Reactor Antineutrino Flux Measurement

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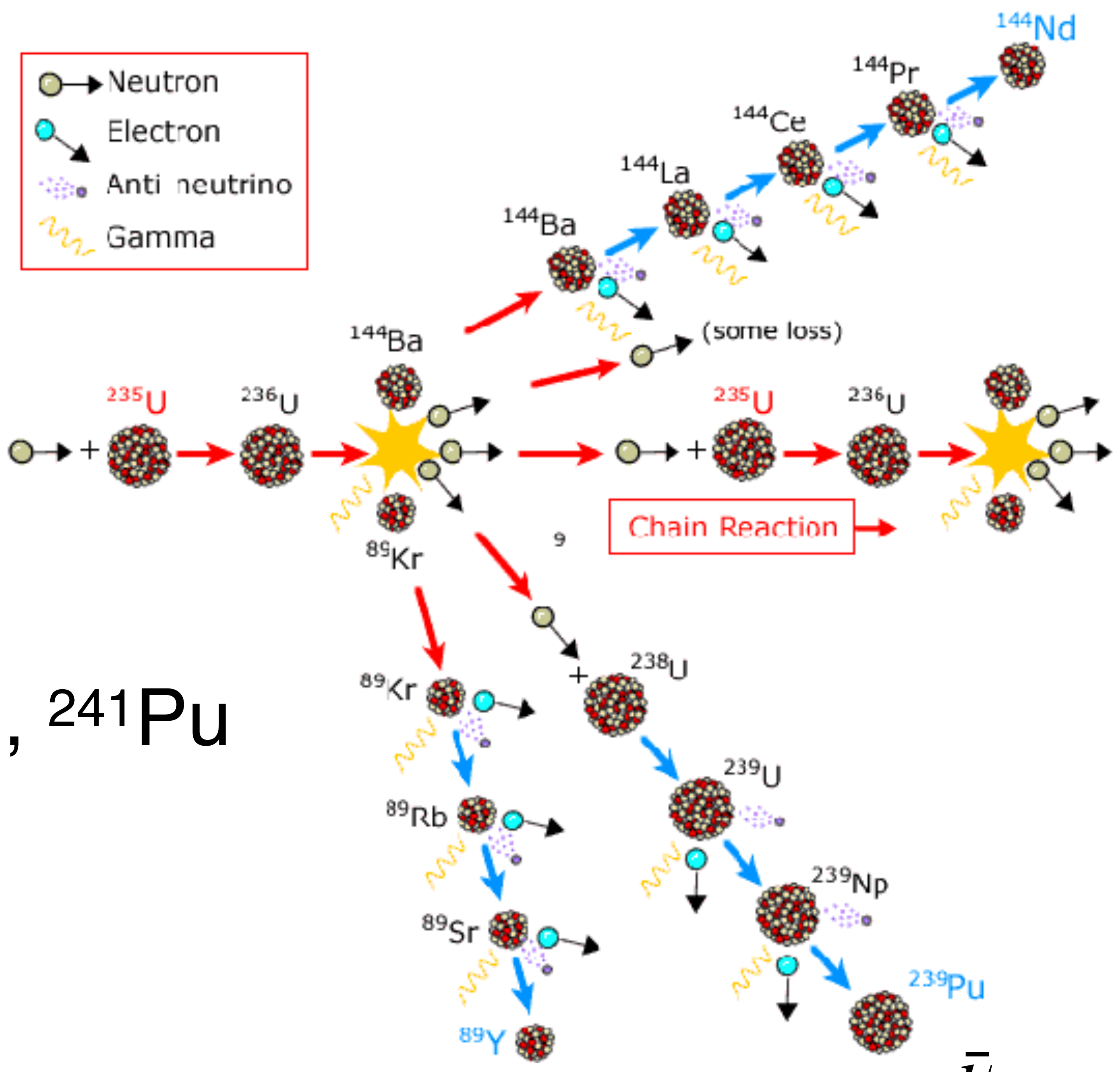
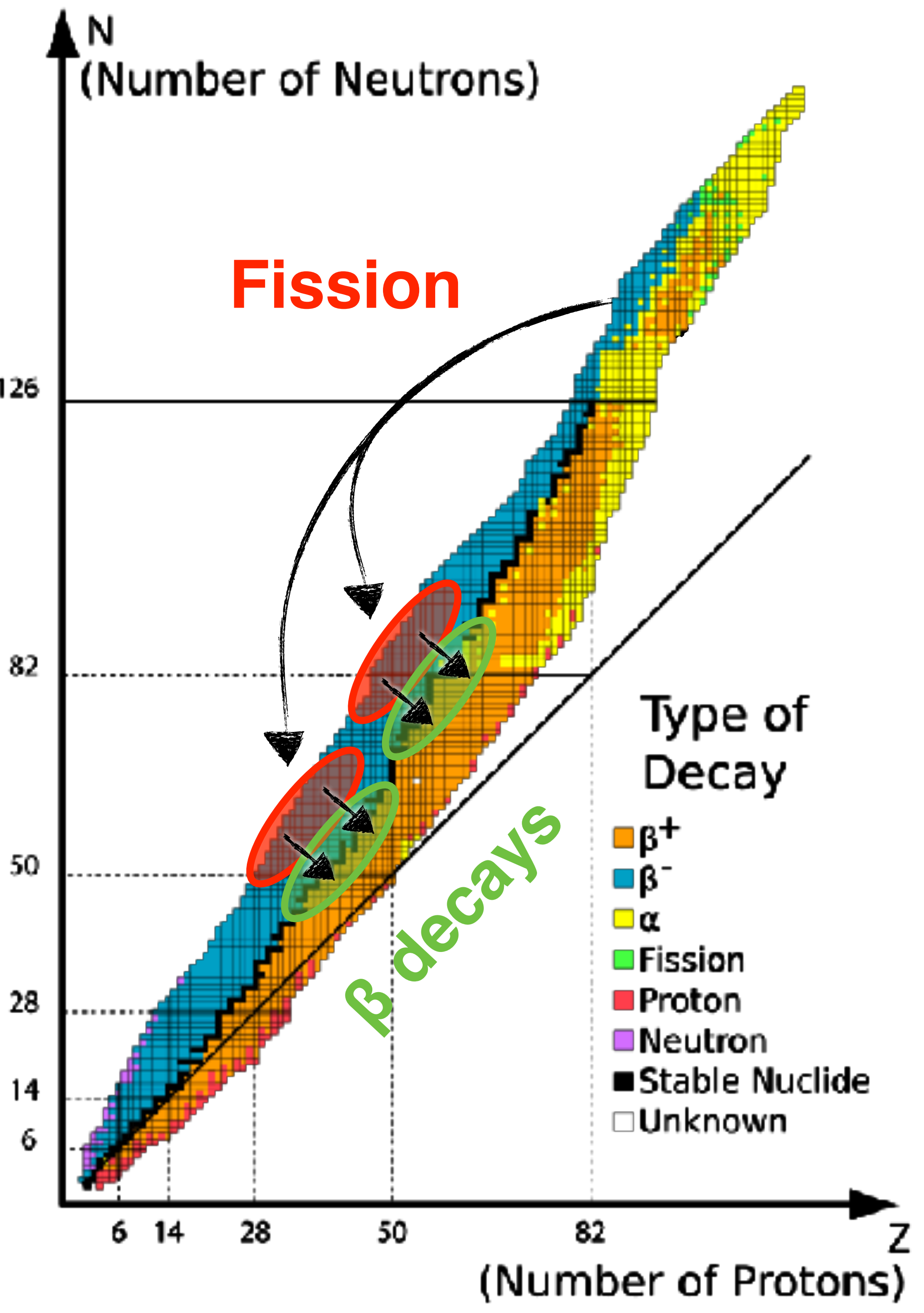
Introduction

- Measurement of the reactor antineutrino fluxes (and spectra) is important
  - For fundamental physics: Oscillation parameters (θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31}), sterile neutrinos?
  - For applied physics: Benchmark our prediction models (or provide data-driven prediction)
- Historically moving from:
  - Total flux measurement } This talk
  - Isotopic flux measurement } This talk
  - Isotopic spectrum (&flux) measurement } Talk by C. Roca

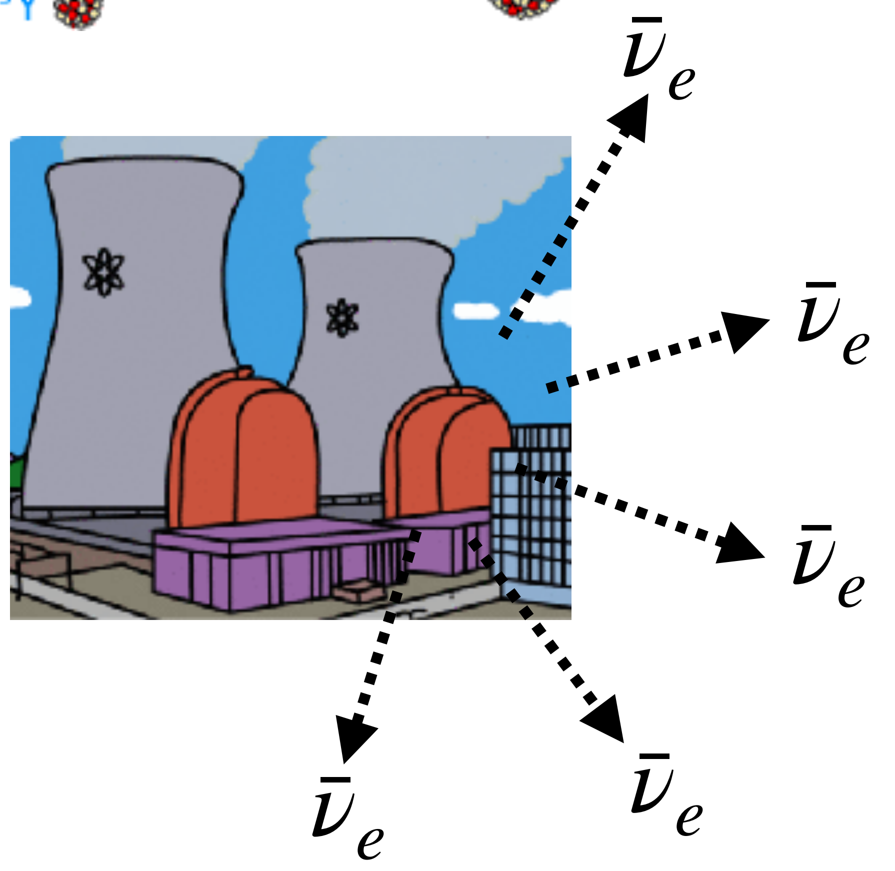
Reactor Antineutrino Production

- Reactor antineutrinos produced in β decays of the neutron-rich fission daughter
  - Only electron antineutrinos
- Commercial reactors
  - Low-enriched uranium fuel (LEU)
  - Fission of four main isotopes **^{235}U**, ^{238}U, **^{239}Pu**, ^{241}Pu
  - About 10^{21} ν/s
- Research reactors
  - Highly enriched fuel (HEU)
  - Fission of **^{235}U** only
  - About 10^{19} ν/s





$$^{A}_{Z}X \rightarrow \,^{A}_{Z+1}X' + e^{-} + \bar{\nu}_e$$



Reactor Antineutrino Detection

- Primary detection method - Inverse beta decay (IBD)
  - Used for almost 70 years now
  - Coincidence between prompt and delayed signal hugely suppress the background
- Reaction embedded how we report reactor antineutrino flux
  - So-called IBD yield (σ) - number of antineutrinos per fission weighted by the IBD cross section

