Enhanced Reactor Antineutrino Flux Predictions:

Feedback from Snowmass

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WoNDRAM, June 2021

Introduction

- Main question addressed by this talk:

Has there been any feedback as part of the Snowmass process motivating the need in HEP for enhanced reactor antineutrino flux predictions?

- Disclaimers:
  - I am addressing this question **only from the point of view of HEP**
  - The relevance of enhanced reactor neutrino predictions for reactor monitoring and nuclear data is addressed on separate talks
  - I only scratch the surface with CEvNS

About Snowmass

- The official channel for providing input to Snowmass so far have been short (max. 2 page) Letters of Interest (LOIs)
  - There is still an opportunity to provide feedback through white papers (deadline in March 2022)

(By the way, could the consensus out of this workshop be captured in one or more white papers?)

- The Snowmass Neutrino Frontier (NF) is divided into 9 topical groups
  - I serve as one of the conveners of the **NF09** topical group focused on “Artificial Neutrino Sources”
  - The **NF07** topical group focuses on “Applications”, which is where reactor monitoring is discussed
- The following three pages list all the LOIs in the radar of NF09 that are relevant to physics with nuclear reactors divided by rough areas:
  - Each LOI has a unique ID number that links to the corresponding pdf. All LOIs are publicly available
  - LOIs that are relevant only to applications or reactor monitoring are not included

Snowmass NF09 LOIs

– Physics with ongoing experiments:

Unique ID	Title
NF086	*Legacy of the Daya Bay Reactor Antineutrino Experiment*
NF185	*Reactor and Geo Neutrinos at SNO+*
NF168	*Forthcoming Science from the PROSPECT-I Data Set*

– Physics with future (planned) experiments:

Unique ID	Title
NF169	*The Expanded Physics Reach of PROSPECT-II*
NF034	*The JUNO Experiment*
NF035	*The JUNO-TAO Experiment*
NF172	*Exploration of a new model for neutrino oscillations using a kiloton-scale neutrino detector at the Advanced Insrumentation Testbed in Boulby England*

– Facilities:

Unique ID	Title
NF108	*ORNL Neutrino Sources for Future Experiments*

(Unique ID numbers link to the LOI pdf)

Snowmass NF09 LOIs

- At the intersection with reactor monitoring and/or new detection technologies:

Unique ID	Title
NF075	CHANDLER: A Technology for Surface-level Reactor Neutrino Detection
NF184	*ROADSTR: A Mobile Antineutrino Detector Platform for enabling Multi-Reactor Spectrum, Oscillation, and Application Measurements*
NF011	*Noble Liquids for the Detection of CEvNS from Artificial Neutrino Sources*
NF180	*Neutrino Physics and Nuclear Security Motivations for the Continued Development of Organic Scintillators with Pulse Shape Discrimination Capability and 6 Li-doping*
NF128	*Mutual Benefits derived from the Application of Neutrino Physics to Nuclear Energy & Safeguards*

- Standard Model tests with reactors antineutrinos:

Unique ID	Title
NF023	*Neutrino Non-Standard Interactions*
NF170	*Electroweak Precision Measurements in low energy neutrino experiments*
NF153	*Measuring Inelastic Charged- and Neutral-current Antineutrino-Nucleus Interactions with Reactor Neutrinos*

(Unique ID numbers link to the LOI pdf)

Snowmass NF09 LOIs

– "Generic" LOI on the prediction and measurement of reactor fluxes:

Unique ID	Title
NF117	*Prediction and Measurement of the Reactor Neutrino Flux and Spectrum*

authored by 18 collaborations!

– Reactor modeling:

Unique ID	Title
NF140	*High-Resolution Multiphysics Reactor Modeling for the Antineutrino Source Term*

– Computing:

Unique ID	Title
CompF095	*Quantum Computing Applications to Reactor Antineutrino Experiments*

(Unique ID numbers link to the LOI pdf)

Snowmass NF09 Workshop

- We also held a workshop on Artificial Neutrino Sources in early December 2020
  - The reactor antineutrino portion was held jointly with NF07:

https://indico.fnal.gov/event/46020/

Friday, 4 December

9:00 AM → 11:45 AM **Reactor Antineutrinos (NF09 and NF07 combined)**

9:00 AM — **Brief introduction to the Session** (5m)
Speakers: J. Pedro Ochoa (University of California at Irvine), Nathaniel Bowden (LLNL)
Workshop_Intro.pdf

9:05 AM — **Importance of understanding reactor antineutrino emission for basic science, monitoring, and engineering** (30m)
Speakers: Andrew Conant (Oak Ridge National Laboratory), Dr XIANYI ZHANG (Lawrence Livermore National Laboratory)
NF09_Conant_Zha...

9:35 AM — **Reactor antineutrino predictions: current status and expected improvements** (30m)
Speaker: muriel fallot (Subatech (univ. Nantes, CNRS-in2p3, IMTA))
TalkSnowmassWor...

