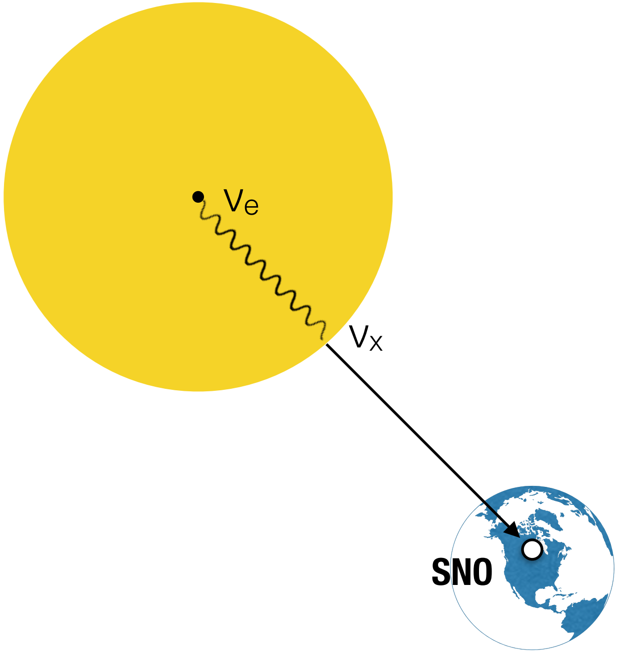
- **Cowan and Reines** used a reactor to **discover the neutrino** in 1956

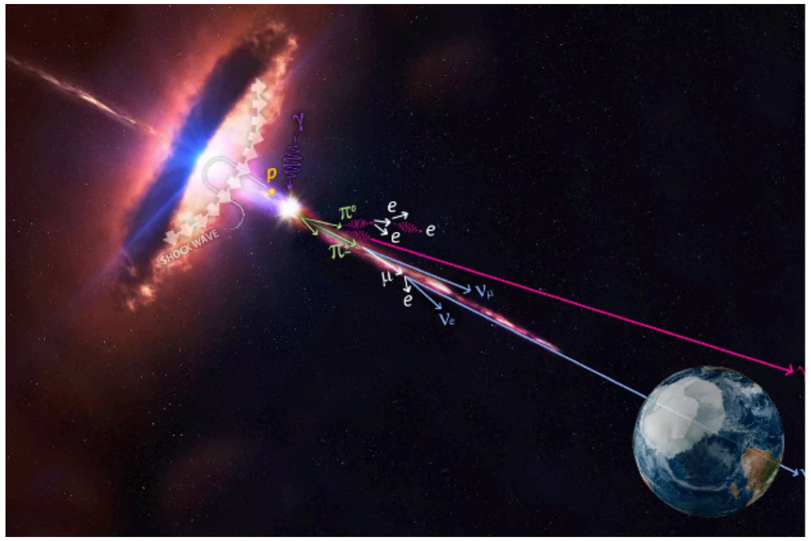




- Since then we observed neutrinos from the sun, atmosphere, distant astronomical objects, earth crust, and produced neutrino beams in accelerators



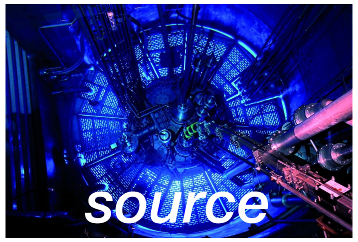




- Basic strategy of **massive detectors** (water- & scintillator-based) and detection technique exploited for years in several generations of experiments

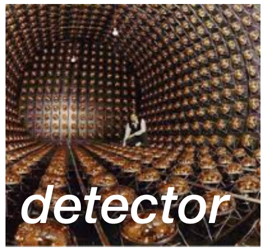
Neutrino Oscillation

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



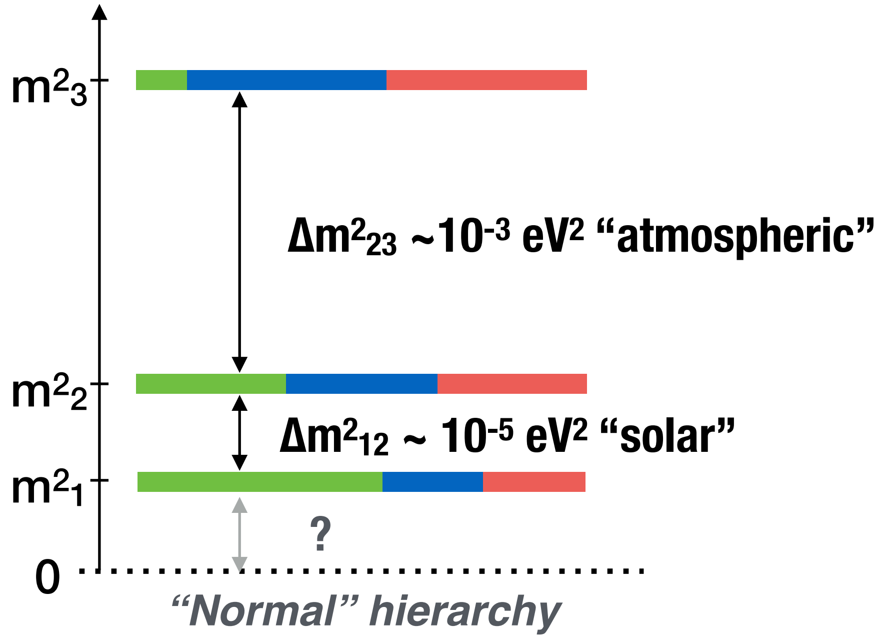
$\nu_e \xrightarrow{\nu_1 \quad \nu_2 \quad \nu_3}$ ν_e? ν_μ? ν_τ?

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



- **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

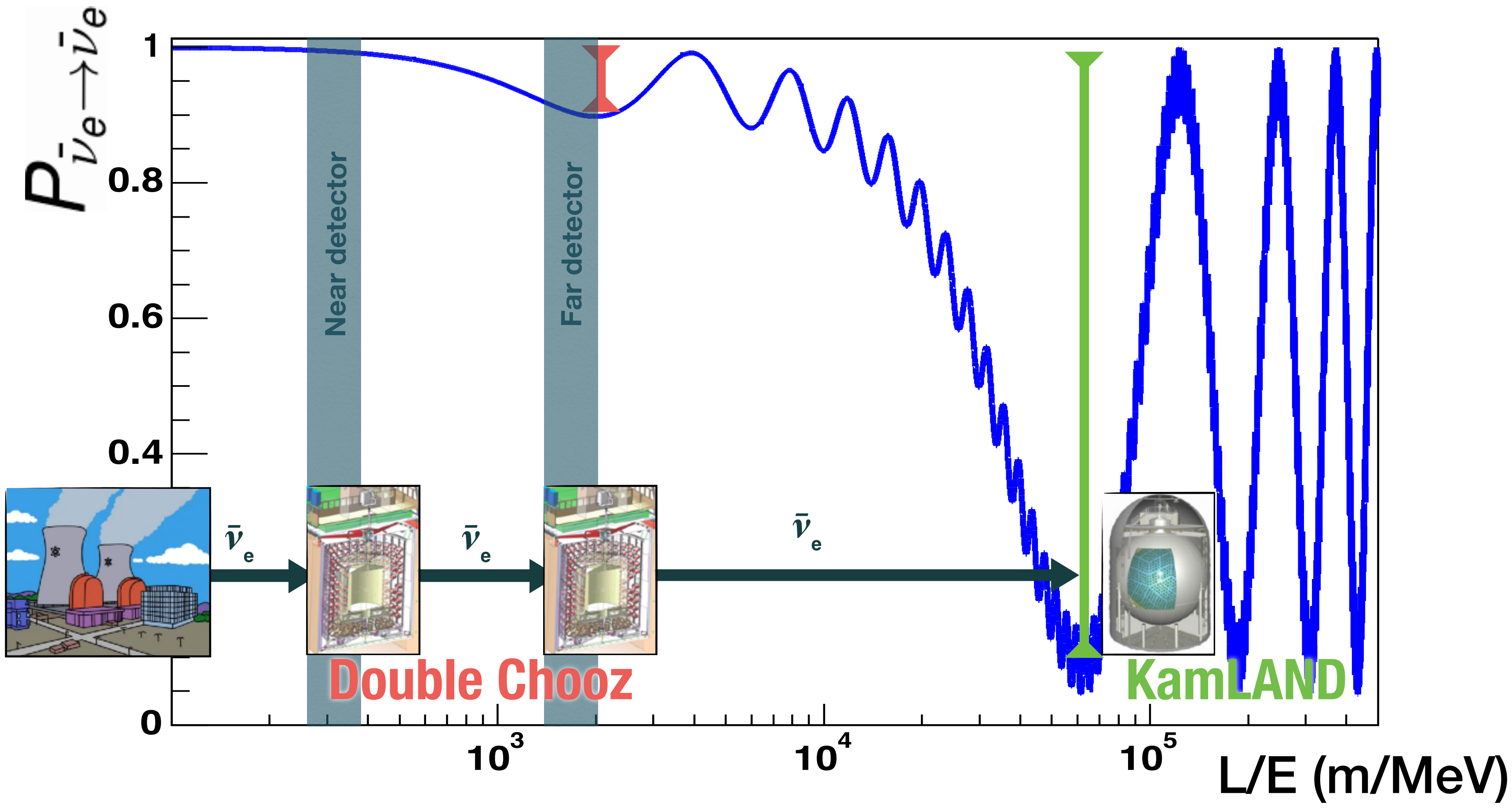
- solar neutrinos
- **reactor neutrinos**

- Reactor neutrinos contribute to two sectors at different baselines

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

Reactor Antineutrino Oscillation

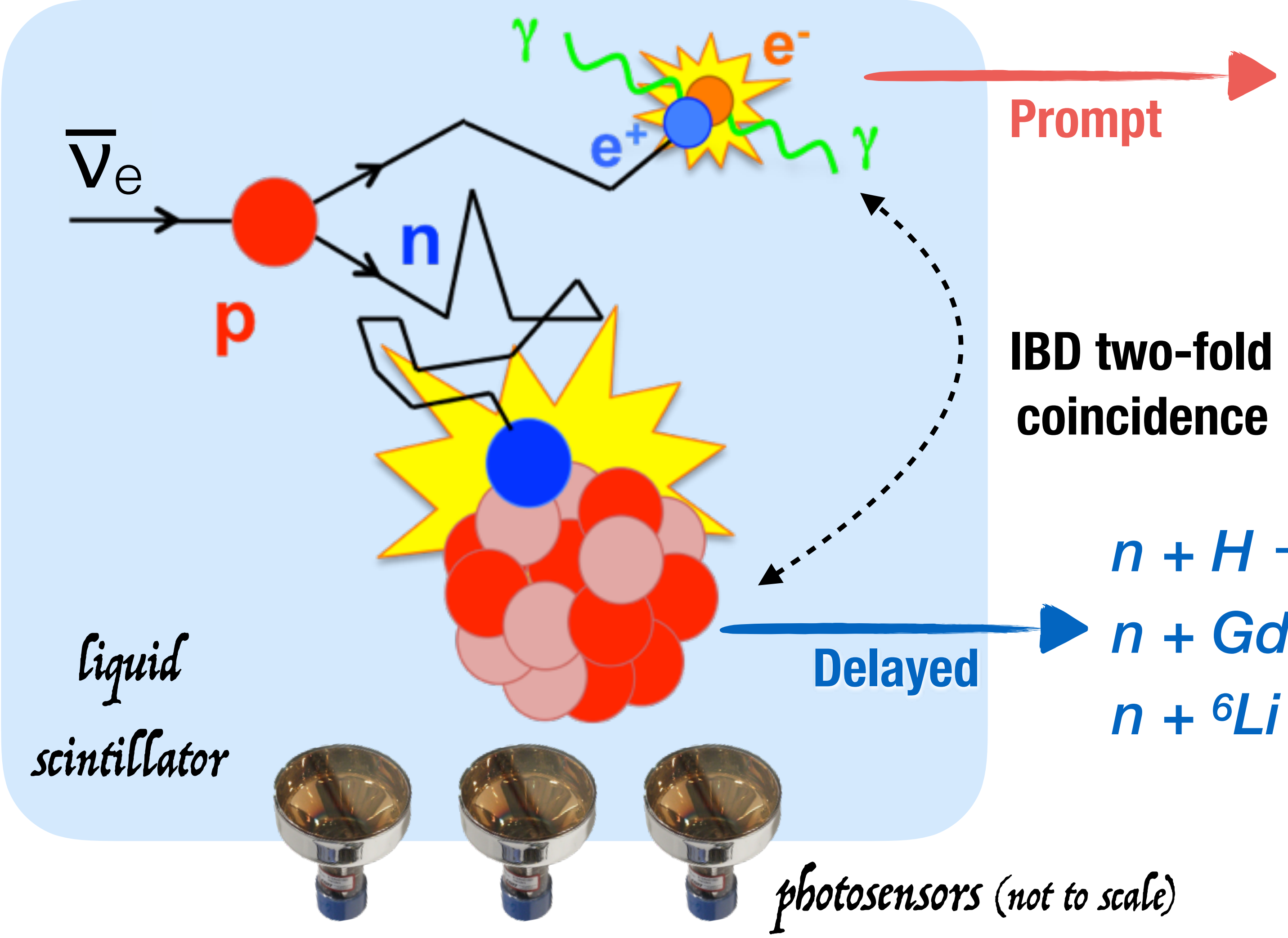
$$P_{\bar{\nu}_e\to\bar{\nu}_e} \simeq 1 - \sin^2(2\theta_{13})\,\sin^2(\Delta m^2_{23}\,L/4E) - \cos^4(\theta_{13})\,\sin^2(2\theta_{12})\,\sin^2(\Delta m^2_{12}\,L/4E)$$



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

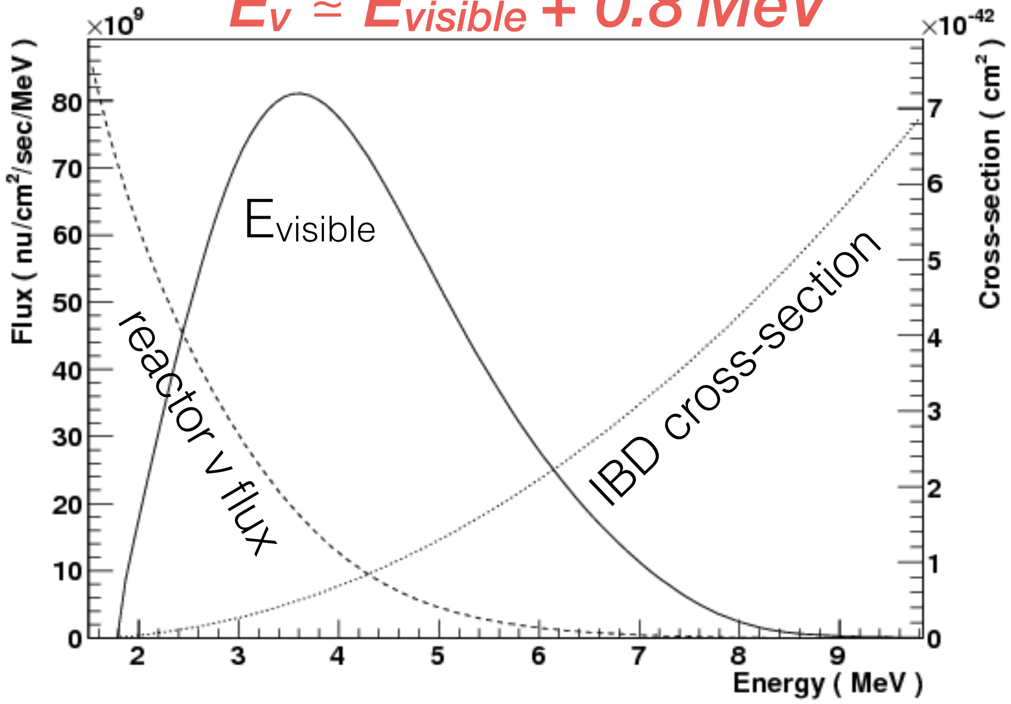
Reactor Antineutrino Detection

- **Signal**: **I**nverse **B**eta **D**ecay in scintillator target



IBD two-fold coincidence

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



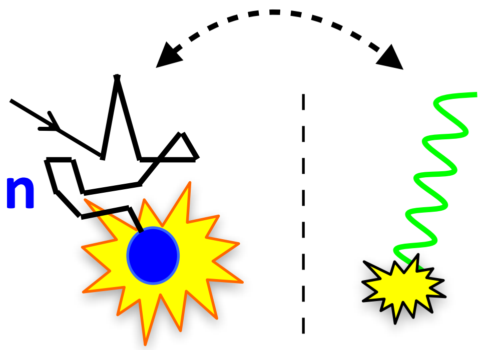
$n + H \rightarrow D + \gamma\ (2.2\ MeV)$

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

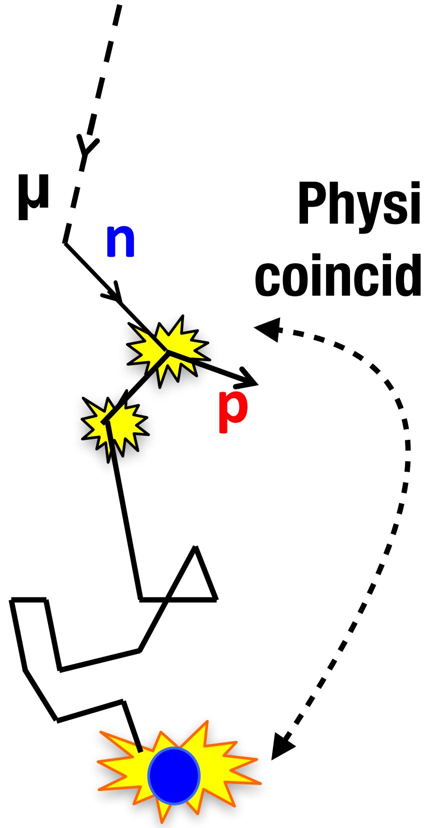
$n + {}^6Li \rightarrow \alpha + {}^3H\ (4.78 MeV)$

- **Background**
  - Cosmic induced (fast n, n-γ from μ spallation)
  - Accidental coincidences between neutrons and high-E γ's

Accidental coincidence



Physical coincidence

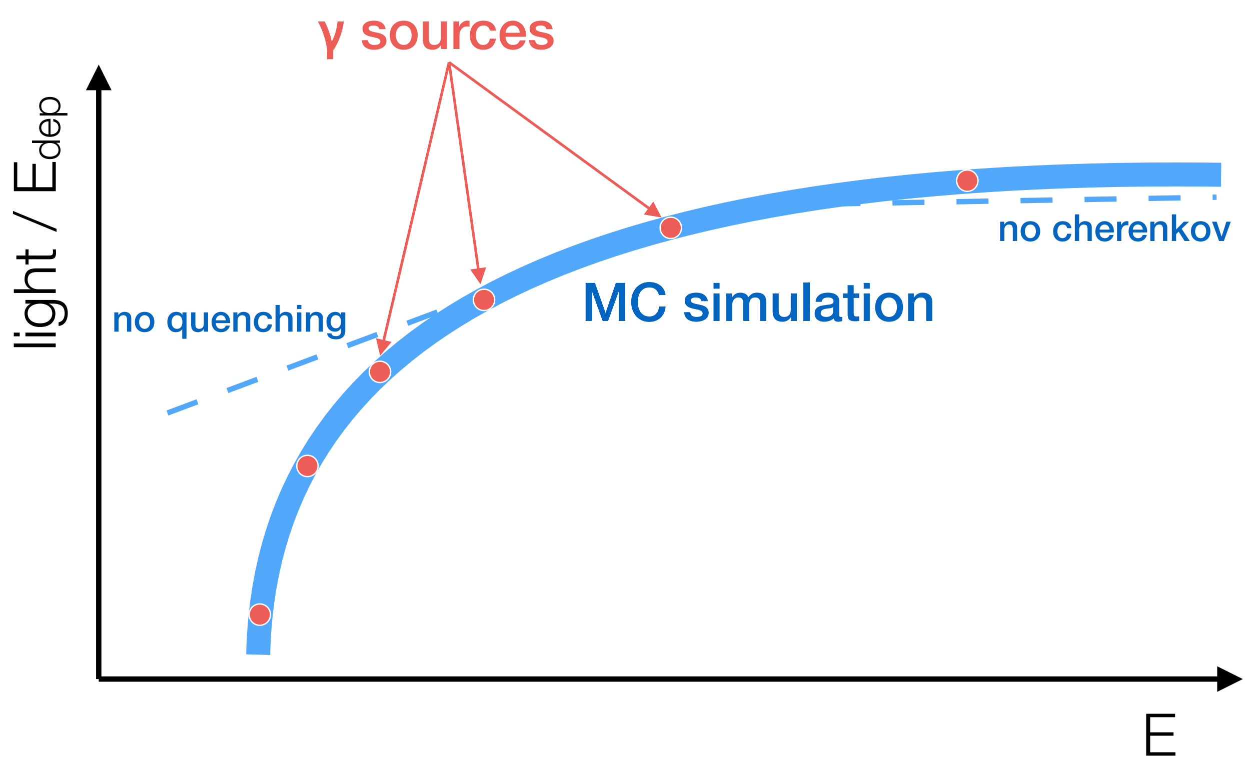


Energy Reconstruction

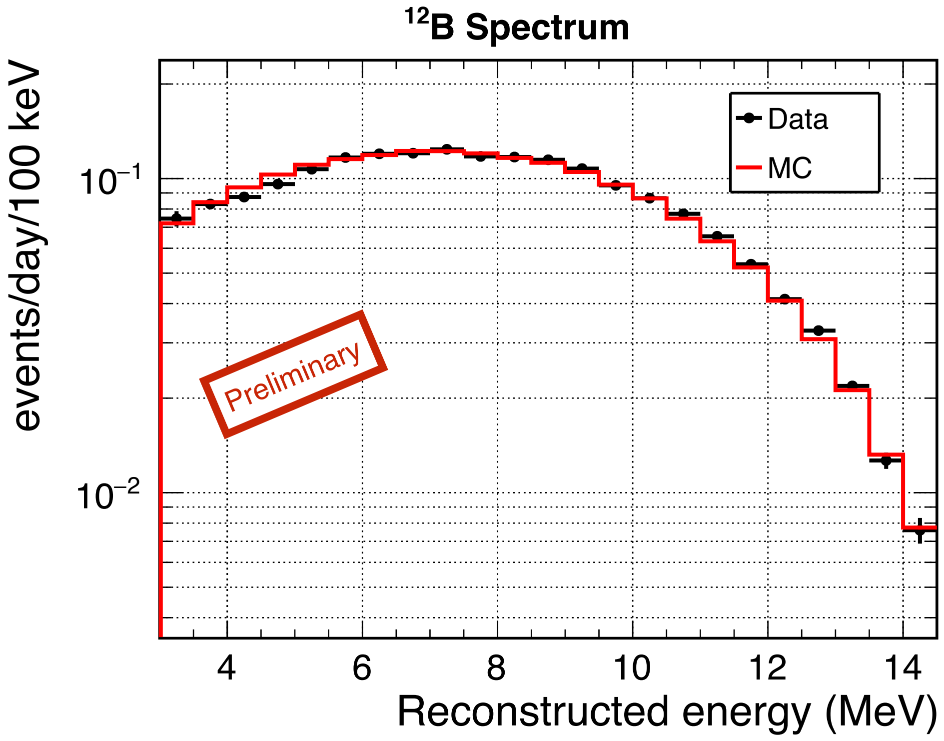
- **Detector response** (energy reconstruction)

  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.