Temporal and spatial coincidence

prompt signal delayed signal

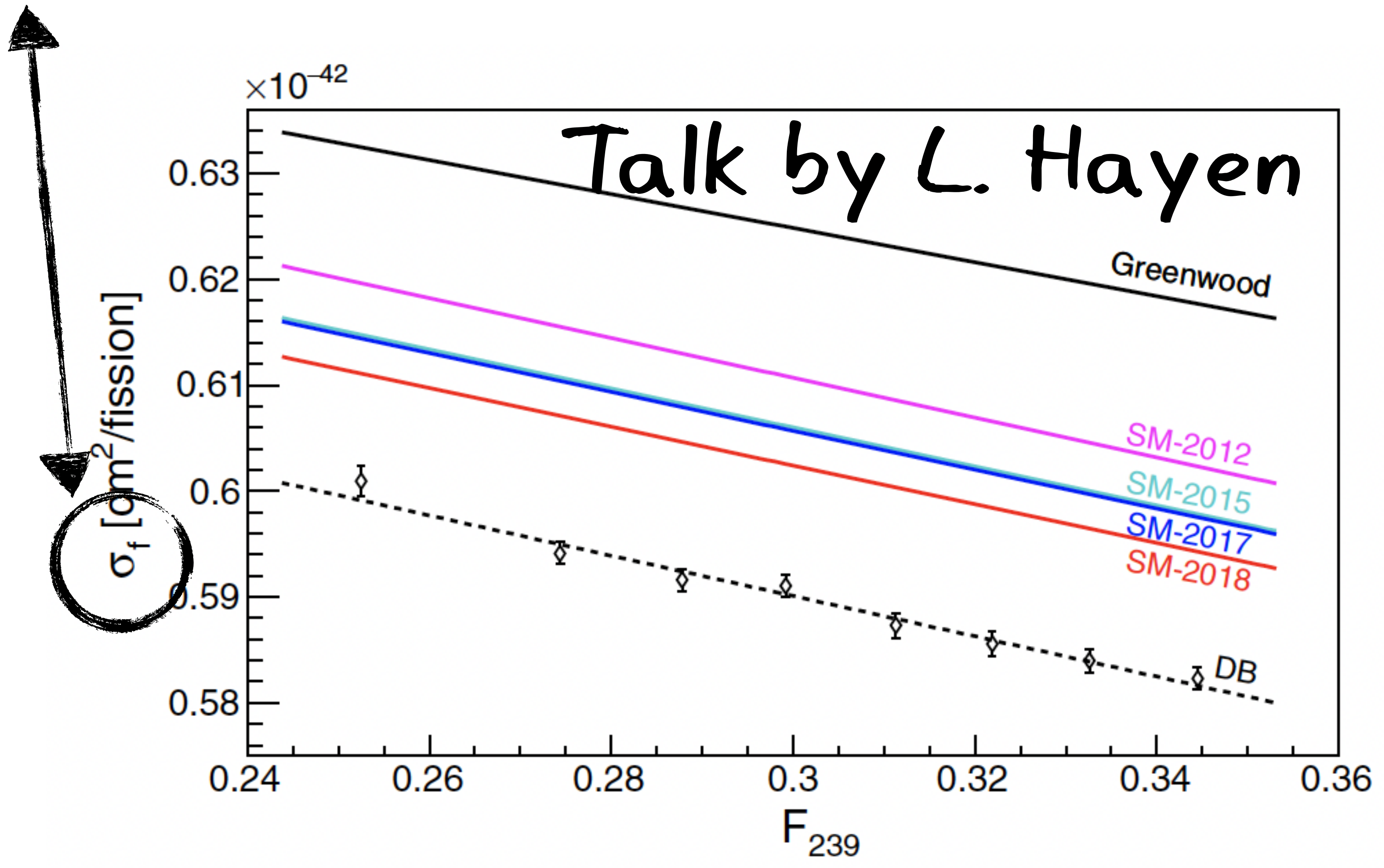
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

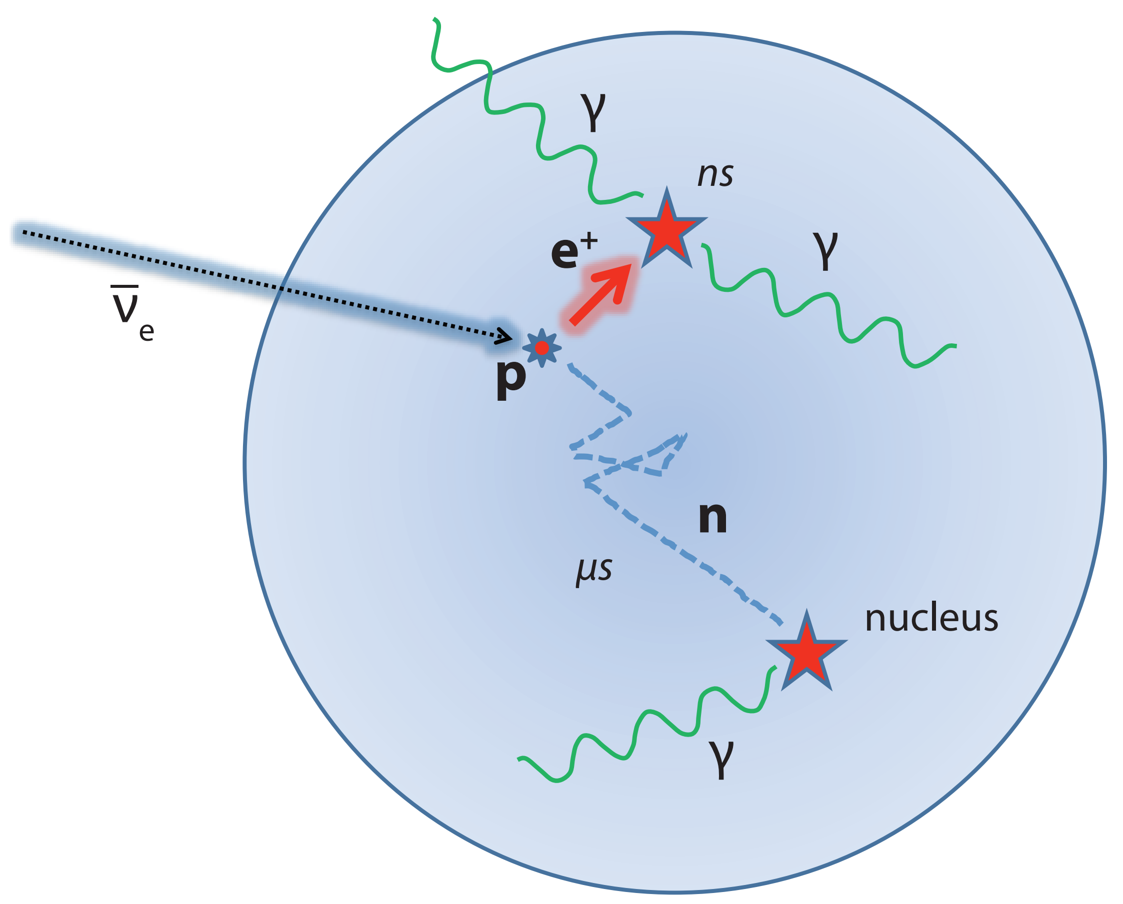
$$\rightsquigarrow n + H \rightarrow D + \gamma \ (2.22 \text{ MeV})$$

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

$$\rightsquigarrow n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma\text{'s} \ (9 \text{ MeV})$$

$$\rightsquigarrow n + Li \rightarrow Li \rightarrow \alpha + T \ (4.78/{\sim}0.5 \text{ MeV})$$

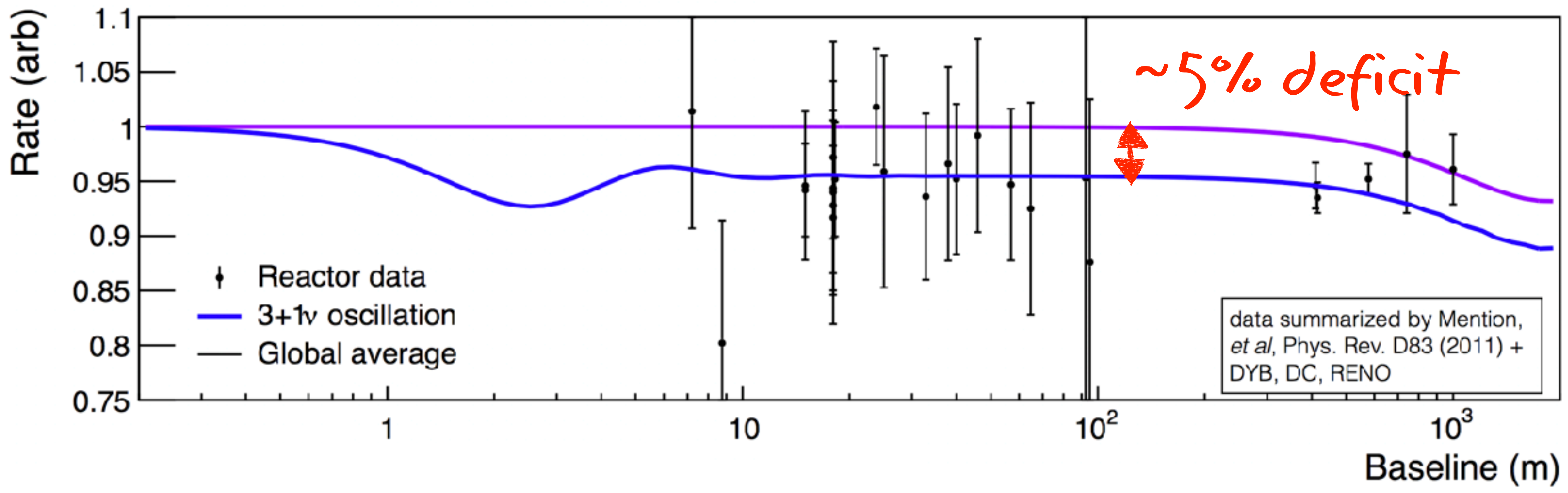




Total Reactor Antineutrino Flux and RAA

- Historically, the most precise measurements of the total reactor antineutrino flux (four main isotopes) was done at commercial reactors (Bugey-4, Double Chooz, Daya Bay, …)
- Deficit in the total measured flux w.r.t. the classical Huber+Mueller et al. (HM) prediction led to the so-called Reactor Antineutrino Anomaly (RAA) in 2011