10:05 AM — **Reactor antineutrino experiments: current status and future program** (30m)
Speakers: Bryce Littlejohn (Illinois Institute of Technology), Bryce Littlejohn
BRL_SpecFlux_Fut...

10:35 AM — **Global strategy and experimental effort beyond the planned program** (30m)
Speaker: Patrick Huber (Virginia Tech)
NF09.pdf

11:05 AM — **Break** (10m)

11:15 AM — **Panel Discussion** (30m)
Panelists: Muriel Fallot, Leendert Hayen, Patrick Huber, Bryce Littlejohn, Alejandro Sonzogni.

- Presentations are available online and we encourage you to take a look

Based on the information collected so far, and on informal conversations with some of you, here are some **very tentative** thoughts…

Neutrino Oscillations

- The lack of precise enough reactor antineutrino predictions has not been a show stopper for neutrino oscillation measurements

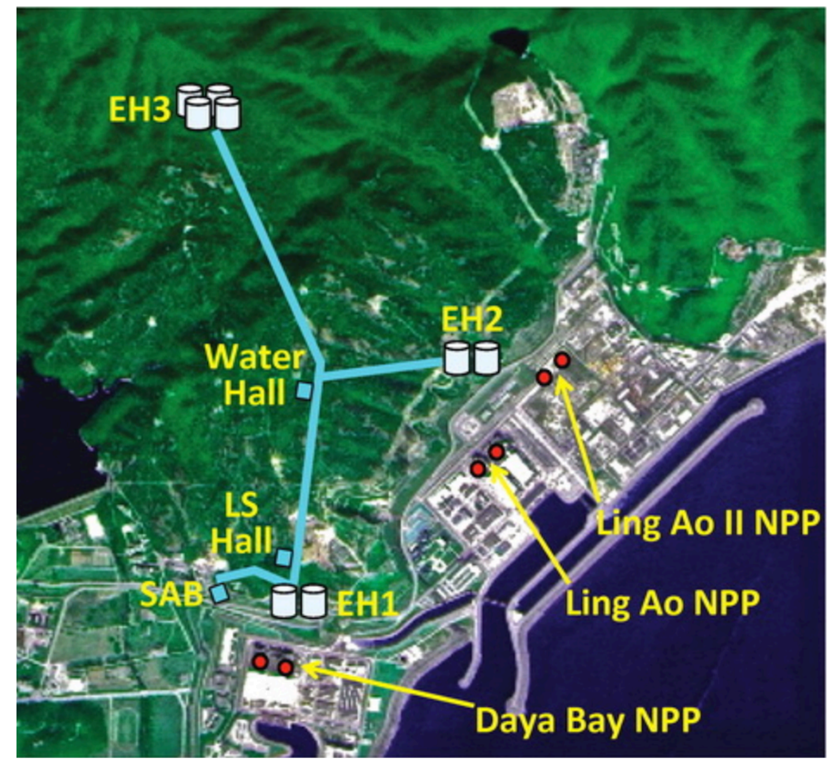
Strategy: make a relative measurement

1) Between near and far detectors

Example: Daya Bay

$$\frac{R_{Far}}{R_{Near}} = \left(\frac{\Phi_{Far}}{\Phi_{Near}}\right)\left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\epsilon_{Far}}{\epsilon_{Near}}\right)\left(\frac{P^{osc}_{Far}}{P^{osc}_{Near}}\right)$$

observed $\bar{\nu}_e$ ratio — $\bar{\nu}_e$ flux — baseline — # of protons — detection efficiency — oscillation



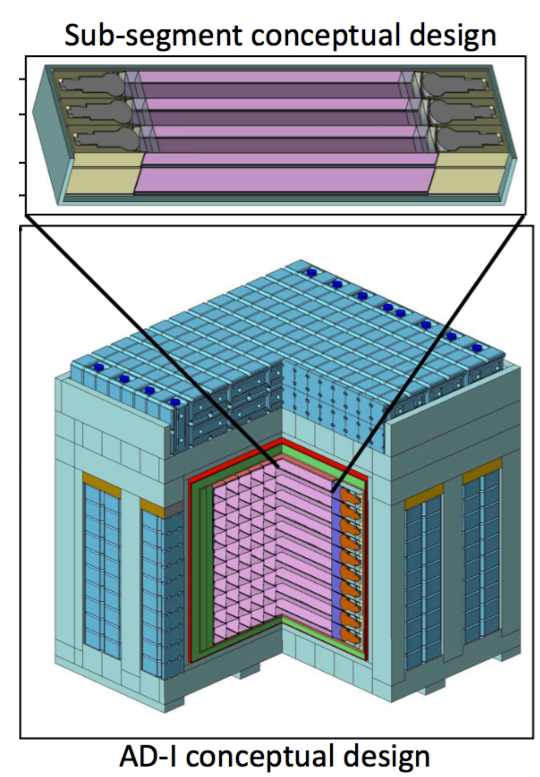
Size of near-far flux difference due to oscillations in Daya Bay: ~6%

This difference is proportional to $\sin^2 2\theta_{13}$, which is measured to ~3.5%