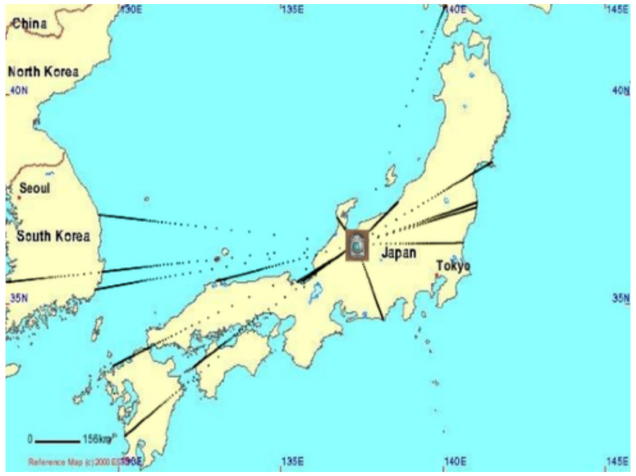


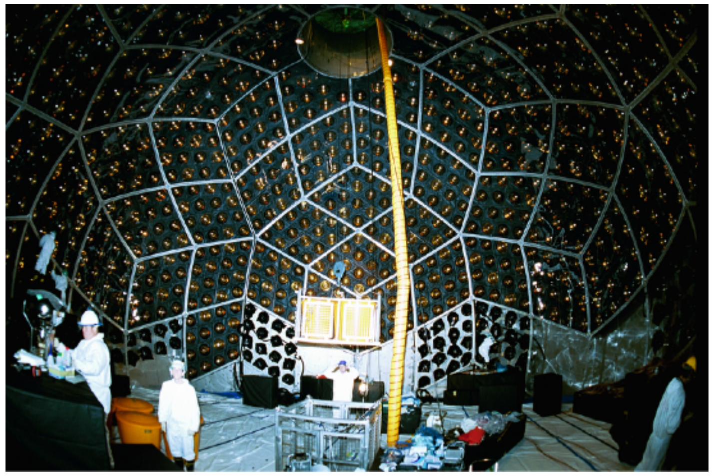
Outline

- Neutrino mixing and reactor antineutrinos
- **Legacy of the 2nd generation of reactor neutrino experiment**
- Anomalies challenging the 3-family framework
- The hunt for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino spectral estimation
- The future of reactor neutrinos: JUNO

KamLAND and the Solar Neutrino Sector

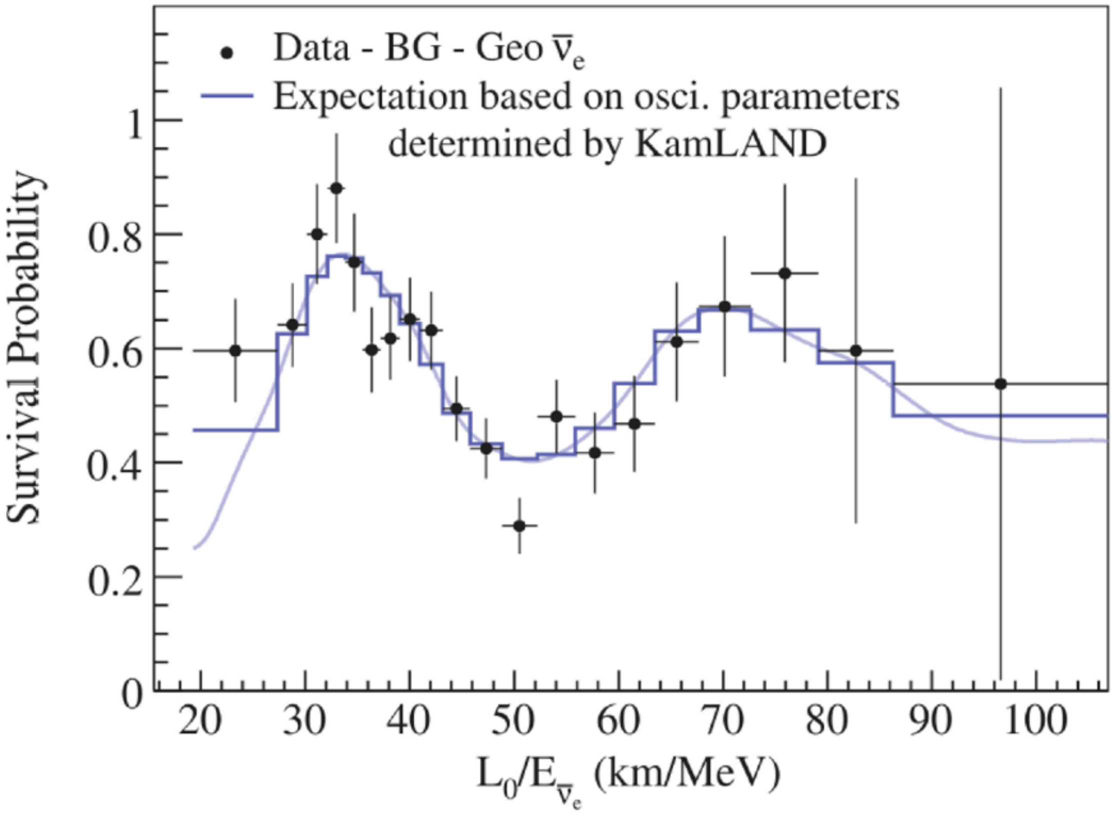
- **KamLAND** (2002-2011) - first large liquid scintillator experiment after Cowan-Reines



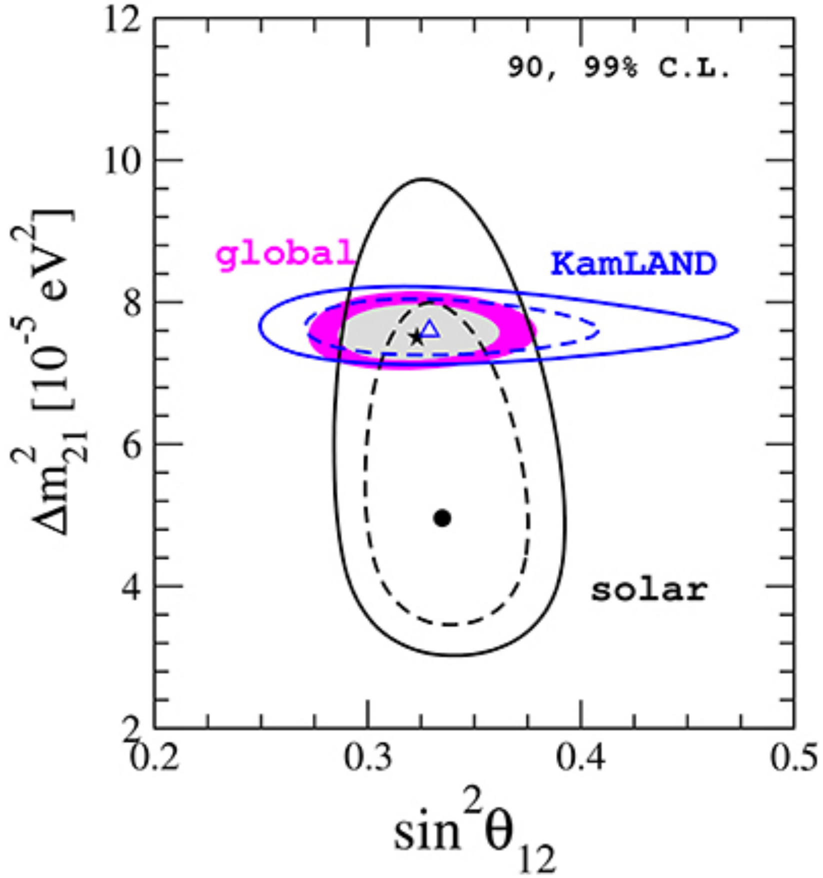


- Provided **accurate measurements** in the “solar sector” (**θ_{12}**, **Δm^2_{12}**)

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



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



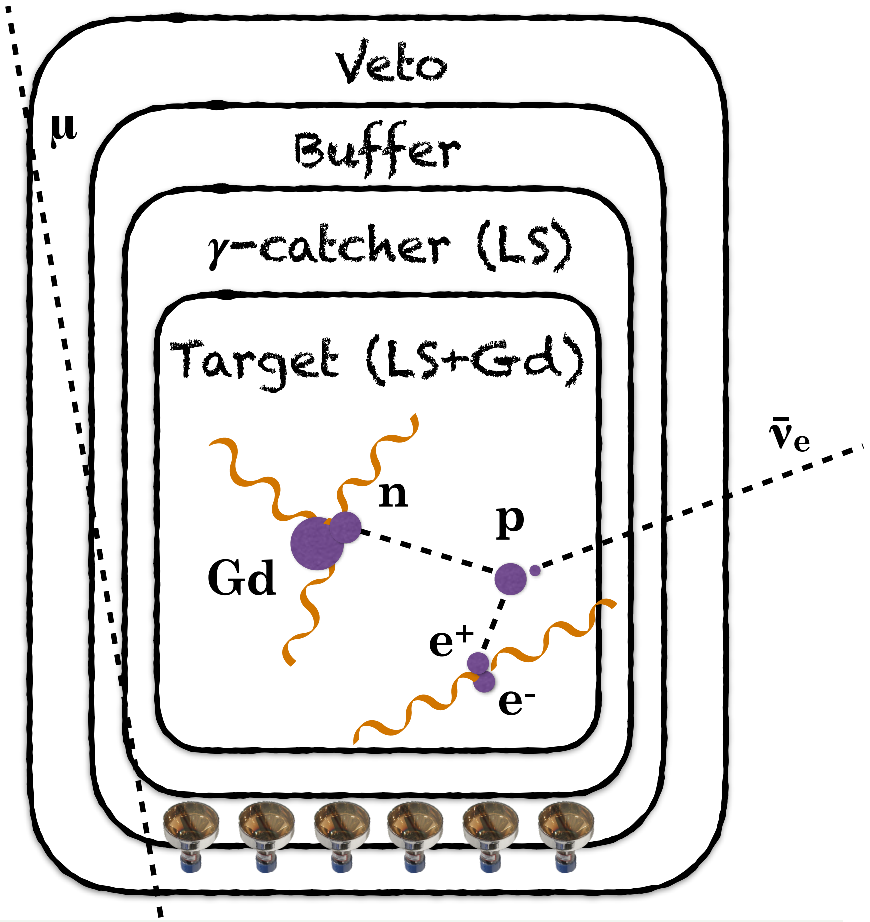
The Measurement of θ_{13}

- Only upper limits on θ_{13} as for 2010 (CHOOZ)

- **Three experiments searches for θ_{13}** started in 2011:

  Double Chooz, Daya Bay, RENO

- Similar design and well-established technique based on liquid scintillator and neutron detection via capture on Gd



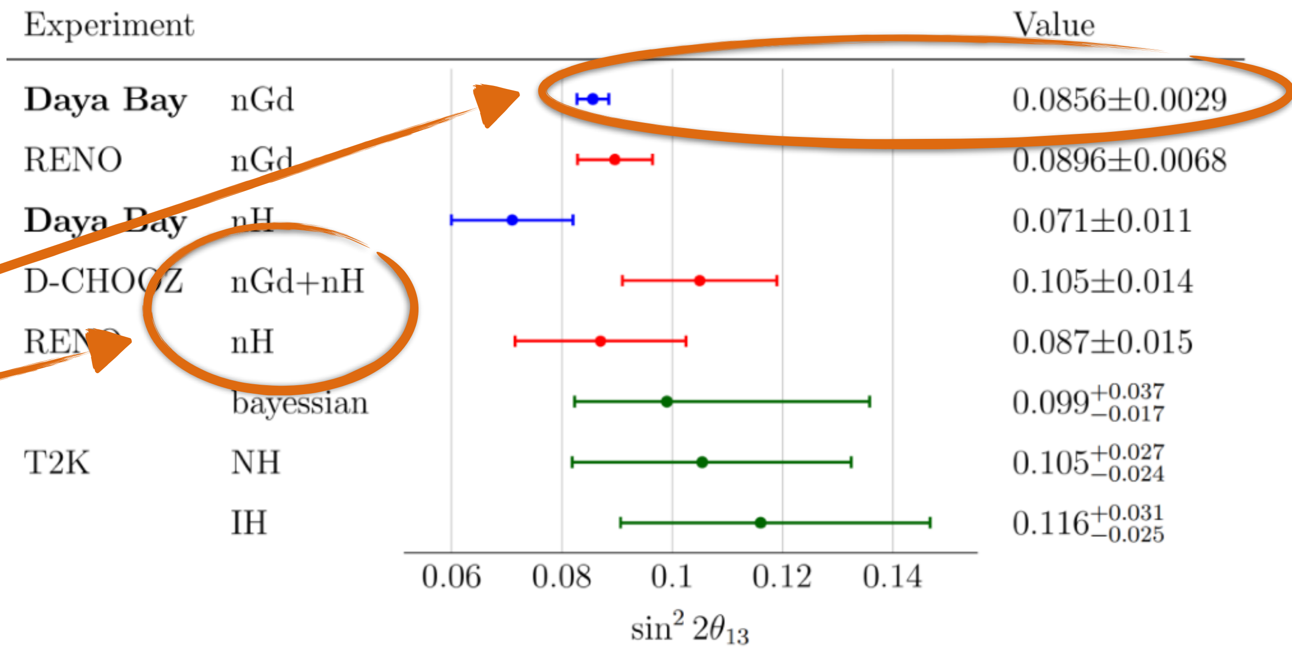
(2011-2021)

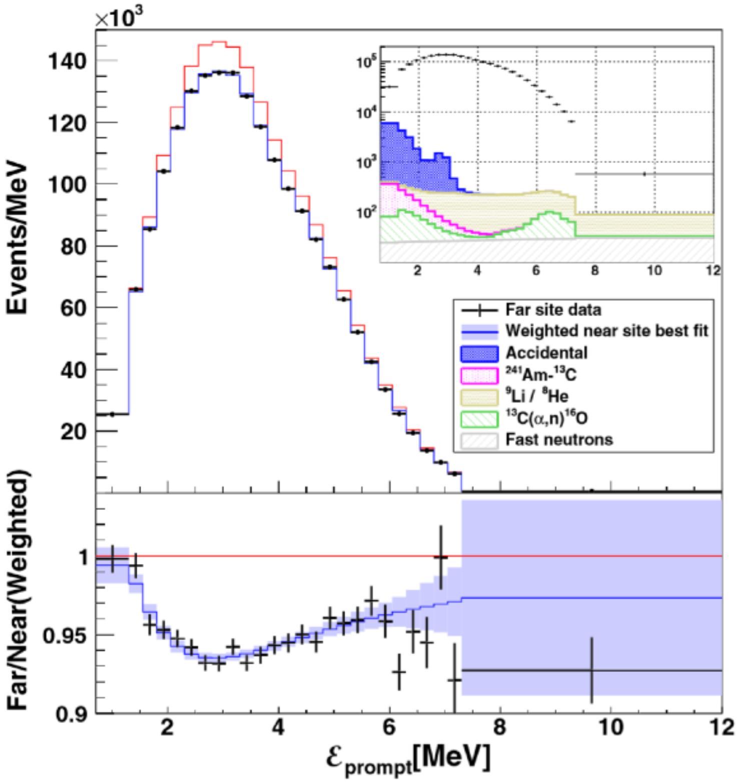
(2011-2017)

Latest Results of 2nd Generation Reactor Neutrino Experiments

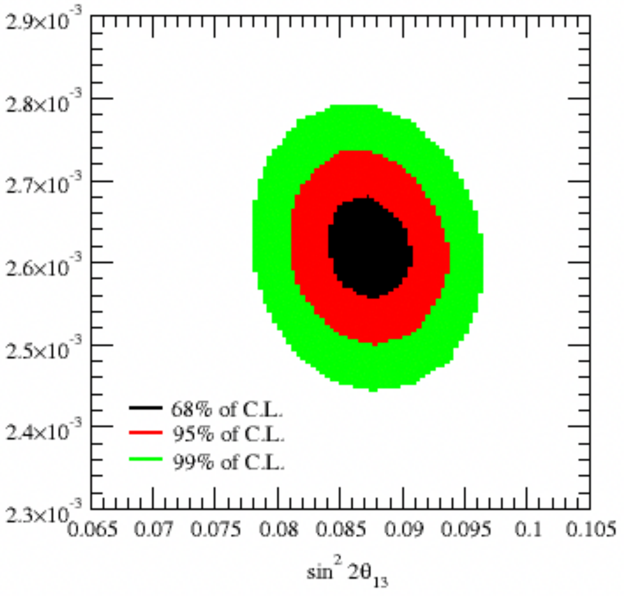
- Double Chooz, Daya Bay, and RENO released their latest results in Neutrino 2020

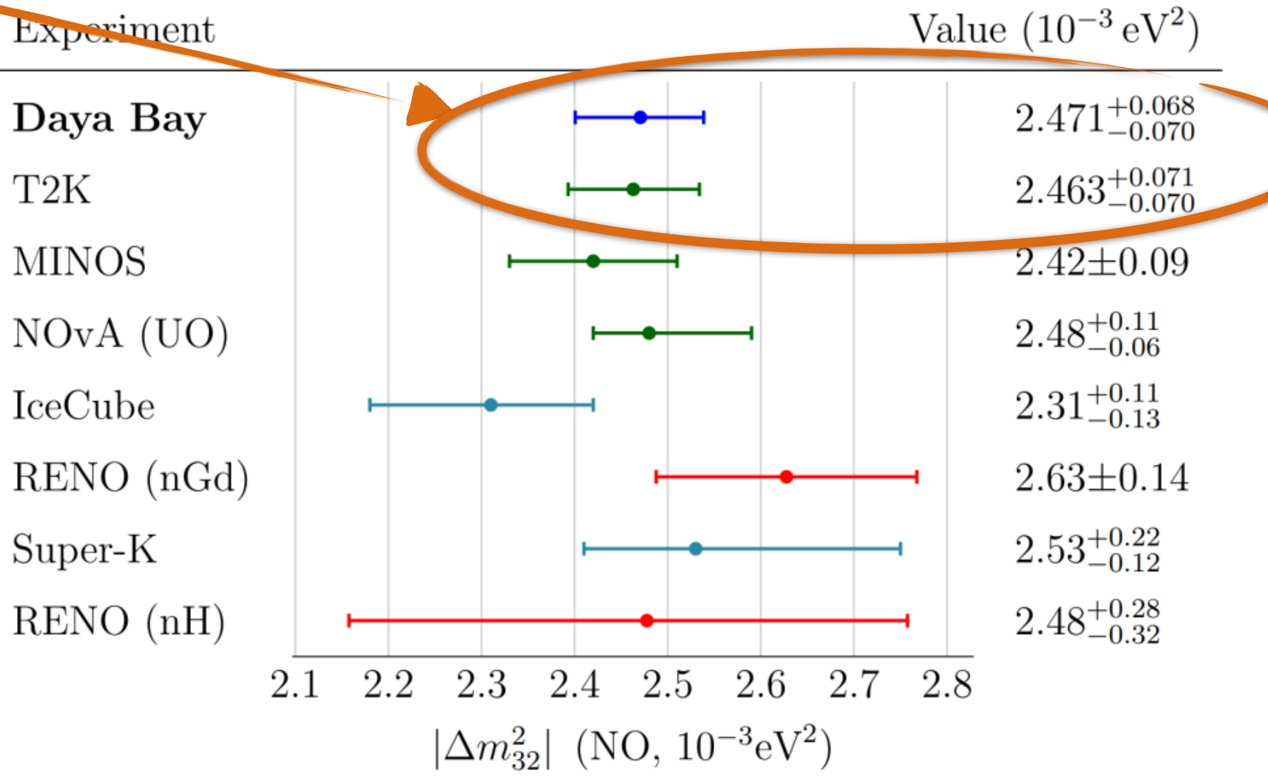
- Thanks to good detector characterisation (σ_{sys} <1%) and high statistics ($\mathcal{O}10^4$ IBDs):
  - θ_{13} now most precisely measured U_{PMNS} parameter
  - Different detection techniques
  - Δm^2_{13} also measured





Double Chooz, Daya Bay, and RENO combined results





Outline

- Neutrino mixing and reactor antineutrinos
- Legacy of the 2nd generation of reactor neutrino experiment
- **Anomalies challenging the 3-family framework**
- The hunt for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino spectral estimation
- The future of reactor neutrinos: JUNO

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)

reactor thermal power

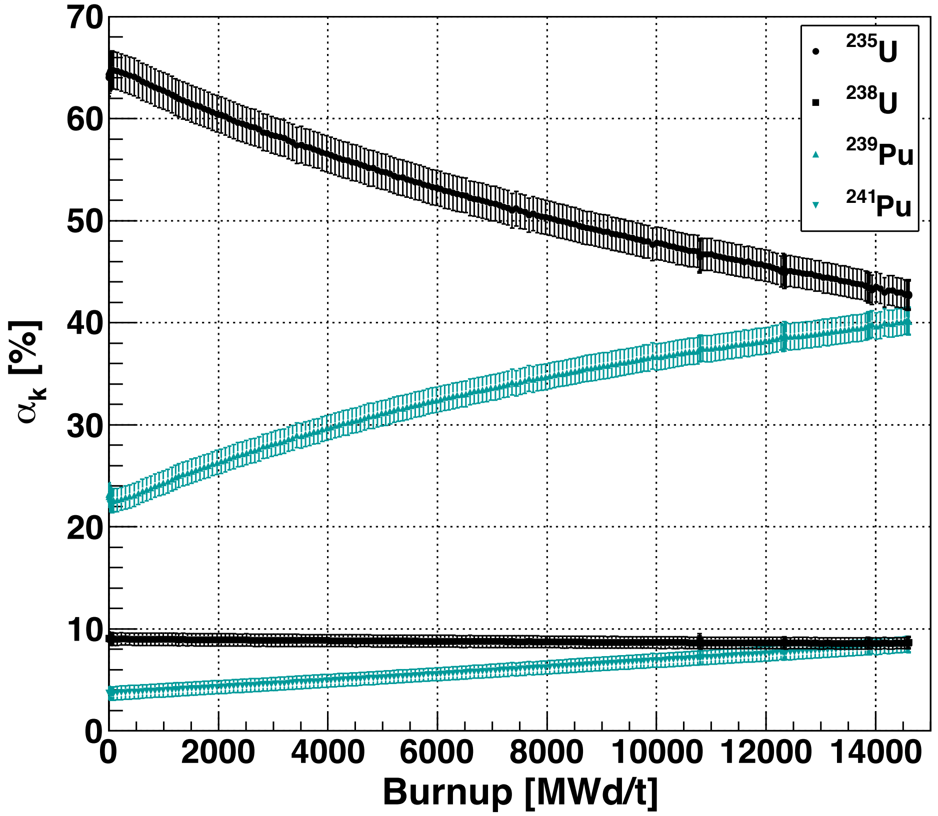
$$N_{IBD}(E_{\bar{\nu}_e}, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle (t)} \times \langle \sigma_f \rangle (E_{\bar{\nu}_e}, t)$$

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

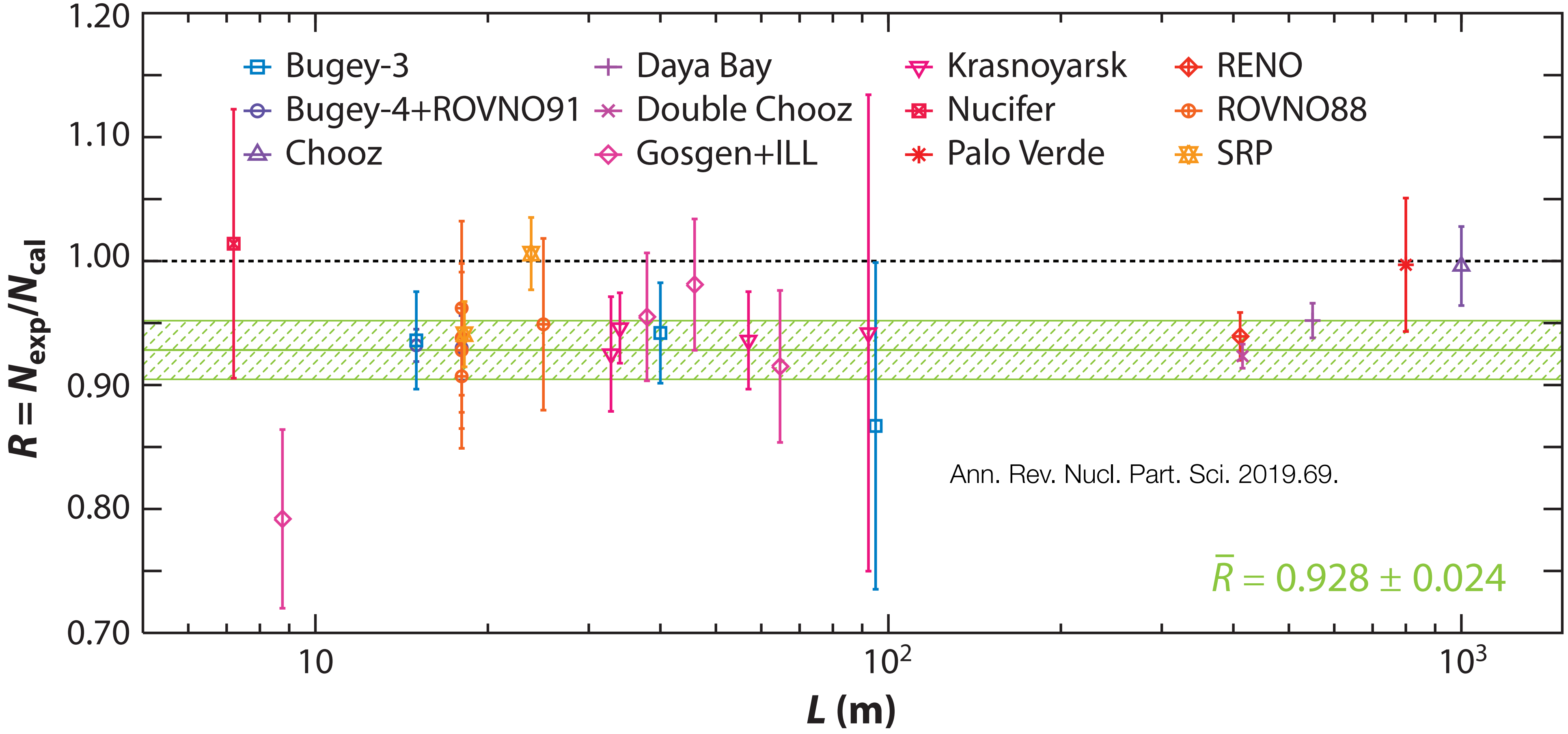
  Mueller et al., Phys. Rev. C **83.5** (2011): 054615

  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.