Phys. Rev. C 84, 024617
Phys. Rev. C 83, 054615

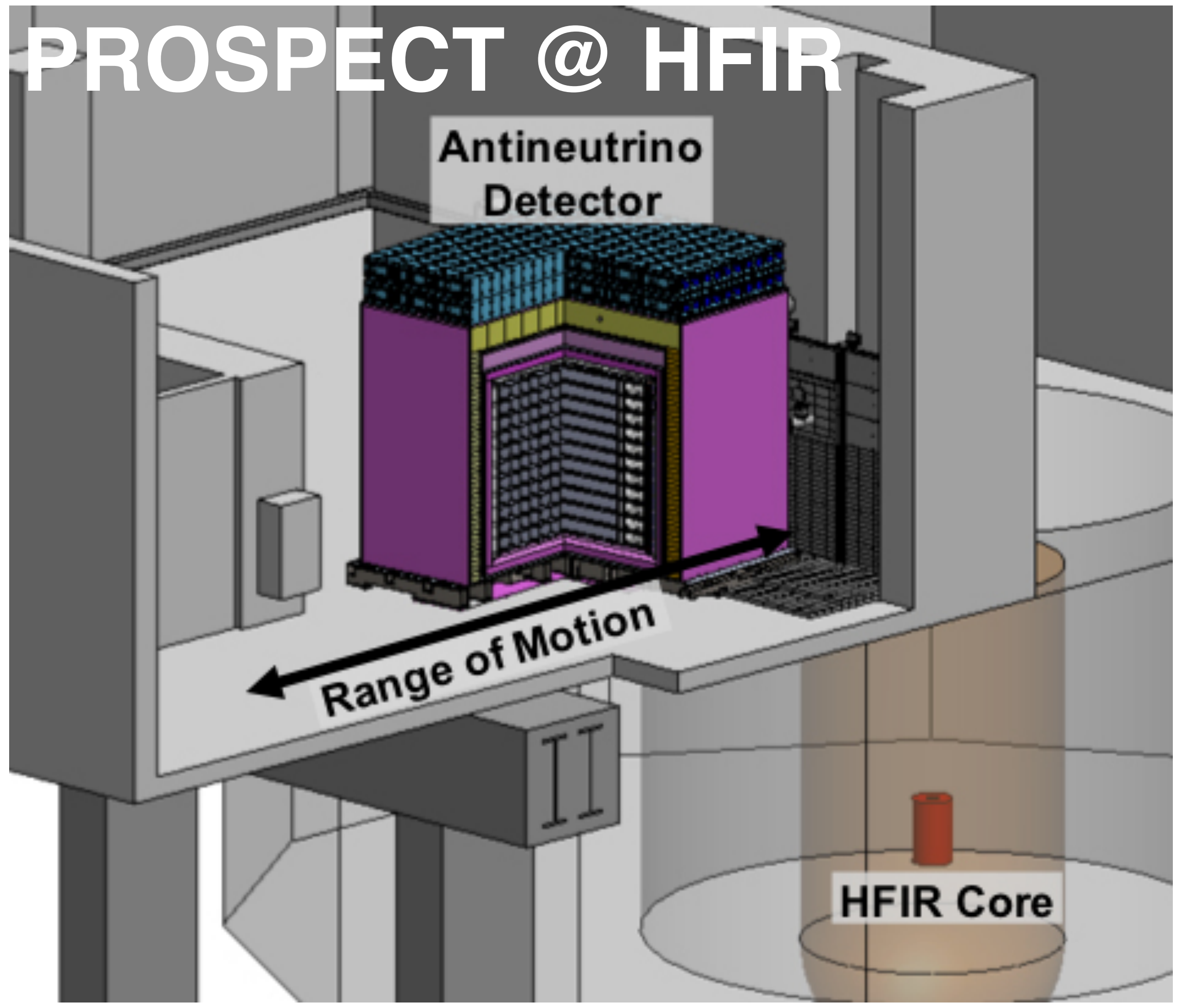


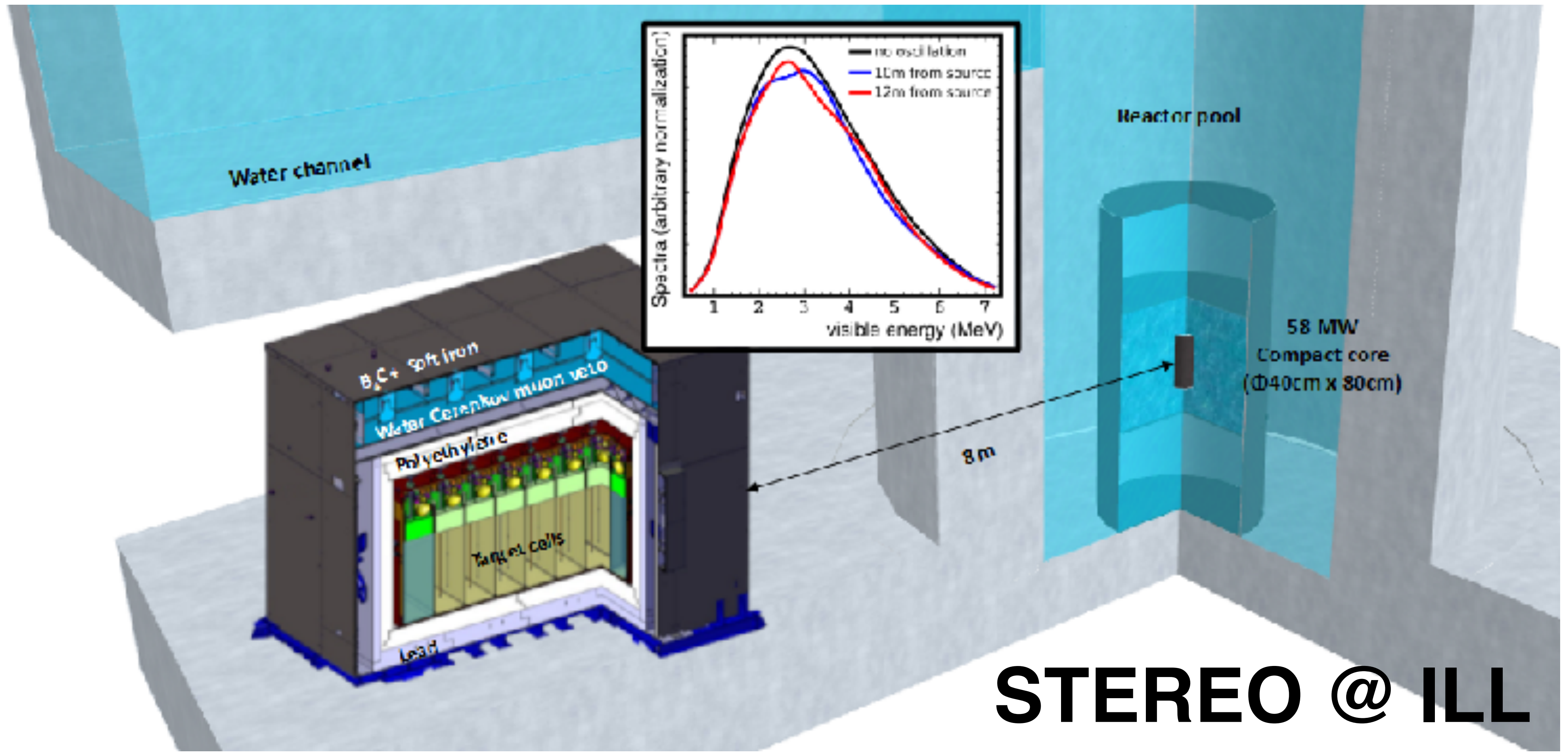
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

- Might be explained by the existence of light sterile neutrino mixing m_ν~1 eV
- Total flux measurement cannot not distinguish between sterile neutrinos and inaccurate prediction
  - More information from the measurement of fluxes by isotopes

Isotopic Flux Measurement at HEU Reactors

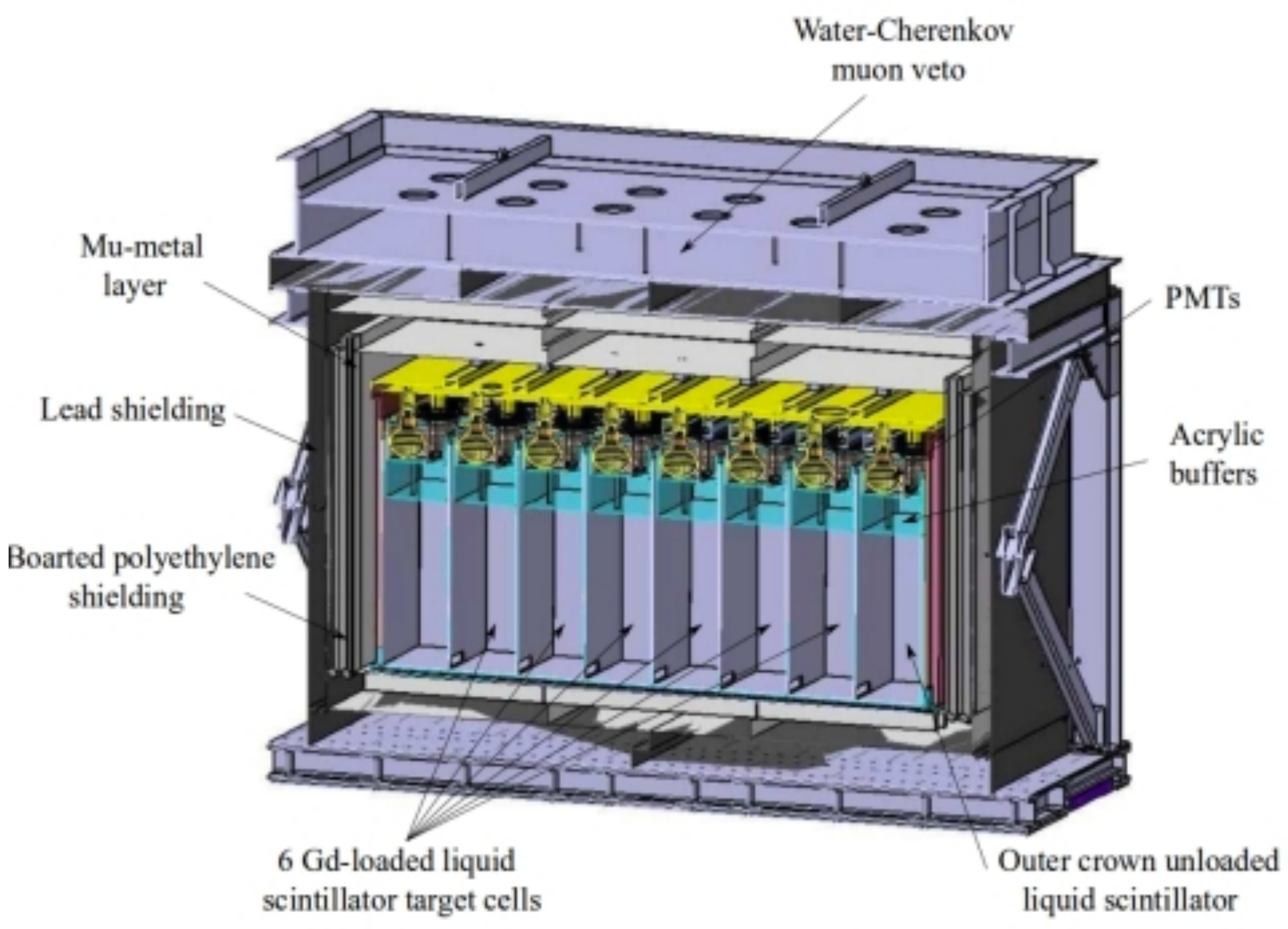
- Experiments such as STEREO, PROSPECT, SoLid
- Advantages
  - HEU reactors - isotopic measurement per se, fuel only ^{235}U
  - On-off reactor period
  - Close to a reactor allows to explore ~1 eV sterile neutrinos
- Challenges w.r.t. LEU reactor experiments
  - Lower statistics
  - Non-fission antineutrinos
  - More background from being closer to the surface and reactor itself

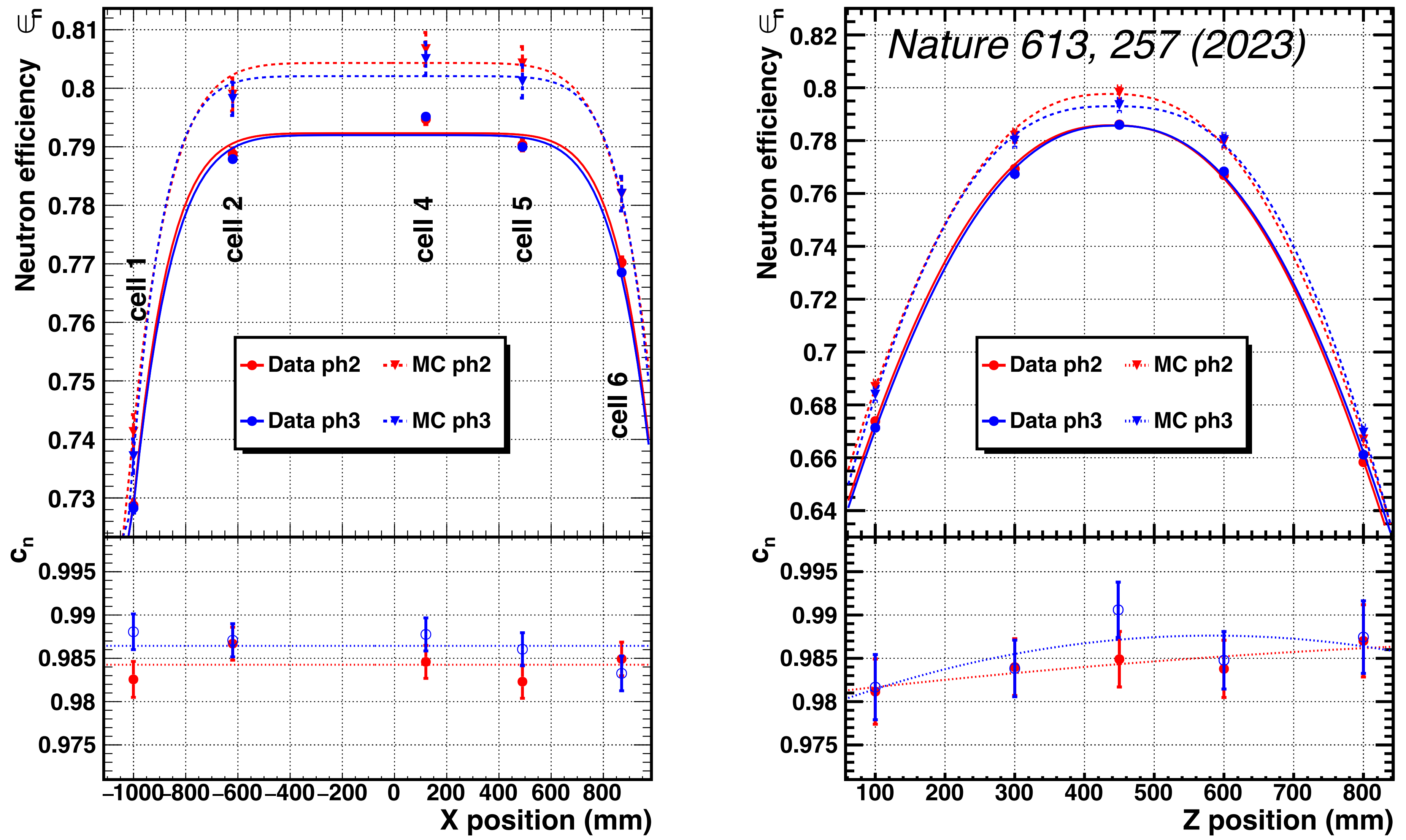




The STEREO Experiment (as an Example)

