Current & Future Reactor Antineutrino Measurements

J. Pedro Ochoa-Ricoux

University of California at Irvine

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Introduction

- Main question addressed by this talk:

*What is the **state of the art knowledge** on reactor antineutrino emission from direct measurements?*

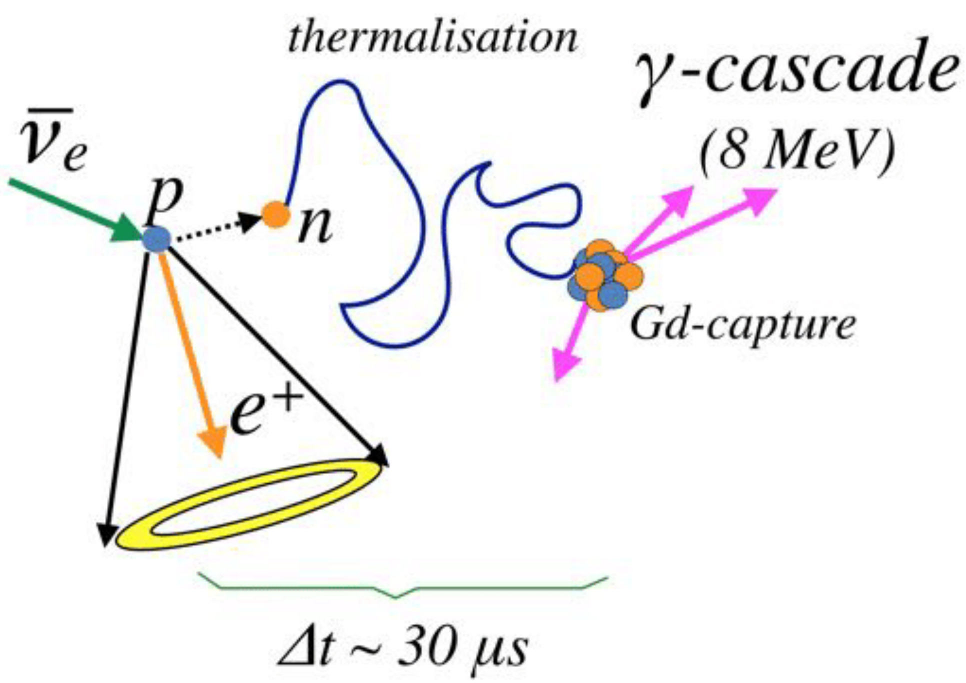
- Will focus on experiments using the Inverse Beta Decay (IBD) reaction, which is where our best knowledge currently comes from

prompt energy = kinetic energy of positron + annihilation with electron

prompt event

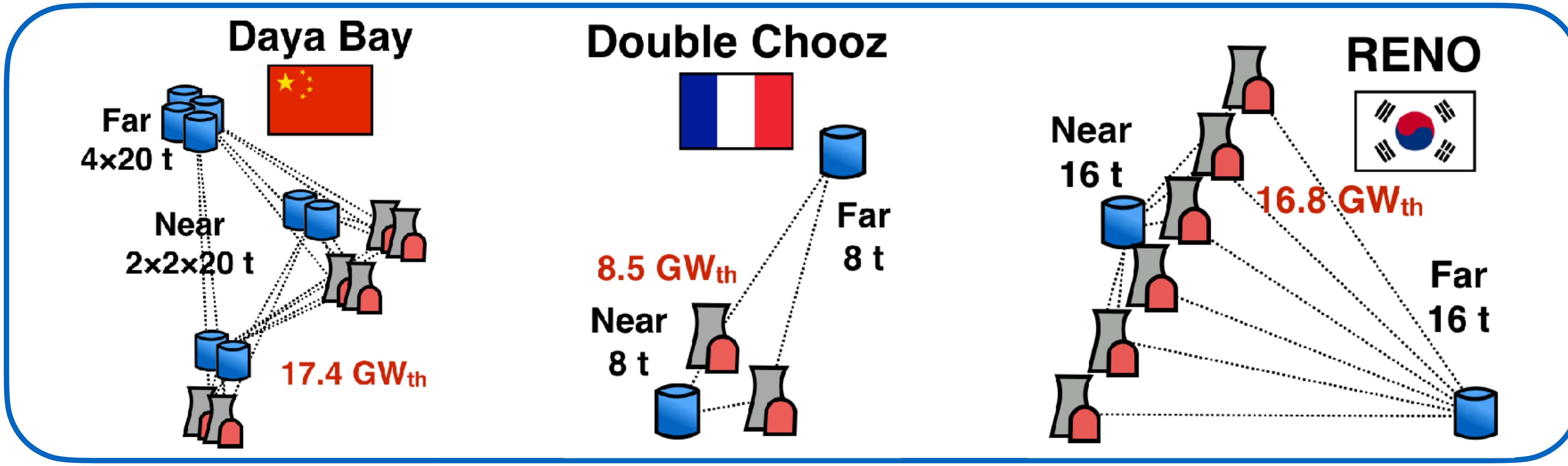
IBD reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$

delayed event



θ_{13} Experiments

- There was a very significant leap forward with the advent of the experiments designed to measure the θ_{13} mixing angle:

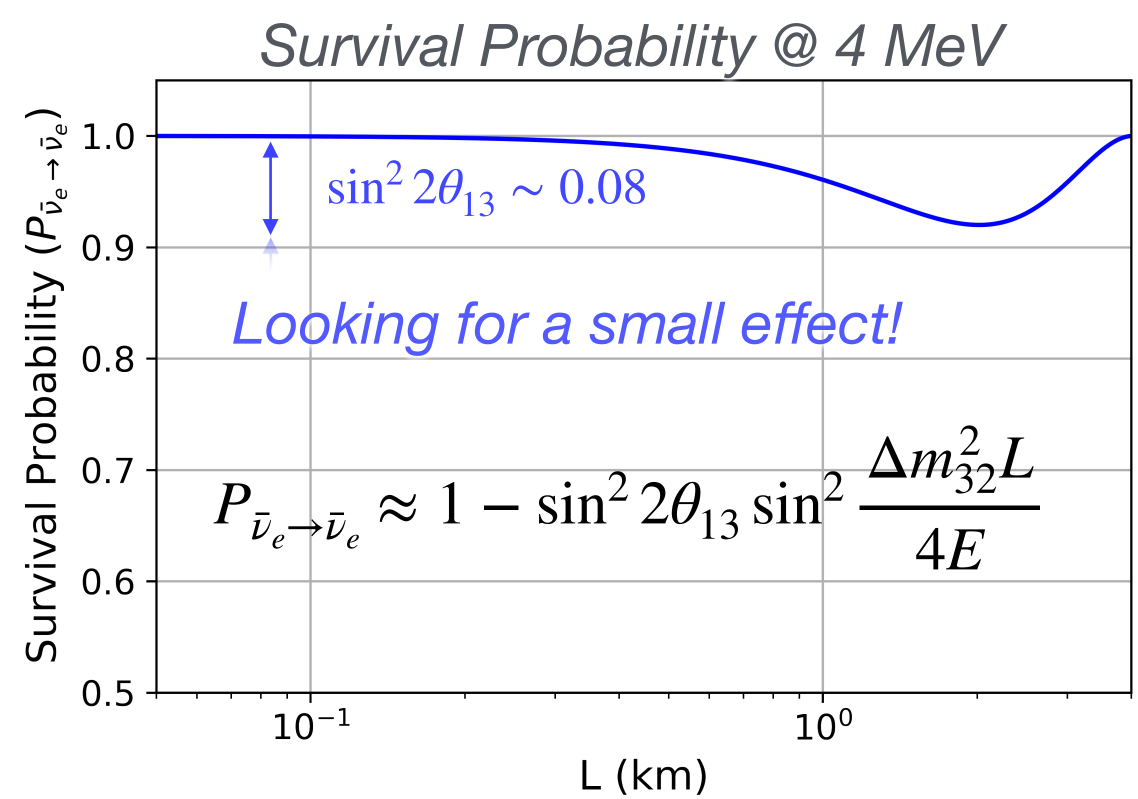


Need to keep uncertainties under control:

- Need large statistics
- Need near & far detectors to cancel systematic uncertainties!

*Note: all of these experiments use **Low Enriched Uranium (LEU)** reactors*

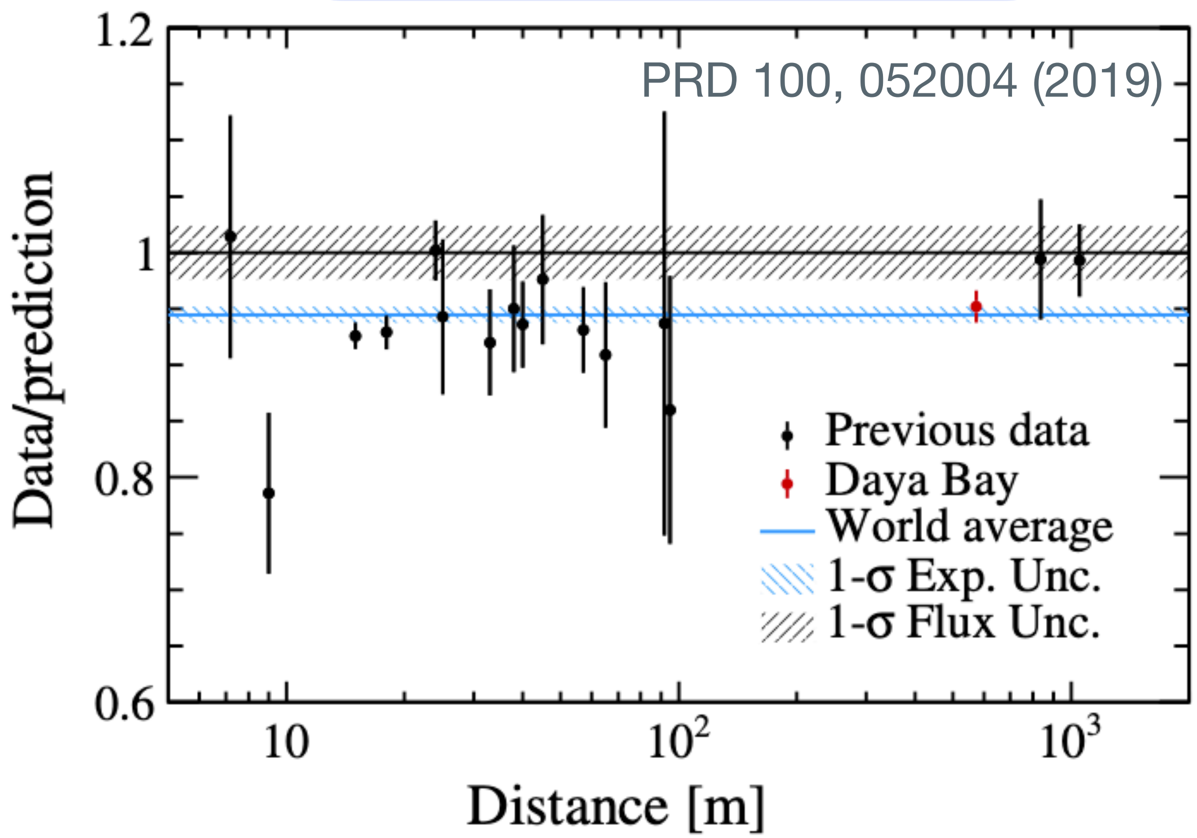
(Disclaimer: I am a Daya Bay collaborator)



Total Yield

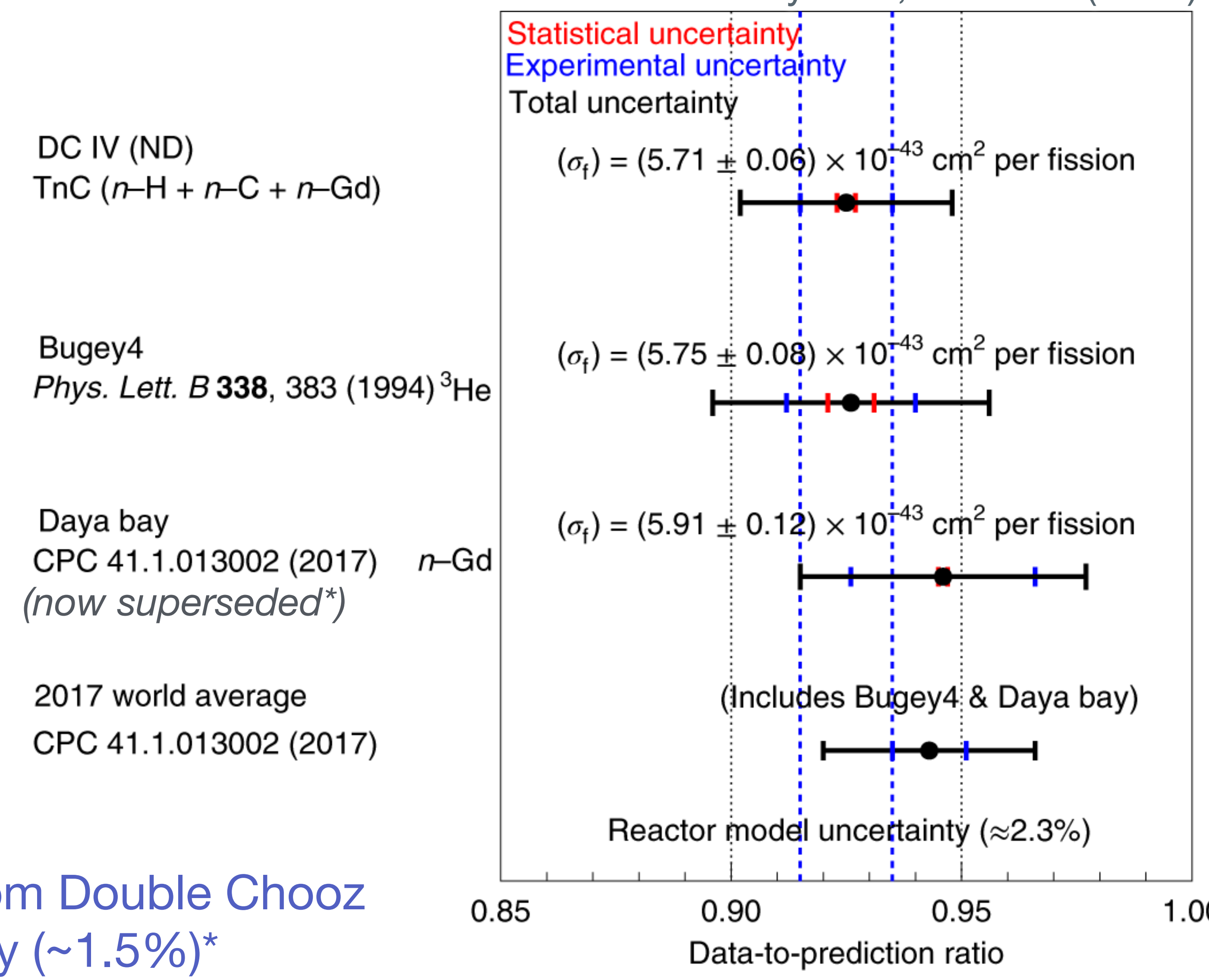
- Start with the total yield, i.e. time-averaged yield from all isotopes (^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu)
- Average global yield (mean cross-section per fission) **now determined to < 1%**