- Can cancel not only reactor flux uncertainties, but also absolute detection efficiencies and detector response effects
- Current detectors achieve relative (absolute) efficiency uncertainties of ~0.2% (~1.5%)

2) Between the different cells in a segmented detector

Example: PROSPECT



Works when oscillation length is comparable with the size of the detector

Hard to see relative measurements becoming unnecessary, especially given current (and future) precision of oscillation parameters

Neutrino Oscillations

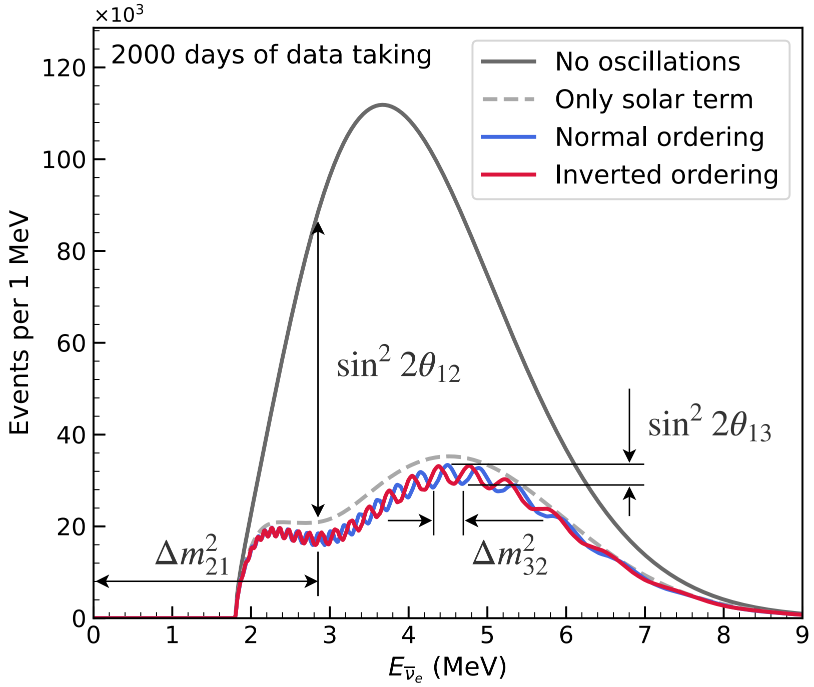
- In fact, oscillation measurements have been one of the main drivers behind direct measurements of reactor antineutrino fluxes

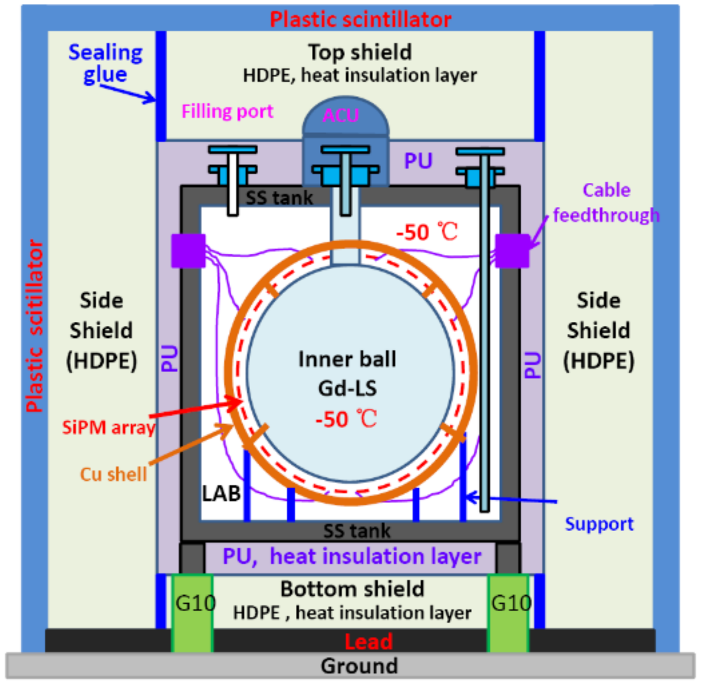
It seems this trend will continue, at least in the near future

Example: JUNO

- JUNO = 20 kton liquid scintillator detector at 53 km from 8 nuclear reactors in China
- JUNO will deploy a **satellite detector** called TAO near one of the Taishan 4.6 GW_{th} cores to measure the spectrum shape