- Segmented Gd-doped liquid scintillator experiment
- Located ~10 m from the 58 MW_{th} reactor at ILL
- Knowing the detection efficiency and background rates crucial to get your yield right
  - Energy calibration not so important for the flux measurement (depending on your selection cuts)
- Used techniques to measure and suppress the background
  - On-off reactor period
  - Pulse shape discrimination
- Proper estimation of the (delayed IBD) neutron efficiency using an Am-Be neutron source
  - Still the largest systematics

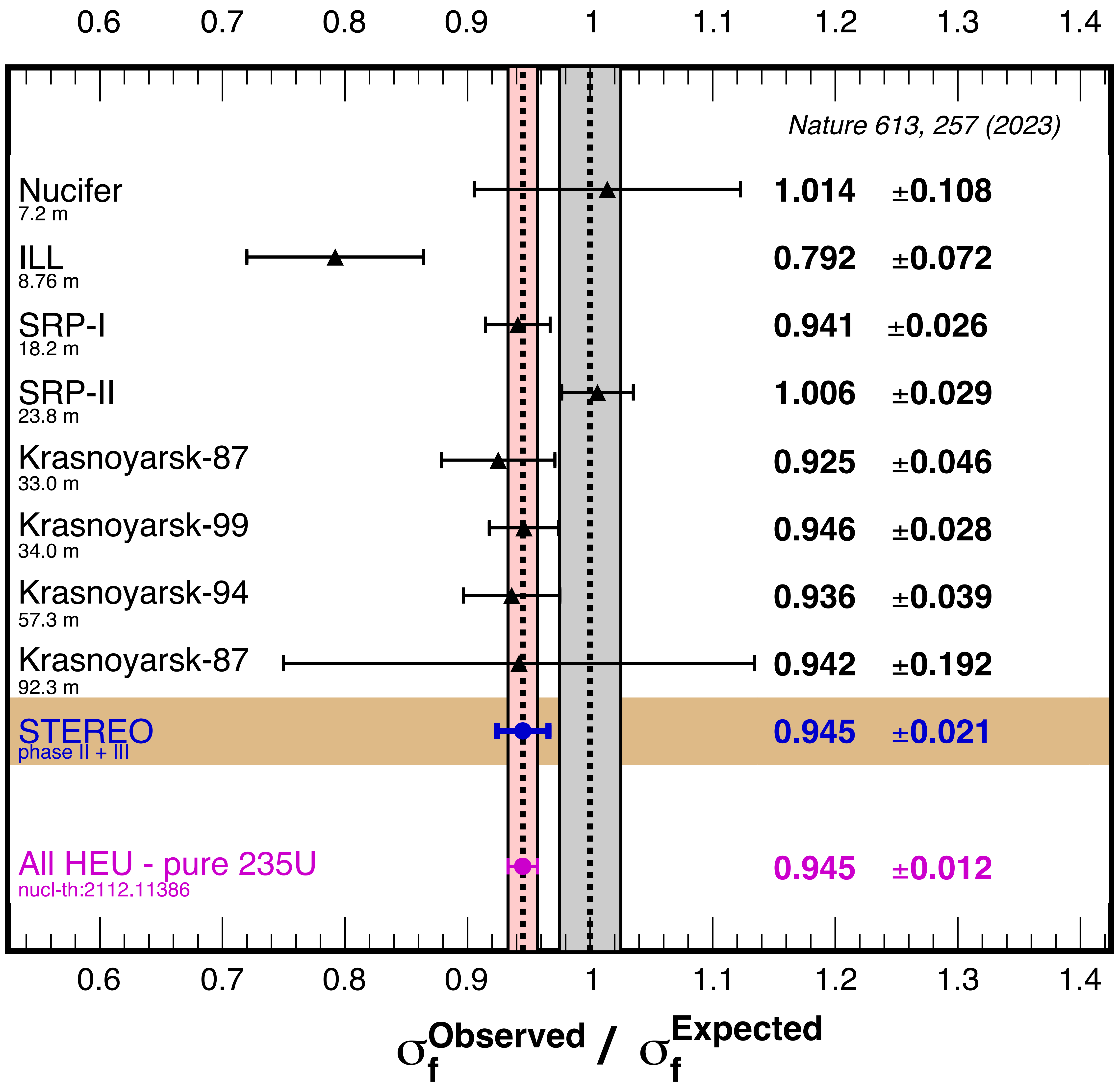




STEREO Result

- The most precise measurement from HEU reactors
  - Precision ~2.2%
- Measured yield lower than Huber + Mueller at al. model prediction
  - Deficit of 5.5% goes along with RAA
- No sterile neutrino mixing signal observed (based on the spectrum measurement)

Hope to see PROSPECT here one day :)



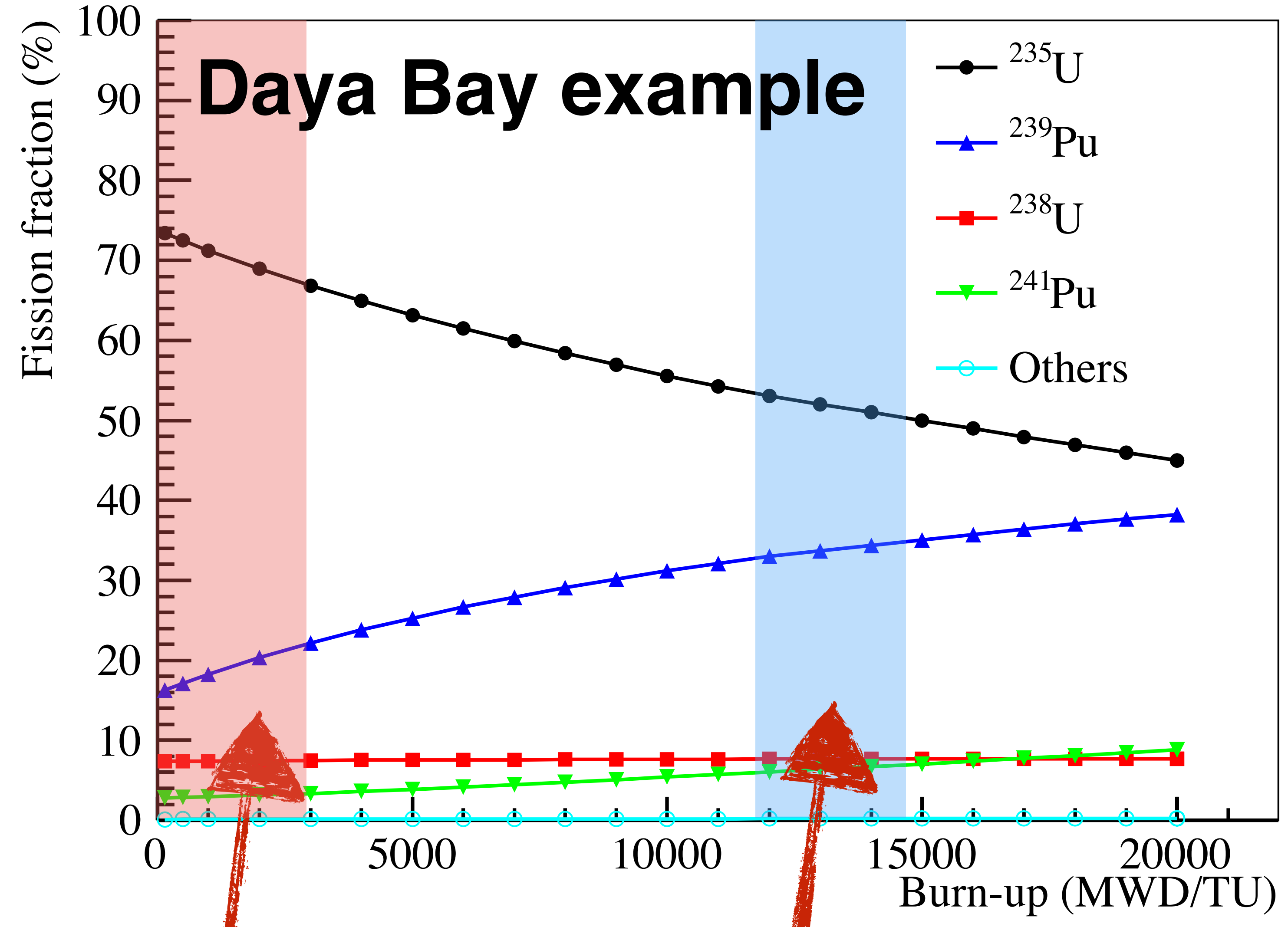
Fuel Evolution in LEU Reactors

- Constantly getting neutrinos from all four isotopes ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu - separation possible due to the fuel composition evolution

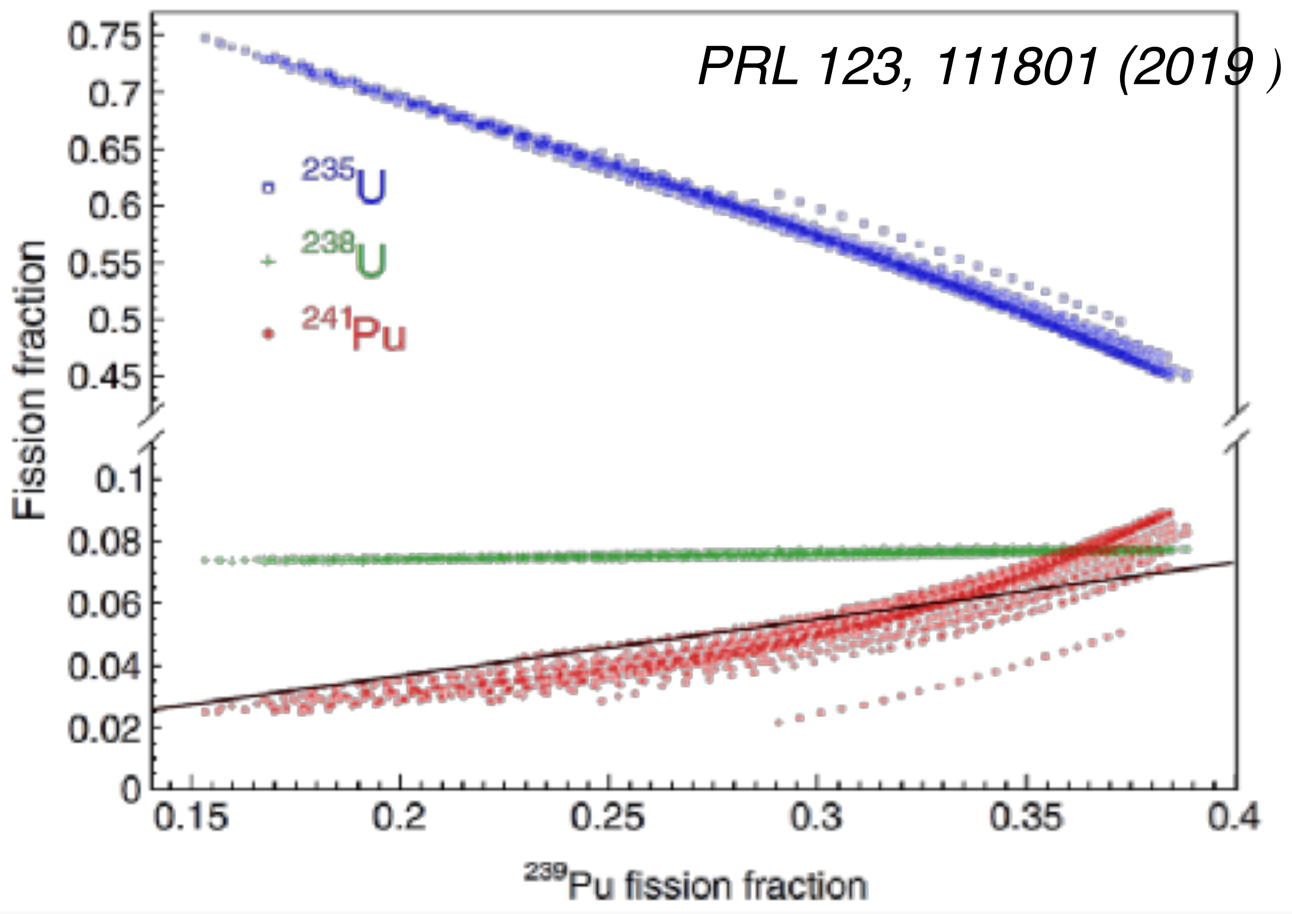
$$\sigma_f = \sum_i f_i \times \sigma_f^i$$