Data/Prediction vs. Baseline



Data/Prediction

Nat. Phys. 16, 558-564 (2020)



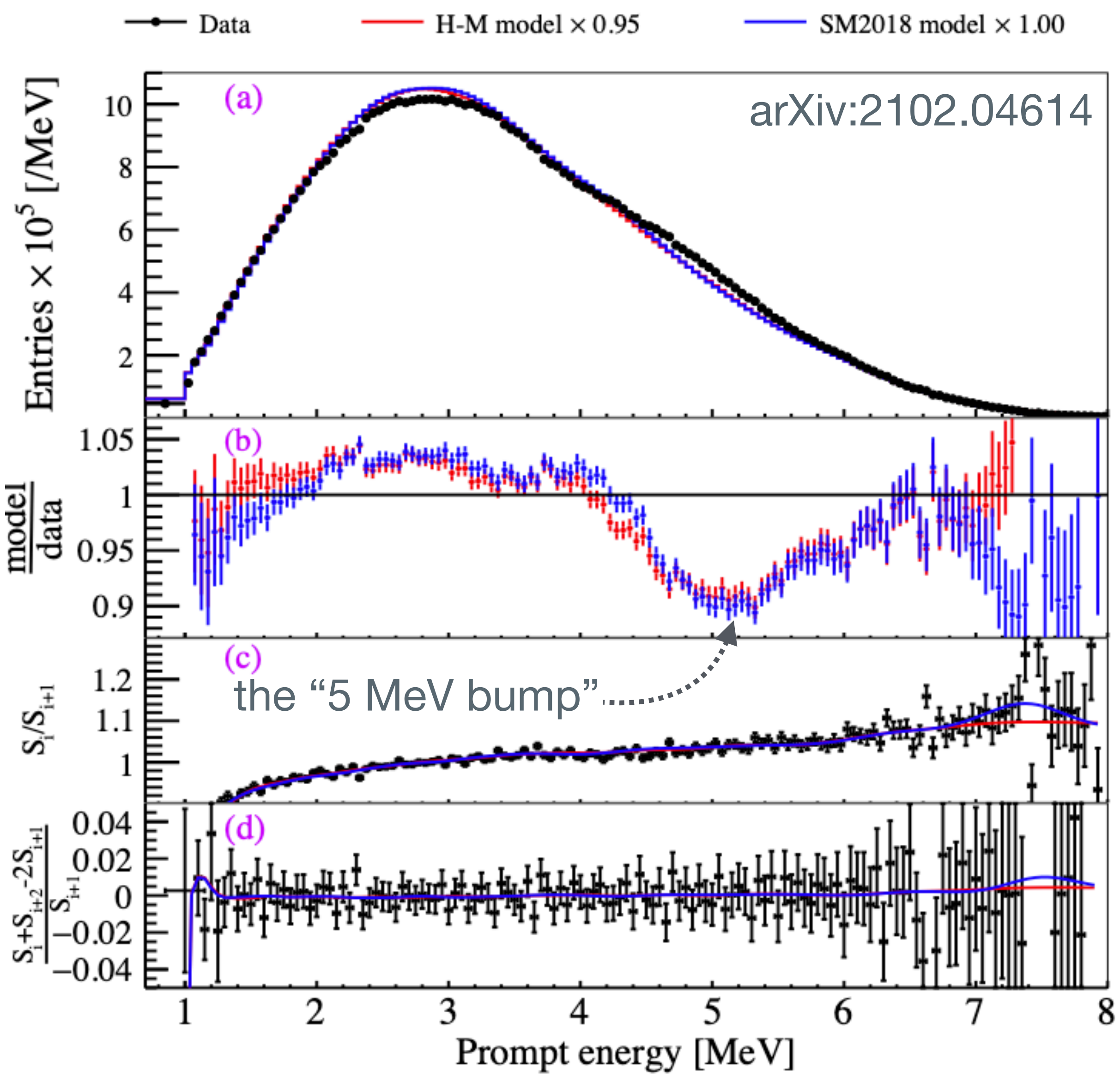
- Most precise measurements come from Double Chooz (~1%), Bugey4 (~1.4%), and Daya Bay (~1.5%)*
- Discrepancy with Huber+Mueller (HM) model is the so-called Reactor Antineutrino Anomaly

* *see PRL 123, 111801 (2019). There is also a recent not-yet-published measurement from RENO that is consistent*

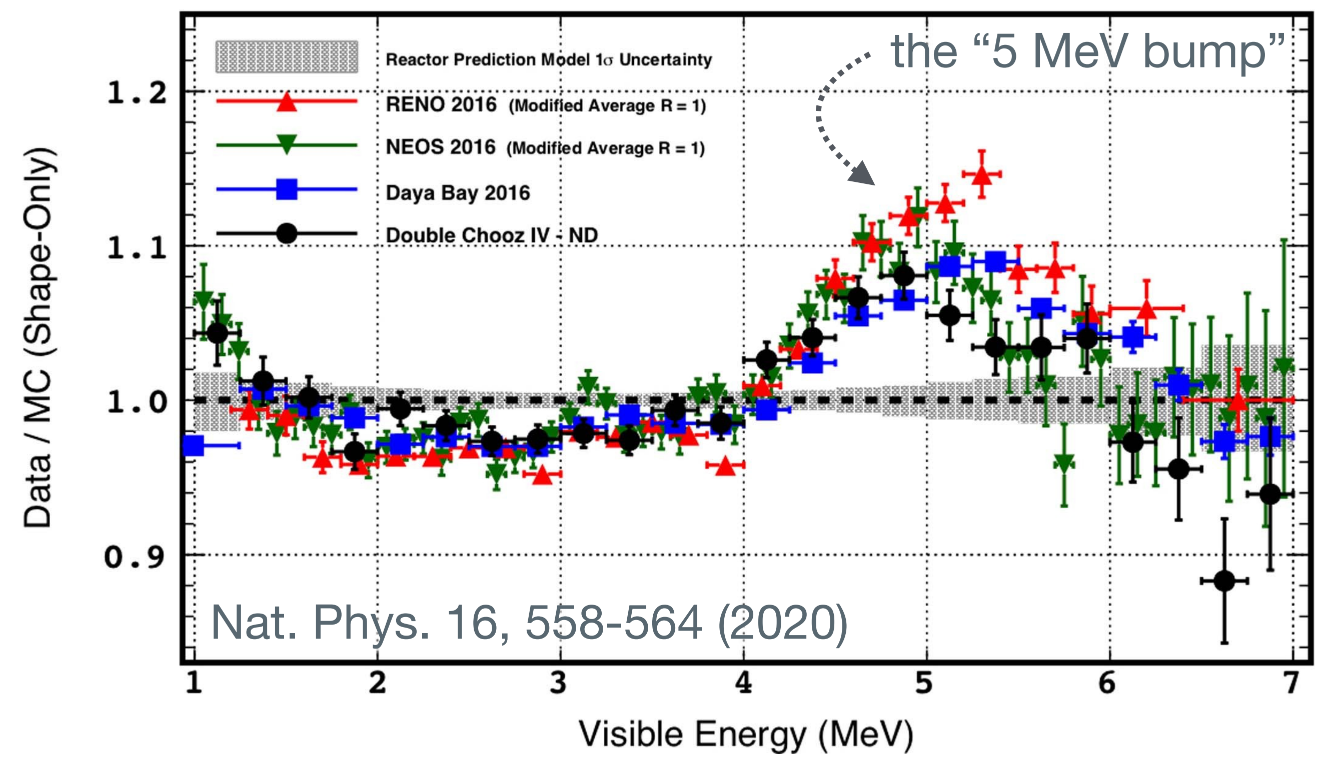
Spectral Shape

- Have also measured the total prompt energy spectrum very precisely:

Spectral Shape
(Daya Bay)



Data/Model



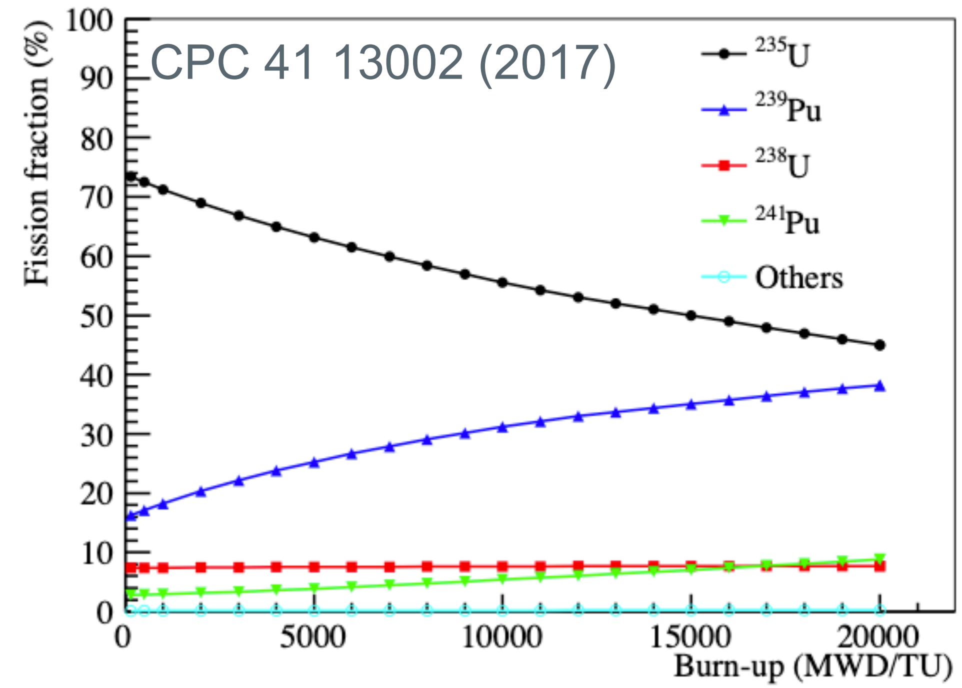
Error bars include stat + syst uncertainties and are <**0.6%** **for 2-5 MeV** region

"5 MeV bump" (4-6 MeV excess) appears roughly consistent among experiments

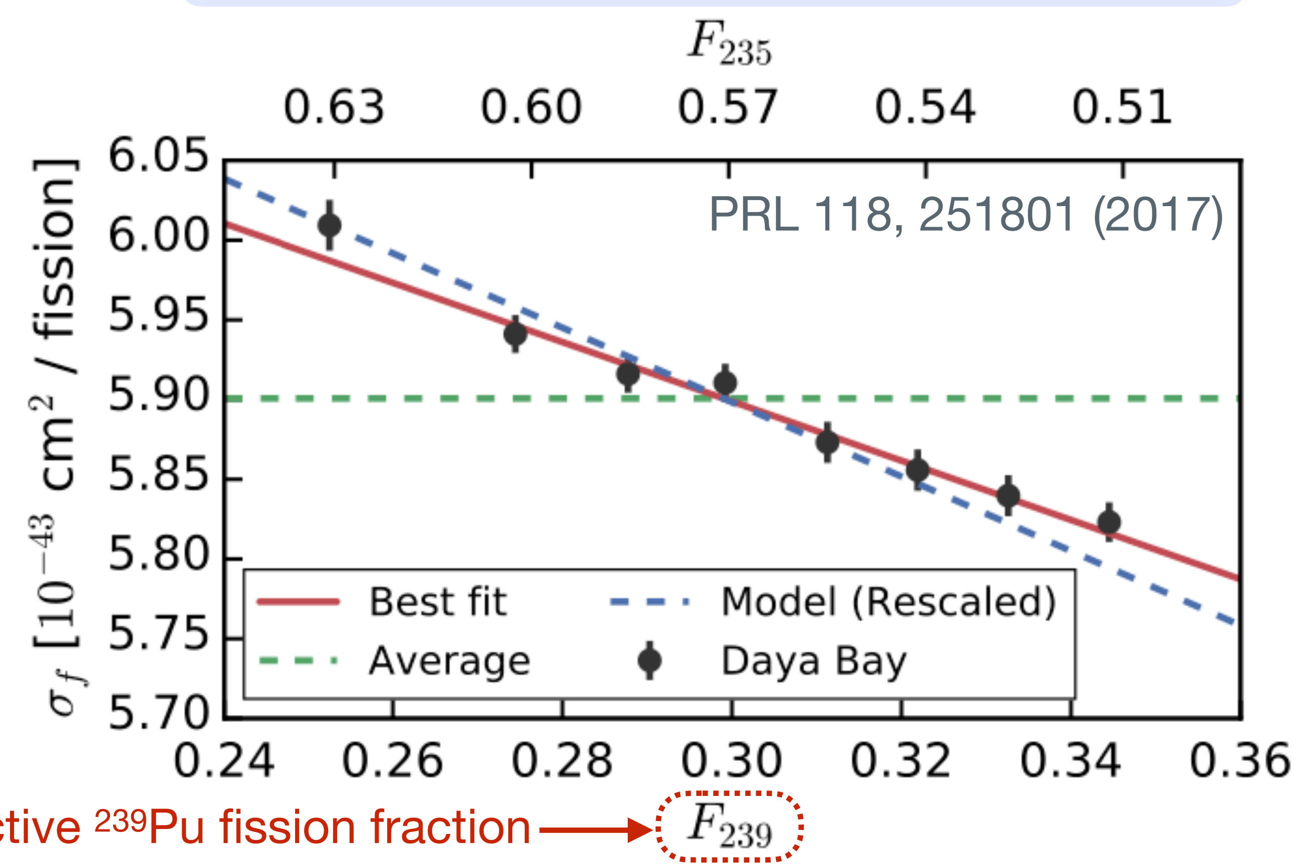
Challenges

- These results cannot be directly adopted in other scenarios/experiments:
  - They correspond to a specific combination of fission fractions
    - Yield and spectral shape vary from isotope to isotope
    - ^{239}Pu yield is lower than ^{235}U, so total rate will decrease as fuel cycle progresses
  - They are folded in with the detector response (i.e. they are in terms of E_{prompt})
- Solution? Two-pronged approach:
  - (i) Look at the yield's evolution with fuel composition: allows to disentangle the contribution from each isotope
  - (ii) Unfold the spectra ($E_{\text{prompt}} \rightarrow E_{\bar{\nu}_e}$)