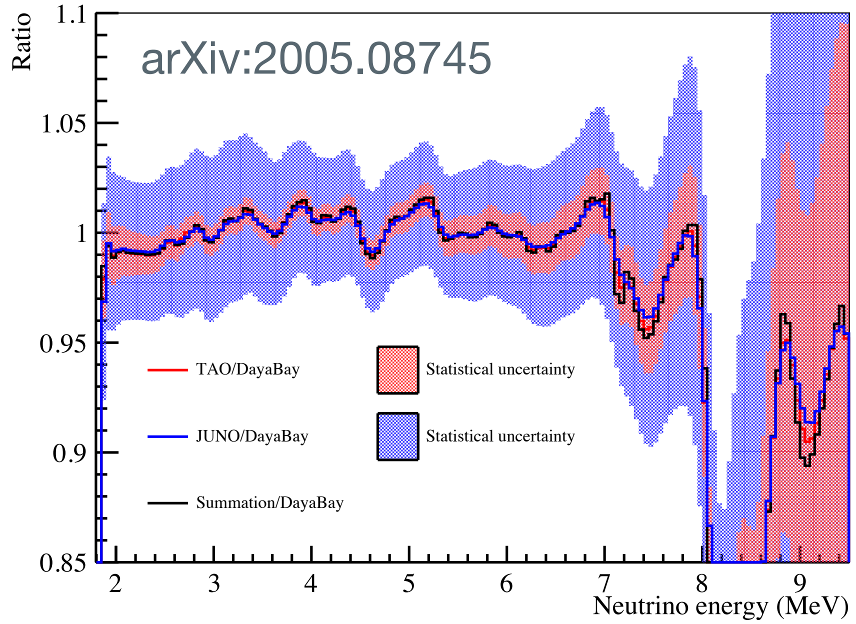
JUNO will measure the mass ordering and three oscillation parameters to sub-% precision by studying the fine structure in the oscillated spectrum





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

TAO's high-statistics & high-resolution spectrum measurement will be a reference for JUNO, other experiments, and nuclear databases