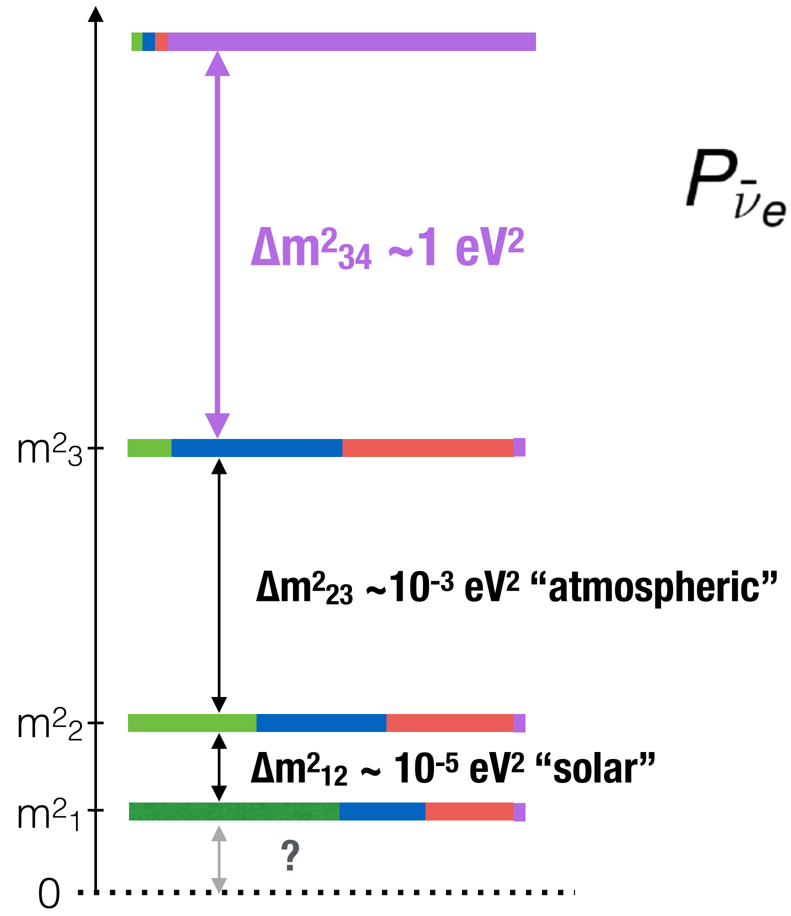
The Light Sterile Neutrino

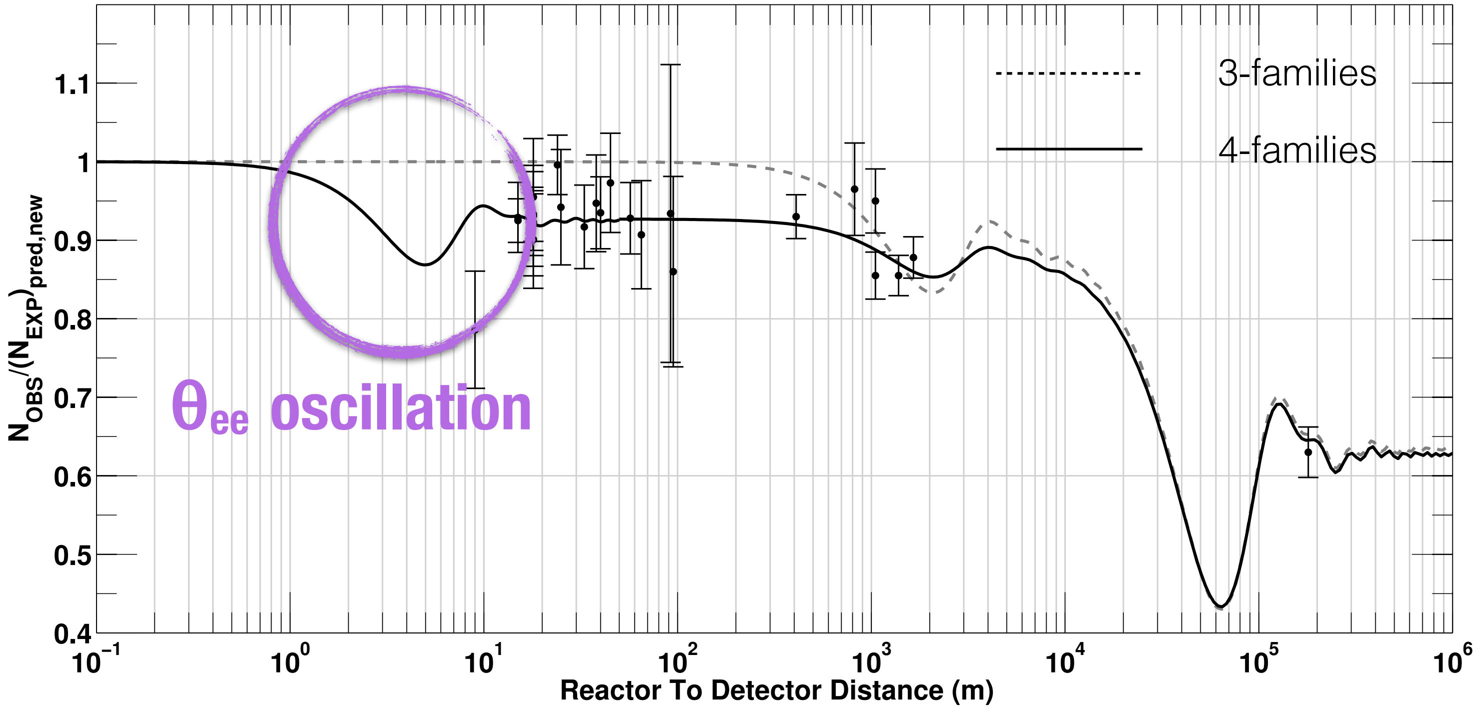
- Adding a **new neutrino** (0.1-1 eV mass) consisting almost exclusively of an **extra sterile flavour** can account for the observed deficit

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

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

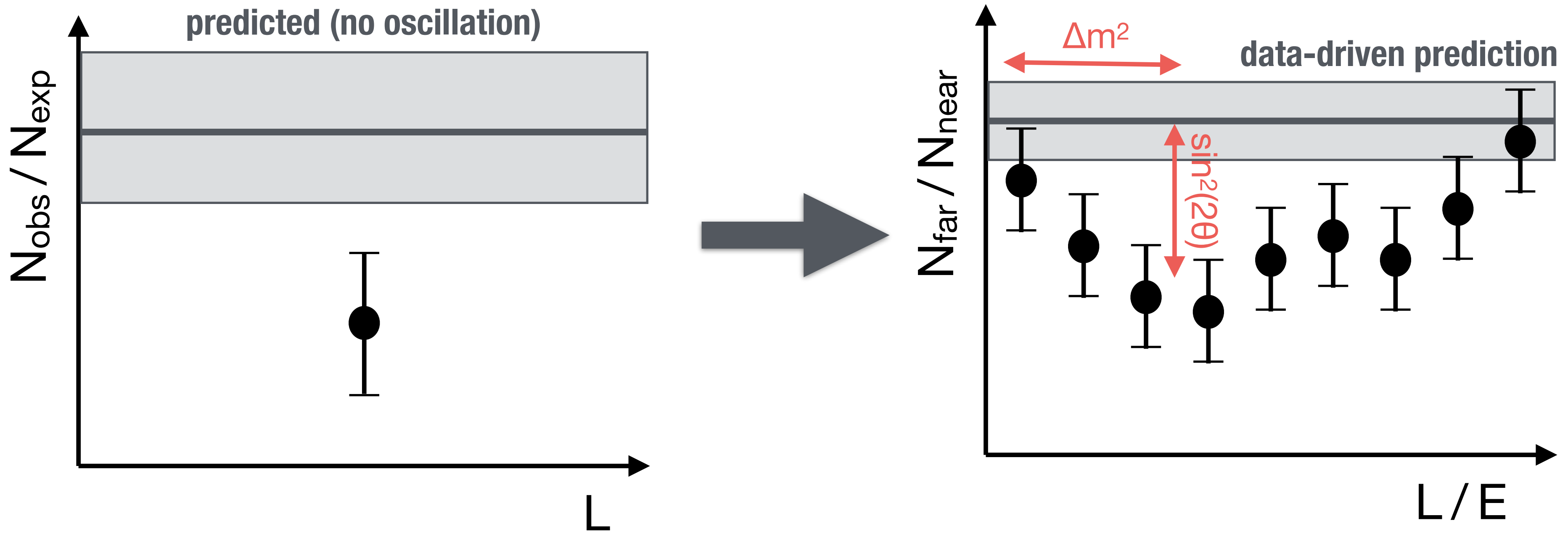
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L \lesssim 10m) \simeq 1 - \sin^2(\theta_{ee}) \sim^2 (1.27 \Delta m^2_{14} L/E)$$



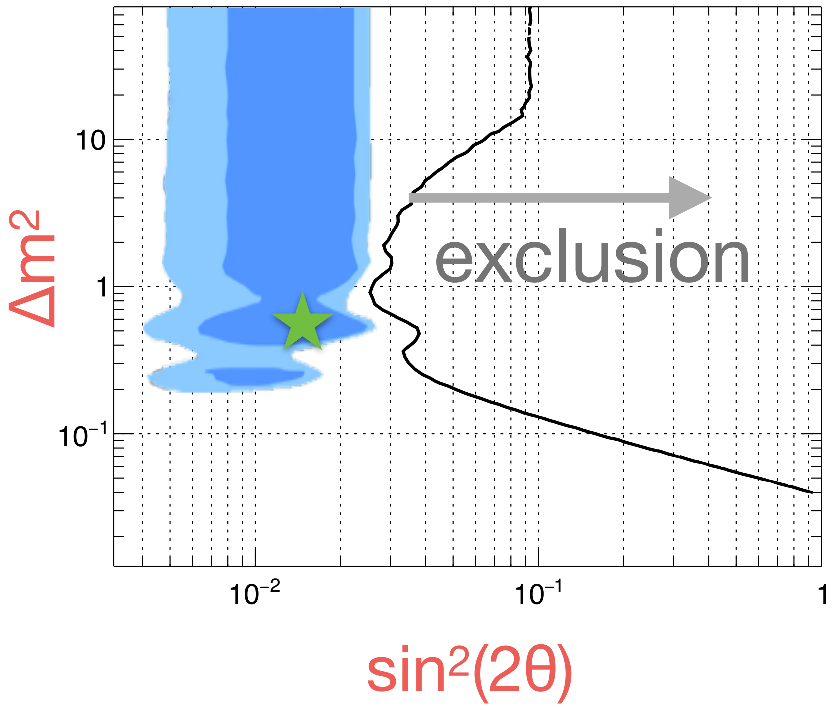


Search for the Light Sterile Neutrino

- 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

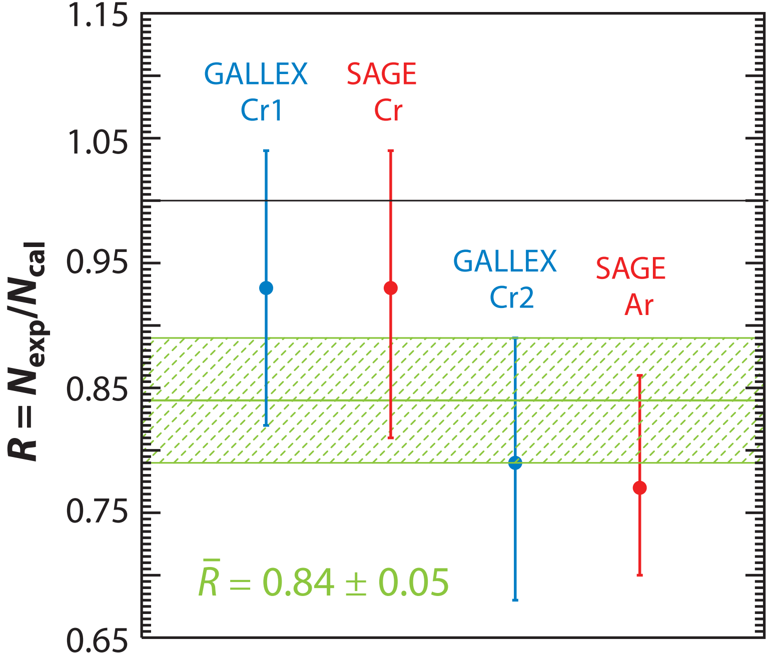
- **Gallium anomaly** - **disappearance of ν_e** measured with radioactive sources in gallium experiments GALLEX and SAGE (rate only)

- **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**

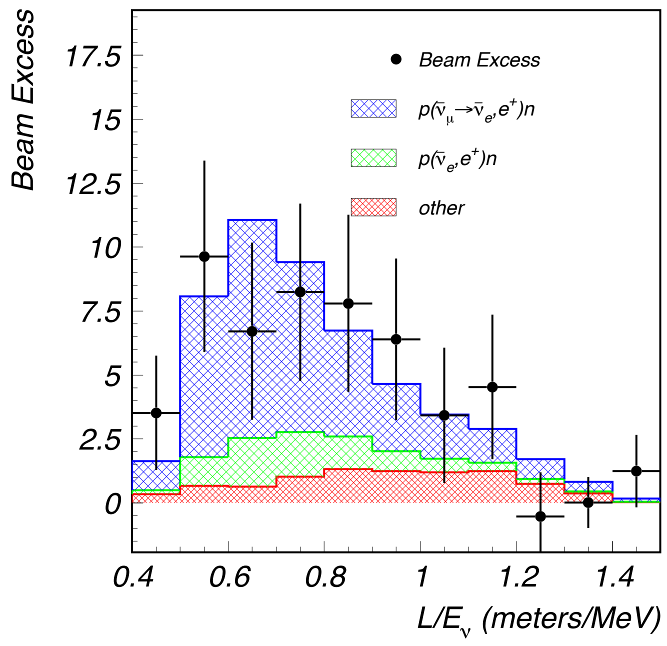
Phys. Lett. B **685:47** (2010)

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



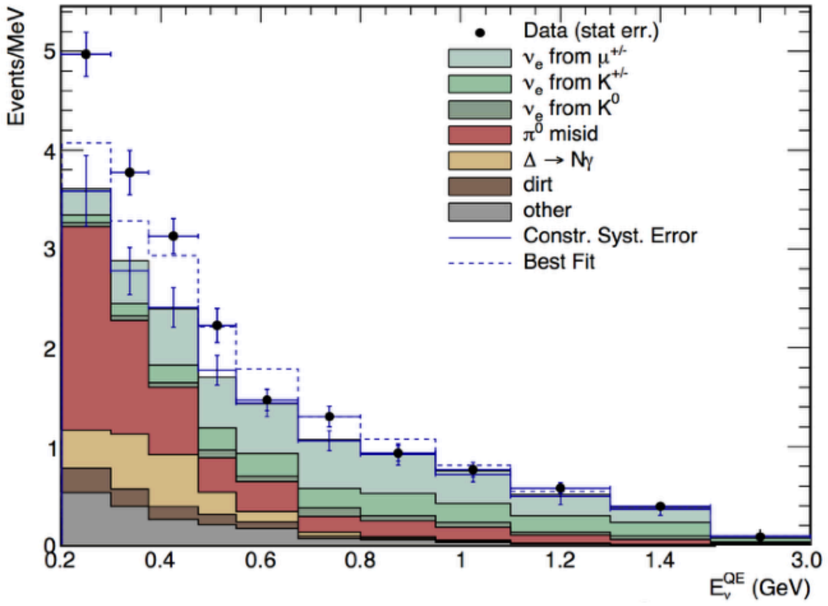
Phys. Rev. D **64:112007** (2001)

LSND



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

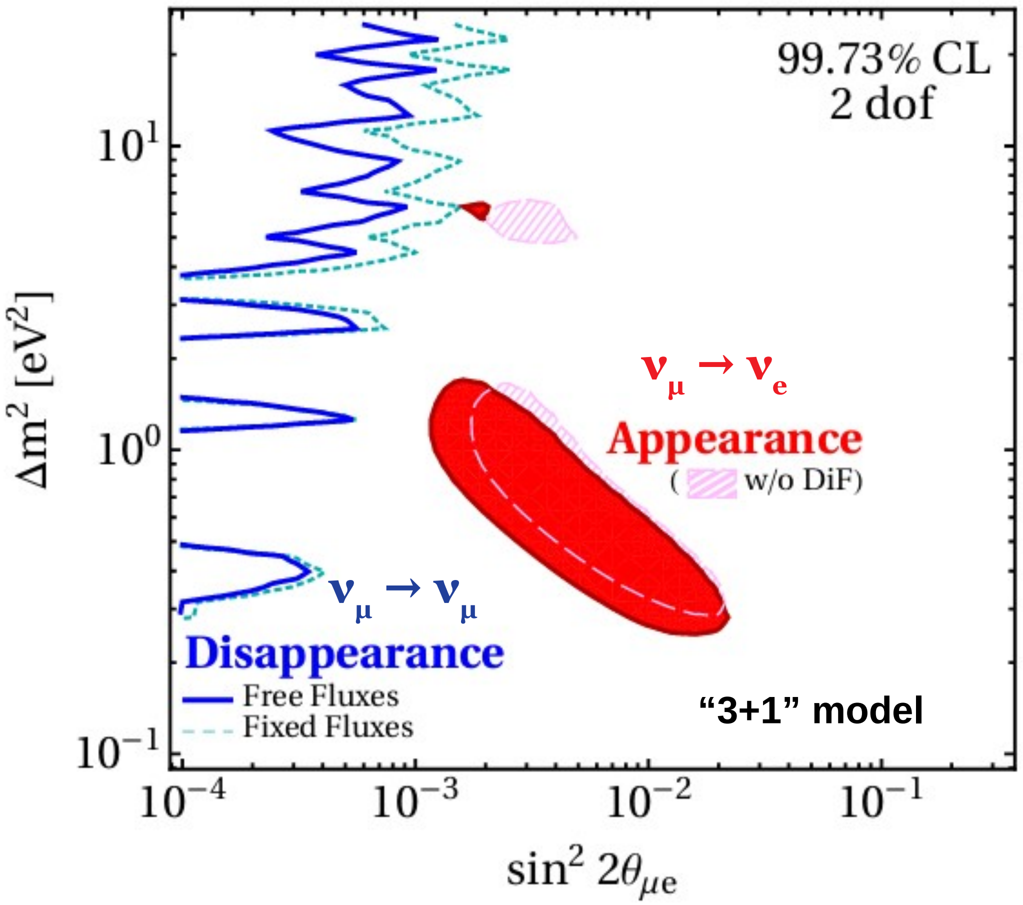
MiniBooNE



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)



Reactor neutrino experiments provide the strongest probe for U_{e4}

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

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

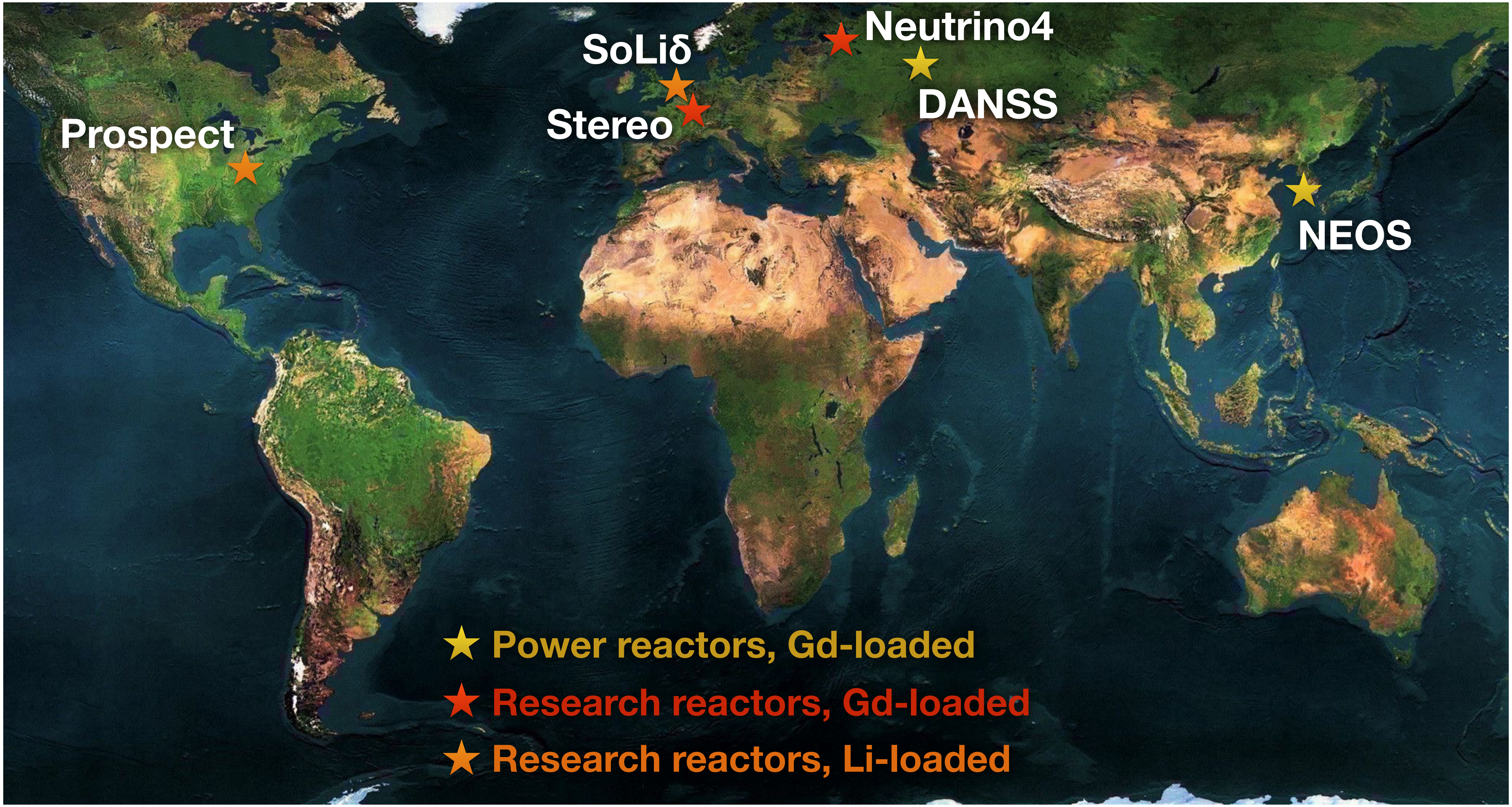
$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

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

Outline

- Neutrino mixing and reactor antineutrinos
- Legacy of the 2nd generation of reactor neutrino experiment
- Anomalies challenging the 3-family framework
- **The hunt for the light sterile neutrino**
- Sterile neutrinos vs reactor neutrino spectral estimation
- The future of reactor neutrinos: JUNO

A World-Wide Hunt

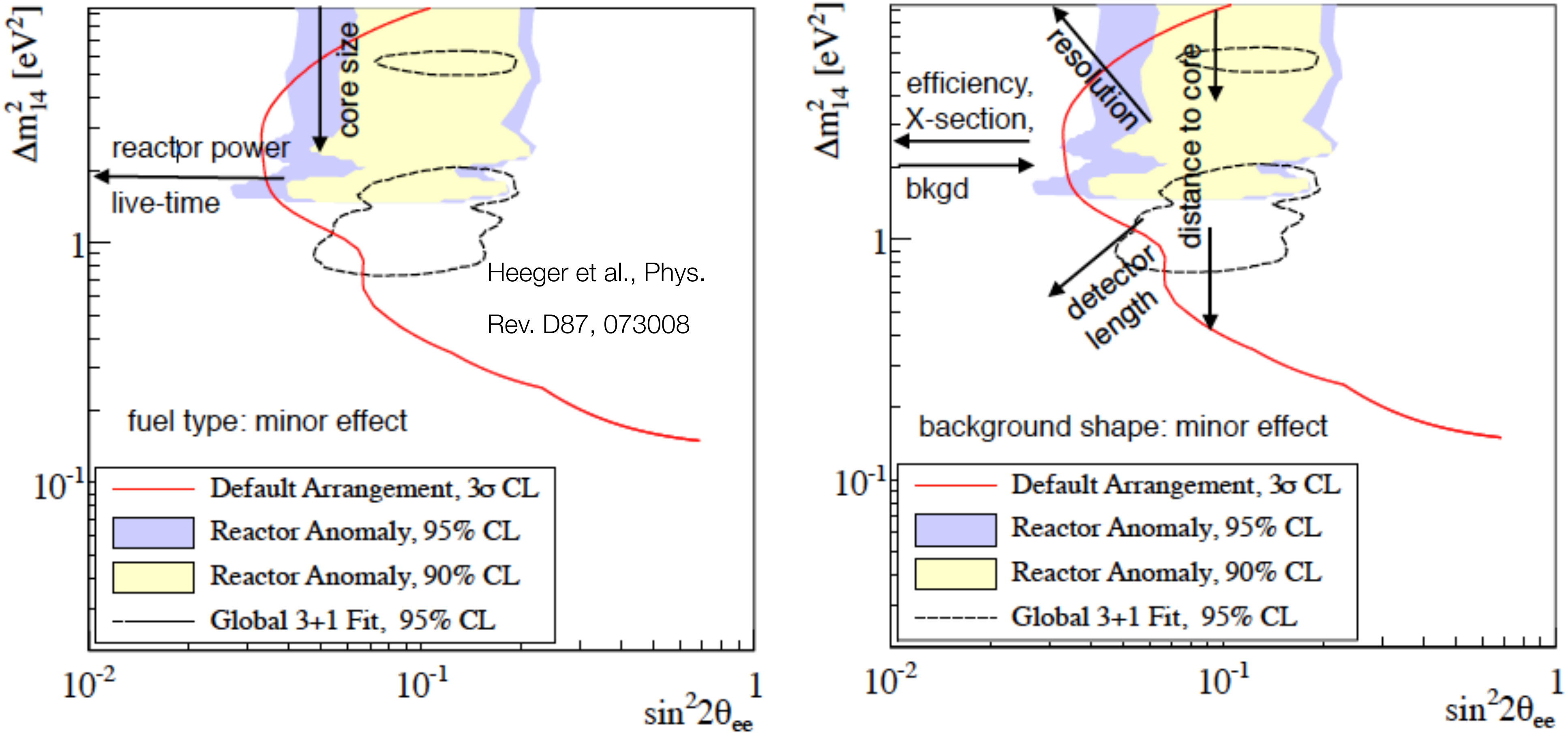


A World-Wide Hunt (This Talk)

Technical slides ahead

- ★ 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
$L_{osc} < E_{res}$

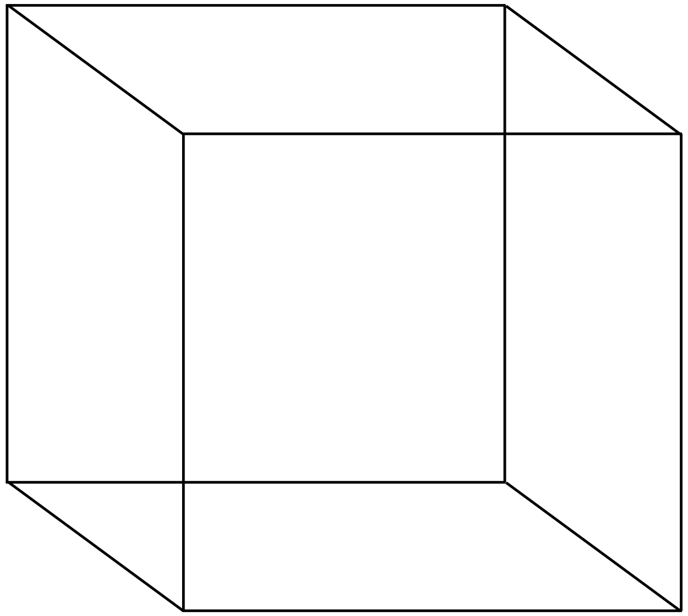
★$\Delta m^2 \sim 1$ eV^2
Can resolve oscillation

★$\Delta m^2 < 0.1$ 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 sensitivity @ low energy, fuel evolution (burnup)

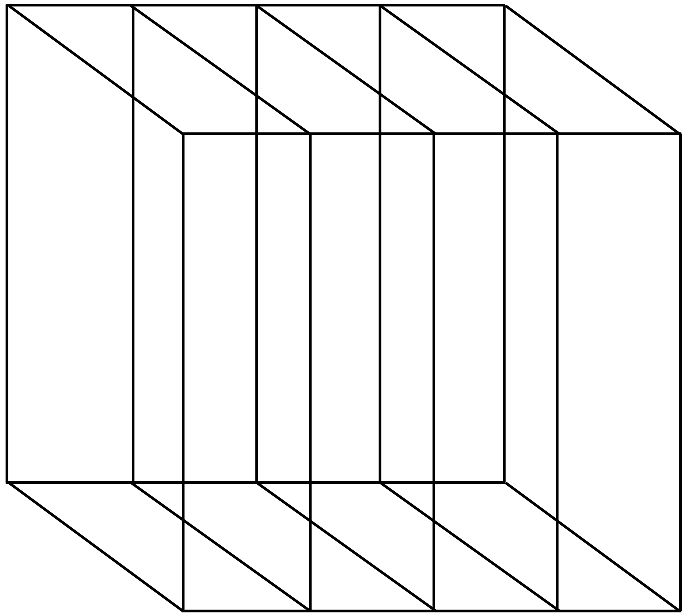
Comparing Different Technologies

no-segmentation



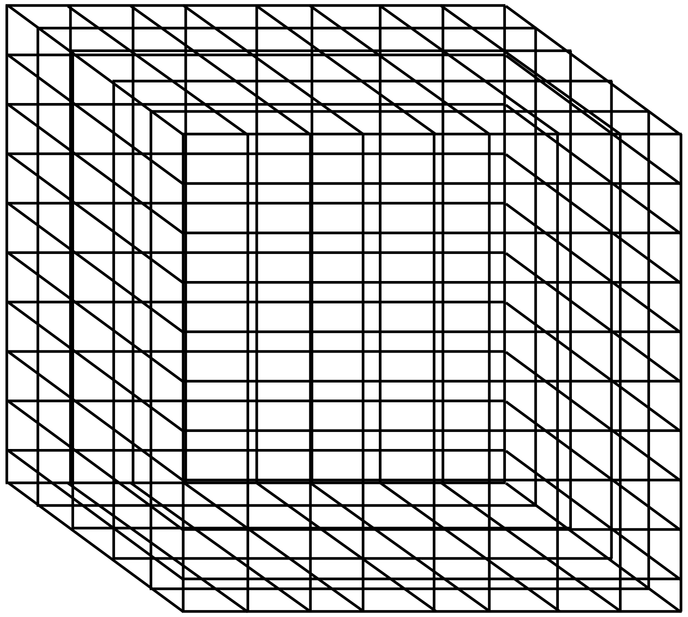
★compare $\bar{\nu}$ spectrum with prediction