Evolution of fission fractions with burn-up



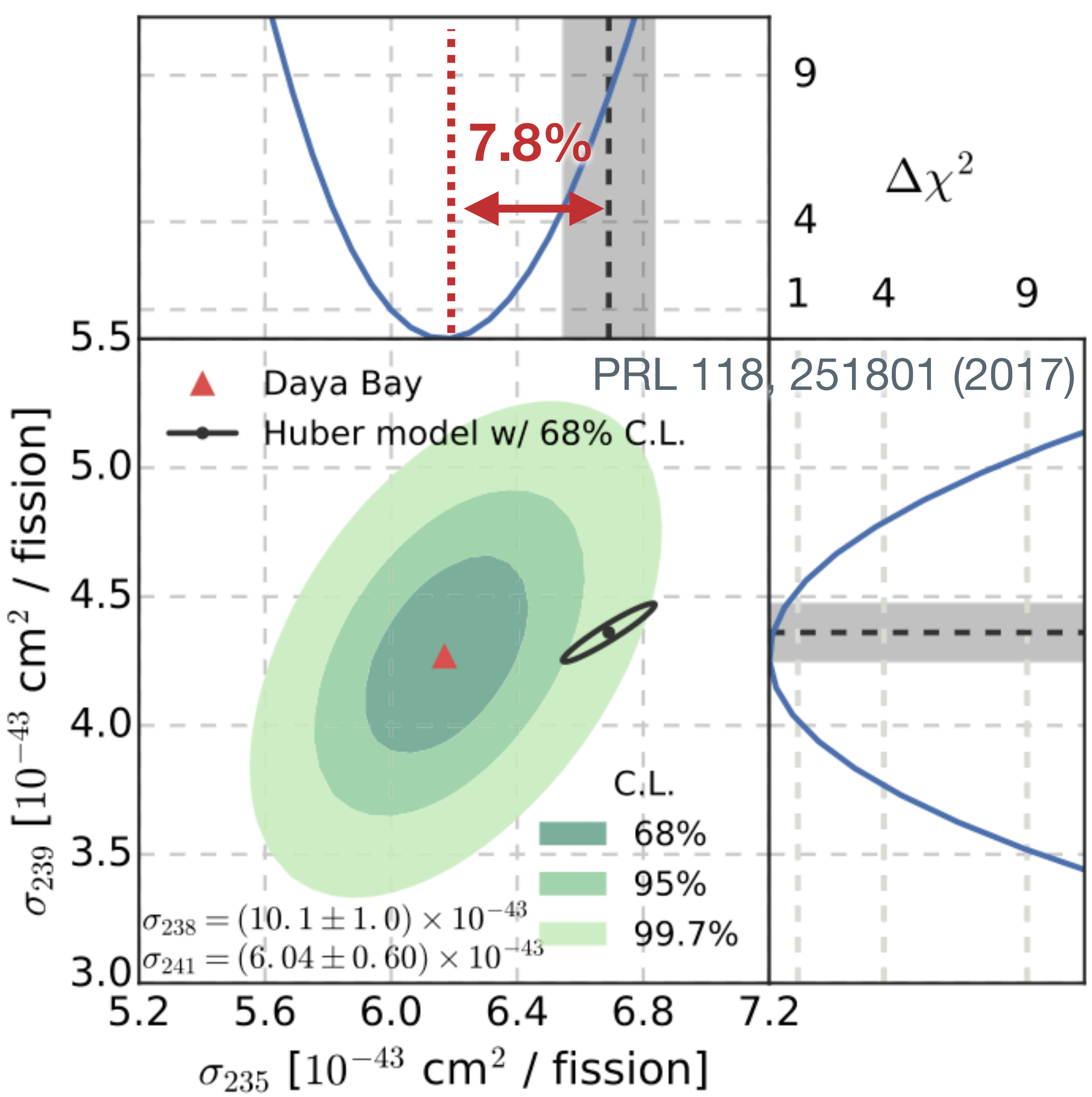
Total yield with fission fraction (Daya Bay)



(i) Isotopic Yields and Spectra

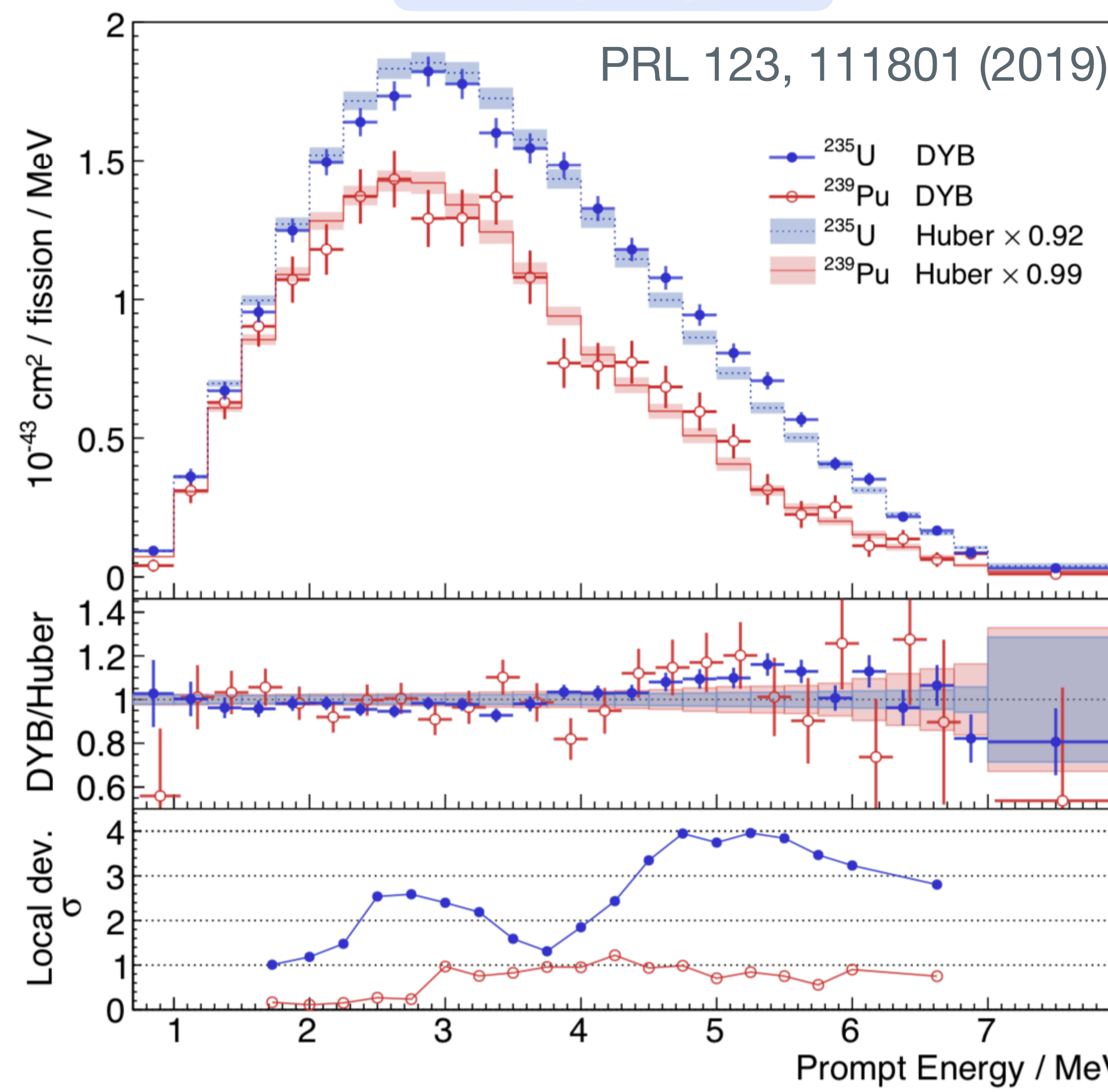
- The evolution with fuel composition allows to extract the individual yields and spectra for the two main isotopes: ^{235}U and ^{239}Pu

Isotopic Yields
(Daya Bay)



(suggests ^{235}U is main contributor to Reactor Antineutrino Anomaly)

Isotopic Spectra
(Daya Bay)

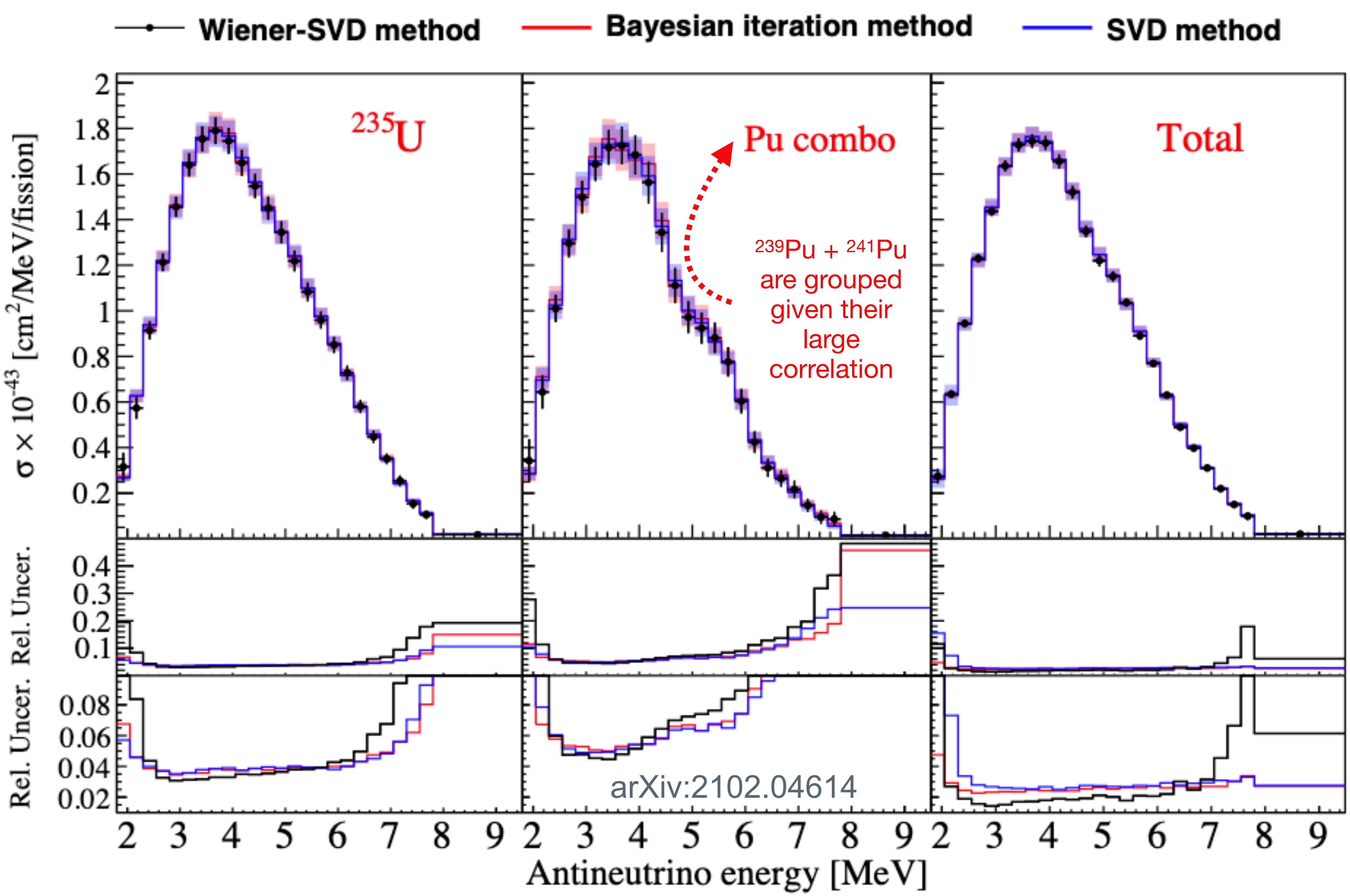


(first measurement of individual spectra with commercial reactors)

Comments: have to make conservative assumptions about the contributions from ^{238}U and ^{241}Pu.
RENO released consistent yields in PRL 122, 232501 (2019)

(ii) Unfolding

- "Remove" the detector response by unfolding the spectra (3 different methods):