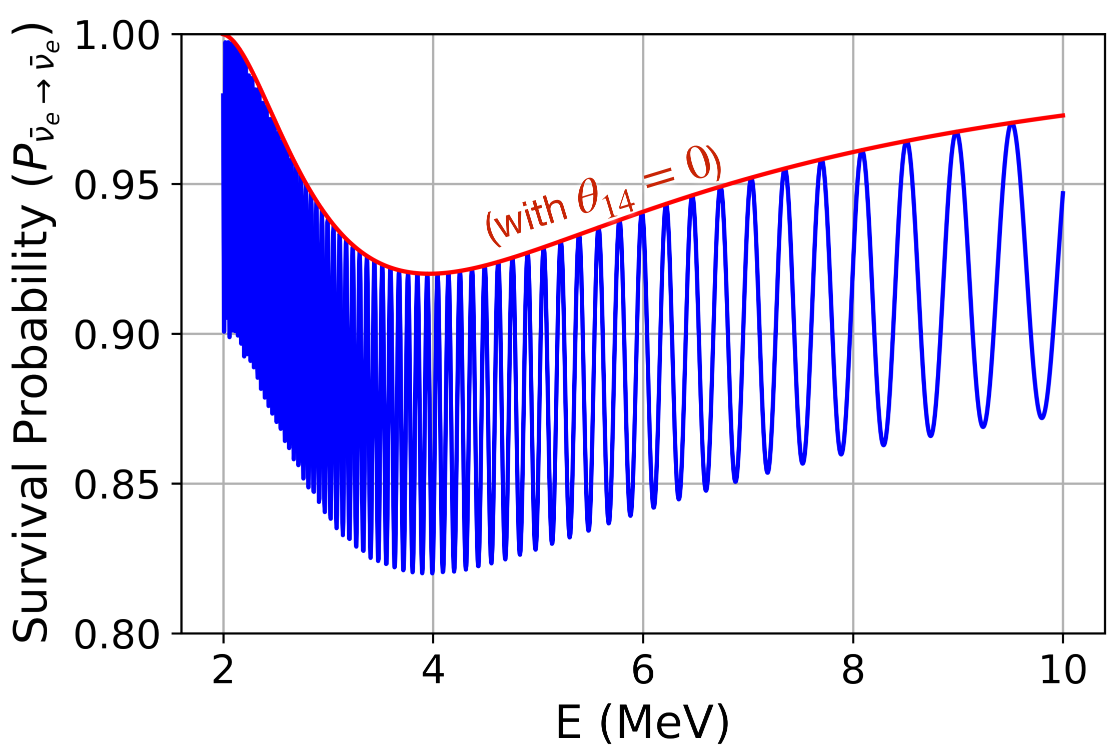


Sterile Neutrino Searches

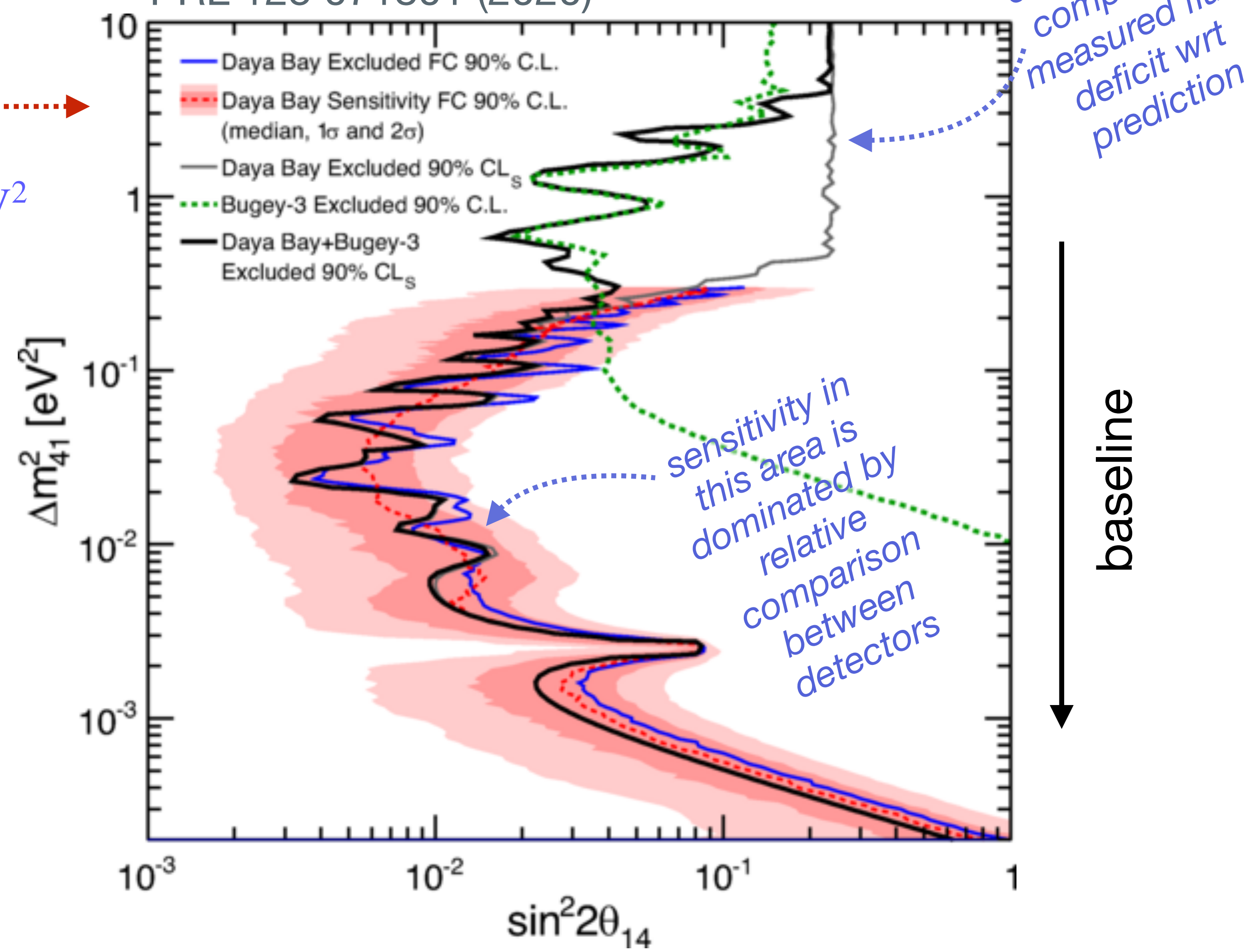
- On the other hand, reactor-based sterile neutrino searches at very high Δm^2_{41} values would have to rely on predictions

Example: Daya Bay

Survival Probability with $\sin^2(2\theta_{14}) = 0.1$ and $\Delta m^2_{41} = 0.2\ \mathrm{eV}^2$



PRL 125 071801 (2020)



- For high values of Δm^2_{41} the spectral distortion is smeared because of the finite energy resolution
- Oscillation effects reduce to a flat rate deficit across all energies
- Near-far measurements impossible for very high values of Δm^2_{41} where oscillation length is too small (near detector cannot be "near enough")