“coarse” segmentation



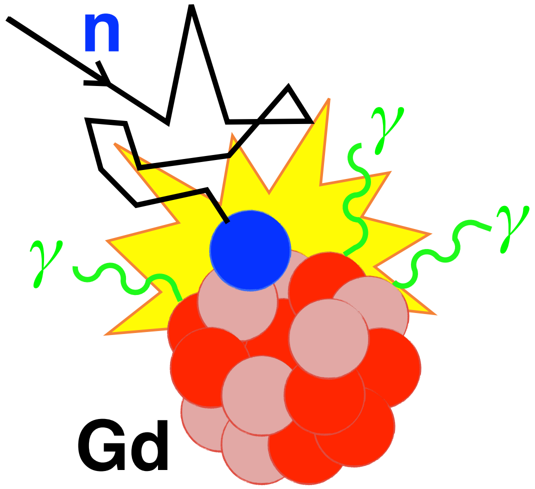
★compare spectra in different segments

“fine” segmentation

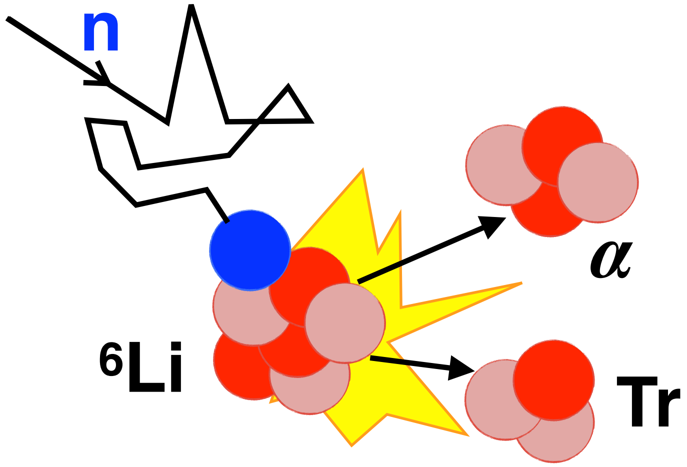


★Background rejection using topology

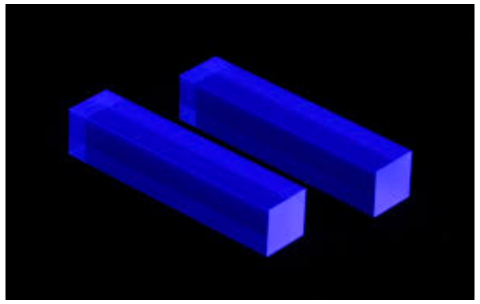
★Ultimate size limited by dead matter / inter calibration



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



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



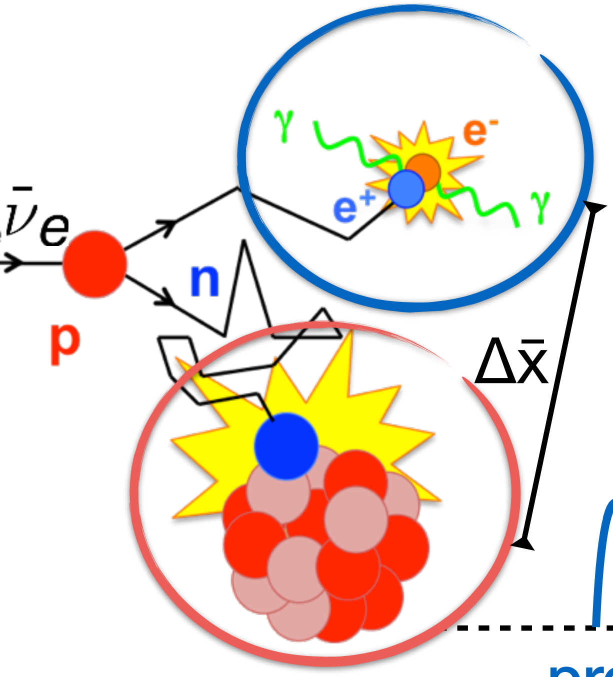
★better segmentation less edge-effects

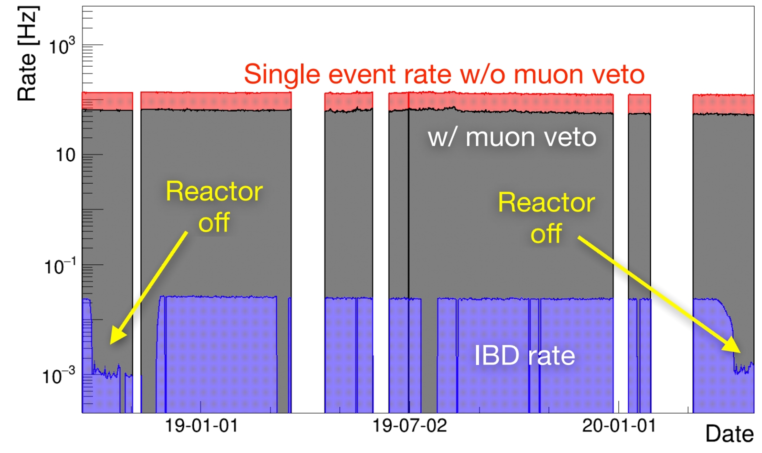
★allows larger volumes

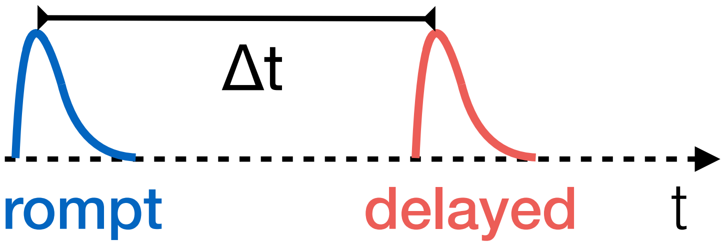
Challenges of the Short Baseline

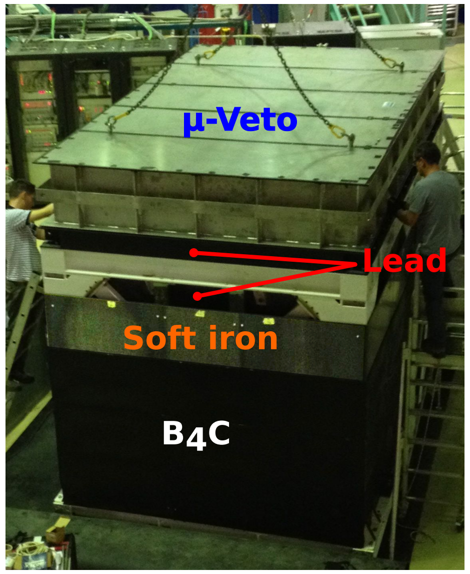
- Main challenge of the searches @ very short baseline: **background**
  - Surface level → cosmics
  - Reactor facilities → neutrons

- Strategies to deal with background
  - **IBD topology** itself (**E_{prompt}**, $E_{delayed}$, **Δt**, **$\Delta \bar{x}$**) allows to remove the sea of single-events
  - Pack your detector in shielding layers (PE, B, Fe, $H_2 0$) and put active vetoes
  - Use pulse shape discrimination (PSD)
  - Estimate **accidental coincidences** and **cosmogenic background** (reactor OFF) and **subtract statistically** (high statistics → small error)

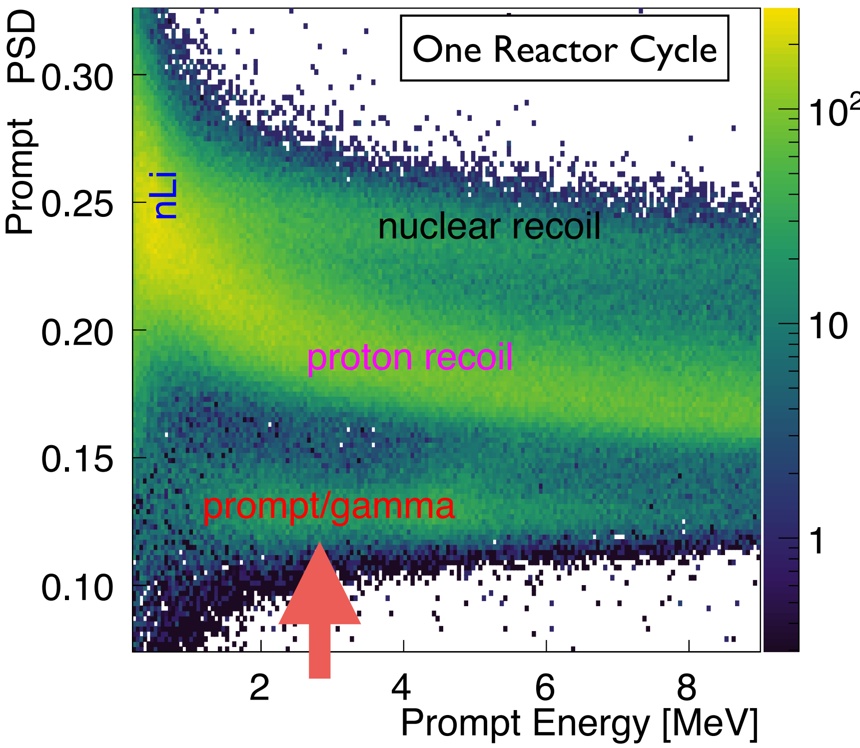




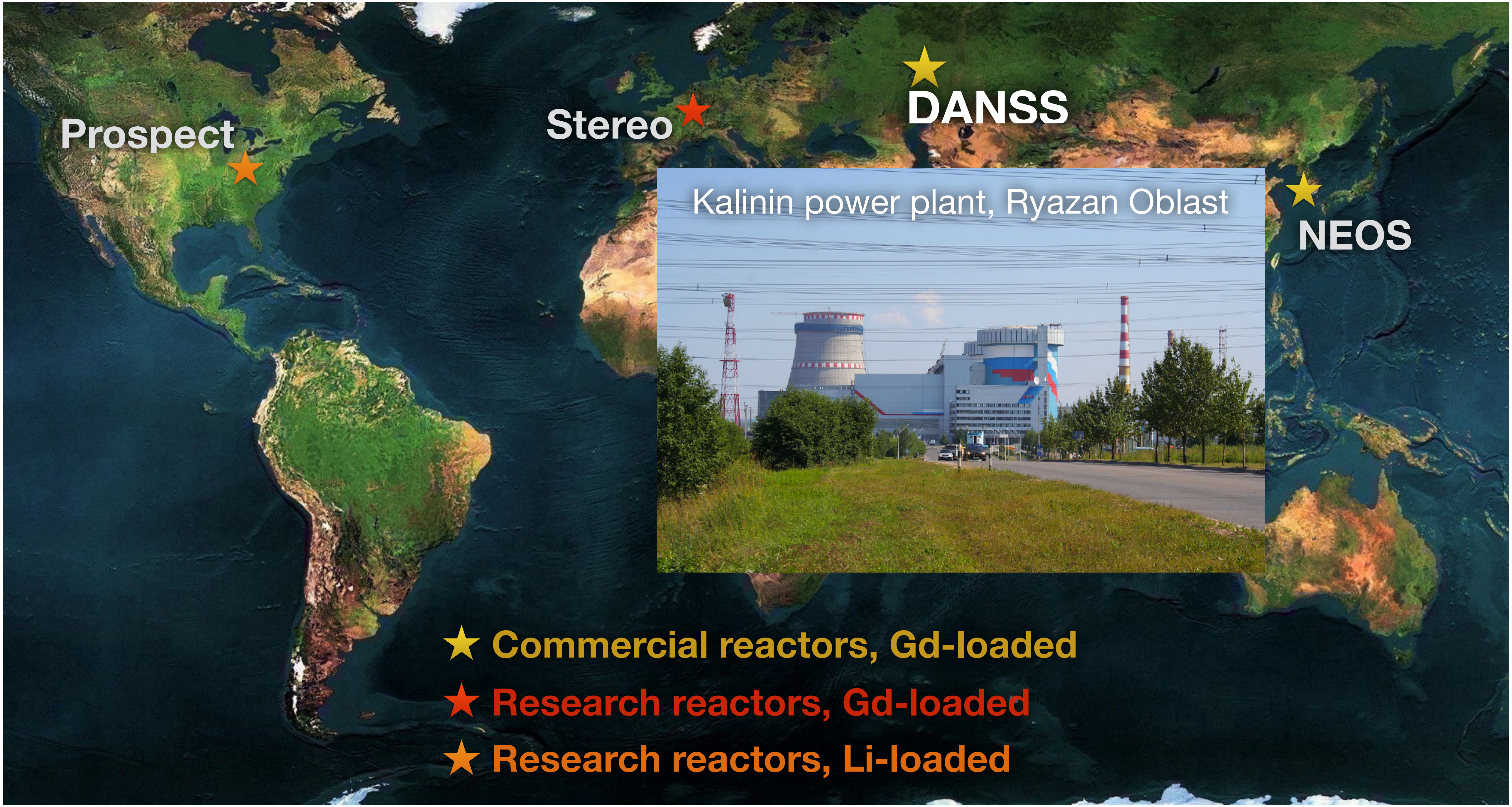




arXiv:2006.11210v2 [hep-ex] 1 Jul 2020

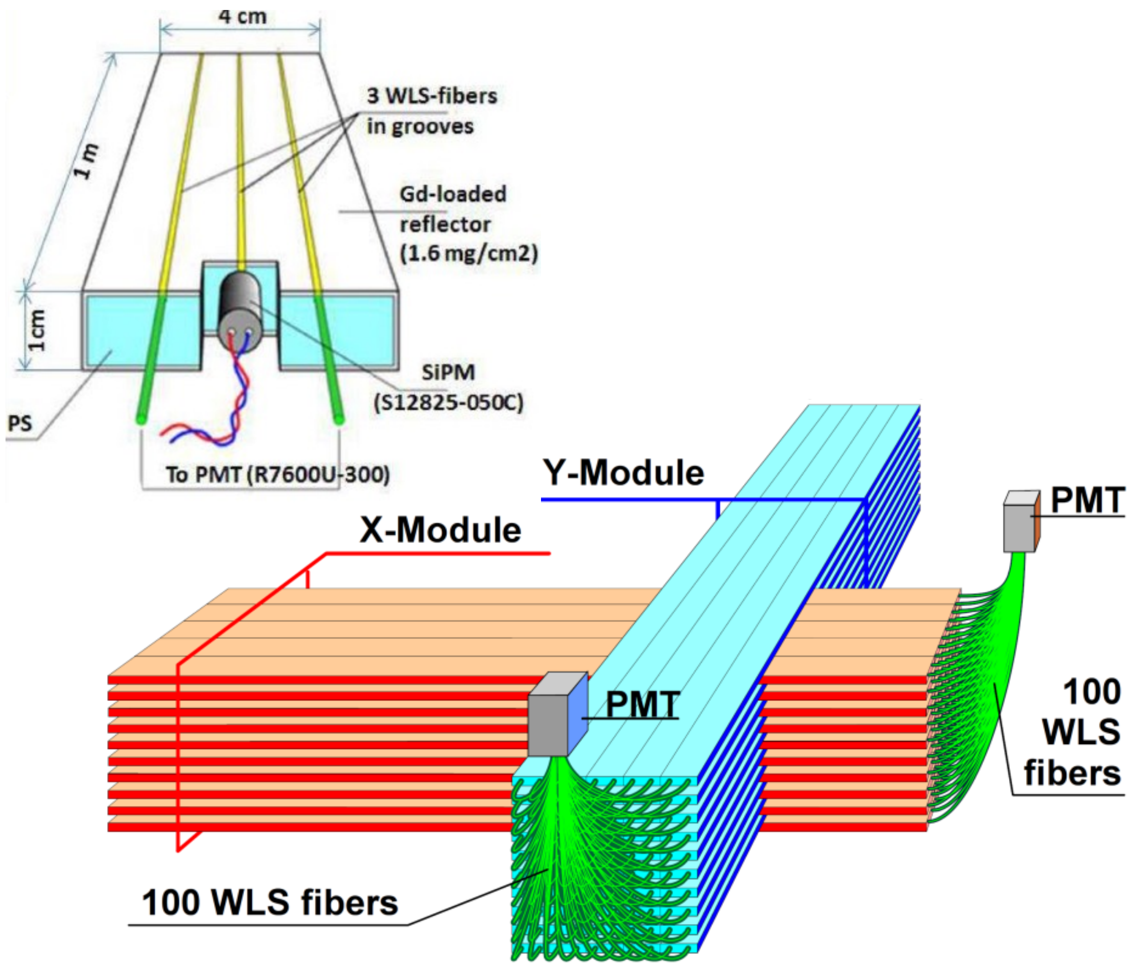


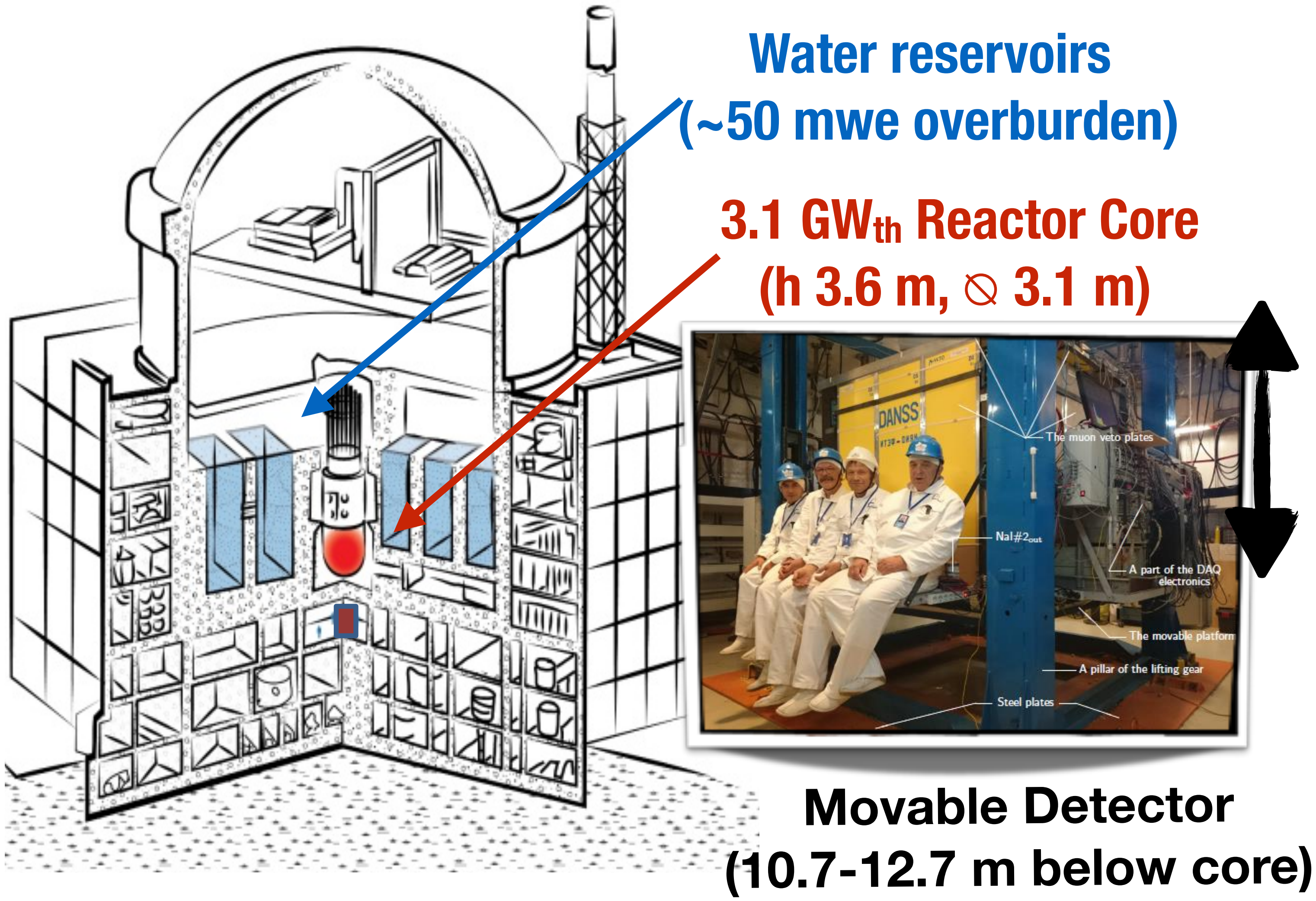
DANSS


Prospect
Stereo
DANSS
NEOS
Kalinin power plant, Ryazan Oblast
★ Commercial reactors, Gd-loaded
★ Research reactors, Gd-loaded
★ Research reactors, Li-loaded

The DANSS Detector

- ~m^3 highly-segmented ν spectrometer: **2500 Gd-coated plastic scintillator strips** arranged in 50 modules (combined readout)
- 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%)





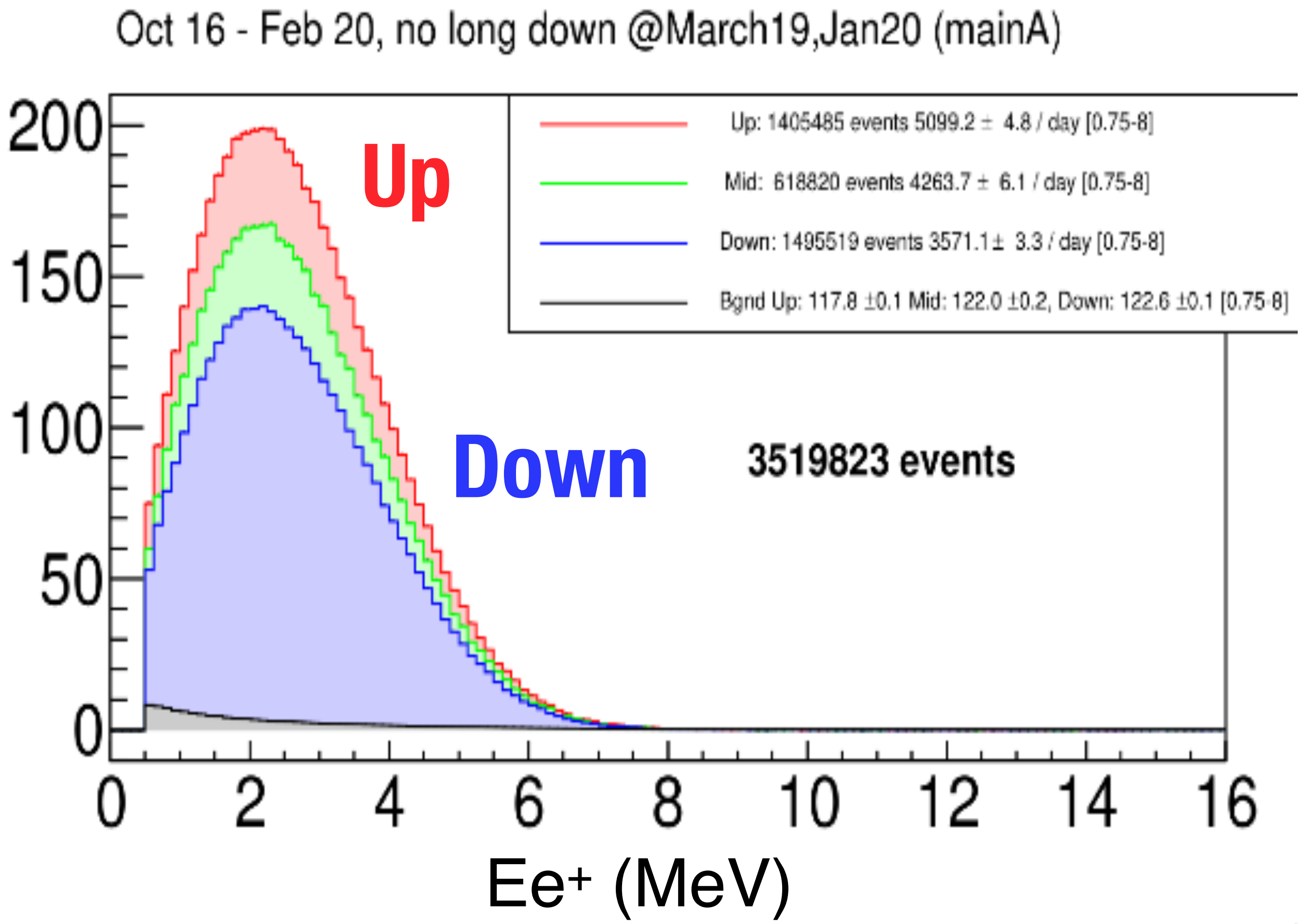
Water reservoirs (~50 mwe overburden)

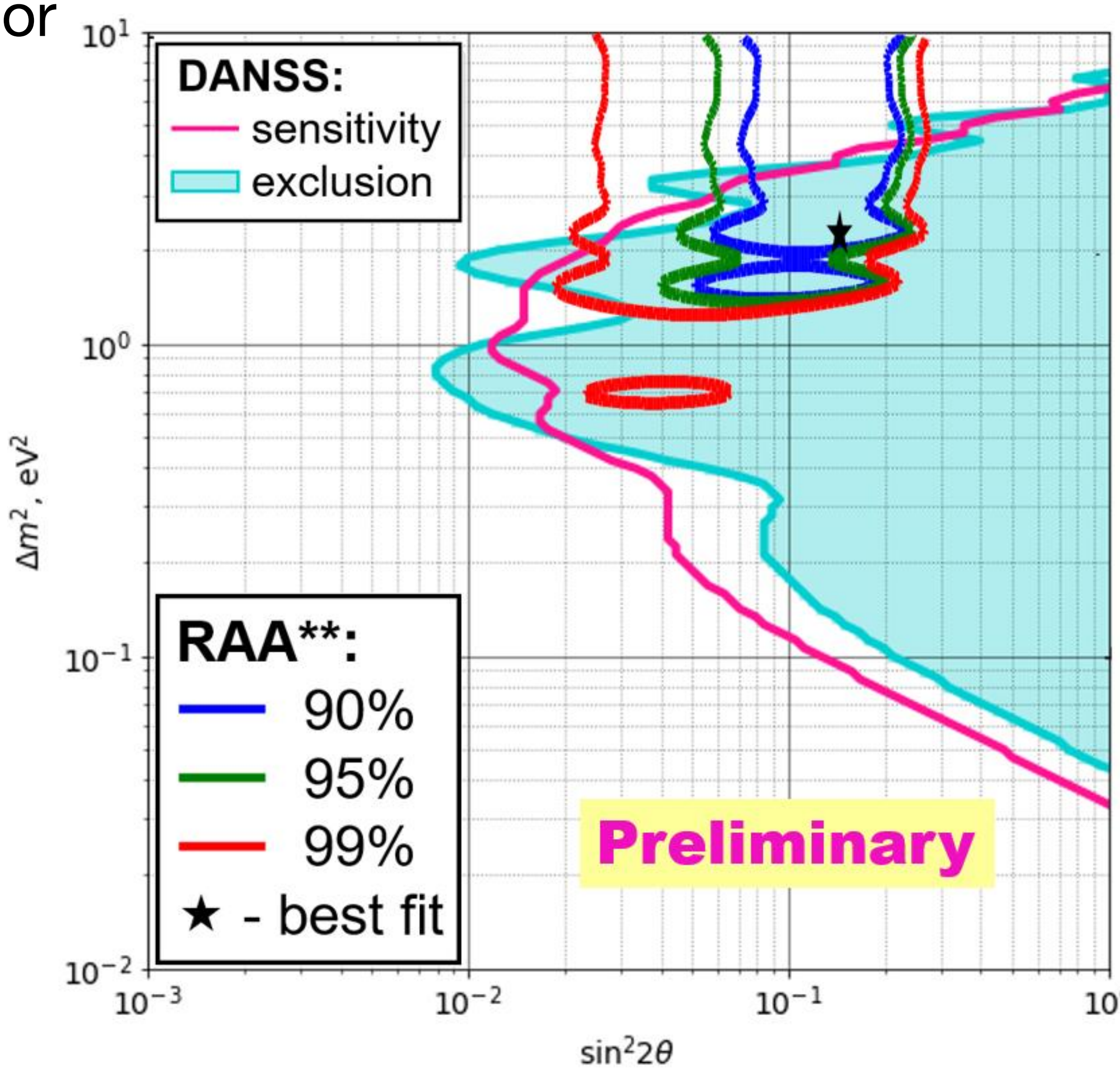
3.1 GW$_{th}$ Reactor Core (h 3.6 m, ⌀ 3.1 m)