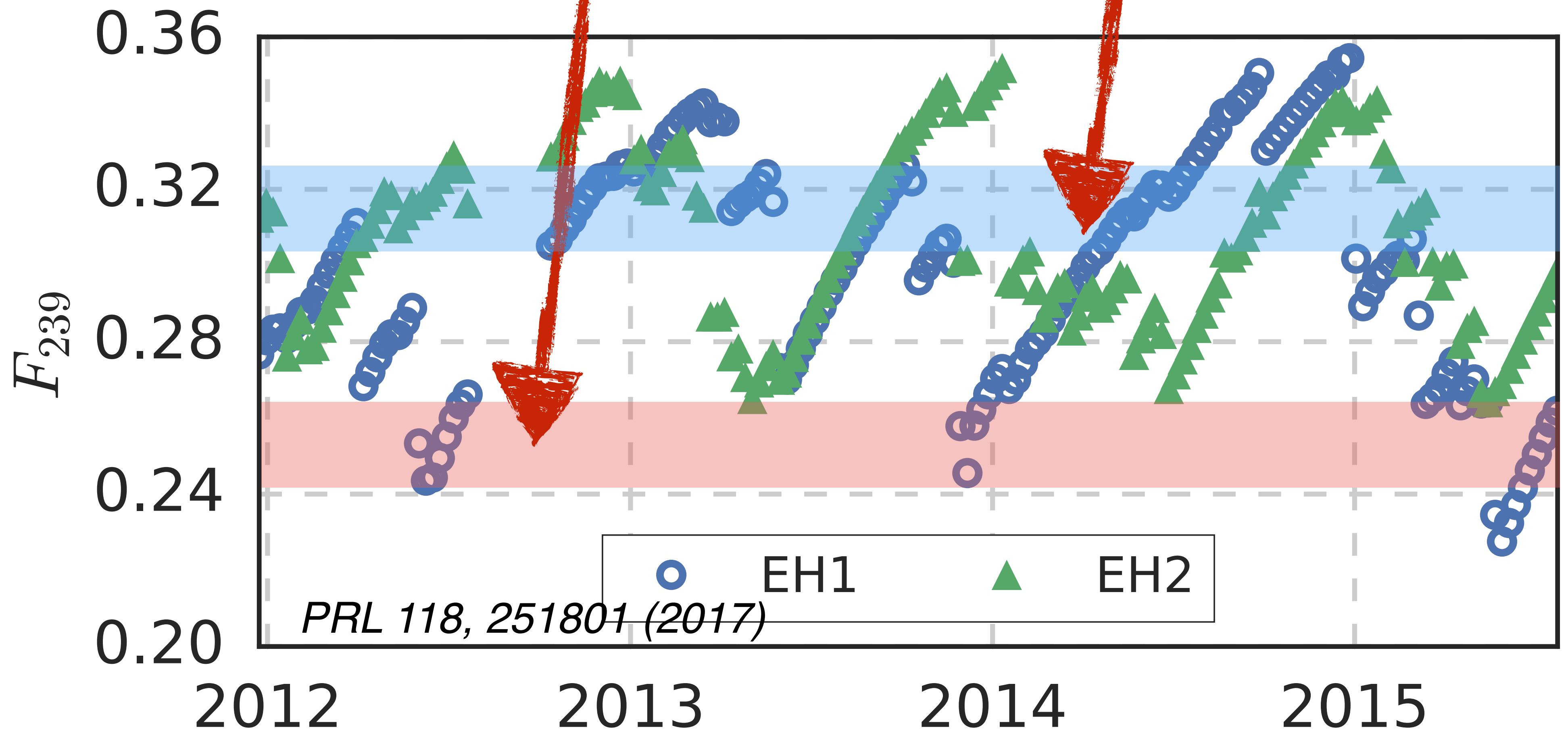
Total $\bar{\nu}_e$ yield — Isotope fission fraction — Isotope $\bar{\nu}_e$ yield

$$\sigma_f^{235U} \neq \sigma_f^{238U} \neq \sigma_f^{239Pu} \neq \sigma_f^{241Pu}$$



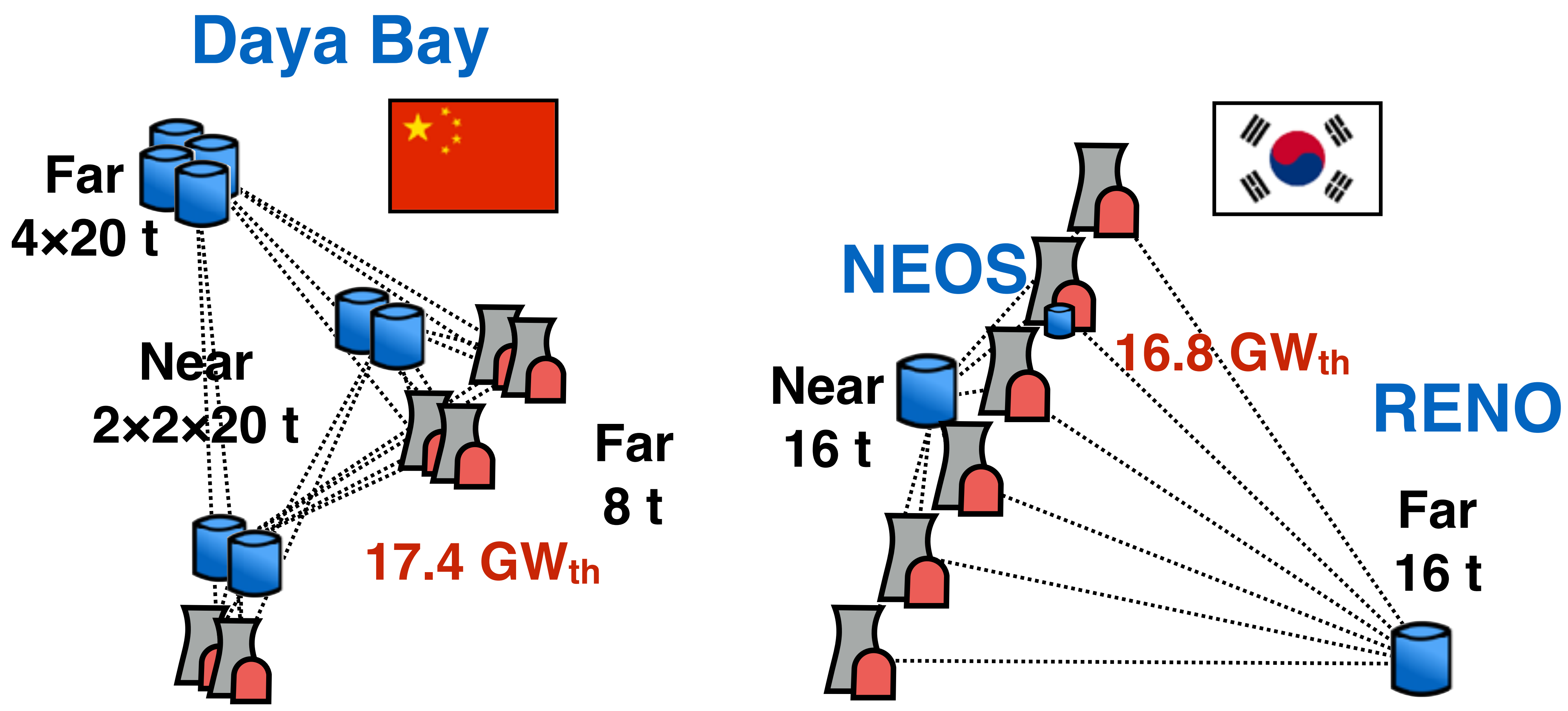
- In reality, we extract dominant contributions of ^{235}U and ^{239}Pu while having conservative uncertainties on the ^{238}U and ^{241}Pu
  - In some analyses, we combine ^{239}Pu+^{241}Pu





Isotopic Flux Measurement at LEU Reactors

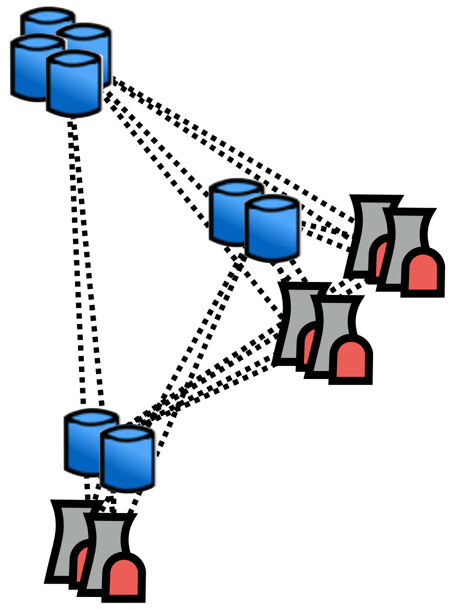
- Experiments such as Daya Bay, RENO, NEOS, etc.
  - DYB&RENO - primary purpose to measure θ_{13}
- Advantages
  - High statistics - permits the fuel evolution study
  - (Mostly) reasonable overburden
- Challenges w.r.t. HEU reactor experiments
  - Antineutrinos from all four isotopes
  - More than one reactor in the vicinity
  - Usually no (full) on-off reactor period