Unfolded Isotopic Spectra
(Daya Bay)

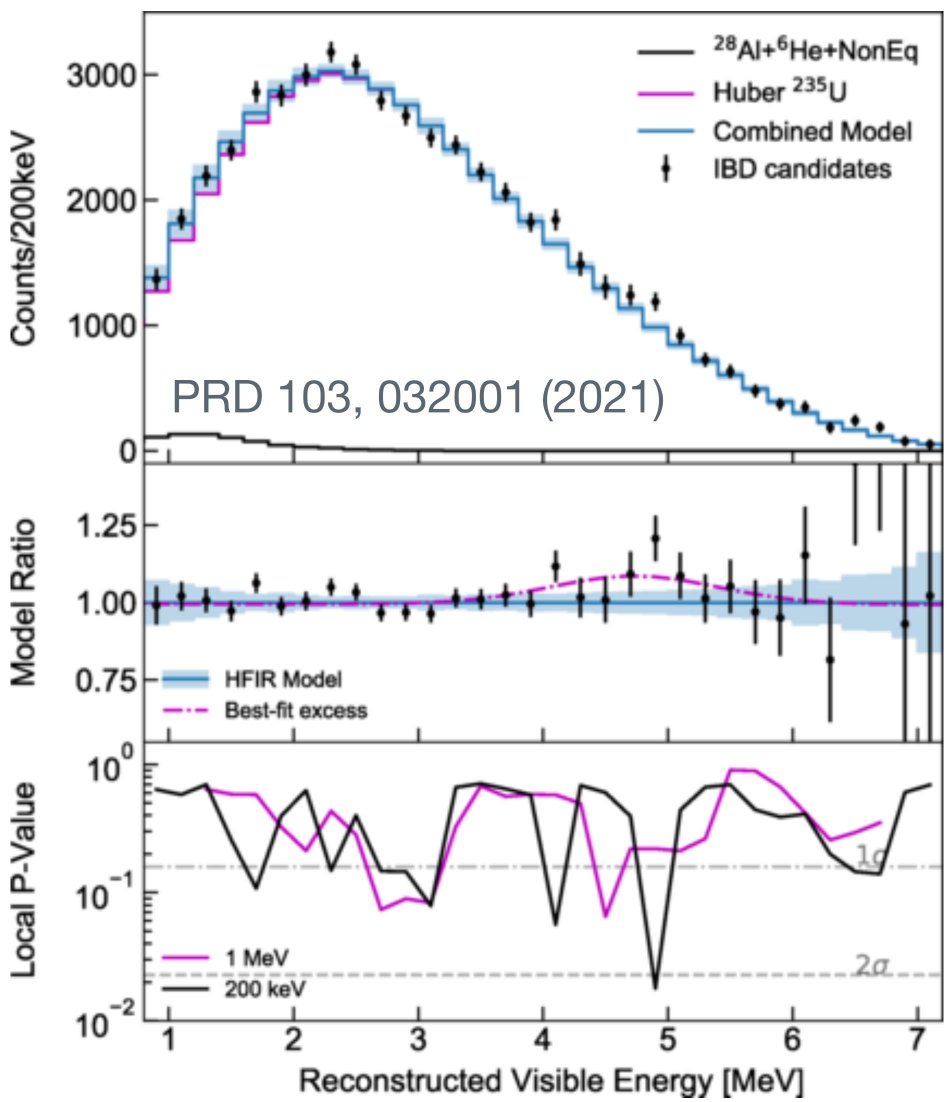
Provide a **data-based** spectrum prediction for other experiments with different fission fractions to **2% precision**

Isotopic spectra uncertainties dominated by statistics and ^{238}U & ^{241}Pu model uncertainties

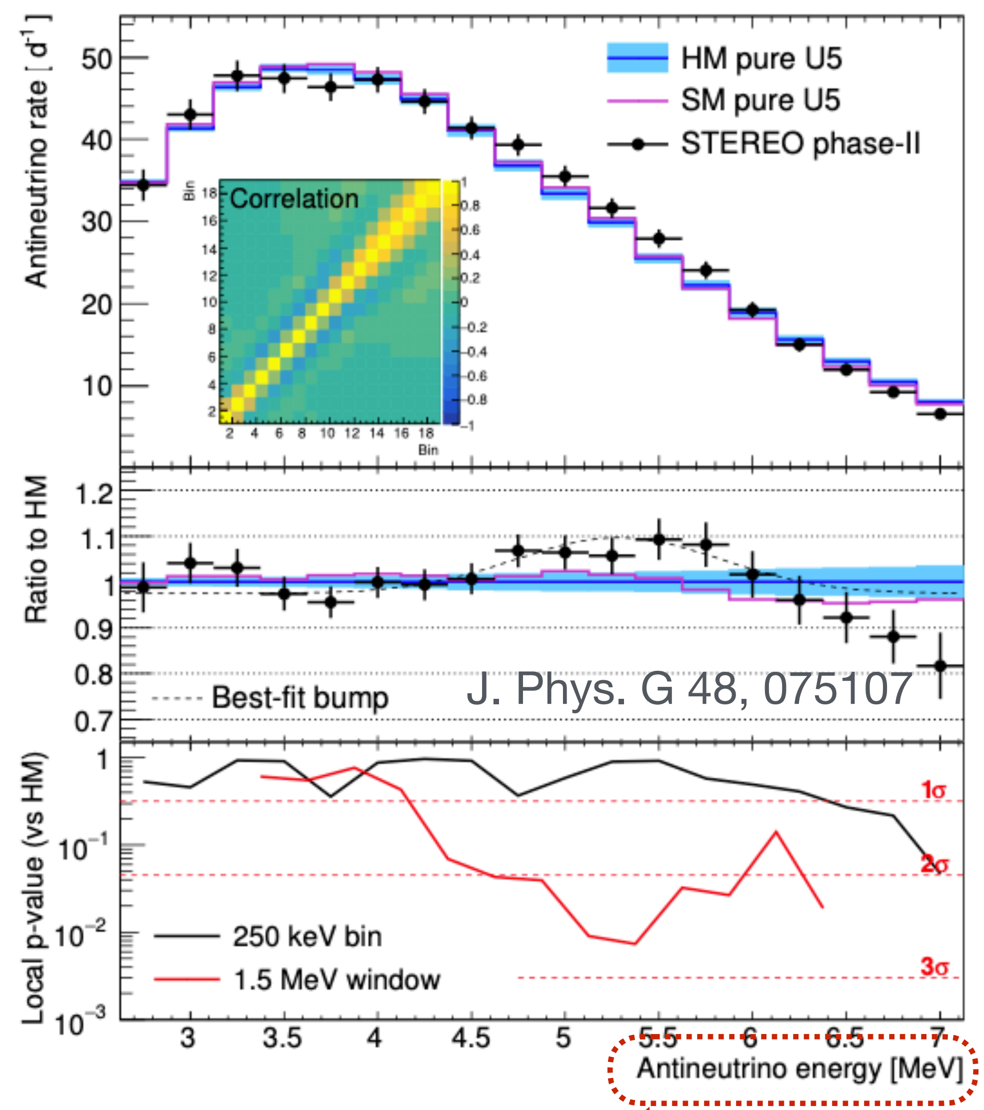
HEU Experiments

- Placing a detector very near a Highly Enriched Uranium (HEU) reactor enables a direct measurement of the ^{235}U yield and spectrum

^{235}U Spectral Measurement (PROSPECT)



^{235}U Spectral Measurement (STEREO)



unfolded!

Joint analyses are ongoing between PROSPECT and STEREO (see backup), as well as between PROSPECT and Daya Bay

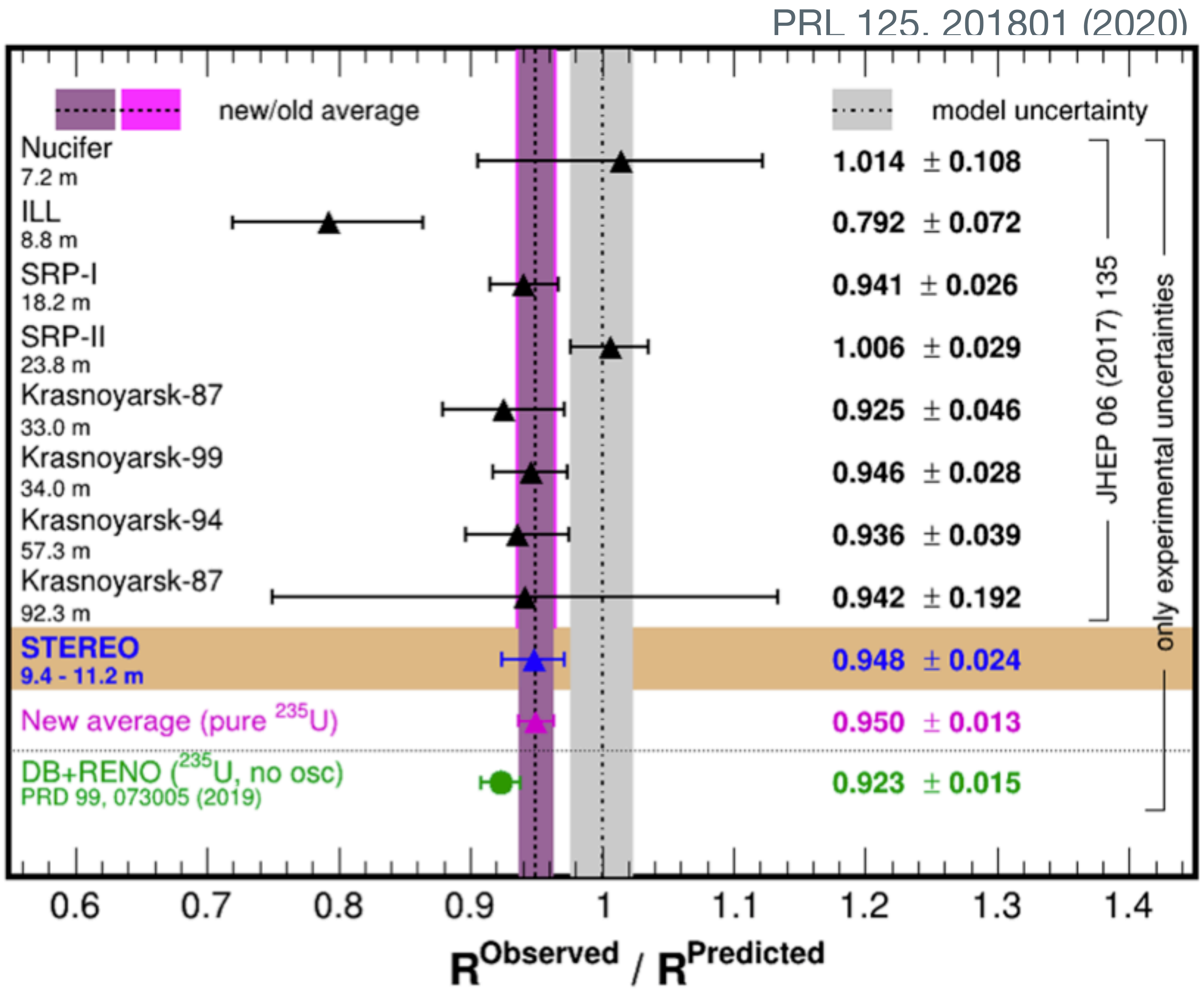
Goal is to ensure consistency and increase precision

^{235}U spectrum uncertainty in 2-5 MeV region is **~4%** for PROSPECT, STEREO and Daya Bay experiments (see backup)

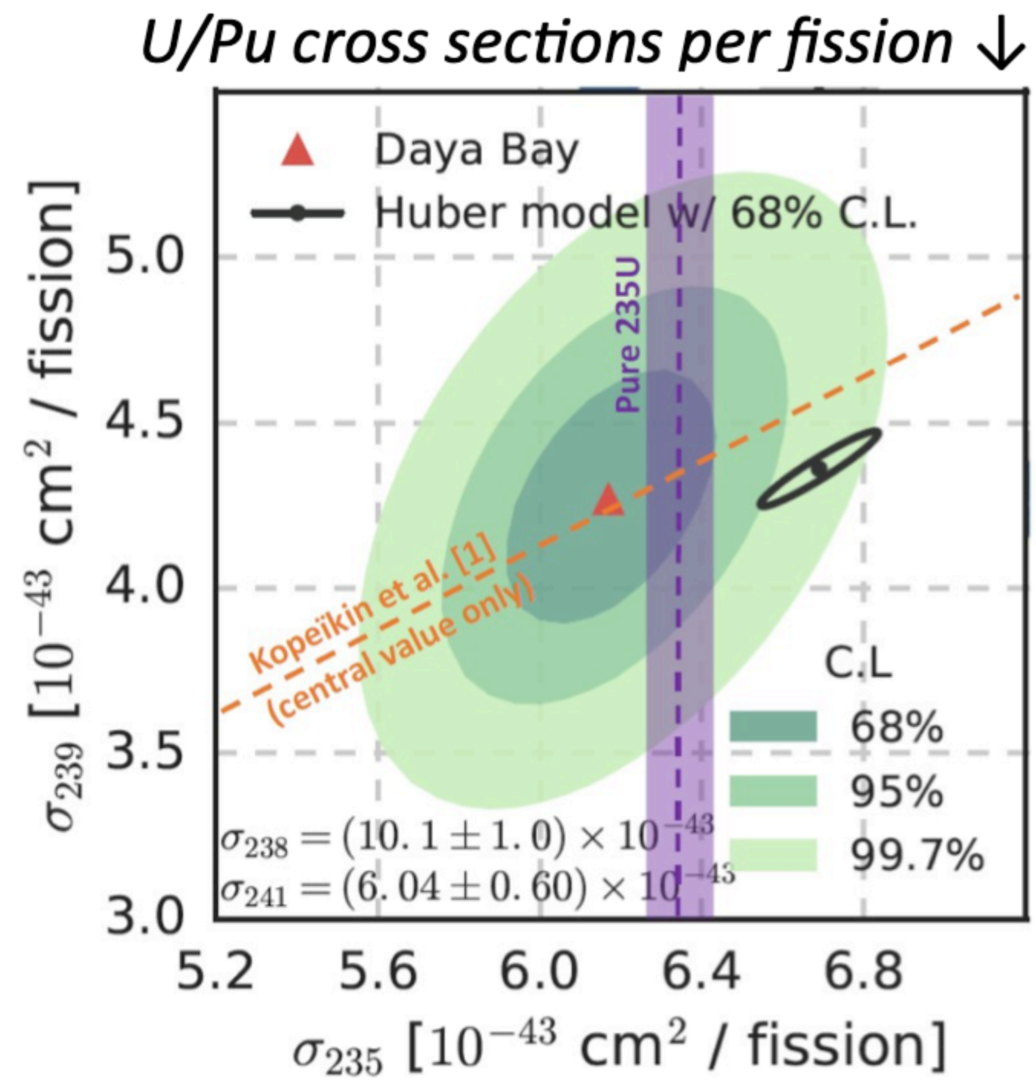
^{235}U Yield

- So far LEU and HEU experiments give us a consistent story for the ^{235}U yield:

^{235}U Yield Data/Prediction



Isotopic Yields



(from M. Licciardi's talk at Moriond 2021)

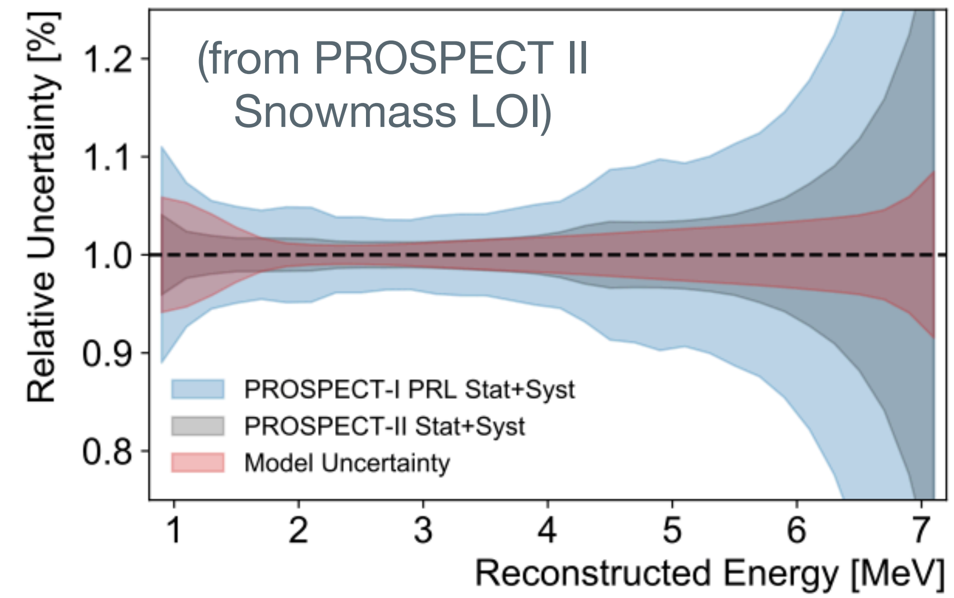
With ~2.5% precision, STEREO has the most precise pure ^{235}U yield measurement

Note: there are many other short baseline LEU and HEU experiments that we do not have time to cover here

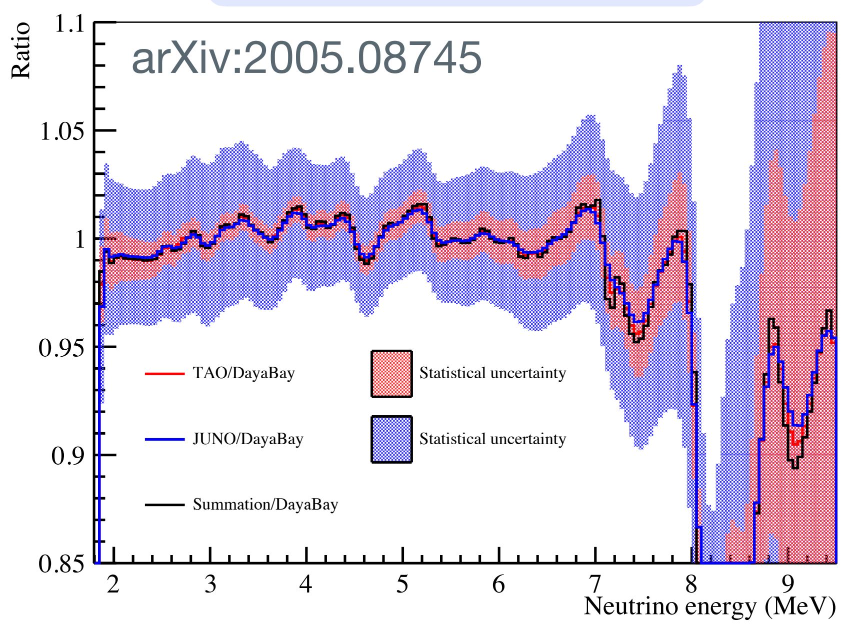
Future

- Expect more results from Daya Bay and RENO with their final data sets
- Expect new results from STEREO with ~twice the current data
- The PROSPECT collaboration is pursuing an upgrade
- JUNO will deploy a satellite detector called TAO near one of the Taishan 4.6 GW_{th} cores:

^{235}U Spectrum Uncertainties (PROSPECT)



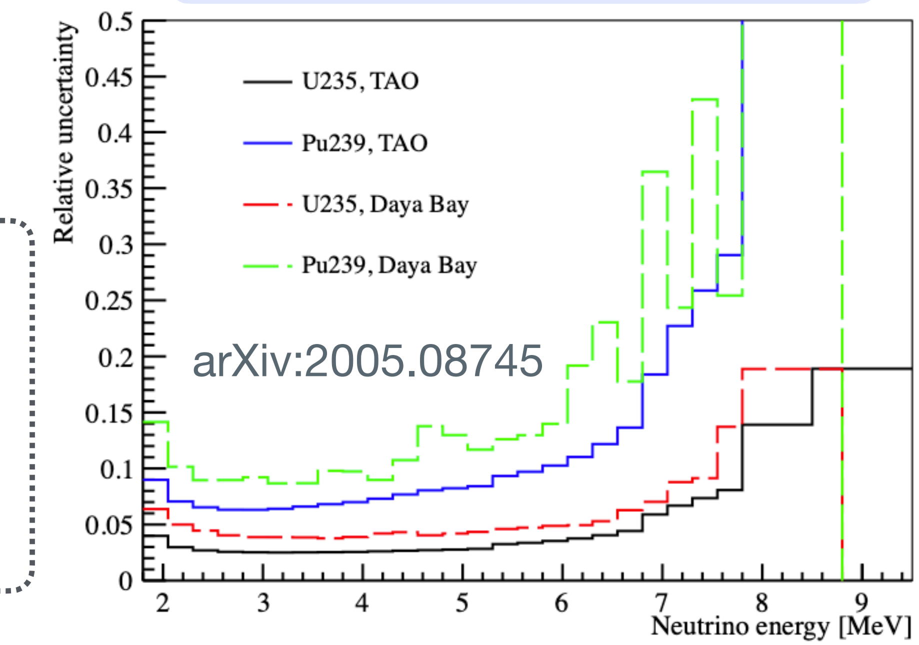
Fine Structure and Stat. Uncertainty (JUNO-TAO)



- 1 ton fiducial Gd-LS volume
- SiPM and Gd-LS at -50°C
- ~1.7% @ 1 MeV energy resolution

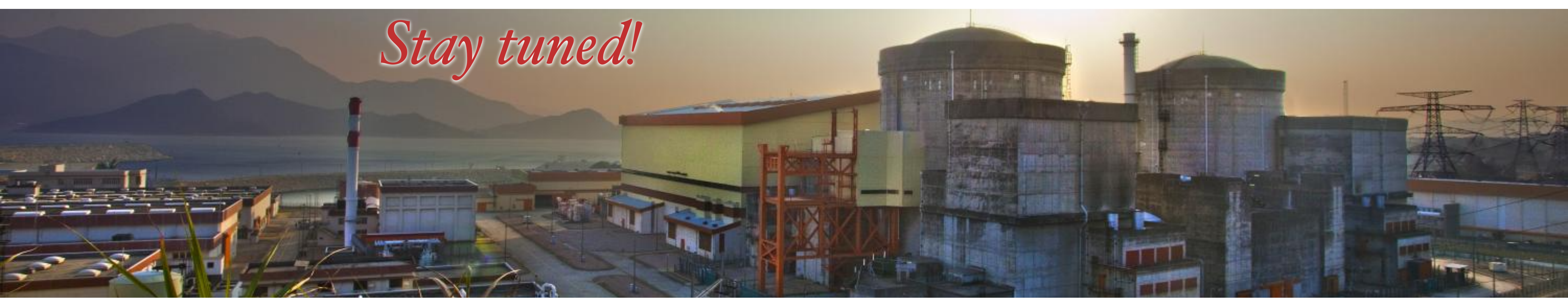
- Reference spectrum for JUNO and other experiments
- Benchmark for nuclear databases
- Isotopic yields and spectra

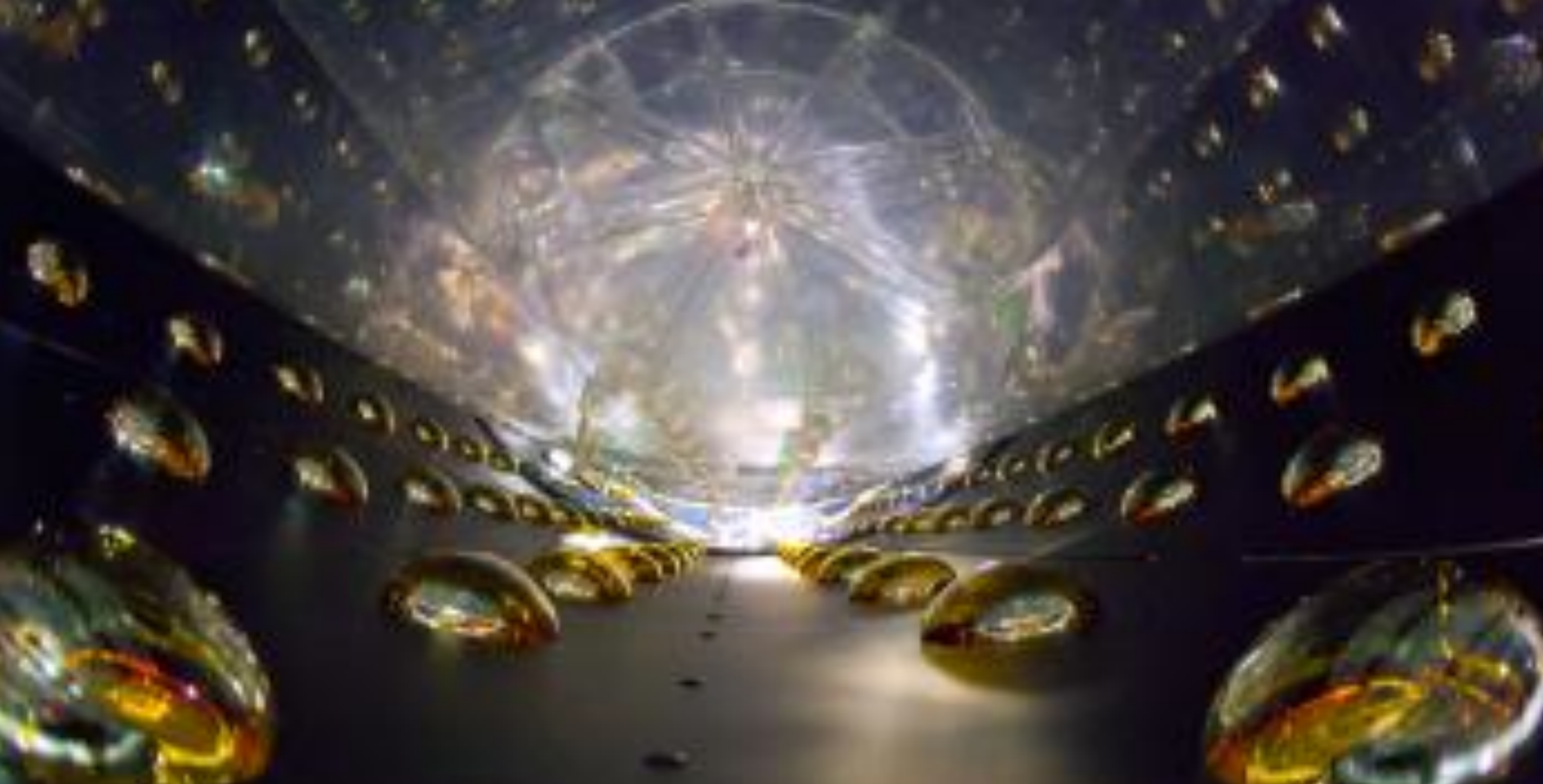
Isotopic Spectra Uncertainties (JUNO-TAO)



Summary & Outlook

- Neutrino physics have been done with nuclear reactors to exquisite precision:
  - Despite lacking a precise enough prediction of reactor antineutrino fluxes!
- Great progress in characterizing reactor antineutrino emission achieved in the last decade by LEU and HEU experiments:
  - Time-averaged yield and prompt spectrum measured to $\lesssim 1\,\%$
  - ^{235}U and ^{239}Pu isotopic yields and unfolded spectra determined to several %
  - Can make data-based prediction of reactor antineutrino spectrum to $2\,\%$
- Expect even more progress…
  - Some current experiments are still producing results, and anticipate projects like PROSPECT II and JUNO-TAO coming online soon