Movable Detector (10.7-12.7 m below core)

DANSS Results

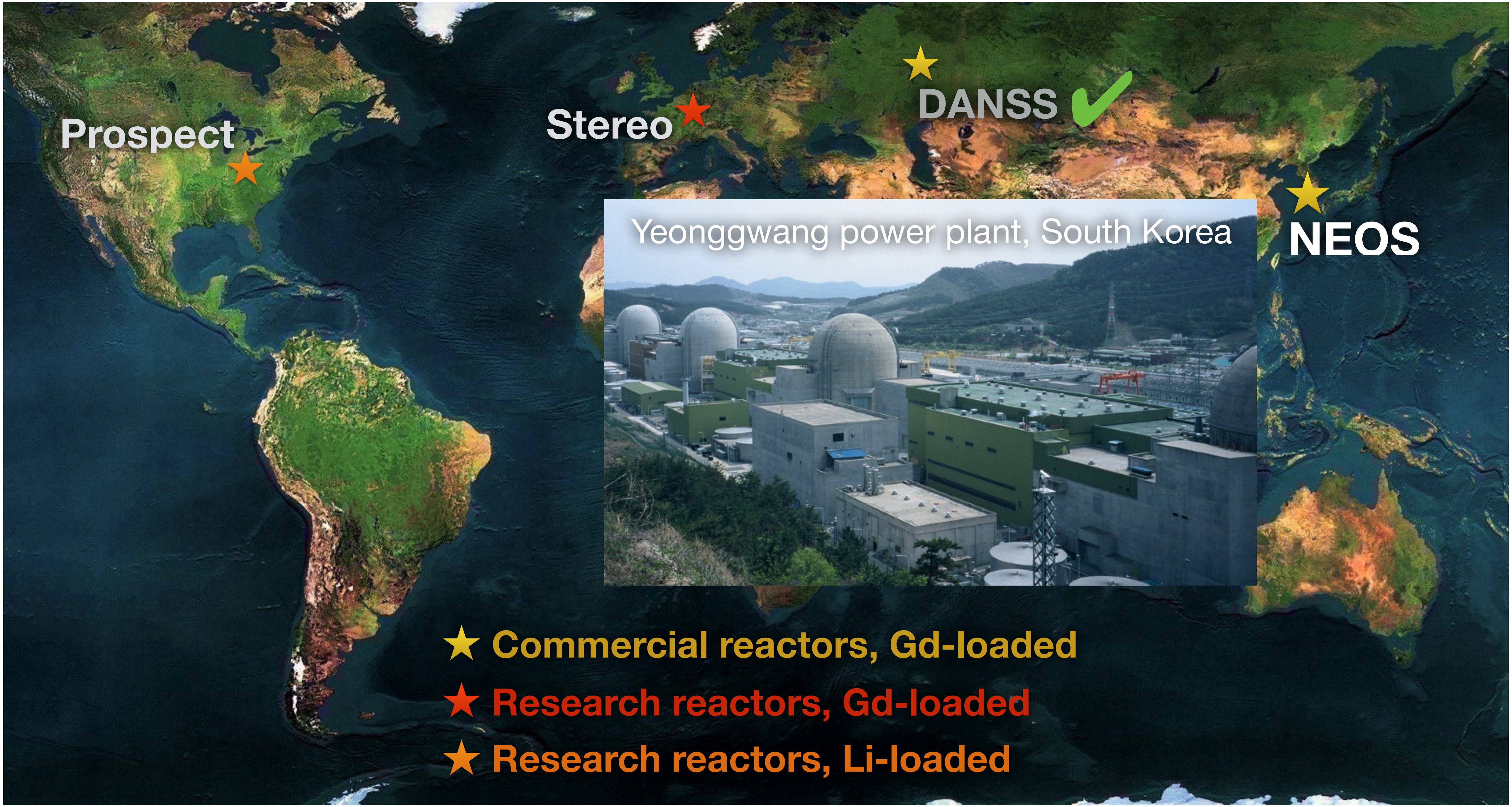
- 3.5 ×10^6 IBDs (~5000/day) collected from April 2016, **excellent S/B (~60)**
- Oscillation hypotheses tested by comparing “up” and “down" e^+ spectra
  → **large portion of RAA excluded** @ 95% CL; indication of **spectral distortion**
- Ongoing improvement of **MC modelling** and evaluation of **systematics**, preparation of phase-II with more SiPM and better scintillator





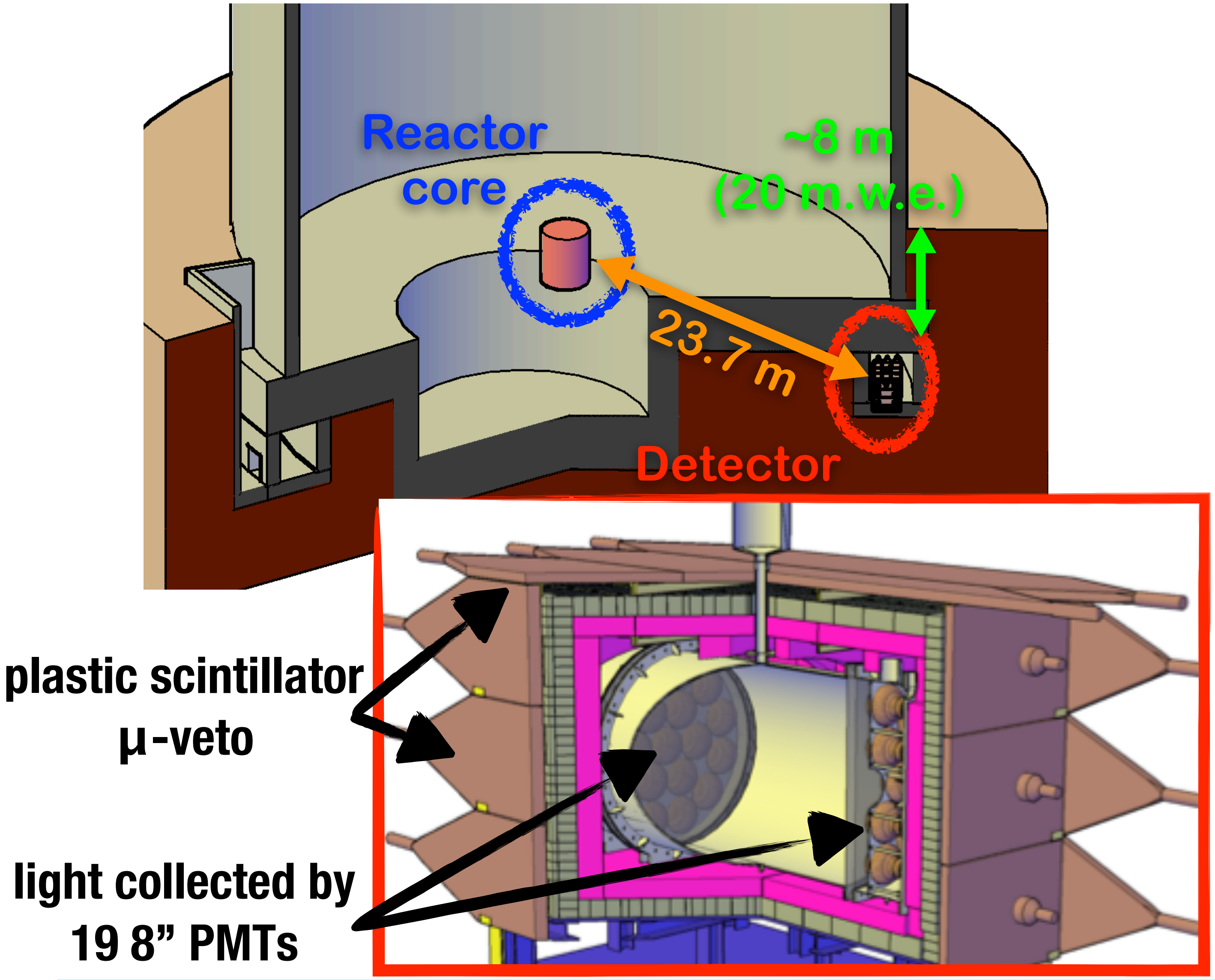
** - G.Mention J.Phys.:Conf.Ser. 408 (2013) 012025

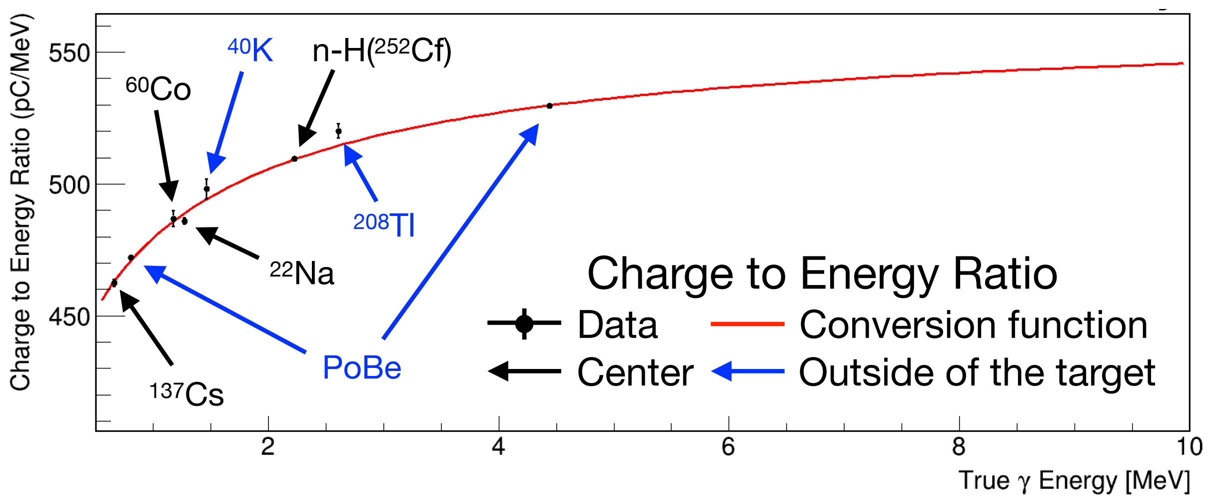
NEOS

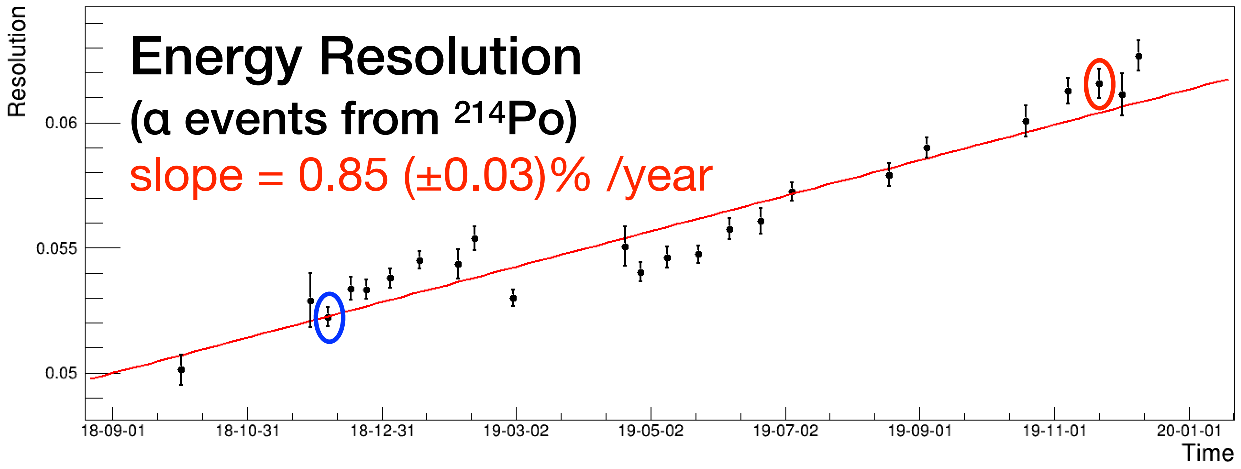

Prospect
Stereo
DANSS ✓
NEOS
Yeonggwang power plant, South Korea
★ Commercial reactors, Gd-loaded
★ Research reactors, Gd-loaded
★ Research reactors, Li-loaded

The NEOS Detector

- **Homogeneous 1008 L Gd-loaded** (0.48%) **liquid scintillator**
- Background mitigation: B-PE + Pb passive shielding, muon veto
- Energy calibration: several γ sources, energy scale tested on ^{12}B
- Observed a **degradation of light yield** resulting in an **increase in E_{res}** & **2.4% IBD loss**



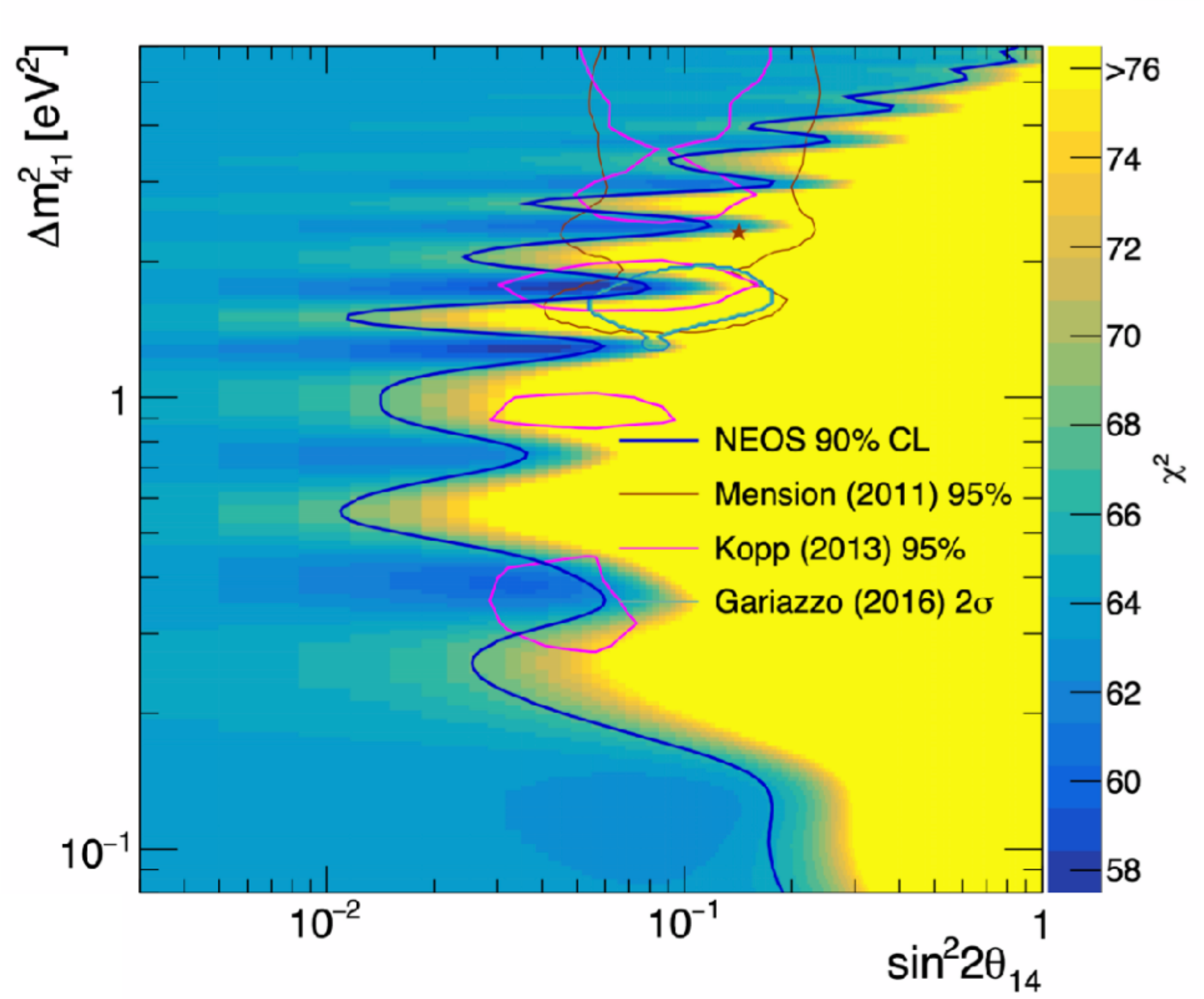




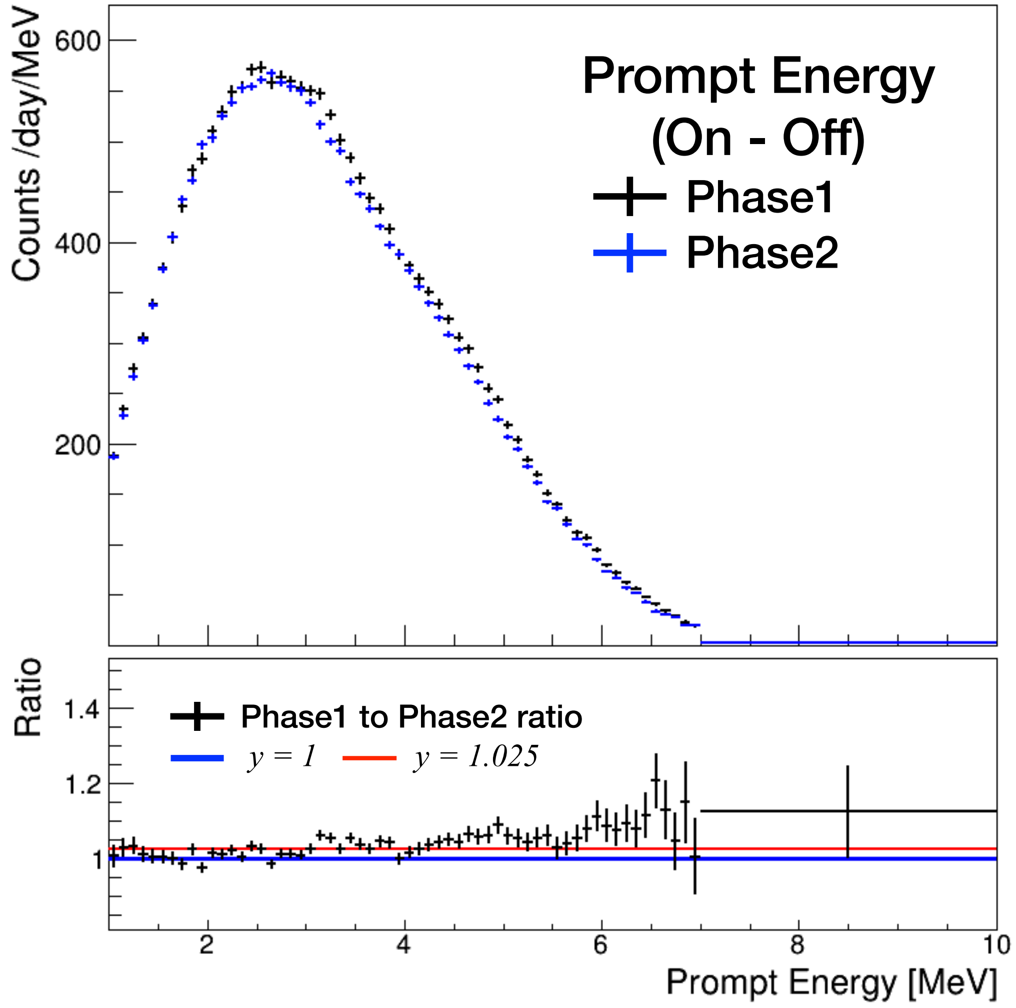
NEOS Results

- **Oscillation analysis 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**

- **New phase-II** (Sep 2018 - Sept 2020) **spectrum** recently released
  - Data-MC comparison will be publishedafter MC tuning
  - Expected X2 increase in exclusion plot



NEOS Preliminary



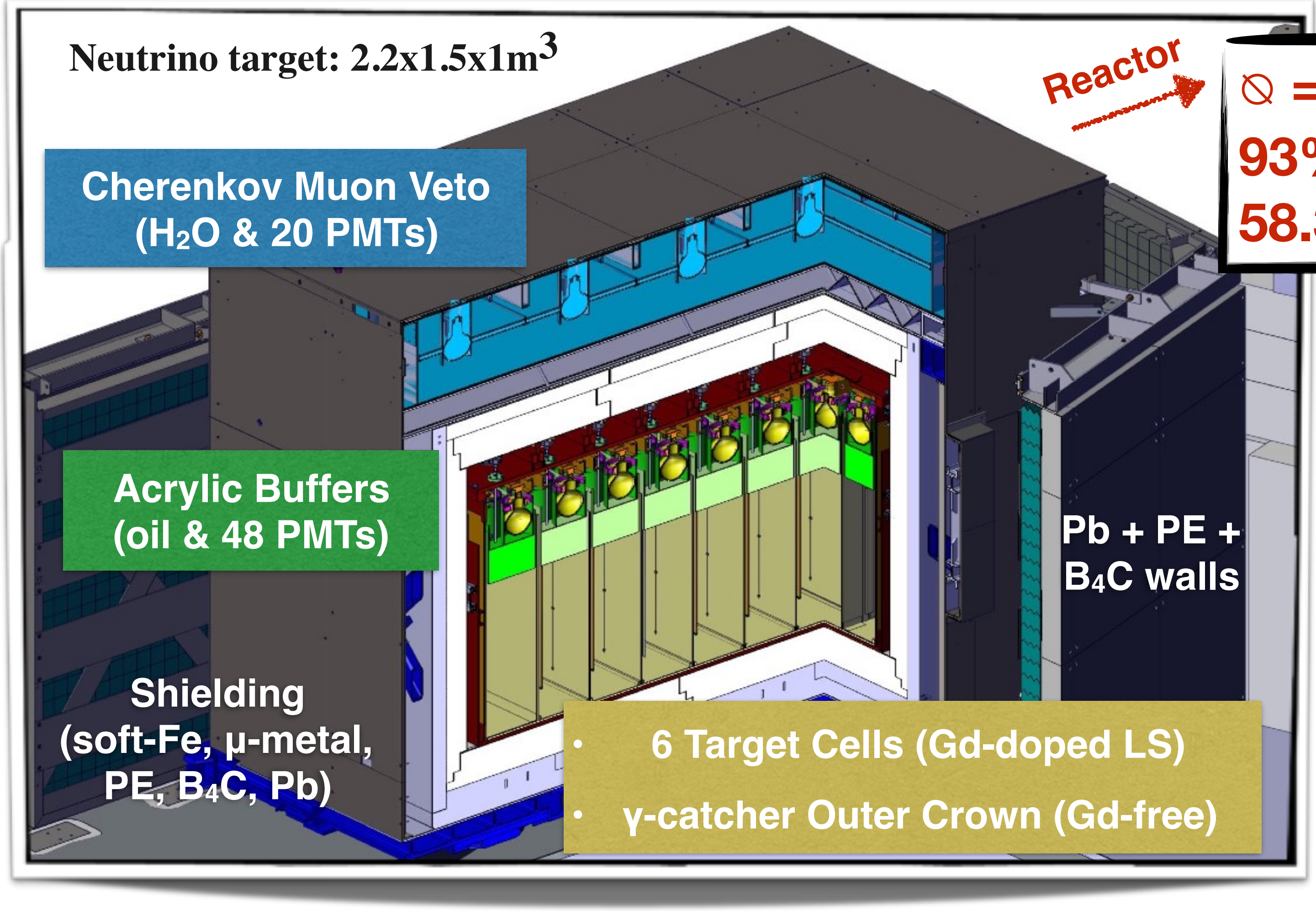
STEREO


Prospect
Stereo
DANSS ✓
NEOS ✓
Institut Laue-Langevin, Grenoble
★ Commercial reactors, Gd-loaded
★ Research reactors, Gd-loaded
★ Research reactors, Li-loaded