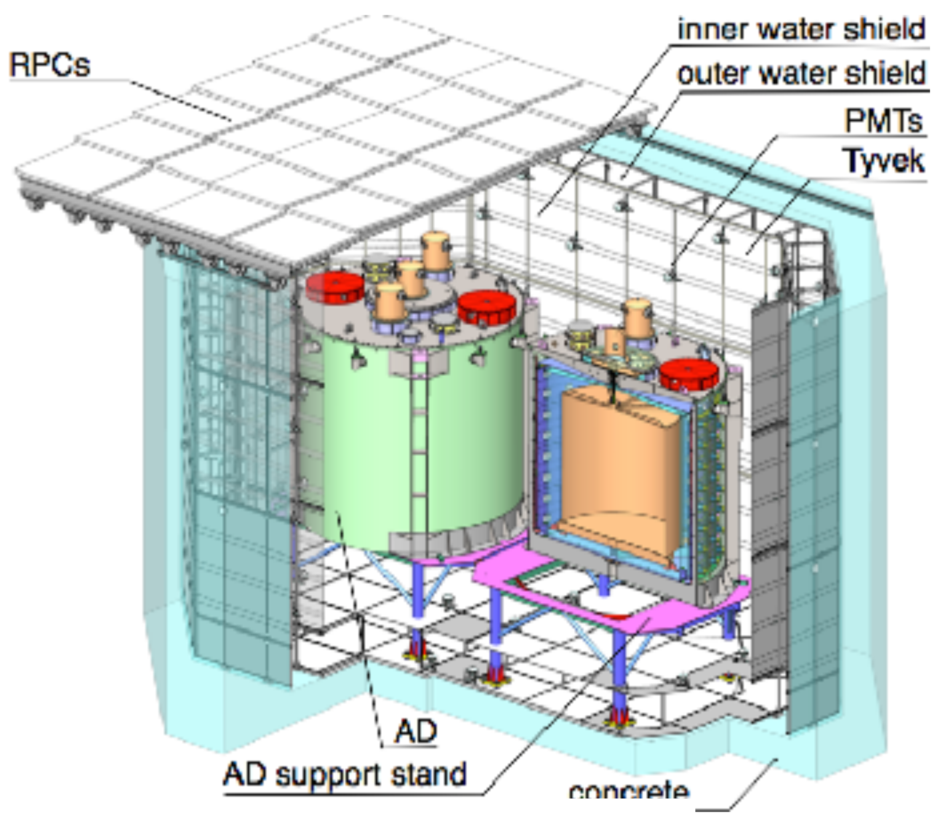


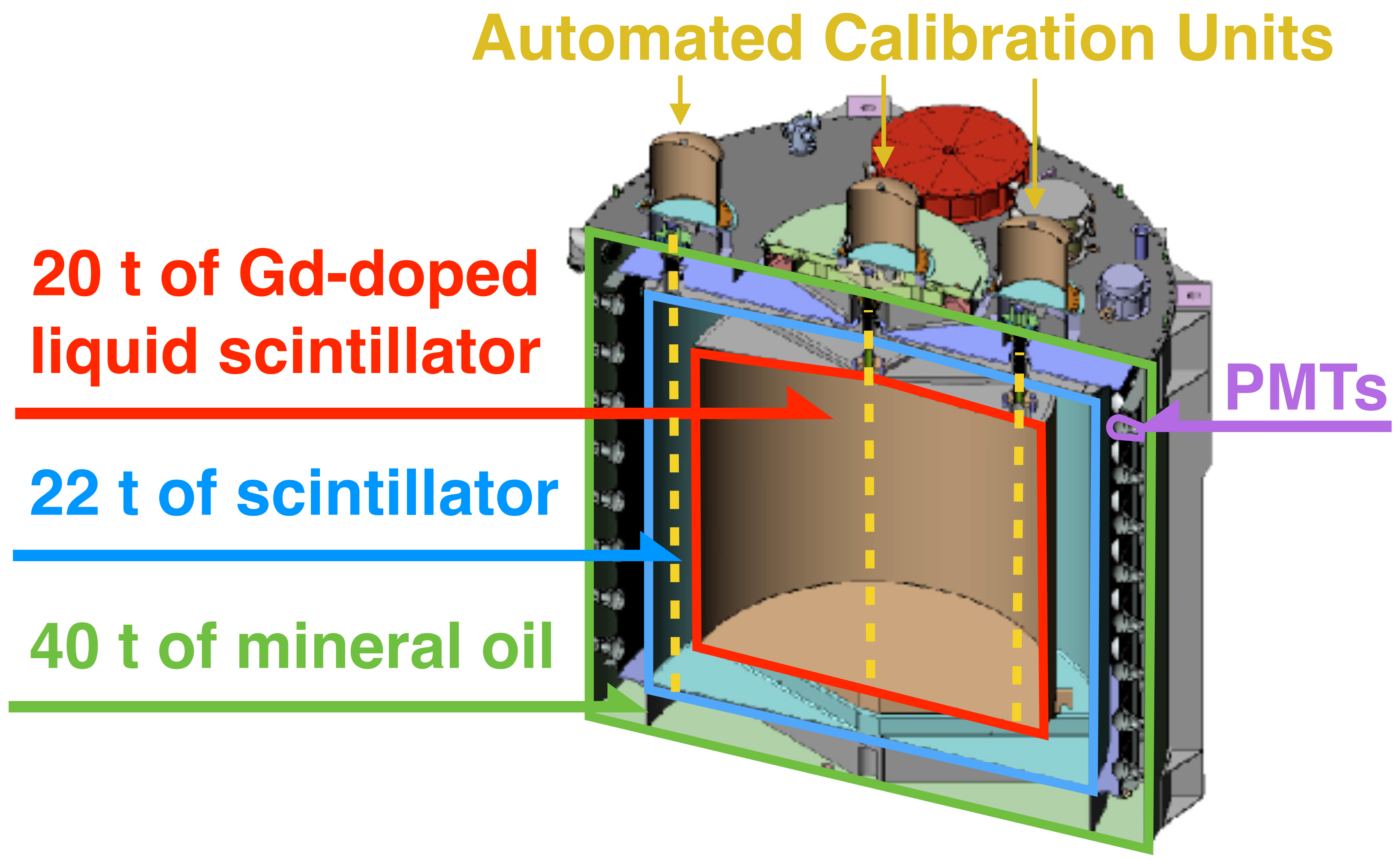
	Power [GW$_{th}$]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]
Daya Bay	17.4	2×2×20 4×20	365, 490 1650	250 860
RENO	8.5	16 16	290 1380	120 450
NEOS	2.8	0.8	24	20

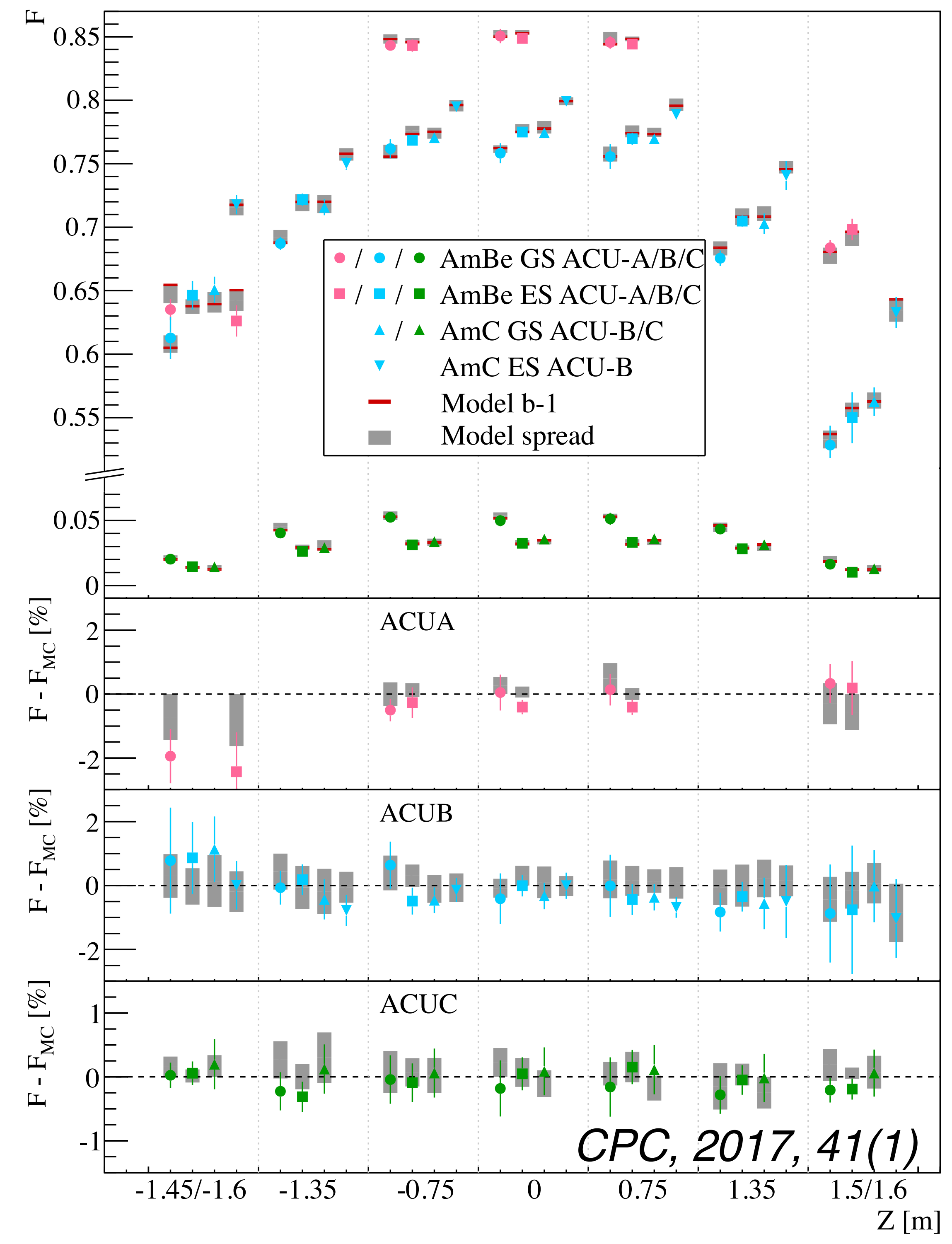
The Daya Bay Experiment (as an Example)

- Eight functionally identical three-zone liquid scintillator detectors
- Placed in water pools at three underground experimental halls
- Located ~350-1900 m from the six 2.9 GW_{th} reactors at Daya Bay and Ling Ao nuclear power plants
- Low-background experiment with B/S < 2%
- Precise determination of the (delayed IBD) neutron efficiency during a special campaign using an Am-Be and Am-C neutron sources
  - Neutron efficiency improved
  - Number of target protons dominates the systematics