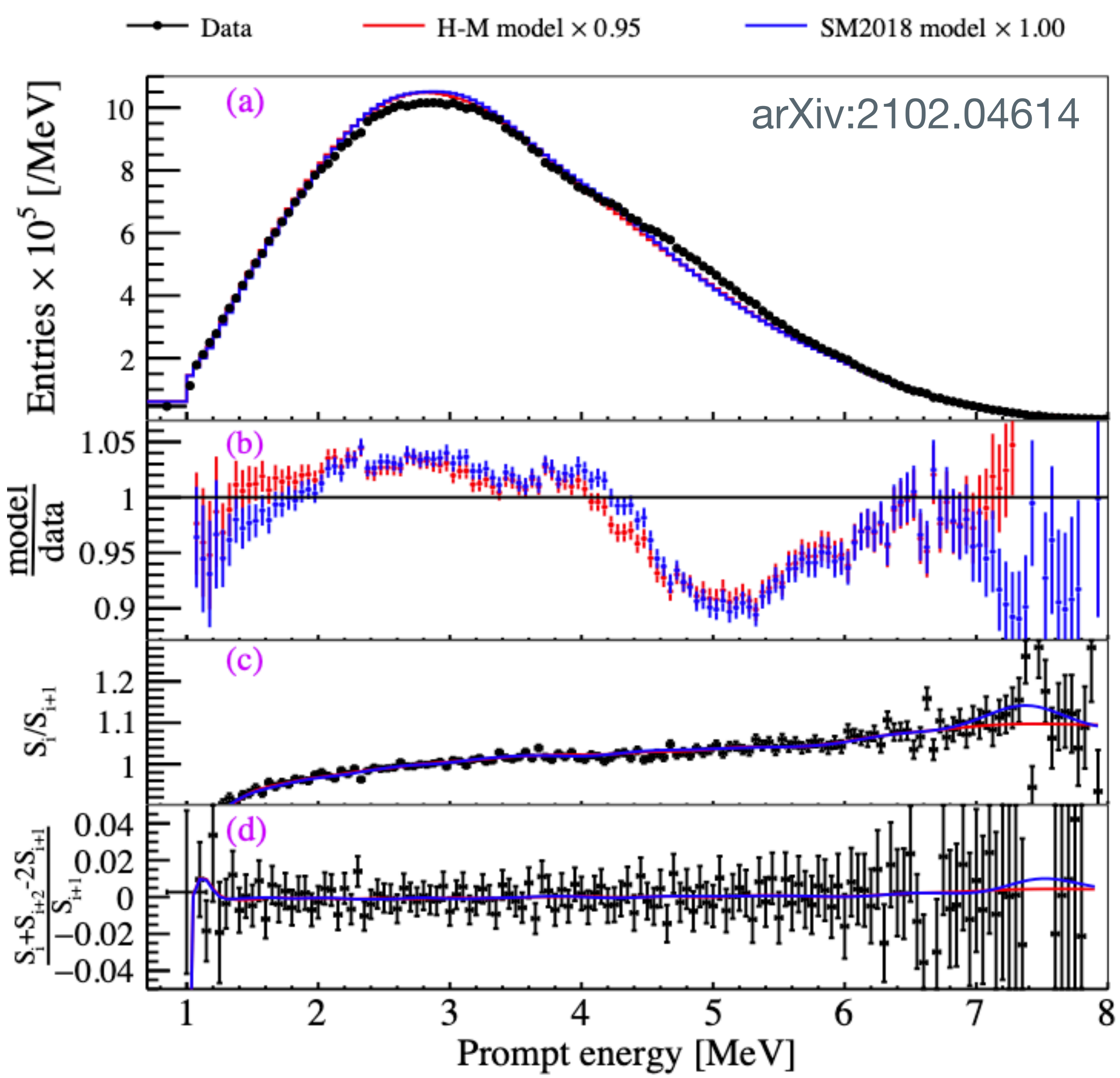


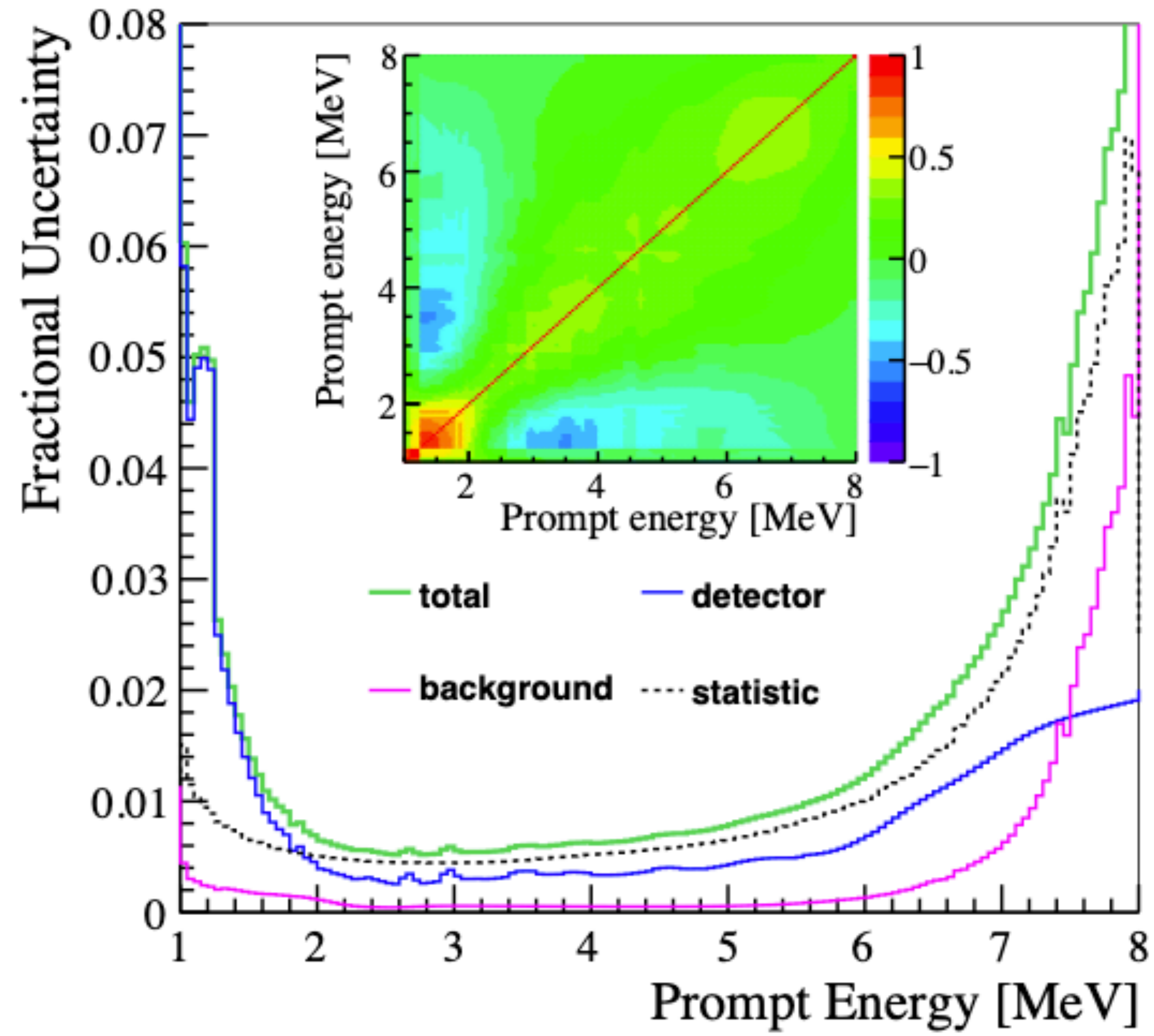


Thank you for your attention!