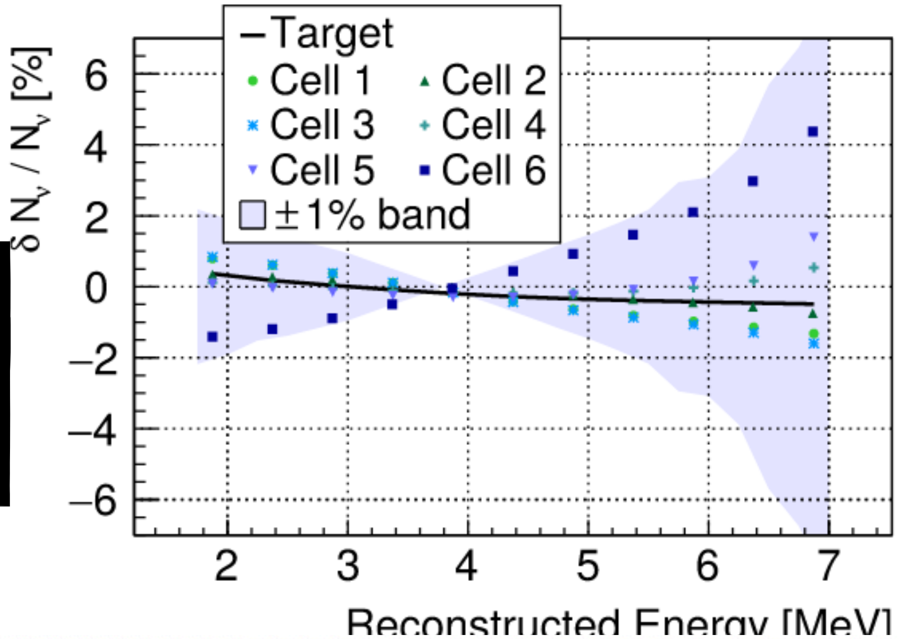
The STEREO Experiment

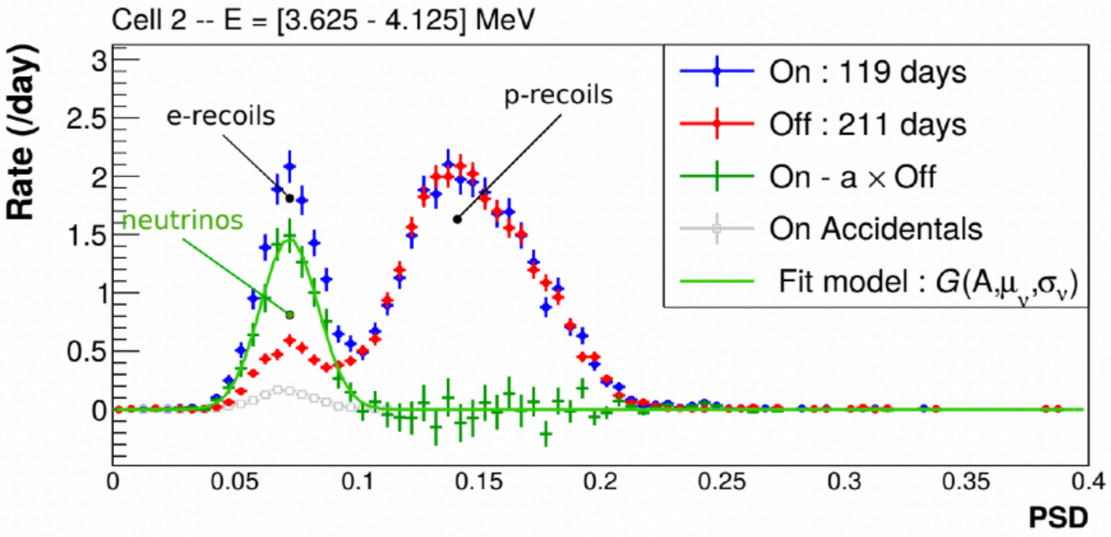
- **6 cells** filled with **Gd-loaded liquid scintillator** (9-11 m from reactor core)
- Energy calibration anchored to ^{54}Mn, measured with different sources, tested on ^{12}B (~1.5% systematics)
- **PSD (Q_{tail}/Q_{tot})** to discriminate neutrinos from dominant remaining cosmic background (On and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

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



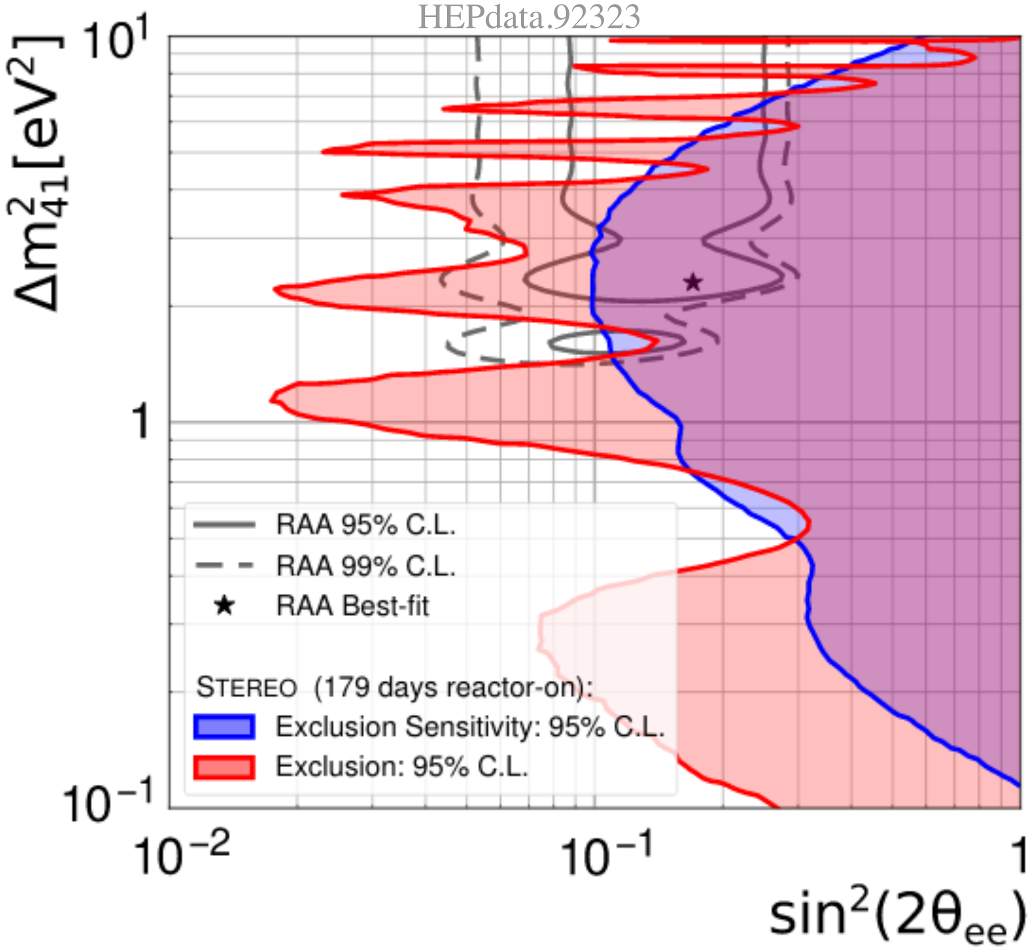
⦰ = 37 cm
93% ^{235}U
58.3 MW_{th}

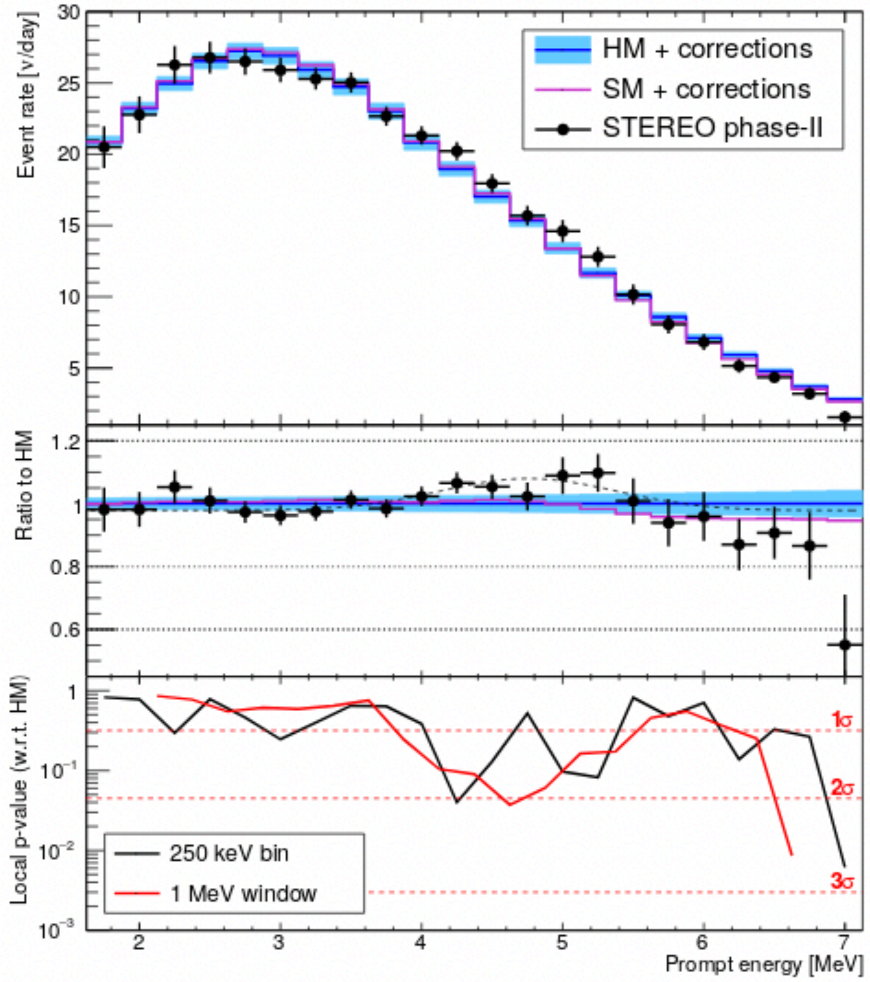




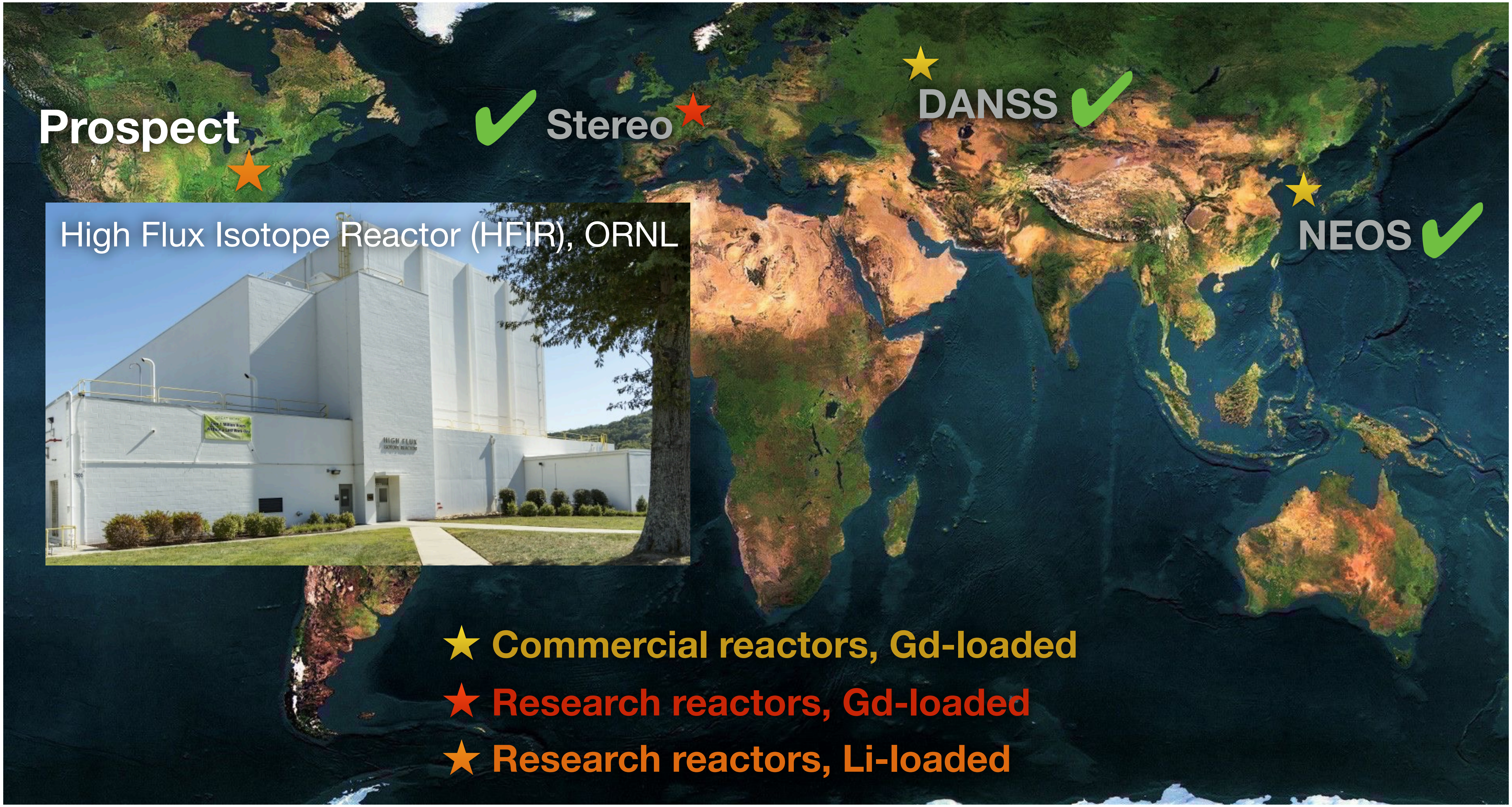
STEREO Results

- Cell-to-cell relative **oscillation analysis** with **phase-I and -II combined data** (65k IBDs, 179 days ON + 235 OFF), S/B ~1 after PSD
- **Absolute ^{235}U rate and spectral shape (newly released)** analysis with phase-II data (119 days ON + 211 OFF)
- Compact core & short baseline → **little damping of oscillation**; but **little overburden**, noise from reactor facility (core, neighbours)
- Expected factor X2 increase in sensitivity with full dataset (end of 2020)





PROSPECT



★ Commercial reactors, Gd-loaded

★ Research reactors, Gd-loaded

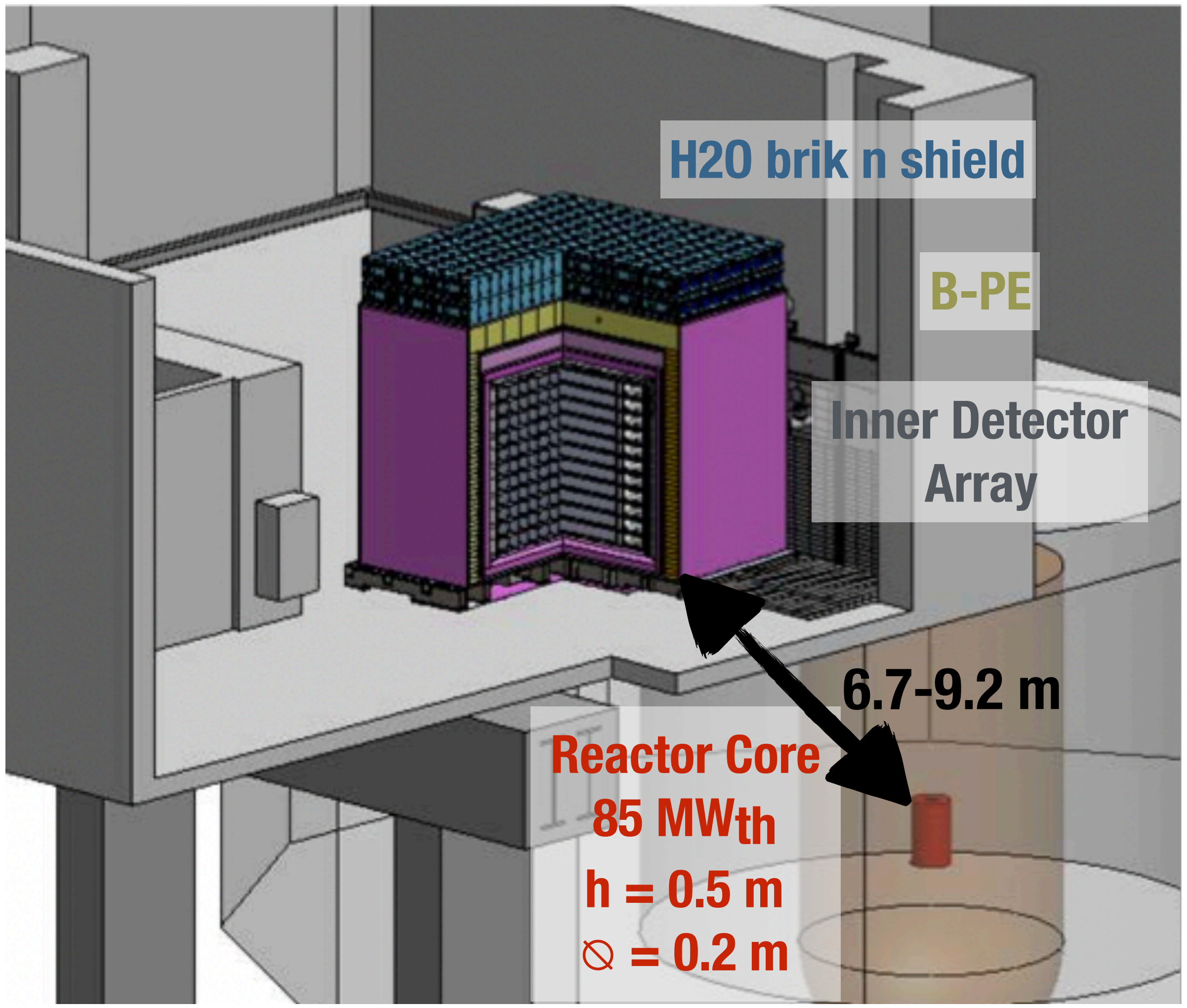
★ Research reactors, Li-loaded

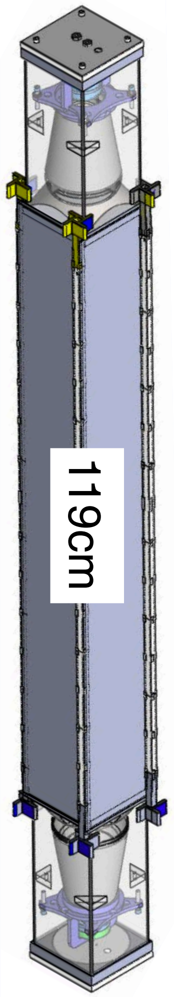
The PROSPECT Experiment

- **4-ton ^{6}Li-loaded segmented liquid scintillator** consisting **11x14 optically separated segments** with double-ended PMT readout (good E_{res}, 3D reconstruction)

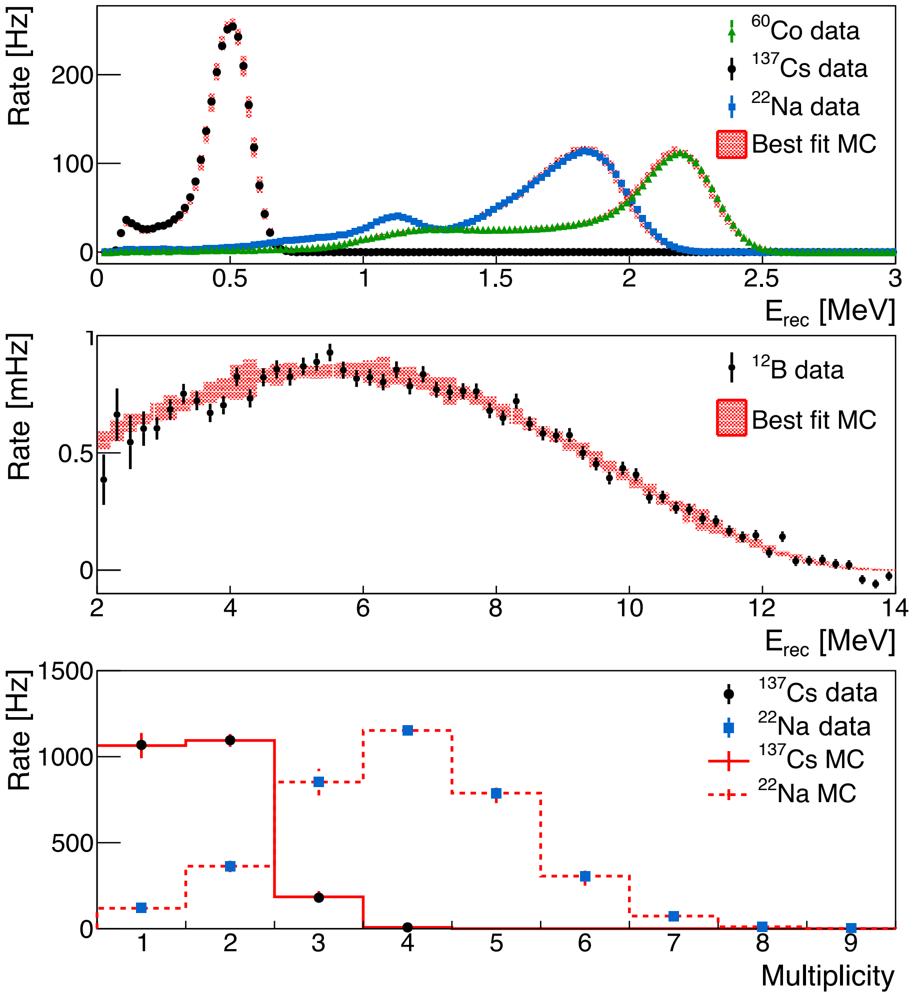
- Background mitigation: PSD + veto + topological cuts + fiducialisation (3 ton) → S/B > 1

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



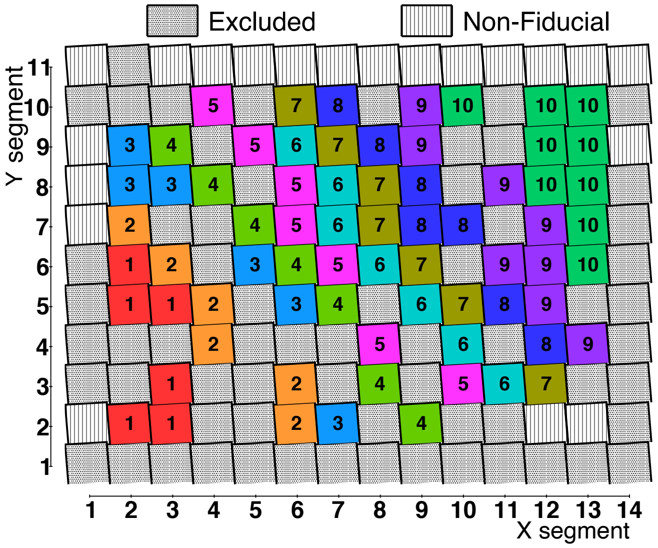


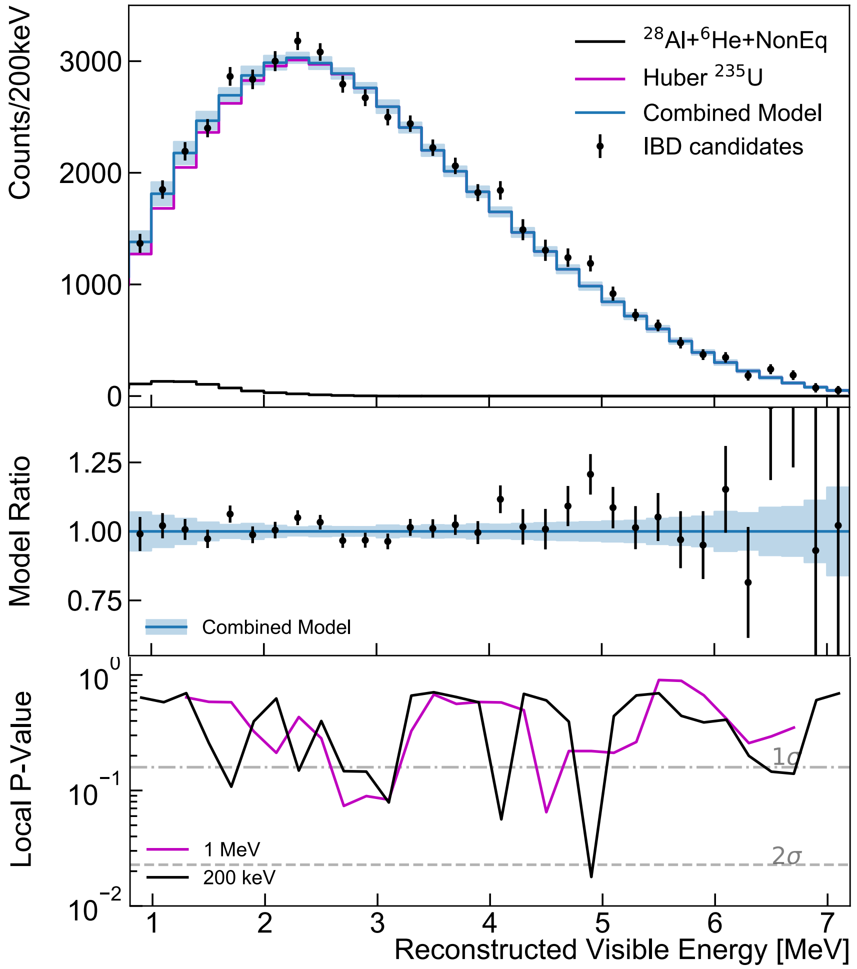
Robust MC model

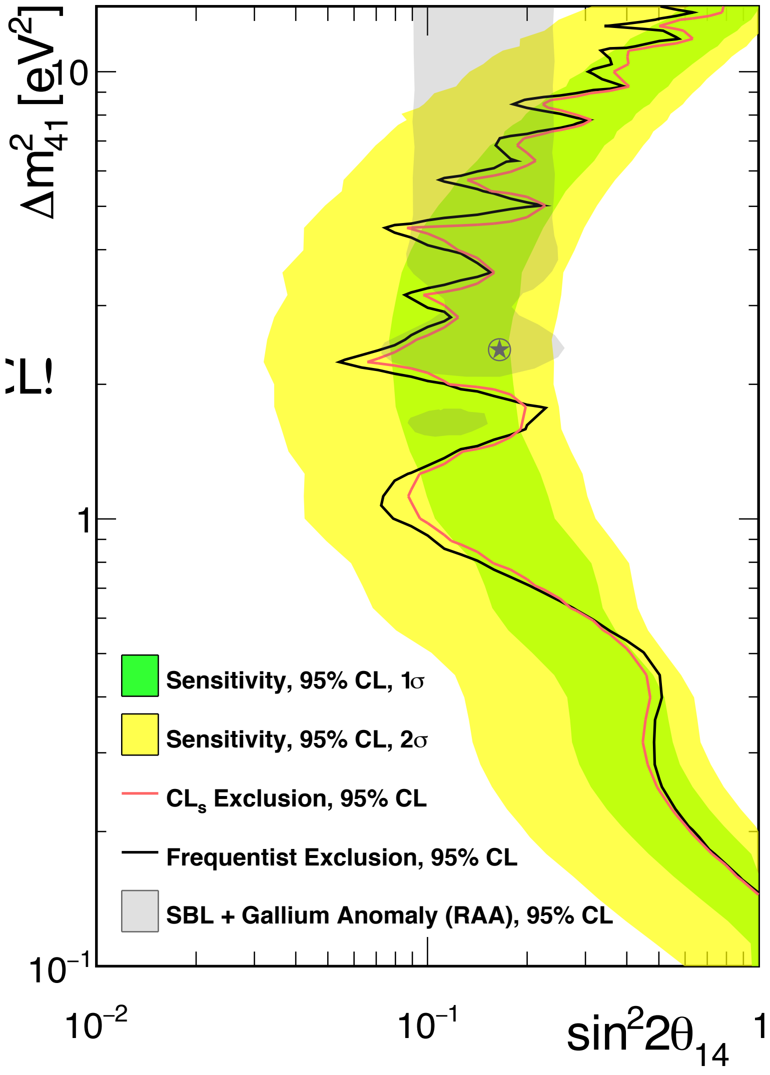


PROSPECT Results

- Recently released results with 50k neutrinos from 96 days ON + 73 days OFF **high statistics** (530 IBD/day) **and S/B** (>1) **for a HEU** arXiv:2006.11210v2 [hep-ex] 1 Jul 2020
- Oscillation search with 16 E and 10 baseline bins → RAA best fit excluded at 98.5% CL
- Pure ^{235}U spectrum measurement, consistent with model
- Data taking stopped, but can improve analysis using dead cells (+50%) and combined analysis with STEREO and Data Bay is underway