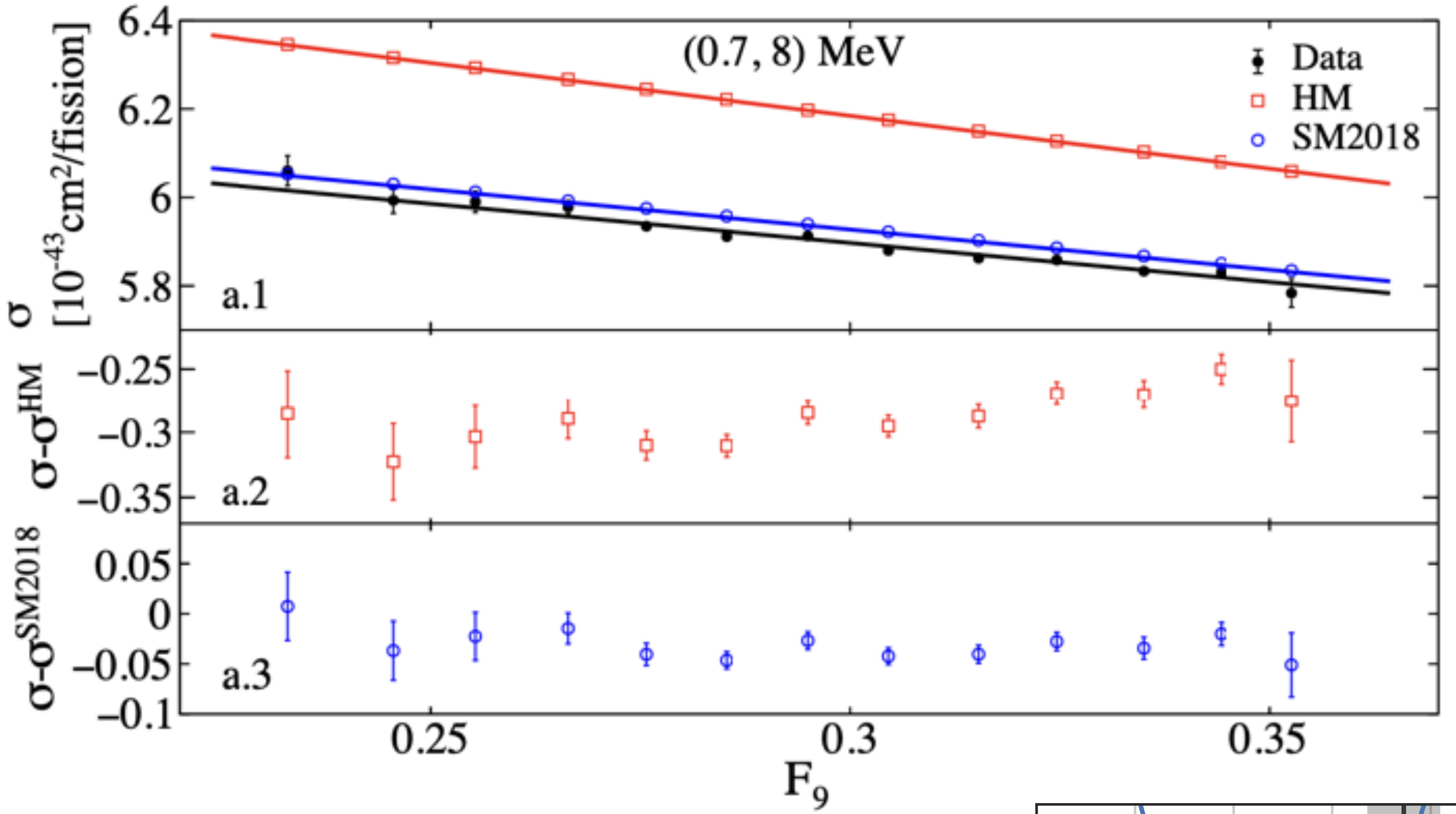








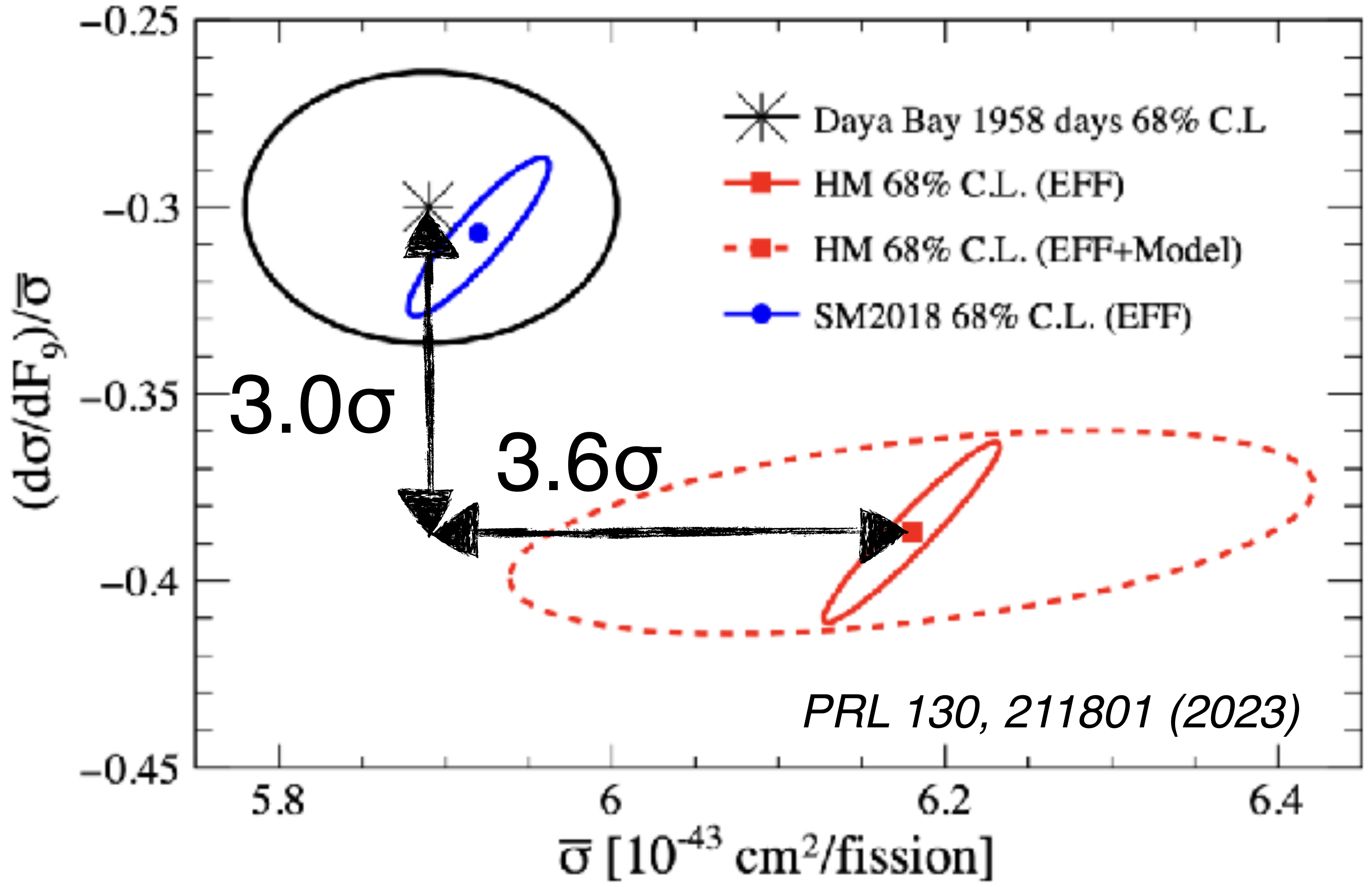
$$\sigma^{\mathrm{Lin},g} = \bar{\sigma}\{1 + [(d\sigma/dF_9)/\bar{\sigma}](F_9^g - \bar{F}_9)\}$$



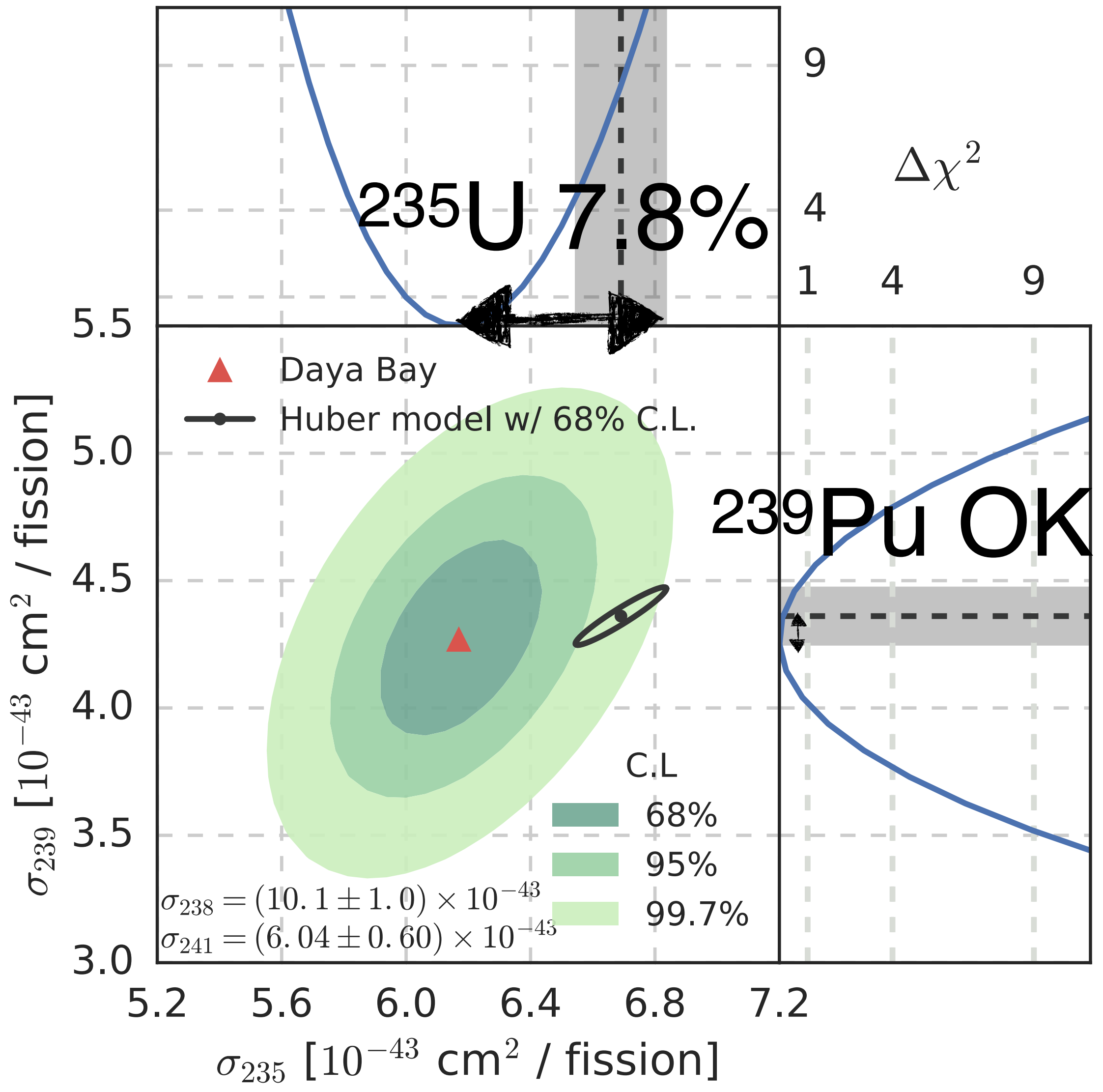
- Total IBD yield evolution observed as a function of ^{239}Pu fission fraction
- Linear fit to get the average IBD yield $\bar{\sigma}$ and the slope of the evolution $(d\sigma/F_9)/\bar{\sigma}$
  - Both quantities are not compatible the HM model
  - But agree with a summation model (SM2018)

PRL 123, 022502 (2019)

- Evolution used to extract individual isotopic yields for ^{235}U and ^{239}Pu
  - ^{239}Pu agrees with the HM model
  - 7.8% deficit in ^{235}U (5.5% @ STEREO) ➔ Primary contributor to RAA
- Unequal deficit weakens the sterile neutrino hypothesis (but cannot lead to the discovery)
- RENO results consistent, NEOS a bit different (despite being at one of RENO's core)



PRL 130, 211801 (2023)



PRL 118, 251801 (2017)