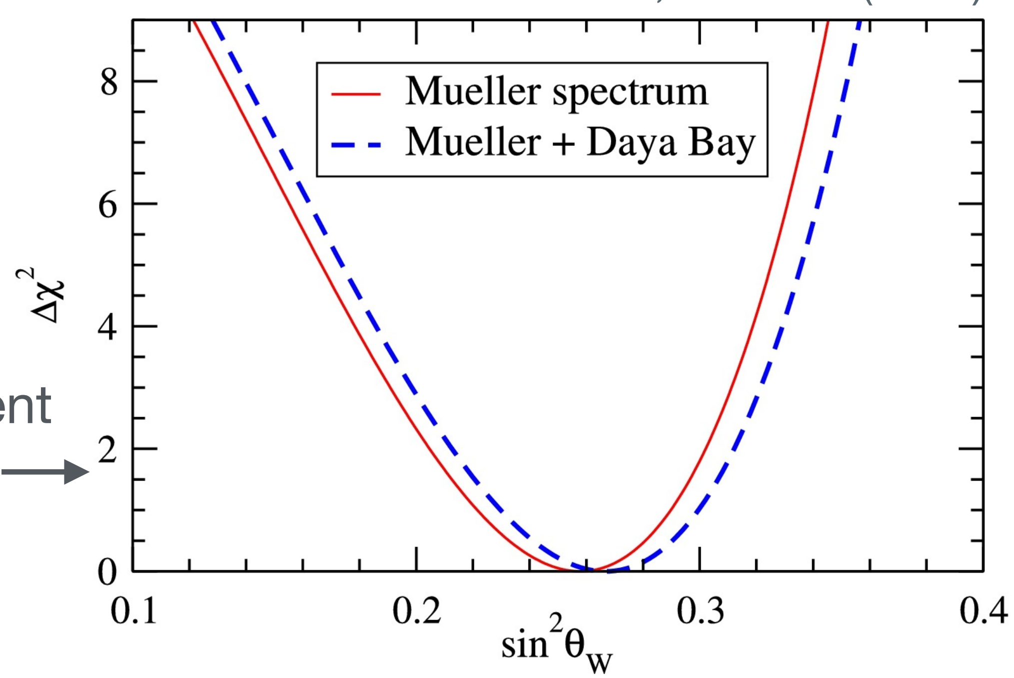
New Physics

- Reactor flux predictions may also be important for experiments testing the Standard Model or searching for physics beyond it:

Reactor-based neutrino electron-scattering

TEXONO's result changes with different flux assumptions →

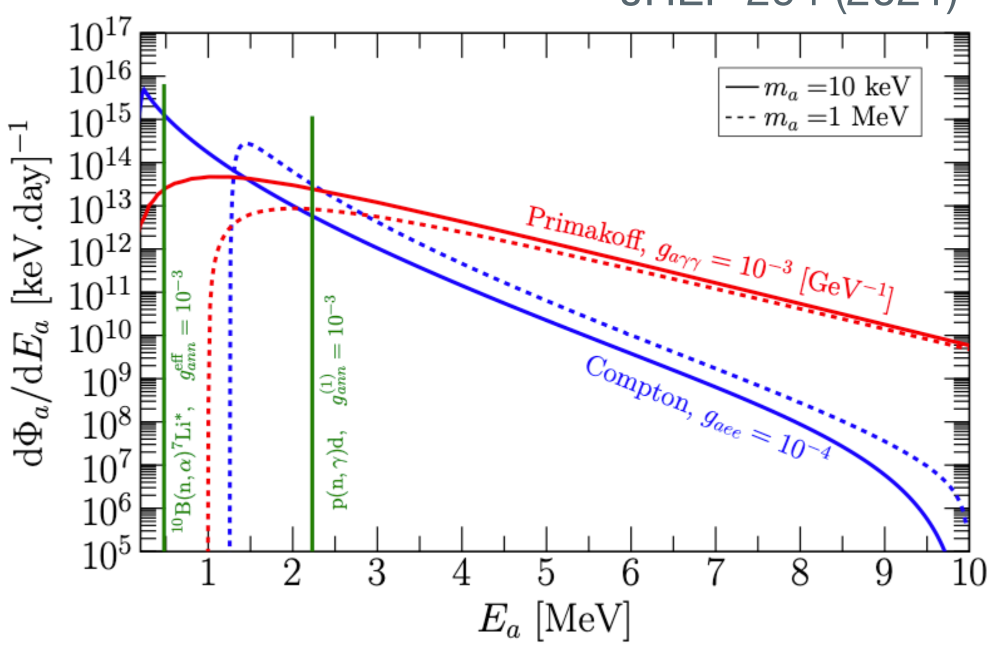
PLB 761, 450-455 (2016)



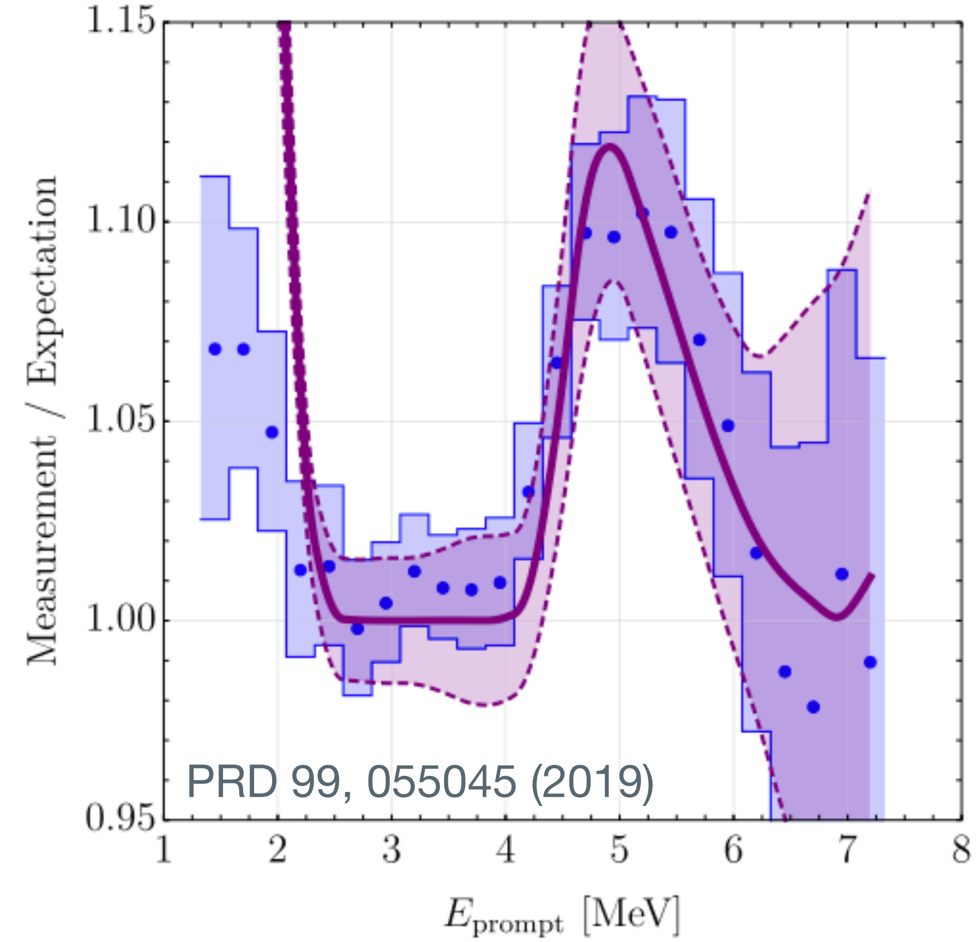
Reactor-based searches for axion-like particles (ALPs)