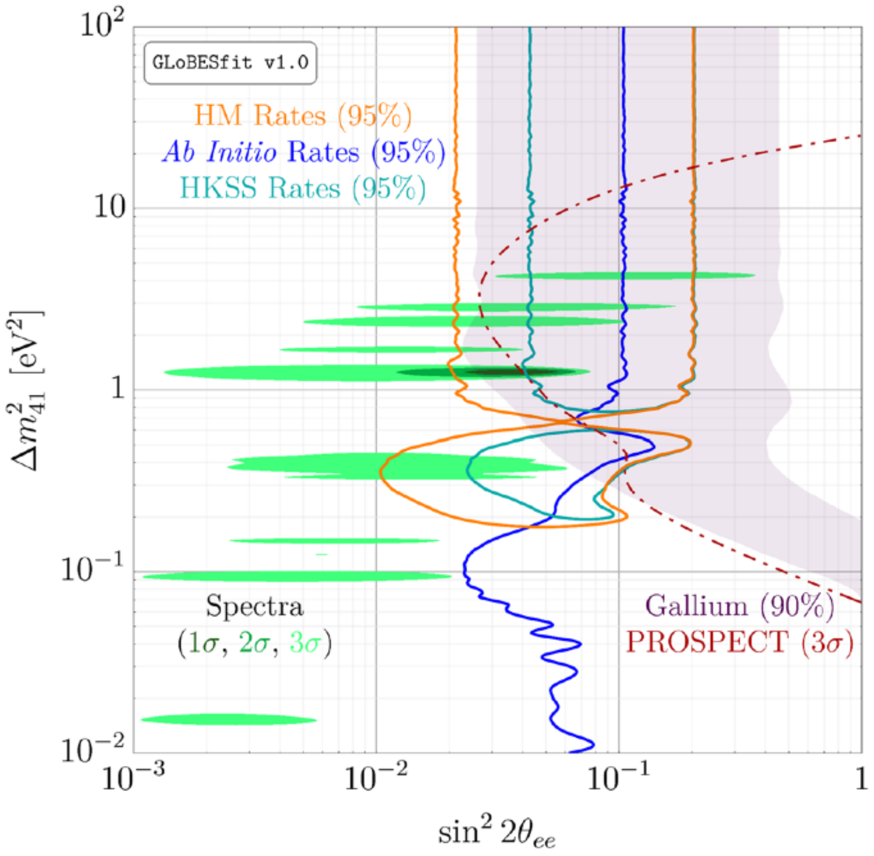
Reactor Anomaly and Recent Results: the Global Picture

- Each of the e**experiments mentioned so far excluded a large portion of the RAA parameter space**, nevertheless a significant part remain unexplored

- **Combining results** is **not easy** (different statistical methods) **but underway**

  Giunti et al. PRD 99, 073005 (2019)
  arXiv:1906.00045v3
  S. Boeser et al. PPNPP 111 103736 (2019)
  Phys. Rev. D 101, 015008 (2020)

- **To solve the RAA**, we must **tackle the problem from both experimental** (increase statistics, detector upgrades) **and theoretical side** (new models, better corrections)



Outline

- Neutrino mixing and reactor antineutrinos
- Legacy of the 2nd generation of reactor neutrino experiment
- Anomalies challenging the 3-family framework
- The quest for the light sterile neutrino
- **Sterile neutrinos vs reactor neutrino spectral estimation**
- The future of reactor neutrinos: JUNO

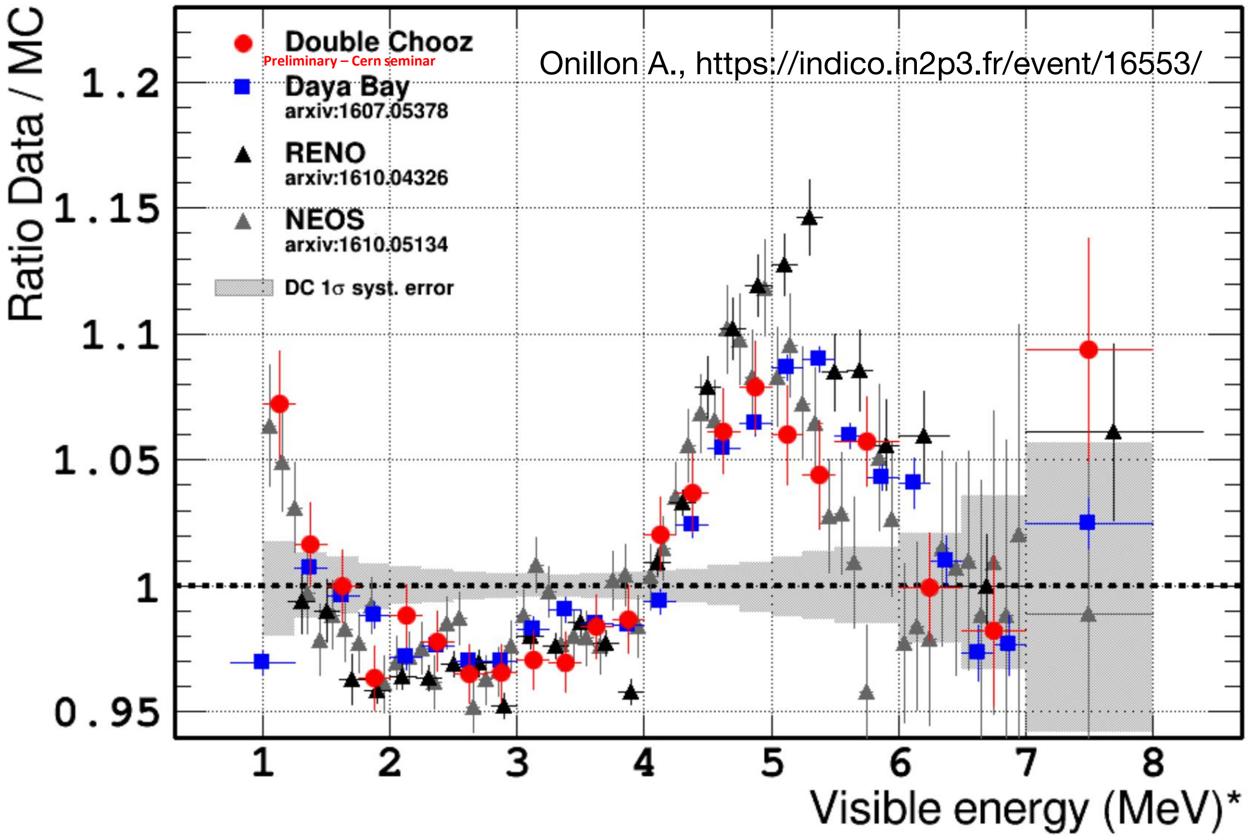
Spectral Distortion at 6 MeV

- **Anomalous spectral distortion @ E_ν ~ 6 MeV** in θ_{13}-aimed neutrino experiments (2014)

- **Model uncertainties perhaps underestimated**

- Peak position not identical (or event present) in all experiments → energy scale impacts sensitivity to this effect

- Can be due to **unknown branches** (isotope related) → accurate ^{235}U spectrum measurement can isolate source of the distortion and constrain models

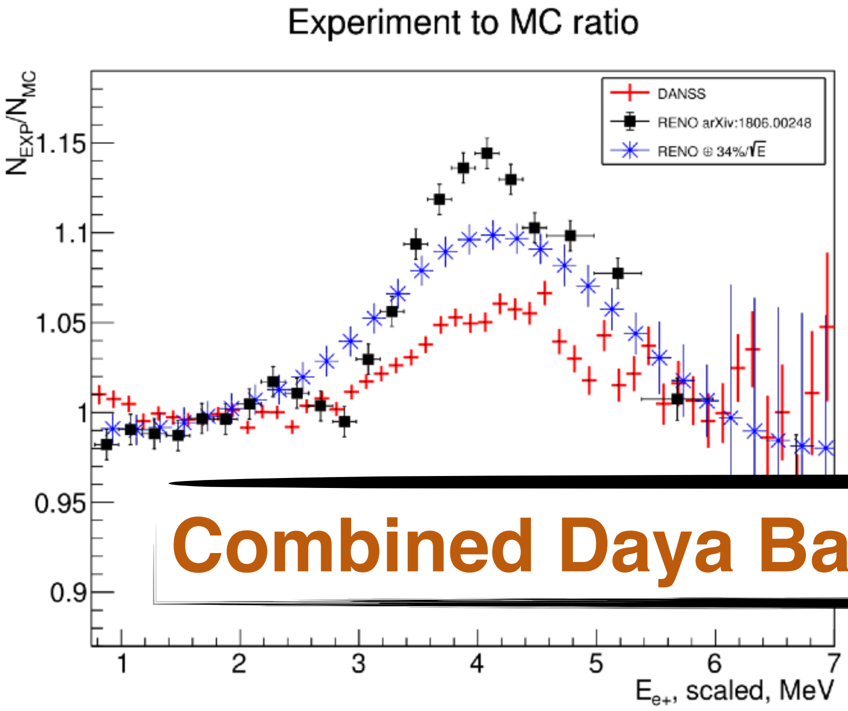


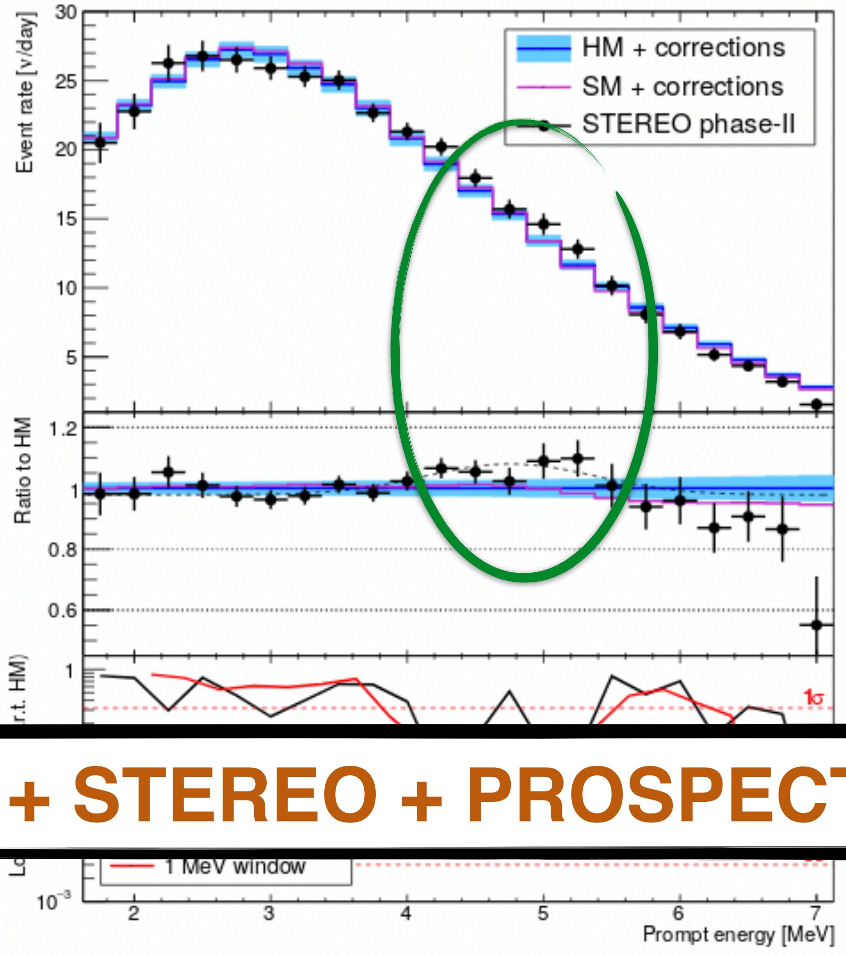
Onillon A., https://indico.in2p3.fr/event/16553/

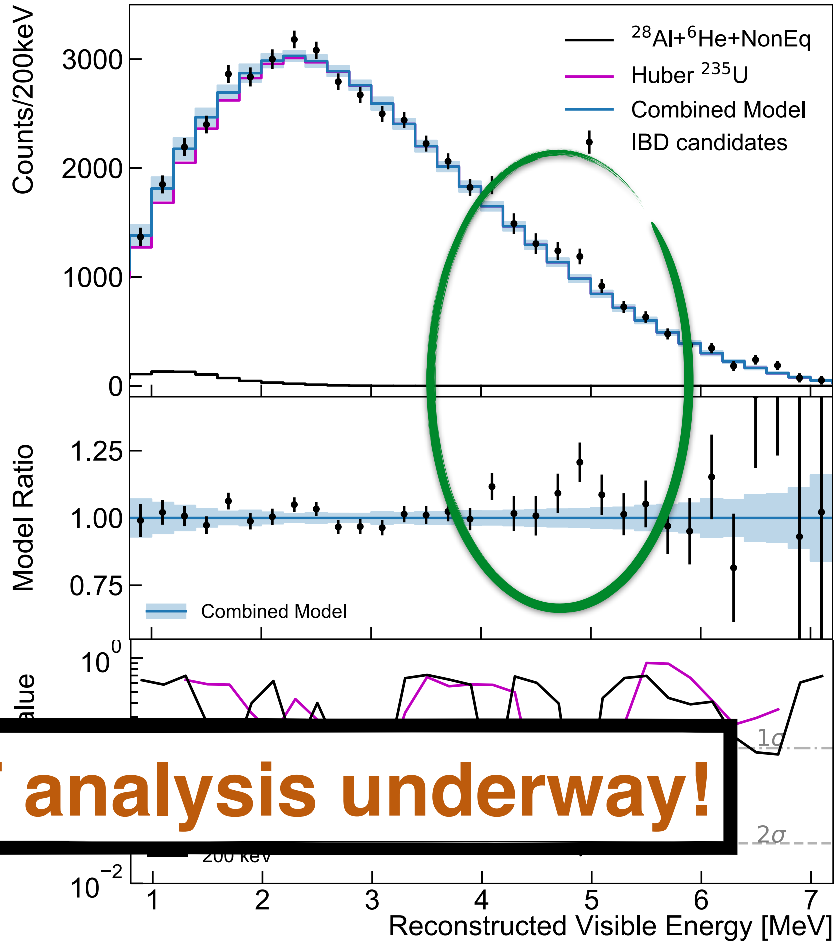
* can slightly differ from one experiment to another due to detector effects

Is the Distortion Isotope Related?

- **NEOS & DANSS** with LEU (**^{235}U + ^{239}Pu**) **see an excess**
  - NEOS sees comparable excess to Double Chooz / Daya Bay / RENO
  - DANSS also sees less significant excess (less robust E scale and poor E_{res} ~20%)
- STEREO & PROSPECT with HEU (**~100% ^{235}U**) recently released their spectra
  - **STEREO confirms an excess** of (10.1±2.9) % @ (4.8±0.2) MeV
  - **PROSPECT: no bump disfavoured** @ 2.2σ CL and **^{235}U-only bump disfavoured** @ 2.4σ CL





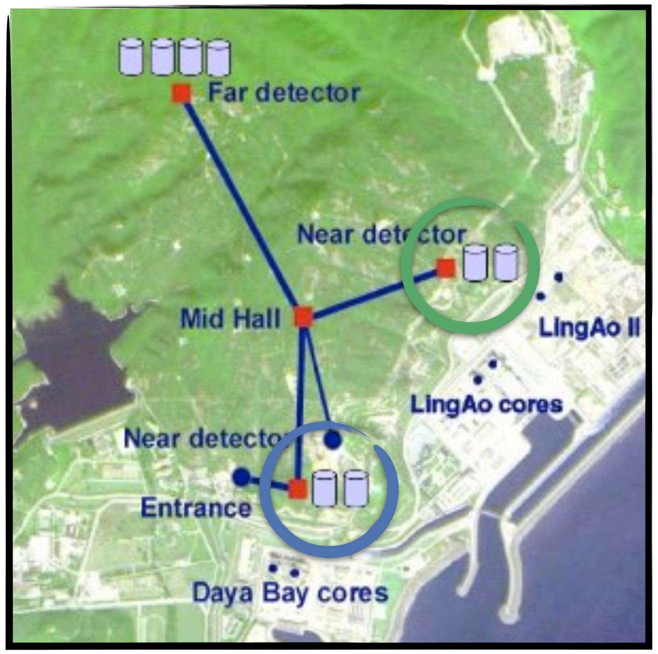


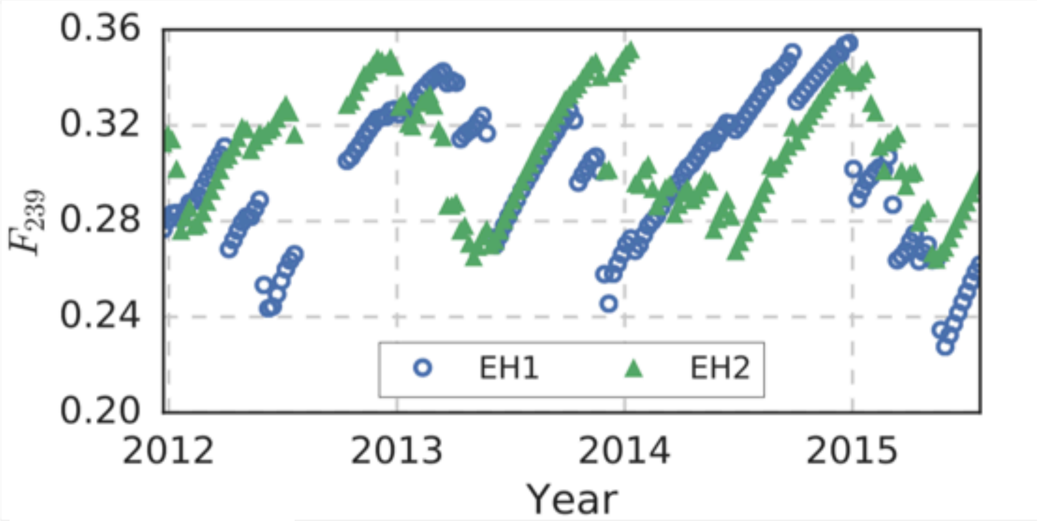
Combined Daya Bay + STEREO + PROSPECT analysis underway!

Reactor Flux Decomposition by Isotope

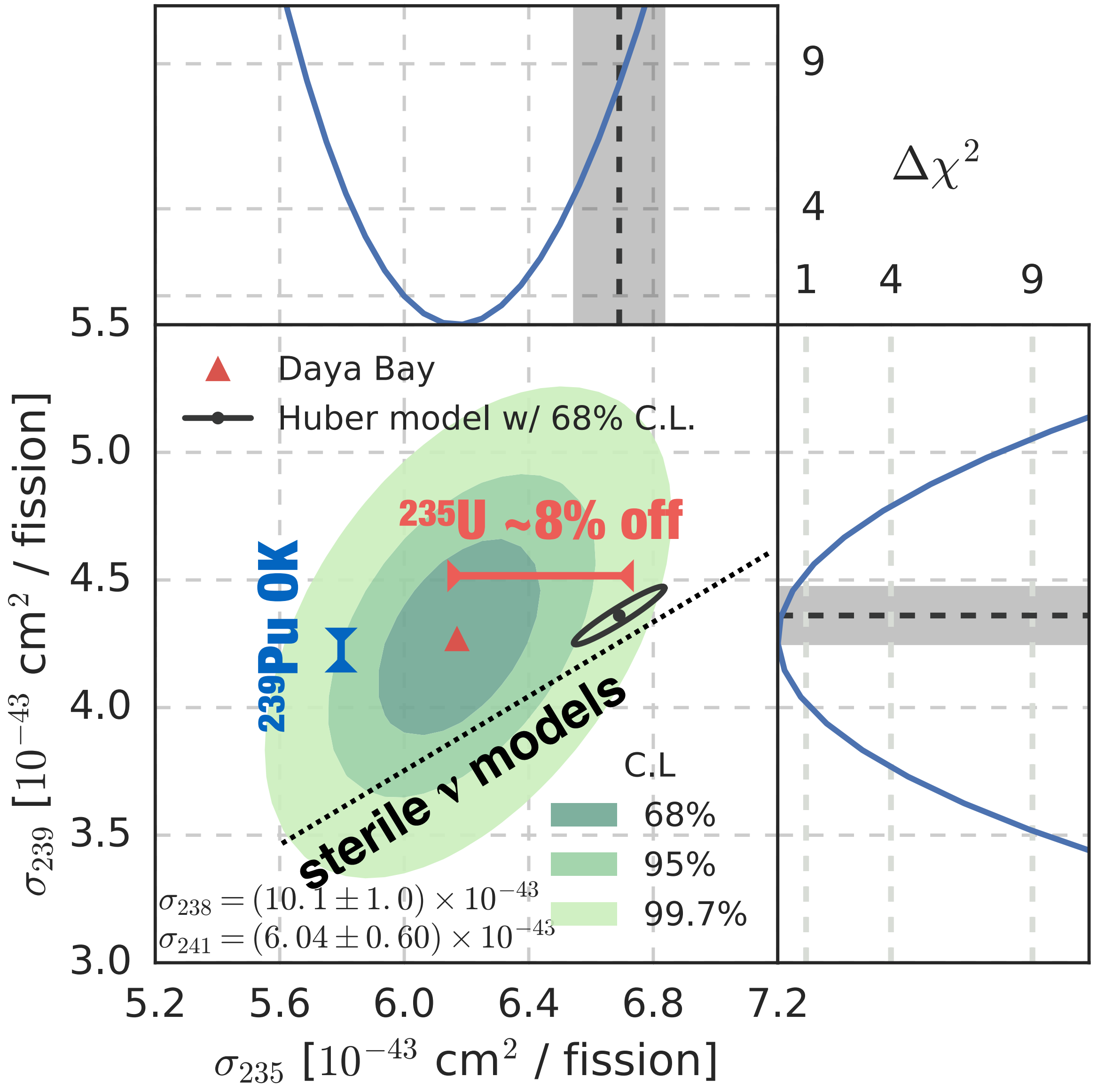
- Thanks to the huge statistics (~10^6 IBD) **Daya Bay** and RENO can **separate ^{235}U and ^{239}Pu contribution to neutrino flux**

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





arXiv:1704.01082v2 (Jun 2017)

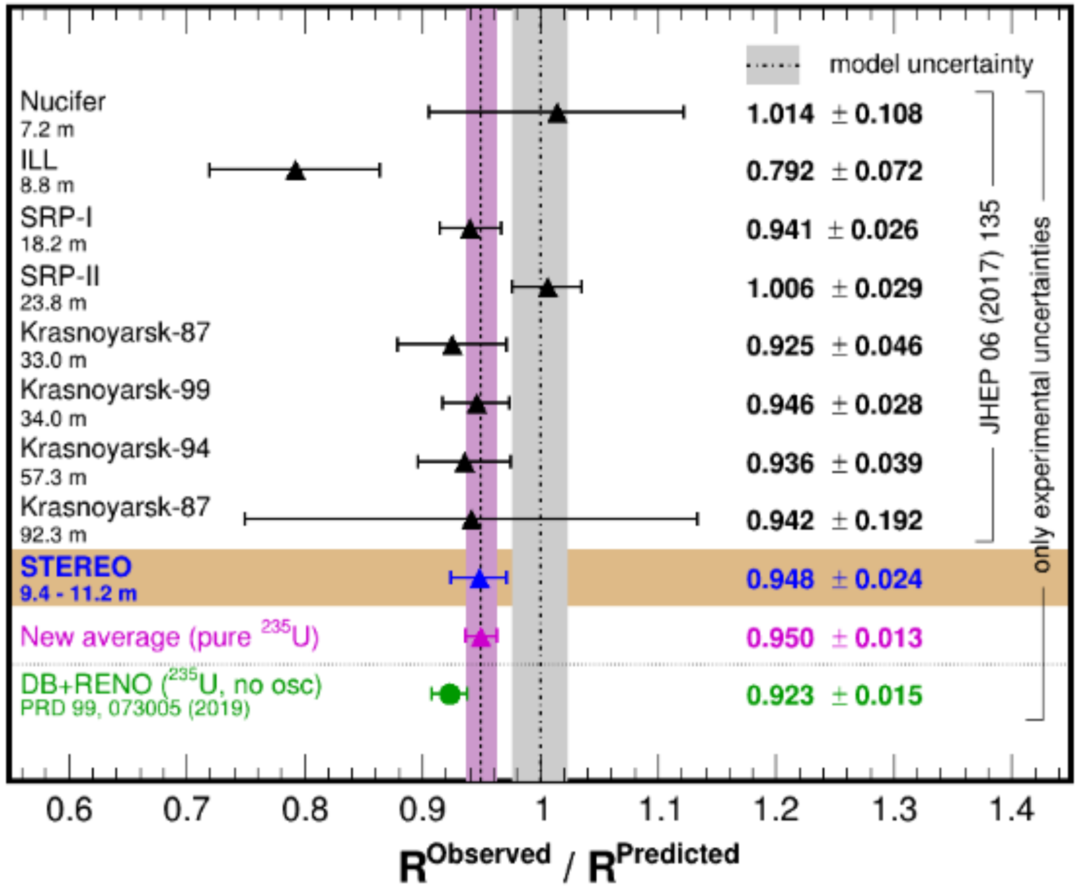


Reactor Flux and ^{235}U

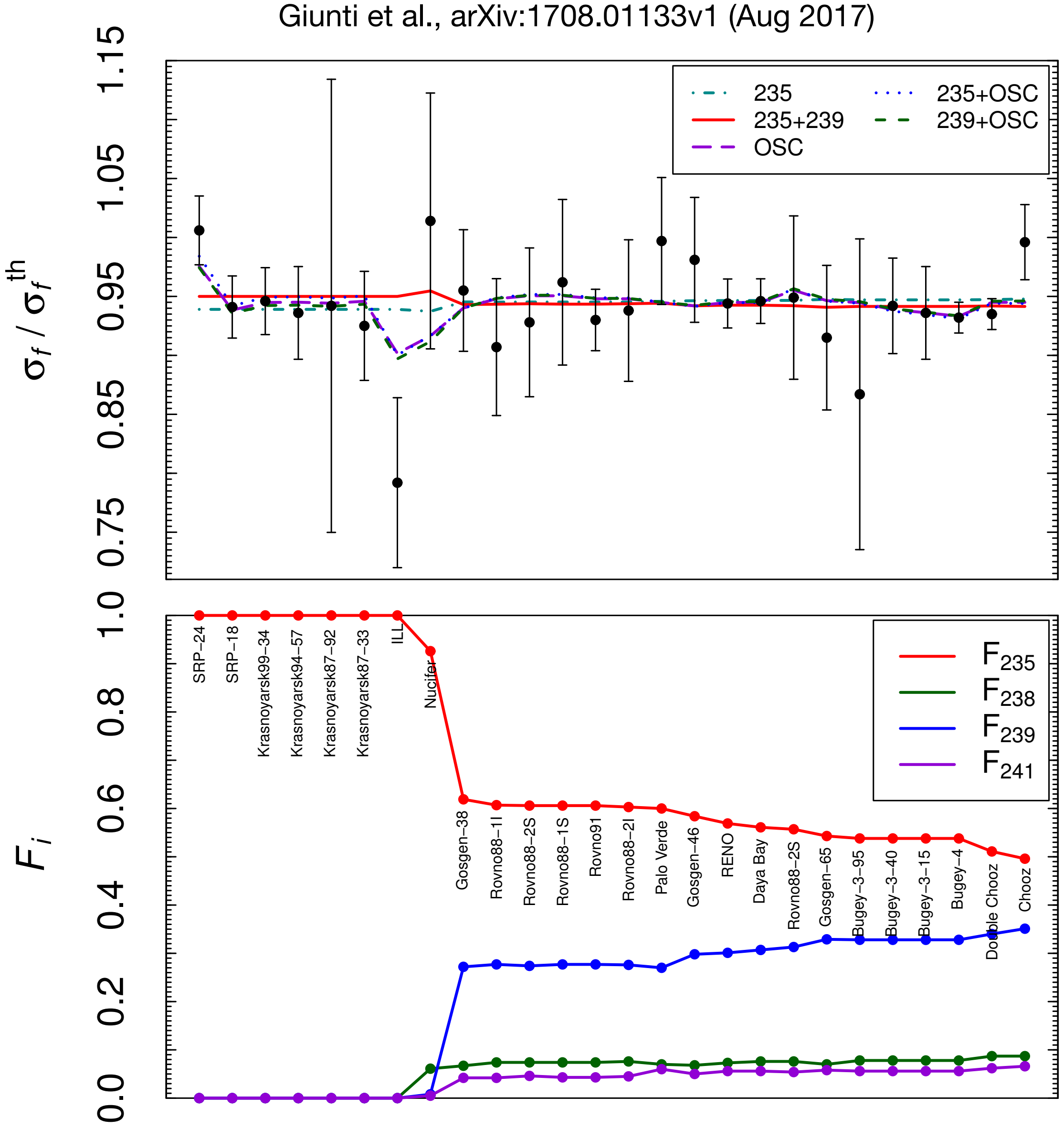
- Previous measurements show **no dependency of flux deficit from fuel composition**