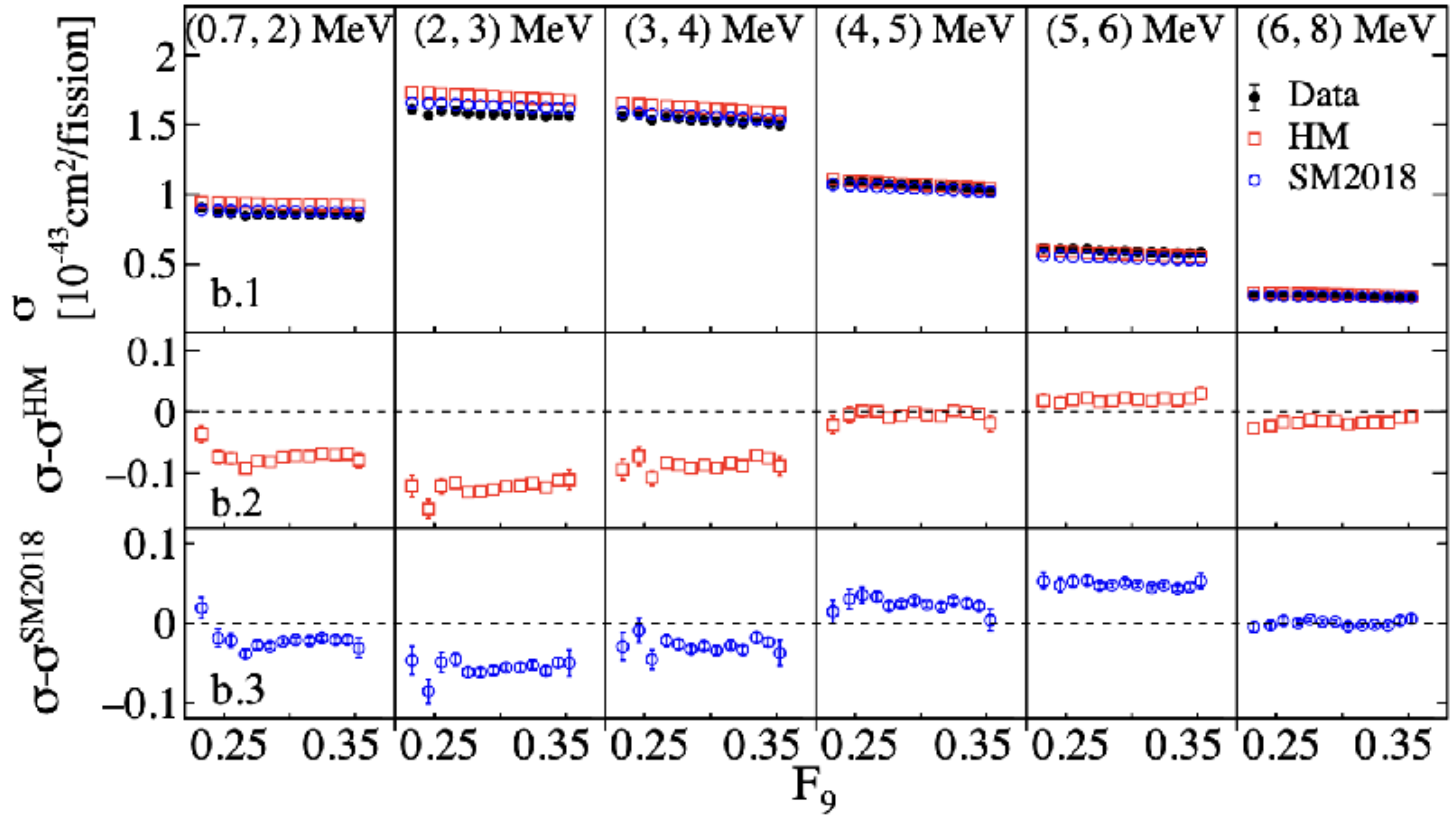
Further Looking at the Spectrum

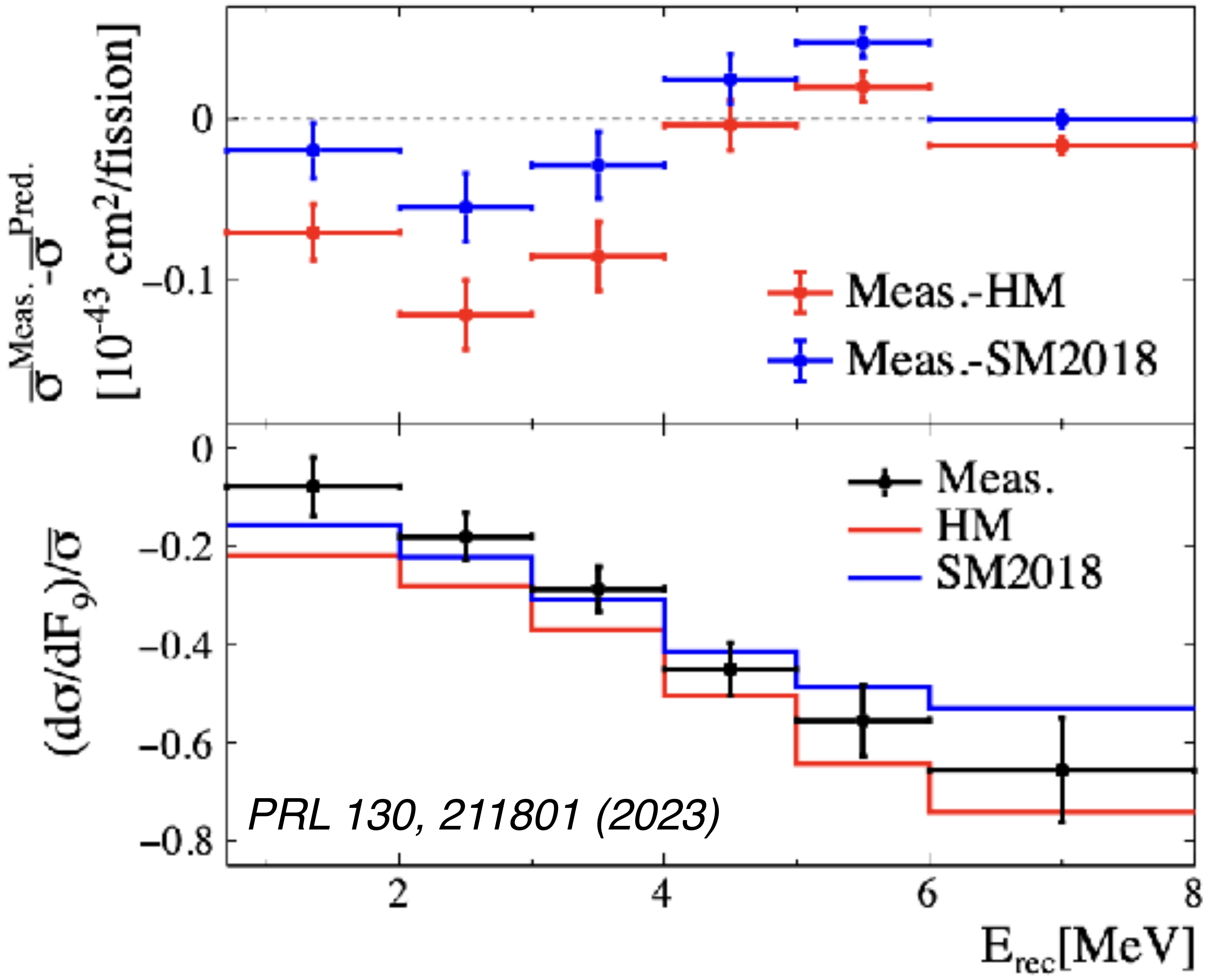
- Experiments shift to get complex information - flux&spectrum
  - Essentially flux measurement for energy bins

Talk by C. Roca

- Fuel evolution for several energy bins at Daya Bay
  - Measured spectrum (average yield in each bin) not consistent with HM and SM2018 models
  - Evolution slope fine for SM2018, small tension with HM

	$\bar{\sigma}^e$		$[(d\sigma/dF_9)/\bar{\sigma}]^e$	
Model	χ^2/NDF	N_σ	χ^2/NDF	N_σ
HM	675/6	25σ	11/6	1.8σ
SM2018	748/6	27σ	5.5/6	0.7σ





Conclusions

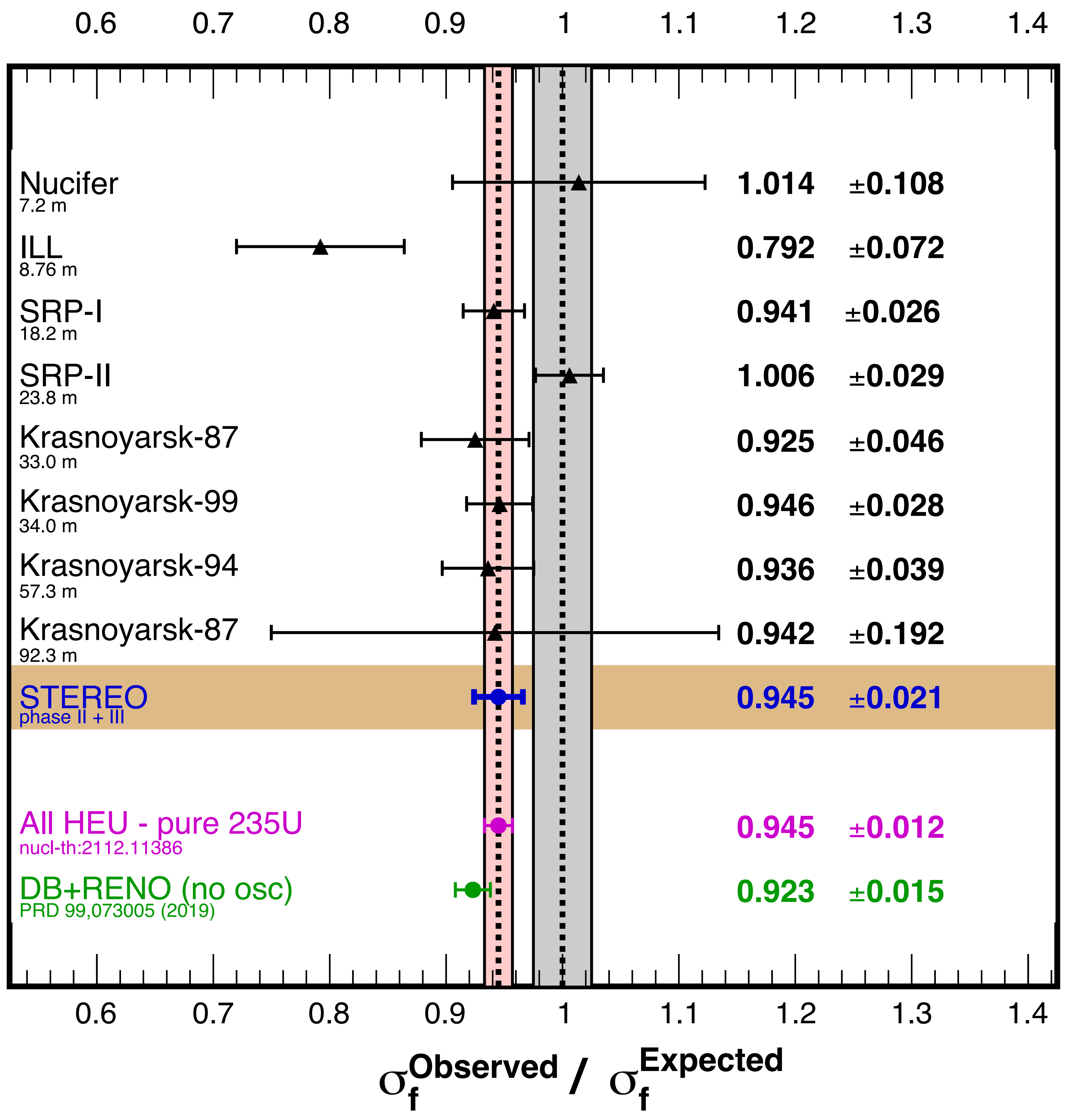
- Great progress in the measurement of the isotopic yields of the reactor antineutrinos both from LEU and HEU reactors shed more light on the RAA
  - ^{235}U yield lower than HM model and about the same as in summation model (SM2018)
  - ^{239}Pu yield consistent with both HM and summation models
- More flux(&spectrum) results to come
  - Possible combined LEU+HEU analyses e.g. PROSPECT+STEREO+Daya Bay
  - New measurements from e.g. PROSPECT, RENO, JUNO-TAO)

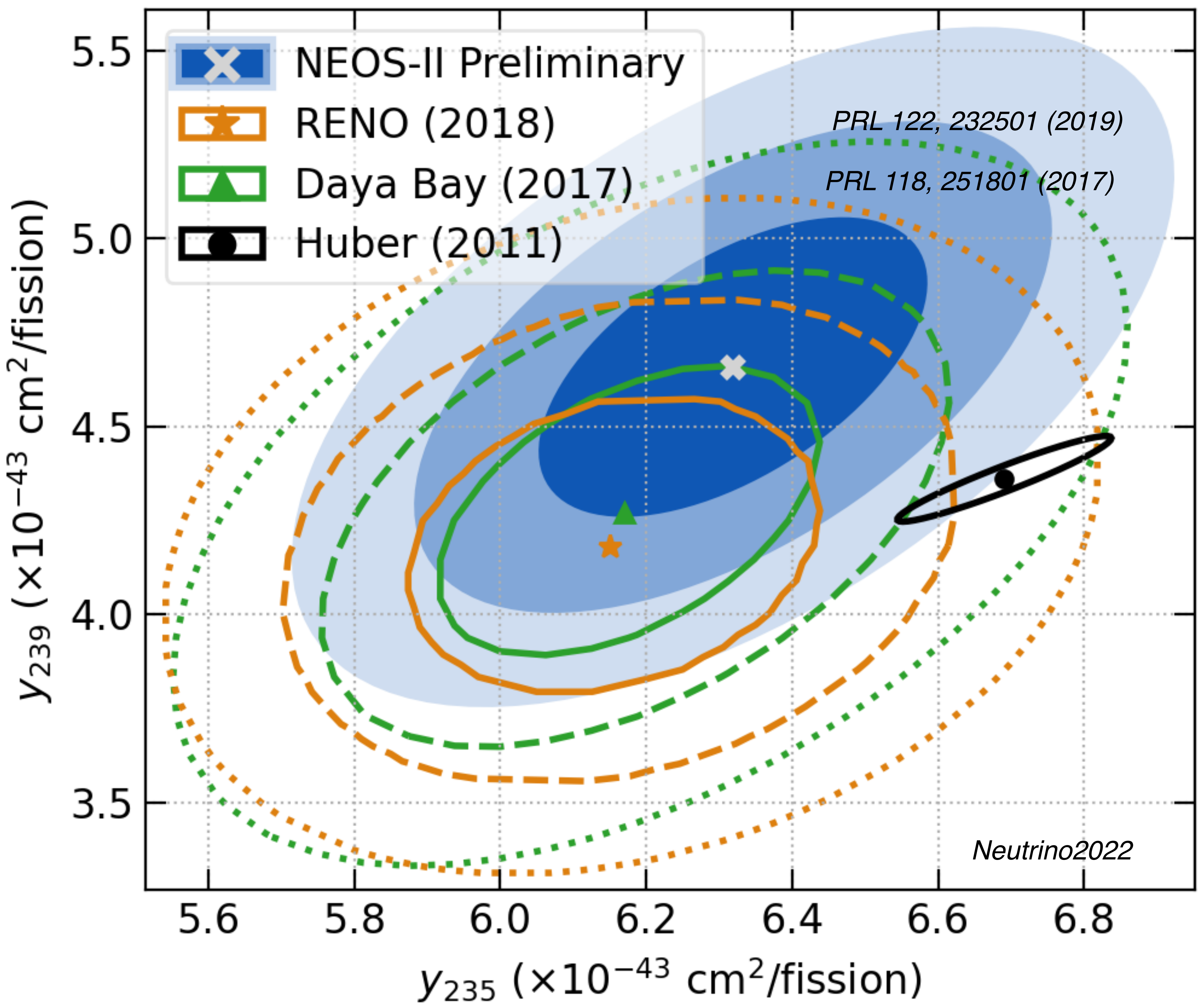
Talk by B. Littlejohn   Talk by H. Steiger

- Shift towards the complex flux&spectrum measurement needed to
  - Further benchmark the prediction models across range of energies (e.g. SM2018 agrees with data for total flux, but does not match for each energy)
  - Sterile neutrino mixing can be discovered by the oscillation pattern observation in the spectrum

Extras

Plots


0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4
Nucifer
7.2 m
1.014 ±0.108
ILL
8.76 m
0.792 ±0.072
SRP-I
18.2 m
0.941 ±0.026
SRP-II
23.8 m
1.006 ±0.029
Krasnoyarsk-87
33.0 m
0.925 ±0.046
Krasnoyarsk-99
34.0 m
0.946 ±0.028
Krasnoyarsk-94
57.3 m
0.936 ±0.039
Krasnoyarsk-87
92.3 m
0.942 ±0.192
STEREO
phase II + III
0.945 ±0.021
All HEU - pure 235U
nucl-th:2112.11386
0.945 ±0.012
DB+RENO (no osc)
PRD 99,073005 (2019)
0.923 ±0.015
$\sigma_f^{Observed} / \sigma_f^{Expected}$


NEOS-II Preliminary
RENO (2018)
Daya Bay (2017)
Huber (2011)
PRL 122, 232501 (2019)
PRL 118, 251801 (2017)
Neutrino2022
5.5 5.0 4.5 4.0 3.5
5.6 5.8 6.0 6.2 6.4 6.6 6.8
y_{239} ($\times 10^{-43}$ cm^2/fission)
y_{235} ($\times 10^{-43}$ cm^2/fission)