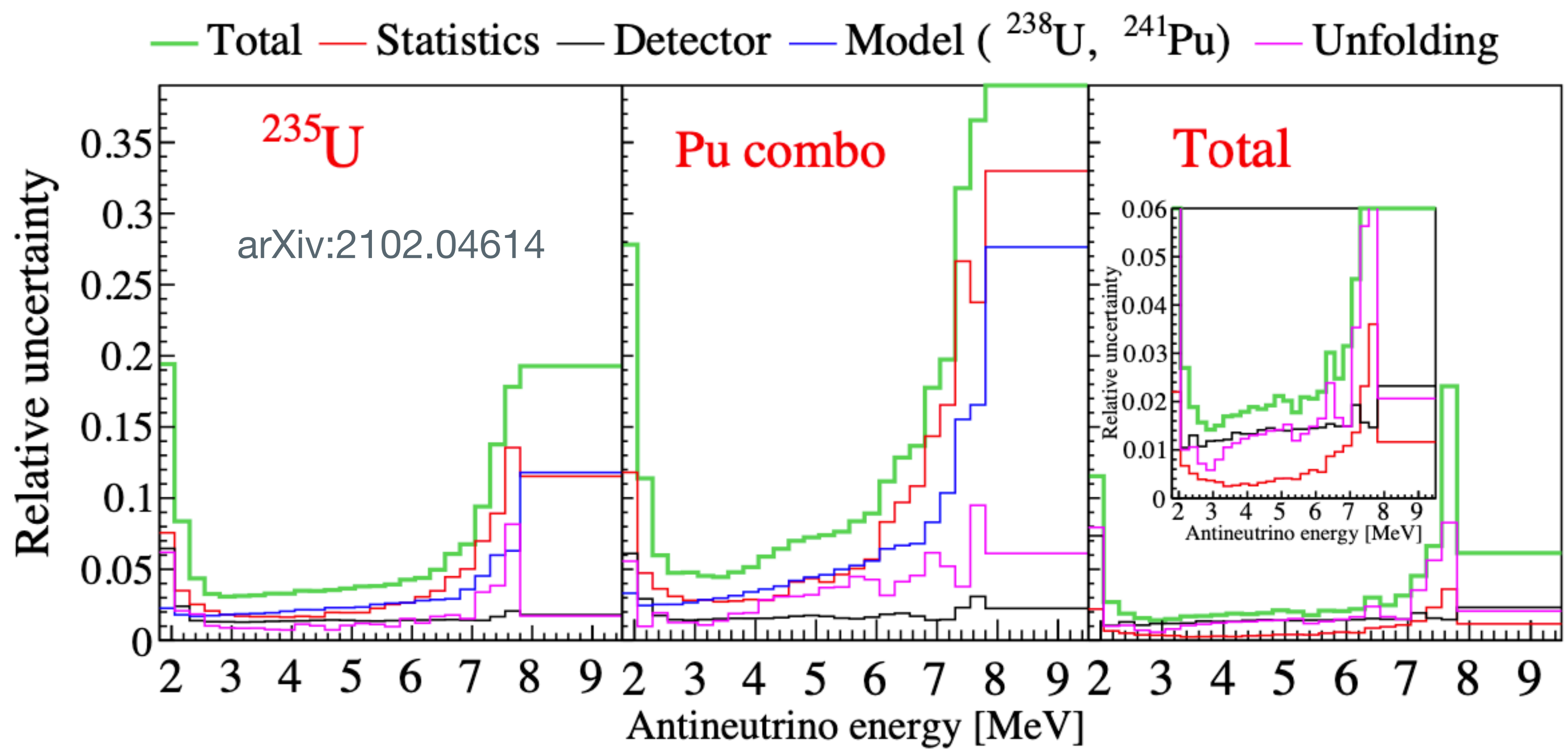
Backup

Prompt Spectrum from Daya Bay



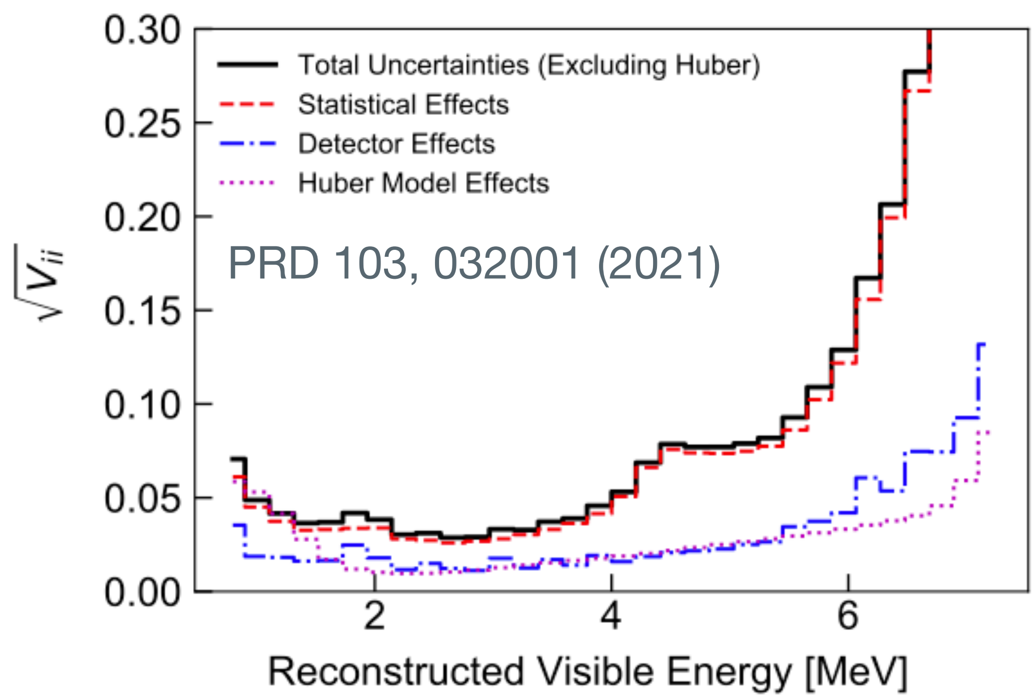


^{235}U Spectra Uncertainties

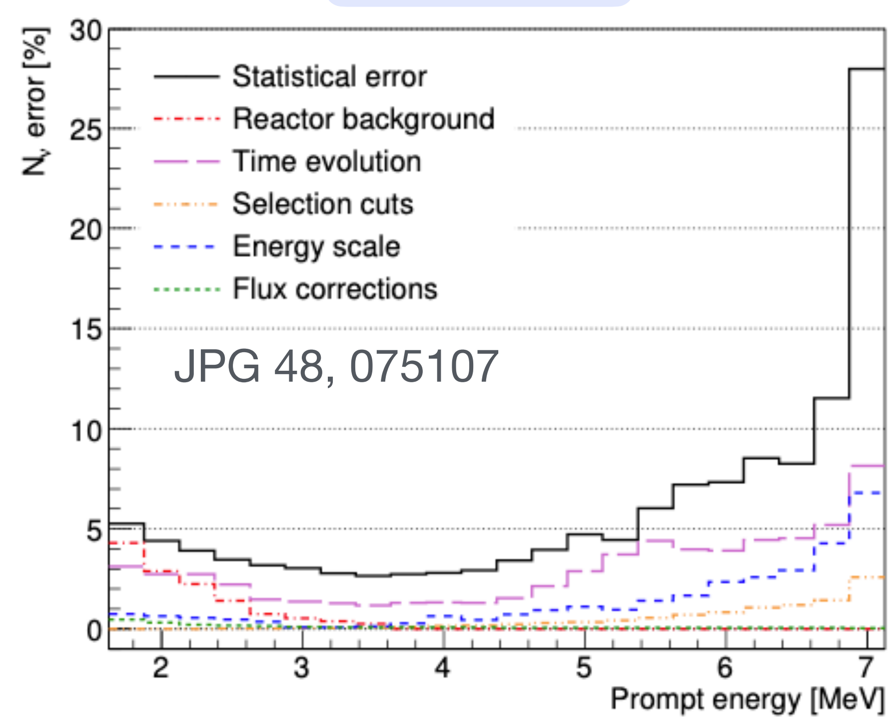


Daya Bay

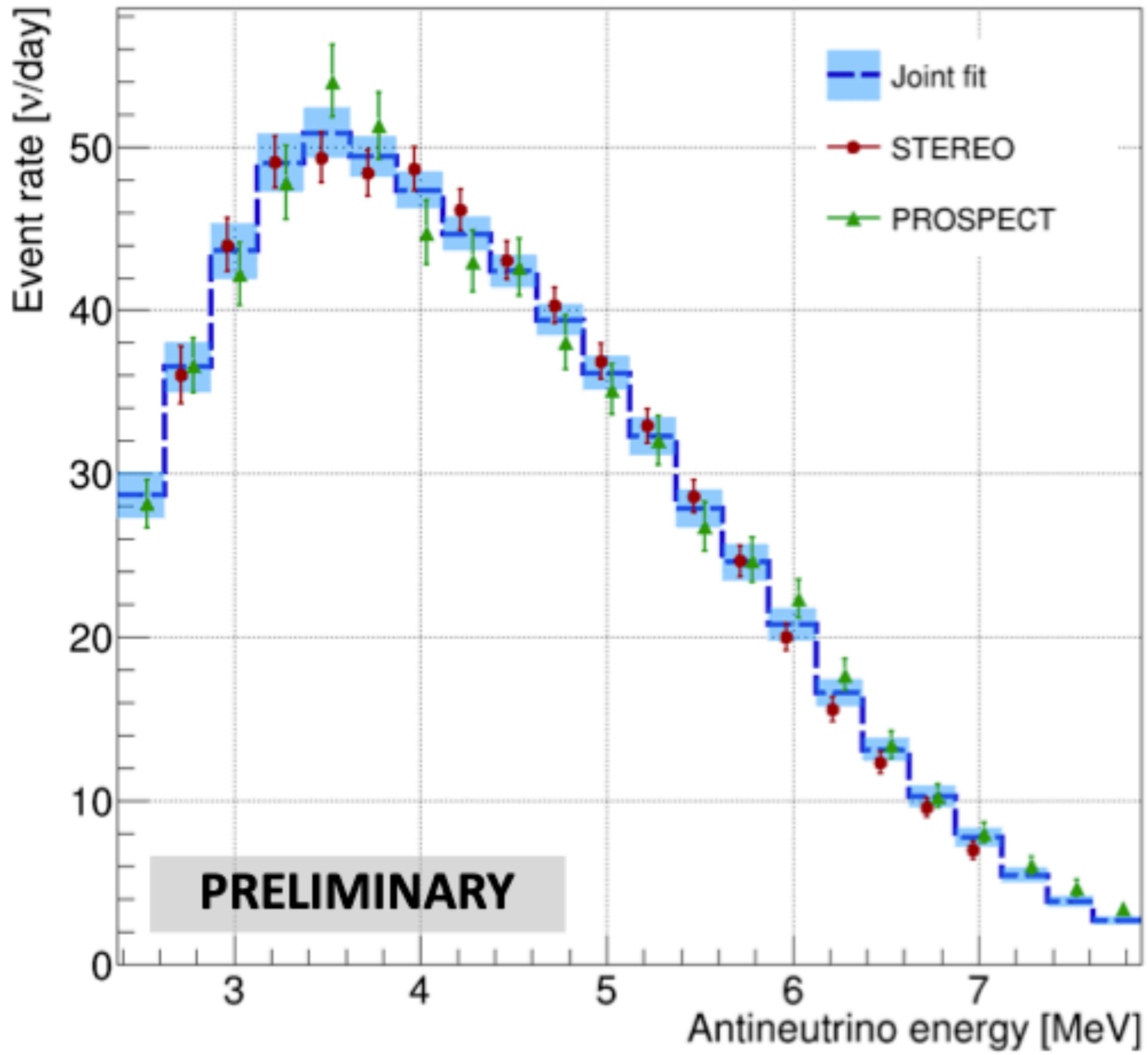
PROSPECT



STEREO

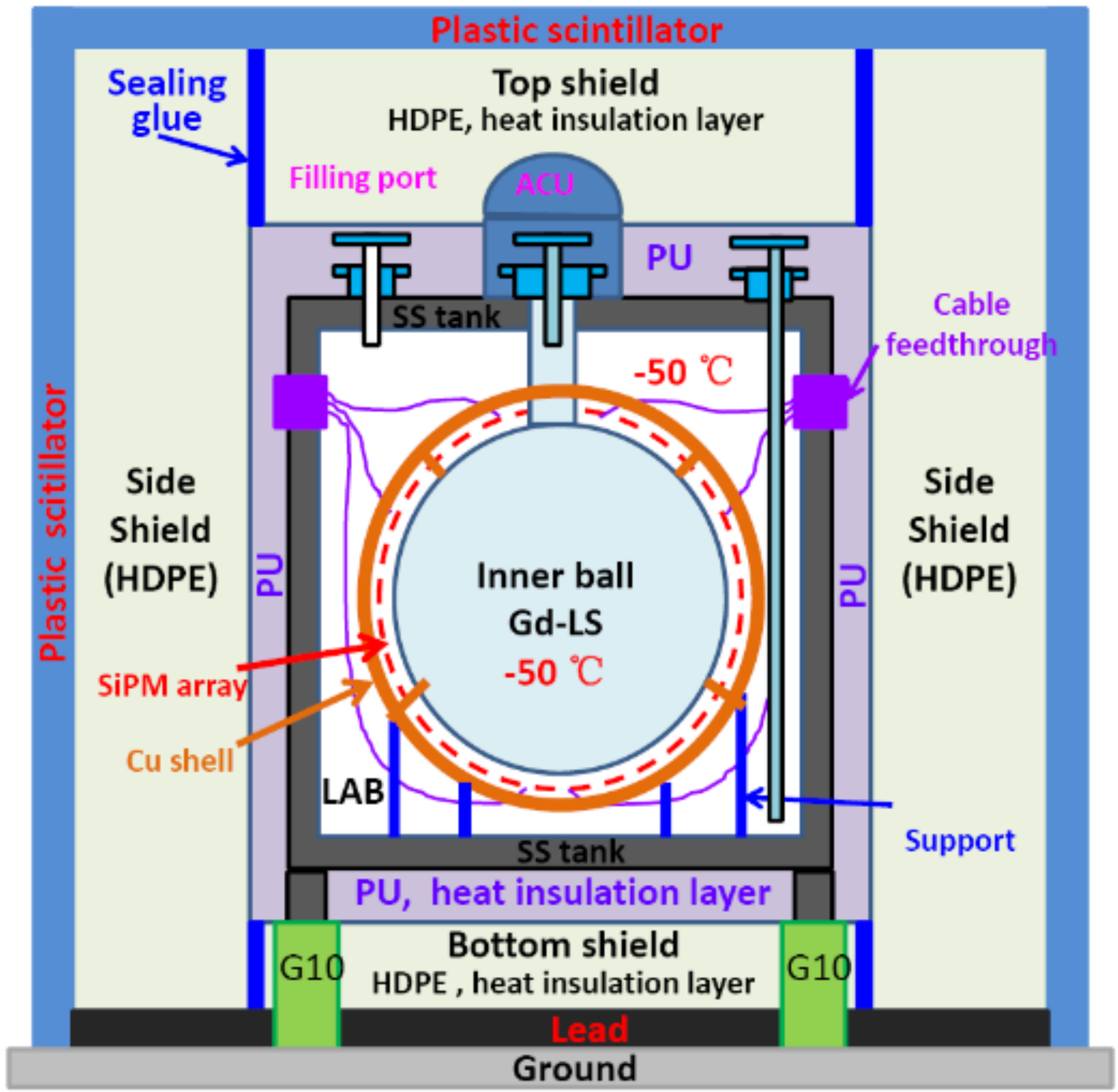


STEREO and PROSPECT



(from M. Licciardi's talk at Moriond 2021)