"Typical" ALP flux from 4 GW reactor core →

JHEP 294 (2021)



Exotic scenarios to explain the "5 MeV bump"



PRD 99, 055045 (2019)

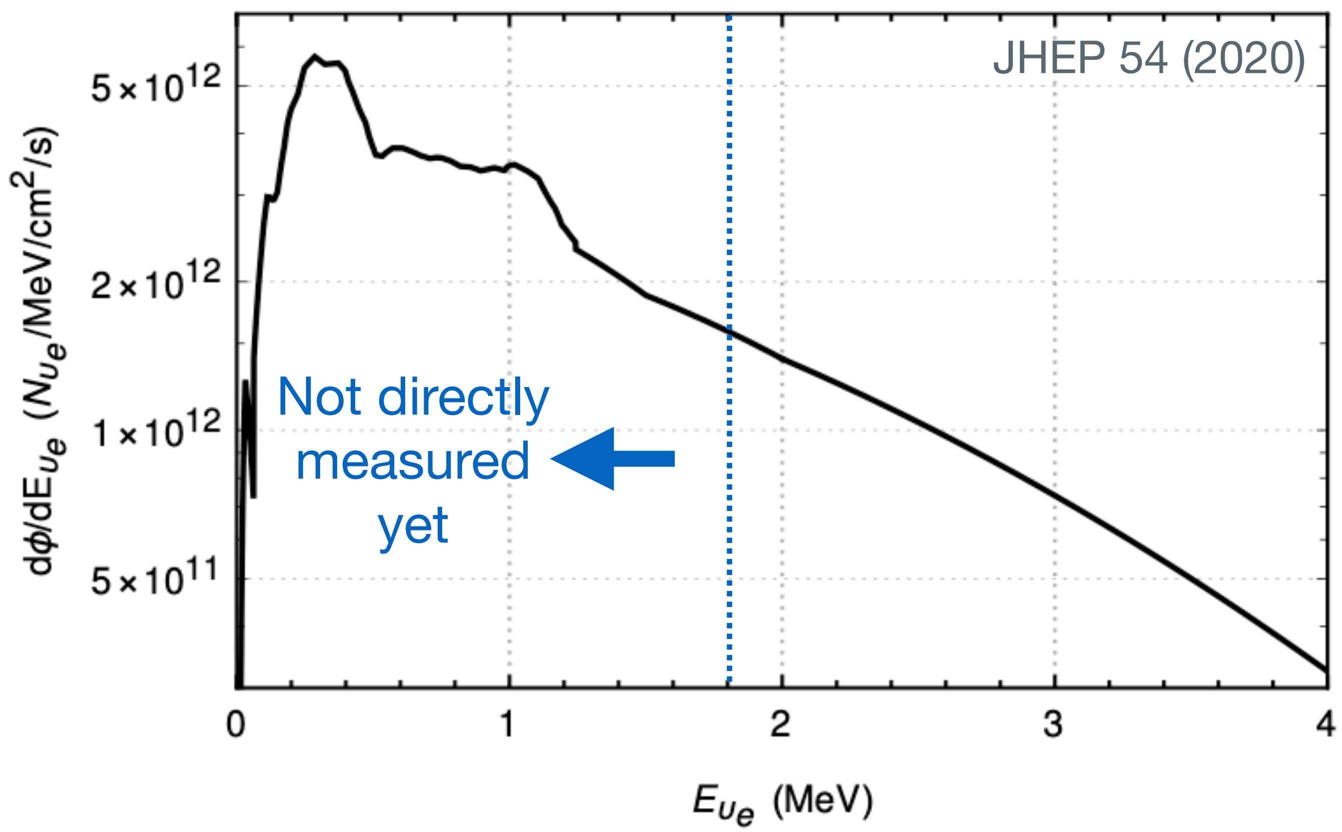
↑

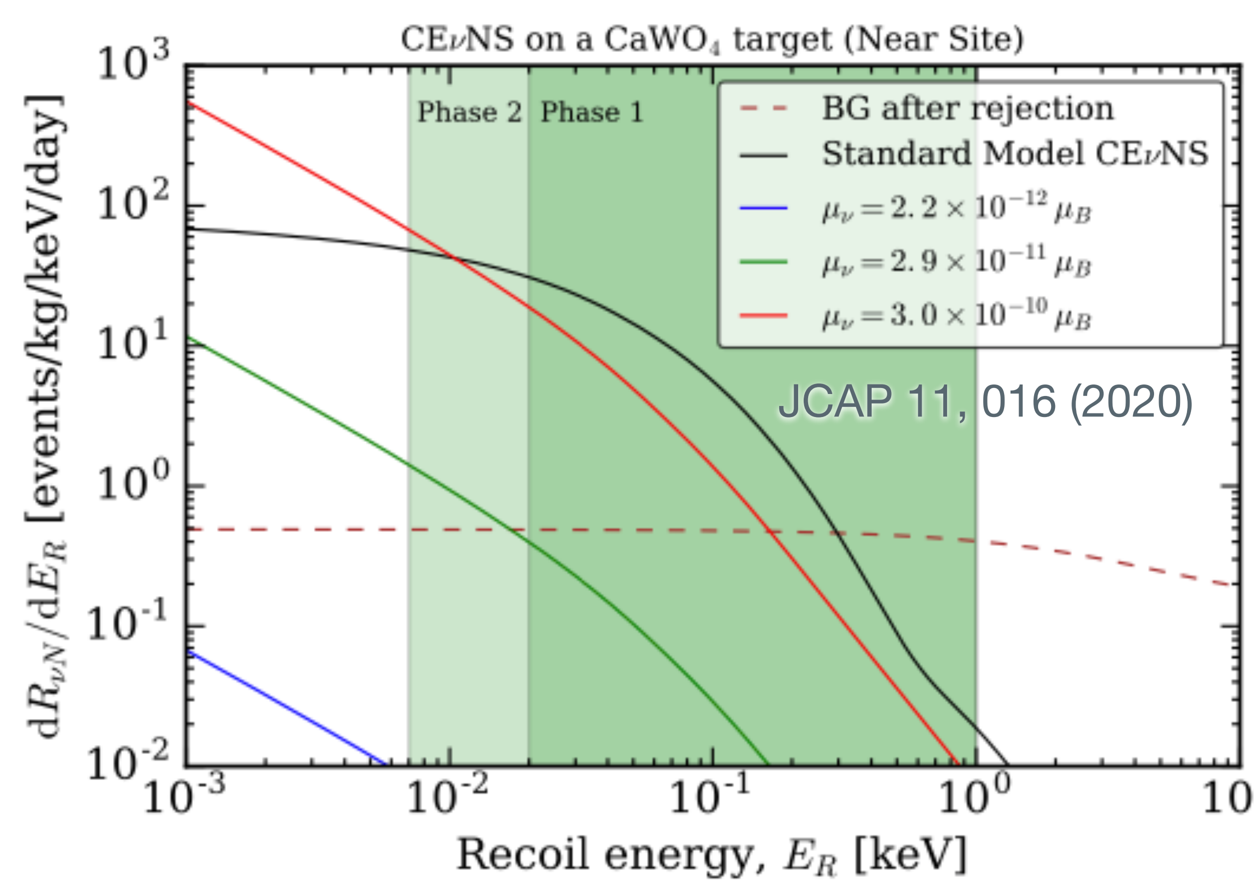
$^{13}C(\bar{\nu}, \bar{\nu}'n)^{12}C^{(*)}$ produced via non-standard interactions

New Physics

- CEvNS is an excellent probe for new physics:
  - No direct constraints from IBD measurements below 1.8 MeV threshold
  - Have to rely on the prediction in that region
- Many exotic scenarios can potentially be explored:
  - Neutrino magnetic moment
  - Non-standard Interactions
  - Massive scalar and vector mediators

  (this is not an exhaustive list)
- At this point it seems current prediction precision is not a limitation, but this could definitely change





Concluding Thoughts

- Some very preliminary thoughts:
  - Areas where enhanced reactor neutrino predictions are **less likely** to make an impact:
    - Neutrino oscillation parameter measurements
    - Determination of the mass hierarchy with reactors
  - Areas where enhanced reactor neutrino predictions are **more likely** to have an impact:
    - Probing the existence of sterile neutrinos with reactors
    - Reactor-based searches beyond the Standard Model
- Hard to be very concrete at this point:
  - It is likely that many more applications start appearing once reactor antineutrino predictions with increased precision become a reality: “build it and they will come”