- ^{235}U and ^{239}Pu fluxes are normalised on separate unique β-spectrum measurements @ ILL (80's)
  - Urgency for a **cross-check** and to test **new model for conversion to neutrino spectra**
  - Need corrections tuned on single experiments

arXiv:2004.04075



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



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

Limits of Current Neutrino Spectrum Models

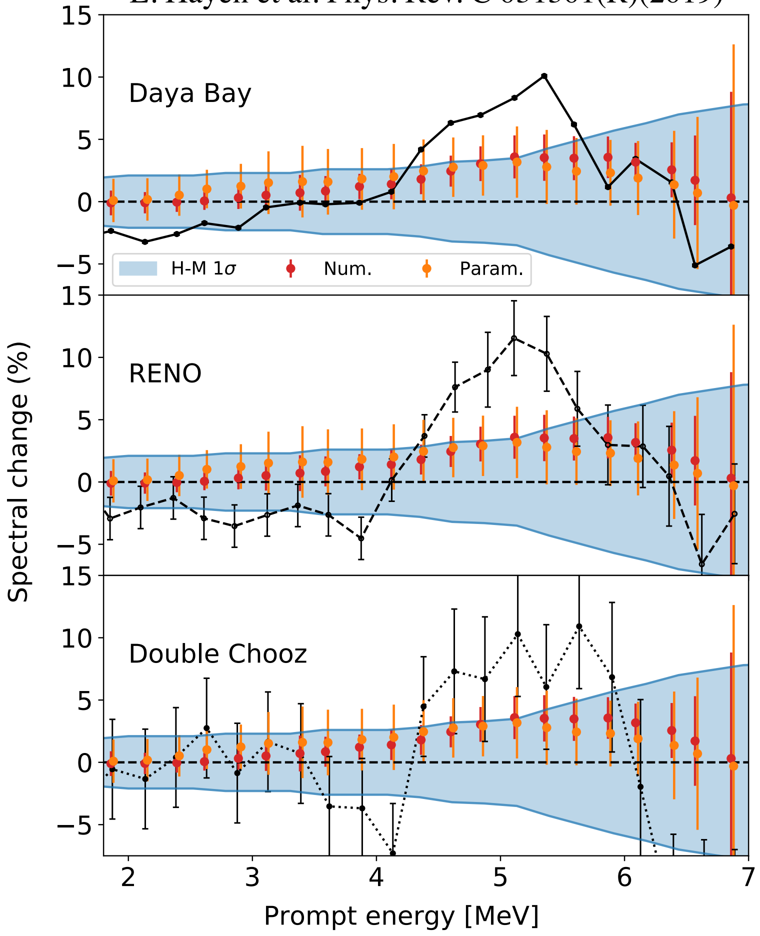
- Converted spectra (^{235}U, Pu)
  - Large uncertainty for weak magnetism term

P. Huber PRC84,024617(2011)
D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015)

  - Impact of the selection of average effective Z distributions used in the fit of the ILL spectra (up to 5%)
  - **Treatment of forbidden decays could change both normalisation & spectral shape** → measurements of the shape factors for the most important forbidden decays crucial

A . Hayes et al. Phys. Rev. Lett. 112, 202501 (2014)
D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015)
X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314
L. Hayen et al. Phys. Rev. C 031301(R)(2019) and PRC.100.054323

L. Hayen et al. Phys. Rev. C 031301(R)(2019)



- Summation method (^{238}U)
  - Incomplete or biased nuclear decay schemes
  - Pandemonium effect

J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

→ Can be solved by total absorption γ-ray spectroscopy measurements (data-model discrepancy reduced to <2%)

M. Fallot et al. PRL 109,202504 (2012), SM-2012

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
  - **Exclude** the **active-sterile oscillation**
  - Constrain models and test validity of rate and shape predictions

- **Model improvement can help solve the anomalies**

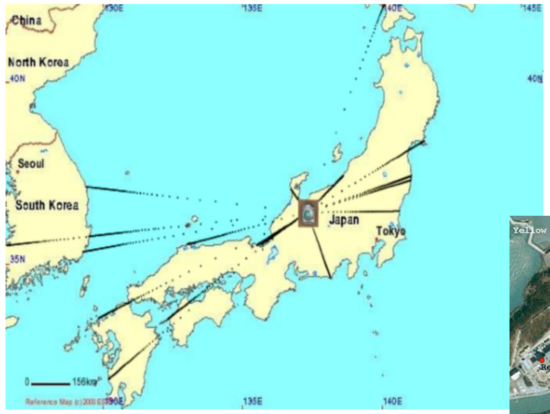
Outline

- Neutrino mixing and reactor antineutrinos
- Legacy of the 2nd generation of reactor neutrino experiment
- Anomalies challenging the 3-family framework
- The quest for the light sterile neutrino
- Sterile neutrinos vs reactor neutrino spectral estimation
- **The future of reactor neutrinos: JUNO**

History of Reactor Neutrino Experiments

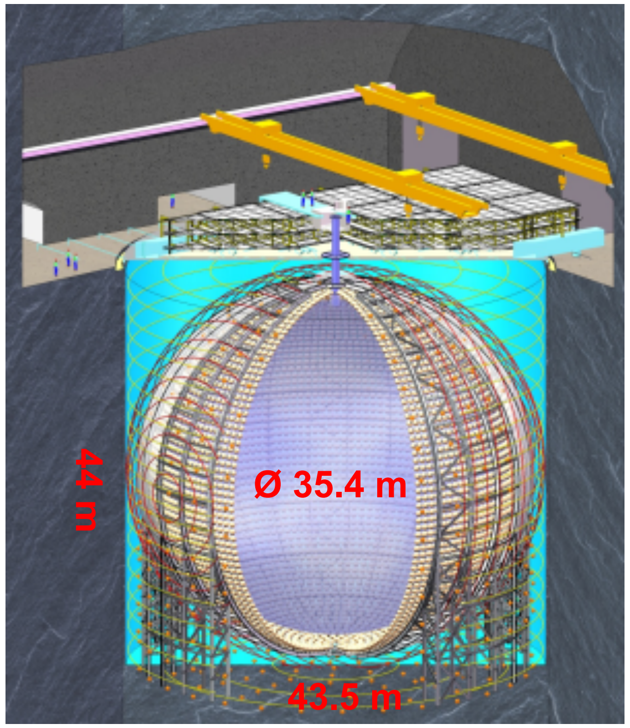
Mass/Baseline

- 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**

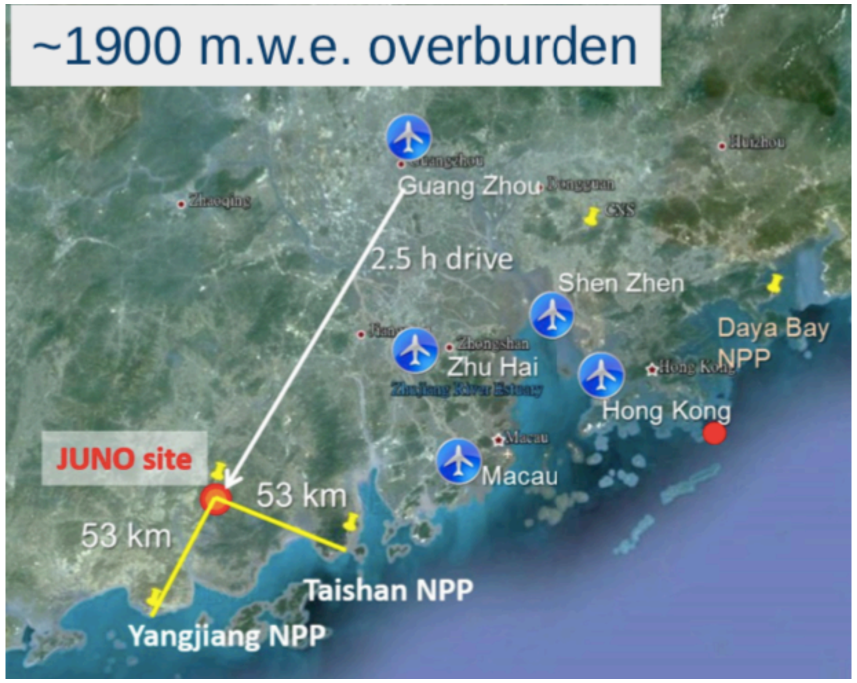


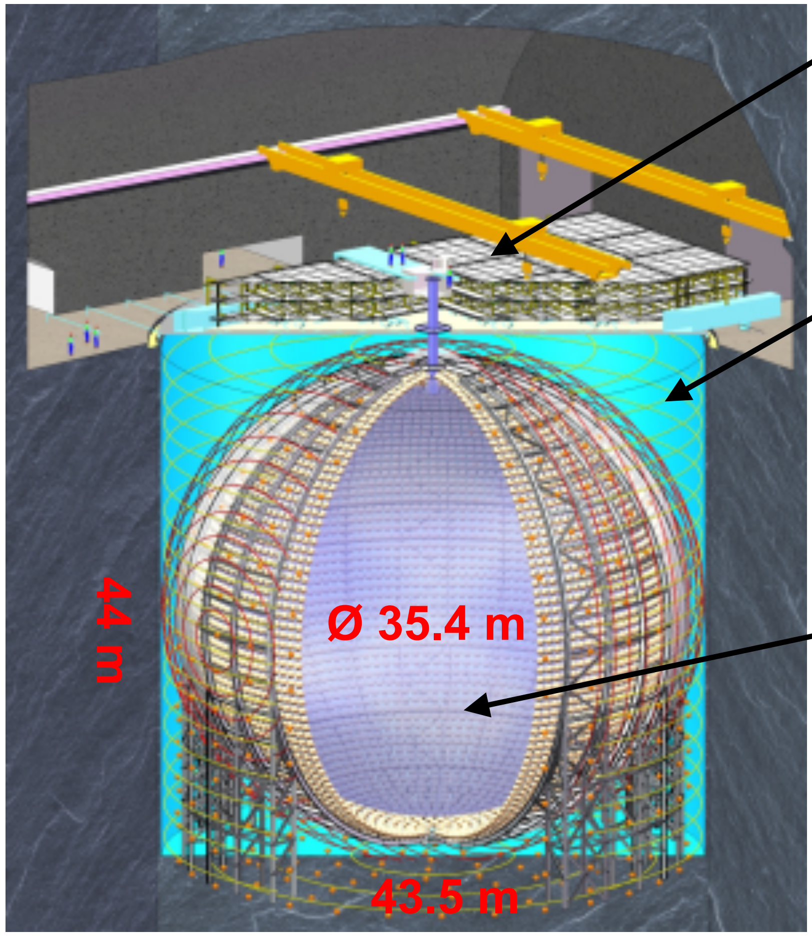
- 20 kt
- 50 km baseline
- **Wide program**

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**





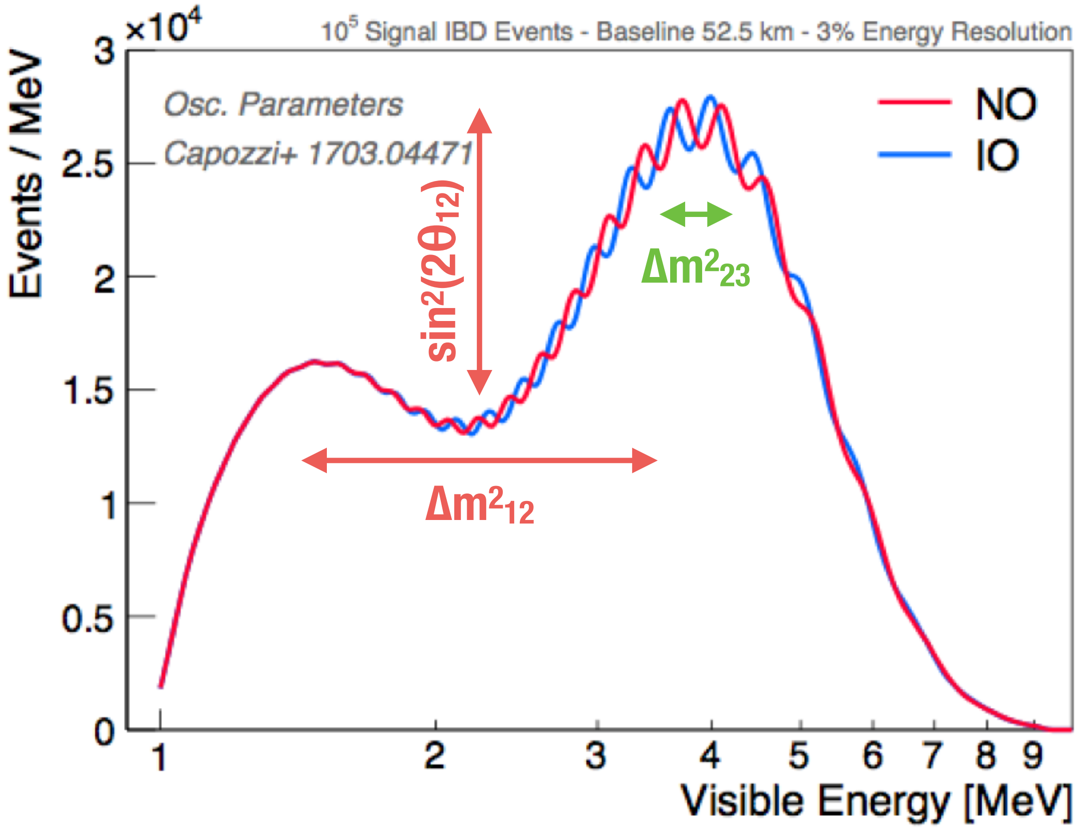
Top μ tracker
- 3 plastic scintillator layers
- ~50% coverage

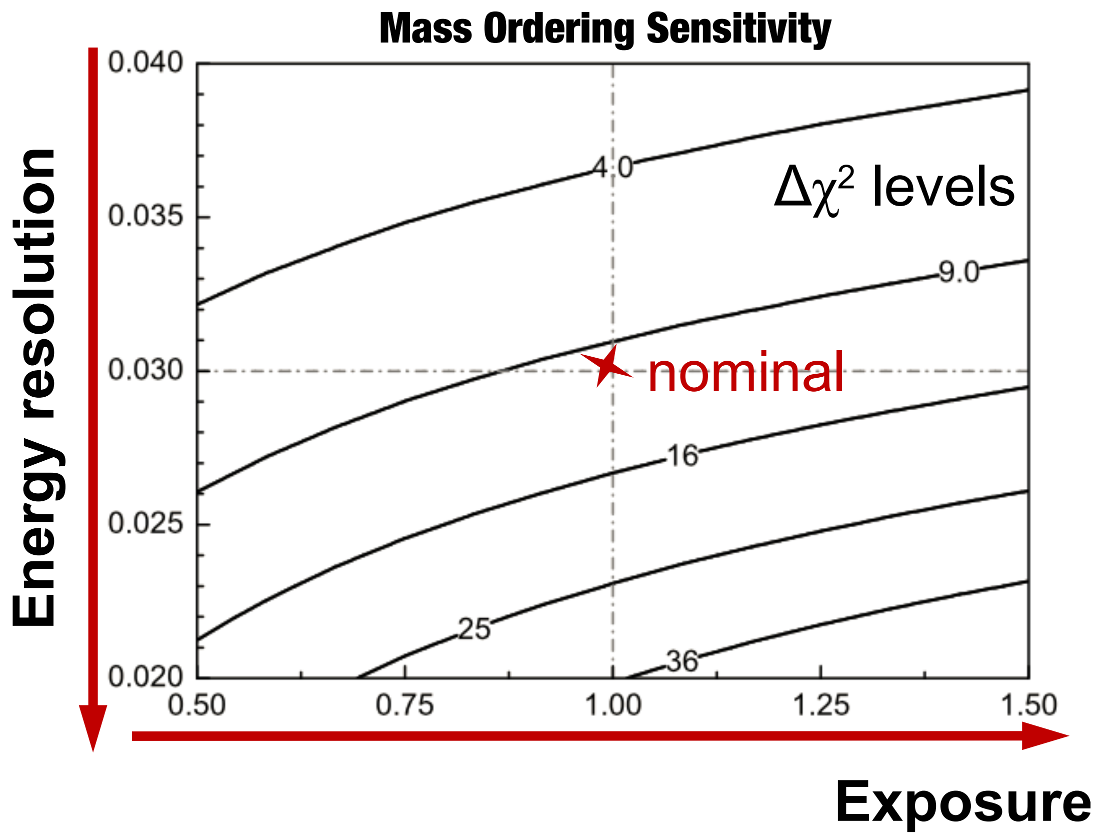
H_2O Cherenkov μ veto
- 2400 20" PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%

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

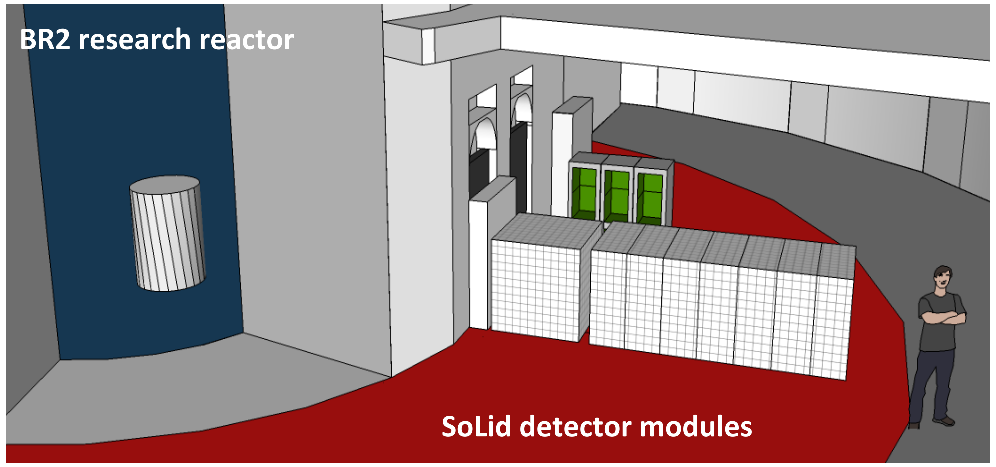
A World-Wide Hunt - Table

	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

SoLid

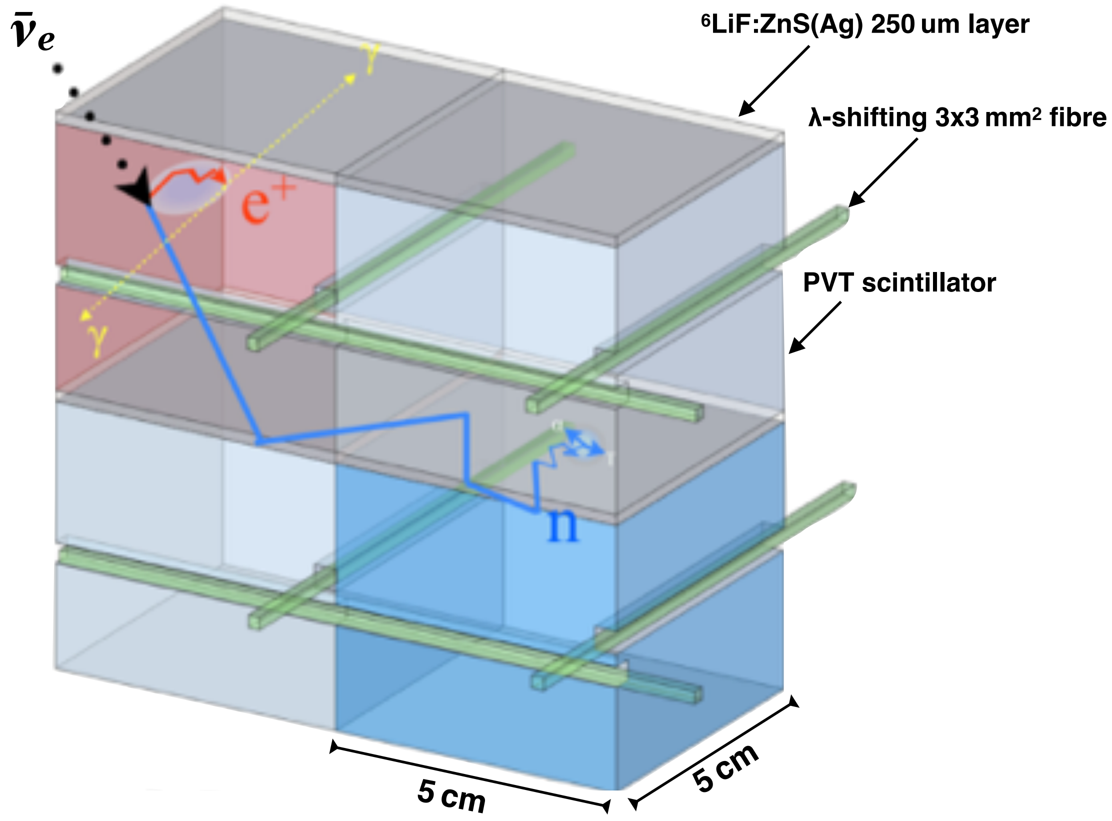
- @ 60 MWth compact-core (0.5 m diameter) BR2 reactor in Mol (Belgium), baseline range ~ 5.5 - 10 m

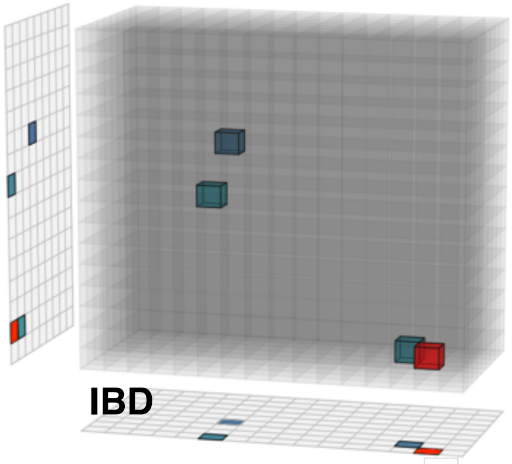
- Highly 3D segmented detector
  - $5\times5\times5 cm^3$ PVT cubes (optically separated)
  - ^{6}LiF:ZnS(Ag) for neutron identification
  - Optical fibers and silicon PMTs

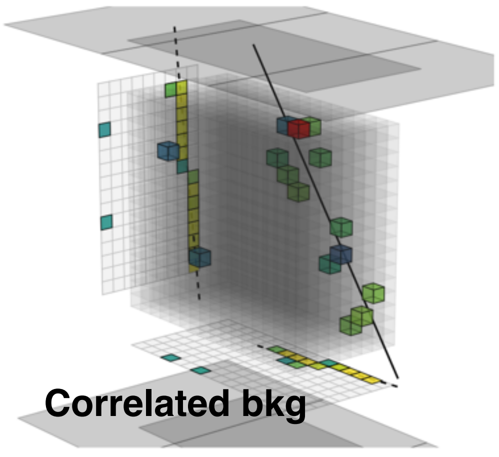


- Event topology used to identify IBD's

- Currently under commissioning





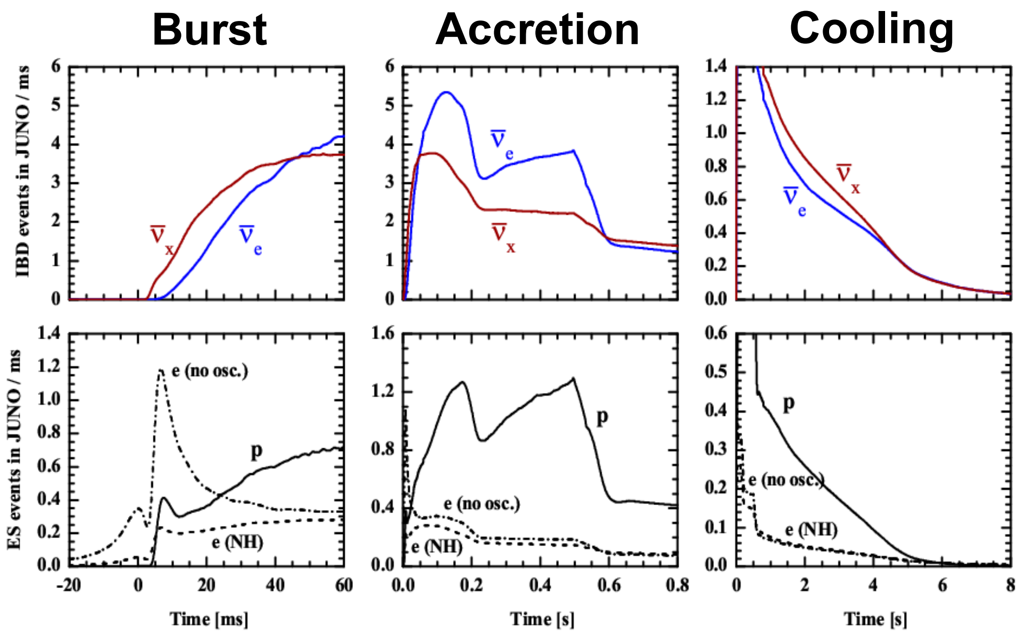


Sterile Neutrinos and Cosmological Constraints

- 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