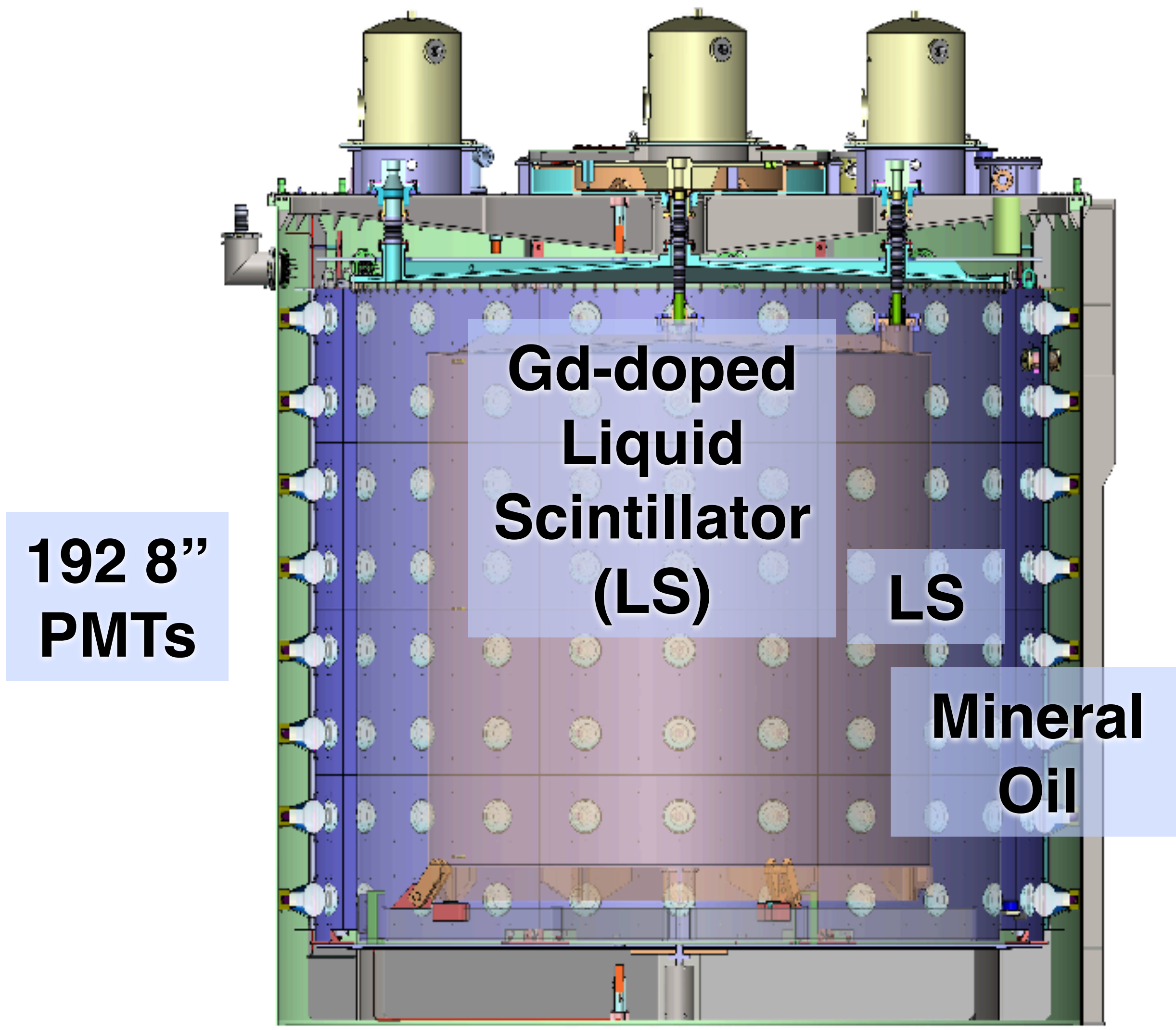
Design of JUNO-TAO



arXiv:2005.08745

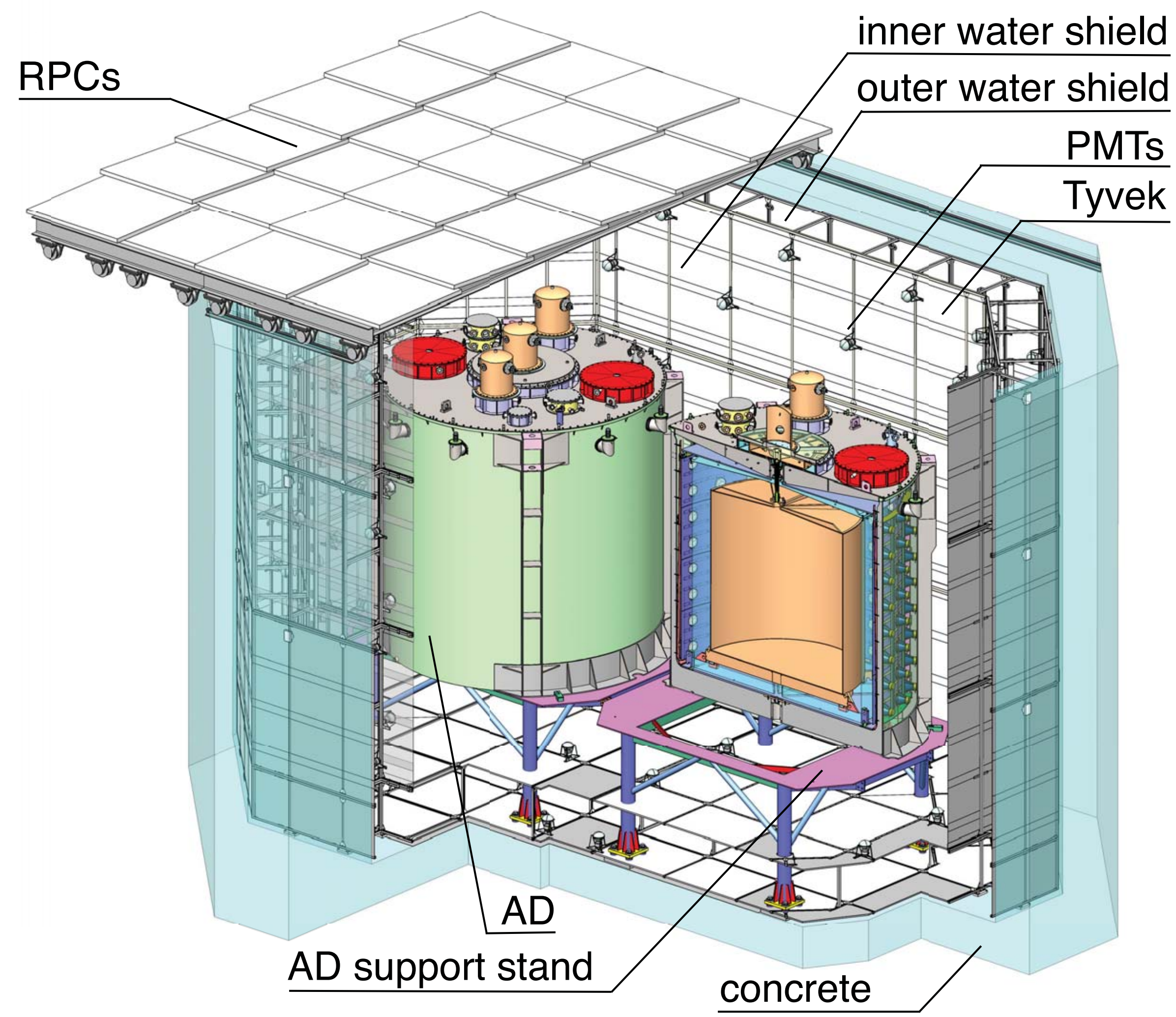
Detection Technology

- The three θ_{13} experiments rely on very similar detection technology
- Use Daya Bay as an example:



Energy resolution:

$\sigma_E/E \cong 8.5\%/\sqrt{E[\text{MeV}]}$

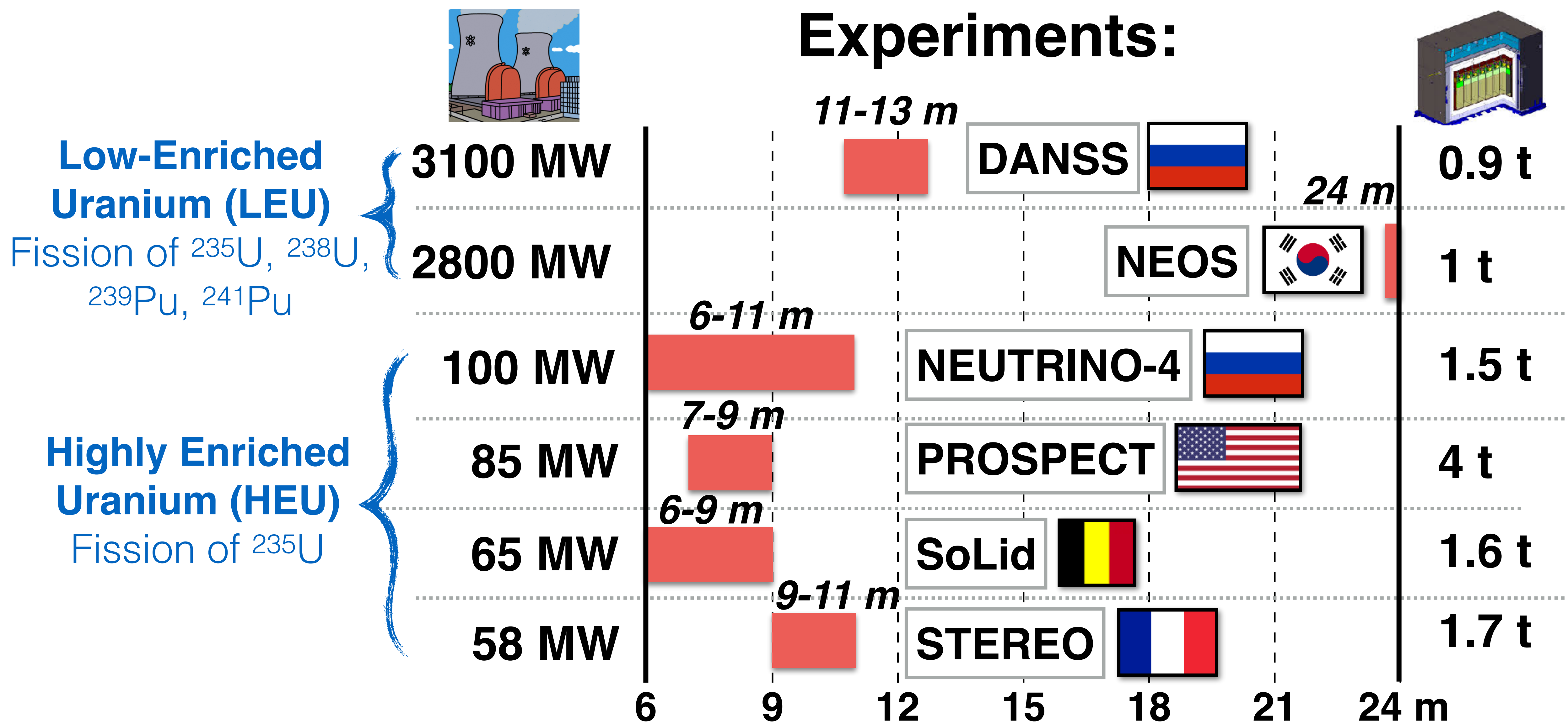


Double purpose: shield the detectors and veto cosmic ray muons

NIM A 811, 133 (2016)

Short Baseline Neutrino Experiments

- Main goals: Sterile neutrinos, reactor $\bar{\nu}_e$ measurements, reactor monitoring
- Rich program of ton scale detectors 6-30 m far from LEU&HEU reactors



+ (mini-)CHANDLER, JUNO-TAO, NuLAT

Short Baseline Neutrino Experiments

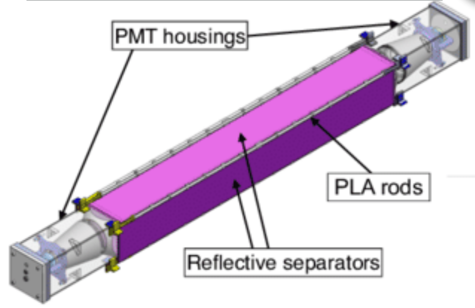
- Similar baseline, large diversity in detector design

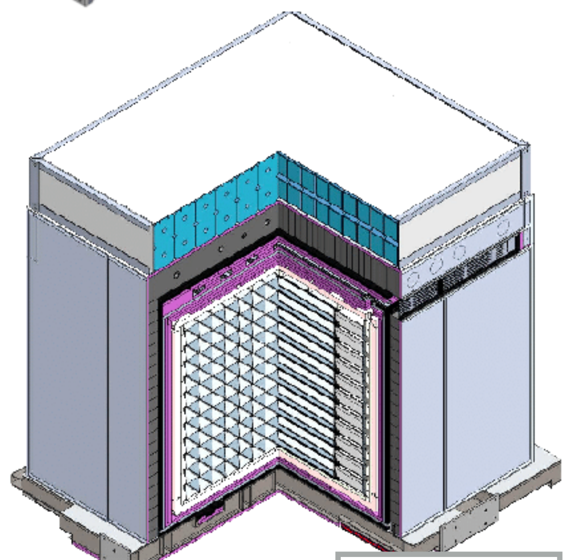
Segmentation:
S Segmented
U Unsegmented

Doping:
Gd Gadolinium
Li Lithium

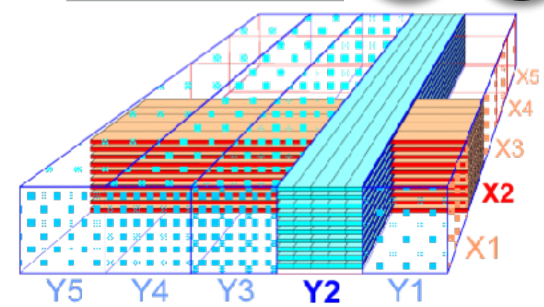
Scintillator:
LS Liquid
PS Plastic

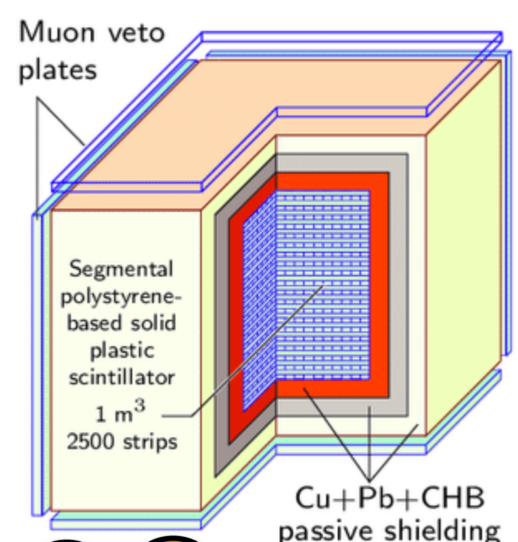
PROSPECT S Li LS



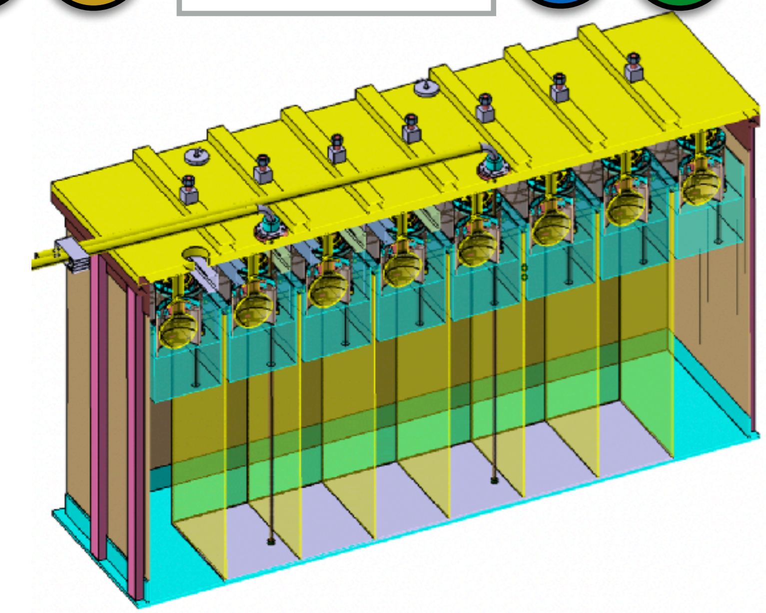


DANSS S Gd PS

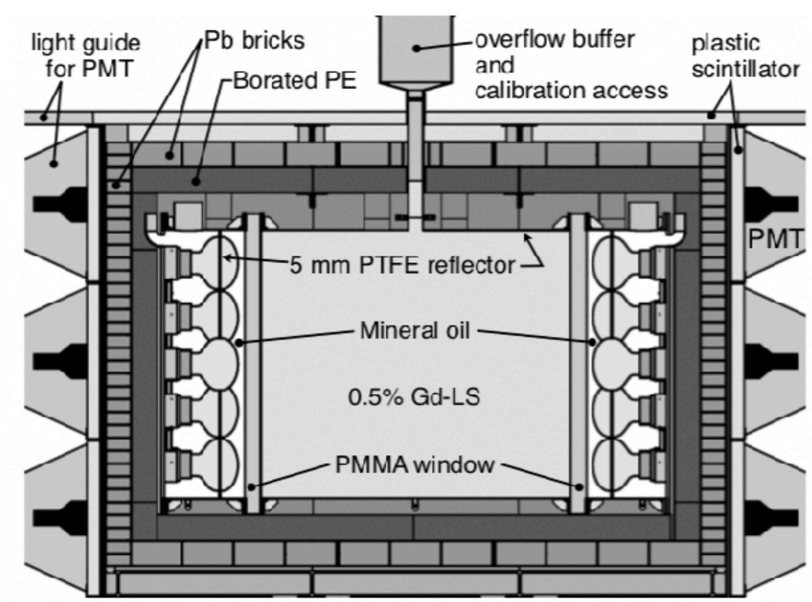




STEREO S Gd



NEOS U Gd LS



SoLid S Li PS